THE SINGULAR SUPPORT OF SHEAVES IS $\gamma$-COISOTROPIC

STÉPHANE GUILLERMOU AND CLAUDE VITERBO

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CONTENTS

1. Introduction 1
2. Notation, comments and acknowledgements 2
3. Reminders on the singular support of sheaves 3
4. Quantization of Hamiltonian isotopies 5
5. Spectral invariants for sheaves and Lagrangians 7
5.1. Definition of spectral invariants 9
5.2. The case of Hamiltonian maps 11
5.3. Defining $\gamma$-coisotropic subsets 13
6. The $\gamma_g$-metric on sheaves 14
6.1. The $\gamma_g$-topology 15
6.2. Link with spectral invariants 18
6.3. $\gamma_g$-limits and colimits 22
7. Proof of Theorem 1.2 26
8. $\gamma$-coisotropic vs cone-coisotropic 27
8.1. A $\gamma$-coisotropic set is cone-coisotropic 27
8.2. A cone-coisotropic set that is not $\gamma$-coisotropic 31
9. Questions and comments 33
Appendix A. Persistence modules and Barcodes 36
Appendix B. Decomposition in the completion of $D_{lc}(\mathbb{R})$ 38
B.1. Limits of constructible sheaves 38
B.2. Decomposition in $D_{lc}(\mathbb{R})$ 42
Appendix C. Comparing different interleaving metrics on $D(N \times \mathbb{R})$. 45
Appendix D. Local Floer cohomology 49

SG: UMR 5582 du CNRS Institut Fourier, Université Grenoble Alpes, CS 40700 38058 Grenoble cedex 9 - France
CV: Université Paris-Saclay, CNRS, Laboratoire de mathématiques d’Orsay, 91405, Orsay, France. Part of this paper was written as the author was a member of DMA, École Normale Supérieure, 45 Rue d’Ulm, 75230 Cedex 05, FRANCE.
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1. Introduction

In [Vit92], a metric, denoted $\gamma$, was introduced on the set $\mathcal{L}(T^* N)$ of Lagrangians Hamiltonianly isotopic to the zero section in $T^* N$, where $N$ is a compact manifold and on $\mathcal{D}H\text{am}_c(T^* N)$ the group of Hamiltonian maps with compact support for $N = \mathbb{R}^n$ or $T^n$ (and in [Vit06] it was extended to $\mathcal{D}H\text{am}_c(T^* N)$ for general compact $N$). The metric was generalized by Schwartz and Oh to general symplectic manifolds $(M, \omega)$ using Floer cohomology for the Hamiltonian case (see [Sch00; Oh05]), and by [Lec08] for the Lagrangian case. The notion of $\gamma$-coisotropic sets in a symplectic manifold was defined in [Vit22]. A similar definition was due to Usher [Ush19] in the setting of Hofer distance under the name of “locally rigid”. Notice that this yields a weaker notion: $\gamma$-coisotropic implies locally rigid in the sense of Usher.

In the context of sheaves on manifolds, there is a notion of coisotropic sets in the sense of Kashiwara-Schapira (see [KS90], definition 6.5.1, p. 271 and Definition 8.2), that the authors call involutivity. To avoid any confusion with other notions, we shall use the term cone-coisotropic for their definition as it is defined using the contingent and paratingent cones (see [Bou32]). With this notion, Kashiwara and Schapira proved

**Theorem 1.1** ([KS90], theorem 6.5.4, p. 272). Given a sheaf $\mathcal{F} \in D^b(N)$, its singular support $SS(\mathcal{F})$ is cone-coisotropic.

The aim of this paper is to prove that

**Theorem 1.2.** Given a sheaf $\mathcal{F} \in D^b(N)$, its singular support $SS(\mathcal{F})$ is $\gamma$-coisotropic.

Theorem 1.2 implies Theorem 1.1 since we shall prove the following connection between the two notions

**Proposition 1.3.** Let $V$ be a closed subset in $(M, \omega)$. If $V$ is $\gamma$-coisotropic then it is cone-coisotropic.

**Remark 1.4.** This is related to questions asked by Vichery in section 4 of [Vic13]. Our result, together with Proposition 1.3, stating that a $\gamma$-coisotropic set is cone-coisotropic, gives a more natural proof of the Kashiwara-Schapira theorem. Moreover, as opposed to the notion of cone-coisotropic, which is only invariant by $C^1$ symplectic diffeomorphisms, the notion of

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1Assuming $[\omega]\pi_2(M, L) = 0$, $\mu_L \pi_2(M, L) = 0$, where $\mu_L$ is the Maslov class of $L$. 
\(\gamma\)-coisotropic set is invariant by homeomorphisms preserving \(\gamma\), in particular by symplectic homeomorphisms, i.e. homeomorphisms which are \(C^0\) limits of symplectic diffeomorphisms. Along the way we prove a number of results relating the singular support and the spectral norm \(\gamma\).

2. Notation, comments and acknowledgements

Since our results are local, we shall assume from now on that \(N\) is a compact manifold. The following definitions will turn out useful:

- The category \(D(N)\) is the unbounded derived category of sheaves of \(k\)-vector spaces on \(N\), for some given field \(k\), but except in Appendix \(\[\text{B}\]\) the reader may assume we are dealing with its bounded version. For the operations on sheaves associated to a continuous map \(f : M \rightarrow N\) that is \(f^{-1}, f_*, f_! f_i\) and the two operations \(\otimes, \mathcal{H}\text{om}\) and their derived versions, \(f^{-1}, R f_* R f_! f^!\) and \(\otimes, R\mathcal{H}\text{om}\) on \(D(N)\) we refer to [KS90].
- Choosing a real analytic structure on \(N\) we set \(D_c(N)\) to be the category of constructible complexes \(F\), i.e. complexes such that, for some subanalytic stratification, the restriction of \(F\) to each stratum is locally constant and of finite rank.
- For \(\mathcal{F} \in D(N)\), \(SS(\mathcal{F})\) is the singular support (also called microsupport) defined by Kashiwara-Schapira in [KS90]. We set \(SS^*(\mathcal{F}) = SS(\mathcal{F}) \cap (T^* N \setminus 0_N)\).
- For an open set \(U\) in the symplectic manifold \((M, \omega)\) we denote by \(\mathcal{D}\text{ham}_c(U)\) the set of time one flows of Hamiltonian with compact support contained in \(U\).

We thank Pierre Schapira for useful conversations. While writing this paper, we realized that some of the results in Subsection \(\[\text{B.3}\]\) were independently discovered by Asano and Ike in [AI22].

3. Reminders on the singular support of sheaves

Let \(N\) be a manifold, \(k\) a field and \(D(N)\) the derived category of sheaves of \(k\)-vector spaces on \(N\). For \(\mathcal{F} \in D(N)\) we recall that \(SS(\mathcal{F}) \subset T^* N\) is the closed conic subset defined by Kashiwara-Schapira as the closure of the set of points \((x; \xi)\) such that \((R\Gamma_{\{f \geq 0\}} \mathcal{F})_x \neq 0\) for some function of class \(C^1\) such that \(f(x) = 0\) and \(d f_x = \xi\). It is called microsupport or singular support of \(\mathcal{F}\).

The functor \(R\Gamma_{\{f \geq 0\}}\) does not commute with infinite direct sums and \((-)_x\) does not commute with infinite direct products. Here are two variations on the definition which have these commutation properties. For the statement of the lemmas we introduce the following definition.
Definition 3.1. Let $\Omega \subset T^* N \setminus 0_N$ be an open conic subset. We call $\Omega$-lens a locally closed subset $\Sigma$ of $N$ with the following properties: $\Sigma$ is compact and there exists an open neighbourhood $U$ of $\Sigma$ and a function $g : U \times [0,1] \to \mathbb{R}$ of class $C^1$ such that

1. $dg_t(x) \in \Omega$ for all $(x, t) \in U \times [0,1]$, where $g_t = g|_{U \times \{t\}}$, 
2. $\{g_t < 0\} \subset \{g_{t'} < 0\}$ if $t \leq t'$, 
3. the hypersurfaces $\{g_t = 0\}$ coincide on $U \setminus \Sigma$, 
4. $\Sigma = \{g_1 < 0\} \setminus \{g_0 < 0\}$.

We recall that $SS^* (k_{\{g_0 < 0\}}) = \{(x; \lambda dg_t(x)); g_t(x) = 0, \lambda > 0\}$. Using the triangle $k_{\{g_0 < 0\}} \to k_{\{g_1 < 0\}} \to k_{\Sigma} +1$ and the “triangle inequality” for the singular support (see [KS90]) we obtain $SS^* (k_{\Sigma}) \subset \Omega$. The next lemma is essentially a reformulation of the definition of the singular support.

Lemma 3.2. Let $\mathcal{F} \in D(N)$ and let $\Omega \subset T^* N \setminus 0_N$ be an open conic subset. Then $SS(\mathcal{F}) \cap \Omega = \emptyset$ if and only if $R\text{Hom}(k_{\Sigma}, \mathcal{F}) \simeq 0$ for any $\Omega$-lens $\Sigma$.

Proof. (i) We first assume $SS(\mathcal{F}) \cap \Omega = \emptyset$. We recall that $R\text{Hom}(k_V, \mathcal{F}) \simeq R\Gamma(V; \mathcal{F})$ for any open subset $V$ of $N$. Using the notations in the definition of $\Omega$-lens we have a distinguished triangle $k_{\{g_0 < 0\}} \to k_{\{g_1 < 0\}} \to k_{\Sigma} +1$. Applying $R\text{Hom}(\cdot, \mathcal{F}|_U)$ to this triangle we obtain the result, using the non-characteristic deformation lemma ([KS90], Prop. 2.7.2) and the definition of the singular support.

(ii) We assume that there exists $(x_0; \xi_0) \in SS(\mathcal{F}) \cap \Omega$. Hence we can find $(x_1; \xi_1) \in \Omega$ (close to $(x_0; \xi_0)$) and a function $f : N \to \mathbb{R}$ of class $C^1$ such that $f(x_1) = 0$, $df(x_1) = \xi_1$ and $(R\Gamma_{\{f \geq 0\}} \mathcal{F})_{x_1} \neq 0$. Now we can find a basis of open neighbourhoods of $x_1$, say $U_n, n \in \mathbb{N}$, such that $\Sigma_n := \{f \geq 0\} \cap U_n$ is an $\Omega$-lens. Then there exists $n$ such that $R\Gamma(U_n; R\Gamma_{\{f \geq 0\}} \mathcal{F}) \neq 0$ and the
The singular support of sheaves is $\gamma$-coisotropic result follows from

\[
\Gamma(U_n; \Gamma(f \geq 0; \mathcal{F})) \simeq \Gamma(N; R\mathcal{H}om(kU_n, R\mathcal{H}om(k[f \geq 0]; \mathcal{F}))) \\
\simeq \Gamma(N; R\mathcal{H}om(k\Sigma_n, \mathcal{F})) \simeq R\mathcal{H}om(k\Sigma_n, \mathcal{F})
\]

\[ \square \]

The functor $R\mathcal{H}om(k\Sigma, -)$ commutes with direct products but not with direct sums. Here is a dual version of the previous lemma using the functor $R\Gamma(N; k\Sigma \otimes -)$ which commutes with direct sums.

**Lemma 3.3.** Let $\mathcal{F} \in D(N)$ and let $\Omega \subset T^*N \setminus 0_N$ be an open conic subset. Then $SS(\mathcal{F}) \cap \Omega = \emptyset$ if and only if $R\Gamma(N; k\Sigma \otimes \mathcal{F}) \simeq 0$ for any $\Omega^a$-lens $\Sigma$, where $\Omega^a$ is the antipodal set of $\Omega$, that is, its image by $(x; \xi) \mapsto (x; -\xi)$.

The first author thanks Pierre Schapira for a suggestion simplifying the next proof.

**Proof.** Let $\Sigma$ be an $\Omega^a$-lens. We write it as the difference of the two closed sets $\Sigma$ and $Z = \Sigma \setminus \Sigma$. We can find two families of open neighbourhoods of $\Sigma$, say $\{U_n\}_{n \in \mathbb{N}}$, and $Z$, say $\{V_n\}_{n \in \mathbb{N}}$, such that, for all $n$, we have: $V_n \subset U_n$ and $U_n \setminus V_n$ is an $\Omega^a$-lens. For each $n$ we have the commutative diagram of restriction maps

\[
\begin{array}{ccc}
R\Gamma(U_n; \mathcal{F}) & \xrightarrow{\iota_n} & R\Gamma(V_n; \mathcal{F}) \\
\downarrow & & \downarrow \\
R\Gamma(N; \mathcal{F} \otimes k\Sigma) & \xrightarrow{\iota} & R\Gamma(N; \mathcal{F} \otimes kZ)
\end{array}
\]

The cone of $\iota$ is $R\Gamma(N; k\Sigma \otimes \mathcal{F})$, so we want to prove that $\iota$ is an isomorphism, that is, $\iota$ induces an isomorphism on all cohomology groups. The cone of $\iota_n$ is $R\mathcal{H}om(kU_n \setminus V_n, F)$ and the previous lemma says that $\iota_n$ is an isomorphism. Now the result follows from $H^i(N; \mathcal{F} \otimes k\Sigma) = \lim_n H^i(U_n; \mathcal{F})$ and $H^i(N; \mathcal{F} \otimes kZ) = \lim_n H^i(V_n; F)$, for all $i$ (see [KS90, Rem. 2.6.6]).

The previous two lemmas give the following proposition (see [KS90, Ex. 5.7]), away from the zero-section. To deal with the zero-section we use $SS(\mathcal{F}) \cap 0_N = \text{supp}(\mathcal{F})$.

**Proposition 3.4.** Let $\mathcal{F}_n \in D(N)$, $n \in \mathbb{N}$, be given. Then $SS(\bigoplus_n \mathcal{F}_n) \subset \bigcup_n SS(\mathcal{F}_n)$ and $SS(\bigcap_n \mathcal{F}_n) \subset \bigcup_n SS(\mathcal{F}_n)$. 

4. Quantization of Hamiltonian isotopies

Everything in the next subsection is from \cite{GKS} or \cite{KS90}. Given \( \varphi \), a homogeneous Hamiltonian map from \( T^* N \setminus 0_N \) to \( T^* N \setminus 0_N \), Guillermou, Kashiwara and Schapira associate a Kernel, that is an element of \( D^b(N \times N) \), noted \( K_\varphi \) having the following properties\footnote{In fact in \cite{GKS} the authors associate to a Hamiltonian isotopy \( \varphi^s \) a Kernel \( \mathcal{K}_\varphi \in D^b(N \times N \times [0, 1]) \) such that \( \mathcal{K}_\varphi|_{N \times N \times \{s\}} = K_\varphi^s \).} First \( K_\varphi \) is a quantization of the homogeneous Lagrangian \( \Lambda_\varphi = \{(z, \varphi(z)) | z \in T^* N \} \subset T^* N \times T^* N \) in the sense that \( SS^*(K_\varphi) = \Lambda_\varphi \), where we set for short, for a sheaf \( \mathcal{F} \) on a manifold \( N \),

\[
SS^*(\mathcal{F}) = SS(\mathcal{F}) \cap (T^* N \setminus 0_N)
\]

Before we state the second property we recall the \textit{composition} of sheaves:

\textbf{Definition 4.1.} Let \( \mathcal{F} \in D^b(M) \) and \( K \in D^b(M \times N) \). We define

\[
K(\mathcal{F}) = \mathcal{F} \circ K = Rq_N(K \otimes q_M^{-1} \mathcal{F}) \in D^b(N),
\]

where \( q_M, q_N \) are the projections of \( M \times N \) on \( M \) and \( N \) respectively.

The second property is then:

\textbf{Proposition 4.2} (See Proposition 7.1.2(ii) in \cite{KS90} and \cite{GKS}, formula (1.12)). We have

\[
SS^*(K_\varphi(\mathcal{F})) = \varphi(\mathcal{S}^*(\mathcal{F}))
\]

Now if \( \varphi \) is an exact non-homogeneous symplectic map from \( T^* M \) to \( T^* N \) (i.e. \( PdQ - pdq \) is exact), we replace \( \Lambda_\varphi \) by the homogeneous lift of the graph of \( \varphi \), say \( \hat{\Lambda}_\varphi \subset \overline{T^* M} \times T^* N \times T^* \mathbb{R} \), given by

\[
\hat{\Lambda}_\varphi = \{ (q, -\tau p, Q(q, p), \tau P(q, p), F(q, p), \tau) | \varphi(q, p) = (Q, P), \tau > 0 \}
\]

where \( dF = PdQ - pdq \). Note that considering \( \hat{\Lambda}_\varphi \) as a correspondence in \( \overline{T^* M} \times T^* N \times T^* \mathbb{R} \), if \( L \) is an exact Lagrangian in \( T^* M \) and

\[
\hat{L} = \{ (q, \tau p, f_L(q, p), \tau) | (q, p) \in L, \tau \geq 0 \}
\]

we have \( \hat{\Lambda}_\varphi \circ \hat{L} = \hat{\varphi}(L) \).

From now on we assume \( M = N \) and \( \varphi \) is a Hamiltonian map with compact support (which will always be the case in this paper), the existence of a quantization \( \mathcal{K}_\varphi \) for \( \hat{\Lambda}_\varphi \) follows from the homogeneous case by considering \( \hat{\Lambda}_\varphi \) as a deformation of \( \hat{\Lambda}_{\text{id}} \). Since \( \hat{\Lambda}_{\text{id}} \) is quantized by \( k_{\Delta_N \times \{0, +\infty\}} \) we conclude by Proposition 4.2. However we have to be careful that the singular support is slightly bigger than desired:

\[
SS^*(k_{\Delta_N \times \{0, +\infty\}}) = \hat{\Lambda}_{\text{id}} \cup \{ (q, p, q, -p, t, 0) | t \geq 0 \}
\]
but its intersection with $\{\tau > 0\}$ is equal to $\hat{\Lambda}_{id}$. We can find a homogeneous map $\psi$ acting on $T^* (N^2 \times \mathbb{R}) \setminus 0_{N^2 \times \mathbb{R}}$ such that $\psi$ is the identity map near $\{\tau = 0\}$ and $\psi(\Lambda_{id}) = \hat{\Lambda}_\varphi$. We remark that $\varphi$ can be lifted to a homogeneous map $\hat{\varphi}$ acting on $T^* (N \times \mathbb{R}) \setminus \{\tau = 0\}$ (we homogenize the Hamiltonian function) but we cannot use $id_{T^* N} \times \hat{\varphi}$ for $\psi$, as would be natural, since it is not defined everywhere outside the zero section.

Now we set

$$\mathcal{K}_\varphi = K_\varphi(k_{\Delta_N \times [0, +\infty[})$$

and we find

$$SS^* (\mathcal{K}_\varphi) = \hat{\Lambda}_\varphi \cup \{(q, p, q, -p, t, 0) \mid t \geq 0\}$$

If we consider the whole isotopy $\varphi_s$ and choose $t_0$ big enough so that $\hat{\Lambda}_{\varphi_s}$ is contained in $T^* (N^2 \times | - t_0 \, t_0|)$ for all $s \in [0, 1]$, then we see that $SS^* (\mathcal{K}_{\varphi_s}) \cap T^* U$ is independent of $s$, where $U = N^2 \times (\mathbb{R} \setminus [-t_0 \, t_0])$. By [KS90, Prop. 5.4.5] we deduce that

$$\mathcal{K}_\varphi|_{N^2 \times | -\infty, -t_0|} \simeq 0, \quad \mathcal{K}_\varphi|_{N^2 \times |0, +\infty||N^2 \times |0, +\infty|}$$

In other words $\mathcal{K}_\varphi = \mathcal{K}_id = k_{\Delta_N \times [0, +\infty[}$ outside of a compact set.

**Remark 4.3.** We could obtain the existence of $\mathcal{K}_\varphi$ when $M = N$ and $\varphi$ has compact support without assuming that $\varphi$ is Hamiltonian by adapting the result of [Gui12; Vit19] (see Theorem 5.1). In loc. cit. the existence of a quantization is proved for a Legendrian of $T^1 N$ which is the lift of a compact exact Lagrangian of $T^* N$. Here the graph of $\varphi$ is not compact but coincides with the diagonal $T_{\Delta_N} N^2$ outside a compact set (if we choose $F = 0$ at infinity) so it should not be too difficult to extend the result in our situation.

Since we use $\mathcal{K}_\varphi$, defined over $N^2 \times \mathbb{R}$, instead of sheaf defined over $(N \times \mathbb{R})^2$, we change slightly the composition functor as follows, which becomes a mixture of $\circ$ and the convolution $*$ (see Section 5 for the definition)

**Definition 4.4.** Let $\mathcal{F} \in D^b (M \times \mathbb{R})$ and $\mathcal{K} \in D^b (M \times N \times \mathbb{R})$. We define

$$\mathcal{K}^\circ (\mathcal{F}) = \mathcal{F} \otimes \mathcal{K} = R_{q_2} R_{q_1} (q_1^{-1} \mathcal{K} \otimes q_1^{-1} \mathcal{F}) \in D^b (N \times \mathbb{R}),$$

where the maps $q_{1, 2} : M \times N \times \mathbb{R}^2 \to M \times N \times \mathbb{R}$, $q_1 : M \times N \times \mathbb{R}^2 \to M \times \mathbb{R}$, $s : M \times N \times \mathbb{R}^2 \to N \times \mathbb{R}$ are defined by $q_{1, 2}(x, y, t_1, t_2) = (x, y, t_1, t_2)$, $q_1(x, y, t_1, t_2) = (x, t_2)$, $s(x, y, t_1, t_2) = (x, y, t_1 + t_2)$.

Now we obtain a non homogeneous version of Proposition 4.2.

**Proposition 4.5.** For a compactly supported Hamiltonian map $\varphi$ from $T^* N$ to itself and any $\mathcal{F} \in D^b (N \times \mathbb{R})$ with $SS(\mathcal{F}) \subset \{\tau \geq 0\}$, we have $SS^* (\mathcal{K}_\varphi (\mathcal{F})) = \hat{\varphi}(SS^* (\mathcal{F}))$. 
In particular, for \( L \in \mathcal{L}(T^* N) \) we have \( \text{SS}^*(\mathcal{K}_q(\mathcal{F}_L)) = \text{SS}^*(\mathcal{F}_q(L)) \) and, by uniqueness of the quantization (see Theorem 5.1, (4)), \( \mathcal{K}_q^\otimes(\mathcal{F}_L) \cong \mathcal{F}_q(L) \).

5. Spectral invariants for sheaves and Lagrangians

For \( M \) a symplectic manifold, (here we only need \( M = T^* N \)), if \( \Lambda(M) \) is the bundle of Lagrangians subspaces of the tangent bundle to \( M \), with fibre the Lagrangian Grassmannian \( \Lambda(T_x M) \cong \Lambda(n) \), we denote by \( \bar{\Lambda}(M) \) the bundle induced by the universal cover \( \bar{\Lambda}(n) \to \Lambda(n) \).

When using coefficients others than \( \mathbb{Z}/2\mathbb{Z} \) we assume we have a lifting \( \bar{G}_L \) of the Gauss map \( G_L : L \to \Lambda(T^* N) \) given by \( x \mapsto T_x L \) to \( \bar{\Lambda}(T^* N) \). This is called a grading. Given a graded \( L \), the canonical automorphism of the covering induces a new grading and we denote it as \( L[1] \) (or \( \bar{L}[1] \)), and its \( k \)-th iteration as \( L[k] \) (or \( \bar{L}[k] \)). The grading yields an absolute grading for the Floer homology \(^3\) and hence for the complex of sheaves in the Theorem stated below. We refer to [Sei00] for more details on this, but point out that we shall never mention explicitly the grading.

An exact Lagrangian in \( T^* N \) is a pair \( (L, f_L) \) such that \( df_L = \lambda|_L \) where \( \lambda = pdq \) is the Liouville form. For an exact Lagrangian, a grading always exists since the obstruction to its existence is given by the Maslov class, and for exact Lagrangians in \( T^* N \) the Maslov class vanishes, as was proved by Kragh and Abouzaid (see [Kra13] and also the sheaf-theoretic proof by [Gui12]). When \( f_L \) is implicit we only write \( L \), for example \( 0_N \) means \( (0_N, \bar{G}_L) \). A Lagrangian brane is a triple \( \bar{L} = (L, f_L, \bar{G}_L) \), where \( L \) is a compact Lagrangian. For \( c \) a real constant, we write \( T_c \bar{L} = (L, f_L + c, \bar{G}_L) \). We also use the notation \( \bar{L} + c \) or \( L + c \) if the grading is irrelevant (as it will be most of the time).

Let \( L \) be a Lagrangian in \( T^* N \) and

\[
\hat{L} = \{ (q, \tau p, f_L(q, p), \tau) \mid (q, p) \in L, \tau \geq 0 \}
\]

the homogenized Lagrangian in \( T^* (N \times \mathbb{R}) \).

Similarly for Hamiltonian maps in an exact manifold \((M, \omega = d\lambda)\) we look for pairs \((\varphi, F)\) such that \( \varphi^* \lambda - \lambda = dF \) on \( M \).

To state the next result we recall the two adjoint functors, \( * \) and \( \mathcal{H}\text{om}^* \), on the category \( D(N \times \mathbb{R}) \) introduced by Tamarkin in [Tam08]. First we set \( s, q_1, q_2 : N \times (\mathbb{R})^2 \to N \times \mathbb{R} \) given by \( s(x, t_1, t_2) = (x, t_1 + t_2), q_1(x, t_1, t_2) = (x, t_1) \).

\(^3\) Without this extra piece of information, the Floer cohomology \( FH^k(L_1, L_2) \) is generally defined only up to a shift in grading. However, when \( L_2 = \varphi_{L_1}^q(L_1) \), there is an absolute grading, \textit{a priori} depending on the choice of \( H \). However in our situation we do not assume \( L_1 \) is Hamiltonianly isotopic to \( L_2 \), so the grading is required to have an absolute grading of the Floer cohomology.
(x, t_1), q_2(x, t_1, t_2) = (x, t_2) and we define

\[ \mathcal{F} * \mathcal{G} = R\mathcal{S}(q_1^{-1}\mathcal{F} \otimes q_2^{-1}\mathcal{G}), \]

\[ \mathcal{H}\text{om}^*(\mathcal{F}, \mathcal{G}) = Rq_1^* R\mathcal{H}\text{om}(q_2^{-1}\mathcal{F}, s^!\mathcal{G}) \]

Then \( \mathcal{H}\text{om}^* \) is the adjoint of \( * \) in the sense that

\[ \text{Mor}_{D(N \times \mathbb{R})}(\mathcal{F}, \mathcal{H}\text{om}^* (\mathcal{G}, \mathcal{H})) = \text{Mor}_{D(N \times \mathbb{R})} (\mathcal{F} * \mathcal{G}, \mathcal{H}) \]

We recall some properties of \( \mathcal{H}\text{om}^* \). We denote by \( D_{\tau \geq 0}(N \times \mathbb{R}) \) the subcategory of \( D(N \times \mathbb{R}) \) of objects with singular support contained\(^4\) in \( \{ \tau \geq 0 \} \). A base change formula gives, for any \( c \in \mathbb{R} \), and \( \mathcal{F}, \mathcal{G} \in D^b(N \times \mathbb{R}) \)

\[ R\Gamma_{N \times [-c]}(N \times \mathbb{R}; \mathcal{H}\text{om}^* (\mathcal{F}, \mathcal{G})) = R\text{Hom}(\mathcal{F}, T_{c*}(\mathcal{G})), \]

with \( T_c : N \times \mathbb{R} \to N \times \mathbb{R}, (x, t) \mapsto (x, t + c) \). Note that \( T_c \mathcal{L} = T_c \mathcal{L} \).

For \( \mathcal{H} \) with singular support in \( \{ \tau \geq 0 \} \), we have a morphism

\[ R\Gamma_{N \times [a,b]}(N \times \mathbb{R}; \mathcal{H}) \to R\Gamma_{N \times [a,b]}(N \times \mathbb{R}; \mathcal{H}) \to R\Gamma_{N \times [a]}(N \times \mathbb{R}; \mathcal{H}) \]

for any \( a \leq b \). We remark that the cone of this morphism is \( R\Gamma_{N \times [a,b]}(N \times \mathbb{R}; \mathcal{H}) \). Using (5.1) we deduce a morphism, say \( u \), from \( R\text{Hom}(\mathcal{F}, T_{c*}(\mathcal{G})) \) to \( R\text{Hom}(\mathcal{F}, T_{d*}(\mathcal{G})) \) for any \( c \leq d \). Taking \( \mathcal{F} = \mathcal{G}, c = 0 \) the image of \( \text{id}_\mathcal{G} \) gives

\[ \tau_{0,d} : \mathcal{G} \to T_{d*}(\mathcal{G}) \quad \text{for any } d \geq 0 \]

(we come back to this in §6). Then \( u \) is nothing but the composition with \( T_{d*}(\tau_{0,d-c}) \).

According to [Gui12] and [Vit19] we have

**Theorem 5.1.** To each \( L \in \mathcal{L}(T^* N) \) we can associate \( \mathcal{F}_L \in D^b(N \times \mathbb{R}) \) such that

1. \( \text{SS}(\mathcal{F}_L) = \hat{L} \).
2. \( \mathcal{F}_L \) is simple (cf. [KS90, Def. 7.5.4]), \( \mathcal{F}_L = 0 \) near \( N \times \{ -\infty \} \) and \( \mathcal{F}_L = k_{N \times \mathbb{R}} \) near \( N \times \{ +\infty \} \).
3. We have an isomorphism

\[ F\mathcal{H}^*(L_0, L_1; a, b) = H_{N \times [a,b]}^*(N \times \mathbb{R}; \mathcal{H}\text{om}^*(\mathcal{F}_{L_0}, \mathcal{F}_{L_1})) \]

4. \( \mathcal{F}_L \) is unique satisfying properties (1) and (2).
5. There is a natural product map

\[ \mathcal{H}\text{om}^*(\mathcal{F}_{L_1}, \mathcal{F}_{L_2}) \otimes \mathcal{H}\text{om}^*(\mathcal{F}_{L_2}, \mathcal{F}_{L_3}) \to \mathcal{H}\text{om}^*(\mathcal{F}_{L_1}, \mathcal{F}_{L_3}) \]

\(^4\)This category contains the “Tamarkin category” which is the left orthogonal of \( D_{\tau \geq 0}(N \times \mathbb{R}) \). The sheaves \( \mathcal{F}_L \) belongs to the Tamarkin category. The category \( D_{\tau \geq 0}(N \times \mathbb{R}) \) is stable by \( * \) and \( \mathcal{H}\text{om}^* \). The Tamarkin category is stable by \( * \) but not \( \mathcal{H}\text{om}^* \): typically when \( N \) is a point we have \( \mathcal{H}\text{om}^* (k_{[a,\infty]}, k_{[b,\infty]}) \approx k_{[-\infty, b-a]} \) [1].
We have seen that $N_0$ near $0$.

Definition of spectral invariants.

5.1. Remarks

(1) Note that we have

$$F_{T_{L,L}} = T_{c^*}(F_L)$$

(2) In case $L$ has a Generating Function Quadratic at infinity, $S(x, \xi)$ defined on the vector bundle $E \xrightarrow{\pi} N$, we can take for $F_L$ the complex $R(\pi \times \text{id}_R)_*(k_{U_S})$ where $U_S = \{(x, \xi, t) | S(x, \xi) \leq t\}$.

5.1. Definition of spectral invariants. Now we can give a sheafy definition of the spectral invariants introduced in [Vit92]. The next formulation appears in [Vic13] (see also [Vit22]).

In fact the invariants can be defined for objects $F$ of $D_{t \geq 0}(N \times \mathbb{R})$ satisfying:

\[ F|_{N \times [-\infty, -t_0]} \simeq 0, \quad F|_{N \times [t_0, +\infty]} \simeq k_{N \times \mathbb{R}|_{N \times [t_0, +\infty]}} \quad \text{for some } t_0. \]

We have seen that $F_L$ satisfies (5.3) for any $L \in \mathcal{L}(T^* N)$. For $F_1, F_2 \in D_{t \geq 0}(N \times \mathbb{R})$ satisfying (5.3), $\mathcal{H}om^*(F_1, F_2)$ is $k_{N \times \mathbb{R}|[1]}$ near $N \times \{-\infty\}$ and $0$ near $N \times \{+\infty\}$. Using 5.1 and $H_0^0(N \times \mathbb{R}; k_{N \times \mathbb{R}|[1]}) = k$, we deduce a natural morphism $F_1 \to T_{c^*}(F_2)$, for any $c$ big enough, which restricts to $\text{id}: k_{N \times \mathbb{R}} \to k_{N \times \mathbb{R}}$ near $N \times \{+\infty\}$. More generally $H_0^*(N \times \mathbb{R}; k_{N \times \mathbb{R}|[1]}) \simeq H^*(N; k_N)$ and any class $\alpha \in H^d(N; k_N)$ yields a morphism

$$u(\alpha, F_1, F_2, c): F_1 \to T_{c^*}(F_2)[d],$$

for $c$ large enough, which restricts to $\alpha: k_{N \times \mathbb{R}} \to k_{N \times \mathbb{R}|[d]}$ near $N \times \{+\infty\}$ (using $\text{Mor}(k_N, k_N[d]) \simeq H^d(N; k_N)$). The cup product corresponds to the composition, and for $c$ (and $t_0$) large enough this is summarized by the following diagram

$$
\begin{array}{ccc}
H^*(N, k) \simeq R\Gamma(N, k_N) & \xrightarrow{\simeq} & R\text{Hom}(F_1, T_{c^*}F_2) \\
\downarrow \cong & & \downarrow \cong \\
R\text{Hom}(k_{N \times [t_0, +\infty]}, k_{N \times [t_0, +\infty]}) & \xrightarrow{\simeq} & R\text{Hom}(F_1|_{N \times [t_0, +\infty]}, T_{c^*}F_2|_{N \times [t_0, +\infty]})
\end{array}
$$

inducing in cohomology a map

$$H^*_N(N \times [\lambda, +\infty]) (N \times \mathbb{R}; \mathcal{H}om^*(F_{L_1}, F_{L_2})) \otimes H^*_N(N \times [\mu, +\infty]) (N \times \mathbb{R}; \mathcal{H}om^*(F_{L_2}, F_{L_3}))$$

$$\downarrow \cup_*$$

$$H^*_N(N \times [\lambda + \mu, +\infty]) (N \times \mathbb{R}; \mathcal{H}om^*(F_{L_1}, F_{L_3}))$$

that coincides through the above identifications with the triangle product in Floer cohomology.
Definition 5.3. For $\mathcal{F}_1, \mathcal{F}_2 \in D_{r \geq 0}(N \times \mathbb{R})$ satisfying (5.3) and $\alpha \in H^d(N; k_N)$ we set

$$c(\alpha, \mathcal{F}_1, \mathcal{F}_2) = -\inf\{c; \exists u: \mathcal{F}_1 \to T_{c^+}(\mathcal{F}_2)[d], \; u|_{N \times t_0, +\infty} = \alpha, \text{ for } t_0 \gg 0\}$$

(Here $t_0$ is big enough so that both $\mathcal{F}_1$ and $T_{c^+}(\mathcal{F}_2)$ satisfy (5.3).) We also set $c_-(\mathcal{F}_1, \mathcal{F}_2) = c(1, \mathcal{F}_1, \mathcal{F}_2)$, if $N$ is oriented with fundamental class $\mu_N$, $c_+(\mathcal{F}_1, \mathcal{F}_2) = c(\mu_N, \mathcal{F}_1, \mathcal{F}_2)$ and $\gamma(\mathcal{F}_1, \mathcal{F}_2) = c_+(\mathcal{F}_1, \mathcal{F}_2) - c_-(\mathcal{F}_1, \mathcal{F}_2)$.

For $L_1, L_2 \in \mathcal{L}(T^* N)$ we set $c(\alpha, L_1, L_2) = c(\alpha, \mathcal{F}_{L_1}, \mathcal{F}_{L_2})$ and define $c_\pm(L_1, L_2)$, $\gamma(L_1, L_2)$ in the same way. Finally we set $c_\pm(L) = c_\pm(0, N, L)$.

It is not difficult to see that

$$c_-(\mathcal{F}_1, \mathcal{F}_2) = \inf\{c(\alpha, \mathcal{F}_1, \mathcal{F}_2); \; \alpha \in H^*(N; k_N)\}$$

and

$$c_+(\mathcal{F}_1, \mathcal{F}_2) = \sup\{c(\alpha, \mathcal{F}_1, \mathcal{F}_2); \; \alpha \in H^*(N; k_N)\}$$

Indeed, a class $\alpha$ induces by multiplication $v: \mathcal{F}_2 \to \mathcal{F}_2[d]$, $v|_{N \times t_0, +\infty} = \alpha$; now if we have $u: \mathcal{F}_1 \to T_{c^+}(\mathcal{F}_2)[0]$, $u|_{N \times t_0, +\infty} = 1$, then $v \circ u: \mathcal{F}_1 \to T_{c^+}(\mathcal{F}_2)[d]$ satisfies $v \circ u|_{N \times t_0, +\infty} = \alpha$ so $c(1, \mathcal{F}_1, \mathcal{F}_2) \leq c(\alpha, \mathcal{F}_1, \mathcal{F}_2)$.

Using the construction of the sheaf $\mathcal{F}_L$ by using Floer cohomology it is easy to see that the present definition of $c(\alpha, \mathcal{F}_{L_1}, \mathcal{F}_{L_2})$ coincides with the definition of $c(\alpha, L_1, L_2)$ using Floer cohomology. In particular, we have that $c_+(\mathcal{F}_{L_1}, \mathcal{F}_{L_2}) = -c_-(\mathcal{F}_{L_2}, \mathcal{F}_{L_1})$ and this can be extended to the general case of $\mathcal{F}_1, \mathcal{F}_2$ using [Vit19].

We have given the definition using the right hand side of (5.1). We can also rewrite it with the left hand side as follows. Let us set $\mathcal{H} = R_t \mathcal{H} \text{om}^*(\mathcal{F}, \mathcal{G})$, where $t: N \times \mathbb{R} \to \mathbb{R}$ is the projection. Then $\mathcal{H}$ contains all the information about the spectral invariants. More precisely (5.1) is isomorphic to $R \Gamma_{[-c]}(\mathcal{H})$ and $\mathcal{H}$ has its singular support in $\{t \geq 0\}$ so we have the morphisms

$$R \Gamma(N; k_N) \cong R \Gamma_{[-t_0]}(\mathbb{R}; \mathcal{H}) \xrightarrow{\sim} R \Gamma_{[-t_0, -c]}(\mathbb{R}; \mathcal{H}) \cong R \Gamma_{[-c]}(\mathbb{R}; \mathcal{H})$$

for $t_0 \gg 0$ and any $c \leq t_0$. To find the spectral invariants we look for the infimum on the $c$ such that a given class is in the image of the composition of this morphisms.

Remark 5.4. We can see that the infimum in Definition 5.3 is actually a minimum, at least when $\mathcal{F}$ is of the form $\mathcal{F}_L$. Indeed, this follows either by identifying the spectral invariants of the Definition to those obtained by using Floer cohomology, or by appealing to the theory of persistence modules and barcodes (see Appendix A, Proposition A.1).

We notice the following immediate consequence of the definitions
Proposition 5.5. There exists a morphism \( u : \mathcal{F}_{L_1} \to \mathcal{F}_{L_2} \) such that \( u = \text{Id} \) at \( +\infty \) if and only if \( c_-(L_1, L_2) \geq 0 \). In particular there is a morphism \( k_{N \times [0, +\infty]} \to \mathcal{F} \) if and only if \( c_-(L) \geq 0 \).

5.2. The case of Hamiltonian maps. If \( \varphi \) is a Hamiltonian map of \( T^*\mathbb{R}^n \) with compact support, we define the spectral invariants of \( \varphi \) as those of its graph, say \( \Gamma_\varphi \subset T^*\mathbb{R}^n \times T^*\mathbb{R}^n \), compactified in the following way: we choose a symplectomorphism \( \psi : T^*\mathbb{R}^n \times T^*\mathbb{R}^n \to T^*\Gamma_\text{id} \) such that \( \psi(\Gamma_\text{id}) = 0_{\Gamma_\text{id}} \); then \( \psi(\Gamma_\varphi) \) coincides with the zero-section outside a compact set and we can compactify it as \( \Gamma_\varphi^c \) in the cotangent bundle of the sphere. In particular \( \Gamma_\text{id}^c = 0_{S^{2n}} \) and the invariants of \( \varphi \), \( c_+(\varphi) \), \( c_-(\varphi) \), are defined as those of \( (\Gamma_\varphi^c, 0_{S^{2n}}) \). This is well-defined since another choice of \( \psi \) would give a pair \( (\Gamma_\varphi^c, 0_{S^{2n}}) \) symplectomorphic to \( (\Gamma_\varphi^c, 0_{S^{2n}}) \).

On the other hand we have seen in §4 that \( \varphi \) has an associated sheaf \( \mathcal{K}_\varphi \in D(\mathbb{R}^{2n+1}) \). In the next paragraph we explain how we can turn the above definition of \( c_+(\varphi) \), \( c_-(\varphi) \) into Definition 5.6 which uses \( \mathcal{K}_\varphi \), \( \mathcal{K}_\text{id} \) and not the intermediate symplectomorphism \( \psi \).

Equivalence with Definition 5.6. We first remark that we don’t really need to compactify \( \Gamma_\text{id} \) into the sphere to obtain the invariants. Let \( D_1 \) be the subcategory of \( D_{\tau \geq 0}(\Gamma_\text{id} \times \mathbb{R}) \) of complexes isomorphic to \( k_{\Gamma_\text{id} \times \mathbb{R}} \) for some \( c \) and \( D_2 \) be the subcategory of \( D_{\tau \geq 0}(S^{2n} \times \mathbb{R}) \) of complexes isomorphic to \( k_{S^{2n} \times \mathbb{R}} \) near \( \infty \times \mathbb{R} \). Then the compactification and the restriction map induce functors \( \alpha : D_1 \to D_2 \) and \( \beta : D_2 \to D_1 \) such that \( \beta \circ \alpha = \text{id} \), \( \alpha(\tau_{a,b}(\mathcal{F})) = \tau_{a,b}(\alpha(\mathcal{F})) \). We deduce that \( c_-(\alpha(\mathcal{F}_1), \alpha(\mathcal{F}_2)) = c_-(\mathcal{F}_1, \mathcal{F}_2) \) (we remark that \( c_- \) makes sense even in the non compact case). In particular

\[
(5.5) \quad c_-(\varphi) = c_-(\mathcal{F}_{\Gamma_\varphi^c}, \mathcal{F}_{0_{S^{2n}}}) = c_-(\mathcal{F}_{\Gamma_\varphi}, \mathcal{F}_{0_{S^{2n}}})
\]

Now the symplectomorphism \( \psi \) induces an equivalence of categories between \( \mathcal{K}_{\psi}^\otimes : D_{\tau \geq 0}(\mathbb{R}^{2n+1}) \approx D_{\tau \geq 0}(\Gamma_\text{id} \times \mathbb{R}) \) which commutes with the translation \( T_\tau \) in the last variables. We have \( \mathcal{K}_{\psi}^\otimes(\mathcal{K}_{\varphi}) = \mathcal{F}_{\psi} \) and we obtain from (5.5) that the spectral invariant \( c_-(\varphi) \) we have defined above coincides with the one in Definition 5.6 below. To obtain \( c_+ \) we use \( c_+(\mathcal{F}_1, \mathcal{F}_2) = -c_-(\mathcal{F}_2, \mathcal{F}_1) \).

The existence of \( \mathcal{K}_{\psi} \) doesn’t really follow from §4 because \( \psi \) is not compactly supported. But the choice of \( \psi \) is irrelevant and we can choose \( \psi : T^*\mathbb{R}^{2n} \to T^*\mathbb{R}^{2n} \) given by \( \psi(q_1, q_2, p_1, p_2) = (q_1, p_2, p_1 + p_2, q_1 - q_2) \). In this case we can give a direct construction of \( \mathcal{K}_{\psi} \) as follows. Let us define \( \Sigma^+ \subset \mathbb{R}^{2n+1} \) by \( \Sigma^+ = \{ (q_1, q_2, Q_1, Q_2, t) \mid Q_1 = q_1, t \geq (q_1 - q_2)Q_2 \} \), whose boundary is the projection of the lift \( \Lambda_{\psi} \) of the graph of \( \psi \) to the base. Then we can check that \( \mathcal{K}_{\psi} = k_{\Sigma^+} \) is the quantization of \( \psi \).
This justifies that both definitions coincide for a Hamiltonian map of $T^*S^n$ obtained from a compactly supported map of $T^*\mathbb{R}^n$. In the next paragraph we see that the case of a Hamiltonian map of $T^*N$ with support in a Darboux chart is reduced to this case.

Support in a Darboux chart. Let $S_\varphi(q, P, \xi)$ be a generating function quadratic at infinity for $\Gamma_\varphi$ over $\Delta_{\mathbb{R}^{2n}}$, that is,

$$
\begin{align*}
p - P &= \frac{\partial S_\varphi}{\partial q}(q, P; \xi) \\
Q - q &= \frac{\partial S_\varphi}{\partial P}(q, P; \xi) \\
\frac{\partial S_\varphi}{\partial \xi}(q, P; \xi) &= 0
\end{align*}
$$

Since $\varphi$ is compactly supported, so is $S_\varphi$ in the $q, P$ variables, that is, $S_\varphi(q, P; \xi) = B(\xi)$ where $B$ is a non-degenerate quadratic form, for $|q| + |P|$ large enough. We can then extend $S_\varphi$ to a generating function quadratic at infinity on a bundle over $S^{2n}$ (see [Vit92]), and $c_\pm(\varphi)$ are defined as

$$
c_+(\varphi) = \inf\{t \mid T \cup \mu_{S^{2n}} \neq 0 \text{ in } H^*(S^c, S^{-\infty})\},
$$

$$
c_-(\varphi) = \inf\{t \mid T \cup 1 \neq 0 \text{ in } H^*(S^{1}, S^{-\infty})\},
$$

where $T$ is the Thom class associated to the negative bundle of $B$ and $S^{-\infty}$ means $S^{-c}$ for $c$ large enough. Note that these coincide with the spectral invariants defined using Floer cohomology (see [Vit95]).

Now if $\varphi$ is defined on $T^*N$ but has support in a Darboux chart, it can be considered either as a compact supported Hamiltonian map on $T^*N$ or on $\mathbb{R}^{2n}$ and we can define the spectral invariants in two ways (using Floer cohomology). By an easy pseudoconvexity argument (see Appendix D) we can see that these two definitions of $c_\pm(\varphi)$ do coincide.

Sheaf definition of spectral invariants for a Hamiltonian map. Now we can give another formulation of the definition of $c_\pm(\varphi)$. Let $N$ be a compact manifold and let $\varphi$ be a Hamiltonian map of $T^*N$ with compact support. We consider its homogenized graph $\hat{\Lambda}_\varphi \subset T^*N \times T^*N \times T^*\mathbb{R}$ as in §4 We have associated to $\varphi$ its quantization $\mathcal{K}_\varphi$, with singular support $\hat{\Lambda}_\varphi$, and it coincides with $\mathcal{K}_{id} = \kappa_{\Delta_N \times [0, +\infty]}$ outside a compact subset of $N^2 \times \mathbb{R}$. Now $\text{Hom}^+(\mathcal{K}_{id}, \mathcal{K}_\varphi)$ has similar properties as $\text{Hom}^+(\mathcal{F}_{L_1}, \mathcal{F}_{L_2})$, namely, it is $\kappa_{\Delta_N \times \mathbb{R}}[1]$ near $N^2 \times (-\infty)$ and $0$ near $N^2 \times (+\infty)$. As in the case of compact Lagrangians we have $H^*_\text{Hom}^+(N^2 \times \mathbb{R}; \kappa_{\Delta_N \times \mathbb{R}}[1]) = H^*(N; \kappa_N)$ and any class $\alpha \in H^d(N; \kappa_N)$ yields a morphism

$$
u(\alpha, \varphi, c) : \mathcal{K}_{id} \to T_{c^*}(\mathcal{K}_\varphi)[d],
$$

for $c$ big enough, which restricts to $\alpha : \kappa_{\Delta_N \times \mathbb{R}} \to \kappa_{\Delta_N \times \mathbb{R}}[d]$ near $N \times (+\infty)$ (using $\text{Hom}(\kappa_{\Delta_N}, \kappa_{\Delta_N}[d]) \simeq H^d(N; \kappa_N)$.
Definition 5.6. For a compactly supported Hamiltonian map \( \varphi \) of \( T^* N \) and \( \alpha \in H^d(N; k_N) \) we set

\[
c(\alpha, \varphi) = -\inf\{c; \exists u: \mathcal{K}_{id} \to T_{t_0}^* (\mathcal{K}_\varphi)[d], \ u|_{N^2 x | t_0, +\infty|} = \alpha, \ for \ t_0 \gg 0\}
\]

(Here \( t_0 \) is big enough so that over \( N^2 x | t_0, +\infty| \) we have \( T_{c^*}(\mathcal{K}_\varphi) \simeq k_N x \mathbb{R}^d \).

We also set \( c_-(\varphi) = c(1, \varphi), \ c_+(\varphi) = c(\mu_N, \varphi) \) and \( \gamma(\varphi) = c_+(\varphi) - c_-(\varphi) \).

If \( \psi \) is another compactly supported Hamiltonian map, we set \( \gamma(\varphi, \psi) = \gamma(\varphi \psi^{-1}) \).

We have \( c_-(\varphi) = \inf\{c(\varphi, \alpha); \ \alpha \in H^*(N; k_N)\} \) and \( c_+(\varphi) = \sup\{c(\varphi, \alpha); \ \alpha \in H^*(N; k_N)\} \).

Since \( \Gamma(\varphi) \) coincides with the zero section outside a compact set, we have \( c_-(\varphi) \leq 0 \leq c_+(\varphi) \) as in [Vit92] and \( c_+(\varphi) = -c_-(\varphi^{-1}) \).

Note the following analogue of Proposition 5.5

Lemma 5.7. Let \( \varphi \) be a compact supported Hamiltonian map. Then there is a morphism \( \mathcal{K}_{id} \to \mathcal{K}_\varphi \) in \( D^b(N x N x \mathbb{R}) \) equal to \( \text{Id} \) at \( +\infty \) if and only if \( c_-(\varphi) = 0 \). Analogously there is a morphism \( \mathcal{K}_\varphi \to \mathcal{K}_{id} \) in \( D^b(N x N x \mathbb{R}) \) if and only if \( c_+(\varphi) = 0 \).

5.3. Defining \( \gamma \)-coisotropic subsets. For an open set \( U \) in the symplectic manifold \( (M, \omega) \) we denote by \( \mathcal{D}H\mathcal{m}_c(U) \) the set of time one flows of Hamiltonian with compact support contained in \( U \).

Definition 5.8 (see definition 6.1 in [Vit22]). Let \( V \) be a set in \( (M, \omega) \). We say that \( V \) is \( \gamma \)-coisotropic at \( x \in V \) if, for all pairs of balls \( B(x, \eta) \subset B(x, \varepsilon) \) with \( 0 < \eta < \varepsilon \), there is a \( \delta > 0 \) such that, for all \( \varphi \) in \( \mathcal{D}H\mathcal{m}_c(B(x, \varepsilon)) \) and satisfying \( \varphi(V) \cap B(x, \eta) = \varphi \), we have \( \gamma(\varphi) > \delta \).

We shall say that \( V \) is \( \gamma \)-coisotropic if it is non-empty and \( \gamma \)-coisotropic at each \( x \in V \).

We refer to [Vit22], in particular section 6, for properties and examples of \( \gamma \)-coisotropic subsets. In particular we remind the reader of the following result from [Vit22]

Proposition 5.9. Let \( \varphi \) be a homeomorphism preserving \( \gamma \), for example a \( C^0 \)-limit of Hamiltonian maps (usually called Hamiltonian homeomorphisms) and \( V \) a \( \gamma \)-coisotropic set. Then, the image by \( \varphi \) of \( V \) is a \( \gamma \)-coisotropic set.

Note that the completion of \( \mathcal{L}(T^* N) \) for \( \gamma \) is denoted by \( \mathcal{L}(T^* N) \). In [Vit22] the \( \gamma \)-support of an element \( L \) in \( \mathcal{L}(T^* N) \) was defined, and it was proved that it must be a \( \gamma \)-coisotropic subset.
6. The $\gamma$-metric on sheaves

We shall define the analogue of the $\gamma$ distance between sheaves. It is also a sheaf analogue of the barcode distance (see [KS18] or [AI20]) and relies on the morphism $\tau$ introduced by Tamarkin (see [Tam08] or [GKS, Prop. 4.8]) that we have already encountered in (5.2).

To define $\tau$ in general we recall that the subcategory $D_{t \geq 0}(N \times \mathbb{R})$ of $D(N \times \mathbb{R})$ can be characterized as follows (see [KS90, Prop. 5.2.3, 3.5.4]). Let $P$ be the endofunctor of $D(N \times \mathbb{R})$ defined by

$$P(\mathcal{F}) = Rs_*(\mathcal{F} \boxtimes k_{[0, +\infty]})$$

with $s: N \times \mathbb{R}^2 \to N \times \mathbb{R}$, $(x, t_1, t_2) \mapsto (x, t_1 + t_2)$ (this is almost $\mathcal{F} \boxtimes k_{N \times [0, +\infty]}$ up to replacing from $Rs_1$ to $Rs_*$). Then the natural morphism $k_{(0, +\infty)} \to k_{(0)}$ induces a morphism $P(\mathcal{F}) \to \mathcal{F}$ and $D_{t \geq 0}(N \times \mathbb{R})$ is formed by the $\mathcal{F}$ such that $P(\mathcal{F}) \to \mathcal{F}$ is an isomorphism. Now we have in general $Rs_*(\mathcal{F} \boxtimes k_{(c)}) = T_{c*}(\mathcal{F})$, where $T_c(x, t) = (x, t + c)$ and we obtain in the same way, using the morphism $k_{[0, +\infty]} \to k_{(c)}$, a morphism $P(\mathcal{F}) \to T_{c*}(\mathcal{F})$ for any $c \geq 0$. In particular we have a morphism of endofunctors defined on $D_{t \geq 0}(N \times \mathbb{R})$ for any $c \geq 0$

$$\tau_{0, c}(\mathcal{F}): \mathcal{F} \to T_{c*}(\mathcal{F})$$

We shall call this morphism the Tamarkin morphism.

The case of $D_{t \geq 0}(N \times \mathbb{R})$ is in fact sufficient for this paper but we can consider a slightly more general case without modifying the proofs. Let $g: T^*N \setminus 0_N \to \mathbb{R}$ be a 1-homogeneous autonomous Hamiltonian function and let $D_{g \geq 0}(N)$ be the full subcategory of $D(N)$ formed by the $\mathcal{F}$ with $SS^*(\mathcal{F}) \subset \{g \geq 0\}$. We let $\varphi^t = \varphi^t_g: T^*N \setminus 0_N \to T^*N \setminus 0_N$ be the corresponding homogeneous flow. We set for short $K^a_\varphi(\mathcal{F}) = \mathcal{F} \circ K^a_\varphi$.

We consider the lifting of the graph of the whole isotopy $\varphi^t$ to Lagrangian in $T^*(N \times N \times \mathbb{R})$ given by

$$\{(q, p, Q_t(q, p), P_t(q, p), t, g(q, p))\},$$

where $\varphi^t(q, p) = Q_t(q, p), P_t(q, p)$ and the associated kernel $K^a_\varphi \in D(N^2 \times \mathbb{R})$. Then $K^a_\varphi(\mathcal{F}) \in D(N \times \mathbb{R})$ is such that $K^a_\varphi(\mathcal{F})|_{N \times \{a\}} = K^a_\varphi(\mathcal{F})$. Now, if $\mathcal{F} \in D_{g \geq 0}(N)$, then $K^a_\varphi(\mathcal{F}) \in D_{t \geq 0}(N \times \mathbb{R})$. Indeed a point of $SS^*(K^a_\varphi(\mathcal{F}))$ is written $(q, p, Q, P, t, \tau)$ with $(q, p) \in SS^*(\mathcal{F})$ and $\tau = g(q, p)$. We thus have the Tamarkin morphism $\tau_{0, c}(K^a_\varphi(\mathcal{F})): K^a_\varphi(\mathcal{F}) \to T_{c*}(K^a_\varphi(\mathcal{F}))$ for $c \geq 0$. Restricting to $N \times \{a\}$ and setting $b = a + c$ we obtain

$$\tau_{a, b}(\mathcal{F}): K^a_\varphi(\mathcal{F}) \to K^b_\varphi(\mathcal{F}), \quad \text{for } a \leq b.$$
The morphisms $\tau_{a,b}$ are invariant by $K_{\varphi}^t$, for any $t$, and compatible with composition:

\begin{equation}
K_{\varphi}^t(\tau_{a,b}(\mathcal{F})) = \tau_{a+t,b+t}(K_{\varphi}^t(\mathcal{F})),
\end{equation}

\begin{equation}
\tau_{a,c}(\mathcal{F}) = \tau_{b,c}(\mathcal{F}) \circ \tau_{a,b}(\mathcal{F}), \quad \text{for } a \leq b \leq c
\end{equation}

6.1. **Examples.**

1. Let $N = \mathbb{R}$ and $g$ be the norm given by the standard metric, so $g(t,\tau) = |\tau|$. Then $\varphi^a(t,\tau) = (t + a \frac{\tau}{|\tau|}, \tau)$. As a result $K_{\varphi^a}(k_{[x,y]}) = k_{[x+a,y+a]}$ and $SS(K_{\varphi^a}) = \{ (t, t + a \frac{\tau}{|\tau|}, \tau, \tau) \} \subset T^*(\mathbb{R}^2)$.

2. In the case of $N \times \mathbb{R}$ and $g = \tau$ we recover the case we introduced in the first paragraph (and originally due to Tamarkin).

3. If $g$ is non negative we have $D_{g \geq 0}(N) = D(N)$. Typically $g$ is the norm given by a Riemannian metric and $\varphi^g$ is the normalized geodesic flow. In this case, denoting by $B(x, r)$ the open ball at $x$ of radius $r$, we find

\begin{equation}
K_{\varphi}^a(k_{B(x,r)}) = \begin{cases} k_{B(x+r,a)} & \text{for } -r < a < r_{\text{inj}} - r, \\ k_{B(x-r-a)}[\dim N] & \text{for } -r_{\text{inj}} - r < a \leq -r, \end{cases}
\end{equation}

and

\begin{equation}
K_{\varphi}^a(k_{B(x,r)}) = \begin{cases} k_{B(x,a)} & \text{for } r - r_{\text{inj}} \leq a \leq r, \\ k_{B(x,a-r)}[\dim N] & \text{for } r < a < r + r_{\text{inj}}, \end{cases}
\end{equation}

where $r_{\text{inj}}$ is the injectivity radius.

6.1. **The $\gamma_g$-topology.** The following definition is the analogue of the spectral metric (in the case $g = \tau$) (and a sheaf analogue of the barcode distance). It is introduced in [KS18] or [AI20] (up to a small modification).

**Definition 6.2.** Let $g : T^* N \setminus 0_N \to \mathbb{R}$ be a 1-homogeneous autonomous Hamiltonian function and $\varphi = \varphi^g_t$ its flow. For $\mathcal{F}, \mathcal{G} \in D_{g \geq 0}(N)$, we let $\gamma_g(\mathcal{F}, \mathcal{G}) \in [0, \infty]$ be the infimum of the $c \geq 0$ for which there exist $a, b \geq 0$ such that $a + b = c$ and such that there are morphisms

\begin{equation}
u : \mathcal{F} \to K_{\varphi}^a(\mathcal{G}), \quad v : \mathcal{G} \to K_{\varphi}^b(\mathcal{F})\end{equation}

satisfying $K_{\varphi}^a(\nu) \circ u = \tau_{0,a+b}(\mathcal{F})$ and $K_{\varphi}^b(\nu) \circ v = \tau_{0,a+b}(\mathcal{G})$.

The authors thank N. Vichery for the next remark.

**Remark 6.3.** The case $D_{g \geq 0}(N)$ is not really more general than the case $D_{\tau \geq 0}(N \times \mathbb{R})$. Indeed the functor $K_{\varphi}(-) : D(N) \to D(N \times \mathbb{R})$ is fully faithful and we have $T_{a*}(K_{\varphi}(-)) \simeq K_{\varphi}(K_g(-))$. Hence, for $\mathcal{F}, \mathcal{G} \in D_{g \geq 0}(N)$ we have $\gamma_g(\mathcal{F}, \mathcal{G}) = \gamma_T(K_{\varphi}(\mathcal{F}), K_{\varphi}(\mathcal{G}))$. 
The definition in [KS18] requires \( a = b \) which leads to a bigger distance, say \( \gamma'_g \), with \( \gamma'_g \leq \gamma_g \leq 2 \gamma_g \). The definition in [AI20] only asks \( \tau'_g(u) \circ u = \tau_{0,a+b}(\mathcal{F}) \) and \( \tau'_g(u') \circ u' = \tau_{0,a+b}(\mathcal{G}) \), for two possibly different morphisms \( u', v' \). This leads to a smaller distance but we don't know if it is equivalent to \( \gamma_g \). Lemma 6.8 below says that \( \gamma_g \) is equivalent to \( \inf[\gamma_g(\mathcal{C}(u), 0); u : \mathcal{F} \to \mathcal{G}] \), where \( \mathcal{C}(u) \) denotes the cone of \( u \).

**Lemma 6.4.** For \( \mathcal{F}, \mathcal{G}, \mathcal{H} \in D_{g \geq 0}(N) \) we have

1. \( \gamma_g(\mathcal{F}, \mathcal{G}) = \gamma_g(K^i(\mathcal{F}), K^i(\mathcal{G})) = \gamma_g(\mathcal{G}, \mathcal{F}) \).
2. \( \gamma_g(\mathcal{F}, \mathcal{H}) \leq \gamma_g(\mathcal{F}, \mathcal{G}) + \gamma_g(\mathcal{G}, \mathcal{H}) \).
3. \( \gamma_g(0, \mathcal{F}) = \inf(t \geq 0; \tau_{0,t}(\mathcal{F}) = 0) \).
4. If \( \mathcal{F} \) satisfies \( \gamma_g(\mathcal{F}, 0) = 0 \), then \( \mathcal{F} \simeq 0 \).
5. For any distinguished triangle \( \mathcal{F} \to \mathcal{G} \to \mathcal{H} \to \mathcal{F} \), we have \( \gamma_g(0, \mathcal{G}) \leq \gamma_g(0, \mathcal{F}) + \gamma_g(0, \mathcal{H}) \).
6. For composable morphisms \( u, v \) with cones \( \mathcal{C}(u), \mathcal{C}(v), \mathcal{C}(v \circ u) \), we have \( \gamma_g(0, \mathcal{C}(v \circ u)) \leq \gamma_g(0, \mathcal{C}(u)) + \gamma_g(0, \mathcal{C}(v)) \).

**Proof.** (1) follows from [6.2] and (3) follows from the definition of \( \gamma_g \). The triangular inequality (2) is proved in [AI20] Prop. 4.11.

Let us prove (4). By Remark 6.3 we can assume that \( N = M \times \mathbb{R} \) and \( g = \tau \). Let \( x_0 \in M \) be given and let \( i : [x_0] \times \mathbb{R} \to M \times \mathbb{R} \) be the inclusion. We have \( \tau_{a,b}(i^{-1}(\mathcal{F})) = i^{-1}(\tau_{a,b}(\mathcal{F})) \) and it follows that \( \gamma_g(i^{-1}(\mathcal{F}), i^{-1}(\mathcal{G})) \leq \gamma_g(\mathcal{F}, \mathcal{G}) \).

If \( \mathcal{F} \neq 0 \), there exists \( x_0 \) such that \( i^{-1}(\mathcal{F}) \neq 0 \). Hence we can assume that \( N = \mathbb{R} \). We can also take \( g = \lvert \tau \rvert \) (it is differentiable on \( T^* \mathbb{R} \setminus 0 \mathbb{R} \)) instead of \( g = \tau \). The corresponding \( \tau \) morphisms, say \( \tau^g_{a,b} \), coincide with \( \tau_{a,b} \) on \( D_{\tau \geq 0}(\mathbb{R}) \) but they are defined on \( D(\mathbb{R}) \). Up to shifting \( \mathcal{F} \) in degrees and translating, we can assume that \( H^0\mathcal{F}_0 \neq 0 \). Hence there exists \( u \in H^0(\mathcal{F}) \) with \( u_0 \neq 0 \). Interpreting \( u \) as a morphism and choosing a map \( v : \mathcal{F}_0 \to k \) non-vanishing on the germ defined by \( u \), we get that the composition of \( v \) and \( u; k_{-\varepsilon,\varepsilon}[1] \to \mathcal{F} \to k_{[0]} \) is the canonical morphism. Now the morphisms \( \tau^g_{0,\delta}(-) \), for \( 0 < \delta < \varepsilon \) give the commutative diagram (using Example 6.1) where the vertical arrows are given by \( \tau^g_{0,\delta} \)

\[
\begin{array}{ccc}
k_{1-\varepsilon,\varepsilon} & \xrightarrow{u} & \mathcal{F} \\
\downarrow & & \downarrow v \\
k_{1-\varepsilon+\delta,\varepsilon-\delta} & \xrightarrow{\omega} & T_{\delta,+}(\mathcal{F}) \xrightarrow{k_{1-\delta,\delta}[1]}
\end{array}
\]

We have \( \omega \circ v \neq 0 \) and we deduce that \( \tau^g_{0,\delta}(\mathcal{F}) \neq 0 \), as required.

Let us prove (5) (a similar but more detailed argument will be given in the proof of Lemma 6.8(i)). If \( \tau_{0,a}(\mathcal{F}) = 0 \), then \( \tau_{0,a}(\mathcal{G}) \circ u = K^0_g(u) \circ
\[ \tau_{0,a}(\mathcal{F}) = 0 \text{ and } \tau_{0,a}(\mathcal{G}) \text{ factorizes through } \nu. \] In the same way, if \( \tau_{0,b}(\mathcal{H}) = 0 \), then \( \tau_{0,b}(\mathcal{G}) \) factorizes through \( K^b_\varphi(\nu) \). Hence \( \tau_{0,a+b}(\mathcal{G}) \) factorizes through \( K^b_\varphi(\nu) \circ K^n_\varphi(\mu) = 0. \) We conclude with (3).

We deduce (6) from (5) since, by the octaedron axiom, the three cones appear in a distinguished triangle. \( \square \)

If \( N \) is real analytic and \( \mathcal{F}, \mathcal{G} \) are constructible and satisfy \( \gamma_g(\mathcal{F}, \mathcal{G}) = 0 \), then \( \mathcal{F} \simeq \mathcal{G} \) (see [PSW] and also Proposition B.7 for limits of constructible sheaves). However \( \gamma_g \) is only a pseudo-metric as shown by Berkouk and Ginot (see [BG18], proposition 6.9) and the following example.

**Example 6.5.** We define two sheaves on the real line \( \mathcal{F} = \bigoplus_{x \in \mathbb{Q}} k_{[x, \infty]} \) and \( \mathcal{G} = \bigoplus_{x \in \mathbb{Q}^*} k_{[x, \infty]} \), where \( \mathbb{Q}^* = \mathbb{Q} \setminus \{0\} \). We remark that \( K^1_\varphi(\mathcal{F}) \simeq T_{\epsilon_{0+}}(\mathcal{F}) \), where \( T_{\epsilon}(x) = x + t. \) For a given \( \epsilon > 0 \) we choose a bijection \( f : \mathbb{Q} \to \mathbb{Q}^* \) such that \( x \leq f(x) \leq x + \epsilon \), for all \( x \in \mathbb{Q} \), and we define \( u = \bigoplus_{x \in \mathbb{Q}} u_x : \mathcal{F} \to \mathcal{G}, \) \( v = \bigoplus_{x \in \mathbb{Q}^*} v_x : \mathcal{G} \to T_{\epsilon_{x+}} \mathcal{F} \) where \( u_x : k_{[x, \infty]} \to k_{[0, \infty]} \) and \( v_x : k_{[x, \infty]} \to k_{[f^{-1}(x) + \epsilon, \infty]} \) are the natural morphisms. Using \( u, v \) we see that \( \gamma_g(\mathcal{F}, \mathcal{G}) \leq \epsilon. \) Hence \( \gamma_g(\mathcal{F}, \mathcal{G}) = 0. \)

**Definition 6.6.** We denote by \( \gamma_g \) the topology associated to the pseudo-distance \( \gamma_g. \) In other words a sequence \( (\mathcal{F}_j)_{j \geq 1} \) in \( D(N) \) \( \gamma_g \)-converges to \( \mathcal{F} \) if and only if \( \lim_j \gamma_g(\mathcal{F}_j, \mathcal{F}) = 0. \)

**Remark 6.7.** In view of the Lemma 6.8 a sequence \( (\mathcal{F}_n)_{n \in \mathbb{N}} \) converges to \( \mathcal{F} \) if and only if there exist a sequence of positive numbers \( (\epsilon_n)_{n \in \mathbb{N}} \) converging to 0 and morphisms \( u_n : \mathcal{F}_n \to K^n_g(\mathcal{F}) \) such that \( \gamma(0, \mathcal{E}(u_n)) \) converges to 0.

Part 2 in the next lemma is analogue to [AI20, Lem. 4.14].

**Lemma 6.8.** Let \( u : \mathcal{F} \to \mathcal{F}' \) be a morphism in \( D(N) \) and let \( \mathcal{C} \) be the cone of \( u. \)

1. If there exists \( v : \mathcal{F}' \to K^e_g(\mathcal{F}) \) such that \( v \circ u = \tau_{0,e} \) and \( K^e_g(u) \circ v = \tau_{0,2e} \), then \( \gamma(\mathcal{E}(v), 0) \leq 2\epsilon. \)

2. If \( \gamma(\mathcal{C}, 0) < \epsilon, \) then there exists \( v : \mathcal{F}' \to K^{2e}_g(\mathcal{F}) \) such that \( v \circ u = \tau_{0,2e} \) and \( K^{2e}_g(u) \circ v = \tau_{0,4e} \).

**Proof.** (1) We consider the morphism of triangles given by the functorial morphism (6.1),

\[
\begin{array}{ccccccccc}
\mathcal{F} & \xrightarrow{u} & \mathcal{F}' & \xrightarrow{a} & \mathcal{C} & \xrightarrow{\beta} & \mathcal{F}[1] \\
\downarrow{\nu} & & \downarrow{f} & & \downarrow{g} & & \downarrow{\gamma} \\
K^e_g(\mathcal{F}) & \xrightarrow{} & K^e_g(\mathcal{F}') & \xrightarrow{} & K^e_g(\mathcal{C}) & \xrightarrow{} & K^e_g(\mathcal{F})[1]
\end{array}
\]
Proposition 6.9. Let $M$ be a manifold and $I$ an open interval of $\mathbb{R}$. We have $f = K^c_\varphi(a) \circ \tau_{0,e}(\mathcal{F}) = K^c_\varphi(a \circ u) \circ v = 0$. In the same way $g$ also vanishes. Since $\tau_{0,e}(\mathcal{E}) \circ \alpha = f$ vanishes, $\tau_{0,e}(\mathcal{E})$ factorizes through $\beta$ as $\tau_{0,e}(\mathcal{E}) = h \circ \beta$. Hence $\tau_{0,2e}(\mathcal{E}) = K^c_\varphi(\tau_{0,e}(\mathcal{E})) \circ \tau_{0,e}(\mathcal{E}) = K^c_\varphi(h) \circ K^c_\varphi(\beta) \circ \tau_{0,e}(\mathcal{E}) = K^c_\varphi(h) \circ g$ vanishes, which means $\gamma(\mathcal{E}) = 0 \leq 2\varepsilon$.

Since $\tau_{0,e}(\mathcal{E}) = 0$, both morphisms $f$ and $g$ vanish. Since $K^c_\varphi(a) \circ \tau_{0,e}(\mathcal{F}') = f$ vanishes, $\tau_{0,e}(\mathcal{F}')$ factorizes as $\tau_{0,e}(\mathcal{F}') = K^c_\varphi(u) \circ w$ for some $w$.

In the same way, the vanishing of $g$ gives a factorization $\tau_{0,e}(\mathcal{F}) = w' \circ u$ but we cannot say that $w = w'$.

We set $v = K^c_\varphi(w') \circ \tau_{0,e}(\mathcal{F}')$: $\mathcal{F}' \to K^c_\varphi(\mathcal{F})$. In the following computation we omit abusively to write $K^c_\varphi$ and write $\tau$ for whatever $\tau_{-,-}(-)$. A diagram chase on the diagram below gives $v \circ u = w' \circ \tau \circ u = w' \circ u \circ \tau = \tau \circ \tau = \tau$ and $u \circ v = u \circ w' \circ \tau = u \circ u \circ w = u \circ v = u \circ u \circ w = u \circ v = u \circ v = \tau \circ \tau = \tau$, as required.

\[
\begin{array}{cccc}
\mathcal{F} & \xrightarrow{u} & \mathcal{F}' \\
\downarrow & & \downarrow \\
K^c_\varphi(\mathcal{F}) & \xrightarrow{v} & K^c_\varphi(\mathcal{F}') \\
\downarrow & & \downarrow \\
K^c_\varphi(\mathcal{F}) & \xrightarrow{w'} & K^c_\varphi(\mathcal{F}') \\
\end{array}
\]

\[\square\]

6.2. Link with spectral invariants. In this paragraph we work on $N \times \mathbb{R}$ and choose $g = \tau$. So we work with the category $D_{r \geq 0}(N \times \mathbb{R})$ as in §5. We prove Propositions 6.11 and 6.13 which explain the relations between the $\gamma_\tau$-distance and the spectral invariants.

We first give a useful variation on the Morse theorem for sheaves. The following result is mentioned in [Nad16, §6.1].

**Proposition 6.9.** Let $M$ be a manifold and $I$ an open interval of $\mathbb{R}$. Let $\mathcal{F} \in D(M), \mathcal{G} \in D(M \times I)$ and set $\mathcal{G}_t = \mathcal{G}|_{M \times \{t\}}$ for $t \in I$. We assume

1. there exists a compact set $C$ of $M$ such that $\mathcal{G}|_{(M \setminus C) \times I}$ is of the form $\mathcal{G}' \boxtimes k_I$ for some $\mathcal{G}' \in D(M \setminus C),$
2. $SS^*(\mathcal{G}) \cap (0_M \times T^* I) = \varnothing,$
3. $SS^*(\mathcal{F} \times T^* I) \cap SS^*(\mathcal{G}) = \varnothing.$

Then $R\mathcal{H}om(\mathcal{F}, \mathcal{G}_t)$ does not depend on $t \in I$.

**Proof.** We let $i_t: M \times \{t\} \to M \times I$, $t \in I$, be the inclusion. We set $\mathcal{H} = R\mathcal{H}om(\mathcal{F} \boxtimes k_I, \mathcal{G})$. By [KS90, Prop. 5.4.14], condition 3 gives $SS(\mathcal{H}) \subset$
Let $\mathcal{F} \in D_{\tau \geq 0}(N \times \mathbb{R})$ and $t_0$ satisfy (5.3). We assume that $SS(\mathcal{F}) \cap SS(T_{c*}(\mathcal{F})) \subset 0_{N \times \mathbb{R}}$ for any $c \neq 0$. Then the restriction map

$$RHom(\mathcal{F}, T_{c*}(\mathcal{F})) \to RHom(\mathcal{F}|_U, T_{c*}(\mathcal{F})|_U) \simeq RHom(k_U, k_U) \simeq \Gamma(N; k_N)$$

is an isomorphism for any $c > 0$, where $U = N \times ]c + t_0, +\infty[$. In particular, if $u : \mathcal{F} \to T_{c*}(\mathcal{F})$ is id near $+\infty$, then $u = \tau_{0,c}(\mathcal{F})$.

When $SS^*(\mathcal{F})$ is the cone over a Legendrian, the hypothesis means that there is no Reeb chord. In particular the hypothesis is satisfied for the sheaves $\mathcal{F}_L, L \in \mathcal{L}(T^*N)$.

**Proof.** We are going to apply Proposition 6.9 with $M = N \times \mathbb{R}$, $I = ]0, d]$ for $d > 0$ and $\mathcal{G} = \delta^{-1}(\mathcal{F})$, where $\delta : N \times \mathbb{R}^2 \to N \times \mathbb{R}$ is the map

$$(x, t_1, t_2) \mapsto (x, t_1 - t_2)$$

so that $\mathcal{G}|_{N \times \mathbb{R} \times [c]} = T_{c*}(\mathcal{F})$.

For $a < b$, $\mathcal{G}$ is constant on $N \times ]-\infty, a - t_0[ \times [a, b]$ and $N \times ]b + t_0, +\infty[ \times [a, b]$. Hence $\mathcal{G}$ satisfies (1) in Proposition 6.9. It is not difficult to check (2) since its singular support is contained in the conormal of $t_1 = t_2$ that is $\tau_1 + \tau_2 = 0$. For (3) it follows from the hypothesis on $SS(\mathcal{F})$. The proposition gives $RHom(\mathcal{F}, T_{c*}(\mathcal{F})) \simeq RHom(\mathcal{F}, T_{d*}(\mathcal{F}))$, for any $0 < c \leq d$. □

**Proposition 6.11.** Let $L_1, L_2 \in \mathcal{L}(T^*N)$. Then

$$\gamma_1(\mathcal{F}_{L_1}, \mathcal{F}_{L_2}) = \begin{cases} 
  c_+(L_1, L_2) & \text{if } c_-(L_1, L_2) > 0, \\
  -c_-(L_1, L_2) & \text{if } c_+(L_1, L_2) < 0, \\
  c_+(L_1, L_2) - c_-(L_1, L_2) & \text{else.}
\end{cases}$$

**Proof.** We recall that $\mathcal{F}_{L_1} \simeq k_{N \times \mathbb{R}}$ near $+\infty$ and that $-c_-(L_1, L_2)$ is the infimum on the $a$ such that there exists $u : \mathcal{F}_{L_1} \to T_{a*}(\mathcal{F}_{L_2})$ restricting to $id_{k_{N \times \mathbb{R}}}$ near $+\infty$. Similarly $c_+(L_1, L_2)$ is the infimum on the $b$ such that there exists $u : \mathcal{F}_{L_2} \to T_{b*}(\mathcal{F}_{L_1})$ restricting to $id_{k_{N \times \mathbb{R}}}$ near $+\infty$. We
then have $T_{a^*}(v) \circ u = \tau_{0,a^+b}(\mathcal{F}_L)$ and $T_{b^*}(u) \circ v = \tau_{0,a^+b}(\mathcal{F}_L)$ by Corollary 6.10. Hence $u, v$ satisfy Definition 6.2 except that here $a, b$ may be negative. Assuming moreover $a, b \geq 0$ we find that $\gamma_T(\mathcal{F}_L, \mathcal{F}_L)$ is less than the right hand side of the equality in the statement.

Conversely, if $\gamma_T(\mathcal{F}_L, \mathcal{F}_L) < c$, there exists $a, b, u, v$ as above with $a + b = c$, $a, b \geq 0$ but $u, v$ only satisfy the condition on the composition. Near $+\infty$ we only know that they are $u = \lambda_u \mathrm{id}_{k_{N \times \mathbb{R}}}$, $v = \lambda_v \mathrm{id}_{k_{N \times \mathbb{R}}}$ (indeed $\text{Hom}(k_{N \times \mathbb{R}}, k_{N \times \mathbb{R}}) = k$). Since $T_{a^*}(v) \circ u = \tau_{0,a^+b}(\mathcal{F}_L)$, we have $\lambda_u \lambda_v = 1$. Hence $\lambda_u, \lambda_v$ are not zero and, replacing $u, v$ by a non zero multiple, we can assume that $u = v = \mathrm{id}_{k_{N \times \mathbb{R}}}$ near $+\infty$. We deduce $a \geq \max(-c_-(L_1, L_2), 0), b \geq \max(c_+(L_1, L_2), 0)$. □

**Remark 6.12.** Note that in [Vit22] the metric on $\mathcal{L}(T^*N)$ is defined by $c(L_1, L_2) = |c_+(L_1, L_2)| + |c_-(L_1, L_2)|$ as . The map $L \mapsto \mathcal{F}_L$ is then a bi-Lipschitz embedding. Indeed if $c_-(L_1, L_2) > 0$ then $\gamma_T(\mathcal{F}_L, \mathcal{F}_L) = c_+(L_1, L_2)$ and since $c_-(L_1, L_2) \leq c_+(L_1, L_2)$, we have

$\gamma_T(\mathcal{F}_L, \mathcal{F}_L) \leq c(L_1, L_2) = c_+(L_1, L_2) + c_-(L_1, L_2) \leq 2 \gamma_T(\mathcal{F}_L, \mathcal{F}_L)$

If $c_+(L_1, L_2) < 0$ the same inequality holds by exchanging $L_1, L_2$. Finally if $c_-(L_1, L_2) < 0 \leq c_+(L_1, L_2)$ we have $\gamma_T(\mathcal{F}_L, \mathcal{F}_L) = c_+(L_1, L_2) - c_-(L_1, L_2)$ hence

$\gamma_T(\mathcal{F}_L, \mathcal{F}_L) = c(L_1, L_2)$

So, in all three cases we have

$\gamma_T(\mathcal{F}_L, \mathcal{F}_L) \leq c(L_1, L_2) \leq 2 \gamma_T(\mathcal{F}_L, \mathcal{F}_L)$

The proof of Proposition 6.11 works exactly the same way for Hamiltonian maps, replacing the condition “$\mathcal{F}_L \simeq k_{N \times \mathbb{R}}$ near $+\infty$” by “$\mathcal{K}_\varphi \simeq k_{\Lambda_N \times \{0, +\infty\}}$ near $+\infty$”. Since we know that $c_-(\varphi) \leq 0 \leq c_+(\varphi)$ by [Vit92] we obtain the following statement:

**Proposition 6.13.** Let $\varphi_1, \varphi_2$ be compactly supported Hamiltonian maps of $T^* N$. Then $\gamma_T(\mathcal{K}_{\varphi_1}, \mathcal{K}_{\varphi_2}) = \gamma(\varphi_1, \varphi_2)$.

We end this section by the useful result that $\otimes$ is Lipschitz for the $\gamma_T$-distance.

**Lemma 6.14.** Let $M, N, P$ be manifolds and $\mathcal{K}_1 \in D_{\tau \geq 0}(M \times N \times \mathbb{R}), \mathcal{K}_2 \in D_{\tau \geq 0}(N \times P \times \mathbb{R})$. Then, for any $a \in \mathbb{R}$, we have natural isomorphisms $T_{a^*}(\mathcal{K}_1 \otimes \mathcal{K}_2) \simeq T_{a^*}(\mathcal{K}_1) \otimes \mathcal{K}_2 \simeq \mathcal{K}_1 \otimes T_{a^*}(\mathcal{K}_2)$ and, through these isomorphisms, we have the equalities, for any $a \leq b$,

$\tau_{a,b}(\mathcal{K}_1 \otimes \mathcal{K}_2) = \tau_{a,b}(\mathcal{K}_1) \otimes \mathcal{K}_2 = \mathcal{K}_1 \otimes \tau_{a,b}(\mathcal{K}_2)$
Remark 6.15. The notation $\tau_{a,b}(\mathcal{K}_1 \otimes \mathcal{K}_2)$ means that we apply the functor $\otimes$ to the morphism $\tau_{a,b}(\mathcal{K}_1)$. This means that $(\tau_{a,b}(\mathcal{K}_1) \otimes \mathcal{K}_2)$ is a morphism

$$\tau_{a,b}(\mathcal{K}_1) \otimes \mathcal{K}_2 : T_{a*}(\mathcal{K}_1) \otimes \mathcal{K}_2 \rightarrow T_{b*}(\mathcal{K}_1) \otimes \mathcal{K}_2$$

Proof. In the proof the manifolds $M, N, P$ play an auxiliary role and we can consider that our sheaves live on $\mathbb{R}$ to simplify the notations. Hence $\mathcal{K}_1 \otimes \mathcal{K}_2 = R_S(\mathcal{K}_1 \boxtimes \mathcal{K}_2)$ where $S: \mathbb{R}^2 \rightarrow \mathbb{R}$ is the sum. The isomorphisms then follow from the equalities $T_a \circ s = s \circ (T_a \times \text{id}_\mathbb{R}) = s \circ (\text{id}_\mathbb{R} \times T_a)$. However to prove the equalities of morphisms we need to be more precise.

Let $(t_1, t_2, \tau_1, \tau_2)$ be the coordinates on $T^*\mathbb{R}^2$. Then the singular support of $\mathcal{K}_1 \boxtimes \mathcal{K}_2$ is contained in $\{\tau_1 \geq 0\} \times \{\tau_2 \geq 0\}$ and, setting $g_u = u\tau_1 + (1-u)\tau_2$, $\mathcal{K}_1 \boxtimes \mathcal{K}_2$ belongs to $D_{g_u \geq 0}(\mathbb{R}^2)$ for any $u \in [0, 1]$. Let us write $\tau_{a,b}^u$ for the morphism $\tau_{a,b}$ induced by $g_u$. Then $\tau_{a,b}^1$ gives $\tau_{a,b}(\mathcal{K}_1) \otimes \mathcal{K}_2$ by applying $R_S$ and $\tau_{a,b}^0$ gives $\mathcal{K}_1 \otimes \tau_{a,b}(\mathcal{K}_2)$. It remains to see that $\tau_{a,b}^u$ gives the same morphism for all $u$. We define $\mathcal{K} = \mathcal{K}_1 \boxtimes \mathcal{K}_2 \boxtimes k_{[0,1]} \in D(\mathbb{R}^2 \times [0, 1])$ and $g = u\tau_1 + (1-u)\tau_2$. Then $K \in D_{g \geq 0}(\mathbb{R}^2 \times [0, 1])$ (here we are cheating a little bit because the singular support is not defined on a manifold with boundary – however we can replace $[0, 1]$ by $]-\varepsilon, 1 + \varepsilon[, and $u$ by a smooth function with values in $[0, 1]$ which is 0 on $]-\varepsilon, 0]$ and 1 on $[1, 1 + \varepsilon[$. We thus obtain a morphism $\tau_{a,b}^g : T_{a*}(\mathcal{K}) \rightarrow T_{b*}(\mathcal{K})$ where $T_c'(t_1, t_2, u) = (t_1 + uc, t_2 + (1-u)c, u)$. Let $s': \mathbb{R}^2 \rightarrow [0, 1] \rightarrow \mathbb{R} \times [0, 1]$ be the sum of the first two variables. Then $s' \circ T_c' = T_c \times \text{id}_{[0,1]}$ and $g_{a,b}$ induces $\tau_{a,b}^g: (T_{a*}(\mathcal{K}_1 \boxtimes \mathcal{K}_2)) \boxtimes k_{[0,1]} \rightarrow (T_{b*}(\mathcal{K}_1 \boxtimes \mathcal{K}_2)) \boxtimes k_{[0,1]}$ which restricts to $\tau_{a,b}^g$ along $\mathbb{R} \times \{s\}$. Now restricting along $\mathbb{R} \times \{s\}$ always induces the same isomorphism $\text{Hom}(\mathcal{F} \boxtimes k_{[0,1]}, \mathcal{G} \boxtimes k_{[0,1]}) \rightarrow \text{Hom}(\mathcal{F}, \mathcal{G})$, for all $\mathcal{F}, \mathcal{G}$, namely, the inverse of the isomorphism induced by the pull-back along the projection to $[0, 1]$. This concludes the proof.

We deduce an analogue of [PS21], theorem 2.4.1, in our situation.

Lemma 6.16. Let $\mathcal{K}_1, \mathcal{K}_2 \in D_{t \geq 0}(M \times N \times \mathbb{R})$ and $\mathcal{F} \in D_{t \geq 0}(M \times \mathbb{R})$. Then $\mathcal{K}_j \otimes \mathcal{F} \in D_{t \geq 0}(N \times \mathbb{R})$ and we have

$$\gamma_t(\mathcal{K}_1 \otimes \mathcal{F}, \mathcal{K}_2 \otimes \mathcal{F}) \leq \gamma_t(\mathcal{K}_1, \mathcal{K}_2)$$

Proof. We have $\gamma_t(\mathcal{K}_1, \mathcal{K}_2) < c$, for a given $c$, if and only if there exist $a, b \geq 0$ with $a + b = c$ and morphisms $u: \mathcal{K}_1 \rightarrow T_{a*}(\mathcal{K}_2)$, $v: \mathcal{K}_2 \rightarrow T_{b*}(\mathcal{K}_1)$ satisfying the conditions in Definition 6.2. The morphisms induce $u \circ \text{id}_{\mathcal{F}}, v \circ \text{id}_{\mathcal{F}}$ which also satisfies the conditions of the definition by Lemma 6.14.
6.3. \( \gamma \)-limits and colimits. In this paragraph we shall prove that any sequence \((\mathcal{F}_n)_{n \in \mathbb{N}}\) which \( \gamma \)-converges to \( \mathcal{F} \) can be turned into an inductive system whose homotopy colimit is \( \mathcal{F} \). We recall the notion of homotopy colimit in \( D(N) \) (see [BN93, Def. 2.1])

**Definition 6.17.** Let \((\mathcal{F}_n, f_n)_{n \in \mathbb{N}}\), with \( f_n : \mathcal{F}_n \to \mathcal{F}_{n+1} \), be an inductive system in \( D(N) \); then \( \text{hocolim}_n \mathcal{F}_n \) is the cone of the morphism

\[
\text{id} - f : \bigoplus_{n \geq 0} \mathcal{F}_n \to \bigoplus_{n \geq 0} \mathcal{F}_n
\]

where \( f = \bigoplus_{n \geq 0} f_n \).

We thus have a distinguished triangle

\[
\bigoplus_{n \geq 0} \mathcal{F}_n \xrightarrow{\text{id} - f} \bigoplus_{n \geq 0} \mathcal{F}_n \xrightarrow{p} \text{hocolim}_n \mathcal{F}_n \xrightarrow{+1}
\]

However, like any cone, \( \text{hocolim}_n \mathcal{F}_n \) is only defined up to (non unique) isomorphism and the morphism \( p \) itself is not uniquely defined. For a given triangle (6.3) and for any \( n_0 \in \mathbb{N} \), we have a morphism \( i_{n_0} : \mathcal{F}_{n_0} \to \text{hocolim}_n \mathcal{F}_n \) defined as \( i_{n_0} = p \circ j_{n_0} \) where \( j_{n_0} \) is the obvious morphism to the sum. For another choice of triangle, with \( p' \) instead of \( p \), there exists an automorphism \( \psi \) of \( \text{hocolim}_n \mathcal{F}_n \) such that \( p' = \psi \circ p \). Then \( i'_{n_0} = p' \circ j_{n_0} \) is “conjugate” to \( i_{n_0} \) in the sense \( i'_{n_0} = \psi \circ i_{n_0} \).

We recall the “nine diagram” from [BBD82, Prop. 1.1.11] (see [KS06, Ex. 10.6] where it is stated precisely which arrows are given and which ones are obtained), a variant of the octaederon axiom. We assume to be given a commutative square as on the top left corner of the diagram below and four distinguished triangles (two vertical and two horizontal) given by the unmarked solid arrows. The arrows marked [1] are just translations of already defined solid arrows.

The proposition claims that the dotted arrows can be chosen to make all squares commutative, except for the one with \( Z^2 \) at its top left corner, which is anticommutative, and the new line and the new column are distinguished triangles.

\[
\begin{array}{cccc}
X^0 & \rightarrow & X^1 & \rightarrow & X^2 & \rightarrow & X^0[1] \\
| & | & | & | & | & | & | \\
Y^0 & \rightarrow & Y^1 & \rightarrow & Y^2 & \rightarrow & Y^0[1] \\
| & | & | & | & | & | & | \\
Z^0 & \rightarrow & Z^1 & \rightarrow & Z^2 & \rightarrow & Z^0[1] \\
| & | & | & | & | & | & | \\
X^0[1] & \rightarrow & X^1[1] & \rightarrow & X^2[1] & \rightarrow & X^0[2]
\end{array}
\]
Remark 6.18. Using the nine diagram built on the square

\[
\begin{array}{ccc}
\bigoplus_{n \geq n_0} \mathcal{F}_n & \xrightarrow{id-f} & \bigoplus_{n \geq n_0} \mathcal{F}_n \\
\downarrow & & \downarrow \\
\bigoplus_{n \geq 0} \mathcal{F}_n & \xrightarrow{id-f} & \bigoplus_{n \geq 0} \mathcal{F}_n
\end{array}
\]

we can check that \( \text{hocolim}_{n \geq 0} \mathcal{F}_n \simeq \text{hocolim}_{n \geq n_0} \mathcal{F}_n \). With the above notations, we take \( X^0 = X^1 = \bigoplus_{n \geq n_0} \mathcal{F}_n, Y^0 = Y^1 = \bigoplus_{n \geq 0} \mathcal{F}_n, Z^0 = Z^1 = \bigoplus_{0 \leq n \leq n_0 - 1} \mathcal{F}_n \). The map from \( Z^0 \) to \( Z^1 \) is also equal to \( \text{id} - f \), but as is an upper triangular finite-dimensional matrix with \( \text{Id} \) on the diagonal, so it is invertible. This implies \( Z^2 = 0 \). As a result the vertical arrow from \( X^2 \) to \( Y^2 \) is an isomorphism (in \( D(N) \)).

A more general statement of the following Lemma can be found in Lemma 13.33.4 of [Stacks, Section 0A5K]. It tells us, as we might expect, that the limit of a subsequence coincides with the limit of the original sequence.

Lemma 6.19. Let \( (\mathcal{F}_n, f_n)_{n \in \mathbb{N}} \) be an inductive system in \( D(N) \) and \( \sigma : \mathbb{N} \rightarrow \mathbb{N} \) an increasing map. Then the compositions of the \( f_n \)'s define an inductive system \( (\mathcal{F}_{\sigma(n)}, f'_{\sigma(n)}) \) and there exists an isomorphism \( j : \text{hocolim}_n \mathcal{F}_{\sigma(n)} \simeq \text{hocolim}_n \mathcal{F}_n \) such that \( j \circ i'_{\sigma(n)} = i_{\sigma(n)} \), where \( i'_{\sigma(n)} \) is the morphism \( i \) for \( (\mathcal{F}_{\sigma(n)}) \).

A family of morphisms \( u_n : \mathcal{F}_n \rightarrow \mathcal{G} \) such that \( u_{n+1} \circ f_n = u_n \) induces a morphism \( u : \text{hocolim}_n \mathcal{F}_n \rightarrow \mathcal{G} \) such that \( u \circ i_n = u_n \) for all \( n \). Indeed we have \( \bigoplus_n u_n \circ (\text{id} - f) = 0 \), hence \( \bigoplus_n u_n \) factorizes as \( \bigoplus_n u_n = u \circ p \). Again this morphism \( u \) is not uniquely defined.

Lemma 6.20. Let \( (\mathcal{F}_n, f_n)_{n \in \mathbb{N}}, \) with \( f_n : \mathcal{F}_n \rightarrow \mathcal{F}_{n+1} \), be an inductive system in \( D(N) \). We let \( \mathcal{C} (f_n) \) be the cone of \( f_n \) and we assume that \( \sum_n \gamma_g (\mathcal{C} (f_n), 0) \) is finite. Then the sequence \( (\mathcal{F}_n)_{n \in \mathbb{N}} \) \( \gamma_g \)-converges to \( \text{hocolim}_k \mathcal{F}_k \). More precisely, if we let \( i_n : \mathcal{F}_n \rightarrow \text{hocolim}_k \mathcal{F}_k \) be the morphism defined after (6.3), we have \( \gamma_g (\mathcal{C} (i_n), 0) \leq 2 \sum_{k=n}^{\infty} \gamma_g (\mathcal{C} (f_k), 0) \).

Proof. Let \( n_0 \) be given. We set for short \( \mathcal{I} = \bigoplus_{n \geq n_0} \mathcal{F}_n, \mathcal{C} = \text{hocolim}_n \mathcal{F}_n \). We checked that \( \mathcal{C} \) is the cone of \( u = \text{id} - \bigoplus_{n \geq n_0} f_n : \mathcal{I} \rightarrow \mathcal{I} \). We also consider the similar sum but associated to the constant sequence \( \mathcal{G}_n = \mathcal{F}_{n_0} \) for all \( n \geq n_0 \) and \( \mathcal{F} = \bigoplus_{n \geq n_0} \mathcal{G}_n \). We define \( w : \mathcal{F} \rightarrow \mathcal{I} \) as \( \text{id} - s \) where \( s_n : \mathcal{G}_n \rightarrow \mathcal{G}_{n+1} \) is induced by \( \text{id} \mathcal{F}_{n_0} \). The cone of \( w \) is \( \mathcal{G}_{n_0} \). We let \( f^m_n : \mathcal{F}_n \rightarrow \mathcal{F}_m \) be the composition of the \( f_k \)'s and we define \( F = \bigoplus_{n \geq m} f^m_n : \mathcal{F} \rightarrow \mathcal{I} \). Then \( F \circ w = u \circ F \) and the nine diagram recalled above gives the commutative (except for one anticommuting square) diagram of distinguished
where \( \mathcal{S}' = \bigoplus_{n \geq n_0} \mathcal{C}(f_n^{m}) \), \( j_{n_0} \) is conjugate to \( i_{n_0} \) (unfortunately we cannot say they are equal because of the ambiguity in the definition of the cone) and \( \mathcal{C}(j_{n_0}) \) is the cone of \( j_{n_0} \).

We set \( r : \mathcal{F}_{n_0} \to \mathcal{T} \) be the inclusion of the first factor. The morphisms \( r \) and \( w \) give a splitting \( \mathcal{T} \cong \mathcal{F}_{n_0} \oplus \mathcal{T} \) and it follows that \( q \circ r \) is an isomorphism. Since \( i_{n_0} \) is “conjugate” to \( p \circ F \circ r \) (see after (6.3)), it is also conjugate to \( j_{n_0} \) and \( \mathcal{C}(j_{n_0}) \cong \mathcal{C}(i_{n_0}) \).

Now we claim that \( \gamma_{g}(\mathcal{C}(f_n^{m}),0) \leq \sum_{k=0}^{m-1} \gamma_{g}(\mathcal{C}(f_k),0) \). We prove this by induction on \( m - n \). When \( m = n + 1 \) this is clear. Since \( f_n^{m+1} = f_m \circ f_n^{m} \), we have, using Lemma 6.8, there exist \( f_n : \mathcal{F}_n \to K_{q}^{2^{-n}}(\mathcal{F}_{n+1}) \) such that \( \gamma_{g}(\mathcal{C}(f_n),0) \leq 2^{-n+1} \). We then set \( \epsilon_n = \sum_{k \geq n} 2^{-k} \) and \( \mathcal{F}'_n = K_{q}^{\leq n}(\mathcal{F}_n) \) so \( f_n \) induces a map \( f'_n : \mathcal{F}'_n \to \mathcal{F}'_{n+1} \) and according to Lemma 6.20, \( \mathcal{F}'_n \gamma_{g} \) converges to \( \text{hocolim} \mathcal{F}_n \). Since \( \gamma_{g}(\mathcal{F}_n,\mathcal{F}'_n) \leq \epsilon_n \) we have that \( (\mathcal{F}_n)_{n \geq 1} \) has the same limit.

Proof. Let \( (\mathcal{F}_n)_{n \in \mathbb{N}} \) be a Cauchy sequence. Up to taking a subsequence we can assume that \( \gamma_{g}(\mathcal{F}_n,\mathcal{F}_m) \leq 2^{-n} \) for any \( n \leq m \). In particular, by Lemma 6.6, there exist \( f_n : \mathcal{F}_n \to K_{q}^{2^{-n}}(\mathcal{F}_{n+1}) \) such that \( \gamma_{g}(\mathcal{C}(f_n),0) \leq 2^{-n+1} \). We then set \( \epsilon_n = \sum_{k \geq n} 2^{-k} \) and \( \mathcal{F}'_n = K_{q}^{\leq n}(\mathcal{F}_n) \) so \( f_n \) induces a map \( f'_n : \mathcal{F}'_n \to \mathcal{F}'_{n+1} \) and according to Lemma 6.20, \( \mathcal{F}'_n \gamma_{g} \) converges to \( \text{hocolim} \mathcal{F}_n \). Since \( \gamma_{g}(\mathcal{F}_n,\mathcal{F}'_n) \leq \epsilon_n \) we have that \( (\mathcal{F}_n)_{n \geq 1} \) has the same limit.

We just proved that to a Cauchy sequence we can associate a limit that is a homotopy colimit. In the next Proposition we prove that conversely any \( \gamma_{g} \)-limit of a sequence \( (\mathcal{F}_n)_{n \in \mathbb{N}} \) is a homotopy colimit of some
Lemma 6.23. Let $\mathcal{F} \in D(N)$ and let $\varepsilon_n > 0$ be a sequence decreasing to 0. We have an inductive system $(K_{\phi}^{-\varepsilon_n}(\mathcal{F}_n), \tau_{-\varepsilon_n,-\varepsilon_{n+1}}(\mathcal{F}))$. Then the maps $\tau_{-\varepsilon_n,0}(\mathcal{F})$ induce an isomorphism $\text{hocolim} K_{\phi}^{-\varepsilon_n}(\mathcal{F}_n) \to \mathcal{F}$.

Proof. Let $\tau : \text{hocolim} K_{\phi}^{-\varepsilon_n}(\mathcal{F}_n) \to \mathcal{F}$ be the morphism induced by the maps $\tau_{-\varepsilon_n,0}(\mathcal{F})$. With the notation $i_n$ of Lemma 6.20 we have $\tau \circ i_n = \tau_{-\varepsilon_n,0}(\mathcal{F})$. By the octaedron axiom there exists a distinguished triangle relating the cones of these maps and Lemma 6.4 implies that $\gamma_{g}(0, \mathcal{C}(\tau)) \leq \gamma_{g}(0, \mathcal{C}(i_n)) + \gamma_{g}(0, \mathcal{C}(\tau_{-\varepsilon_n,0}(\mathcal{F}))$. By Lemma 6.8 $\gamma_{g}(0, \mathcal{C}(\tau_{-\varepsilon_n,-\varepsilon_{n+1}}(\mathcal{F}))) \leq 2(\varepsilon_n - \varepsilon_{n+1})$ and we can apply Lemma 6.20. Hence $\gamma_{g}(0, \mathcal{C}(i_n))$ goes to 0 and $\gamma_{g}(0, \mathcal{C}(\tau))$ is as small as desired. So $\mathcal{C}(\tau) \simeq 0$ and $\tau$ is an isomorphism.

Proposition 6.24. Let $\mathcal{F} \in D(N)$ be a sequence in $D(N)$ which $\gamma_{g}$-converges to $\mathcal{F}$. Then, up to taking a subsequence, there exist a sequence of positive numbers $(\varepsilon_n)_{n \in \mathbb{N}}$ converging to 0 and morphisms $f_n : K_{\phi}^{-\varepsilon_n}(\mathcal{F}_n) \to K_{\phi}^{-\varepsilon_{n+1}}(\mathcal{F}_{n+1})$, $u_n : K_{\phi}^{-\varepsilon_n}(\mathcal{F}_n) \to \mathcal{F}$ such that $u_{n+1} \circ f_n = u_n$, for all $n$, and the morphism $\text{hocolim} K_{\phi}^{-\varepsilon_n}(\mathcal{F}_n) \to \mathcal{F}$ induced by the $u_n$'s (see after (6.3)) is an isomorphism.

Proof. We set $\alpha_n = 2^{-n}$. Up to taking a subsequence we can assume that $\gamma_{g}(\mathcal{F}_n, \mathcal{F}) \leq \alpha_{n+1}$ for each $n$. This implies the existence of $0 \leq \beta_n \leq \alpha_{n+1}$ and morphisms $\nu_n : \mathcal{F} \to K_{\phi}^{\beta_n}(\mathcal{F}_n)$, $w_n : K_{\phi}^{\alpha_n}(\mathcal{F}_{\sigma(n)}) \to K_{\phi}^{-\varepsilon_{n+1}}(\mathcal{F})$ such that $w_n \circ \nu_n = \tau_{0, \alpha_{n+1}}(\mathcal{F})$. Translating these morphisms by $K_{\phi}^{\varepsilon_n}(\mathcal{F})$ and alternating the $\mathcal{F}_n$ and the $K_{\phi}^{-\varepsilon_n}(\mathcal{F})$ we obtain an inductive system

$$
\cdots \to K_{\phi}^{-\varepsilon_{n+1}}(\mathcal{F}) \xrightarrow{K_{\phi}^{-\varepsilon_n}(\nu_n)} K_{\phi}^{-\varepsilon_n}(\mathcal{F}_n) \xrightarrow{K_{\phi}^{-\varepsilon_{n+1}}(w_n)} K_{\phi}^{-\varepsilon_n}(\mathcal{F}) \\
\xrightarrow{K_{\phi}^{-\varepsilon_{n+1}}(\nu_{n+1})} K_{\phi}^{-\varepsilon_{n+1}}(\mathcal{F}_{n+1}) \xrightarrow{K_{\phi}^{-\varepsilon_{n+1}}(w_{n+1})} K_{\phi}^{-\varepsilon_n}(\mathcal{F}_n) \to \cdots
$$

where $\varepsilon_n = \alpha_n - \beta_n$. We define $f_n = K_{\phi}^{-\alpha_{n+1}}(\nu_{n+1}) \circ K_{\phi}^{-\varepsilon_n}(w_n)$ and $u_n = \tau_{-\alpha_{n+1},0}(\mathcal{F}) \circ K_{\phi}^{-\varepsilon_n}(w_n)$. The result follows from Lemmas 6.19 and 6.23.

7. Proof of Theorem 1.2

Let $\mathcal{F} \in D(N)$. We want to prove that around a point $z_0 \in SS(\mathcal{F})$ there is no sequence $(\varphi_j)_{j \geq 1}$ in $\mathcal{D}$ such that $\lim_j \varphi_j = \text{Id}$ and $\varphi_j(\text{SS}(\mathcal{F})) \cap B(z_0, \eta) = \emptyset$. We argue by contradiction and assume the existence of such a sequence. Let $\mathcal{K}_{\varphi_j}$ be the sheaf in $D^b(N \times N \times \mathbb{R})$ inducing $\varphi_j$ as recalled in §4. We denote by $T^{*}_{\tau > 0}(N \times \mathbb{R})$ the subset of
THE SINGULAR SUPPORT OF SHEAVES IS $\gamma$-COISOTROPIC

$T^*(N \times \mathbb{R})$ given by $\tau > 0$ and we set $\rho: T^*_{\tau > 0}(N \times \mathbb{R}) \to T^* N, (x, t, \xi, \tau) \mapsto (x, \xi/\tau)$. Then $\rho(SS(\mathcal{K}^\circ_{\phi_j}(\mathcal{F})) \cap T^*_{\tau > 0}(N \times \mathbb{R})) = \phi_j(SS(\mathcal{F}))$ does not intersect $B(z_0, \eta)$. We want to prove that this implies that $SS(\mathcal{F}) \cap B(z_0, \eta) = \emptyset$.

We will use the following propositions.

**Proposition 7.1.** Let $(\phi_j)_{j \geq 1}$ be a sequence in $\mathcal{D}\mathcal{Mam}_c(T^* N)$ such that $\gamma - \lim \phi_j = \text{Id}$ and $\mathcal{K}^\circ_{\phi_j}$ its quantization in $D^b(N \times N \times \mathbb{R})$. Then for all $\mathcal{F} \in D^b(N)$ we have

$$\gamma_g - \lim \mathcal{K}^\circ_{\phi_j} = \mathcal{K}^\circ_{\text{Id}} = \mathcal{F} \otimes k_{[0, +\infty)} \in D^b(N \times \mathbb{R})$$

**Proof.** This follows from Lemma 6.16 and Proposition 6.13. □

**Remark 7.2.** Note that $\phi_j(SS(\mathcal{F}))$ is not a homogeneous manifold, and $SS(\mathcal{K}^\circ_{\phi_j}(\mathcal{F})) \subset T^* (N \times \mathbb{R})$ represents the homogenization of $\phi_j(SS(\mathcal{F}))$.

Now for a sequence $(X_j)_{j \geq 0}$ of subsets of a topological space $Z$, its topological upper and lower limits are defined as

$$\limsup X_j = \bigcap_n \bigcup_{j \geq n} X_j$$

$$= \left\{ x \in Z \mid \exists (x_j)_{j \geq 1}, x_j \in X_j \text{ for infinitely many } j, \lim x_j = x \right\}$$

$$\liminf X_j = \left\{ x \in Z \mid \exists (x_j)_{j \geq 1}, x_j \in X_j, \lim x_j = x \right\}$$

Obviously $\liminf_j X_j \subset \limsup_j X_j$. We have

**Proposition 7.3.** Let $M$ be a manifold and let $g: T^* M \setminus 0_M \to \mathbb{R}$ be a 1-homogeneous autonomous Hamiltonian function. If $(\mathcal{F}_j)_{j \geq 1}$ is a sequence such that $\gamma_g - \lim \mathcal{F}_j = \mathcal{F}$ then we have

$$SS(\mathcal{F}) \subset \liminf \mathcal{F}(\mathcal{F}_j)$$

**Proof.** By Proposition 6.24 up to taking a subsequence and replacing $\mathcal{F}_j$ by $K_{\phi_j^*}(\mathcal{F}_j)$, for some sequence $(\varepsilon_j)$ converging to 0, we can assume that there exist morphisms $f_j: \mathcal{F}_j \to \mathcal{F}_{j+1}$ such that $\text{hocolim} \mathcal{F}_j \xrightarrow{\sim} \mathcal{F}$. The homotopy colimit is defined by a distinguished triangle where the other two terms are $\bigoplus_{n \geq n_0} \mathcal{F}_n$ (we can indeed restrict to $\bigoplus_{n \geq n_0}$ by Remark 6.18). By the triangle inequality for singular supports and Proposition 3.4 this implies that $SS(\mathcal{F}) \subset \liminf_j SS(\mathcal{F}_j)$. Now let $p = (x, \xi) \notin \liminf_j SS(\mathcal{F}_j)$, we can find a subsequence $\mathcal{F}_{\sigma(j)}$, such that $p \notin \limsup_j SS(\mathcal{F}_{\sigma(j)}); \text{ but } \mathcal{F}_{\sigma(j)} \text{ has limit } \mathcal{F}$, so $p \notin SS(\mathcal{F})$. As a result we have $SS(\mathcal{F}) \subset \liminf_j SS(\mathcal{F}_j)$. □
We may now conclude the proof of the Theorem. As indicated above, we argue by contradiction and assume \( SS(\mathcal{F}) \) is not \( \gamma \)-coisotropic at \( z_0 = (x_0, p_0) \in SS(\mathcal{F}) \). Then there is a sequence \( (\varphi_j)_{j \geq 1} \) of Hamiltonian maps and an open ball \( B(z_0, \eta) \) such that

1. \( (\varphi_j)_{j \geq 1} \) \( \gamma \)-converges to \( id \),
2. \( \varphi_j(SS(\mathcal{F})) \cap B(z_0, \eta) = \emptyset \).

The first statement together with Proposition 7.1 implies that \( K_{\varphi_j}(\mathcal{F}) \xrightarrow{\gamma} K_{id}(\mathcal{F}) = \mathcal{F} \boxtimes k_{[0, +\infty]} \) and Proposition 7.3, applied with \( M = N \times \mathbb{R} \) and \( g = \tau \), then gives

\[
SS(\mathcal{F}) \times \{(0) \times \mathbb{R}\} = SS(K_{id}(\mathcal{F})) \subseteq \liminf_j SS(K_{\varphi_j}(\mathcal{F}))
\]

Using \( \rho(SS(K_{\varphi_j}(\mathcal{F})) \cap T^*_\mathbb{R}(N \times \mathbb{R})) = \varphi_j(SS(\mathcal{F})) \) we deduce \( SS(\mathcal{F}) \subseteq \liminf_j \varphi_j(SS(\mathcal{F})) \). In particular \( SS(\mathcal{F}) \cap B(z_0, \eta) = \emptyset \) by the hypothesis (2), which gives a contradiction.

8. \( \gamma \)-COISOTROPIC VS CONE-COISOTROPIC

8.1. A \( \gamma \)-coisotropic set is cone-coisotropic. Our goal in this section is to prove Proposition 1.3.

Following Bouligand (see [Bou32]), one may define for a point \( x \) in a subset \( V \) in a smooth manifold, two cones:

**Definition 8.1.** The paratingent cone of a set \( V \) at \( x \) is

\[
C^+(x, V) = \left\{ \lim_{n} c_n(x_n - y_n) \mid x_n, y_n \in V, c_n \in \mathbb{R}, \lim_n x_n = x, \lim_n y_n = x, \lim_n c_n = +\infty \right\}
\]

The contingent cone of a set \( V \) at \( x \) is

\[
C^-(x, V) = \left\{ \lim_{n} c_n(x_n - x) \mid x_n \in V, c_n \in \mathbb{R}, \lim_n x_n = x, \lim_n c_n = +\infty \right\}
\]

Clearly \( C^-(x, V) \subset C^+(x, V) \). Note that \( C^+(x, V) \) is invariant by \( \nu \mapsto -\nu \), while it is not necessarily the case for \( C^-(x, V) \). We then have the following definition, which appears under the name “involutivity” in the book of Kashiwara and Schapira

**Definition 8.2** (Cone-coisotropic, see [KS90], definition 6.5.1 p. 271). We shall say that \( V \) is cone-coisotropic if whenever a hyperplane \( H \) is such that \( C^+(x, V) \subset H \) then the symplectic orthogonal of \( H \), \( H^w \) is contained in \( C^-(x, V) \).

**Proof of Proposition 1.3**. We want to prove that if \( V \) is not cone-coisotropic at \( z \in V \) then it is not \( \gamma \)-coisotropic at \( z \). For \( H \) a hyperplane we set \( n_H \) the normal to \( H \) (for the usual scalar product). Let us assume that \( z \in V \) is...
such that $C^+(z, V) \subset H$ and $H^\omega \notin C^-(z, V)$. This will follow from the next two lemmata. \hfill \square

**Lemma 8.3.** Let $V$ be a closed set, $z \in V$ and $H$ a hyperplane such that $C^+(z, V) \subset H$. Then there exists a continuous function $f_{H, V}$ defined in a neighbourhood of $z$ in $H$ such that $f_{H, V}(z) = 0$ and $d_G f_{H, V}(z) = 0$, where $d_G$ is the Gâteaux derivative, and such that for any neighbourhood $C^+_\epsilon(z, V)$ of $C^+(z, V)$ we have for $\delta$ small enough

$$V \cap B(z, \delta) \subset \{ z + x + f_{V}(x)n_H \mid x \in C^+_\epsilon(z, V) \}$$

**Proof.** We can assume for simplicity that $z = 0$. For $x \in H$ let $V_x = V \cap (x + \mathbb{R}n_H)$. We claim that for $x$ close enough to 0, $V_x$ contains at most one point. Indeed, if this was not the case, we would have sequences $(y_n)_{n \geq 1}, (w_n)_{n \geq 1}$ converging to 0 such that $y_n - w_n = t_n n_H$ with $t_n \neq 0$. But then by definition of $C^+(0, V)$, we would have $n_H \in C^+(0, V)$ a contradiction.

As a result, on the closed set $\Gamma \subset H$ defined as the set of $x$ such that $V_x$ is non empty, we have a function $f$ such that

$$x \in \Gamma \iff (x, f(x)) \in V$$

Let us prove $f$ is continuous on $\Gamma$, at least in a neighbourhood of 0. If this was not the case, there would be a sequence $(z^n)_{n \geq 1}$ converging to 0 and for each $n$ two sequences $(x_k^n)_{k \geq 1}, (y_k^n)_{k \geq 1}$ such that $\lim_k x_k^n = \lim_k y_k^n = z^n$ and $\lim_k f(x_k^n) \neq \lim_k f(y_k^n)$. Setting $u_k^n = (x_k^n, f(x_k^n)), v_k^n = (y_k^n, f(y_k^n))$ we have

$$u_k^n - v_k^n = (x_k^n - y_k^n, f(x_k^n) - f(y_k^n))$$

which can be normalized so that, for any $n$, it has a limit $(0, 1)$ when $k \rightarrow +\infty$. As a result for $k = k(n)$ large enough, setting $u_n = u_{k(n)}^n, v_n = v_{k(n)}^n$, there is a $\tau_n$ so that

$$\|\tau_n(u_n - v_n) - (0, 1)\| < 1/3$$
so we can find a converging subsequence to a vector $w$ which does not belong to $H$. Since $w \in C^+(0, V)$ we have a contradiction. From now on we replace $\Gamma$ by $\Gamma \cap B(0, r)$ with $r$ small enough so that $f$ is now continuous on $\Gamma$.

Let us now prove that $\lim_{|x| \to 0, x \in \Gamma} \frac{f(x)}{|x|} = 0$. Indeed, if we had a sequence $x_k$ in $\Gamma$ converging to 0 and such that $\lim_{k} \frac{f(x_k)}{|x_k|} \neq 0$, the sequence of vectors $\frac{1}{|x_k|}(x_k, f(x_k))$ would have a limit which does not belong to $H$, so $C^+(0, V) \not\subset H$, a contradiction.

We now will extend $f$ to $f_{H, V}$ such that

1. $f_{H, V}(x) = f(x)$ for $x \in \Gamma$
2. $f_{H, V}$ is continuous
3. $d_G(f_{H, V}(0)) = 0$

For this we can assume for simplicity that $r = 1$ and write $x = \rho \cdot \theta$ with $0 \leq \rho \leq 1, \theta \in S^{n-1}$. We write $g(s, \theta) = f(e^s \cdot \theta)$ with $s \in ]-\infty, 0]$ and identify $\Gamma$ with its image in $]-\infty, 0] \times S^{n-1}$. Now let $g_n(s, \theta)$ be a continuous function defined on $C_n = ]-n - 1, -n + 1[ \times S^{n-1}$ for $n \in \mathbb{N}$, coinciding with $g$ on $\Gamma \cap C_n$ and having the same bound, i.e.

$$\sup\{g_n(s, \theta) \mid (s, \theta) \in C_n\} = \sup\{g(s, \theta) \mid (s, \theta) \in \Gamma \cap C_n\}$$

$$\inf\{g_n(s, \theta) \mid (s, \theta) \in C_n\} = \inf\{g(s, \theta) \mid (s, \theta) \in \Gamma \cap C_n\}$$

Such a function exists by Tietze’s extension theorem.

Now let $\chi_n$ be a partition of unity subordinated to the covering of $]-\infty, 0] \times S^{n-1}$ by the $C_n$. We set

$$G(s, \theta) = \sum_{n \geq 0} \chi_n(s) g_n(s, \theta)$$

Note that this is well defined since whenever $g_n(s, \theta)$ is not defined, we have $\chi_n(s, \theta) = 0$, so we set $\chi_n(s) g_n(s, \theta) = 0$ outside of $C_n$. And since whenever $g_n(s, \theta)$ is defined and $(s, \theta) \in \Gamma$ we have $g_n(s, \theta) = g(s, \theta)$, we see that $F$ is an extension of $G$. We now set

$$f_{H, V}(e^s \cdot \theta) = G(s, \theta)$$
Properties (1) and (2) are then obvious. As for the third one, we notice that
\[ \sup \{ f_{H,V}(x) \mid |x| \leq e^{-n} \} = \sup \{ G(s, \theta) \mid (s, \theta) \mid s \leq -n \leq \]
\[ \sup \sup_{k \geq n} \{ g_k(s, \theta) \mid (s, \theta) \in C_k \} \leq \sup \{ g(s, \theta) \mid (s, \theta) \in \Gamma, s \leq -n \leq \}
\[ \sup \{ f(x) \mid x \in \Gamma, |x| \leq e^{-n} \} \]
We see that since \( \lim_{t \to 0} f(x) = 0 \) we have \( \lim_{x \to 0} \frac{f_{H,V}(x)}{|x|} = 0. \)
As a result
\[ \lim_{t \to 0} \frac{1}{t} (f_{H,V}(th) - f_{H,V}(0)) = 0 \]
and we may conclude that \( d_G f_{H,V}(z) = 0. \)

**Lemma 8.4.** Let \( f \) be a continuous function on the hyperplane \( H \) such that \( d_G f(0) = 0 \) and \( C \) a cone in \( H \) not containing \( H^0 \). Set \( \widetilde{C} = \{ x + f(x) n_H \mid x \in C \} \)

Then for any positive \( \epsilon \), there is a Hamiltonian map \( \varphi \) such that \( \gamma(\varphi) \leq \epsilon \) and
\[ \varphi(\widetilde{C} \cap B(0, 1)) \cap B(0, 1) = \emptyset \]

**Proof.** We shall assume w.l.o.g. that \( H = \{ p_n = 0 \} \) and \( z = 0 \), so that \( H^0 \) is given by the direction \( q_n \). First let us mention that the case \( f = 0 \) is trivial.
Just take a Hamiltonian \( H(p_n) \) such that \( H(0) = 0, H'(0) = A \) and \( H \) is \( C^0 \) small, \( A \) being chosen so that in \( B(0, 1) \) we have
\[ C \cap B(0, 1) \cap (A \frac{\partial}{\partial q_n} + C) = \emptyset \]
This extends to the case where \( f \) is smooth. Indeed, let us set \( K(q_n, f(q_n, \bar{q}, \bar{p}), \bar{q}, \bar{p}) = 0 \) and \( \frac{\partial K}{\partial p_n} (q_n, f(q_n, \bar{q}, \bar{p}), \bar{q}, \bar{p}) = A \). We have, for any \( (q_n, p_n, \bar{q}, \bar{p}) \in \widetilde{C} \),
\[ \varphi_H^t(q_n, p_n, \bar{q}, \bar{p}) = (q_n + At, p_n(t), \bar{q}(t), \bar{p}(t)) \] hence
\[ \varphi_K^t(\widetilde{C}) \cap B(0, 1) = \emptyset \]
Of course we have to truncate the flow, so that it is unchanged on the trajectory of points in \( \varphi_K^t(\widetilde{C}) \cap B(0, 1) \), but this is not difficult.

Note that the same holds if we replace \( \widetilde{C} \) by the region
\[ \widetilde{C}_{g,g'} = \{ (q_n, p_n, \bar{q}, \bar{p}) \mid (q_n, \bar{q}, \bar{p}) \in C, g(q_n, \bar{q}, \bar{p}) \leq p_n \leq g'(q_n, \bar{q}, \bar{p}) \} \]
where \( g \leq g' \) are smooth functions with \( dg(0) = dg'(0) = 0 \), except that now we cannot have \( \gamma(\varphi_K) \) arbitrarily small because \( K \) has oscillation bounded from below by \( A\|g - g'\|_{C^0} \). Indeed we must have \( \frac{\partial K}{\partial p_n} = A \) on
a segment in the $p_n$ direction of length $g'(q_n \tilde{q}, \tilde{p}) - g'(q_n \tilde{q}, \tilde{p})$. However we can assume $\gamma(q_K) \leq A\|g - g'\|_{C^0} + \epsilon$ with $\epsilon > 0$ arbitrarily small.

The general case is obtained as follows. We take a sequence $g_k \leq f \leq g'_k$ such that $\|g_k - g'_k\|_{C^0(B(0,r))}$ goes to zero with $k$. We can then displace $\bar{C}_{g_k, g'_k}$ hence $\bar{C}$ by a map with $\gamma(q_k) \leq A\|g_k - g'_k\|_{C^0(B(0,r))} + \epsilon_k$. As $k$ goes to infinity, we may let $\epsilon_k$ go to zero. This concludes our proof. □

Remark 8.5. The proof actually shows that $V$ is locally rigid in the sense of Usher (see [Ush19]). So we have that $\gamma$-coisotropic implies locally rigid which implies cone-coisotropic.

8.2. A cone-coisotropic set that is not $\gamma$-coisotropic. Let $K_a$ be the central Cantor set of ratio $a$. In other words we set

$$F_1 = [0, a] \cup [1 - a, 1]$$

$$F_2 = [0, a^2] \cup [a(1 - a), a] \cup [1 - a, 1 - a + a^2] \cup [1 - a^2, 1]$$

and $K_a = \bigcap_n F_n$.

Proposition 8.6. For $a < 2^{-2n}$, the set $X = K_a^{2n}$ is cone-coisotropic but not $\gamma$-coisotropic.

Proof. We claim that $C^+(z, X)$ is not contained in any hyperplane. Indeed for $x \in K = K_a$ the cone $C^+(x, K)$ is never empty since any point in
K is a cluster point of K. In fact C^{-}(x,K) is either \( \mathbb{R} \), \( \mathbb{R}_{+} \) or \( \mathbb{R} \) depending whether x is the limit of points of K less than x, the limit of points of K greater than x or both, and \( C^{+}(x,K)=\mathbb{R} \). Even though the paratingent cone of a product does not necessarily contain the product of the paratingent cones of the factors, in the present case \( C^{+}(z,X) \) contains the rays \( \{0^{j-1}\} \times C^{+}(x_{j},K) \times \{0^{n-j}\} \) where \( z=(x_{1},...,x_{2n}) \), and \( 0^{k}=(0,...,0) \in \mathbb{R}^{k} \). Therefore \( C^{+}(z,X) \) is not contained in any hyperplane and \( X \) is trivially cone-coisotropic.

We now claim \( X \) is not \( \gamma \)-coisotropic. Pick \( z \in X \) and balls \( B(z,\varepsilon) \), \( B(z,\eta) \), \( 0<\eta<\varepsilon \). Let \( k \) big enough (to be made precise later). Since \( K \) is contained in \( F_{k} \) which consists of \( 2^{k} \) intervals of length \( a^{k} \), our \( X \) is contained in a family \( \mathcal{I} \) of cubes of edge length \( a^{k} \) with \( \|\mathcal{I}\| = 2^{2nk} \). The projection \( (q,p) \mapsto (q_{2},...,q_{n},p_{1},...,p_{n}) \) maps \( \mathcal{I} \) to a family \( \mathcal{I}' \) of cubes of \( \mathbb{R}^{2n-1} \) (again these cubes have edge length \( a^{k} \) and \( \|\mathcal{I}'\| = 2^{(2n-1)k} \)). We choose disjoints neighbourhoods \( U_{1}, U_{2},...,U_{N} \), of the cubes in \( \mathcal{I}' \). For a given \( i_{0} \in \mathcal{I}', \) let \( j_{1}, j_{2},...,N_{1} \), be the cubes of \( \mathcal{I} \) contained in \( B(z,\varepsilon) \cap (\mathbb{R} \times U_{i_{0}}) \), ordered according to the \( q_{1} \) variable. Let \( N_{1} \) be the maximal index \( j \) such that \( C_{j} \) meets \( B(z,\eta) \). We push all cubes \( C_{2},...,C_{N_{1}} \) to the left, close to \( C_{1} \), in the space between \( B(z,\varepsilon) \) and \( B(z,\eta) \) (if \( k \) is big enough), as follows. We move \( C_{2} \) by a translation \( T_{2} \) with direction \( -\partial q_{1} \), so that \( T_{2}(C_{2}) \) is close to \( C_{1} \). Then we move \( C_{3} \) by a similar translation \( T_{3} \), so that \( T_{3}(C_{3}) \) is close to \( T_{2}(C_{2}) \). We go on until \( C_{N_{1}} \). We have thus accumulated at most \( 2^{k} \) cubes of edge length \( a^{k} \) near \( C_{1} \). Since \( a<1/2 \), we have room to put all these cubes in \( B(z,\varepsilon) \setminus B(z,\eta) \) for \( k \) big enough.

Now the translation \( T_{j} \) can be realized by a Hamiltonian function of the form \( h_{j}=h(p_{1})\rho_{j}(q,p) \), where \( h' = 1 \) and \( \rho_{j} \) is a bump function vanishing outside \( B(z,\varepsilon) \cap (\mathbb{R} \times U_{i_{0}}) \) and over \( C_{1} \cup \cdots \cup T_{j-1}(C_{j-1}) \cup C_{j+1} \cup \cdots \cup C_{N_{1}} \) and equals to 1 over the path swept by \( C_{j} \). We have \( \|h\| \sim a^{k} \) and we apply the isotopy for a length of time less than \( \varepsilon < 1 \). We have to do this less than \( |\mathcal{I}'| \) times. Since we chose \( a < 2^{-2^{n}} \), the composition of all these isotopies has norm as small as required.

\[ \square \]

**Remark 8.7.** We can weaken the assumption \( a < 2^{-2^{n}} \) to \( a < 1/4 \) at the expense of a more complicated proof.

**Question 8.8.** Find an example where the image of a smooth non-coisotropic submanifold \( C \) by a symplectic homeomorphism, \( \varphi \), is such that \( \varphi(C) \) is cone-coisotropic (but will not be \( \gamma \)-coisotropic by [Vit22]).
9. Questions and Comments

We gather in this section a number of questions that sprang up naturally while writing this paper.

**Question 9.1.** What is the $\gamma_g$-distance of $k_X$ and $k_Y$ for two closed sets $X, Y$. If $X, Y$ do not have the same cohomology, the distance is infinite. So we can focus on the case when $Y = X_\varepsilon$ is an $\varepsilon$-neighbourhood of $X$. When is it true that $\gamma_g(k_X, k_{X_\varepsilon}) \leq C\varepsilon$? Or when do we have $\gamma - \lim k_{X_\varepsilon} = k_X$?

For the next four questions we choose on $N$ a real analytic structure. We let $D_{lc}(N)$ be the category of limits of constructible sheaves considered in Appendix B.

**Question 9.2.** In Appendix B we describe the objects of $D_{lc}(\mathbb{R})$ with micro-support contained in $\{r \geq 0\}$. Is there a similar description in the general case?

**Question 9.3.** Using Lemma B.3 and the proof of Lemma B.1 it is probably not hard to see that $D_{lc}(N)$ is a triangulated category. If we have a map $f: N \to M$, can we find conditions so that $Rf_*(D_{lc}(N)) \subset D_{lc}(M)$, $f^{-1}(D_{lc}(M)) \subset D_{lc}(N)$?

For example this is true for a map of the type $f \times \text{id}_\mathbb{R}: N \times \mathbb{R} \to M \times \mathbb{R}$, if we consider the $\gamma_r$-distance, because $Rf_*$ and $f^{-1}$ are Lipschitz for this distance. In general $f^{-1}$ is not Lipschitz: take $f: \mathbb{R} \to \mathbb{R}^2$, $x \mapsto (x, 0)$, and $D_\varepsilon$ the closed disc with center $(0, 1)$ and radius $1 - \varepsilon$; then $\gamma_g(k_{D_0}, k_{D_\varepsilon}) = \varepsilon$ but $\gamma_g(f^{-1}(k_{D_0}), f^{-1}(k_{D_\varepsilon})) = +\infty$ (here $g(q, p) = ||p||$). Hence it is not clear that $f^{-1}(D_{lc}(M)) \subset D_{lc}(N)$.
**Question 9.4.** Let $D_{\text{dom}}(N)$ be the subcategory of $D(N)$ generated in the triangulated sense by the $k_U$, where $U$ runs over the domains with smooth boundary. It should not be difficult to prove that $D_{\text{dom}}(N) \subset D_{lc}(N)$ by approximating domains with smooth boundary by domains with analytic boundary. Is it true that, for any subanalytic open subset $V$ of $X$ and any $\varepsilon > 0$, there exists a domain $U$ with smooth boundary such that $U \subset V$ and $K_{\varphi_{\varepsilon}}(k_U) \approx k_U$ with $U_\varepsilon$ open and $V \subset U_\varepsilon$? In this case we can see that $D_{lc}(N)$ coincides with the $\gamma$-closure of $D_{\text{dom}}(N)$, which would imply that $D_{lc}(N)$ only depends on the smooth structure of $N$.

**Question 9.5.** Let $D_{\text{tri}}(N)$ be the set of sheaves which are constructible with respect to some (non-fixed!) triangulation of $N$. Do the $\gamma$-closures of $D_{\text{dom}}(N)$ and $D_{\text{tri}}(N)$ coincide? Are they equal to $D_{lc}(N)$?

We remind the reader of the following (see [KS18], theorem 2.11, and [PS21], corollary 2.4.2)

**Proposition 9.6.** We have for all 1-Lipschitz maps $f : M \to N$ the inequality

$$\gamma_g((Rf)_*\mathcal{F}, (Rf)_*\mathcal{G}) \leq \gamma_g(\mathcal{F}, \mathcal{G})$$

**Question 9.7.** Can we give conditions on $\mathcal{F}, \mathcal{G}$ (for example $\gamma_g(\mathcal{F}, \mathcal{G}) < \infty$) such that the opposite inequality

$$\gamma_g(\mathcal{F}, \mathcal{G}) \leq C \sup_{f \in \text{Lip}_1(X, \mathbb{R})} \gamma_{|\tau|}(Rf_*(\mathcal{F}), Rf_*(\mathcal{G}))$$

holds for some constant $C$?

**Question 9.8.** Let $f$ be a continuous function on $N$. Then $\mathcal{F}_f = k_{\{(x, t) | f(x) \leq t\}}$ is a sheaf on $N \times \mathbb{R}$, and Vichery defined a subdifferential as

$$\partial f = SS(\mathcal{F}_f) \cap \{\tau = 1\}/(t) \subset T^*N$$

Its intersection with $T^*_xN$ is $\partial f(x)$. On the other hand $df \in \hat{\mathcal{L}}(T^*N)$, so we may ask whether

$$SS(\mathcal{F}_f) \cap \{\tau = 1\}/(t) = \partial f = \gamma - \text{supp}(df)$$

This leads to more general questions. First notice the following

**Proposition 9.9.** There is a functor $Q : \hat{\mathcal{L}}(T^*N) \to D_{lc}(N \times \mathbb{R})$ extending the usual quantization from [Gui12; Vit19]. Moreover $Q$ is bi-Lipschitz of ratio 2 from $(\hat{\mathcal{L}}(T^*N), \gamma)$ to $(D_{lc}(N \times \mathbb{R}), \gamma_T)$.

**Proof.** Let $L_n$ be a Cauchy sequence in $\mathcal{L}(T^*N)$. Then $\mathcal{F}_{L_n}$ is a Cauchy sequence in $D_{lc}(N \times \mathbb{R})$. The map $L \to \mathcal{F}_L$ is a bi-Lipschitz map from the metric $c$ to the (pseudo-) metric $\gamma_T$. As we saw in Remark 6.12, the metric $\gamma_T$ is bounded between $1/2c$ and $c$ where $c$ is the metric defined on
\( \mathcal{L}(T^* N) \) in \([\text{Vit}22]\) by \( c(\tilde{L}_1, \tilde{L}_2) = |c_+(L_1, L_2)| + |c_-(L_1, L_2)| \). Since according to Proposition B.7, the metric \( \gamma_T \) is a bona fide metric in \( D_{tc}(N \times \mathbb{R}) \), limits are unique and the limit of \( \mathcal{F}_{n} \) is well-defined. \( \square \)

**Question 9.10.** Set \( \rho(x, t; \xi, \tau) = (x; \xi / \tau) \). Given \( \Lambda \in \hat{\mathcal{L}}(T^* N) \), do we have \( \gamma - \text{supp}(\Lambda) = \rho(\text{SS}^*(Q(\Lambda))) \)?

A positive answer would also imply a positive answer to Question 9.8, i.e. \( \partial f = \gamma - \text{supp}(df) \) by taking \( \Lambda_n = df_n \) for some sequence of differentiable functions converging to \( f \).

**Question 9.11.** Can one characterize the sheaves \( \mathcal{F} \) such that there exists an element \( \hat{\text{SS}}(\mathcal{F}) \) in \( \mathcal{L}(T^* N) \) so that \( \text{SS}(\mathcal{F}) = \gamma - \text{supp}(\hat{\text{SS}}(\mathcal{F})) \)? In the previous question we considered the \( \mathcal{F} \) for which are \( \gamma \)-limits of sheaves \( \mathcal{F}_j \) quantizing some exact Lagrangian.

Let us give an example of such a situation: let \( M, N \) be closed manifolds. For a map \( f \in C^\infty(M, N) \) set \( \Lambda_f \) be the correspondence in \( T^* M \times T^* N \) defined by

\[
\Lambda_f = \{(x, p_x, y, p_y) \mid y = f(x), p_y \circ df(x) = -p_x \}
\]

Now let \( f_n \) be a sequence of smooth maps \( C^0 \)-converging to \( f \in C^0(M, N) \). For \( \mathcal{F} \in D^b(M) \) the sequence \( (R(f_n)_* \mathcal{F})_{n \geq 1} \) \( \gamma \)-converges to \( Rf_* \mathcal{F} \) and \( \text{SS}(R(f_n)_* \mathcal{F}) \subset \Lambda_{f_n} \circ \text{SS}(\mathcal{F}) \). Thus \( \text{SS}(R(f_n)_* \mathcal{F}) \) should \( \gamma \)-converge to a subset of \( \Lambda_f \circ \text{SS}(\mathcal{F}) \). Of course since \( f \) is only \( C^0 \), \( \Lambda_f \) is not defined as a set, but it is well defined in \( \hat{\mathcal{L}}(T^* N \times T^* M) \), hence \( \Lambda_f \circ \text{SS}(\mathcal{F}) \in \hat{\mathcal{L}}(T^* N) \). Thus we expect \( \hat{\text{SS}}(Rf_* \mathcal{F}) = \Lambda_f \circ \text{SS}(\mathcal{F}) \) and \( \text{SS}(Rf_* \mathcal{F}) \subset \gamma - \text{supp}(\Lambda_f \circ \text{SS}(\mathcal{F})) \).

**Question 9.12.** Let \( \mathcal{F}_n \) be a sequence in \( D(N) \) \( \gamma_g \)-converging to \( \mathcal{F}_\infty \). We set \( \Lambda_n = \text{SS}(\mathcal{F}_n) \) and we assume that \( \Lambda_n \) Hausdorff converges to \( \Lambda_{\infty} \). We know that \( \text{SS}(\mathcal{F}_\infty) \subset \Lambda_{\infty} \) but when is it true that \( \Lambda_{\infty} = \text{SS}(\mathcal{F}_\infty) \)? We can prove it if \( \Lambda_{\infty} \) is a smooth Lagrangian or more generally minimally \( \gamma \)-coisotropic. Indeed Proposition \([7,3]\) shows that \( \text{SS}(\mathcal{F}_\infty) \subset \Lambda_{\infty} \) and the involutivity of the singular support gives the equality (by an argument similar to the one in the proof of Proposition \([9,13]\)). Assuming \( N = M \times \mathbb{R} \) and the \( \mathcal{F}_n \) are quantizations of exact Lagrangian, Proposition \([9,13]\) shows that this still hold when \( \Lambda_{\infty} \) is the conification of some \( \varphi(L_0) \) for \( L_0 \) smooth Lagrangian, \( \varphi \) a symplectic homeomorphism.

Note however that the answer cannot be positive in general: Let \( f(x) \) be a smooth bounded function on \( \mathbb{R} \), such that \( \max f' = 1, \min f' = -1 \). Let \( f_n(x) = f(nx)/n \) and \( \mathcal{F}_n = k_{[\varepsilon, f_n(x)]} \). Then \( \mathcal{F}_n \) converges to \( \mathcal{F}_\infty = k_{\mathbb{R} \times [0, \infty]} \) but \( \text{SS}(\mathcal{F}_n) \) converges to a set \( \Lambda_{\infty} \) bigger than \( \text{SS}(\mathcal{F}_\infty) \). In fact \( \Lambda \) is the cone over a “cross” \( C \) in \( T^* \mathbb{R} \) with \( C = \{0 \} \cup ([0] \times [-1, 1]) \).
Proposition 9.13. Let $L = \varphi(L_0)$ where $L_0$ is smooth Lagrangian and $\varphi \in \mathcal{H}_{\gamma}(M, \omega) = \overline{\mathcal{G}am}(M, \omega) \cap \text{Homeo}(M)$. Then any closed proper subset of $L$ is not $\gamma$-coisotropic.

Proof. Let $L' \subset L$. Since being $\gamma$-coisotropic is invariant by $\mathcal{G}am(M, \omega) \cap \text{Homeo}(M)$ it is enough to prove the Proposition for $L_0$ i.e. in the smooth case. Now there is a ball $B(z, r)$ in $L$ such that $B(z, r) \cap L' = \{z'\}$. Moreover we may choose $r$ to be arbitrarily small. Let us consider a flow on $L$ such that $\rho^t(B(z, r)) \subset B(z', r)$. In a chart containing $B(z, 2r)$ we may assume that $\rho^t$ is a translation. Then $\rho^1(L') \cap B(z', r) = \emptyset$. Since if $X_t$ is the vector field generating $\rho^t$, the Hamiltonian written in action-angle coordinates (i.e. $L$ is given locally by $p = 0$) can be chosen of the form $\chi(|p|)\langle p, X_t(x) \rangle$ for some bump function $\chi$, and this can be made arbitrarily small. As a result, $L'$ is not $\gamma$-coisotropic.

Figure 5. Proof of Proposition 9.13

Question 9.14. Let $V$ be $\gamma$-coisotropic of dimension $n$. Then for $z \in V$ and $\varepsilon$ small enough we have $V \setminus B(z, \varepsilon)$ is not coisotropic.

Appendix A. Persistence Modules and Barcodes

For this section we refer also to [Zha20].

We have already noticed after Definition 5.3 that the spectral invariants of $L_1, L_2 \in \mathcal{L}(T^*N)$ are encoded in the sheaf over $\mathbb{R}$ given by $\mathcal{H} = R t_* \mathcal{H}\text{om}^* (\mathcal{F}_1, \mathcal{F}_2)$, where $t: N \times \mathbb{R} \to \mathbb{R}$ is the projection, because of the isomorphism

$$R\Gamma_{N \times \{t\}} (N \times \mathbb{R}; \mathcal{H}\text{om}^* (\mathcal{F}_{L_1}, \mathcal{F}_{L_2})) \cong R\Gamma_{\{t\}} (\mathbb{R}; \mathcal{H})$$

We recall that $\mathcal{H}$ belongs to the category $D_{\tau \geq 0}(\mathbb{R})$ of sheaves with singular support in $\{\tau \geq 0\}$. 
We remark that $D_{\tau \geq 0}(R)$ contains the derived category of persistence modules, where by a persistence module, we mean a constructible sheaf on $(R, \leq)$. We refer to [Bar94; Cha+09; ELZ02; KS18; ZC05] for the theory and applications. Such a persistence module is uniquely defined by the finite-dimensional vector spaces $V_t = \mathcal{F}([-\infty, t])$ and the linear maps $r_{s,t} : V_t \rightarrow V_s$ defined for $s \leq t$, such that

1. for $s < t < u$ we have $r_{u,t} \circ r_{s,t} = r_{s,u}$,
2. $\lim_{t \rightarrow s} V_t = V_s$ where the limit is that of the directed system given by the $r_{s,t},$
3. $r_{t,t} = \text{Id}$.

It is a well-known result that persistence modules have a decomposition as sum of barcodes: this is Gabriel’s theorem ([Gab72] on quivers in the finite case and Crawley-Boevey’s theorem ([Cra15]) in the locally finite case. More precisely, using Gabriel’s theorem and the fact that any complex of objects in an Abelian category of homological dimension 1 is the sum of its cohomology, we find: any $\mathcal{F} \in D_{\tau \geq 0}(R)$ which is constructible for a finite stratification can be written $\mathcal{F} = \bigoplus_{j \in \mathcal{I}} k_{[a_j, b_j]}[-n_j]$, where $\mathcal{I}$ is a finite family, and this decomposition is unique up to isomorphism. (The hypothesis that the singular support is in $\{\tau \geq 0\}$ is useless here.) We remark that the stratification consists only of a finite set of points in $R$ and the connected components of its complement, where $\mathcal{F}$ is constant. This finite set is thus the projection to $R$ of $SS^*(\mathcal{F})$. If $L \in \mathcal{L}(T^*N)$ is generic in the sense that $L$ meets $0_N$ transversally, then $Rt_*(\mathcal{F}_L)$ is of the above type, where the stratification is given by the set of actions of the points in $L \cap 0_N$.

In [KS18] it is explained how to go from the case of a finite stratification to the case of a locally finite one (then $\mathcal{I}$ is at most countable). By [Cra15] the same result holds in fact (at least in $D_{\tau \geq 0}(R)$) under the more general hypothesis that $\mathcal{F}_x$ is finite dimensional for all $x \in R$. However the sheaves we encounter in this paper are not necessarily of this type: if $f$ is the function $f(x) = x^2 \sin(1/x)$ and $\mathcal{F} = Rt_*(k_{[t \geq f(x)]})$, then $\mathcal{F}_0$ is infinite dimensional. But, by a small perturbation of $L$, we see that all sheaves of the form $Rt_*(\mathcal{F}_L)$ are in the closure of the set of constructible sheaves. Using Corollary B.11 we deduce:

**Proposition A.1.** Let $L_1, L_2 \in \mathcal{L}(T^*N)$. Then there exists an at most countable family $\mathcal{I}$ (which is finite in the case of transverse intersection) such that

$$(Rt)_*(\mathcal{H}om^*(\mathcal{F}_{L_1}, \mathcal{F}_{L_2})) = \bigoplus_{j \in \mathcal{I}} k_{[a_j, b_j]}[-n_j],$$

where for each $j \in \mathcal{I}$ we have $a_j \in R \cup \{-\infty\}$, $b_j \in R$, $n_j \in \mathbb{Z}$. Moreover there is a unique $j_-$ such that $a_{j_-} = -\infty$ and $n_{j_-} = -1$ and then $b_{j_-} = $
The formula follows from Theorem 5.1.

More generally, with the notations of the proposition we let $\mathcal{I}_\infty$ be the set of $j$ such that $a_j = -\infty$. Then $H^*_t((R)t)_*(\mathcal{H}\text{om}^*(\mathcal{F}_1, \mathcal{F}_2))) = \bigoplus_{j \in \mathcal{I}_\infty} k[-n_j]$, for $t_0 \ll 0$, and we deduce that the spectral invariants $c(a, L_1, L_2)$ are the $b_j$’s with $j \in \mathcal{I}_\infty$.

Note that the filtered Floer cohomology, $FH^*(L_1, L_2; -\infty, t)$ defines a persistence module equal to the one obtained from $\mathcal{H}\text{om}^*(\mathcal{F}_1, \mathcal{F}_2)$ as follows from Theorem 5.1.

It will be useful to remind the reader that

**Lemma A.2** (see [KS18], (1.10)).

$$\text{RHom}(k[a, b], k[c, d]) \simeq \begin{cases} k & \text{for } a \leq c < b \leq d, \\ k[-1] & \text{for } c < a \leq b < d, \\ 0 & \text{otherwise}. \end{cases}$$

**Proof.** The formula $k[c, d] = \text{RHom}(k[d, c], k[\underline{d}])$ together with the adjunction between $\otimes$ and $\mathcal{H}\text{om}$ give $\text{RHom}(k[a, b], k[c, d]) \simeq \text{RHom}(k[a, c], k[b, d])$, where $I = [a, b] \cap [c, d]$. If $I$ is half closed or empty, the result is 0. The two other cases correspond to $I$ open or $I$ closed.  

**APPENDIX B. Decomposition in the completion of $D_{IC}(\mathbb{R})$**

**B.1. Limits of constructible sheaves.** We assume in this section that $N$ is endowed with a real analytic structure and a real analytic metric $g$. We recall that we work with coefficients in a field $k$. We denote by $D_c(N)$ the subcategory of $D(N)$ of constructible sheaves. We let $D_{IC}(N)$ be the set of objects which are limits of constructible sheaves with respect to the $\gamma_g$-topology.

**Lemma B.1.** Let $\mathcal{F}, \mathcal{G} \in D_{IC}(N)$ with compact supports and $a < b$. Then the morphism $\text{Hom}(\mathcal{F}, K^a_p(\mathcal{G})) \to \text{Hom}(\mathcal{F}, K^b_p(\mathcal{G}))$ induced by $\tau_{a,b}(\mathcal{G})$ has finite dimensional image.

**Proof.** We set $c = (b-a)/2$. Applying $K^{-c}_p$ we identify $\text{Hom}(\mathcal{F}, K^b_p(\mathcal{G}))$ with $\text{Hom}(K^{-c}_p(\mathcal{F}), K^{b-c}_p(\mathcal{G}))$ and the morphism of the lemma gets identified with

$$f : \text{Hom}(\mathcal{F}, K^a_p(\mathcal{G})) \to \text{Hom}(K^{-c}_p(\mathcal{F}), K^{b-c}_p(\mathcal{G}))$$

$$u \mapsto \tau_{a,b-c}(\mathcal{G}) \circ u \circ \tau_{c,0}(\mathcal{F})$$

Since $\mathcal{F}, \mathcal{G} \in D_{IC}(N)$, there exist constructible sheaves $\mathcal{F}', \mathcal{G}'$ and morphisms $K^{-c}_p \mathcal{F} \xrightarrow{u_1} \mathcal{F} \xrightarrow{u_2} \mathcal{F}$, $K^a_p(\mathcal{G}) \xrightarrow{v_1} \mathcal{G}' \xrightarrow{v_2} K^{b-c}_p(\mathcal{G})$ such that $u_2 \circ$
\[ u_1 = \tau_{-c,0}(\mathcal{F}), \quad v_2 \circ v_1 = \tau_{a,b-c}(\mathcal{G}). \]

We choose a compact set \( Z \) containing the supports of \( \mathcal{F} \) and \( K_{\phi}^c \mathcal{F} \). Applying the functor \((-)_Z\) we obtain \( K_{\phi}^c \mathcal{F} \xrightarrow{(u_1)_Z} \mathcal{F} \xrightarrow{(u_2)_Z} \mathcal{F} \) and we still have \( (u_2)_Z \circ (u_1)_Z = (u_2 \circ u_1)_Z = \tau_{-c,0}(\mathcal{F}) \). So we may assume from the beginning that \( \mathcal{F}' \) has a compact support. Now \( f \) factorizes through \( \text{Hom}(\mathcal{F}', \mathcal{G}') \) which is finite dimensional. \( \square \)

As a consequence, for a given \( \epsilon > 0 \), the images of \( \text{Hom}(\mathcal{F}, K_{\phi}^\delta(\mathcal{G})) \) in \( \text{Hom}(\mathcal{F}, K_{\phi}^{\epsilon}(\mathcal{G})) \), for \( 0 < \delta \leq \epsilon \), stabilize when \( \delta \to 0 \). In other words the projective system \( (\text{Hom}(\mathcal{F}, K_{\phi}^{1/n}(\mathcal{G})))_{n \in \mathbb{N}} \), with morphisms induced by \( \tau_{1/(n+1),1/n}(\mathcal{G}) \), satisfies the Mittag-Leffler criterion. Let us introduce the notations, for \( \epsilon > 0 \), \( \text{Hom}_{\epsilon}(\mathcal{F}, \mathcal{G}) = \text{Im}(\text{Hom}(\mathcal{F}, K_{\phi}^{\epsilon}(\mathcal{G})) \to \text{Hom}(\mathcal{F}, \mathcal{G})) \) and \( \text{Hom}_{(\epsilon)}(\mathcal{F}, \mathcal{G}) = \bigcap_{0 < \epsilon} \text{Hom}_\delta(\mathcal{F}, \mathcal{G}) \). A consequence of Lemma B.3 below is that \( \text{Hom}_\epsilon(\mathcal{F}, \mathcal{G}) = \text{Hom}_{(\epsilon)}(\mathcal{F}, \mathcal{G}) \). We will mainly consider

\[ \text{Hom}_{(\epsilon)}(\mathcal{F}, K_{\phi}^{\epsilon}(\mathcal{G})) = \bigcap_{0 < \delta \leq \epsilon} \text{Im}(\text{Hom}(\mathcal{F}, K_{\phi}^{\delta}(\mathcal{G})) \to \text{Hom}(\mathcal{F}, K_{\phi}^{\epsilon}(\mathcal{G}))) \]

By Lemma \[ B.3 \] this space has finite dimension and, by construction, the morphisms \( \text{Hom}_{(\epsilon)}(\mathcal{F}, K_{\phi}^{\epsilon}(\mathcal{G})) \to \text{Hom}_{(\epsilon')}(\mathcal{F}, K_{\phi}^{\epsilon'}(\mathcal{G})) \), for \( 0 < \epsilon \leq \epsilon' \), are surjective.

In the next lemma \( \text{Ab} \) denotes the category of Abelian groups and \( D(\text{Ab}) \) its derived category. The statement is a well known consequence of the Mittag-Leffler condition; it is for example a variation on [KS90 Prop. 1.12.4].

**Lemma B.2.** Let \( (A_n, a_n), a_n \colon A_n \to A_{n-1} \), be a projective system in \( D(\text{Ab}) \) and define \( \text{holim}_n A_n \) by the distinguished triangle \( \text{holim}_n A_n \to \prod_n A_n \xrightarrow{\alpha} \prod_n A_n \xrightarrow{\alpha} \Pi_n A_n \xrightarrow{1} \Pi_n A_n \xrightarrow{1} \Pi_n A_n \xrightarrow{1} \Pi_n A_n \xrightarrow{1} \Pi_n A_n \xrightarrow{1} \Pi_n A_n \). We assume that \( H^i A_n \) satisfies the Mittag-Leffler criterion, for some \( i \). Then \( H^{i+1}(\text{holim}_n A_n) \approx \lim_{\to} H^{i+1} A_n \).

**Proof.** In \( \text{Ab} \) the product \( \Pi \) is exact, hence \( H^i \) and \( \Pi \) commute and we have a long exact sequence \( \prod_n H^i A_n \xrightarrow{H^i \alpha} \prod_n H^i A_n \to H^{i+1}(\text{holim}_n A_n) \to \prod_n H^{i+1} A_n \to \prod_n H^{i+1} A_n \). Hence the statement is equivalent to the surjectivity of \( H^i \alpha \). We write for short \( B_n = H^i A_n, b_n = H^i a_n \) and \( B_n^\infty = \text{im}(B_m \to B_n) \) for \( m \gg n \). We let \( b_n^\infty, \tilde{b}_n \) be the maps induced by \( b_n \) on \( B_n^\infty, B_n / B_n^\infty \). We have \( H^i \alpha = \text{id} - \Pi \tilde{b}_n \) and the commutative diagram

\[
\begin{array}{cccccc}
0 & \longrightarrow & \prod B_n^\infty & \longrightarrow & \prod B_n & \longrightarrow & \prod B_n / B_n^\infty & \longrightarrow & 0 \\
\downarrow \text{id} - \Pi b_n^\infty & & \downarrow \text{id} - \Pi b_n & & \downarrow \text{id} - \Pi \tilde{b}_n & & \\
0 & \longrightarrow & \prod B_n^\infty & \longrightarrow & \prod B_n & \longrightarrow & \prod B_n / B_n^\infty & \longrightarrow & 0
\end{array}
\]
We see that $\text{id} - \prod b_n$ is surjective because the $b_n$'s are surjective. Let us write $t = \prod b_n$. By the Mittag-Leffler criterion, for each $n$, there exists $m \geq n$ such that $b_{n+1} \circ b_{n+2} \circ \cdots \circ b_m$ is the zero map. It follows that $t' = \sum_{i=0}^{\infty} t^i$ is well-defined. Hence $\text{id} - t$ is an isomorphism, with inverse $t'$.

We deduce that $\text{id} - \prod b_n$ is also surjective, as required. 

**Lemma B.3.** Let $\mathcal{F}, \mathcal{G} \in D_{lc}(N)$ with compact supports. We have natural isomorphisms

$$ \text{Hom}(\mathcal{F}, \mathcal{G}) \xrightarrow{\sim} \lim_{n} \text{Hom}_{(1/n)}(\mathcal{F}, K_{\phi}^{1/n}(\mathcal{G})) \xrightarrow{\sim} \lim_{n} \text{Hom}(\mathcal{F}, K_{\phi}^{1/n}(\mathcal{G})) $$

and, for any $n$, the map $\text{Hom}(\mathcal{F}, \mathcal{G}) \to \text{Hom}_{(1/n)}(\mathcal{F}, K_{\phi}^{1/n}(\mathcal{G}))$, $u \mapsto [u]_n := \tau_{0,1/n}(\mathcal{G}) \circ u$, is surjective.

**Proof.** By Lemma 6.23 we have $\text{hocolim} K_{\phi}^{-1/n}(\mathcal{F}) \xrightarrow{\sim} \mathcal{F}$ and we deduce $\text{RHom}(\mathcal{F}, \mathcal{G}) \xrightarrow{\sim} \text{holim} \text{RHom}(\mathcal{F}, K_{\phi}^{1/n}(\mathcal{G}))$. Since the projective system of vector spaces $H^{-1} \text{RHom}(\mathcal{F}, K_{\phi}^{1/n}(\mathcal{G}))$ satisfies Mittag-Leffler, Lemma B.2 gives $\text{Hom}(\mathcal{F}, \mathcal{G}) \xrightarrow{\sim} \lim \text{Hom}(\mathcal{F}, K_{\phi}^{1/n}(\mathcal{G}))$. The second isomorphism of the lemma and the last assertion are clear by the definition of $\text{Hom}_{(1/n)}$. 

**Lemma B.4.** For $\mathcal{F}, \mathcal{G}, \mathcal{H} \in D_{lc}(N)$ with compact supports, the composition induces a well-defined map, for any $n$,

$$ \circ_n : \text{Hom}_{(1/n)}(\mathcal{F}, K_{\phi}^{1/n}(\mathcal{G})) \times \text{Hom}_{(1/n)}(\mathcal{G}, K_{\phi}^{1/n}(\mathcal{H})) \to \text{Hom}_{(1/n)}(\mathcal{F}, K_{\phi}^{1/n}(\mathcal{H})) $$

$$(\tilde{u}, \tilde{v}) \mapsto \tilde{v} \circ_n \tilde{u} := [v \circ u]_n,$$

where $u, v$ in $\text{Hom}(\mathcal{F}, \mathcal{G})$, $\text{Hom}(\mathcal{G}, \mathcal{H})$ satisfy $[u]_n = \tilde{u}$, $[v]_n = \tilde{v}$, and we use the notation $[-]_n$ of Lemma B.3. This turns $\text{Hom}_{(1/n)}(\mathcal{F}, K_{\phi}^{1/n}(\mathcal{F}))$ into an algebra which is a finite dimensional quotient of $\text{Hom}(\mathcal{F}, \mathcal{F})$ and whose unit is $\tau_{0,1/n}(\mathcal{F})$ (assuming $\mathcal{F} \neq 0$ and $n$ is big enough so that $\tau_{0,1/n}(\mathcal{F}) \neq 0$ – see Lemma 6.4).

**Proof.** It is enough to see that if $[u]_n = 0$ or $[v]_n = 0$, then $[v \circ u]_n = 0$. For $u$ this follows from the commutative diagram

\[
\begin{array}{ccccccccc}
\mathcal{F} & \xrightarrow{u} & \mathcal{G} & \xrightarrow{v} & \mathcal{H} \\
|u|_n \downarrow & & \tau_{0,1/n}(\mathcal{G}) \downarrow & & \tau_{0,1/n}(\mathcal{H}) \\
K_{\phi}^{1/n}(\mathcal{G}) & \xrightarrow{K_{\phi}^{1/n}(v)} & K_{\phi}^{1/n}(\mathcal{H})
\end{array}
\]

which shows that $[v \circ u]_n = K_{\phi}^{1/n}(v) \circ [u]_n$. The case $[v]_n = 0$ is similar. 

□
Lemma B.5. Let \( \mathcal{F}, \mathcal{G} \in D_{lc}(\mathbb{N}) \) with compact supports such that \( \gamma_\mu(\mathcal{F}, \mathcal{G}) = 0 \). We set \( A_n = \text{Hom}_{(1/n)}(\mathcal{F}, K_{\varphi}^{1/n}(\mathcal{F})) \) and let \( A_n^\times \) be its subset of invertible elements. We also define, using the notation \( \circ_n \) of Lemma [B.4]

\[
B_n = \{ (u, v) \in \text{Hom}_{(1/n)}(\mathcal{F}, K_{\varphi}^{1/n}(\mathcal{G})) \times \text{Hom}_{(1/n)}(\mathcal{G}, K_{\varphi}^{1/n}(\mathcal{F})); \quad v \circ_n u = \tau_{0,1/n}(\mathcal{F}), \quad u \circ_n v = \tau_{0,1/n}(\mathcal{G}) \}
\]

Then

1. for any \( n \) the set \( B_n \) is non empty,
2. for any \( n \) and any \((u, v) \in B_n\), the maps \( \alpha_{u,v} : A_n^\times \to B_n, \quad a \mapsto (u \circ_n a, a^{-1} \circ_n v) \) and \( \beta_{u,v} : B_n \to A_n^\times, \quad (u', v') \mapsto v \circ_n u' \), are mutually inverse bijections,
3. for \( m \geq n \) the natural map \( B_m \to B_n \) is surjective.

Proof. [1] By Lemma [B.1] there exists \( m \geq n \) such that \( \text{Hom}_{(1/n)}(\mathcal{F}, K_{\varphi}^{1/m}(\mathcal{G})) \) is the image of \( \text{Hom}(\mathcal{F}, K_{\varphi}^{1/m}(\mathcal{G})) \) in \( \text{Hom}(\mathcal{F}, K_{\varphi}^{1/n}(\mathcal{G})) \) (and the same with \( \mathcal{F}, \mathcal{G} \) switched). Since \( \gamma_\mu(\mathcal{F}, \mathcal{G}) = 0 \), we can find \( u_1 : \mathcal{F} \to K_{\varphi}^{1/2m}(\mathcal{G}) \) and \( v_1 : \mathcal{G} \to K_{\varphi}^{1/2m}(\mathcal{F}) \) such that \( u_1 \circ K_{\varphi}^{1/2m}(v_1) \) and \( v_1 \circ K_{\varphi}^{1/2m}(u_1) \) are the morphisms \( \tau \). Letting \( u \) be the image of \( u_1 \) in \( \text{Hom}_{(1/n)}(\mathcal{F}, K_{\varphi}^{1/n}(\mathcal{G})) \) and defining \( v \) in the same way, we then have \( (u, v) \in B_n \).

[2] We first remark that \( \beta_{u,v}(u', v') \) belongs to \( A_n^\times \); indeed the inverse of \( v \circ_n u' \) is \( v' \circ_n u \). Now \( \beta_{u,v}(\alpha_{u,v}(a)) = v \circ_n u \circ_n a = a \) and \( \alpha_{u,v}(\beta_{u,v}(u', v')) = (u \circ_n v \circ_n u', v' \circ_n u \circ_n v) = (u', v') \).

[3] We pick \((u, v) \in B_m \) and let \((\bar{u}, \bar{v})\) be its image by the natural map \( B_m \to B_n \). We obtain a commutative diagram

\[
\begin{array}{ccc}
A'_m & \xrightarrow{\alpha_{u,v}} & B_m \\
\downarrow q & & \downarrow \\
A'_n & \xrightarrow{\alpha_{\bar{u},\bar{v}}} & B_n
\end{array}
\]

where the horizontal maps are bijections and the vertical map \( q \) is surjective by Lemma [B.6]. The result follows.

Lemma B.6. Let \( A, B \) be finite dimensional algebras over \( k \) and let \( f : A \to B \) be a surjective algebra morphism. Then the map induced on the sets of invertible elements \( f^\times : A^\times \to B^\times \) is also surjective.

Proof. We pick \( x \in A \) and assume that \( f(x) \) is invertible. We have to prove that there exists \( z \in \ker(f) \) such that \( x + z \) is invertible. We let \( A' = \langle x \rangle \) be the subalgebra of \( A \) generated by \( x \) and define similarly \( B' = \langle f(x) \rangle \). The maps \( u : k[X] \to A, \quad X \mapsto x, \) and \( f \circ u \) identify \( A' \) and \( B' \) with quotients
of \( k[X] \). Since \( k[X] \) is principal, we can write \( A' = k[X]/\langle PQ \rangle \), with \( x = [X]_{A'} \), and \( B' = k[X]/\langle Q \rangle \), with \( f(x) = [X]_{B'} \).

Since \( f(x) \) is invertible in \( B \), it is not a zero divisor and we have \( X \mid Q \). Let us write \( P = X^n P' \) with \( X \mid P' \). We set \( R = X + P' Q \). Then \( f([R]_{A'}) = f(x) \). We claim that \([R]_{A'} \) is invertible, which concludes the proof. We have to check that \( \langle R, PQ \rangle = k[X] \). Let \( D \) be a generator of \( \langle R, PQ \rangle \). Then \( D \mid X^m R - PQ = X^{m+1} \). Either \( X \mid D \), but then \( X \mid R \) and finally \( X \mid P'Q \) which is false, or \( D \in k^\times \) and we are done.

**Proposition B.7.** Let \( \mathcal{F}, \mathcal{G} \) be elements in \( D_{lc}(N) \) with coefficients in a field \( k \) and having compact supports. Assume that that \( \gamma_g(\mathcal{F}, \mathcal{G}) = 0 \). Then \( \mathcal{F} \cong \mathcal{G} \).

**Question B.8.** Is the Proposition true if we replace the field \( k \) by \( \mathbb{Z} \) or more generally a ring ?

**Proof.** If \( \mathcal{F} = 0 \), then \( \gamma_g(0, \mathcal{G}) = 0 \) and we obtain \( \mathcal{G} = 0 \) by Lemma 6.4. We assume \( \mathcal{F} \neq 0 \), hence \( \tau_{0,1/n}(\mathcal{F}) \neq 0 \) for \( n \) big enough. We use the notation \( B_n \) of Lemma B.5. By this lemma the inductive system \( \cdots \to B_n \to B_{n-1} \to \cdots \) is made of surjective maps between non empty sets for \( n \gg 0 \). Hence its limit is non empty and we deduce a pair \((u, v) \in \text{Hom}(\mathcal{F}, \mathcal{G}) \times \text{Hom}(\mathcal{F}, \mathcal{G})\) such that \((|u|)_n, [v]|_n) \in B_n \) for all \( n \), that is, \([v^0 u]|_n = \tau_{0,1/n}(\mathcal{F})\) and \([u^0 v]|_n = \tau_{0,1/n}(\mathcal{G})\). Let \( \mathcal{C} \) be the cone of \( u \). For any \( n \) we have the following morphism of triangles given by the morphisms \( \tau_{0,1/n}(-) \):

\[
\begin{array}{cccccc}
\mathcal{F} & \xrightarrow{u} & \mathcal{G} & \xrightarrow{v} & \mathcal{C} & \xrightarrow{u} \mathcal{F}[1] \\
K_{\varphi}^{1/n}(\mathcal{F}) \downarrow & & K_{\varphi}^{1/n}(\mathcal{G}) \downarrow & & K_{\varphi}^{1/n}(\mathcal{C}) \downarrow & & K_{\varphi}^{1/n}(\mathcal{F})[1], \\
\end{array}
\]

where both maps \( \tau_{0,1/n}(\mathcal{F}) \) and \( \tau_{0,1/n}(\mathcal{G}) \) factorize through \([v]|_n\). By the same argument as in the proof of Lemma 6.4(ii) we deduce that \( \tau_{0,2/n}(\mathcal{C}) = 0 \). Hence \( \gamma_g(0, \mathcal{C}) \leq 2/n \), for any \( n \). Thus the cone of \( u \) vanishes and \( u \) is an isomorphism.

**B.2. Decomposition in \( D_{lc}(\mathbb{R}) \).** Let \( \text{Mod}(\mathbb{R}) \) be the category of sheaves of \( k \)-vector spaces on \( \mathbb{R} \). We consider it as usual as the full subcategory of \( D(\mathbb{R}) \) of complexes concentrated in degree 0. A sheaf \( \mathcal{F} \in \text{Mod}(\mathbb{R}) \) which is constructible with respect to a finite stratification of \( \mathbb{R} \) is described by a quiver representation of type \( A_n \). Hence Gabriel theorem implies that \( \mathcal{F} \) is decomposed as \( \mathcal{F} \cong \bigoplus_{\mathcal{I} \subseteq \mathcal{J}} k_{\mathcal{J}} \) where \( \mathcal{I} \) is a finite family of intervals. In this section we extend this result to \( \gamma_g \)-limits of constructible sheaves under the assumption that the microsupport is contained in \( \{ \tau \geq 0 \} \).
Let $\text{Int}^+$ be the set of intervals of the form $[a, b]$, $a \in \mathbb{R}$, $b \in \mathbb{R} \cup \{+\infty\}$. We endow $\text{Int}^+$ with the order

$$[a, b] \leq [a', b'] \quad \text{if and only if} \quad a \leq a' \text{ and } b \leq b'$$

By Lemma A.2 for $I, I' \in \text{Int}^+$ we have $\text{Hom}(k_I, k_{I'}) = k$ canonically if and only if $I \cap I' \neq \emptyset$ and $I \subseteq I'$ and in this case we denote by $e_I^{I'}$ its generator. Otherwise $\text{Hom}(k_I, k_{I'}) = 0$ and we set $e_I^{I'} = 0$. For $I \subseteq I' \subseteq I''$ we have $e_I^{I'} \circ e_I^{I''} = e_I^{I''}$. For two finite families $\mathcal{I}, \mathcal{I}' \subseteq \text{Int}^+$ and $\mathcal{G} = \bigoplus_{I \in \mathcal{I}} k_I$, $\mathcal{G}' = \bigoplus_{I' \in \mathcal{I}'} k_{I'}$, we obtain a natural morphism

$$E = E_{\mathcal{G}}: \text{Mat}_{1I}(\mathcal{I} \times \mathcal{I}) \to \text{Hom}(\mathcal{G}, \mathcal{G}') \quad (a_{I', I})_{I' \in \mathcal{I}'} \in \mathcal{G}' \longrightarrow \sum_a a_{I', I} e_I^{I'},$$

where $\text{Mat}_{1I}$ denotes the space of lower triangular matrices $(a_{I', I} \neq 0)$ implies $I \subseteq I'$. The map $E$ is surjective and, for three families $\mathcal{I}, \mathcal{I}', \mathcal{I}''$, we have $E_{\mathcal{G}}(B) \circ E_{\mathcal{G}'}(A) = E_{\mathcal{G}}(BA)$.

**Lemma B.9.** Let $\mathcal{I}, \mathcal{I}' \subseteq \text{Int}^+$ be two finite families and $\mathcal{G} = \bigoplus_{I \in \mathcal{I}} k_I$, $\mathcal{G}' = \bigoplus_{I' \in \mathcal{I}'} k_{I'}$. Let $\epsilon > 0$ be given and let $u : \mathcal{G} \to \mathcal{G}'$, $v : \mathcal{G}' \to T_\epsilon^*(\mathcal{G})$ be such that $v \circ u = \tau_{0, \epsilon}(\mathcal{G})$. We assume that each $I \in \mathcal{I}$ is of length $> \epsilon$. Then there exist an isomorphism $\phi : \mathcal{G}' \cong \mathcal{G}''$ and an injective map $\sigma : \mathcal{I} \to \mathcal{I}'$ such that $I \leq \sigma(I)$ for all $I \in \mathcal{I}$ (for the order $\leq$ defined in (B.1)) and the natural morphisms $k_I \to k_{\sigma(I)}$.

**Proof.** We set $\mathcal{I}' = \{T_\epsilon(I); I \in \mathcal{I}\}$. In view of the discussion after (B.1) we can find lower triangular matrices $A \in \text{Mat}_{1I}(\mathcal{I}' \times \mathcal{I})$, $B \in \text{Mat}_{1I}(\mathcal{I}'' \times \mathcal{I'})$ representing $u, v$. Then $BA \in \text{Mat}_{1I}(\mathcal{I}'' \times \mathcal{I})$ is lower triangular. We identify $\mathcal{I}$ and $\mathcal{I}''$ through $T_\epsilon$ and we claim that $BA \in \text{Mat}_{1I}(\mathcal{I} \times \mathcal{I})$ is still lower triangular. We take $I_1, I_2 \in \mathcal{I}$ and assume that $0 \neq (BA)_{I_1, I_2} = \sum_{J \in \mathcal{I}'} B_{T_\epsilon(I_1), J} A_{J, I_2}$. There exists $J$ such that $B_{T_\epsilon(I_1), J} A_{J, I_2} \neq 0$, hence $I_2 \leq J \leq T_\epsilon(I_1)$. If we assume moreover that $I_2 \neq I_1$ we must have $T_\epsilon(I_1) \cap I_2 \neq \emptyset$ because $I_1$ and $I_2$ are of length $> \epsilon$. Hence $e_{I_2}^{T_\epsilon(I_1)} \neq 0$ and we deduce that the decomposition of $v \circ u$ on the basis of $e_{I_2}^{T_\epsilon(I_1)}$’s has a non zero coefficient on $e_{I_2}^{T_\epsilon(I_1)}$. Since $v \circ u = \tau_{0, \epsilon}(\mathcal{G})$ this means that $I_1 = I_2$, contradicting $I_2 \neq I_1$. Hence $I_2 \leq I_1$, as claimed.

Finally $BA$ is lower triangular (in $\text{Mat}_{1I}(\mathcal{I} \times \mathcal{I})$) and has entries 1 along the diagonal since it is invertible. In particular $|\mathcal{I}| \leq |\mathcal{I}'|$, $A$ has rank $|\mathcal{I}|$, we can decompose $\mathcal{I}'$ as $\mathcal{I}' = \mathcal{I} \cup \mathcal{I}'_1$ and find an invertible matrix $A' \in \text{Mat}_{1\mathcal{I}}(\mathcal{I}' \times \mathcal{I}')$ such that the block $\mathcal{I} \times \mathcal{I}$ in $A'A$ is the identity matrix. Now let $\sigma$ be the map given by the partition $\mathcal{I}' = \mathcal{I} \cup \mathcal{I}'_1$ and $\phi$ be the morphism induced by $A'$.

**Proposition B.10.** Let $\mathcal{F} \in \text{Mod}(\mathbb{R})$ such that $SS(\mathcal{F}) \subset \{(t; \tau) \in T^*\mathbb{R}; \tau \geq 0\}$. We assume that $\mathcal{F}$ is a $\gamma_g$-limit of constructible sheaves $\mathcal{F}_n \in \text{Mod}(\mathbb{R})$ such
that $SS(\mathcal{F}_n) \subset \{(t; \tau) \in T^*\mathbb{R}; \tau \geq 0\}$. Then there exists an at most countable set of intervals $\mathcal{I}$ such that $\mathcal{F} \simeq \bigoplus_{I \in \mathcal{I}} k_I$.

We notice that the singular support hypothesis in the proposition implies that our intervals are of the type $[a, b[ \cup [a, \infty[ \cup ]-\infty, b[.

**Proof.** (i) Up to taking a subsequence we can assume $\gamma_g(\mathcal{F}, \mathcal{F}_n) \leq \varepsilon_n = 2^{-n}$. For each $n$ there exists a finite family $\mathcal{I}_n \subset Int^+$ such that $\mathcal{F}_n := \bigoplus_{I \in \mathcal{I}_n} k_I$. By Proposition 6.24 we can assume, up to translating $\mathcal{F}_n$, by less than $\varepsilon_n$ that there exist compatible morphisms $f_n: \mathcal{F}_n \rightarrow \mathcal{F}_{n+1}$ and that $\text{hocolim} \mathcal{F}_n \simeq \mathcal{F}$. Since $\mathcal{F}_n \in \text{Mod}(\mathbb{R})$, we have $\text{hocolim} \mathcal{F}_n \simeq \lim \mathcal{F}_n$.

(ii) It remains to check that $\lim \mathcal{F}_n$ is decomposed. For this we modify the $f_n$'s using Lemma B.9. We let $\mathcal{J}_n \subset \mathcal{I}_n$ be the set of intervals of length $> 2n\varepsilon_n$ and we set $\tilde{\mathcal{F}}_n = \bigoplus_{I \in \mathcal{J}_n} k_I$. We first put the $\tilde{f}_n$'s in “diagonal form”, $\tilde{\mathcal{F}}_n$ (see the diagram (B.2)). Lemma B.9 applied with $f_0|_{\bar{\mathcal{F}}_0}: \bar{\mathcal{F}}_0 \rightarrow \mathcal{F}_1$ gives an injective map $\sigma_0: \mathcal{J}_0 \rightarrow \mathcal{I}_1$ and an isomorphism $\phi_1: \mathcal{F}_1 \simeq \bar{\mathcal{F}}_1$ such that $\phi_1 \circ f_0\mid \bar{\mathcal{F}}_0$ has a “diagonal form” (that is, it is the sum of the natural morphisms $k_I \rightarrow k_{\sigma_0(I)}$). We set $\tilde{f}_0 = \phi_1 \circ f_0$ and $f_1 = f_1 \circ \phi_1^{-1}$. Now we apply the lemma with $f_1'\mid \bar{\mathcal{F}}_1: \bar{\mathcal{F}}_1 \rightarrow \bar{\mathcal{F}}_2$ and obtain $\phi_2: \bar{\mathcal{F}}_2 \simeq \bar{\mathcal{F}}_2$ and $\sigma_1: \mathcal{I}_1 \rightarrow \mathcal{J}_2$. We set $\tilde{f}_1 = \phi_2 \circ f_1'$ and $f_2 = f_2 \circ \phi_2^{-1}$. We go on inductively and end up with a sequence of injective maps $\sigma_n: \mathcal{J}_n \rightarrow \mathcal{I}_{n+1}$ and morphisms $\tilde{f}_n: \mathcal{F}_n \rightarrow \mathcal{F}_{n+1}$ such that $\tilde{f}_n$ restricted to $\tilde{\mathcal{F}}_n$ has a “diagonal form”.

(iii) With our definition of $\mathcal{J}_n$ we have moreover $\sigma_n(\mathcal{J}_n) \subset \mathcal{J}_{n+1}$. Indeed, modifying $g_n$ as $\tilde{g}_n = T_{\varepsilon_n}(g_n) \circ g_n \circ \phi_{n+1}^{-1}$, we see that $\tilde{g}_n \circ \tilde{f}_n = \tau_{0,\varepsilon_n}(\mathcal{F}_n)$.

It follows that, for any $[a, b[ \in \mathcal{J}_n$ and $[a', b'] = \sigma_n([a, b])$, we must have
\(a \leq a' \leq a + \varepsilon_n\) and \(b \leq b' \leq b + \varepsilon_n\). Hence \(b' - a' \geq b - a - \varepsilon_n \geq 2\varepsilon_n - \varepsilon_n = 2\varepsilon_{n+1}\), which shows that \([a', b'] \in \mathcal{I}_{n+1}\).

We can then define \(\tilde{f}_n = \tilde{f}_n|_{\mathcal{F}_n}: \mathcal{F}_n \to \mathcal{F}_{n+1}\) and \(\tilde{f}_n\) has a “diagonal form” with respect to the inclusion \(\sigma_n|_{\mathcal{F}_n}: \mathcal{F}_n \hookrightarrow \mathcal{F}_{n+1}\). For a given \(I \in \mathcal{I}_n\) we write \(\sigma_k \circ \sigma_{k-1} \circ \cdots \circ \sigma_n(I) = [a_k, b_k]\); the sequences \((a_k), (b_k)\) are non decreasing and have limits, say \(a_\infty, b_\infty\). Then \(\lim k|_{a_k, b_k} = k|_{a_\infty, b_\infty}\). We set \(I_\infty = [a_\infty, b_\infty]\). We let \(\mathcal{J}\) be the increasing union of the \(\mathcal{J}_n\)'s. Then each element of \(\mathcal{J}\) corresponds to an interval \(I_\infty\) as above and we have proved \(\lim \tilde{\mathcal{F}}_n = \bigoplus_{I_\infty \in \mathcal{J}} \mathcal{F}_k\). By Lemma \(6.20\) the maps \(\mathcal{F}_k \to \lim \tilde{\mathcal{F}}_n\) and \(\mathcal{F}_k \to \lim \mathcal{F}_n\) have cones which go to 0 when \(k \to \infty\). It follows by Lemma \(6.4\) that the natural map \(\lim \tilde{\mathcal{F}}_n \to \lim \mathcal{F}_n\) has a cone which is arbitrarily close to 0, hence it is an isomorphism.

**Corollary B.11.** We recall that \(k\) is a field. Let \(\mathcal{F} \in D_{Ic}(\mathbb{R}) \cap D_{\tau \geq 0}(\mathbb{R})\) be a limit of constructible objects of \(D_{\tau \geq 0}(\mathbb{R})\). We assume that \(\mathcal{F}\) is constant outside \([-A, A]\) for some \(A\). Then there exists an at most countable set of intervals \(\mathcal{I}\) and integers \(d_I, I \in \mathcal{I}\), such that \(\mathcal{F} = \bigoplus_{I \in \mathcal{I}} k_I[d_I]\).

**Proof.** If we prove the result for \(\mathcal{F} \otimes k_{[-A-1, A+1]}\) we deduce the result for \(\mathcal{F}\) by gluing the decomposition with the constant sheaves \(\mathcal{F} \otimes k_{[-\infty, -A]}\) and \(\mathcal{F} \otimes k_{[A, \infty]}\). Hence we can assume \(\mathcal{F}\) has compact support.

As in the case of constructible sheaves the result follows from Proposition \(B.10\) and a decomposition of a complex as sum of its cohomology. However we didn’t prove that limits of constructible sheaves have no Ext\(^2\) so we have to be careful to decompose the cohomology before we take the limit, as follows.

There exists a sequence of constructible objects \(\mathcal{F}_n \in D_{\tau \geq 0}(\mathbb{R})\) which \(\gamma_g\)-converges to \(F\). Since \(\text{Ext}^2(\mathcal{G}, \mathcal{G}') = 0\) for any two constructible \(\mathcal{G}, \mathcal{G}' \in \text{Mod}(\mathbb{R})\), we have \(\mathcal{F}_n \cong \bigoplus_{i \in \mathbb{Z}} H^i \mathcal{F}_n[-i]\) (see for example [KS06, Cor. 13.1.20]).

In \(D_{\tau \geq 0}(\mathbb{R})\) we have \(K_G^a(-) = T_{a*}(-)\), where \(T_g\) is as usual the translation by \(a\), and this functor commutes with the cohomology, that is, \(H^i(T_{a*}(\mathcal{G})) \cong T_{a*}(H^i(\mathcal{G}))\). It follows that \(\gamma_g(H^i(\mathcal{G}, H^i(\mathcal{G}')) \leq \gamma_g(\mathcal{G}, \mathcal{G}')\), for any \(\mathcal{G}, \mathcal{G}' \in D_{\tau \geq 0}(\mathbb{R})\). Hence \(H^i \mathcal{F}_n \gamma_g\)-converges to \(H^i \mathcal{F}\).

It follows that \(\mathcal{F}_n \cong \bigoplus_i H^i \mathcal{F}_n[-i]\) \(\gamma_g\)-converges to \(\bigoplus_i H^i \mathcal{F}[-i]\). By unicity of the limit (Proposition \(B.7\)) we have \(\mathcal{F} = \bigoplus_i H^i \mathcal{F}[-i]\). Now the result follows from Proposition \(B.10\) \(\square\).

**APPENDIX C. COMPARING DIFFERENT INTERLEAVING METRICS ON \(D(N \times \mathbb{R})\).**

To prove Theorem \(1.2\) we have used the distance \(\gamma_\tau\) on sheaves over \(N \times \mathbb{R}\) and the fact that its restriction to sheaves associated with Hamiltonian maps coincides with the spectral distance (see Proposition \(6.13\)).
We can also consider the distance \( \gamma_g \) on sheaves, where \( g \) is some Riemannian metric on \( N \). For the sake of completeness we describe the distance \( \gamma_g \) from the point of view of spectral distance and we prove that the distances \( \gamma_r \) and \( \gamma_g \) induce equivalent topologies (when restricted to sheaves associated with Hamiltonian maps).

In the following we let \( H: T^*N \to \mathbb{R} \) be a function which coincides with \((q,p) \mapsto \|p\|_g\) outside a compact neighbourhood of \( 0_N \) and \( \varphi = \varphi_H \) denotes its Hamiltonian flow. We will use spectral invariants and sheaves for \( \varphi \) but in §4 and §5 we only defined them for compactly supported isotopies. However we can extend them to a positive Hamiltonian \( H \) as follows. Let \( H_r \) be a truncation of \( H \) to the disc bundle of \( T^*N \) of radius \( r \), so that \( H_r \) is an increasing sequence of Hamiltonians converging to \( H \). Then the homogeneous lift of \( s \mapsto \varphi_{H_r}^{-s} \circ \varphi_{H_{r+1}}^s \) to \( T^*(N \times \mathbb{R}) \setminus 0_N \times \mathbb{R} \) is a non negative Hamiltonian isotopy. Hence we have a natural map \( \mathcal{K}_{id} \to \mathcal{K}_{\varphi_{H_r}^{-s} \circ \varphi_{H_{r+1}}^s} \), or equivalently, \( \mathcal{K}_{\psi_{H_r}^s} \to \mathcal{K}_{\psi_{H_{r+1}}^s} \). We define \( \mathcal{K}_\psi \) as the homotopy colimit of this inductive system (say \( r \) runs over the integers). In the same way \( c_+ (\varphi_{r}^{-s}) = 0 \) if \( \lim_{r} c_+ (\varphi_{r}^{-s}) = 0 \). We shall prove that the sequence is in fact stationary, so this means \( c_+ (\varphi_{r}^{-s}) = 0 \) for \( r \) large enough.

Now Lemma 5.7 extends as follows: there are morphisms \( \mathcal{K}_\psi \to \mathcal{K}_{\psi_{H_r}^s} \to \mathcal{K}_{\psi_{H_{r+1}}^s} \) if and only if \( c_+ (\varphi_{r}^{-s}) \) and \( c_+ (\varphi_{r}^{-s}) = 0 \). Using Corollary 6.10 we obtain

**Lemma C.1.** If \( c_+ (\varphi_{s}^r) = 0 \) and \( c_+ (\varphi_{s}^r \psi^{-1}) = 0 \), the composition of the map of the map \( \mathcal{K}_\psi \to \mathcal{K}_{\psi^s} \) and \( \mathcal{K}_{\psi^s} \to \mathcal{K}_{\psi \psi^s} \) coincides with the canonical map \( \mathcal{K}_\psi \to \mathcal{K}_{\psi^2 \psi} \).

Now we may define the distance \( \gamma_g \) on \( \text{Ham}(T^*N) \) as follows

**Definition C.2.** We set

\[
c_-^g (\psi) = - \inf \{ s \geq 0 \mid c_- (\varphi_s^r \psi) = 0 \}
\]

and

\[
c_+^g (\psi) = - c_-^g (\psi^{-1}) = \inf \{ s \geq 0 \mid c_+ (\varphi_{-s}^r \psi) = 0 \}
\]

Finally we set

\[
\gamma^g (\psi) = c_+^g (\psi) - c_-^g (\psi)
\]

**Proposition C.3.** We have

1. The function \( \gamma^g \) defines a metric by \( \gamma^g (\psi_1, \psi_2) = \gamma^g (\psi_1 \psi_2^{-1}) \).
2. The topologies defined by \( \gamma^g \) and \( \gamma \) coincide.

**Proof.** (1) Apply section 3 of [PS21] to the Kernels \( \mathcal{K}_{\psi^s} \) (or the symplectic flow \( \varphi^s \)).
We shall first prove that $c_+ (\psi) \leq C_W c_+^g (\psi)$ and $\gamma (\psi) \leq C_W \gamma^g (\psi)$ for all $\psi$ such that $\text{supp}(\psi) \subset K$. We consider $c_+ (\varphi^{-s} \psi)$ and remember that $\varphi^s$ is generated by a positive homogeneous Hamiltonian $H$. By a classical argument (see e.g. [Vit92], lemma 4.7 p. 699) the map $s \mapsto c_+ (\varphi^{-s} \psi)$ is piecewise $C^1$ and where it is $C^1$ we have
\[
\frac{d}{ds} c_+ (\varphi^{-s} \psi) \bigg|_{s=s_0} = -K_s (z)
\]
where $K_s$ is the Hamiltonian associated to the map $\varphi^{-s} \psi$ and $z$ is some fixed point of $\varphi^{-s} \psi$ having non-negative action. Indeed, if $S_s$ is a Generating function Quadratic at infinity for $\varphi^{-s} \psi$ we know that $c_+ (\varphi^{-s} \psi)$ is a critical value of $S_s$ and is non-negative. It thus corresponds to fixed points of $\varphi^{-s} \psi$ with non-negative action and its derivative is $\frac{d}{ds} S_s (\xi_z) \bigg|_{s=s_0} = -K_s (z)$ where $\xi_z$ corresponds to $z$, one of the fixed points such that $S_s (\xi_z) = c_+ (\varphi^{-s} \psi)$.

In our case, if $z$ is outside the support of $\psi$, the fixed point is a fixed point of $\varphi^{-s} \psi$ and these have action 0 since $H$ is 1-homogeneous (as on an orbit $p \dot{q} - H(q, p) = p \frac{\partial H}{\partial p} - H(q, p) = 0$). So we only need to estimate $H$ in the support of $\psi$ and we set $W$ to be a neighbourhood of this support. Then if $C_W = \sup \{ H(x, p) \mid (x, p) \in W \}$ we have
\[
\frac{d}{ds} c_+ (\varphi^{-s} \psi) \bigg|_{s=s_0} \geq -C_W
\]
so that
\[
c_+ (\varphi^{-s} \psi) - c_+ (\psi) \geq -C_W s
\]
and if $c_+ (\varphi^{-s} \psi) = 0$ we have
\[
C_W s \geq c_+ (\psi)
\]
hence
\[
c_+ (\psi) \leq C_W c_+^g (\psi)
\]
Applying the same to $\varphi^{-1}$, we get
\[
\gamma (\psi) \leq C_W \gamma^g (\psi)
\]
Note that we also proved that $\gamma (\varphi^{-r} \psi)$ is stationary for $r$ such that $B(0, r)$ contains the support of $\psi$.

Conversely, let us write $\varphi^s = \xi^s_r \circ \eta^s_r$ where $\xi^s_r$ (resp. $\eta^s_r$) is the flow of $f_r (H)$ (resp. $(1 - f_r) (H)$) where $f_r$ is a function given by
\[
(1) \quad f_r (t) = t \text{ for } t \geq 2r
\]
\[
(2) \quad f_r (t) = \frac{3r}{2} \text{ for } t \leq r
\]
(3) $f_r$ is non-decreasing

Note that the flows $\xi^s_r, \eta^s_r$ are autonomous, commute, and $f_r (H)$ is bounded from below by $\frac{3r}{2}$ and $\eta^s_r$ is supported in a ball of radius $K \cdot r$. 

Then
\[ c_+(\varphi^{-s}\psi) = c_+(\xi^{-s}\eta_r^{-s}\psi) \leq c_+(\eta_r^{-s}\psi) - \frac{3r}{2}s \]
as long as \( c_+(\varphi^{-s}\psi) > 0 \) so we have
\[ \frac{3r}{2}c_+^G(\psi) \leq c_+(\eta_r^{-s}\psi) \leq \pi K^2 \cdot r^2 + c_+(\psi) \]
As a result if \( c_+(\psi_j) \) converges to zero, let \( r_j = \sqrt{c_+(\psi_j)} \). Then
\[ c_+^G(\psi_j) \leq \frac{2}{3}\left(\pi K \cdot r_j + \frac{c_+(\psi_j)}{r_j}\right) \leq \frac{2}{3}(\pi K + 1)\sqrt{c_+(\psi_j)} \]
and we deduce that \( \lim_j c_+^G(\psi_j) = 0. \)

**Figure 6.** The function \( f_r \)

**Remark C.4.**
1. We do not know if the metrics \( \gamma \) and \( \gamma^G \) are equivalent, only that they define the same topology.
2. Here is an analogy for the difference between \( \gamma \) and \( \gamma^G \). Consider the following norm on \( C^0_b(X,\mathbb{R}) \): we first define
\[ \max_f(g) = \inf_s \{ s \geq 0 | \max_f(g - sf) \leq 0 \} \]
and
\[ \min_f(g) - \max_f(-g) = \inf_s \{ s \geq 0 | \min_f(g + sf) \geq 0 \} \]
Then we set $\|g\|_f = \max_f(g) - \min_f(g)$. Provided

$$0 < \inf_{x \in X} f(x) \leq \sup_{x \in X} f(x) < +\infty$$

it is obvious that $\|\cdot\|_f$ and $\|\cdot\|$ are equivalent.

**Appendix D. Local Floer cohomology**

Our goal is to prove the following statement, which was used in Subsection 5.2.

Let $\varphi$ be a Hamiltonian map supported in a Darboux chart, $V$. Since $\Gamma(\varphi)$ coincides with the diagonal, $\Gamma(\mathrm{Id})$ outside $W = V \times V$, we can consider two types of Floer cohomology:

1. $FH^*(\varphi, W)$ obtained by using an almost complex structure making $\partial W$ pseudoconvex and building the boundary operator by considering only the Floer trajectories contained in $W$

2. The full Floer cohomology $FH^*(\varphi) = FH^*(\Gamma(\varphi, \Delta))$

Note that we may also restrict the action to some interval $[a, b]$.

**Proposition D.1.** The above two Floer cohomologies coincide. The same holds when restricting the action to $[a, b]$.

This is a special case of the following. Let $L_t$ be an exact Lagrangian isotopy supported in a pseudoconvex domain $W$ (i.e. $L_t$ is constant outside $W$). We can consider $FH^*_{[a, b]}(L_1, L_0; W)$ and $FH^*_{[a, b]}(L_1, L_0)$.

**Proposition D.2.** We have $FH^*_{[a, b]}(L_1, L_0; W) = FH^*_{[a, b]}(L_1, L_0)$.

**Proof.** We may assume that $W$ is contained in a Weinstein neighbourhood of $L_0$. We shall then use the structure of the cotangent bundle to write in these coordinates $s \cdot (q, p) = (q, sp)$ and $s \cdot L_1$ is the image of $L_1$ by the action of $s$. We have that $FH^*_{[sa, sb]}(s \cdot L_1, L_0; W)$ does not depend on $s$, since the intersection points $s \cdot L_1 \cap L_0$ are constant, their action is multiplied by $s$. We choose an almost complex structure making $\partial W$ pseudoconvex and such that $L_0 \cap \partial W$ is a Legendrian, say $\Lambda_0$, and for all $x \in \Lambda_0$ we have $JT_x \Lambda_0 \subset T_x \partial W$.

Then the holomorphic strips cannot exit from $W$ by pseudoconvexity, since an interior point of such a curve cannot be tangent to $\partial W$ and if the boundary of the strip in $L_j$ was tangent to $\partial W$ then the holomorphic curve would be tangent to $\partial W$ from inside, which is again impossible by pseudoconvexity. As a result the coboundary map defining $FH^*_{[sa, sb]}(s \cdot L_1, L_0; W)$ is also constant. Of course the same holds for $FH^*_{[a, b]}(L_1, L_0)$, as in that case we do not even have to worry about the location of the holomorphic strips. Now for $s$ small enough all holomorphic strips must have area less than any given $\varepsilon$; but there is a positive
\( \varepsilon_0 \) such that no holomorphic strip of area less than \( \varepsilon_0 \) can exit from \( \partial W \) (by a monotonicity argument). As a result for \( s \) small enough we have
\[
FH_{[sa,sb]}^*(s \cdot L_1, L_0; W) = FH_{[sa,sb]}^*(s \cdot L_1, L_0)
\]
and this implies the Proposition.

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