Title: Naturalness - How Religion Turned into Math

Date: Nov 14, 2017 11:00 AM

URL: http://pirsa.org/17110133

Abstract: Naturalness arguments have been extremely influential in the foundations of physics during the last decades. I explain why they are based on faulty reasoning.

Naturalness

How Religion Turned into Math

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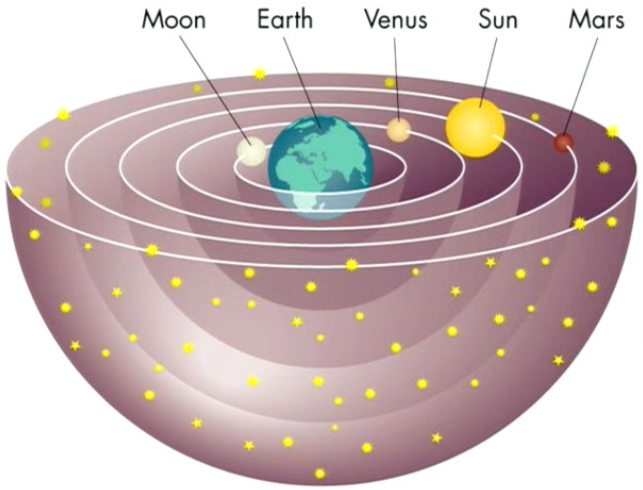
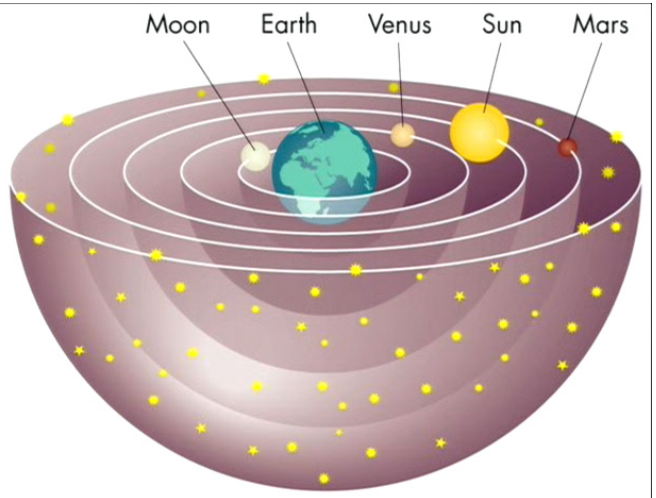
The Problem with Heliocentrism



- If the Earth moves, the stars should move.
- The parallax couldn't be observed.
- Astronomers concluded the stars are much farther away than the planets.
- They also, mistakenly, thought the stars would have to be gigantically large.
- This seemed "not natural."

The Problem with Heliocentrism



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Origins

"It is necessary to preserve in these matters some decent proportion, lest things reach out to infinity and the just symmetry of creatures and visible things concerning size and distance be abandoned: it is necessary to preserve this symmetry because God, the author of the universe, loves appropriate order, not confusion and disorder."

no arbitrary choices

~ Tycho Brahe

Dirac and the Large Numbers

"Any two of the very large dimensionless numbers occurring in Nature are connected by a simple mathematical relation, in which the coefficients are of the order of magnitude unity."

~ Paul Dirac

age of universe

$$\frac{T_0}{e^2/(m_e\, c^2)} \approx \frac{e^2}{G\, m_p m_e}$$

time it takes light to cross an atom

gravitational force between electron and proton

Naturalness (general)

- Dimensionless numbers shouldn't be much larger or smaller than 1.
- Unnatural numbers are "finetuned" and arbitrary and ugly.
- They "scream for explanation."
- Rationale: A finetuned number is unlikely.

Unlike simplicity, naturalness is not a requirement about the *number* of assumptions but about the *type* of assumptions.

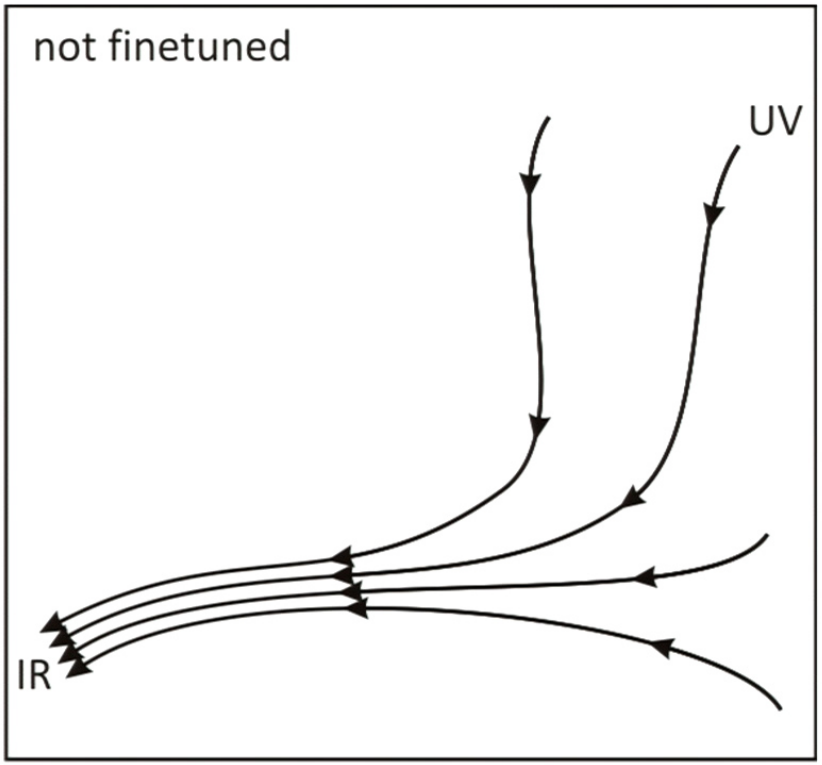
Naturalness (technical)

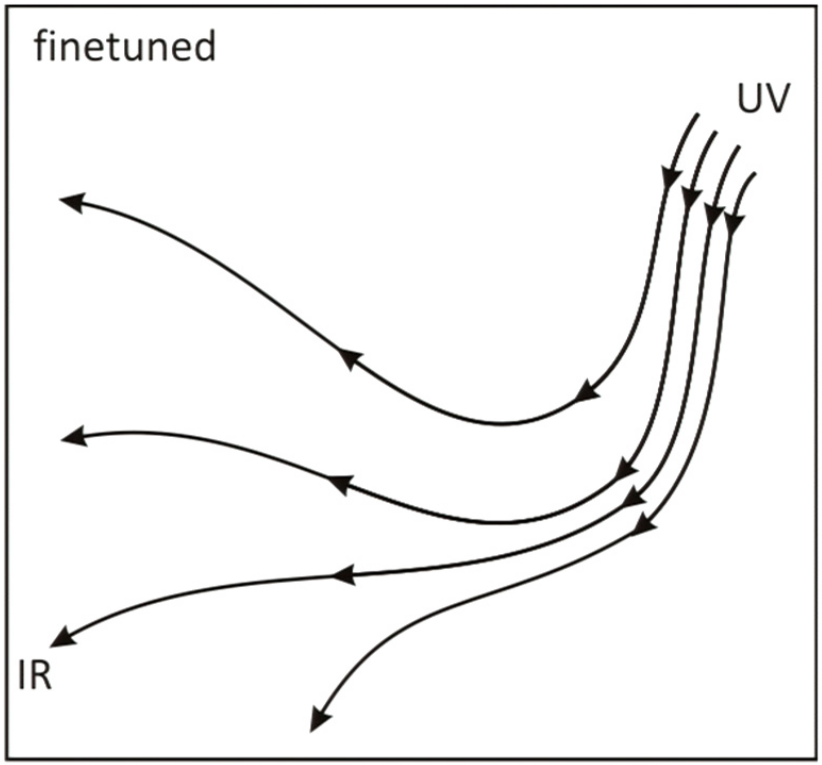
Applicable to quantum field theory only.

Parameters at low energy (IR) are not highly sensitive to the choice of (presumed more fundamental) parameters at high energies (UV).

This is often referred to as “the UV physics decouples.” But note that changing the parameters in the UV is not a physical process. It’s a “virtual” move in the landscape.

Theory Space





It's really not all that hard to see. Or is it?

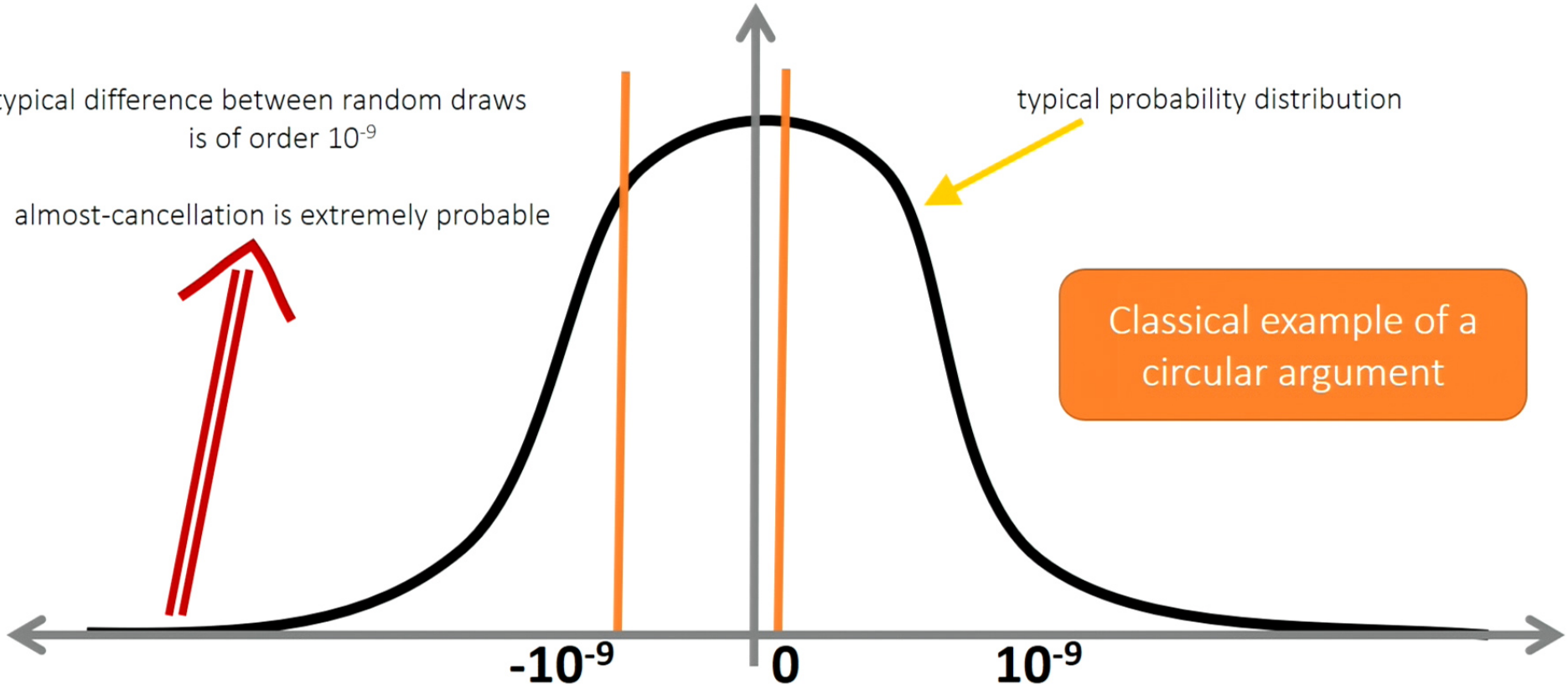
Probabilities are ill-defined without a probability distribution.

Duh. But ask them where the distribution comes from.

Most common strategies:

a) Deny.
   You need no probability distribution to lead a naturalness argument.
b) Distract.
   You can chose a probability distribution but it doesn't matter.
c) Defer.
   But everyone else does it too.

The Typical Argument Looks Like This



natural width of distribution is of order 10^{-9}

Naturalness at the LHC

- The Higgs is the only known (fundamental) scalar. Its mass receives a contribution from quantum effects.
- This contribution is assumed to be of the order of the cutoff scale, which is much larger than the observed mass.
- This could be cancelled by an almost but not exactly equal bare mass. But this almost-cancellation would be finetuned.
- Supersymmetry cancels the quantum contribution. When broken, it leaves a contribution at the susy-breaking scale, “explaining” the small mass.

Why does it matter?

Because naturalness arguments

1. made physicists believe in supersymmetry, which has been sought for since the 1990s. Unsuccessfully.
2. made physicists believe the LHC should see something besides the Higgs. That didn't happen.
3. made physicists believe that dark matter is made of WIMPs or axions. These have been sought for since the mid 1980s.
4. have been used for 30+ years to judge the promise of theories. This strategy produced nothing of value.

But Naturalness Works! (or so they say)

- Smallness of electron mass: new physics no later than ~ 70 MeV

  → positron (.5 MeV)

- Smallness of difference between mass of neutral and charged pions: new physics no later than ~ 850 MeV

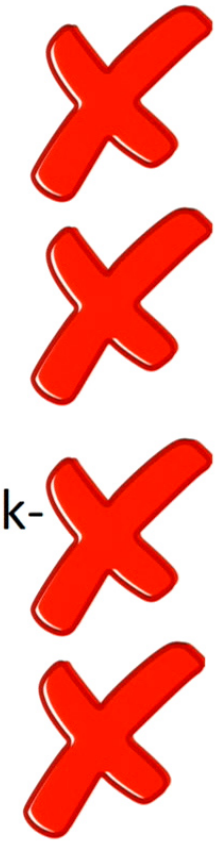
  → ρ-meson (770 MeV)

- Absence of flavor changing neutral currents: new physics no later than 2 GeV

  → charm quark (1.3 GeV)

But Naturalness Doesn't Work

- **Cosmological constant**: 30 orders of magnitude smaller than what the Planck-scale cutoff suggests.
- **Where's the axion?** To solve the strong CP problem, protect the smallness of θ parameter by the Pecci-Quinn U(1) symmetry. The particle associated to the field hasn't been found.
- **Higgs mass:** Is 15 orders of magnitude smaller than what the Planck-scale/GUT cutoff suggests. This means new physics no later than a TeV.
- **The WIMP miracle**: What about it?



More Problems with Naturalness

- All axioms are infinitely unlikely anyway. What's the big deal with a constant?
- Technical naturalness: If there's a TOE, what distribution are we even talking about?
- How much finetuning is required depends on how precisely you can measure the constant. Suppose the Higgs mass was 1.0966574443278047888733004 times the Planck mass. That would also be finetuned to 15+ digits.

More Numerology

U(1)xSU(2)xSU(3) doesn't look pretty enough

Couplings seem to unify with Supersymmetry!

(And with many other SM extensions)

Except that there's no evidence for this.

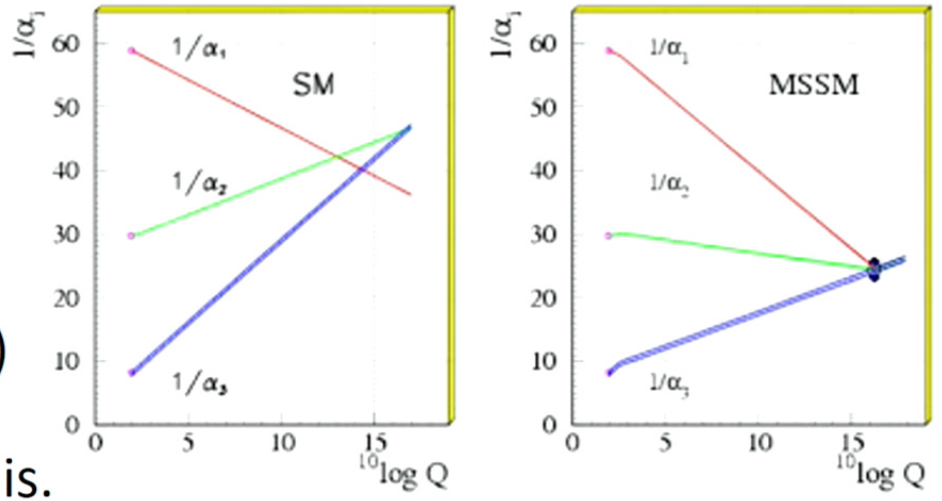
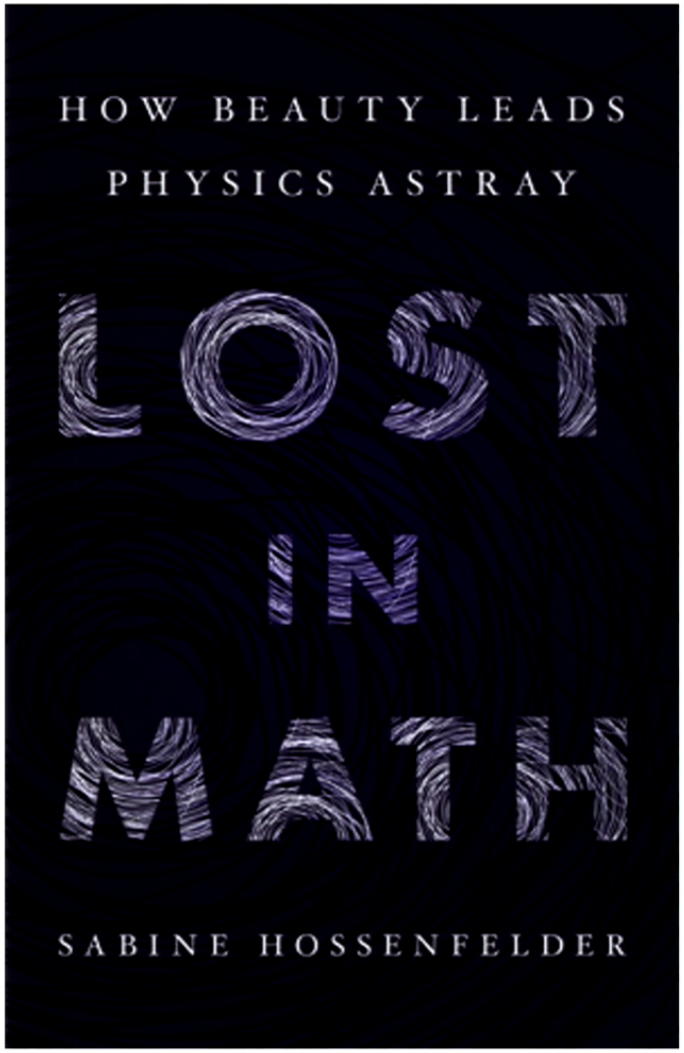


Figure: D.I. Kazakov, hep-ph/0012288

Conclusions

- Naturalness is not mathematically well-defined without a probability distribution.
- Defining the probability distribution turns the criterion ad absurdum.
- It's not enough to discard of naturalness – we have to understand what went wrong and why to avoid repeating our mistakes.

If intuition fails, more rigor is required, not less.



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