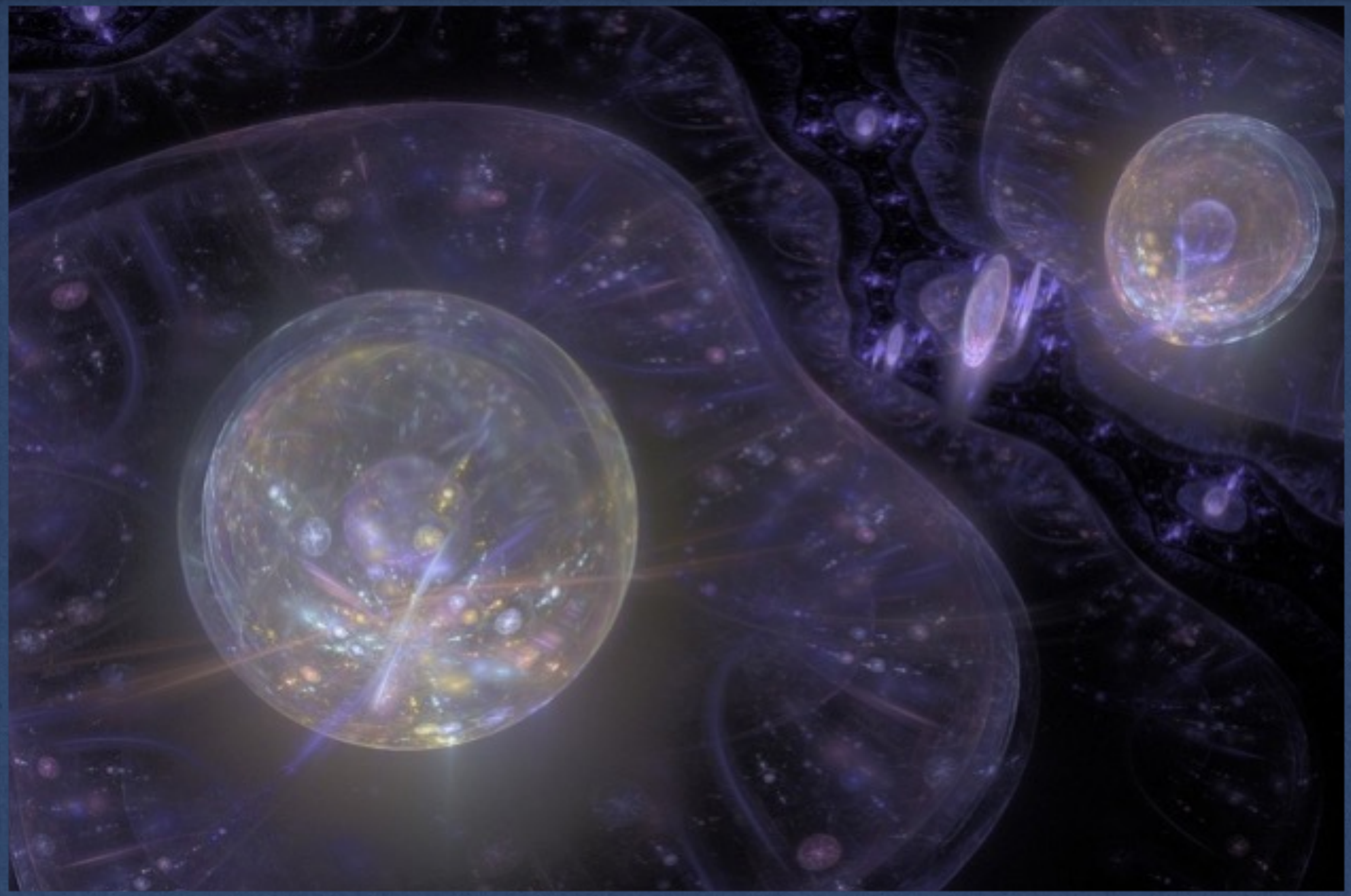
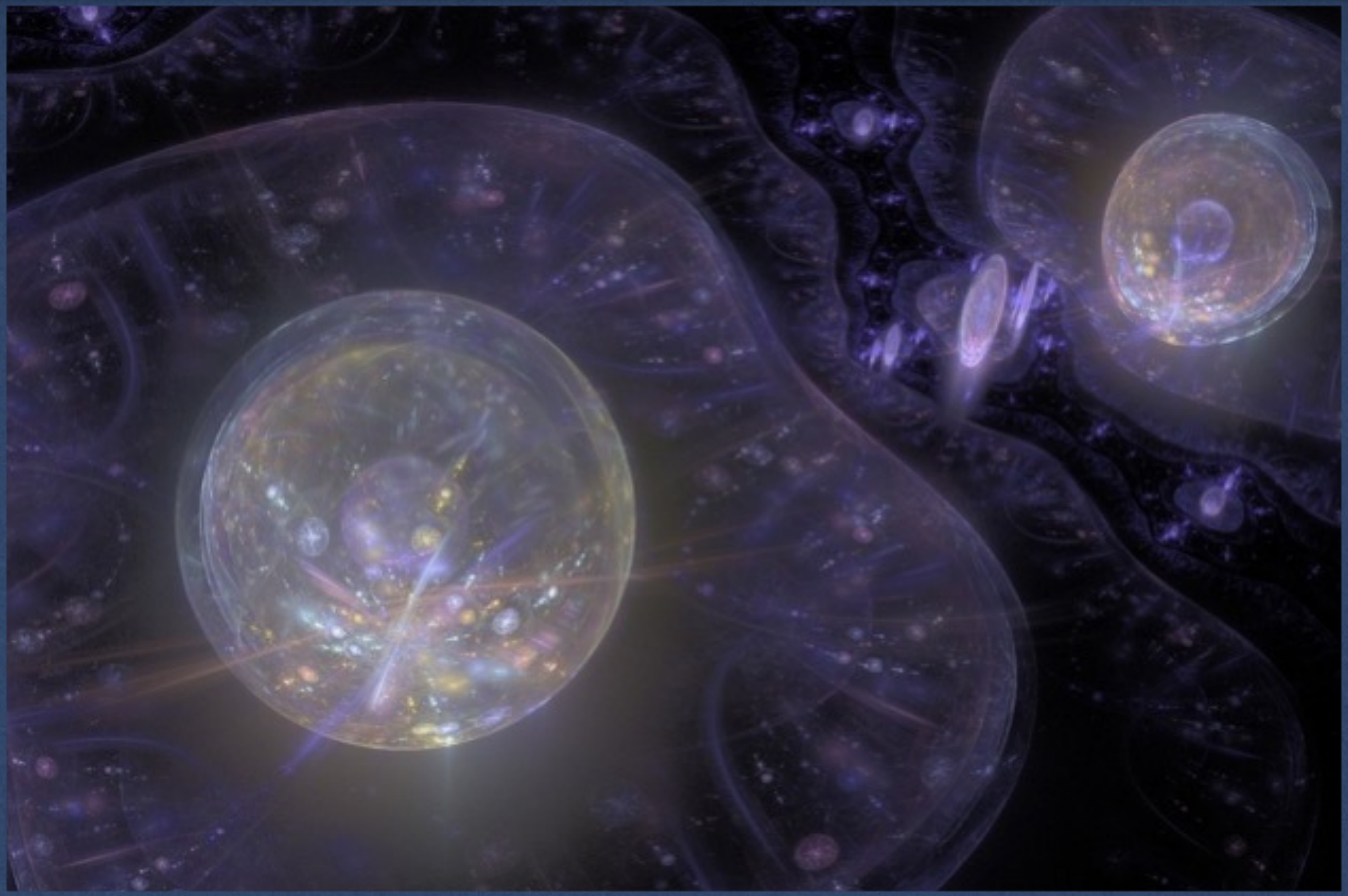


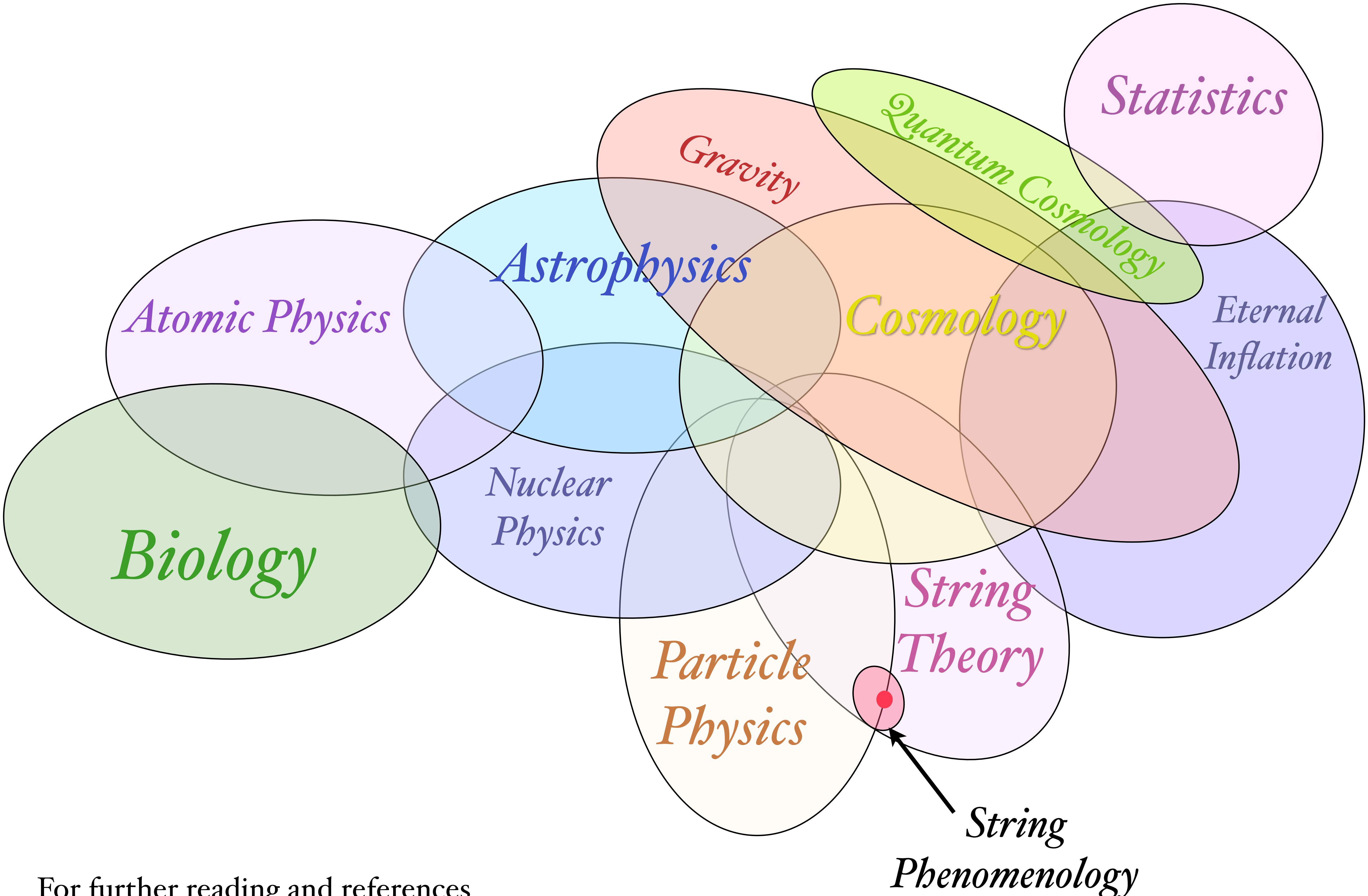
Particle Physics in the Multiverse

Bert Schellekens, Nikhef, Amsterdam

Tbilisi, 25-27 Sept. 2015



Particle Physics in the Multiverse



For further reading and references

Rev. Mod. Phys. 85 (2013) pp. 1491-1540

"What I'm really interested in is whether God could have made the world in a different way; that is, whether the necessity of logical simplicity leaves any freedom at all."

A. Einstein

I would like to state a theorem which at present can not be based upon anything more than a faith in the simplicity, i.e. intelligibility, of nature: There are no arbitrary constants that is to say, nature is so constituted that it is possible logically to lay down such strongly determined laws that within these laws only rationally completely determined constants occur (not constants, therefore, whose numerical value could be changed without destroying the theory)

Quoted by Andre Linde in arXiv:1402.0526

There is a most profound and beautiful question associated with the observed coupling constant.... It is a simple number that has been experimentally determined to be close to 1/137.03597. It has been a mystery ever since it was discovered more than fifty years ago, and all good theoretical physicists put this number up on their wall and worry about it.

R. Feynman

Some formulas for α

$$\alpha = 2^{-4}3^{-3}\pi$$

W. Heisenberg

$$\alpha = \frac{9}{16\pi^3}\sqrt[4]{\frac{\pi}{5!}}$$

A. Wyler

$$\alpha = \frac{\cos(\pi/137)}{137}\frac{\tan(\pi/(137\times 29))}{\pi/(137\times 29)}$$

F. Gilson

$$\frac{1}{\alpha} = \pi^{\pi e/2} + \sqrt{e^3 - 1}$$

???

H. Georgi,
Fourth workshop on Grand Unification, Philadelphia,1983

The physics of grand unification can provide a partial answer to some of the questions left unanswered at lower scales by correlating the properties of quarks and leptons. But the fundamental problem still remains: What makes the gauge structure and fermion content of the world special and unique?

This puzzle, which I will call the "uniqueness" puzzle, simply cannot be answered in the context of conventional quantum field theory (QFT). Conventional QFT does not single out any particular gauge structure. Thus we might expect the uniqueness question to be answered at some large scale M_B where conventional quantum field theory breaks down.

Expectations for String Theory

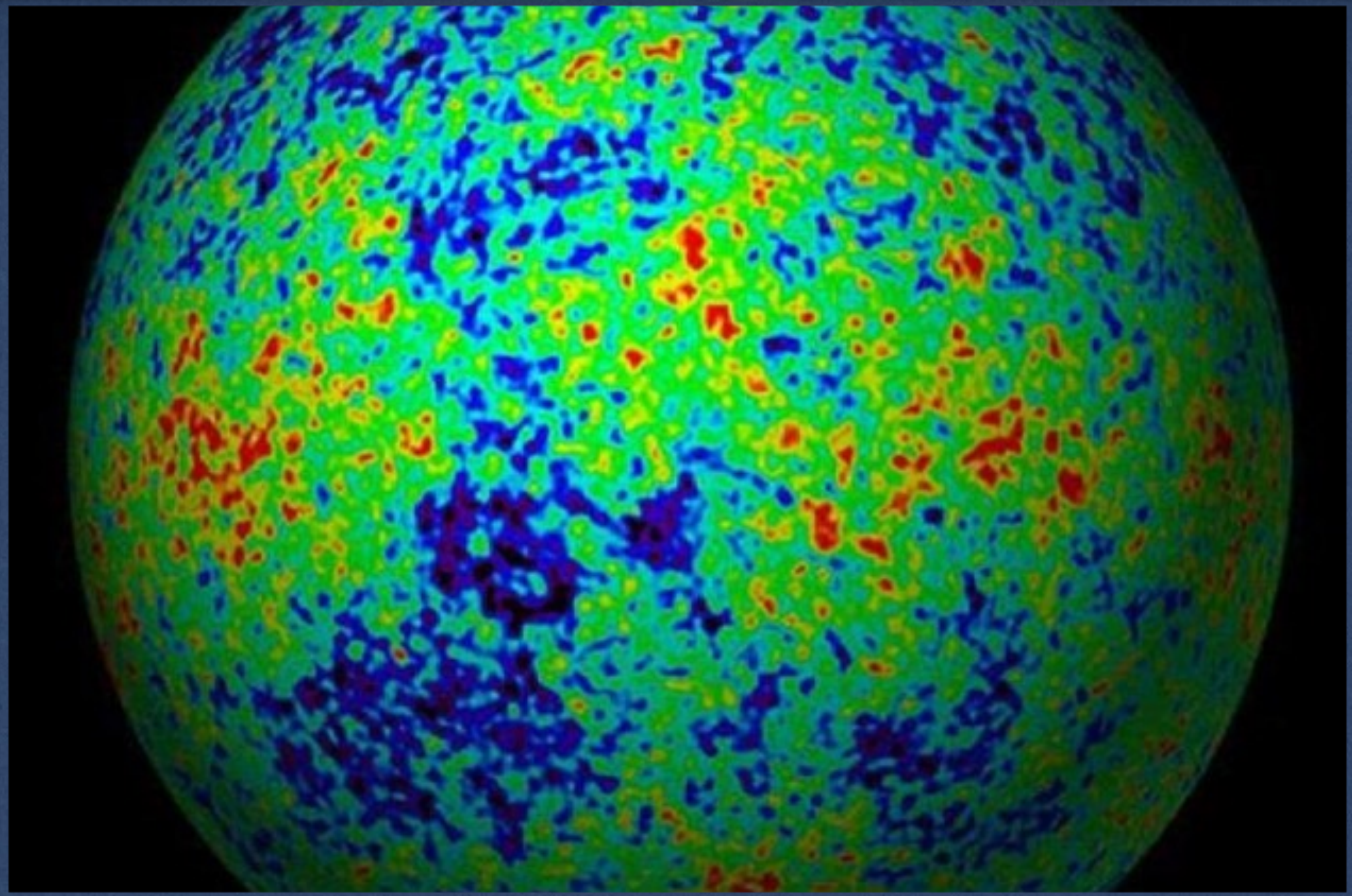
"The hope is that the constraints imposed on such theories solely by the need for mathematical consistency are so strong that they essentially determine a single possible theory uniquely, and that by working out the consequences of the theory in detail one might eventually be able to show that there must be particles with precisely the masses, interactions, and so on, of the known elementary particles: in other words, that the world we live in is the only possible one."

From "The Problems of Physics" by Antony Legget (1987)

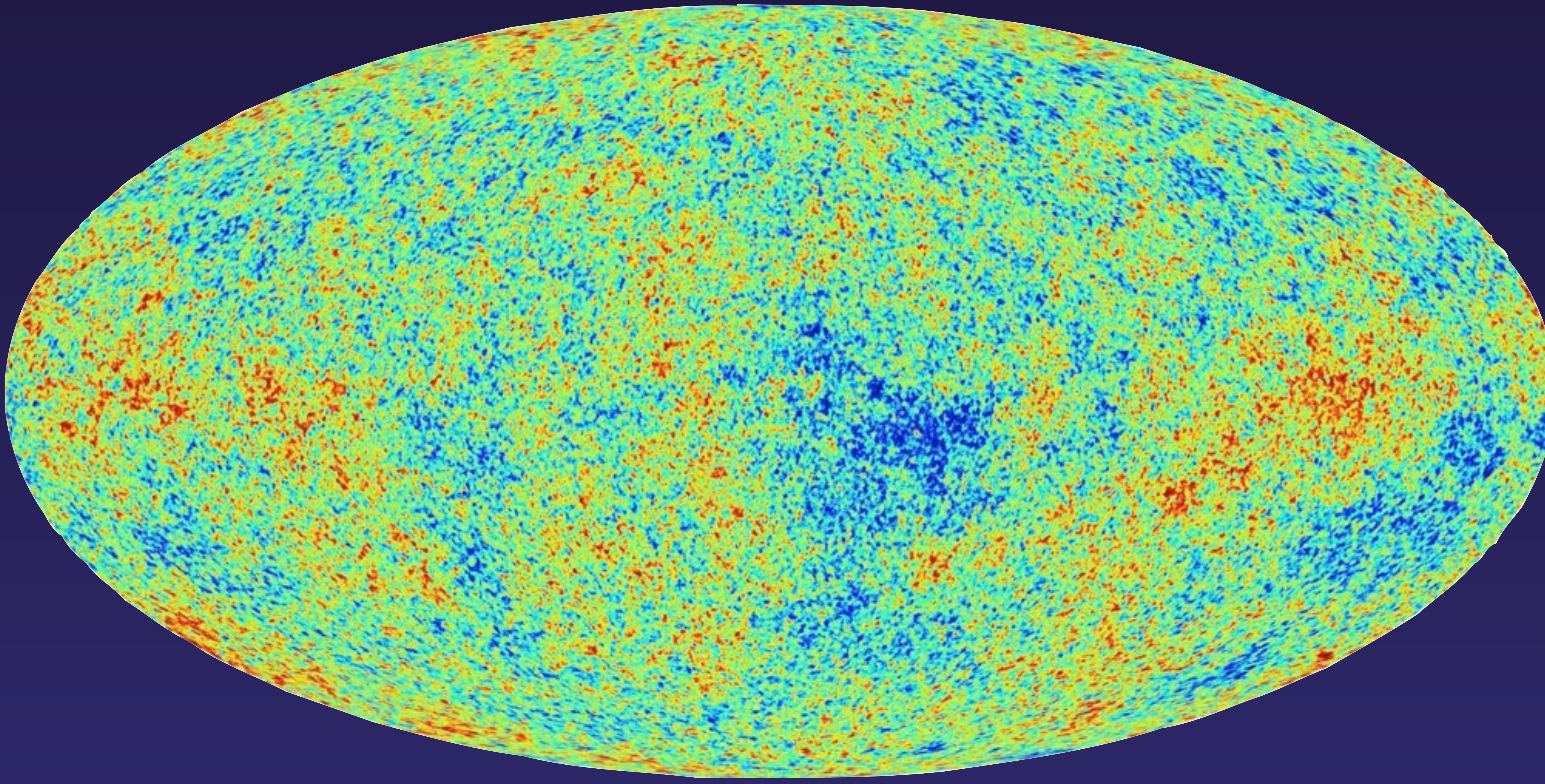
Paul Steinhardt
Albert Einstein Professor in Science, Departments of Physics and Astrophysical Sciences, Princeton University

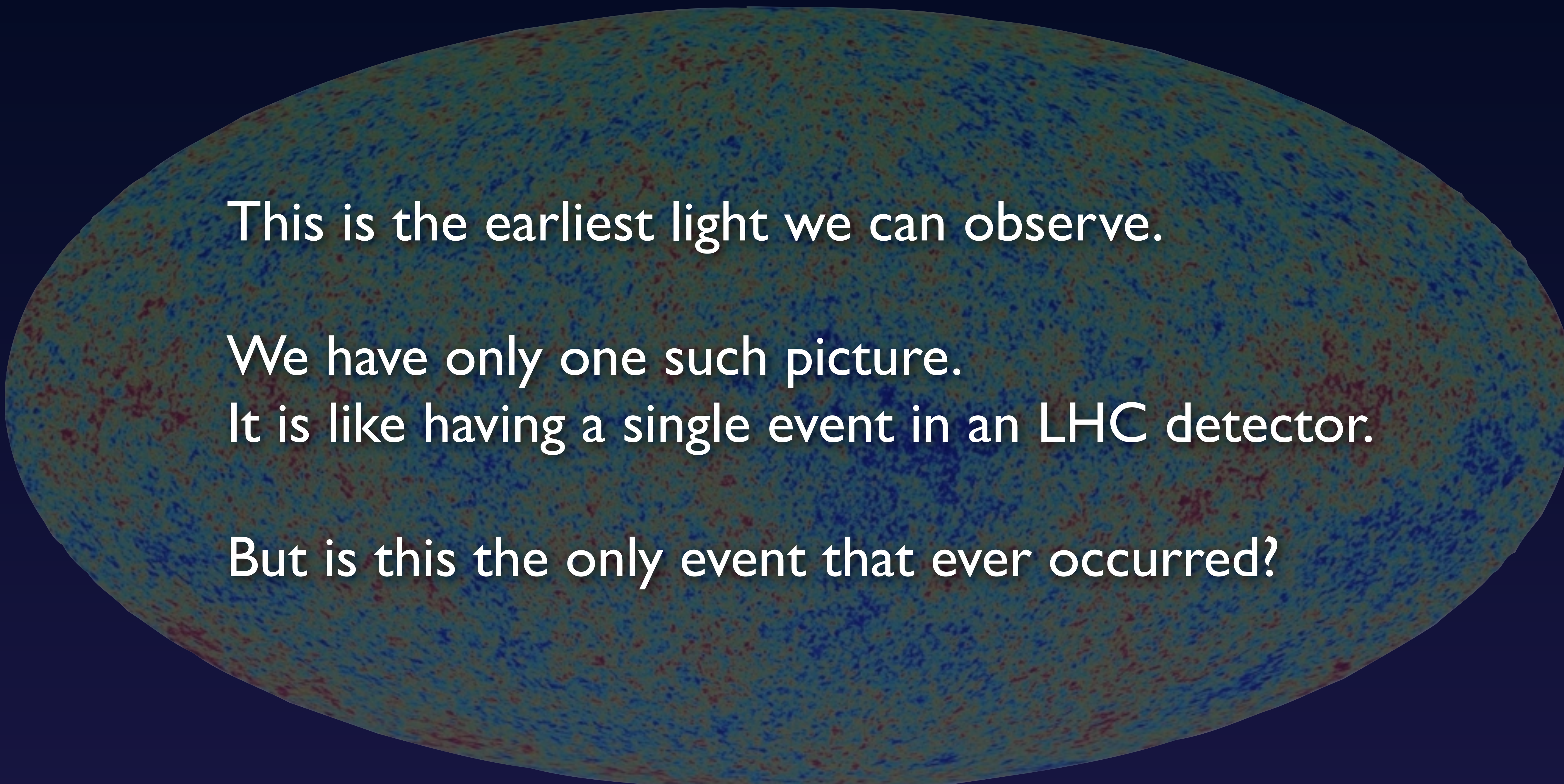
"String theory was supposed to explain why elementary particles could only have the precise masses and forces that they do. After more than 30 years investment in each of these ideas, theorists have found that they are not able to achieve these ambitious goals"

2014



I. The Multiverse

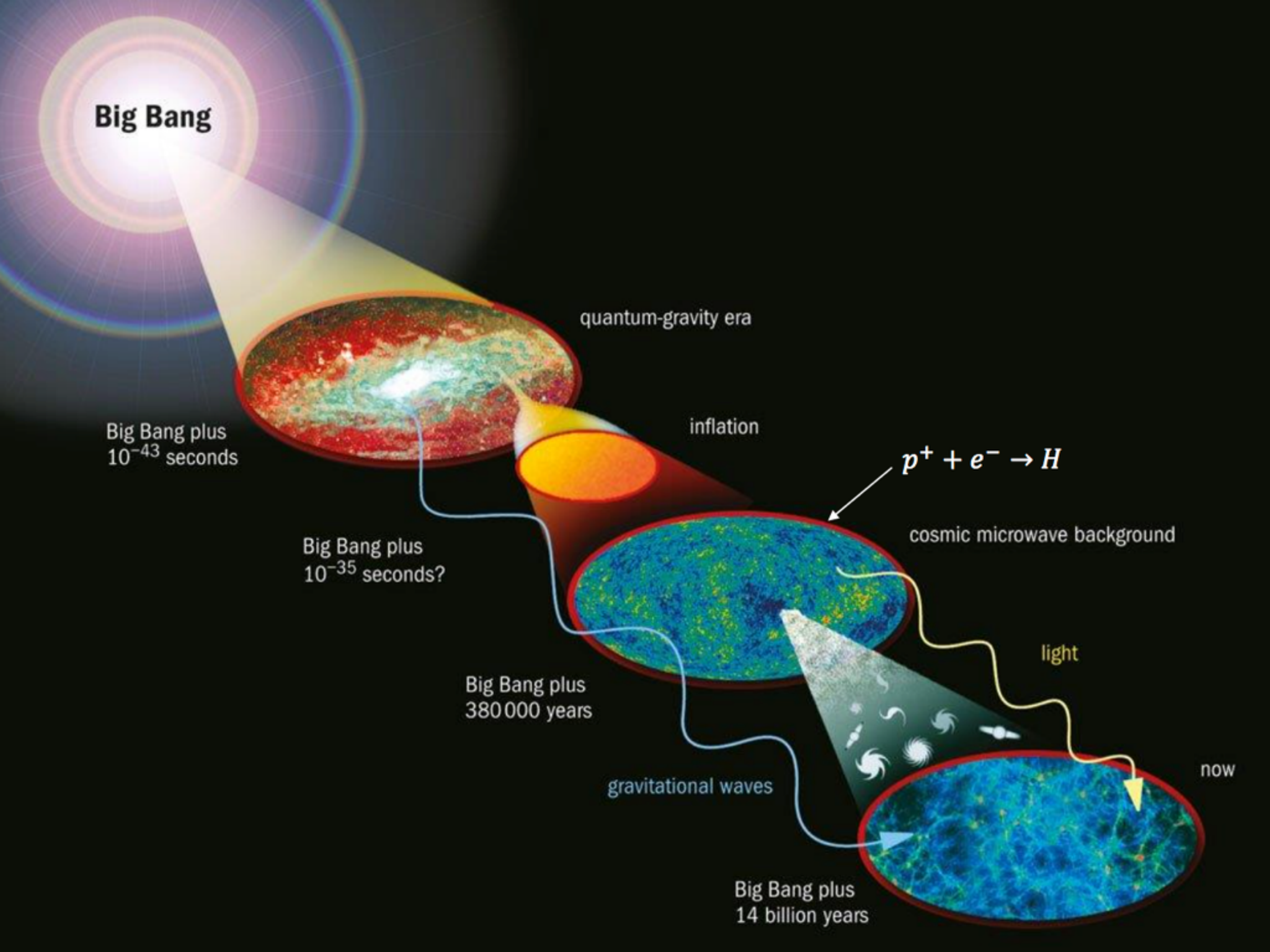




This is the earliest light we can observe.

We have only one such picture.
It is like having a single event in an LHC detector.

But is this the only event that ever occurred?



Big Bang
quantum-gravity era
Big Bang plus
10^{-43} seconds
inflation
$p^+ + e^- \rightarrow H$
cosmic microwave background
Big Bang plus
10^{-35} seconds?
light
Big Bang plus
380 000 years
gravitational waves
now
Big Bang plus
14 billion years

Common sense suggests that it is not.

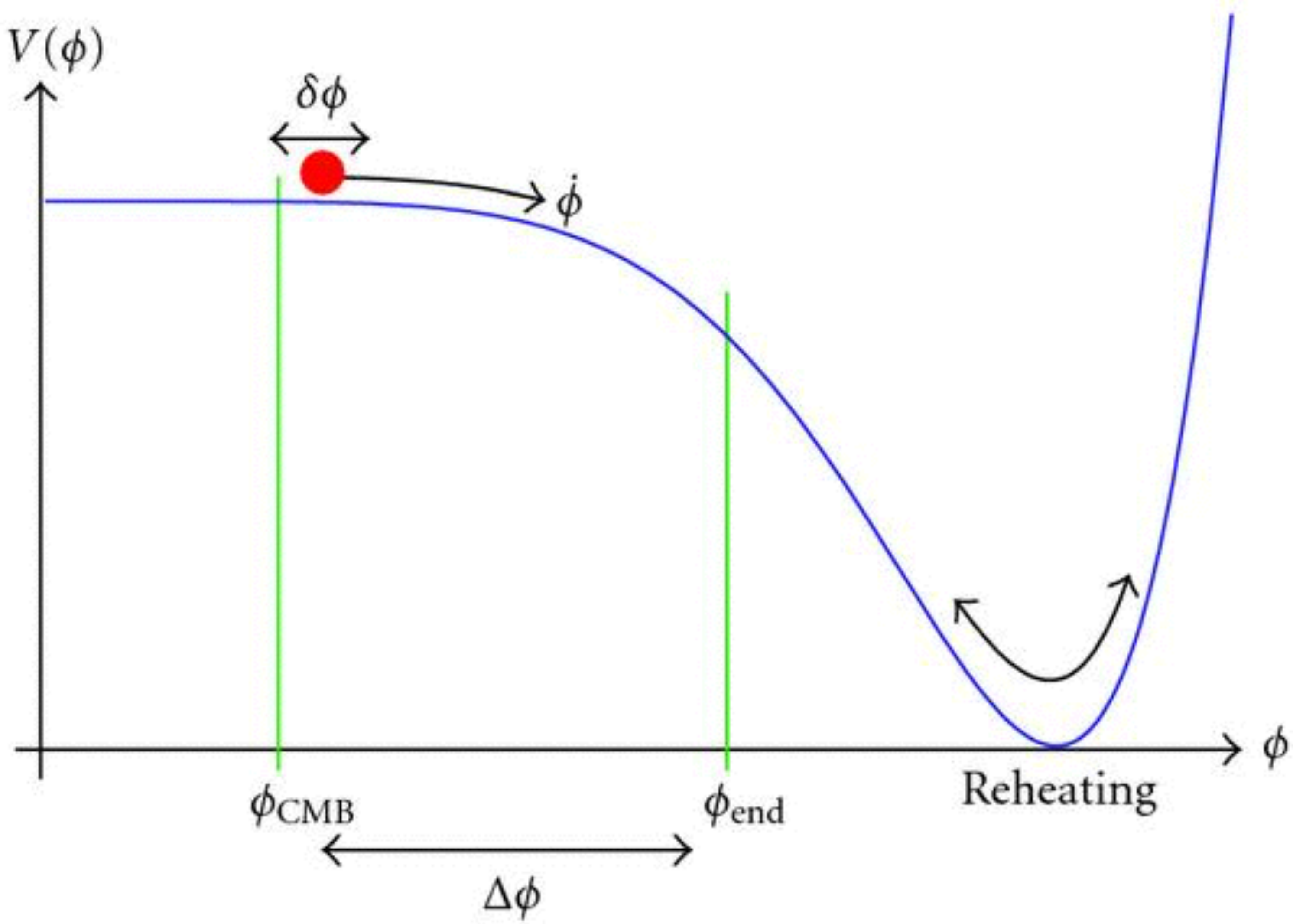
Is all we can see all there is?

Furthermore the theory that correctly describes the CMB fluctuations, inflation, predicts that there is an infinity of such "events".

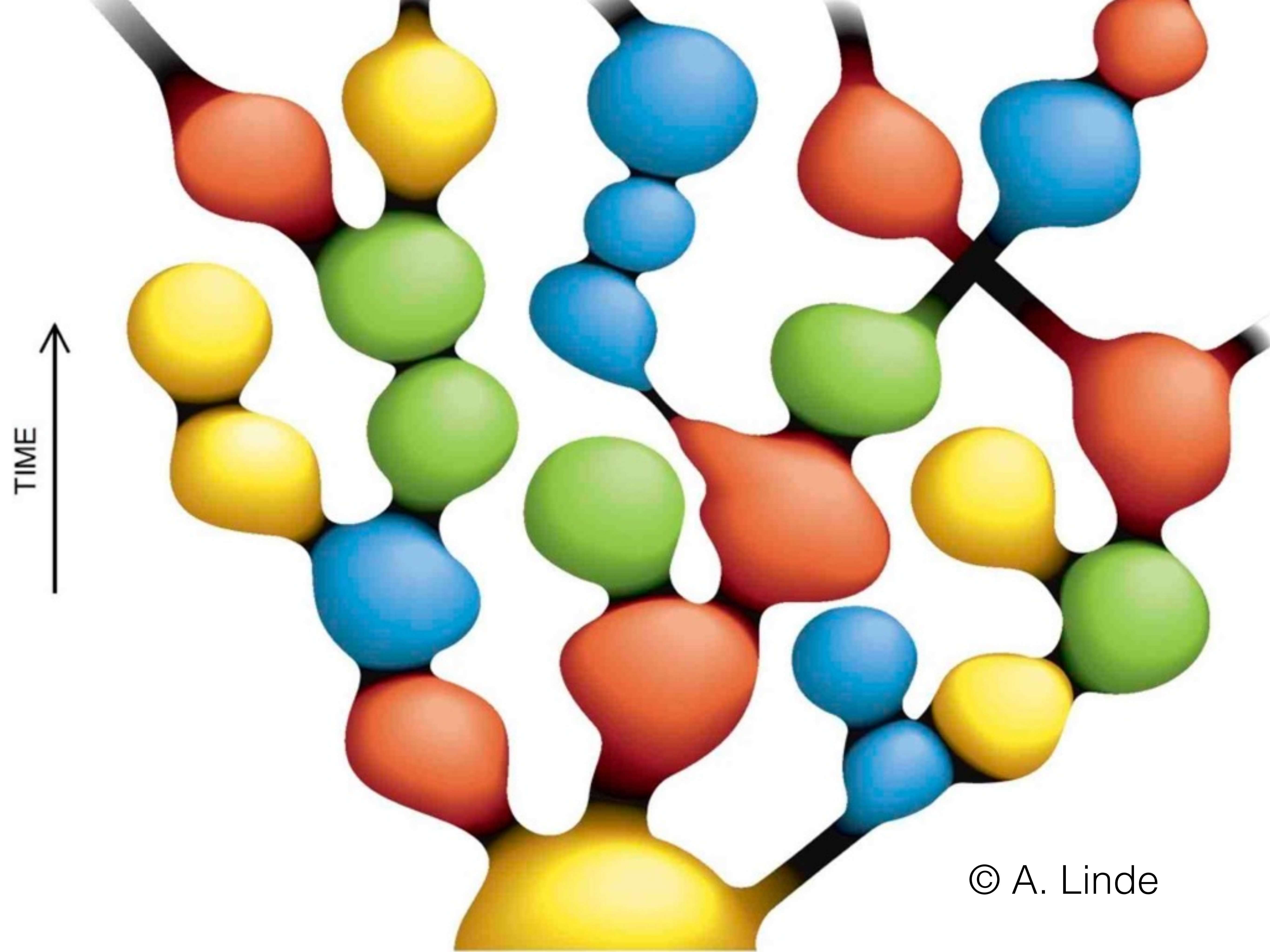
"If the universe contains at least one inflationary domain of a sufficiently large size, it begins unceasingly producing new inflationary domains."

Andrei Linde (1994)

Eternal Inflation

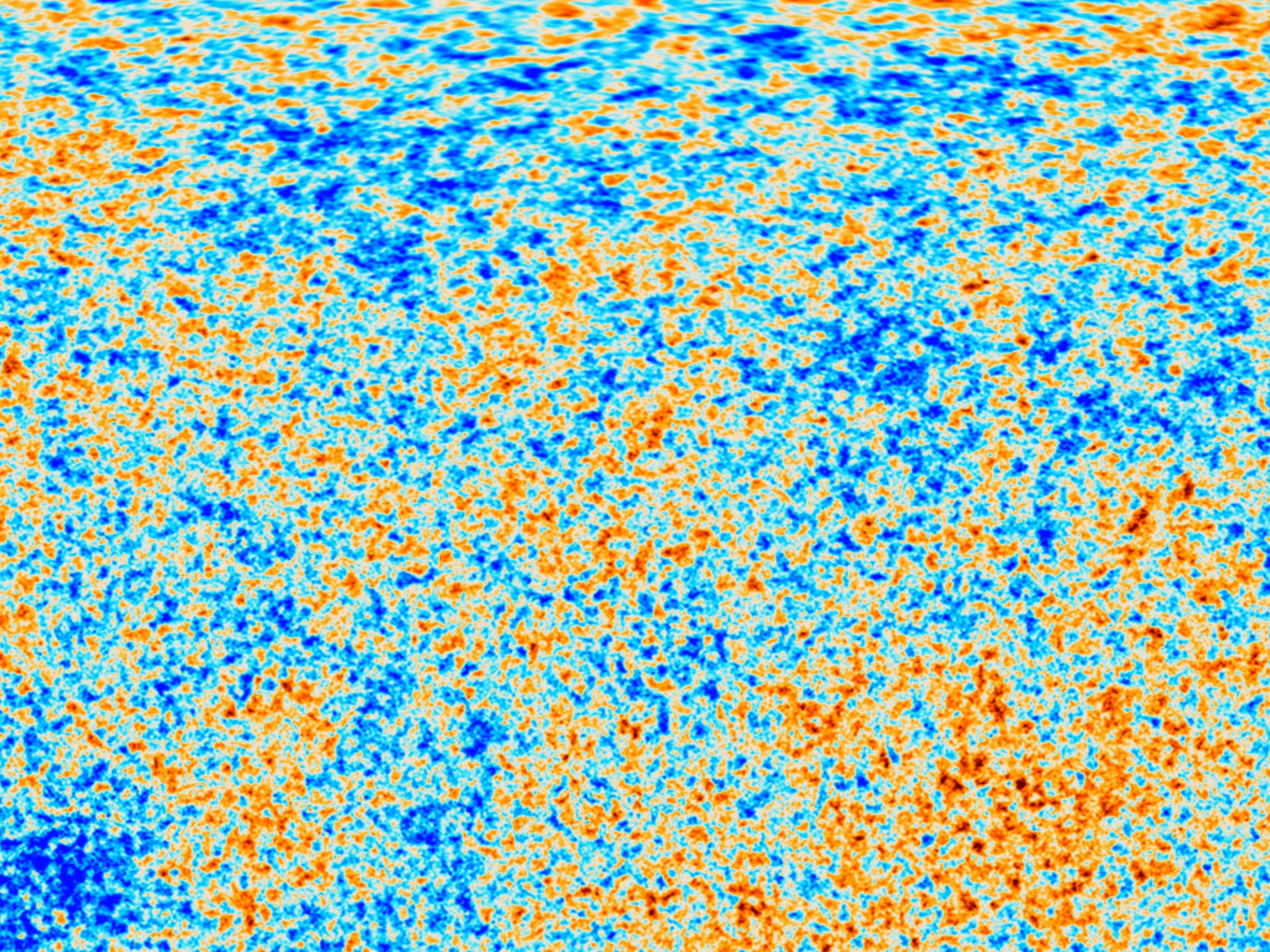


© D. Baumann


TIME
© A. Linde

So what would these other universe look like?
(and is there anyone to look at them?)

At the very least the CMB fluctuations would be different.



But is that all that changes?

Could the laws of physics themselves be different?

If so, what are the allowed changes?

Consider the pillars of modern physics:

Quantum Mechanics:

Cannot be modified in any way we know

General Relativity:

We can change space-time dimension, cosmological constant ("vacuum energy"), curvature.

The Standard Model:

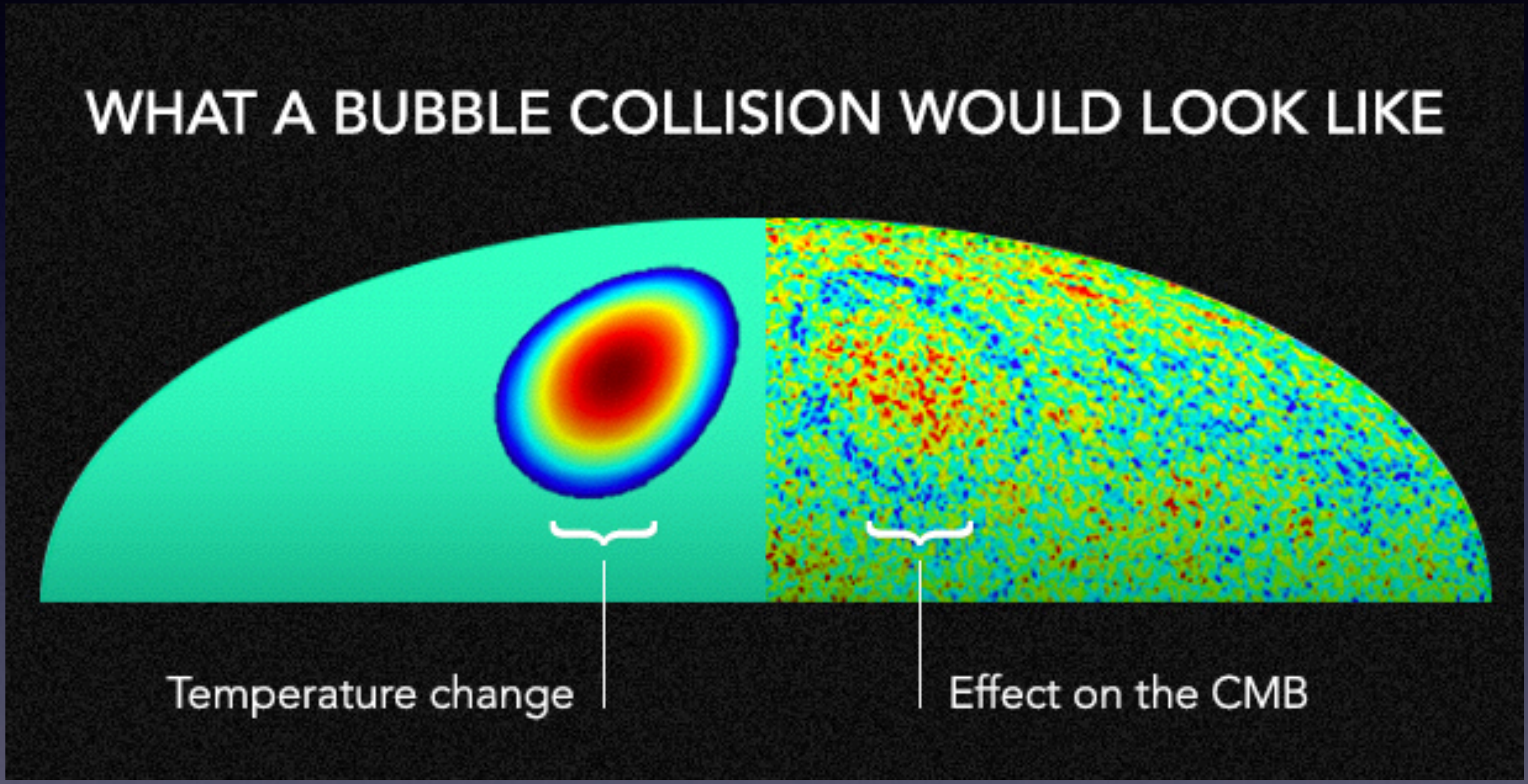
Many options for change: the gauge group, the particle representations (charges), and all continuous parameters.

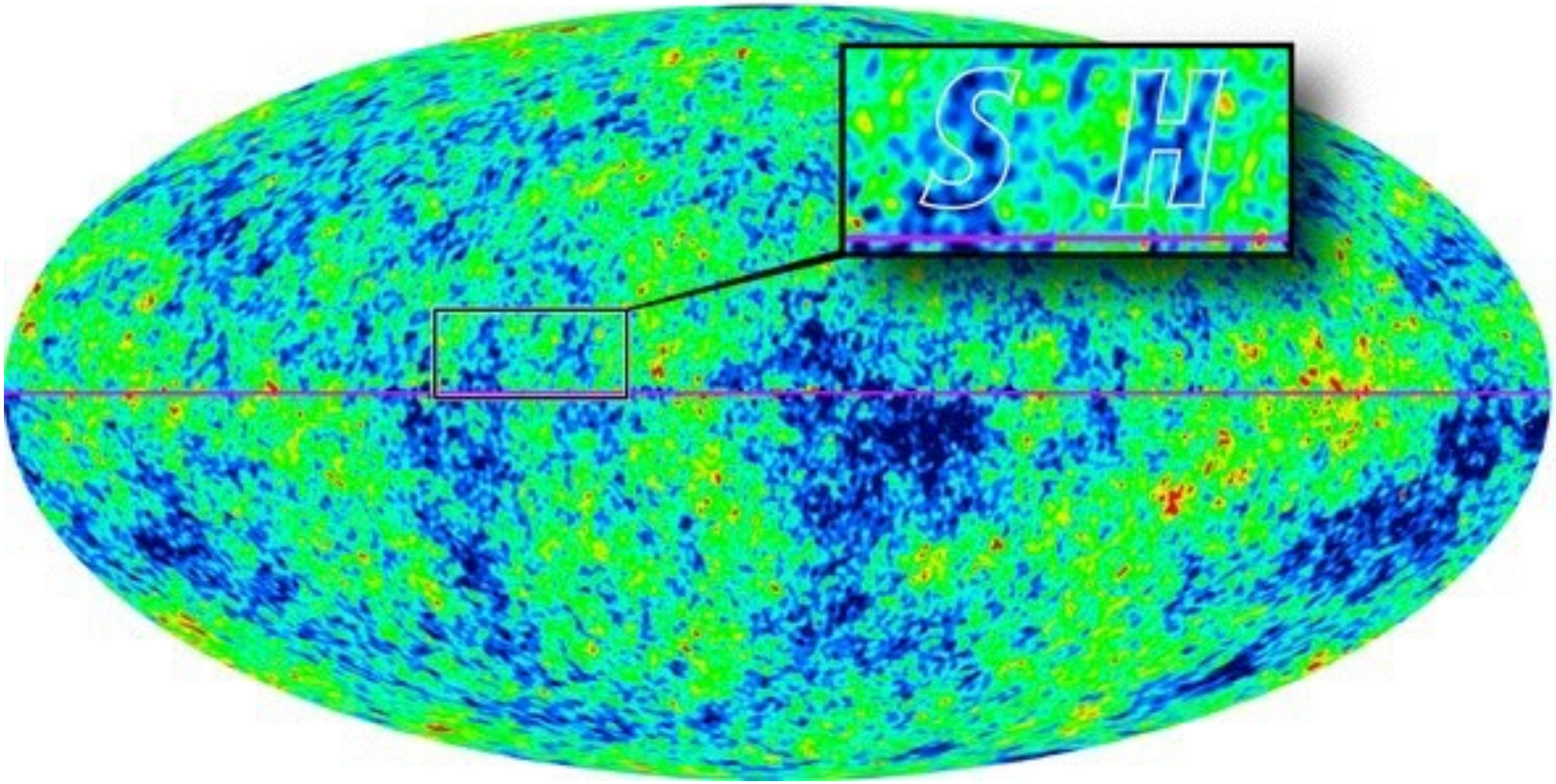
But who cares about alternatives?

Phenomenological objection:
Shouldn't we be satisfied in understanding just our own universe?

Philosophical objection:
We (probably) cannot see these other universes.
(perhaps as signals of "bubble collisions" in the CMB.
Or perhaps as information encoded in the CMB radiation?)

So this is not science…?


WHAT A BUBBLE COLLISION WOULD LOOK LIKE
Temperature change
Effect on the CMB


S H

The answer to the phenomenological objection is that most of Standard Model phenomenology is aimed at the “why” questions.

Why $SU(3)\times SU(2)\times U(1)$, why quarks and leptons, why three families, why these strange masses, why such large hierarchies?

Surely, if these could be different in other universes, this is relevant to the answer.

Suppose the number of families could be different.
Then clearly we can never derive this number.

Then just the following options are left:

- In our universe, the number 3 came out purely by chance.
- In the full ensemble of universes, 3 is statistically favored.
  Very tricky: all multiplicities are infinite, so it is not immediately obvious how to compare them.
  This is know as the "multiverse measure problem".
  Despite a lot of work and some progress, there is no generally accepted solution yet.
- Any number other than 3 cannot be observed, because life cannot exist unless there are 3 families.
  This is (a form of) the anthropic principle.

In this case there is no known anthropic argument.

A guess might be:
1. Three families are needed for CP-violation in the CKM matrix,
2. CP-violation is needed for baryogenesis
3. A net number of baryons is crucial for life.

But:

- This argument would also allow four families.
- The CP-phase in the CKM matrix is not sufficient.
- There are probably other CP violating phases in the couplings of Majorana neutrinos.
  They can lead to baryogenesis via leptogenesis.
  This requires only two families.

The philosophical objection

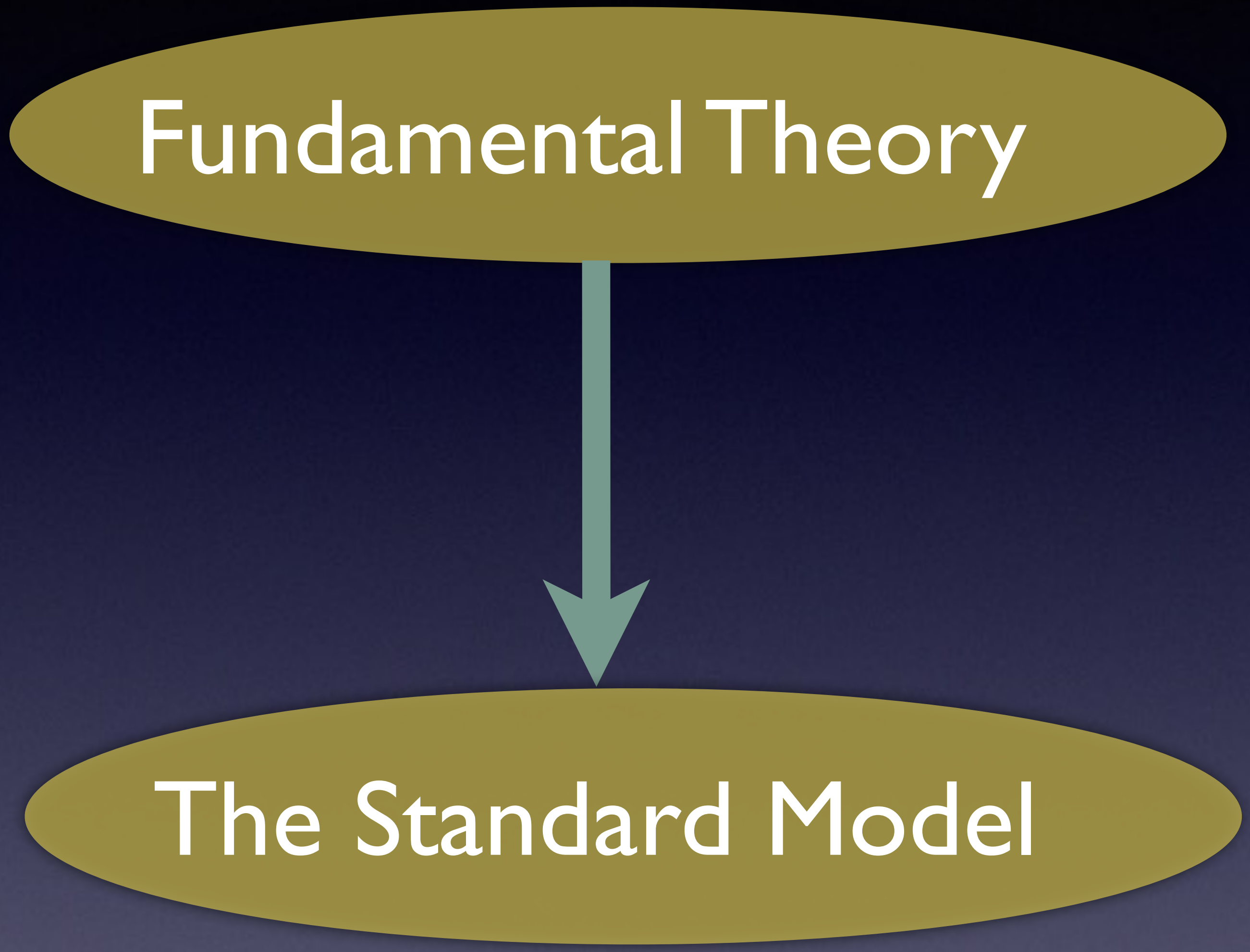
Let us assume the worst-case scenario:
Other universes are unobservable in principle.

Then it is still possible that we will find a theory that *demonstrably* contains our Standard Model, and contains many other gauge theories as well.

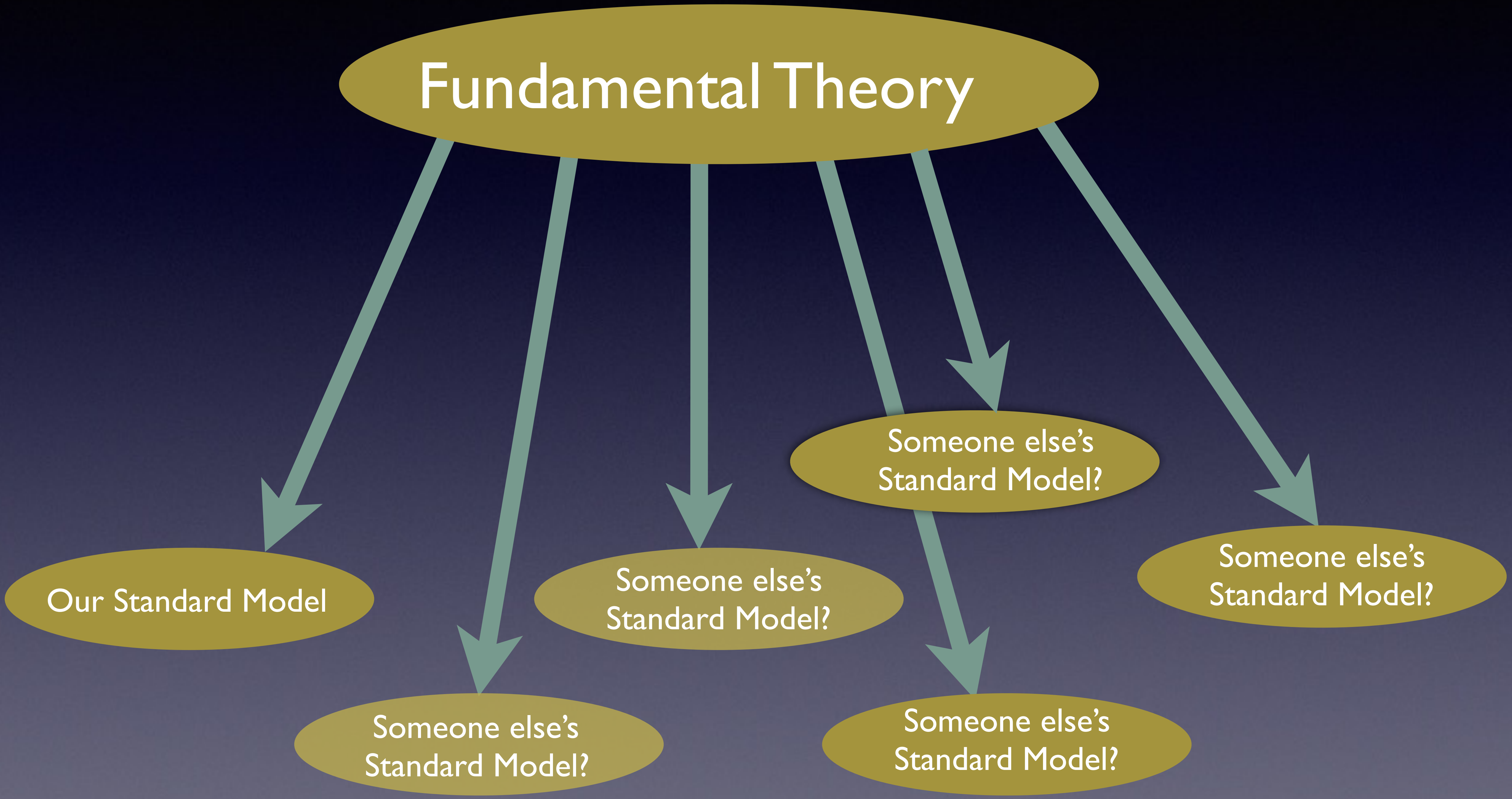
We could confirm that theory either

- By correct predictions in our own Universe
- By deriving it from a principle of Nature

Instead of:



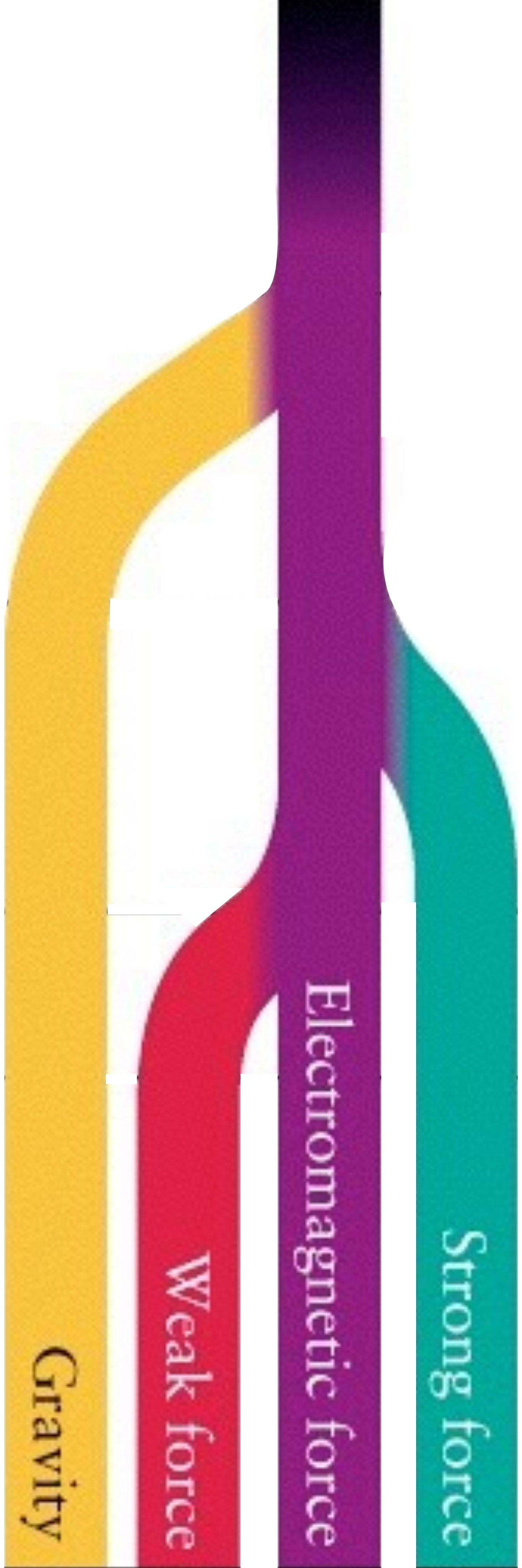
We would have:



S. Weinberg, in "Living in the Multiverse" (2005)

In the Austin airport on the way to this meeting I noticed for sale the October issue of a magazine called *Astronomy*, having on the cover the headline "Why You Live in Multiple Universes." Inside I found a report of a discussion at a conference at Stanford, at which Martin Rees said that he was sufficiently confident about the multiverse to bet his dog's life on it, while Andrei Linde said he would bet his own life. As for me, I have just enough confidence about the multiverse to bet the lives of both Andrei Linde *and* Martin Rees's dog.

II. Unification



String Theory?

GUT?

Electro-weak

Grand Unification

Gauge group $SU(3) \times SU(2) \times U(1)$

One family: $(3, 2, \frac{1}{6}) + (3^*, 1, \frac{1}{3}) + (3^*, 1, -\frac{2}{3}) + (1, 2, -\frac{1}{2}) + (1, 1, 1) \ +(1, 0, 0)$

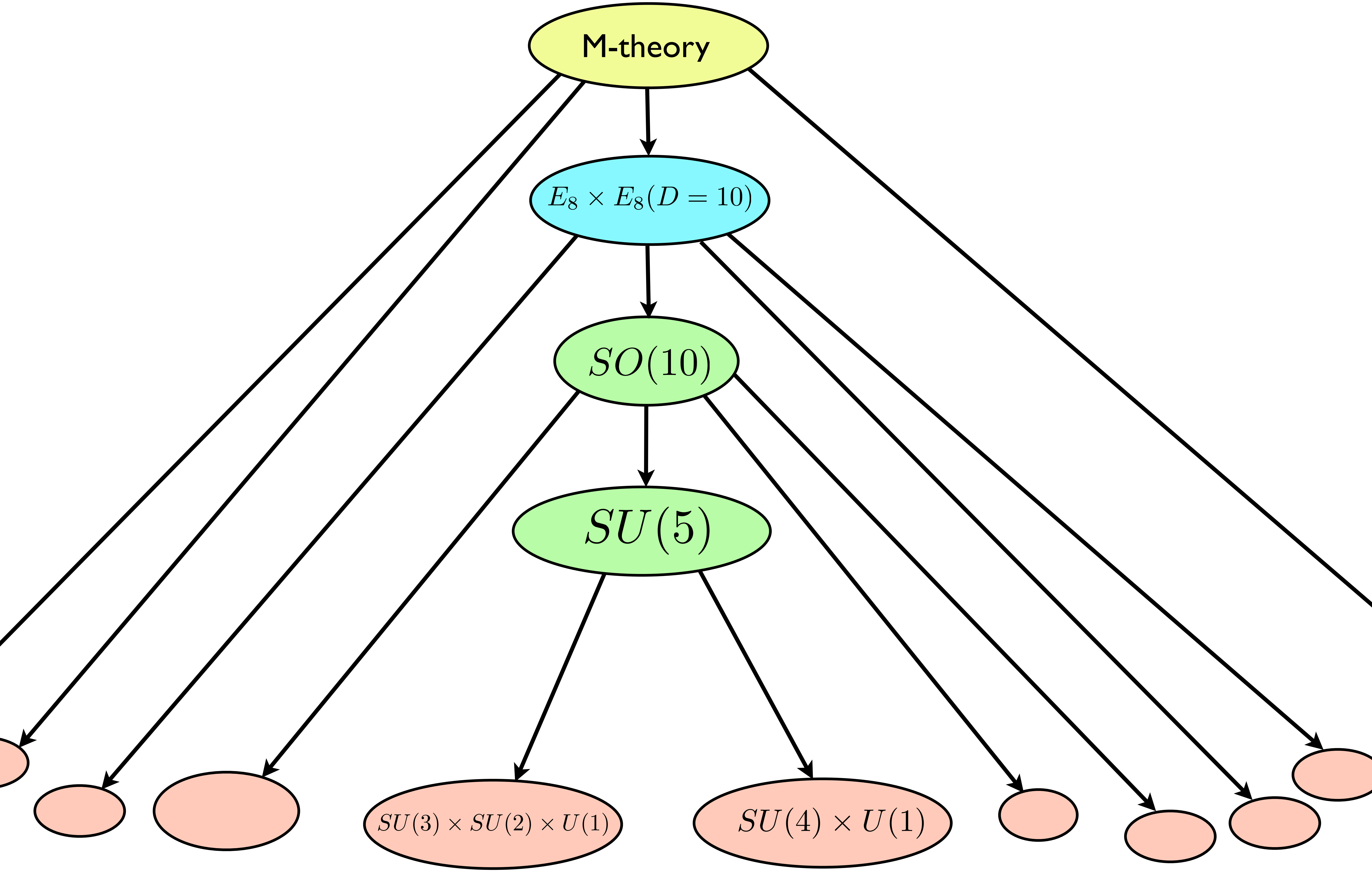
Higgs $+(1, 2, -\frac{1}{2})$

Structure looks arbitrary.

The most popular explanation is Grand Unified Theories

One family: $(5^*) + (10) + (1)$ of $SU(5)$

(16) of $SO(10)$


M-theory
$E_8 \times E_8 (D = 10)$
$SO(10)$
$SU(5)$
$SU(3) \times SU(2) \times U(1)$
$SU(4) \times U(1)$

String Theory

The 1986 String Revolution

An explosion of papers and vacua:

Candelas,Horowitz, Strominger, Witten
Dixon, Vafa, Harvey, Witten
……………
Strominger
Kawai, Tye, Lewellen
Lerche, Lüst, Schellekens
Antoniadis, Bachas, Kounnas
Ibanez, Nilles, Quevedo
Narain, Sarmadi, Vafa
……………

Calabi-Yau manifolds
Orbifolds

A. Strominger
"Superstrings with Torsion", 1986

All predictive power seems to have been lost.

All of this points to the overwhelming need to find a dynamical principle for determining the ground state, which now appears more imperative than ever.

Lerche, Lüst, Schellekens
"Chiral, Four-dimensional Heterotic Strings From Self-Dual Lattices", 1986

. . . $(\Gamma_{22} \times D_3 \times (D_7)^9)_L$, a Euclidean lattice of dimension 88. A lower limit on the total number of such lattices is provided by the Siegel mass formula [21] [22]

this number is of order 10^{1500} !

It seems that not much is left of the once celebrated uniqueness of string theory.

In four dimensions things are far more complicated. In the worst possible case we have a lattice $\Gamma_{22;14} = (\Gamma_{22})_L \times (D_5 \times (D_1)^9)_R$, which can be mapped to $(\Gamma_{22} \times D_3 \times (D_7)^9)_L$, a euclidean lattice of dimension 88. A lower limit on the total number of such lattices is provided by the Siegel mass formula [21] [22]

$$\sum_{\Lambda} g(\Lambda)^{-1} = (8k)^{-1} B_{4k} \prod_{j=1}^{4k-1} (4j)^{-1} B_{2j}, \tag{5.1}$$

where the sum is over all even self-dual lattices of dimension $8k$, and $g(\Lambda)$ is the order of the automorphism group of Λ. Because $g(\Lambda) \geqslant 1$ the right hand side is a lower limit of the number of lattices (B_{2j} are the Bernoulli numbers). For $k = 11$ this number is of order 10^{1500}!

* A more reasonable but less rigorous estimate can be made by observing that the 88-dimensional lattice has (at most) 32 factors, so that combinatorically their classification should be similar to the classification of even self-dual lattices of dimension 32 with D_1 lattices as building blocks. On the basis of such an estimate one would still expect a very large number of solutions.

The actual number is

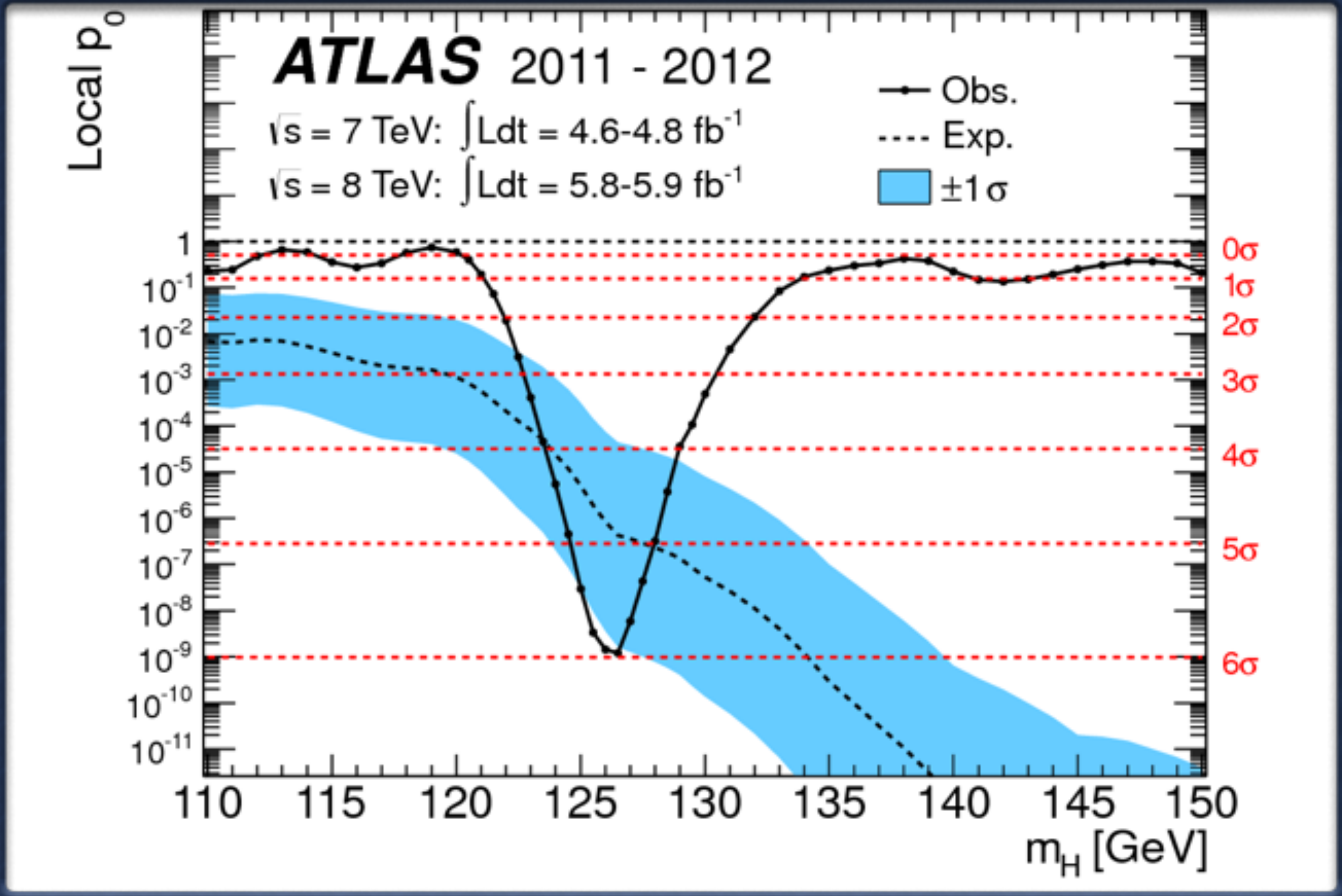
$$\frac{\begin{array}{l}28828057420469634065999536535536155842065086922080853538984439551199133819000558760947052474565851434674120967796766355895 1\\577295279008725702279578858099556070642887164428345636181703539362916493828664832262798280879533906856341368554779410767322\\917610720983055163706476135037818392025217235782950745217191830223209495429766903985820510780966889267834337175858276142160\\745242015826356829483560681248200858959990674335933942905918281521769790287262990709457379764792913635359138351362493098578\\497575381436329442145995280031770656323805559499189436018271763077144823089799090573474453384288020033959243770070092574247\\932583489907794066646937140055364569423858604635037218917200432131436957638870102597239829134337988638890436715564645907806\\576250529048337296031946159664539308058934641787425405406480737417294441892751775118523427456157975096479184243428355881302\\764065549143448157244744678697675901739379699752662922037818713124994059166633172192672544495952828337015412861970807544203\\26758310825359298137813346856823787025048415153152451114861404864714106729144460466701059767975347053049827019482175273\end{array}}{\begin{array}{l}88902570399915349148522977165111379912617173514847835595863711470724069201527646673366163896538193 46\\4168146364205130292397170746149318720379630387200000000000000000000000000\end{array}}$$

$$\sim 10^{930}$$

This is a mathematical lower limit on the number of Euclidean Self-dual lattices of dimension 88, needed for our construction. The upper limit on the number of such lattices is

$$\sim 10^{1090}$$

The actual number of heterotic strings is much smaller than any of these numbers.



Local p_0
ATLAS 2011 - 2012
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 5.8-5.9 fb^{-1}
Obs.
Exp.
$\pm 1\sigma$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0σ
1σ
2σ
3σ
4σ
5σ
6σ
110 115 120 125 130 135 140 145 150
m_H [GeV]

III. Scalars

The first scalar particle, the Higgs boson, has just been found. It is a Lorentz singlet, but it couples to quarks and leptons.

It was hard enough to find, but gauge singlet scalars are even harder to find, especially if they are very massive.

Is all we can see all there is?

If fundamental scalars exist, polynomials of these scalars would multiply all terms in the Langrangian.

For example, in QED

$$\frac{1}{\alpha} F_{\mu\nu} F^{\mu\nu} \rightarrow P(\frac{\phi_i}{M}) F_{\mu\nu} F^{\mu\nu}$$

(M is the Planck Mass)

The value of the fine structure constant α is determined by the v.e.v. of the fields φ_i.

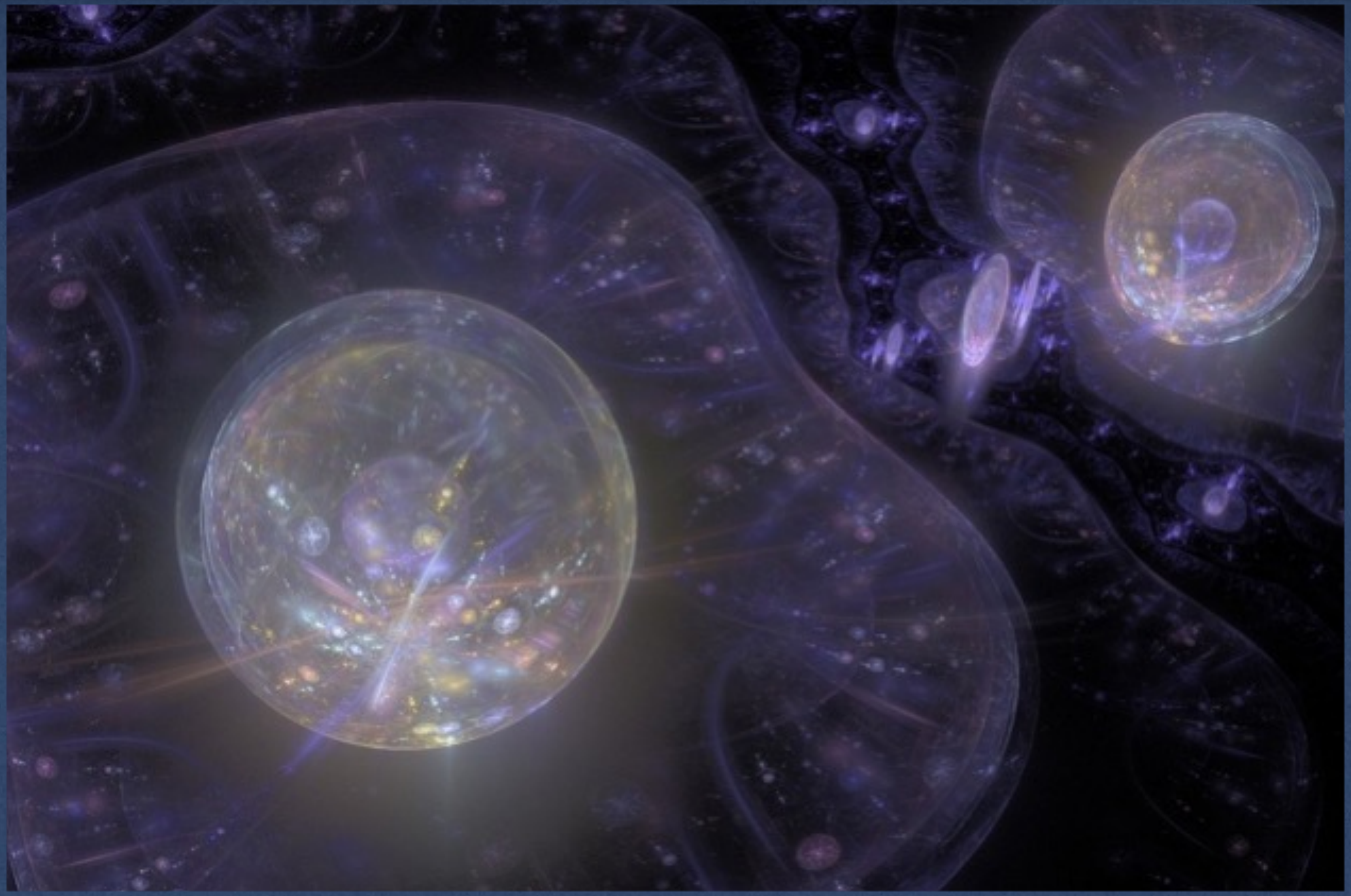
The same is true for all other Standard Model parameters:
All Standard Model parameter are "environmental".

In string theory, hundreds of such scalars exist ("moduli").
Their potentials are believed to have a huge number of minima ("The String Theory Landscape"), of order $10^{hundreds}$

Bousso, Polchinski (2000)
Kallosh, Linde, Kachru, Trivedi (2003)
Douglas (2003)

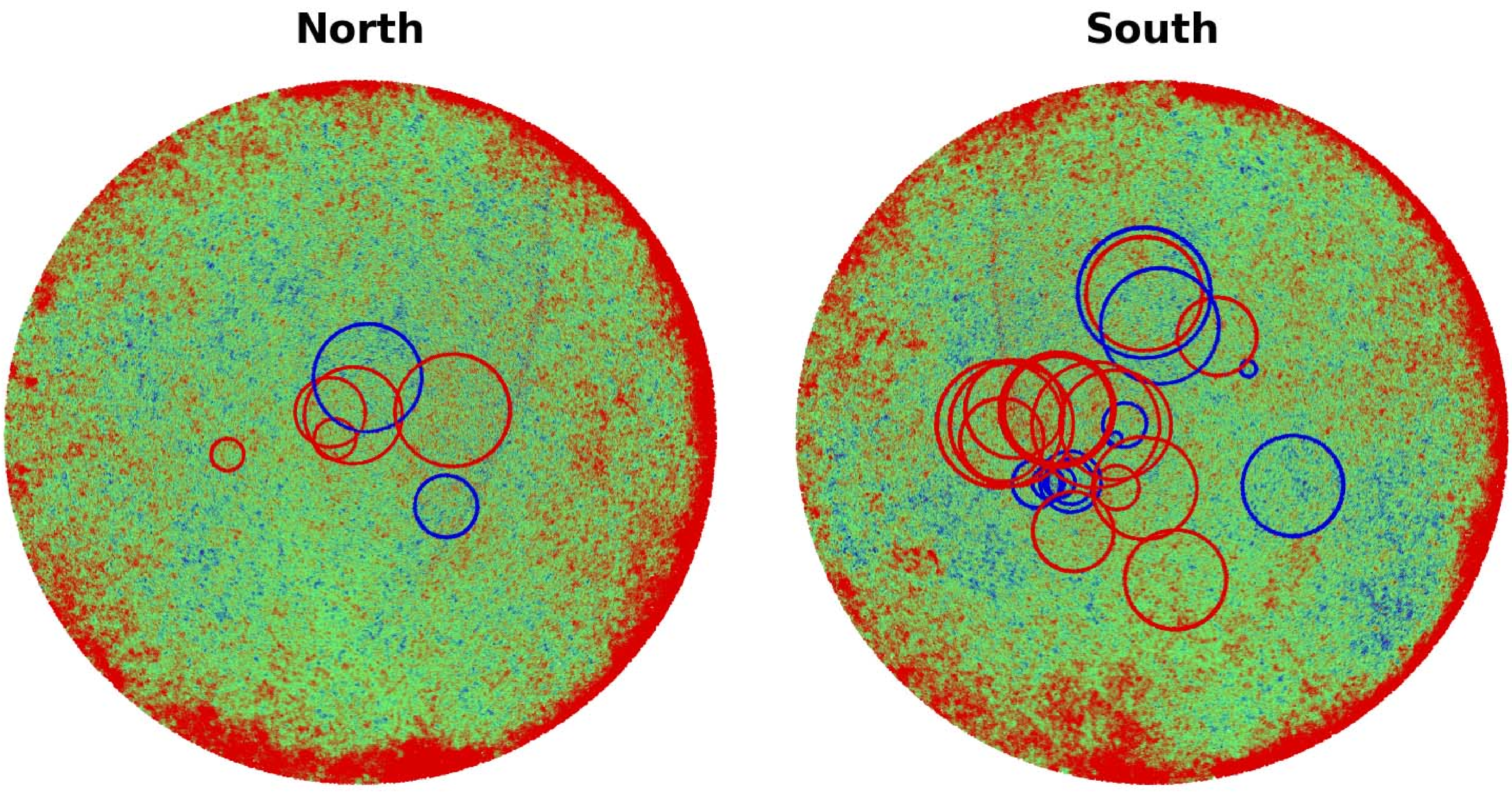
"The Anthropic Landscape of String Theory"
L. Susskind (2003)

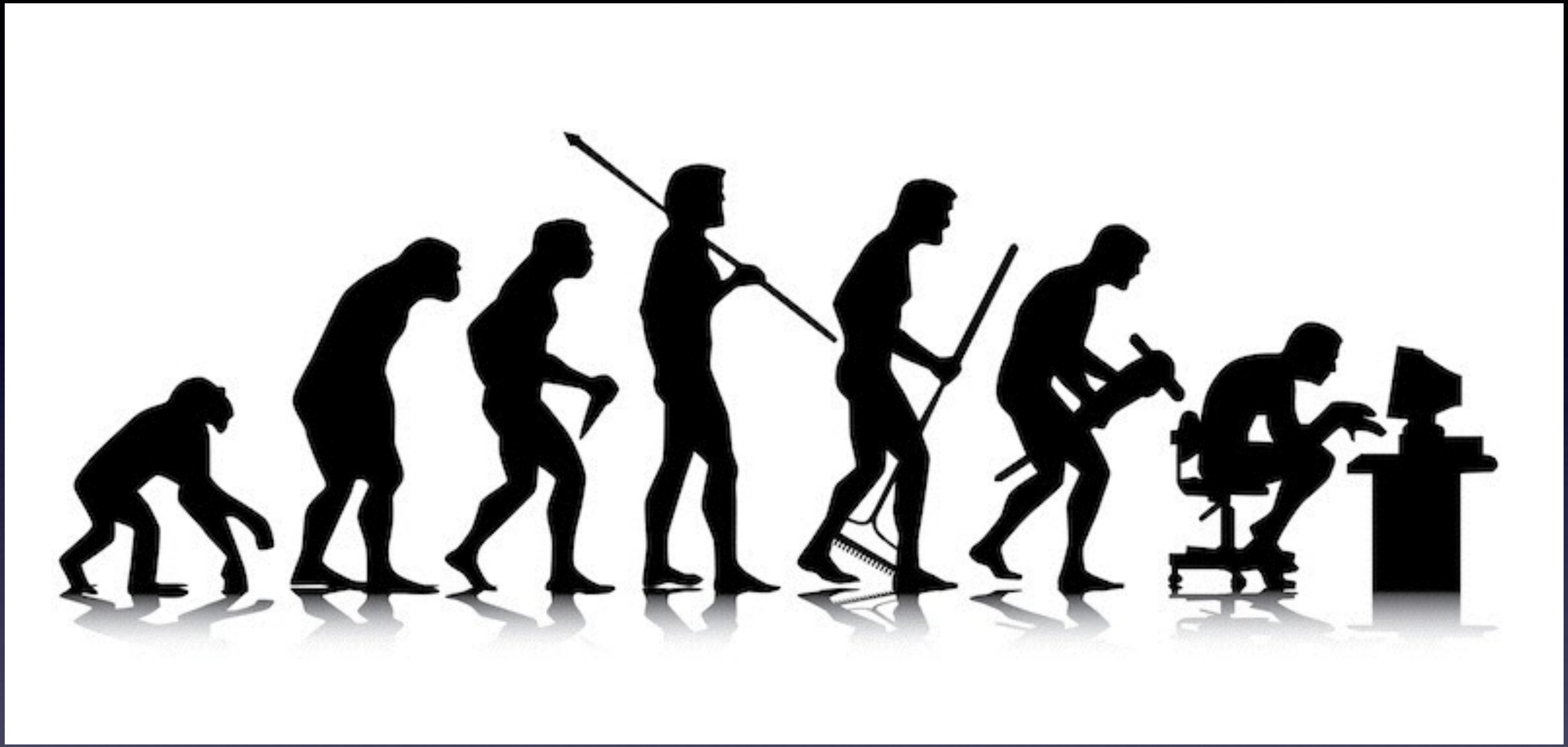
Flux compactifications



Particle Physics in the Multiverse

An, Meissner, Nurowski
(see also Gurzadyan and Penrose)





IV. Anthropic Arguments

Anthropic Features of the Standard Model

- The proton (uud) is stable against decay to a neutron (ddu)

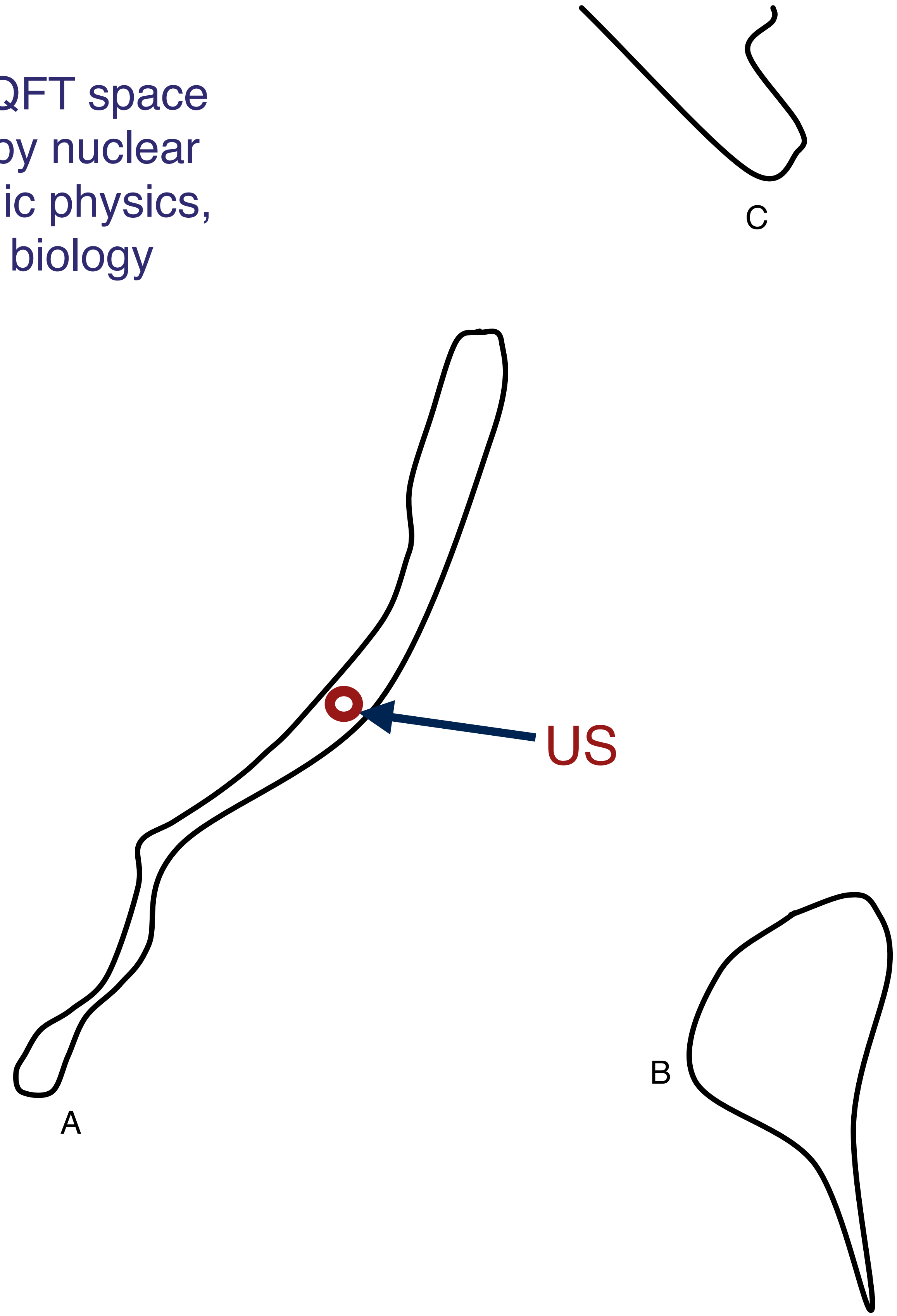
$$p \to n + e^{+} + \nu$$

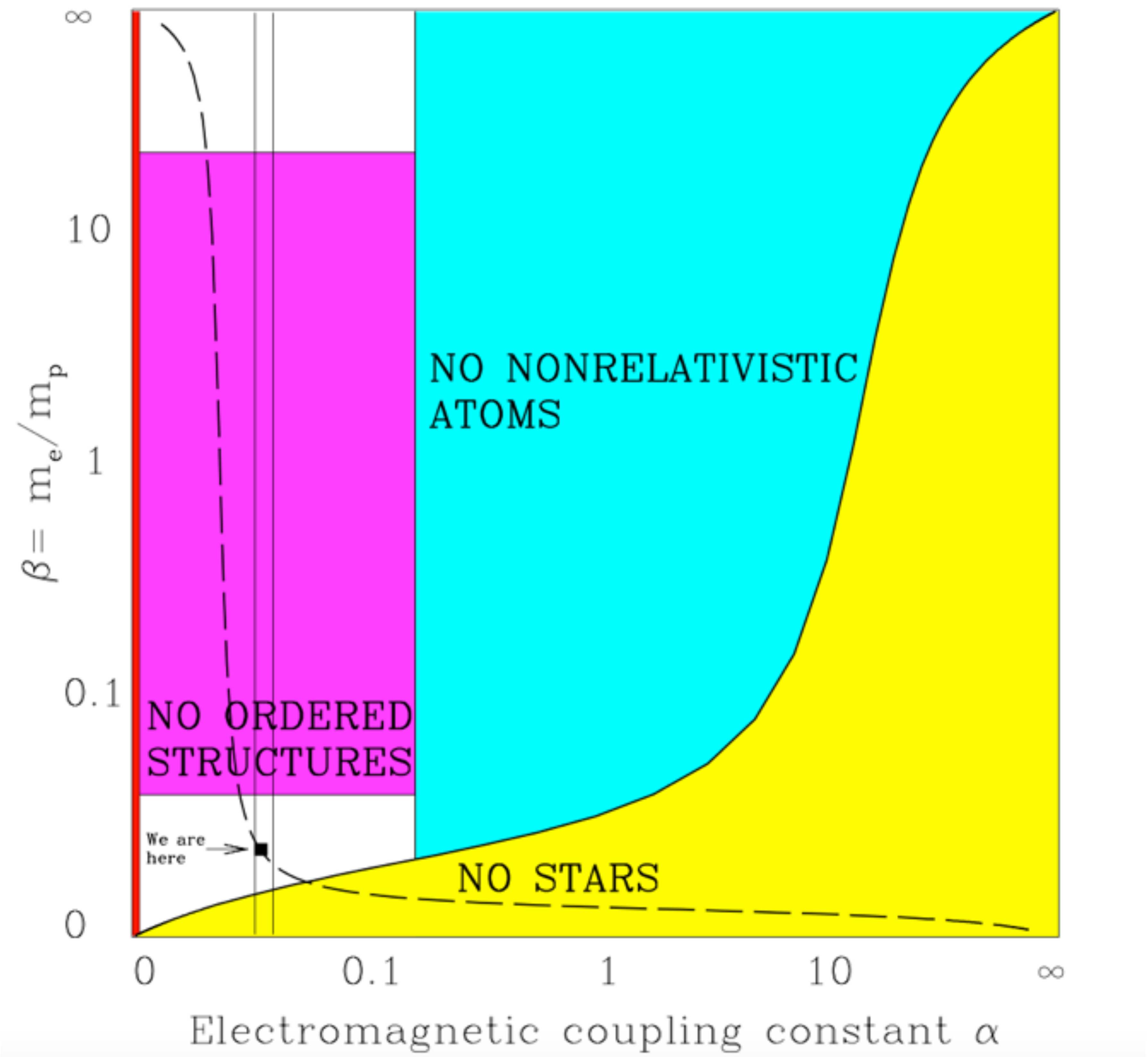
Electromagnetic forces lower the neutron mass with respect to the proton mass. This is solved by the fact that the up-quark is extremely light.

- The neutron should be unstable, to prevent a neutron dominated universe. This limits the electron mass to

$$m_e < m_n - m_p = 1.29\mathrm{MeV}$$

Contours in QFT space determined by nuclear physics,atomic physics, chemistry, biology





M. Tegmark. Is the theory of everything merely the ultimate ensemble theory? *Annals Phys.*, 270:1–51, 1998.

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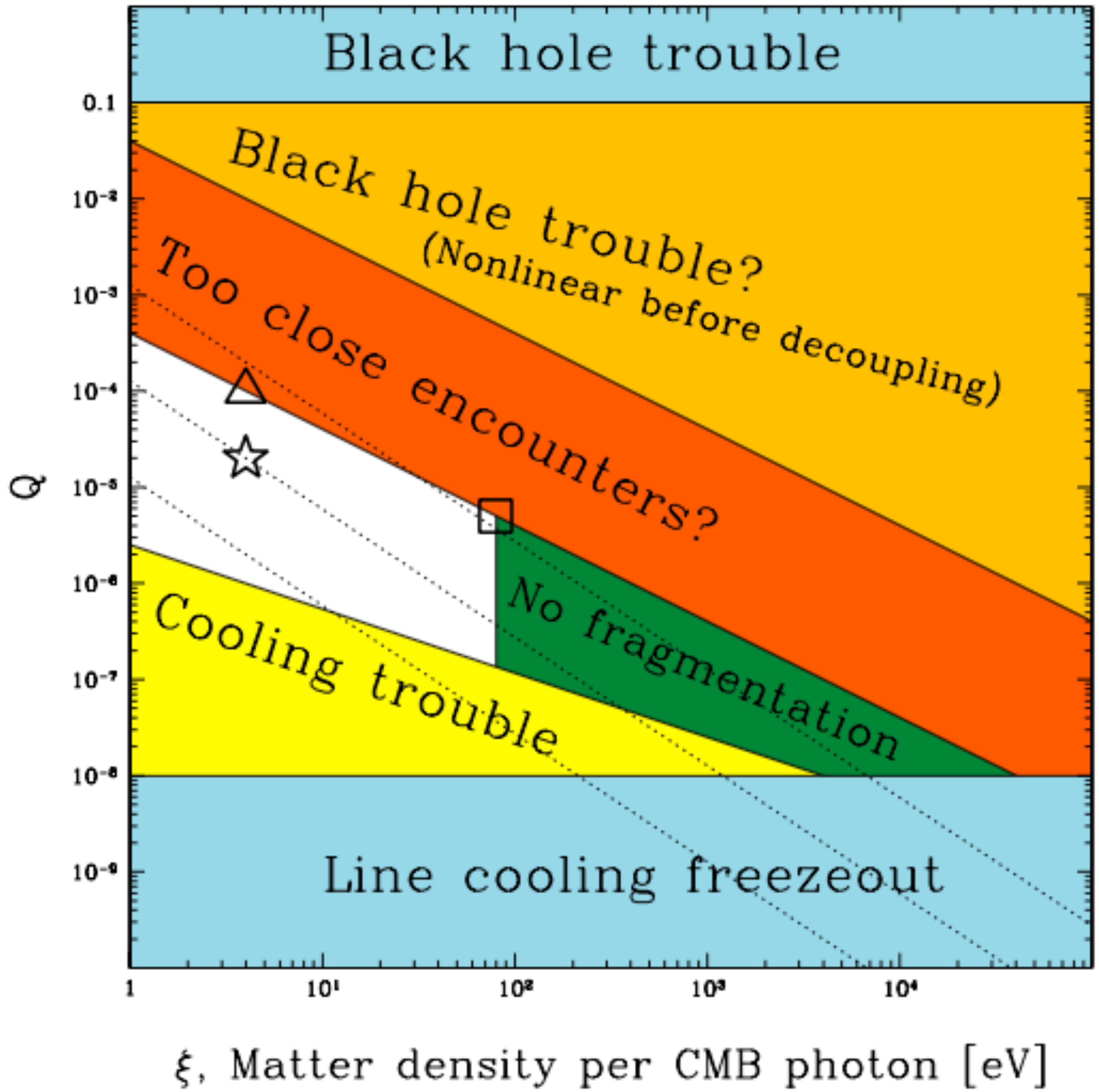


M. Tegmark, A. Aguirre, M. Rees, and F. Wilczek. Dimensionless constants, cosmology and other dark matters. *Phys.Rev.*, D73:023505, 2006.

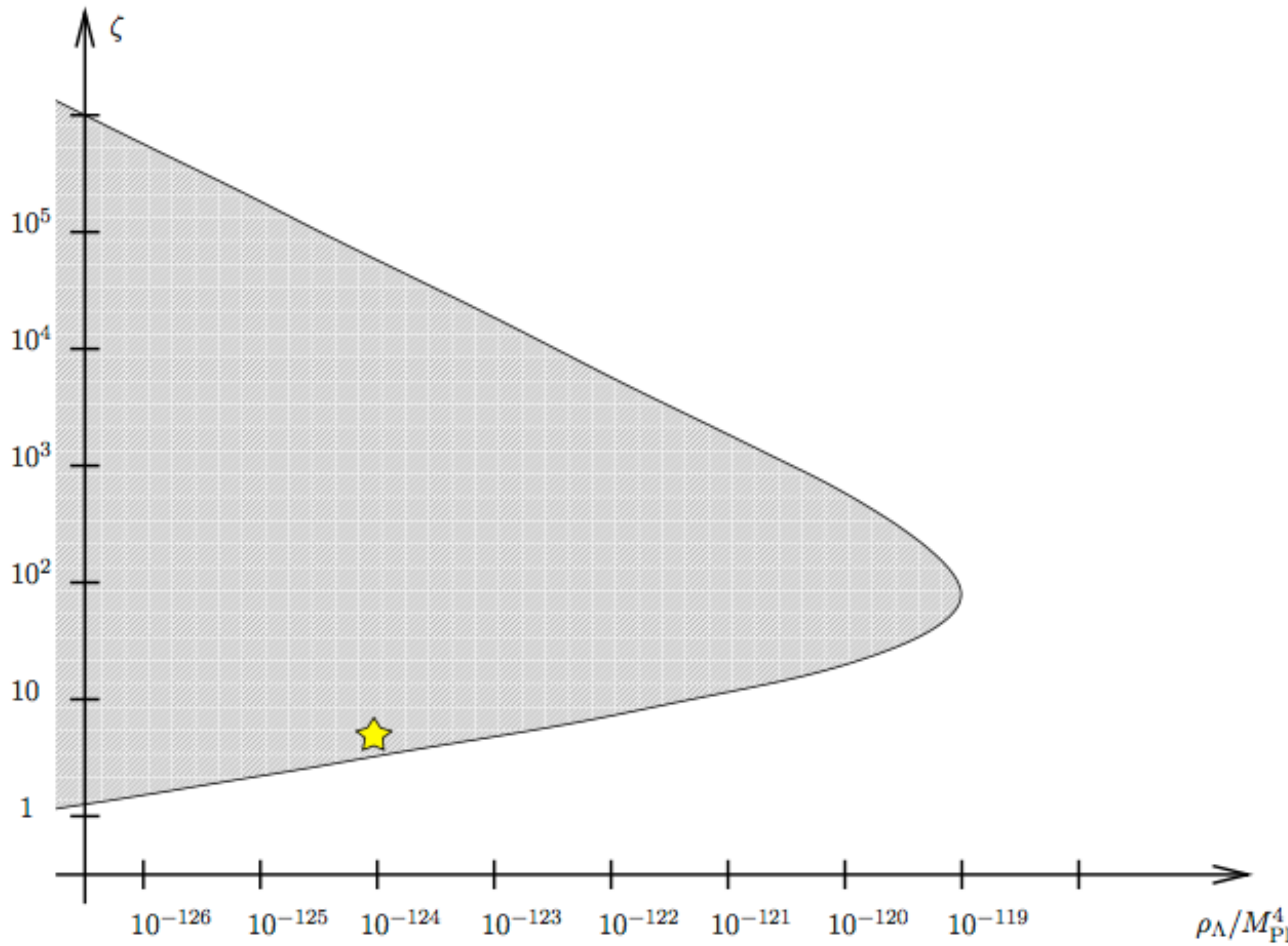
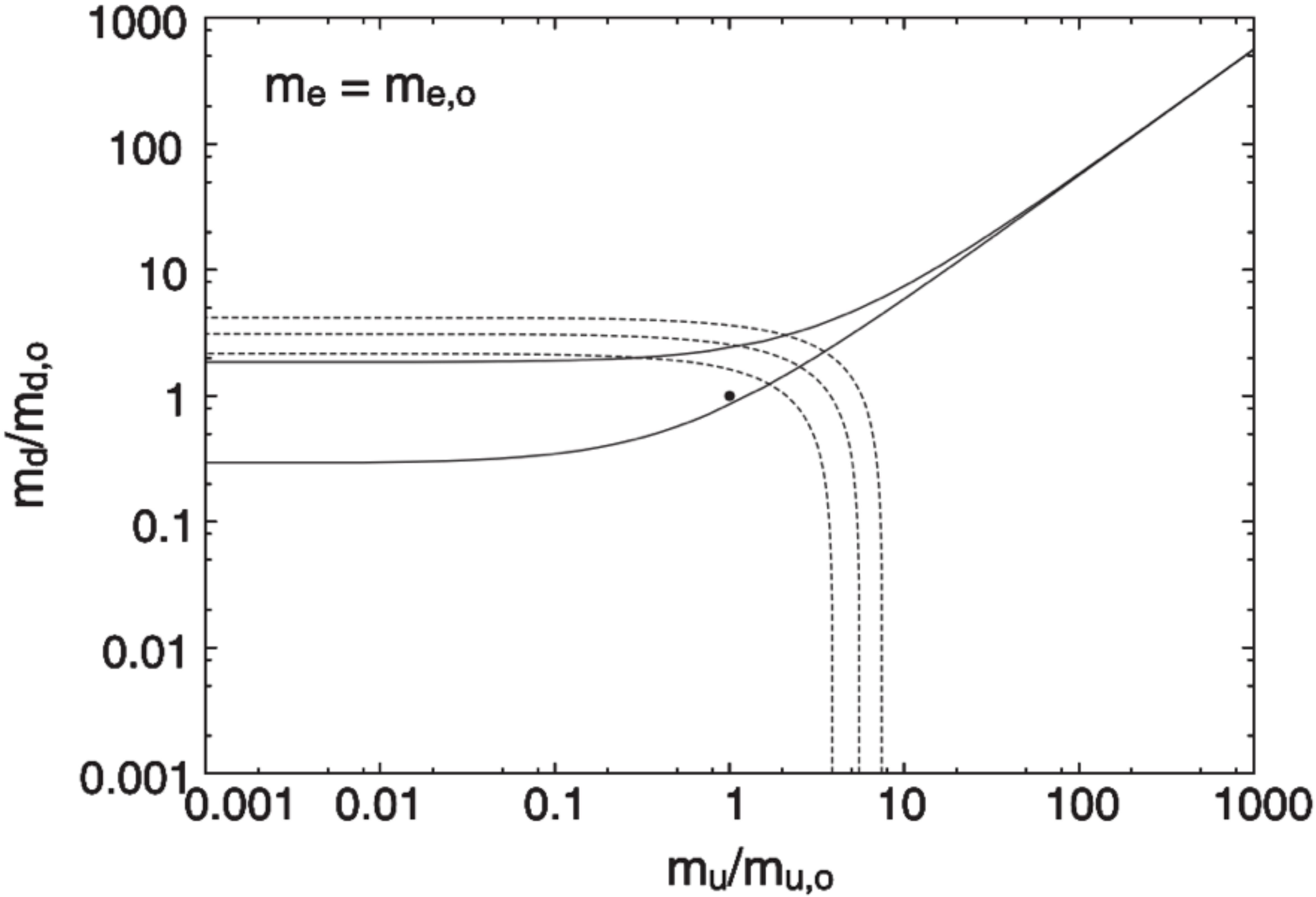


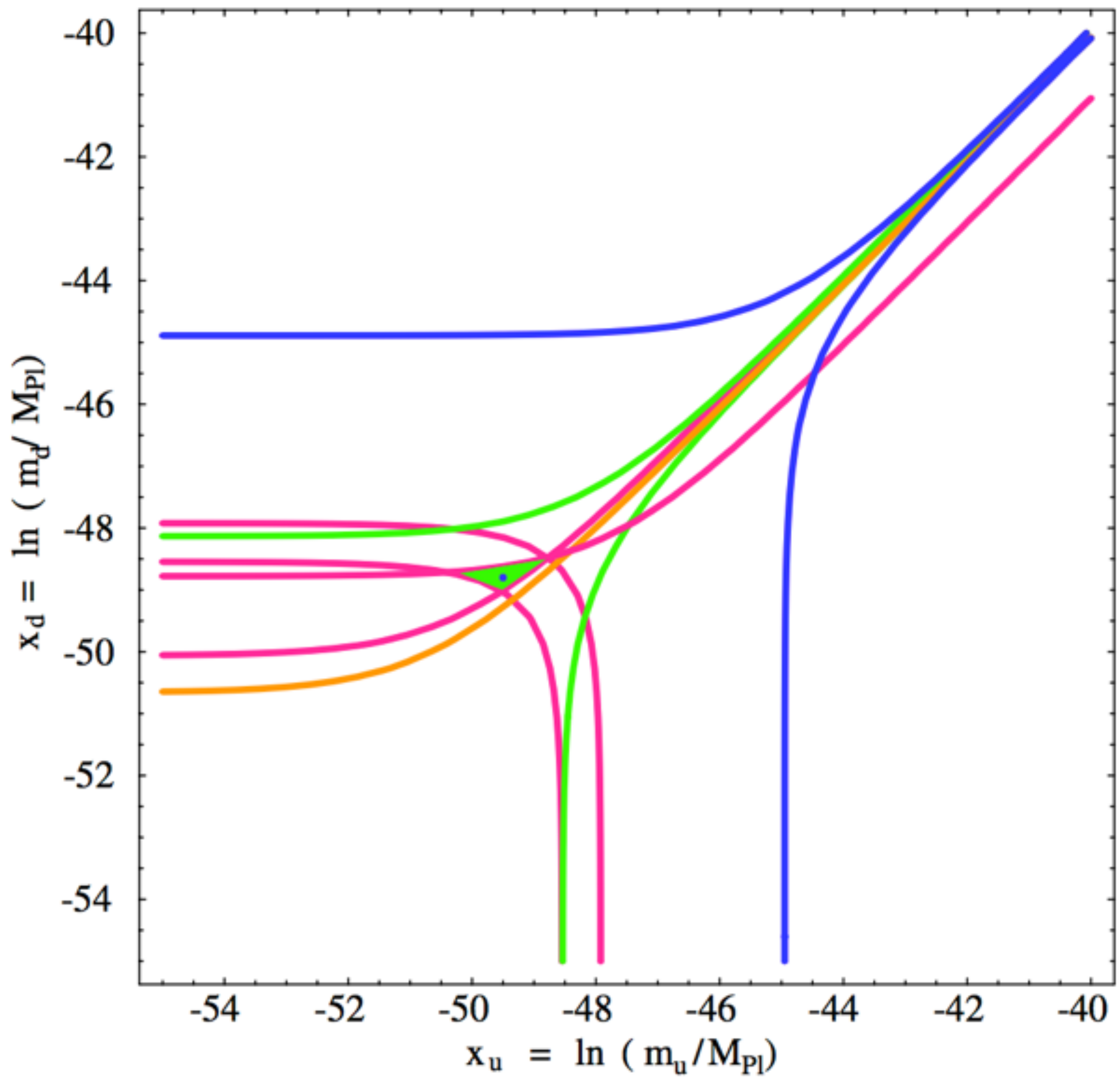
FIG. 1: A schematic picture of the region in Λ-ζ space for which gravitationally bound structures containing $10^{11} M_\odot$ of baryons form. The star represents our universe.

S. Hellerman and J. Walcher. Dark matter and the anthropic principle. *Phys.Rev.*, D72:123520, 2005.

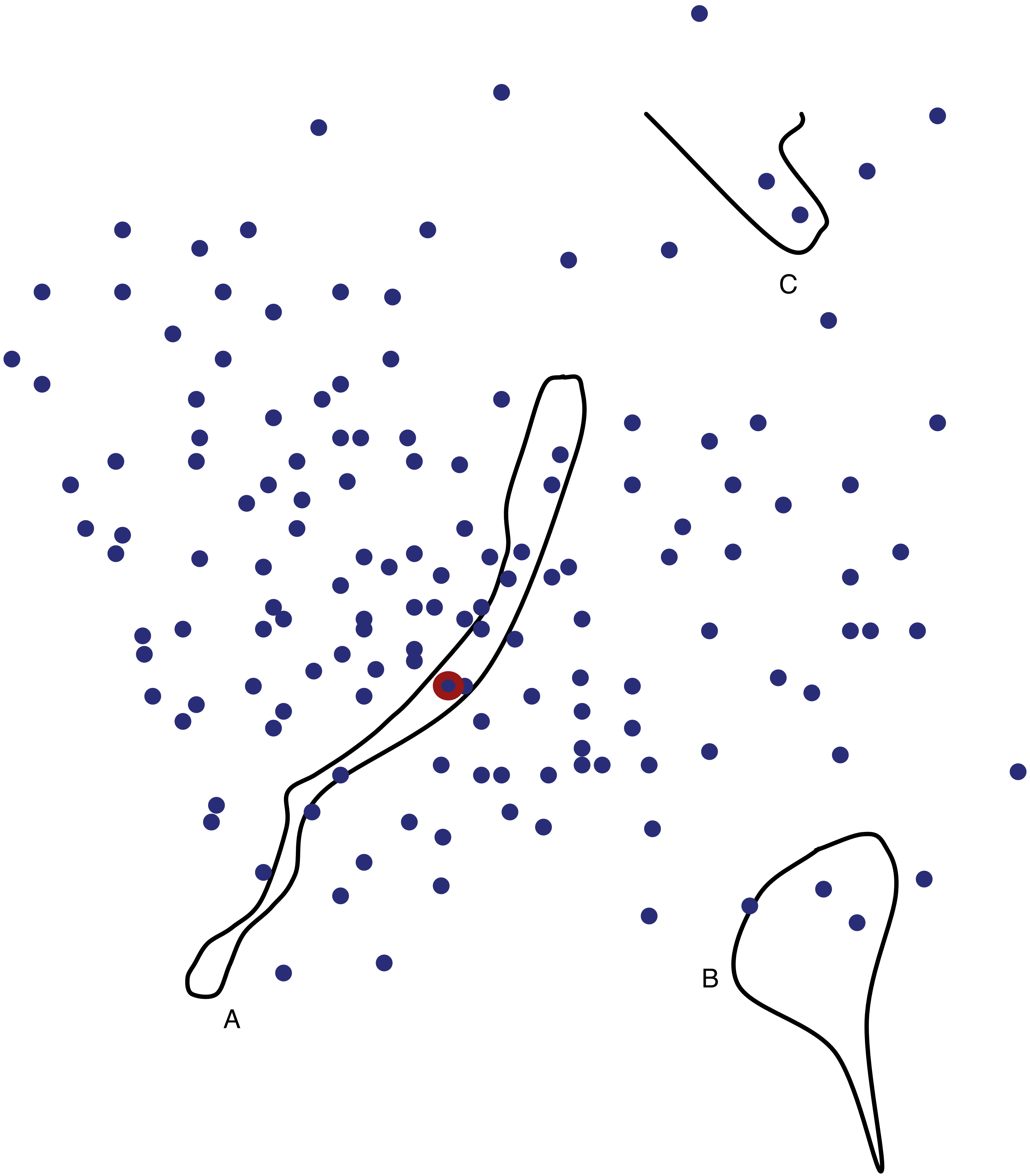


L. J. Hall and Y. Nomura. Evidence for the Multiverse in the Standard Model and Beyond. *Phys.Rev.*, D78:035001, 2008.

S. M. BARR AND ALMAS KHAN



S. Barr and A. Khan. Anthropic tuning of the weak scale and of m(u) / m(d) in two-Higgs-doublet models. *Phys.Rev.*, D76:045002, 2007.


C
B
A

A Linde,
“Eternally Existing Selfreproducing Chaotic Inflationary Universe.”, 1986

“… an enormously large number of compactifications which exist e.g. in the theories of superstrings should not be considered as a difficulty but as a virtue of these theories, since it increases the probability of the existence of mini-universes in which life our type may appear… “

Levels of anthropic reasoning

- **Tautological:**
  There exist fundamental theory points outside the anthropic contours. We don't live there.

  Analog: there exist other planets.

- **Explanation of apparent anthropic fine-tunings:**
  With a sufficiently dense point cloud, it is no surprise that one point falls within an anthropic domain

  Analog: there are so many other planets that the existence of a habitable one is no surprise.

- **Post/Predictive:**
  If we can actually compute the most likely parameter values. This requires knowledge of multiverse probabilities. Furthermore it requires the "principle of mediocrity" (Vilenkin).

  Analog: compute the length of a day from habitability. ***(Press, Lightman, Peierls, Gold, 1983)***

Fallacies and misconceptions

- Brandon Carter introduced the term “Anthropic Principle” in 1973, as an alternative to the “Copernican Principle”. The latter states that we do not have a privileged position in the universe, whereas the Anthropic Principle states that we do. But this is only true in the sense of observer bias. Copernicus stated that nothing in the fundamental laws of astronomy singled out planet Earth, and analogously I am assuming that nothing in the fundamental laws of nature will refer to human beings. But that is an assumption…

- Some people think that the notion of “observer” in quantum mechanics, or the nebulous concept of “consciousness” may cast some doubts on that assumption.

- Rejecting this assumption leads to the “strong anthropic principle”, which states that the laws of physics must be such that humans or observers must exist. We do not consider this.

- From our perspective, “Anthropic Principle” is a double misnomer. It is not a principle of nature, and it is not about human beings, only “observers”.

- Anthropic arguments as discussed earlier are merely an inevitable consequence of parameter variation in the multiverse. I don’t know how to discuss them outside the context of a multiverse.

- Once we understand the fundamental laws of physics, anthropic arguments will be nothing more than a footnote.

Fallacies and misconceptions

- But as long as we do not know the fundamental laws of physics, anthropic arguments can provide a guiding principle.
- Anthropic arguments do not have to make falsifiable predictions. It is the fundamental theory (the blue dots) that must be falsifiable, at least theoretically.
- Anthropic arguments will never fully determine the Standard Model. Plenty of SM parameters (e.g. the τ mass) are irrelevant for life.
- Furthermore, one should expect a (large?) multitude of habitable regions.

Fallacies and misconceptions

- Even in combination with a fundamental theory, anthropic arguments will not uniquely determine the Standard Model (it is unreasonable to expect that just one blue dot lands in an anthropic contour).

- If there is a ensemble of laws of physics with well-defined statistical distributions, this by itself will not determine the Standard Model either.

- If we are really lucky, a statistical ensemble together with anthropic contours may determine the Standard Model. But:

Fallacies and misconceptions

- Anthropic contours are rarely sharp lines. They are contour plots showing the region in parameter space exceeding a value we think is essential for observers to exist. Even particle decay thresholds are not sharp. Beyond the line where the proton becomes unstable, there is a region where it lives “long enough”.

- We should avoid the “anthropocentric trap”. Perhaps life can exist without Oxygen, Carbon, Hydrogen. Perhaps hydrogen can be replaced by deuterium or tritium in chemistry, etc.

- On the other hand, the fact that we cannot possible explore the full parameter space of QFT does not make the entire exercise worthless. We can stay “close to home” and see how the SM stands out from its environment (or not).

- Some people adopt the point of view that life is “generic” in QFT. But if that is the case, one must still wonder why it was realized in such an apparently fine-tuned way in our own environment. Generic regions in QFT space will not look fine-tuned at all.

An extremely optimistic scenario

(Having your cake and eating it too)

Imagine an ensemble with an extremely large hierarchy of probabilities. Suppose the different universes in the multiverse, ordered according to probability have probabilities 1, 10^{-100}, 10^{-200}, 10^{-300}, etc. Then the first one to land within the anthropic contours is vastly more probably then the second. This would be nearly as good as a unique derivation of the SM, but would still have the huge ensemble to explain anthropic fine-tunings.

However, in such a scenario one would expect to end up deeply in the tail of the distributions.

Braun and Watari, Phys Rev. D 90, 121901,2014

a gauge group on 7-branes. In the choice of $(B_3, [S])$ in (9) with $n = 0$, for example, vacua with the rank-4 SU(5) unification constitutes only the fraction $e^{-\Delta K/6} \approx e^{-3000}$ of the entire flux vacua (smaller than the fraction 10^{-120} for the cosmological constant). The authors do not provide their interpretations for this inconvenient prediction; a popular attitude will be to hint at poor understanding of string theory, to count on cosmological factors that we did not study here, and/or to resort to anthropics.

Arguments against uniqueness

- ✓ Eternal Inflation.
  (or at least: no argument for uniqueness of our universe)

- ✓ Unification.
  (all current ideas allow many low energy options)

- ✓ Scalars.
  (Why should Standard Model parameters be absolute constants?)

- ✓ Anthropic arguments.
  (The Standard Model does not look like a mathematically unique point in QFT space)

Arguments in favor of uniqueness

The Cosmological Constant

Vacuum Energy

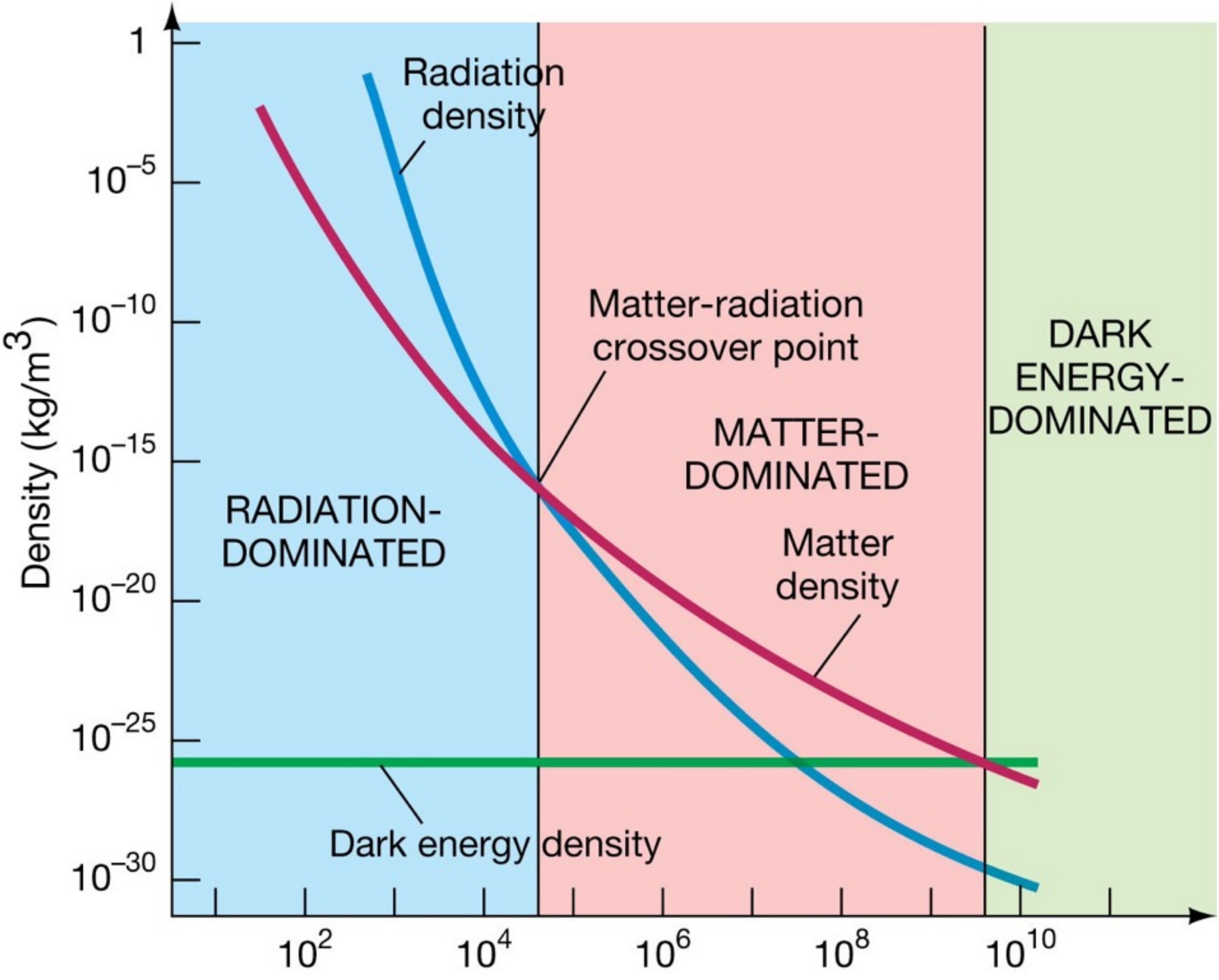
Einstein equation

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

Vacuum energy in Quantum Field Theory

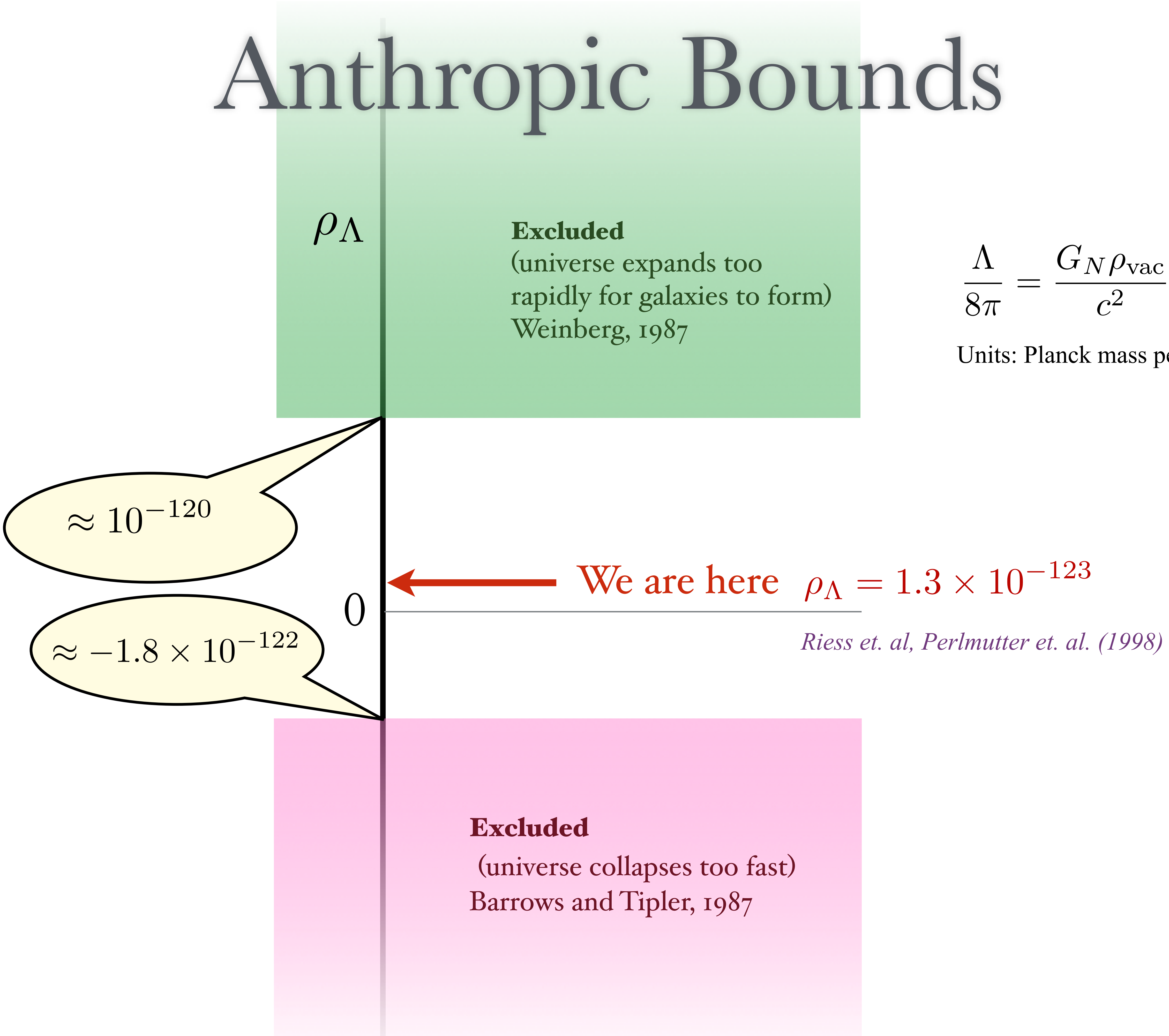
$$T_{\mu\nu} = -\rho_{\mathrm{vac}} g_{\mu\nu}$$

Irrelevant in the absence of gravity.
But gravity sees it as a contribution to Λ.



Radiation density
Matter-radiation crossover point
DARK ENERGY-DOMINATED
MATTER-DOMINATED
RADIATION-DOMINATED
Matter density
Dark energy density
Density (kg/m3)
1
10−5
10−10
10−15
10−20
10−25
10−30
10^2
10^4
10^6
10^8
10^10

Anthropic Bounds



$$\frac{\Lambda}{8\pi} = \frac{G_N \rho_{\text{vac}}}{c^2} := \rho_\Lambda$$

Units: Planck mass per Planck volume

C.C. versus S.M.

An anthropic explanation requires more than 10^{120} points.

But:
Λ is less obviously a true variable of the laws of physics than the standard model parameters.

The latter are clearly decoupled from what we do not know yet: gravity.
But Λ only makes sense in the presence of gravity.
And gravity is precisely the big unknown.

But one candidate theory of gravity, string theory, does seem to have the required large number of "vacua" (minima of the scalar potential).

Fluxes

To have a chance of finding one minimum in the anthropic domain, we need a moduli potential with at least 10^{120} minima.

Each minimum would not only have a different vacuum energy, but different values for all parameters, like α.

This can be achieved by quantized background fields (“fluxes”) winding around topological cycles of a compactification manifold.

These fields are multi-index anti-symmetric tensor generalizations of the vector potential A_μ of the electromagnetic field: $A_{\mu_1,\ldots,\mu_n}$

In Minkowski space, these fields manifest themselves as three-form fields $A_{\mu\nu\rho}$

Bousso, Polchinski (2000)

Three form fields

$$A_{\mu\nu\rho} \rightarrow F_{\mu\nu\rho\sigma} = \partial_{[\sigma} A_{\mu\nu\rho]}$$

Action with four-form contribution

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2\kappa^2} R - \Lambda_{\mathrm{bare}} - \frac{Z}{48} F_4^2 \right)$$

Solution to equations of motion

$$F^{\mu\nu\rho\sigma} = c\epsilon^{\mu\nu\rho\sigma}$$

Contribution to the cosmological constant

$$\Lambda = \Lambda_{\mathrm{bare}} + \frac{1}{2} \frac{Zc^2}{2}$$

In String Theory:

- The constant c is quantized
- There are many such four-form fields

$$\Lambda = \Lambda_{\text{bare}} + \frac{1}{2}\sum_{i}^{N_{\text{flux}}} n_i^2 y_i^2$$

If the values of y_i are incommensurate and N_{flux} sufficiently large, Λ can be tuned to a very small value (starting with negative Λ_{bare} of natural size).

$$N_{\text{vacua}} \approx \left[N_{\text{values}}\right]^{N_{\text{flux}}}$$

(M. Douglas, 2003)

The basic estimate for numbers of flux vacua [4] is

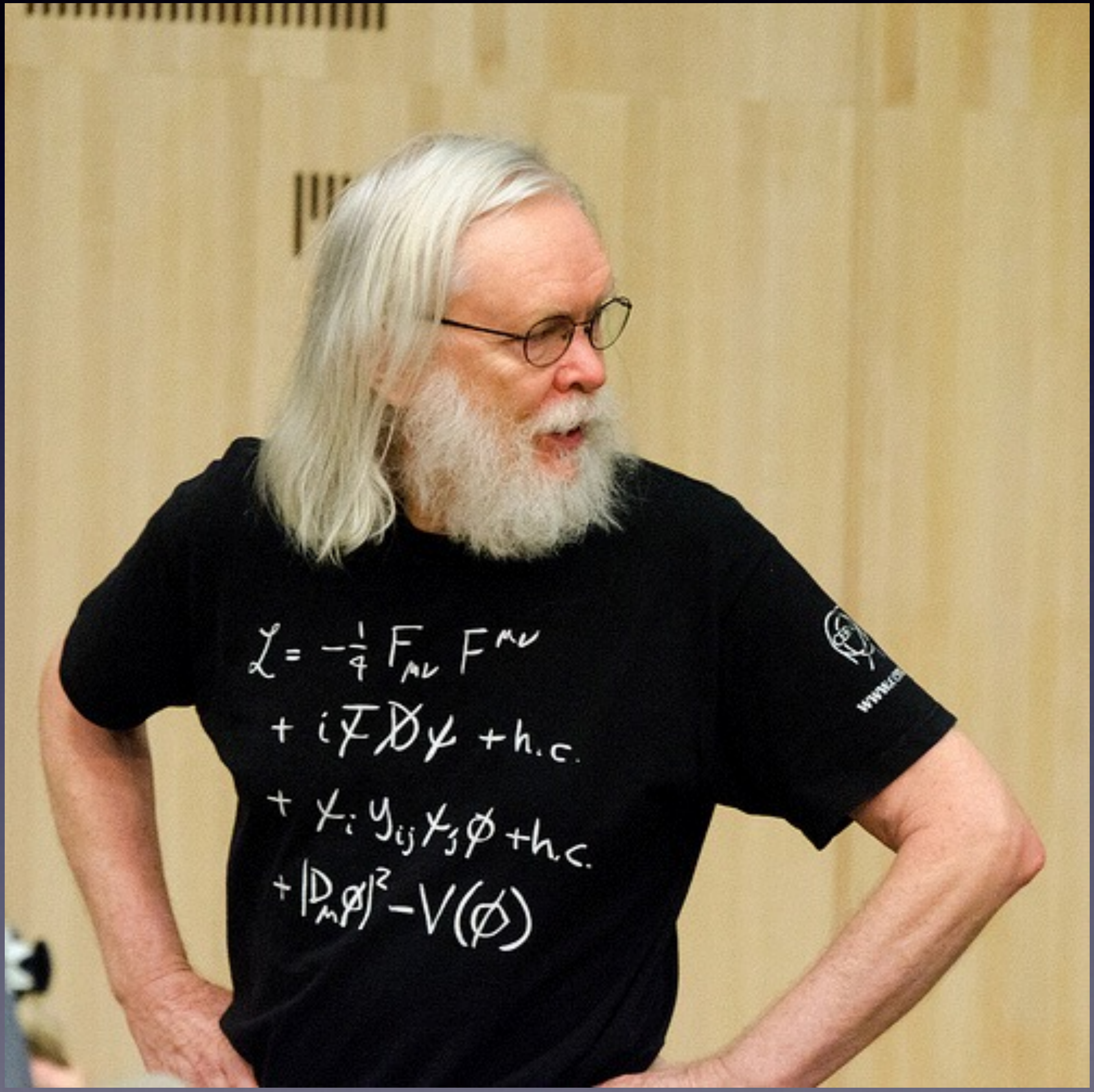
$$\mathcal{N}_{vac} \sim \frac{(2\pi L)^{K/2}}{(K/2)!}[c_n]$$

where K is the number of distinct fluxes ($K = 2b_3$ for IIb on CY_3) and L is a "tadpole charge" ($L = \chi/24$ in terms of the related CY_4). The "geometric factor" $[c_n]$ does not change this much, while other multiplicities are probably subdominant to this one.

Typical $K \sim 100 - 400$ and $L \sim 500 - 5000$, leading to $\mathcal{N}_{vac} \sim 10^{500}$.

A nuisance turned into a virtue!

The Standard Model



If the multiverse picture is true, one would expect to find some not especially nice gauge theory, with a not especially nice choice of matter and not especially nice parameter values, which can be consistently extrapolated to the Planck scale, because that is where it came from.

Which is more or less what we have right now, after the Higgs discovery.

This is a historic moment:
Atomic, nuclear and hadronic physics do not qualify.

Why Now?

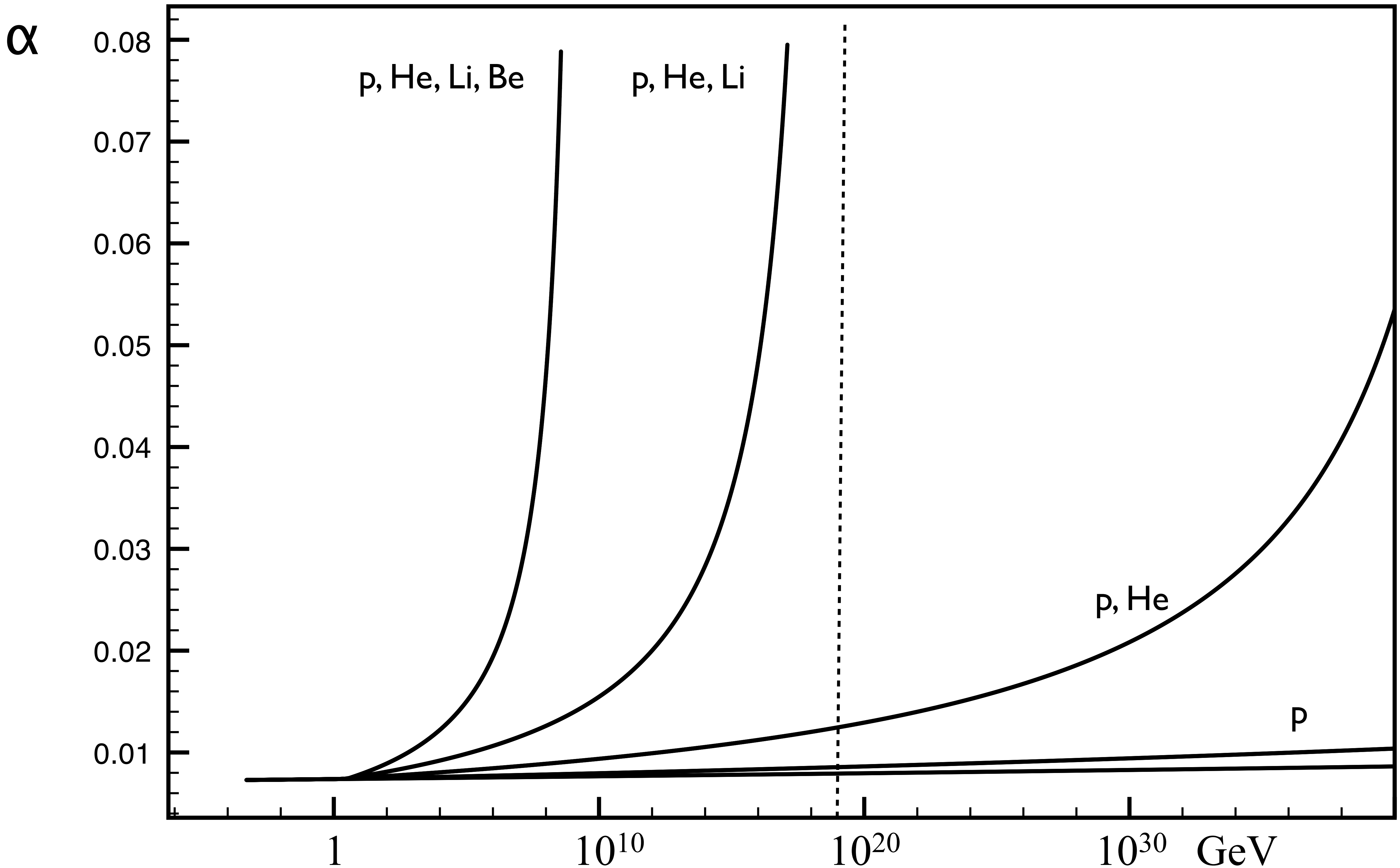
Atomic Physics

Nuclei as fundamental particles, plus an electron:

- Masses not fine-tuned.
- Fine-structure constant α not fine-tuned.
- Charges belong to the set of integers; changing them does not reduce complexity.
- Landau Poles!

Nuclear Physics

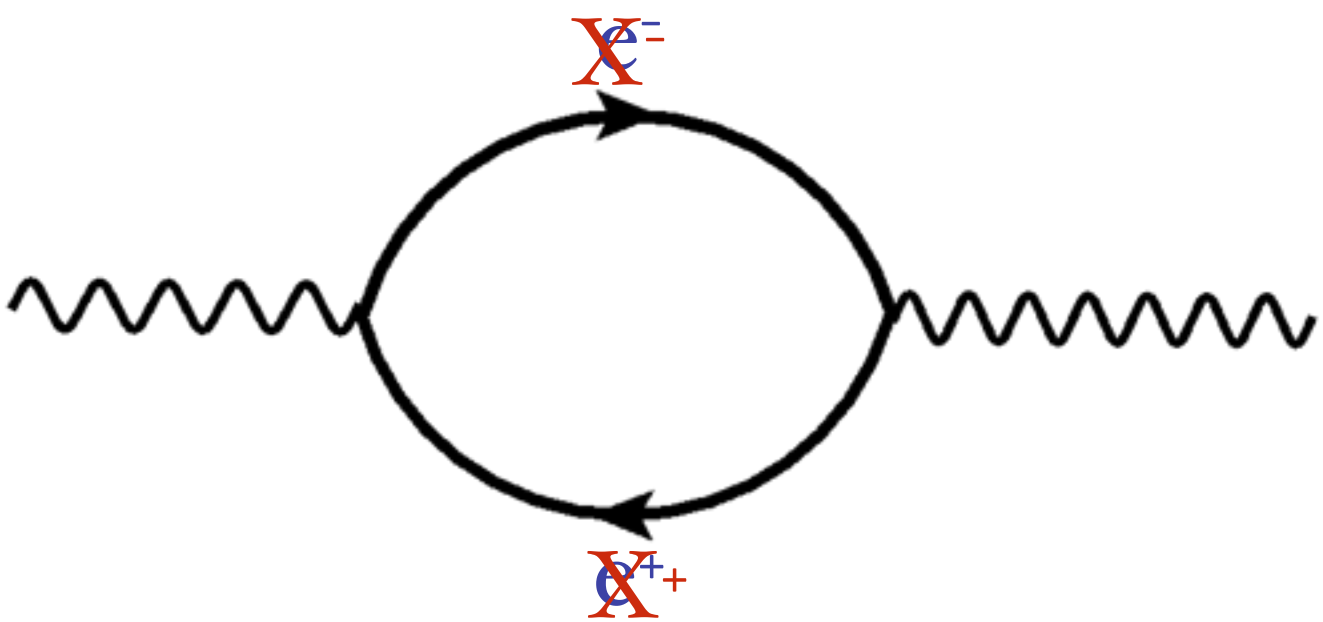
Not a theory, nothing can be varied.
Not even the proton mass.



α
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
p, He, Li, Be
p, He, Li
p, He
p
1
10^10
10^20
10^30
GeV

Most variations in Nuclear Physics are invalid.
By now we know what really can be varied:
The QCD coupling constant and the quark masses.
You can’t draw any conclusions if you move “out of physics”.

But how can a theory ever be immune to what we do not know yet?



Physics at shorter distances (space-time structure, new particles) gives rise to an infinity of unknowns....

But:

In the Standard Model all these unknowns can be “packaged” together in a finite number of parameters (plus corrections of order $E/M_{\rm New}$).

This makes the theory intrinsically insensitive to $M_{\rm New}$

Experimentally $M_{\rm New}$ is at least about 1 TeV, well beyond the scale of Nuclear Physics.

Theoretically, the Standard Model can be extrapolated much further than that, perhaps until $M_{\rm Planck}=10^{19}$ GeV.

Furthermore this is equally true for the relatives of the Standard Model: other gauge theories, with other groups, representations and parameters.

What can be varied?

Answer: everything!

For all (sufficiently small) changes we stay in the domain of well-defined QFT's. Furthermore, all changes can be made independently.

No need to ask questions like:
"Can I change the up-quark mass without changing the top quark mass?"

"Can I change α without changing Λ_{QCD} or the weak coupling, assuming coupling unification?"

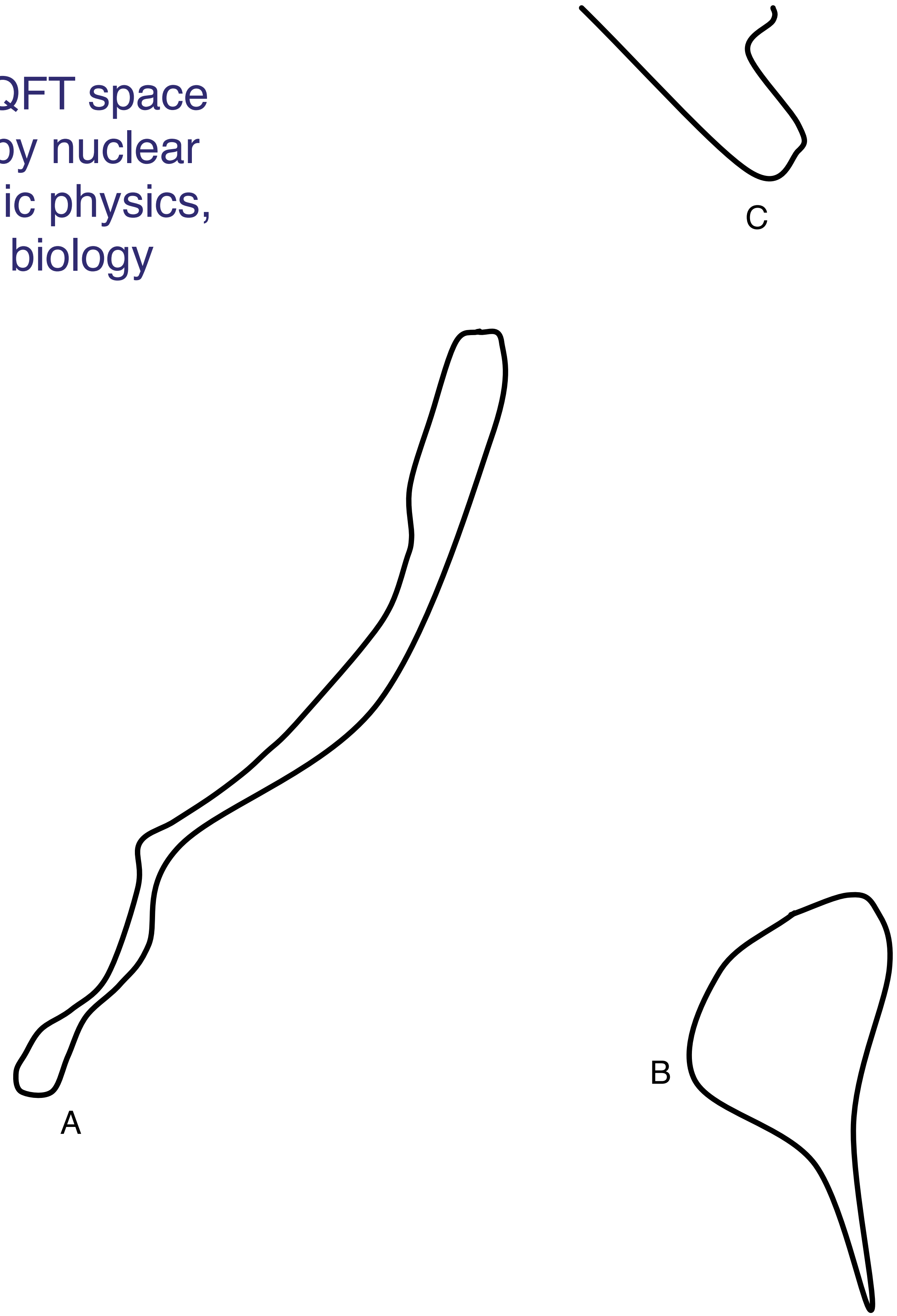
We do not have to take any new physics into account, because it all decouples from the nuclear/atomic physics computations relevant for the anthropic contours.

Suppose some fundamental UV completion of the SM complete determines $m_e = .511\ \text{MeV}$.

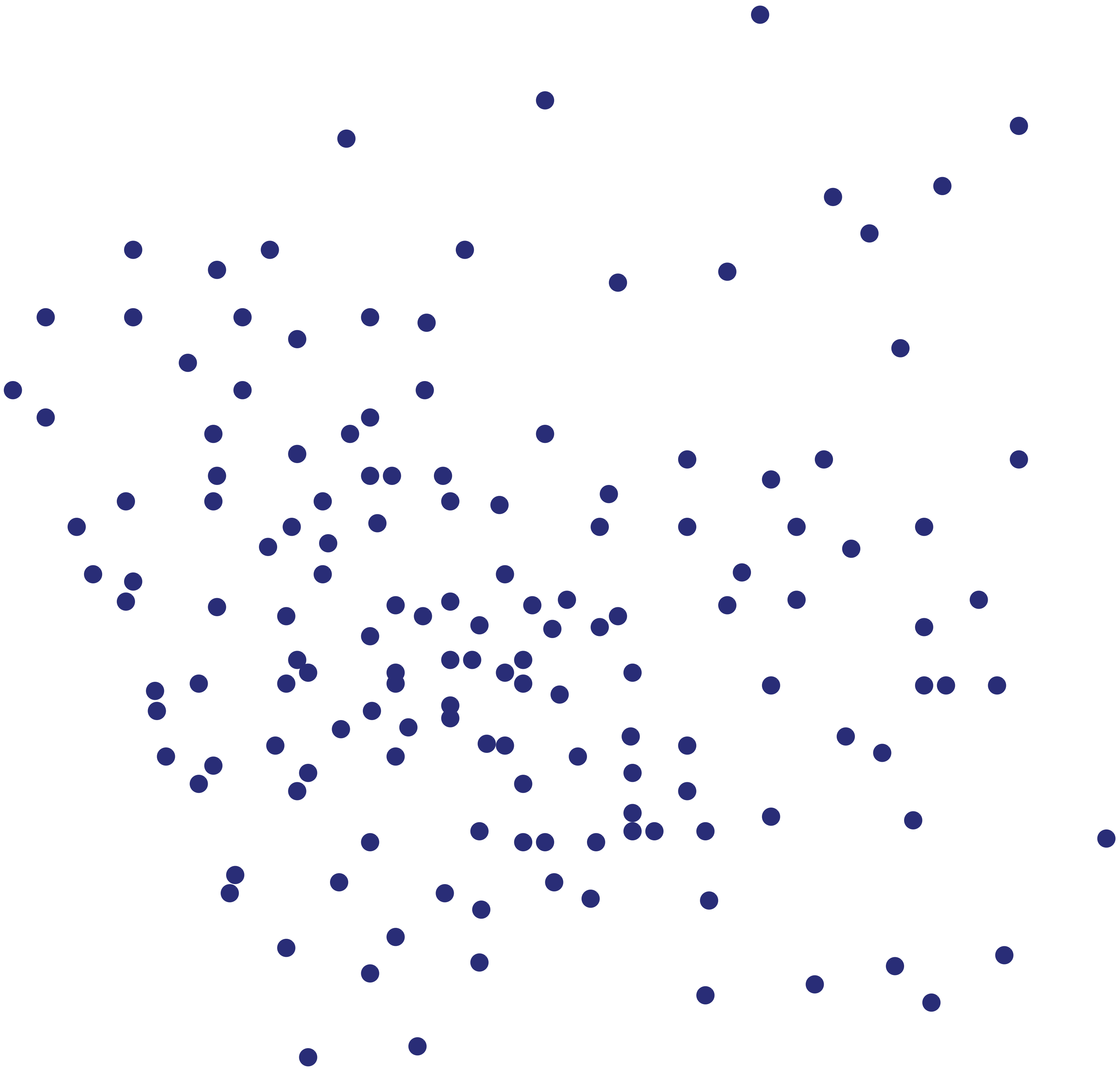
Even then we can still talk about atomic physics with different values of m_e.

If we limit our variations to SM parameters, there is a complete decoupling between the following computations:

Contours in QFT space determined by nuclear physics,atomic physics, chemistry, biology



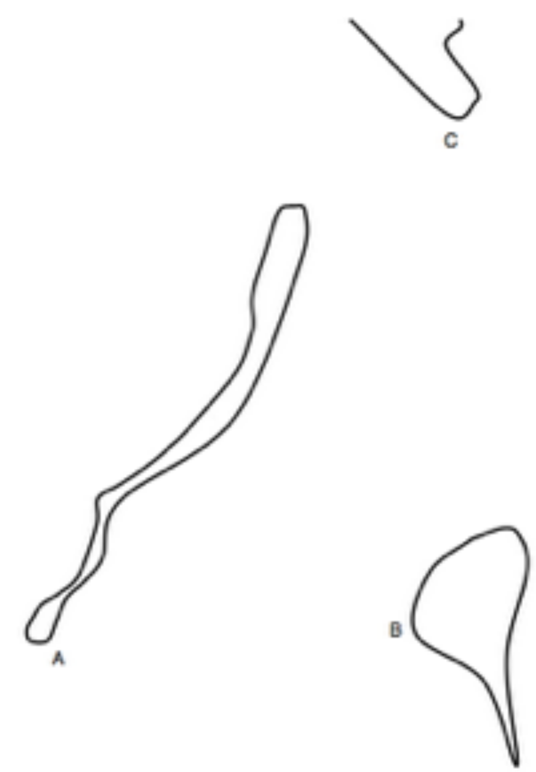
and



Some computation in a fundamental theory
(e.g. Calabi-Yau compactification with fluxes, branes, etc)

The ultimate scientific goal is this:

So what is the point of computing this?



What’s the point of anthropic computations?

- Appreciate the SM and its special place in QFT.
- Make correct decisions about what is really fine-tuned and what is not.
- Postdictions: understand the value of certain parameters anthropically.
- Predictions?
  Requires a parameter value that has not yet been measured to be crucial for our existence. Not likely, because our existence constitutes a measurement.

The Standard Model

Gauge Group $SU(3) \times SU(2) \times U(1)$

Quarks and leptons

$$3 \left\{ (3, 2, \frac{1}{6}) + (3^*, 1, \frac{1}{3}) + (3^*, 1, -\frac{2}{3}) + (1, 2, -\frac{1}{2}) + (1, 1, 1) \right\} + (1, 0, 0)$$

Higgs $(1, 2, -\frac{1}{2})$ Gives masses to all quark and leptons

Most general interactions respecting all the symmetries: 28 parameters
These can only be measured, not computed.
Some of them have strange value (small dimensionless ratios, like 10^{-6})

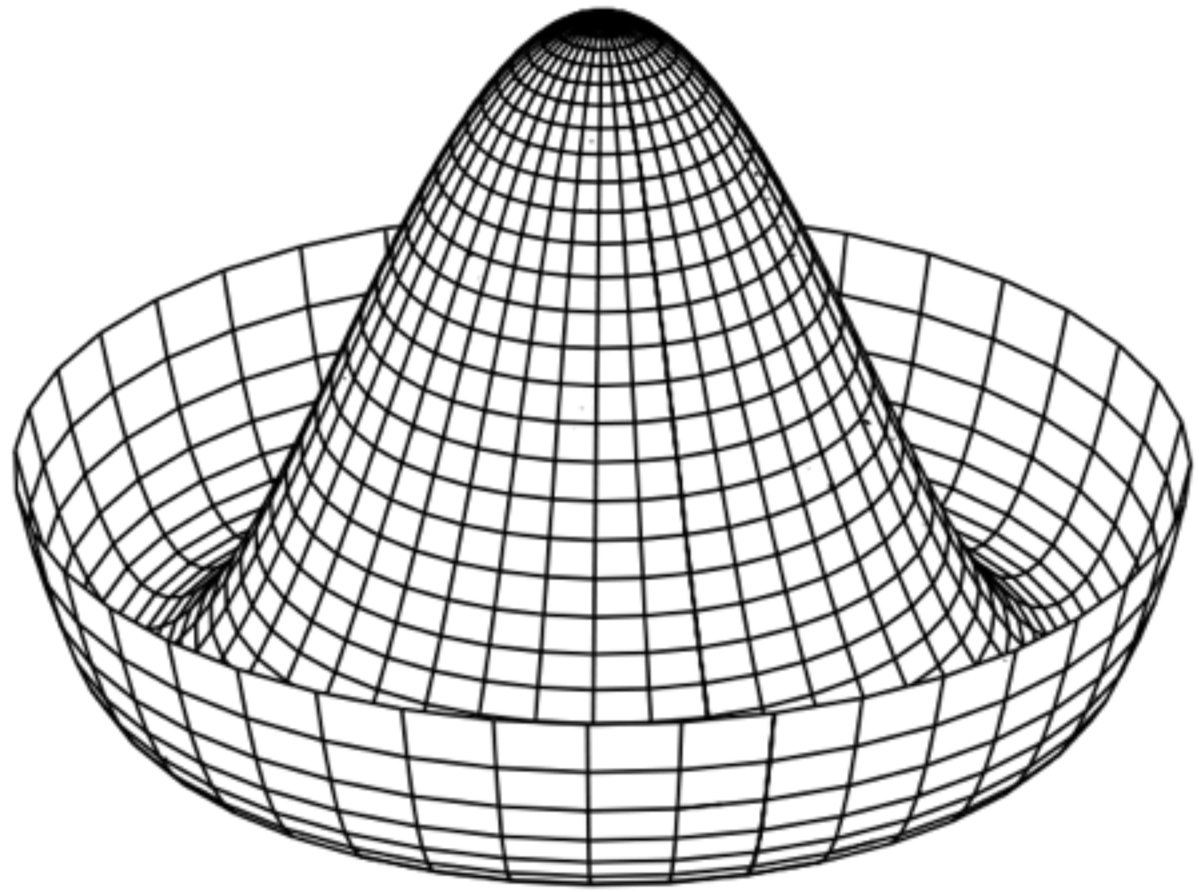
This gives a theory that correctly describes all known interactions except gravity.

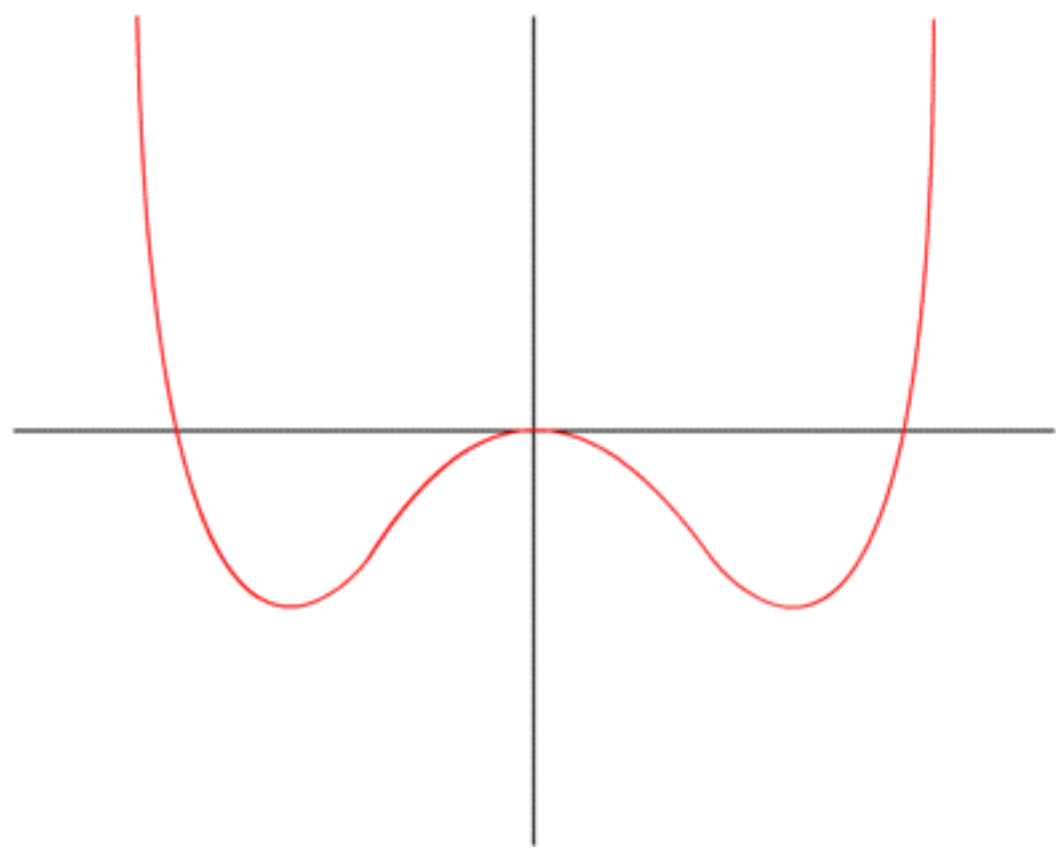
Parameters

- g_1, g_2, g_3 $\rightarrow \alpha$, Λ_{QCD}, $\sin^2(\vartheta_W)$
- λ, μ^2
- Yukawa coupling matrices (for charge 2/3, -1/3, -1):
  3 complex 3×3 matrices with 54 parameters
  $\rightarrow$ 6 quark masses, 3 lepton masses, 4 CKM angles
- $\vartheta_{QCD} < 10^{-10}$, strong interaction CP violation

- Neutrinos: probably 3 masses, 4 PMNS angles and 2 Majorana phases (assuming see-saw mechanism with unobservable heavy singlet neutrinos)

19 parameters in the SM, 28 with the standard neutrino extension





$$\lambda\phi^4 - \mu^2\phi^2$$

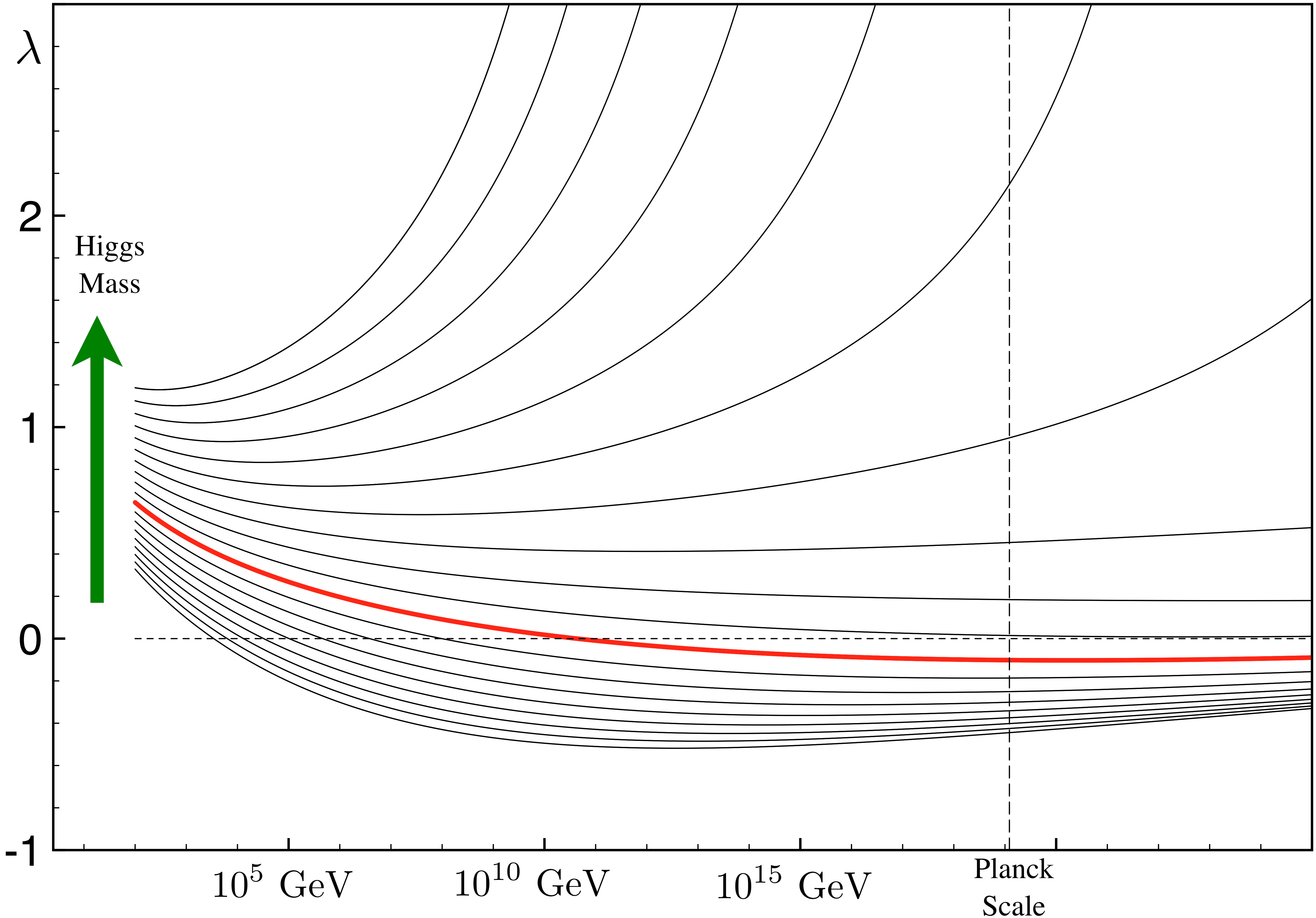
All Standard Model parameters "run" with energy

$$\frac{d}{dt}\bar{g}(t) = \beta(\bar{g}(t))$$

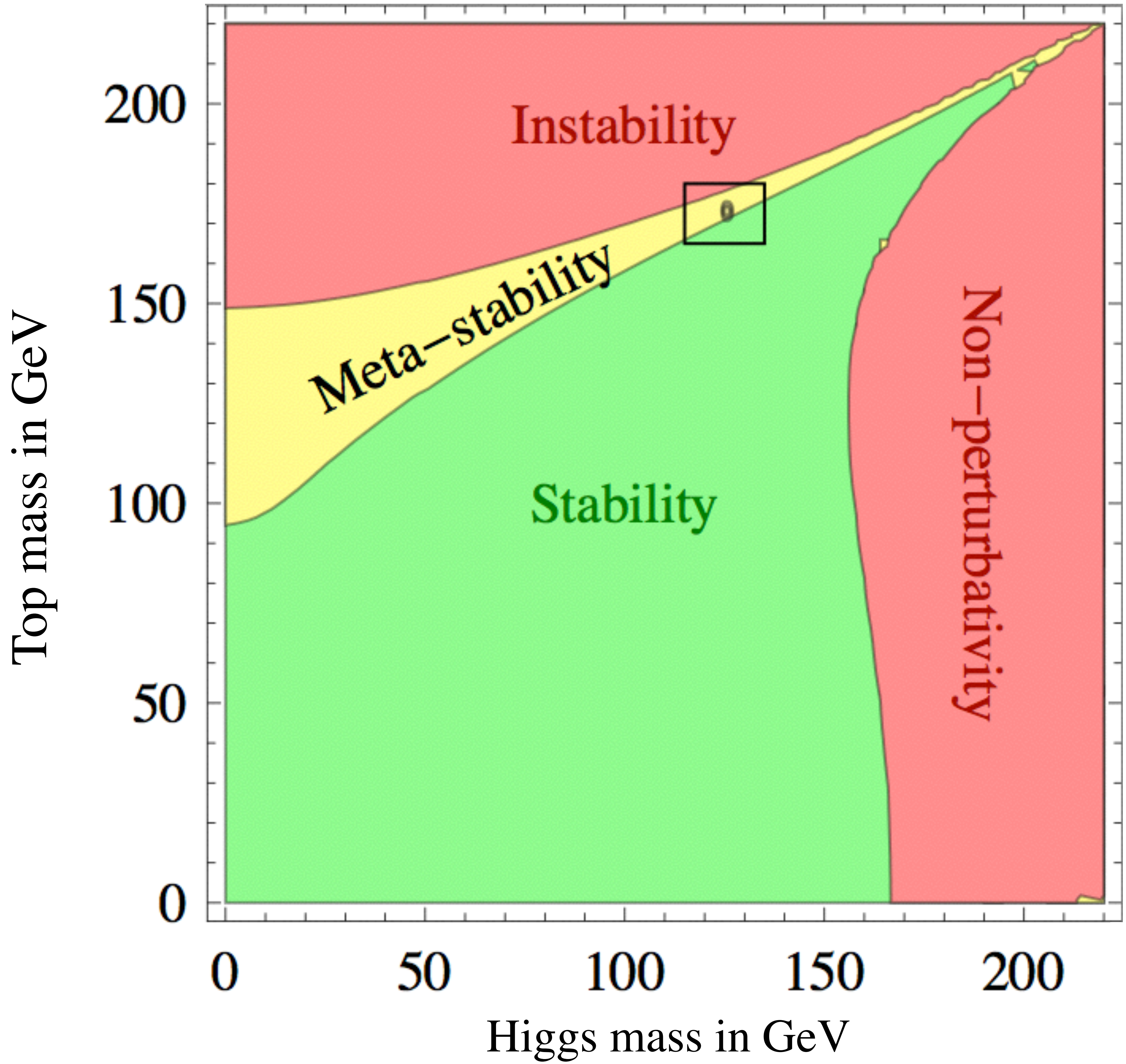
$$t \;\propto\; \log(\text{Energy})$$

In particular, the Higgs self-coupling λ runs

$$\beta(\lambda) = \frac{1}{16\pi^2}\left[6\lambda^2 - 24y^4 + 12\lambda y^2 - \lambda(9g_2^2 + 3g_1^2) + \frac{9}{2}g_2^4 + 3g_2^2 g_1^2 + \frac{3}{2}g_1^4\right] + \ldots$$



λ
2
1
0
-1
Higgs
Mass
10^5 GeV
10^10 GeV
10^15 GeV
Planck
Scale



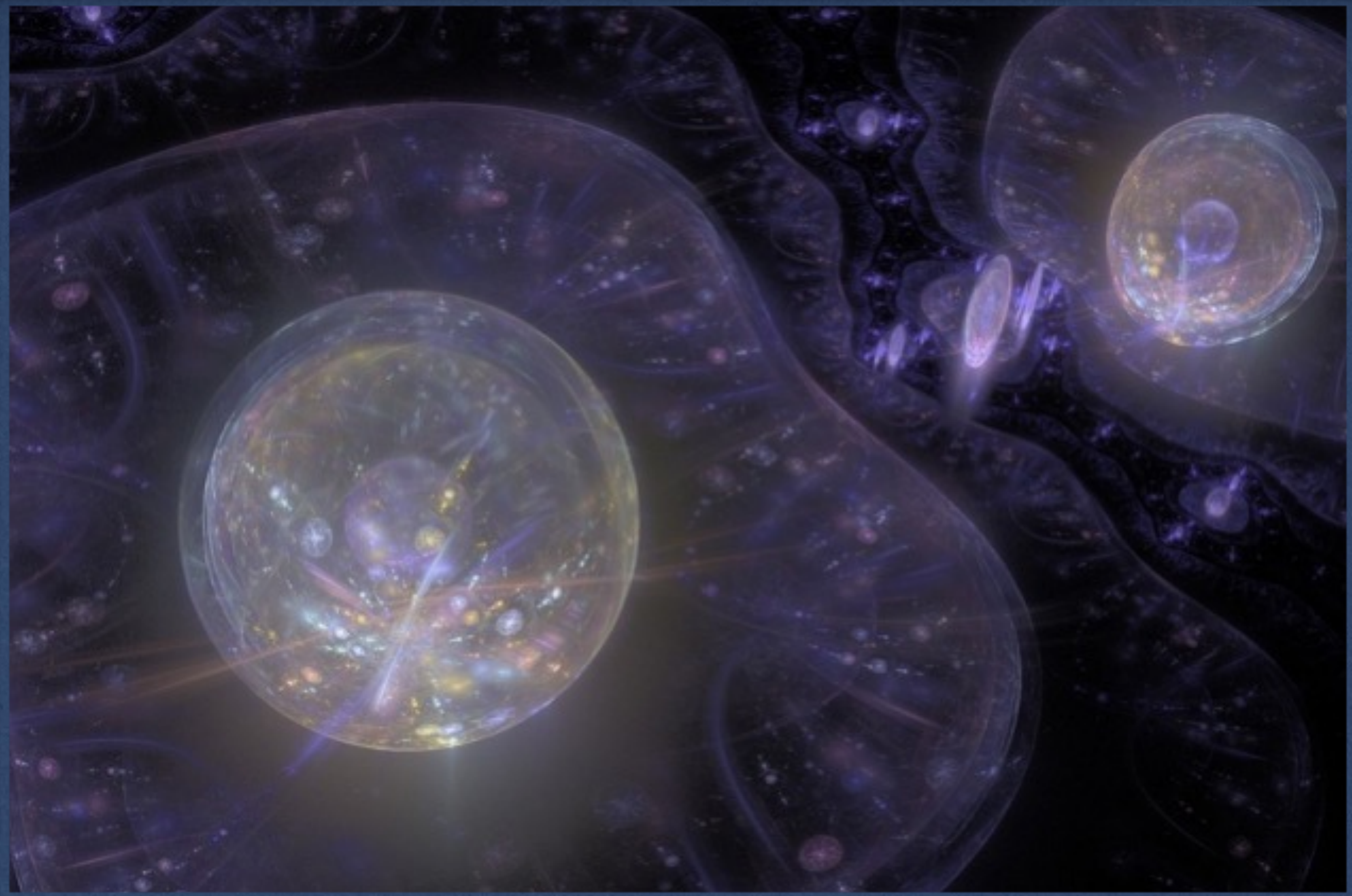
From DeGrassi et. al, arXiv:1205.6497

Anthropic Features of the Standard Model

- **Structure:**
  - $U(1)$ with massless photon seems essential.
  - Strong interactions (nuclear physics, sun)
  - Weak interactions to protect chiral fermions?
- **Scales:**
  - Strong scale ($\Lambda_{\rm QCD}$) determines proton mass.
  - Weak scale determines quark, lepton masses
  - Both must be much smaller than $M_{\rm plank}$ $(10^{19}$ GeV$)$ and not too different from each other.
- **Parameters:**

  $m_u,\ m_d,\ m_e,\ \alpha,\ \alpha_{\rm QCD}$ are clearly important.

  (Other masses in order of decreasing relevance:
  $m_H,\ m_t,\ m_\nu$; .... $m_s,\ m_\mu$; .... $m_c,\ m_b,\ m_\tau$)



Particle Physics in the Multiverse

Problems and Worries

Problems:

(Clearly requiring something beyond the Standard Model)

- Gravity
- Dark matter
- Baryogenesis
- Inflation.

Worries:

(Problems that may exist only in our minds)

- Choice of gauge group and representations
- Why three families?
- Charge quantization
- Quark and lepton mass hierarchies, CKM matrix.
- Small neutrino masses.
- Strong CP problem.
- Gauge hierarchy problem
- Dark Energy (non-zero, but very small)

The Hierarchy Problem

"Weakness of gravity"

Maximal number of constituents of a compact object:

$$\left(\frac{m_{\text{Planck}}}{m_p}\right)^3$$

For a "brain" with 10^{24} protons to be stable, we need $m_p < 10^{-8}\, m_{\text{Planck}}$

arXiv:0807.3697v1 [astro-ph] 23 Jul 2008

Stars In Other Universes: Stellar structure with different fundamental constants

Fred C. Adams

Michigan Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, MI 48109

E-mail: fca@umich.edu

Abstract. Motivated by the possible existence of other universes, with possible variations in the laws of physics, this paper explores the parameter space of fundamental constants that allows for the existence of stars. To make this problem tractable, we develop a semi-analytical stellar structure model that allows for physical understanding of these stars with unconventional parameters, as well as a means to survey the relevant parameter space. In this work, the most important quantities that determine stellar properties — and are allowed to vary — are the gravitational constant G, the fine structure constant α, and a composite parameter $\mathcal{C}$ that determines nuclear reaction rates. Working within this model, we delineate the portion of parameter space that allows for the existence of stars. Our main finding is that a sizable fraction of the parameter space (roughly one fourth) provides the values necessary for stellar objects to operate through sustained nuclear fusion. As a result, the set of parameters necessary to support stars are not particularly rare. In addition, we briefly consider the possibility that unconventional stars (e.g., black holes, dark matter stars) play the role filled by stars in our universe and constrain the allowed parameter space.

Adams considers variations of α, α_G

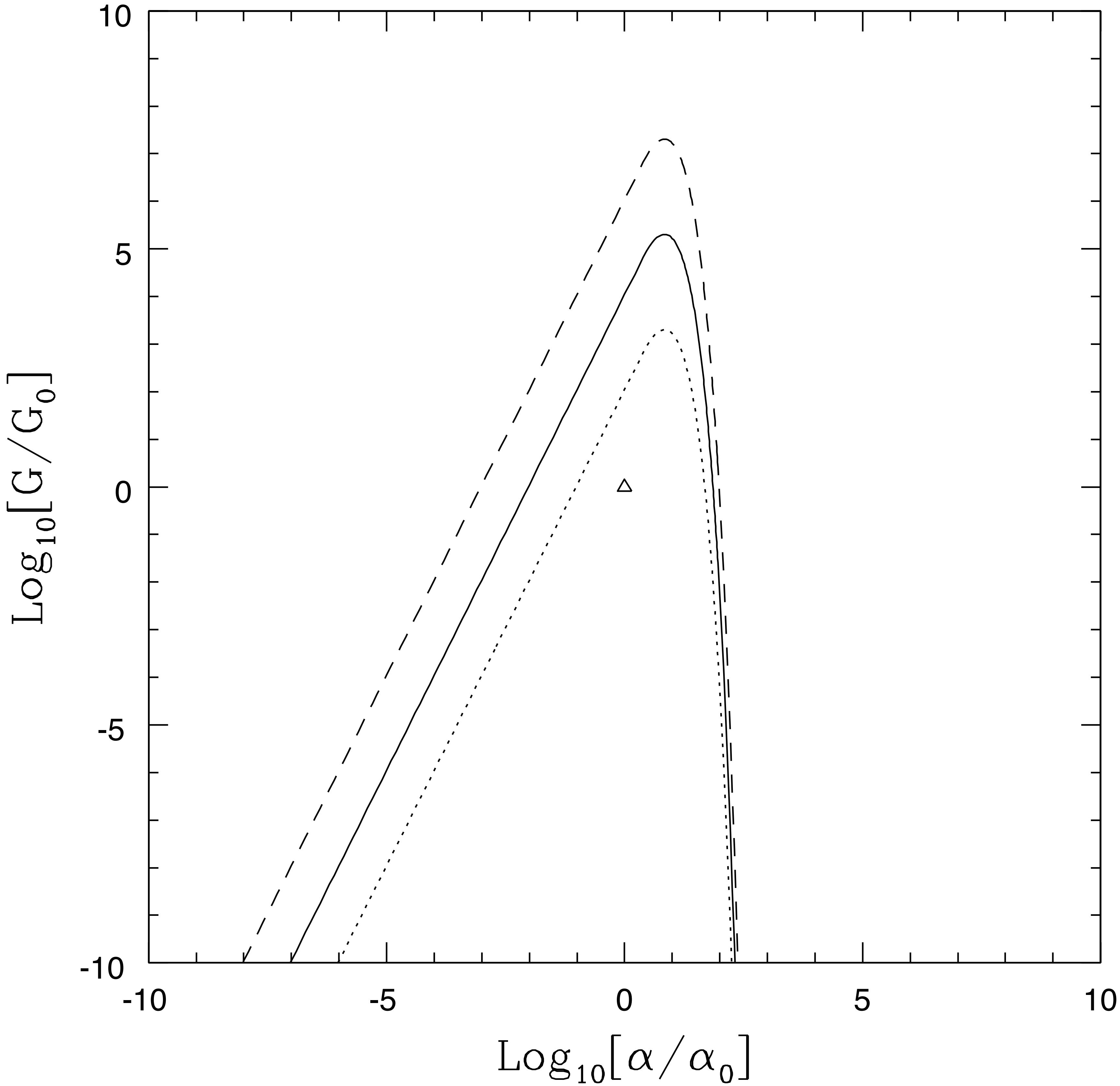
$$\alpha_G = \frac{Gm_P^2}{\hbar c} \approx 6 \times 10^{-39}$$

and the "nuclear burning constant" $\mathcal{C}$

$$\mathcal{C} = \frac{\langle \Delta E \rangle R_{12}}{\rho^2 \Theta^2} \exp[3\Theta] = \frac{8 \langle \Delta E \rangle S(E_0)}{\sqrt{3} \pi \alpha m_1 m_2 Z_1 Z_2 m_R c}$$

Stellar luminosity is proportional to $\mathcal{C}$

(dimension m^{-3})



10
5
0
-5
-10
-10
-5
0
5
10
$\mathrm{Log}_{10}[G/G_0]$
$\mathrm{Log}_{10}[\alpha/\alpha_0]$

The Hierarchy Problem

Renormalization of scalar masses

$$\mu^2_{\text{phys}} = \mu^2_{\text{bare}} + \sum_i a_i \Lambda^2$$

Computable statistical cost of about 10^{-34} for the observed hierarchy. This is the “hierarchy problem”.

Renormalization of fermion masses

$$\lambda_{\text{phys}} = \lambda_{\text{bare}} \left(\sum_i b_i \log(\Lambda/Q) \right)$$

Statistical cost determined by landscape distribution of λ_{bare}

The Hierarchy Problem

Four competing options for getting the required hierarchy:

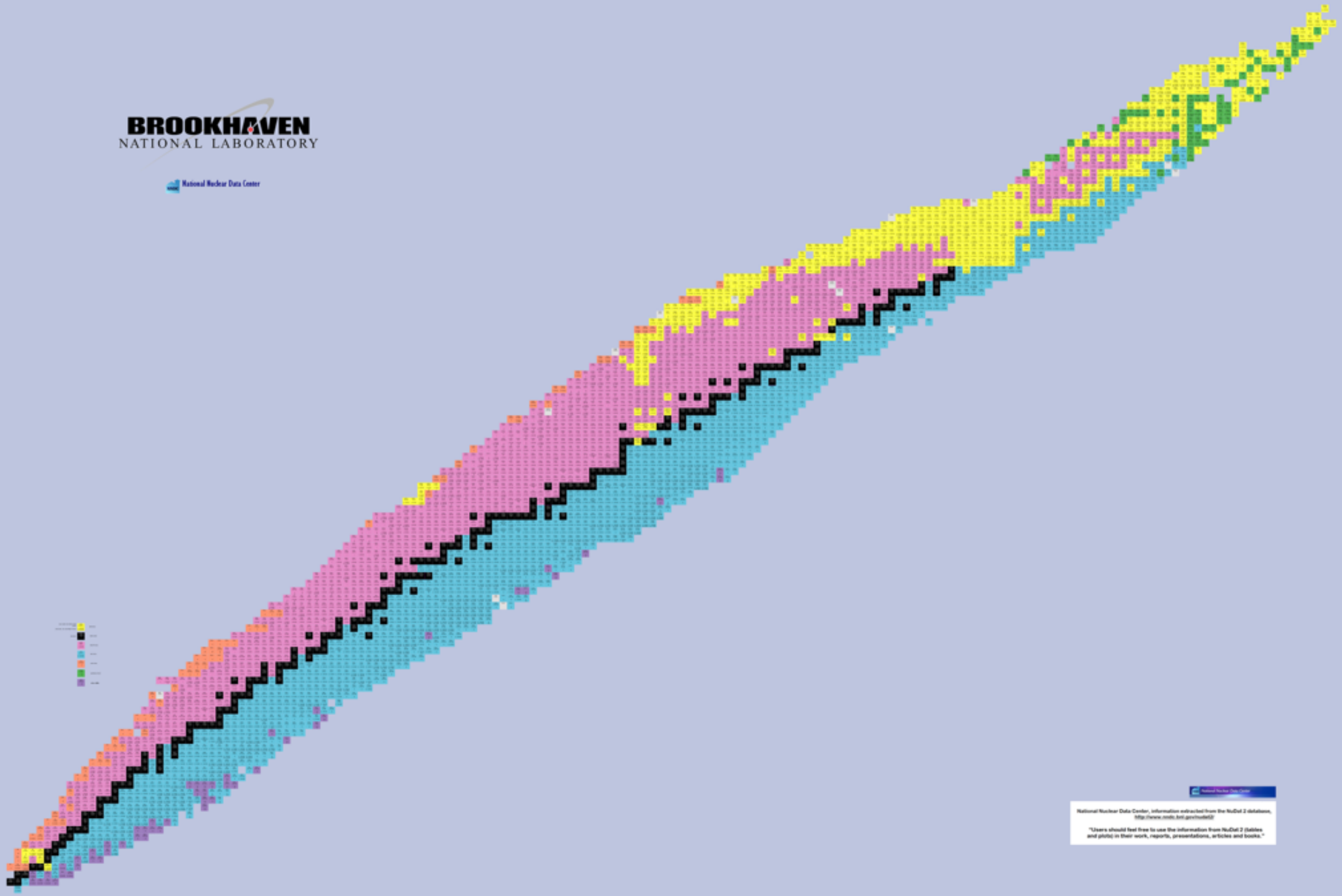
1. Just a Higgs boson
2. Fundamental Dirac Masses
3. Low energy supersymmetry
4. Dynamical symmetry breaking

Quark masses

Quark masses I: Nuclear Stability

BROOKHAVEN
NATIONAL LABORATORY

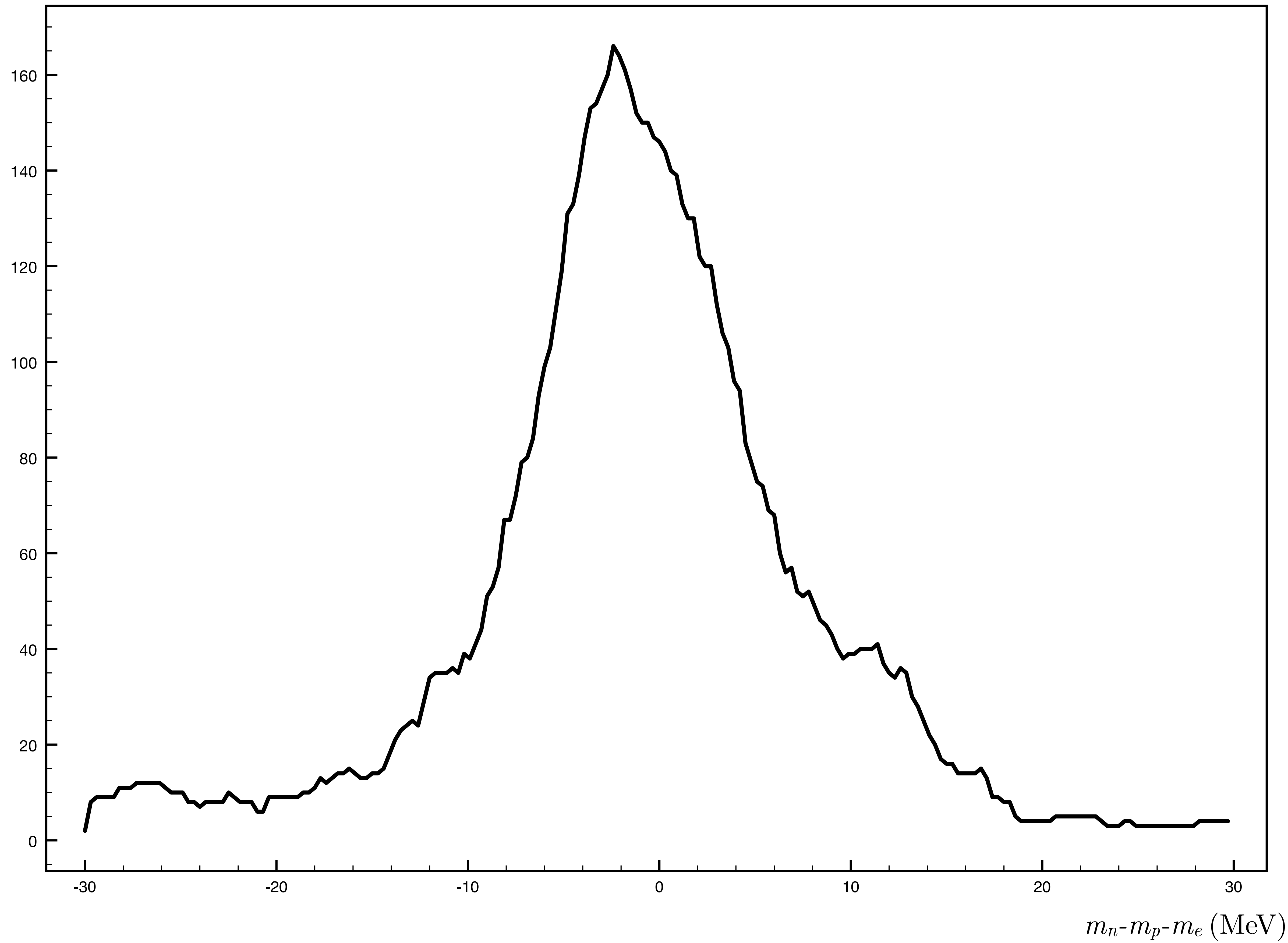
National Nuclear Data Center



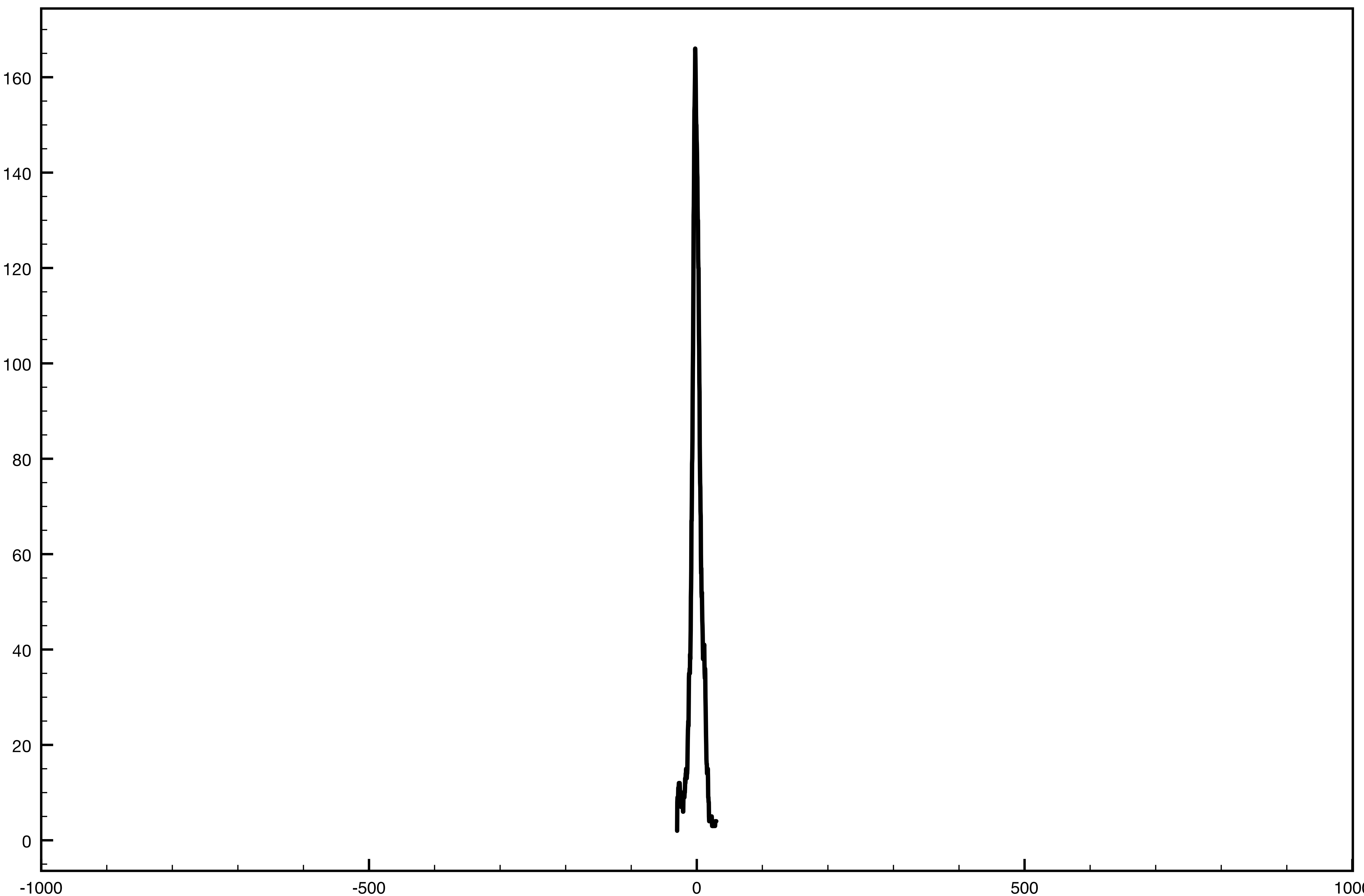
National Nuclear Data Center, information extracted from the NuDat 2 database, http://www.nndc.bnl.gov/nudat2/

"Users should feel free to use the information from NuDat 2 (tables and plots) in their work, reports, presentations, articles and books."

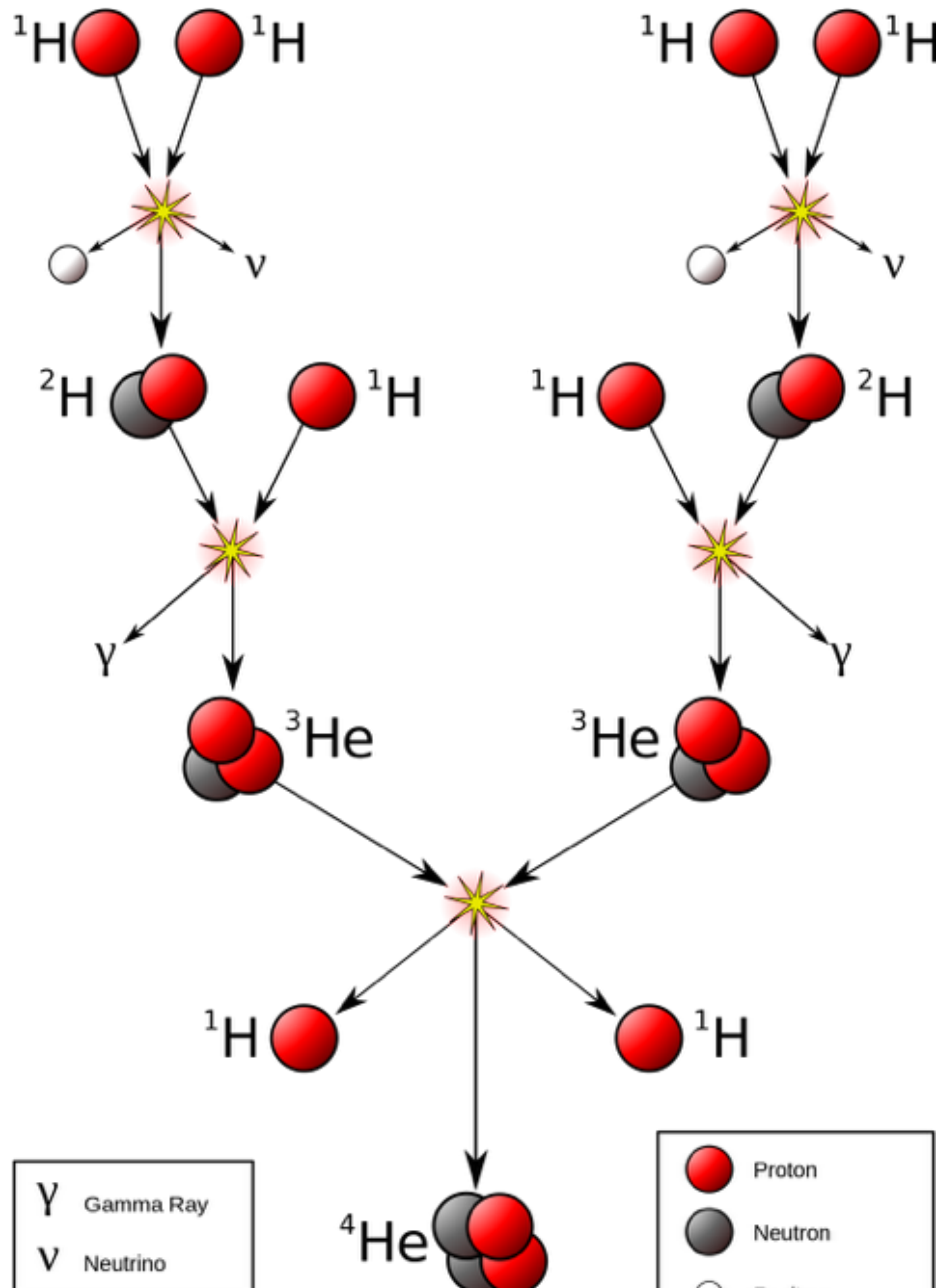
Atom	$\Delta_{\min}$	$\Delta_{\max}$	$\delta_{\min}$	$\delta_{\max}$
^{1}H	0	∞	$-.782$	∞
^{2}H	-2.2	$+2.2$	-3.0	$+1.44$
^{3}H	-8.5	$+.762$	-9.27	$-.018$
^{4}He	-22.7	$+23.6$	-23.5	$+22.8$
$^{12}_{6}C$	-12.6	$+18.12$	-13.4	$+17.34$
$^{14}_{7}N$	$+.62$	$+5.92$	$-.157$	$+5.14$
$^{16}_{8}O$	-9.6	$+16.2$	-10.4	$+15.4$



160
140
120
100
80
60
40
20
0
-30
-20
-10
0
10
20
30
m_n-m_p-m_e (MeV)

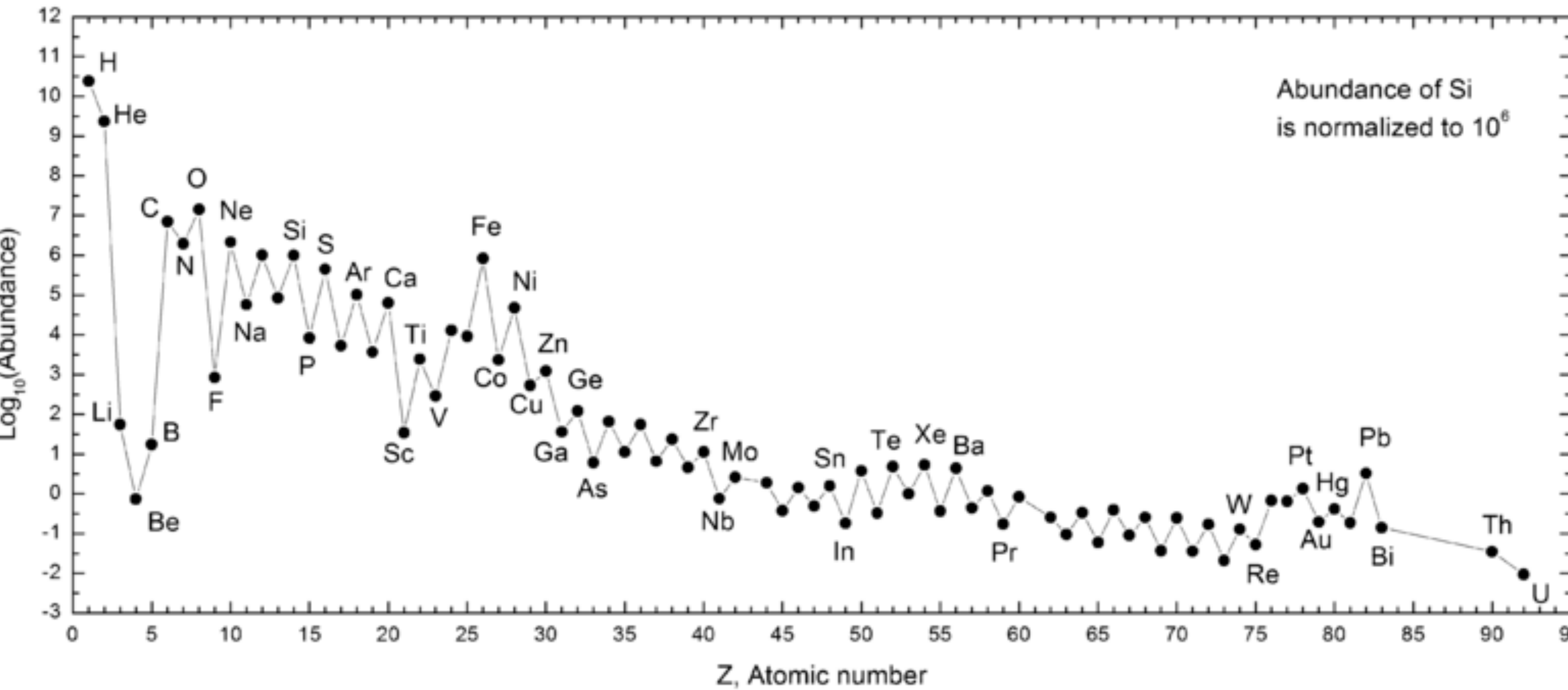


160
140
120
100
80
60
40
20
0
-1000
-500
0
500
1000



¹H
¹H
¹H
¹H
ν
ν
²H
¹H
¹H
²H
γ
γ
³He
³He
¹H
¹H
⁴He
γ Gamma Ray
ν Neutrino
Proton
Neutron
Positron

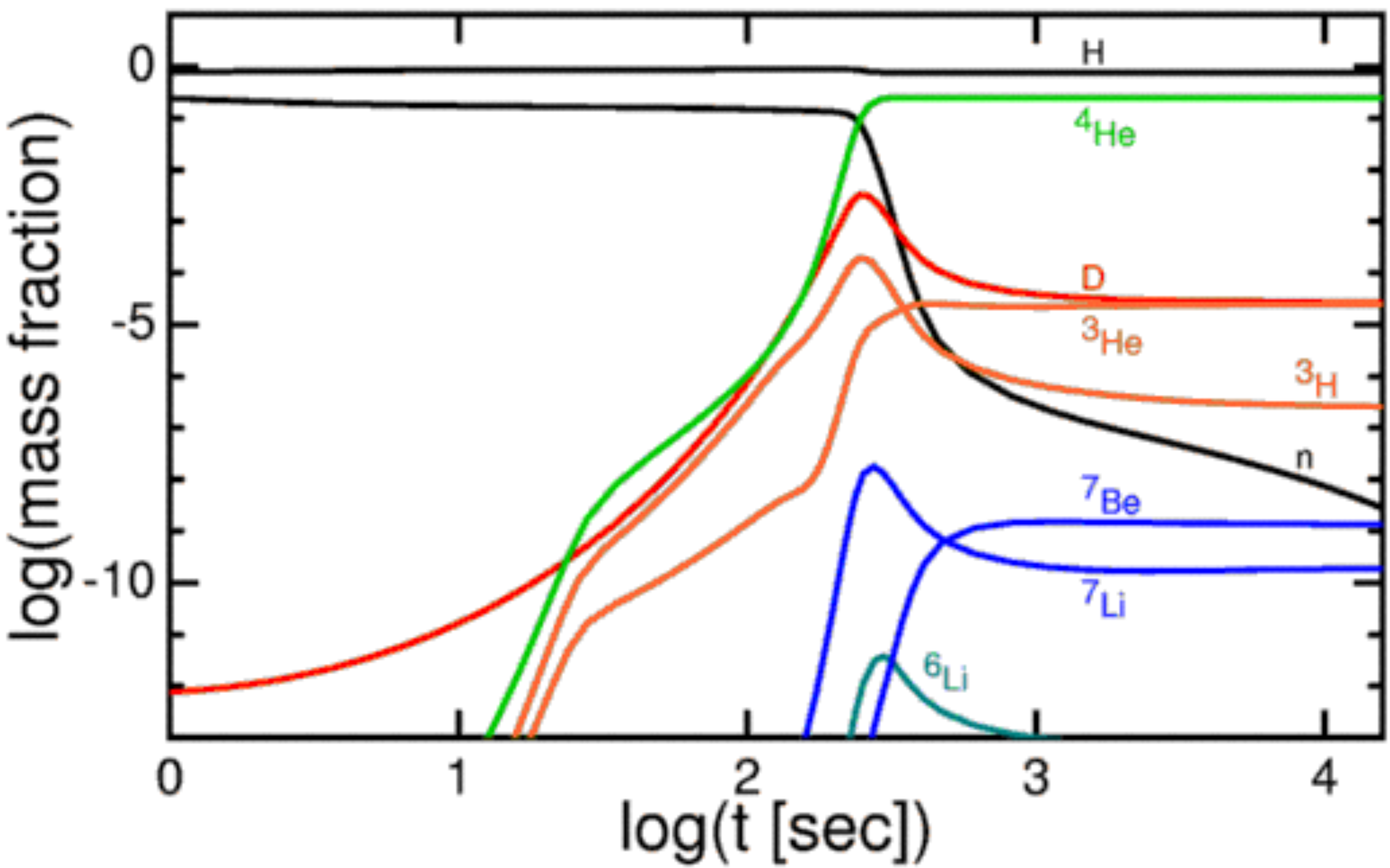
Quark masses II: Abundances



Abundance of Si
is normalized to 10^6
Log_{10}(Abundance)
Z, Atomic number
H
He
Li
Be
B
C
N
O
F
Ne
Na
Si
P
S
Ar
Ca
Sc
Ti
V
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Zr
Nb
Mo
Sn
In
Te
Xe
Ba
Pr
W
Re
Pt
Au
Hg
Pb
Bi
Th
U

Quark masses II: Abundances

Big Bang Nucleosynthesis



log(mass fraction)
0
-5
-10
0
1
2
3
4
log(t [sec])
H
4He
D
3He
3H
n
7Be
7Li
6Li

Quark masses II: Abundances

Stellar Nucleosynthesis

Gribbin, John, and Martin Rees. 1989. *Cosmic coincidences: Dark matter, mankind, and anthropic cosmology*. New York: Bantam Books.

Hoyle said, in effect, "since we exist, then carbon must have an energy level at 7.6 MeV." Then the experiments were carried out and the energy level was measured. As far as we know, this is the only genuine anthropic principle prediction; all the rest are "predictions" that *might* have been made in advance of the observations, if anyone had the genius to make them, but that were never in fact made in that way. . . . There is no better evidence to support the argument that the Universe has been designed for our benefit—tailor-made for man.[8]

An anthropic myth: Fred Hoyle's carbon-12 resonance level

Helge Kragh

ON NUCLEAR REACTIONS OCCURRING IN VERY HOT STARS. I. THE SYNTHESIS OF ELEMENTS FROM CARBON TO NICKEL

F. HOYLE*

MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

Received December 22, 1953

The yield of C^{12} per cubic centimeter per second is given immediately by inserting $A_0 = 4$, $Z_0 = 2$, and $A_1 = 8$, $Z_1 = 4$, in the formulae of the previous section. The important energy level of the C^{12} nucleus in the present problem is one very recently identified by Dunbar, Pixley, Wenzel, and Whaling (1953). This level occurs at about 7.68 mev above ground level, which corresponds to a value of E_R of about 0.31 mev. (It will be recalled that E_R is measured relative to the sum of the masses of Be^8 and α-particle, this being about 7.37 mev above the ground level of C^{12}.) Assuming, as we shall do in this paper, that the $Be^8 + \alpha$ reaction through this level is not forbidden by strict selection rules, the resonance contribution from it quite overwhelms not only the nonresonance yield but also the resonance contributions from other levels.

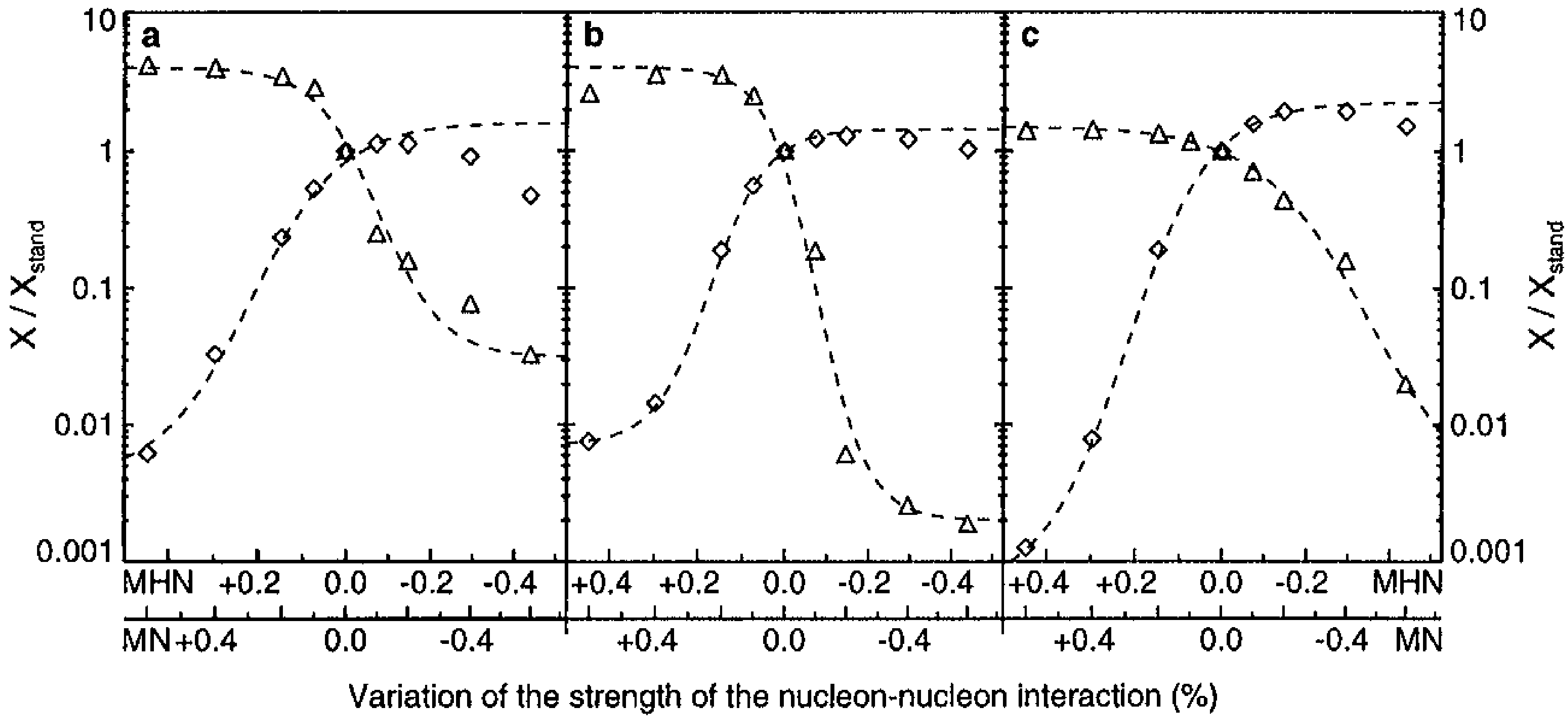
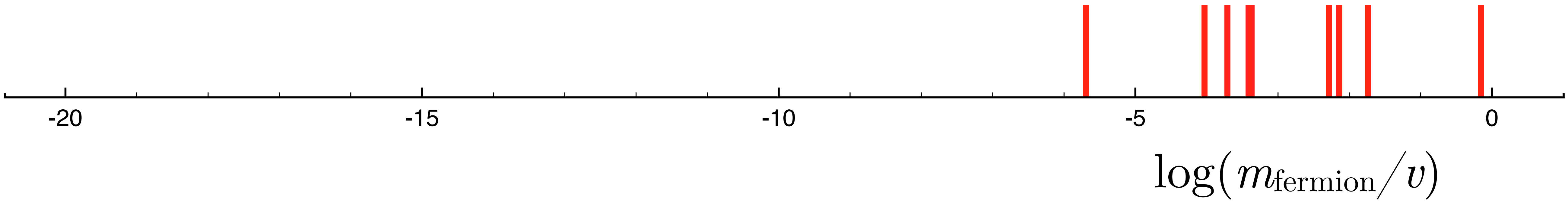


Figure 2. The change of the carbon (△) and oxygen (◇) mass abundances (X) through variations of the strength of the strong interaction. They are shown in panels a, b, and c for stars with masses of 20, 5, and $1.3M_{\odot}$, respectively, in units of the standard values X_{stand}. The variations of the strength of the strong interaction are given for the two effective N-N forces MHN and MN. The dashed curves are drawn to guide the eye.

Quark masses III: Distributions

The fermion mass hierarchy



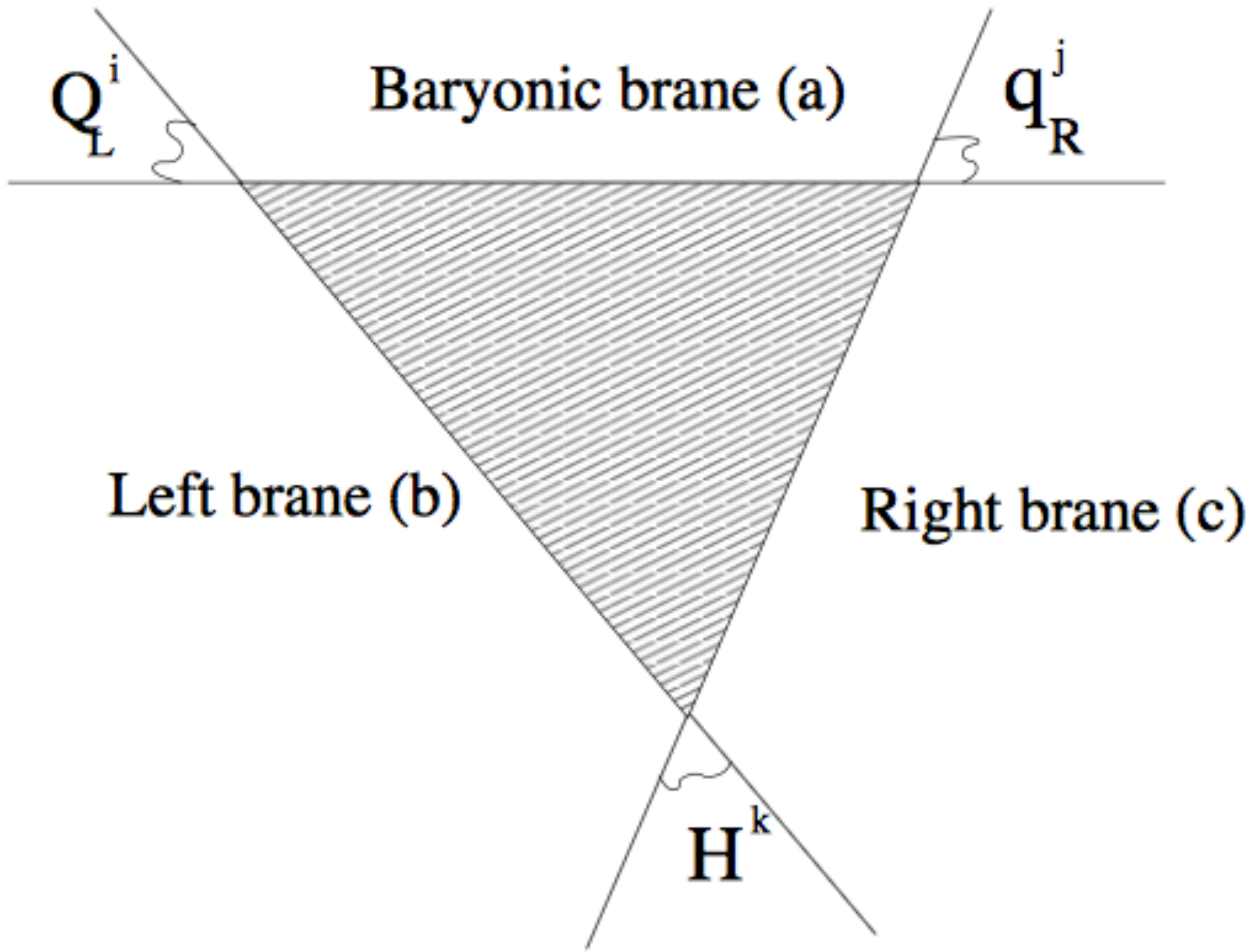
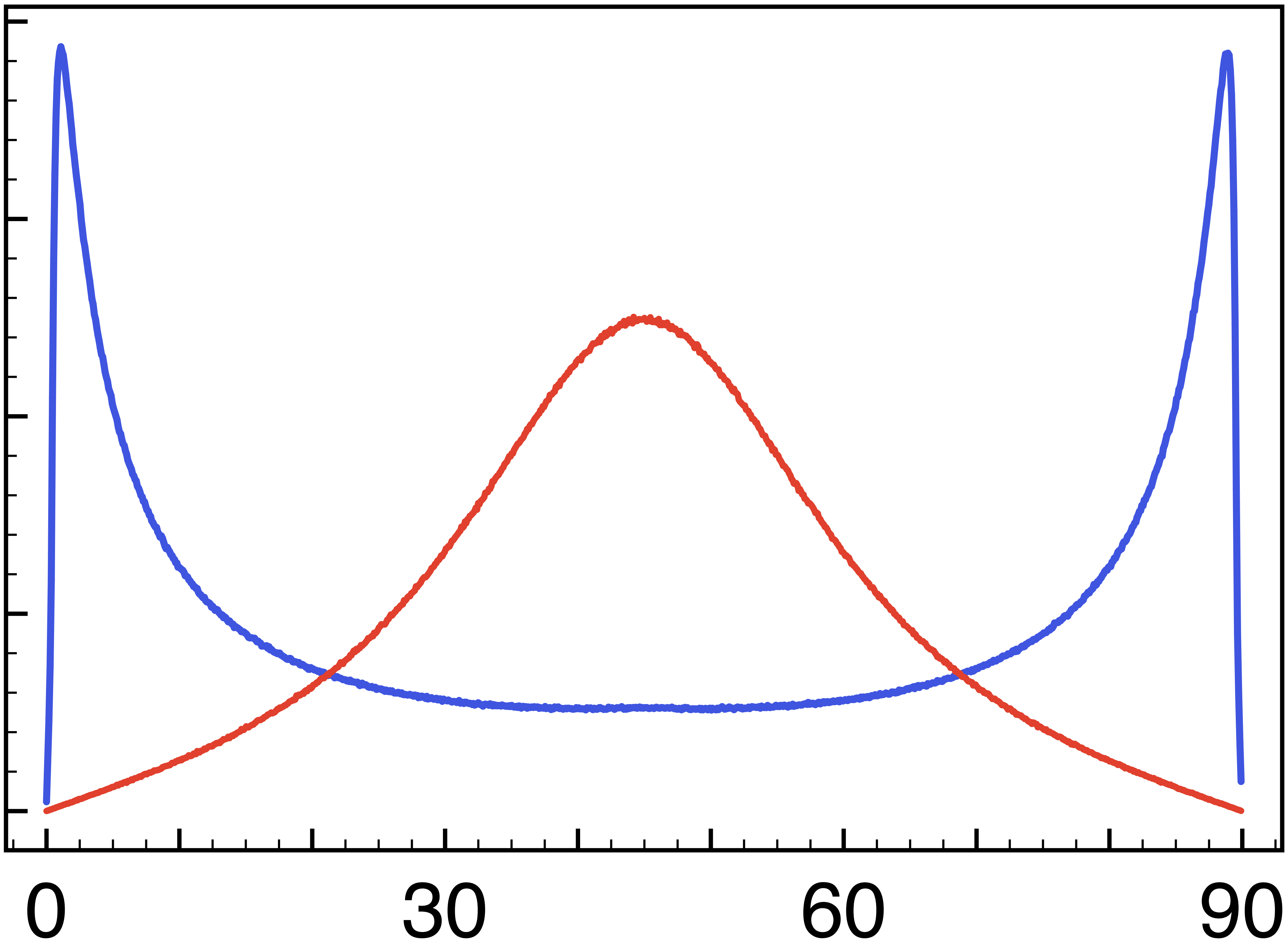


Figure 1: Yukawa coupling between two quarks of opposite chirality and a Higgs boson.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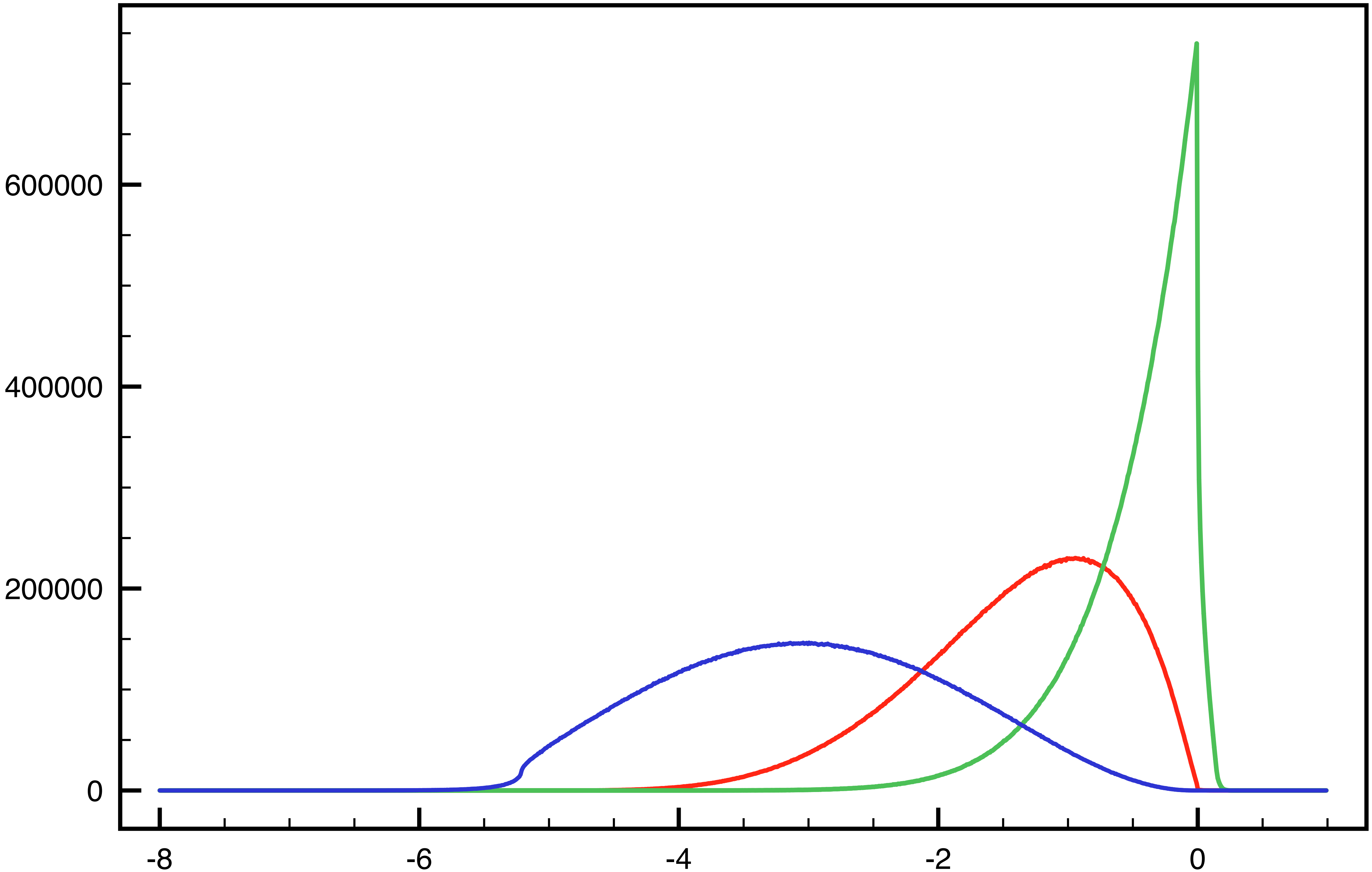
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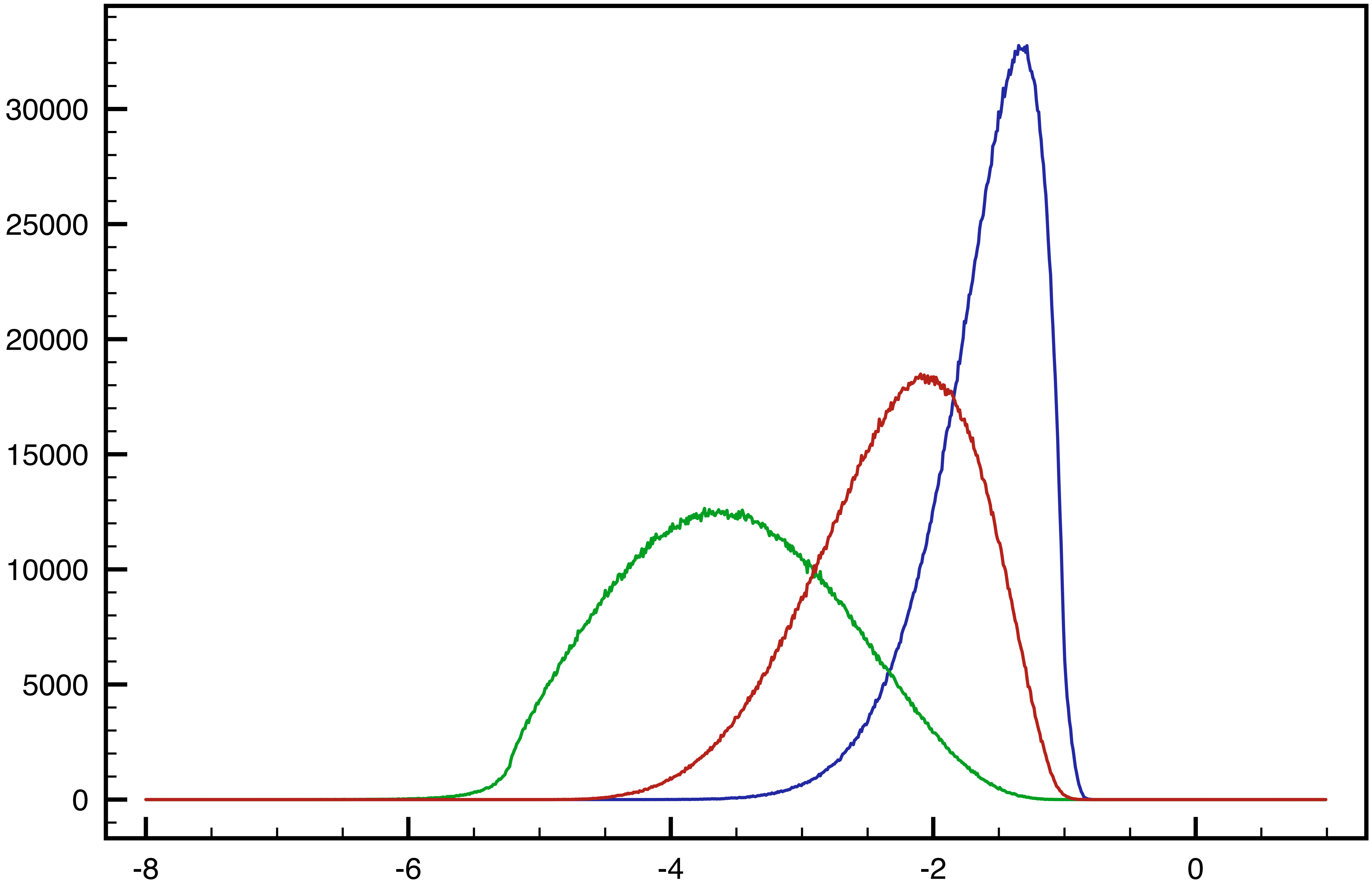

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Lepton masses

The Structure of the Standard Model

Beatriz Gato-Rivera, Bert Schellekens

Nucl.Phys. B883 (2014) 529-580

Our goal:

Derive the discrete structure of the Standard Model:
The gauge group and representations.

The standard approach is to use Grand Unification.

But this does not really work.

Grand Unification

The simplicity is undeniable:

$$SU(3)\times SU(2)\times U(1) \quad \subset \quad SU(5) \quad \subset \quad SO(10)$$

One family matter representation (left-handed)

$$(3,2,\frac{1}{6})+(3^*,1,\frac{1}{3})+(3^*,1,-\frac{2}{3})+(1,2,-\frac{1}{2})+(1,1,1)\ +(1,0,0)$$

Fits beautifully in the $(\mathbf{16})$ of $SO(10)$

And the coupling constants meet each other if there is low energy supersymmetry.

So how could this be wrong?

Grand Unification

Even if correct, GUTs do not lead to a derivation of the SM structure:

- Even the smallest group, $SU(5)$, can break in two ways, to $SU(3)\times SU(2)\times U(1)$ or $SU(4)\times U(1)$.
- The Standard Model Higgs is not determined, and does not fit in an $SU(5)$ multiplet.
- In QFT the representations are determined if one assumes some kind of minimality, but what is the motivation for that?
- No top-down arguments selecting $SU(5)$ or $SO(10)$.

We will show that in a certain minimal string setting where GUT realizations are available, anthropic arguments work far better:

- Gauge group determined to be $SU(3)\times SU(2)\times U(1)$.
- Matter determined to be a number of standard families.
- Correct charge quantization without GUTs.
- Standard Model Higgs determined.

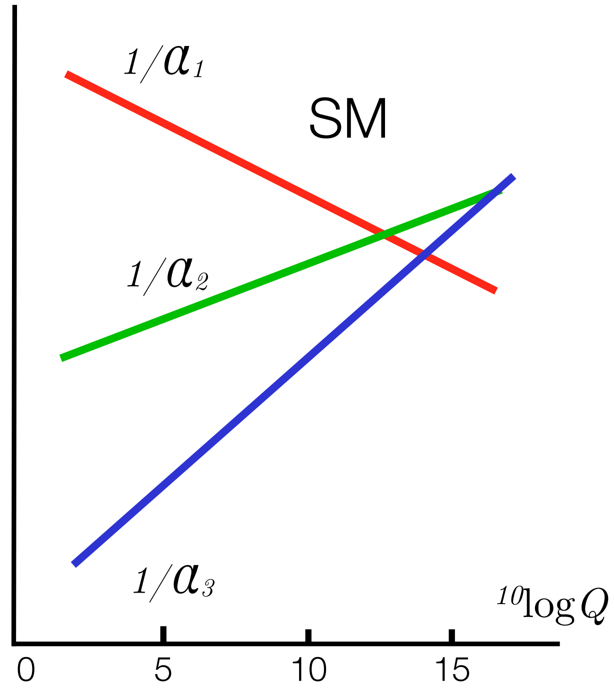
Assuming at least one unbroken non-abelian and at least one unbroken electromagnetic interaction

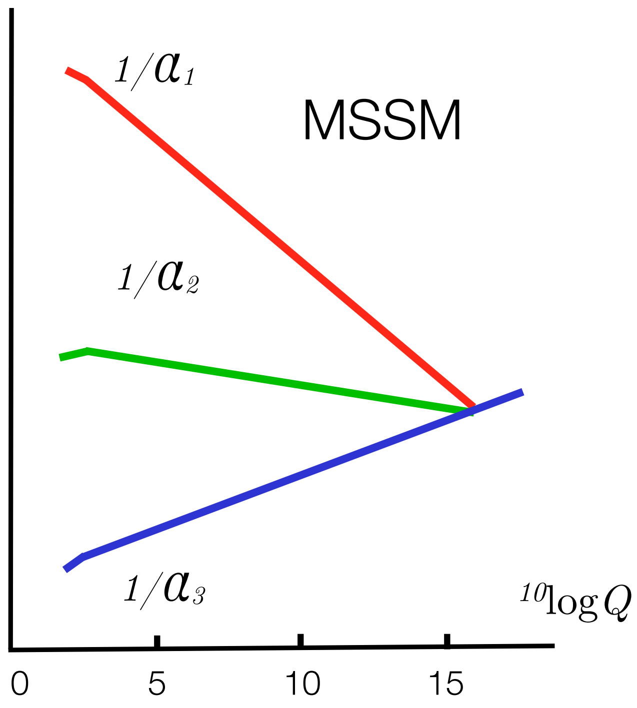
GUTs, Anomalies and Charge Quantization

GUTs, Anomalies and Charge Quantization

If there is no low-energy supersymmetry, the three gauge coupling constants do not converge.

This removes one of the arguments in favor of GUTs.





But the arguments based on family structure and charge quantization remain valid.

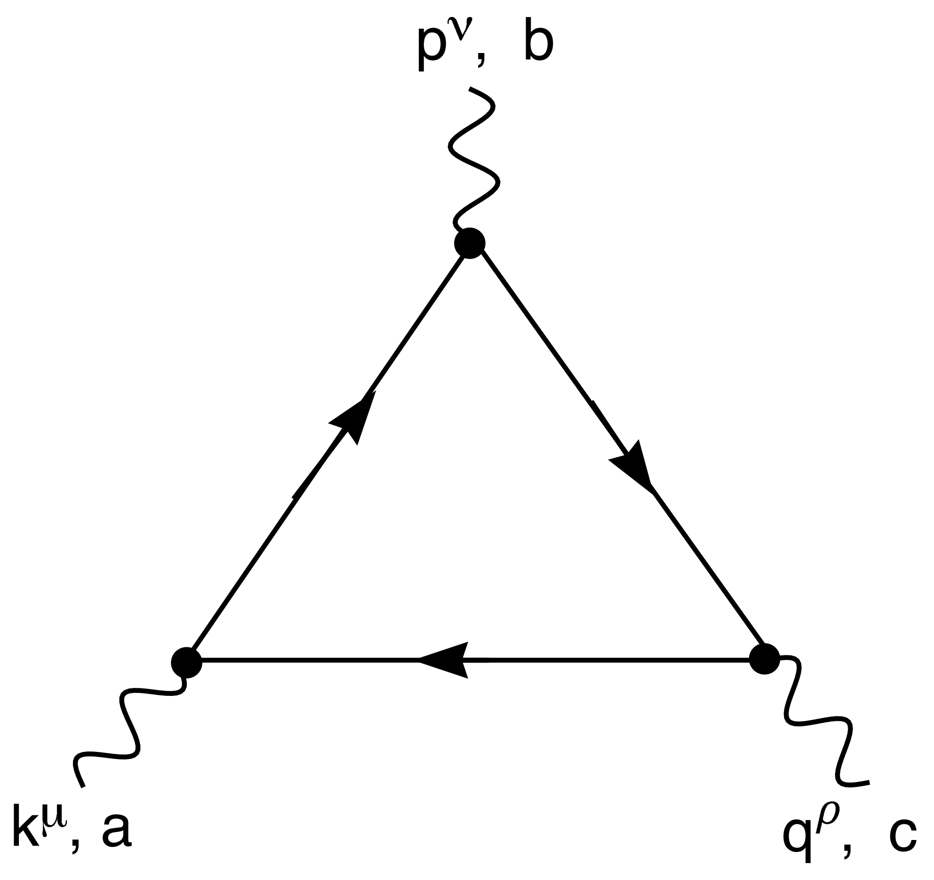
GUTs, Anomalies and Charge Quantization

The observed charged quantization is excellent evidence for BSM physics.

Imagine we end up with a consistent theory of quantum gravity that imposes no constraints on QFT. Then this would allow particles with arbitrary real charges. It is hard to accept that we just happen to live in a universe with quantized charges.

One often hears the arguments that anomaly cancellation imposes charge quantization.

Triangle anomalies



		SU(3)	SU(2)	$SU(3)^2$ x U(1)	$SU(2)^2$ x U(1)	$U(1)^3$	(Grav) x U(1)
Q	(3,2,1/6)	2	0	1/3	1/2	1/36	1
U*	(3*,1,-2/3)	-1	0	-2/3	0	-8/9	-2
D*	(3*,1,1/3)	-1	0	1/3	0	1/9	1
L	(1,2,-1/2)	0	0	0	-1/2	-1/4	-1
E*	(1,1,1)	0	0	0	0	1	1
	Sum	0	0	0	0	0	0

Old QFT arguments

Geng and Marshak (1989)

A single SM family (without right-handed neutrino) is the smallest non-trivial chiral anomaly-free representation of $SU(3)\times SU(2)\times U(1)$.

OK, but:

- There are **three** families.
- There probably are right-handed neutrinos.
- Why is the smallest representation preferred anyway?

See also:

Minahan, Ramond, Warner (1990), *Geng and Marshak (1990)*

GUTs, anomalies and Charge Quantization

Anomaly cancellation does *not* impose charge quantization:

One can add scalars or Dirac fermions of arbitrary real charge.

But even for chiral matter anomaly cancellation is not enough:
one could add an entire family with rescaled charges.

Such rescalings are not possible if one wishes to couple the
extra family to the SM Higgs.

GUTs, anomalies and Charge Quantization

One can try to impose one-family charge quantization on all three families by requiring that they all couple to the same Higgs.

But even that does not work:
One can have chiral fermions with irrational charges (in SM units) that get their mass from the SM Higgs

$$(3, 2, \frac{1}{6} - \frac{x}{3}) + (\bar{3}, 1, -\frac{2}{3} + \frac{x}{3}) + (\bar{3}, 1, \frac{1}{3} + \frac{x}{3})$$
$$+(1, 2, -\frac{1}{2} + x) + (1, 1, 1 - x) + (1, 1, -x)$$

Charge Quantization

We need some kind of BSM physics to explain charge quantization.

The most promising candidate for such a theory is string theory.

String theory is likely to quantize the charges.

If we already have string theory, do we also need GUTs?

The String Theory Landscape

String theory certainly not predict the Standard Model uniquely. As far as we know it leads to a huge ensemble ("landscape") of possibilities, realized in a multiverse.

So then how can we hope to derive the Standard Model?

We still have two clues, that are inevitable in a large landscape:

- Anthropic arguments
- Landscape distributions

The String Theory Landscape

The anthropic argument we will use is that the spectrum must be sufficiently complicated. In our universe this is achieved by quarks binding into protons and neutrons, which bind into nuclei, which together with electrons form atoms.

We cannot really derive this from $SU(3) \times SU(2) \times U(1)$, and hence we can certainly not expect to be able to derive this from any QFT that is more complicated.

But in some simpler theories the existence of a complicated set of bound states can be plausibly ruled out.

The String Theory Landscape

More complicated QFT's that *cannot* be anthropically ruled out certainly exist, for example

$$SU(5)\times SU(2)\times U(1)$$

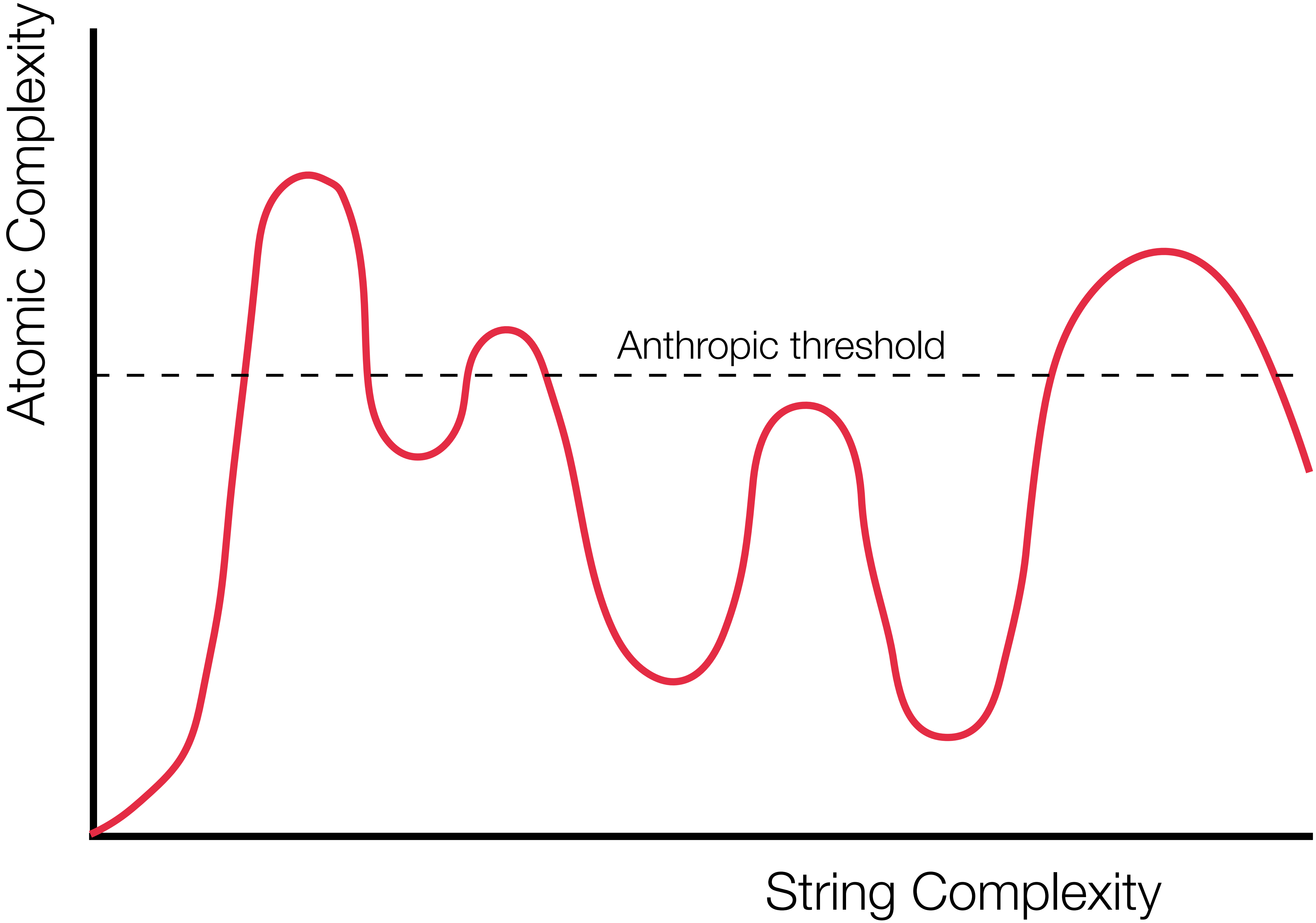
With fifth-integer fractionally charged quarks.

So anthropic arguments alone will not do, given our current knowledge about strongly interacting gauge theories.

The String Theory Landscape

The hope is then that we can establish that the Standard Model is the simplest one with a complicated spectrum.

Then one may also hope that landscape statistics prefers simpler QFT's over more complicated ones.


Atomic Complexity
Anthropic threshold
String Complexity

The String Theory Landscape

The hope is then that we can establish that the Standard Model is the simplest one with a complicated spectrum.

Then one may also hope that landscape statistics prefers simpler QFT's over more complicated ones.

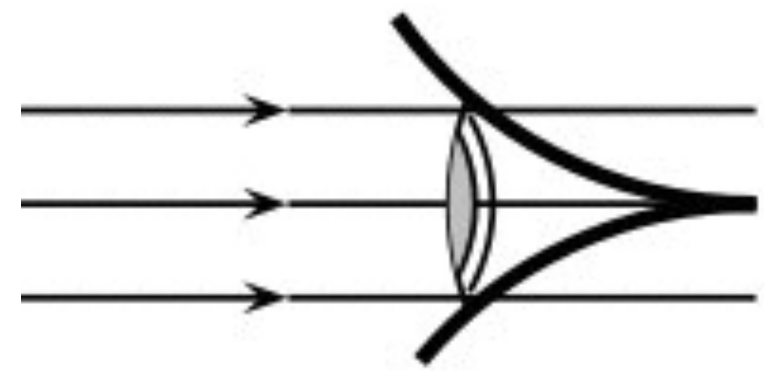
Here "simpler" means smaller gauge groups, smaller representations, fewer participating building blocks (e.g. membranes).

In string theory all these quantities are indeed fundamental limited, and hence their distribution will approach zero for large values.

Towards a derivation of the Standard Model

Main anthropic assumption:

To have observers we will need electromagnetism and a handful of particles with various charges.



We are not asking for a particular quantization, and we are *not* requiring particles of charge 6 (Carbon) to exist, but too simple sets will not do (e.g. charges $-1,1,2$: just Hydrogen and Helium)

So perhaps one could just “emulate” atomic physics with some fundamental particles with charges $-1,1,2,...,N$ for sufficiently large N: fundamental “electrons” and “nuclei”.

Towards a derivation of the Standard Model

So to get a substantial number of light atoms, we have to solve a hierarchy problem for each of the constituents.

In the Standard Model this is solved by getting the particle masses from a single Higgs.

There may be landscape distribution arguments to justify this.

Is having N light fermions* statistically more costly than having a single light boson? (The N fermions can be either elementary nuclei or the two light quarks and the electron; then $N=3$)

(*) Our nuclei can be bosons and fermions, but that is not essential

The Hierarchy Problem

One would also have to show that one fundamental scalar wins against dynamical Higgs mechanism or low energy supersymmetry.

Not enough is known theoretically to decide this, so we take experiment as our guiding principle.

Currently it seems we have a single Higgs + nothing.

This suggests that in a landscape the Higgs is not the *origin* but the *solution* of the Hierarchy problem: it could be the optimal way to create the anthropically required large hierarchy.

This would immediately imply that there is only a single Higgs.

No Higgs?

Statistically, no Higgs is better than one.
If there is a credible alternative to the SM with only dynamical symmetry breaking, that would be a serious competitor.

But generically these theories will have a number of problems.

Consider the SM without a Higgs. It is well-known that in that case the QCD chiral condensate will act like a composite Higgs and give mass to the quarks. The photon survives as a massless particle.

But the quark masses are not tuneable, and the leptons do not acquire a mass.

Massless charged leptons turn the entire universe into an opaque particle-antiparticle plasma.
(C. Quigg, R. Shrock, Phys.Rev. D79 (2009) 096002)

Lessons:

1. Dynamical Symmetry Breaking can play the role of the Higgs mechanism
2. Dynamical Symmetry Breaking should not make the photon massive
3. There should not be any massless charged leptons

String Theory

String Theory Input

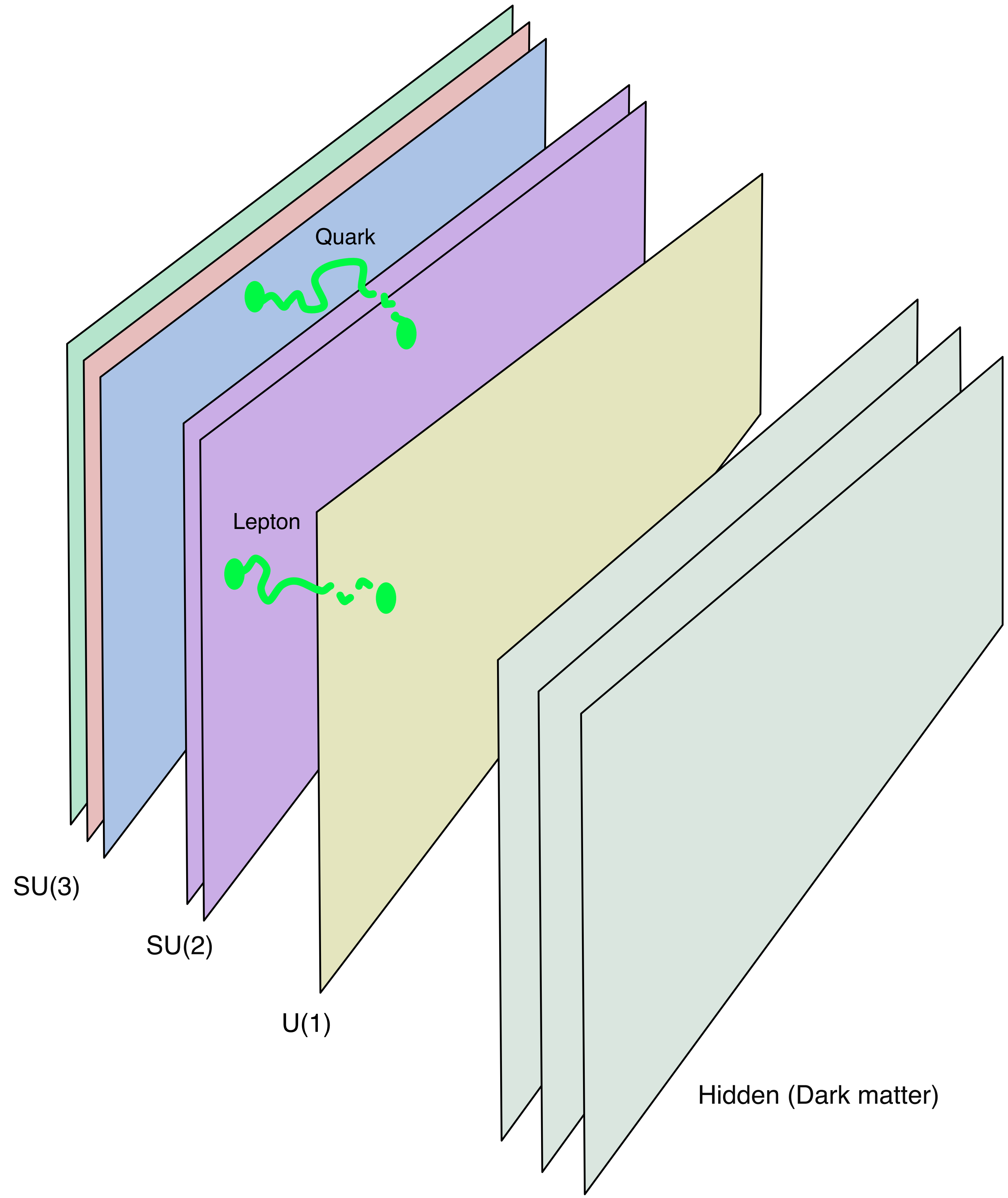
We would like to enumerate all QFT’s with a gauge group and chiral matter. All non-chiral matter is assumed to be heavy, with the exception of at most one scalar field, the Higgs. We demand that after the Higgs gets a vev, and that when all possible dynamical symmetry breakings have been taken into account, at least one massless photon survives, and all charged leptons* are massive.

This condition is very restrictive, but still has an infinite number of solutions in QFT.

So at this point we invoke string theory. Its main rôle is to restrict the representations. It also provides a more fundamental rationale for anomaly cancellation.

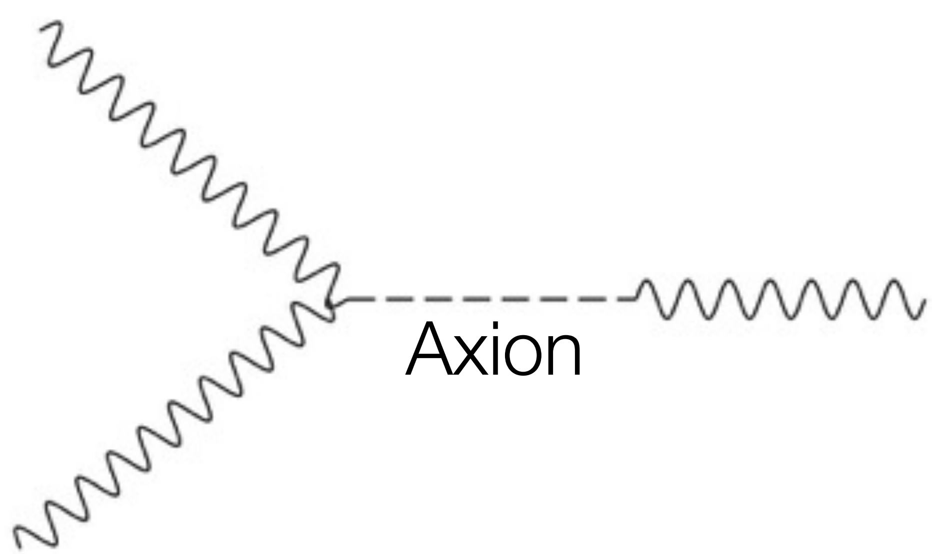
*lepton: a fermion not coupling to any non-abelian vector boson

Intersecting Brane Models



Intersection brane models

- Intersections of branes in extra dimensions determine the massless spectrum.
- Brane multiplicities are subject to a constraint: tadpole cancellation (automatically implies absence of triangle anomalies in QFT).
- Massless photons may mix with axions and acquire a mass.



(Green-Schwarz mechanism)

Intersecting Brane Models

We will assume that all matter and the Higgs bosons are massless particles in intersecting brane models. Then the low-energy gauge groups is a product of $U(N)$, $O(N)$ and $Sp(N)$ factors.

The low energy gauge group is assumed to come from S stacks of branes.
There can be additional branes that do not give rise to massless gauge bosons: $O(1)$ or $U(1)$ with a massive vector boson due to axion mixing.

All matter (fermions as well a the Higgs) are bi-fundamentals, symmetric or anti-symmetric tensors, adjoints or vectors (open strings with one end on a neutral brane)

We start with $S = 1$, and increase S until we find a solution.

Intersecting Brane Models: $S{=}1$

Chan-Paton group can be $U(N)$, $O(N)$ or $Sp(N)$, but only $U(N)$ can be chiral.

Matter can be symmetric or anti-symmetric tensors or vectors.
Chiral multiplicities $S,\ A,\ K$; charges $2q,\ 2q,\ q$.

Anomaly cancellation:

$$\begin{aligned} KNq^3+\tfrac{1}{2}N(N+1)S(2q)^3+\tfrac{1}{2}N(N-1)A(2q)^3 &= 0 \\ KNq+\tfrac{1}{2}N(N+1)S(2q)+\tfrac{1}{2}N(N-1)A(2q) &= 0 \\ Kq+(N+2)S(2q)+(N-2)A(2q) &= 0 \end{aligned}$$

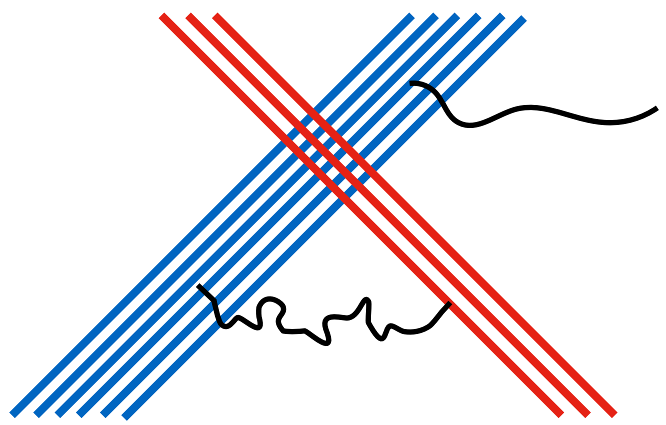
Solutions: $K{=}S{=}A{=}0$ or $q{=}0$. In the former case, there is no chiral spectrum, in the latter case no electromagnetism.

Higgs symmetry breaking could still produce a $U(1)$, but the choice of Higgses is limited to vectors and rank-2 (anti)-symmetric tensors or adjoints.

Adjoints never turn a chiral spectrum into a non-chiral one.

The others produces a $U(1)$ only for a symmetric tensor breaking $SU(2)$ to $SO(2)$. But $SU(2)$ is not chiral, so by assumption all matter then has Planck scale masses.

Two stack models



$$SU(M) \times SU(N) \times U(1)$$

(We have only considered unitary branes so far)

$$Y = q_a Q_a + q_b Q_b$$

$q_a, \;\; q_b$ determined by axion couplings

Q	$(M, N, q_a + q_b)$
U	$(A, 1, 2q_a)$
D	$(\overline{M}, 1, -q_a)$
S	$(S, 1, 2q_a)$
X	$(M, \overline{N}, q_a - q_b)$
L	$(1, \overline{N}, -q_b)$
T	$(1, S, 2q_b)$
E	$(1, A, 2q_b)$

Anomalies

$SU(M) \times SU(N) \times U(1)$

S W Y

There are six kinds of anomalies:

SSS
WWW } From tadpole cancellation: also for $M,\ N < 3$

YYY

SSY

WWY

GGY Mixed gauge-gravity

At most one linear combination of the $U(1)$'s is anomaly-free

Anomalies

$$\begin{aligned}(S+U)\tilde{q}_a &= C_1\\(T+E)\tilde{q}_b &= -C_2\\(D+8U)\tilde{q}_a &= (4+M)C_1+NC_2\\L\tilde{q}_b+D\tilde{q}_a &= 0\\2E\tilde{q}_b+2U\tilde{q}_a &= C_1-C_2\end{aligned}$$

$$\tilde{q}_a \equiv Mq_a,\ \tilde{q}_b \equiv Nq_b$$

$$C_1 = -(Q-X)\tilde{q}_b$$

$$C_2 = (Q+X)\tilde{q}_a$$

Only five independent ones. In most cases of interest,the stringy $SU(2)^3$ anomaly is not an independent constraint.

Cubic charge dependence can be linearized.

($q_a = 0$ and/or $q_b = 0$ must be treated separately)

Abelian theories

Single $U(1)$: Higgs must break it, no electromagnetism left

$U(1) \times U(1)$: No solution to anomaly cancellation for two stacks

So in two-stack models we need at least one non-abelian factor in the high-energy theory.

Strong Interactions

It is useful to have a non-abelian factor in the low-energy theory as well, since the elementary particle charge spectrum is otherwise too poor. We need some additional interaction to bind these particles into bound states with larger charges (hadrons and nuclei in our universe).

For this to work there has to be an approximately conserved baryon number. This means that we need an $SU(M)$ factor with $M \geq 3$, and that this $SU(M)$ factor does not become part of a larger group at the "weak" scale.

Note that $SU(2)$ does not have baryon number, and the weak scale is near the constituent mass scale. We cannot allow baryon number to be broken at that scale.

But let's just call this an additional assumption.

Higgs Choice

This implies that at least one non-abelian factor is not broken by the Higgs. We take this factor to be $U(M)$.

Therefore we do not consider bi-fundamental Higgses breaking both $U(M)$ and $U(N)$. We assume that $U(N)$ is the broken gauge factor. Then the only Higgs choices are **L**,**T** and **E**.

We will assume that $U(M)$ it is strongly coupled in the IR-regime and stronger than $U(N)$.

$SU(M) \times U(1)$ $(i.e.\ N{=}1)$

Higgs can only break $U(1)$, but then there is no electromagnetism.

Hence there will be a second non-abelian factor, broken by the Higgs.

$M = 3,\ N = 2$

Higgs = L

Decompose L, E, T: chiral charged leptons avoided only if

$$L = E,\ T = 0$$

Substitute in anomaly equation:

$$S\tilde{q}_a = \left(\frac{5 - N - M}{2M}\right) C_1$$

For $M = 3,\ N = 2$: $S = 0$

Therefore we get standard QCD without symmetric tensors.

$M = 3,\ N = 2$

Quark sector

$$Q(3, q_a) + Q(3, q_a + 2q_b) + X(3, q_a) + X(3, q_a - 2q_b) - U(3, -2q_a) - D(3, q_a)$$

$$Q + X - D = 0$$

$Q = U$ **if and only if** $q_a + 2q_b = -2q_a$

or

$X = U$ **if and only if** $q_a - 2q_b = -2q_a$

In both cases we get an $SU(5)$ type charge relation, and hence standard charge quantization

$M = 3,\ N = 2$

Hence either $Q = 0$ ***or*** $X = 0$; the choice is irrelevant.

Take $X = 0$.

Then $D = Q = U,\ T = 0,\ L = E$

Remaining anomaly conditions: $L = Q$

Hence the only solution is a standard model family, occurring Q times.

The branes **a** and **b** are in principle unrelated, and can generally not be combined to a $U(5)$ stack

$M = 3,\ N = 2$

Higgs = T

The symmetric tensor can break $SU(2)\times U(1)$ in two ways, either to $U(1)$, in the same way as **L**, or to $SO(2)$.

Breaking to $U(1)$ (same subgroup as L)

No allowed Higgs couplings to give mass to the charged components of L, E and T, so we must require $E = L = T = 0$. Then there is no solution.

Breaking to $SO(2)$

Then $SO(2)$ must be electromagnetism. Y-charges forbid cubic T couplings, so $T = 0$ to avoid massless charged leptons. Quark charge pairing (to avoid chiral QED, broken by QCD) requires $Q = -X$. **If we also require $S = 0$, everything vanishes.**

Note: stronger dynamical assumption: $S = 0$

$M > 3$ and/or $N > 2$: lepton pairing

Lepton charge pairing: $-L + (N-1)E + (N+1)T = 0$

Combined with the five anomaly constraints this gives the following solution

$$\begin{aligned}
U\tilde{q}_a &= \tfrac{3+M}{6} C_1 \\
S\tilde{q}_a &= \tfrac{3-M}{6} C_1 \\
D\tilde{q}_a &= N C_2 - \tfrac{M}{3} C_1 \\
L\tilde{q}_b &= -N C_2 + \tfrac{M}{3} C_1 \\
E\tilde{q}_b &= -\tfrac{1}{2} C_2 + \tfrac{M}{6} C_1 \\
T\tilde{q}_b &= -\tfrac{1}{2} C_2 - \tfrac{M}{6} C_1
\end{aligned}$$

$$C_1 = -(Q - X)\tilde{q}_b$$

$$C_2 = (Q + X)\tilde{q}_a$$

For $M = 3$, $S = 0$ automatically!

$M > 3$ and/or $N > 2$: quark pairing

$Q \neq -X$: Left-handed and righthanded quark representations have different dimensions. Then no subgroup of $SU(N)$ is non-chiral.
Hence dynamical symmetry breaking breaks $SU(N)$ completely.

But $SU(N) \times U(1)$ ***does*** contain a current that is non-chiral.
Note that now U and D participate, which are neutral under $SU(N)$, but carry a $U(1)$ charge. The surviving $U(1)$ symmetry must be a linear combination

$$Q_{\rm em} = \Lambda + Y,$$

where $\Lambda \in SU(N)$. There can be at most one such $U(1)$ factor.
This is the only symmetry that can survive DSB+Higgs breaking.

($Q = -X$: see paper)

$M > 3$ and/or $N > 2$

$\Lambda = \text{diag}(\lambda_1, \ldots, \lambda_N)$ (surviving Higgs + any DSB)

Charges of Q: $q_a + q_b + \lambda_i$

Charges of X: $q_a - q_b - \lambda_i$

Charges of D: $-q_a$

Charges of U, S: $2q_a$

Lepton Charges: $q_b + \lambda_i;\ 2q_b + \lambda_i + \lambda_j$

Define $q_b + \lambda_i = \alpha q_a$

Quark charge pairing is possible only for $\alpha = 0,\ \pm 3$

All solutions satisfy Standard Model charge quantization!

$M > 3$ and/or $N > 2$

We can obtain a solution for any Q and X

$$\Lambda : n \times \{-q_b\} + n_+ \times \{-q_b + 3q_a\} + n_- \times \{-q_b - 3q_a\}$$

$$n_+ = \frac{Q}{R}$$

$$n_- = -\frac{X}{R}$$

$$N = n + n_+ + n_-$$

$$R = -(Q + X)\frac{\tilde{q}_a}{\tilde{q}_b} \in \mathbb{Z}$$

The trace of Λ must vanish

$$\mathrm{Tr}\ \Lambda = \tilde{q}_b \left(\frac{3}{M} - 1 \right)$$

Hence $M = 3$!

$M > 3$ and/or $N > 2$

The spectrum can be computed

$$D = n(Q+X)$$
$$U = (N-n)(Q+X)$$
$$L = nR$$
$$E = \frac{1}{2}\left(N-n+1\right)R$$
$$T = -\frac{1}{2}\left(N-n-1\right)R$$

Absence of massless charged leptons only for $N=2$!

Conclusions

- The Standard Model is the only anthropic solution within the set of two-stack models.
- Family structure, charge quantization, the weak interactions and the Higgs choice are all derived.
- Standard Model charge quantization works the same way, for any value of N, even if $N+3 \neq 5$.
- The GUT extension offers no advantages, only problems (doublet-triplet splitting)
- Only if all couplings converge (requires susy), GUTs offer an advantage.
- The general class is like a GUT with its intestines removed, keeping only the good parts: **GUTs without guts**.