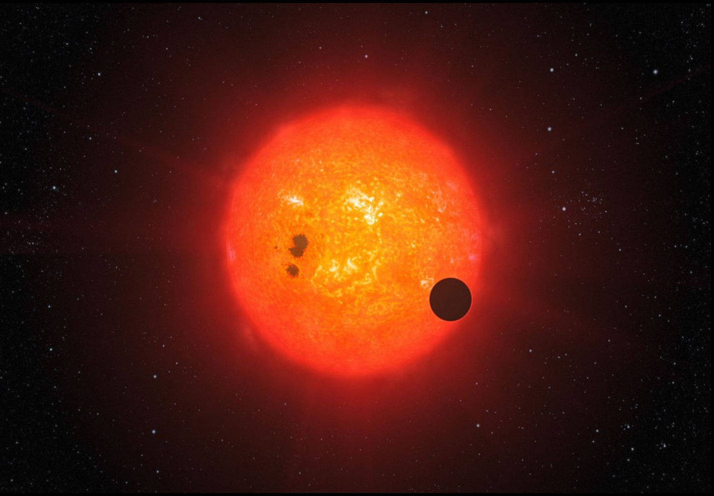


Seek a minor Sun:

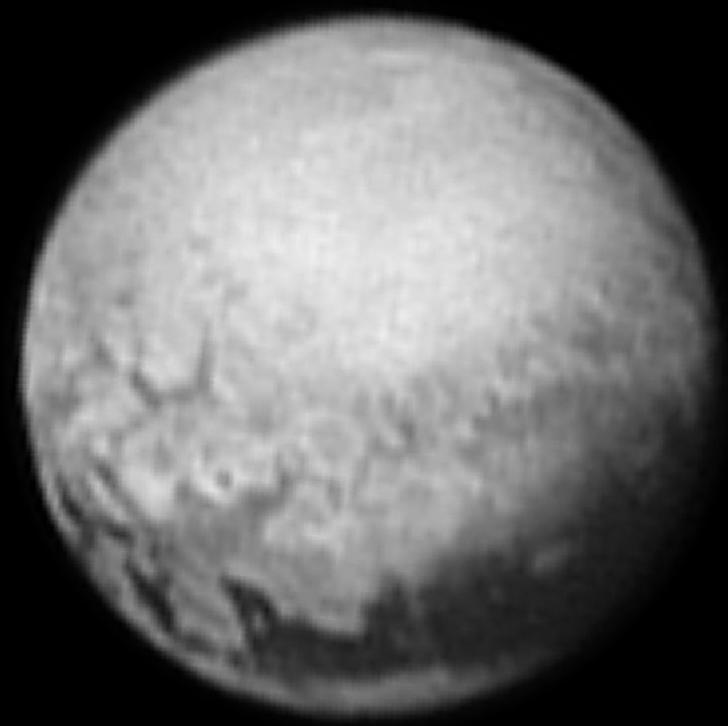
The Distrbution of Habitable Planets in the Hertzsprung-Russell-Rosenberg Diagram

Eric Gaidos

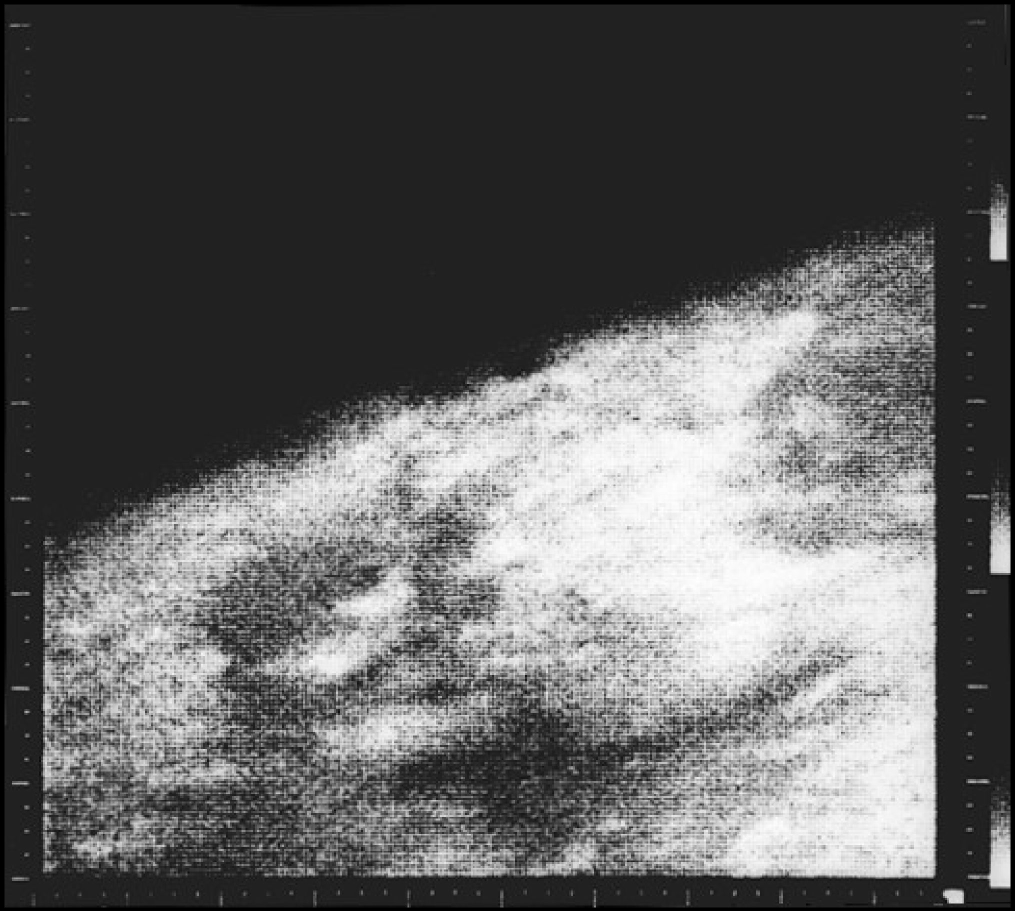
Department of Geology & Geophysics, University of Hawaii
and Observatoire de Sauverny, University of Geneva

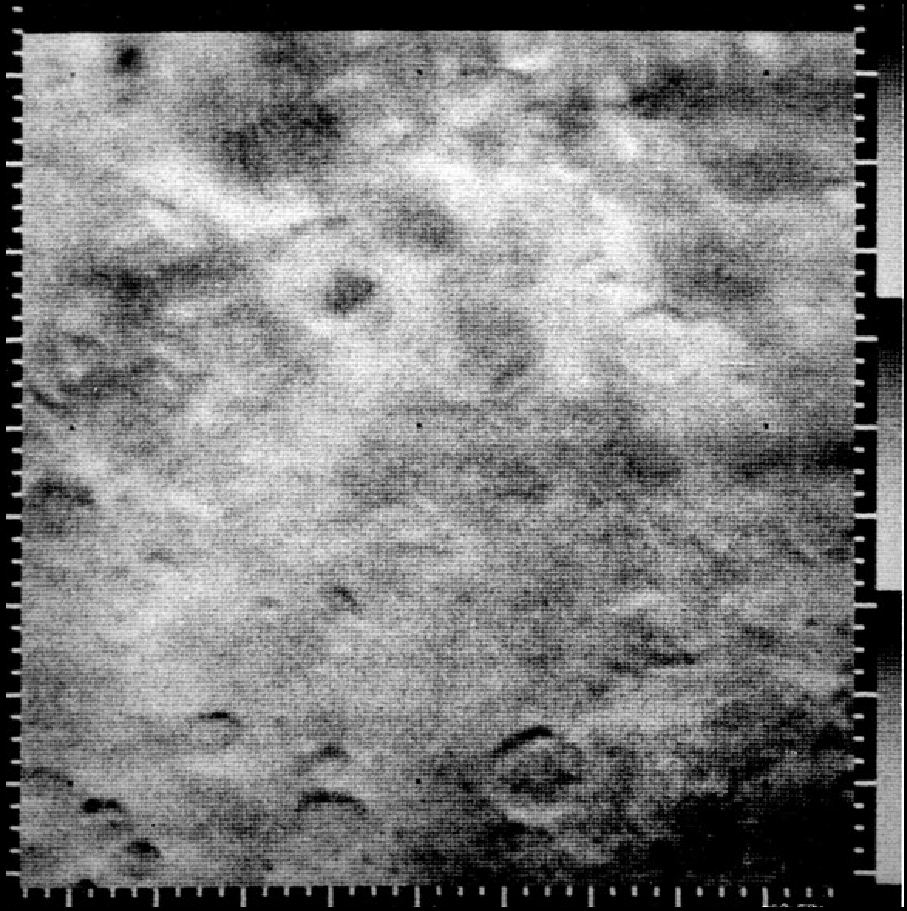

Jupiter
Venus
A Planetary Conjnction from Cyprus

Pluto Encounter: July 14, 2015

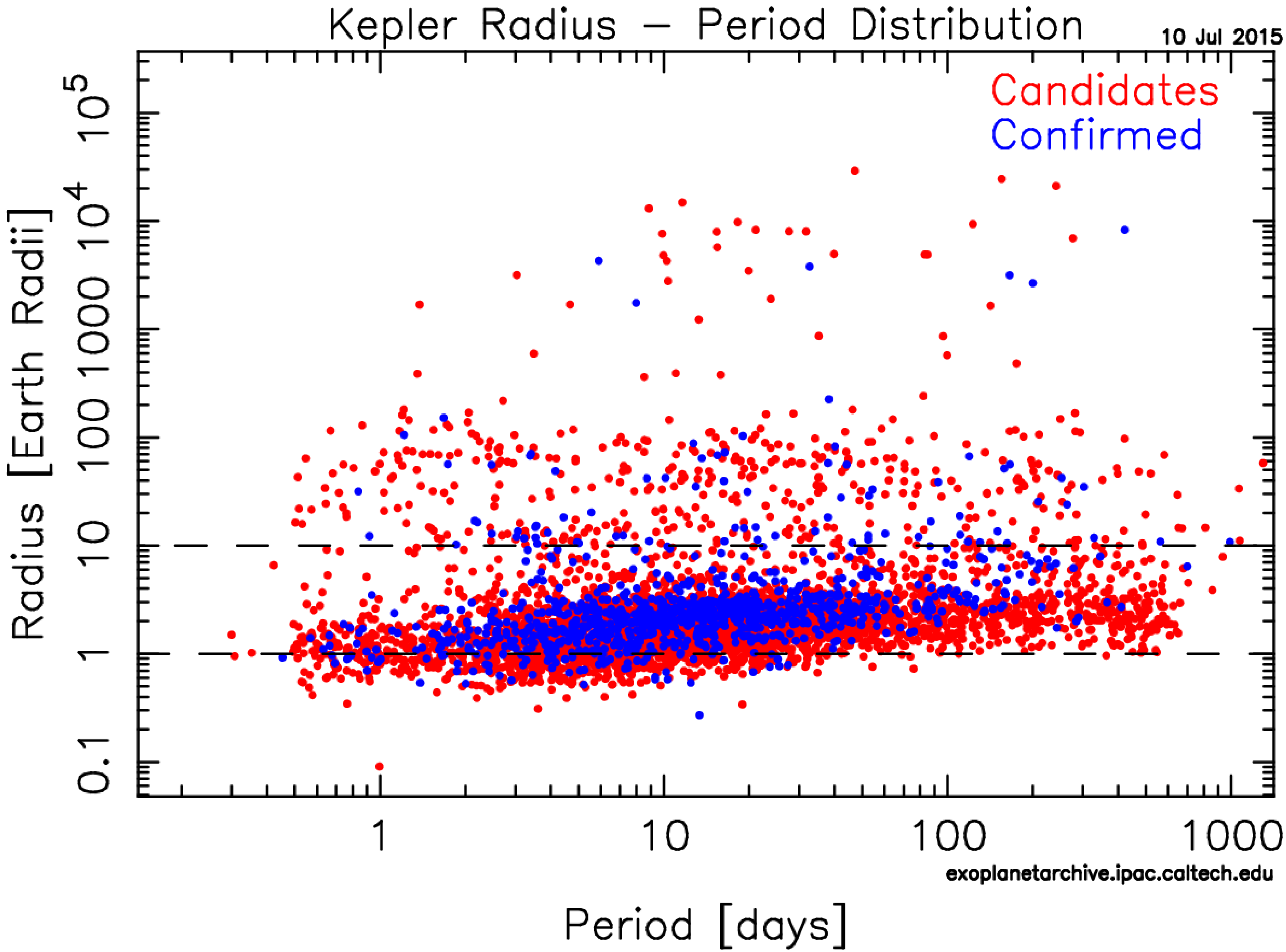


Mars Encounter: July 14, 1965

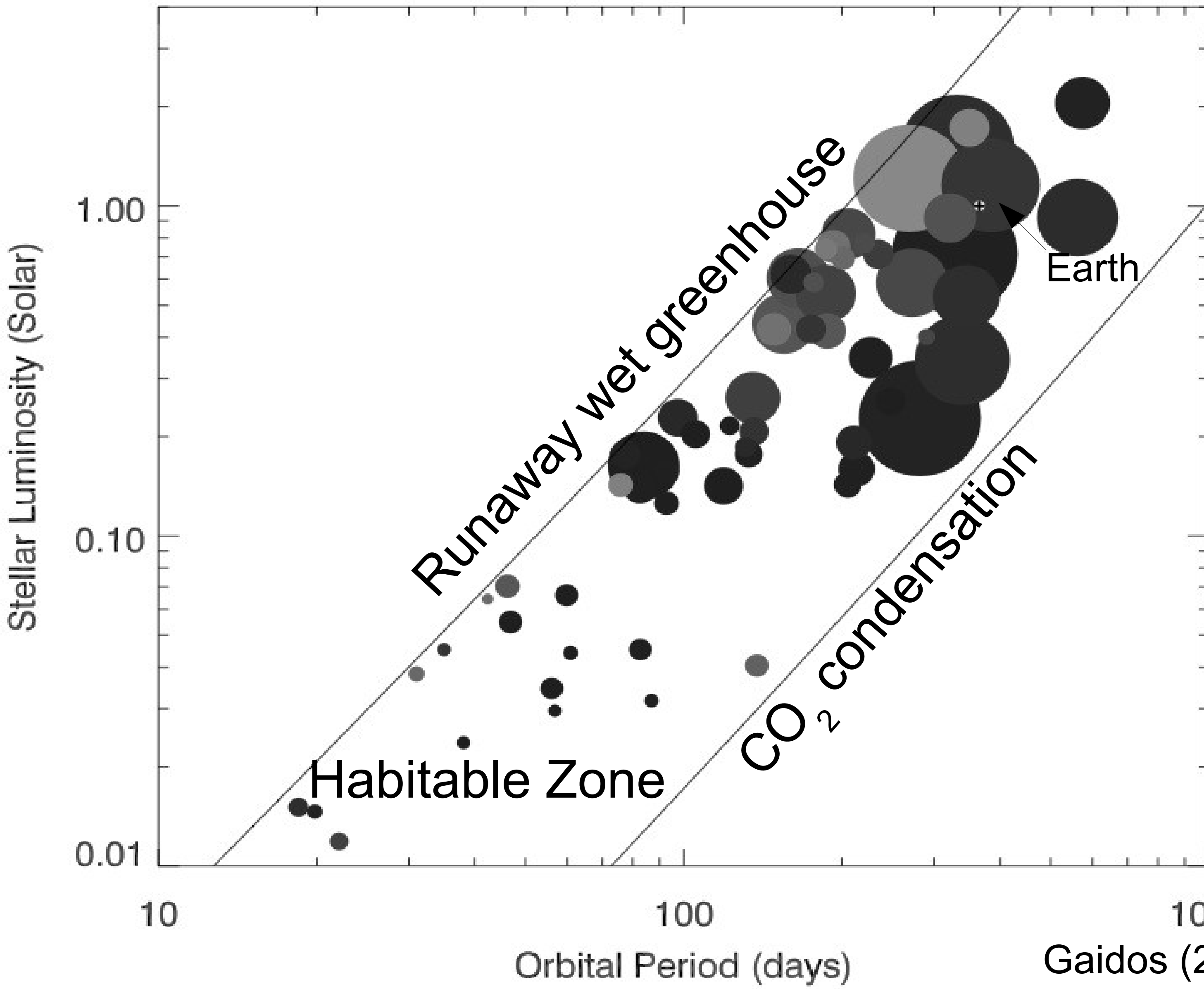




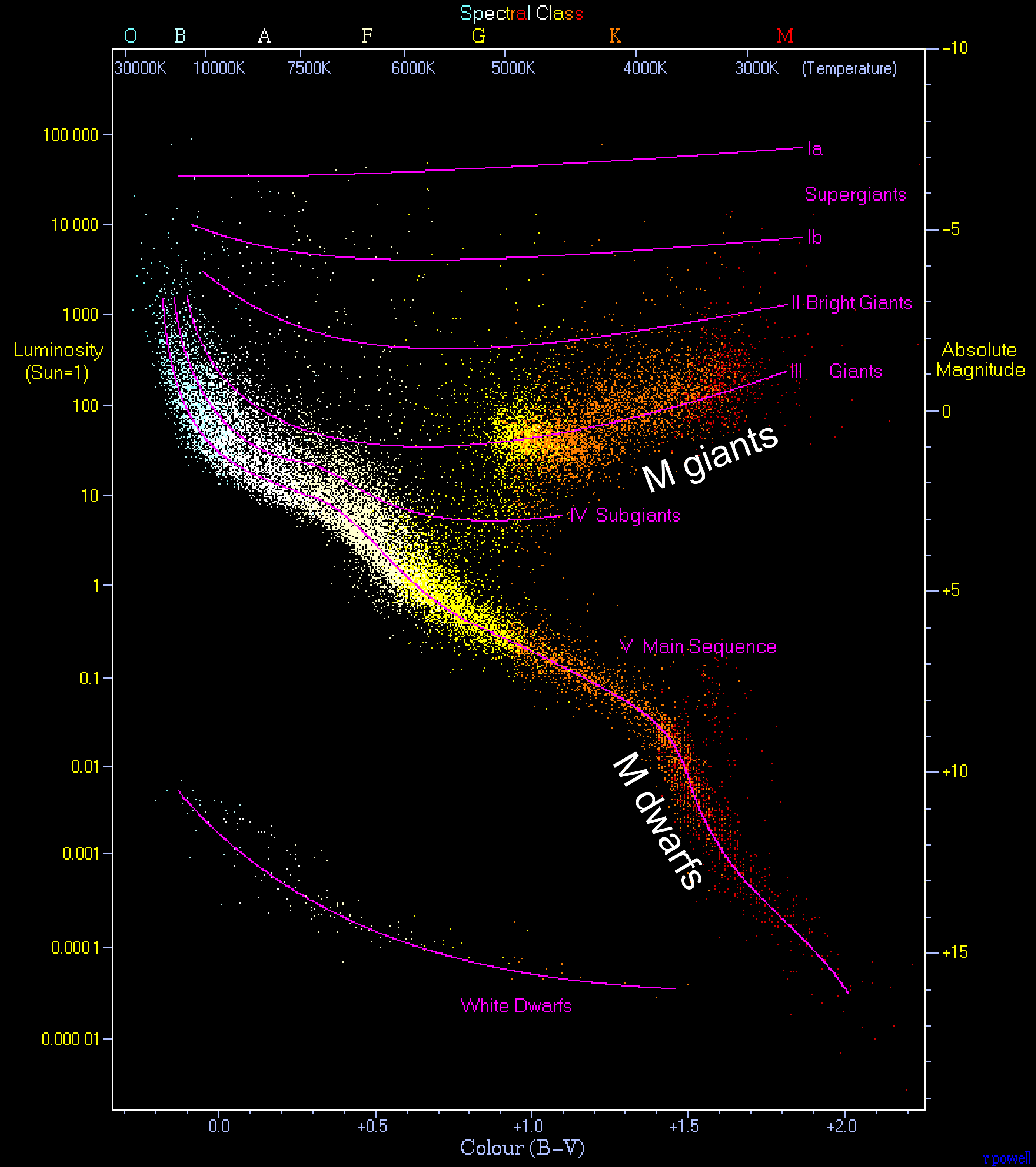
Points of Darkness in the Sky of Modern Astronomy



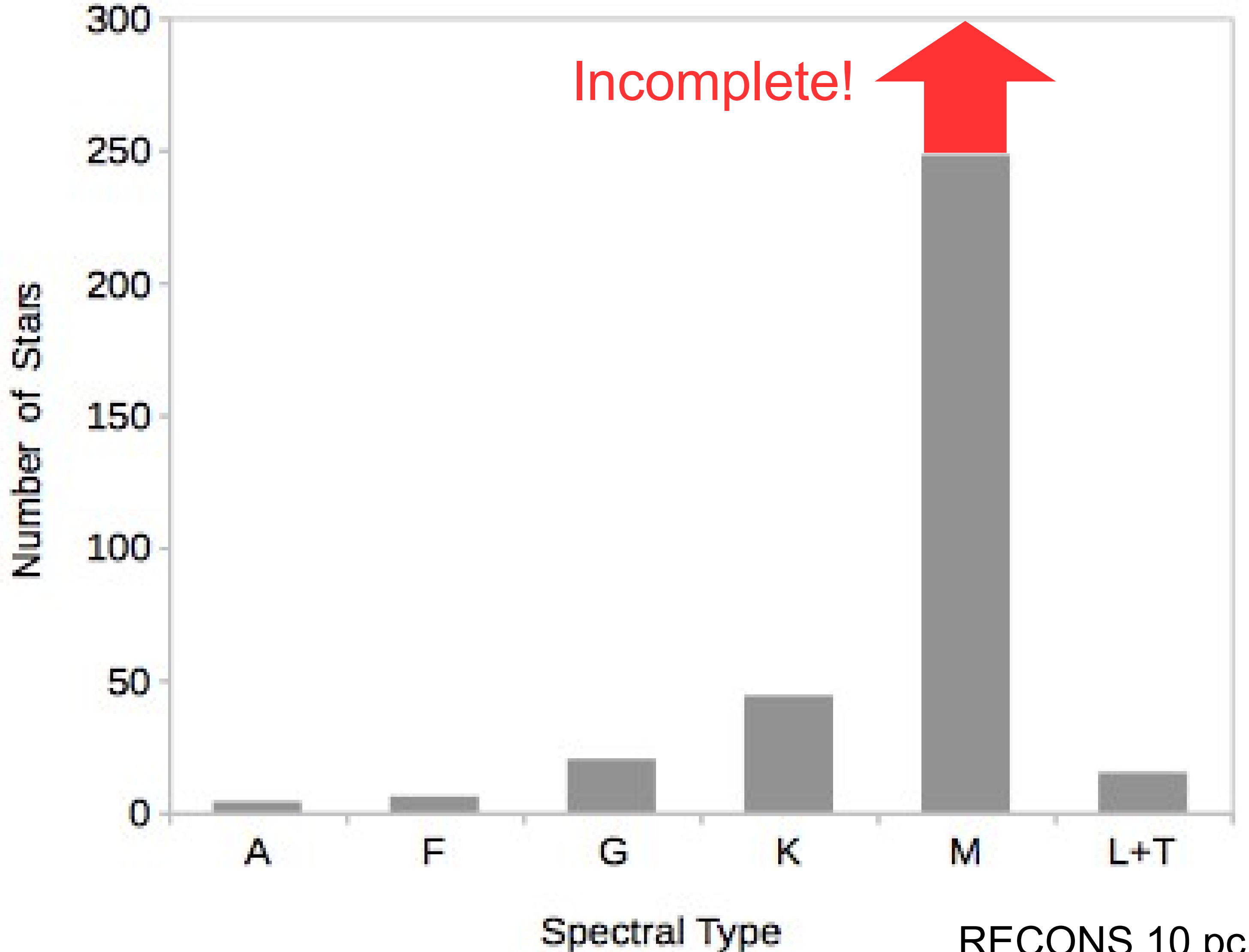
Most Small Candidate Planets in the "Habitable Zone" Orbit M Dwarfs



Gaidos (2013)

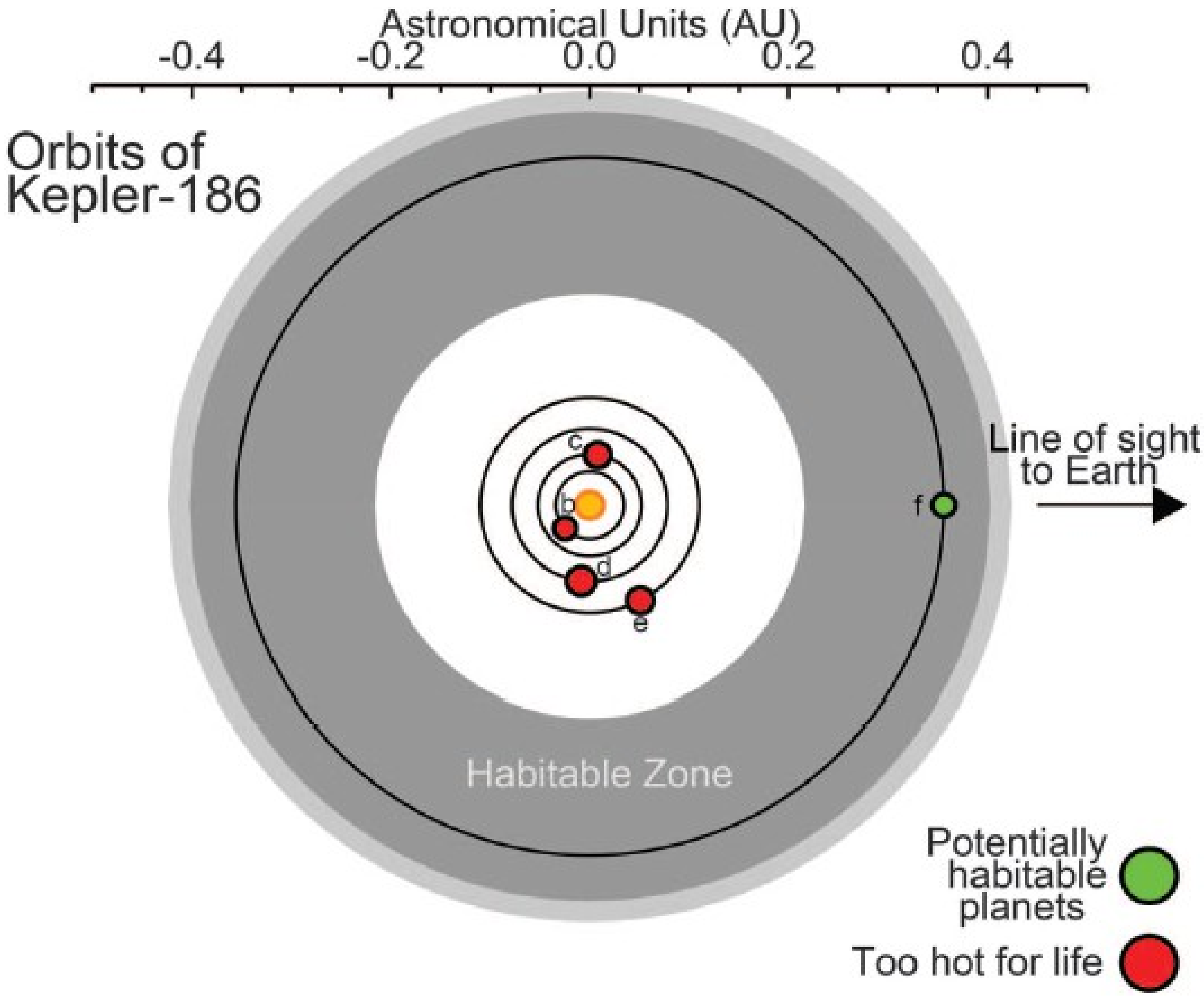

Spectral Class
O
B
A
F
G
K
M
30000K
10000K
7500K
6000K
5000K
4000K
3000K
(Temperature)
Luminosity (Sun=1)
100 000
10 000
1000
100
10
1
0.1
0.01
0.001
0.0001
0.000 01
Absolute Magnitude
-10
-5
0
+5
+10
+15
Ia
Supergiants
Ib
II Bright Giants
III Giants
IV Subgiants
V Main Sequence
White Dwarfs
M giants
M dwarfs
0.0
+0.5
+1.0
+1.5
+2.0
Colour (B–V)
r powell

At least 75% of nearby stars are M dwarfs



RECONS 10 pc survey

“Confirmed” Earth-Size Planets in the Habitable Zone



Quintana et al. (2014)

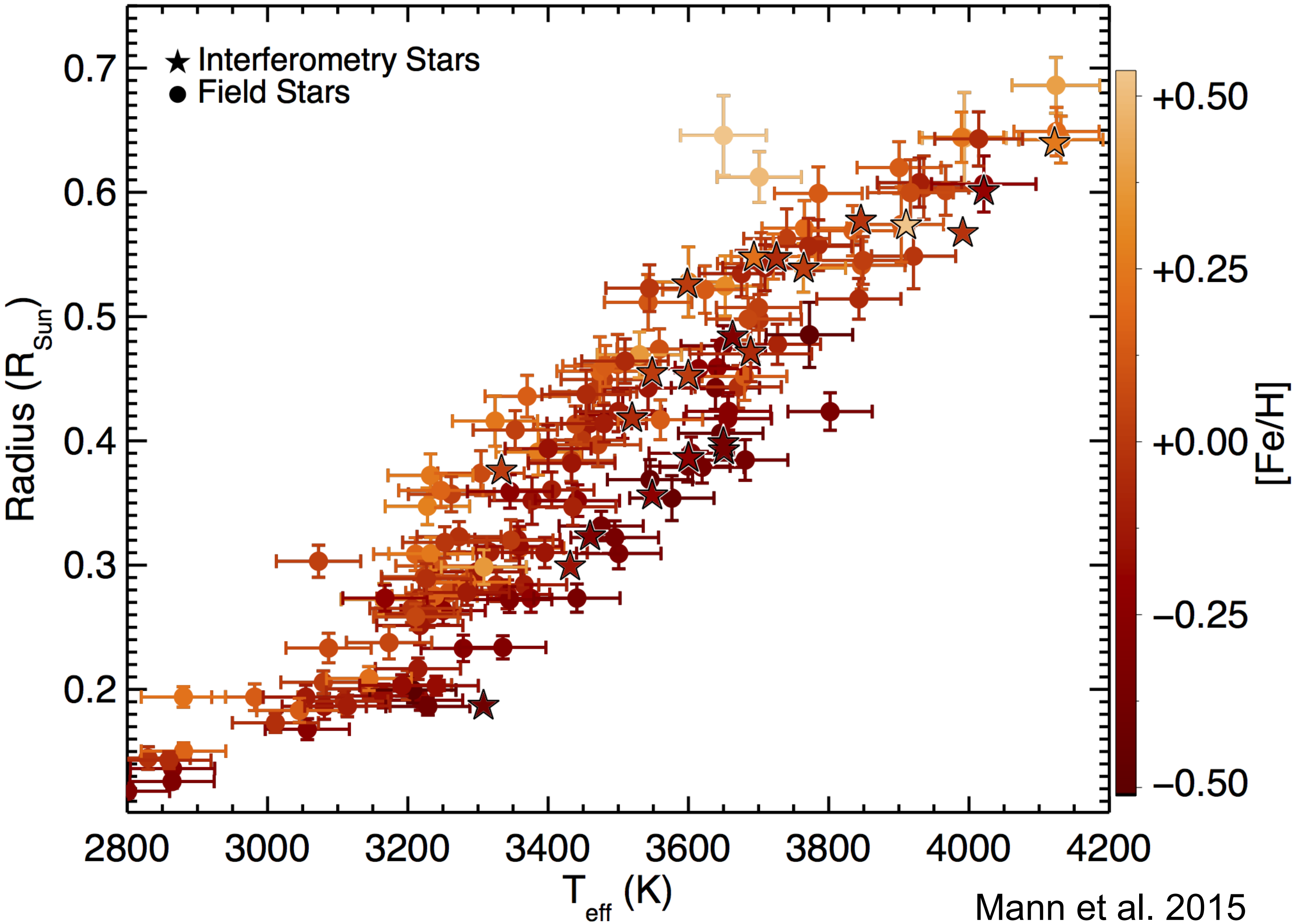
Habitable “Real Estate” in the Galaxy

Table 10
Total EHZ by Spectral Type

SpType	5 pc Sample No. of Stars	EHZ (AU)	Total 10 pc Sample No. of Stars	EHZ (AU)
A	0(1)	...	3 (4)	13.2
F	0(1)	...	4 (6)	4.9
G	3	2.6	14 (21)	11.9
K	7	2.9	34 (35)	15.4
M	48(50)	3.3	384*(400)*	26.1*

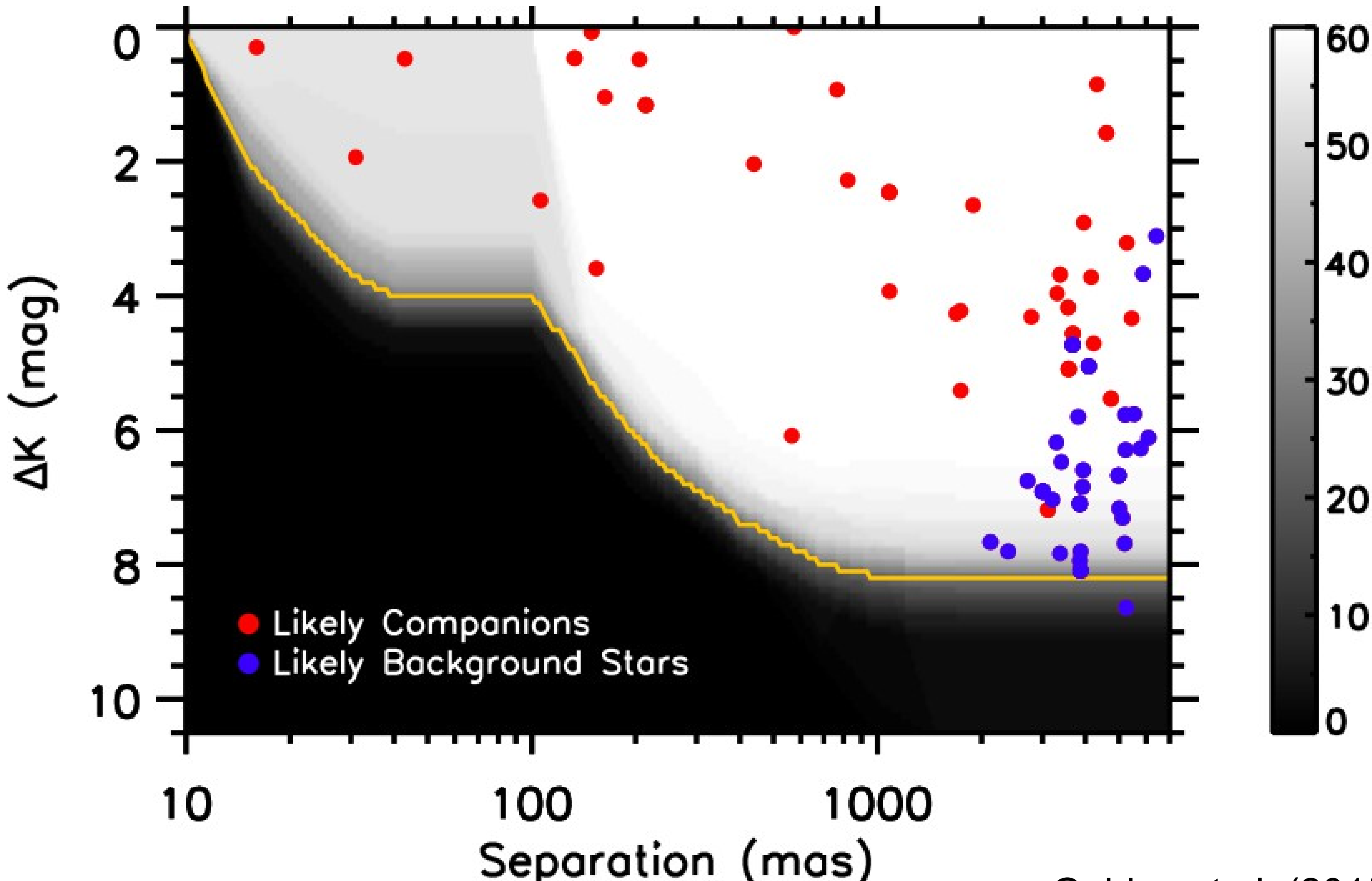
Cantrell et al. (2013)

A New Temperature-Metallicity-Radius Relationship for M Dwarf Stars



Mann et al. 2015

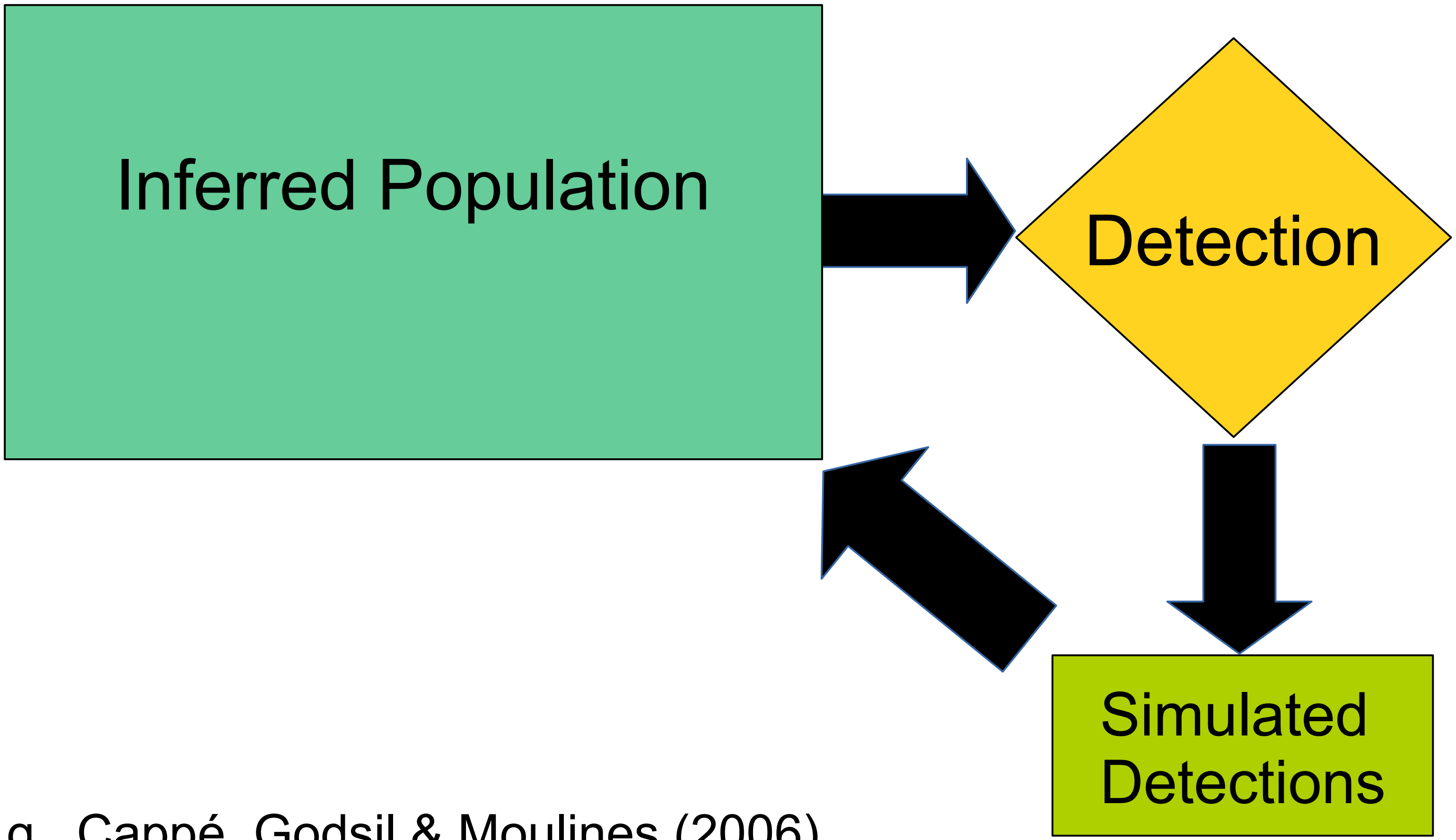
Adaptive Optics and Non-Redundant Aperture Masking Imaging



Gaidos et al. (2015)

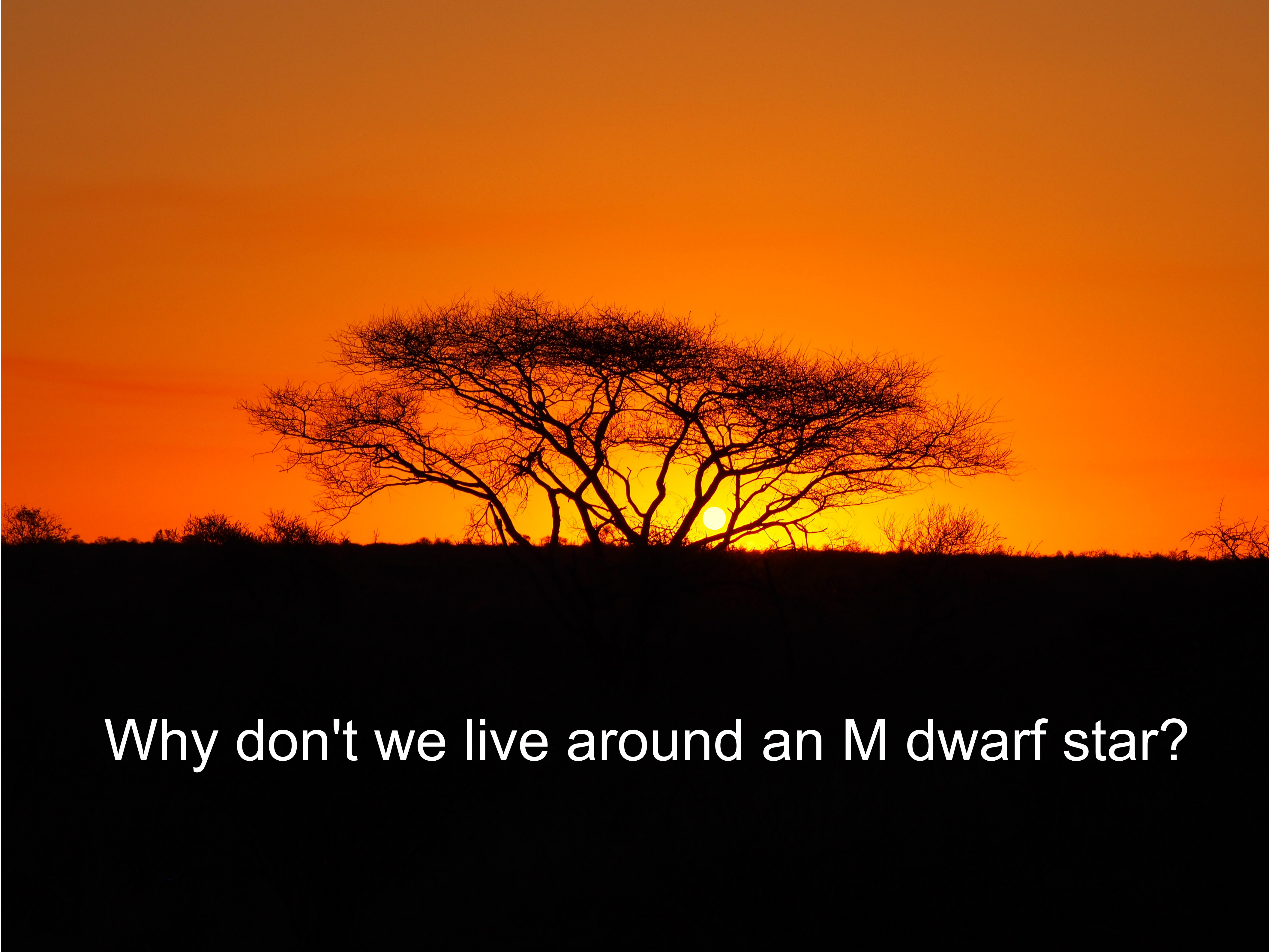
Bin-less Estimation of the Planet Population

Method of Iterative Monte Carlo (MIMC)



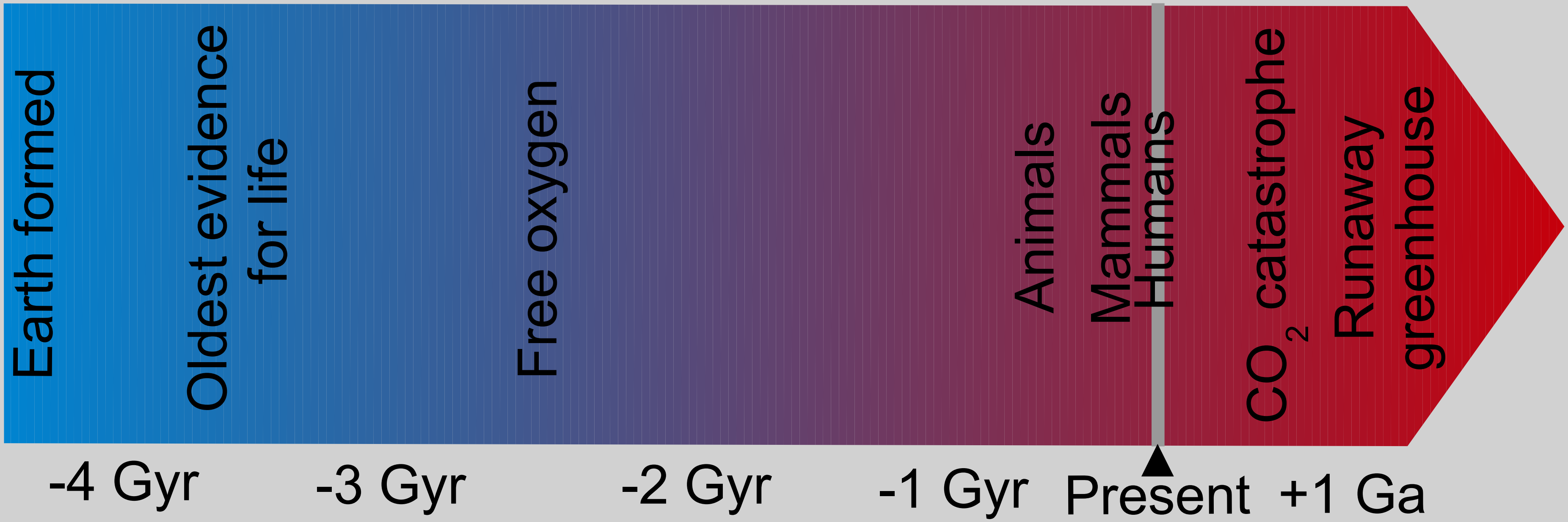
See: e.g., Cappé, Godsil & Moulines (2006)

Silburt et al. (2015)


Why don't we live around an M dwarf star?

Emergence of Intelligence on Earth: Just in Time?

Why so early?



Why so late?

- Complete coincidence
- Life evolves inevitably and rapidly on suitable planets (Sagan conjecture)
- Life (and intelligence) almost never evolves and the timing is a selection effect (Carter conjecture)
- Our understanding of lifetime of Earth's biosphere is incorrect

The Carter Conjecture and Statistics of Rare Events

"Hard Steps" in the Evolution of Life

t_{max} = maximum time for success

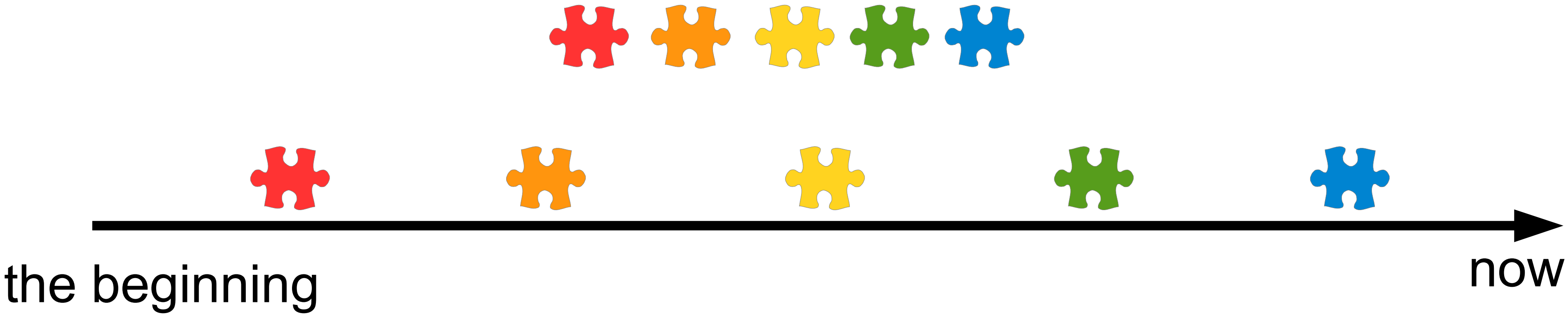
t_e = mean time between successes

$$Easy: t_e << t_{\max}$$
$$\langle t \rangle = t_e$$
$$p(success) \approx 1$$

$$Hard: t_e >> t_{\max}$$
$$\langle t \rangle = \frac{1}{2} t_{\max}$$
$$p(success) = \frac{t_{\max}}{t_e} << 1$$

Carter (1983)

The Case of Multiple Hard Steps

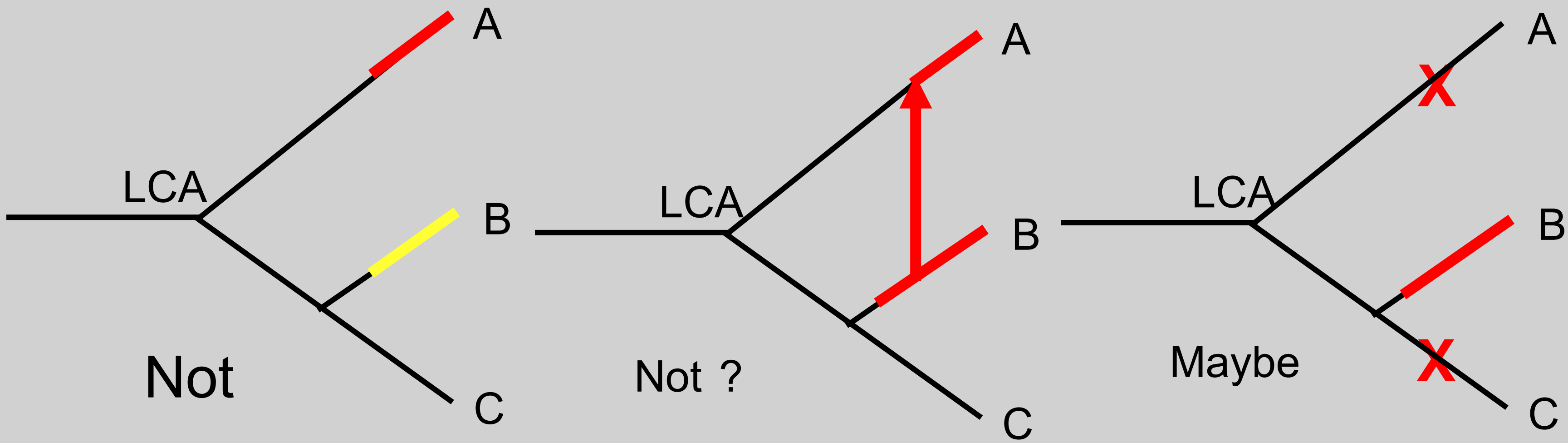


N hard steps: $\langle t_N \rangle = \frac{N}{N+1} t_{\max}$ $\quad p_N \sim \left(\frac{t_{\max}}{t_e} \right)^N$

For Earth:

t_{max} = 5.2 Gyr and t_N = 4.5 Gyr → N ~ 6

If N ≠ 1 Which Evolutionary Steps Were "Hard"?

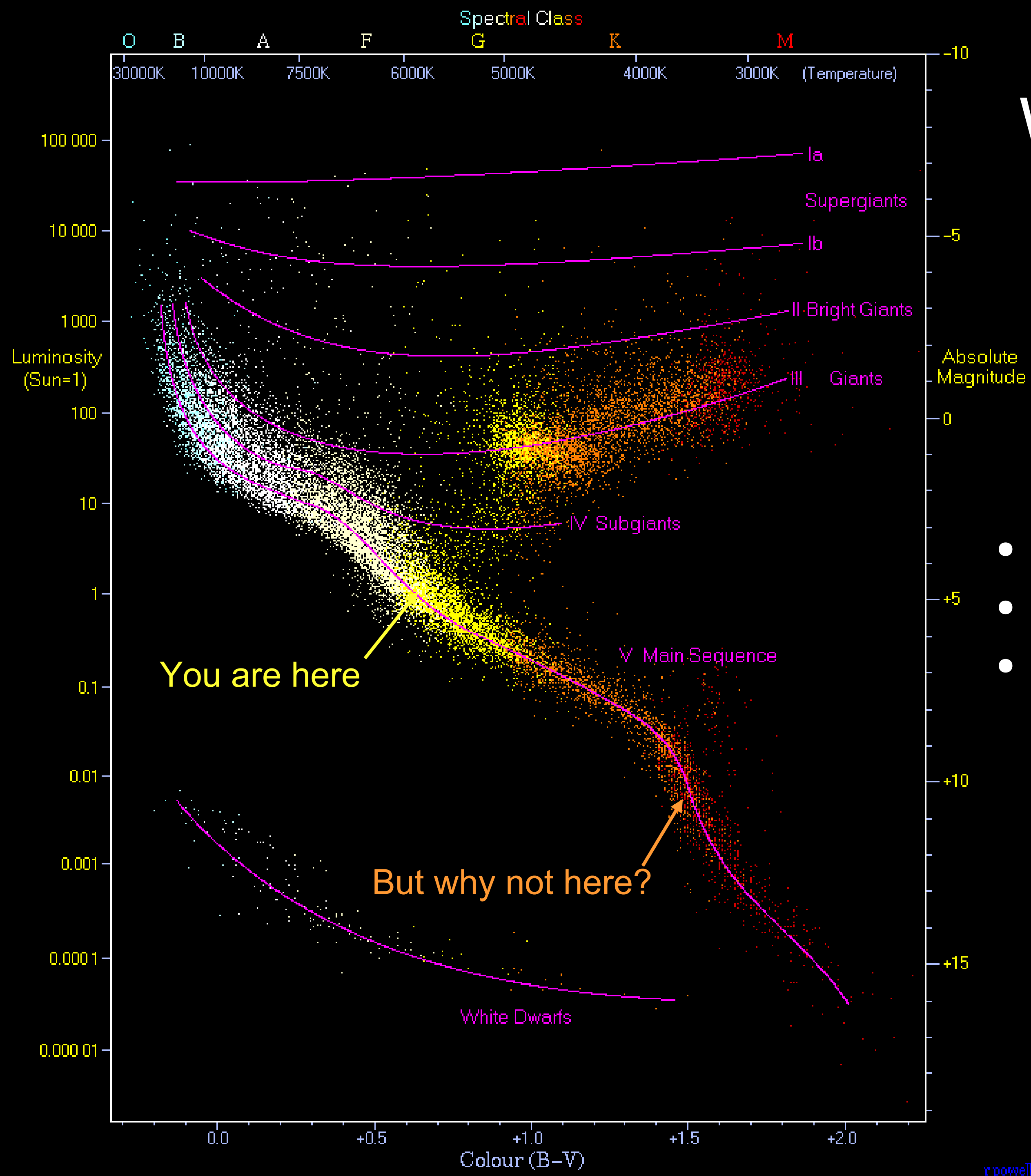


~~Use of sunlight as energy source~~

~~Multicellularity~~

~~Evolution of large brains or "intelligence"~~

Oxygenic photosynthesis?



Why not M dwarfs?

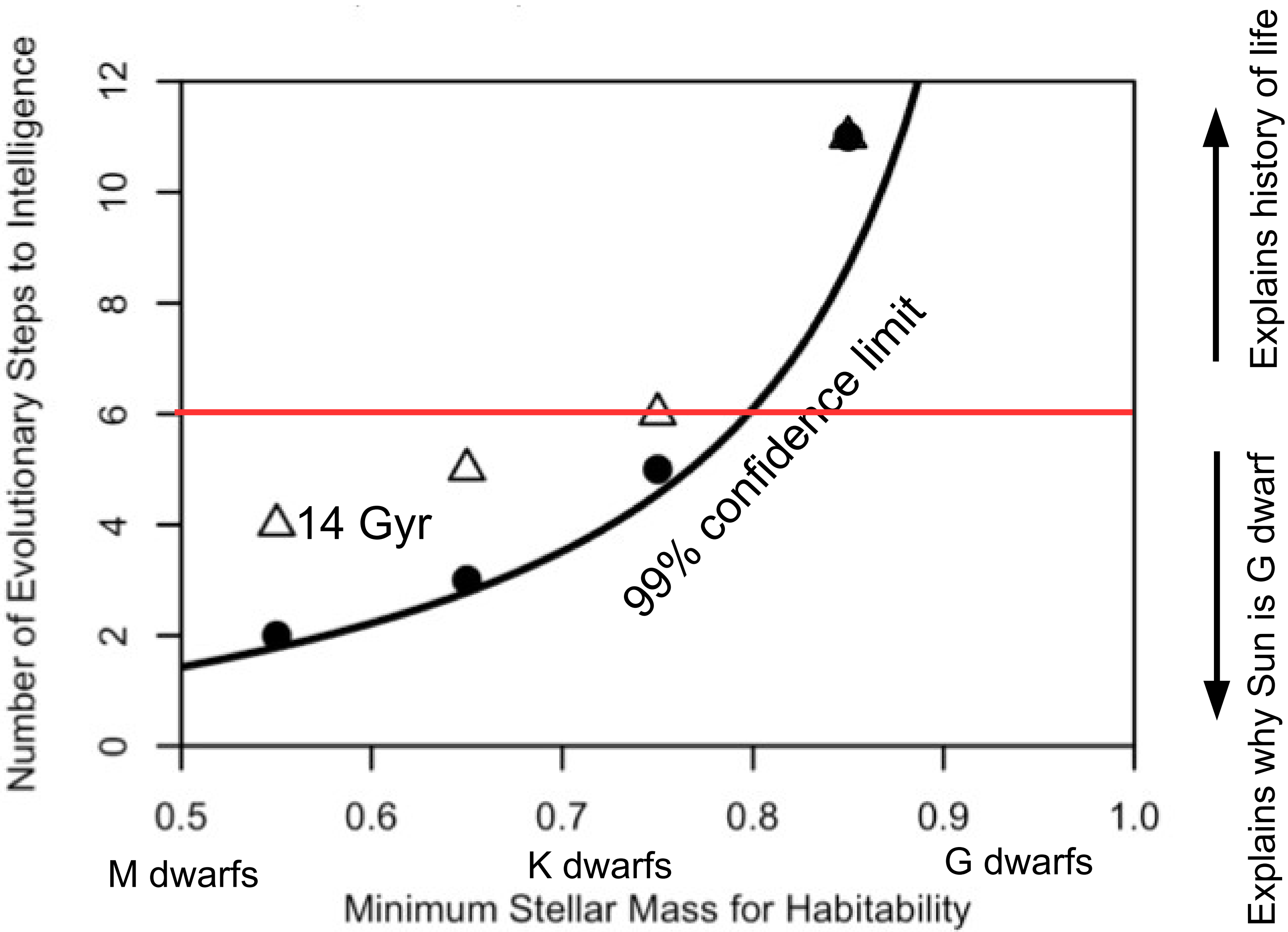
- Many more M dwarfs
- More planets per star
- Longer main sequence life

Quantifying the Odds

Probability of intelligence around a star of mass M_S	$P(M_S) = n_{stars}(M_S)\, x\, p_N(t_{\max})$
Number of stars (IMF)	$n_{stars} \sim \frac{1}{M_S^{3.6}}$
Time planet spends in the HZ	$t_{\max} \sim \frac{1}{M_S^{3}}$
Probability of N successes	$p_N \sim t_{\max}^{N}$
Resulting scaling law	$P(M_S) \sim \frac{1}{M_S^{3N+3.6}}$

If N = 6 then M dwarf star hosts favored by a factor of 400,000,000

Avoiding the Paradox

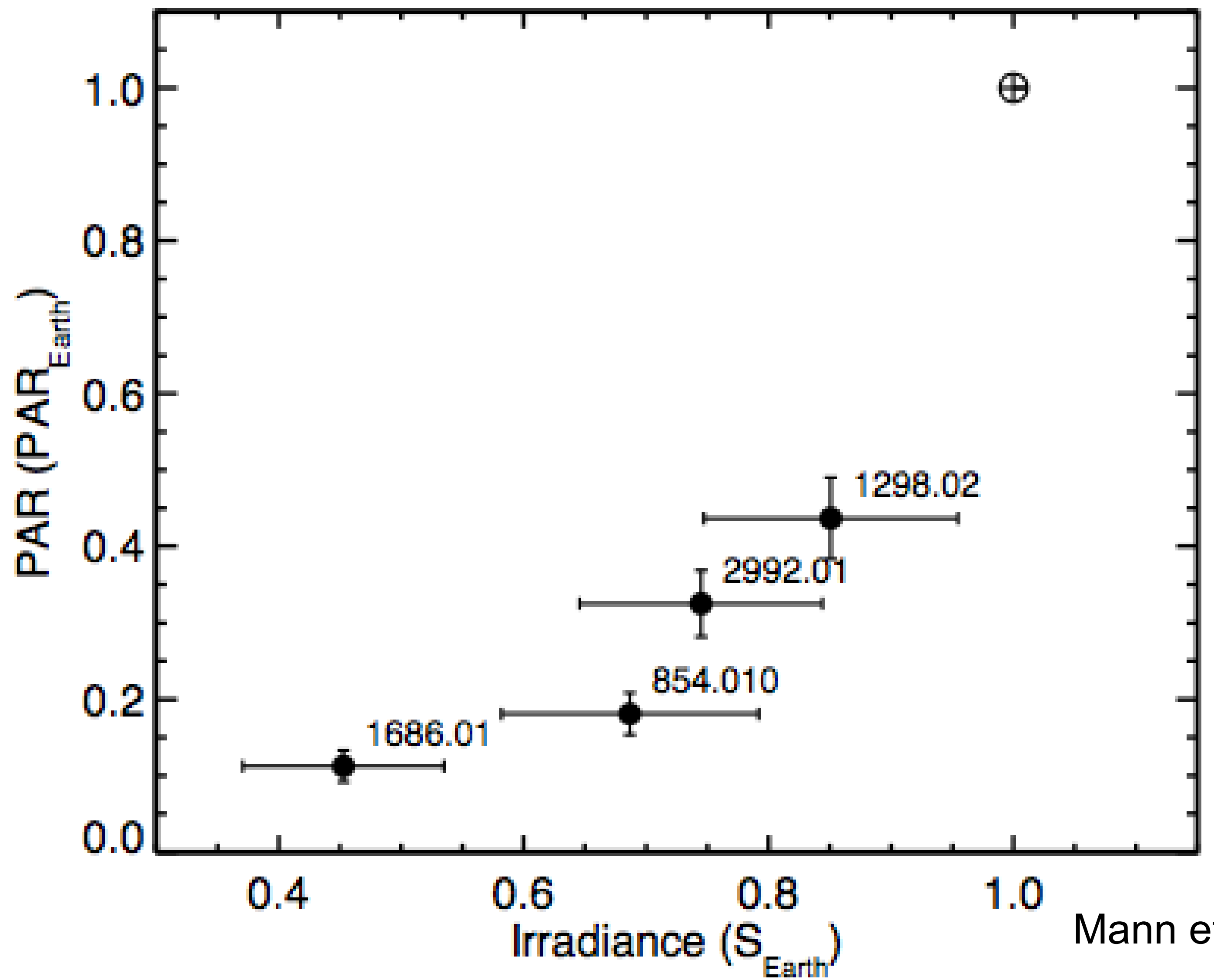


Are M Dwarf Planets Dead?

- High collision speeds and devolatilization of planets (Lissauer 2007)
- Coronal mass ejections and erosion of atmospheres (Lammer et al. 2007)
- Stellar spectrum and climate stability (Shields et al. 2014)
- Tidal locking and climate stability (Jorgi 1997, Yang et al. 2013)
- High UV and loss of atmospheres (Luger & Barnes 2015)

Planets around M Dwarfs are not Earth-like or Habitable?

e.g., insufficient photosynthetic active radiation (PAR)



Mann et al. (2013)

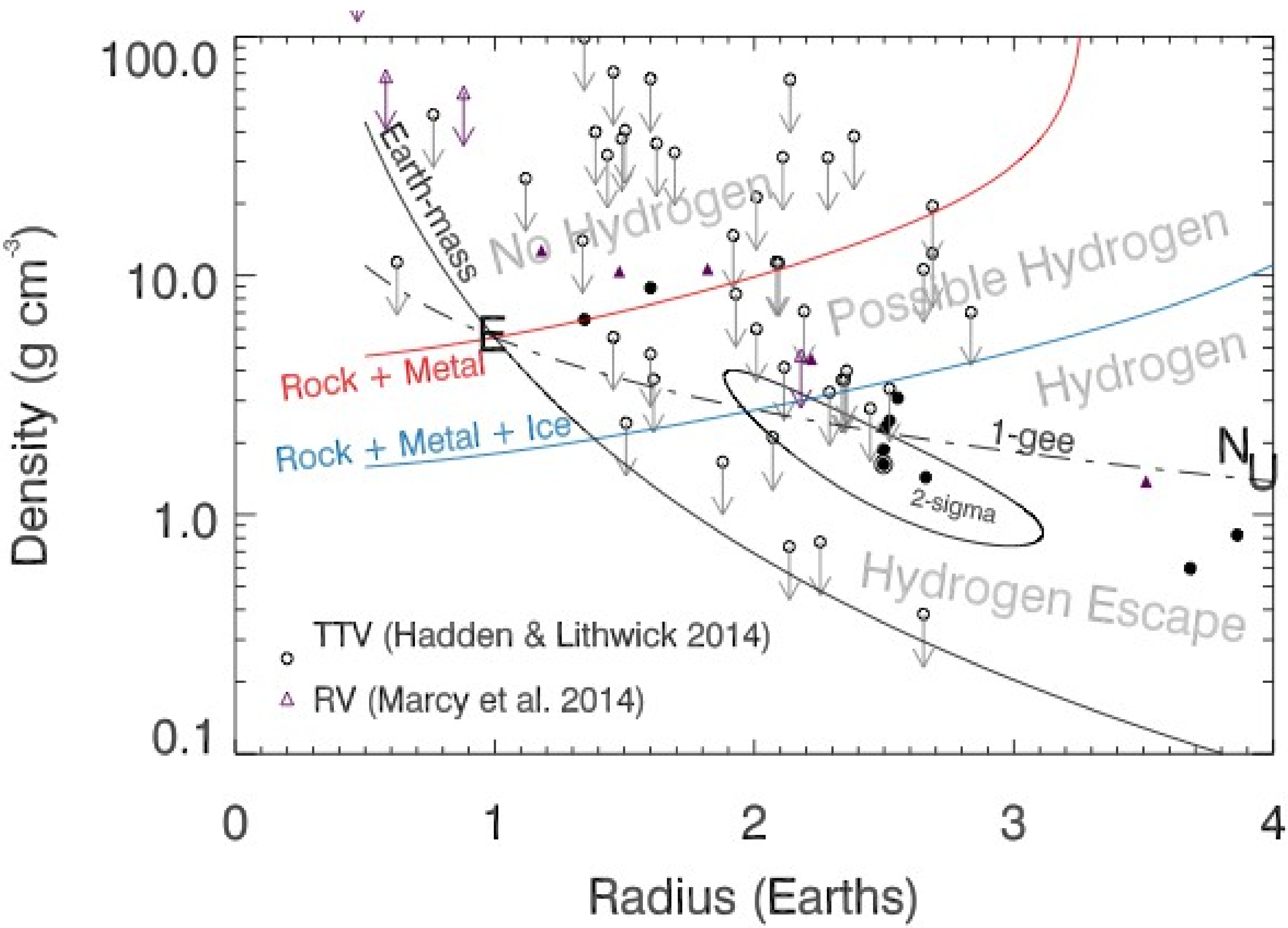
N is sensitive to the value of t_{max}

$$N = \frac{t_{max}}{t_{max} - 4.5\,Gyr}$$

What is t_{max} (lifetime of biosphere) for the Earth?

- Tractable climate problem
- Corresponds to the inner edge of the habitable zone
- Currently only a prediction by models
- Venus provides only an endpoint
- Exoplanets could provide answers, or at least constraints
- A view of Earth's future, and a constraint on t_M ... and N?

Cautionary Tale: K/M Dwarf Planets with Mass Constraints



First Spacecraft “Image” of Another Planet