1. Introduction

1.1. In the paper [Art04], Arthur explained his classification of the discrete automorphic spectrum for classical groups in the particular case of $\text{GSp}_4 \cong \text{GSpin}_5$. Later, in [Art13] he proved this classification for quasi-split special orthogonal and symplectic groups of arbitrary rank, but now with trivial similitude factor. The classification stated in [Art04] is important for applications of the Langlands program to arithmetic. In particular, it is used in [Mok14] to associate Galois representations to Hilbert–Siegel modular forms, and these Galois representations have been used to prove modularity lifting theorems relating to abelian surfaces, for example in [BCGP]. It is therefore desirable to have an unconditional proof of this classification. While it is expected that the methods of [Art13] could be used to handle $\text{GSpin}$ groups, the proofs involve a very complicated induction, which even in the case of $\text{GSpin}_5$ would involve the use of groups of much higher rank, so there does not seem to be any way to give a (short) direct proof of the classification of $\text{GSpin}_5$ by following the arguments of [Art13].

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In this paper, we fill this gap in the literature by giving a proof of the classification announced in [Art04]. We also prove some new results concerning the compatibility of the local Langlands correspondences for $\text{Sp}_4$ and $\text{GSp}_4$. While, like Arthur, our main technique is the stable (twisted) trace formula, and we make substantial use of the results of [Art04] for the group $\text{Sp}_4$, we also rely on a number of additional ingredients that are only available in the particular case of $\text{GSp}_4$; in particular, we crucially use:

- the exterior square functoriality for $\text{GL}_4$ proved in [Kim03] (and completed in [Hen09]);
- the results of [GT11a]: the local Langlands correspondence for $\text{GSp}_4$ (established using theta correspondences), and the generic transfer to $\text{GSp}_4$ (with local-global compatibility at all places) for essentially self dual cuspidal automorphic representations of $\text{GL}_4$ of symplectic type;
- the results of [CG15], which check the compatibility of the local Langlands correspondence of [GT11b] with the predicted twisted endoscopic character relations of [Art04] in the tempered case.

We now briefly explain the strategy of our proof, and the structure of the paper. We begin in Section 2 with a precise statement of the results of [Art13] and of their conjectural extension to $\text{GSpin}$ groups. Roughly speaking, these statements consist of:

1. An assignment of global parameters (formal sums of essentially self-dual discrete automorphic representations of $\text{GL}_n$) to discrete automorphic representations of classical groups.
2. A description of packets of local representations in terms of local versions of the global parameters (which in particular gives the local Langlands correspondence for classical groups).
3. A multiplicity formula, precisely describing which elements of global packets are automorphic, and the multiplicities with which they appear in the discrete spectrum.

In Arthur’s work these statements are all proved together as part of a complicated induction, but in this paper (which of course uses Arthur’s results for $\text{Sp}_4$) we are able to prove the first two statements independently, and then use them as inputs to the proof of the third statement.

In section 3 we study the local packets. In the tempered case, the work has already been done in [CG15], and by again using that [Art13] has taken care of the cases where the similitude character is a square, we are reduced to constructing the local packets in two special non-tempered cases. We do this “by hand”, following the much more general results proved in [MW06] and [AMR15].

As a consequence of the stabilisation of the twisted trace formula [MW16a,MW16b], we can apply the twisted trace formula for $\text{GL}_4 \times \text{GL}_1$ to associate a global parameter to any discrete automorphic representation of $\text{GSpin}_5$ (which is a twisted endoscopic group for $\text{GL}_4 \times \text{GL}_1$ endowed with the automorphism $g \mapsto g^{-1}$). We recall the details of this twisted trace formula in section 4, which we hope can serve as an introduction to the results of [MW16a,MW16b] for the reader not already familiar with them. In section 5 we briefly recall results about the restriction of representations to subgroups, which we apply to the case of restriction from $\text{GSp}_4$ to $\text{Sp}_4$. 
In section 6 we show that the global parameter associated to a discrete automorphic representation of $\text{GSp}_4$ by the stable twisted trace formula is of the form predicted by Arthur, by making use of the symplectic/orthogonal alternative for $\text{GL}_2$ and $\text{GL}_4$, the (known) description of automorphic representations of quasi-split inner forms of $G_{\text{Spin}}_4$ in terms of Asai representations, and the tensor product functoriality $\text{GL}_2 \times \text{GL}_2 \to \text{GL}_4$ of $\mu$. We also make use of $\mu$ in two ways: if the similitude character is a square, then by twisting we can immediately reduce to the results of $\mu$. If the similitude character is not a square, then the possibilities for the parameter are somewhat constrained, and we are able to further constrain them by using the fact that by restricting to $\text{Sp}_4$ and applying the results of $\mu$, we know the possible forms of the exterior square of the parameter.

In section 7 we prove the global multiplicity formula in much the same way as $\mu$, as a consequence of the stable (twisted) trace formulae for $\text{GL}_4 \times \text{GL}_1$ and $G_{\text{Spin}}_5$, together with the twisted endoscopic character relations already established.

Finally, in section 8 we show that the local Langlands correspondences for $\text{Sp}_4$ established in $\mu$ and $\mu$ coincide. The correspondence of $\mu$ was constructed by restricting the correspondence for $\text{GSp}_4$ of $\mu$ to $\text{Sp}_4$, which by the results of $\mu$ is characterised using twisted endoscopy for $\text{GL}_4 \times \text{GL}_1$. The correspondence for $\text{Sp}_4$ obtained in $\mu$ is characterised using twisted endoscopy for $\text{GL}_5$.

In the discrete case we prove this by a global argument, by realising the parameter as a local factor of a cuspidal automorphic representation, and using the exterior square functoriality for $\text{GL}_4$ of $\mu$ and $\mu$. In the remaining cases the parameter arises via parabolic induction, and we are able to treat it by hand. We are also able to use these arguments to give a precise description in terms of Arthur parameters of the restrictions to $\text{Sp}_4$ of irreducible admissible tempered representations of $\text{GSp}_4$ over a $p$-adic field.

We end this introduction with a small disclosure, and a comparison to other work. While we have said that the results of this paper are unconditional, they are only as unconditional as the results of $\mu$ and $\mu$. In particular, they depend on cases of the twisted weighted fundamental lemma that were announced in $\mu$, but whose proofs have not yet appeared in print, as well as on the references $\mu$, $\mu$, $\mu$, and $\mu$ in $\mu$, which at the time of writing have not appeared publicly.

The strategy of using restriction to compare the representation theory of reducible groups related by a central isogeny is not a new one; indeed it goes back at least as far to the comparison of $\text{GL}_2$ and $\text{SL}_2$ in $\mu$. In the case of symplectic groups, there is the paper $\mu$ mentioned above; while this does not make any use of trace formula techniques, we use some of its ideas in Section 8 when we compare the different constructions of the local Langlands correspondence.

More recently, there is the work of Xu, in particular $\mu$ and $\mu$, which also builds on $\mu$, using the groups $G_{\text{Sp}}_n$ and $G_{\text{O}}_n$ where we use the groups $G_{\text{Spin}}_n$ (of course, these cases overlap for $G_{\text{Sp}}_4$). However, the emphasis of Xu’s work is rather different, and is aimed at constructing “coarse $L$-packets” (which in the case of $G_{\text{Sp}}_4$ are unions of $L$-packets lying over a common $L$-packet for $\text{Sp}_4$), and proving a multiplicity formula for automorphic representations grouped together in a similar way. Xu’s results are more general than ours in that they apply to groups
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1.3. Notation and conventions.

1.3.1. Algebraic groups. We will use the boldface notation $\mathbf{G}$ for an algebraic group over a local field or a number field, and we use the Roman version $G$ for reductive groups over $\mathbb{C}$, or their complex points. Thus for example if $F$ is a number field, we will write $\text{GL}_n$ for the general linear group over $F$, with Langlands dual group $\hat{\text{GL}}_n = \text{GL}_n$, which we will also sometimes write as $\hat{\text{GL}}_n = \text{GL}_n(\mathbb{C})$.

For a real connected reductive group $G$, write $g = \mathbb{C} \otimes \mathbb{R} \text{Lie}(G(\mathbb{R}))$, and let $K$ be a maximal compact subgroup of $G(\mathbb{R})$. When working adelically we will sometimes abusively call $(g,K)$-modules “representations of $G(\mathbb{R})$”. This should cause no confusion as we will mostly be considering unitary representations in this global setting (see [Wal88, Theorem 3.4.11], [War72, Theorem 4.4.6.6]), and distinguish between $(g,K)$-modules and representations of $G(\mathbb{R})$ when considering non-unitary representations.

1.3.2. The local Langlands correspondence. If $K$ is a field of characteristic zero then we write $\text{Gal}_K$ for its absolute Galois group $\text{Gal}(K/K)$. If $K$ is a local or global field of characteristic zero, then we write $W_K$ for its Weil group. If $K$ is a local field of characteristic zero, then we write $\text{WD}_K$ for its Weil–Deligne group, which is $W_K$ if $K$ is Archimedean, and $W_K \times \text{SU}(2)$ otherwise.

If $\pi$ is an irreducible admissible representation of $\text{GL}_N(F)$ ($F$ local) or $\text{GL}_N(A_F)$ ($F$ global), then $\omega_\pi$ will denote its central character. We write rec for the local Langlands correspondence normalised as in [HT01], so that if $F$ is a local field of characteristic zero, then $\text{rec}(\pi)$ is an $N$-dimensional representation of $\text{WD}_F$. If $F$ is $p$-adic then for this normalisation a uniformiser of $F$ corresponds to the geometric Frobenius automorphism.

1.3.3. The discrete spectrum. Let $G$ be a connected reductive group over a number field $F$. Write

$$G(\mathbb{A}_F)^1 = \{ g \in G(\mathbb{A}_F) \mid \forall \beta \in X^*(G)^{\text{Gal}_F}, |\beta(g)| = 1 \},$$

so that $G(F) \backslash G(\mathbb{A}_F)^1$ has finite measure. Let $\mathfrak{A}_G$ be the biggest central split torus in $\text{Res}_{F/\mathbb{Q}}(G)$, and let $\mathfrak{A}_G$ be the vector group $\mathfrak{A}_G(\mathbb{R})^0$. Then $G(\mathbb{A}_F) = G(\mathbb{A}_F)^1 \times \mathfrak{A}_G$. We write

$$\mathcal{A}^2(G) = \mathcal{A}^2(G(F)\backslash G(\mathbb{A}_F) \backslash \mathbb{A}_G) = \mathcal{A}^2(G(F) \backslash G(\mathbb{A}_F)^1)$$

for the space of square integrable automorphic forms. This decomposes discretely, i.e. it is canonically the direct sum, over the countable set $\Pi_{\text{dis}}(G)$ of discrete automorphic representations $\pi$ for $G$, of isotypical components

$$\mathcal{A}^2(G)_\pi$$

which have finite length.

If $\chi_G$ is a character of $\mathfrak{A}_G$, we could more generally consider the space of $\chi_G$-equivariant square integrable automorphic forms

$$\mathcal{A}^2(G) = \mathcal{A}^2(G(F) \backslash G(\mathbb{A}_F), \chi_G).$$
Since we can reduce to the case $\chi_G = 1$ considered above by twisting, we will almost never use this more general definition.

2. Arthur’s classification

2.1. $G\text{Spin}$ groups. We now recall the results announced in [Art04] for $G\text{Sp}_4$, as well as those for $\text{Sp}_4$ proved in [Art13]. In fact, for convenience we begin by recalling the conjectural extension of Arthur’s results to $G\text{Spin}$ groups of arbitrary rank, and then explain what is proved in [Art13].

We work with the following quasi-split groups over a local or global field $F$ of characteristic zero:

- The split groups $G\text{Spin}_{2n+1}$.
- The split groups $\text{Sp}_{2n} \times \text{GL}_1$.
- The quasi-split groups $G\text{Spin}_{2n}^\alpha$.

Here we can define the groups $G\text{Spin}_{2n+1}$ and $G\text{Spin}_{2n}^\alpha$ as follows. If $\alpha \in F^×/(F^×)^2$, we have the quasi-split special orthogonal group $SO_{2n}^\alpha$, which is defined as the special orthogonal group of the quadratic space given by the direct sum of $(n - 1)$ hyperbolic planes and the plane $F[X]/(X^2 - \alpha)$ equipped with the quadratic form equal to the norm. We have the spin double cover

$$0 \to \mu_2 \to \text{Spin}_{2n}^\alpha \to SO_{2n}^\alpha \to 0,$$

and we set

$$G\text{Spin}_{2n}^\alpha := (\text{Spin}_{2n}^\alpha \times \text{GL}_1)/\mu_2$$

where $\mu_2$ is embedded diagonally. Note that $G\text{Spin}_{2n}^\alpha$ is split if and only if $\alpha = 1$. We define the split group $G\text{Spin}_{2n+1}$ in the same way. This expedient definition is of course equivalent to the usual, more geometric one (see [Knu91, Ch. IV, §6]). The spinor norm is induced by the usual, more geometric one (see [Knu91, Ch. IV, §6]). The corresponding dual groups are as follows.

| $G$ | $\hat{G}$ |
|-----|-----|
| $G\text{Spin}_{2n+1}$ | $G\text{Sp}_{2n}(\mathbb{C})$ |
| $\text{Sp}_{2n} \times \text{GL}_1$ | $G\text{SO}_{2n+1}(\mathbb{C}) \times \text{GL}_1(\mathbb{C})$ |
| $G\text{Spin}_{2n}^\alpha$ | $G\text{SO}_{2n}(\mathbb{C})$ |

Let $\mu : \text{GL}_1 \to \mathbb{Z}(G)$ be dual to the surjective “similitude factor” morphism $\hat{\mu} : \hat{G} \to \text{GL}_1(\mathbb{C})$. Note that in the case $G = \text{Sp}_{2n} \times \text{GL}_1$, $\mu : \text{GL}_1 \to \mathbb{Z}(G)$ is the map $x \mapsto (1, x^2)$, and it is the only case where it is not injective. Moreover the image of $\mu$ is $\mathbb{Z}(G)^0$ except in the case $G = G\text{Spin}_{2n}^\alpha$.

We set $^{\mu}\hat{G} = \hat{G} \rtimes W_F$, where the action of $W_F$ on $\hat{G}$ is trivial except in the case that $G = G\text{Spin}_{2n}^\alpha$ with $\alpha \neq 1$, in which case the action of $W_F$ factors through $\text{Gal}(F(\sqrt{\alpha}/F) = \{1, \sigma\}$, and $\sigma$ acts by outer conjugation on $G\text{SO}_{2n}$. More precisely, in this case we identify $G \rtimes \text{Gal}(F(\sqrt{\alpha}/F)$ with $G\text{O}_{2n}(\mathbb{C})$ as follows: if $G\text{SO}_{2n}$ is obtained from the symmetric bilinear form $B$ on $\mathbb{C}e_1 \oplus \cdots \oplus \mathbb{C}e_{2n}$ given by $B(e_i, e_j) = \delta_{i,2n+1-j}$, then $1 \rtimes \sigma$ is the element of $G\text{O}_{2n}(\mathbb{C})$ which interchanges $e_n$ and $e_{n+1}$ and fixes the other $e_i$.

We have the standard representation

$$\text{Std}_G : {}^L G \to \text{GL}_N(\mathbb{C}) \times \text{GL}_1(\mathbb{C}),$$
where \( N = N(\tilde{G}) = 2n \) if \( G = \text{GSpin}_{2n}^\alpha \) or \( G = \text{GSpin}_{2n+1} \), and \( N = 2n + 1 \) if \( G = \text{Sp}_{2n} \times \text{GL}_1 \). In the first two cases the representation is trivial on \( W_r \), and is given by the product of the standard \( N \)-dimensional representation of \( \tilde{G} \) and the similitude character. In the final case it is given by the product of the natural inclusion \( O_{2n+1}(\mathbb{C}) \subset \text{GL}_{2n+1}(\mathbb{C}) \) and the identity on \( \text{GL}_1(\mathbb{C}) \). The standard representation realises \( G \) as an elliptic twisted endoscopic subgroup of \( \text{GL}_N \times \text{GL}_1 \), as we will explain below.

We set \( \text{sign}(G) = 1 \) if \( G = \text{GSpin}_{2n}^\alpha \) or \( \text{GL}_1 \times \text{Sp}_{2n} \), and \( \text{sign}(G) = -1 \) if \( G = \text{GSpin}_{2n+1} \) (equivalently, we set \( \text{sign}(G) = -1 \) if and only if \( \tilde{G} \) is symplectic).

2.2. Levi subgroups and dual embeddings. As in our description of the dual group \( \text{SO}_{2n} \) above, we may realise the groups \( \text{SO}_{2n}^\alpha \) and \( \text{SO}_{2n+1} \) as matrix groups using an antidiagonal symmetric bilinear form (block antidiagonal with a \( 2 \times 2 \) block in the middle for \( \text{SO}_{2n}^\alpha \) with \( \alpha \neq 1 \)). Let \( B \) be the Borel subgroup consisting of upper diagonal elements (block upper diagonal in the case of \( \text{SO}_{2n}^\alpha \)). Let \( T \) be the subgroup of diagonal (resp. block diagonal) elements. This Borel pair being given, we can now consider standard parabolic subgroups and standard Levi subgroups. (We recall that we only need to consider Levi subgroups up to conjugacy; indeed, given a Levi subgroup \( L \) of a parabolic \( P \), we obtain an \( L \)-embedding \( ^L L \hookrightarrow ^P G \), which up to \( G \)-conjugacy is independent of the choice of \( P \).)

It is well-known that the standard Levi subgroups are parametrised as follows. Consider ordered partitions \( n = \sum_{i=1}^r n_i + m \), where \( m > 0 \) if \( G = \text{SO}_{2n}^\alpha \) with \( \alpha \neq 1 \), and \( m \neq 1 \) if \( G = \text{SO}_{2n}^1 \). Such a partition yields a standard Levi subgroup \( L \) of \( G \) isomorphic to \( \text{GL}_{n_1} \times \cdots \times \text{GL}_{n_r} \times \text{GL}_m \) where \( G_m \) is a group of the same type as \( G \) of absolute rank \( m \). Explicitly, an isomorphism is given by

\[
(g_1, \ldots, g_r, h) \mapsto \text{diag} \left( g_1, \ldots, g_r, h, S_{n_1}^{-1} t g_r^{-1} S_{n_r}, \ldots, S_{n_1}^{-1} t g_1^{-1} S_{n_1} \right),
\]

where \( S_n \) denotes the antidiagonal \( n \times n \) matrix with 1’s along the antidiagonal. For \( G = \text{SO}_{2n}^\alpha \) and \( m = 0 \) and \( n_i > 1 \), there are two standard Levi subgroups of \( G \) corresponding to the partition \( n = \sum_{i=1}^r n_i \); the one described above and its image under the outer automorphism of \( \tilde{G} \). This completes the parameterisation of all standard Levi subgroups of special orthogonal groups. Standard Levi subgroups of \( \text{Sp} \) and \( \text{GSpin} \) admit a similar description.

Denote \( G' = \text{GSpin}_{2n}^\alpha \) if \( G = \text{SO}_{2n}^\alpha \) and \( G' = \text{GSpin}_{2n+1} \) if \( G = \text{SO}_{2n+1} \). Parabolic subgroups of \( G' \) correspond bijectively to parabolic subgroups of \( G \), and the same goes for their Levi subgroups. Consider \( L \) as above, and let \( L' \) be its preimage in \( G' \). An easy root-theoretic exercise shows that there exists a unique isomorphism

\[
\text{GL}_{n_1} \times \cdots \times \text{GL}_{n_r} \times G'_m \cong L'
\]

lifting \([2.2.1] \) such that for any \( 1 \leq i \leq r \), the composition of the induced embedding of \( \text{GL}_{n_i} \) in \( G' \) with the spinor norm \( G' \to \text{GL}_1 \) is det. Alternatively, the embeddings \( \text{GL}_{n_i} \to \text{GSpin}_{2n}^1 \) can be constructed geometrically using the definition of \( \text{GSpin} \) groups via Clifford algebras (see \([Knu91\text{ Ch. IV, §6.6}] \)), and the above parameterisation of \( L' \) easily follows. The conjugacy class of \( L' \) under \( G'(F) \) is determined by the multi-set \( \{n_1, \ldots, n_r\} \).

Dually, this corresponds to identifying the dual Levi subgroup \( \tilde{L} \) of \( \tilde{G} = \text{GSO}_{2n} \) or \( \text{GSpin}_{2n} \), with \( \text{GL}_{n_1} \times \cdots \times \text{GL}_{n_r} \times \tilde{G}'_m \) via the block diagonal embedding:

\[
(g_1, \ldots, g_r, h) \mapsto \text{diag} \left( g_1, \ldots, g_r, h, S_{n_1}^{-1} t g_r^{-1} S_{n_r}, \ldots, S_{n_1}^{-1} t g_1^{-1} S_{n_1} \right).
\]
2.3. Endoscopic groups and transfer. Before stating the conjectural parameterisation, we need to recall some definitions and results about endoscopy. We begin by recalling that an endoscopic datum for a connected reductive group $G$ over a local field $F$ is a tuple $(H, \mathcal{H}, s, \xi)$ (almost) as in [KS99] §2.1:

- $H$ is a quasi-split connected reductive group over $F$,
- $\xi : \hat{H} \to \hat{G}$ is a continuous embedding,
- $\mathcal{H}$ is a closed subgroup of $L^*G$ which surjects onto $W_F$ with kernel $\xi(\hat{H})$,
- such that the induced outer action of $W_F$ on $\xi(\hat{H})$ coincides with the usual one on $\hat{H}$ transported by $\xi$, and such that there exists a continuous splitting $W_F \to \mathcal{H}$,
- and $s \in \hat{G}$ is a semisimple element whose connected centraliser in $\hat{G}$ is $\xi(\hat{H})$ and such that the map $W_F \to \hat{G}$ induced by $h \in \mathcal{H}$ sends $s$ to $\hat{h}s^{-1}h^{-1}$ takes values in $Z(\hat{G})$ and is trivial in $H^1(W_F, Z(G))$.

Note that we modified the notation slightly: in [KS99] $\mathcal{H}$ is not contained in $L^*G$ and instead $\xi$ is an embedding of $\mathcal{H}$ in $L^*G$. We choose this convention because in contrast to the general case where $z$-extensions are a necessary complication, in all cases that we will consider the embedding $\xi : \hat{H} \to \hat{G}$ will admit a (non-unique) extension as $\xi : L^*H \to L^*G$. Of particular importance are the elliptic endoscopic data, which are those for which the identity component of $\xi(Z(\hat{H})_{\text{GalF}})$ is contained in $Z(\hat{G})$.

For $G$ belonging to the three families introduced in Section 2.1 the groups $H$ will be products whose factors are either general linear groups, or quotients by non-trivial $(s \notin Z(\hat{G}))$ elliptic endoscopic datum of $G$. They are as follows.

- If $G = GSpin_{2n+1}$, then $H = (GSpin_{2n+1} \times GSpin_{2k+1})/GL_1$ with $a+b = n$, $ab \neq 0$, and the quotient is by $GL_1$ embedded as $z \mapsto (\mu(z), \mu(z)^{-1})$.
- If $G = Sp_{2n} \times GL_1$, then $H = (Sp_{2a} \times GL_1 \times GSpin^a_{2b})/GL_1 \cong Sp_{2a} \times SO_{2b} + GL_1$, where $a + b = n$, $ab \neq 0$, and $a \neq 1$ if $b = 1$.
- If $G = GSpin^a_{2n}$, then $H = (GSpin^a_{2a} \times GSpin^a_{2b})/GL_1$, where $a + b = n$, $\beta = a$, $\beta \neq 1$ if $a = 1$, and $\gamma \neq 1$ if $b = 1$.

In this paper we will also need one case of twisted endoscopy. Recall [MW16a] §1.1.1 that if $F$ is a local field of characteristic zero (in the paper we will also take $F$ to be a number field), and $G$ is a connected reductive group defined over $F$, then a twisted space $\tilde{G}$ for $G$ is an algebraic variety over $F$ which is simultaneously a left and right torsor for $G$. Consider the split group $GL_n \times GL_1$ over a local or global field of characteristic zero $F$, and let $\theta$ be the automorphism of $GL_n \times GL_1$ given by $\theta(g, x) = (Jg^{-1}J^{-1}, x \det g)$, where $J$ is the antidiagonal matrix with alternating entries $-1, 1, -1, \ldots$ (that is, $J_{ij} = (-1)^{i+j}d_{i,n+1-j}$). The reason for defining $\theta$ in this way is that it fixes the usual pinning $\mathcal{E}$ of $G$ consisting of the upper-triangular Borel subgroup, the diagonal maximal torus and $((\delta_{a+b, a+1}), 1)_{1 \leq a \leq n-1}$. Then $\tilde{G} = GL_n \times GL_1 \times \{\theta\}$ is a twisted space which happens to be a connected component of the non-connected reductive group $GL_n \times GL_1 \times \{1, \theta\}$.

There is a notion of a twisted endoscopic datum $(H, \mathcal{H}, s, \xi)$ for the pair $(GL_n \times GL_1, \theta)$, for which we again refer to [KS99] §2.1 (taking $\omega$ there to be equal to 1, as we will throughout this paper, and using the same convention as above for $\xi$) and
for simplicity we can and do choose the maximal compact subgroup $\delta$ and $\kappa$ and $G_{\text{Spin}}$ and $G_{\text{L}}$ a non-trivial continuous character. This is the Whittaker datum as sociated to transfer factors, which we denote by $\Delta[\cdot]$ rather than a fixed automorphism of $G$ (not fixing a base point), are more general than those used in most of [KS99], due to an assumption in [KS99] that is only removed in (5.4) there. Note in particular the notion of twisted endoscopic space

[8] [MW16a §VI.3.1]. We will explicitly describe all of the elliptic twisted endoscopic data (up to isomorphism) in the case $n = 4$ in Section 4.2 below. In the present section we shall only need the fact that if $H$ is one of the groups considered in Section 2.1 (denoted $G$ there), then $H$ is part of an elliptic twisted endoscopic subgroup of $(GL_{N_F(H)} \times GL_1, \theta)$.

Remark 2.3.1. The definitions in [MW16a] and [MW16b], using twisted spaces rather than a fixed automorphism of $G$ (not fixing a base point), are more general than those used in most of [KS99], due to an assumption in [KS99] that is only removed in (5.4) there. Note in particular the notion of twisted endoscopic space

[8] [MW16a §1.1.7]. In the cases considered in this paper, where $G$ is either $G$ (standard endoscopy) or $G \rtimes \theta$ where $\theta \in \text{Aut}(G)$ fixes a pinning $\mathcal{E}$ of $G$ (defined over $F$, i.e. stable under $\text{Gal}_F$), this notion simplifies and we are under the assumption of [KS99] (3.1)]. Namely, the torsor $\mathcal{Z}(G, \mathcal{E})$ under $\mathcal{Z}(G) := Z(G)/(1 - \theta)Z(G)$ defined in [MW16a I.1.2] is trivial with a natural base point $1 \times \theta$, and so for any endoscopic datum $(H, \mathcal{H}, \delta, \xi)$ for $\tilde{G}$, the twisted endoscopic space $\tilde{H} := H \times Z(G)\mathcal{Z}(\tilde{G})$ is trivial with natural base point $1 \times \theta$, where $\theta$ now acts trivially on $H$. For this reason we can ignore twisted endoscopic spaces in the rest of the paper, and simply consider endoscopic groups as in most of [KS99].

We now very briefly recall the notion of (geometric) transfer in the setting of endoscopy. Suppose that $F$ is a local field of characteristic zero, and that $(G, \mathcal{G})$ belongs to one of the four families of twisted spaces considered above, that is $G = G_{\text{Spin}}_{2n+1}$, $Sp_{2n} \times GL_1$ or $G = G_{\text{Spin}}_n^1$ with $\mathcal{G} = G$, or $G = GL_n \times GL_1$ with $\mathcal{G} = G \rtimes \theta$. Given an endoscopic datum $\varepsilon = (H, \mathcal{H}, \delta, \xi)$ for $G$, and a choice of an extension $^LG$ of the embedding $\xi$, Kottwitz and Shelstad defined transfer factors in [KS99], that is a function on the set of matching pairs of strongly regular semisimple $G(F)$-conjugacy classes in $\mathcal{G}(F)$ and regular semisimple stable conjugacy classes in $H(F)$. In general such a function is only canonical up to $C^\times$, but in all cases considered in this paper there is a Whittaker datum $\omega = (U, \lambda)$ of $G$ fixed by an element of $G(F)$ and this provides [KS99] §5.3 a normalisation of transfer factors, which we denote by $\Delta[\varepsilon, ^LG, \omega]$. To be more precise we use the transfer factors called $\Delta_D$ in [KS], corresponding to the normalisation of the local Langlands correspondence identifying uniformizers to geometric Frobenii. In all cases of ordinary endoscopy one can choose an arbitrary Whittaker datum of $G$.

In the case that $G = G_{\text{Spin}}_n^1$, there is an outer automorphism $\delta$ of $G$ which preserves the Whittaker datum. This $\delta$ can be chosen to have order 2 and be induced by an element of the orthogonal group having determinant $-1$; if $F$ is Archimedean, for simplicity we can and do choose the maximal compact subgroup $K$ of $G(F)$ to be $\delta$-stable.

In this paper we are particularly interested in the case $G = G_{\text{Spin}}_n^1$. By Hilbert’s theorem 90 the morphism $G_{\text{Spin}}_{2n+1}(F) \rightarrow SO_{2n+1}(F)$ is surjective, so $G_{\text{Spin}}_{2n+1}$ is of adjoint type and there is up to conjugation by $G_{\text{Spin}}_{2n+1}(F)$ only one Whittaker datum in this case.

For $G = (GL_n \times GL_1) \rtimes \theta$ we choose for $U$ the subgroup of unipotent upper triangular matrices in $GL_n$ and $\lambda((g_{i,j})) = \kappa(\sum_{i=1}^{n-1} g_{i,i+1})$ where $\kappa : F \rightarrow S^1$ is a non-trivial continuous character. This is the Whittaker datum associated to $\mathcal{E}$ and $\kappa$. This Whittaker datum is fixed by $\theta$ (this is the reason for the choice of this particular $\theta$ in its $G(F)$-orbit).
forms on \( \tilde{G} \). We may transfer the \( \tilde{G} \) exists recalled above. Most importantly, this transfer of orbital integrals on \( \tilde{G} \) for the algebra of \( \tilde{G} \)-finite smooth compactly supported distributions on \( \tilde{G} \) with \( \mathbb{C} \)-coefficients.

Under convolution, the space \( \mathcal{H}(\tilde{G}) \) is a bi-\( \mathcal{H}(\tilde{G}) \)-module, where \( \mathcal{H}(G) \) is the usual (non-twisted) Hecke algebra for \( G \).

In the case that \( G = GSp_{2n} \), we let \( \mathcal{H}(G) \) denote the subalgebra of \( \mathcal{H}(G) \) consisting of \( \delta \)-stable distributions, and otherwise we set \( \mathcal{H}(G) = \mathcal{H}(G) \) and \( \delta = 1 \).

An admissible twisted representation of \( G \) is by definition a pair \((\pi, \pi)\) consisting of an admissible representation \( \pi \) of \( G(F) \) and a map \( \pi \) from \( G \) to the automorphism group of the underlying vector space of \( \pi \), which satisfies

\[
\pi(gg') = \pi(g)\pi(g)\pi(g')
\]

for all \( g, g' \in G(F), \gamma \in \tilde{G} \). (This is the special case \( \omega = 1 \) of the notion of an \( \omega \)-representation of a twisted space, which is defined in \([MW16a]\).) If \( F = \mathbb{R} \) or \( \mathbb{C} \) there is an obvious notion of \((g, \tilde{K})\)-module where \( \tilde{K} \subset G(F) \) is a torsor under \( \tilde{K} \) normalising \( K \).

We will consider (invariant) linear forms on \( \mathcal{H}(G) \). In particular, for each admissible representation \( \pi \) of \( G(F) \), there is the linear form

\[
tr(\pi(f(g)dg)) = tr\left( \int_{G(F)} f(g)\pi(g)dg \right).
\]

If \( F \) is Archimedean and \( \pi \) is an admissible \((g, \tilde{K})\)-module the action of \( \mathcal{H}(G) \) is not obviously well-defined but it is so when \( \pi \) arises as the space of \( K \)-finite vectors of an admissible Banach representation of \( G(F) \), independently of the choice of this realisation (see \([Wa72]\) p. 326, Theorem 4.5.5.2)). In this paper all \((g, \tilde{K})\)-modules will naturally arise in this way, even with “Hilbert” instead of “Banach”, although not all of them will be unitary.

We write \( I(G) \) for the quotient of \( \mathcal{H}(G) \) by the subspace of those distributions \( f(g)dg \) with the property that for any semisimple strongly regular \( \gamma \in G(F) \), the orbital integral \( O_\gamma(f(g)dg) \) vanishes. There is a natural topology on \( I(G) \): see \([MW16a]\) I.5.2. Similarly, we write \( SI(G) \) for the quotient by the subspace for which the stable orbital integrals \( SO_\gamma(f(g)dg) \) vanish. We say that a continuous linear form on \( \mathcal{H}(G) \) is stable if it descends to a linear form on \( SI(G) \).

Given an endoscopic datum \((H, \mathcal{H}, s, \xi)\) for \( G \), and our choice of Whittaker datum, there is a notion of transfer from \( I(G) \) to \( SI(H) \) (see \([KS99]\) §5.5, \([MW16a]\) §I.2.4 and IV.3.4): this transfer is defined by the property that it relates the values of orbital integrals on \( G \) to stable orbital integrals on \( H \), using the transfer factors recalled above. Most importantly, this transfer exists \([Wa97]\, [Ng¹01]\, [She12]\). Dually, we may transfer stable continuous linear forms on \( \mathcal{H}(H) \) to continuous linear forms on \( \mathcal{H}(G) \).
In the twisted case where $\tilde{G} = (\text{GL}_N \times \text{GL}_1) \rtimes \theta$ over a $p$-adic field $F$, the chosen Whittaker datum yields a hyperspecial maximal compact subgroup $K$ of $G(F)$ (see [CSS0]), which is stable under $\theta$, so it is natural to consider the hyperspecial subspace (see [MW16a §1.6]) $\tilde{K} = K \rtimes \theta$ of $G(F)$. For any unramified endoscopic datum $(H, \mathcal{H}, \check{s}, \xi)$ for $G$ (also defined in [MW16a §1.6]), with the above trivialisation of $H$, the associated $H_{\text{ad}}(F)$-orbit of hyperspecial subspaces of $\tilde{H}$ is simply the obvious one, that is the set of $K' \rtimes \theta$ where $K'$ is a hyperspecial maximal compact subgroup of $H(F)$.

By the existence of transfer and [LMW15, LW15] (in the case of standard endoscopy), the twisted fundamental lemma is now known for all elements of the unramified Hecke algebra, with no assumption on the residual characteristic. We formulate it in our situation, which is slightly simpler than the general case by the above remarks.

**Theorem 2.3.3.** Let $G$ be a twisted group over a $p$-adic field $F$ belonging to one of the four families introduced at the beginning of this section. Assume that $G$ is unramified. Let $(H, \mathcal{H}, \check{s}, \xi)$ be an unramified endoscopic datum for $G$. Choose an unramified $L$-embedding $\xi : \mathcal{H} \rightarrow \mathcal{G}$ extending $\xi$. Let $\tilde{K}$ be the hyperspecial subspace of $G(F)$ associated to the chosen Whittaker datum for $G$. Let $1_{\tilde{K}}$ be the characteristic function of $\tilde{K}$ multiplied by the $G(F)$-invariant measure on $G(F)$ such that $\tilde{K}$ has volume 1. Let $b : \mathcal{H}(G(F) // K) \rightarrow \mathcal{H}(H(F_v) // K_v)$ be the morphism dual to

$$\left( \mathcal{H} \times \text{Frob} \right)^{ss} / \mathcal{H} \rightarrow \left( \tilde{G} \times \text{Frob} \right)^{ss} / \tilde{G}$$

via the Satake isomorphisms (see [Bo79 §7]). Then for any $f \in \mathcal{H}(G(F_v) // K)$, $b(f)$ is a transfer of $f * 1_{\tilde{K}}$.

**Remark 2.3.4.** In the above setting, there is a natural notion of unramified twisted representation: extend an unramified representation $(\pi, V)$ of $G(F)$ which is isomorphic to its twist by $\tilde{G}(F)$ to a twisted representation by imposing that $\tilde{K}$ acts trivially on $V^{\tilde{K}}$.

**2.4. Local parameters.** Let $F$ be a local field of characteristic zero. Let $\Psi^+(G)$ denote the set of $\tilde{G}$-conjugacy classes of continuous morphisms

$$\psi : WD_F \times SL_2(\mathbb{C}) \rightarrow \mathcal{G}$$

such that

- the composite with the projection $\mathcal{G} \rightarrow W_F$ is the natural projection $WD_F \times SL_2(\mathbb{C}) \rightarrow W_F$,
- for any $w \in WD_F$, $\psi(w)$ is semisimple, and
- the restriction $\psi|_{SL_2(\mathbb{C})}$ is algebraic.

We let $\Psi(G) \subset \Psi^+(G)$ be the subset of bounded parameters. By a standard argument (see for example the proof of [GT11a Lem. 6.1]), the $\{1, \delta\}$-orbit of a parameter $\psi$ is determined by the data of the conjugacy class of $\text{Std}_G \circ \psi$. Let $\Psi(G)$ and $\Psi^+(G)$ be the set of $\{1, \delta\}$-orbits of parameters as above.

For $\psi \in \Psi^+(G)$ let $\varphi_\psi$ be the Langlands parameter associated to $\psi$, that is $\psi$ composed with the embedding

$$w \in WD_F \mapsto \left( w, \text{diag}(|w|^{1/2}, |w|^{-1/2}) \right) \in WD_F \times SL_2(\mathbb{C}).$$
Remark 2.4.4. Part (3) of this conjecture gives the local Langlands correspondence for tempered representations of $G$, determined by their traces.

Remark 2.4.2. Note that the uniqueness of the classification is clear from properties (1) and (2) and Proposition 2.4.3 below, as irreducible representations are uniquely determined by their traces. This is [Art13, Cor. 2.1.2] slightly generalised from $I$ and $S$ of $\tilde{\Psi}$, which we will denote by $I$ and $S$.

We can now formulate the conjectures on local Arthur packets in terms of endoscopic transfer relations.

Conjecture 2.4.1. Let $G = GSp_{2n+1}$, $Sp_{2n} \times GL_1$ or $GSpin_{2n}$. Then there is a unique way to associate to each $(\psi) \in \tilde{\Psi}(G)$ a multi-set $\Pi_\psi$ of $\{1, \delta\}$-orbits of irreducible smooth unitary representations of $G(F)$, together with a map $\Pi_\psi \to S_\psi$, which we will denote by $\pi \mapsto (\cdot, \pi)$, such that the following properties hold.

1. Let $\pi_{GL}$ be the representation of $GL_N(F) \times GL_1(F)$ associated to $(\text{Std}_G \circ \psi)$ by the local Langlands correspondence for $GL_N(\hat{G}) \times GL_1$, and let $\tilde{\pi}_{GL}$ be its extension to $GL_N(\hat{G}) \times GL_1(F) \times \theta$ recalled in Section 3.2. Then

$$\sum_{\pi \in \Pi_\psi} (s, \pi) \pi \text{ is stable and its transfer to } GL_N(\hat{G}) \times GL_1(F) \times \theta,$$

is $\text{tr} \tilde{\pi}_{GL}$, i.e. for any $f \in I((GL_N(\hat{G}) \times GL_1(F) \times \theta)$ having transfer $f' \in SI(G)$ we have

$$\text{tr} \tilde{\pi}_{GL}(f) = \sum_{\pi \in \Pi_\psi} (s, \pi) \pi(f').$$

2. Consider a semisimple $s \in C_\psi$ with image $\bar{s}$ in $S_\psi$. The pair $(\psi, s)$ determines an endoscopic datum $(H, H, s, \xi)$ for $G$ (with $H = \text{Cent}(s, G)$), and if we fix an $L$-embedding $L \xi : L H \to L G$ extending $\xi$ we obtain $\psi' : WD_F \times SL_2(C) \to L H$ such that $\psi = L \xi \circ \psi'$. Then for any $f \in I(G)$ with transfer $f' \in SI(H)$, we have:

$$\sum_{\pi \in \Pi_\psi} (s, \pi) \pi(f) = \sum_{\pi' \in \Pi_\psi'} (s, \pi') \pi'(f').$$

3. If $\psi|_{SL_2(C)} = 1$, then the elements of $\Pi_\psi$ are tempered and $\Pi_\psi$ is multiplicity free, and the map $\Pi_\psi \to S_\psi$ is injective; if $F$ is non-Archimedean, then it is bijective. Every tempered irreducible representation of $G(F)$ belongs to exactly one such $\Pi_\psi$.

Remark 2.4.2. Note that the uniqueness of the classification is clear from properties (1) and (2) and Proposition 2.4.3 below, as irreducible representations are determined by their traces.

Proposition 2.4.3 (Arthur). In the situation of Conjecture 2.4.1, the transfer map $I(GL_N(\hat{G}) \times GL_1) \to SI(G)$ is surjective.

Proof. This is [Art13, Cor. 2.1.2] slightly generalised from $GL_N$ to $GL_N \times GL_1$. Note that the general version of [Art13, Prop. 2.1.1] was later proved in [MW16a, 5.4.11] (see §IV.3.4 loc. cit. to extend to the Archimedean case with $K$-finiteness).

Remark 2.4.4. Part (3) of this conjecture gives the local Langlands correspondence for tempered representations of $G(F)$ (up to outer conjugacy in case $G =$...


GSpin\(_{2n}\). It can be extended to give the local Langlands correspondence for all local parameters \(\psi \in \Psi^+(G)\) with \(\psi|_{\text{SL}_2(\mathbb{C})} = 1\); indeed if Conjecture 2.4.1 is known for all \(G\), then a version can be deduced for \(\Psi^+(G)\) using the Langlands classification (see \[Lan89\], \[Sil78\] and \[SZ14\]).

**Remark 2.4.5.** In the case where \(F\) is Archimedean and for an arbitrary reductive group the local Langlands correspondence was established by Langlands and Shelstad (see \[She10\], \[She08\]). Compatibility with twisted endoscopy was proved by Mezo \[Mez16\] (under a minor assumption, see (3.10) loc. cit., which is satisfied in all cases considered in the present article) up to a constant which a priori might depend on the parameter (see \[AMR15\] Annexe C).

**Remark 2.4.6.** If \(F\) is \(p\)-adic and \(G\) is unramified over \(F\), then there is a unique \(G(F)\)-conjugacy class of hyperspecial maximal compact subgroups of \(G(F)\) which is compatible with the Whittaker datum fixed above (in the sense of \[CSS80\]), and we will say that a representation of \(G(F)\) is unramified if it is unramified with respect to a subgroup in this conjugacy class.

If \(\psi \in \Psi^+(G)\) and \(\psi|_{\text{WD}_F}\) is unramified, then assuming the conjecture the packet \(\Psi_\psi\) contains a unique unramified (orbit of) representation. It has Satake parameter \(\varphi_\psi\) (up to outer conjugation if \(G = \text{GSpin}^\circ_{2n}\)) and corresponds to the trivial character on \(S_\psi\). This follows from the fundamental lemma (Theorem 2.3.3).

**Remark 2.4.7.** By \[Mœg11\] if \(F\) is \(p\)-adic and the conjecture holds then the packets \(\Pi_\psi\) are sets rather than multi-sets.

### 2.5. Global parameters and the conjectural multiplicity formula.

Now let \(F\) be a number field, and fix a continuous unitary character \(\chi : \mathbb{A}_F^\times / F^\times \to \mathbb{C}^\times\). If \(\pi\) is a cuspidal automorphic representation of \(\text{GL}_N/F\) such that \(\pi^\vee \otimes \chi \cong \pi\), then we say that \(\pi\) is \(\chi\)-self dual. Note that this implies that \(\omega_{\pi}^2 = \chi^N\) (so in particular if \(N\) is odd, then \(\chi = (\omega_{\pi} \chi^{(1-N)/2})^2\) is a square).

If \(\pi\) is \(\chi\)-self dual and \(S\) is a big enough set of places of \(F\) then precisely one of the \(L\)-functions \(L^S(s, \chi^{-1} \otimes \mathbb{A}^2(\pi))\) and \(L^S(s, \chi^{-1} \otimes \text{Sym}^2(\pi))\) has a pole at \(s = 1\), and this pole is simple (see \[Sha97\]). In the former case we say that \((\pi, \chi)\) is of symplectic type, and set \(\text{sign}(\pi, \chi) = -1\), and in the latter we say that it is of orthogonal type, and we set \(\text{sign}(\pi, \chi) = 1\).

We write \(\Psi(\text{GL}_N \times \text{GL}_1, \chi)\) for the set of formal unordered sums \(\psi = \bigoplus_i \pi_i|_{d_i}\), where the \(\pi_i\) are \(\chi\)-self dual automorphic representations for \(\text{GL}_{N_i}/F\) and the \(d_i \geq 1\) are integers (which are to be thought of as the dimensions of irreducible algebraic representations of \(\text{SL}_2(\mathbb{C})\)), with the property that \(\sum_i N_i d_i = N\). We refer to such a sum as a *parameter*, and say that it is *discrete* if the (isomorphism classes of) pairs \((\pi_i, d_i)\) are pairwise distinct.

**Remark 2.5.1.**

1. By the main result of \[MW89\], a discrete automorphic representation \(\pi\) of \(\text{GL}_N/F\) with \(\pi^\vee \otimes \chi \cong \pi\) gives rise to an element of \(\Psi(\text{GL}_N \times \text{GL}_1, \chi)\).

Indeed, there is a natural bijection between such representations \(\pi\) and the elements of \(\Psi(\text{GL}_N \times \text{GL}_1, \chi)\) of the form \(\pi[d]\) (that is, the elements where the formal sum consists of a single term). We will use this bijection without further comment below.
(2) The set of formal parameters $\Psi(\tilde{G}_N \times \tilde{G}_1, \chi)$ that we consider does not contain all non-discrete $\chi$-self-dual parameters, for example those containing a summand of the form $\pi \boxplus (\chi \otimes \pi')$ for a non-$\chi$-self-dual cuspidal automorphic representation $\pi$ for $\tilde{G}_m$. Our ad hoc definition will turn out to be convenient when we will consider the discrete part of (the stabilisation of) trace formulas.

**Definition 2.5.2.** Let $G = GSp_{2n+1}, Sp_{2n} \times GL_1$ or $GSp_{2n}$ over $F$. We let $\tilde{\Psi}_{disc}(G, \chi)$ be the subset of $\tilde{\Psi}(\tilde{G}_N(G), \chi)$ given by those $\psi = \boxplus_i \pi_i[d_i]$ with the properties that

- $\psi$ is discrete,
- for each $i$, we have $\text{sign}(\pi_i, \chi) = (-1)^{d_i-1}\text{sign}(G)$,
- if $G = GSp_{2n}$, then $\chi^{-n} \prod_i \omega^{d_i}_{\pi_i}$ is the quadratic character corresponding to the extension $F_n/F$.

(Conditions analogous to this last bullet point could be formulated for the other groups $G$, but in fact they are conjecturally automatically satisfied.)

If $G \neq GSp_{2n}$ we also let $\Psi_{disc}(G, \chi) = \tilde{\Psi}_{disc}(G, \chi)$. The reason for writing $\tilde{\Psi}$ in the case of even $GSp$ groups is that this set only sees orbits of (substitutes for) Arthur-Langlands parameters under outer conjugation.

As a particular case of the above definition, for $\pi$ a cuspidal automorphic representation for $\tilde{G}_N/F$ such that $\chi \otimes \pi' \simeq \pi$ there is a unique group $G$ as above such that $N(G) = N$ and $\pi[1] \in \tilde{\Psi}_{disc}(G)$.

**Conjecture 2.5.3.** For $\pi$ and $G$ as above and for each place $v$ of $F$, the representation $(\text{rec}(\pi_v), \text{rec}(\chi_v))$ factors through $\text{Std}_G : \hat{G} \to \tilde{G}_N(G)(\mathbb{C}) \times GL_1(\mathbb{C})$, so that we can regard $(\pi_v, \chi_v)$ as an element of $\tilde{\Psi}^+(G(F_v))$.

**Remark 2.5.4.**

1. This conjecture is the analogue of [Art13 Theorem 1.4.1] (reformulated using Theorem 1.3.3 loc. cit.). In particular it holds for $G = Sp_{2n} \times GL_1$.

2. Since we do not know the generalised Ramanujan conjecture for $GL_n$, and do not wish to assume it, we can at present only hope to establish that the local parameters $\psi_v$ are elements of $\tilde{\Psi}^+(G(F_v))$; they are, however, expected to be elements of $\tilde{\Psi}(G(F_v))$.

Given a global parameter $\psi \in \tilde{\Psi}_{disc}(G, \chi)$, we define groups $C_\psi, S_\psi, S'_{\chi}$ as follows. For each $i$, there is a unique group $G_i$ of the kind we are considering for which $\pi_i \in \tilde{\Psi}_{disc}(G_i, \chi_i)$. We let $L_\psi$ denote the fibre product of the $\hat{G}_i$ over $W_F$. Then there is a map $\psi : L_\psi \times \tilde{G}_L \to \hat{G}$ such that $\text{Std}_G \circ \psi$ is conjugate to $\boxplus_i \text{Std}_G \otimes \nu_{d_i}$, where $\nu_{d_i}$ is the irreducible representation of $SL_2(\mathbb{C})$ of dimension $d_i$. The map $\psi$ is well-defined up to the action of Aut($\hat{G}$). We let $C_\psi$ be the centraliser of $\psi$, and similarly define $S_\psi$ and $S'_{\chi}$.

For each finite place $v$, under Conjecture 2.5.3 (applied to the $\pi_i$'s) we may form a local Arthur-Langlands parameter $\psi_v^0 : WD_{F_v} \times SL_2(\mathbb{C}) \to L_\psi$. Composing with $\psi$, we obtain $\psi_v \in \tilde{\Psi}^+(G(F_v))$. The composition of $\psi_v$ with $\text{Std}_G$ is given by

- $\chi_v$ on the $GL_1$ factor,
- the direct sum of the representations $\varphi_{\pi_i,v} \otimes \nu_{d_i}$ on the $GL_N(G)$ factor, where $\varphi_{\pi_i,v} = \text{rec}(\pi_i[v])$. 

Conjecture 2.5.6 below makes precise the expectation that the elements of the corresponding multi-sets $\Pi_\psi$ of Conjecture 2.4.1 are the local factors of the discrete automorphic representations of $G$ with multiplier $\chi$. Before stating it, we need to introduce some more notation and terminology.

For each place $v$ of $F$, write $\mathcal{H}(G_v)$ for the Hecke algebra defined after Definition 2.3.2 and write $\mathcal{H}(G)$ for the restricted tensor product of the $\mathcal{H}(G_v)$. Assuming Conjecture 2.5.3 we have an obvious map $S_\psi \to S_{\tilde{\psi}}$ for each $v$, and we can associate to $\psi$ a global packet (a multi-set) of representations of $\mathcal{H}(G)$:

$$\Pi_\psi := \{ \otimes_v \pi_v : \pi_v \in \Pi_{\psi_v} \text{ with } \pi_v \text{ unramified for all but finitely many } v \}.$$  

For each $\pi \in \Pi_\psi$, we have the associated character on $S_{\psi}$,

$$\langle x, \pi \rangle := \prod_v \langle x_v, \pi_v \rangle$$

(note that by Remark 2.4.16 we have $\langle \cdot, \pi_v \rangle = 1$ for all but finitely many $v$, so this product makes sense).

Associated to each $\psi$ is a character $\varepsilon_\psi : S_{\psi} \to \{\pm 1\}$ which can be defined explicitly in terms of symplectic $\varepsilon$-factors. In the case $\chi = 1$ this is defined in [Art13 Theorem 1.5.2], and this definition can be extended to the case of general $\chi$ without difficulty. Since we will only need the case $G = \text{GSpin}_5$ in this paper, and in this case the characters $\varepsilon_\psi$ are given explicitly in [Art10] and are recalled below in Remark 6.1.4 we do not give the general definition here.

**Definition 2.5.5.** $\Pi_\psi(\varepsilon_\psi)$ is the subset of $\Pi_\psi$ consisting of those elements for which $\langle \cdot, \pi \rangle = \varepsilon_\psi$.  

This is the correct definition only because the groups $S_{\psi_v}$ are all abelian.

Recall that we have fixed a maximal compact subgroup $K_\infty$ of $G(F \otimes_Q \mathbb{R})$ in Section 2.3. Let $g = C \otimes_R \text{Lie}(G(F \otimes Q \mathbb{R}))$. We write $A^2(G(F) \backslash G(\mathbb{A}_F), \chi)$ for the space of $\chi$-equivariant (where the action of $\mathbb{A}_F^{\times} / F^{\times}$ is via $\mu$) square integrable automorphic forms on $G(F) \backslash G(\mathbb{A}_F)$. It decomposes discretely under the action of $G(\mathbb{A}_{F,f}) \times (g, K_\infty)$.

**Conjecture 2.5.6.** Assume that Conjectures 2.4.1 and 2.5.3 hold. Then there is an isomorphism of $\mathcal{H}(G)$-modules

$$A^2(G(F) \backslash G(\mathbb{A}_F), \chi) \cong \bigoplus_{\psi \in \overline{\Psi}_{\text{disc}}(G, \chi)} m_\psi \bigoplus_{\pi \in \Pi_\psi(\varepsilon_\psi)} \pi,$$

where $m_\psi = 1$ unless $G = \text{GSpin}_{2n}$, in which case $m_\psi = 2$ if and only if each $N_i$ is even.

### 2.6. The results of [Art13].

As we have already remarked, the conjectures above are all proved in [Art13] in the case that $\chi = 1$. As we now explain, the case that $\chi$ is a square follows immediately by a twisting argument. The main results of this paper are a proof of Conjectures 2.4.1 (Theorem 3.1.1) and 2.5.6 (Theorem 7.4.1) in the case that $G = \text{GSpin}_5 \cong \text{GSp}_4$ for general $\chi$. Conjecture 2.5.3 for $G = \text{GSpin}_n$ is a consequence of [GT11a], see Proposition 7.3.1. The case that $\chi$ is a square will be a key ingredient in our arguments, as if $\chi$ is not a square, then it is easy to see that there are considerably fewer possibilities for the parameters $\psi$, and this will reduce the number of ad hoc arguments that we need to make. Moreover
The local Langlands correspondence for $GSp_4$ was characterised by relations with $\eta$. The necessary endoscopic character relations were then proved in [CG15].

**Theorem 2.6.1** (Arthur). If $\chi = \eta^2$ is a square, then Conjectures 2.4.1, 2.5.3 and 2.5.6 hold.

**Proof.** Given a $\chi$-self dual cuspidal automorphic representation $\pi$, the twist $\pi \otimes \eta^{-1}$ is self dual. Similarly, we may twist the local parameters by the restriction to $W_F$, of the character corresponding to $\eta^{-1}$, and we can also twist representations of $G(F)$ and $G(F_v)$ by $\eta^{-1}$.

All of the conjectures are easily seen to be compatible with these twists, so we reduce to the case $\chi = 1$. In this case, representations of $GSpin_{2n+1}$, (resp. $GSpin_2^{\alpha}$, resp. $Sp_{2n} \times GL_1$) with trivial similitude factor (recall that this was defined in Section 2.1 as the composition of the central character with $\mu$) are equivalent to representations of $SO_{2n+1}$, (resp. representations of $SO_2^{\alpha}$, resp. pairs given by a representation of $Sp_{2n}$ and a character of $GL_1$ of order 1 or 2), so the conjectures are equivalent to the main results of [Art13].

In particular, since in the case $G = Sp_{2n} \times GL_1$ the character $\chi$ is always a square, Theorem 2.6.1 always holds in this case.

**2.7. Low rank groups.** If $N(\hat{G}) \leq 3$ then Conjectures 2.4.1, 2.5.3 and 2.5.6 also hold unconditionally.

1. If $N = 1$ the results are tautological.
2. If $N = 2$ then $G = GSpin_4$ or $G = GSpin_2^{\alpha}$. In the first case $G \simeq GL_2$ and the results are also tautological. In the second case where $G = GSpin_2^{\alpha} \simeq \text{Res}_{F/\mathbb{Q}}(GL_1)$ we are easily reduced to the well-known Theorem 2.7.1 below, the symplectic/orthogonal alternative for $GL_2$.
3. If $N = 3$ then $G = Sp_2 \times GL_1$ and we are reduced to a special case of Theorem 2.6.1. Note that the local Langlands correspondence and the multiplicity formula in this case go back to Labesse–Langlands [LL79] and [Ram00].

**Theorem 2.7.1.** Let $\pi$ be a $\chi$-self dual cuspidal automorphic representation of $GL_2$. Then either

1. $\chi = \omega_2$, and $L^S(s, 2\chi) \otimes \chi^{-1}$ has a pole at $s = 1$; or
2. $\omega_2 \chi^{-1}$ is the quadratic character given by some quadratic extension $E/F$, $\pi$ is the automorphic induction of a character of $\mathbb{A}_E^\times/E^\times$ which is not fixed by the non-trivial element of $\text{Gal}(E/F)$, and $L^S(s, \text{Sym}^2(\pi) \otimes \chi^{-1})$ has a pole at $s = 1$.

**Proof.** Certainly $L^S(s, 2\chi) \otimes \chi^{-1}$ has a pole at $s = 1$ if and only if $\chi = \omega_2$. So if $L^S(s, \text{Sym}^2(\pi) \otimes \chi^{-1})$ has a pole at $s = 1$, we see that $\omega_2 \chi^{-1}$ is a non-trivial quadratic character corresponding to an extension $E/F$. Since we always have $\pi^\vee \otimes \omega_2 \cong \pi$, this implies that $\pi \cong \pi \otimes (\omega_2 \chi^{-1})$, and it follows (see [Lan80 end of §2]) that $\pi$ is the automorphic induction of a character of $\mathbb{A}_E^\times/E^\times$ which is not fixed by the non-trivial element of $\text{Gal}(E/F)$.

**2.8. The local Langlands correspondence for $GSp_4$.** Let $F$ be a p-adic field. The local Langlands correspondence for $GSp_4(F)$ was established in [GT11a], but was characterised by relations with $\gamma$-factors, rather than endoscopic character relations. The necessary endoscopic character relations were then proved in [CG15]. In particular, we have:
Theorem 2.8.1 (Chan–Gan). If \( F \) is a \( p \)-adic field then Conjecture [2.4.1] holds for \( \text{GSpin}_5 \) and parameters \( \psi \) which are trivial on \( \text{SL}_2(\mathbb{C}) \), i.e. tempered Langlands parameters.

Proof. Parts (1) and (2) of Conjecture [2.4.1] are an immediate consequence of the main theorem of [CG15] (note that bounded parameters are automatically generic, in the sense that their adjoint \( L \)-functions are holomorphic at \( s = 1 \)). Part (3) then follows from the main theorem of [GT11a]. □

Remark 2.8.2. Recall from Remark 2.4.5 that over an Archimedean field the local Langlands correspondence and (ordinary) endoscopic character relations are known in complete generality, and the twisted endoscopic character relations are known up to a constant (which might depend on the parameter).

If \( F \) is Archimedean and \( \psi \) is a tempered and non discrete Langlands parameter for \( \text{GSpin}_5 \), then the twisted endoscopic character relation was verified in [CG15, §6], which amounts to saying that the above constant (the only ambiguity in Mezo’s theorem) is 1. In Proposition 7.2.1 below we will show using a global argument as in [AMR15, Annexe C] that this also holds for the discrete tempered \( \psi \).

3. Construction of missing local Arthur packets for \( \text{GSpin}_5 \)

3.1. Local packets. Let \( F \) be a local field of characteristic zero. In this section we complete the proof of the following theorem, which completes the proof of Conjecture [2.4.1] for \( \text{GSpin}_5 \).

Theorem 3.1.1. Let \( \psi : \text{WD}_F \times \text{SL}_2 \rightarrow \hat{\text{GSp}}_4 \) be an element of \( \Psi(\text{GSpin}_5) \). Then there is a unique multi-set \( \Pi_\psi \) of irreducible smooth unitary representations of \( \text{GSpin}_5(F) \), together with a map \( \Pi_\psi \rightarrow S_\psi \), which we will simply denote by \( \pi \mapsto \langle \cdot, \pi \rangle \), such that the following holds:

(1) Let \( \pi_{\Gamma,\psi} \) be the representation of \( \Gamma(F) \) associated to \( \text{Std}_{\text{GSpin}_5} \circ \varphi_\psi \) by the local Langlands correspondence, and let \( \pi_{\psi} \) be its extension to \( \overline{\Gamma}(F) \) (Whittaker-normalised as explained in Section 3.2). Then the linear form \( \sum_{\pi \in \Pi_\psi} \langle s_{\psi}, \pi \rangle \text{tr} \pi \) on \( I(\text{GSpin}_5(F)) \) is stable and its transfer to \( \overline{\Gamma} \) is \( \text{tr} \pi_{\psi} \).

(2) Consider a semisimple \( s \in \text{Cent}(\psi, \text{GSp}_4) \), and denote by \( \bar{s} \) its image in \( S_\psi \). The pair \( (\psi, s) \) determines an endoscopic datum \( (H, \mathcal{H}, s, \xi) \) for \( \text{GSpin}_5 \), as well as \( \psi' : \text{WD}_F \times \text{SL}_2 \rightarrow \hat{H} \) such that \( \psi = \xi \circ \psi' \). Then for any \( f \in I(\text{GSpin}_5(F)) \) we have

\[
\sum_{\pi \in \Pi_\psi} \langle \bar{s}_{\psi}, \pi \rangle \text{tr} \pi(f) = \sum_{\pi' \in \Pi_{\psi'}} \langle s_{\psi'}, \pi' \rangle \text{tr} \pi'(f').
\]

Note that in the second point \( H \) is either \( \text{GSpin}_5 \) or a quotient of a product of general linear groups by a split torus, and so \( \Pi_{\psi'} \) is well-defined. In the latter case it is a singleton and \( S_{\psi'} \) is trivial.

As we recalled above (Theorems [2.6.1] [2.8.1] and Remark [2.8.2]) this theorem is already known in the following cases:

- if \( \hat{\mu} \circ \psi \) is a square,
- if \( F \) is \( p \)-adic and \( \psi|_{\text{SL}_2} = 1 \),
- if \( F \) is Archimedean, \( \psi|_{\text{SL}_2} \) and \( \psi \) is not discrete.
We will prove the case where \( F \) is Archimedean, \( \psi \) tempered discrete and \( \chi \) not a square later in Proposition 7.2.1, since we will use a global argument using the stabilisation of the trace formula.

This section is devoted to the proof of Theorem 3.1.1 in the remaining cases, where \( \psi_{|L_2} \) is not trivial and \( \tilde{\mu} \circ \psi \) is not a square. It is easy to see that \( \mathrm{Std}_{\text{GSpin}} \circ \psi \simeq (\varphi[2], \chi) \), where \( \varphi : WD_F \to GL_2 \) is \( \chi \)-self-dual of orthogonal type. Then \( \varphi \) factors through \( W_F \) and \( \det \varphi/(\tilde{\mu} \circ \psi) \) has order 1 or 2. There are two cases to consider.

1. If \( \varphi \) is irreducible then \( \det \varphi/(\tilde{\mu} \circ \psi) \) has order 2. Let \( E/F \) be the corresponding quadratic extension and denote \( c \) the non-trivial element of \( \text{Gal}(E/F) \).

   We have \( \varphi \simeq \text{Ind}_{E/F} \mu \) for a character \( \mu : E^\times \to \mathbb{C}^\times \) such that \( \mu^c = \mu \) and \( \mu|_{F^\times} = \chi \). Then \( \text{Cent}(\psi, GSp_4) = Z(GSp_4) \) and so we simply have to produce \( \Pi_\psi = \{\pi\} \) such that \( \text{tr} \pi \) transfers to the trace of \( \pi^E \).

2. If \( \varphi \) is reducible then \( \varphi = \eta_1 \oplus \eta_2 \) with \( \eta_1 \eta_2 = \chi \) and \( \eta_1 \neq \eta_2 \). Then \( \text{Cent}(\psi, GSp_4) = \{\text{diag}(u_{11}^1, u_{11}^2)\} \) and so we are led to define \( \Pi_\psi = \{\text{Ind}_{E/F}^G \psi \} \) where \( L \simeq GL_2 \times GSp_n \). Then the second point in Theorem 3.1.1 is automatically satisfied (see [CG15, §6.6]), and again we have to check that the twisted endoscopic character relation holds.

We will prove these two cases separately, distinguishing between the cases where \( F \) is \( p \)-adic, real, or complex (in which case only the second case occurs). Before doing so, we recall some material on Whittaker normalisations.

### 3.2. Whittaker normalisation for general linear groups

In this section \( F \) denotes a local field of characteristic zero, \( G = GL_n \times GL_1 \) over \( F \) and \( G = G \rtimes \theta \). Following [MW06, §5], [Sha10], [AMR15, §8] we briefly recall the Whittaker normalisation of extensions to \( G(F) \) of irreducible representations of \( G(F) \) fixed by \( \theta \). Recall that we have fixed a \( \theta \)-stable Whittaker datum \((U, \lambda)\) for \( G \). If \( F \) is Archimedean for simplicity we choose the maximal compact subgroup \( K \) to be \( O_n(F) \times \{\pm 1\} \) (resp. \( U(n) \times U(1) \)) if \( F \) is real (resp. complex), so that \( \theta(K) = K \).

First consider the case of essentially tempered representations. Let \( \pi \) be an essentially tempered (in particular, essentially unitary) irreducible representation of \( G(F) \). By [Sha74] there exists a continuous Whittaker functional \( \Omega \) for \( \pi \). If \( F \) is \( p \)-adic this is just an element of the algebraic dual of the space \( \pi_K \) of smooth vectors. If \( F \) is Archimedean this is a continuous functional on the space \( \pi_\infty \) of smooth vectors for the topology defined by seminorms as in [Sha74, p. 183]. Now if \( \pi \) is fixed by \( \theta \), define \( \tilde{\pi}(\theta) \) as the unique element \( A \in \text{Isom}(\pi, \pi^\theta) \) such that \( \Omega \circ A = \Omega \). This does not depend on the choice of \( \Omega \). So we have an extension \( \tilde{\pi} \) of \( \pi \) to a representation of \( G(F) \), well-defined using the Whittaker datum \((U, \lambda)\).

Next consider representations parabolically induced from a \( \theta \)-stable parabolic subgroup. Fix the usual (diagonal) split maximal torus \( T \) of \( G \), as well as the usual (upper triangular) Borel subgroup \( B = TU \) of \( G \). Both are \( \theta \)-stable. Let \( w_G \) be the longest element of the Weyl group \( W(T, G) \). Let \( P = MN \) be a standard parabolic subgroup of \( G \), with standard Levi subgroup \( M \supset T \). Assume that \( P \) is \( \theta \)-stable, which means that \( M = (GL_{n_1} \times \cdots \times GL_{n_\ell}) \times GL_1 \) (block diagonal) with \( n_i = n_{i+1-i} \) for all \( i \). Let \( \sigma \) be an irreducible admissible representation of \( M(F) \) fixed by \( \theta \), that is \( \sigma \simeq (\sigma_1 \otimes \cdots \otimes \sigma_\ell) \otimes \chi \) with \( (\det \circ \chi) \otimes \sigma_\ell^\vee \simeq \sigma_{\ell+1-i} \) for all \( i \). Let \( D_M \) be the largest split torus which is a quotient of \( M \), so that we have a
canonical isogeny $A_M \to D_M$. In the present case we have a natural identification $D_M \simeq GL^r_1 \times GL_1$ via the determinants $GL_{n_1} \to GL_1$. For $\nu \in X^*(D_M) \otimes \mathbb{C}$ inducing a character of $M(F)$, consider the parabolically induced (normalised) representation $\pi_\nu := Ind_{P(F)}^{G(F)} \sigma \otimes \nu$. We also assume that $\nu = (\nu_1, \ldots, \nu_r, \nu_0)$ is fixed by $\theta$, i.e. $\nu_i + \nu_{i+1-i} = \nu_0$ for all $i$. Let $w_M$ be the longest element of $W(T, M)$ (for $B \cap M$) and $w = w_G w_M$. Let $P^- = MN^- \sigma$ be the parabolic subgroup of $G$ opposite to $P$ with respect to $M$, and let $P' = M'N' = wP^-w^{-1} = w_G P^-w_G^{-1}$ be the standard parabolic subgroup conjugated to $P^-$. Choose a lift $\tilde{w}$ of $w$ in $H_G(F)(T)$. Let $\lambda_M^\tilde{w} : (M \cap U)(F) \to S^1$ be the generic character defined by $\lambda_M^\tilde{w}(u) = \lambda(\tilde{w} u \tilde{w}^{-1})$. Assume that the space $Hom_{(M \cap U)(F)}(\sigma, \lambda_M^\tilde{w})$ of Whittaker functionals for $\sigma$ with respect to $\lambda_M^\tilde{w}$ is non-zero and thus one-dimensional, and fix a basis $\Omega_\sigma$ of this line. In the $p$-adic case, according to a theorem of Rodier ([Rod73], [CSS0], explained in [Sha10] §3.4) we then have that $Hom_{U(F)}(Ind_{P(F)}^{G(F)}(\sigma \otimes \nu), \lambda)$ also has dimension one. A basis $\Omega_{\pi_\nu}$ can be made explicit: for $f$ in the space of $Ind_{P}^{G} \sigma \otimes \nu$ whose support is contained in the big cell $P(F) w^{-1} U(F)$,

$$\Omega_{\pi_\nu}(f) := \int_{N'(F)} \Omega_\sigma(f(\tilde{w}^{-1} n))\lambda(n)^{-1} dn$$

is well-defined (the integrand is smooth and compactly supported). For arbitrary $f$ the same formula holds with $N'(F)$ replaced by large enough open compact subgroup which depends on $f$ but not on $\nu$ (as usual realising the vector space underlying $Ind_{P(F)}^{G(F)} \sigma \otimes \nu$ independently of $\nu$ by restriction to $K$), so that $\nu \mapsto \Omega_{\pi_\nu}(f)$ is holomorphic.

The Archimedean case is more subtle, since the notion of Whittaker functional requires a topology on the underlying space of the representation to be well-behaved (it is not defined directly on $(g, K)$-modules). So in this case one considers the smooth parabolically induced representation $\pi_\nu := Ind_{P(F)}^{G(F)}(\sigma_\infty \otimes \nu)$, whose subspace $\pi_\nu,K$ of $K$-finite vectors is naturally isomorphic to the $(g, K)$-module algebraically induced from $\sigma_{M(F) \cap K}$ (see [BW00] §3.7). Assume that the central character of $\sigma$ is unitary. Then the integral (3.2.1) is absolutely convergent for $\nu \in X^*(D_M) \otimes \mathbb{C}$ satisfying

$$\forall \alpha \in \Phi(T, N), \langle \alpha^\vee, \Re \nu \rangle > 0,$$

and extends analytically to $X^*(D_M) \otimes \mathbb{C}$ ([Sha10] Theorem 3.6.4]). The proof of Theorem 3.6.7 in [Sha10] also shows uniqueness (up to a scalar) of a Whittaker functional for $Ind_{P(F)}^{G(F)}(\sigma_\infty \otimes \nu)$ (note that the argument for uniqueness only involves the Jordan–Hölder factors of a principal series representation, and so one may replace $P$ by another parabolic subgroup of $G$ admiting $M$ as a Levi factor and such that the opposite of (3.2.2) is satisfied, so that any generic subquotient of $Ind_{P}^{G} \sigma \otimes \nu$ appears as a quotient).

We can now treat the $p$-adic and Archimedean cases together. Assume that $\nu$ is chosen so that $End_{G(F)}(\pi_\nu) = \mathbb{C}$. This is the case if the central character of $\sigma$ is unitary and $\nu$ satisfies (3.2.2) (this follows from the fact that $\pi_\nu$ then has a unique irreducible quotient which occurs with multiplicity one in its composition series), or if $-\nu$ satisfies (3.2.2) ($\pi_\nu$ then has a unique irreducible subrepresentation). Then one can define the action of $\theta$ on $\pi_\nu$ to be the unique $A_\theta \in End(\pi_\nu)$ such that $A_\theta \circ \pi_\nu(g) = \pi_\nu(\theta(g)) \circ A_\theta$ for all $g \in G(F)$ and $\Omega_{\pi_\nu} \circ A = \Omega_{\pi_\nu}$. This can be made
more explicit in the case at hand, see [MW06, §5.2]. The operator $A_\vartheta$ does not depend on the choice of $\bar{w}$ made above.

For this definition we followed [AMR15, §8]. As explained there, the resulting canonical extension of $\pi_\nu$ coincides with the extension defined by Arthur in [Art13, §2.2], by [MW06, §5.2] and analytic continuation (see [AMR15, Remarque 8.3]).

Finally, consider an arbitrary irreducible smooth representation $\pi$ of $G(F)$ (admissible $(g, K)$-module in the Archimedean case). By the Langlands classification ([Lan89, Lemmas 3.14 and 4.2], [Sil78], [BW00, Chapter IV]), $\pi$ is the unique irreducible quotient of $\text{Ind}_G^S(\sigma \otimes \nu)$ (resp. unique irreducible subrepresentation of $\text{Ind}_P^G(\sigma \otimes \nu)$) for $\nu \in X^*(D_M) \otimes \mathbb{C}$ satisfying (3.2.2), with $\sigma$ tempered (in particular, with unitary central character) and the pair $(P, \sigma \otimes \nu)$ is well-defined up to conjugation. These two realisations of $\pi$ as quotient (resp. subrepresentation) of a parabolically induced representation give two canonical extensions of $\pi$ to $G$, by the above. In fact these two canonical extensions coincide: consider the composition

$$\text{Ind}_P^G(\sigma \otimes \nu) \to \pi \to \text{Ind}_P^G(\sigma \otimes \nu)$$

which is clearly non-zero. From the properties of these induced representations mentioned above it follows that $\dim \text{Hom}_{G(F)}(\text{Ind}_P^G(\sigma \otimes \nu), \text{Ind}_P^G(\sigma \otimes \nu)) \leq 1$. Therefore the above composition coincides with the usual intertwining operator by [Wal03, Théorème IV.1.1], [VW90] (up to a scalar and a normalising factor to make this intertwining operator holomorphic at $\nu$). But this operator varies analytically if we vary $\nu$, and generically it is an isomorphism between irreducible parabolically induced representations, thus generically it intertwines the two $A_\vartheta$'s, and by continuity this also holds for the original $\nu$.

3.3. Proof of Theorem 3.1.1 We now prove Theorem 3.1.1 in the cases described at the end of Section 3.3.

Proof in the first case for $F$ $p$-adic. The proof is a very special case of the generalisation of [MW06, Théorème 4.7.1] to essentially self-dual representations. See also [Mœg06].

Let $\rho$ be the supercuspidal representation of $GL_2(F)$ such that $\text{rec}(\rho) = \varphi$. Then $\chi \otimes \rho^\vee \simeq \rho$. We will give an ad hoc definition of $\Pi_{\psi}$, using special cases of results of [MW06] to check compatibility with twisted endoscopy for $GL_4 \times GL_1$. In [MW06] Mœglin and Waldspurger consider self-dual parameters, and we will argue that their arguments extend to the case at hand without substantial modification, the essential input being compatibility of local Langlands for $GSpin_5$ for twisted endoscopy (and the same for $GSpin_4$ and $GSpin_1$, which is trivial).

Let $\Delta$ be the diagonal embedding $SU(2) \hookrightarrow SU(2) \times SL_2(\mathbb{C})$, so that $\psi \circ \Delta$ is the essentially tempered Langlands parameter obtained by tensoring $\varphi$ with the 2-dimensional irreducible representation of the factor $SU(2)$ of $WD_F$. Then $\text{Cent}(\psi \circ \Delta, GSpin_4) = Z(GSpin_4)$, and so $\Pi_{\psi \circ \Delta}$ (as defined by Gan–Takeda in [GT11a]) consists of a single irreducible discrete series representation $\pi_{\psi \circ \Delta}$ of $GSpin_5(F)$. Let $P$ be the standard parabolic subgroup of $GSpin_5$ with Levi subgroup $L \simeq GL_2 \times GSpin_1$ (conventions as in Section 2.2). Then $\text{Jac}_P(\pi_{\psi \circ \Delta}) = \rho_1 \det^{|1/2|} \otimes \chi$ where Jac denotes the normalised Jacquet module. We briefly recall the proof. Let $\pi_{\psi \circ \Delta}^G$ be the (discrete) representation of $GL_4(F)$ corresponding to $\text{pr}_1 \text{Std} \psi \circ \Delta : WD_F \to GL_4(\mathbb{C})$. Denoting by $P_{GL}$ the upper block triangular parabolic subgroup of $GL_4$ with Levi subgroup $GL_2 \times GL_2$, it is well-known that $\text{Jac}_{GL}(\pi_{\psi \circ \Delta}^G) =$
\[ \rho | \det |^{1/2} \rho | \det |^{-1/2}. \] Let \( \pi_{\psi}^{G} \) be the Whittaker-normalised (see Section 3.2 or MW06 §5.1) extension of \( \pi_{\psi}^{GL} \otimes \chi \) to \( \bar{\Gamma}(F) \). By (iii) in the main theorem of CG15 we have that \( \tr \pi_{\psi}^{G} \) is a transfer of \( \tr \pi_{\psi}^{\Delta} \). The parabolic subgroup \( P^{GL} \times GL_1 \) of \( \Gamma \) is stable under \( \theta \), write \( \bar{P} = (P^{GL} \times GL_1) \times \theta \). By (an obvious generalisation of) MW06 Lemma 4.2.1, \( \tr \Jac_P(\pi_{\psi}^{G}) \) is a transfer of \( \tr \Jac_P(\pi_{\psi}^{\Delta}) \), and thus \( \Jac_P(\pi_{\psi}^{\Delta}) = \rho | \det |^{1/2} \chi \). By Frobenius reciprocity, \( \pi_{\psi}^{\Delta} \) is naturally a subrepresentation of \( \Ind_{P}^{GSpin}(\rho | \det |^{1/2} \otimes \chi) \). By BZ77 Theorem 2.8 this parabolic induction has length \( \leq 2 \) and so the cokernel of

\[ \pi_{\psi}^{\Delta} \rightarrow \Ind_{P}^{GSpin}(\rho | \det |^{-1/2} \otimes \chi) \]

is an irreducible Langlands quotient which we denote \( \pi_{\psi} \). We let \( \Pi_{\psi} = \{ \pi_{\psi} \} \). Since \( \Cent(\psi, GSp_4(\mathbb{C})) = \mathbb{C}^{\times} \), we only have to check the twisted endoscopic character relation (Theorem 3.1.1 (1)). Following MW06, this will be a consequence of comparing the short exact sequence

\[ 0 \rightarrow \pi_{\psi}^{\Delta} \rightarrow \Ind_{P}^{GSpin}(\rho | \det |^{1/2} \otimes \chi) \rightarrow \pi_{\psi} \rightarrow 0 \]

with a similar one for \( \bar{\Gamma} \).

We have a short exact sequence of representations of \( \Gamma(F) = GL_4(F) \times GL_1(F) \):

\[ 0 \rightarrow \pi_{\psi}^{GL} \otimes \chi \rightarrow \mathcal{E}_1(\pi_{\psi}^{GL}) \otimes \chi \rightarrow \pi_{\psi} \otimes \chi \rightarrow 0 \]

obtained as in MW06 Prop. 3.1.2, by applying functorial constructions to \( \pi_{\psi}^{GL} \) to get a resolution of \( \pi_{\psi}^{\Delta} \) by sums of standard modules except possibly for the last term, which is defined as a cokernel and shown to be irreducible with Langlands parameter \( (\psi \circ \Delta)^{\sharp} = \psi \) (the general definition of \( \psi^{\sharp} \) is given in MW06 §3.1.2). The definition of the middle term is

\[ \mathcal{E}_1(\pi_{\psi}^{GL}) := \Ind_{P}^{GL}(Jac_{PGL}(\pi_{\psi}^{\Delta})) = \Ind_{P}^{GL}(\rho | \det |^{1/2} \otimes \chi | \det |^{-1/2}) \]

and in the present case Mœglin and Waldspurger’s resolution does not involve any non-trivial “proj”, so that the resolution actually goes back to Aub05, SS97. Following Mœglin and Waldspurger one can extend \( \pi_{\psi}^{GL} \otimes \chi \) from \( \Gamma(F) \) to \( \Gamma^+(F) \) by choosing an action of \( \theta \) (see MW06 §§1.7-1.9), that we denote by \( \theta_{MW} \). The resolution (3.3.2) inherits an action of \( \theta \) by functoriality (see MW06 §3.2), and fortunately the resulting action on \( \pi_{\psi}^{GL} \otimes \chi \) happens to coincide with \( \theta_{MW} \) (see MW06 Lemma 3.2.2), in which we have \( j(\psi) = 1 \) and so \( \beta(\psi \circ \Delta, \rho, \leq d) = +1 \). Another way to choose an extension of \( \pi_{\psi}^{GL} \otimes \chi \) (resp. \( \pi_{\psi}^{G} \otimes \chi \) to \( \theta \) is to use Whittaker functionals and the Langlands classification as we recalled in Section 3.3.2. Denote the resulting actions of \( \theta \) by \( \theta_{W} \). In general \( \theta_{W} \) and \( \theta_{MW} \) differ by a sign, but here fortunately \( \theta_{W} = \theta_{MW} \) on both \( \pi_{\psi}^{GL} \otimes \chi \) and \( \pi_{\psi}^{G} \otimes \chi \) (a special case of MW06 Prop. 5.4.1)). Thus we have a well-defined extension

\[ 0 \rightarrow (\pi_{\psi}^{GL} \otimes \chi)^{+} \rightarrow (\mathcal{E}_1(\pi_{\psi}^{GL}) \otimes \chi)^{+} \rightarrow (\pi_{\psi}^{GL} \otimes \chi)^{+} \rightarrow 0 \]

of (3.3.2) to \( \Gamma^+(F) \). The trace of the left term is known to be the transfer of \( \tr \pi_{\psi}^{\Delta} \). By compatibility of stable transfer with Jacquet modules [MW06, Lemme 4.2.1] and parabolic induction (a consequence of the explicit formula for parabolic induction ([vD72, Clo84, Lem10 §7.3, Corollaire 3])), the trace of the middle term is the
transfer of the middle term of (3.3.1). So we can conclude that 
\( \text{tr} \left( \pi_{\psi}^{\text{GL}} \otimes \chi \right)^+ \) is 
the transfer of \( \text{tr} \pi_{\psi} \).

\( \square \)

**Proof in the second case for p-adic \( F \).** This is similar to the previous case but now 
\( \varphi : W_F \rightarrow \text{GL}_2(\mathbb{C}) \) is reducible and so it defines a principal series representation 
of \( \text{GL}_2(F_v) \). Write \( \varphi \simeq \text{rec}(\eta_1) \oplus \text{rec}(\eta_2) \), so that \( \chi = \eta_1 \eta_2 \). As explained above 
we can assume that \( \eta_1 \neq \eta_2 \). Define \( \pi_{\psi} = \text{Ind}_{P}^{\text{GSpin}_2}((\eta_1 \circ \text{det}) \otimes \chi) \) where 
the standard parabolic subgroup \( P \) has \( \text{Levi} \ L \simeq \text{GL}_2 \times \text{GSpin}_2 \) and \( \Pi_{\psi} = \{ \pi_{\psi} \} \). The 
representation \( \pi_{\psi} \) is certainly irreducible (see Mégard [1.4.2]), but since this is not 
 necessary to prove the Theorem we simply take the definition \( \Pi_{\psi} = \{ \pi_{\psi} \} \) to mean 
that \( \Pi_{\psi} \) is the multi-set of constituents of \( \pi_{\psi} \).

Consider the parabolic induction for \( \text{GL}_4 \times \text{GL}_1 \)

\[
(3.3.4) \quad \pi_{\psi}^\Gamma := \text{Ind}_{B_{\psi}}^{\text{GL}_4}((\eta_1 \circ \text{det}) \otimes (\eta_2 \circ \text{det})) \otimes \chi
\]
where \( B^{\psi}_{GL} \) is the standard Borel subgroup of \( \text{GL}_4 \), which coincides with the canonical 
action of \( \theta \) on this parabolic induction by (the obvious generalisation of) [MW06] 
Lemme 3.2.1.

Let us sketch the proof of the fact that these two actions of \( \theta \) on \( \pi_{\psi}^\Gamma \) coincide. 
It will be convenient to denote \( \sigma_1 \times \cdots \times \sigma_r \) for the parabolic induction (using the 
standard parabolic) of an admissible representation \( \sigma_1 \otimes \cdots \otimes \sigma_r \) of \( \text{GL}_{n_1}(F) \times \cdots \times \text{GL}_{n_r}(F) \) to \( \text{GL}_{n_1+\cdots+n_r}(F) \). Recall that for any \( s \in C \) the parabolic induction 
\( \eta_2 \cdot |^{1/2+s} \times \eta_1 \cdot |^{-1/2-s} \) is irreducible by [BZ76] Theorem 3, since the assumption 
that \( \chi = \eta_1 \eta_2 \) is not a square implies that \( \eta_1|_{\text{GL}_2} \neq \eta_2|_{\text{GL}_2} \). The intertwining 
operator 
\[
I_s : \eta_2 \cdot |^{1/2+s} \times \eta_1 \cdot |^{-1/2-s} \rightarrow \eta_1 \cdot |^{-1/2-s} \times \eta_2 \cdot |^{1/2+s}
\]
defined by the usual integral formula for \( \Re(s) \gg 0 \), is rational in \( q^{-s} \) (where \( q \) is 
the cardinality of the residue field of \( F \)) by [Wal03] Théorème IV.1.41, and so there 
is a polynomial \( r(s) \) in \( q^{-s} \) such that \( r(s)I_s \) is well-defined and non-zero for any \( s \), 
and therefore an isomorphism. It induces an isomorphism \( I_{s,\text{norm}} \):

\[
\eta_1 \cdot |^{1/2} \times \eta_2 \cdot |^{1/2+s} \times \eta_1 \cdot |^{-1/2-s} \times \eta_2 \cdot |^{-1/2} \rightarrow I_s \eta_1 \cdot |^{-1/2-s} \times \eta_2 \cdot |^{1/2+s} \times \eta_2 \cdot |^{-1/2}.
\]

Denote \( \pi_{1,s} \) (resp. \( \pi_{2,s} \)) the LHS (resp. RHS). Since \( \eta_2 \cdot |^{-1/2} = \chi / (\eta_2 \cdot |^{1/2}) \) and 
\( \eta_1 \cdot |^{-1/2-s} = \chi / (\eta_2 \cdot |^{1/2+s}) \), there is a canonical extension of \( \pi_{1,s} \otimes \chi \) to \( \Gamma^+(F) \) 
(see [MW06] §1.3). Denote by \( \theta_I \) this canonical action of \( \theta \) on the space of \( \pi_{1,s} \otimes \chi \) 
(one can easily check that it does not depend on \( s \)), so that for \( s = 0 \) we recover the 
Whittaker normalisation on (3.3.5). The irreducible representation 

\[
\left( (\eta_1 \cdot |^{1/2} \times \eta_1 \cdot |^{-1/2-s}) \otimes (\eta_2 \cdot |^{1/2+s} \times \eta_2 \cdot |^{-1/2}) \right) \otimes \chi
\]
of the $\theta$-stable parabolic subgroup $P \times GL_1$ of $G$ is also fixed by $\theta$, and so $\pi_{2,s} \otimes \chi$
also admits a canonical extension to $F(F)$. Denote $\theta_2$ this canonical action of $\theta$ on
the space of $\pi_{2,s} \otimes \chi$, which for $s = 0$ recovers the canonical action on the
quotient $S(3,3,4)$. An easy computation that we skip shows that for $R(s) \gg 0$ we
have $I_{s,\text{norm}} \circ \theta_1 = \theta_2 \circ I_{s,\text{norm}}$, and the case of an arbitrary $s \in \mathbb{C}$ follows by analytic
continuation.

\textbf{Proof in the first case for $F = \mathbb{R}$}. This is similar to the first case for $F$ a $p$-adic
field except we now follow arguments of [AMR15]. For $a \in \frac{1}{2} \mathbb{Z}_{\geq 0}$ let $I_a$ be the
tempered Langlands parameter $W_{\mathbb{R}} \rightarrow GL_2(\mathbb{C})$ obtained by inducing the character
$z \mapsto (z/\bar{z})^a \equiv (z/|z|)^{2a}$ of $\mathbb{C}^\times$. Up to twisting we can assume that $\varphi = I_a$ with
$a > 0$ integral, with $\chi$ equal to the sign character sign of $W_{\mathbb{R}}$. Let $\pi^{GL_1}$ be the
irreducible unitary representation of $GL_4(\mathbb{R})$ associated to $\varphi$. Let $\chi : GL_1(\mathbb{R}) \rightarrow \{\pm 1\}$
be the sign character, so that $\chi \otimes (\pi^{GL_1})^* \simeq \pi^{GL_1}$. As in the $p$-adic case we
have the Whittaker-normalised extension $\pi^{GL_4}_\psi$ of $\pi^{GL_1} \otimes \chi$.

We have a (short) resolution from [Joh84] (see [AMR15] §6.2 where this resolution is made completely explicit for $GL_2$, and parameters $I_w[n]$ for $w \in \frac{1}{2} \mathbb{Z}_{>0}$)

$$0 \rightarrow \pi^{GL_4}_\psi \rightarrow \pi^{GL_1}_{|z|^{1/2}} \times \pi^{GL_1}_{|z|^{-1/2}} \rightarrow \pi^{GL_2}_{I_{a+1/2}} \times \pi^{GL_2}_{I_{a-1/2}} \rightarrow 0$$

where $| \cdot |$ is the norm character of $W_{\mathbb{R}}$ (i.e. the square of the usual absolute value on $\mathbb{C}^\times$ and $|t| = 1$) and we denoted parabolic induction for standard parabolic subgroups of $GL$ as in the $p$-adic case. In [AMR15 Lemme 9.9] only the first case occurs, so comparing normalisations (Whittaker and imposed by induction in Johnson’s construction of the resolution) is particularly simple: we obtain the analogue of [AMR15 Théorème 9.7] with $A_s = A_s^+$.

\textbf{Proof in the second case for $F = \mathbb{R}$ or $\mathbb{C}$}. Up to twisting we can assume that $\varphi \simeq 1 \oplus \chi$ with $\chi = \text{sign}$ in the real case and $\chi(z) = (z/\bar{z})^a |z|^t$ with $a \in \frac{1}{2} \mathbb{Z}\setminus\mathbb{Z}$ and $t \in \mathbb{R}$ in the complex case. The proof is identical to the $p$-adic case and we do not repeat the argument. Note that the complex case is the analogue of [MR15 Prop. 6.5].

\section{Stabilisation of the twisted trace formula}

We now state the stabilisation of the twisted trace formula proved by Mœglin and Waldspurger in [MW16a, MW16b] following the case of ordinary (i.e. non-twisted) endoscopy proved by Arthur in [Art02, Art01, Art03] (also following [Lan83, Kot86, Lab99], and of course [LW13]). We recall some of the definitions needed to state the stabilisation, and mention some simplifications occurring in the cases at hand.

\subsection{The discrete part of the spectral side.}

Consider a connected reductive group $G$ over a number field $F$ and an automorphism $\theta$ of $G$ of finite order. Let $G = G \times \theta$. Let $A_0$ be a maximal split torus in $G$. We will only consider Levi subgroups of $G$ which contain $A_0$. Let $K = \prod_v K_v$ be a good maximal compact subgroup of $G(A_F)$ with respect to $A_0$ as in [LW13 §3.1]. Choose a minimal parabolic subgroup $P_0$ of $G$ containing $A_0$.

Following [MW16b §X.5], let us recall the terms occurring in the discrete part of the spectral side of the twisted trace formula. To work with discrete automorphic spectra it is necessary to fix central characters (at least on a certain subgroup of
the centre), and we follow [MW16b, §X.5.1]. We now elaborate on the notation for the discrete automorphic spectrum introduced in Section [I.3.3.3]. Recall that $\mathfrak A_G$ denotes the vector group $A_G(\mathbb R)^0$ where $A_G$ is the biggest central split torus in $\text{Res}_{F/Q}(G)$. Then $G(\mathbb A_F) = G(\mathbb A_F)^1 \times \mathfrak A_G$, where

$$G(\mathbb A_F)^1 = \{ g \in G(\mathbb A_F) \mid \forall \beta \in X^+(G)^{\text{Gal}_F}, |\beta(g)| = 1 \},$$

so that $G(F) \backslash G(\mathbb A_F)^1$ has finite measure. Let $\mathfrak A_G = \mathfrak A_G^\theta$. Then $\mathfrak A_G = (1-\theta)(\mathfrak A_G) \times \mathfrak A_G$

In the general definition of twisted endoscopy one considers a character $\omega$ of $G(\mathbb A_F)$; in all cases considered in this paper we have $\omega = 1$. Mœglin and Waldspurger consider a character $\chi_G$ of $\mathfrak A_G$ which is trivial on $\mathfrak A_G$ and satisfies $\theta(\chi_G) = \chi_G |_{\mathfrak A_G}$; since we will always have $\omega = 1$, in this paper, we will have $\chi_G = 1$.

Let $L$ be a Levi subgroup of $G$. Up to conjugating by $G(F)$ we can assume that $L$ is the standard Levi subgroup of a standard parabolic subgroup $P$ of $G$. There is a canonical splitting $\mathfrak A_L = \mathfrak A_G \times \mathfrak A_{G,L}$ (with $\mathfrak A_{G,L}$ included in the derived subgroup of $G(F \otimes_Q \mathbb R)$), and we write $\chi_{G,L}$ for the extension of $\chi_G$ to $\mathfrak A_L$ such that $\chi_{G,L}|_{\mathfrak A_G} = 1$. As remarked above in all cases considered in this paper we simply have $\chi_{G,L} = 1$. The space of square integrable automorphic forms $A^2(L(F) \backslash L(\mathbb A_F), \chi_{G,L})$ decomposes discretely, i.e. it is canonically the direct sum, over the countable set $\Pi_{\text{disc}}(L,\chi_{G,L})$ of discrete automorphic representations $\pi_L$ for $L$ such that $\pi_L|_{\mathfrak A_L} = \chi_{G,L}$, of isotypical components

$$A^2(L(F) \backslash L(\mathbb A_F), \chi_{G,L})_{\pi_L}$$

which have finite length. Denote by $U_P$ the unipotent radical of $P$. Recall [MW94, §I.2.17] the space $A^2(U_P(\mathbb A_F)L(F) \backslash G(\mathbb A_F), \chi_{G,L})$ of smooth $K$-finite functions $\phi$ on $U_P(\mathbb A_F)L(F) \backslash G(\mathbb A_F)$ such that for any $k \in K$,

$$x \mapsto \delta_P(x)^{-1/2}(x)\phi(xk)$$

is an element of $A^2(L(F) \backslash L(\mathbb A_F), \chi_{G,L})$. In other words,

$$A^2(U_P(\mathbb A_F)L(F) \backslash G(\mathbb A_F), \chi_{G,L}) = \text{Ind}_{P(\mathbb A_F)}^{G(\mathbb A_F)} (A^2(L(F) \backslash L(\mathbb A_F), \chi_{G,L}))^{K-\text{fin}}.$$

This space is endowed with the usual left action of $H(G)$, which we will denote by $\rho_P^G$. If $\pi_L$ is an irreducible admissible representation of $L(\mathbb A_F)$ such that $\omega_{\pi_L}|_{\mathfrak A_L} = \chi_{G,L}$, denote by

$$A^2(U_P(\mathbb A_F)L(F) \backslash G(\mathbb A_F), \chi_{G,L})_{\pi_L}$$

the sub-$H(G)$-module of $A^2(U_P(\mathbb A_F)L(F) \backslash G(\mathbb A_F), \chi_{G,L})$ consisting of functions $\phi$ such that for any $k \in K$,

$$x \mapsto \delta_P(x)^{-1/2}(x)\phi(xk) \in \mathfrak A^2(L(F) \backslash L(\mathbb A_F), \chi_{G,L})_{\pi_L}.$$

Let $W(L, \tilde G) = N_{G(F)}(L)/L(F)$, where the action of $\tilde G(F)$ on $G$ is the adjoint action coming from the definition of a twisted space [MW16b, §I.1.1]. For $\tilde w \in W(L, \tilde G)$ and $f(\tilde x)d\tilde x \in H(\tilde G)$, we have a map [MW16b, bottom of p. 1204]

$$\rho_{P,\tilde w}^G(f) : A^2(U_P(\mathbb A_F)L(F) \backslash G(\mathbb A_F), \chi_{G,L}) \to A^2(U_{\tilde w}(P)(\mathbb A_F)L(F) \backslash G(\mathbb A_F), \chi_{G,L}),$$

$$\phi \mapsto \left(g \mapsto \int_{G(\mathbb A_F)} \phi(\tilde w^{-1}g\tilde x)f(\tilde x)d\tilde x \right)$$
and for $f_1, f_2 \in \mathcal{H}(G)$ and $f_2 \in \mathcal{H}(\widetilde{G})$ we have
\[
\rho_{\tilde{G}, \tilde{w}}(f_1 \ast f_2 \ast f_3) = \rho_{\tilde{w}(P)}(f_1) \circ \rho_{\tilde{G}, \tilde{w}}(f_2) \circ \rho_{\tilde{G}}(f_3).
\]

If $\pi_L$ is an irreducible admissible representation of $L(\mathbb{A}_F)$ such that $\omega_{\pi_L}|_{\mathcal{A}_L} = \chi_{G,L}$, then for any $f \in \mathcal{H}(\tilde{G})$, $\rho_{\tilde{G}, \tilde{w}}(f)$ restricts to
\[
\mathcal{A}^2(U_P(\mathbb{A}_F)L(F) \backslash G(\mathbb{A}_F), \chi_{G,L})_{\tilde{w}(\pi_L)} \rightarrow \mathcal{A}^2(U_{\tilde{w}(P)}(\mathbb{A}_F)L(F) \backslash G(\mathbb{A}_F), \chi_{G,L})_{\tilde{w}(\pi_L)}
\]
where $\tilde{w}(\pi_L) = \pi_L \circ \text{Ad}(\tilde{w}^{-1})$.

By meromorphic continuation of the usual integral formula, there is an intertwining operator
\[
M_{\tilde{P}|\tilde{w}(P)}(0) : \mathcal{A}^2(U_{\tilde{w}(P)}(\mathbb{A}_F)L(F) \backslash G(\mathbb{A}_F), \chi_{G,L}) \rightarrow \mathcal{A}^2(U_P(\mathbb{A}_F)L(F) \backslash G(\mathbb{A}_F), \chi_{G,L}).
\]
Since $\chi_{G,L}$ is unitary, $M_{\tilde{P}|\tilde{w}(P)}(0)$ is well-defined (i.e. holomorphic) at 0, and is in fact unitary. Moreover for any irreducible admissible representation $\pi_L$ of $L(\mathbb{A}_F)$, $M_{\tilde{P}|\tilde{w}(P)}(0)$ restricts to
\[
\mathcal{A}^2(U_{\tilde{P}}(\mathbb{A}_F)L(F) \backslash G(\mathbb{A}_F), \chi_{G,L})_{\tilde{w}(\pi_L)} \rightarrow \mathcal{A}^2(U_P(\mathbb{A}_F)L(F) \backslash G(\mathbb{A}_F), \chi_{G,L})_{\tilde{w}(\pi_L)}.
\]
Therefore for $f \in \mathcal{H}(\tilde{G})$ the composition $M_{\tilde{P}|\tilde{w}(P)}(0) \circ \rho_{\tilde{G}, \tilde{w}}(f)$ maps
\[
\mathcal{A}^2(U_P(\mathbb{A}_F)L(F) \backslash G(\mathbb{A}_F), \chi_{G,L})
\]
to itself and restricts to
\[
\mathcal{A}^2(U_P(\mathbb{A}_F)L(F) \backslash G(\mathbb{A}_F), \chi_{G,L})_{\tilde{w}(\pi_L)} \rightarrow \mathcal{A}^2(U_P(\mathbb{A}_F)L(F) \backslash G(\mathbb{A}_F), \chi_{G,L}_{\tilde{w}(\pi_L)}).
\]

We can finally recall the contribution of $L$ to the discrete part of the spectral side of the twisted trace formula for $\tilde{G}$. For $f \in \mathcal{H}(\tilde{G})$, let
\[
I_{\text{disc, } L}^{\tilde{G}}(f) = |W(L, \tilde{G})|^{-1} \sum_{\tilde{w} \in W(L, \tilde{G})_{\text{reg}}} |\det (\tilde{w} - 1|_{\mathcal{A}_L})|^{-1} \text{tr} \left( M_{\tilde{P}|\tilde{w}(P)}(0) \circ \rho_{\tilde{G}, \tilde{w}}(f) \right)
\]
where $W(L, \tilde{G})_{\text{reg}}$ is the set of $\tilde{w} \in W(L, \tilde{G})$ such that $(\alpha_{\tilde{G}})^{\tilde{w}} = 0$. As the notation suggests, $I_{\text{disc, } L}^{\tilde{G}}(f)$ only depends on $f$ and the $G(F)$-conjugacy class of $L$. In fact it depends on $f$ only via its image in $I(\tilde{G})$. The fact that the trace of $M_{\tilde{P}|\tilde{w}(P)}(0) \circ \rho_{\tilde{G}, \tilde{w}}(f)$ on $\mathcal{A}^2(U_P(\mathbb{A}_F)L(F) \backslash G(\mathbb{A}_F), \chi_{G,L})$ is well-defined and equals the absolutely convergent sum
\[
\sum_{\pi_L \in \Pi_{\text{disc}(L, \chi_{G,L})} \atop \tilde{w}(\pi_L) = \pi_L} \text{tr} \left( M_{\tilde{P}|\tilde{w}(P)}(0) \circ \rho_{\tilde{G}, \tilde{w}}(f) \right) \mathcal{A}^2(U_P(\mathbb{A}_F)L(F) \backslash G(\mathbb{A}_F), \chi_{G,L})_{\tilde{w}(\pi_L)}
\]
is a consequence of work of Finis, Lapid and Müller, as explained in [LWT13, §14.3] and [MW16b, §X.5.2 and X.5.3].

The most interesting case is of course for $L = G$, since $I_{\text{disc, } G}^{\tilde{G}}(f)$ is simply the trace of $f$ on the discrete automorphic spectrum for $G$ and $\chi_G$. We will recall below the refinement of discrete terms by infinitesimal character and Hecke eigenvalues following Arthur and Mœglin–Waldspurger, that allows one to forget about convergence issues and work with finite sums. But first we make explicit the condition $\tilde{w}(\pi_L) \simeq \pi_L$ in the cases at hand.
(1) For $G = \text{GL}_N \times \text{GL}_1$ and a standard (i.e. block diagonal) Levi $L \simeq \left( \prod_{k \geq 1} (\text{GL}_k)^{n_k} \right) \times \text{GL}_1$ (where $n_k = 0$ for almost all $k$ and $\sum_{k \geq 1} kn_k = N$), there always exists an element of $\widetilde{G}(F)$ normalising $L$ (for example $\theta_0 : g \mapsto (g^{-1})$, and $W(L,G) \simeq \prod_{k \geq 1} S_{n_k}$. For $w = (\sigma_k)_{k \geq 1} \theta_0 \in W(L,G)$, $w$ is regular if and only if for every $k \geq 1$, the decomposition of $\sigma_k$ in cycles only involves cycles of odd length. For such a regular $w$ and if $\pi = (\bigotimes_{k \geq 1} (\pi_{k,1} \otimes \cdots \otimes \pi_{k,n_k})) \otimes \chi$ is an irreducible admissible representation of $L(\mathbb{A}_F)$, then $\tilde{w}(\pi) \simeq \pi$ if and only if each $\pi_{k,i}$ satisfies $\pi_{k,i}^\vee \otimes \chi \simeq \pi_{k,i}$ and for every $k \geq 1$, the isomorphism class of $(\pi_{k,i})_{1 \leq i \leq n_k}$ is fixed by $\sigma_k$.

(2) In the non-twisted cases $G = \text{GSpin}_{n+1}$ or $\text{GSpin}_{2n}$, recall that in Section [22] we chose $L \simeq \prod_{k \geq 1} (\text{GL}_k)^{n_k} \times G_m$ where $m + \sum_{k \geq 1} kn_k = n$ and $G_m$ is a $\text{GSpin}$ group of the same type as $G$ of absolute rank $m$. There is a natural embedding $W(L,G) \rightarrow \prod_{k \geq 1} (\{\pm 1\}^{n_k} \times S_{n_k})$ which is surjective unless $G = \text{GSpin}_{2n}$, $m = 0$, and there exists an odd $k \geq 1$ such that $n_k > 0$, in which case it is of index two.

An element $w = ((\varepsilon_{k,i})_{1 \leq i \leq n_k} \times \sigma_k)_{k \geq 1}$ is regular if and only if for every $k \geq 1$ and every cycle $(i_1 \cdots i_r)$ appearing in the decomposition of $\sigma_k$, $\prod_{j=1}^r \varepsilon_{k,i_j} = -1$. For such $w \in W(L,G)^{\text{reg}}$ and $\pi_L \simeq \bigotimes_{k \geq 1} (\pi_{k,1} \otimes \cdots \otimes \pi_{k,n_k}) \otimes \pi_{G_m}$ an irreducible admissible representation of $L(\mathbb{A}_F)$, we have $w(\pi_L) \simeq \pi_L$ if and only

(a) for every $k \geq 1$ and $1 \leq i \leq n_k$, $\pi_{k,i}^\vee \otimes \chi \simeq \pi_{k,i}$ where $\chi : \mathbb{A}_F^\times \rightarrow \mathbb{C}^\times$ is $\pi_{G_m} \circ \mu$, and

(b) for every $k \geq 1$ the isomorphism class of $(\pi_{k,i})_{1 \leq i \leq n_k}$ is fixed by $\sigma_k$.

We now recall from [MW16b, p. 1212] the refinement of the discrete part of the spectral side of the twisted trace formula by infinitesimal characters (using Arthur’s theory of multipliers) and families of Satake parameters.

**Definition 4.1.2.**

(1) Let $IC(G)$ be the set of semisimple conjugacy classes in the Lie algebra of the dual group (over $\mathbb{C}$) of $\text{Res}_{F/\mathbb{Q}}(G)$. This is the set where infinitesimal characters for irreducible representations of $G(F \otimes_{\mathbb{Q}} \mathbb{R})$ live. In the twisted case let $IC(G) = IC(G)^\theta$. For $\pi_\infty$ an irreducible admissible representation of $G(F \otimes_{\mathbb{Q}} \mathbb{R})$, denote by $\nu(\pi_\infty) \in IC(G)$ its infinitesimal character.

(2) Let $S$ be a large enough (i.e. containing $V_{\text{ram}}$ as in [MW16b, VI.1.1]) finite set of places of $F$. Let $FS^S(G) = \prod_{v \in S} \left( \hat{G} \rtimes \text{Frob}_v \right) \text{ss} / \hat{G}$, and in the twisted case let $FS^S(\hat{G}) = (FS^S(G))^\theta$. Write also $FS(G) = \lim_{S} FS^S(G)$ and in the twisted case $FS(\hat{G}) = \lim_{S} FS^S(\hat{G})$. If $\pi = \otimes'_v \pi_v$ is an irreducible admissible representation of $G(\mathbb{A}_F)$, we will write $c(\pi)$ for the associated element of $FS(G)$ via the Satake isomorphisms.

(3) For $\nu \in IC(\hat{G})$, $S$ as above, $c^S = (c_v)_{v \in S} \in FS^S(\hat{G})$, and $L$ a Levi subgroup of $G$, let $\Pi_{\text{disc}}(L,\hat{G},\nu,c^S)$ be the set of $\pi_L \in \Pi_{\text{disc}}(L,\hat{G},\nu,c^S)$ such that the infinitesimal character of $\pi_L,\infty$ maps to $\nu$ via Lie $\left( \text{Res}_{F/\mathbb{Q}}(L) \right) \rightarrow$ Lie $\left( \text{Res}_{\mathbb{F}/\mathbb{Q}}(G_v) \right)$, and for every $v \notin S$, $\pi_{L,v}$ is unramified for $K_v$, and its Satake parameter maps to $c_v$ via $L \rightarrow \hat{L}$ for $f \in \bigotimes_{v \in S} \mathcal{H}(\hat{G}(F_v))$, let
\[ I^\mathcal{G}_\text{disc, } \nu, \varsigma^\mathcal{S}(f) = |W(\mathbf{L}, \mathbf{G})|^{-1} \sum_{\tilde{w} \in W(\mathbf{L}, \mathcal{G})_{\text{reg}}} \det (\tilde{w} - 1 | \mathcal{G}_\mathbf{L}^\mathcal{G}) |^{-1} \sum_{\pi_\mathbf{L} \in \Pi_{\text{disc}}(\mathbf{L}, \chi_{\mathbf{G}, \mathbf{L}})_{\nu, \varsigma^\mathcal{S}}} \text{tr}_{\pi_\mathbf{L}}(f), \]

where we write

\[ \text{tr}_{\pi_\mathbf{L}}(f) = \left( M_{\mathbf{P}, \tilde{w}(\mathbf{P})}(0) \circ \rho^\mathcal{G}_\mathbf{P}, \tilde{w}(f) \right) \bigg| \mathcal{A}^2(U_{\mathbf{P}}(\mathcal{A}_F)L(F) \backslash \mathbf{G}(\mathcal{A}_F), \chi_{\mathbf{G}, \mathbf{L}})_{\nu, \varsigma^\mathcal{S}} \bigg). \]

Finally let

\[ I^\mathcal{G}_\text{disc, } \nu, \varsigma^\mathcal{S}(f) = \sum_L I^\mathcal{G}_{\text{disc, } \nu, \varsigma^\mathcal{S}}(f) \]

where the sum is over $\mathbf{G}(F)$-conjugacy classes of Levi subgroups of $\mathbf{G}$.

Seeing this as a sum over triples $(\mathbf{L}, \tilde{w}, \pi_\mathbf{L})$, all but finitely many terms vanish. Indeed, if we fix $\nu$, $S$, $\varsigma^\mathcal{S}$ and an idempotent $e$ of $\bigotimes_{v \in S} \mathcal{H}(\mathbf{G}(F_v))$, then there is a finite set $\Upsilon(\nu, S, \varsigma^\mathcal{S}, e)$ of triples $(\mathbf{L}, \tilde{w}, \pi_\mathbf{L})$ such that for any $f \in \bigotimes_{v \in S} \mathcal{H}(\mathcal{G}(F_v))$ for which $e \ast f = f \ast e = f$, the terms corresponding to $(\mathbf{L}, \tilde{w}, \pi_\mathbf{L}) \not\in \Upsilon(\nu, S, \varsigma^\mathcal{S}, e)$ in the double sum defining $I^\mathcal{G}_\text{disc, } \nu, \varsigma^\mathcal{S}(f)$ all vanish.

**Remark 4.1.4.** (1) By [JS81] and [MW89], taking the image in $FS(\mathcal{G}_N)$ is injective on formal sums of elements of $\Pi_{\text{disc}}(\mathcal{G}_n, \chi)$ (note that it is essential that all of the summands are $\chi$ self-dual for the same character $\chi$). For this reason we will often identify such formal sums and their image.

(2) In [MW16b] Meeglin–Waldspurger multiply (4.1.3) by $j(\mathcal{G})^{-1} := |\det(1 - \vartheta| \mathcal{A}_F/\mathcal{A}_\mathcal{G})|^{-1}$, but this factor is also present in $\iota(\mathcal{G}, \mathbf{H})$ with their definition.

**Definition 4.1.5.** (1) We will say that $\varsigma^\mathcal{S} \in FS(\mathcal{G})$ occurs in $I^\mathcal{G}_\text{disc}$ if there exists $\nu \in IC(\mathcal{G})$ and $f \in \mathcal{H}(\mathcal{G})$ such that up to enlarging $S$ we have $I^\mathcal{G}_{\text{disc, } \nu, \varsigma^\mathcal{S}}(f) \neq 0$.

(2) Let $\mathbf{D}$ be an induced central torus in $\mathbf{G}$, so that there is a dual morphism $^L\mathbf{G} \to {}^L\mathbf{D}$. For $\varsigma^\mathcal{S} \in FS(\mathcal{G})$ occurring in $I^\mathcal{G}_\text{disc}$ we define the central character of $\varsigma^\mathcal{S}$ to be the (unique by weak approximation for $\mathbf{D}$ [PR94] Proposition 7.3) character $\omega_\varsigma : \mathcal{A}_\mathbf{G}(\mathcal{A}_F)/\mathcal{A}_\mathbf{G}(F) \to \mathbb{C}^\times$ such that for almost all places $v$ of $F$, the Langlands parameter of $(\omega_\varsigma)_v$ equals the image of $c_v$ in $^L\mathbf{D}$.

Note that in all cases considered in this paper the connected centre of $\mathbf{G}$ is split and so one can take $\mathbf{D}$ to be the full connected centre.

**Lemma 4.1.6.** Let $\mathbf{G} = \mathcal{G}_N \times \mathcal{G}_1$ and $\mathcal{G} = \mathbf{G} \times \vartheta$. If $c \in FS(\mathcal{G})$ occurs in $I^\mathcal{G}_\text{disc}$ and $\chi$ is the central character of $c$, then there is a unique $\psi \in \Psi(\mathcal{G}, \chi)$ such that $c$ is associated to $\psi$.

**Proof.** This simply follows from Remark 4.1.4 (1) and the above description in the case at hand of the pairs $(\tilde{w}, \pi_\mathbf{L})$ with $\tilde{w} \in W(\mathbf{L}, \mathcal{G})_{\text{reg}}$, $\pi_\mathbf{L} \in \Pi_{\text{disc}}(\mathbf{L})$ and $\pi_\mathbf{L} \simeq \pi_\mathbf{L}$.

\[ \square \]

**Remark 4.1.7.** Let $\mathbf{G} = \mathcal{G}_N \times \mathcal{G}_1$ and $\mathcal{G} = \mathbf{G} \times \vartheta$. 

was chosen so that the usual pinning of \( GL_F \) over \( We consider twisted endoscopy with \( \pi, \chi \). Elliptic endoscopic groups.

4.2. \( \tilde{\theta} \) Denote the following form.

\[
\begin{pmatrix}
\hat{\chi} & g,x \\
H & \det
\end{pmatrix}(1) \quad \text{For } G_{\Spin}^4(S) \quad \text{of}
\begin{pmatrix}
\hat{\chi} & g,x \\
H & \det
\end{pmatrix}(2) \quad \text{It follows from } [JS81], [MW89] \text{ and Lemma 4.1.6 that for}
\begin{pmatrix}
\hat{\chi} & g,x \\
H & \det
\end{pmatrix}(3) \quad \text{For } c
\begin{pmatrix}
\hat{\chi} & g,x \\
H & \det
\end{pmatrix}(4) \quad \text{Denote}
\begin{pmatrix}
\hat{\chi} & g,x \\
H & \det
\end{pmatrix}(5) \quad \text{such}
\end{pmatrix}
\begin{pmatrix}

\theta(\hat{\chi} g,x) = (\hat{\chi} g^{-1} \hat{J}^{-1} x, x \det g)
\end{pmatrix}

(1) For \( \Phi \) a parabolic subgroup of \( G \) with Levi \( L \) and \( \pi_L \in \Pi(\Phi, \chi_{G,L}) \), the parabolically induced representation \( \mathcal{A}^2(\Phi \otimes \chi_{L})L(F) \backslash G(\mathbb{A}_F) \) is irreducible by \( MW89 \) (implying multiplicity one for the discrete automorphic spectrum for \( L \) and \( Ber84 \) [0.2], \( VOG86 \) Theorem 17.6] (irreducibility of unitary parabolic induction for general linear groups).

(2) It follows from \( JS81 \), \( MW89 \) and Lemma [4.1.6] that for \( c \in FS(G) \) occurring in \( r_{\text{disc}}^L \) \( L \) is determined by \( c \).

(3) For \( S \subset S' \), the linear form \( I^S_{\text{disc},\nu,c} \) on \( I(G) \) is simply the tensor product of \( I^S_{\text{disc},\nu,c} \) with the unramified linear form on \( I(G) \) corresponding to the Satake parameters \( \nu \in S', \nu S' = S \) (see Remark 2.3.4). This is particular to \( \text{GL}_n \) and is a direct consequence of strong multiplicity one. Also by strong multiplicity one for a given \( c \in FS(G) \) there is at most one \( \nu \in IC(G) \) such that \( I_{\text{disc},\nu,c} \neq 0 \). By these remarks, for \( c \in FS(G) \) we have a well-defined linear form \( I_{\text{disc},\nu,c}^S \) on \( I(G) \), whose restriction to \( I(G) \) (for large enough \( S \)) is \( I^S_{\text{disc},\nu,c} \) for the unique \( \nu \) such that this is non-zero, or 0 if no such \( \nu \) exists.

4.2. Elliptic endoscopic groups. Consider the split group \( \Gamma = \text{GL}_4 \times \text{GL}_1 \) over \( F \) and its automorphism \( \theta : (g, x) \mapsto (J^tg^{-1}J^{-1}, x \det g) \), where

\[
J = \begin{pmatrix}
0 & 0 & 0 & -1 \\
0 & 0 & 1 & 0 \\
0 & -1 & 0 & 0 \\
1 & 0 & 0 & 0
\end{pmatrix}
\]

was chosen so that the usual pinning of \( \text{GL}_4 \times \text{GL}_1 \) is stable under \( \theta \). Note that if \( (\pi, \chi) \) is a representation of \( \Gamma(F_v) \) for some place \( v \) of \( F \), then \( (\pi, \chi) \circ \theta \simeq (\hat{\pi} \otimes (\chi \circ \det), \chi) \). The dual group \( \hat{\Gamma} \) is naturally identified with \( \text{GL}_4(\mathbb{C}) \times \text{GL}_1(\mathbb{C}) \), and \( \hat{\theta}(g,x) = (\hat{J}^tg^{-1}J^{-1}x, x) \), where \( \hat{J} = J \) (but with coefficients in a different field).

Denote \( \hat{\Gamma} = \Gamma \times \{1, \theta\} \). We consider twisted endoscopy with \( \omega = 1 \).

Then the elliptic endoscopic data \( (H, \mathcal{H}, s, \xi) \) for \( \hat{\Gamma} \) are easily seen to be of the following form.

1. \( H = G_{\Spin}^5 \), dual \( \hat{H} = G_{\Spin}^4 \), for \( s = 1 \): The first projection identifies \( \xi_1(G_{\Spin}^5) = \hat{\Gamma} \) with the general symplectic group defined by \( \hat{J} \), and the “similitude factor” morphism \( G_{\Spin}^5 \to \text{GL}_4 \) equals \( pr_2 \circ \xi_1|_{G_{\Spin}^5} \). Both \( \Gamma \) and \( G_{\Spin}^5 \) are split, so there is an obvious choice for \( L^s(\xi) : L^s G_{\Spin}^5 \to L^s \hat{\Gamma} \).

2. \( G_{\Spin}^4 \), with \( \alpha \in F^\times / F_{\times}^2 \), dual \( \widetilde{G_{\Spin}^4} = GSO_4 \) with action of \( \text{Gal}(E/F) \) if \( \alpha \) is not a square, where \( E = F(\sqrt{\alpha}) \). Pick \( s = \text{diag}(-1, -1, 1, 1) \), then \( \hat{\Gamma}^{\text{Ad}(s) \circ \theta} \) is \( \text{GO}_4 \) for the Gram matrix

\[
\begin{pmatrix}
0 & 0 & 0 & 1 \\
0 & 0 & -1 & 0 \\
0 & -1 & 0 & 0 \\
1 & 0 & 0 & 0
\end{pmatrix}
\]
If $\alpha = 1$ the group $\text{GSpin}_4$ is split and we choose the obvious $L\xi$. Otherwise let $c$ be the non-trivial element of $\text{Gal}(E/F)$, and define $L\xi$ by mapping $1 \times c$ to
\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}, 1.
\]

(3) $R^\alpha := (\text{GSpin}_2^\alpha \times \text{GSpin}_4^\alpha)/\{(z,z^{-1})|z \in \text{GL}_1\}$, for non-trivial $\alpha$. The dual $\widehat{R}^\alpha$ is the subgroup of $\text{GSO}_2 \times \text{GSp}_2$ of pairs of elements with equal similitude factors, and $\text{Gal}(E/F)$ acts on the first factor. Let $s = \text{diag}(-1,1,1,1)$, so that
\[
\xi^\alpha_1(\widehat{R}^\alpha) = \{\text{diag}(x_1,A,x_2) | A \in \text{GL}_2, x_1x_2 = \text{det} A\}.
\]
Define $L\xi$ by mapping $1 \times c$ to
\[
\begin{pmatrix}
0 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0
\end{pmatrix}, 1.
\]

We also need to consider the elliptic endoscopic groups for $\text{GSpin}_5$ and $\text{GSpin}_4$. Let $H_1$ be the unique non-trivial elliptic endoscopic group for $\text{GSpin}_5$, so that $H_1 \simeq \text{GL}_2 \times \text{GL}_2/\{(zI_2,z^{-1}I_2)\}$. Then $\tilde{H}_1$ is the subgroup of $\text{GSp}_2(\mathbb{C}) \times \text{GSp}_2(\mathbb{C})$ of pairs of elements with equal similitude factors, so we have an obvious embedding of dual groups $\tilde{H}_1 \to \text{GSpin}_5 = \text{GSp}_4(\mathbb{C})$, inducing an embedding of $L$-groups $L\xi' : L\tilde{H}_1 \to L\text{GSpin}_5$.

Let $H_2^\alpha$ be the elliptic endoscopic group for $\text{GSpin}_4$ associated to $\alpha \in F^\times/F^\times 2$, $\alpha \neq 1$, so that $H_2^\alpha \simeq \text{GSpin}_2^\alpha \times \text{GSpin}_2^\alpha/\{(z,z^{-1})|z \in \text{GL}_1\}$. Recall that $\text{GSpin}_2^\alpha$ is naturally isomorphic to $\text{Res}_{F(\sqrt{\alpha})/F}\text{GL}_1$. Then $H_2^\alpha$ is the subgroup of $\text{GSO}_2(\mathbb{C}) \times \text{GSO}_2(\mathbb{C})$ consisting of pairs of elements with equal similitude factors, so we again have an obvious embedding of dual groups $\tilde{H}_2^\alpha \to \text{GSpin}_4 = \text{GSO}_4(\mathbb{C})$. If $\alpha = 1$ then this trivially extends to an embedding of $L$-groups, while if $\alpha \neq 1$, writing $\text{Gal}(F(\sqrt{\alpha})/F) = \{1,c\}$, define $L\xi' : L\tilde{H}_2^\alpha \to L\text{GSpin}_4$ by mapping $1 \times c$ to
\[
\begin{pmatrix}
0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0
\end{pmatrix}, 1.
\]

4.3. Stabilisation of the trace formula. We will need to use the stabilisation of the (twisted) trace formula for $\Upsilon$ and its elliptic endoscopic groups. Consider the latter first: let $(H,H,s,\xi)$ be an elliptic endoscopic datum for $(\Upsilon,\tilde{\Upsilon})$. The stabilisation of the trace formula for $H$ is as follows. Fix $\nu \in \text{IC}(H)$, $S$ a big enough set of places, and $c \in \text{FS}^S(H)$. Choose representatives $(H',\tilde{H}',s,\xi)$ for the isomorphism classes of elliptic endoscopic data for $H$, and for each representative choose $L\xi' : L\tilde{H}' \to L\tilde{H}$ extending $\xi$ (for example as in the previous section). It induces maps $L\xi : \text{FS}(H') \to \text{FS}(H)$ and $L\xi : \text{IC}(H') \to \text{IC}(H)$. Inductively
define a linear form on \( I(H(F_S)) \) by

\[
(4.3.1) \quad S^H_{\text{disc,} \nu, e}(f) := f^H_{\text{disc,} \nu, e}(f) - \sum_{e' = (H', \hat{H}', \nu', \xi')} \iota(e') \sum_{C_{\nu'} \supset C_\nu} S^{H'}_{\text{disc,} \nu', e'}(f^{H'})
\]

where the sum is over equivalence classes of nontrivial elliptic endoscopic data for \( H \), \( f^{H'} \) is a transfer of \( f \) (see Section 2.3), and the constants \( \iota(e') \) are recalled after the following theorem.

**Theorem 4.3.2** ([Art02 Global Theorems 2 and 2' and Lemma 7.3(b)]). The linear form \( S^H_{\text{disc,} \nu, e} \) is stable, i.e. factors through \( SI(H(F_S)) \).

Note that in general \( 4.3.1 \) is only well-defined thanks to Theorem 4.3.2 applied to \( H' \). However, for the groups \( H \) considered here, and for any non-trivial endoscopic group \( H' \), the only elliptic endoscopic group for \( H' \), and so \( S^{H'}_{\text{disc}} = I^{H'}_{\text{disc}} \).

Let us recall the definition of \( \iota(e') \), both for ordinary endoscopy and for twisted endoscopy. Assume that \( \hat{G} \) is a twisted space and \( \epsilon = (H, \hat{H}, s, \xi) \) is an elliptic endoscopic datum. Let

\[
\iota(e) = \frac{\tau(G)}{\tau(H)} \left| \frac{\pi_0 \left( \hat{Z}(\hat{G})^{\text{Gal}} \cap \hat{T}^{\theta,0} \right)}{|\pi_0(\text{Aut}(\epsilon))|} \right|
\]

where \( \tau \) is the Tamagawa number and the superscript 0 denotes the identity component. We have not included the factor \( |\det(1 - \theta| ...)|^{-1} \) from [MW16b VI.5.1] because of Remark 4.1.4 (2); compare with the definition on p. 109 of [KS99] using [MW16b Lem. 6.4.B]. Recall [MW16b p. 693] that there is a short exact sequence

\[
1 \to \left( \hat{Z}(\hat{G})/Z(\hat{G}) \cap \hat{T}^{\theta,0} \right)^{\text{Gal}} \to \text{Aut}(\epsilon)/\hat{H} \to \text{Out}(\epsilon) \to 1.
\]

In the ordinary (non-twisted) case we have \( \hat{T}^{\theta,0} = \hat{T} \supset Z(\hat{G}) \) and thus \( \iota(e) = \tau(\hat{G})\tau(\hat{H})^{-1}|\text{Out}(\epsilon)|^{-1} \). The only twisted case that we need in this paper is the case of \( \hat{\Gamma} \), when \( \hat{T}^{\theta,0} = \{((t_1, \ldots, t_k), x)|\forall i, t_i = t_{i-1}^{-1}x\} \) and so \( Z(\hat{G}) \cap \hat{T}^{\theta,0} \simeq \mathbb{C}^\times \). Similarly it is easy to see that \( Z(\hat{G})/Z(\hat{G}) \cap \hat{T}^{\theta,0} \simeq \mathbb{C}^\times \) with trivial action of \( \text{Gal} \), so we can conclude that \( \iota(\epsilon) = \tau(\hat{\Gamma})\tau(\hat{H})^{-1}|\text{Out}(\epsilon)|^{-1} \) for any elliptic endoscopic datum \( \epsilon = (H, \hat{H}, s, \xi) \) of \( \hat{\Gamma} \).

Let us make the constant \( \iota(\epsilon) \) explicit in the only two cases where it will be needed in this paper:

1. For the elliptic endoscopic group \( H_1 \) of \( \text{GSpin}_5 \), \( \iota(\epsilon) = 1/4 \).
2. For the elliptic endoscopic group \( \text{GSpin}_5 \) of \( \hat{\Gamma} \), \( \iota(\epsilon) = 1 \).

We can finally state the stabilisation of the twisted trace formula for \( (\Gamma, \hat{\Gamma}) \). As in the case of ordinary endoscopy we fix representatives \( \epsilon = (H, \hat{H}, s, \xi) \) of isomorphism classes of elliptic endoscopic data for \( \hat{\Gamma} \) and for each \( \epsilon \) we also choose an \( L \)-embedding \( \hat{\xi} : \hat{L}_H \to \hat{L}_G \) extending \( \xi \) (for example the ones defined in the previous section).

**Theorem 4.3.3** ([MW16b X.8.1]). For any \( \nu \) and \( e \) we have

\[
I_{\text{disc,} \nu, e}(f) = \sum_{\epsilon = (H, \hat{H}, s, \xi)} \iota(\epsilon) \sum_{C_{\nu'} \supset C_\nu} S^{H'}_{\text{disc,} \nu', e'}(f^{H'})
\]

where the first sum is over equivalence classes of elliptic endoscopic data for \( \hat{\Gamma} \).
5. Restriction of automorphic representations

5.1. Restriction for general groups. Let us recall a consequence of [HST12 §4] that we will need. Since in all cases considered in this paper the assumption of [Che18] Proposition 1 (iii) will be satisfied, one can use the more precise result of [Che18] (which can be formally generalised from cuspidal to square-integrable forms) instead. Consider an injective morphism \( G \hookrightarrow G' \) between connected reductive groups over a number field \( F \) such that \( G \) is normal in \( G' \) and \( G'/G \) is a torus. Choose a maximal compact subgroup \( K_\infty' \) of \( G'(F \otimes Q \mathbb{R}) \); then \( K_\infty := G(F \otimes Q \mathbb{R}) \cap K_\infty' \) is a maximal compact subgroup of \( G(F \otimes Q \mathbb{R}) \). Note that if \( \pi' \) is an irreducible unitary admissible \((g',K_\infty') \times G'(A,F,F)\)-module then \( \text{Res}_G^G(\pi') \) is a unitary admissible \((g,K_\infty) \times G(\mathbb{A}_{F,F})\)-module, but it has infinite length in general. We have a \((g,K_\infty) \times G(\mathbb{A}_{F,F})\)-equivariant map

\[
\text{res}_G^G : \mathcal{A}^2(\mathfrak{A}_G; G'(F) \backslash G'(\mathbb{A}_F)) \rightarrow \mathcal{A}^2(\mathfrak{A}_G G(F) \backslash G(\mathbb{A}_F))
\]

obtained by restricting automorphic forms. The fact that \( \text{res}_G^G \) takes values in \( \mathcal{A}^2(\mathfrak{A}_G G(F) \backslash G(\mathbb{A}_F)) \) is a routine verification, except for square-integrability which follows from the proof of [HST12 Lemma 4.19] (see also Remark 4.20 op. cit.). If \( \pi' \in \Pi_{\text{disc}}(G') \) and \( \iota : \pi' \hookrightarrow \mathcal{A}^2(\mathfrak{A}_G G'(F) \backslash G'(\mathbb{A}_F)) \), then \( \text{Res}_G^G(\iota(\pi')) \) is naturally identified with a quotient of \( \text{Res}_G^G(\pi') \). This quotient can be proper and of infinite length, but in any case it is non-zero. In particular there exists an irreducible constituent \( \pi \) of \( \text{Res}_G^G(\pi') \) such that \( \pi \in \Pi_{\text{disc}}(G) \). In this situation we will say that \( \pi \) is an automorphic restriction of \( \pi' \). Unsurprisingly, this notion of compatibility is compatible with the Satake isomorphism at almost all places:

**Lemma 5.1.1** (Satake). Suppose that \( \pi \simeq \otimes_v \pi_v \in \Pi_{\text{disc}}(G) \) is an automorphic restriction of \( \pi' \simeq \otimes_v \pi'_v \in \Pi_{\text{disc}}(G') \), then for almost all places \( v \) of \( F \) the Satake parameter \( c(\pi_v) \) of \( \pi_v \) is the image of \( c(\pi'_v) \) under the natural map

\[
(\mathcal{G}' \times \text{Frob}_v)^{ss} / \mathcal{G}' - \text{conj} \rightarrow (\mathcal{G} \times \text{Frob}_v)^{ss} / \mathcal{G} - \text{conj}.
\]

**Proof.** For almost all places \( v \), \( \pi_v \) is the unique unramified direct summand in \( \text{Res}_{G(F_v)}^{G(F')}(\pi'_v) \). The result follows from [Sat03 §7.2] applied to \( G \times T \rightarrow G' \), where \( T \) is any central torus in \( G \) isogenous to \( G'/G \), and the translation in terms of dual groups [Bor79 Prop. 6.7].

Let us now formulate a direct consequence of [HST12 Theorem 4.14], ignoring multiplicities.

**Theorem 5.1.2** (Hiraga–Saito). The map \( \text{res}_G^G \) is surjective, and so any discrete automorphic representation for \( G \) is an automorphic restriction of a discrete automorphic representation for \( G' \). In other words, there exists a surjective map

\[
\text{ext}_G^G : \Pi_{\text{disc}}(G) \rightarrow \Pi_{\text{disc}}(G') / (G'(\mathbb{A}_F) / G(\mathbb{A}_F) G(F) \mathfrak{A}_G)^{\vee}
\]

such that for any \( \pi' \in \text{ext}_G^G(\pi) \), \( \pi \) is a subrepresentation of \( \text{Res}_G^G(\pi') \).

In general this map \( \text{ext}_G^G \) is not uniquely determined.

We will mainly use this result for \( \text{Sp}_4 \hookrightarrow G\text{Spin}_5 \). This will be fruitful thanks to exterior square functoriality for \( G\text{L}_4 \) [Kim03] and the commutativity of the
following commutative diagram of dual groups:

\[
\begin{array}{ccc}
\hat{\text{GSpin}}_5 & \rightarrow & \hat{\text{Sp}}_4 = \text{SO}_5 \\
\downarrow^{\xi} & & \downarrow^{\text{Std} \oplus 1} \\
\text{GL}_4 \times \text{GL}_1 & \rightarrow & \text{SL}_6
\end{array}
\]

where \( f := \bigwedge^2 (\text{pr}_1) \otimes \text{pr}_2^{-1} \).

6. Global Arthur–Langlands parameters for \( \text{GSpin}_5 \)

6.1. Classification of global parameters. Let \( \chi : \mathbb{A}_F^\times / F^\times \rightarrow \mathbb{C}^\times \) be a continuous unitary character. Recall the set \( \Psi(\hat{\Gamma}, \chi) \) of formal global parameters defined in Section 2.3

In this section we will denote the functorial transfer \( \text{GL}_2 \times \text{GL}_2 \rightarrow \text{GL}_4 \) by \((\pi_1, \pi_2) \mapsto \pi_1 \boxtimes \pi_2\) (we will only need this in the weak sense, i.e., compatibility with Satake parameters at all but finitely many places). This transfer exists for cuspidal representations by [Ram00], and is easily extended to discrete representations:

- if \( \pi_1 = \eta[2] \) for some character \( \eta \) and \( \pi_2 \) is cuspidal, then \( \pi_1 \boxtimes \pi_2 = \eta \boxtimes \pi_2[2] \).
- if \( \pi_1 = \eta_1[2] \) and \( \pi_2 = \eta_2[2] \), then \( \pi_1 \boxtimes \pi_2 = \eta_1 \eta_2 \boxplus \eta_1 \eta_2[3] \).

Recall that in Section 4.2 we fixed a representative \((\hat{H}, H, s, \xi)\) for each equivalence class of elliptic endoscopic data for \( \hat{\Gamma} \), and in each case an \( L \)-embedding \( L\xi : L\hat{\Gamma} \rightarrow L\hat{\Gamma} = \hat{\Gamma} \times W_F \). We also fixed, for each \( H \) as above, a representative \((H', H', s', \xi')\) for each equivalence class of elliptic endoscopic data for \( H \), as well as an \( L \)-embedding \( L\xi' : L\hat{\Gamma} \rightarrow L\hat{\Gamma} \). We use this generic notation in the following Proposition, which shows that we may associate a parameter in the set \( \Psi(\hat{\Gamma}, \chi) \) to each discrete automorphic representation of \( \text{GSpin}_4 \) or \( \text{GSpin}_5 \) with central character \( \chi \); we will refine this in Propositions 6.1.5 and 6.1.6 to show that these parameters are in fact contained in the subsets \( \Psi_{\text{disc}}(\text{GSpin}_4, \chi), \Psi_{\text{disc}}(\text{GSpin}_5, \chi) \) respectively.

**Proposition 6.1.1.**

1. For \( L \) a proper Levi subgroup of \( \text{GSpin}_5 \), any \( c \in FS(\text{GSpin}_5) \) occurring in \( i_{\text{disc}}^{\text{GSpin}_5, L} \) such that \( \widehat{\mu}(c) = c(\chi) \) satisfies \( L\xi(c) \in \Psi(\hat{\Gamma}, \chi) \) and is not discrete.

2. Let \( H = (\text{GL}_2 \times \text{GL}_2) / \{(zI_2, z^{-1}I_2) | z \in \text{GL}_1\} \) be the unique non-trivial elliptic endoscopic group for \( \text{GSpin}_5 \). Then any \( c \in FS(H) \) occurring in \( i_{\text{disc}}^{H} \) satisfies \( L\xi(c) \in \Psi(\hat{\Gamma}, \chi) \).

3. Let \( H' \) be a non-trivial elliptic endoscopic group for \( \text{GSpin}_4 \). Then any \( c \in FS(H') \) occurring in \( i_{\text{disc}}^{H'} \) satisfies \( L\xi(c) \in \Psi(\hat{\Gamma}, \chi) \).

4. For \( L \) a Levi subgroup of \( \text{GSpin}_4 \), any \( c \in FS(\text{GSpin}_4) \) occurring in \( i_{\text{disc}}^{\text{GSpin}_4, L} \) such that \( \widehat{\mu}(c) = c(\chi) \) satisfies \( L\xi(c) \in \Psi(\hat{\Gamma}, \chi) \). If \( L \neq \text{GSpin}_4 \) then \( L\xi(c) \) is not discrete.

5. Any \( c \in FS(\text{GSpin}_4) \) occurring in \( S_{\text{disc}}^{\text{GSpin}_4} \) such that \( \widehat{\mu}(c) = c(\chi) \) satisfies \( L\xi(c) \in \Psi(\hat{\Gamma}, \chi) \).

6. Any \( c \in FS(\text{GSpin}_5) \) occurring in \( S_{\text{disc}}^{\text{GSpin}_5} \) such that \( \widehat{\mu}(c) = c(\chi) \) satisfies \( L\xi(c) \in \Psi(\hat{\Gamma}, \chi) \).
(7) Any \( c \in \text{FS}(\text{GSpin}_4) \) associated to a discrete automorphic representation for \( \text{GSpin}_5 \) with central character \( \chi \) satisfies \( L\xi(c) \in \Psi(\mathfrak{F}, \chi) \).

Proof. We use repeatedly the description of \( \mathcal{I}^G_{\text{disc}} \) explained in Section 4.1, namely that if \( c \in \text{FS}(\mathfrak{G}) \) occurs in \( \mathcal{I}^G_{\text{disc}} \), then there is a regular element \( \tilde{w} \in W(L, \mathfrak{G}) \), and \( \pi_L \in \Pi_{\text{disc}}(L) \) such that \( \pi_{\tilde{w}} \simeq \pi \) and \( c(\pi_L) \) maps to \( c \) via \( \mathcal{I}^L \to \mathcal{I}^G \).

(1) The possible proper Levi subgroups \( L \) and the embeddings \( \mathcal{I}^L \to \mathcal{I}^G_{\text{disc}} \) are listed in Section 2.2. In the case at hand, the possibilities are

\[
\begin{align*}
&\text{(a) } \text{GL}_1 \times \text{GSpin}_4 \cong \text{GL}_1 \times \text{GL}_2, \\
&\text{(b) } \text{GL}_2 \times \text{GSpin}_1 \cong \text{GL}_2 \times \text{GL}_1, \quad \text{and} \\
&\text{(c) } \text{GL}_1 \times \text{GL}_1 \times \text{GSpin}_1 \cong \text{GL}_1 \times \text{GL}_1 \times \text{GL}_1.
\end{align*}
\]

In the first case we find that the corresponding parameter is of the form \( \eta \oplus \pi \boxplus \eta \), where \( \pi \) is a unitary discrete automorphic representation of \( \text{GL}_2(\mathcal{A}_F) \) with \( \omega_\pi = \chi \) and \( \eta^2 = \chi \); in the second case, the parameter is of the form \( \eta \boxplus \pi \), where \( \pi \) is a unitary discrete automorphic representation of \( \text{GL}_2(\mathcal{A}_F) \) such that \( \pi^\vee \otimes \chi \simeq \pi \); and in the third case that the parameter is of the form \( \eta_1 \boxplus \eta_2 \boxplus \eta_3 \boxplus \eta_1 \) with \( \eta_1^2 = \eta_2^2 = \chi \).

(2) By the description of \( H \) as a quotient, \( c \) corresponds to a pair \((\pi_1, \pi_2)\) with each \( \pi_i \) either an element of \( \Pi_{\text{disc}}(\text{GL}_2) \) with \( \omega_{\pi_i} = \chi \) or \( \eta \boxplus \eta \) with \( \eta^2 = \chi \). It is easy to check that \( (L\xi \circ L\xi')(c) = (c(\pi_1) \oplus c(\pi_2), c(\chi)) \), so that the corresponding parameter is \( \pi_1 \boxplus \pi_2 \).

(3) This is similar to the previous two parts. Write \( H' = H_3^\circ \) as in Section 1.2 so that an element of \( \Pi_{\text{disc}}(H') \) is given by a pair of automorphic representations \( \rho_1, \rho_2 \) for the torus \( \text{GSpin}_4^2 \simeq \text{Res}_{E/F}(\text{GL}_1) \) (here \( E = F(\sqrt{5}) \)) whose restrictions to \( \text{GL}_1 \) are equal to \( \chi \). Then via the natural embedding \( \text{GSpin}_4^2 = \text{GSO}_2 \times \text{Gal}(E/F) \to \text{GL}_2 \), we have \( (L\xi \circ L\xi')(c) = (c(\pi_1) \oplus c(\pi_2), c(\chi)) \) where \( \pi_1 \) and \( \pi_2 \) are the cuspidal automorphic representations for \( \text{GL}_2 \) with central character \( \chi \) automorphically induced (for \( E/F \)) from \( \rho_1 \) and \( \rho_2 \) seen as unitary characters of \( \mathcal{A}_E/E^\times \).

(4) Recall that \( \text{GSpin}_4 \) is isomorphic to the subgroup of elements of \( \text{GL}_2 \times \text{GL}_2 \) such that the determinants of the two elements are equal. Accordingly, if \( c \) is discrete automorphic, i.e. its occurs in \( \mathcal{I}^\text{GSpin}_4_{\text{disc}} \), then by Theorem 5.1.2 it comes from the automorphic restriction of some \( (\pi_1, \pi_2) \in \Pi_{\text{disc}}(\text{GL}_2 \times \text{GL}_2) \), with \( c(\omega_{\pi_1})c(\omega_{\pi_2}) = c(\chi) \) and so \( \omega_{\pi_1}, \omega_{\pi_2} = \chi \). Then \( L\xi(c) = (c(\pi_1) \otimes c(\pi_2), c(\chi)) \), and the corresponding parameter is \( \pi_1 \boxplus \pi_2 \).

Otherwise \( c \) occurs in \( \mathcal{I}^\text{GSpin}_4_{\text{disc}} \) for some proper Levi subgroup. By the description given in Section 2.2 we see that \( L \) is isomorphic to \( \text{GL}_2 \times \text{GSpin}_4^1 \cong \text{GL}_2 \times \text{GL}_1 \) or to \( \text{GL}_1 \times \text{GL}_1 \times \text{GSpin}_1 \cong \text{GL}_1 \times \text{GL}_1 \times \text{GL}_1 \).

In either case we can compute explicitly as in (1), and we find that we obtain parameters of the form \( \pi \boxplus \pi \), where \( \pi \) is a discrete automorphic representation of \( \text{GL}_2(\mathcal{A}_F) \) such that \( \pi^\vee \otimes \chi \simeq \pi \), and parameters of the form \( \eta_1 \boxplus \eta_2 \boxplus \eta_3 \boxplus \eta_1 \) with \( \eta_1^2 = \eta_2^2 = \chi \).

(5) This follows immediately from the stable trace formula 13.1 for \( \text{GSpin}_4 \) and the two previous points.

(6) This follows from the stable twisted trace formula of Theorem 13.3. Observe that we can associate an element of \( \Psi(\mathfrak{F}, \chi) \) to any family of Satake parameters occurring in \( \mathcal{S}^\text{GSpin}_4_{\text{disc}} \) or to \( \mathcal{I}^\mathfrak{F}_{\text{disc}} \); in the former case this is the content of [5], and in the latter case it follows from Lemma 4.1.6.
Proposition 6.1.3.

We can now prove the symplectic/orthogonal alternative for $\text{GL}_4$. This is well known, and can also be proved using the theta correspondence or converse theorems; indeed, [AS14, Thm. 4.26] proves a corresponding result for $\text{GSpin}$ groups of arbitrary rank, showing that a $\chi$-self dual cuspidal automorphic representation $\pi$ of $\text{GL}_n$ arises as the transfer of a globally generic representation of a $\text{GSpin}$ group which is uniquely determined by the data of which of the corresponding symmetric and alternating square $L$-functions has a pole, together with the central character of $\pi$.

However, our emphasis here is slightly different (we wish to determine which representations have Satake parameters which occur in the discrete spectrum of $\text{GSpin}_5$), and in any case we find it instructive to show how this follows from the trace formula together with Kim’s exterior square transfer [Kim03].

The following remark will help us to distinguish parameters coming from different endoscopic subgroups.

Remark 6.1.2. The sets
\[ \{L^s(\text{FS}(\text{GSpin}_5))\} \cup L^s(\text{FS}(\text{GSpin}_4)) \] (where $\alpha \in F^x/F^{x,2}$ is non-trivial) are pairwise disjoint, because we can recover $\alpha$ as follows (by the definition of $L^s$): for $H = \text{GSpin}_4$ or $H = \text{Spin}_4$, $c^S \in \text{FS}(H)$ and $(g^S, x_0^2) = L^s(c^S)$, for any $v \notin S$, then $v$ splits in $F(\sqrt{\alpha})$ if and only if $\det g_v = x_v^2$. On the other hand if $H = \text{GSpin}_5$ or $H = \text{GSpin}_4$ then we always have $\det g_v = x_v^2$.

Proposition 6.1.3. Let $\pi$ be a $\chi$-self dual cuspidal automorphic representation for $\text{GL}_4$, and let $S$ be a finite set of places of $F$ containing all Archimedean places and all non-Archimedean places where $\pi$ is ramified.

1. If there are cuspidal automorphic representations $\pi_1$ for $\text{GL}_2$ such that $\omega_1 \omega_2 = \chi$ and $\pi \cong \pi_1 \boxtimes \pi_2$, then $L^S(s, \text{Sym}^2(\pi) \otimes \chi^{-1})$ has a pole at $s = 1$, and there exists $c' \in \text{FS}(\text{GSpin}_4)$ occurring in $S^S_{\text{GSpin}_4}$ and such that $L^s(c') = (c(\pi), c(\chi))$.

2. If $\omega_\pi \neq \chi^2$, then $\pi$ is an Asai transfer from a cuspidal automorphic representation of $\text{GL}_2/E$, for $E = F(\sqrt{\alpha})$, the quadratic extension of $F$ corresponding to the quadratic character $\chi^2/\omega_\pi$, and $L^S(s, \text{Sym}^2(\pi) \otimes \chi^{-1})$ has a pole at $s = 1$. Furthermore there exists $c' \in \text{FS}(\text{GSpin}_4)$ occurring in $S^S_{\text{GSpin}_4}$ and such that $L^s(c') = (c(\pi), c(\chi))$.

3. Otherwise (i.e. if $\omega_\pi = \chi^2$ and $\pi$ does not come from a pair of automorphic cuspidal representations for $\text{GL}_2$ as in (1)) $L^S(s, \Lambda^2(\pi) \otimes \chi^{-1})$ has a pole at $s = 1$, $c := L^{-1}(c(\pi), c(\chi)) \in \text{FS}(\text{GSpin}_5)$ occurs in $S^S_{\text{GSpin}_5}$, and for any large enough $S$ and any $v \in IC(\text{GSpin}_5)$
\[ S^S_{\text{GSpin}_5} = S^S_{\text{GSpin}_5} = S^S_{\text{GSpin}_5}. \]

Proof. (1) It suffices to note that
\[ L^S(s, \Lambda^2(\pi_1 \boxtimes \pi_2) \otimes (\omega_1 \omega_2)^{-1}) = L^S(s, \text{ad}^0(\pi_1))L^S(s, \text{ad}^0(\pi_2)) \]
is holomorphic at $s = 1$ since for each $i = 1, 2$ the automorphic representation $ad^0(\pi_i)$ defined in [GJ78] is either

(a) a self-dual cuspidal automorphic representation for $GL_4$ ([GJ78 Theorem 9.3]),
(b) $\eta \boxplus \sigma$ where $\eta$ is a character of order two and $\sigma$ is a self-dual cuspidal automorphic representation for $GL_2$ such that $\eta \otimes \sigma \simeq \sigma$ ([GJ78 Remark 9.9] with $\Omega/\Omega'$ of order two),
(c) $\eta_1 \boxplus \eta_2 \boxplus \eta_1 \eta_2$ where $\eta_1$ and $\eta_2$ are distinct characters of order two ([GJ78 Remark 9.9] with $\Omega/\Omega'$ of order two).

As in the proof of Proposition 6.1.1 (4) we see that the element $\eta(c') \in FS(GSpin_4)$ which is the image of $(c(\pi_1), c(\pi_2))$ via either of the two tensor product morphisms $GL_2 \times GL_2 \to GSO_4 = GSpin_4$ occurs in $\tilde{i}GSpin_4$ and $S_{disc}^{GSpin_4}$, and satisfies $\tilde{L}^\xi(c') = (c(\pi), c(\chi))$.

(2) By Remark 4.1.7 (2) we know that $(c(\pi), c(\chi))$ does not occur in $\tilde{i}GSpin_4$ for any proper Levi subgroup $L$ of $\Gamma$. Since $(\pi, \chi)$ occurs with multiplicity one in the discrete automorphic spectrum for $\Gamma$, the automorphic extension $\bar{\pi}$ of $\pi$ to $\bar{\Gamma}$ (provided by [GJ78, Proposition A.5]) for the $p$-adic case, the Archimedean case is proved similarly and so $(c(\pi), c(\chi))$ occurs in $\tilde{i}GSpin_4$.

In the stabilisation of the twisted trace formula (Theorem 4.3.3), this contribution comes from at least one elliptic endoscopic datum, i.e. there is an elliptic endoscopic group $H$ and $c' \in FS(H)$ occurring in $S_{disc}^H$ such that $\tilde{L}^\xi(c') = (c(\pi), c(\chi))$.

The character $\omega_\pi/\chi^2$ corresponds to some quadratic extension $E = F(\sqrt{\alpha})$, and by Remark 6.1.2 in the stabilisation of the twisted trace formula for $\tilde{\Gamma}$ this contribution must come from $S_{disc}^{GSpin_4}$ or $S_{disc}^R$ (a priori non-exclusively). In the latter case, we see that $\pi$ has the same Satake parameters as $\pi_1 \boxplus \pi_2$, where $\pi_1$ is either a discrete automorphic representation for $GL_2$ with central character $\chi$, or $\pi_1 = \eta \boxplus \eta$ with $\eta^2 = \chi$, and $\pi_2$ is a cuspidal $\chi$-self-dual automorphic representation for $GL_2$, corresponding to the extension $E/F$; but either possibility contradicts [JS81].

Thus $(c(\pi), c(\chi))$ comes from $S_{disc}^{GSpin_4}$.

- If it comes from $S_{disc}^H = I_{disc}^H$ for some elliptic endoscopic group $H \neq GSpin_4^{\alpha}$ for $GSpin_4^{\alpha}$ then

$$H \simeq GSpin_4^{\beta} \times GSpin_4^{\gamma}/\{(z, z^{-1})|z \in GL_1\}$$

for some $\beta, \gamma \in F^x/F^{x,2} \setminus \{1\}$ satisfying $\beta \gamma = \alpha$. Recall that $GSpin_4^{\beta} \simeq Res_{F(\sqrt{\beta})/F} GL_1$. Then we see that $\pi = \pi_1 \boxplus \pi_2$ where $\pi_1$ (resp. $\pi_2$) is the automorphic induction of a character of $k_F(\sqrt{\beta})/F(\sqrt{\beta})$ (resp. $k_F(\sqrt{\gamma})/F(\sqrt{\gamma})$) and this contradicts the cuspidality of $\pi$.

- If $(c(\pi), c(\chi))$ comes from $\tilde{i}GSpin_4^{\alpha}$ for the proper Levi subgroup $L \simeq GL_1 \times GSpin_4^{\alpha}$ then $\pi = \eta \boxplus \pi_1 \boxplus \eta$ where $\eta^2 = \chi$ and $\pi_1$ is the automorphic induction of a character of $k_F/E^x$ and we also get a contradiction with the cuspidality of $\pi$.

Therefore $(c(\pi), c(\chi))$ comes from a discrete automorphic representation for $GSpin_4^{\alpha}$. As explained in [AR11 §2.2] (i.e. using Theorem 5.1.2 for $GSpin_4^{\alpha} \hookrightarrow Res_{E/F} GL_2$), this is equivalent to $\pi$ being the Asai transfer of
a cuspidal automorphic representation \( \pi_E \) of \( \text{GL}_2(\mathbb{A}_E) \). Then \( L^S(s, \Lambda^2 \pi \otimes \chi^{-1}) = L^S(s, \text{Ind}^E_F(\text{Sym}^2 \pi_E \otimes \omega_{\pi_E}^r) \otimes \chi^{-1}) \), where \( \omega_{\pi_E}^r \) is the Gal\((E/F)\)-conjugate of \( \omega_{\pi_E} \).

If \( \pi_E \) is not dihedral then \( \Lambda^2 \pi \) is cuspidal by \([AR11]\ Prop. 3.2\), so it is enough to consider the case that \( \pi_E \) is dihedral, induced from a character \( \chi_{E'} \) of \( \mathbb{A}_{E}'/(E')^\times \), where \( E'/E \) is a quadratic extension. Then \( \text{Sym}^2 \pi_E = \text{Ind}^E_F \chi_{E'}^S \otimes \chi_{E'}^E|_{\mathbb{A}_E^\times} \), and it is easy to verify explicitly that the isobaric representation \( \text{Ind}^E_F(\text{Sym}^2 \pi_E \otimes \omega_{\pi_E}^r) \otimes \chi^{-1} \) cannot contain the trivial character.

(3) As in the previous case, \((c(\pi), c(\chi))\) occurs in \( I^S_{\text{disc}} \). By Remark \([6.1.2]\) in the stabilisation of the twisted trace formula for \( \hat{\Gamma} \) this contribution comes from \( H = \text{GSpin}_4 \) or \( H = \text{GSpin}_5 \) on the right-hand side. In the former case, as \( \text{GSpin}_4 \) embeds into \( \text{GL}_2 \times \text{GL}_2 \), we would be in the situation of part (1); so it must occur in \( S_{\text{disc}}^{\text{GSpin}_5} \). Moreover, it cannot come from \( S_{\text{disc}}^{H,1} \) or \( I_{\text{disc}}^{\text{GSpin}_5, 1} \) for a proper Levi \( L \), as by (the proof of) Proposition \([6.1.1]\) this would contradict strong multiplicity one, so we can conclude that \( I_{\text{disc},c}^{\text{GSpin}_5, \text{GSpin}_5} = S_{\text{disc}}^{\text{GSpin}_5} \) is not identically zero.

In particular there is a discrete automorphic representation \( \Pi \) for \( \text{GSpin}_5 \) such that \( L^S(\chi, \Pi) = (c(\pi), c(\chi)) \). Let \( \Pi' \) be an automorphic restriction (in the sense of Section \([5]\) of \( \Pi \) to \( \text{Sp}_4 \). Then \( \Pi' \) is a discrete automorphic representation for \( \text{Sp}_4 \), and Arthur associates a discrete parameter \( \psi' \in \Psi_{\text{disc}}(\text{Sp}_4) \) to \( \Pi' \) (see Theorem \([2.6.1]\)).

Now \( \Lambda^2(c(\pi)) \otimes c(\chi)^{-1} = 1 \oplus c(\psi') \) (see the commutative diagram \([5.1.3]\)) and so \( L^S(s, \Lambda^2(\pi) \otimes \chi^{-1}) = \zeta^S(s) L^S(s, \psi') \). Moreover by \([Kim03]\ Thm. 5.3.1), \( 1 \oplus c(\psi') \) is associated to a (unique) isobaric sum of unitary cuspidal representations, and by \([JS81]\ Thm. 4.4\) the same holds for \( \psi' \). This implies that \( L^S(s, \psi') \) does not vanish on the line \( \Re(s) = 1 \), by the main result of \([JS77]\). \( \Box \)

Remark 6.1.4. By Theorem \([2.7.1]\) and Proposition \([6.1.3]\) we see that \( \Psi_{\text{disc}}(\text{GSpin}_5) \) is the subset of \( \Psi(\hat{\Gamma}, \chi) \) consisting of pairs \((\psi, \chi)\) with \( \psi \) of the following kinds. (We have labelled them in the same way as in \([Art04]\). The groups \( S_\psi \) are easy to compute; for the values of \( \varepsilon_\psi \), see \([Art13]\ (1.5.6)].)

(a) cuspidal automorphic representations \( \pi \) of \( \text{GL}_4 \) such that \( \pi^\vee \otimes \chi \simeq \pi \) and \( L^S(s, \chi^{-1} \otimes \Lambda^2 \pi) \) has a pole at \( s = 1 \). (General type, \( S_\psi = 1, \varepsilon_\psi = 1 \).)

(b) \( \pi_1 \oplus \pi_2 \) where \( \pi_i \) are cuspidal automorphic representations of \( \text{GL}_2 \), \( \omega_{\pi_1} = \omega_{\pi_2} = \chi \) and \( \pi_1 \neq \pi_2 \). (Yoshida type, \( S_\psi = \mathbb{Z}/2\mathbb{Z}, \varepsilon_\psi = 1 \).)

(c) \( \pi[2] \) for a cuspidal automorphic representation for \( \text{GL}_2 \) such that \( \omega_{\pi}/\chi \) has order 2 (i.e. \( \pi, \chi \) is of orthogonal type, which means that \( \pi \) is automorphically induced from a character \( \eta : \mathbb{A}_E^\times/E^\times \to \mathbb{C}^\times \) for the quadratic extension \( E/F \) corresponding to \( \omega_{\pi}/\chi \), such that \( \eta^2 \neq \eta \) and \( \eta|_{\mathbb{A}_E^\times/E^\times} = \chi \)).

(Soudry type, \( S_\psi = 1, \varepsilon_\psi = 1 \).)

(d) \( \pi \oplus \eta[2] \) with \( \pi \) cuspidal for \( \text{GL}_2 \) and \( \omega_{\pi} = \eta^2 = \chi \). (Saito–Kurokawa type, \( S_\psi = \mathbb{Z}/2\mathbb{Z}, \varepsilon_\psi = \text{sgn} \) if \( \varepsilon(1/2, \pi \otimes \eta^{-1}) = -1 \), and \( \varepsilon_\psi = 1 \) otherwise.)

(e) \( \eta_1[2] \oplus \eta_2[2] \) with \( \eta_1^2 = \eta_2^2 = \chi \) and \( \eta_1 \neq \eta_2 \). (Howe–Piatetski-Shapiro type, \( S_\psi = \mathbb{Z}/2\mathbb{Z}, \varepsilon_\psi = 1 \).)

(f) \( \eta[4] \) with \( \eta^2 = \chi \). (One dimensional type, \( S_\psi = 1, \varepsilon_\psi = 1 \).)
Proposition 6.1.5. For $c \in FS(G\Spin_5)$ associated to a discrete automorphic representation $\Pi$ of $G\Spin_5$, with central character $\chi$, the associated element of $\Psi(\bar{\Gamma}, \chi)$ (by Proposition 6.1.1) belongs to the subset $\Psi_{disc}(G\Spin_5)$.

Proof. As in the proof of Proposition 6.1.3 we use an automorphic restriction $\Pi'$ of $\Pi$ to $(G\Spin_5)_{der} \simeq Sp_4$, and the associated parameter $\psi'$, which we know to be discrete. We know that $1 \oplus c(\psi') = \Lambda^2 (c(\psi)) \otimes c(\chi)^{-1}$.

By Theorem 2.6.1 we can and do assume that $\eta$ is not a square. In particular, this implies that $\psi$ does not have a summand of the form $\eta(2)$ or $\eta(4)$ (as the condition that $\eta$ is $\chi$-self dual forces $\eta^2 = \chi$). In addition, if $\psi = \psi_1 \oplus \psi_2$, then $c(\psi') = \left( \Lambda^2 (c(\psi_1)) \otimes c(\chi)_1^{-1} \right) \otimes \text{ad}^0 (c(\psi_1))$, which contradicts the discreteness of $\psi'$. Thus we have the following possibilities for $\psi$.

1. $\psi = \psi_1 \oplus \psi_2$ where $\psi_1$ is a cuspidal automorphic representation for $GL_2$ such that $\psi_1^2 \otimes \chi \simeq \psi_1$ and $\psi_1 \neq \psi_2$. We need to show that $\omega_{\pi_1} = \chi$, i.e. that $\pi_1, \chi$ is of symplectic type. Suppose not. We have $\omega^2 = \chi^2$, and by Remark 6.1.2 we also have $\omega_{\pi_1} \omega_{\pi_2} = \chi^2$ and so $\omega_{\pi_1} = \omega_{\pi_2}$. Then we find that $\Lambda^2 (\psi) \otimes \chi = (\omega_{\pi_1} / \chi) \otimes (\omega_{\pi_2} / \chi) \otimes (\chi^{-1} \Pi \otimes \pi_2)$. Since $\omega_{\pi_1} / \chi = \omega_{\pi_2} / \chi$ is a non-trivial quadratic character, this cannot be written as $1 \otimes \psi'$ with $\psi'$ discrete, a contradiction.

2. $\psi = |2\rangle$, where $\pi$ is a cuspidal automorphic representation for $GL_2$ such that $\psi = \psi' \otimes \chi \simeq \pi$. In this case we need to check that $\omega_{\pi} / \chi$ has order 2, i.e. is non-trivial. But if $\chi = \omega_{\pi}$ then $\psi' = \Lambda^2 (|2\rangle) \otimes \omega_{\pi}^{-1} = \text{ad}^0 (|2\rangle) \otimes [3]$, which cannot be written as an isobaric sum of 1 and discrete automorphic representations for general linear groups, a contradiction.

3. $\psi = |1\rangle$ where $\pi$ is a cuspidal automorphic representation for $GL_4$ such that $\pi^2 \otimes \chi \simeq \pi$. In this case we need to check that $(\pi, \chi)$ is of symplectic type, i.e. that $L^S(s, \Lambda^2 (\pi) \otimes \chi)$ has a pole at $s = 1$. Exactly as in the proof of Proposition 6.1.3, we have $L^S(s, \Lambda^2 (\pi) \otimes \chi) = \zeta^S(s)L^S(s, \psi')$, and $L^S(s, \psi')$ does not vanish on the line $\Re(s) = 1$, as required. □

Proposition 6.1.6.

(1) For $c \in FS(G\Spin_4)$ associated to a discrete automorphic representation $\pi$ for $G\Spin_4$ having central character $\chi$, the element $L^c(\xi)(c) \in \Psi(\bar{\Gamma}, \chi)$ associated to $c$ by Proposition 6.1.1 belongs to $\Psi_{disc}(G\Spin_4, \chi)$.

(2) For $c \in FS(G\Spin_4)$, occurring in $S_{disc}(G\Spin_4)$, such that $\mu(c) = c(\chi)$ and such that $L^c(\xi)(c)$ is discrete, we have that $L^c(\xi)(c) \in \Psi_{disc}(G\Spin_4, \chi)$.

Proof. (1) By Theorem 2.6.1 we can and do assume that $\chi$ is not a square. As explained in the proof of Proposition 6.1.4, the parameter of $\pi$ is of the form $\pi_1 \otimes \pi_2$, where $\pi_1, \pi_2$ are discrete automorphic representations of $GL_2$ with $\omega_{\pi_1} \omega_{\pi_2} = \chi$. If neither $\pi_1, \pi_2$ were cuspidal, then $\chi$ would be a square, so we may assume that $\pi_1$ is cuspidal. If $\pi_2 = \eta(2)$ then $\pi_1 \otimes \pi_2 = \pi_3(2)$ where $\pi_3 = \eta \otimes \pi_1$, so $\omega_{\pi_3} = \chi$, and it follows from Theorem 2.7.1 that this parameter belongs to $\Psi_{disc}(G\Spin_4, \chi)$.

It remains to consider the case that $\pi_1, \pi_2$ are both cuspidal. If $\pi_1 \otimes \pi_2$ is cuspidal, then the parameter belongs to $\Psi_{disc}(G\Spin_4, \chi)$ by Proposition 6.1.3. If $\pi_1 \otimes \pi_2$ is not cuspidal, then since $\omega_{\pi_1} \omega_{\pi_2} = \chi$ is not a square, $\pi_1$ cannot be a twist of $\pi_2$, and it follows from Theorem A of the appendix
of $\chi$ (A.2.2)), so it again follows from Theorem 2.7.1 that this parameter belongs to $\Psi_{\text{disc}}(\text{GSpin}_4, \chi)$, as required.

(2) By Proposition 6.1.1 (4) and the stabilisation of the trace formula for $\text{GSpin}_4$, either $c$ is associated to a discrete automorphic representation for $\text{GSpin}_4$, or there exists $\alpha \in F^\times/F^\times \backslash \{1\}$ and $c' \in FS(H_2^+) \cap H_2^+$ such that $c = \xi c'$. The first case we conclude by the previous point, so we are left to consider the second case. Denote $E = F(\sqrt{\alpha})$ and $\text{Gal}(E/F) = \{1, \sigma\}$. By the description of $H_2^+$ in Section 4.2 we obtain that $c = c(\pi_1) \oplus c(\pi_2)$ where each $\pi_i$ is a cuspidal automorphic representation automatically induced for $E/F$ from a character $\chi_i$ of $\mathbb{A}_E/E^\times$ such that $\chi_i|_{\mathbb{A}_E^+} = \chi$ and $\chi_1, \chi_1^\sigma, \chi_2, \chi_2^\sigma$ are pairwise distinct, and again we conclude by Theorem 2.7.1.

\section{Multiplicity formula}

In this section we prove the multiplicity theorem for $\text{GSpin}_5$ (Theorem 7.4.1), which describes the discrete automorphic spectrum in terms of the packets $\Pi_{\psi}(\varepsilon, \psi)$ defined in Definition 2.6.3. We begin with some preliminaries.

\subsection{Canonical global normalisation versus Whittaker normalisation}

Recall from Remark 4.1.7 that for $G = GL_N \times GL_1$ and $\tilde{G} = G \times \theta$, for a Levi subgroup $L$ of $G$ and $\pi_L \in \Pi_{\text{disc}}(L)$ the parabolically induced representation $\tilde{A}(U_P(\mathbb{A}_F)L(F) \backslash G(\mathbb{A}_F))_{\pi_L}$ is irreducible. For $w \in W(L, G)$ we have a canonical (“automorphic”) extension of this representation of $G(\mathbb{A}_F)$ to $\tilde{G}$, denoted $M_{P(\varpi)}(w) \circ P_{\oplus}^{\tilde{G}, \tilde{w}}$ in Section 4. We have another canonical normalisation of this extension, namely the Whittaker normalisation recalled in Section 3.2.

\textbf{Lemma 7.1.1 (Arthur).} These two extensions coincide.

\textbf{Proof.} The proof of [Art13 Lemma 4.2.3] readily extends to the case at hand. $\square$

\subsection{The twisted endoscopic character relation for real discrete tempered parameters.}

\textbf{Proposition 7.2.1.} Let $\varphi : W_\mathbb{R} \to \text{GSpin}_4$ be a discrete parameter. Then the twisted endoscopic character relation holds for $\Pi_{\varphi}$ (as defined by Langlands in [Lan89]), i.e. part 2 of Theorem 3.1.1 holds.

Recall that for $\varphi$ such that $\tilde{\mu} \circ \varphi$ is a square, this twisted endoscopic character relation is a direct consequence of [Mez10] and [AMR15 Annexe C].

\textbf{Proof.} We use a global argument similar to (but simpler than) [AMR15 Annexe C]. Up to twisting we can assume that $\text{Std}_{\text{GSpin}_5} \circ \varphi \simeq (I_{a_1} \oplus I_{a_2} \oplus \text{sign } 2a_1)$, where $a_1, a_2 \in \frac{1}{2}\mathbb{Z}_{>0}$ are such that $a_1 - a_2 \in \mathbb{Z}_{>0}$ (and as before, $I_a = \text{Ind}_{\mathbb{C}^\times}^{\mathbb{R}^\times}(z \mapsto (z/\bar{z})^a)$). Fix a continuous character $\chi : \mathbb{A}^\times/\mathbb{R}_{>0}^\times \to \mathbb{C}^\times$ such that $\chi|_{\mathbb{R}^\times} = \text{sign } 2a_1$. There are cuspidal automorphic representations $\pi_1, \pi_2$ for $GL_2/Q$ with central characters $\omega_{\pi_1} = \omega_{\pi_2} = \chi$ and such that $\text{rec}(\pi_i, \infty) = I_{a_i}$ (apply [Ser97 Proposition 4] with $n = 1, k = 2a_i + 1$ fixed and $N$ of the form $\ell \text{cond}(\chi)$ where $\text{cond}(\chi)$ is the conductor of $\chi$ and $\ell \to +\infty$ prime). Let $\psi = \pi_1 \boxplus \pi_2 \in \Psi_{\text{disc}}(\text{GSpin}_5, \chi)$, so that $\psi_\infty = \varphi$.
By [Mez16] there is \( z(\varphi) \in \mathbb{C}^\times \) such that for any \( f_\infty \in I(\tilde{\Gamma}_R) \) we have
\[
\text{tr} \, \tilde{\pi}_\psi^F(f_\infty) = z(\varphi) \left( \text{tr} \, \pi_\psi^+ (f') + \text{tr} \, \pi_\psi^- (f'_\infty) \right)
\]
where \( \pi_\psi^+ \) (resp. \( \pi_\psi^- \)) is the generic (resp. non-generic) element of \( \Pi_\varphi \), i.e. \( \langle \cdot, \pi_\psi^+ \rangle \) (resp. \( \langle \cdot, \pi_\psi^- \rangle \)) is the trivial (resp. non-trivial) character of \( S_\varphi \). We need to show that \( z(\varphi) = 1 \). Recall that for any finite prime \( p \) the twisted endoscopic character relation
\[
\text{tr} \, \tilde{\pi}_\psi^F(p) = \sum_{\pi_p \in \Pi_{\psi_p}} \text{tr} \, \pi_p(f'_p)
\]
holds by the main theorem of [CG15].

In the discrete part of the trace formula for \( \tilde{\Gamma} \), the contribution \( I^F_{\text{disc}, c(\psi)} \) of \( c(\psi) \) only comes from \( L = \text{GL}_2 \times \text{GL}_2 \) and \( \tilde{\omega} = \theta_0 \), using notation as in the discussion preceding Definition 4.1.2. By Lemma 7.1.1 and since \( \det(\tilde{\omega} - 1|\mathcal{F}_\Gamma^L) = 2 \) this contribution is (on \( I(\tilde{\Gamma}_S) \) for \( S \) containing \( \infty \) and all places where \( \pi_1 \) or \( \pi_2 \) ramify)
\[
\prod_{v \in S} h_v \mapsto \frac{1}{2} \prod_v \text{tr} \, \tilde{\pi}_\psi^F(h_v)
\]
(7.2.2) where \( \tilde{\pi}_\psi^F \) is the Whittaker-normalised extension to \( \tilde{\Gamma}(F_v) \) of the irreducible parabolically induced representation \( \pi_{1,v} \times \pi_{2,v} \). Thus we get for \( h = \prod_{v \in S} h_v \in I(\tilde{\Gamma}_S) \)
\[
I^F_{\text{disc}, c(\psi)}(h) = \frac{z(\varphi)}{2} \prod_{v \in S} \sum_{\pi_v \in \Pi_{\psi_v}} \text{tr} \, \pi_v(h_v)^{\text{GSpin}_5}
\]
By the stabilisation of the twisted trace formula (Theorem 4.3.3 and Remark 6.1.2 and Proposition 6.1.6 (2) which imply that the endoscopic groups \( \text{GSpin}_5^\alpha \) and \( \mathbb{R}^\alpha \) have vanishing contributions corresponding to \( c(\psi)^S \), 7.2.2 equals
\[
S_{\text{disc}, c(\psi)}(h^{\text{GSpin}_5})
\]
By surjectivity of the transfer map \( h \mapsto h^{\text{GSpin}_5} \) (Proposition 7.4.3), this determines the stable linear form \( S_{\text{disc}, c(\psi)}(h^{\text{GSpin}_5}) \). Let
\[
H = (\text{GL}_2 \times \text{GL}_2) / \{(zI_2, z^{-1}I_2) \mid z \in \text{GL}_1\}
\]
be the unique non-trivial elliptic endoscopic group for \( \text{GSpin}_5 \). The \( (\nu(\psi), c(\psi)^S) \)-part of the stabilisation of the trace formula (Theorem 4.3.2) for \( \text{GSpin}_5 \) now reads, for \( f = \prod_{v \in S} f_v \in I(\text{GSpin}_5) \),
\[
I^{\text{GSpin}_5}_{\text{disc}, \nu(\psi), c(\psi)^S}(f) = \frac{z(\varphi)}{2} \prod_{v \in S} \sum_{\pi_v \in \Pi_{\psi_v}} \text{tr} \, \pi_v(f_v) + \frac{1}{4} \sum_{\nu' \rightarrow \nu(\psi)} S^{H}_{\text{disc}, \nu', c^S}(f^H).
\]
Now \( S^H_{\text{disc}, \nu', c^S} = I^H_{\text{disc}, \nu', c^S} \) is non-vanishing if and only if \( (\nu', c^S) \) is associated to \( (\pi_1, \pi_2) \) or to \( (\pi_2, \pi_1) \), in which case it equals \( \text{tr} \, (\pi_1 \otimes \pi_2) \) or \( \text{tr} \, (\pi_2 \otimes \pi_1) \). By the endoscopic character relations, in either case we have
\[
S^H_{\text{disc}, \nu', c^S}(f^H) = \prod_{v \in S} \sum_{\pi_v \in \Pi_{\psi_v}} (s, \pi_v) \, \text{tr} \, \pi_v(f_v),
\]
where $s$ is the non-trivial element of $\mathcal{S}_\psi$. Thus we obtain

$$I_{\text{disc}, \nu(c(\psi))}^{G\text{Spin}_5}(f) = \sum_{\left(\pi_v\right) \in \Pi_{\psi}} \frac{z(\varphi) + \prod_{\nu \in S} \langle s, \pi_v \rangle}{2} \prod_{\nu \in S} \text{tr} \pi_v(f_\nu).$$

By Proposition 6.1.1 (1) the left-hand side simply equals the trace of $f$ in the $(\nu(\psi), c(\psi)^S)$-part of the discrete automorphic spectrum for $G\text{Spin}_5$. Varying $S$, the above equality means that the multiplicity of $\pi = \otimes'_v \pi_v \in \Pi_{\psi}$ in $A^2(G\text{Spin}_5)$ equals $\frac{z(\varphi) + \langle s, \pi \rangle}{2}$. Comparing with [CG13, Theorem 3.1] (which relies on the theta correspondence and not trace formulas) for any $\pi$ we finally obtain $z(\varphi) = 1$. \hfill \Box

**Remark 7.2.3.** Arguing as in Lemma C.1 of [AMR15] one could certainly prove the Proposition without using [CG13, Theorem 3.1], since $|z(\varphi)| = 1$ and $(z(\varphi)-1)/2 \in \mathbb{Z}_{\geq 0}$ imply $z(\varphi) = 1$ (consider the multiplicity of $\pi_{\infty} \otimes \bigotimes_p \pi_p$ where $\langle s, \pi_p \rangle = +1$ for all $p$).

### 7.3. Local parameters

In this section we obtain Arthur’s multiplicity formula for $G\text{Spin}_5$, by formally using the stable twisted trace formula and twisted endoscopic character relations to get the desired expression for $s_{\text{disc}, c}^{G\text{Spin}_5}$ for $c$ corresponding to $\psi \in \Psi_{\text{disc}}(G\text{Spin}_5)$, and then the stable trace formula for $G\text{Spin}_5$.

We begin with the following important point, which is Conjecture 2.5.3 for $G = G\text{Spin}_5$.

**Proposition 7.3.1.** If $\pi$ is a $\chi$-self dual cuspidal automorphic representation of $GL_4(\mathbb{A}_F)$ of symplectic type, then for any place $v$ of $F$, the pair $(\text{rec}(\pi_v), \text{rec}(\chi_v))$ is of symplectic type, i.e. factors through $G\text{Sp}_4(\mathbb{C})$.

**Proof.** This follows from [GT11a, Thm. 12.1], which shows that $\pi$ arises as the transfer of a (globally generic) automorphic representation $\Pi$ of $G\text{Sp}_4(\mathbb{A}_F)$, and that at each place $v$, the pair $(\text{rec}(\pi_v), \text{rec}(\chi_v))$ is obtained from the $L$-parameter associated to $\Pi_v$ by the main theorem of [GT11a]. \hfill \Box

**Remark 7.3.2.** There are at least two alternative ways of proving Proposition 7.3.1. One is to use the main results of [Kim03] and [Hen09], which imply in particular that for each place $v$ the representation $\bigwedge^2 \text{rec}(\pi_v) \otimes \text{rec}(\chi_v)^{-1}$ contains the trivial representation, together with a case by case analysis. The other is to follow the argument of [Art13, §8.1].

### 7.4. The global multiplicity formula

Given Proposition 6.1.5, the multiplicity formula is morally equivalent to the following formula for any $\psi \in \Psi_{\text{disc}}(G\text{Spin}_5)$, $f \in \mathcal{H}(G\text{Spin}_5)$ and $S$ large enough:

$$s_{\text{disc}, \nu(c(\psi))}^{G\text{Spin}_5}(\psi) = \begin{cases} \frac{z_{\psi}(s\psi)}{|S\psi|} \sum_{\pi \in \Pi_{\psi}} \langle s\psi, \pi \rangle \text{tr} \pi & \text{if } \nu = \nu(\psi) \\ 0 & \text{otherwise.} \end{cases}$$

This is the simplification (for discrete parameters) of the general stable multiplicity formula (see [Art13, Theorem 4.1.2]).

We now prove the multiplicity formula; the following theorem is Conjecture 2.5.6 specialised to the case $G = G\text{Spin}_5$. We write $\Pi_{\psi}(\varepsilon_\psi)$ for the set of representations defined in 2.5.5 (with no tilde, since we are working with $G\text{Spin}_5$).
Theorem 7.4.1. There is an isomorphism of $\mathcal{H}(\text{GSpin}_5)$-modules

\[(7.4.2)\quad A^2(\text{GSpin}_5) \cong \bigoplus_{\pi \in \Pi_{\text{disc}}(\text{GSpin}_5, \chi)} \prod_{\chi: \mathbb{A}_F^\times / F^\times \mathbb{R}_{>0} \to \mathbb{C}^\times} \prod_{\psi \in \Psi_{\text{disc}}(\text{GSpin}_5, \chi)} \prod_{\pi \in \Pi_{\psi}(\chi)} \pi \]

where $\chi$ runs over the continuous (automatically unitary) characters.

Proof. Fix a continuous character $\chi: \mathbb{A}_F^\times / F^\times \mathbb{R}_{>0} \to \mathbb{C}^\times$, and write

\[A^2(\text{GSpin}_5, \chi)\]

for the space of $\chi$-equivariant square-integrable automorphic forms on which $\mathbb{A}_F^\times / F^\times$ acts via $\chi$. For any $\nu \in IC(G)$ and $c \in FS(G)$, write

\[A^2(\text{GSpin}_5, \chi)_{\nu, c} := \lim_S A^2(\text{GSpin}_5, \chi)_{\nu, c}.\]

Then we have

\[A^2(\text{GSpin}_5, \chi) = \bigoplus_{\nu \in IC(G)} \bigoplus_{c \in FS(G)} A^2(\text{GSpin}_5, \chi)_{\nu, c}.\]

Indeed, it follows from Proposition 6.1.5 that for any $c$ with $A^2(\text{GSpin}_5, \chi)_{\nu, c} \neq 0$, there is some $\psi \in \Psi_{\text{disc}}(\text{GSpin}_5, \chi)$ such $L(\xi(c(\pi))) = c(\psi)$, and it follows that $\nu \in IC(G)$ and $\psi \in \Psi_{\text{disc}}(\text{GSpin}_5, \chi)$, we have

\[(7.4.3)\quad A^2(\text{GSpin}_5, \chi)_{\nu, c} \cong \begin{cases} \bigoplus_{\pi \in \Pi_{\psi}(\chi)} \pi & \text{if } \nu = \nu(\psi) \\ 0 & \text{if } \nu \neq \nu(\psi). \end{cases}\]

Fix $\nu \in IC(G)$ and $\psi \in \Psi_{\text{disc}}(\text{GSpin}_5, \chi)$. If $\chi$ is a square, then we are done by Theorem 2.6.1 (that is, by reducing to $SO_5$, already proved by Arthur). So we only have to consider the following cases:

1. Cuspidal $\pi$ for $GL_4$ such that $\pi^V \otimes \chi \simeq \pi$ and $(\pi, \chi)$ is of symplectic type.
2. $\pi_1 \boxplus \pi_2$ where the $\pi_i$’s are distinct cuspidal automorphic representations for $GL_2$ with $\omega_{\pi_i} = \chi$ (Yoshida type).
3. $\pi[2]$ where $\pi$ is a cuspidal automorphic representation for $GL_2$ such that $\omega_{\pi}/\chi$ is a quadratic character, i.e. $\pi^V \otimes \chi \simeq \pi$ and $(\pi, \chi)$ is of orthogonal type (Soudry type).

In case (2), the multiplicity formula is a special case of [CG15, Theorem 3.1], proved using the global theta correspondence. So we can and do assume that we are in case (1) or case (3), so that in particular $S_{\psi} = 1$ and $\varepsilon_{\psi} = 1$. Furthermore, in either case we know that for any place $v$, the parameter $\psi_v$ of symplectic type, i.e. factors through $GSp_4$ (in case (1) this is Proposition 7.3.1 and in case (3) it follows from Theorem 2.6.1).

We will prove (7.4.3) by computing $j^G(\text{GSpin}_5, \text{GSp}_4)(f)$ for each $f \in \mathcal{H}(\text{GSpin}_5)$, which by definition is the trace of $f$ on the left hand side of (7.3.3) (note that this is well-defined, and equal to $j^G(\text{GSpin}_5, \text{GSp}_4)(f)$ for any sufficiently large $S$). To this end, note firstly that by Proposition 6.1.1 (1), we know that for any proper Levi $L$ of $\text{GSpin}_5$, and for any $c \in FS(\text{GSpin}_5)$ occurring in $j^G(\text{GSpin}_5, L)$, with central
character $\chi$, we have $L\xi(c) \in \Psi(\Gamma, \chi) \setminus \Psi_{\text{disc}}(\text{GSpin}_5, \chi)$. Consequently, we see that for any $\psi \in \Psi_{\text{disc}}(\text{GSpin}_5, \chi)$, we have

$$f_{\text{GSpin}_5}^{\text{disc}, \psi(c)} = f_{\text{GSpin}_5}^{\text{disc}, \psi(c)}.$$

(7.4.4)

Denoting as usual the unique non-trivial elliptic endoscopic group of $\text{GSpin}_5$ by $H$, we have that $S_{\text{disc}, \psi, c} = S_{\text{disc}, \psi, c}$. By surjectivity of $\text{FS}(H)$ such that $L\xi(c') = c(\psi)$ (because the proof of Proposition 6.1.1 (2) shows that any critical occurring in $S_{\text{disc}}$ is such that $L\xi \circ L\xi(c')$ is a sum of at least two discrete automorphic representations of general linear groups). It follows that we have

$$f_{\text{GSpin}_5}^{\text{disc}, \psi(c)} = S_{\text{disc}, \psi, c}.$$ 

(7.4.5)

By Proposition 6.1.6 (2), for any $c'$ occurring in $S_{\text{disc}}$, we have $L\xi(c') \neq c(\psi)$, so that (using also Remark 6.1.2) the contribution of $\psi$ to the stabilisation of the twisted trace formula for $\Gamma$ simply reads

$$f_{\text{disc}, \psi, c(\psi)}(h) = S_{\text{disc}, \psi, c(\psi)}(h \text{GSpin}_5)$$

where on the right-hand side $c(\psi)$ denotes the unique element of $FS(\text{GSpin}_5)$ which is the preimage of $c(\psi)$ in $FS(\Gamma)$ by $L\xi$, and similarly for $\nu$ seen as an element of $IC(\text{GSpin}_5)$. By surjectivity of $h \mapsto h \text{GSpin}_5$, (see Proposition 2.4.3), and Remark 4.1.7, this implies that $S_{\text{disc}, \nu, c(\psi)}$ vanishes identically if $\nu \neq \nu(\psi)$. In the definition of $f_{\text{disc}, \nu, c(\psi)}$ as a sum over Levi subgroups, the only non-vanishing summand corresponds to $I = \text{GL}_4$. By Lemma 7.1.1 we have for $h = \prod_v h_v \in I(\Gamma)$

$$f_{\text{disc}, \nu, c(\psi)}(h) = \prod_v \text{tr} \pi_{\psi_v}(h_v).$$

Applying Theorem 3.11 [1] (or rather its extension to parameters in $\Psi^+(\text{GSpin}_5)$ via parabolic induction; see [Art13 §1.5]) to the right-hand side of this equality and using (7.4.6) we obtain

$$S_{\text{disc}, \nu, c(\psi)}(\prod_v f_v) = \prod_v \sum_{\pi_v \in \Pi_{\psi_v}} \text{tr} \pi_v(f_v).$$

Combining this with (7.4.4) and (7.4.5), we conclude that

$$f_{\text{GSpin}_5, \text{GSpin}_5}^{\text{disc}, \nu, c(\psi)}(\prod_v f_v) = \begin{cases} \prod_v \sum_{\pi_v \in \Pi_{\psi_v}} \text{tr} \pi_v(f_v) & \text{if } \nu = \nu(\psi) \\ 0 & \text{if } \nu \neq \nu(\psi) \end{cases}$$

Recalling that $S_{\psi} = 1$ and $\varepsilon_{\psi} = 1$, this is equivalent to (7.4.3) so we are done. \hfill $\square$

**Remark 7.4.7.** A consequence of the multiplicity formula and [AS14] is that for any discrete automorphic representation $\pi$ for $\text{GSpin}_5$ which is formally tempered (i.e. of general or Yoshida type), there exists a globally generic discrete automorphic representation $\pi'$ for $\text{GSpin}_5$ such that for any place $v$ of $F$, $\pi_v$ and $\pi'_v$ have the same Langlands parameter. Indeed letting $\psi \in \Psi_{\text{disc}}(\text{GSpin}_5, \chi)$ be the parameter of $\pi$ (well-defined by the multiplicity formula), Shahidi’s conjecture (proved in [GT11a]) implies that there is a unique representation in $\Pi_{\psi}$ which is generic at each place. In fact the multiplicity formula asserts that it is automorphic with multiplicity one. By (the converse part of) [AS14] Theorem 4.26 there exists a globally generic discrete (even cuspidal) automorphic representation $\pi'$ for $\text{GSpin}_5$.
such that $\pi_v' \simeq \pi_v$ for almost all $v$. In particular $\pi'$ has parameter $\psi$, and for any place $v$ of $F$, $\pi_v'$ is generic.

Note that in the case $\chi = 1$, Arthur used the analogue of [AS14] in order to prove Shahidi’s conjecture: see [Art13, Proposition 8.3.2]. More precisely, he used the descent theorem of Ginzburg, Rallis and Soudry (and thus indirectly the converse theorem of Cogdell, Kim, Piatetski-Shapiro and Shahidi).

Remark 7.4.8. Let $G$ be an inner form of $GSpin_5$ over a number field $F$. Using the stabilisation of the trace formula for $G$ qualitatively (i.e. only considering families of Satake parameters), we see that for any $\pi \in \Pi_{disc}(G, \chi)$, there is a well-defined $\psi \in \Psi(\tilde{\Gamma}, \chi)$ such that $c(\pi) = (c(\psi), c(\chi))$. Moreover if $\psi$ is discrete then $\psi \in \Psi_{disc}(GSpin_5, \chi)$. If $\psi \in \Psi_{disc}(GSpin_5, \chi)$ is tempered (i.e. either of general type or of Yoshida type) then using the stabilisation of the trace formula quantitatively and the endoscopic character relations proved in [CG15] for inner forms as well, one could certainly prove the multiplicity formula for the part of the discrete automorphic spectrum for $G$ corresponding to $(c(\psi), c(\chi)) \in FS(G)$. The proof would be similar to those of Proposition 7.2.1 and Theorem 7.4.1. Note however that to even state the multiplicity formula, one has to fix a normalisation of local transfer factors satisfying a product formula. This normalisation was achieved in [Kal] and used in [Ta] to prove the multiplicity formula for certain inner forms of symplectic groups. It would thus be necessary to compare Kaletha’s normalisation of local transfer factors for the non-split inner form of $GSp_4$ realised as a rigid inner twist with Chan–Gan’s ad hoc normalisation [CG15 §4.3].

8. Compatibility of the local Langlands correspondences for $Sp_4$ and $GSpin_5$

In this section, we study the compatibility of the local Langlands correspondence with restriction from $GSp_4(F) \simeq GSpin_5(F)$ to $Sp_4(F)$, where $F$ is a $p$-adic field. We do not consider the case of Archimedean places, which could certainly be done by a careful examination of the Langlands–Shelstad correspondence.

8.1. Compatibility with restriction. Let $F$ be a $p$-adic field. The proof of the existence of the local Langlands correspondence for $GSp_4(F) \simeq GSpin_5(F)$ in [GT11a] used the theta correspondence, and its compatibility with the correspondence stated in [Art04] (characterised by (twisted) endoscopic character relations) was proved in [CG15]. In the paper [GT10], a local Langlands correspondence for $Sp_4(F)$ was deduced from the correspondence for $GSp_4(F)$ by restriction. This correspondence is uniquely characterised by the commutativity of the diagram

$$
\begin{array}{ccc}
\Pi(GSpin_5) & \longrightarrow & \Phi(GSpin_5) \\
\downarrow & & \downarrow^{{\text{pr}}} \\
\Pi(Sp_4) & \longrightarrow & \Phi(Sp_4)
\end{array}
$$

where $\Pi(GSpin_5)$ (resp. $\Pi(Sp_4)$) is the set of equivalence classes of irreducible admissible representations of $GSpin_5(F)$ (resp. $Sp_4(F)$), $\Phi(GSpin_5)$ (resp. $\Phi(Sp_4)$) is the set of equivalence classes of continuous semisimple representations of WD$_F$ valued in $GSp_4(\mathbb{C})$ (resp. $SO_5(\mathbb{C})$), the horizontal arrows are the local Langlands correspondences, and $\text{pr}$ is the projection $GSp_4(\mathbb{C}) \to PGSp_4(\mathbb{C}) \cong SO_5(\mathbb{C})$. The
left hand vertical arrow is not in fact a map at all, but a correspondence, given by taking any restriction of an element of $\Pi(\text{GSpin}_5)$ to $\text{Sp}_4(F)$.

Of course, [Art13] gives another definition of the local Langlands correspondence for $\text{Sp}_4$, which is characterised by twisted endoscopy for $GL_5$. It is not obvious that this correspondence agrees with that of [GT10]; this amounts to proving the commutativity of the diagram (8.1.1), where now the horizontal arrows are the correspondences characterised by twisted endoscopy. Proving this is the main point of this section; we will also prove a refinement, describing the constituents of the restrictions of representations of $\text{GSpin}_5(F)$ to $\text{Sp}_4(F)$ in terms of the parameterisation of $L$-packets.

We begin by recalling some results about restriction of admissible representations, most of which go back to [GK82], and are explained in the context of $\text{GSpin}_{2n}$ in [GT10]. They are also proved in [Xu16], which we refer to as a self-contained reference. If $\tilde{\pi}$ is an irreducible admissible representation of $\text{GSpin}_5(F)$, then $\tilde{\pi}|_{\text{Sp}_4(F)}$ is a direct sum of finitely many irreducible representations of $\text{Sp}_4(F)$ ([Xu16 Lem. 6.1]), and these representations are pairwise non-isomorphic ([AP06 Thm. 1.4]). Furthermore if $\pi$ is an irreducible admissible representation of $\text{Sp}_4(F)$, then there exists an irreducible representation $\tilde{\pi}$ of $\text{GSpin}_5(F)$ whose restriction to $\text{Sp}_4(F)$ contains $\pi$, and $\tilde{\pi}$ is unique up to twisting by characters ([Xu16 Cor. 6.3, 6.4]). There is also an analogue of these statements for $L$-parameters, which is that $L$-parameters for $\text{Sp}_4$ may be lifted to $\text{GSpin}_5$, and such lifts are unique up to twist; see [GT10 Prop. 2.8] (see also [Lab85 Théorème 7.1] for a more general lifting result).

In particular, it follows that if $\pi \in \Pi(\text{Sp}_4)$, and $\tilde{\pi}$ lifts $\pi$, with $L$-parameter $\varphi_{\tilde{\pi}}$, then $pr \circ \varphi_{\tilde{\pi}}$ depends only on $\pi$ (because $\varphi_{\tilde{\pi}}$ is well-defined up to twist, as $\tilde{\pi}$ itself is); we need to show that it is equal to the $L$-parameter of $\pi$ defined by the local Langlands correspondence of [Art13].

**Theorem 8.1.2.** The diagram (8.1.1) commutes, where the horizontal arrows are the correspondences of [Art13, Art04] determined by twisted endoscopy; that is, the local Langlands correspondences for $\text{Sp}_4$ of [GT10] and [Art13] coincide.

**Proof.** By the preceding discussion, it suffices to show that for each irreducible admissible representation $\pi$, there is some lift $\tilde{\pi}$ of $\pi$ such that $\varphi_{\tilde{\pi}} = pr \circ \varphi_{\tilde{\pi}}$.

We begin with the case that $\pi$ is a discrete series representation. Then by [Clo86 Thm. 1B] and Krasner’s lemma, we can find a totally real number field $K$, a finite place $v$ of $K$, and a discrete automorphic representation $\Pi$ of $\text{Sp}_4(\mathcal{A}_K)$, such that:

1. $K_v \cong \mathbb{F}$ (so we identify $K_v$ with $\mathbb{F}$ from now on).
2. $\Pi_v \cong \pi$.
3. at each infinite place $w$ of $K$, $\Pi_w$ is a discrete series representation.
4. for some finite place $w$ of $K$, $\Pi_w$ is a discrete series representation whose parameter is irreducible when composed with $\text{Std}_{\text{Sp}_4}: \text{SO}_5 \to \text{GL}_5$ (for example the parameter which is trivial on $W_{K_w}$ and the “principal $\text{SL}_2$” on $\mathbb{SU}(2))$.

By Theorem 6.1.2 there is a discrete automorphic representation $\bar{\Pi}$ of $\text{GSpin}_5(\mathcal{A}_K)$ such that $\bar{\Pi}|_{\text{Sp}_4(\mathcal{A}_K)}$ contains $\Pi).$ We can and do assume that the infinitesimal character of $\Pi$ is sufficiently regular, so that in particular the parameter $\psi$ of $\Pi$ is tempered. By (4) above, $\psi$ is just a self-dual representation for $\text{GL}_5/K$ with trivial central character. Write $\tilde{\psi}$ for the parameter of $\bar{\Pi}.$
As in the proof of Proposition 6.1.33 (i.e. comparing at the unramified places using (6.1.3)), we see that $1 ⊠ ψ = \Lambda^2(ψ) ⊗ \omega_ψ^{-1}$. Given the possibilities in Remark 6.1.3 we see (using [GT1a78] to rule out the case $ψ = π[2]$, see the proof of Proposition 6.1.33 (1)) that $ψ$ is necessarily tempered. If $ψ = π_1 ⊠ π_2$ was of Yoshida type then we would have $ψ = 1 ⊠ (π_1 \boxtimes π_2)$, a contradiction. Therefore $ψ$ is of general type, i.e. a $χ$-self-dual cuspidal automorphic representation for $GL_4/K$ of symplectic type for some character $χ$ of $A_K^\times/K^\times$. By the main results of [Kim03] and [Hen09], the Langlands parameter of $1 ⊠ ψ$ at $v$ equals $\Lambda^2(rec(ψ_v)) ⊗ rec(\omega_ψ)^{-1}$, which implies that $φ_{Π_v} = pr φ_{Π_v}$. Taking $Π = Π_v$, we are done in this case.

We now treat the case that the parameter $φ_π$ is not discrete, but is bounded modulo centre. Recall that a minimal Levi subgroup $L_M$ of $LSp_4$ such that $φ_π(WD_F) ⊂ ^cM$ is unique up to conjugation by $Cent(φ_π, Sp_4)$ [Bor79 Proposition 3.6]. Then $φ_π$ factors through a well-defined discrete parameter $φ_M : WD_F → LM$. Since $Sp_4$ is quasi-split we have a natural identification of $L^cM$ with the $L$-group of a Levi subgroup $M$ of $GSp_4$ (well-defined up to conjugation by normalisers in $Sp_4$, resp. $Sp_3$). Since $φ_π$ is assumed to be non-discrete we have $L^cM ≠ LSp_4$. It follows from the construction in [Art13] (see the proof of Proposition 2.4.3 loc. cit., in particular (2.4.13)) that $π$ is a constituent of the parabolic induction $Ind_{P(F)}^{G(F)} π_M$, where $P$ is any parabolic subgroup of $Sp_4$ with Levi $M$, and $π_M$ is in the $L$-packet of $φ_M$. Recall that this $L$-packet is defined via the natural identification $M$ with a product of copies of $GL$ groups with $Sp_{2a}$ for some $0 ≤ a < 2$, using rec for the $GL$ factors and Arthur’s local Langlands correspondence for the $Sp$ factor.

Write $M = \tilde{M} ∩ Sp_4$ where $\tilde{M}$ is a Levi subgroup of $GSp_4$, and similarly $P = \tilde{P} ∩ Sp_4$. Let $π_M$ be an essentially discrete series representation of $M(F)$ whose restriction to $M(F)$ contains $π_M$. Then there is an irreducible constituent $π$ of the (semisimple) parabolic induction $Ind_{P(F)}^{GSp_{4}(F)} π_M$ such that $π$ is a restriction of $π$. We will prove that $φ_π = pr φ_{π_M}$. Note that for non-discrete parameters, the local Langlands correspondence for $GSpin_5(F)$ of [GT1a] is also compatible with parabolic induction (see [CG15] §6.6 and [GT1113] Prop. 13.1), i.e. the parameter of $π$ is $φ_{π_M}$ (the Langlands parameter of $π_M$) composed with $L^cM ⊂ L GSpin_5$. Note that $\tilde{M}$ is isomorphic to a product of $GL$ and for such a group the (bijective) local Langlands correspondence is well-defined, i.e. it does not depend on the choice of an isomorphism. This follows from compatibility of rec with twisting, central characters and duality. The same argument shows that any morphism with normal image between two such groups is also compatible with the local Langlands correspondence. We have a commutative diagram

$$
\begin{array}{ccc}
L\tilde{M} & \longrightarrow & L GSpin_5 \\
\downarrow pr & & \downarrow pr \\
LM & \longrightarrow & LSp_4
\end{array}
$$

so that to conclude that $φ_π = pr φ_{π_M}$ it is enough to show that $φ_M = pr φ_{π_M}$, which is simply a compatibility of local Langlands correspondences for $M$ and $\tilde{M}$. There are three cases to consider. We write the standard parabolic subgroups of
We do not justify the embedding \( M \hookrightarrow \tilde{M} \), as this is a simple but tedious exercise in root data.

- \( \tilde{M} = GL^2_1 \times GSpin_1, M = GL^2_1, \) the embedding \( M \hookrightarrow \tilde{M} \) is \( (x_1, x_2) \mapsto (x_1 x_2, x_1/x_2, x_1^{-1}) \). This case is trivial.

- \( \tilde{M} = GL_2 \times GSpin_1, M = Sp_2 \times GL_1, \) the embedding \( M \hookrightarrow \tilde{M} \) is \( (g, x_1) \mapsto (gx_1, x_1^{-1}) \). This case is not formal as for the factor \( Sp_2 \) the local Langlands correspondence that is used is Arthur’s from \([Art13]\) and it is not obvious that it is compatible with rec for \( GL_2 \), in other words that Arthur’s local Langlands correspondence for \( Sp_2 \approx SL_2 \) (characterised by twisted endoscopy for \( GL_3 \)) coincides with Labesse-Langlands \([LL79]\). Fortunately Arthur verified this compatibility in \([Art13, Lemma 6.6.2]\).

- \( \tilde{M} = GL_1 \times GSpin_3, M = GL_1 \times GL_2, \) the embedding \( M \hookrightarrow \tilde{M} \) is \( g \mapsto (\det g, g/\det g) \) where we have identified \( GSpin_3 \) with \( GL_2 \). This case also follows from the above remark about the local Langlands correspondence for groups isomorphic to a product of \( GL \).

Finally, we must treat the case that \( \varphi \) is not bounded modulo centre. The description of the \( L \)-packets in this case is again in terms of parabolic inductions from Levi subgroups (“Langlands classification”). This is well-known and completely general (see \([Sil78], [SZ14]\)). The argument is similar to the above reduction, except that \( P \) and \( \tilde{P} \) are uniquely determined by a positivity condition and that \( \pi \) and \( \tilde{\pi} \) are unique quotients of standard modules and not arbitrary constituents. We do not repeat the argument. \( \square \)

We now examine the restriction from \( GSpin_5(F) \) to \( Sp_4(F) \) more closely, proving a slight refinement of the results of \([GT10]\). In \([GT10, App. A]\), a detailed qualitative description of the constituents of \( \tilde{\pi}|_{Sp_4(F)} \) is given, which is obtained by examining the local Langlands correspondence (see \([GT10, \S5, 6]\) for the corresponding calculations with \( L \)-parameters). However, since the local Langlands correspondence of \([GT10]\) is not characterised in terms of twisted and ordinary endoscopic character relations, they cannot describe precisely which elements of the \( L \)-packets for \( Sp_4(F) \) arise as the restrictions of given elements of the \( L \)-packets for \( GSpin_5(F) \).

Theorem 8.3.2 below answers this question. In its proof, we need to make use of the results of Section 5 for \( SO_4 \hookrightarrow H \) where

\[
H = (GL_2 \times GL_2) / \{(zI_2, z^{-1}I_2) \mid z \in GL_1\}
\]

is the non-trivial elliptic endoscopic group of \( GSpin_5 \). Here \( SO_4 \) is identified with the subgroup of pairs \((a, b)\) with \((\det a)(\det b) = 1\). Indeed, \( H \) may be identified with the subgroup \( GSO_4 \) of \( GO_4 \) given by the elements for which \( \det = \nu^2 \), where \( \nu \) is the similitude factor.

Note that \( SO_4 \) is an elliptic endoscopic group for \( Sp_4 \) and that we have the following commutative diagram:

\[
\begin{align*}
\hat{H} \quad &\xrightarrow{L\xi'} \quad \hat{SO}_4 = SO_4 \\
GSpin_5 = GSp_4 \quad &\xrightarrow{L\xi} \quad \hat{Sp}_4 = SO_5
\end{align*}
\]
8.2. Multiplicity one. In studying restriction from $H$ to $SO_4$ we will make use of the following variant of the results of [AP06]. In fact, we could prove the special case that we need in a simpler but more ad-hoc fashion by using the description of $H$ in terms of $GL_2$, but it seems worthwhile to prove this more general result.

**Proposition 8.2.1.** Let $n \geq 1$, and let $V$ be a vector space of dimension $2n$ over $F$ endowed with a non-degenerate quadratic form $q$. Let $\pi$ be an irreducible admissible representation of $GSO(V, q) = GSO(V, q)(F)$. Then the irreducible constituents of the restriction $\pi|_{SO(V, q)}$ are pairwise non-isomorphic.

**Proof.** By [AP06, Theorem 2.3], it suffices to show that there is an algebraic anti-involution $\tau$ of $GSO(V, q)$ which preserves $SO(V, q)$ and takes each $SO(V, q)$-conjugacy class in $GSO(V, q)$ to itself. To define $\tau$, we set $\tau(g) = \nu(g)\delta^n g^{-1}\delta^{-n}$ where $\delta \in O(V, q)$ is an involution with $\det \delta = -1$. This obviously preserves $SO(V, q)$, so we need only check that it also preserves $SO(V, q)$-conjugacy classes in $GSO(V, q)$.

To see this, we claim that it is enough to show that we can write $g = xy$ with $x \in O(V, q)$, $y \in GO(V, q)$ (so $\nu(y) = \nu(g)$) satisfying $x^2 = 1$, $\det(x) = (-1)^n$, $y^2 = \nu(y)$. Indeed, we then have

$$\tau(g) = \nu(g)\delta^n g^{-1}\delta^{-n} = \delta^n \nu(y) y^{-1} x^{-1} \delta^{-n} = \delta^n y x \delta^{-n} = (x \delta^{-n})^{-1} g(x \delta^{-n}),$$

as required. The result then follows from Lemma 8.2.2 below, which is a slight refinement of [RV16, Thm. A].

**Lemma 8.2.2.** Let $n \geq 0$, let $K$ be a field of characteristic 0, and let $V$ be a vector space of dimension $2n$ over $K$ endowed with a non-degenerate quadratic form $q$. If $g \in GSO(V, q)$ then we can write $g = xy$ with $x \in O(V, q)$, $y \in GO(V, q)$ satisfying $x^2 = 1$, $\det(x) = (-1)^n$, $y^2 = \nu(y)$.

**Proof.** We argue by induction on $n$, the case $n = 0$ being trivial. Suppose now that $n > 0$. By [RV16, Thm. A], we can write $g = xy$ with $x \in O(V, q)$, $y \in GO(V, q)$ satisfying $x^2 = 1$, $y^2 = \nu(y) = \nu(g)$. If $\det(x) = (-1)^n$ then we are done, so suppose that $\det(x) = (-1)^{n+1}$ and so $\det(y) = (-1)^{n+1}\nu(y)^n$.

Since $y^2 = \nu(y)$, any eigenvalue (in an extension of $K$) of $y$ is a square root of $\nu(y)$. Since $\det(y) = (-1)^{n+1}\nu(y)^n$, we see that the two eigenspaces of $y$ do not have equal dimension. It follows that $\nu(y)$ is a square, as otherwise the characteristic polynomial of $y$ would be a power of the irreducible polynomial $X^2 - \nu(y)$. So the eigenvalues of $y$ are in $K$, and up to dividing $g$ and $y$ by one of these eigenvalues we can assume that $g \in SO(V, q)$ and $y \in O(V, q)$ with $\det(y) = (-1)^{n+1}$. Then $y$ has an eigenspace (for an eigenvalue $\pm 1$) of dimension at least $n + 1$. The same analysis applies to $x$, and it follows that there is a subspace $W$ (the intersection of these eigenspaces for $x$ and $y$) of dimension at least 2 of $V$ on which $g$ acts by a scalar which is $\pm 1$.

Up to replacing $g$ by $-g$ and $y$ by $-y$, we can assume that $\det(g-1)$ has dimension at least 2. We have a canonical $g$-stable decomposition of $V$ as the direct sum of $\ker((g-1)^{2n})$ and its orthogonal complement, and they both have even dimension over $K$ since $g \in SO(V, q)$ with $\dim_K V$ even. If $g$ is not unipotent, we conclude using the induction hypothesis for the restriction of $g$ to $\ker((g-1)^{2n})$ and to its orthogonal complement.

Suppose for the rest of the proof that $g$ is unipotent. If $n = 1$ the conclusion is trivial, so assume that $n > 1$, so that $SO(V, q)$ is semisimple. By Jacobson–Morozov (see for example [Bou05, Ch. VIII §11]) there is an algebraic morphism
\( \text{SL}_2 \to \text{SO}(V, q) \) mapping \( \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \) to \( g \), unique up to conjugation by the centraliser of \( g \) in the subgroup \( \text{Aut}_e(\text{so}(V, q)) \) of \( \text{SO}(V, q)/\{ \pm 1 \} \) where \( \text{Aut}_e \) is the subgroup of automorphisms of the Lie algebra generated by exponentials of nilpotent elements. For \( d \geq 1 \) fix an irreducible representation \( U_d \) of \( \text{SL}_2 \) of dimension \( d \) as well as a non-degenerate \((-1)^d\)-symmetric \( \text{SL}_2 \)-invariant pairing \( B_d \) on \( U_d \). We have a canonical decomposition

\[
V = \bigoplus_{d \geq 1} U_d \otimes V_d
\]

where \( V_d = (V \otimes_K U_d^*)^\text{SL}_2 \). The quadratic form \( q \) corresponds to an element of

\[
(\text{Sym}^2 V^*)^\text{SL}_2 = \bigoplus_{d \geq 1 \text{ odd}} \text{Sym}^2(V^d) \oplus \bigoplus_{d \geq 2 \text{ even}} \bigwedge^2 V^d
\]

and non-degeneracy of \( q \) is equivalent to non-degeneracy of each factor. Writing each \( V_d \) for \( d \) odd (resp. even) as an orthogonal direct sum of quadratic lines (resp. planes endowed with a non-degenerate alternate form), we are left to prove a decomposition \( g' = x'y' \) in the following cases.

1. \( V' \) has odd dimension \( 2m + 1 \) and is endowed with a non-degenerate quadratic form \( q' \) and a unipotent automorphism \( g' \). Applying [RV16 Thm. A] we obtain \( g' = x'y' \) with \( x', y' \) involutions in \( \text{O}(V, q) \). Up to replacing \( (x', y') \) by \( (-x', -y') \) we can assume that \( \det(x') = \pm 1 \) as we may desire.

2. \( V' = U_{2m} \otimes V'' \) where \( V'' \) is 2-dimensional and endowed with a non-degenerate alternating form \( B'' \), and \( g' = g'' \otimes I_{V''} \in \text{SO}(V', q') \) for \( q' \) the quadratic form corresponding to the symmetric bilinear form \( B' = B_{2m} \otimes B'' \) and \( g'' \) a unipotent element of \( \text{Sp}(U_{2m}, B_{2m}) \). Applying [RV16 Thm. A] again we can write \( g'' = x''y'' \) where \( x'', y'' \) are involutions in \( \text{GSp}(U_{2m}, B_{2m}) \) having similitude factor \(-1\). Similarly write \( I_{V''} = x''y'' \) where \( x'', y'' \) are involutions in \( \text{GSp}(V'', B'') \) having similitude factor \(-1\). Then \( g' = (x' \otimes x'')(y' \otimes y'') \) is the desired decomposition as a product of involutions in \( \text{SO}(V', q') \).

### 8.3. Restriction of local Arthur packets

We now give our description of the restriction of representations of \( \text{GSpin}_5(F) \). Recall that if \( \varphi : \text{WD}_F \to \text{GSp}_4 \) is a bounded parameter, then the corresponding component group \( S_\varphi \) is either trivial or is \( \mathbb{Z}/2\mathbb{Z} = \{ 1, s \} \). In the former case, the \( L \)-packet \( \Pi_\varphi \) associated to \( \varphi \) is a singleton, and in the latter case it is a pair \( \{ \pi^+, \pi^- \} \), where \( \pi^\pm \) is characterised by the fact that \( \text{tr} \pi^+ - \text{tr} \pi^- \) is the transfer to \( \text{GSpin}_5(F) \) of \( \text{tr} \pi_{\varphi_H} \) where \( \varphi_H \in \Phi(H) \) is the parameter mapping to \( (\varphi, s) \) via \( L \xi' \). In either case, if we write \( \varphi' = \text{pr} \circ \varphi \), then by [GT10 Prop. 2.8], we have

\[
\bigoplus_{\pi \in \Pi_\varphi} \pi|_{\text{Sp}_4(F)} \cong \bigoplus_{\pi' \in \Pi_{\varphi'}} \pi'.
\]

(Indeed, this follows from Theorem 8.1.2 the fact that lifts of representations of \( \text{Sp}_4(F) \) to \( \text{GSp}_4(F) \) are unique up to twist, and the fact that the restrictions of representations of \( \text{GSp}_4(F) \) to \( \text{Sp}_4(F) \) are semisimple and multiplicity free.)

The following theorem improves on this result by giving a precise description of the restrictions of the individual elements of \( \Pi_\varphi \).
Theorem 8.3.2. Let \( \varphi \) be a bounded \( L \)-parameter, and write \( \varphi' = \text{pr} \circ \varphi \), so that \( S_\varphi \hookrightarrow S_{\varphi'} \). Write \( \Pi_\varphi \) and \( \Pi_{\varphi'} \) for the respective \( L \)-packets. If \( S_\varphi \) is trivial, and \( \Pi_\varphi = \{\pi\} \), then

\[
\pi|_{\text{Sp}_4(F)} \cong \bigoplus_{\pi' \in \Pi_{\varphi'}} \pi'.
\]

If \( S_\varphi = \mathbb{Z}/2\mathbb{Z} = \{1, s\} \), and \( \Pi_\varphi = \{\pi^+, \pi^-\} \) as above, then

\[
\pi^\pm|_{\text{Sp}_4(F)} \cong \bigoplus_{\pi' \in \Pi_{\varphi'}} \pi'.
\]

Proof. In the case that \( S_\varphi \) is trivial, this is (8.3.1), so we may suppose that \( S_\varphi \) is non-trivial, so that \( \varphi \) is endoscopic. We can write \( \varphi = \varphi_1 \oplus \varphi_2 \) where \( \varphi_1, \varphi_2 : \text{WD}_F \to \text{GL}_2 \) are bounded with same determinant; that is, \( \varphi = L\xi' \circ \varphi_H \), where \( \varphi_H = \varphi_1 \times \varphi_2 : \text{WD}_F \times \text{SL}_2(C) \to H \). Via \( L\xi' \) we can see \( s \) as the non-trivial element of \( Z(H)/Z(\text{GSpin}_5) \), i.e. the image of \( (1, -1) \in H \subset \text{GL}_2 \times \text{GL}_2 \). Then by Conjecture 2.4.1 (2) for \( \text{GSpin}_5 \) (i.e. the main theorem of [CG15]), we have an equality of traces

\[
\text{tr} \pi^+(f) - \text{tr} \pi^-(f) = \sum_{\pi_H \in \Pi_{\varphi_H}} \text{tr} \pi_H(f_H).
\]

Applying Conjecture 2.4.1 (2) (or rather Theorem 2.6.1) for \( \text{Sp}_4 \), and writing \( \varphi_H \) for the composite of \( \varphi_1 \) and \( \varphi_2 \), we also have an equality of traces

\[
\sum_{\pi' \in \Pi_{\varphi'}} \text{tr} \pi'(f) - \sum_{\pi' \in \Pi_{\varphi'}} \text{tr} \pi'(f) = \sum_{\pi'_{\text{SO}_4} \in \Pi_{\varphi'_H}} \text{tr} \pi'_{\text{SO}_4}(f').
\]

The result now follows from (8.3.1) and Theorem 8.3.3 below. \( \square \)

We end with a result on the restriction of representations from \( H \cong \text{GSO}_4 \) to \( \text{SO}_4 \) that we used in the course of the proof of Theorem 8.3.2. The arguments are very similar to those for \( \text{GSpin}_5 \), but are rather simpler, as \( H \) has no non-trivial elliptic endoscopic groups. Since \( H \) is isomorphic to the quotient of \( \text{GL}_2 \times \text{GL}_2 \) by a split torus, the local Langlands correspondence for \( H \), and the corresponding endoscopic character identities, are easily deduced from those for \( \text{GL}_2 \). The correspondence and endoscopic character identities for \( \text{SO}_4 \) are of course proved in [Art13] (up to the outer automorphism \( \delta \)).

By Proposition 8.2.1 if \( \pi \) is an irreducible admissible representation of \( H(F) \), then \( \pi|_{\text{SO}_4(F)} \) is a direct sum of representations occurring with multiplicity one. The proof of [GT10] Lem. 2.6] goes through unchanged and shows that \( \pi_1|_{\text{SO}_4(F)} \), \( \pi_2|_{\text{SO}_4(F)} \) have a common constituent if and only if \( \pi_1, \pi_2 \) differ by a twist by a character. By [GT10] Lem. 2.7], the analogous statement is also true for \( L \)-parameters: every \( L \)-parameter \( \varphi' : \text{WD}_F \to \text{SO}_4(C) \) arises from some \( \varphi : \text{WD}_F \to H(C) \), which is unique up to twist.

Theorem 8.3.3. Let \( \varphi : \text{WD}_F \to \hat{H}(C) \) be a bounded \( L \)-parameter, and let \( \varphi' : \text{WD}_F \to \text{SO}_4(C) \) be the parameter obtained from (8.1.3). Let \( \pi \) be the tempered
irreducible representation of $H$ associated to $\varphi$. Then
$$\pi|_{\hat{H}(SO_4(F))} \cong \bigoplus_{\pi' \in \Pi_{\varphi'}} \pi'.$$

Proof. By the preceding discussion, we need to show that for each bounded $L$-parameter $\varphi' : WD_F \to SO_4(\mathbb{C})$ (up to outer conjugacy), and each $\pi' \in \Pi_{\varphi'}$, there is some $\pi$ lifting $\pi'$ (or $\pi^{\delta}$) whose $L$-parameter $\varphi$ lifts $\varphi'$.

Suppose firstly that $\varphi'$ is discrete. As in the proof of Theorem 8.1.2, by Krasner’s lemma and [Clo86, Thm. 1B], we can find a totally real number field $K$, a finite place $v$ of $K$, and a discrete automorphic representation $\Pi_{\varphi'}$ of $SO_4(\hat{A}_K)$, such that:

- $K_v \cong F$ (so we identify $K_v$ with $F$ from now on).
- $\Pi_{\varphi'} = \pi'$.
- at each infinite place $w$ of $K$, $\Pi_w$ is a discrete series representation.

By Theorem 5.1.2, there is a discrete automorphic representation $\Pi$ of $H(\hat{A}_K)$ such that $\Pi|_{SO_4(\hat{A}_K)}$ contains $\Pi_{\varphi'}$. Then $\Pi$ corresponds to a pair $\pi_1, \pi_2$ of discrete automorphic representations of $GL_2(\hat{A}_K)$ with equal central characters. The condition that $\Pi_w$ is a discrete series representation at an infinite place $w$ of $K$ implies that $\pi_1$ and $\pi_2$ are cuspidal.

We now consider the following commutative diagram of dual groups:

$$
\begin{array}{ccc}
\hat{H} & \to & SO_4 \cong \hat{SO}_4 \\
\downarrow & & \downarrow \\
GL_2 \times GL_2 & \to & GL_4
\end{array}
$$

(8.3.4)

where the vertical arrows are the natural inclusions, and the lower horizontal arrow is given by $(g, h) \mapsto (\det g)^{-1} g \otimes h$. Since the functorial transfer from $GL_2 \times GL_2$ to $GL_4$ exists (as we recalled at the beginning of Section 8), we may compare at the unramified places and then use strong multiplicity one to compare at the ramified places, and we obtain that the composite $WD_F \varphi' : \hat{H} \to GL_2 \times GL_2 \to GL_4$ is given by $\varphi_{1,v} \otimes \varphi_{2,v}$, where $\varphi_{1,v}, \varphi_{2,v}$ are the $L$-parameters of $\pi_{1,v}$ and $\pi_{2,v}$ respectively. Since the $L$-parameter of $\Pi_v$ is $\varphi_{1,v} \oplus \varphi_{2,v}$, we can take $\pi = \Pi_v$, so we are done in the case that $\varphi'$ is discrete.

Suppose now that $\varphi'$ is not discrete. Then one can argue as in the proof of 8.1.2 since both local Langlands correspondences for $H$ and $SO_4$ are compatible with parabolic induction. In fact the proof is simpler since all proper Levi subgroups are simply products of $GL$, and we do not repeat the argument.

\begin{remark}
Theorem 8.3.2 (or rather its straightforward extension from tempered to generic parameters) gives the complete spectral description of the automorphic restriction map of Section 8 for $Sp_4 \subset GSpin_5$ for formally tempered global parameters. This is the analogue of the results of Labesse–Langlands [LL79] (ignoring inner forms) and the multiplicity one theorem of Ramakrishnan for $SL_2$ [Ram00].

It would perhaps be interesting to extend this to parameters which are not formally tempered, but in the interests of brevity we do not consider this question here.
\end{remark}

References

[AMR15] Nicolás Arancibia, Colette Mœglin, and David Renard, Paquets d’Arthur des groupes classiques et unitaires, http://arxiv.org/abs/1507.01432 2015.
[AP06] Jeffrey D. Adler and Dipendra Prasad, *On certain multiplicity one theorems*, Israel J. Math. 153 (2006), 221–245.

[AR11] Mahdi Asgari and A. Raghuram, *A cuspidality criterion for the exterior square transfer of cusp forms on GL(4)*, On certain L-functions, Clay Math. Proc., vol. 13, Amer. Math. Soc., Providence, RI, 2011, pp. 33–53.

[Art01] James Arthur, *A stable trace formula. II. Global descent*, Invent. Math. 143 (2001), no. 1, 157–220.

[Art02] James Arthur, *A stable trace formula. I. General expansions*, J. Inst. Math. Jussieu 1 (2002), no. 2, 175–277.

[Art03] James Arthur, *A stable trace formula. III. Proof of the main theorems*, Ann. of Math. (2) 158 (2003), no. 3, 769–873.

[AS14] Mahdi Asgari and Freydoon Shahidi, *Image of functoriality for general spin groups*, Manuscripta Math. 144 (2014), no. 3-4, 609–638.

[Aub95] Anne-Marie Aubert, *Dualité dans le groupe de Grothendieck de la catégorie des représentations lisses de longueur finie d’un groupe réductif p-adique*, Trans. Amer. Math. Soc. 347 (1995), no. 6, 2179–2189.

[BCGP] George Boxer, Frank Calegari, Toby Gee, and Vincent Pilloni, *Abelian surfaces over totally real fields are potentially modular*, in preparation.

[Ber84] Joseph N. Bernstein, *P-invariant distributions on GL( N ) and the classification of unitary representations of GL(N) (non-Archimedean case)*, Lie group representations, II (College Park, Md., 1982/1983), Lecture Notes in Math., vol. 1041, Springer, Berlin, 1984, pp. 50–102.

[Bor79] A. Borel, *Automorphic L-functions*, Automorphic forms, representations and L-functions (Proc. Sympos. Pure Math., Oregon State Univ., Corvallis, Ore., 1977), Part 2, Proc. Sympos. Pure Math., XXXIII, Amer. Math. Soc., Providence, R.I., 1979, pp. 27–61.

[CL10] Pierre-Henri Chaudouard and Gérard Laumon, *Le lemme fondamental pondéré. I. Constructions géométriques*, Compos. Math. 146 (2010), no. 6, 1416–1506.

[Clo08] Laurent Clozel, *Théorème d’Atiyah-Bott pour les variétés p-adiques et caractères des groupes réductifs*, Mém. Soc. Math. France (N.S.) (1984), no. 15, 39–64, Harmonic analysis on Lie groups and symmetric spaces (Kleebach, 1983).

[Clo86] Laurent Clozel, *On limit multiplicities of discrete series representations in spaces of automorphic forms*, Invent. Math. 83 (1986), no. 2, 265–284.

[CS80] W. Casselman and J. Shalika, *The unramified principal series of p-adic groups. II. The Whittaker function*, Compositio Math. 41 (1980), no. 2, 207–231.

[GJ78] Stephen Gelbart and Hervé Jacquet, *A relation between automorphic representations of GL(2) and GL(3)*, Ann. Sci. École Norm. Sup. (4) 11 (1978), no. 4, 471–542.
ARTHUR’S MULTIPLICITY FORMULA FOR $GSp_4$ AND RESTRICTION TO $Sp_4$

[GT10] Wee Teck Gan and Shuichiro Takeda, The local Langlands conjecture for $Sp(4)$, Int. Math. Res. Not. IMRN (2010), no. 15, 2987–3038.

[GT11a] Wee Teck Gan and Shuichiro Takeda, The local Langlands conjecture for $GSp(4)$, Ann. of Math. (2) 173 (2011), no. 3, 1841–1882.

[GT11b] Wee Teck Gan and Shuichiro Takeda, Theta correspondences for $GSp(4)$, Represent. Theory 15 (2011), 670–718.

[Hal95] Thomas C. Hales, The geometry and cohomology of some simple Shimura varieties, Annals of Mathematics Studies, vol. 151, Princeton University Press, Princeton, NJ, 2001, With an appendix by Vladimir G. Berkovich.

[Kim03] Henry H. Kim, Functoriality for the exterior square of $GL_4$ and the symmetric fourth of $GL_2$, J. Amer. Math. Soc. 16 (2003), no. 1, 139–183, With appendix 1 by Dinakar Ramakrishnan and appendix 2 by Kim and Peter Sarnak.

[Lab85] J.-P. Labesse, Cohomologie, $L$-groupes et fonctorialité, Compositio Math. 55 (1985), no. 2, 163–184.

[Lan80] Robert P. Langlands, Base change for $GL(2)$, Annals of Mathematics Studies, vol. 96, Princeton University Press, Princeton, N.J.; University of Tokyo Press, Tokyo, 1980.

[Lan83] R. P. Langlands, Les débuts d’une formule des traces stables, Publications Mathématiques de l’Université Paris VII [Mathematical Publications of the University of Paris VII], vol. 13, Université de Paris VII, U.E.R. de Mathématiques, Paris, 1983.

[Lan89] R. Langlands, On the classification of irreducible representations of real algebraic groups, Representation theory and harmonic analysis on semisimple Lie groups, Math. Surveys Monogr., 31, AMS, 1989, pp. 101–170.

[Lem10] Bertrand Lemaire, Caractères tordus des représentations admissibles, http://arxiv.org/abs/1007.3576 2010.

[LL79] J.-P. Labesse and R. P. Langlands, L-indistinguishability for $SL(2)$, Canad. J. Math. 31 (1979), no. 4, 726–785.
[LMW15] Bertrand Lemaire, Colette Mœglin, and Jean-Loup Waldspurger, *Le lemme fondamental pour l'endoscopie tordue: réduction aux éléments unités*, http://arxiv.org/abs/1506.03383, 2015.

[LW13] Jean-Pierre Labesse and Jean-Loup Waldspurger, *La formule des traces tordue d'après le Friday Morning Seminar*, CRM Monograph Series, vol. 31, American Mathematical Society, Providence, RI, 2013, With a foreword by Robert Langlands [dual English/French text].

[LW15] Bertrand Lemaire and Jean-Loup Waldspurger, *Le lemme fondamental pour l'endoscopie tordue: le cas où le groupe endoscopique non ramifié est un tore*, http://arxiv.org/abs/1511.08606, 2015.

[Mez16] Paul Mezo, *Tempered spectral transfer in the twisted endoscopy of real groups*, J. Inst. Math. Jussieu 15 (2016), no. 3, 569–612.

[Mœg11] Colette Mœglin, *Multiplicité 1 dans les paquets d’Arthur aux places p-adiques*, *On certain L-functions*, Clay Math. Proc., vol. 13, Amer. Math. Soc., Providence, RI, 2011, pp. 333–374.

[Mok14] Chung Pang Mok, *Galois representations attached to automorphic forms on GL(2) over CM fields*, Compos. Math. 150 (2014), no. 4, 523–567.

[MR15] Colette Mœglin and David Renard, *Paquets d’Arthur des groupes classiques complexes*, http://arxiv.org/abs/1507.01432, 2015.

[MW89] Colette Mœglin and Jean-Loup Waldspurger, *Le spectre résiduel de GL(n)*, Ann. Sci. École Norm. Sup. (4) 22 (1989), no. 4, 605–674.

[MW94] ______, *Décomposition spectrale et séries d’Eisenstein*, Progress in Mathematics, vol. 113, Birkhäuser Verlag, Basel, 1994, Une paraphrase de l’Écriture. [A paraphrase of Scripture].

[MW96] ______, *Sur le transfert des traces d’un groupe classique p-adique à un groupe linéaire tordu*, Selecta Math. (N.S.) 12 (2006), no. 3–4, 433–515.

[MW16a] Colette Mœglin and Jean-Loup Waldspurger, *Stabilisation de la formule des traces tordue*, vol. 1, Springer International Publishing, 2016.

[MW16b] ______, *Stabilisation de la formule des traces tordue*, vol. 2, Springer International Publishing, 2016.

[Ngô10] Bao Châu Ngô, *Le lemme fondamental pour les algèbres de Lie*, Publ. Math. Inst. Hautes Études Sci. (2010), no. 111, 1–169.

[PR94] Vladimir Platonov and Andrei Rapinchuk, *Algebraic groups and number theory*, Pure and Applied Mathematics, vol. 139, Academic Press, Inc., Boston, MA, 1994, Translated from the 1991 Russian original by Rachel Rowen.

[Ram00] Dinakar Ramakrishnan, *Modularity of the Rankin-Selberg L-series, and multiplicity one for SL(2)*, Ann. of Math. (2) 152 (2000), no. 1, 45–111.

[Rod73] François Rodier, *Whittaker models for admissible representations of reductive p-adic split groups*, 425–430.

[RV16] A. Roche and C. R. Vinroot, *A factorization result for classical and similitude groups*, ArXiv e-prints (2016).

[Sat63] Ichirō Satake, *Theory of spherical functions on reductive algebraic groups over p-adic fields*, Inst. Hautes Études Sci. Publ. Math. (1963), no. 18, 5–69.

[Ser97] Jean-Pierre Serre, *Répartition asymptotique des valeurs propres de l’opérateur de Hecke Tp*, J. Amer. Math. Soc. 10 (1997), no. 1, 75–102.

[Sha74] J. A. Shalika, *The multiplicity one theorem for GLn*, Ann. of Math. (2) 100 (1974), 171–193.

[Sha97] Freydoon Shahidi, *On non-vanishing of twisted symmetric and exterior square L-functions for GL(n)*, Pacific J. Math. (1997), no. Special Issue, 311–322, Olga Taussky-Todd: in memoriam.

[Sha10] ______, *Eisenstein series and automorphic L-functions*, American Mathematical Society Colloquium Publications, vol. 58, American Mathematical Society, Providence, RI, 2010.

[She08] D. Shelstad, *Tempered endoscopy for real groups. III. Inversion of transfer and L-packet structure*, Represent. Theory 12 (2008), 389–402.
[She10], Tempered endoscopy for real groups. II. Spectral transfer factors, Automorphic forms and the Langlands program, Adv. Lect. Math. (ALM), vol. 9, Int. Press, Somerville, MA, 2010, pp. 236–276.

[She12], On geometric transfer in real twisted endoscopy, Ann. of Math. (2) 176 (2012), no. 3, 1919–1985.

[Sil78] Allan J. Silberger, The Langlands quotient theorem for $p$-adic groups, Math. Ann. 236 (1978), no. 2, 95–104.

[SS97] Peter Schneider and Ulrich Stuhler, Representation theory and sheaves on the Bruhat-Tits building, Inst. Hautes Études Sci. Publ. Math. (1997), no. 85, 97–191.

[SZ14] Allan J. Silberger and Ernst-Wilhelm Zink, Langlands Classification for L-Parameters, http://arxiv.org/abs/1007.3576 2014.

[Tai] Olivier Taibi, Arthur’s multiplicity formula for certain inner forms of special orthogonal and symplectic groups, [http://wwwf.imperial.ac.uk/~otaibi/cpctmult.pdf](http://wwwf.imperial.ac.uk/~otaibi/cpctmult.pdf), to appear in Journal of the European Mathematical Society.

[vD72] G. van Dijk, Computation of certain induced characters of $p$-adic groups, Math. Ann. 199 (1972), 229–240.

[Vog86] David A. Vogan, Jr., The unitary dual of GL(n) over an Archimedean field, Invent. Math. 83 (1986), no. 3, 449–505.

[VW90] D. A. Vogan, Jr. and N. R. Wallach, Intertwining operators for real reductive groups, Adv. Math. 82 (1990), no. 2, 203–243.

[Wal88] Nolan R. Wallach, Real reductive groups. I, Pure and Applied Mathematics, vol. 132, Academic Press, Inc., Boston, MA, 1988.

[Wal97] J.-L. Waldspurger, Le lemme fondamental implique le transfert, Compositio Math. 105 (1997), no. 2, 153–236.

[Wal03] ———, La formule de Plancherel pour les groupes $p$-adiques (d’après Harish-Chandra), J. Inst. Math. Jussieu 2 (2003), no. 2, 235–333.

[War72] Garth Warner, Harmonic analysis on semi-simple Lie groups. I, Springer-Verlag, New York-Heidelberg, 1972, Die Grundlehren der mathematischen Wissenschaften, Band 188.

[Xu16] Bin Xu, On a lifting problem of L-packets, Compos. Math. 152 (2016), no. 9, 1800–1850.

[Xu17] ———, L-packets of quasisplit GSp(2n) and GO(2n), Mathematische Annalen (2017). E-mail address: toby.gee@imperial.ac.uk

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