Explanations for Fine Tuning

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TALK OUTLINE

Part I: The physics of constants and units

Part II: How physicists diagnose fine-tuning

Part III: Some examples of fine tuned constants

Part IV: My own take on proposed explanations

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The fine tuning argument is about certain types of

physics constants

which seem to permit life
only for a *narrow range* of values

and yet they seem to in fact take those values
(otherwise we wouldn't be here)

WHY?

provides some evidence that the universe was designed by a Creator who wanted to produce life...

We can't make a fine tuning argument about any old constant. It needs to have two qualities:

namely it must be

FUNDAMENTAL

and

DIMENSIONLESS

[the next few slides will explain what these terms mean and why they are important...]

A **dimensionful** constant is one which has units:

$c = 2.998 \times 10^8$ meters / second (speed of light)

$\hbar = 1.05 \times 10^{-34}$ Joules x seconds (Planck's constant)

$g = 9.8$ meters / (seconds)^2 (acceleration on Earth's surface)

the numerical value in front depends on the *choice of units* system,
therefore it is a human convention---it doesn't mean anything deep by itself!

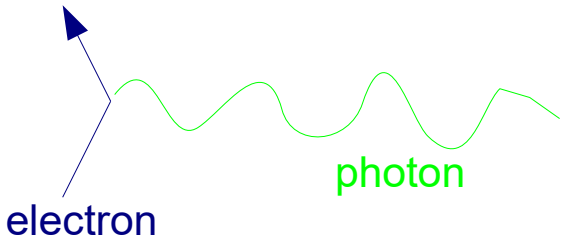
A **dimensionless** constant has no units, it's just a number.

E.g. the ratio between the mass of the electron and proton: $m_p/m_e = 1836.15...$

Or the fine-structure constant (related to the charge *e* of an electron or proton):

$$\alpha = \frac{e^2}{\hbar c} = 1/137.036...$$

probabilities for an electron to emit or aborb a photon are proportional to α



Thus it is a potentially meaningful question to ask why these numbers are the way that they are...

(The study of units is also called

dimensional analysis

It is a surprisingly useful tool,
used in every branch of physics)

A **derived** constant is one whose value can be deduced from other deeper facts about physics and math, for example:

- mathematical constants like π, whose values are necessary truths
- physics constants that can *in principle* be calculated from a more fundamental theory, e.g. the boiling point of water, or the proton mass
- environmental “constants” that depend on contingent matters of fact, e.g. the acceleration due to Earth's gravity

A **fundamental** physics constant is a parameter in our current most basic theories of physics (e.g. the Standard Model of particle physics) whose value cannot be determined by any calculation.

examples include strengths of the 4 forces, masses of matter particles

the only way to determine its value is through *experiment*

(unless somebody comes up with a deeper theory of physics which explains things with fewer parameters...)

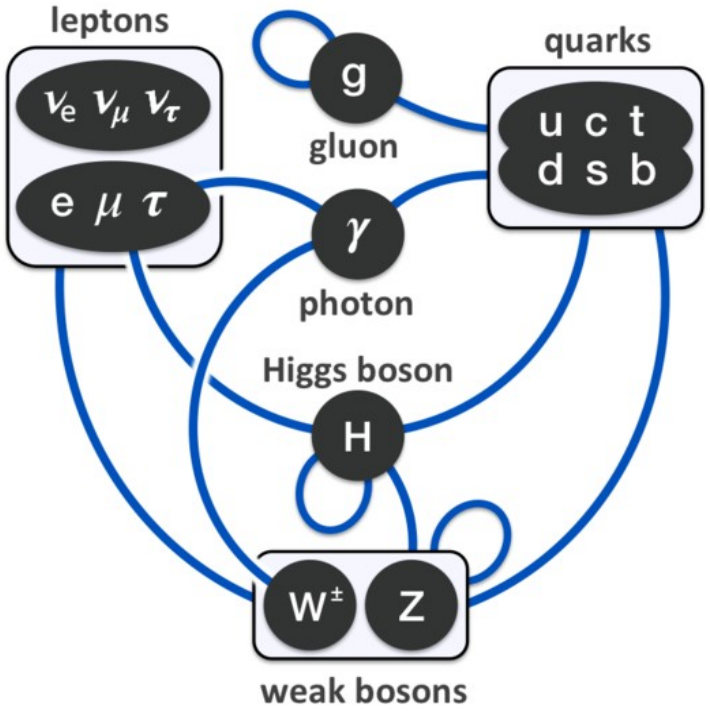
the fine tuning argument is about **fundamental** parameters,
not derived ones

(because the derived ones already
have explanations in terms of
deeper physics theories)

What are these parameters?

There are 26 dimensionless constants in the Standard Model of particle physics + Gravity

The Standard Model particles & their interactions



gravity is not shown,
but it interacts with *everything*...

includes parameters related to:

1) the strengths of the 4 forces

gravity, strong, weak, EM (i.e. fine-structure const.)

2) the masses of various particles

(which come from their interaction with the Higgs field, recently detected by the Large Hadron Collider)

3) the energy density of the vacuum

(a.k.a. the "cosmological constant", which causes repulsive antigravity at large distances)

+ likely additional parameters describing dark matter, inflation, & other poorly known stuff!

"Fine tuning" is the observation that some (not all) of these parameters seem to take on special values needed for life (and other complex structures) to exist.

It is NOT CONTROVERSIAL among physicists that these "anthropic coincidences" exist. Even atheistic physicists who work in the relevant areas mostly acknowledge it is true.

The question is what is the explanation for this phenomenon?

Is it because the universe was created by a God?

Or is there perhaps some physics reason?

[Before we can answer these questions, we need to explore the scientific & philosophical ideas behind fine tuning in a little more detail...]

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Wilsonian approach

The modern approach to thinking about these constants is due to Kenneth Wilson, (Nobel Prize 1982).

Basic ideas:

1) The laws of Nature are size dependent: big objects do not obey the same rules as little objects (discovered by Galileo).

2) So we ought to think of the "constants" of Nature as really being dependent on the "size" at which we choose to measure them!

3) The laws of Nature at *long* distance scales are described by an **effective field theory**, which is an *approximation* to reality, that ignores the stuff taking place at *short* distance scales.

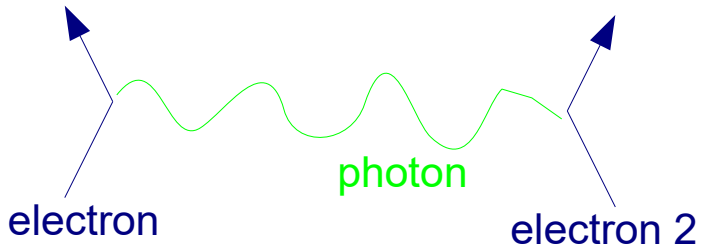
4) There is a systematic way to determine the constants at large distances from the constants at short distances, called the **renormalization group flow**

The importance of a constant depends on the scale you measure it at

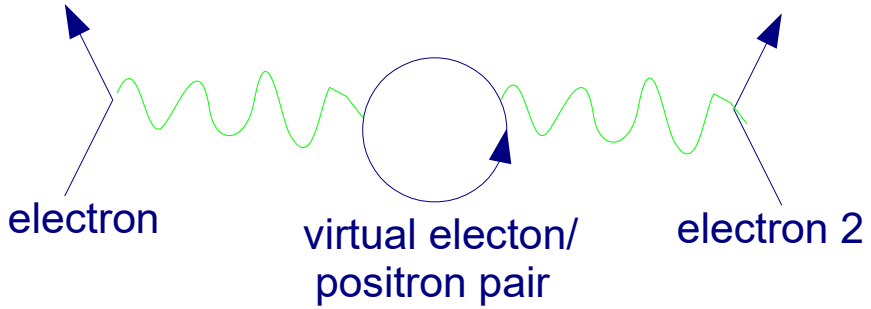
This happens for 2 *different* reasons:

Dimensional analysis: Dimensionful constants have units (e.g. meters). A meter is huge compared to the atomic scale, tiny compared to a galaxy.

Quantum effects: Quantum field theory says the vacuum is full of virtual particles which modify the values of all constants (whether or not they have units):



the EM force between 2 electrons is due to photons being exchanged between them



but the vacuum is actually full of quantum fluctuating pairs of electrons & positirons that "screen" the photons

their net effect is to make EM weaker at long distances

quantum effects modify *all* constants of Nature,
unless they are "protected" (fixed in value) by some symmetry principle

Renormalization group flow

Given the values of the constants at short distances,
you can determine the value of the constant at long distances

3 possibilities:

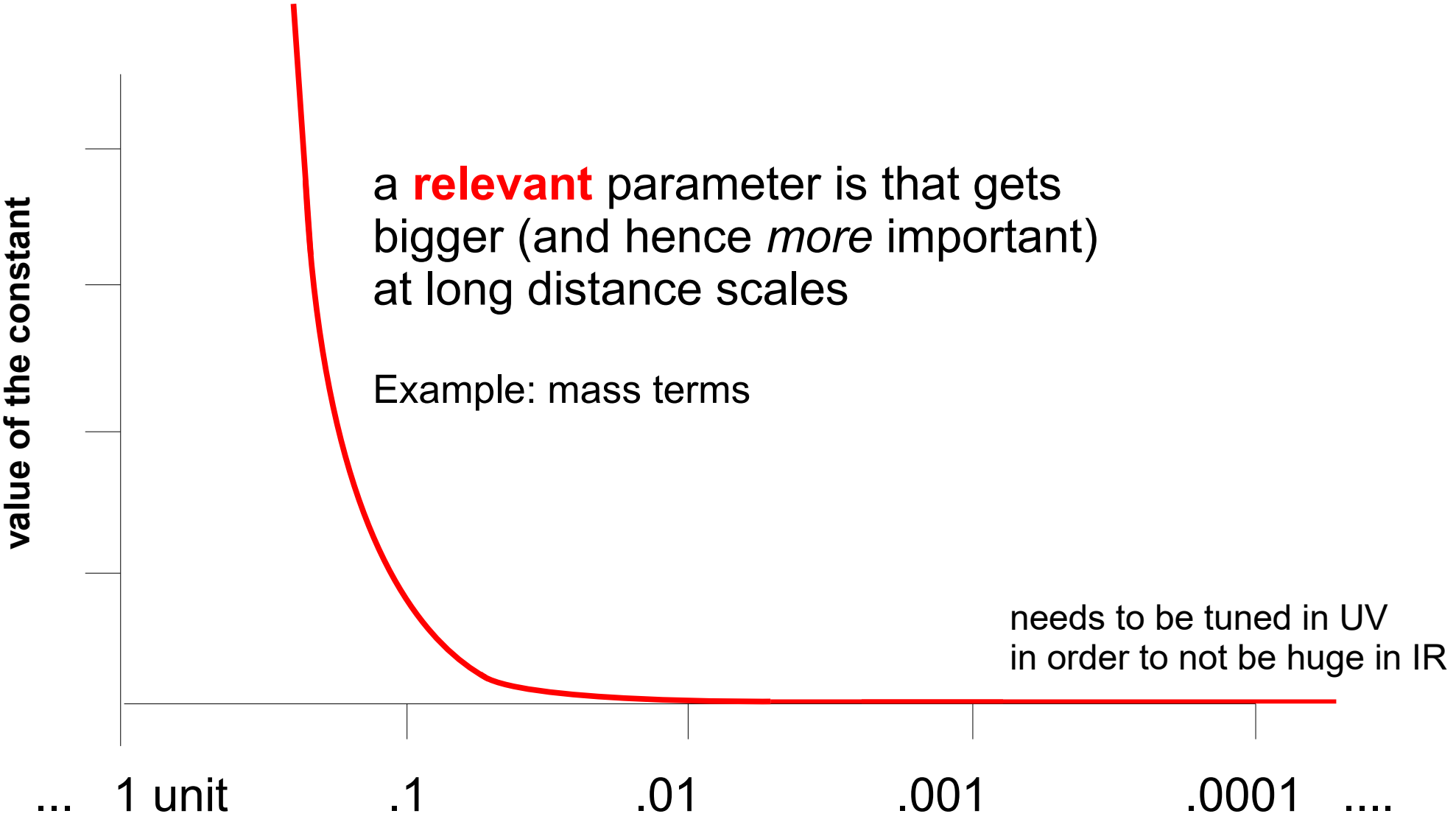
- An irrelevant parameter becomes much *less* important at large distances
(called that because mostly these parameters are *irrelevant* to life at bigger distance scales)

- A relevant parameter becomes much *more* important at large distances.

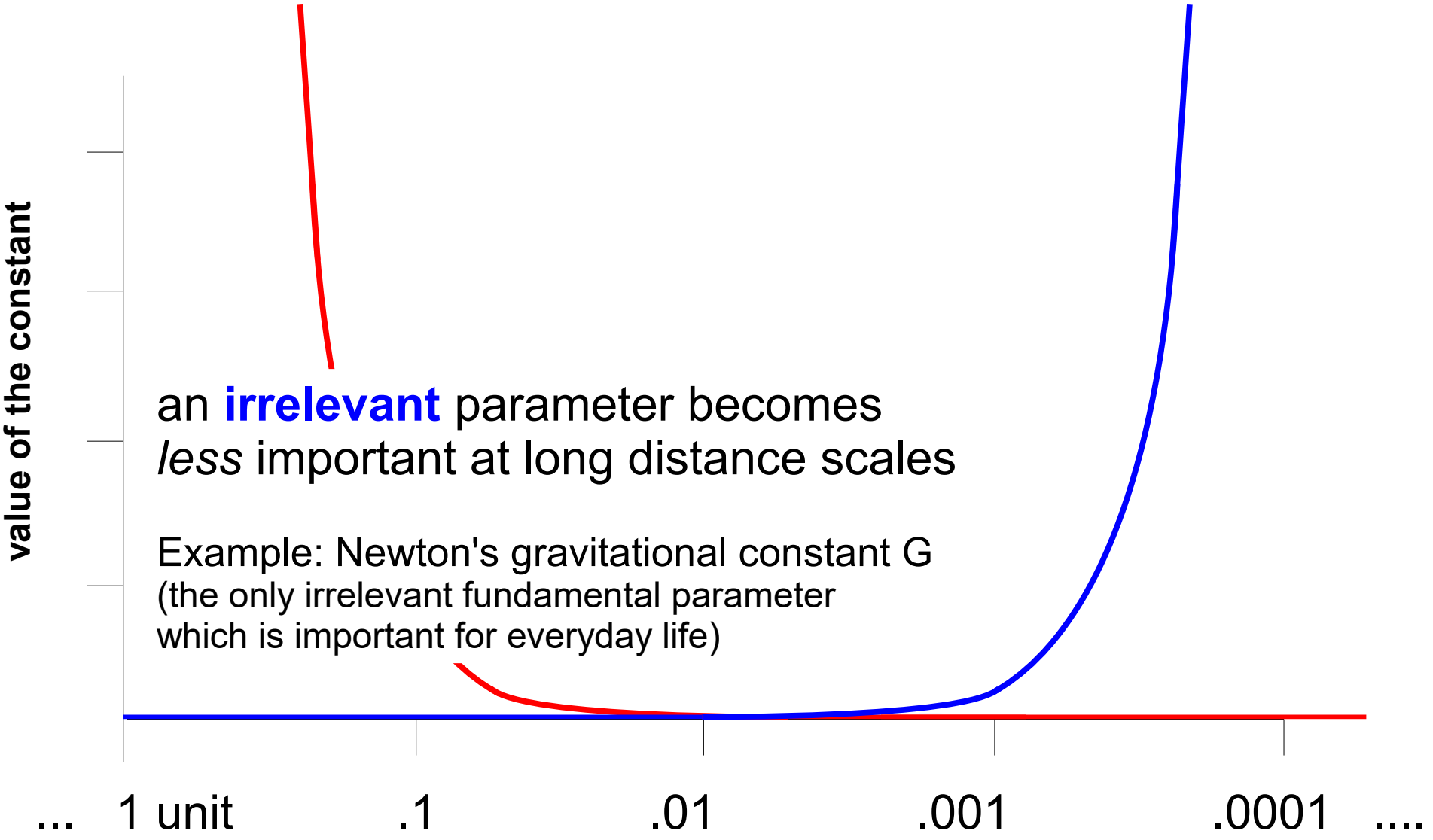
- A marginal parameter stays about the same, although it may change slightly

Physicists can use dimensional analysis (the study of units)
to determine which category a given constant falls under

Cartoon of the Renormalization Group Flow



Cartoon of the Renormalization Group Flow

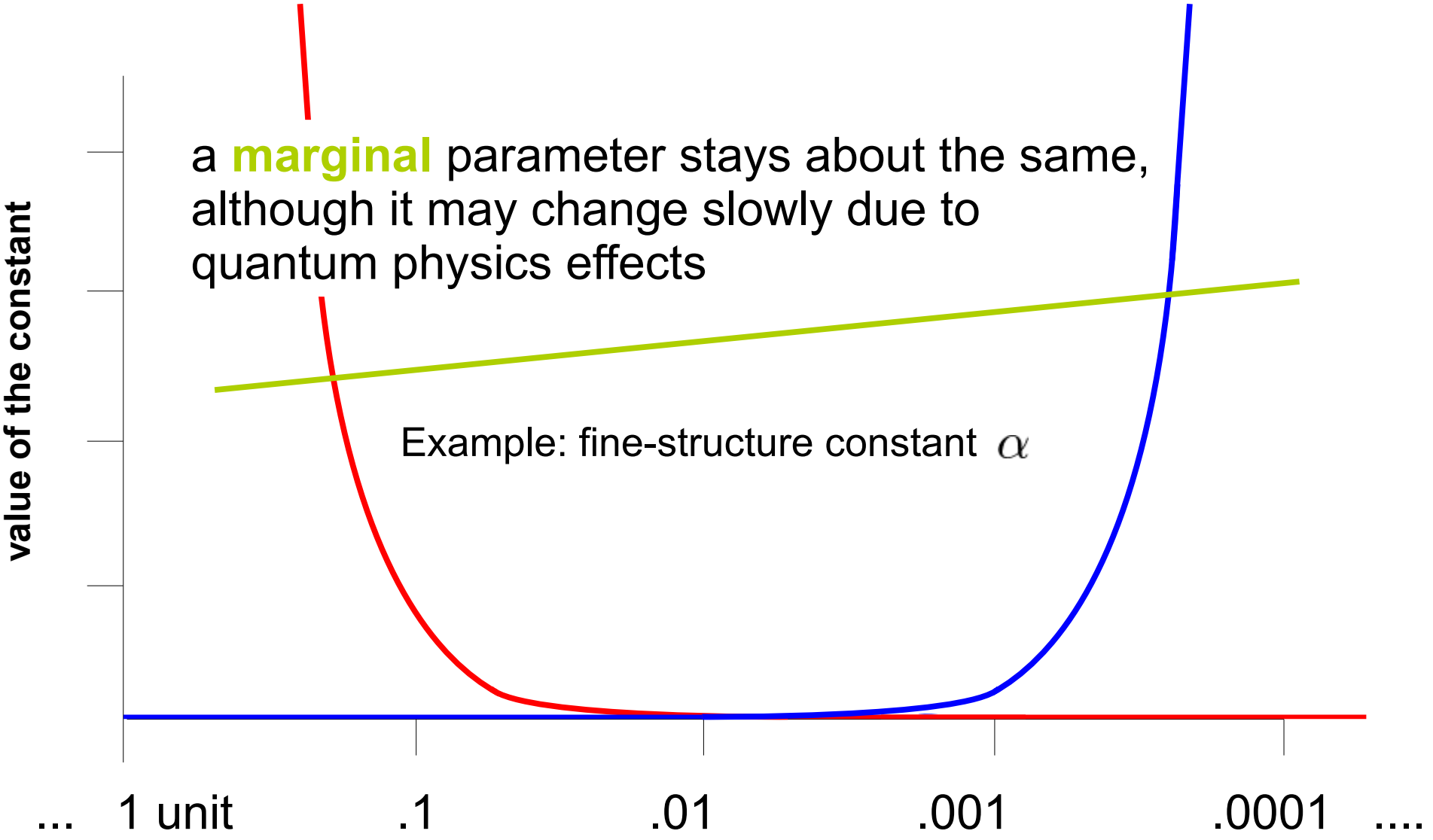


long distances
(poetically called “IR”
after “infrared”)

**plot of distance
(log scale)**

short distances
(poetically called “UV”
after “ultraviolet”)

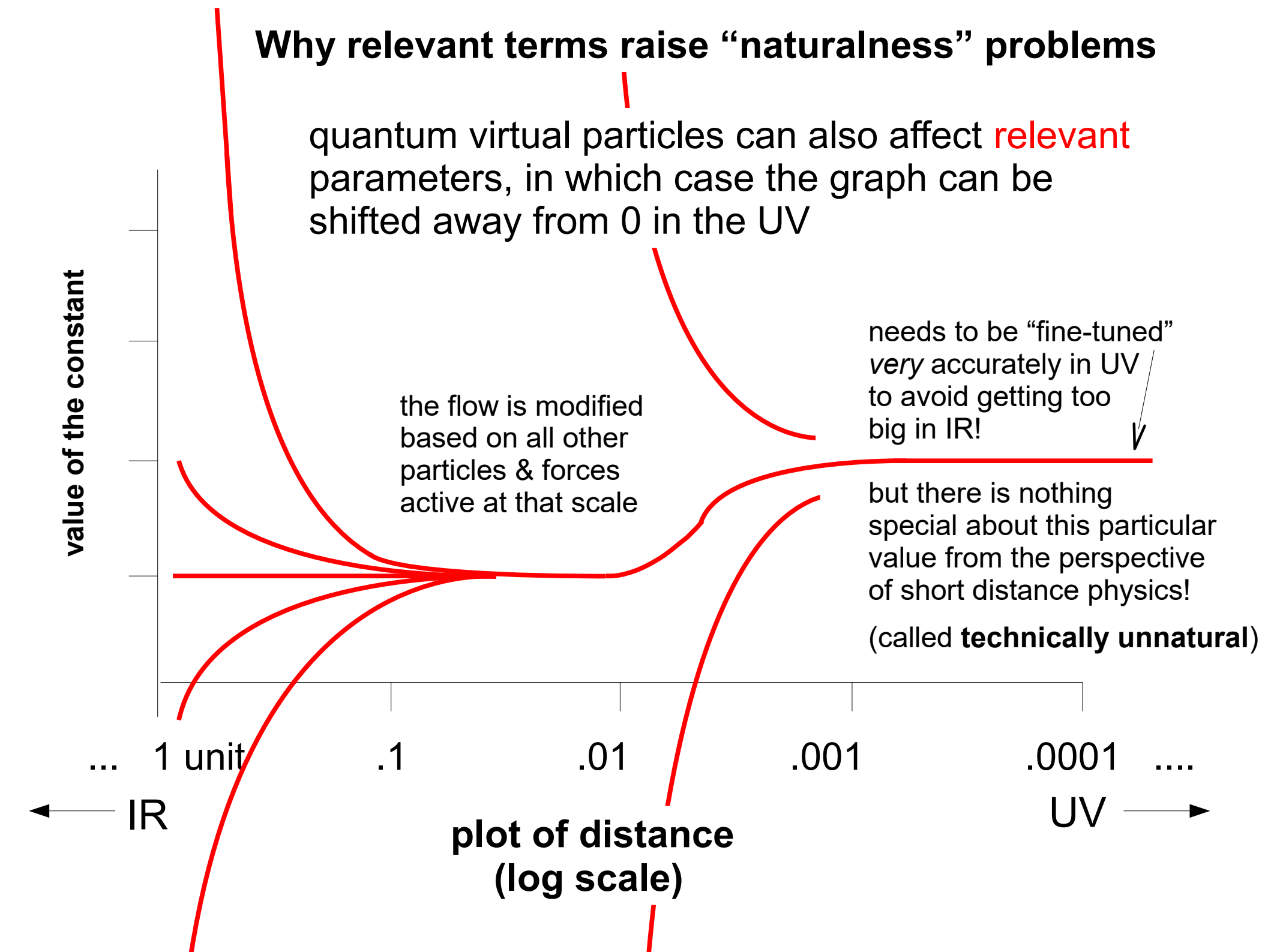
Cartoon of the Renormalization Group Flow



long distances (poetically called “IR” after “infrared”)

plot of distance (log scale)

short distances (poetically called “UV” after “ultraviolet”)


Why relevant terms raise “naturalness” problems
quantum virtual particles can also affect relevant parameters, in which case the graph can be shifted away from 0 in the UV
value of the constant
needs to be “fine-tuned” very accurately in UV to avoid getting too big in IR!
the flow is modified based on all other particles & forces active at that scale
but there is nothing special about this particular value from the perspective of short distance physics!
(called technically unnatural)
... 1 unit .1 .01 .001 .0001 ....
IR
UV
plot of distance (log scale)

2 examples of “technically unnatural” **relevant** parameters:

THE COSMOLOGICAL CONSTANT

and the

THE HIGGS MASS

[these fundamental physics parameters
which will play a starring role in the next section...]

“Scientific Reductionism”

1) the behavior of a physical system is determined
by the laws of Nature acting on its *smallest* parts,

2) *without regard* to any consequences for complexity, life, meaning etc.
at large distance scales

*[many Naturalists and Materialists seem to be motivated
by ideas roughly like this, and seems to account for at least
part of their skepticism towards certain religious ideas]*

Obviously reductionistic approaches are *sometimes* a useful technique
for thinking about Nature. The question is whether the principle is FULLY valid

S.R. seems to *predict* that the constants of Nature in the UV
should take “natural” (i.e. non-fine tuned) values

...and as we shall see this prediction seems to be wrong!

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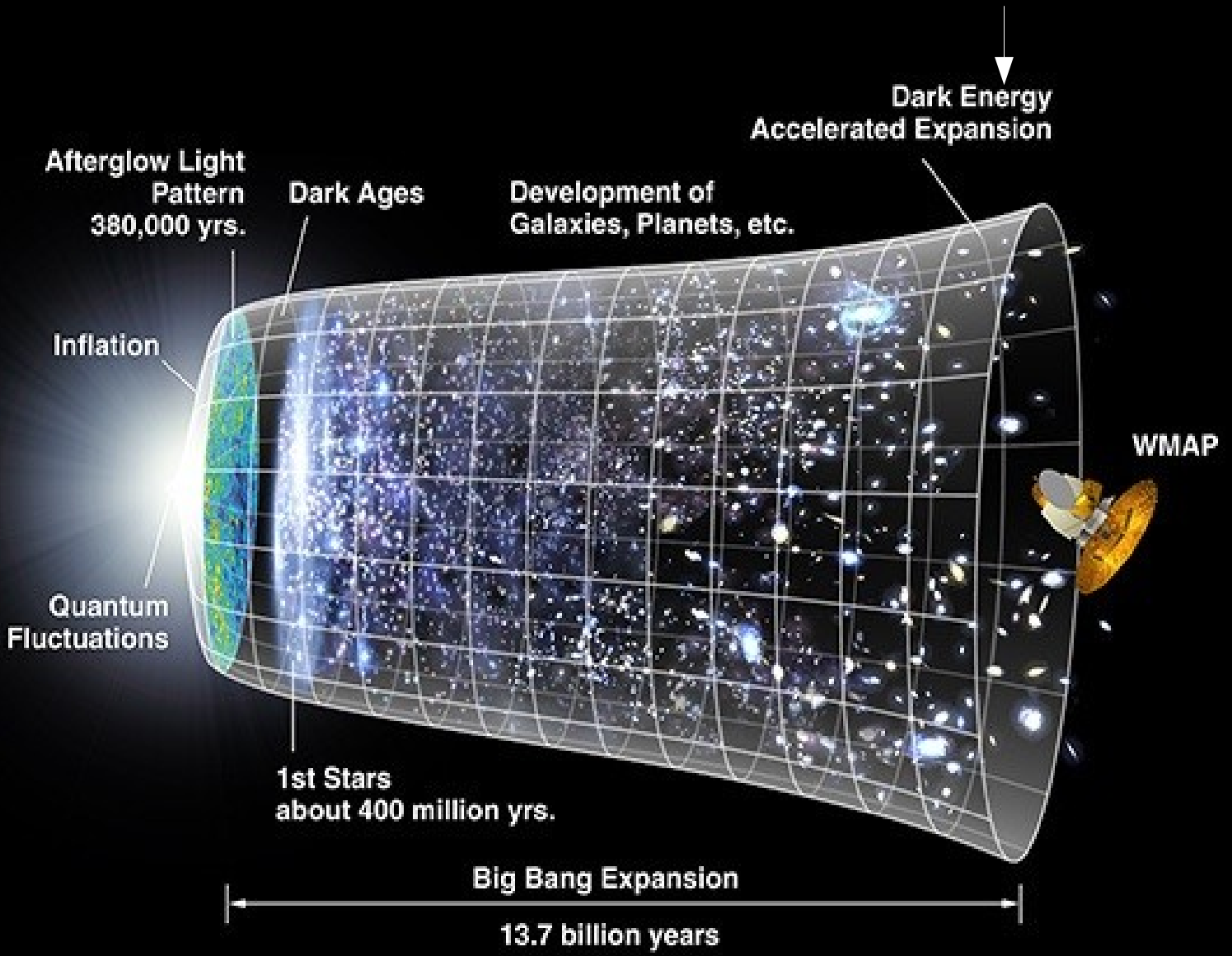
Instances of Fine Tuning involving RELEVANT parameters

EXHIBIT #1: COSMOLOGICAL CONSTANT



Positive energy density of empty space causes accelerating expansion
energy comes from scale ~10^{-5} meters

NASA/WMAP Science Team

EXHIBIT #2: HIGGS POTENTIAL

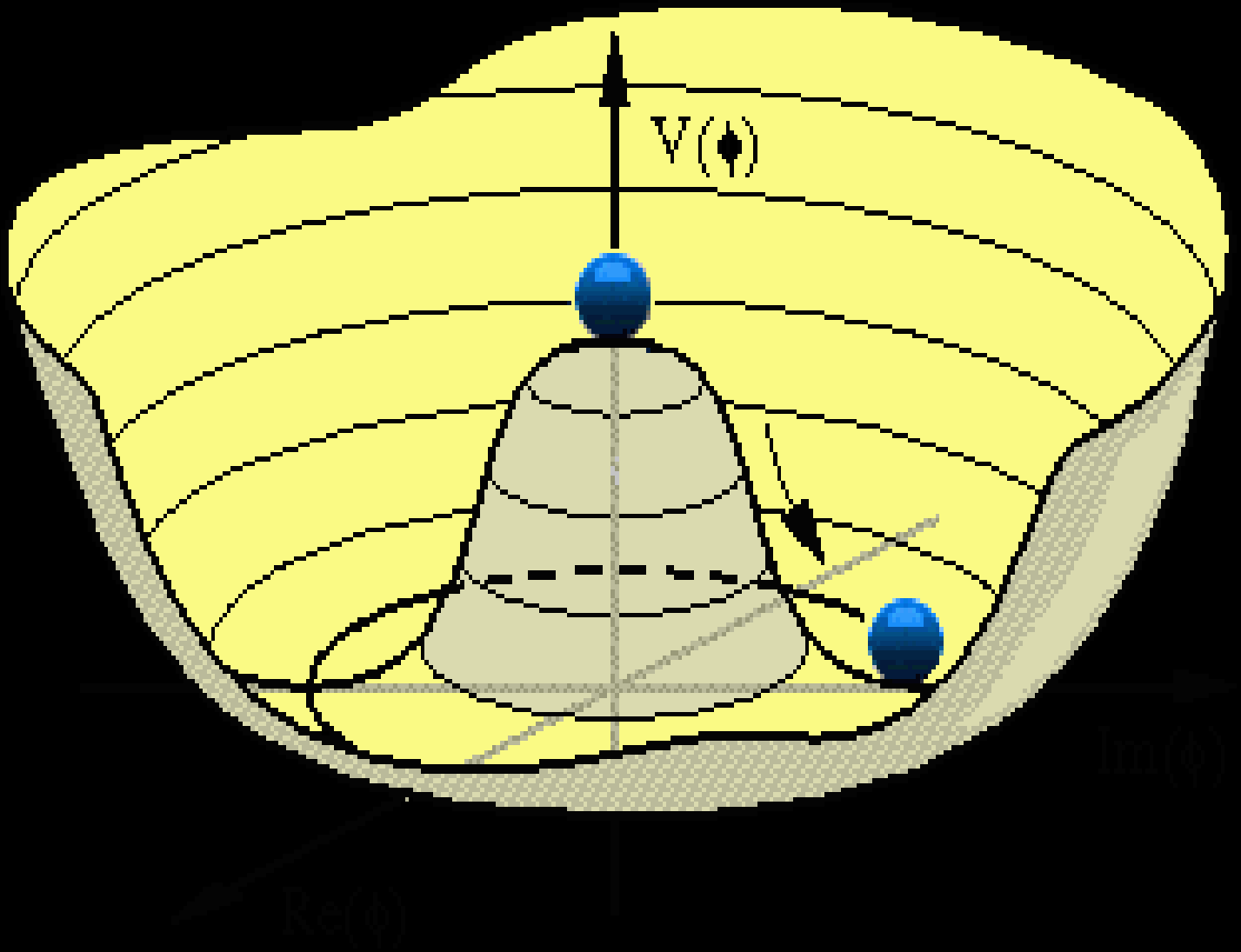


Image from
Wim de Boer et al.

Most symmetric field configuration is unstable, “rolls down” & breaks symmetry
Gives all the other particles in the S.M. their masses!
Takes place at length scale 10^{-18} meters

How fine tuned are the Higgs and Cosmological Constant?

These are both examples of relevant parameters which are fine-tuned in the UV in a technically unnatural way. + and – contributions from quantum effects must cancel to very high precision!

Makes sense not to worry about lengths shorter than Planck scale $(\sim 10^{-35}\,\text{meters})$ since shorter distances may not even exist!

Compare to Higgs $(\sim 10^{-18}\,\text{meters})$ and C.C. scales $(\sim 10^{-5}\,\text{meters})$ to get dimensionless ratio:

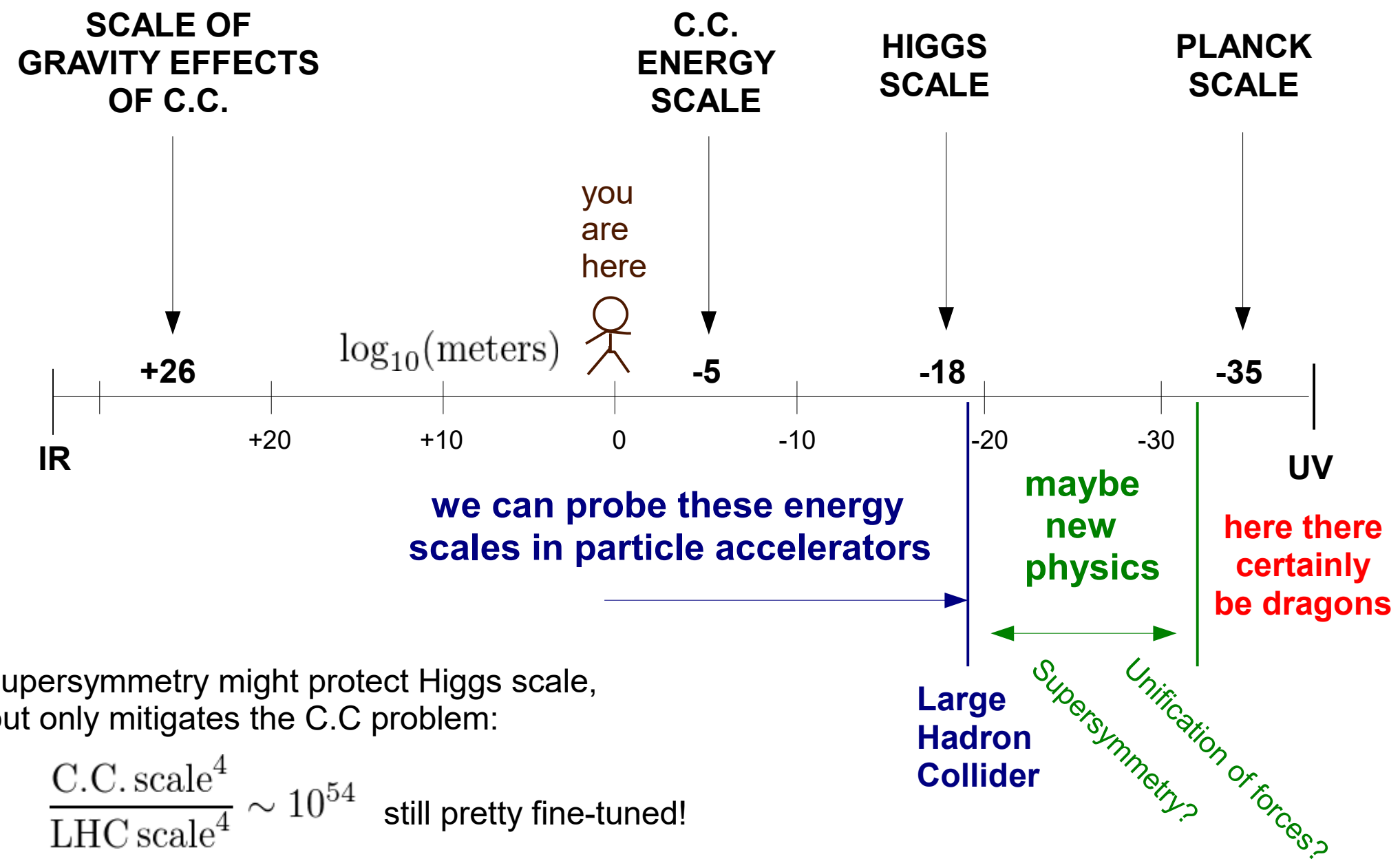
$$\frac{\text{Higgs scale}^2}{\text{Planck scale}^2} \sim 10^{34}$$

$$\frac{\text{C.C. scale}^4}{\text{Planck scale}^4} \sim 10^{122}$$

this is how accurately physics at the Planck scale needs to be fine-tuned to get the world we see!

Note: the exponents 2 and 4 are not arbitrary; these are the powers of the Higgs and C.C. scales which enter into the equations for the RG flow!

Could new physics help?



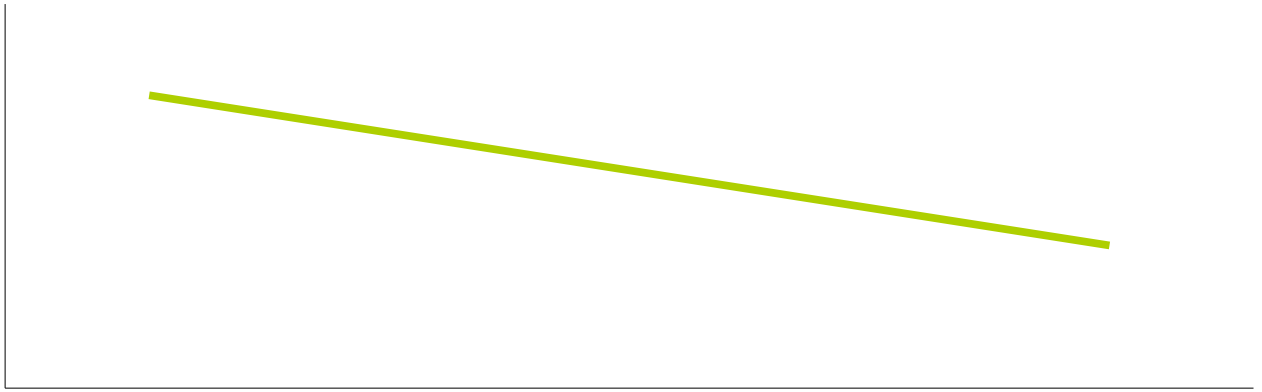
supersymmetry might protect Higgs scale,
but only mitigates the C.C problem:

$$\frac{\text{C.C. scale}^4}{\text{LHC scale}^4} \sim 10^{54}$$

still pretty fine-tuned!

Instances of Fine Tuning involving MARGINAL parameters

Other instances of fine-tuning involve **marginal** parameters



Typically involve much smaller amounts of fine-tuning, e.g. ~1%

Also challenges Scientific Reductionism because there seems to be no particular reason for these parameters to take on life-supporting values

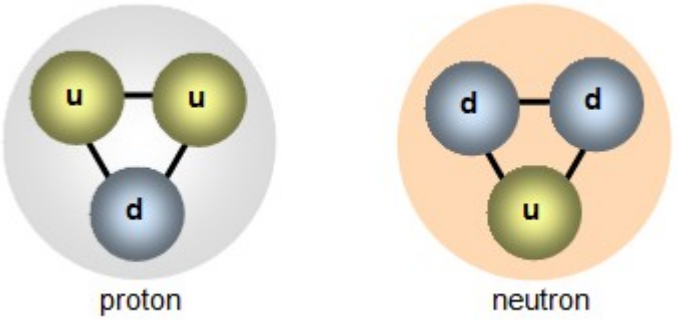
(If the value of a marginal parameter is very close to 0, there might be a physics explanation in the UV. But what could explain why it takes some random value needed for life?)

First an NON fine-tuned example: why is the proton so light?

Protons are about 10^{-19} times the mass of the Planck scale

(as a result the gravitational attraction between 2 protons is enormously weaker than their electrostatic repulsion)

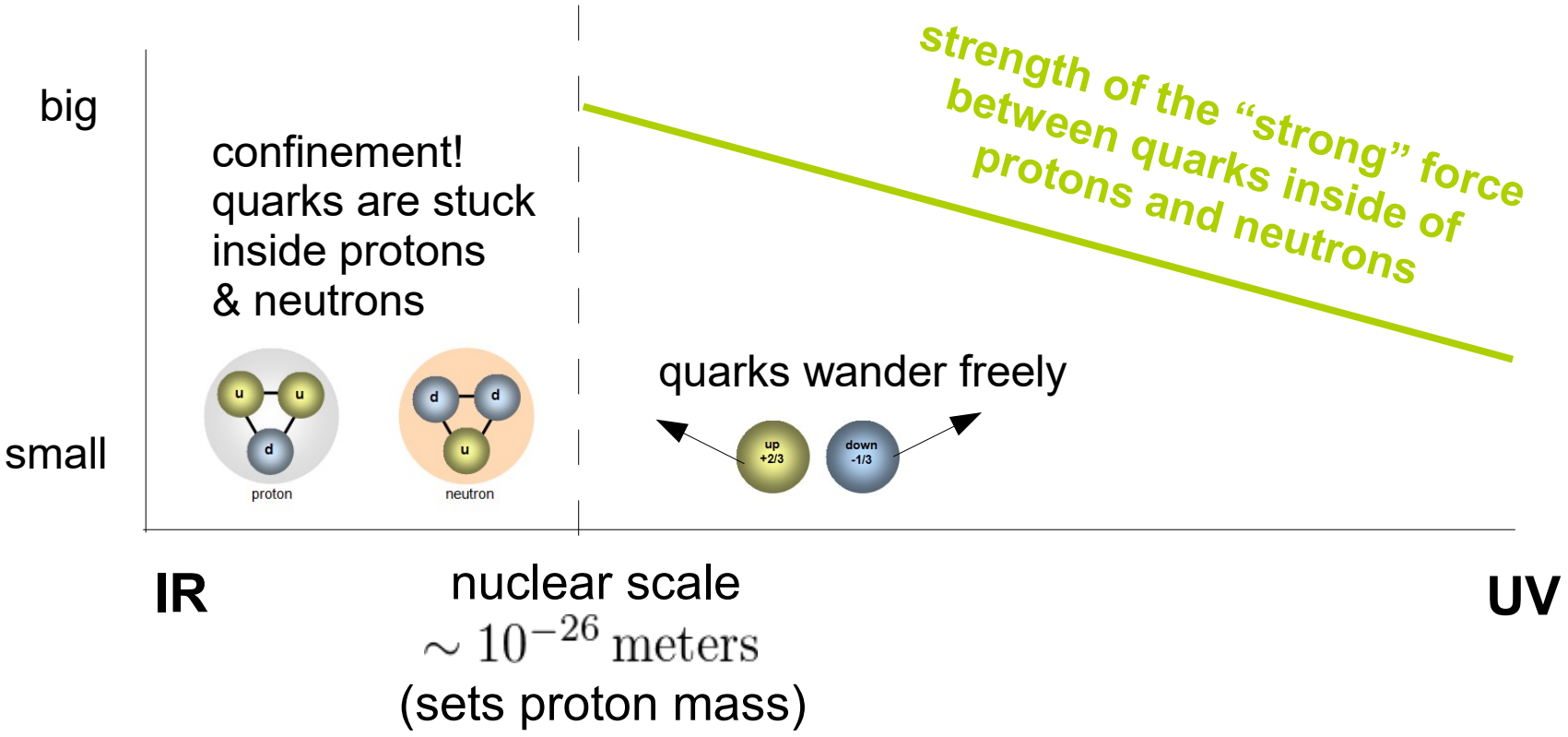
Some authors *wrongly* consider this large ratio an instance of fine tuning, but there is a perfectly good physical explanation for why it is so large:



Protons (and neutrons) are made of smaller particles called quarks,
but the bulk of the proton mass comes from the strong force,
not the quark masses. And the strong force is **marginal** so...

Mass of the proton is not fine tuned

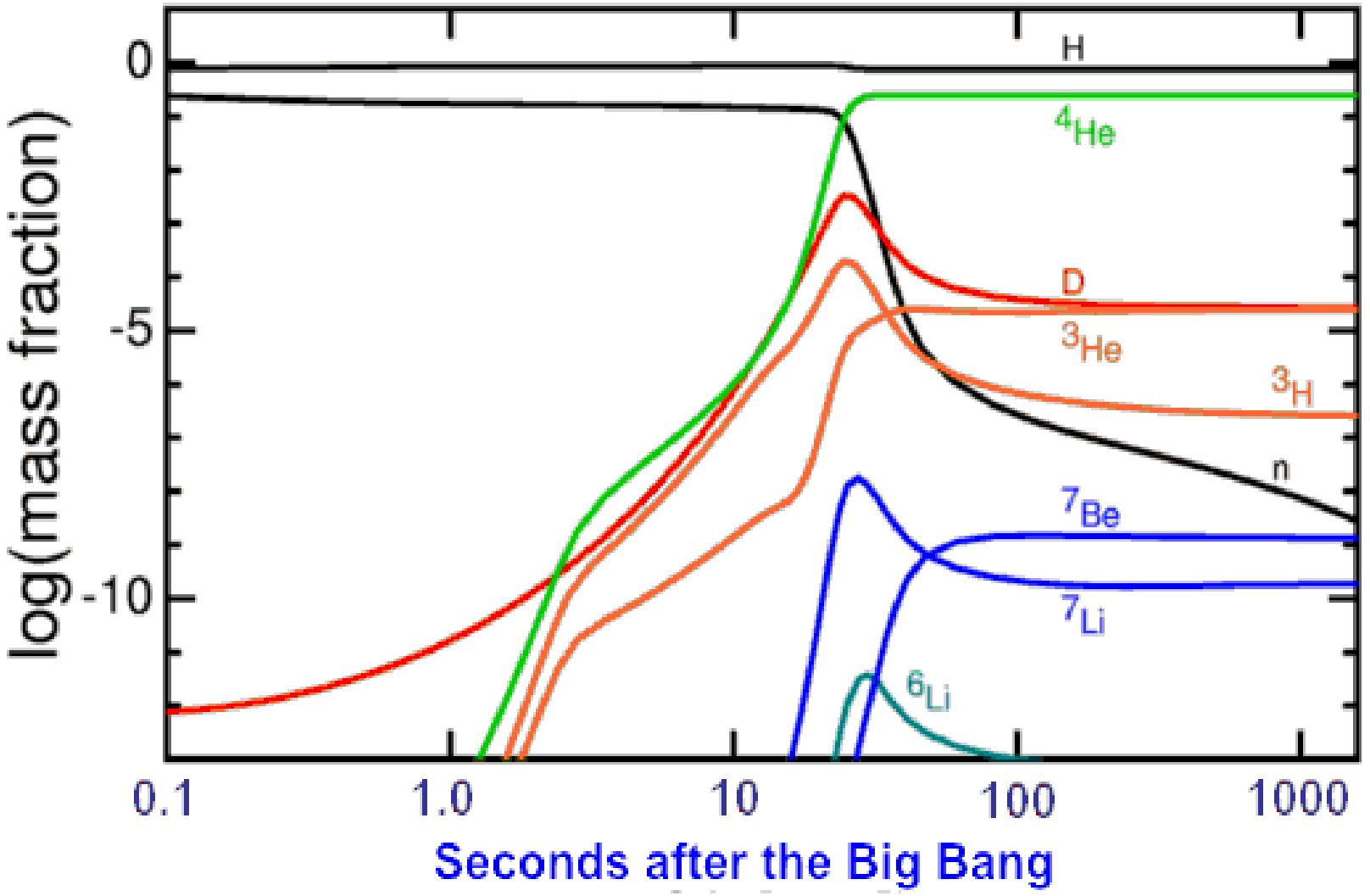
$$\frac{\text{Proton scale}}{\text{Planck scale}} \sim 10^{19}$$



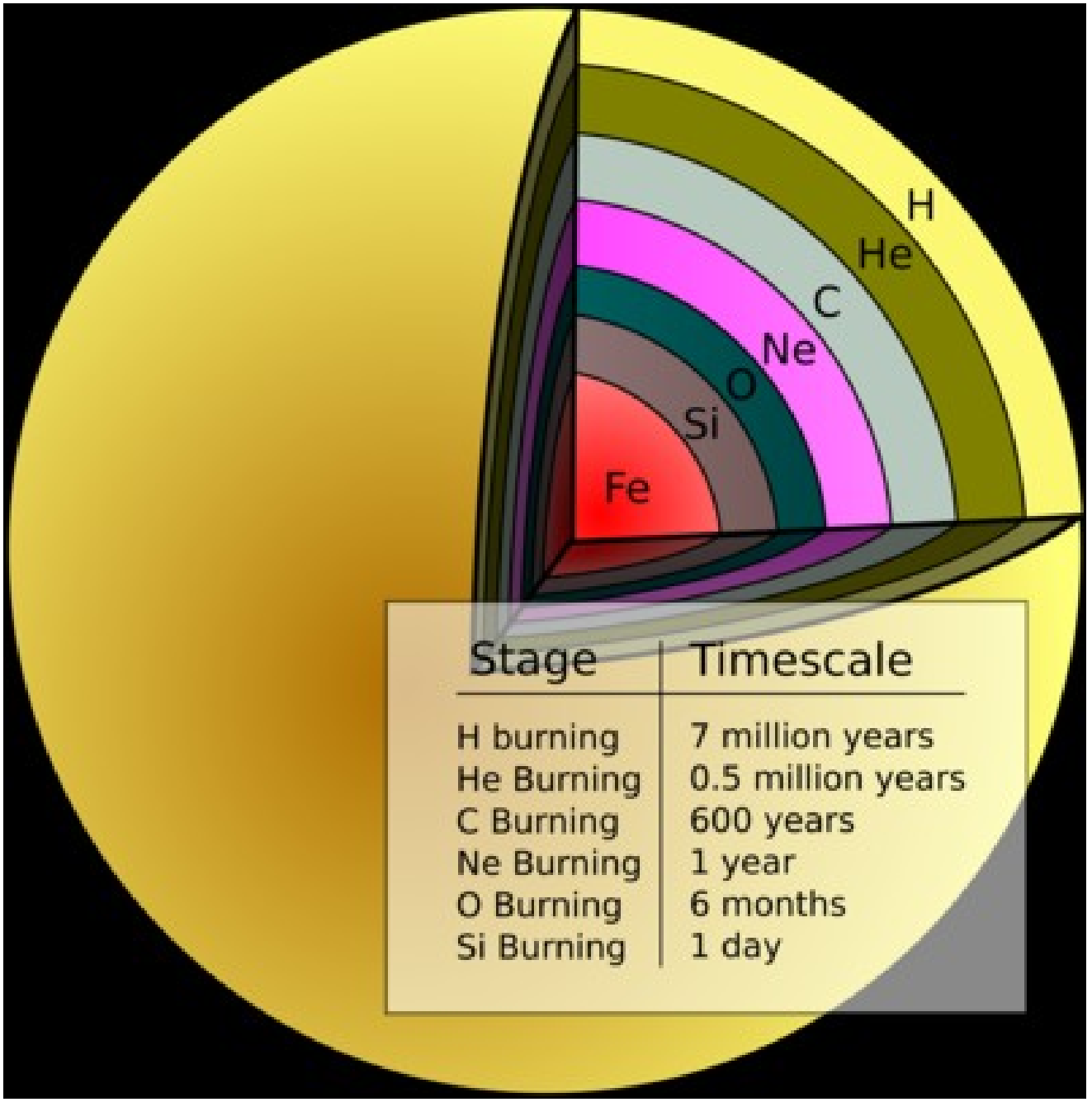
moral: Must study RG flow to diagnose fine-tuning! Consult your local physicist...

although the proton mass is not fine-tuned *by itself*, it is an important coincidence that it is close in mass to the fundamental quarks and leptons (that get their mass from the Higgs)

Big Bang Nucleosynthesis only produces light elements

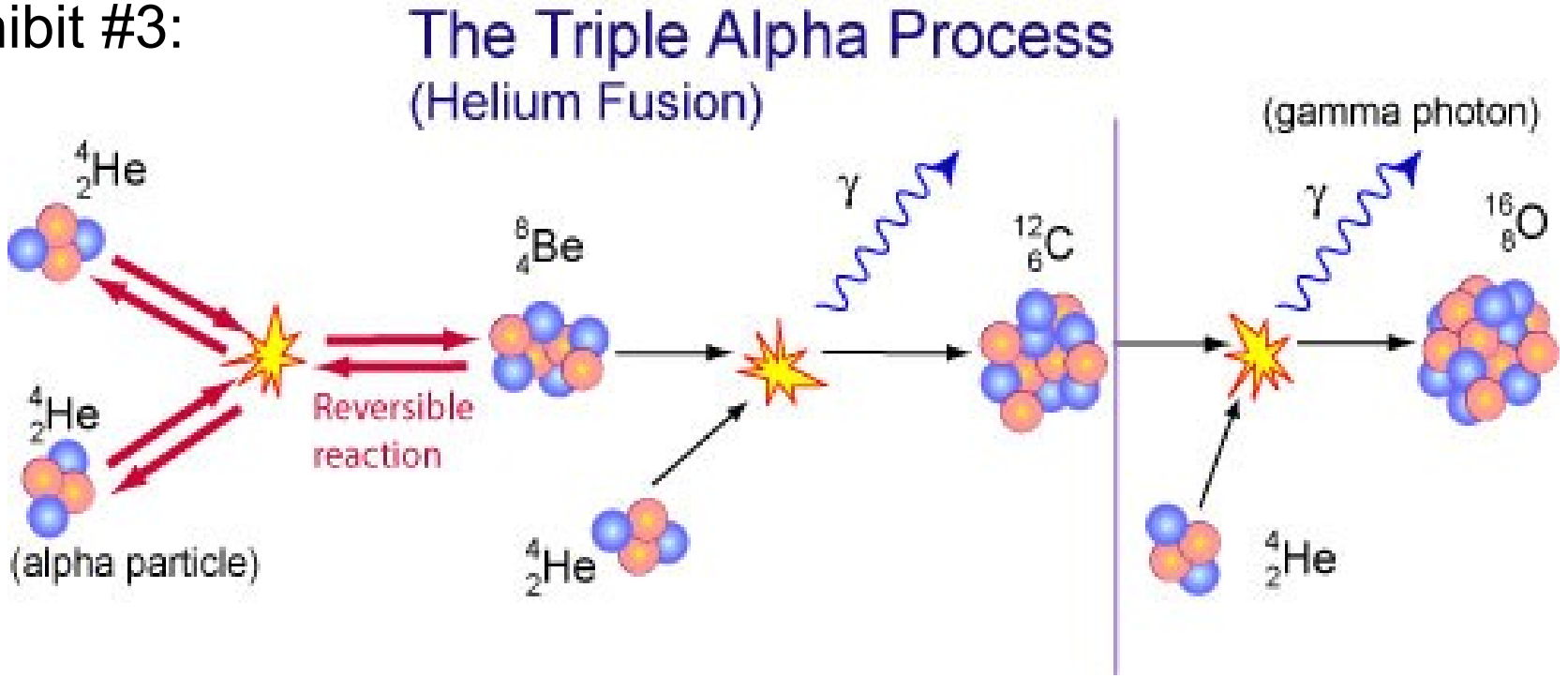


Heavier elements are created in stars



A. C. Phillips, The Physics of Stars, 2nd Edition (Wiley, 1999)

Exhibit #3:

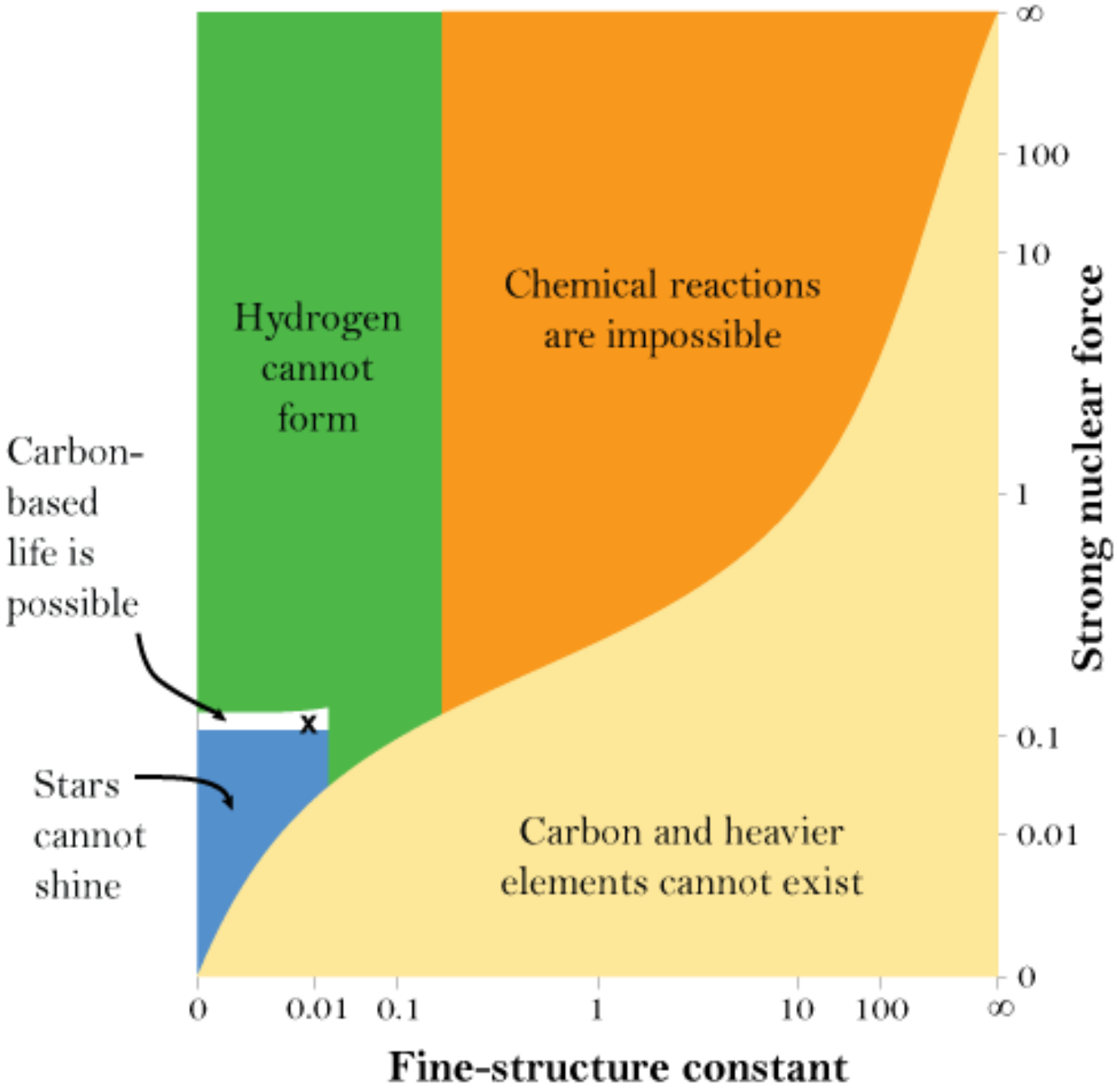


Be-8 is an unstable element. But one of the energy levels of a C-12 nucleus happens to have nearly the same energy as 3 He-4's!

This allows carbon (and thus heavier elements) to be produced in stars.

Requires fine tuning of light quark masses to 1% precision to get significant amounts of both carbon and oxygen!
(Oberhummer, Csótó, & Schlattl 2001)

Exhibit #4: Additional fine tuning needed for stars & chemistry



triple alpha constraint not included

figure by Luke Barnes

Other (less convincing) kinds of fine-tuning

* Initial Conditions in Cosmology

1) universe started in a very low entropy state,
necessary to get 2nd law of thermodynamics

odds of happening if state is randomly selected: $1 \text{ in } 10^{10^{120}}$

but there's no particular reason why the initial state should be random...

2) inflation helps explain why the universe is "flat" to about $1 \text{ in } 10^{60}$
(early universe on knife's edge between expanding too fast and too slow)

(although inflation *itself* requires some fine tuning to get it to work...)

* Specialness of the Solar System

issue here is that we know there are many other solar systems...

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(starting with the silliest ones...)

1. “If the universe didn't permit life, we wouldn't be around to notice, therefore no explanation is required!”

My response:

Suppose you were found as a baby on a beach by adoptive parents... you grow up and nobody has ever discovered your true parents.

2 possible scenarios:

A) you had a mother & father in the usual way
B) you were spontaneously assembled out of the sea foam

nobody would say that A & B are equally good, because if neither had happened you wouldn't be around to ask the question

2. “We just got lucky!”

My response:

Are you kidding me? Maybe for one of the 1% cases, but 10^{-122} *is a ridiculously tiny number. No reasonable person could think that the universe being designed by God (or one of the other proposed explanations) is* ***that*** *unlikely!*

3. “Sure, carbon based life requires fine tuning, but maybe other forms of life could exist if the constants were different?”

My response:

It's hard to imagine what sort of life could exist in a universe without stars and/or complex chemistry...

but in the case of the Cosmological Constant, it is simply impossible:

** If the C.C. were the expected size & negative, the universe would collapse in about* 10^{-43} *seconds*

** If the C.C. were the expected size & positive, “objects” separated by more than* 10^{-35} *meters would be unable to communicate*

*no complex objects of **any sort** would be possible, let alone life!*

*(also, a bit of a red herring, since the parameters would still be fine-tuned to permit **carbon** based life, and this doesn't explain why...)*

4. “Maybe there is a deeper theory of physics which allows us to calculate all the values of the constants”

My response:

If we actually had that theory and did the calculation and got the right answer, that would be an excellent explanation.

*But if we are simply hypothesizing that there **is** such a theory, we need to really consider a large number of subhypotheses:*

1. *Deeper Theory exists and predicts constant has value* X_1
2. *Deeper Theory exists and predicts constant has value* X_2
3. *Deeper Theory exists and predicts constant has value* X_3

$$\vdots \qquad \vdots \qquad \vdots$$

*and so on for every possible value. Unless there's a reason to think that the subhypotheses which allow life are more likely (and that would require endorsing some **other** explanation) the prior odds of the fine-tuned hypothesis is just as small as the “getting lucky” case.*

5. “There must be some unknown physics mechanism to explain why these parameters take special values”

My response:

Physicists have basically classified all possible symmetries which a quantum field theory could have. (Haag–Lopuszanski–Sohnius theorem). Places limits on possible solutions.

1) Several ideas to solve the Higgs heirarchy problem. Most popular method is supersymmetry, but this has not yet been seen at the LHC so the simplest models are fine-tuned at 1% level.

2) Very hard to solve C.C. problem since we can observe physics at the relevant energy scales and it seems nothing weird is going on. Also very hard to construct theories in which the C.C. is dynamically adjusted to 0 (while still allowing spacetime to be curved by matter...)

3) As far as stars and chemistry are concerned, hard to see why those values would be special from the point of view of new physics at short distances

6. “Perhaps scientific reductionism is just wrong. Somehow the fundamental rules of the universe care about big things, like stars and galaxies”

My response:

It's always possible. But this is starting to get pretty weird.

And vague. Reductionism has to be wrong in some pretty specific ways to explain fine tuning.

I'm not aware of any well-motivated hypotheses along these lines.

Except one: once you start thinking that some aspect of the universe is sufficiently like a mind to care about life and goodness and so forth...

7. “Maybe there's a God after all, who wanted an interesting and beautiful universe, maybe with some intelligent life to appreciate it all.”

My response:

I already believe in God for other reasons (e.g. the Resurrection of Jesus).
So to me this is the most likely explanation.

Note that this allows you to keep the aspects of reductionism that work.
There is still ordinary local physics at short distance scales,
but a creative mind, distinct from the cosmos, had purposes for it.

“But that doesn't prove the God of traditional religion!”

True. If we only know about the physics of fine tuning, we can't deduce all of the attributes of God. However:

* A God who wanted beauty and/or life may care about goodness in general.

* It also makes sense that a personal Deity might want to make other persons to have relationships with them.

Physics by itself not enough for a relationship with God, but it should make people take claims that God has revealed himself more seriously!

8. “What if there are a gazillion universes, each with different laws of physics, and we just happen to be in one of the few that supports life?”

My response:
I like reading about multiverses as much as any science fiction fan!
But to get this to work you need to combine 2 speculative ingredients:

> ***1.*** *Deep laws of physics that allow many different effective theories in different regions of the universe, &*
>
> ***2.*** *A mechanism for generating lots of different universes (at least* 10^{60} *with supersymmetry,* 10^{150} *without.)*

#1 seems likely if string theory is true
(a promising theory of quantum gravity not yet supported by experiment)

#2 “eternal inflation”: some models of inflation, parts of the universe keep inflating forever, with an ∞ *number of “bubble universes” embedded inside.*

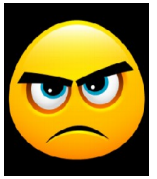
Question: given the large number of “dud” universes that don't support life, in what sense does this count as an explanation...?

PARADOXES GALORE

The bad news is that nobody knows how to calculate probabilities when there is (or even *might be*) a multiverse!

1. Measure problem: the odds of a given universe looking like our own are

$$\frac{\#\,\text{like ours}}{\text{total}\,\#} = \frac{\infty}{\infty} = ?!?$$



2. Boltzman Brains: in a big enough universe, people will form randomly from quantum fluctuations, and by some ways of counting you might be more likely to be one of those than a "real" you...

(note: this might be a problem even with a single universe)

3a. Some approaches lead to the **Doomsday Paradox** (in which your predictions depend on the number of future people who are *going* to live)

3b. Other approaches assign a probability of 1 to every possible observation in an infinitely large universe/multiverse... not predictive!

until these awful paradoxes are resolved, I can't tell you whether the multiverse should count as an explanation of life or not...

“So do these paradoxes refute the multiverse then?”

Not so clear. Similar paradoxes pop up in other contexts as well

(e.g. trying to decide to what extent the existence of human life
makes it more likely for there to be alien life elsewhere (say, in our galaxy)

need a general approach to dealing with hypotheses that predict different
numbers of people...)

So, although it is not my preferred explanation of fine tuning,
it seems fair to give the mulitverse the benefit of the doubt.

Maybe somebody might come up with a way of sensibly thinking
about it. Then one could check if it makes other predictions that
are confirmed by observation...

My Conclusion:

So I think that
Fine Tuning strongly suggests the existence of:

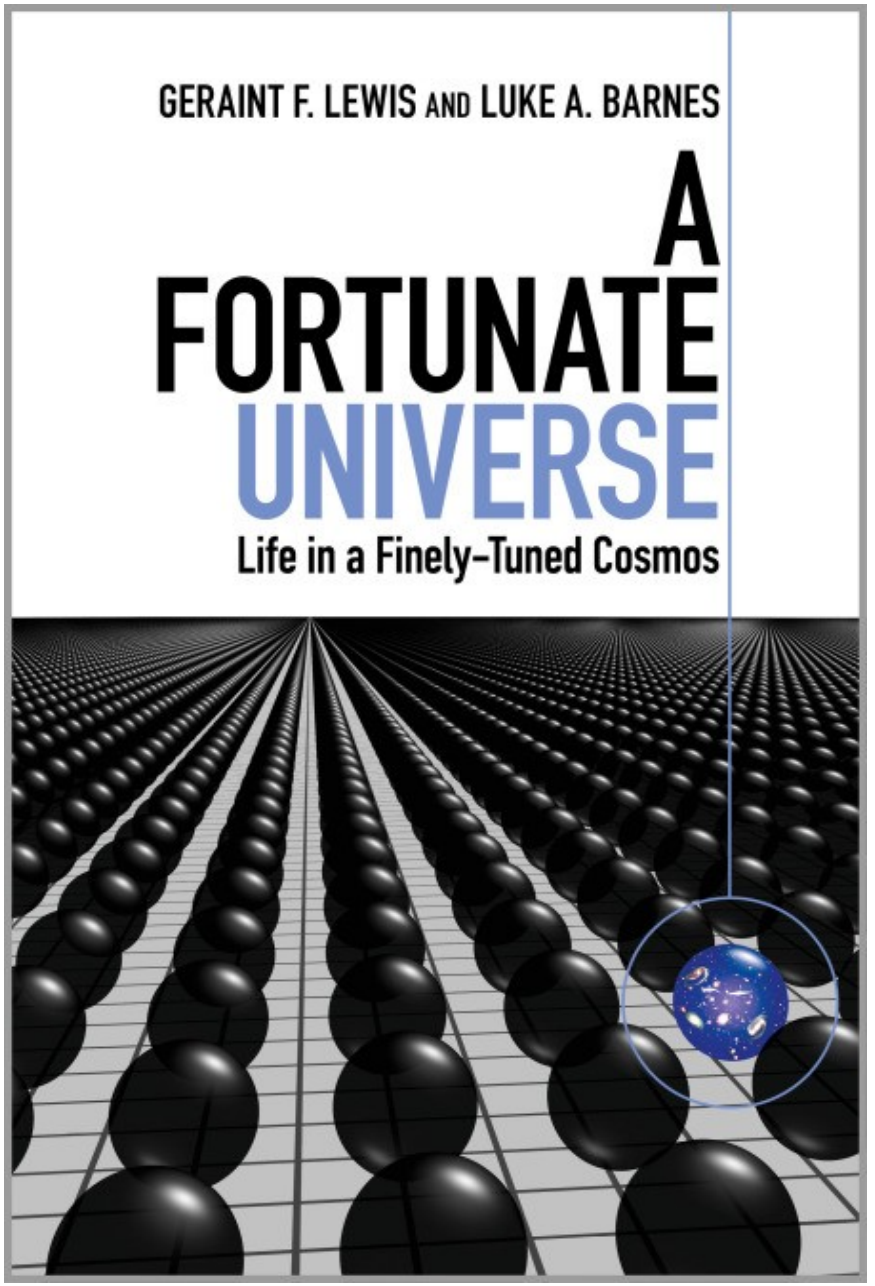
GOD

or

MULTIVERSE

(or both)

BOOK RECOMMENDATION



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