#### TERRESTRIAL PLANETS ACROSS SPACE AND TIME

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# ABSTRACT

The study of cosmology, galaxy formation and exoplanetary systems has now advanced to a stage where a cosmic inventory of terrestrial planets may be attempted. By coupling semi-analytic models of galaxy formation to a recipe that relates the occurrence of planets to the mass and metallicity of their host stars, we trace the population of terrestrial planets around both solar-mass (FGK type) and lower-mass (M dwarf) stars throughout all of cosmic history. We find that the mean age of terrestrial planets in the local Universe is  $8 \pm 1$  Gyr and that the typical planet of this type is located in a spheroid-dominated galaxy with total stellar mass about twice that of the Milky Way. We estimate that hot Jupiters have depleted the population of terrestrial planets around FGK stars at redshift z = 0 by no more than  $\approx 10\%$ , and predict that  $\approx 1/3$  of the terrestrial planets in the local Universe are orbiting stars in a metallicity range for which such planets have yet to be been detected. When looking at the inventory of planets throughout the whole observable Universe (i.e. in all galaxies on our past light cone) we argue for a total of  $\approx 2 \times 10^{19}$  and  $\approx 7 \times 10^{20}$  terrestrial planets around FGK and M stars, respectively. Due to the hierarchical formation of galaxies and lookback-time effects, the average terrestrial planet on our past light cone has an age of just  $1.7 \pm 0.2$  Gyr and is sitting in a galaxy with a stellar mass a factor of  $\approx 2$  lower than that of the Milky Way. These results are discussed in the context of cosmic habitability, the Copernican principle and the prospects of searches for extraterrestrial intelligence at cosmological distances.

Subject headings: Planets and satellites: terrestrial planets – galaxies: formation – cosmology: miscellaneous - extraterrestrial intelligence

#### 1. INTRODUCTION

The use of transit photometry and radial velocity measurements have in recent years allowed the detection and characterization of large numbers of exoplanets in the same size and mass range as Earth (see Winn & Fabrycky 2015 for a recent review). By coupling the observed occurrence rate of such terrestrial planets to models of star and galaxy formation, it has now become possible to predict the prevalence of Earth-like planets in the Milky Way (e.g. Gonzalez et al. 2001; Lineweaver 2001; von Bloh et al. 2003; Lineweaver et al. 2004; Prantzos 2008; Gowanlock et al. 2011; Guo et al. 2011; Bonfils et al. 2013) and Andromeda (Carigi et al. 2013; Spitoni et al. 2014), in other galaxies in the local volume (Gonzalez et al. 2001; Sundin 2006; Suthar & McKay 2012; Dayal et al. 2015) and even throughout the observable Universe (Wesson 1990; Lineweaver et al. 2007; Behroozi & Peeples 2015; Olson 2015).

The cosmic evolution of the this planet population is relevant for a number of issues in the intersection between of astrobiology, cosmology and SETI (the Search for Extraterrestrial Intelligence). The current age distribution of such planets enters arguments concerning the timing of biogenesis (e.g. von Bloh et al.

2003; Cirkovic 2004; Vukotic & Cirkovic 2007) and anthropic selection biases affecting cosmological parameters (e.g. Lineweaver et al. 2007; Egan & Lineweaver 2008; Barreira & Avelino 2011; Larsen et al. 2011), whereas the distributions of planets among galaxies of different type in the local Universe and throughout the observable Universe (i.e. galaxies on our past light cone) are relevant for the prospects of SETI on extragalactic scales (e.g. Annis 1999; Wright et al. 2014a,b; Griffith et al. 2015; Olson 2015; Zackrisson et al. 2015; Garrett 2015). Here, we extend on previous attempts to model the cosmological distribution of planets by coupling semi-analytical models of galaxy formation to a recipe for planet formation that depends on both stellar mass and stellar metallicity. Using this machinery, we predict the spatial and temporal distribution of terrestrial planets (hereafter TPs) in both the local and distant Universe. Throughout this paper, we define TPs as planets in the size and mass range  $\approx 0.5$ –2.0  $R_{\oplus}$ ,  $\approx 0.5$ –10  $M_{\oplus}$  (i.e. both Earth-like planets and and Super-Earths), thereby including solidsurface planets up to largest sizes that could potentially allow habitable conditions according to the definition by Alibert (2014).

Our computational approach is similar to that of Behroozi & Peeples (2015), but differs in the details of the recipe for TP formation, by extending the inventory from solar-like stars (spectral type FGK) to also include low-mass stars (M dwarfs), in the treatment of the stellar metallicity distribution within each galaxy and by presenting our census of TPs in the observable Universe in terms of galaxies on our past light cone (the case relevant for high-redshift SETI) rather than for the galaxies in the present-day Hubble volume.

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In Section 2, we describe our recipe for TP formation and the galaxy formation models used. Our predicted cosmic inventory of TPs in the local and distant Universe is presented in Section 3. Section 4 features a discussion on the potential habitability of these planets and the relevance of our results for the Copernican principle and extragalactic SETI. We also present a comparison to previous estimates to characterize the properties of the exoplanet population on cosmological scales and discuss the associated uncertainties. Section 5 summarizes our findings.

#### 2. MODELS

#### 2.1. Planet formation

Our recipe for TP formation is similar to that of Lineweaver (2001), in which different metallicitydependent probabilities are adopted for the formation of terrestrial and giant planets, and in which TPs are assumed to be destroyed by close-orbit giants ("hot Jupiters"). This computational machinery is here applied to a wider class of stars, with parameters updated to reflect recent advances in exoplanet studies and with planet formation probabilities that depend on both stellar metallicity and mass.

Kepler data show that the occurrence rate of TPs of size  $R = 1 - 2 R_{\oplus}$  with orbital periods P < 400 days around solar type FGK-stars may be as high as  $f_{\rm TP,FGK} \approx 0.40$  (Petigura et al. 2013). Furthermore, the consensus of both transit and Doppler RV surveys is that the occurrence rate of small rocky planets with  $R = 0.5 - 2.0R_{\oplus}$  orbiting M-dwarf stars is  $f_{\rm TP,M} \approx 1$  (e.g. Dressing & Charbonneau 2013, 2015; Bonfils et al. 2013; Tuomi et al. 2014).

Both observations and simulations indicate that stars in metal-enriched environments yield a greater number of giant planets as opposed to metal-poor environments (e.g. Armitage & Rice 2005; Johnson et al. 2010). With increasing evidence for a metallicity-correlation, Fischer & Valenti (2005) proposed that the occurrence rate of close-in Jupiter-sized giant planets orbiting FGKtype stars can be described by a simple power law. Further investigation of low-mass stars such as M-dwarfs by e.g. Gaidos & Mann (2014) suggests that the power law cannot be described by the same parameters for both solar type stars (FGK) and low-mass M-dwarfs, implying that there is also a mass correlation embedded in the prevalence of giant planets. Here, we adopt the probability of forming giant planets described by Gaidos & Mann (2014):

$$f_{\rm FG}([{\rm Fe/H}], M_*) = f_0 10^{a[{\rm Fe/H}]} M_*^b,$$
 (1)

where  $M_*$  is the mass of the star in solar masses,  $f_0$  a constant factor estimated to be 0.070 by Gaidos & Mann (2014), a is the metallicity parameter estimated to be  $1.80 \pm 0.31$  and  $1.06 \pm 0.42$  for spectral types FGK and M respectively and b the mass correlation parameter assumed to be 1.

Following Lineweaver (2001), we assess the probability of harbouring TPs,  $P_{\rm HTP}$ , by estimating the number of TPs formed as described above, and appraise how many are destroyed by migrating giant planets described by Equation 1 as

$$P_{\rm HTP} = P_{\rm FTP} (1 - P_{\rm FG}), \qquad (2)$$

where  $P_{\rm FT}$  is the probability of forming a TP and  $P_{\rm FG}$  is the probability of forming a close-orbit giant planet, thus destroying the prospect of harbouring a TP in the process.

This approach admittedly neglects the intriguing possibility that TPs may reform in the wake of a migrating Jupiter or otherwise survive the ordeal (e.g. Fogg & Nelson 2009). While no candidates for TPs at orbits outside that of a hot Jupiter have so far been found, we in Section 3 present the fraction of TPs that are lost to hot Jupiters, so that the size of the population potentially missing from our inventory may be estimated.

It is very likely that the probability of forming TPs require a minimum threshold of metallicity for the host star. At the low-metallicity end, we therefore assume a gradual decrease in the probability of forming terrestrial planets. In earlier work by e.g. Prantzos (2008), the probability to form Earth-like planets is depicted as a step-function going from zero probability to maximum probability at [Fe/H] = -1. Our recipe on the other hand includes stars down to  $[Fe/H] \approx -2.2$ , where the minimum mass solar nebula would have insufficient heavy materials to form a terrestrial planet by our definition. However, stars in the low-metallicity regime would most likely struggle in order to form terrestrial planets and we therefore assume a  $P_{FTP}$  function given by:

$$P_{FTP}(Z) = f_{\rm TP} \ k(Z). \tag{3}$$

Here, we adopt  $f_{\text{TP}} = 1$  for M dwarfs and  $f_{\text{TP}} = 0.4$  for FGK stars. The low-metallicity cut-off is given by:

$$k(Z) = \frac{Z - 0.0001}{0.001 - 0.0001} \tag{4}$$

for  $-2.2 \leq [Fe/H] \leq -1$ , but k(Z) = 0 for [Fe/H] < -2.2and k(Z) = 1 for [Fe/H] > -1.

To be consistent with the isochrones used to estimate stellar lifetimes (see Section 2.2), we adopt a solar metallicity of  $Z_{\odot} = 0.152$ . We further probe the consequences of our assumed gradual cutoff for the prevalence of terrestrial planets in Section 4.5.

The resulting probability for FGK and M stars to harbour TPs is shown in Figure 1. Our recipe implies an identical metallicity dependence at the low-metallicity end for FGK and M type stars, but a more pronounced probability decrease at the high-metallicity end in the case of FGK stars. This machinery for relating the formation and destruction probability for TPs is very similar to that used by Lineweaver (2001) and Prantzos (2008) for FGK stars, but differs in the details of the adopted metallicity dependencies. As a result, our probability distribution for the occurrence of TPs around FGK stars is far less peaked around the solar value than that of Lineweaver (2001), but still features a high-metallicity drop-off more pronounced than that of Prantzos (2008). Since neither Behroozi & Peeples (2015) nor Dayal et al. (2015) assume that Jupiters have any adverse effects on the formation of Earth-like planets around FGK stars, our recipe leads to a smaller number of TPs around highmetallicity hosts of this kind.

# 2.2. Galaxy formation

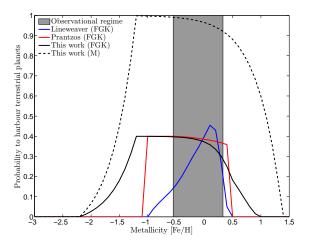


FIG. 1.— The adopted metallicity-dependent probability for FGK (black solid line) and M stars (black dashed) to harbour TPs. The blue line depicts the metallicity relation derived by Lineweaver (2001) and the red line the relation used by Prantzos (2008). The gray area describes the metallicity regime in which detections of TPs have so far been made.

Semi-analytical models represents a powerful tool to connect high-redshift galaxies to their present-day descendants (for a review, see Baugh 2006). Here, we use such models to trace the formation of stars and the buildup of heavy elements within galaxies throughout cosmic history.

In this paper, we base our primary results on the version of the Durham semi-analytic model GALFORM described in Baugh (2005) The Durham model has been demonstrated to reproduce the luminosity function of LBGs at  $z \approx 3$ , present-day optical and near- and far-infrared luminosity functions and the sizeluminosity relation for  $z \approx 0$  late-type galaxies (Baugh 2005; González et al. 2009). It is also in fair agreement with the observed cosmic star formation history (Madau & Dickinson 2014). When possible, we also use the independent semi-analytic model Galacticus (Benson 2012) to cross-check the robustness of important conclusions.

From the Durham semi-analytical model, we extract the galaxy population within a simulated comoving box of side 64Mpc/h in 50 redshifts snapshots between z=0 and z=10. This gives us between  $\approx 200$  (z = 10) and  $\approx 36000$  (z = 0) galaxies per snapshot. The stellar mass range of these galaxies is  $\sim 10^7$  to  $\sim 10^{12} M_{\odot}$ at z=0. However, to avoid potential resolution problems at the low-mass end, we will throughout this paper focus on galaxies in the  $M \gtrsim 10^8 M_{\odot}$  mass range. This is not likely to affect our results in any significant ways, since both our own models and extrapolations of the observed galaxy stellar mass function to lower-mass objects (Kelvin et al. 2014; Moffett et al. 2015) indicate that the fraction of stellar mass locked up in  $M < 10^8 M_{\odot}$  galaxies is at the sub-percent level.

From every redshift, we extract the internal age and metallicity distribution of the stars of all galaxies. By adopting the Kroupa (2001) stellar initial mass function, we derive the number of FGK type (assumed mass range 0.6–1.2  $M_{\odot}$ ) and M dwarf (0.08–0.6  $M_{\odot}$ ) subtypes in each metallicity and age bin and use mass- and

 TABLE 1

 Terrestrial planets in the local Universe

	Host		
	FGK	Μ	FGKM
Mean age of terrestrial planet (Gyr)	8.1	8.4	8.4
Terrestrial planets per $M_{\odot}$	0.048	2.1	2.1
Fraction lost to hot Jupiters	0.095	0.011	0.013
Fraction outside observed [Fe/H] range	0.31	0.36	0.36

metallicity-dependent stellar lifetimes from the PARSEC v1.2S isochrones (Bressan et al. 2012; Chen et al. 2014; Tang et al. 2014) isochrones to remove dead stars from the inventory. Finally, we apply the mass- and metallicity dependent planet occurrence recipe of Section 2.1 to calculate the number of TPs within the age and metallicity bin of each galaxy at every redshift.

#### 2.3. Cosmology

When converting redshifts into time and computing cosmological volumes required to reconstruct our past light cone, we adopt a flat  $\Lambda$  Cold Dark Matter ( $\Lambda$ CDM) cosmology with  $\Omega_M = 0.308$ ,  $\Omega_{\lambda} = 0.692$  and Hubble constant  $H_0 = 67.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (Planck collaboration 2015), giving a current age to the Universe of  $t_0 \approx 13.8$ Gyr. When comparing ages of typical planetary ages at various cosmological epochs to the age of the Earth, Earth is assumed to be 4.54 Gyr old (Dalrymple 2001).

## 3. Results

#### 3.1. Terrestrial planets in the local Universe

Table 1 summarizes a number of statistical quantities predicted by our model for the population of TPs in the local Universe (i.e. averaged over all galaxies within the simulated volume at redshift z = 0). The average age of TPs around FGK stars and M dwarfs is currently  $\approx 8.1$ Gyr and  $\approx 8.4$  Gyr, respectively (i.e. more than 3.5 Gyr older than Earth). The oldest TPs in our simulation have ages of around  $\approx 13$  Gyr (by comparison, the oldest TP) known so far has an age of  $\approx 11$  Gyr; Campante et al. 2015). The small difference between the mean ages of TPs around FGK and M type hosts is due to a close cancellation of two different effects that act in opposite directions: The lower lifetimes of FGK stars compared to M dwarfs leads to lower ages for planets of FGK stars, whereas the more efficient destruction of TPs by giant planets around high-metallicity FGK stars compared to high-metallicity M dwarfs means that a higher fraction of the FGK TPs surviving to the present day formed at earlier, less-metal enriched epochs and hence should be older.

The fraction of FGK planets lost due to the exhausted lifetimes of their host stars is no more than 15%, since only the most massive stars (mass higher than  $\approx 0.95 \ M_{\odot}$ , although with a slight metallicity dependence) have lifetimes shorter than the current age of the Universe.

The mean age of TPs shows a dependence on current galaxy mass, as shown in Figure 2. The highestmass galaxies (in the local Universe, this corresponds to giant elliptical galaxies) harbour the oldest planets, as expected from the high average ages of stars in such systems. While the age difference between TPs around FGK and M stars is very low in high-mass galaxies, TPs

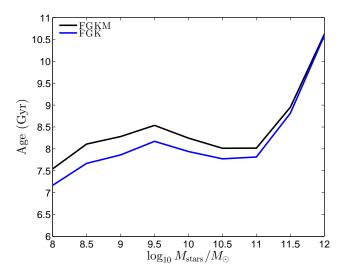


FIG. 2.— The mean age of TPs as a function of galaxy stellar mass at z = 0. The black line represents TPs around FGKM stars, whereas the blue line represents the FGK subpopulation.

around FGK stars become slightly younger than those around M stars for low-mass galaxies, leading to an offset of up to 0.5 Gyr at the low-mass end. This effect is mainly due to the mass-metallicity relation of galaxies and the metallicity-lifetime relation for stars. Galaxies at the high-mass end of Figure 2 have higher metallicities, which leads – within the metallicity range spanned by most stars in the simulations – to FGK stars with longer lifetimes, and consequently to a lower fraction of old FGK stars that are removed from the inventory due to expired lifetimes.

On global scales, the number of TPs per stellar population mass has a current average of  $\approx 2 \ M_{\odot}^{-1}$  at redshift z = 0. Since M dwarfs greatly outnumber the FGK stars, this quantity is completely dominated by TPs around M dwarfs, and the corresponding value for TPs around FGK hosts is about 40 times lower ( $\approx 0.05 \ M_{\odot}^{-1}$ ).

Hot Jupiters are expected to have diminished the current population of TPs around FGK stars by no more than  $\approx 10\%$ . Given our assumptions in Section 2.1, this fraction is even smaller for M dwarfs ( $\approx 1\%$ ).

Our model moreover predicts that  $\approx 1/3$  of the TPs are orbiting FGK and M type stars in the metallicity range for which TPs have yet to be detected (i.e. outside the gray region in Fig. 1). For both host types, most of these are at metallicities  $-1.2 \leq [Fe/H] \leq -0.5$ ), i.e. just below the lowest-metallicity planet hosts found so far (Torres et al. 2015). This conclusion is remarkably robust to the details of the adopted metallicity dependence of the planet occurrence model at [Fe/H] < -1.2. Even if the probability to harbour TPs were to remain constant down to zero metallicity, this would boost the total number of TPs outside the metallicity range of current detections by less than 3%, simply because the fraction of stars at these very low metallicities is so small.

The full metallicity distribution of the TP population in the local Universe is shown in Figure 3. The distribution for FGK hosts (blue), displays a slight skewness towards lower metallicities compared to the FGKM hosts (black; dominated by M dwarfs), due to the more efficient destruction of TPs by migrating giants around FGK stars at high metallicities. The red line demonstrate the effect

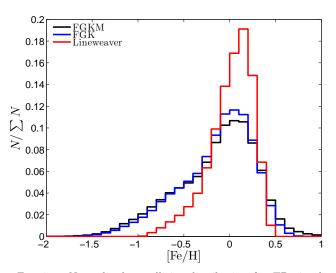


FIG. 3.— Normalized metallicity distribution for TPs in the galaxy population at z = 0. The black and blue solid lines represent the predictions for FGKM and FGK stellar hosts in the case of our default metallicity dependence for TP formation. The red line depicts the corresponding case for FGK stars under the assumption of the Lineweaver (2001) metallicity dependence.

of using the original metallicity relation by Lineweaver (2001), which makes the distribution peak more strongly around the solar metallicity. As expected, our adopted relation has significantly more planets at [Fe/H]  $\leq -0.25$ . This directly affects the expected prevalence of TPs in low-mass galaxies, where such metallicities are common. The Lineweaver (2001) recipe would render galaxies at  $M_{\rm stars} \lesssim 10^9 \ M_{\odot}$  largely barren of TPs. No corresponding decline in planet numbers is predicted by our model, as demonstrated in Figure 4, where the predicted number of TPs per stellar population mass is plotted as a function of galaxy mass.

Instead, this quantity stays roughly constant at  $\approx 2$ throughout the  $M_{\rm stars} = 10^9 - 10^{11} M_{\odot}$  mass range, and only drops slightly (by  $\approx 20-40\%$ ) for FGKM host stars in low-mass galaxies (~  $10^8 M_{\odot}$ ) due to a lack of heavy elements from which TPs are made, and - in the case of FGK host stars - for high-mass galaxies ( $\sim 10^{12} M_{\odot}$ ) due to the destruction of TPs by hot Jupiters in highmetallicity systems. A typical galaxy in the mass range of the Milky Way (stellar mass  $4-6\times 10^{10} M_{\odot}$ ; McMillan 2011) is expected to harbour  $\approx 1 \times 10^{11}$  TPs around M stars and  $2 \times 10^9$  TPs around FGK stars. The lowmetallicity cut-off is not expected to cause any order-ofmagnitude decline in the planet population of galaxies until one enters the  $\leq 10^7$  galaxy mass range. This is in the mass range where the resolution limit of our GAL-FORM galaxy catalogs may affect the detailed galaxy statistics, but the same trend is also evident with Galacticus, which does not suffer from the same limitations at this mass scale.

In Figure 5, we show the distribution of TPs across the galaxies of different masses at z = 0. The average galaxy mass of the TP-weighted distribution is  $\approx 8 \times 10^{10} M_{\odot}$  when considering planets around FGK stars and  $\approx 9 \times 10^{10} M_{\odot}$  for planets around FGKM stars. Hence, the typical TP is located in a galaxy slightly more massive than the Milky Way. Interestingly, this suggests that most TPs are locked up in spheroid-

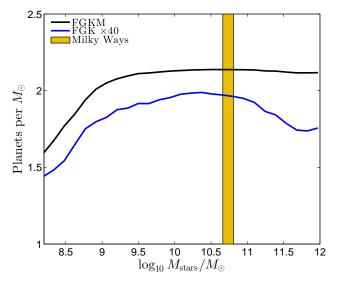


FIG. 4.— TPs per unit stellar population mass for galaxies of different mass at z = 0. The relation for FGK hosts (blue line) has been boosted by a factor of 40 to illustrate the difference in shape compared to the relation for FGKM hosts (black line). The amber colored patch indicates the mass of the Milky Way.

dominated galaxies and not in disk-dominated galaxies, since the former type starts to dominate at stellar masses  $M \gtrsim 10^{10} M_{\odot}$  (Kelvin et al. 2014; Moffett et al. 2015). The fact that Earth does not appear to be located in the most common type of TP-bearing galaxy indicates a mild violation of the Copernican/mediocrity principle, which we discuss further in Section 4.1.

Another interesting consequence of Figure 4 is that galaxies like the Large Magellanic Cloud (LMC; stellar mass  $M_{stars} \approx 2 \times 10^9 M_{\odot}$ ; Harris & Zaritsky 2009) are predicted not to be significantly depleted in TPs, but to harbour  $\approx 8 \times 10^7$  (around FGK stars) and  $\approx 4 \times 10^9$  (FGKM stars) of these. This is stark contrast to the conclusion reached by Zinnecker (2003), who argued that galaxies in the LMC metallicity range may be unable to form TPs as large as Earth. However, we note that transit data have already started to turn up rocky planets even larger than Earth (Buchhave et al. 2012; Torres et al. 2015) at metallicities at the upper range of those relevant for the inner regions of LMC (Piatti & Geisler 2013). Based on the observed agemetallicity relation for the LMC (Piatti & Geisler 2013) and the LMC star formation history of Harris & Zaritsky (2009), our metallicity recipe for planet occurrence suggests that the average TP in the LMC should be significantly younger than the cosmic average – the mean age is predicted to be about 1 Gyr older than Earth for TPs around M dwarfs, and 0.2 Gyr older than Earth for TPs around FGK stars.

# 3.2. Terrestrial planets throughout the observable Universe

In our census of TPs throughout the observable Universe, we consider the population of TPs within all galaxies on our past light cone – i.e. within a spherical volume whose outer radius is bounded by the maximum light travel time distance allowed by the current age of the Universe, and within which the cosmic epoch considered is a function of distance (or, equivalently, redshift z) from

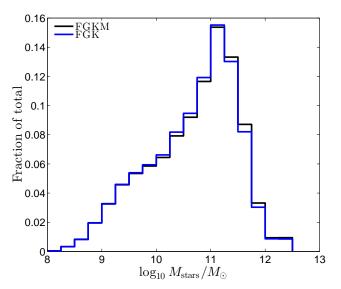


FIG. 5.— The distribution of TPs across the z = 0 galaxy population. The differently colored lines in the two panels represent the FGKM (black solid) and FGK (blue solid) hosts.

us. Galaxies, stars and planets at larger distances within this volume are seen at progressively earlier epochs in the history of the Universe. This definition of "observable Universe" differs from that of Behroozi & Peeples (2015), which instead consider the *current* state of the planet population in a cosmological volume of this order. However, due to the finite speed of light, the latter population cannot be directly observed.

In Table 2 we present our results concerning the statistical quantities for the population of TPs on our past light cone. The total number of TPs around FGKM stars in the observable Universe is estimated at  $\approx 8 \times 10^{20}$ . Analogous to the case at  $z \approx 0$  (Section 3.1), this number is completely dominated by M dwarf planets ( $\approx 98\%$ ), and the corresponding number for FGK stars is  $\approx 2 \times 10^{19}$ .

Since galaxy formation progresses hierarchically, highmass galaxies were more rare in the past. The mean galaxy mass was therefore lower at earlier epochs on our past light cone, and the distribution of TPs across the galaxy population is therefore somewhat different compared to the local Universe. This is demonstrated in Figure 6, which shows that the typical TP on our past light cone is sitting inside a galaxy of slightly lower mass (average mass  $M_{\rm stars} \approx 2 \times 10^{10} M_{\odot}$ ) than the Milky Way ( $\approx 4-6 \times 10^{10} M_{\odot}$ ).

Since the typical ages of TPs decrease as more distant regions on our past light cone are considered, the average TP age in the observable Universe comes out at  $\approx 1.7$ billion year, i.e. almost 3 Gyr *younger* than Earth. The age distribution at a few different redshifts, along with the total distribution for the whole observable Universe is shown in Figure 7a. The mean TP age on the past light cone as the maximum redshift is increased in shown in Figure 7b. This quantity approaches the average age of TPs throughout the whole observable Universe reported in Table 2 at  $\approx 5$  and does not change as higher redshifts are considered, due to the small number of planets at earlier epochs. The age difference between TPs (around both FGK and M hosts; solid line) and the stellar population (dashed line) is very small at all redshifts,

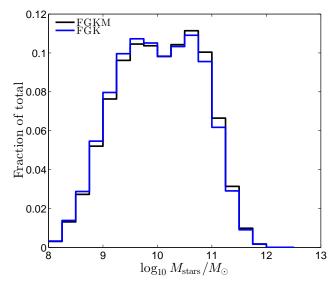


FIG. 6.— The distribution of TPs across galaxies of different stellar masses on our past light cone. The differently colored lines represent the FGKM (black solid) and FGK (blue solid) stellar hosts. The average TP is sitting in a galaxy with stellar mass  $M_{\rm stars}\approx 2\times 10^{10}~M_{\odot}.$ 

which indicates that the mean ages of TPs can in fact be estimated quite accurately solely from the cosmic star formation history.

In Figure 8, we show the cumulative number of TP within the volume subtended by our past lightcone out to some maximum redshift. As the redshift approaches that of the earliest epochs of star formation, the number approaches the total number of TPs in the observable Universe. As seen, the number increases relatively little beyond the peak of cosmic star formation ( $z \approx 2$ ; Madau & Dickinson 2014). This stems from the fact that the increase in light cone volume at higher redshifts is unable to compensate for the lower star formation activity at earlier epochs. For example, the cosmic star formation rate drops by a factor of  $\approx 10$  between z = 2 and z = 7, whereas the increase in comoving volume spanned by these redshifts only grows by a factor of  $\approx 2$ . As a result, we find that 90% of all TPs on our past light cone are at z < 3.3. When considering only planets older than Earth, this limit is reached at even lower redshifts, since no objects older than Earth can exist at z > 1.4 in the adopted cosmology. Hence, we find that 90% of the TPs older than Earth are at z < 0.8.

# 4. DISCUSSION

## 4.1. Habitability

While the focus of this paper is on the prevalence of *TPs* on cosmological scales, it is primarily the subset of TPs that are able to sustain life that are relevant for astrobiology and SETI. While the requirements for planet habitability remains much debated (for a recent review see Gonzalez 2014), the most common approach when discussing habitability on galactic scales is to start from a condition on the ability for planets to maintain liquid water (usually based on some variation on the moist greenhouse circumstellar zone of Kasting et al. 1993; e.g. Kopparapu 2013; Petigura et al. 2013).

Current attempts to estimate the occurrence rate of TPs located in the circumstellar habitable zone indi-

TABLE 2TERRESTRIAL PLANETS IN THE OBSERVABLE UNIVERSE

	Host		
	FGK	Μ	FGKM
Total number	1.7e19	7.4e20	7.6e20
Mean age of terrestrial planet (Gyr)	1.7	1.7	1.7
Terrestrial planets per $M_{\odot}$	0.049	2.2	2.2
Fraction lost to hot Jupiters	0.08	< 0.01	0.01
Fraction outside observed [Fe/H] range	0.36	0.38	0.38

cate a fraction  $\approx 0.1$  for solar-type stars (Petigura et al. 2013; Batalha 2014) and  $\approx 0.3-0.5$  for M dwarfs (Kopparapu et al. 2013; Dressing & Charbonneau 2015). These estimates are lower by factors of  $\approx 1/4$  (FGK hosts) and  $\approx 1/3-1/2$  (M dwarfs) compared to the occurrence rates adopted in section 2.1 ( $\approx 1/4$ ) for the full TP population. Hence, a first-order approach would be to simply scale down the number of planets in Table 1 and 2 by factors of this order.

So far, we have included all planets of size R = $1.0 - 2.0R_{\oplus}$  in our definition of TPs. However, the habitability of super-Earths (R = 1.5 - 2.0) is still a matter of debate. Seager et al. (2013) argue that super-Earths need to be studied in individual cases, as those that develop a gaseous envelope may not be very habitable. Adibekvan et al. (2015) also argue for a metallicity dependency for the potential habitability of super-Earths, arguing that super-Earths around metal-poor stars are found on tighter orbits than super-Earths around more metal-rich stars. By removing super-Earths from our estimates (and hence only including terrestrial planets of size  $R = 1.0 - 1.5 R_{\oplus}$ ), we reduce the occurrence rates of TPs in habitable zones to roughly half of those previously stated ( $\approx 0.04 \& 0.16$  for FGK-stars and M-dwarfs respectively).

Another open question is whether M-dwarfs can be associated with habitability in the same sense as solar-type stars. X-rays, extreme ultraviolet radiation and flares produced by low-mass stars may drastically erode a stable atmosphere and therefore the prospects of liquid water (e.g. Scalo 2007; Segura et al. 2015; Luger & Barnes 2015). Sengupta (2015) argue that only a handful of the M-dwarfs with confirmed planets in the habitable zone meet the criteria for having Earth-like habitable conditions. Planets within the habitable zone of low-mass stars may also experience synchronous rotation and be tidally locked (Kasting et al. 1993), leading to an unstable climate (Kite et al. 2011).

Hence, a most conservative approach could involve excluding M dwarfs from the habitability discussion altogether and simply consider the FGK planets in Table 1 and 2. Adopting this strategy and removing super-Earths from the TP inventory would then give an estimate of  $\sim 2 \times 10^{18}$  habitable planets around FGK stars in the observable Universe.

On galactic scales, there are possibly mechanisms other than the circumstellar habitable zone that affects the ability of planets to sustain life. Proposed effects include supernovae (e.g. Ruderman 1974; Lineweaver et al. 2004; Prantzos 2008; Gowanlock et al. 2011; Carigi et al. 2013; Spitoni et al. 2014; Dayal et al. 2015), gamma-ray bursts (e.g. Thomas et al. 2005; Ejzak et al. 2007; Piran & Jimenez 2014), active galac-

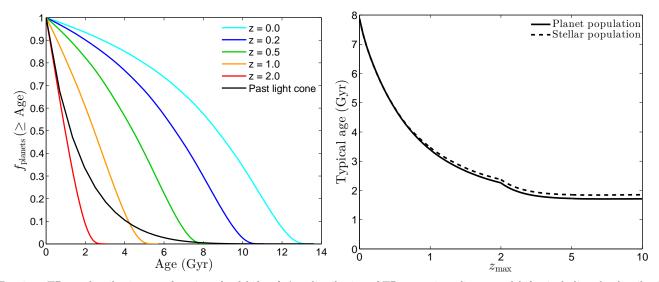


FIG. 7.— TP age distribution as a function of redshift. **a)** Age distribution of TPs at various discrete redshifts, including the distribution predicted when the entire observable Universe is considered. **b)** The average age of TPs around FGKM hosts within the volume on our past light cone out to limiting redshift  $z_{\text{max}}$ . The cosmic mean of 1.7 Gyr is reached at  $z \approx 5$ .

tic nuclei (Clarke 1981; Gonzalez 2005), cosmic rays (e.g. Atri et al. 2013), Oort cloud comet perturbations (e.g. Feng & Bailer-Jones 2014), encounters with interstellar clouds (Kataoka et al. 2013) and the dynamical and annihilation effects of dark matter (Rampino 2015). Mellot & Thomas (2011) presents an excellent review on various types of radiation-based threats to life.

While mechanisms of this type are outside the scope of this paper, the expected redshift trend (which is relevant for the SETI argument in section 4.3) is to make life on TPs more difficult to sustain at earlier times in the history of the Universe. High-redshift galaxies have higher specific star formation rates (e.g. Feulner et al. 2005) and a higher prevalence of active nuclei (e.g. Aird et al. 2012). Since high-redshift galaxies are also more compact (Shibuya et al. 2015), events of this type will affect larger number of planets, and the size evolution will also increases the Oort cloud perturbations due to close encounters with other stars.

#### 4.2. Why are we not living in an elliptical galaxy?

By convolving the mass distribution of TPs from Fig. 5 with the distribution of morphological types as a function of galaxy mass from Moffett et al. (2015), we estimate that 3/4 of TPs are locked up in spheroid-dominated galaxies (out of which  $\approx 1/2$  is elliptical galaxies and  $\approx$  1/4 early-type disks), and not in disk-dominated galaxies like the Milky Way (likely morphological type Sbc). This means, that if Earth had been randomly drawn from the cosmological population of TPs, the most likely outcome would seemingly have been for it not to be located in a Milky Way-type system. This, by itself, indicates a mild violation of the Copernican/mediocrity principle (mild, because our position isn't extremely im $probable^{6}$ ), but the balance could potentially be shifted back in favour of disk-dominated galaxies by habitability arguments. This requires that there is a mechanism that reduces the fraction of habitable TPs in spheroid-

dominated systems compared to disk-dominated ones. However, studies into the habitability of elliptical galaxies (Suthar & McKay 2012; Dayal et al. 2015) have so far not uncovered any such mechanism. In fact, Dayal et al. (2015) argue that massive ellipticals should exhibit much *better* conditions for life than the Milky Way (by orders or magnitude in terms of number of habitable planets at fixed stellar mass). Taken at face value, this would mean trouble for the mediocrity principle, as we would have to accept that we ended up where we are because of an unlikely lottery draw. But maybe there is more to the lottery than we have hither realized? There are several important differences between disks and spheroids that have so far received very little attention in the context of astrobiology – including the prevalence and properties of active galactic nuclei, the propagation properties of cosmic rays and the fraction of stars in high-density regions. More detailed studies of the impact that mechanisms of this type may have on the habitability of planets would be very valuable.

# 4.3. The prospects of extragalactic SETI

While most SETI projects have so far focused on the Milky Way, the case for Extragalactic SETI remains strong (e.g. Wright et al. 2014a; Zackrisson et al. 2015; Olson 2015). If the probability for the emergence of intelligent life is sufficiently small, we could well be the only advanced civilization in the Milky Way. If so, our only chance of detecting intelligent life elsewhere in the Universe would be to extend the search radius. Extragalactic SETI would also seem the only way to gauge the prevalence of civilizations very high on the Kardashev (1964) scale (close to type III), since the Milky Way does not appear to host such a super-civilization.

If one adopts the admittedly anthropocentric view that intelligent life primarily develops on TPs, then our results have some bearing on the maximum distance to which it would make sense to push extragalactic SETI. Naively, one would expect that the probability for the emergence of an advanced civilization in an given cosmological volume is proportional to the number of TPs, modulo some

 $<sup>^{6}</sup>$  Certainly no more so than the slight deviations between the properties of the Sun and other similar stars explored by Robles et al. (2008)

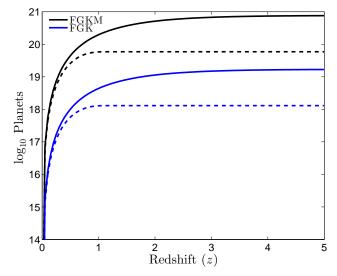


FIG. 8.— Cumulative number of TPs in the whole sky out to a given redshift. At high redshifts, these quantities tend towards the numbers relevant for the whole observable Universe. The black and blue lines refer to TPs around FGKM and FGK stars, respectively. Solid lines refer to all planets irrespective of age, whereas dashed lines refer to planets older than Earth.

correction for habitability and age effects.

By extending the redshift limit of such searches, one increases the cosmological volume probed, but since one is – due to the finite light travel time – at the same time probing earlier epochs in the history of the Universe, the number of TPs within the search radius does not increase indefinitely. As discussed in section 3.2 and shown in Figure 8, the cumulative growth of the number of planets in the observable Universe slows down considerably beyond the peak of cosmic star formation ( $z \approx 2$ ).

If one furthermore assumes that it typically takes several billion years for intelligent life to arise (some 4.5 Gyr in the case of humans – and please note that the Carter (1983) argument suggests that the typical time scale may be much longer than this), then only the  $z \leq 2$  part of the Universe becomes relevant. For TPs older than Earth, only a very small fraction (< 10%) will be at z > 0.8. When factoring in habitability considerations (section 4.1), which will tend to further favour the lowdensity environment in the low-redshift Universe, and the escalating difficulties in detecting signatures (either signals or signs of astroengineering) of intelligent lifeforms at large distances, it seems that the prospects of extragalactic SETI should peak at redshifts below  $z \approx 1-2$ .

#### 4.4. Comparison to previous studies

A small number of previous studies have attempted to assess the properties – both ages and absolute numbers – of terrestrial or Earth-like planets on cosmological scales. Here, we present a detailed comparison.

A coarse, early estimate of the total number of "habitable planets" (without clearly defining what was meant by this) in the observable Universe was presented by Wesson (1990). This estimate, despite being based on a different cosmological model and an unevolving galaxy population – happens to lie within two orders of magnitude of our more modern estimate. By assuming ~  $10^{10}$ habitable planets per galaxy and ~  $10^{10}$  galaxies in the Universe, Wesson argues for ~  $10^{20}$  habitable planets in the observable Universe. This is one order of magnitude higher than our TP estimate (Table 2) and about two orders of magnitudes higher than our estimate for the number of habitable planets around FGK stars (section 4.1).

Lineweaver (2001) estimate the average TP in the z = 0 Universe to be  $1.8 \pm 1.9$  Gyr older than Earth. While consistent with our estimate within the errorbars, this is still noticeably lower than our best estimate ( $\approx 3.5$ Gyr older than Earth; see Table 1). The discrepancy is largely driven by the much stronger metallicity dependence adopted by Lineweaver, which pushes the peak of TP formation forward in time by cutting off planet formation at subsolar metallicities (see Figure 1 for a comparison). The cosmic star formation history adopted by Lineweaver actually peaks somewhat earlier (by  $\approx 0.7$ Gyr) than what is supported by current observations (Madau & Dickinson 2014) and adopted in our models. Without the stronger metallicity selection, this would otherwise have driven the Lineweaver estimate to older ages than favoured in the current study.

Behroozi & Peeples (2015) also present formation time statistics for Earth-like planets (assumed to make up a fixed fraction of TPs around FGK stars) both in Milky Way-mass galaxies and over cosmological volumes at z = 0. Whereas our distributions appear very similar similar for galaxies in the mass range of the Milky Way, the look-back time to the median formation epoch that they derive for the full galaxy population lies  $\approx 0.7$  Gyr earlier than ours. As far as we can tell, this is unlikely to be due the differences in our planet occurrence recipes, but rather reflects slight differences in the star formation histories and metallicity distributions predicted by our respective semi-analytic models. Part of the reason for our younger ages also lies in the fact that our age statistics omit stars that have reached the end of their lifetimes by z = 0.

Behroozi & Peeples (2015) also report that there are  $\sim 10^{19}$  Earth-like planets on the past light cone, which – when taking into account the scaling factor of  $\approx 0.25$  between our mutual definitions of *terrestrial* and *Earth-like* – lies within a factor of a few from our estimate.

A simple and commonly used exercise to estimate the number of terrestrial/habitable/Earth-like planets in the observable Universe is to adopt a literature value for the corresponding number in the Milky Way, assign this number to the large number of galaxies detected in a deep, high-redshift survey like the Hubble Ultra Deep Field or the Hubble Extreme Deep Field, and correct the outcome for the limited sky coverage of the survey. This estimate neglects differences between high-redshift galaxies and the Milky Way (in terms of metallicity and mass) and the completeness of the imaging survey used. On the other hand, the modest difference in the number of planets per stellar mass in the Milky Way compared to the cosmic average (cmp. Table 1 & 2) implies that metallicity isn't the issue. Howevever, galaxy mass may still be. If we were to adopt our estimate for the number of TPs around FGKM stars in the Milky Way ( $\approx 1 \times 10^{11}$ ; see section 3.1), multiply by the number of galaxies in the Hubble Ultra Deep Field ( $\sim 10^4$ ) and correct for the limited sky coverage of the latter ( $\approx 7.4 \times 10^{-8}$ ), we would arrive at  $\approx 1.4 \times 10^{22}$  – almost a factor of 20 higher than

our estimate.

The primary reason for this discrepancy is that the typical galaxy mass on our past lightcone is *lower* than that of the Milky Way – in our simulations, the average galaxy mass in the observable Universe (without any weighting by the probability of this object to host TPs) is  $\approx 4 \times 10^9 M_{\odot}$ . After applying this correction, this observational method results in an estimate that lies within a factor of  $\approx 2$  of our result.

#### 4.5. Uncertainties

A study such as this, which attempts to extrapolate results on the TP population from our local neighbourhood to the whole Universe obviously carries substantial uncertainties. In the following, we attempt to identify the factors that dominate the error budget, and to attach reasonable error bars to our main results.

#### 4.5.1. Galaxy formation

The results presented in this paper rely heavily on semi-analytic models of galaxy formation to trace the formation of TPs across space and time, but consistency checks using observational data can in some cases be carried out to test the robustness of our results. For instance, the average age of TPs is primarily determined by the cosmic star formation history, and while the star formation history predicted by GALFORM is already in reasonable agreement with observations at  $z \leq 8$ , we can derive an alternative estimate by simply adopting the fitting function for the cosmic star formation history presented by Madau & Dickinson (2014) while keeping the metallicity distribution from GALFORM. The resulting average age differs from that presented in Table 1 by  $\approx 0.2$  Gyr and in Table 2 by  $\approx 0.01$  Gyr. This approach also alters the total number of planets in the observable Universe by  $\approx 20\%$ . A comparison between our best estimate on the number of planets in the observable Universe and that resulting from either the Behroozi & Peeples (2015) study, or from attaching the model-inferred number of planets per galaxy to galaxy counts in deep fields (section 4.4), suggests consistency to within a factor of a few. We therefore adopt a conservative 0.5 dex uncertainty on all estimates on estimates of planet numbers in Table 2. We take the outcome of the comparison to the results of Behroozi & Peeples (2015) (section 4.4) to reflect the likely age uncertainties stemming from systematic uncertainties in semi-analytic models and adopt a 0.1 dex error on all age estimates.

#### 4.5.2. Cosmological parameters

Uncertainties on the parameters of the adopted cosmological model (within the framework of  $\Lambda$ CDM cosmology) primarily translate into an uncertainty on the age of the Universe as a function of redshift and on the calculation of cosmological volumes in our analysis, thereby shifting the age scale for the cosmic population of TPs and the planet counts. However, variations in  $\Omega_M$ ,  $\Omega_\Lambda$  and  $H_0$  at the level motivated by the differences between the parameter sets favoured by the recent WMAP-9 (Hinshaw et al. 2013) and Planck (Planck collaboration 2015) surveys have a relatively small impact on our results, amounting to age uncertainties of < 0.1 Gyr and  $\approx 0.2$  dex uncertainties in

planet counts. A somewhat larger uncertainty comes from the fact that the galaxy catalogs originally generated by GALFORM (Baugh 2005) were based on the  $\Omega_M = 0.3, \ \Omega_{\lambda} = 0.7, \ H_0 = 70 \ \mathrm{km \ s^{-1} \ Mpc^{-1}}$  version of the  $\Lambda$ CDM cosmology, with  $\sigma_8 = 0.93$  (a somewhat higher power spectrum normalization than favoured by the Planck collaboration 2015), whereas the Galacticus catalogs were originally based on  $\Omega_M = 0.25$ ,  $\Omega_{\lambda} = 0.75$ ,  $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}, \sigma_8 = 0.9.$  However, the shift in the age-redshift relation resulting from these slight inconsistencies remains at the < 0.3 Gyr level. Other effects on the predicted galaxy population are degenerate with the many assumptions going into the semi-analytic machinery, giving errorbars on planet counts that are likely to be captured by the 0.5 dex uncertainty we argue for in section 4.5.1.

#### 4.5.3. Stellar initial mass function

The results presented in this paper are based on the assumption that the fraction of FGKM stars can be estimated using Kroupa (2001) stellar initial mass function (IMF). Alternative IMFs, like the log-normal form proposed by Chabrier (2003) will inevitably lead to slightly different ratios of solar-type to low-mass stars. To assess how this affects our estimates of the number of TPs, we have recomputed the planet formation history assuming the Chabrier (2003) instead of the Kroupa (2001) IMF when estimating the fraction of FGK and M stars forming within each age bin of the simulated galaxies. Since the Chabrier (2003) IMF is predicting a smaller fraction of stellar mass locked up in low-mass stars, the number of FGK stars is boosted at the expense of type M stars. As a result, the number of TPs around FGKM stars is reduced by  $\approx 40\%$  while the corresponding number around FGK stars is boosted by  $\approx 30\%$ . No significant changes in planetary ages are introduced because of this. However, the possibility that the stellar IMF may be a function of both time and environment has been raised (e.g. Chabrier et al. 2014), and this could introduce uncertainties larger than the ones considered here.

#### 4.5.4. Planet formation

The occurrence rates of TPs at low metallicities are admittedly highly uncertain, but as argued in Section 3.1, our results are remarkably robust to the reasonable adjustments of the planet occurrence recipe at the low metallicity end, simply because of the low fraction of low-metallicity stars. Adopting the minimum metallicity for the formation of low-mass planets (including the TPs discussed here) of  $[Fe/H] \lesssim -1.8$  advocated by Hasegawa & Pudritz (2014) would affect the number estimates at the sub-percent level. By assuming a step function similar to that of Prantzos (2008) with a steep drop in probability to form terrestrial planets at [Fe/H] = -1.0, we decrease the total number of terrestrial planets on our past light-cone by < 5%. On the other hand, in a scenario where terrestrial planet formation has no metallicity dependency at all and we let the occurrence of terrestrial planets be constant at the low-metallicity end, we obtain an increment of terrestrial planets by < 3%.

The possibility that TPs may reform in the wake of migrating Jupiters (e.g. Fogg & Nelson 2009) may boost

the fraction of TPs somewhat, but according to our estimates (Tables 1 and 2), this only affects the total population of TPs at the < 10% level.

When it comes to the fraction of TPs in the circumstellar habitable zone, the uncertainties become much larger, since the observational occurrence rate of such planets around FGK stars alone is uncertain by almost an order of magnitude (e.g. Lissauer et al. 2014), and the the habitability of both M-dwarfs and super-Earths are debatable.

# 4.5.5. Total error budget

Based on the considerations above, we adopt an error of  $\pm 0.1$  dex on our age estimates and an error on the total number of TPs of 0.5 dex. This does not, however, include uncertainties related to potential variations of the shape/slope of the stellar initial mass function at the low-mass end with time and/or environment, since such variations remain poorly constrained and could have a very large impact on the number of M dwarfs.

#### 5. SUMMARY

Our model for cosmic planet formation indicates that:

- The average age of TPs orbiting FGK and M stars is  $\approx 8 \pm 1$  Gyr for the local volume and  $1.7 \pm 0.2$ Gyr for TPs in the whole observable Universe (on our past light cone). The lower age in the latter case stems from the lookback-time effect, in which distant regions of the Universe are seen at an earlier cosmic epochs.
- While most TPs in the local Universe are sitting in galaxies slightly more massive (average stellar population mass  $\approx 8-9 \times 10^{10}$ ) than the Milky Way, most TPs on our past light cone are in lowermass galaxies (average stellar population mass  $\approx$  $2 \times 10^{10}$ , i.e. a factor of  $\approx 2-3$  lower than that of the Milky Way).
- The number of TPs per unit stellar mass at  $z \approx 0$ remains almost constant for galaxies in the stellar mass range ~  $10^9-10^{11} M_{\odot}$ , but drops sharply for galaxies with masses <  $10^8 M_{\odot}$  due to the low metallicities of such systems. Whereas large satellite galaxies like the LMC are expected not to be depleted in TPs, the ultrafaint dwarf galaxies detected in the vicinity of the Milky Way are expected

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to contain very few such planets. The TPs in the LMC are expected to have an average age of 0.2Gyr (FGK hosts) to 1 Gyr (M dwarf hosts) older than Earth.

- The total number of TPs in a Milky way-mass galaxy at z = 0 is  $\log_{10} N_{\rm TP} \approx 9.3 \pm 0.5$  for TPs around FGK stars and  $\log_{10} N_{\rm TP} \approx 11.0 \pm 0.5$  for TPs around M dwarfs.
- The number of TPs in the whole observable Universe are  $\log_{10} N_{\rm TP} \approx 19.2 \pm 0.5$  (FGK hosts) and  $\log_{10} N_{\rm TP} \approx 20.9 \pm 0.5$  (M dwarf hosts).
- About 1/3 of the TPs in the local Universe are orbiting stars at metallicities lower than those for which such planets have so far been detected.
- About 3/4 of the TPs in the local Universe are located in spheroid-dominated galaxies. This implies a mild violation of the Copernican/mediocrity principle, which seems to be further augmented when supernova sterilization in different types of galaxies is taken into account (Daval et al. 2015). We speculate that some hitherto unrecognized mechanism related to the habitability of spheroidal systems may explain this anomaly.
- Only a small fraction ( $\leq 10\%$ ) of the TPs on our past light cone are at redshifts  $z \geq 3.3$ , and when considering the subset of these planets older than Earth, this redshift limit drops to  $z \gtrsim 0.8$ . Under the assumption that the emergence of intelligent life is tied to the formation of TPs, the prospects of extragalactic SETI efforts are therefore expected to peak at relatively low redshifts.

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