

Astrobiological evolution and the number of critical steps

Reasons for (cautious) optimism?

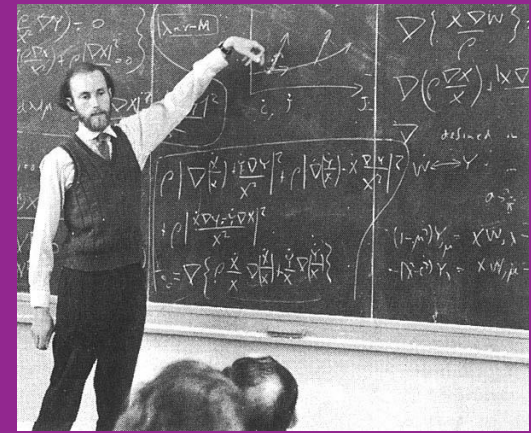


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The main thesis



WE ARE WITNESSING A **PARADIGM SHIFT** IN STUDYING HABITABILITY IN TERMS OF CORRELATIONS, WHICH HAS BEEN PROVOKED (IN PART) BY THE WORK OF CARTER!



It is what opposes that helps.

Heraclitus of Ephesus (cca. 540BC)

“3 canonical questions” of astrobiology

- How does life begin and develop?
- Does life exist elsewhere in the universe?
- What is the future of life and intelligence on Earth and in space?

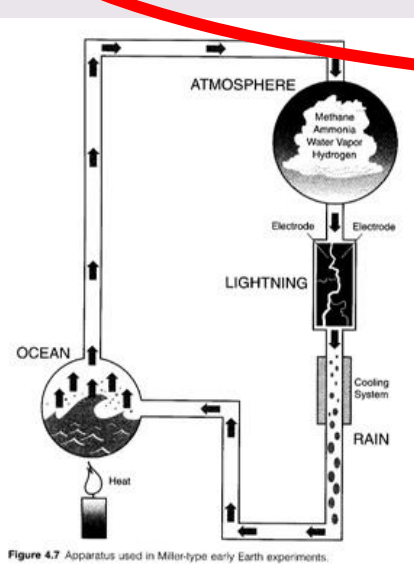
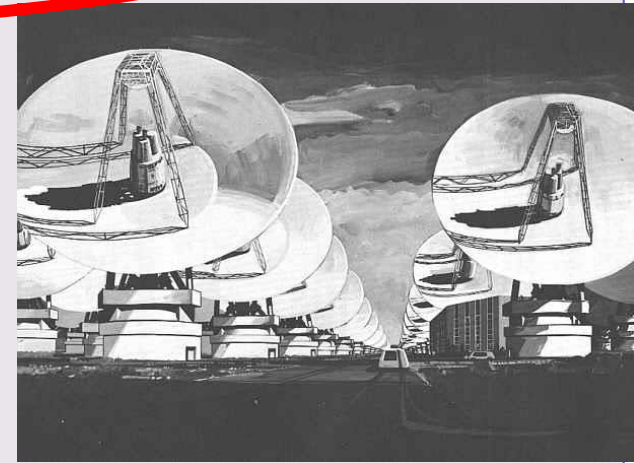
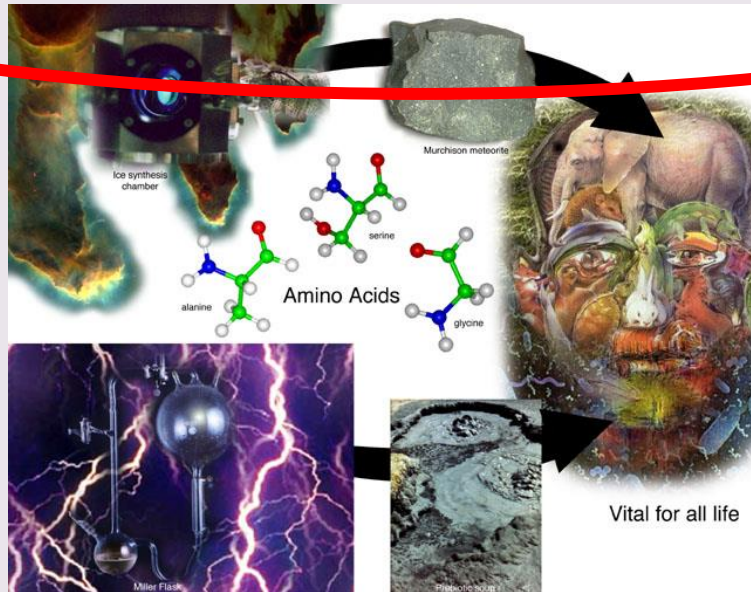


Figure 4.7 Apparatus used in Miller-type early Earth experiments.

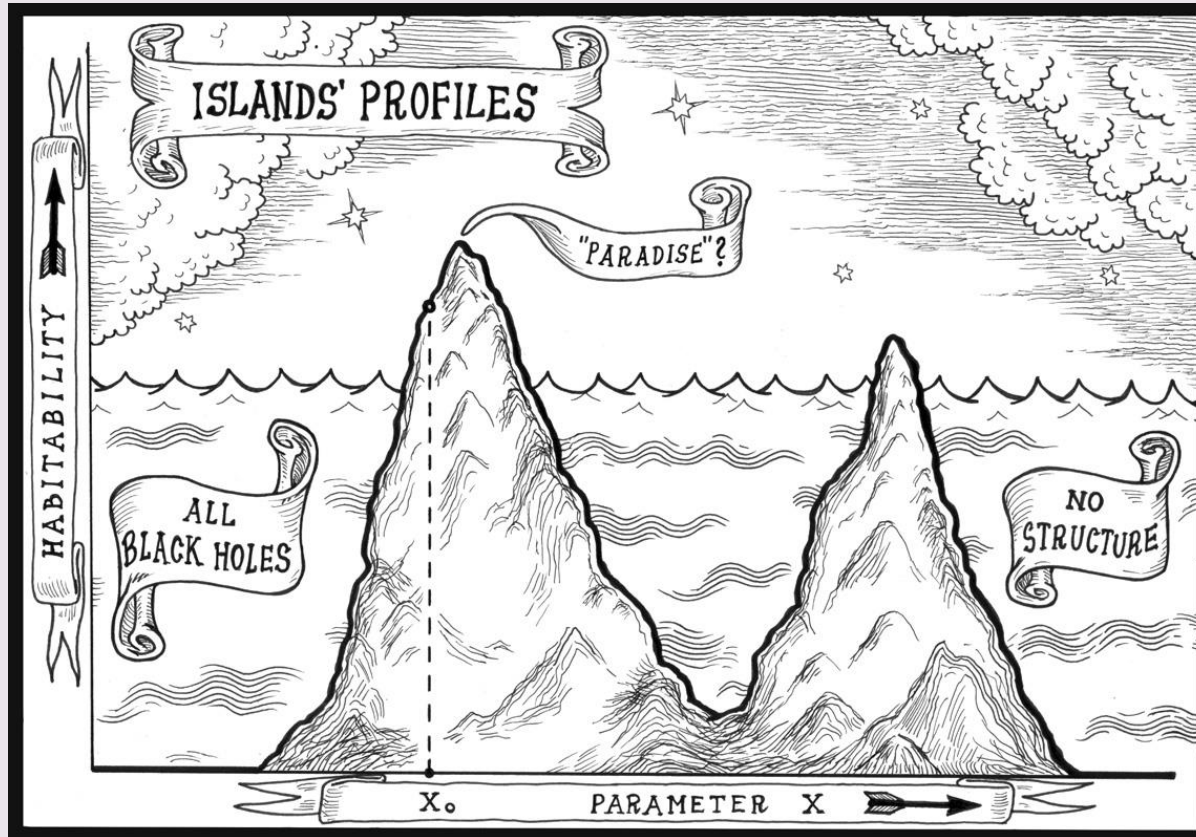


A major inspiration for astrobiology...

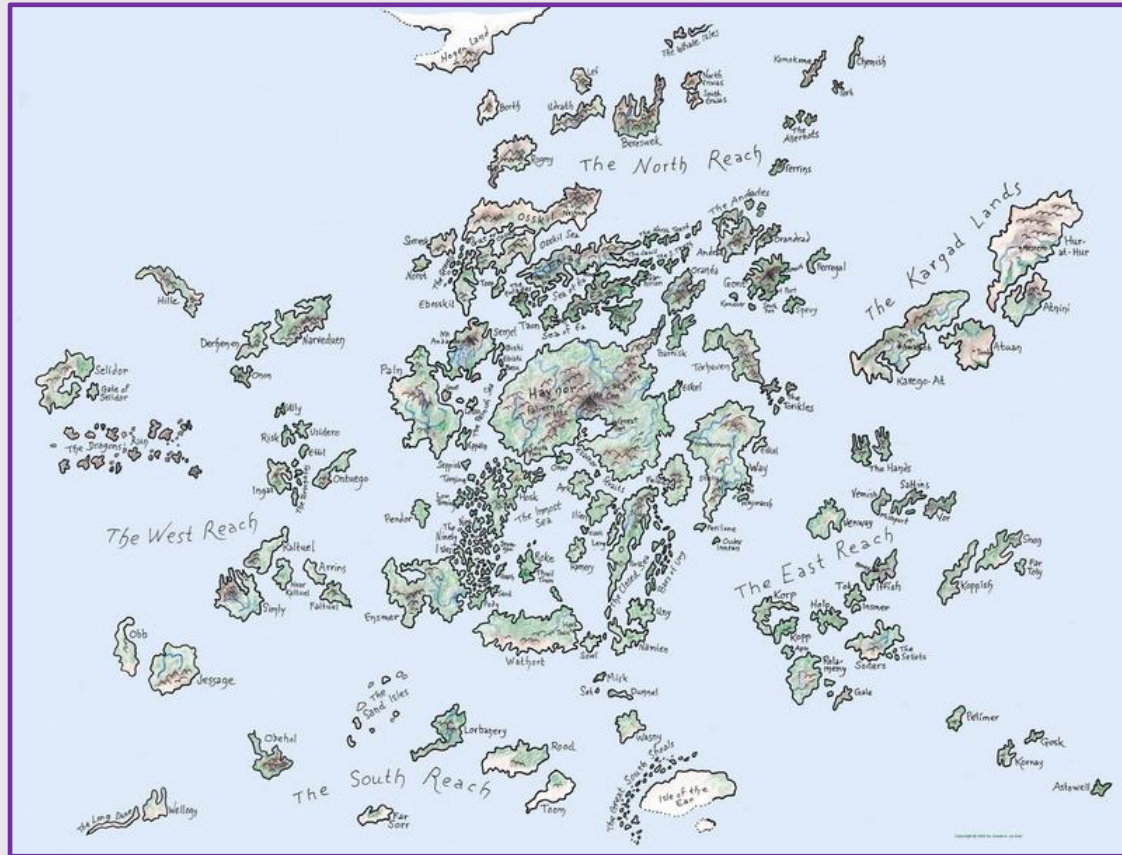


- 1) **1974**: “Large number coincidences and the anthropic principle in cosmology,” in M. S. Longair (ed.) *Confrontation of cosmological theories with observational data* (D. Reidel Publishing), 291-298.
- 2) **1983**: “The anthropic principle and its implications for biological evolution,” *Philos. Trans. R. Soc. London A* **310**, 347-363.
- 3) **1993**: “The Anthropic Selection Principle and the Ultra-Darwinian Synthesis,” in *The Anthropic Principle*, ed. by F. Bertola & U. Curi (CUP), 33-66.
- 4) **2008**: “Five- or six-step scenario for evolution?” *Int. J. Astrobiol.* **7**, 177-182.
- 5) **2012**: “Hominid evolution: genetics versus memetics,” *Int. J. Astrobiol.* **11**, 3-13.

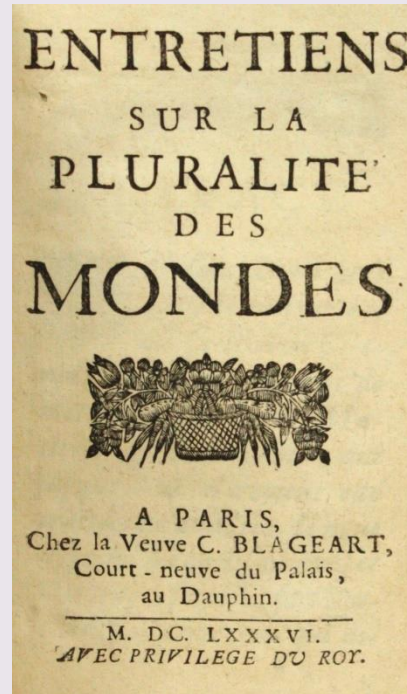
Anthropic principle has always been about **habitability**



Mapping of the archipelago?



While some forms of anthropic thinking existed for a long time...



...the modern, serious, workable formulation is **Carter (1974)**!

3 classic SETI-skeptical arguments



- Fermi's paradox (1950, re-discovered mid-1970s)
- The argument from biological contingency (Simpson 1964)
- **Anthropic argument (Carter 1983)**

Carter's argument in a nutshell



- **Independent** timescales for the evolution of intelligence:
 - ✦ Astrophysical: t^*
 - ✦ Biological: t_b
- **PLANETARY SCIENCE:** In the Solar System $t^* \approx t_b$.
- **PHILOSOPHY:** In general, either $t^* \gg t_b$ or $t_b \gg t^*$.



- The $t^* \gg t_b$ case improbable - unclear why the **first** datapoint is $t^* \approx t_b$.
- \Rightarrow probabilistic reasons for

$t_b \gg t^*$ in general

(+ observation-selection explains $t^* \approx t_b$ in our own backyard)



intelligence must be very rare in this epoch!



“Are we the first?”

Eddington limit vs. Jim Peebles

$$\simeq 6 \times 10^4 \text{ erg s}^{-1} \text{ g}^{-1}$$

$$\simeq 1.5 \times 10^4 \text{ erg s}^{-1} \text{ g}^{-1}$$



“A remarkable coincidence!”
(Peebles 1993, p. 366)

Criticisms of CA



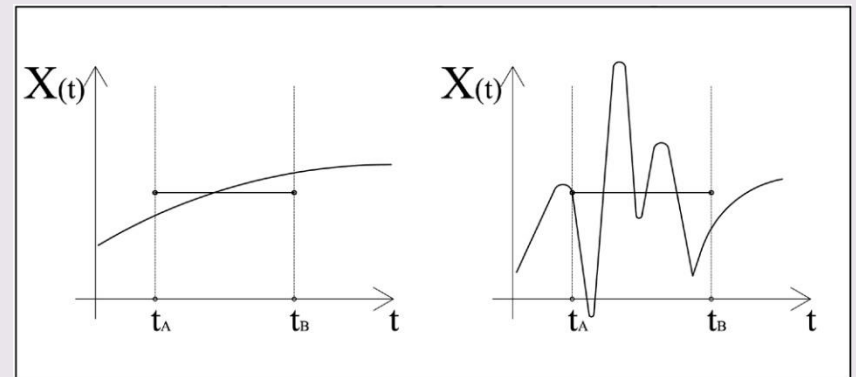
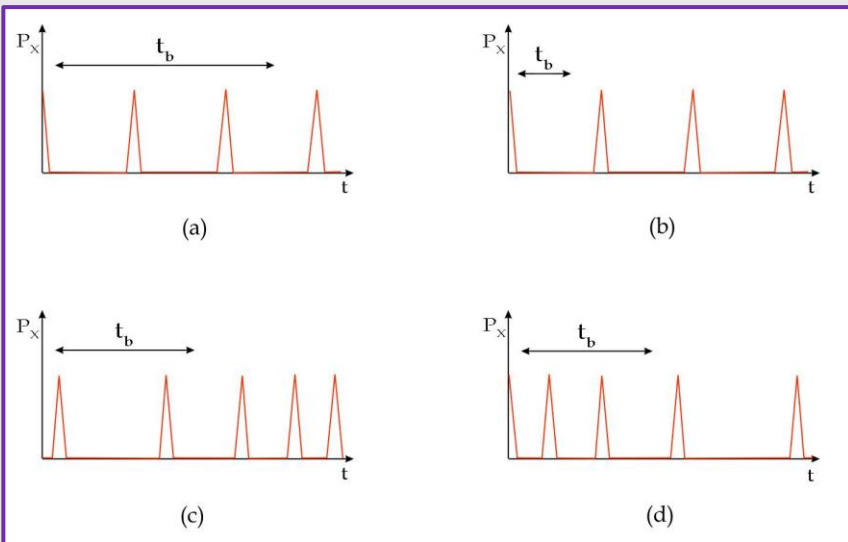
- “Common sense”: sometimes, coincidence is – just that.
- Wilson (1994): we don’t know enough to exclude $t^* \sim t_b$ regime.
- Livio (1999): the ozone formation process induces correlations!
- Ćirković et al. (2009): the closed-box assumption fails!

How many astrophysical timescales?



Timescale forcing

“The mean is not the message”



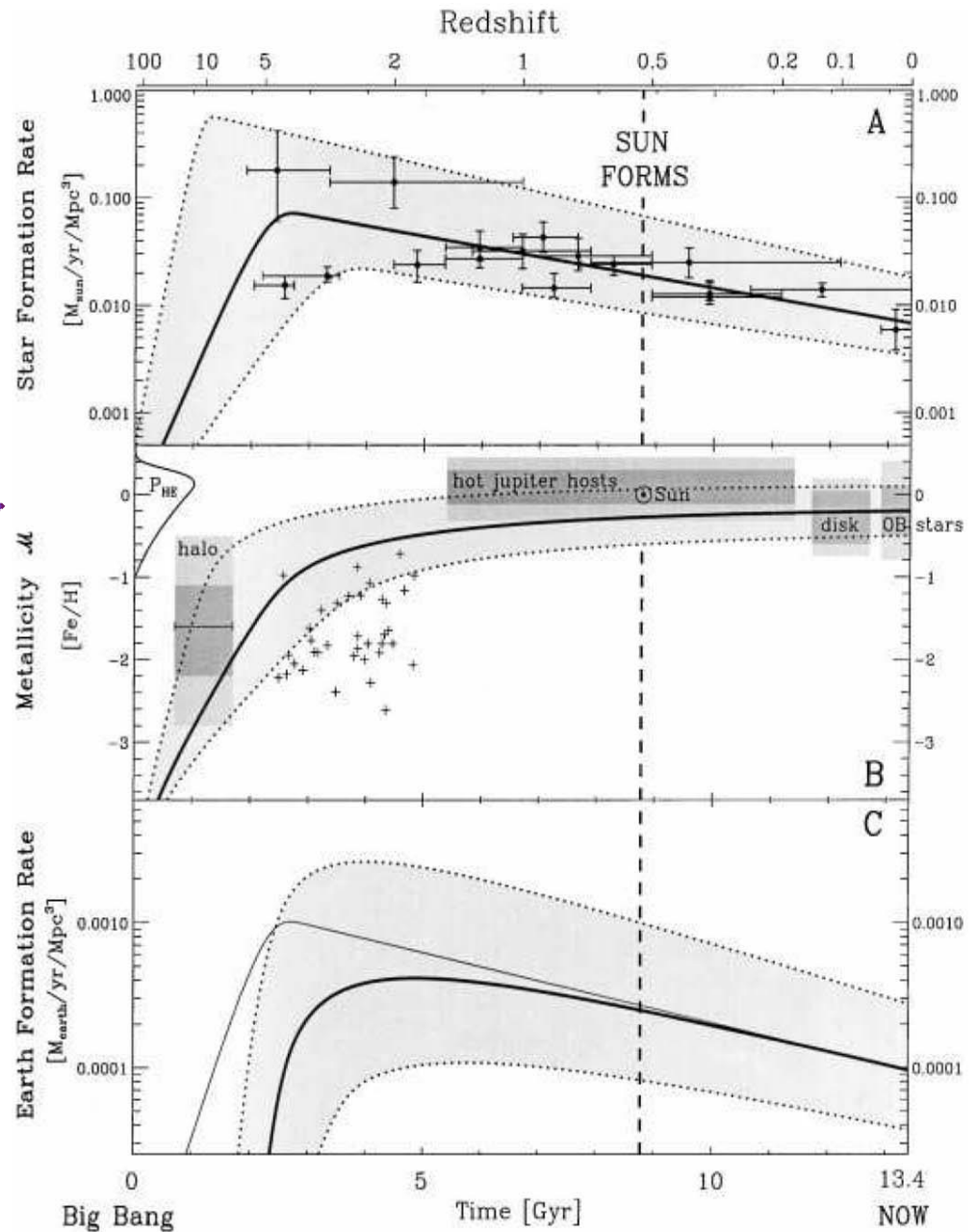
The most curious case (of observers)



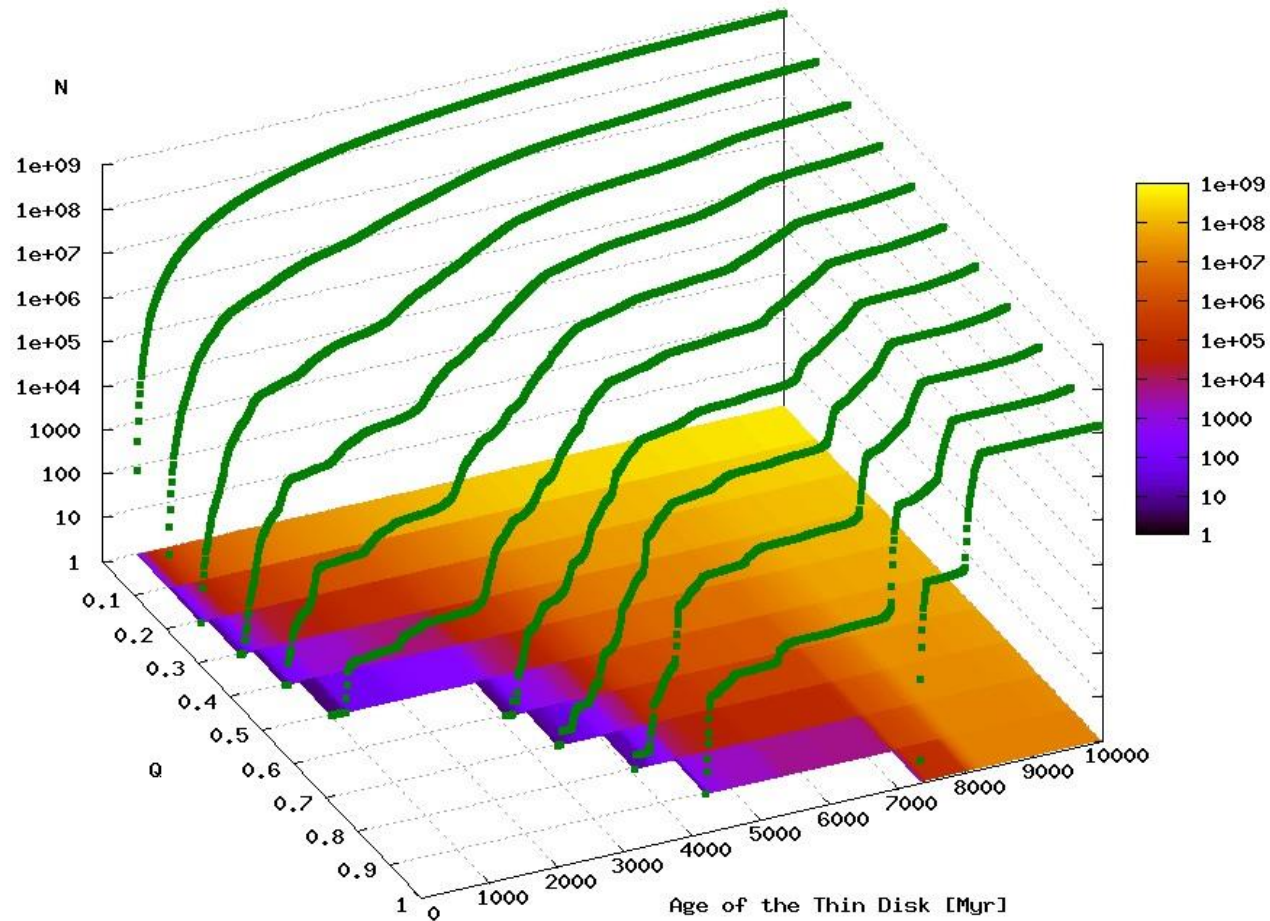
**“ It is not important who the suspect is.
It is important who the suspect is. ”**

Hercule Poirot

Lineweaver's initial conditions



“Astrobiological landscape”



The number of hard/critical steps?

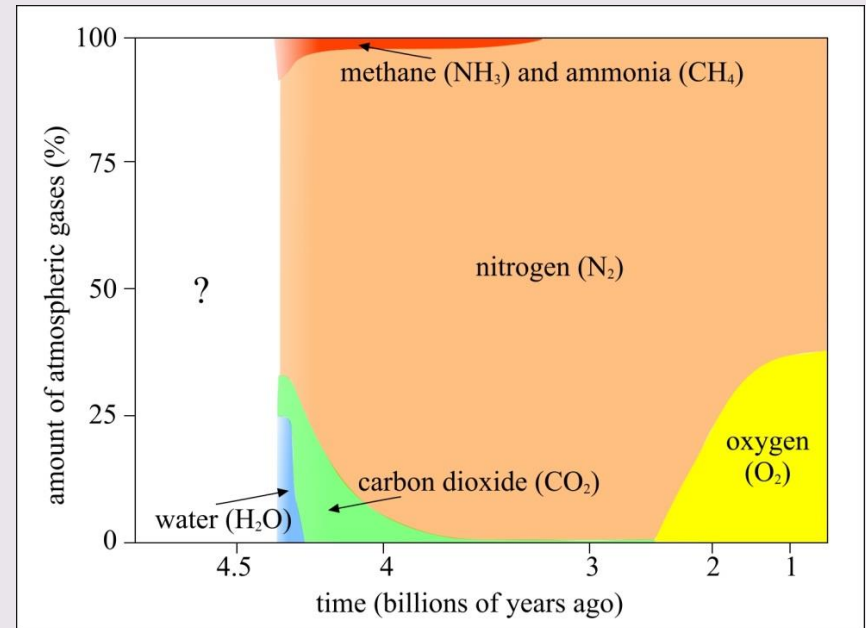


- n critical steps to intelligence?

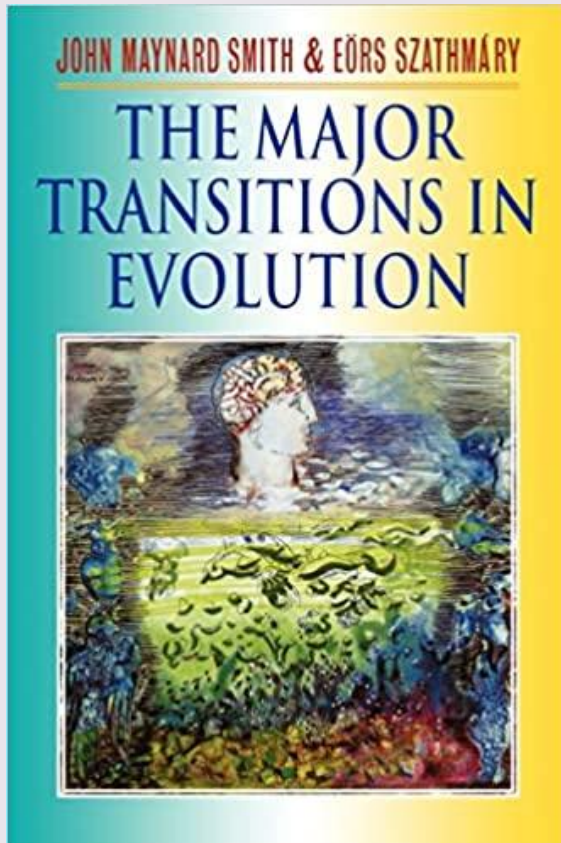
- Key insight:

$$\langle t_{n/n} \rangle = \frac{n}{n+1} t^*$$

- Originally $n = 1$ or 2 , today best fit would be 5 or 6 .

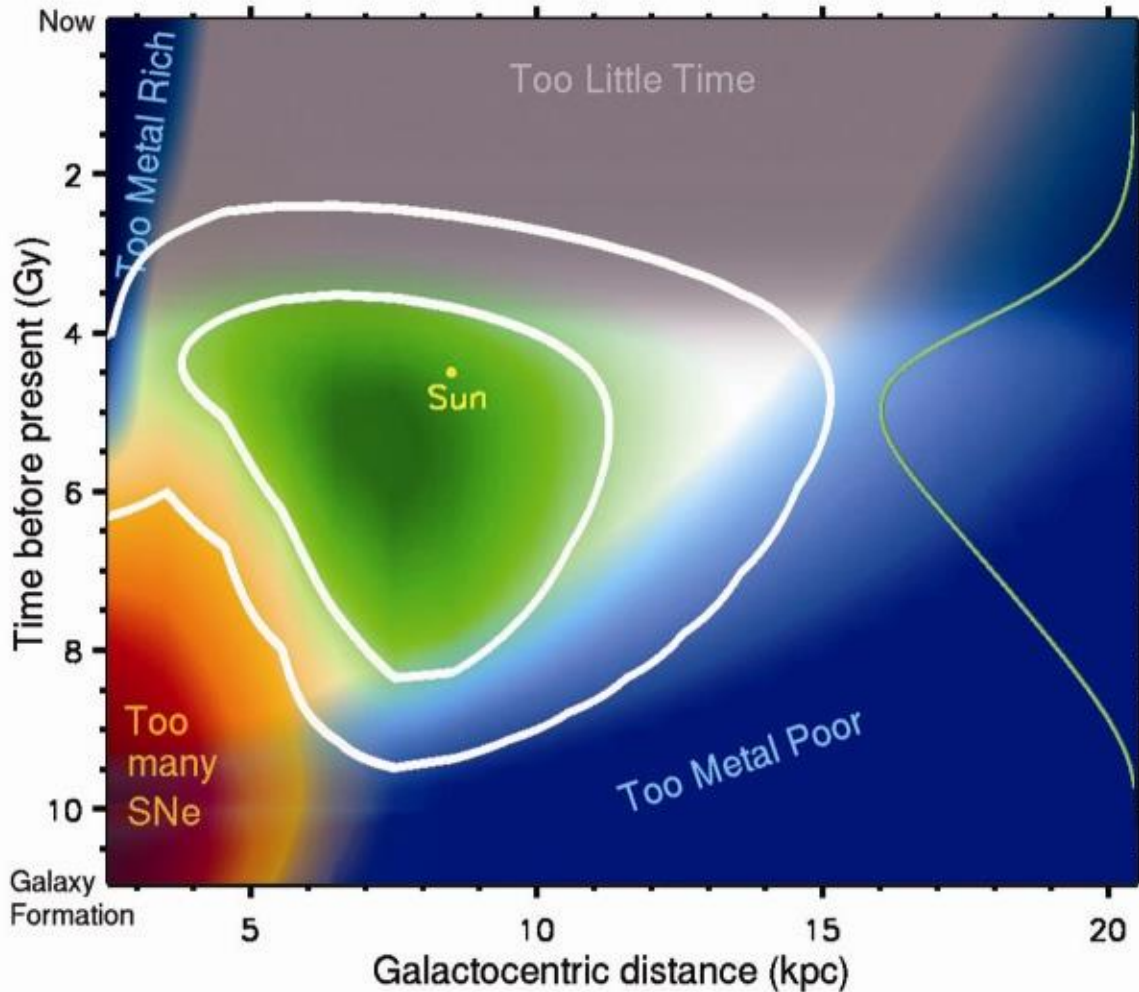


1983 + 12 = 1995 (!)



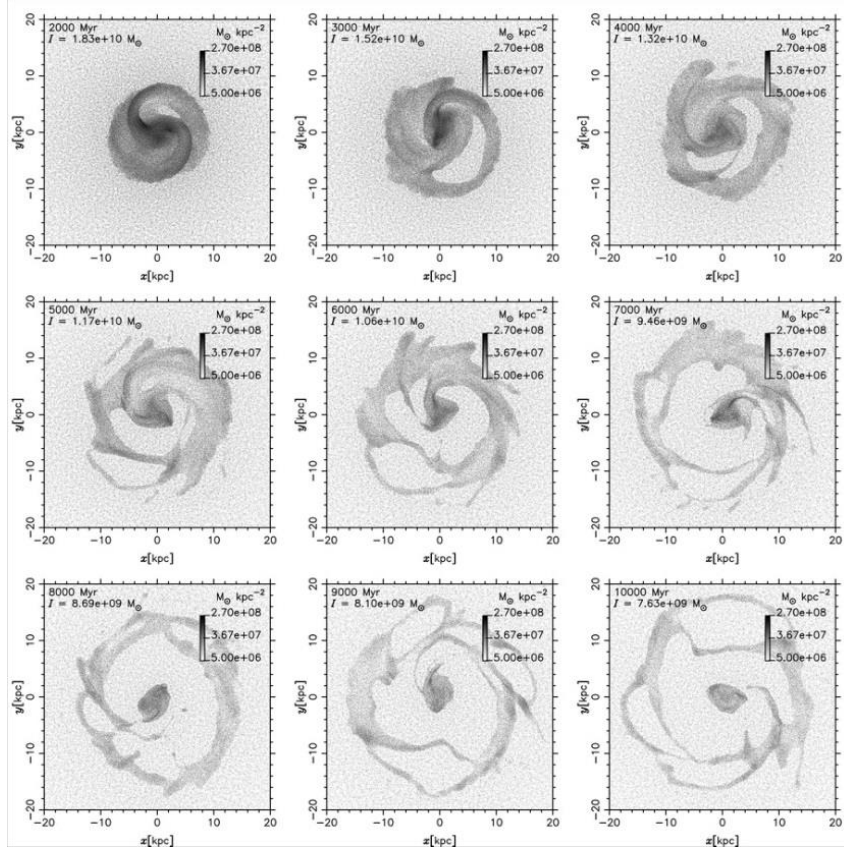
- Carter's discussion of hard steps significantly precedes their introduction in evolutionary biology!

The Galactic Habitable Zone (GHZ)



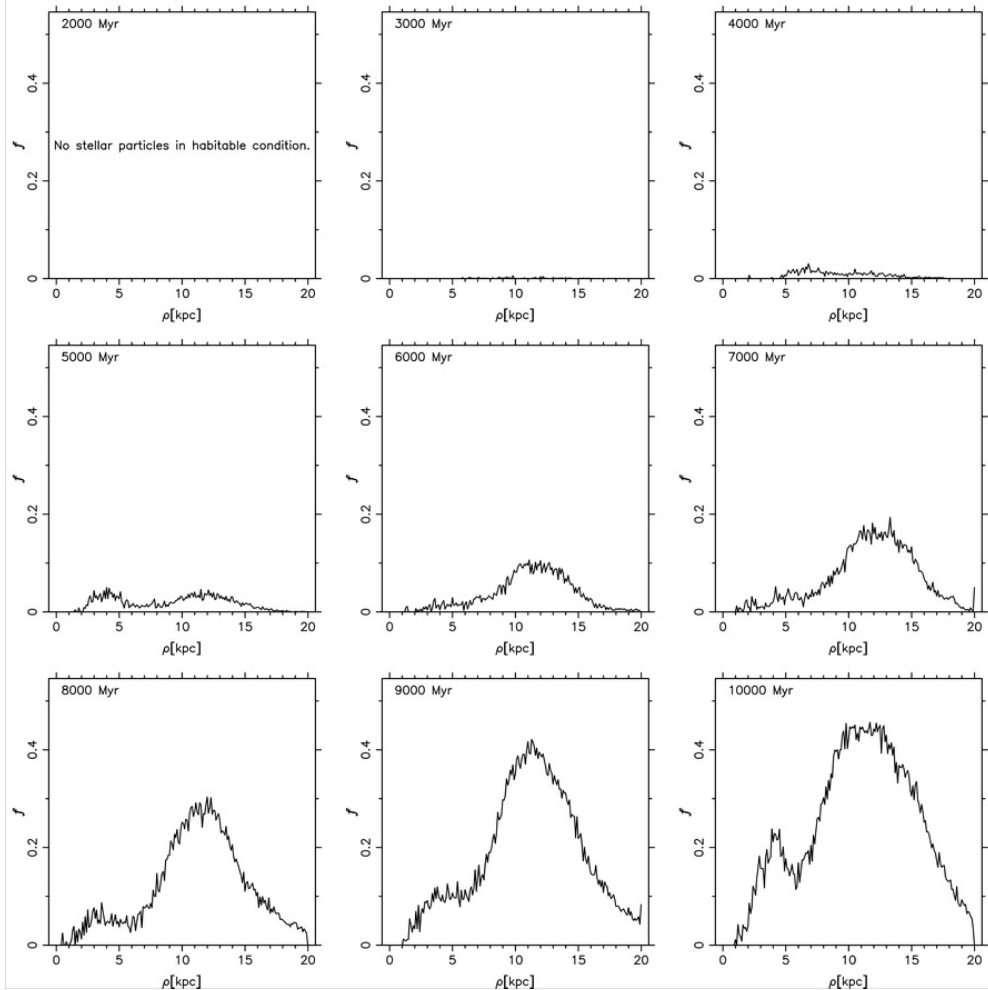
- Gonzalez, Brownlee and Ward (2001)
- Lineweaver (2001, 2004)

More precise results from numerical simulations



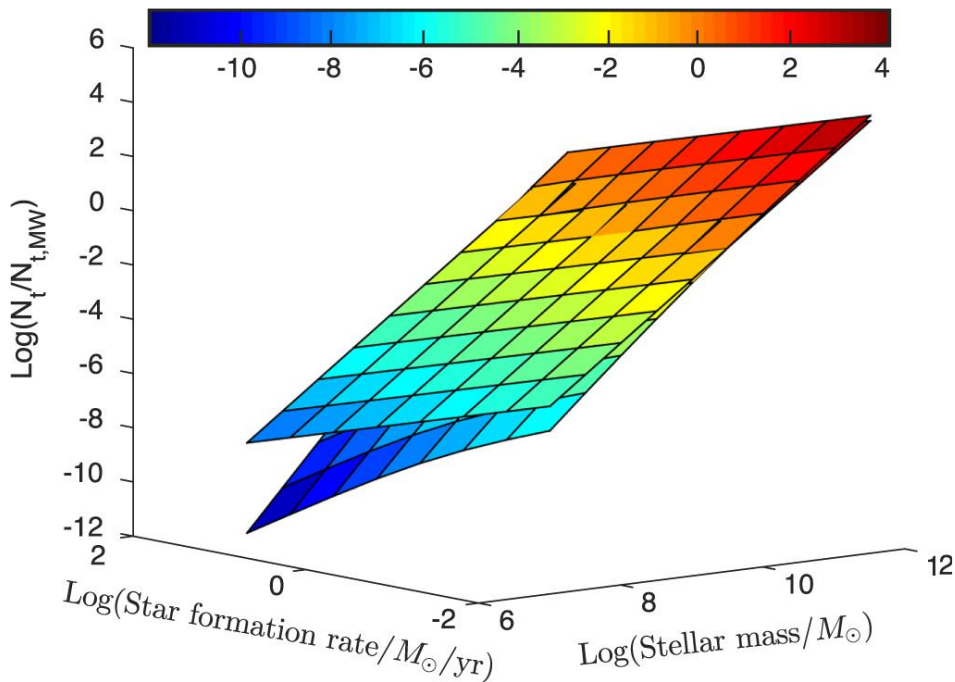
- Vukotić et al. (2016)
- Forgan et al. (2017)
- **The first application** of the cosmological N-body simulations to GHz.
- **Gadget2** N-body SPH code.
- Mass resolution still poor...

Continual habitability



- Complex structure and evolution of GHZ.
- In general, more weight on higher ρ .

A controversy: are early-type galaxies in fact more habitable?

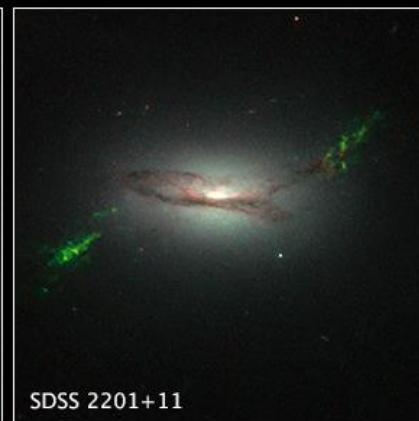
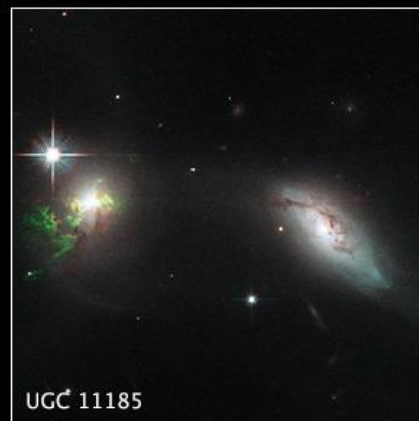
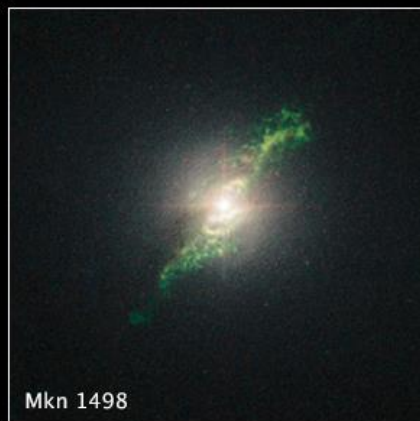
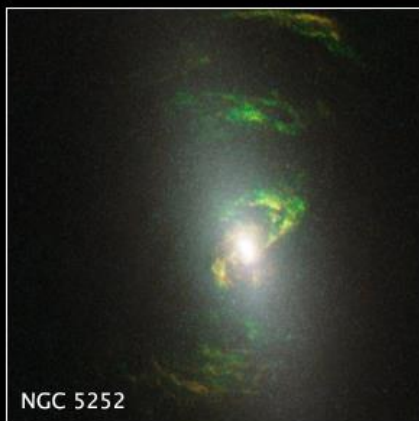
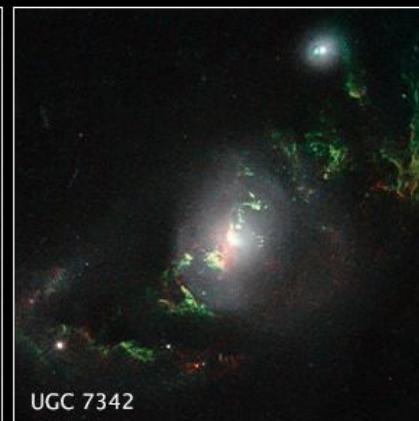
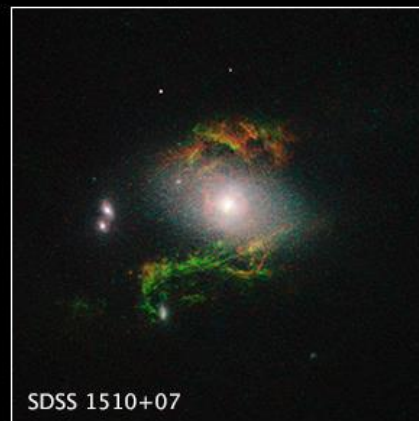
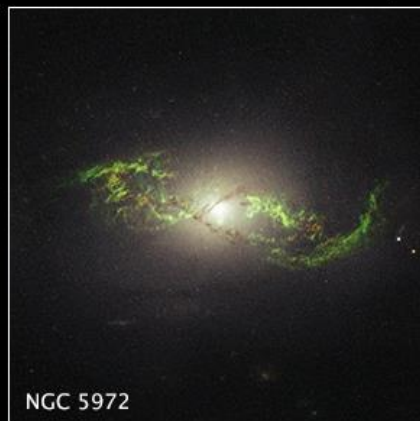
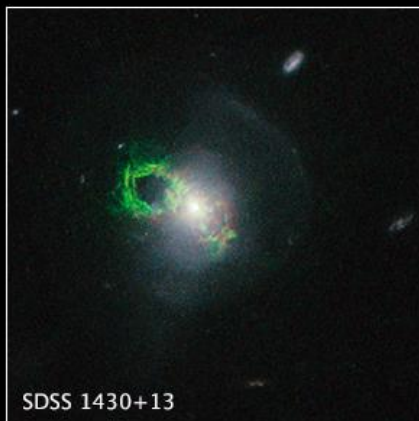


- Dayal et al. (2015): more terrestrial planets per unit mass in ellipticals.
- Even with metallicity corrections, the effect of catastrophic explosions still dominant...
- Quite open and live research question!

Habitability of galaxies



Extended Gas in Active Galaxies ■ *Hubble Space Telescope* ■ WFC2 ■ ACS/WFC ■ WFC3/UVIS



NASA and ESA

STScI-PRC15-13a

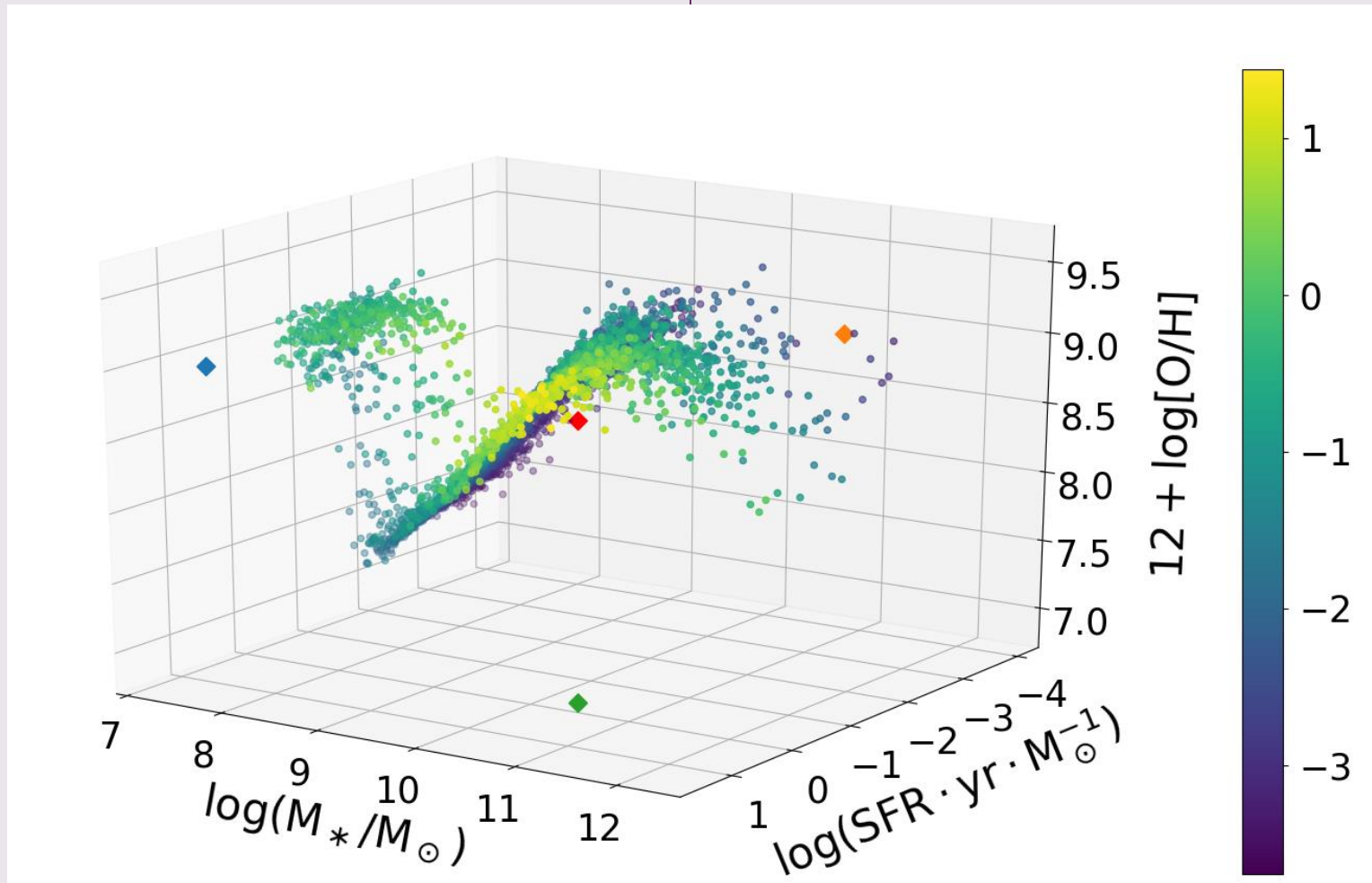
The Copernican mirror



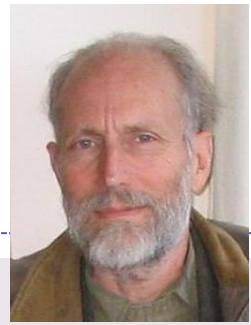
- If the Earth/Milky Way/Local Group is **typical in its reference class** --
- \Rightarrow by better understanding the reference class, we understand our habitat better!



Using a better simulation...



Many roads and pathways...



- **Problem 1:** We do not know all the laws relevant for the increase of complexity.
- **Problem 2:** The parameter space is VERY big!
- **Problem 3:** contingency vs. convergence?
- **Problem 4:** the role of information carrier (cf. **Carter 2012**)? ...

The game is afoot!

How many kingdoms know us not!

Blaise Pascal (cca. 1650)



THANK YOU FOR YOUR ATTENTION!