The possible, the plausible and the probable: fine-tuning in the physical universe

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part 1

fine-tuning and the anthropic principle

what is fine-tuning?

Dirac's large number hypothesis

the anthropic principle

Dirac's large number hypothesis

- Weyl (1919): radius of Universe ~ radius of particle whose rest energy is equal to the electron gravitational energy → radius Universe / radius electron ~ 10^{42}
- Eddington (1931): number of charged particles in the Universe ~ 10^{42}
- Dirac (1938): age of the Universe → electrical to gravitational force ration between proton and electron $$t_H \sim \frac{e^2}{4\pi\varepsilon_0 G m_e m_p} \sim 10^{40} \Rightarrow G \propto t^{-1}$$ **numerology?**

> It is proposed that all the very large dimensionless numbers which can be constructed from the important natural constants of cosmology and atomic theory are connected by simple mathematical relations involving coefficients of the order of magnitude unity. The main consequences of this assumption are investigated and it is found that a satisfactory theory of cosmology can be built up from it.

Dirac. Proc. Royal Soc. 165 (1938) 199.

- Milne (1935): the relation between G and t allows for general relativity to work without space-time having a structure → epistemological advantages of hypothesis
- Jordan (1937): constants have to become dynamical fields within a general field-theory framework that enables the treatment of **varying constants**.

LARGE NUMBER COINCIDENCES AND
THE ANTHROPIC PRINCIPLE IN COSMOLOGY

BRANDON CARTER
Dept. of Applied Mathematics and Theoretical Physics, University of Cambridge, U.K.

My own interest in this matter arose from reading Bondi's (1959) book *Cosmology* in which certain widely known 'large number coincidences' are listed as evidence justifying the introduction of various exotic theories (e.g. involving departures from normally accepted physical conservation laws) of which early examples were the 'varying *G*' theories of Dirac and Jordan. I am now convinced of the opposite thesis: i.e. that far from being evidence in favour of exotic theories these coincidences should rather be considered as confirming 'conventional' (General Relativistic Big Bang) physics and cosmology which could in principle have been used to predict them all in advance of their observation. However these predictions do require the use of what may be termed the *anthropic principle* to the effect that what we can expect to observe must be restricted by the conditions necessary for our presence as observers. (Although our situation is not necessarily *central*, it is inevitably privileged to some extent.)

B. Carter. Proc. IAU Symposium Confrontation of cosmological theories with observational data (1974).

The anthropic principle and its implications for biological evolution

By B. Carter, F.R.S.
Groupe d'Astrophysique Relativiste, Observatoire de Paris – Meudon, 5 Place Jules Janssen, 92 Meudon, France

In the form in which it was originally expounded, the *anthropic principle* was presented as a warning to astrophysical and cosmological theorists of the risk of error in the interpretation of astronomical and cosmological information unless due account is taken of the biological restraints under which the information was acquired. However, the converse message is also valid: biological theorists also run the risk of error in the interpretation of the evolutionary record unless they take due heed of the astrophysical restraints under which evolution took place. After an introductory discussion of the ordinary ('weak') anthropic principle and of its more contestable ('strong') analogue, a new application of the former to the problem of the evolution of terrestrial life is presented. It is shown that the evidence suggests that the evolutionary chain included at least one but probably not more than two links that were highly improbable (*a priori*) in the available time interval.

Carter. Phil. Trans. R. Soc. Lond. A 310 (1983) 347.

the anthropic principle(s)

weak anthropic principle

- essentially selection bias
- because observers are within a privileged position, the Universe must be such that it allows for their existence
- explanations sometimes involve concepts like multiverse

strong anthropic principle

- the Universe *must be* such that it allows the emergence of observers
- the observer plays a role in the evolution of the Universe

what is a fundamental parameter?

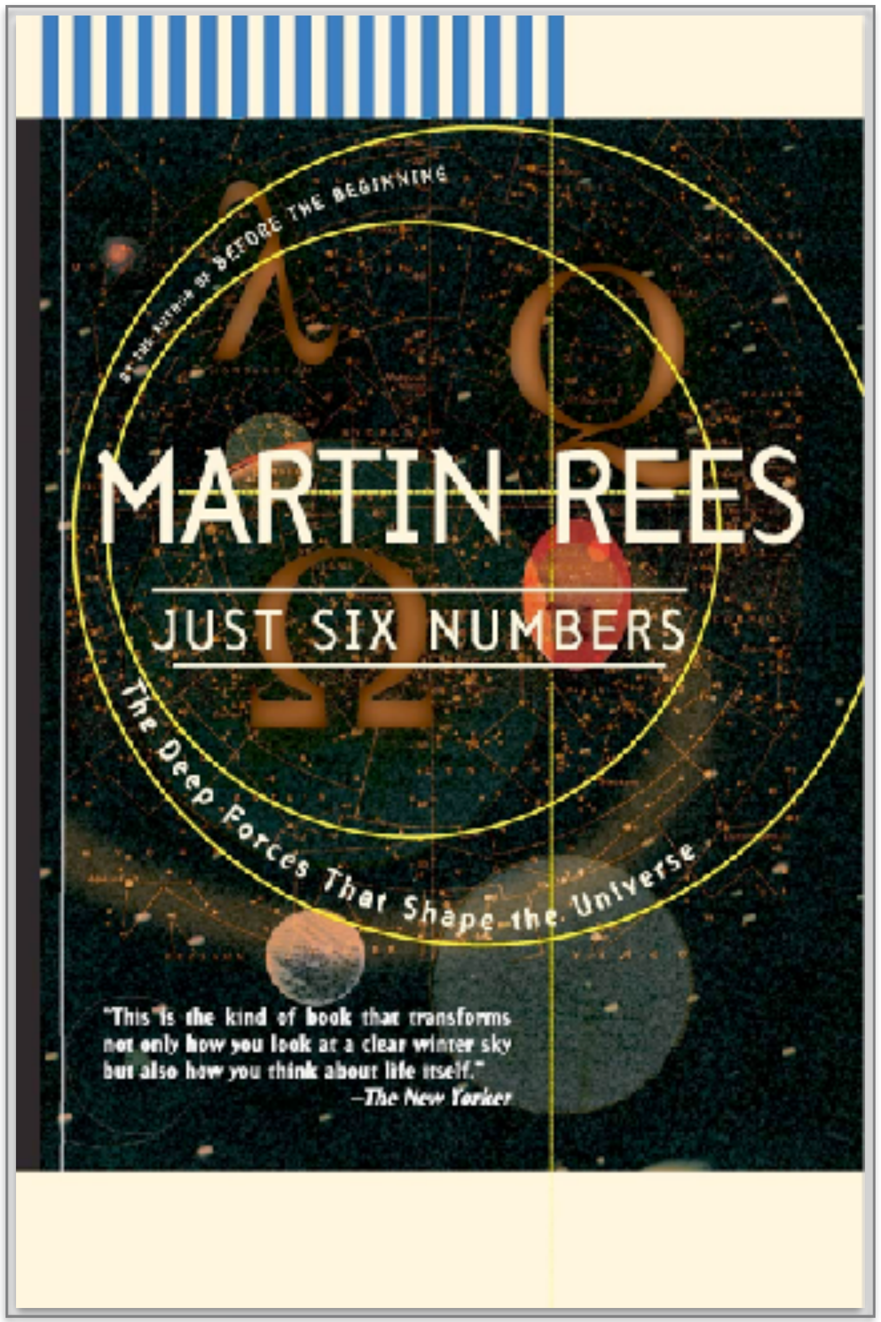
- fine-tuning arguments require **fundamental** and **dimensionless** quantities
- **dimensionless** quantity: no units

dimensionful	$m_p = 1.67 \times 10^{-27}$ kg $m_e = 9.11 \times 10^{-31}$ kg	dimensionless	$\dfrac{m_e}{m_p} = 0.00054$

- **fundamental** quantity: cannot be written in terms of others*

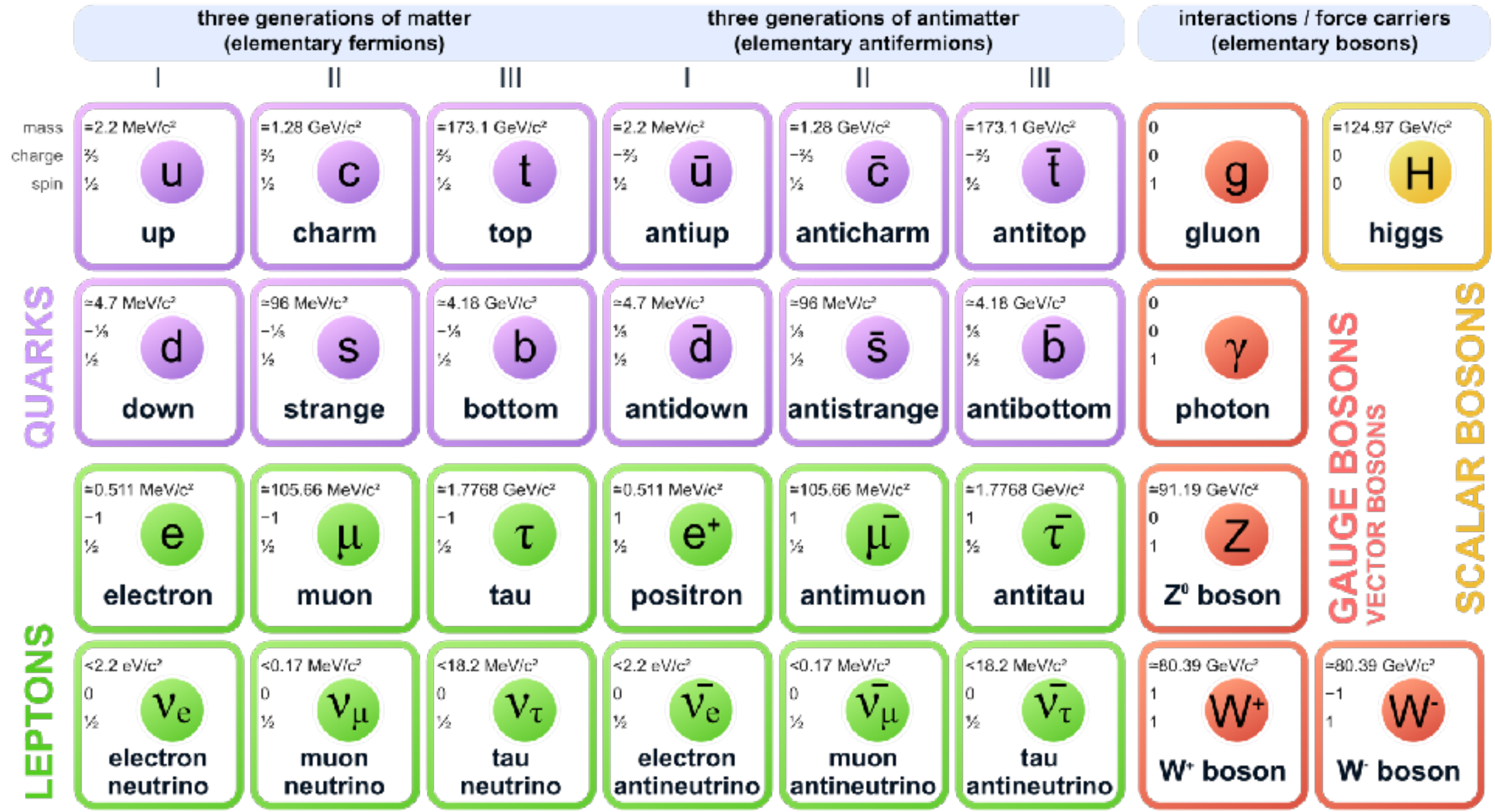
which quantities are fundamental?
how many quantities are fundamental?

...for our existence



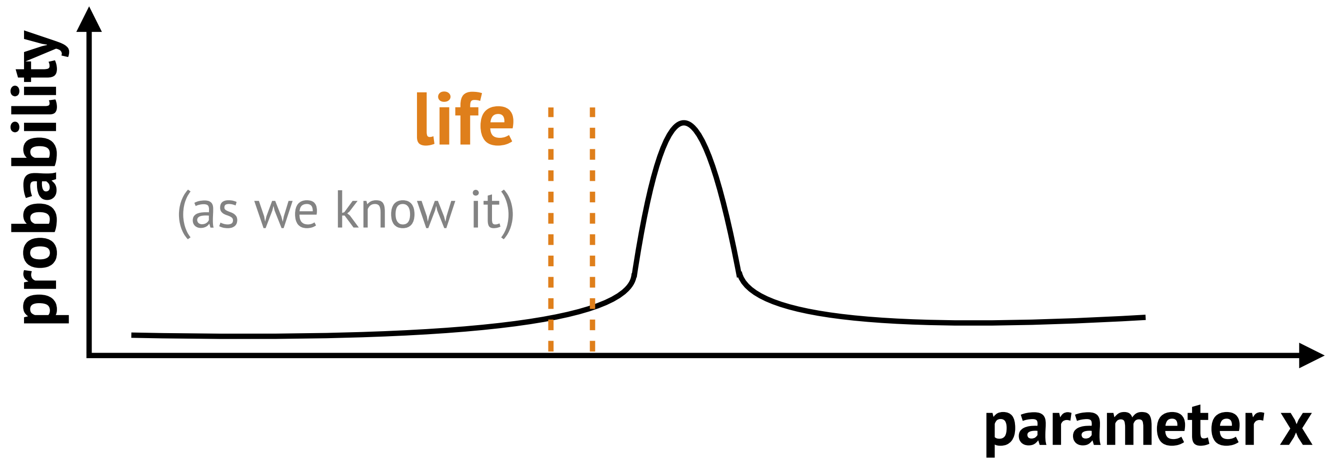
- electrical-to-gravitational force ratio ~10^{38}
- strength of nuclear binding ~ 0.007
- density of matter in the Universe relative to the critical density ~ 0.3
- cosmological constant relative to the critical density ~ 0.7
- amplitude of density fluctuations
- number of spatial dimensions

are these six numbers sufficient?

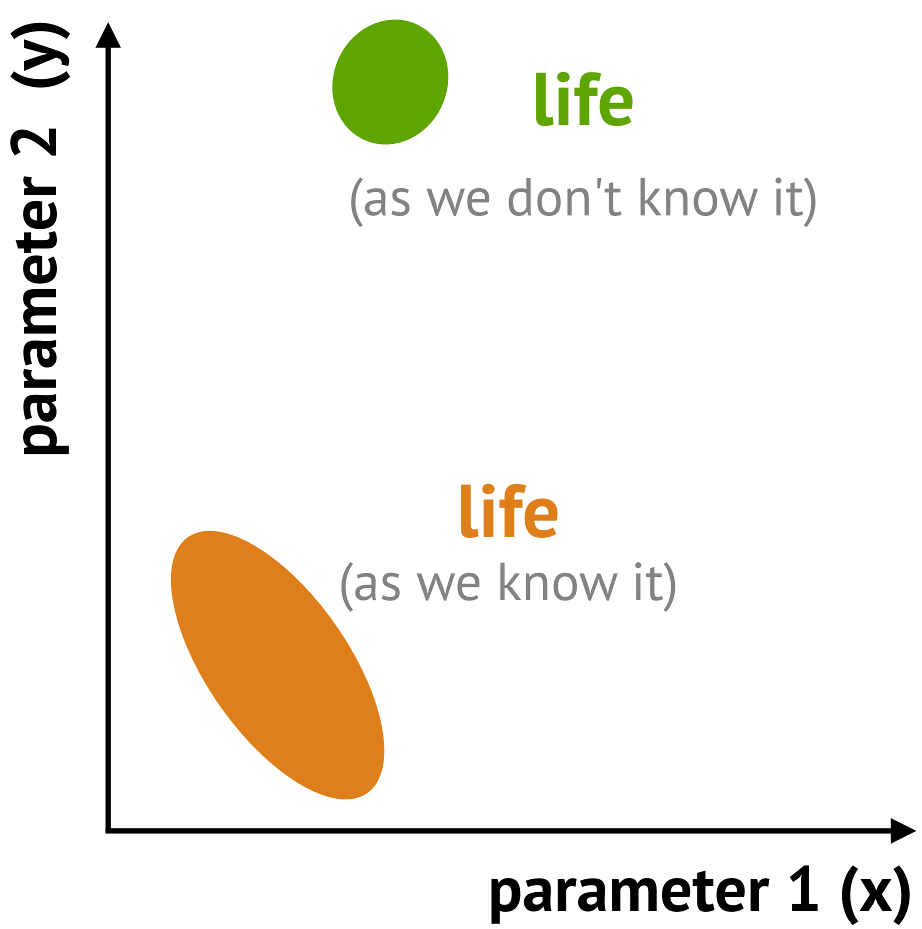

three generations of matter (elementary fermions)
three generations of antimatter (elementary antifermions)
interactions / force carriers (elementary bosons)
I
II
III
I
II
III
mass
charge
spin
QUARKS
≈2.2 MeV/c^2 ⅔ ½ u up
≈1.28 GeV/c^2 ⅔ ½ c charm
≈173.1 GeV/c^2 ⅔ ½ t top
≈2.2 MeV/c^2 −⅔ ½ ū antiup
≈1.28 GeV/c^2 −⅔ ½ c̄ anticharm
≈173.1 GeV/c^2 −⅔ ½ t̄ antitop
0 0 1 g gluon
≈124.97 GeV/c^2 0 0 H higgs
≈4.7 MeV/c^2 −⅓ ½ d down
≈96 MeV/c^2 −⅓ ½ s strange
≈4.18 GeV/c^2 −⅓ ½ b bottom
≈4.7 MeV/c^2 ⅓ ½ d̄ antidown
≈96 MeV/c^2 ⅓ ½ s̄ antistrange
≈4.18 GeV/c^2 ⅓ ½ b̄ antibottom
0 0 1 γ photon
LEPTONS
≈0.511 MeV/c^2 −1 ½ e electron
≈105.66 MeV/c^2 −1 ½ μ muon
≈1.7768 GeV/c^2 −1 ½ τ tau
≈0.511 MeV/c^2 1 ½ e^+ positron
≈105.66 MeV/c^2 1 ½ $\bar{\mu}$ antimuon
≈1.7768 GeV/c^2 1 ½ $\bar{\tau}$ antitau
≈91.19 GeV/c^2 0 1 Z Z^0 boson
<2.2 eV/c^2 0 ½ ν_e electron neutrino
<0.17 MeV/c^2 0 ½ ν_μ muon neutrino
<18.2 MeV/c^2 0 ½ ν_τ tau neutrino
<2.2 eV/c^2 0 ½ $\bar{\nu}_e$ electron antineutrino
<0.17 MeV/c^2 0 ½ $\bar{\nu}_\mu$ muon antineutrino
<18.2 MeV/c^2 0 ½ $\bar{\nu}_\tau$ tau antineutrino
≈80.39 GeV/c^2 1 1 W^+ W^+ boson
≈80.39 GeV/c^2 −1 1 W^- W^- boson
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS

fundamental quantities

minimal Standard Model	19 parameters
extended Standard Model	19+7 parameters
cosmological constant	1 parameter
cosmological parameters	4-10 parameters
parameters related to fundamental constants	> 5 parameters
	>36 parameters



$$\text{probability} = \frac{\text{total area of parameter space}}{\text{area that allows for life}}$$



definition: a parameter x is said to be **fine-tuned** for *A* if in the space of all possible values it could have, the probability of outcomes leading to *A* is much smaller than the probability of outcomes not leading to *A*.

- **parameter:** physical constants and parameters
- **initial conditions**: small changes in initial values majorly changes outcomes

fine-tuning explanations

- it is merely a coincidence
- actually, we don't know if there are other observers in our universe (not so finely tuned)
- there is a multiverse, so fine-tuning is not a problem
- this universe is as unlikely as any other
- there is no way of knowing what would happen in other universe
- unlikely events may still happen
- there will always be observers because evolution always finds a way
- we don't know what life is; it could be different
- the anthropic principle is a good explanation for fine-tuning
- fine-tunings will disappear if we understand better the laws of Nature
- ...

part 2

some examples of fine-tuning

preface: scales

particle masses

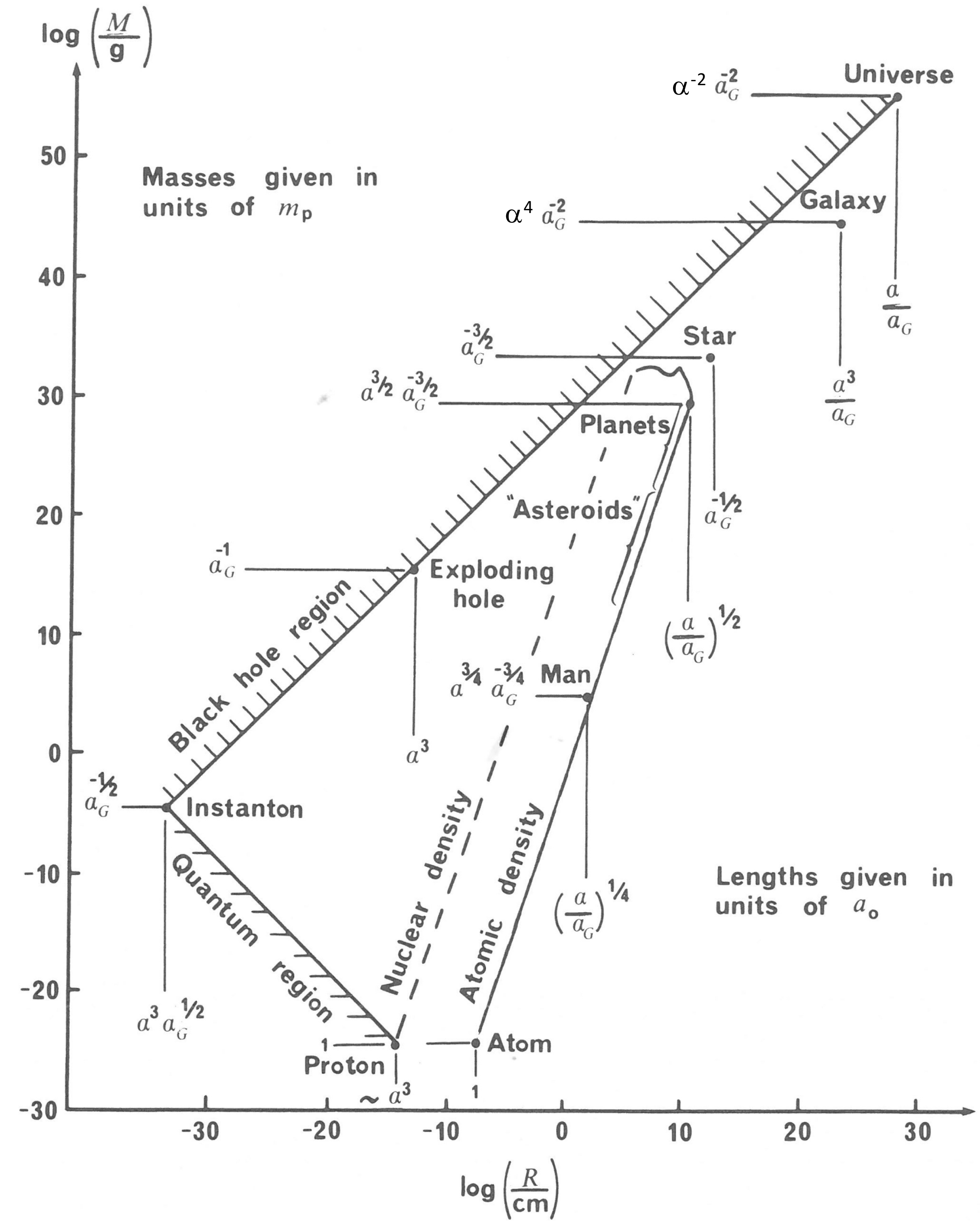
density fluctuations

number of dimensions

fine-structure constants and scales

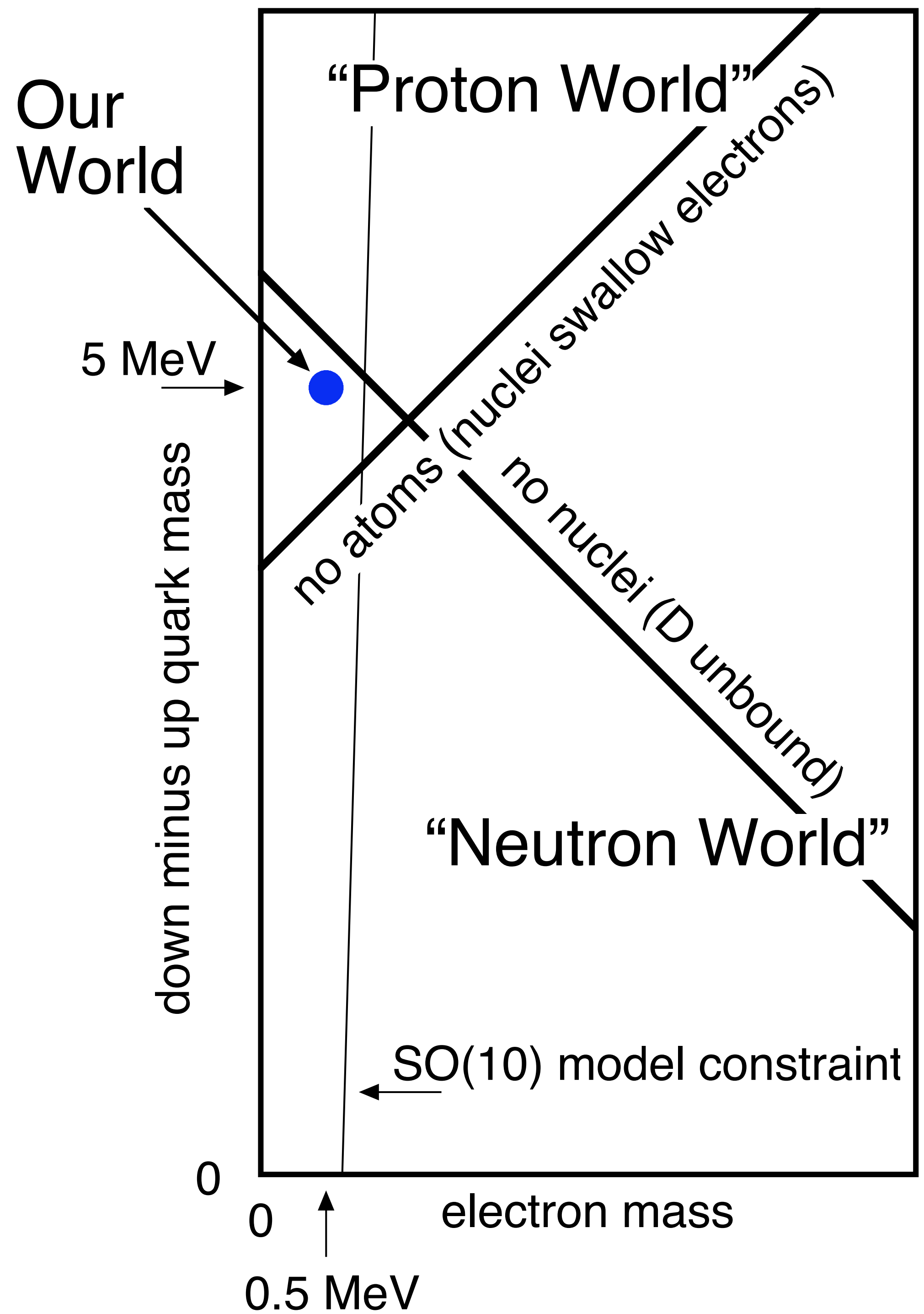
interaction	fine-structure constant
electromagnetic	$\alpha = \dfrac{e^2}{4\pi\varepsilon_0 \hbar c} \approx \dfrac{1}{137}$
gravitational	$\alpha_g = \dfrac{G m_p^2 c}{\hbar c} \approx 5 \times 10^{-39}$
weak	$\alpha_w = \dfrac{G_F m_e^2 c}{\hbar^3}$
strong	$\alpha_s = \dfrac{1}{\beta_0} \dfrac{1}{\ln\left(\dfrac{E^2}{\Lambda_s^2}\right)} \sim 1$

simple physical considerations → scales of most objects can be written as: $\alpha^a \alpha^b$



Carr & Rees. Nature 278 (1979) 605.

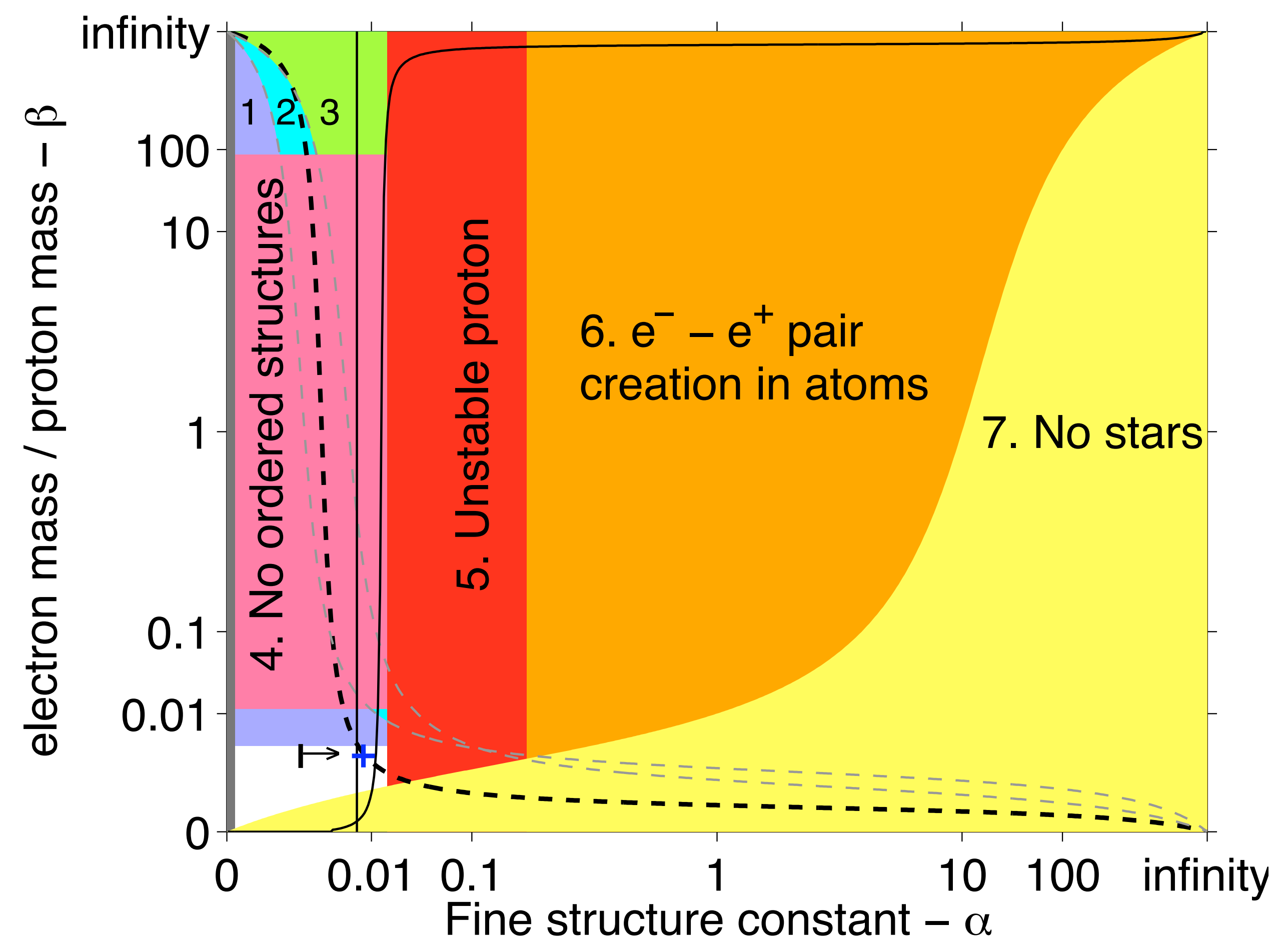
electron and quark masses



Hogan. Rev. Mod. Phys. 72 (2000) 1149.

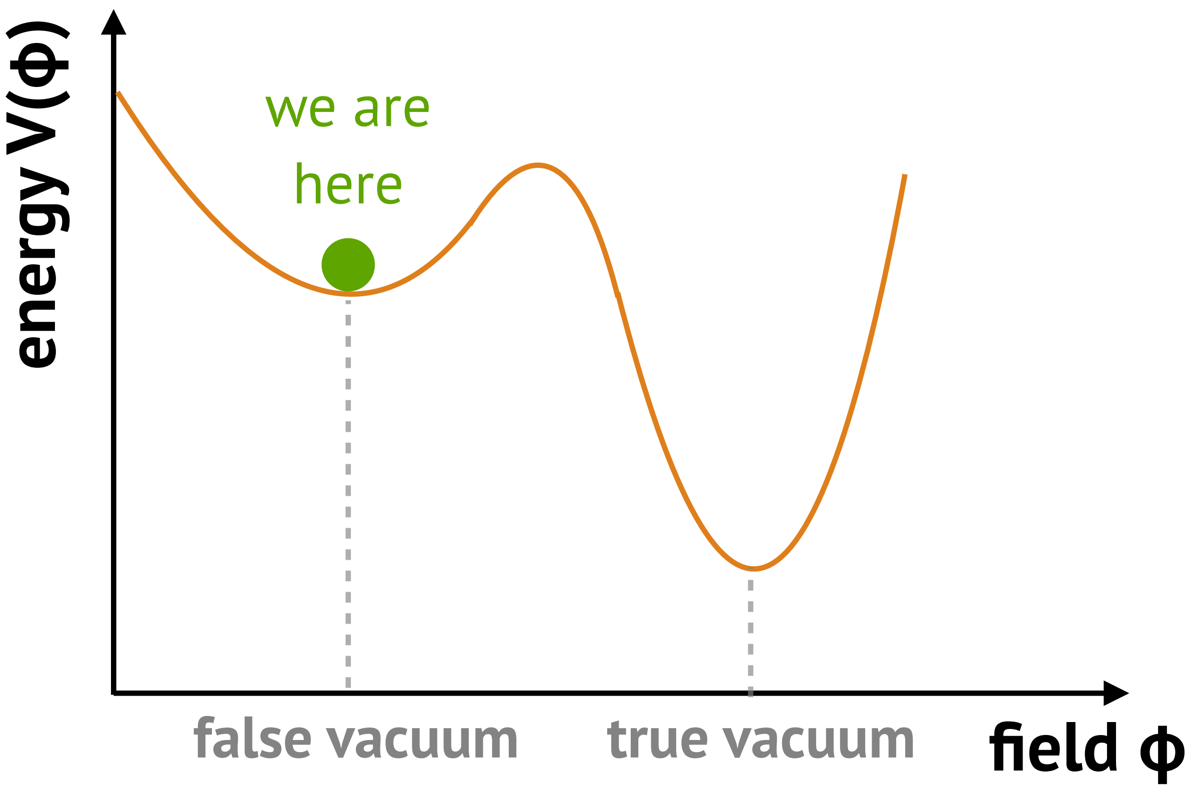
electron-to-proton mass ratio

- hydrogen existence: $m_e < m_n - m_p$
- stable atoms: electron orbital radius larger than nuclear radius:
  $\alpha / \alpha_s << m_p/m_e$
- energy of chemical reactions much smaller than energy of nuclear reactions:
  $(\alpha / \alpha_s)^2 << m_p/m_e$
- molecular structure only stable for:
  $(m_e/m_p)^{1/4} << 1$
- stability of proton requires: $\alpha < m_d - m_u / m_\pi$
- if $\alpha >> 1$ the motion of electrons around the nucleus do not produce pairs
- too small stars won't be able to ignite and sustain fusion; too large radiation overcomes thermal pressure: $m_e/m_p >> \alpha^2$



Barnes. Pub. Astron. Soc. Australia 29 (2012) 529.

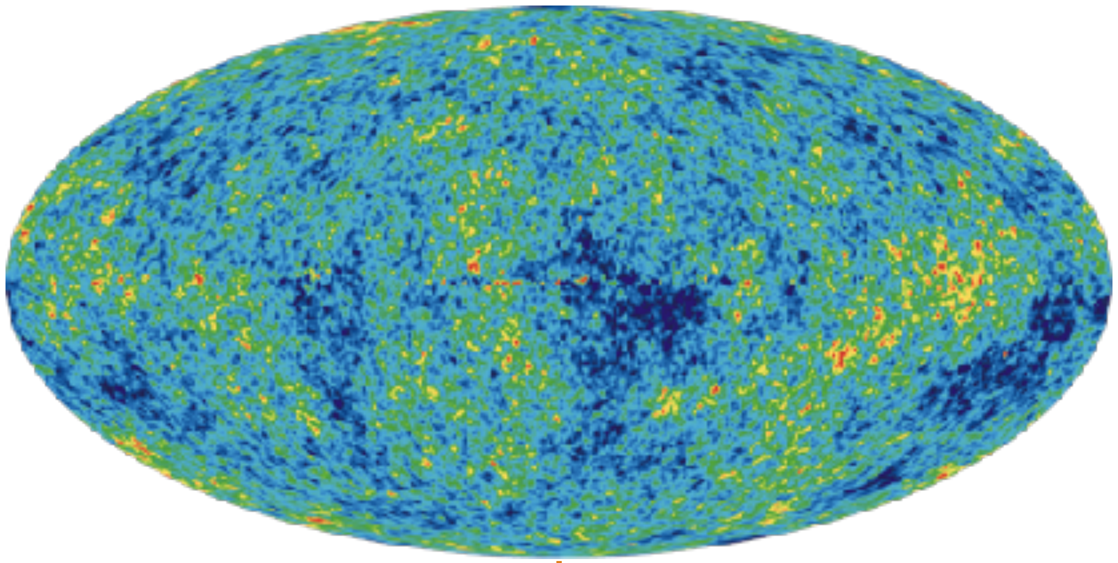
non-anthropic tuning: the Higgs mass

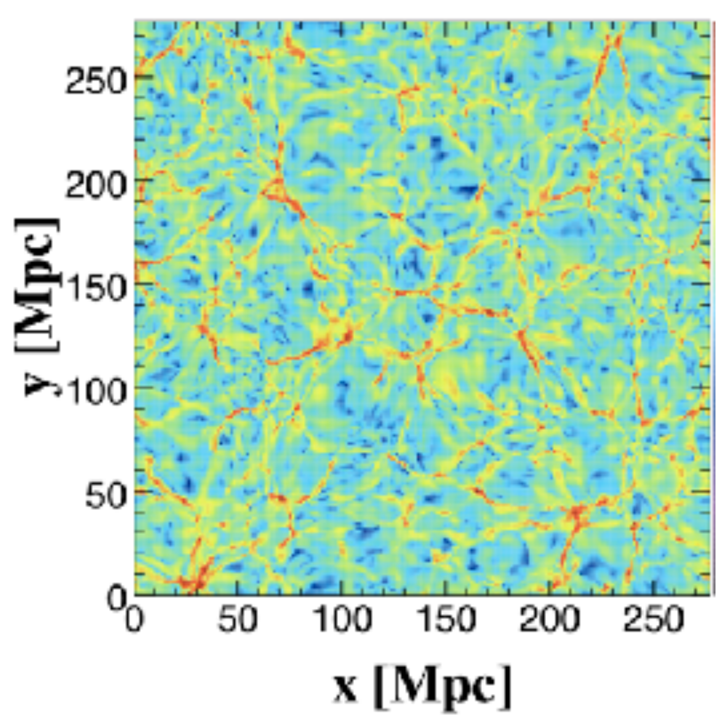


- high-energy processes increase chance of *local* tunelling
- the creation of bubbles of true vacuum may affect neighbouring regions → *global* changes
- mass Higgs: 125 GeV/c^2
- mass heaviest particle (top quark): 173 GeV/c^2

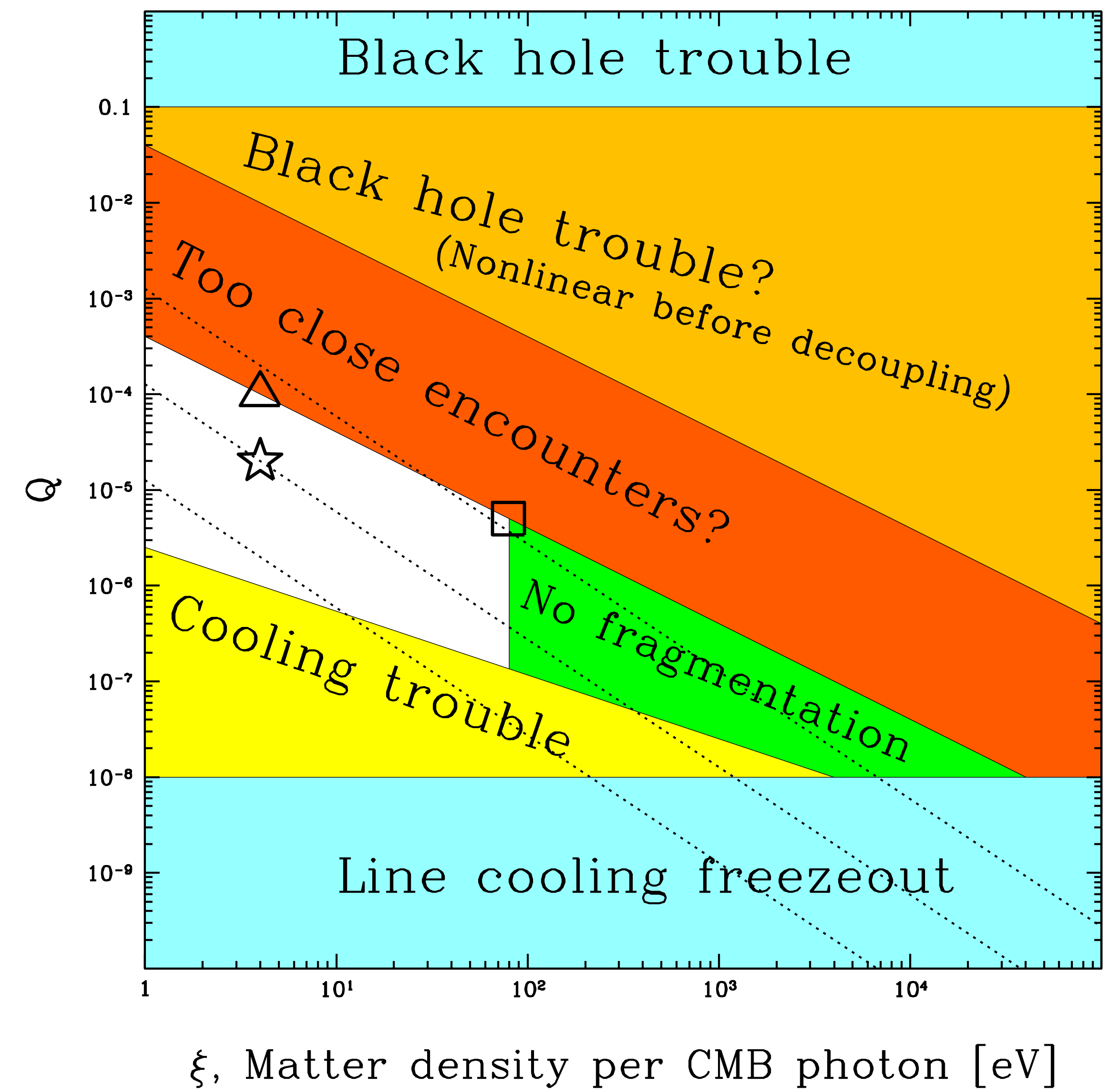
Degrassi et al. JHEP 08 (2012) 098.

- CMB anisotropies correlate with amplitude of density fluctuations
- density fluctuations form structures





Alves Batista et al. Phys. Rev. D 96 (2017) 023010



Tegmark, Aguirre, Rees, Wilczek. Phys. Rev. D 73 (2006) 023505.

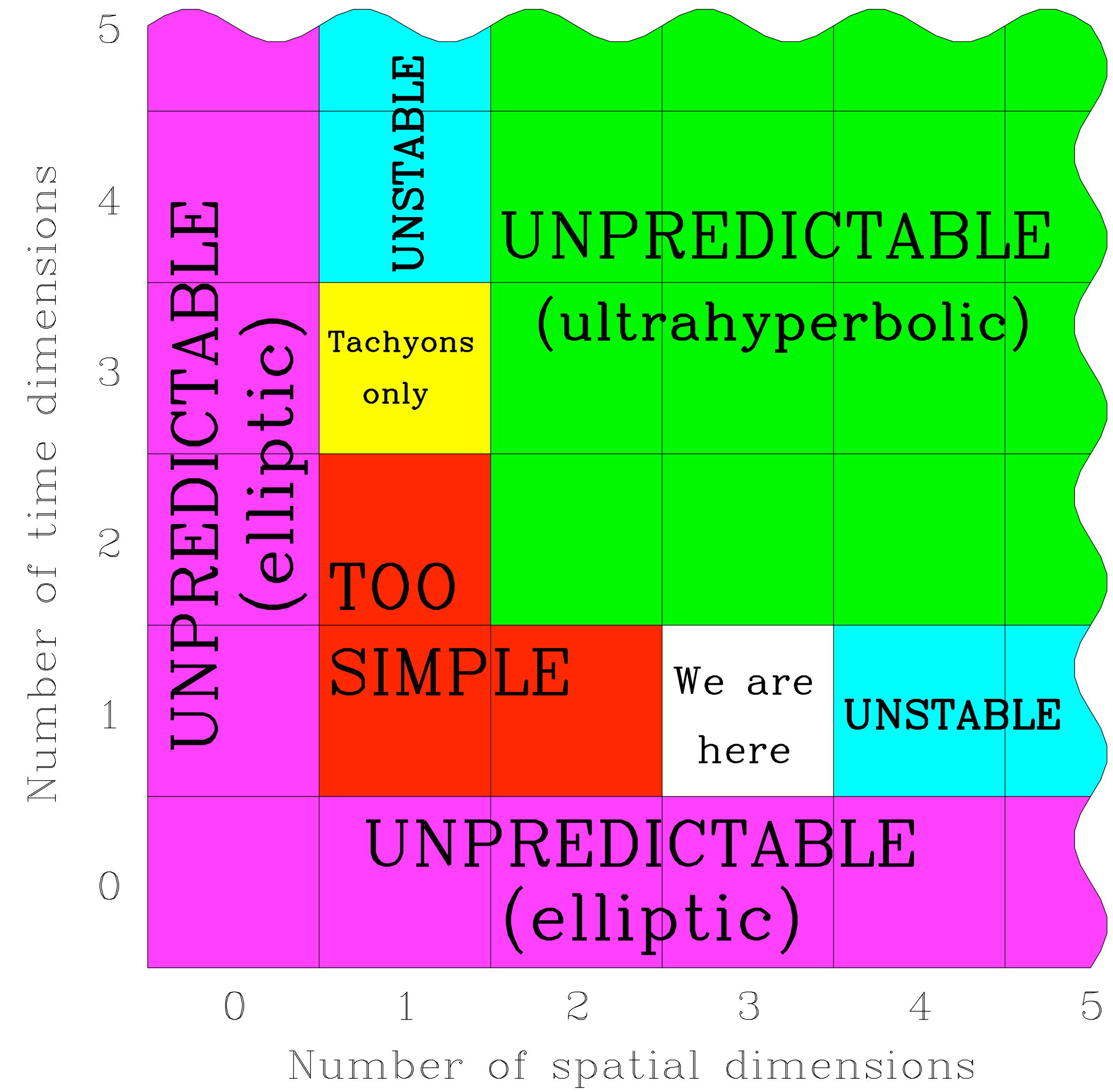
- planetary orbits: central-force problem

$$F(r) = -\frac{\mathrm{d}V}{\mathrm{d}r}$$

- consider general form for a potential

$$V(r) \propto r^a$$

- Bertrand's theorem: only two types of potentials lead to stable orbits: a=-1 (electromagnetism, gravity) and a=1 (harmonic oscillator)
- advantages of d=3: signal transmission and information processing; stable orbits



Tegmark. Class. Quantum Grav. 14 (1997) L69.

part 3

habitable universe(s)

when is life first possible?

when is life more likely?

how long does life lasts for?

the coincidence "problem" - why now?

once life emerges on a planet, for how long can it survive?

Sloan, Alves Batista, Loeb. Scientific Reports 7 (2017) 5419. arXiv:1707.04253

what can sterilise all life on a planet?

- asteroid impacts
- supernovae
- gamma-ray bursts
- death of host star
- disruption by wandering objects
- stellar winds (?)

life-threatening effects

- stripping of atmosphere
- fragmentation
- radiation levels
- pressure
- temperature

dominates

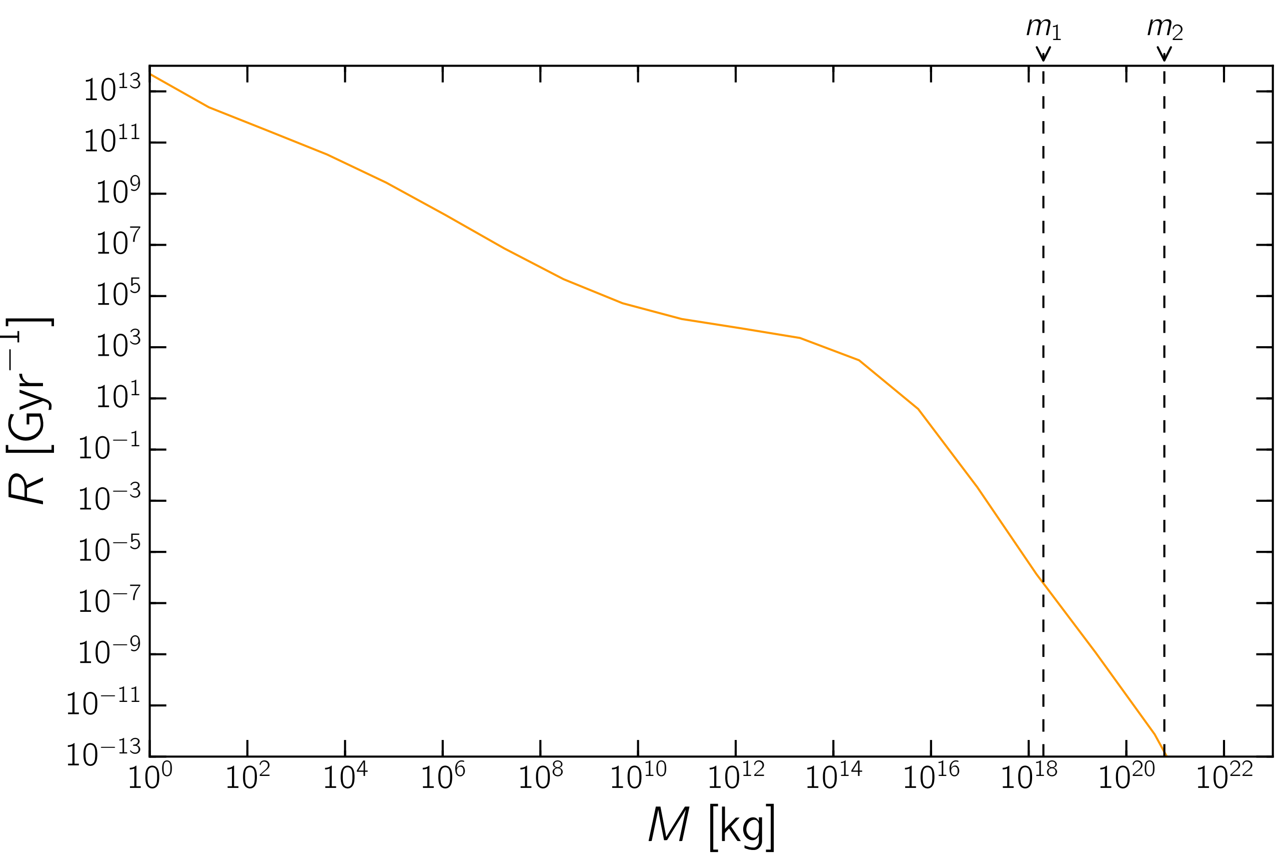
hardy creatures: tardigrades

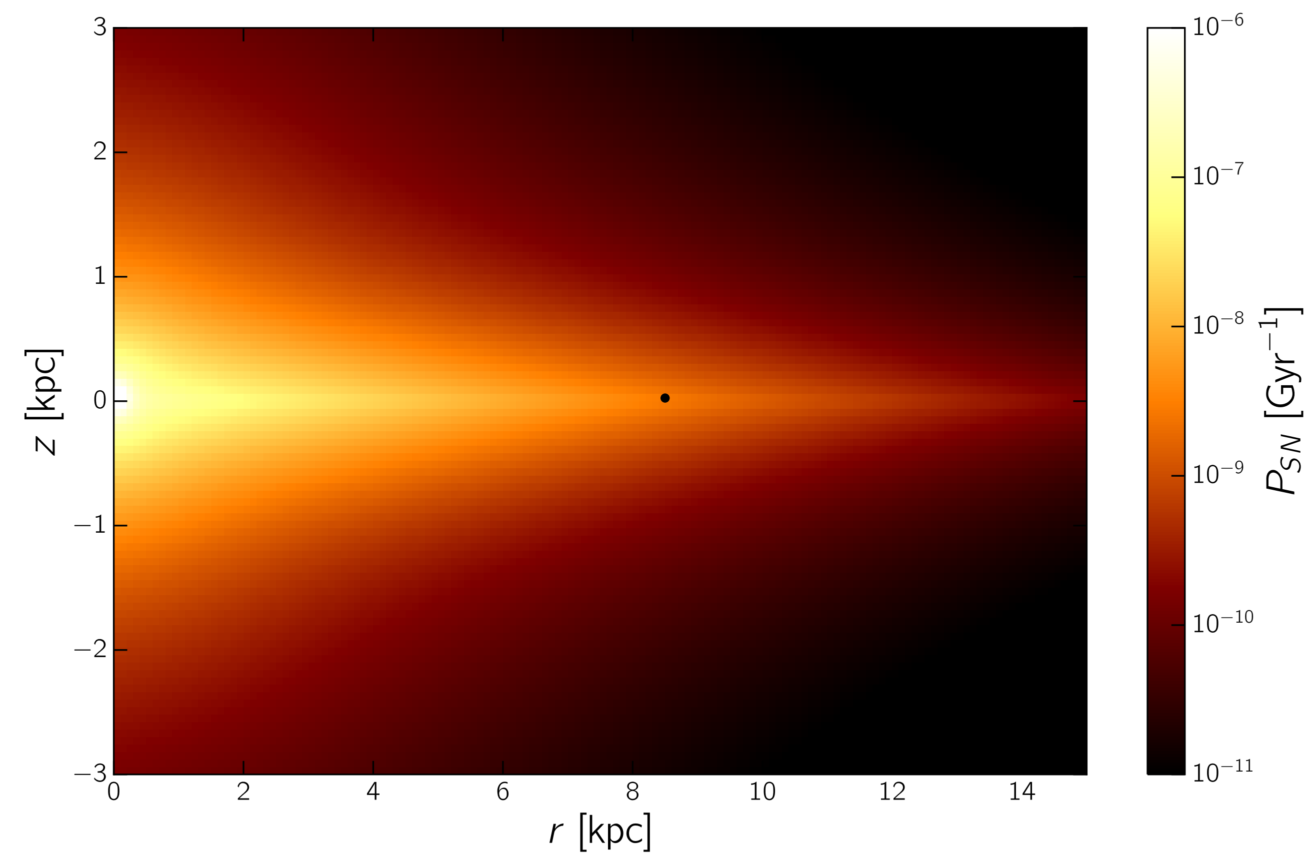
Sloan, Alves Batista, Loeb. Scientific Reports 7 (2017) 5419. arXiv:1707.04253

- low temperatures: -272 ^{o}C for ~10 min; -20 ^{o}C for decades
- high temperatures: 150 ^{o}C for a few minutes
- pressure: 0 - 1200 atm
- radiation levels: up to 7000 Gy
- can reduced their metabolism almost completely → cryptobiosis
- good candidates for the last survivors on Earth

asteroid and supernova treats

Sloan, Alves Batista, Loeb. Scientific Reports 7 (2017) 5419. arXiv:1707.04253





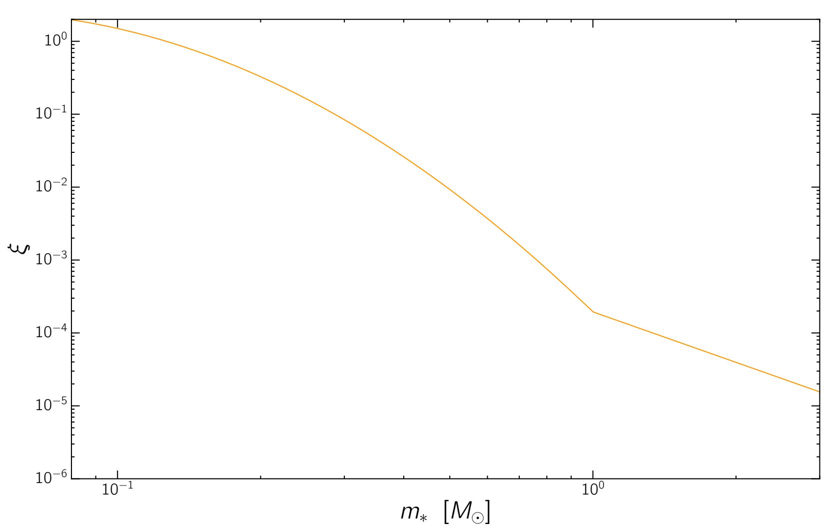
when is life more likely?

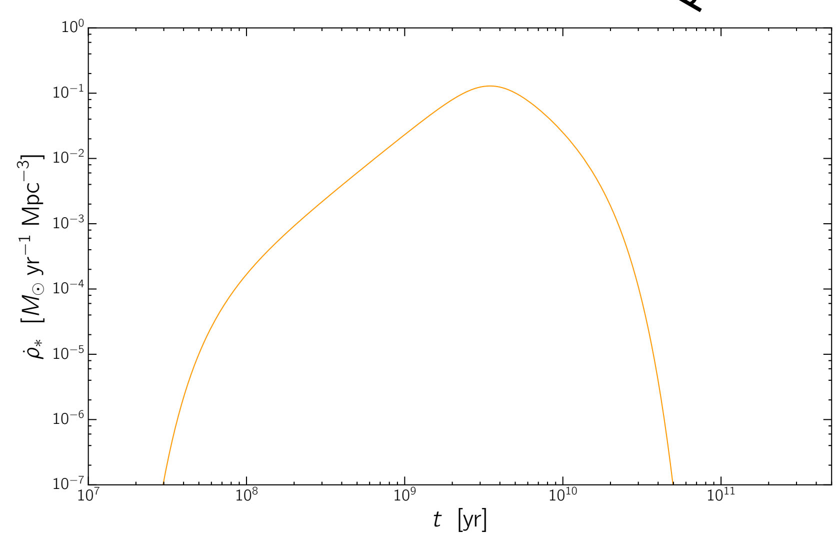
when is life likely?

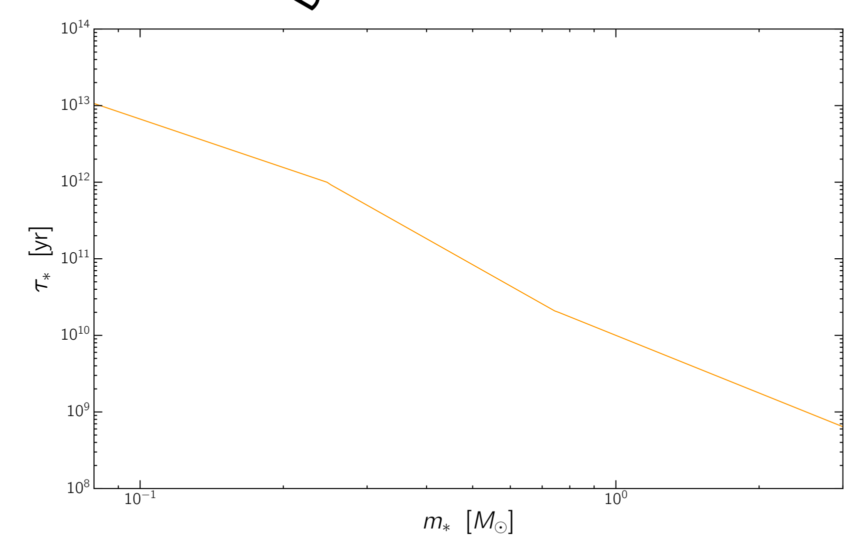
Loeb, Alves Batista, Sloan. JCAP 08 (2016) 040. arXiv:1606.08448

master equation

$$\frac{dP}{dt}(t) = \frac{1}{N}\int_0^t dt' \int_{m_{min}}^{m_{max}} dm' \underbrace{\xi(m')}_{\text{initial mass function}} \underbrace{\dot{\rho}_\star(t', m')}_{\text{star formation rate}} \underbrace{\eta_{\text{Earth}}(m')}_{\text{probability of finding Earth-like planets in the HZ}} \underbrace{p(\text{life}|\text{HZ})}_{\text{probability of finding life in a habitable planet}} \underbrace{g(t-t', m')}_{\text{window function: birth/death of stars}}$$







η_{Earth} = 0.19; Kepler observations + no mass dependence

p(life|HZ): constant

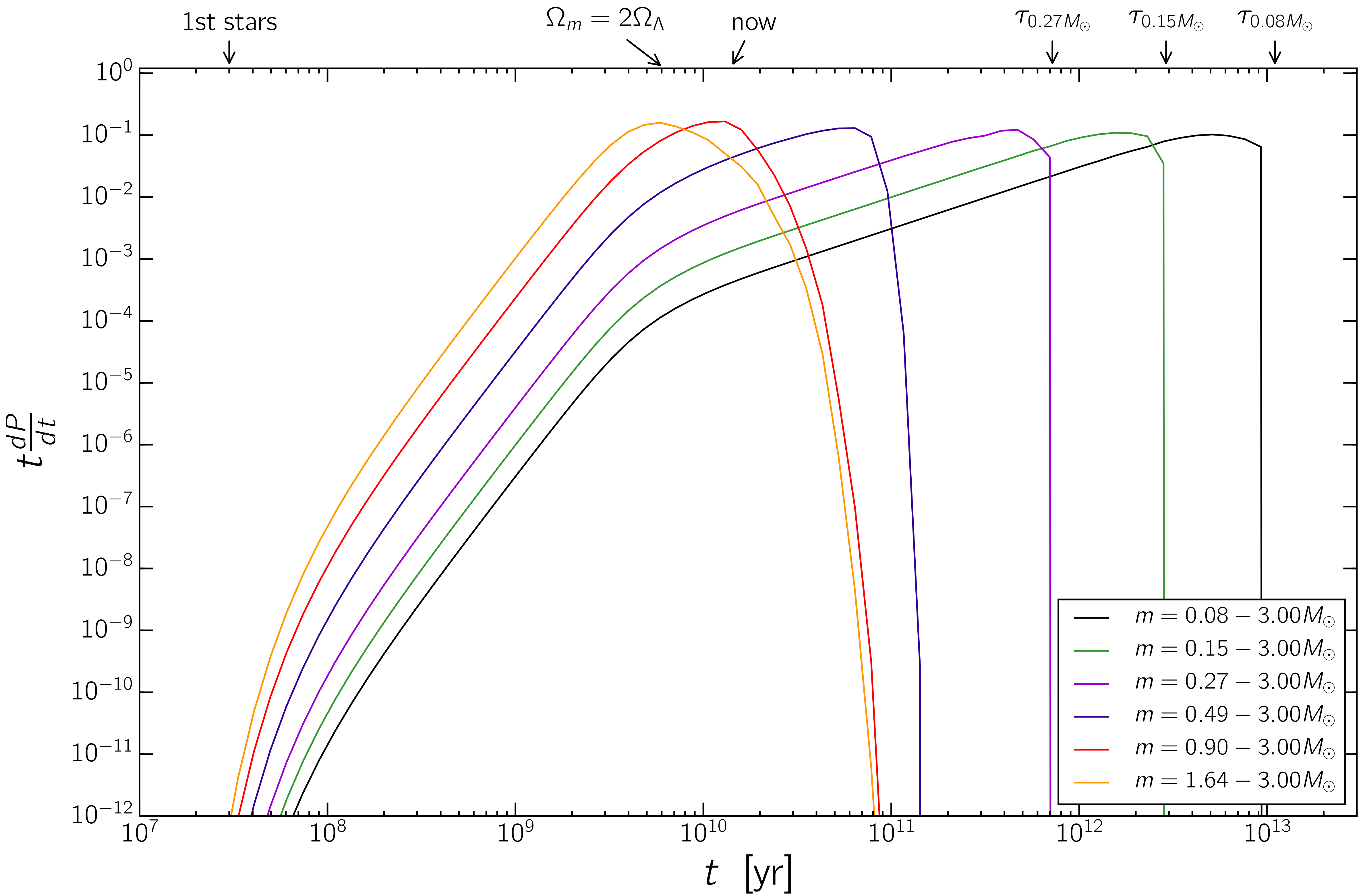
g(t-t', m'): 1 whilst star lives; 0 otherwise

m_{min} = 0.08M_{sun}; brown dwarf mass threshold

m_{max} = 3M_{sun}; lifetime allows emergence of life

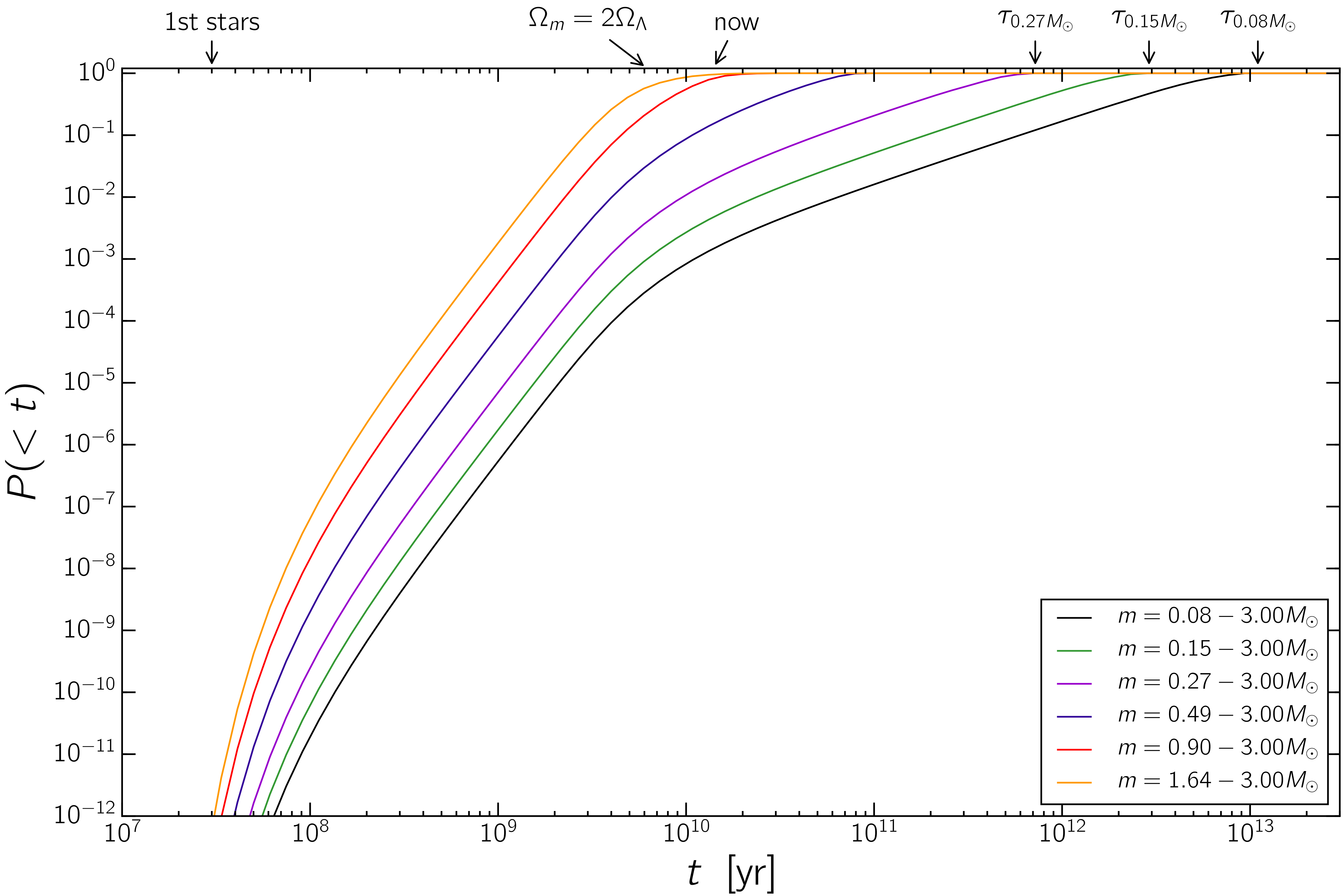
when is life likely?

Loeb, Alves Batista, Sloan. JCAP 08 (2016) 040. arXiv:1606.08448



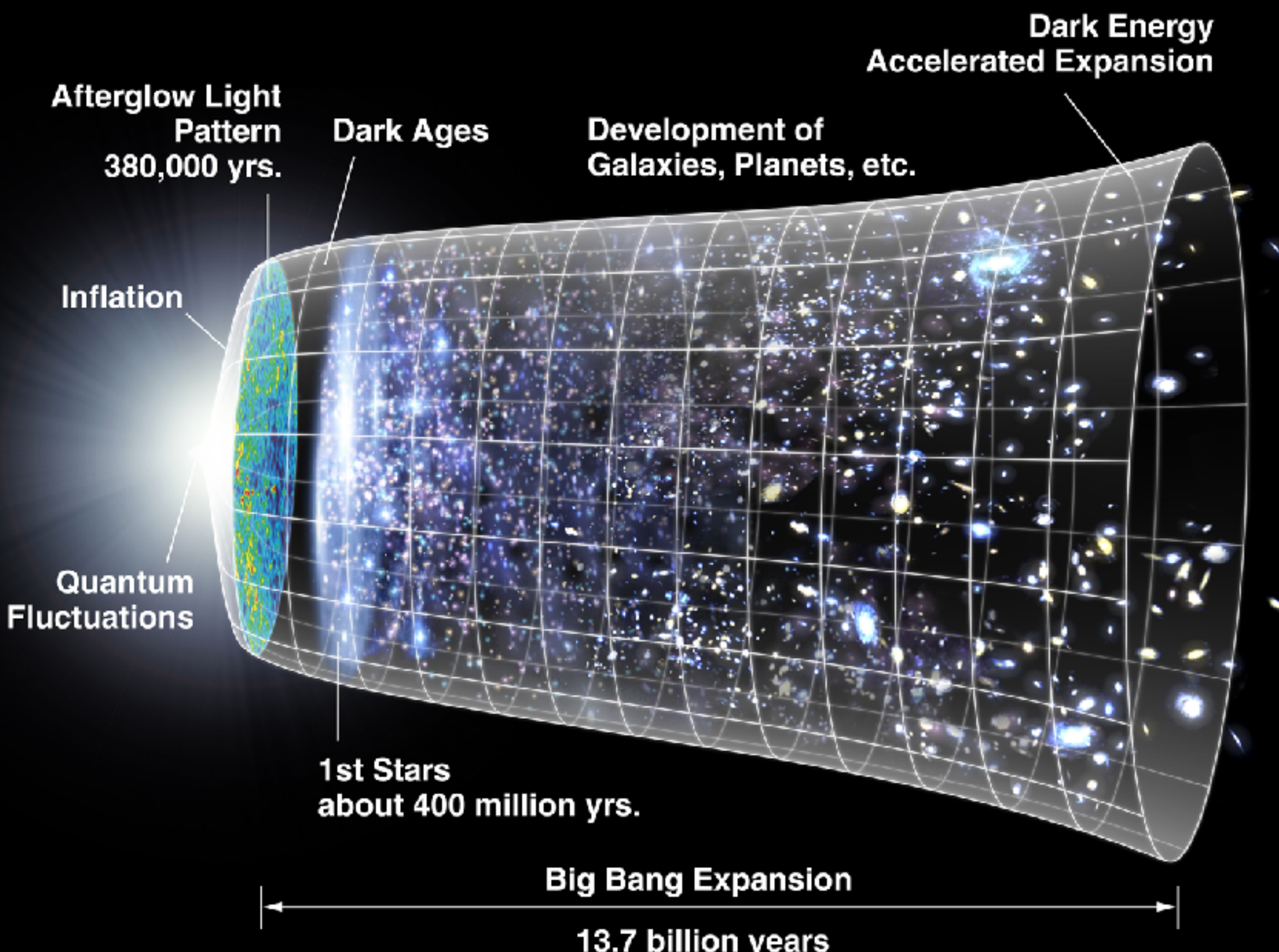
when is life likely?

Loeb, Alves Batista, Sloan. JCAP 08 (2016) 040. arXiv:1606.08448

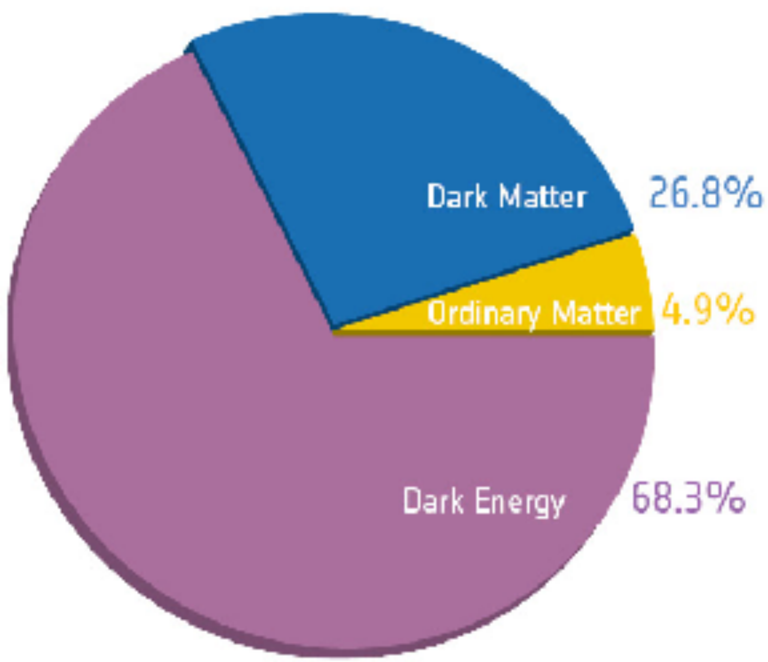


the coincidence "problem": why now?

a brief history of the universe



cosmic inventory



$$H(z) = H_0\sqrt{\Omega_\Lambda + \Omega_k(1+z)^{-2} + \Omega_m(1+z)^{-3} + \Omega_r(1+z)^{-4}}$$

H_0: Hubble constant

Ω_Λ: dark energy density

Ω_k: energy density curvature

Ω_m: energy density matter

Ω_r: energy density radiation

why do we live at a time when $\Omega_m \sim \Omega_\Lambda$?

the cosmological constant "problem"

Einstein's field equation

$$R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

energy-momentum tensor

$$T_{\mu\nu} = (\rho + p)U_\mu U_\nu + p g_{\mu\nu}$$

Friedmann equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{R^2(t)}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

- expected vacuum energy density from QFT: $\rho_{\Lambda,th} \sim M_{Pl}^4 \sim (10^{25}$ eV$)^4 \sim 10^{109}$ J m^{-3}
- observed cosmological constant: $\rho_{\Lambda,obs} \sim 10^{-11}$ J m^{-3}
- discrepancy: $\rho_{\Lambda,th} / \rho_{\Lambda,obs} \sim 10^{120}$
- *"the worst theoretical prediction in the history of physics"*
- anthropic upper bound on Λ → $\Omega_\Lambda \sim$ 10-100 $\Omega_{m,0}$ (Weinberg 1987)
- 120 orders of magnitude discrepancy seem unnatural
- parameters be of O(1) → matter of aesthetics or intrinsic feature of the theory?

VOLUME 59, NUMBER 22 PHYSICAL REVIEW LETTERS 30 NOVEMBER 1987

Anthropic Bound on the Cosmological Constant

Steven Weinberg
Theory Group, Department of Physics, University of Texas, Austin, Texas 78712
(Received 5 August 1987)

In recent cosmological models, there is an "anthropic" upper bound on the cosmological constant Λ. It is argued here that in universes that do not recollapse, the only such bound on Λ is that it should not be so large as to prevent the formation of gravitationally bound states. It turns out that the bound is quite large. A cosmological constant that is within 1 or 2 orders of magnitude of its upper bound would help with the missing-mass and age problems, but may be ruled out by galaxy number counts. If so, we may conclude that anthropic considerations do not explain the smallness of the cosmological constant.

PACS numbers: 98.80.Dr, 04.20.Cv

Weinberg's argument

- if Λ is different in different patches of universe → all observers should measure similar Λ (or there would be no observers)
- if Λ small or negative → universe re-collapses quickly
- if Λ large → expansion is too fast → no time for structure formation

part 4

philosophical digressions

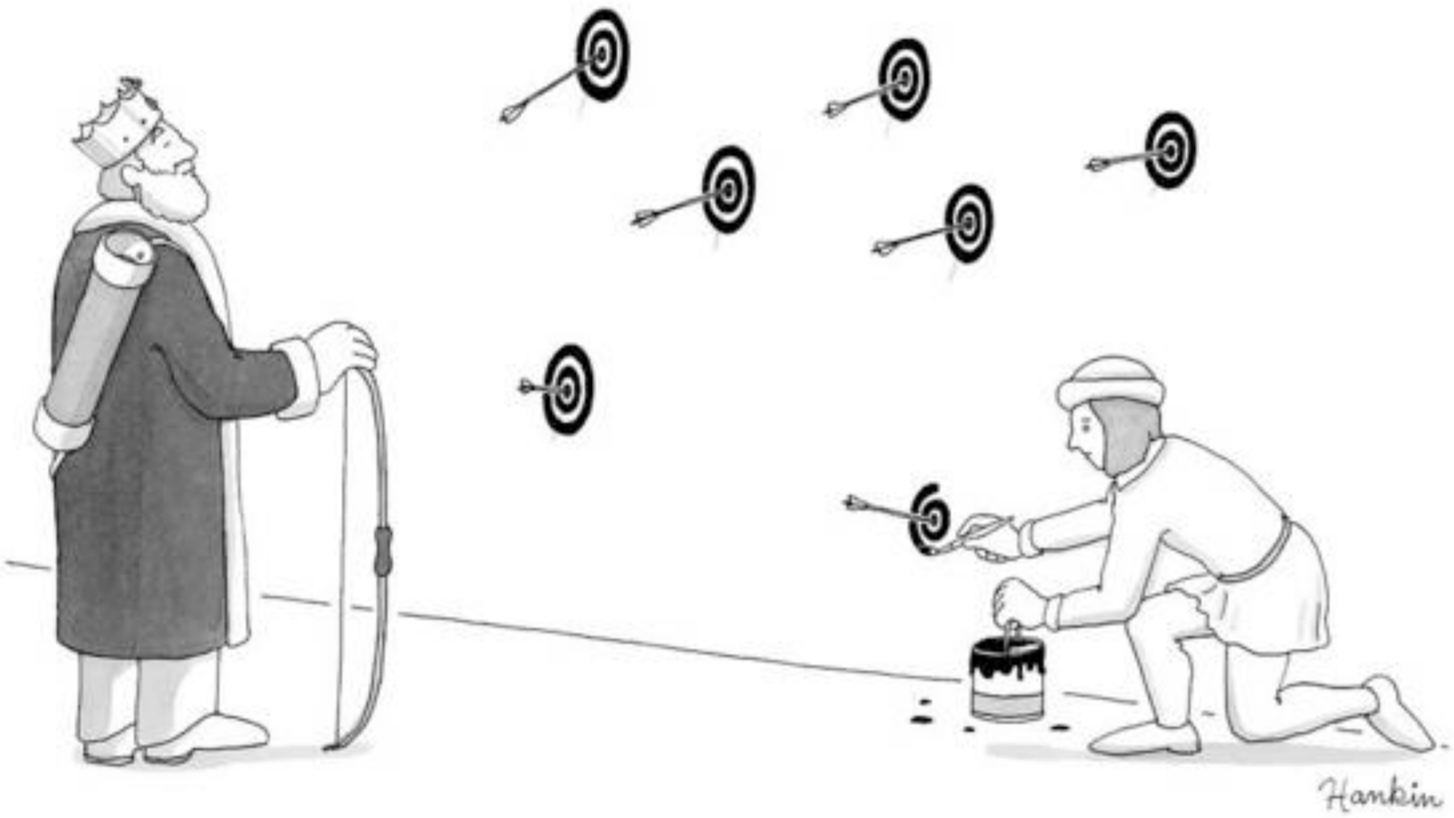
when is life first possible?

when is life more likely?

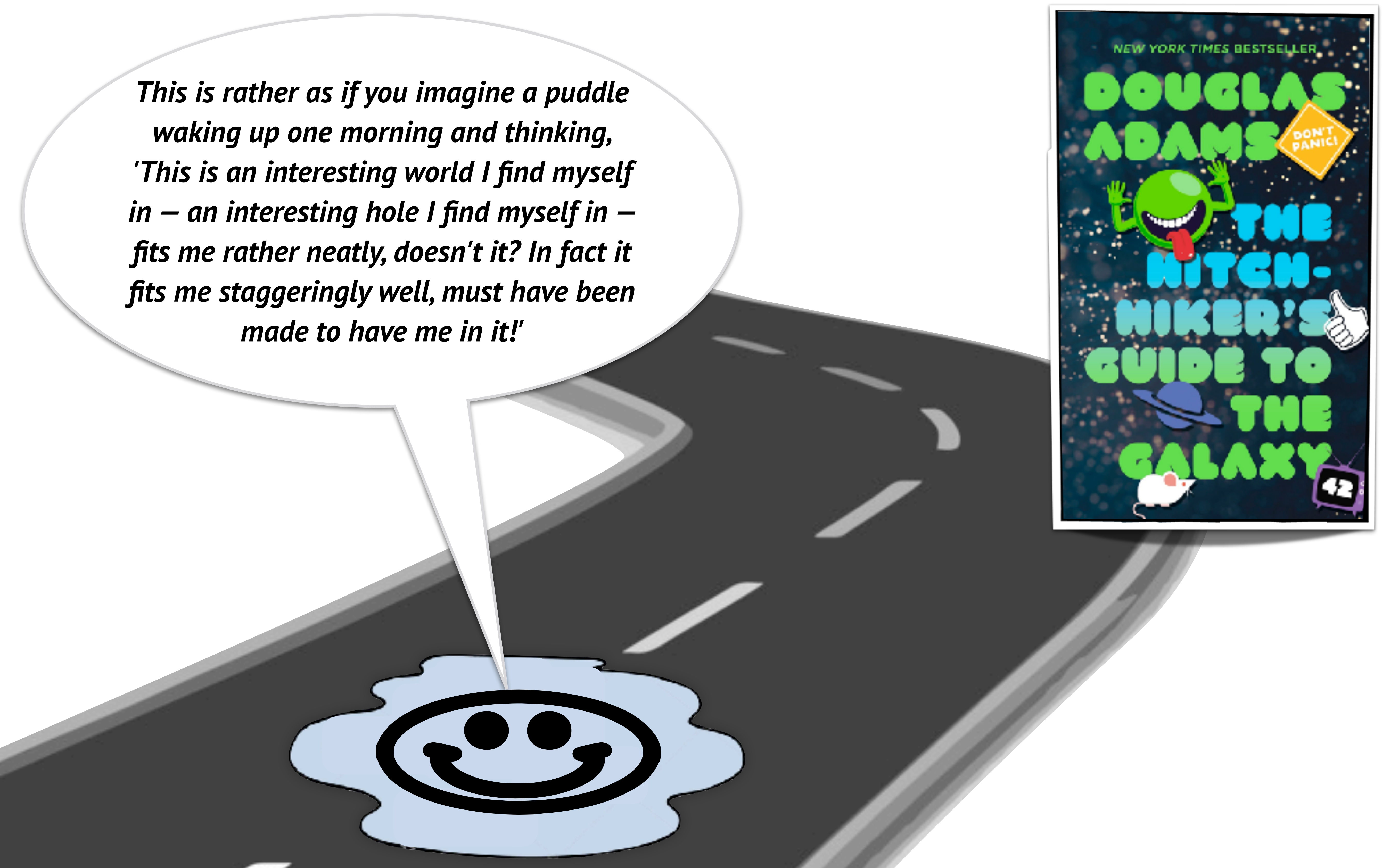
how long does life lasts for?

on fine-tuning explanations

"There is something stunningly narrow about how the Anthropic Principle is phrased. Yes, only certain laws and constants of nature are consistent with our kind of life. But essentially the same laws and constants are required to make a rock. So why not talk about a Universe designed so rocks could one day come to be, and strong and weak Lithic Principles? If stones could philosophize, I imagine Lithic Principles would be at the intellectual frontiers."

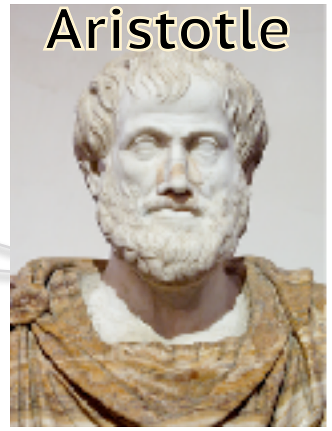


anthropic arguments and fine-tuning



fine-tuned for what?

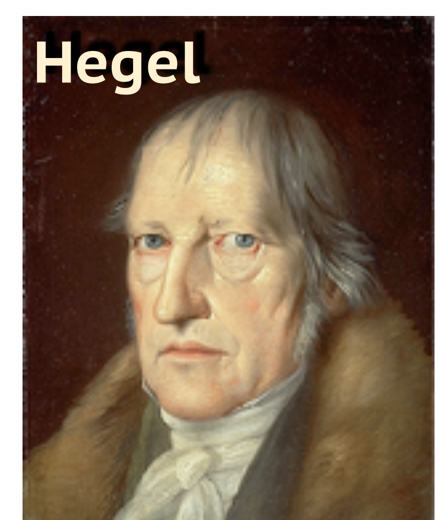
> *"We do not have knowledge of a thing until we have grasped its why, that is to say, its cause."*



Aristotle's four causes

- material cause
- formal cause
- moving cause
- final cause ⟶ **teleology**

- an object is an end *if and only if* the conceptual umbrella to which the object belongs is also the cause of the object
- *Naturzwecke*: purpose of Nature
- natural explanation for how organisms can have functions and how biological purposes exist



- knowledge is built through dialectics: combination of thesis + antithesis
- *Aufhebung*: parts of a whole are "recycled" → emergence of complexity

- **scientific reductionism:** big things can be understood by looking into their individual parts.
- Hegel's view on teleology is anti-reductionist: it provides a stronger framework to investigate large-scale things as possible emergent phenomena
- **physicalism:** the Universe can be fully characterised in terms of physics, even if the "right" theories haven't been found yet
- ***what about the physical laws?***

- Leibniz: we live in the best of all possible worlds
- **possible worlds:** everything that is physically conceivable
- possible worlds: **epistemological** resource or **ontological** entity?
- will a "final theory" explain all possible worlds?
- "final theory" has fine-tunings: is it really final?

fine-tuning and the multiverse

- fine-tunings can be easily explained if there is a **multiverse**
- each universe in this multiverse is one of Leibniz's possible worlds

hierarchy of the multiverse

- type I: different Hubble volumes
- type II: different post-inflationary regions
- type III: different branches of wave function
- type IV: different mathematical structures

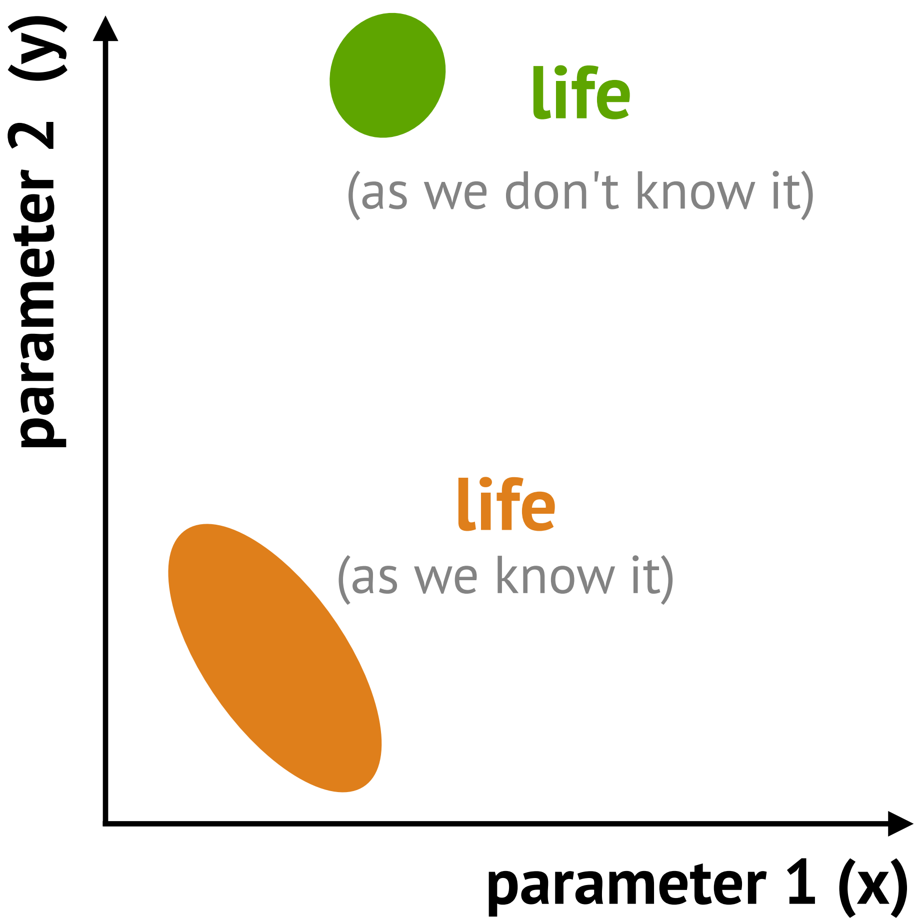
Tegmark . Found. Phys. 38 (2008) 101.

Bayes's theorem $$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

what is the probability of my theory being right?

$$P(T|D) = \frac{P(T)P(D|T)}{P(T)P(D|T) + P(\bar{T})P(D|\bar{T})}$$

- $P(T)$: prior
- $P(D|T)$: likelihood: how well does the theory describe the data
- $P(\bar{T})$: competing theories
- $P(D|\bar{T})$: how good is the competition



$$P(T|D) = \frac{P(T)P(D|T)}{P(T)P(D|T) + P(\bar{T})P(D|\bar{T})}$$

prior: $P(T)$

$x_{min} \leqslant x \leqslant x_{max}$

$y_{min} \leqslant y \leqslant y_{max}$

- the prior is not objective
- if the minimum or the maximum values are unbounded, there is no way to ensure convergence of the probabilities
- distribution of priors in the **multiverse**?

the (meta)physics of the multiverse

G. Ellis & J. Silk. Nature 516 (2014) 321.

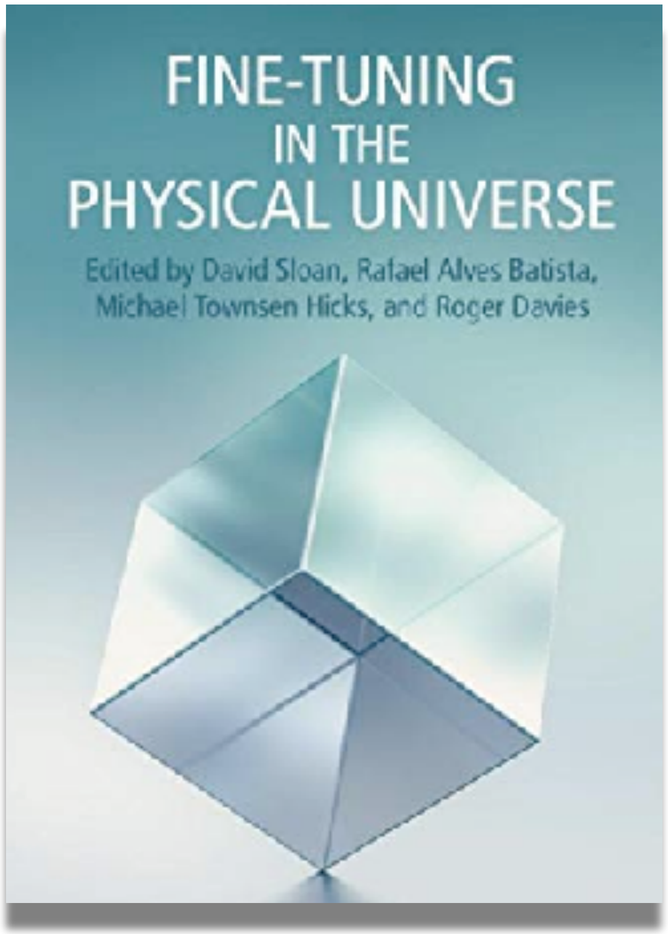
Defend the integrity of physics

Attempts to exempt speculative theories of the Universe from experimental verification undermine science, argue **George Ellis** and **Joe Silk**.

In the meantime, journal editors and publishers could assign speculative work to other research categories — such as mathematical rather than physical cosmology — according to its potential testability. And the domination of some physics departments and institutes by such activities could be rethought[1,2].

The imprimatur of science should be awarded only to a theory that is testable. Only then can we defend science from attack. ■

- fine-tuning is a controversial topic
- the Universe seems to be such that it enables the emergence of life
- once life emerges, it is surprisingly resilient to astrophysical events (asteroids, SNe, GRBs, ...)
- the universe should brim with life (mostly around low-mass stars) in the far future (~10 trillion years from now) - unless low-mass stars are inhospitable
- is the observed cosmological constant "bio-friendly"? → apparently NOT, although there seems to be an anthropic upper bound
- fine-tuning can be seen as a tracer of where new physics might be needed
- the debate around fine-tuning seem to be distancing itself from well-grounded physics
- will a "final theory" be fine-tuned?



Cambridge University Press, 2020.

https://www.youtube.com/channel/UC6-K31vDhklob9Yrx1AWxiQ

"Consolidation of Fine-Tuning". https://finetune.physics.ox.ac.uk/