

# APPLICATIONS OF INFINITY-BOREL CODES TO DEFINABILITY AND DEFINABLE CARDINALS

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ABSTRACT. Assume  $\text{ZF} + \text{AD}^+ + \text{V} = \text{L}(\mathcal{P}(\mathbb{R}))$ . If  $H \subseteq \mathbb{R}$  has the property that there is a nonempty OD set of reals  $K$  so that  $H$  is  $\text{OD}_z$  for any  $z \in K$ , then  $H$  is OD.

Assume  $\text{ZF} + \text{AD}^+ + \neg\text{AD}_{\mathbb{R}} + \text{V} = \text{L}(\mathcal{P}(\mathbb{R}))$ . Then there is a cardinal strictly between  $|\omega_1|^{<\omega_1}$  and  $|\omega_1|^{\omega_1} = |\mathcal{P}(\omega_1)|$ .

Assume  $\text{ZF} + \text{AD}^+$ .  $S_1 = \{f \in [\omega_1]^{<\omega_1} : \sup(f) = \omega_1^{L[f]}\}$  does not inject into  ${}^\omega\text{ON}$ , the class of  $\omega$ -sequences of ordinals. This implies  $|\mathbb{R}| < |S_1|$  and  $|\omega_1|^\omega < |\omega_1|^{<\omega_1}$ .

Assuming  $\text{ZF} + \text{AD}^+$ . Let  $X$  be a surjective image of  $\mathbb{R}$  and let  $\mathcal{P}_{\omega_1}(X) = \{A \subseteq X : |A| < \omega_1\}$ . If  $\omega_1 \leq |\mathcal{P}_{\omega_1}(X)|$ , then  $\omega_1 \leq |X|$ . If  $|\mathcal{P}(\omega_1)| = |\omega_1|^{\omega_1} \leq |\mathcal{P}_{\omega_1}(X)|$ , then  $|\mathbb{R} \sqcup \omega_1| \leq |X|$ .

$\text{ZF} + \text{AD}_{\mathbb{R}}$  implies that the uncountable cardinals below  $|\mathbb{R} \times \omega_1|$  are  $\omega_1$ ,  $|\mathbb{R}|$ ,  $|\mathbb{R} \sqcup \omega_1|$ , and  $|\mathbb{R} \times \omega_1|$ . An elaborate structure of cardinals below  $|\mathbb{R} \times \omega_1|$  will be described under the assumption of  $\text{ZF} + \text{AD}^+ + \neg\text{AD}_{\mathbb{R}} + \text{V} = \text{L}(\mathcal{P}(\mathbb{R}))$ .

## 1. INTRODUCTION

An  $\infty$ -Borel code is simply a pair  $(S, \varphi)$  where  $S$  is a set of ordinals and  $\varphi$  is a formula of set theory. The set of reals defined by  $(S, \varphi)$  is  $\mathfrak{B}_{(S, \varphi)}^1 = \{x \in \mathbb{R} : L[S, x] \models \varphi(S, x)\}$ . If  $A$  is a set of reals, then one says that  $(S, \varphi)$  is an  $\infty$ -Borel code for  $A$  if and only if  $\mathfrak{B}_{(S, \varphi)}^1 = A$ . An  $\infty$ -Borel code for  $A$  is a highly absolute definition for  $A$  in the sense that to determine members of  $x \in A$ , one simply needs to go into  $L[S, x]$ , which is the minimal model of ZFC containing the code  $S$  and  $x$ , and ask whether  $L[S, x] \models \varphi(S, x)$ . Note that for any inner model  $M \models \text{ZF}$  with  $S \in M$ ,  $(\mathfrak{B}_{(S, \varphi)}^1)^M = \mathfrak{B}_{(S, \varphi)}^1 \cap M$ .

The axiom of determinacy, AD, states that certain two player games have a winning strategy for one of the two players. Mathematics under AD is often regarded as being more effective, uniform, or definable. Woodin [20] isolated an extension of AD called  $\text{AD}^+$  which include  $\text{DC}_{\mathbb{R}}$ , a technical statement called ordinal determinacy, and all sets of reals have an  $\infty$ -Borel code. The existence of  $\infty$ -Borel codes strengthens the claim that  $\text{AD}^+$  captures definable combinatorics.

It is not known if AD can prove any of the three statements in  $\text{AD}^+$ . Kechris [11] and Woodin showed that if  $L(\mathbb{R}) \models \text{AD}$ , then  $L(\mathbb{R}) \models \text{AD}^+$ . Moreover, Woodin showed that in natural models of  $\text{AD}^+$ , i.e. those models which satisfy  $\text{ZF} + \text{AD} + \text{V} = \text{L}(\mathcal{P}(\mathbb{R}))$ , more is known about the structure of  $\infty$ -Borel codes. In particular, in models of the form  $L(J, \mathbb{R}) \models \text{AD} + \text{DC}_{\mathbb{R}}$ , Woodin's result that  $L(J, \mathbb{R})$  is a symmetric collapse extension of  $\text{HOD}_J^{L(J, \mathbb{R})}$  outlines a procedure to obtain  $\infty$ -Borel codes from definitions witnessing ordinal definability.

Under  $\text{AD}^+$ , the Vopěnka forcing of nonempty OD subsets of  $\mathbb{R}$  ordered by  $\subseteq$  becomes a very powerful tool. In the presence of strongly absolute definitions provided by the  $\infty$ -Borel codes, the method of the Vopěnka forcing in local models of the form  $\text{HOD}_S^{L[S, X]}$ , where  $S$  is a fixed set of ordinals and  $X$  varies over the Turing degrees, combined with the ultraproduct  $\prod_{X \in \mathcal{D}} \text{HOD}_S^{L[S, X]} / \mu$  where  $\mu$  is the Martin measure on Turing degrees is especially useful for combinatorics under  $\text{AD}^+$ .

For instance, similar techniques were used by Woodin to prove the perfect set dichotomy (see [2]) which generalized the Silver's  $\Pi_1^1$  equivalence relation dichotomy ([17]) and by Hjorth [9] to prove the more general  $E_0$ -dichotomy which generalize the  $E_0$ -dichotomy of Harrington-Kechris-Louveau [7]. It is also used in Woodin result that countable section uniformization for relations on  $\mathbb{R} \times \mathbb{R}$  holds under  $\text{AD}^+$  (see [14] or [2]). Such techniques are also used in [5] to answer a question of Foreman that there are Suslin lines in  $L(\mathbb{R}) \models \text{AD}$ .

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In [4], the  $\infty$ -Borel codes, Vopěnka forcing, and the ultraproduct is used to show that if  $\langle E_\alpha : \alpha < \omega_1 \rangle$  is a sequence of equivalence relations on  $\mathbb{R}$  such that  $|\mathbb{R}/E_\alpha| = |\mathbb{R}|$ , then the disjoint union  $\bigsqcup_{\alpha < \omega_1} \mathbb{R}/E_\alpha$  is in bijection with  $\mathbb{R} \times \omega_1$ .

This article provides some new applications of  $\infty$ -Borel codes and the Vopěnka forcing to questions about ordinal definability and definable cardinals assuming  $\text{AD}^+$  or specifically in natural models of  $\text{AD}^+$ .

Harrington, Shore, and Slaman [8] showed that if  $H \subseteq \mathbb{R}$  has the property that there is a nonempty  $\Sigma_1^1$   $K \subseteq \mathbb{R}$  so that  $H$  is  $\Sigma_1^1(z)$  for any  $z \in K$ , then  $H$  is  $\Sigma_1^1$ . In other words, if  $H$  is  $\Sigma_1^1$  in any parameters  $z$  from a nonempty  $\Sigma_1^1$  set  $K$ , then  $H$  is actually  $\Sigma_1^1$  with no parameters.

One can ask if similar phenomenon hold for other notions of lightface definability. Ordinal definability is a strong notion of definability which is closed under nearly any operation which does not introduce non-ordinal parameters. One can ask if  $H \subseteq \mathbb{R}$  is  $\text{OD}_z$  in any parameter  $z$  from a nonempty OD set of reals  $K$ , then is  $H$  ordinal definable with no parameters.

The answer is generally not positive under ZF since Fact 3.2 shows that in the Sacks generic extension of the constructible universe  $L$ , the Sacks generic real is  $\text{OD}_z$  from any nonconstructible  $z$  but the Sacks generic real is not OD. However, in natural models of  $\text{AD}^+$  the answer is positive:

**Theorem 3.1** *Assume  $\text{ZF} + \text{AD}^+ + \text{V} = \text{L}(\mathcal{P}(\mathbb{R}))$ . Let  $J$  be a set of ordinals. Let  $H \subseteq \mathbb{R}$ . Let  $K \subseteq \mathbb{R}$  be nonempty and  $\text{OD}_J$ . If  $H$  is  $\text{OD}_{J,z}$  for all  $z \in K$ , then  $H$  is  $\text{OD}_J$ .*

Using the arguments of Woodin in the proof that  $L(J, \mathbb{R}) \models \text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  is a symmetric collapse extension of  $\text{HOD}_J^{L(J, \mathbb{R})}$ , one can show that in  $L(J, \mathbb{R})$ , there is a set of ordinals  $\mathbb{X}$  which “absorbs” functions of various types. As an example, this means that for any function  $\Phi : [\omega_1]^{\omega_1} \rightarrow [\omega_1]^{<\omega_1}$  (or  $\Phi : \mathbb{R} \times \omega_1 \rightarrow \mathbb{R} \times \omega_1$ ), there is a real  $e$  so that for all  $z$  with  $e \leq_{\mathbb{X}} z$ , and  $f \in [\omega_1]^{\omega_1} \cap L[\mathbb{X}, z]$ ,  $\Phi(f) \in L[\mathbb{X}, z]$  and  $\Phi \cap L[\mathbb{X}, z] \in L[\mathbb{X}, z]$ . This function absorption idea is especially useful for studying definable cardinality under  $\text{AD}^+$  and for producing intermediate cardinals in natural models of  $\text{AD}^+$ .

[3] shows that  $||[\omega_1]^{<\omega_1}| < ||[\omega_1]^{\omega_1}| = |\mathcal{P}(\omega_1)|$  by establishing an almost everywhere continuity phenomenon for functions of the form  $\Phi : [\omega_1]^{\omega_1} \rightarrow \omega_1$ . Section 4 gives a more set theoretic argument as well as other conditions on cardinals  $\kappa$  which implies that  $||[\kappa]^{<\kappa}| < ||[\kappa]^{\kappa}|$ . This section also shows that in models of the form  $L(J, \mathbb{R})$ , where  $J$  is a set of ordinals, there is cardinal intermediate between  $||[\omega_1]^{<\omega_1}|$  and  $||[\omega_1]^{\omega_1}|$ :

**Theorem 4.10** *Assume  $\text{ZF} + \text{AD}^+$ . Let  $J \subseteq \text{ON}$  be a set of ordinals so that  $V = L(J, \mathbb{R})$ . Let  $\mathbb{X} = (J, \omega \mathbb{O}_J)$ . Define  $N_1^J$  by*

$$N_1^J = \bigcup_{r \in \mathbb{R}} ((\omega_1^{L(J, \mathbb{R})})^+)^{L[\mathbb{X}, r]} = \{(r, \alpha) : \alpha < ((\omega_1^{L(J, \mathbb{R})})^+)^{L[\mathbb{X}, r]}\}.$$

*One has the following cardinal relations:  $\neg(|N_1^J| \leq |\omega_1|^{<\omega_1})$ ,  $|\mathbb{R} \times \omega_1| < |N_1^J| < |\mathbb{R} \times \omega_2|$ ,  $|N_1^J| < ||[\omega_1]^{\omega_1}|$ ,  $\neg(|[\omega_1]^{\omega}| \leq |N_1^J|)$ , and  $||[\omega_1]^{<\omega_1}| < ||[\omega_1]^{<\omega_1} \sqcup N_1^J| < ||[\omega_1]^{\omega_1}|$ .*

Intuitively,  $[\omega_1]^{\omega}$  and  $[\omega_1]^{<\omega_1}$  appear to be distinct subsets of  $\mathcal{P}(\omega_1)$  in terms of cardinality. It is implicit in [19] that under  $\text{ZF} + \text{AD}_{\mathbb{R}} + \text{DC}$ ,  $||[\omega_1]^{\omega}| < ||[\omega_1]^{<\omega_1}|$ . It appears that these cardinal distinctions are obtain through an analysis of the set  $S_1 = \{f \in [\omega_1]^{<\omega_1} : \sup(f) = \omega_1^{L[f]}\}$ , defined by Woodin. Section 5 will study  $S_1$  using  $\infty$ -Borel codes and the function absorption idea under  $\text{AD}^+$ .

In just AD, one can show that  $|\mathbb{R}| \leq |S_1|$  and  $\neg(\omega_1 \leq |S_1|)$ . However, all other interesting properties of  $S_1$  appear to be only known under the existence of  $\infty$ -Borel codes. The main property of  $S_1$  is that it does not inject into the class of  $\omega$ -sequences of ordinals.

**Theorem 5.7** *Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and all sets of reals have  $\infty$ -Borel codes. Then there is no injection of  $S_1$  into  ${}^{\omega}\text{ON}$ , the class of  $\omega$ -sequences of ordinals.*

This result can then be used to give the following cardinal computation under  $\text{AD}^+$ :

**Theorem 5.8** *Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and all sets of reals have  $\infty$ -Borel codes. Then  $|\mathbb{R}| < |S_1|$  and*

$$|[\omega_1]^\omega| < |[\omega_1]^{<\omega_1}|.$$

The proof of Theorem 5.7 involves finding a filter which is generic over a models ZFC for a forcing in this model which is countable in the real world satisfying AD. If one would like to imitate this argument to establish similar results on  $\omega_2$ , then the naturally associated forcing in a model of ZFC would be uncountable in even the real world and hence one may not have generics for this forcing. Thus the  $\text{AD}^+$  methods in Theorem 5.7 are not suitable for generalization to  $\omega_2$ .

$S_1$  by its definition involves notions of constructibility which makes  $\infty$ -Borel definition quite useful for studying its cardinal properties. However  $[\omega_1]^\omega$  and  $[\omega_1]^{<\omega_1}$  are purely combinatorial objects whose cardinal distinctions should be obtainable under AD alone. By establishing an almost everywhere continuity result for functions of the form  $\Phi : [\omega_1]^\epsilon \rightarrow \omega_1$ , where  $\epsilon < \omega_1$ , [6] shows in just AD that  $|[\omega_1]^\omega| < |[\omega_1]^{<\omega_1}|$ . This argument provides the suitable template for studying combinatorics on  $\omega_2$ . By establishing an almost everywhere continuity result for functions of the form  $\Phi : [\omega_2]^\epsilon \rightarrow \omega_2$ , where  $\epsilon < \omega_2$ , [6] shows in AD that  $|[\omega_2]^\omega| < |[\omega_2]^{<\omega_1}| < |[\omega_2]^{\omega_1}| < |[\omega_2]^{<\omega_2}|$ .

Using the properties of  $S_1$ , one can answer an interesting question of Zapletal: If  $X$  is a set, let  $\mathcal{P}_{\omega_1}(X) = \{A \subseteq X : |A| < \omega_1\}$  and let  $\mathcal{P}_{\text{WO}}(X)$  be the collection of  $A \subseteq X$  which are wellorderable. Zapletal asked that if  $\mathcal{P}_{\omega_1}(X)$  has certain cardinal properties, then what can be said about the cardinal properties of  $X$ . A concrete question would be if  $\omega_1$  injects into  $\mathcal{P}_{\omega_1}(X)$ , then does  $\omega_1$  already inject into  $X$ ? The following gives a positive answer:

**Theorem 6.6** *Assuming  $\text{ZF} + \text{AD}^+$ , for all cardinals  $\kappa < \Theta$  and all sets  $X$  which are surjective images of  $\mathbb{R}$ ,  $\kappa \leq |\mathcal{P}_{\text{WO}}(X)|$  implies  $\kappa < |X|$ . In particular,  $\kappa \leq |\mathcal{P}_{\omega_1}(X)|$  implies  $\kappa \leq |X|$ .*

**Corollary 6.7** *Assume  $\text{ZF} + \text{DC}_{\mathbb{R}} + \text{AD}$  and all sets of reals have  $\infty$ -Borel codes. Let  $X$  be a set which is a surjective image of  $\mathbb{R}$ . Then  $\omega_1 \leq |\mathcal{P}_{\text{WO}}(X)|$  implies  $\omega_1 \leq |X|$ . In particular,  $\omega_1 \leq |\mathcal{P}_{\omega_1}(X)|$  implies  $\omega_1 \leq |X|$ .*

One can ask what other sets  $Y$  has the property that if  $Y$  injects into  $\mathcal{P}_{\omega_1}(X)$ , then  $X$  already has a copy of  $Y$ . Note that  $\mathcal{P}_{\omega_1}(\omega_1) = [\omega_1]^{<\omega_1}$ . Thus for any uncountable  $Y \subseteq [\omega_1]^{<\omega_1}$  such that  $|Y| \neq \omega_1$ ,  $Y$  injects into  $\mathcal{P}_{\omega_1}(\omega_1)$ , but  $Y$  does not inject into  $\omega_1$ . This reflection property fails for any  $Y \subseteq [\omega_1]^{<\omega_1}$  such that  $|Y| \neq \omega_1$ . Naturally, one can ask if  $[\omega_1]^{\omega_1}$  injects into  $\mathcal{P}_{\omega_1}(X)$ , then what can be said about the cardinality of  $X$ . The following results shows that  $X$  must contain a copy of  $\omega_1$  and  $\mathbb{R}$ :

**Theorem 6.10** *Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and all sets of reals have an  $\infty$ -Borel code. Let  $X$  be a set which is a surjective image of  $\mathbb{R}$ . If  $|[\omega_1]^{\omega_1}| \leq |\mathcal{P}_{\omega_1}(X)|$ , then  $|\mathbb{R} \sqcup \omega_1| \leq |X|$ .*

A natural conjecture would be that if  $[\omega_1]^{\omega_1}$  injects into  $\mathcal{P}_{\omega_1}(X)$ , then  $[\omega_1]^{\omega_1}$  already injects into  $X$ . However, an easier question may be if  $[\omega_1]^{\omega_1}$  injects into  $\mathcal{P}_{\omega_1}(X)$ , then does  $\mathbb{R} \times \omega_1$  inject into  $X$ ?

Woodin [19] showed using elaborate  $\text{AD}^+$  techniques that under  $\text{ZF} + \text{AD}_{\mathbb{R}} + \text{DC}$ , the uncountable cardinals below  $[\omega_1]^\omega$  are  $\omega_1$ ,  $|\mathbb{R}|$ ,  $|\mathbb{R} \sqcup \omega_1|$ ,  $|\mathbb{R} \times \omega_1|$ , and  $[\omega_1]^\omega$ . Using a simple uniformization argument, Corollary 7.6 shows that under  $\text{ZF} + \text{AD}_{\mathbb{R}}$ , the uncountable cardinals below  $|\mathbb{R} \times \omega_1|$  are  $\omega_1$ ,  $|\mathbb{R}|$ ,  $|\mathbb{R} \sqcup \omega_1|$ , and  $|\mathbb{R} \times \omega_1|$ . Woodin showed that if  $\text{AD}_{\mathbb{R}}$  fails, then there may be other cardinals below  $|\mathbb{R} \times \omega_1|$ .

The final section studies the uncountable cardinals below  $|\mathbb{R} \times \omega_1|$  in natural models of  $\text{AD}^+ + \neg \text{AD}_{\mathbb{R}}$  such as  $L(J, \mathbb{R})$  where  $J$  is a set of ordinals which “absorbs” all functions from  $\mathbb{R} \times \omega_1$  into  $\mathbb{R} \times \omega_1$ . Let  $\mathfrak{V}$  denote all the cardinals  $\mathcal{X}$  below  $|\mathbb{R} \times \omega_1|$  such that  $\neg(\omega_1 \leq \mathcal{X})$ . Fact 7.4 shows that every cardinal  $\mathcal{Z} \leq |\mathbb{R} \times \omega_1|$  is either in  $\mathfrak{V}$  or is the disjoint union of  $\omega_1$  with some cardinal in  $\mathfrak{V}$ . Thus a complete understanding of  $\mathfrak{V}$  would elucidate the structure of the cardinals below  $|\mathbb{R} \times \omega_1|$ .

Let  $\mathcal{D}_J$  and  $\mu_J$  denote the  $J$ -constructible degrees and the Martin measures on  $J$ -degrees, respectively. For any  $F : \mathbb{R} \rightarrow \omega_1$  which is  $J$ -invariant, let  $W_1^J = \bigsqcup_{r \in \mathbb{R}} \omega_{F(r)}^{L[J, r]}$ . For any  $\mathcal{F} \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J$ , there exists an everywhere increasing  $J$ -invariant  $F : \mathbb{R} \rightarrow \omega_1$  which represents  $\mathcal{F}$ . Let  $Y_{\mathcal{F}}^J = |W_1^J|$  for any everywhere increasing  $J$ -invariant  $F : \mathbb{R} \rightarrow \omega_1$  which represents  $\mathcal{F}$ . (It can be shown that  $Y_{\mathcal{F}}^J$  is independent of the choice of  $F$ .)

Woodin showed that  $\prod_{X \in \mathcal{D}_J} \omega_1^{L[J, X]} / \mu_J = \omega_1$  for any set of ordinals  $J$  and  $\prod_{X \in \mathcal{D}_J} \omega_2^{L[J, X]} = \Theta$  if  $J$  is an “ultimate  $\infty$ -Borel code” in  $V = L(J, \mathbb{R})$ . For  $\alpha < \omega_1$ , let  $F^\alpha : \mathbb{R} \rightarrow \omega_1$  be the constant function taking value  $\alpha$ . It can be shown that  $F^\alpha$  represents the ordinal  $\alpha$  in  $\prod_{\mathcal{D}_J} \omega_1 / \mu_J$ . Thus  $Y_\alpha^J = |W_{F^\alpha}^J|$  for each  $\alpha < \omega_1$ .

Let  $\mathfrak{Y} = \{Y_{\mathcal{F}}^J : \mathcal{F} \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J\}$ .  $\mathfrak{Y} \subseteq \mathfrak{V}$ . It can be shown that  $Y_0^J = Y_1^J = |\mathbb{R}|$ . If  $\mathcal{F}_1 < \mathcal{F}_2$  in the ultrapower ordering, then  $Y_{\mathcal{F}_1}^J < Y_{\mathcal{F}_2}^J$ . Also for any  $\mathcal{Y} \in \mathfrak{V}$ , there is some  $\mathcal{F} \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J$  so that  $\mathcal{Y} \leq Y_{\mathcal{F}}^J$ . By analyzing the behavior of  $\mathcal{F} \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J$  which are successor ordinals and limit ordinals of cofinality  $\omega$ , one can show that  $\langle Y_\alpha^J : \alpha < \omega_1 \rangle$  is the  $\omega_1$ -length initial segment of  $\mathfrak{Y}$  (which recall is the collection of all cardinals below  $|\mathbb{R} \times \omega_1|$  without a copy of  $\omega_1$ ). The following summarizes the results of Section 7.

**Theorem:** Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and  $V = L(J, \mathbb{R})$  where  $J$  is a set of ordinals which absorbs function from  $\mathbb{R} \times \omega_1$  to  $\mathbb{R} \times \omega_1$ .

$\langle Y_{\mathcal{F}}^J : \mathcal{F} \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J \setminus \{0\} \rangle$  is an order preserving injection of the ultraproduct ordering into  $\mathfrak{Y}$  with the injection ordering.

$\mathfrak{Y}$  is cofinal in  $\mathfrak{V}$ : For all  $\mathcal{X} \in \mathfrak{V}$ , there is an  $\mathcal{F} \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J \setminus \{0\}$  so that  $\mathcal{X} \leq Y_{\mathcal{F}}^J$ .

For any  $\mathcal{X} \in \mathfrak{V}$  and  $F \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J \setminus \{0\}$ , either  $\mathcal{X} \leq Y_{\mathcal{F}}^J$  or  $Y_{\mathcal{F}}^J \leq \mathcal{X}$ .

$\{Y_\alpha^J : \alpha < \omega_1\}$  is the  $\omega_1$ -length initial segment of  $\mathfrak{V}$ : for cardinals  $\mathcal{X}$  below  $|\mathbb{R} \times \omega_1|$  so that  $\neg(\omega_1 \leq \mathcal{X})$ , either there exists an  $\alpha < \omega_1$  so that  $\mathcal{X} = Y_\alpha^J$  or for all  $\alpha < \omega_1$ ,  $Y_\alpha^J \leq \mathcal{X}$ .

A very appealing conjecture given these results is that  $\mathfrak{V} = \mathfrak{Y}$ . Let  $F^{\omega_1} : \mathbb{R} \rightarrow \omega_1$  be defined by  $F^{\omega_1}(x) = \omega_1^{L[J, x]}$ . It can be shown that  $F^{\omega_1}$  represents  $\omega_1$  in  $\prod_{\mathcal{D}_J} \omega_1 / \mu_J$ . Is  $Y_{\omega_1}^J = |W_{F^{\omega_1}}^J|$  the  $\omega_1^{\text{th}}$  cardinal in  $\mathfrak{V}$  in the sense that for all  $\mathcal{X} \in \mathfrak{V}$  such that  $\mathcal{X} \leq Y_{\omega_1}^J$ , there is an  $\alpha \leq \omega_1$  so that  $\mathcal{X} = Y_\alpha^J$ ? The difficulty is that the behavior of cardinals below  $Y_{\mathcal{F}}^J$  where  $\mathcal{F}$  has uncountable cofinality is not well understood.

## 2. BASICS

This section summarizes some properties about  $\infty$ -Borel codes, Vopěnka forcing, and the Martin measure that will be needed throughout the paper. The reader can refer to [2] for a detailed exposition of these ideas at least in the  $L(\mathbb{R}) \models \text{AD}$  setting.

**Definition 2.1.** Let  $S \subseteq \text{ON}$  be a set of ordinals and  $\varphi$  be a formula of set theory. The pair  $(S, \varphi)$  is called an  $\infty$ -Borel code. For any  $n \in \omega$ , define  $\mathfrak{B}_{(S, \varphi)}^n = \{x \in \mathbb{R}^n : L[S, x] \models \varphi(S, x)\}$ .

If  $A \subseteq \mathbb{R}^n$ , then  $(S, \varphi)$  is an  $\infty$ -Borel code for  $A$  if and only if  $\mathfrak{B}_{(S, \varphi)}^n = A$ .

A set  $A \subseteq \mathbb{R}^n$  is said to be  $\infty$ -Borel if and only if it has an  $\infty$ -Borel code.

Note that an  $\infty$ -Borel set of reals has a very absolute definition in the following sense: If  $A \subseteq \mathbb{R}$  is  $\infty$ -Borel with  $\infty$ -Borel code  $(S, \varphi)$ , then  $x \in A$  is determined completely by whether  $\varphi(S, x)$  holds in the minimal model of ZFC,  $L[S, x]$ , containing the code  $(S, \varphi)$  and the real  $x$ .

**Definition 2.2.** Let  $n > 0$  and  $S \subseteq \text{ON}$  be a set of ordinals. Let  ${}_n\mathbb{O}_S$  denote the forcing of nonempty  $\text{OD}_S$  subsets of  $\mathbb{R}^n$  ordered by  $\subseteq$  with largest element  $1_{{}_n\mathbb{O}_S} = \mathbb{R}^n$ . One will write  $\mathbb{O}_S$  for  ${}_1\mathbb{O}_S$ .

Since there is an  $S$ -definable bijection of  $\text{OD}_S$  with  $\text{ON}$ , one can transfer  ${}_n\mathbb{O}_S$  onto the ordinals. In this way,  ${}_n\mathbb{O}_S$  is a forcing in  $\text{HOD}_S$ .

**Definition 2.3.** Let  $S$  be a set of ordinals. For each  $k \in \omega$ , let  $b_k = \{x \in \mathbb{R} : x(k) = 1\}$ . Note that  $b_k \in \mathbb{O}_S$ . Let  $\dot{x}_{\text{gen}} = \{(\check{k}, b_k) : k \in \omega\}$ . Note that  $\dot{x}_{\text{gen}}$  is an  $\mathbb{O}_S$ -name which adds a real.

One can formulate the analogous  ${}_n\mathbb{O}_S$ -name  $\dot{x}_{\text{gen}}^n$  for adding an element of  $\mathbb{R}^n$  for all  $n \geq 1$ .

**Fact 2.4.** (Woodin) Assume  $\text{ZF} + \text{AD} + \text{V} = \text{L}(\mathcal{P}(\mathbb{R}))$ . Let  $S$  be a set of ordinals. For each  $x \in \mathbb{R}^n$ ,  $G_x^n = \{p \in {}_n\mathbb{O}_S : x \in p\}$  is a  $\text{HOD}_S$ -generic filter so that  $\dot{x}_{\text{gen}}^n[G_x^n] = x$  and  $\text{HOD}_S[G_x^n] = \text{HOD}_S[x]$ .

**Fact 2.5.** ([9] Theorem 2.4, [2] Fact 8.1) Let  $M$  be a transitive inner model of ZF. Let  $S \in M$  be a set of ordinals. Suppose  $K \in \text{HOD}_S^M$  is a set of ordinals and  $\varphi$  is a formula. Let  $N$  be a transitive inner model with  $\text{HOD}_S^M \subseteq N$ . Suppose  $p = \{x \in \mathbb{R} : L[K, x] \models \varphi(K, x)\}$  is a condition of  $\mathbb{O}_S^M$ . Then  $N \models p \Vdash_{\mathbb{O}_S^M} L[\check{K}, \dot{x}_{\text{gen}}] \models \varphi(\check{K}, \dot{x}_{\text{gen}})$ .

**Definition 2.6.** (Woodin, [20] Section 9.1)  $\text{AD}^+$  consists of the following:

- (1)  $\text{DC}_{\mathbb{R}}$ .
- (2) Every  $A \subseteq \mathbb{R}$  is  $\infty$ -Borel.
- (3) For all  $\lambda < \Theta$ ,  $A \subseteq \mathbb{R}$ , and continuous  $\pi : {}^\omega \lambda \rightarrow \mathbb{R}$ ,  $\pi^{-1}[A]$  is determined.

Models satisfying  $\text{ZF} + \text{AD}^+ + \text{V} = \text{L}(\mathcal{P}(\mathbb{R}))$  are called natural models of  $\text{AD}^+$ . Woodin showed that these either are models of  $\text{AD}_{\mathbb{R}}$  or take the form  $V = L(J, \mathbb{R})$  for a set of ordinals  $J$ :

**Fact 2.7.** (Woodin, [1] Corollary 3.2) Assume  $\text{ZF} + \text{AD}^+ + \neg \text{AD}_{\mathbb{R}} + \text{V} = \text{L}(\mathcal{P}(\mathbb{R}))$ . Then there is a set of ordinals  $J$  so that  $V = L(J, \mathbb{R})$ .

Many results about  $L(\mathbb{R})$  proved by Vopěnka forcing can be relativized to an analogous statement about models of the form  $L(J, \mathbb{R})$ .

**Fact 2.8.** (Woodin, [1] Theorem 3.4) Assume  $\text{ZF} + \text{AD}^+ + \text{V} = \text{L}(\mathcal{P}(\mathbb{R}))$ . Let  $J$  be a set of ordinals and  $A \subseteq \mathbb{R}$ . If  $A$  is  $\text{OD}_J$ , then  $A$  has an  $\text{OD}_J$   $\infty$ -Borel code.

**Fact 2.9.** (Woodin, [1] Theorem 2.8) Assume  $\text{ZF} + \text{AD}^+ + \text{V} = \text{L}(\mathcal{P}(\mathbb{R}))$ . Let  $J$  be a set of ordinals. There is some set of ordinals  $\mathbb{X}$  so that  $\text{HOD}_J = L[\mathbb{X}]$ .

*Proof.* See [2] Corollary 7.21 for a proof of this under  $\text{AD} + \text{V} = L(\mathbb{R})$ .  $\square$

Woodin's works showing that  $L(J, \mathbb{R}) \models \text{AD} + \text{DC}_{\mathbb{R}}$  is a symmetric collapse extension of  $\text{HOD}_J^{L(J, \mathbb{R})}$  gives additional information about  $\infty$ -Borel codes in such models. In particular, it shows the existence of an ultimate  $\infty$ -Borel code mentioned above which will be particularly useful in this article for "absorbing fragments of functions" in relevant models of ZFC.

Assume  $V = L(J, \mathbb{R}) \models \text{AD} + \text{DC}_{\mathbb{R}}$ . For each  $m \leq n < \omega$ , let  $\pi_{n,m} : \mathbb{R}^n \rightarrow \mathbb{R}^m$  be the projection of  $\mathbb{R}^n$  onto  $\mathbb{R}^m$ . One can induce map  $\pi_{n,m} : {}_n\mathbb{O}_J \rightarrow {}_m\mathbb{O}_J$  by  $\pi_{n,m}(p) = \pi_{n,m}[p]$ , where the latter  $\pi_{n,m} : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is the projection map. These maps  $\pi_{n,m} : {}_n\mathbb{O}_J \rightarrow {}_m\mathbb{O}_J$  are forcing projections. Let  ${}_\omega\mathbb{O}_J$  denote the finite support direct limit induced by  $\langle {}_n\mathbb{O}_J, \pi_{n,m} : 1 \leq m \leq n \rangle$ . Let  $\pi_{\omega,n} : {}_\omega\mathbb{O}_J \rightarrow {}_n\mathbb{O}_J$  be the natural associated projection map.

Each  $s \in \mathbb{R}^n$  induces canonically an  ${}_n\mathbb{O}_J$ -generic filter over  $\text{HOD}_J^{L(J, \mathbb{R})}$  denoted by  $G_s^n$ . Using  $\pi_{\omega,n}$ , let  ${}_\omega\mathbb{O}_J/G_s^n$  refer to the associated remainder forcing. Moreover, every  $G \subseteq {}_n\mathbb{O}_J$  which is  ${}_n\mathbb{O}_J$ -generic over  $\text{HOD}_J$  adds a generic element of  $\mathbb{R}^n$ . For each  $n$ , let  $\tau_n$  be the  ${}_\omega\mathbb{O}_J$ -name for the real in the last coordinate of the generic  $n$ -tuple of reals added by the  ${}_n\mathbb{O}_J$ -generic filter induced from an  ${}_\omega\mathbb{O}_J$ -generic filter. Let  $\mathbb{R}_{\text{sym}}$  be the  ${}_\omega\mathbb{O}_J$ -name for the set  $\{\tau_n : n \in \omega\}$ .

**Fact 2.10.** (Woodin) Suppose  $L(J, \mathbb{R}) \models \text{AD} + \text{DC}_{\mathbb{R}}$ . Let  $s \in \mathbb{R}^n$ ,  $z \in L[J, {}_\omega\mathbb{O}_J, s]$ , and  $\varphi$  is a formula. Then  $L(J, \mathbb{R}) \models \varphi(J, s, z)$  if and only if

$$L[J, {}_\omega\mathbb{O}_J, s] \models 1_{{}_\omega\mathbb{O}_J/G_s^n} \Vdash_{{}_\omega\mathbb{O}_J/G_s^n} L(\check{J}, \dot{\mathbb{R}}_{\text{sym}}) \models \varphi(\check{z}, \dot{x}_{\text{gen}}^n).$$

Fact 2.10 can be used to show that in  $L(J, \mathbb{R}) \models \text{AD} + \text{DC}_{\mathbb{R}}$ , for any  $A \subseteq \mathbb{R}$ , there is an  $r \in \mathbb{R}$  and a formula  $\varphi$  so that  $(J \oplus {}_\omega\mathbb{O}_J \oplus r, \varphi)$  forms an  $\text{OD}_{J,s}$   $\infty$ -Borel code for  $A$ , where  $J \oplus {}_\omega\mathbb{O}_J \oplus r$  is a set of ordinals that codes these three objects in some fixed way. It also gives following result.

**Fact 2.11.** (Woodin) Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and there is a set  $J \subseteq \text{ON}$  so that  $V = L(J, \mathbb{R})$ . For each  $x \in \mathbb{R}$ ,  $\text{HOD}_{J,x}^{L(J, \mathbb{R})} = L[J, {}_\omega\mathbb{O}_J, x]$ .

A more detailed exposition of these above results can be found in [2] in the  $L(\mathbb{R})$  case. It should be noted that here these results are stated for the Vopěnka forcing  $\mathbb{O}$ . These results are initially proved using  $\mathbb{A}$  which is the forcing of nonempty sets of reals with  $\text{OD}$   $\infty$ -Borel codes. It is then shown that  $\mathbb{O}$  and  $\mathbb{A}$  are the same.

**Definition 2.12.** Let  $x \leq_{\text{Turing}} y$  indicate that  $x$  is Turing reducible to  $y$ . Let  $x \equiv_{\text{Turing}} y$  indicate  $x \leq_{\text{Turing}} y$  and  $y \leq_{\text{Turing}} x$ . Let  $\mathcal{D} = \mathbb{R}/\equiv_{\text{Turing}}$  denote the collection of Turing degrees. For  $X, Y \in \mathcal{D}$ , let  $X \leq Y$  indicate that there is some  $x \in X$  and  $y \in Y$  so that  $x \leq_{\text{Turing}} y$ . If  $X \in \mathcal{D}$ , then the Turing cone above  $X$  is the set  $\{Y \in \mathcal{D} : X \leq Y\}$ . The Martin's measure  $\mu$  on  $\mathcal{D}$  is the collection of subsets of  $\mathcal{D}$  which contain a Turing cone.

If  $J \subseteq \text{ON}$  is a set of ordinals. On  $\mathbb{R}$ , define  $x \leq_J y$  if and only if  $x \in L[J, y]$ . Let  $x \equiv_J y$  if and only if  $x \leq_J y$  and  $y \leq_J x$ . Let  $\mathcal{D}_J = \mathbb{R}/\equiv_J$  denote the collection of  $J$ -constructibility degrees. If  $X, Y \in \mathcal{D}_J$ , then

let  $X \leq Y$  indicates that there exist  $x \in X$  and  $y \in Y$  so that  $x \leq_J y$ . If  $X \in \mathcal{D}_J$ , then the  $J$ -cone above  $X$  is the set  $\{Y \in \mathcal{D}_J : X \leq Y\}$ . Let  $\mu_J$  be collection of subsets of  $\mathcal{D}_J$  which contain a  $J$ -cone.

**Fact 2.13.** (Martin) Assume  $\text{ZF} + \text{AD}$ .  $\mu$  is a countably complete ultrafilter. For any  $J \subseteq \text{ON}$ ,  $\mu_J$  is a countably complete ultrafilter.

**Fact 2.14.** (Woodin, [1] Section 2.2) Assume  $\text{ZF} + \text{AD}^+$ .  $\prod_{X \in \mathcal{D}} \text{ON}/\mu$  and if  $J$  is a set of ordinals,  $\prod_{X \in \mathcal{D}_J} \text{ON}/\mu_J$  are wellorderings.

**Corollary 2.15.** Assume  $\text{ZF} + \text{AD}^+$ . Let  $S \subseteq \text{ON}$  be a set of ordinals.  $\prod_{X \in \mathcal{D}} \text{HOD}_S^{L[S, X]}/\mu$  is wellfounded.

*Proof.* Suppose  $F \in \prod_{X \in \mathcal{D}} \text{HOD}_S^{L[S, X]}/\mu$ . Let  $f$  be a function  $\mathcal{D}$  such that  $[f]_\mu = F$ . Define  $\phi(f)$  by  $\phi(f)(X) = \text{rk}^{\text{HOD}_S^{L[S, X]}}(f(X))$ . Let  $\Phi : \prod_{X \in \mathcal{D}} \text{HOD}_S^{L[S, X]}/\mu \rightarrow \prod_{X \in \mathcal{D}} \text{ON}/\mu$  be defined by  $\Phi([f]_\mu) = [\phi(f)]_\mu$ .  $\Phi$  is a well defined function. Moreover, it has the property that if  $F \in G$ , then  $\Phi(F) < \Phi(G)$ . Fact 2.14 implies that  $\prod_{X \in \mathcal{D}} \text{HOD}_S^{L[S, X]}/\mu$  is wellfounded.  $\square$

### 3. OD IN OD IS OD

As customary, one writes  $\mathbb{R}$  for  ${}^\omega 2$ , which is the collection of functions  $f : \omega \rightarrow 2$ .

**Theorem 3.1.** Assume  $\text{ZF} + \text{AD}^+ + \text{V} = \text{L}(\mathcal{P}(\mathbb{R}))$ . Let  $J$  be a set of ordinals. Let  $H \subseteq \mathbb{R}$ . Let  $K \subseteq \mathbb{R}$  be nonempty and  $\text{OD}_J$ . If  $H$  is  $\text{OD}_{J, z}$  for all  $z \in K$ , then  $H$  is  $\text{OD}_J$ .

*Proof.* For simplicity, assume  $J = \emptyset$ . By Fact 2.9, let  $\mathbb{X} \in \text{HOD}^V$  be such that  $\text{HOD}^V = L[\mathbb{X}]$ . Using the constructibility ordering of  $L[\mathbb{X}]$ , let  $\langle (S_\alpha, \varphi_\alpha) : \alpha \in \text{ON} \rangle$  enumerate all the  $\infty$ -Borel codes in  $L[\mathbb{X}] = \text{HOD}^V$ . (This is merely the canonical constructibility enumeration of all pairs  $(S, \varphi)$  in  $\text{HOD}^V = L[\mathbb{X}]$  where  $S$  is a set of ordinals and  $\varphi$  is a formula.) The main observation is that for any  $X \in \mathcal{D}$ ,  $\text{HOD}^V = L[\mathbb{X}] \subseteq \text{HOD}_X^{L[\mathbb{X}, X]}$  and therefore the sequence  $\langle (S_\alpha, \varphi_\alpha) : \alpha \in \text{ON} \rangle$  is definable in  $\text{HOD}_X^{L[\mathbb{X}, X]}$  uniformly (by the same formula using  $\mathbb{X}$  as a parameter for all  $X \in \mathcal{D}$ ). In particular, every  $\text{OD}^V$   $\infty$ -Borel code belongs to  $\text{HOD}_X^{L[\mathbb{X}, X]}$ .

Claim 1: For any  $R \subseteq \mathbb{R}$ ,  $R$  is  $\text{OD}_z^V$  for some  $z \in \mathbb{R}$  if and only if there is some  $\text{OD}^V$   $\infty$ -Borel code  $(S, \varphi)$  so that

$$R = (\mathfrak{B}_{(S, \varphi)}^2)_z = \{x \in \mathbb{R} : (z, x) \in \mathfrak{B}_{(S, \varphi)}^2\} = \{x \in \mathbb{R} : L[S, z, x] \models \varphi(S, z, x)\}.$$

*Proof.*  $(\Rightarrow)$  Suppose  $R$  is  $\text{OD}_z^V$ . There is some formula  $\varsigma$  so that  $x \in R \Leftrightarrow V \models \varsigma(z, x, \bar{\alpha})$  where  $\bar{\alpha}$  is a tuple of ordinals. Let  $R' = \{(a, b) \in \mathbb{R}^2 : \varsigma(a, b, \bar{\alpha})\}$ .  $R'$  is an  $\text{OD}^V$  subsets of  $\mathbb{R}^2$ . By Fact 2.8, there is some  $(S, \varphi) \in \text{HOD}^V$  so that  $\mathfrak{B}_{(S, \varphi)}^2 = R'$ . Then  $R = (\mathfrak{B}_{(S, \varphi)}^2)_z$ .  $(\Leftarrow)$  is clear.  $\square$

Since  $K \subseteq \mathbb{R}$  is  $\text{OD}^V$ ,  $K$  has an  $\infty$ -Borel code  $(U, \psi) \in \text{HOD}^V$  by Fact 2.8. Since  $K \neq \emptyset$ , let  $z^* \in K$ . Let  $Z^* = [z^*]_{\equiv_{\text{Turing}}}$ . Throughout this entire argument, one will only work on the Turing cone above  $Z^*$ .

For all  $X \in \mathcal{D}$ , since  $(U, \psi) \in \text{HOD}^V = L[\mathbb{X}] \subseteq L[\mathbb{X}, X]$ ,  $(U, \psi) \in \text{HOD}_X^{L[\mathbb{X}, X]}$ . For any  $X \geq Z^*$ , let  $q^X = \{x \in \mathbb{R}^{L[\mathbb{X}, X]} : L[U, x] \models \psi(U, x)\}$ . Note that  $q^X$  is  $\text{OD}_X^{L[\mathbb{X}, X]}$ . Since  $z^* \in \mathbb{R}^{L[\mathbb{X}, X]}$ ,  $z^* \in K$ , and  $(U, \psi)$  is the  $\infty$ -Borel code for  $K$ , one has  $V \models L[U, z^*] \models \psi(U, z^*)$ . Thus  $L[\mathbb{X}, X] \models L[U, z^*] \models \psi(U, z^*)$ . Thus  $z^* \in q^X$  and  $q^X \neq \emptyset$ . It has been shown that  $q^X \in \mathcal{O}_X^{L[\mathbb{X}, X]}$ .

(Case I) There is a cone of  $X \in \mathcal{D}$  so that there are no atoms in

$$\mathcal{O}_X^{L[\mathbb{X}, X]} \restriction q^X = \{p \in \mathcal{O}_X^{L[\mathbb{X}, X]} : p \leq_{\mathcal{O}_X^{L[\mathbb{X}, X]}} q^X\}.$$

Let  $Z^{**} \in \mathcal{D}$  with  $Z^{**} \geq Z^*$  be a base of a cone for which the Case I assumption holds. Now suppose  $X \in \mathcal{D}$  with  $X \geq Z^{**}$ .

Claim 2: There is a sequence  $\mathcal{J} = \langle J_n : n \in \omega \rangle$  of dense open subsets of  $\mathcal{O}_X^{L[\mathbb{X}, X]} \restriction q^X$  and a sequence of ordinals  $\langle \epsilon_n : n \in \omega \rangle$  so that for all  $h \in \mathbb{R}$  which are  $\mathcal{O}_X^{L[\mathbb{X}, X]} \restriction q^X$ -generic with respect to  $\mathcal{J}$ , the following holds:

- (1)  $h \in K$ .
- (2)  $h$  is  $\mathbb{O}_X^{L[\mathbb{X}, X]} \restriction q^X$ -generic over  $\text{HOD}_X^{L[\mathbb{X}, X]}[y]$  for all  $y \in \mathbb{R}^{L[\mathbb{X}, X]}$ .
- (3) There is some  $m \in \omega$  so that  $H = (\mathfrak{B}_{(S_{\epsilon_m}, \varphi_{\epsilon_m})}^2)_h$ .

*Proof.* Since  $L[\mathbb{X}, X] \models \text{ZFC}$  and  $V \models \text{AD}$ ,  $\omega_1^V$  is inaccessible in  $\text{HOD}_X^{L[\mathbb{X}, X]}$ . This can be used to show that  $\mathbb{O}_X^{L[\mathbb{X}, X]} \restriction q^X$  is a countable atomless forcing. In  $V$ , fix a forcing isomorphism  $\Phi : \mathbb{O}_X^{L[\mathbb{X}, X]} \restriction q^X \rightarrow \mathbb{C}$ , where  $\mathbb{C}$  is the Cohen forcing. (Specifically  $\mathbb{C} = (\leq^{\omega 2}, \leq_{\mathbb{C}})$  is the forcing of finite binary strings ordered by  $\leq_{\mathbb{C}}$  which is reverse string inclusion. Note there is generally no way to uniformly choose  $\Phi$  depending on the degree  $X$ .) Let  $\mathcal{E}$  be the collection of all dense open subsets of  $\mathbb{O}_X^{L[\mathbb{X}, X]} \restriction q^X$  which belongs to  $\text{HOD}_X^{L[\mathbb{X}, X]}[y]$  for some  $y \in \mathbb{R}^{L[\mathbb{X}, X]}$ . Since  $V \models \text{AD}$ ,  $L[\mathbb{X}, X] \models \text{ZFC}$ , and  $\text{HOD}_X^{L[\mathbb{X}, X]}[y] \models \text{ZFC}$  for all  $y \in \mathbb{R}^{L[\mathbb{X}, X]}$ , one has that  $\mathcal{E}$  is countable in  $V$ . Let  $\mathcal{F} = \{\Phi[D] : D \in \mathcal{E}\}$ . Then  $\mathcal{F}$  is a countable collection of dense open subsets of Cohen forcing  $\mathbb{C}$ .

For each  $g \in \mathbb{R}$ , let  $G_g^{\mathbb{C}} \subseteq \mathbb{C}$  be the derived  $\mathbb{C}$ -filter defined by  $G_g^{\mathbb{C}} = \{g \restriction n : n \in \omega\}$ . One say that  $g$  is  $\mathbb{C}$ -generic with respect to  $\mathcal{F}$  if and only if  $G_g^{\mathbb{C}}$  intersects each dense open set in  $\mathcal{F}$ . Similarly if  $\mathcal{J}$  is a collection of dense open subsets of  $\mathbb{O}_X^{L[\mathbb{X}, X]} \restriction q^X$ , one says that a real  $x \in \mathbb{R}$  is  $\mathbb{O}_X^{L[\mathbb{X}, X]} \restriction q^X$ -generic with respect to  $\mathcal{J}$  if and only if there is an  $\mathbb{O}_X^{L[\mathbb{X}, X]} \restriction q^X$ -generic filter  $G \subseteq \mathbb{O}_X^{L[\mathbb{X}, X]} \restriction q^X$  so that  $G$  meets each dense open set in  $\mathcal{J}$  and  $\dot{x}_{\text{gen}}[G] = x$ .

Since  $\mathcal{F}$  is countable in  $V$ , let  $C \subseteq \mathbb{R}$  be the comeager set of reals which are  $\mathbb{C}$ -generic with respect to  $\mathcal{F}$ . Let  $B$  be the collection of reals which are  $\mathbb{O}_X^{L[\mathbb{X}, X]} \restriction q^X$ -generic over  $\text{HOD}_X^{L[\mathbb{X}, X]}[y]$  for all  $y \in \mathbb{R}^{L[\mathbb{X}, X]}$ . By the definition of  $\Phi$ ,  $\mathcal{E}$ , and  $\mathcal{F}$ , the forcing isomorphism  $\Phi$  induces a bijection  $\tilde{\Phi} : B \rightarrow C$ .

For each  $g \in C$ , let  $G_{\tilde{\Phi}^{-1}(g)} = \Phi^{-1}[G_g^{\mathbb{C}}]$ .  $G_{\tilde{\Phi}^{-1}(g)}$  is an  $\mathbb{O}_X^{L[\mathbb{X}, X]} \restriction q^X$ -generic filter over  $\text{HOD}_X^{L[\mathbb{X}, X]}[y]$  for all  $y \in \mathbb{R}^{L[\mathbb{X}, X]}$ . Note that  $\dot{x}_{\text{gen}}[G_{\tilde{\Phi}^{-1}(g)}] = \tilde{\Phi}^{-1}(g)$ . Since  $q^X \in G_{\tilde{\Phi}^{-1}(g)}$  and  $q_X$  is a condition of the form mentioned in Fact 2.5,

$$\text{HOD}_X^{L[\mathbb{X}, X]}[G_{\tilde{\Phi}^{-1}(g)}] \models L[U, \tilde{\Phi}^{-1}(g)] \models \psi(U, \tilde{\Phi}^{-1}(g)).$$

Thus

$$V \models L[U, \tilde{\Phi}^{-1}(g)] \models \psi(U, \tilde{\Phi}^{-1}(g)).$$

Since  $(U, \psi)$  is the  $\infty$ -Borel code for  $K$ ,  $\tilde{\Phi}^{-1}(g) \in K$ . It has been shown that whenever  $g \in C$ ,  $\tilde{\Phi}^{-1}(g) \in K$ .

By assumption,  $H$  is  $\text{OD}_x$  for all  $x \in K$ . In particular, for each  $g \in C$ ,  $H$  is  $\text{OD}_{\tilde{\Phi}^{-1}(g)}$ . By Claim 1, there is some  $\epsilon \in \text{ON}$  so that  $H = (\mathfrak{B}_{(S_{\epsilon}, \varphi_{\epsilon})}^2)_{\tilde{\Phi}^{-1}(g)}$ . Define  $\Psi : C \rightarrow \text{ON}$  by  $\Psi(g)$  is the least such  $\epsilon$ .

Under AD, a wellordered union of meager sets is meager, therefore, there must be some  $\epsilon \in \text{ON}$  so that  $\Psi^{-1}[\{\epsilon\}]$  is nonmeager. Let  $\delta_0 \in \text{ON}$  be the least ordinal so that  $\Psi^{-1}[\{\delta_0\}]$  is nonmeager. Suppose  $\delta_{\xi} \in \text{ON}$  has been defined. If  $\bigcup_{\alpha \geq \delta_{\xi}} \Psi^{-1}[\{\alpha\}]$  is meager, then declare the construction to have finished. Otherwise, again using the fact that wellordered unions of meager sets are meager under AD, there is a least ordinal  $\delta_{\xi+1}$  greater than  $\delta_{\xi}$  so that  $\Psi^{-1}[\{\delta\}]$  is nonmeager. If  $\xi$  is a limit ordinal and  $\delta_{\zeta}$  has been defined for all  $\zeta < \xi$ , then let  $\delta_{\xi} = \sup\{\delta_{\zeta} : \zeta < \xi\}$ . Since all sets of reals have the Baire property under AD and the topology on  $\mathbb{R}$  has the countable chain condition, there must be a countable  $\lambda \in \text{ON}$  so that the construction is finished at stage  $\lambda$ .

As  $\lambda$  is countable, one can enumerate  $\langle \delta_{\xi} : \xi < \lambda \rangle$  by  $\langle \epsilon_n : n \in \omega \rangle$ . Let  $D = \bigcup_{n \in \omega} \Psi^{-1}[\{\epsilon_n\}]$  which is comeager by definition of  $\lambda$  being the ordinal by which the construction finished.

Since  $D$  is comeager, there is a sequence  $\langle I_n : n \in \omega \rangle$  of topologically dense open subsets of  $\mathbb{R}$  so that  $\bigcap_{n \in \omega} I_n \subseteq D$ . Let  $J_n = \{\Phi^{-1}(\sigma) : \sigma \in \mathbb{C} \wedge N_{\sigma} \subseteq I_n\}$ , where  $N_{\sigma} = \{f \in \mathbb{R} : \sigma \subseteq f\}$  is the basic open subset of  $\mathbb{R}$  determined by  $\sigma$  and recall that  $\mathbb{C} = \leq^{\omega 2}$ . Define  $\mathcal{J} = \langle J_n : n \in \omega \rangle$  which is a sequence of dense open subsets of  $\mathbb{O}_S^{L[\mathbb{X}, X]} \restriction q^X$ . Note that if  $x$  is  $\mathbb{O}_X^{L[\mathbb{X}, X]} \restriction q^X$ -generic with respect to  $\mathcal{J} = \langle J_n : n \in \omega \rangle$ , then  $\tilde{\Phi}(x) \in D$ . Since  $D \subseteq C$  and by the observation above,  $G_x = G_{\tilde{\Phi}^{-1}(\tilde{\Phi}(x))}$  is  $\mathbb{O}_X^{L[\mathbb{X}, X]} \restriction q^X$ -generic over  $\text{HOD}_X^{L[\mathbb{X}, X]}[y]$  for all  $y \in \mathbb{R}^{L[\mathbb{X}, X]}$  and  $x = \dot{x}_{\text{gen}}[G_x]$ . This completes the proof of Claim 2.  $\square$

One will construct a sequence of conditions in  $\mathbb{O}_X^{L[\mathbb{X}, X]} \restriction q^X$  for as long as possible:

Let  $p_{-1} = q^X$ .

Suppose one has succeeded to construct  $p_k$ .

(Subcase i) There is some  $y \in \mathbb{R}^{L[\mathbb{X}, X]}$  and some  $u \leq_{\mathbb{O}_X^{L[\mathbb{X}, X]} \upharpoonright q^X} p_k$  so that

$$y \notin H \wedge \text{HOD}_X^{L[\mathbb{X}, X]}[y] \models u \Vdash_{\mathbb{O}_X^{L[\mathbb{X}, X]}} L[\check{S}_{\epsilon_{k+1}}, \dot{x}_{\text{gen}}, \check{y}] \models \varphi_{\epsilon_{k+1}}(\check{S}_{\epsilon_{k+1}}, \dot{x}_{\text{gen}}, \check{y})$$

or

$$y \in H \wedge \text{HOD}_X^{L[\mathbb{X}, X]}[y] \models u \Vdash_{\mathbb{O}_X^{L[\mathbb{X}, X]}} L[\check{S}_{\epsilon_{k+1}}, \dot{x}_{\text{gen}}, \check{y}] \models \neg \varphi_{\epsilon_{k+1}}(\check{S}_{\epsilon_{k+1}}, \dot{x}_{\text{gen}}, \check{y})$$

In this case, let  $p_{k+1} \in \mathbb{O}_X^{L[\mathbb{X}, X]}$  be the least  $u \in J_{k+1}$  according to the canonical wellordering of  $\text{HOD}_X^{L[\mathbb{X}, X]}$ .

(Subcase ii) Subcase i fails. Declare that the construction has failed at stage  $k+1$ .

**Claim 3:** The construction must fail at some stage.

*Proof.* Suppose the construction never failed. Then one would have successfully produced a sequence  $\langle p_k : k \in \omega \rangle$  in  $\mathbb{O}_X^{L[\mathbb{X}, X]} \upharpoonright q^X$  with the properties specified above. Let  $\hat{G}$  be the  $\mathbb{O}_X^{L[\mathbb{X}, X]} \upharpoonright q^X$ -generic filter produced by  $\leq_{\mathbb{O}_X^{L[\mathbb{X}, X]} \upharpoonright q^X}$ -upward closing  $\{p_k : k \in \omega\}$ . By construction,  $p_k \in J_k$ . Hence  $\hat{G}$  is  $\mathbb{O}_X^{L[\mathbb{X}, X]} \upharpoonright q^X$ -generic filter with respect to  $\mathcal{J}$ . Let  $h = \dot{x}_{\text{gen}}[\hat{G}]$  be the associated  $\mathbb{O}_X^{L[\mathbb{X}, X]} \upharpoonright q^X$ -generic real. By Claim 2,  $h \in K$ ,  $h$  is  $\mathbb{O}_X^{L[\mathbb{X}, X]} \upharpoonright q^X$ -generic over  $\text{HOD}_X^{L[\mathbb{X}, X]}[y]$  for all  $y \in \mathbb{R}^{L[\mathbb{X}, X]}$ , and there is some  $m \in \omega$  so that  $H = (\mathfrak{B}_{(S_{\epsilon_m}, \varphi_{\epsilon_m})}^2)_h$ . However, the construction did not fail at stage  $m$ . Without loss of generality,  $p_k$  was found with the property that there is some  $y \in \mathbb{R}^{L[\mathbb{X}, X]}$  so that

$$y \notin H \wedge \text{HOD}_X^{L[\mathbb{X}, X]}[y] \models u \Vdash_{\mathbb{O}_X^{L[\mathbb{X}, X]}} L[\check{S}_{\epsilon_{k+1}}, \dot{x}_{\text{gen}}, \check{y}] \models \varphi_{\epsilon_{k+1}}(\check{S}_{\epsilon_{k+1}}, \dot{x}_{\text{gen}}, \check{y})$$

Thus

$$\text{HOD}_X^{L[\mathbb{X}, X]}[y][H] \models L[S_{\epsilon_k}, h, y] \models \varphi_{\epsilon_k}(S_{\epsilon_k}, h, y).$$

Thus

$$V \models L[S_{\epsilon_k}, h, y] \models \varphi_{\epsilon_k}(S_{\epsilon_k}, h, y).$$

Since  $H = (\mathfrak{B}_{(S_{\epsilon_m}, \varphi_{\epsilon_m})}^2)_h$ , this implies that  $y \in H$ . However, it was also assumed that  $y \notin H$ . Contradiction. This completes the proof of Claim 3.  $\square$

**Claim 4:** For all  $X \geq Z^{**}$ , there is some  $p \in \mathbb{O}_X^{L[\mathbb{X}, X]}$  and some ordinal  $\epsilon$  so that for all  $y \in \mathbb{R}^{L[\mathbb{X}, X]}$ ,  $y \in H$  if and only if  $\text{HOD}_X^{L[\mathbb{X}, X]}[y] \models p \Vdash_{\mathbb{O}_X^{L[\mathbb{X}, X]}} L[\check{S}_\epsilon, \dot{x}_{\text{gen}}, \check{y}] \models \varphi(\check{S}_\epsilon, \dot{x}_{\text{gen}}, \check{y})$ .

*Proof.* By Claim 3, the construction described above must fail at some stage  $k$ . This means that the forcing relation written above in  $\text{HOD}_X^{L[\mathbb{X}, X]}[y]$  for  $p_{k-1}$  and the  $\infty$ -Borel code  $(S_{\epsilon_k}, \varphi_{\epsilon_k})$  can be used to determine membership of  $y \in H$  for any  $y \in \mathbb{R}^{L[\mathbb{X}, X]}$ . This completes the proof of Claim 4.

As mentioned in the proof of Claim 2, one non-uniformly selected a forcing isomorphism  $\Phi$ . The choice of  $\Phi$  is irrelevant since one will only need the existence of any condition  $p$  with the above property in Claim 4.  $\square$

For  $X \geq Z^{**}$ , using the canonical wellordering of  $\text{HOD}_X^{L[\mathbb{X}, X]}$ , let  $\langle p_\alpha^X : \alpha < \delta^X \rangle$ , where  $\delta^X \in \text{ON}$ , be the canonical enumeration of  $\mathbb{O}_X^{L[\mathbb{X}, X]} \upharpoonright q^X$ .

In summary, it has been established that for any  $y \in \mathbb{R}$ , if one drops into a local model  $\text{HOD}_X^{L[\mathbb{X}, X]}[y]$ , where  $X$  is a sufficiently strong Turing degree (i.e.  $X \geq Z^{**} \oplus [y]_{\text{Turing}}$ ), then one can determine membership of  $y$  in  $H$  by merely two pieces of information: a condition  $p \in \mathbb{O}_X^{L[\mathbb{X}, X]}$  and an ordinal  $\epsilon$ . Note that  $p$  is coded by an ordinal since one can identify  $p$  with the least ordinal  $\alpha < \delta^X$  so that  $p = p_\alpha^X$ . Next one will show that roughly all this local information can be captured by just two ordinals by taking an ultrapower by  $\mu$ .

Using Claim 4, let  $\Sigma_{\alpha^*} : \mathcal{D} \rightarrow \text{ON}$  be defined by  $\Phi_{\alpha^*}(X)$  is the least  $\alpha$  so that  $p_\alpha^X$  satisfies Claim 4 for some  $\epsilon$  whenever  $X \geq Z^{**}$ . For other  $X \in \mathcal{D}$ , let  $\Sigma_{\alpha^*}(X) = 0$ . Define  $\Sigma_{\epsilon^*} : \mathcal{D} \rightarrow \text{ON}$  by  $\Sigma_{\epsilon^*}(X)$  is the least  $\epsilon$  satisfying Claim 4 with respect to  $p_{\Sigma_{\alpha^*}(X)}$  whenever  $X \geq Z^{**}$ . For other  $X \in \mathcal{D}$ , let  $\Sigma_{\epsilon^*}(X) = 0$ .

$[\Sigma_{\alpha^*}]_\mu$  and  $[\Sigma_{\epsilon^*}]_\mu$  are ordinals since  $\prod_{X \in \mathcal{D}} \text{ON}/\mu$  is a wellordering by Fact 2.14. Let  $\alpha^* = [\Sigma_{\alpha^*}]_\mu$  and  $\epsilon^* = [\Sigma_{\epsilon^*}]_\mu$ .

**Claim 5:**  $H$  is OD.



*Proof.* Note that for  $y \in \mathbb{R}$ ,  $y \in H$  if and only if for any  $\Sigma_0, \Sigma_1 : \mathcal{D} \rightarrow \text{ON}$  so that  $[\Sigma_0]_\mu = \alpha^*$  and  $[\Sigma_1]_\mu = \epsilon^*$ , for a cone of  $X \in \mathcal{D}$ ,

$$\text{HOD}_{\mathbb{X}}^{L[\mathbb{X}, X]}[y] \models p_{\Sigma_0(X)}^X \Vdash_{\mathbb{O}_{\mathbb{X}}^{L[\mathbb{X}, X]}} L[\check{S}_{\Sigma_1(X)}, \dot{x}_{\text{gen}}, \check{y}] \models \varphi_{\Sigma_1(X)}(\check{S}_{\Sigma_1(X)}, \dot{x}_{\text{gen}}, \check{y}).$$

The latter is ordinal definable (using the two ordinals  $\alpha^*$  and  $\epsilon^*$ ). The expression successfully defines  $H$  by the definition of  $\alpha^* = [\Sigma_{\alpha^*}]_\mu$  and  $\epsilon^* = [\Sigma_{\epsilon^*}]_\mu$  as well as Claim 4.  $\square$

The theorem is complete in the setting of Case I.

(Case II) There is a cone of  $X \in \mathcal{D}$  so that there is an atom in  $\mathbb{O}_{\mathbb{X}}^{L[\mathbb{X}, X]} \restriction q^X$ .

Let  $Z^{**} \geq Z^*$  be the base of a cone satisfying the Case II assumption.

Fix an  $X \geq Z^{**}$ . Let  $p \leq_{\mathbb{O}_{\mathbb{X}}^{L[\mathbb{X}, X]} \restriction q^X} q^X$  be an atom.

**Claim 6:** There is some  $r \in K \cap \text{HOD}_{\mathbb{X}}^{L[\mathbb{X}, X]}$ . Note that  $r \in K$  implies there is an ordinal  $\epsilon$  so that  $H = (\mathfrak{B}_{(S_\epsilon, \varphi_\epsilon)}^2)_r$ .

*Proof.* Since  $p \in \mathbb{O}_{\mathbb{X}}^{L[\mathbb{X}, X]}$ , one has that  $p \neq \emptyset$ . Let  $r \in p$ . Let  $G_r^1 = \{p \in \mathbb{O}_{\mathbb{X}}^{L[\mathbb{X}, X]} : r \in p\}$ . By Fact 2.4,  $G_r^1$  is an  $\mathbb{O}_{\mathbb{X}}^{L[\mathbb{X}, X]}$ -generic filter over  $\text{HOD}_{\mathbb{X}}^{L[\mathbb{X}, X]}$  and  $\dot{x}_{\text{gen}}[G_r^1] = r$ . Also  $p \in G_r^1$ . Therefore thinking of reals as subsets of  $\omega$ , for each  $n \in \omega$ ,  $n \in r$  if and only if  $p \Vdash_{\mathbb{O}_{\mathbb{X}}^{L[\mathbb{X}, X]}} \check{n} \in \dot{x}_{\text{gen}}$  since  $p$  was assumed to be an atom and hence has no nontrivial extensions. The latter is  $\text{OD}_{\mathbb{X}}^{L[\mathbb{X}, X]}$ . This shows that  $r \in \text{HOD}_{\mathbb{X}}^{L[\mathbb{X}, X]}$ . (Since  $r \in p$  was arbitrary, this argument actually shows that  $p = \{r\}$ .) Since  $p \leq_{\mathbb{O}_{\mathbb{X}}^{L[\mathbb{X}, X]}} q^X$  and  $p \in G_r^1$ , one has that  $r \in q^X$ . By definition of  $q^X$ , one has that  $L[U, r] \models \Psi(U, r)$ . Since  $(U, \psi)$  is the  $\infty$ -Borel code for  $K$ ,  $V \models r \in K$ . It has been shown that  $r \in K \cap \text{HOD}_{\mathbb{X}}^{L[\mathbb{X}, X]}$ .  $\square$

Let  $\langle r_\alpha^X : \alpha < \delta^X \rangle$ , where  $\delta^X \in \text{ON}$ , be the enumeration of  $\mathbb{R}^{\text{HOD}_{\mathbb{X}}^{L[\mathbb{X}, X]}}$  according to the canonical wellordering of  $\text{HOD}_{\mathbb{X}}^{L[\mathbb{X}, X]}$ . Define  $\Sigma_{\alpha^*} : \mathcal{D} \rightarrow \text{ON}$  by  $\Sigma_{\alpha^*}(X)$  is the least ordinal  $\alpha$  so that  $r_\alpha^X$  satisfies Claim 6 whenever  $X \geq Z^{**}$ . Otherwise, let  $\Sigma_{\alpha^*}(X) = 0$ . Let  $\Sigma_{\epsilon^*} : \mathcal{D} \rightarrow \text{ON}$  be defined by  $\Sigma_{\epsilon^*}(X)$  is the least  $\epsilon \in \text{ON}$  so that  $H = (\mathfrak{B}_{(S_\epsilon, \varphi_\epsilon)}^2)_{r_{\Sigma_{\alpha^*}(X)}^X}$  whenever  $X \geq Z^{**}$ . Otherwise, let  $\Sigma_{\epsilon^*}(X) = 0$ .

Again since  $\prod_{X \in \mathcal{D}} \text{ON}/\mu$  is a wellordering by Fact 2.14,  $[\Sigma_{\alpha^*}]_\mu$  and  $[\Sigma_{\epsilon^*}]_\mu$  are ordinals. Let  $\alpha^* = [\Sigma_{\alpha^*}]_\mu$  and  $\epsilon^* = [\Sigma_{\epsilon^*}]_\mu$ .

**Claim 7:**  $H$  is OD.

*Proof.* Note that for all  $y \in \mathbb{R}$ ,  $y \in H$  if and only if for all  $\Sigma_0, \Sigma_1 : \mathcal{D} \rightarrow \text{ON}$  so that  $[\Sigma_0]_\mu = \alpha^*$  and  $[\Sigma_1]_\mu = \epsilon^*$ , for a cone of  $X \in \mathcal{D}$ ,

$$L[S_{\Sigma_1(X)}, r_{\Sigma_0(X)}^X, y] \models \varphi_{\Sigma_1(X)}(S_{\Sigma_1(X)}, r_{\Sigma_0(X)}^X, y).$$

This equivalence is true by Claim 6 and the definitions of  $\Sigma_{\alpha^*}$  and  $\Sigma_{\epsilon^*}$ . The latter is ordinal definable (using the ordinals  $\alpha^*$  and  $\epsilon^*$ ).  $\square$

The theorem has been shown in Case II as well. The entire argument is complete.  $\square$

Some assumptions beyond ZF or ZFC are necessary to prove the conclusion of Theorem 3.1. The next results shows that in a Sacks forcing extension of the constructible universes  $L$ , there is a nonempty OD set  $K$  and a real  $g$  so that  $g$  is  $\text{OD}_z$  for any  $z \in K$  but  $g$  is not OD.

**Fact 3.2.** Let  $\mathbb{S}$  denote the Sacks forcing of perfect trees. Let  $G \subseteq \mathbb{S}$  be an  $\mathbb{S}$ -generic filter over  $L$ .

In  $L[G]$ : Let  $K = \mathbb{R}^{L[G]} \setminus \mathbb{R}^L$  be the collection of nonconstructible reals.  $K$  is an OD sets of reals. Let  $g \in \mathbb{R}^{L[G]}$  be the  $\mathbb{S}$ -generic real over  $L$  derived from  $G$ . Then  $g$  is  $\text{OD}_z$  for any  $z \in K$ , but  $g$  is not OD.

*Proof.* A perfect tree is a subset  $p$  of  ${}^{<\omega}2$  with the property that for all  $\sigma, \tau \in {}^{<\omega}2$ , if  $\sigma \subseteq \tau$  and  $\tau \in p$ , then  $\sigma \in p$ . Let  $\mathbb{S}$  consists of the collection of perfect trees. Define  $p \leq_{\mathbb{S}} q$  if and only if  $p \subseteq q$ . The largest element is  $1_{\mathbb{S}} = {}^{<\omega}2$ . Sacks forcing is  $\mathbb{S} = (\mathbb{S}, \leq_{\mathbb{S}}, 1_{\mathbb{S}})$ . If  $p \in \mathbb{S}$ , then define  $[p] = \{f \in {}^{<\omega}2 : (\forall n)(f \restriction n \in p)\}$ . If  $r \in \mathbb{R}$ , then let  $G_r^{\mathbb{S}} = \{p \in \mathbb{S} : r \in [p]\}$ . If  $G_r^{\mathbb{S}}$  is an  $\mathbb{S}$ -generic filter over  $L$ , then one says that  $r$  is an  $\mathbb{S}$ -generic real over  $L$ . See [10] Chapter 15 for the basic facts about the Sacks forcing  $\mathbb{S}$ .

Fix  $G \subseteq \mathbb{S}$  a Sacks generic filter over  $L$ . Work in  $L[G]$ . Let  $g$  be the Sacks generic real derived from  $G$ , i.e.  $\{g\} = \bigcap_{p \in G} [p]$ .

Let  $K = \mathbb{R}^{L[G]} \setminus \mathbb{R}^L$  be the collection of nonconstructible reals. This set  $K$  is OD. Using a fusion argument, one can reconstruct  $g$  from any nonconstructible real  $z$  (that is  $z \in K$ ) using only parameters in  $L$ . (This is the argument used in [10] Theorem 15.34 to show that  $g$  is a real of minimal constructibility degree. It also shows that every element of  $K$  is itself an  $\mathbb{S}$ -generic real for some  $\mathbb{S}$ -generic filter over  $L$ .) So  $g$  is  $\text{OD}_z$  for any  $z \in K$ .

However  $g$  is not OD. Suppose otherwise that  $g$  was OD. Then there must be some formula  $\varphi$  and some ordinal  $\epsilon$  so that  $g$  is the unique solution  $v \in L[G]$  to  $L[G] \models \varphi(v, \epsilon)$ . Therefore, there is some  $q \in G$  so that  $L \models q \Vdash_{\mathbb{S}} \varphi(\dot{x}_{\text{gen}}, \epsilon)$  where  $\dot{x}_{\text{gen}}$  is the canonical  $\mathbb{S}$ -name for the generic real added by an  $\mathbb{S}$ -generic filter. Since  $q$  is still a perfect tree in  $L[G]$ ,  $[q]^{L[G]}$  must contain a nonconstructible real  $h$  with  $h \neq g$ . As mentioned above, by the fusion argument of [10] Theorem 15.34,  $h$  is also  $\mathbb{S}$ -generic over  $L$ . Let  $G_h^{\mathbb{S}} = \{p \in \mathbb{S} : h \in [p]\}$  be the  $\mathbb{S}$ -generic filter over  $L$  derived from  $h$  so that  $\dot{x}_{\text{gen}}[G_h^{\mathbb{S}}] = h$ . Note that  $G_h^{\mathbb{S}} \in L[G]$  and  $q \in G_h^{\mathbb{S}}$ . Thus  $L[G_h^{\mathbb{S}}] \models \varphi(h, \epsilon)$ . Since [10] Theorem 15.34 implies every nonconstructible real in  $L[G]$  has minimal constructibility degree,  $L[G] = L[G_h^{\mathbb{S}}]$ . Hence  $L[G] \models \varphi(h, \epsilon)$  and  $h \neq g$ . This contradicts  $g$  being the unique solution in  $L[G]$  to  $\varphi(v, \epsilon)$ .  $\square$

#### 4. CARDINALS BELOW $[\omega_1]^{\omega_1}$

**Fact 4.1.** *Assume ZF. Suppose  $\kappa$  is a cardinal which is inaccessible in any inner model of ZFC. Then  $||[\kappa]^{<\kappa}| < |[\kappa]^\kappa|$ .*

*Proof.* Suppose there was an injection  $\Phi : [\kappa]^\kappa \rightarrow [\kappa]^{<\kappa}$ . Consider  $\hat{\Phi} \subseteq [\kappa]^\kappa \times \kappa$  defined by  $(f, \alpha) \in \hat{\Phi} \Leftrightarrow \alpha \in \Phi(f)$ . Note that if  $f \in L[\hat{\Phi}]$ , then  $\Phi(f) \in L[\hat{\Phi}]$ .

Identify the predicate  $\Phi$  with  $\hat{\Phi}$ . Then  $L[\Phi] \models \text{ZFC}$  and  $L[\Phi] \models \text{"}\Phi \text{ is an injection"}$ . By Cantor's theorem,  $L[\Phi] \models |[\kappa]^\kappa| = 2^\kappa > \kappa$ . However, since  $L[\Phi]$  thinks  $\kappa$  is inaccessible,  $L[\Phi] \models |[\kappa]^{<\kappa}| = |2^{<\kappa}| = \kappa$ . Then within  $L[\Phi]$ ,  $\Phi$  induces an injection of  $2^\kappa$  into  $\kappa$  which is not possible.  $\square$

**Fact 4.2.** *Assume ZF. Suppose  $\kappa$  is a cardinal such that there is a  $\kappa$ -complete nonprincipal ultrafilter on  $\kappa$ . Let  $M$  be any inner model of ZFC. Then  $\kappa$  is inaccessible in  $M$ .*

*Proof.* Let  $\mu$  be a  $\kappa$ -complete measure on  $\kappa$ . It is clear that  $\kappa$  is regular in  $M$ .

Suppose  $\kappa$  is not a strong limit cardinal in  $M$ . Then there is a  $\delta < \kappa$  so that  $M \models |\mathcal{P}(\delta)| \geq \kappa$ . Since  $M \models \text{ZFC}$ , one can find a  $\kappa$ -length sequence of distinct subsets of  $\delta$ ,  $\langle A_\alpha : \alpha < \kappa \rangle$ .

For each  $\beta < \delta$ , let  $C_\beta^0 = \{\alpha < \kappa : \beta \notin A_\alpha\}$  and  $C_\beta^1 = \{\alpha < \kappa : \beta \in A_\alpha\}$ . Since  $C_\beta^0 \cup C_\beta^1 = \kappa$  and  $\mu$  is a measure, there is some  $i_\beta \in 2$  so that  $C_\beta^{i_\beta} \in \mu$ . Let  $A = \{\beta : i_\beta = 1\}$ . Since  $\mu$  is  $\kappa$ -complete and  $\delta < \kappa$ ,  $C = \bigcap_{\beta < \delta} C_\beta^{i_\beta} \in \mu$ . Since  $\mu$  is nonprincipal, let  $\alpha_0, \alpha_1 \in C$  with  $\alpha_0 \neq \alpha_1$ . Then  $A_{\alpha_0} = A_{\alpha_1} = A$ . This contradicts  $\langle A_\alpha : \alpha < \kappa \rangle$  being a sequence of distinct subsets of  $\delta$ .  $\square$

**Fact 4.3.** ([15] Theorem 3.2) *Assume ZF. Let  $\kappa$  be a cardinal. Let  $\eta < \kappa$  be a limit ordinal. The partition relation  $\kappa \rightarrow (\kappa)_2^{\eta+\eta}$  implies that the  $\eta$ -club filter on  $\kappa$ ,  $W_\kappa^\eta$ , is a normal  $\kappa$ -complete ultrafilter on  $\kappa$ .*

**Fact 4.4.** *Assume ZF + AD.*

(Solovay)  $\omega_1 \rightarrow (\omega_1)_2^{\omega_1}$  and therefore  $\omega_1$  is measurable. (Martin)  $\omega_2 \rightarrow (\omega_2)_2^\alpha$ , for each  $\alpha < \omega_2$ , and therefore  $\omega_2$  is measurable.

([12]) Suppose  $A \subseteq \mathbb{R}$ . Let  $\delta_A$  be the least ordinal so that  $L_\delta(A, \mathbb{R}) \prec_1 L(A, \mathbb{R})$ .  $\delta_A \rightarrow (\delta_A)_2^{\delta_A}$  and hence  $\delta_A$  is measurable.

**Theorem 4.5.** *Assume ZF + AD.*

$|[\omega_1]^{<\omega_1}| < |[\omega_1]^{\omega_1}|$ .  $|[\omega_2]^{<\omega_2}| < |[\omega_2]^{\omega_2}|$ . For any set  $A \subseteq \mathbb{R}$ ,  $|[\delta_A]^{<\delta_A}| < |[\delta_A]^{\delta_A}|$ .

More generally, for any cardinal  $\kappa$  satisfying the partition relation  $\kappa \rightarrow (\kappa)_2^{\omega+\omega}$ , one has  $|[\kappa]^{<\kappa}| < |[\kappa]^\kappa|$ .

The argument that  $|[\omega_1]^{<\omega_1}| < |[\omega_1]^{\omega_1}|$  presented above was suggested by Neeman and is simpler than the original argument. The original argument, presented below, involved absorbing a fragment of an arbitrary injection into a suitable ZFC model. This idea is a powerful technique for studying cardinalities under  $\text{AD}^+$  and especially for producing intermediate cardinals under  $\text{AD}^+ + \neg \text{AD}_{\mathbb{R}}$ .

**Fact 4.6.** Assume  $V = L(J, \mathbb{R}) \models \text{AD} + \text{DC}_{\mathbb{R}}$  where  $J$  is a set of ordinals. Suppose  $\Phi : [\kappa]^\kappa \rightarrow [\kappa]^{<\kappa}$ . Then there is a  $e \in \mathbb{R}$  so that for all  $x \in \mathbb{R}$  with  $e \leq_{J, \omega \mathbb{O}_J} x$  (which refers to the  $(J, \omega \mathbb{O}_J)$ -constructibility reduction relation), one has the following properties:

(i) For all  $f \in [\kappa]^\kappa \cap L[J, \omega \mathbb{O}_J, x]$ ,  $\Phi(f) \in L[J, \omega \mathbb{O}_J, x]$ .

(ii)  $\Phi \cap L[J, \omega \mathbb{O}_J, x] \in L[J, \omega \mathbb{O}_J, x]$ .

(i) and (ii) together imply that  $\Phi \cap L[J, \omega \mathbb{O}_J, x]$  is a function which is even a set in  $L[J, \omega \mathbb{O}_J, x]$ .

*Proof.* In  $L(J, \mathbb{R})$ , every set is  $\text{OD}_{J,e}$  for some real  $e$ . Let  $\varphi$  be a formula and let  $\bar{\alpha}$  be a tuple of ordinals so that

$$(f, \sigma) \in \Phi \Leftrightarrow L(J, \mathbb{R}) \models \varphi(J, e, \bar{\alpha}, f, \sigma)$$

Now fix  $x \in \mathbb{R}$  so that  $e \in L[J, \omega \mathbb{O}_J, x]$ . By Fact 2.10 and the above, one has that for all  $(f, \sigma) \in ([\kappa]^\kappa \times [\kappa]^{<\kappa}) \cap L[J, \omega \mathbb{O}_J, x]$

$$(f, \sigma) \in \Phi \Leftrightarrow L[J, \omega \mathbb{O}_J, x] \models 1_{\omega \mathbb{O}_J / G_x^n} \Vdash_{\omega \mathbb{O}_J / G_x^1} L(\check{J}, \dot{\mathbb{R}}_{\text{sym}}) \models \varphi(J, e, \bar{\alpha}, f, \sigma).$$

By comprehension in  $L[J, \omega \mathbb{O}_J, x]$ , one see that (ii) follows.

Note that for each  $f \in [\kappa]^\kappa$  and  $\beta \in \kappa$ , one has that

$$\beta \in \Phi(f) \Leftrightarrow L(J, \mathbb{R}) \models (\exists \sigma)(\varphi(J, e, \bar{\alpha}, f, \sigma) \wedge \beta \in \sigma).$$

(Here  $\sigma \in [\kappa]^{<\kappa}$  is construed as a subset of  $\kappa$ .)

So for each  $x \in \mathbb{R}$  so that  $e \in L[J, \omega \mathbb{O}_J, x]$ , if  $f \in L[J, \omega \mathbb{O}_J, x]$ , one has

$$\beta \in \Phi(f) \Leftrightarrow L[J, \omega \mathbb{O}_J, x] \models 1_{\omega \mathbb{O}_J / G_x^1} \Vdash_{\omega \mathbb{O}_J / G_x^1} L(J, \dot{\mathbb{R}}_{\text{sym}}) \models (\exists \sigma)(\varphi(J, e, \bar{\alpha}, f, \sigma) \wedge \beta \in \sigma).$$

Again by comprehension in  $L[J, \omega \mathbb{O}_J, x]$ , one has that  $\Phi(f) \in L[J, \omega \mathbb{O}_J, x]$  and thus (i).  $\square$

The following result due to Steel is proved by inner model theoretic techniques:

**Fact 4.7.** (Steel, [18] Theorem 8.27) Assume  $\text{ZF} + \text{AD} + \text{V} = \text{L}(\mathbb{R})$ . If  $\kappa$  is regular, then  $\text{HOD}_x \models \text{“}\kappa \text{ is measurable”}$ .

**Theorem 4.8.** Assume  $\text{ZF} + \text{AD} + \text{V} = \text{L}(\mathbb{R})$ . Suppose  $\kappa < \Theta$  is regular. Then  $||[\kappa]^{<\kappa}| < |[\kappa]^\kappa|$ .

*Proof.* If  $\kappa < \Theta$  is regular, then Fact 4.7 implies that  $\text{HOD}_x^{L(\mathbb{R})} \models \text{“}\kappa \text{ is measurable”}$  for any  $x \in \mathbb{R}$ . Let  $\mathbb{X} = \omega \mathbb{O}$ . By Fact 2.11,  $\text{HOD}_x^{L(\mathbb{R})} = L[\mathbb{X}, x]$ .

Now suppose that there is an injection  $\Phi : [\kappa]^\kappa \rightarrow [\kappa]^{<\kappa}$ . By Fact 4.6, there is an  $e \in \mathbb{R}$  so that  $\Phi \cap L[\mathbb{X}, e] \in L[\mathbb{X}, e]$  and this set is a function in  $L[\mathbb{X}, e]$ . Let  $\Psi = \Phi \cap L[\mathbb{X}, e]$ . By absoluteness,  $L[\mathbb{X}, e] \models \text{“}\Psi : [\kappa]^\kappa \rightarrow [\kappa]^{<\kappa} \text{ is an injection”}$ . However, since  $\kappa$  is measurable in  $\text{HOD}_e = L[\mathbb{X}, e]$ , one has that  $L[\mathbb{X}, e] \models |[\kappa]^{<\kappa}| = \kappa$ . By Cantor’s theorem applied in  $L[\mathbb{X}, e]$ , it is impossible such an injection can exist.  $\square$

By Theorem 4.5,  $|[\omega_1]^{<\omega_1}| < |[\omega_1]^{\omega_1}|$ . A natural question at this point would be whether it is possible under  $\text{ZF} + \text{AD}$  that there exists a set  $K$  such that  $|[\omega_1]^{<\omega_1}| < |K| < |[\omega_1]^{\omega_1}|$ . Next, it will be shown that such a set exists under  $\text{ZF} + \text{AD}^+ + \neg \text{AD}_{\mathbb{R}} + \text{V} = \text{L}(\mathcal{P}(\mathbb{R}))$ . Recall under this assumption, there is a set of ordinal  $J$  so that  $V = L(J, \mathbb{R})$ .

**Definition 4.9.** Assume  $\text{ZF} + \text{AD}^+$ . Let  $J \subseteq \text{ON}$  be a set of ordinals so that  $V = L(J, \mathbb{R})$ . Let  $\mathbb{X} = (J, \omega \mathbb{O}_J)$ .

$$N_1^J = \bigsqcup_{r \in \mathbb{R}} ((\omega_1^{L(J, \mathbb{R})})^+)^{L[\mathbb{X}, r]} = \{(r, \alpha) : \alpha < ((\omega_1^{L(J, \mathbb{R})})^+)^{L[\mathbb{X}, r]}\}.$$

In other words, this is a disjoint union over  $r \in \mathbb{R}$  of the successor of  $\omega_1^{L(J, \mathbb{R})}$  as computed in  $L[\mathbb{X}, r]$ .

**Theorem 4.10.** Assume  $\text{ZF} + \text{AD}^+$  and there is a set of ordinals  $J \subseteq \text{ON}$  so that  $V = L(J, \mathbb{R})$ . Then  $\neg(|N_1^J| \leq |[\omega_1]^{<\omega_1}|)$ ,  $|\mathbb{R} \times \omega_1| < |N_1^J| < |\mathbb{R} \times \omega_2|$ ,  $|N_1^J| < |[\omega_1]^{\omega_1}|$ ,  $\neg(|[\omega_1]^\omega| \leq |N_1^J|)$ , and  $|[\omega_1]^{<\omega_1}| < |[\omega_1]^{<\omega_1} \sqcup N_1^J| < |[\omega_1]^{\omega_1}|$ .

*Proof.* Let  $\mathbb{X} = (J, \omega \mathbb{O}_J)$ .

Suppose there is an injection  $\Phi : N_1^J \rightarrow [\omega_1]^{<\omega_1}$ . By the idea of Fact 4.6, there is an  $e \in \mathbb{R}$  so that  $\Phi \cap L[\mathbb{X}, e] \in L[\mathbb{X}, e]$  and  $L[\mathbb{X}, e]$  thinks that  $\Phi = \Phi \cap L[\mathbb{X}, e]$  is an injective function with domain  $N_1^J \cap L[\mathbb{X}, e]$ . Thus with the model  $L[\mathbb{X}, e]$ , the restriction of  $\Phi$  to  $\{e\} \times ((\omega_1^{L(J, \mathbb{R})})^+)^{L[\mathbb{X}, e]}$  is an injection into  $([\omega_1^{L(J, \mathbb{R})}]^{<\omega_1^{L(J, \mathbb{R})}})^{L[\mathbb{X}, e]}$ . This is impossible since the inaccessibility of  $\omega_1^{L(J, \mathbb{R})}$  in the model  $L[\mathbb{X}, e]$  implies

that  $L[\mathbb{X}, e] \models |\omega_1^{L(J, \mathbb{R})}|^{<\omega_1^{L(J, \mathbb{R})}} = \omega_1^{L(J, \mathbb{R})}$ . This shows that  $\neg(N_1^J \leq [\omega_1]^{<\omega_1})$ . This also implies  $|[\omega_1]^{<\omega_1}| < |[\omega_1]^{<\omega_1} \sqcup N_1^J|$ .

Suppose there is an injection  $\Phi : N_1^J \rightarrow \mathbb{R} \times \omega_1$ . Using the same idea as the proof of Fact 4.6, there is an  $e$  so that  $\Phi \cap L[\mathbb{X}, e] \in L[\mathbb{X}, e]$  and  $L[\mathbb{X}, e]$  thinks that  $\Phi \cap L[\mathbb{X}, e]$  is an injective function with domain  $N_1^J \cap L[\mathbb{X}, e]$ . Let  $\tilde{\Phi} = \Phi \cap L[\mathbb{X}, e]$ . Then  $L[\mathbb{X}, e] \models \text{"}\tilde{\Phi} \text{ restricted to } \{e\} \times ((\omega_1^{L(J, \mathbb{R})})^+)^{L[\mathbb{X}, e]} = \{e\} \times (\omega_1^{L(J, \mathbb{R})})^+ \text{ is an injection of } \{e\} \times (\omega_1^{L(J, \mathbb{R})})^+ \text{ into } \mathbb{R} \times \omega_1^{L(J, \mathbb{R})}\text{"}$ . Note that  $L[\mathbb{X}, e] \models |\mathbb{R}| < \omega_1^{L(J, \mathbb{R})}$  since  $\omega_1^{L(J, \mathbb{R})}$  is inaccessible in  $L[\mathbb{X}, e]$ . Thus  $L[\mathbb{X}, e] \models |\mathbb{R} \times \omega_1^{L(J, \mathbb{R})}| = \omega_1^{L(J, \mathbb{R})}$ . It is impossible that  $L[\mathbb{X}, e]$  has an injection of the successor  $\omega_1^{L(J, \mathbb{R})}$  (as computed in  $L[\mathbb{X}, e]$ ) into  $\omega_1^{L(J, \mathbb{R})}$ . This establishes  $\neg(|N_1^J| \leq |\mathbb{R} \times \omega_1|)$ .

Suppose there is an injection  $\Phi : \mathbb{R} \times \omega_2 \rightarrow N_1^J$ . Again using the idea for Fact 4.6, there is an  $e$  so that  $\Phi \cap L[\mathbb{X}, e] \in L[\mathbb{X}, e]$  and  $L[\mathbb{X}, e]$  thinks that  $\tilde{\Phi} = \Phi \cap L[\mathbb{X}, e]$  is a function with domain  $(\mathbb{R} \times \omega_2^{L(J, \mathbb{R})}) \cap L[\mathbb{X}, e]$ . Since  $L[\mathbb{X}, e] \models \text{AC}$  and there are no uncountable wellordered sequences of distinct reals,  $L[\mathbb{X}, e] \models |\mathbb{R}| < \omega_1^{L(J, \mathbb{R})}$ . Since AD implies that  $\omega_1$  and  $\omega_2$  are measurable, the argument of Fact 4.2 implies that there are no uncountable wellordered sequence of distinct reals and no  $\omega_2$  length sequence of distinct subsets of  $\omega_1$ . Thus  $\mathbb{R}^{L[\mathbb{X}, e]}$  is countable and for each  $r \in \mathbb{R}$ ,  $((\omega_1^{L(J, \mathbb{R})})^+)^{L[\mathbb{X}, r]} < \omega_2^{L(J, \mathbb{R})}$ . Hence  $L[\mathbb{X}, e] \models |\bigsqcup_{r \in \mathbb{R}} ((\omega_1^{L(J, \mathbb{R})})^+)^{L[\mathbb{X}, r]}| < \omega_2^{L(J, \mathbb{R})}$ . Thus it is impossible that  $L[\mathbb{X}, e]$  thinks that  $\tilde{\Phi}$  restricted to  $\{e\} \times \omega_2^{L(J, \mathbb{R})}$  is an injection of  $\{e\} \times \omega_2^{L(J, \mathbb{R})}$  into  $L[\mathbb{X}, e] \cap N_1^J = \bigsqcup_{r \in \mathbb{R} \cap L[\mathbb{X}, e]} ((\omega_1^{L(J, \mathbb{R})})^+)^{L[\mathbb{X}, r]}$ . This establishes that  $\neg(|\mathbb{R} \times \omega_2| \leq |N_1^J|)$ .

As observed above, for each  $r \in \mathbb{R}$ ,  $((\omega_1^{L(J, \mathbb{R})})^+)^{L[\mathbb{X}, r]} < \omega_2^{L(J, \mathbb{R})}$ . Thus it is clear that  $N_1^J$  is a subset of  $\mathbb{R} \times \omega_2$ . Thus  $|\mathbb{R} \times \omega_1| < |N_1^J| < |\mathbb{R} \times \omega_2|$ .

For each  $r \in \mathbb{R}$ , define in  $L[\mathbb{X}, r]$ ,  $A_r = \{f \in [\omega_1^{L(J, \mathbb{R})}]^{\omega_1^{L(J, \mathbb{R})}} : \min(f) \geq \omega\}$ . Observe that  $L[\mathbb{X}, r] \models |A_r| = |[\omega_1^{L(J, \mathbb{R})}]^{\omega_1^{L(J, \mathbb{R})}}| = |\omega_1^{L(J, \mathbb{R})}| \geq (\omega_1^{L(J, \mathbb{R})})^+$ . Let  $\Psi_r : ((\omega_1^{L(J, \mathbb{R})})^+)^{L[\mathbb{X}, r]} \rightarrow A_r$  be an injection derived from the wellordering of  $A_r$  coming from the global constructibility wellordering of  $L[\mathbb{X}, r]$ . (Note that  $\langle \Psi_r : r \in \mathbb{R} \rangle$  does exist as a set in  $L(J, \mathbb{R})$ .) Out in  $L(J, \mathbb{R})$ , define an injection  $\Gamma : N_1^J \rightarrow [\omega_1]^{<\omega_1}$  by  $\Gamma(r, \alpha) = r \cdot \Psi_r(\alpha)$ , which is well defined if one considers  $\mathbb{R}$  as  $[\omega]^\omega$ , the collection of strictly increasing  $\omega$ -sequence in  $\omega$ , and the fact that  $\min \Psi_r(\alpha) \geq \omega$  since  $\Psi_r(\alpha) \in A_r$ .  $\Gamma$  witnesses that  $|N_1^J| \leq |[\omega_1]^{<\omega_1}|$ .

Let  $\text{add} : \omega_1 \times [\omega_1]^{<\omega_1} \rightarrow [\omega_1]^{<\omega_1}$  be defined by  $\text{add}(\alpha, f)(\beta) = \alpha + f(\beta)$ , whenever  $\beta < \text{dom}(f)$ . If  $B \subseteq \omega_1$ , let  $\text{enum}_B : \omega_1 \rightarrow \omega_1$  denote the increasing enumeration of  $B$ . Let

$$\Lambda(f) = \langle \sup(f) \rangle^{\wedge} \text{add}(\sup(f), f)^{\wedge} \text{enum}_{\omega_1 \setminus \text{rang}(\text{add}(\sup(f), f))}.$$

In words,  $\Lambda(f)$  first outputs  $\sup(f)$ , then put down the values  $\sup(f) + f(\beta)$  for each  $\beta < \text{dom}(f)$ , and then fills up the rest with an increasing enumerating of the remaining countable ordinals.  $\Lambda$  is an injection of  $[\omega_1]^{<\omega_1}$  into  $[\omega_1]^{<\omega_1}$ .

Let  $A = \{f \in [\omega_1]^{<\omega_1} : \min(f) \geq \omega\}$ . Observe that  $|A| = |[\omega_1]^{<\omega_1}|$ . Note that  $\Lambda[A]$  and  $\Gamma[N_1^J]$  are disjoint subsets of  $[\omega_1]^{<\omega_1}$  since for any  $f \in \Lambda[A]$ ,  $\min(f) \geq \omega$  but for all  $f \in \Gamma[N_1^J]$ ,  $\min(f) < \omega$ . Thus one can merge these two injections together to obtain an injection of  $[\omega_1]^{<\omega_1} \sqcup N_1^J$  into  $[\omega_1]^{<\omega_1}$ . This shows that  $|[\omega_1]^{<\omega_1} \sqcup N_1^J| \leq |[\omega_1]^{<\omega_1}|$ .

Now suppose  $\Phi : [\omega_1]^\omega \rightarrow N_1^J$  is an injection. Let  $\pi : \mathbb{R} \times \omega_2 \rightarrow \mathbb{R}$  denote the projection onto the first coordinate. Thinking of  $N_1^J \subseteq \mathbb{R} \times \omega_2$ ,  $\pi \circ \Phi : [\omega_1]^\omega \rightarrow \mathbb{R}$ . Thinking of  $\mathbb{R}$  as  $\omega_2$ , let  $\sigma_n : \mathbb{R} \rightarrow 2$  be defined to be the projection onto the  $n^{\text{th}}$ -coordinate, that is,  $\sigma_n(r) = r(n)$ . Thus for each  $n \in \omega$ ,  $\sigma_n \circ \pi \circ \Phi : [\omega_1]^\omega \rightarrow 2$ . By the correct-type partition relation,  $\omega_1 \rightarrow_* (\omega_1)_2^\omega$ , there is a club  $C_n$  and  $i_n \in 2$  so that for all  $f \in [C_n]_*^\omega$ ,  $\sigma_n(\pi(\Phi(f))) = i_n$ , where  $[C_n]_*^\omega$  is the collection of all  $f \in [C_n]^\omega$  which are of the correct type. (See [2] Section 2 for the definition of functions of correct type, the correct-type partition relation, and its equivalence with the usual partition property.) By  $\text{AC}_\omega^\mathbb{R}$ , let  $\langle C_n : n \in \omega \rangle$  be such that  $C_n$  is a club subset of  $\omega_1$  which is homogeneous for  $\sigma_n \circ \pi \circ \Phi$  in the sense above for each  $n \in \omega$ . Let  $s \in \mathbb{R}$  be defined by  $s(n) = i_n$ . Let  $C = \bigcap_{n \in \omega} C_n$ . Then for all  $f \in [C]_*^\omega$ ,  $\pi(\Phi(f)) = s$ . Thus  $\Phi$  restricted to  $[C]_*^\omega$  is an injection of  $[C]_*^\omega$  into  $\{s\} \times ((\omega_1^{L(J, \mathbb{R})})^+)^{L[\mathbb{X}, e]}$ . This is impossible since  $[C]_*^\omega$  is not wellorderable under AD. This shows  $\neg(|[\omega_1]^\omega| \leq |N_1^J|)$ .

Now suppose  $\Phi : [\omega_1]^{<\omega_1} \rightarrow [\omega_1]^{<\omega_1} \sqcup N_1^J$ . Define  $P : [\omega_1]^{<\omega_1} \rightarrow 2$  by

$$P(f) = \begin{cases} 0 & \Phi(f) \in [\omega_1]^{<\omega_1} \\ 1 & \Phi(f) \in N_1^J \end{cases}$$

By  $\omega_1 \rightarrow (\omega_1)_2^{\omega_1}$ , let  $C \subseteq \omega_1$  with  $|C| = \omega_1$  and homogeneous for  $P$ . If  $C$  is homogeneous for 0, then  $\Phi$  gives an injection of  $[C]^{\omega_1}$  (which is in bijection with  $[\omega_1]^{\omega_1}$ ) into  $[\omega_1]^{<\omega_1}$ . This contradicts Theorem 4.5. Suppose  $C$  was homogeneous for  $P$  taking value 1. Then  $\Phi$  is an injection of  $[C]^{\omega_1}$  into  $N_1^J$ . From this, one obtains an injection of  $[\omega_1]^\omega$  into  $N_1^J$ . But it was shown above that  $\neg(|[\omega_1]^\omega| \leq |N_1^J|)$ .

This completes the proof of the theorem.  $\square$

Note that the failure of  $\text{AD}_\mathbb{R}$  is important. With  $\text{AD}_\mathbb{R}$ , one can not have a set  $\mathbb{X}$  that absorb fragments of functions as in Fact 4.6. Moreover, the natural analog of the  $N_1^J$  sets under  $\text{AD}_\mathbb{R}$  are simply in bijection with  $\mathbb{R} \times \omega_1$ .

**Fact 4.11.** *Assume  $\text{ZF} + \text{AD}_\mathbb{R}$ . Let  $S \subseteq \text{ON}$  be a set of ordinals. Let  $N = \bigsqcup_{r \in \mathbb{R}} ((\omega_1^V)^+)^{L[S, r]}$ . Then  $|N| = |\mathbb{R} \times \omega_1|$ .*

*Proof.* Using a prewellordering on  $\mathbb{R}$  of length  $\omega_1$ , one can code subsets of  $\omega_1$  (and also subsets of  $\omega_1 \times \omega_1$ ) by reals using the Moschovakis coding lemma. Define a relation  $R \subseteq \mathbb{R} \times \mathbb{R}$  by  $R(x, y)$  if and only if  $y$  codes a subset of  $\omega_1 \times \omega_1$  which is a wellordering of  $\omega_1$  of ordertype  $((\omega_1^V)^+)^{L[S, x]}$ . By  $\text{AD}_\mathbb{R}$ , let  $F : \mathbb{R} \rightarrow \mathbb{R}$  be a uniformizing function for  $R$ . For each  $x \in \mathbb{R}$ , let  $\Psi_x : \omega_1^V \rightarrow ((\omega_1^V)^+)^{L[S, x]}$  be the bijection induced by the wellordering on  $\omega_1$  coded by  $F(x)$  according to the fixed prewellordering of length  $\omega_1$ .

Define  $\Phi : \mathbb{R} \times \omega_1 \rightarrow N$  by  $\Phi(x, \alpha) = \Psi_x(\alpha)$ .  $\Phi$  is a bijection.  $\square$

A natural question, is under  $\text{AD}_\mathbb{R}$ , is there an intermediate cardinal between  $|[\omega_1]^{<\omega_1}|$  and  $|[\omega_1]^{\omega_1}|$ ?

## 5. CARDINALITY OF $S_1$

**Definition 5.1.** (Woodin) Let  $S_1 = \{f \in [\omega_1]^{<\omega_1} : \sup(f) = \omega_1^{L[f]}\}$ .

Woodin [19] defines the set  $S_1$  and establishes a very elaborate dichotomy which asserts that  $S_1$  has a very special position among uncountable subsets of  $[\omega_1]^{<\omega_1}$ .

**Fact 5.2.** ([19] Theorem 19) (Woodin's  $S_1$  dichotomy) *Assume  $\text{ZF} + \text{DC} + \text{AD}_\mathbb{R}$ . If  $X \subseteq [\omega_1]^{<\omega_1}$  is uncountable, then either  $|X| \leq |[\omega_1]^\omega|$  or  $|S_1| \leq |X|$ .*

The proof of the Woodin's  $S_1$  dichotomy is very elaborate. This section will present some elementary arguments to establish several of the basic cardinal properties of  $S_1$  under  $\text{AD}^+$ .

The next result shows that  $S_1$  contains a copy of  $\mathbb{R}$  but has no uncountable wellorderable subsets. These properties are mentioned in [19] without a proof, but for completeness, one will reproduce the brief argument given in [4].

**Fact 5.3.** (Woodin) *Assume  $\text{ZF}$ .  $|\mathbb{R}| \leq |S_1|$ .*

*Assume  $\text{ZF}$  and there are no uncountable wellorderable sets of reals. Then  $\neg(\omega_1 \leq |S_1|)$ .*

*Proof.* For this proof, consider  $\mathbb{R}$  as the collection of infinite subsets of  $\omega$ . For each  $r \in \mathbb{R}$ , let  $A_r = r \cup \{\alpha : \omega \leq \alpha < \omega_1^{L[r]}\}$ . Let  $f_r \in [\omega_1]^{<\omega_1}$  be the increasing enumeration of  $A_r$ . Note that  $\omega_1^{L[f_r]} = \omega_1^{L[r]} = \sup(f_r)$ . Thus  $f_r \in S_1$ . The function  $\Phi : \mathbb{R} \rightarrow S_1$  defined by  $\Phi(r) = f_r$  is an injection.

Suppose  $\Phi : \omega_1 \rightarrow S_1$  is an injection.

Claim:  $\sup\{\omega_1^{L[\Phi(\alpha)]} : \alpha < \omega_1\} = \omega_1$ :

To see this, suppose not. Let  $\epsilon = \sup\{\sup(\Phi(\alpha)) : \alpha < \omega_1\}$  and  $\epsilon < \omega_1$ . Since  $\Phi$  maps into  $S_1$ , one has that  $\sup\{\omega_1^{L[\Phi(\alpha)]} : \alpha < \omega_1\} = \sup\{\sup(\Phi(\alpha)) : \alpha < \omega_1\} = \epsilon < \omega_1$ . Then  $\Phi$  would be a injection into  $[\epsilon + 1]^{<\epsilon+1}$  which is in bijection with  $\mathbb{R}$ . This is impossible since there are no uncountable wellorderable set of reals.

Let  $\varpi : \omega_1 \times \omega_1 \rightarrow \omega_1$  be a constructible bijection, for instance the Gödel pairing function. Think of  $S_1 \subseteq [\omega_1]^{<\omega_1}$  as subsets of  $\omega_1$ . Then let  $\tilde{\Phi} = \{\varpi(\alpha, \beta) : \beta \in \Phi(\alpha)\}$ . Note that  $\tilde{\Phi}$  is a subset of  $\omega_1$  which codes the function  $\Phi$ . That is,  $\Phi \in L[\tilde{\Phi}]$ . Therefore, one has that  $\Phi \in L[\Phi] \models \text{ZFC}$ .

Since there are no uncountable wellordered set of reals, one has that  $\omega_1^{L[\Phi]} < \omega_1$ . By the claim, there is some  $\alpha < \omega_1$  so that  $\omega_1^{L[\Phi(\alpha)]} > \omega_1^{L[\Phi]}$ . However, since  $\Phi \in L[\Phi]$ ,  $\Phi(\alpha) \in L[\Phi]$ . Thus one has  $\omega_1^{L[\Phi(\alpha)]} \leq \omega_1^{L[\Phi]}$ . Contradiction.  $\square$

Woodin  $S_1$ -dichotomy (Fact 5.2) and Fact 5.3 are not sufficient to distinguish  $|S_1|$  from  $|\mathbb{R}|$ , or  $|\omega_1|^\omega$  from  $|\omega_1|^{<\omega_1}$ . Next, Theorem 5.7 will be shown in order to make these distinctions. (These cardinal distinctions seem to be implicit in [19].)

The most interesting properties of  $S_1$  require at least some of the properties of  $\text{AD}^+$ .

First one will fix a simple coding for elements of  $^{<\omega_1}\omega_1$  by reals.

**Definition 5.4.** Let  $\rho : \omega \times \omega \rightarrow \omega$  denote a fixed recursive and bijection pairing function. Thinking of  $\mathbb{R}$  as  ${}^\omega 2$ , one can code relations on  $\omega$  by reals. That is, for each  $x \in X$ , let  $R_x(n, m) \Leftrightarrow x(\rho(n, m)) = 1$ . Recall  $\text{WO}$  is the collection of  $x$  so that  $R_x$  is a wellordering on  $\omega$ .

For each  $x \in \mathbb{R}$ , let  $x_n \in \mathbb{R}$  be defined by  $x_n(k) = x(\rho(n, k))$ .

Say that  $x \in \text{BS}$  if and only if  $x_0 \in \text{WO}$  and for all  $n \in \omega$ ,  $(x_1)_n \in \text{WO}$ . For each  $x \in \text{BS}$ , let  $\sigma_x : \text{ot}(x_0) \rightarrow \omega_1$  defined by  $\sigma(\alpha) = \beta$  if and only if for the unique  $n \in \omega$  with rank  $\alpha$  according to the wellordering  $R_{x_0}$ ,  $\text{ot}((x_1)_n) = \beta$ .

In this way, every  $\sigma \in {}^{<\omega_1}\omega_1$  has a code  $x \in \text{BS}$  so that  $\sigma_x = \sigma$ .

**Fact 5.5.** Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$ , and all sets of reals have  $\infty$ -Borel codes. Suppose  $R \subseteq {}^{<\omega_1}\omega_1 \times \kappa$ , where  $\kappa < \Theta$ . Then there is a set of ordinals  $S \subseteq \text{ON}$  and a formula  $\vartheta$  so that for all  $\sigma \in {}^{<\omega_1}\omega_1$  and  $\alpha < \kappa$

$$R(\sigma, \beta) \Leftrightarrow L[S, \sigma] \models \vartheta(S, \sigma, \beta)$$

If  $\Phi : {}^{<\omega_1}\omega_1 \rightarrow {}^\omega \kappa$  is a function, then there is a set of ordinals  $S$  so that for all  $\sigma \in {}^{<\omega_1}\omega_1$ ,  $\Phi(\sigma) \in L[S, \sigma]$ .

*Proof.* Since  $\kappa < \Theta$ , let  $\preceq$  be a prewellordering on  $\mathbb{R}$  of length  $\kappa$ . Let  $(J', \phi')$  be an  $\infty$ -Borel code for  $\preceq$ . Let  $\varphi : \mathbb{R} \rightarrow \kappa$  be the associated ranking function of  $\preceq$ .

Fix  $R \subseteq {}^{<\omega_1}\omega_1 \times \kappa$ . Let  $\tilde{R} \subseteq \mathbb{R} \times \mathbb{R}$  be defined by

$$\tilde{R}(x, y) \Leftrightarrow x \in \text{BS} \wedge R(\sigma_x, \varphi(y)).$$

Let  $(J'', \phi'')$  be an  $\infty$ -Borel code for  $\tilde{R}$ .

Let  $J$  be a set of ordinal coding in some fixed constructible way the two sets of ordinals  $J'$  and  $J''$ . Let  $\omega \mathbb{O}_J$  be the finite support direct limit of the Vopěnka forcing  $\langle {}_n \mathbb{O}_J, \pi_{n,m} : 0 < m \leq n < \omega \rangle$ . Let  $S$  be a set of ordinals that codes  $(J, \omega \mathbb{O}_J)$ .

Fix  $\sigma \in {}^{<\omega_1}\omega_1$ . Observe that the forcing  $\text{Coll}(\omega, \text{sup}(\sigma))$  over  $L[J, \sigma]$  canonically adds a surjection of  $\omega$  onto  $\text{sup}(\sigma)$ . From this, one can canonically obtain a bijection of  $\omega$  with  $\text{sup}(\sigma)$ . Thus one can naturally produce an element of  $\text{BS}$  which codes  $\sigma$  in any  $\text{Coll}(\omega, \text{sup}(\sigma))$ -generic extension of  $L[S, \sigma]$ . Let  $\tau_\sigma$  be a  $\text{Coll}(\omega, \text{sup}(\sigma))$ -name in  $L[S, \sigma]$  for this naturally produce element of  $\text{BS}$  which codes  $\sigma$ .

Let  $\vartheta$  be the following formula:  $\vartheta(S, \sigma, \beta)$  if and only if

$$\begin{aligned} 1_{\text{Coll}(\omega, \text{sup}(\sigma))} \Vdash_{\text{Coll}(\omega, \text{sup}(\sigma))} L[J, \omega \mathbb{O}_J, \tau_\sigma] \models 1_{\omega \mathbb{O}_J / G_{\tau_\sigma}^1} \Vdash_{\omega \mathbb{O}_J / G_{\tau_\sigma}^1} \\ L(J, \dot{\mathbb{R}}_{\text{sym}}) \models (\exists y)(\varphi(y) = \beta \wedge L[J'', \tau_\sigma, y] \models \phi''(J'', \tau_\sigma, y)) \end{aligned}$$

In the above, “ $\varphi(y) = \beta$ ” is an abbreviation for a statement asserting that  $\beta$  is the rank of  $y$  in the prewellordering defined by the  $\infty$ -Borel code  $(J', \phi')$ .

It is very important that “ $\varphi(y) = \beta$ ” is expressed in this way. The purpose of using  $L(J, \mathbb{R})$  and Woodin’s results on the symmetric collapse is to express “ $\varphi(y) = \beta$ ,” which can not be computed correctly by evaluating the prewellordering directly in an inner model of ZFC which can only contain countably many of the reals of the original universe satisfying determinacy.

Claim: For all  $\sigma \in {}^{<\omega_1}\omega_1$ ,  $R(\sigma, \beta)$  if and only if  $L[S, \sigma] \models \vartheta(S, \sigma, \beta)$ .

To see this:  $(\Rightarrow)$  Let  $p \in \text{Coll}(\omega, \text{sup}(\sigma))$ . Since  $\text{sup}(\sigma) < \omega_1$ , the powerset of  $\text{Coll}(\omega, \text{sup}(\sigma))$  computed in  $L[S, \sigma]$  is countable in the real universe satisfying determinacy. In the real world, there is a  $G \subseteq \text{Coll}(\omega, \text{sup}(\sigma))$  containing  $p$  which is  $\text{Coll}(\omega, \text{sup}(\sigma))$ -generic over  $L[S, \sigma]$ . In  $L[S, \sigma][G]$ ,  $\tau_\sigma[G] \in \text{BS}$  is a code for  $\sigma$ , that is  $\sigma_{\tau_\sigma[G]} = \sigma$ . In  $L(J, \mathbb{R})$ , there is a  $y \in \mathbb{R}$  so that  $\varphi(y) = \beta$ . Hence  $\tilde{R}(\tau_\sigma[G], y)$ . Thus

$$L(J, \mathbb{R}) \models (\exists y)(\varphi(y) = \beta \wedge L[J'', \tau_\sigma[G], y] \models \phi''(J'', \tau_\sigma[G], y)).$$

By Fact 2.10,

$$\begin{aligned} L[J, \omega \mathbb{O}_J, \tau_\sigma[G]] \models 1_{\omega \mathbb{O}_J / G_{\tau_\sigma[G]}^1} \Vdash_{\omega \mathbb{O}_J / G_{\tau_\sigma[G]}^1} \\ L(J, \dot{\mathbb{R}}_{\text{sym}}) \models (\exists y)(\varphi(y) = \beta \wedge L[J'', \tau_\sigma[G], y] \models \phi''(J'', \tau_\sigma[G], y)). \end{aligned}$$

In particular,

$$\begin{aligned} L[S, \sigma][G] &\models L[J, \omega \mathbb{O}_J, \tau_\sigma[G]] \models 1_{\omega \mathbb{O}_J / G_{\tau_\sigma[G]}^1} \Vdash_{\omega \mathbb{O}_J / G_{\tau_\sigma[G]}^1} \\ L(J, \dot{\mathbb{R}}_{\text{sym}}) &\models (\exists y)(\varphi(y) = \beta \wedge L[J'', \tau_\sigma[G], y] \models \phi''(J'', \tau_\sigma[G], y)). \end{aligned}$$

By the forcing theorem and the fact that  $p \in G$ , there is a  $q \leq_{\text{Coll}(\omega, \text{sup}(\sigma))}$  so that

$$\begin{aligned} L[S, \sigma] &\models q \Vdash_{\text{Coll}(\omega, \text{sup}(\sigma))} L[J, \omega \mathbb{O}_J, \tau_\sigma] \models 1_{\omega \mathbb{O}_J / G_{\tau_\sigma}^1} \Vdash_{\omega \mathbb{O}_J / G_{\tau_\sigma}^1} \\ L(J, \dot{\mathbb{R}}_{\text{sym}}) &\models (\exists y)(\varphi(y) = \beta \wedge L[J'', \tau_\sigma, y] \models \phi''(J'', \tau_\sigma, y)). \end{aligned}$$

Since  $p \in \text{Coll}(\omega, \text{sup}(\sigma))$  was arbitrary, one has that  $L[S, \sigma]$  believes that  $1_{\text{Coll}(\omega, \text{sup}(\sigma))}$  forces the statement in the forcing language above. Thus  $L[S, \sigma] \models \vartheta(S, \sigma, \beta)$ .

( $\Leftarrow$ ) Since the powerset of  $\text{Coll}(\omega, \text{sup}(\sigma))$  computed in  $L[S, \sigma] \models \text{ZFC}$  is countable in the real world satisfying AD, there exists a  $G$  which is  $\text{Coll}(\omega, \text{sup}(\sigma))$ -generic over  $L[S, \sigma]$ . Note that by the explicit definition of the coding used in BS, one has  $\tau_\sigma[G] \in \text{BS}$  and  $\sigma_{\tau_\sigma[G]} = \sigma$  by absoluteness. Since  $L[S, \sigma] \models \vartheta(S, \sigma, \beta)$ , one has

$$\begin{aligned} L[S, \sigma][G] &\models L[J, \omega \mathbb{O}_J, \tau_\sigma[G]] \models 1_{\omega \mathbb{O}_J / G_{\tau_\sigma[G]}^1} \Vdash_{\omega \mathbb{O}_J / G_{\tau_\sigma[G]}^1} \\ L(J, \dot{\mathbb{R}}_{\text{sym}}) &\models (\exists y)(\varphi(y) = \beta \wedge L[J'', \tau_\sigma[G], y] \models \phi''(J'', \tau_\sigma[G], y)). \end{aligned}$$

Since  $G$  is a set in the real world  $V$ ,

$$\begin{aligned} V &\models L[J, \omega \mathbb{O}_J, \tau_\sigma[G]] \models 1_{\omega \mathbb{O}_J / G_{\tau_\sigma[G]}^1} \Vdash_{\omega \mathbb{O}_J / G_{\tau_\sigma[G]}^1} \\ L(J, \dot{\mathbb{R}}_{\text{sym}}) &\models (\exists y)(\varphi(y) = \beta \wedge L[J'', \tau_\sigma[G], y] \models \phi''(J'', \tau_\sigma[G], y)). \end{aligned}$$

Fact 2.10 implies

$$L(J, \mathbb{R}) \models (\exists y)(\varphi(y) = \beta \wedge L[J'', \tau_\sigma[G], y] \models \phi''(J'', \tau_\sigma[G], y))$$

Since  $(J'', \phi'')$  is the  $\infty$ -Borel code for  $\tilde{R}$ , one has that  $\tilde{R}(\tau_\sigma[G], y)$ . By definition of  $\tilde{R}$  and the fact that  $\tau_\sigma[G] \in \text{BS}$  is a code for  $\sigma$ ,  $R(\sigma, \beta)$  holds.

This concludes the proof of the claim and hence the first statement in the fact.

Now suppose  $\Phi : {}^{<\omega_1}\omega_1 \rightarrow \omega_\kappa$  is a function. Let  $R(\sigma, n, \beta)$  assert that  $\Phi(\alpha)(n) = \beta$ . By the first part, there is a set of ordinals  $S \subseteq \text{ON}$  and a formula  $\vartheta$  so that

$$R(\sigma, n, \beta) \Leftrightarrow L[S, \sigma] \models \vartheta(S, \sigma, n, \beta).$$

Then by comprehension in  $L[S, \sigma]$ , one has that  $\Phi(\sigma) \in L[S, \sigma]$ .  $\square$

A consequence of Fact 5.5 is that (under  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and all sets of reals have  $\infty$ -Borel codes) every subset  $A$  of  $[\omega_1]^{<\omega_1}$  has an  $\infty$ -Borel code  $(S, \varphi)$  in the sense that  $\sigma \in A$  if and only if  $L[S, \sigma] \models \varphi(S, \sigma)$ .

A key idea of the previous argument was to use  $\infty$ -Borel codes to go into a suitable  $L(J, \mathbb{R}) \models \text{ZF} + \text{AD} + \text{DC}$  and then by considering the forcing language  $\text{Coll}(\omega, \text{sup}(\sigma))$ , one can speak of a canonical real coding  $\sigma$ . For  $f \in \omega_\kappa$ , there are various ways to code  $f$  by a real; however, it is unclear where to find or how to uniformly speak of a real coding  $f$  within the ZFC model  $\text{HOD}_J^{(J, \mathbb{R})} = L[J, \omega \mathbb{O}_J]$ .

One can only prove the following weaker result which is quite similar to Fact 4.6:

**Fact 5.6.** *Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and all sets of reals have an  $\infty$ -Borel code. Let  $\Phi : \omega_\kappa \rightarrow {}^{<\omega_1}\omega_1$  be a partial function, where  $\kappa < \Theta$ . Then there is a set of ordinals  $S \subseteq \text{ON}$  so that for all  $z \in \mathbb{R}$ , one has that for all  $f \in \text{dom}(\Phi) \cap L[S, x]$ ,  $\Phi(f) \in L[S, z]$ .*

*Proof.* Since  $\kappa < \Theta$ , let  $\preceq$  be a prewellordering of  $\mathbb{R}$  of length  $\kappa$ . Let  $\varphi$  be its associated ranking function. Let  $(J', \phi')$  denote the  $\infty$ -Borel code for  $\preceq$ .

For each  $x \in \mathbb{R}$ , let  $x_n$  denote the  $n^{\text{th}}$  section of  $x$ . Define  $f_x \in \omega_\kappa$  by  $f_x(n) = \varphi(x_n)$ . In this way, every  $f \in \omega_\kappa$  has an  $x \in \mathbb{R}$  so that  $f_x = f$ .

Define a relation  $R \subseteq \mathbb{R} \times \mathbb{R} \times \mathbb{R}$  by  $R(x, v, w)$  if and only if

$$f_x \in \text{dom}(\Phi) \wedge v, w \in \text{WO} \wedge v \in \text{dom}(\Phi(f_x)) \wedge \Phi(f_x)(\text{ot}(v)) = \text{ot}(w).$$

Let  $(J'', \phi'')$  be an  $\infty$ -Borel code for  $R$ .

Let  $J$  be a set of ordinals that codes  $J'$  and  $J''$  in some fixed constructible manner.

Now work in  $L(J, \mathbb{R}) \models \text{ZF} + \text{AD} + \text{DC}$ . In  $L(J, \mathbb{R})$ ,  $R$  is  $\text{OD}_J$ . Let  $\varsigma$  be a formula so that  $L(J, \mathbb{R}) \models R(x, v, w) \Leftrightarrow L(J, \mathbb{R}) \models \varsigma(J, x, v, w)$ . In  $L(J, \mathbb{R})$ , let  ${}^\omega\mathbb{O}_J$  denote finite support direct limit of  $J$ -Vopěnka forcing.

Define  $\vartheta(z, J, f, \alpha, \beta)$  by

$$1_{{}^\omega\mathbb{O}_J/G_z^1} \Vdash_{{}^\omega\mathbb{O}_J/G_z^1} L(J, \dot{\mathbb{R}}_{\text{sym}}) \models (\exists x, v, w)((\forall n)(\varphi(x_n) = f(n) \wedge \alpha = \text{ot}(v) \wedge \beta = \text{ot}(w) \wedge \varsigma(J, x, v, w))).$$

Then for any  $z \in \mathbb{R}$ , by Fact 2.10, one can conclude that for all  $f \in L[J_{{}^\omega\mathbb{O}_J}, z]$  that  $L(J, \mathbb{R}) \models \Phi(f)(\alpha) = \beta$  if and only if  $L[J_{{}^\omega\mathbb{O}_J}, z] \models \vartheta(z, J, f, \alpha, \beta)$ . By comprehension, one has that  $\Phi(f) \in L[J_{{}^\omega\mathbb{O}_J}, z]$ .  $\square$

**Theorem 5.7.** *Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and all sets of reals have  $\infty$ -Borel codes. Then there is no injection of  $S_1$  into  ${}^\omega\text{ON}$ , the class of  $\omega$ -sequences of ordinals.*

*Proof.* Suppose  $\Phi : S_1 \rightarrow {}^\omega\text{ON}$  is an injection. Since  $\mathbb{R}$  surjects onto  ${}^{<\omega_1}\omega_1$  (for example, BS and the coding from Definition 5.4), one has that  $\mathbb{R}$  surjects onto  $S_1 \subseteq {}^{<\omega_1}\omega_1$ . Thus one can show that  $A = \bigcup \{\text{rang}(\Phi(\sigma)) : \sigma \in S_1\}$  is a collection of ordinals which is a surjective image of  $\mathbb{R}$ . Thus the Mostowski collapse of  $A$  is some ordinal  $\kappa < \Theta$ . Hence from  $\Phi$ , one can derive an injection  $\Psi : S_1 \rightarrow {}^\omega\kappa$ . Since  $\Psi$  is an injection,  $\Psi^{-1} : {}^\omega\kappa \rightarrow S_1$  is a partial function.

Let  $S \subseteq \text{ON}$  be a set of ordinals satisfying Fact 5.5 for the function  $\Psi$  and Fact 5.6 for the partial function  $\Psi^{-1}$ .

Since  $\omega_1$  is measurable in  $L[S] \models \text{ZFC}$ , let  $\zeta < \omega_1$  be an inaccessible cardinal of  $L[S]$ . Let  $\text{Coll}(\omega, < \zeta)$  be the Lévy collapse of  $\zeta$ . Since  $\zeta < \omega_1$  and  $L[S] \models \text{ZFC}$ , the powerset of  $\text{Coll}(\omega, < \zeta)$  is countable in the real world satisfying AD. Thus in the real world, there is a  $G \subseteq \text{Coll}(\omega, < \zeta)$  which is  $\text{Coll}(\omega, < \zeta)$ -generic over  $L[S]$ .

From  $G$  and its generic surjection of  $\zeta$  onto  $\zeta$ , one can find a cofinal function  $g : \zeta \rightarrow \zeta$  so that  $L[g] = L[G]$ . Since  $L[g] = L[G]$ ,  $\omega_1^{L[g]} = \omega_1^{L[G]} = \zeta = \sup(g)$ . Thus  $g \in S_1$ .

By the property of  $S$  from Fact 5.5,  $\Psi(g) \in L[S, g]$ . Since  $\Psi(g) \in {}^\omega\kappa$  and the main property of the Lévy collapse  $\text{Coll}(\omega, < \zeta)$ , there exists some  $\xi < \zeta$  so that  $\Psi(g) \in L[S][G \restriction \xi]$ . By using the  $\text{Coll}(\omega, \xi)$ -generic obtained from  $G$ , one sees that there is a real  $z \in L[S][G]$  so that  $L[S][G \restriction \xi] \subseteq L[S][z]$ . Thus  $\Psi(g) \in L[S, z]$ . By the property of  $S$  from Fact 5.6 for the partial function  $\Psi^{-1}$ , one has that  $g = \Psi^{-1}(\Psi(g)) \in L[S, z]$ . Thus  $L[S][G] = L[S][g] \subseteq L[S][z] \subseteq L[S][G \restriction \xi + 1]$ . It is impossible that  $L[S][G] = L[S][G \restriction \xi + 1]$  for any  $\xi < \zeta$ .

It has been shown that no such injection can exist.  $\square$

**Theorem 5.8.** *Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and all sets of reals have  $\infty$ -Borel codes. Then  $|\mathbb{R}| < |S_1|$  and  $|\omega_1|^\omega < |\omega_1|^{<\omega_1}$ .*

*Proof.* Since  $|\mathbb{R}| = |\omega^\omega|$ , Theorem 5.7 implies that there is no injection of  $S_1$  into  $\mathbb{R}$  or  $|\omega_1|^\omega$ . Thus  $|\mathbb{R}| < |S_1|$ . Since  $S_1 \subseteq |\omega_1|^{<\omega_1}$  and  $S_1$  does not inject into  $|\omega_1|^\omega$ , one has that  $|\omega_1|^\omega < |\omega_1|^{<\omega_1}$ .  $\square$

## 6. COUNTABLE POWERSSET OPERATION

**Definition 6.1.** Let  $X$  be a set. Let  $\mathcal{P}_{\omega_1}(X) = \{A \subseteq X : |A| \leq \aleph_0\}$  be the collection of countable subsets of  $X$ .

**Fact 6.2.** (Woodin's perfect set dichotomy) *Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and all sets of reals have an  $\infty$ -Borel code. Let  $E$  be an equivalence relation on  $\mathbb{R}$ . Then exactly one of the following holds:*

- (1)  $\mathbb{R}/E$  is wellorderable.
- (2)  $\mathbb{R}$  injects into  $\mathbb{R}/E$ .

*Morover, if  $\mathbb{R}/E$  is wellorderable and if  $(S, \varphi)$  is an  $\infty$ -Borel code for  $E$ , then there is a uniform procedure that takes  $(S, \varphi)$  to an  $\text{OD}_S^{L(S, \mathbb{R})}$  wellordering of  $\mathbb{R}/E$ .*

*Proof.* This result is attributed to Woodin by Hjorth [9]. A proof of these results can be found [2] Section 8 and [4] which give particular attention to the uniformity aspects of (1) and (2).  $\square$

**Definition 6.3.** Let  $X$  be a set. Let  $\mathcal{P}_{\text{WO}}(X) = \{A \subseteq X : A \text{ is wellorderable}\}$ . Note that  $\mathcal{P}_{\omega_1}(X) \subseteq \mathcal{P}_{\text{WO}}(X)$ .



**Fact 6.4.** Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and all sets of reals have  $\infty$ -Borel codes. Let  $\kappa < \Theta$  and  $E$  be an equivalence relation on  $\mathbb{R}$ . Suppose  $\Phi : \kappa \rightarrow \mathcal{P}_{\text{WO}}(\mathbb{R}/E)$  is a function. Then there is a sequence  $\langle <_{\alpha} : \alpha < \kappa \rangle$  so that  $<_{\alpha}$  is a wellordering of  $\Phi(\alpha)$  for each  $\alpha < \kappa$ .

*Proof.* Let  $(J_0, \phi_0)$  be an  $\infty$ -Borel code for  $E$ . Let  $\preceq$  be a prewellordering on  $\mathbb{R}$  of length  $\kappa$ . Let  $\varsigma : \mathbb{R} \rightarrow \kappa$  be the ranking function of  $\preceq$ . Let  $(J_1, \phi_1)$  be an  $\infty$ -Borel code for  $\preceq$ . Define  $R \subseteq \mathbb{R} \times \mathbb{R}$  by  $R(x, y) \Leftrightarrow [y]_E \in \Phi(\varsigma(x))$ . Let  $(J_2, \phi_2)$  be an  $\infty$ -Borel code for  $R$ . Let  $J$  be a set of ordinals that codes  $J_0$ ,  $J_1$ , and  $J_2$ .

Now work in  $L(J, \mathbb{R}) \models \text{ZF} + \text{AD} + \text{DC}$ . Note that from  $J$ , one can recover in  $L(J, \mathbb{R})$ , the sets  $E$ ,  $\preceq$ ,  $R$ , and  $\Phi$ . In fact, all these sets are  $\text{OD}_J^{L(J, \mathbb{R})}$ . Thus for each  $\alpha < \kappa$ ,  $\Phi(\alpha)$  is  $\text{OD}_J^{L(J, \mathbb{R})}$  with a witnessing definition obtained uniformly in  $\alpha$ . Consider  $\bigcup \Phi(\alpha) \subseteq \mathbb{R}$ . Let  $E_{\alpha} = E \upharpoonright \bigcup \Phi(\alpha)$ .  $E_{\alpha}$  is  $\text{OD}_J^{L(J, \mathbb{R})}$  uniformly from the definitions witnessing  $E$  and  $\Phi(\alpha)$  is  $\text{OD}_J^{L(J, \mathbb{R})}$ . The  $\text{OD}_J^{L(J, \mathbb{R})}$  set  $E_{\alpha}$  has an  $\text{OD}_J^{L(J, \mathbb{R})}$   $\infty$ -Borel code obtained uniformly from a definition witnessing that  $E_{\alpha}$  is  $\text{OD}_J^{L(J, \mathbb{R})}$ . (This follows from an application of Fact 2.10.) If the  $\infty$ -Borel codes for each equivalence relation in  $\langle E_{\alpha} : \alpha < \kappa \rangle$  can be obtained uniformly, then Fact 6.2 states that one can uniformly produce a sequence of wellorderings  $\langle <_{\alpha} : \alpha < \kappa \rangle$  so that each  $<_{\alpha}$  is a wellordering of  $(\bigcup \Phi(\alpha))/E_{\alpha}$  which is  $\Phi(\alpha)$ .  $\square$

The following is the “Boldface GCH”. It was established first in  $L(\mathbb{R})$  by Steel. Woodin extended this result to  $\text{AD}^+$ .

**Fact 6.5.** (Woodin) Assume  $\text{ZF} + \text{AD}^+$ . Let  $\kappa < \Theta$  be a cardinal. If  $X \subseteq \mathcal{P}(\kappa)$  is wellorderable, then  $|X| \leq \kappa$ .

**Theorem 6.6.** Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and all sets of reals have  $\infty$ -Borel codes. Suppose  $\kappa < \Theta$  is a cardinal with the property that for all  $\delta < \kappa$ , there is no  $\kappa$  length sequence of distinct subsets of  $\mathcal{P}(\delta)$ . Let  $X$  be a set so that there is a surjection  $\pi : \mathbb{R} \rightarrow X$ . Then  $\kappa \leq |\mathcal{P}_{\text{WO}}(X)|$  implies that  $\kappa \leq |X|$ . In particular,  $\kappa < |\mathcal{P}_{\omega_1}(X)|$  implies  $\kappa \leq |X|$ .

Assuming  $\text{ZF} + \text{AD}^+$ , for all cardinals  $\kappa < \Theta$  and all sets  $X$  which are surjective images of  $\mathbb{R}$ ,  $\kappa \leq |\mathcal{P}_{\text{WO}}(X)|$  implies  $\kappa \leq |X|$ . In particular,  $\kappa < |\mathcal{P}_{\omega_1}(X)|$  implies  $\kappa \leq |X|$ .

*Proof.* Define an equivalence relation on  $\mathbb{R}$  be  $x E y$  if and only if  $\pi(x) = \pi(y)$ . Then  $X$  is in bijection with  $\mathbb{R}/E$ . Thus one will work with  $\mathbb{R}/E$  rather than directly with  $X$ . If  $\kappa \leq |\mathcal{P}_{\text{WO}}(X)|$ , then one has an injection  $\Phi : \kappa \rightarrow \mathcal{P}_{\text{WO}}(\mathbb{R}/E)$ . By Fact 6.4, let  $\langle <_{\alpha} : \alpha < \omega_1 \rangle$  be a sequence so for each  $\alpha < \kappa$ ,  $<_{\alpha}$  is a wellordering of  $\Phi(\alpha)$ .

By using the usual wellordering on  $\kappa$  and the sequence of wellorderings  $\langle <_{\alpha} : \alpha < \kappa \rangle$ , one can define a wellordering of  $\bigcup \Phi[\kappa] = \bigcup \{\Phi(\alpha) : \alpha < \kappa\}$ . Thus  $|\bigcup \Phi[\kappa]|$  is a wellordered cardinal.

The claim is that  $|\bigcup \Phi[\kappa]| \geq \kappa$ . To see this: Suppose  $|\bigcup \Phi[\kappa]| = \delta$  for some  $\delta < \kappa$ . Let  $\Psi : \bigcup \Phi[\kappa] \rightarrow \delta$ . Then  $\Gamma(\alpha) = \Psi[\Phi(\alpha)] = \{\Psi(x) : x \in \Phi(\alpha)\}$  is an injection of  $\kappa$  into  $\mathcal{P}(\delta)$ . However, by assumption, there are no  $\kappa$ -length sequences of distinct subsets of  $\mathcal{P}(\delta)$ . The claim has been shown.

The claim immediately implies that  $\kappa \leq |\mathbb{R}/E| = |X|$ .

In the setting of  $\text{ZF} + \text{AD}^+$ , Fact 6.5 implies that for every cardinal  $\delta < \kappa$ , every wellorderable set of subsets of  $\delta$  has cardinality  $\delta$ . Thus  $\kappa$  can not inject into  $\mathcal{P}(\delta)$ . The second result now follows from the first.  $\square$

**Corollary 6.7.** Assume  $\text{ZF} + \text{DC}_{\mathbb{R}} + \text{AD}$  and all sets of reals have  $\infty$ -Borel codes. Let  $X$  be a set which is a surjective image of  $\mathbb{R}$ . Then  $\omega_1 \leq |\mathcal{P}_{\text{WO}}(X)|$  implies  $\omega_1 \leq |X|$ . In particular,  $\omega_1 \leq |\mathcal{P}_{\omega_1}(X)|$  implies  $\omega_1 \leq |X|$ .

To analyze the cardinal structure of sets  $X$  so that  $||[\omega_1]^{\omega_1}| \leq |\mathcal{P}_{\omega_1}(X)|$ , one needs an almost everywhere (with respect to the strong partition measure) continuity result for functions  $\Phi : [\omega_1]^{\omega_1} \rightarrow \omega_1$ . The result holds in  $\text{ZF} + \text{AD}$  and its proof is quite different from the method used in this article.

**Fact 6.8.** ([3]) Assume  $\text{ZF} + \text{AD}$ . For every function  $\Phi : [\omega_1]^{\omega_1} \rightarrow \omega_1$ , there is a club  $C \subseteq \omega_1$  so that  $\Phi \upharpoonright [C]_*^{\omega_1} \rightarrow \omega_1$  is continuous.

If  $C \subseteq \omega_1$  is club, then  $[C]_*^{\omega_1}$  is the collection of  $f \in [C]^{\omega_1}$  which are of the correct type, i.e. has uniform cofinality  $\omega$  and discontinuous everywhere. One can check that  $||[\omega_1]^{\omega_1}| = |[C]_*^{\omega_1}|$ .  $\Phi \upharpoonright [C]_*^{\omega_1}$  being continuous means that for all  $f \in [C]_*^{\omega_1}$ , there is an  $\alpha < \omega_1$  so that for all  $g \in [C]_*^{\omega_1}$ , if  $f \upharpoonright \alpha = g \upharpoonright \alpha$ , then  $\Phi(f) = \Phi(g)$ .

Zapletal had also asked the authors that if one partitions  $[\omega_1]^{\omega_1}$  into  $\omega_1$  many sets, then must one of the pieces have cardinality  $|[\omega_1]^{\omega_1}|$ , under determinacy assumptions. The almost everywhere continuity property gives a positive answer.

**Fact 6.9.** ([3]) *Assume  $\text{ZF} + \text{AD}$ . Let  $\langle X_\alpha : \alpha < \omega_1 \rangle$  be such that each  $X_\alpha \subseteq [\omega_1]^{\omega_1}$  and  $\bigcup_{\alpha < \omega_1} X_\alpha = [\omega_1]^{\omega_1}$ , then there exists some  $\alpha < \omega_1$  so that  $|X_\alpha| = |[\omega_1]^{\omega_1}|$ .*

**Theorem 6.10.** *Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and all sets of reals have an  $\infty$ -Borel code. Let  $X$  be a set which is a surjective image of  $\mathbb{R}$ . If  $|[\omega_1]^{\omega_1}| \leq |\mathcal{P}_{\omega_1}(X)|$ , then  $|\mathbb{R} \sqcup \omega_1| \leq |X|$ .*

*Proof.* Let  $\pi : \mathbb{R} \rightarrow X$  be a surjection. Again define an equivalence relation on  $\mathbb{R}$  by  $x E y$  if and only if  $\pi(x) = \pi(y)$ . Since  $|X| = |\mathbb{R}/E|$ , one will work with the quotient of  $E$ . Now suppose  $\Phi : [\omega_1]^{\omega_1} \rightarrow \mathcal{P}_{\omega_1}(\mathbb{R}/E)$  is an injection.

Note that  $|[\omega_1]^{\omega_1}| \leq |\mathcal{P}_{\omega_1}(\mathbb{R}/E)|$  implies, in particular, that  $\omega_1 \leq |\mathbb{R}/E|$  by Corollary 6.7. Suppose  $\neg(|\mathbb{R}| \leq |\mathbb{R}/E|)$ . Then the Woodin perfect set dichotomy (Fact 6.2) implies that  $\mathbb{R}/E$  is wellorderable and hence there is some cardinal  $\kappa$  so that  $|\mathbb{R}/E| = \kappa$ . Let  $\Lambda : \mathbb{R}/E \rightarrow \kappa$  be a bijection.

Let  $\Gamma : [\omega_1]^{\omega_1} \rightarrow [\kappa]^{<\omega_1}$  be defined by  $\Gamma(f) = \Lambda[\Phi(f)]$ .  $\Phi(f) \in \mathcal{P}_{\omega_1}(\mathbb{R}/E)$  so  $\Phi(f)$  is a countable subset of  $\mathbb{R}/E$ . Thus  $\Lambda[\Phi(f)] = \{\Lambda(x) : x \in \Phi(f)\}$  is a countable subset of  $\kappa$ .

Let  $\text{ot}(\Lambda[\Phi(f)])$  be the ordertype of this countable subset of  $\kappa$  in the usual ordering on  $\kappa$ , which of course is a countable ordinal. Note that  $\text{ot} \circ \Gamma : [\omega_1]^{\omega_1} \rightarrow \omega_1$ .

By letting  $X_\alpha = (\text{ot} \circ \Gamma)^{-1}(\{\alpha\})$ , one has that  $[\omega_1]^{\omega_1} = \bigcup_{\alpha < \omega_1} X_\alpha$ . By Fact 6.9, there is some  $\alpha < \omega_1$  so that  $|X_\alpha| = |[\omega_1]^{\omega_1}|$ . Let  $\Xi : [\omega_1]^{\omega_1} \rightarrow X_\alpha$  be a bijection.

Since  $\alpha < \omega_1$ , let  $B : \omega \rightarrow \alpha$  be a bijection. For each  $f \in [\kappa]^\omega$ , define  $\Sigma(f) \in [\kappa]^\omega$  by recursion as follow:  $\Sigma(f)(0) = f(B(0))$  and  $\Sigma(f)(n+1) = \Sigma(f)(n) + f(B(n+1))$ . The map  $\Sigma : [\kappa]^\omega \rightarrow [\kappa]^\omega$  is an injection. Then  $\Sigma \circ \Gamma \circ \Xi : [\omega_1]^{\omega_1} \rightarrow [\kappa]^\omega$  is an injection. Since  $|S_1| \leq |[\omega_1]^{\omega_1}|$ , one could derive an injection of  $S_1$  into  $[\kappa]^\omega$ . This violates Theorem 5.7.

It has been shown that  $|\mathbb{R}| \leq |\mathbb{R}/E| = |X|$ . Thus  $|\mathbb{R} \sqcup \omega_1| \leq |\mathbb{R}/E| = |X|$ .  $\square$

## 7. THE CARDINALS BELOW $\mathbb{R} \times \omega_1$

**Definition 7.1.** Let  $\Phi : \mathbb{R} \rightarrow \omega_1$ . Define  $\bigsqcup \Phi = \{(r, \alpha) : \alpha < \Phi(r)\}$ , which is a  $\mathbb{R}$ -index disjoint union of countable ordinals given by the function  $\Phi$ .

**Fact 7.2.** *Assume  $\text{AD}$ . For every  $\Phi : \mathbb{R} \rightarrow \omega_1$ ,  $\omega_1$  does not inject into  $\bigsqcup \Phi$ . If  $\{r : \Phi(r) > 0\}$  is uncountable, then  $|\mathbb{R}| \leq |\bigsqcup \Phi|$ .*

*Proof.* Let  $\pi_1 : \mathbb{R} \times \omega_1 \rightarrow \mathbb{R}$  denote the projection onto the first coordinate. Suppose  $\Psi : \omega_1 \rightarrow \bigsqcup \Phi$  is an injection. Since for all  $r \in \mathbb{R}$ ,  $\Phi(r) < \omega_1$ , the set of  $\alpha$  so that  $\pi_1(\Psi(\alpha)) = r$  is countable. Thus  $X = \{r : (\exists \alpha < \omega_1)(\pi_1(\Psi(\alpha)) = r)\}$  is an uncountable set of reals.  $X$  is wellorderable by setting  $x \sqsubset y$  if and only if the least  $\alpha$  so that  $\pi_1(\Psi(\alpha)) = x$  is less than the least  $\alpha$  so that  $\pi_1(\Psi(\alpha)) = y$ . This is a contradiction since there are no uncountable wellorderable sequence of reals.

Suppose  $Y = \{r : \Phi(r) > 0\}$  is uncountable. By the perfect set property, let  $\Lambda' : \mathbb{R} \rightarrow Y$  be an injection. Then  $\Lambda : \mathbb{R} \rightarrow \bigsqcup \Phi$  defined by  $\Lambda(r) = (\Lambda'(r), 0)$  is an injection.  $\square$

**Fact 7.3.** *For all  $X \subseteq \mathbb{R} \times \omega_1$  such that  $\neg(\omega_1 \leq |X|)$ , there is a  $\Phi : \mathbb{R} \rightarrow \omega_1$  so that  $X \approx \bigsqcup \Phi$ .*

*Proof.* For each  $r \in \mathbb{R}$ , let  $X_r = \{\alpha : (r, \alpha) \in X\}$ . Since  $\omega_1$  does not inject into  $X$ ,  $X_r$  is countable. Let  $\delta_r$  be the ordertype of  $X_r$ . Let  $\varpi_r : X_r \rightarrow \delta_r$  be the associated collapse map. Let  $\Phi : \mathbb{R} \rightarrow \omega_1$  be defined  $\Phi(r) = \delta_r$ . Define  $\Lambda : X \rightarrow \bigsqcup \Phi$  by  $\Lambda(x) = (\pi_1(x), \varpi_{\pi_1(x)}(\pi_2(x)))$ , where  $\pi_1 : \mathbb{R} \times \omega_1 \rightarrow \mathbb{R}$  and  $\pi_2 : \mathbb{R} \times \omega_1 \rightarrow \omega_1$  are the projections onto the first and second coordinate, respectively.  $\Lambda$  is a bijection.  $\square$

**Fact 7.4.** *Assume  $\text{AD}$ . For every  $X \subseteq \mathbb{R} \times \omega_1$ , one of the following holds:*

- (1)  $|X| = |\mathbb{R} \times \omega_1|$ .
- (2)  $|X| = \aleph_1$ .
- (3)  $X$  is an uncountable set such that  $\neg(\omega_1 \leq |X|)$ .
- (4) There is an uncountable  $Y$  so that  $\neg(\omega_1 \leq |Y|)$  and  $|X| = |Y \sqcup \omega_1|$ .
- (5)  $|X| \leq \aleph_0$ .

*Proof.* Let  $X \subseteq \mathbb{R} \times \omega_1$ . For each  $r \in \mathbb{R}$ , let  $X_r = \{\alpha : (r, \alpha) \in X\}$ . Let  $\delta_r = \text{ot}(X_r)$ . For each  $r \in \mathbb{R}$ , let  $\varpi_r : X_r \rightarrow \delta_r$  denote the collapse map.

Let  $A = \{r : |X_r| = \aleph_1\}$ .

Suppose  $A$  is uncountable. Let  $\Psi : \mathbb{R} \rightarrow A$  be a bijection which exists by the perfect set property. Define  $\Lambda : \mathbb{R} \times \omega_1 \rightarrow X$  by  $\Lambda(r, \alpha) = (\Psi(r), \varpi_{\Psi(r)}^{-1}(\alpha))$ .  $\Lambda$  is a bijection. Hence  $|X| = |\mathbb{R} \times \omega_1|$ . This gives possibility (1).

Suppose  $A$  is countable. Then  $\mathbb{R} \setminus A$  is uncountable. Let  $\Phi : \mathbb{R} \rightarrow \omega_1$  be defined by

$$\Phi(r) = \begin{cases} \delta_r & r \notin A \\ 0 & \text{otherwise} \end{cases}$$

Let  $\Lambda : \bigsqcup \Phi \rightarrow X$  be defined by  $\Lambda(r, \alpha) = (r, \varpi_r^{-1}(\alpha))$ .  $\Lambda$  is an injection. In fact, it is a bijection onto  $X \cap (\mathbb{R} \setminus A \times \omega_1)$ . Thus  $X \cap (\mathbb{R} \setminus A \times \omega_1)$  does not contain a copy of  $\omega_1$  by Fact 7.2. If  $B = \{r \in \mathbb{R} \setminus A : \Phi(r) > 0\}$  is uncountable, then  $X \cap (\mathbb{R} \setminus A \times \omega_1)$  is an uncountable set without a copy of  $\omega_1$ . If  $B$  is countable, then since a countable union of countable ordinals is countable,  $X \cap (\mathbb{R} \setminus A \times \omega_1)$  is a countable set.

Suppose  $A$  is countable and nonempty. One can show that a countable union of sets in bijection with  $\omega_1$  is in bijection with  $\omega_1$ . Thus  $X \cap (A \times \omega_1) \approx \omega_1$ .

Assume  $A$  is countable. Note that  $X = X \cap (A \times \omega_1) \sqcup X \cap (\mathbb{R} \setminus A \times \omega_1)$ . If  $A$  is empty and  $B$  is countable, then  $|X| \leq \aleph_0$  which gives case (5). If  $A$  is empty and  $B$  is uncountable, then  $X$  is an uncountable set without a copy of  $\omega_1$  which gives case (3). If  $A$  is nonempty and  $B$  is countable, then  $|X| = \aleph_1$  which gives case (2). If  $A$  is nonempty and  $B$  is uncountable, then  $X$  is a union of two sets: one set which is in bijection with  $\omega_1$  and another set which is an uncountable set without a copy of  $\omega_1$ , which gives case (4).  $\square$

**Fact 7.5.** Assume  $\text{AD}_{\mathbb{R}}$ . Every  $X \subseteq \mathbb{R} \times \omega_1$  such that  $\neg(\omega_1 \leq |X|)$  injects into  $\mathbb{R}$ .

*Proof.* Let  $\text{WO}$  be the set of reals coding wellorderings with underlying domain  $\omega$ .

Let  $X_r = \{\alpha : (r, \alpha) \in X\}$ . Let  $\delta_r = \text{ot}(X_r)$ . Let  $\varpi_r : X_r \rightarrow \delta_r$  be the collapse map of  $X_r$ .

Define  $R \subseteq \mathbb{R} \times \mathbb{R}$  by  $R(x, w)$  if and only if  $w \in \text{WO}$  and  $\text{ot}(w) = \delta_x$ . By  $\text{AD}_{\mathbb{R}}$ , let  $\Sigma : \mathbb{R} \rightarrow \mathbb{R}$  be a uniformization for  $R$ . For each  $w \in \text{WO}$ , for each  $\alpha < \text{ot}(w)$ , let  $\alpha^w$  denote the element of  $\omega$  with rank  $\alpha$  according to  $w$ . (If  $w$  codes a finite ordinal, then let  $n^w = n$ .)

Define  $\Lambda : X \rightarrow \mathbb{R} \times \omega$  by  $\Lambda(x) = (\pi_1(x), (\varpi_{\pi_1(x)}(\pi_2(x))^{\Sigma(\pi_1(x))}))$ .  $\Lambda$  is an injection. Since  $|\mathbb{R} \times \omega| = |\mathbb{R}|$ , the proof is complete.  $\square$

**Corollary 7.6.** Assume  $\text{AD}_{\mathbb{R}}$ . The uncountable cardinals below  $|\mathbb{R} \times \omega_1|$  are  $|\mathbb{R}|$ ,  $\aleph_1$ ,  $|\mathbb{R} \sqcup \omega_1|$ , and  $|\mathbb{R} \times \omega_1|$ .

*Proof.* This follows from Fact 7.4 and Fact 7.5.

This is also a consequence of Woodin's dichotomy below  $|\omega_1|^\omega$  ([19] Theorem 18) which is proved under  $\text{ZF} + \text{DC} + \text{AD}_{\mathbb{R}}$ . However, the proof above under  $\text{AD}_{\mathbb{R}}$  uses an elementary uniformization argument while Woodin's stronger result uses very sophisticated  $\text{AD}^+$  techniques.  $\square$

One will need several facts about  $J$ -constructibility degrees and  $J$ -pointed perfect trees:

**Definition 7.7.** Let  $J$  be a set of ordinal. A perfect tree  $p \subseteq {}^{<\omega}2$  is  $J$ -pointed if and only if for all  $x \in [p]$ ,  $p \leq_J x$ .

**Definition 7.8.** Let  $p$  be a perfect tree on 2.  $s \in p$  is a split node of  $p$  if and only if  $s \hat{\ } 0, s \hat{\ } 1 \in p$ .

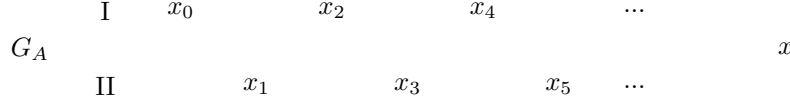
By recursion, define  $\Xi^p : {}^{<\omega}2 \rightarrow {}^{<\omega}2$  by:  $\Xi^p(\emptyset)$  be the least split node of  $p$ . If  $\Xi^p(s)$  has been defined, then let  $\Xi^p(s \hat{\ } i)$  be the least split node of  $p$  extending  $\Xi^p(s) \hat{\ } i$ .

Define  $\Upsilon^p : {}^\omega 2 \rightarrow [p]$  by letting  $\Upsilon(r) = \bigcup_{n \in \omega} \Xi^p(r \upharpoonright n)$ .  $\Upsilon^p$  is called the canonical homeomorphism between  ${}^\omega 2$  and  $[p]$ .

**Fact 7.9.** (Martin) Assume  $\text{AD}$ . For all  $A \subseteq \mathbb{R}$ ,  $A$  or  $\mathbb{R} \setminus A$  contains the body of a Turing-pointed tree. Hence for any set of ordinals  $J$ ,  $A$  or  $\mathbb{R} \setminus A$  contains the body of a  $J$ -pointed tree.

(Martin) The Martin Turing degree measure,  $\mu$ , and the  $J$ -degree measure,  $\mu_J$ , is a countable complete ultrafilter.

*Proof.* Let  $A \subseteq \mathbb{R}$ . Let  $G_A$  denote the game



where Player 1 wins if and only if  $x \in A$ .

Suppose Player 1 has a winning strategy  $\sigma$ . For any  $r \in \mathbb{R}$ , let  $\sigma(r)$  be Player 1's response using  $\sigma$  when Player 2 plays  $r$ . Similarly, if  $t \in {}^{<\omega}\omega$ , then  $\sigma(t)$  is Player 1's response using  $\sigma$  when Player 2 plays  $t$  in the finite partial run of  $G_A$ .

Thinking of  $\sigma$  as an element of  ${}^\omega 2$ , let  $\sigma_n$  denote the  $n^{\text{th}}$  bit of  $\sigma$ . Let  $Z = \{x \in {}^\omega 2 : (\forall n)(x(2n) = \sigma_n)\}$ . Note that  $Z$  is the body of a perfect tree.

Let  $p$  be the  $\subseteq$ -downward closure of  $\{\sigma(x \upharpoonright n) \oplus (x \upharpoonright n) : n \in \omega \wedge x \in Z\}$ . (Recall that if  $s, t \in {}^{<\omega}\omega$  of the same length  $k$ , then  $s \oplus t$  has length  $2k$  where  $(s \oplus t)(2j) = s(j)$  and  $(s \oplus t)(2j+1) = t(j)$  whenever  $j < k$ . If  $x, y \in {}^\omega \omega$ , one can similarly define  $x \oplus y$ .) Observe that  $p$  is a perfect tree and  $p$  is Turing reducible to  $\sigma$ . Suppose  $f \in [p]$ . There is an  $x \in Z$  so that  $f = \sigma(x) \oplus x$ . Since  $\sigma$  is a Player 1 winning strategy,  $f = \sigma(x) \oplus x \in A$ . This shows that  $[p] \subseteq A$ . Note that  $p$  is Turing reducible to  $f$  since  $\sigma_n = f(4n+1)$  for all  $n$ .  $p$  is a Turing pointed tree. Every Turing pointed tree is a  $J$ -pointed tree.

If Player 2 has a winning strategy  $\tau$ , then a similar argument shows that  ${}^\omega 2 \setminus A$  contains the body of a Turing pointed tree.

Suppose  $C \subseteq \mathcal{D}_J$ . Let  $\tilde{C} = \{x \in {}^\omega 2 : [x]_J \in C\}$ . By the above,  $\tilde{C}$  or  $\mathbb{R} \setminus \tilde{C}$  contains the body of a  $J$ -pointed tree  $p$ . Without loss of generality, suppose  $[p] \subseteq \tilde{C}$ . A  $J$ -pointed tree  $p$  has a path which is a representative of any  $J$ -degree above the  $J$ -degree of  $p$ . Thus  $C$  contains the  $J$ -cone above the  $J$ -degree of  $p$ . If  $\mathbb{R} \setminus \tilde{C}$  contains a  $J$ -pointed tree, then the same argument shows that  $\mathcal{D}_J \setminus C$  contains a  $J$ -cone. This shows that  $\mu_J$  is an ultrafilter.

Suppose  $\langle A_n : n \in \omega \rangle$  is a countable sequence from  $\mu_J$ . Using  $\text{AC}_\omega^\mathbb{R}$ , let  $\langle a_n : n \in \omega \rangle$  be a sequence of reals so that for all  $n \in \omega$ ,  $[a_n]_{\equiv_J}$  is the base of  $J$ -cone inside  $A_n$ . Let  $a = \bigoplus a_n$ , where  $\bigoplus$  is some recursion coding of sequences of reals by a real. Then  $[a]_{\equiv_J}$  is a base of a  $J$ -cone within  $\bigcap_{n \in \omega} A_n$ . This shows that  $\mu_J$  is countably complete.  $\square$

**Lemma 7.10.** *Let  $J$  be a set of ordinals. Suppose  $\Sigma : {}^\omega 2 \rightarrow {}^\omega 2$  is a Lipschitz continuous function. Assume that  $\Sigma$  is not constant on any basic neighborhood. Suppose  $p$  is a  $J$ -pointed tree such that  $\Sigma \leq_J p$ . There is a  $J$ -pointed subtree  $q \subseteq p$  so that for all  $r \in [q]$ ,  $\Sigma(r) \oplus q \equiv_J r$ .*

*Proof.* Since  $\Sigma$  is a Lipschitz continuous function,  $\Sigma$  can be considered a Player 2 strategy in a game where both players make moves from  $\{0, 1\}$ . In this way, one will consider  $\Sigma$  as a real. Since  $\Sigma$  is Lipschitz, for each  $u \in {}^{<\omega}2$ , let  $\Sigma(u) \in {}^{|\mathbf{u}|}2$  be the string  $t$  such that every  $x \in {}^\omega 2$  with  $u \subseteq x$ ,  $t \subseteq \Sigma(x)$ . If one considers  $\Sigma$  as a Player 2 winning strategy, then  $\Sigma(u)$  is just the response of Player 2 using  $\Sigma$  when Player 1 plays  $u$ .

Fix a  $J$ -pointed tree  $p$ . One will construct a sequence  $\langle u_s : s \in {}^{<\omega}2 \rangle$  in the tree  $p$  and a sequence of natural numbers  $\langle n_s : s \in {}^{<\omega}2 \rangle$  with the following properties:

- (1) For all  $s \in {}^{<\omega}2$ ,  $u_s \subseteq u_{s \smallfrown i}$  for both  $i \in 2$ .
- (2) For all  $s \in {}^{<\omega}2$ , if  $t \subsetneq s$ , then  $n_t < n_s$ .
- (3) For all  $s \in {}^{<\omega}2$  and  $i \in 2$ ,  $\Sigma(u_{s \smallfrown i})(n_s) = i$ .
- (4) Both  $\langle u_s : s \in {}^{<\omega}2 \rangle$  and  $\langle n_s : s \in {}^{<\omega}2 \rangle$  are Turing computable from  $p \oplus \Sigma$ . Since  $\Sigma \leq_J p$ , both sequences belong to  $L[J, p]$ .

First suppose that such sequences exist. Let  $q$  be the  $\subseteq$ -downward closure of  $\{u_s : s \in {}^{<\omega}2\}$ .  $q$  is a perfect subtree of  $p$ .  $q$  is Turing computable from  $p \oplus \Sigma$  and therefore,  $q \leq_J p$ . Suppose  $r \in [q]$ . Then  $r \in [p]$ . Since  $p$  is  $J$ -pointed,  $p \leq_J r$ . Thus  $q \leq_J r$ . This shows that  $q$  is also a  $J$ -pointed tree.

Let  $f$  be the left-most branch of  $q$ , i.e.  $\Upsilon^q(\bar{0})$  where  $\bar{0} \in {}^\omega 2$  is the constant 0 sequence. Note that  $f \leq_J q$ . Since  $f \in [p]$ ,  $p \leq_J f$ . Thus  $p \leq_J q$  and as a result  $p \equiv_J q$ . Hence  $\Sigma$ ,  $\langle u_s : s \in {}^{<\omega}2 \rangle$ , and  $\langle n_s : s \in {}^{<\omega}2 \rangle$  belong to  $L[J, q]$ .

Now suppose  $r \in [q]$ . As observed above,  $p \leq_J r$ . One seeks to define a sequence  $\langle v_n : n \in \omega \rangle \leq_J q \oplus \Sigma(r)$  in  ${}^{<\omega}2$  so that for all  $n \in \omega$ ,  $v_n \subseteq v_{n+1}$ ,  $|v_n| = n$ , and  $u_{v_n} \subseteq r$ .

Let  $v_0 = \emptyset$ . By construction of  $q$ ,  $u_{v_0} = u_\emptyset \subseteq r$ . Suppose  $v_n$  has been defined. Let  $v_{n+1} = v_n \hat{\ } (\Sigma(r)(n_{v_n}))$ . By the induction hypothesis,  $u_{v_n} \subseteq r$ . If  $r \in [q]$ , then  $u_{v_n \cdot 0}$  or  $u_{v_n \cdot 1}$  is an initial segment of  $r$ . By construction, one can determine which of the two is an initial segment of  $r$  by determining the value of  $\Sigma(r)(n_{v_n})$ . This shows that  $u_{v_{n+1}} \subseteq r$ . This completes the construction of the sequence  $\langle v_n : n \in \omega \rangle$  which is Turing computable from  $\langle u_s : s \in {}^{<\omega}2 \rangle$ ,  $\langle n_s : s \in {}^{<\omega}2 \rangle$ , and  $\Sigma(r)$ . Thus  $\langle v_n : n \in \omega \rangle \leq_J q \oplus \Sigma(r)$ .

Note that  $r = \bigcup_{n \in \omega} u_{v_n}$ . Thus  $r \in L[J, q, \Sigma(r)]$ , i.e.  $r \leq_J q \oplus \Sigma(r)$ .

Also since  $r \in [q]$  and  $q$  is  $J$ -pointed,  $\Sigma \leq_J q \leq_J r$ . Thus  $q \oplus \Sigma(r) \leq_J r$ . It has been shown that  $r \equiv_J q \oplus \Sigma(r)$ .

Therefore, it remains to show that one can construct the sequence  $\langle u_s : s \in {}^{<\omega}2 \rangle$  and  $\langle n_s : s \in {}^{<\omega}2 \rangle$ .

Let  $u_\emptyset = \emptyset$ . Since  $\Sigma$  is not constant, find the least triple  $(u_0, u_1, m)$  so that  $u_0 \in p$ ,  $u_1 \in p$ ,  $u_0(m) = 0$  and  $u_1(m) = 1$ . Let  $n_\emptyset = m$ ,  $u_{\langle 0 \rangle} = u_0$ , and  $u_{\langle 1 \rangle} = u_1$ .

Let  $s \in {}^{<\omega}2$  and  $|s| > 0$ . Suppose  $u_s$  and  $n_{s \upharpoonright |s|-1}$  have been defined. Since  $\Sigma$  is not constant on  $N_{u_s}$ , find the least triple  $(u_0, u_1, m)$  so that  $u_0 \in p$ ,  $u_1 \in p$ ,  $u_s \subseteq u_0$ ,  $u_s \subseteq u_1$ ,  $m > n_{s \upharpoonright |s|-1}$ ,  $|u_0| > m$ ,  $|u_1| > m$ ,  $\Sigma(u_0)(m) = 0$ , and  $\Sigma(u_1)(m) = 1$ . Let  $u_{s \cdot 0} = u_0$ ,  $u_{s \cdot 1} = u_1$ , and  $n_s = m$ .

This produces the sequences  $\langle u_s : s \in {}^{<\omega}2 \rangle$  and  $\langle n_s : s \in {}^{<\omega}2 \rangle$  with the desired property. The proof is complete.  $\square$

**Definition 7.11.** A function  $F : \mathbb{R} \rightarrow \omega_1$  is  $J$ -invariant if and only if for all  $x, y \in \mathbb{R}$ ,  $x \equiv_J y$  implies  $F(x) = F(y)$ .

If  $F : \mathbb{R} \rightarrow \omega_1$  is a  $J$ -invariant function, then let  $\tilde{F} : \mathcal{D}_J \rightarrow \omega_1$  be the induced function on  $\mathcal{D}_J$ . That is  $\tilde{F}(X) = F(x)$ , where  $x \in X$ .

A  $J$ -invariant function  $F$  is everywhere increasing if and only if for all  $x, y \in \mathbb{R}$ ,  $x \leq_J y$  implies  $F(x) \leq F(y)$ .

A  $J$ -invariant function  $F$  is increasing  $\mu_J$ -almost everywhere if and only if there is an  $a \in \mathbb{R}$  so that for all  $x, y \in \mathbb{R}$  with  $a \leq_J x$  and  $a \leq_J y$ ,  $x \leq_J y$  implies that  $F(x) \leq F(y)$ .

**Definition 7.12.** Let  $J$  be a set of ordinals. For each  $\mathfrak{F}, \mathfrak{G} \in \prod_{X \in \mathcal{D}_J} \text{ON}$ , define  $\mathfrak{F} =_{\mu_J} \mathfrak{G}$  if and only if  $\{X \in \mathcal{D}_J : \mathfrak{F}(X) = \mathfrak{G}(X)\} \in \mu_J$ . Let  $\mathfrak{F} <_{\mu_J} \mathfrak{G}$  if and only if  $\{X \in \mathcal{D}_J : \mathfrak{F}(X) < \mathfrak{G}(X)\} \in \mu_J$ .

The ultraproduct  $\prod_{X \in \mathcal{D}_J} \text{ON} / \mu_J$  consists of the equivalence class of  $\prod_{X \in \mathcal{D}_J} \text{ON}$  under  $=_{\mu_J}$ . For two elements  $\mathcal{F}, \mathcal{G} \in \prod_{X \in \mathcal{D}_J} \text{ON} / \mu_J$ , one lets  $\mathcal{F} < \mathcal{G}$  if and only if for all  $\mathfrak{F} \in \mathcal{F}$  and  $\mathfrak{G} \in \mathcal{G}$ ,  $\mathfrak{F} <_{\mu_J} \mathfrak{G}$ .

Let  $\prod_{\mathcal{D}_J} \omega_1 / \mu_J$  consists of the subsets of  $\prod_{X \in \mathcal{D}_J} \text{ON} / \mu_J$  consists of element whose representative is a function  $\mathfrak{F} : \mathcal{D}_J \rightarrow \omega_1$ .

**Fact 7.13.** (Woodin) Assume ZF + AD. Let  $J$  be a set of ordinals.  $\prod_{X \in \mathcal{D}_J} \omega_1^{L[J, X]} / \mu_J = \omega_1$ .

*Proof.* For each  $\alpha < \omega_1$ , let  $F_\alpha : \mathbb{R} \rightarrow \omega_1$  be the constant function taking value  $\alpha$ . Note that  $\tilde{F}_\alpha \in \prod_{X \in \mathcal{D}_J} \omega_1^{L[J, X]}$ . By the countable additivity of  $\mu_J$ ,  $[\tilde{F}_\alpha]_{\mu_J} = \alpha$ . Thus  $\omega_1 \subseteq \prod_{X \in \mathcal{D}_J} \omega_1^{L[J, X]}$ .

Let  $\mathcal{F} \in \prod_{X \in \mathcal{D}_J} \omega_1^{L[J, X]} / \mu_J$ . Let  $F : \mathbb{R} \rightarrow \omega_1$  be a  $J$ -invariant function such that  $\tilde{F}$  is a representative of  $\mathcal{F}$ . Consider the following game from [13] Lemma 3.3:

I	$x_0$	$x_1$	$x_2$	...	$x$
$G_F$					
II	$y_0, z_0$	$y_1, z_1$	$y_2, z_2$	...	$y, z$

Player 2 wins if and only if  $x \leq_J y$ ,  $z \in \text{WO}^{L[J, y]}$ , and  $\text{ot}(z) = F(y)$ .

Claim 1: Player 2 has a winning strategy in this game.

To see this: Suppose otherwise that Player 1 has a winning strategy  $\sigma$ . Consider  $\sigma$  as both a real and as a strategy. Since  $\tilde{F} \in \prod_{X \in \mathcal{D}_J} \omega_1^{L[J, X]}$ , pick a  $y \geq_J \sigma$  such that  $F(y) < \omega_1^{L[J, y]}$ . Pick a  $z \in \text{WO}^{L[J, y]}$  so that  $\text{ot}(z) = F(y)$ . Note that  $\sigma(y, z) \leq_J y$  since  $\sigma, y, z \leq_J y$ . Thus Player 2 has won which contradicts  $\sigma$  being a Player 1 winning strategy. This proves Claim 1.

Thus suppose  $\tau$  is a Player 2 winning strategy. Let  $\pi_1, \pi_2 : \mathbb{R}^2 \rightarrow \mathbb{R}$  be the projection onto the first and second coordinate, respectively. Since  $\tau$  is a winning strategy for Player 2,  $\pi_2[\tau[\mathbb{R}]]$  is a  $\Sigma_1^1$  subset of  $\text{WO}$ . By boundedness, there is a  $\delta < \omega_1$  so that for all  $v \in \pi_2[\tau[\mathbb{R}]]$ ,  $\text{ot}(v) < \delta$ . Now take  $x \geq_J \tau$ . Then  $\tau(x) \leq_J x$  and therefore  $\pi_1(\tau(x)) \leq_J x$ . Since  $\tau$  is a winning strategy for Player 2,  $x \leq_J \pi_1(\tau(x))$ . So  $x \equiv_J \pi_1(\tau(x))$ .

Since  $F$  is  $J$ -invariant,  $F(x) = F(\pi_1(\tau(x))) = \text{ot}(\pi_2(\tau(x))) < \delta$ . Then by the countable additivity of  $\mu_J$ , there is an  $\alpha < \delta$  so that for  $\mu_J$ -almost all  $x$ ,  $F(x) = \alpha$ . Hence  $[\tilde{F}]_{\mu_J} = \alpha$ .

This shows that  $\prod_{X \in \mathcal{D}_J} \omega_1^{L[J,X]} / \mu_J \subseteq \omega_1$  which completes the proof.  $\square$

**Fact 7.14.** Assume  $\text{ZF} + \text{DC}_{\mathbb{R}} + \text{AD}$ . Let  $J$  be a set of ordinals. Every  $J$ -invariant function is increasing  $\mu_J$ -almost everywhere.

*Proof.* Consider the set  $A = \{x \in \mathbb{R} : (\forall y)(x \leq_J y \Rightarrow F(x) \leq F(y))\}$ . Since  $F$  is a  $J$ -invariant function,  $A$  is a  $J$ -invariant set. Let  $\tilde{A} = A / \equiv_J$  be the corresponding set of  $J$ -degree. By Fact 7.9,  $\tilde{A} \in \mu_J$  or  $\mathcal{D}_J \setminus \tilde{A} \in \mu_J$ .

(Case 1) Suppose  $\mathcal{D}_J \setminus \tilde{A} \in \mu_J$ . There is some  $\iota \in \mathbb{R}$  so that for all  $x \in \mathbb{R}$  with  $\iota \leq x$ ,  $x \notin A$ . Let  $C_\iota = \{x \in \mathbb{R} : \iota \leq x\}$ . Thus for all  $x \in C_\iota$ , there is a  $y \in \mathbb{R}$  with  $x \leq_J y$  and  $F(y) < F(x)$ . Since  $\iota \leq_J x \leq_J y$ , one in fact has for all  $x \in C_\iota$ , there is some  $y \in C_\iota$  so that  $F(y) < F(x)$ . Define a binary relation  $R$  on  $C_\iota$  by  $y R x$  if and only if  $F(y) < F(x)$ . By  $\text{DC}_{\mathbb{R}}$ , there is a sequence  $\langle x_n : n \in \omega \rangle$  so that  $F(x_{n+1}) < F(x_n)$ . This contradicts the wellfoundedness of  $\text{ON}$ . Thus Case 1 can not occur.

(Case 2) Suppose  $\tilde{A} \in \mu_J$ . There is some  $\iota \in \mathbb{R}$  so that for all  $x \in \mathbb{R}$  with  $\iota \leq_J x$ ,  $x \in A$ . Suppose  $x, y \in \mathbb{R}$  is such that  $\iota \leq_J x \leq_J y$ . By definition of  $x \in A$ ,  $F(x) \leq F(y)$ .  $F$  is increasing on the cone above  $\iota$ .

Since only Case 2 can occur,  $F$  must be increasing  $\mu_J$ -almost everywhere.  $\square$

**Fact 7.15.** Assume  $\text{ZF} + \text{DC}_{\mathbb{R}} + \text{AD}$ . Let  $J$  be a set of ordinals. Let  $F : \mathbb{R} \rightarrow \omega_1$  be a  $J$ -invariant function. Then there is a  $G : \mathbb{R} \rightarrow \omega_1$  which is a  $J$ -invariant everywhere increasing function such that  $\tilde{F} \sim_{\mu_J} \tilde{G}$ .

*Proof.* By Fact 7.14, there is an  $\iota \in \mathbb{R}$  so that  $F$  is increasing above the  $J$ -cone of  $\iota$ . Define  $G(x) = \sup\{F(z) : \iota \leq_J z \leq x\}$ .  $G$  is  $J$ -invariant.

If  $x \leq_J y$ , then  $\{z : \iota \leq_J z \leq_J x\} \subseteq \{z : \iota \leq_J z \leq_J y\}$ . Thus  $G(x) \leq G(y)$ .  $G$  is everywhere increasing.

If  $x \in \mathbb{R}$  is such that  $\iota \leq_J x$ , then  $G(x) = \sup\{F(z) : \iota \leq_J z \leq x\} = F(x)$  since  $F$  is increasing on the cone above  $\iota$ .  $\square$

**Fact 7.16.** (Woodin, [16] Theorem 5.9) Assume  $\text{AD}$ . Let  $J$  be a set of ordinals. For  $\mu_J$ -almost all  $x \in \mathbb{R}$ ,  $L[J, x] \models \text{CH}$ .

**Fact 7.17.** Assume  $\text{ZF} + \text{DC}_{\mathbb{R}} + \text{AD}$  and  $V = L(J, \mathbb{R})$  for some set of ordinals  $J$ . There is also a set of ordinals  $\mathbb{X}_J$  that absorbs every function on  $\mathbb{R} \times \omega_1$  in the following sense: for every partial function  $\Lambda : \mathbb{R} \times \omega_1 \rightarrow \mathbb{R} \times \omega_1$ , there is a real  $z$ , a formula  $\varphi$ , and an ordinal  $\xi$  so that for all  $(r, \alpha) \in \text{dom}(\Lambda)$ ,  $\Lambda(r, \alpha) \in L[\mathbb{X}_J, z, r]$  and  $\Lambda(r, \alpha) = (s, \beta) \Leftrightarrow L[\mathbb{X}_J, z, r, s] \models \varphi(\mathbb{X}_J, z, \xi, r, \alpha, s, \beta)$ . In this context,  $z$  is said to code  $\Lambda$ .

*Proof.* The proof is quite similar to Fact 4.6 and Fact 5.6. As in those arguments, one can take  $\mathbb{X}_J$  to be  $J \oplus \omega \odot_J$ .  $\square$

**Remark 7.18.** Next one will study the cardinals below  $\mathbb{R} \times \omega_1$  under the failure of  $\text{AD}_{\mathbb{R}}$ . By Fact 2.7, if one is working in the theory  $\text{ZF} + \text{AD}^+ + \text{V} = \text{L}(\mathcal{P}(\mathbb{R})) + \neg \text{AD}_{\mathbb{R}}$ , then there is set of ordinals  $J$  so that  $V = L(J, \mathbb{R})$ . In the rest of this section, one will work with models of the form  $L(J, \mathbb{R}) \models \text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$ . By Fact 7.17, there is an associated set of ordinals  $\mathbb{X}_J \in L(J, \mathbb{R})$  which absorbs all functions  $\Lambda : \mathbb{R} \times \omega_1 \rightarrow \mathbb{R} \times \omega_1$  in  $L(J, \mathbb{R})$ . Without loss of generality by replacing  $J$  with  $\mathbb{X}_J$ , one can assume that  $J$  is a set of ordinals that absorbs all function from  $\mathbb{R} \times \omega_1$  into  $\mathbb{R} \times \omega_1$ .

**Definition 7.19.** Let  $J$  be a set of ordinals. Let  $F : \mathbb{R} \rightarrow \omega_1$  be a  $J$ -invariant function. Define  $\Phi_F : \mathbb{R} \rightarrow \omega_1$  by  $\Phi_F(x) = \omega_{F(x)}^{L[J,x]}$ . Let  $W_F^J = \bigsqcup \Phi_F$ .

**Fact 7.20.** Assume  $\text{ZF} + \text{AD}$ . Let  $F_1, F_2 : \mathbb{R} \rightarrow \omega_1$  be two everywhere increasing  $J$ -invariant functions so that  $\tilde{F}_1 =_{\mu_J} \tilde{F}_2$ . Then  $W_{F_1}^J \approx W_{F_2}^J$ .

*Proof.* Let  $\ell \in \mathbb{R}$  be such that for all  $x \geq_J \ell$ ,  $F_1(x) = F_2(x)$ . By Fact 7.9, let  $p$  be a  $J$ -pointed tree such that  $[p] \subseteq \{x \in \mathbb{R} : \ell \leq_J x\}$ .

Define  $\Lambda : W_{F_1}^J \rightarrow W_{F_2}^J$  by letting  $\Lambda(x, \alpha) = (\Upsilon^p(x), \alpha)$ . Since  $p$  is  $J$ -pointed,  $p \leq_J \Upsilon^p(x)$ . Hence  $p \in L[J, \Upsilon^p(x)]$ . Using  $p$  and  $\Upsilon^p(x)$ , one can Turing compute  $x$ . Thus  $x \leq_J \Upsilon^p(x)$ . Since  $\Upsilon^p(x) \in [p]$ ,  $F_1(\Upsilon^p(x)) = F_2(\Upsilon^p(x))$ . Thus  $\alpha < \omega_{F_1(x)}^{L[J,x]} \leq \omega_{F_1(\Upsilon^p(x))}^{L[J,\Upsilon^p(x)]} = \omega_{F_1(\Upsilon^p(x))}^{L[J,\Upsilon^p(x)]} = \omega_{F_2(\Upsilon^p(x))}^{L[J,\Upsilon^p(x)]}$  since  $x \leq_J \Upsilon^p(x)$ ,  $F_1$  is

everywhere increasing, and  $F_1$  and  $F_2$  are equal on  $[p]$ . This shows that  $\Lambda$  is well defined.  $\Lambda$  is an injection. Thus  $|W_{F_1}^J| \leq |W_{F_2}^J|$ .

By reversing the role of  $F_1$  and  $F_2$  in this argument, one has that  $|W_{F_2}^J| \leq |W_{F_1}^J|$ . Hence  $W_{F_1}^J \approx W_{F_2}^J$ .  $\square$

**Definition 7.21.** Assume  $\text{ZF} + \text{DC}_{\mathbb{R}} + \text{AD}$  and there is a set of ordinals  $J$  so that  $V = L(J, \mathbb{R})$ . For each  $\mathcal{F} \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J$  define the cardinal  $Y_{\mathcal{F}}^J$  to be  $|W_F^J|$  where  $F : \mathbb{R} \rightarrow \omega_1$  is any  $J$ -invariant everywhere increasing function so that  $\tilde{F} \in \mathcal{F}$ . (Note that such an  $F$  exists by Fact 7.15 and this definition is well defined by Fact 7.20.)

**Fact 7.22.** Let  $J$  be a set of ordinals. For every  $\Phi : \mathbb{R} \rightarrow \omega_1$ , there is an everywhere increasing  $J$ -invariant function  $F$  so that  $|\sqcup \Phi| \leq |W_F^J|$ .

Thus every subset of  $\mathbb{R} \times \omega_1$  without a copy of  $\omega_1$  injects into  $W_F^J$  for some everywhere increasing  $J$ -invariant function  $F$ . Of course,  $W_F^J$  also does not contain a copy of  $\omega_1$  since it is of the form  $\sqcup \Phi$  for some function  $\Phi$ .

*Proof.* Let  $F' : \mathbb{R} \rightarrow \omega_1$  be defined by  $F'(x)$  is the ordinal such that  $L[J, x] \models |\Phi(x)| = \aleph_{F'(x)}$ .

For each  $x \in \mathbb{R}$ , let  $\Gamma^x : \Phi(x) \rightarrow \omega_{F'(x)}^{L[J, x]}$  be the  $L[J, x]$ -least bijection. Then  $\Lambda' : \sqcup \Phi \rightarrow W_{F'}^J$  defined by  $\Lambda'(x, \alpha) = (x, \Gamma^x(\alpha))$  is a bijection.

Let  $F(x) = \sup\{F'(z) : z \leq_J x\}$ .  $F'$  is everywhere increasing and  $W_{F'}^J$  injects into  $W_F^J$ .

The last statement follows from Fact 7.3.  $\square$

**Example 7.23.** Let  $J$  be a set of ordinals. Let  $H_0, H_1 : \mathbb{R} \rightarrow \omega_1$  denote the constant 0 and constant 1 function, respectively. Then  $|W_{H_0}^J| = |W_{H_1}^J| = |\mathbb{R}|$ .

*Proof.* Note  $W_{H_0}^J = \sqcup \omega_0^{L[J, x]} \approx \mathbb{R} \times \omega \approx \mathbb{R}$ .

For each  $x \in \mathbb{R}$ , let  $\Gamma^x : \omega_1^{L[J, x]} \rightarrow \mathbb{R}$  denote the  $L[J, x]$ -least injection of  $\omega_1^{L[J, x]}$  into  $\mathbb{R}^{L[J, x]}$ . Define  $\Lambda : W_{H_0}^J \rightarrow \mathbb{R} \times \mathbb{R}$  by  $\Lambda(x, \alpha) = (x, \Gamma^x(\alpha))$ .  $\Lambda$  is an injection witnessing  $|W_{H_1}^J| \leq |\mathbb{R} \times \mathbb{R}| = |\mathbb{R}|$ . Thus  $W_{H_1}^J \approx \mathbb{R}$ .  $\square$

**Fact 7.24.** Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and  $V = L(J, \mathbb{R})$  where  $J$  is a set of ordinals that absorbs all functions from  $\mathbb{R} \times \omega_1$  into  $\mathbb{R} \times \omega_1$  as in Fact 7.17 and Remark 7.18. Suppose  $F_1, F_2 : \mathbb{R} \rightarrow \omega_1$  are two everywhere increasing  $J$ -invariant functions such that  $\tilde{F}_1 <_{\mu_J} \tilde{F}_2$  and  $F_1$  is not  $\mu_J$  almost everywhere equal to 0. Then  $|W_{F_1}^J| < |W_{F_2}^J|$ .

*Proof.* Since  $F_1$  is not  $\mu_J$ -almost everywhere 0 and  $F_1 <_{\mu_J} F_2$ , let  $\ell \in \mathbb{R}$  be such that for all  $x \in \mathbb{R}$  with  $\ell \leq_J x$ ,  $1 \leq F_1(x) < F_2(x)$ . Let  $p$  be a  $J$ -pointed tree such that  $[p] \subseteq \{x \in \mathbb{R} : \ell \leq_J x\}$ . Define  $\Lambda : W_{F_1}^J \rightarrow W_{F_2}^J$  by  $\Lambda(x, \alpha) = (\Upsilon^p(x), \alpha)$ . For all  $(x, \alpha) \in W_{F_1}^J$ ,  $\alpha < \omega_{F_1(x)}^{L[J, x]} \leq \omega_{F_1(\Upsilon^p(x))}^{L[J, \Upsilon^p(x)]} < \omega_{F_2(\Upsilon^p(x))}^{L[J, \Upsilon^p(x)]}$  since  $x \leq_J \Upsilon^p(x)$ ,  $F_1$  is everywhere increasing, and  $\ell \leq_J \Upsilon^p(x)$ . Thus  $\Lambda$  is a well defined injection witnessing  $|W_{F_1}^J| \leq |W_{F_2}^J|$ .

Suppose there was an injection  $\Lambda : W_{F_2}^J \rightarrow W_{F_1}^J$ . Since  $J$  absorbs all functions, let  $z \in \mathbb{R}$  and  $\varphi$  be some formulas such that within  $L[J, z]$ ,  $\Lambda$  is correctly defined in the sense of Fact 7.17. That is, for all  $(r, \alpha) \in W_{F_2}^J$ ,  $\Lambda(r, \alpha) \in L[J, z, r]$  and  $\Lambda(r, \alpha) = (s, \beta) \Leftrightarrow L[J, z, r] \models \varphi(J, z, r, \alpha, s, \beta)$ . By Fact 7.16, let  $e \in \mathbb{R}$  be such that for all  $x \in \mathbb{R}$ ,  $e \leq_J x$  implies that  $L[J, x] \models \text{CH}$ .

Let  $w = z \oplus \ell \oplus e$ . Within  $L[J, w]$ ,  $\Lambda$  as defined by  $\varphi$  is an injection of  $W_{F_2}^J \cap L[J, w]$  into  $W_{F_1}^J \cap L[J, w]$ . In particular, within  $L[J, w]$ , there is an injection of  $\{w\} \times \omega_{F_2(w)}^{L[J, w]}$  into  $W_{F_1}^J \cap L[J, w] \subseteq \mathbb{R}^{L[J, w]} \times \omega_{F_1(w)}^{L[J, w]}$  since  $F_1$  is an everywhere increasing function. Since  $L[J, w] \models \text{CH}$ ,  $|\mathbb{R}^{L[J, w]}| = \omega_1^{L[J, w]}$ . By the definition of  $\ell$ , for all  $x$  such that  $\ell \leq_J x$ ,  $F_1(x) \geq 1$ . Thus in  $L[J, w] \models |\mathbb{R} \times \omega_{F_1(w)}| = \omega_{F_1(w)}$ . Thus within  $L[J, w]$ , one has an injection of  $\omega_{F_2(w)}^{L[J, w]}$  into  $\omega_{F_1(w)}^{L[J, w]}$ . Since  $\ell \leq_J w$ ,  $F_2(w) > F_1(w)$ . Such an injection can not exist in  $L[J, w]$ . Contradiction. This shows  $|W_{F_1}^J| < |W_{F_2}^J|$ .  $\square$

**Corollary 7.25.** (Woodin) Assume  $\text{ZF} + \text{AD}^+ + \neg \text{AD}_{\mathbb{R}} + V = L(\mathcal{P}(\mathbb{R}))$ . There is a set  $X \subseteq \mathbb{R} \times \omega_1$  so that  $|\mathbb{R}| < |X|$  and  $\neg(\omega_1 \leq |X|)$ ,

*Proof.* By Fact 2.7, there is a set of ordinals  $J$  so that  $V = L(J, \mathbb{R})$  and  $J$  absorbs functions. Let  $F^1, F^2 : \mathbb{R} \rightarrow \omega_1$  be the constant function taking value 1 and 2, respectively. By Example 7.23,  $W_{F^1}^J \approx \mathbb{R}$ . Then by Fact 7.24,  $|\mathbb{R}| = |W_{F^1}^J| < |W_{F^2}^J|$ .

The set  $W_{F^2}^J$  is essentially the example in [19] Theorem 25.  $\square$

**Theorem 7.26.** Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and  $V = L(J, \mathbb{R})$  for some set of ordinals  $J$  which absorbs functions from  $\mathbb{R} \times \omega_1$  into  $\mathbb{R} \times \omega_1$ . Let  $\mathfrak{V}$  be the collection of  $|X|$  such that  $X \subseteq \mathbb{R} \times \omega_1$  and  $\neg(\omega_1 \leq |X|)$ ; that is,  $\mathfrak{V}$  is the collection of cardinals of sets below  $\mathbb{R} \times \omega_1$  that do not possess a copy of  $\omega_1$ .

The sequence  $(Y_{\mathcal{F}}^J : \mathcal{F} \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J \setminus \{0\})$  is an order-preserving injection of the wellordering  $\prod_{\mathcal{D}_J} \omega_1 / \mu_J \setminus \{0\}$  with the ultrapower ordering into  $\mathfrak{V}$  with the natural cardinal ordering induced by injections. Moreover, this sequence is cofinal in  $\mathfrak{V}$  in the sense that if  $Y \in \mathfrak{V}$ , then there is a  $\mathcal{F} \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J \setminus \{0\}$  so that  $Y \leq Y_{\mathcal{F}}^J$ .

*Proof.* This is clear from Fact 7.22 and Fact 7.24. Also note that it is necessary to remove 0 for otherwise the sequence would not be injective since  $Y_0^J = |\mathbb{R}| = Y_1^J$  by Example 7.23.  $\square$

**Fact 7.27.** (Woodin) Assume  $\text{ZF} + \text{DC}_{\mathbb{R}} + \text{AD}$  and  $V = L(J, \mathbb{R})$  for some set of ordinals  $J$ . Let  $\mathbb{X}_J = J \oplus_{\omega} \mathbb{O}_J$ . Then  $\prod_{\mathbb{X}_J} \omega_2^{L[\mathbb{X}_J, X]} / \mu_{\mathbb{X}_J} = \Theta^{L(J, \mathbb{R})}$ .

*Proof.* This is shown in [13] Theorem 5.16.  $\square$

As in Remark 7.18, if one has that  $V = L(J, \mathbb{R})$ , one could have always chosen the set of ordinals which absorbed functions to be  $J \oplus_{\omega} \mathbb{O}_J$ . Moreover  $L(J, \mathbb{R}) = L(J \oplus_{\omega} \mathbb{O}_J, \mathbb{R})$ . Thus the length of  $(Y_{\mathcal{F}}^J : \mathcal{F} \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J)$  is quite long.

Let  $\mathfrak{Y} = \{Y_{\mathcal{F}}^J : \mathcal{F} \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J \setminus \{0\}\}$ . A natural question would be is  $\mathfrak{Y}$ , the collection of uncountable cardinals below  $\mathbb{R} \times \omega_1$ , the same as  $\mathfrak{V} = \{|X| : X \subseteq \mathbb{R} \times \omega_1, \neg(\omega_1 \leq |X|)\}$ . Certainly,  $\mathfrak{Y} \subseteq \mathfrak{V}$  and  $\mathfrak{Y}$  is cofinal in  $\mathfrak{V}$ . Moreover, for all  $\mathcal{Y} \in \mathfrak{Y}$  and  $\mathcal{X} \in \mathfrak{V}$ , either  $\mathcal{X} \leq \mathcal{Y}$  or  $\mathcal{Y} \leq \mathcal{X}$ . This will follow from the next result. However, the game in the proof is important for later results.

**Theorem 7.28.** Assume  $\text{ZF} + \text{AD}$ . Let  $J$  be a set of ordinals. Let  $F : \mathbb{R} \rightarrow \omega_1$  be an everywhere increasing  $J$ -invariant function so that for all  $x \in \mathbb{R}$ ,  $F(x) \geq 1$ . Let  $\Phi : \mathbb{R} \rightarrow \omega_1$  be any function. Consider the following game  $S_F^{\Phi}$ :

$$\begin{array}{ccccccc} & I & r_0 & r_1 & r_2 & r_3 & r \\ S_F^{\Phi} & & & & & & \\ & II & x_0 & x_1 & x_2 & x_3 & x \end{array}$$

where Player 1 and Player 2 separately play natural numbers to produce reals  $r$  and  $x$ . Player 2 wins  $S_F^{\Phi}$  if and only if  $L[J, r, x] \models \Phi(r) < \omega_{F(r \oplus x)}$ . If Player 2 has a winning strategy in  $S_F^{\Phi}$ , then  $|\sqcup \Phi| \leq |W_F^J|$ . If Player 1 has a winning strategy in  $S_F^{\Phi}$ , then  $|W_F^J| \leq |\sqcup \Phi|$ .

Thus either  $|\sqcup \Phi| \leq |W_F^J|$  or  $|W_F^J| \leq |\sqcup \Phi|$ .

*Proof.* Statement 1: Suppose Player 2 has a winning strategy  $\tau$ . For each  $r \in \mathbb{R}$ , let  $\tau(r)$  denote the real that Player 2 produces using  $\tau$  when Player 1 plays  $r$ .

Since  $\tau$  is a Player 2 winning strategy, for all  $r \in \mathbb{R}$ ,  $L[J, r, \tau(r)] \models \Phi(r) < \omega_{F(r \oplus \tau(r))}$ . Let  $\Gamma^r : \Phi(r) \rightarrow \omega_{F(r \oplus \tau(r))}^{L[J, r, \tau(r)]}$  denote the  $L[J, r, \tau(r)]$ -least injection of  $\Phi(r)$  into  $\omega_{F(r \oplus \tau(r))}^{L[J, r, \tau(r)]}$ .

Define  $\Lambda : \sqcup \Phi \rightarrow W_F^J$  by  $\Lambda(r, \alpha) = (r \oplus \tau(r), \Gamma^r(\alpha))$ .  $\Lambda$  is an injection witnessing  $|\sqcup \Phi| \leq |W_F^J|$ .

Statement 2: Suppose Player 1 has a winning strategy  $\sigma$ . For each  $x \in \mathbb{R}$ , let  $\sigma(x)$  be the response by Player 1 using  $\sigma$  when Player 2 plays  $x$ .

Since  $\sigma$  is a Player 1 winning strategy, for all  $x \in \mathbb{R}$ ,  $L[J, \sigma(x), x] \models \omega_{F(\sigma(x) \oplus x)} \leq \Phi(\sigma(x))$ . For each  $x \in \mathbb{R}$ , let  $\Gamma^x : \omega_{F(\sigma(x) \oplus x)}^{L[J, \sigma(x), x]} \rightarrow \Phi(\sigma(x))$  be the  $L[J, \sigma(x), x]$ -least injection from  $\omega_{F(\sigma(x) \oplus x)}^{L[J, \sigma(x), x]}$  to  $\Phi(\sigma(x))$ . Note that if  $x_0, x_1 \in \mathbb{R}$  are such that  $\sigma(x_0) = \sigma(x_1)$  and  $\sigma(x_0) \oplus x_0 \equiv_J \sigma(x_1) \oplus x_1$ , then  $\Gamma^{x_0} = \Gamma^{x_1}$ .

By Fact 7.16, let  $e \in \mathbb{R}$  be such that for all  $x \in \mathbb{R}$  with  $e \leq_J x$ ,  $L[J, x] \models \text{CH}$ . By Fact 7.9, let  $p$  be a  $J$ -pointed perfect tree such that  $e \oplus \sigma \leq_J p$ , i.e.  $[p]$  is inside the cone above  $e \oplus \sigma$ .

Note that when one considers  $\sigma : \mathbb{R} \rightarrow \mathbb{R}$  as a Lipschitz function, it can not be constant on any neighborhood since  $\omega_{F(\sigma(x) \oplus x)}^{L[J, \sigma(x), x]} \leq \Phi(\sigma(x))$  and  $F(x) \geq 1$  for all  $x \in \mathbb{R}$ . Thus by Lemma 7.10, there is a  $J$ -pointed perfect subtree  $q \subseteq p$  with the property that for all  $x \in [q]$ ,  $\sigma(x) \oplus q \equiv_J x$ .



Before proceeding, one should give intuition for the next function:  $\sigma$  as a Lipschitz function is not an injection; however, for any  $r \in \sigma[[q]]$ , one knows where the possible preimage of  $r$  come from. Precisely, for any  $r \in \sigma[[q]]$ ,  $\sigma^{-1}[\{r\}] \subseteq \mathbb{R}^{L[r \oplus q]}$ . Thus there are at most  $\mathbb{R}^{L[J, r \oplus q]}$  many  $x \in \mathbb{R}$  so that  $\sigma(x) = r$ . Since  $L[J, r \oplus q] \models \text{CH}$ ,  $L[J, r \oplus q] \models |\mathbb{R}| = \omega_1$ . In anticipation of this many possible  $x$  sharing the same  $r$  as its image, one will split  $\omega_{F(r \oplus q)}^{L[J, r \oplus q]}$  into  $\mathbb{R}^{L[J, r \oplus q]}$  many disjoint pieces of size  $\omega_{F(r \oplus q)}^{L[J, r \oplus q]}$ . This makes room for each of the possible  $x$  such that  $\sigma(x) = r$ . The details are as follows:

For each  $r \in \sigma[[q]]$ , let  $\Pi^r : \mathbb{R}^{L[J, r \oplus q]} \times \omega_{F(r \oplus q)}^{L[J, r \oplus q]} \rightarrow \omega_{F(r \oplus q)}^{L[J, r \oplus q]}$  be the  $L[J, r \oplus q]$ -least injection which exists since  $L[J, r \oplus q] \models \text{CH}$  and  $F(x) \geq 1$  for all  $x \in \mathbb{R}$ .

Define  $\Lambda' : \bigsqcup_{x \in [q]} \omega_{F(x)}^{L[J, x]} \rightarrow \bigsqcup \Phi$  by

$$\Lambda'(x, \alpha) = (\sigma(x), \Gamma^x(\Pi^{\sigma(x)}(x, \alpha))).$$

Note this is well defined since for all  $x \in [q]$ ,  $\sigma \leq_J q \leq_J x$  and thus  $\sigma(x) \oplus x \equiv_J x \equiv_J \sigma(x) \oplus q$ . If  $x \in [q]$  and  $\alpha < \omega_{F(x)}^{L[J, x]}$ , then  $x \in \mathbb{R}^{L[J, x]} = \mathbb{R}^{L[J, \sigma(x) \oplus q]}$  and  $\alpha < \omega_{F(x)}^{L[J, x]} = \omega_{F(\sigma(x) \oplus q)}^{L[J, \sigma(x) \oplus q]}$ . Thus  $(x, \alpha)$  is in the domain of  $\Pi^{\sigma(x)}$ . Also  $\Pi^{\sigma(x)}$  maps into  $\omega_{F(\sigma(x) \oplus q)}^{L[J, \sigma(x) \oplus q]} = \omega_{F(\sigma(x) \oplus x)}^{L[J, \sigma(x) \oplus x]}$  and  $\Gamma^x$  maps from  $\omega_{F(\sigma(x) \oplus x)}^{L[J, \sigma(x) \oplus x]} = \omega_{F(\sigma(x) \oplus q)}^{L[J, \sigma(x) \oplus q]}$  to  $\Phi(\sigma(x))$ .

Suppose  $(x_0, \alpha_0) \neq (x_1, \alpha_1)$  belong to  $\bigsqcup_{x \in [q]} \omega_{F(x)}^{L[J, x]}$ . If  $\sigma(x_0) \neq \sigma(x_1)$ , then it is clear that  $\Lambda'(x_0, \alpha_0) \neq \Lambda'(x_1, \alpha_1)$ . Suppose  $\sigma(x_0) = \sigma(x_1)$ . Let  $r$  denote the common value  $r = \sigma(x_0) = \sigma(x_1)$ . As noted above, since  $x_0, x_1 \in [q]$ , one has  $x_0 \equiv_J \sigma(x_0) \oplus q \equiv_J r \oplus q \equiv_J \sigma(x_1) \oplus q \equiv_J x_1$ . Thus  $x_0, x_1 \in \mathbb{R}^{L[J, r \oplus q]}$ . Since  $x_0 \neq x_1$ ,  $\Pi^r(x_0, \alpha_0) \neq \Pi^r(x_1, \alpha_1)$  since  $\Pi^r$  is an injection. As observed near the beginning of Case 2, if  $\sigma(x_0) = r = \sigma(x_1)$  and  $\sigma(x_0) \oplus x_0 \equiv_J \sigma(x_1) \oplus x_1$ , then  $\Gamma^{x_0} = \Gamma^{x_1}$ . Finally since  $\Gamma^{x_0} = \Gamma^{x_1}$  is an injection, one has  $\Lambda'(x_0, \alpha_0) \neq \Lambda'(x_1, \alpha_1)$ . Thus  $\Lambda'$  is an injection.

Finally, define  $\Lambda'' : W_F^J \rightarrow \bigsqcup_{x \in [q]} \omega_{F(x)}^{L[J, x]}$  by  $\Lambda''(x, \alpha) = (\Upsilon^q(x), \alpha)$ . Note  $x \leq_J \Upsilon^q(x)$  since  $q$  is  $J$ -pointed. Thus  $\omega_{F(x)}^{L[J, x]} \leq \omega_{F(x)}^{L[J, \Upsilon^q(x)]} \leq \omega_{F(\Upsilon^q(x))}^{L[J, \Upsilon^q(x)]}$  since  $F$  is everywhere increasing. Thus  $\Lambda''$  is a well defined injection.

Thus  $|W_F^J| \leq |\bigsqcup_{x \in [q]} \omega_{F(x)}^{L[J, x]}| \leq |\bigsqcup \Phi|$ .  $\square$

**Corollary 7.29.** Assume  $\text{ZF} + \text{AD}$ . Let  $J$  be a set of ordinals. Let  $F : \mathbb{R} \rightarrow \omega_1$  be a  $J$ -invariant function so that  $F(x) \geq 1$  for all  $x \in \mathbb{R}$ . Suppose  $X \subseteq \mathbb{R} \times \omega_1$  and  $\neg(\omega_1 \leq |X|)$ . Then either  $|X| \leq Y_F^J$  or  $Y_F^J \leq |X|$ .

In other words, for all  $\mathcal{X} \in \mathfrak{V}$  and  $\mathcal{Y} \in \mathfrak{V}$ ,  $\mathcal{X} \leq \mathcal{Y}$  or  $\mathcal{Y} \leq \mathcal{X}$ .

*Proof.* By Fact 7.3, there is some  $\Phi : \mathbb{R} \rightarrow \omega_1$  so that  $|X| = |\bigsqcup \Phi|$ . The result now follows from Theorem 7.28.  $\square$

**Theorem 7.30.** Assume  $\text{ZF} + \text{AD}$ . Let  $J$  be a set of ordinals. Let  $F : \mathbb{R} \rightarrow \omega_1$  be an everywhere increasing  $J$ -invariant function. Let  $X \subseteq W_{F+1}^J$ , where  $(F+1)(x) = F(x) + 1$ . Then either  $|X| \leq |W_F^J|$  or  $|W_{F+1}^J| = |X|$ .

*Proof.* By Fact 7.3, there is a  $\Phi : \mathbb{R} \rightarrow \omega_1$  so that  $|X| = |\bigsqcup \Phi|$ .

Consider the game  $S_{F+1}^\Phi$  from Theorem 7.28:

$$\begin{array}{ccccccccc} & \text{I} & r_0 & r_1 & r_2 & r_3 & & r & \\ S_F^X & & & & & & & & \\ & \text{II} & x_0 & x_1 & x_2 & x_3 & & x & \end{array}$$

where Player 1 and Player 2 separately play natural numbers to produce reals  $r$  and  $x$ . Player 2 wins  $S_F^X$  if and only if  $L[J, r, x] \models \Phi(r) < \omega_{F(r \oplus x)+1}$ . By AD, one of the two players has a winning strategy.

(Case 1) By Theorem 7.28, if player 1 has a winning strategy that  $|W_{F+1}^J| \leq |\bigsqcup \Phi| = |X| \leq |W_{F+1}^J|$ . Thus  $|X| = |W_{F+1}^J|$ .

(Case 2) Suppose Player 2 has a winning strategy  $\tau$ . One will need a more careful look at the proof of statement 1 in Theorem 7.28.

For each  $r \in \mathbb{R}$ , let  $\tau(r)$  denote the real that Player 2 produces using  $\tau$  when Player 1 plays  $r$ .

Since  $\tau$  is a Player 2 winning strategy, for all  $r \in \mathbb{R}$ ,  $L[J, r, \tau(r)] \models \Phi(r) < \omega_{F(r \oplus \tau(r))+1}$ . That is,  $L[J, r, \tau(r)] \models |\Phi(r)| \leq \omega_{F(r \oplus \tau(r))}$ . Let  $\Gamma^r : \Phi(r) \rightarrow \omega_{F(r \oplus \tau(r))}^{L[J, r, \tau(r)]}$  denote the  $L[J, r, \tau(r)]$ -least injection of  $\Phi(r)$  into  $\omega_{F(r \oplus \tau(r))}^{L[J, r, \tau(r)]}$ .

Define  $\Lambda : \bigsqcup \Phi \rightarrow W_F^J$  by  $\Lambda(r, \alpha) = (r \oplus \tau(r), \Gamma^r(\alpha))$ .  $\Lambda$  is an injection witnessing  $|\bigsqcup \Phi| \leq |W_F^J|$ .  $\square$

Note that the assumption for Theorem 7.28 and Theorem 7.30 is just  $\text{ZF} + \text{AD}$  and  $J$  is any set of ordinals (with no assumption about function absorption although the two cardinals may degenerate without these assumptions).

**Corollary 7.31.** *Assume  $\text{ZF} + \text{AD} + \text{DC}_{\mathbb{R}}$  and  $V = L(J, \mathbb{R})$  where  $J$  is a set of ordinals which absorbs functions from  $\mathbb{R} \times \omega_1 \rightarrow \mathbb{R} \times \omega_1$ . Then for all  $n \in \omega \setminus \{0\}$ , there are no cardinals between  $Y_n^J$  and  $Y_{n+1}^J$ . In particular, there are no cardinals between  $|\mathbb{R}| = Y_1^J$  and  $Y_2^J$ .*

**Theorem 7.32.** *Assume  $\text{ZF} + \text{DC}_{\mathbb{R}} + \text{AD}$  and  $V = L(J, \mathbb{R})$ , where  $J$  is a set of ordinals. Let  $\mathcal{F} \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J \setminus \{0\}$  be such that  $\text{cof}(\mathcal{F}) = \omega$ . Let  $\langle \mathcal{F}_n : n \in \omega \rangle$  be any  $\omega$ -cofinal sequence through  $\mathcal{F}$ . Then there exists everywhere increasing  $J$ -invariant functions from  $\mathbb{R}$  into  $\omega_1$ ,  $F$  and  $\langle F_n : n \in \omega \rangle$ , so that  $[\bar{F}]_{\mu_J} = \mathcal{F}$  and for all  $n \in \omega$ ,  $[\bar{F}_n]_{\mu_J} = \mathcal{F}_n$ .*

Furthermore, assume  $J$  is a set of ordinals which absorbs functions from  $\mathbb{R} \times \omega_1$  to  $\mathbb{R} \times \omega_1$ . Then for any  $X \subseteq W_F^J$ , either  $|X| = |W_F^J|$  or there exists an  $n \in \omega$  so that  $|X| \leq |W_{F_n}^J|$ .

*Proof.* By Fact 7.15, every  $\mathcal{G} \in \prod_{\mathcal{D}_J} \omega_1 / \mu_J$  has an everywhere increasing  $J$ -invariant  $G : \mathbb{R} \rightarrow \omega_1$  so that  $\mathcal{G} = [\tilde{G}]_{\mu_J}$ . Since  $\text{AD}$  implies  $\text{AC}_{\omega}^{\mathbb{R}}$  and every set in  $L(J, \mathbb{R})$  is ordinal definable from  $J$  and a real, one has that  $L(J, \mathbb{R})$  satisfies  $\text{AC}_{\omega}$ , the full axiom of countable choice. Thus one can obtain  $F$  and  $\langle F_n : n \in \omega \rangle$  as in the first statement of the theorem. One may assume that for all  $n \in \omega$ , for all  $x \in \mathbb{R}$ ,  $F_n(x) \geq 1$ .

Now fix an  $X \subseteq W_F^J$ . Suppose there is no  $n$  so that  $|X| \leq |W_{F_n}^J|$ .

Let  $m \in \omega$ . Suppose  $\langle X_k : k < m \rangle$  is a sequence of disjoint subset of  $X$  and  $X_k \approx W_{F_k}^J$  for all  $k < m$ .

Let  $Y = X \setminus (\bigcup_{k < m} X_k)$ . For each  $r \in \mathbb{R}$ , let  $\delta_r = \text{ot}(Y_r)$ . Let  $\Phi : \mathbb{R} \rightarrow \omega_1$  be defined by  $\Phi(r) = \delta_r$ . Note that  $Y \approx \bigsqcup \Phi$ .

Consider the game  $S_{F_m}^{\Phi}$  from Theorem 7.28.

(Case 1) Suppose Player 2 has a winning strategy in  $S_{F_m}^{\Phi}$ . By Theorem 7.28, there is injection  $\Lambda : \bigsqcup \Phi \rightarrow W_{F_m}^J$ . Since  $Y \approx \bigsqcup \Phi$ , there is an injection of  $Y$  into  $W_{F_m}^J$ .

Note that  $W_{F_m}^J$  is in bijection with  $\bigsqcup_{k \leq m} W_{F_k}^J$ . Since  $X_k \approx W_{F_k}^J$  and  $|W_{F_k}| \leq |W_{F_m}|$  for all  $k < m$ , there are injections of  $X_k$  into  $W_{F_m}^J$ . Thus there is an injection of  $X = Y \sqcup \bigsqcup_{k < m} X_k$  into  $\bigsqcup_{k \leq m} W_{F_k}^J \approx W_{F_m}^J$ . This contradicts the assumption that there is no  $n \in \omega$  so that  $|X| \leq |W_{F_n}^J|$ . So Case 1 can not occur.

(Case 2) Player 1 has a winning strategy in  $S_{F_m}^{\Phi}$ . Theorem 7.28 states that there is an injection  $\Lambda_m : W_m^J \rightarrow Y$ . Let  $X_m$  be the image of this injection.

Consider the tree  $T$  of  $(\Lambda_0, \dots, \Lambda_{m-1})$  so that each  $\Lambda_i : W_{F_i}^J \rightarrow X$  is an injection and for all  $i < j < m$ ,  $\Lambda_i[W_i^J] \cap \Lambda_j[W_j^J] = \emptyset$ . Order this tree by extension. By the analysis above, this tree has no dead branches. Since  $L(J, \mathbb{R}) \models \text{DC}_{\mathbb{R}}$  and all sets are ordinal definable from  $J$  and a real,  $L(J, \mathbb{R}) \models \text{DC}$ . Thus let  $\langle \Lambda_i : i \in \omega \rangle$  be a branch through the tree  $T$ .

Let  $K : \mathbb{R} \times \omega_1 \rightarrow \mathbb{R} \times \omega_1$  by

$$K(r, \alpha) = \begin{cases} F_{\alpha}(r) & \alpha < \omega \\ 0 & \text{otherwise} \end{cases}$$

Since  $J$  absorbs function, as in Fact 7.17, there is an  $\ell_0 \in \mathbb{R}$  so that for all  $x \geq_J \ell_0$  and  $\alpha < \omega_1$ ,  $K(x, \alpha) \in L[J, x]$ . In particular by absorbing  $K$ , one has that for all  $x$  with  $\ell_0 \leq x$ ,  $\langle F_n(x) : n \in \omega \rangle \in L[J, x]$ .

Since  $\langle \mathcal{F}_n : n \in \omega \rangle$  is cofinal through  $\mathcal{F}$ , one can use the countably additivity of  $\mu_J$  to find an  $\ell \geq_J \ell_0$  so that for all  $x \in \mathbb{R}$  with  $\ell \leq_J x$ ,  $\langle F_n(x) : n \in \omega \rangle$  is a cofinal sequence through  $F(x)$ . Let  $p$  be a  $J$ -pointed tree such that  $\ell \leq_J p$ . For each  $s \in [p]$ , let  $\Sigma^s : \omega_{F(x)}^{L[J, s]} \rightarrow \bigsqcup_{n \in \omega} \omega_{F_n(s)}^{L[J, s]}$  by the  $L[J, s]$ -least injection. (Note it is important that  $\langle F_n(s) : s \in \omega \rangle \in L[J, s]$  to make sense of this.)

Let  $\Lambda^* : \bigsqcup_{x \in [p]} \omega_{F(x)}^{L[J, x]} \rightarrow X$  be defined by

$$\Lambda^*(x, \alpha) = \Lambda_{\pi_1(\Sigma^x((x, \alpha)))}(x, \pi_2(\Sigma^x(x, \alpha))).$$

Here one thinks of  $\bigsqcup_{n \in \omega} \omega_{F_n(x)}^{L[J, s]} = \{(n, \alpha) : n \in \omega \wedge \alpha < \omega_{F_n(x)}^{L[J, s]}\}$  as a subset of  $\omega \times \omega_1$ . The functions  $\pi_1 : \omega \times \omega_1 \rightarrow \omega$  and  $\pi_2 : \omega \times \omega_1 \rightarrow \omega_1$  are the projections onto the first and second coordinate, respectively. Here one considers  $W_{F_i}^J \subseteq \mathbb{R} \times \omega_1$ . Observe that  $\Lambda^*$  is an injection.

As usual,  $\Lambda^* : W_{F(x)}^J \rightarrow \bigsqcup_{x \in [p]} \omega_{F(x)}^{L[J, x]}$  defined by  $\Lambda^*(x, \alpha) = (\Upsilon^p(x), \alpha)$  is an injection. It has been shown that  $|W_F^J| \leq |X|$  and hence  $|X| = |W_F^J|$ .  $\square$

By Fact 7.13, the first  $\omega_1$  elements of  $\prod_{\mathcal{D}_J} \omega_1 / \mu_J$  are the elements  $\prod_{X \in \mathcal{D}_J} \omega_1^{L[J, X]} / \mu_J$ . For each  $\alpha < \omega_1$ , let  $F^\alpha : \mathbb{R} \rightarrow \omega_1$  by the constant function  $\alpha$ . Note  $[\tilde{F}^\alpha]_{\mu_J}$  is  $\alpha$  is the ultrapower. So  $Y_\alpha^J = |W_{F^\alpha}^J|$ . From the result shown so far, one can determine the first  $\omega_1$  initial segment of  $\mathfrak{V}$ , the collection of cardinals below  $|\mathbb{R} \times \omega_1|$  without a copy of  $\omega_1$ :

**Theorem 7.33.** *Assume  $\text{ZF} + \text{AD} + V = L(J, \mathbb{R})$  where  $J$  is a set of ordinals which absorbs functions from  $\mathbb{R} \times \omega_1$  into  $\mathbb{R} \times \omega_1$ . The collection of cardinal  $\{Y_\alpha^J : 1 \leq \alpha < \omega_1\}$  is closed under the injection relation,  $\leq$ . That is if  $\mathcal{X}$  is an uncountable cardinal and there is some  $\alpha < \omega_1$  so that  $\mathcal{X} \leq Y_\alpha^J$ , then there is some  $1 \leq \beta \leq \alpha$  so that  $\mathcal{X} = Y_\beta^J$ . Moreover,  $\{Y_\alpha^J : 1 \leq \alpha < \omega_1\}$  is an initial segment of  $\mathfrak{V}$  under the injection relation in the sense that for all  $\mathcal{X} \in \mathfrak{V}$ , either  $\mathcal{X} \in \{Y_\alpha^J : 1 \leq \alpha < \omega_1\}$  or for all  $\alpha < \omega_1$ ,  $Y_\alpha^J \leq \mathcal{X}$ .*

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