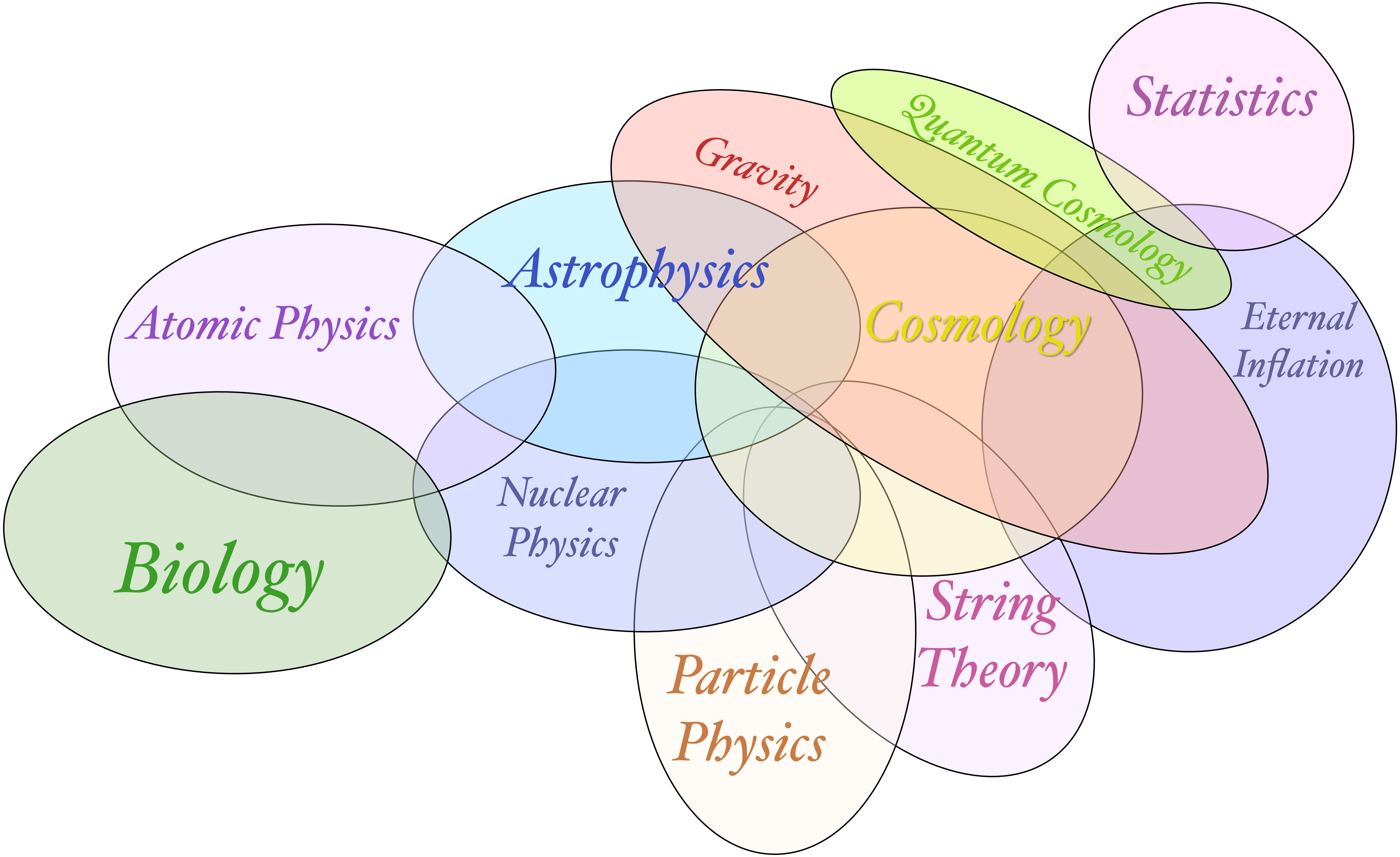
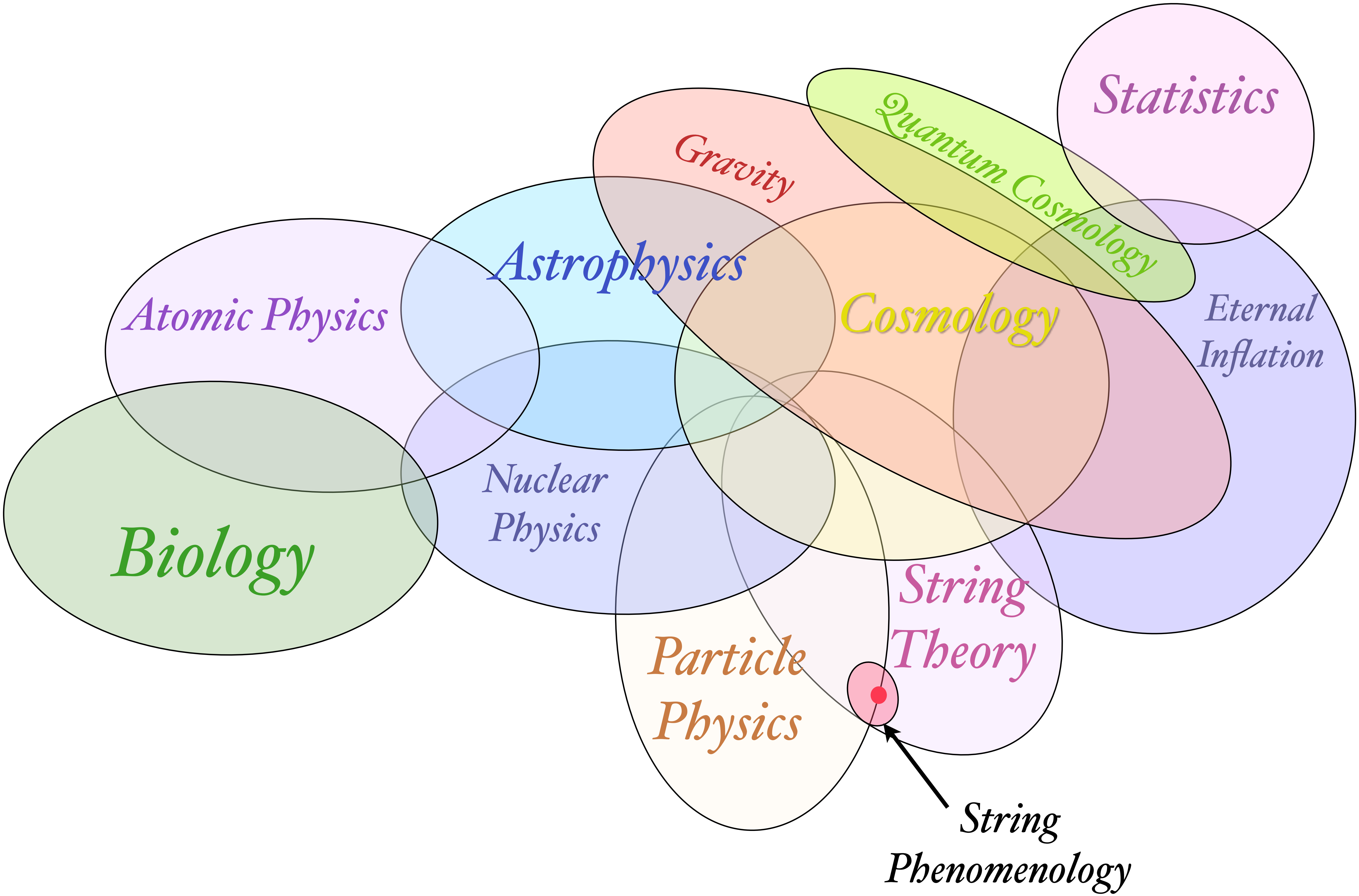
The String Theory Landscape


Statistics
Quantum Cosmology
Gravity
Astrophysics
Atomic Physics
Cosmology
Eternal Inflation
Nuclear Physics
Biology
String Theory
Particle Physics



Statistics
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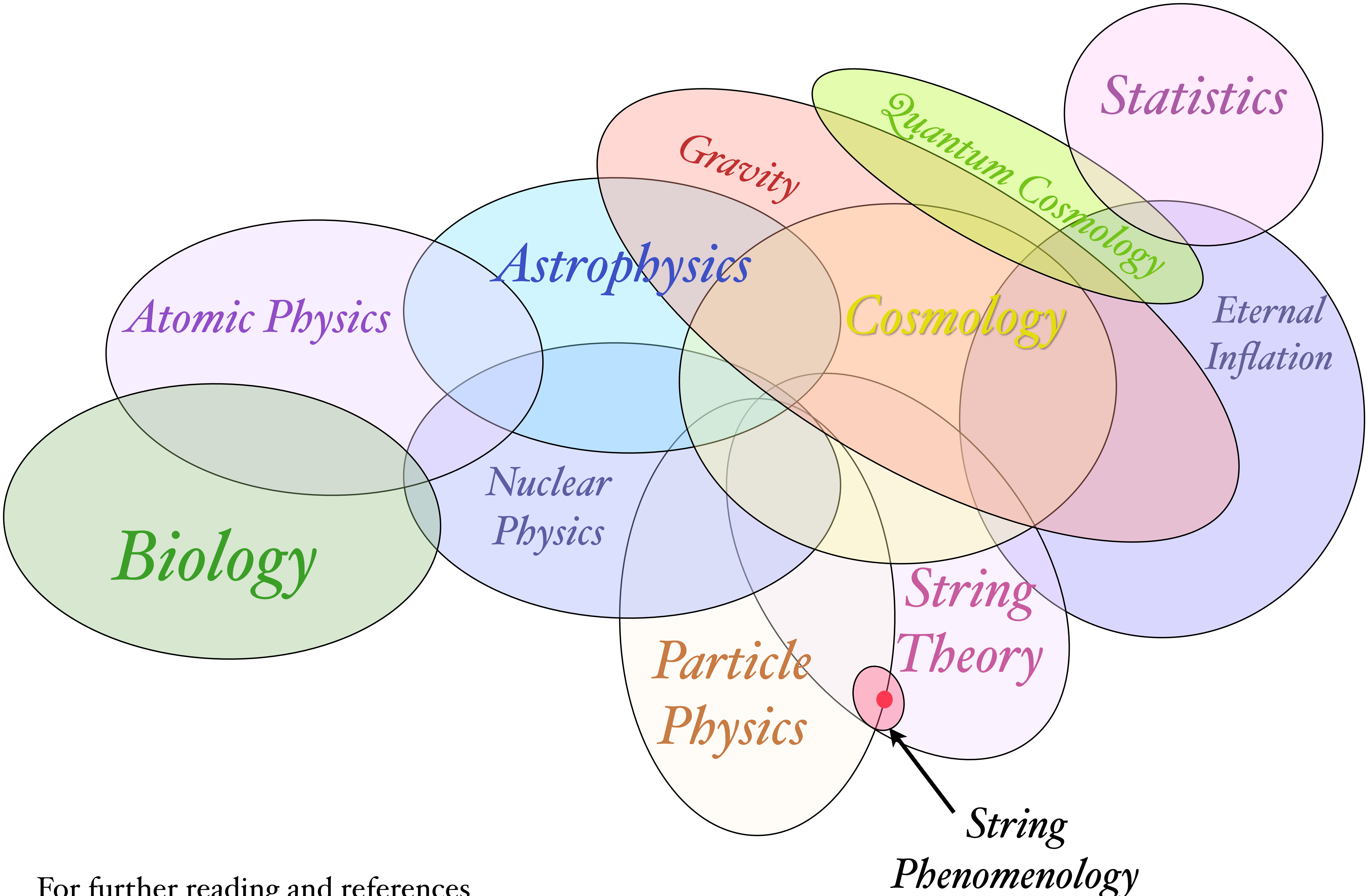
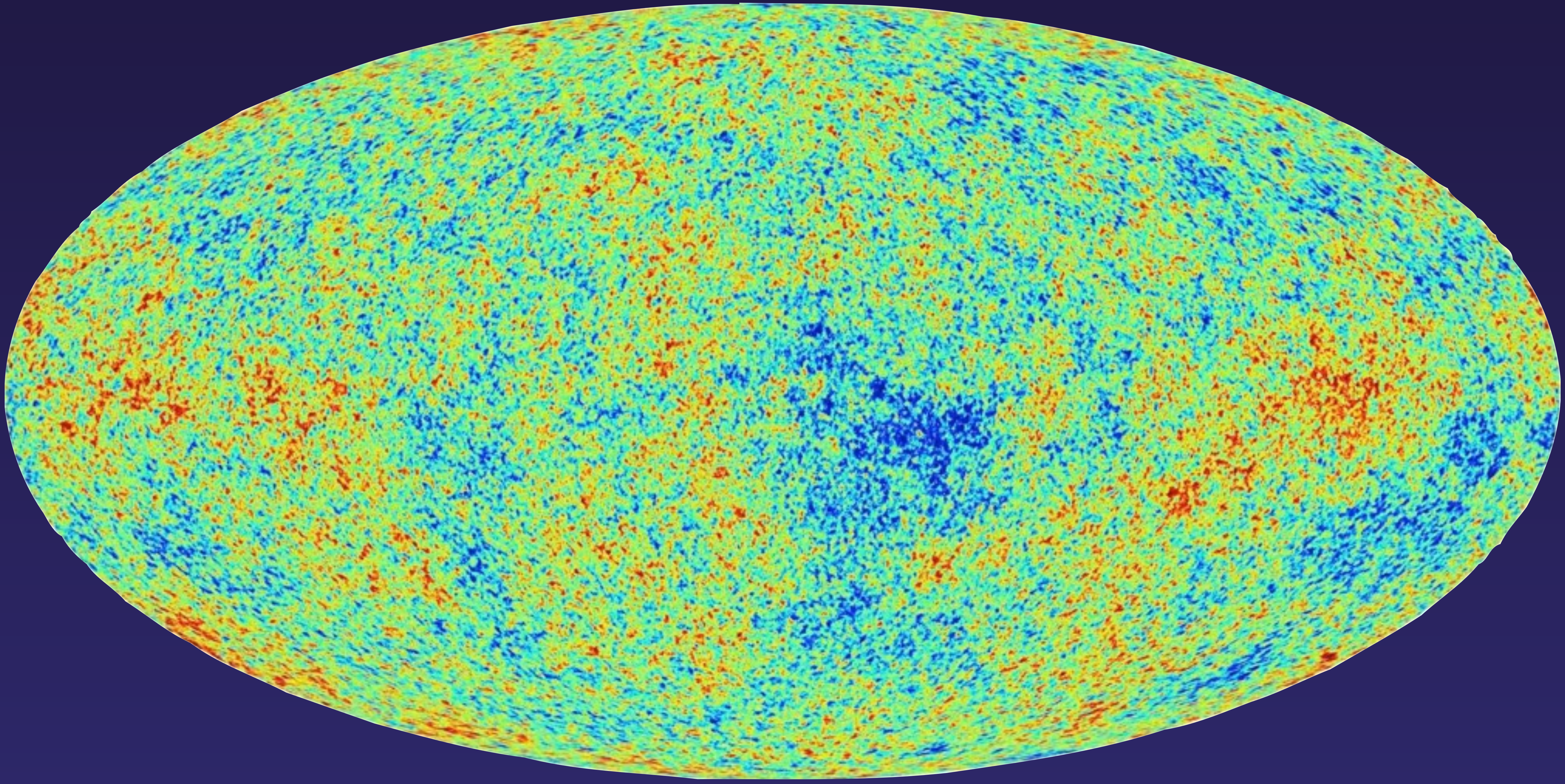
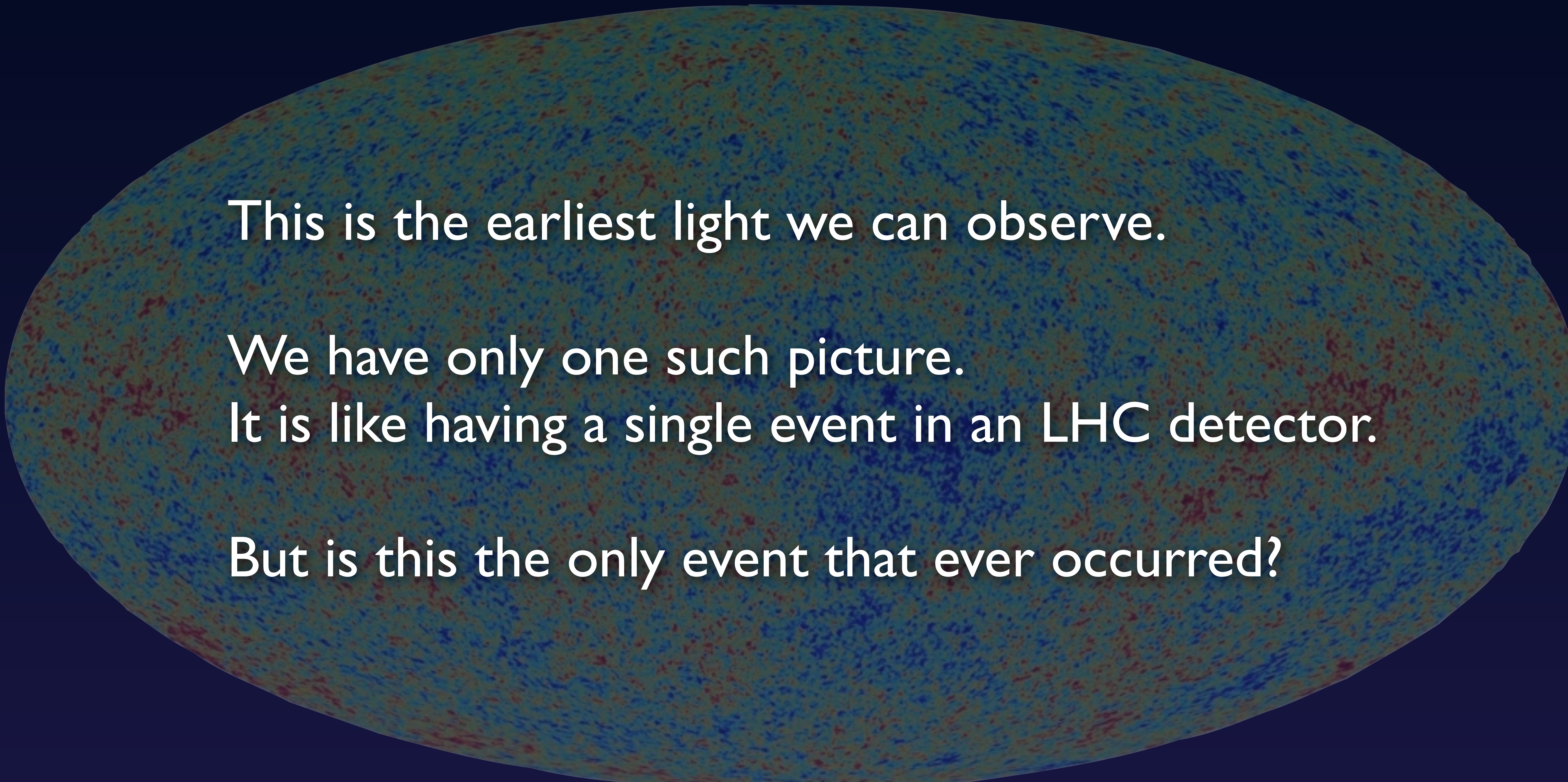
String Phenomenology



For further reading and references

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



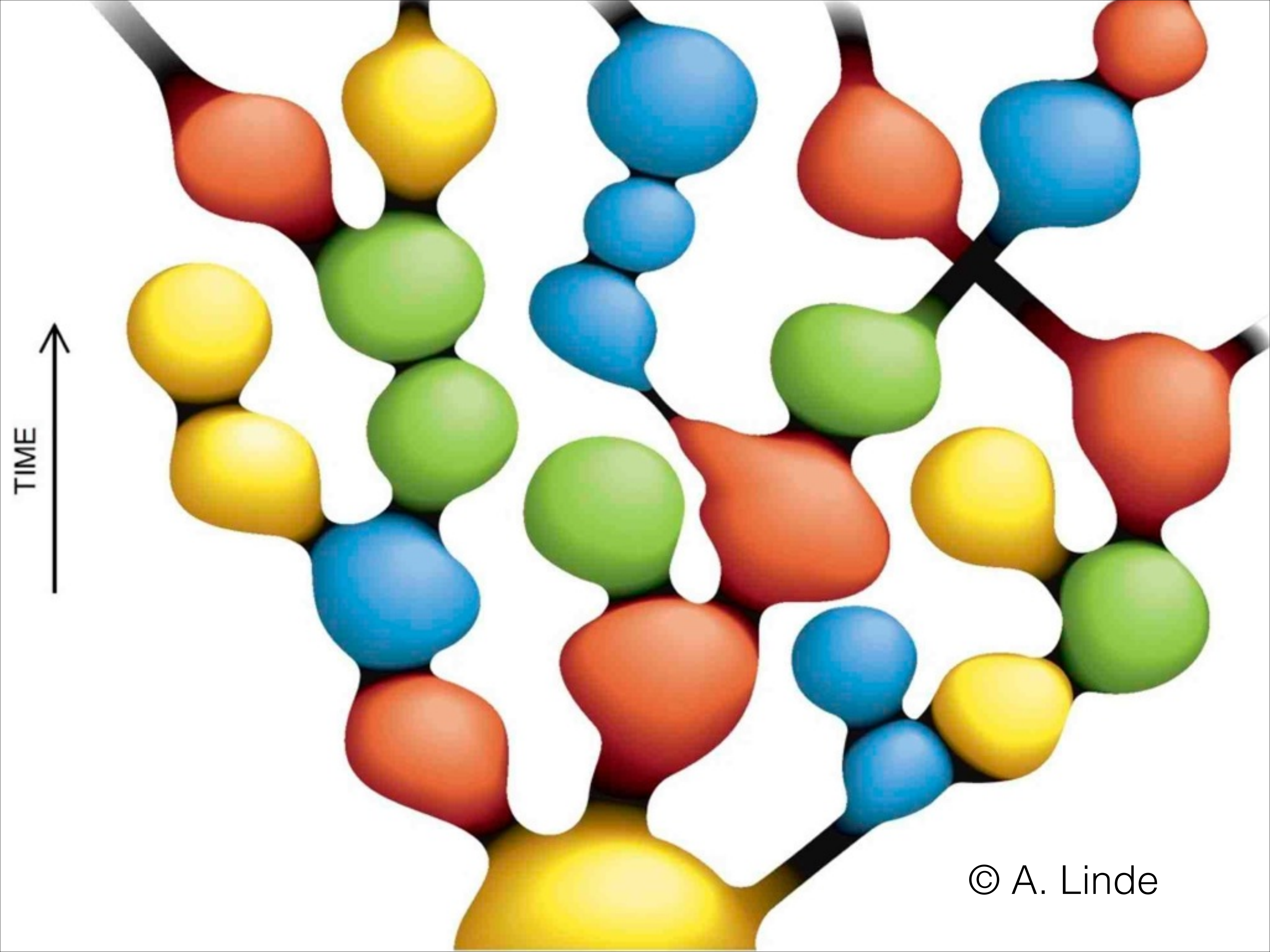

This is the earliest light we can observe.
We have only one such picture.
It is like having a single event in an LHC detector.
But is this the only event that ever occurred?

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."

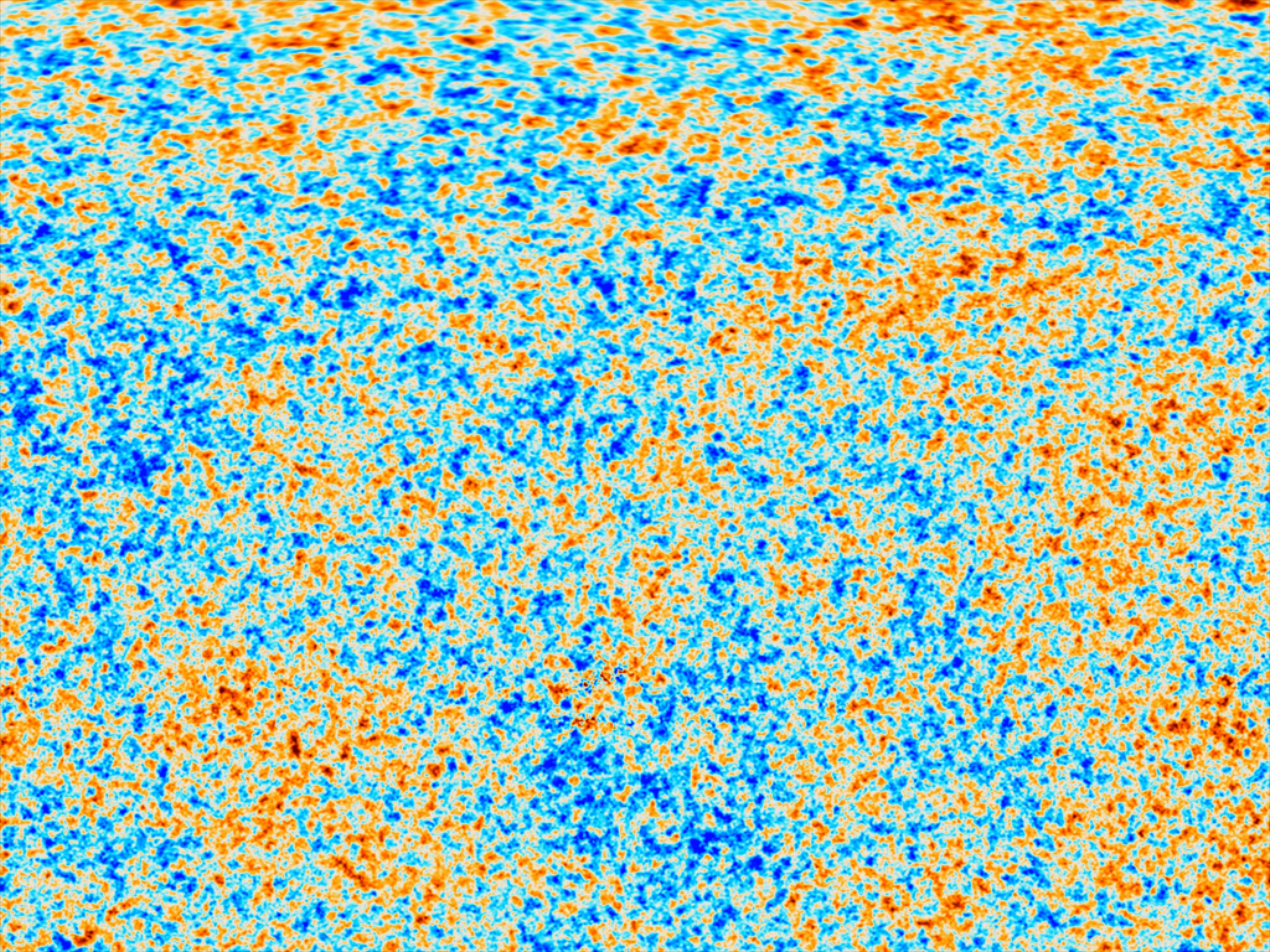
Andrei Linde (1994)

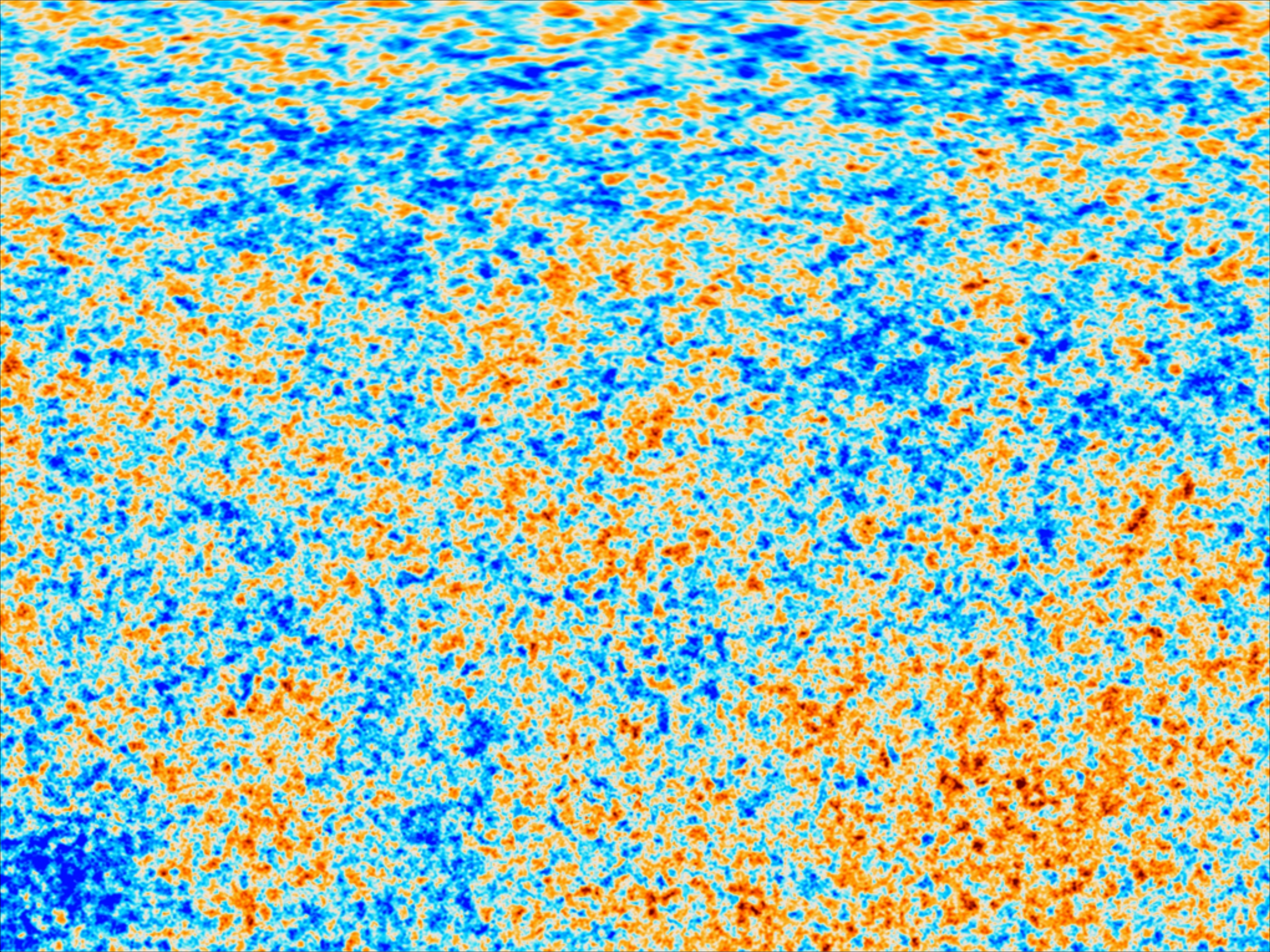

TIME

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.

(

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

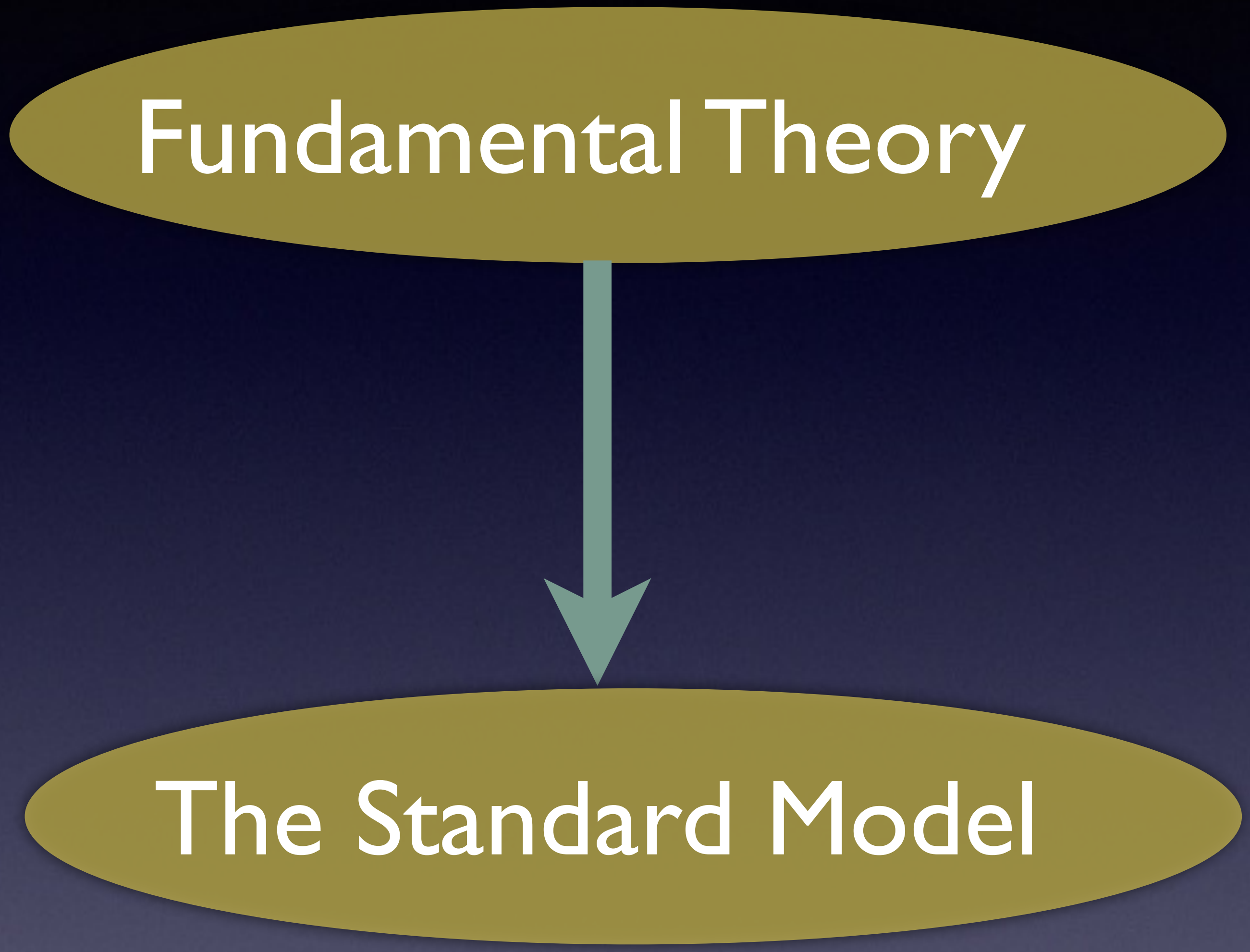
Let us assume the worst-case scenario:
Other universes are unobservable in principle.

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.

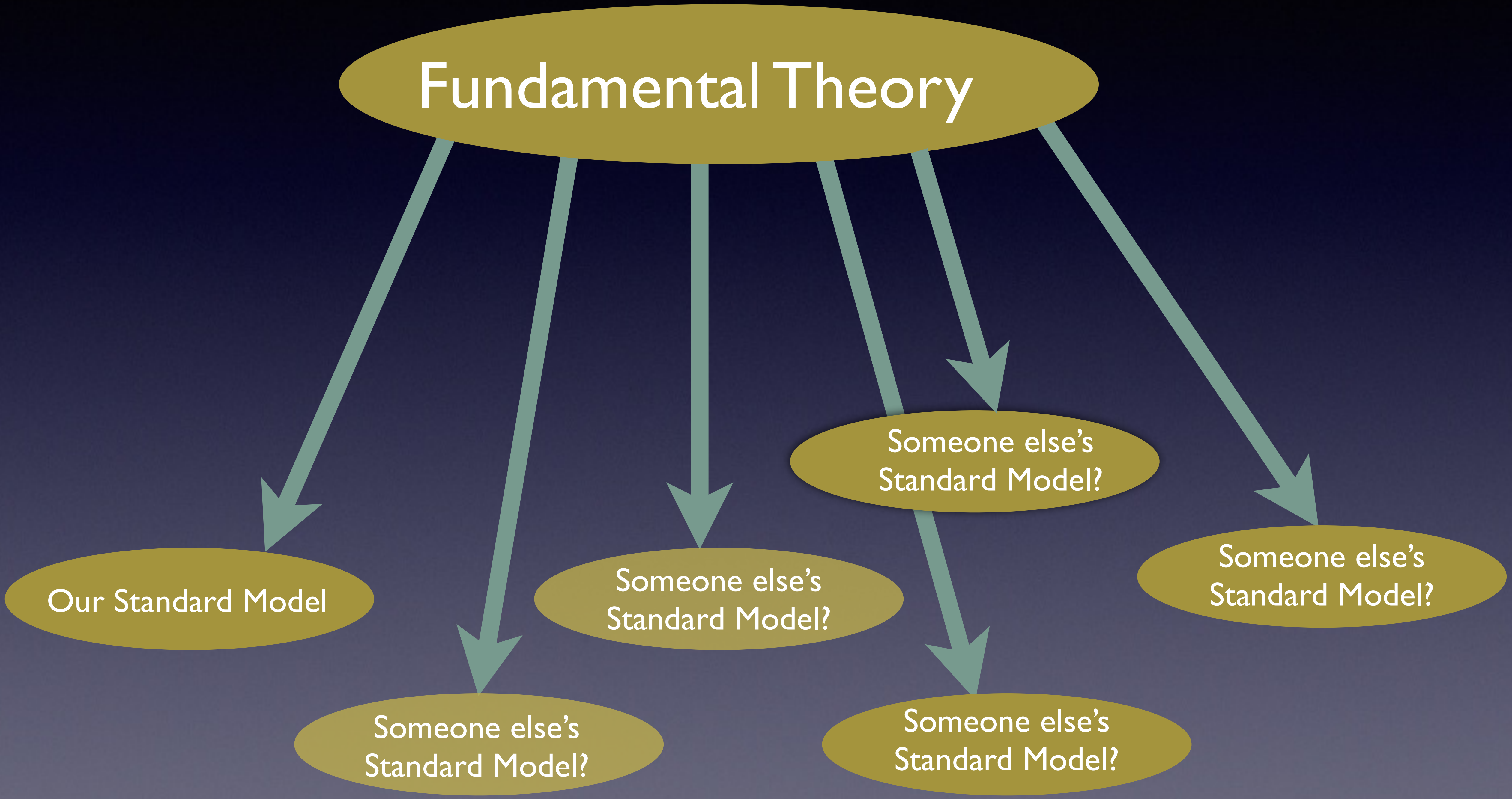
We could confirm that theory either

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

Instead of:



We would have:



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

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

???

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?

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 (Λ_{QCD}) determines proton mass.
  - Weak scale determines quark, lepton masses
  - Both must be much smaller than M_{plank} (10^{19} GeV) and not too different from each other.

- Parameters: m_u, m_d, m_e, α, α_{QCD} are clearly important.
  Less obvious: m_H, m_t, m_ν
  Perhaps not irrelevant: m_s, m_μ
  Probably irrelevant: m_c, m_b, m_τ

Some 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

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

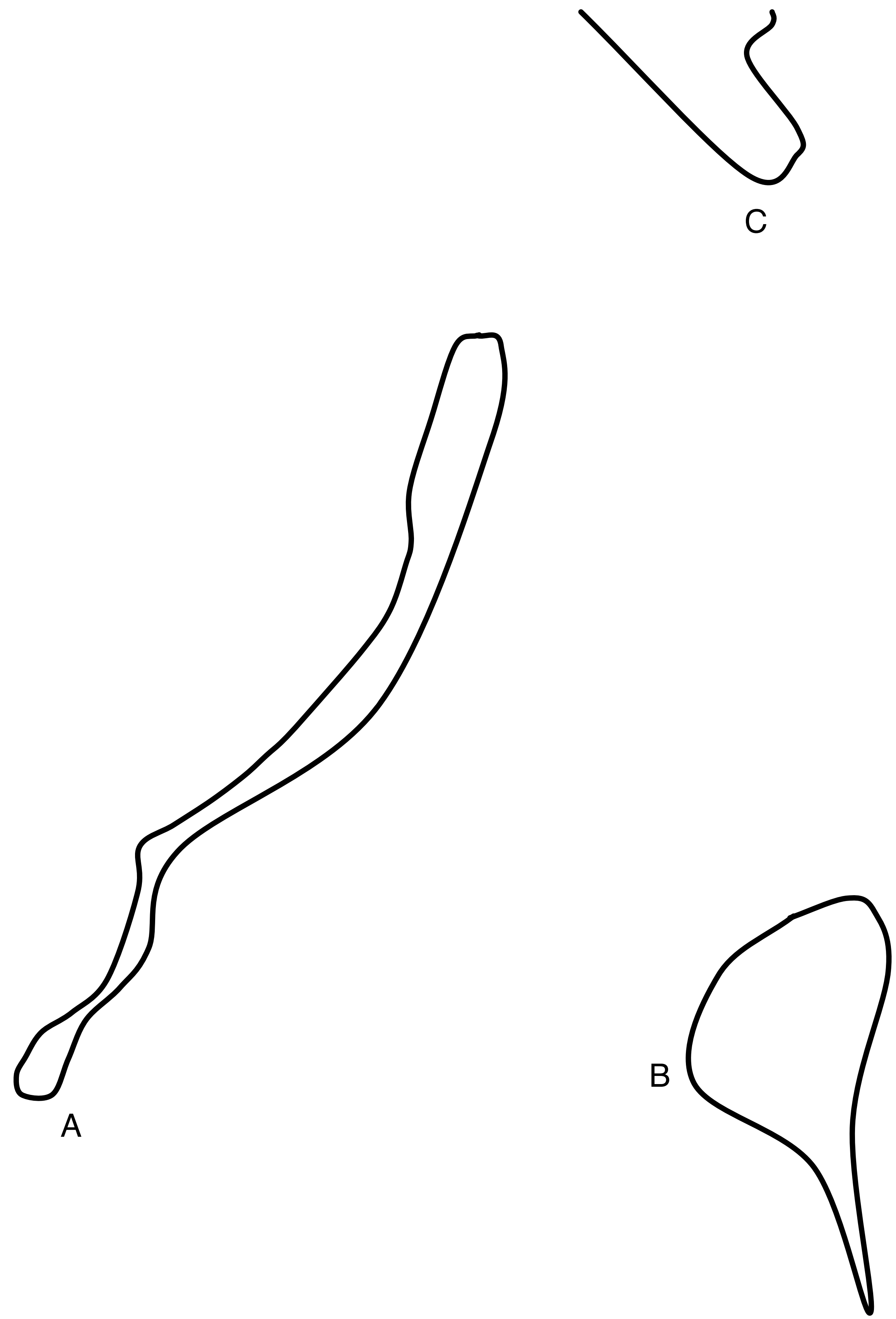
The gauge hierarchy

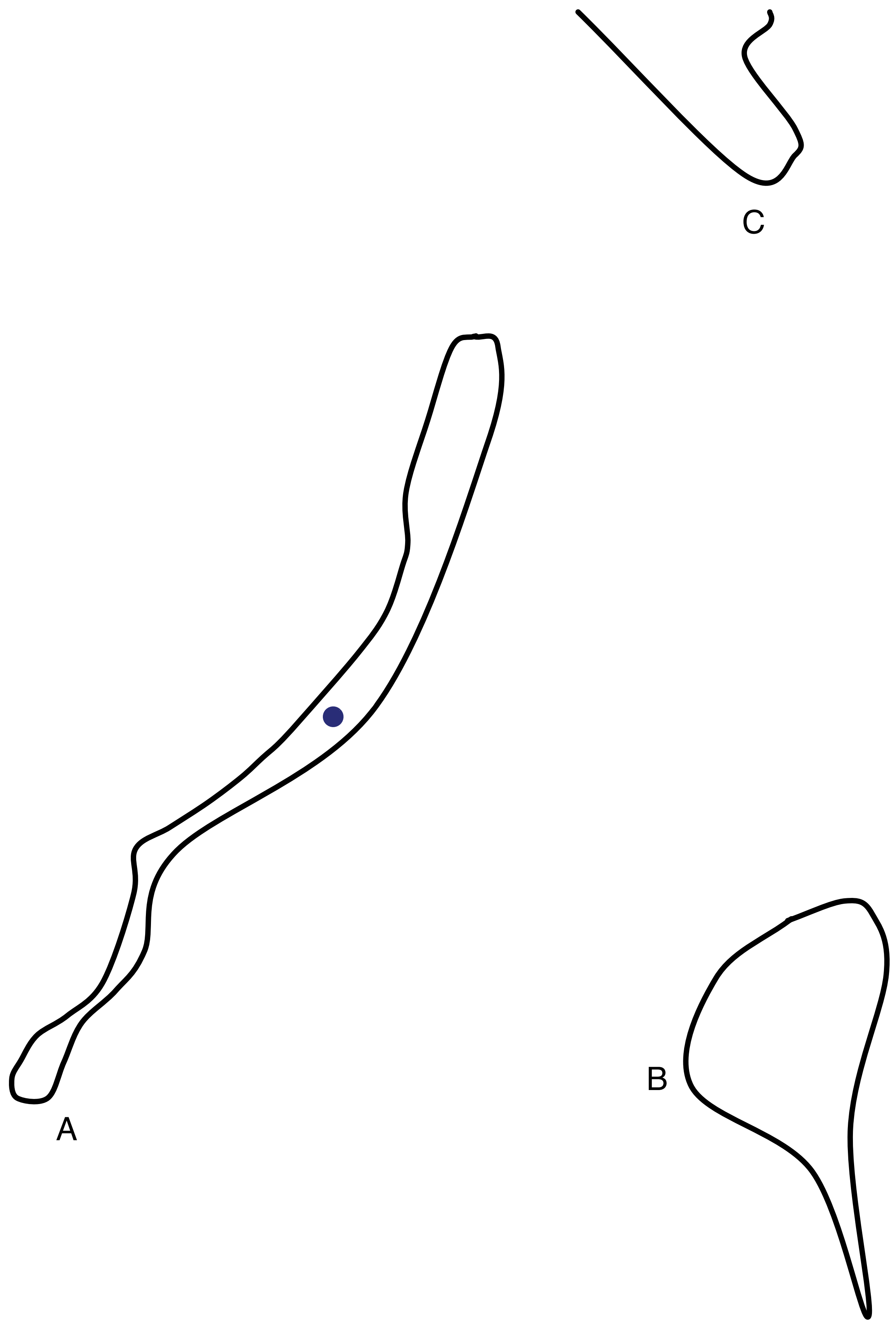
- Weakness of gravity: brains would collapse into black holes.

  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


C
B
A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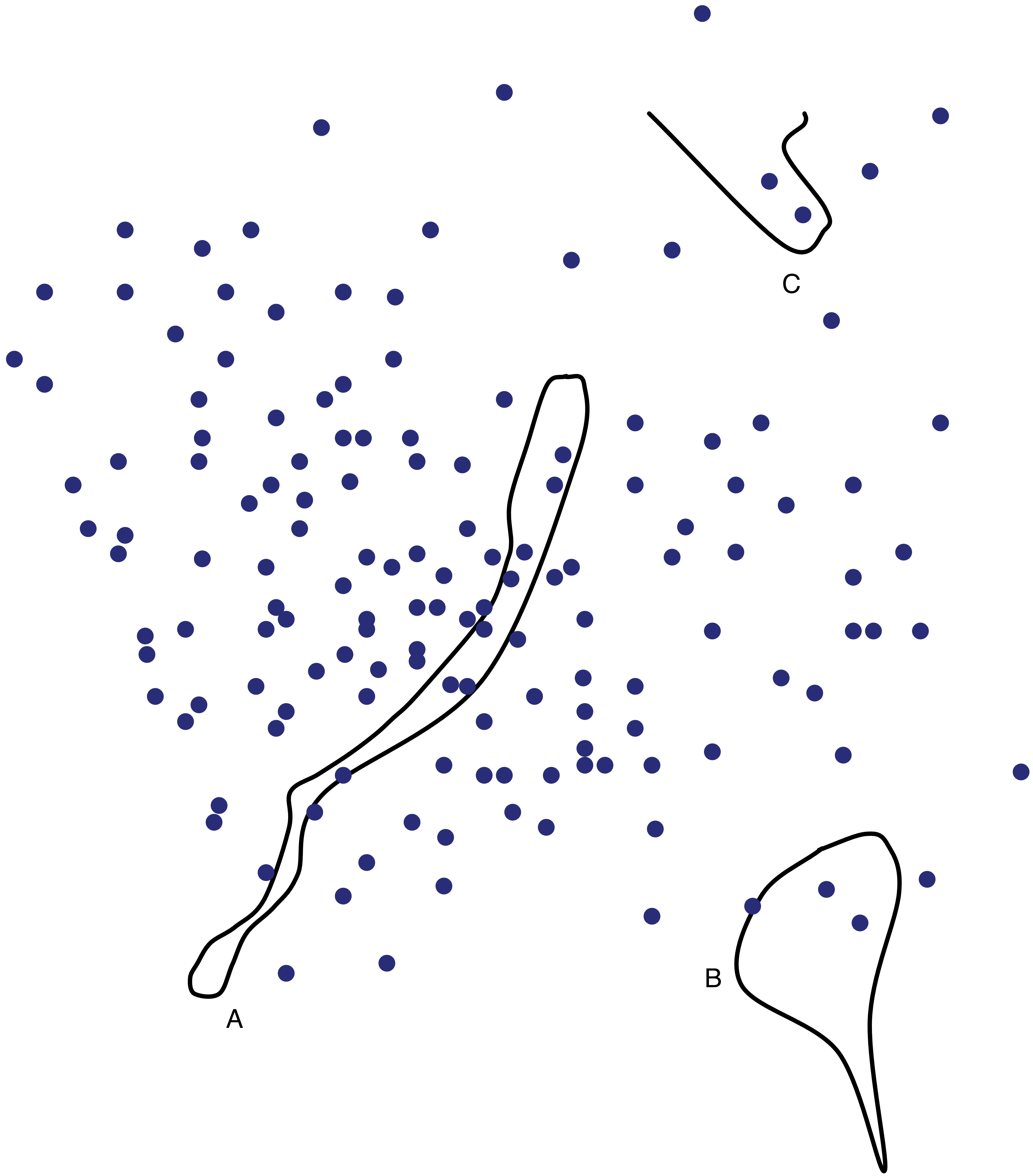
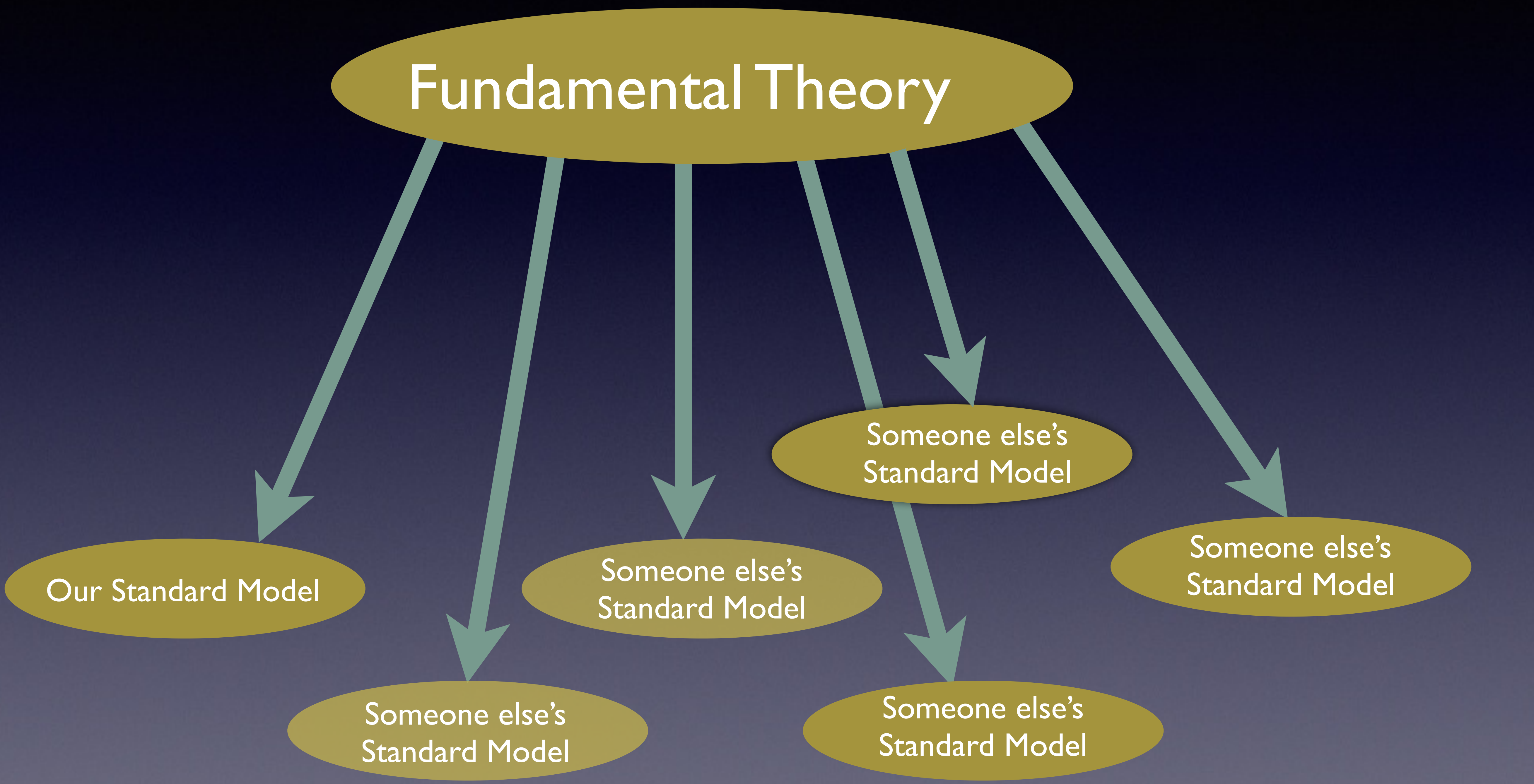

C
B
A

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… "


Fundamental Theory
Our Standard Model
Someone else's Standard Model
Someone else's Standard Model
Someone else's Standard Model
Someone else's Standard Model
Someone else's Standard Model

In favor of this picture:

- Common sense

  Why would the only gauge theory we can observe be the only one that can exist mathematically?

  Is all we can see all there is?

- Anthropic arguments

  The Standard Model appears to be fine-tuned for the existence of (intelligent) life. So how could it be mathematically unique?

- String theory

  If it contains the Standard Model, then surely it contains many others on equal footing with the Standard Model.

- 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

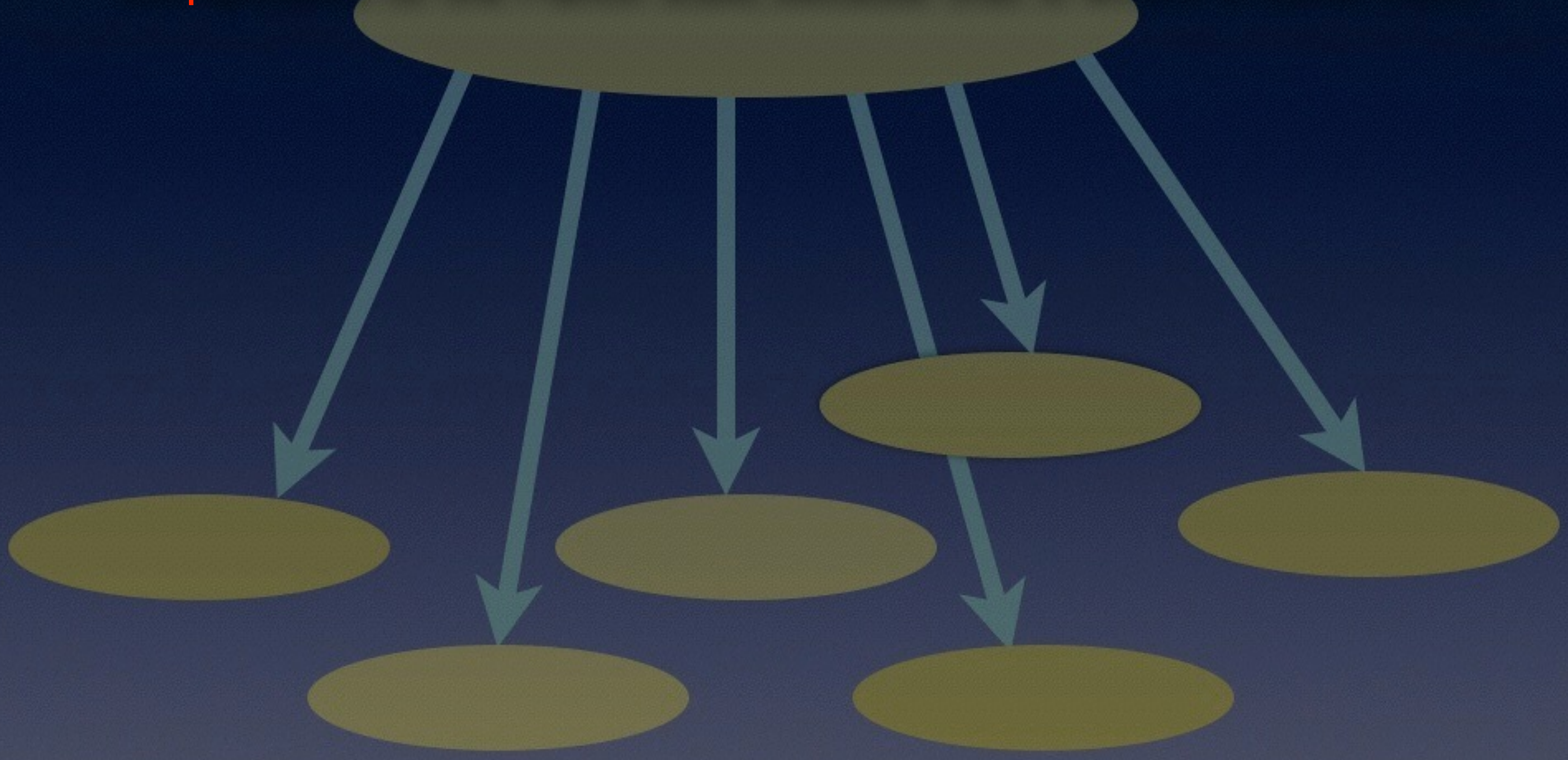
$$\frac{1}{\alpha} F_{\mu\nu} F^{\mu\nu} \rightarrow P(\frac{\phi_i}{M}) F_{\mu\nu} F^{\mu\nu}$$

(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}.
Then 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 $10^{hundreds}$

If the landscape 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.



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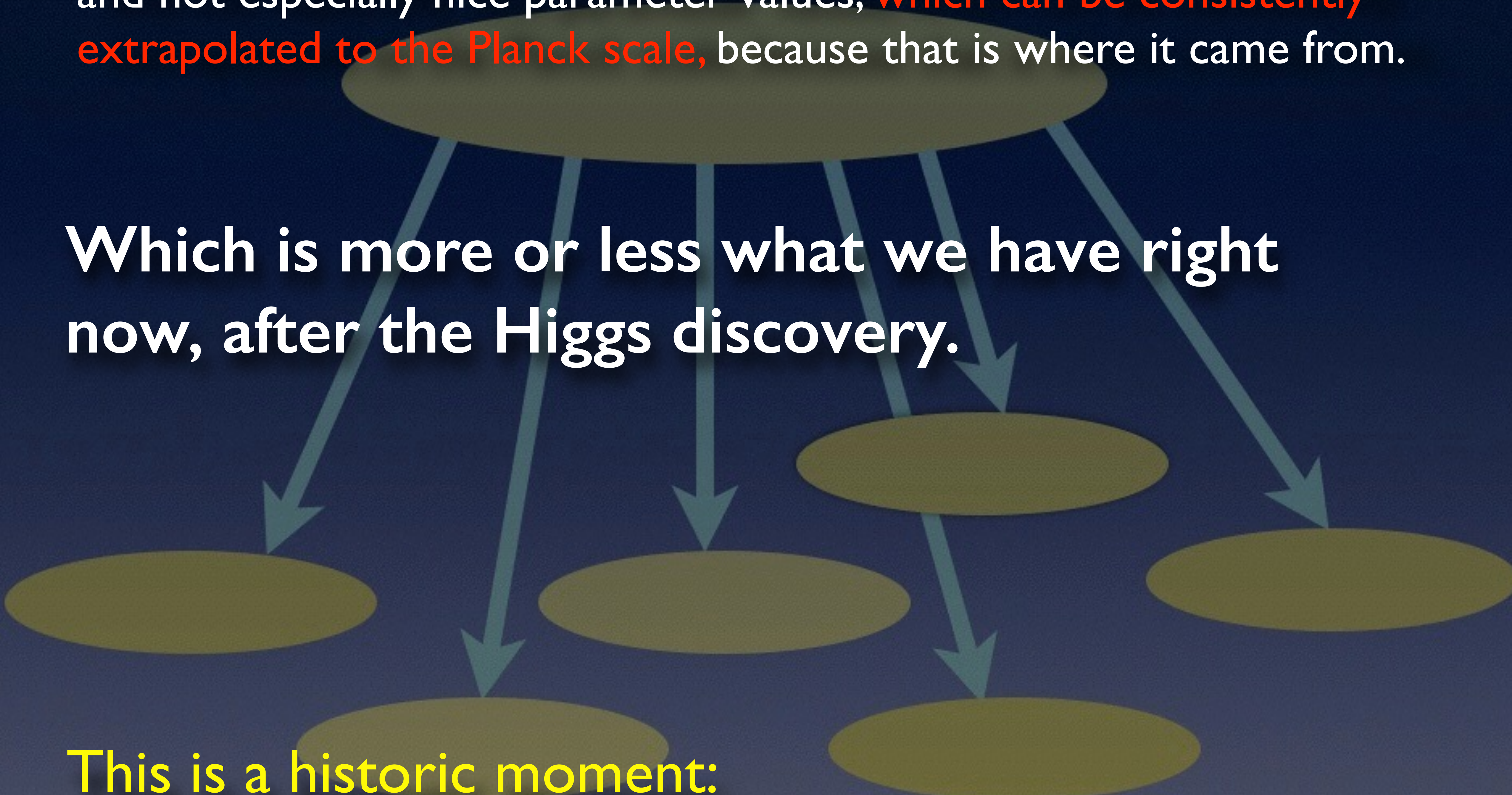

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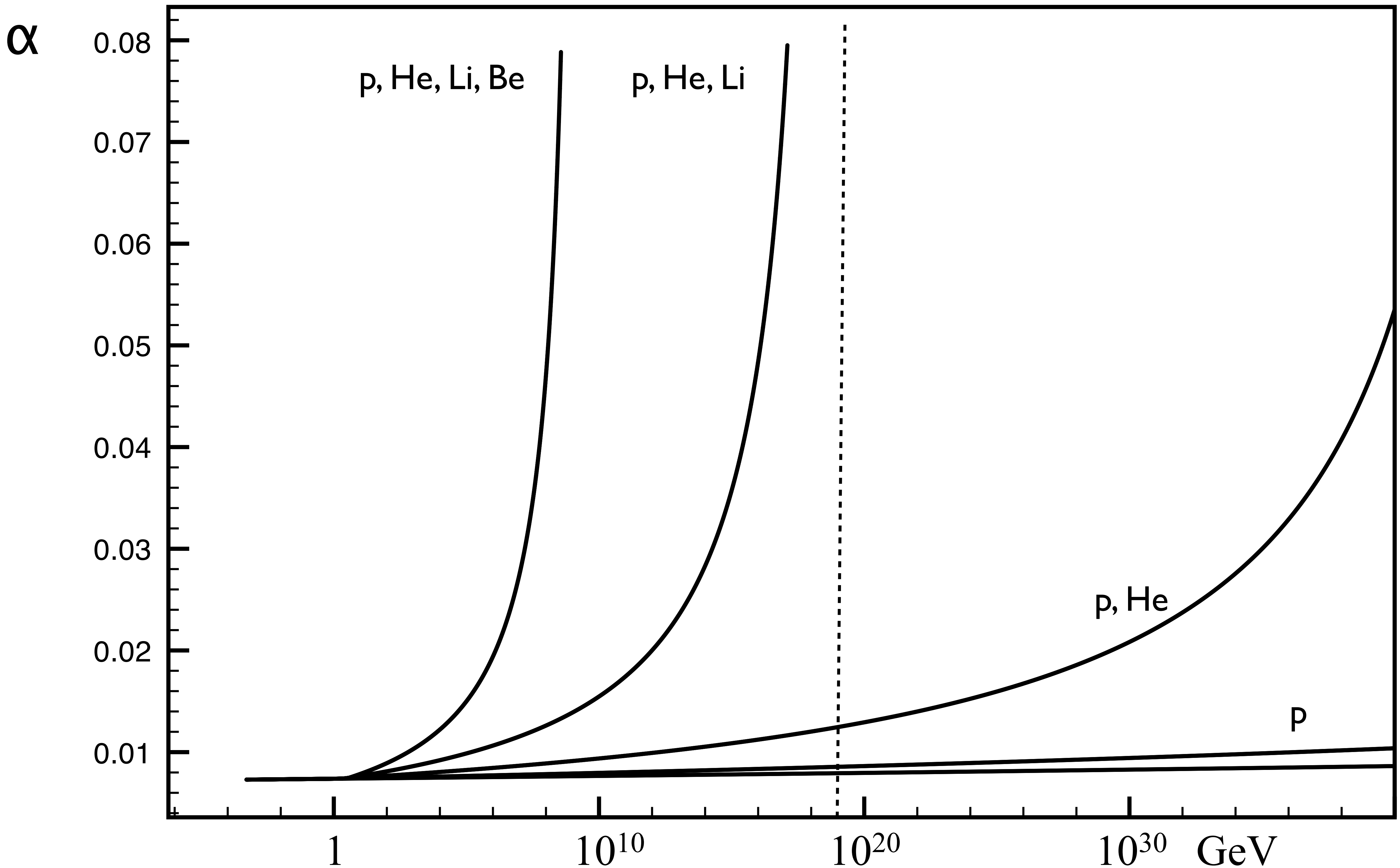
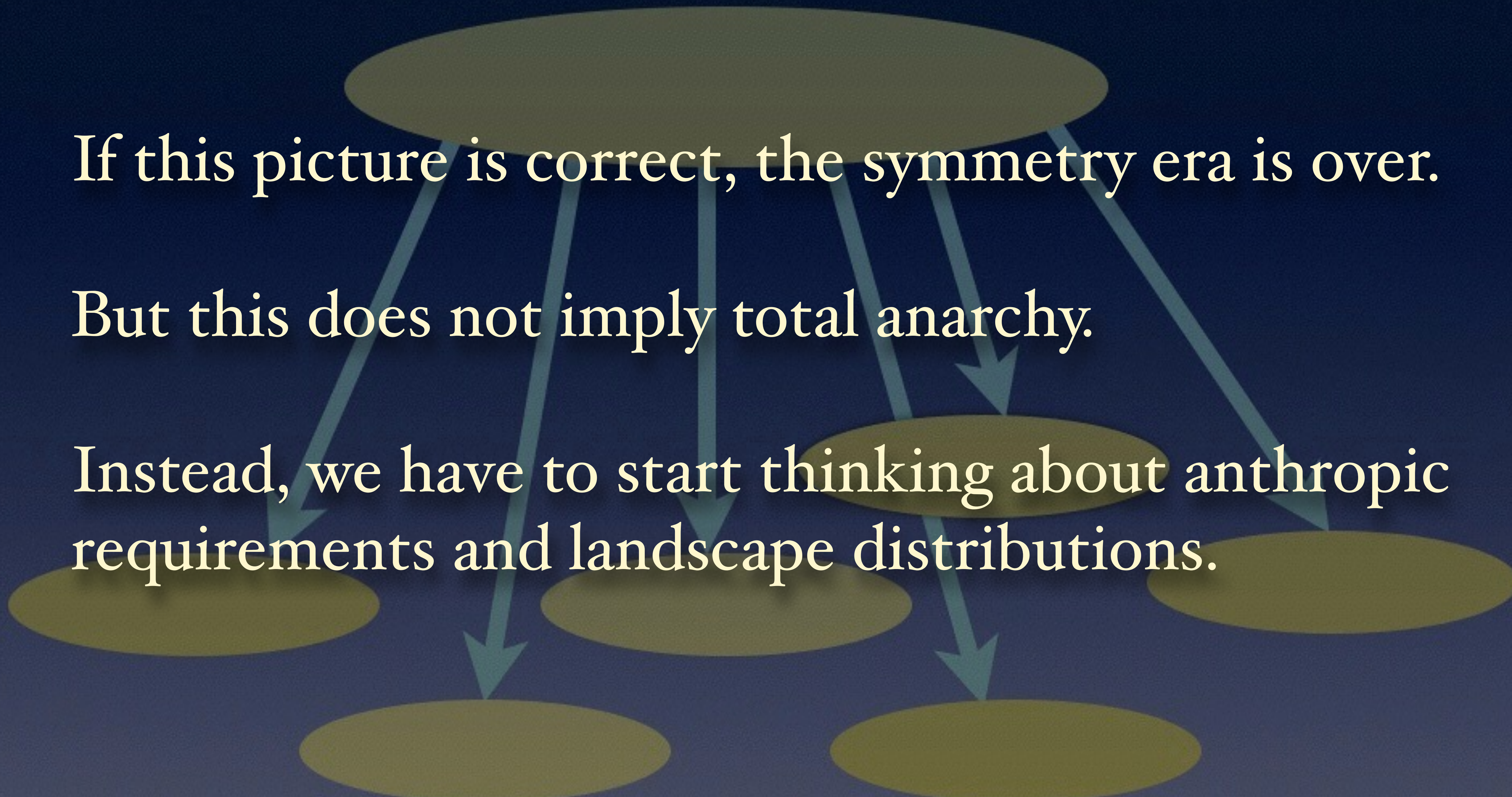
This is a historic moment:
Atomic, nuclear and hadronic physics do not qualify.


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

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.

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 $SO(10)$

Grand Unification?

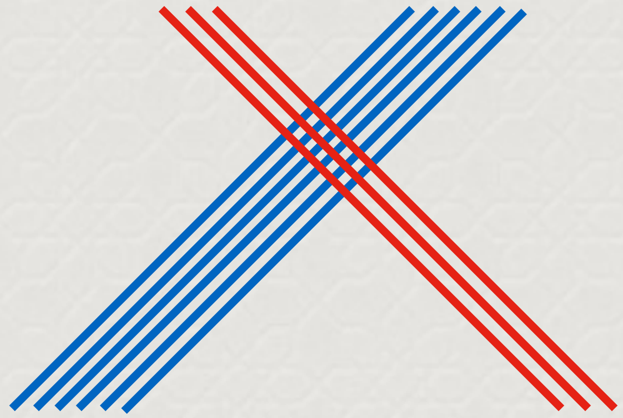
- Higgs does not fit in a GUT rep.
- Breaking to *SU(3)* x *SU(2)* x *U(1)* is not explained

  (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.

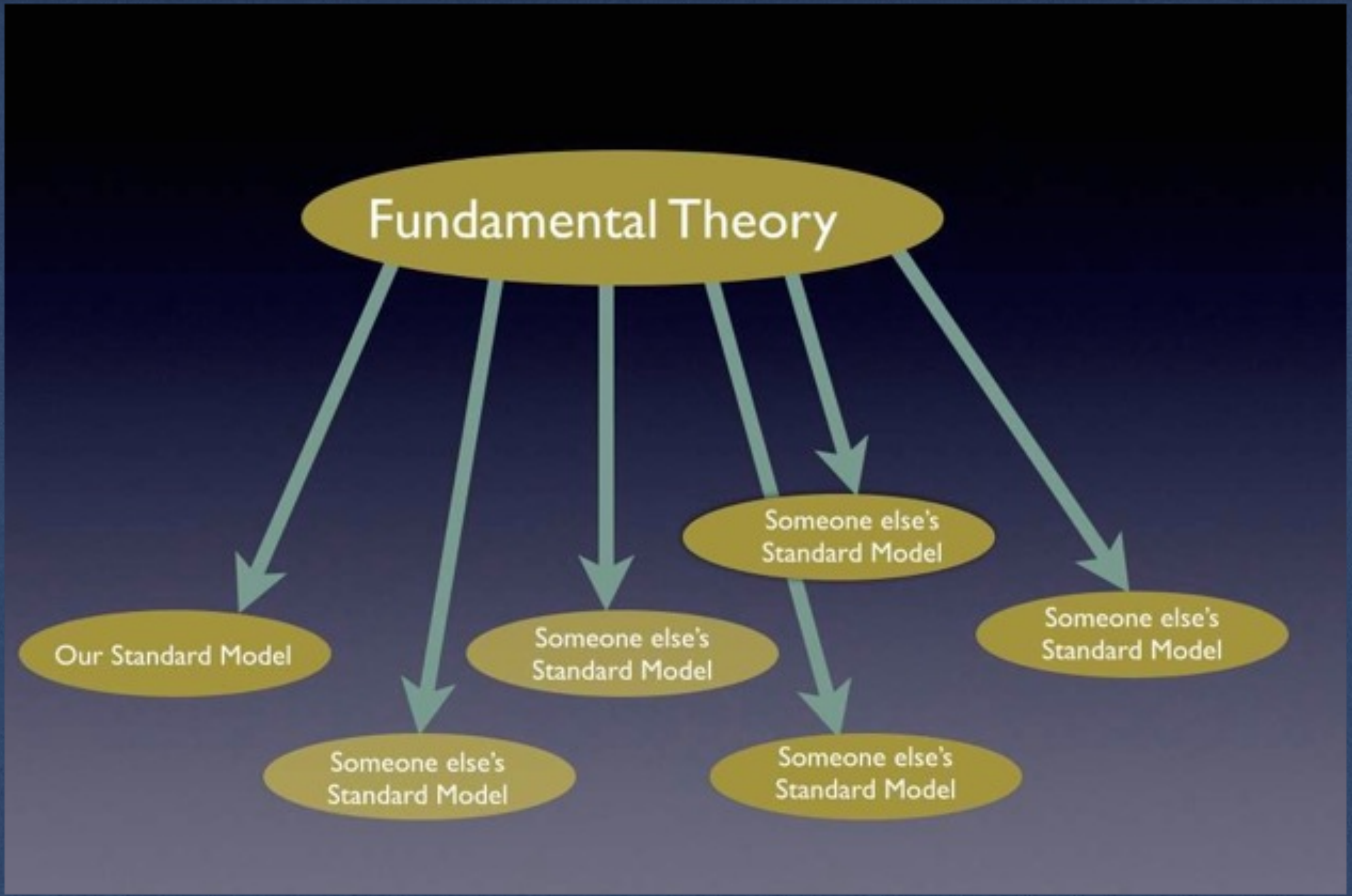
This produces matter coupling to a gauge group $SU(M) \times SU(N) \times U(1)$

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



Which Fundamental Theory?

Alternatives:

What would be better than the string landscape?

- 1 *(anthropic tunings not explained)*
- 10^{30} *(Cosmological constant?)*
- 10^{500}
- $10^{10^{500}}$
- Infinitely dense (Q)
- Continuous infinity (R)

- Infinite sequence of effective theories.
- Fundamentally uncertain (Heisenberg)
- Undecidable (Gödel)
- Beyond science.

- We are too stupid and/or ignorant, and we will never know.

Requirements for a Landscape Theory

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- All parameters should be fixed to some discrete set.

  - We must control all virtual processes ("infinities" of QFT)
  - Including those of quantum gravity.
  - Including all particles we have not observed yet, and all interactions.
  - Particle physics and gravity are intrinsically linked

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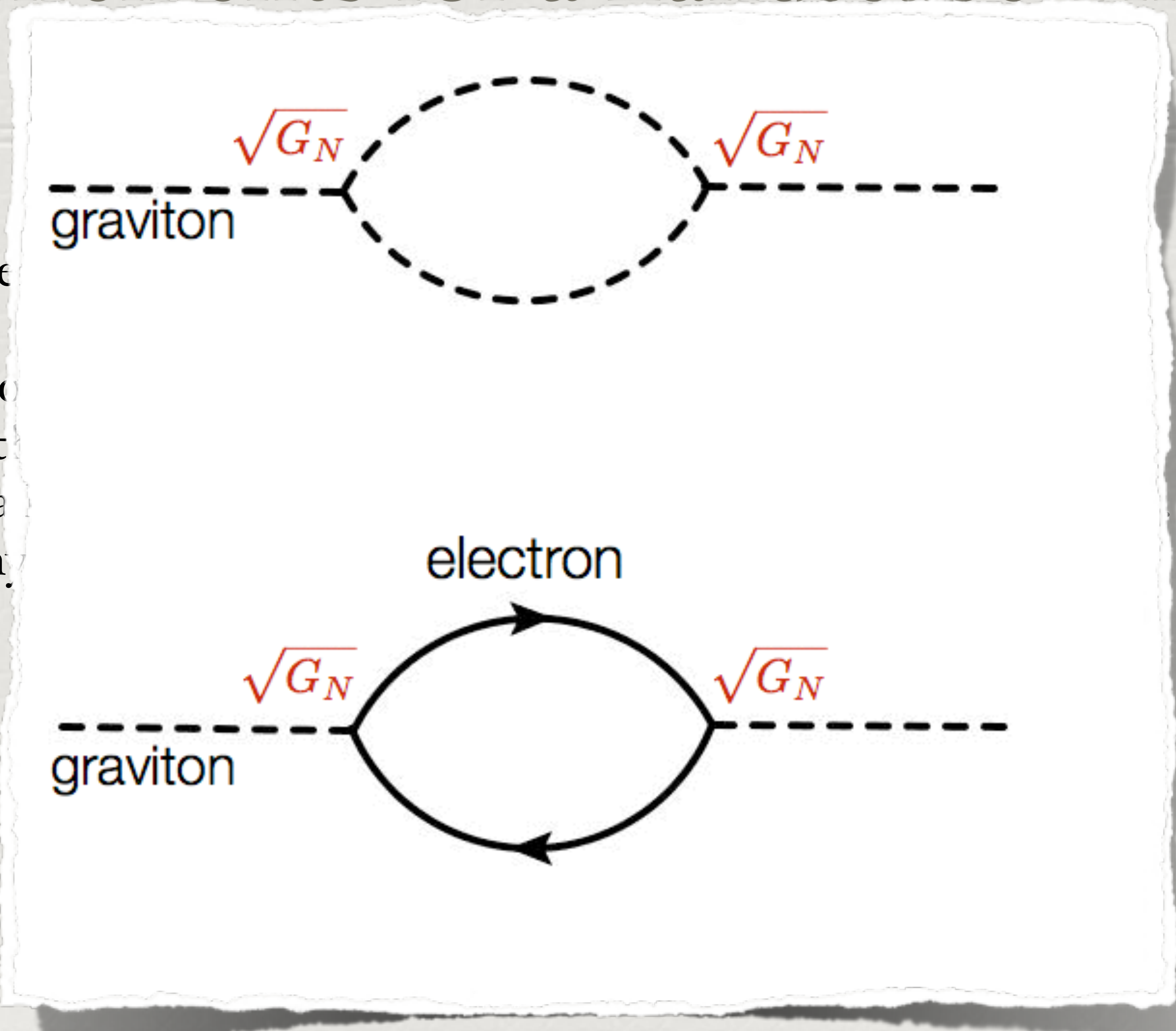

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- There must be a way to end up with a large set of choices of groups and representations.

- Distinct solutions must be connected: we must be able to get to the standard model.

Dynamical Parameters

If we ignore the problems of quantum gravity, perhaps 28 continuous parameters is all we need. This will certainly contain the Standard Model.

However, in QFT there is no relation between QED with α=1/137.039 or α=1/140.

Possible solution: make all parameters dynamical (functions of space-time satisfying equations of motion).

This forces us to think about vacuum energy: changes in parameters will create changes in the energy of the vacuum.

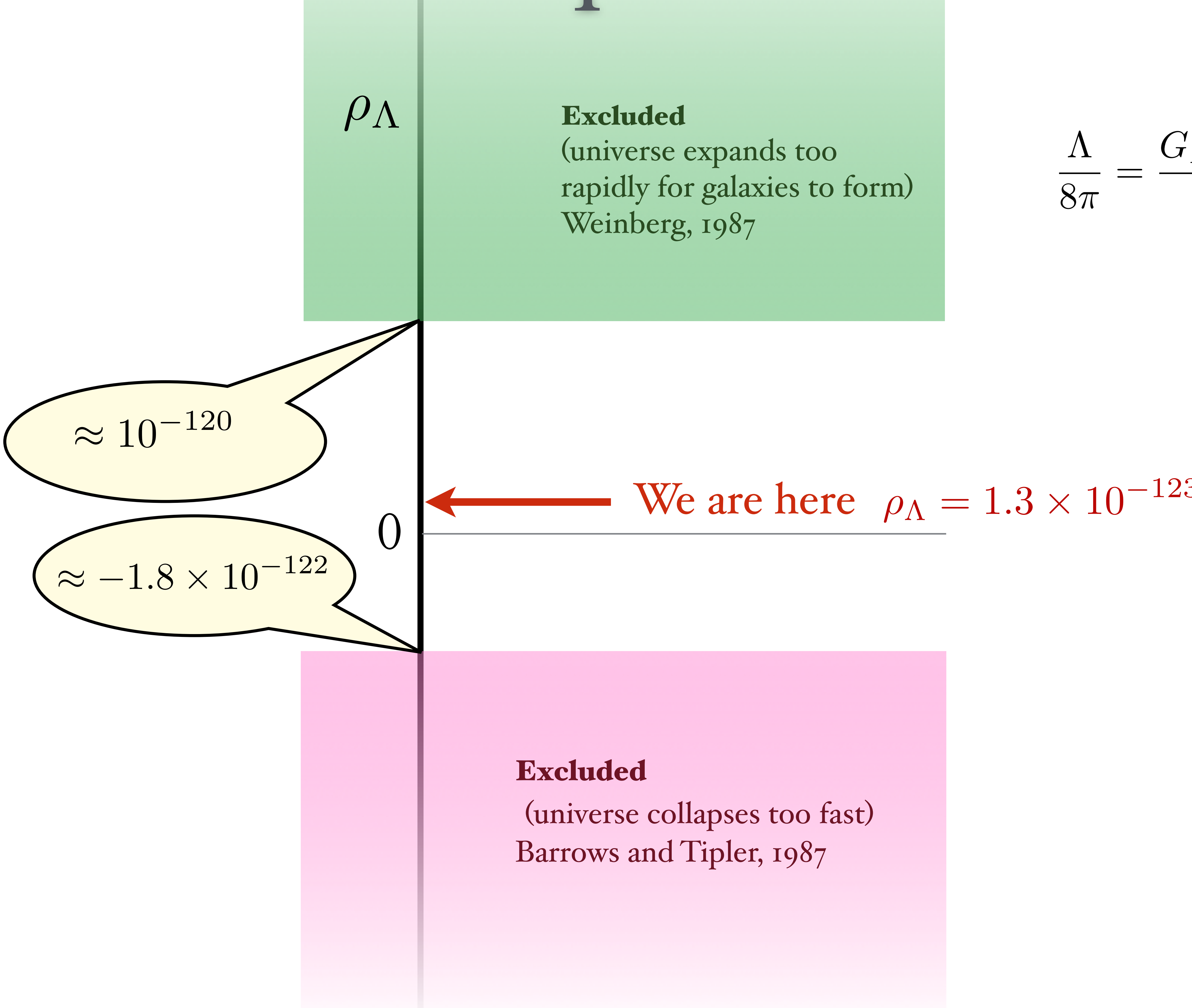
This is irrelevant in QFT, but also uncalculable (sum over the ground state energy of an inifinite number of oscillators). We may regulate it and subtract it for a given value of α, but this is not likely to be correct for a different value of α.

In the presence of gravity, it is no longer irrelevant. However, in the theory we are aiming at, it should be calculable.

Unfortunately, the answer is not likely to be correct.

Anthropic Bounds

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



C.C. versus S.M.

An anthropic explanation requires more than 10^{120} points, assuming a flat distribution.

But:
Λ is less obviously a true variable of the laws of physics than the 28 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.

So if in the true theory of gravity of our universe $\Lambda \equiv 0$ (or if gravity does not couple to vacuum energy), we are "out of physics" if we consider $\Lambda \neq 0$.

Of course, in that case we still have to find a way to explain the current observations.

String Theory

Fundamental Theory Requirements

I: Discrete choices

String theory lives naturally in 10 (or 11) dimensions.

But there is a large choice of space-time backgrounds.

This choice includes 4D Minkowski times a compact manifold.

There is a huge choice of compact backgrounds.

This apparent "embarrassment of choices" is precisely what is needed to get the required richness of choices for the 4D gauge theory.

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But so are many alternatives.

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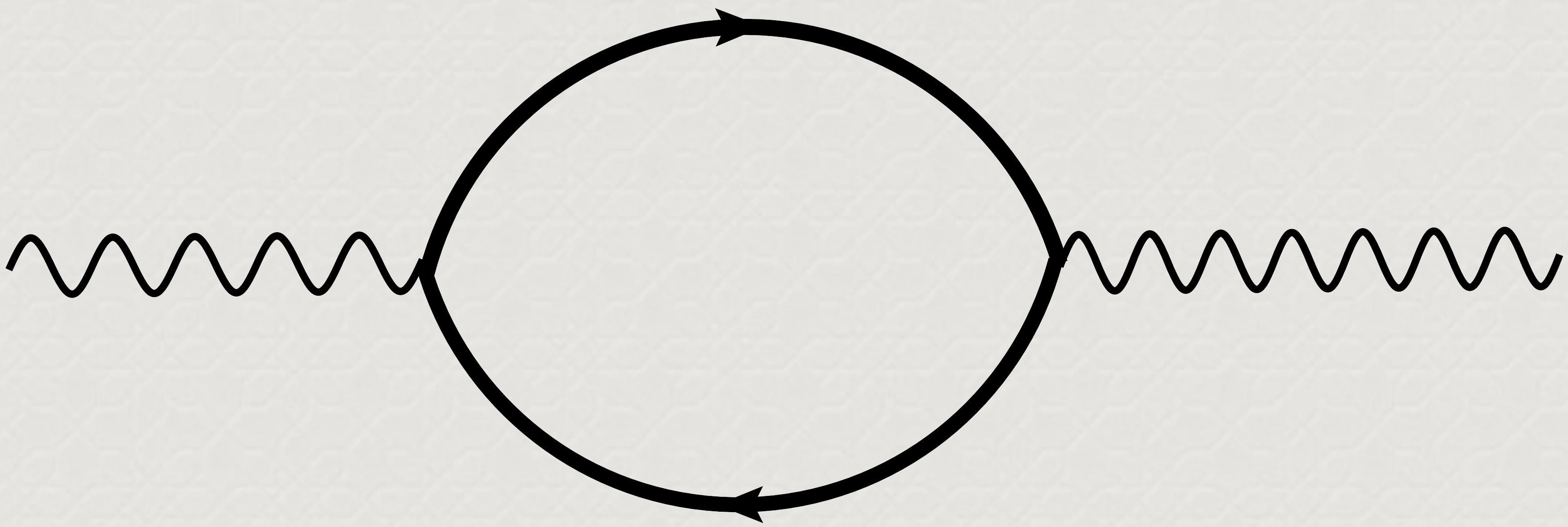
<u>For the discrete choices the anthropic principle is already established in String theory</u>

Fundamental Theory Requirements

II: Finiteness and Completeness



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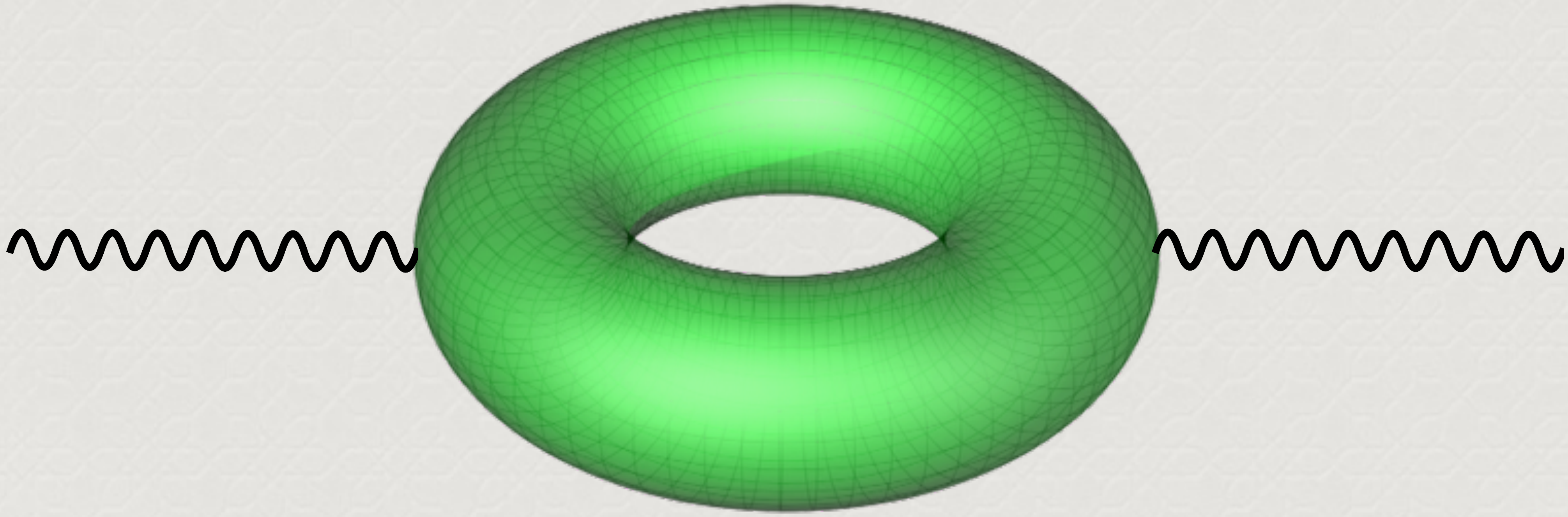

Fundamental Theory Requirements
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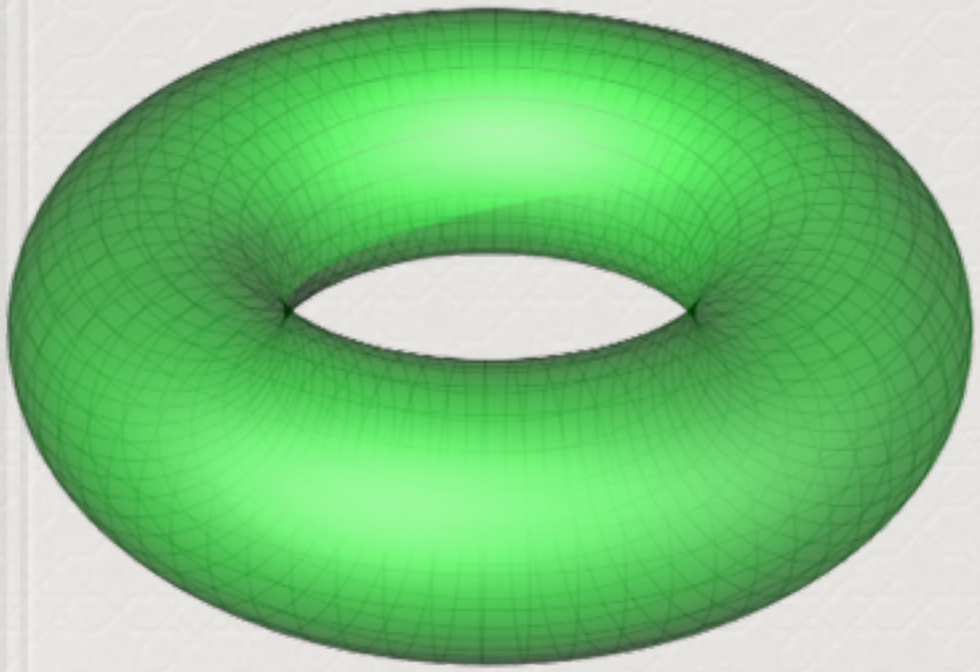

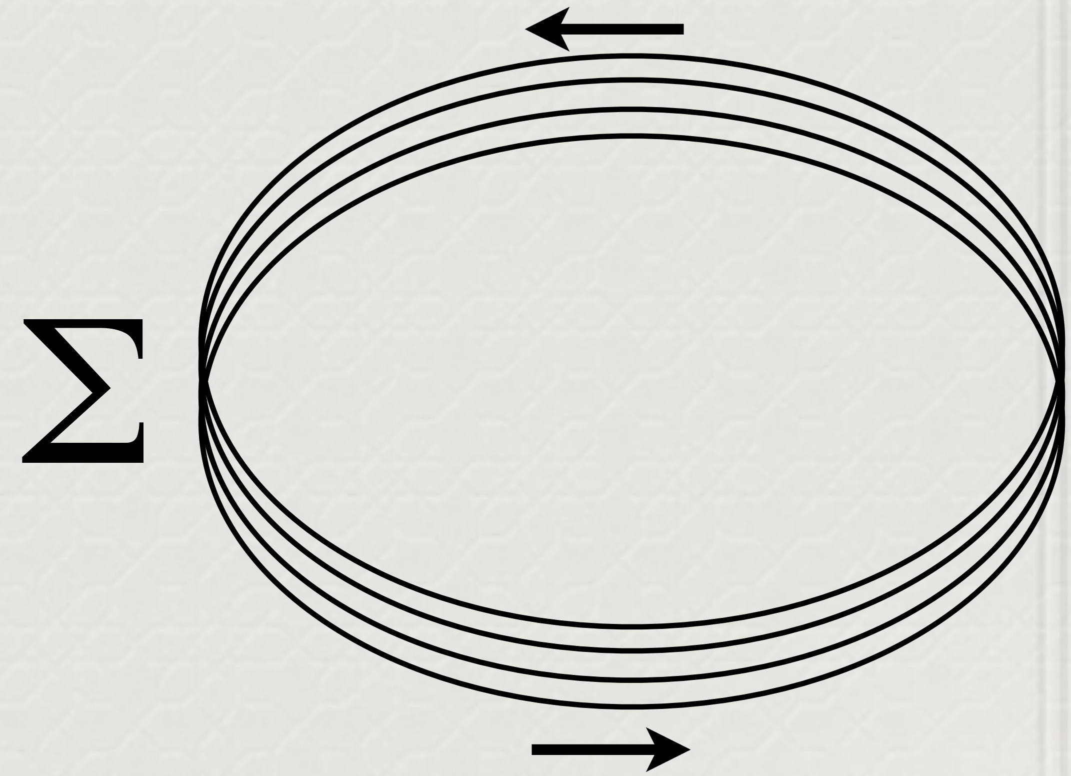

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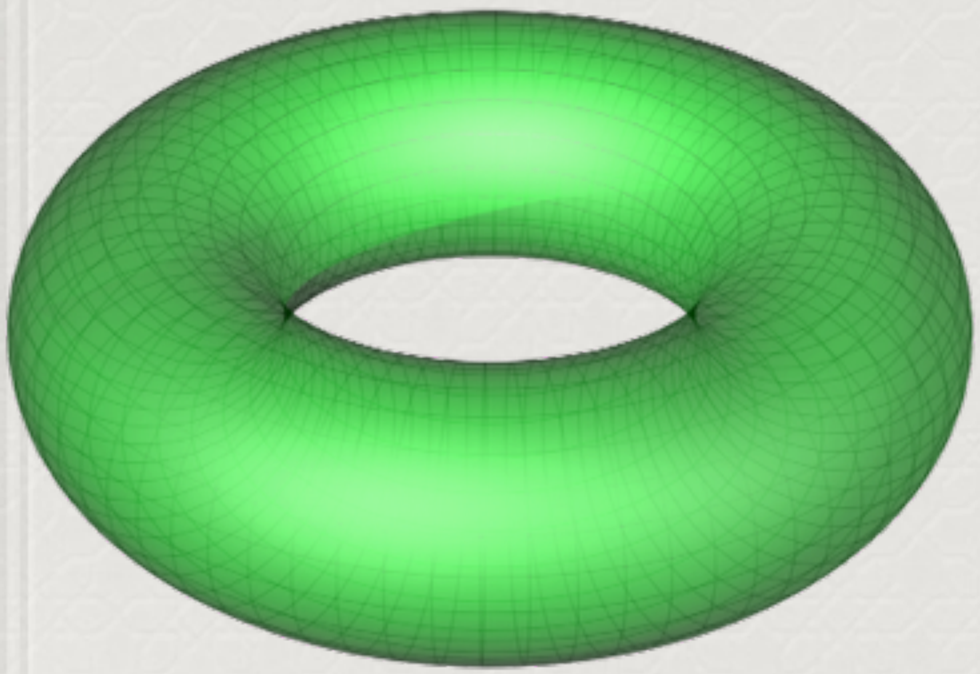
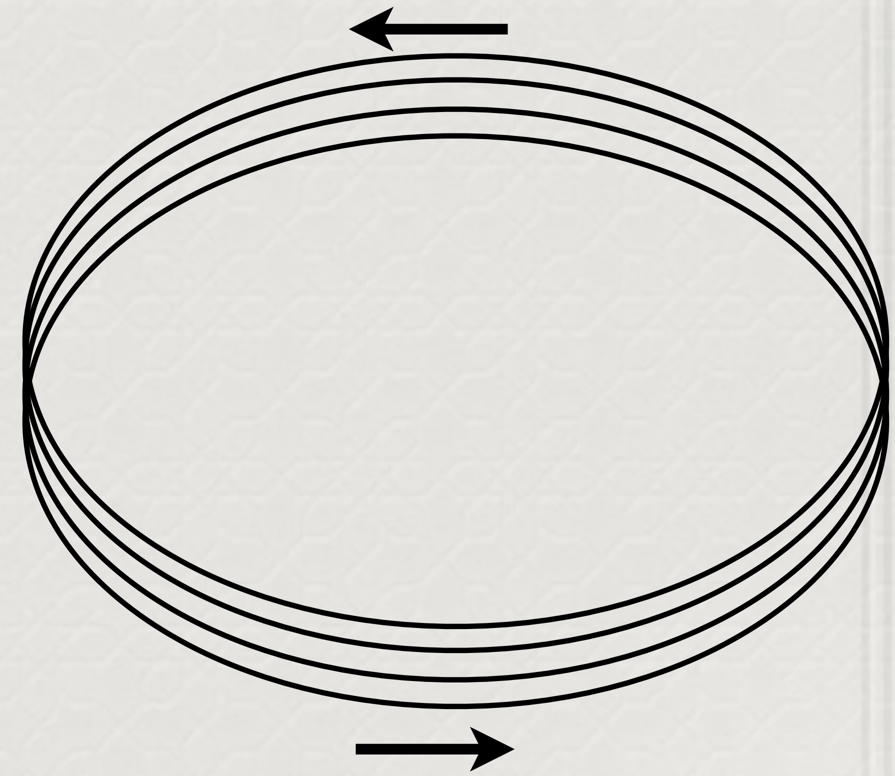


Σ



$$\int \frac{d^2\tau}{(\mathrm{Im}\tau)^{D/2+1}}\ \mathrm{Tr}\ e^{-\mathrm{Im}\tau H}$$

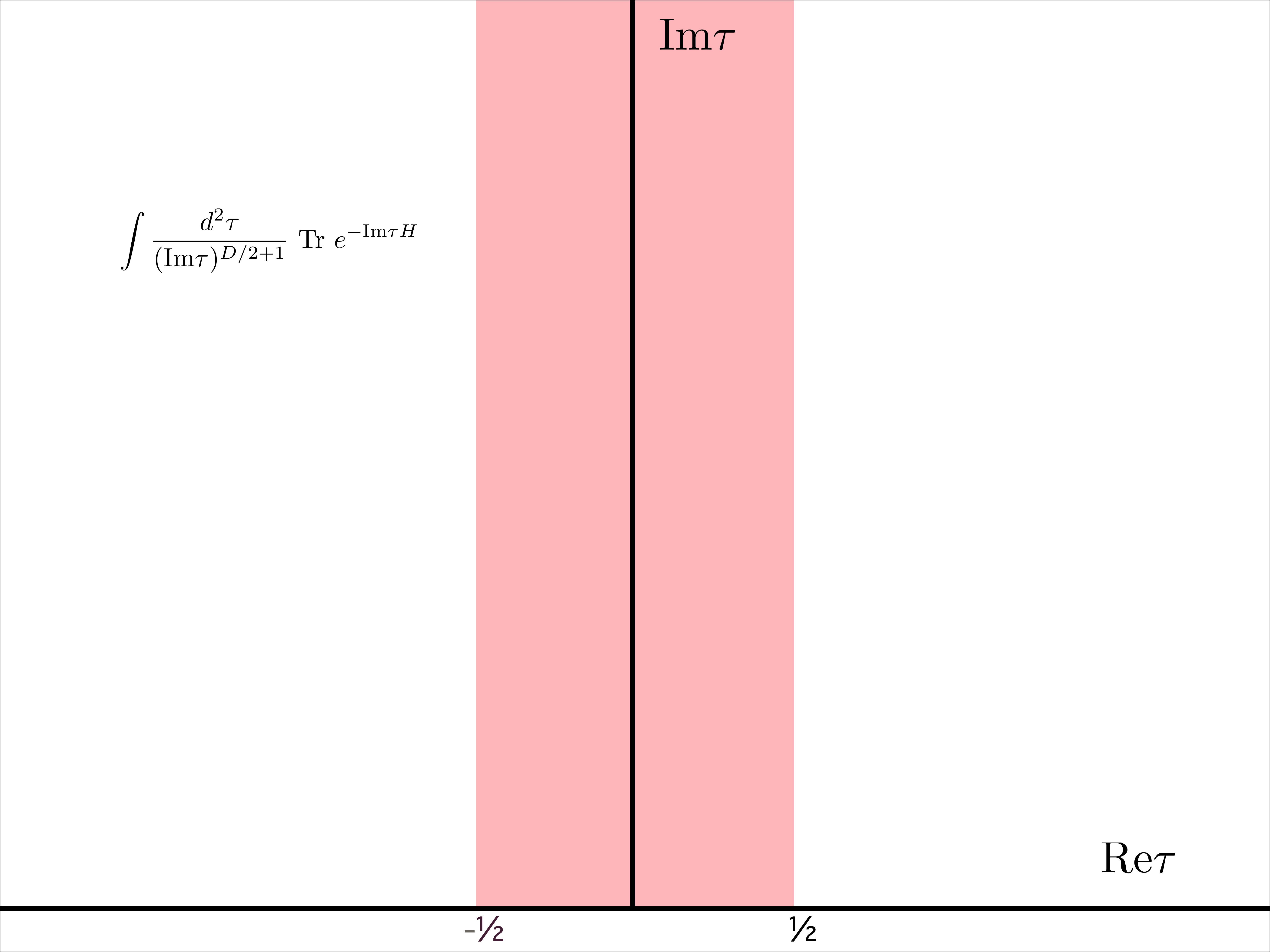
Imτ

$$\int \frac{d^2\tau}{(\mathrm{Im}\tau)^{D/2+1}}\ \mathrm{Tr}\ e^{-\mathrm{Im}\tau H}$$

Reτ

−½ ½

$$\int \frac{d^2\tau}{(\mathrm{Im}\tau)^{D/2+1}}\ \mathrm{Tr}\ e^{-\mathrm{Im}\tau H}$$



Modular Invariance

Must be invariant under $SL_2(\mathbf{Z})/\mathbf{Z}_2$

$$\tau \rightarrow \frac{a\tau + b}{c\tau + d}, \qquad a, b, c, d \in \mathbf{Z}; \quad ad - bc = 1$$

Generated by

$$\tau \rightarrow \tau + 1 \qquad\qquad \tau \rightarrow -\frac{1}{\tau}$$

Modular Invariance

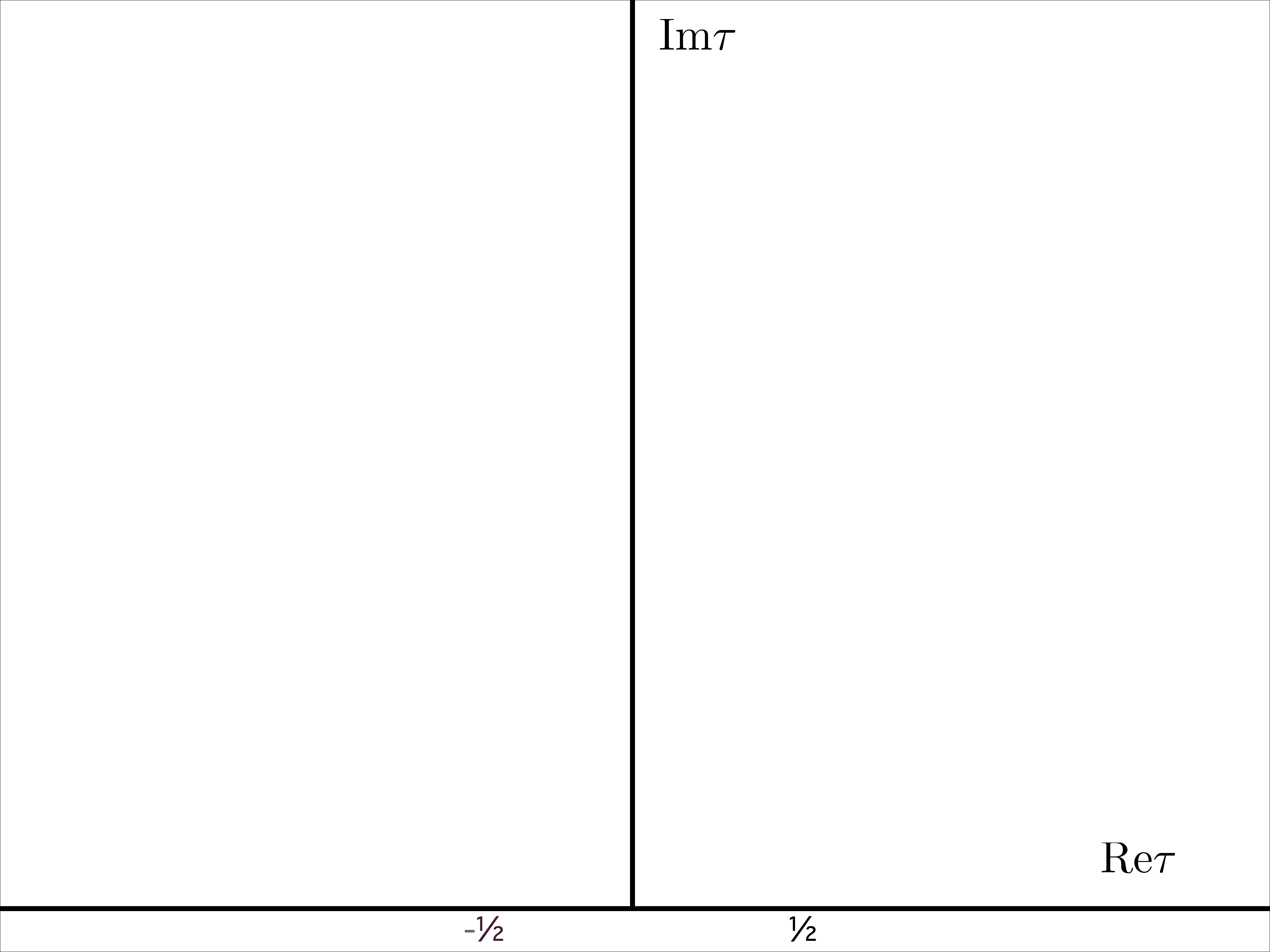
$$\int \frac{d^2\tau}{(\mathrm{Im}\tau)^{D/2+1}} \ \mathrm{Tr}\ e^{-\mathrm{Im}\tau H}$$

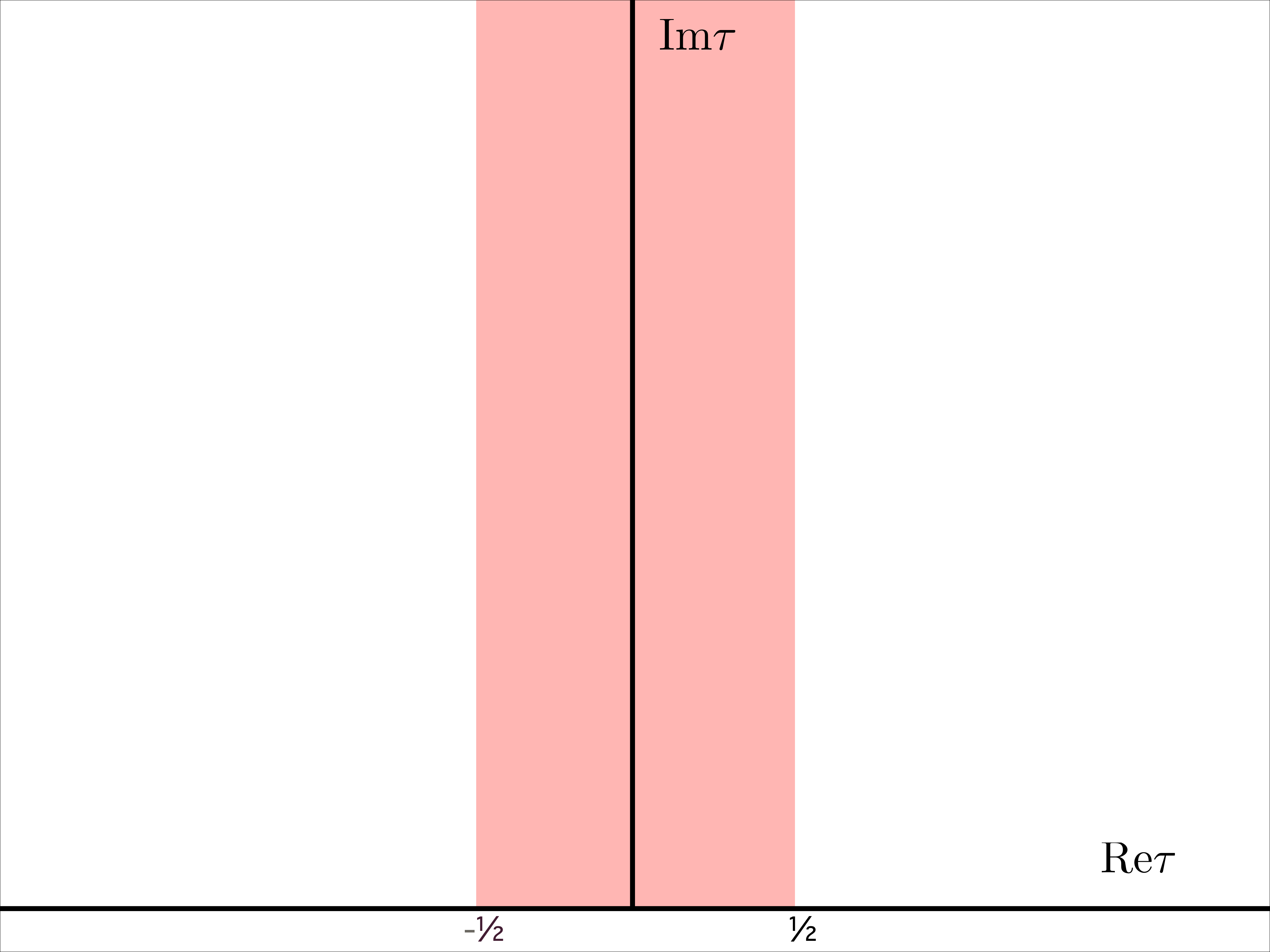
Must be invariant under $SL_2(\mathbf{Z})/\mathbf{Z}_2$

$$\tau \to \frac{a\tau + b}{c\tau + d}, \qquad a, b, c, d \in \mathbf{Z}; \quad ad - bc = 1$$

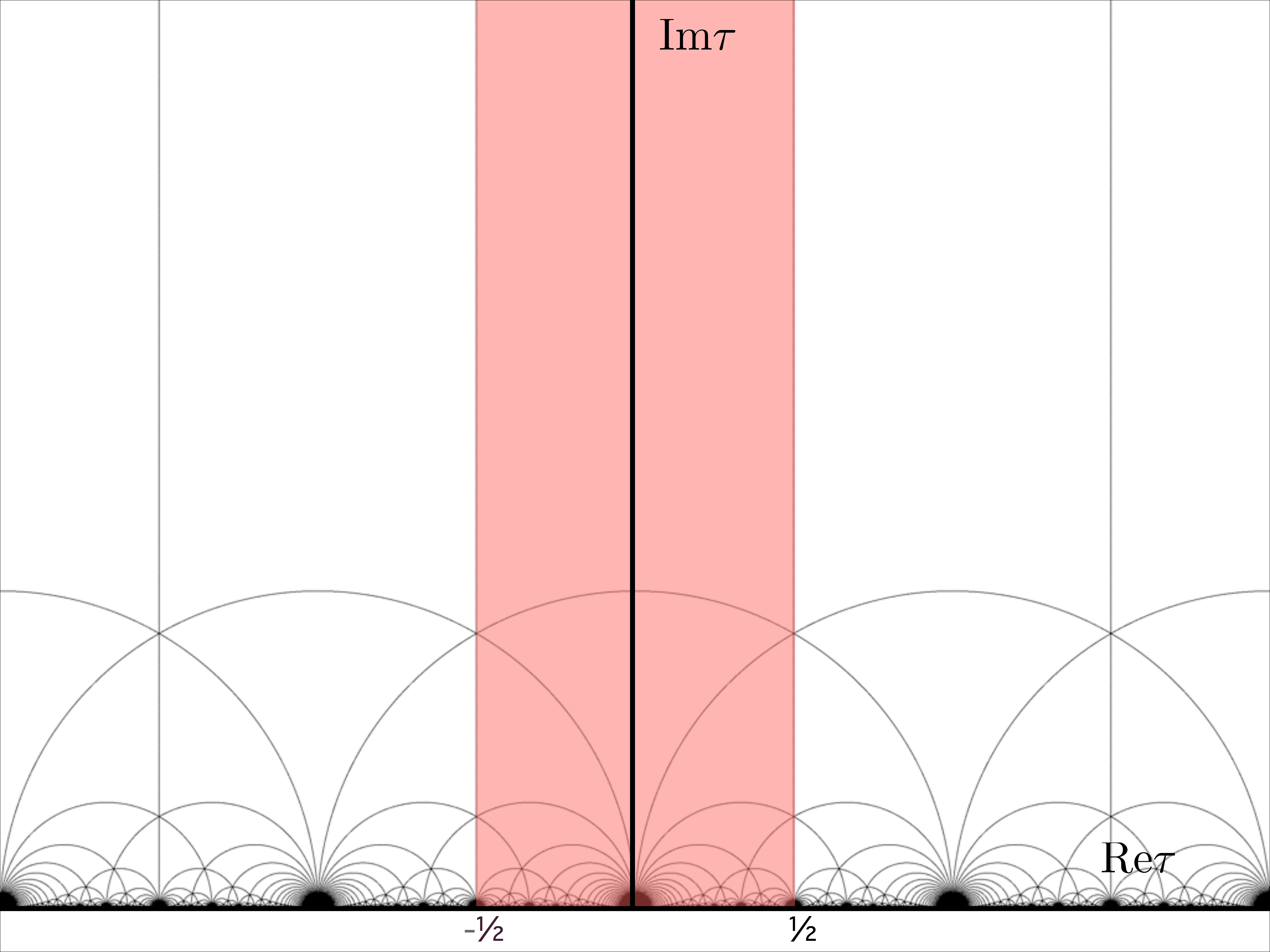
Generated by

$$\tau \to \tau + 1 \qquad\qquad \tau \to -\frac{1}{\tau}$$

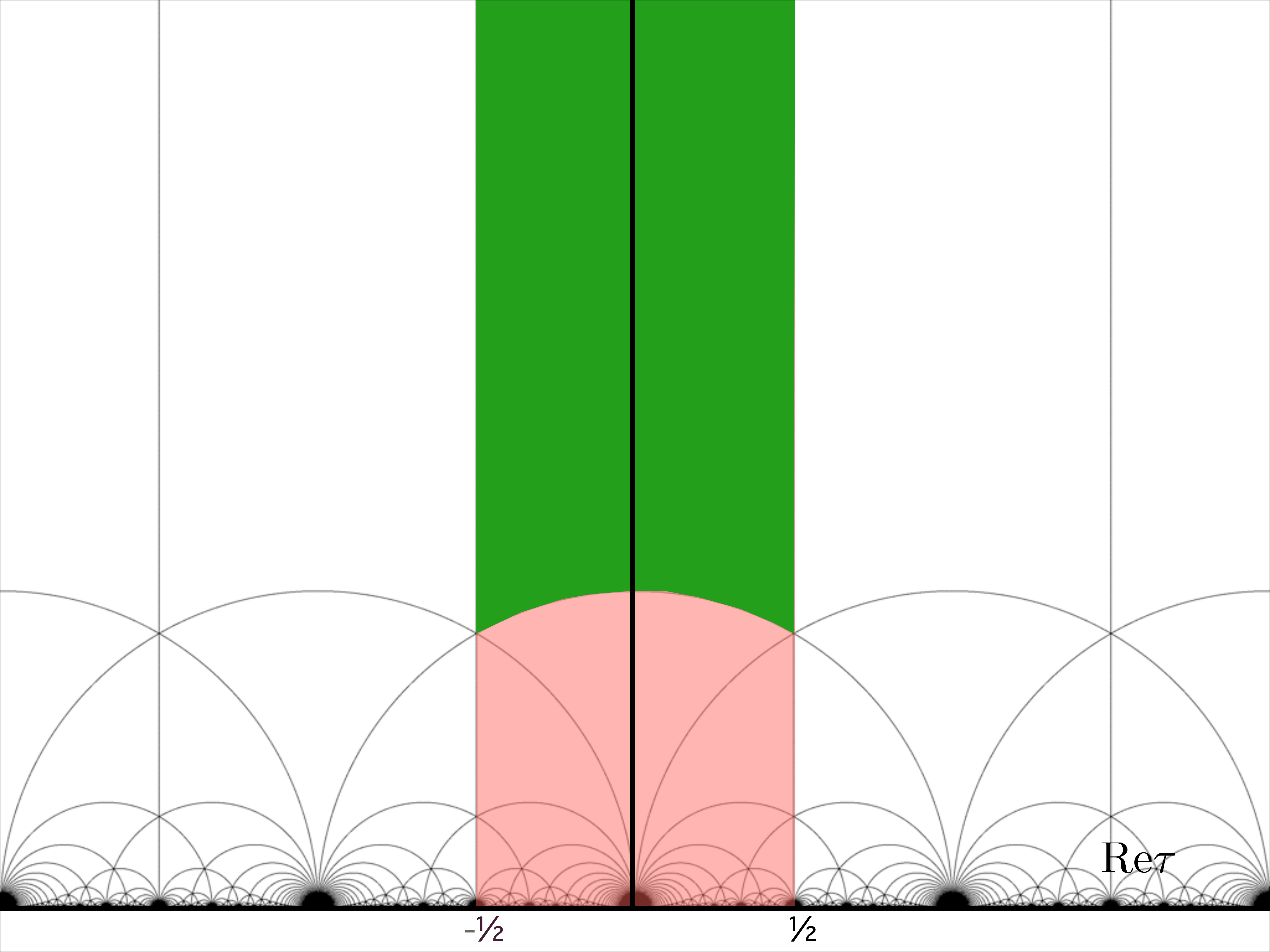

Imτ
Reτ
$-\frac{1}{2}$
$\frac{1}{2}$



Imτ
Reτ
-½
½



Imτ
Reτ
-½
½


Reτ
−½
½

Modular Invariance

Must be invariant under $SL_2(\mathbf{Z})/\mathbf{Z}_2$

$$\tau \rightarrow \frac{a\tau + b}{c\tau + d}, \qquad a, b, c, d \in \mathbf{Z}; \quad ad - bc = 1$$

Strong constraint on H!

These constraints imply that one cannot add particles or remove particles.

Modular Invariance

$$\int \frac{d^2\tau}{(\mathrm{Im}\tau)^{D/2+1}} \ \mathrm{Tr}\ e^{-\mathrm{Im}\tau H}$$

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$$\tau \to \frac{a\tau + b}{c\tau + d}, \qquad a, b, c, d \in \mathbf{Z}; \quad ad - bc = 1$$

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Fundamental Theory Requirements
III: The Cosmological Constant

Bousso and Polchinski (2000)

Quantized generalizations of electric & magnetic fields ("fluxes") living in Minkowski and internal dimensions:

• May wind N times around closed cycles of the internal manifold to help stabilizing some moduli
• Have space-time components that contribute to the cosmological constant.

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

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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

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

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).

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

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Fundamental Theory Requirements

IV: Dynamical Parameters

Fundamental Theory Requirements
IV: Dynamical Parameters

Shapes and size of the handles of internal manifolds give rise to dynamical parameters in the resulting four-dimensional gauge theory: moduli.
("String theory has no parameters")
Often there are hundreds or thousands of moduli.

To first approximation (supersymmetry) these have flat potentials.

It has been a long-standing problem to show that supersymmetry can be broken and that potentials with local minima can be generated ("moduli stabilization").

During the last decade there have been many papers claiming to solve this problem using complicated combinations of tools (branes, orientifold planes, fluxes, instantons, perturbative corrections, ...)

But not everyone is convinced....

(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!

Fundamental Theory Requirements
V: Connections

- Connections between different minima of the potential by Coleman-deLuccia or Hawking-Moss instantons.
- Connections between different topologies by conifold transitions.

Populating the Whole Landscape
Adam R. Brown and Alex Dahlen

Phys. Rev. Lett. 107, 171301 (2011)

"Every de Sitter vacuum can transition to every other de Sitter vacuum despite any obstacle, despite intervening anti–de Sitter sinks, despite not being connected by an instanton. Eternal inflation populates the whole landscape."

Will we ever know?

Dirac about QED (1937):

“Because of its extreme complexity, most physicists will be glad to see the end of it”

But just about a decade later QED had become one of the crown jewels of modern physics, the first component of the Standard Model that was built on the same principles.

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But of course this was driven by experimental results....

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)

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

Dine, Banks, Douglas (2002)

Conclusions

- We may very well live in a multiverse.
- This is not irrelevant. It has a huge impact on our outlook on problems in particle physics and gravity.
- Plenty of possibilities (from theory, experiment and observations) for discovering this is wrong, but no gold-plated method for proving it is correct.