

Ascending paths and forcings that specialize higher Aronszajn trees

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Abstract. We study trees of uncountable regular heights containing ascending paths of small width. This combinatorial property of trees generalizes the concept of a cofinal branch, and it causes trees to be non-special not only in V , but also in every cofinality-preserving outer model of V . Moreover, under certain cardinal-arithmetic assumptions, the non-existence of such paths through a tree turns out to be equivalent to the statement that the given tree is special in a cofinality preserving forcing extension of the ground model. We will use certain combinatorial principles to construct trees without cofinal branches containing ascending paths of small width. In contrast, we will also present a number of consistency results on the non-existence of such trees.

As an application of our results, we show that the consistency strength of a potential forcing axiom for σ -closed, well-met partial orders satisfying the \aleph_2 -chain condition and collections of \aleph_2 -many dense subsets is at least a weakly compact cardinal. In addition, we will use our results to show that the infinite productivity of the Knaster property characterizes weak compactness in canonical inner models. Finally, we study the influence of the Proper Forcing Axiom on trees containing ascending paths.

1. Introduction. The purpose of this paper is to study combinatorial properties of trees of uncountable regular heights that cause these trees to be non-special in a very absolute way. Recall that a partial order \mathbb{T} is a *tree* if it has a unique minimal element $\text{root}(\mathbb{T})$ and all sets of the form $\text{pred}_{\mathbb{T}}(t) = \{s \in \mathbb{T} \mid s <_{\mathbb{T}} t\}$ are well-ordered by $<_{\mathbb{T}}$ for every $t \in \mathbb{T}$. Given a tree \mathbb{T} and $t \in \mathbb{T}$, we define $\text{lh}_{\mathbb{T}}(t)$ to be the order-type of $\langle \text{pred}_{\mathbb{T}}(t), <_{\mathbb{T}} \rangle$ and we define $\text{ht}(\mathbb{T}) = \sup_{t \in \mathbb{T}} \text{lh}_{\mathbb{T}}(t)$ to be the *height* of \mathbb{T} . Moreover, we define $\mathbb{T}(\gamma) = \{t \in \mathbb{T} \mid \text{lh}_{\mathbb{T}}(t) = \gamma\}$ and $\mathbb{T}_{<\gamma} = \{t \in \mathbb{T} \mid \text{lh}_{\mathbb{T}}(t) < \gamma\}$ for every tree \mathbb{T} and $\gamma < \text{ht}(\mathbb{T})$. Finally, given a subset S of $\text{ht}(\mathbb{T})$, we de-

2010 *Mathematics Subject Classification*: Primary 03E05; Secondary 03E35, 03E55.

Key words and phrases: special trees, Aronszajn trees, specialization forcings for trees, productivity of chain conditions, Knaster property, walks on ordinals, Proper Forcing Axiom.

Received 1 March 2016; revised 22 November 2016.

Published online 20 March 2017.

fine $\mathbb{T} \upharpoonright S$ to be the suborder of \mathbb{T} whose underlying set is the set $\bigcup\{\mathbb{T}(\gamma) \mid \gamma \in S\}$.

One of the most basic questions about trees of infinite height is the question of the existence of *cofinal branches*, i.e. the existence of a subset B of the tree \mathbb{T} such that B is linearly ordered by $<_{\mathbb{T}}$ and the set $\{\text{lh}_{\mathbb{T}}(t) \mid t \in B\}$ is unbounded in $\text{ht}(\mathbb{T})$. In particular, the existence of a cofinal branch is upwards-absolute between transitive models of set theory. As phrased by Todorćević in the introduction of [27, Section 6.1], it turns out that a large class of trees of uncountable regular height have no cofinal branches for *very special reasons*.

In what follows, θ will denote an uncountable regular cardinal, and unless otherwise stated, \mathbb{T} will denote a tree of height θ .

DEFINITION 1.1 (Todorćević). Let S be a subset of θ .

- (i) A map $r : \mathbb{T} \upharpoonright S \rightarrow \mathbb{T}$ is *regressive* if $r(t) <_{\mathbb{T}} t$ for every $t \in \mathbb{T} \upharpoonright S$ that is not minimal in \mathbb{T} .
- (ii) We say that S is *non-stationary with respect to \mathbb{T}* if there is a regressive map $r : \mathbb{T} \upharpoonright S \rightarrow \mathbb{T}$ with the property that for every $t \in \mathbb{T}$ there is a function $c_t : r^{-1}\{t\} \rightarrow \theta_t$ such that θ_t is a cardinal smaller than θ and c_t is injective on $\leq_{\mathbb{T}}$ -chains.
- (iii) The tree \mathbb{T} is *special* if the set θ is non-stationary with respect to \mathbb{T} .

Todorćević showed that the above definition generalizes the classical definition of special trees of successor height, i.e. trees of height ν^+ for some infinite cardinal ν that are the union of ν -many antichains (see [24, Theorem 14]). Moreover, his result shows that a tree of height ν^+ is special if and only if the set of all ordinals less than ν^+ of cofinality $\text{cof}(\nu)$ is non-stationary with respect to the given tree.

PROPOSITION 1.2. *If S is a stationary subset of θ that is non-stationary with respect to \mathbb{T} , then there are no cofinal branches through \mathbb{T} . ■*

The above proposition directly shows that the non-existence of cofinal branches through special trees is absolute in a strong sense. If \mathbb{T} is special and W is an *outer model* of the ground model V (i.e. W is a transitive model of ZFC with $V \subseteq W$ and $\text{On} \cap V = \text{On} \cap W$) with the property that θ is a regular cardinal in W , then there are no cofinal branches through \mathbb{T} in W .

In this paper, we want to study special reasons that cause trees without cofinal branches to be non-special in a very absolute way. Examples of such properties were already studied by Baumgartner, Brodsky, Cummings, Devlin, Laver, Rinot, Shelah, Stanley, Todorćević, Torres Pérez and others (see, for example, [4], [6], [7], [23], [26] and [28]). For reasons described later, we will focus on the following property that directly generalizes the concept of cofinal branches and is a consequence of the properties studied in the

above papers. Moreover, this property is preserved in all cardinal-preserving outer models.

DEFINITION 1.3. Given a cardinal $\lambda > 0$, a sequence $\langle b_\gamma : \lambda \rightarrow \mathbb{T}(\gamma) \mid \gamma < \theta \rangle$ of functions is an *ascending path of width λ through \mathbb{T}* if for all $\bar{\gamma} < \gamma < \theta$, there are $\alpha, \bar{\alpha} < \lambda$ such that $b_{\bar{\gamma}}(\bar{\alpha}) <_{\mathbb{T}} b_\gamma(\alpha)$.

Then the existence of a cofinal branch through \mathbb{T} is equivalent to the existence of an ascending path of width 1 through \mathbb{T} . The following lemma shows that the same is true for ascending paths of any finite width. The proof of this result is a modification of Baumgartner's elegant proof of [3, Theorem 8.2]. It is contained in Section 3 below.

LEMMA 1.4. *If there is an ascending path of finite width through \mathbb{T} , then there is a cofinal branch through \mathbb{T} .*

In combination with the above lemma, the following basic observations show that the notion of an ascending path through a tree of height θ is non-trivial if we consider paths of width λ with $\omega \leq \lambda$ and $\lambda^+ < \theta$.

PROPOSITION 1.5.

- (i) *There is an ascending path of width θ through \mathbb{T} .*
- (ii) *Assume that $\theta = \nu^+$ for some cardinal ν . Then there is an ascending path of width ν through \mathbb{T} if and only if for every $\gamma < \theta$, there is $t \in \mathbb{T}(\gamma)$ such that for every $\gamma \leq \delta < \theta$ there is $u \in \mathbb{T}(\delta)$ with the property that $t <_{\mathbb{T}} u$.*

Proof. (i) Fix a sequence $\langle t_\gamma \in \mathbb{T}(\gamma) \mid \gamma < \theta \rangle$. Given $\gamma, \bar{\gamma} < \theta$, define $b_\gamma(\bar{\gamma})$ to be the unique element s of $\mathbb{T}(\gamma)$ with $s <_{\mathbb{T}} t_{\bar{\gamma}}$ if $\gamma < \bar{\gamma}$, and define $b_\gamma(\bar{\gamma}) = t_\gamma$ otherwise. The resulting sequence $\langle b_\gamma \mid \gamma < \theta \rangle$ is an ascending path of width θ through \mathbb{T} .

(ii) First, assume that for every $\gamma < \theta$ there is $t_\gamma \in \mathbb{T}(\gamma)$ such that for every $\gamma \leq \delta < \theta$ there is $u_{\gamma,\delta} \in \mathbb{T}(\delta)$ with $t_\gamma <_{\mathbb{T}} u_{\gamma,\delta}$. Given $\gamma < \theta$, fix a surjection $s_\gamma : \nu \rightarrow \gamma + 1$ and define $b_\gamma(\alpha) = u_{s_\gamma(\alpha),\gamma}$ for all $\alpha < \nu$. If $\bar{\gamma} < \gamma < \theta$, then there are $\alpha, \bar{\alpha} < \nu$ with $\bar{\gamma} = s_\gamma(\alpha) = s_{\bar{\gamma}}(\bar{\alpha})$ and hence $b_{\bar{\gamma}}(\bar{\alpha}) = t_{\bar{\gamma}} <_{\mathbb{T}} u_{\bar{\gamma},\gamma} = b_\gamma(\alpha)$. This shows that the resulting sequence $\langle b_\gamma \mid \gamma < \theta \rangle$ is an ascending path of width θ through \mathbb{T} .

Now, assume that $\langle b_\gamma \mid \gamma < \theta \rangle$ is an ascending path of width ν . If $\gamma < \theta$, then the regularity of θ implies that there is $\alpha < \nu$ with the property that the set $\{\delta < \theta \mid \exists \beta < \nu b_\gamma(\alpha) <_{\mathbb{T}} b_\delta(\beta)\}$ is unbounded in θ . This shows that for all $\gamma < \theta$ we can find $\alpha < \nu$ such that for every $\gamma \leq \delta < \theta$ there is $u \in \mathbb{T}(\delta)$ with $b_\gamma(\alpha) <_{\mathbb{T}} u$. ■

The next lemma shows how ascending paths cause certain trees to be non-special. Its proof is a generalization of the proof of [28, Proposition 2.3]. Given an infinite regular cardinal $\kappa < \theta$, we let S_κ^θ denote the set of all limit

ordinals less than θ of cofinality κ . Moreover, given some cardinal $\lambda < \theta$, we let $S_{>\lambda}^\theta$ denote the set of all limit ordinals less than θ of cofinality greater than λ . The sets $S_{<\lambda}^\theta$, $S_{\leq\kappa}^\theta$ and $S_{\geq\kappa}^\theta$ are defined analogously.

LEMMA 1.6. *Let $\lambda < \theta$ be a cardinal with the property that θ is not a successor of a cardinal of cofinality less than or equal to λ and let $S \subseteq S_{>\lambda}^\theta$ be stationary in θ . If S is non-stationary with respect to \mathbb{T} , then there is no ascending path of width λ through \mathbb{T} .*

Proof. Assume that $\langle b_\gamma : \lambda \rightarrow \mathbb{T}(\gamma) \mid \gamma < \theta \rangle$ is an ascending path through \mathbb{T} . Let $r : \mathbb{T} \setminus S \rightarrow \mathbb{T}$ and $\langle c_t : r^{-1}\{t\} \rightarrow \theta_t \mid t \in \mathbb{T} \rangle$ witness that S is non-stationary with respect to \mathbb{T} . Then there is a club C in θ with $\theta_{r(b_{\bar{\gamma}(\alpha)})} < \gamma$ for all $\gamma \in C$, $\bar{\gamma} < \gamma$ and $\alpha < \lambda$. Since $S \subseteq S_{>\lambda}^\theta$ is stationary in θ , we can find $\delta < \theta$ and $E \subseteq C \cap S$ stationary in θ such that the following statements hold for all $\delta \in E$ and $\alpha < \lambda$:

- (i) $r(b_\gamma(\alpha)) \in \mathbb{T}_{<\delta}$.
- (ii) If $r(b_\gamma(\alpha)) = r(b_{\bar{\gamma}(\alpha)})$ for some $\bar{\gamma} < \gamma$, then $c_{r(b_{\bar{\gamma}(\alpha)})}(b_\gamma(\alpha)) < \delta$.

By our assumptions, there is a cardinal $\nu < \theta$ of cofinality greater than λ and a surjection $s : \nu \rightarrow \delta$. Fix a strictly increasing cofinal sequence $\langle \nu_\xi \mid \xi < \text{cof}(\nu) \rangle$ in ν . Given $\gamma \in E$, there is a minimal $\xi_\gamma < \text{cof}(\nu)$ such that for all $\alpha < \lambda$, there are $\zeta_0, \zeta_1 < \nu_{\xi_\gamma}$ with $r(b_\gamma(\alpha)) \in \mathbb{T}(s(\zeta_0))$ and, if $r(b_\gamma(\alpha)) = r(b_{\bar{\gamma}(\alpha)})$ for some $\bar{\gamma} < \gamma$, then $c_{r(b_{\bar{\gamma}(\alpha)})}(b_\gamma(\alpha)) = s(\zeta_1)$. Then there is $U \subseteq E$ unbounded in θ and $\xi_* < \text{cof}(\nu)$ such that $\xi_* = \xi_\gamma$ for all $\gamma \in U$.

Let γ_* denote that ν th element in the monotone enumeration of U . Given $\gamma \in U \cap \gamma_*$, our assumptions imply that there are $\alpha, \beta < \lambda$ with $b_\gamma(\alpha) <_{\mathbb{T}} b_{\gamma_*}(\beta)$. Since the cofinality of ν is greater than λ , there are $\alpha_*, \beta_* < \lambda$ such that the set

$$A = \{\gamma \in U \cap \gamma_* \mid b_\gamma(\alpha_*) <_{\mathbb{T}} b_{\gamma_*}(\beta_*)\}$$

has cardinality ν . Pick a function $f : A \rightarrow \nu_{\xi_*} \times \nu_{\xi_*}$ with the property that $f(\gamma) = \langle \zeta_0, \zeta_1 \rangle$ implies that $r(b_\gamma(\alpha_*)) \in \mathbb{T}(s(\zeta_0))$ and, if $r(b_\gamma(\alpha_*)) = r(b_{\bar{\gamma}(\alpha_*)})$ for some $\bar{\gamma} < \gamma$, then $c_{r(b_{\bar{\gamma}(\alpha_*)})}(b_\gamma(\alpha_*)) = s(\zeta_1)$. By our assumptions, there are $\gamma_0, \gamma_1, \gamma_2 \in A$ and $\zeta_0, \zeta_1 < \nu_{\xi_*}$ such that $\gamma_0 < \gamma_1 < \gamma_2$ and $f(\gamma_i) = \langle \zeta_0, \zeta_1 \rangle$ for all $i < 3$. Given $i < 3$, we have $r(b_{\gamma_i}(\alpha_*)) \in \mathbb{T}(s(\zeta_0))$ and

$$r(b_{\gamma_i}(\alpha_*)) <_{\mathbb{T}} b_{\gamma_i}(\alpha_*) <_{\mathbb{T}} b_{\gamma_*}(\beta_*).$$

This implies that $r(b_{\gamma_0}(\alpha_*)) = r(b_{\gamma_1}(\alpha_*)) = r(b_{\gamma_2}(\alpha_*))$. In this situation, the above choices ensure that

$$c_{r(b_{\gamma_0}(\alpha_*))}(b_{\gamma_1}(\alpha_*)) = s(\zeta_1) = c_{r(b_{\gamma_0}(\alpha_*))}(b_{\gamma_2}(\alpha_*)).$$

This implies that the nodes $b_{\gamma_1}(\alpha_*)$ and $b_{\gamma_2}(\alpha_*)$ are incompatible in \mathbb{T} , a contradiction. ■

Proposition 1.2 shows that trees containing cofinal branches are not special. Lemma 1.6 allows us to generalize this conclusion to the class of all trees containing ascending paths of small widths.

COROLLARY 1.7. *Let $\lambda < \theta$ be a cardinal with the property that θ is not a successor of a cardinal of cofinality less than or equal to λ . If \mathbb{T} contains an ascending path of width λ , then \mathbb{T} is not special.*

Proof. Our assumptions imply that the set $S_{\lambda^+}^\theta$ is stationary in θ and non-stationary with respect to \mathbb{T} . In this situation, the statement of the corollary follows directly from Lemma 1.6. ■

Note that the above result leaves open the question whether there can be a special tree whose height is the successor of a singular cardinal ν that contains an ascending path of width λ with $\text{cof}(\nu) \leq \lambda < \nu$. After seeing an earlier version of this paper, Chris Lambie-Hanson answered this question affirmatively. In [11], it is shown that if \square_ν holds for some singular cardinal ν , then there is a special ν^+ -Aronszajn tree containing an ascending path of width $\text{cof}(\nu)$.

The above corollary shows that ascending paths cause trees to be non-special in an absolute way: in the situation of the corollary, the tree \mathbb{T} remains non-special in every outer model in which θ and λ satisfy the assumptions of the corollary. We will later show that, if θ and λ satisfy certain cardinal arithmetic assumptions, then the converse of this implication also holds true, i.e. if there is no ascending path of width λ through \mathbb{T} , then \mathbb{T} is special in a forcing extension of the ground model in which the above assumptions on θ and λ hold. This follows from the fact that ascending paths are closely related to maximal antichains in the canonical partial order that specializes a tree of uncountable regular height.

DEFINITION 1.8. Let $\kappa < \theta$ be an infinite regular cardinal. We define $\mathbb{P}_\kappa(\mathbb{T})$ to be the partial order that consists of partial functions from \mathbb{T} to κ of cardinality less than κ that are injective on chains in \mathbb{T} and are ordered by reverse inclusion.

It is easy to see that partial orders of the form $\mathbb{P}_\kappa(\mathbb{T})$ are $<\kappa$ -closed, and forcing with $\mathbb{P}_\kappa(\mathbb{T})$ collapses every cardinal in the interval (κ, θ) . Moreover, if forcing with $\mathbb{P}_\kappa(\mathbb{T})$ preserves the regularity of θ , then the tree \mathbb{T} is special in all $\mathbb{P}_\kappa(\mathbb{T})$ -generic extensions. Therefore it is natural to ask under which conditions this regularity is preserved. We will later show (see Corollary 2.2) that the assumption that forcing with $\mathbb{P}_\kappa(\mathbb{T})$ preserves the regularity of θ implies that $\mu^{<\kappa} < \theta$ for all $\mu < \theta$. Under this cardinal arithmetic assumption, this preservation can be characterized by the non-existence of ascending paths of width less than κ .

THEOREM 1.9. *The following statements are equivalent for every infinite regular cardinal $\kappa < \theta$ with $\mu^{<\kappa} < \theta$ for all $\mu < \theta$:*

- (i) *There is no ascending path of width less than κ through \mathbb{T} .*
- (ii) *The partial order $\mathbb{P}_\kappa(\mathbb{T})$ satisfies the θ -chain condition.*
- (iii) *Forcing with the partial order $\mathbb{P}_\kappa(\mathbb{T})$ preserves the regularity of θ .*

The above remarks show that, in the setting of Theorem 1.9, the three statements listed in the theorem are also equivalent to the statement that there is some outer model W of the ground model V such that κ and θ are regular cardinals in W and \mathbb{T} is a special tree in W . Given an uncountable regular cardinal κ with $\kappa = \kappa^{<\kappa}$, the above theorem allows us to show that the collection of *specializable* trees of height κ^+ (i.e. the collection of all trees that are special in a cofinality-preserving outer model of the ground model V) can be defined through the existence of ascending paths of width less than κ . It is not known to the author whether this collection is also definable if $\kappa < \kappa^{<\kappa}$ (see Question 6.3).

In combination with Lemma 1.4, the above theorem directly implies the statement of a classical result of Baumgartner (see [3, Theorem 8.2] and [5, Lemma 5.3]) stating that the partial order $\mathbb{P}_\omega(\mathbb{T})$ satisfies the θ -chain condition if and only if there is no cofinal branch through \mathbb{T} .

We present an application of the above result to questions dealing with potential generalizations of Martin's Axiom to larger cardinalities. Given a partial order \mathbb{P} , we let $\text{FA}_\theta(\mathbb{P})$ denote the statement that for every collection \mathcal{D} of θ -many dense subsets of \mathbb{P} , there is a \mathcal{D} -generic filter, i.e. a filter F on \mathbb{P} with $D \cap F \neq \emptyset$ for all $D \in \mathcal{D}$. By a result of Shelah (see [22, Theorem 6]), CH implies that there is a σ -closed partial order \mathbb{P} satisfying the \aleph_2 -chain condition and such that $\text{FA}_{\aleph_2}(\mathbb{P})$ fails. This partial order is not *well-met*, i.e. there are compatible conditions without a greatest lower bound in this partial order. Since recent work of Shelah (see [21]) shows that some well-met condition is necessary for such generalizations of Martin's Axiom to hold and results of Baumgartner and Shelah (see [3, Section 4] and [19]) show that such forcing axioms can consistently hold for all σ -closed, well-met partial orders satisfying certain strengthenings of the \aleph_2 -chain condition, it is natural to ask whether the statement that $\text{FA}_{\aleph_2}(\mathbb{P})$ holds for all σ -closed, well-met partial orders \mathbb{P} satisfying the \aleph_2 -chain conditions is consistent.

Note that, given an uncountable regular cardinal κ , every non-atomic $<\kappa$ -closed partial order contains an antichain of cardinality $\kappa^{<\kappa}$. Since we are interested in forcing axioms for partial orders satisfying the κ^+ -chain condition, we will restrict ourselves to cardinals satisfying the cardinal arithmetic assumption $\kappa = \kappa^{<\kappa}$ to obtain non-trivial axioms.

With the help of Todorćević's method of *walks on ordinals* and a result of Todorćević from [26], we will prove the following result showing that the

consistency strength of such a forcing axiom is at least a weakly compact cardinal.

THEOREM 1.10. *Let κ be an uncountable regular cardinal with $\kappa = \kappa^{<\kappa}$. If κ^+ is not weakly compact in \mathbb{L} , then there is a $<\kappa$ -closed, well-met partial order \mathbb{P} satisfying the κ^+ -chain condition with the property that $\text{FA}_{\kappa^+}(\mathbb{P})$ fails.*

Next, we discuss an application of the notion of ascending paths to questions about the productivity of certain chain conditions and characterizations of weak compactness (see, for example, [5] and [17]). Baumgartner's result mentioned above shows that, if \mathbb{T} has no cofinal branches, then the partial order $\mathbb{P}_\omega(\mathbb{T})$ satisfies the θ -chain condition. Since special trees have no cofinal branches, this argument actually shows that finite support products of the partial order $\mathbb{P}_\omega(\mathbb{T})$ satisfy the θ -chain condition in this case. The next theorem is a strengthening of Theorem 1.9. It shows that ascending paths of infinite width provide examples of trees where this chain condition fails in infinite products.

THEOREM 1.11. *The following statements are equivalent for every infinite regular cardinal $\kappa < \theta$ with $\mu^{<\kappa} < \theta$ for all $\mu < \theta$:*

- (i) *There is no ascending path of width less than κ through \mathbb{T} .*
- (ii) *If $\nu \leq \kappa$ is an infinite regular cardinal, then $<\nu$ -support products of the partial order $\mathbb{P}_\nu(\mathbb{T})$ satisfy the θ -chain condition.*

In the following, we are interested in the infinite productivity of stronger chain conditions. Recall that a partial order \mathbb{P} is θ -Knaster if every set of θ -many conditions in \mathbb{P} contains a subset of cardinality θ consisting of pairwise compatible conditions. This property of partial orders is of great interest, because it implies the θ -chain condition and is preserved under finite products. Moreover, it is easy to see that, if θ is weakly compact, then the class of θ -Knaster partial orders is closed under $<\nu$ -support products for every $\nu < \theta$ (see [5, Proposition 1.1] and the proof of Theorem 1.12 in Section 4). It is now natural to ask whether this productivity characterizes weakly compact cardinals. It was shown by Cox and the author that it is consistent that there is an inaccessible cardinal ϑ that is not weakly compact and has the property that the class of ϑ -Knaster partial orders is closed under ν -support products for all $\nu < \vartheta$ (see [5, Theorem 1.13]). In contrast, we will use Theorem 1.11 to show that the infinite productivity of the ϑ -Knaster property characterizes weak compactness in canonical inner models of set theory (so-called *Jensen-style extender models*, see [30]). The proof of the following theorem relies on Todorćević's method of walks on ordinals and results of Schimmerling and Zeman on the existence of square sequences in canonical inner models (see [18] and [31]) that extend the seminal results of Jensen [8].

THEOREM 1.12. *Let $L[E]$ be a Jensen-style extender model. In $L[E]$, the following statements are equivalent for all uncountable regular cardinals ϑ :*

- (i) *ϑ is weakly compact.*
- (ii) *The class of ϑ -Knaster partial orders is closed under ν -support products for all $\nu < \vartheta$.*
- (iii) *ϑ is not the successor of a subcompact cardinal and the class of ϑ -Knaster partial orders is closed under countable support products.*

In particular, it is consistent with the axioms of ZFC that weak compactness is characterized by the countable productivity of the Knaster property.

Next, we present results concerning the existence and non-existence of trees without cofinal branches containing ascending paths of small width. The proofs of most these results make use of the notion of a *narrow system* introduced by Magidor and Shelah [16] and recent results of Lambie-Hanson [13] about these systems. Statements (i), (ii) and (v) of the following theorem are direct consequences of results in [13]. Moreover, (iii) is implicitly proven in the base case of the inductive proof of the main theorem of [15]. Recall that a regular cardinal κ is *indestructibly weakly compact* if κ is weakly compact in every forcing extension by a $<\kappa$ -closed partial order.

THEOREM 1.13.

- (i) *If θ is weakly compact, then every tree of height θ that contains an ascending path of width less than θ has a cofinal branch.*
- (ii) *If $\kappa \leq \theta$ is a θ -compact cardinal, then every tree of height θ that contains an ascending path of width less than κ has a cofinal branch.*
- (iii) *If θ is weakly compact, $\kappa < \theta$ is an uncountable regular cardinal and G is $\text{Col}(\kappa, <\theta)$ -generic over V , then in $V[G]$ every tree of height θ that contains an ascending path of width less than κ has a cofinal branch.*
- (iv) *If $\kappa \leq \theta$ is indestructibly weakly compact, then every tree of height θ that contains an ascending path of width less than κ has a cofinal branch.*
- (v) *If $\kappa \leq \theta$ is θ -compact, $\nu < \kappa$ is an uncountable regular cardinal and G is $\text{Col}(\nu, <\kappa)$ -generic over V , then in $V[G]$ every tree of height θ that contains an ascending path of width less than ν has a cofinal branch.*

Moreover, a result of Lambie-Hanson shows that it is possible to use very strong large cardinal assumptions to prove global non-existence results. In the model constructed in the proof of [13, Theorem 5.2], every tree of uncountable regular height ϑ containing an ascending path of width λ with $\lambda^+ < \vartheta$ has a cofinal branch.

In contrast to the above non-existence results, we will also show that trees without cofinal branches containing ascending paths of small width can be constructed from certain combinatorial principles (see Theorems 4.12 and 5.8). These constructions allow us to derive lower bounds for some of the consistency results listed in Theorem 1.13.

Finally, we study the influence of the *Proper Forcing Axiom* PFA on trees containing ascending paths. We show that PFA implies an analogue of Lemma 1.4 for trees of height greater than ω_1 that contain an ascending path of countable width. In contrast, we show that PFA does not prove a similar conclusion for ascending paths of width ω_1 . Recall that \mathbb{T} is a θ -Souslin tree if the partial order induced by \mathbb{T} satisfies the θ -chain condition. The proof of the second statement of the next theorem relies on a construction of an ω_3 -Souslin tree containing an ascending path of width ω_1 using a partial square principle introduced by Baumgartner (see Definition 5.5).

THEOREM 1.14. *Assume that PFA holds.*

- (i) *If $\theta > \omega_1$, then every tree of height θ that contains an ascending path of width ω has a cofinal branch.*
- (ii) *There is a partial order \mathbb{P} with the property that, whenever G is \mathbb{P} -generic over V , then PFA holds in $V[G]$ and in $V[G]$ there is an ω_3 -Souslin tree that contains an ascending path of width ω_1 .*
- (iii) *If κ is a strongly compact cardinal and G is $\text{Col}(\omega_2, <\kappa)$ -generic over V , then, in $V[G]$, PFA holds and every tree of regular height greater than ω_2 that contains an ascending path of width ω_1 has a cofinal branch.*

We outline the structure of this paper. Section 2 contains the proofs of Theorems 1.9 and 1.11. In Section 3, we will prove Lemma 1.4 and Theorem 1.13. The proofs of Theorems 1.10 and 1.12 are contained in Section 4. Theorem 1.14 is proven in Section 5. In Section 6, we list several open questions motivated by the above results.

2. Ascending paths and antichains. This section is devoted to the proofs of Theorems 1.9 and 1.11. We start by showing that the cardinal arithmetic assumptions of Theorem 1.9 are necessary for the equivalence of statements (i)–(iii).

Given a regular cardinal $\kappa < \theta$, let $\text{Add}(\kappa, \theta)$ denote the partial order consisting of partial functions $f : \theta \xrightarrow{\text{par}} 2$ of cardinality less than κ ordered by reverse inclusion. Then forcing with $\text{Add}(\kappa, \theta)$ adds θ -many Cohen subsets of κ to the ground model. Moreover, given an ordinal $\mu \geq \kappa$, we let $\text{Col}(\kappa, \mu)$ denote the partial order consisting of partial injections $i : \kappa \xrightarrow{\text{par}} \mu$

of cardinality less than κ ordered by reverse inclusion. This partial order is forcing equivalent to the usual Levy collapse of μ to κ .

PROPOSITION 2.1. *If $\kappa < \theta$ is a regular cardinal and $\kappa \leq \mu < \theta$, then there is a forcing projection $\pi : \mathbb{P}_\kappa(\mathbb{T}) \rightarrow \text{Add}(\kappa, \theta) \times \text{Col}(\kappa, \mu)$.*

Proof. Fix a sequence $\langle t_\gamma \in \mathbb{T}(\gamma) \mid \gamma < \theta \rangle$ with $t_\gamma <_{\mathbb{T}} t_\mu$ for all $\gamma < \mu$. Pick a condition p in $\mathbb{P}_\kappa(\mathbb{T})$. Define $f(p)$ to be the unique condition in $\text{Add}(\kappa, \theta)$ with $\text{dom}(f(p)) = \{\gamma < \theta \mid t_{\mu+\gamma} \in \text{dom}(p)\}$ and

$$f(p)(\gamma) = 1 \Leftrightarrow p(t_{\mu+\gamma}) \text{ is an odd ordinal}$$

for all $\gamma \in \text{dom}(f(p))$. Moreover, define $i(p)$ to be the unique condition in $\text{Col}(\kappa, \mu)$ with $\text{dom}(i(p)) = \{p(t_\gamma) \mid \gamma < \mu, t_\gamma \in \text{dom}(p)\}$ and $i(p)(p(t_\gamma)) = \gamma$ for all $\gamma < \mu$ with $t_\gamma \in \text{dom}(p)$. It is easy to check that the resulting map

$$\pi : \mathbb{P}_\kappa(\mathbb{T}) \rightarrow \text{Add}(\kappa, \theta) \times \text{Col}(\kappa, \mu), \quad p \mapsto \langle f(p), i(p) \rangle,$$

is a forcing projection. ■

COROLLARY 2.2. *If $\kappa < \theta$ is a regular cardinal such that forcing with $\mathbb{P}_\kappa(\mathbb{T})$ preserves the regularity of θ , then $\mu^{<\kappa} < \theta$ for all $\mu < \theta$.*

Proof. Assume, towards a contradiction, that there is $\kappa \leq \mu < \theta$ with $\mu^{<\kappa} \geq \theta$. Let G be $\mathbb{P}_\kappa(\mathbb{T})$ -generic over V . By Proposition 2.1, we can find $H_0, H_1 \in V[G]$ such that H_0 is $\text{Add}(\kappa, \theta)$ over V and H_1 is $\text{Col}(\kappa, \mu)$ -generic over V . Then $V[H_0]$ contains a bijection between κ and $\kappa^{<\kappa}$, and $V[H_1]$ contains a bijection between κ and μ . This shows that $V[G]$ contains a surjection from κ onto θ . ■

The following proposition shows how ascending paths induce antichains in infinite products of partial orders of the form $\mathbb{P}_\kappa(\mathbb{T})$.

PROPOSITION 2.3. *If $\langle b_\gamma : \lambda \rightarrow \mathbb{T}(\gamma) \mid \gamma < \theta \rangle$ is an ascending path through \mathbb{T} and κ is an infinite regular cardinal, then the corresponding full support product $\prod_{\lambda \times \lambda} \mathbb{P}_\kappa(\mathbb{T})$ does not satisfy the θ -chain condition.*

Proof. Given $\gamma < \theta$, let \vec{p}_γ denote the unique condition in $\prod_{\lambda \times \lambda} \mathbb{P}_\kappa(\mathbb{T})$ with the property that $\text{dom}(\vec{p}_\gamma(\alpha, \bar{\alpha})) = \{b_\gamma(\alpha), b_\gamma(\bar{\alpha})\}$ and

$$\vec{p}_\gamma(\alpha, \bar{\alpha})(b_\gamma(\alpha)) = \vec{p}_\gamma(\alpha, \bar{\alpha})(b_\gamma(\bar{\alpha})) = 0$$

for all $\alpha, \bar{\alpha} < \lambda$. By our assumption, the sequence $\langle \vec{p}_\gamma \mid \gamma < \theta \rangle$ is an injective enumeration of an antichain in $\prod_{\lambda \times \lambda} \mathbb{P}_\kappa(\mathbb{T})$. ■

The starting point of the proof of Theorem 1.11 is the following basic observation.

PROPOSITION 2.4. *If $\kappa < \theta$ is an infinite regular cardinal and $p, q \in \mathbb{P}_\kappa(\mathbb{T})$ are incompatible, then either*

$$p \upharpoonright (\text{dom}(p) \cap \text{dom}(q)) \neq q \upharpoonright (\text{dom}(p) \cap \text{dom}(q))$$

or there are $s \in \text{dom}(p) \setminus \text{dom}(q)$ and $t \in \text{dom}(q) \setminus \text{dom}(p)$ with the property that $p(s) = q(t)$ and the nodes s and t are compatible in \mathbb{T} . ■

In particular, given regular cardinals $\nu \leq \kappa < \theta$, every antichain in $\mathbb{P}_\nu(\mathbb{T})$ is an antichain in $\mathbb{P}_\kappa(\mathbb{T})$.

PROPOSITION 2.5. *Let κ be an infinite regular cardinal and let $\mathbb{D}_\kappa(\mathbb{T})$ denote the set of all conditions p in the partial order $\mathbb{P}_\kappa(\mathbb{T})$ with the property that for all $s, u \in \text{dom}(p)$ with $\text{lh}_\mathbb{T}(s) < \text{lh}_\mathbb{T}(u)$, there is $t \in \text{dom}(p)$ with $t <_\mathbb{T} u$ and $\text{lh}_\mathbb{T}(s) = \text{lh}_\mathbb{T}(t)$. Then the set $\mathbb{D}_\kappa(\mathbb{T})$ is dense in $\mathbb{P}_\kappa(\mathbb{T})$.*

Proof. Pick a condition p in $\mathbb{P}_\kappa(\mathbb{T})$ and set $A = \{\text{lh}_\mathbb{T}(t) \mid t \in \text{dom}(p)\}$. Define D to be the set of all $s \in \mathbb{T}$ such that $\text{lh}_\mathbb{T}(s) \in A$ and $s \leq_\mathbb{T} t$ for some $t \in \text{dom}(p)$. Then D is a subset of \mathbb{T} of cardinality less than κ with $\text{dom}(p) \subseteq D$, and we can find a function $q : D \rightarrow \kappa$ such that $q \upharpoonright \text{dom}(p) = p$, $q \upharpoonright (D \setminus \text{dom}(p))$ is an injection and $q[D \setminus \text{dom}(p)] \subseteq \kappa \setminus \text{ran}(p)$. We conclude that $q \in \mathbb{D}_\kappa(\mathbb{T})$ with $q \leq_{\mathbb{P}_\kappa(\mathbb{T})} p$. ■

In the proof of Theorem 1.11, we want to restrict ourselves to trees that satisfy the following normality condition.

DEFINITION 2.6. We say that a tree \mathbb{T} *does not split at limit levels* if for all $\gamma \in \theta \cap \text{Lim}$ and all $t_0, t_1 \in \mathbb{T}(\gamma)$ with $t_0 \neq t_1$, we can find $\bar{\gamma} < \gamma$ and $s_0, s_1 \in \mathbb{T}(\bar{\gamma})$ such that $s_0 \neq s_1$ and $s_i <_\mathbb{T} t_i$ for all $i < 2$.

Note that a standard construction (see [10, Section III.3]) shows that for every tree \mathbb{T} of height θ there is a tree $\bar{\mathbb{T}}$ of height θ that does not split at limit levels such that \mathbb{T} is isomorphic to the tree $\bar{\mathbb{T}} \upharpoonright (\theta \setminus \text{Lim})$. This means that the existence of an ascending path of width λ through $\bar{\mathbb{T}}$ implies the existence of an ascending path of width λ through \mathbb{T} . Moreover, Proposition 2.4 shows that every antichain in a product of the partial order $\mathbb{P}_\kappa(\mathbb{T})$ induces an antichain of the same size in the corresponding product of the partial order $\mathbb{P}_\kappa(\bar{\mathbb{T}})$. In combination, this shows that, in order to prove (i) \Rightarrow (ii) in Theorem 1.11, it suffices to prove this implication for all trees of height θ that do not split at limit levels.

Proof of Theorem 1.11. Let $\nu \leq \kappa < \theta$ be infinite regular cardinals with $\mu^{<\kappa} < \theta$ for all $\mu < \theta$.

First, assume that \mathbb{T} contains an ascending path of width $\lambda < \kappa$. Then Proposition 2.3 shows that for every regular cardinal $\nu \leq \kappa$, the full support product $\prod_{\lambda \times \lambda} \mathbb{P}_\nu(\mathbb{T})$ does not satisfy the θ -chain condition.

In the other direction, assume that there is a $<\kappa$ -support product of the partial order $\mathbb{P}_\nu(\mathbb{T})$ that does not satisfy the θ -chain condition. By the above remarks, we may assume that \mathbb{T} does not split at limit levels. Moreover, our cardinal arithmetic assumption allows us to find $\mu < \kappa$ and an injective enumeration $\langle \vec{p}_\gamma \mid \gamma < \theta \rangle$ of an antichain in the full support product $\mathbb{P} =$

$\prod_{\mu} \mathbb{P}_{\nu}(\mathbb{T})$. By Proposition 2.5, there is a sequence $\langle \vec{q}_{\gamma} \mid \gamma < \theta \rangle$ of conditions in \mathbb{P} such that $\vec{q}_{\gamma} \leq_{\mathbb{P}} \vec{p}_{\gamma}$ and $\vec{q}_{\gamma}(\beta) \in \mathbb{D}_{\nu}(\mathbb{T})$ for all $\gamma < \theta$ and $\beta < \mu$.

Fix $\gamma \in S_{\kappa}^{\theta}$. Set $A_{\gamma} = \{\langle t, \beta \rangle \in \mathbb{T} \times \mu \mid t \in \text{dom}(\vec{q}_{\gamma}(\beta))\}$ and pick a bijective enumeration $\langle t_{\gamma}(\alpha) \mid \alpha < \lambda_{\gamma} \rangle$ of the set

$$\{t \in \mathbb{T}(\gamma) \mid \exists \beta < \mu \exists u \in \text{dom}(\vec{q}_{\gamma}(\beta)) t \leq_{\mathbb{T}} u\}$$

for some cardinal $\lambda_{\gamma} < \kappa$. Since \mathbb{T} does not split at limit levels, there is $r(\gamma) < \gamma$ and an injection $\iota_{\gamma} : \lambda_{\gamma} \rightarrow \mathbb{T}(r(\gamma))$ with the property that $A_{\gamma} \cap (\mathbb{T}_{<\gamma} \times \mu) \subseteq \mathbb{T}_{<r(\gamma)} \times \mu$ and $\iota_{\gamma}(\alpha) <_{\mathbb{T}} t_{\gamma}(\alpha)$ for all $\alpha < \lambda_{\gamma}$.

By our assumptions, we may apply Fodor's Lemma to find $\lambda < \kappa$, $\rho < \theta$, $E \subseteq S_{\kappa}^{\theta}$ stationary in θ and a sequence $\langle H_{\beta} \subseteq \rho \mid \beta < \mu \rangle$ such that $\lambda = \lambda_{\gamma}$, $\rho = r(\gamma)$ and $H_{\beta} = \{\text{lh}_{\mathbb{T}}(s) \mid s \in \text{dom}(\vec{q}_{\gamma}(\beta)) \cap \mathbb{T}_{<\gamma}\}$ for all $\gamma \in E$ and $\beta < \mu$. In this situation, our cardinal arithmetic assumption allows us to use the Δ -system lemma to find $F \subseteq E$ unbounded in θ , $Q \subseteq \mathbb{T} \times \mu$ and $R \subseteq \mathbb{T}(\rho)$ such that the set $\{A_{\gamma} \mid \gamma \in F\}$ is a Δ -system with root Q and the set $\{\text{ran}(\iota_{\gamma}) \mid \gamma \in F\}$ is a Δ -system with root R . Next, we use the pigeonhole principle and our cardinal arithmetic assumption to find $U \subseteq F$ unbounded in θ , $B \subseteq \lambda$, a map $c : Q \rightarrow \nu$ and an injection $\iota : B \rightarrow R$ such that $c(t, \beta) = \vec{q}_{\gamma}(\beta)(t)$, $B = \{\alpha < \lambda \mid \iota_{\gamma}(\alpha) \in R\}$ and $\iota(\alpha) = \iota_{\gamma}(\alpha)$ for all $\gamma \in U$, $\alpha \in B$ and $\langle t, \beta \rangle \in Q$.

Pick $\gamma_0, \gamma_1 \in U$ such that $\gamma_0 < \gamma_1$ and $A_{\gamma_0} \subseteq \mathbb{T}_{<\gamma_1} \times \mu$. Since the conditions \vec{q}_{γ_0} and \vec{q}_{γ_1} are incompatible in \mathbb{P} , there is a $\beta < \mu$ such that the conditions $\vec{q}_{\gamma_0}(\beta)$ and $\vec{q}_{\gamma_1}(\beta)$ are incompatible in $\mathbb{P}_{\nu}(\mathbb{T})$. By the above choices, we have

$$\vec{q}_{\gamma_0}(\beta)(t) = c(t, \beta) = \vec{q}_{\gamma_1}(\beta)$$

for all $t \in \text{dom}(\vec{q}_{\gamma_0}(\beta)) \cap \text{dom}(\vec{q}_{\gamma_1}(\beta))$. In this situation, Proposition 2.4 shows that there are $t_0 \in \text{dom}(\vec{q}_{\gamma_0}(\beta))$ and $t_1 \in \text{dom}(\vec{q}_{\gamma_1}(\beta))$ such that $\vec{q}_{\gamma_0}(\beta)(t_0) = \vec{q}_{\gamma_1}(\beta)(t_1)$ and $t_I <_{\mathbb{T}} t_{1-I}$ for some $I < 2$.

Assume, towards a contradiction, that $t_I \in \mathbb{T}_{<\gamma_I}$. Then $\text{lh}_{\mathbb{T}}(t_I) \in H_{\beta}$ and there is an $s \in \text{dom}(\vec{q}_{\gamma_{1-I}}(\beta))$ with $\text{lh}_{\mathbb{T}}(s) = \text{lh}_{\mathbb{T}}(t_I)$. Since $\vec{q}_{\gamma_{1-I}}(\beta) \in \mathbb{D}_{\nu}(\mathbb{T})$, we can find $t \in \text{dom}(\vec{q}_{\gamma_{1-I}}(\beta))$ with $t <_{\mathbb{T}} t_{1-I}$ and $\text{lh}_{\mathbb{T}}(s) = \text{lh}_{\mathbb{T}}(t)$. But then $t = t_I \in Q$ and

$$\vec{q}_{\gamma_{1-I}}(\beta)(t_I) = c(t_I, \beta) = \vec{q}_{\gamma_I}(\beta)(t_I) = \vec{q}_{\gamma_{1-I}}(\beta)(t_{1-I}),$$

a contradiction.

The above computations show that $t_I \notin \mathbb{T}_{<\gamma_I}$. This implies $I = 0$ and $t_1 \notin \mathbb{T}_{<\gamma_1}$, because $\text{dom}(\vec{q}_{\gamma_0}(\beta)) \subseteq \mathbb{T}_{<\gamma_1}$ and $\text{dom}(\vec{q}_{\gamma_1}(\beta)) \cap \mathbb{T}_{<\gamma_1} \subseteq \mathbb{T}_{<\rho}$. Then there are $\alpha_0, \alpha_1 < \lambda$ with $t_{\gamma_0}(\alpha_0) \leq_{\mathbb{T}} t_0$ and $t_{\gamma_1}(\alpha_1) \leq_{\mathbb{T}} t_1$. In particular, this implies that $\lambda > 0$. By the above choices, we have

$$\iota_{\gamma_0}(\alpha_0) <_{\mathbb{T}} t_{\gamma_0}(\alpha_0) \leq_{\mathbb{T}} t_0 <_{\mathbb{T}} t_1$$

and $\iota_{\gamma_1}(\alpha_1) <_{\mathbb{T}} t_{\gamma_1}(\alpha_1) \leq_{\mathbb{T}} t_1$. This implies that $\iota_{\gamma_0}(\alpha_0) = \iota_{\gamma_1}(\alpha_1) \in R$ and

$\alpha_0, \alpha_1 \in B$. But then $\iota(\alpha_0) = \iota_{\gamma_0}(\alpha_0) = \iota_{\gamma_1}(\alpha_1) = \iota(\alpha_1)$ and $\alpha_0 = \alpha_1$. Since $t_{\gamma_0}(\alpha_0) \leq_{\mathbb{T}} t_0 <_{\mathbb{T}} t_1$, $t_{\gamma_1}(\alpha_0) \leq_{\mathbb{T}} t_1$ and

$$\text{lh}_{\mathbb{T}}(t_{\gamma_0}(\alpha_0)) = \gamma_0 < \gamma_1 = \text{lh}_{\mathbb{T}}(t_{\gamma_1}(\alpha_0)),$$

we can conclude that $t_{\gamma_0}(\alpha_0) <_{\mathbb{T}} t_{\gamma_1}(\alpha_0)$.

Given $\gamma < \theta$ and $\alpha < \lambda$, let $\delta \in U \setminus \gamma$ be minimal with $A_{\delta} \subseteq \mathbb{T}_{<\delta} \times \mu$ for all $\bar{\delta} \in U \cap \delta$ and define $b_{\gamma}(\alpha)$ to be the unique element of $\mathbb{T}(\gamma)$ with $b_{\gamma}(\alpha) \leq_{\mathbb{T}} t_{\gamma}(\alpha)$. By the above computations, if $\bar{\gamma} < \gamma < \theta$, then there is $\alpha < \lambda$ with $b_{\bar{\gamma}}(\alpha) <_{\mathbb{T}} b_{\gamma}(\alpha)$. This shows that the resulting sequence $\langle b_{\gamma} : \lambda \rightarrow \mathbb{T}(\gamma) \mid \gamma < \theta \rangle$ is an ascending path of width less than κ through the tree \mathbb{T} . ■

Proof of Theorem 1.9. Let $\kappa < \theta$ be a regular cardinal with $\mu^{<\kappa} < \theta$ for all $\mu < \theta$. If forcing with the partial order $\mathbb{P}_{\kappa}(\mathbb{T})$ does not preserve the regularity of θ , then $\mathbb{P}_{\kappa}(\mathbb{T})$ does not satisfy the θ -chain condition and Theorem 1.11 shows that there is an ascending path of width less than κ through \mathbb{T} . In the other direction, assume that there is an ascending path of width less than κ through \mathbb{T} , and forcing with $\mathbb{P}_{\kappa}(\mathbb{T})$ preserves the regularity of θ . Let G be $\mathbb{P}_{\kappa}(\mathbb{T})$ -generic over V . In $V[G]$, \mathbb{T} contains an ascending path of width less than κ , and θ is not the successor of a cardinal of cofinality less than κ . In this situation, Corollary 1.7 implies that \mathbb{T} is not special in $V[G]$, a contradiction. ■

Note that the proof of Theorem 1.11 shows that if $\kappa < \theta$ is a regular cardinal with $\mu^{<\kappa} < \theta$ for all $\mu < \theta$ and there is an ascending path of width $\lambda < \kappa$ through \mathbb{T} , then there is such a path $\langle b_{\gamma} : \lambda \rightarrow \mathbb{T}(\gamma) \mid \gamma < \theta \rangle$ with the additional property that for all $\bar{\gamma} < \gamma < \theta$ there is an $\alpha < \lambda$ with $b_{\bar{\gamma}}(\alpha) <_{\mathbb{T}} b_{\gamma}(\alpha)$. In the general terminology of [4], such a path is called an \mathcal{F}_{λ} -ascent path through \mathbb{T} . It is not known to the author whether the existence of an \mathcal{F}_{λ} -ascent path is always equivalent to the existence of an ascending path of width λ (see Question 6.4).

3. Narrow systems and ultrafilters. In this section, we will prove the non-existence results stated in Lemma 1.4 and Theorem 1.13. These proofs rely on the notion of *narrow systems* introduced by Magidor and Shelah [16], and recent results of Lambie-Hanson [13].

DEFINITION 3.1 ([16, Definition 2.2]). Let ϑ be a limit ordinal, let D be an unbounded subset of ϑ and let $\lambda > 0$ be a cardinal.

- (i) A set \mathcal{R} of binary transitive relations on $D \times \lambda$ is a ϑ -system of width λ on D if the following statements hold:
 - (a) If $\gamma, \bar{\gamma} \in D$, $\alpha, \bar{\alpha} < \lambda$ and $R \in \mathcal{R}$ with $\langle \bar{\gamma}, \bar{\alpha} \rangle R \langle \gamma, \alpha \rangle$, then $\bar{\gamma} < \gamma$.

- (b) If $\gamma, \gamma_0, \gamma_1 \in D$, $\alpha, \alpha_0, \alpha_1 < \lambda$ and $R \in \mathcal{R}$ are such that $\gamma_0 \leq \gamma_1$ and $\langle \gamma_i, \alpha_i \rangle R \langle \gamma, \alpha \rangle$ for all $i < 2$, then $\langle \gamma_0, \alpha_0 \rangle R \langle \gamma_1, \alpha_1 \rangle$.
- (c) If $\gamma, \bar{\gamma} \in D$ with $\bar{\gamma} < \gamma$, then there are $\alpha, \bar{\alpha} < \lambda$ and $R \in \mathcal{R}$ with $\langle \bar{\gamma}, \bar{\alpha} \rangle R \langle \gamma, \alpha \rangle$.
- (ii) A ϑ -system \mathcal{R} of width λ is *narrow* if $|\mathcal{R}| < \lambda^+ < |\vartheta|$.
- (iii) Given a ϑ -system \mathcal{R} of width λ on D and $R \in \mathcal{R}$, a subset B of $D \times \lambda$ is an *R-branch through \mathcal{R}* if for all $\langle \gamma_0, \alpha_0 \rangle, \langle \gamma_1, \alpha_1 \rangle \in B$ with $\langle \gamma_0, \alpha_0 \rangle \neq \langle \gamma_1, \alpha_1 \rangle$ there is an $i < 2$ with $\langle \gamma_i, \alpha_i \rangle R \langle \gamma_{1-i}, \alpha_{1-i} \rangle$.
- (iv) Given a ϑ -system \mathcal{R} of width λ on D and $R \in \mathcal{R}$, an *R-branch through \mathcal{R}* is *cofinal* if the set $\{\gamma \in D \mid \exists \alpha < \lambda \langle \gamma, \alpha \rangle \in B\}$ is unbounded in ϑ .
- (v) Given a ϑ -system \mathcal{R} of width λ on D and a set \mathcal{B} of cardinality at most λ with the property that every element of \mathcal{B} is an *R-branch through \mathcal{R}* for some $R \in \mathcal{R}$, we call \mathcal{B} a *full set of branches through \mathcal{R}* if for every $\gamma \in D$ there are $B \in \mathcal{B}$ and $\alpha < \lambda$ with $\langle \gamma, \alpha \rangle \in B$.

A simple cardinality argument shows that the existence of a full set of branches through a narrow θ -system \mathcal{R} implies the existence of a cofinal branch through \mathcal{R} .

It is easy to see that if a tree \mathbb{T} has no cofinal branches and there is an ascending path of width λ through \mathbb{T} , then there is a θ -system \mathcal{R} of width λ such that $|\mathcal{R}| = 1$ and there are no cofinal branches through \mathcal{R} . This shows that the statements of Lemma 1.4 and Theorem 1.13 follow from the next lemma. Most of the statements of the lemma already appear in [13]. For the sake of completeness, we also present the proofs of these results.

LEMMA 3.2.

- (i) *A narrow θ -system of finite width has a full set of branches.*
- (ii) *If θ is weakly compact, then every narrow θ -system has a full set of branches.*
- (iii) *If $\kappa \leq \theta$ is θ -compact, then every narrow θ -system of width less than κ has a full set of branches.*
- (iv) *If $\kappa \leq \theta$ is indestructibly weakly compact, then every narrow θ -system of width less than κ has a cofinal branch.*
- (v) *If θ is weakly compact, $\kappa < \theta$ is an uncountable regular cardinal and G is $\text{Col}(\kappa, < \theta)$ -generic over V , then in $V[G]$ every narrow θ -system has a cofinal branch.*
- (vi) *If $\kappa \leq \theta$ is θ -compact, $\nu < \kappa$ is an uncountable regular cardinal and G is $\text{Col}(\nu, < \kappa)$ -generic over V , then in $V[G]$ every narrow θ -system of width less than ν has a cofinal branch.*

The proof of the last three statements relies on the following preservation lemma proven by Lambie-Hanson [13].

LEMMA 3.3 ([13, Lemma 4.1]). *Let $\kappa < \theta$ be an infinite regular cardinal, let D be an unbounded subset of θ and let \mathcal{R} be a narrow θ -system of width less than κ on D . If there is a $<\kappa$ -closed partial order \mathbb{P} with the property that in some \mathbb{P} -generic extension there is a complete set of branches through \mathcal{R} , then there is a cofinal branch through \mathcal{R} in V .*

The idea used in the proof of the next lemma is taken from Baumgartner's elegant proof of [3, Theorem 8.2]. Recall that, given a collection \mathcal{S} of subsets of some set D , a filter \mathcal{F} on D is an \mathcal{S} -ultrafilter if for all $S \in \mathcal{S}$, either $S \in \mathcal{F}$ or $D \setminus S \in \mathcal{F}$.

LEMMA 3.4. *Let θ be an uncountable regular cardinal and let $\kappa < \theta$ be a cardinal. Then for every narrow θ -system \mathcal{R} of width less than κ there is a collection $\mathcal{S}_{\mathcal{R}}$ of θ -many subsets of θ such that:*

- (i) *If there is a $<\kappa$ -closed $\mathcal{S}_{\mathcal{R}}$ -ultrafilter on θ that consists of unbounded subsets of θ , then there is a full set of branches through \mathcal{R} .*
- (ii) *If there is a $<\kappa$ -closed partial order \mathbb{P} with the property that forcing with \mathbb{P} adds a $<\kappa$ -closed $\mathcal{S}_{\mathcal{R}}$ -ultrafilter on θ that consists of unbounded subsets of θ , then \mathcal{R} has a cofinal branch in V .*

Proof. Let D be an unbounded subset of θ , let $0 < \lambda < \kappa$ be a cardinal and let \mathcal{R} be a narrow θ -system of width λ on D . Set $\mathcal{I} = \lambda \times \lambda \times \mathcal{R}$. Define $\mathcal{S}_{\mathcal{R}}$ to be the set consisting of all subsets of D of the form

$$S_{\gamma, I} = \{\delta \in D \mid \langle \gamma, \alpha_I \rangle R_I \langle \delta, \beta_I \rangle\}$$

for some $\gamma \in D$ and $I = \langle \alpha_I, \beta_I, R_I \rangle \in \mathcal{I}$. Then $\mathcal{S}_{\mathcal{R}}$ has cardinality θ .

Both of the above assumptions imply that there is a $<\kappa$ -closed partial order \mathbb{P} , a filter G on \mathbb{P} that is generic over V and a $<\kappa$ -closed $\mathcal{S}_{\mathcal{R}}$ -ultrafilter \mathcal{F} on D in $V[G]$ that consists of unbounded subsets of θ . Work in $V[G]$. Given $\gamma \in D$, we have

$$D \setminus (\gamma + 1) = \bigcup \{S_{\gamma, I} \mid I \in \mathcal{I}\}.$$

In this situation, our assumptions on \mathcal{F} imply that there is a sequence $\langle I_\gamma \mid \gamma \in D \rangle$ with the property that $S_{\gamma, I_\gamma} \in \mathcal{F}$ for all $\gamma \in D$. Given $I \in \mathcal{I}$, define

$$B_I = \{\langle \gamma, \alpha_I \rangle \mid \gamma \in D, I = I_\gamma\}.$$

Pick $I \in \mathcal{I}$ and $\gamma_0, \gamma_1 \in D$ with $\gamma_0 < \gamma_1$ and $I = I_{\gamma_0} = I_{\gamma_1}$. Then we have $S = S_{\gamma_0, I} \cap S_{\gamma_1, I} \in \mathcal{F}$ and our assumptions imply that there is a $\delta \in S$ with $\delta > \gamma_i$ for all $i < 2$. This implies that $\langle \gamma_i, \alpha_I \rangle R_I \langle \delta, \beta_I \rangle$ for all $i < 2$. By the definition of narrow systems, this implies that $\langle \gamma_0, \alpha_I \rangle R_I \langle \gamma_1, \alpha_I \rangle$.

The above computations show that B_I is an R_I -branch through \mathcal{R} for every $I \in \mathcal{I}$. Since $\langle \gamma, \alpha_I \rangle \in B_I$ for all $\gamma \in D$, the set $\{B_I \mid I \in \mathcal{I}\}$ is a full set of branches through \mathcal{R} in $V[G]$. By Lemma 3.3, this implies that there is a cofinal branch through \mathcal{R} in V . ■

Proof of Lemma 3.2. (i) Let \mathcal{U} be an ultrafilter on θ that extends the filter of cobounded subsets of θ . Then \mathcal{U} is closed under finite intersections and consists of unbounded subsets of θ . If \mathcal{R} is a narrow θ -system of finite width, then \mathcal{U} is an $\mathcal{S}_{\mathcal{R}}$ -ultrafilter and we can use the first part of Lemma 3.4 to conclude that there is a full set of branches through \mathcal{R} .

(ii) Assume that θ is weakly compact and let \mathcal{R} be a narrow θ -system. By the filter property of weakly compact cardinals, there is a non-principal $<\kappa$ -closed $\mathcal{S}_{\mathcal{R}}$ -ultrafilter on θ and the above statement follows directly from the first part of Lemma 3.4.

(iii) Assume that $\kappa \leq \theta$ is θ -compact. By the filter property of θ -compact cardinals, there is a $<\kappa$ -closed ultrafilter on θ that extends the filter of all cobounded subsets of θ . In this situation, the first part of Lemma 3.4 implies that every narrow θ -system of width less than κ has a full set of branches.

(iv) Assume that $\kappa \leq \theta$ is indestructibly weakly compact, let \mathcal{R} be a narrow θ -system of width less than κ and let G be $\text{Col}(\kappa, \theta)$ -generic over V . Then κ is weakly compact in $V[G]$ and the proof of (ii) shows that there is a non-principal $<\kappa$ -closed $\mathcal{S}_{\mathcal{R}}$ -ultrafilter in $V[G]$. In this situation, the second part of Lemma 3.4 shows that there is a cofinal branch through \mathcal{R} in V .

(v) Assume that θ is weakly compact, $\kappa < \theta$ is an uncountable regular cardinal and G is $\text{Col}(\kappa, <\theta)$ -generic over V . Let \mathcal{R} be a narrow θ -system in $V[G]$ and let $\mathcal{S}_{\mathcal{R}}$ denote the corresponding collection of subsets of θ given by Lemma 3.4. Since the partial order $\text{Col}(\kappa, <\theta)$ satisfies the θ -chain condition, there is a $\text{Col}(\kappa, <\theta)$ -name $\dot{S} \in H(\theta^+)^V$ with $\mathcal{S}_{\mathcal{R}} = \dot{S}^G$.

Work in V and pick an elementary submodel M of $H(\theta^+)$ of cardinality θ with $\dot{S} \in M$ and ${}^{<\theta}M \subseteq M$. By the embedding property of weakly compact cardinals, there is a transitive set N of cardinality θ with ${}^{<\theta}N \subseteq N$ and an elementary embedding $j : M \rightarrow N$ with critical point θ . Then $\text{Col}(\kappa, <\theta)$ is an element of M and $j(\text{Col}(\kappa, <\theta))$ is isomorphic to $\text{Col}(\kappa, <\theta) \times \text{Col}(\kappa, [\theta, j(\theta)))$ both in V and in N .

Let H be $\text{Col}(\kappa, [\theta, j(\theta)))$ -generic over $V[G]$. Then we can lift j to an elementary embedding $j_* : M[G] \rightarrow N[G, H]$. Let

$$\mathcal{F} = \{A \in \mathcal{P}(\theta) \cap M[G] \mid \theta \in j_*(A)\}$$

be the induced $M[G]$ -ultrafilter in $V[G, H]$. Since $\text{Col}(\kappa, [\theta, j(\theta)))$ is $<\kappa$ -closed and $\mathcal{S}_{\mathcal{R}} \in M[G]$, the filter \mathcal{F} is a non-principal $<\kappa$ -closed $\mathcal{S}_{\mathcal{R}}$ -ultrafilter on θ in $V[G, H]$ and the second part of Lemma 3.4 shows that \mathcal{R} has a cofinal branch in $V[G]$.

(vi) Assume that $\kappa \leq \theta$ is θ -compact, $\nu < \kappa$ is an uncountable regular cardinal and G is $\text{Col}(\nu, <\kappa)$ -generic over V . In V , the θ -compactness of κ yields an elementary embedding $j : V \rightarrow M$ with critical point κ such that $j[\theta] \subseteq \lambda$ for some $\lambda < j(\theta)$. Then $j(\text{Col}(\kappa, <\theta))$ is isomorphic to the partial order $\text{Col}(\kappa, <\theta) \times \text{Col}(\kappa, [\theta, j(\theta)))$ both in V and in M . Let H be

$\text{Col}(\kappa, [\theta, j(\theta)])$ -generic over $V[G]$. Then we can lift j to an elementary embedding $j_* : V[G] \rightarrow M[G, H]$ in $V[G, H]$. Define $\mathcal{F} = \{A \in \mathcal{P}(\theta)^{V[G]} \mid \lambda \in j_*(A)\}$. Since $\text{Col}(\kappa, [\theta, j(\theta)])$ is $<\kappa$ -closed, we deduce that \mathcal{F} is a $<\kappa$ -closed $V[G]$ -ultrafilter on θ in $V[G, H]$ that consists of unbounded subsets of θ . With the help of the second part of Lemma 3.4, we conclude that in $V[G]$ every narrow θ -system has a cofinal branch. ■

As mentioned in Section 1, the results of [13] also provide a global non-existence result for trees without cofinal branches containing ascending paths of small width. In the proof of [13, Theorem 5.2], Lambie-Hanson starts with a model containing a proper class of supercompact cardinals and produces a class forcing extension in which every narrow ϑ -system for an uncountable regular cardinal ϑ has a cofinal branch. By the above remarks, every tree of uncountable regular height ϑ containing an ascending path of width λ with $\lambda^+ < \vartheta$ has a cofinal branch in this model.

4. Trees constructed from walks on ordinals. This section contains the proofs of Theorems 1.10 and 1.12. These proofs show that certain combinatorial principles allow us to construct trees with very specific properties. The construction of these trees uses the concept of *walks on ordinals* and their characteristics introduced by Todorćević.

DEFINITION 4.1 (Todorćević).

- (i) A sequence $\vec{C} = \langle C_\gamma \mid \gamma < \theta \rangle$ is a *C-sequence of length θ* if the following statements hold for all $\gamma < \theta$:
 - (a) If γ is a limit ordinal, then C_γ is a club subset of γ .
 - (b) If $\gamma = \bar{\gamma} + 1$, then $C_\gamma = \{\bar{\gamma}\}$.
- (ii) Let $\vec{C} = \langle C_\gamma \mid \gamma < \theta \rangle$ be a *C-sequence of length θ* .
 - (a) Given $\gamma \leq \delta < \theta$, the *walk from δ to γ through \vec{C}* is the unique sequence $\langle \varepsilon_0, \dots, \varepsilon_n \rangle$ of ordinals satisfying $\varepsilon_0 = \delta$, $\varepsilon_n = \gamma$ and $\varepsilon_{i+1} = \min(C_{\varepsilon_i} \setminus \gamma)$ for all $i < n$. In this situation, we define the *full code of the walk from δ to γ through \vec{C}* to be the sequence

$$\rho_0^{\vec{C}}(\gamma, \delta) = \langle \text{otp}(C_{\varepsilon_0} \cap \gamma), \dots, \text{otp}(C_{\varepsilon_{n-1}} \cap \gamma) \rangle.$$

- (b) Given $\delta < \kappa$, we define

$$\rho_0^{\vec{C}}(\cdot, \delta) : \delta + 1 \rightarrow <^\omega \theta, \quad \gamma \mapsto \rho_0^{\vec{C}}(\gamma, \delta).$$

- (c) We define $\mathbb{T}(\rho_0^{\vec{C}})$ to be the tree of height θ consisting of all functions of the form $\rho_0^{\vec{C}}(\cdot, \delta) \upharpoonright \gamma$ with $\gamma \leq \delta < \theta$ ordered by inclusion.

Recall that a tree \mathbb{T} is a θ -Aronszajn tree if \mathbb{T} has no cofinal branches and $|\mathbb{T}(\gamma)| < \theta$ for all $\gamma < \theta$. The following results of Todorćević show how such sequences can be used to construct θ -Aronszajn trees.

LEMMA 4.2 ([25, Lemma 1.3]). *If $\vec{C} = \langle C_\gamma \mid \gamma < \theta \rangle$ is a C -sequence and $\gamma < \theta$, then $|\mathbb{T}(\rho_0^{\vec{C}})(\gamma)| \leq |\{C_\delta \cap \gamma \mid \gamma \leq \delta < \theta\}| + \aleph_0$.*

LEMMA 4.3 ([25, Lemma 1.7]). *The following statements are equivalent for every C -sequence $\vec{C} = \langle C_\gamma \mid \gamma < \theta \rangle$ of length θ :*

- (i) *There is a cofinal branch through the tree $\mathbb{T}(\rho_0^{\vec{C}})$.*
- (ii) *There is a club subset C of θ and $\xi < \theta$ such that for all $\xi \leq \gamma < \theta$ there is $\gamma \leq \delta < \theta$ with $C \cap \gamma = C_\delta \cap [\xi, \gamma)$.*

We will now show that trees of the form $\mathbb{T}(\rho_0^{\vec{C}})$ do not contain ascending paths of small width if they contain no cofinal branches and the underlying sequence \vec{C} is coherent in the following sense.

DEFINITION 4.4. Given $S \subseteq \theta$, we say that a C -sequence $\vec{C} = \langle C_\gamma \mid \gamma < \theta \rangle$ is S -coherent if $C_{\bar{\gamma}} = C_\gamma \cap \bar{\gamma}$ for all $\gamma \in \theta \cap \text{Lim}$ and $\bar{\gamma} \in \text{Lim}(C_\gamma) \cap S$.

The proof of the following lemma relies on some computations of full codes of walks that are presented in detail in [9, Section 3].

LEMMA 4.5. *Let $\lambda < \theta$ be a cardinal, let $S \subseteq S_{>\lambda}^\theta$ be stationary in θ and let \vec{C} be an S -coherent C -sequence of length θ . If the tree $\mathbb{T}(\rho_0^{\vec{C}})$ contains an ascending path of width λ , then $\mathbb{T}(\rho_0^{\vec{C}})$ has a cofinal branch.*

Proof. Let $\vec{C} = \langle C_\gamma \mid \gamma < \theta \rangle$. Set $\mathbb{T} = \mathbb{T}(\rho_0^{\vec{C}})$ and $\rho_0 = \rho_0^{\vec{C}}$. Assume, towards a contradiction, that $\langle b_\gamma : \lambda \rightarrow \mathbb{T}(\gamma) \mid \gamma < \theta \rangle$ is an ascending path through \mathbb{T} .

Given $\gamma \in S$ and $\alpha < \lambda$, let $\gamma \leq \delta_\gamma^\alpha < \theta$ be minimal with the property that $b_\gamma(\alpha) = \rho_0(\cdot, \delta_\gamma^\alpha) \upharpoonright \gamma$, let $\langle \varepsilon_\gamma^\alpha(0), \dots, \varepsilon_\gamma^\alpha(n_\gamma^\alpha) \rangle$ denote the walk from δ_γ^α to γ through \vec{C} and let $k_\gamma^\alpha \leq n_\gamma^\alpha$ be minimal with $C_{\varepsilon_\gamma^\alpha(k_\gamma^\alpha)} \cap \gamma$ unbounded in γ . By our assumptions, we can find $\mu \leq \nu < \theta$ and $E \subseteq S \setminus (\nu + 1)$ stationary in θ such that $\max(C_{\varepsilon_\gamma^\alpha(l)} \cap \gamma) < \mu$ and $\min(C_\gamma \setminus \mu) = \nu$ for all $\gamma \in E$, $\alpha < \lambda$ and $l < k_\gamma^\alpha$.

CLAIM 1. *If $\gamma_0, \gamma_1 \in E$ and $\alpha < \lambda$ with $\gamma_0 < \gamma_1$ and $b_{\gamma_0}(\alpha) <_{\mathbb{T}} b_{\gamma_1}(\alpha)$, then $k_{\gamma_0}^\alpha = k_{\gamma_1}^\alpha$.*

Proof. Note that our assumptions imply that $\nu \in C_{\varepsilon_{\gamma_i}^\alpha(k_{\gamma_i}^\alpha)}$ for all $i < 2$. Given $i < 2$, we can combine this observation with [9, Lemma 3.2] to see that the sequence $\langle \varepsilon_{\gamma_i}^\alpha(0), \dots, \varepsilon_{\gamma_i}^\alpha(k_{\gamma_i}^\alpha), \nu \rangle$ is the walk from $\delta_{\gamma_i}^\alpha$ to ν through \vec{C} . Since our assumptions imply that $\rho_0(\nu, \delta_{\gamma_0}^\alpha) = \rho_0(\nu, \delta_{\gamma_1}^\alpha)$, we conclude that

$$k_{\gamma_0}^\alpha = \text{lh}(\rho_0(\nu, \delta_{\gamma_0}^\alpha)) - 1 = \text{lh}(\rho_0(\nu, \delta_{\gamma_1}^\alpha)) - 1 = k_{\gamma_1}^\alpha. \quad \blacksquare$$

CLAIM 2. *If $\gamma_0, \gamma_1 \in E$ with $\gamma_0 < \gamma_1$, then $C_{\gamma_0} = C_{\gamma_1} \cap \gamma_0$.*

Proof. By our assumption, there is an $\alpha < \lambda$ with $b_{\gamma_0}(\alpha) <_{\mathbb{T}} b_{\gamma_1}(\alpha)$. In this situation, Claim 1 shows that $k_{\gamma_0}^\alpha = k_{\gamma_1}^\alpha$. Set $k = k_{\gamma_0}^\alpha$ and pick an ordinal $\xi \in C_{\gamma_0} \cap [\mu, \gamma_0)$. Since our assumptions imply that $C_{\gamma_0} = C_{\varepsilon_{\gamma_0}^\alpha(k)} \cap \gamma$ and hence $\xi \in C_{\varepsilon_{\gamma_0}^\alpha(k)}$, an application of [9, Lemma 3.2] shows that $\langle \varepsilon_{\gamma_0}^\alpha(0), \dots, \varepsilon_{\gamma_0}^\alpha(k), \xi \rangle$ is the walk from $\delta_{\gamma_0}^\alpha$ to ξ through \vec{C} . Another application of [9, Lemma 3.2] shows that $\langle \varepsilon_{\gamma_1}^\alpha(0), \dots, \varepsilon_{\gamma_1}^\alpha(k) \rangle$ is an initial segment of the walk from $\delta_{\gamma_1}^\alpha$ to ξ . In this situation, $\rho_0(\xi, \delta_{\gamma_0}^\alpha) = \rho_0(\xi, \delta_{\gamma_1}^\alpha)$ implies that $\langle \varepsilon_{\gamma_1}^\alpha(0), \dots, \varepsilon_{\gamma_1}^\alpha(k), \xi \rangle$ is the walk from $\delta_{\gamma_1}^\alpha$ to ξ through \vec{C} . In particular, this shows that ξ is an element of $C_{\varepsilon_{\gamma_1}^\alpha}$. Since our assumptions also imply that $C_{\gamma_1} = C_{\varepsilon_{\gamma_1}^\alpha} \cap \gamma_1$, we conclude that $\xi \in C_{\gamma_1}$. Therefore $C_{\gamma_0} \subseteq C_{\gamma_1}$, and hence we have $\gamma_0 \in \text{Lim}(C_{\gamma_1}) \cap S$ and S -coherence implies $C_{\gamma_0} = C_{\gamma_1} \cap \gamma_0$. ■

Claim 2 implies that $C = \bigcup \{C_\gamma \mid \gamma \in E\}$ is a club in θ with $C_\gamma = C \cap \gamma$ for all $\gamma \in E$. Using Lemma 4.3, we conclude that \mathbb{T} has a cofinal branch. ■

We will later show that it is not possible to prove Lemma 4.5 without some coherence assumption on the C -sequence (see Theorem 4.12).

DEFINITION 4.6 (Todorćević). We say a C -sequence $\vec{C} = \langle C_\gamma \mid \gamma < \theta \rangle$ is a $\square(\theta)$ -sequence if \vec{C} is θ -coherent and there is no club C in θ with $C_\gamma = C \cap \gamma$ for all $\gamma \in \text{Lim}(C)$.

If \vec{C} is a $\square(\theta)$ -sequence, then Lemmas 4.3 and 4.2 imply that $\mathbb{T}(\rho_0^{\vec{C}})$ is a θ -Aronszajn tree. In combination with Lemma 4.5, this yields the following result.

COROLLARY 4.7. *If \vec{C} is a $\square(\theta)$ -sequence and λ is a cardinal with $\lambda^+ < \theta$, then the tree $\mathbb{T}(\rho_0^{\vec{C}})$ does not contain an ascending path of width λ . ■*

Seminal results of Jensen and Todorćević (see [8, Section 6] and [25, Theorem 1.10]) show that the existence of a constructible $\square(\theta)$ -sequence follows from the assumption that θ is not weakly compact in L . In combination with the main result of [26], these results allow us to prove Theorem 1.10.

Proof of Theorem 1.10. Let κ be an uncountable cardinal such that $\kappa = \kappa^{<\kappa}$ and κ^+ is not weakly compact in L . In this situation, [25, Theorem 1.10] implies that there is a $\square(\kappa^+)$ -sequence, and [26, Theorem 3] implies that there is a $\square(\kappa^+)$ -sequence \vec{C} with the property that the tree $\mathbb{T} = \mathbb{T}(\rho_0^{\vec{C}})$ is not special. Then the partial order $\mathbb{P}_\kappa(\mathbb{T})$ is $<\kappa$ -closed and well-met. Moreover, Corollary 4.7 shows that there are no ascending paths of width less than κ through \mathbb{T} , and by our assumptions on κ , we can apply Theorem 1.9 to conclude that $\mathbb{P}_\kappa(\mathbb{T})$ satisfies the κ^+ -chain condition. Given $t \in \mathbb{T}$, define D_t to be the dense subset $\{p \in \mathbb{P}_\kappa(\mathbb{T}) \mid t \in \text{dom}(p)\}$ of $\mathbb{P}_\kappa(\mathbb{T})$.

Since \mathbb{T} is a κ^+ -Aronszajn tree, the collection $\mathcal{D} = \{D_t \mid t \in \mathbb{T}\}$ has cardinality κ^+ . But then there is no \mathcal{D} -generic filter on $\mathbb{P}_\kappa(\mathbb{T})$, because the existence of such a filter would imply that \mathbb{T} is special. This shows that $\text{FA}_{\kappa^+}(\mathbb{P}_\kappa(\mathbb{T}))$ fails. ■

In the remainder of this section, we will prove Theorem 1.12. The following definition and lemmas are crucial for the proof.

DEFINITION 4.8. A C -sequence $\vec{C} = \langle C_\gamma \mid \gamma < \theta \rangle$ avoids a subset S of θ if $\text{Lim}(C_\gamma) \cap S = \emptyset$ holds for all $\gamma \in \text{Lim} \cap \theta$.

LEMMA 4.9 ([5, Lemma 6.7]). *There is a club D in θ with the property that whenever \vec{C} is a C -sequence of length θ that avoids a subset S of θ , then $D \cap S$ is non-stationary with respect to $\mathbb{T}(\rho_0^{\vec{C}})$.*

LEMMA 4.10 ([5, Lemma 6.4]). *Assume that \mathbb{T} is a θ -Aronszajn tree that does not split at limit levels. If there is a stationary subset S of θ such that S is non-stationary with respect to \mathbb{T} , then the partial order $\mathbb{P}_\omega(\mathbb{T})$ is θ -Knaster.*

Note that trees of the form $\mathbb{T}(\rho_0^{\vec{C}})$ for some C -sequence \vec{C} consist of functions ordered by inclusion and therefore such trees do not split at limit levels. In the following, we will start from the assumption that there is a $\square(\theta)$ -sequence that avoids a stationary set consisting of ordinals of small cofinality, and use the above lemma to find a C -sequence \vec{C} of length θ with the property that the tree $\mathbb{T}(\rho_0^{\vec{C}})$ is a θ -Aronszajn tree containing an ascending path of small width and the property that the partial order $\mathbb{P}_\omega(\mathbb{T}(\rho_0^{\vec{C}}))$ is θ -Knaster. The path constructed will satisfy the following stronger property first considered by Laver (see [7] and [23]). In the general terminology of [4], such paths are called \mathcal{F}_λ^{bd} -ascent paths.

DEFINITION 4.11 (Laver). Let $\lambda > 0$ be a cardinal. Then a λ -ascent path through \mathbb{T} is a sequence $\langle b_\gamma : \lambda \rightarrow \mathbb{T}(\gamma) \mid \gamma < \theta \rangle$ with the property that for all $\gamma, \tilde{\gamma} < \theta$, there is a $\tilde{\lambda} < \lambda$ such that $b_{\tilde{\lambda}}(\alpha) \leq_{\mathbb{T}} b_\gamma(\alpha)$ for all $\tilde{\lambda} < \alpha < \lambda$.

In [26], Todorćević constructed a θ -Aronszajn tree containing such a κ -ascent path assuming the existence of a $\square(\theta)$ -sequence $\vec{C} = \langle C_\gamma \mid \gamma < \theta \rangle$ with the property that there is an infinite regular cardinal $\kappa < \theta$ such that the cardinal θ is not the successor of a cardinal of cofinality κ and the set $\{\gamma < \theta \mid \text{otp}(C_\gamma) = \kappa\}$ is stationary in θ . The results of [12, Section 3] show that this assumption is slightly stronger than the assumptions of the next theorem. This theorem also shows that the conclusion of Lemma 4.5 does not hold without some coherence assumptions on the sequence \vec{C} .

THEOREM 4.12. *Let $\lambda < \theta$ be an infinite regular cardinal and let $S \subseteq S_\lambda^\theta$ be stationary in θ . Assume that there is a $\square(\theta)$ -sequence that avoids S . Then*

there is a C -sequence \vec{C} of length θ that avoids S and has the property that the tree $\mathbb{T}(\rho_0^{\vec{C}})$ is a θ -Aronszajn tree that contains a λ -ascent path.

Proof. Fix a $\square(\theta)$ -sequence $\vec{D} = \langle D_\gamma \mid \gamma < \theta \rangle$ that avoids S and let A denote the set of all ordinals less than θ that are divisible by $\omega \cdot \lambda$, i.e. $A = \{\omega \cdot \lambda \cdot \gamma \mid \gamma < \theta\}$. Then $0 \in A$ and A is closed in θ .

In the following, we inductively construct a sequence

$$\langle \langle C_{\gamma+\omega \cdot \alpha} \mid \alpha < \lambda \rangle \mid \gamma \in A \rangle$$

that satisfies the following statements for all $\gamma \in A$:

- (i) $C_\gamma = D_\gamma$.
 - (ii) If $0 < \alpha < \lambda$, then $C_{\gamma+\omega \cdot \alpha}$ is a club in $\gamma + \omega \cdot \alpha$ with $C_{\gamma+\omega \cdot \alpha} \cap S = \emptyset$.
 - (iii) If $\tilde{\gamma} < \gamma$ and $0 < \alpha < \lambda$, then there is $\bar{\gamma} < \min(A \setminus \tilde{\gamma}) + \omega \cdot \lambda$ with
- $$(4.1) \quad C_{\gamma+\omega \cdot \alpha} \cap \tilde{\gamma} = (C_{\bar{\gamma}} \cup \{\bar{\gamma}\}) \cap \tilde{\gamma}.$$
- (iv) If $\gamma \in A \setminus S$ and $\bar{\gamma} \in \text{Lim}(A \cap D_\gamma)$, then $C_{\gamma+\omega \cdot \alpha}$ is an end-extension of $C_{\bar{\gamma}+\omega \cdot \alpha}$ for all $0 < \alpha < \lambda$.
 - (v) If $\tilde{\gamma} \in A \cap \gamma$, then there is $\tilde{\lambda} < \lambda$ such that $C_{\gamma+\omega \cdot \alpha}$ is an end-extension of $C_{\tilde{\gamma}+\omega \cdot \alpha}$ for all $\tilde{\lambda} < \alpha < \lambda$.

In the construction of this sequence, we will distinguish several cases:

CASE 0: $\gamma = 0$. Define $C_{\omega \cdot \alpha} = \omega \cdot \alpha$ for all $\alpha < \lambda$.

CASE 1: A is bounded in $\gamma > 0$. Pick ordinals $\gamma_0 \leq \gamma_1 < \gamma$ with the property that $\gamma_1 = \max(A \cap \gamma)$ and either $\text{Lim}(A \cap D_\gamma) \neq \emptyset$ and $\gamma_0 = \max(\text{Lim}(A \cap D_\gamma))$ or $\text{Lim}(A \cap D_\gamma) = \emptyset$ and $\gamma_0 = \gamma_1$. By our induction hypothesis, there is $\lambda_1 < \lambda$ such that $C_{\gamma_1+\omega \cdot \alpha}$ is an end-extension of $C_{\gamma_0+\omega \cdot \alpha}$ for all $\lambda_1 < \alpha < \lambda$. Set $\lambda_0 = 0$ and $\lambda_2 = \lambda$. Given $0 < \alpha < \lambda$, pick $i < 2$ with $\lambda_i < \alpha \leq \lambda_{i+1}$ and define

$$C_{\gamma+\omega \cdot \alpha} = C_{\gamma_i+\omega \cdot \alpha} \cup \{\gamma_i + \omega \cdot \alpha\} \cup (\gamma, \gamma + \omega \cdot \alpha).$$

Given $0 < \alpha < \lambda$, the set $C_{\gamma+\omega \cdot \alpha}$ is a club in $\gamma + \omega \cdot \alpha$ that is disjoint from S . Moreover, for all $\tilde{\gamma} < \gamma$ and $0 < \alpha < \lambda$, we can find $i < 2$ with

$$C_{\gamma+\omega \cdot \alpha} \cap \tilde{\gamma} = (C_{\gamma_i+\omega \cdot \alpha} \cup \{\gamma_i + \omega \cdot \alpha\}) \cap \tilde{\gamma}.$$

Together with our induction hypothesis, this allows us to find an ordinal $\bar{\gamma} < \min(A \setminus \tilde{\gamma}) + \omega \cdot \lambda$ such that (4.1) holds. If $\text{Lim}(A \cap D_\gamma) \neq \emptyset$, then our induction hypothesis implies that $C_{\gamma+\omega \cdot \alpha}$ is an end-extension of $C_{\bar{\gamma}+\omega \cdot \alpha}$ for all $\bar{\gamma} \in \text{Lim}(A \cap D_\gamma)$ and $0 < \alpha < \lambda$, because the above construction ensures that $C_{\gamma+\omega \cdot \alpha}$ is an end-extension of $C_{\gamma_0+\omega \cdot \alpha}$ for all $0 < \alpha < \lambda$. Finally, for every $\tilde{\gamma} \in A \cap \gamma$ there is $\lambda_1 \leq \tilde{\lambda} < \lambda$ such that $C_{\gamma_1+\omega \cdot \alpha}$ is an end-extension of $C_{\tilde{\gamma}+\omega \cdot \alpha}$ for all $\tilde{\lambda} < \alpha < \lambda$, and this implies that $C_{\gamma+\omega \cdot \alpha}$ is an end-extension of $C_{\tilde{\gamma}+\omega \cdot \alpha}$ for all $\tilde{\lambda} < \alpha < \lambda$.

CASE 2: A is unbounded in γ and $\text{Lim}(A \cap D_\gamma)$ is bounded in γ . Then $\text{cof}(\gamma) = \omega$ and we can pick a strictly increasing sequence $\langle \gamma_n \in A \mid n < \omega \rangle$ cofinal in γ such that $\text{Lim}(A \cap D_\gamma) \neq \emptyset$ implies $\gamma_0 = \max(\text{Lim}(A \cap D_\gamma))$. By our induction hypothesis, we can find a strictly increasing sequence $\langle \lambda_n < \lambda \mid n < \omega \rangle$ such that $\lambda_0 = 0$, $C_{\gamma_{n+1} + \omega \cdot \alpha}$ is an end-extension of $C_{\gamma_n + \omega \cdot \alpha}$ for all $n < \omega$ and $\lambda_{n+1} \leq \alpha < \lambda$, and if $\text{cof}(\lambda) = \omega$, then this sequence is cofinal in λ . Then $C_{\gamma_n + \omega \cdot \alpha}$ is an end-extension of $C_{\gamma_m + \omega \cdot \alpha}$ for all $m \leq n < \omega$ and $\lambda_n \leq \alpha < \lambda$. Set $\lambda_\omega = \sup_{n < \omega} \lambda_n \leq \lambda$. Note that $\lambda_\omega < \lambda$ implies that $\lambda > \omega$ and $\gamma \notin S$. Given $0 < \alpha < \lambda_\omega$, let $n < \omega$ be maximal with $\lambda_n \leq \alpha$ and define

$$C_{\gamma + \omega \cdot \alpha} = C_{\gamma_n + \omega \cdot \alpha} \cup \{\gamma_\beta + \omega \cdot \alpha\} \cup (\gamma, \gamma + \omega \cdot \alpha).$$

Given $\lambda_\omega \leq \alpha < \lambda$, define

$$C_{\gamma + \omega \cdot \alpha} = \bigcup \{C_{\gamma_n + \omega \cdot \alpha} \mid n < \omega\} \cup [\gamma, \gamma + \omega \cdot \alpha).$$

Then the set $C_{\gamma + \omega \cdot \alpha}$ is a club in $\gamma + \omega \cdot \alpha$ that is disjoint from S for all $0 < \alpha < \lambda$. If $\tilde{\gamma} < \gamma$ and $0 < \alpha < \lambda$, then there is an $n < \omega$ with

$$C_{\gamma + \omega \cdot \alpha} \cap \tilde{\gamma} = (C_{\gamma_n + \omega \cdot \alpha} \cup \{\gamma_n + \omega \cdot \alpha\}) \cap \tilde{\gamma}.$$

In combination with our induction hypothesis, this shows that there is an ordinal $\bar{\gamma} < \min(A \setminus \tilde{\gamma}) + \omega \cdot \lambda$ such that (4.1) holds. Next, observe that $\text{Lim}(A \cap D_\gamma) \neq \emptyset$ implies that $C_{\gamma + \omega \cdot \alpha}$ is an end-extension of $C_{\gamma_0 + \omega \cdot \alpha}$ for all $0 < \alpha < \lambda$. If $\bar{\gamma} \in \text{Lim}(A \cap D_\gamma)$ and $0 < \alpha < \lambda$, then $\gamma_0 \in A \setminus S$, $\bar{\gamma} \in \text{Lim}(A \cap D_{\gamma_0})$ and our induction hypothesis together with the above observation shows that $C_{\gamma + \omega \cdot \alpha}$ is an end-extension of $C_{\bar{\gamma} + \omega \cdot \alpha}$. Finally, pick $\tilde{\gamma} \in A \cap \gamma$. By induction hypothesis, there are $n < \omega$ and $\lambda_n \leq \tilde{\lambda} < \lambda$ such that $\tilde{\gamma} \leq \gamma_n$ and $C_{\gamma_n + \omega \cdot \alpha}$ is an end-extension of $C_{\tilde{\gamma} + \omega \cdot \alpha}$ for all $\tilde{\lambda} < \alpha < \lambda$. Fix $\tilde{\lambda} < \alpha < \lambda$ and let $\beta \leq \omega$ be maximal such that $\lambda_\beta \leq \alpha$. Then $\beta \geq n$, $C_{\gamma + \omega \cdot \alpha}$ is an end-extension of $C_{\gamma_n + \omega \cdot \alpha}$ and therefore $C_{\gamma + \omega \cdot \alpha}$ is an end-extension of $C_{\tilde{\gamma} + \omega \cdot \alpha}$.

CASE 3: $\text{Lim}(A \cap D_\gamma)$ is unbounded in γ and $\gamma \notin S$. Define

$$C_{\gamma + \omega \cdot \alpha} = \bigcup \{C_{\bar{\gamma} + \omega \cdot \alpha} \mid \bar{\gamma} \in \text{Lim}(A \cap D_\gamma)\} \cup [\gamma, \gamma + \omega \cdot \alpha)$$

for all $0 < \alpha < \lambda$. If $\gamma_0, \gamma_1 \in \text{Lim}(A \cap D_\gamma)$ with $\gamma_0 < \gamma_1$, then we know that $\gamma_0 \in \text{Lim}(A \cap D_{\gamma_1})$ and our induction hypothesis implies that $C_{\gamma_1 + \omega \cdot \alpha}$ is an end-extension of $C_{\gamma_0 + \omega \cdot \alpha}$ for all $0 < \alpha < \lambda$. This shows that for all $0 < \alpha < \lambda$, the set $C_{\gamma + \omega \cdot \alpha}$ is a club in $\gamma + \omega \cdot \alpha$ that is disjoint from S . Moreover, if $\tilde{\gamma} < \gamma$ and $0 < \alpha < \lambda$, then there is $\gamma_0 \in \text{Lim}(A \cap D_\gamma)$ with $C_{\gamma + \omega \cdot \alpha} \cap \tilde{\gamma} = C_{\gamma_0 + \omega \cdot \alpha} \cap \tilde{\gamma}$, and by our induction hypothesis, this shows that there there is a $\bar{\gamma} < \min(A \setminus \tilde{\gamma}) + \omega \cdot \lambda$ such that (4.1) holds. Next, the induction hypothesis shows that $C_{\gamma + \omega \cdot \alpha}$ is an end-extension of $C_{\bar{\gamma} + \omega \cdot \alpha}$ for all $\bar{\gamma} \in \text{Lim}(A \cap D_\gamma)$ and $0 < \alpha < \lambda$. Finally, if $\tilde{\gamma} \in A \cap \gamma$, then the induction hypothesis implies that there are $\bar{\gamma} \in \text{Lim}(A \cap D_\gamma)$ and $\tilde{\lambda} < \lambda$ such that

$\tilde{\gamma} \leq \bar{\gamma}$, $C_{\tilde{\gamma}+\omega \cdot \alpha}$ is an end-extension of $C_{\tilde{\gamma}+\omega \cdot \alpha}$ for all $\tilde{\lambda} < \alpha < \lambda$, and $C_{\gamma+\omega \cdot \alpha}$ is an end-extension of $C_{\tilde{\gamma}+\omega \cdot \alpha}$ for all $\tilde{\lambda} < \alpha < \lambda$.

CASE 4: $\text{Lim}(A \cap D_\gamma)$ is unbounded in γ and $\gamma \in S$. Then $\text{cof}(\gamma) = \lambda$ and there is a sequence $\langle \gamma_\alpha \in \text{Lim}(A \cap D_\gamma) \mid \alpha < \lambda \rangle$ that is strictly increasing, continuous and cofinal in γ . Given $0 < \alpha < \lambda$, define

$$C_{\gamma+\omega \cdot \alpha} = C_{\gamma_\alpha+\omega \cdot \alpha} \cup \{\gamma_\alpha + \omega \cdot \alpha\} \cup (\gamma, \gamma + \omega \cdot \alpha).$$

Given $0 < \alpha < \lambda$, the set $C_{\gamma+\omega \cdot \alpha}$ is a club in $\gamma + \omega \cdot \alpha$ that is disjoint from S . Next, if $\tilde{\gamma} < \gamma$ and $0 < \alpha < \lambda$, then

$$C_{\gamma+\omega \cdot \alpha} \cap \tilde{\gamma} = (C_{\gamma_\alpha+\omega \cdot \alpha} \cup \{\gamma_\alpha + \omega \cdot \alpha\}) \cap \tilde{\gamma}$$

and our induction hypothesis yields $\bar{\gamma} < \min(A \setminus \tilde{\gamma}) + \omega \cdot \lambda$ such that (4.1) holds. Finally, pick $\tilde{\gamma} \in A \cap \gamma$. Then the induction hypothesis allows us to find $\tilde{\alpha} \leq \tilde{\lambda} < \lambda$ such that $\tilde{\gamma} \leq \gamma_{\tilde{\alpha}}$ and $C_{\gamma_{\tilde{\alpha}}+\omega \cdot \alpha}$ is an end-extension of $C_{\tilde{\gamma}+\omega \cdot \alpha}$ for all $\tilde{\lambda} < \alpha < \lambda$. Fix $\tilde{\lambda} < \alpha < \lambda$. Since $\gamma_\alpha \in A \setminus S$ and $\gamma_{\tilde{\alpha}} \in \text{Lim}(A \cap D_{\gamma_\alpha})$, the induction hypothesis implies that $C_{\gamma_\alpha+\omega \cdot \alpha}$ is an end-extension of $C_{\gamma_{\tilde{\alpha}}+\omega \cdot \alpha}$, so $C_{\gamma+\omega \cdot \alpha}$ is an end-extension of $C_{\tilde{\gamma}+\omega \cdot \alpha}$.

This completes our inductive construction. We let \vec{C} denote the resulting C -sequence. Set $\mathbb{T} = \mathbb{T}(\rho_0^{\vec{C}})$ and $\rho_0 = \rho_0^{\vec{C}}$.

CLAIM 1. *The tree \mathbb{T} is a θ -Aronszajn tree.*

Proof. Pick $\gamma < \theta$. Since \vec{D} is a $\square(\theta)$ -sequence, we have

$$|\{C_\delta \cap \gamma \mid \delta \in A \setminus \gamma\}| \leq |\gamma| + \aleph_0 < \theta.$$

Moreover, the above construction ensures that

$$\begin{aligned} & |\{C_{\delta+\omega \cdot \alpha} \cap \gamma \mid \gamma + \omega \cdot \lambda \leq \delta \in A, 0 < \alpha < \lambda\}| \\ & \leq |\{(C_\delta \cup \{\delta\}) \cap \gamma \mid \delta < \min(A \setminus \gamma) + \omega \cdot \lambda\}| < \theta. \end{aligned}$$

In combination, this shows that $|\{C_\delta \cap \gamma \mid \gamma \leq \delta < \theta\}| < \theta$.

Together with Lemma 4.2, the above computations show that $|\mathbb{T}(\gamma)| < \theta$ for all $\gamma < \theta$. Since \vec{C} avoids S , we can apply Proposition 1.2 and Lemma 4.9 to conclude that there are no cofinal branches through \mathbb{T} . This proves that \mathbb{T} is a θ -Aronszajn tree. ■

Given $\gamma \in A$ and $\alpha < \lambda$, define

$$t_\gamma(\alpha) = \rho_0(\cdot, \gamma + \omega \cdot (1 + \alpha)) \upharpoonright \gamma \in \mathbb{T}(\gamma).$$

CLAIM 2. *If $\gamma, \tilde{\gamma} \in A$ with $\tilde{\gamma} < \gamma$, then there is $\tilde{\lambda} < \lambda$ such that $t_{\tilde{\gamma}}(\alpha) <_{\mathbb{T}} t_\gamma(\alpha)$ for all $\tilde{\lambda} < \alpha < \lambda$.*

Proof. By the above construction, we can find $\tilde{\lambda} < \lambda$ with the property that $C_{\gamma+\omega \cdot \alpha}$ is an end-extension of $C_{\tilde{\gamma}+\omega \cdot \alpha}$ for all $\tilde{\lambda} < \alpha < \lambda$. By the definition of ρ_0 , this implies that $t_{\tilde{\gamma}}(\alpha) <_{\mathbb{T}} t_\gamma(\alpha)$ for all $\tilde{\lambda} < \alpha < \lambda$. ■

Given $\gamma < \theta$ and $\alpha < \lambda$, set $\delta = \min(A \setminus \gamma)$ and define $b_\gamma(\alpha)$ to be the unique element of $\mathbb{T}(\gamma)$ with $b_\gamma(\alpha) \leq_{\mathbb{T}} t_\delta(\alpha)$. Then Claim 2 shows that the resulting sequence $\langle b_\gamma : \lambda \rightarrow \mathbb{T}(\gamma) \mid \gamma < \theta \rangle$ is a λ -ascent path through \mathbb{T} . ■

Before we prove Theorem 1.12, we use the above theorem to reprove a result of [26] on lower bounds for the consistency strength of the conclusion of Theorem 1.13(iii). Note that the lower bound derived is strictly smaller than the upper bound given by the theorem (see Question 6.5).

COROLLARY 4.13. *Assume that $\theta > \omega_1$ and there is a $\square(\theta)$ -sequence \vec{C} with the property that the tree $\mathbb{T}(\rho_0^{\vec{C}})$ is special.*

- (i) *If θ is not a successor of a cardinal of cofinality ω , then there is a C -sequence \vec{C} of length θ with the property that $\mathbb{T}(\rho_0^{\vec{C}})$ is a θ -Aronszajn tree that contains an ω -ascent path.*
- (ii) *If θ is a successor of a cardinal of cofinality ω , then there is a C -sequence \vec{C} of length θ with the property that $\mathbb{T}(\rho_0^{\vec{C}})$ is a θ -Aronszajn tree that contains an ω_1 -ascent path.*

Proof. Let $\kappa < \theta$ be a regular cardinal with the property that θ is not a successor of a cardinal of cofinality κ . Then a combination of [26, Lemma 4] with [12, Proposition 30] implies that there is a $\square(\theta)$ -sequence \vec{D} and $S \subseteq S_\kappa^\theta$ stationary in θ such that \vec{D} avoids S . By Theorem 4.12, this proves the corollary. ■

Note that results of Jensen show that the assumption of Corollary 4.13 holds if θ is not a Mahlo cardinal in L (see [26, Theorem 2]). Moreover, Jensen's classical definition of \square_κ -sequences provides examples of sequences with the above property.

DEFINITION 4.14 (Jensen). Let κ be an infinite cardinal. A \square_κ -sequence is a κ^+ -coherent C -sequence $\vec{C} = \langle C_\gamma \mid \gamma < \kappa^+ \rangle$ with $\text{otp}(C_\gamma) \leq \kappa$ for all $\gamma < \kappa^+$.

Basic computations contained in [26] show that for every \square_κ -sequence \vec{C} , the tree $\mathbb{T}(\rho_0^{\vec{C}})$ is a special κ^+ -Aronszajn tree. Using results from inner model theory, this shows that the non-existence of Aronszajn trees containing ascending paths of width at most ω_1 at the successor of a singular cardinal or the successor of a weakly compact has very large consistency strength.

Proof of Theorem 1.12. Assume that V is a Jensen-style extender model and let ϑ be an uncountable regular cardinal.

First, assume that ϑ is weakly compact. Let $\nu < \vartheta$, let $\mathbb{P} = \prod_{\eta < \rho} \mathbb{P}_\eta$ be a ν -support product of ϑ -Knaster partial orders and let $\langle \vec{p}_\gamma \mid \gamma < \vartheta \rangle$ be a sequence of conditions in \mathbb{P} . By the Δ -system lemma, there is an unbounded subset S of ϑ and a subset R of ρ of cardinality at most ν such that $\text{supp}(p_\eta) \cap$

$\text{supp}(p_{\bar{\eta}}) = R$ for all $\eta, \bar{\eta} \in S$ with $\eta \neq \bar{\eta}$. Then there is a unique function $c : S \times S \rightarrow R \cup \{\rho\}$ such that the following statements hold for all $\gamma, \bar{\gamma} \in S$:

- $c(\gamma, \bar{\gamma}) = \rho$ if and only if the conditions \vec{p}_γ and $\vec{p}_{\bar{\gamma}}$ are compatible in \mathbb{P} .
- If $c(\gamma, \bar{\gamma}) < \rho$, then $c(\gamma, \bar{\gamma})$ is the minimal element η of R such that the conditions $\vec{p}_\gamma(\eta)$ and $\vec{p}_{\bar{\gamma}}(\eta)$ are incompatible in \mathbb{P}_η .

Since ϑ is weakly compact and each partial order \mathbb{P}_η satisfies the ϑ -chain condition, there is $U \subseteq S$ unbounded in ϑ with $c(\gamma, \bar{\gamma}) = \rho$ for all $\gamma, \bar{\gamma} \in U$. Then the sequence $\langle \vec{p}_\gamma \mid \gamma \in U \rangle$ consists of pairwise compatible conditions in \mathbb{P} .

Next, assume that ϑ is neither weakly compact nor the successor of a subcompact cardinal. If ϑ is inaccessible, then [31, Theorem 0.1] shows that there is a $\square(\vartheta)$ -sequence \vec{C} and $S \subseteq S_\omega^\vartheta$ stationary in ϑ such that \vec{C} avoids S . In the other case, if ϑ is the successor of a cardinal κ that is not subcompact, then [18, Theorem 0.1] shows that there is a \square_κ -sequence, and a combination of [12, Proposition 30] with [12, Corollary 32] shows that in this case we can also find a $\square(\vartheta)$ -sequence \vec{C} and $S \subseteq S_\omega^\vartheta$ stationary in ϑ such that \vec{C} avoids S . By Lemma 4.9 and Theorem 4.12, this implies that there is a club D in ϑ and a ϑ -Aronszajn tree \mathbb{T} such that there is an ascending path of width ω through \mathbb{T} and the set $D \cap S$ is non-stationary with respect to \mathbb{T} . Then Lemma 4.10 shows that the partial order $\mathbb{P}_\omega(\mathbb{T})$ is ϑ -Knaster, and Proposition 2.3 implies that the full support product $\prod_\omega \mathbb{P}_\omega(\mathbb{T})$ is not ϑ -Knaster.

Finally, assume that ϑ is the successor of a subcompact cardinal κ . Since subcompact cardinals are weakly compact, we have $\kappa = \kappa^{<\kappa}$ and a classical result of Specker shows that there is a normal special ϑ -Aronszajn tree \mathbb{T} . Then Lemma 4.10 implies that the partial order $\mathbb{P}_\omega(\mathbb{T})$ is ϑ -Knaster. In this situation, Proposition 1.5 shows that \mathbb{T} contains an ascending path of width κ , and Proposition 2.3 shows that the full support product $\prod_\kappa \mathbb{P}_\omega(\mathbb{T})$ is not ϑ -Knaster. ■

5. PFA and ascending paths. In this section, we prove the three statements of Theorem 1.14. We start by showing how the theory of *guessing models* developed by Viale and Weiß [29] can be used to show that the Proper Forcing Axiom implies the non-existence of trees containing ascending paths of countable width without cofinal branches. Basically the same implication was independently proven by Lambie-Hanson [13, Section 10]. For the sake of completeness, we still present this short application of the results of [29]. Given a set X and a cardinal κ , we let $\mathcal{P}_\kappa(X)$ denote the collection of all subsets of X of cardinality less than κ .

DEFINITION 5.1. Let ϑ be an uncountable regular cardinal and let M be an elementary substructure $H(\vartheta)$.

- (i) A set $X \in H(\vartheta)$ is *M-approximated* if $X \cap Y \in M$ for all Y in $M \cap \mathcal{P}_{\omega_1}(M)$.
- (ii) A set $X \in H(\vartheta)$ is *M-guessed* if there is an $Y \in M$ with the property that $X \cap M = Y \cap M$.
- (iii) M is a *guessing model* if for all $A \in M$ and every $X \subseteq A$ that is M -approximated, the set X is M -guessed.

DEFINITION 5.2 ([29]). Given an uncountable regular cardinal κ , we let $\text{ISP}(\kappa)$ denote the statement that for every regular cardinal $\vartheta > \kappa$, the collection of all guessing models is stationary in $M \in \mathcal{P}_\kappa(H(\vartheta))$.

THEOREM 5.3 ([29, Theorem 4.8]). *PFA implies $\text{ISP}(\omega_2)$.*

The following result also appeared as [13, Theorem 10.2].

LEMMA 5.4. *If $\text{ISP}(\kappa)$ holds and $\theta \geq \omega_2$, then every narrow θ -system of width ω has a cofinal branch.*

Proof. Let \mathcal{R} be a narrow θ -system of width ω , let $\vartheta > \theta$ be a regular cardinal with $\mathcal{R} \in H(\vartheta)$ and let $M \in \mathcal{P}_{\omega_2}(H(\vartheta))$ be a guessing model with $\mathcal{R} \in M$. Set $\delta = \sup(M \cap \theta) < \theta$. Then $\text{cof}(\delta) = \omega_1$, because our assumptions imply that every subset of $M \cap \delta$ of order-type ω is contained in M . Also, by our assumptions, there are $\beta < \lambda \subseteq M$ and $R \in \mathcal{R} \subseteq M$ such that the set

$$\{\gamma \in D \cap M \mid \exists \alpha < \lambda \langle \gamma, \alpha \rangle R \langle \delta, \beta \rangle\}$$

is unbounded in δ . Set

$$A = \{\langle \gamma, \alpha \rangle \in D \times \lambda \mid \langle \gamma, \alpha \rangle R \langle \delta, \beta \rangle\}.$$

Then $A \subseteq D \times \lambda \in M$ is a branch through \mathcal{R} .

Pick $X \in M \cap \mathcal{P}_{\omega_1}(M)$. Since $\text{cof}(\delta) = \omega_1$, we can find $\gamma \in D \cap M$ and $\alpha < \lambda$ such that $A \cap X \subseteq \gamma \times \lambda$ and $\langle \gamma, \alpha \rangle R \langle \delta, \beta \rangle$. Then

$$A \cap X = \{\langle \bar{\gamma}, \bar{\alpha} \rangle \in D \times \lambda \mid \langle \bar{\gamma}, \bar{\alpha} \rangle \in X, \langle \bar{\gamma}, \bar{\alpha} \rangle R \langle \gamma, \alpha \rangle\} \in M.$$

The above computations show that A is M -approximated and hence it is M -guessed. This shows that there is $B \in M$ with $B \subseteq D \times \lambda$ and $A \cap M = B \cap M$. In M , the set B is a cofinal R -branch through \mathcal{R} . By elementarity, \mathcal{R} has a cofinal branch in V . ■

In the following, we will show that PFA is compatible with the existence of an ω_3 -Souslin tree that contains an ascending path of width ω_1 . This proof uses the weak square principle introduced by Baumgartner in unpublished work and parallels the constructions of [13, Section 9].

DEFINITION 5.5 (Baumgartner). Let κ be an infinite regular cardinal, let B be a subset of κ^+ with $S_\kappa^{\kappa^+} \subseteq B \subseteq \text{Lim}$ and let $\vec{C} = \langle C_\gamma \mid \gamma < \kappa^+ \rangle$ be

a C -sequence. We say that \vec{C} is a \square_κ^B -sequence if the following statements hold:

- (i) $\text{otp}(C_\gamma) \leq \kappa$ for all $\gamma < \kappa^+$.
- (ii) If $\gamma \in B \cap \text{Lim}$ and $\bar{\gamma} \in \text{Lim}(C_\gamma)$, then $\bar{\gamma} \in B$ and $C_{\bar{\gamma}} = C_\gamma \cap \bar{\gamma}$.

In contrast to \square_κ -sequences, such sequences can be added by $<\kappa$ -directed closed forcings that preserve the regularity of κ^+ .

LEMMA 5.6 ([2, Fact 2.7]). *If κ is an infinite regular cardinal, then there is a partial order \mathbb{P} with the following properties:*

- (i) \mathbb{P} is $<\kappa$ -directed closed and $(\kappa + 1)$ -strategically closed.
- (ii) If G is \mathbb{P} -generic over V , then there is a \square_κ^B -sequence in $V[G]$.

The following observation shows that we can modify a given \square_κ^B -sequence to obtain a sequence that avoids a stationary subset of a given stationary set.

PROPOSITION 5.7. *Let κ be an infinite regular cardinal with the property that there is a \square_κ^B -sequence.*

- (i) *The set B is a fat stationary subset of κ^+ . In particular, $B \cap S_\nu^{\kappa^+}$ is stationary in κ^+ for every regular cardinal $\nu \leq \kappa$.*
- (ii) *If $S \subseteq B$ is stationary in κ^+ , then there is $A \subseteq S$ stationary in κ^+ and a \square_κ^B -sequence $\vec{C} = \langle C_\gamma \mid \gamma < \kappa^+ \rangle$ such that $A \cap \text{Lim}(C_\gamma) = \emptyset$ for all $\gamma \in B$.*

Proof. Let $\vec{D} = \langle D_\gamma \mid \gamma < \kappa^+ \rangle$ be a \square_κ^B -sequence.

(i) We may assume that κ is uncountable, as otherwise the statement holds trivially. Let C be a club in κ^+ . Pick $\gamma \in \text{Lim}(C) \cap S_\kappa^{\kappa^+} \subseteq B$. Then $(C \cap \text{Lim}(C_\gamma)) \cup \{\gamma\}$ is a closed subset of $B \cap C$ of order-type $\kappa + 1$. By [1, Lemma 1.2], this argument shows that B is fat stationary in κ^+ .

(ii) By our assumptions, we have $\text{otp}(C_\gamma) < \gamma$ for all $\gamma \in S \setminus (\kappa + 1)$. This allows us to find $\xi \leq \kappa$ and $A \subseteq S$ stationary in κ^+ such that $\text{otp}(D_\gamma) = \xi$ for all $\gamma \in A$. Then $|A \cap \text{Lim}(D_\gamma)| \leq 1$ for all $\gamma \in B$. If $\gamma \in B$ and $A \cap \text{Lim}(D_\gamma) = \{\bar{\gamma}\}$, then we define $C_\gamma = D_\gamma \cap (\bar{\gamma}, \gamma)$. In the other case, if either $\gamma \in \kappa^+ \setminus B$ or $\gamma \in B$ and $A \cap \text{Lim}(D_\gamma) = \emptyset$, then we define $C_\gamma = D_\gamma$. The resulting sequence $\langle C_\gamma \mid \gamma < \kappa^+ \rangle$ is a C -sequence with $\text{otp}(C_\gamma) \leq \kappa$ and $A \cap \text{Lim}(C_\gamma) = \emptyset$ for all $\gamma < \kappa^+$. If $\gamma \in B$ and $\bar{\gamma} \in \text{Lim}(C_\gamma)$, then $\bar{\gamma} \in \text{Lim}(D_\gamma)$, $\bar{\gamma} \in B \setminus A$, $D_{\bar{\gamma}} = D_\gamma \cap \bar{\gamma}$ and the above computation implies that $C_{\bar{\gamma}} = C_\gamma \cap \bar{\gamma}$. ■

In combination with certain fragments of the GCH, the above principle allows us to construct Souslin trees containing ascending paths of small width.

THEOREM 5.8. *Let κ be an uncountable regular cardinal satisfying $2^\kappa = \kappa^+$ and $2^{\kappa^+} = \kappa^{++}$. If there is a $\square_{\kappa^+}^B$ -sequence, then there is a κ^{++} -Souslin tree that contains a κ -ascent path.*

Proof. Set $\vartheta = \kappa^{++}$. By our assumptions and Proposition 5.7, there is a \square_{κ}^B -sequence $\vec{C} = \langle C_\gamma \mid \gamma < \vartheta \rangle$ and $A \subseteq B \cap S_\kappa^\vartheta$ stationary in ϑ such that $A \cap \text{Lim}(C_\gamma) = \emptyset$ for all $\gamma \in B$. Set $\bar{B} = B \cup \{0\}$. Results of Shelah (see [20]) show that our assumptions imply that $\diamond(E)$ holds for all $E \subseteq S_{\leq \kappa}^\vartheta$ stationary in ϑ . This allows us to fix a $\diamond(A)$ -sequence $\langle A_\gamma \mid \gamma \in A \rangle$.

We construct the following objects by induction on $\gamma < \vartheta$:

- (i) A *subtree* \mathbb{T} of ${}^{<\vartheta}2$ of height ϑ (i.e. \mathbb{T} is a tree of height ϑ that consists of functions $t : \gamma \rightarrow 2$ with $\gamma < \vartheta$ ordered by inclusion and is closed under initial segments) with the following properties:
 - (a) If $\gamma < \vartheta$, then $|\mathbb{T}(\gamma)| < \vartheta$ and every element of $\mathbb{T}(\gamma)$ has two distinct direct successors in $\mathbb{T}(\gamma + 1)$.
 - (b) If $\nu \leq \kappa$ and $\langle t_\xi \mid \xi < \nu \rangle$ is an ascending sequence in \mathbb{T} with the property that $\sup_{\xi < \nu} \text{lh}_{\mathbb{T}}(t_\xi) \notin A$, then $\bigcup_{\xi < \nu} t_\xi \in \mathbb{T}$.
 - (c) If $t \in \mathbb{T}$ and $\text{lh}_{\mathbb{T}}(t) \leq \gamma < \vartheta$, then there is $u \in \mathbb{T}(\gamma)$ with $t \subseteq u$.
- (ii) An injection $\iota : \mathbb{T} \rightarrow \vartheta$ with the following properties:
 - (a) If $s, t \in \mathbb{T}$ with $\text{lh}_{\mathbb{T}}(s) < \text{lh}_{\mathbb{T}}(t)$, then $\iota(s) < \iota(t)$.
 - (b) If $\gamma \in A$ and the $(\iota \upharpoonright \mathbb{T}_{< \gamma})$ -preimage of A_γ is a maximal antichain in $\mathbb{T}_{< \gamma}$, then for every $u \in \mathbb{T}(\gamma)$ there is a $t \in \mathbb{T}_{< \gamma}$ with $t \subseteq u$ and $\iota(t) \in A_\gamma$.
- (iii) A sequence $\langle a_\gamma : \kappa \rightarrow \mathbb{T}(\gamma) \mid \gamma \in \bar{B} \rangle$ of functions such that:
 - (a) If $\gamma \in B \setminus A$ and $\bar{\gamma} \in \text{Lim}(C_\gamma)$, then $a_{\bar{\gamma}}(\alpha) \subseteq a_\gamma(\alpha)$ for all $\alpha < \kappa$.
 - (b) If $\gamma, \bar{\gamma} \in \bar{B}$ with $\bar{\gamma} < \gamma$, then there is a $\bar{\kappa} < \kappa$ with $a_{\bar{\gamma}}(\alpha) \subseteq a_\gamma(\alpha)$ for all $\bar{\kappa} \leq \alpha < \kappa$.

In the inductive construction of the above objects, we have to distinguish several cases and subcases:

CASE 0: $\gamma = 0$. Set $\mathbb{T}(0) = \{\emptyset\}$ and $a_0(\alpha) = \emptyset$ for all $\alpha < \kappa$.

CASE 1: $\gamma = \bar{\gamma} + 1$. Define $\mathbb{T}(\gamma) = \{t \in {}^\gamma 2 \mid t \upharpoonright \bar{\gamma} \in \mathbb{T}(\bar{\gamma})\}$. In this situation, our induction hypothesis ensures that $|\mathbb{T}(\gamma)| < \vartheta$ and hence there is an injection $\iota \upharpoonright \mathbb{T}_{< \gamma + 1} : \mathbb{T}_{< \gamma + 1} \rightarrow \vartheta$ that extends the previous injections and satisfies the above requirement.

CASE 2: $\gamma \in S_{< \kappa}^\vartheta$. Define $\mathbb{T}(\gamma) = \{t \in {}^\gamma 2 \mid \forall \bar{\gamma} < \gamma \ t \upharpoonright \bar{\gamma} \in \mathbb{T}(\bar{\gamma})\}$. Then our induction hypothesis implies that for every $t \in \mathbb{T}_{< \gamma}$ there is a $u \in \mathbb{T}(\gamma)$ with $t \subseteq u$. Moreover, our assumptions imply that $\gamma^{< \kappa} < \vartheta$, and this shows that $|\mathbb{T}(\gamma)| < \vartheta$. In particular, we can use our induction hypothesis to find

an injection $\iota|\mathbb{T}_{<\gamma+1} : \mathbb{T}_{<\gamma+1} \rightarrow \vartheta$ that extends the previous injections and satisfies the above requirements.

Now, assume that γ is an element of B . In the construction of the function $a_\gamma : \kappa \rightarrow \mathbb{T}(\gamma)$, we distinguish several subcases:

SUBCASE 2.1: $\text{Lim}(C_\gamma)$ is unbounded in γ . Then we define $a_\gamma(\alpha) = \bigcup\{a_{\bar{\gamma}}(\alpha) \mid \bar{\gamma} \in \text{Lim}(C_\gamma)\}$ for all $\alpha < \kappa$. In this situation, our induction hypothesis implies that $a_\gamma(\alpha) \in \mathbb{T}(\gamma)$ for all $\alpha < \kappa$. Given $\bar{\gamma} \in B \cap \gamma$, there is $\gamma_0 \in \text{Lim}(C_\gamma)$ with $\bar{\gamma} \leq \gamma_0$ and our induction hypothesis shows that there is $\bar{\kappa} < \kappa$ with $a_{\bar{\gamma}}(\alpha) \subseteq a_{\gamma_0}(\alpha)$ for all $\bar{\kappa} \leq \alpha < \kappa$. This shows that $a_{\bar{\kappa}}(\alpha) \subseteq a_\gamma(\alpha)$ for all $\bar{\kappa} \leq \alpha < \kappa$.

SUBCASE 2.2: $\gamma \in \text{Lim}(B)$ and $\text{Lim}(C_\gamma)$ is bounded in γ . Then $\text{cof}(\gamma) = \omega$ and there is a strictly increasing sequence $\langle \gamma_n \in B \cap \gamma \mid n < \omega \rangle$ cofinal in γ such that $\text{Lim}(C_\gamma) \neq \emptyset$ implies $\gamma_0 = \max(\text{Lim}(C_\gamma))$. By our induction hypothesis, there is a strictly increasing sequence $\langle \kappa_n < \kappa \mid n < \omega \rangle$ such that $\kappa_0 = 0$ and $a_{\gamma_n}(\alpha) \subseteq a_{\gamma_{n+1}}(\alpha)$ for all $n < \omega$ and $\kappa_{n+1} \leq \alpha < \kappa$. Then $a_{\gamma_m}(\alpha) \subseteq a_{\gamma_n}(\alpha)$ for all $m \leq n < \omega$ and $\kappa_n \leq \alpha < \kappa$. Given $n < \omega$ and $\kappa_n \leq \alpha < \kappa_{n+1}$, we define $a_\gamma(\alpha)$ to be some element of $\mathbb{T}(\gamma)$ that extends $a_{\gamma_n}(\alpha)$. In the other case, if $\sup_{n < \omega} \kappa_n \leq \alpha < \kappa$, then we define $a_\gamma(\alpha) = \bigcup\{a_{\gamma_n}(\alpha) \mid n < \omega\} \in \mathbb{T}(\gamma)$. Then the above choices ensure that $a_{\gamma_n}(\alpha) \subseteq a_\gamma(\alpha)$ for all $n < \omega$ and $\kappa_n \leq \alpha < \kappa$. In particular, we have $a_{\gamma_0}(\alpha) \subseteq a_\gamma(\alpha)$ for all $\alpha < \kappa$, and our induction hypothesis implies that $a_{\bar{\gamma}}(\alpha) \subseteq a_\gamma(\alpha)$ for all $\bar{\gamma} \in \text{Lim}(C_\gamma)$ and $\alpha < \kappa$. Finally, fix $\bar{\gamma} \in \bar{B} \cap \gamma$ and pick $n < \omega$ with $\bar{\gamma} \leq \gamma_n$. By the induction hypothesis, there is $\kappa_n \leq \bar{\kappa} < \kappa$ with $a_{\bar{\gamma}}(\alpha) \subseteq a_{\gamma_n}(\alpha)$ for all $\bar{\kappa} \leq \alpha < \kappa$. By the above computations, we have $a_{\bar{\gamma}}(\alpha) \subseteq a_\gamma(\alpha)$ for all $\bar{\kappa} \leq \alpha < \kappa$.

SUBCASE 2.3: $\gamma \notin \text{Lim}(B)$ and $\sup(\gamma \cap \bar{B}) \in \bar{B}$. Then $\text{Lim}(C_\gamma)$ is bounded in γ and there are $\gamma_0 \leq \gamma_1 < \gamma$ such that $\gamma_0, \gamma_1 \in \bar{B}$, $\gamma_1 = \max(\bar{B} \cap \gamma)$, $\text{Lim}(C_\gamma) \neq \emptyset$ implies $\gamma_0 = \max(\text{Lim}(C_\gamma))$, and $\text{Lim}(C_\gamma) = \emptyset$ implies $\gamma_0 = \gamma_1$. By our induction hypothesis, there is a $\kappa_1 < \kappa$ with $a_{\gamma_0}(\alpha) \subseteq a_{\gamma_1}(\alpha)$ for all $\kappa_1 \leq \alpha < \kappa$. Set $\kappa_0 = 0$ and $\kappa_2 = \kappa$. Given $\alpha < \kappa$, pick $i < 2$ with $\kappa_i \leq \alpha < \kappa_{i+1}$ and define $a_\gamma(\alpha)$ to be some element of $\mathbb{T}(\gamma)$ that extends $a_{\gamma_i}(\alpha)$. Given $\alpha < \kappa$, we have $a_{\gamma_0}(\alpha) \subseteq a_\gamma(\alpha)$ and the induction hypothesis implies that $a_{\bar{\gamma}}(\alpha) \subseteq a_\gamma(\alpha)$ for all $\bar{\gamma} \in \text{Lim}(C_\gamma)$. Finally, if $\bar{\gamma} \in \bar{B} \cap \gamma$, then $\bar{\gamma} \leq \gamma_1$ and the induction hypothesis allows us to find $\kappa_1 \leq \bar{\kappa} < \kappa$ with $a_{\bar{\gamma}} \subseteq a_{\gamma_1}(\alpha)$ for all $\bar{\kappa} \leq \alpha < \kappa$. This implies that $a_{\bar{\gamma}} \subseteq a_\gamma(\alpha)$ for all $\bar{\kappa} \leq \alpha < \kappa$.

SUBCASE 2.4: $\gamma \notin \text{Lim}(B)$ and $\tilde{\gamma} = \sup(\gamma \cap \bar{B}) \notin \bar{B}$. Then $\text{Lim}(C_\gamma)$ is bounded in γ by $\tilde{\gamma}$ and $\lambda = \text{cof}(\tilde{\gamma}) \leq \kappa$. Pick a strictly increasing continuous sequence $\langle \gamma_\beta < \tilde{\gamma} \mid \beta < \lambda \rangle$ that is cofinal in $\tilde{\gamma}$ such that $\gamma_{\beta+1} \in B$ for all $\beta < \lambda$, $\text{Lim}(C_\gamma) \neq \emptyset$ implies $\gamma_0 = \max(\text{Lim}(C_\gamma))$, and $\text{Lim}(C_\gamma) = \emptyset$ implies

$\gamma_0 = 0$. By our induction hypothesis, there is a strictly increasing continuous sequence $\langle \kappa_\beta < \kappa \mid \beta < \lambda \rangle$ such that $\kappa_0 = 0$ and $a_{\gamma_\beta}(\alpha) \subseteq a_{\gamma_{\beta+1}}(\alpha)$ for all $\kappa_{\beta+1} \leq \alpha < \kappa$ and $\bar{\beta} \leq \beta < \lambda$ with $\gamma_{\bar{\beta}} \in B$. Set $\kappa_\lambda = \sup_{\beta < \lambda} \kappa_\beta \leq \kappa$. Fix $\alpha < \kappa$ and let $\beta \leq \lambda$ be maximal with $\kappa_\beta \leq \alpha$. Then the above definitions and the induction hypothesis imply that

$$\bar{a}_\gamma(\alpha) = \bigcup \{a_{\gamma_{\bar{\beta}}}(\alpha) \mid \bar{\beta} < \max\{\beta, 1\}, \gamma_{\bar{\beta}} \in B\} \in \mathbb{T}_{<\gamma}.$$

Define $a_\gamma(\alpha)$ to be an element of $\mathbb{T}(\gamma)$ with $\bar{a}_\gamma(\alpha) \subseteq a_\gamma(\alpha)$. Then we have $a_{\gamma_0}(\alpha) \subseteq a_\gamma(\alpha)$ for all $\alpha < \kappa$. In particular, if $\bar{\gamma} \in \text{Lim}(C_\gamma)$, then our induction hypothesis implies that $a_{\bar{\gamma}}(\alpha) \subseteq a_\gamma(\alpha)$ for all $\alpha < \kappa$. Finally, pick $\bar{\gamma} \in \gamma \cap B$. Then $\bar{\gamma} < \tilde{\gamma}$ and we can find $\bar{\beta} < \lambda$ and $\kappa_{\bar{\beta}+1} \leq \bar{\kappa} < \kappa$ with $\bar{\gamma} < \gamma_{\bar{\beta}} \in B$ and $a_{\bar{\gamma}}(\alpha) \subseteq a_{\gamma_{\bar{\beta}}}(\alpha)$ for all $\bar{\kappa} \leq \alpha < \kappa$. Fix $\bar{\kappa} \leq \alpha < \kappa$ and let $\beta \leq \lambda$ be maximal with $\alpha \geq \kappa_\beta$. Then $\beta > \bar{\beta}$ and $a_{\gamma_{\bar{\beta}}}(\alpha) \subseteq \bar{a}_\gamma(\alpha)$. This allows us to conclude that $a_{\bar{\gamma}}(\alpha) \subseteq a_\gamma(\alpha)$.

CASE 3: $\gamma \in S_\kappa^\vartheta \setminus A$. Define $\mathbb{T}(\gamma) = \{t \in \gamma 2 \mid \forall \bar{\gamma} < \gamma \ t \upharpoonright \bar{\gamma} \in \mathbb{T}(\bar{\gamma})\}$. As above, our assumptions and the induction hypothesis imply that $|\mathbb{T}(\gamma)| < \vartheta$ and we can find an injection $\iota \upharpoonright \mathbb{T}_{<\gamma+1} : \mathbb{T}_{<\gamma+1} \rightarrow \vartheta$ with the desired properties.

Now, assume that $\gamma \in B$. Since $\text{cof}(\gamma) > \omega$, we know that $\text{Lim}(C_\gamma) \subseteq B$ is unbounded in γ and the induction hypothesis shows that

$$a_\gamma(\alpha) = \bigcup \{a_{\bar{\gamma}}(\alpha) \mid \bar{\gamma} \in \text{Lim}(C_\gamma)\} \in \mathbb{T}(\gamma)$$

for all $\alpha < \kappa$. Moreover, the induction hypothesis directly implies that this sequence has the desired properties.

CASE 4: $\gamma \in A$. Since $\text{cof}(\gamma) > \omega$, there is a strictly increasing continuous sequence $\langle \gamma_\alpha \in \text{Lim}(C_\gamma) \mid \alpha < \kappa \rangle$ cofinal in γ . Pick a maximal antichain \mathcal{A} in $\mathbb{T}_{<\gamma}$ such that \mathcal{A} is equal to the $(\iota \upharpoonright \mathbb{T}_{<\gamma})$ -preimage of A_γ if this preimage is a maximal antichain in $\mathbb{T}_{<\gamma}$. Let $\mathbb{T}_{\mathcal{A}}$ denote the set of all $t \in \mathbb{T}_{<\gamma}$ with $s \leq_{\mathbb{T}} t$ for some $s \in \mathcal{A}$. Given $t \in \mathbb{T}_{\mathcal{A}}$, our induction hypothesis allows us to find $u_t \in \gamma 2$ such that $t \subseteq u_t$ and $u_t \upharpoonright \bar{\gamma} \in \mathbb{T}(\bar{\gamma})$ for all $\bar{\gamma} < \gamma$. We define $\mathbb{T}(\gamma) = \{u_t \mid t \in \mathbb{T}_{\mathcal{A}}\}$. Then the induction hypothesis implies that $|\mathbb{T}(\gamma)| < \vartheta$ and we can find a suitable injection $\iota \upharpoonright \mathbb{T}_{<\gamma+1} : \mathbb{T}_{<\gamma+1} \rightarrow \vartheta$. Moreover, if the $(\iota \upharpoonright \mathbb{T}_{<\gamma})$ -preimage of A_γ is a maximal antichain in $\mathbb{T}_{<\gamma}$, then the above construction ensures that for every $u \in \mathbb{T}(\gamma)$ there is a $t \in \mathbb{T}_{<\gamma}$ with $t \subseteq u$ and $\iota(t) \in A_\gamma$. Finally, the maximality of \mathcal{A} in $\mathbb{T}_{<\gamma}$ implies that for every $\alpha < \kappa$ there is an $\bar{a}_\gamma(\alpha) \in \mathbb{T}_{\mathcal{A}}$ with $a_{\gamma_\alpha}(\alpha) \subseteq \bar{a}_\gamma(\alpha)$. Define $a_\gamma(\alpha) = u_{\bar{a}_\gamma(\alpha)} \in \mathbb{T}(\gamma)$ for all $\alpha < \kappa$. Pick $\bar{\gamma} \in \bar{B} \cap \gamma$. Then we can find $\bar{\alpha} < \bar{\kappa} < \kappa$ such that $\bar{\gamma} < \gamma_{\bar{\alpha}}$ and $a_{\bar{\gamma}}(\alpha) \subseteq a_{\gamma_{\bar{\alpha}}}(\alpha)$ for all $\bar{\kappa} \leq \alpha < \kappa$. Fix $\bar{\kappa} \leq \alpha < \kappa$. Then $\bar{\alpha} < \alpha$, $\gamma_{\bar{\alpha}} \in B \setminus A$ and $\gamma_{\bar{\alpha}} \in \text{Lim}(C_{\gamma_\alpha})$. Using the induction hypothesis, we conclude that

$$a_{\bar{\gamma}}(\alpha) \subseteq a_{\gamma_{\bar{\alpha}}}(\alpha) \subseteq a_{\gamma_\alpha}(\alpha) \subseteq \bar{a}_\gamma(\alpha) \subseteq a_\gamma(\alpha).$$

CASE 5: $\gamma \in S_{\kappa^+}^\vartheta$. Then $A \cap \text{Lim}(C_\gamma) = \emptyset$ and $\text{otp}(C_\gamma) = \kappa^+$. Given $t \in \mathbb{T}_{<\gamma}$, this shows that we can use our induction hypothesis to construct $u_t \in {}^\gamma 2$ with $t \subseteq u_t$ and $u_t \upharpoonright \bar{\gamma} \in \mathbb{T}(\bar{\gamma})$ for all $\bar{\gamma} < \gamma$. Next, define $a_\gamma(\alpha) = \bigcup \{a_{\bar{\gamma}}(\alpha) \mid \bar{\gamma} \in \text{Lim}(C_\gamma)\}$ for each $\alpha < \kappa$. Given $\alpha < \kappa$, the induction hypothesis shows that $a_\gamma(\alpha) \in {}^\gamma 2$ and $a_\gamma(\alpha) \upharpoonright \bar{\gamma} \in \mathbb{T}(\bar{\gamma})$ for all $\bar{\gamma} < \gamma$. We define $\mathbb{T}(\gamma) = \{u_t \mid t \in \mathbb{T}_{<\gamma}\} \cup \{a_\gamma(\alpha) \mid \alpha < \kappa\}$. Then the induction hypothesis implies that $|\mathbb{T}(\gamma)| < \vartheta$ and we can find a suitable injection $\iota \upharpoonright \mathbb{T}_{<\gamma+1} : \mathbb{T}_{<\gamma+1} \rightarrow \vartheta$. Finally, the induction hypothesis implies that the function $a_\gamma : \kappa \rightarrow \mathbb{T}(\gamma)$ has the desired properties.

This completes the inductive construction of \mathbb{T} and $\iota : \mathbb{T} \rightarrow \vartheta$.

CLAIM. *The tree \mathbb{T} is a ϑ -Souslin tree.*

Proof. By the above construction, \mathbb{T} is a tree of height ϑ . Let \mathcal{A} be a maximal antichain in \mathbb{T} . Using the properties of ι , we can construct a club C in ϑ with the property that $\text{ran}(\iota \upharpoonright \mathbb{T}_{<\gamma}) = \gamma \cap \text{ran}(\iota)$ and $\mathcal{A} \cap \mathbb{T}_{<\gamma}$ is a maximal antichain in $\mathbb{T}_{<\gamma}$ for all $\gamma \in C$. Then there is $\gamma \in A \cap C$ such that A_γ is equal to the ι -image of $\mathcal{A} \cap \mathbb{T}_{<\gamma}$. So the $(\iota \upharpoonright \mathbb{T}_{<\gamma})$ -preimage of A_γ is a maximal antichain in $\mathbb{T}_{<\gamma}$, and for every $u \in \mathbb{T}(\gamma)$ there is a $t \in \mathbb{T}_{<\gamma}$ with $t \subseteq u$ and $\iota(t) \in A_\gamma$. This shows that $\mathcal{A} \subseteq \mathbb{T}_{<\gamma}$ and $|\mathcal{A}| < \vartheta$. ■

Given $\gamma < \vartheta$ and $\alpha < \kappa$, set $\delta = \min(\bar{B} \setminus \gamma)$ and let $b_\gamma(\alpha)$ denote the unique element of $\mathbb{T}(\gamma)$ with $b_\gamma(\alpha) \subseteq a_\delta(\alpha)$. By the above constructions, if $\bar{\gamma} < \gamma < \vartheta$, then there is a $\bar{\kappa} < \kappa$ such that $b_{\bar{\gamma}}(\alpha) \subseteq b_\gamma(\alpha)$ for all $\bar{\kappa} \leq \alpha < \kappa$. This shows that the resulting sequence $\langle b_\gamma(\alpha) : \kappa \rightarrow \mathbb{T}(\gamma) \mid \gamma < \vartheta \rangle$ is a κ -ascent path through \mathbb{T} . ■

In the remainder of this section, we will combine the above results with a theorem of Larson from [14] on the preservation of PFA under $<\omega_2$ -directed closed forcings to derive Theorem 1.14.

Proof of Theorem 1.14. Assume that PFA holds.

(i) Assume that $\theta > \omega_1$ and \mathbb{T} contains an ascending path of width ω . Then Theorem 5.3 implies that $\text{ISP}(\omega_2)$ holds, and Lemma 5.4 states that every narrow θ -system of width ω has a cofinal branch. This shows that \mathbb{T} has a cofinal branch.

(ii) Let $\dot{\mathbb{P}}$ be a $\text{Col}(\omega_3, 2^{\omega_2})$ -name for the partial order given by Lemma 5.6 for ω_2 and let $G * H$ be $(\text{Col}(\omega_3, 2^{\omega_2}) * \dot{\mathbb{P}})$ -generic over V . Since the partial order $(\text{Col}(\omega_3, 2^{\omega_2}) * \dot{\mathbb{P}})$ is $<\omega_2$ -directed closed, the results of [14] show that PFA holds in $V[G, H]$ and this implies that $2^{\omega_1} = \omega_2$ holds in $V[G, H]$. Moreover, since \mathbb{P}^G is $(\omega_2 + 1)$ -strategically closed in $V[G]$, we have

$$(2^{\omega_2})^{V[G, H]} = (2^{\omega_2})^{V[G]} = \omega_3^{V[G]} = \omega_3^{V[G, H]}.$$

Finally, there is a $\square_{\omega_2}^B$ -sequence in $V[G, H]$ and Theorem 5.8 shows that there is an ω_3 -Souslin tree with an ω_1 -ascent path in $V[G, H]$.

(iii) Assume that κ is strongly compact and let G be $\text{Col}(\omega_2, <\kappa)$ -generic over V . Then the results of [14] show that PFA holds in $V[G]$. In $V[G]$, if \mathbb{T} is a tree of regular height greater than ω_2 containing an ascending path of width ω_1 , then Theorem 1.13(v) implies that \mathbb{T} has a cofinal branch. ■

6. Open questions. We close this paper with a list of questions raised by the above results. Given an uncountable cardinal κ with $\kappa = \kappa^{<\kappa}$, Theorem 1.9 shows that a tree of height κ^+ is specializable if and only if it contains no ascending paths of width less than κ . It is natural to ask whether this equivalence holds without the cardinal arithmetic assumption.

QUESTION 6.1. *If κ is an uncountable regular cardinal and \mathbb{T} is a tree of height κ^+ that does not contain an ascending path of width less than κ , is \mathbb{T} specializable?*

The following special case of this question is motivated by Theorem 1.14.

QUESTION 6.2. *Assume that PFA holds. Is every tree of height ω_2 without a cofinal branch specializable?*

A negative answer to Question 6.1 would leave open the possibility that specializable trees can be characterized by some combinatorial property.

QUESTION 6.3. *If κ is an uncountable regular cardinal, is the class of specializable trees of height κ^+ definable in V ?*

The proof of Theorem 1.11 in Section 2 shows that, under the cardinal-arithmetic assumptions of the theorem, the existence of an ascending path through \mathbb{T} is equivalent to the existence of such a path with seemingly stronger compatibility properties. It is not known to the author whether this equivalence holds without the assumptions of the theorem.

QUESTION 6.4. *If the tree \mathbb{T} contains an ascending sequence of width λ , is there a sequence $\langle b_\gamma : \lambda \rightarrow \mathbb{T}(\gamma) \mid \gamma < \theta \rangle$ such that for all $\bar{\gamma} < \gamma < \theta$ there is an $\alpha < \lambda$ with $b_{\bar{\gamma}}(\alpha) <_{\mathbb{T}} b_\gamma(\alpha)$?*

Theorem 1.13(iii) shows that it is possible to obtain a model in which every tree of height ω_2 that contains an ascending path of width ω has a cofinal branch. The discussion following the proof of Corollary 4.13 shows that this statement implies that ω_2 is Mahlo in L . Therefore it is natural to ask for the exact consistency strength of this statement.

QUESTION 6.5. *Does the assumption that every tree of height ω_2 that contains an ascending path of width ω has a cofinal branch imply that ω_2 is a weakly compact cardinal in L ?*

The obvious strategy to answer Question 6.5 positively is to show that the extra assumptions on the $\square(\theta)$ -sequence in Theorem 4.12 are not necessary.

QUESTION 6.6. *Does the existence of a $\square(\theta)$ -sequence imply the existence of a θ -Aronszajn tree that contains an ascending path of width λ with $\lambda^+ < \theta$?*

Acknowledgements. During the preparation of this paper, the author was partially supported by DFG-grant LU2020/1-1. This research was partially done whilst the author was a visiting fellow at the Isaac Newton Institute for Mathematical Sciences in the programme ‘Mathematical, Foundational and Computational Aspects of the Higher Infinite’ (HIF) funded by EPSRC grant EP/K032208/1. The author would like to thank the organizers for the opportunity to participate in this programme. Moreover, the author would like to thank Assaf Rinot for helpful discussions on the topic of the paper. Finally, the author would like to thank the anonymous referee for the careful reading of the manuscript.

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