String Landscape and the Swampland

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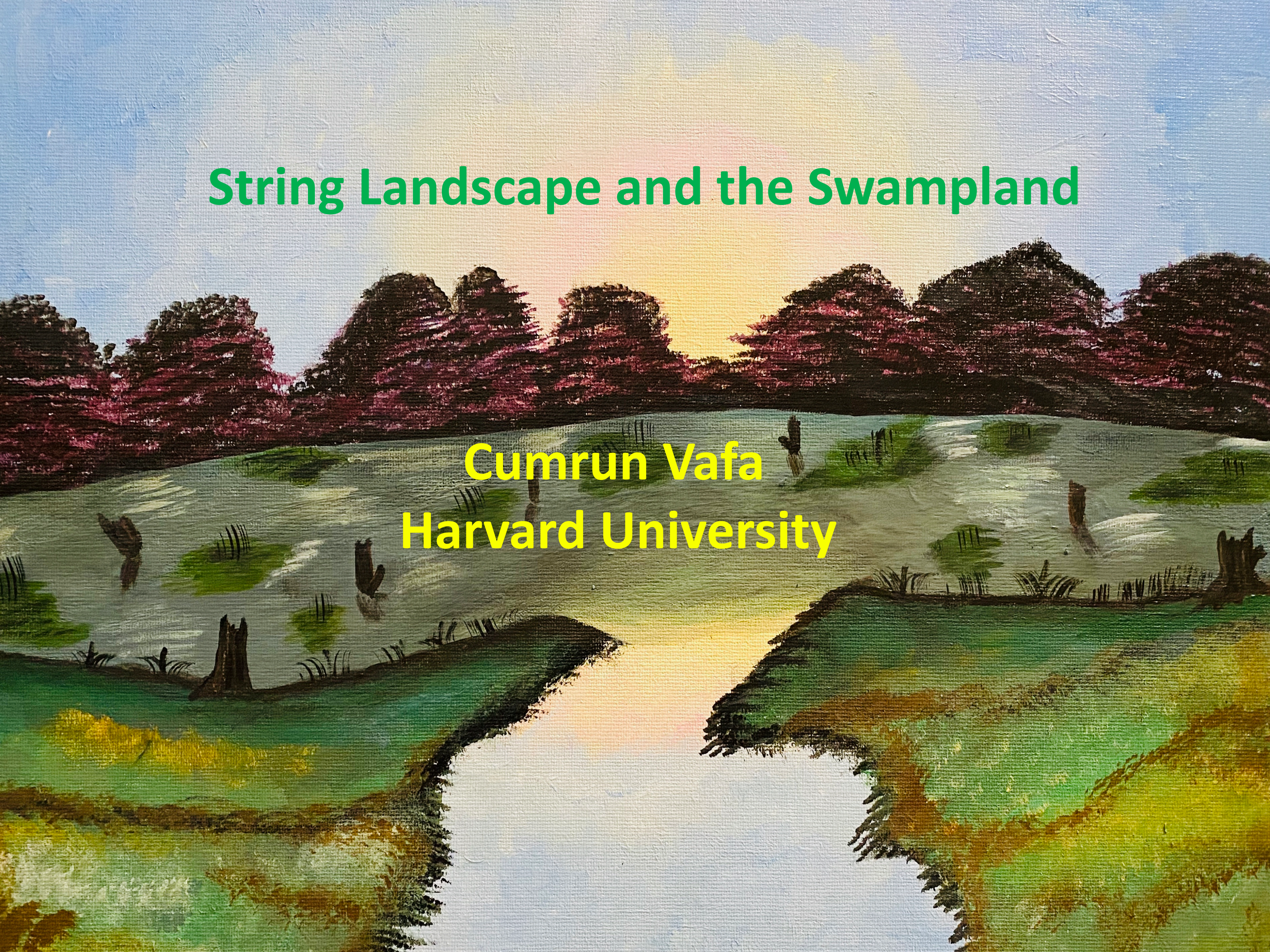
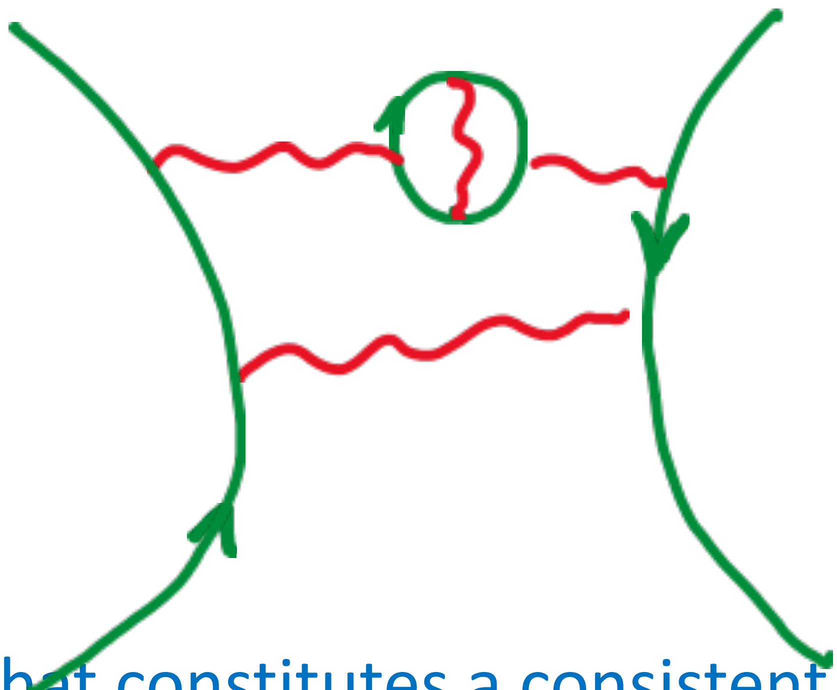


Quantum Field Theories—without gravity included—

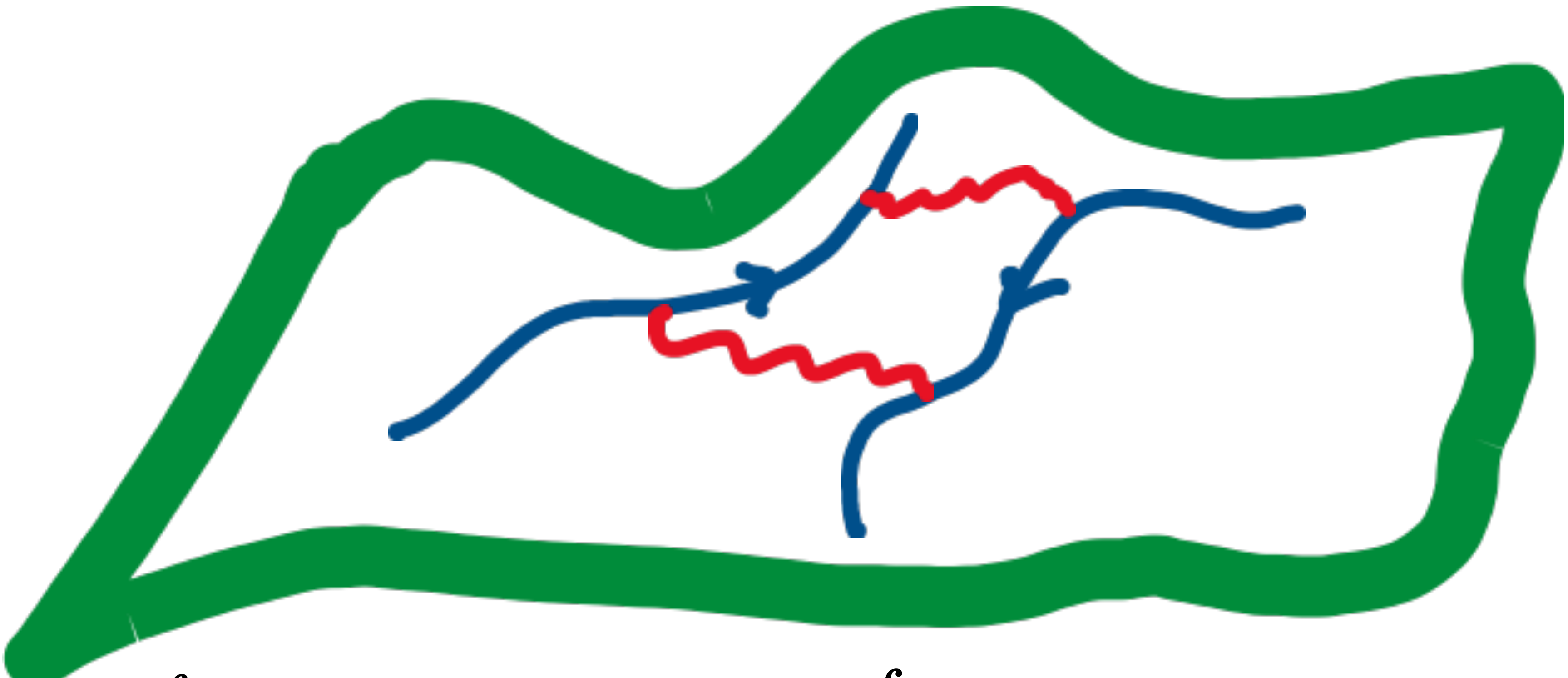
are well understood. They beautifully describe the

interaction of all the elementary particles we know:



We know what constitutes a consistent QFT without gravity.

To include gravity (Einstein's theory) and describe it in quantum theory we need to `Couple the QFT to Gravity' we need to consider fluctuating spacetime instead of fixed flat space:



$$S = \int R + \mathscr{L}_0(A, \psi, g) \qquad\qquad \int DgDAD\psi \ \exp(iS)$$

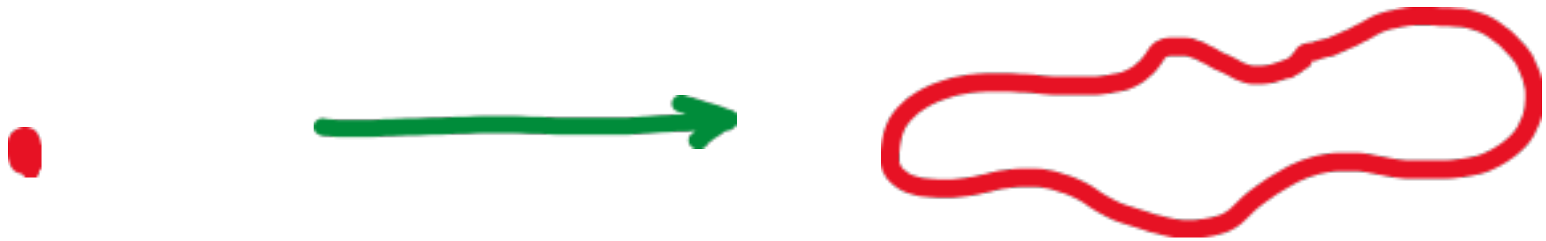
This approach does not work!
The infinities appearing in the Feynman diagrams are incurable and so a conventional approach to quantizing gravity does not work as Feynman discovered in 1960's!

The most natural conclusion from this would have been:
Gravity cannot be coupled to quantum fields consistently and should always be viewed only as a background!

But that is unacceptable because we do have both QM and dynamical gravity in our universe!

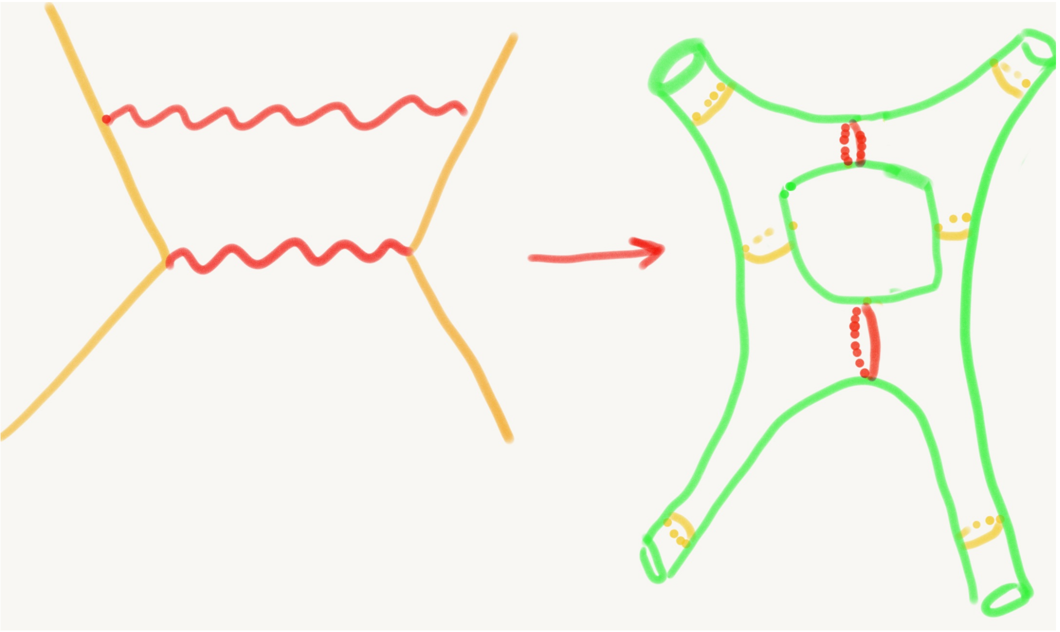
String theory solves this issue:

The point particles are replaced by extended string and this leads to consistent quantum theories of gravity.



String theory solves this issue:

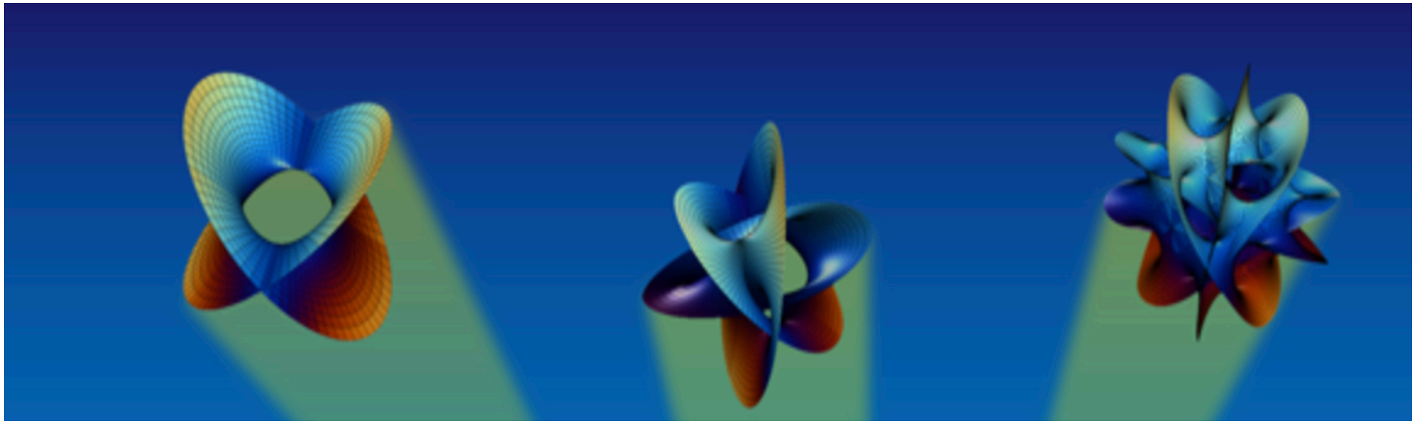
The point particles are replaced by extended string and this leads to consistent quantum theories of gravity. The infinitely many additionally oscillation modes of the string are crucial in resolving the inconsistencies of the associated Feynman diagrams.

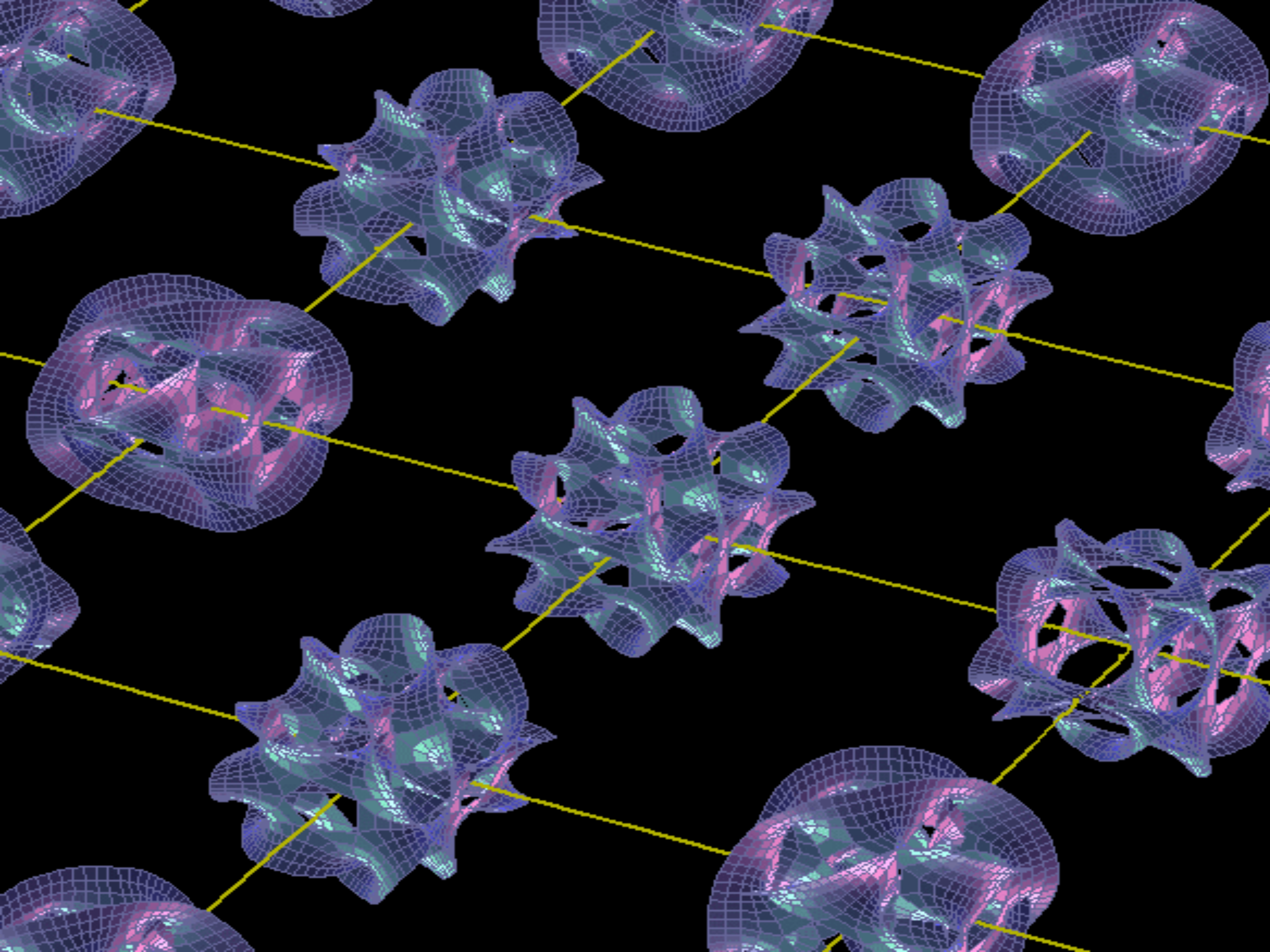


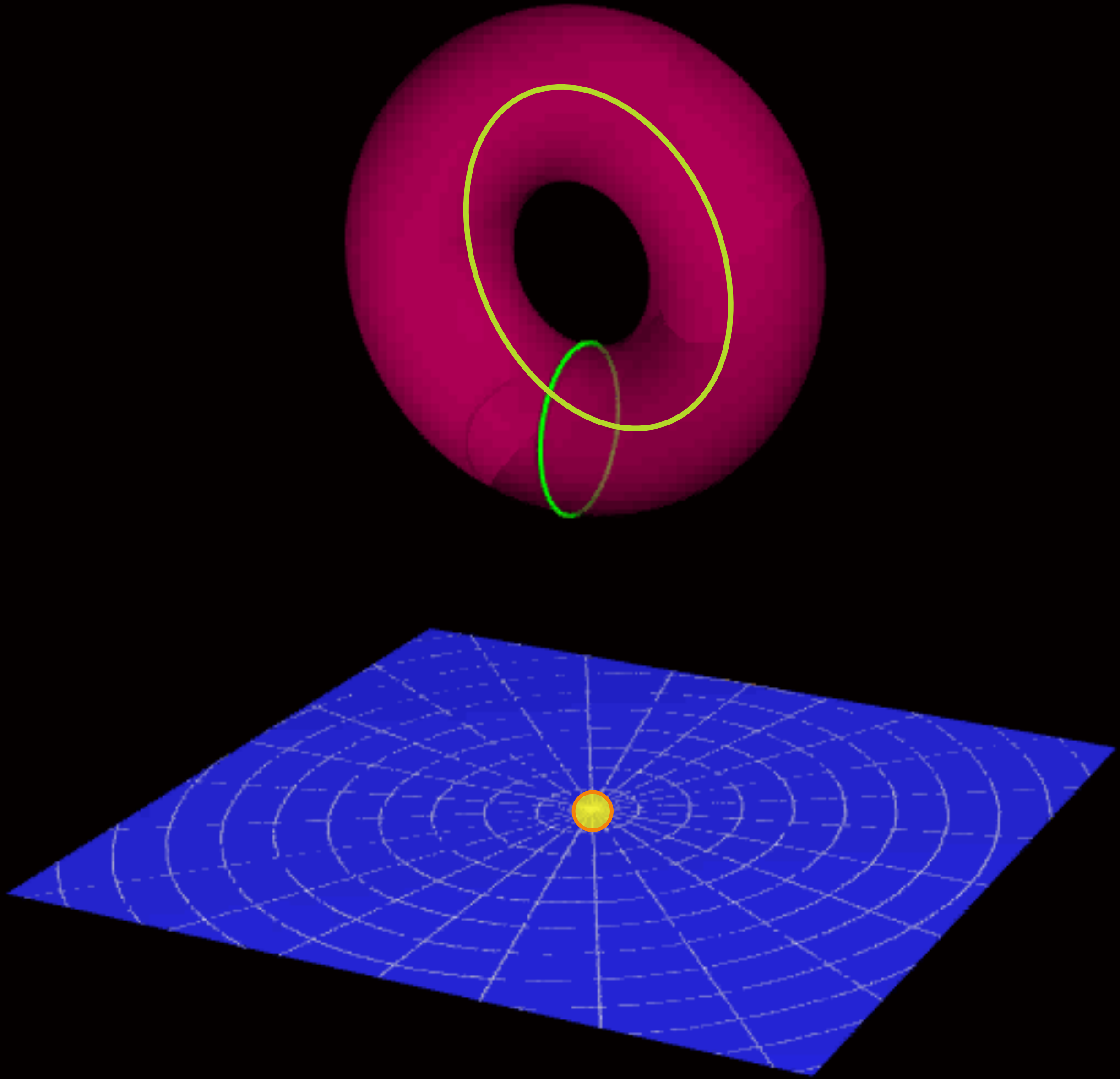
But can we get every consistent QFT in 4 dimensions coupled to gravity from string theory?

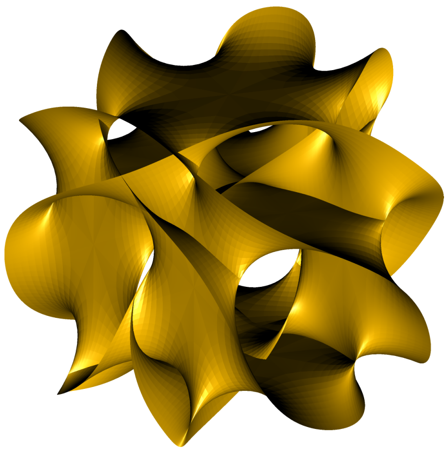
String theory comes with 6 extra dimensions. These should be viewed as compact tiny spaces which have thus far avoided detection.

Many solutions to what the extra compact dimensions can look like.

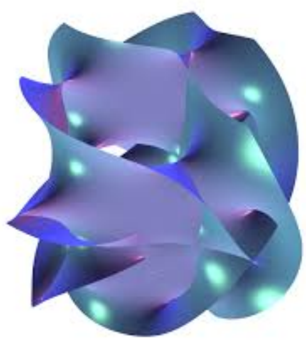








$$G = SU(4),\ \ 2\ generations,\ etc\,.$$



$$G = SU(3)\times SU(5),\ certain\ matter\ Reps\,.$$

?

$$Arbitrary\ consistent\ QFT$$?

It seems we cannot get arbitrary QFT's.

Indeed we seem to obtain only a finite number of QFT's from string theory.

For example with maximal supersymmetry in 4 dimensions ($\mathcal{N} = 4$) the rank of gauge groups we get from string theory is always less than 23. In particular $G = SU(M),\ M > 23$ (all of which are consistent QFT's) do not arise in string theory (coupled to gravity in 4d)!

The QFT's from string theory form a measure 0 of consistent QFT's. It appears that Feynman was almost right: A generic consistent QFT cannot be consistently coupled to gravity!

This raises two questions:

1-Does the fact that most QFT’s do not arise in string theory a deficiency of string theory or a general conclusion about consistency requirements for coupling to quantum gravity?

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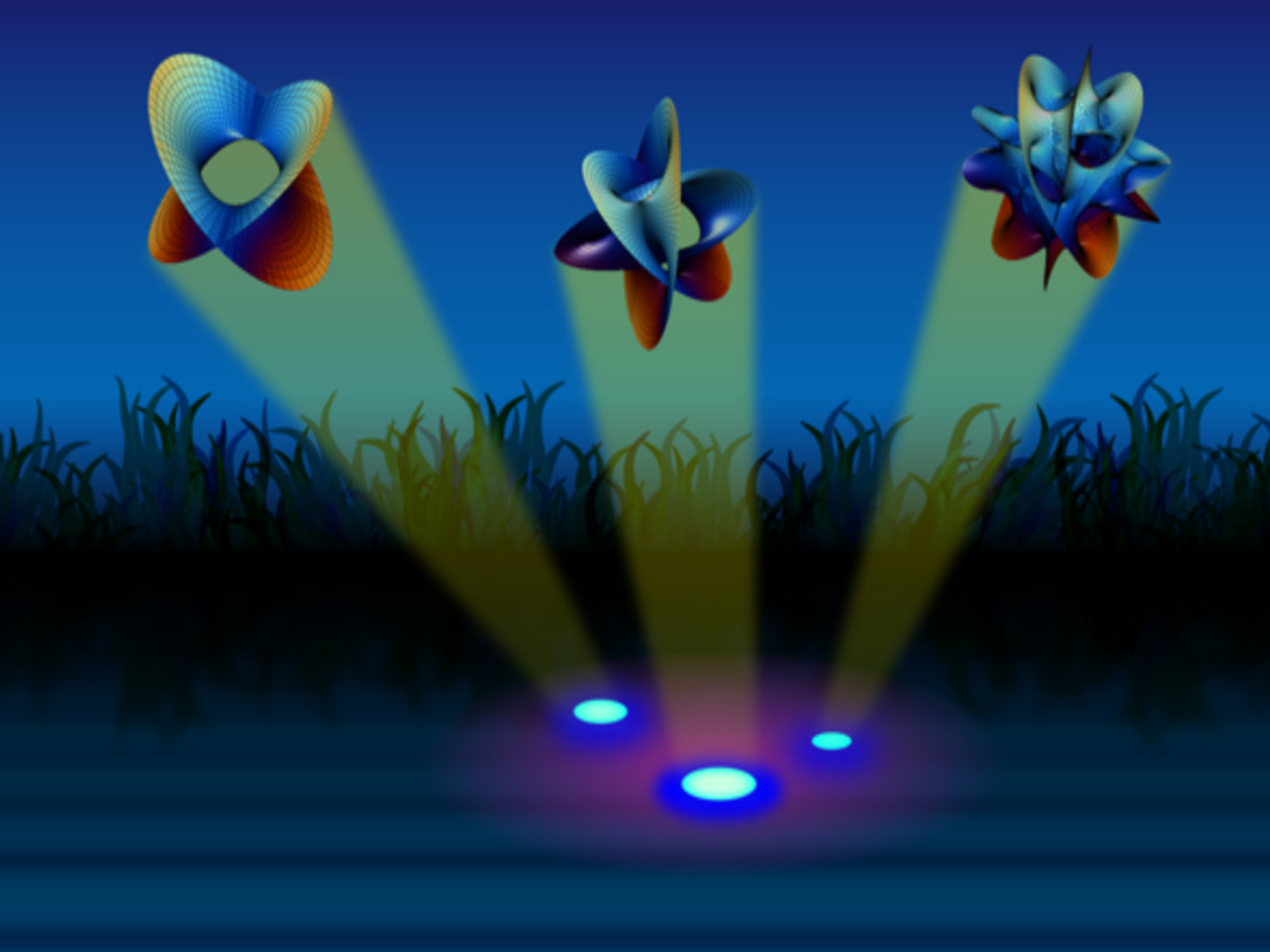
Evidence is emerging that this is not a deficiency of string theory but subtle reasons for consistency of quantum gravity.
Connections with basic facts of quantum gravity such as unitarity and quantum consistency of black holes.

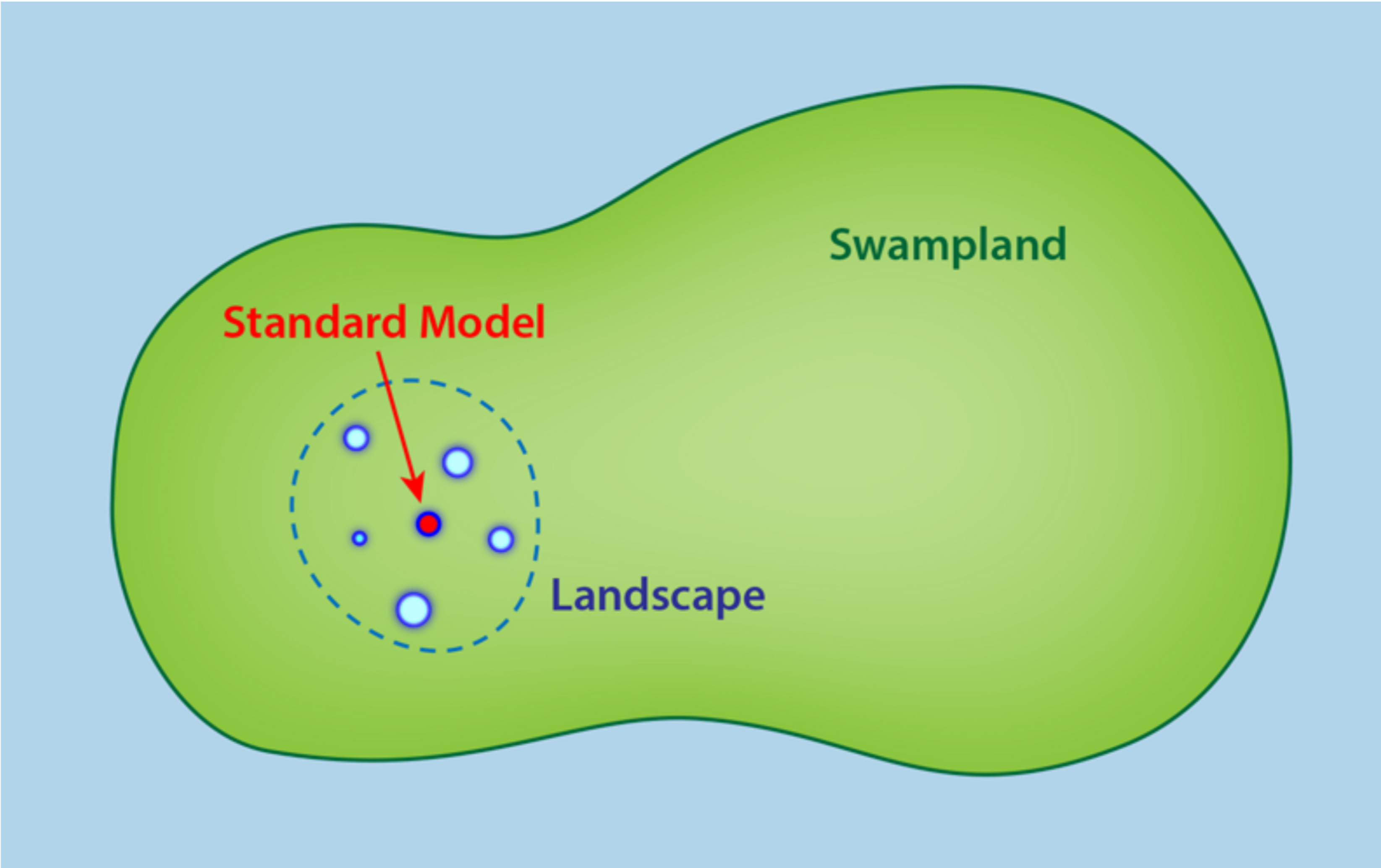
This raises two questions:

1-Does the fact that most QFT’s do not arise in string theory a deficiency of string theory or a general conclusion about consistency requirements for coupling to quantum gravity?

2-What criteria distinguish a ``good’’ QFT (part of the string landscape) from ``bad’’ QFT’s (swampland) which do not arise in consistent quantum gravity theories?

Swampland Program





APS/Alan Stonebraker

Some Proposed Requirements to be in Landscape

1-No Global Symmetries

2-Uniqueness of quantum gravity
(Cobordism Conjecture)

3-All gauge charges appear in the spectrum.
(Completeness)

4-Finite effective range for fields
(Duality Conjecture)

5-The theory admits light higher dimensional objects
(as in string theory)

6-Gravity is always the weakest force
(Weak Gravity Conjecture)

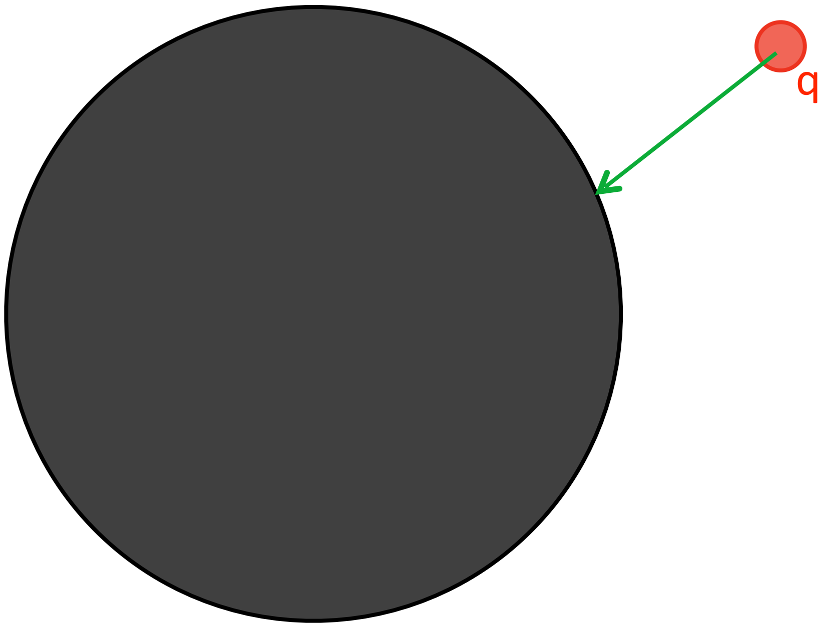
7-Restrictions on critical points of $V>0$ and cosmological implications
(dS Conjectures)

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).

Black holes have thermodynamical properties (Bekenstein-Hawking). In particular they carry an entropy: $S=(A/4)$ where A is the area of the horizon.

1-No Global Symmetries



Throw a conserved global charge in a black hole

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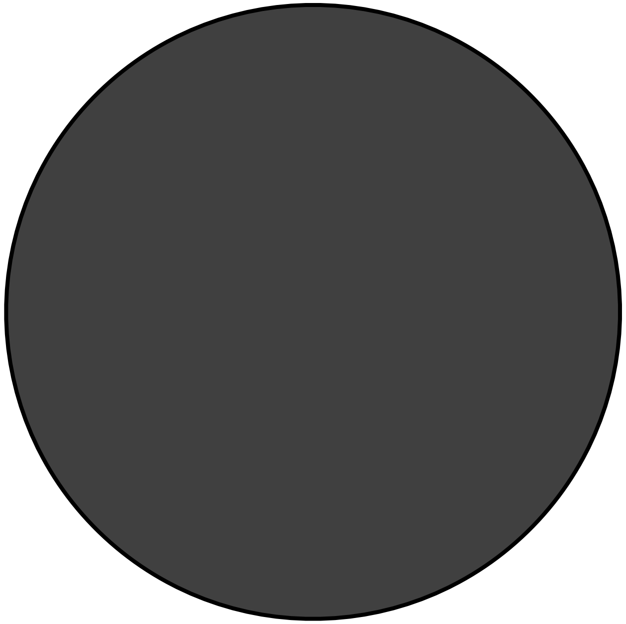

Throw a conserved global charge in a black hole and they would not be conserved due to black hole evaporation!

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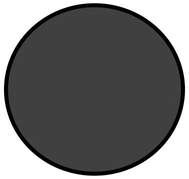

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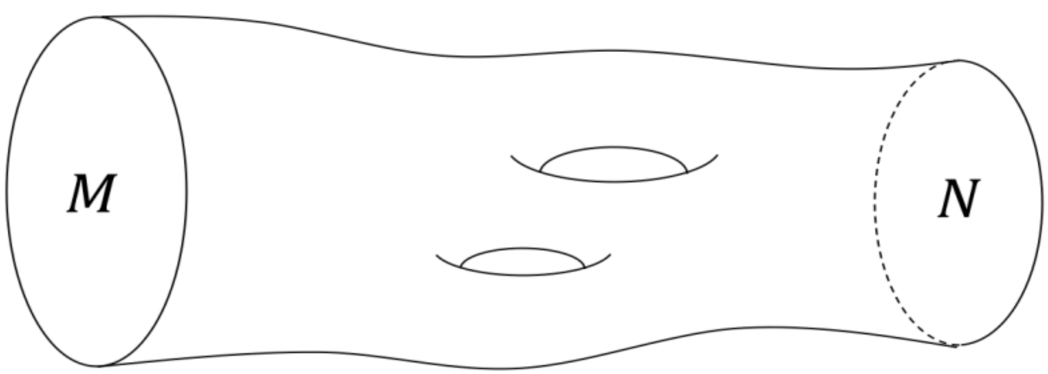
2-Uniqueness of Quantum Gravity

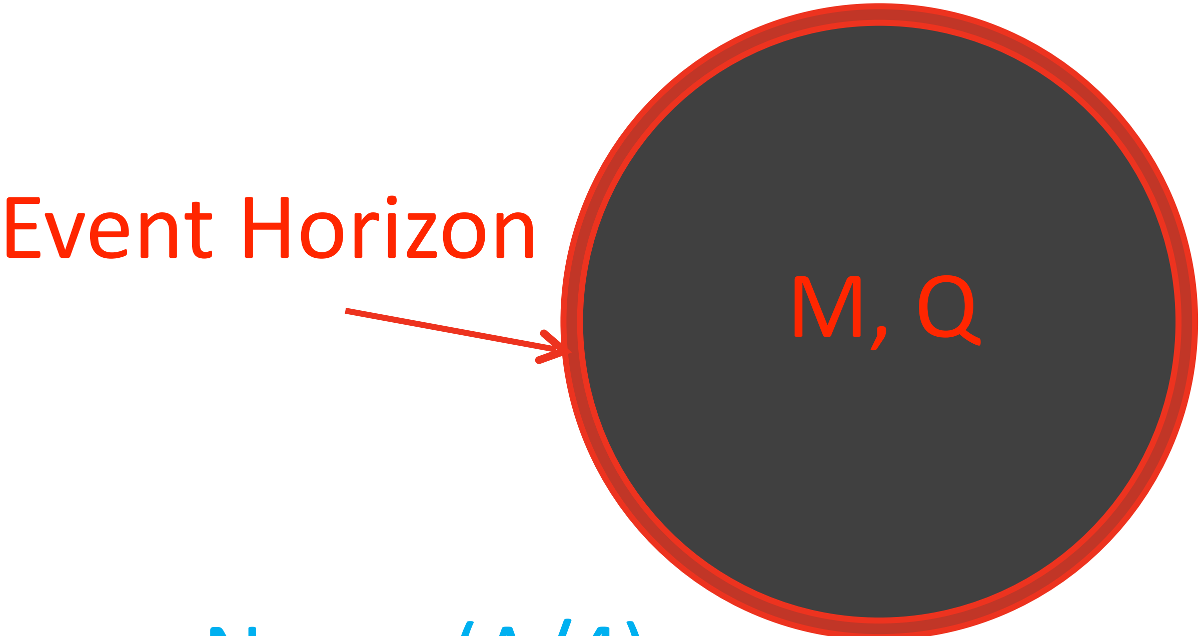
A generalization of no global symmetry conjecture.
Any consistent quantum gravity can be deformed to any other through finite action physical processes.
In the context of string landscape this means any compactification of string theory can be continuously deformed to any other with finite action—no global charge to distinguish them. (Cobordism Conjecture)



Criterion 3-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:



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

$$1=(Q+1)-(Q)$$

Criterion 4: Finite Range for Fields

(Duality Conjecture/Distance Conjecture)

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

$$-\infty < \phi < +\infty$$

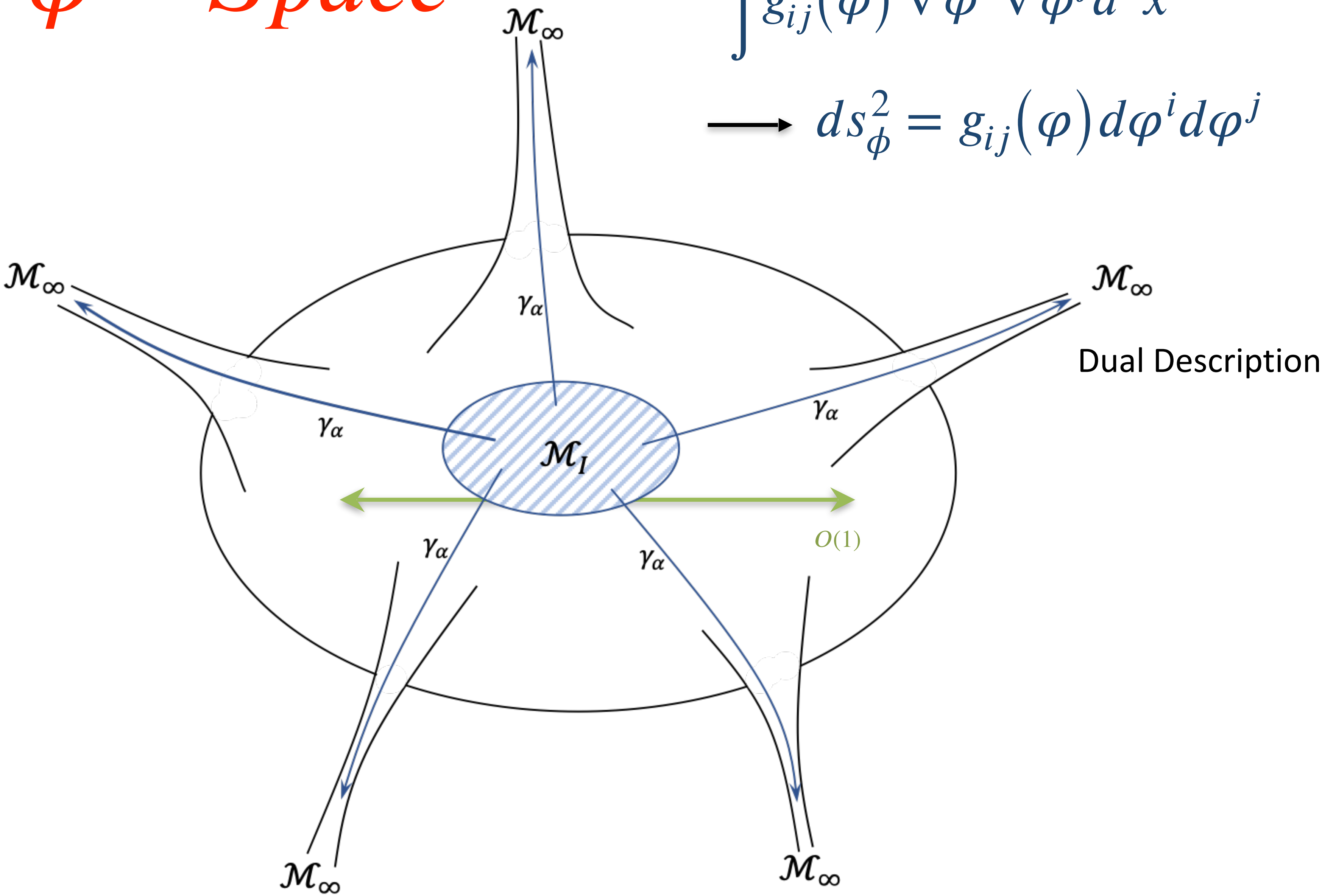
However with gravity it seems the range of this field for a given effective theory description cannot be any bigger than Planck scale:

$$\Delta\phi \leq O(1)\ M_{pl}$$

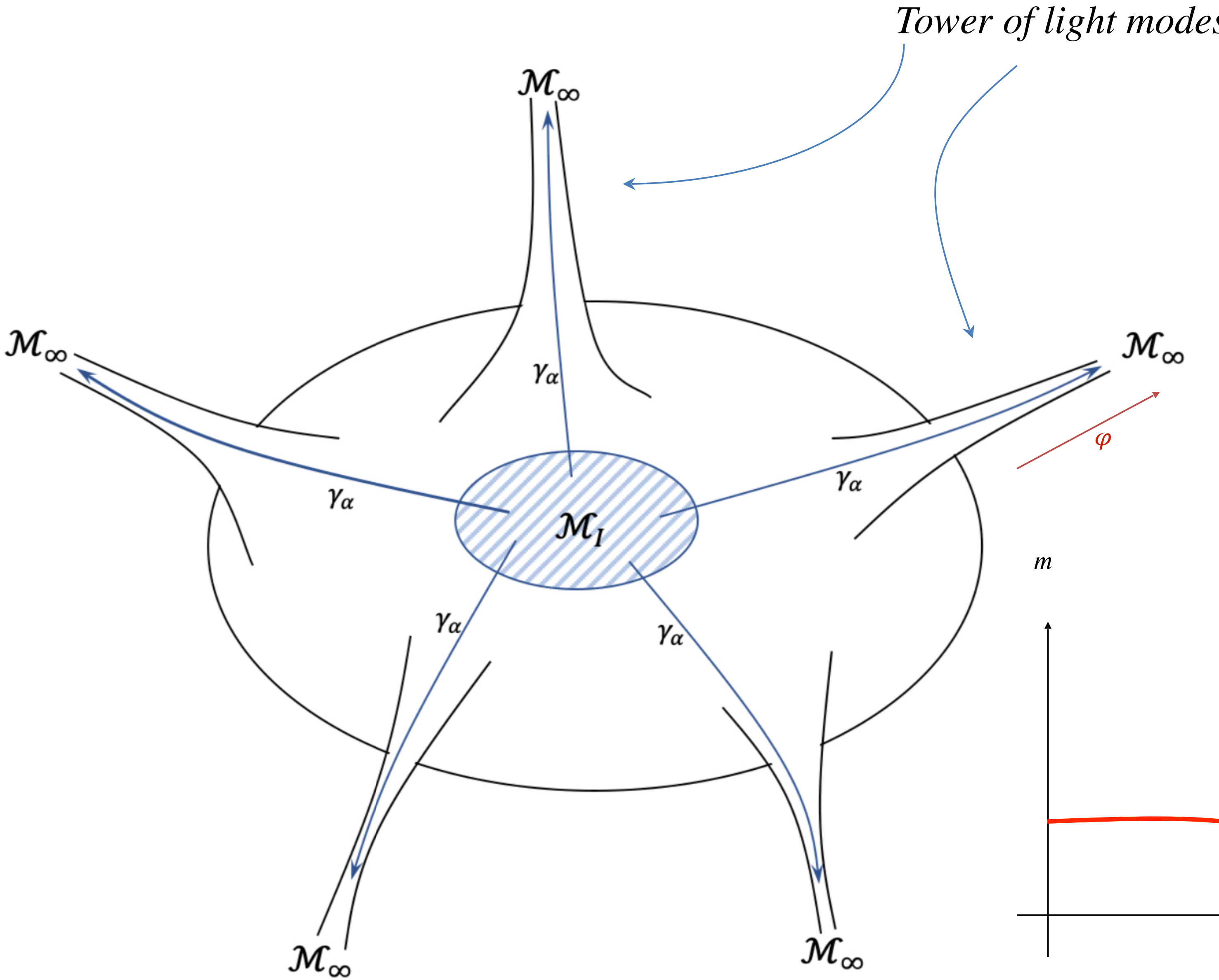
$\varphi - Space$

$$\int g_{ij}(\varphi)\,\nabla\varphi^i\,\nabla\varphi^j d^4x$$

$$\longrightarrow\ ds_\phi^2 = g_{ij}(\varphi)\,d\varphi^i d\varphi^j$$

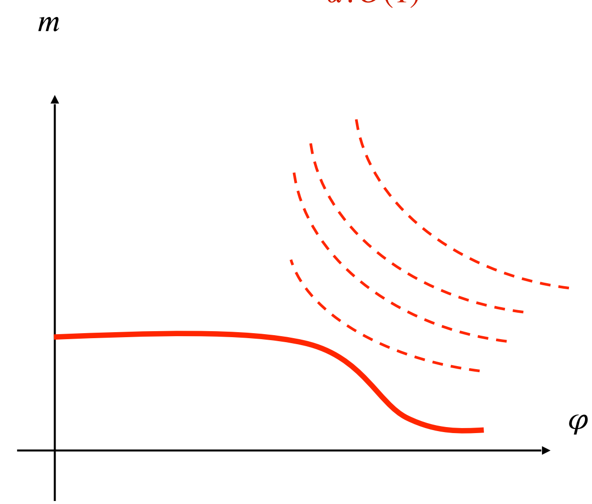


Distance conjecture is a reflection of string dualities



$$m \sim A e^{-\alpha\varphi}$$

$\alpha : O(1)$



A potential application of the distance conjecture:

The cosmological constant can be viewed as a distance in field space (through the backreaction of the metric). Thus we can view

$$\Lambda = e^{-\phi} \qquad\qquad \phi \sim 300$$

$$m \sim e^{-a\phi} \to m \sim \Lambda^a \qquad\qquad a \sim O(1)$$

$$m_\nu \sim \Lambda^{1/4}$$

Criterion 5: Extended Objects

There must be 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

$$R = e^{\phi}$$

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

$$R \gg 1 \rightarrow \phi \gg 0$$

Indeed as $\phi \gg 0$ we begin to get light KK modes (momentum modes around circle become light $E \sim 1/R \sim e^{-\phi}$) and so the effective field theory ignoring these modes is not reliable.

However we can also go the other way: $\phi \ll 0$ $(R \rightarrow 0)$. The duality conjecture predicts something should become light.

But how is that possible? KK modes are becoming heavier. For a theory of particles this is not possible.

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 6: Gravity as the Weakest Force

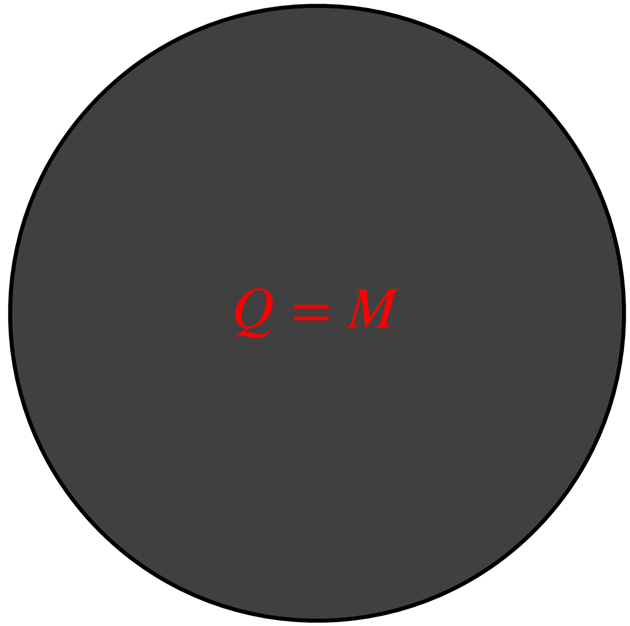
In string compactifications it has been observed that whenever we have charged particles, the electric force between the elementary charged states are stronger than their gravitational attraction (true for our universe):

$F_g = m^2/r^2$ $\quad$ $F_e = e^2/r^2$

$$m < e$$

$$electron: \quad 10^{-23} \ll 10^{-1}$$

Black Hole Explanation of WGC:



$$Q - q \leq M - m \ \& \ Q = M$$

$$\rightarrow m \leq q$$

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

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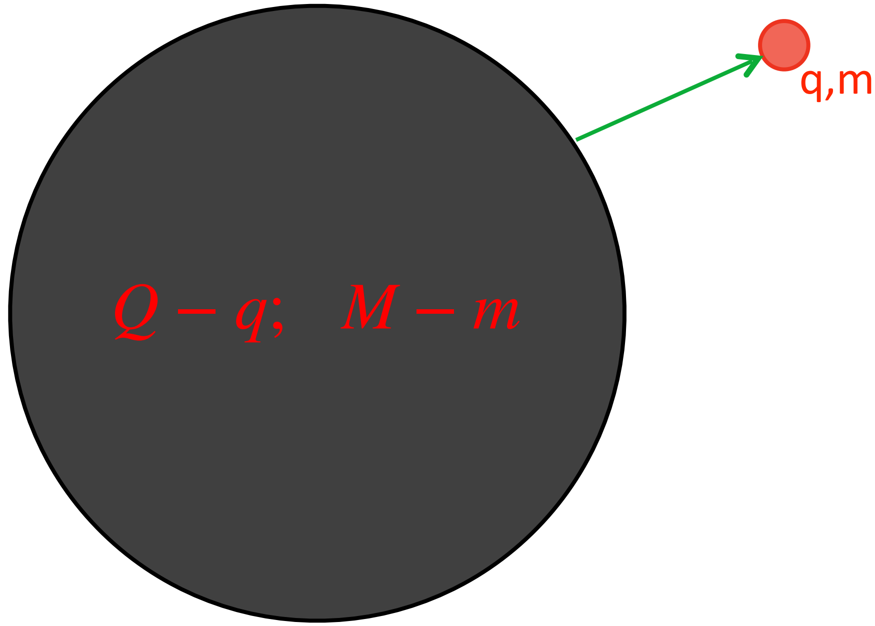

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Further evidence for WGC:

Pure Maxwell theory coupled to Einstein gravity leads to naked singularity (singularities not hidden behind a horizon) in regions with strong E-field.

WGC leads to avoiding it:

1- Completeness of spectrum—> There must be charged states.
2-WGC implies they cannot be too heavy $m<q$.
3-When electric field become large at exactly the right moment charged massive modes get created leading to screening of the E-field and avoiding naked singularity! (consistent with ``Cosmic Censorship'')

Another application of WGC to our universe

In de Sitter space (where we have $\Lambda > 0$) evaporation of small and large charged black holes leads to the condition of existence of states: $$q^{1/2}\Lambda^{1/4} < m < q$$

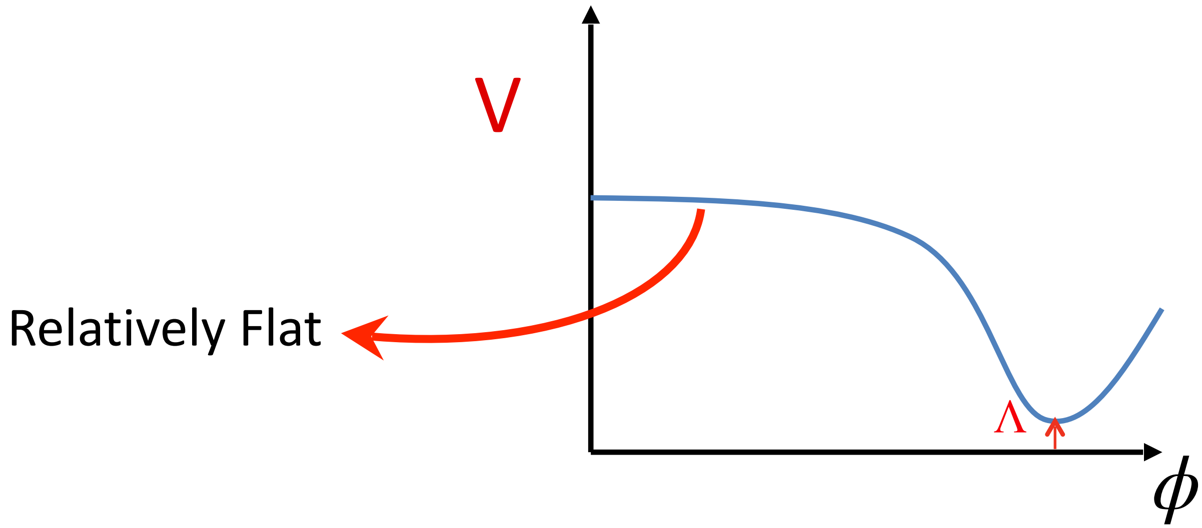
Assuming our universe is approximately dS this leads to prediction for minimal charged state: $$10^{-31} < m < 10^{-1}$$

Consistent with electron mass $m \sim 10^{-23}$

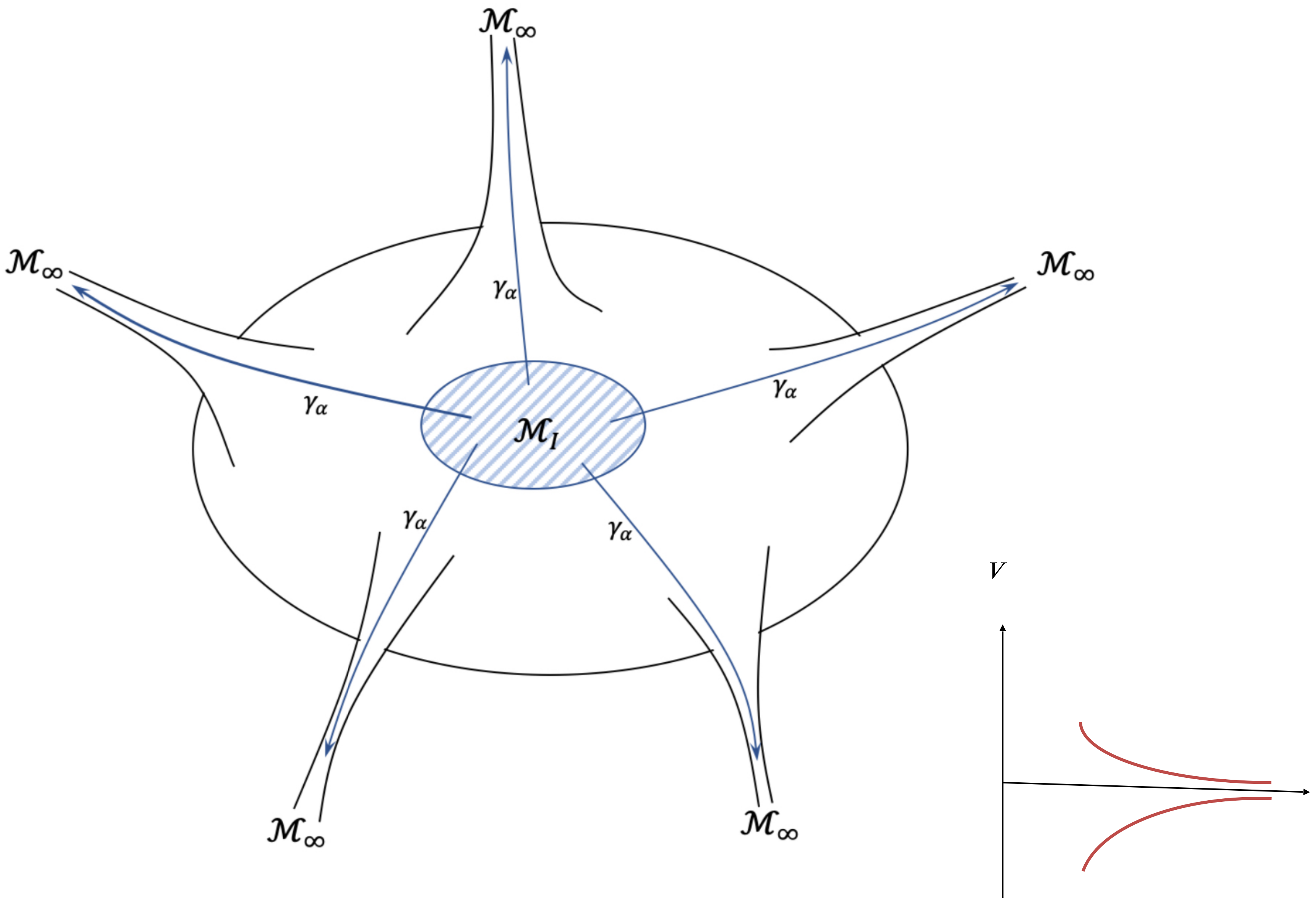
Also interesting that lower bound is m_ν

7- Restrictions on critical points of V>0 or how flat V can get?

An important question for early cosmology. (inflation) and late cosmology (dark energy):



Difficult problem: Supersymmetry must be broken


$\mathcal{M}_\infty$
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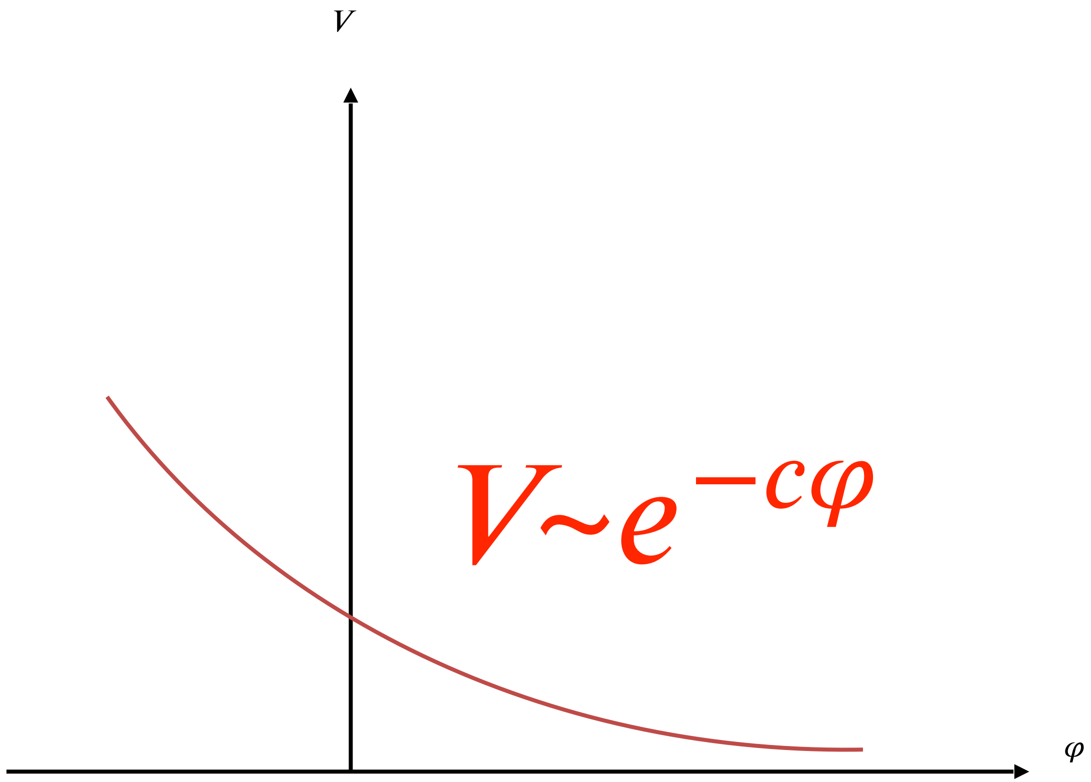
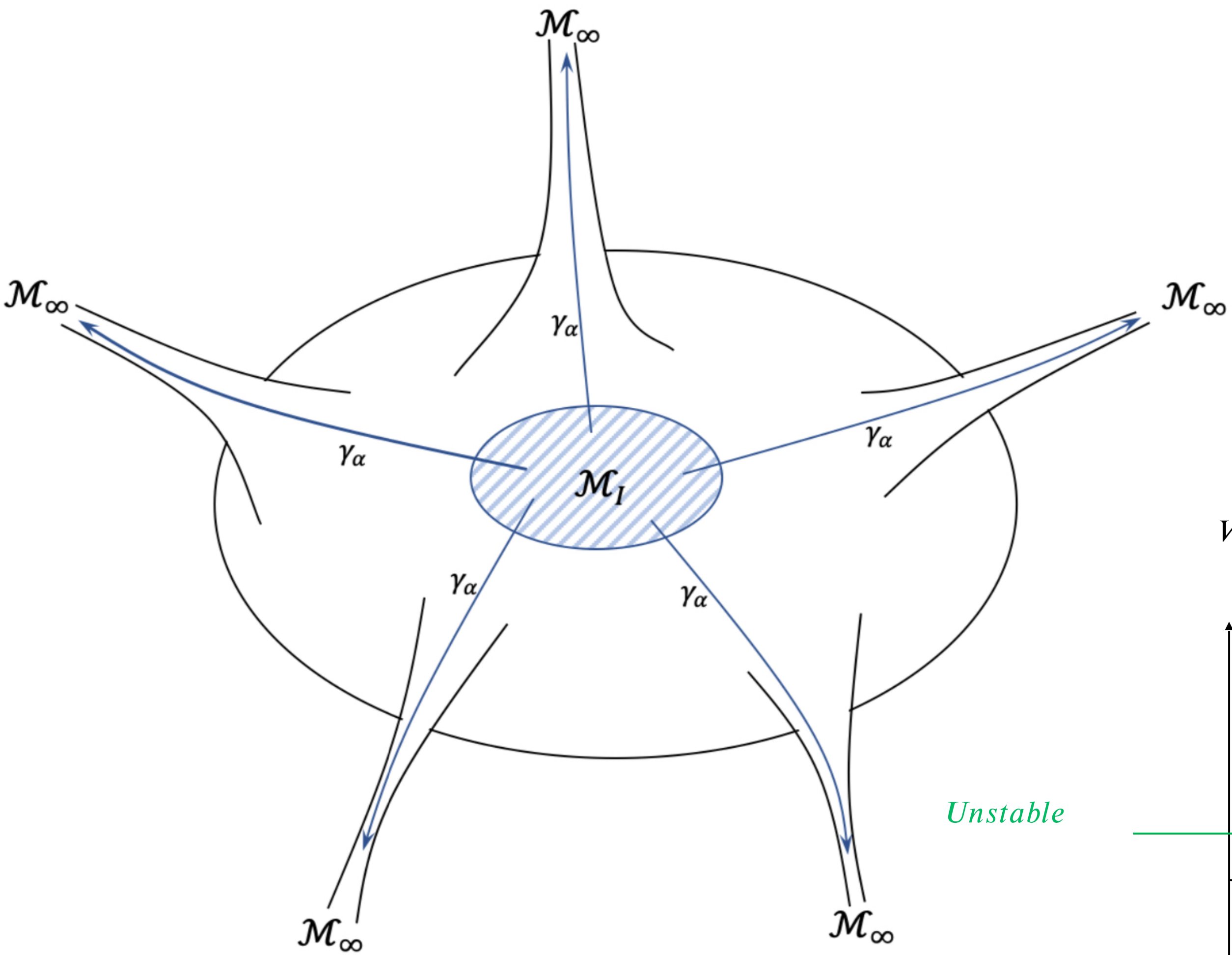
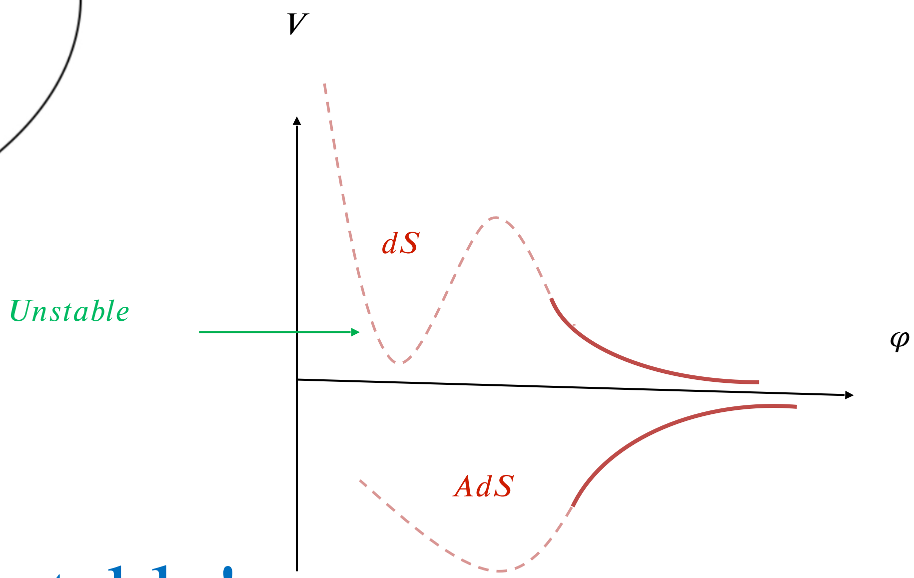
γ_α
$\mathcal{M}_I$
V
φ



General String compactification analysis of known examples suggests for large enough field:

$$\left.\frac{|V'|}{V}\right|_{\infty} \geq \sqrt{\frac{2}{3}}$$



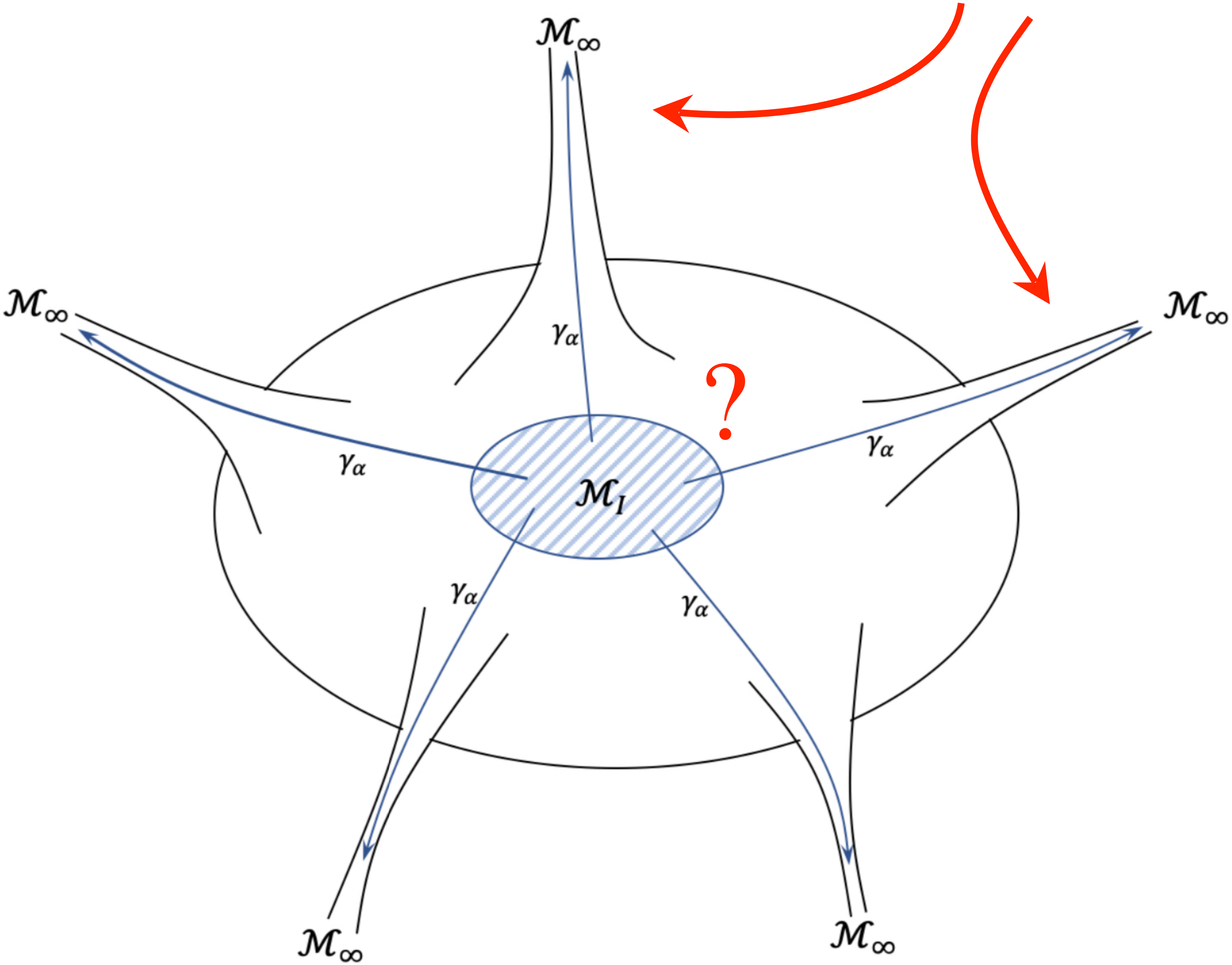


No model of dark energy is stable!

We are not sure if dS exists and if they do, how unstable they may be.

A (dS) Swampland constraint at large field values:
(Fits nicely with the idea of a light tower with mass $m \sim e^{-a\phi}$ contributing to V by m^4)

$$|V'| > cV$$

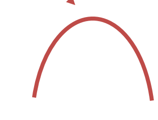


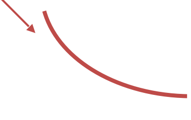
Three possibilities, studied so far, for V inside:

1) No restrictions. (Unnatural, given very specific boundary behavior for V leading to instability)

Related

2) The dS Swampland conjecture: Either V is sufficiently unstable (V”/V <-c’) or |V’|>cV everywhere.





3) Trans-Planckian Censorship Conjecture (TCC): sub-Planckian modes cannot cross the Hubble horizon:

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

Explains the asymptotic behavior $\left.\frac{|V'|}{V}\right|_{\infty} \geq \sqrt{\frac{2}{3}}$

Swampland Conjectures and Inflation:

Inflation not ruled out but typical scenarios seem at least highly fine tuned! The duality conjecture leads to prediction that we cannot have natural arbitrarily large field inflation, because we get a tower of light states and that interferes with inflation. Multi-field may overcome this.

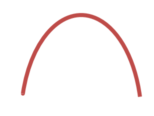
(2) Slope conjecture: For example Plateau models, c<0.02 lead to rather small numbers.

(3) TCC:

$$V \lesssim M_{pl}^{\frac{8}{3}}\left(T_0 T_{eq}\right)^{\frac{2}{3}} \sim \left(10^9 GeV\right)^4$$

$$\epsilon < 10^{-31}$$

$$r < 10^{-30}$$



Puzzles of early universe arise after one makes one major assumption which is at odds with what we have learned in string theory and their dualities:

The main assumption is that you can use Einstein's equation and the description of spacetime all the way back to early times;
However, string theory dualities casts doubt on this assumption: Whenever we consider taking extreme limits in string theory (like $T \to \infty, a \to 0$), the description we start with breaks down and a new description with a new dual spacetime takes over.

Present and Future:

If we assume dS Swampland conjecture we can only be in rolling potential situation. Moreover, in a short time we will roll more than Mp leading to a phase transition.

Estimated time
$$\tau < N\frac{1}{H_0}$$
$$(N \sim 30)$$

If we assume (TCC) it can be either the above scenario, or short-lived meta-stable dS:

$$\tau < \frac{1}{\sqrt{\Lambda}}\ln\frac{1}{\sqrt{\Lambda}} \sim 2\ Tyrs$$

Either of the dS conjectures explains one version of the coincidence problem of why the time scale associated to measured value of the dark energy $\tau \sim \frac{1}{\sqrt{\Lambda}}$ is close to the current age of the universe. The lifetime of the universe cannot be much longer. So in any universe where dark energy is measured (i.e. is a sizable fraction of universe's energy budget) the time scale associated to dark energy is the same as the age of that universe (it could not have been discovered much later, because the universe would have decayed away or transitioned to a new phase!).

Conclusion

Swampland conditions can lead to potentially observable consequences for particle physics and cosmology. Almost all QFT's are in swampland. Therefore fine tunings (such as hierarchy problem) may end up having different solution.

Severe restrictions on consistent QG theories.

These ideas suggest restrictions on light matter fields; moreover positive energy in the context of quantum gravity lead to local and global instabilities— may explain coincidence problem. New ideas (dualities) expected to play a key role for early universe.

Thank You!