Title: String Theory Landscape and the Swampland

Speakers: Cumrun Vafa

Series: Colloquium

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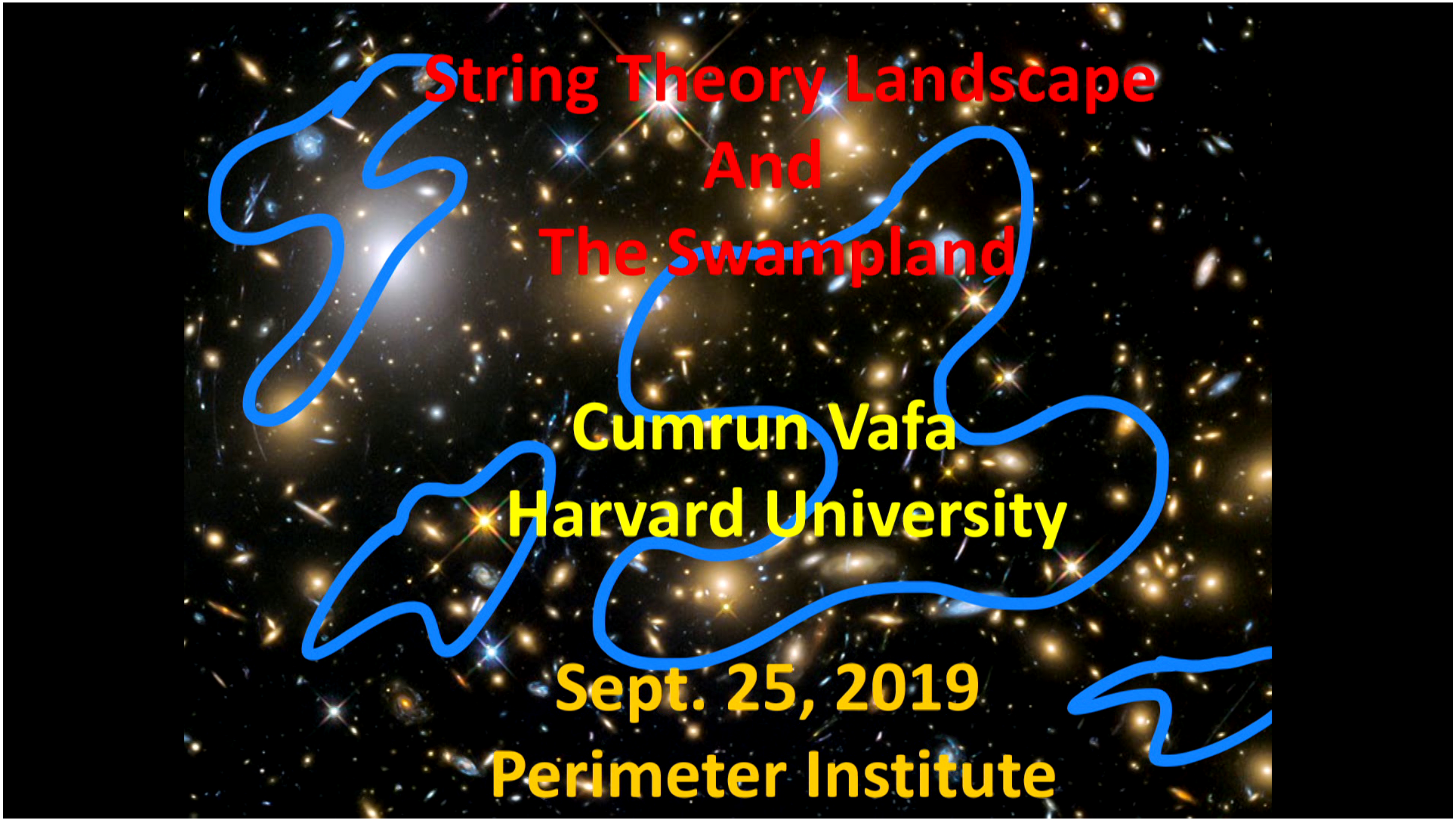
Abstract: In this talk I review some of what we have learned from string theory about the criteria one needs for a quantum theory to be able to consistently couple to quantum gravity (the landscape) as opposed to one that looks consistent but cannot be consistently coupled to gravity (the swampland). Moreover, I review some of the cosmological implications of these conditions for our universe.


String Theory Landscape
And
The Swampland
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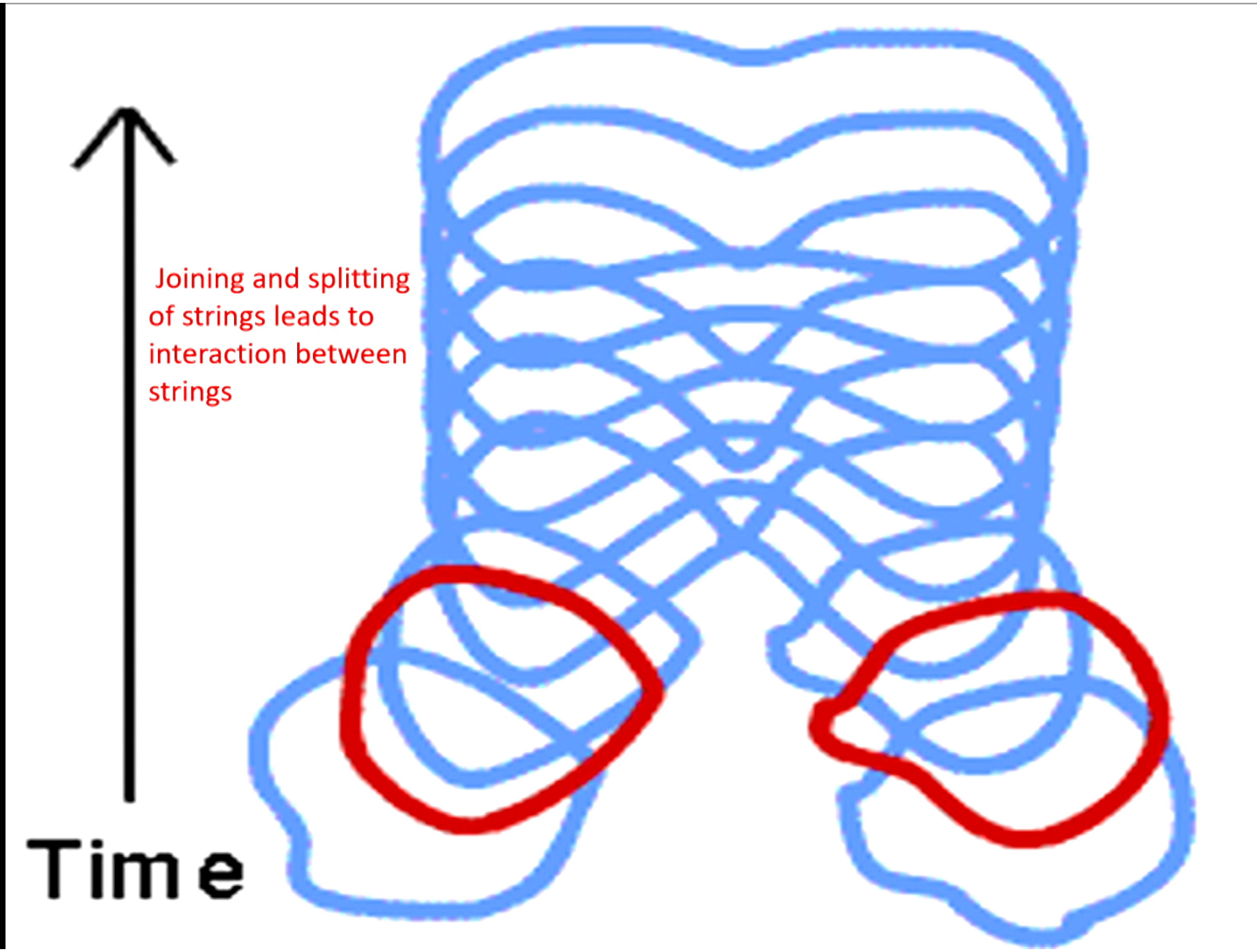
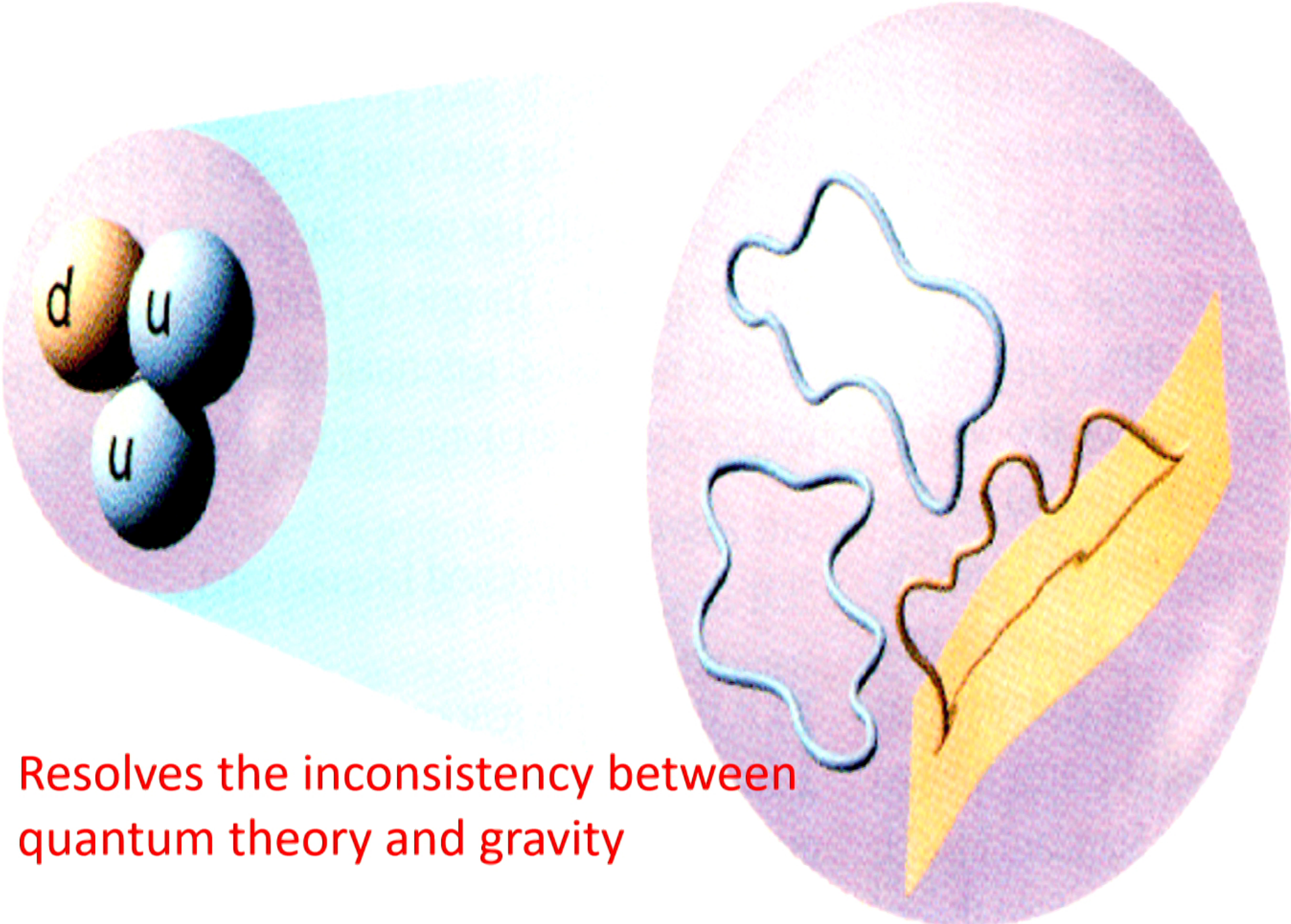
Harvard University
Sept. 25, 2019
Perimeter Institute

String Theory:

A consistent framework which unifies quantum theory and Einstein's theory of gravity—a highly non-trivial accomplishment!


Joining and splitting of strings leads to interaction between strings
Time

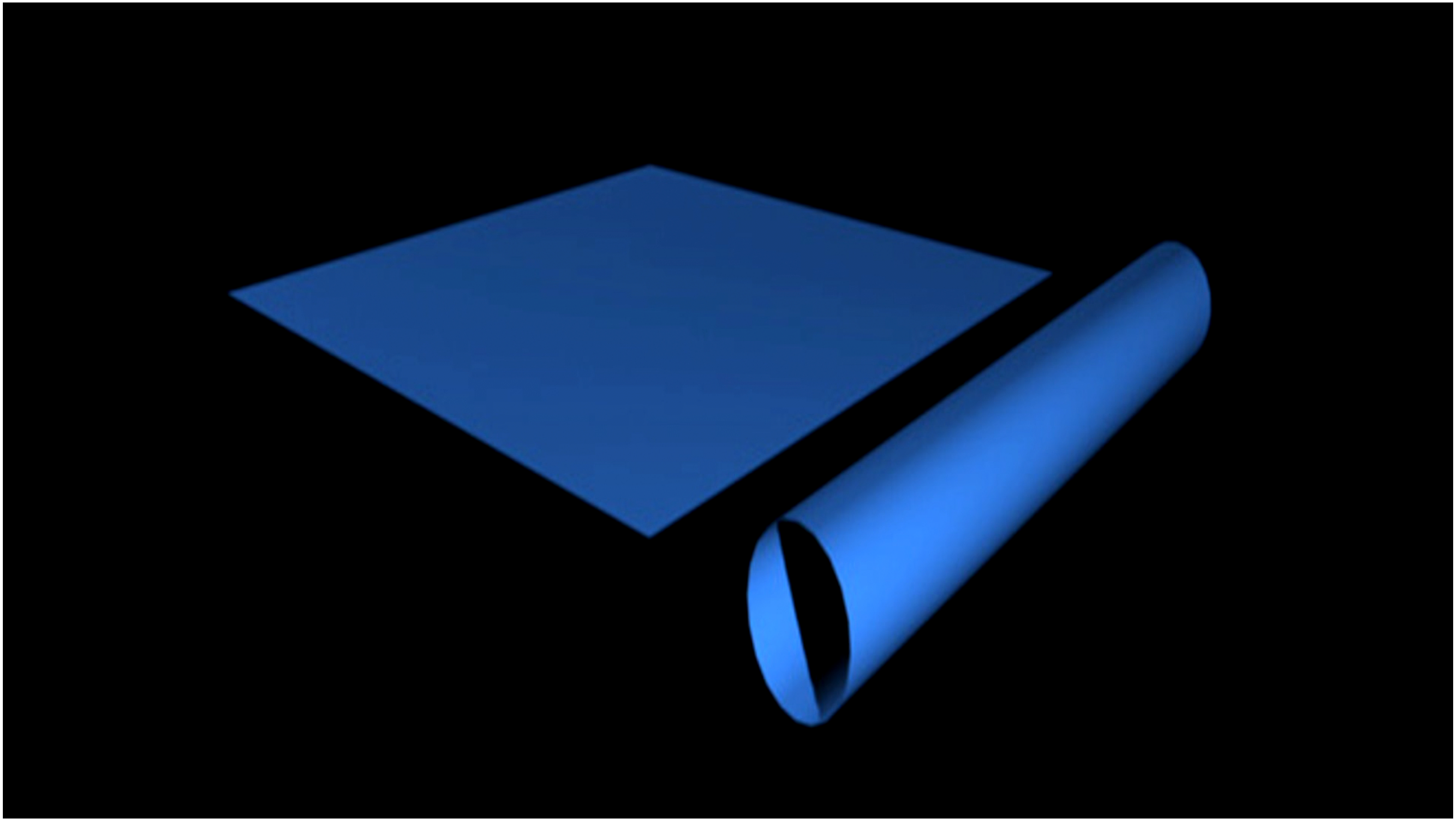


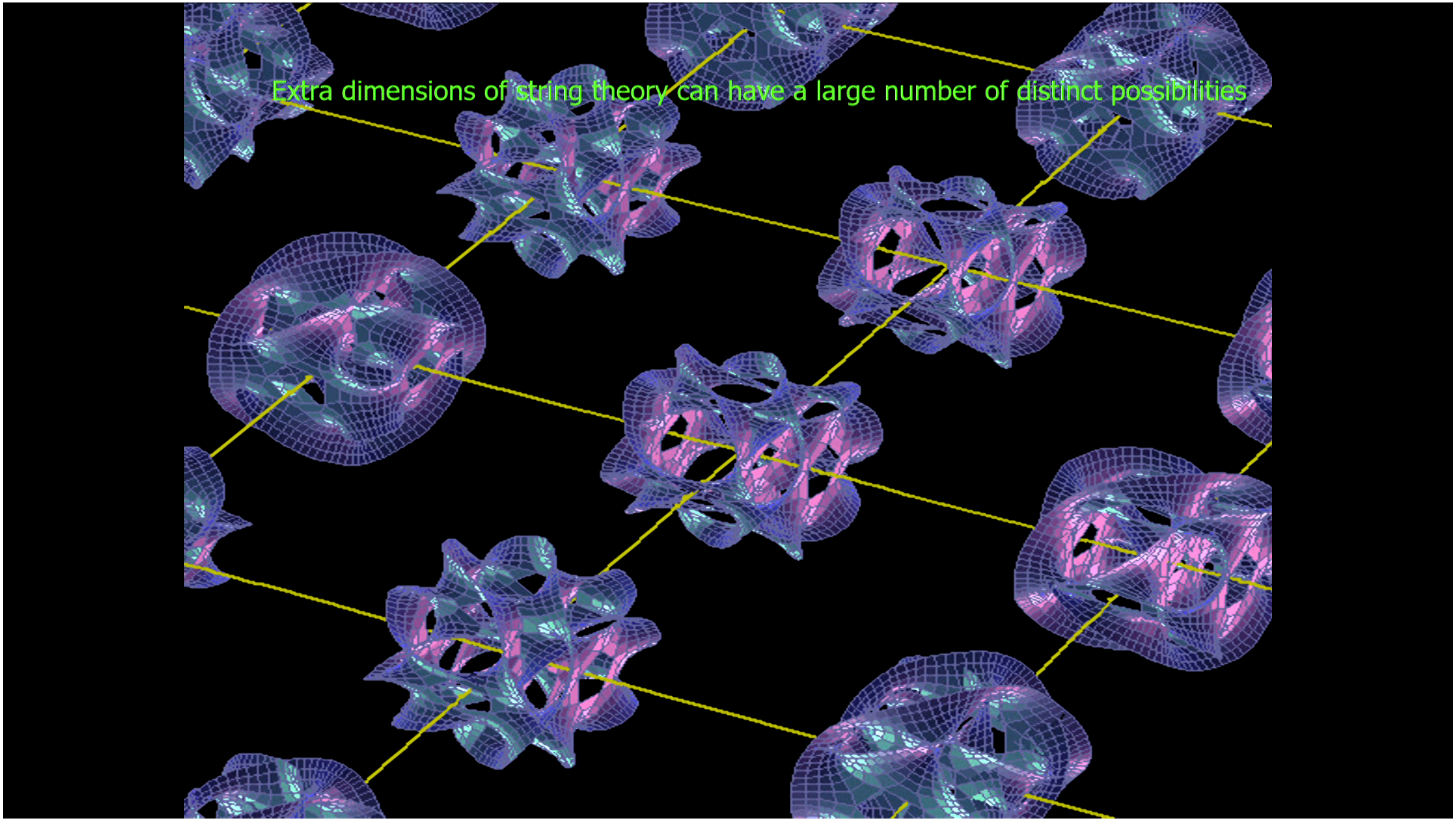
Resolves the inconsistency between quantum theory and gravity

Extra Dimensions

One of the novel features of string theory is the prediction that there are extra dimensions, beyond 3 spatial dimensions and 1 time.

These must be tiny to avoid experimental detection to date.



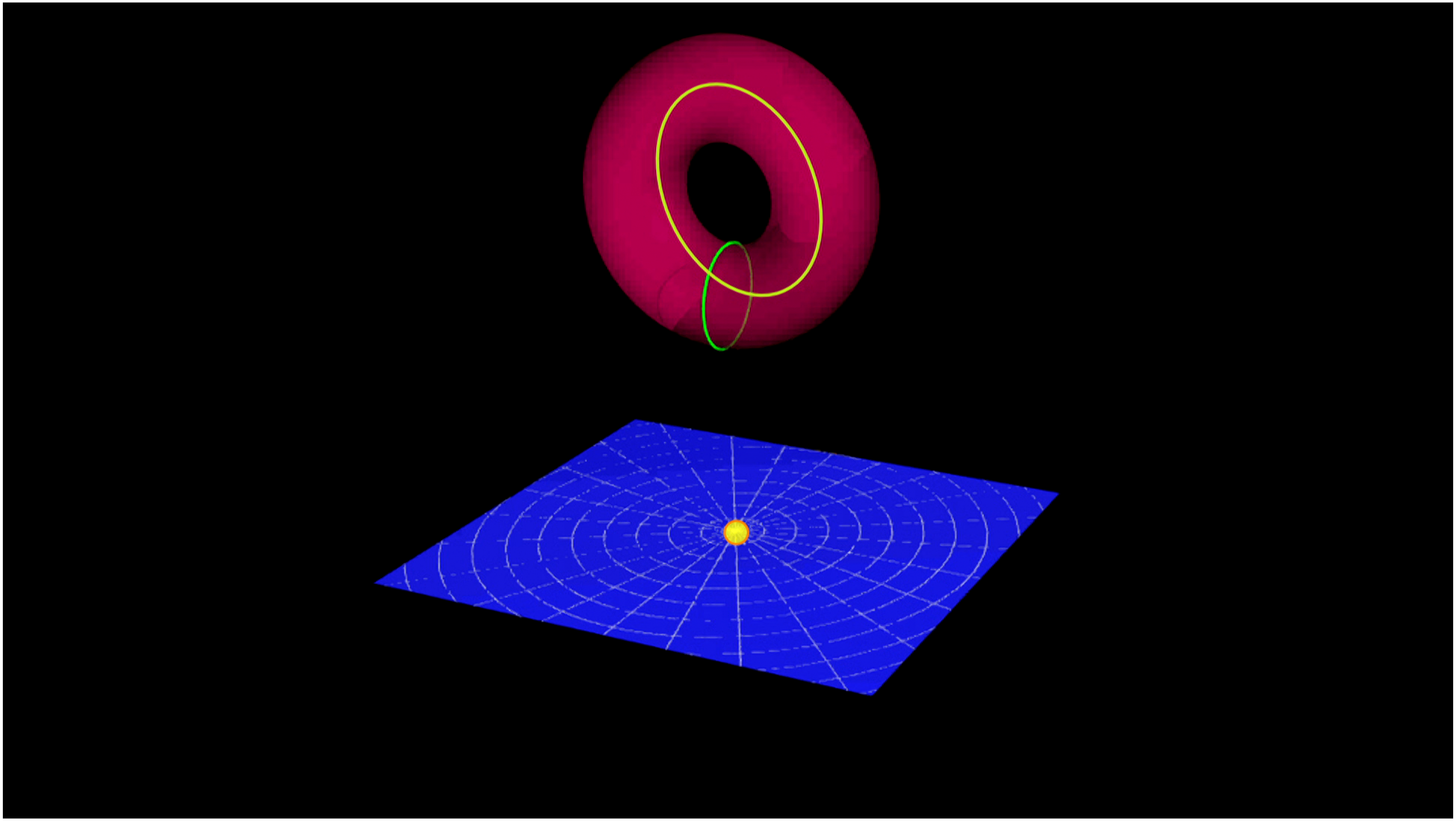

Extra dimensions of string theory can have a large number of distinct possibilities

The physical properties observed in 3+1 dimensions depends on the choice of the compact tiny space:

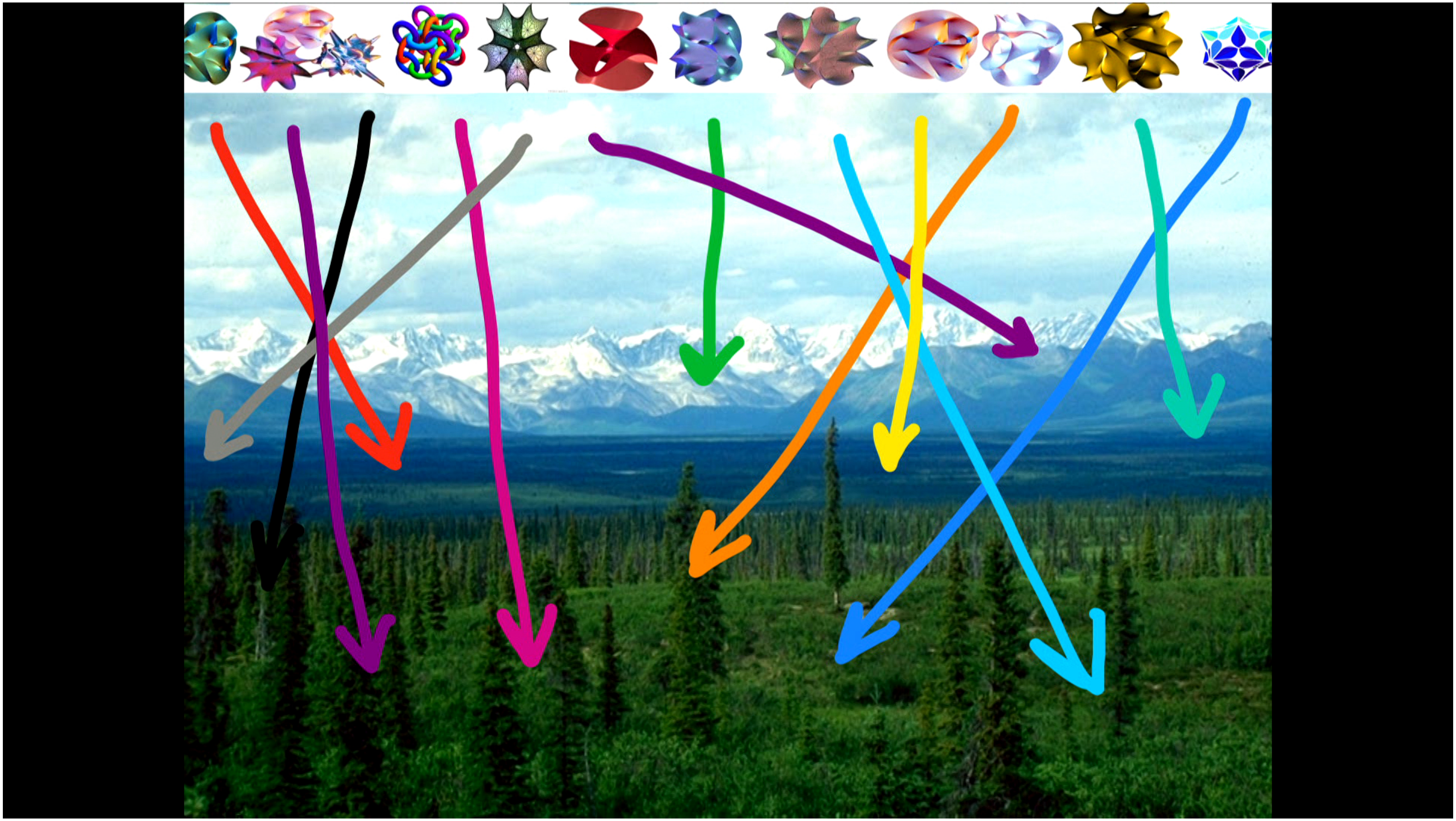
Number of forces, particles and their masses, etc.

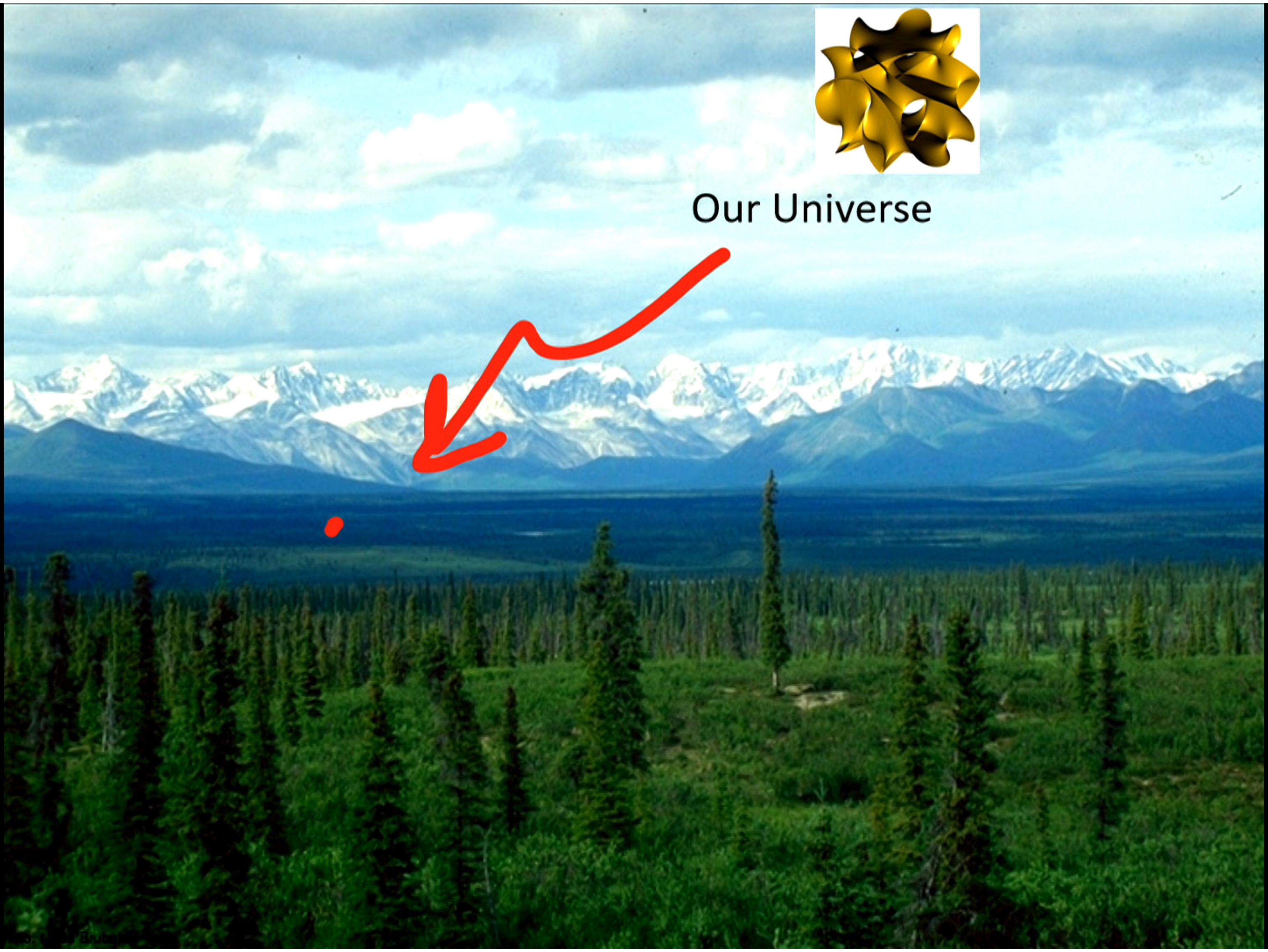
Since there are a vast number of allowed tiny spaces which are allowed we get a huge number of consistent possible effective 3+1 dimensional theories;

The String Landscape




This leads to the vast string landscape




Our Universe

Going from compactifications choices to the landscape is too cumbersome because there are a HUGE number of consistent choices.

This raises the question:

Can we just reverse this and pick a consistent looking 3+1 dimensional theory and not worry which compactification leads to it and simply extract the relevant 3+1 dimensional physics?

Landscape of string vacua is vast.

Can any imaginable universe occur as a point in the string landscape?

NO!

MOST consistent looking theories in 3+1 dimensions are apparently inconsistent and never arise from string theory: They belong to the Swampland!


Swampland!

Main question:

What distinguishes the landscape from swampland?

Or equivalently: What additional consistency conditions are necessary in a quantum theory of gravity which are absent when we remove gravity?

We do not know!

What we know:

1-Not all consistent-looking theories arise from string theory.

2-Some of these observations can be captured by some principles and at least some of them can be motivated based on quantum gravitational arguments and in particular on black hole physics.

3-These can lead to some specific predictions which have concrete consequences for cosmology and particle phenomenology of our universe.

Aim for this talk:

Present some of the landscape criteria that we have discovered and explain their motivation and explain some of their observable consequences.

String Landscape and Swampland

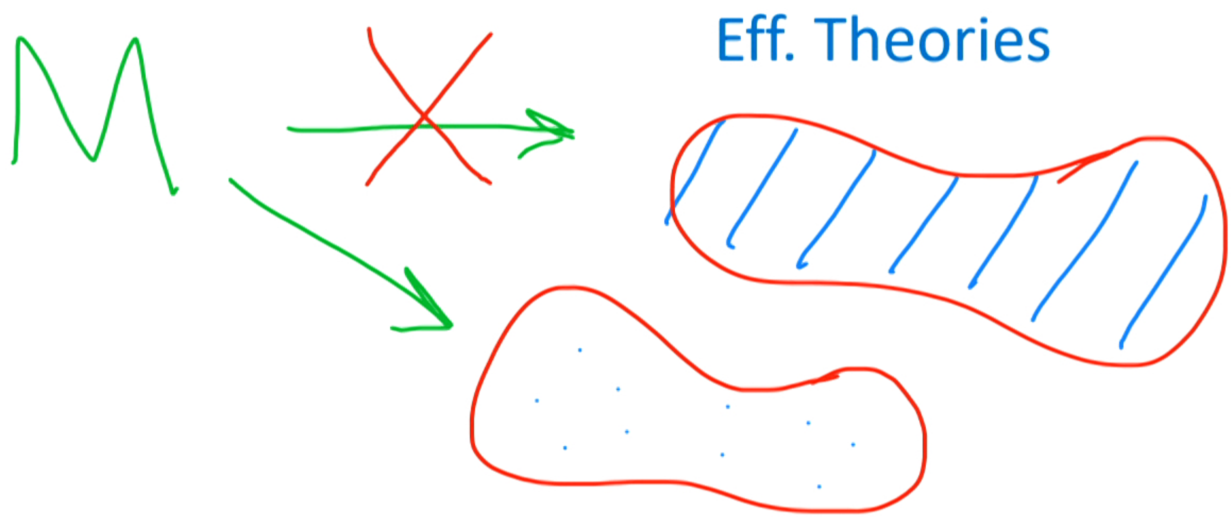
In string theory we construct vacua by going from higher dimensions (say 10,11,12) to lower dimensions by compactification: D—>d through a manifold M.

M ——————→ d-dimensional physics

Huge # of possible M's—> huge string landscape
Invert the map: Just start from any consistent looking effective theory in d dimensions and let string theorists worry about finding the M!

However we have learned this is not a correct picture:

Almost no consistent looking effective theory can be coupled to gravity consistently and belong to the String Swampland! The ones that can couple to gravity consistently are rare!



1-The only allowed continuous symmetries are gauge symmetries.

2-All gauge charges appear in the spectrum.

3-Finite range for fields.

4-The theory must admit light higher dimensional objects.

5-Gravity is always the weakest force:

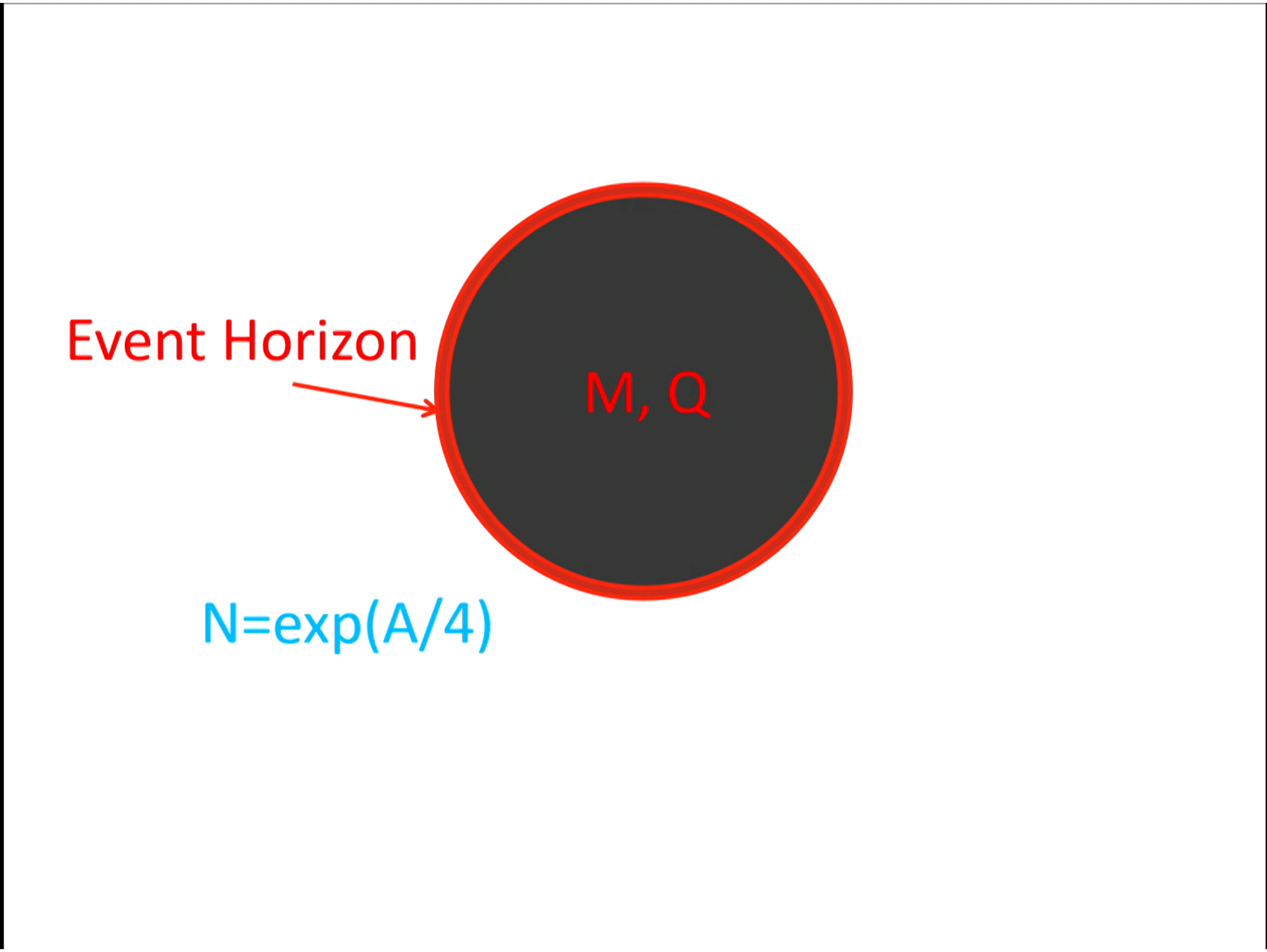
6-Consequences for cosmology

de Sitter space (and the fate of our universe)?

Some basic facts about black holes:

Fix a charge Q and a mass M. Then as long as M>Q there is a black hole. The extreme case M=Q can also occur (extremal black holes).

1-All black holes have an event horizon where if anything crosses, it cannot get out.
2-Black holes have thermodynamical properties (Bekenstein-Hawking). In particular they carry an entropy: $S=(A/4)$ where A is the area of the horizon


Event Horizon
M, Q
N=exp(A/4)

3-All black holes disappear by gradually emitting elementary particles (modulo some extremal cases in supersymmetric theories). After the gradual decay (`Hawking radiation') nothing is left and there is no imprint of the BH left.

Criterion 1: Only Gauge Symmetries

There are no global symmetries allowed. Suppose to the contrary there were: Then we could drop a particle carrying that global charge inside a black hole. The mass of the BH goes up, but nothing else changes: Since the charge is global, and not gauged, no electric field detectable outside horizon. BH evaporates—> leaving no trace of the charged object. Leads to violation of the global charge. (Approximate symmetry OK)

Criterion 2: All Charges in the Spectrum

Suppose we have a U(1) gauge symmetry. All integral charges Q are in principle allowed to exist. Are there such states in the theory for all charges?

Without gravity, apriori no reason. For example we can have a pure U(1) Maxwell theory with no charged states at all.

With gravity the story changes:

Pick a charge Q

Consider a BH with that charge

S=A/4 which implies there exist many states with charge Q!

Also: if we don't have all charges in the spectrum we end up getting extra global symmetries in conflict with criterion 1.

Criterion 3: Finite Range for Fields

Consider a field φ. Without gravity we usually have no restriction on its range:

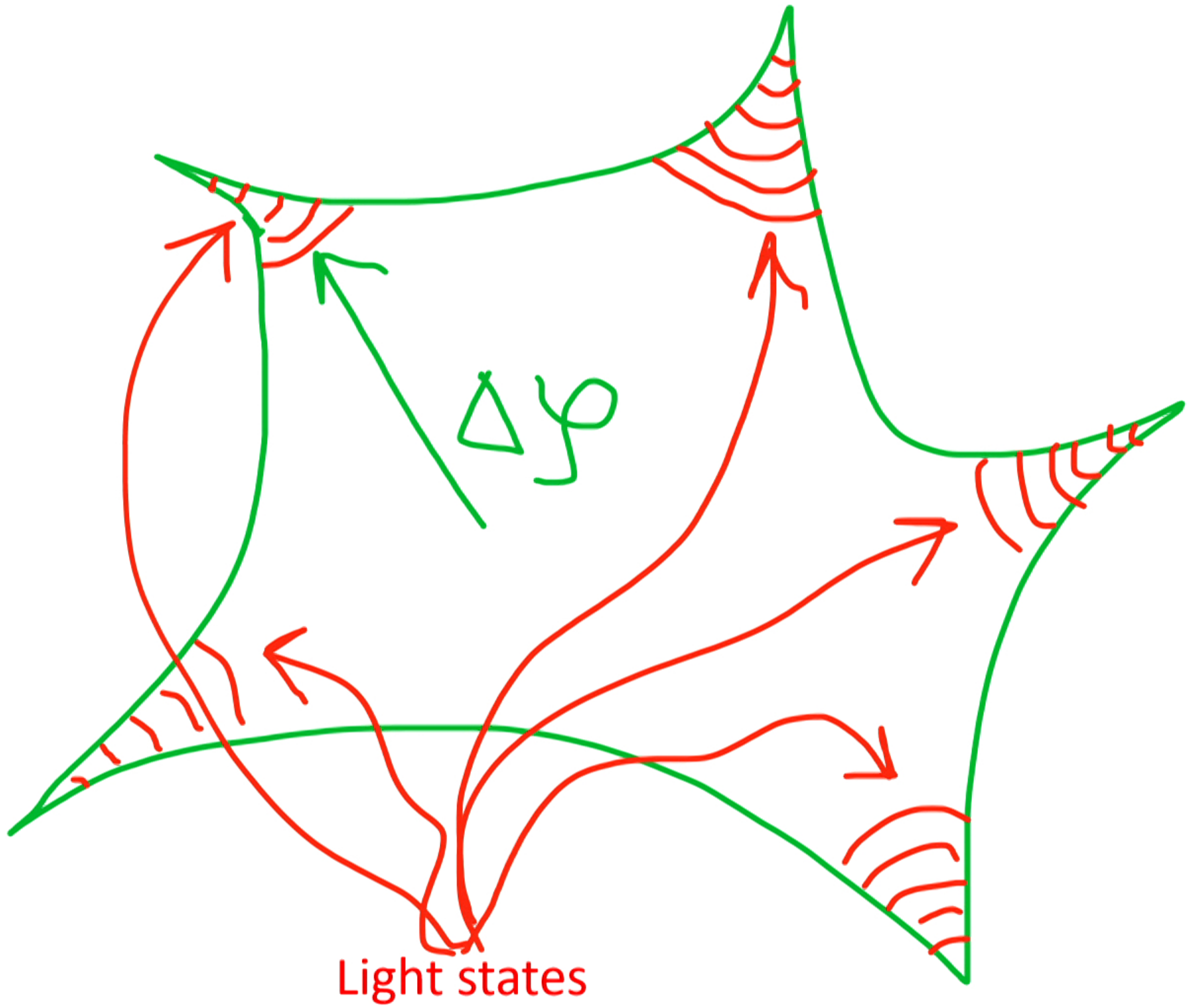
$$-\infty < \varphi < +\infty$$

However with gravity it seems the range of this field for a given effective description cannot be any bigger than Planck scale:

$$|\Delta\varphi| < M_p$$

We do not have a deep explanation of this fact but it is observed in all examples of string compactifications that it is the case: If you try to increase the range beyond Planck range some new light states emerge, invalidating the effective field theory.

$$m \sim e^{-\alpha \frac{|\Delta\varphi|}{Mp}}$$


Δφ
Light states

Criterion 4: Extended Objects

There must be light extended objects in any theory of quantum gravity (like M-theory membrane or strings in string theory). This also follows (at least heuristically) from the previous criterion:

Consider compactifying the theory on a circle of radius $R = e^{\varphi}$

$$L = \frac{1}{2}(\partial\varphi)^2$$

$$R \gg 1 \rightarrow \varphi \gg 0$$

Indeed as $\varphi \geq 1$ we begin to get light KK modes (momentum modes around circle become light) and so the effective field theory ignoring these modes is not reliable. This is consistent with the fields having a finite range. However we can go the other way: $\varphi \ll 0$. The general principle predicts something should become light.

$R \to 0$ some light states must appear. But how is that possible? KK modes are becoming heavier.

The only natural mechanism for this to happen is if we have extended objects like string or membranes which can wrap the circle and as the circle becomes small they become light!

Criterion 5: Gravity as the Weakest Force

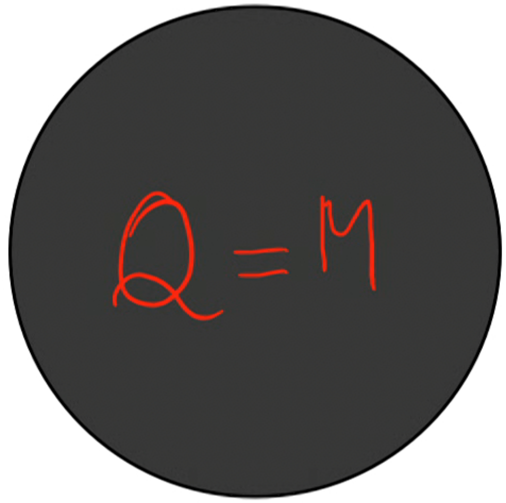
In string compactifications it has been observed that whenever we have charged particles, the electric force between the elementary charged states are stronger than their gravitational attraction (true for our universe):

$$F_e = \frac{e^2}{r^2}$$

$$F_g = \frac{m^2}{r^2}$$

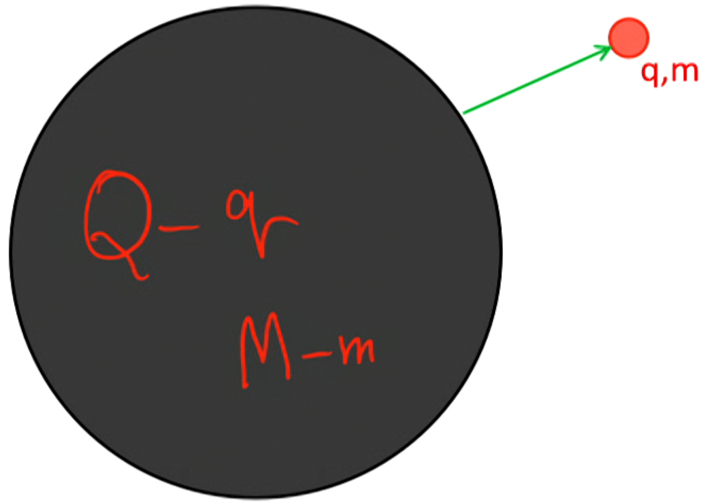
$$m \leq e$$

Black Hole Explantion of WGC:



Undergoes Hawking Radiation

Black Hole Explantion of WGC:



$$Q - q < M - m \quad , \quad Q = M$$

$$\Longrightarrow \quad m < q$$

m=q can only occur for susy case (BPS states)

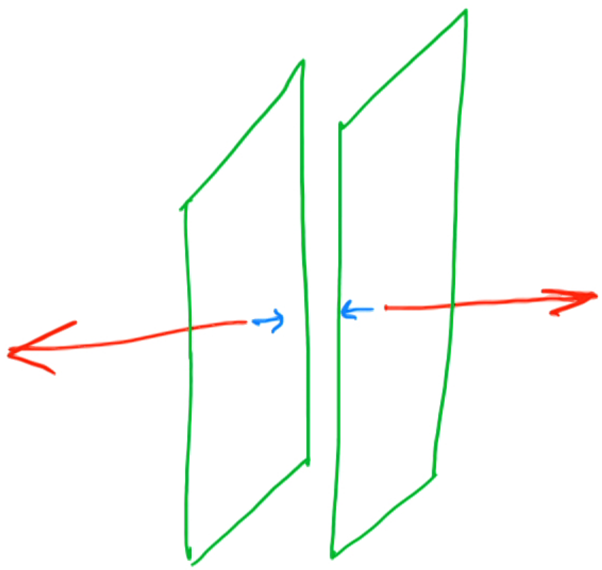
Further evidence of WGC:

Pure Maxwell theory coupled to gravity violates cosmic censorship: For sufficiently strong electric fields we find naked singularities which are not surrounded by a horizon as follows from CCC.

Resolution: There must be charged particles whose charge is less than its mass (WGC), so when electric field is strong enough it creates charged particles which gets rid of singularity!

Extension of WGC from particles to membranes:

Attractive gravitational force between membranes is weaker than electric replusion:



This suggests that (except in the SUSY case where they are exactly equal) the membranes will not be holding together. These would have typically led to AdS. No non-supersymmetric AdS is stable!

If we consider compactification of our universe on a circle we end up getting AdS for some range of masses/types of neutrinos. Since this is not allowed it implies a restriction on allowed neutrino masses/types!

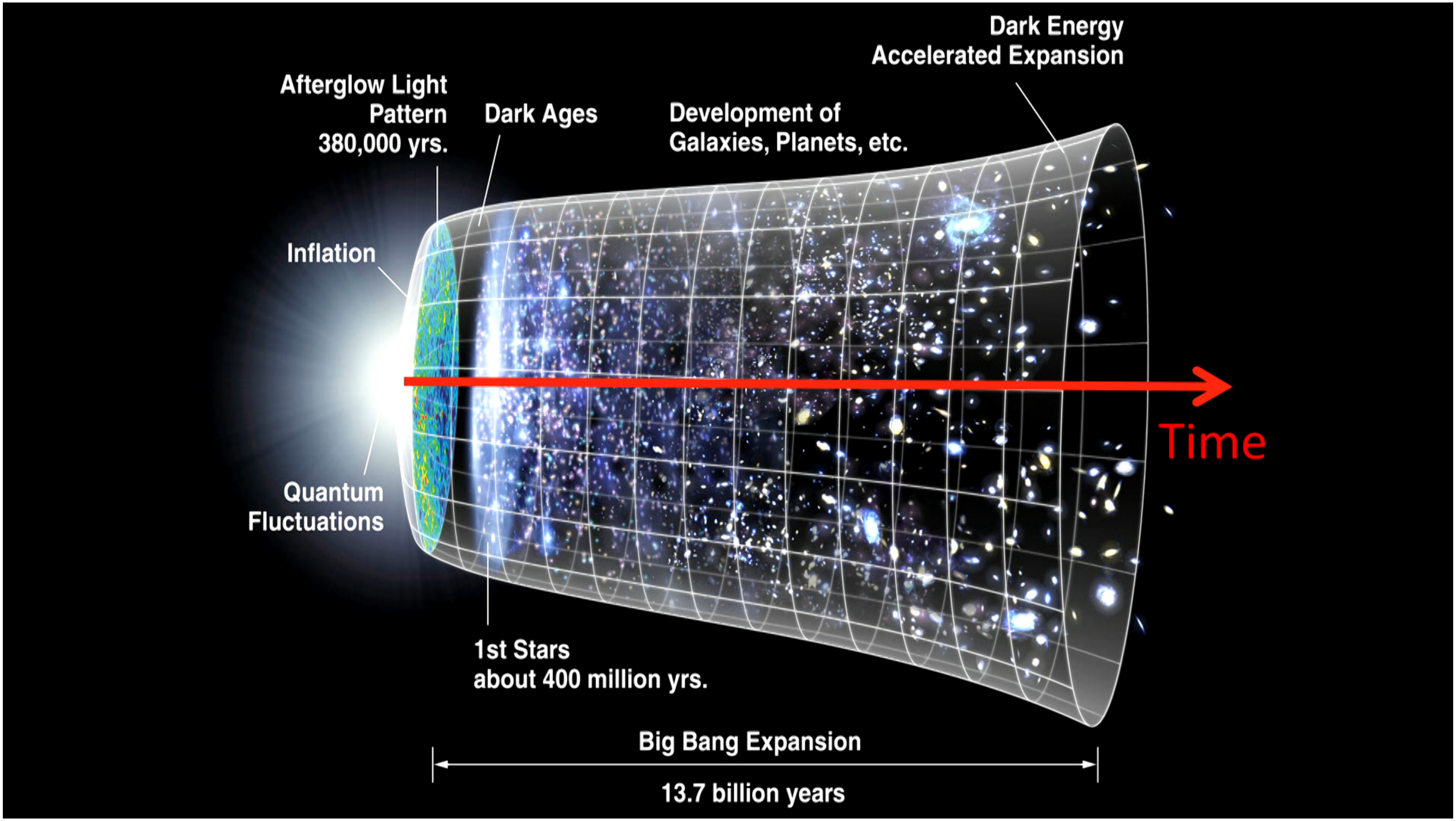
Ibanez et.al. have extended this to explain why the weak scale cannot be too high:

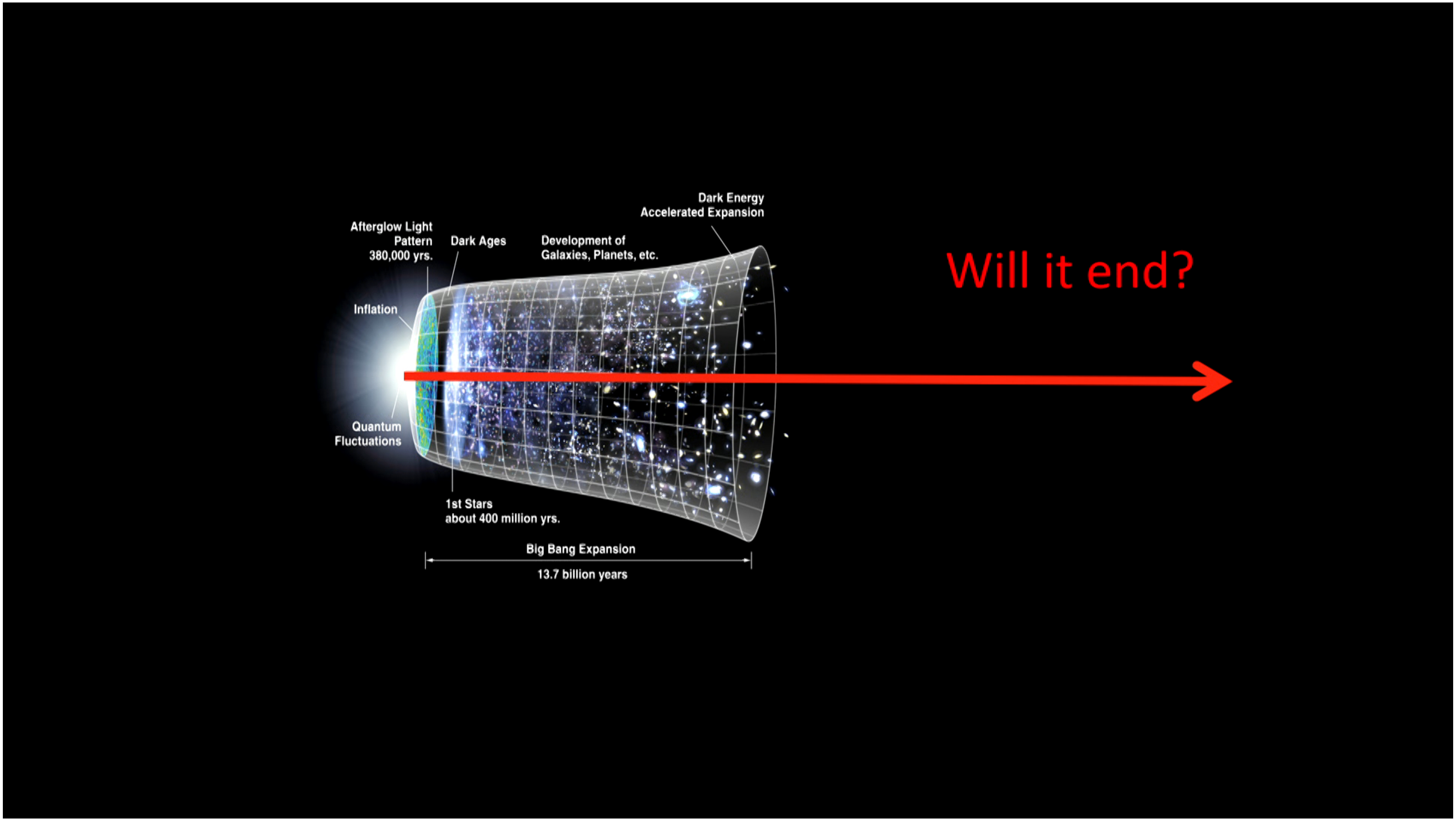
$$M_W \lesssim 10^{2-4}\ \text{GeV}$$

Providing a partial explanation of hierarchy from WGC!

6-Swampland and Cosmology?

Can we learn anything about cosmological questions from swampland idea?


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Time
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years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Big Bang Expansion
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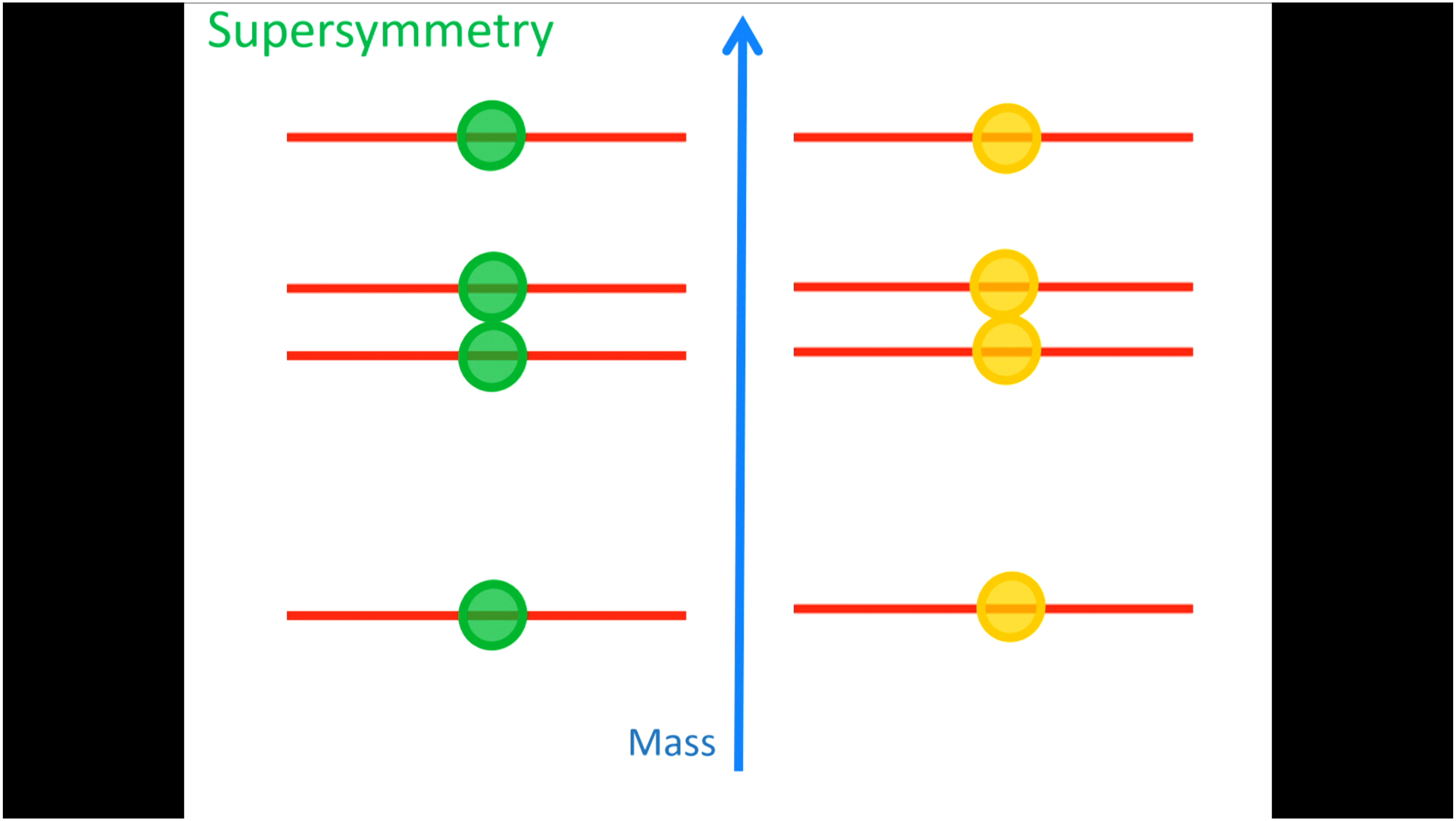
Will it end?

String theory landscape:

The only universes that last forever have a special property called supersymmetry.

All the other universes which could have conceivably lasted forever seem to belong to the swampland!


Supersymmetry
Mass

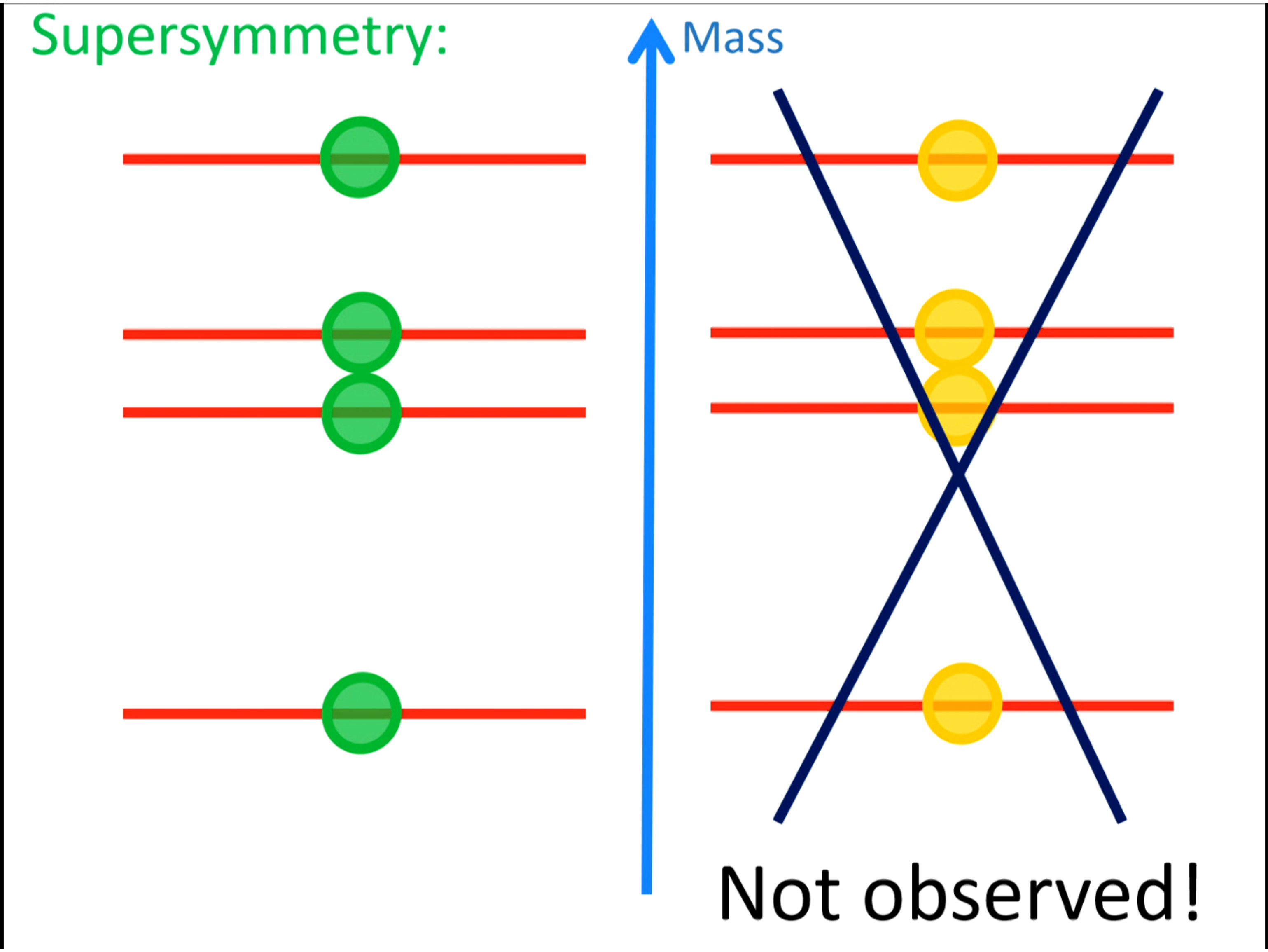
For supersymmetric case:

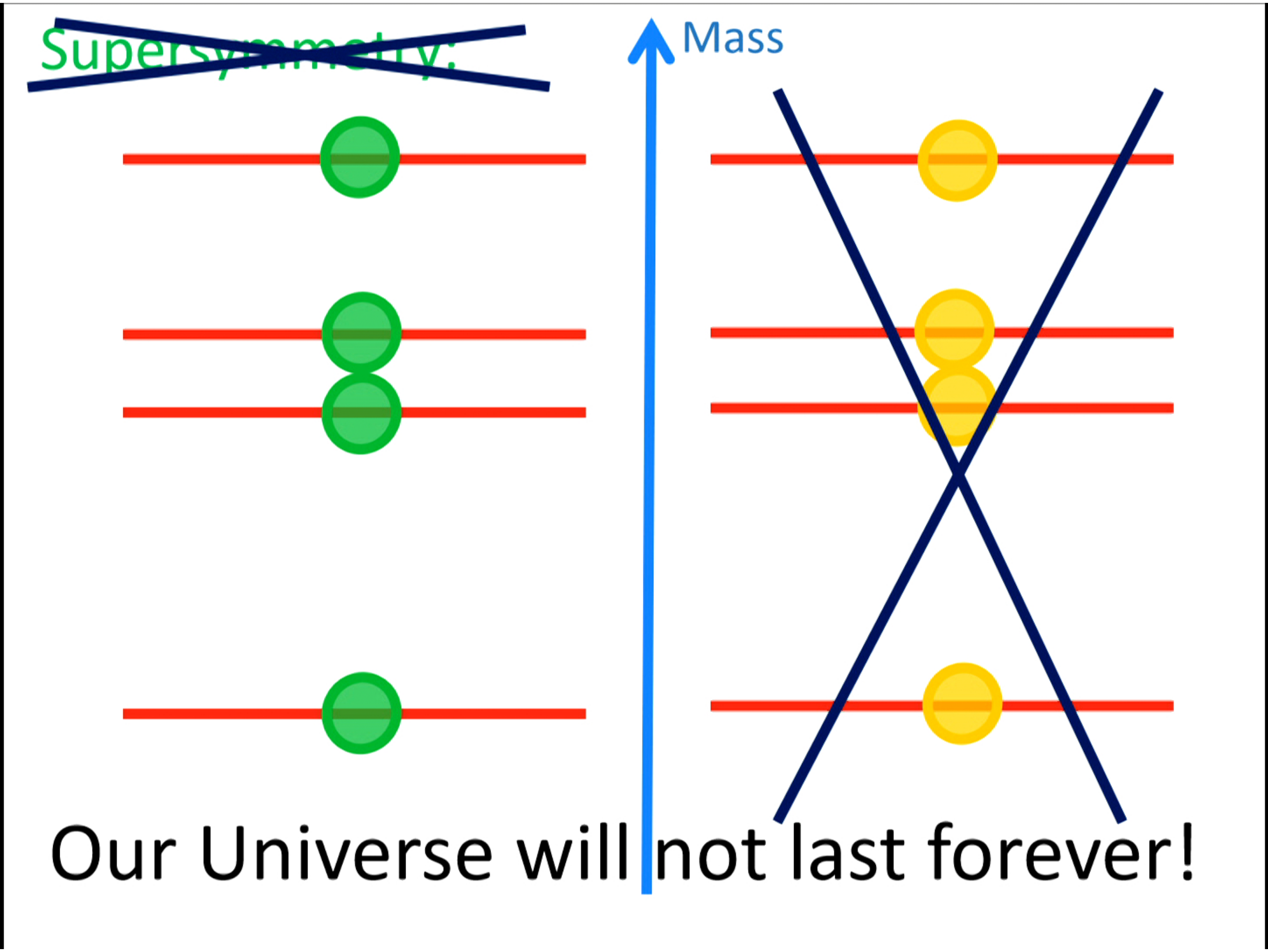
We have learned quite a bit about supersymmetric compactifications of string theory.

The allowed solutions for non-compact space are of two types:

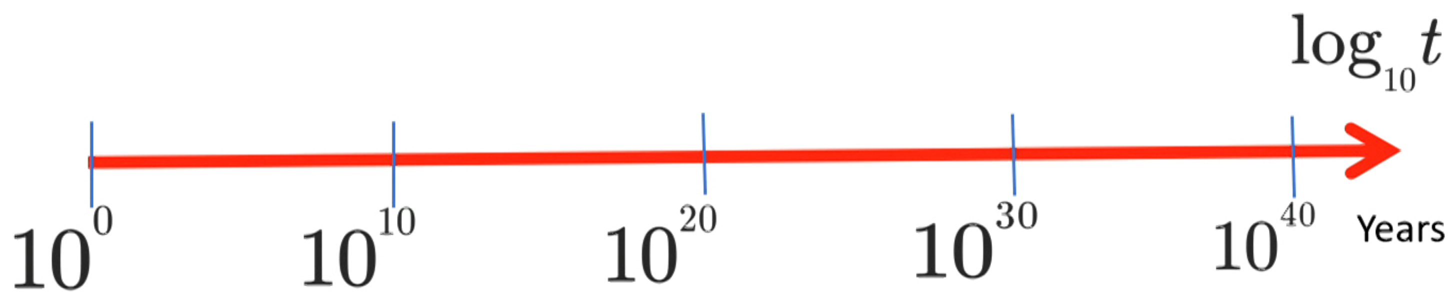
Minkowski—With 0 cosmological constant.

AdS—With negative cosmological constant.
Many absolutely stable. No stable solution known without SUSY. No SUSY dS solutions.


Supersymmetry:
Mass
Not observed!


Supersymmetry:
Mass
Our Universe will not last forever!

How long do we have?

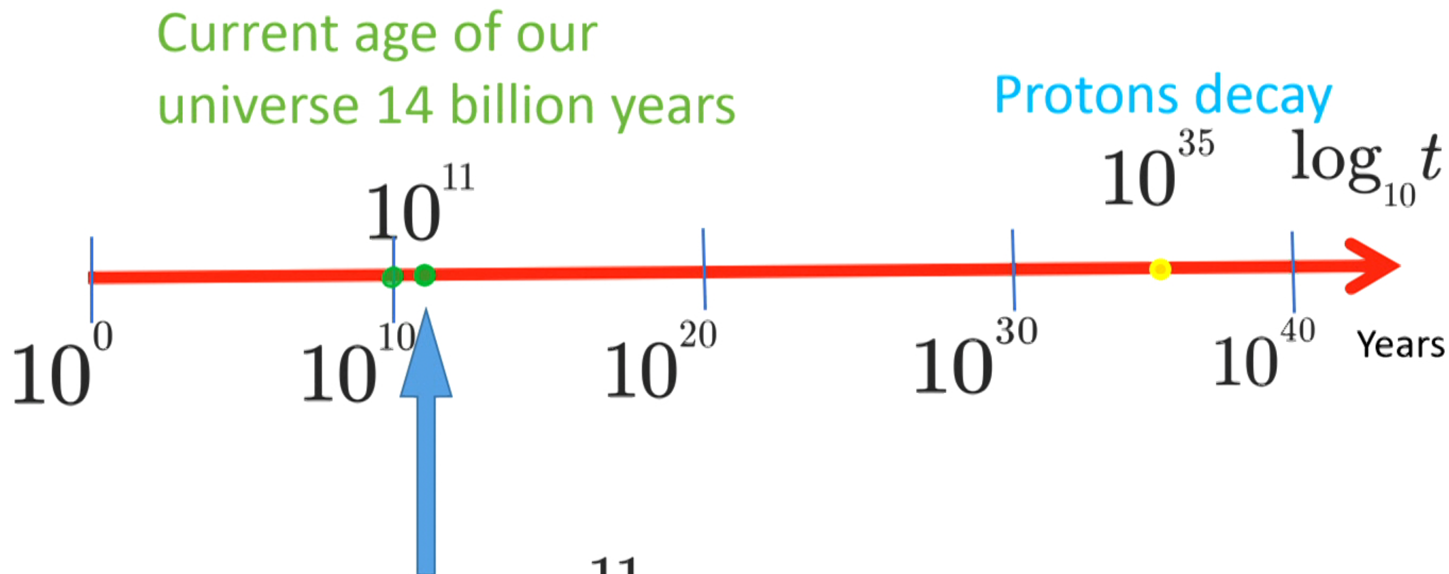


Our universe has dark energy.

Dark Energy, leads to a natural time scale:

$$t_{\wedge} = \frac{1}{\sqrt{\Lambda}}$$

How long do we have?



$$t_\Lambda = 10^{11}$$

About 100 billion years!

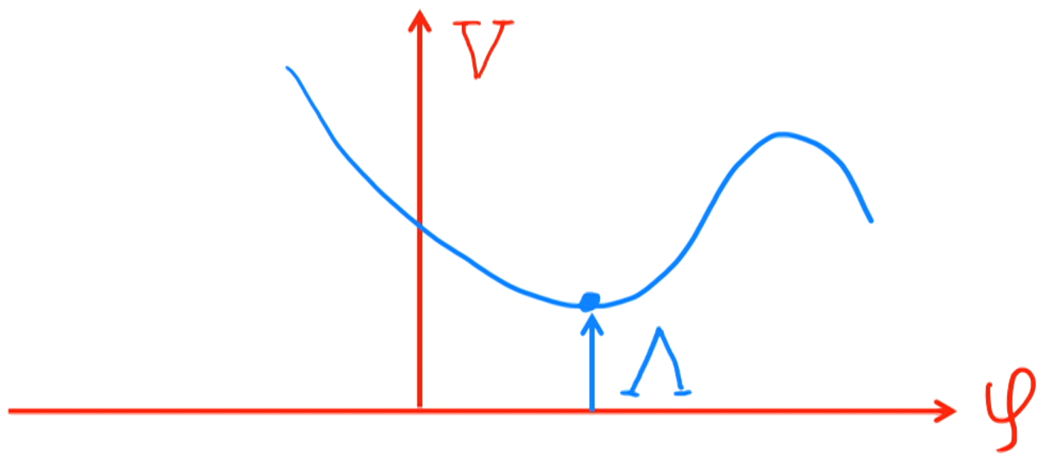
Is this a coincidence?!

How about non-susy dS?

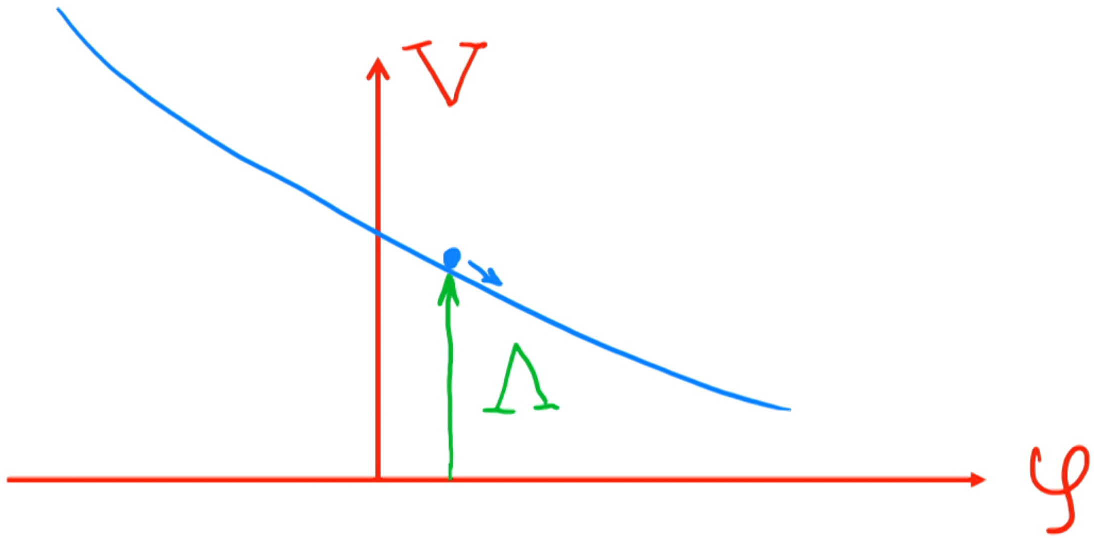
Why care about dS?

Because we think we may live in one!

$$\Lambda > 0$$



Why not rolling scalar potentials (quintessence)?



The scalar would typically couple to some matter fields and its rolling would lead to observable effects. But, e.g., from z=1 till now

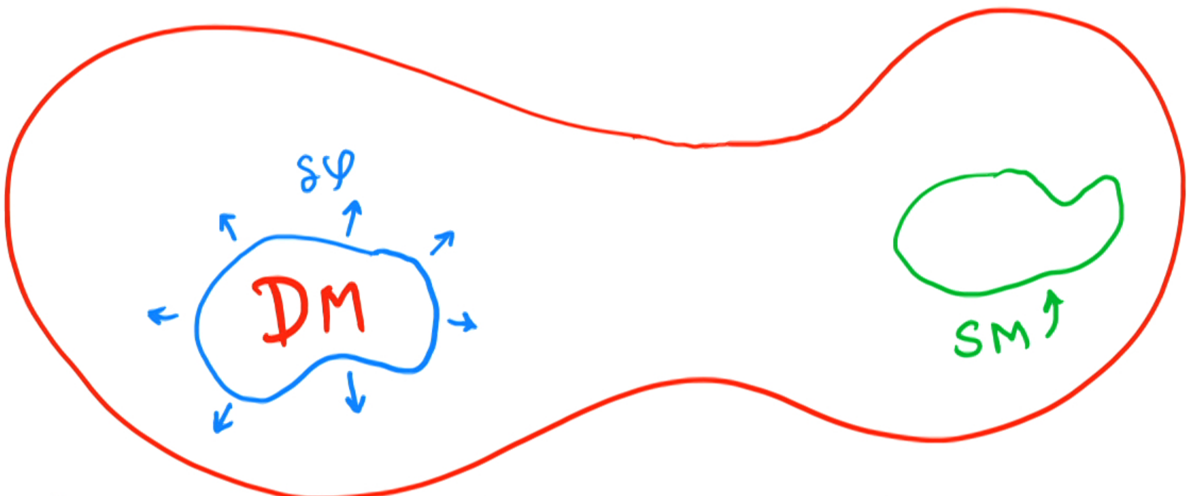
$$\frac{\delta\alpha}{\alpha} < 10^{-6}$$

Also the coupling of the scalar field to matter would give rise to a new `fifth force' which would be detectable at astrophysical distance. The idea that the scalar field should couple to something is natural in string theory.
The fifth force would lead to apparent violations of equivalence principle.

The existence of fifth force is strongly bounded based on astrophysical observations, making this rather implausible.

Not a good argument:

The scalar field should couple strongly to SOME fields but not necessarily visible matter fields making their detection more difficult:



The scalar field could couple more strongly to DM.
The rolling scalar anticipates DM and can be part of it.

But there is another strange feature of quintessence models:

Not only
(in Planck units)

$$V \sim 10^{-122}$$

But also for the quintessence models not to be in contradiction with observational bounds on w we need

$$|\nabla V| \leq 10^{-122}$$

Sounds like double fine tuning unless we can naturally have $|\nabla V| \approx V$

1-The dS Swampland Conjecture

2-TransPlanckian Censorship Conjecture;

-A new swampland condition:

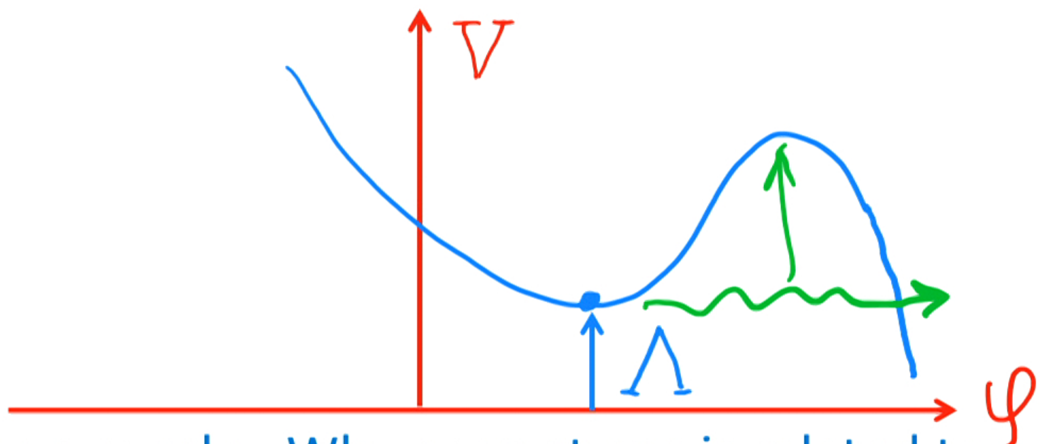
Lower bound $|\nabla V| \geq cV$ for c>0

-TCC: Sub-Planckian quantum fluctuations should remain quantum

$$\frac{a_f}{a_i} < \frac{1}{H_f}$$

Future

If we lived in dS space, the lifetime of the universe, before there is a phase transition can be arbitrarily large and typically has nothing to do with the time scale set by the dark energy:



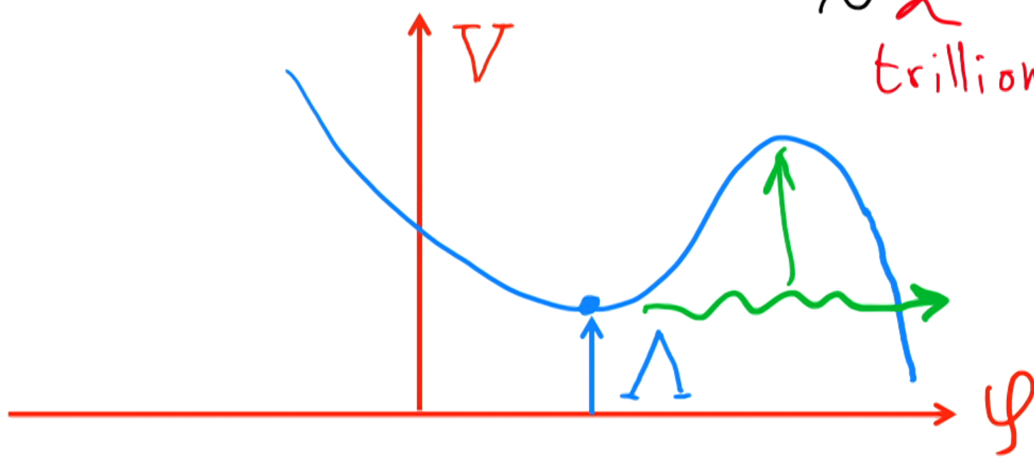
This leaves a puzzle: Why current age is related to

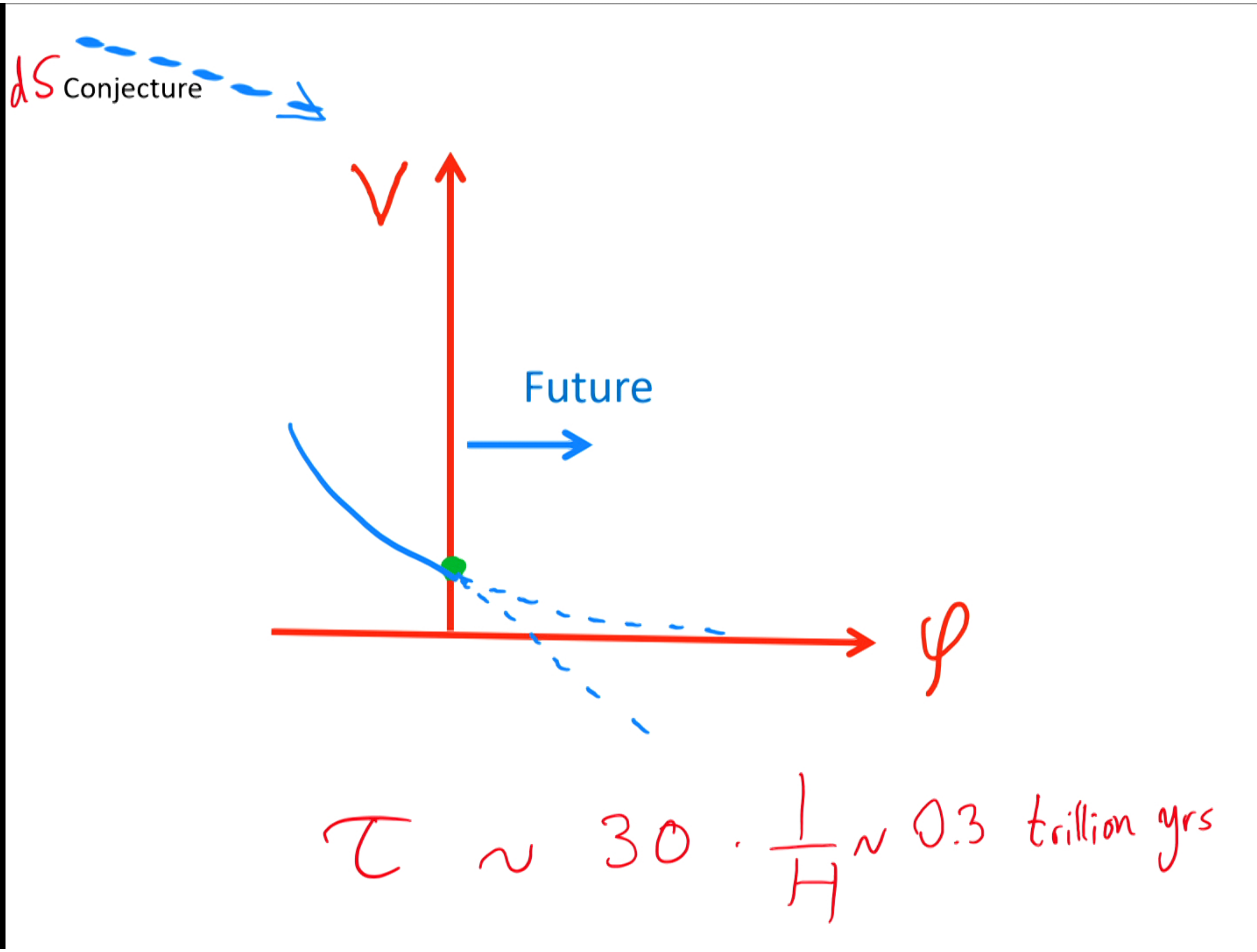
$\tau \sim H^{-1} \sim 1/\sqrt{\Lambda}$?

Future

$$\text{TCC} \rightarrow \tau \lesssim \frac{1}{H} \log \frac{1}{H}$$

~ 2 trillion yrs




dS Conjecture
V
Future
φ
τ ~ 30 · 1/H ~ 0.3 trillion yrs

Early Universe

Either Conjecture has tensions with inflation:

The dS slope conjecture and field range bound makes inflation at least fine tuned.

The TCC conjecture would not allow high scale inflation. V is less than $(10^9 \text{GeV})^4$ and again its initial conditions should be highly fine tuned.

We should look for stringy alternatives to inflation.

Conclusion

The swampland ideas are beginning to be sharpened, extended and better understood.

They define some universal properties of consistent quantum gravitational theories.

They could have dramatic implications about our universe.