NOW WHAT?

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"A critical look to past, present and future"

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"By the time we discover the Higgs boson it will almost be an anti-climax in comparison to the excitement about supersymmetry"

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...so fortunately the bar is pretty low

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"
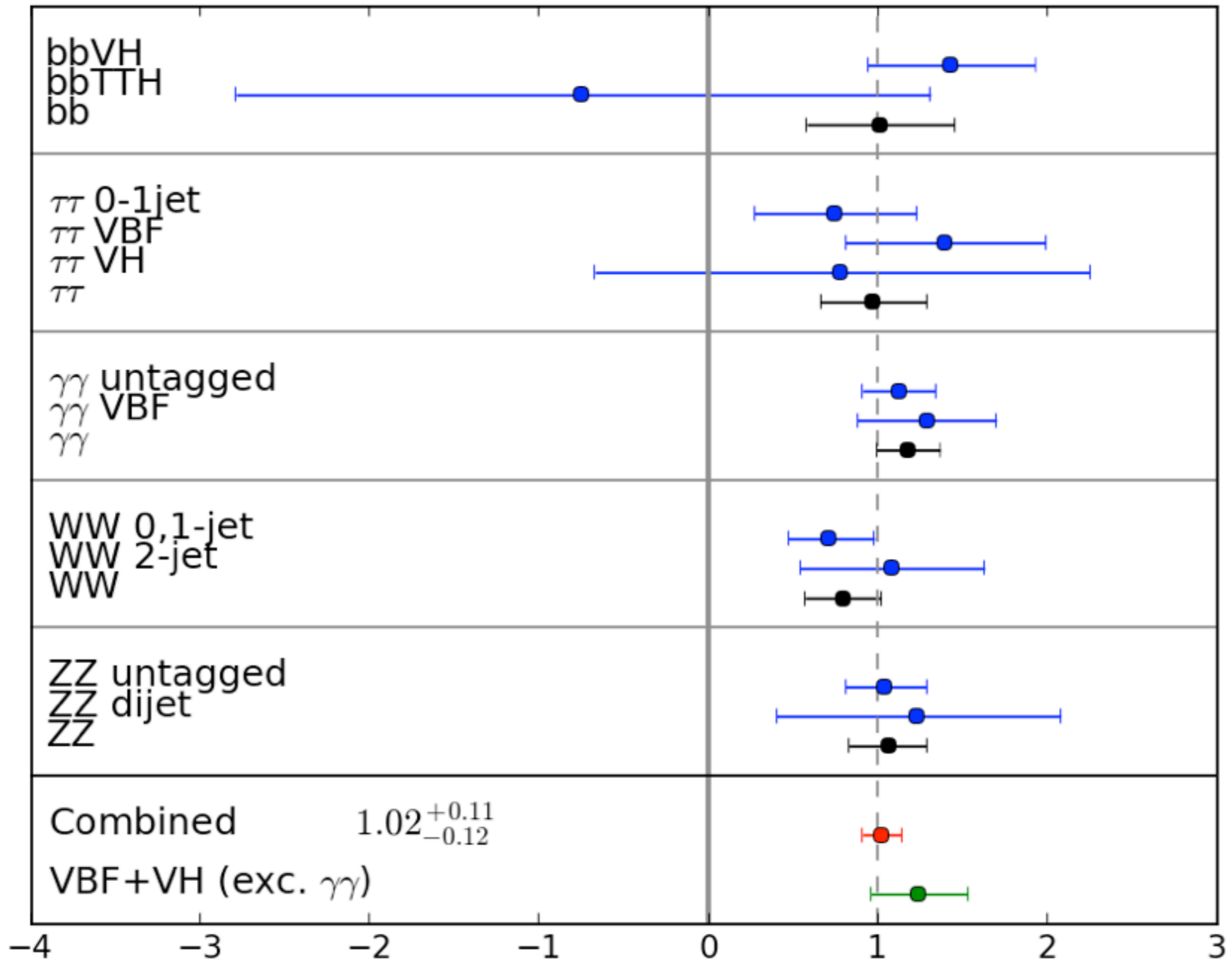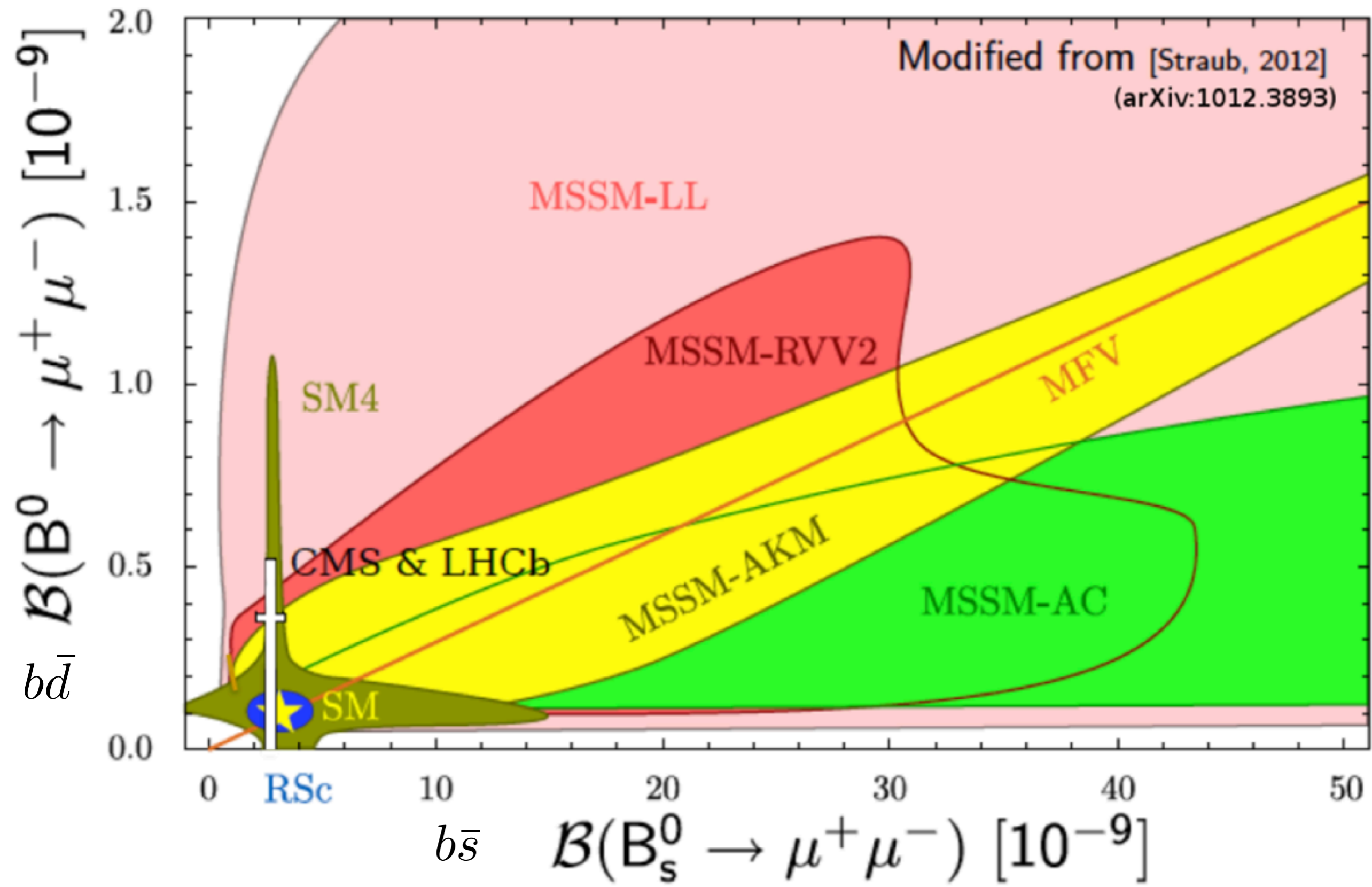
But it has worked!

No New Physics

The Standard Model

is

Phenomenal

GLOBAL

From Ellis and You, Arxiv:1303.3879

LHCb+CMS combined

Why do we want new physics?

- The old physics was a lot of fun!
  One of the greatest stories in science history
  > 30 Nobel prizes.

- There are unsolved problems.

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)

PROBLEMS AND WORRIES

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*(Clearly requiring something beyond the Standard Model)*

- Gravity
- Dark matter
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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?
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From DeGrassi et. al, **arXiv:1205.6497**
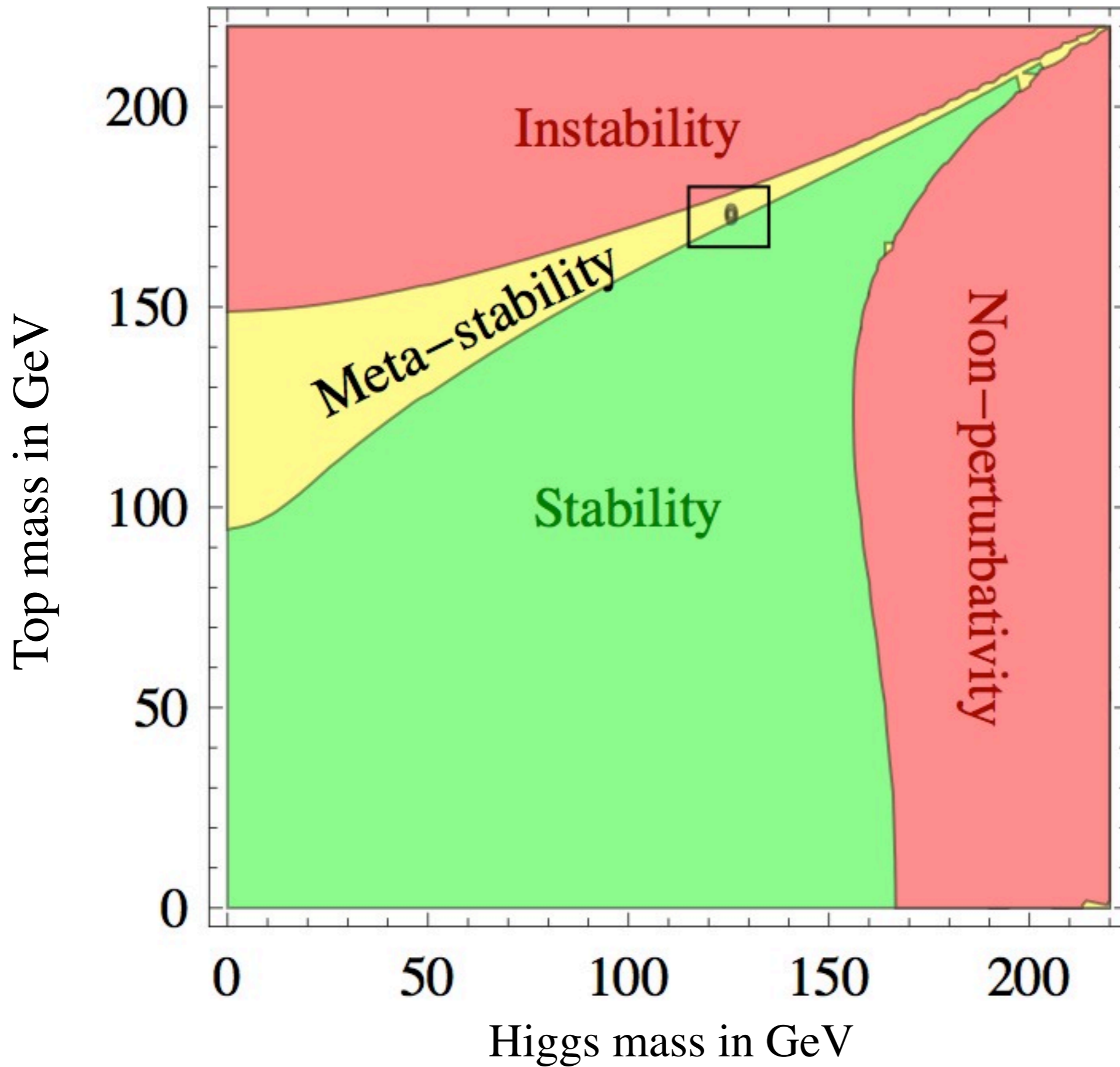
The Singlet Era?

If we see nothing, the most radical explanation is that there is nothing. The second most radical explanation is that everything else is singlets.

All problems and several worries can be solved by singlets:
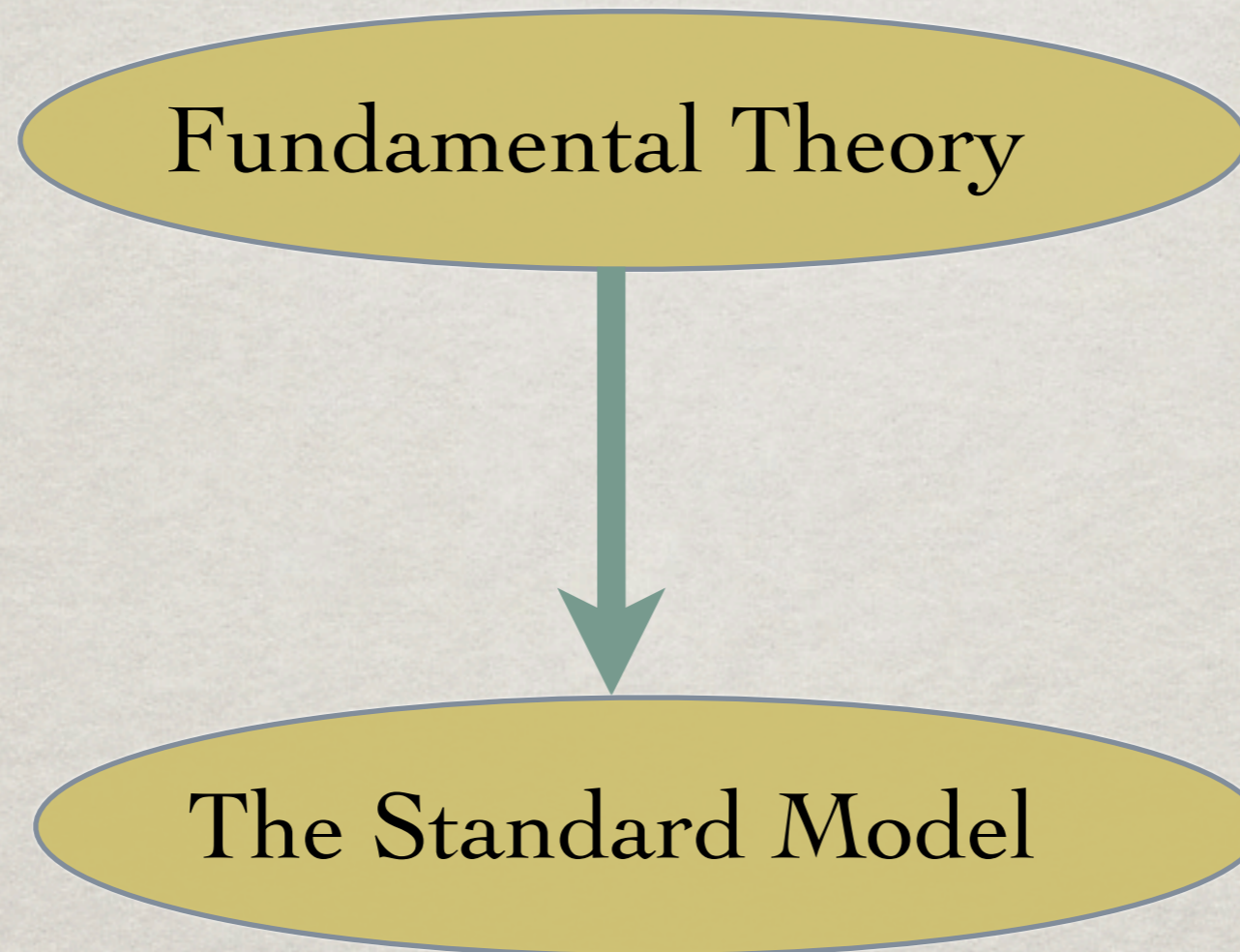
- Dark matter
  (axions or singlet neutrinos)
- Baryogenesis
  (Leptogenesis using Majorana phases of neutrinos)
- Inflation
  (perhaps even just the Higgs can do it)
- Strong CP problem
  (axions)
- Small neutrino masses
  (see-saw mechanism using singlet neutrinos)

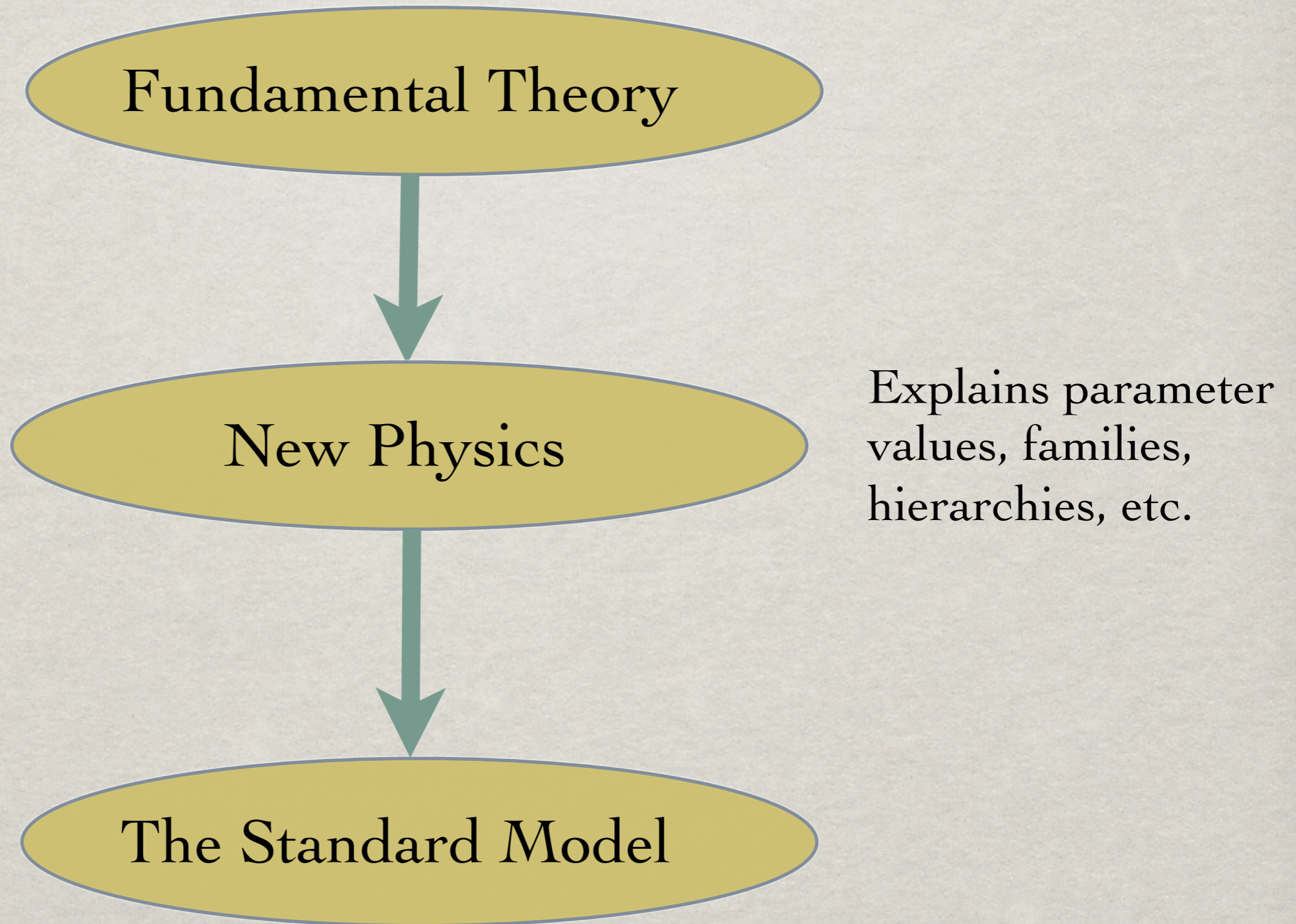Radical new physics is only needed to deal with some of the worries

Why Worry?

The old paradigm:

The BSM Paradigm:

The Landscape Paradigm:

This picture is suggested by:

- The Multiverse

  Inflation suggests an eternal process of creation of new universes.
  Why should they all have the same laws of physics?

- String Theory

  Large number of "string vacua" known since 1986.
  Now called the "String Theory Landscape".

- 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.
  And it smells a lot like anthropocentrism.

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 ugly gauge group.
- Some strange (but anomaly-free) choice of matter.
- Some weird choice of parameter values.
- And the whole model should extrapolate consistently to the Planck scale.

That's exactly what we have right now!

Atomic Physics ✗

Nuclear Physics ✗

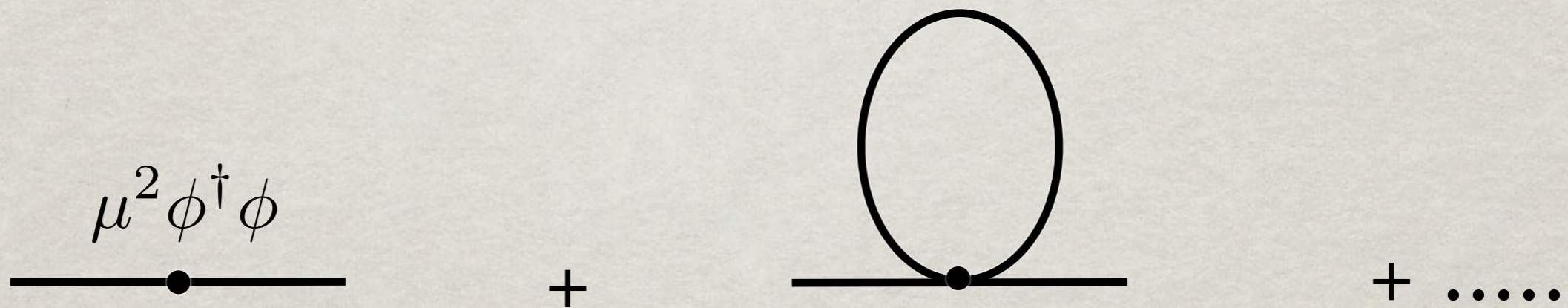Hadronic Physics ✗

The Standard Model ✓
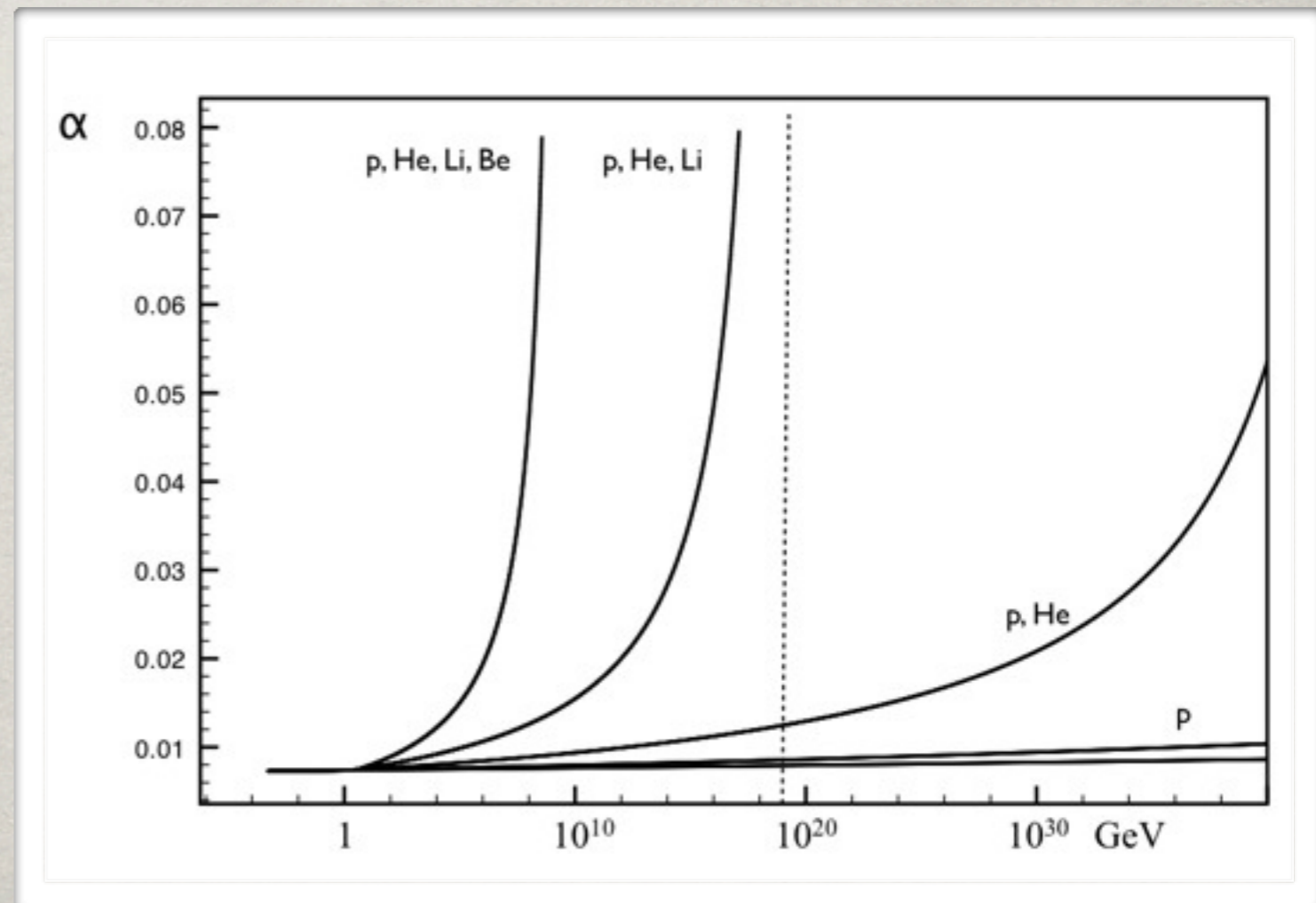
The Hierarchy Worry

Weak scale $\approx$ 100 GeV

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

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

$$\mu^2 \phi^\dagger \phi \qquad + \qquad \qquad + \ldots.$$

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,

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.

Ways Out

- The hierarchy is a misconception in QFT. *(e.g Jegerlehner,* **arXiv:1305.6652***)*
  People claiming this ignore new physics scales.
  Not clear how they want to deal with gravity.

- There are no physics scales beyond the weak scale.
  Perhaps the Planck energy is just an energy scale, without new physics.
  (Shaposhnikov et. al).

- The Planck scale is an illusion.
  Because of large extra dimension, the true Planck scale is defined in 4+n dimensions.
  This could be as low as the weak scale: no new physics above the weak scale.
  But this predicts gravitational phenomena at the weak scale. Not seen so far.
  (Arkani-Hamed, Dimopoulos, Dvali, 1998)

- The Hierarchy is a problem that requires elaborate new physics.
  Supersymmetry, compositeness, technicolor,....

- There is a hierarchy, but we should not worry about it.

Anthropic?

- Weakness of gravity: brains would collapse into black holes.

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

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

- For more arguments see my review:

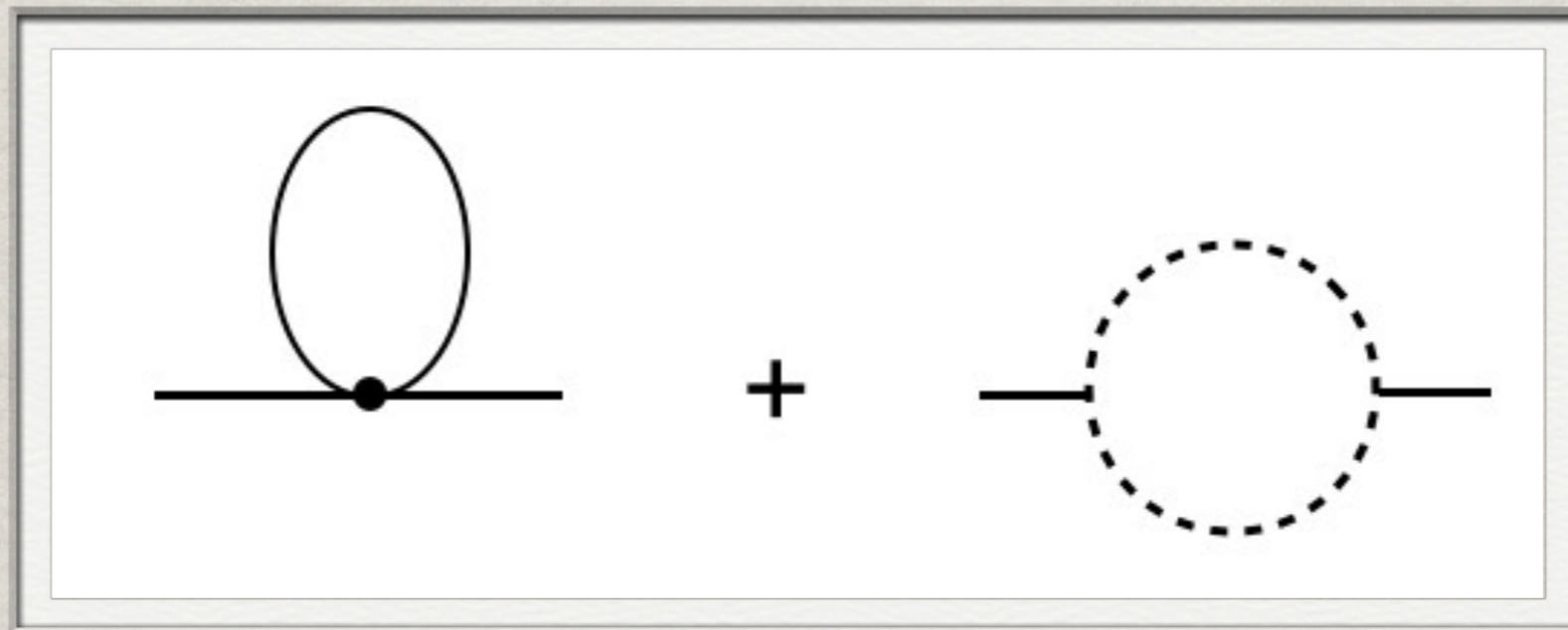 Rev. Mod. Phys. 85 (2013) pp. 1491-1540

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."

Supersymmetry

Kills the quadratic divergences order by order by cancelling bosonic and fermionic loops.

"Technically natural"

Intuitively, this looks better. But it does not determine the weak scale. The only way to make it precise is to consider ensembles of theories.

The cost of supersymmetry

In a *technically non-natural* theory we know the distribution of theories, because it is generated by quantum corrections.

In a large ensemble, the fraction of theories with a large hierarchy $\mu \ll M_{\text{Planck}}$ is

$$\left(\frac{\mu^2}{M_{\text{Planck}}^2} \right)$$

In a *technically natural* theory we do not know the distribution, so we may hope it is better. But this can only be established assuming a definite ensemble.

In a region of the string theory landscape, Douglas (2004) and Susskind (2004) concluded that the distributions are like this:

$$\left(\frac{\mu^2}{M_{\text{susy}}^2} \right) \left(\frac{M_{\text{susy}}^2}{M_{\text{Planck}}^2} \right)^N$$

μ Weak Scale

M_{susy} Susy breaking scale

N Number of susy breaking terms

Later work found additional suppression factors; the net effect is unknown. But you are not better off if you simply ignore this...

GUTs?

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

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

Structure looks arbitrary
Charge quantization not explained by *SU(3)* x *SU(2)* x *U(1)*
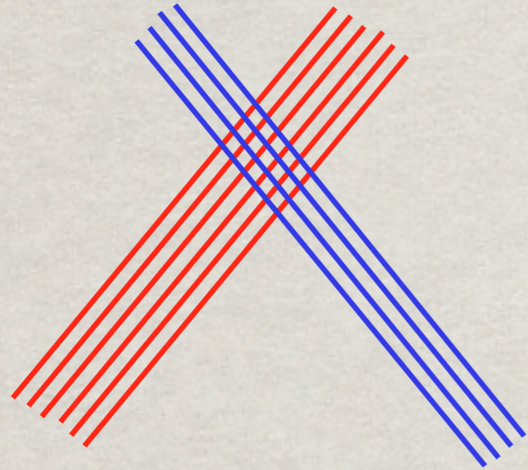
The most popular explanation is Grand Unified Theories

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

(16) of $SO(10)$

GUTs?

- Higgs does not fit in a GUT rep.
- Breaking to *SU(3)* x *SU(2)* x *U(1)* is not explained
  There are alternatives, like *SU(4)* x *U(1)*.
- Choice of representations is not explained

An Anthropic alternative

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

This produces matter coupling to a gauge group *SU(M)* x *SU(N)* x *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

Coincidences

○ The GUT Coincidence
  Families fit in $SU(5)$ representation
  Couplings converge the same value at 10^{16} GeV (requires susy)

○ SM holds until the Planck scale.

○ The Shaposhnikov-Wetterich coincidence **arXiv:0912.0208**

This results in $m_H = m_{\min} = 126$ GeV, with only a few GeV uncertainty.
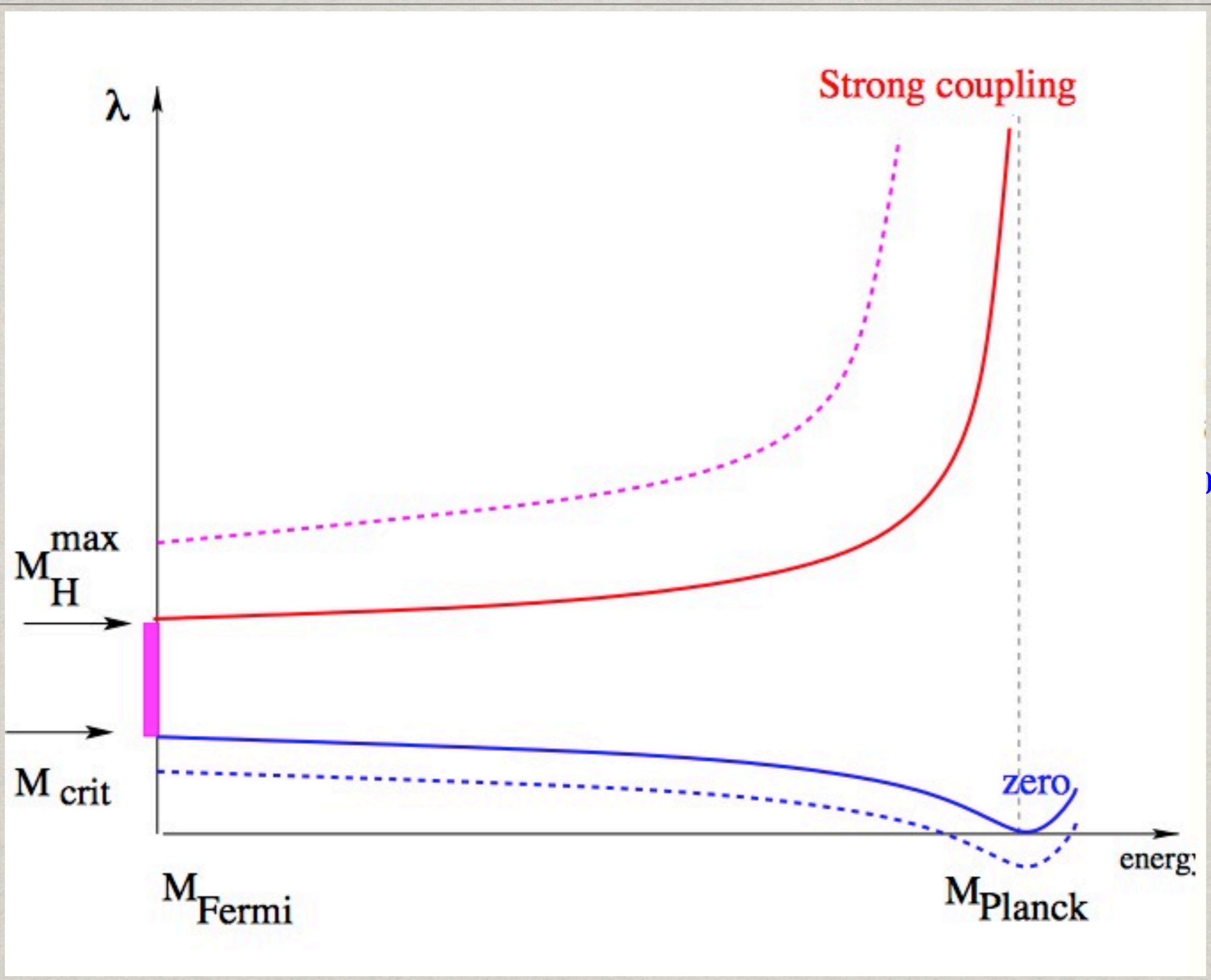short distance running and holds for a wide class of extensions of the SM as

$$125.7 \pm 0.4 = 129.3 \pm 2.0$$

Higgs self coupling touches zero at the Planck scale

○ The Koide mass formula

$$\frac{m_e + m_\mu + m_\tau}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2} = \frac{2}{3}$$

$$(\min = \tfrac{1}{3}; \max = 1)$$

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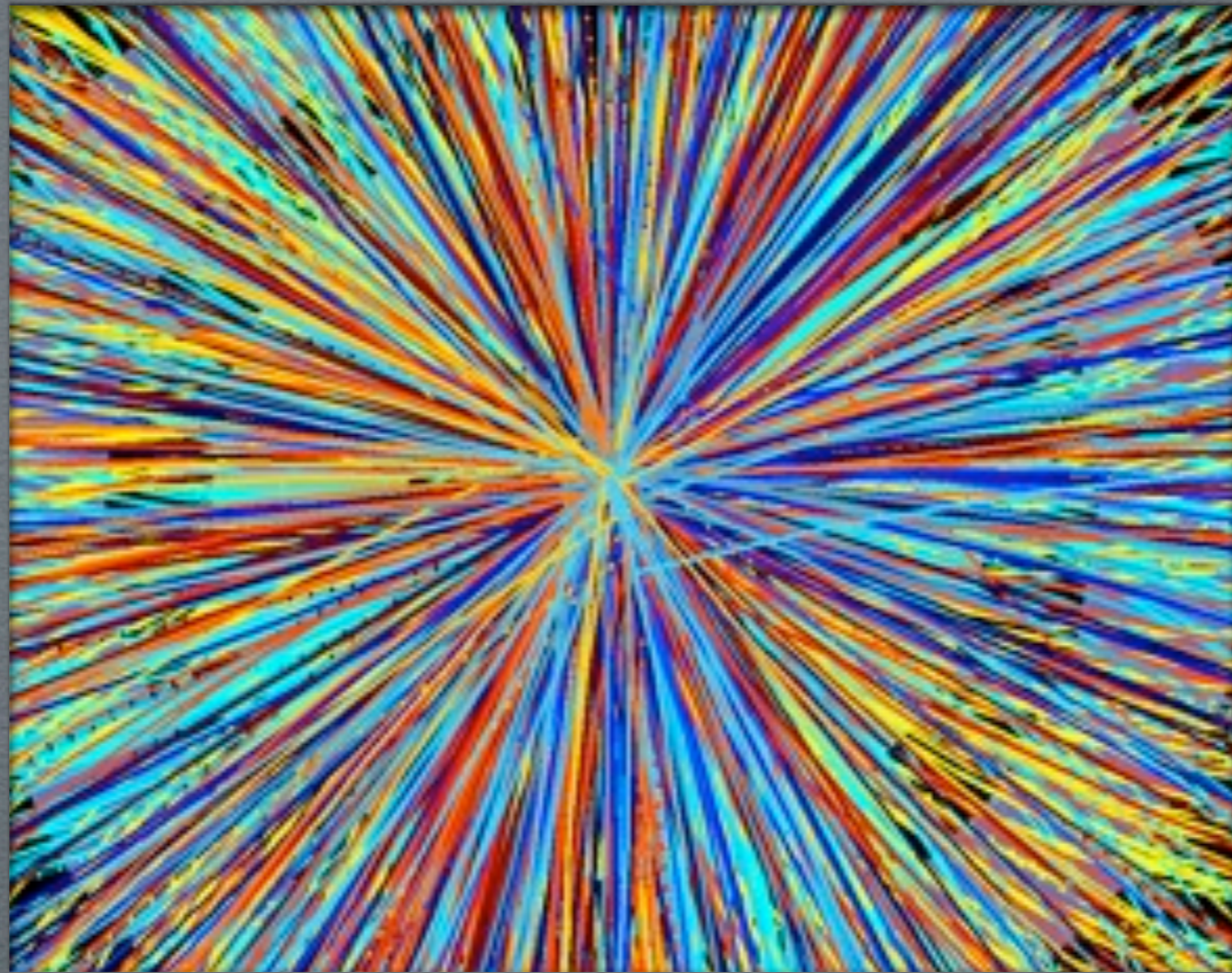
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Future Discoveries?

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, ...

Snoopy

Proposal to Search for Heavy Neutral Leptons at the SPS

W. Bonivento[1,2], A. Boyarsky[3], H. Dijkstra[2], U. Egede[4], M. Ferro-Luzzi[2], B. Goddard[2], A. Golutvin[4], D. Gorbunov[5], R. Jacobsson[2], J. Panman[2], M. Patel[4], O. Ruchayskiy[6], T. Ruf[2], N. Serra[7], M. Shaposhnikov[6], D. Treille[2 (‡)]

A new fixed-target experiment at the CERN SPS accelerator is proposed that will use decays of charm mesons to search for Heavy Neutral Leptons (HNLs), which are right-handed partners of the Standard Model neutrinos. The existence of such particles is strongly motivated by theory, as they can simultaneously explain the baryon asymmetry of the Universe, account for the pattern of neutrino masses and oscillations and provide a Dark Matter candidate.

Parameter space of heavy neutral leptons
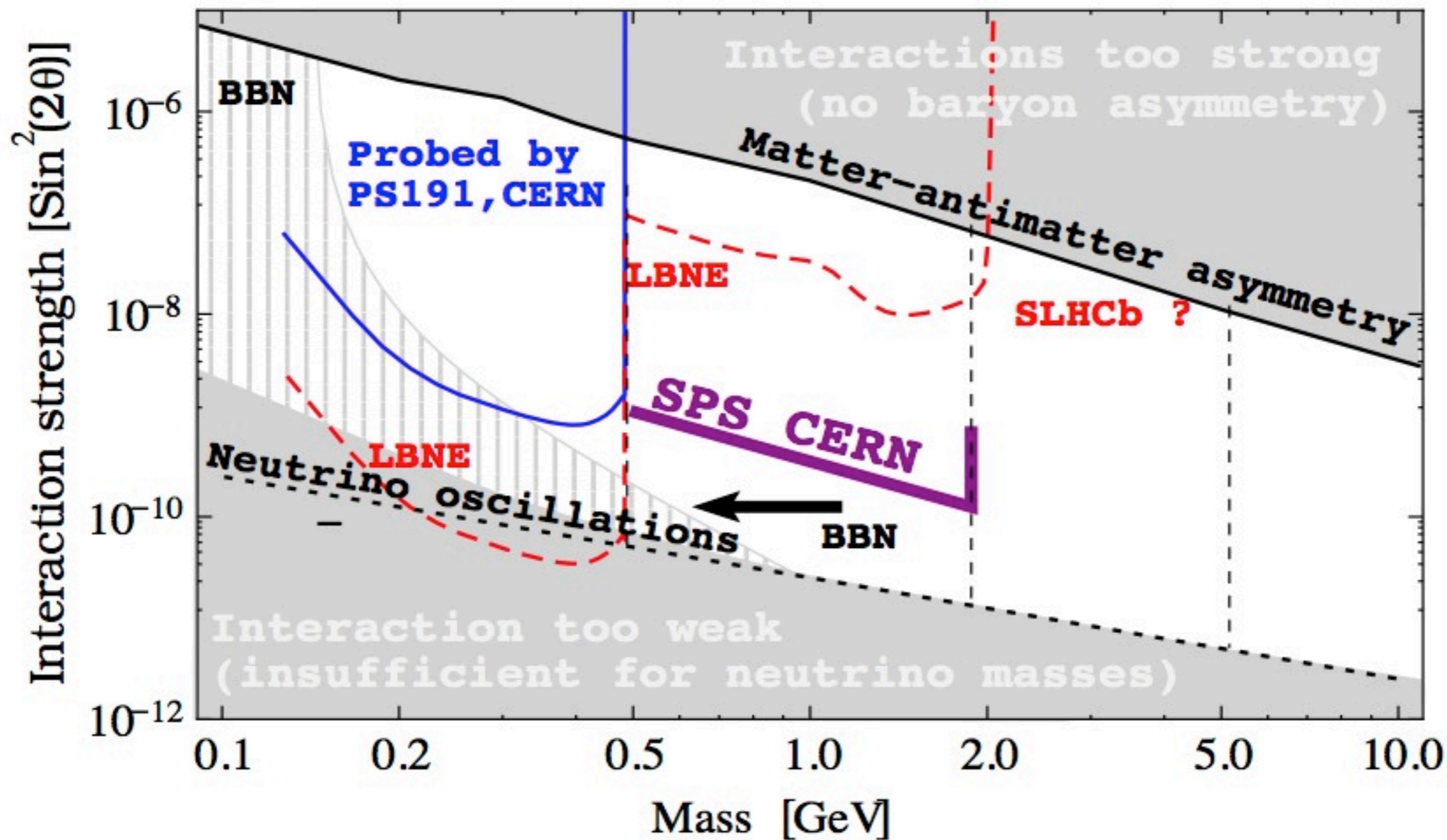
Magenta – dedicated experiments, see the Expression of Interest [arXiv:1310.176]. Also in Proposal to European Strategy Preparatory Group[arXiv:1301.5516]

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.

Variations in Constants of Nature

Spatial variation in the fine-structure constant – new results from VLT/UVES

Julian A. King, John K. Webb, Michael T. Murphy, Victor V. Flambaum, Robert F. Carswell[3] Matthew B. Bainbridge, Michael R. Wilczynska and F. Elliot Koch.

"We derive values of $\Delta\alpha/\alpha \equiv (\alpha_z - \alpha_0)/\alpha_0$ from 154 absorbers, and combine these values with 141 values from previous observations at the Keck Observatory in Hawaii. In the VLT sample, we find evidence that α increases with increasing cosmological distance from Earth. However, as previously shown, the Keck sample provided evidence for a smaller α in the distant absorption clouds. Upon combining the samples an apparent variation of α across the sky emerges which is well represented by an angular dipole model."

$$\Delta\alpha/\alpha \approx .5 \times 10^{-5}$$

A Stringent Limit on a Drifting Proton-to-Electron Mass Ratio from Alcohol in the Early Universe

Julija Bagdonaite, Paul Jansen, Christian Henkel, Hendrick L. Bethlem, Karl M. Menten, Wim Ubachs

"we deduced a constraint of $\Delta\mu/\mu = (0.0 \pm 1.0) \times 10^{-7}$ at redshift z=0.89"

If confirmed this has huge consequences

- Evidence against derivability of the Standard Model and its parameters
  In particular, against fine structure constant numerology.

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

- Evidence against the string theory landscape
  (in particular the tuning of vacuum energy)

$$\Lambda = \ldots + \frac{1}{\alpha} \int d^4 x F_{\mu\nu} F^{\mu\nu} + \ldots = 10^{-120} \times (M_{\mathrm{Planck}})^4$$

Dine, Banks, Douglas (2002)

Conclusions

- This is a historic moment.

- Perhaps it is just an interlude.
  If LHC finds anything new, the show continues.
  We can start peeling away the next shell of the onion.

- But perhaps we have just removed the last shell.
  This would imply a change of perspective for the entire field, with profound implications.

Have we entered the multiverse era?