Swampland
and a
Unification of the Dark Sector

Cumrun Vafa
Harvard University

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Perimeter Institute for Theoretical Physics

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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

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QG consistency captured by Swampland criteria sheds light.

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The Distance/Duality Conjecture ⇒ Unification of Dark Sector

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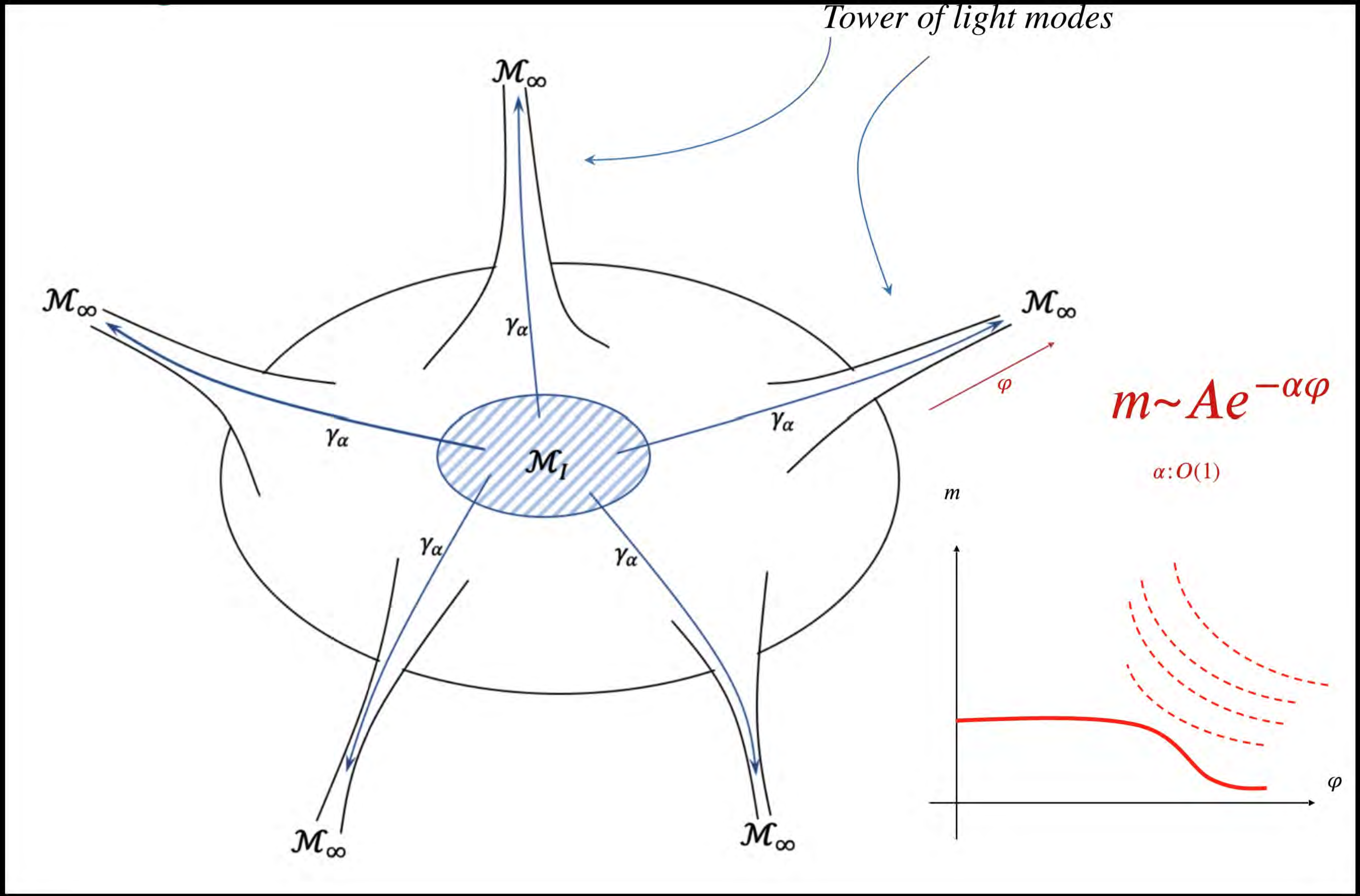
Novel unexplored type of dark matter

Distance/Duality Conjecture

[OV, 06]



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

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

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

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

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 $\sim \Lambda^{-1/4}$!

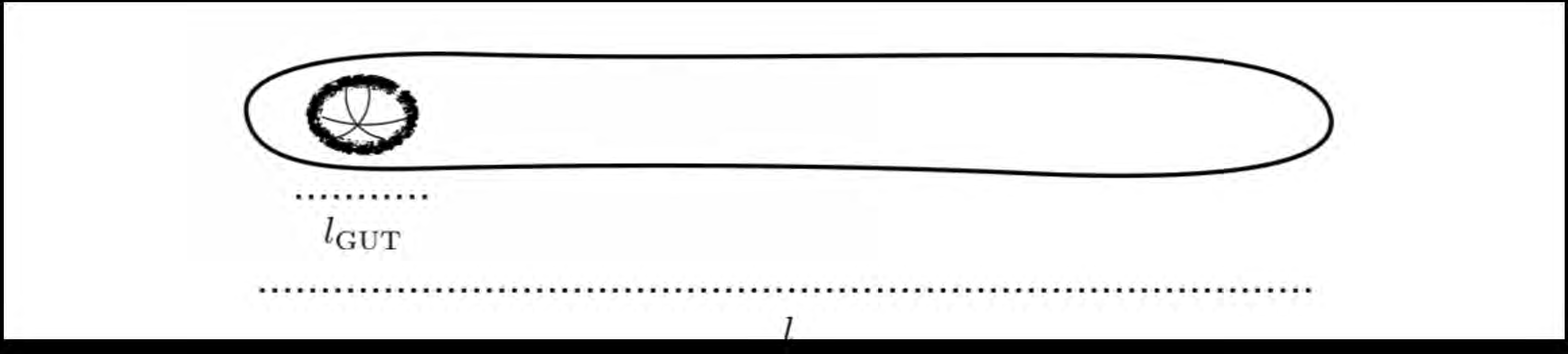
Fundamental Planck scale in 5-th dimension

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

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

Phenomenological aspects

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



Two potential applications in particle physics:

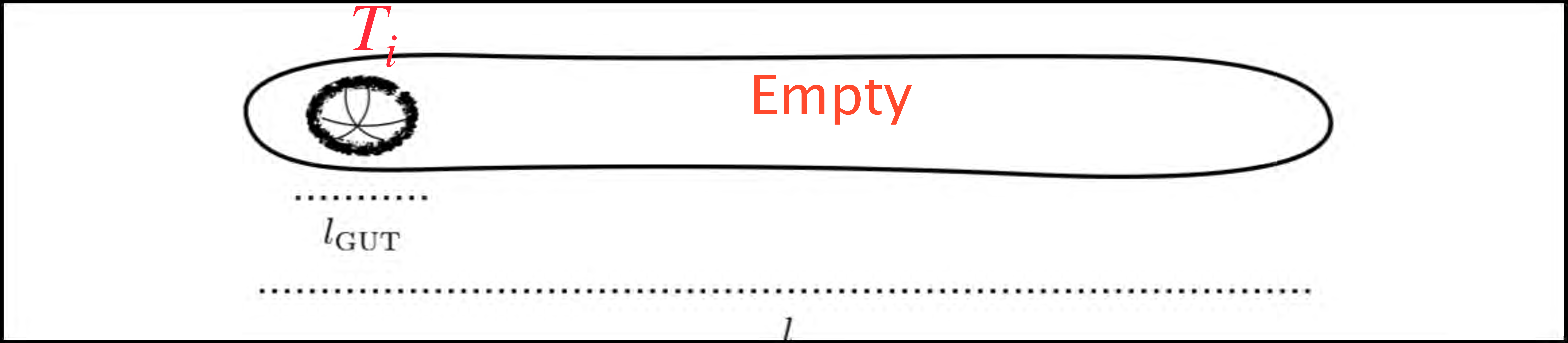
Instability in Higgs potential at $10^{11} GeV$: may be related to higher Planck scale at $10^{10} GeV$.

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



$T_i \geq 1$ MeV

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

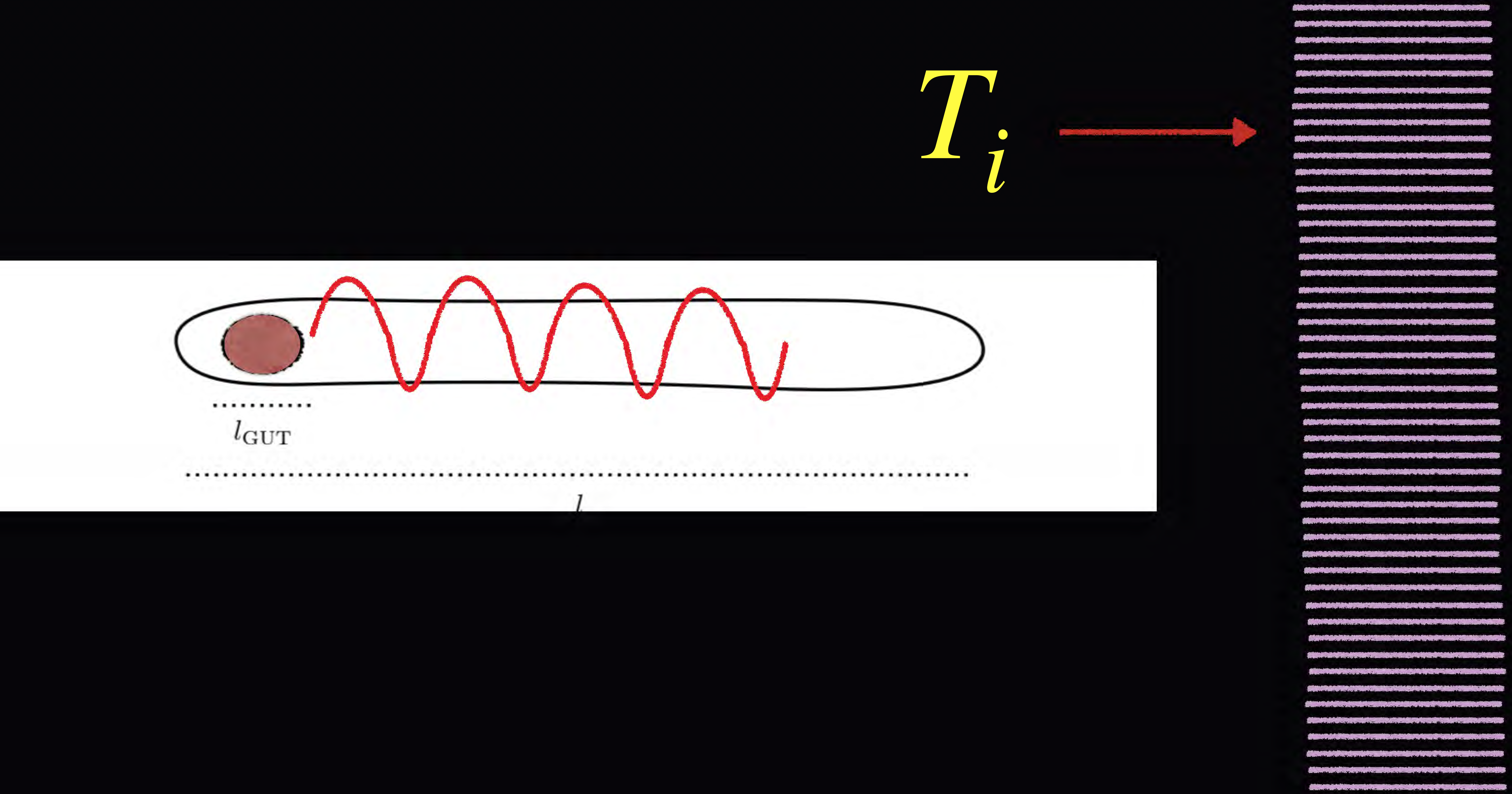
$$\frac{1}{\hat{M}_p^{3/2}} \int d^4x\, h_{\mu\nu}(x,z)\Big|_{z=0} T^{\mu\nu}(x)$$

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

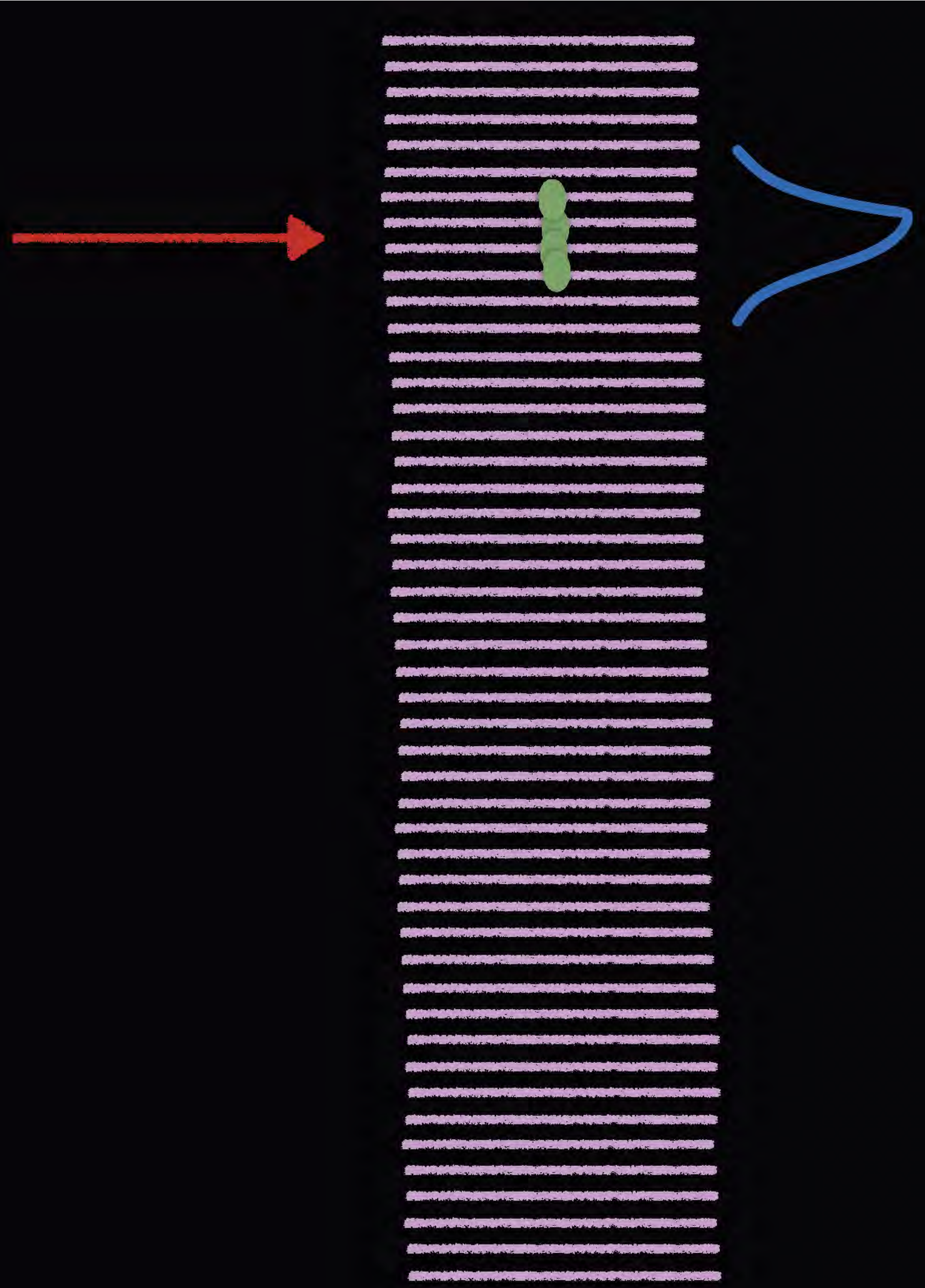
$$h^0_{\mu\nu} = graviton, \qquad h^n_{\mu\nu} \quad n \neq 0 \quad \text{KK gravitons}$$

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

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


T_i
l_{GUT}
l

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]):

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

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

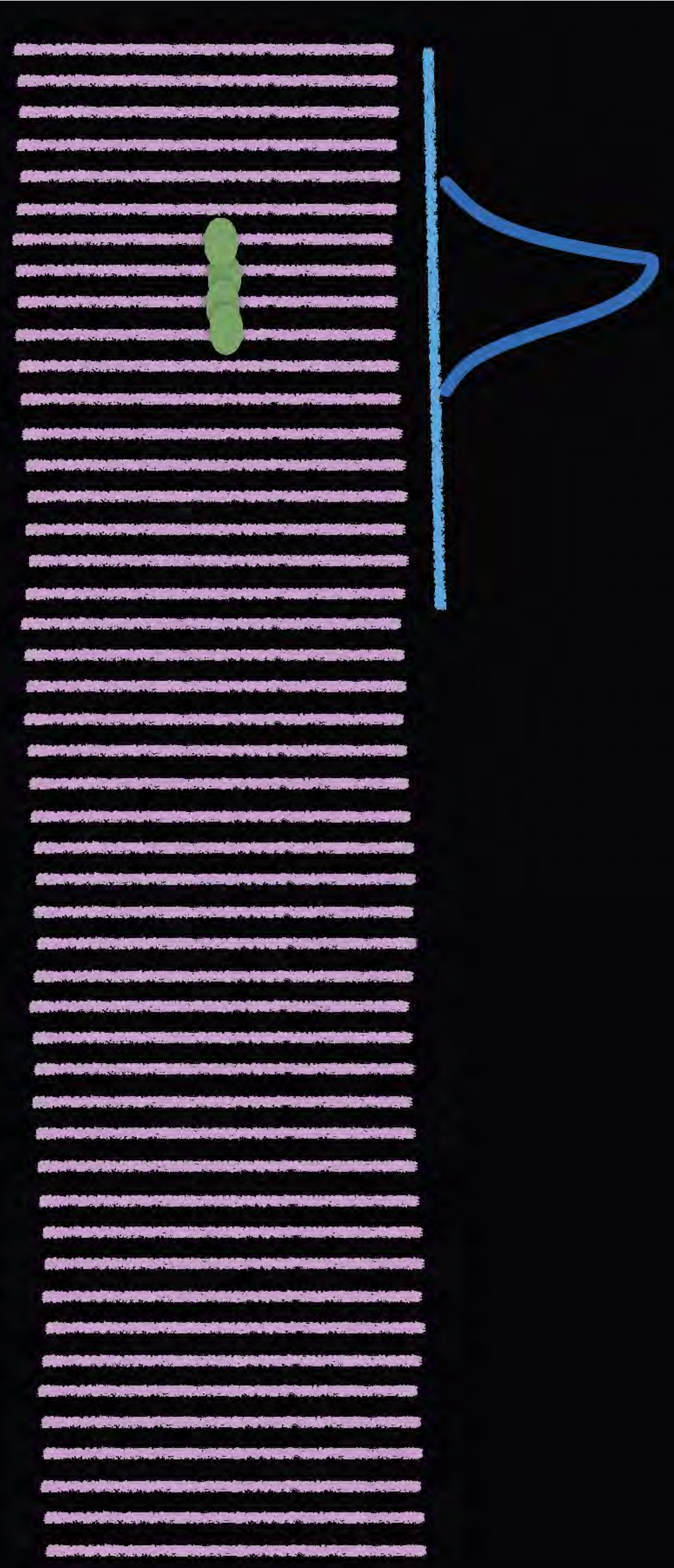
Using the coupling of 4d stress tensor to 5d gravitons we can find the rate of energy density produced in KK modes:

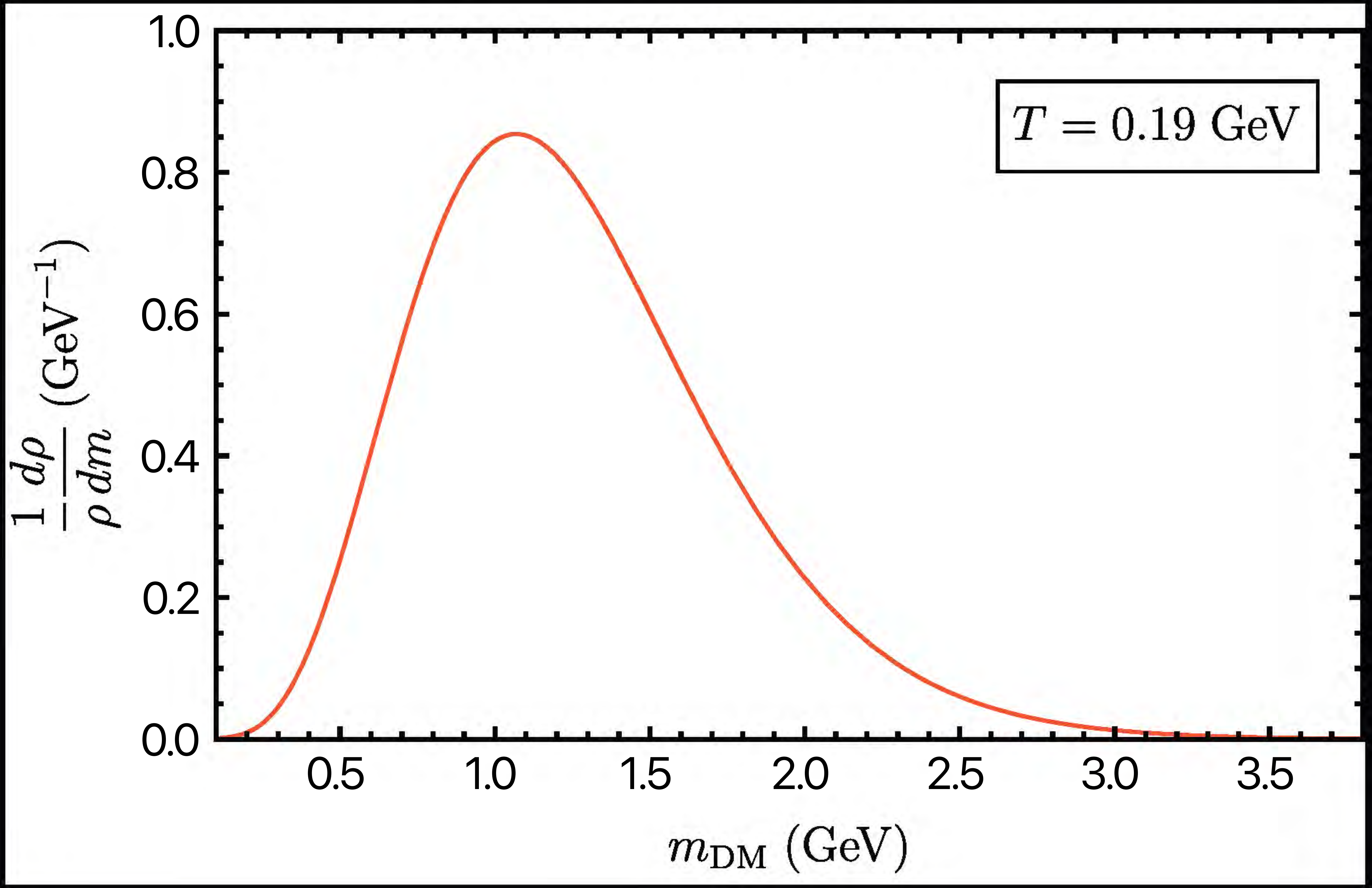
$$\frac{d\rho_{DM}}{dt} \sim \frac{T^8}{\hat{M}_p{}^3} \Rightarrow T_{MR} = \frac{T_i^3}{M_{KK}M_P} \sim \frac{\Lambda^{\frac{1}{2}}M_p}{\Lambda^{\frac{1}{4}}M_p} \sim \Lambda^{\frac{1}{4}} = T_\Lambda$$

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

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!

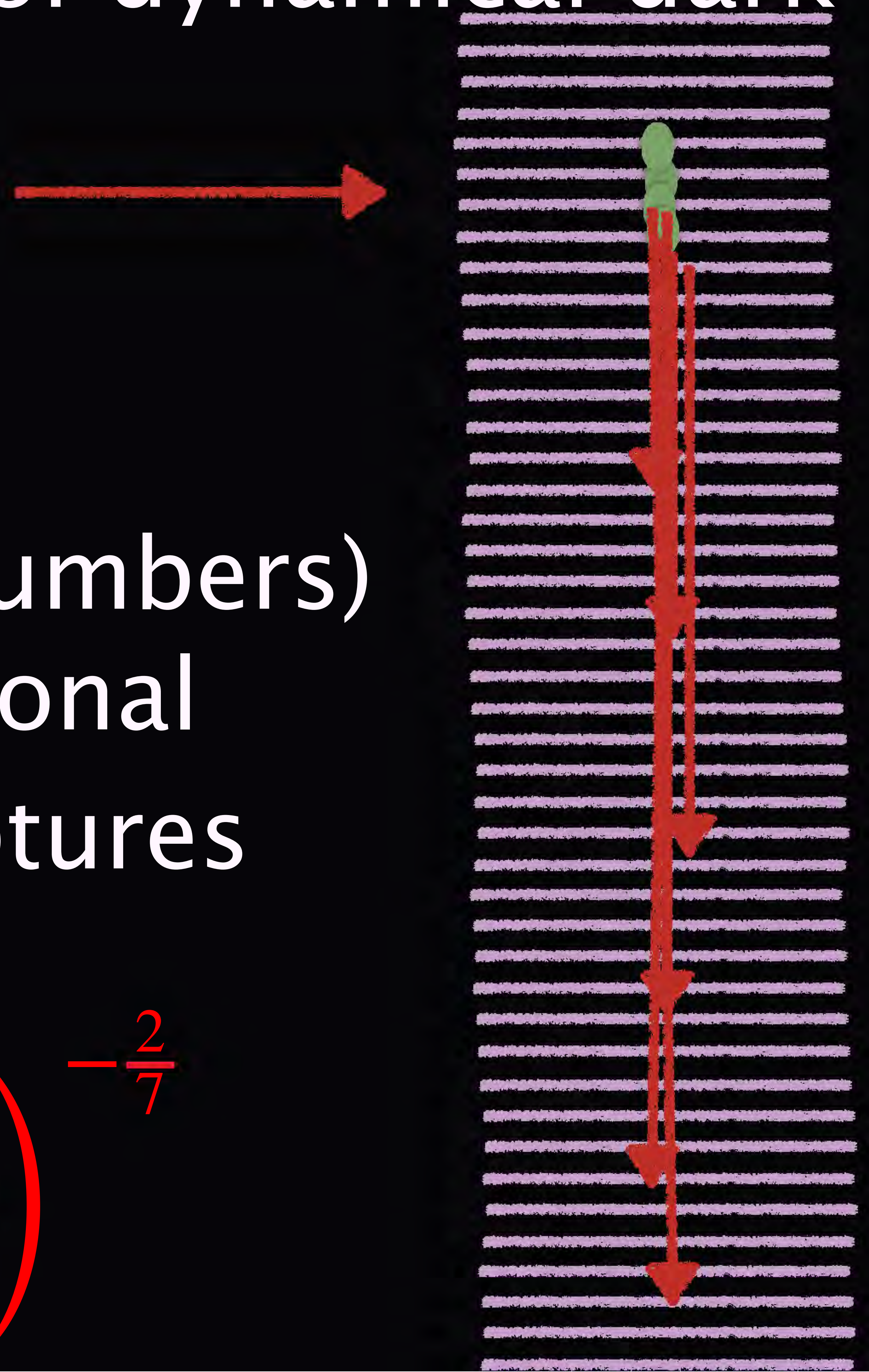
T_i




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

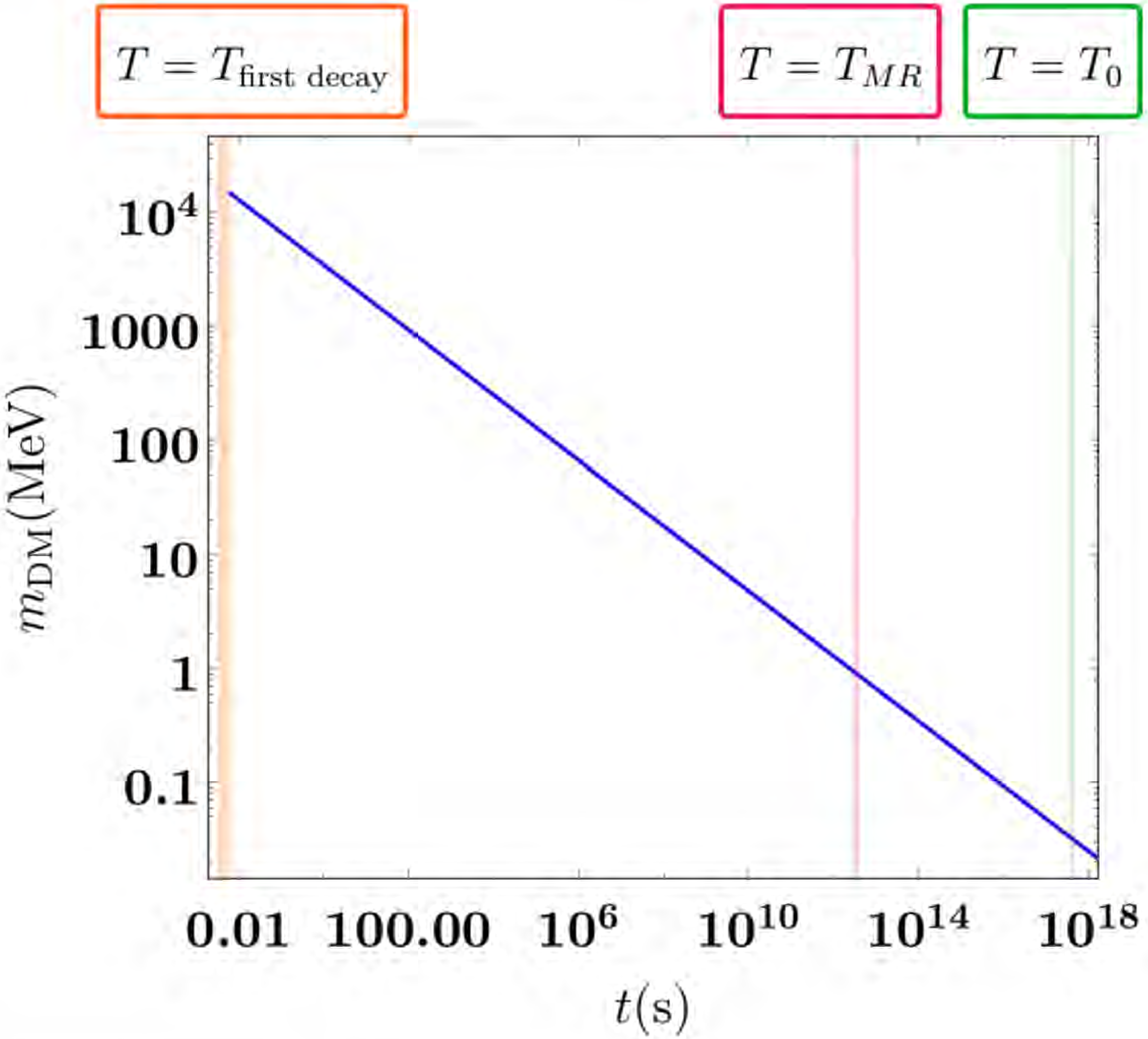
Once produced they lower their mass by decaying mostly to lower KK modes by gravitational interactions (and in the process the total energy density of dark matter does not change appreciably)—A special case of dynamical dark matter scenario [DT,11]

$$T_i \sim GeV$$



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

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


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

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

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

Using

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

we learn

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

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

but decaying DM mass cannot be too large due to

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

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

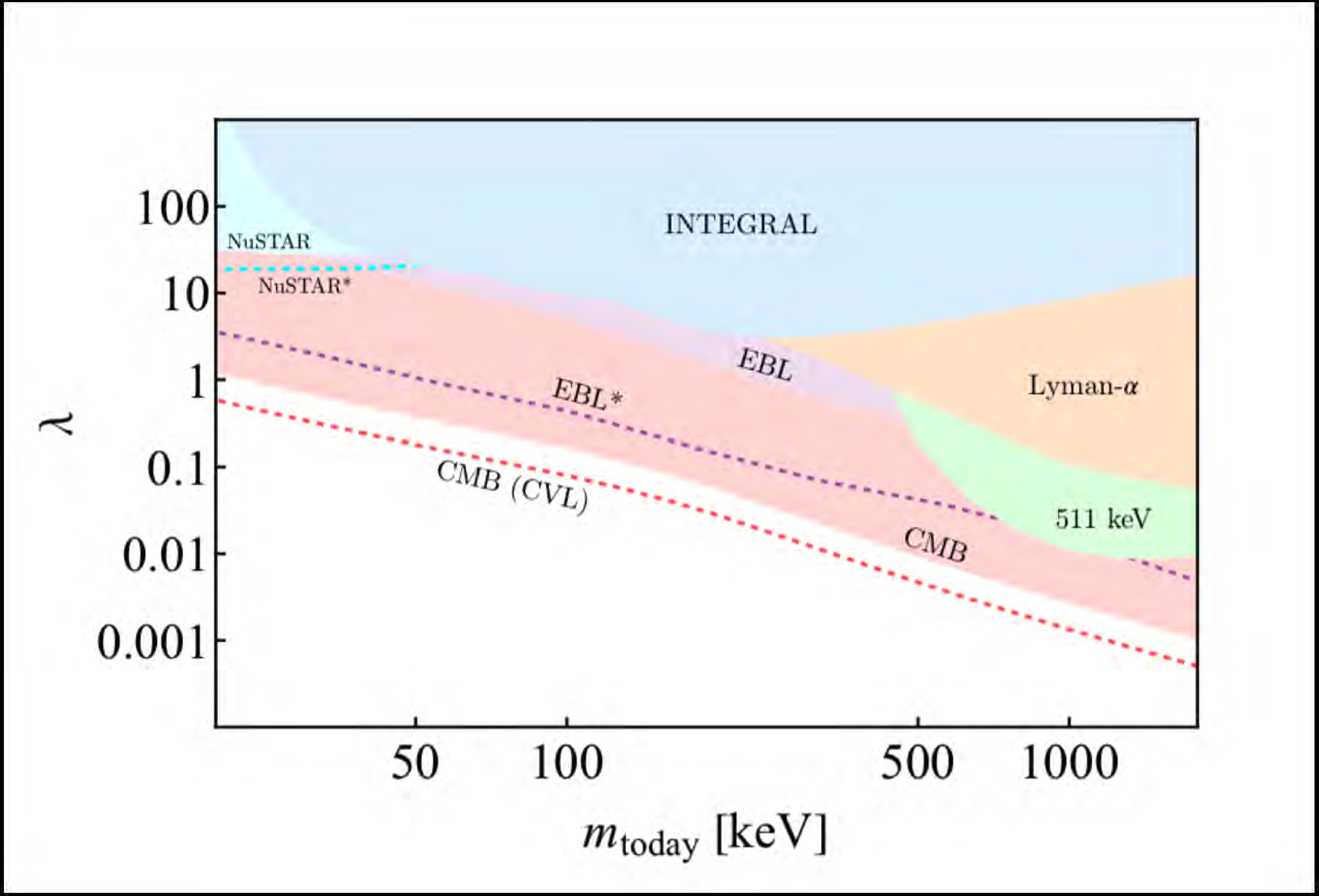
That they lower their mass is a necessary ingredient to be consistent with observation. They also decay to photons:

$$g \to \gamma\gamma$$

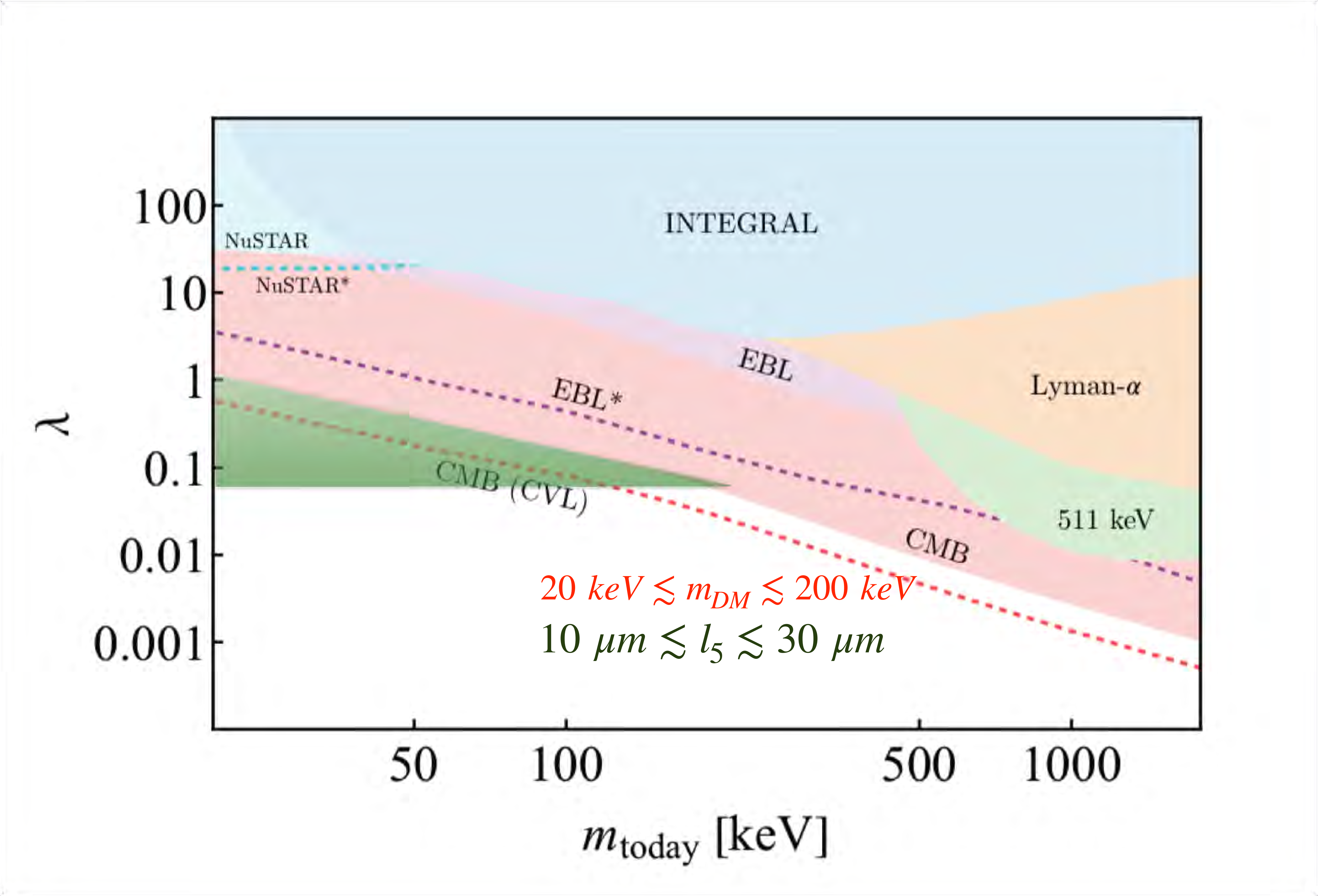
would affect CMB anisotropies. To be consistent with observational bounds their mass should be below MeV

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

Astrophysical bounds:



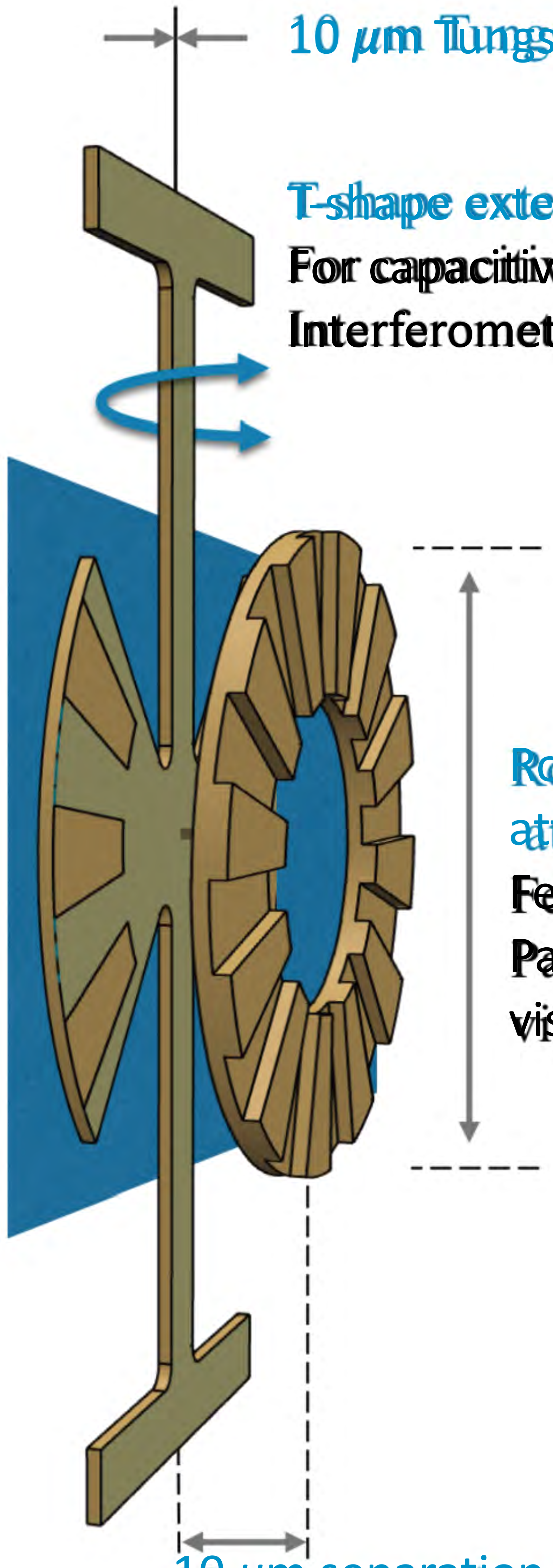
Astrophysical bounds:



$20\ keV \lesssim m_{DM} \lesssim 200\ keV$

$10\ \mu m \lesssim l_5 \lesssim 30\ \mu m$

New ISLE at the Conrad Observatory



10 *μm* Tungsten fibre

T-shape extensions
For capacitive feedback with
Interferometric readout

Electromagnetic shield

Torsion pendulum
Microfabricated
Modified Fourier-Bessel
pattern

Rotating Fourier-Bessel attractor (Ø = 8 cm)
Femtosecond laser machined
Pattern on this side for
visualization (not to scale)

10 *μm* separation (not to scale)

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…

New ISLE at the Conrad Observatory

Conrad Observatory

Main challenges for ISLE at separations ≲ 10 μm

Sensitivity to to see ultra-feeble forces Nanoradian precision (meter stick on the moon!)	Easier part
Understanding all systematic effects (spurious signals)	Harder part
- Gravity gradients	Can be handled
- Magnetic impurities	High-purity materials needed
- Electromagnetic shield	Technological challenge
- Vibrations, Patch effects, thermal effects	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):

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

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).