TAME STRUCTURES VIA MULTIPLICATIVE CHARACTER SUMS ON VARIETIES OVER FINITE FIELDS

MINH CHIEU TRAN

Abstract. We study the model theory of \((\mathbb{F}; <, \chi)\) where the field \(\mathbb{F}\) is an algebraic closure of a finite field and \(\chi\) is an ordering on the multiplicative group \(\mathbb{F}^\times\) induced by a group embedding \(\chi : \mathbb{F}^\times \to \mathbb{C}^\times\). Using number-theoretic bounds on multiplicative character sums over finite fields and Weyl’s criterion for equidistribution, we establish a number of properties about the interaction between \(\chi\) and the underlying field structure. We axiomatize these properties using first-order logic, show that the resulting theory is model complete, and obtain an analogue of a theorem by Ax.

1. Introduction

Pseudo-finite fields are important examples of tame structures in model theory; see [Cha97] for a survey. The study of these structures began with Ax, who used results about counting points on varieties over finite fields and Chebotarev’s density theorem to show that a field is pseudo-finite if and only if it is elementarily equivalent to a non-principal ultraproduct of finite fields. In this paper we show that related results about multiplicative character sums on varieties over finite fields yield tame structures in a rather different fashion. This answers a version of a question of van den Dries, Hrushovski and Kowalski which we loosely interpret as asking for applications of character and exponential sums in model theory. (However, we do not use results in [Kow07] as they suggested.)

Throughout, \(\mathbb{F}\) is an algebraic closure of a finite field and \(\chi\) is a group embedding from \(\mathbb{F}^\times\) to \(\mathbb{C}^\times\), where \(\mathbb{F}^\times\) and \(\mathbb{C}^\times\) are the multiplicative groups of \(\mathbb{F}\) and the field of complex numbers \(\mathbb{C}\) respectively. Let \(U(p) \subseteq \mathbb{C}^\times\) be the group of roots of unity with order coprime to \(p\) when \(p\) is prime and the group of roots of unity when \(p\) is zero. Let \(T \subseteq \mathbb{C}^\times\) be the unit circle. Then \(\text{Image}_{\chi} = U(p) \subseteq T\) where \(p = \text{char}(\mathbb{F})\).

We denote by \(<\) the natural ordering on the field of real numbers \(\mathbb{R}\). Identifying the interval \([0, 1) \subseteq \mathbb{R}\) with \(T\) via \(\alpha \mapsto e^{2\pi i\alpha}\), the above \(<\) induces cyclic orderings on \(T\) and \(U(p)\) for \(p\) either prime or zero which we also denote by \(<\). Define \(\chi\) on \(\mathbb{F}^\times\) to be the pullback of \(<\) on \(T\) by \(\chi\) and view \(\chi\) as a binary relation on \(\mathbb{F}\). We will show that \((\mathbb{F}; <, \chi)\) is model theoretically tame for all \(\mathbb{F}\) and \(\chi\) as above.

We can think of the above \((\mathbb{F}; <, \chi)\) as an amalgam of two simpler structures: the algebraically closed field \(\mathbb{F}\) and the “cyclically ordered” group \((\mathbb{F}^\times; <, \chi)\). The latter can be identified via \(\chi\) with \((U(p); <)\) where \(p = \text{char}(\mathbb{F})\). This suggests studying the model theory of \((\mathbb{F}; <, \chi)\) by first analyzing each of these two structures and then understanding the way they are “glued” together.
The above approach leads to studying \((F; <_\chi)\) in a slightly richer language which does not introduce extra definable sets. This is necessary as when \(p\) is prime, \((U(p); <)\) does not admit quantifier elimination in the language of groups with a relation symbol for <. For \(c \in U(p)\) with \(p\) either prime or zero and \(n \in \mathbb{N}^+\), define the “winding number” \(w_n(c, n)\) as the number of elements of the set
\[
\{ k \in \mathbb{Z} : 0 \leq k \leq n - 1, c^{k+1} < c^k \}.
\]
For \(p\) either prime or zero, let \(\mathcal{P}\) denote the family \((\mathcal{P}_n^r)_{n,r}\) of unary relations on \(U(p)\) where \(n\) ranges over \(\mathbb{N}^+\), \(r\) is in \(\{0, \ldots, n-1\}\) and \(\mathcal{P}_n^r \subseteq U(p)\) is the set
\[
\{ a \in U(p) : \text{there is } c \in U(p) \text{ with } c^n = a \text{ and } w_n(c, n) = r \}.
\]
The expansion \((U(p); <, \mathcal{P})\) of \((U(p); <)\) by the family \(\mathcal{P}\) is then a structure in the language \(L_m\) extending the language of groups with a binary predicate symbol for < and a family of unary predicate symbols for \(\mathcal{P}\). With \((F^*_\chi; <_\chi)\) identified with \((U(p); <)\) via \(p = \text{char}(F)\), define \(\mathcal{P}_\chi\) on \(F^*_\chi\) to be the pullback of \(\mathcal{P}\) by \(\chi\) and view \(\mathcal{P}_\chi\) as a family of unary relations on \(F\). Then \((F^*_\chi; <_\chi, \mathcal{P}_\chi)\) is an \(L_m\)-structure isomorphic to \((U(p); <, \mathcal{P})\) where \(p = \text{char}(F)\) and \((F; <_\chi, \mathcal{P}_\chi)\) is a structure in the language \(L_c\) obtained by combining \(L_m\) and the language of rings \(L_r\). We call the structures \((F; <_\chi, \mathcal{P}_\chi)\) for varying \(F\) and \(\chi\) the standard models.

We observe a number of immediate first-order properties of the standard models. For \(p\) either prime or zero, let \(\text{ACFO}_{\mathcal{P}}^0\) be a set of \(L_c\)-sentences such that an \(L_c\)-structure \((F; <, \mathcal{P})\) is a model of \(\text{ACFO}_{\mathcal{P}}^0\) if and only if it has the following properties:

1. \(F\) is an algebraically closed field of characteristic \(p\);
2. \((F^*_\chi; <_\chi)\) is an algebraically closed field of characteristic \(p\); \((T_m, p)\) is the theory of \((U(p); <, \mathcal{P})\) in \(L_m\).

When \(p\) is prime, the above are precisely the first-order properties of the components \(F\) and \((F^*_\chi; <_\chi, \mathcal{P}_\chi)\) in a standard models \((F; <_\chi, \mathcal{P}_\chi)\) with \(\text{char}(F) = p\). A weaker theory is also later needed. Replacing \(T_m, p\) in (2) with the set \(T_{m, p}(\forall)\) of its universal consequences, we get a set \(\text{ACFO}_{\mathcal{P}}^0\) of \(L_c\)-sentences (where the superscript “\(\forall\)” is read as “double minus”). What can be said about the components \(F\) and \((F^*_\chi; <_\chi, \mathcal{P}_\chi)\) in a standard models \((F; <_\chi, \mathcal{P}_\chi)\) as \(\text{char}(F)\) varies? If \(T\) is a theory in a language \(L\), we let \([T]\) denotes the class of \(T\)-models. Set
\[
[\text{ACFO}^+] = \bigcup_p [\text{ACFO}_{\mathcal{P}}^0] \quad \text{and} \quad [\text{ACFO}^-] = \bigcup_p [\text{ACFO}_{\mathcal{P}}^-].
\]

Theorem \[\text{[12]}\] below allows us to choose sets of \(L_c\)-statements \(\text{ACFO}^+\) and \(\text{ACFO}^-\) such that \([\text{ACFO}^+]\) and \([\text{ACFO}^-]\) are their classes of models respectively; it is easy to see that standard models and ultra-products of standard models are then models of both \(\text{ACFO}^+\) and \(\text{ACFO}^-\).

Heuristically, a structure in \([\text{ACFO}^-]\) is obtained by “gluing” a structure in \([\text{ACF}]\) and a structure in \([T_m]\) in such a way that the multiplicative group of the former matches the underlying multiplicative group of the latter. We will show using results on character sums that in a standard model \((F; <_\chi, \mathcal{P}_\chi)\), the components \(F\) and \((F^*_\chi; <_\chi, \mathcal{P}_\chi)\) interact with one another in a random manner on top of their obvious agreement on \(F^*_\chi\). A consequence of this “number-theoretic randomness” is that the standard models satisfy a first-order notion of “genericity.” This makes our example \((F; <_\chi, \mathcal{P}_\chi)\) analogous to known examples of adding a generic predicate as in \[\text{[CP98]}\] and \[\text{[Che14]}\], amalgamating simple structures as in \[\text{Tsu01}\] and adding a generic linear order as in \[\text{SS12}\]. We will adapt the techniques in these papers to establish the tameness of our structure.
We make the above precise. Suppose $F \models \text{ACF}$. A quasi-affine variety (over $F$) is for us a nonempty open subset of an irreducible closed subset of some $F^m$, the latter equipped with its Zariski topology. A quasi-affine variety $V \subseteq F^m$ is **multiplicatively large** if for all $(k_1, \ldots, k_m) \in \mathbb{Z}^m \setminus \{(0, \ldots, 0)\}$ and all $c \in F^\times$, $V \cap (F^\times)^m$ is not contained in the solution set of the equation

$$x_1^{k_1} \cdots x_m^{k_m} = c.$$ 

Suppose moreover $(F; <, \mathcal{P}_n^\times)$ is in $[\text{ACFO}^-]$. The **order topology** on $(F^\times)^m$ is defined for $m = 1$ as the topology which has a basis consisting of the semi-open intervals $\{a : 1 \leq a < c'\}$ and the open intervals $\{a : c < a < c'\}$ with $c, c' \in F^\times$, and for $m > 1$ as the product of the order topologies on the $m$ copies of $F^\times$. We say that $X \subseteq F^m$ is **order-dense** if $X \cap (F^\times)^m$ is dense in $(F^\times)^m$ with respect to the order topology.

We say that $(F; <, \mathcal{P}) \in [\text{ACFO}^-]$ is **generic** if all multiplicatively large quasi-affine varieties over $F$ are order-dense. Let $[\text{ACFO}]$ and $[\text{ACFO}_p]$ be the classes of structures in $[\text{ACFO}^-]$ and $[\text{ACFO}^-]$ that are generic. Theorem 1.2 below shows that $[\text{ACFO}]$ and $[\text{ACFO}_p]$ are the classes of models of $L_{c^2}$-theories with corresponding name. Our notion of **genericity** is non-trivially equivalent to the translation of the notions with that name in CP98, Tsu01 and SS12. The modifications allows a closer link to the “number-theoretic randomness” that we need. In section 2, we prove that:

**Theorem 1.1.** The standard models are generic.

Our strategy is to prove for a multiplicatively large quasi-affine variety $V \subseteq F^m$ in $(F; <, \mathcal{P})$ the stronger statement that the image of the set $V^\times(F_{p^\times}) = V \cap (F_{p^\times})^m$ under $\chi$ becomes equidistributed in $\mathbb{T}$ as $k \to \infty$. This uses number theoretic bounds on character sums and Weyl’s criterion for equidistribution.

Section 3 gives us the right to use compactness:

**Theorem 1.2.** $[\text{ACFO}^\times]$, $[\text{ACFO}^-]$, and $[\text{ACFO}]$ are $\forall 3$-axiomatizable.

We need to show that (2) in the definition of ACFO$^-$ is $\forall 3$-axiomatizable. This follows essentially from the quantifier elimination for $(U_{(p)}; <, \mathcal{P})$. Using an idea implicit in Gun08, $(U_{(p)}; <, \mathcal{P})$ can be linked to the structure $(\mathbb{Z}_{(p)}; <, \mathcal{D}, \pm 1)$ where $\mathcal{D} = (\mathcal{D}_n)_{n \in \mathbb{N}}$ and $\mathcal{D}_n \subseteq \mathbb{Z}_{(p)}$ is the predicate for divisibility by $n$. By results in We81, $(\mathbb{Z}_{(p)} <, \mathcal{D}, 1)$ has quantifier elimination. From this, we can deduce the quantifier elimination of $(U_{(p)}; <, \mathcal{P})$. We also need to show that genericity is $\forall 3$-axiomatizable. This can be reduced to showing that multiplicative largeness is definable in a family. The reduction step has an analogue in CP98, Tsu01 and SS12, but the next step of proving the resulting statement requires new ideas. In particular, our proof uses the Zilber’s indecomposability theorem and the fact that every connected algebraic subgroup of an algebraic torus must be a subtorus.

In Section 4 we study the logical tameness of ACFO. The main theorem is:

**Theorem 1.3.** ACFO is the model completion of ACFO$^\times$. Definable sets in an ACFO-model are one-to-one coordinate projections of quantifier-free definable sets.

Given $(F; <, \mathcal{P}_n^\times) \models \text{ACFO}$, let $\text{Abs}(F)$ be the prime model of ACF contained in $F$ and let $<$ and $\mathcal{P}$ be defined on $\text{Abs}(F)$ by restriction. We deduce a criterion for two models of ACFO to be elementarily equivalent:

**Corollary 1.4.** The ACFO-models $(F; <, \mathcal{P})$ and $(F'; <, \mathcal{P})$ are elementarily equivalent if and only if $(\text{Abs}(F); <, \mathcal{P})$ and $(\text{Abs}(F'); <, \mathcal{P})$ are isomorphic.
When\( p \) is prime, we obtain a detailed study of \((\text{Abs}(F);<,\mathcal{P})\) in a model \((F;<,\mathcal{P})\) of \(\text{ACFO}_p\). This yields in particular the following converse of Theorem 1.1

**Proposition 1.5.** If \((F;<,\mathcal{P})\models \text{ACFO}_p\) for \(p\) prime, then \((\text{Abs}(F);<,\mathcal{P})\) is a standard model and is therefore a model of \(\text{ACFO}_p\).

The above is surprising as the given definition and the proof of Theorem 1.1 seem to suggest that the notion of genericity is rather weak. Combining with Theorem 1.1 and Theorem 1.3 we get the following analogue of Ax’s theorem:

**Corollary 1.6.** An \(L_c\)-structure is a model of \(\text{ACFO}\) if and only if it is elementarily equivalent to an ultraproduct of standard models.

Using Theorem 1.3 and results from computational number theory we obtain:

**Proposition 1.7.** The theory \(\text{ACFO}\) is decidable.

Let \(\text{acl}_t\) be the algebraic closure operator with respect to \(L_t\) and let \(\text{acl}_c\) and \(\text{dcl}_c\) be the algebraic closure and definable closure operators with respect to \(L_c\). We get:

**Proposition 1.8.** In a model of \(\text{ACFO}\), \(\text{acl}_t\), \(\text{dcl}_c\) and \(\text{acl}_c\) coincide.

There are a number of new ideas in the proof of the main theorem compared to its counterparts in [CP98], [Tsu01] and [SS12]. First, as mentioned before, our notion of genericity is not trivially equivalent to the translation of the notions with the same name in those papers. We therefore need to bridge this gap in the proof that \(\text{ACFO}\) is model complete. In particular, we need to understand the appropriate notion of dimension in \((\mathcal{U}_{(p)};<,\mathcal{P})\). This is done by again linking \((\mathcal{U}_{(p)};<,\mathcal{P})\) to \((\mathcal{Z}_{(p)};<,\mathcal{D},\pm 1)\) and using the results in [Tow13]. Second, the structures in [CP98], [Tsu01] and [SS12] can be seen as free amalgams of two simpler structures, while in \((F;<,\mathcal{P}_\lambda)\), \(F\) and \((F^*;<,\mathcal{P}_\lambda)\) agree on \(F^*\). This brings unexpected difficulties. To resolve these, we need among other things the fact that the common reduct of \(\text{ACF}_p\) and \(T_{m,p}\) to the language \(L_g\) of groups has quantifier elimination.

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**2. Genericity of the Standard Models**

Throughout \(k\) and \(l\) range over the integers, \(m\) and \(n\) range over the natural numbers (which include zero) and \(p\) ranges over the set \(\{n \in \mathbb{N} : n \text{ is zero or prime}\}\). Let \(x = (x_1,\ldots,x_m)\) and \(y = (y_1,\ldots,y_n)\) be tuples of variables. If \(a\) is in \(X^m\) then \(a = (a_1,\ldots,a_m)\) with \(a_i \in X\) for \(i \in \{1,\ldots,m\}\).

Assume also in this section that \(k \geq 1\), \(p = \text{char}(\mathbb{F})\), \(q = p^l\) for \(l \geq 1\), \(\mathbb{F}_q\) is the subfield of \(\mathbb{F}\) with \(q\) elements, \(P\) is in \(\mathbb{F}_q[x]\) and \(V \subseteq \mathbb{F}_q^m\) is a quasi-affine variety of dimension \(d\) definable in the field sense over \(\mathbb{F}_q\). Toward Theorem 1.1 we need two number theoretic results:

**Lemma 2.1** (Lang-Weil Estimate). \(|V(\mathbb{F}_q^*)| = q^{kd} + O(q^{k(d-\frac{1}{2})})\) as \(k \to \infty\).
In this section, we use the following conventions in addition to those introduced in Section 1. We apply Lemma 2.1 and Lemma 2.2 with $P$ the characteristic function of the associated Kummer sheaf $\mathcal{L}_\chi$ to the pullback of the associated Kummer sheaf $\mathcal{L}_\chi$ to $V$ by $P$ (see 1.7 of [Del77]). In the appendix we provide a more elementary proof depending only on a Weil style bound.

We will also need a variation of Weyl’s criterion for equidistribution. For $b, b' \in \mathbb{T}^m$, we write $b < b'$ if $b_i < b'_i$ for all $i \in \{1, \ldots, m\}$. For $b, b' \in \mathbb{T}^m$ such that $b < b'$, set

$$V(b, b') = \prod_{j=1}^m \left( (b'_j - b_j) \right)$$

with $1: \mathbb{T} \to [0,1] \subseteq \mathbb{R}$ mapping $e^{2\pi i \alpha}$ to $\alpha$.

For the rest of the section, $(X_k)_{k \in \mathbb{N}}$ is a sequence of finite subsets of $\mathbb{T}^m$. We say that $(X_k)_{k \in \mathbb{N}}$ becomes equidistributed in $\mathbb{T}^m$ if

$$\lim_{k \to \infty} \left( \frac{1}{|X_k|} \right) \sum_{a \in X_k} a_1^{l_1} \cdots a_m^{l_m} = 0 \quad \text{for all } l \in \mathbb{Z}^m \setminus \{(0, \ldots, 0)\}.$$

**Lemma 2.3 (Weyl’s Criterion).** The sequence $(X_k)_{k \in \mathbb{N}}$ becomes equidistributed in $\mathbb{T}^m$ if and only if

$$\lim_{k \to \infty} \left( \frac{1}{|X_k|} \right) \sum_{a \in X_k} a_1^{l_1} \cdots a_m^{l_m} = 0 \quad \text{for all } l \in \mathbb{Z}^m \setminus \{(0, \ldots, 0)\}.$$

**Proof.** The proof is the same as that for Weyl’s criterion for equidistribution of sequence. See for example page 112 of [SS03].

**Proof of Theorem 2.1.** It suffices to show that if $V \subseteq (\mathbb{F}^m)^m$ is multiplicatively large and $X_k$ is the image of $V(\mathbb{F}_{q^k})$ under $\chi$, then the sequence $(X_k)_{k \in \mathbb{N}}$ becomes equidistributed. Using Weyl’s criterion, we need to verify that

$$\lim_{k \to \infty} \left( \frac{1}{|X_k|} \right) \sum_{a \in X_k} \chi(a_1^{l_1} \cdots a_m^{l_m}) = 0.$$

Apply Lemma 2.1 and Lemma 2.2 with $P = x_1^{l_1} \cdots x_m^{l_m}$ noting that $P$ is non-constant on $V$ as $V$ is multiplicatively large.

### 3. Axiomatization

In this section, we use the following conventions in addition to those introduced in the first paragraph of the preceding section. Let $L$ be a language. If $x$ is a tuple of variables, let $L(x)$ be the set of $L$-formulas with free variables in $x$; in particular, $L(\neg)$ is the set of all $L$-sentences. Denote by $[L]$ the class of all $L$-structures and by $([L], \rightarrow)$ the category whose objects are $L$-structures and whose morphisms are $L$-embeddings. For $T \subseteq L(\neg)$, define $([T], \rightarrow)$ to be the full subcategory of $([L], \rightarrow)$ whose objects are $T$-models. Suppose $(M; \ldots) \subseteq (M'; \ldots)$ are $L$-structures and $X \subseteq M^m$ is definable. Then we set $X(M')$ to be the subset of $(M')^m$ defined by an
A $L$-formula with parameters over $M$ that defines $X$; note that $X(M')$ is independent of the choice of the $L$-formula in the preceding statement. Suppose $R$ is a relation on a set $M$ and $M' \subseteq M$. The relation on $M'$ which is obtained by restricting $R$ to $M'$ is also denoted by $R$.

In the first half of this section, we prove that ACFO$^-$ and ACFO$^+$ have $\forall 3$-axiomatizations in $L_c$. We deduce this essentially from a quantifier elimination result for $(U_p);<,\mathcal{P})$. This is done by linking a class of structures containing $(U_p);<,\mathcal{P})$ to another class of structures with better known model theory.

Let $\mathbb{Z}_p$ be the usual localization of $\mathbb{Z}$ at the prime ideal $(p)$. This definition still applies when $p$ is zero, in which case $\mathbb{Z}_p(0) = \mathbb{Q}$. For $n > 0$, let $\mathcal{D}_n \subseteq \mathbb{Z}_p$ be the unary relation for divisibility by $n$. Let $\mathcal{D}$ be $(\mathcal{D}_n)_{n>0}$ and $(\mathbb{Z}_p);<,\mathcal{D},\pm 1)$ be the expansion of the ordered abelian group $(\mathbb{Z}_p);<)$ by the family $\mathcal{D}$ and the constants $1$ and $-1$. Then $(\mathbb{Z}_p);<,\mathcal{D}_n,\pm 1)$ is a structure in the language $L_a$ extending the language of order groups by a predicate symbol for each $n$ and constant symbols for 1 and $-1$. Let $T_a$ be the class of $L_a$-structures $(G;<,\mathcal{D},\pm 1)$ such that:

1. $(G;<)$ is an ordered additive abelian group; $1$ is a distinguished positive element and $-1$ is a distinguished negative element such that $(1) = 1 > 0$;
2. The family of unary predicate $\mathcal{D}$ on $G$ is defined as above replacing $\mathbb{Z}_p$ with $G$;
3. there is at most one prime $l$ such that $\neg \mathcal{D}_l(1)$;
4. if $l$ is prime with $\mathcal{D}_l(1)$ and $q = l^k$ with $k > 1$, then for all $\alpha \in G$, $\mathcal{D}_q(\alpha)$;
5. if $l$ is a prime such that $\neg \mathcal{D}_l(1)$ and $q = l^k$ with $k \in \mathbb{N}_{\geq 1}$, then for all $\alpha \in G$, there is exactly one $r \in \{0, 1, \ldots, q - 1\}$ such that $\mathcal{D}_q(\alpha + r \cdot (-1))$;
6. for all $n > 0$ and $\beta, \beta' \in G$ with $\beta < \beta'$, there is $\alpha \in G$ with $\beta < \alpha < \beta'$ and $\mathcal{D}_n(\alpha)$.

When $p$ is prime, we define $T_{a,p}$ by adding to the above list the property that $\neg \mathcal{D}_p(1)$; when $p$ is zero, we define $T_{a,p}$ by adding to the above list the property that $\mathcal{D}_l(1)$ for all prime $l$. Clearly, $(\mathbb{Z}_p);<,\mathcal{D},\pm 1)$ is a model of $T_{a,p}$ and is uniquely $L_a$-embeddable into an arbitrary model of $T_{a,p}$. We can easily see that the classes $T_a$ and $T_{a,p}$ for arbitrary $p$ have $\forall 3$-axiomatizations in $L_a$ and that $T_a = \bigcup_{p} T_{a,p}$.

**Lemma 3.1.** The theory $T_a$ admits quantifier elimination. For all $p$ either prime or zero, $T_{a,p}$ is complete.

**Proof.** By (1) and (5) of the definition, every model of $T_a$ is a dense regular ordered abelian group as defined in [RZ60]. By a result in [Wei81], $T_a$ admits quantifier elimination in $L_a$; a more model theoretic proof can also be easily obtained (see [vdD00]). For all $p$, an arbitrary model of $T_{a,p}$ extends a copy of $(\mathbb{Z}_p);<,\mathcal{D}_n,\pm 1)$ as $L_a$-structure. Hence, $T_{a,p}$ is complete. \qed
The structure \((\mathbb{Z}_p; \cdot, 0, 1)\) can be constructed from \((U; \cdot, 0, 1)\). The group homomorphism \(\alpha \mapsto e^{2\pi i \alpha}\) maps \(\mathbb{Z}_p\) onto \(U\) with kernel \(\mathbb{Z}\). We can therefore identify the underlying set of \(\mathbb{Z}_p\) with that of \(\mathbb{Z} \times U\). Moreover, we can equip \(\mathbb{Z} \times U\) with an \(L\)-structure. Let \(a, a'\) be in \(U\). Define \(+\) on \(\mathbb{Z} \times U\) by

\[
(k, a) + (k', a') = \begin{cases} 
(k + k', aa') & \text{if } a \leq aa' \text{ in } (U; \cdot, 0, 1), \\
(k + k' + 1, aa') & \text{otherwise}.
\end{cases}
\]

Let \(<\) be the lexicographic ordering on \(\mathbb{Z} \times U\). Let \(D = (D_n)_{n \geq 0}\) be given by

\[
(k, a) \in D_n \text{ if and only if } a \in \mathcal{P}_n \text{ and } k \equiv r \pmod{n}.
\]

Finally, the constants \(-1, 0\) and \(1\) on \(\mathbb{Z} \times U\) are defined to be the pairs \((-1, 1)\), \((0, 1)\) in \(\mathbb{Z} \times U\) and \((1, 1)\) in \(\mathbb{Z} \times U\), respectively. By construction, \((\mathbb{Z}_p; \cdot, 0, 1)\) is \(L\)-isomorphic to \((\mathbb{Z} \times U; \cdot, 0, 1)\).

Replacing \(U\) with \(M\) and \(\mathbb{Z}_p\) with \(G\), we get the definition of the \(L\)-cover \((G; <, \cdot, 0, 1)\) of \((M; <, \cdot, 0, 1)\) as a class. This defines a functor \(\mathcal{F}_a\) from \((T_m(\mathcal{V}), \cdot)\) to \([[L_a], \cdot])

**Lemma 3.2.** For all \(p\), \(\mathcal{F}_a(T_m, p) \in T_{n,p}\) and \(\mathcal{F}_a(T_m, p) \in T_{n,p}\). Moreover, \(\mathcal{F}_a(T_m, p) \in T_{n,p}\) and \(\mathcal{F}_a(T_m, p) \in T_{n,p}\).

**Proof.** To prove \(\mathcal{F}_a(T_m, p) \in T_{n,p}\), suppose \((M; <, \cdot, 0, 1)\) and \((G; <, \cdot, 0, 1)\) is its \(L\)-cover. For each \(m > 0\), we let

\[
G_m = \{k : -m \leq k \leq m\} \times M
\]

and get \((G_m; R, <, \cdot, 0, 1)\) by viewing \(+\) on \(G\) as a ternary relation \(R\) on \(G\) and restricting \((G; R, <, \cdot, 0, 1)\) to \(G_m\) in the obvious way. We note that \((G; <, \cdot, 0, 1) = T_{n,p}\) if and only if \((G_m; R, <, \cdot, 0, 1)\) satisfy the truncated version of (1) to (5) in the definition of \(T_{n,p}\) for all \(m\).

For all \(m > 0\), \((G_m; R, <, \cdot, 0, 1)\) is interpretable in \((M; <, \cdot, 0, 1)\). Moreover, this can be done without using parameters. Hence, \((G; <, \cdot, 0, 1) = T_{n,p}\) if and only if \((M; <, \cdot, 0, 1)\) is a particular set of \(L\)-statements. Since \((\mathbb{Z}_p; <, 0, 1)\) is \(T_{n,p}\), this particular set of \(L\)-statements holds in the \(T_{n,p}\) model \((U; \cdot, 0, 1)\). The conclusion follows from the fact that \(T_{n,p}\) is complete.

As \(\mathcal{F}_a\) is a functor, it follows that \(\mathcal{F}_a(T_m, p) \in T_{n,p}\). The second statement is immediate. \(\square\)

Conversely, \((U; <, \cdot, 0, 1)\) is interpretable in \((\mathbb{Z}_p; <, 0, 1)\). The set \(U\) can be identified with \(\mathbb{Z}_p \cap [0, 1) = \{\alpha \in \mathbb{Z}_p : 0 \leq \alpha < 1\}\) via \(\alpha \mapsto (2\pi i)^{-1} \log(a)\). We equip an \(L\)-structure on \(\mathbb{Z}_p \cap [0, 1)\). Define \(\cdot\) on \(\mathbb{Z}_p \cap [0, 1)\) by setting

\[
\alpha \cdot \beta = \begin{cases} 
\alpha + \beta & \text{if } \alpha + \beta < 1 \text{ in } (\mathbb{Z}_p; <, 0, 1), \\
\alpha + \beta + (-1) & \text{otherwise}.
\end{cases}
\]

Define \(<\) on \(\mathbb{Z}_p \cap [0, 1)\) by restricting \(<\) on \(\mathbb{Z}_p\) and \(\mathcal{P} = (\mathcal{P}_n)_{n \geq 0, r \in \{0, \ldots, n-1\}}\) on \(\mathbb{Z}_p \cap [0, 1)\) by setting \(\alpha \in \mathcal{P}_n\) if and only if \(\alpha + r \cdot 1 \in \mathcal{D}_n\). Then the identification between \(U\) and \(\mathbb{Z}_p \cap [0, 1)\) gives us an isomorphism of \(L\)-structures.

Replacing \(U\) with \(M\), \(\mathbb{Z}_p\) with \(G\) and \(\mathbb{Z}_p \cap [0, 1)\) with \(G \cap [0, 1)\) defined in the obvious way, we get the definition of the \(L\)-truncation \((M; <, \cdot, 0, 1)\) of a \(T_m(\mathcal{V})\) model \((G; <, 0, 1)\). This defines a functor \(\mathcal{F}_m\) from \((T_m(\mathcal{V}), \cdot)\) to \([[L_m], \cdot])\).
Lemma 3.3. For all \( p \), \( \mathcal{F}_m(T_{n,p}) \subseteq T_{m,p} \) and \( \mathcal{F}_m(T_{n,p}(\forall)) \subseteq T_{m,p}(\forall) \). Moreover, \( \mathcal{F}_m(T_n) \subseteq T_m \) and \( \mathcal{F}_m(T_n(\forall)) \subseteq T_m(\forall) \).

Proof. For all \( p \), the \( L_m \)-truncation of the \( T_{n,p} \)-model \( (\mathbb{Z}_p; <, \mathcal{D}_n, \pm 1) \models T_{n,p} \) is isomorphic to \( (\cup(p); <, \mathcal{P}) \models T_{m,p} \) and hence a model of \( T_{m,p} \). Moreover, \( T_{n,p} \) is complete and \( L_m \)-truncations are interpretable in the corresponding \( T_{n,p} \)-models independent of the model choice. Hence, \( \mathcal{F}_m(T_{n,p}(\forall)) \subseteq T_{m,p}(\forall) \). As \( \mathcal{F}_m \) is a functor, \( \mathcal{F}_m(T_{n,p}(\forall)) \subseteq T_{m,p}(\forall) \). The second statement is immediate. \( \square \)

Lemma 3.4. A model of \( T_{m,p}(\forall) \) is naturally isomorphic to the \( L_m \)-truncation of its \( L_\alpha \)-cover. Moreover, the functors \( \mathcal{F}_n \) and \( \mathcal{F}_m \) are adjoint.

Proof. By Lemma 3.2 \( \mathcal{F}_n(T_n(\forall)) \subseteq T_n(\forall) \), and so the construction of \( L_m \)-truncation of \( L_\alpha \)-cover is allowed. The first statement can then be easily checked. The second statement is not used and left to the interested reader. \( \square \)

Proposition 3.5. The classes \( T_m(\forall) \) and \( T_m \) are first-order axiomatizable. The theory \( T_m \) has quantifier elimination and hence has an \( \forall \exists \)-axiomatization.

Proof. We show that \( T_m \) is first order axiomatizable and the statement for \( T_m(\forall) \) easily follows. Since \( T_m = \cup(p) T_{m,p} \) and \( T_{m,p} \) is first order axiomatizable for all \( p \), we have that \( T_m \) is closed under elementary equivalence. Suppose \( I \) is an infinite index set and for every \( i \in I \), \( (M_i; <, \mathcal{P}) \) is the \( L_m \)-truncation of \( (G_i; <, \mathcal{D}, \pm 1) \models T_n \). As \( (M_i; <, \mathcal{P}) \) is interpretable in \( (G_i; <, \mathcal{D}, \pm 1) \) independent of the choice of \( i \), for and ultra filter \( \mathcal{U} \) on \( I \), we have that

\[
\prod_{i \in I} (M_i; <, \mathcal{P})/\mathcal{U} \cong \mathcal{F}_m \left( \prod_{i \in I} (G_i; <, \mathcal{D}, 1)/\mathcal{U} \right).
\]

By the preceding two lemmas, \( T_m \) is closed under arbitrary ultra product. The desired conclusion follows by standard model theory (see Theorem 4.1.12 of [CK90]).

For the second statement, suppose \( (M; <, \mathcal{P}) \) is an \( L_m \)-substructure of both \( (M_1; <, \mathcal{P}) \models T_m \) and \( (M_2; <, \mathcal{P}) \models T_m \). \( \varphi \) is in \( L_m(x) \) and \( \alpha \) is in \( M^m \). By standard quantifier elimination test (see Theorem 3.1.4 of [Mar02]), we need:

\[
(M_1; <, \mathcal{P}, \alpha) \models \varphi(\alpha) \iff (M_2; <, \mathcal{P}, \alpha) \models \varphi(\alpha).
\]

By the preceding two lemmas and the functoriality of \( \mathcal{F}_n \) and \( \mathcal{F}_m \), we can arrange that: \( (M; <, \mathcal{P}) \) is the \( L_m \)-truncation of \( (G; <, \mathcal{D}, \pm 1) \models T_n(\forall) \). \( (M_i; <, \mathcal{P}) \) is the \( L_m \)-truncation of \( (G_i; <, \mathcal{D}, \pm 1) \models T_{n,p}(\forall) \) for \( i \in \{1, 2\} \) and \( (G_2; <, \mathcal{D}, \pm 1) \) is a common \( L_\alpha \)-substructure of \( (G_1; <, \mathcal{D}, \pm 1) \) and \( (G_2; <, \mathcal{D}, \pm 1) \). Since the interpretation of a \( L_m \)-truncation of a model of \( T_\alpha(\forall) \) inside that model is independent of the choice of the model, there is \( \psi(x) \in L_m(x) \) such that for all \( \beta \in M_i \) and \( i \in \{1, 2\} \):

\[
(M_i; <, \mathcal{P}, \beta) \models \varphi(\beta) \iff (G_i; <, \mathcal{D}, \pm 1, \beta) \models \psi(\beta).
\]

Therefore our problem reduces to showing that: \( (G_1; <, \mathcal{D}, \pm 1, \alpha) \models \psi(\alpha) \iff (G_2; <, \mathcal{D}, \pm 1, \alpha) \models \psi(\alpha) \). This follows from quantifier elimination of \( T_n \). \( \square \)

Proof of Theorem 3.3 part 1. We show that \( ACFO^+ \) and \( ACFO^- \) have \( \forall \exists \)-axiomatization in \( L_c \). We note that \( (F; <, \mathcal{P}) \models ACFO^+ \) if and only if \( F \models ACF_0 \) and \( (F^*; <, \mathcal{P}) \models T_m(\forall) \) and \( \text{char}(F) = p \iff \neg \exists p^0(1) \). For \( ACFO^+ \), we replace \( T_m \) with \( T_m(\forall) \). The conclusion hence follows from the preceding proposition. \( \square \)
In the second half of this section, we show that ACFO has a \( \forall \exists \)-axiomatization in \( L_c \). This needs a further understanding of the notion of multiplicative largeness. In the rest of the section, \( F \) is an algebraically closed field, \( V \subseteq F^m \) is a quasi-affine variety and \( V^* = V \cap (F^*)^m \). The multiplicative group \((F^*)^m\) has underlying set \((F^*)^m\) and multiplication given by \( ab = (a_1b_1, \ldots, a_mb_m) \) for \( a, b \in (F^*)^m \).

**Lemma 3.6.** If \( M \) is an algebraic subgroup of the multiplicative group \((F^*)^m\) then \( M \) is the set of elements of \((F^*)^m\) satisfying a system of polynomial equations each of which has the form \( x_1^{k_1} \cdots x_m^{k_m} = 1 \) with \( k_1, \ldots, k_m \in \mathbb{Z} \).

**Proof.** This is Corollary 3.2.15 in [BG06]. There is an extra assumption that the field is of characteristic 0 in the given reference but the proof of this particular result goes through even without this assumption.

**Corollary 3.7.** The quasi-affine variety \( V \) is multiplicatively large if and only if for some (equivalently for all) \( b \in V^* \), the only definable subgroup of \((F^*)^m\) containing \( b^{-1}V^* \) is \((F^*)^m\).

**Proof.** For the forward direction, let \( V \) be multiplicatively large and let \( M \) be a definable subgroup of \((F^*)^m\) containing \( b^{-1}V^* \) for an arbitrary \( b \in V^* \). By a well known result (see Lemma 7.4.9 of [Mar02]), \( M \) is an algebraic group. Hence \( M \), is the set of elements of \((F^*)^m\) satisfying a system of polynomials equations as in the preceding lemma. Suppose \( x_1^{k_1} \cdots x_m^{k_m} = 1 \) with \( k_1, \ldots, k_m \in \mathbb{Z} \) is one of the equation in the system. Then all \( a \in V^* \) satisfies:

\[
x_1^{k_1} \cdots x_m^{k_m} = b_1^{k_1} \cdots b_m^{k_m}.
\]

As \( V \) is multiplicatively large, \( k_1 = \ldots = k_m = 0 \). Thus, \( M = (F^*)^m \).

The reverse direction is straight forward noting that \( V \) not multiplicatively large implies that for some \( k_1, \ldots, k_m \in \mathbb{Z} \) not all zero, \( b^{-1}V^* \) for any \( b \in V^* \) satisfies \( x_1^{k_1} \cdots x_m^{k_m} = 1 \) which defines a nontrivial subgroup of \((F^*)^m\).

Suppose \( M \) is a multiplicative group and \( X_1, \ldots, X_n \) are subset of \( M \). We set \( X_1 \cdots X_n = \{ a_1 \cdots a_n : a_i \in X_i \text{ for } 1 \leq i \leq n \} \). Moreover, if \( X_1 = \ldots = X_n = X \), then we set \( X^k = X_1 \cdots X_n \).

**Lemma 3.8** (Zilber’s Indecomposability Theorem). Let \( (M; \cdot, \ldots) \) be a multiplicative group of finite Morley rank and let \( (X_i)_{i \in I} \) be a collection indecomposable definable subsets of \( M \) containing 1. Then there are \( k > 0 \) and \( i_1, \ldots, i_k \in I \) with possible repetition such that \( X_{i_1} \cdots X_{i_k} \), is the group generated by \( (X_i)_{i \in I} \).

**Proof.** See Theorem 7.3.2 of [Mar02].

**Corollary 3.9.** There is \( k > 0 \) such that \((b^{-1}V^*)^k = (b^{-1}V^*)^{k+1}\) for some \( b \in V^* \). Moreover, \( V \) is multiplicatively large if and only if for such \( k \) we also have that \((b^{-1}V^*)^k = (F^*)^m\).

**Proof.** The first is immediate from the preceding lemma noting that \( 1 \in b^{-1}V \) and \( b^{-1}V \) is indecomposable (see Exercise 7.6.13 of [Mar02]). The second statement follows from Corollary 3.5 since \((b^{-1}V^*)^k\) as in the first statement is the smallest definable subgroup of \((F^*)^m\) containing \( b^{-1}V \).
Let \( M \) be a structure in a language \( L \). Recall that a family \((X_s)_{s \in S}\) of subset of \( M^n \) is definable if \( S \subseteq M^n \) for some \( n \) is definable and there is definable \( X \subseteq M^{m+n} \) such that for all \( s \in S \), \( X_s = \{ a \in M^m : (a, s) \in X \} \). If \( M \approx M' \), then we define \((X_s')_{s \in S'} \) to be the family \((X_s')_{s \in S'} \) where \( S' = S(M') \) and for \( s \in S \), \( X'_s = \{ a' \in (M')^m : (s', s') \in X' \} \) with \( X' = X(M') \).

**Lemma 3.10.** Let \((X_s)_{s \in S}\) be an \( L_r \)-definable family of subsets of \( F^m \). Then the set \( \{ s \in S : X_s \text{ is a quasi-affine variety} \} \) is definable in \( L_r \).

**Proof.** See Theorem 10.2.1 of [Joh16]. \( \square \)

**Lemma 3.11.** Let \((V_s)_{s \in S}\) be an \( L_r \)-definable family of subsets of \( F^m \) which are varieties over \( F \). Then \( \{ s \in S : V_s \text{ is multiplicatively large} \} \) is definable in \( L_r \).

**Proof.** Let \((V_s)_{s \in S}\) be as given. We first prove that if \( F \subseteq F' \) then the family \((V_s')_{s \in S'} = (V_s)_{s \in S}(F') \) is a family of varieties over \( F' \). We note that if \( F' \subseteq F'' \), then \( V'_s \) is a quasi-affine variety over \( F' \) if and only if \( V'_s(F'') \) is a quasi-affine variety over \( F'' \). Hence, by extending \( F' \) further if needed, we can arrange that \( F' \) is sufficiently saturated. From the preceding lemma, the set

\[ S'_s = \{ s' \in S' : V'_s \text{ is a quasi-affine variety} \} \]

is definable. Moreover, any automorphism of \( F' \) fixing \( F \) also fixes \( S'_s \), so \( S'_s \) is definable over \( F' \). Suppose \( S' \setminus S'_s \neq \emptyset \). As \( F \subseteq F' \), there is \( s \in (S' \setminus S'_s) \cap F^m \). Since \( V_s \) is a quasi-affine variety over \( F \), \( V'_s = V_s(F') \) is a quasi-affine variety over \( F' \), contradiction.

For \( n > 0 \), let \( S_k \) be the set of \( s \in S \) such that for some \( b \in V_s \) we have \((b^{-1}V_s)^k = (b^{-1}V_s)^{k+1} \). Clearly, \( S_k \) is definable for all \( n > 0 \) and \( S = \bigcup_{k > 0} S_k \) by the first statement of Corollary 3.9. Suppose \( F \subseteq F' \) and \((V_s')_{s \in S'} = (V_s)_{s \in S}(F') \). As \((V_s')_{s \in S'} \) is a family of varieties over \( F' \), a similar argument yields \( S' = \bigcup_{k > 0} S'_k \) with \( S'_k \) defined similarly. It is easy to see that \( S'_k = S_k(F') \). Therefore,

\[ S(F') = \bigcup_{k > 0} S_k(F') \]

A standard compactness argument gives us \( S = S_k \) for some \( k > 0 \). The desired conclusion then follows from the second statement of Corollary 3.9. \( \square \)

**Corollary 3.12.** \((X_s)_{s \in S}\) be an \( L_r \)-definable family of subsets of \( F^m \). Then the set \( \{ s \in S : X_s \text{ is a multiplicatively large variety over } F \} \) is definable in \( L_r \). \( \square \)

**Proof of Theorem 7.2, part 2.** We show that ACFO has a \( \forall \exists \) axiomatization. Suppose \( (F; <, \mathcal{P}) \models \text{ACFO} \). We will write \( b < b' \) for \( b, b' \in (F^r)^m \) if \( b_i < b'_i \) as \( i \) ranges over \( \{1, \ldots, m\} \). From the preceding corollary and quantifier elimination of ACF, for all \( n \) and all \( \varphi \in L_r(x, y) \), there is a quantifier free formula \( \psi_{\varphi} \in L_r(y) \) which defines

\[ \{ s \in F^n : \varphi(x, s) \text{ defines a multiplicatively large variety} \} \]

On the other hand, quantifier elimination for ACF implies that for every variety \( V \) we can find \( n \), a quantifier free formula \( \varphi \in L_r(x, y) \), \( s \in F^n \) such that \( V \) is the set defined by \( \varphi(x, s) \). As a consequence, \((F; <, \mathcal{P}) \models \text{ACFO} \) if and only if for all choices of \( m, n \) and a quantifier free formula \( \varphi \in L_r(x, y) \) we have that for all \( s \in F^n \) with \( \psi_{\varphi}(s) \), for all \( b, b' \in (F^r)^m \), with \( b < b' \), there is \( a \in (F^r)^m \) with \( \varphi(a, s) \) and \( b < a < b' \). The desired conclusion follows. \( \square \)
4. Logical tameness

In this section, we use the following conventions in addition to those introduced in the first paragraphs of the preceding two sections. Let \( F \) range over the class of models of \( ACF \), let \( V \) range over the set of quasi-affine subvarieties of \( F^m \) and set

\[
V^\times = V \cap (F^x)^m.
\]

For an \( L_m \)-structure \( M \) and a subset \( A \) of \( M \), we denote by \( acl^M_\times(A) \) and \( dcl^M_\times(A) \) the model-theoretic algebraic closure and definable closure of \( A \) in \( M \); when the context is clear, we omit the superscript \( M \). The operators \( acl, acl_\times, dcl, dcl_\times \) are defined likewise. We will use the term \textit{algebraic independence} in the field-theoretic sense. If \( M \) is a multiplicative group, \( a = (a_i)_{i \in I} \) is a (possibly infinite) tuple of elements in \( M \); \( A \) a subset of \( M \), let \( (a)^M \) and \( (A)^M \) be the subgroups of \( M \) generated by \( \{a_i : i \in I\} \) and \( A \) respectively; again when the context is clear, we omit the superscript \( M \).

As \( 0 \in F^\times \), a model \((F^\times; <, \mathcal{P})\) of \( ACFO^\times \) is not an amalgam of \( F \) and \((F^\times; <, \mathcal{P})\) over \( F^\times \) in the strict sense. Hence, it is convenient to replace \( F \) by a structure expanding the multiplicative group \( F^\times \) with relations “remembering” the additive structure. For any \( m \), define the \( m \)-ary relation \( A_m \) on \( F^\times \) to be the set

\[
\{ a \in (F^\times)^m : a_1 + \cdots + a_m = 0 \}.
\]

Let \((F^\times; A)\) be the expansion of the multiplicative abelian group \( F^\times \) by the family \( A = (A_m) \) and the constant \(-1\), which we viewed as a part of \( F^\times \). Then \((F^\times; A)\) is a structure in a language \( L^\times_r \) extending the language \( L^\times_r \) of groups by adding for every \( m \) a predicate symbol for \( A_m \) and a constant symbol for \(-1\). We call \((F^\times; A)\) the \( L^\times_r \)-reduct of \( F \). This defines a functor \( \mathcal{T}_r^\times \) from \([ACF], \to \) to \(([L^\times_r], \to) \), analogus to the preceding lemma, we have:

**Lemma 4.1.** There are \( L^\times_r \)-theories \( ACFO^\times \) and \( ACFO^\times_p \) such that \([ACF^\times] = \mathcal{T}_r^\times[ACF] \) and \([ACFO^\times_p] = \mathcal{T}_r^\times[ACFO_p] \). Moreover, \( ACFO^\times \) is bi-interpretable with \( ACF \), and \( ACFO^\times_p \) is bi-interpretable with \( ACFO_p \);\( ACF^\times \) has quantifier elimination, and \( ACFO^\times_p \) is complete.

Let \((F; <, \mathcal{P})\) be a model of \( ACFO^\times \) and let \((F^\times; A)\) be the associated \( L^\times_r \)-structure of \( F \). Then \((F^\times; A; <, \mathcal{P})\) is a structure in a language \( L^\times_r \) which is the union of \( L^\times_r \) and \( L_m \). We call \((F^\times; A; <, \mathcal{P})\) the \( L^\times_r \)-reduct of \((F; <, \mathcal{P})\). This defines a functor \( \mathcal{T}_r^\times \) from \([ACFO^\times], \to \) to \(([L^\times_r], \to) \). Analogously to the preceding lemma, we have:

**Lemma 4.2.** There are \( L^\times_r \)-theories \( ACFO^\times \) and \( ACFO^\times_p \) such that we have \([ACFO^\times] = \mathcal{T}_r^\times[ACFO] \) and \([ACFO^\times_p] = \mathcal{T}_r^\times[ACFO_p] \). Moreover, \([ACFO^\times] \) is bi-interpretable with \([ACF] \), and \([ACFO^\times_p] \) is bi-interpretable with \([ACFO_p] \).

We will deduce the model completeness of \( ACFO^\times \) from that of \( ACFO^\times \). The underlying idea is to link our notion of \textit{genericity} and the translation of the notions with the same name \([CP98] \), \([Tsu01] \) and \([SS12] \) and adapt their proofs. For multiplicative abelian groups \( M \) and \( M' \) such that the former is a subgroup of the latter and \( a' \in (M')^m \), we say that \( a' \) is \textit{multiplicatively independent} over \( M \) if

\[
(a'_1)^{k_1} \cdots (a'_m)^{k_m} \notin M \text{ for all } (k_1, \ldots, k_m) \in \mathbb{Z}^m \backslash \{(0, \ldots, 0)\}.
\]

Let \((M; \ldots)\) be an \( L \)-structure with \( M \) a multiplicative abelian group. An \( L \)-definable \( X \subseteq M^m \) \textit{permits multiplicatively independence} in \( L \) if there is an \( L \)-elementary extension \((M'; \ldots)\) such that \( X(M') \) contains \( a' \) multiplicatively independent over \( M \).
Under the suitable translation, \((F;\prec,\mathcal{P}) \models \text{ACFO}^-\) with \(L^*_a\)-reduct \((F^x;\prec,\mathcal{P})\) is generic in the sense of [CP’98], [Tsu01] and [SS12] if for all \(X \subseteq (F^x)^m\) which is definable and permits multiplicative independence in \(L^*_a\) and all \(Y \subseteq (F^x)^m\) which is definable and permits multiplicative independence in \(L_m\), we have \(X \cap Y \neq \emptyset\). The link to our notion of multiplicative largeness can be easily seen:

**Lemma 4.3.** Suppose \((F^x;\mathcal{A}) \models \text{ACF}^x\) is the \(L^*_a\)-reduct of \(F\). Then \(V^x \subseteq (F^x)^m\) permits multiplicative independence in \(L^*_a\) if and only if \(V\) is multiplicatively large.

**Proof.** The forward implication is immediate from the definition and the backward implication follows easily from compactness. \(\square\)

**Corollary 4.4.** Suppose \((F^x;\mathcal{A}) \models \text{ACF}^x\) is the \(L^*_a\)-reduct of \(F\) and \(X \subseteq (F^x)^m\) is definable \(L^*_a\). Then \(X\) permits multiplicative independence in \(L^*_a\) if and only if there is multiplicatively large \(V \subseteq F^m\) such that \(V^x \subseteq X\).

**Proof.** The backward implication is immediate from the preceding lemma. Suppose \((F^x;\mathcal{A})\) is the \(L^*_a\)-reduct of \(F\) and \(X\) is as given. Then \(X\) is a restriction to \(F^m\) of an \(L_a\)-definable set in \(F\). By quantifier elimination of ACF,

\[
X = V_1^x \cup \ldots \cup V_k^x \quad \text{where} \quad V_i^x = V_i \cap (F^x)^m
\]

and \(V_i\) is a quasi-affine variety for \(i \in \{1, \ldots, k\}\). If \(X\) permits multiplicative independence, then \(V_i^x\) does so for some \(i \in \{1, \ldots, k\}\). The conclusion then follows from the preceding lemma. \(\square\)

The link to our notion of order-dense is not as straightforward. Let \((M;\prec,\mathcal{P})\) be a model of \(T_{m,p}\). A multiplicative group operation can be defined on \(M^m\) in the obvious way. For \(a, b \in M^m\), we set \(a \prec b\) if \(a_i < b_i\) for all \(i \in \{1, \ldots, m\}\). Let \(q = p^l\) with \(l \geq 1\) if \(p\) is prime and \(q = 1\) if \(p\) is zero. A set \(H \subseteq M^m\) is a \(q\)-hyper-arc if there are \(b,b' \in M^m\) and \(e \in M^m\) such that \(b \prec be, b' \prec b'e\) and

\[
H = \{a \in M^m : a \prec b', \text{ and } ae \in (\mathbb{F}_q^p)^m\}.
\]

We will show in Lemma 4.6 below that a \(L_m\)-definable \(Y \subseteq M^m\) permits multiplicative independence in \(L_m\) if and only if there is a \(q\)-hyper-arc \(H \subseteq Y\). In the special case where \(q = 1\), we simply call \(H\) a hyper-arc. It is easy to see that a set \(X \subseteq M^m\) is order-dense if and only if \(X \cap H \neq \emptyset\) for every hyper-arc \(H \subseteq M^m\).

Again we need to make use of the links between the models of \(T_{a,p}\) and \(T_{m,p}\). For additive abelian groups \(G\) and \(G'\) such that the former is a subgroup of the latter and \(\alpha'\) in \((G')^m\), we say that \(\alpha'\) is linearly independent over \(G\) if

\[
k_1\alpha'_1 + \ldots + k_m\alpha'_m \notin G \quad \text{for all} \quad (k_1, \ldots, k_m) \in \mathbb{Z}^m \setminus \{(0, \ldots, 0)\}.
\]

The above is simply a restatement of the previous definition for multiplicative independence as the difference between additive and multiplicative group is purely symbolic. Likewise, we obtain an obvious definition for permitting linear independence. Let \((G;\prec,\mathcal{D},\pm1) \models T_{a,p}\). We can view \(G^m\) as an additive group in an obvious way. For \(\alpha, \beta \in G^m\), we write \(\alpha < \beta\) if \(\alpha_i < \beta_i\) for all \(i \in \{1, \ldots, m\}\). Again, let \(q = p^l\) with \(l \in \mathbb{N}\) if \(p\) is prime and \(q = 1\) if \(p\) is zero. We call \(H \subseteq G^m\) a \(q\)-hyper-rectangle if there are \(\beta < \beta' \in G^m\) and \(\varepsilon \in G^m\) such that

\[
H = \{\alpha \in G^m : \beta < \alpha < \beta' \text{ and } \alpha + \varepsilon \in (\mathcal{D}_q)^m\}.
\]

We note the reader that the definitions of \(q\)-hyper-arc and \(q\)-hyper-rectangle are not completely parallel with the former slightly more restrictive.
Lemma 4.5. Suppose \((G; <, \mathcal{D}, \pm 1) \models T_{a,p}\) and \(Y \subseteq G^m\) is definable in \(L_a\). Then \(X\) permits linear independence in \(L_m\) if and only if there is a \(q\)-hyper-rectangle \(H \subseteq Y\).

Proof. This follows from section 3 of [Tow13].

Corollary 4.6. Suppose \((M; <, \mathcal{P}) \models T_{m,p}\) and \(X \subseteq M^m\) is definable in \(L_m\). Then \(X\) permits multiplicative independence in \(L_m\) if and only if there is a \(q\)-hyper-arc \(H \subseteq X\).

Proof. Throughout the proof, suppose \((M; <, \mathcal{P})\) and \(X\) are as given. Then by Lemma 3.2 \((M; <, \mathcal{P})\) has \(L_a\)-cover \((G; <, \mathcal{D}, \pm 1) \models T_{a,p}\). From the construction of \(L_m\)-truncation and Lemma 3.4 there is a bijection
\[
i: M \rightarrow \{\alpha \in G : 0 \leq \alpha < 1\}
\]
which induces an \(L_m\)-isomorphism between \((M; <, \mathcal{P})\) and the \(L_m\)-truncation of \((G; <, \mathcal{D}, \pm 1)\). As usual, we also denote by \(\iota\) the induced map on \(M^m\) for arbitrary \(m \geq 0\). In view of the preceding lemma, it suffices to show the following:

1. \(X\) permits multiplicative independence in \(L_m\) if and only if \(\iota(X) \subseteq G^m\) permits linear independence in \(L_a\).

2. \(H \subseteq M^m\) is a \(q\)-hyper-arc in \((M; <, \mathcal{P})\) if and only if \(\iota(H)\) is a \(q\)-hyper-rectangle in \((G; <, \mathcal{D}, \pm 1)\).

We prove the forward direction of (1) and omit the backward direction as they are very similar. Suppose \(X\) permits multiplicative independence. Then we can find an elementary extension \((M'; <, \mathcal{P})\) of \((M; <, \mathcal{P})\), a formula \(\varphi_m \in L_m(x)\) which defines both \(X\) in \((M; <, \mathcal{P})\) and \(X(M')\) in \((M'; <, \mathcal{P})\), and \(\alpha \in X(M')\) multiplicatively independent over \(M\). Again from the construction of \(L_m\)-truncation and Lemma 3.4, \((M'; <, \mathcal{P})\) has \(L_a\)-cover \((G'; <, \mathcal{D}, \pm 1) \models T_{a,p}\) and there is a bijection
\[
i': M' \rightarrow \{\alpha' \in G' : 0 \leq \alpha' < 1\}
\]
which induces an \(L_m\)-isomorphism between \((M'; <, \mathcal{P})\) and the \(L_m\)-truncation of \((G'; <, \mathcal{D}, \pm 1)\). Then \(\varphi_m\) also defines \(\iota(X)\) in the \(L_m\)-truncation of \((G; <, \mathcal{D}, \pm 1)\) and \(\iota'(X(M'))\) in \(L_m\)-truncation of \((G; <, \mathcal{D}, \pm 1)\). As the interpretation of the \(L_m\)-truncation is independent of the choice of the model, there is a formula \(\varphi_a \in L_a(x)\) which defines both \(\iota(X)\) in \((G; <, \mathcal{D}, \pm 1)\) and \(\iota'(X(M'))\) in \((G; <, \mathcal{D}, \pm 1)\). On the other hand, as \(T_a\) is a functor from \((T_{m,p}, \rightarrow)\) to \((T_{a,p}, \rightarrow)\) and \(T_a\) admit quantifier elimination, \((G; <, \mathcal{D}, \pm 1) \models L_a(G'; <, \mathcal{D}, \pm 1)\). Hence,
\[
i'(X(M')) = \iota(X)(G').
\]
Therefore \(\alpha' = \iota'(a')\) is in \(\iota(X)(G')\). Suppose \(\alpha'\) has \(k_1\alpha'_1 + \ldots + k_m\alpha'_m = \gamma\) with \(\gamma \in G\). Let \(\delta \in G\) be the unique element such that \(0 \leq \delta < 1\) and \(\gamma = \delta + l \cdot 1\) for some \(l\). We can easily check that \((a'_1)^{k_1}\ldots(a'_m)^{k_m} = \iota^{-1}(\delta)\). This implies that \(k_1 = \ldots = k_m = 0\) and so \(\alpha'\) is linearly independent over \(G\).

To get (2), we need to show for \(H \subseteq \{\alpha \in G^m : 0 \leq \alpha_i < 1\ \text{for} \ 1 \leq i \leq m\}\) and \(H\) is a \(q\)-hyper-rectangle that there are \(\beta, \beta' \in G^m\) and \(\varepsilon \in G^m\) as in the definition of \(q\)-hyper-rectangle but moreover with
\[
0 \leq \beta_i < \beta'_i < 1 \ \text{and} \ 0 < \beta_i + \varepsilon_i < \beta'_i + \varepsilon_i < 1 \ \text{for} \ i \in \{1, \ldots, m\}.
\]
The \(\beta, \beta', \varepsilon\) in the preceding statement can be chosen as a model of \(T_{a,p}\) is regularly dense (see [Tow13] for details). The checking (2) is then straight forward from the definitions. □
Proposition 4.7. The theory ACFO$^*$ is model complete and therefore has a ∀∃-axiomatization.

Proof. Let $(F^*: A, <, \mathcal{P})$ and $((F')^*: A, <, \mathcal{P})$ be arbitrary models of ACFO$^*$ such that the former is an $L^*_c$-substructure of the latter. By a standard test [Mar02 Exercise 3.4.12], it suffices to show that the former is existentially closed in the latter. We can arrange that $(F^*: A, <, \mathcal{P})$ and $((F')^*: A, <, \mathcal{P})$ are the $L^*_c$-reducts of models $(F; <, \mathcal{P})$ and $(F'; <, \mathcal{P})$ of ACFO respectively and that $(F; <, \mathcal{P})$ is an $L_c$-substructure of $(F'; <, \mathcal{P})$.

With the same settings as above, we will reduce the problem to showing $X \cap Y \neq \emptyset$ for an $L^*_c$-definable $X \subseteq (F^*)^m$ and an $L_m$-definable set $Y \subseteq (F^*)^n$ such that

$$\text{if } X' = X(F'), \ Y' = Y(F') \text{ then } X' \cap Y' \neq \emptyset.$$ 

For our purpose, if $\varphi^*(x) \in L^*_c,F^*(x)$ is quantifier free and defines a non-empty set in $((F')^*: A, <, \mathcal{P})$, we need to show that $\varphi^*(x)$ also defines in $(F^*: A, <, \mathcal{P})$ a non-empty set. As $\varphi^*$ is quantifier free, it is a disjunction of conjunctions of atomic formulas. We can easily reduce to the case where $\varphi^*$ is just a conjunction of atomic formulas. The only operations here is multiplication which belong to both $L^*_c$ and $L_m$, so it is easy to choose $X$ and $Y$ that provide the desired reduction.

Still with the same settings, we reduce the problem further to showing $X \cap Y \neq \emptyset$ for $X$ and $Y$ permitting multiplicative independence in $L^*_c$ and $L_m$ respectively. Suppose

$$X' = X(F'), \ Y' = Y(F'), \ a' \in X' \cap Y', \text{ and } M = \langle F^*, a \rangle \subseteq (F')^*.$$ 

Then the finitely generated group $M/F^*$ is a subgroup of $(F')^*/F^*$ and hence torsion free. Therefore, $M/F^*$ is isomorphic to $\mathbb{Z}^n$ as a group for some $n \geq 0$. As a consequence, we can find an $b' \in M^*$ multiplicatively independent over $F$ such that

$$a' = f(b')$$

where $f = (f_1, \ldots, f_m)$ and $f_i$ is of the form $cy_1^{k_1} \cdots y_n^{k_n}$ with $c \in F^*$ and $k_1, \ldots, k_n \in \mathbb{Z}$ for $i \in \{1, \ldots, m\}$. It is clear that $f^{-1}(X)$ and $f^{-1}(Y)$ permit multiplicative independence in $L^*_c$ and $L_m$ respectively. Moreover, if $f^{-1}(X) \cap f^{-1}(Y) \neq \emptyset$, then $X \cap Y \neq \emptyset$. Hence, we achieved the desired reduction.

Finally, we show $X \cap Y \neq \emptyset$ for $X$ and $Y$ permitting multiplicative independence in $L^*_c$ and $L_m$ respectively. By Corollary 4.4 and Corollary 4.6, it suffices to show for an arbitrary multiplicatively large quasi-affine variety $V \subseteq (F^*)^m$ and an arbitrary $q$-hyper arc $H$ that

$$V \cap H \neq \emptyset.$$ 

If either $\text{char}(F) = 0$ or $\text{char}(F) = p$ and $q = p^0 = 1$, then a $q$-hyper arc is simply a hyper arc and the desired conclusion follows from the genericity of $(F; <, \mathcal{P})$. Suppose $\text{char}(F) = p$ and $q = p^l$ for $l > 0$. By multiplicatively translating $V, H$ we can reduce to the case where

$$H = \{a \in (F^*)^m : b < a < b', \text{ and } a \in (p^0_q)^m\}$$

with $b < b'$ elements in $(F^*)^m$. Shrinking $H$ if needed we can arrange that $b$ and $b'$ are in $p^0_q$. Let Frob denotes the automorphism on $F$ mapping $a$ to $a^p$ as well as the induced automorphism on $F^m$ for arbitrary $m \geq 0$. We can then reduce to the previous case by replacing $V$ with Frob$^{-l}(V)$ and $H$ with the hyper arc

$$\{a \in (F^*)^m : a^q \in H \text{ and } a^2 \leq \ldots \leq a^q\}.$$ 

The desired conclusion thus follows.
proof of Theorem 4.3 part 1. We show that ACFO is model complete. Suppose $(F_1; <, P)$ and $(F_2; <, P)$ are models of ACFO and the former is an $L_c$-substructure of the latter. We have that $(F_1; <, P)$ is interpretable in its $L_c^+$-reduct $(F_1^+: A, <, P)$. A similar statements holds substituting by $(F_2; <, P)$ and $(F_2^+: A, <, P)$. Moreover, the interpretations can be chosen to preserve the inclusion between $(F_1; <, P)$ and $(F_2; <, P)$. The conclusion then follows from the preceding proposition. □

Next, we will show that every model of ACFO can be $L_c$-embedded into a model of ACFO. This will be deduced from a stronger result about ACFO$^+_p$ for $p$ either prime or zero. We need a quantifier elimination result for $U_{(p)}$.

Let $L_n$ be the language of multiplicative groups and let $T_{g,p}$ with $p$ either prime or zero be the class of structures $M$ in $L_n$ such that:

1. $M$ is a divisible abelian group;
2. for all $n > 0$, if $a, b \in M$ both have order $n$, then there is $k \in \{1, \ldots, n\}$ such that $a^k = b$;
3. For all $n > 0$, the number of $n$-th roots of 1 is $n/p^k$ where $p^k$ is the highest power of $p$ dividing $n$. (When $p$ is zero, the number of $n$-th roots of 1 is exactly $n$ because the highest power of 0 dividing $n$ is $0^h = 1$).

We can easily see that $T_{g,p}$ is $\exists$-axiomatizable for arbitrary $p$ and $\bigcup_{(p)} T_{g,p}$. Hence, if $F \models ACF_p$, then $F^* \models T_{g,p}$ and if $(M; <, P) = T_{m,p}$, then $M \models T_{g,p}$.  

Lemma 4.8. For $p$ either prime or 0, the theory $T_{g,p}$ has quantifier elimination and is complete.

Proof. In this proof, let $M$ and $M'$ be models of $T_{g,p}$ such that $M'$ is $|M|^+$-saturated and let $f$ be an $L_n^-$-partial isomorphism from $M$ to $M'$ (that is, $f$ is an $L_n^-$-isomorphism from an $L_n^-$-substructure of $M$ to an $L_n^-$-substructure of $M'$). By a standard test, it suffices to show that either Domain$(f) = M$ or there is an $L_n^-$-partial-isomorphism from $M$ to $M'$ which properly extends $f$.

Suppose the settings are as above and Domain$(f) \neq M$. We will describe the extensions of $f$ in different cases and leave the routine checking to the reader. If Domain$(f)$ is not a group, extend $f$ by mapping $ab^{-1}$ to $f(a)(f(b))^{-1}$. In all the remaining cases, we will describe the choices of $a \in M \setminus$ Domain$(f)$ and $a' \in M' \setminus$ Image$(f)$; the extension of $f$ is then given by

$$a^k b \mapsto (a')^k f(b) \quad \text{for } k \in \mathbb{Z} \text{ and } b \in \text{Domain}(f)$$

Consider the case when there is an $l$-th root of unity $a \in M \setminus$ Domain$(f)$ with $l$ a prime. Then clearly, $l \neq p$. By (2) in the definition of $T_{g,p}$, Domain$(f)$ and Image$(f)$ contain no $l$-root of unity other than $1$. Choose $a'$ to be a root of unity in $M' \setminus$ Image$(f)$, which must exist because of property (3) in the definition of $T_{g,p}$. The next case is when Domain$(f)$ contains all roots of unity of prime order in $M$, $l$ is a prime and $a \in M \setminus$ Domain$(f)$ is such that $a^l \in$ Domain$(f)$. As any other $l$-th root of $a'$ multiplicatively differs from $a$ by an $l$-th root of unity, Domain$(f)$ contains no $l$-th root of $a^l$. Hence, Image$(f)$ contains no $l$-th root of $f(a^l)$. Choose $a'$ an $l$-th root of $f(a^l)$ which must exist as $M$ is divisible. The last case is when Domain$(f)$ is divisibly closed in $M$, and $a \in M \setminus$ Domain$(f)$. Choose $a'$ in $M'$ multiplicatively independent over Image$(f)$ which must exist because $M'$ is $|M|^+$-saturated.

When $n$ is co-prime with $p$, the group of $n$-roots of 1 in a model of $T_{g,p}$ is cyclic of size $n$ by (2) and (3). Hence, any model of $T_{g,p}$ is a $L_n^-$-extension of a copy of $U_{(p)}$ which is a model of $T_{g,p}$. Thus, $T_{g,p}$ is complete. □
Proposition 4.9. If \((M;\mathcal{A},<,\mathcal{P})\) is an \(L^{*_c}\)-structure with \((M;\mathcal{A})\vDash \text{ACF}^*_p(\forall)\) and \((M;<,\mathcal{P})\vDash T_{m,p}(\forall)\), then \((M;\mathcal{A},<,\mathcal{P})\) can be \(L^{*_c}\)-embedded into a model of \(\text{ACF}^{*}_p\).

Proof. Throughout the proof, suppose \((M;\mathcal{A},<,\mathcal{P})\) is as in the statement of the lemma. We first show that \((M;\mathcal{A},<,\mathcal{P})\) can be \(L^{*_c}\)-embedded into \((F^*;\mathcal{A},<,\mathcal{P})\) such that \((F^*;\mathcal{A})\vDash \text{ACF}^*_p\) and \((F^*;<,\mathcal{P})\vDash T_{m,p}(\forall)\). Clearly, there is \((F^*;\mathcal{A})\vDash \text{ACF}^*_p\) extending \((M;\mathcal{A})\) as an \(L^{*_c}\)-structure. We can also find \((N,<,\mathcal{P})\vDash T_{m,p}\) which is \(|F|^+\)-saturated and extend \((M;<,\mathcal{P})\) as an \(L_m\)-structure. By the remark just before the preceding lemma, we have that:

\[
F^* \vDash T_{g,p} \quad \text{and} \quad N \vDash T_{g,p}.
\]

Since \(T_{g,p}\) has quantifier elimination and \(N\) is \(|F|^+\)-saturated, \(F^*\) can be embedded as \(L_g\)-structure into \(N\) over \(M\). We can then equip \(F^*\) with relations \(<\) and \(\mathcal{P}\) by pullback. It is easy to see that \((F^*;\mathcal{A},<,\mathcal{P})\) has the desired properties by construction.

We next show that \((M;\mathcal{A},<,\mathcal{P})\) can be \(L^{*_c}\)-embedded into \((F^*;\mathcal{A},<,\mathcal{P})\) with \((F^*;\mathcal{A})\vDash \text{ACF}^*_p\) and \((F^*;<,\mathcal{P})\vDash T_{m,p}\).

We observe that a similar construction as in the preceding paragraph allow us to obtain \((M';\mathcal{A},<,\mathcal{P})\) \(L^{*_c}\)-extending \((M;\mathcal{A},<,\mathcal{P})\) such that \((M';\mathcal{A})\vDash \text{ACF}^*_p(\forall)\) and \((M';<,\mathcal{P})\vDash T_{m,p}\). We also remind the reader that both \(\text{ACF}^*_p\) and \(T_{m,p}\) have \(\forall\)-axiomatization. Therefore, to obtain the desired \((M';\mathcal{A},<,\mathcal{P})\), we alternate the construction in the preceding paragraph and the construction in the observation and take union.

Let \((F^*;\mathcal{A},<,\mathcal{P})\) be an \(L^{*_c}\)-structure with \((F^*;\mathcal{A})\vDash \text{ACF}^*_p\), \((F^*;<,\mathcal{P})\vDash T_{m,p}\). Suppose \(L^{*_c}\)-definable set \(X \subseteq (F^*)^m\) and \(L_m\)-definable set \(Y \subseteq (F^*)^m\) permits multiplicative independence in \(L^{*_c}\) and \(L_m\) respectively. We construct an \(L^{*_c}\)-extension \(((F')^*;\mathcal{A},<,\mathcal{P})\) of \((F^*;\mathcal{A},<,\mathcal{P})\) such that

\[
((F')^*;\mathcal{A})\vDash \text{ACF}^*_p, ((F')^*;<,\mathcal{P})\vDash T_{m,p} \quad \text{and} \quad X((F')^*) \cap Y((F')^*) \neq \emptyset.
\]

By given conditions of \(X\) and \(Y\), we can find \((N_1;\mathcal{A})\) elementarily extending \((F^*;\mathcal{A})\) and \((N_2;<,\mathcal{P})\) elementarily extending \((F^*;<,\mathcal{P})\) with \(a' \in X(N_1)\) and \(b' \in X(N_2)\) such that \(a', b'\) are multiplicatively independent over \(M\). Then there is a unique multiplicative \(L_g\)-isomorphism

\[
i : (F^*, a') \to (F^*, b')
\]

fixing \(F^*\) and mapping \(a'\) to \(b'\). We equip \((F^*, a')\) with \(<\) and \(\mathcal{P}\) by pullback. Hence,

\[
((F^*, a');\mathcal{A})\vDash \text{ACF}^*_p(\forall) \quad \text{and} \quad (F^*(a');<,\mathcal{P})\vDash T_{m,p}(\forall).
\]

Then \(((F^*, a');\mathcal{A},<,\mathcal{P})\) can be \(L^{*_c}\)-embedded into \(((F')^*;\mathcal{A},<,\mathcal{P})\) with \(((F')^*;\mathcal{A})\vDash \text{ACF}^*_p\) and \(((F')^*;<,\mathcal{P})\vDash T_{m,p}\) by the preceding paragraph. We note that \(a'\) is in \(X((F')^*)\) because \(\text{ACF}^*_p\) has quantifier elimination and \(a'\) is in \(Y((F')^*)\) because \(T_{m,p}\) has quantifier elimination. Therefore \(X((F')^*) \cap Y((F')^*) \neq \emptyset\) as desired.

The main statement of the lemma follows from an application of the construction of the second paragraph, then repeated applications of the construction of the preceding paragraph for suitable choices of \(X, Y\) and taking union. \(\square\)
Proof of Theorem 4.3. Part 2. We show that an arbitrary model of ACFO\(^\kappa\) can be \(L_\kappa\)-embedded into a model of ACFO. Suppose \((F;\prec,P)\) is a model of ACFO\(^\kappa\). Then for some \(p\),

\[(F^p;A) \models ACFO^\kappa_p\] and \((F^\prec;\prec,P) \models T_{m,p}(\forall)\).

By the preceding lemma, \((F^p;A,\prec,P)\) can be \(L_\kappa^p\)-embedded into a model \(((F^\prime)^p;A,\prec,P)\) of ACFO\(^\kappa\). By replacing 0 of \(F^\prime\) if necessary, we can arrange that \((F;\prec,P)\) is \(L_\kappa\)-embeddable into \((F^\prime;\prec,P) \models ACFO_p\).

Toward proving that ACFO is the model completion of ACFO\(^\kappa\), the last component is showing that ACFO\(^\kappa\) has the amalgamation property.

**Lemma 4.10.** Let \(F = ACF\) be \(\kappa^+\)-saturated and \(a, b, c\) tuples of element in \(F\) of size \(\kappa\). If \(a\) is algebraically independent over \(b\), then there is \(a'\) algebraically independent over \(b, c\) such that \(tp_r(a', b) = tp_r(a, b)\).

**Proof.** Suppose \(F, a, b, c\) are as given. We can arrange that \(a\) is a finite tuple. As ACF is stable, we can find \(a'\) such that \(tp_r(a' | b, c)\) is the non-forking extension of \(tp_r(a | b)\). By characterization of forking in ACF, \(trdeg(a | b, c) = trdeg(a | b)\). The conclusion thus follows.

**Lemma 4.11.** Suppose \((M;\prec,P) \models T_{m,p}\), \(a \in M\) and \(b\) is a tuple of elements in \(M\). Then \(a \in acl_m(b)\) if and only if \(a\) is multiplicative dependent over \(b\).

**Proof.** For the forward direction, let \((M;\prec,P), a, b\) be as given and \(a \in acl_m(b)\). We can arrange that \(b\) is a multiplicatively independent tuple of elements of length \(n\). By assumption, we can find \(\varphi \in L_n(x, y)\) such that \(a\) is an element of the finite set defined by \(\varphi(x, b)\). We moreover arrange that for all \(b' \in M^n\), the set defined by \(\varphi(x, b')\) has finitely many elements. Hence, the set defined by \(\varphi(x, y)\) in \((U_p;\prec,P)\) viewed as a \(L_m\)-substructure of \((M;\prec,P)\) does not contain a \(q\)-hyperarc. By Corollary 4.6, \((a, b)\) is not multiplicatively independent over \(U_p\). As \(b\) is multiplicatively independent, \(a\) is multiplicatively dependent over \(b\). The backward direction is immediate.

**Lemma 4.12.** Let \((M;\prec,P) \models T_{m,p}\) be \(\kappa^+\)-saturated and \(a, b, c\) be tuples of element in \(F\) of size \(\kappa\). If \(a\) is multiplicatively independent over \(b\), then there is \(a'\) multiplicatively independent over \(b, c\) such that \(tp_m(a', b) = tp_m(a, b)\).

**Proof.** Suppose \((M;\prec,P), a, b, c\) are as given. We can arrange that \(a\) is a tuple indexed by an ordinal \(\alpha\). For \(\alpha = 0\), there is nothing to prove so we first consider the case \(\alpha = 1\). By the preceding lemma, \(a \notin acl_m(b)\). By compactness and \(\kappa\)-saturation of \(M\), there is \(a'\) such that \(tp_m(a', b) = tp_m(a, b)\) and \(a \notin acl_m(b, c)\).

Suppose we have proven the statement for all \(\beta < \alpha\). The case where \(\alpha\) is a limit ordinal is immediate, so suppose \(\alpha = \beta + 1\). Then \(a = (a_{<\beta}, a_\beta)\). By induction hypothesis, there is \(a'_{<\beta}\) such that \(a'_{<\beta}\) is multiplicatively independent over \((b, c)\) and

\[tp_m(a_{<\beta}, b) = tp_m(a'_{<\beta}, b)\]

As \((M;\prec,P)\) is \(\kappa^+\)-saturated, we can find \(a'_p \in M\) such that

\[tp_m(a', b) = tp_m(a, b)\] with \(a' = (a'_{<\beta}, a'_\beta)\).

We can arrange to have \(a'_p\) multiplicatively independent over \((a'_{<\beta}, b, c)\) by the preceding paragraph. The conclusion follows.
A theory $T$ in a language $L$ has the **disjoint amalgamation property** if for all $M,M_1,M_2 \models T$ such that $M_1,M_2$ extends $M$, we can find $M' \models T$ and $L$-embeddings $\iota : M \rightarrow M'$, $\iota_1 : M_1 \rightarrow M'$ and $\iota_2 : M_2 \rightarrow M'$ such that $\iota_1, \iota_2$ extends $\iota$ and $\iota_1(M_1) \cap \iota_2(M_2) = \iota(M)$.

**Proposition 4.13.** $\text{ACFO}^*$ has the disjoint amalgamation property.

**Proof.** Throughout this proof, suppose $(F_1;\langle \cdot , \cdot \rangle),(F_2;\langle \cdot , \cdot \rangle)$ are models of $\text{ACFO}^*$ extending $(F;\langle \cdot , \cdot \rangle) \models \text{ACFO}^*$ as $L_c$-structures. We construct a model $(F^*;\langle \cdot , \cdot \rangle)$ of $\text{ACFO}^*$ and $L_c$-embeddings $\iota, \iota_1$ and $\iota_2$ as in the above definition.

As $\text{ACF}$ has quantifier elimination and hence has amalgamation property, we can find an algebraically closed field $K$ extending $F$ and $L_c$-embeddings $f : F \rightarrow K$, $f_1 : F_1 \rightarrow K$ and $f_2 : F_2 \rightarrow K$ such that $f_1, f_2$ extend $f$. We will replace $K, f_1$ and $f_2$ if necessary to also have that
\[ f_1(F_1) \cap f_2(F_2) = f(F), \]
and so $f_1(F^*_1) \cap f_2(F^*_2) = f(F^*)$.

We can arrange that $K$ is sufficiently saturated and $f, f_1, f_2$ are identity map. Let $a$ be an transcendence basis of $F_1$ over $F$. By Lemma 4.10, we can find $a'$ algebraically independent over $F_2$ realizing the same type as $a$ over $F$. Let $F^*_1$ be the algebraic closure in the field sense of $a'$. Then there is an $L_c$-isomorphism
\[ r : F_1 \rightarrow F^*_1 \]
which is identity on $F$ and maps $a$ to $a'$. If $a'$ is a finite tuple, we have $F^*_1 \cap F_2 = F$ because algebraic independence satisfies exchange properties. In general, we still have $F^*_1 \cap F_2 = F = F^*_1$ is the union of the algebraic closures of finite sub-tuples of $a'$. Replace $\text{id} : F_1 \rightarrow K$ by $\text{id} \circ r : F_1 \rightarrow K$ we achieve $f_1(F_1) \cap f_2(F_2) = f(F)$.

We also have that there is $N = T_m$ extending $(F^*;\langle \cdot , \cdot \rangle)$ as $L_m$-structure and $L_m$-embedding $g : F^* \rightarrow N$, $g_1 : F^*_1 \rightarrow N$ and $g_2 : F^*_2 \rightarrow N$ such that $g_1, g_2$ extends $g$ and
\[ g_1(F^*_1) \cap g_2(F^*_2) = g(F^*). \]

The proof is the same as the above proof but use multiplicative independence instead of algebraic independence and Lemma 4.12 instead of 4.10.

Keeping the notations as in the preceding two paragraph, we have that
\[ (f_1(F^*_1), f_2(F^*_2)) \models_{L_A} (g_1(F^*_1), g_2(F^*_2)) \]
where the former is the subgroup of $K^*$ generated by $f_1(F^*_1), f_2(F^*_2)$ and the latter is the subgroup of $N$ generated by $g_1(F^*_1), g_2(F^*_2)$. This allows us to equip an $L^*_{c}$-structure on $M = \langle f_1(F^*_1), f_2(F^*_2) \rangle$ with $A$ defined by restriction from the $L^*_{c}$-reduct $(K^*:A)$ of $K$ and $\langle \cdot , \cdot \rangle$ defined by pullback. By construction,
\[ (M;A) \models \text{ACFO}^*_c(\forall) \quad \text{and} \quad (M;\langle \cdot , \cdot \rangle) \models T_{m,p}(\forall). \]
Therefore, by 4.19, we can find a $L^*_{c}$-reduct $((F')^*:A,\langle \cdot , \cdot \rangle)$ of $(F^*;\langle \cdot , \cdot \rangle) \models \text{ACFO}$ and an $L^*_{c}$-embedding $j^*$ from $(M;A,\langle \cdot , \cdot \rangle)$ into $((F')^*:A,\langle \cdot , \cdot \rangle)$. Set
\[ \iota^* = j^* \circ (f \upharpoonright F^*), \quad \iota_1^* = j^* \circ (f_1 \upharpoonright F^*_1) \quad \text{and} \quad \iota_2^* = j^* \circ (f_2 \upharpoonright F^*_2). \]
Clearly, $\iota^*_1, \iota^*_2$ extends $\iota^*$ and $\iota^*_1(F^*_1) \cap \iota^*_2(F^*_2) = \iota^*(F^*)$. We can easily extends them to obtain $\iota, \iota_1, \iota_2$ with the desired properties. \hfill $\square$

**Proof of Theorem** 4.3 part 3. By a standard test (see Exercise 3.4.14 of [Mar02]), the preceding proposition together with part 1 and 2 of the proof implies that $\text{ACFO}$ is the model completion of $\text{ACFO}^*$. \hfill $\square$
For the rest of the section, \( z = (z_1, \ldots, z_k) \) is a \( k \)-tuple of variables with \( k > 0 \) and \( t \) is a single variable. We deduce the last part of Theorem \([L.3]\) from a description of definable sets in a model of ACFO*. A formula \( \varphi^* \in L^*_c(x) \) is a special formula associated to \( P \in \mathbb{Z}[z,t] \) if it has the form
\[
\exists z (z_1 < \ldots < z_k \land \rho P(x,z) \land \varphi^*_c(x,z) \land \varphi_m(x,z))
\]
where \( \varphi^*_c \) is in \( L_c(x,z) \), \( \varphi_m \) is in \( L_m(x,z) \), and \( \rho P(x,z) \) is a formula in \( L_r(x,z) \) such that for all \( a \in (F^*)^m \) and \( c \in (F^*)^k \), \( \rho P(a,c) \) if and only if \( c_1, \ldots, c_k \) are the only zeros of \( P(t,a) \) in \( F^* \). The latter has a first-order expression as we can define the multiplicity of a root of \( P \) using derivations of \( P \) and ACFO* is bi-interpretable with ACFO.

**Lemma 4.14.** Let \((F;<,\mathcal{P})\) and \((F';<,\mathcal{P}')\) be models of ACFO* with \( L^*_c\)-reducts \((F^*:A,<,\mathcal{P})\) and \((F'^*:A,<,\mathcal{P}')\) respectively. Suppose \( a \in (F^*)^m \) and \( a' \in (F'^*)^m \) are such that \( F;<,\mathcal{P};a) \models \varphi^*(a) \) implies \((F';<,\mathcal{P};a') \models \varphi^*(a') \) for all special formulas \( \varphi^* \in L^*_c(x) \). Then there is an \( L_c\)-isomorphism from \((\acl(a);<,\mathcal{P})\) to \((\acl(a');<,\mathcal{P}')\) sending \( a \) to \( a' \).

**Proof.** Suppose the notations are as given. It is easy to see that \( F \) and \( F' \) have the same characteristic. Choose a sequence \((P_l)_{l>0}\) of polynomials in \( \mathbb{Z}[t,x]\) such that defining \( Z^*_l,F \) for \( l > 0 \) to be the set of zeros of \( P_l(t,a) \) in \( F^* \), we have that
\[
\bigcup_{l>0} Z^*_l,F = \acl(a)\{0\} \quad \text{and} \quad Z^*_l,F \subseteq Z^*_{l+1,F} \text{ for all } l > 0.
\]
Define \( Z^*_l,F \), similarly for \( l > 0 \). From the hypothesis, for any \( l > 0 \), there is a unique map \( f^*_l : Z^*_l,F \to Z^*_l,F' \) such that \( f^*_l \) respect the restriction of the graph of multiplication and the relations \( A, <, \) and \( \mathcal{P} \). For \( l' \in \mathbb{N}^+ \), we have that \( f^*_l \) extends \( f^*_l \) which is constructed similarly. Then \( f^* = \bigcup_{l>0} f^*_l \) is an \( L^*_c\)-embedding sending \( a \) to \( a' \). It is also easy to see that \( \image(f^*) \cup \{0\} \) is algebraically closed in \( F' \). Hence, \( f^* \) can be extended to an \( L_c\)-isomorphism as desired. \( \square \)

**Proposition 4.15.** Every formula in \( L^*_c(x) \) is equivalent to a disjunction of special formulas in \( L^*_c(x) \) across all models of ACFO*.

**Proof.** We note that if \((F;<,\mathcal{P}) \models \text{ACFO} \) and \( a \in (F^*)^m \), then \((\acl(a);<,\mathcal{P})\) is a model of ACFO*. By a standard test, the preceding lemma, the bi-interpretability between ACFO and ACFO*, and the previous parts of theorem \([L.3]\) every formula in \( L^*_c(x) \) is equivalent to a positive boolean combination of special formulas in \( L^*_c(x) \) across all models of ACFO. The conclusion follows the observation that if \( \varphi_P \) and \( \varphi_Q \) are special formulas associated to \( P \) and \( Q \), then \( \varphi_P \land \varphi_Q \) is equivalent to a disjunction of special formulas associated to \( PQ \). \( \square \)

**Proof of Theorem \([L.3]\) part 4.** We show that in a fixed \((F;<,\mathcal{P}) \models \text{ACFO} \), definable sets are one-to-one coordinate projections of quantifier-free definable sets. We note that the collection of the latter contains \( \{0\} \) and for every \( m \) the subsets of \( (F^*)^m \) which are defined by special formulas in the \( L^*_c\)-reduct \((F^*:A,<,\mathcal{P})\) of \((F;<,\mathcal{P})\); moreover this collection is closed under finite disjunction and Cartesian product. The desired conclusion then follows from the preceding proposition and the bi-interpretability between ACFO and ACFO*. \( \square \)

**Proof of Corollary \([L.4]\)** The forward direction follows by applying Lemma \([L.14]\) when \( a \) is the empty tuple. The backward direction follows from Theorem \([L.3]\) noting that if \((F;<,\mathcal{P}) \models \text{ACFO} \) then \((\abs(F);<,\mathcal{P}) \models \text{ACFO}^a \). \( \square \)
The above leads to trying to understand \( \text{Abs}(F; <, \mathcal{P}) \) in \( (F; <, \mathcal{P}) \models \text{ACFO} \). There are some good answers in the case where \( \text{char}(F) \) is prime.

**Proof of Proposition 1.3.** Suppose \( (F; <, \mathcal{P}) \models \text{ACFO} \) has \( \text{char}(F) = p \neq 0 \). In this case \( \text{Abs}(F) = \text{acl}_t(F_p) \) and hence \( \text{Abs}^+(F) = \text{acl}_m(\emptyset) \) in \( F^\times \). As the \( T_{a,p} \)-model \( (\mathbb{Z}(p); <, \mathcal{D}, \pm 1) \) is uniquely \( L_a \)-embeddable into any model of \( T_{a,p} \) and \( \mathcal{F}_m \) is functorial, there is a map \( \delta : \mathbb{U}(p) \to F^\times \) which is an \( L_m \)-embedding of \( (\mathbb{U}(p); <, \mathcal{P}) \) into \( (F^\times; <, \mathcal{P}) \). The image \( \delta(\mathbb{U}(p)) \) is precisely \( \text{acl}_m(\emptyset) \). Therefore \( (\text{Abs}^+(F); <, \mathcal{P}) \) is \( L_m \)-isomorphic to \( (\mathbb{U}(p); <, \mathcal{P}) \) via the isomorphism \( \delta^{-1} : \text{Abs}(F) \to \mathbb{U}(p) \). This is the same as saying \( (\text{Abs}(F); <, \mathcal{P}) \) is the standard model correspond to \( \text{Abs}(F) \) and the character map \( \iota \circ \delta^{-1} \) where \( \iota \) is the canonical embedding of \( \mathbb{U}(p) \) into \( \mathbb{C} \). The remaining part of the statement follows from Theorem 1.3. \( \square \)

Let \( p \) be prime. For each \( n > 0 \), let \( \Phi_{p,n} \in \mathbb{Z}[x] \) with \( |x| = 1 \) be the \( p^n - 1 \)-th cyclotomic polynomial. Viewed as an element of \( F_p[x] \) with \( |x| = 1 \) in an obvious way, \( \Phi_{p,n} \) factors into \( \varphi(p^n - 1)/n \) monic irreducible polynomials, each of degree \( n \), in \( F[p][x] \) where \( \varphi \) is the Euler totient. We will call each of the irreducible component an \( (p, n) \)-cyclotomic factor. Suppose \( \Psi = (\Psi_n)_{n>0} \) with \( \Psi_n \) a \( (p, n) \)-cyclotomic factor for \( n > 0 \). We say that \( \Psi \) is a coherent sequence of \( (p, n) \)-cyclotomic factors if for all \( n, n' \in \mathbb{N} \) with \( 0 < n < n' \), for all roots \( a \) of \( \Psi_n \) in \( F_p \), there is a root \( a' \) of \( \Psi_{n'} \) in \( F_{p^{n'}} \) such that with

\[
a = (a')^k \quad \text{where} \quad k = \frac{p^{n'} - 1}{p^n - 1}.
\]

We denote by \( \text{Coh}_p \) the set of all coherent sequences of \( (p, n) \)-cyclotomic factor.

Suppose \( F \) is the algebraic closure of \( F_p \), \( \chi : F^\times \to \mathbb{C} \) is an injective multiplicative preserving map and \( (F; <, \mathcal{P}) \) is the associated standard model. Let \( a_n \) be the smallest \( p^n - 1 \)-th root of unity with respect to < and \( \Psi_n \) the monic minimal polynomial of \( a_n \). Then \( \Psi_{F,\chi} = (\Psi_n)_{n>0} \) is a coherent sequence of \( (p, n) \)-cyclotomic factors. If \( (F'; <, \mathcal{P}) \) is a standard model given by \( \chi' : (F')^\times \to \mathbb{C} \) and is isomorphic to \( (F; <, \mathcal{P}) \), then the similarly defined \( \Psi_{F';\chi'} \) is the same as \( \Psi_{F,\chi} \). Let \( \text{Elec}_p \) be the collection of isomorphism classes of standard models \( (F; <, \mathcal{P}) \). We note that this is also the collection of elementary equivalence classes of \( \text{ACFO}_p \) by Corollary 1.3.

The above define a map \( \text{Inv} : \text{Elec}_p \to \text{Coh}_p \). We have that:

**Proposition 4.16.** The map \( \text{Inv} : \text{Elec}_p \to \text{Coh}_p \) is a bijection.

**Proof.** Suppose \( \Psi = (\Psi_n)_{n>0} \) is a coherent sequence of \( (p, n) \)-cyclotomic factors. By Konig’s lemma we can choose a sequence \( (a_n)_{n>0} \) such that for all \( n > 0 \), \( a_n \) is a solution of \( \Psi_n \) in \( F_{p^n} \) of \( a_n \) and the relationship between \( a_n \) and \( a_{n'} \) is as specified in the above equation. Let \( F \) be the algebraic closure of \( F_p \), define \( \chi : F^\times \to \mathbb{C} \) by mapping \( a_n \) to the smallest \( (p^n - 1) \)-th root of unity in \( \mathbb{T} \) with respect to < on \( \mathbb{T} \). We can check that \( \Psi_{F,\chi} = \Psi_{F,\chi} \).

Suppose \( (F; <, \mathcal{P}) \) and \( (F'; <, \mathcal{P}) \) has \( \Psi_{F',\chi'} = \Psi_{F,\chi} \). Let \( (a_n)_{n>0} \) be the sequence of smallest \( p^n - 1 \)-th root in \( (F; <, \mathcal{P}) \) and \( (a'_n)_{n>0} \) defined likewise for \( (F'; <, \mathcal{P}) \). Then as \( \Psi_{F',\chi'} = \Psi_{F,\chi} \), there is a unique field isomorphism \( \iota : F \to F' \) mapping \( a_n \to a'_n \) for \( n > 0 \). We can check that under \( \iota \), \( \chi \) maps to \( \chi' \) and therefore \( (F; <, \mathcal{P}) \) and \( (F'; <, \mathcal{P}) \) are isomorphic. \( \square \)
We understand the case where \( p \) is zero much less. However, we still have:

**Proposition 4.17.** If \( (F; <, \mathcal{P}) \models \text{ACFO}_0 \) then \( (\text{Abs}(F); <, \mathcal{P}) \models \text{ACFO}_{\mathcal{O}} \).

**Proof.** Suppose \( (F; <, \mathcal{P}) \) is as given. As every model of \( \text{ACFO}^+ \) is embeddable into a model of \( \text{ACFO} \) by Theorem 1.3, we can arrange that \( (F; <, \mathcal{P}) \not\models \text{ACFO} \). The case where \( \text{char}(F) = p \) is covered in the preceding proof, so we assume \( \text{char}(F) = 0 \). Let \( (G; <, \mathcal{D}, \pm 1) \) be the \( L_{a,0} \)-cover of \( (F^\times; <, \mathcal{P}) \). It suffices to check that \( (G; <, \mathcal{D}, \pm 1) \models T_{a,0} \) or in other words, all \( (k,a) \) with \( a \in F^\times \) is \( n \)-divisible in \( G \). We can arrange that \( 0 \leq k < n \). The equation \( x^n = a \) has exactly \( n \) solutions \( c_1, \ldots, c_n \). Therefore, for some \( i \in \{1, \ldots, n\} \), we must have \( n \cdot (0, c_i) = (k,a) \). The conclusion follows. \( \square \)

We next prove decidability results about ACFO and ACFO\(_p\) for arbitrary \( p \).

**Lemma 4.18.** The classes ACFO and ACFO\(_p\) for an arbitrary \( p \) have recursively axiomatization.

**Proof.** We first prove that the set of statements true in all models of \( T_a \) is recursive. For arbitrary \( p \), \( T_{a,p} \) is recursively axiomatizable and complete and hence the set of statements true in all models of \( T_{a,p} \) is recursive. The set of statements true in all models of \( T_a \) is recursively enumerable as \( T_a \) has a recursive axiomatization. On the other hand, a statement is not true in all models of \( T_a \) if and only if it is not true in some model of \( T_{a,p} \). Hence, this set is also recursively enumerable as well. Thus, the set of statements true in all models of \( T_a \) is recursive.

We proves the main statement of the lemma. Since every model of \( T_m \) is interpretable in a model of \( T_a \), therefore the set of statements true in all models of \( T_m \) is also recursive. It is well known that ACF has a recursive axiomatization. Therefore \( \text{ACFO}^- \) is recursively axiomatizable. The schema in part 2 of the proof of theorem 1.2 is also recursively axiomatizable. Thus, ACFO is recursively axiomatizable. It follows that \( \text{ACFO}_p \) also have recursive axiomatization. \( \square \)

Let \( M \) be a multiplicative group. Suppose \( c \) is in \( M^k \). Let \( S_c \) be the set of \( i \in \{1, \ldots, k\} \) such that \( c_i \) is multiplicatively dependent over \( c_1, \ldots, c_{i-1} \). Again, \( z = (z_1, \ldots, z_k) \). For \( i \in S_c \), let \( \varepsilon_i(z) \) be the equation \( z_i^{l_i} \cdots z_k^{l_k} = z_i^{l_i'} \cdots z_k^{l_k'} \) satisfied by \( a \) such that for all \( j \in \{1, \ldots, i\} \), \( l_j \geq 0 \), \( l_j' = 0 \), and \( l_i > 0 \) is chosen to be smallest possible. Set \( \theta \in L_m(z) \) to be the formula \( \bigwedge_{i \in S_c} \varepsilon_i(z) \). We call the above \( \theta \) the **multiplicative dependence pattern** of \( c \). We also denote by \( \theta \) the obvious interpretations of the above multiplicative dependence pattern in \( L_m, L^*_m, L_t, L^*_c \) and \( L_e \). The following lemma is an immediate observation:

**Lemma 4.19.** Suppose \( M, M' \) are multiplicative groups and \( c \in M^k, c' \in (M')^k \) are such that \( c \) and \( c' \) have the same multiplicative dependence pattern. Then \( \langle c \rangle \equiv_{L_e} \langle c' \rangle \)

where the former is the subgroup of \( M \) generated by \( c \) and the later is defined for \( c' \) and \( M' \). \( \square \)
Suppose $P \in \mathbb{Z}[t]$ is non-zero. Let $c_1, \ldots, c_k$ be all the non-zero roots of $P$ in a field $K$. For a permutation $\sigma$ in $S_k$, set $c_{\sigma} = (c_{\sigma(1)}, \ldots, c_{\sigma(k)})$. Then define $\Theta_P(K)$ to be the set of multiplicative dependence patterns of $c_{\sigma}$ as $\sigma$ ranges over $S_k$. Clearly, $\Theta_P(K) = \Theta_P(K)$ for fields $K, K'$ such that $K \cong_{L_i} K'$. Define $\Theta_P(ACF_p)$ to be $\Theta_P(F) = \mathbb{A}_F$.

**Lemma 4.20.** There is an algorithm which compute for given $p$ and given non-zero $P \in \mathbb{Z}[t]$ the set $\Theta_P(ACF_p)$.

**Proof.** We first show for fixed prime $p$ that there is an algorithm which compute for given non-zero $P \in \mathbb{Z}[t]$ the set $\Theta_P(ACF_p)$. Suppose $P$ has degree $k \geq 0$. We observe that $\Theta_P(ACF_p) = \Theta_P(\mathbb{F}_q)$ where $q = p^k$. Choose a $\xi$ be a primitive root of unity in $\mathbb{F}_q$. We note that any non-zero root of $P$ in $\mathbb{F}_q$ can be written as power of $\xi$. From here we can find $\Theta_P(\mathbb{F}_q)$. It is easy to see that all the above steps can be carried out algorithmically.

It remains to show that there is an algorithm which compute for given non-zero $P \in \mathbb{Z}[t]$ the set $\Theta_P(ACF_0)$. We will first describe a pseudo algorithm and then argue that the steps of this can be done algorithmically. Find the splitting field $K$ of $P$ over $\mathbb{Q}$. Let $c_1, \ldots, c_k$ be the non-zero roots of $P$ in $K$. It is easy to see that $\Theta_P(ACF_0) = \Theta_P(K)$. Moreover, computing $\Theta_P(K)$ can be reduced to the problem of finding a set of generator for the additive group $\{(l_1, \ldots, l_k) \in \mathbb{Z}^k : c_1^{l_1} \cdots c_k^{l_k} = 1\}$ through solving linear equations over $\mathbb{Z}$.

We consider an intermediate problem of finding a set of generators for the additive group $\{(l_1, \ldots, l_k) \in \mathbb{Z}^k : c_1^{l_1} \cdots c_k^{l_k} \text{ is a unit in } \mathcal{O}_K\}$. Find a finite set of prime ideals $p_1, \ldots, p_m$ of the ring of integers $\mathcal{O}_K$ which consists of all the prime ideals in the factorizations of the fractional ideals $(c_1), \ldots, (c_m)$. For $i \in \{1, \ldots, m\}$, let $v_i : K^* \to \mathbb{Z}$ be the valuation associated to $p_i$. We obtain the desired set of generators by solving the system of $m$ equations where the $i$-th equation is $l_1v_i(c_1) + \cdots + l_kv_i(c_k) = 0$ for $i \in \{1, \ldots, m\}$.

We note that the group $\{(l_1, \ldots, l_k) \in \mathbb{Z}^k : c_1^{l_1} \cdots c_k^{l_k} = 1\}$ is a subgroup of the group $\{(l_1, \ldots, l_k) \in \mathbb{Z}^k : c_1^{l_1} \cdots c_k^{l_k} \text{ is a unit in } \mathcal{O}_K\}$. The later is isomorphic to $\mathbb{Z}^{k'}$ with $k' \geq 0$. Hence, after a change of basis and using the preceding paragraph we can reduce to the following problem: for given $d_1, \ldots, d_{k'}$ in the unit group of $\mathcal{O}_K$, find a set of generators of the additive group $\{(l_1, \ldots, l_{k'}) \in \mathbb{Z}^{k'} : (d_1)^{l_1} \cdots (d_{k'})^{l_{k'}} = 1\}$.

Choose $u_1, \ldots, u_n, u_{n+1}$ be a set of generator of the unit group of $\mathcal{O}_K$ such that $u_1, \ldots, u_n$ are multiplicative independent and $u_{n+1}$ generates the group of roots of unity in $K$. Suppose for $i \in \{1, \ldots, k'\}$, we have $d_i = u_1w_1(d_i)u_1 \cdots u_nw_{n+1}(d_i)$ with $w_1(d_i), \ldots, w_{n+1}(d_i) \in \mathbb{Z}$. We obtain the desired set of generators by solving the system of $n+1$ equations where the $i$-th equation is $l_1w_1(d_i) + \cdots + l_{k'}w_{k'}(d_{k'}) = 0$ and the $(n+1)$-th equation is $l_1w_{n+1}(d_1) + \cdots + l_{k'}w_{n+1}(d_{k'}) \equiv 0 \pmod{h}$ where $h$ is the order of $u_{n+1}$.

We note that the all the above steps can be done algorithmically. The non-trivial steps include: finding $K$, finding $\mathcal{O}_K$ in $K$, finding $p_1, \ldots, p_m$ in $K$, finding $v_i(c_j)$ for $i \in \{1, \ldots, m\}$ and $j \in \{1, \ldots, k\}$ as in the third paragraph, and finding $u_1, \ldots, u_n, u_{n+1}$ as in the forth paragraph. These are standard results of computational algebraic number theory which can be found in [Coh93, 4.2, 4.6, 4.8, 6.5] □
Lemma 4.21. Suppose \( \exists z (z_1 < \ldots < z_k \land \rho_p(z) \land \varphi_r(z) \land \varphi_m(z)) \) is a special statement associated to \( P \in \mathbb{Z}[t] \) and \( \theta \in L_q(z) \) is a multiplicative dependence pattern. Then for all \( p \), the following are equivalent:

1. The statement \( \exists z (\theta(z) \land \rho_p(z) \land \varphi_r(z)) \) holds in some model (all models) of \( ACF_p \) and the statement \( \exists z (\theta(z) \land (z_1 < \ldots < z_k) \land \varphi_m(z)) \) holds in some model (all models) of \( T_{m,p} \).
2. The statement \( \exists z (\theta(z) \land (z_1 < \ldots < z_k) \land \rho_p(z) \land \varphi_r(z) \land \varphi_m(z)) \), holds in some model of \( ACFO_p \).

Proof. We will only prove (1) implies (2) as the other direction is clear. Suppose \( F \models ACF_p \), \( c \in F^k \) satisfies \( \theta(z) \land \rho_p(z) \land \varphi_r(z) \), \( (M;<,\mathcal{P}) \models T_{m,p} \) and \( d \in M^k \) satisfies \( \theta(z) \land (z_1 < \ldots < z_k) \land \varphi_m(z) \). Then, by Lemma 4.19 there is an \( L^*_c \)-isomorphism \( \iota : (c) \to (d) \). We can equip \( (c) \) with an \( L^*_c \)-structure with \( A \) defined by restriction from the \( L^*_c \)-reduct \( (F^*; A) \) of \( F \) and \( <,\mathcal{P} \) defined by pullback. Then

\[
(c) A \models ACF^*_p (\forall) \land ((c); <,\mathcal{P}) \models T_{m,p}(\forall).
\]

By Proposition 4.19 \((c); A, <, \mathcal{P}\) can be embedded as an \( L^*_c \)-structure into \((F^*; A, <, \mathcal{P})\). As \( ACF^*_p \) and \( T_{m,p} \) have quantifier elimination, \( c \) satisfies

\[
\theta(z) \land (z_1 < \ldots < z_k) \land \rho_p(z) \land \varphi_r(z) \land \varphi_m(z).
\]

The conclusion follows. \( \square \)

Proof of Proposition 4.7. It suffices to show that the set of all \( L_c \)-statements which hold in all models of \( ACFO \) is recursive. By Lemma 4.18 \( ACFO \) has a recursive axiomatization, so the set \( \{ \sigma \in L_c : ACFO_p \models \sigma \} \) is recursively enumerable. Hence, it remains to showing that the set

\[
\{ \sigma \in L_c : (F; <, \mathcal{P}) \models \neg \sigma \text{ for some } (F; <, \mathcal{P}) \models ACFO_p \}
\]

is also recursively enumerable. This reduces to the problem of finding an algorithm to decide for a given \( p \) and a given \( L_c \)-statement \( \neg \sigma \) whether \( \neg \sigma \) can hold in some model of \( ACFO_p \). By Lemma 4.19 we can arrange that the \( \neg \sigma \) is a special formula \( \exists z (z_1 < \ldots < z_k \land \rho_p(z) \land \varphi_r(z) \land \varphi_m(z)) \) associated to \( P \in \mathbb{Z}[t] \) as in the preceding lemma. By Lemma 4.20 this reduces to finding an algorithm deciding whether

\[
\exists z (\theta(z) \land (z_1 < \ldots < z_k) \land \rho_p(z) \land \varphi_r(z) \land \varphi_m(z))
\]

holds in some model of \( ACFO_p \). Such an algorithm exists by the preceding lemma and the decidability of \( ACF_p \) and \( T_{m,p} \). \( \square \)

Proof of Proposition 4.8. We first show that \( acl_c \) and \( acl_l \) coincide. Let \( (F_1; <, \mathcal{P}) \) be a model of \( ACFO \) and \( A \in F_1 \). It is clear that \( acl_c(A) \subseteq acl_l(A) \). Suppose \( a \in F_1 \) is in \( acl_c(A) \); hence \( (F_1; <, \mathcal{P}) \) is a model of \( ACFO^* \). By Proposition 4.13 and Theorem 1.3 we can arrange that there are \( ACFO \)-models \( (F_2; <, \mathcal{P}) \) and \( (F^*; <, \mathcal{P}) \) such that both \( (F_1; <, \mathcal{P}) \) and \( (F_2; <, \mathcal{P}) \) are \( ACFO \)-submodels of \( (F^*; <, \mathcal{P}) \) and \( F_1 \cap F_2 = F \). By the preceding theorem, \( \varphi(x) \) also define a set with \( k \)-elements in \( F_2 \) and in \( F^* \). This implies all the elements defined by \( \varphi(x) \) must be in \( F \). The fact that \( acl_c \) coincides with \( acl_l \) simply follows from the fact that in \( (F; <, \mathcal{P}) \models ACFO \), \( < \) is a total ordering on \( F^* \). \( \square \)
5. Further Questions

The results obtained in this paper still leave several open questions about models of ACFO. We expect that ACFO is inp-minimal and have made some progress toward proving this. From Proposition ??, any model of ACFO interprets a random graph. Does every model of ACFO interpret a \((n+1)\)-random \((n+1)\)-hyper graph for arbitrary \(n > 0\)? We would also like to obtain more information about definable equivalent relations, definable groups in models of ACFO.

The tameness of models of ACFO suggests related structures might also be tame. Let \((\mathbb{F}, \mathbb{C}; \chi, \mathbb{R})\) be the two-sorted structures with \(\mathbb{R}\) viewed as a unary relation on \(\mathbb{C}\). We expect that this structure is tame with the induced structure on \(\mathbb{F}\) bi-interpretable with \((\mathbb{F}; <)\). We only consider in this paper structure induced on \(\mathbb{F}\) by an injective multiplicative character \(\chi : \mathbb{F}^* \to \mathbb{C}^*\). It might also be fruitful to remove the injective assumption, to consider instead additive characters, mixed characters, multiple characters and character into the multiplicative group \(\mathbb{C}_l^*\) where \(\mathbb{C}_l\) is the valued field of \(l\)-adic complex numbers with \(l\) a prime different from \(\text{char}(\mathbb{F})\). We are still looking for a structure to apply results in [Kow07]. One candidate is \(\prod_{p \in \mathbb{P}} (\mathbb{F}_p; <_p)/\mathcal{U}\) where \(\mathbb{P}\) is the set of all primes, \(\mathcal{U}\) is an ultra-filter on \(\mathbb{P}\) and \((\mathbb{F}_p; <_p)\) is the \(L_\omega\)-structure obtained in similar fashion as \((\mathbb{F}; <)\) with \(\mathbb{F}\) replaced by \(\mathbb{F}_p\) and \(\chi\) replaced by a group embedding \(\chi_p : \mathbb{F}_p^* \to \mathbb{C}^*\). However, there are evidences that this structure defines arithmetic.

We end with two vague questions. The tameness of ACFO is a consequence of equidistribution, a very common phenomenon in mathematics. Are there more examples of this type? Are there applications of ACFO in number theory?

6. Appendix: A more elementary proof of lemma 2.2

We keep the notations in the first paragraphs of section 2 and 3, the paragraph before Lemma 2.10 and moreover assume in this appendix that \(k \geq 1\), \(p = \text{char}(\mathbb{F})\), \(q = p^l\) for \(l \geq 1\) and \(\mathbb{F}_q\) is the subfield of \(\mathbb{F}\) with \(q\) elements. If \(P\) is a system of polynomials in \(\mathbb{F}[x]\), let \(Z(P)\) be the zero set of \(P\) in \(\mathbb{F}^m\). Let \(\mathbb{P}^m\) be the \(m\)-dimension projective space over \(\mathbb{F}\). A quasi-projective variety over \(\mathbb{F}\) is an open subset of an irreducible closed subset of some \(\mathbb{P}^m\), the latter equipped with its Zariski topology. Let \(V\) ranges over the quasi-affine or quasi-projective varieties over \(\mathbb{F}\) and \(F\) ranges over the subfields of \(\mathbb{F}\). The set \(V(F)\) of \(F\)-rational points of \(V\) consists of \(a \in V\) with coordinates in \(F\) when \(V\) is quasi-affine and consists of \(a \in V\) which has homogeneous coordinates in \(F\) when \(V\) is quasi-projective; note that \(V\) is not required to be definable over \(F\) in the field sense. If \(V \subseteq \mathbb{P}^m\) is quasi-projective, the \(i\)-th quasi-affine piece of \(V\) is the quasi-affine variety \(V \cap U_i\) where \(U_i\) identified with \(\mathbb{F}^m\) is the set of \(a \in \mathbb{P}^m\) with non-zero \(i\)-th homogeneous coordinate.

We say \(V\) is \(F\)-definable if \(V\) is quasi-affine and definable over \(F\) in \(L_r\), or if \(V\) is quasi-projective and all affine pieces of \(V\) are \(F\)-definable. In our case, this definition essentially agrees with the field theoretic definition as every algebraic extension of \(F\) is separable.

**Lemma 6.1.** Let \(G = \text{Gal}(\mathbb{F} \mid F)\). Then \(G\) acts naturally on \(\mathbb{F}^m\). For quasi-affine \(V \subseteq \mathbb{F}^m\), the following are equivalent:

(1) \(V\) is \(F\)-definable;
(2) \(V\) is \(G\) invariant;
(3) There are systems \(P,Q\) of polynomials in \(F[x]\) such that \(V = Z(P) \setminus Z(Q)\).
Let $F' \subseteq \mathbb{F}$ be a finite Galois extension of $F$ such that $W$ is defined by polynomials $P'_1, \ldots, P'_k \in F'[x]$. Set $G' = \text{Gal}(F'/F')$, so $G/G' = \text{Gal}(F'/F)$. Then $W$ is also defined by the system $P$ consisting of $P_1, \ldots, P_k \in F[x]$ where

$$P_i = \prod_{\sigma \in G'/G} \sigma(P'_i) \text{ for } i \in \{1, \ldots, k\}.$$ 

Argue similarly for $T$, we get $Q$. The desired conclusion follows.

Let $\mathbb{F}(V)$ be the field of $F$-rational functions on $V$ as usual. Suppose $V$ is moreover $F$-definable. We say $f \in \mathbb{F}(V)$ is $F$-definable if either $V$ is quasi-affine and $f$ is definable over $F$ in $L$, or if $V$ is quasi-projective and the restriction of $f$ to all affine pieces of $V$ is $F$-definable. If $V$ is quasi-affine, then let $F(V)$ be the field consisting of the elements $f$ of $\mathbb{F}(V)$ such that there are $P, Q \in F[x]$ with $Q$ nonzero on $V$ and $f = PQ^{-1}$ in $\mathbb{F}(V)$. If $V$ is quasi-projective, let $F(V)$ be $F(W)$ where $W$ is any quasi-affine piece of $V$. Again, in this case the model theoretic definition and the field theoretic definition coincides:

**Lemma 6.2.** Let $G = \text{Gal}(\mathbb{F} | F)$. For quasi-affine $V \subseteq \mathbb{F}^m$ definable over $F$ and $f \in \mathbb{F}(V)$, the following are equivalent:

1. $f$ is definable over $F$;
2. $f$ is $G$-invariant under the natural action of $G$ on $\mathbb{F}(V)$;
3. $f$ is in $F(V)$.

**Proof.** It is immediate that (1) implies (2) and (3) implies (1); we show that (2) implies (3). We make a number of preparations. Suppose $G, V, f$ are as stated and $f$ is $G$-invariant. We can find a finite extension $F'$ of $F$ such that $f$ is in $F'(V)$, or in other words, $f = PQ^{-1}$ in $\mathbb{F}(V)$ where $P, Q$ are in $F'[x_1, \ldots, x_m]$ and $Q$ is nonzero on $V$. We note that $F'$ is automatically a Galois extension of $F$ as $G$ is pro-cyclic. Again, set $G' = \text{Gal}(\mathbb{F} | F')$, so $G/G' = \text{Gal}(F' | F)$.

We first consider the case when $[G : G'] = [F' : F] = n$ with $p \nmid n$. Note that

$$f = \frac{1}{n} \sum_{\sigma \in G/G'} \frac{\sigma(P)}{\sigma(Q)}$$

is in $\mathbb{F}(V)$. It easily follows that $f$ is in $F(V)$.

We next consider the case when $[F' : F] = p$. Then

$$f^p = \prod_{\sigma \in G/G'} \frac{\sigma(P)}{\sigma(Q)}$$

is in $F(V)$. On the other hand, as $V$ is irreducible in $\mathbb{F}$, $F(V)$ is linearly disjoint with $F'$ over $F$. Therefore, $[F'(V) : F(V)] = [F' : F]$. As $[F' : F']$ is separable, $[F'(V) : F(V)]$ is also separable. Thus, $f^p$ is in $F(V)$ implies $f$ is in $F'(V)$.

For the general case where there is no restriction on $[F' : F]$, the conclusion follows the fact that there is a chain of fields

$$F = F'_0 \subseteq \ldots F'_k = F'$$

such that $[F'_i : F'_i]$ is equal to $p$ or coprime to $p$ for $i \in \{0, \ldots, k-1\}$. □
Let \( \dim(V) \) be the dimension of \( V \) in the sense of algebraic geometry. A constructible \( X \subseteq \mathbb{F}^m \) has the form \( V_1 \cup \ldots \cup V_k \) where \( V_i \subseteq \mathbb{F}^m \) is a quasi-affine varieties over \( \mathbb{F} \) for all \( i \in \{1, \ldots, k\} \). The dimension \( \dim(X) \) of such \( X \) is defined as \( \max_{1 \leq i \leq k} \dim(V_i) \). Constructible subsets of \( \mathbb{F}^m \) and their dimensions are defined similarly replacing quasi-affine varieties with quasi-projective varieties. A constructible \( C \subseteq V \) is a curve on \( V \) if \( \dim(C) = 1 \). A curve on \( V \) is irreducible if it is moreover a quasi-affine or quasi-projective variety.

Suppose \( C \subseteq \mathbb{F}^m \) is an \( F \)-definable irreducible curve. Then \( \text{trdeg}(F(C) \mid F) = 1 \).

Let \( \bar{C}(F) \) be the set of all discrete valuations \( v : F(C) \rightarrow \mathbb{Z} \) which has \( v(F) = \{0\} \). The set \( \mathcal{O}_v = \{ f \in F(C) : v(f) \geq 0 \} \) is then a subring of \( F(C) \) with maximal ideal \( \mathfrak{m}_v = f \in F(C) : v(f) > 0 \). The residue field \( F_v = \mathcal{O}_v/\mathfrak{m}_v \) is a finite extension of \( F \). Set \( \text{deg}(v) = [F_v : F] \). Given \( f \in F(C) \), let \( \bar{Z}_{C,f}(F) \) be the set of \( v \in \bar{C}(F) \) such that \( v(f) > 0 \) and let \( \bar{P}_{C,f}(F) \) be the set of \( v \in \bar{C}(F) \) such that \( v(f) < 0 \). For justification of the claims in this paragraph, see [Sti09, Chapter 1].

The main number theoretic ingredient for proving Lemma 2.2 is the following Weil style bound which is a a weakening of [Per91, Proposition 4.5]:

**Lemma 6.3.** Suppose \( C \) is a smooth projective irreducible curve of geometric genus \( g \) definable over \( \mathbb{F}_q \) and \( f \in \mathbb{F}_q(C) \) is not a constant. Then

\[
\left| \sum_{a \in \text{dom} f(\mathcal{F}_q)} \chi(f(a)) \right| \leq \left( 2g - 2 + \sum_{v \in \bar{Z}_{C,f}(\mathcal{F}_q) \cup \bar{P}_{C,f}(\mathcal{F}_q)} \text{deg}(v) \right) \sqrt{q}.
\]

We note that Lemma 6.3 calls for an upper bound on a character sum over a variety. In view of the preceding lemma, a natural strategy is to obtain a "fibration" of the variety into a family of curves and get an upper bound for the sum over the "fibration" of the right-hand-side expression for each curve. There are two difficulties to carry out this idea: (1) The curves in the "fibration" might not be irreducible or smooth; (2) the right-hand-side expression is not clearly bounded across the "fibration".

The following lemma is used frequently to show definability of various properties in definable families of sets:

**Lemma 6.4.** Suppose \( (X_s)_{s \in S} \) is an \( L_1 \)-definable family of subsets of \( \mathbb{F}^m \). There is definable \( S_d \subseteq S \) for \( d \in \mathbb{N} \) and definable \( S_v \subseteq S \) such that for all elementary extension \( \mathbb{F}' \) of \( \mathbb{F} \) and with \( (X_s')_{s' \in S'} = (X_s)_{s \in S} (\mathbb{F}') \), we have the following:

1. \( S_d(\mathbb{F}') = \{ s' \in S' : \dim(X_s') = d \} \).
2. \( S_v(\mathbb{F}') = \{ s' \in S' : X_s' \text{ is a quasi-affine variety over } \mathbb{F}' \} \).

**Proof.** Suppose \( (X_s)_{s \in S} \), as above. As dimension coincides with Morley rank in ACF which is strongly minimal, \( S_d = \{ s \in S : \dim(X_s) = d \} \) is definable. We note that if \( X \subseteq \mathbb{F}^m \) has \( \dim(X) = d \), then there is a definable finite-to-finite relation from \( X \) to \( \mathbb{F}^d \) and so \( \dim(X(\mathbb{F}')) = d \). The proof that \( S_d \) satisfies (1) follows the same strategy used in the first paragraph of Lemma 3.11.

By Lemma 3.10, \( S_v = \{ s \in S : X_s \text{ is a quasi-affine variety over } \mathbb{F} \} \) is definable. Moreover, \( S_v \) satisfies (2) by the the first paragraph of Lemma 3.11. \( \square \)

**Corollary 6.5.** Let \( \mathbb{F}' \) be an elementary extension of \( \mathbb{F} \). Then \( (C_s)_{s \in S} \) is a definable family of curves on quasi-affine \( V \) if and only if \( (C_s)_{s \in S} (\mathbb{F}') \) is a family of curves on \( V(\mathbb{F}') \). Moreover, \( (C_s)_{s \in S} \) is a family of irreducible curves on \( V \) if and only if \( (C_s)_{s \in S} (\mathbb{F}') \) is a family of irreducible curves on \( V(\mathbb{F}') \).
In the context of our goal, the lemma below can be thought of as reducing an arbitrary “fibration” to a “fibration” with irreducible fibers.

**Lemma 6.6.** Suppose \((C_s)_{s \in S}\) is a definable family of curves on quasi-affine \(V\). There is a family \((D_t)_{t \in T}\) of irreducible curves on \(V\) and \(N \in \mathbb{N}\) such that for all \(s \in S\), \(C_s\) is a union at most \(N\) irreducible curves from \((D_t)_{t \in T}\) and \(N\) many points.

**Proof.** We will give this proof as a demonstration of a standard technique which we will omit details in the later proofs. Suppose \((C_s)_{s \in S}\) is as given. The idea is to use compactness to show that \(S\) can be definably partitioned into \(S_1, \ldots, S_k\) such that for every \(i \in \{1, \ldots, k\}\), the subfamily \((C_s)_{s \in S_i}\) behaves uniformly in such a way which make the desired conclusion obvious.

For the remaining part of the proof, let \(F'\) be an elementary extension of \(F\). We have the following facts:

1. \((C_s)_{s \in S}(F')\) is a family of curves on \(V(F')\) by the preceding lemma;
2. every curve over \(F\) is a union of some \(k\) irreducible curves and some \(l\) points;
3. for every curve \(C'\) on \(F'\); there are systems \(P, Q \in \mathbb{Z}[x, y]\) such that \(C' = Z(P(x, y)) \cap Z(Q(x, y))\) for \(b' \in (F')^n\); recall that \(y = (y_1, \ldots, y_n)\).

Let \(C\) be a choice of \(k, l, n \in \mathbb{N}\) and systems \(P, Q, T_1, \ldots, T_k, \alpha_1, \ldots, \alpha_k\) of polynomials in \(\mathbb{Z}[x, y]\). We note that there are only countably many such \(C\). Let \(R_C^1\) be the set of \((s', b') \in S(F') \times (F')^n\) such that

1. for \(i \in \{1, \ldots, k\}\), the set \(Z(P_i(x, b')) \cap Z(Q_i(x, b'))\) is an irreducible curve;
2. \(C'_{s'} = \{a^{(1)}, \ldots, (a^{(l)}\} \cup \bigcup_{i=1}^k Z(P_i(x, b')) \cap Z(Q_i(x, b'))\) where \(C'_{s'}\) is the curve in the family \((C_s)_{s \in S}(F')\) corresponding to \(s'\) and \(a^{(1)}, \ldots, a^{(l)}\) are some \(l\) points on \(V(F')\).

Let \(R_C\) be defined likewise with \(F'\) replaced by \(F\). Using lemma 5.4, it is easy to see that \(R_C^1\) is definable and is moreover equal to \(R_C(F')\). Let \(R_C^1(F')\) be the projection of \(R_C\) on \(S\). Then \(R_C^1(F')\) is the projection of \(R_C(F')\) for all elementary extension \(F'\) of \(F\).

We obtain a partition \(S_1, \ldots, S_k\) of \(S\) such that for each \(i \in \{1, \ldots, k\}\) there is a choice of \(C\) as in the preceding paragraph such that \(S_i \subset R_C^1(F')\). By (2) and (3), for all \(F'\) elementary extension of \(F\), we have that

\[S(F') = \bigcup_C R_C^1(F')\]

By a standard compactness argument and the fact that \(F'\) was chosen arbitrarily, there are finitely many choices \(C_1, \ldots, C_k\) obtained in a similar way as \(C\) such that \(S = \bigcup_{i=1}^k R_C^1\). By routine manipulations, we obtain \(S_1, \ldots, S_k\) as desired.

We next construct the family \((D_t)_{t \in T}\) as describe. We first consider the special case where there is a choice \(C\) as in the preceding paragraph such that \(S \subset R_C^1\). Choose distinct elements \(b_1, \ldots, b_k \in F\). Let \(T\) be the set of \(t = (t_1, \ldots, t_{n+1})\) in \(\mathbb{F}^{n+1}\) such that for some \(i \in \{1, \ldots, k\}\), \(t_{n+1} = b_i\) and

\[Z(P_i(x, t_1, \ldots, t_n)) \cap Z(Q_i(x, t_1, \ldots, t_n))\]

is an irreducible curve. For \(t \in T\), let

\[D_t = Z(P_i(x, t_1, \ldots, t_n)) \cap Z(Q_i(x, t_1, \ldots, t_n))\]

Let \(N = \max\{k, l\}\) and check that \((D_t)_{t \in T}\) and \(N\) are as desired. The general case follows easily from the above special case as the disjoint union of finitely many definable families is definable.
We next account for the fact that the curves in the “fibration” might not be smooth.

**Lemma 6.7.** Suppose \((C_s)_{s \in S}\) is a definable family of irreducible curves on quasi-affine \(V\) and \(f \in \mathcal{F}(V)\). For each \(s \in S\), suppose \(D_s\) is a smooth projective curve birationally equivalent to \(C_s\). Then there is \(N \in \mathbb{N}\) such that as \(s\) ranges over \(S\), either \(|C_s \cap \text{Dom} f| \) is finite or there is an open subset \(U_s\) of \(C_s\) and an open subset \(W_s\) of \(D_s\) such that \(W_s \subseteq \text{Dom} f\), \(U_s\) is isomorphic to \(W_s\) and \(|(C_s \setminus U_s) \cup (D_s \setminus W_s)| < N\).

**Proof.** Let \(\mathbb{F}'\) be an elementary extension of \(\mathbb{F}\) and \(\mathbb{P}'^m\) be the \(m\)-dimensional projective space over \(\mathbb{F}'\). We have the following facts in addition to (1), (2) and (3) in the proof of the preceding lemma:

1. every irreducible curve over \(\mathbb{F}'\) is birational to a smooth irreducible closed curve on \(\mathbb{P}'^3\);
2. a closed curve on \(\mathbb{P}'^3\) is the zero set of a system of homogeneous polynomials which can be obtained by adding parameters from \(\mathbb{F}'\) into a system of polynomials with coefficient in \(\mathbb{Z}\);
3. if \(C, D\) are quasi-affine curves over \(\mathbb{F}'\), a rational map from \(C\) to \(D\) is given by substituting parameters from \(\mathbb{F}'\) into a rational function with integer coefficients;
4. if two curves \(C, D\) over \(\mathbb{F}\) are birational, there is open \(U \subseteq C\) and \(W \subseteq D\) such that \(U, W\) are isomorphic and \((C \setminus U) \cup (D \setminus W)\) is finite;
5. A curve \(C\) is smooth at \(p \in C\) if and only if the zero set of the Jacobian at \(p\) of the system of equations defining \(C\) is one-dimensional.

The proof proceeds in a similar fashion as the preceding lemma. \(\square\)

We next address (2) in the remark above lemma 6.4. The following lemma concerns with the component \(2g - 2\) in the right-hand-side expression of Lemma 6.3.

**Lemma 6.8.** Suppose \((C_s)_{s \in S}\) is a definable family of irreducible curves on quasi-affine \(V\). There is \(N \in \mathbb{N}\) such that for all \(s \in S\), \(C_s\) has genus \(g_s < N\).

**Proof.** Let \(\mathbb{F}'\) be an elementary extension of \(\mathbb{F}\), we have the following facts:

1. every irreducible curve is birational to a closed curve in \((\mathbb{F}')^2\);
2. a closed curve on \((\mathbb{F}')^2\) is the zero set of a system of polynomials which can be obtained by adding parameters from \(\mathbb{F}'\) into a system of polynomials with integer coefficients;
3. if \(C, D\) are quasi-affine curves over \(\mathbb{F}'\), a rational map from \(C\) to \(D\) is given by substituting parameters from \(\mathbb{F}'\) into a rational function with integer coefficients;
4. the geometric genus is a birational invariants of irreducible curves;
5. the geometric genus of a curve in \((\mathbb{F}')^2\) is bounded above by its arithmetic genus
6. every irreducible curve in \(\mathbb{F}'^2\) is the zero set of an irreducible polynomial \(P \in \mathbb{F}[z_1, z_2];\)
7. the arithmetic genus of the zero set of irreducible \(P \in \mathbb{F}[z_1, z_2]\) is \(\frac{1}{2} \deg P(\deg P - 1)\).

Again, the proof is similar to Lemma 6.6 with the use Lemma 6.4. Alternatively, this lemma may be proven using flattening straitfification and semi-continuity theorems. \(\square\)
Suppose $C$ is an irreducible curve on $V$ and $f \in \mathbb{F}(V)$ is such that Domain$(f) \cap C$ is open in $C$. Then $f|C$ is in $\mathbb{F}(C)$. Lemma 6.2 shows that if $C, f$ are moreover definable over $\mathbb{F}_q$, then $f|C$ is in $\mathbb{F}_q(C)$. The following lemma allows us to deal with the remaining part of the right-hand-side expression of Lemma 6.3.

**Lemma 6.9.** Suppose $(C_s)_{s \in S}$ is a definable family of irreducible curves on a quasi-affine variety $V$. $f$ is in $\mathbb{F}(V)$. There is $N \in \mathbb{N}$ such that for all $\mathbb{F}_q$ and all $C_s$ in the above family with $V, C_s, f$ definable over $\mathbb{F}_q$, Dom$(f) \cap C_s$ open in $C_s$ and $f|C_s$ non-constant on $C_s$ we have:

$$\left| \sum_{v \in \mathbb{Z}_{C_s, f_s}(\mathbb{F}_q)} \deg(v) \right| < N \text{ where } f_s = f|C_s.$$  

**Proof.** Suppose $(C_s)_{s \in S}$, $f$ are as in the first statement of the lemma and $\mathbb{F}_q, C_s, f_s$ are as in the second statement of the lemma. By definition, $v \in \mathbb{Z}_{C_s, f_s}$ implies $v(f_s) > 0$. Hence,

$$\left| \sum_{v \in \mathbb{Z}_{C_s, f_s}(\mathbb{F}_q)} \deg(v) \right| \leq \left| \sum_{v \in \mathbb{Z}_{C_s, f_s}(\mathbb{F}_q)} v(f) \deg(v) \right| \leq [\mathbb{F}_q(C_s) : \mathbb{F}_q(f|C_s)]$$

where the second inequality is by [Sti09, Prop 1.3.3]. As $C_s$ is absolutely irreducible, we have $[\mathbb{F}_q(C_s) : \mathbb{F}_q(f|C_s)] = [\mathbb{F}(C_s) : \mathbb{F}(f|C_s)]$ [Per91 (1.2)]. We also have that

$$[\mathbb{F}(C_s) : \mathbb{F}(f)] = \max_{a \in \text{image } f} |f^{-1}(a) \cap C_s|.$$

By algebraic boundedness of ACF or an argument similar to Lemma 6.6, the above has an upper bound $N_1 \in \mathbb{N}$ independent of the choice of $C_s$ satisfying the stated properties. Note that $v \in \mathbb{Z}_{C, f}$ if and only if $v \in \mathbb{Z}_{C, f|f}$. Therefore, the above argument also gives us an upper bound $N_2 \in \mathbb{N}$ of $\left| \sum_{v \in \mathbb{Z}_{C, f}(\mathbb{F}_q)} \deg(v) \right|$ independent of the choice of $C_s$ satisfying the stated properties. Clearly, $N = N_1 + N_2$ is the desired upper bound. 

**Lemma 6.10.** Suppose $(C_s)_{s \in S}$ is a definable family of curve on a quasi-affine variety $V$ and $f$ is in $\mathbb{F}(V)$. Then there is $N \in \mathbb{N}$ such that for all $\mathbb{F}_q$ and all $C_s$ in the above family with $V, f$ definable over $\mathbb{F}_q$, Dom$(f) \cap C_s$ open in $C_s$ and $f$ non-constant on $C_s$, we have:

$$\left| \sum_{a \in \text{Dom}(f)(\mathbb{F}_q) \cap C_s} \chi(f(a)) \right| \leq N q^{\frac{1}{2}}.$$  

**Proof.** Suppose $(C_s)_{s \in S}$, $f$ are as stated. By Lemma 6.4, we can arrange that $(C_s)_{s \in S}$ is a definable family of irreducible curves. We first show that there is $N_1 \in \mathbb{N}$ such that for all $\mathbb{F}_q$ and all $C_s$ as in the statement of the lemma and $C_s$ is moreover not definable over $\mathbb{F}_q$ then

$$|\text{Dom}(f)(\mathbb{F}_q) \cap C_s| < N_1.$$ 

Suppose $\mathbb{F}_q$ and $C_s$ are as stated. Let Frob denote the map $\mathbb{F} \to \mathbb{F}, a \mapsto a^q$ and the induced map on $\mathbb{F}^m$ for $m > 0$. Then $\text{Dom}(f)(\mathbb{F}_q) \cap C_s \subseteq C_s \cap \text{Frob}^{-1}(C_s)$ which is finite. The conclusion follows from the preceding lemma noting that the family $(\text{Frob}^{-1}C_s)_{s \in S}$ is also definable.
We next show that there is $N_2 \in \mathbb{N}$ such that for all $\mathbb{F}_q$ and all $C_s$ as in the statement of the lemma and $C_s$ is moreover definable over $\mathbb{F}_q$ then
\[
\left| \sum_{a \in \text{Dom}_f(\mathbb{F}_q) \cap C_s} \chi(f(a)) \right| \leq N_2 q^{\frac{1}{2}}.
\]
Suppose $\mathbb{F}_q$ and $C_s$ are as stated. Then $f_s = f|C_s$ is a non-constant element in $\mathbb{F}_q(C_s)$. It immediately follows that $\text{Dom}_f(\mathbb{F}_q) \cap C_s = \text{Dom}_s(\mathbb{F}_q)$. We note that the normalization of $C_s$ is also definable over $\mathbb{F}_q$. Therefore, for each $s \in S$, there is a smooth projective curve $D_s$ definable over $\mathbb{F}_q$ and birational equivalence $\iota : C_s \to D_s$.

Let $h_s$ be the image of $f_s$ under the isomorphism from $F(C_s)$ to $F(D_s)$ induced by $\iota$. Applying Lemma 6.3 noting that the right-hand-side expression of this lemma is invariant under birational equivalence, we get:
\[
\left| \sum_{a \in \text{Dom}_h(\mathbb{F}_q)} \chi(h_s(a)) \right| \leq \left( 2g_s - 2 + \sum_{v \in \mathbb{Z}_{C_s, f_s}(\mathbb{F}_q) \cup \mathbb{P}_{C_s, f_s}(\mathbb{F}_q)} \deg(v) \right) \sqrt{q}.
\]
Let $N_3$ be the bound in 6.8 and $N_4$ be the bound in 6.9. By Lemma 6.7 there is $U_s$ open in $C_s$, $W_s$ open in $D_s$ such that the restriction of $\iota$ is an isomorphism from $U_s$ to $W_s$ and $|C_s \cap U_s| + |D_s \cap W_s| < N_5$ where $N_5$ is the bound in Lemma 6.7. Putting everything together we have:
\[
\left| \sum_{a \in \text{Dom}_f(\mathbb{F}_q) \cap C_s} \chi(f(a)) \right| \leq \left| \sum_{a' \in \text{Dom}_f(\mathbb{F}_q) \cap C'_s} \chi(f(a')) \right| + N_5 \leq (2N_3 + N_4)q^{1/2} + N_5.
\]
Then $N_2 = 2N_3 + N_4 + N_5$ is the desired bound which is independent of the choice of $C_s$ with the stated properties.

Finally, it is easy to see that $N = N_1 + N_2$ where $N_1, N_2$ are obtained in the previous paragraphs is a desired bound for the lemma.

**Proposition 6.11.** Suppose $V \subseteq \mathbb{F}^m$ is a quasi-affine of dimension $d$ and $f \in F(V)$ is nonconstant on $V$. There is $N \in \mathbb{N}$ such that if $V, f$ are definable over $\mathbb{F}_q$, then:
\[
\left| \sum_{a \in \text{Dom}_f(\mathbb{F}_q)} \chi(f(a)) \right| \leq Nq^{d-\frac{1}{2}}.
\]

*Proof.* Suppose $V, d$ and $f$ are as given. We make a number of observations and arrangements. As $f$ is non-constant, $d > 0$. If $V, f$ are definable over $\mathbb{F}_q$, then $\text{Domain}_f$ is also definable over $\mathbb{F}_q$. We can therefore replace $V$ with Domain$f$ and assume that $f$ is regular on $V$. Replacing $V$ with the graph of $f$ and replace $m$ with $m + 1$ if necessary, we arrange that $f = \pi_m$ where $\pi_m : \mathbb{F}^m \to \mathbb{F}$ is the projection to the first coordinate for $m > 0$.

We will show by induction on dimension an auxiliary result which implies that $V$ has a “good fibration”. Let $F$ be a finite subfield of $\mathbb{F}$ such that $V$ is definable over $F$ and $F$ is minimal with respect to these properties. For $m > 0$, let $\rho_m : \mathbb{F}^m \to \mathbb{F}^{m-1}$ be the projection on the last $m - 1$ coordinates. We will construct a (Zariski) open subset $U$ of $V$, an open subset $D$ of $\mathbb{F}^d$, an open subset $S$ of $\mathbb{F}^{d-1}$ and a “reduction map” $r : V \to \mathbb{F}^d$ with the following properties:

1. $U, D, S, r$ are definable over $F$;
2. $U \subseteq \text{Domain}(r)$, $r(U) = D$ and $\rho_d(D) = S$;
3. $\pi_m = \pi_d \circ r$ on $U$.
We consider the special case when \( m = d \). Then \( V \) is open in \( \mathbb{F}^m = \mathbb{F}^d \) and the image of \( V \) under \( \rho \) contains an open subset \( S \) of \( \mathbb{F}^{d-1} \). We can arrange that \( S \) satisfies (2) of Lemma 6.2 and so \( F \)-definable. Let \( U = D = h^{-1}(S) \cap V \) and \( r \) be the identity map. We check that this choice satisfies the desired conditions.

We consider another special case where \( d = 1 \). As \( \pi_m \) is non-constant, by an argument similar to the preceding paragraph, there is an open set \( D \) of \( F \) such that \( D \) is definable over \( F \) and \( D \) is contained in the image of \( \pi_m \). Let \( S \) be the set of one element \( \mathbb{F}^0 \), let \( U \) be \( V \cap \pi_m^{-1}(D) \) and let \( r \) be \( f \mid U \). We check that this choice satisfies the desired conditions.

Towards the use of induction, suppose \( m > d \) and \( d > 1 \) and we have proven the statement for all \( V', m' \) and \( d' \) with similar settings such that \( m' < m \). Let \( \tau_m : \mathbb{F}^m \to \mathbb{F}^{m-1} \) be the projection on the first \( m-1 \) coordinates. Using Lemma 6.2 and arguing similarly as the third paragraph to obtain an open subset \( V' \) of \( \pi_m(V) \) such that \( V' \) is definable over \( F \). By induction hypothesis, we can choose \( U', D', S', r' \) satisfies the desired condition for \( V', m-1 \) and \( d' = \dim(V') \). Consider the case where \( d' = d \). Set

\[
U = \tau_m^{-1}(U') \cap V, \quad D = D', \quad S = S' \quad \text{and} \quad r = r' \circ \tau_m.
\]

We check that this satisfies the desired condition. Consider the case where \( d' = d-1 \). Set

\[
U = \tau_m^{-1}(U') \cap V, \quad D = \tau_d^{-1}(D'), \quad S = \tau_d^{-1}(S');
\]

\[
r : V \to F^d, \quad a = (a_1, \ldots, a_m) \mapsto (r' \circ \tau_m(a), a_m),
\]

Shrink \( U, D, S \) further if needed we make \( r(U) = D, \rho_d(D) = S \) and \( U, D \) definable over \( F \). We can check that all the conditions are satisfied.

Suppose \( V \) is definable over \( \mathbb{F}_q \). We claim that \( F \subseteq \mathbb{F}_q \). Let \( \sigma \) be in \( \Gal(\mathbb{F} | \mathbb{F}_q) \). Then as \( \Gal(\mathbb{F} | \mathbb{F}_p) \) is abelian, \( \Gal(F | \mathbb{F}_p), \sigma \) is \( \Gal(\mathbb{F} | \mathbb{F}^p) \) where \( \mathbb{F}^p \subseteq F \) and \( F' \) in an extension of \( \mathbb{F}_p \). Then every elements of \( \Gal(\mathbb{F} | \mathbb{F}^p) \) fixes \( V \) set-wise and so \( V \) is definable over \( F' \). By minimal assumption of \( F \), we must have \( F' = F \). Therefore \( \sigma \) is in \( \Gal(\mathbb{F} | \mathbb{F}) \). The desired conclusion follows.

Therefore, \( U, D, S, r \) obtained in the previous paragraphs are also definable over \( \mathbb{F}_q \). For each \( s \in S \) set

\[
L_s = D \cap \rho_1^{-1}(s) \quad \text{and} \quad C_s = U \cap r^{-1}(L_s) = U \cap (\rho_d \circ r)^{-1}(s).
\]

As \( r \) is \( \mathbb{F}_q \)-definable, by Lemma 6.2 if \( a \in U(\mathbb{F}_q) \), then \( \rho_d \circ r(a) \) is in \( \mathbb{F}_q^{d-1} \). Therefore, \( U(\mathbb{F}_q) = \bigcup_{s \in S(\mathbb{F}_q)} C_s(\mathbb{F}_q) \). For each \( s \in S(\mathbb{F}_q) \), we also have \( C_s \) is definable over \( \mathbb{F}_q \) and \( \pi_m(C_s) = \pi_m \circ r(C_s) = \pi_m(L_s) \) is nonconstant as \( L_s \) is open in \( \pi_m^{-1}(s) \). Hence,

\[
\left| \sum_{a \in U(\mathbb{F}_q)} \chi(f(a)) \right| \leq \sum_{s \in S(\mathbb{F}_q)} \left| \sum_{a \in C_s(\mathbb{F}_q)} \chi(f(a)) \right| \leq q^{d-1}B_1q^{d-2} = B_1q^{d-2}
\]

with \( B_1 \) the bound from Lemma 6.10. On the other hand,

\[
\left| \sum_{a \in (V \setminus U)(\mathbb{F}_q)} \chi(f(a)) \right| \leq |(V \setminus U)(\mathbb{F}_q)| \leq B_2q^{d-1}
\]

with \( B_2 \) the bound given by Lemma 2.1. Thus, \( B = B_1 + B_2 \) is the desired bound. □
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