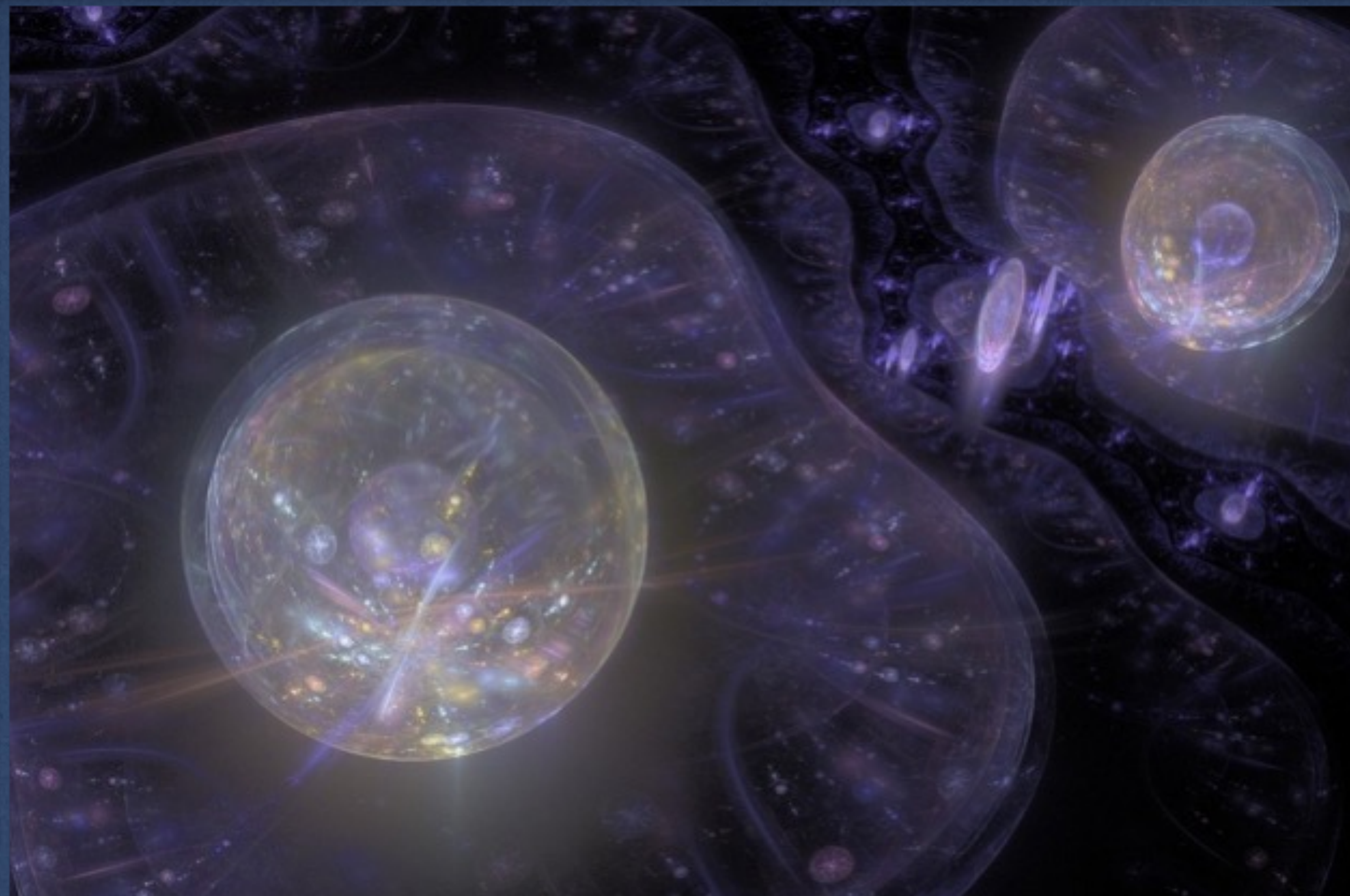


Particle Physics in the Multiverse

CSIC Madrid, 17-6-2015

The Higgs discovery

During the past two decades we heard lots of skeptical comments, like:

"LHC is so complicated, they will never get it to work"

"Detectors, if they work at all, will be unable to isolate individual events; huge data flows are unmanageable"

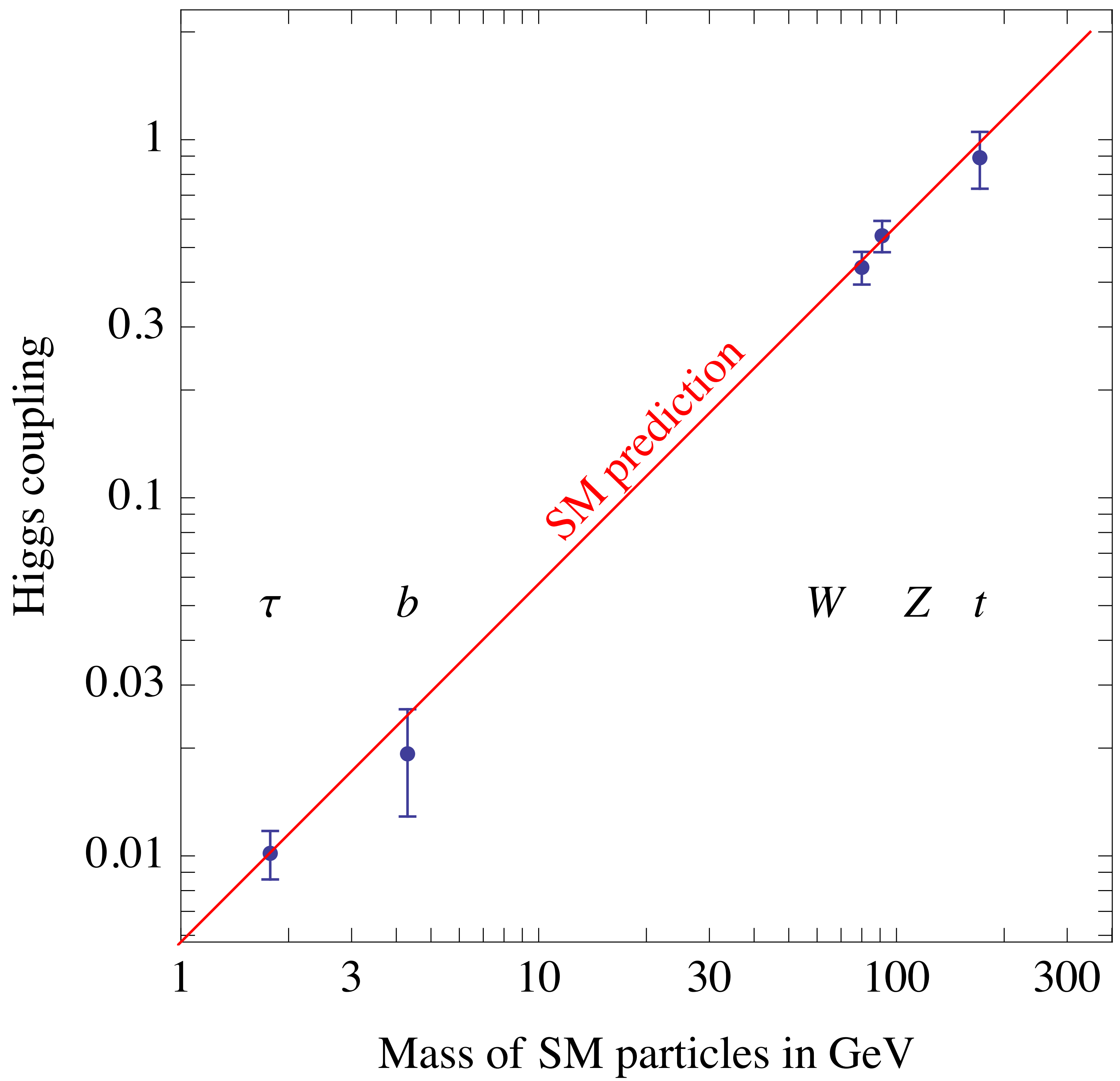
"The Higgs mechanism with its silly quartic potential is just a simple model. This cannot be the real world"

But it has worked!

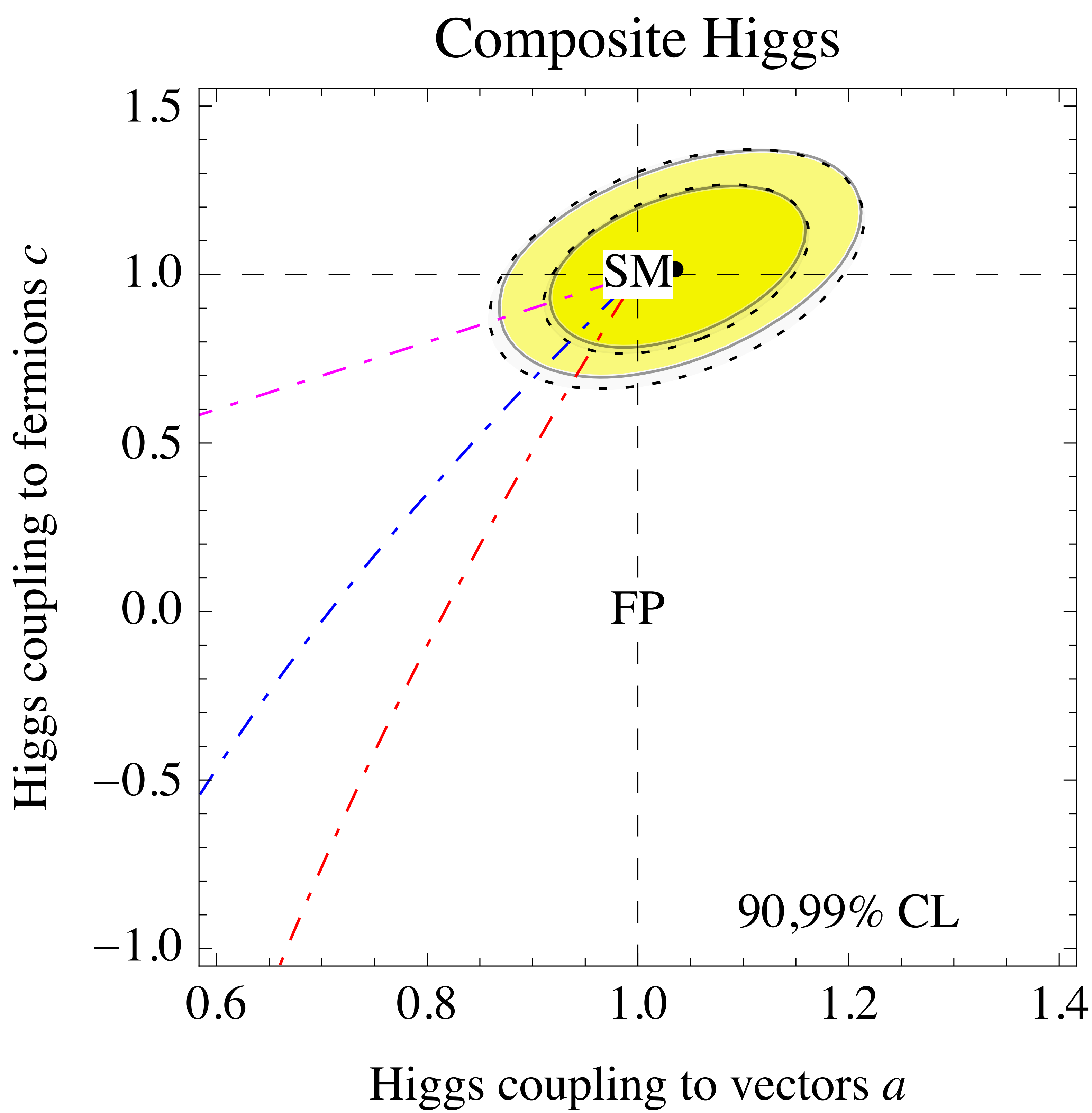
No New Physics

The Standard Model is Phenomenal

Fit to Higgs couplings



From Giardino et. al. arXiv:1303.3570



Composite Higgs
1.5
1.0
0.5
0.0
−0.5
−1.0
0.6
0.8
1.0
1.2
1.4
Higgs coupling to fermions c
Higgs coupling to vectors a
SM
FP
90,99% CL

Why do people want new physics?

- The old physics was a lot of fun!
  One of the greatest stories in science history
  > 30 Nobel prizes.
- Most people don't like the Standard Model
- There are unsolved problems.

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: 19 parameters
(not including neutrino masses)

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.

Problems and Worries

Problems:

(Clearly requiring something beyond the Standard Model)

- Gravity
- Dark matter
- Inflation
- Baryogenesis.

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)

Problems and Worries

Problems:

(Clearly requiring something beyond the Standard Model)

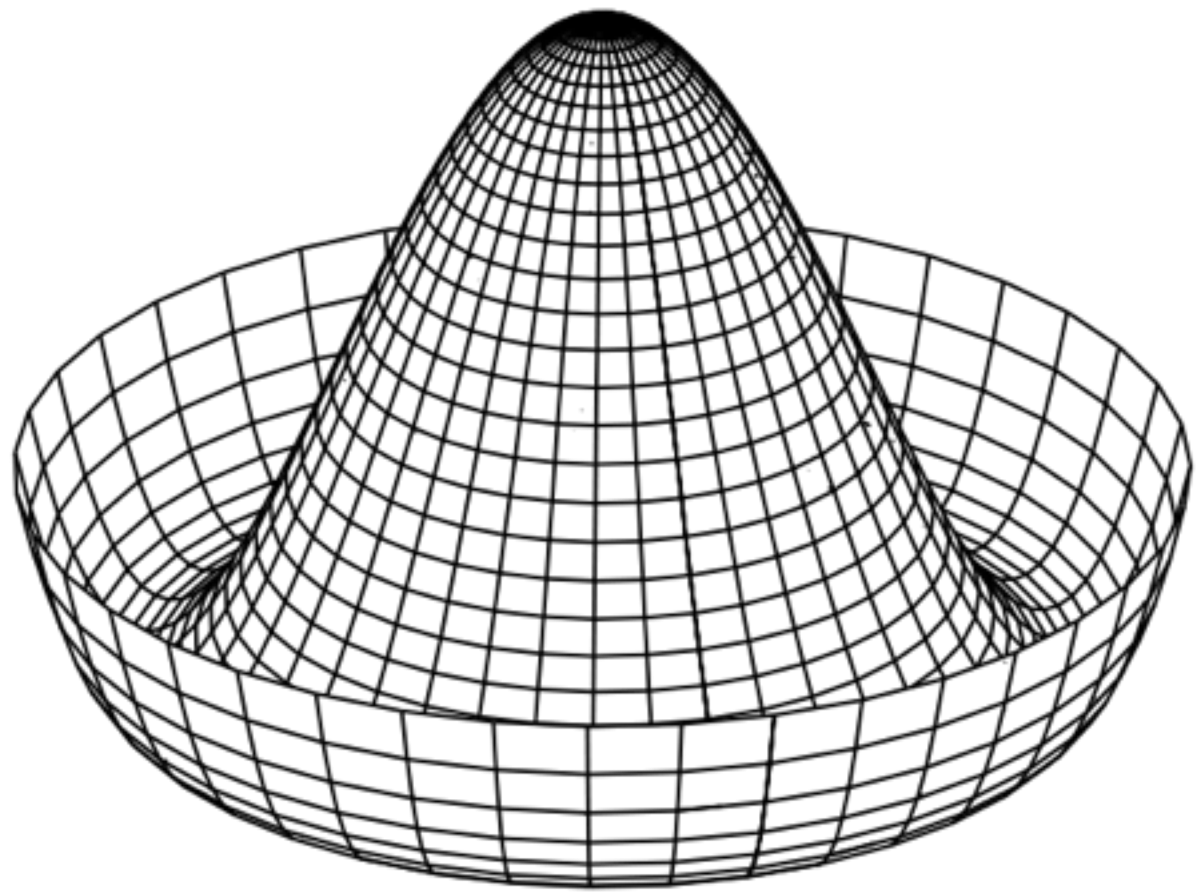
- Gravity
- Dark matter
- Inflation
- Baryogenesis.

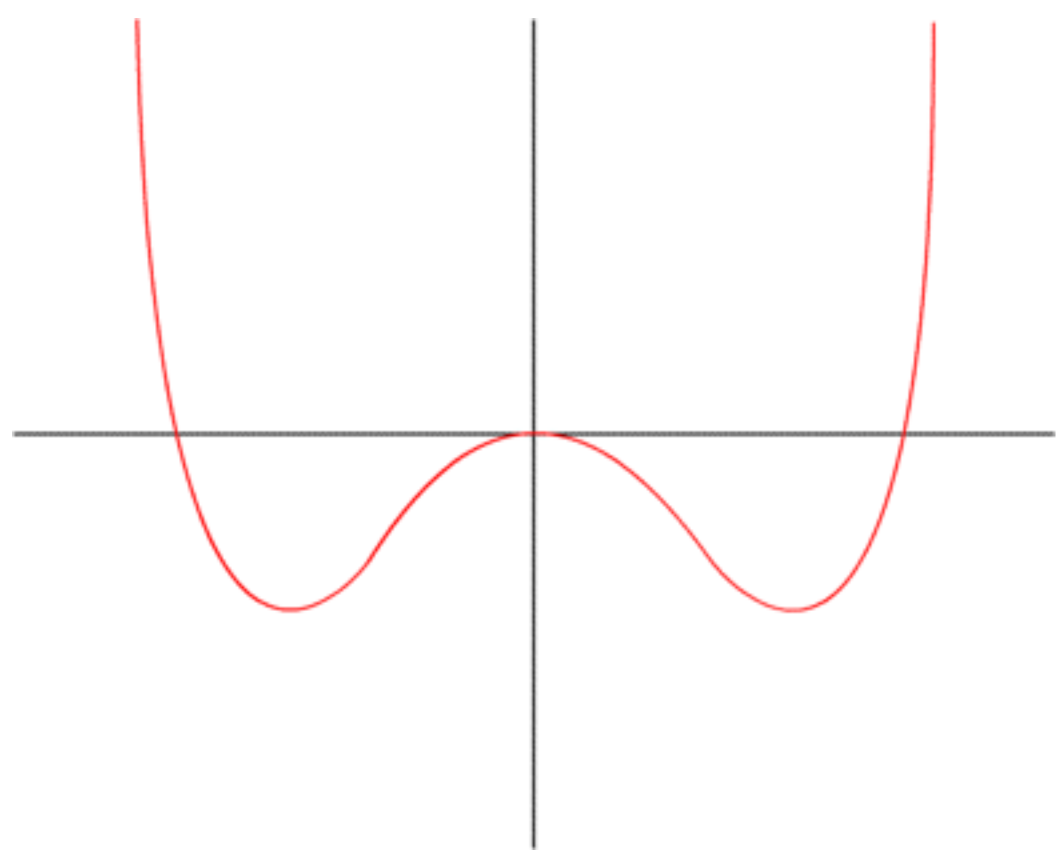
A Potential Problem: *stability of the Higgs Potential*

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)





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

Running Parameters

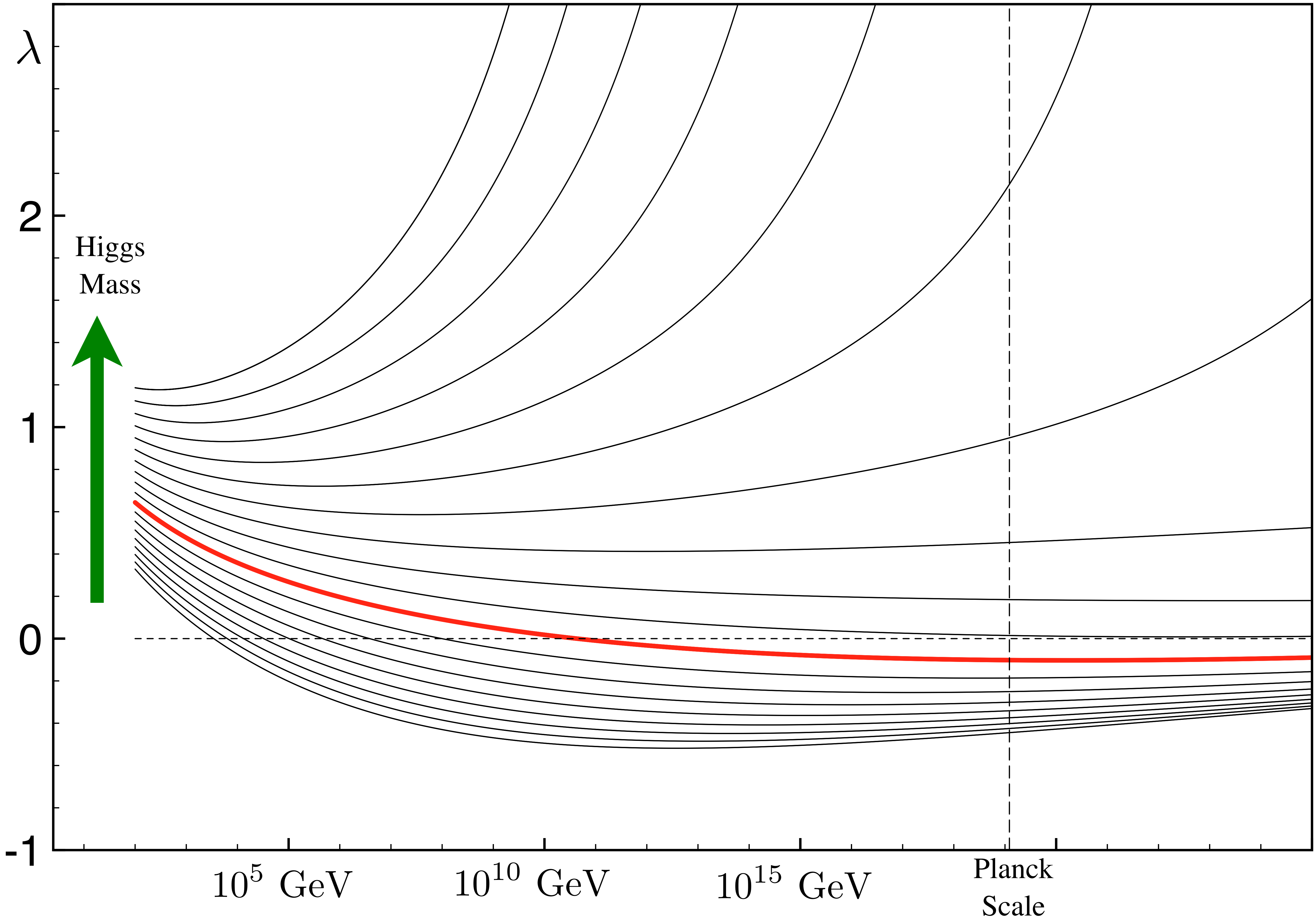
All Standard Model parameters "run" with energy

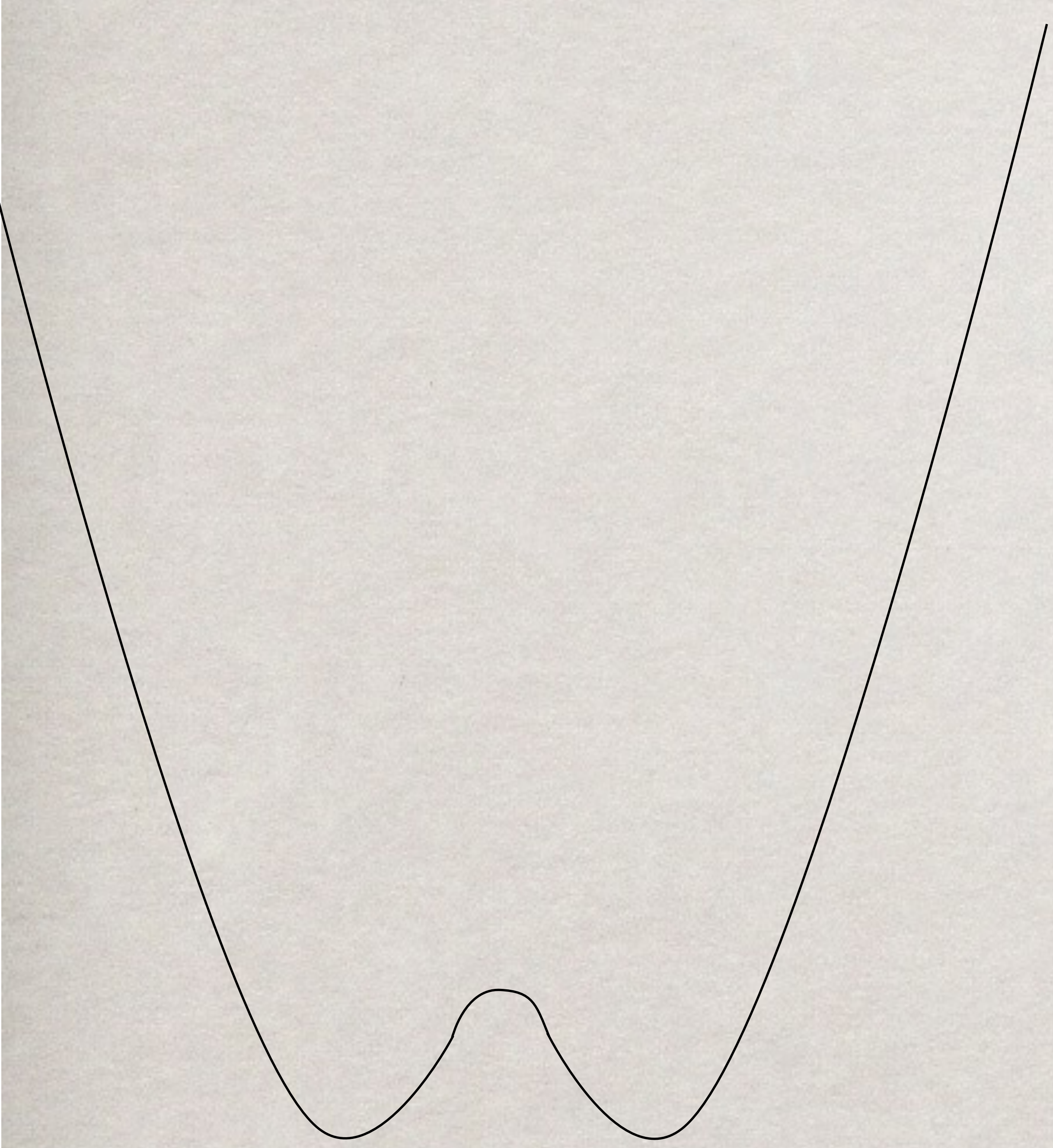
$$\frac{d}{dt}\bar{g}(t) = \beta(\bar{g}(t))$$

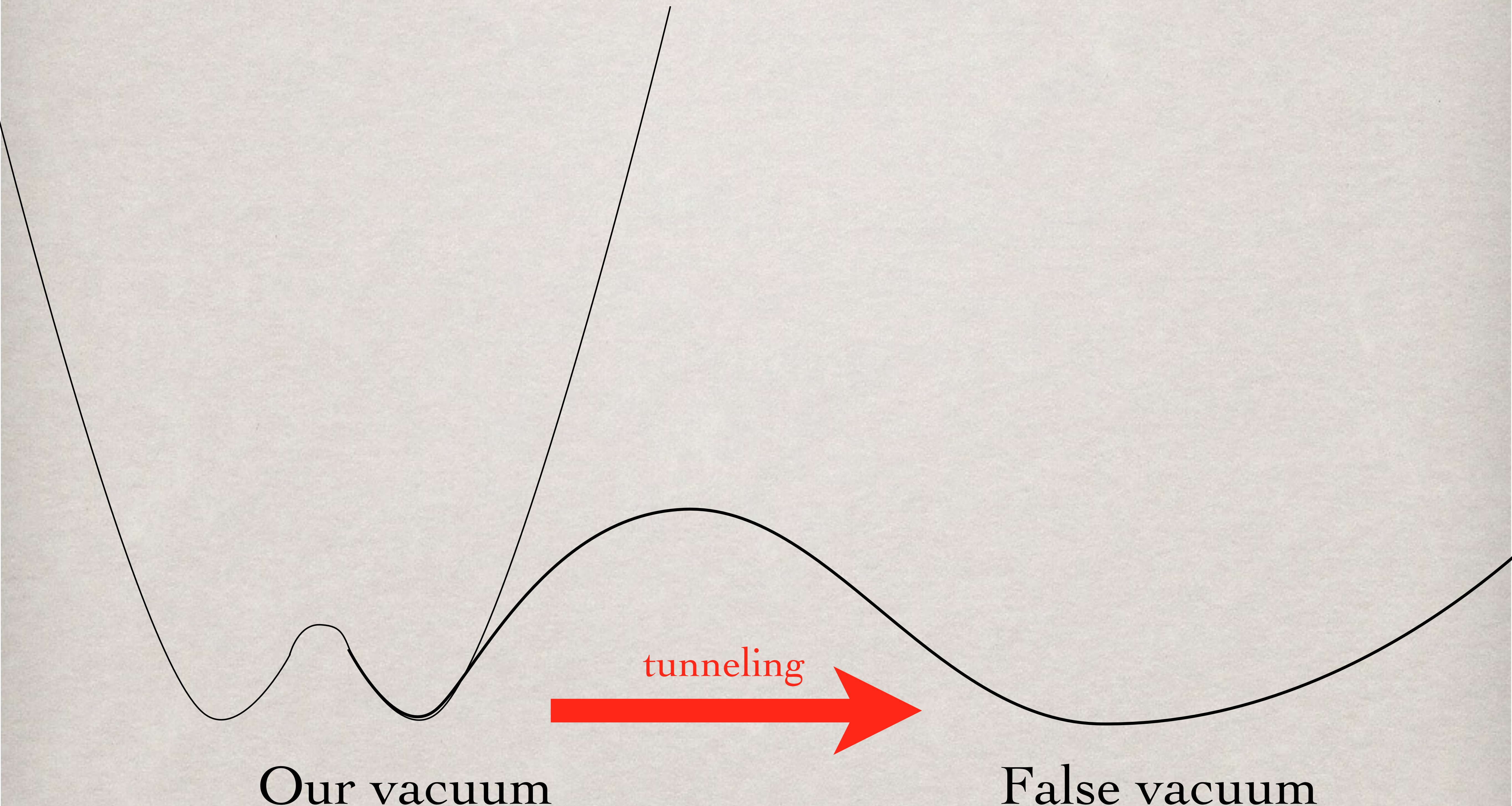
$$t \;\propto\; \log(\text{Energy})$$

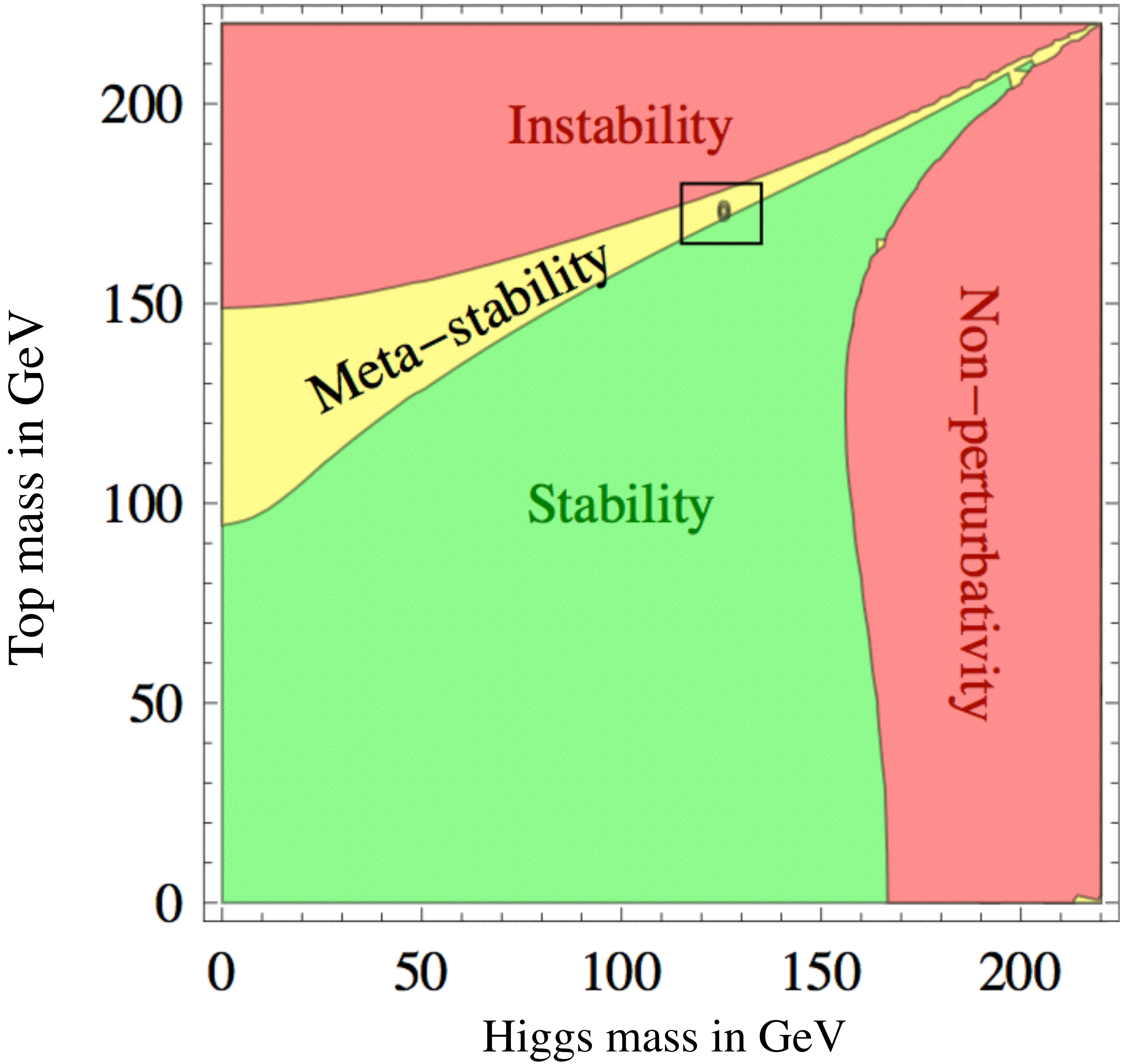
In particular, the Higgs self-coupling λ runs

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


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




tunneling
Our vacuum
False vacuum



From DeGrassi et. al, arXiv:1205.6497

The Singlet Era?

If we see nothing, the most radical explanation is that there **is** nothing.
The second most radical explanation is that everything else is invisible: not coupled to the SM.

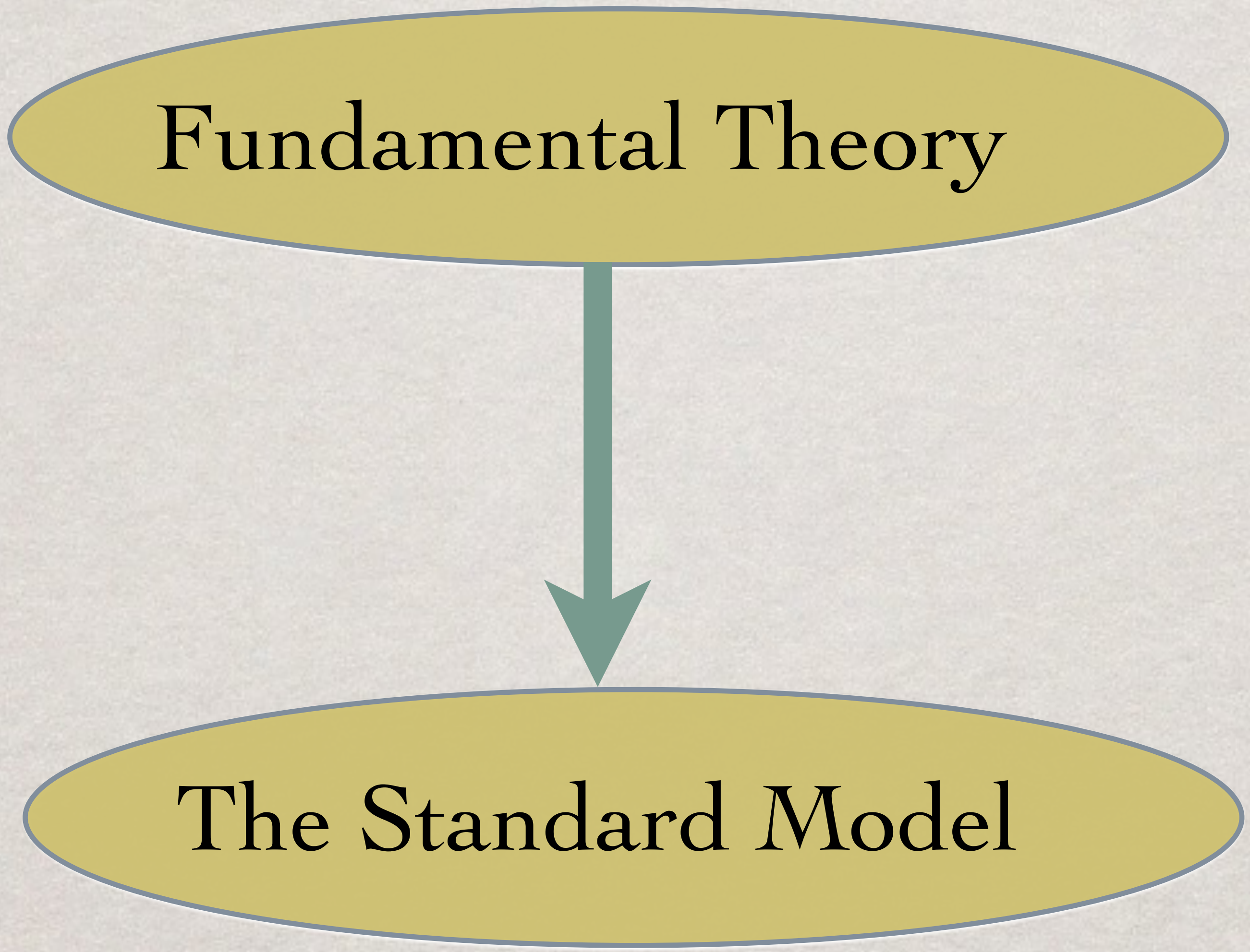
All problems and several worries can be solved by singlets:

- Dark matter
  (axions or singlet neutrinos)
- Baryogenesis
  (Leptogenesis using Majorana phases of neutrinos)
- Inflation
  (perhaps even just the Higgs can do it)
- Strong CP problem
  (axions)
- Small neutrino masses
  (see-saw mechanism using singlet neutrinos)

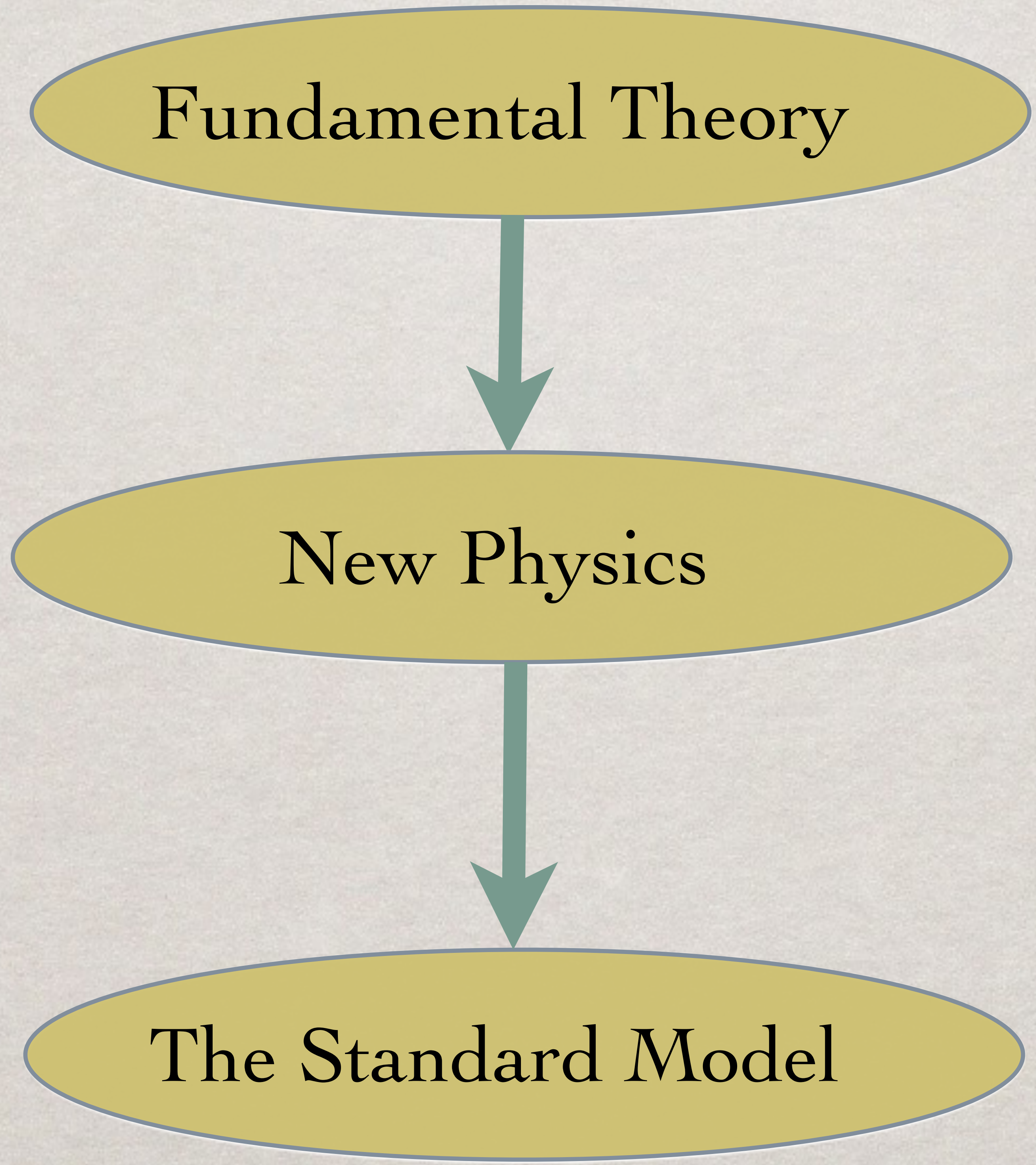
Radical new physics is only needed to deal with some of the worries

Why Worry?

The old “Einstein” paradigm:

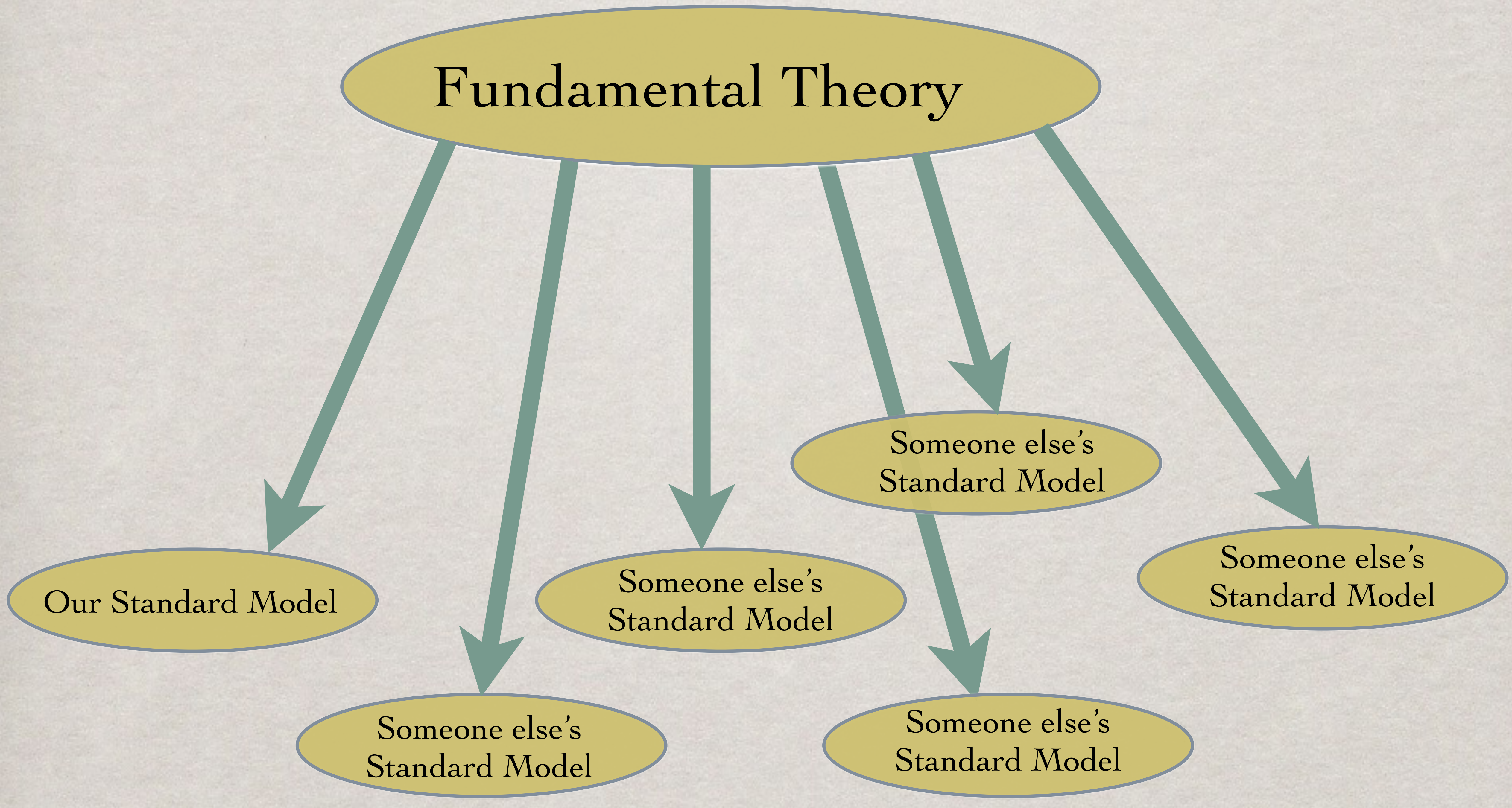


The BSM Paradigm:



Explains parameter values, families, hierarchies, etc.

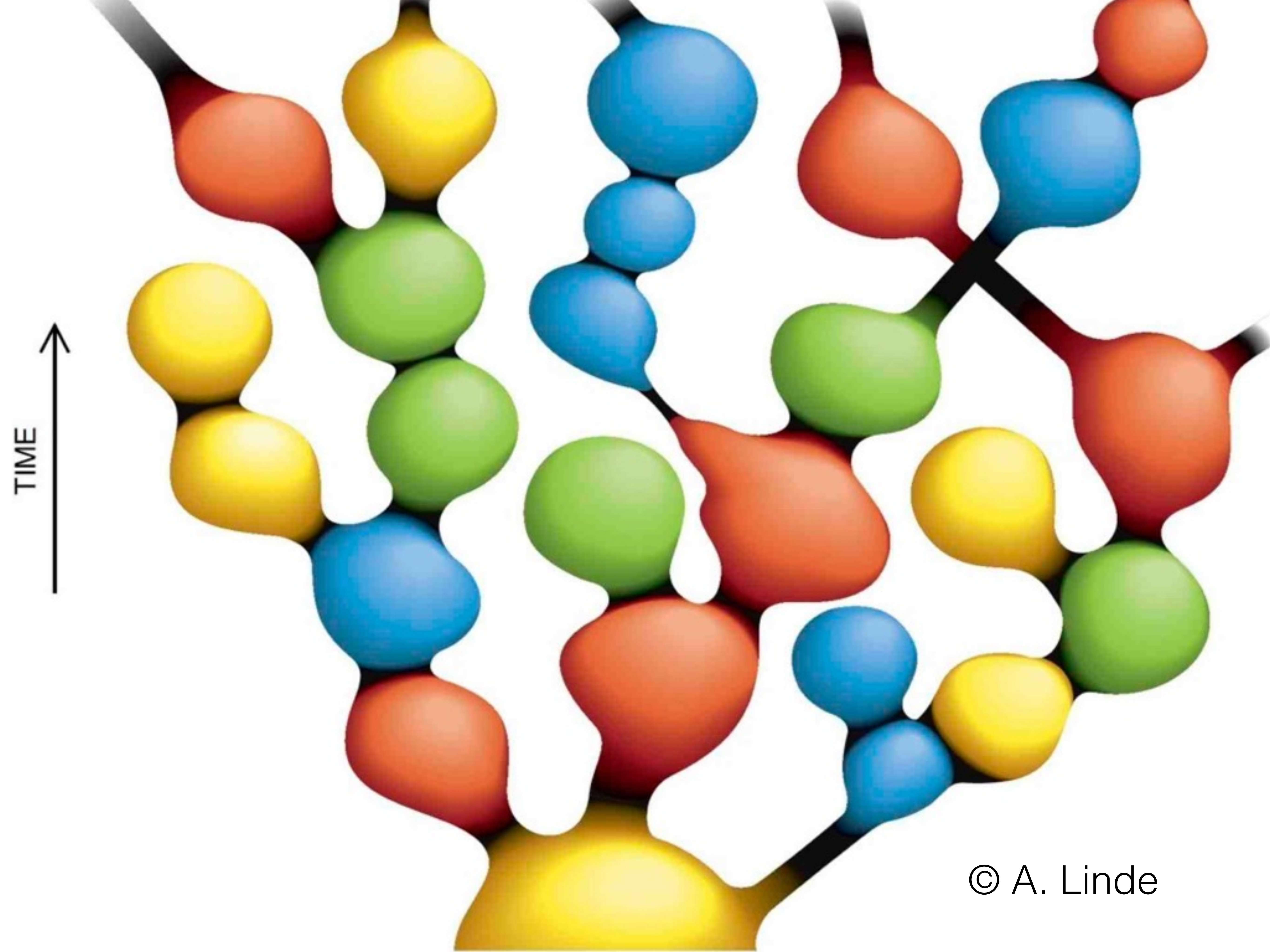
The Landscape Paradigm:



This picture is suggested by:

- The Multiverse

  Inflation suggests an eternal process of creation of new universes. *(Linde, Vilenkin, Guth)*
  Why should they all have the same laws of physics?


TIME
© A. Linde

This picture is suggested by:

- The Multiverse

  Inflation suggests an eternal process of creation of new universes. *(Linde, Vilenkin, Guth)*
  Why should they all have the same laws of physics?

- String Theory

  Large number of "string vacua" known since 1986. *(Schellekens, 1998)*
  Now called the "String Theory Landscape". *(Susskind, 2003)*

- Anthropic fine-tunings

  The Standard Model is tuned for life, suggesting that it won't be mathematically unique.

Examples of Anthropic Bounds

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

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

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

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

This picture is suggested by:

- The Multiverse
  Inflation suggests an eternal process of creation of new universes. *(Linde, Vilenkin, Guth)*
  Why should they all have the same laws of physics?
- String Theory
  Large number of "string vacua" known since 1986. *(Schellekens, 1998)*
  Now called the "String Theory Landscape". *(Susskind, 2003; Douglas, ….)*
- Anthropic fine-tunings
  The Standard Model is tuned for life, suggesting that it won't be mathematically unique.
- Common sense
  There is no argument for uniqueness, it is just a belief.
  Is all we can see all there is?

This **does** require physics beyond the Standard Model:
A large ensemble of physically connected "vacua".

The only known candidate is the string theory landscape.

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

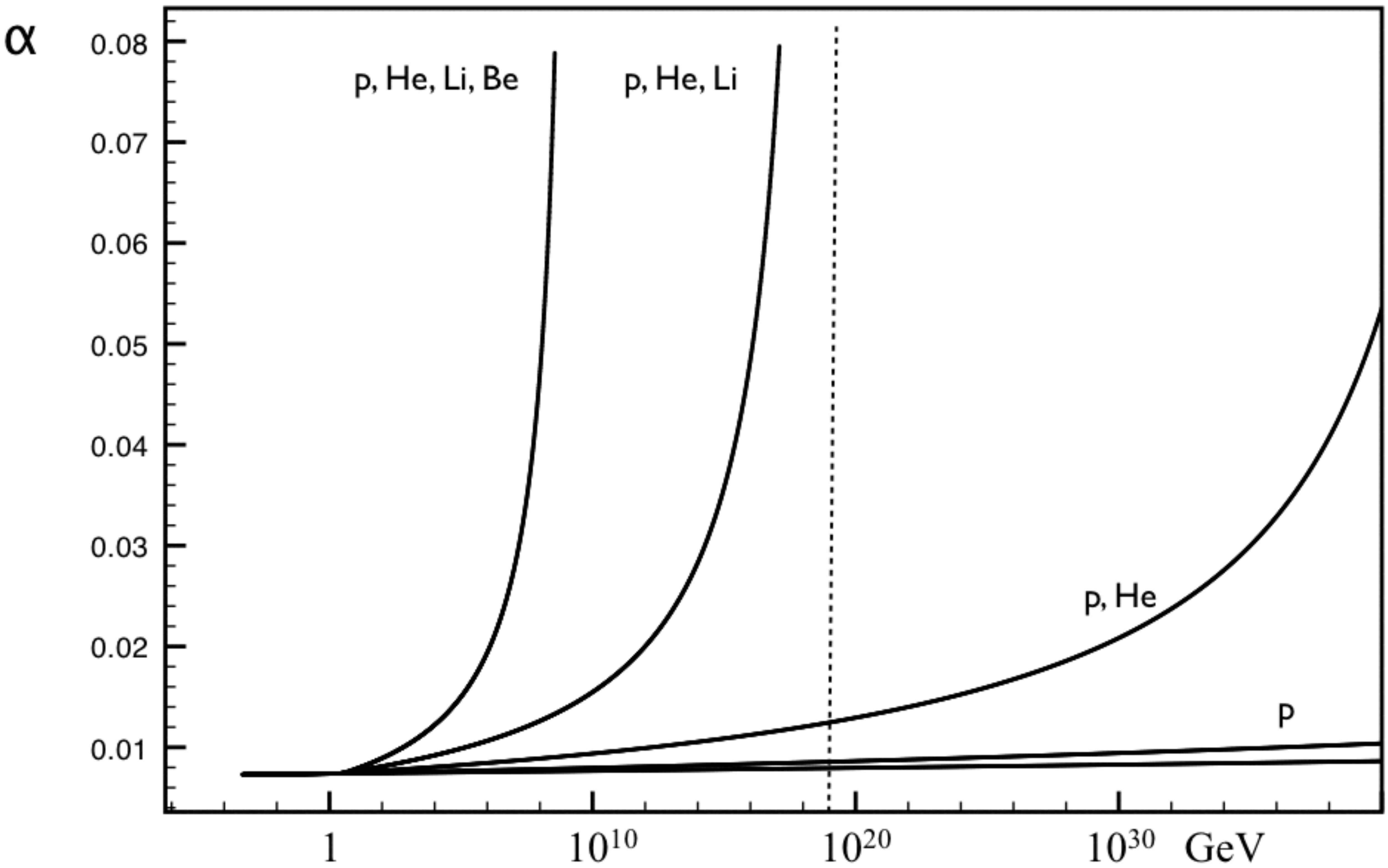
If this is true one would expect

- Some gauge group, nothing mathematically special.
- Some choice of matter, nothing mathematically special.
- Some choice of parameter values, nothing mathematically special.
- And the whole model should extrapolate consistently to the Planck scale.

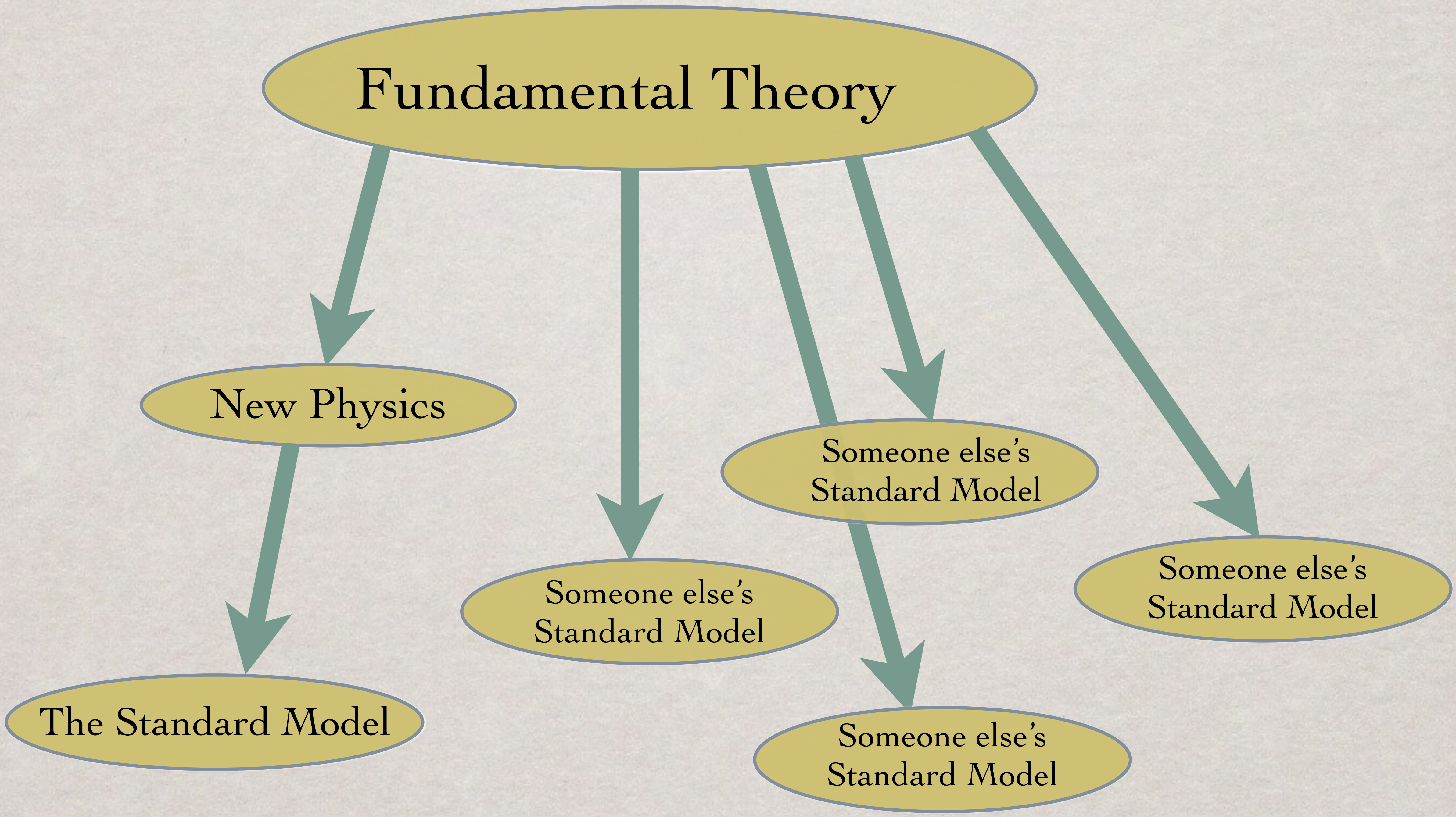
That's exactly what we have right now!

Atomic Physics	✗
Nuclear Physics	✗
Hadronic Physics	✗
The Standard Model	✓

Running of α in Atomic Physics



The Einstein and landscape points of view could both be correct:



But then the consistency of the SM until the Planck scale is just an accident

The Hierarchy Worry

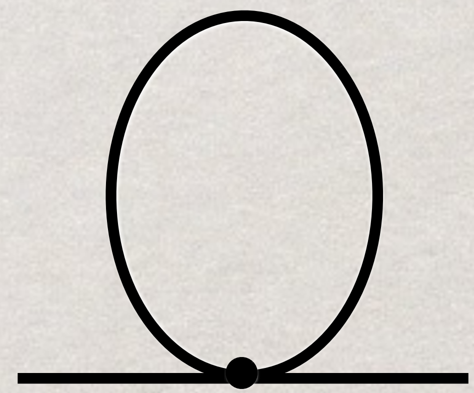
$$\text{Weak scale} \approx 100 \text{ GeV}$$

$$\text{Planck scale} \approx 10^{19} \text{GeV}$$

$$E_{\text{Planck}} = \sqrt{\frac{\hbar c^5}{G}}$$

$\mu^2 \phi^\dagger \phi$

+



+ .....

The loop correction is divergent, but is assumed to be cut off at some new physics scale Λ, below or at most at the Planck scale.

If there exist heavy particles with mass M, they will contribute a correction proportional to M^2 to μ^2: "unnatural"

Problem or Worry?

In a finite theory, the full expression for μ^2 is

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

But only μ_{phys} is measurable.
Even if it is much smaller than each term in the sum, this has no physical consequences.

There is no hierarchy problem, just a hierarchy worry.

The Standard Model is perfectly fine as it is.

Is the hierarchy anthropic?

Weakness of gravity: brains would collapse into black holes.

Maximal number of constituents: $$\left(\frac{m_{\text{Planck}}}{m_p}\right)^3$$

For a "brain" with 10^{24} protons not to be a black hole, we need $m_{\text{p}} < 10^{-8}\, m_{\text{Planck}}$

To have stars (stellar nucleosynthesis, energy source), we need a hierarchy roughly like the one we observe.

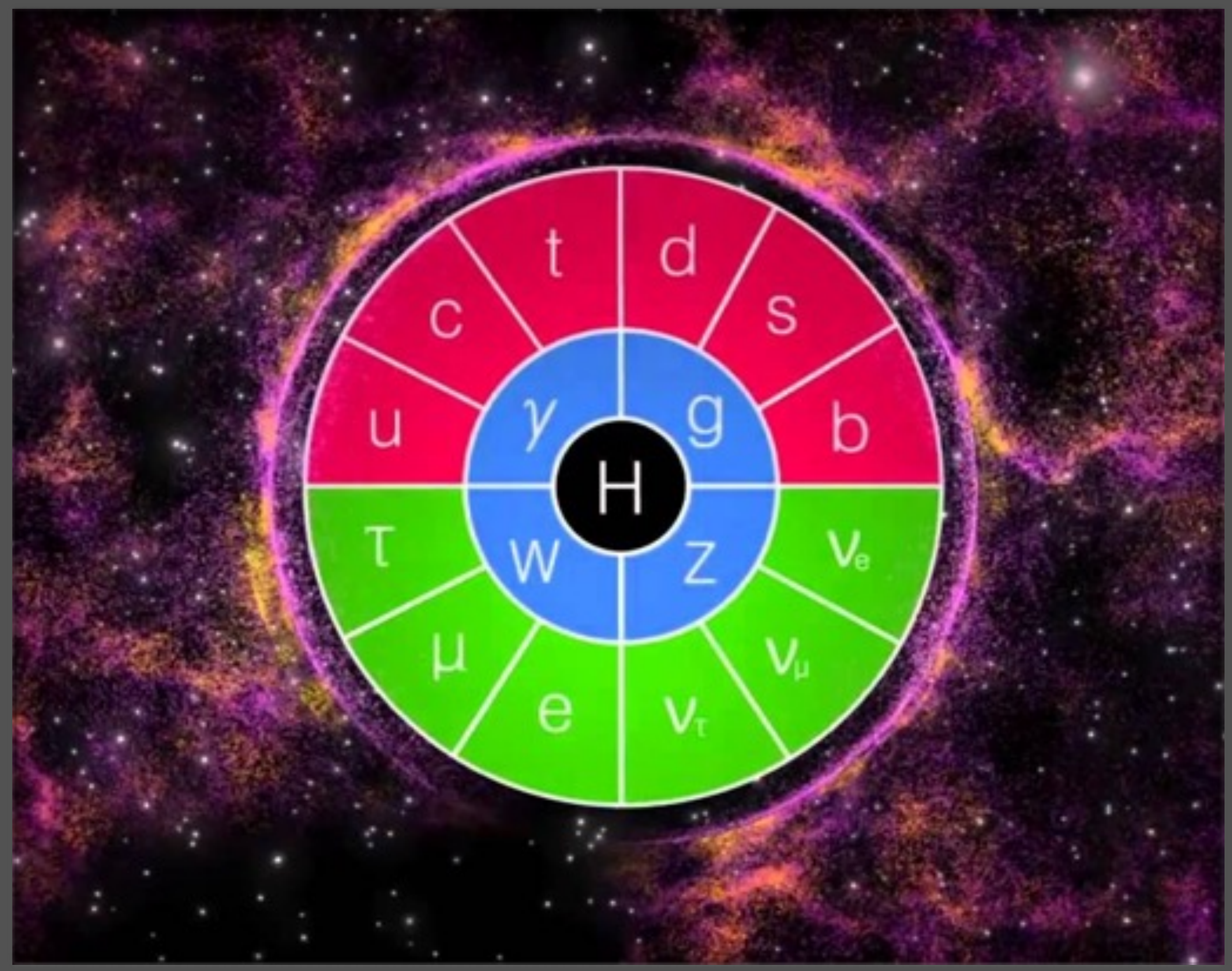
(F. Adams: "Stars In Other Universes", arXiv:0807.3697)

Agrawal et. al. (1998): Weak scale hierarchy from nuclear stability

Anthropic or New Physics?

S. Weinberg (2005)

"If the electroweak symmetry breaking scale is anthropically fixed, then we can give up the decades long search for a natural solution of the hierarchy problem."



A Derivation of the Standard Model Structure

Based on Nucl.Phys. B883 (2014) 529-580 with B. Gato Rivera

GUTs?

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

Charge quantization not explained by $SU(3)\times SU(2)\times \mathrm{U}(1)$

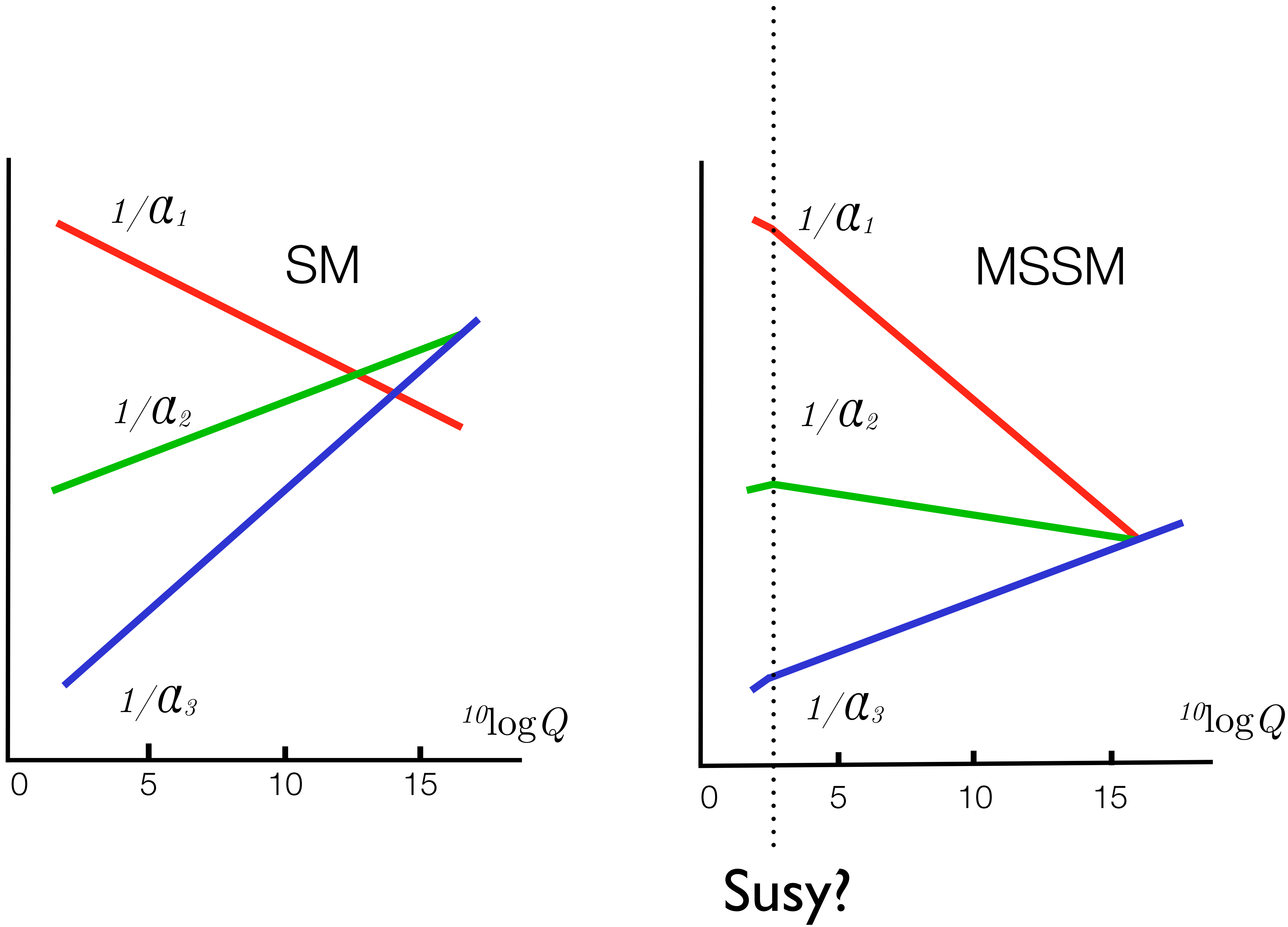
The most popular explanation is Grand Unified Theories

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

(16) of $SO(10)$

GUTs?

- Higgs does not fit in a GUT representation.
- Breaking to $SU(3)\times SU(2)\times U(1)$ is not explained. There are alternatives, like $SU(4)\times U(1)$.
- Choice of representations is not explained.
- Choice of GUT gauge group is not explained.
- No evidence for coupling convergence (yet?)



SM
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
${}^{10}\log Q$
0
5
10
15
MSSM
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
${}^{10}\log Q$
0
5
10
15
Susy?

Anthropic assumptions

- Sufficiently rich "atomic" physics (at least one massless photon and some (meta)stable charged particles)
- Hierarchy between the scale of the atomic mass scales and gravity

We are not demanding carbon, stars, galaxies, nucleosynthesis, abundances, weak interactions(*)….

cf. Harnik, Kribs, Perez, "A universe without weak interactions"

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 “(technical) 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

This has led to the idea that perhaps we should try to get theories with only logarithmically renormalized parameters and no quadratically renormalized scalars.

For example, the Higgs could be a composite, or the supersymmetric partner of a fermion.

All of this predicts “new physics”, which has not been found so far.

The Single Higgs Hypothesis

If we accept the current status quo, apparently nature has chosen to pay the huge price of a single scalar to create the hierarchy.

[It remains to be shown that is statistically cheaper than having fundamental Dirac particles with small masses, or than solutions to the technical hierarchy problem (susy, compositenes, ….). Requires landscape studies.]

But then this price is going to be payed only once: there should be just one Higgs.

The Single Higgs Hypothesis

The single Higgs has to perform a non-trivial task

- Charged particles with non-abelian interactions ("quarks") must be combined into non-chiral pairs.
  (Otherwise non-abelian interactions break electromagnetism).

- Charged particles without non-abelian interactions ("leptons") must acquire a mass.
  (Otherwise the entire universe turns into an opaque lepton-antilepton plasma).
  (C. Quigg, R. Shrock, Phys.Rev. D79 (2009) 096002)

This is almost precisely what the Higgs achieves in our universe! ("origin of all mass")

String Theory

Look for theories with precisely this feature: Higgs makes chiral matter non-chiral, with massive leptons

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

The solutions can be enumerated in any theory that imposes restrictions on the choice of representation.

Here we use string theory for that purpose.

Intersecting Brane Models

We will assume that all matter and the Higgs bosons are massless particles in intersecting brane models.

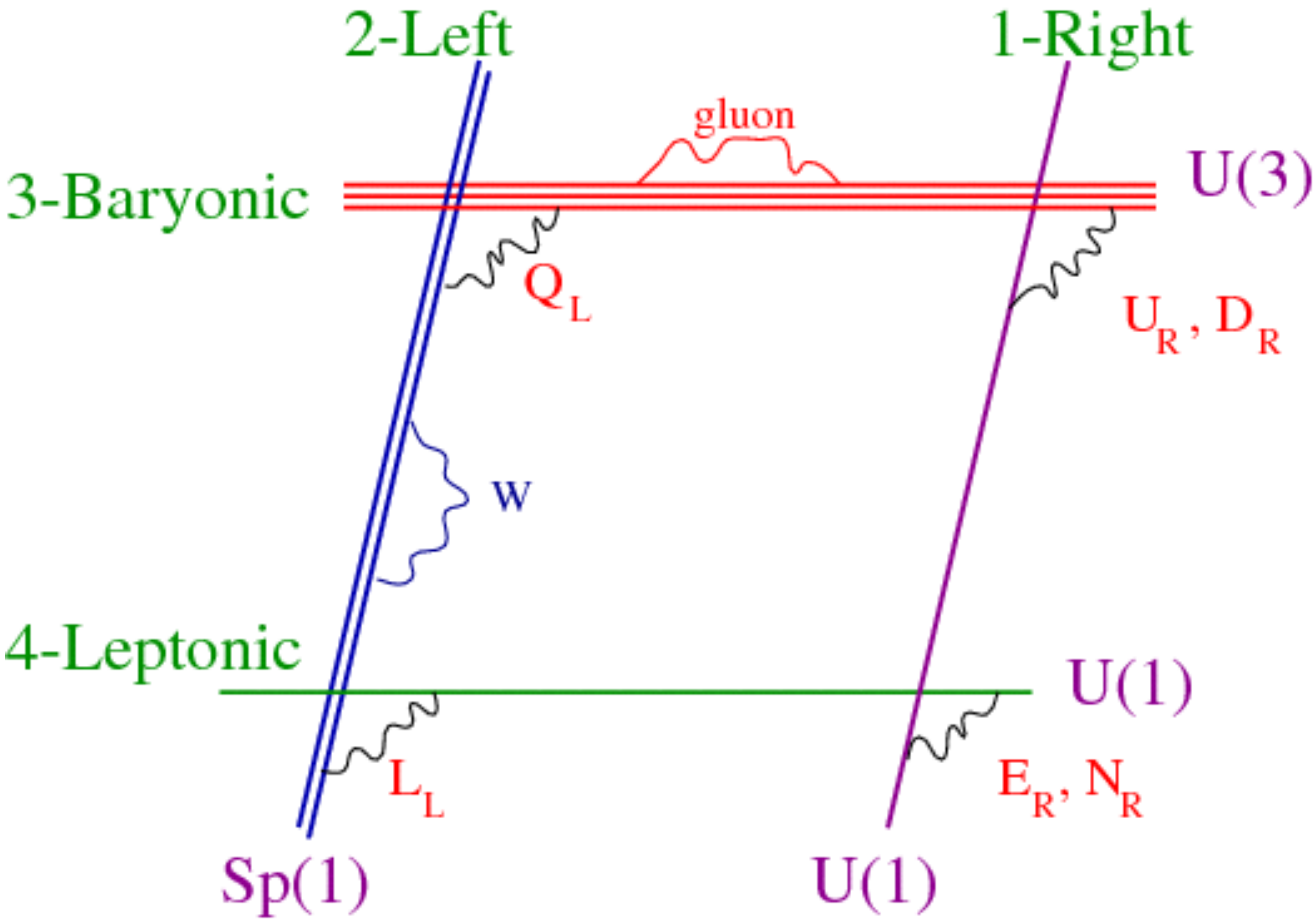
These are characterized by higher-dimensional membranes, coinciding with our four-dimensional world, and intersecting each other in some additional, compact dimensions.

A stack of N membranes is observed as a $U(N)$, $O(N)$ or $Sp(N)$ gauge group. Hence the gauge group is a product of $U(N)$, $O(N)$ and $Sp(N)$ factors.

Matter is limited to a handful of choices. It originates from open strings with one end on one stack, and the other on another (or the same) stack.
Massless particles (the Standard Model) originate from the brane intersections.

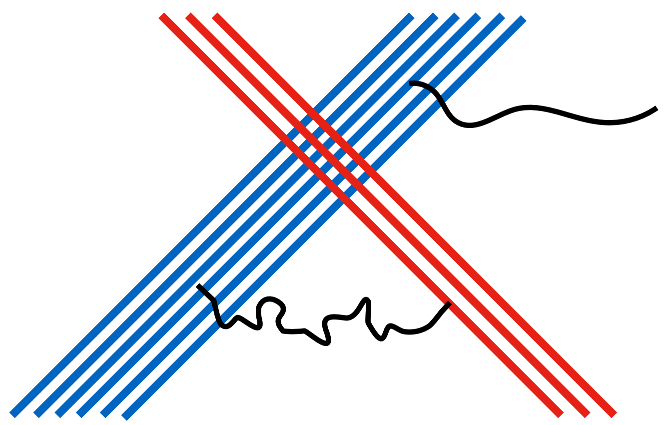
The low energy gauge group is assumed to come from S stacks of branes.

$S=1$ is easy to rule out, so we need at least $S=2$.



“Madrid model” (Ibañez, Marchesano, Rabadan)

Two stack models



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

(We have only considered unitary branes so far)

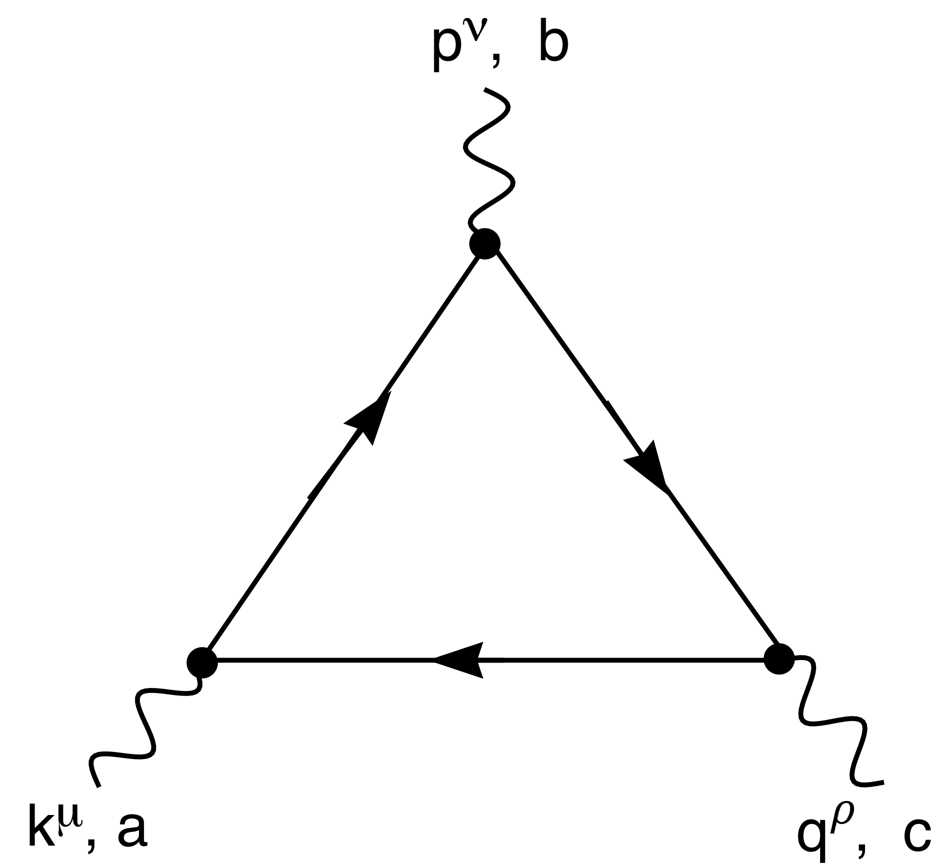
$$Y = q_a Q_a + q_b Q_b$$

$q_a, \;\; q_b$ 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	$(1, A, 2q_b)$

Anomaly Cancellation

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



$$\tilde{q}_a \equiv M q_a,\ \tilde{q}_b \equiv N q_b$$

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

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

(q_a=0, q_b=0 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:
The “weak interactions”.

$$M = 3,\ N = 2$$

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

$$M = 3,\ N = 2$$

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

$$M = 3,\ N = 2$$

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

$$M = 3,\ N = 2$$

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 $N > 2$

- No solution for quark pairing for $M{>}3$
- Non-trivial solutions with quark and lepton pairing exist for $M{=}3,\ N{>}2$

  (This involves considering the most general $Q{+}\Lambda$, where Q is the external $U(1)$, and Λ a generator in the flavor group, left unbroken by dynamical symmetry breaking)

- All of them satisfy standard model charge quantization, even though $M{+}N \neq 5$
- But massless charged leptons can be avoided only for $N{=}2$

Conclusions

- The Standard Model is the only anthropic solution within the set of two-stack models.
- Family structure (and hence family repetition), 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 if all couplings converge (requires susy), GUTs offer an advantage.

Anthropics

vs.

Aesthetics

Anthropics

(concerns existence of observers)

vs.

Aesthetics

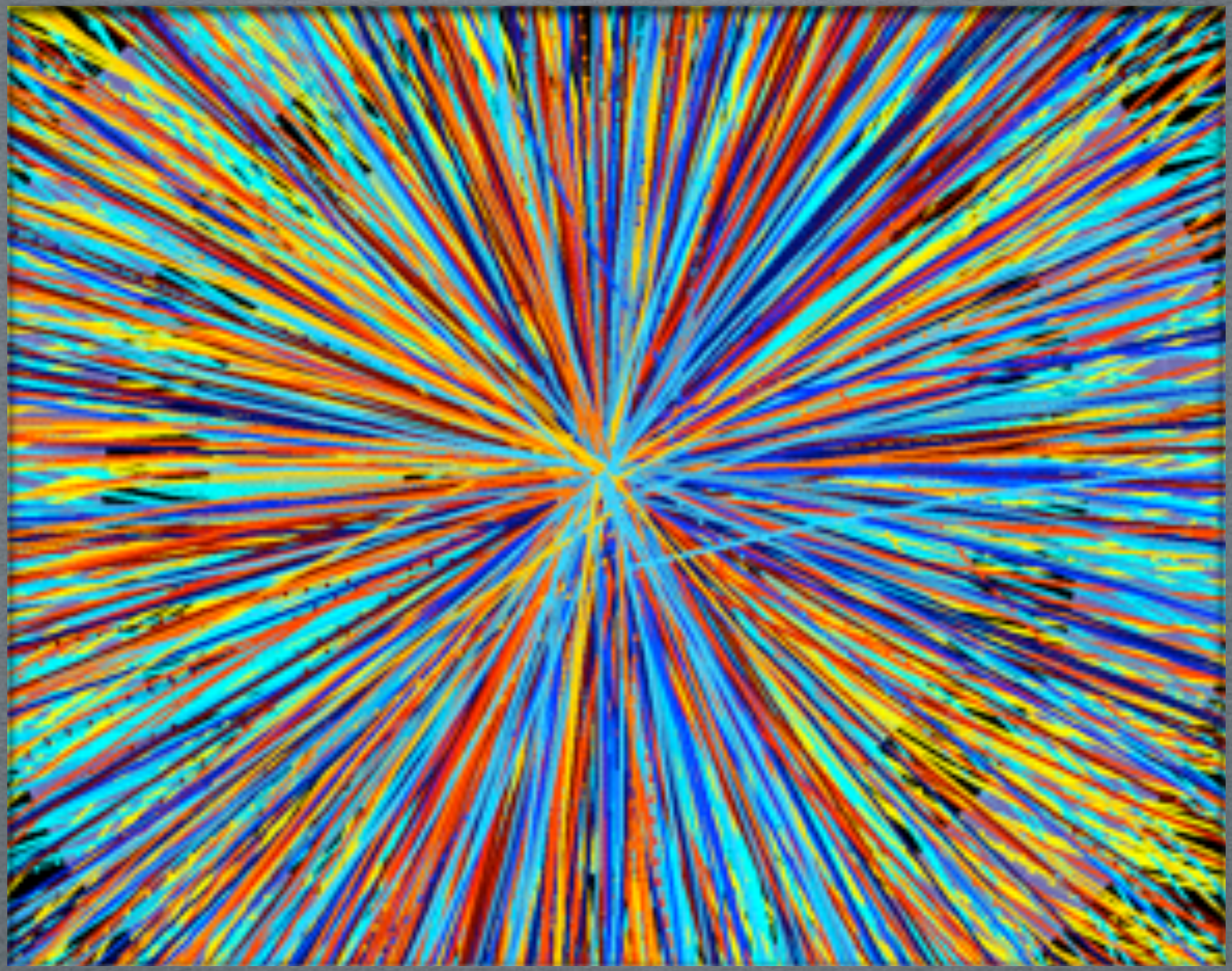
Anthropics

(concerns existence of observers)

vs.

Aesthetics

(concerns happiness of observers)



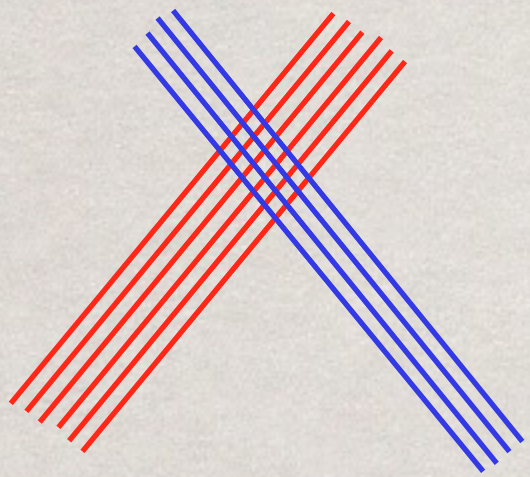
Future Discoveries?

ATLAS, CMS, ALICE, LHCb, CDF, D0, TOTEM, LHCf, MoEDAL, COMPASS, NA61/SHINE, DIRAC, ALPHA, ASACUSA, AEGIS, ATRAP, AMS, CAST, nTOF, OSQAR, XENON, LUX, DAMA, EDELWEISS, ADMX, CRESST, PICASSO, PVLAS, IAXO, REAPR, ALPS-II, CDMS, ZEPLIN-III, WArP, COUPP, KIMS, NAIAD, ANAIS, GEODM, EURECA, SIMPLE, TEXONO, CoGeNT, MAJORANA, XMASS, ArDM, DEAP, DarkSide, MiniCLEAN, DRIFT, NEWAGE, MIMAC, DMTPC, ANTARES, BDUNT, BOREXINO, DAYA BAY, Double Chooz, EXO-200, HALO, IceCube, KamLAND, KM3NeT, MINERvA, MiniBooNE, MINOS, NEMO, NOvA, OPERA, RENO, SNO+, Super-Kamiokande, GERDA, CANDLES, CUORE, NEXT-100, TROITSK, KATRIN, MARE, ECHo, Project8, Pierre Auger, PAMELA, MAGIC, HESS, DES, SDSS, Fermi-LAT, CLIO, LIGO, GEO-600, LCGT, MiniGrail, NGO, Virgo, CryoEDM, Planck, ACBAR, AMI, AMiBA, ACT, APEX, CAPMAP, POLARBEAR, LOFAR, VLT/UVES, Keck, ...

Possible observations in the Singlet Era

- Direct or indirect (photons from annihilation) evidence for dark matter particles. This would mean the end of the singlet era.
- Evidence for a neutrino Majorana mass (neutrinoless 2β-decay)
- Sterile neutrinos
- Axions
- Electric dipole moment of the neutron
- Magnetic monopoles
- Proton decay
- Something totally unexpected.

An Anthropic alternative



Stacks of *M* and *N* intersecting branes.

This produces matter coupling to a gauge group $SU(M) \times SU(N) \times U(1)$

Require

- Massless photon
- No massless charged leptons
- > 3 distinct stable atoms

Standard Model group and families are the only solution
The Higgs choice is determined

Charge quantization without GUTs
In the absence of susy, GUTs only offer disadvantages

B. Gato-Rivera and A. N. Schellekens, arXiv:1401.1782