# Reflections on the Dark Dimension

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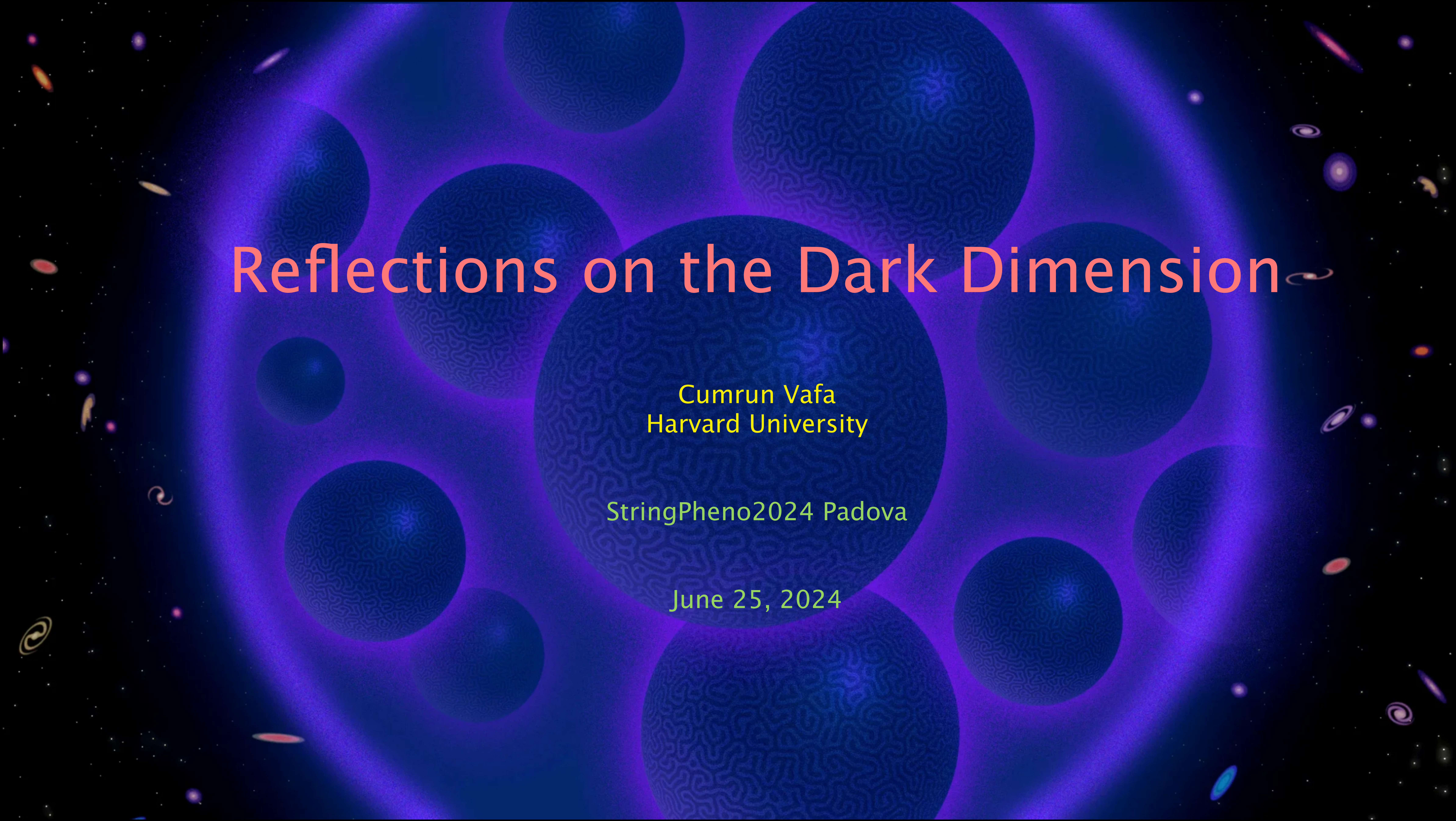


Samuel Velasco/Quanta Magazine

# Dark Dimension Scenario 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

C. Dvorkin, E. Gonzalo, G. Obied, C.V.
Dark Dimension and Decaying Dark Matter Gravitons
arXiv.org/2311.05318

C.V.
Swamplandish Unification of the Dark Sector
arXiv.org/2402.00981

N. Gendler, C.V.
Axions in the Dark Dimension
arXiv.org/2404.15414

String theory is believed to be a fundamental theory of nature leading to a consistent theory of quantum gravity.

Yet, it is believed that we have no concrete predictions based on it. In this talk I would like to present some concrete predictions from string theory, testable by current experiments.

# Hierarchy of Scales Puzzles

Dirac:
Why do we have such strange small (large) numbers?

Updated version:

$$\Lambda \sim 10^{-120} M_p^4$$

$$\tau_{\text{now}}^{-1} \sim 10^{-60} \sim 10^{-40}\,\text{GeV}$$

$$m_\nu \sim 10^{-30} \sim 10^{-10}\,\text{GeV}$$

$$\Lambda_{\text{QCD}} \sim \alpha\Lambda_{\text{weak}} \sim 10^{-20} \sim \ 1\,\text{GeV}$$

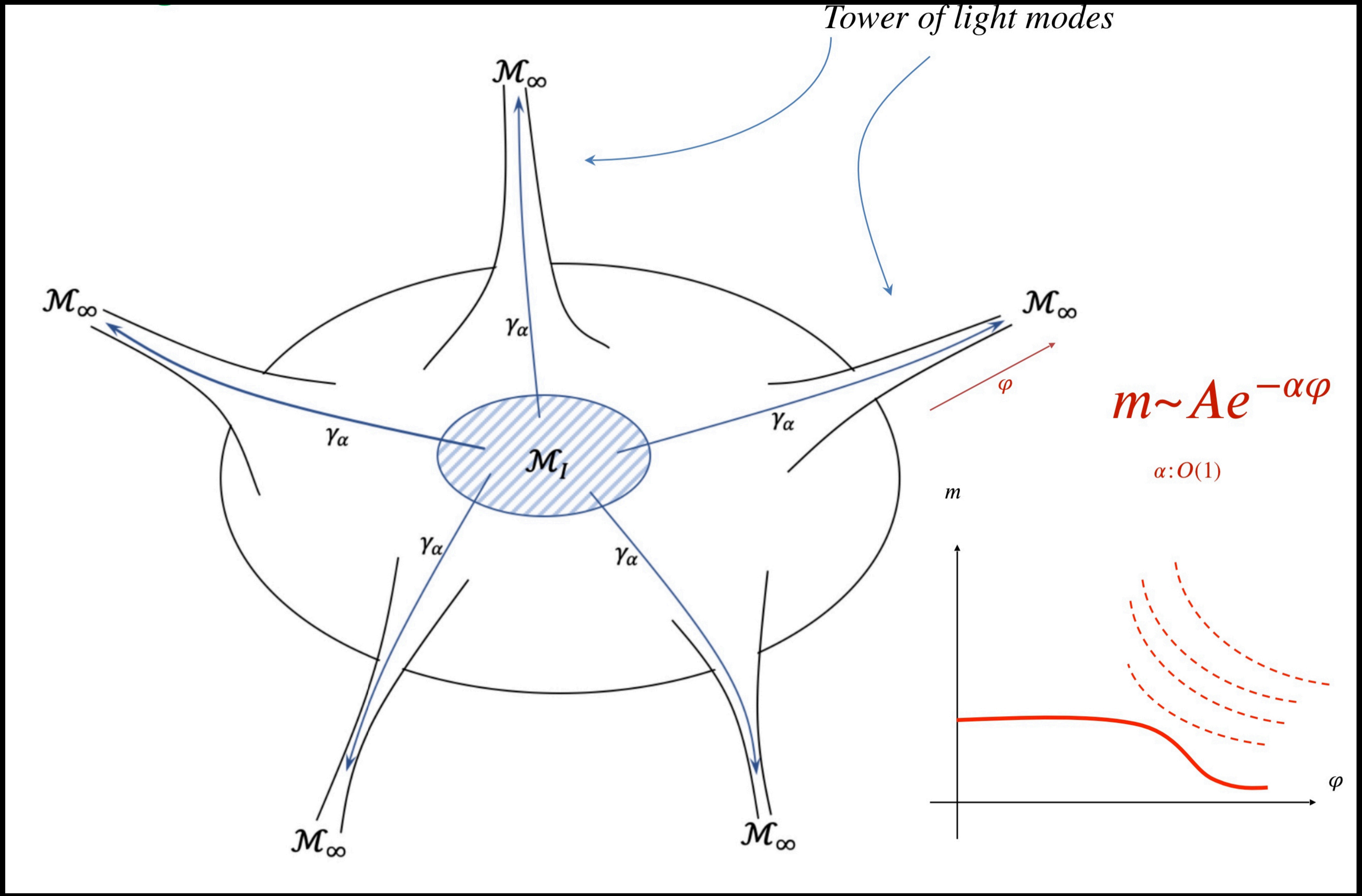
$$\Lambda_{\text{Higgs inst.}} \sim 10^{-10} \sim 10^{10}\,\text{GeV}$$

What is the nature of dark matter?
Is it related to dark energy?

The smallness of the dark energy and the weakness of interactions of the dark matter are prominent features.
Any relation between these features?

In this talk I review the Dark Dimension Scenario and the new developments in that direction which gives a promising answer to some of these questions. I also explain how the parameters in this model are highly restricted.

# Distance/Duality Conjecture
# [OV, 06]



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

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

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 we expect

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

Upper range Higuchi bound, lower range 1-loop vacuum energy. This in particular means gravity gets modified at the scale of m.

Let us apply this to our universe where $\Lambda \sim 10^{-122}$

The only possibility given the observations that Newtonian force law works at least up to $30\mu m$ (Adelberger et al) is the lower bound

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

$$\lambda m = \Lambda^{\frac{1}{4}} = \Lambda^{\frac{3}{12}}$$

$$m \sim .01 - .1eV \qquad l = m^{-1} \sim 1 - 10\mu m$$

# 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 for n extra dimensions:

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

(for n extra mesoscopic dimensions)–Only consistent with experiment for n=1 and gives Planck mass of

$$\hat{M} \sim (\Lambda^{\frac{1}{4}})^{\frac{1}{3}} = \Lambda^{\frac{1}{12}} \sim 10^{10} GeV$$

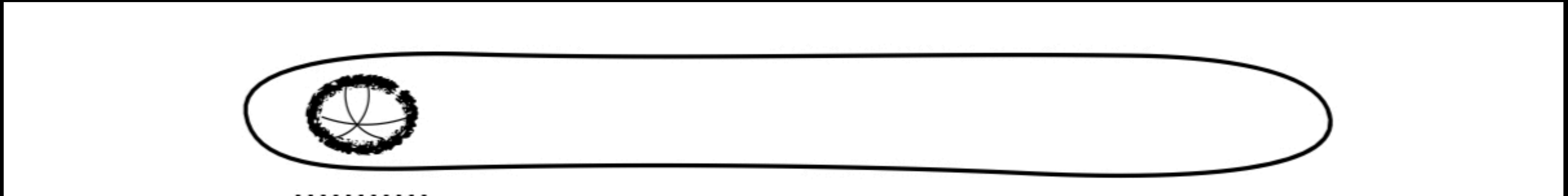
The Dark Dimension: One extra mesoscopic dimension of length in microns!
This leads to a fundamental Planck scale in higher dimension

$$\hat{M} \sim m^{\frac{1}{3}} \sim (\Lambda^{\frac{1}{4}})^{\frac{1}{3}} \sim \Lambda^{\frac{1}{12}} \sim 10^{10}\ GeV$$

unlike the Large Extra Dimension scenarios which were motivated by making weak scale the fundamental scale $\hat{M} \sim TeV$. This led to $n \geq 2$ extra dimensions, unlike the Dark dimension.

# Phenomenological aspects

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



Three potential applications to particle physics:

1) Instability in Higgs potential (which has become possible thanks to results from CERN) at $10^{11} GeV$; may be related to higher Planck scale at $10^{10} GeV$.

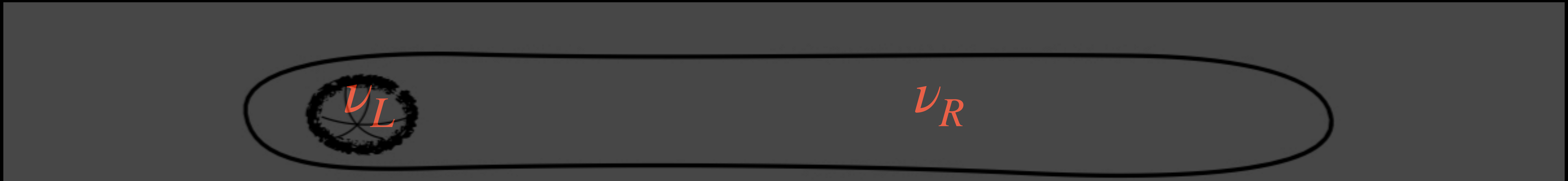
2) Neutrino physics: 5d bulk fermions coupled to $\nu_L$ on the brane can act as right-handed neutrinos [DDG,ADDM, 98]; the couplings to SM neutrinos give the active neutrinos the expected mass thanks to dark dimension parameters.

$$\mathcal{M} = \begin{pmatrix} 0 & \frac{\alpha\langle H\rangle}{\sqrt{l\hat{M}}} \\ \frac{\alpha\langle H\rangle}{\sqrt{l\hat{M}}} & \frac{1}{l} \end{pmatrix} \quad \Longrightarrow \quad m_\nu = \frac{\alpha^2 < H^2 >}{\hat{M}}$$

$$\alpha H \sim \Lambda^{\frac{1}{6}} \sim GeV$$

We get:

$$m_\nu \sim \frac{(\Lambda^{\frac{1}{6}})^2}{\Lambda^{\frac{1}{12}}} \sim \Lambda^{\frac{1}{4}} \sim 10\ meV$$



This suggests fermionic KK tower can act as a tower of sterile neutrino.
Higgs vev is compactible with lack of higherarchy between active and sterile neutrino mass scales.

$$m_\nu \sim m_{tower} \sim m_{sterile}$$

In other words: if a mechanism is found to explain lack of hierarchy in the neutrino sector (active and sterile neutrino having similar masses) leads to electroweak hierarchy $< \alpha H > \sim \Lambda^{\frac{1}{12}} \sim GeV$

Third potential application to particle physics:

3) Axion physics: the axion decay constant must satisfy by WGC

$$f_a \leq M_p$$

However, we can say something more refined if we assume the axion is on the SM brane and the brane has 5d Planckian thickness. 5d axion would have had an action

$$\int \hat{f}_a^{\,3} |d\theta|^2 d^4x dz, \qquad \hat{f}_a < \widehat{M}_{pl}$$

If axion was not localized to the brane this would give

$$f_a^2 = \hat{f}_a^3 L < \hat{M}_{pl}^{\,3} L = M_{pl}^2$$

However, if it is localized, to $L = \hat{l}_{pl}$ this would give instead

$$f_a^2 = \hat{f}_a^3 L < \hat{M}_{pl}^{\,3} \hat{l}_{pl} = \hat{M}_{pl}^2$$

$$f_a \leq \widehat{M}_p \sim 10^{10} GeV$$

This naturally solves the fine tuning problem QCD axion suffers from:

$$10^9 GeV < f_a < 10^{13} GeV$$

Lower bound comes from astrophysical cooling bounds, and the upper bound by overproduction. So we learn given this bound:

$$f_a \sim 10^{10} GeV \sim \Lambda^{\frac{1}{12}}$$

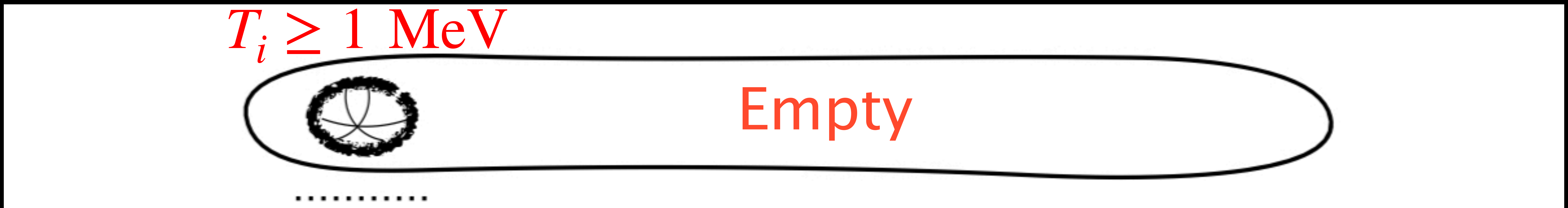
$$m_a \sim \frac{\Lambda_{QCD}^2}{f_a} \sim \frac{\Lambda^{\frac{2}{6}}}{\Lambda^{\frac{1}{12}}} \sim \Lambda^{\frac{3}{12}} \sim 10^{-1} eV \sim m_\nu \sim m_{tower}$$

This range of axion mass is exactly in the range which the continuation of the experiments done here at CERN will be sensitive to:

IAXO (International Axion Observatory) whose `baby version’ is currently scheduled to being operating in Hamburg in the next 5–10 years is such an experiment.

# COSMOLOGY

We present a cosmological scenario which is forced on us (other ones have been proposed [AAL 22,23]).
In order to incorporate cosmology we need to assume we have ended up with:



What fixes the initial temperature on the brane?

$$T_i \lesssim m_\phi$$

where $\phi$ are fields controlling the extra dimension geometry of the SM brane.

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

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

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

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

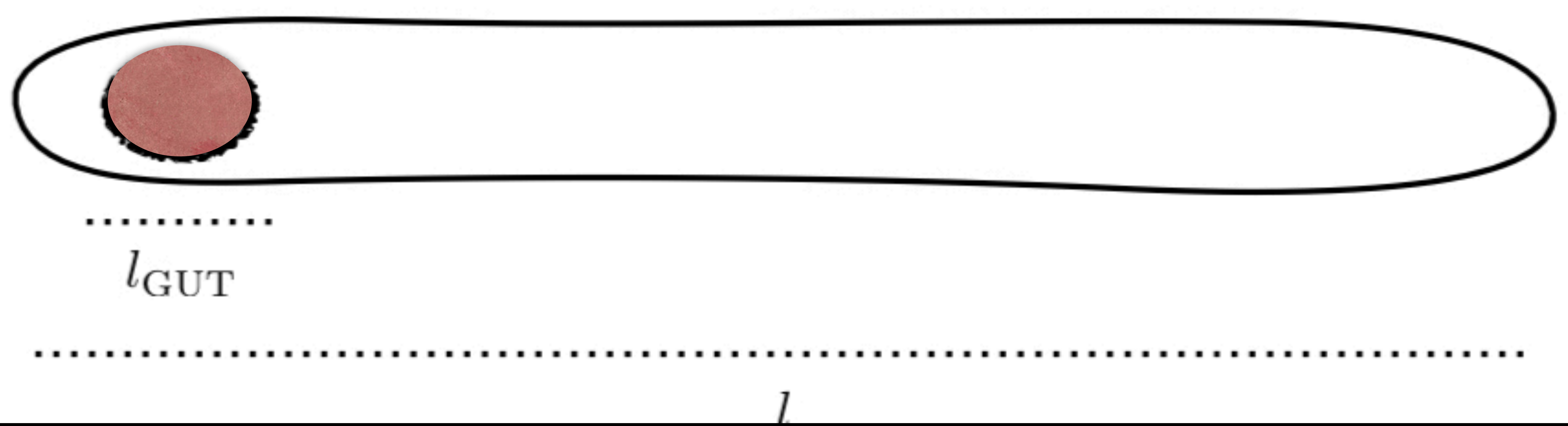
$$\frac{1}{\hat{M}_p^{3/2}} \int d^4x \, h_{\mu\nu}(x,z)\Big|_{z=0} T^{\mu\nu}(x)$$

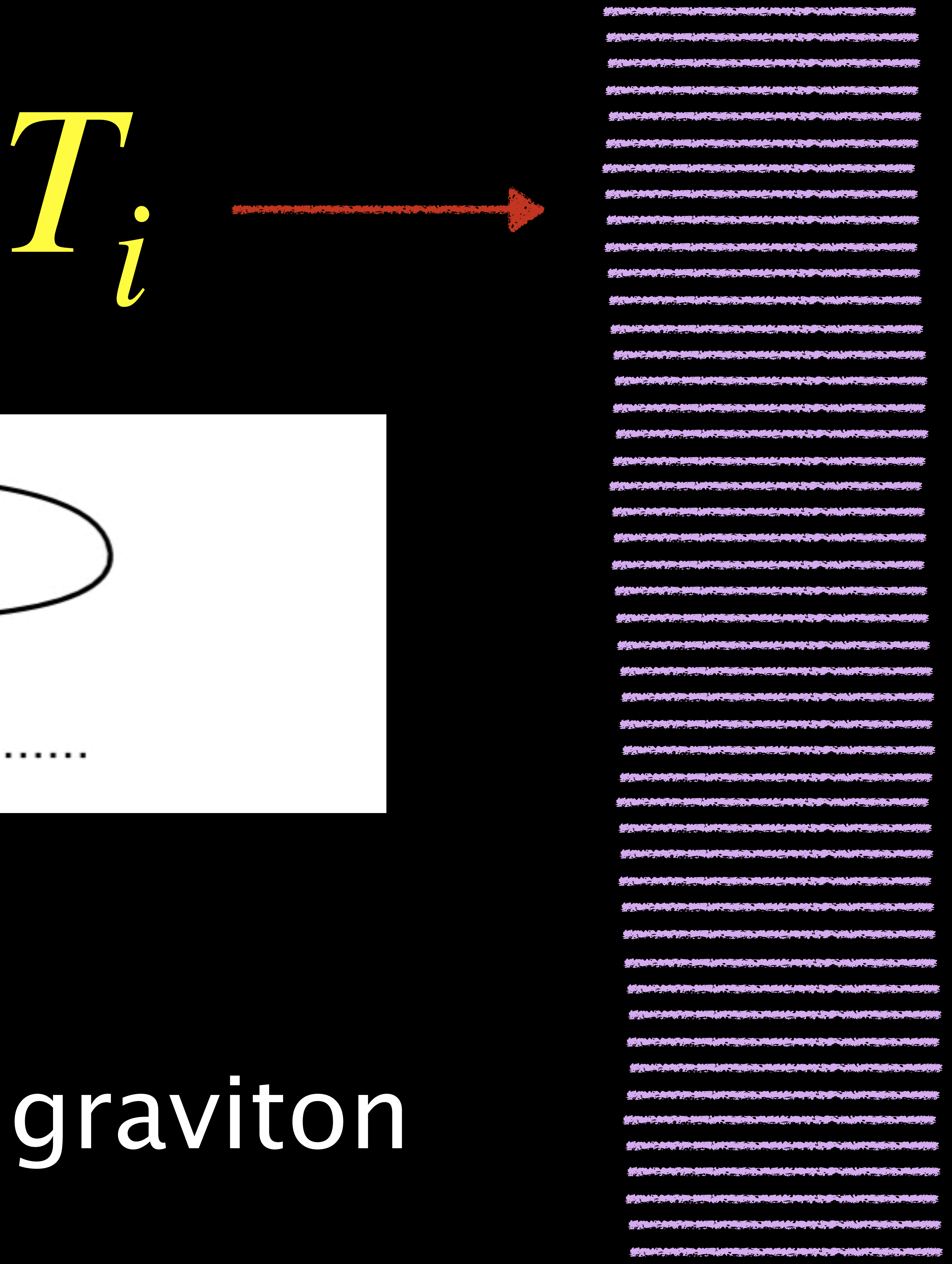
$$h_{\mu\nu}(x,z) = \sum_n h^n_{\mu\nu}(x)\phi_n(z)$$

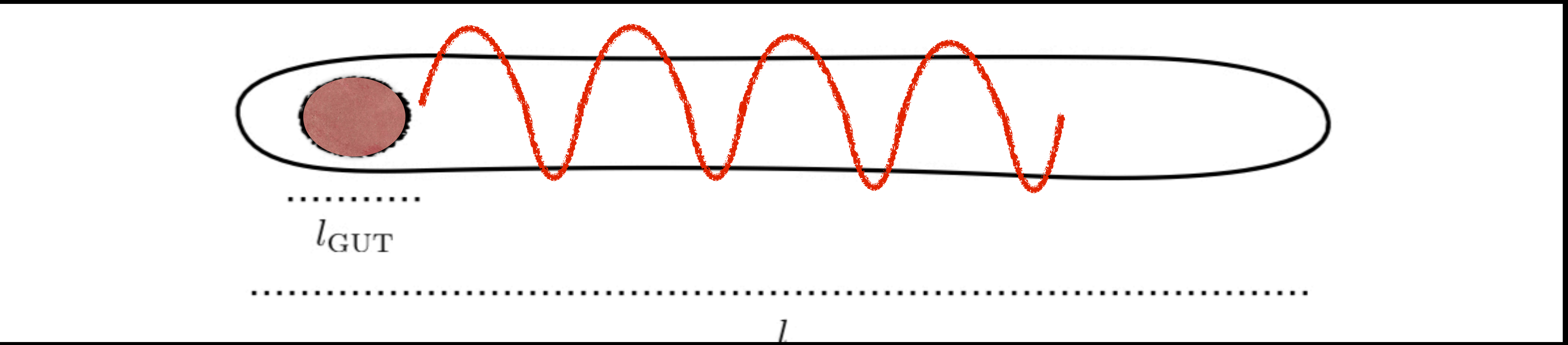
$$h^0_{\mu\nu} = graviton, \qquad h^n_{\mu\nu} \quad n \neq 0 \quad \text{KK gravitons}$$

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

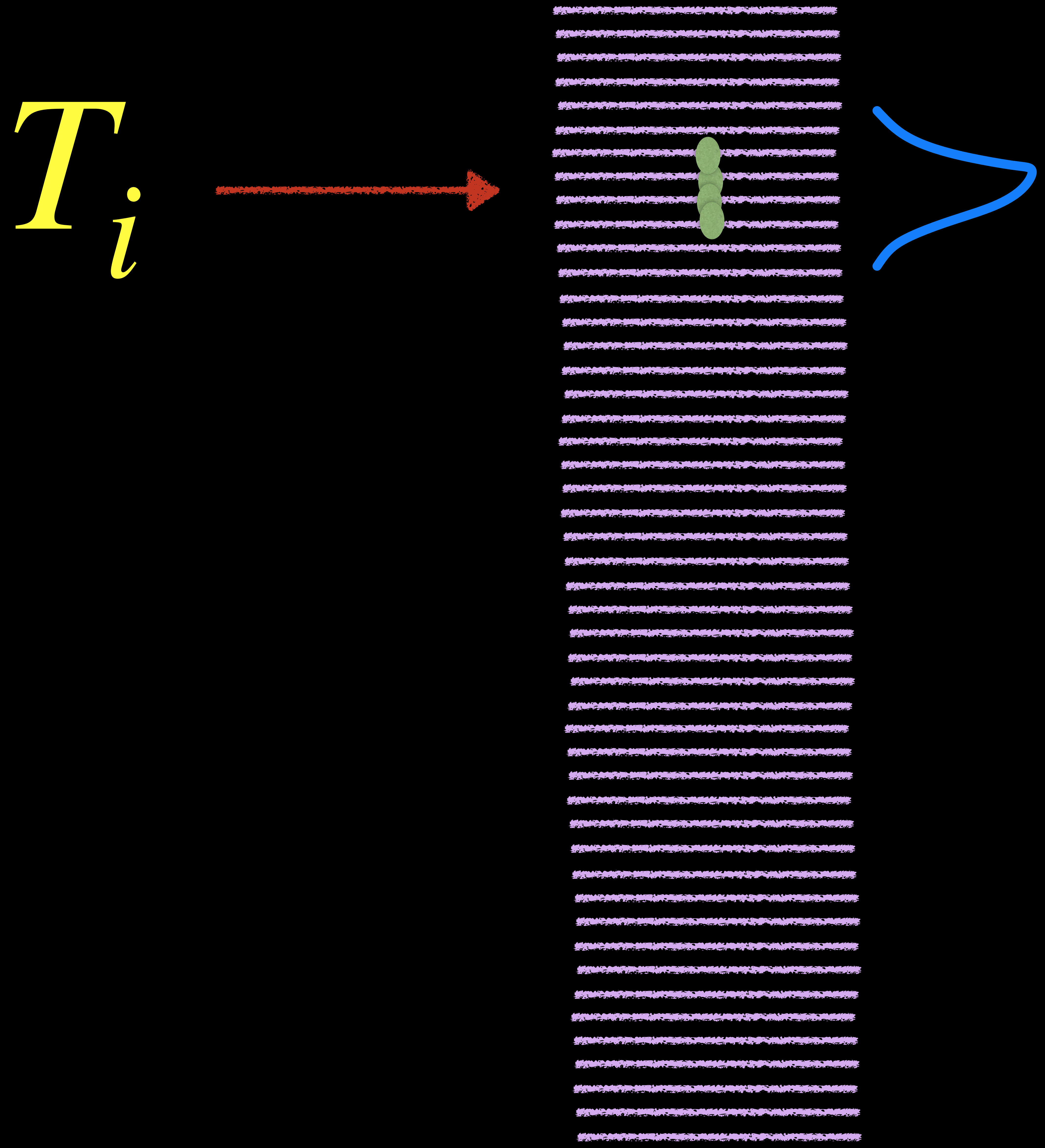
$$\sim \frac{1}{M_p} \sum_n \int d^4x \, h^n_{\mu\nu}(x) T^{\mu\nu}(x)$$

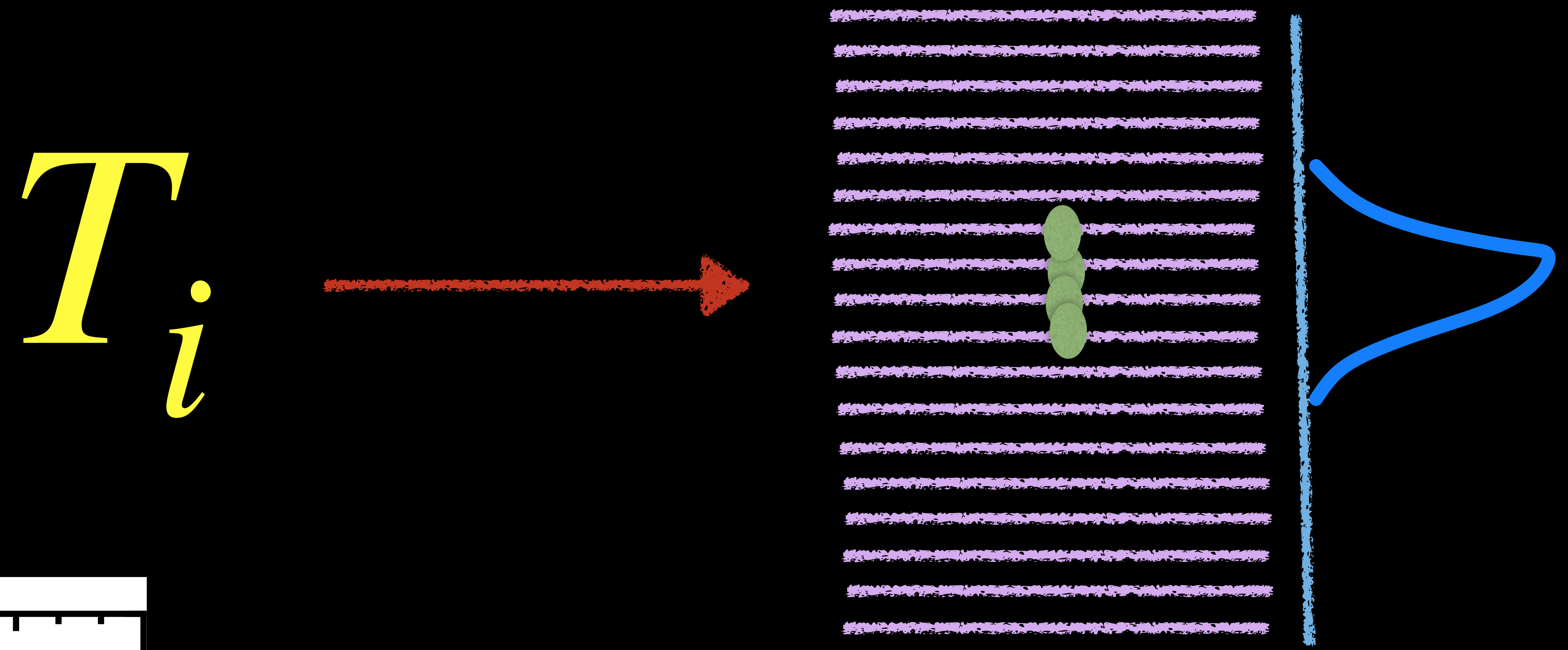

$l_{\rm GUT}$

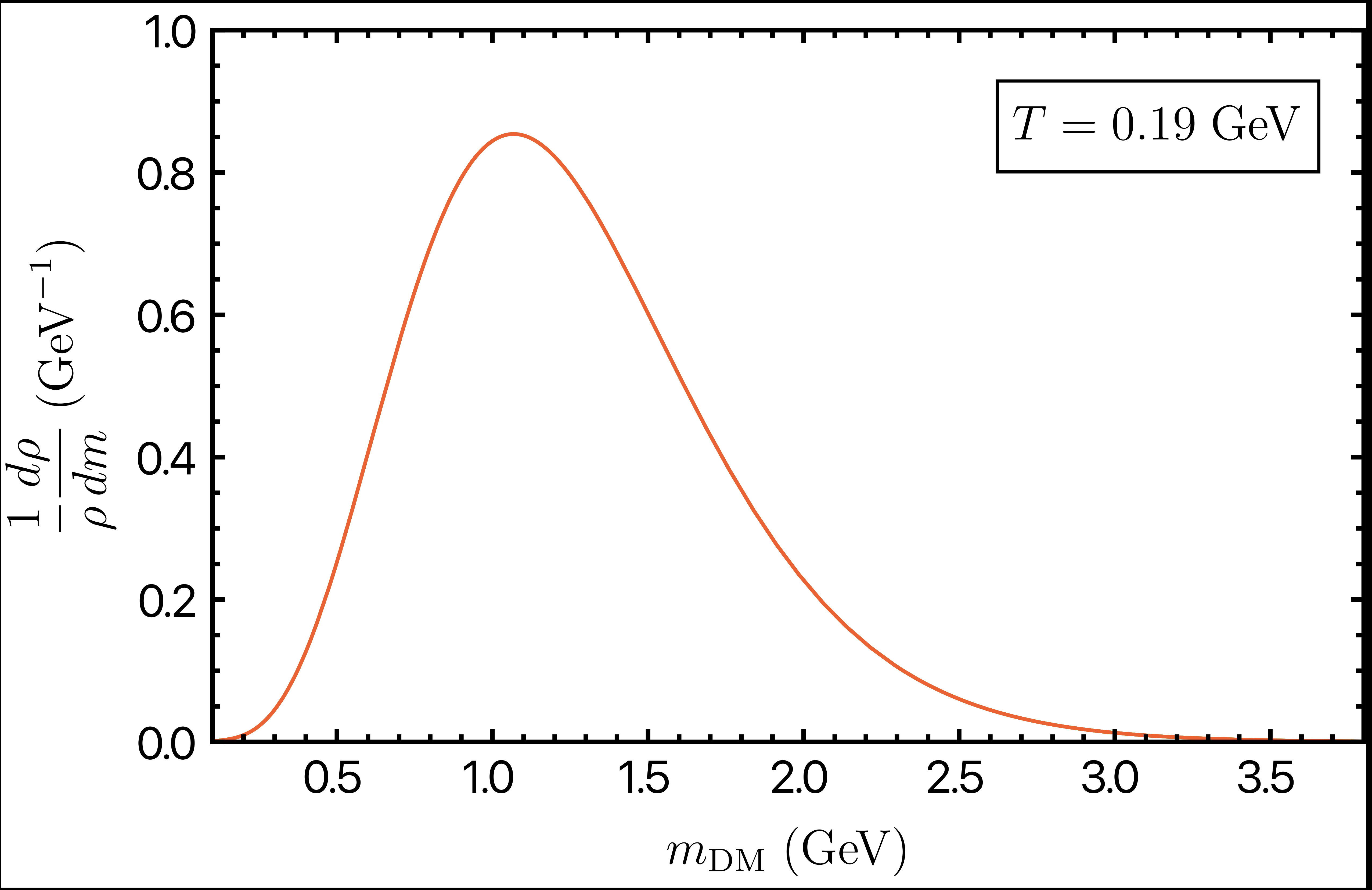



Dark matter is excitation of graviton
in the dark dimension!

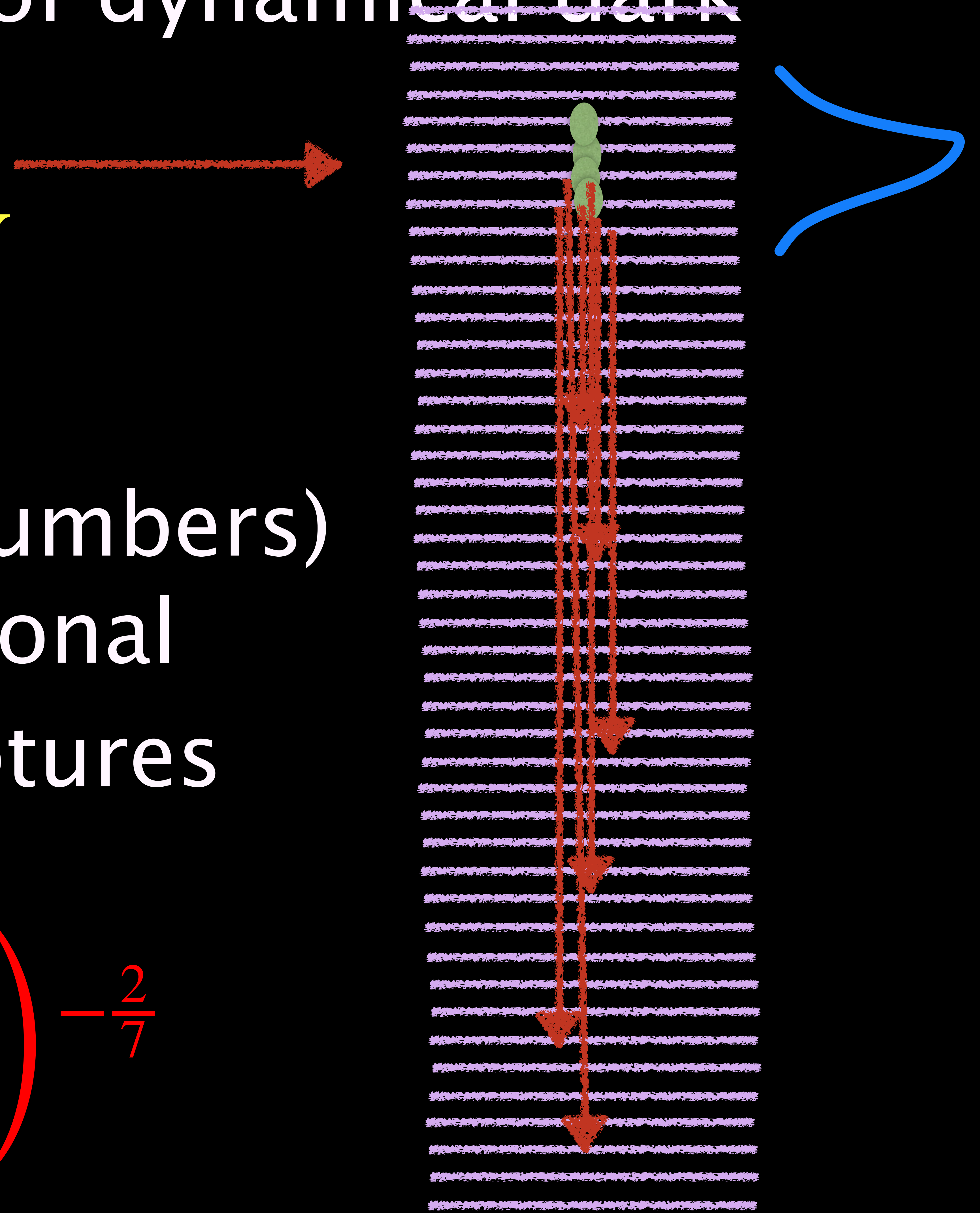

$T_i$


$T_i$


1.0
0.8
0.6
0.4
0.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
$T = 0.19$ GeV
$\frac{1}{\rho}\frac{d\rho}{dm}$ (GeV$^{-1}$)
$m_{\rm DM}$ (GeV)

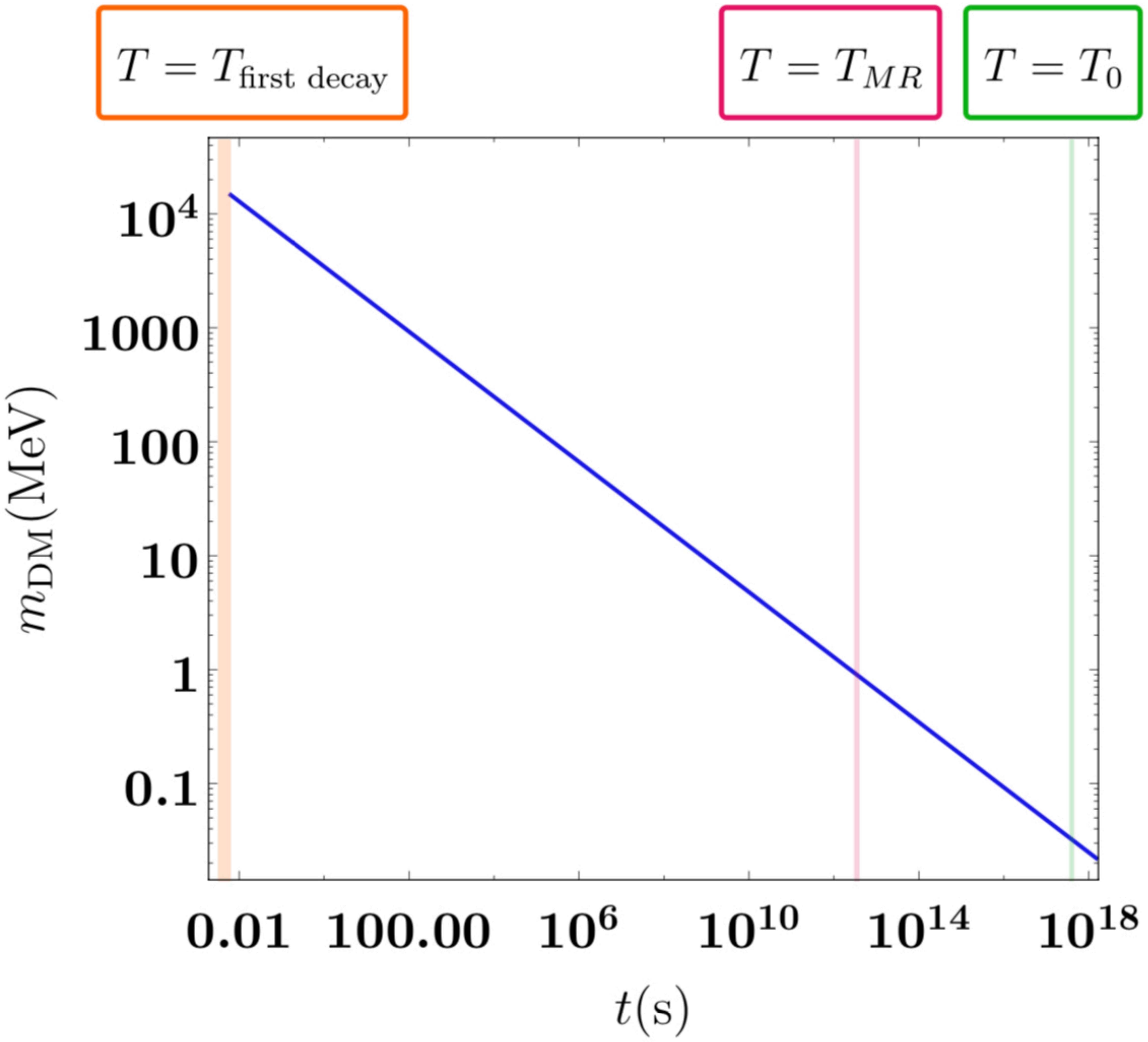
Once produced they lower their mass by decaying mostly to lower KK modes by gravitational interactions (and in the process the total energy density of dark matter does not change appreciably)—A special case of dynamical dark matter scenario [DT,11]

$$T_i \sim GeV$$



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

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



$T = T_{\text{first decay}}$
$T = T_{MR}$
$T = T_0$
$10^4$
1000
100
10
1
0.1
$m_{\rm DM}(\rm MeV)$
0.01
100.00
$10^6$
$10^{10}$
$10^{14}$
$10^{18}$
$t(\rm s)$

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

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

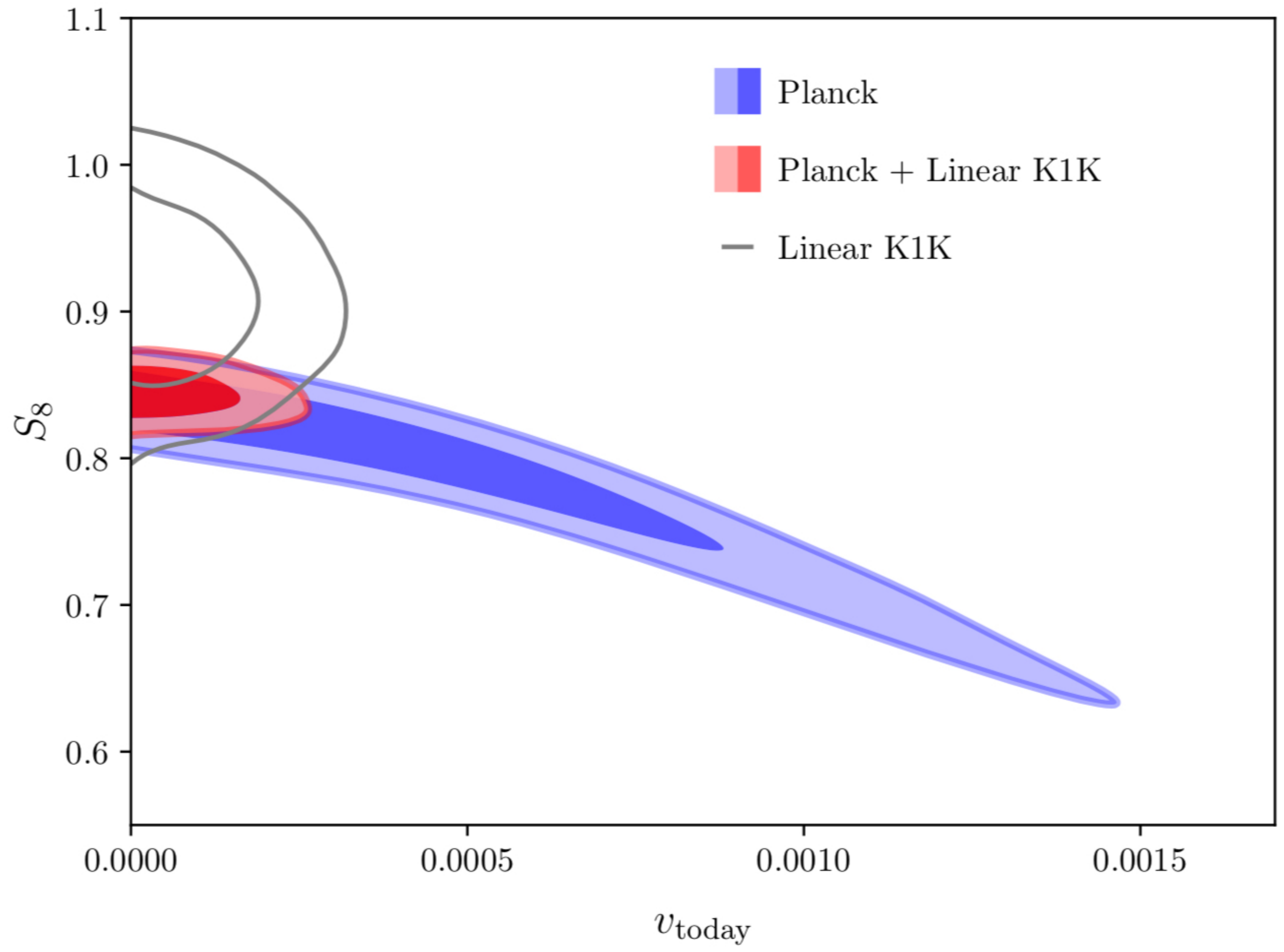
Using

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

we learn

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

Could impact structure formation.



1.1
1.0
0.9
0.8
0.7
0.6
$S_8$
0.0000
0.0005
0.0010
0.0015
$v_{\rm today}$
Planck
Planck + Linear K1K
Linear K1K

# Narrowing the Parameter Range

The fact that violation of KK quantum number $\delta$ has to be small suggests the dark dimension is very smooth. Together with the axion physics having a Planckian thickness for the SM brane suggests a scenario very similar to Horava-Witten picture (suggested in the context of Dark Dimension by Schwarz)-i.e. heterotic $E_8 \times E_8$ at strong coupling with Planckian 6-manifold (like CY) which breaks or confines one $E_8$ and breaks the other to SM.

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

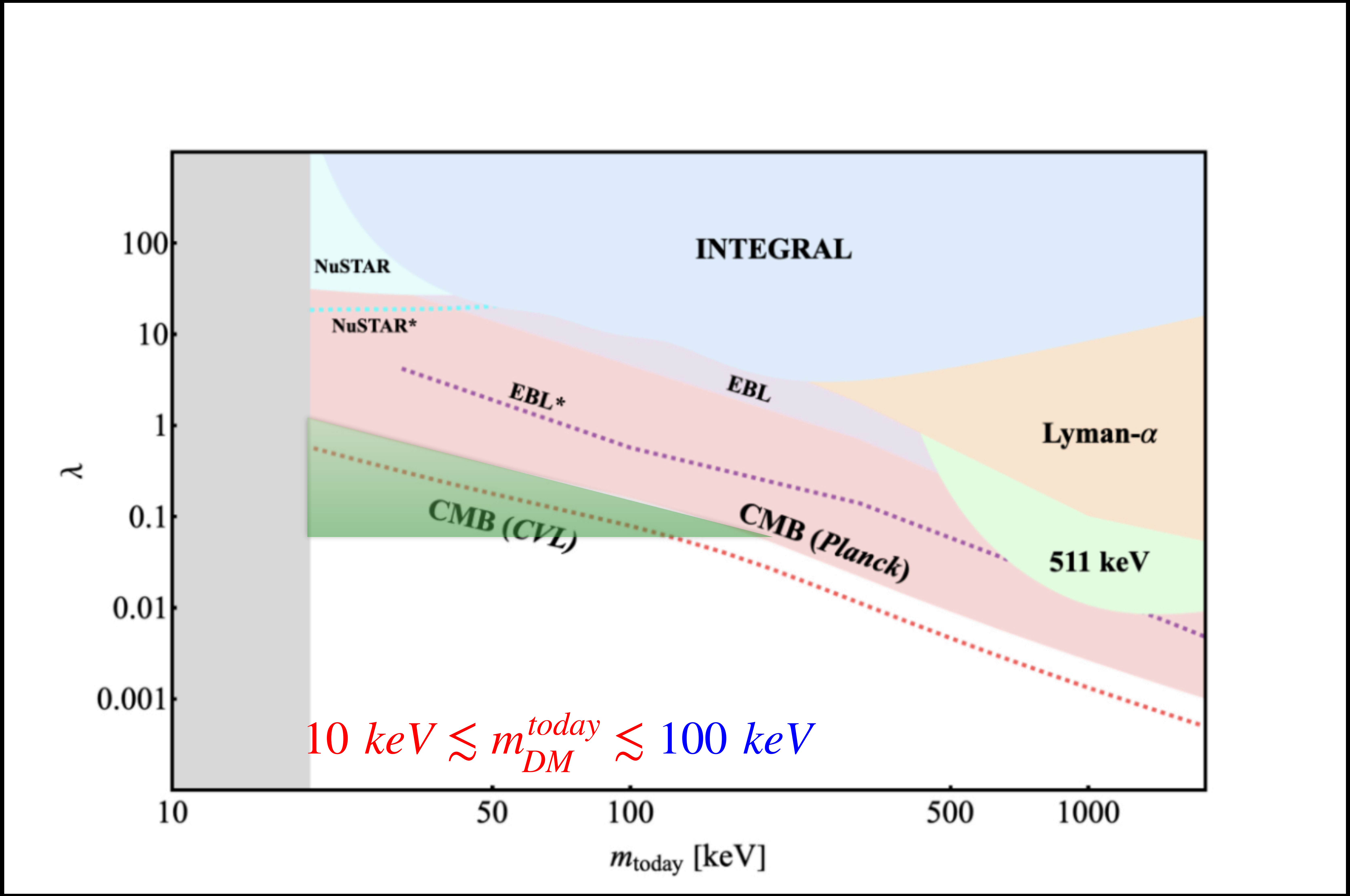
but decaying DM mass cannot be too large due to

$$DM \to \gamma\gamma, e^+e^-, \ldots$$

Leads to a narrow range for the diameter of extra dimension:

$$1\mu m \lesssim L \lesssim 10\mu m$$

# Astrophysical bounds (using the work of Slatyer et.al.,...):



# Summary

Small dark energy + Swampland + observations

↓

The Dark Dimension in the micron range

Unification of dark sector

DM=tower of graviton excitations in the dark dimension

No direct detection of DM possible

axion mass similar to neutrinos similar to tower mass scale

Possible Unification of hierarchies (Dirac's dream):

$$\Lambda^{0} \sim M_p \sim 1$$

$$\Lambda^{\frac{1}{12}} \sim \widehat{M}_p, f_a, \Lambda^{\text{Higgs}}_{\text{inst.}} \sim 10^{-10}$$

$$\Lambda^{\frac{2}{12}} \sim \Lambda_{\text{QCD}}, \alpha\Lambda_{\text{weak}}, T_i \sim 10^{-20}$$

$$\Lambda^{\frac{3}{12}} \sim m_\nu, m_a, m_{\text{dark tower}} \sim 10^{-30}$$

$$\Lambda^{\frac{6}{12}} \sim H_0 \sim \tau^{-1}_{\text{now}} \sim 10^{-60}$$