Swamplandish Predictions for Cosmology

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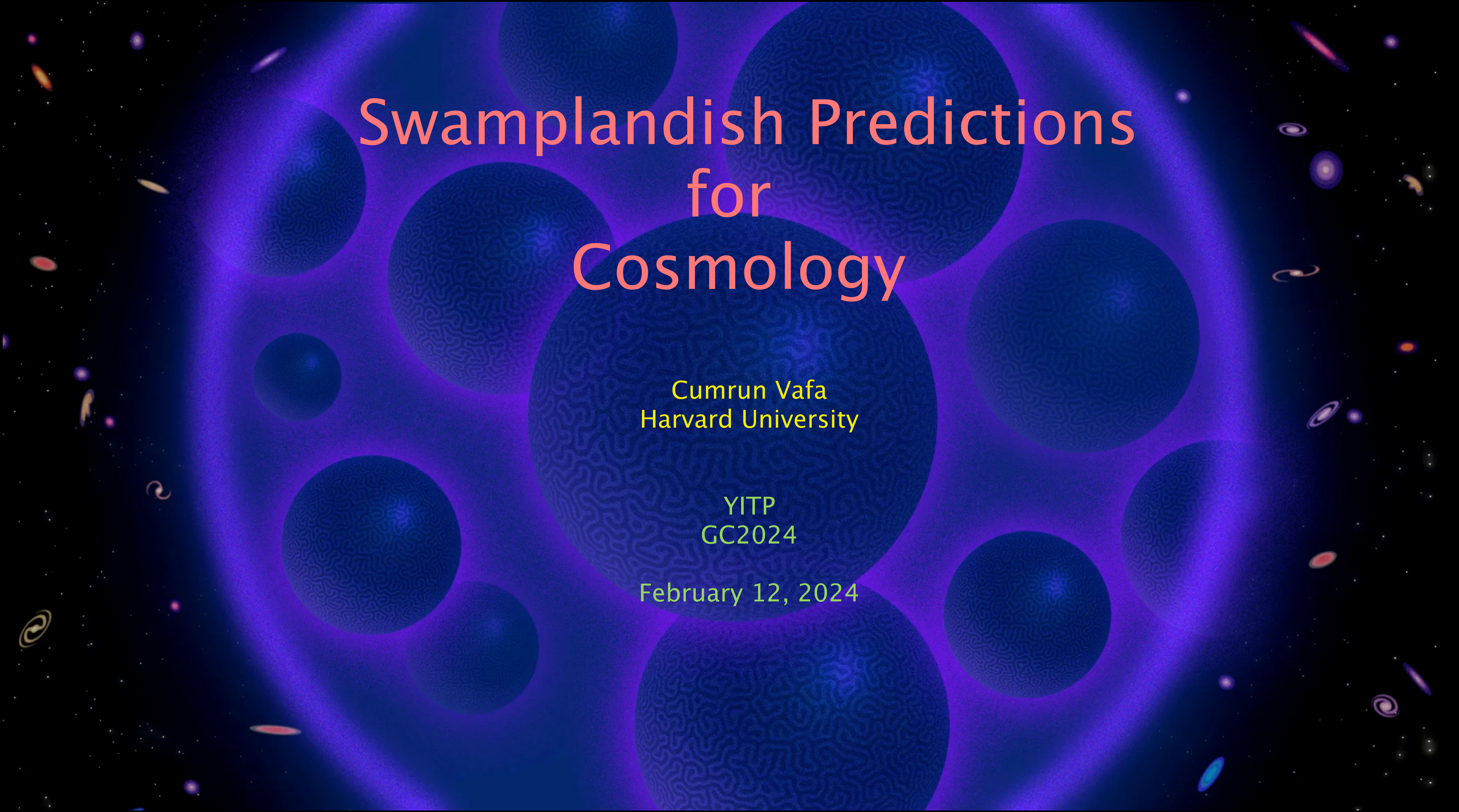


Samuel Velasco/Quanta Magazine

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

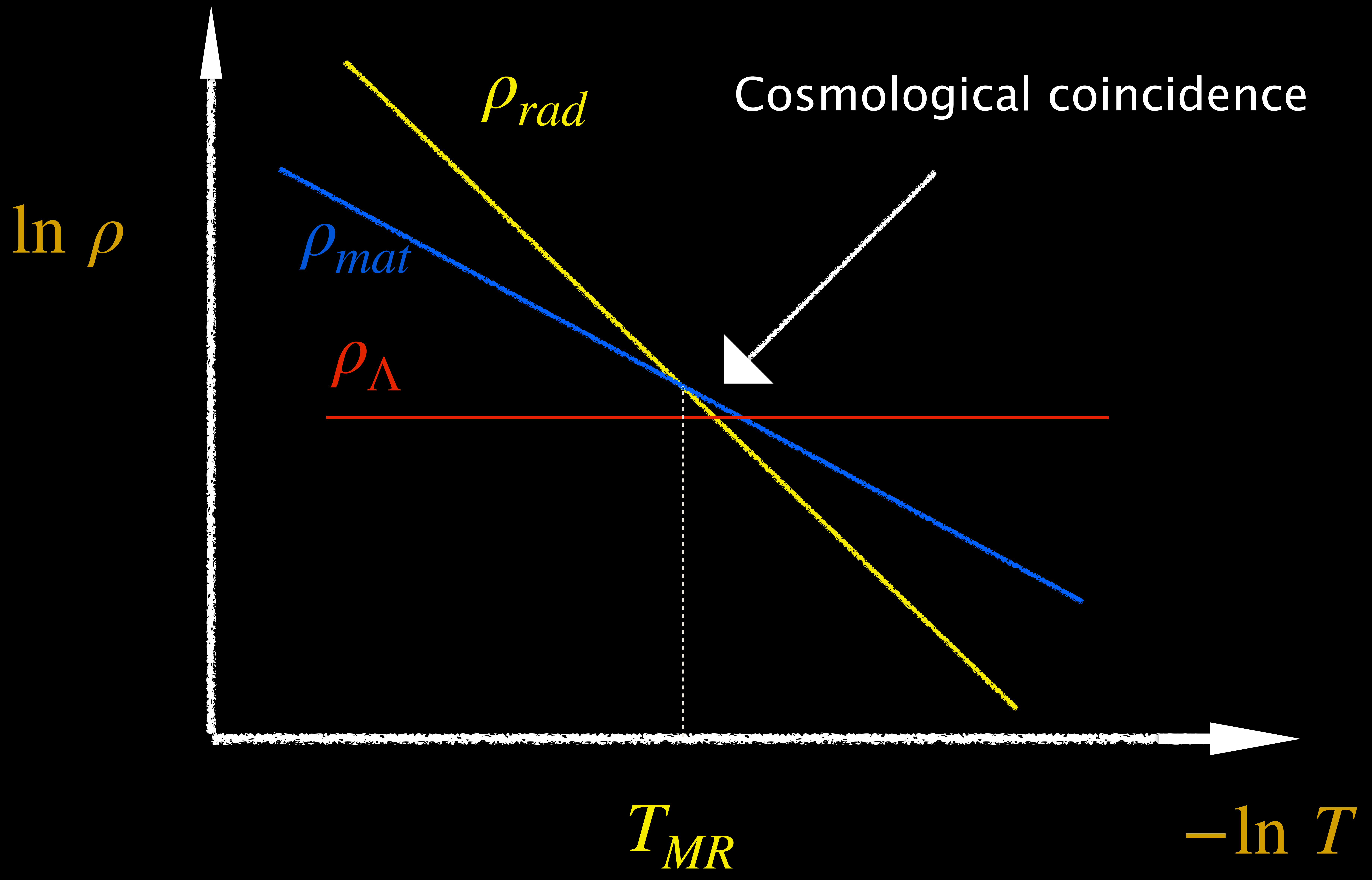
Some Puzzles of Cosmology

Why do we live now?

$$\tau_{now} \sim \frac{1}{\sqrt{\Lambda}}$$

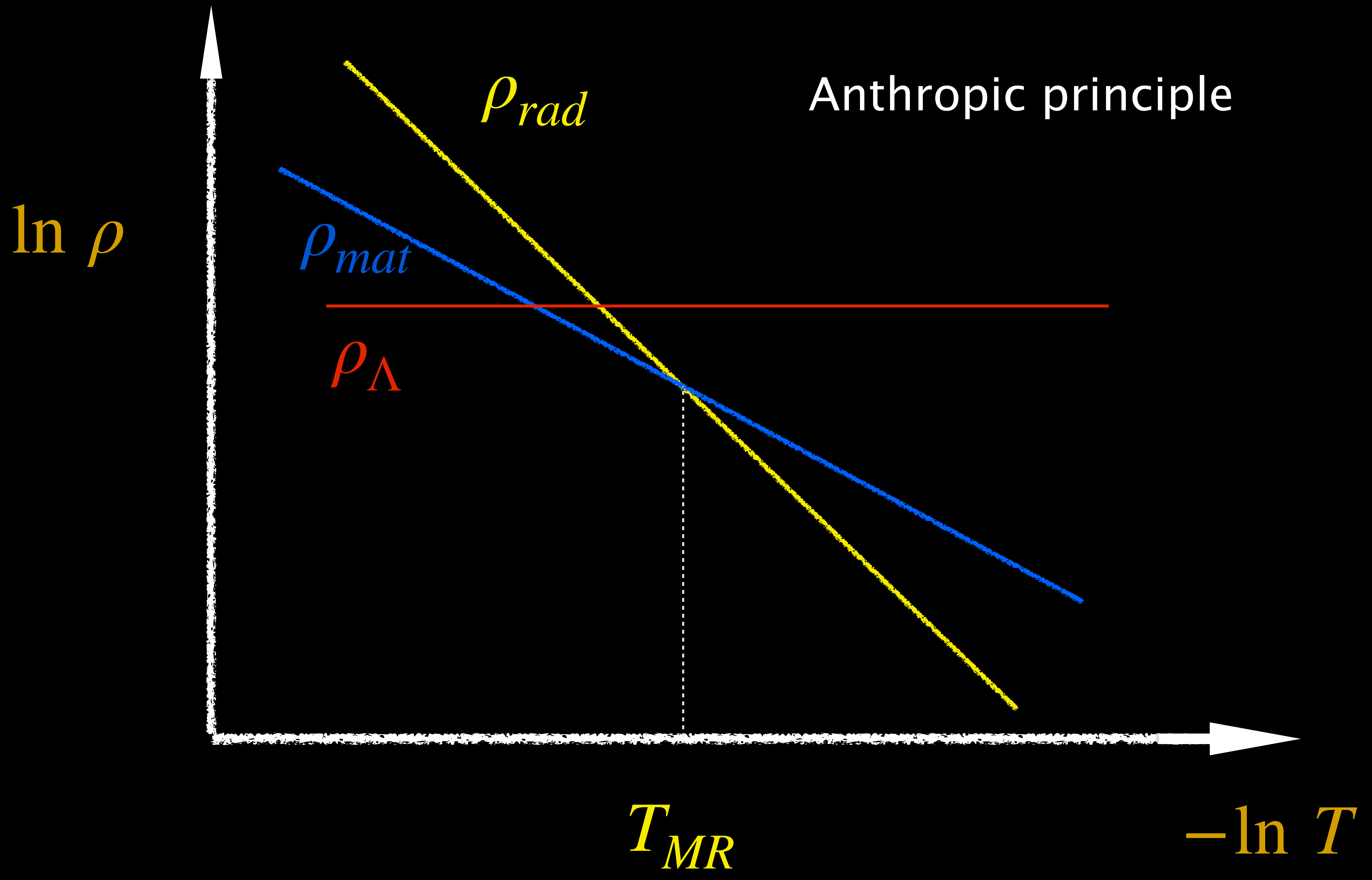
Why the Matter-Radiation equality is close to where the dark energy takes over?

$$T_{MR}^4 \sim \Lambda$$

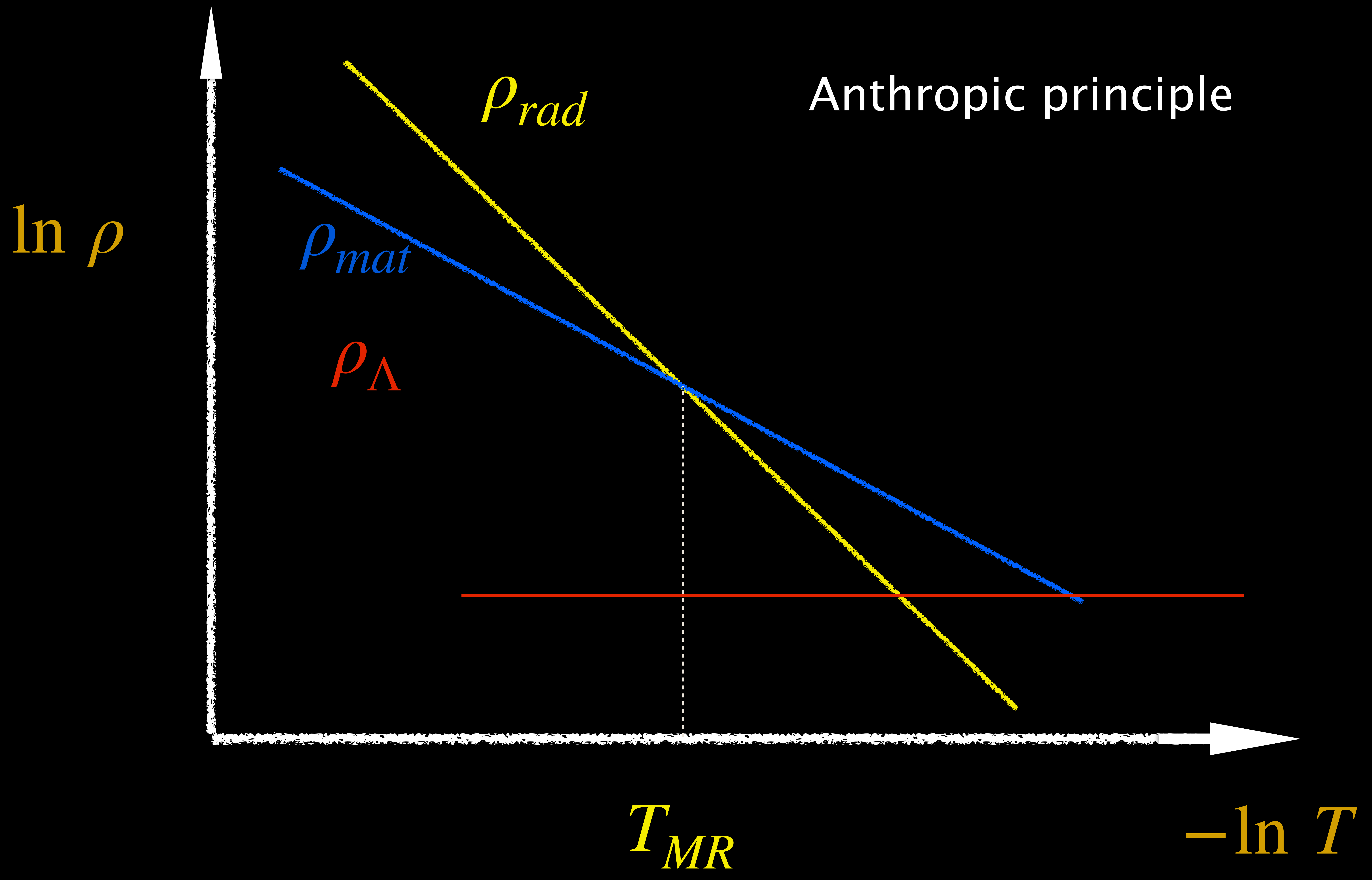


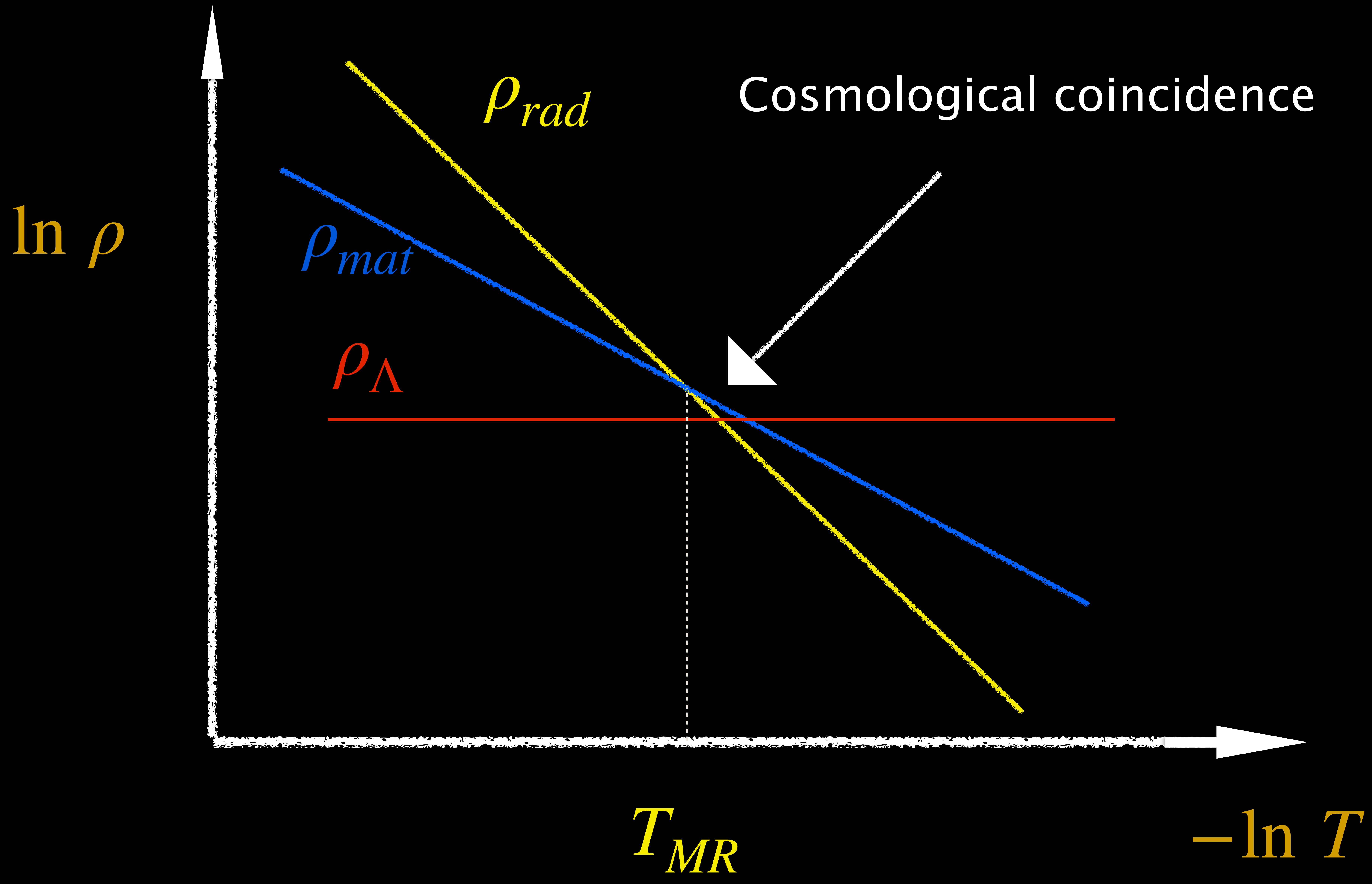
Cosmological coincidence
ρ_{rad}
$\ln\rho$
ρ_{mat}
ρ_{Λ}
T_{MR}
$-\ln T$

Anthropic principle



Anthropic principle




ρ_{rad}
Cosmological coincidence
$\ln \rho$
ρ_{mat}
ρ_{Λ}
T_{MR}
$-\ln T$

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?

Quantum gravity seems unrelated to these questions.
Nevertheless, I will argue in this talk that quantum gravity sheds light on all these questions.

Swampland Program: Summarizes lessons about QG we have learned from string theory. It turns out these general lessons lead to insights into this questions.

Transplanckian Censorship Conjecture (TCC) $\Rightarrow$ why now

The Distance/Duality Conjecture $\Rightarrow$ Unification of Dark Sector

$\Lambda \sim 10^{-122} \ll 1 \Rightarrow$ light tower (weakly interacting)

$$\text{light tower} = \text{dark matter}$$

Novel unexplored type of dark matter: graviton excitation in the internal space

Combination of TCC and Distance conjecture $\Rightarrow$ Coincidence problem

Transplanckian Censorship Conjecture
[BV, 19]

In an expanding universe subplanckian regions cannot exit the horizon of a dS space.
Motivation: Subplanckian modes cannot freeze

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

$$\frac{a_f}{a_i} \cdot l_{pl} < \frac{1}{H_f}$$

Evidence:

In all string theory examples

$$V \sim \exp(-\alpha\phi); \quad \phi \gg 1, \qquad \alpha \geq \frac{2}{\sqrt{d-2}}$$

This statement is equivalent to ruling out inflation in asymptotic field region.

And, field regions with $V \sim V_0$ are bounded

$$\Delta\phi \lesssim \sqrt{(d-2)(d-1)} \;\; \log(1/V_0)$$

Both of these coefficients can be shown to follow from TCC!

Applications:

TCC and Why Now Problem

Why do we live at an epoch where the dark energy has just taken over, i.e. $\tau_{now} \sim \frac{1}{\sqrt{\Lambda}} \sim \frac{1}{H}$?

Explanation: $\exp(\tau_{max} H).1 < \frac{1}{H} \rightarrow \tau_{max} < \frac{1}{H}\log(\frac{1}{H})$

$$\tau_{typical} \sim \frac{1}{H}$$

Note that this also implies that if particles which interact with gravitational strength were created at some cosmological epoch, for them to have decayed away before dS decays away (i.e. to ever have a dS phase), their mass cannot be too small:

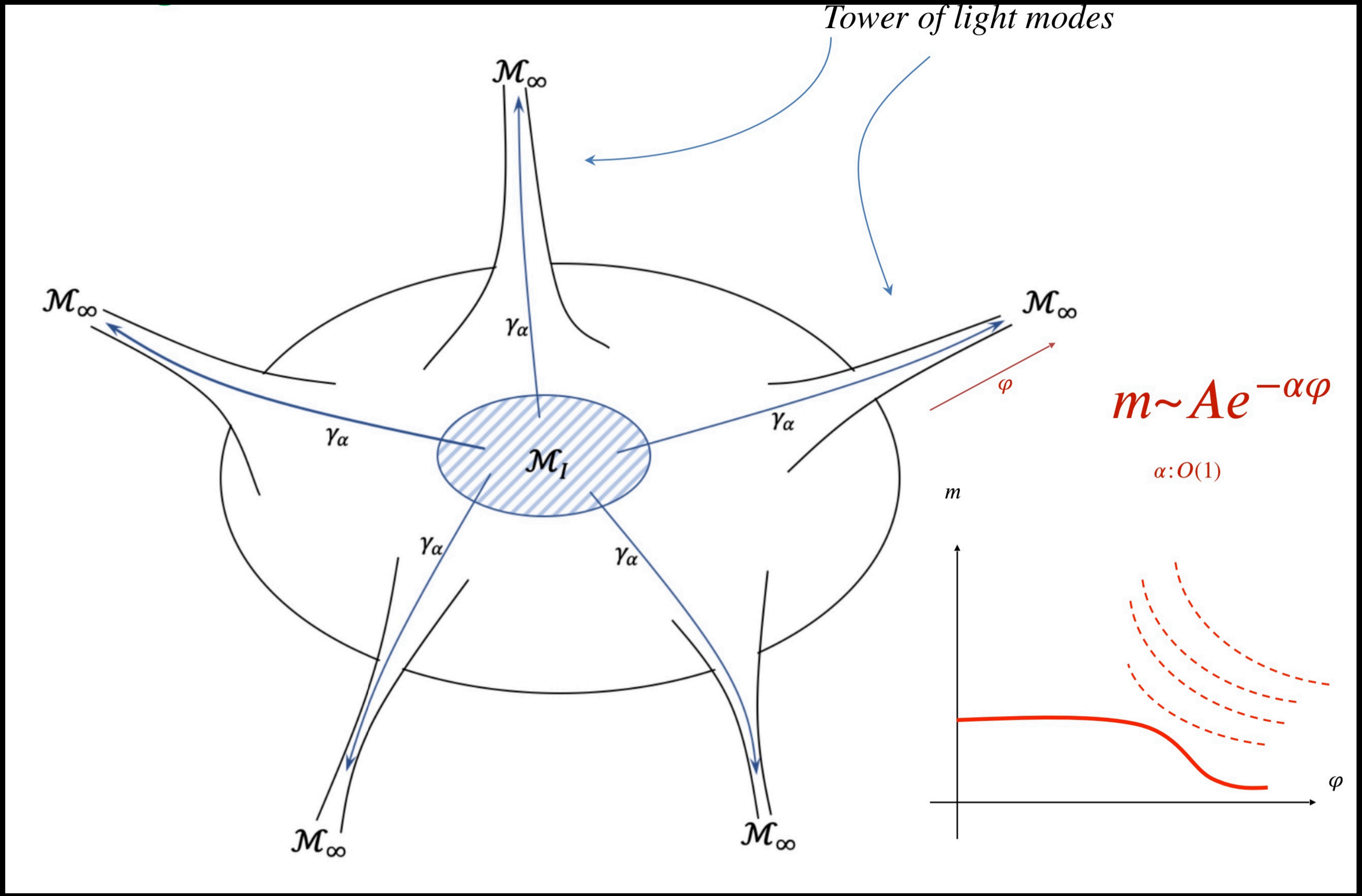
$$\Gamma \sim \frac{m^3}{M_p^2} > H \sim \Lambda^{\frac{1}{2}} \rightarrow m > \Lambda^{\frac{1}{6}} \sim 0.1GeV$$

The moduli fields of internal manifold interact with gravitational stength. So to have settled in a 4d dS geometry it would be therefore safe to have an initial temperature so the internal geometry is fixed:

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

We will see that this temperature plays a key role in solving the coincidence problem.

Distance/Duality Conjecture [OV, 06]



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

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

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.

The Dark Dimension: One extra mesoscopic dimension of length .1-10 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 $V < A \exp\left[\frac{-2\phi}{\sqrt{(d-1)(d-2)}}\right]$ as is needed for a quasi-dS solution which we live in today.

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

$$m \sim \Lambda^{1/4} \sim 10\ meV$$

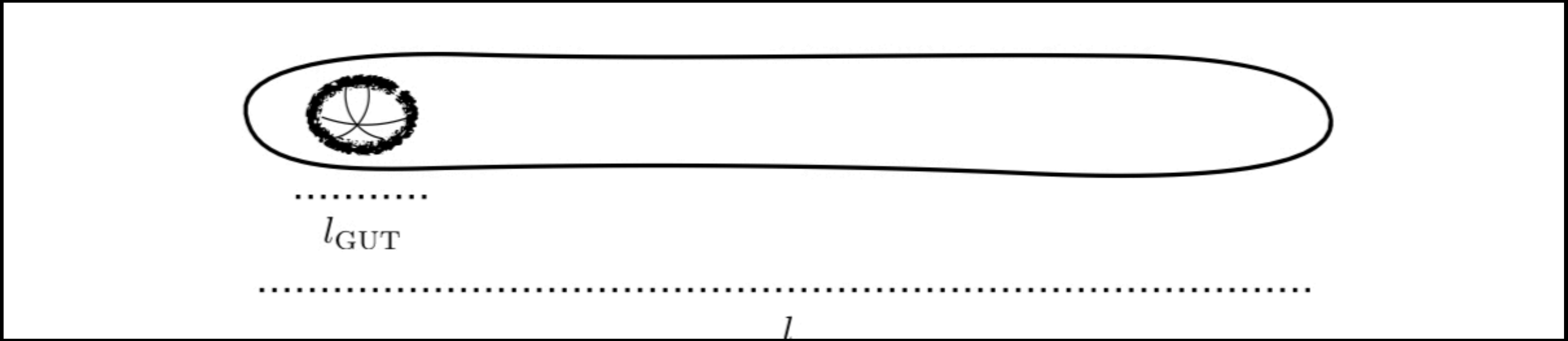
KK tower of one mesoscopic dimension in the micron range:

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).

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:

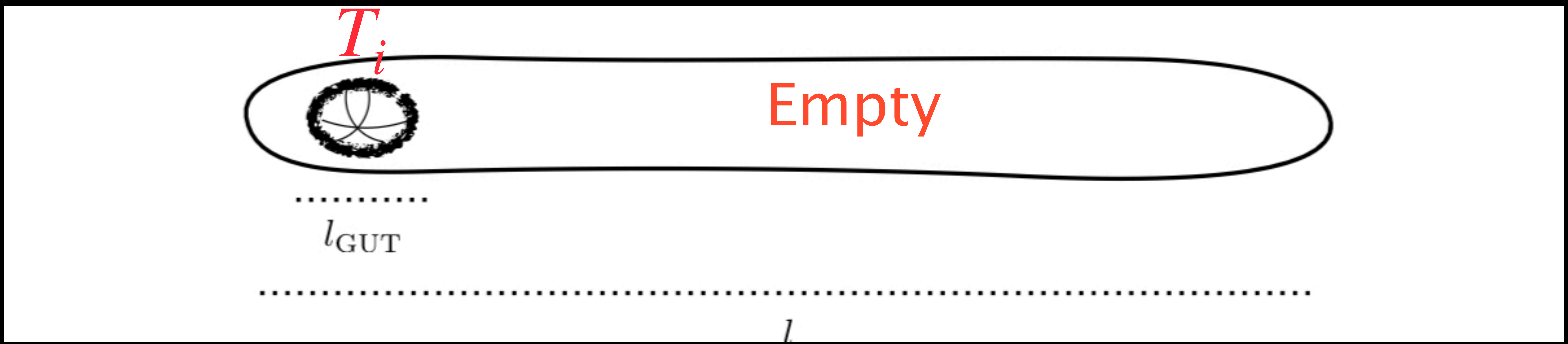
Instability in Higgs potential at $10^{11} GeV$: may be related to higher Planck scale at $10^{10} GeV$.

Neutrino physics: 5d bulk fermions coupled to ν_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.

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 (other ones have been proposed [AAL 22,23]).
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:

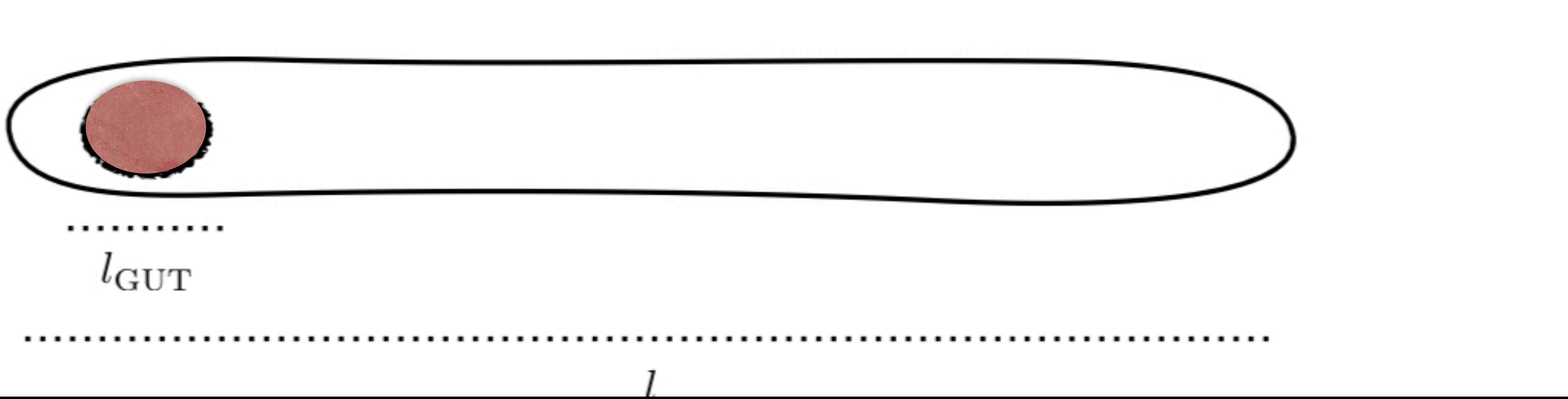
$$\frac{1}{\hat{M}_p^{3/2}} \int d^4x\, h_{\mu\nu}(x,z)\Big|_{z=0} T^{\mu\nu}(x)$$

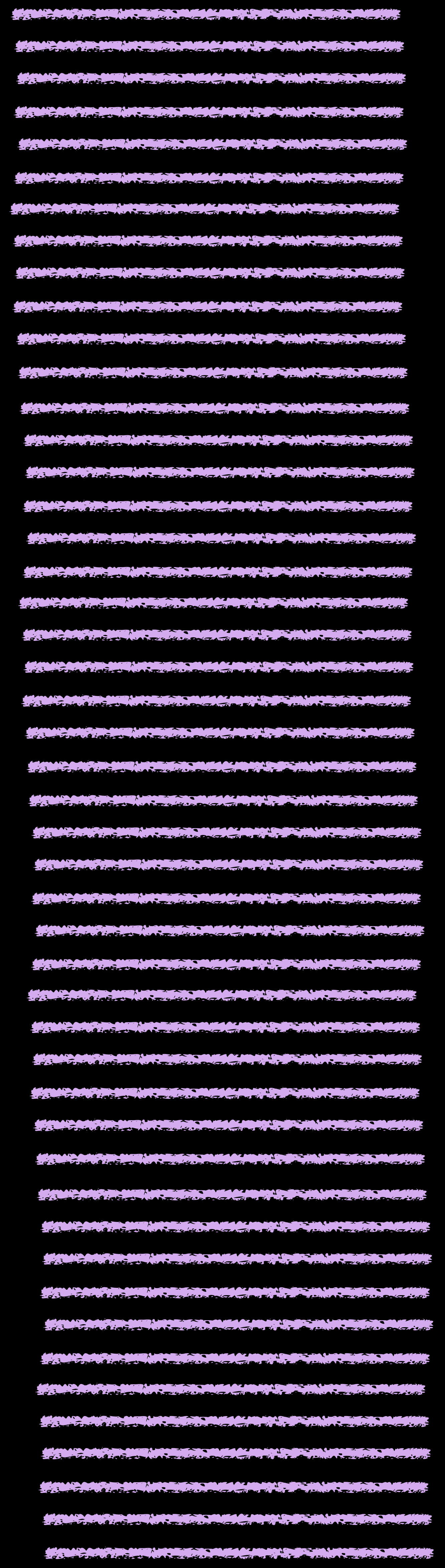
$$h_{\mu\nu}(x,z) = \sum_n h^n_{\mu\nu}(x)\phi_n(z)$$

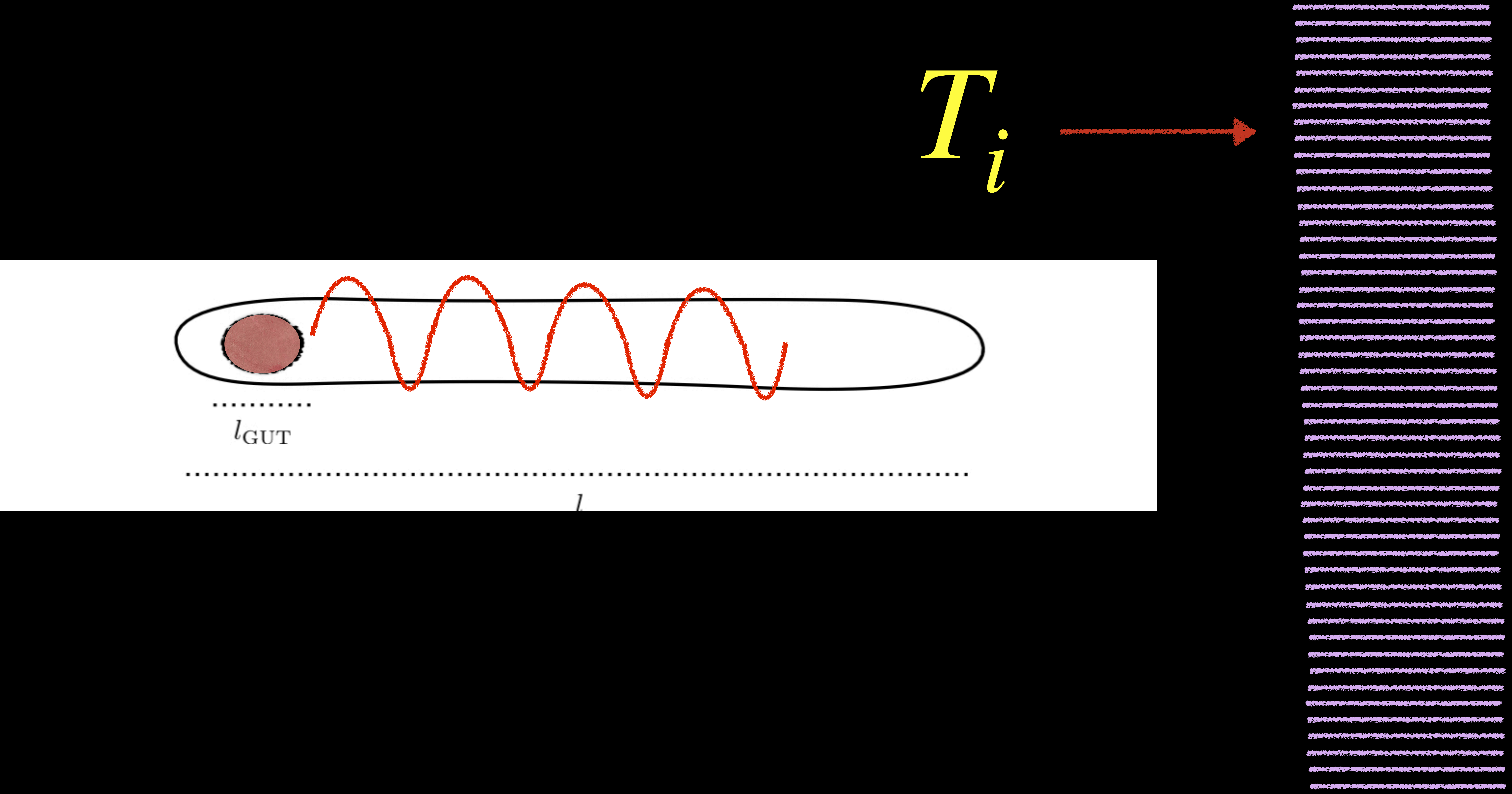
$h^0_{\mu\nu} = graviton,$ $\quad h^n_{\mu\nu} \quad n \neq 0 \quad$ KK gravitons

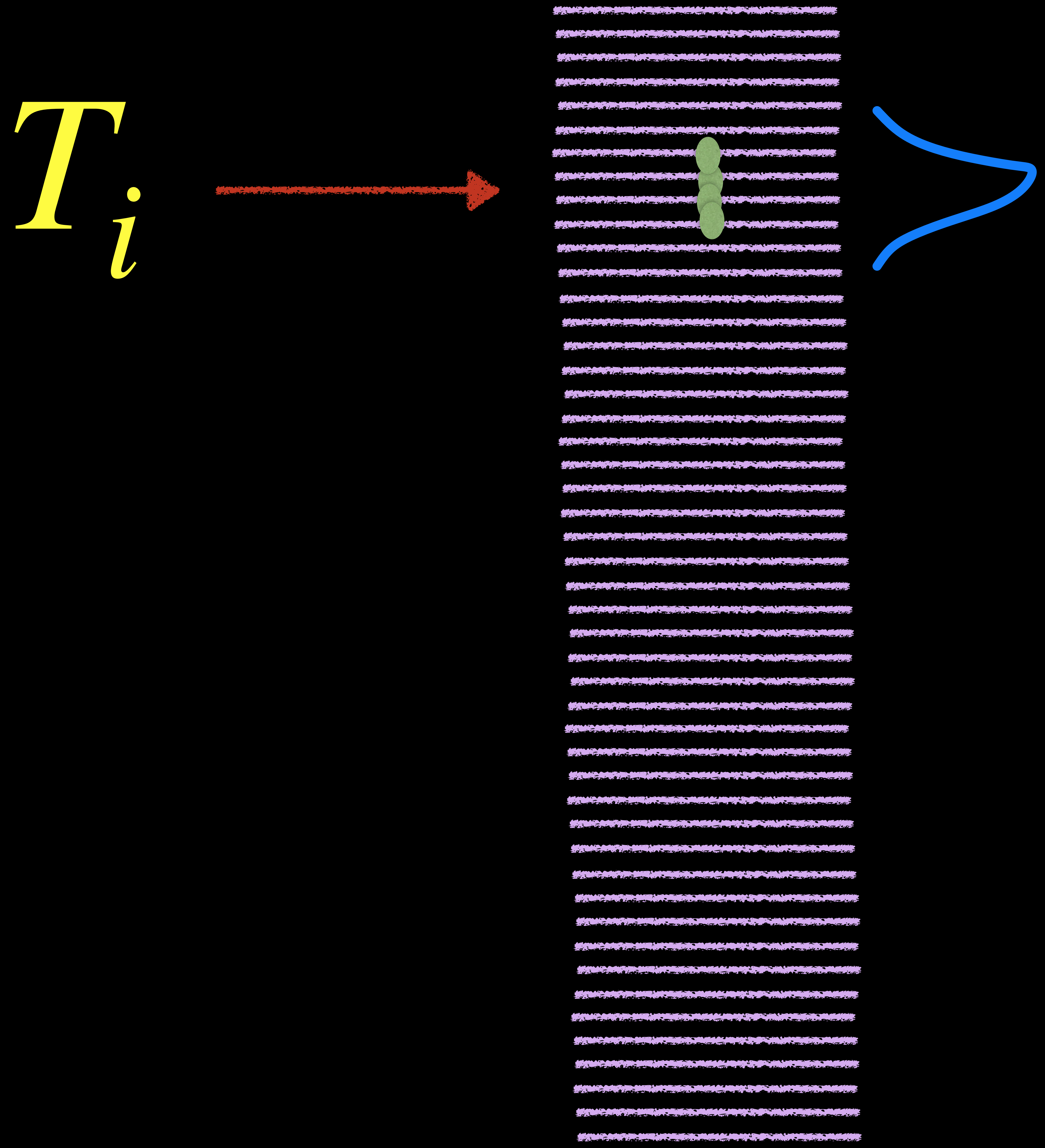
$$m_n \sim n \cdot m_{KK} \sim \frac{n}{l}$$

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


l_{GUT}
l




T_i
l_{GUT}


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

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

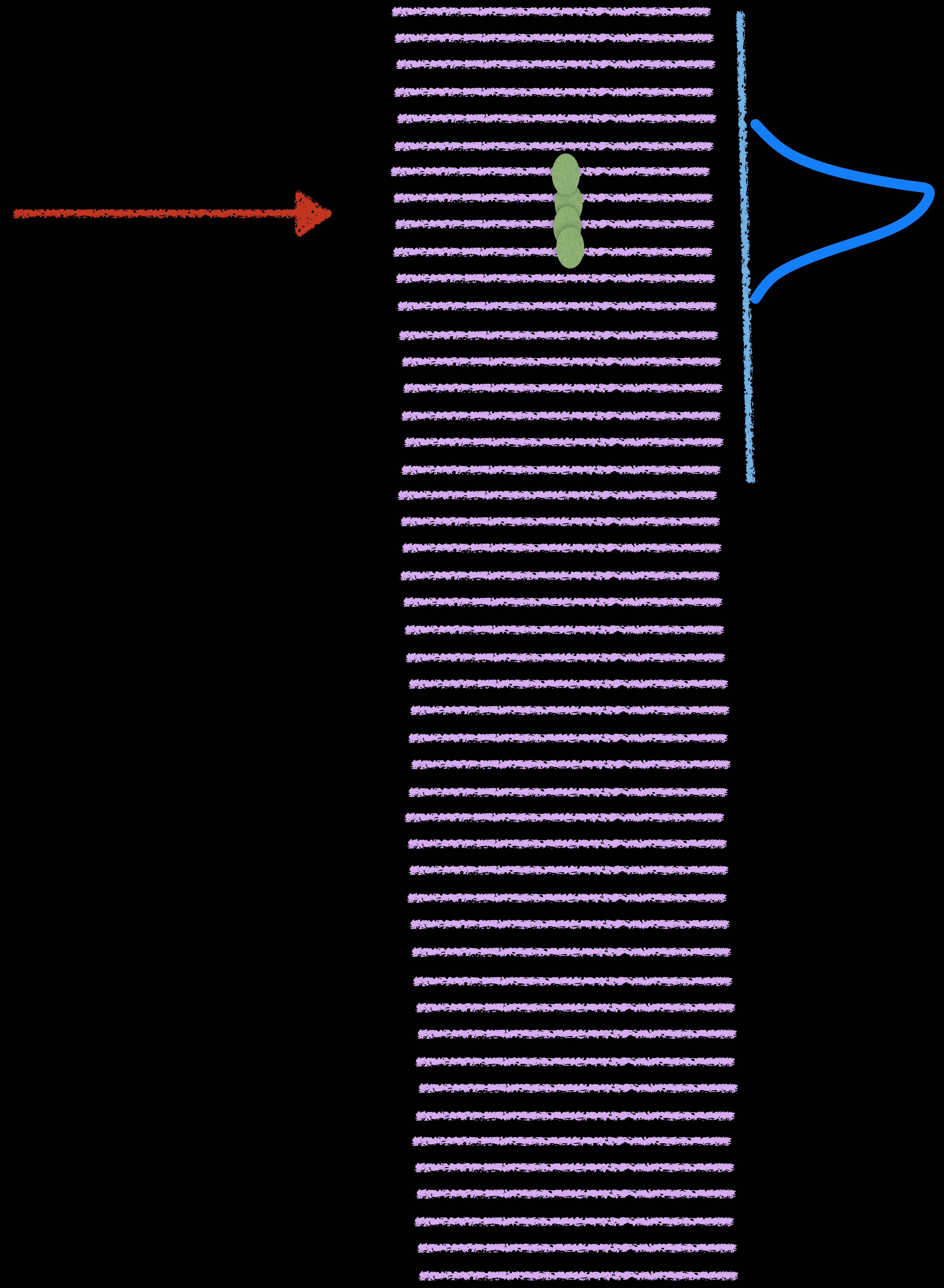
Using the coupling of 4d stress tensor to 5d gravitons we can find the rate of energy density produced in KK modes:

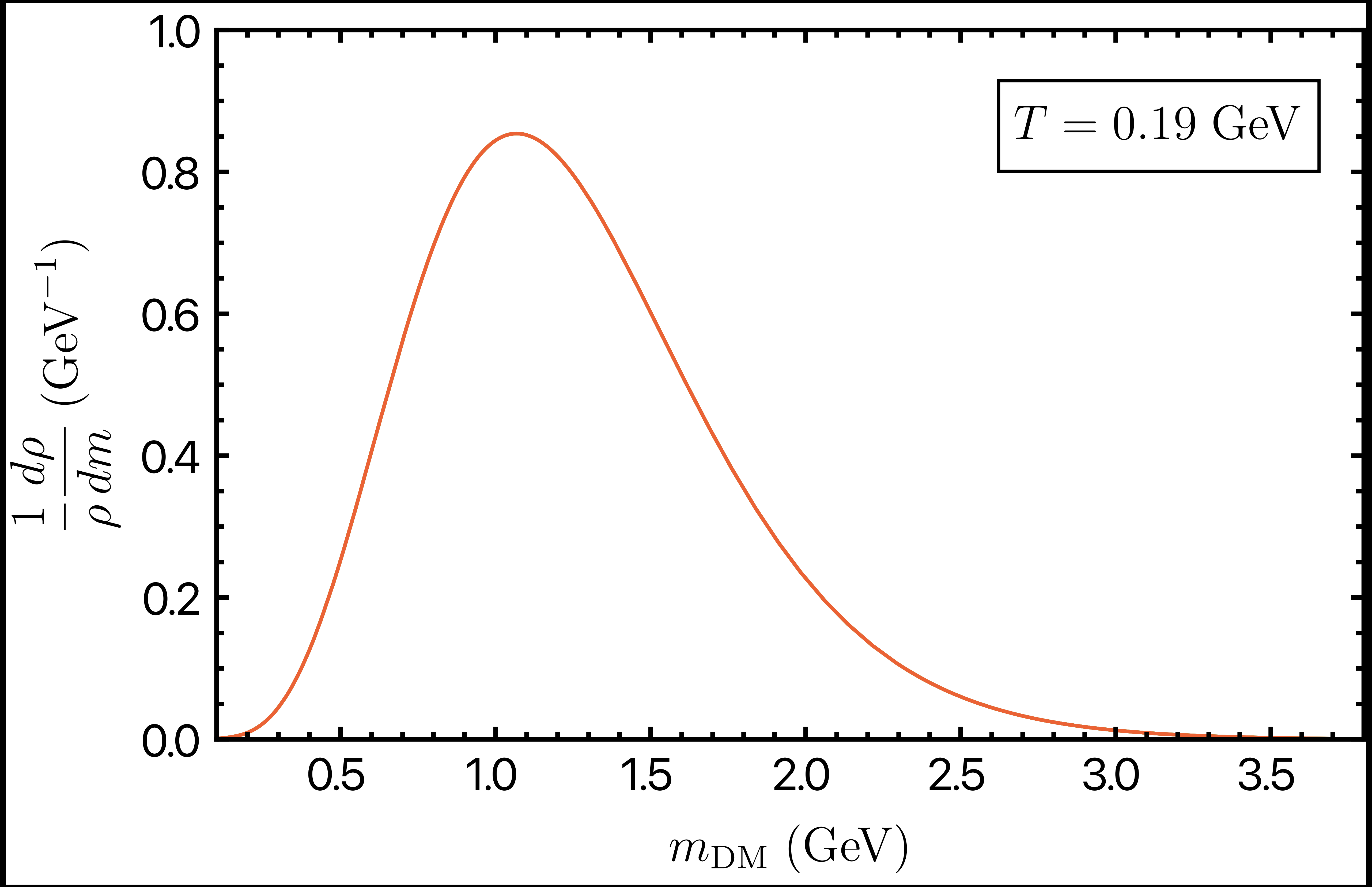
$$\frac{d\rho_{DM}}{dt} \sim \frac{T^8}{\hat{M}_p^{\ 3}} \Rightarrow T_{MR} = \frac{T_i^3}{M_{KK} M_P} \sim \frac{\Lambda^{\frac{1}{2}} M_p}{\Lambda^{\frac{1}{4}} M_p} \sim \Lambda^{\frac{1}{4}} = T_\Lambda$$

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

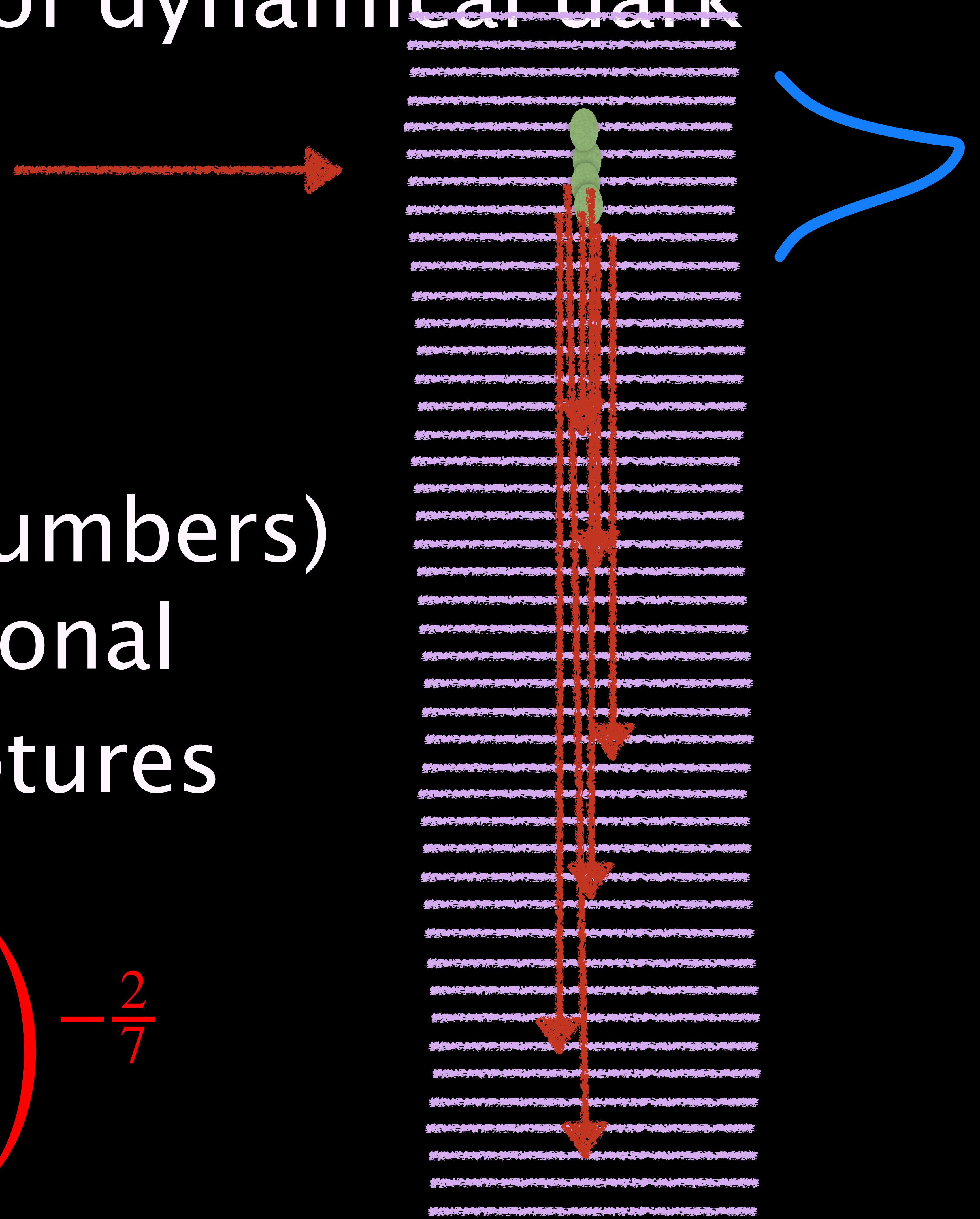




$T = 0.19$ GeV
1.0
0.8
0.6
0.4
0.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
$\frac{1}{\rho}\frac{d\rho}{dm}$ (GeV^{-1})
$m_{\rm DM}$ (GeV)

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]

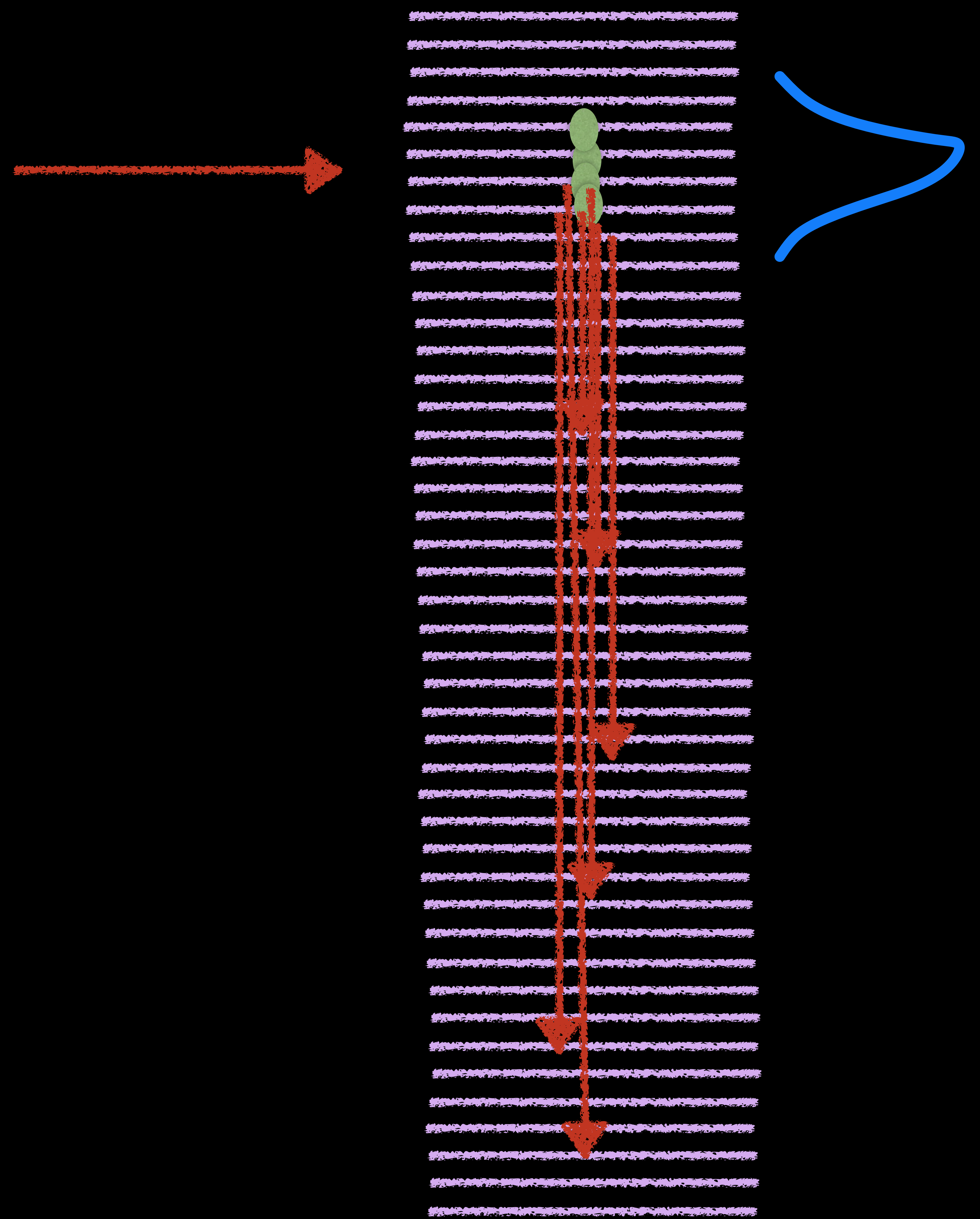
$$T_i \sim GeV$$

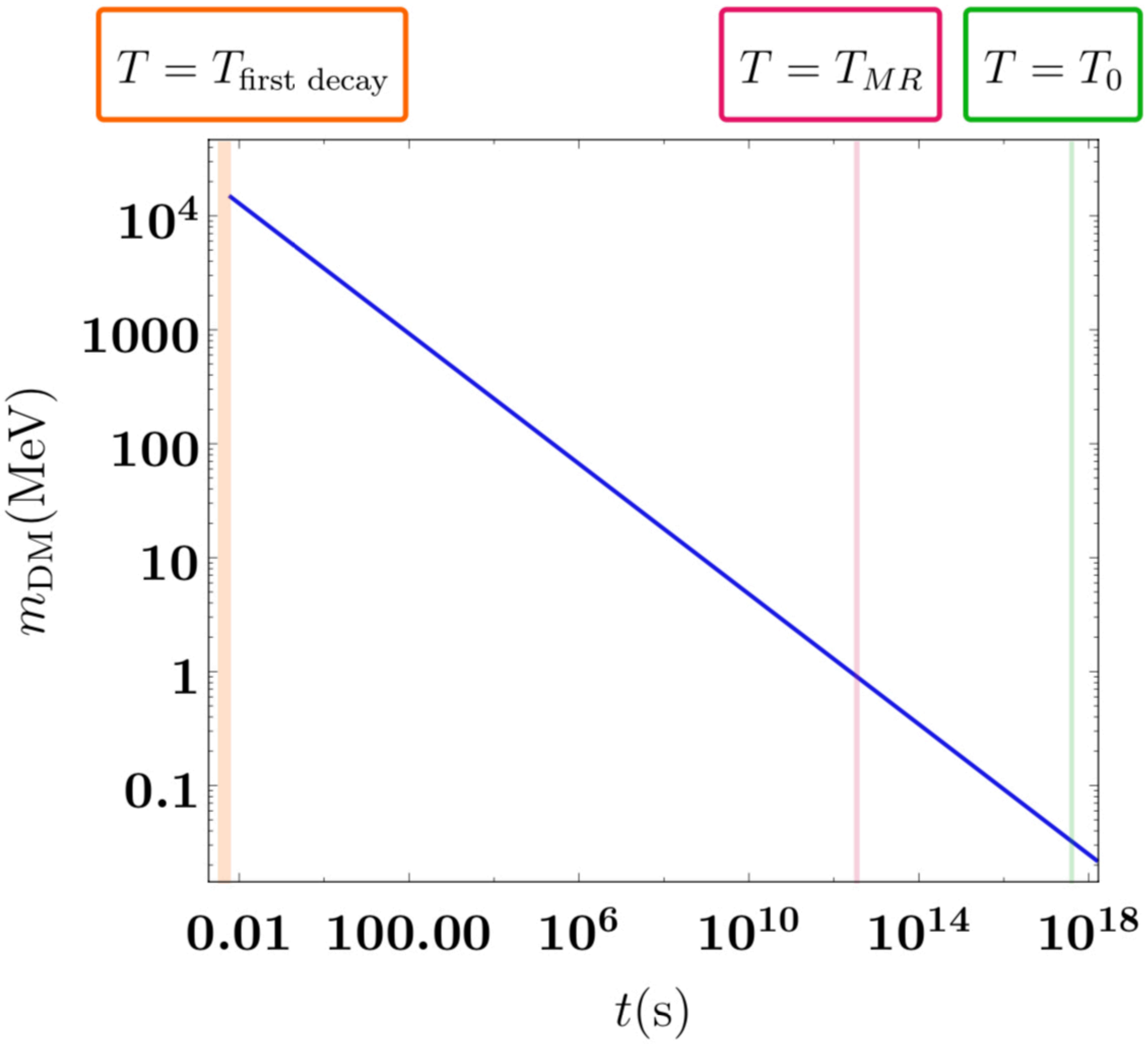


The decay rate is fixed (Up to $\mathcal{O}(1)$ numbers) by assuming amplitudes are gravitational strength and aparameter δ which captures violation of KK quantum number:

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

$$T_i \sim GeV$$





$T = T_{\text{first decay}}$
$T = T_{MR}$
$T = T_0$
$m_{\text{DM}}(\text{MeV})$
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

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

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

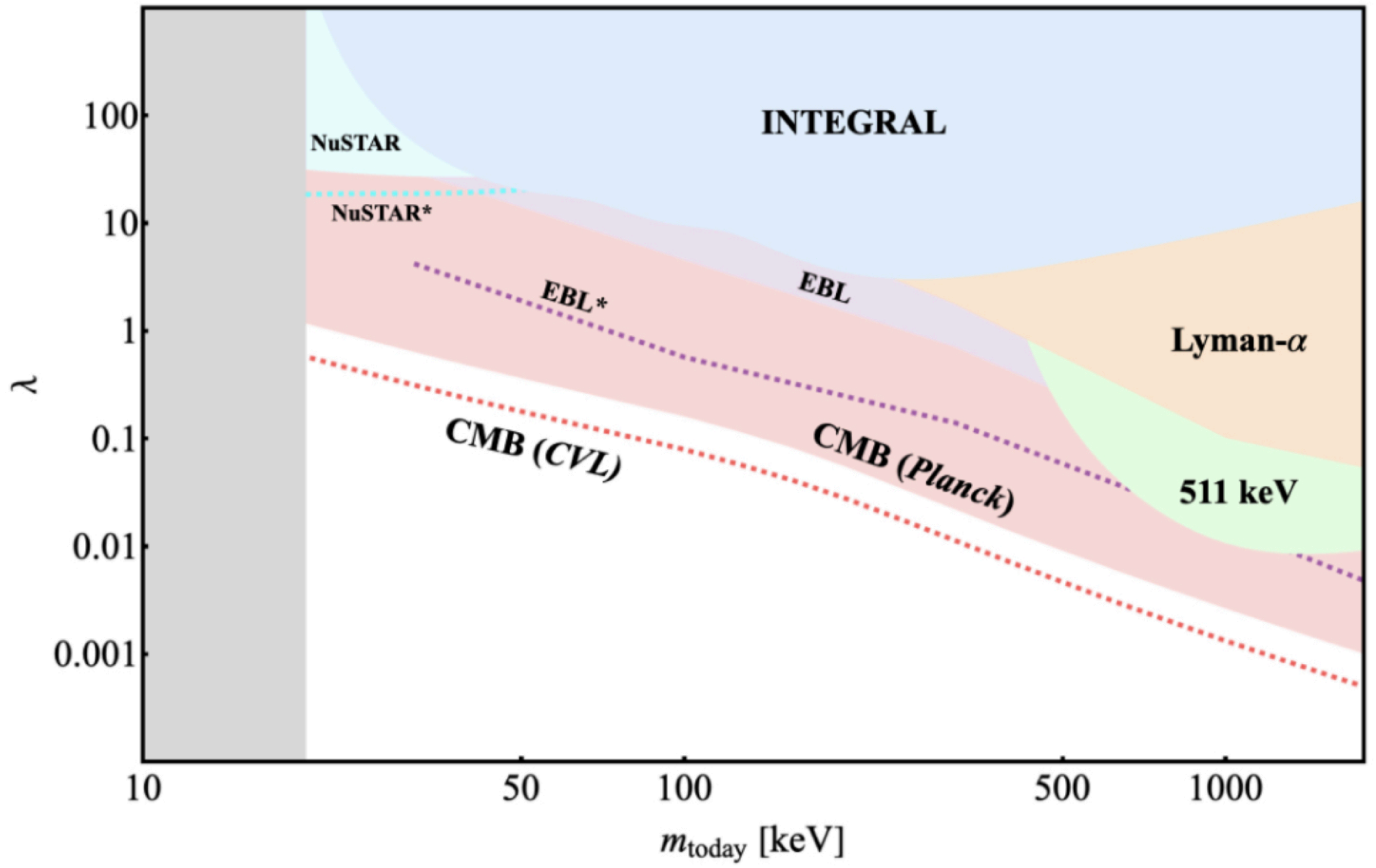
That they lower their mass is a necessary ingredient to be consistent with observation. They also decay to photons:

$$g \to \gamma\gamma$$

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



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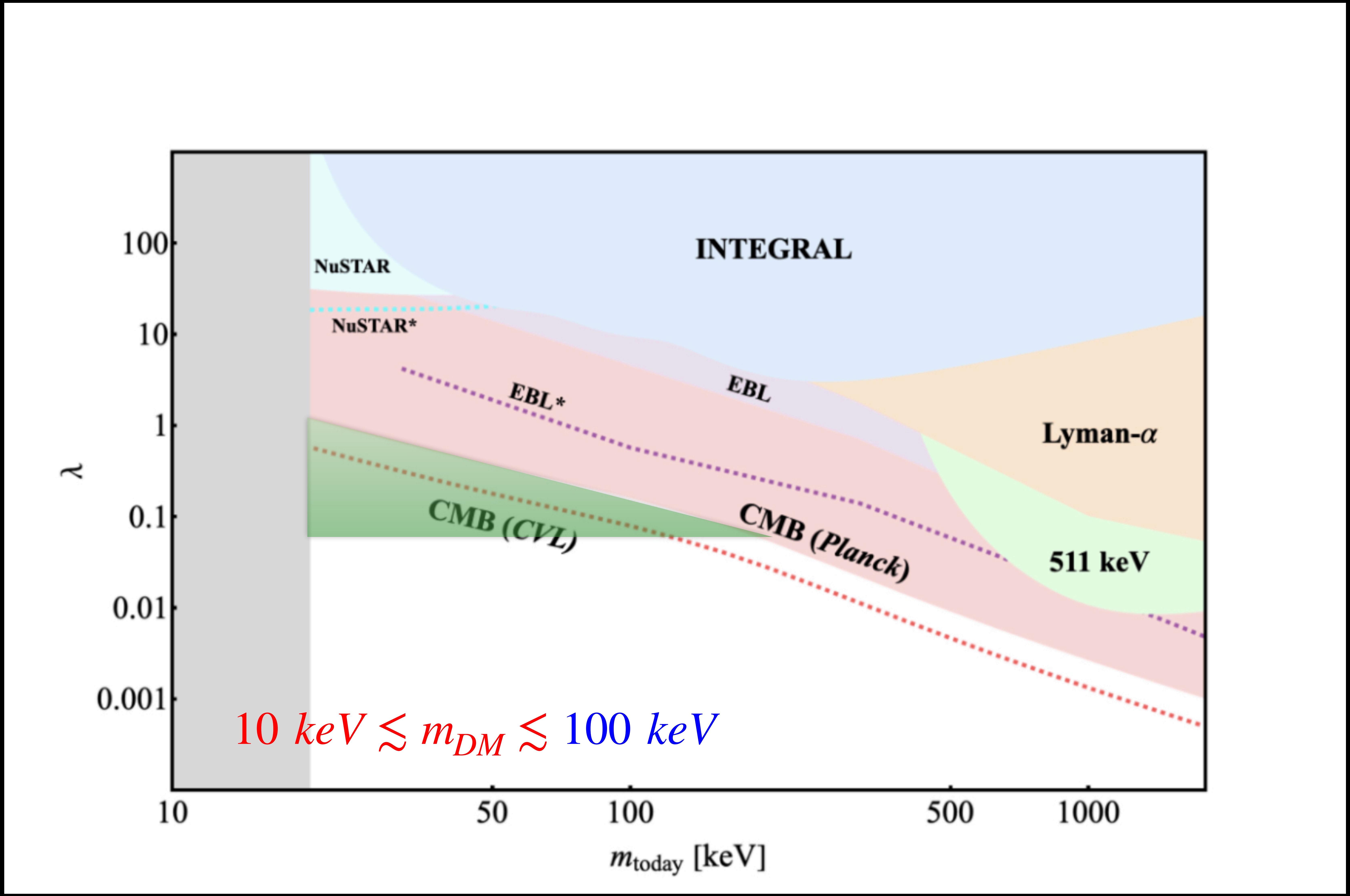
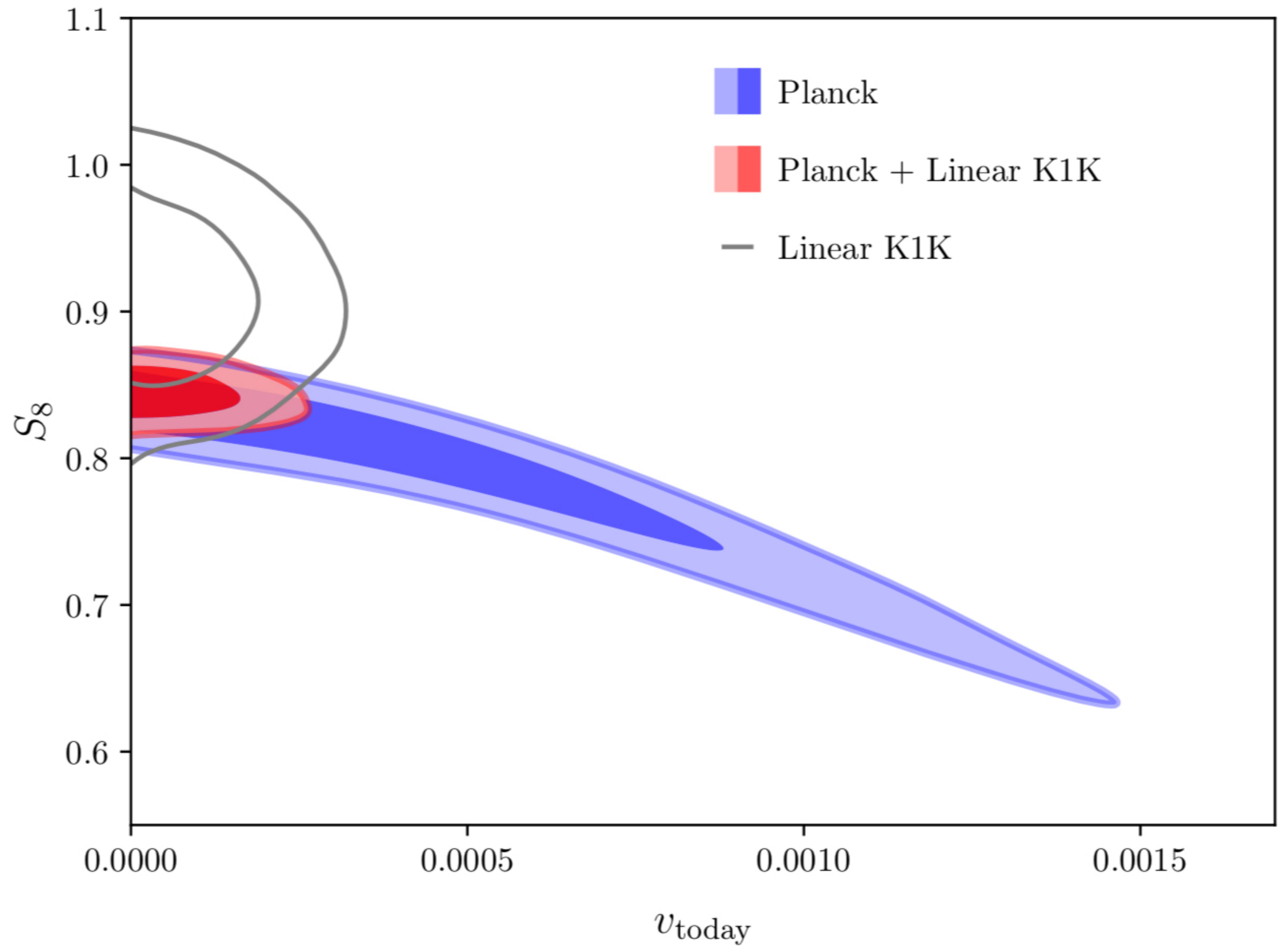


When the dark matter decays some of the mass some of the mass of the dark matter gets converted to kinetic energy, thus giving a kick to the pair of lower mass dark matter created.

One can estimate this, and we find that assuming the 5-th dimension is rather smooth and has an approximate conservation of KK momentum

$$v_{today} \sim \Lambda^{\frac{1}{28}} \sim 10^{-4}$$

This could have impact on 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

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):

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

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.

Coincidence of many interesting phenomenological aspects including a resolution of S_8 tension!