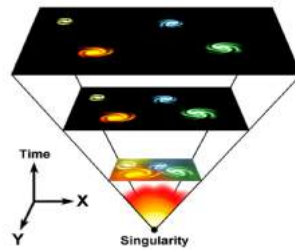


## REASSESSING THE FINE-TUNINGS IN PHYSICS AND COSMOLOGY

Bernard Carr, Queen Mary University of London



Crete, 19 June 2017

Brandon Carter introduces **Anthropic** Principle in 1974



## PREVIOUS TEMPLETON PROJECT

In 2000 'Cosmology & Fine-Tuning' programme awarded grant to BC, Robert Crittenden, Martin Rees & Neil Turok 'Fundamental physics and the problem of our existence'

Cambridge 2001

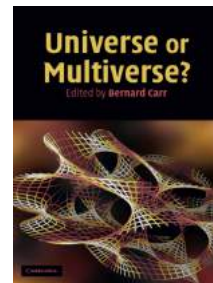
**Anthropic Arguments in Fundamental Physics and Cosmology**

Stanford 2003

**Universe or Multiverse?**

Cambridge 2005

**Expectations of a Final Theory**



## CAMBRIDGE 2001



### CHANGE IN ATTITUDE TO FINE-TUNING



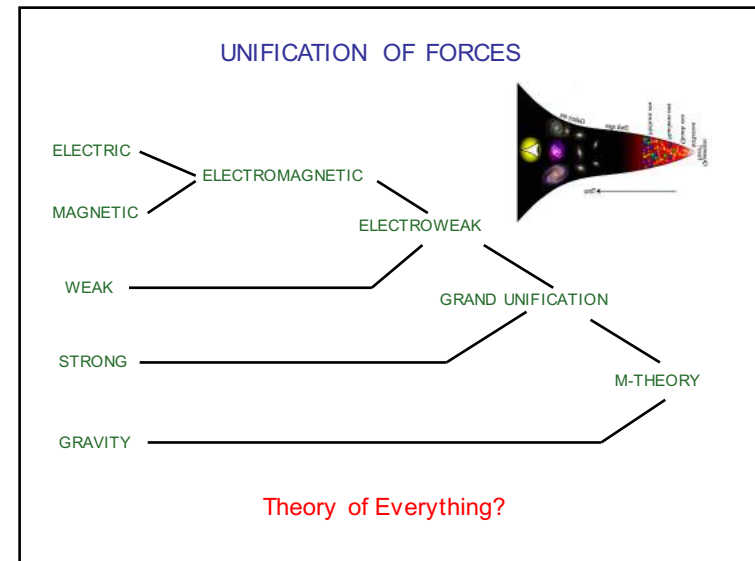
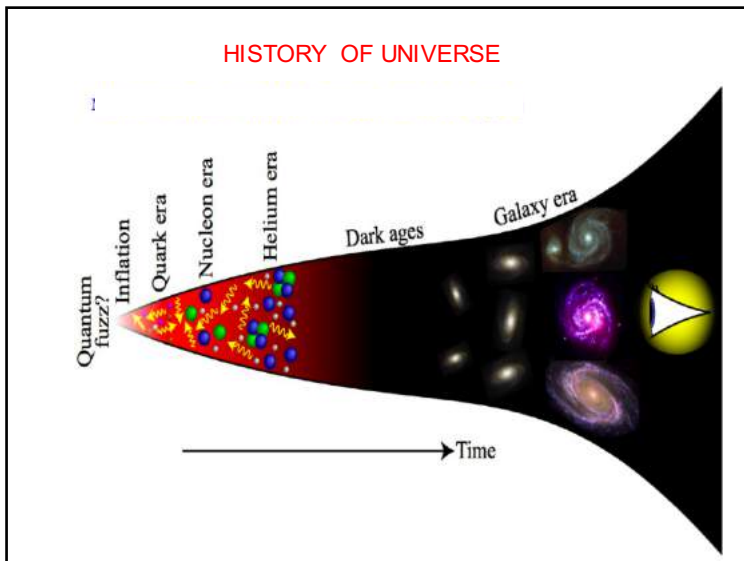
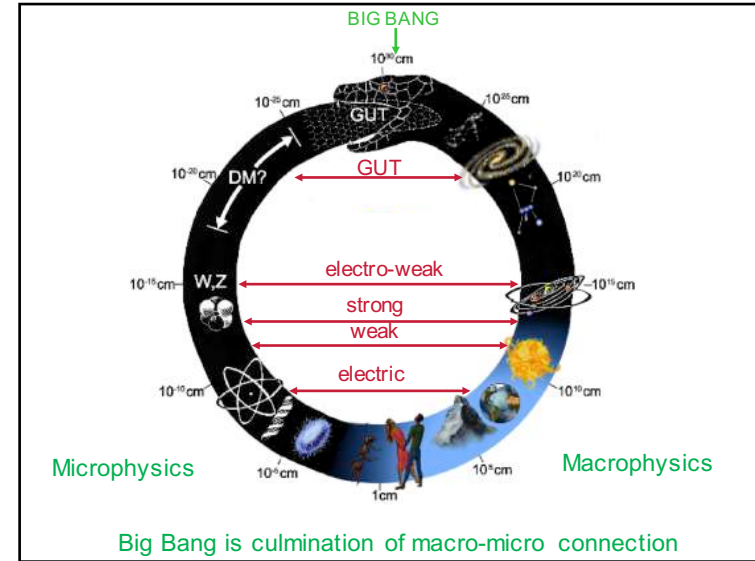
Frank Wilczek

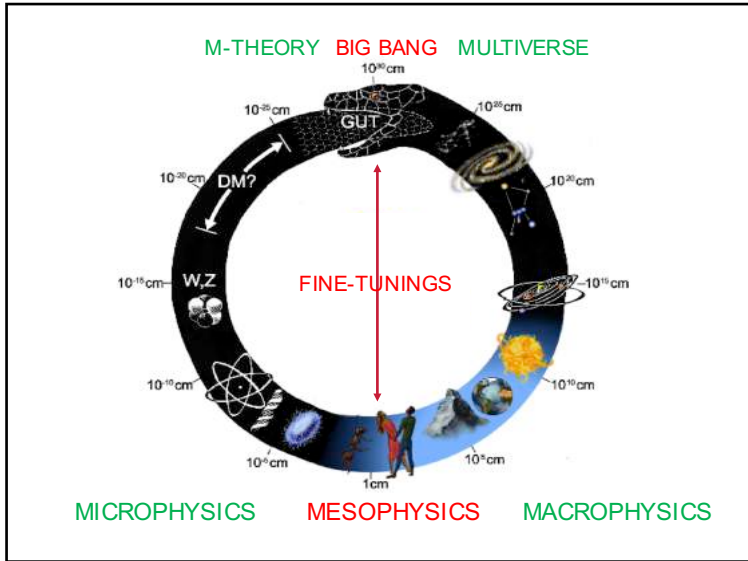
“The previous gathering [2001] had a defensive air. It prominently featured a number of physicists who subsisted on the fringes, voices in the wilderness who had for many years promoted strange arguments about conspiracies among fundamental constants and alternative universes. Their concerns and approaches seemed totally alien to the consensus vanguard of theoretical physics, which was busy successfully constructing a unique and mathematically perfect Universe. Now [2005] the vanguard has marched off to join the prophets in the wilderness.”



Steven Weinberg

“We usually mark advances in the history of science by what we learn about nature, but at certain critical moments the most important thing is what we discover about science itself. These discoveries lead to changes in how we score our work, in what we consider to be an acceptable theory.”





The completion of the Cosmic Uroborus represents the triumph of physics .....but also poses a dilemma

M-theory      Multiverse

**Defend the integrity of physics**

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

Ellis & Silk, Nature (2015)

**ANTHROPOCENTRIC VIEW**

Humans are “central” to the Universe

**MECHANISTIC VIEW**

Universe exists independent of our awareness of it.  
Humans are irrelevant

**ANTHROPIC VIEW**

Some features of the Universe are “explained”  
by requirement that observers should arise

**EVOLVING COMPLEXITY VIEW**

Big Bang should lead to increasing order and complexity, culminating in mind

**DIFFERENT TYPES OF TUNING**

Physics => natural coincidences between scales of structure

Mass and length scale of many objects depend on G and e

	Mass/ $m_p$	Size/ $a_0$
Universe	$\alpha^{-2} \alpha_G^{-2}$	$\alpha^{-1} \alpha_G^{-1}$
Galaxy	$\alpha^4 \alpha_G^{-2}$	$\alpha^3 \alpha_G^{-1}$
Star	$\alpha_G^{-3/2}$	$\alpha_G^{-1/2}$
Jupiter	$\alpha^{3/2} \alpha_G^{-3/2}$	$\alpha^{1/2} \alpha_G^{-1/2}$
Human	$\alpha^{3/4} \alpha_G^{-3/4}$	$\alpha^{1/4} \alpha_G^{-1/4}$
Proton	1	1
Planck	$\alpha_G^{-1/2}$	$\alpha^3 \alpha_G^{-1/2}$

$m_p$  = proton mass

$a_0$  = atom size

$\alpha = e^2/(hc) = 1/137$

$\alpha_G = Gm_p^2/(hc) = 5 \times 10^{-39}$

Size of human ~ geometric mean of Planck and Universe

Number of stars in Universe  $\alpha^{-2} \alpha_G^{-1/2}$

Number of galaxies in Universe  $\alpha^{-6}$

Number of stars in Galaxy  $\alpha^4 \alpha_G^{-1/2}$

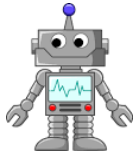
### DIFFERENT TYPES OF TUNING

Physics => 'natural' coincidences between scales of structure

Selection effects for when and where observers exist  
=> **Weak Anthropic Principle**

### WHY IS UNIVERSE AS BIG AS IT IS?

#### Mechanistic View



Time since big bang is  $t_0 \sim 10^{10}$  y  
=> size of observable universe is  $ct_0 \sim 10^{10}$  ly

**No particular reason for this!**

#### Anthropic View

**Bob Dicke**



Life requires heavy elements made in stars  
=> no life before lifetime of star  $t_s \sim 10^{10}$  y

No stars left for  $t \gg 10^{10}y$   
=> life exists when  $t \sim 10^{10}y$  => size  $\sim 10^{10}$  ly

**This explains coincidence**  $t_0 \sim t_s \sim \alpha_G^{-1} t_p \sim 10^{10}y$

### DIFFERENT TYPES OF TUNING

Physics => 'natural' coincidences between scales of structure

Selection effect for when and where observers exist  
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Fine-tunings between some physical constants needed for observers but not predicted => **Strong Anthropic Principle**

**SAP becomes WAP in multiverse proposal**

PHYSICAL CONSTANTS

Quantity	Symbol	Value in our universe
Speed of light	$c$	$299792458 \text{ m s}^{-1}$
Gravitational constant	$G$	$6.673 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$
(Reduced) Planck constant	$\hbar$	$1.05457148 \times 10^{-34} \text{ m}^2 \text{ kg s}^{-1}$
Planck mass-energy	$m_{Pl} = \sqrt{\hbar c/G}$	$1.2209 \times 10^{22} \text{ MeV}$
Mass of electron; proton; neutron	$m_e; m_p; m_n$	0.511; 938.3; 939.6 MeV
Mass of up; down; strange quark	$m_u; m_d; m_s$	(Approx.) 2.4; 4.8; 104 MeV
Ratio of electron to proton mass	$\beta$	$(1836.15)^{-1}$
Gravitational coupling constant	$\alpha_G = m_p^2/m_{Pl}^2$	$5.9 \times 10^{-39}$
Hypercharge coupling constant	$\alpha_1$	1/38.4
Weak coupling constant	$\alpha_2$	1/29.6
Strong force coupling constant	$\alpha_s = \alpha_3$	0.1187
Fine structure constant	$\alpha = \frac{\alpha_1 \alpha_2}{\alpha_1 + \alpha_2}$	1/127.9 (1/137 at low energy)
Higgs vacuum expectation value	$v$	246.2 GeV
QCD scale	$\Lambda_{QCD}$	$\approx 200 \text{ MeV}$
Yukawa couplings	$\Gamma_i = \sqrt{2}m_i/v$	Listed in Tegmark et al. (2006)
Hubble constant	$H$	71 km/s/Mpc (today)
Cosmological constant (energy density)	$\Lambda (\rho_\Lambda)$	$\rho_\Lambda = (2.3 \times 10^{-3} \text{ eV})^{-4}$
Amplitude of primordial fluctuations	$Q$	$2 \times 10^{-5}$
Total matter mass per photon	$\xi$	$\approx 4 \text{ eV}$
Baryonic mass per photon	$\xi_{\text{baryon}}$	$\approx 0.61 \text{ eV}$

Which constants are fundamental and how many are independent?

DIMENSIONLESS COUPLING CONSTANTS

- Strong force  $\alpha_s \sim 10$
- Electric force  $\alpha_e \sim 10^{-2}$
- Weak force  $\alpha_W \sim 10^{-10}$
- Gravitational force  $\alpha_G \sim 10^{-40}$

Will the Final Theory of Everything explain these values?

PLANETS AND STARS

Stars have mass  $\sim \alpha_G^{-3/2} m_p$

Division between stars with convective and radiative envelopes at  $\sim \alpha_G^{-2} \alpha^{10} m_p$

$\Rightarrow \alpha_G \sim \alpha_e^{20}$

This relationship is required for life but unexplained by physics

Constrains  $e$  to 3% (Page 2007)



Page relations (arXiv:1703.03462)

In Planck units to within a few percent:

$$m_p = e^{18} \quad m_e = e^{21} \quad t_0 = e^{-57} \quad \Lambda_0 = e^{114}$$

Carter condition  $\Rightarrow m_p^3 = m_e^2 e^{12} \Rightarrow$  these expressions!

Renormalization group argument  $\Rightarrow \alpha^{-1} = -(10/\pi) \ln m_p$

$$\Rightarrow e^2 \ln e = \pi/180$$

$$M_E = e^{-30} \quad R_E = e^{-39} \quad 1 \text{ AU} = e^{-43} \quad 1 \text{ d} = e^{-44} \quad 1 \text{ y} = e^{-47}$$

Scales in terms of Planck length Why is  $\alpha_G$  so small?

Dicke  $\Rightarrow$  age of universe  $\sim \alpha_G^{-1} t_p \Rightarrow \alpha_G < t_p / (\text{time for life}) \lll 1$   
 Number of stars in Universe  $\sim \alpha_G^{-1/2} \Rightarrow \alpha_G < (\text{prob of life})^2 \lll 1$

SUPERNOVAE AND BIG BANG NUCLEOSYNTHESIS

Supernovae explosions  $\Rightarrow \alpha_G \sim \alpha_W^4$

This also relates to primordial helium production ( $Y_p = 100\%$  or  $0\%$ ) and explains why baryonic and dark matter densities are comparable

This relationship is required for life but unexplained by physics

TRIPLE-ALPHA COINCIDENCE

(Hoyle 1953)

$${}^4\text{He} + {}^4\text{He} + Q_1 \rightarrow {}^8\text{Be} + \gamma \quad (Q_1 = 95 \text{ keV})$$

$${}^4\text{He} + {}^8\text{Be} \rightarrow {}^{12}\text{C} + \gamma + Q_2 \quad (Q_2 = 7.4 \text{ MeV})$$

Life requires carbon made in stars through  $3\alpha$  reaction  
 Beryllium would decay too soon but for finely-tuned resonance  
 Strong interaction tuned to 0.1%  
 (Livio et al 1989, Oberhummer et al. 2000, Ekstrom et al. 2009)  
 This might be viewed as anthropic prediction?

CONSTRAINTS FROM CHEMISTRY

$\alpha_S$  increased by 2%  $\Rightarrow$  all protons go into diprotons at BBNS  $\Rightarrow$  no H-burning stars  $\Rightarrow$  no time for life

$\alpha_S$  increased by 10%  $\Rightarrow$  all protons into nuclei of unlimited size  $\Rightarrow$  no interesting chemistry

$\alpha_S$  decreased by 5%  $\Rightarrow$  deuterons unbound  $\Rightarrow$  only hydrogen  $\Rightarrow$  no interesting chemistry

Other constraints involve masses

$$m_e/m_p \sim 10\alpha^2$$

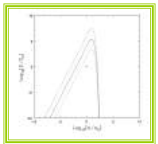
$$m_n - m_p \sim 2m_e$$

But QCD strength and quark mass are more fundamental (Hogan)

**Fred Adams**

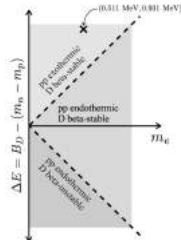
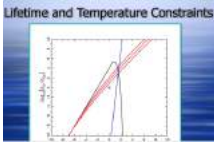
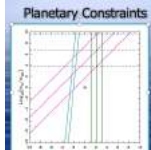
*Stars in other universes are not rare as sometimes claimed. Parameter space for working stars spans orders of magnitude.*

*F Adams (2008) JCAP, 08010*  
*F Adams, K Coppess, A Bloch (2015) JCAP, 09030*  
*F Adams (2016) JCAP, 02042*  
*F Adams & E Grohs (2017) Astropart Phys 91, 90*



**Luke Branes**

*Barnes (2015) JCAP, 1250*  
*Barnes & G Lewis (2017) arXiv:1703.0716*

DIFFERENT TYPES OF TUNING

Physics => 'natural' coincidences between scales of structure


Selection effect for when and where observers exist  
=> **Weak Anthropic Principle**

Fine-tunings between physical constants needed for observers but not predicted by physics => **Strong Anthropic Principle**

Fine-tunings of cosmological parameters for observers

*Just Six Numbers (Martin Rees)*

- 1. N = electrical force/gravitational force  $\sim 10^{38}$*
- 2. E = strength of nuclear binding = 0.007*
- 3.  $\Omega$  = matter density in universe in critical units = 0.3*
- 4.  $\Lambda$  = cosmological constant in critical units = 0.7*
- 5. Q = seeds for cosmic structures = 1/100,000*
- 6. D = number of spatial dimensions = 3*



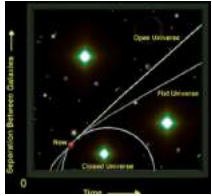
CONSTRAINTS ON MATTER DENSITY PARAMETER

$\Omega = \rho/\rho_{crit}$

$\Omega \gg 1 \Rightarrow$  Universe collapses before  $t_s$

$\Omega \ll 1 \Rightarrow$  fluct'ns freeze before gal's form

$\Rightarrow 0.1 < \Omega < 10$



Nowadays inflation predicts  $\Omega=1$  to great precision

But inflation itself requires fine-tuning!



CONSTRAINTS ON PHOTON-TO-BARYON RATIO

$$S \sim 10^9$$

Matter-dominated before Dicke time  $\Rightarrow S < a_G^{-1/4} \sim 10^{10}$

Radiation-dominated at BBNS  $\Rightarrow S > (m_p/m_e)^{4/3} (a_W^4/a_G)^{1/6} \sim 10^4$

Nowadays assume S reflects baryon asymmetry before  $10^{-5}s$

Baryosynthesis at GUT epoch  $\Rightarrow S \sim \alpha_x^{-n} < a_G^{-1/4} \Rightarrow a_G < \alpha^{4n}$

cf. star condition for  $n=5$

AMPLITUDE OF FLUCTUATIONS

$Q \ll 10^{-6} \Rightarrow$  gas cannot collapse into gravitationally bound structures

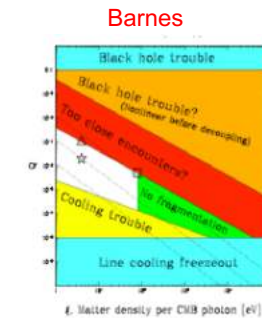
$Q \gg 10^{-3} \Rightarrow$  regions collapse to big black holes rather than stars

Various physical conditions  $\Rightarrow$

$$a^{-1} \ln(\alpha^{-2})^{-16/9} a_G (\beta/\xi)^{4/3} \Omega_b^{-2/3} \lesssim Q \lesssim a^{16/7} a_G^{4/7} \beta^{12/7} \xi^{-8/7} \quad (\Lambda=0)$$

(Tegmark & Rees 1998)

Q should be close to boundary of life-permitting range



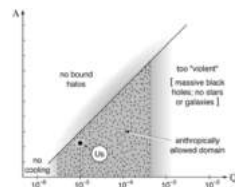
COSMOLOGICAL CONSTANT

120 orders of magnitude larger than expected

$$10^{-56} \text{cm}^{-2} \vee 10^{56} \text{cm}^{-2}$$

Galaxies cannot form unless  $\Omega_\Lambda < 0.6$  (Weinberg 1987)

This also constrains combinations of  $\Lambda$  and  $Q$



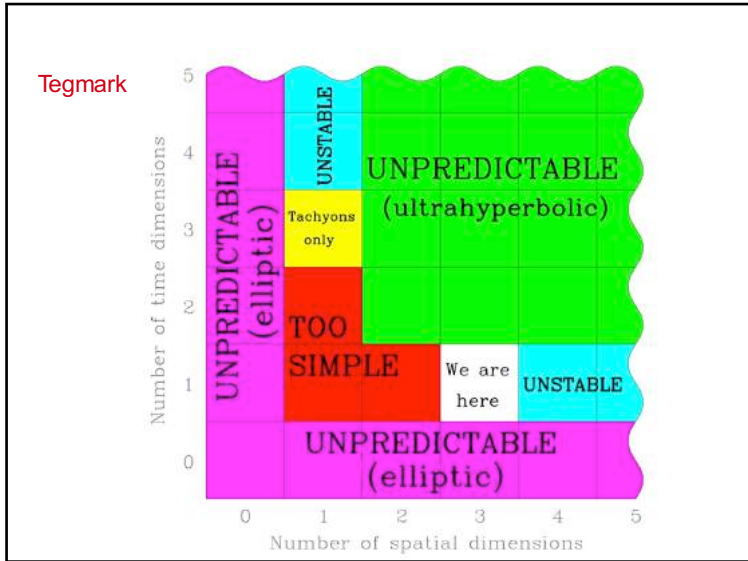
(Livio & Rees 2006)

“Anthropic principle is only known solution to cosmological constant problem” (Linde & Vanchrin 2010)

Barnes (2011)

- “There is not a single natural solution to the cosmological constant problem. ... [With the discovery that  $\Lambda > 0$ ] The cosmological constant problem became suddenly harder, as one could no longer hope for a deep symmetry setting it to zero.” (Arkani-Hamed et al. 2005)
- “Throughout the years many people ... have tried to explain why the cosmological constant is small or zero. The overwhelming consensus is that these attempts have not been successful.” (Susskind 2005, pg. 357)
- “No concrete, viable theory predicting  $\rho_\Lambda = 0$  was known by 1998 [when the acceleration of the universe was discovered] and none has been found since.” (Bousso 2008)
- “There is no known symmetry to explain why the cosmological constant is either zero or of order the observed dark energy.” (Hall & Nomura 2008)
- “As of now, the only viable resolution of [the cosmological constant problem] is provided by the anthropic approach.” (Vilenkin 2010)





DIFFERENT TYPES OF TUNING

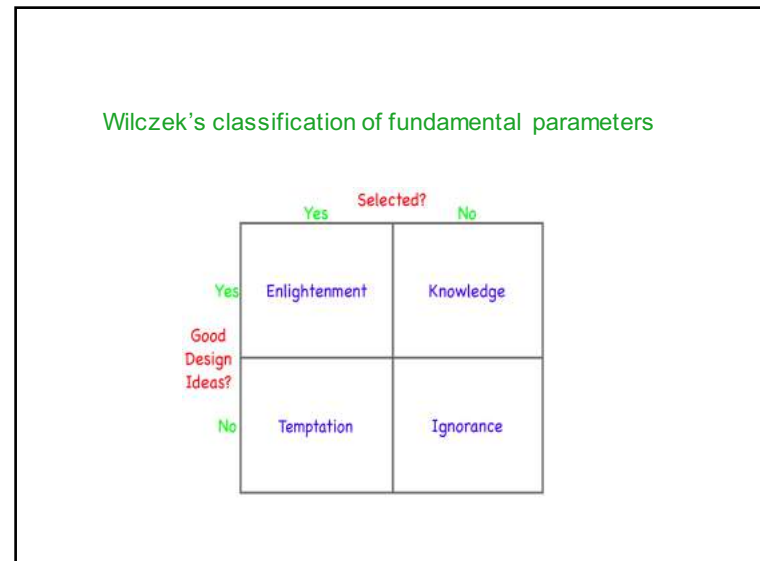
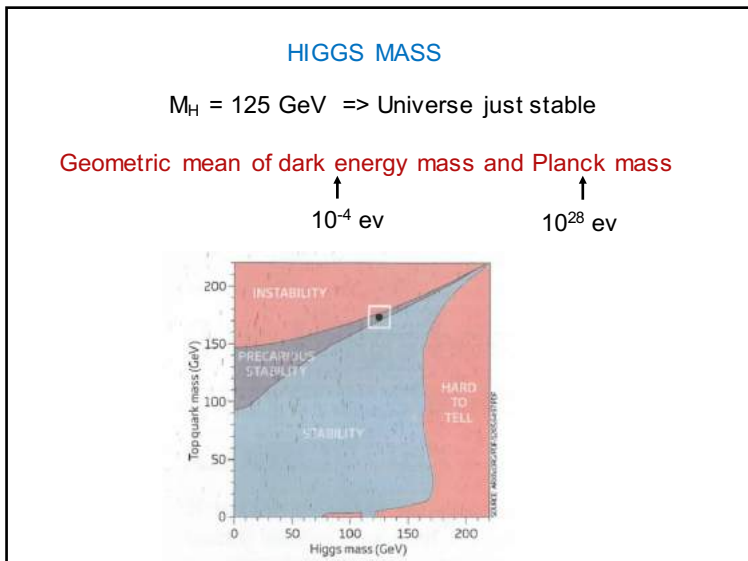
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Fine-tunings of cosmological parameters for observers

Non-anthropoc fine-tunings




**PRO**




I do not feel like an alien in this Universe. The more I examine the Universe and examine the details of its architecture, the more evidence I find that the Universe in some sense must have known we were coming. (Freeman Dyson 1979)

**ANTI**



The influence of the anthropic principle on contemporary cosmological models has been sterile. It has explained nothing and it has even had a negative influence. I would opt for rejecting the anthropic principle as needless clutter in the conceptual repertoire of science. (Heinz Pagels 1972)





**MIDDLE WAY**



The anthropic principle is a middle ground between the primitive anthropocentrism of the pre-Copernican age and the equally unjustifiable antithesis that no place or time in the Universe can be privileged in any way. (Brandon Carter 1974)

“Anthropos” = Man

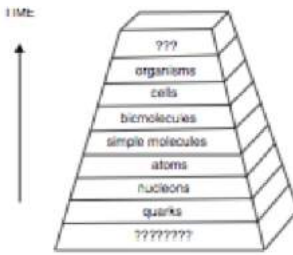
**Q: What counts as an observer?**

- A human? 
- A mouse? 
- A robot? 
- A photon? 

Consciousness? Life? Complexity?

Tegmark

**PYRAMID OF COMPLEXITY**



↑ TIME

Development of complexity during big bang requires many fine-tunings

Precise selection criterion may not be crucial because pyramid may inevitably culminate in mind once it starts to arise

**TUNINGS REQUIRED FOR BIG BANG**

log(t/s)	Event	Condition	Anthropic significance
+17.5	Present epoch	$\Omega < 10$	Else premature recollapse
+17.0	Planet formation	$\alpha_G > \alpha^{20}$	Need convective stars
+16.5	Metals from stars	$\alpha_G \sim \alpha^4$ $\alpha_G < \alpha^{20}$	Need supernovae Need radiative stars
+16	Carbon from stars	$ \Delta\alpha_S  < 0.005\alpha_S$	Need triple-alpha resonance
+16	Galaxy formation	$\Omega > 0.1$	Overdense regions must bind
+11	End of radiation era	$S < \alpha_G^{-1/4}$	Must precede galaxy formation
+2	Big Bang nucleosynthesis	$\alpha_G < \alpha_W^4$ $\Delta\alpha_S < 0.02\alpha_S$ $\Delta\alpha_S > 0.02\alpha_S$	Else all hydrogen → helium Else all hydrogen → diprotons Else deuterons unbound
-30	Axion production	$\theta \ll 1$	Need enough baryons
-34	Baryosynthesis	$\alpha_G > \alpha^{4n}$	Need enough photons
-35	Inflation	$V''' \ll V$	Need enough inflation

### EXPLANATION OF FINE-TUNINGS?

Multiverse    Consciousness    God

Physics    Metaphysics    Theology

But opinions of boundary differ - boggle threshold!

Physics    Metaphysics    Theology

Self-creation    Multiverse    Consciousness

### The cosmology/metacosmology boundary

Cosmology    Meta-cosmology

is fuzzy and evolving

George Efstathiou "Such ideas may sound wacky now, just like the Big Bang theory did three generations ago. But then we got evidence and it changed the whole way we think about the universe"

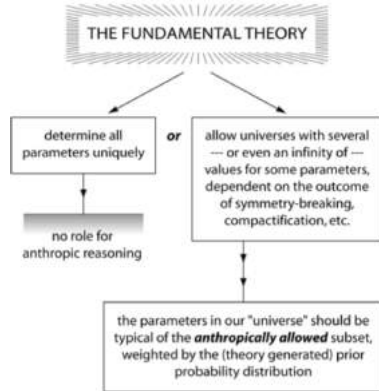
### OBJECTIONS TO ANTHROPIC PRINCIPLE

- Just a coincidence (how many? how fine?)

Victor Stenger "The Fallacy of Fine-Tuning: Why Universe is not Designed for Life". Luke Barnes "The Fine-Tuning of the Universe for Intelligent Life"

- Tunings are mainly *post hoc*  
Triple- $\alpha$  and  $\Lambda$  were predictions
- Too anthropocentric (carbon-based?)  
Fine tunings relate to *complexity* rather than life
- Anthropic arguments don't explain exact values  
Multiverse accommodates this
- Final theory may predict constants uniquely and hence tunings  
But it would remain coincidence that these values allows life
- Too philosophical or theological  
Need some explanation, metacosmology evolves to cosmology

Status of anthropic principle depends on final theory of physics



### MULTIVERSE SCENARIOS

COSMOLOGY

PARTICLE PHYSICS

Cyclic model  
Eternal Inflation  
Colliding branes

Quantum many worlds  
String landscape  
Quantum cosmology

### Opposing the multiverse



“The multiverse theory cannot make any testable predictions because it can explain anything at all.”

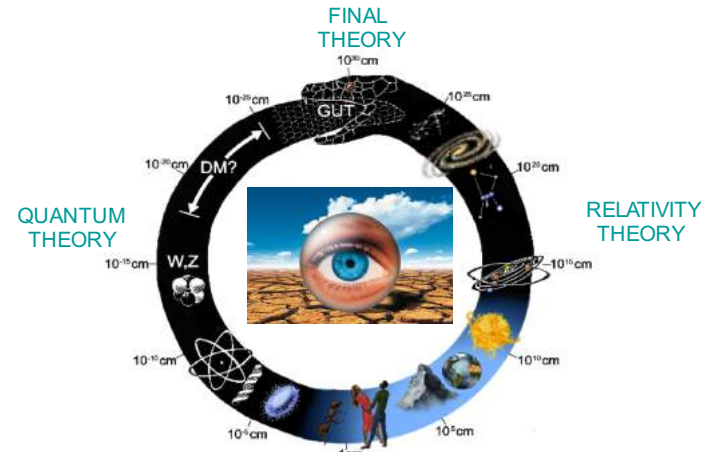
“Can one maintain one has a genuine scientific theory when direct and indeed indirect tests of the theory are impossible?”

### Defending the multiverse



“Multiverse part of science if predicted by physical theory”

“One needs some degree of falsifiability, but the question is, how much and how soon?”



Will marriage of quantum and relativity theory elucidate tunings?