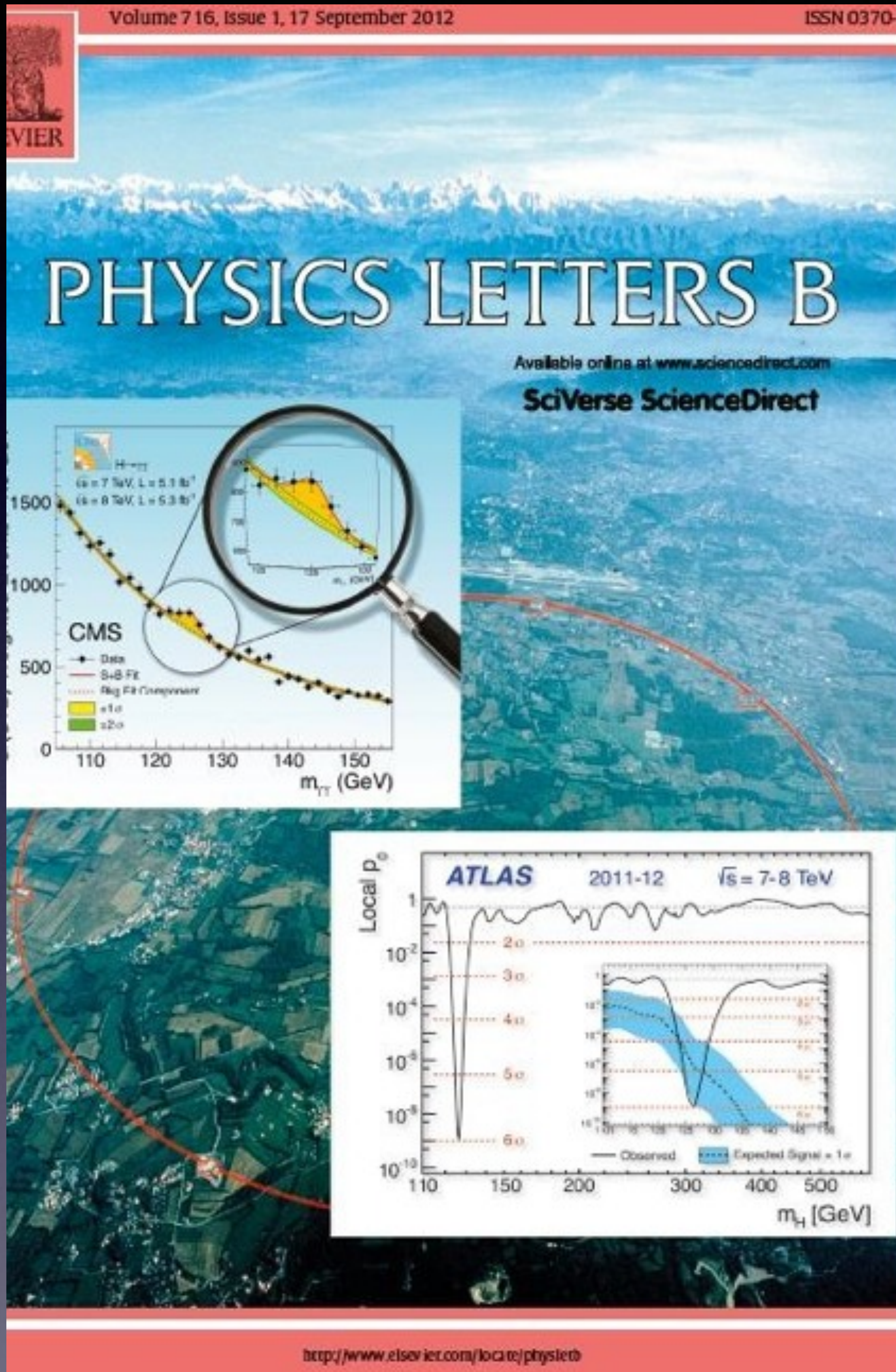
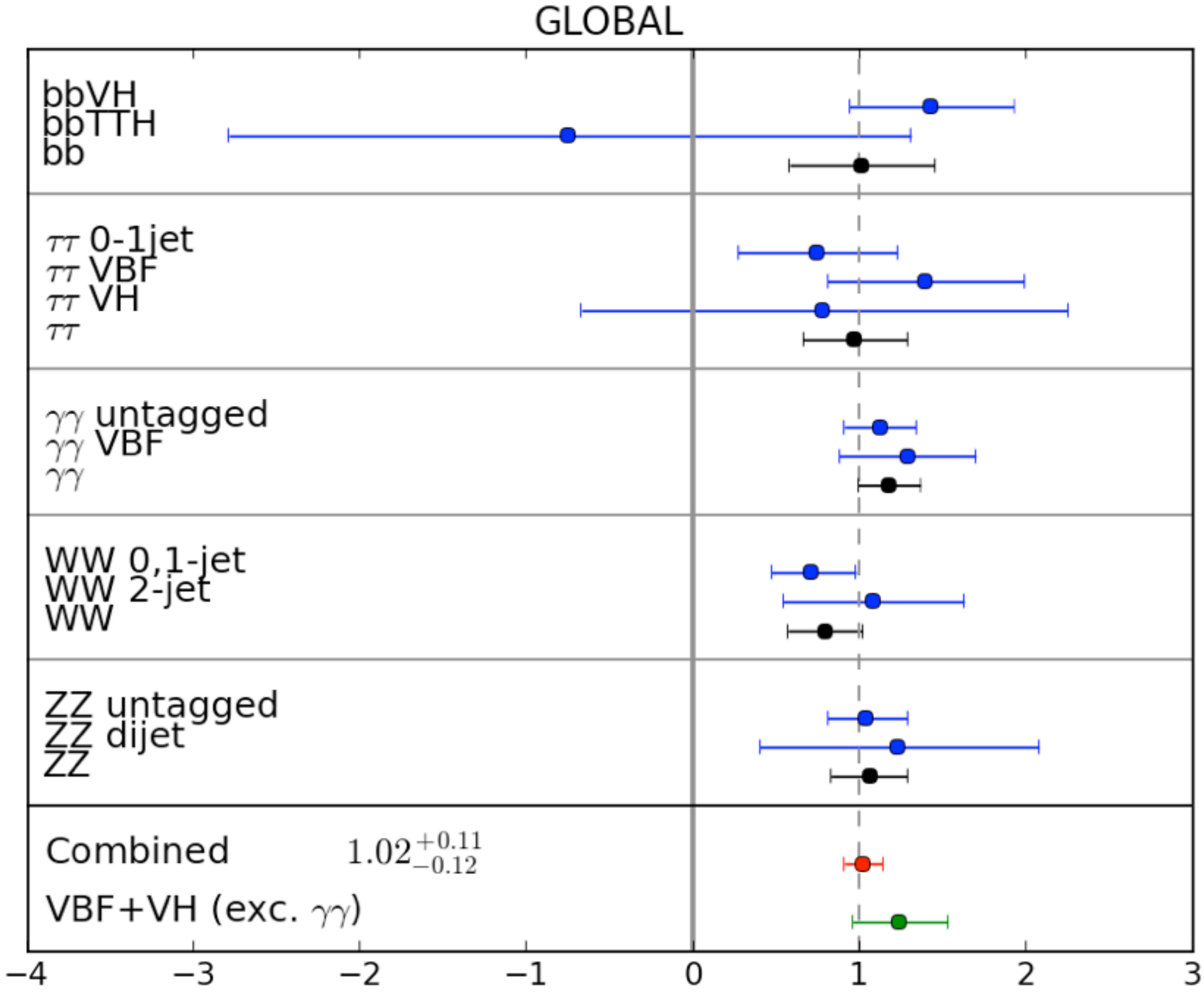
Particle Physics in the Multiverse

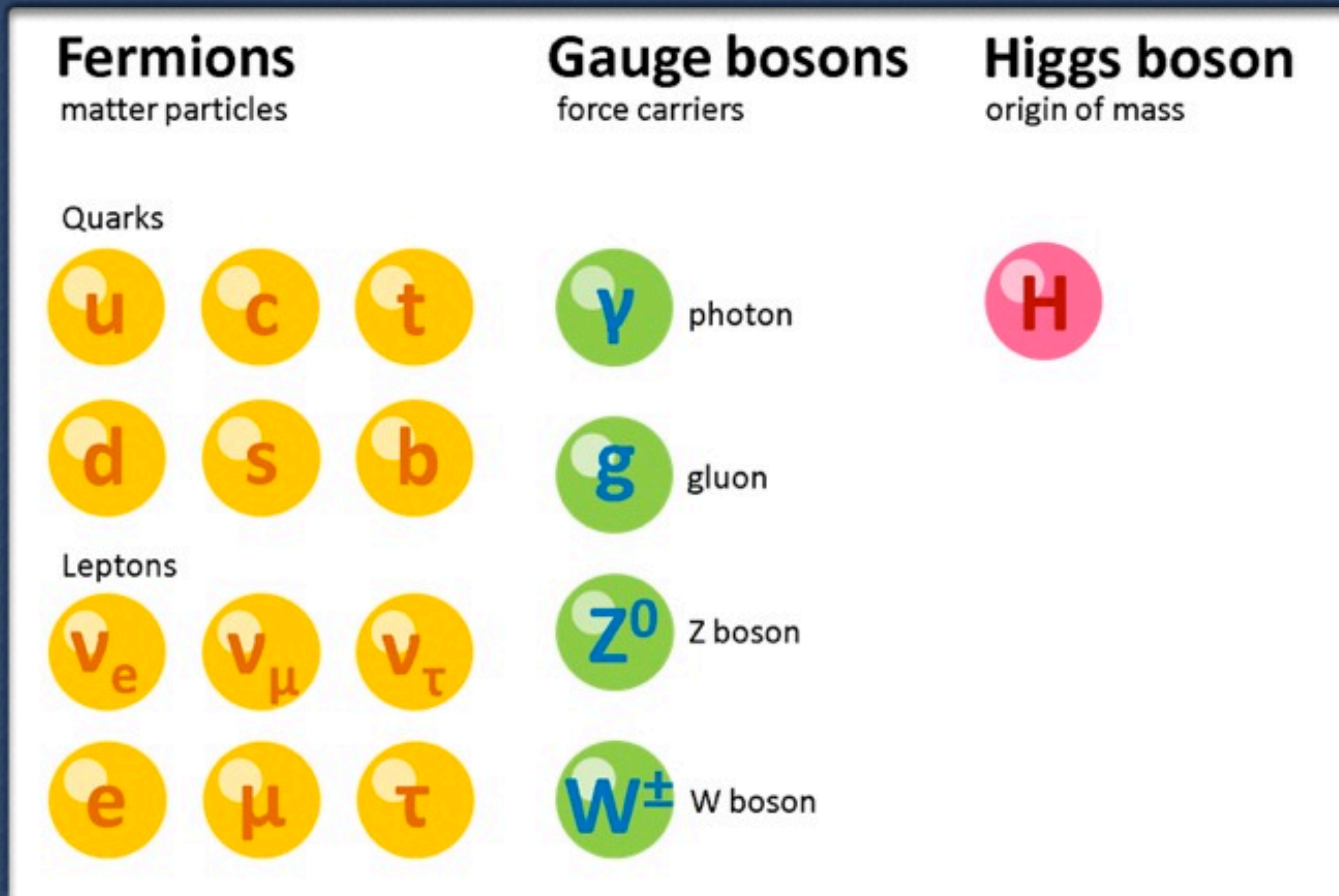

Volume 716, Issue 1, 17 September 2012
PHYSICS LETTERS B
Available online at www.sciencedirect.com
SciVerse ScienceDirect
CMS
m_{γγ} (GeV)
ATLAS
2011-12
√s = 7-8 TeV
Local p0
mH [GeV]
http://www.elsevier.com/locate/physletb

No New Physics

The Standard Model is Phenomenal



From Ellis and You, Arxiv:1303.3879



The Standard Model

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 quarks 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.

Running Coupling Constants

All Standard Model parameters “run” with energy

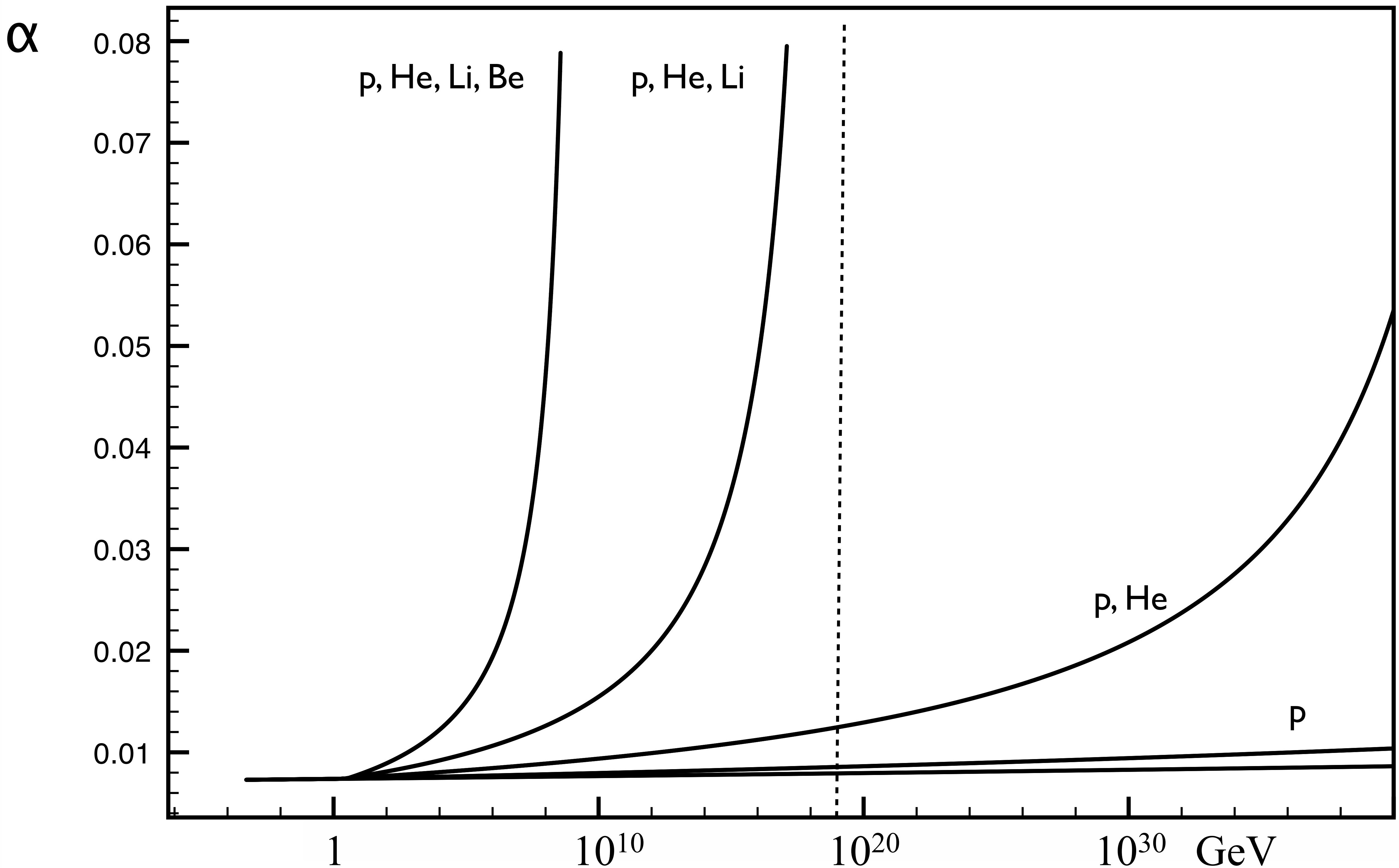
$$\frac{d}{dt}\bar{g}(t) = \beta(\bar{g}(t))$$

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

The Standard Model
Extrapolation to the Planck scale

The Standard Model remains consistent for energy scales up to the Planck scale ($10^{19} \times m_{\text{proton}}$)

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



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

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)

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A Potential Problem: *stability of the Higgs Potential*

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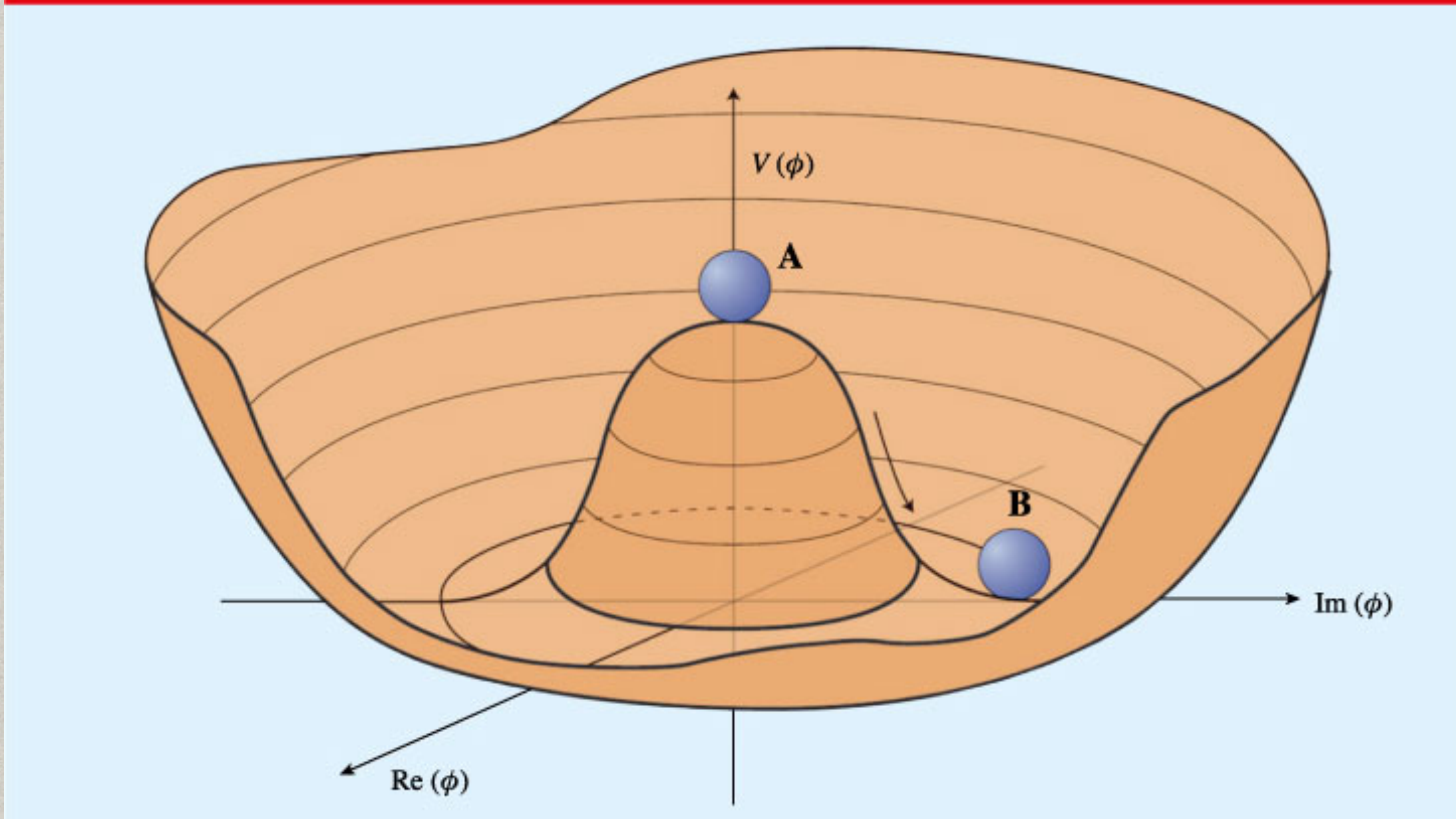
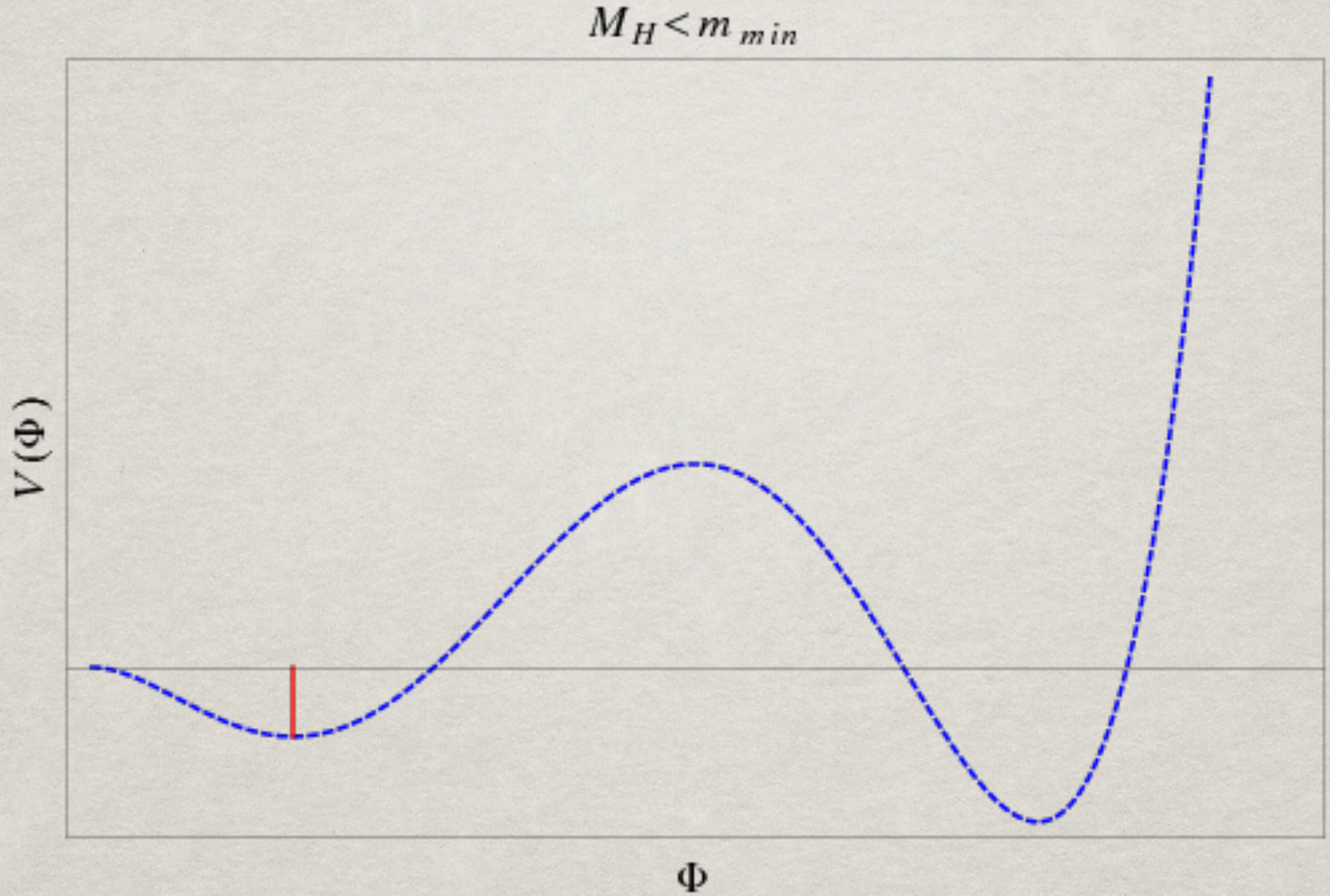
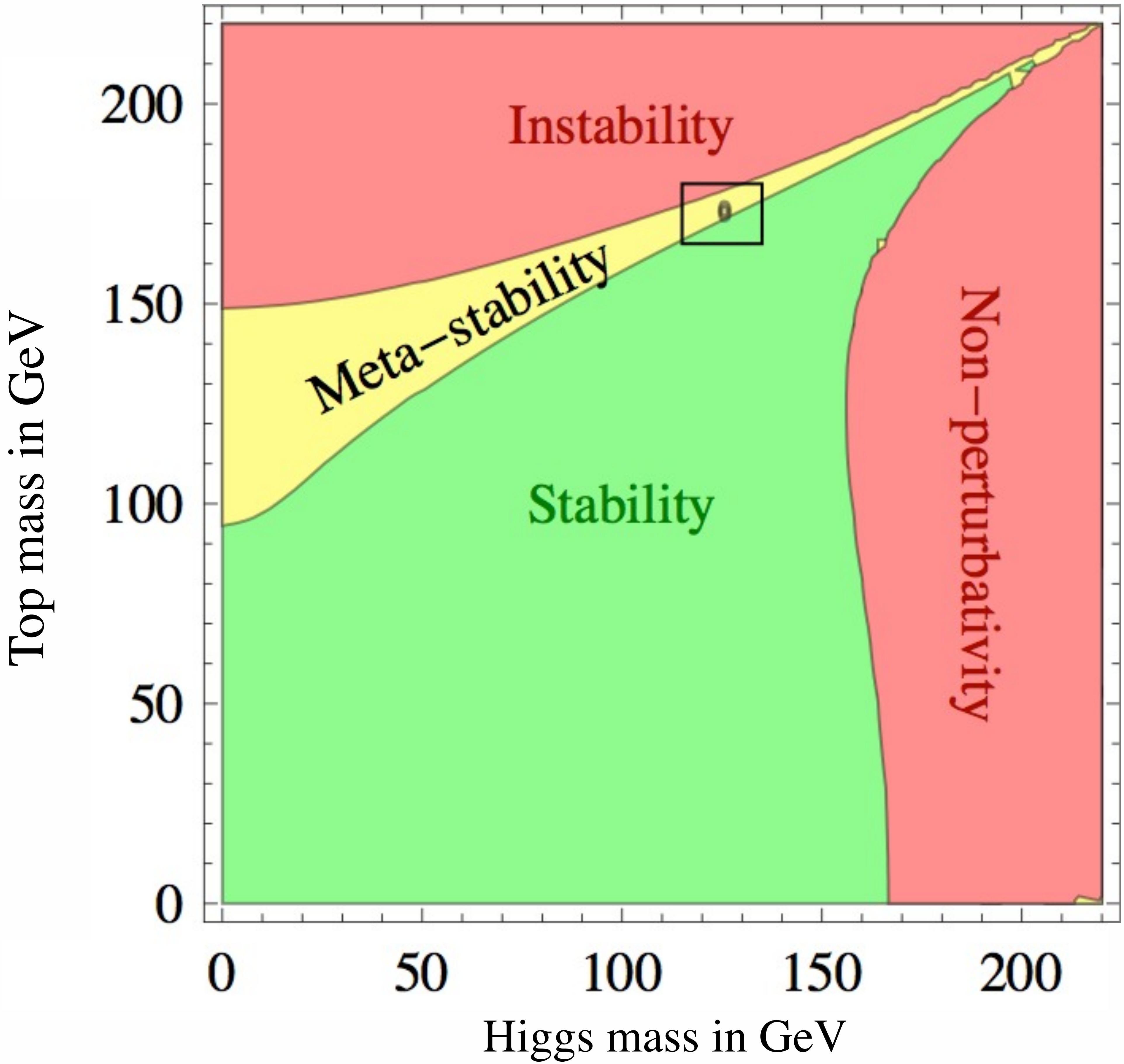

V (ϕ)
A
B
Im (ϕ)
Re (ϕ)



$M_H < m_{min}$
$V(\Phi)$
Φ



From DeGrassi et. al, arXiv:1205.6497

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The Singlet Era?

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 (supersymmetry, Grand Unification, ...) is only needed to deal with some of the worries

Paradigm Shift?

"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

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

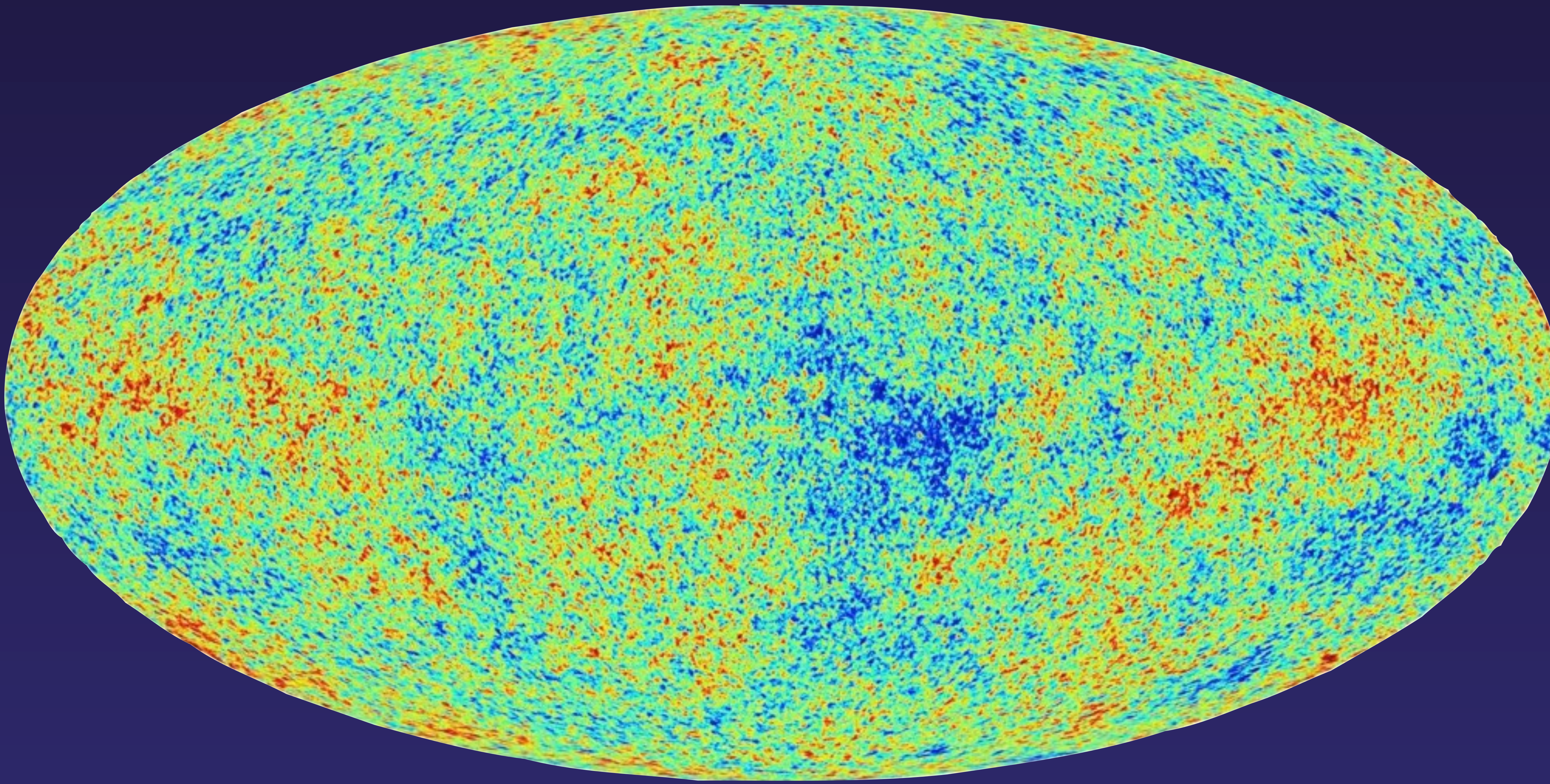
Some formulas for α

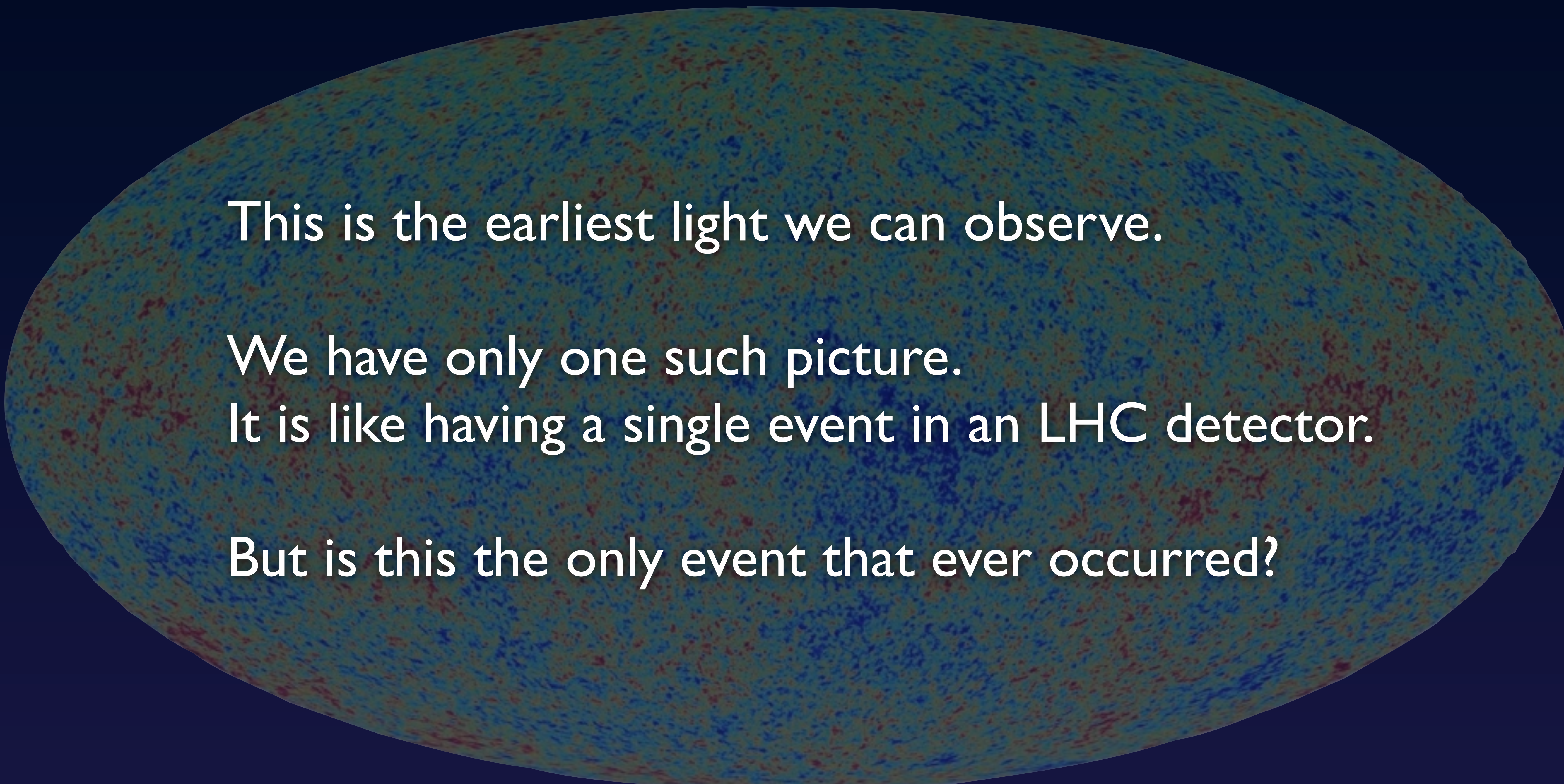
$$\alpha = 2^{-4}3^{-3}\pi$$ *W. Heisenberg*

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

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

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





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.

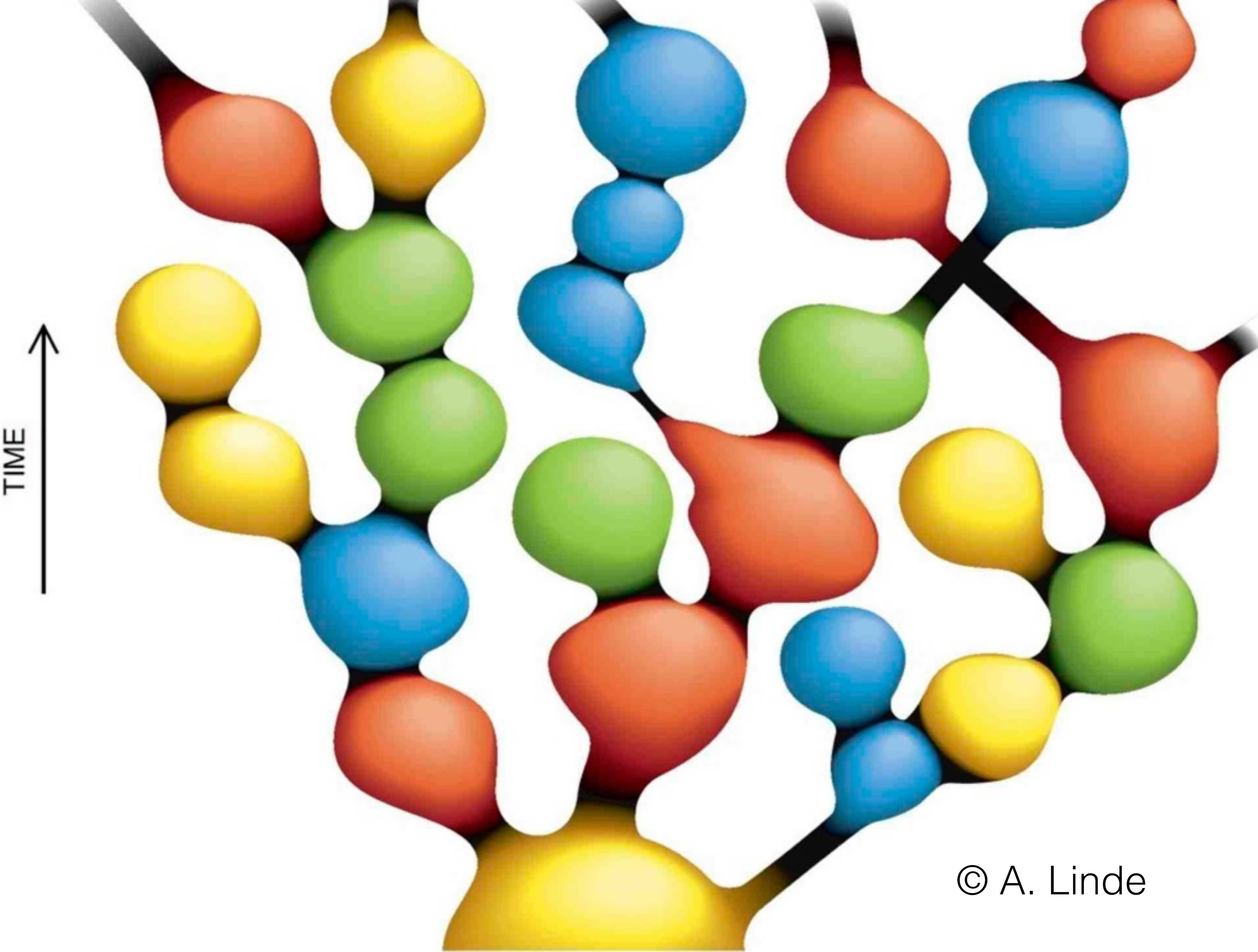
But is this the only event that ever occurred?

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”.

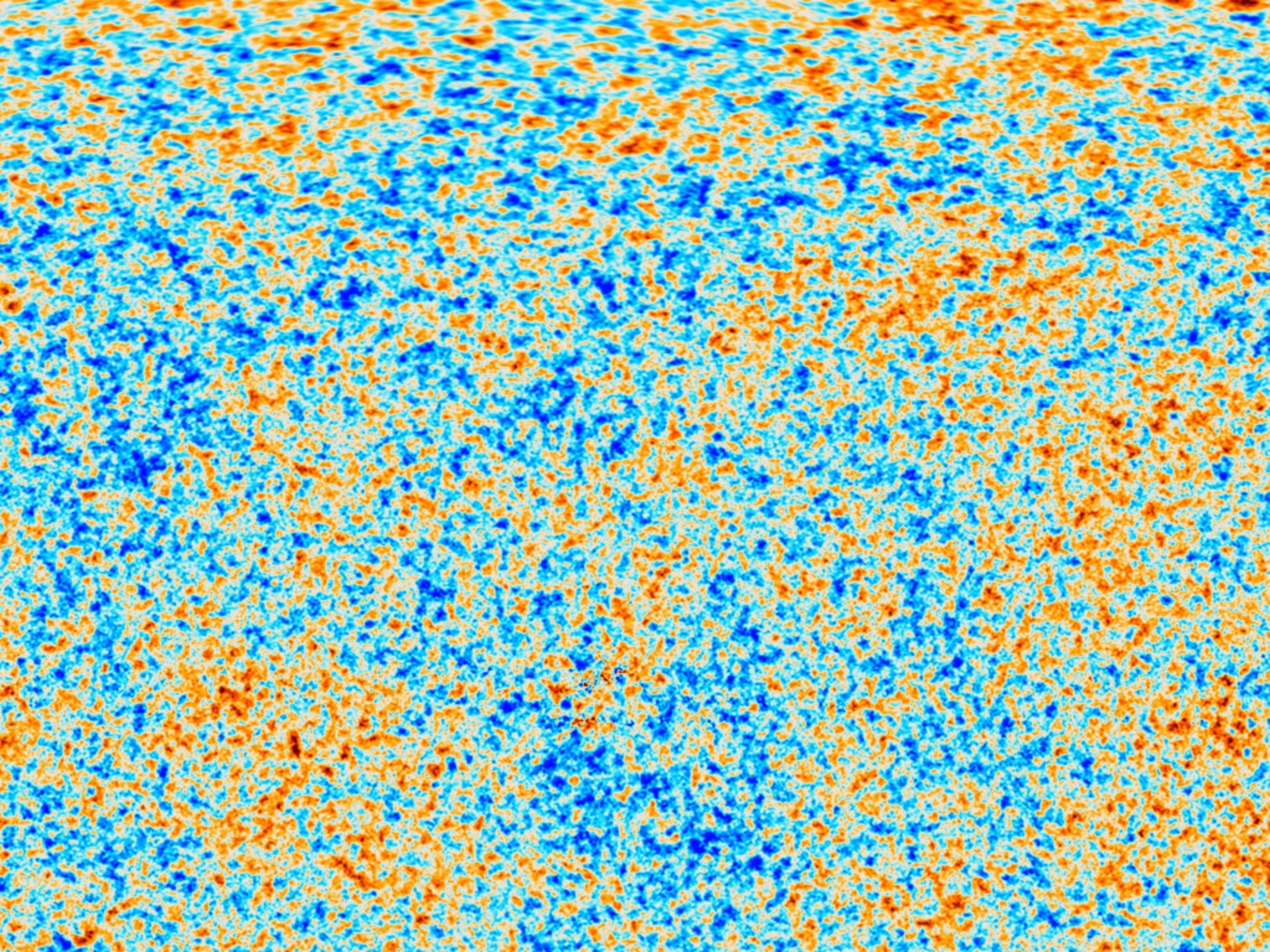
“If the universe contains at least one inflationary domain of a sufficiently large size, it begins unceasingly producing new inflationary domains.”

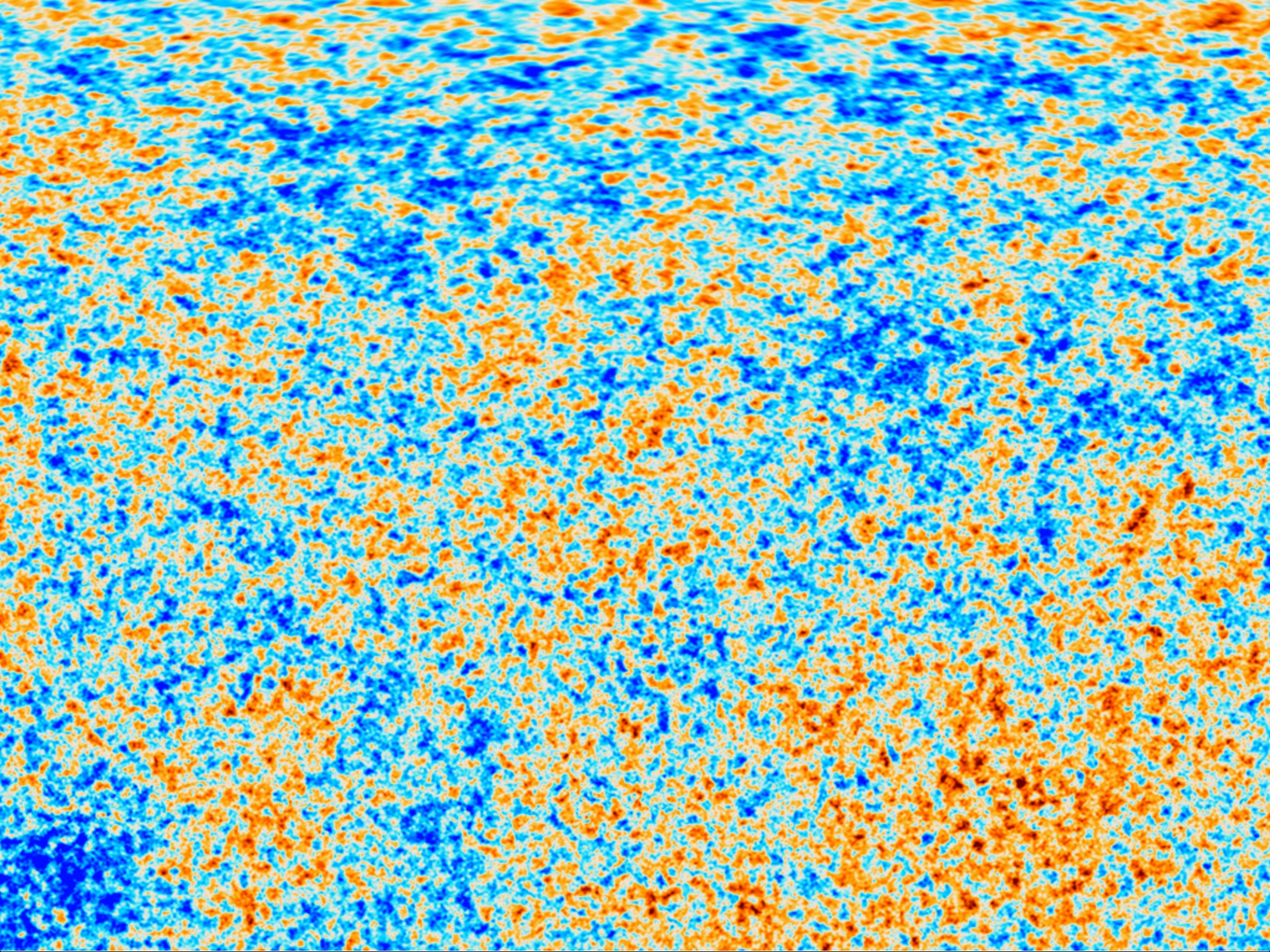
Andrei Linde (1994)


TIME

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:

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?

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, a few billion years from now. Or perhaps as information encoded in the CMB radiation, but only in principle)

So this is not science...

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

Why $SU(3)xSU(2)xU(1)$, 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.

The philosophical objection

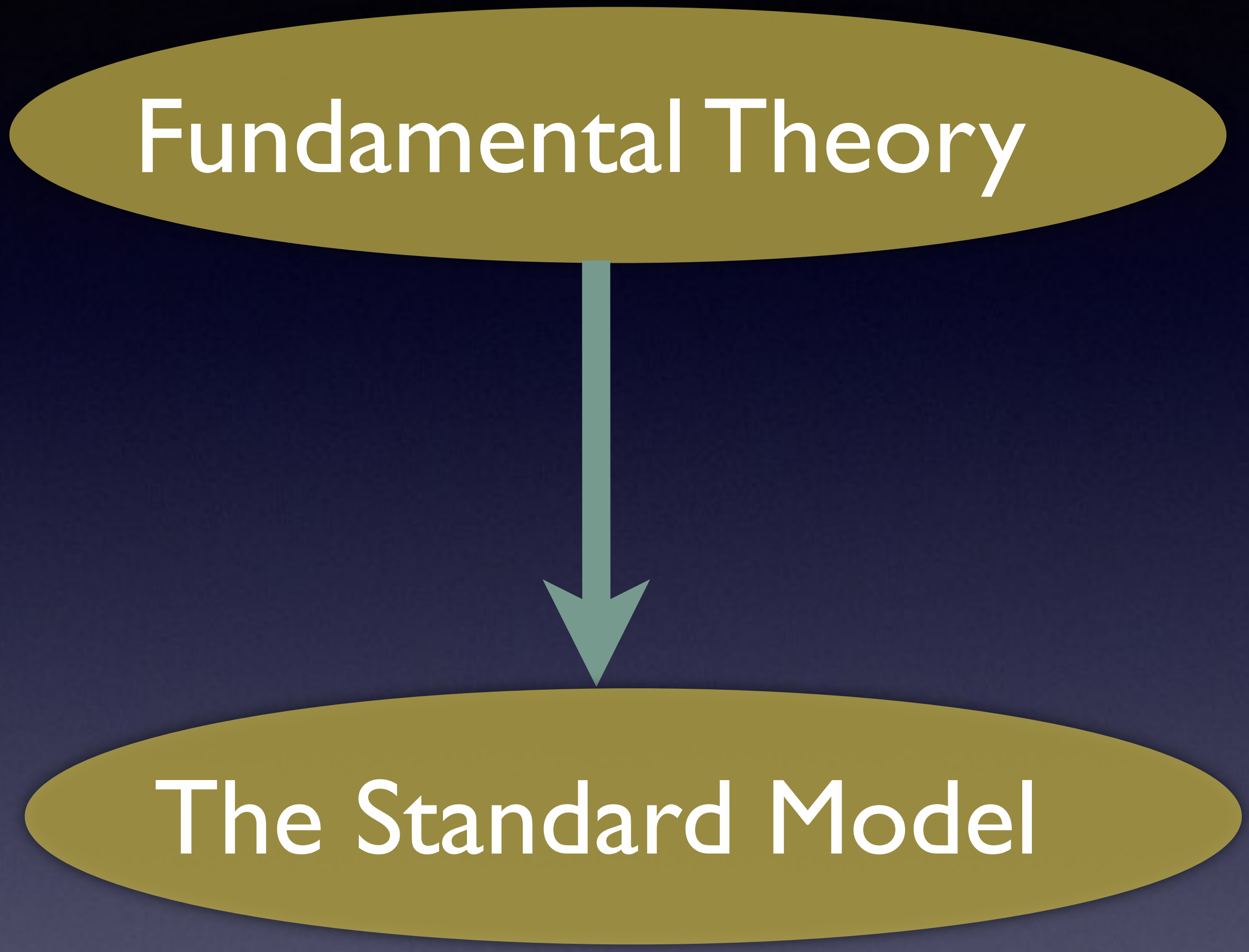
Let us assume the worst-case scenario:
Other universes are unobservable in principle.

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.

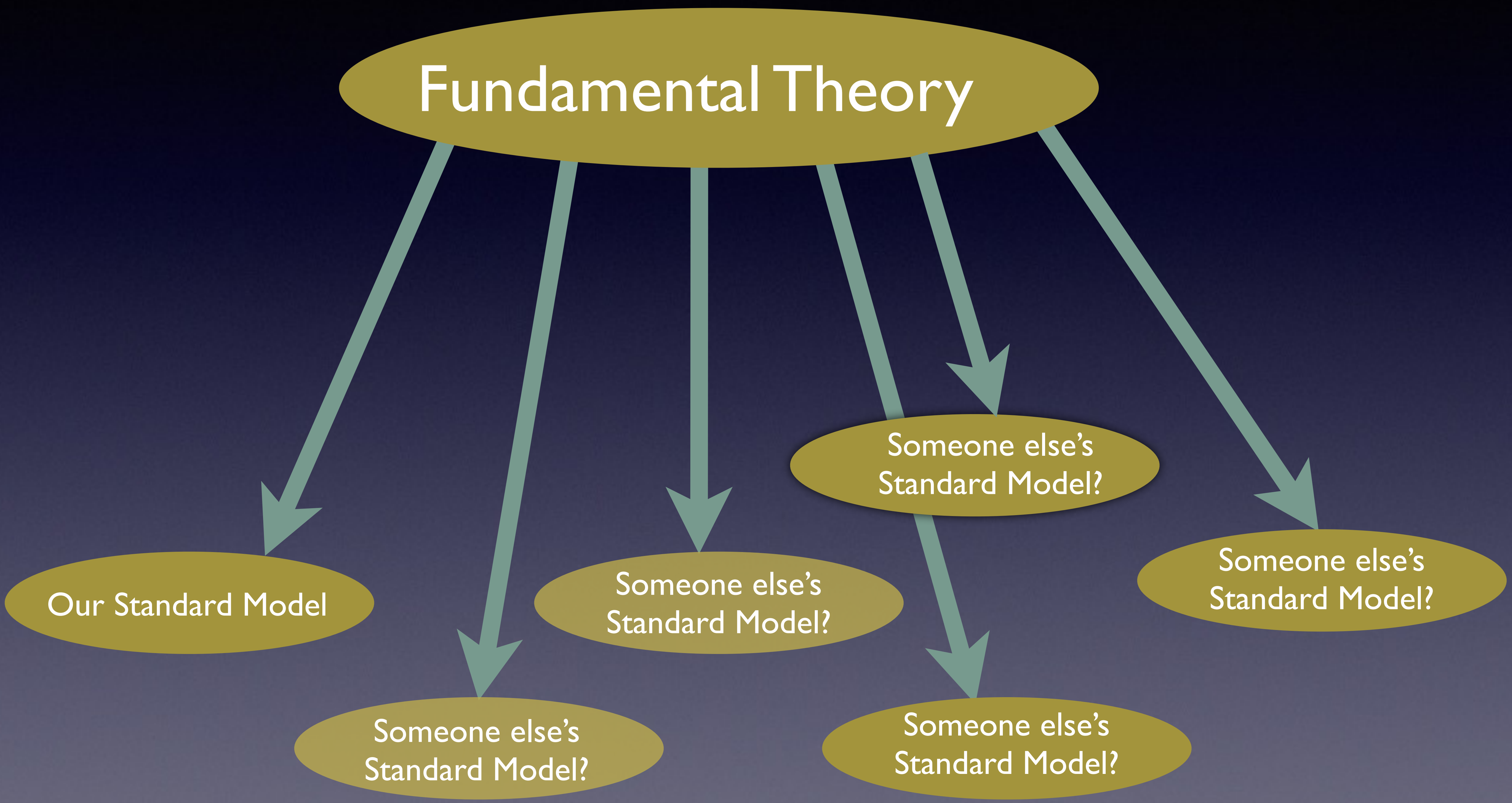
We could confirm that theory either

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

Instead of:



We would have:

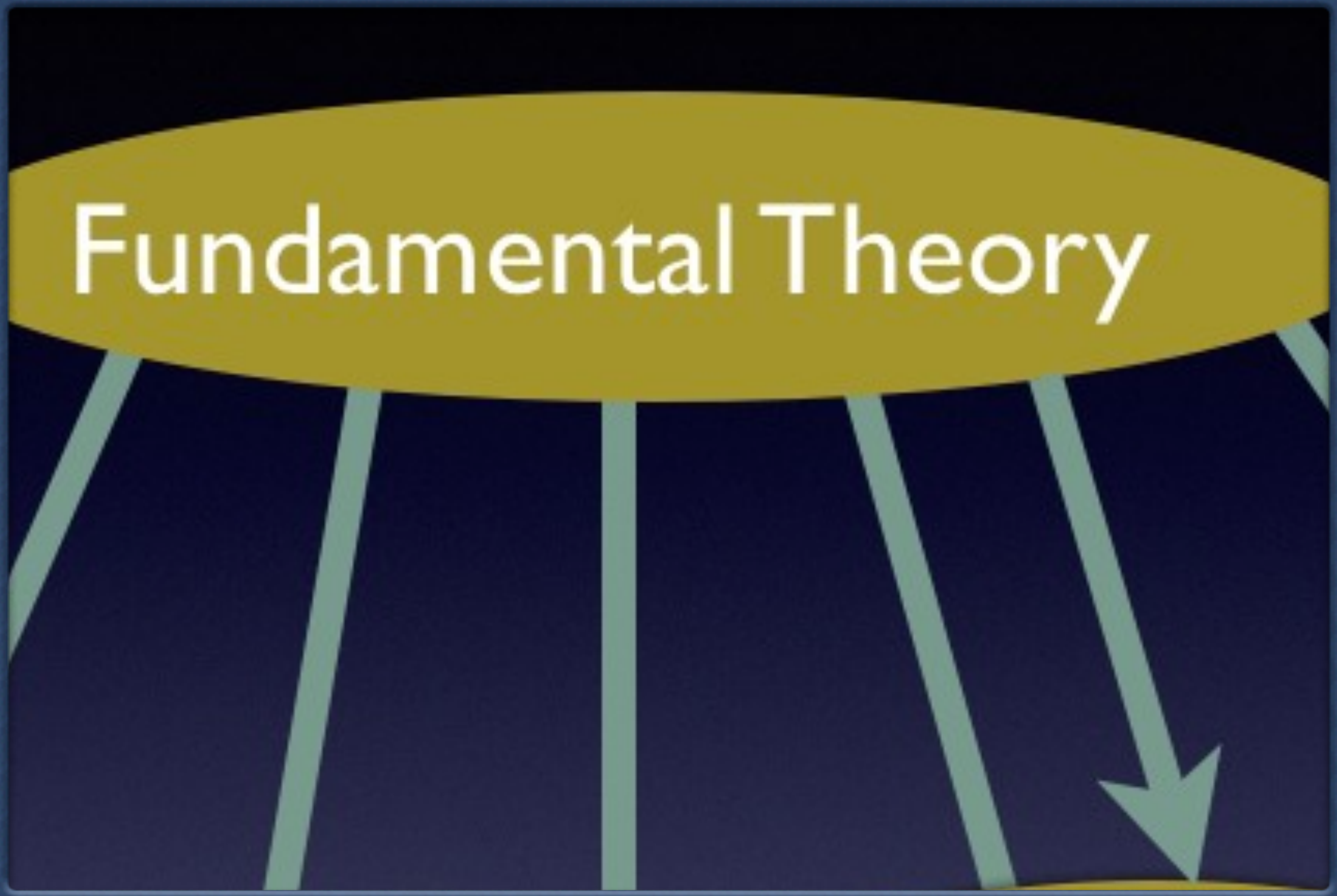


If this is true one would expect:

- Some gauge group.
- Some choice of matter.
- Some choice of parameter values.
- Consistent extrapolation to the Planck scale.

} But not mathematically unique in any way

That's exactly what we have right now!



String Theory

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.*"

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

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.

But what did this mean?

Some anthropic constraints

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

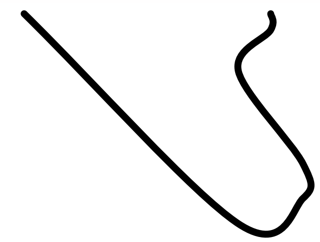
$$p \rightarrow n + e^+ + \nu$$

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.

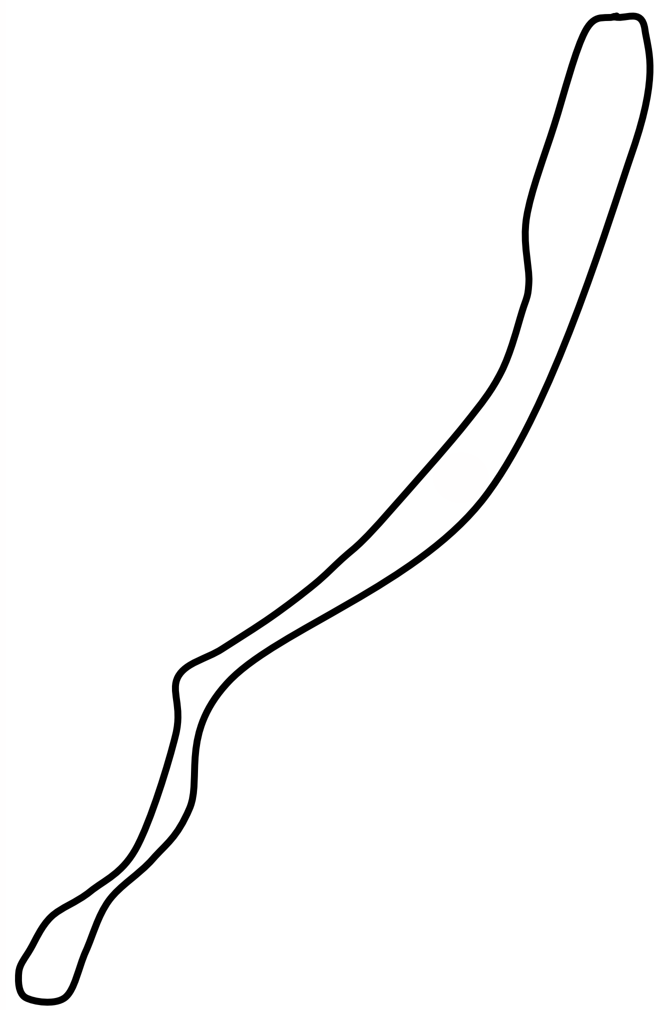
- The neutron should be unstable, to prevent a neutron dominated universe. This limits the electron mass to

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

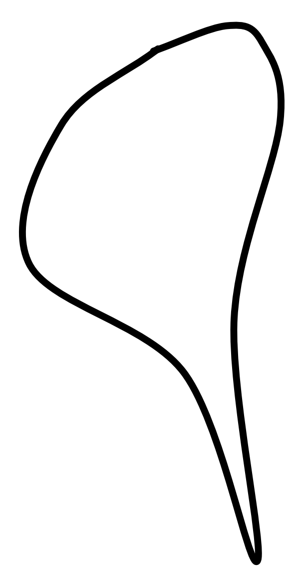
(See Rev. Mod. Phys. 85 (2013) pp. 1491-1540 for more)



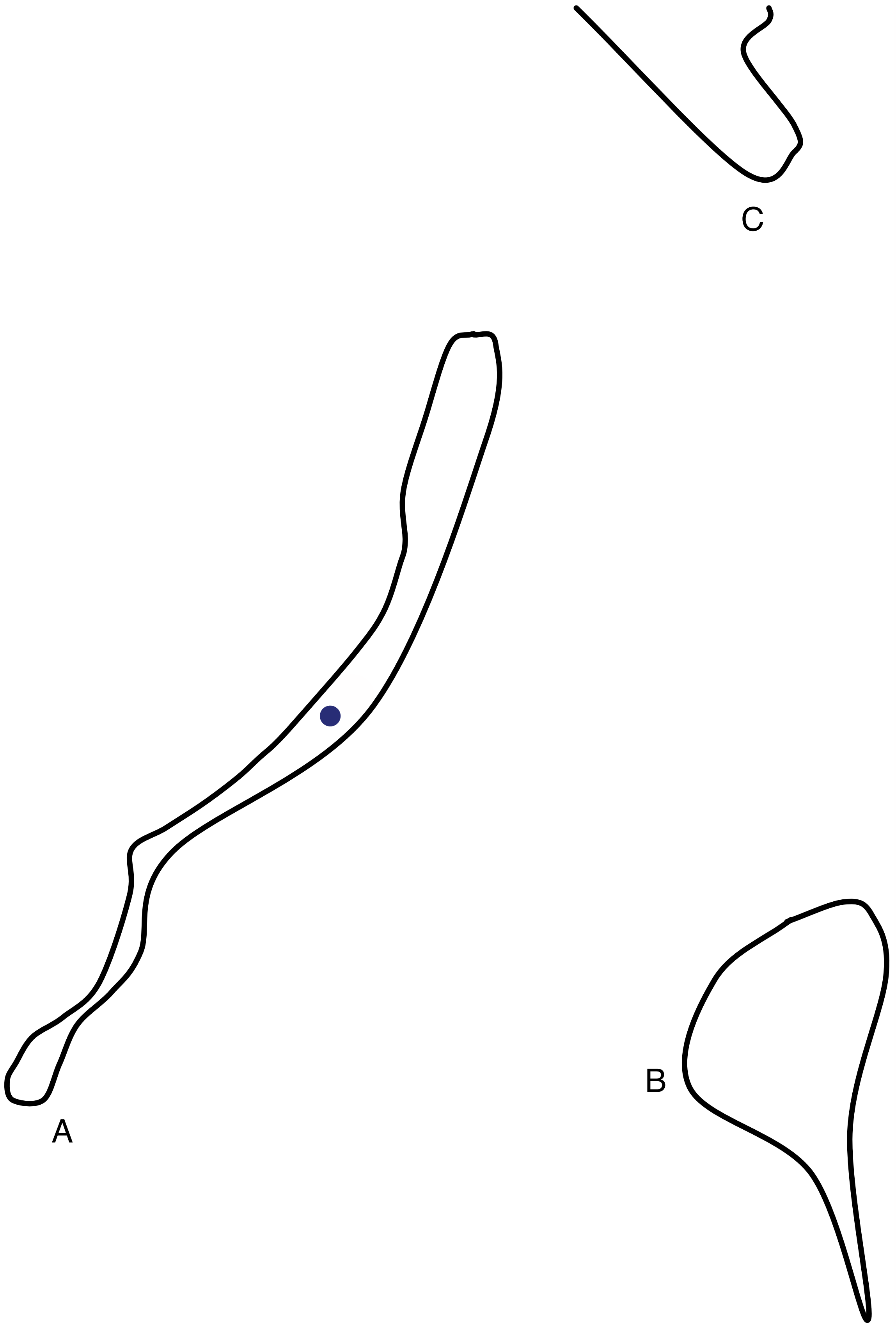
C



A



B


C
A
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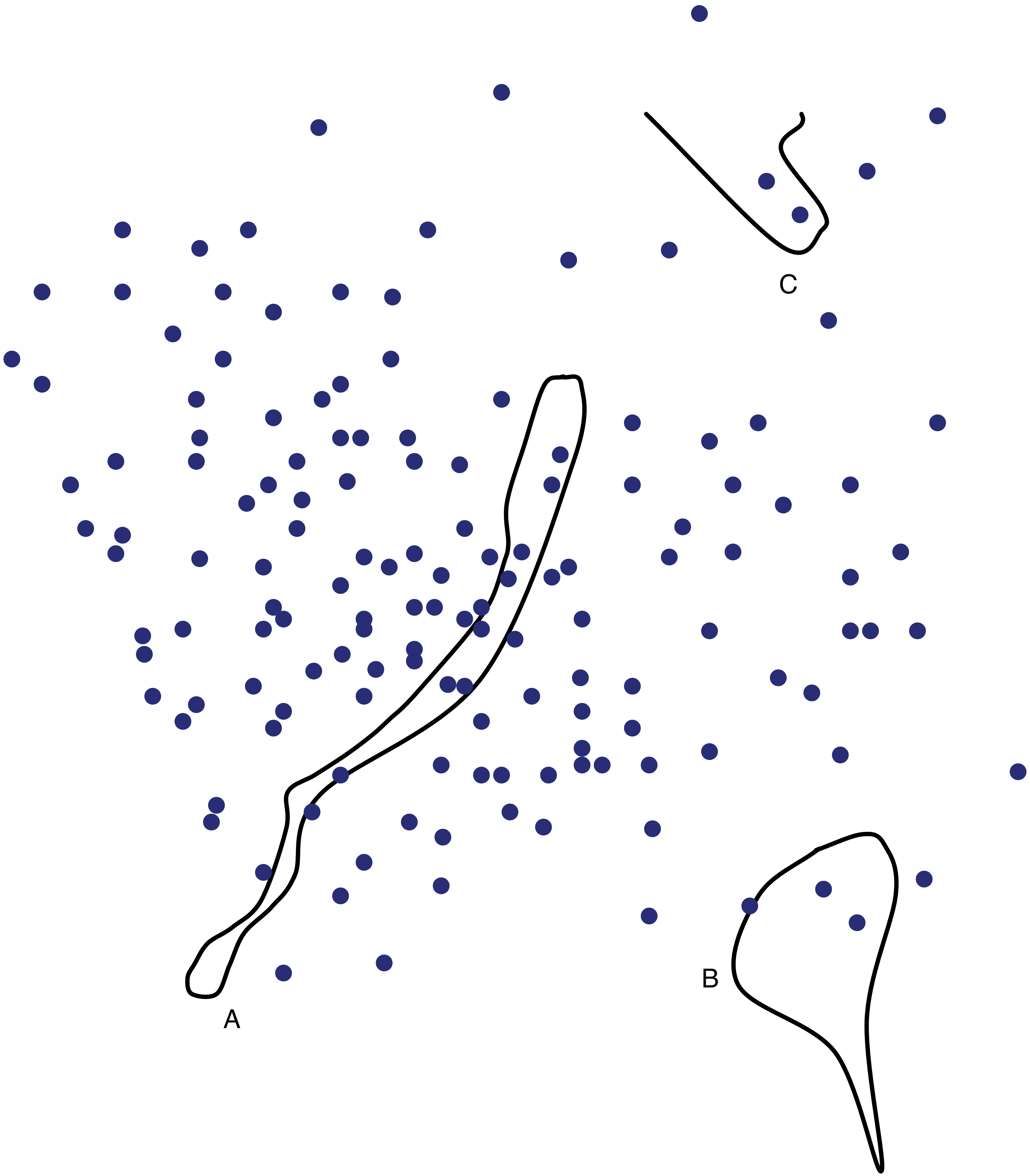

C
A
B

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… “

Scalars

The first scalar particle, the Higgs boson, has just been found. It is a Lorentz singlet, but not a gauge singlet.

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

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

(M is the Planck Mass)

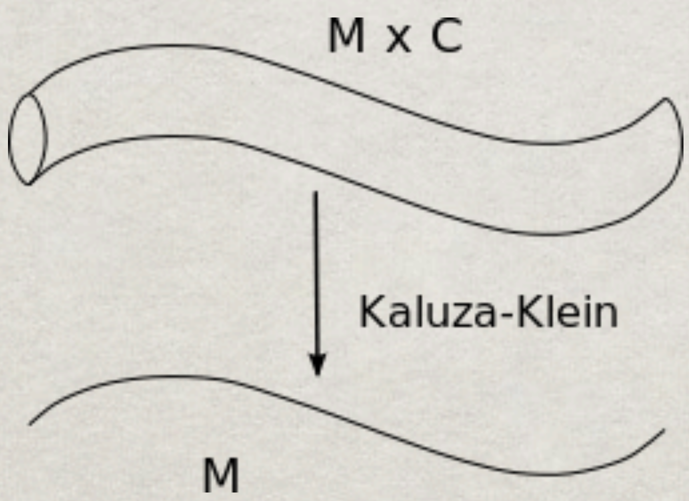
The value of the fine structure constant α is determined by the vacuum expectation values of the fields ϕ_i.

Then all Standard Model parameter are “environmental”.

Compactification and Moduli

In string theory, hundreds of such scalars exist ("moduli").

String theories in four space-time dimensions are obtained from compactifications of ten-dimensional string theories.



The moduli correspond to shape parameters of a compactification manifold. All Standard Model parameters depend on them.

Their potentials are believed to have a huge number of minima ("the String Theory Landscape"), of order $10^{hundreds}$

This make a discussion of vacuum energy inevitable.

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

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

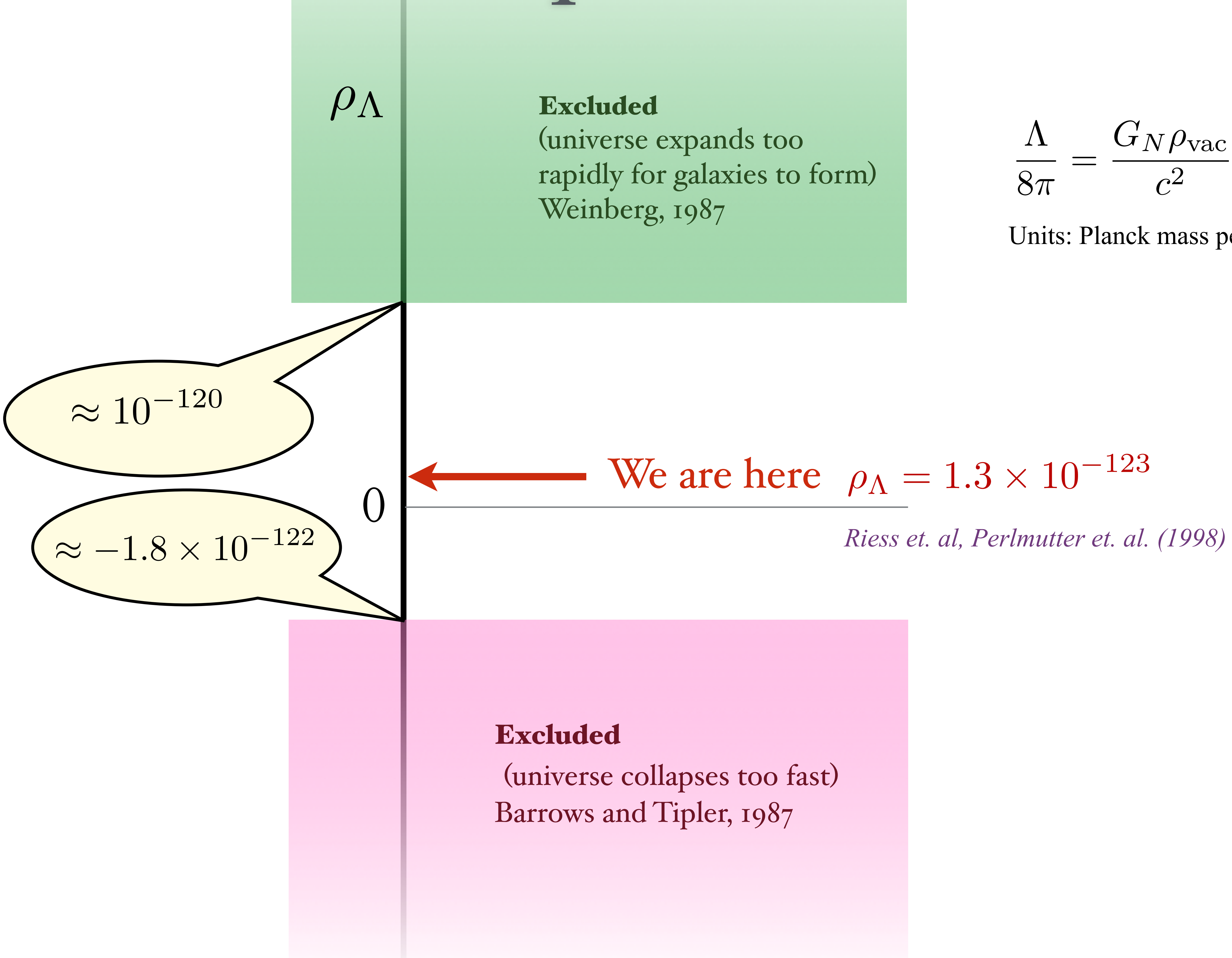
Irrelevant in the absence of gravity.
But gravity sees it as a contribution to Λ.

In QED, for fixed α, it is just a constant.
It clearly cannot be ignore if we allow α to change.

Anthropic Bounds

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

Units: Planck mass per Planck volume



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

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

Solution to equations of motion

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

Contribution to the cosmological constant

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

In String Theory:

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

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

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).

$$N_{\mathrm{vacua}} \approx [N_{\mathrm{values}}]^{N_{\mathrm{flux}}}$$

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. **Mon.Not.Roy.Astron.Soc. 422 (2012) 3370-3413** **(arXiv:1202.4758)**

"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 **Science 339 (6115), 46 (2012)**

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"

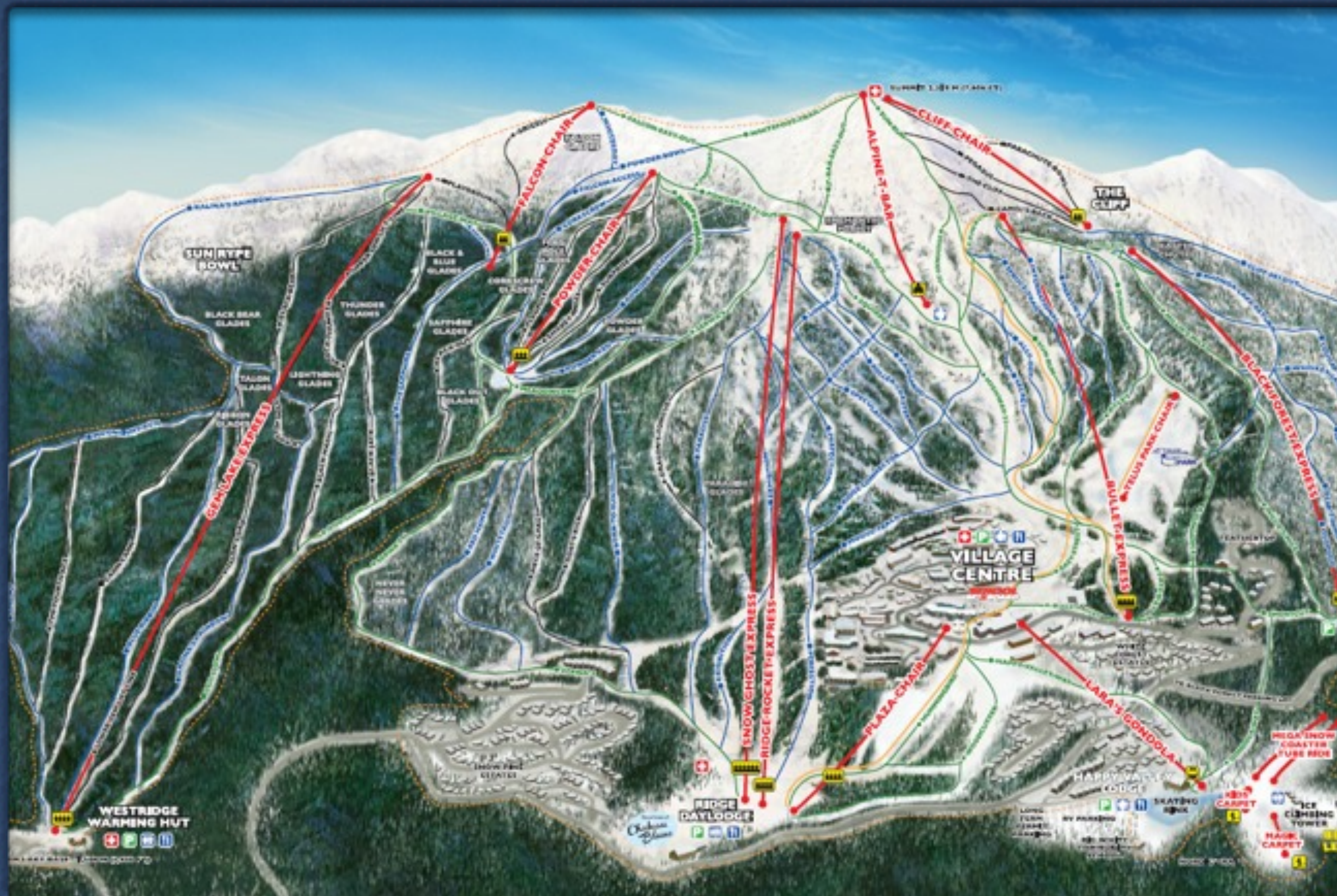
If confirmed this has huge consequences

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

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

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

Dine, Banks, Douglas (2002)



Grand Unification

Grand Unification

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
Charge quantization not explained by *SU(3)* x *SU(2)* x *U(1)*

The most popular explanation is Grand Unified Theories

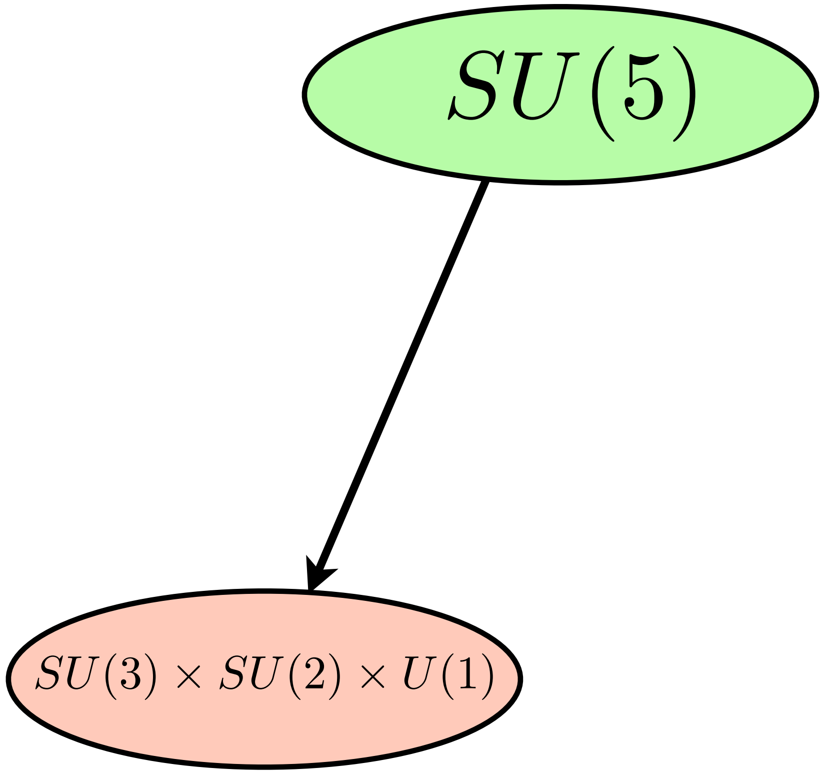
One family: $(5^*) + (10) + (1)$ of $SU(5)$

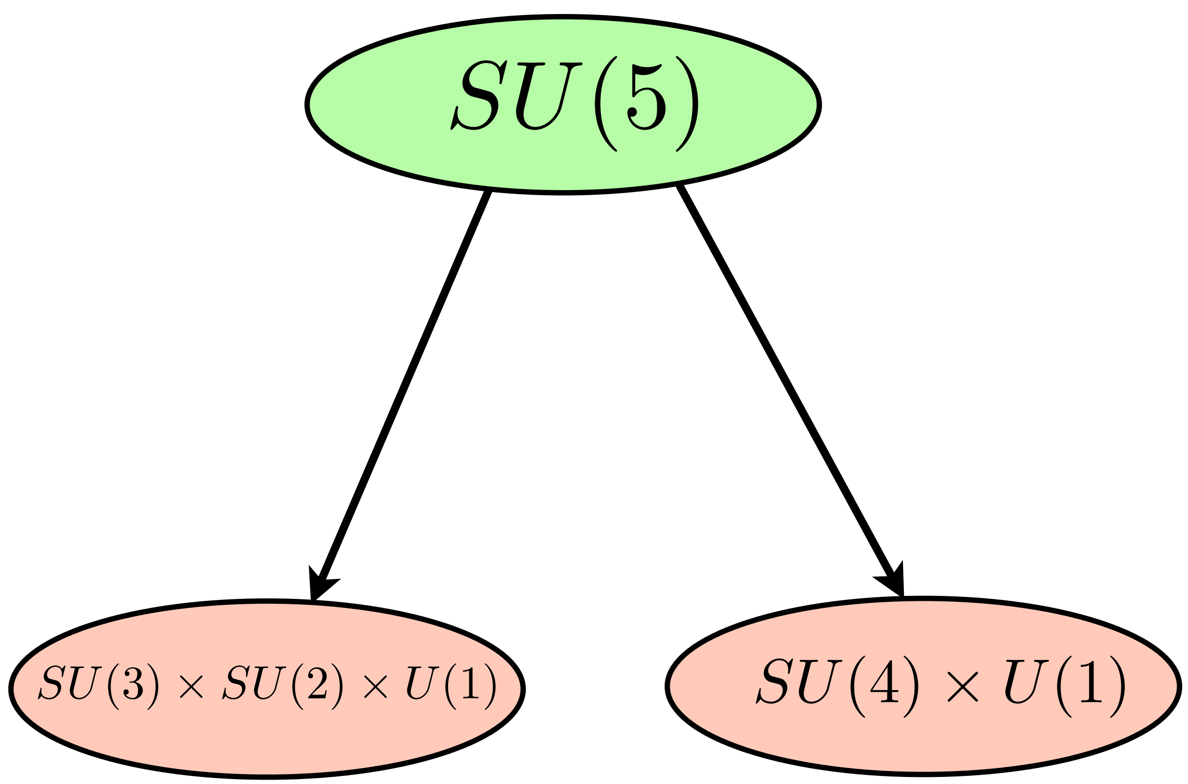
(16) of $SO(10)$

String Theory?

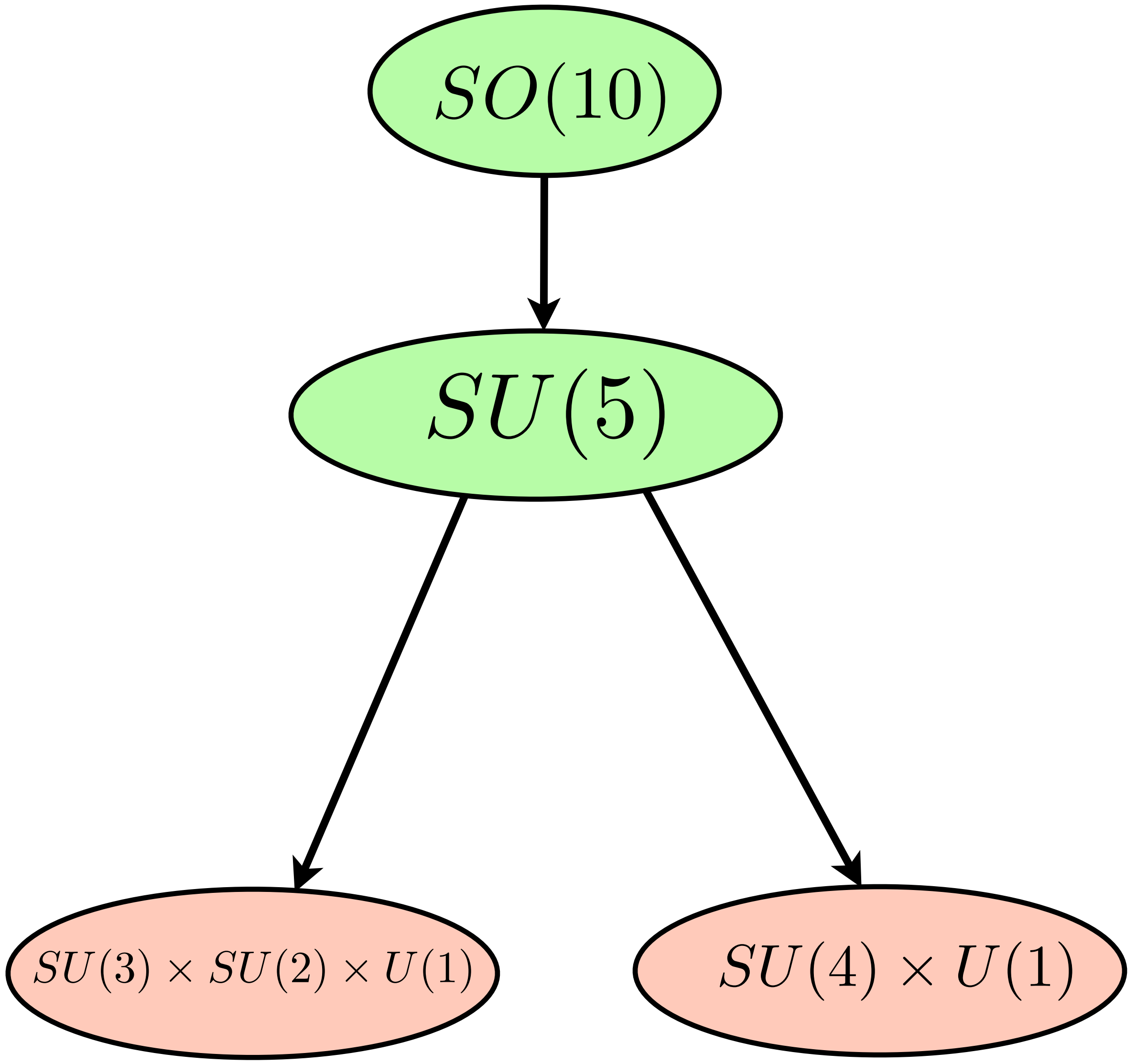
GUT?

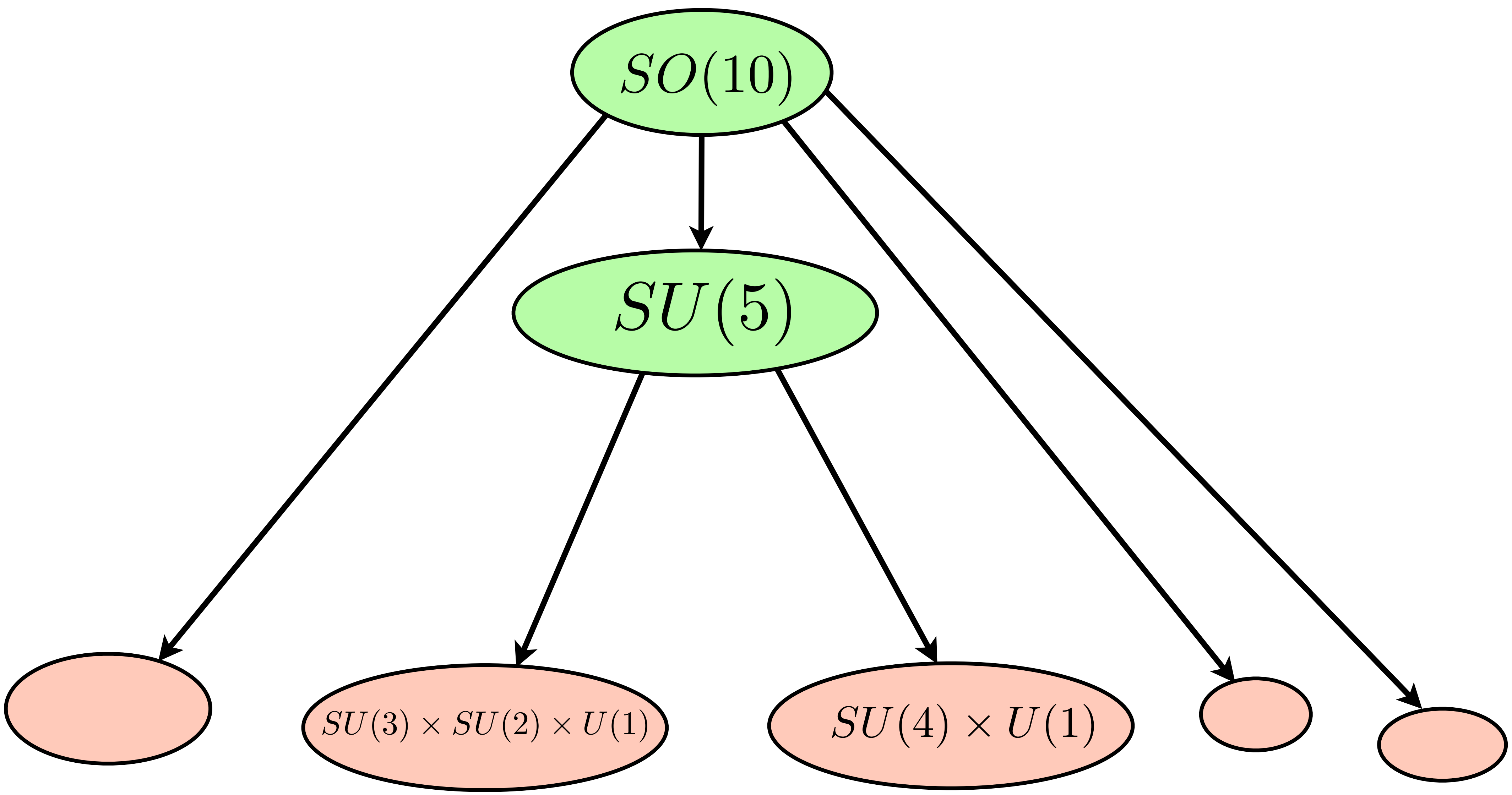
Electro-weak


$SU(5)$
$SU(3) \times SU(2) \times U(1)$

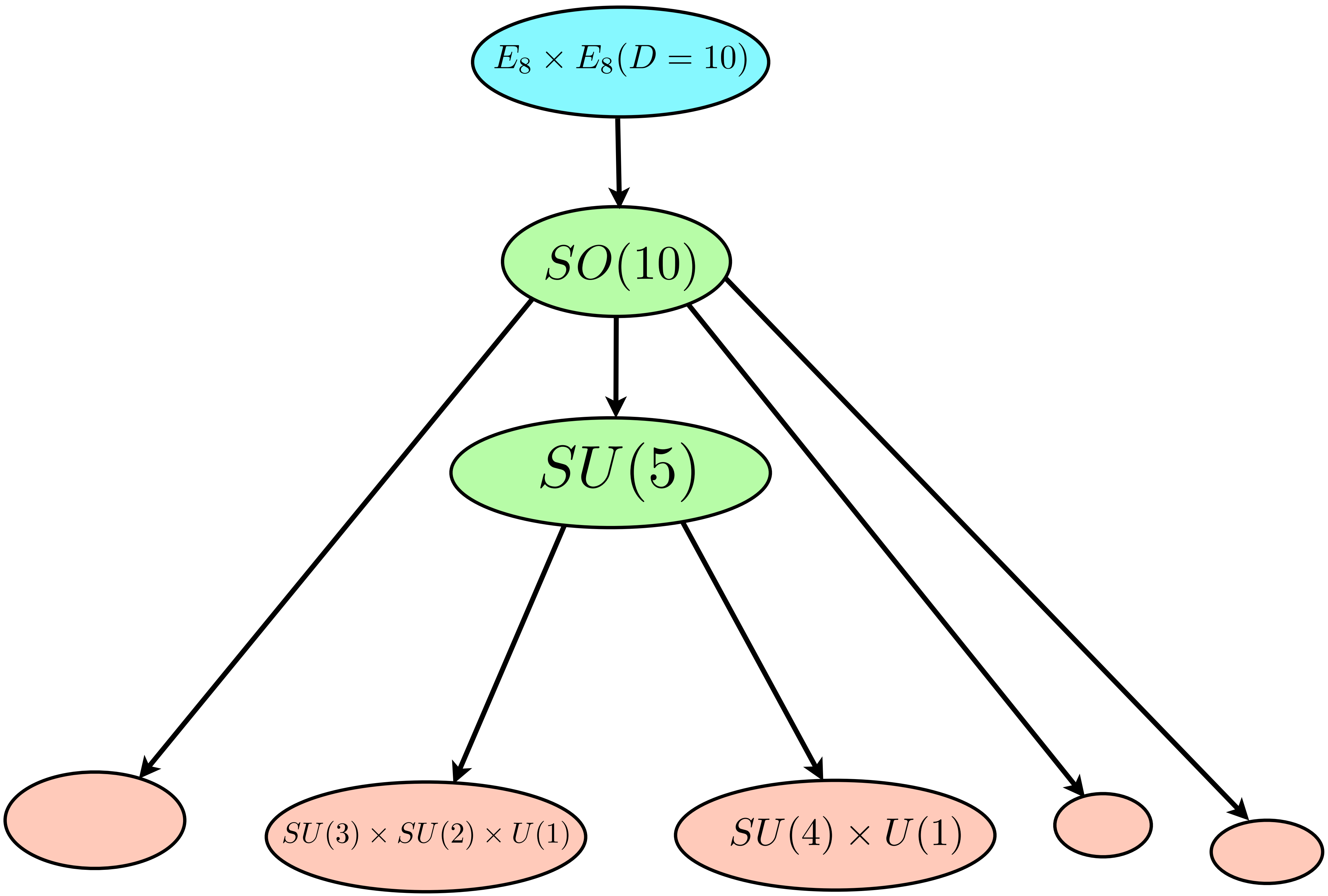


$SU(5)$
$SU(3) \times SU(2) \times U(1)$
$SU(4) \times U(1)$

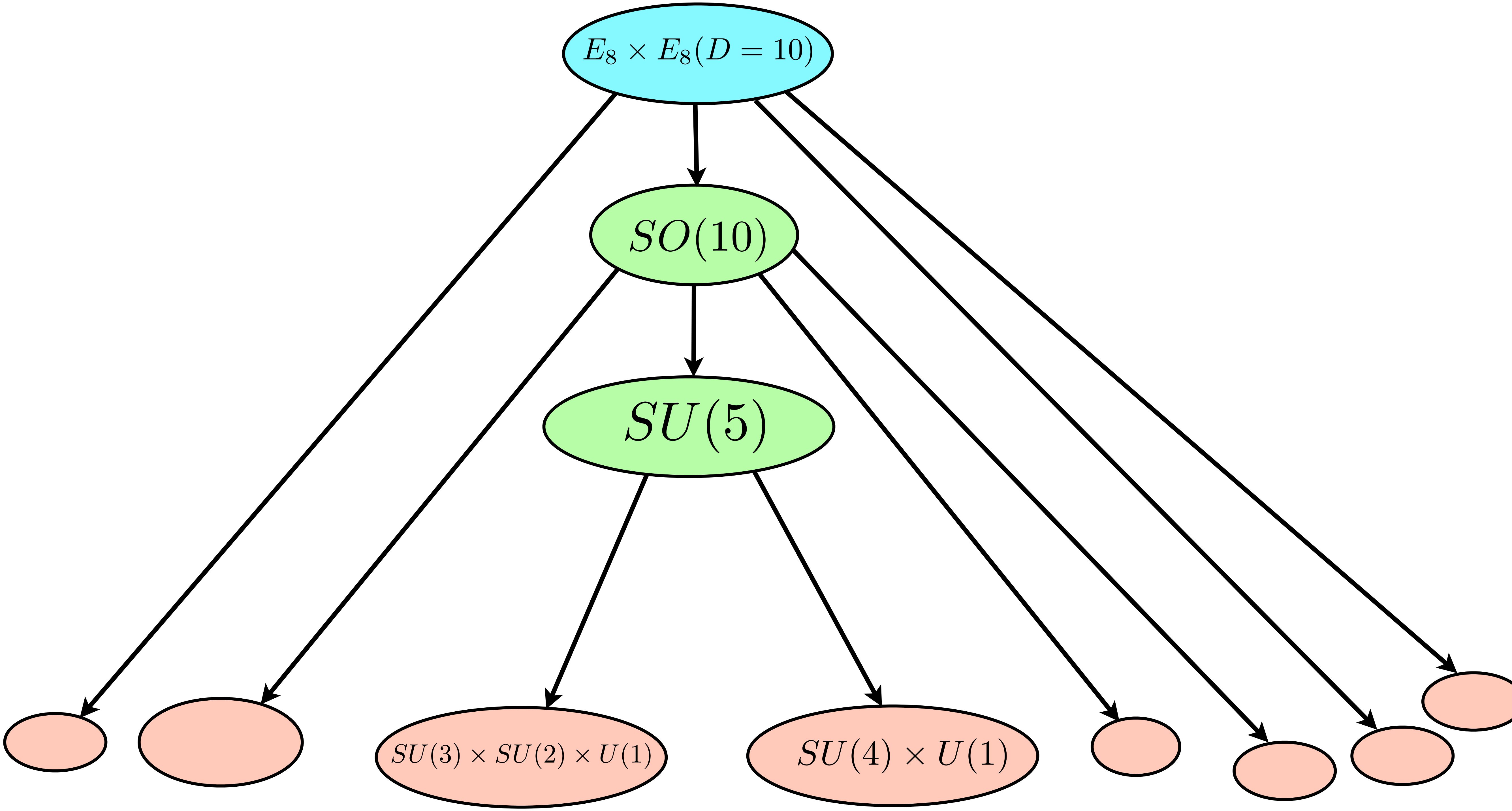

$SO(10)$
$SU(5)$
$SU(3) \times SU(2) \times U(1)$
$SU(4) \times U(1)$



$SO(10)$
$SU(5)$
$SU(3)\times SU(2)\times U(1)$
$SU(4)\times U(1)$



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



$E_8 \times E_8 (D=10)$
$SO(10)$
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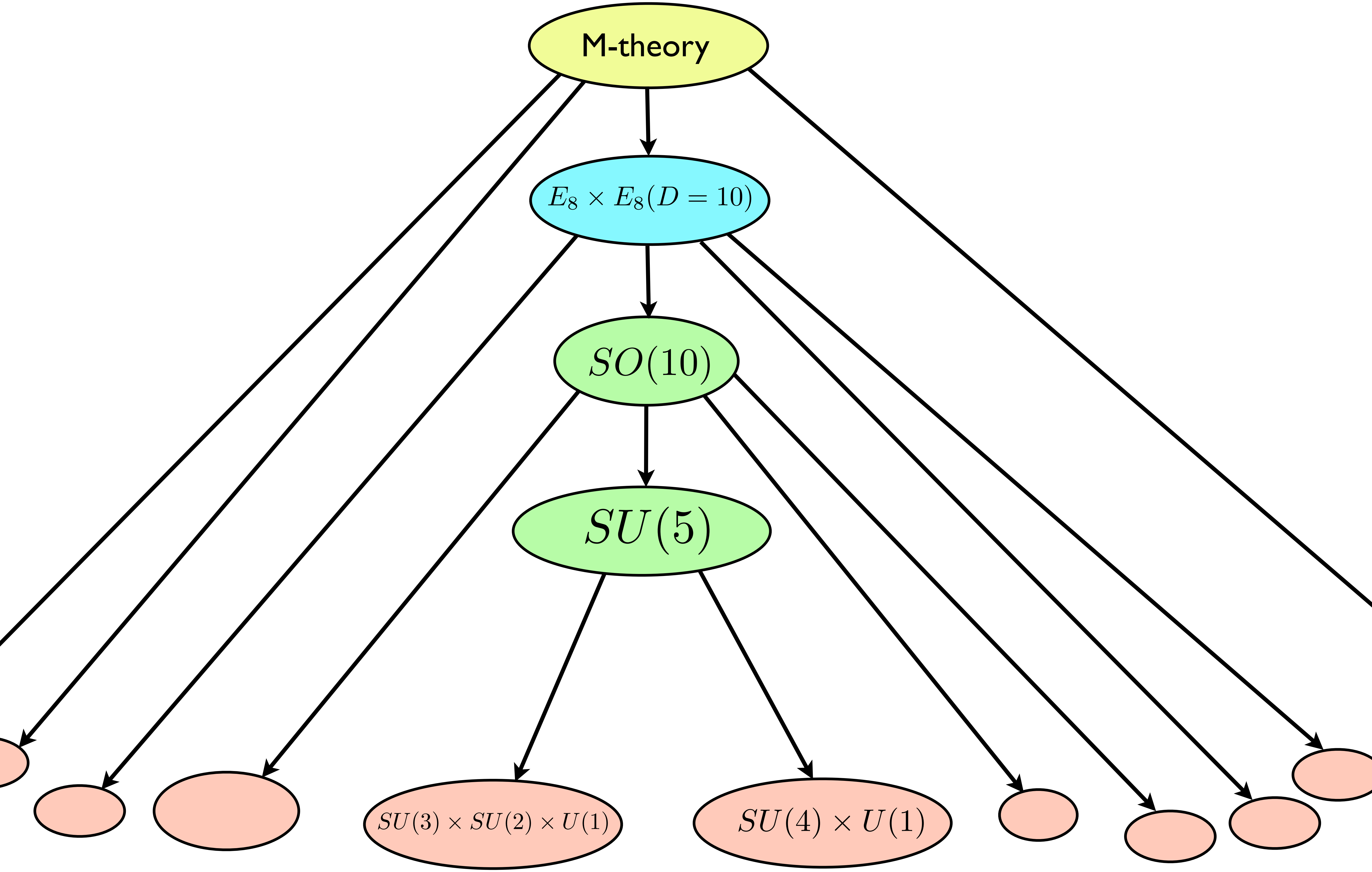

M-theory
$E_8 \times E_8 (D = 10)$
$SO(10)$
$SU(5)$
$SU(3) \times SU(2) \times U(1)$
$SU(4) \times U(1)$

ONLIGHT BASIN
Lone Mountain
Elevation 11,166 ft.
Moonlight Basin from
Big Sky Resort
ACCESS WITH
LONE PEAK TICKET
BACKCOUNTRY ACCESS GATE
NORTH SUMMIT
SNOWFIELD
Cedar Mountain
The Sphinx
Big Sky Resort
ACCESS WITH
LONE PEAK TICKET
Moonlight Basin from
Big Sky Resort
ACCESS WITH
LONE PEAK TICKET
the HEADWATERS
DEEPWATER
BOWL
HORSESHOE
BOWL
STILLWATER BOWL
STILLWATER
TRAVERSE
HEADWATERS
CHAIRLIFT
EXPERTS ONLY
by Backcountry Access and Moonlight Basin,
debris site that features buried avalanche transmitters -
for beacon and probe work within resort bounds. It is
Basin and Big Sky Resort ticket holders.
Moonlight Basin
from Big Sky Resort
ACCESS WITH
LONE PEAK TICKET
BACKCOUNTRY ACCESS GATE
Future Terrain
BEACON
BASIN
MOONLIGHT
LODGE
MADISON
BASE AREA
BLAZING SADDLES
SLEDDING HILL
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A JACK N
SIGNATURE

Grand Unification?

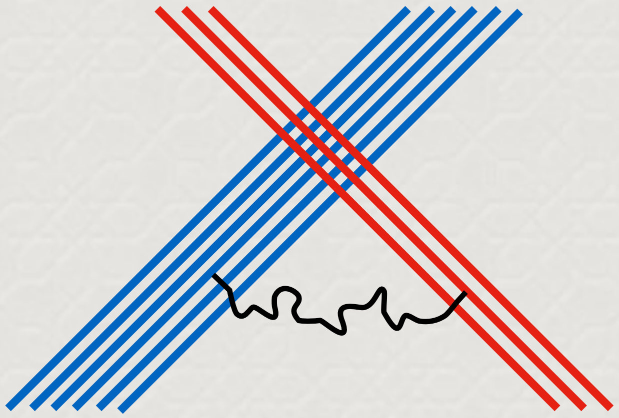
- Higgs does not fit in a GUT rep.
- Breaking to *SU(3)* x *SU(2)* x *U(1)* is not explained

  (There are alternatives, like *SU(4)* x *U(1)*.)
- Choice of representations is not explained

We can solve all of these problems by replacing symmetry by an anthropic argument

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

An Anthropic Alternative



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

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

Anthropic requirements:

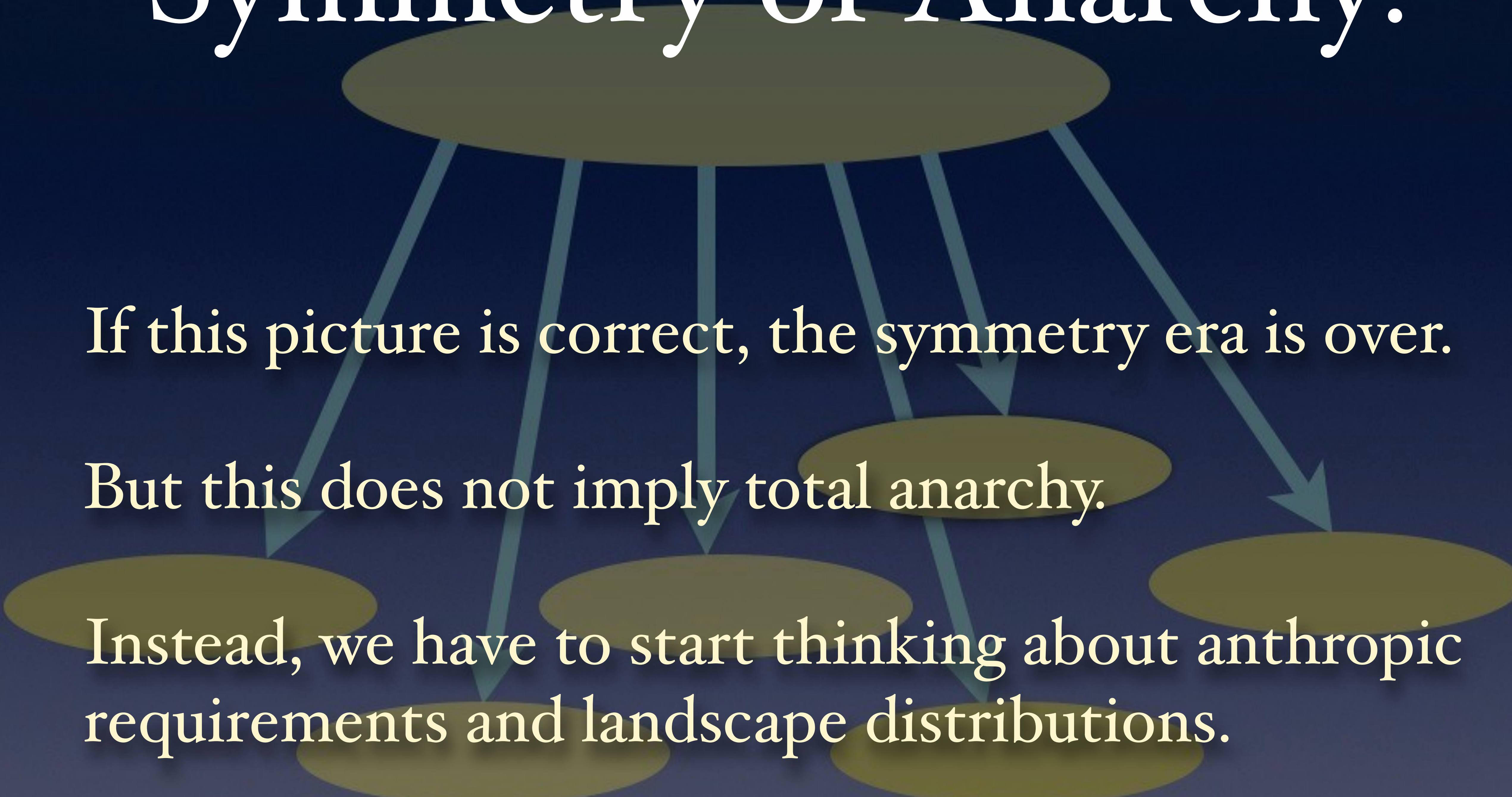
- Massless photon
- No massless charged leptons
- > 3 distinct stable atoms

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

Conclusions

Symmetry or Anarchy?



If this picture is correct, the symmetry era is over.

But this does not imply total anarchy.

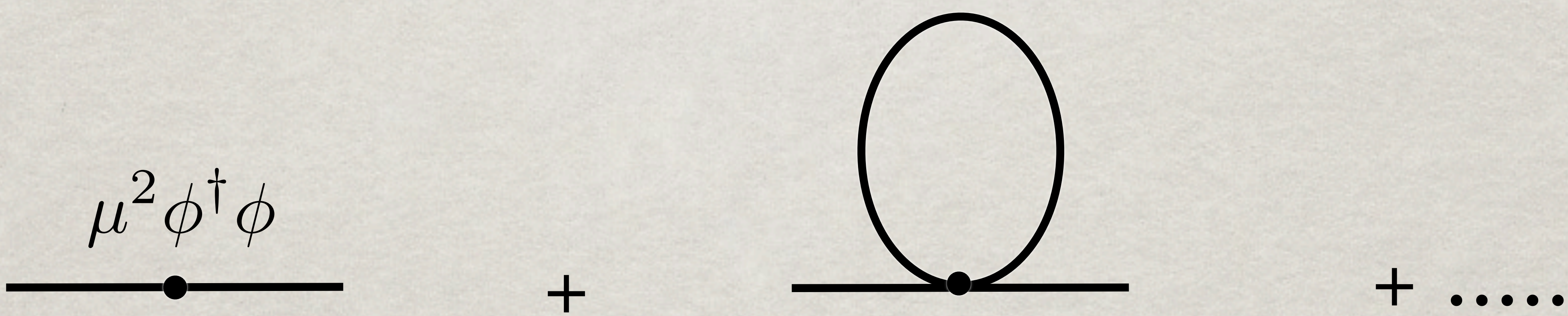
Instead, we have to start thinking about anthropic requirements and landscape distributions.

The Hierarchy Worry

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

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

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



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.

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 $m_{\text{p}} < 10^{-8}\, m_{\text{Planck}}$

- For more arguments see my review:

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

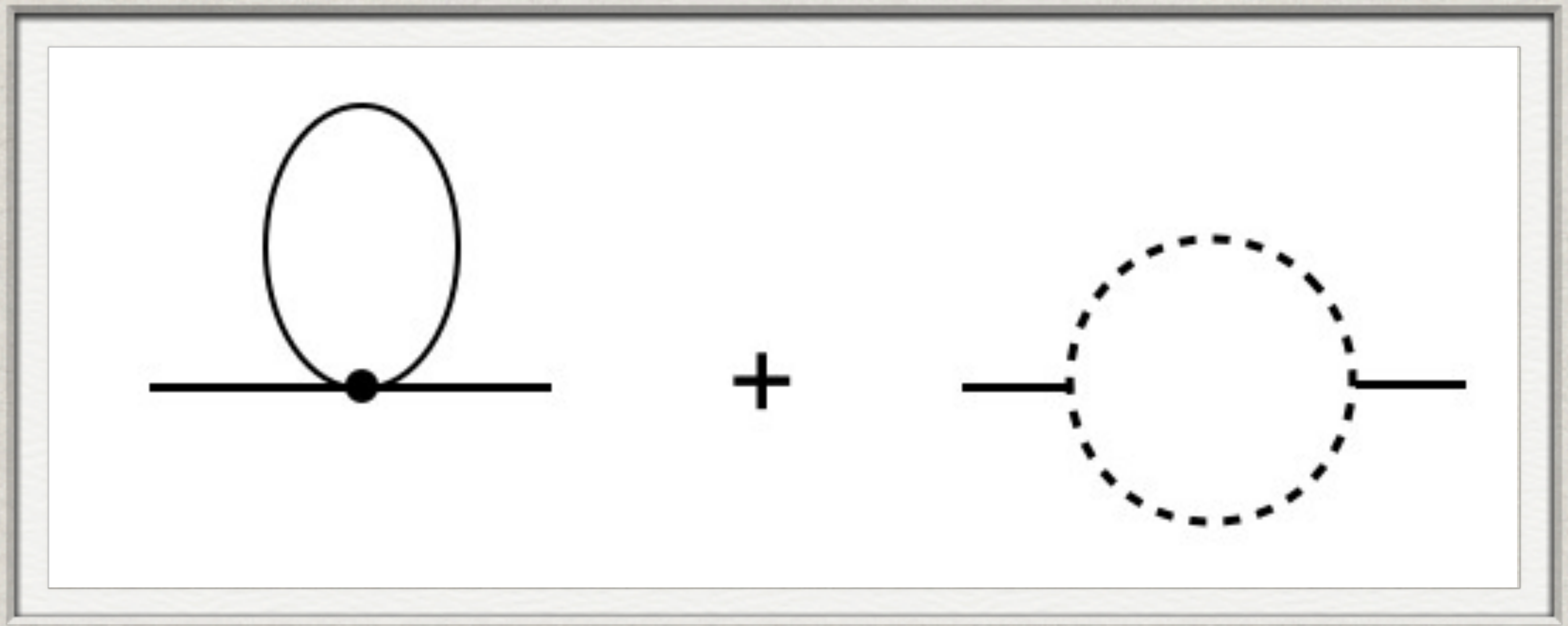
Anthropic or New Physics?

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 $\mu \ll M_{\rm Planck}$ is

$$\left(\frac{\mu^2}{M^2_{\rm Planck}}\right)$$

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:

$$\left(\frac{\mu^2}{M^2_{\rm susy}}\right)\left(\frac{M^2_{\rm susy}}{M^2_{\rm Planck}}\right)^N$$

μ	Weak Scale
$M_{\rm susy}$	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...