

The background of the slide is a deep space image filled with numerous galaxies and star clusters, appearing as bright yellow and white points of light against a dark blue and black sky. A thick, hand-drawn blue line meanders across the slide, starting from the top left, looping around the title, and extending towards the bottom right.

String Theory Landscape And The Swampland

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Harvard University

March 8, 2018

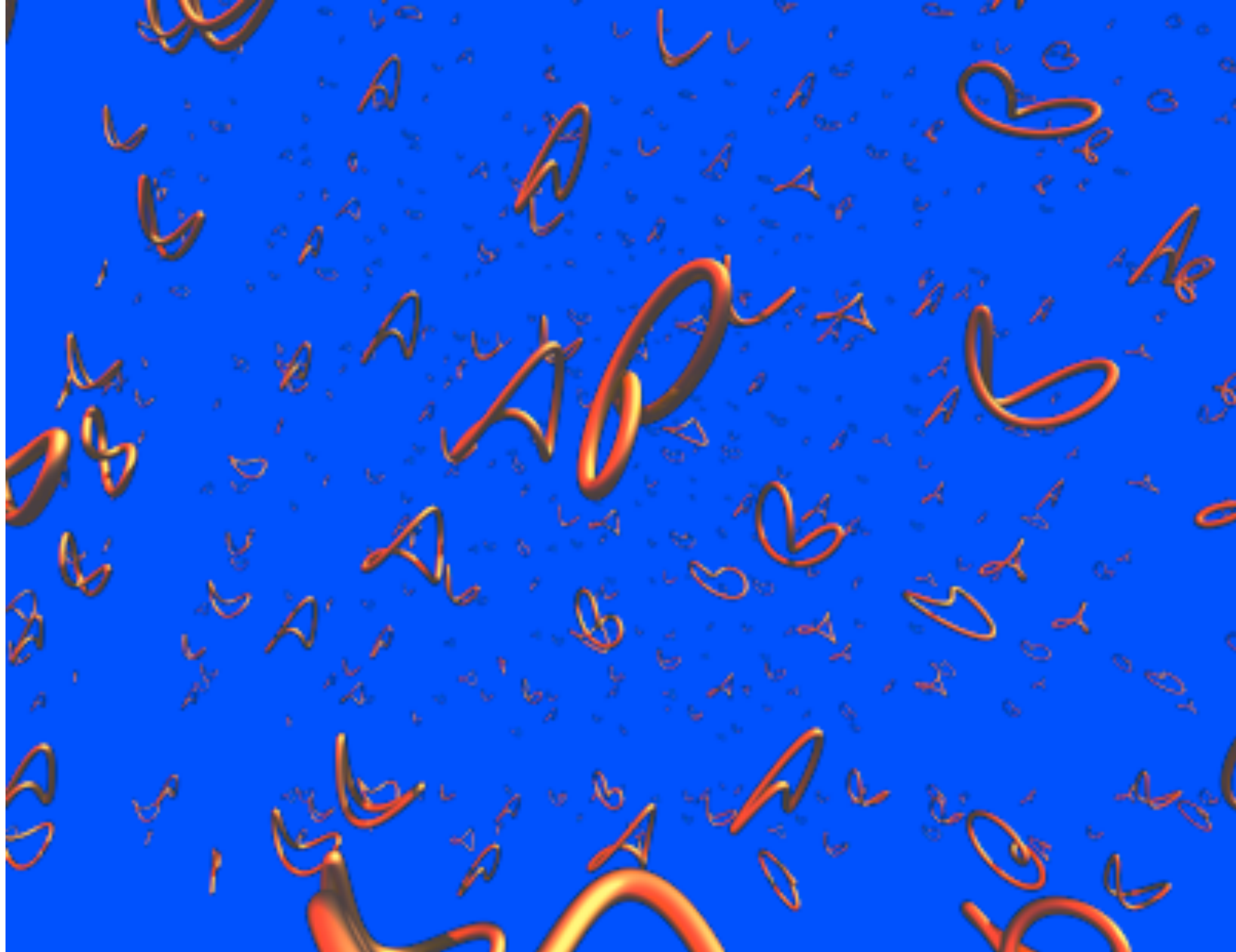
String Theory:

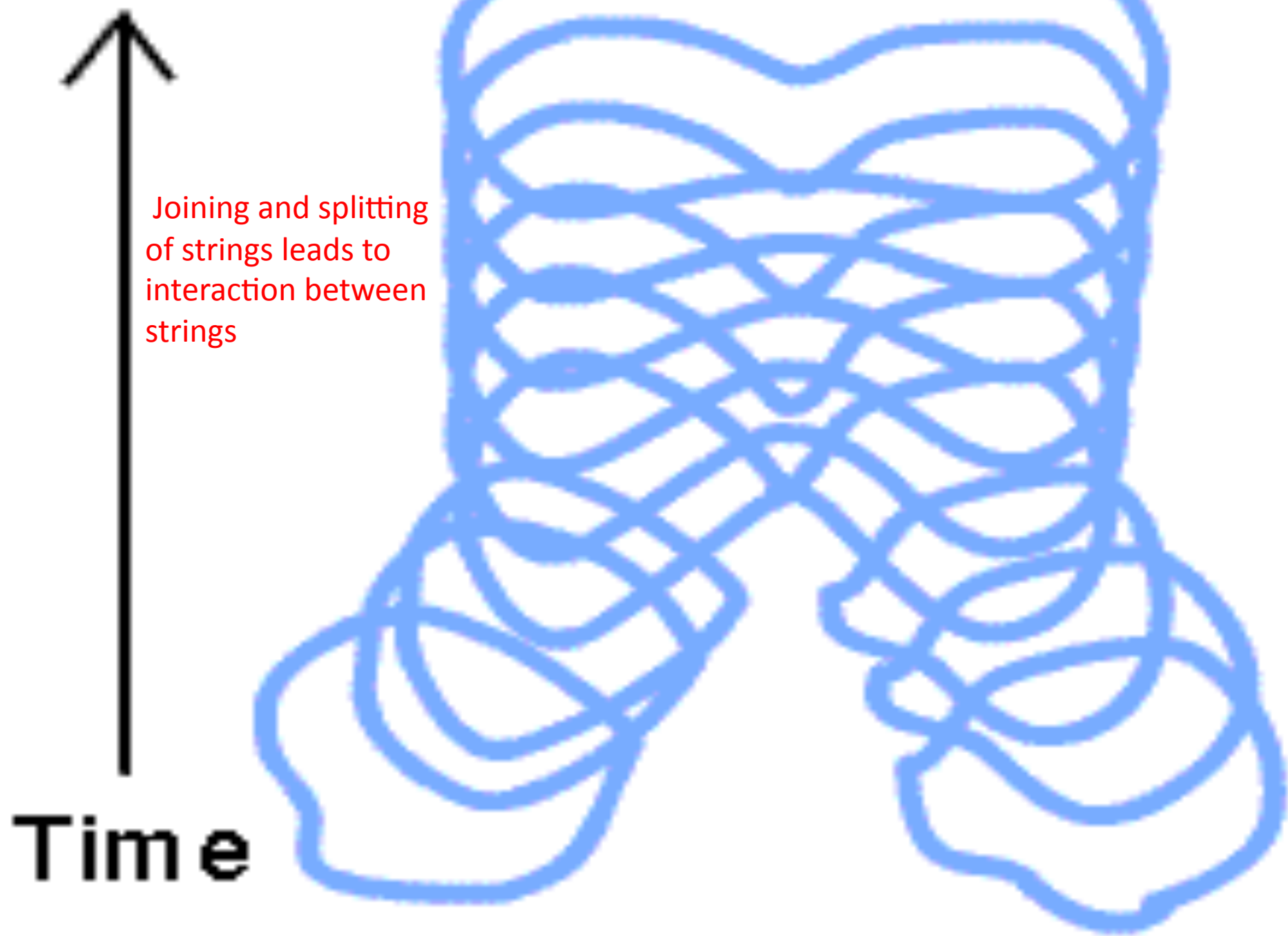
A consistent framework which unifies quantum theory and Einstein's theory of gravity—a highly non-trivial accomplishment!

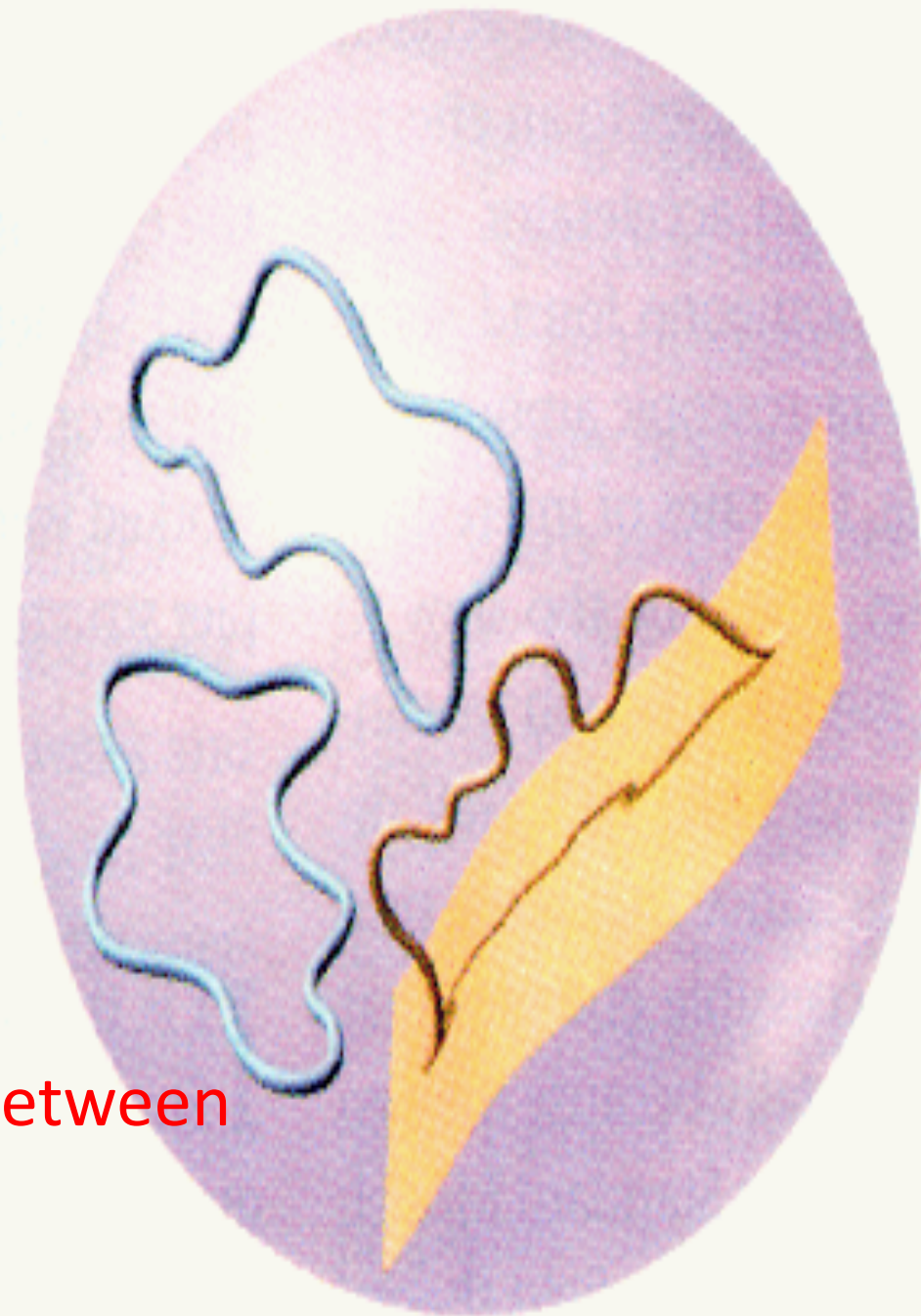




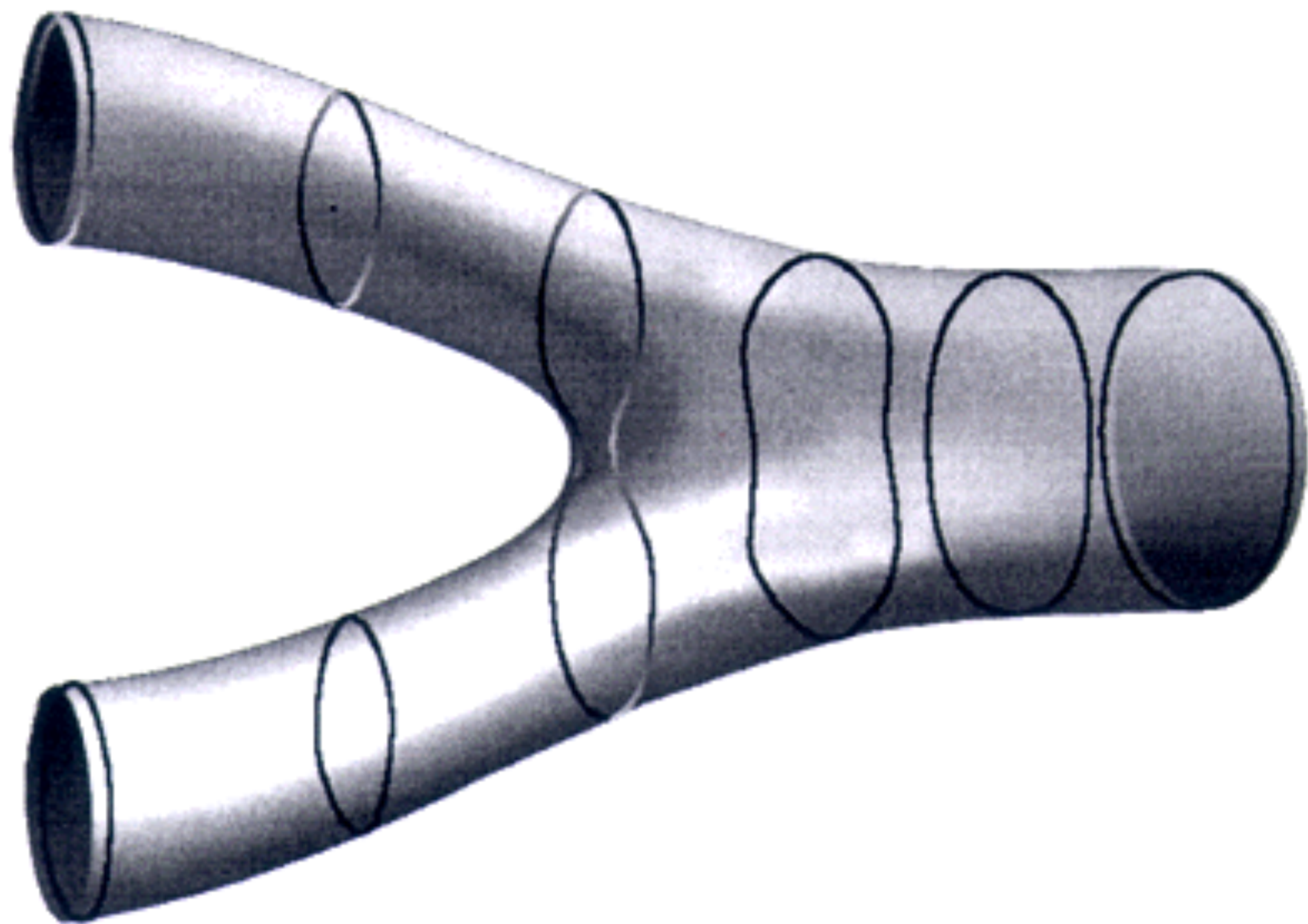








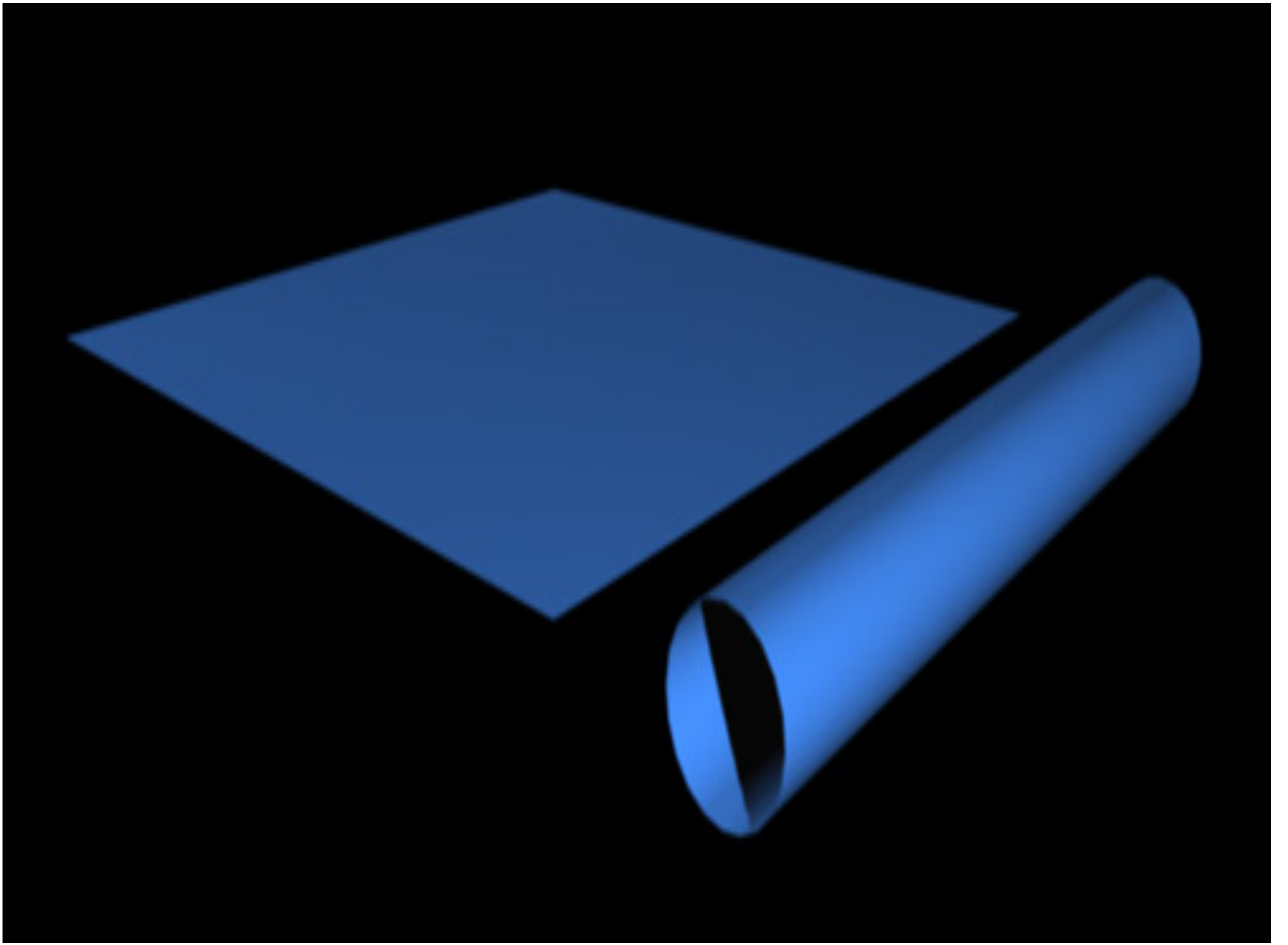
Resolves the inconsistency between
quantum theory and gravity

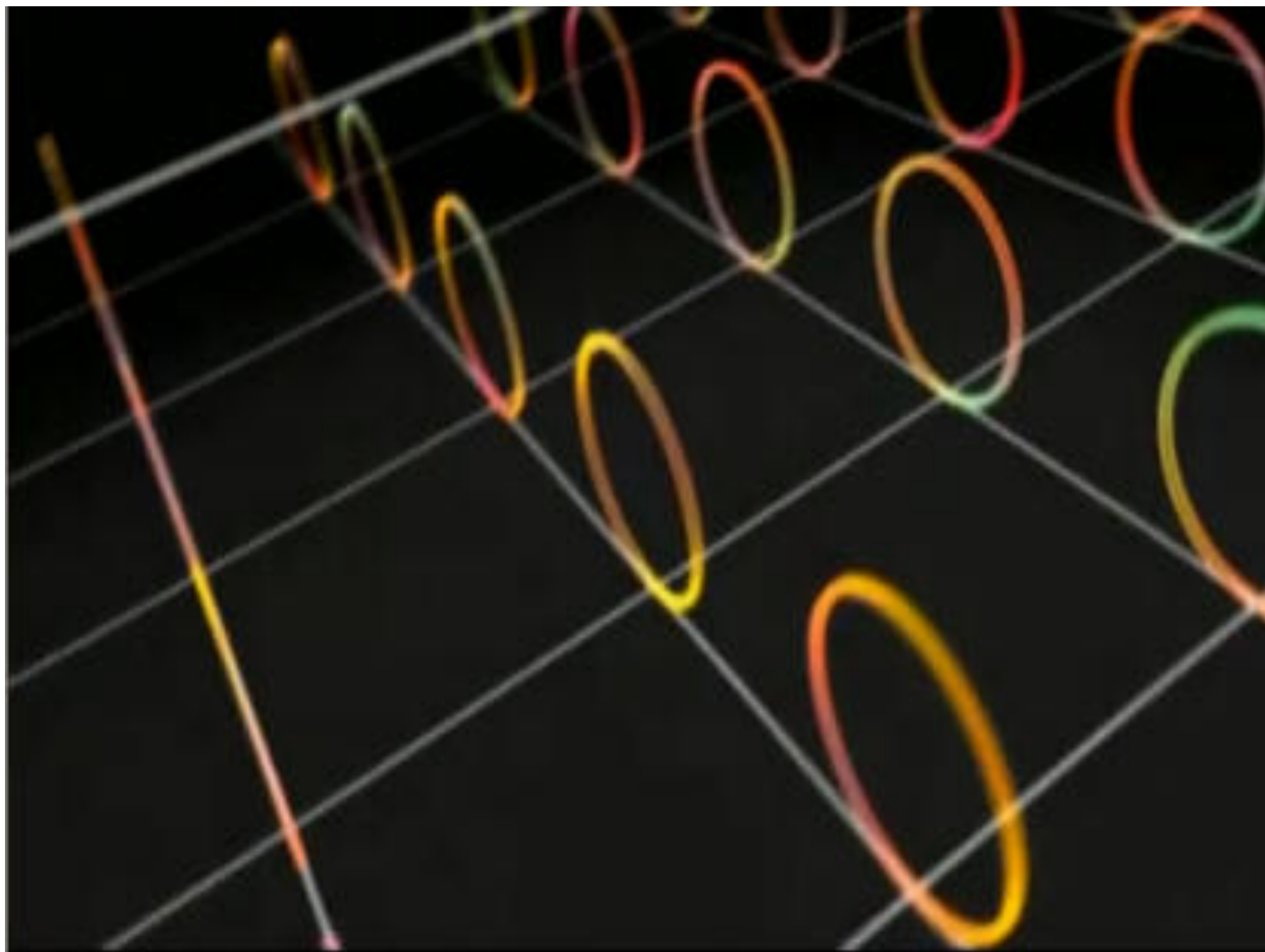


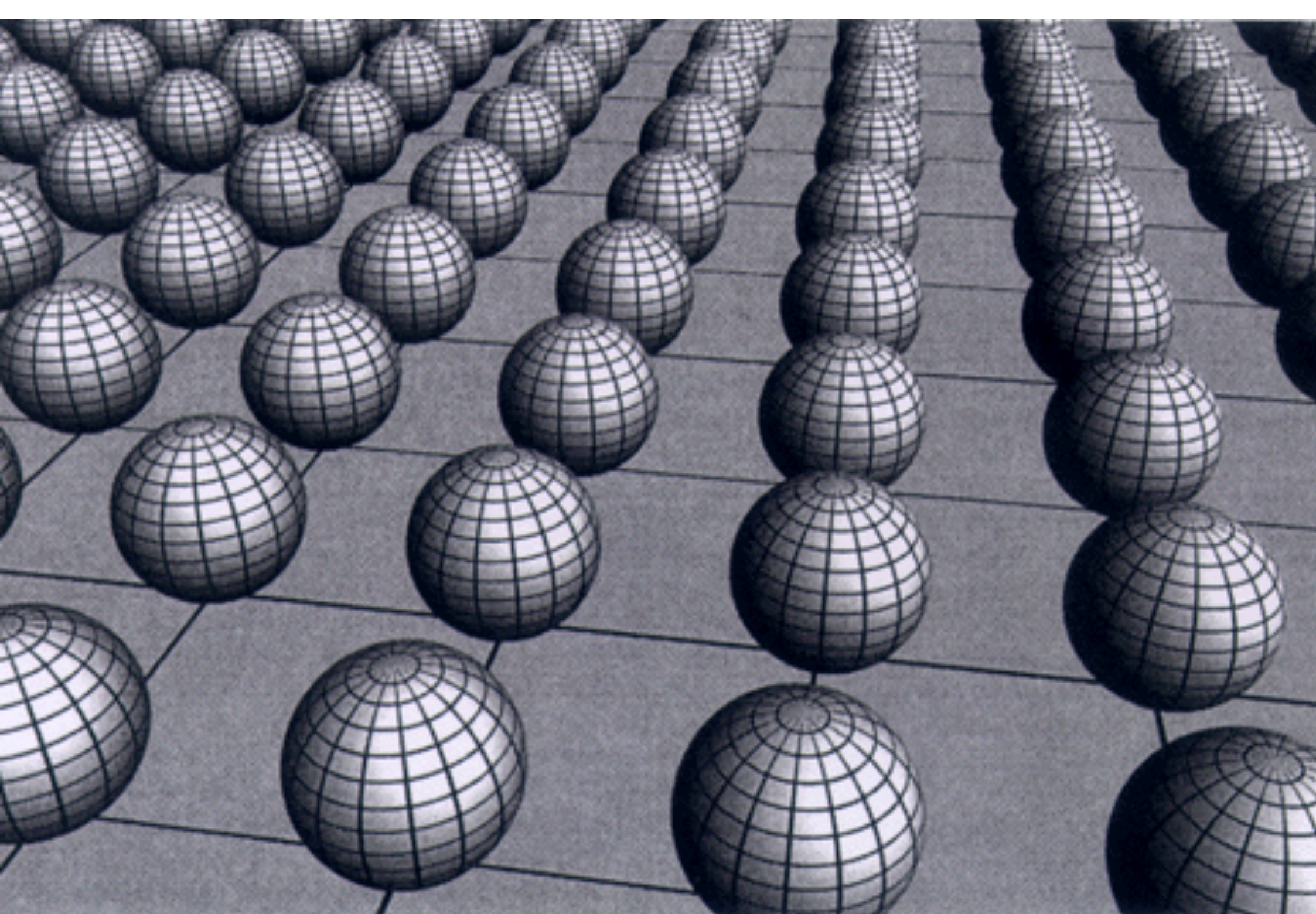
Extra Dimensions

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

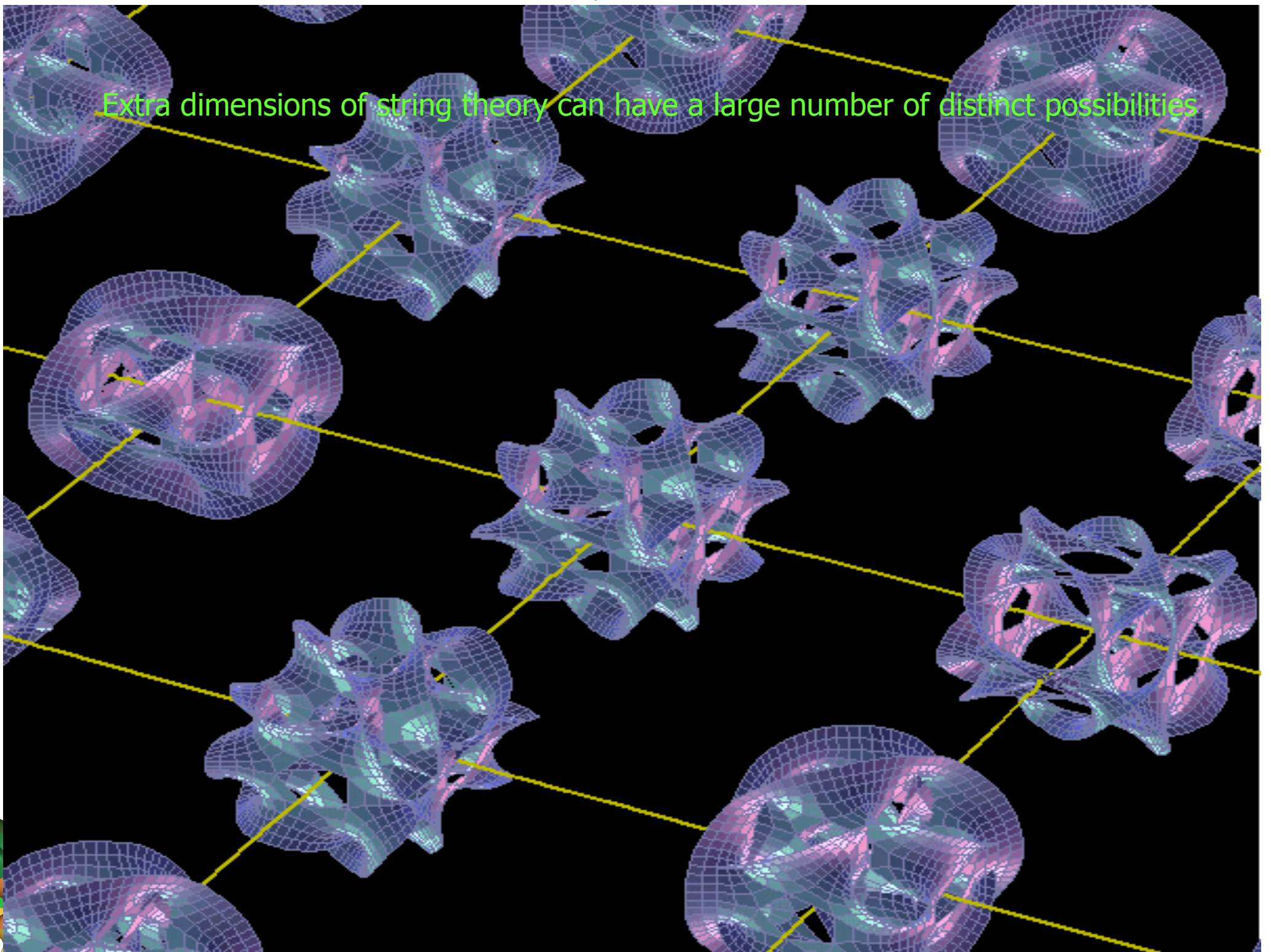
These must be tiny to avoid experimental detection to date.

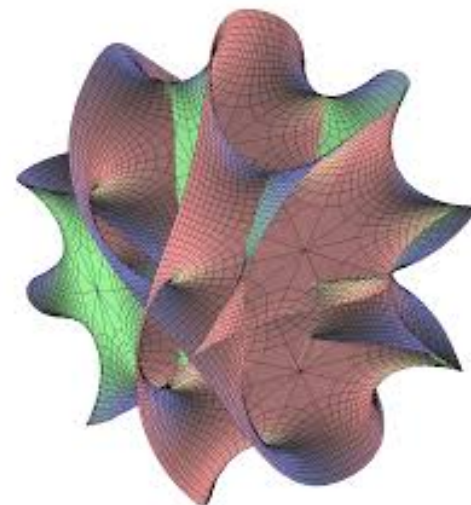
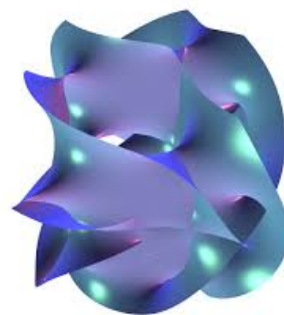
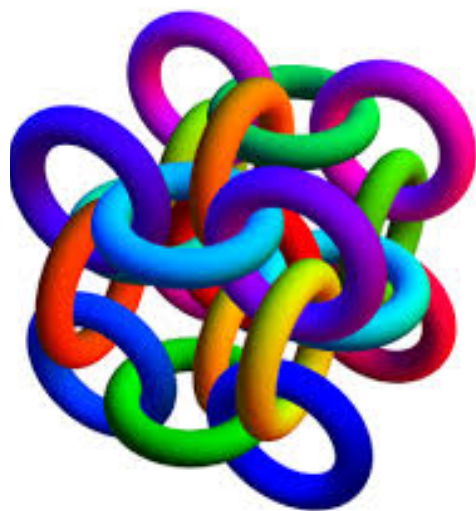
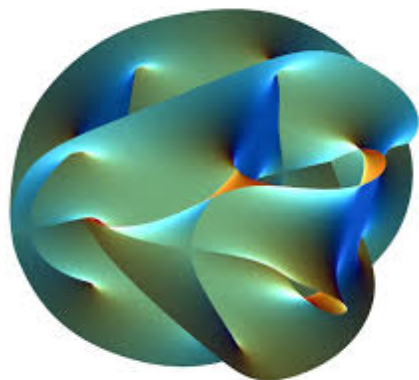
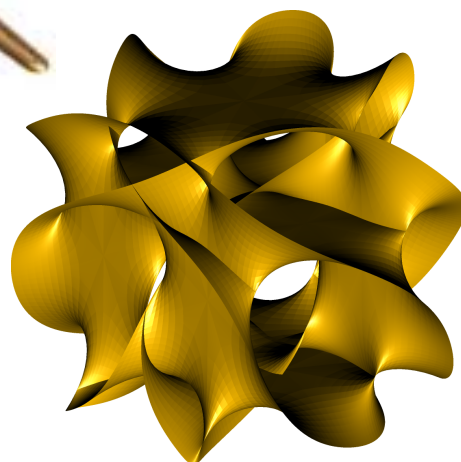
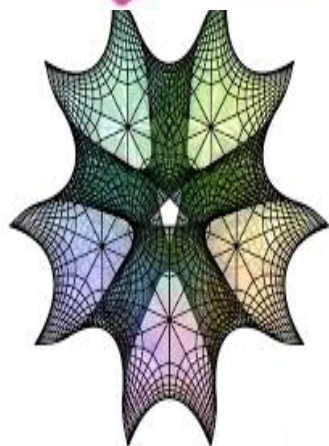
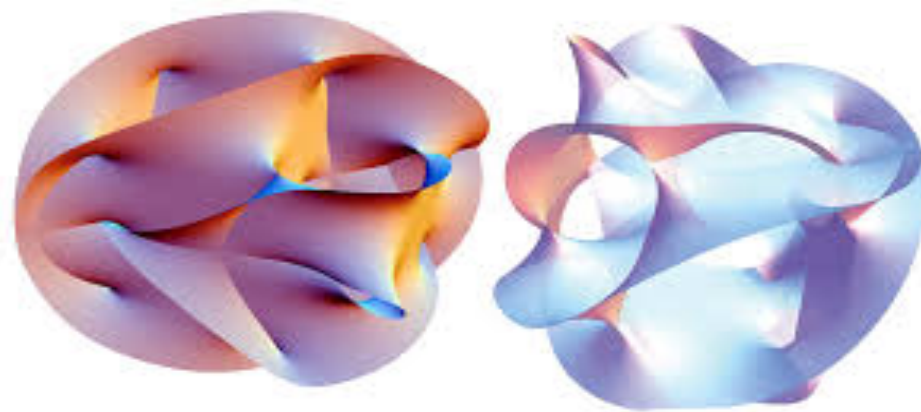


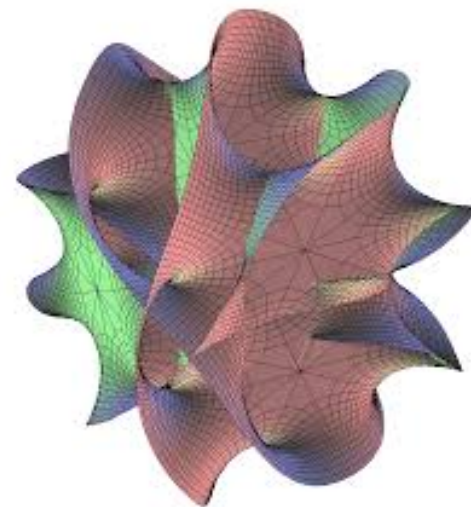
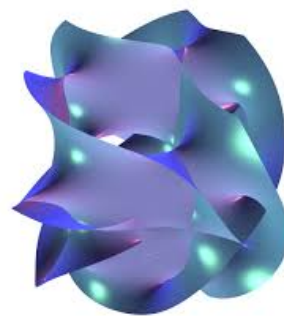
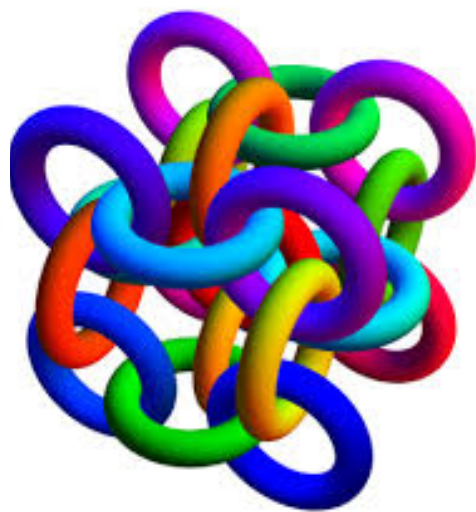
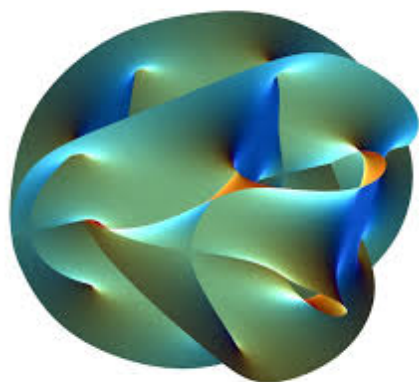
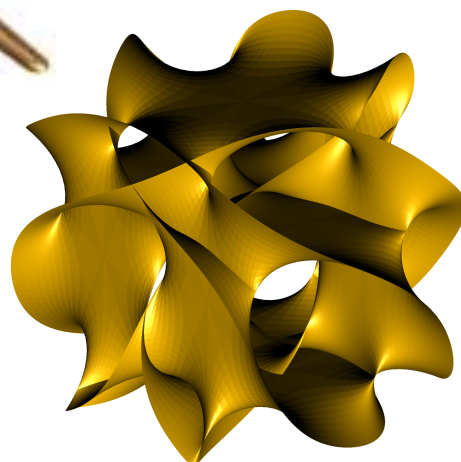
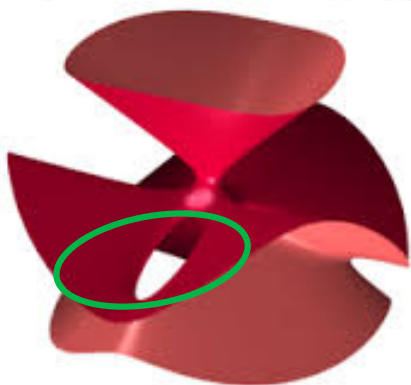
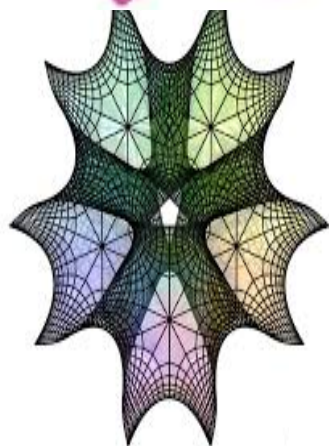
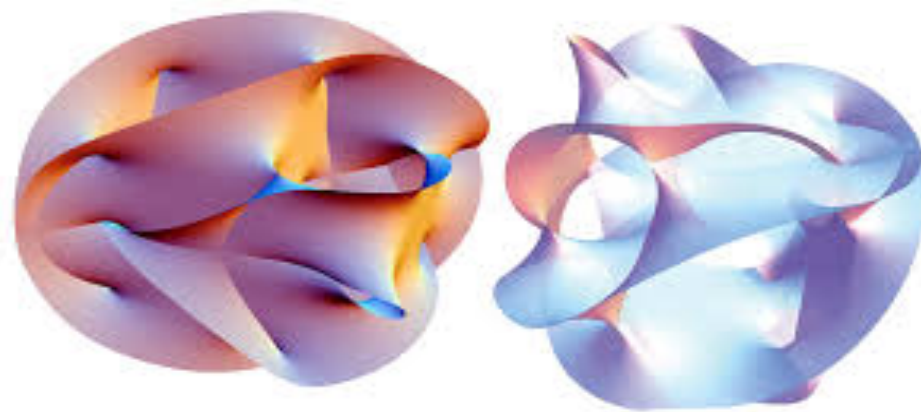


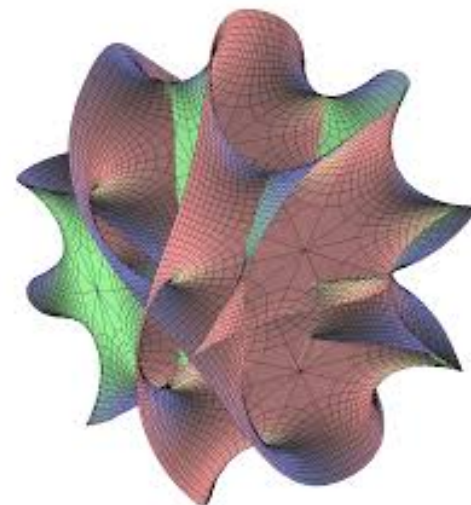
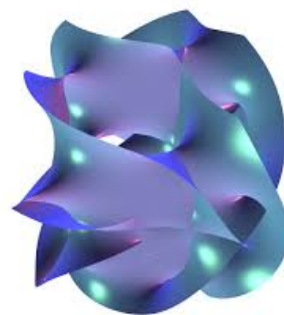
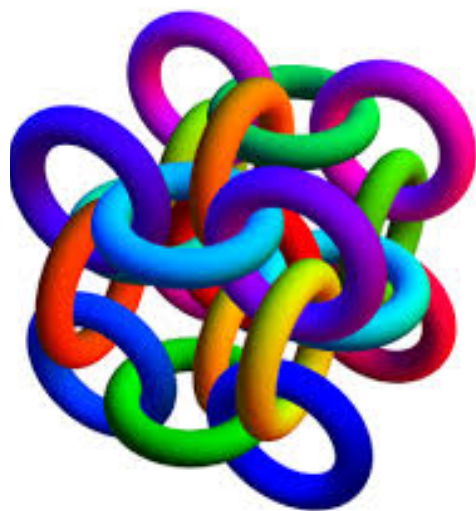
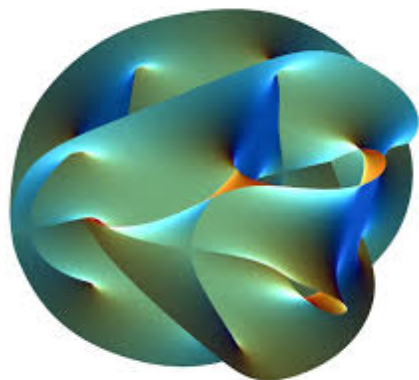
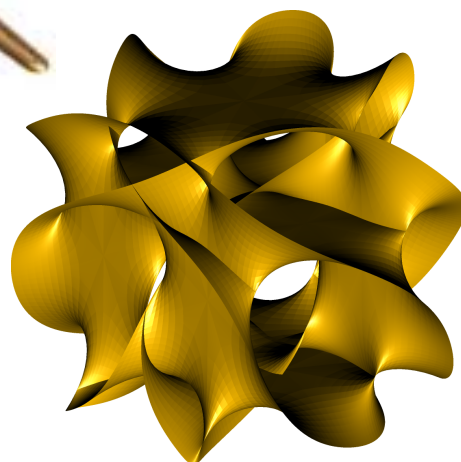
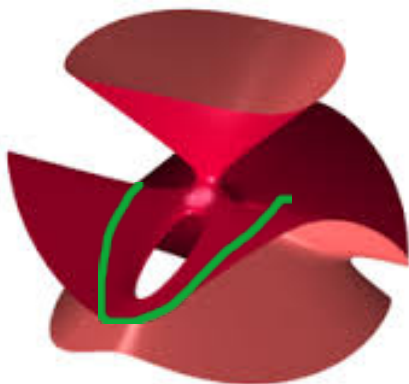
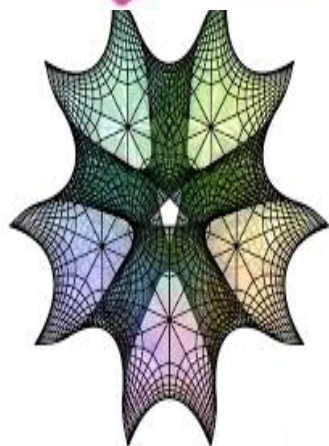
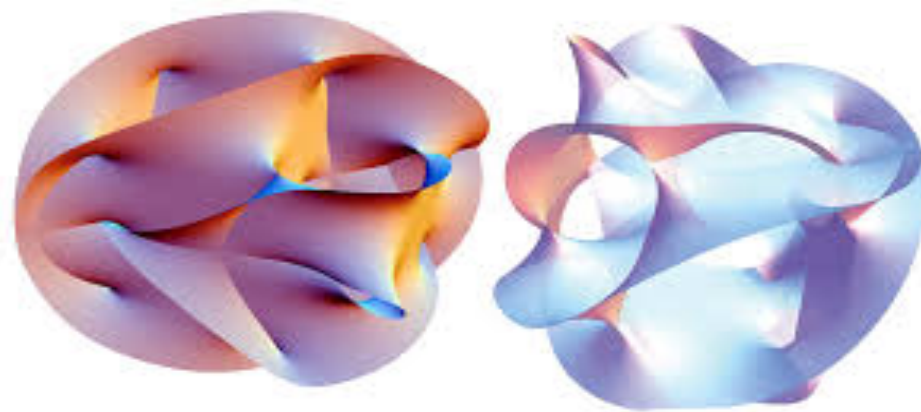


Extra dimensions of string theory can have a large number of distinct possibilities







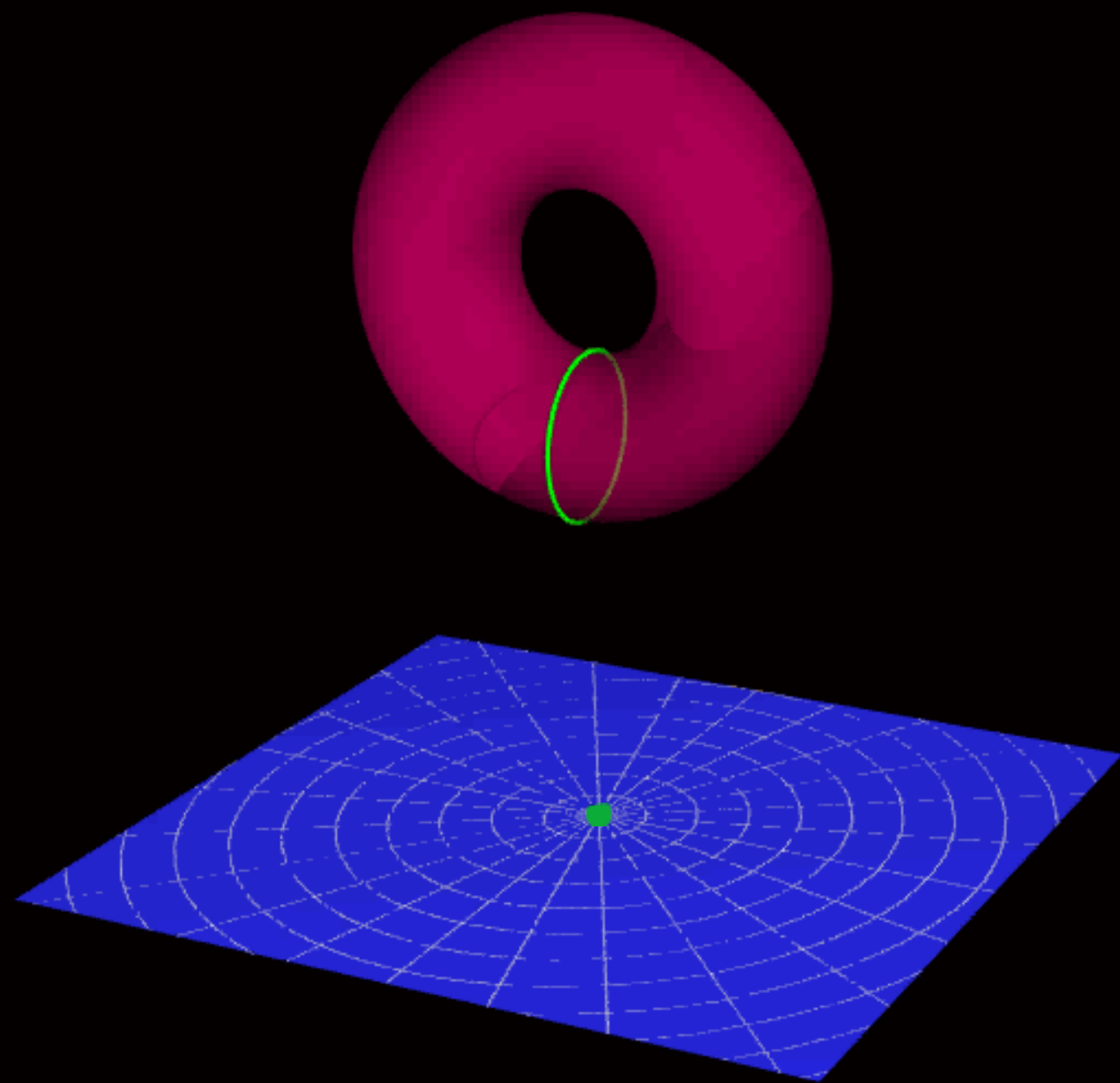


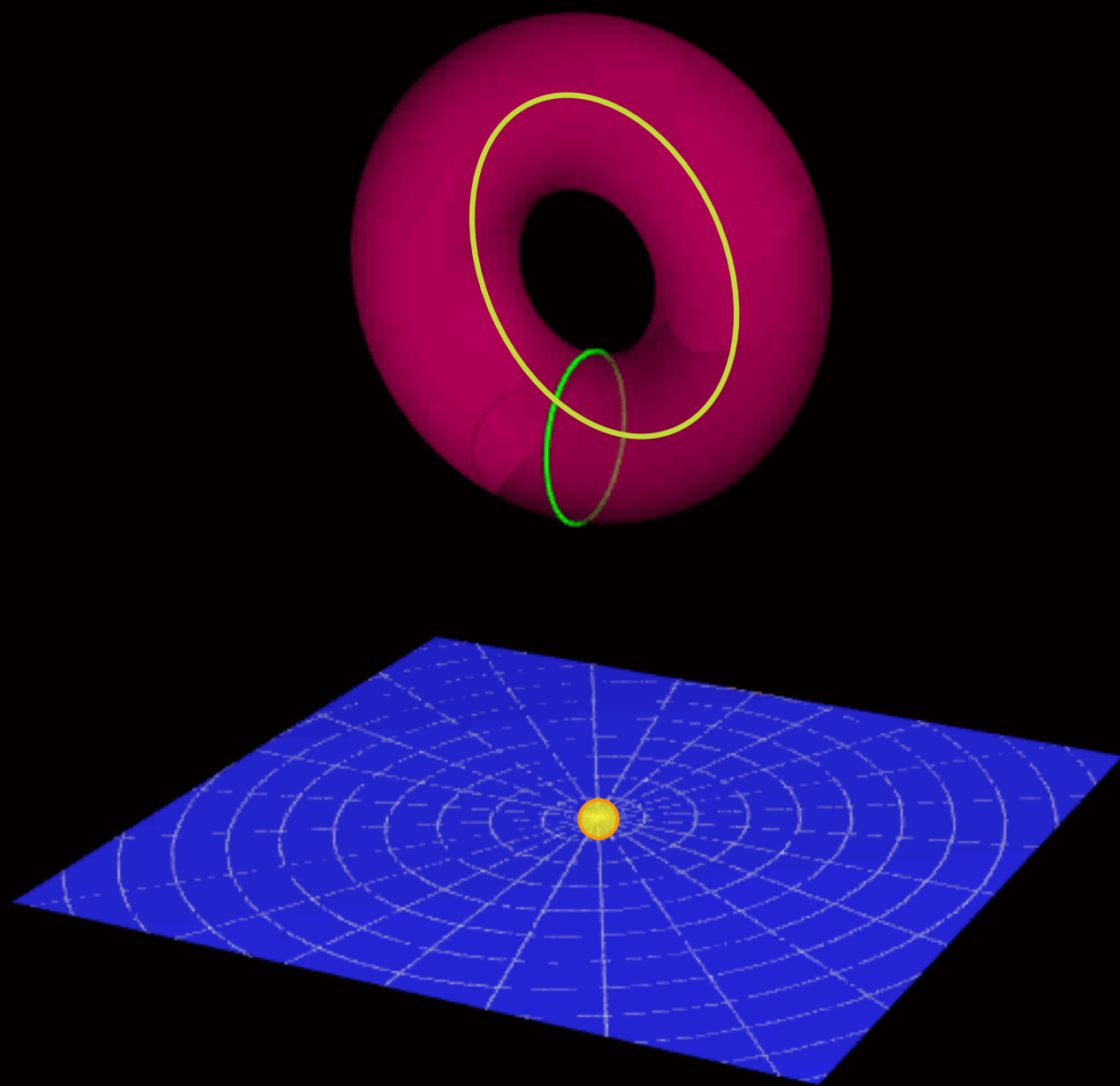
The physical properties observed in 3+1 dimensions depends on the choice of the compact tiny space:

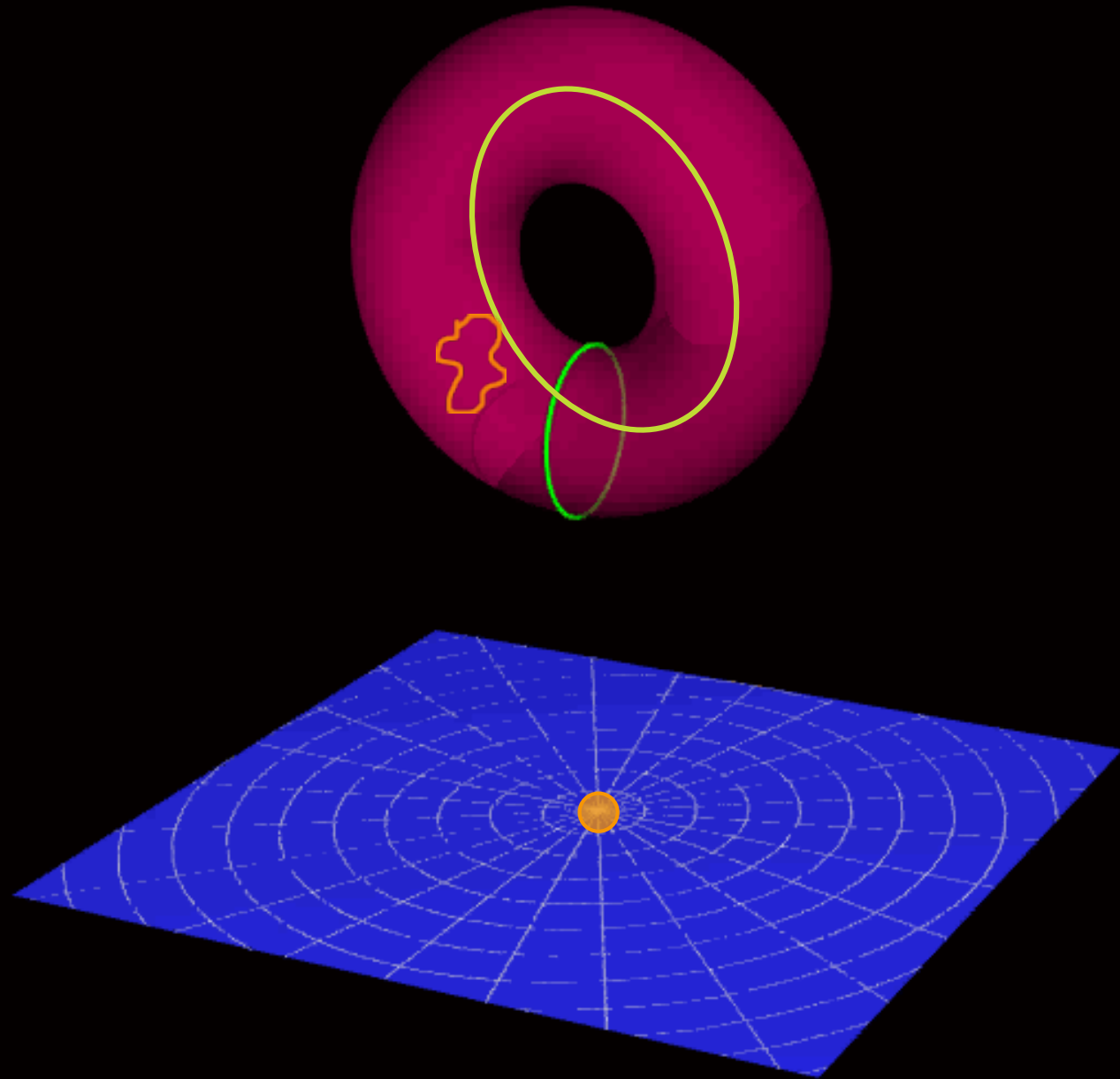
Number of forces, particles and their masses, etc.

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

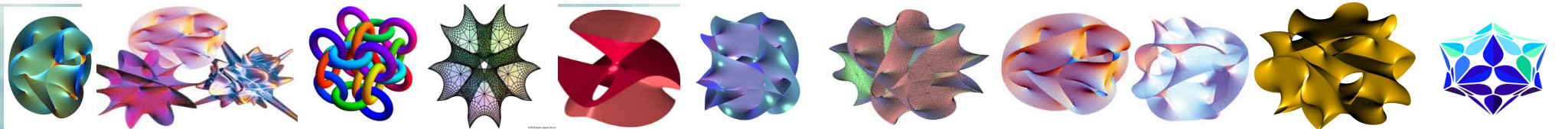


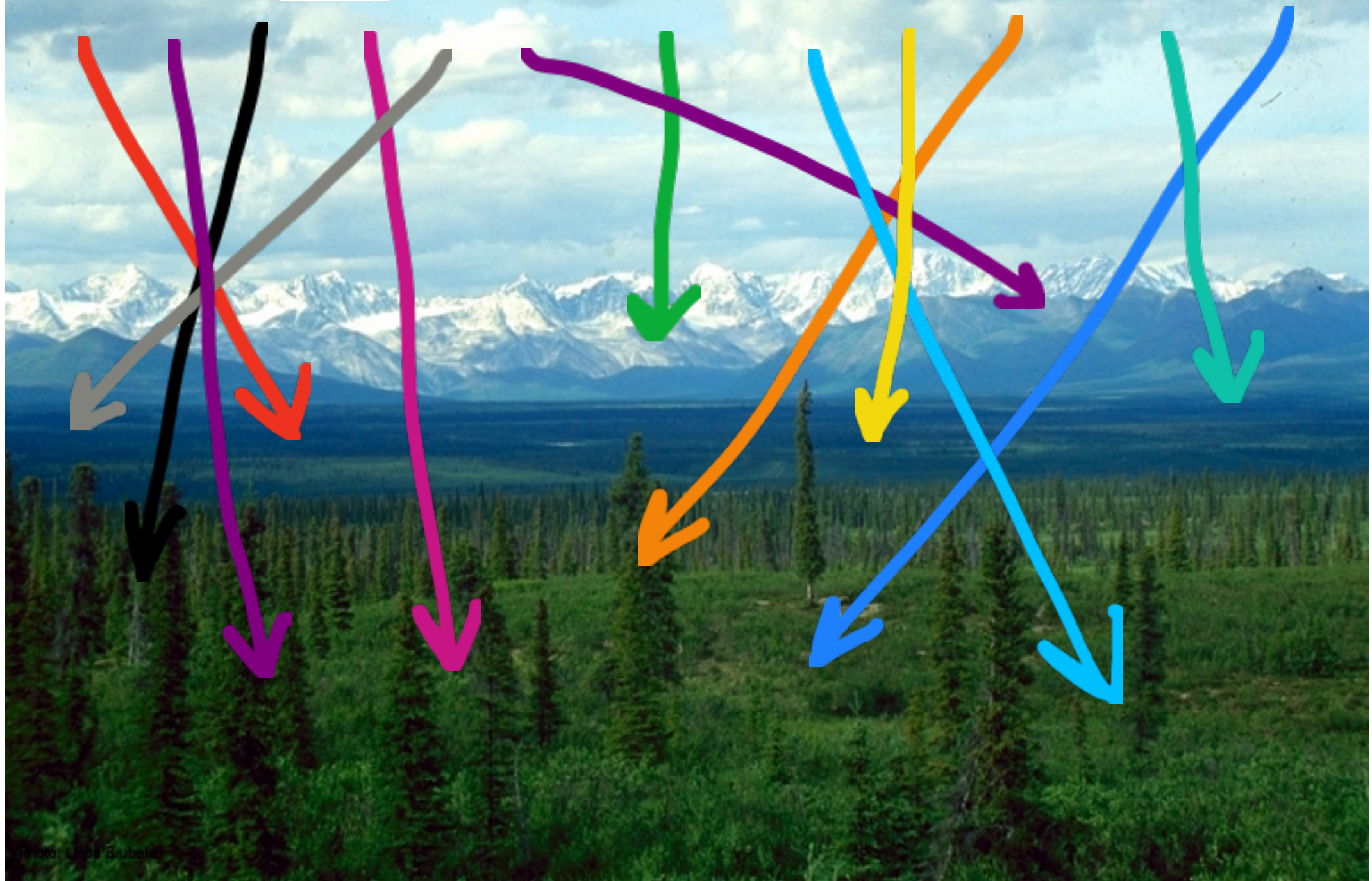
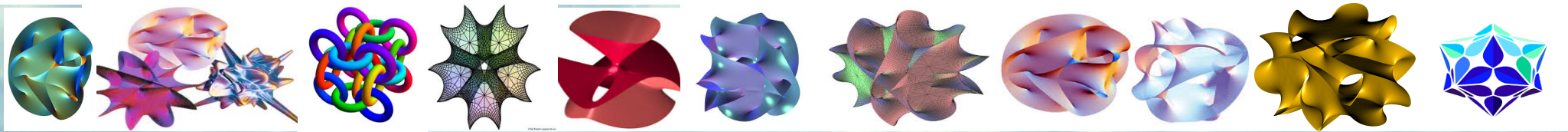


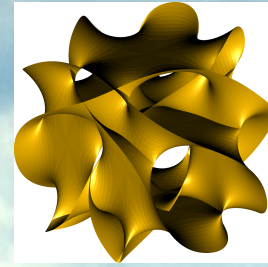


This leads to the vast string landscape









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?

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?

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.

- 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:
(Consequences for cosmology and particle phenomenology)
- 6-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

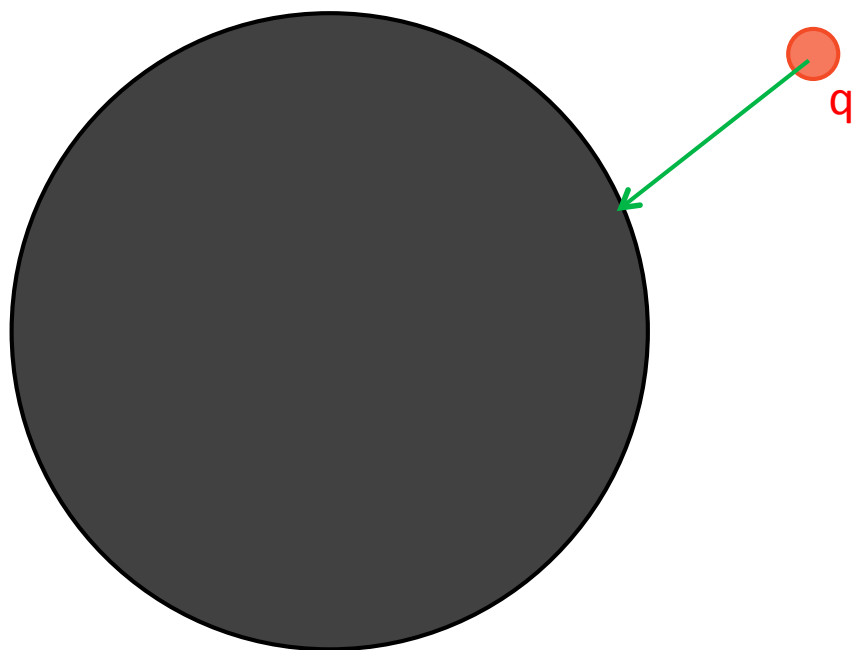
$$N = \exp(A/4)$$

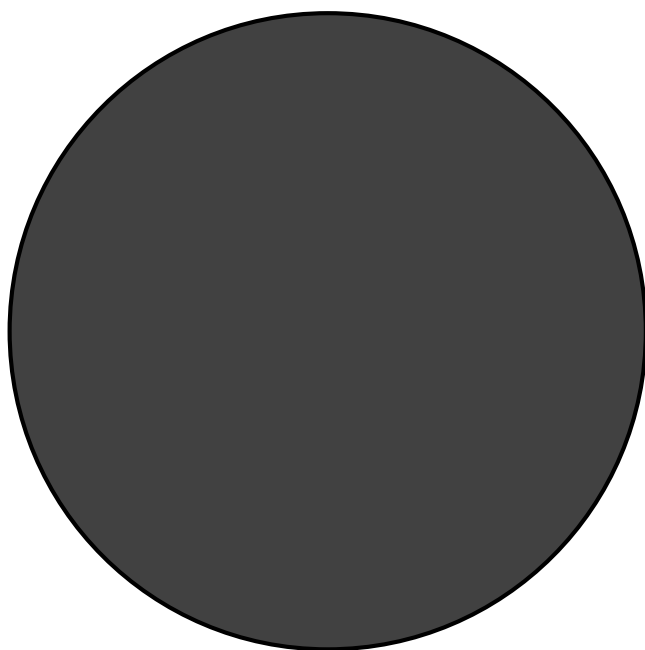
3-All black holes disappear by gradually emitting elementary particles (modulo some extremal cases in supersymmetric theories). After the gradual decay ('Hawking radiation') nothing is left and there is no imprint of the BH left.

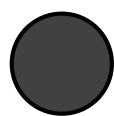
Criterion 1: Only Gauge Symmetries

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, a priori 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 !

Criterion 3: Finite Range for Fields

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

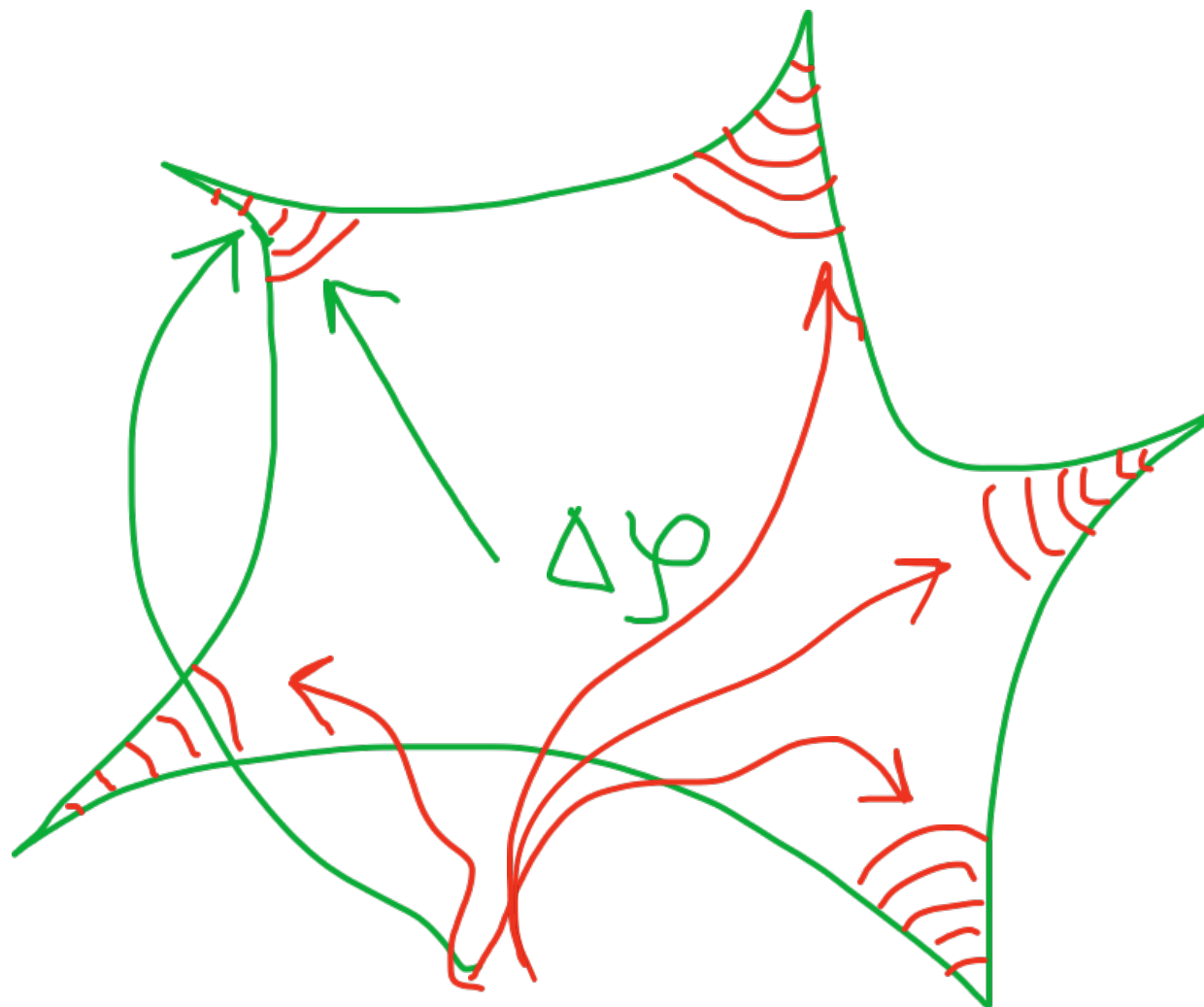
$$-\infty < \varphi < +\infty$$

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.

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



Light states

Consequence for inflation:

We cannot have long range inflation models!

(We cannot ignore light states that will emerge as the field ranges over Planck scale—the energy in the inflaton field will go into producing such light states instead of rolling)

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.

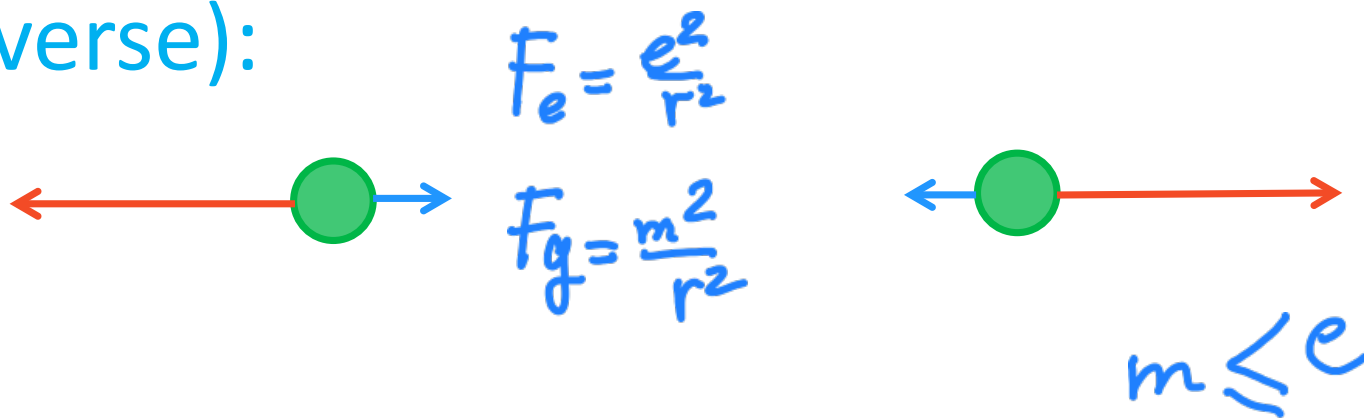
$R \rightarrow 0$ some light states must appear.

But how is that possible? KK modes are becoming heavier.

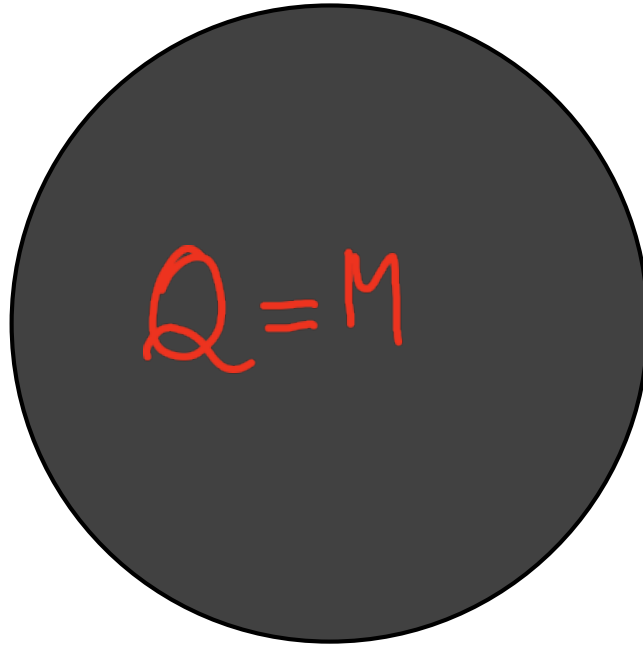
The only natural mechanism for this to happen is if we have extended objects like string or membranes which can wrap the circle and as the circle becomes small they become light!

Criterion 5: Gravity as the Weakest Force

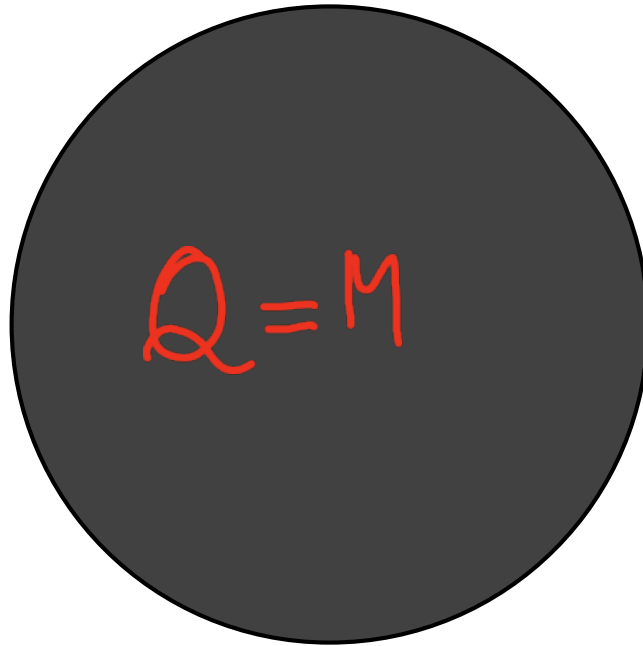
In string compactifications it has been observed that whenever we have charged particles, the electric force between the elementary charged states are stronger than their gravitational attraction (true for our universe):


$$F_e = \frac{e^2}{r^2}$$
$$F_g = \frac{m^2}{r^2}$$
$$m \leq e$$

Black Hole Explanation of WGC:

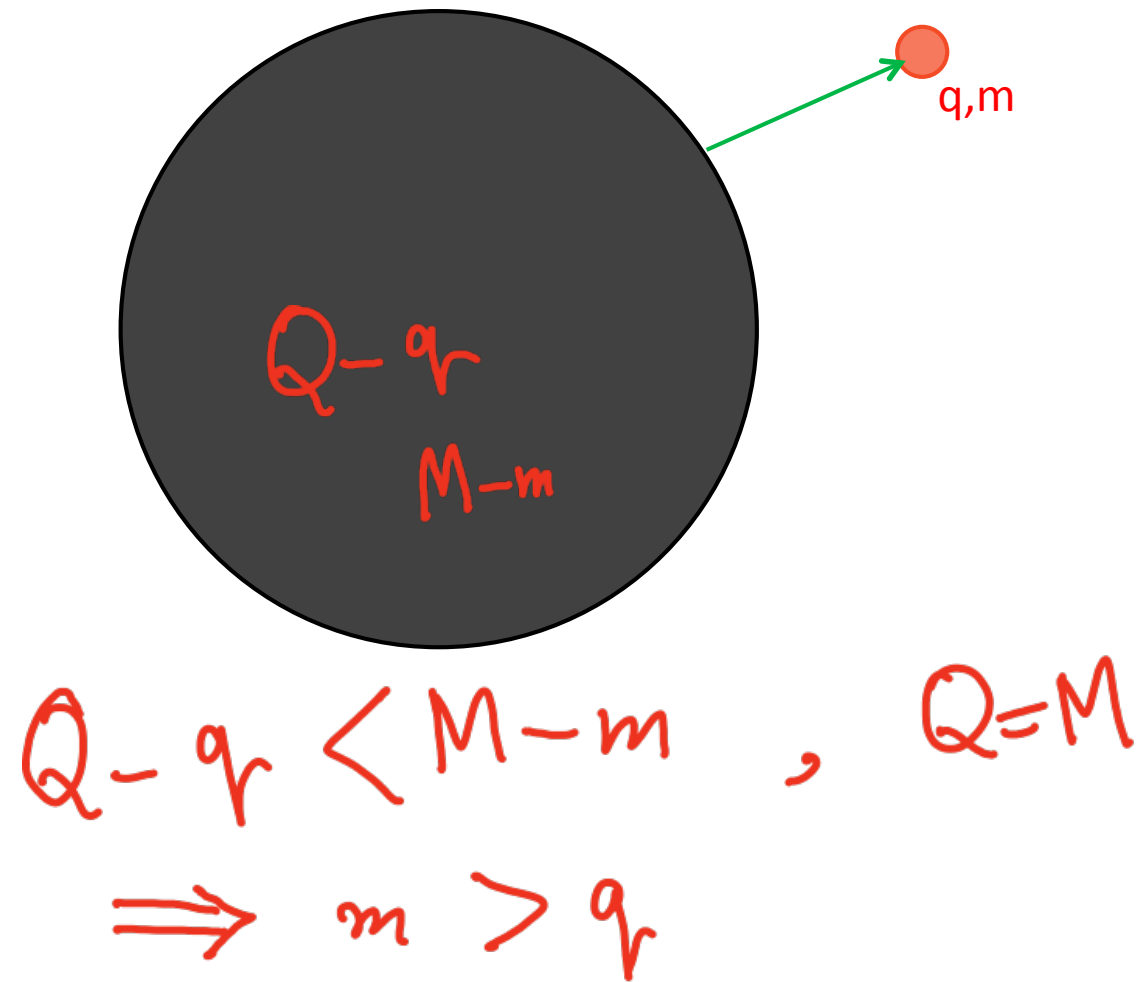


Black Hole Explanation of WGC:



Undergoes Hawking Radiation

Black Hole Explanation of WGC:



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

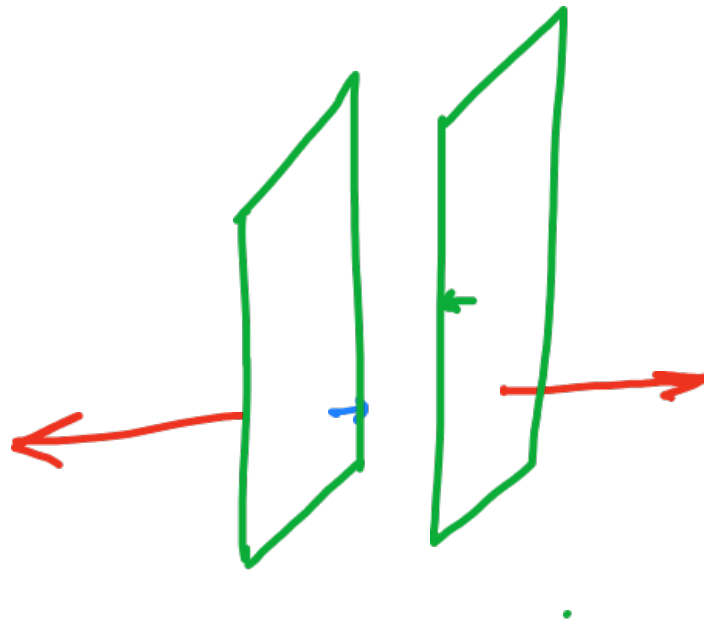
Further evidence of WGC:

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 repulsion:



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:

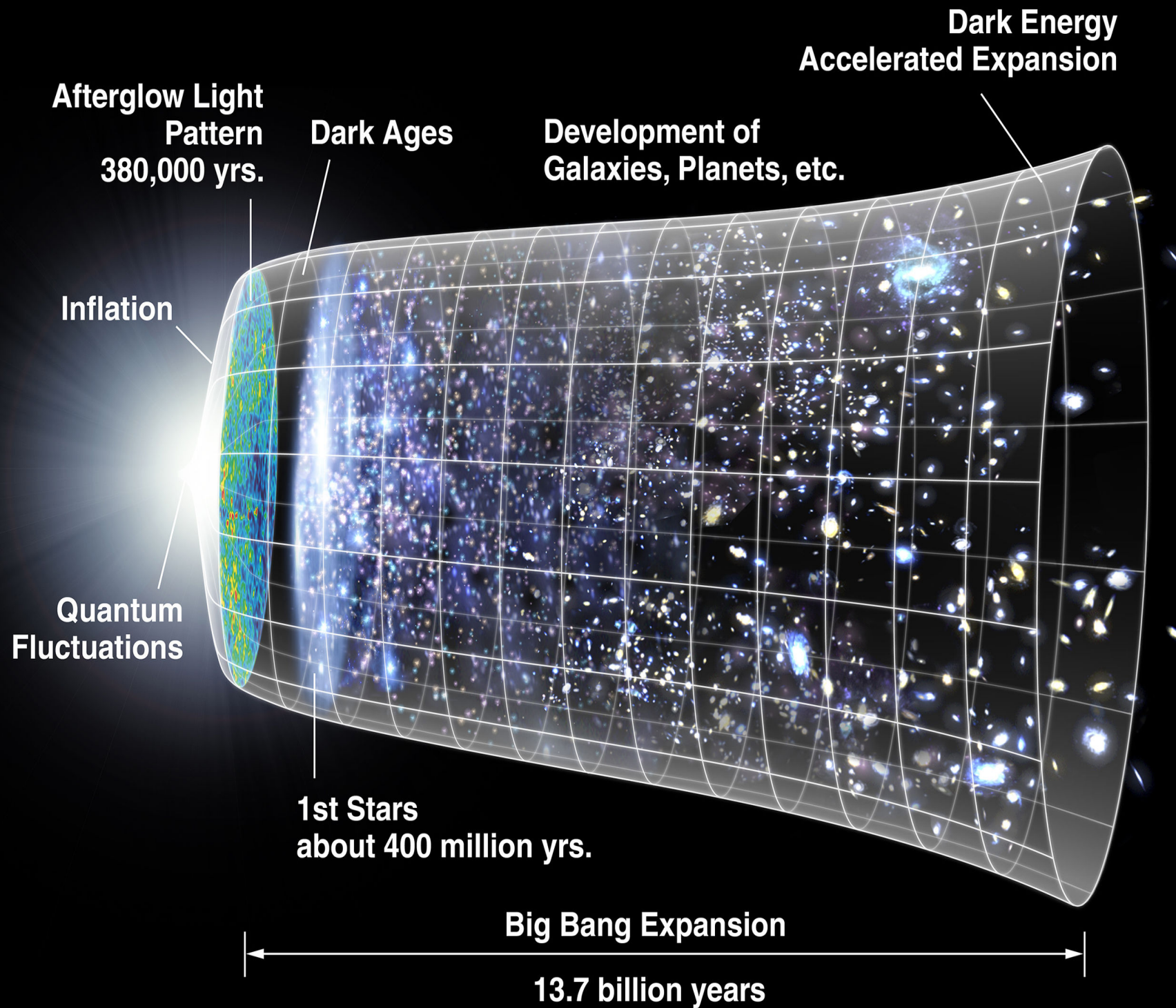
$$M_w \lesssim 10^{2-4} \text{ GeV}$$

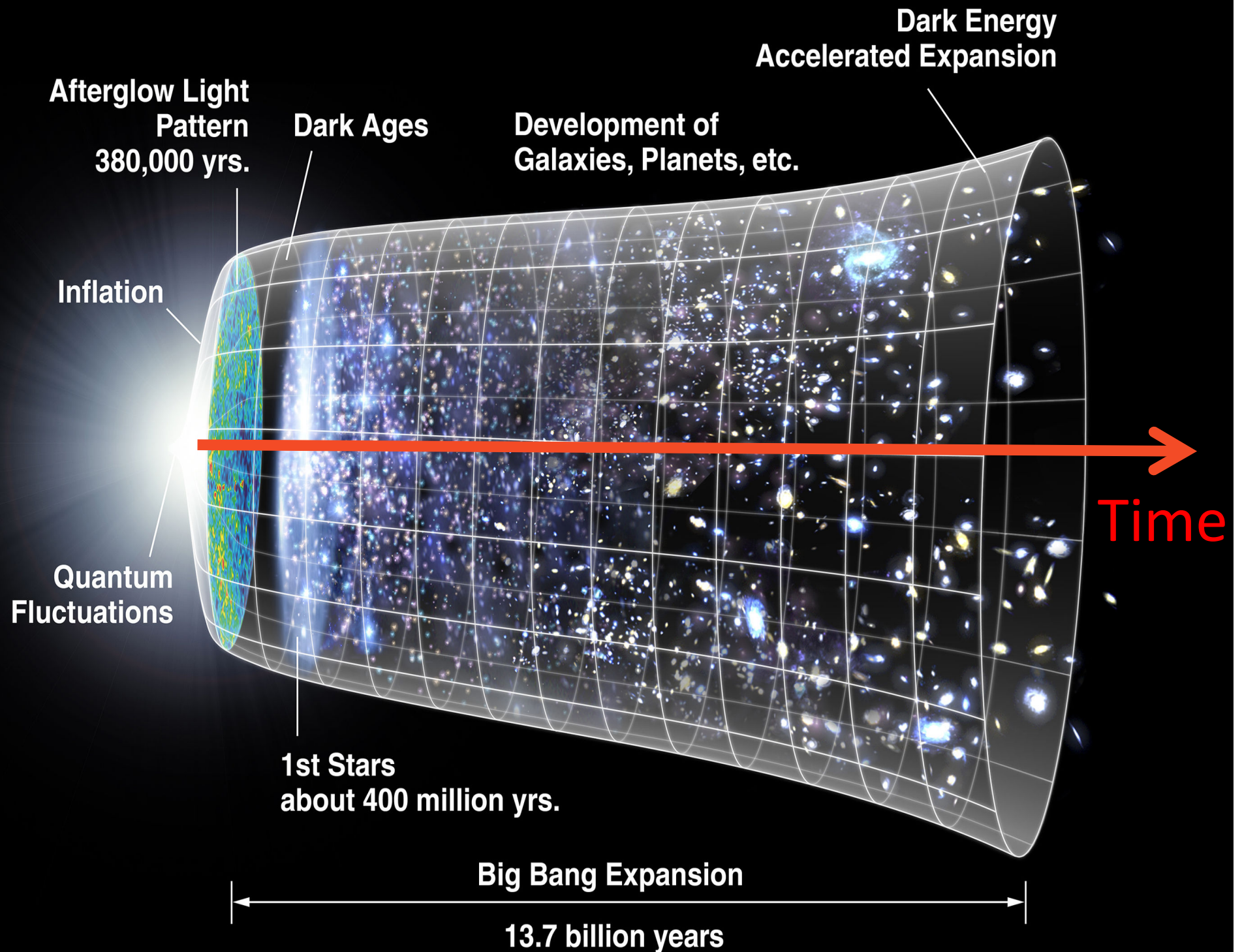
Providing a partial explanation of hierarchy from WGC!

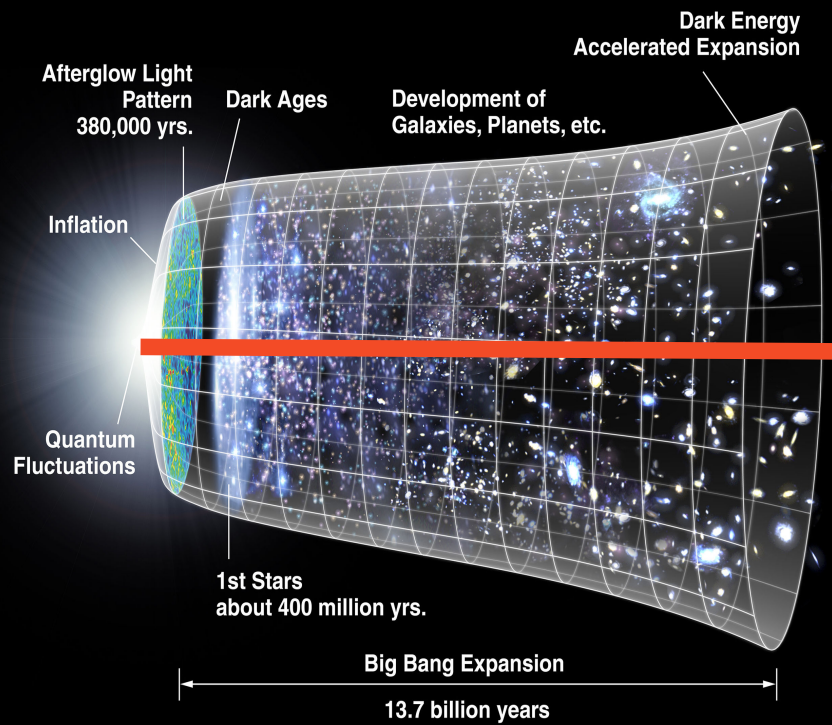
Criterion 6: The Fate of our Universe

We know the universe had a beginning.
Does it have an end?

A swampland conjecture suggests that this is
indeed the case:







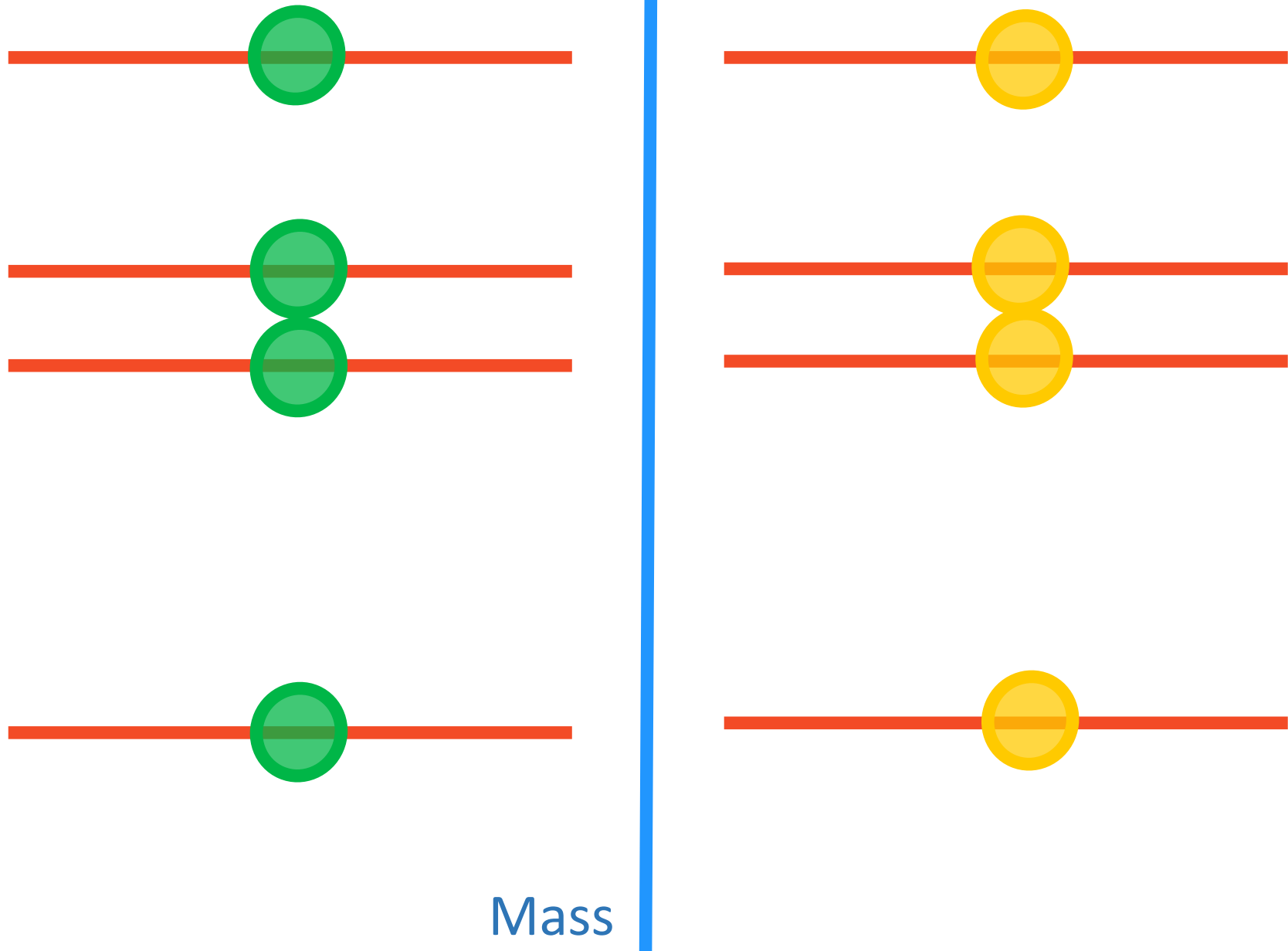
Will it end?

String theory landscape:

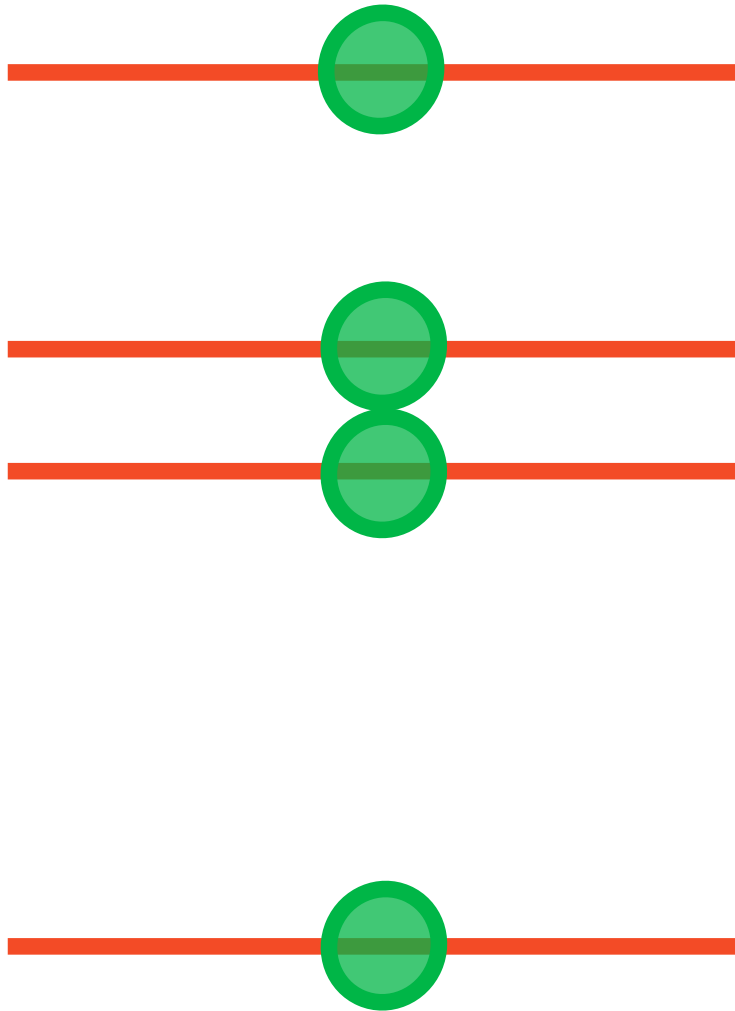
The only universes that last forever have a special property called **supersymmetry**.

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

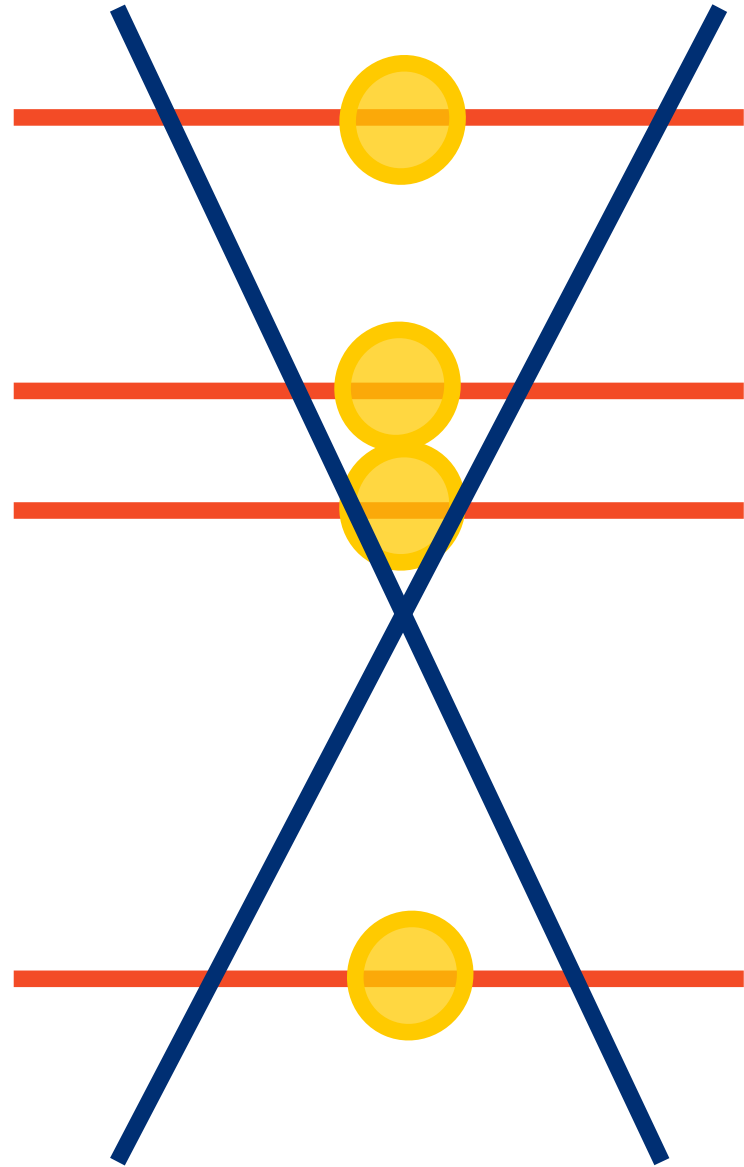
Supersymmetry



Supersymmetry:

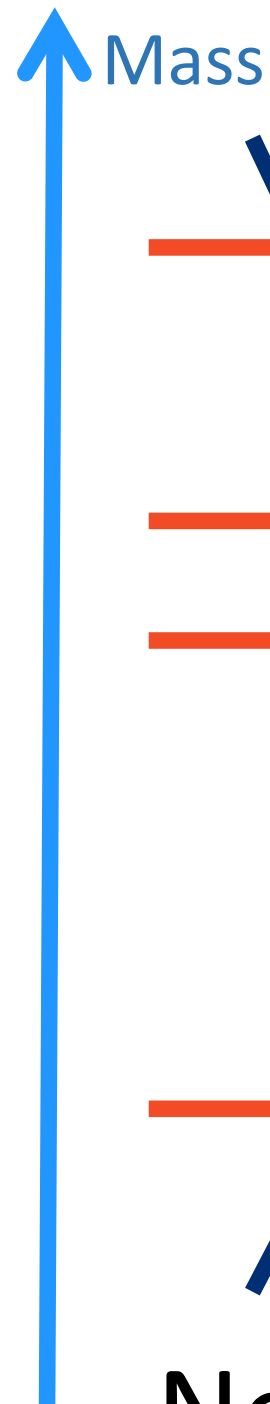
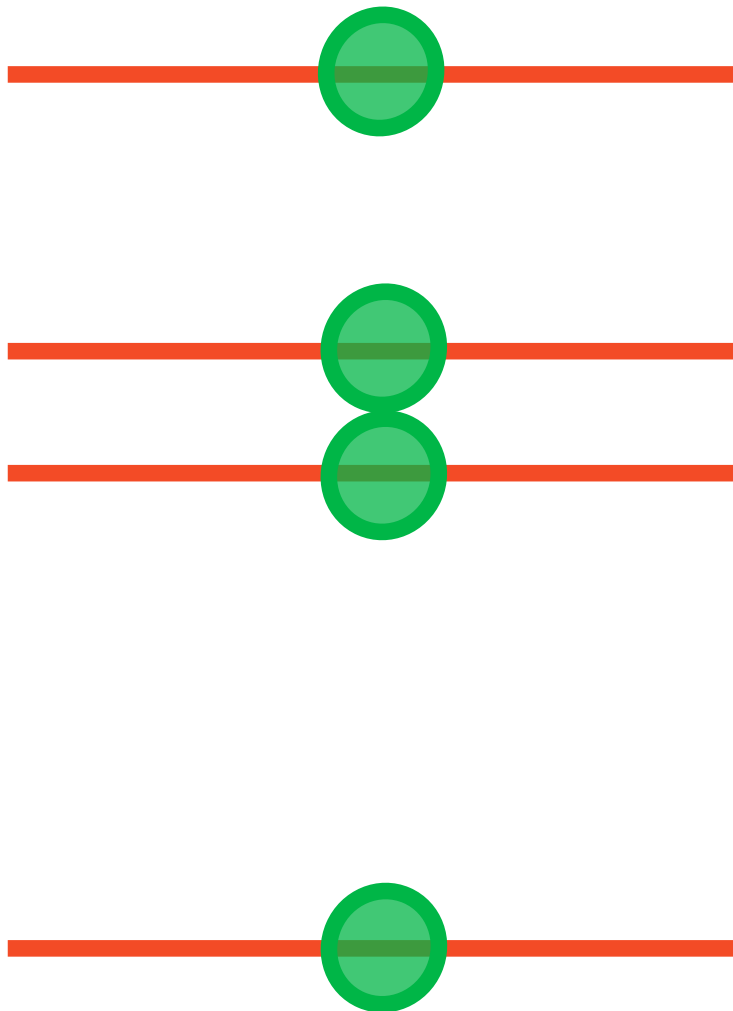


Mass



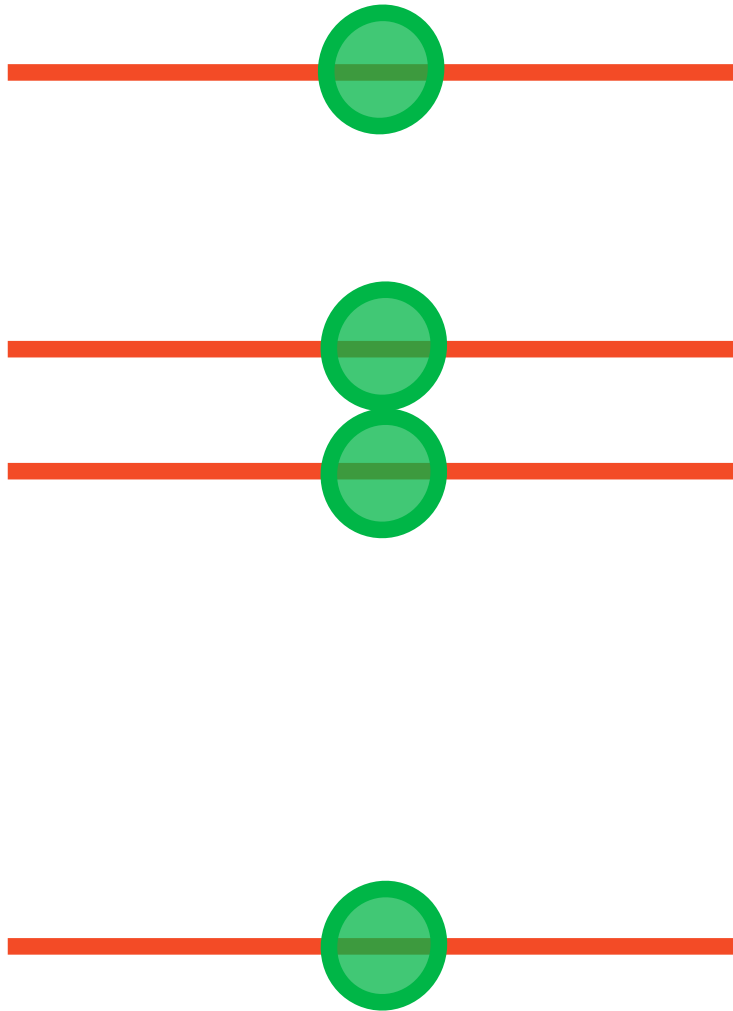
Not observed!

~~Supersymmetry:~~

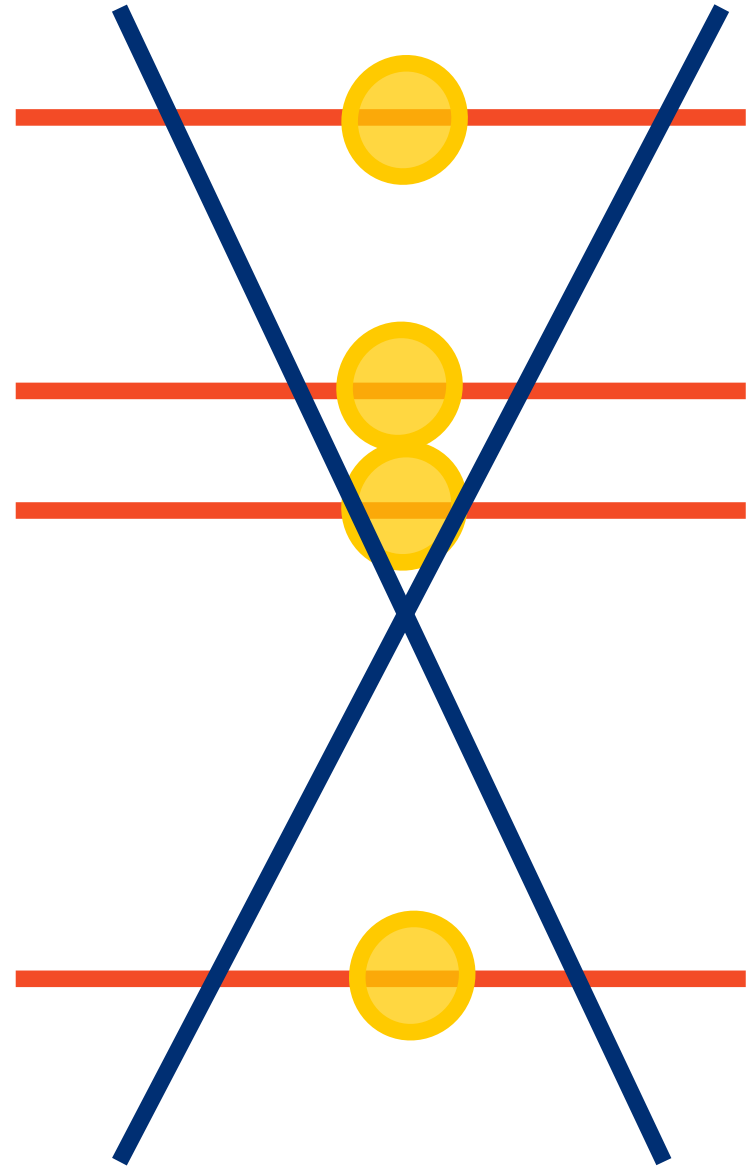


Not observed!

~~Supersymmetry:~~

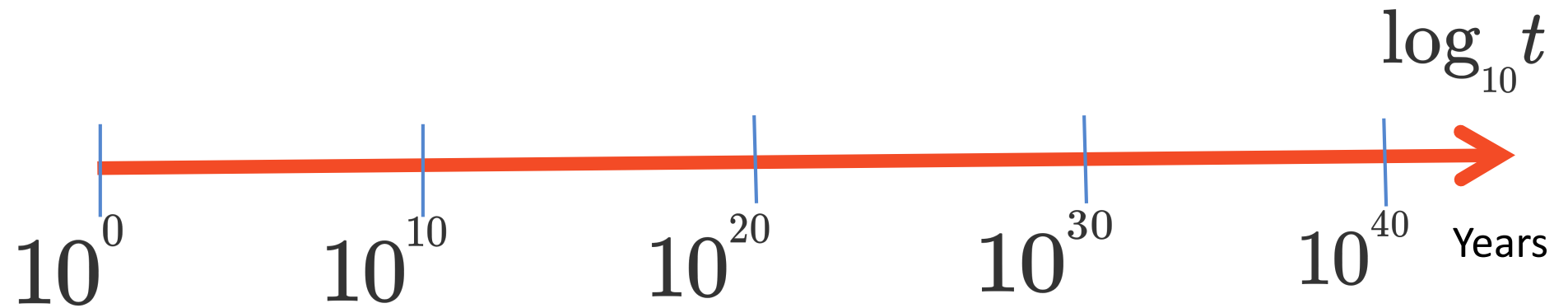


Mass ↑



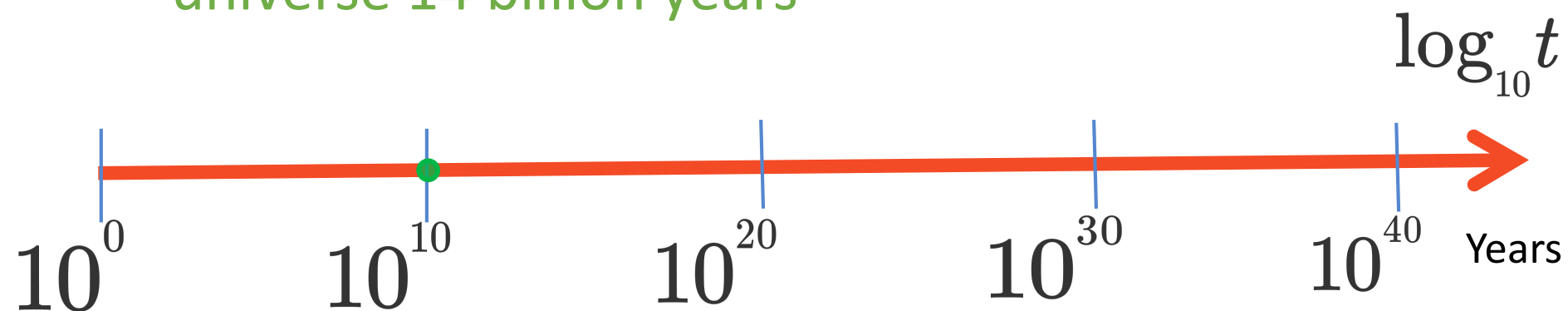
Our Universe will not last forever!

How long do we have?



How long do we have?

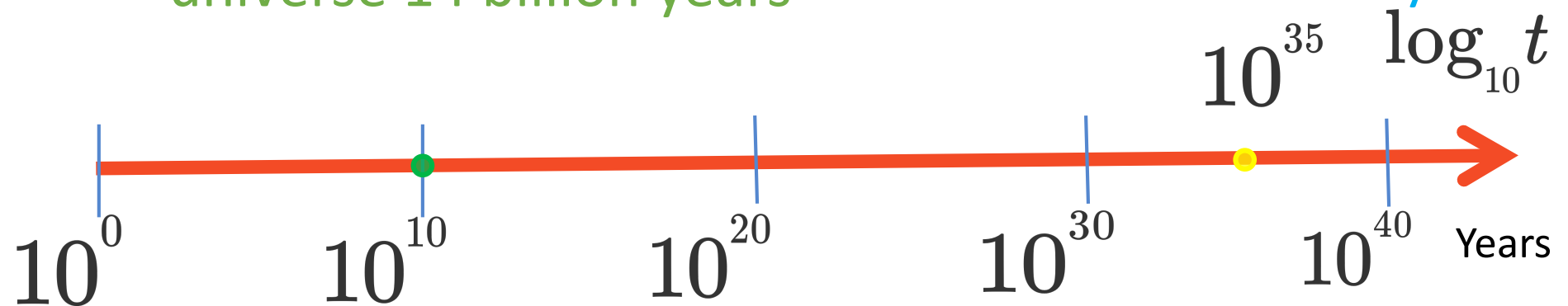
Current age of our
universe 14 billion years



How long do we have?

Current age of our
universe 14 billion years

Protons decay



Our universe has dark energy.

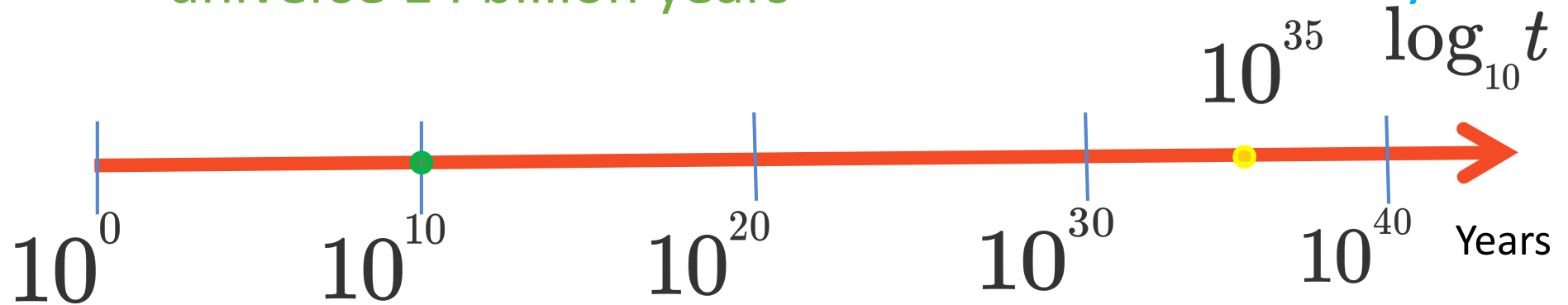
Dark Energy, leads to a natural time scale:

$$t_E = \frac{1}{\sqrt{E}}$$

How long do we have?

Current age of our
universe 14 billion years

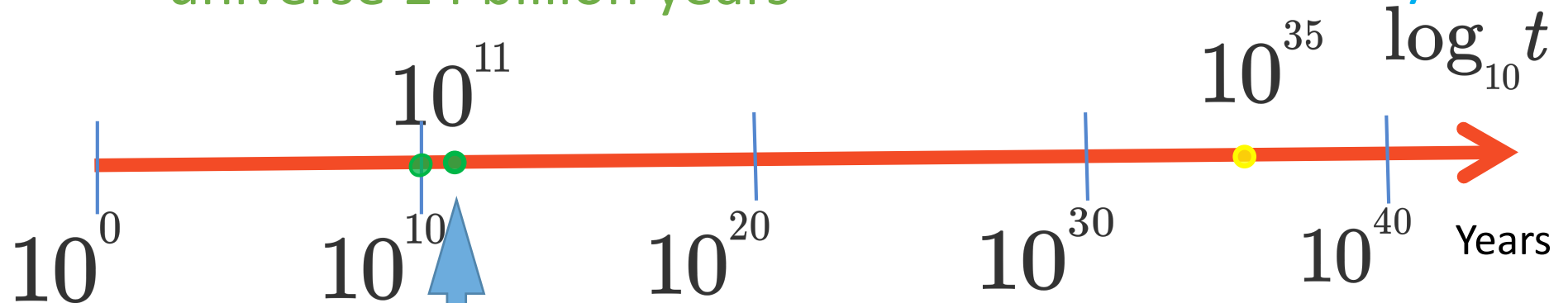
Protons decay



How long do we have?

Current age of our
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Protons decay



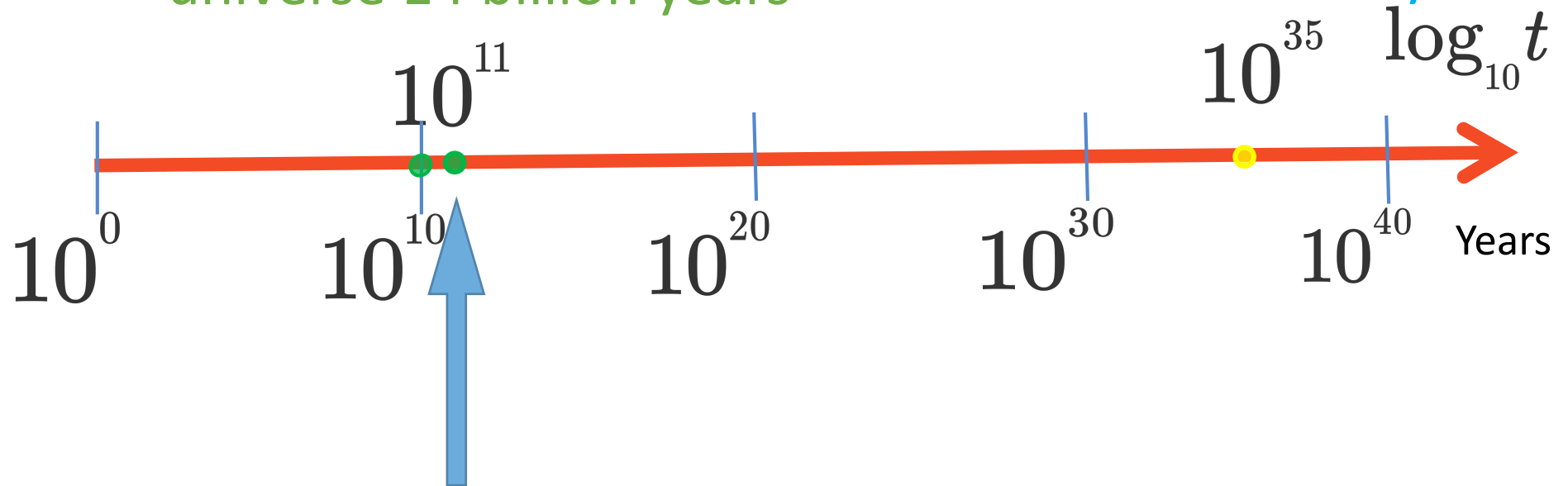
$$t_E = 10^{11}$$

About 100 billion years!

How long do we have?

Current age of our
universe 14 billion years

Protons decay



$$t_E = 10^{11}$$

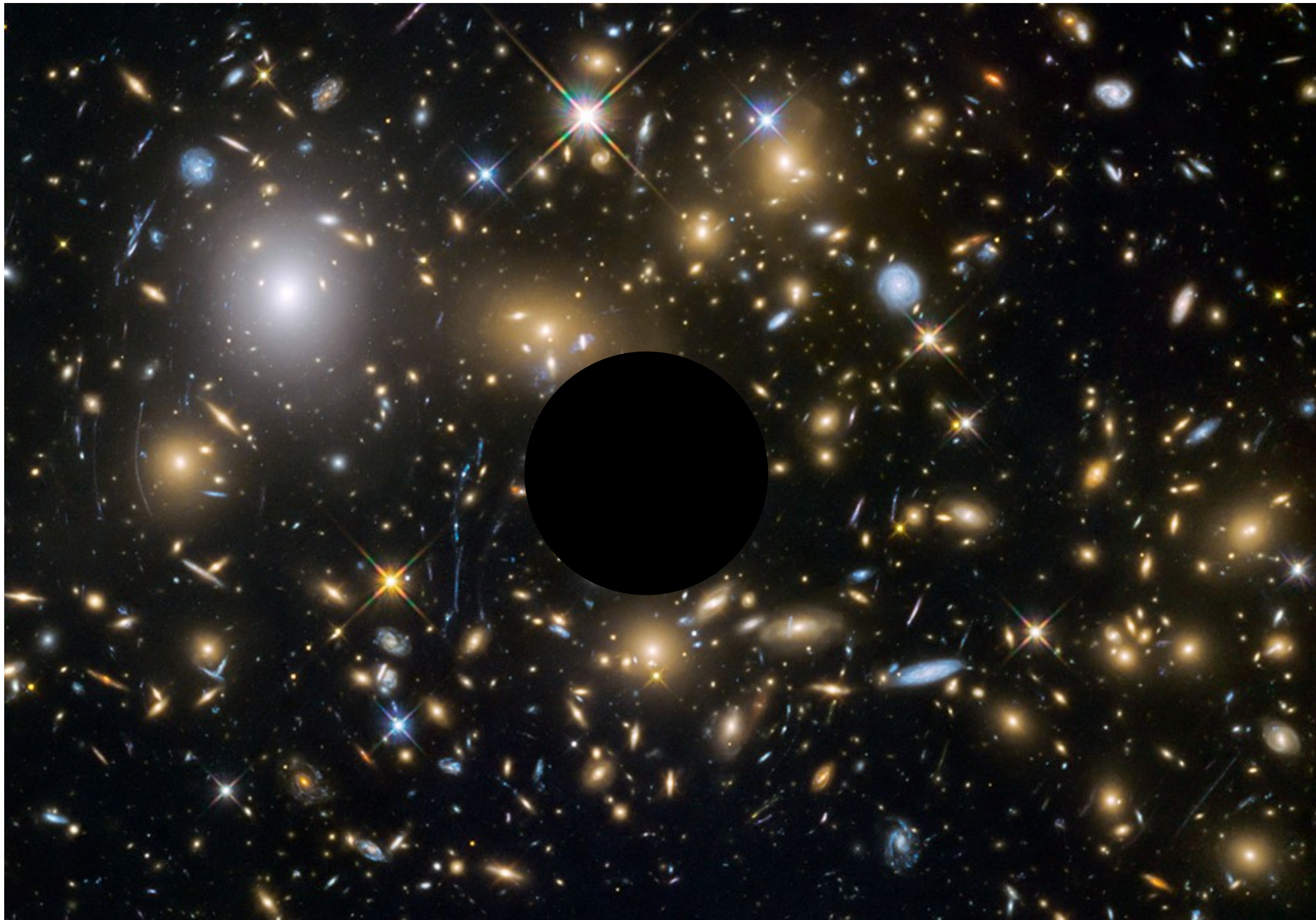
About 100 billion years!

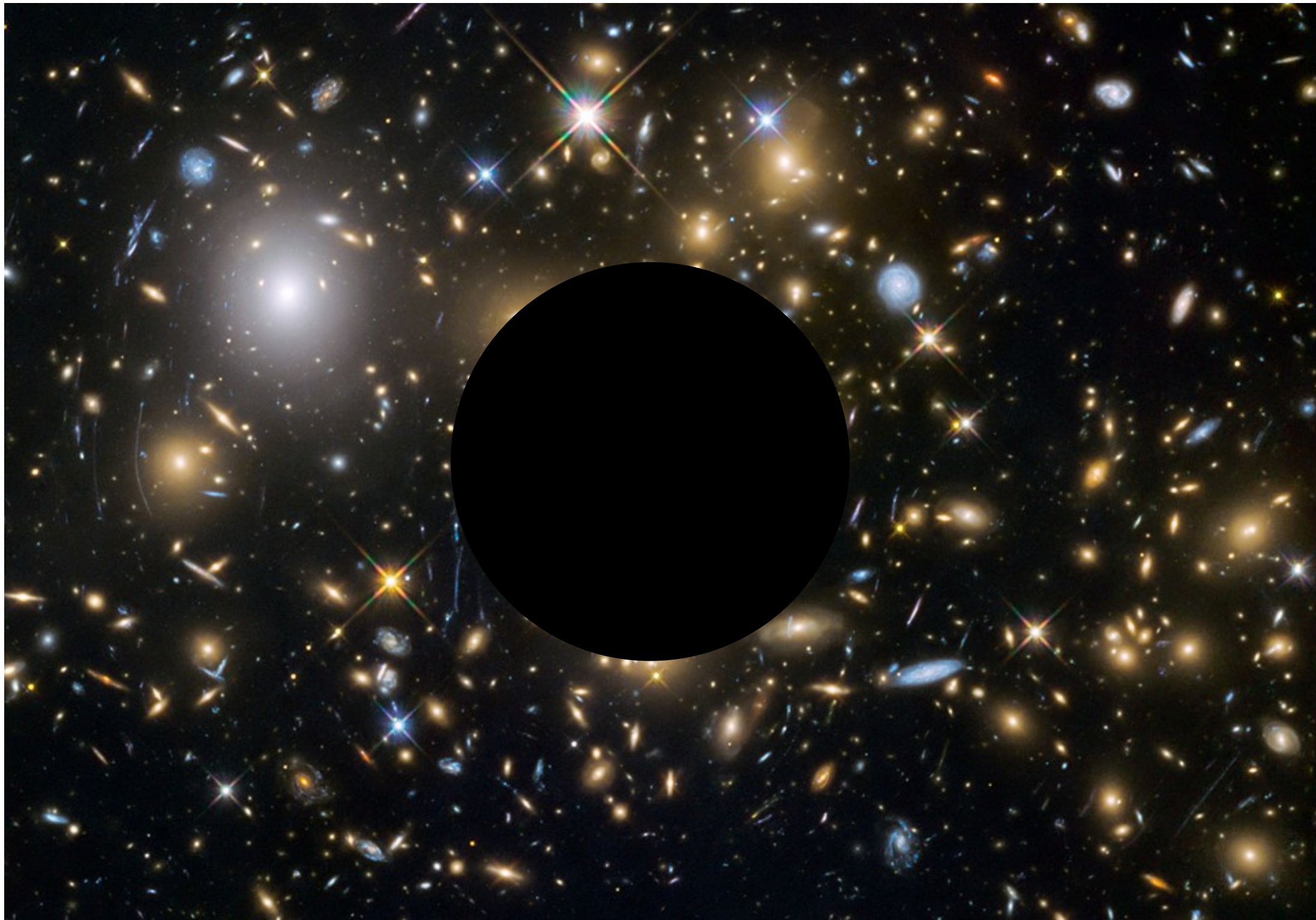
Is this a coincidence?!

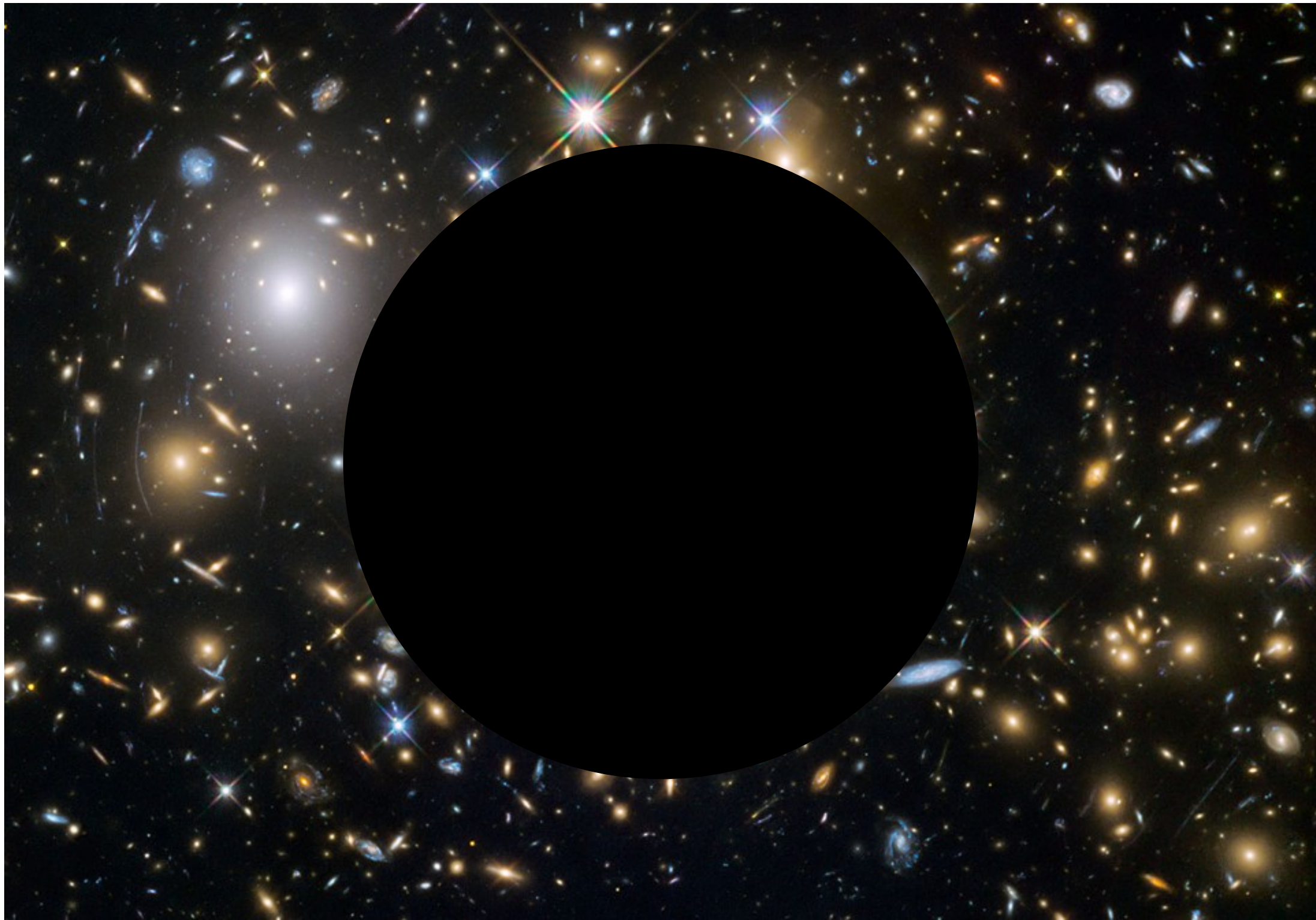


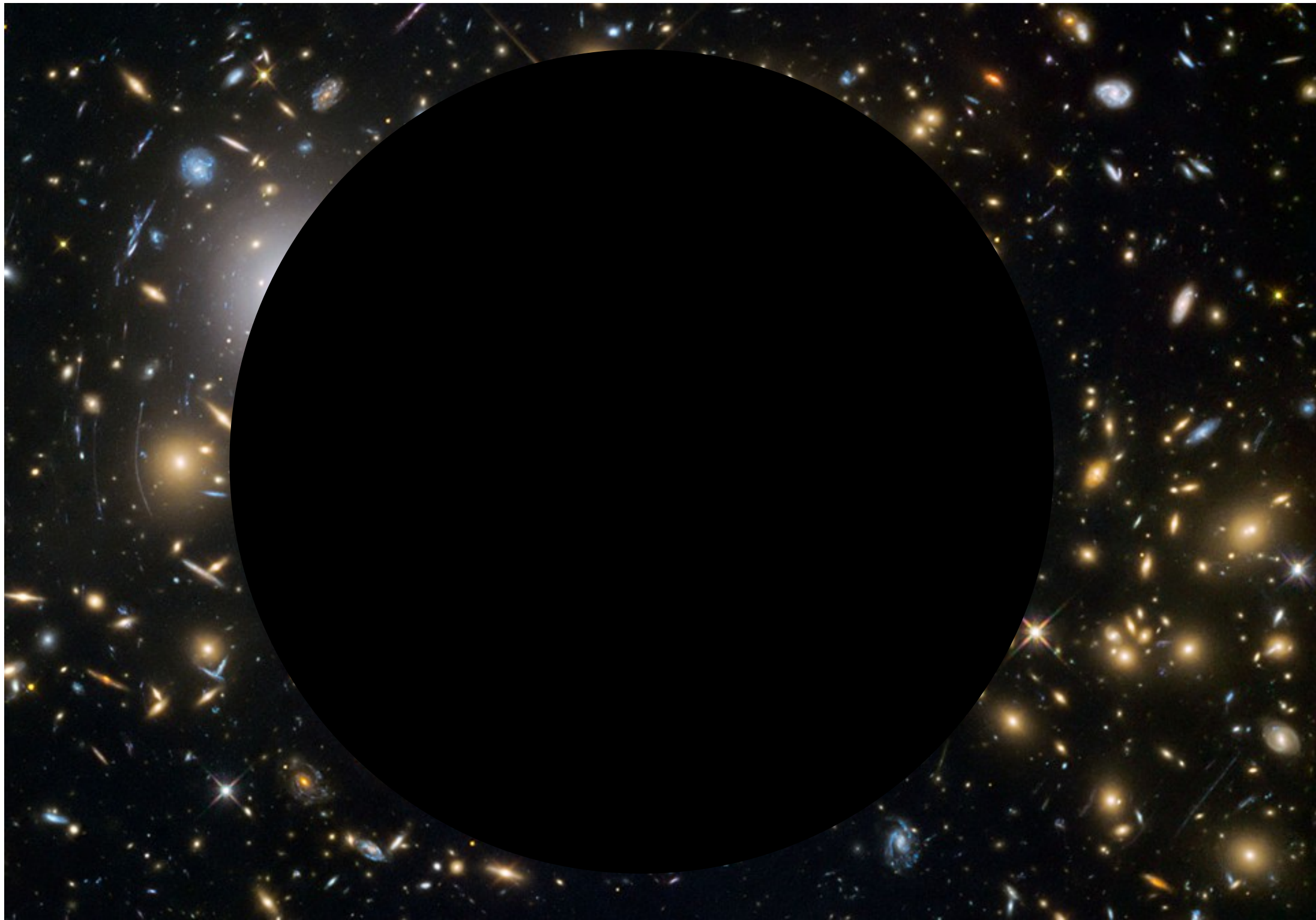


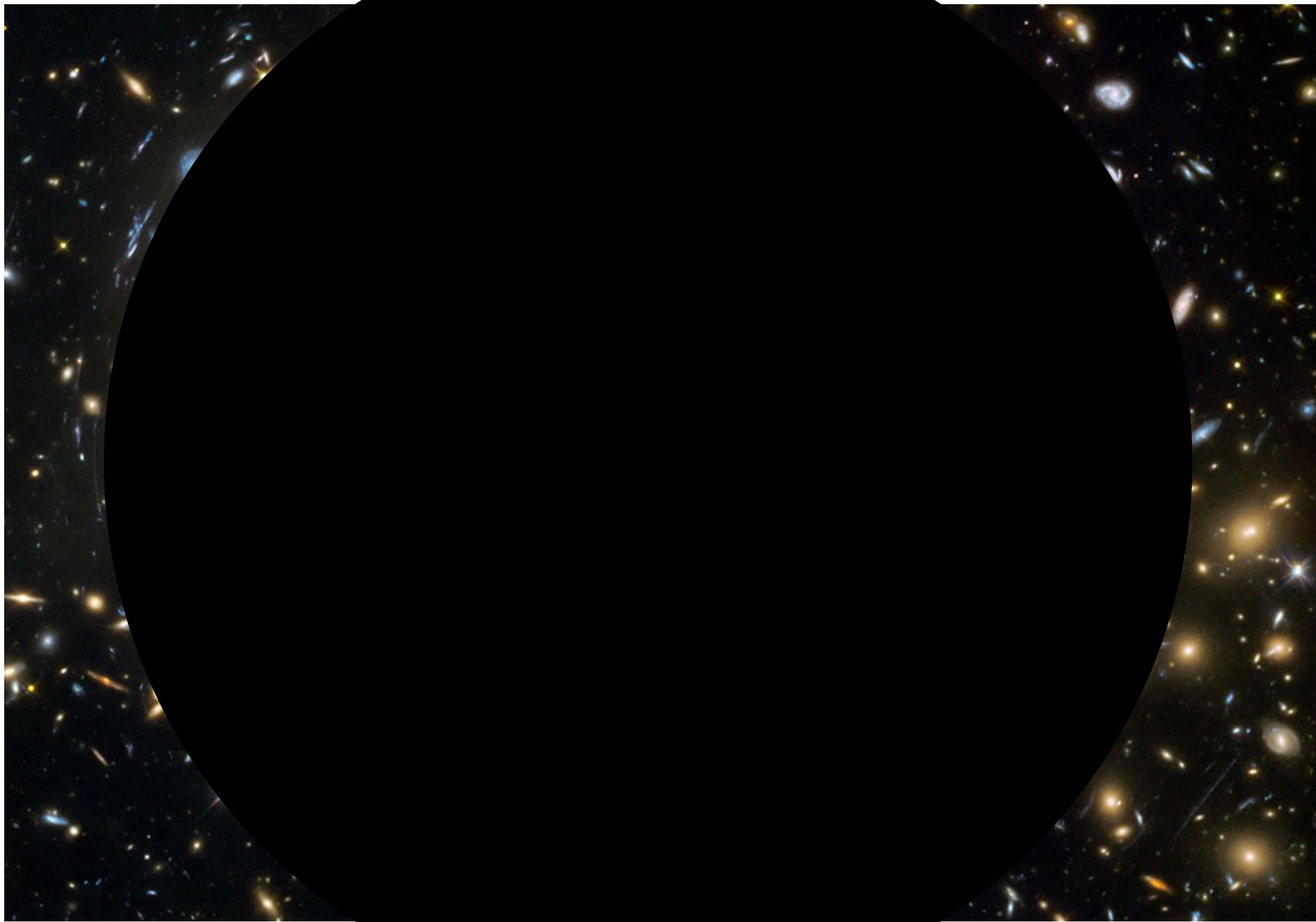


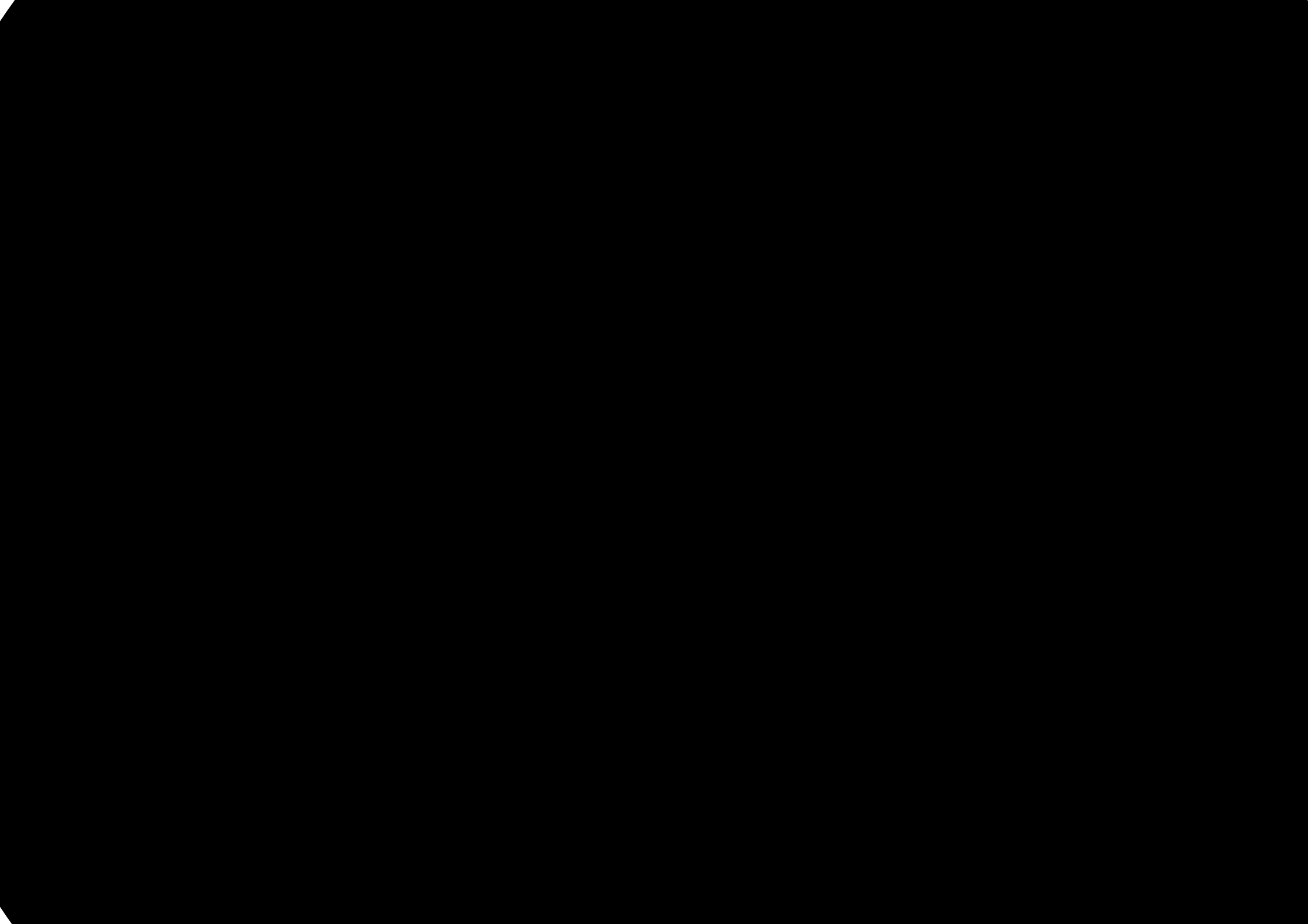












The End!