Multiverse Predictions for Habitability

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[1904. ?????]

Introduction

- Multiverse Hypothesis:

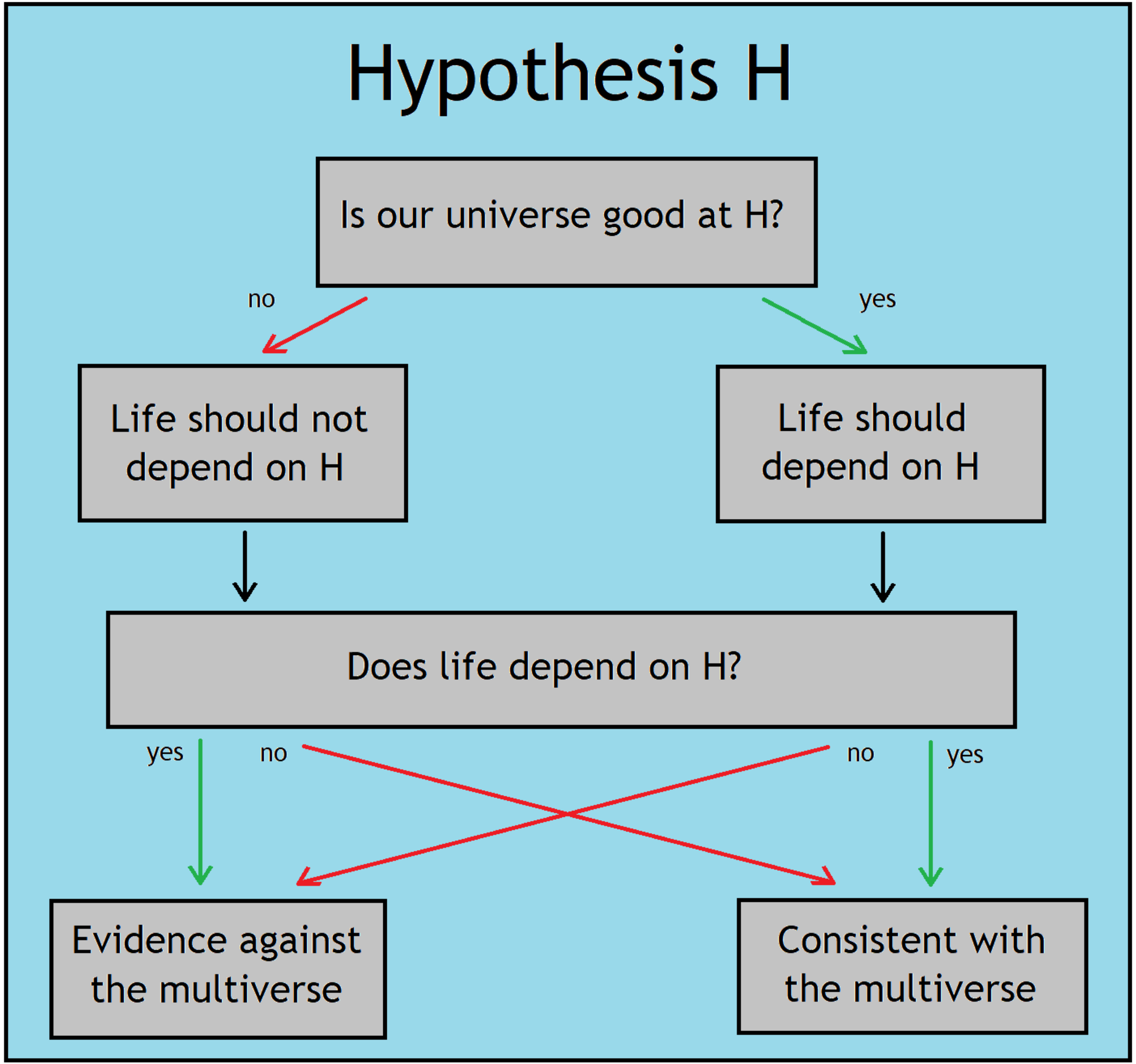
The laws of physics may be different elsewhere

- Anthropic Principle:

We can only live someplace where life can exist [Carter 83] [Barrow & Tipler 88]

- Principle of Mediocrity:

We should expect to be typical observers [Vilenkin 95]


Hypothesis H
Is our universe good at H?
no
yes
Life should not depend on H
Life should depend on H
Does life depend on H?
yes
no
no
yes
Evidence against the multiverse
Consistent with the multiverse

Drake Equation

$$N_{\text{obs}} = N_{\text{stars}} \times f_{\text{p}} \times n_{\text{e}} \times f_{\text{bio}} \times f_{\text{int}} \times N_{\frac{\text{obs}}{\text{civ}}}$$

[Gleiser 10]
[Frank & Sullivan 16]

Focus on the variables $\alpha = \frac{e^2}{4\pi}, \quad \beta = \frac{m_e}{m_p}, \quad \gamma = \frac{m_p}{M_{pl}}$

$$\alpha_{\text{obs}} = \frac{1}{137}, \quad \beta_{\text{obs}} = \frac{1}{1836}, \quad \gamma_{\text{obs}} = 3.9 \times 10^{-19}$$

Figures of Merit

$P(\alpha_{obs})$, $P(\beta_{obs})$, $P(\gamma_{obs})$,

$P(M_{sun})$, P(now)

- H stable: $\alpha_{max}=2.1\ \alpha_{obs}$
- Galaxies cool: $\alpha_{min}= .2\ \alpha_{obs}$
- Stars/fusion: $\beta_{max}=2.2\ \beta_{obs}$
- Stellar lifetime: $\gamma_{max}=134\ \gamma_{obs}$

Number of Stars

Simplifying assumption: nearly all gas inside galaxies eventually becomes stars.

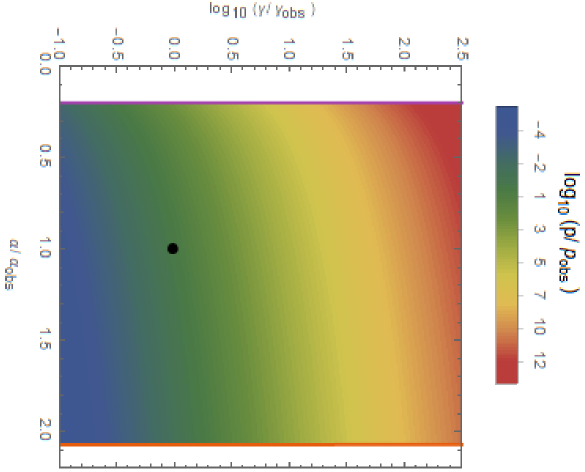
$$\Rightarrow N_{\text{stars}} \sim \frac{1}{\langle M_\star \rangle}$$

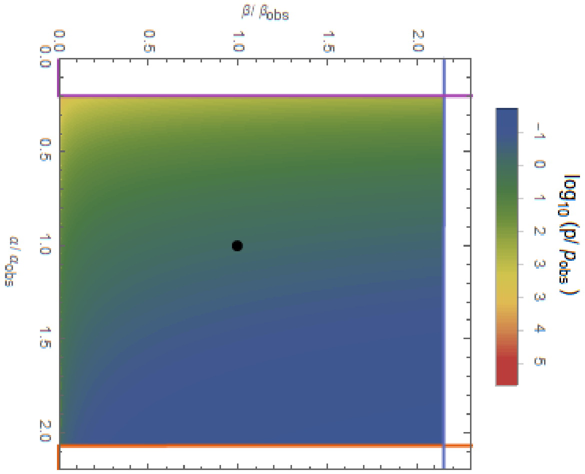
Minimum mass capable of fusion: $M_{\min} \propto \dfrac{\alpha^{3/2}}{\beta^{3/4}} \dfrac{M_{pl}^3}{m_p^2}$ [Adams 08]

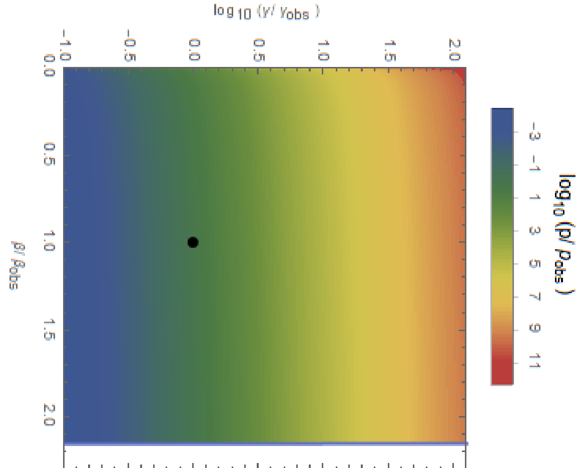
$$P(\text{obs}) \propto \frac{\gamma^2}{\alpha^{3/2}\,\beta^{1/4}}$$

$$\mathbb{P}(\alpha_{\text{obs}}) = .20, \quad \mathbb{P}(\beta_{\text{obs}}) = .44, \quad \mathbb{P}(\gamma_{\text{obs}}) = 4.2 \times 10^{-7}$$

Life should depend on stellar properties







Is P(life) proportional to stellar lifetime?

$$t_\star(\lambda) = 110\,\frac{\alpha^2\, M_{pl}^2}{\lambda^{5/2}\, m_e^2\, m_p} \qquad\qquad \lambda = \frac{M_\star}{M_{ch}}$$

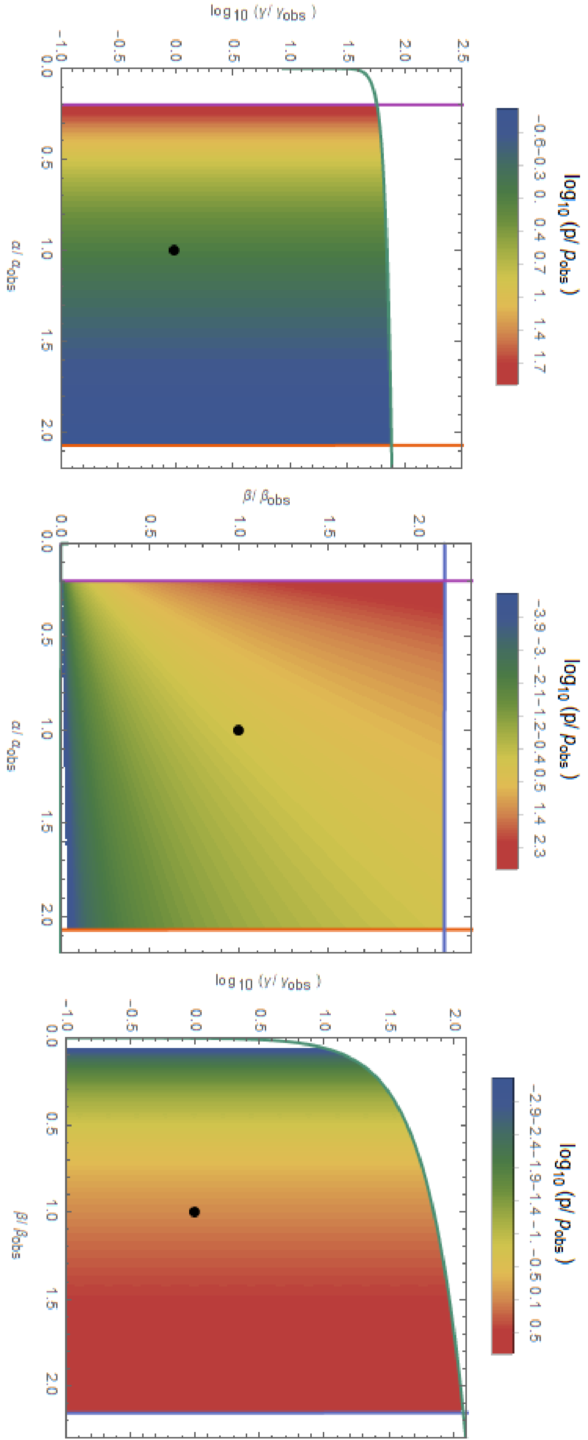
What is the minimum timescale to develop intelligence?

Simplest ansatz: 10^{30} "ticks of the molecular clock"

$$t_{\rm mol} \sim 30\,\frac{m_p^{1/2}}{\alpha^2\, m_e^{3/2}} \implies \lambda_{\rm max} \propto \alpha^{8/5}\,\beta^{-1/5}\,\gamma^{-4/5}$$

$$\mathbb{P}(\alpha_{obs}) = .251, \quad \mathbb{P}(\beta_{obs}) = .196, \quad \mathbb{P}(\gamma_{obs}) = .007$$

Should not find more life around older stars



Is photosynthesis necessary?

Vastly important for life:

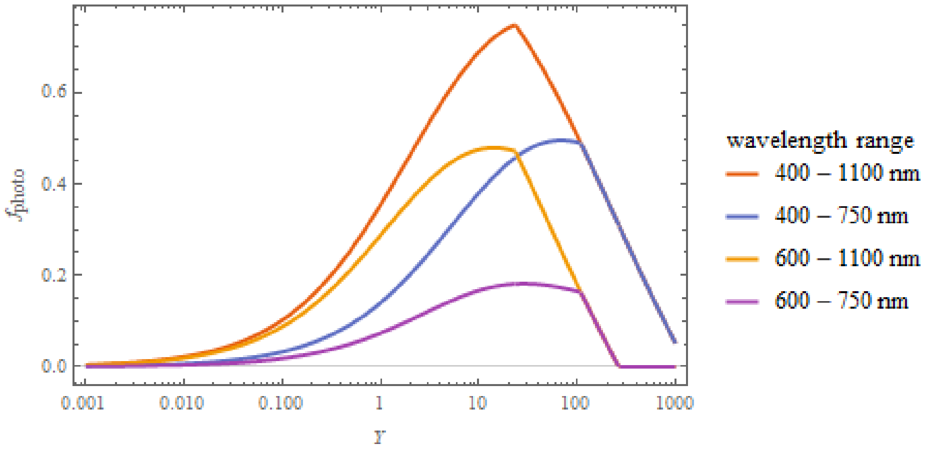
- Sun produces by far the most free energy on earth
- Produces O_2, aerobic metabolism necessary for animals [Catling+ 05]

Not automatic!

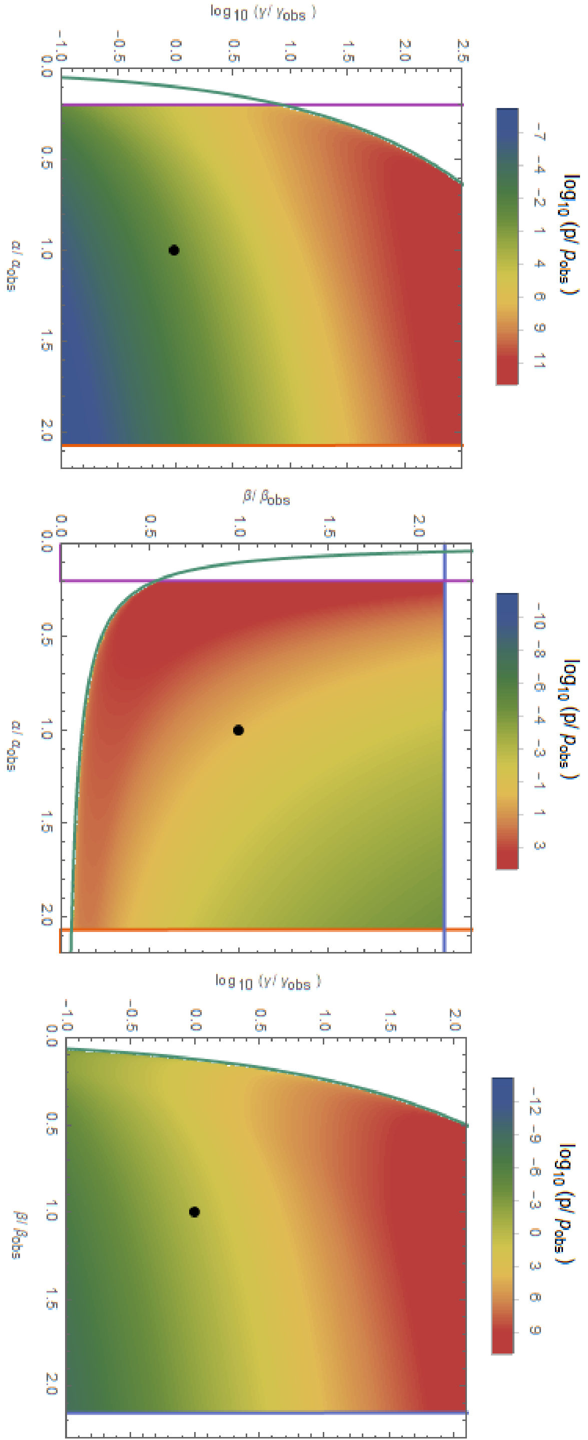
$$T_\star \approx E_{\text{atomic}} \iff \gamma \approx \alpha^6 \beta^2$$

[Press & Lightman 83]

$$\text{this work: } \gamma \approx \alpha^{63/20}\, \beta^{137/40}$$



$$\mathbb{P}(\alpha_{\text{obs}}) = .32, \quad \mathbb{P}(\beta_{\text{obs}}) = .23, \quad \mathbb{P}(\gamma_{\text{obs}}) = 5.2 \times 10^{-7}$$



Entropy production

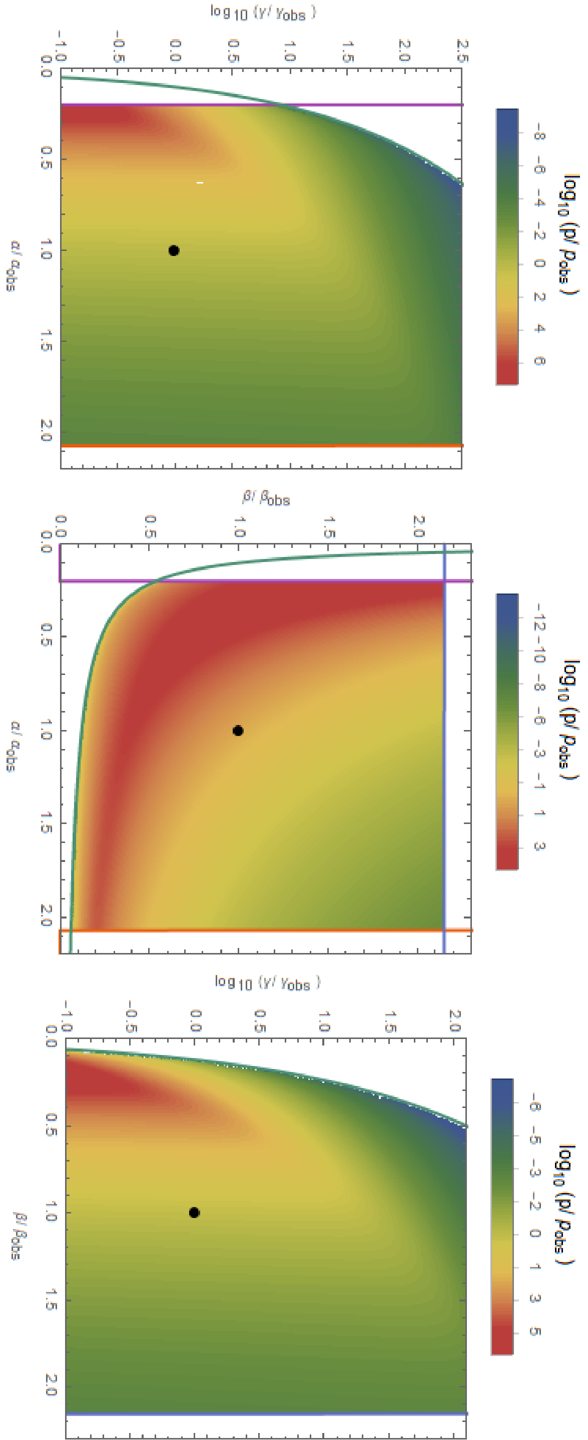
Entropy sets the ultimate size of the biosphere [Wolpert 16]

$$P \propto \Delta S_{\text{tot}} \sim \frac{L_\star}{T_\star}\frac{A_\oplus}{4\,\text{AU}^2}\,t_\star \sim \frac{\alpha^{17/2}\,\beta^2}{\gamma^{17/4}}$$

$$\begin{aligned}
\dot{S}_{\text{solar}} &\sim 10^{36}\,\frac{\text{bits}}{\text{sec}} \\
S_{\text{bacteria}} &\sim 10^{11} \\
\dot{S}_{\text{turnover}} &\sim 10^{30}\,\frac{\text{cells}}{\text{year}} \\
\dot{S}_{\text{biosphere}} &\sim 10^{34}\,\frac{\text{bits}}{\text{sec}}
\end{aligned}$$

$$\mathbb{P}(\alpha_{obs}) = .19, \quad \mathbb{P}(\beta_{obs}) = .45, \quad \mathbb{P}(\gamma_{obs}) = .32$$

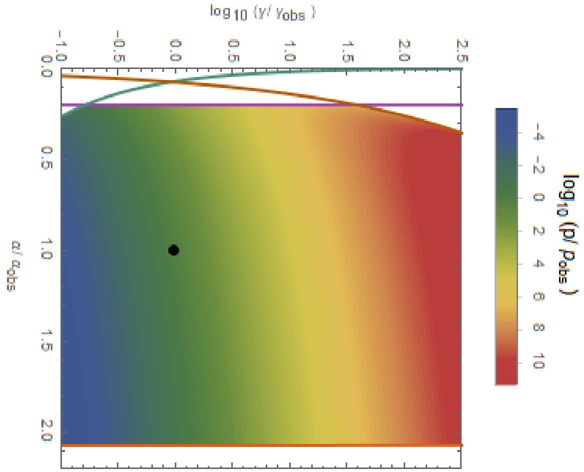
Life should correlate with entropy and depend on photosynthesis



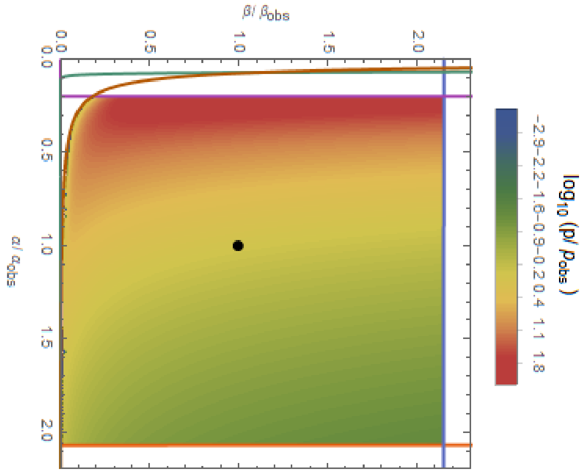
What fraction of stars have planets?

- Minimum metallicity: $t_{clump} < t_{disk}$ $\quad Z_{\rm min} \sim \dfrac{\gamma^{1/2}}{\alpha^3\,\beta^{1/2}}$

[Johnson & Li 12]
[Ercolano & Clarke 10]



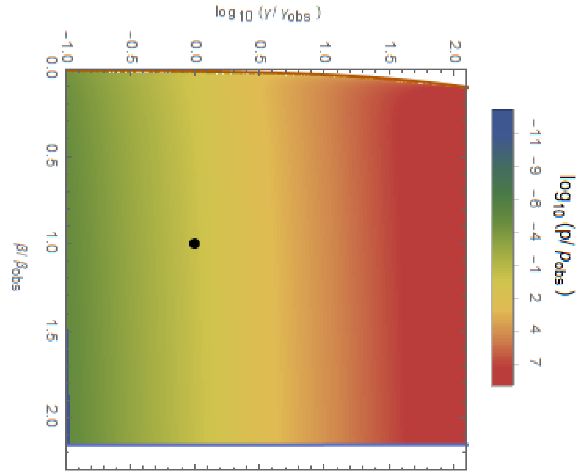
- Smallest metal retaining galaxy: $\quad M_{\rm ret} \sim \dfrac{\alpha^3\,m_e^{5/2}\,M_{pl}^3}{m_p^{9/2}}$



- Supernovae: $t_{SN} < t_{star\ formation}$

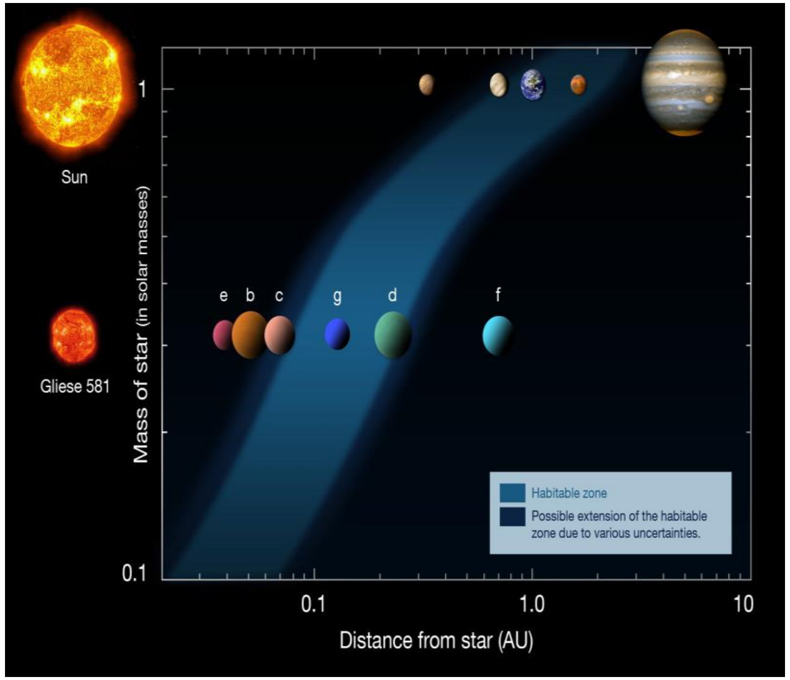
- Hot Jupiters: $\quad f_{\rm hj} = 1 - \dfrac{Z^2}{Z_{\rm max}^2}, \quad Z_{\rm max} \sim \alpha^{13/8}\,\beta^{3/2}$

[Fischer & Valenti 05]



$$\mathbb{P}(\alpha_{obs}) = .18, \quad \mathbb{P}(\beta_{obs}) = .44, \quad \mathbb{P}(\gamma_{obs}) = .31$$

Is life only on temperate planets?



[Center for Planetary Science]

Necessary for liquid water

Classic definition of "Habitable Zone"

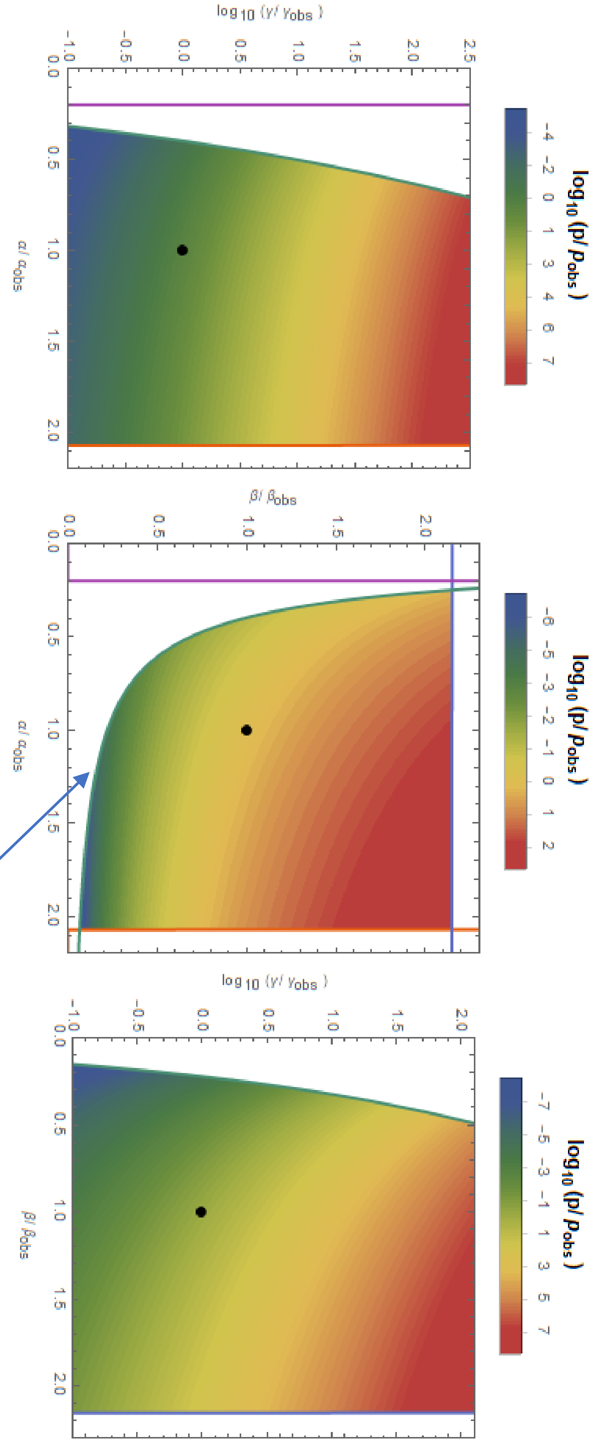
$$\Delta a_{\text{temp}} \sim a_{\text{spacing}}$$

phase changes　　disk evolution

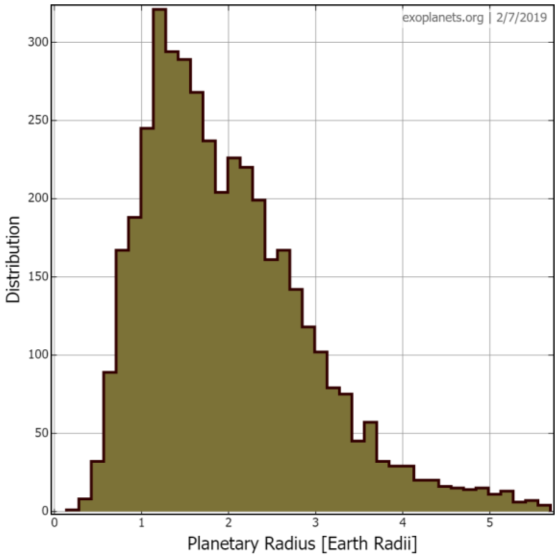
$$f_{\text{temp}} \sim \frac{\Delta a_{\text{temp}}}{a_{\text{spacing}}} \sim \frac{\alpha^{11/2}\,\beta^{7/4}}{\gamma^{5/8}}$$

Disks larger than habitable zone: $\frac{\gamma^{1/2}}{\alpha^5\,\beta^2} < 100 \times (\text{obs})$

$$\mathbb{P}(\alpha_{obs}) = .24, \quad \mathbb{P}(\beta_{obs}) = .37, \quad \mathbb{P}(\gamma_{obs}) = .15$$



Is life only on Earth mass planets?



Peak in mass distribution near Earth mass

[Pettigura+ 13][Ginzburg+ 17][Owen&Wu 17][Zeng+ 18]

Terrestrial: escape velocity ≈ thermal velocity

$$\Rightarrow .3 < \frac{M}{M_\oplus} < 4$$

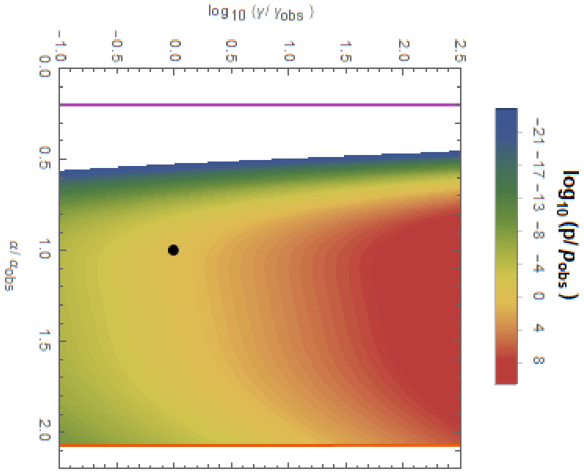
Planet size set by amount of initial material [Kokubo+ 06]

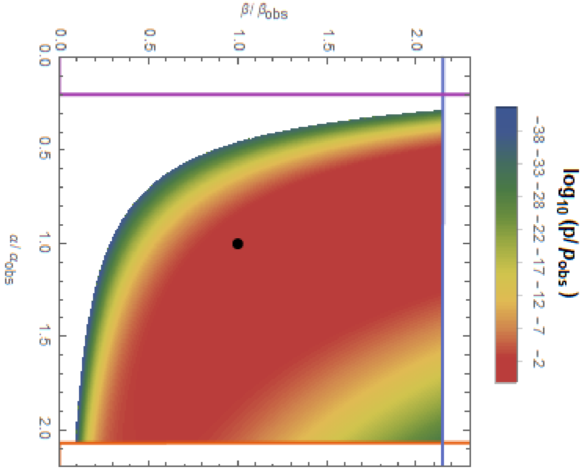
$$M_{\rm planet} \sim \left(\frac{4\pi\, \Sigma\, a^{5/2}\, \rho^{1/6}}{M_\star^{1/2}}\right)^{3/2}$$ [Schlichting 14]

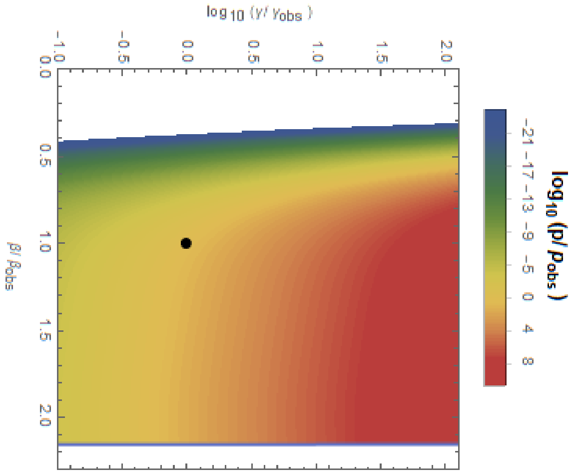
$$\frac{M_{\rm planet}}{M_{\rm terr}} \propto \frac{1}{\alpha^{9/2}\, \beta^{45/16}}$$

$\mathbb{P}(\alpha_{obs}) = .38, \quad \mathbb{P}(\beta_{obs}) = .25, \quad \mathbb{P}(\gamma_{obs}) = .007$ w/o M_{star} dependence

$\mathbb{P}(\alpha_{obs}) = .23, \quad \mathbb{P}(\beta_{obs}) = .26, \quad \mathbb{P}(\gamma_{obs}) = .41$ w/ M_{star} dependence







Is life more probable on larger planets?

$$P(\text{life}) \propto A_{\text{planet}}?$$

- More 'sites' for emergence
- High fractal dimension, scales as R_{planet}^3 [Hazen 17]

$$P_{\text{size}} \sim N_{\text{sites}} \sim \frac{V_{\text{clay}}\, \rho_{\text{A}}}{L_{\text{mol}}^2} \propto \frac{\alpha^{1/4}\, \beta^{15/8}}{\gamma^3}$$

The opposite problem as before!

$$\mathbb{P}(\alpha_{obs}) = .37, \quad \mathbb{P}(\beta_{obs}) = .11, \quad \mathbb{P}(\gamma_{obs}) = .01$$

Do not expect more life on larger planets

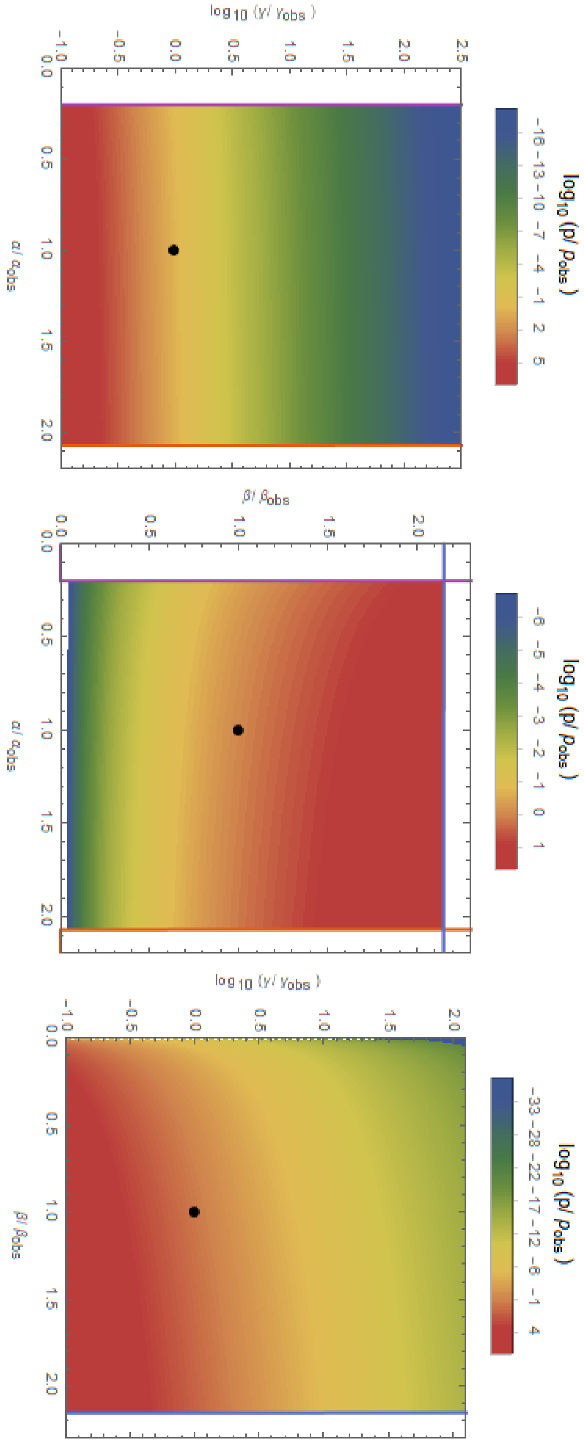
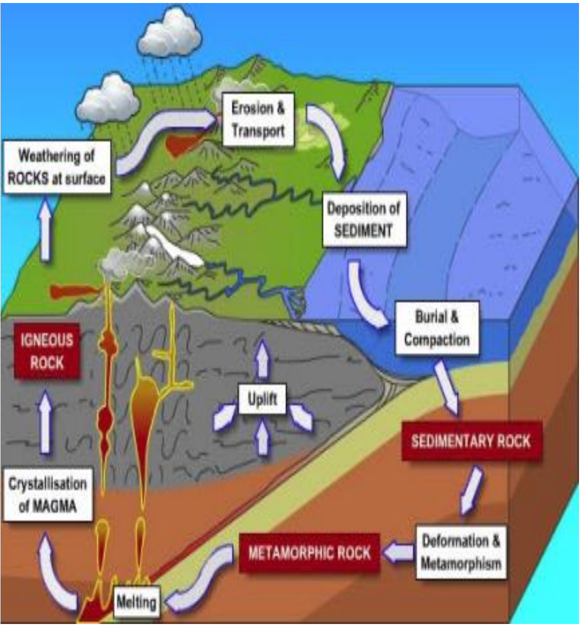


Plate Tectonics



- Created continents
- Recycles minerals into biosphere
- Stabilizing climate feedback loop [Walker, Hayes & Kasting 81]

$$CO_2 + CaSiO \rightarrow CaCO + SiO_2$$

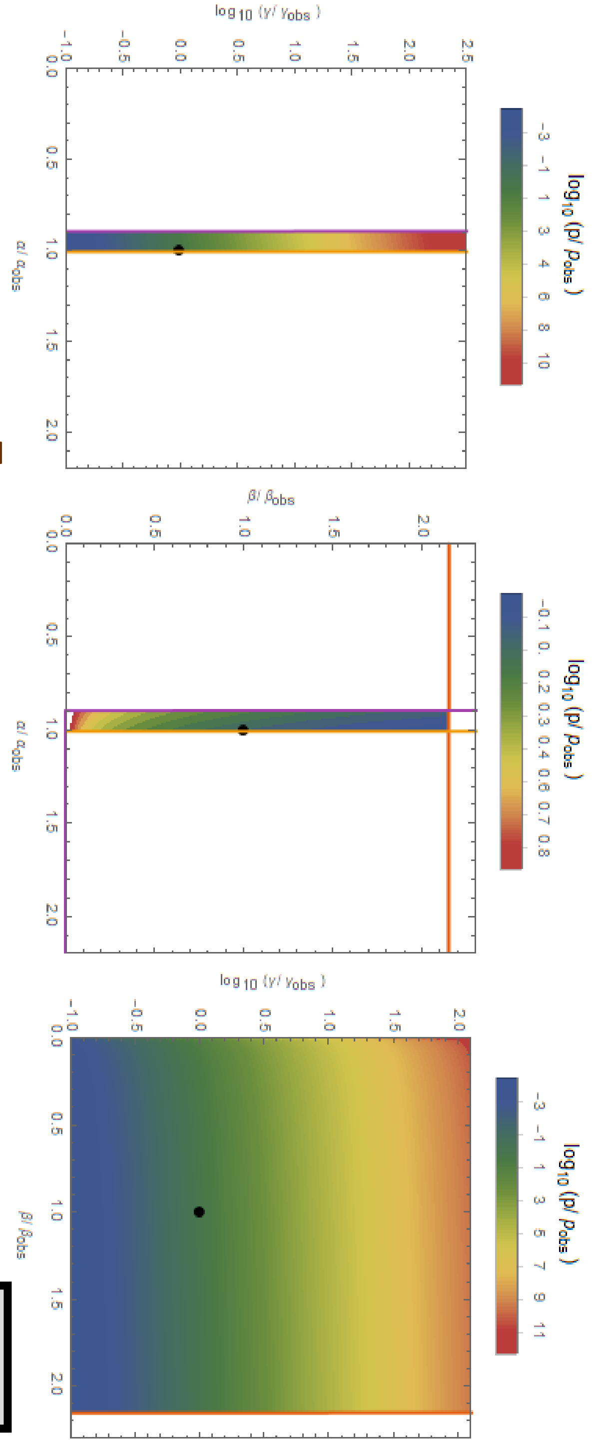
- "A living rock"

Reliant on radioactivity, $t_{1/2} \propto e^{\frac{a Z}{\sqrt{\Delta E_b}}}$

no Gyr decays unless $\frac{1}{153} < \alpha < \frac{1}{136}$

$\mathbb{P}(\alpha_{obs}) = .064, \quad \mathbb{P}(\beta_{obs}) = .38, \quad \mathbb{P}(\gamma_{obs}) = .20$

Plate tectonics should not really be essential



Why are we around a yellow star?

Weighting by entropy greatly favors smaller stars $\Delta S_{\text{tot}} \propto \frac{1}{M_\star^3}$

$P(M_{sun})=.01\%$

Criteria	$P(M_{sun})$ number	$P(M_{sun})$ Entropy
none	.14	.0001
TL	.84	.53
flares	.35	.02
photo (optimistic)	.31	.02
photo (pessimistic)	.56	.42

There must be something wrong with smaller stars, but what?

- Tidal locking
- Flares $P(M)=2\%$
- Photosynthesis not possible with red light

$$\lambda_{\text{TL}} \sim \alpha^{5/2}\,\beta^{1/2}\,\gamma^{-4/11}$$
$$\lambda_{\text{flares}} \sim \alpha^{3}\,\beta\,\gamma^{-1/2}$$
$$\lambda_{\text{photo}} \sim \alpha^{3}\,\beta\,\gamma^{-1/2}$$

Why did life take so long?

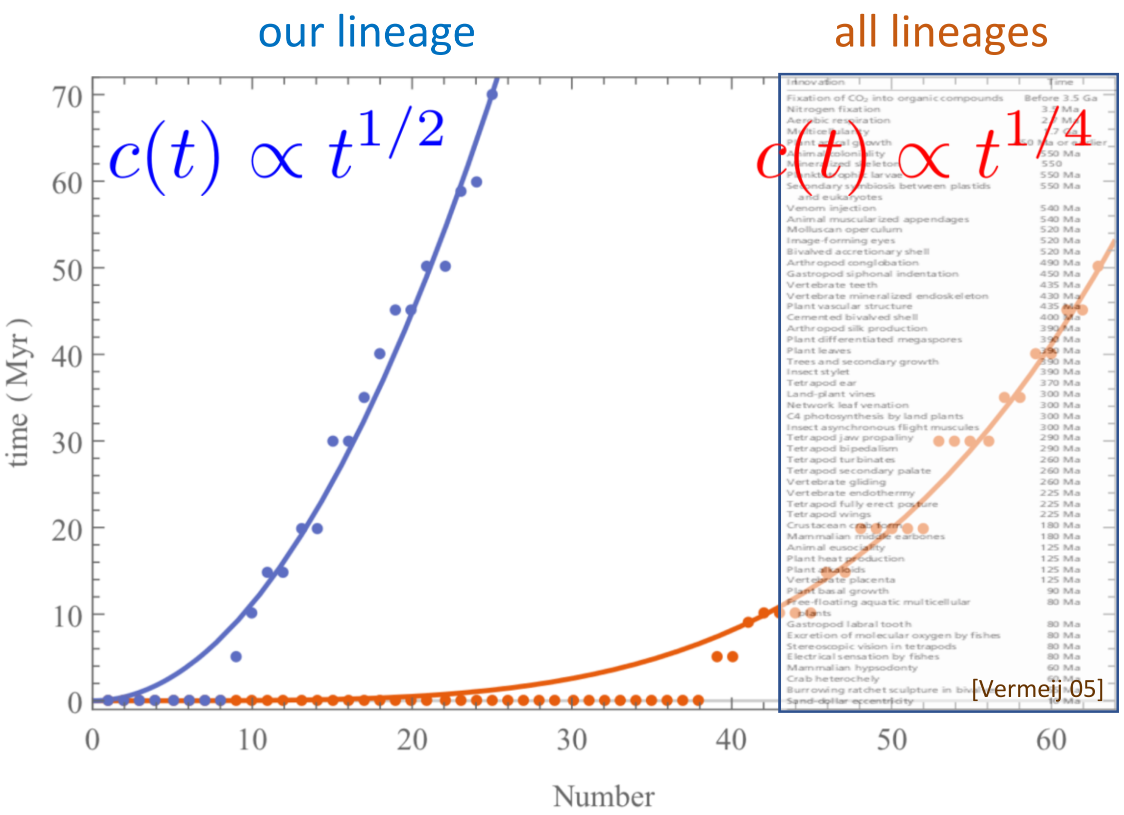
1. Hard step model: [Carter 83]

$$h(t) \propto t^{n_{\text{hard}}} \implies \langle t_{\text{int}} \rangle = \frac{n_{\text{hard}}}{n_{\text{hard}} + 1} t_{\text{hab}}$$

Sequence of hard steps:

- origin of life
- photosynthesis
- eukaryogenesis
- intelligence

[Szathmary & Maynard Smith 95]



$$\mathbb{P}(\alpha_{obs}) = .12, \quad \mathbb{P}(\beta_{obs}) = .044, \quad \mathbb{P}(\gamma_{obs}) = 2.2 \times 10^{-9}$$

The hard step model cannot be true

Why did life take so long?

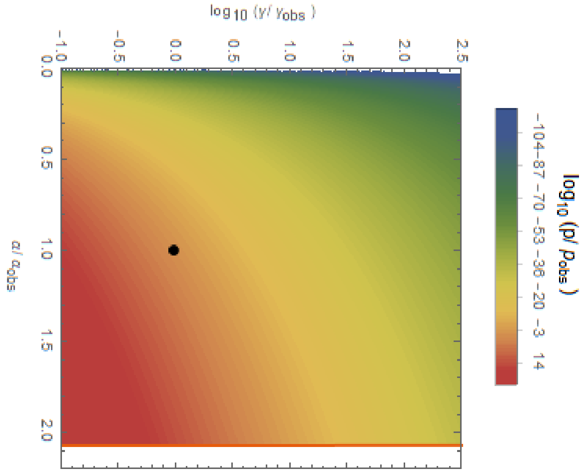
2. Bated breath model: [Livio 99]

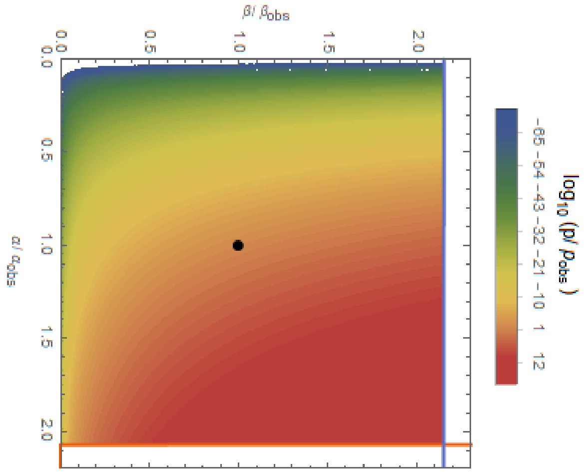
$$t_{O_2} = \frac{N_{\mathrm{atm}}}{\Phi_{\mathrm{XUV}}\, A_\oplus}$$

$$\frac{t_{O_2}}{t_\star} = f(M_\star), \quad f \text{ decreasing}$$

$P(.2)_{\text{Universe}}$ =56%, $P(.2)_{\text{Multiverse}}$=5%

Inconsistent!



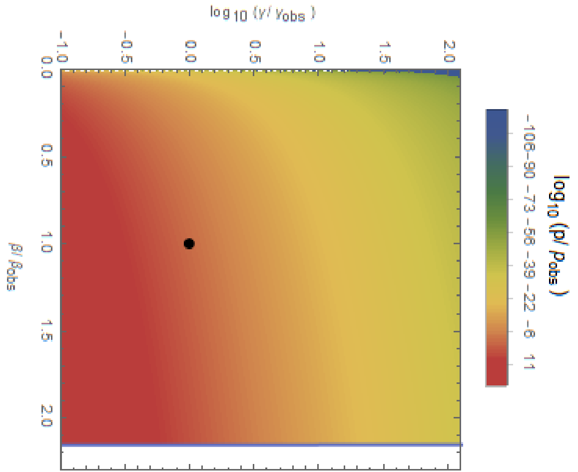


3. Easy Stroll model: [Simpson 17]

Distribution of habitable lifetimes is steep

Consistent!

Oxidation time was not the bottleneck



Conclusions

According to the multiverse, complex life:

- Should depend on stellar properties
- Does not depend on stellar lifetime
- Needs photosynthesis
- Is set by entropy production
- Does not depend on planet size
- Does not need plate tectonics
- Cannot be around red dwarfs
- Is not hard step
- Was not waiting on oxygenation

OR ELSE WE WOULD NOT LIVE IN THIS UNIVERSE

Can also include:

Obliquity, eccentricity, composition, planetary system architecture, water abundance, water properties, nutrient flux, C/O, Mg/Si, availability of P, binary stars, hot Jupiter systems, icy moons, rogue planets, location in galaxy, spiral vs elliptical, different origin of life hypotheses, extinction factors: comets, asteroids, volcanos, grbs, SN, AGN,…