Swampland and the Dark Sector

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HirosiFest @ Kavli IPMU

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So far we have written 28 articles together
starting from 1990!
including 3 on Swampland program with 500+ citations

My talk today will focus on my recent papers which is the direct result of my papers with Hirosi on the Swampland Program

I will explain how two of the Swampland criteria:

The Distance/Duality Conjecture (2006)
dS Conjecture (2018)

which Hirosi and I conjectured

sheds light on the
Dark Sector in our Universe

Based on two papers:

M. Montero, I. Valenzuela, C.V.
arxiv.org/2205.12293

E. Gonzalo, M. Montero, G. Obied, C.V.
arxiv.org/2209.09249

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”

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

Plan for the talk:

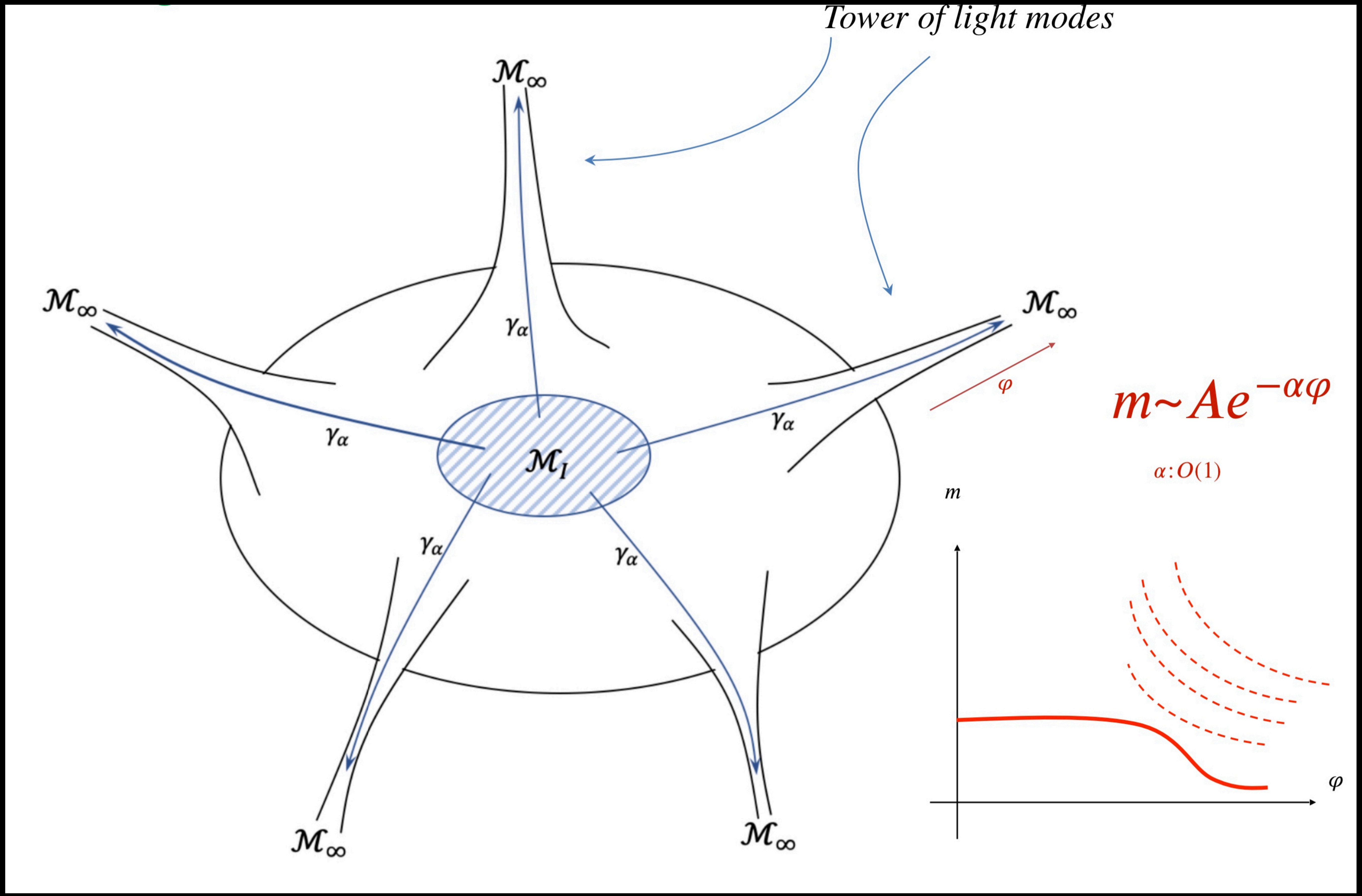
1-Swampland criteria:
Distance/Duality conjecture

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

4-Cosmological Aspects:
Prediction of Dark matter as KK gravitons
Explanation of coincidence problem

Distance/Duality Conjecture
[Ooguri,V. 2006]



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]).

Most of the evidence for the distance conjecture comes from SUSY examples of string landscape but it seems to apply also to non-supersymmetric ones.

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

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

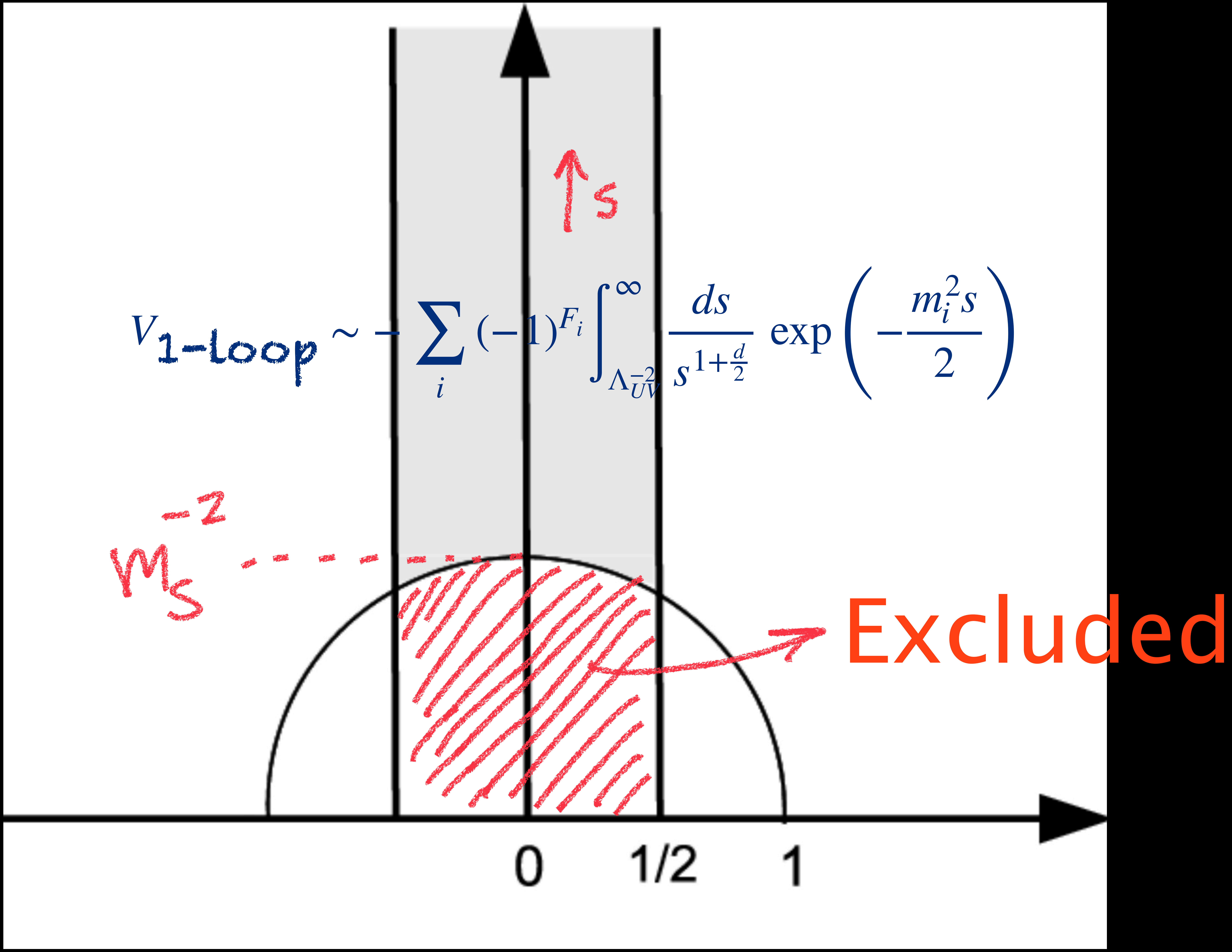
(Upper range Higuchi bound,
lower range 1-loop vacuum energy)

Solution to the cosmological constant problem, because:

$$\Lambda \sim m^{\frac{1}{\alpha}}$$

This means the light tower cutoff and not the UV cutoff determine the cosmological constant!

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



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

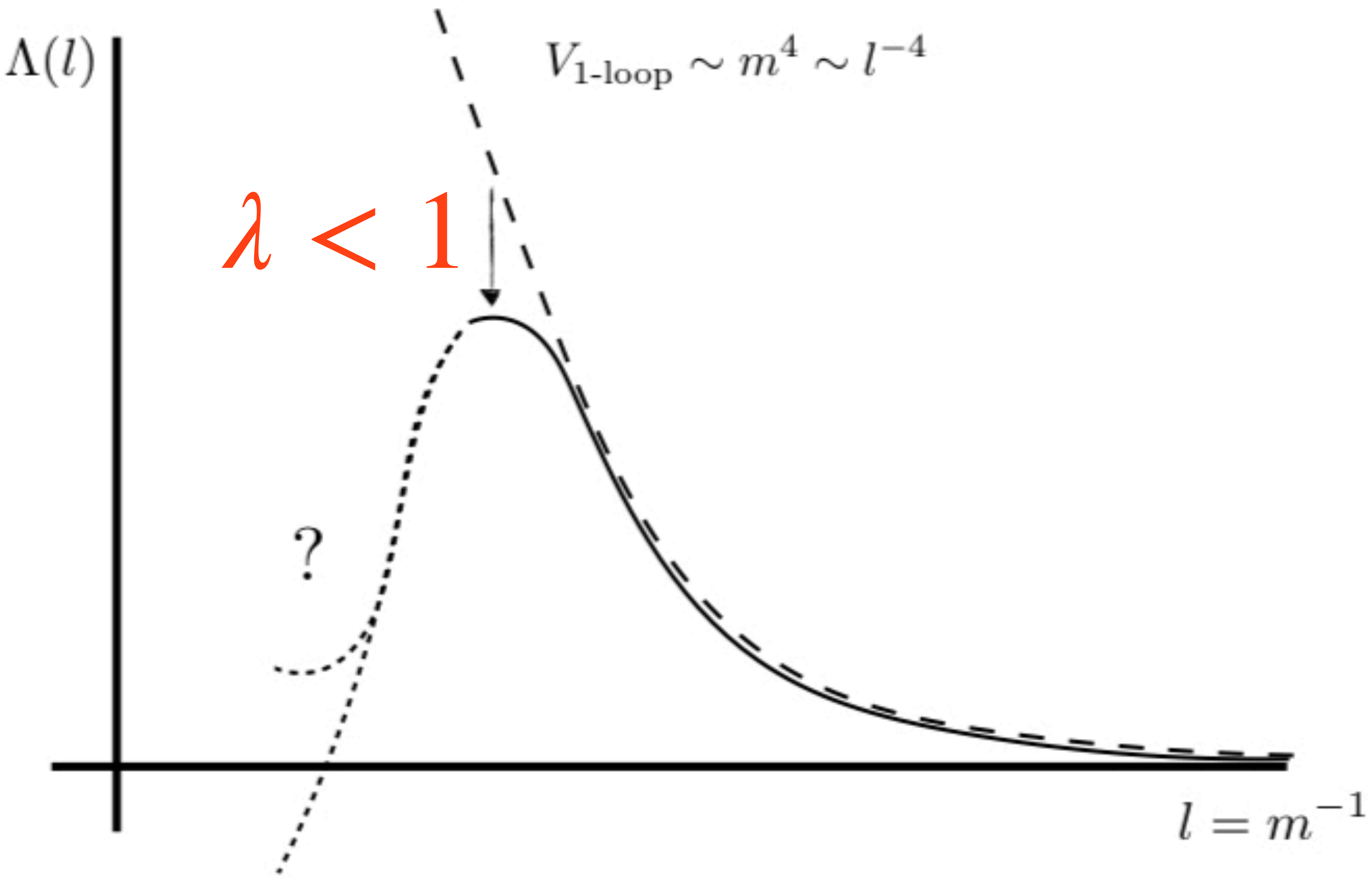
$$m \sim |\Lambda|^{\alpha} \text{ with } \frac{1}{4} \leq \alpha \leq \frac{1}{2}.$$

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 $\alpha = \frac{1}{d} = \frac{1}{4}$

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

If $\lambda = 1$, this would give $m^{-1} \sim 88\mu m$ which is ruled out. 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. $\lambda^4 \geq m^{\frac{1}{2}}$, which leads to $\lambda \sim 10^{-1} - 10^{-3}$ and

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

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 and decays of the trapped KK modes created after supernova explosions leaves a trace in the resulting neutron stars.

Avoiding Neutron-star excess heat PSR J0952+0755) extra dimensions with length scale in the micron range ruled out except 1 extra dimension! [Hannestad et.al.'03]

- For the case of a single extra dimension: l < 44 μm
- For the case of two extra dimensions:l< .00016 μm-Too small based on Swampland!

…. 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

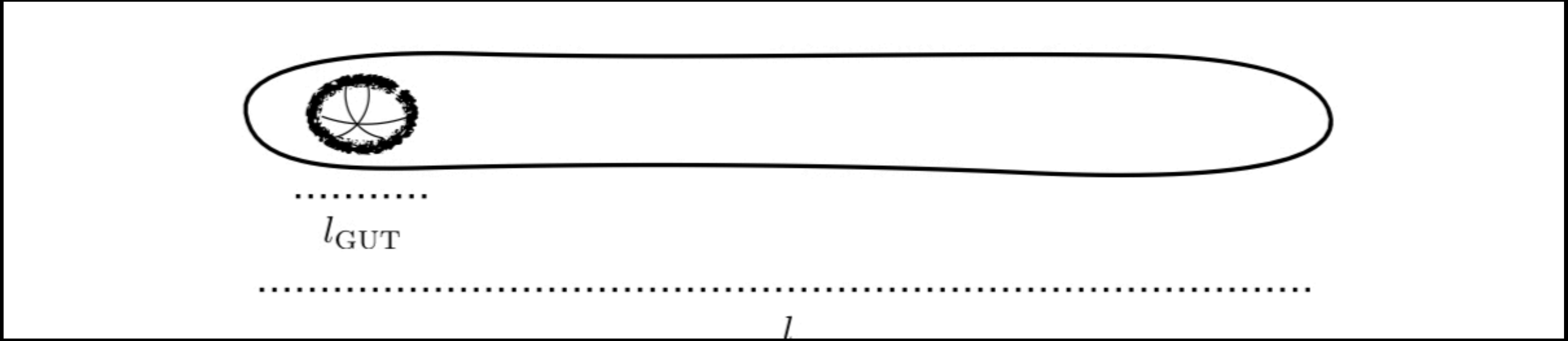
$$\hat{M} \sim m^{\frac{1}{3}} M_{pl}^{\frac{2}{3}} \sim \lambda^{-\frac{1}{3}} \Lambda^{\frac{1}{12}} M_{pl}^{\frac{2}{3}} \sim 10^{9} - 10^{10} GeV$$

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:)



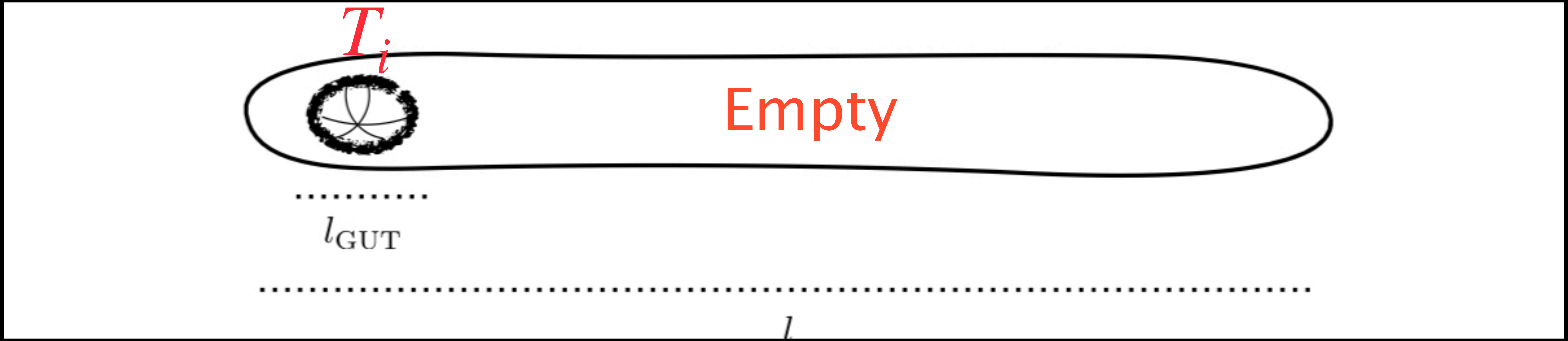
Assuming that bulk dynamics and GUT dynamics communicate and avoid significant hierarchy in neutrino masses (sterile and active neutrinos having similar masses) this would fix the Higgs vev:

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

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.

COSMOLOGY

In order to incorporate cosmology we need to assume we somehow have ended up with:



$T_i \geq 1$ MeV

The interaction of SM brane modes and the bulk graviton is universal:

$$\frac{1}{\hat{M}_p^{3/2}} \int d^4x \, h_{\mu\nu}(x,z)\Big|_{z=0} T^{\mu\nu}(x)$$

$$h_{\mu\nu}(x,z) = \sum_n h^n_{\mu\nu}(x)\phi_n(z)$$

$h^0_{\mu\nu} = graviton,$ $\quad h^n_{\mu\nu} \quad n \neq 0 \quad \text{KK gravitons}$

$$m_n \sim n \cdot m_{KK} \sim \frac{n}{l}$$

$$\sim \frac{1}{M_p} \sum_n \int d^4x \, h^n_{\mu\nu}(x) T^{\mu\nu}(x)$$

Using this we can find the rate of energy density produced in KK modes:

$$\frac{d\rho_{DM}}{dt} \sim \frac{T^8}{\hat{M}_p^3} \Rightarrow \frac{dy_{DM}}{dt} \sim \frac{T^5}{\hat{M}_p{}^3} \qquad (y_{DM} \sim \frac{\rho_{DM}}{T^3})$$

Using $T^2 \sim \dfrac{M_p}{t}$ and $\hat{M}_p^3 = m_{KK} M_p^2$ and integrating over time:

$$y_{DM} \sim \frac{T_i^3 M_p}{\hat{M}_p{}^3} \sim \frac{T_i^3}{M_{KK} M_p}$$

$$\Rightarrow T_{MR} = \frac{T_i^3}{M_{KK} M_P}$$

$$y_{rad} \sim \frac{\rho_{rad}}{T^3} \sim T$$

What fixes the initial temperature?

$$T_i \lesssim m_\phi$$

where ϕ are fields controlling the extra dimension geometry. Existence of dS phase: They should decay before dS decays which by dS Conjecture [Ooguri et. al., 2018] is expected to be Hubble scale $\Rightarrow$ Decay rate $\gtrsim \Lambda^{\frac{1}{2}}$.
They couple gravitationally so

$\Gamma_{decay} \sim \dfrac{m_\phi^3}{M_p^2} \gtrsim \Lambda^{\frac{1}{2}} \Rightarrow m_\phi \gtrsim \Lambda^{\frac{1}{6}} M_p^{\frac{1}{3}}$ suggesting

$$T_i \sim \Lambda^{\frac{1}{6}} M_p^{\frac{1}{3}}$$

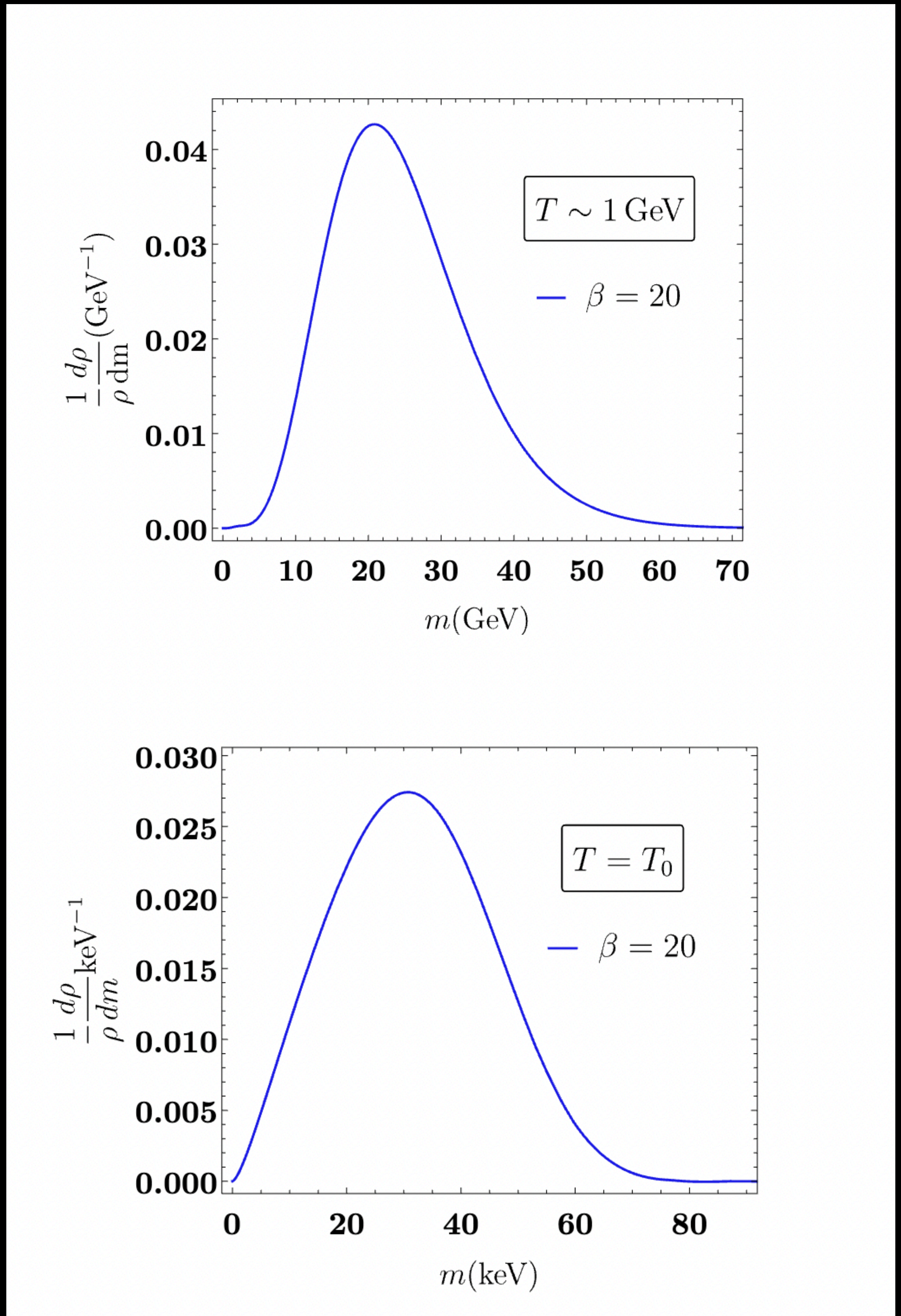
$$T_{MR} = \frac{T_i^3}{M_{KK} M_P} \Rightarrow T_{MR} \sim \frac{\Lambda^{\frac{1}{2}} M_p}{\Lambda^{\frac{1}{4}} M_p} \sim \Lambda^{\frac{1}{4}} = T_\Lambda$$

This solves the coincidence problem! (This happens for (n,d)=(3,8),(2,6),(1,4),(0,2) where $n = \frac{d}{2} - 1.$)

We start with $T_i \sim \Lambda^{\frac{1}{6}} M_p^{\frac{1}{3}} \sim 1GeV$ and this gives the right abundance of dark matter in the form of dark gravitons!

Both Why Now and Coincidence are explained by dS conjecture!

Once produced they lower their mass by decaying mostly to lower KK modes (and in the process the total energy density of dark matter does not change appreciably)



That they lower their mass is a necessary ingredient to be consistent with observation. They also decay to photons:

$$g \to \gamma\gamma$$

would affect CMB anisotropies. To be consistent with observational bounds their mass should be below MeV

$$\Gamma_d \sim \frac{m_{DM}^3}{M_p^2}$$

We end up with $m_{DM} \sim 1 - 100\ \mathrm{keV}$ which is consistent with this bound.

$$m_{\mathrm{DM}} \sim A\frac{M_P^{\frac{4}{7}}\,\Lambda^{\frac{1}{28}}}{t^{\frac{2}{7}}} \sim \Lambda^{\frac{5}{28}} M_p^{\frac{2}{7}} \ \text{(today)}$$

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]

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' !). Leads to a natural DM candidate: the dark graviton.

Possible Unification of hierarchies (Dirac's dream):

$$t_{now} \sim \Lambda^{\frac{-1}{2}} \qquad m_\nu \sim \lambda^{-1}\Lambda^{\frac{1}{4}}$$

$$l_{meso} \sim \lambda\Lambda^{\frac{-1}{4}} \qquad m_{\mathrm{DM}} \sim \Lambda^{\frac{5}{28}}M_{pl}^{\frac{2}{7}}$$

$$T_{MR} \sim \Lambda^{\frac{1}{4}} \qquad \langle H\rangle \sim y^{-1}\lambda^{\frac{-2}{3}}\Lambda^{\frac{1}{6}}M_{pl}^{\frac{1}{3}}$$

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

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!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Happy Birthday
Dear Hirosi!