The Dark Dimension and the Swampland

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Based on work
with
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Consistent theories of quantum gravity:

Very restrictive.

Consistency of QFT insufficient.

Naive Naturalness ideas fail

Swampland Program

Swampland Program aims to find criteria to distinguish consistent vs. inconsistent QG. These criteria replace the notion of naturalness.

The aim of this talk is to combine Swampland criteria together with observations in the context of the "cosmological hierarchy problem"

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

to show that we live in a specific corner of the QG landscape.

Plan for the talk:

1-Swampland criteria:

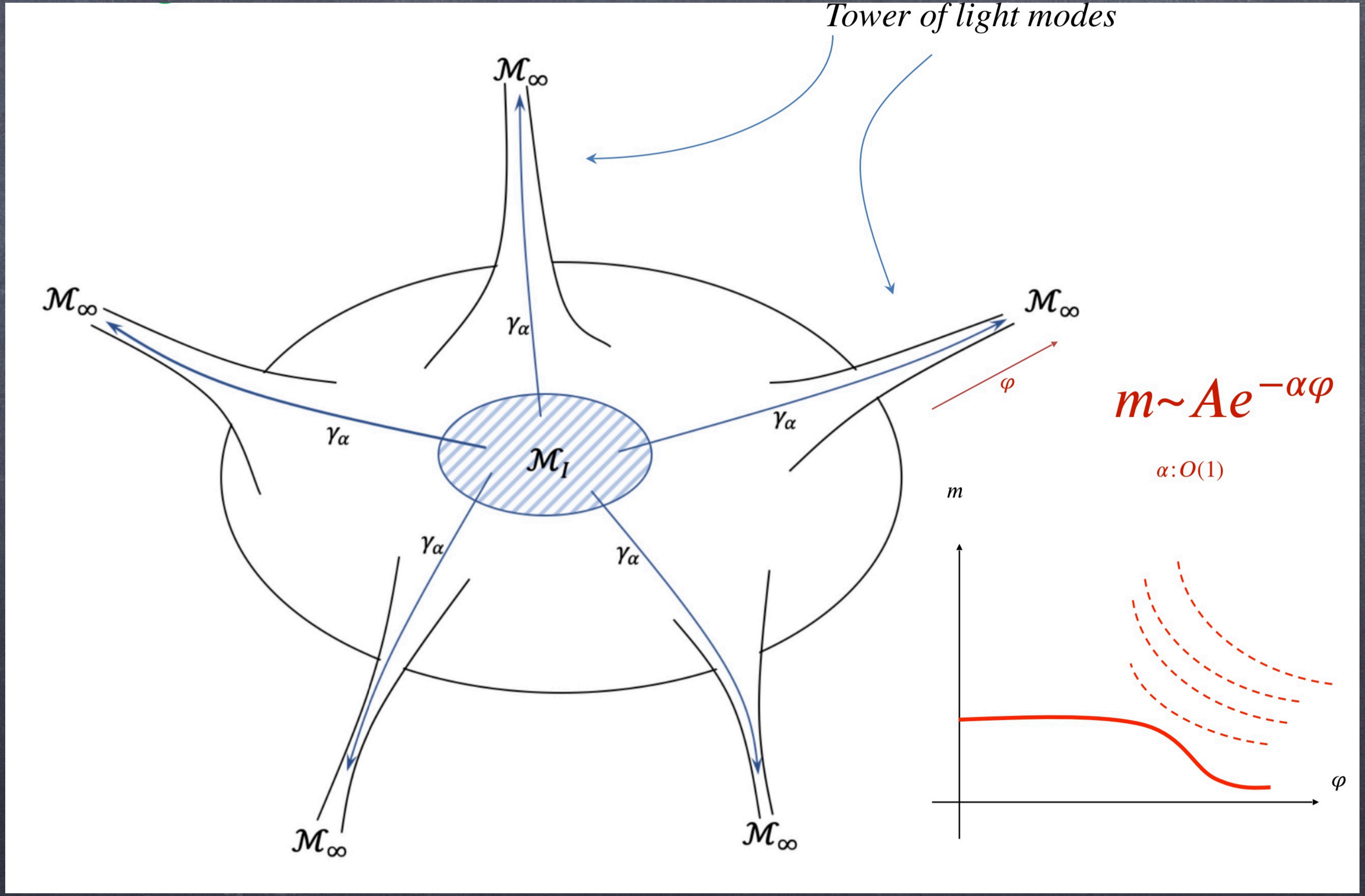
Distance/Duality conjecture

2-Application to observed Universe

3-Phenomenological aspects and a unification of hierarchies:

Mesoscopic dimension, neutrino masses, Higgs mass, prediction of a new UV scale, ...

Distance/Duality Conjecture [OV '06]; [LPV '19]:



Moreover the tower of light states is either a tower of KK modes, or light string states. Strong evidence from string theory ("The String emergence proposal" [LLW '19]).

In the context of dS/AdS the cosmological constant plays the role as an effective field $\Lambda = \pm e^{-\phi}$ thus we have a tower of states whose masses go as

$$m \sim |\Lambda|^{\alpha}$$

where

$$\frac{1}{d} \leq \alpha \leq \frac{1}{2} \quad \text{for } \Lambda > 0$$

(Upper range Higuchi bound,
lower range 1-loop vacuum energy)

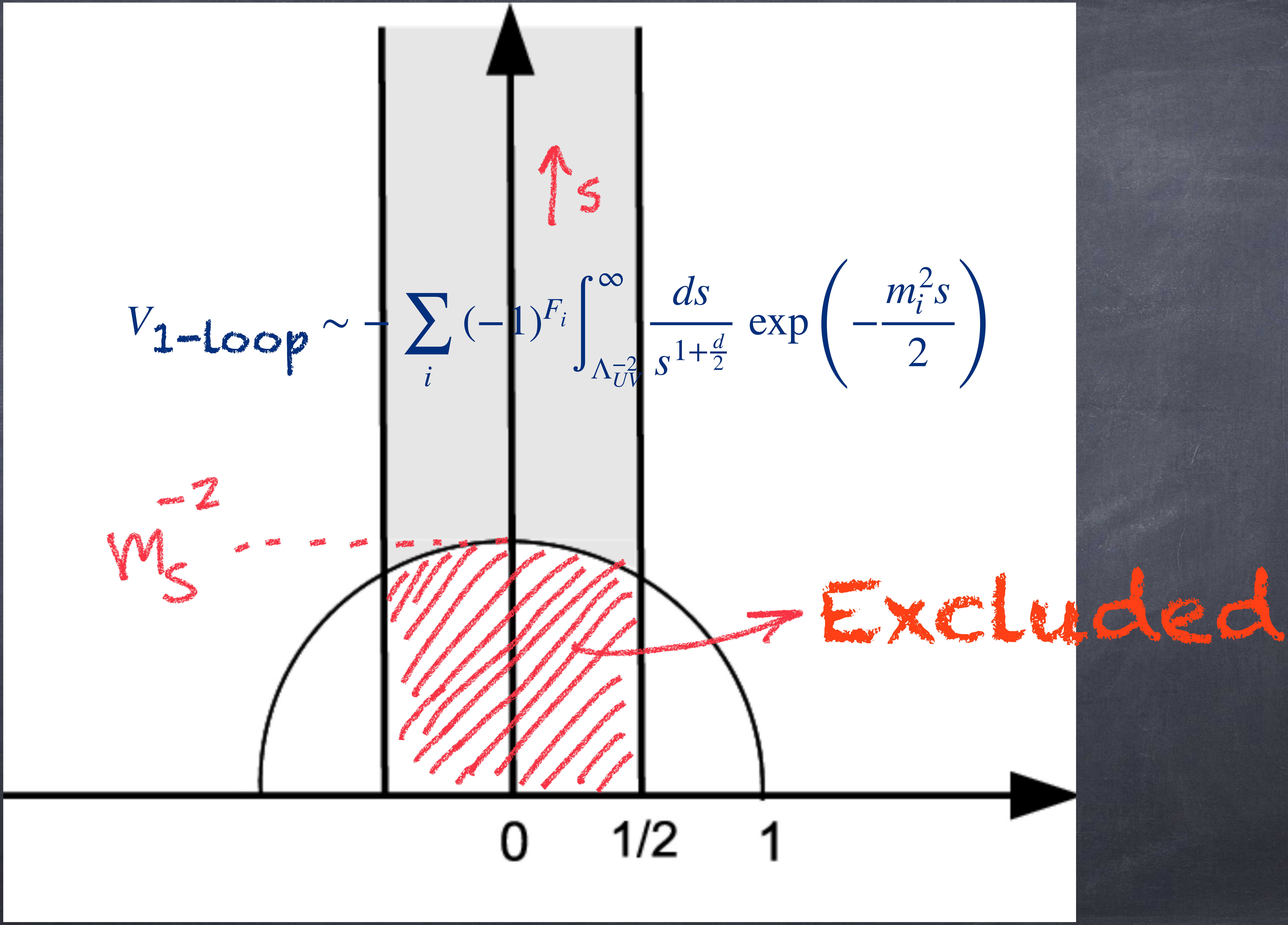
Note that this is surprising from EFT: Why do light towers alone dictate Λ?

Example: Non-SUSY compactifications of string theory in weak coupling limit.
$V_{1-loop} \sim m_s^d$ (positive if more light fermions than bosons as in O(16)xO(16) strings)

$(g_s \to 0) \Rightarrow V \to 0$ (conformal invariance) and $m_s \sim g_s^a,\ a > 0.$

Magic of modular invariance: only light tower of string modes contribute.
The contribution of higher mass states are screened as they are redundant dof.

$$V_{1\text{-loop}} \sim -\sum_i (-1)^{F_i} \int_{\Lambda_{UV}^{-2}}^{\infty} \frac{ds}{s^{1+\frac{d}{2}}} \exp\left(-\frac{m_i^2 s}{2}\right)$$



Application to our Universe

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

This is an extreme range in field space. We thus predict using distance conjecture that there is either a tower of light string or KK modes whose mass scales as

$$m \sim |\Lambda|^{\alpha} \text{ with } \frac{1}{4} \leq \alpha \leq \frac{1}{2}.$$

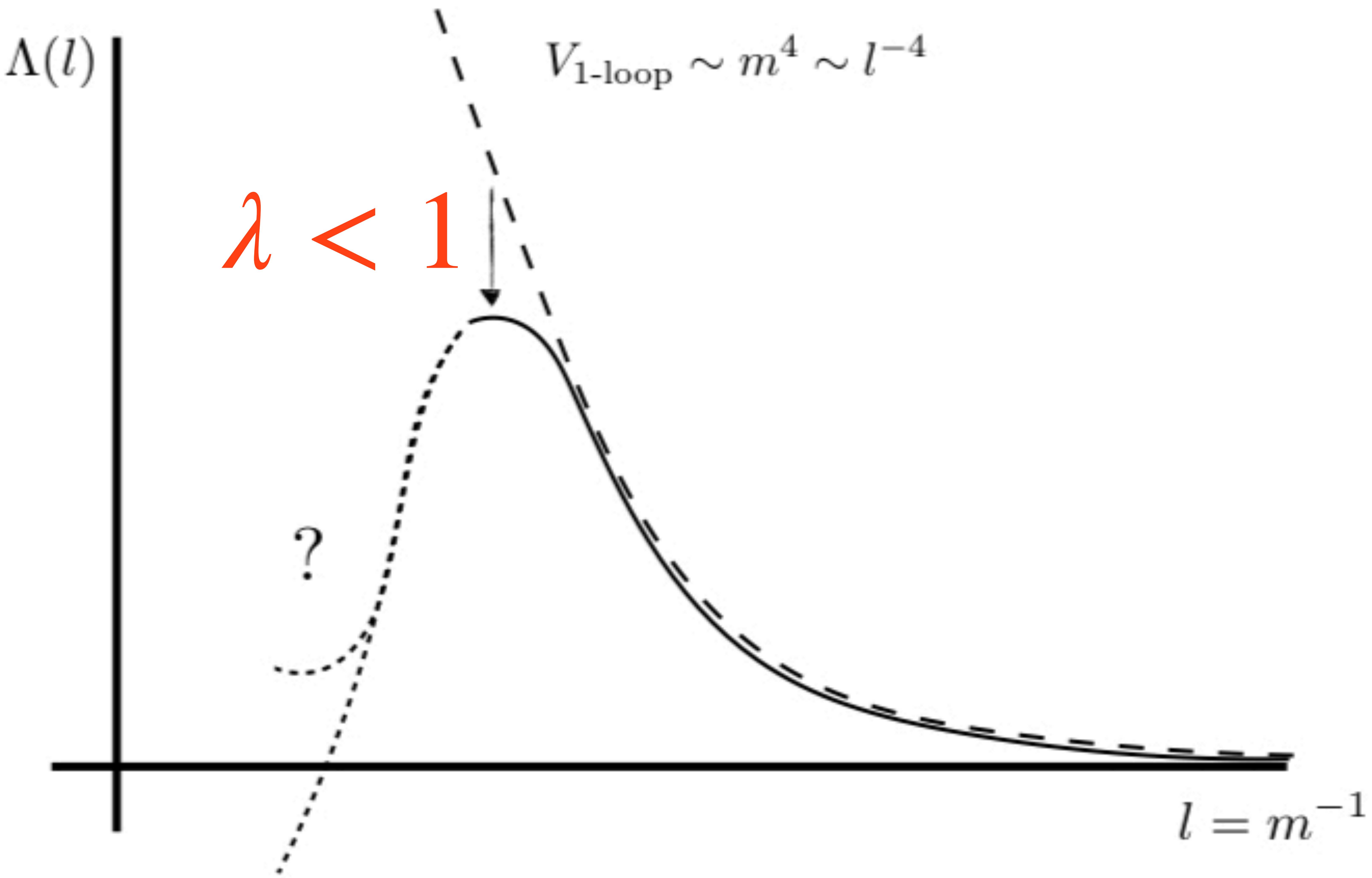
This in particular means gravity gets modified at the scale of m. The only possibility given the observations that Newtonian force law works up to about $30\mu m$ is the lower bound $\alpha = \frac{1}{d} = \frac{1}{4}$

$$\lambda m = \Lambda^{\frac{1}{4}}$$

This gives $m^{-1} \sim \lambda(88\mu m)$.

We now estimate

$$\lambda \sim 10^{-1} - 10^{-3}$$



$\Lambda(l)$
$V_{\text{1-loop}} \sim m^4 \sim l^{-4}$
$\lambda < 1$
?
$l = m^{-1}$

Moreover for the asymptotic growth to have set in and not to lead to change in exponent of m, λ cannot be too small, i.e. $\lambda \geq m^{\frac{1}{2}}$, which leads to $\lambda \sim 10^{-1} - 10^{-3}$ and

$$m^{-1} \sim (0.1 - 10)\,\mu m$$

This is consistent with current observations which shows Newton's law valid at least till $30\mu m$ [Adelberger et. al.].

KK tower or string tower?

Cannot be a string tower, effective theory of gravity valid far above eV

Must be a KK tower!

How many extra mesoscopic dimensions?

The gravity becomes strong at the higher dimensional Planck scale

$$\hat{M} = m^{\frac{n}{n+2}} M_{pl}^{\frac{2}{n+2}}$$

(for n extra mesoscopic dimensions)-

For n>2 this gives $\hat{M} < TeV$ so it is ruled out. For n=2 this gives TeV scale.

However, emission of the KK modes leaves a trace in neutron stars and supernova explosions (can potentially cool a proto-neutron star too fast to be compatible with observations if the tower is too light).

This leads to [Hannestad et.al. '20] extra dimensions with length scale in the micron range to be ruled out except 1 extra dimension!

- For the case of two extra dimensions: $l < .00016\ \mu m$. Too small!

- For the case of a single extra dimension: $l < 44\ \mu m$

.... So we predict

The Dark Dimension: One extra mesoscopic dimension of length .1-10 micron!
This leads to a fundamental Planck scale in higher dimension

$$\hat{M} \sim m^{\frac{1}{3}} M_{pl}^{\frac{2}{3}} \sim \lambda^{-\frac{1}{3}} \Lambda^{\frac{1}{12}} M_{pl}^{\frac{2}{3}} \sim 10^9 - 10^{10} GeV$$

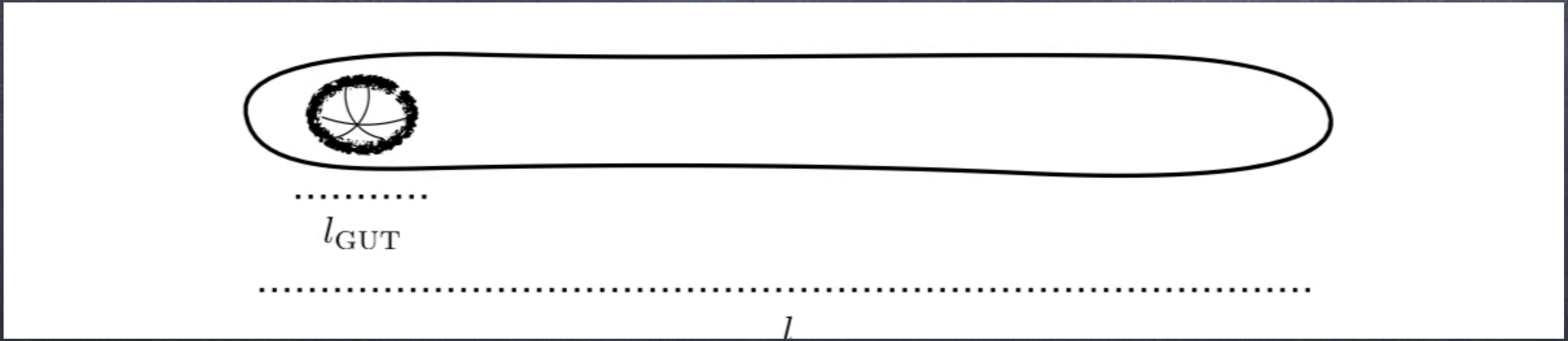
Comparing to large extra dimension scenarios [A'90,ADD'98,DDG'98,RS'99] the motivation and results are very different:
Those approaches bring down the Planck scale to the weak scale to solve the EW hierarchy. For example in ADD the number of large extra dimensions is 4 (or more) with length scale $10^{-12}m$ (or smaller).
We are motivated instead by Cosmological hierarchy and Swampland ideas (consistency of QG) and the only option is 1 extra dimension in the micron range.

Phenomenological aspects

GUT brane: Should be localized in the mesocopic dimension for its coupling not to be too weak:

$$\frac{1}{e^2} = V_{SM}\,\hat{M}^4 \sim 10^2$$

(A nice example is F-theory GUT model:)



Neutrinos: Given that the bulk must have extra fermions it is natural to identify them as sterile neutrinos 3-components of which can act as right-handed neutrino to give active neutrinos a mass. Indeed this has already been studied in the context of LED [ADDM-R,DDG]. However the scenario we have is more in line with [Carena et.al.'17]:

$$\mathscr{M} = \begin{pmatrix} 0 & \frac{y\langle H\rangle}{\sqrt{l\hat{M}}} \\ \frac{y\langle H\rangle}{\sqrt{l\hat{M}}} & \frac{1}{l} \end{pmatrix}$$

Leads to $m_\nu = \frac{y^2 < H^2 >}{\hat{M}}$

With $y \sim 10^{-2} - 10^{-3}$

$$M_{GUT}^{eff} = y^{-2}\hat{M} \sim 10^{15} - 10^{16} GeV$$

Assuming that bulk dynamics and GUT dynamics communicate and avoid significant hierarchy in neutrino masses (sterile and active neutrinos having similar masses) this would fix the Higgs vev:

$$\frac{y^2\langle H\rangle^2}{\hat{M}} \sim \frac{1}{l} \Rightarrow \langle H\rangle \sim \frac{1}{y}\sqrt{\frac{\hat{M}}{l}} \sim \frac{\Lambda^{1/6}M_{pl}^{1/3}}{y\,\lambda^{2/3}} \sim 10 - 10^3\,GeV$$

Instability in Higgs potential at $10^{11} GeV$ may be avoided in our scenario because that is where we hit the higher Planck scale and we get new towers of charged states and black holes. Especially if this scale restores SUSY the instability would be avoided.

Other Phenomenological aspects:

-Neutrino oscillations (SBL anomalies with eV sterile neutrino –Hannestad et.al.+many other works)

-Ultra High Energy cosmic ray cutoff is close to $\hat{M}$. GZK limit; any observable effects?
[arXiv 2205.13931, Anchordoqui]

-H_0 tension resolution by the "Early Dark Energy" scenarios may be relevant here (scalar radion field playing a key role).

-Wider options for DM (Primordial BH)
[arXiv 2206.07071, Anchordoqui, Antoniadis, Lust]

Work in progress with Gonzalo, Montero, Obied and Valenzuela on cosmological aspects.

Summary

Small dark energy + Swampland + observations uniquely lead to a single mesoscopic dimension **The Dark Dimension** in the micron range
(we resisted the temptation of calling it the 'omicron' !).

Possible **Unification of hierarchies (Dirac's dream)**:

$$l_{macro} \sim \Lambda^{-1/2}; \qquad m_\nu \sim \lambda^{-1}\Lambda^{1/4}$$

$$l_{meso} \sim \lambda\Lambda^{-1/4}. \qquad \langle H \rangle \sim y^{-1}\lambda^{-2/3}\Lambda^{1/6}M_{pl}^{1/3}$$

$$\hat{M} \sim \lambda^{-1/3}\Lambda^{1/12}M_{pl}^{2/3}$$

$$M_{GUT} \sim y^{-2}\lambda^{-1/3}\Lambda^{1/12}M_{pl}^{2/3}$$

Easily falsifiable: improvement on the precision measurement of deviation from Newton's law by a factor of 10-100.
Or improvement of astrophysical bounds.

Coincidence of many interesting phenomenological aspects!