

Title: Research Talk 3 - Swampland and a Unification of the Dark Sector

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Swampland and a Unification of the Dark Sector

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Strings 2023
Perimeter Institute for Theoretical Physics

July 24, 2023

Based on

M. Montero, I. Valenzuela, C.V.

The Dark Dimension and the Swampland

arxiv.org/2205.12293

E. Gonzalo, M. Montero, G. Obied, C.V.

Dark Dimension Gravitons as Dark Matter

arxiv.org/2209.09249

J. Law-Smith, G. Obied, A. Prabhu, C.V.

Astrophysical Constraints on Decaying Dark Gravitons

arxiv.org/2307.11048

And

C. Dvorkin, E. Gonzalo, G. Obied, C.V. to appear

Dark energy and dark matter

Among the most mysterious features of our universe

The two **seem to be unrelated**

The smallness of the dark energy

The weakness of interactions with visible sector

Quantum gravity seems unrelated to these questions

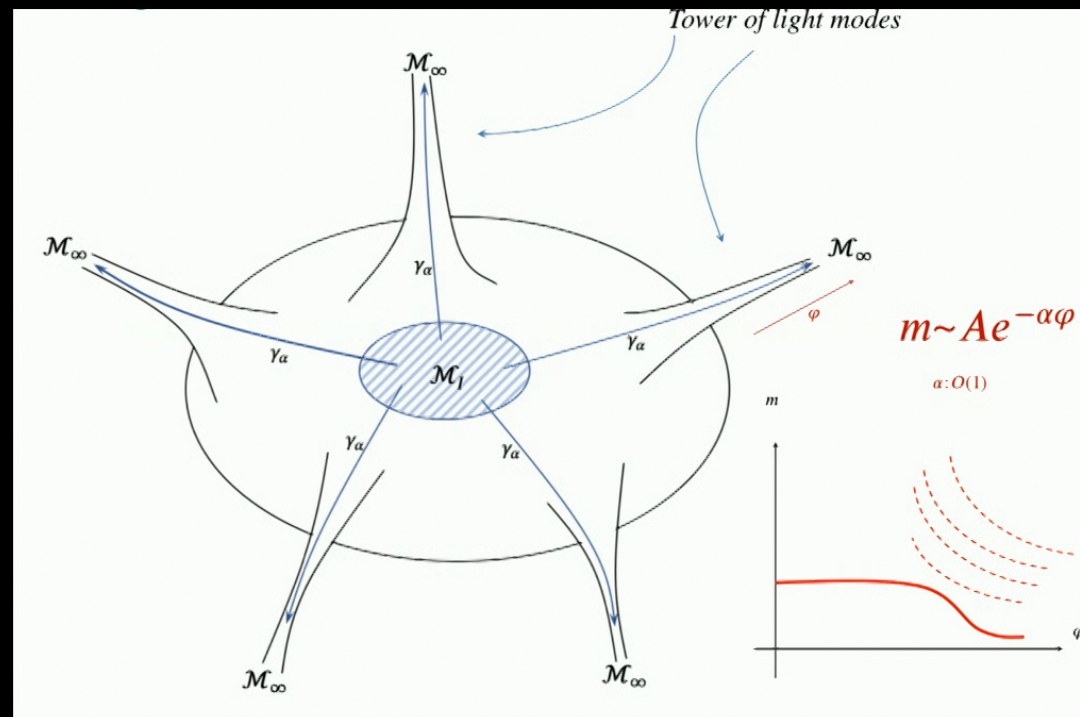
QG consistency captured by Swampland criteria sheds light.

I will explain how

The Distance/Duality Conjecture \Rightarrow Unification of Dark Sector

$$\Lambda \sim 10^{-122} \ll 1 \Rightarrow \text{light tower}$$

Distance/Duality Conjecture [OV, 06]



Moreover the tower of light states is either a tower of KK modes ($d \rightarrow D$), or light string states. Strong evidence from string theory (“The Emergent String proposal” [LLW,19]). In that case it is easy to show

$$m \sim \exp(-\alpha\phi); \quad \frac{1}{\sqrt{d-2}} \leq \alpha \leq \sqrt{\frac{D-2}{(D-d)(d-2)}}$$

In the context of dS/AdS the distance conjecture has a generalization [LPV,18] where the smallness of cosmological constant leads to the prediction of a tower of light states: $m \sim |\Lambda|^\alpha$. A lot of evidence for this in the AdS case. For (quasi) dS

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

Upper range Higuchi bound, lower range 1-loop vacuum energy.

Combined with observational data: Newtonian gravity valid up to $30\mu m$ [Adelberger et.al., 20] (and not too fast cooling of neutron stars) the only option is

$$m \sim \Lambda^{1/4} \sim 6 \text{ meV}$$

KK tower of one mesoscopic dimension in the micron range:

The Dark Dimension

(Different in motivation and predictions from LED scenario [ADD,98] which was motivated by attempting to explain EW hierarchy ($M_w \sim \hat{M}_{pl}$) and requires 2 or more extra dimensions).

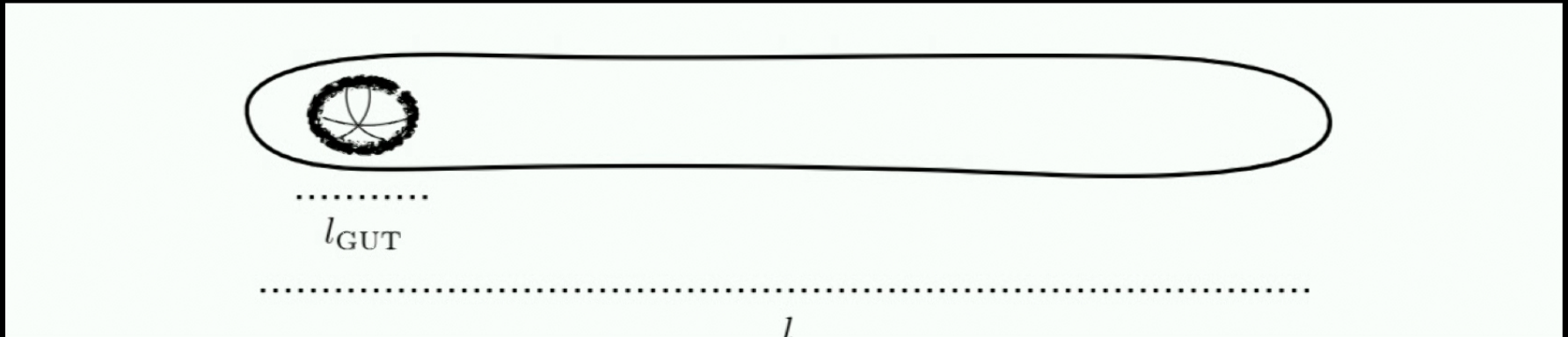
The Dark Dimension: One extra mesoscopic dimension of length 0.1–30 micron $\sim \Lambda^{-1/4}$!
Fundamental Planck scale in 5-th dimension

$$\hat{M} \sim 10^9 - 10^{10} \text{ GeV}$$

One extra dimension decompactification is consistent with the theoretical expectation that this can lead to flattest potential $V < A \exp \left[\frac{-2\phi}{\sqrt{(d-1)(d-2)}} \right]$ as is needed for a quasi-dS solution which we live in today.

Phenomenological aspects

GUT/Standard model brane: Should be localized in the mesoscopic dimension, otherwise we get a large number of copies of SM fields separated by meV–eV mass scale:



Two potential applications in **particle physics**:

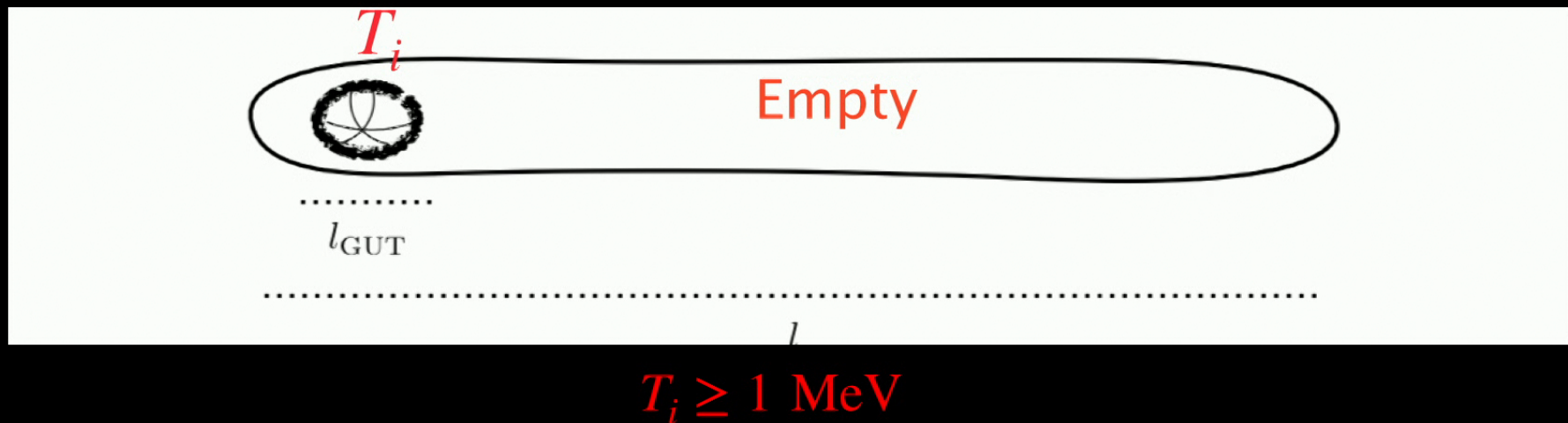
Instability in Higgs potential at $10^{11} GeV$: may be related to higher Planck scale at $10^{10} GeV$.

Neutrino physics: bulk fermions coupled to ν_L on the brane can act as right-handed neutrinos [DDG, ADDM, 98]; the couplings to SM neutrinos automatically give the active neutrinos the expected mass **thanks to dark dimension parameters**.

The fact that the KK tower mass scale is close to neutrino mass $m_\nu \sim \Lambda^{1/4}$, suggests fermionic KK tower can act as sterile neutrino. Higgs vev is compactible with **lack of higherarchy** between active and sterile neutrino mass scales.

COSMOLOGY

We present an appealing cosmological scenario
(see [AAL 22,23] for some other scenarios)
In order to incorporate cosmology we need to
assume we have ended up with:



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

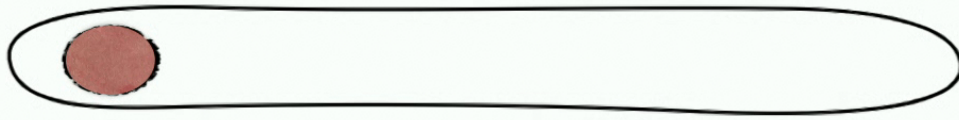
$$\frac{1}{\hat{M}_p^{3/2}} \int d^4x h_{\mu\nu}(x, z) \Big|_{z=0} T^{\mu\nu}(x)$$

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

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

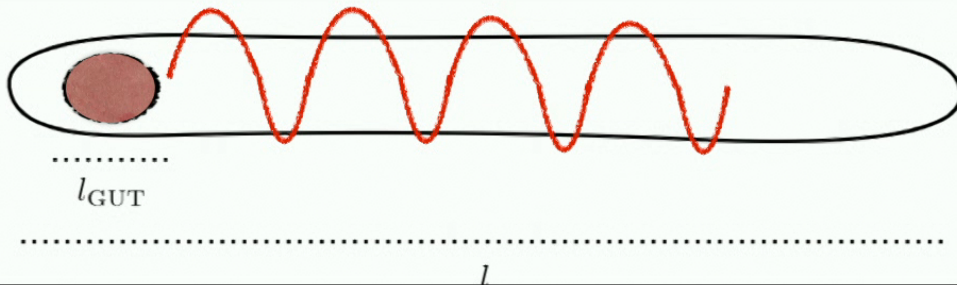
$$m_n \sim n \cdot m_{KK} \sim \frac{n}{l}$$

$$\sim \frac{1}{M_p} \sum_n \int d^4x h_{\mu\nu}^n(x) T^{\mu\nu}(x)$$



[Redacted text block]

T_i



T_i



What fixes the initial temperature?

$$T_i \lesssim m_\phi$$

where ϕ are fields controlling the extra dimension geometry of the SM brane.

Existence of dS phase: moduli fields should decay before dS decays (\sim Hubble scale [BV19]):

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

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

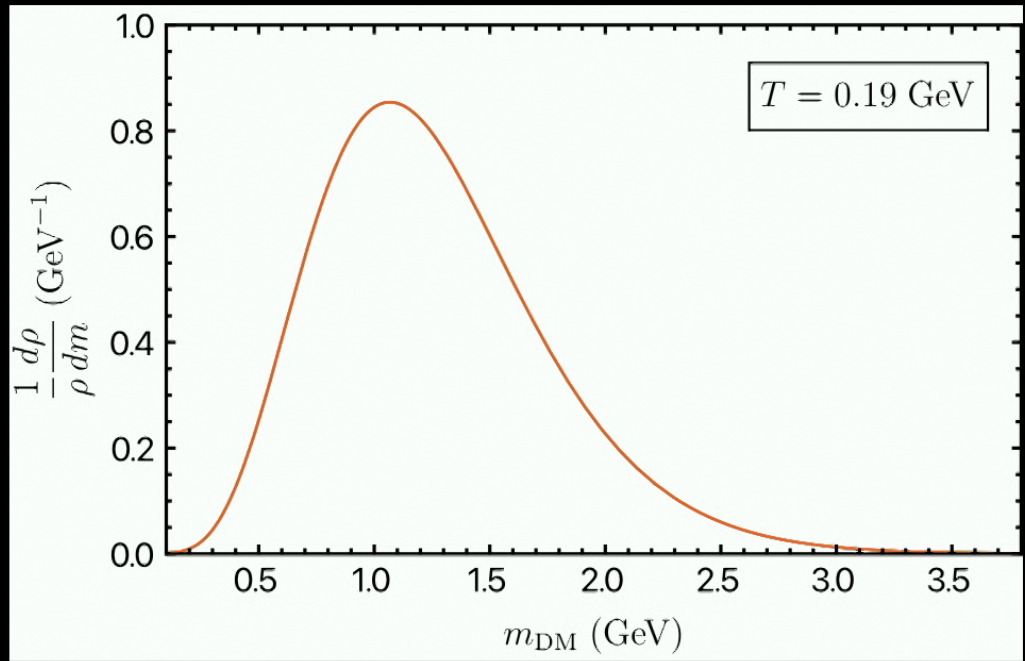
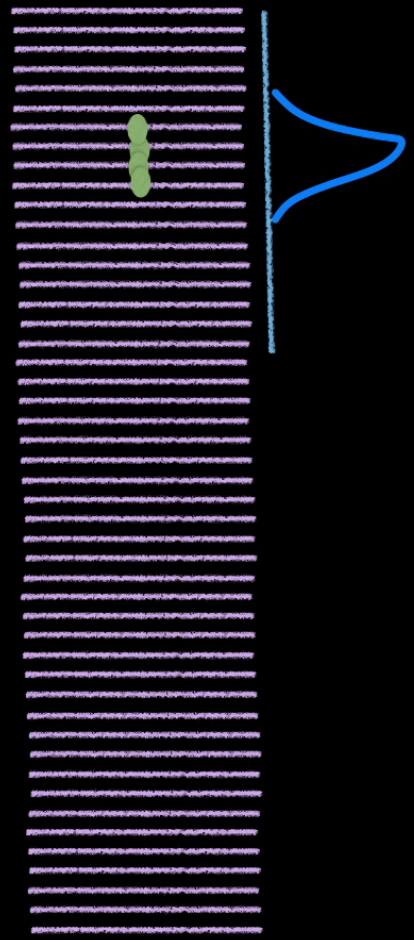
Using the coupling of 4d stress tensor to 5d gravitons we can find the rate of energy density produced in KK modes:

$$\frac{d\rho_{DM}}{dt} \sim \frac{T^8}{\hat{M}_p^3} \Rightarrow T_{MR} = \frac{T_i^3}{M_{KK}M_P} \sim \frac{\Lambda^{\frac{1}{2}}M_p}{\Lambda^{\frac{1}{4}}M_p} \sim \Lambda^{\frac{1}{4}} = T_\Lambda$$

Automatically explains the **coincidence problem** (MR equality T is close to the T where dark energy takes over). No need for anthropic principle to explain this coincidence!

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

T_i

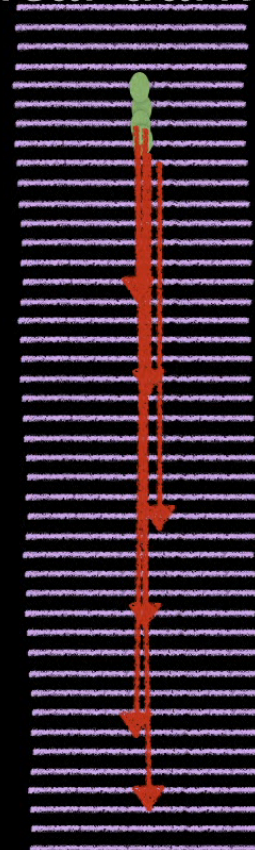


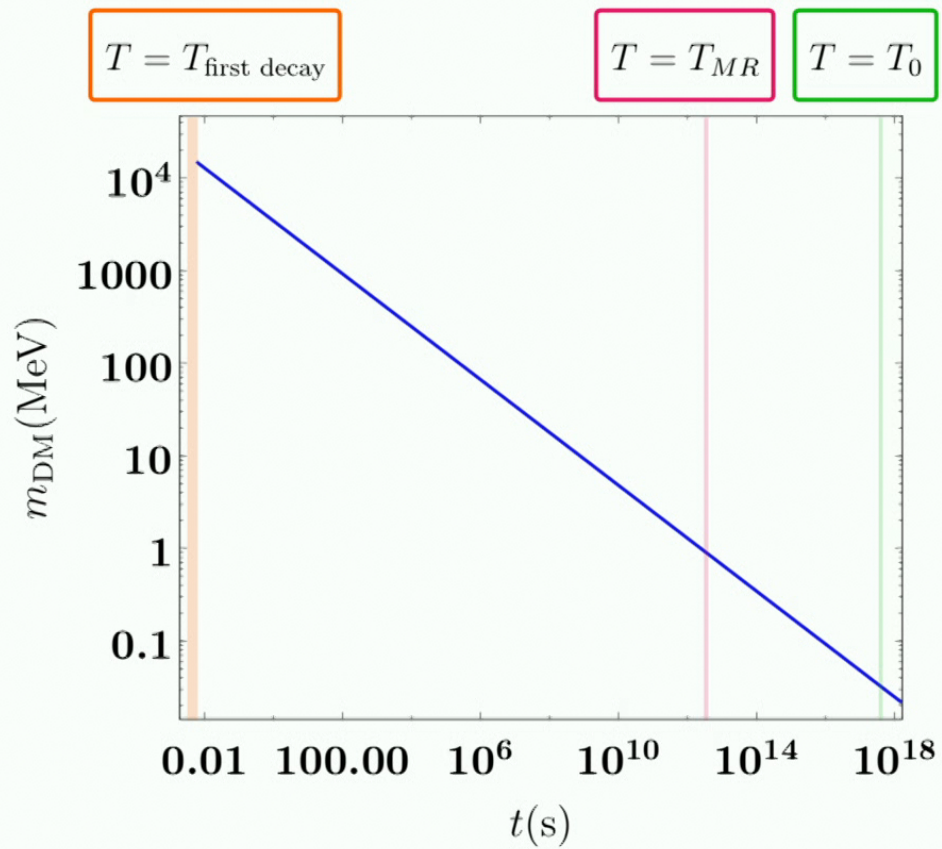
Once produced they lower their mass by decaying mostly to lower KK modes by gravitational interactions (and in the process the total energy density of dark matter does not change appreciably)—A special case of dynamical dark matter scenario [DT,11]

$$T_i \sim GeV \longrightarrow$$

The decay rate is fixed (Up to $\mathcal{O}(1)$ numbers) by assuming amplitudes are gravitational strength and a parameter δ which captures violation of KK quantum number:

$$m_{DM}(t) \sim m_{DM}(t_0) \left(\frac{t}{t_0} \right)^{-\frac{2}{7}}$$





In our model the dark matter gives a kick velocity which assuming an almost homogenous 5th dimension leads to

$$v \sim \sqrt{\delta \cdot \frac{m_{KK}}{m_{DM}}} \quad \text{where } \delta \sim O(1)$$

Using

$$m_{DM} \sim \Lambda^{\frac{5}{28}}; m_{KK} \sim \Lambda^{\frac{1}{4}}$$

we learn

$$v \sim \Lambda^{\frac{1}{28}} \sim 10^{-\frac{122}{28}} \sim 10^{-4} c$$

$$l_5 < 30\mu m \rightarrow m_{KK} > 0.006 eV \rightarrow m_{DM} > 20 keV$$

but decaying DM mass cannot be too large due to

$$DM \rightarrow \gamma\gamma, e^+e^-, \dots$$

$$\Gamma_d^{tot} \sim H(t) \sim \frac{1}{t} \Rightarrow m_{DM} \sim A \frac{M_p^4 \Lambda^{\frac{1}{28}}}{t^{\frac{2}{7}}} \sim \Lambda^{\frac{5}{28}} M_p^{\frac{2}{7}} \quad (\text{today})$$

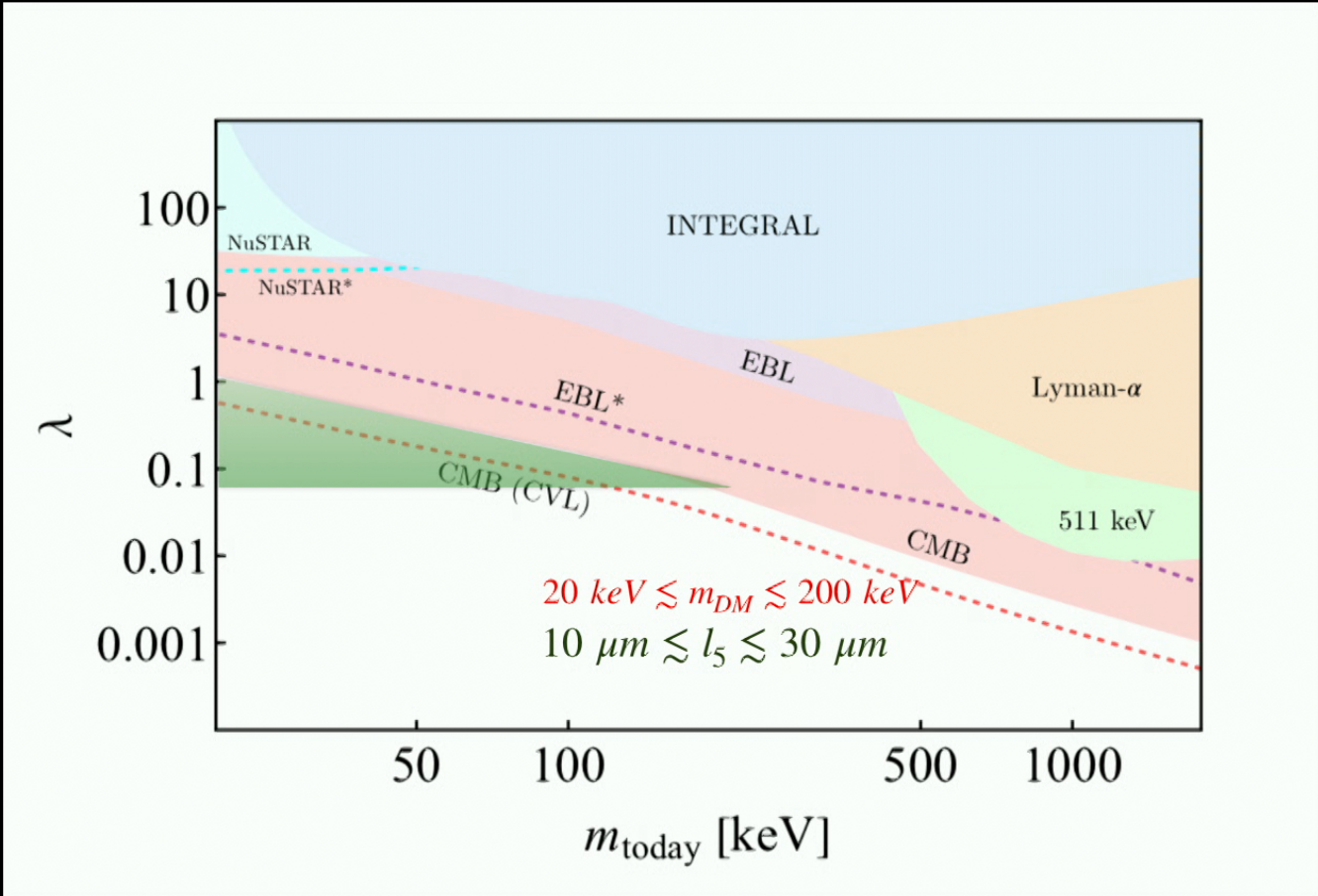
That they lower their mass is a necessary ingredient to be consistent with observation. They also decay to photons:

$$g \rightarrow \gamma\gamma$$

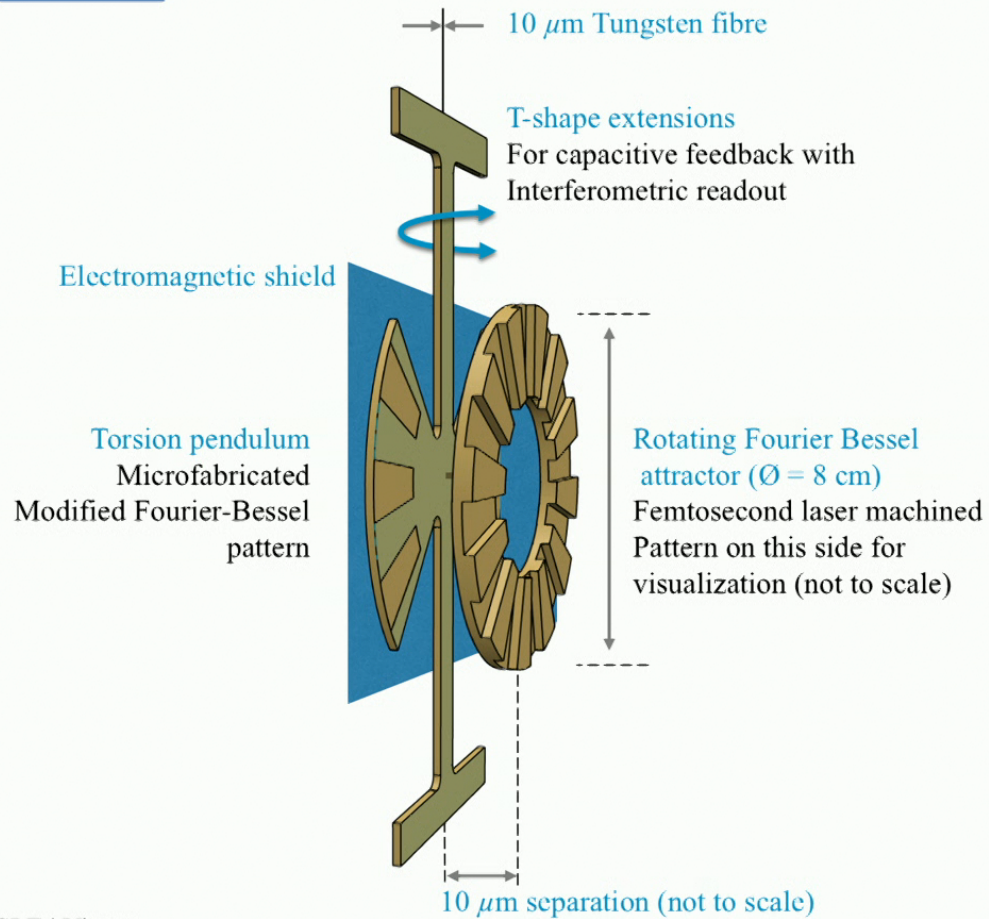
would affect CMB anisotropies. To be consistent with observational bounds their mass should be below MeV

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

Astrophysical bounds:



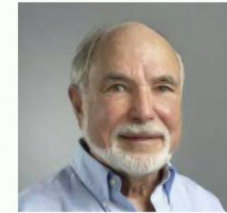
New ISLE at the Conrad Observatory



ISLE core team



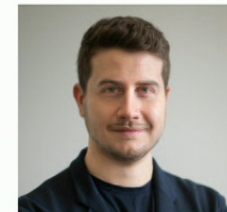
Markus Aspelmeyer
IQOQI Vienna & University of Vienna



Eric Adelberger
University of Washington



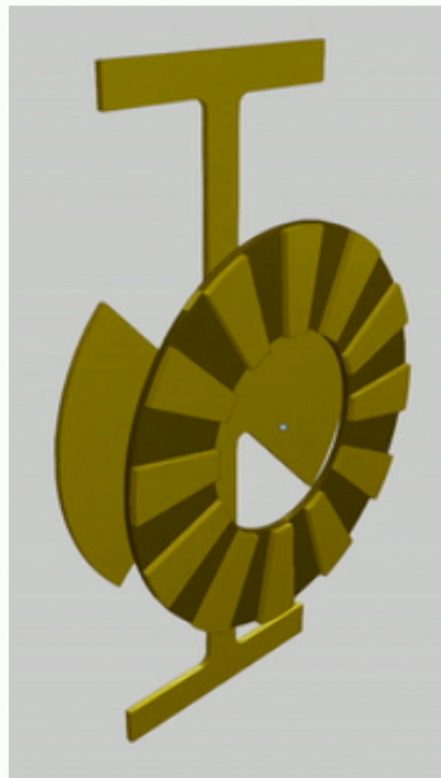
Armin Shayeghi
IQOQI Vienna



Pietro Zito
IQOQI Vienna

Theory support: Cumrun Vafa (Harvard)
 Microfabrication support: Michael Trupke (IQOQI Vienna)
 Control system support: Andreas Kugi (TU Vienna)

Postdocs and graduate students tba...



Sensitivity to see ultra-feeble forces
Nanoradian precision (meter stick on the moon!)

Understanding all systematic effects (spurious signals)

- Gravity gradients
- Magnetic impurities
- Electromagnetic shield

- Vibrations, Patch effects, thermal effects

Easier part

Harder part

Can be handled
High-purity materials needed
Technological challenge

Major challenge!



Conrad Observatory, July 2021

Summary

Small dark energy + Swampland + observations uniquely lead to a single mesoscopic dimension **The Dark Dimension** in the micron range.

Leads to a natural DM candidate: the dark graviton. **Unification of dark sector.**

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

$$\begin{array}{ll} t_{now} \sim \Lambda^{-\frac{1}{2}} & m_\nu \sim \Lambda^{\frac{1}{4}} \\ l_{meso} \sim \Lambda^{-\frac{1}{4}} & m_{DM} \sim \Lambda^{\frac{5}{28}} \\ T_{MR} \sim \Lambda^{\frac{1}{4}} & \langle H \rangle \sim \Lambda^{\frac{1}{6}} \\ \hat{M} \sim \Lambda^{\frac{1}{12}} & v \sim \Lambda^{\frac{1}{28}} \end{array}$$

Easily falsifiable: improvement on the precision measurement of deviation from Newton's law by a factor of 10 (under way)!

Or improvement of astrophysical bounds.

Detailed study of structure formation needed

(taking into account the kick velocity of dark matter decays).