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Probabilities of Earth-like evolution by *easy* and *hard* steps

5th Workshop of the Italian Astrobiology Society

Life in a Cosmic Context

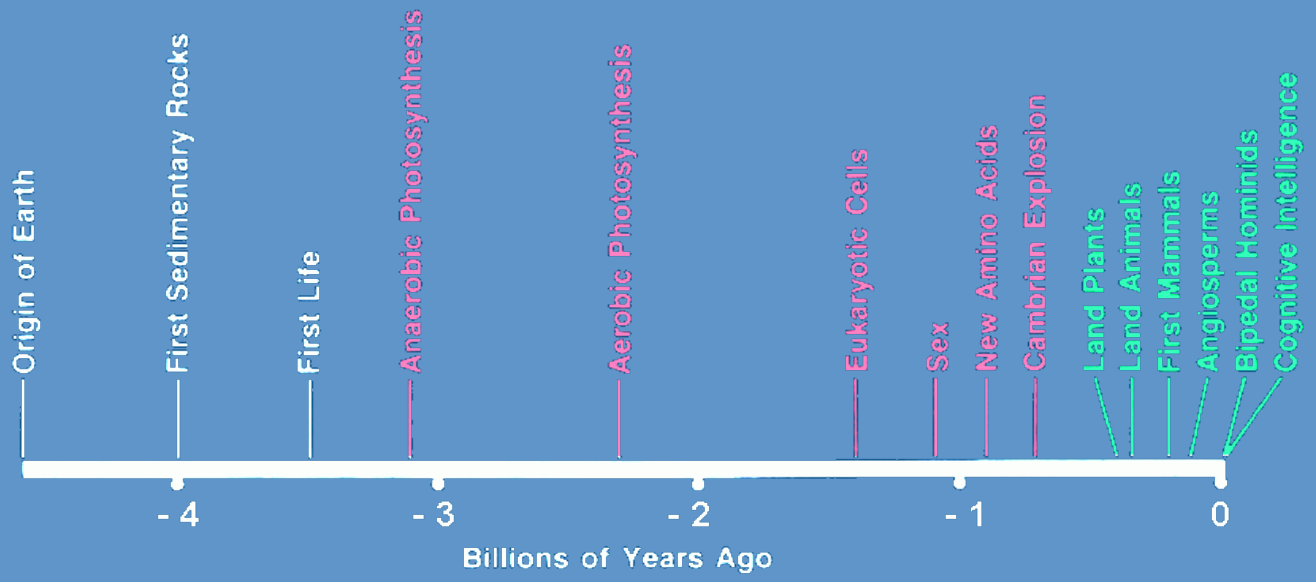
15-17 September 2015, Trieste, Italy

INTELLIGENCE is *RARE* or *COMMON*?

Sequence of *n* evolutionary steps

Hardness of a step: *h* = *T* (spontaneous) / *T* (biosphere)

Olson (1985)



$$f_i = p_P \cdot p_{PO} \cdot p_E \cdot p_S \cdot p_A \cdot p_{CE} \cdot p_{LP} \cdot p_{LA} \cdot p_{FM} \cdot p_A \cdot p_{BP} \cdot p_{CI} = 10^{-6} ?$$

Ornstein '82

CONDITIONED PROBABILITY

Analytical or *numerical* approach?

Basic: **Carter (2008) - Watson (2008)**

Distribuzioni

Binomiale:

$$P(n,k) = \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k}$$

Carter:

$$P(n,k,t) = \frac{n!\,t^{k-1}(t-\tau)^{n-k}}{(k-1)!(n-k)!\,\tau^n}$$

p **<<** (eventi rari) **;** ***n*** **>>**

n

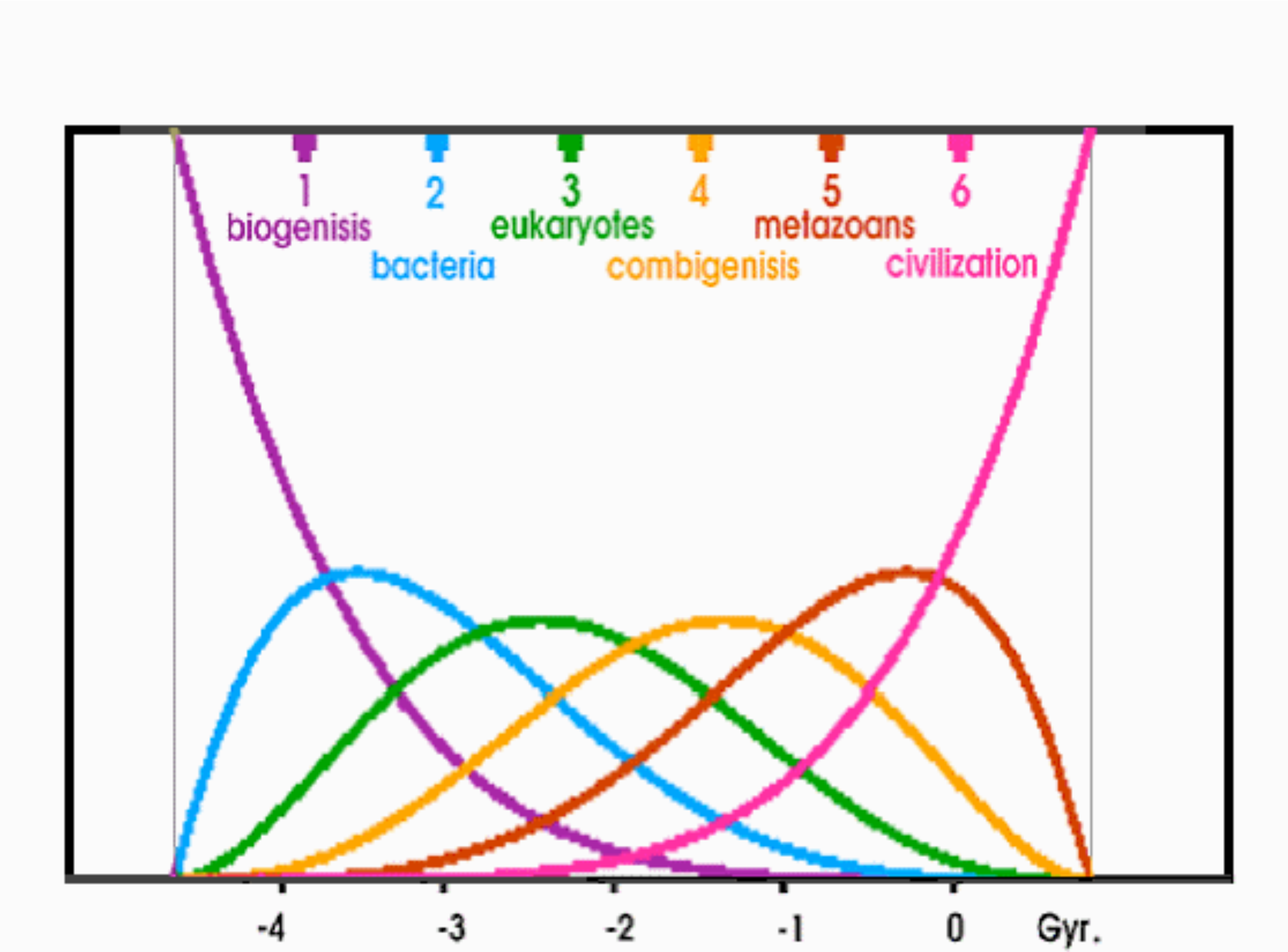
Poissoniana:

$$P(n,\lambda) = \frac{e^{-\lambda}\lambda^n}{n!}$$

(*n*,λ) → (*n*,λ,*t*)

Erlang:

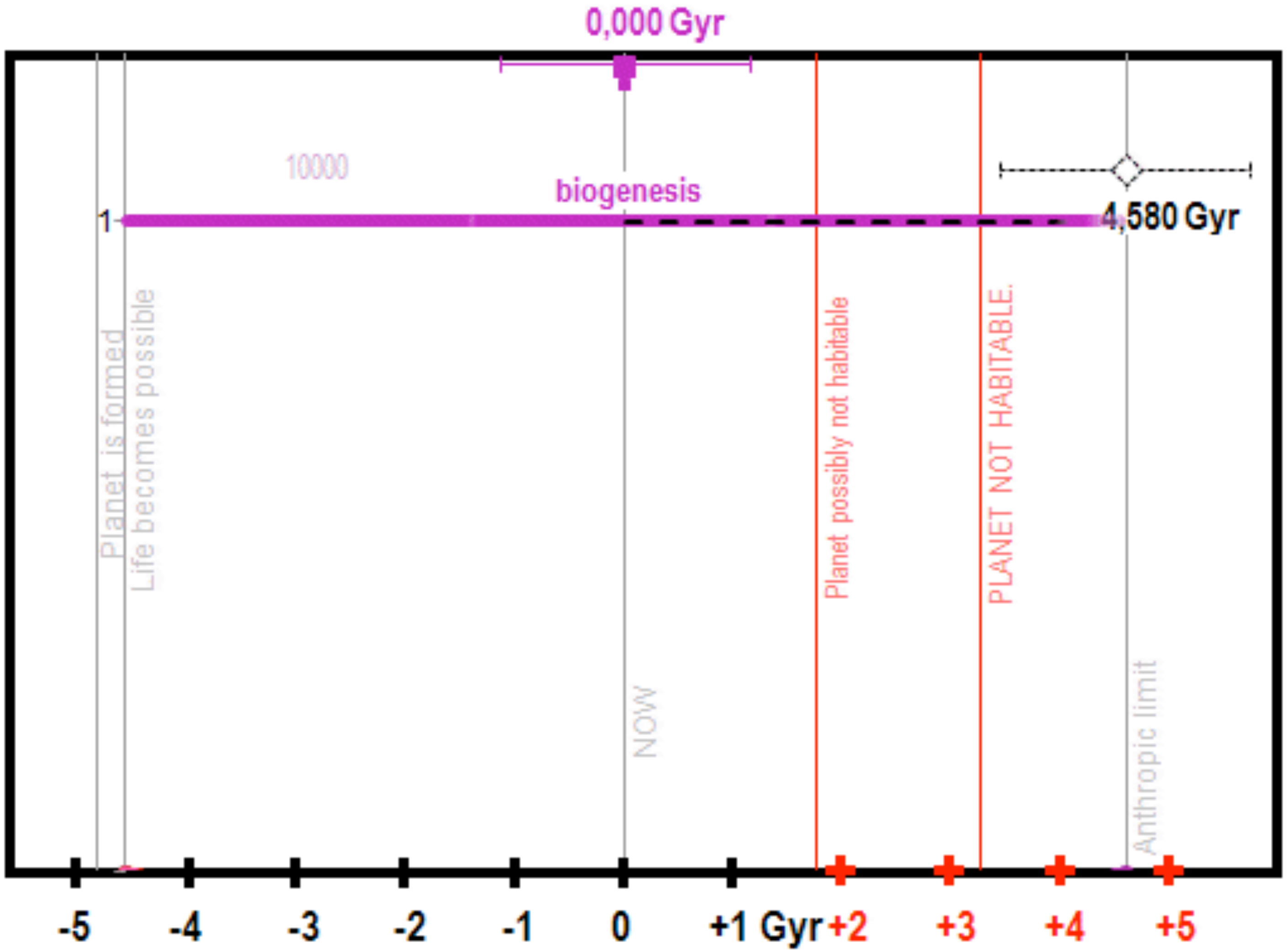
$$P(n,\lambda,t) = \frac{e^{-\lambda t}\lambda^n t^{n-1}}{(n-1)!}$$


1
biogenisis
2
bacteria
3
eukaryotes
4
combigenisis
5
metazoans
6
civilization
-4
-3
-2
-1
0
Gyr.

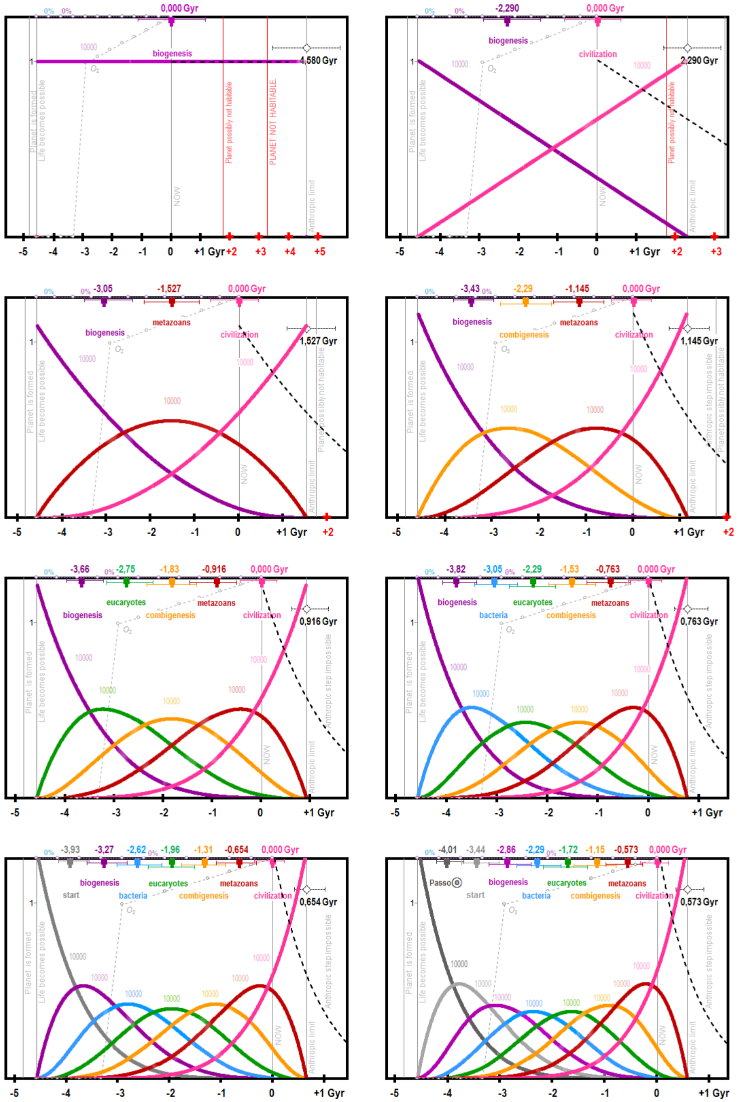
MULTIPLE MODELS

$n = 1,\ldots 8$

Changing the number of steps



0,000 Gyr
10000
biogenesis
1
4,580 Gyr
Planet is formed
Life becomes possible
NOW
Planet possibly not habitable
PLANET NOT HABITABLE.
Anthropic limit
-5
-4
-3
-2
-1
0
+1 Gyr
+2
+3
+4
+5

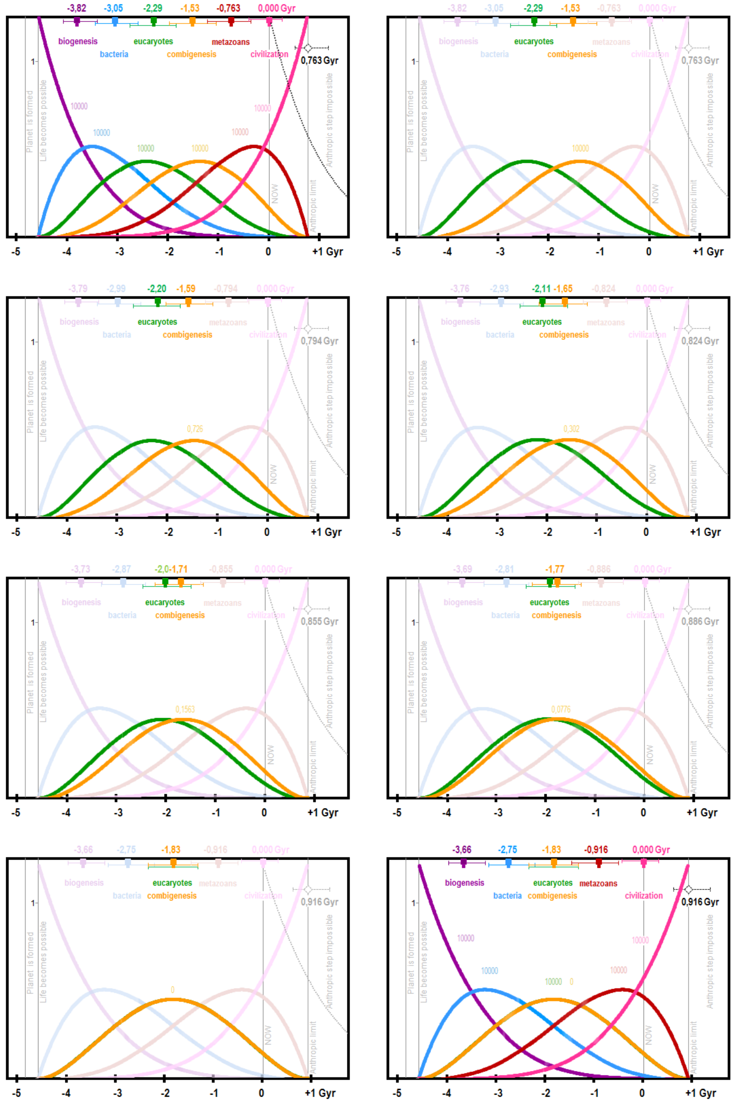


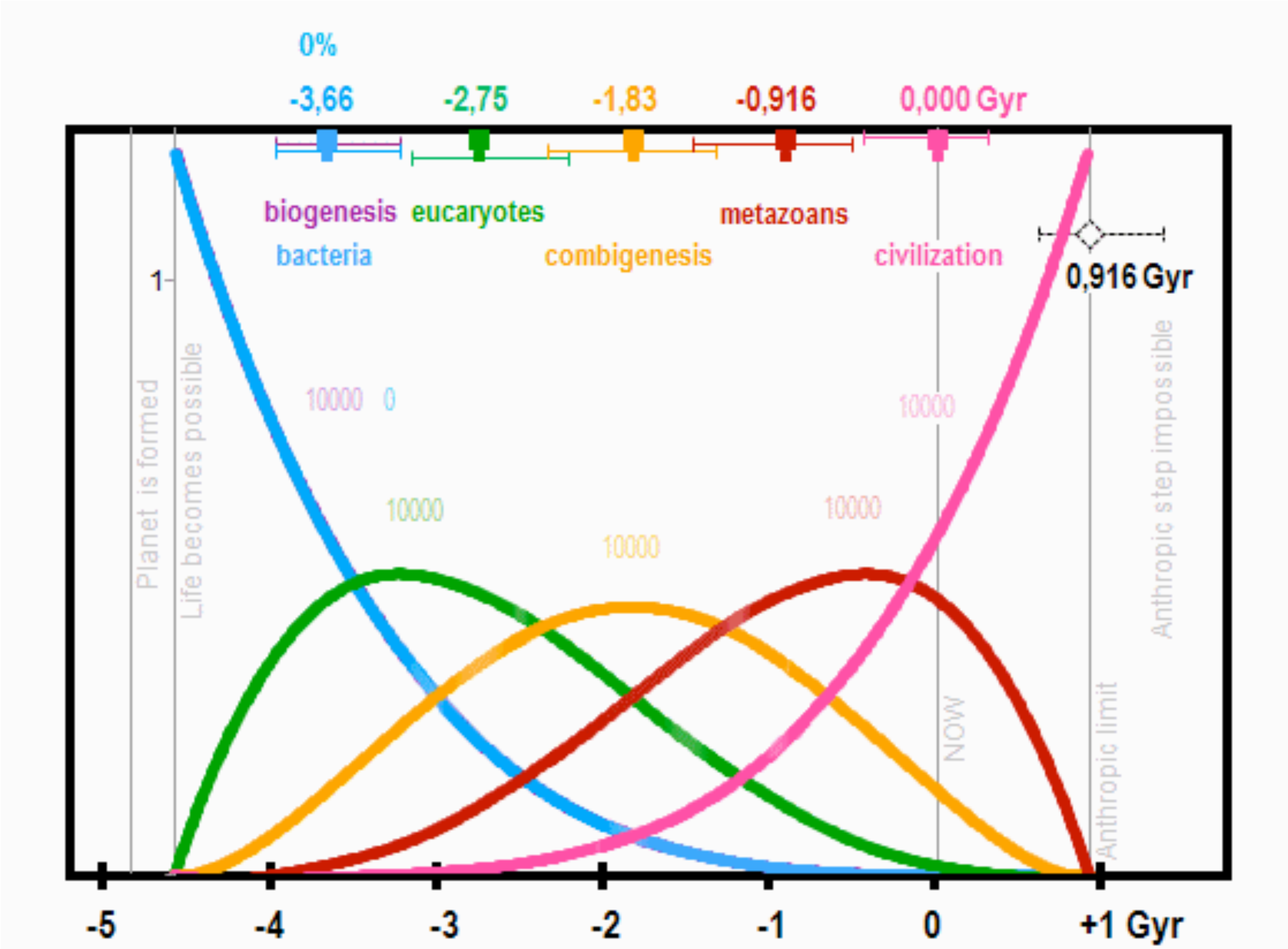
0,000 Gyr
biogenesis
4,580 Gyr
Planet possibly not habitable
PLANET NOT HABITABLE
NOW
Anthropic limit
-2,290
civilization
2,290 Gyr
-3,05
-1,527
metazoans
1,527 Gyr
-3,43
-2,29
-1,145
combigenesis
1,145 Gyr
-3,66
-2,75
-1,83
-0,916
eucaryotes
0,916 Gyr
-3,82
-3,05
-2,29
-1,53
-0,763
bacteria
0,763 Gyr
-3,93
-3,27
-2,62
-1,96
-1,31
-0,654
start
0,654 Gyr
-4,01
-3,44
-2,86
-2,29
-1,72
-1,15
-0,573
0,573 Gyr
Planet is formed
Life becomes possible
Anthropic step impossible
10000
-5
-4
-3
-2
-1
0
+1 Gyr
+2
+3
+4
+5

INTERMEDIATE MODELS

$n = 6 \longrightarrow n = 5$

Changing the hardness of a single step


-3,82
-3,05
-2,29
-1,53
-0,763
0,000 Gyr
biogenesis
bacteria
eucaryotes
combigenesis
metazoans
civilization
0,763 Gyr
Planet is formed
Life becomes possible
Anthropic step impossible
Anthropic limit
NOW
-5
-4
-3
-2
-1
0
+1 Gyr
-2,20
-1,59
0,794 Gyr
-2,11
-1,65
0,824 Gyr
0,855 Gyr
-1,77
0,886 Gyr
-1,83
0,916 Gyr
-3,66
-2,75
-0,916

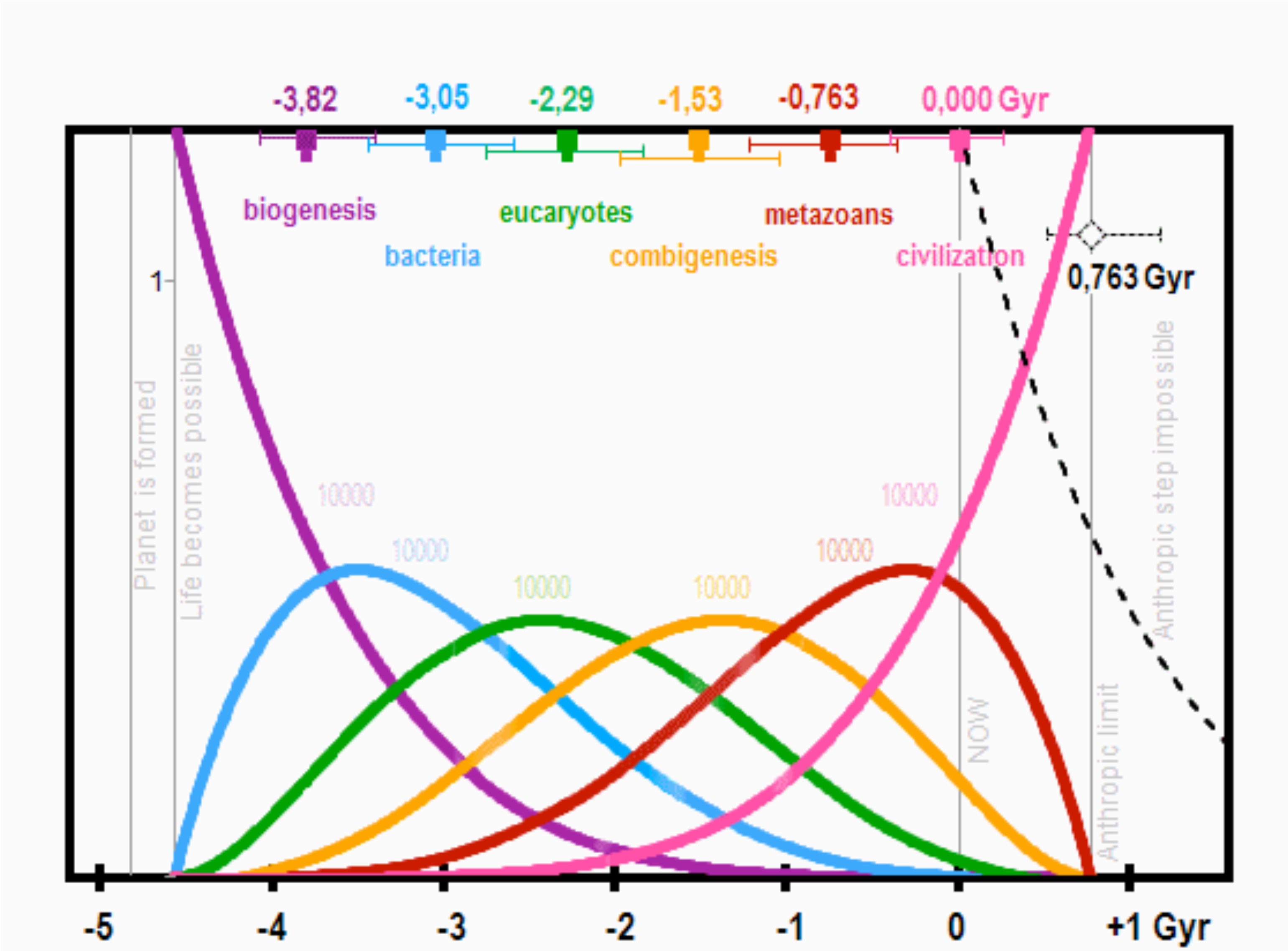


0%
-3,66
-2,75
-1,83
-0,916
0,000 Gyr
biogenesis
bacteria
eucaryotes
combigenesis
metazoans
civilization
0,916 Gyr
1
Planet is formed
Life becomes possible
10000
0
10000
10000
10000
10000
NOW
Anthropic limit
Anthropic step impossible
-5
-4
-3
-2
-1
0
+1 Gyr

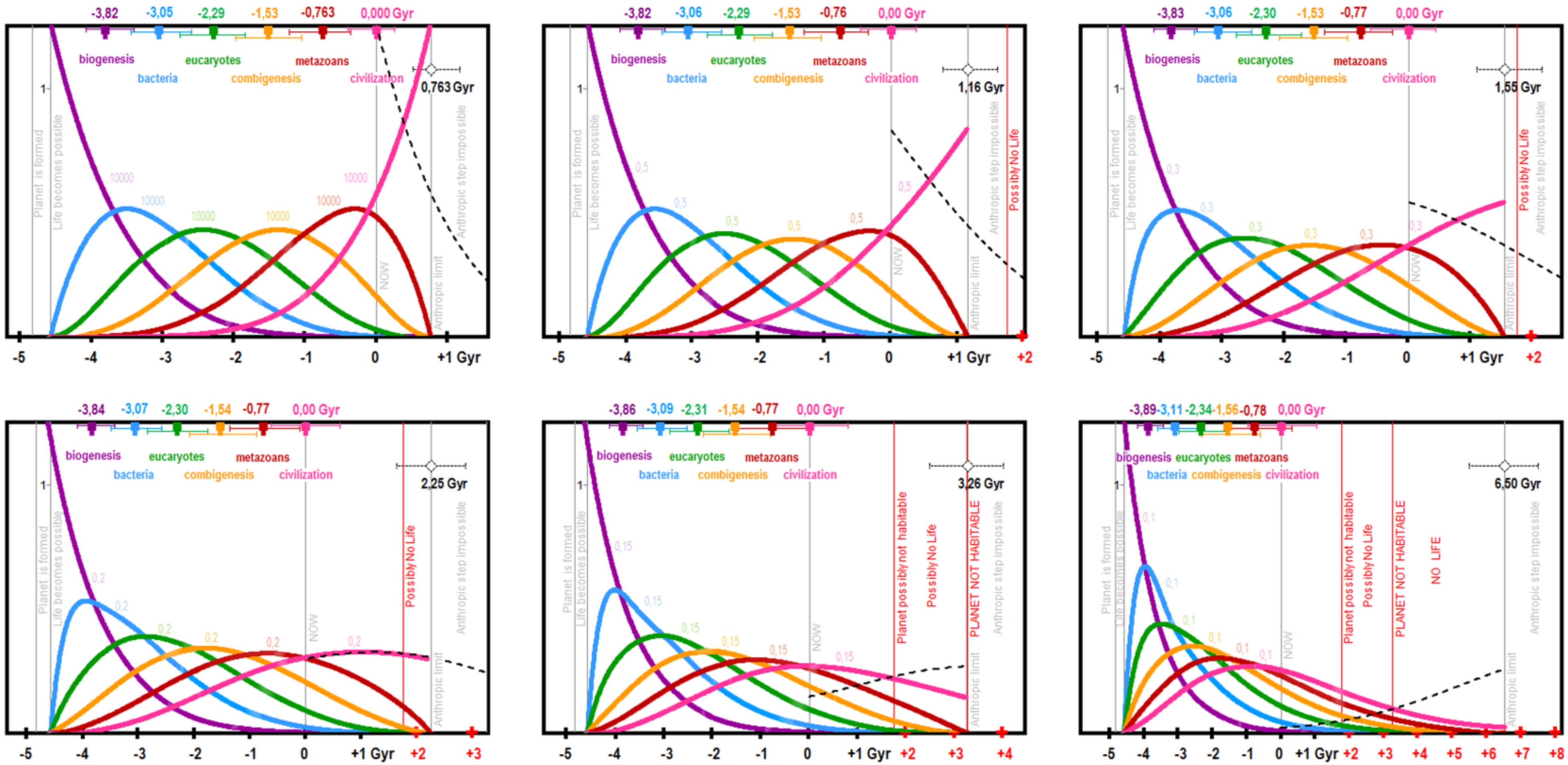
HARD vs. EASY

h = 10000 ⟶ 0.1

Better Hard?



-3,82
-3,05
-2,29
-1,53
-0,763
0,000 Gyr
biogenesis
bacteria
eucaryotes
combigenesis
metazoans
civilization
0,763 Gyr
1
Planet is formed
Life becomes possible
10000
10000
10000
10000
10000
10000
NOW
Anthropic limit
Anthropic step impossible
-5
-4
-3
-2
-1
0
+1 Gyr

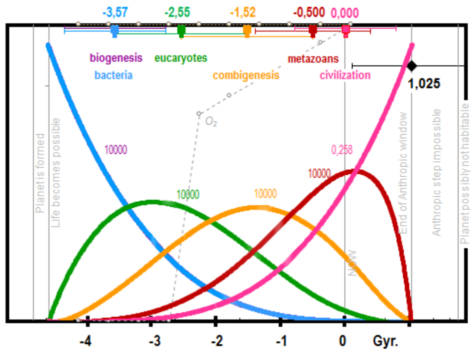


-3,82 -3,05 -2,29 -1,53 -0,763 0,000 Gyr
biogenesis bacteria eucaryotes combigenesis metazoans civilization
0,763 Gyr
Planet is formed
Life becomes possible
NOW
Anthropic limit
Anthropic step impossible
-5 -4 -3 -2 -1 0 +1 Gyr
-3,82 -3,06 -2,29 -1,53 -0,76 0,00 Gyr
1,16 Gyr
Possibly No Life
-5 -4 -3 -2 -1 0 +1 Gyr +2
-3,83 -3,06 -2,30 -1,53 -0,77 0,00 Gyr
1,55 Gyr
Possibly No Life
-5 -4 -3 -2 -1 0 +1 Gyr +2
-3,84 -3,07 -2,30 -1,54 -0,77 0,00 Gyr
2,25 Gyr
Possibly No Life
-5 -4 -3 -2 -1 0 +1 Gyr +2 +3
-3,86 -3,09 -2,31 -1,54 -0,77 0,00 Gyr
3,26 Gyr
Planet possibly not habitable
Possibly No Life
PLANET NOT HABITABLE
-5 -4 -3 -2 -1 0 +1 Gyr +2 +3 +4
-3,89 -3,11 -2,34 -1,56 -0,78 0,00 Gyr
6,50 Gyr
Planet possibly not habitable
Possibly No Life
PLANET NOT HABITABLE
NO LIFE
-5 -4 -3 -2 -1 0 +1 Gyr +2 +3 +4 +5 +6 +7 +8

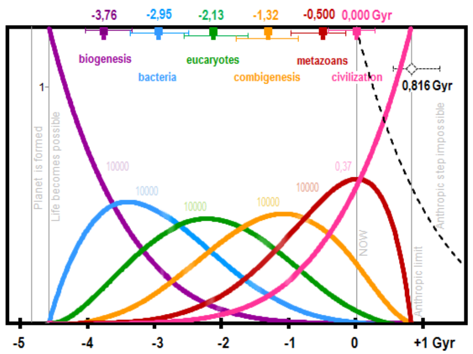
COGNITIVE INTELLIGENCE

$h = .37$ for $n = 6$

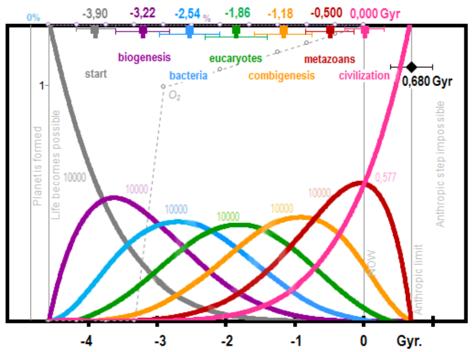
Optimizing the last step



-3,57
-2,55
-1,52
-0,500
0,000
biogenesis
eucaryotes
bacteria
combigenesis
metazoans
civilization
1,025
Planet is formed
Life becomes possible
End of Anthropic window
Anthropic step impossible
Planet possibly not habitable
NOW
10000
0,258
-4
-3
-2
-1
0
Gyr.



-3,76
-2,95
-2,13
-1,32
-0,500
0,000 Gyr
biogenesis
eucaryotes
metazoans
bacteria
combigenesis
civilization
0,816 Gyr
Planet is formed
Life becomes possible
Anthropic step impossible
Anthropic limit
NOW
10000
0,37
1
-5
-4
-3
-2
-1
0
+1 Gyr

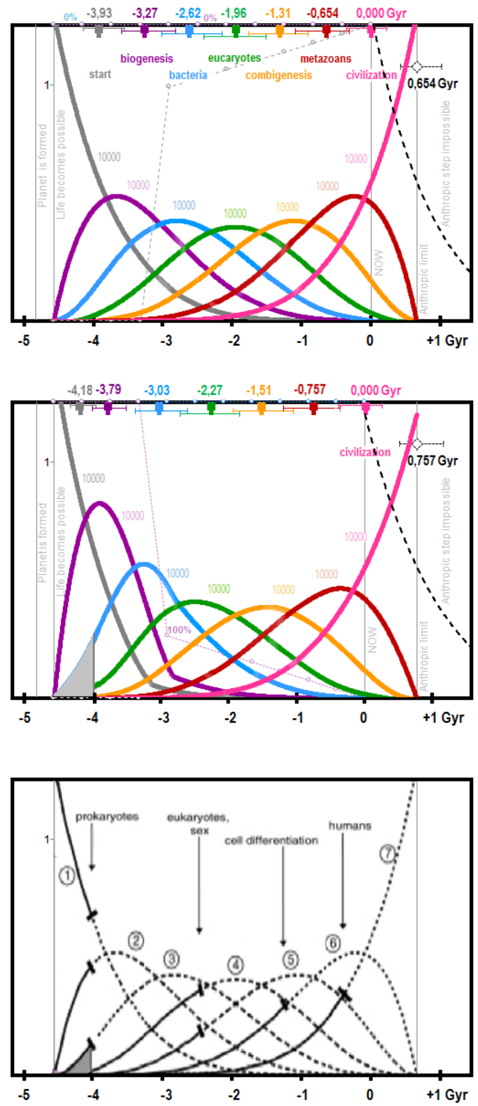


0%
-3,90
-3,22
-2,54
-1,86
-1,18
-0,500
0,000 Gyr
biogenesis
eucaryotes
metazoans
start
bacteria
combigenesis
civilization
0,680 Gyr
Planet is formed
Life becomes possible
Anthropic step impossible
Anthropic limit
NOW
10000
0,577
1
-4
-3
-2
-1
0
Gyr.

ENVIRONMENTAL EFFECTS

Weight **[$F(t)$] = 0% ÷ 100%**

Modulating the distributions by a function $F(t)$

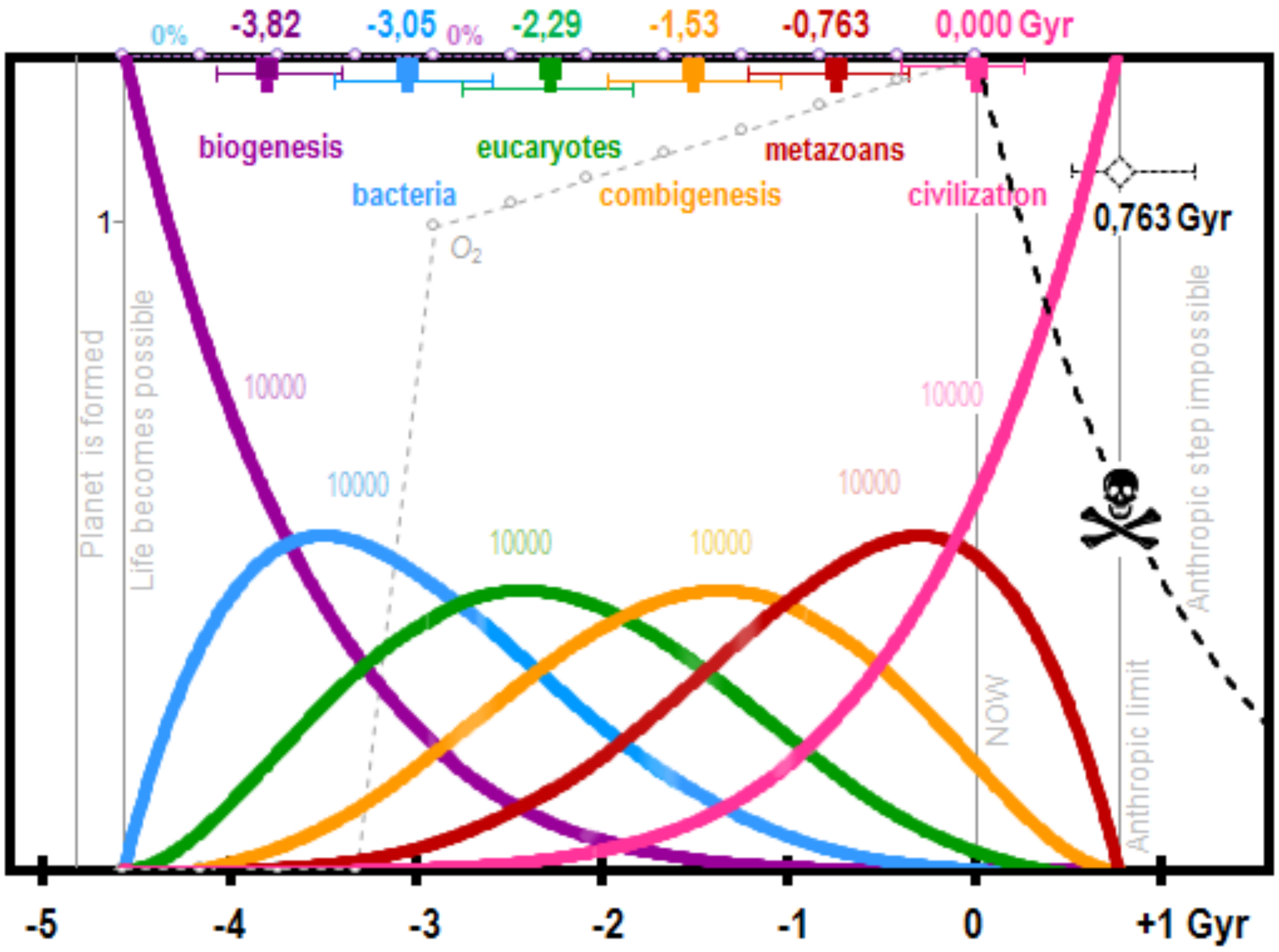


0%
-3,93
-3,27
-2,62
0%
-1,96
-1,31
-0,654
0,000 Gyr
start
biogenesis
bacteria
eucaryotes
combigenesis
metazoans
civilization
0,654 Gyr
Planet is formed
Life becomes possible
Anthropic step impossible
Anthropic limit
NOW
-5
-4
-3
-2
-1
0
+1 Gyr
-4,18
-3,79
-3,03
-2,27
-1,51
-0,757
0,000 Gyr
civilization
0,757 Gyr
100%
prokaryotes
eukaryotes,
sex
cell differentiation
humans

“END OF THE WORLD”

…see the Poster

When will the planet exit from the HZ?



0%
-3,82
-3,05
0%
-2,29
-1,53
-0,763
0,000 Gyr
biogenesis
eucaryotes
metazoans
bacteria
combigenesis
civilization
0,763 Gyr
1
O_2
Planet is formed
Life becomes possible
10000
10000
10000
10000
10000
10000
NOW
Anthropic limit
Anthropic step impossible
-5
-4
-3
-2
-1
0
+1 Gyr

“Curve of the End of the World” in the *hard life* scenario

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Easy and *Hard* scenarios

Common expectations for widespread life in the universe are theoretically supported by the *easy life* scenario, which considers the biological evolution as a sequence of highly probable transitions, occurring on any habitable planet, possibly leading from biogenesis to intelligence.

On the opposite side, a less-popular scientific point of view (yet Copernican) is the *hard life* scenario, supposing that the Earth might be a rare case of planetary evolution due to a sequence of low-probability transitions, which we notice only because of the (anthropic) selection effect requiring the presence of observers.

The steps of evolution

The number *n* of critical evolutionary steps considered in the literature [1] [2], according to biological and paleontological issues, is generally small (from 5 to 7), and the probability distributions for a sequence of *hard* steps are known analytically.

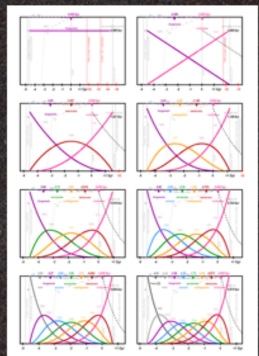

Figure 1 – Probability distributions in the *hard life* scenario, computed for a number *n* of evolutionary steps ranging from 1 to 8 (hardness h=10000 is used for all steps).

Low-*n* distributions have only mathematical meaning, while for terrestrial evolution Carter [1] and Watson [2] assumed 6 and 7 steps, respectively. The distribution with 8 steps is shown here for the first time.

A more general conception admits that the hypothetical sequence of evolutionary transitions, leading to intelligent life, may include *hard* and *easy* steps as well.

In the present work the computations are performed numerically. This allows to study the general probability distributions with both *hard* and *easy* evolutionary steps, and even the effect of possible environmental factors.

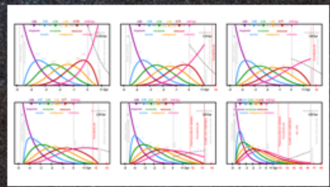

Figure 2 – *Easy life* models evolve rapidly in the early planetary biosphere, which is not the case of the slow-developing terrestrial life. The colored upper numbers mark the expectation time in Gyr (weighted average of probability curve) for each transition.

The *hardness* of an evolutionary step is defined as the ratio $h = T / T_0$, where T is the average time required by the event to occur spontaneously and T_0 is the lifespan of the planet's biosphere. If $h > 1$ the step is considered to be *hard*, while $h << 1$ means the step is *easy*.

We may question how severely *hard*, or comfortably *easy*, have been the steps of terrestrial evolution. Numerical computations allow to vary the *hardness* progressively, showing that more *easy* scenarios ($h < 0.5$) are poorly compatible with the lifespan of our biosphere.

The “Curve of Death”

The *hard life* model has the well-known property of producing equally spaced transitions within the lifetime of the biosphere, so explaining the early occurrence of the first step (biogenesis) soon after the crustal solidification on Earth.

Symmetrically, the last step (cognitive intelligence) must be near the closure of the opportunity window, that is the end of planetary habitability. This is the reason of the predictive nature of the *hard life* model: in simple words we are close to the “end of the world”.

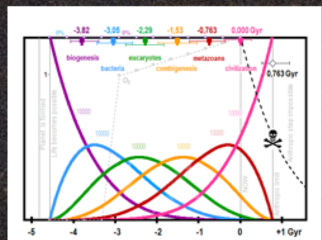

Figure 3 – The “Curve of the end of the World” is the dashed black line on the right. It has a mirror-like shape with respect to the curve of the last step (pink color) and it starts from $t = 0$ (now).

This curve describes the probability that the “End of the World” (egress of the Earth from the Habitable Zone) might occur at a given time in the future, depending on the parameters of the model. Its average value is the probable time remaining before the end of the biosphere, which is equal to the duration of the last step (here 0.763 Gyr)

Discussion

The results, displayed in the Figures below, show that *hard* scenarios with larger number of steps (n > 6 or 7) imply uncomfortably short lifetimes for the biosphere.

On the other side, the presence of a single *easy* step leading from metazoa to cognitive intelligence, has the reassuring effect of lengthening the expected biospheric lifetime, in better agreement with the predictions of solar main-sequence evolution.

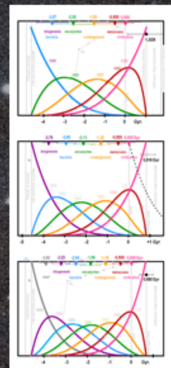

Figure 4 – *Easy* final step with n = 5, 6, 7.

This *easy* final transition has the additional consequence of better matching the time interval between the appearance of animals and the appearance of humans, which is known by paleontology to be shorter than the other steps (about 0.5 Gyr).

The numerical distributions reported here are referred to a general methodological framework which is presented by the Author in Session 6 of this Workshop.

Basic references

[1] Carter, 2008, Int. J. Astrobiology, 7, 177

[2] Watson, 2008, Astrobiology, 8, 175

Contact

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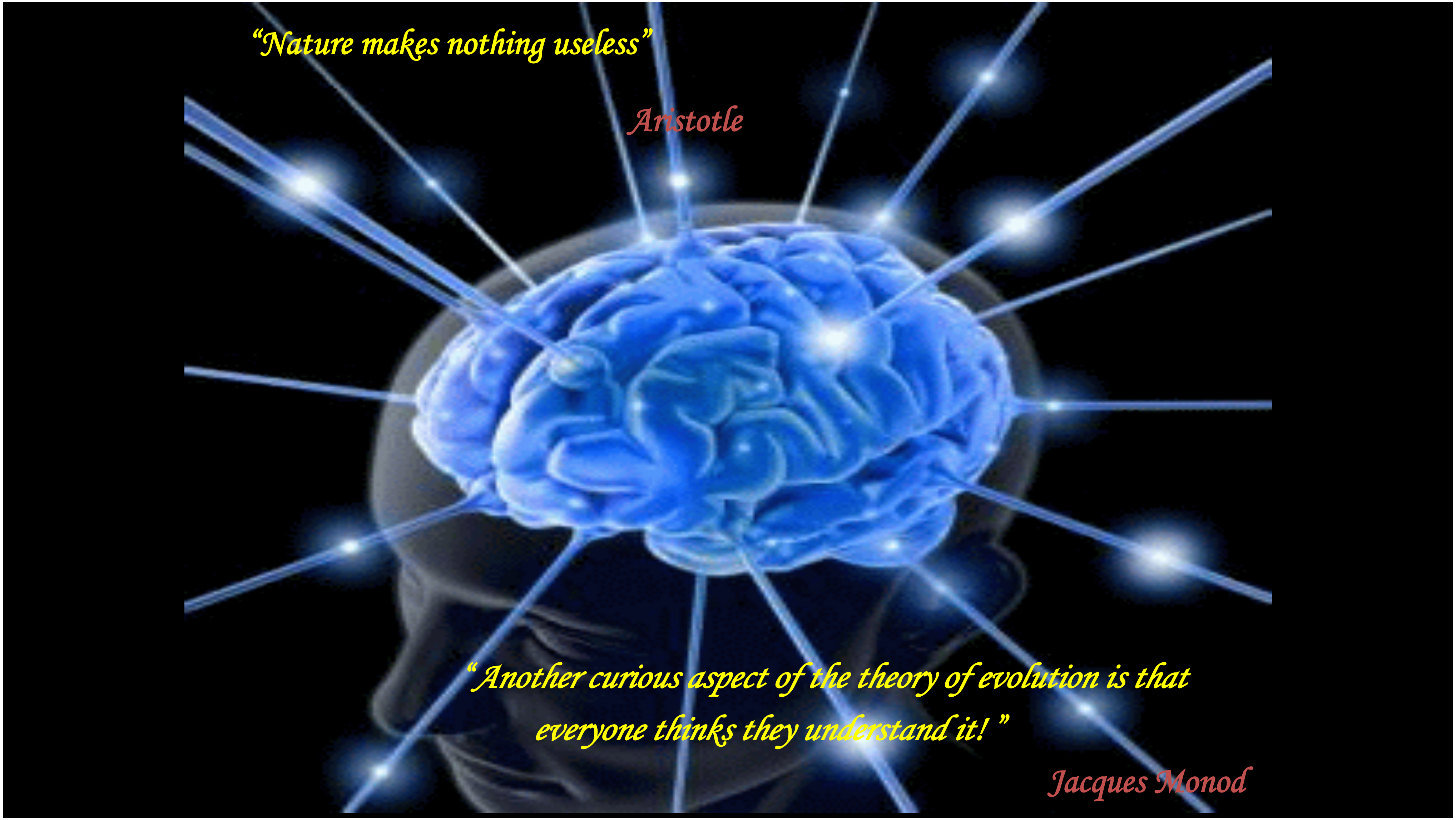
"Nature makes nothing useless"
Aristotle
" Another curious aspect of the theory of evolution is that everyone thinks they understand it! "
Jacques Monod