

Almost Galois ω -Stable classes

John T. Baldwin*
University of Illinois at Chicago

Paul B. Larson†
Miami University
Oxford, Ohio USA

Saharon Shelah‡
Hebrew University of Jerusalem
Rutgers University

May 25, 2013

Abstract

Theorem. Suppose that an \aleph_0 -presentable Abstract Elementary Class (AEC), \mathbf{K} , has the joint embedding and amalgamation properties in \aleph_0 and $< 2^{\aleph_1}$ models in \aleph_1 . If \mathbf{K} has only countably many models in \aleph_1 , then all are small. If, in addition, \mathbf{K} is almost Galois ω -stable then \mathbf{K} is Galois ω -stable.

1 Introduction

This paper concerns two aspects of pseudo-elementary classes in $L_{\omega_1, \omega}$, the reducts to a vocabulary $\tau \subseteq \tau^+$ of models of an $L_{\omega_1, \omega}(\tau^+)$ -sentence. In the first two sections we investigate the relationship among the number of countable models of such a class, Scott ranks, and the number of small (i.e., having a countable $L_{\omega_1, \omega}$ -elementary submodel) models and large (not small) models of the class in \aleph_1 ; this yields some technical information about putative counterexamples to Vaught's conjecture. Building on this material, in the third section, we treat such classes as abstract elementary classes and investigate variations on Galois ω -stability. In the final section we use the results presented here and in [3] to prove a theorem on the absoluteness of \aleph_1 -categoricity for pseudo-elementary classes in $L_{\omega_1, \omega}$.

We call an Abstract Elementary Class (AEC) *almost Galois ω -stable* if for every countable model M , E_M (the equivalence relation of 'same Galois type over M ') does not have a perfect set of equivalence classes. The immediate impetus for this paper was [3], which studied what Baldwin and Larson called *analytically presented* Abstract Elementary Classes. These classes are called by many names: pseudo-elementary classes in $L_{\omega_1, \omega}$, \aleph_0 -presentable classes, PC_{\aleph_0} [23], $\text{PC}(\aleph_0, \aleph_0)$, $\text{PCT}(\aleph_0, \aleph_0)$ [1] or, in the language of Keisler [12], PC_δ in $L_{\omega_1, \omega}$. In this paper we will most often refer to them as \aleph_0 -presented. The term 'analytically presented' emphasizes that one can deduce from Burgess's theorem on analytic equivalence relations that if such a class is almost Galois ω -stable then each equivalence relation E_M has at most \aleph_1 equivalence classes. This topic first arose in [23] and several of the arguments here just expand ideas

*Research partially supported by Simons travel grant G5402

†Supported in part by NSF Grant DMS-0801009.

‡Research partially supported by NSF grant no: DMS 1101597, and German-Israeli Foundation for Scientific Research & Development grant no. 963-98.6/2007. Publication number 1003. Part of f1179 on the Shelah Archive. All authors thank Rutgers University.

Shelah mentioned there; for further background on the context see [3, 1, 21]. Our main goal is to prove that an almost Galois ω -stable \aleph_0 -presentable Abstract Elementary Class with only countably many models in \aleph_1 is Galois ω -stable. This extends earlier work by Hyttinen-Kesala [10] and Kueker [14] proving the result for sentences of $L_{\omega_1, \omega}$ with no requirement on the number of uncountable models.

Each class of models in this paper is \aleph_0 -presented. A major tool for this investigation is to expand models of set theory by predicates encoding relevant properties of the models (for some vocabulary τ) being studied. This approach appears in Shelah's analysis in [18], Section VII, connecting the Hanf number for omitting families of types with the well-ordering number for classes defined by omitting types.

In [17], expanding the vocabulary to describe an analysis of the syntactic types allowed the construction of a 'small' (Definition 2.2) uncountable model in an \aleph_0 -presentable class \mathbf{K} from an uncountable model that is small with respect to every countable fragment of $L_{\omega_1, \omega}$. In Lemma 2.7, we use this method to show that if, in addition, there are only countably many models in \aleph_1 , then they are each small. In Section 3, we combine this technique with constructions using iterated models of set theory to show the main theorem as stated in the abstract.

2 Small Models

We refer the reader to [1, 21] for the definition of Abstract Elementary Class (AEC).

Assumption 2.1. $\mathbf{K} = (K, \leq_K)$ is an AEC which is \aleph_0 -presented. Specifically, \mathbf{K} is the class of reducts to τ of a class defined by a sentence $\phi \in L_{\omega_1, \omega}(\tau^+)$, where τ^+ is a countable vocabulary extending τ .

This section deals with syntactic $(L_{\omega_1, \omega})$ -types in \aleph_0 -presentable classes. As such the arguments are primarily syntactic and are minor variants on arguments Shelah used in [17, 19, 23]. In particular, no amalgamation assumptions are used in this section.

Definition 2.2. 1. A τ -structure M is L^* -small for L^* a countable fragment of $L_{\omega_1, \omega}(\tau)$ if M realizes only countably many L^* -types (i.e. only countably many L^* - n -types over \emptyset for each $n < \omega$.)

2. A τ -structure M is called locally τ -small if for every countable fragment L^* of $L_{\omega_1, \omega}(\tau)$, M realizes only countably many L^* -types.

3. A τ -structure M is called small or $L_{\omega_1, \omega}$ -small if M realizes only countably many $L_{\omega_1, \omega}(\tau)$ -types.

Note that 'small' is a much stronger requirement than 'locally small'. If $\tau \subseteq \tau'$ and $N \in \tau'$, we say that N is locally τ -small when $N \upharpoonright \tau$ is. We emphasize τ when the ambient larger vocabulary plays a significant role. The following standard fact plays a key role below (see also pages 47-48 of [1]).

Fact 2.3. *Each small model satisfies a Scott-sentence, a complete sentence of $L_{\omega_1, \omega}$.*

We quickly review the proof of this fact, as the details will be important later. For any model M over a countable vocabulary τ , we can define for each finite tuple \mathbf{a} (of size n) from M the n -ary formulas $\phi_{\mathbf{a}, \alpha}(\bar{x})$ ($\alpha < \omega_1$) as follows.

- $\phi_{\mathbf{a}, 0}(\bar{x})$ is the conjunction of all atomic formulas satisfied by \mathbf{a} ,
- $\phi_{\mathbf{a}, \alpha+1}(\bar{x})$ is the conjunction of the following three formulas:
 - $\phi_{\mathbf{a}, \alpha}(\bar{x})$

- $\bigwedge_{c \in M} \exists w \phi_{\mathbf{a}c, \alpha}(\bar{x}, w)$
- $\forall w \bigvee_{c \in M} \phi_{\mathbf{a}c, \alpha}(\bar{x}, w)$
- for limit $\beta < \omega_1$, $\phi_{\mathbf{a}, \beta}(\bar{x}) = \bigwedge_{\alpha < \beta} \phi_{\mathbf{a}, \alpha}$.

The apparent uncountability of the conjunctions in the previous definition is obviated by identifying formulas $\phi_{\mathbf{a}c, \alpha}$ and $\phi_{\mathbf{a}'c, \alpha}$ when they are equivalent in M . Working by induction on α , one gets that if M is L^* -small for each countable fragment L^* of $L_{\omega_1, \omega}(\tau)$, then the set of formulas $\phi_{\mathbf{a}, \alpha}$ is countable for each α , letting a range over all finite tuples from M . Finally, if M is small there exists an α such that

$$M \models \forall \bar{x} (\phi_{\mathbf{a}, \alpha}(\bar{x}) \rightarrow \phi_{\mathbf{a}, \alpha+1}(\bar{x}))$$

for all finite tuples \mathbf{a} . Then

$$\phi_{\langle \rangle, \alpha} \wedge \bigwedge_{\mathbf{a} \in M^{< \omega}} \forall \bar{x} (\phi_{\mathbf{a}, \alpha}(\bar{x}) \rightarrow \phi_{\mathbf{a}, \alpha+1}(\bar{x}))$$

is a Scott sentence for M . Fixing the least such α , we say that M has Scott rank α .

We will also use the following fundamental result (see [12] or Theorem 5.2.5 of [1]; the notion of fragment is explained in both books). Roughly speaking, the fragment generated by a countable subset X of $L_{\omega_1, \omega}(\tau)$ is the closure of X under first order operations. We preserve Keisler's terminology to emphasize that the theorem deals only with the number of models and does not involve the choice of 'elementary embedding' on the class.

Theorem 2.4 (Keisler). *If a PC_δ over $L_{\omega_1, \omega}$ class \mathbf{K} has an uncountable model but less than 2^{ω_1} models of power \aleph_1 then \mathbf{K} is locally τ -small. That is, for any countable fragment L^* of $L_{\omega_1, \omega}(\tau)$, each $M \in \mathbf{K}$ realizes only countably many L^* -types over \emptyset .*

By just changing a few words in the proof of Theorem 6.3.1 of [1], (originally in [17]) one can obtain the following result, which was implicit in [23].

Theorem 2.5. *If \mathbf{K} is an \aleph_0 -presentable AEC and some model $M \in \mathbf{K}$ of cardinality \aleph_1 is locally τ -small, then \mathbf{K} has a $L_{\omega_1, \omega}(\tau)$ -small model N of cardinality \aleph_1 .*

Proof. Let ϕ be the τ^+ -sentence whose reducts to τ are the members of \mathbf{K} . Without loss of generality we may assume the universe of M is ω_1 . Add to τ^+ a binary relation $<$, interpreted as the usual order on ω_1 . Using the fact that M realizes only countably many types in any τ -fragment, define a continuous increasing chain of countable fragments L_α for $\alpha < \aleph_1$ such that

- for each quantifier free (first order) n -type over the empty set realized in M , the conjunction of the type is in L_0 , and
- the conjunction of each type in L_α that is realized in M is a formula in $L_{\alpha+1}$.

Extend the similarity type further to τ' by adding new $(2n + 1)$ -ary predicates $E_n(x, \mathbf{y}, \mathbf{z})$ and $(n + 1)$ -ary functions f_n for each $n \in \omega$. Let M satisfy $E_n(\alpha, \mathbf{a}, \mathbf{b})$ if and only if \mathbf{a} and \mathbf{b} realize the same L_α -type, and let the interpretation of f_n map M^{n+1} into ω in such a way that $E_n(\alpha, \mathbf{a}, \mathbf{b})$ if and only if $f_n(\alpha, \mathbf{a}) = f_n(\alpha, \mathbf{b})$ for all suitable $\alpha, \mathbf{a}, \mathbf{b}$. Then the following hold.

1. The equivalence relations $E_n(\beta, \bar{x}, \bar{y})$ refines $E_n(\alpha, \bar{x}, \bar{y})$ if $\beta > \alpha$;

2. $E_n(0, \mathbf{a}, \mathbf{b})$ implies that \mathbf{a} and \mathbf{b} satisfy the same quantifier free τ -formulas;
3. If $\beta > \alpha$ and $E_n(\beta, \mathbf{a}, \mathbf{b})$, then for every c_1 there exists c_2 such that $E_{n+1}(\alpha, c_1 \mathbf{a}, c_2 \mathbf{b})$, and
4. f_n witnesses that for any $a \in M$, each equivalence relation $E_n(a, \bar{x}, \bar{y})$ has only countably many classes.

All these assertions can be expressed by an $L_{\omega_1, \omega}(\tau')$ sentence χ . Let L^* be the smallest τ' -fragment containing $\chi \wedge \phi$. Now by the Lopez-Escobar bound on $L_{\omega_1, \omega}$ definable well-orderings, Theorem 5.3.8 of [1], there is a τ' -structure N of cardinality \aleph_1 satisfying $\chi \wedge \phi$ such that there is an infinite decreasing sequence $d_0 > d_1 > \dots$ in N (alternately, one could use Lemma 2.5 of [3] for this step). For each n , let $E_n^+(\bar{x}, \bar{y})$ denote the assertion that for some i , $E_n(d_i, \bar{x}, \bar{y})$.

Using 1), 2) and 3) one can prove by induction on quantifier rank (for all $n \in \omega$ simultaneously) that for all n -ary $L_{\omega_1, \omega}(\tau)$ formulas μ , and all finite tuples \mathbf{a}, \mathbf{b} from N , if $E_n^+(\mathbf{a}, \mathbf{b})$ holds then $N \models \mu(\mathbf{a})$ if and only if $N \models \mu(\mathbf{b})$. To see this, suppose that this assertion holds for all n and all θ with quantifier rank at most γ . Let $\mu(\bar{z})$ be an n -ary formula of the form $(\exists x)\theta(\bar{z}, x)$, where θ has quantifier rank γ . Let \mathbf{a}, \mathbf{b} be n -tuples from N for which $E_n^+(\mathbf{a}, \mathbf{b})$ holds and $N \models \mu(\mathbf{a})$. Then for some i , $E_n(d_i, \mathbf{a}, \mathbf{b})$ and for some a , $N \models \theta(\mathbf{a}, a)$. By condition 3) above there is a b such that $E_{n+1}(d_{i+1}, \mathbf{a}, a, \mathbf{b}, b)$. By our induction hypothesis we have $N \models \theta(\mathbf{b}, b)$ and so $N \models \mu(\mathbf{b})$.

Now, for each n , $E_n(d_0, \bar{x}, \bar{y})$ refines $E_n^+(\bar{x}, \bar{y})$ and by 4) $E_n(d_0, \bar{x}, \bar{y})$ has only countably many classes, so $N \upharpoonright \tau$ is small. $\square_{2.5}$

Definition 2.6. We say a countable structure is extendible if it has an $L_{\omega_1, \omega}$ -elementary extension to an uncountable model.

Lemma 2.7. Suppose that \mathbf{K} is the class of reducts to τ of a class defined by a sentence $\phi \in L_{\omega_1, \omega}(\tau^+)$, where τ^+ is a countable vocabulary extending τ . If some uncountable $M \in \mathbf{K}$ is locally τ -small but is not $L_{\omega_1, \omega}(\tau)$ -small then

1. There are at least \aleph_1 pairwise-inequivalent complete sentences of $L_{\omega_1, \omega}(\tau)$ which are satisfied by uncountable models in \mathbf{K} ;
2. \mathbf{K} has uncountably many small models in \aleph_1 that satisfy distinct complete sentences of $L_{\omega_1, \omega}(\tau)$;
3. \mathbf{K} has uncountably many extendible models in \aleph_0 .

Proof. Suppose that M is a model in \mathbf{K} with cardinality \aleph_1 that is locally τ -small but is not $L_{\omega_1, \omega}(\tau)$ -small. Let M^+ be an expansion of M to a τ^+ -structure satisfying ϕ . We construct a sequence of τ^+ -structures $\{N_\alpha^+ : \alpha < \omega_1\}$ each with cardinality \aleph_1 and an increasing continuous family of countable fragments $\{L'_\alpha : \alpha < \omega_1\}$ of $L_{\omega_1, \omega}(\tau)$ and sentences χ_α such that:

1. $L'_0(\tau)$ is first order logic on τ ;
2. all the models N_α^+ satisfy ϕ ;
3. for each $\alpha < \omega_1$, $N_\alpha^+ \upharpoonright \tau$ is $L_{\omega_1, \omega}(\tau)$ -small;
4. χ_α is the $L_{\omega_1, \omega}(\tau)$ -Scott sentence of N_α^+ ;
5. $L'_{\alpha+1}(\tau)$ is the smallest fragment of $L_{\omega_1, \omega}(\tau)$ containing $L'_\alpha(\tau) \cup \{\neg\chi_\alpha\}$;

6. For limit δ , $L'_\delta(\tau) = \bigcup_{\alpha < \delta} L'_\alpha(\tau)$;
7. For each α , $N_\alpha \equiv_{L'_\alpha(\tau)} M$.

Working by recursion, suppose that we have constructed N_α for all $\alpha < \beta$, for some countable ordinal β . This determines each χ_α ($\alpha < \beta$) as the Scott sentence of N_α and also determines $L'_\beta(\tau)$. Since M is not small, $M \models \neg\chi_\alpha$ for each $\alpha < \beta$. Apply Theorem 2.5 to M and the restriction of \mathbf{K} to models $L'_\beta(\tau)$ -elementarily equivalent to M to construct N_β .

Now the N_α are pairwise non-isomorphic since each satisfies a distinct complete sentence χ_α of $L_{\omega_1, \omega}(\tau)$, so conclusions 1) and 2) are satisfied. And each N_α has a countable elementary submodel with respect to $L'_{\alpha+1}(\tau)$, so there are at least \aleph_1 non-isomorphic extendible models in \aleph_0 as well. $\square_{2.7}$

Putting together Theorem 2.4 and Lemma 2.7, we have the following.

Corollary 2.8. *If an \aleph_0 -presented AEC \mathbf{K} has only countably many models in \aleph_1 , then every model in \mathbf{K} is small.*

Lemma 2.7 leads to several corollaries connected to the Vaught conjecture. First we recall the following result of Harnik and Makkai [8].

Theorem 2.9 (Harnik-Makkai). *If $\sigma \in L_{\omega_1, \omega}$ is a counterexample to Vaught's Conjecture then it has a model of cardinality \aleph_1 which is not small.*

Corollary 2.10. *If $\phi \in L_{\omega_1, \omega}$ is a counterexample to the Vaught conjecture then ϕ has \aleph_1 extendible countable models.*

Proof. If $\phi \in L_{\omega_1, \omega}$ is a counterexample to Vaught's conjecture, then every uncountable model of ϕ is locally small. The result then follows from Theorem 2.9 and Lemma 2.7. $\square_{2.10}$

Su Gao pointed out another argument for this observation. By Becker [4], the Vaught conjecture holds for countable models such that $\text{aut}(M)$ is a 'cli' group (admits a compatible left-invariant complete metric). By Gao [6], $\text{aut}(M)$ is 'cli' if and only if M is not extendible. Thus if there is failure of Vaught's conjecture there must be \aleph_1 extendible countable models.

Remark 2.11. Clearly, if \mathbf{K} has only countably many models in \aleph_1 then \mathbf{K} has at most \aleph_0 non-isomorphic extendible countable models (since each uncountable model is $L_{\omega_1, \omega}$ -equivalent to at most one model in \aleph_0). The three conclusions of Lemma 2.7 are easily seen to be equivalent; we separated them in the statement because both the countable and uncountable models arose naturally in the proof. The converse of Lemma 2.7 asserts if that \mathbf{K} has uncountably many extendible countable models and a locally small model in \aleph_1 then it has a non-small model in \aleph_1 . Theorem 2.9 shows this is true if the hypothesis is changed to 'uncountably many countable models, but not a perfect set of countable models', without requiring extendibility. In general, the converse is false. The empty theory in a vocabulary with \aleph_0 constants has 2^{\aleph_0} models (depending on which constants are identified) in each of \aleph_1 and \aleph_0 ; all are small. But joint embedding and amalgamation fail even under first order elementary submodel. Example 2.1.1 of [2] is a sentence of $L_{\omega_1, \omega}$ giving rise to an AEC, with a particular notion of $\prec_{\mathbf{K}}$ (weaker than first order), which satisfies amalgamation and joint embedding and is \aleph_1 -categorical, and for which the model in \aleph_1 is small. In this case there are 2^{\aleph_0} countable models, but only one of them is extendible.

Definition 2.12. *A sentence σ of $L_{\omega_1, \omega}$ is large if it has uncountably many countable models. A large sentence σ is minimal if for every sentence ϕ either $\sigma \wedge \phi$ or $\sigma \wedge \neg\phi$ is not large.*

As part of their proof of Theorem 2.9, Harnik and Makkai showed that any counterexample to Vaught's conjecture can be strengthened to a minimal counterexample. We call a model of cardinality \aleph_1 *large* if it is not $L_{\omega_1, \omega}$ -small in the sense of Definition 2.2. Lemma 2.7 implies that if ϕ has a large model in \aleph_1 then ϕ is large.

Corollary 2.13. *If ϕ is a minimal counterexample to Vaught's conjecture then ϕ has a large model in \aleph_1 , and all large models of ϕ in \aleph_1 are $L_{\omega_1, \omega}$ -elementarily equivalent.*

Proof. Theorem 2.9 says that ϕ has a large model N . Suppose that $\phi \in L_{\omega_1, \omega}$ holds in N . The fact that $\phi \wedge \psi$ has a large model implies by Lemma 2.7 that $\phi \wedge \psi$ has uncountably many models in \aleph_0 . By minimality, $\phi \wedge \neg\psi$ has only countably many models in \aleph_0 and so by Lemma 2.7 again, all uncountable models of $\phi \wedge \neg\psi$ are small. $\square_{2.13}$

Harrington (see the discussion in [15]) showed that any counterexample to Vaught's conjecture had models in \aleph_1 with Scott ranks (as sentences in $L_{\omega_2, \omega}$) up to \aleph_2 .

Question 2.14. *Can one say anything about the embedability relation on the large models of a counterexample to Vaught's conjecture?*

2.1 Connections with the Morley Analysis

We pause to connect this analysis in Section 2.2 with a related but subtly distinct procedure.

Definition 2.15. 1. **Morley's Analysis** Let \mathbf{K} be the class of models of a sentence of $L_{\omega_1, \omega}$.

- (a) Let $L_0^{\mathbf{K}}$ be the set of first order τ -sentences.
- (b) Let $L_{\alpha+1}^{\mathbf{K}}$ be the smallest fragment generated by $L_{\alpha}^{\mathbf{K}}$ and the sentences of the form $(\exists \mathbf{x}) \wedge p(\mathbf{x})$ where p is an $L_{\alpha}^{\mathbf{K}}$ -type realized in a model in \mathbf{K} .
- (c) For limit δ , $L_{\delta}^{\mathbf{K}} = \bigcup_{\alpha < \delta} L_{\alpha}^{\mathbf{K}}$.

- 2. \mathbf{K} is scattered if and only if for each $\alpha < \omega_1$, $L_{\alpha}^{\mathbf{K}}$ is countable.

Recall Morley's theorem, which is key to his approach to Vaught's conjecture.

Theorem 2.16 (Morley). *If \mathbf{K} is the class of models of a sentence in $L_{\omega_1, \omega}$ that has less than 2^{\aleph_0} models of power \aleph_0 then \mathbf{K} is scattered.*

Remark 2.17. We cannot conclude that \mathbf{K} is scattered from just counting models in \aleph_1 , even from the hypothesis that \mathbf{K} is \aleph_1 -categorical. Again, Example 2.1.1 of [2] (Remark 2.11) is \aleph_1 -categorical and has joint embedding for $\prec_{\mathbf{K}}$. But there are 2^{\aleph_0} first order types that give models that are not even first order mutually embeddable and the class \mathbf{K} is not scattered.

Remark 2.18. The sequence of languages in Theorem 2.5 might be labeled L_{α}^M . They come about by applying the Morley analysis solely to the types realized in M . So this gives a slower growing sequence of languages than the Morley analysis. We replace the conclusion of scattered in Theorem 2.16 with locally small. If \mathbf{K} has either less than 2^{\aleph_0} models in \aleph_0 or less than 2^{\aleph_1} models in \aleph_1 , then every uncountable model of \mathbf{K} is locally small.

Remark 2.19. The arguments of Morley and Shelah have different goals. Being scattered is a condition on all models of an (in the interesting case for the Vaught conjecture) an *incomplete* sentence in $L_{\omega_1, \omega}$. The Shelah argument contracts \mathbf{K} to a smaller class where every model is small and thus finds a $\mathbf{K}' \subset \mathbf{K}$ that is small and is axiomatized by a complete sentence. The hard part is to make sure \mathbf{K}' has an uncountable model. In the most used case, \mathbf{K} and *a fortiori* \mathbf{K}' is \aleph_1 -categorical.

2.2 Alternate proofs using Scott sentences

In this subsection we prove alternate versions of Theorem 2.5 and part of Lemma 2.7. Theorem 2.20 can be used in place of Theorem 2.5 in all of our applications of Theorem 2.5, and the basic use of ill-foundedness is the same. The ill-foundedness can be obtained either Lopez-Escobar or by iterated models of set theory. In the proof of Theorem 3.13, we use iterated models of set theory to obtain ill-foundedness; they can be obtained either by ultrafilters or by a use of Lopez-Escobar. For convenience we use the theory ZFC° from [3]. Any theory strong enough to carry out the construction of Scott sentences should be sufficient.

Theorem 2.20. *Let τ be a countable vocabulary, let M be a τ -structure, and let N be an ω -model of ZFC° with ω_1^N ill-founded. Let β be the ordinal isomorphic to the longest well-founded initial segment of ω_1^N . Suppose that, in N , M is locally τ -small and either large or small with Scott rank in the ill-founded part of N . Then M is small, and the Scott rank of M is exactly β .*

Proof. Let t be the Scott rank of M in N if N thinks that M is small, and ω_1^N otherwise. Let

$$\langle \phi_{\mathbf{a},s} : \mathbf{a} \in M^{<\omega}, s < t \rangle$$

be the set of formulas defined in N in the first t many steps of the search for a Scott sentence for M . Then

$$\langle \phi_{\mathbf{a},\alpha} : \mathbf{a} \in M^{<\omega}, \alpha < \beta \rangle$$

is also the set of formulas defined in V in the first β many steps of the search for a Scott sentence for M . Since the Scott rank of M in N is in the ill-founded part of N if it exists, the Scott rank of M in V is at least β .

We claim that for any $n \in \omega$ and any pair \mathbf{a}, \mathbf{b} of n -tuples from M , if $\phi_{\mathbf{a},s} = \phi_{\mathbf{b},s}$ for any ill-founded $s < t$, then \mathbf{a} and \mathbf{b} satisfy all the same $L_{\omega_1,\omega}(\tau)$ -formulas in M (from the point of view of V). To see this, suppose that this assertion holds for all n and all formulas θ with quantifier rank at most γ . Let $\mu(\bar{z})$ be an n -ary formula of the form $(\exists x)\theta(\bar{z}, x)$, where θ has quantifier rank γ . Let \mathbf{a}, \mathbf{b} be n -tuples from N , let $s < t$ be an ill-founded ordinal of N such that $\phi_{\mathbf{a},s} = \phi_{\mathbf{b},s}$, and suppose that $M \models \mu(\mathbf{a})$. Then there is an ill-founded $r < s$, and for any such r , $\phi_{\mathbf{a},r} = \phi_{\mathbf{b},r}$. Since $M \models \mu(\mathbf{a})$, there is a $c \in M$ such that $M \models \theta(\mathbf{a}, c)$. Since $r < s$ and $\phi_{\mathbf{a},s} = \phi_{\mathbf{b},s}$, $\phi_{\mathbf{a},r+1} = \phi_{\mathbf{b},r+1}$, which means that there is some $d \in M$ such that $\phi_{\mathbf{b},d,r} = \phi_{\mathbf{a},c,r}$. Thus by our induction hypothesis, $M \models \theta(\mathbf{b}, d)$ and thus $M \models \mu(\mathbf{b})$.

For each $n \in \omega$ and each pair \mathbf{a}, \mathbf{b} of n -tuples from M , if $\phi_{\mathbf{a},\alpha} = \phi_{\mathbf{b},\alpha}$ for all $\alpha < \beta$, then $\phi_{\mathbf{a},s} = \phi_{\mathbf{b},s}$ for some ill-founded $s < t$, since if $\phi_{\mathbf{a},r} \neq \phi_{\mathbf{b},r}$ for any $r < t$, then N thinks that there is a least such r , and there is no least ill-founded ordinal of N . It follows then that the Scott rank of M (in V) is exactly β . \square

Lemma 2.21 will make up part of the proof of our main theorem (Theorem 3.13). The proof is in fact a simplified part of the main argument in the proof of that theorem.

Lemma 2.21. *Suppose that \mathbf{K} is the class of reducts to τ of a class defined by a sentence $\phi \in L_{\omega_1,\omega}(\tau^+)$, where τ^+ is a countable vocabulary extending τ . If \mathbf{K} has a model in \aleph_1 that is locally τ -small, but is not $L_{\omega_1,\omega}(\tau)$ -small then \mathbf{K} has small models in \aleph_1 of club many distinct Scott ranks.*

Proof. Suppose that M is a model in \mathbf{K} with cardinality \aleph_1 that is locally τ -small but is not $L_{\omega_1,\omega}(\tau)$ -small. Fix a regular cardinal $\theta > 2^{2^{\aleph_1}}$. It suffices to show that for every countable elementary submodel X of $H(\theta)$ with τ, ϕ and M in X , there exists a small model in \mathbf{K} of cardinality \aleph_1 whose Scott rank is $X \cap \omega_1$. Fix such an X . Let P be the transitive collapse of X , and let $\rho: X \rightarrow P$ be the corresponding collapsing map. Then $\rho(\omega_1) = \omega_1^P$ is the ordinal $X \cap \omega_1$.

By iterating the construction in [13], one can find an elementary extension P' of P with corresponding elementary embedding $\pi: P \rightarrow N$, with critical point ω_1^P , such that ω_1^N is ill-founded and uncountable, and such that the wellfounded ordinals of N are exactly the members of ω_1^P . Since ω_1^N is ill-founded, Theorem 2.20 implies that $\pi(\rho(M))$ is $L_{\omega_1, \omega}(\tau)$ -small, with Scott rank equal to the longest wellfounded initial segment of ω_1^N , which is $X \cap \omega_1$. \square

3 Almost Galois Stability

Fixing a coding of hereditarily countable sets by real numbers, the notion of Galois types naturally induces an equivalence relation on the reals. For each countable $M \in \mathbf{K}$ we let E_M denote the corresponding equivalence relation for Galois types over M (this notation was used in [3]). If \mathbf{K} is \aleph_0 -presented, then each E_M is an analytic equivalence relation, and by Burgess's trichotomy for analytic equivalence relations, E_M has either countably many equivalence classes, \aleph_1 , or a perfect set of inequivalent reals.¹ Because there are two notions of weak-stability in the literature of AEC ([10, 21], we call the following notion *almost Galois ω -stability*.

Definition 3.1. \mathbf{K} is almost Galois ω -stable if for no countable model M , E_M has a perfect set of equivalence classes.

The next example shows that Galois types are very much a property of the monster model. If $M \prec N$ and $a \in N - M$, $\text{ga} - \text{tp}(a/M)$ cannot be determined by just looking at N in isolation.

Example 3.2. Let \mathbf{K} be the set of structures in the language with a single equivalence relation E that have infinitely many elements in each class and exactly \aleph_0 classes. Let $\prec_{\mathbf{K}}$ be the relation of first order elementarity. This gives an \aleph_0 -presentable class. There are \aleph_0 models in \aleph_1 (given by the number of classes that have cardinality \aleph_0 and \aleph_1 respectively). Let M be the \aleph_1 -saturated model in \mathbf{K} of cardinality \aleph_1 ; it has uncountably many elements in each class. Let M_0 be a countable submodel of M .

Given an element a of a model $N \in \mathbf{K}$, let $[a]_N$ denote the E -equivalence class of a as interpreted in N . Let \mathbf{K}' be the class of countable models $N \in \mathbf{K}$ containing M_0 for which

$$\{[a]_N : a \in M_0 \wedge |[a]_N \setminus [a]_{M_0}| = m\} \text{ is finite,}$$

for each $m \in \omega$ and every E -class in N intersection M_0 . For each $N \in \mathbf{K}'$, let $c_N : \omega \rightarrow \omega$ be defined by setting

$$c_N(m) = |\{[a]_N : a \in M_0 \wedge |[a]_N \setminus [a]_{M_0}| = m\}|.$$

Then for each $c: \omega \rightarrow \omega$ there is an $N \in \mathbf{K}'$ for which $c_N = c$, and for any two $N, N' \in \mathbf{K}'$, N and N' are isomorphic via an isomorphism fixing M_0 setwise if and only if $c_N = c_{N'}$. Furthermore, even among the elements N of \mathbf{K}' for which c_N is the constant function 1, there are 2^{\aleph_0} many models (corresponding naturally to the permutations of ω) which are not isomorphic via isomorphisms fixing M_0 pointwise, although they are isomorphic.

Finally, if N and N' are elements of \mathbf{K}' with $N \subseteq N'$, then $c_N = c_{N'}$ if and only if $[a]_N = [a]_{N'}$ for every $a \in M_0$ with $[a]_N$ finite (in which case there is an isomorphism between N and N' fixing M_0 pointwise). To see this, suppose that the latter statement is false and consider the least m for which there is an $a \in M_0$ with $m = |[a]_N \setminus [a]_{M_0}| \neq |[a]_{N'} \setminus [a]_{M_0}|$. Then $c_N(m) > c_{N'}(m)$.

¹Alternately, letting τ be the vocabulary associated to \mathbf{K} , the set of τ -structures with domain ω can be viewed as a Polish space, with the set of countable models in \mathbf{K} as an analytic subset. See [7].

Remark 3.3 (Amalgamation, joint embedding, and maximal models). In this remark, we collect a number of easy and well-known observations about the properties in its title. These observations should provide a background for understanding the choice of some ‘background hypotheses’ below. If an AEC has no maximal models then it has arbitrarily large models. In general the converse fails; but the converse holds under joint embedding with one exception: an AEC with a *unique* maximal model² may satisfy joint embedding.

Assuming amalgamation, the relation ‘ M and N have a common strong extension’ is an equivalence relation and each equivalence class is an AEC with joint embedding. Often we will assume amalgamation and joint embedding to avoid assuming only amalgamation and then having to restrict to one joint embedding class. Failure to make this assumption yields to trivial counterexamples. There are no universal models for the class of algebraically closed fields (because of characteristic) but fixing the characteristic (that is the joint embedding class) yields a family of classes each with the joint embedding property. The technique of restricting to an equivalence class is illustrated by the generalization of Theorem 3.13 to Corollary 3.20.

Amalgamation and some form of joint embedding easily allows one to show the following (see Corollary 8.23 of [1]); we give two variants. Note that in the second case the Galois-saturated model may not be unique.

Lemma 3.4. *Suppose that \mathbf{K} is almost Galois ω -stable and satisfies amalgamation in \aleph_0 .*

1. *If \mathbf{K} has joint embedding in \aleph_0 then there is a unique Galois-saturated model M in \aleph_1 .*
2. *If $N \in \mathbf{K}$ is countable and has an uncountable extension in \mathbf{K} , then there is a Galois-saturated model M in \aleph_1 with $N \prec_{\mathbf{K}} M$.*

Proof. For the first part, carefully construct an interweaving enumeration the Galois types over an increasing chain of countable models in order type ω_1 so that each Galois type over each model in the chain is realized. For uniqueness, suppose that M and M' are Galois-saturated models in \aleph_1 . Choose countable $M_0 \prec_{\mathbf{K}} M$ and $M'_0 \prec_{\mathbf{K}} M'$. By joint embedding there is a countable M_1 that $\prec_{\mathbf{K}}$ -extends both M_0 and M'_0 . Applying Galois saturation, a countable induction that M_1 is a $\prec_{\mathbf{K}}$ -structure of both M and M' . Then an \aleph_1 induction using Galois saturation shows M and M' are isomorphic (over M_1).

For the second part, let \mathbf{K}_N be the equivalence class under joint embedding of the models that are jointly embeddable with N . Apply the first argument to this class. $\square_{3.4}$

Note that without joint embedding we cannot conclude uniqueness of Galois saturated models. As in the situation of Lemma 3.4, there may be models which are Galois saturated with respect to a sub-AEC that are mutually non-embeddable. In particular, there may be countable models that are not extendible, even when there is a unique Galois-saturated model in \aleph_1 .

For any AEC \mathbf{K} , if $M, N \in \mathbf{K}$ and $M \prec_{\mathbf{K}} N$, then M is a substructure of N , but the definition of AEC does not require even that M be a first-order elementary submodel of N . Before proving the main result of this section, Theorem 3.13, we prove a lemma which reduces the proof to the case where $M \prec_{\mathbf{K}} N$ implies $L_{\omega_1, \omega}(\tau)$ -elementarity. A similar reduction appears in Theorem 3.6 E) of [23] and Lemma 2.5 of [17].

Definition 3.5. *Let \mathbf{K} be an AEC in a countable similarity type τ , with Löwenheim-Skolem number \aleph_0 , such that \mathbf{K} has a unique Galois-saturated model M in \aleph_1 that is small.*

Let $\mathbf{K}^ = \{N \in \mathbf{K} : |N| = \aleph_0 \wedge N \prec_{\mathbf{K}'} M\}$, where $N_0 \prec_{\mathbf{K}'} N_1$ if $N_0 \prec_{\mathbf{K}} N_1$ and $N_0 \prec_{\infty, \omega} N_1$.*

Let $(\mathbf{K}', \prec_{\mathbf{K}'})$ be the closure of $(\mathbf{K}^, \prec_{\mathbf{K}'})$ under isomorphism and direct limits of arbitrary length.*

²Maximal means there is no extension, even one isomorphic to itself.

To discuss the relationship between (almost) Galois stability of \mathbf{K} and \mathbf{K}' , we introduce some notation. We first give a standard equivalent for the definition of Galois type, but parameterized for the comparisons we need here. The class \mathbf{K}_0 below will be \mathbf{K} or \mathbf{K}' in our applications. This construction is implicit in [23] and in the extension of those arguments towards the construction of examples of a good frame in [22] and chapter III of [21]. The next lemma shows the properties of the induced class \mathbf{K}' . We describe a slightly more general situation from [21] in Remark 3.10

Notation 3.6. Let \mathbf{K}_0 be an AEC with a (\mathbf{K}_0, \aleph_1) -homogenous-universal model M in \aleph_1 .

1. If $M_0 \prec_{\mathbf{K}_0} M$, $\mathbb{S}_{\mathbf{K}_0}(M_0)$ is the collection of orbits of elements of M under $\text{aut}_{M_0}(M)$ (the automorphisms of M fixing M_0 pointwise).
2. $\alpha(\mathbf{K}_0) = \sup\{|\mathbb{S}_{\mathbf{K}_0}(M_0)| : M_0 \in \mathbf{K}_0, |M_0| = \aleph_0\}$.

We need to require the joint embedding property to guarantee that (\mathbf{K}, \aleph_1) -homogeneous-universal is equivalent to Galois saturated. Most of the argument for the next lemma would work if we just assume there is a unique Galois saturated model (which is small); but it might not be universal (in either \mathbf{K} or \mathbf{K}'). (See Chapter 16 of [1] or Remark 1 of [20] for more detailed remarks.)

Lemma 3.7. Let \mathbf{K} be an AEC in a countable similarity type τ , with Löwenheim-Skolem number \aleph_0 , with joint embedding and the amalgamation property in \aleph_0 . Suppose further that unique Galois-saturated model M in \aleph_1 is small. Then the following hold.

1. $(\mathbf{K}', \prec_{\mathbf{K}'})$ is an AEC with Löwenheim-Skolem number \aleph_0 .
2. M is (\mathbf{K}', \aleph_1) -homogenous-universal.
3. $(\mathbf{K}', \prec_{\mathbf{K}'})$ satisfies amalgamation in \aleph_0 .
4. For every $M_0 \in \mathbf{K}'_{\aleph_0}$, $\mathbb{S}_{\mathbf{K}}(M_0) = \mathbb{S}_{\mathbf{K}'}(M_0)$.
5. $\alpha(\mathbf{K}) = \alpha(\mathbf{K}')$.
6. If $(\mathbf{K}, \prec_{\mathbf{K}})$ is \aleph_0 -presented then so is $(\mathbf{K}', \prec_{\mathbf{K}'})$.
7. \mathbf{K}' is \aleph_0 -categorical.

Proof. 1) The coherence and unions of chains axioms are immediate on \mathbf{K}^* . For Löwenheim-Skolem, note that M can be written as an increasing chain of \mathbf{K}' -submodels. Thus, \mathbf{K}^* is a weak AEC in the sense of Definition 16.10 of [1] and so $(\mathbf{K}', \prec_{\mathbf{K}'})$ is an AEC by Exercise 16.12 or earlier works of Shelah.

2) Let $M_0 \prec_{\mathbf{K}'} M_1$ be countable. Then there are \mathbf{K}' -maps f and g such that $f(M_0) \prec_{\mathbf{K}'} M$ and $g(M_1) \prec_{\mathbf{K}'} M$ by the definition of \mathbf{K}' . But since M is (\mathbf{K}, \aleph_1) -homogenous-universal, there is an h in $\text{aut}(M)$ mapping $f(M_0)$ onto $g(M_0)$. Since both $\prec_{\mathbf{K}}$ and $\prec_{\mathbf{K}'}$ are preserved by automorphisms, h is a \mathbf{K}' -map. So $h \circ g$ is a \mathbf{K}' embedding of M_1 into M extending f .

3) Suppose $M_0 \prec_{\mathbf{K}'} M_1, M_2$. Then there are \mathbf{K}' -embeddings of M_1 and M_2 over M_0 into M . So amalgamation holds.

4) The Galois types are determined by $\text{aut}_{M_0} M$ which does not depend on the choice of AEC.

5) We have that $\alpha(\mathbf{K}) \geq \alpha(\mathbf{K}')$ since the supremum is taken over a smaller set. But for each $M_0 \in \mathbf{K}'_{\aleph_0}$, there is an $M_1 \in \mathbf{K}'_{\aleph_0}$ with $M_0 \prec_{\mathbf{K}} M_1 \prec_{\mathbf{K}'} M$ and by the extendability of \mathbf{K} -Galois types, and part 4, $|\mathbb{S}_{\mathbf{K}}(M_0)| \leq |\mathbb{S}_{\mathbf{K}}(M_1)| = |\mathbb{S}_{\mathbf{K}'}(M_1)|$ so $\alpha(\mathbf{K}) = \alpha(\mathbf{K}')$.

6) Let τ' and $\tau'' = \tau' \cup \{P\}$ be the vocabularies which witness that \mathbf{K} is \aleph_0 -presented. Let ψ_1 be the τ' sentence whose reducts are the models in \mathbf{K} ; let ψ_2 be the τ'' sentence whose reducts are pairs (N, M) with $N \prec_{\mathbf{K}} M$. Further suppose ϕ is the Scott sentence of M . The following sentences witness that $(\mathbf{K}', \prec_{\mathbf{K}'})$ is \aleph_0 -presented: $\hat{\psi}_1 = \psi_1 \wedge \phi$ and $\hat{\psi}_2 = \psi_2 \wedge \chi$ where $(M, N) \models \chi$ if $M \prec_{L^*} N$ where L^* is least countable fragment containing ϕ .

7) is evident since N is small. $\square_{3.7}$

Conclusion 5 immediately yields.

Corollary 3.8. *Under the hypotheses of Lemma 3.7,*

- $(\mathbf{K}, \prec_{\mathbf{K}})$ is Galois ω -stable if and only if $(\mathbf{K}', \prec_{\mathbf{K}'})$ is;
- $(\mathbf{K}, \prec_{\mathbf{K}})$ is almost Galois ω -stable if and only if $(\mathbf{K}', \prec_{\mathbf{K}'})$ is.

Moreover, the hypothesis of joint embedding is in some ways only a convenience; see Corollary 3.20. If \mathbf{K} has the amalgamation property then joint embedability is an equivalence relation and each of the equivalence classes is an AEC with joint embedding preserving the other properties defining AEC's. At least one class fails Galois ω -stability if \mathbf{K} does. But some classes may not have any uncountable models.

The following variants on an example of Jarden and Shelah [11] will illustrate the situation and also provide some context for Theorem II.3.4 of [21]. That theorem aims to construct a good frame from an \aleph_0 -presentable class that has few models in \aleph_1 , is \aleph_0 -categorical, has amalgamation in \aleph_0 and is ω -Galois stable or at least ω -almost Galois stable. We show several of these conditions are necessary. In particular, these examples are not \aleph_0 -categorical. Note that one use of Lemma 3.7 is to extract an \aleph_0 -categorical AEC from a given AEC with few models in \aleph_1 . Recall that there are only \aleph_1 countable linear orders that are one transitive (any two points are automorphic) [16].

Example 3.9. Let τ contain equality, a binary symbol $<$, and another binary relation symbol E . Let $(\mathbf{K}, \prec_{\mathbf{K}})$ be the class of τ -structures such that each $M \in \mathbf{K}$ is a partially ordered set such that each component is a countable 1-transitive linear order. Further E is an equivalence relation; each class intersects each component in exactly one point. Moreover E induces an order-isomorphism between each pair of components. $M \prec_{\mathbf{K}} N$ means $M \subseteq N$ but each element of $N - M$ is incomparable with all elements of M .

\mathbf{K} is an \aleph_0 -presentable AEC. It has exactly \aleph_1 models in each infinite cardinality. It is almost Galois ω -stable but not Galois ω -stable. \mathbf{K}_{\aleph_0} satisfies the amalgamation property but does *not* satisfy the joint embedding property. There are in fact \aleph_1 , pairwise non-isomorphic Galois saturated models in \aleph_1 ; each model is \aleph_1 copies of a particular 1-transitive order.

There is no countable fragment L^* such that syntactic type in L^* is the same as the Galois type in \mathbf{K} .

Remark 3.10. In chapters I and II (e.g. II.3.4) of [21], Shelah makes a somewhat more general argument. Add to Definition 3.5 a third clause: For each countable $M \in \mathbf{K}$, let $\mathbf{K}_M = \{N \in \mathbf{K} : |N| = \aleph_0 \wedge M \prec_{\mathbf{K}'} N\}$, where $\prec_{\mathbf{K}'}$ is defined as before. It is again straightforward to see that each \mathbf{K}_M is an \aleph_0 categorical AEC. If there are less than 2^{\aleph_1} models in \aleph_1 of \mathbf{K} and a fortiori of each \mathbf{K}_M then under $2^{\aleph_0} < 2^{\aleph_1}$, \mathbf{K}_M has the amalgamation property and since all models are extension of a single one, the joint embedding property. Then Shelah argues that by way of the notion of ‘materialization of types’ (Chapter 1 of [21]) one can deduce almost Galois stability.

Because the joint embedding property fails, Lemma 3.7 does not apply to this example. Applying the construction in Definition 3.5 gives rise to \aleph_1 distinct \aleph_0 -presentable AEC; each is categorical in every infinite cardinality; each is ω -stable. In each derived AEC, Galois type is equivalent to syntactic type.

The refined AEC, where all components have the same order type, are indexed by ϕ_α for $\alpha < \omega_1$, which list the Scott sentences of countable transitive linear orders. Exercise 14.28 of Rosenstein [16] shows that the transitive order \mathbb{Z}^α has Scott rank $\omega \cdot \alpha + 1$. We return to the example of [11] to cast a little more light on the current situation.

Example 3.11. Let τ contain equality and a binary symbol $<$. Let $(\mathbf{K}, \prec_{\mathbf{K}})$ be the class of τ structures such that each $M \in \mathbf{K}$ is a partially ordered set such that each component is a countable 1-transitive linear order. $M \prec_{\mathbf{K}} N$ means $M \subseteq N$ but each element of $N - M$ is incomparable with all elements of M .

\mathbf{K} is an \aleph_0 -presentable AEC. It has exactly \aleph_1 countable models and 2^{\aleph_1} in \aleph_1 . It is almost Galois ω -stable but not Galois ω -stable. \mathbf{K}_{\aleph_0} satisfies the amalgamation property and the joint embedding property. Thus there is a unique Galois saturated model in \aleph_1 .

Neither Lemma 3.7 nor II.3.4 (page 285) of [21] applies because the Galois saturated model is not *locally small* in the first case and there are too many models in \aleph_1 in the second. Nevertheless there are \aleph_1 restrictions of \mathbf{K} to AEC \mathbf{K}_α , where models in \mathbf{K}_α contain only components satisfying ϕ_α . Each of them is Galois ω -stable. In each \mathbf{K}_α , galois types are equivalent to syntactic types in an appropriate fragment L_α .

Question 3.12. Find an example of an \aleph_0 -presented AEC with the joint embedding and amalgamation properties that has $< 2^{\aleph_1}$ models in \aleph_1 and is strictly almost Galois ω -stable.

By Theorem 3.13 below, \mathbf{K} must fail joint embedding or have at least \aleph_1 models in \aleph_1 .

Corollary 3.20 derives a slightly weaker conclusion in the absence of the joint embedding property.

Theorem 3.13. Suppose that \mathbf{K} is an \aleph_0 -presented AEC which satisfies amalgamation, and JEP for countable models, and that \mathbf{K} is almost Galois ω -stable. If \mathbf{K} has only countably many models in \aleph_1 , then

1. For every countable $N \in \mathbf{K}$ there is a countable fragment $L^*(\tau')$ of the expanded language τ' where constants are added for each member of N such that for every $M \in \mathbf{K}$ with $N \prec_{\mathbf{K}} M$ and $N \prec_{\infty, \omega} M$, M is $L^*(\tau')$ -atomic. This implies
2. \mathbf{K} is Galois ω -stable.

Proof. The proof of Theorem 3.13 takes up the rest of this section. By Corollary 2.8, all models in \mathbf{K} are small. Applying Lemma 3.4, let M be a small Galois-saturated model of cardinality \aleph_1 , and let ϕ be the Scott sentence of M . By Lemma 3.7 and Corollary 3.8, by replacing \mathbf{K} by \mathbf{K}' (but still calling it \mathbf{K}) we may assume that the relation $\prec_{\mathbf{K}}$ implies full $L_{\omega_1, \omega}(\tau)$ -elementarity.

Notation 3.14. Fix any countable model $M_0 \in \mathbf{K}$. Let $\tau' = \tau'_M$ be the extension of τ formed by adding new constant symbols c_i ($i \in \omega$), and let M' be a τ' -structure expanding M , where the interpretation of the c_i 's enumerates M_0 .

Now there are three cases; we will show cases 1) and 2a) contradict the hypothesis of almost Galois ω -stability while case 2b) implies statement 1) of Theorem 3.13 which yields statement 2): Galois ω -stability.

1. For some countable fragment $L^*(\tau')$ of $L_{\omega_1, \omega}(\tau')$, there are uncountably many $L^*(\tau')$ -types realized in M' .
2. For every countable fragment $L_0(\tau')$ of $L_{\omega_1, \omega}(\tau')$, only countably many $L_0(\tau')$ -types are realized in M' . Then one of the following holds.

- (a) The model M' is not $L_{\omega_1, \omega}(\tau')$ -small.
- (b) The model M' is $L_{\omega_1, \omega}(\tau')$ -small, so for some countable fragment $L^*(\tau')$, M' has a Scott sentence in $L^*(\tau')$;

In Case 1, there exists a perfect set of syntactic types in $L^*(\tau')$. Since $\prec_{\mathbf{K}}$ implies $L_{\omega_1, \omega}(\tau)$ -elementarity, this implies the existence of a perfect set of Galois types over M_0 , contradicting the almost Galois ω -stability of \mathbf{K} .

The bulk of the proof derives a contradiction from Case 2a. Since \mathbf{K} is almost Galois ω -stable but not Galois ω -stable, there exists a countable $M_0 \in \mathbf{K}$ such that E_{M_0} has exactly \aleph_1 equivalence classes and satisfies 2a). We use this model to show case 2a) is impossible. Note that only this case requires that there are only countably many models in \aleph_1 .

Definition 3.15. *Suppose that a model M with cardinality \aleph_1 is the union of an uncountable chain of countable models $\langle M_\alpha : \alpha < \omega_1 \rangle$. For each $\alpha < \omega_1$, let F_α be an automorphism of M mapping M_0 onto M_α . Then we say that $\langle M_\alpha, F_\alpha : \alpha < \omega_1 \rangle$ is a nice decomposition of M , and we let $F_{\alpha, \beta}$ denote $F_\beta \circ F_\alpha^{-1}$.*

Recall that ϕ is the Scott sentence for M . Let $\bar{M} = \langle M_\alpha : \alpha < \omega_1 \rangle$ be such that (as above) M_0 is the model enumerated by \mathbf{c} , $M = \bigcup_{\alpha < \omega_1} M_\alpha$ and the following hold for each $\alpha < \omega_1$:

- M_α is a countable element of \mathbf{K} ;
- $M_\alpha \prec_{\mathbf{K}} M$;
- $M_\alpha \models \phi$;
- M_α is a proper subset of $M_{\alpha+1}$;
- if α is a limit ordinal, then $M_\alpha = \bigcup_{\beta < \alpha} M_\beta$.

The models M_α are all isomorphic, as they satisfy the same Scott sentence. As M is Galois saturated, there is a set $\bar{F} = \{F_\alpha : \alpha < \omega_1\}$ such that $\langle M_\alpha, F_\alpha : \alpha < \omega_1 \rangle$ is a nice decomposition of M .

Let τ^+ be the expansion of our vocabulary τ' to the τ' of Theorem 2.5 (i.e., add the symbols E_n, f_n ($n \in \omega$), and a binary relation ordering the domain of M in order type ω_1 ; alternately, using Theorem 2.20 we could skip this step). Fix a regular cardinal θ large enough so that M', τ^+, \bar{M} and \bar{F} are elements of $H(\theta)$ (to apply the methods of [3], we need θ to be larger than $2^{2^{\aleph_1}}$).

Let $\langle X_\alpha : \alpha < \omega_1 \rangle$ be a properly \subseteq -increasing continuous chain of countable elementary submodels of \mathcal{A} . In particular $\omega_1^A \in X_0$ and for every $\alpha < \omega_1$ there is a countable ordinal $\beta \in X_{\alpha+1} - X_\alpha$. For each $\alpha < \omega_1$, let P_α be the transitive collapse of X_α , and let $\rho_\alpha : X_\alpha \rightarrow P_\alpha$ be the corresponding collapsing map. Then $\rho_\alpha(\omega_1) = \omega_1^{P_\alpha}$ is the ordinal $X_\alpha \cap \omega_1$.

The following is a paraphrase of Theorem 2.1 of [9] (Hutchinson built on work of Keisler and Morley [13]; Enayat provides a useful source on this work in [5]). The following argument can also be carried out via iterated ultrapowers as in [3]. Section 4 of [9] describes the fragment of ZFC needed for Fact 3.16; this fragment is easily seen to follow from the theory ZFC° of [3].

Fact 3.16. *Let \mathcal{B} be a countable model of ZFC and c a regular cardinal in \mathcal{B} . Then there is a countable elementary extension \mathcal{C} of \mathcal{B} such that each a such that $\mathcal{B} \models a \in c$ is fixed (i.e. has no new elements in \mathcal{C}) but c is enlarged and there is a least new element of \mathcal{C} .*

Either iterating the construction in Fact 3.16, or by an iteration of ultrapowers of models of set theory as in Lemma 1.5 of [3], construct a family $\{P'_\alpha : \alpha < \omega_1\}$ of countable models of set theory so that, for each $\alpha < \omega_1$, there is an elementary extension of P_α to P'_α (with corresponding elementary embedding $\chi_\alpha : P_\alpha \rightarrow P'_\alpha$) such that

1. the critical point of χ_α is $\omega_1^{P_\alpha}$, so $\omega_1^{P_\alpha}$ is an initial segment of $\omega_1^{P'_\alpha}$;
2. $\omega_1^{P'_\alpha}$ is ill-founded,
3. in V , there is a continuous increasing ω_1 -sequence $\langle t'_\gamma : \gamma < \omega_1 \rangle$ consisting of elements of $\omega_1^{P'_\alpha}$

Item 3 above implies in particular that each $\omega_1^{P'_\alpha}$ is uncountable. Each P'_α can be realized as the union of an increasing elementary chain of models $\langle P_\gamma : \gamma < \omega_1 \rangle$, where $P_0^\alpha = P_\alpha$,

$$P'_\alpha = \bigcup_{\gamma < \omega_1} P_\gamma^\alpha$$

for limit α , and each $P_{\gamma+1}^\alpha$ can be obtained by applying Fact 3.16 (or a generic ultrapower) to P_γ^α . Then each t'_γ (the c of Fact 3.16) can be taken to be $\omega_1^{P_\gamma^\alpha}$.

Recall that M is the union of the continuous \subseteq -increasing chain $\langle M_\alpha : \alpha < \omega_1 \rangle$. It follows then for each $\alpha < \omega_1$, that $M_{\omega_1^{P_\alpha}} = \rho_\alpha(M) \subset P_\alpha$, and that $M_{\omega_1^{P_\alpha}}$ has cardinality \aleph_1 in P_α . For each $\alpha < \omega_1$, let $N_\alpha = \chi_\alpha(M_{\omega_1^{P_\alpha}})$ and let $N'_\alpha = \chi_\alpha(\rho_\alpha(M'))$. Then each N'_α is an expansion of N_α via the given enumeration of M_0 by the constants c_i , and it has cardinality \aleph_1 in P'_α .

In the argument for Theorem 2.5 replace the appeal to Lopez-Escobar (Theorem 5.3.8 of [1]) with the observation that the induced ordering on N'_α is not well-founded by construction. The rest of the argument for Theorem 2.5 (or Theorem 2.20) shows that, in V , each N'_α is small for $L_{\omega_1, \omega}(\tau')$. Nevertheless, by the elementarity of $\chi_\alpha \circ \rho_\alpha$, each P'_α thinks that N'_α is not $L_{\omega_1, \omega}(\tau')$ -small.

Since \overline{M} is a sequence indexed by ω_1 in V (or in X_α), $\chi_\alpha(\rho_\alpha(\overline{M}))$ is a sequence indexed by $\omega_1^{P'_\alpha}$ in P'_α . So, in P'_α , for each element t of its ω_1 , there is a t -th element of the sequence, which we denote by M_t^α . Furthermore, in P'_α , $\chi_\alpha(\rho_\alpha(\overline{F}))$ is a set $\{F_t^\alpha : t \in \omega_1^{P'_\alpha}\}$ consisting of automorphisms of N_α , such that each $F_t^\alpha \in P'_\alpha$ is an automorphism of N_α sending M_0 to M_t^α . Each F_t^α is then an automorphism of N_α in V also.

Since each N'_α is small, each N_α is as well. Since we are assuming that there are *only countably many models* in \mathbf{K} of cardinality \aleph_1 , there exists an uncountable set $S \subseteq \omega_1$ such that N_{α_0} and N_{α_1} are isomorphic (in V) for all α_0, α_1 in S . Fix for a moment a pair of elements α_0, α_1 of S and an isomorphism $\pi : N_{\alpha_0} \rightarrow N_{\alpha_1}$. Applying item 3 above and the continuity (in the sense of P'_{α_j} , for $j = 0, 1$) of the sequences $\langle M_t^{\alpha_0} : t \in \omega_1^{P'_{\alpha_0}} \rangle$ and $\langle M_t^{\alpha_1} : t \in \omega_1^{P'_{\alpha_1}} \rangle$, there must be $t_0 \in \omega_1^{P'_{\alpha_0}}$ and $t_1 \in \omega_1^{P'_{\alpha_1}}$ such that π maps $M_{t_0}^{\alpha_0}$ onto $M_{t_1}^{\alpha_1}$. To see this, start with $\gamma_0 = 0$ and, for each $n \in \omega$, let γ_{n+1} be large enough so that

$$\pi[M_{t_{\gamma_0}}^{\alpha_0}] \subseteq M_{t_{\gamma_{n+1}}}^{\alpha_1}$$

and

$$\pi^{-1}[M_{t_{\gamma_n}}^{\alpha_1}] \subseteq M_{t_{\gamma_{n+1}}}^{\alpha_0}.$$

Then let $s_0 = t_{\sup_{n \in \omega} \gamma_n}^{\alpha_0}$ and let $s_1 = t_{\sup_{n \in \omega} \gamma_n}^{\alpha_1}$. By the continuity in item 3, the s_j 's are in the respective P'_{α_j} , for $j \in \{0, 1\}$. So, for each j , by the continuity in P'_{α_j} of $M_t^{\alpha_j}$,

$$M_{s_j}^{\alpha_j} = \bigcup_{n < \omega} M_{t_{\gamma_n}^{\alpha_j}}^{\alpha_j}.$$

Then $(F_{s_1}^{\alpha_1})^{-1} \circ \pi \circ F_{s_0}^{\alpha_0}$ is an isomorphism of N_{α_0} and N_{α_1} fixing M_0 setwise, though not necessarily pointwise.

Finally, we show that for each $\alpha_0 < \omega_1$ such an isomorphism is impossible for sufficiently large $\alpha_1 < \omega_1$.

Each model P'_α thinks that N'_α is small for every countable fragment of $L_{\omega_1, \omega}(\tau')$ but not $L_{\omega_1, \omega}(\tau')$ -small. Thus, from the point of view of P'_α , there is no ordinal t such that $\phi_{\bar{a}, t}(\bar{x}) \equiv \phi_{\bar{a}, t+1}(\bar{x})$ (in the terms of the Scott construction) for all finite tuples \bar{a} of N'_α . For each well-founded ordinal γ of P'_α (this includes the members of $\omega_1^{P'_\alpha} = \omega_1 \cap X_\alpha$, by item 1 above), and each finite tuple \bar{a} of N'_α , P'_α sees the same formula $\phi_{\bar{a}, \gamma}(\bar{x})$ that the true universe V does, which means that the Scott sentence for N'_α has rank at least $\omega_1 \cap X_\alpha$ (and slightly more than this, in fact, in the approach from [3]). Alternately, Lemma 2.21 implies that the Scott rank of N'_α is exactly the wellfounded part of $\omega_1^{P'_\alpha}$.

Now choose $\alpha_0, \alpha_1 \in S$ such that $\omega_1 \cap X_{\alpha_1}$ is greater than the Scott rank (in V) of N'_{α_0} . Since permuting the constants c_i in terms of their enumeration of M_0 has no effect on the rank of the Scott sentence for N'_{α_1} , there cannot be then an isomorphism of N_{α_0} and N_{α_1} fixing M_0 setwise, since this would imply that N'_{α_0} and N'_{α_1} have the same Scott rank (indeed, their Scott sentences would differ only by a permutation of the c_i 's). Thus we have a contradiction in case 2a.

We have ruled out cases 1) and 2a) and are left with case 2b). We show that Case 2b) gives the conclusions of Theorem 3.13. We use the following remark.

Remark 3.17. Suppose that a τ -structure M is small. Then there is a countable fragment L_1 of $L_{\omega_1, \omega}(\tau)$ such that M is L_1 -atomic. That is, for any $\mathbf{a} \in M$, there is $\chi_{\mathbf{a}}(\mathbf{x}) \in L_1$ such that for any $\lambda(\mathbf{x}) \in L_{\omega_1, \omega}$ if $M \models \lambda(\mathbf{a})$, then

$$M \models (\forall \mathbf{x})[\chi_{\mathbf{a}}(\mathbf{x}) \rightarrow \lambda(\mathbf{x})].$$

Namely, let L_1 be the least countable fragment containing the canonical Scott sentence of M .

Since we have reduced to case 2b) we have the hypotheses of the following Lemma for any countable $M_0 \in \mathbf{K}$. Note that although we have a Galois-saturated model in power \aleph_1 , *a priori*, it might realize countably many Galois types over some countable submodel.

Lemma 3.18. *Assume that M' is $L_{\omega_1, \omega}(\tau')$ -small and Galois saturated for \mathbf{K} . Then for some $L^*(\tau')$, M' is $L^*(\tau')$ -atomic. This implies that M realizes only countably many Galois types over M_0 .*

Proof. By Remark 3.17 applied in the vocabulary τ' , M' is atomic in $L^*(\tau')$, the countable fragment in which M' has a Scott sentence; this is Theorem 3.13.1. We will show that for any $a \in M$ the $L^*(\tau')$ -type of a determines the Galois type (in \mathbf{K}) of a over M_0 . Since M' is $L_{\omega_1, \omega}(\tau')$ -small, it follows that only countably many Galois types over M_0 are realized in M . Suppose that some $a, b \in M$ realize the same $L^*(\tau')$ -type in M' . Then this type is given by a formula in $L^*(\tau')$, by $L^*(\tau')$ -atomicity. There exists a countable $\hat{M} \in \mathbf{K}$ such that $M_0 a b \subset \hat{M} \prec_{L^*(\tau')} M$, and, as \hat{M} is $L^*(\tau')$ -atomic, there exists an automorphism g of \hat{M} , fixing M_0 pointwise with $g(a) = b$. Thus, a and b have the same Galois type over M_0 . So M realizes only countably many Galois types over M_0 . Since M_0 was an arbitrary countable model, we have Theorem 3.13.2. $\square_{3.18}$

This completes the proof of the main theorem. $\square_{3.13}$

Remark 3.19. Note that argument ruling out case 2a) uses the set theoretic argument to find \aleph_1 τ' -small models in \aleph_1 with distinct τ' -Scott rank. By the automorphism argument, this contradicts the assumption that there are only \aleph_0 τ -models in \aleph_1 .

We return to the slightly more complicated situation where joint embedding is not assumed.

Corollary 3.20. *Suppose \mathbf{K} is an AEC satisfying the hypotheses of Theorem 3.13 except the joint embedding property. Then \mathbf{K} contains a countable family of sub-AEC \mathbf{K}_i , which each satisfy Theorem 3.13.*

Proof. Since there are only countably many models in \aleph_1 , the equivalence relation of common extension has at most countably many classes. Each satisfies the hypothesis and therefore the conclusion of Theorem 3.13 $\square_{3.20}$

4 Categoricity

It is shown in [3] (see Theorems 2.1 and 6.2) that, given an \aleph_0 -presented AEC \mathbf{K} , the statement that \mathbf{K} has an uncountable model is Σ_1^1 in a real coding \mathbf{K} , and the statement that \mathbf{K} is almost Galois ω -stable is Π_1^1 in a real coding \mathbf{K} . These statements are therefore absolute. Amalgamation for such a \mathbf{K} is easily seen to be Π_2^1 in a code for \mathbf{K} . In this section we apply Theorem 3.13 to prove the following theorem.

Theorem 4.1. *Suppose that \mathbf{K} is an \aleph_0 -presented almost Galois ω -stable AEC with Löwenheim-Skolem number \aleph_0 , satisfying amalgamation and having a model of cardinality \aleph_1 . The assertion that \mathbf{K} is \aleph_1 -categorical is then absolute, as it is equivalent to a statement of the form $\phi_1 \wedge \phi_2$, where ϕ_1 and ϕ_2 are Π_2^1 and Σ_2^1 , respectively, in a code for \mathbf{K} .*

Proof. Let \mathbf{K}' be the result of removing from \mathbf{K} all countable models with no uncountable extensions in \mathbf{K} . Then \mathbf{K}' is an AEC, and the proof of Theorem 2.1 of [3] shows that \mathbf{K}' is still \aleph_0 -presented (as $M \in \mathbf{k}$ having an uncountable \mathbf{K} -extension is Σ_1^1), with the same real parameter as \mathbf{K} .

As \mathbf{K} satisfies amalgamation, \mathbf{K}' does as well. It suffices then to prove the theorem for \mathbf{K}' .

Let ϕ_1 be the statement that joint embedding holds for \mathbf{K}' . Then ϕ_1 is Π_2^1 in a code for \mathbf{K} .

Let ϕ_2 be the conjunction of the following statements.

1. All uncountable models in \mathbf{K} satisfy the same Scott sentence in $L_{\omega_1, \omega}$.

\square This needs some detail - is the statement that all \mathbf{K} -extendible countable models in \mathbf{K} (i.e. all members of \mathbf{K}') satisfy the same Scott sentence?

2. There exist a countable $N \in \mathbf{K}'$ and a countable fragment L_1 of the expanded language where constants are added for each member of N such that for every $M \in \mathbf{K}'$ with $N \prec_{\mathbf{K}} M$ and $N \prec_{\infty, \omega} M$, M is L_1 -atomic.
3. There do not exist $N \prec_{\mathbf{K}} M$ with N countable and M uncountable, such that only countably many Galois types over N are realized in M , and some Galois type over N is not realized in M .

Clause (1) is naturally expressed as a Σ_2^1 statement (using the proof of Theorem 2.1 in [3]) in a real parameter for \mathbf{K} (and can also be expressed by a Π_2^1 statement saying that all models in \mathbf{K} which are

uncountable in countable ω models of ZFC° are isomorphic). Clause (2) is easily seen to be Σ_2^1 in a real parameter for \mathbf{K} . Theorem 6.1 of [3] shows that clause (3) is Π_1^1 in a real coding \mathbf{K} .

Suppose now that \mathbf{K} is \aleph_1 -categorical. Then ϕ_1 clearly holds. Corollary 2.8 implies that all uncountable models of any \aleph_1 -categorical \aleph_0 -presented AEC satisfy the same Scott sentence, giving clause (1). By Lemma 3.13.1, we have clause (2) for all countable $N \in \mathbf{K}'$. Lemma 3.13.2 implies Galois ω -stability for \mathbf{K}' . Thus by Lemma 3.4 there is a Galois saturated model of cardinality \aleph_1 in \mathbf{K} , which implies clause (3) by categoricity.

For the other direction, ϕ_1 , clause (1) and Lemma 3.4 imply that \mathbf{K} has a small uncountable Galois saturated model. By Lemma 3.18, clause (2) implies that \mathbf{K} is Galois ω -stable. Then item (3) implies that the Galois saturated model is the only model in \mathbf{K} of cardinality \aleph_1 . \square

References

- [1] John T. Baldwin. *Categoricity*. Number 51 in University Lecture Notes. American Mathematical Society, Providence, USA, 2009. www.math.uic.edu/~jbaldwin.
- [2] J.T. Baldwin, T. Hyttinen, and M. Kesälä. Beyond first order logic: From number of structures to structure of numbers part II. *Bulletin of Iranian Math. Soc.*, 2011. Available online at <http://www.iranjournals.ir/ims/bulletin/> in press.
- [3] J.T. Baldwin and Paul Larson. Iterated elementary embeddings and the model theory of infinitary logic. preprint http://homepages.math.uic.edu/~jbaldwin/pub/galois_typesjan25.pdf.
- [4] H. Becker. Polish group actions: Dichotomies and generalized elementary embeddings. *The Journal of the American Mathematical Society*, 11:397–449, 1998.
- [5] A. Enayat. On certain elementary extensions of models of set theory. *Transactions of the American Mathematical Society*, 283:705–715, 1984.
- [6] Su Gao. On automorphism groups of countable structures. *The Journal of Symbolic Logic*, 63:891–896, 1996.
- [7] Su Gao. *Invariant Descriptive Set Theory*. CRC Press, 2009.
- [8] V. Harnik and M. Makkai. A tree argument in infinitary model theory. *Proceedings of the American Mathematical Society*, 67:309–314, 1977.
- [9] John E. Hutchinson. Elementary extensions of countable models of set theory. *J. Symbolic Logic*, 41:139–145, 1976.
- [10] T. Hyttinen and M. Kesälä. Independence in finitary abstract elementary classes. *Ann. Pure Appl. Logic*, 143(1-3):103–138, 2006.
- [11] A. Jarden and S. Shelah. Good frames with a weak stability. preprint: Shelah archive Sh875, 201x.
- [12] H.J. Keisler. *Model theory for Infinitary Logic*. North-Holland, 1971.
- [13] H.J. Keisler and M. Morley. Elementary extensions of models of set theory. *Israel Journal of Mathematics*, 5:331–348, 1968.

- [14] D. W. Kueker. Abstract elementary classes and infinitary logics. *Annals of Pure and Applied Logic*, 156:274–286, 2008.
- [15] D. Marker. Scott ranks of counterexamples to Vaught’s conjecture. Notes from 2011; <http://homepages.math.uic.edu/~marker/harrington-vaught.pdf>.
- [16] J. Rosenstein. *Linear Orderings*. Academic Press, New York, 1982.
- [17] S. Shelah. Categoricity in \aleph_1 of sentences in $L_{\omega_1, \omega}(Q)$. *Israel Journal of Mathematics*, 20:127–148, 1975. paper 48.
- [18] S. Shelah. *Classification Theory and the Number of Nonisomorphic Models*. North-Holland, 1978.
- [19] S. Shelah. Classification theory for nonelementary classes. I. the number of uncountable models of $\psi \in L_{\omega_1 \omega}$ part A. *Israel Journal of Mathematics*, 46:3:212–240, 1983. paper 87a.
- [20] S. Shelah. Categoricity of abstract elementary class in two successive cardinals. *Israel Journal of Mathematics*, 126:29–128, 2001. paper 576.
- [21] S. Shelah. *Classification Theory for Abstract Elementary Classes*. Studies in Logic. College Publications www.collegepublications.co.uk, 2009. Binds together papers 88r, 600, 705, 734 with introduction E53.
- [22] S. Shelah. Categoricity of abstract elementary classes: going up inductive step. preprint 600, 200x.
- [23] Saharon Shelah. Classification of nonelementary classes II, abstract elementary classes. In J.T. Baldwin, editor, *Classification theory (Chicago, IL, 1985)*, pages 419–497. Springer, Berlin, 1987. paper 88: Proceedings of the USA–Israel Conference on Classification Theory, Chicago, December 1985; volume 1292 of *Lecture Notes in Mathematics*.