Quantum Gravity and Predictions for Our Universe

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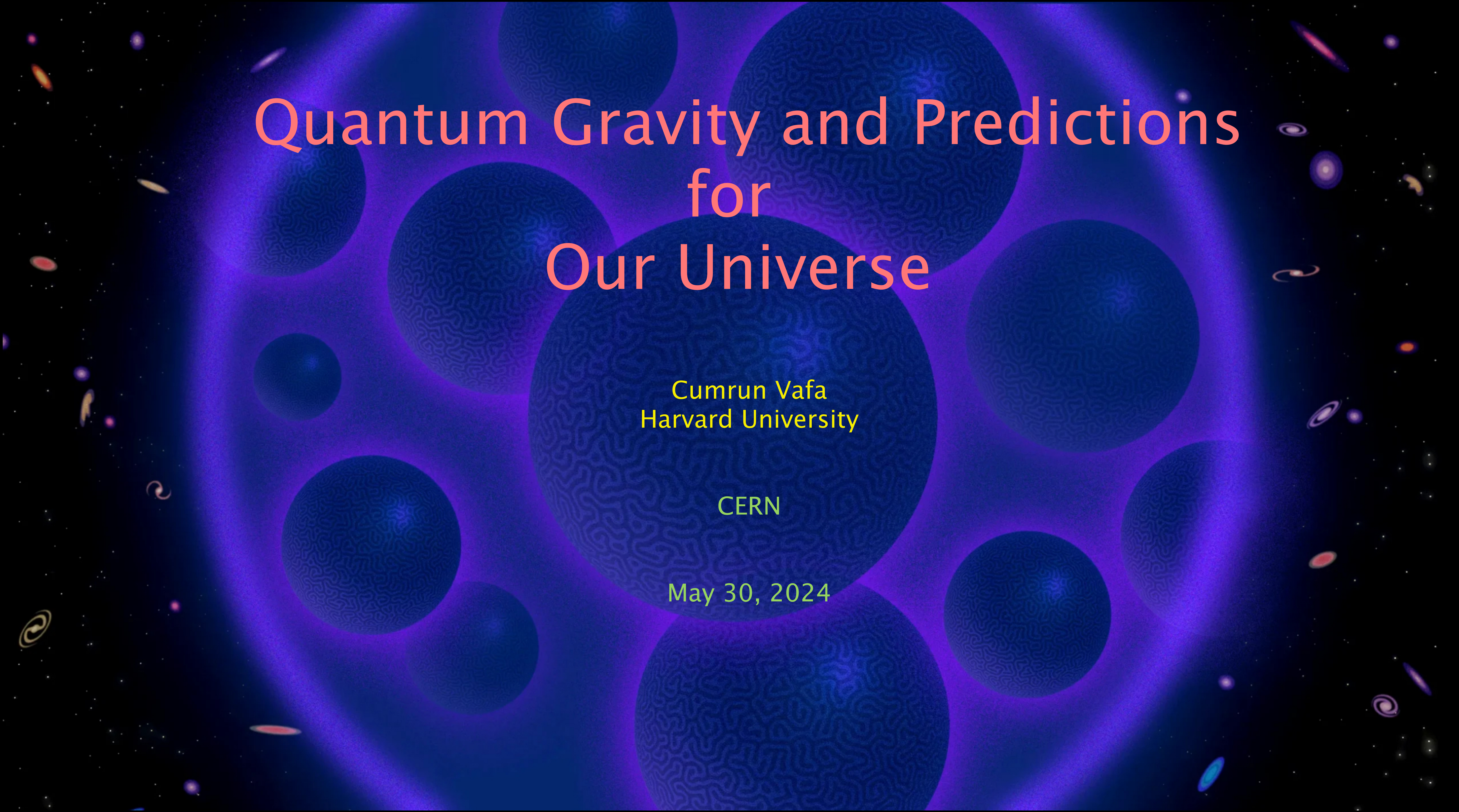


Samuel Velasco/Quanta Magazine

Based on many papers in string theory literature

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?

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

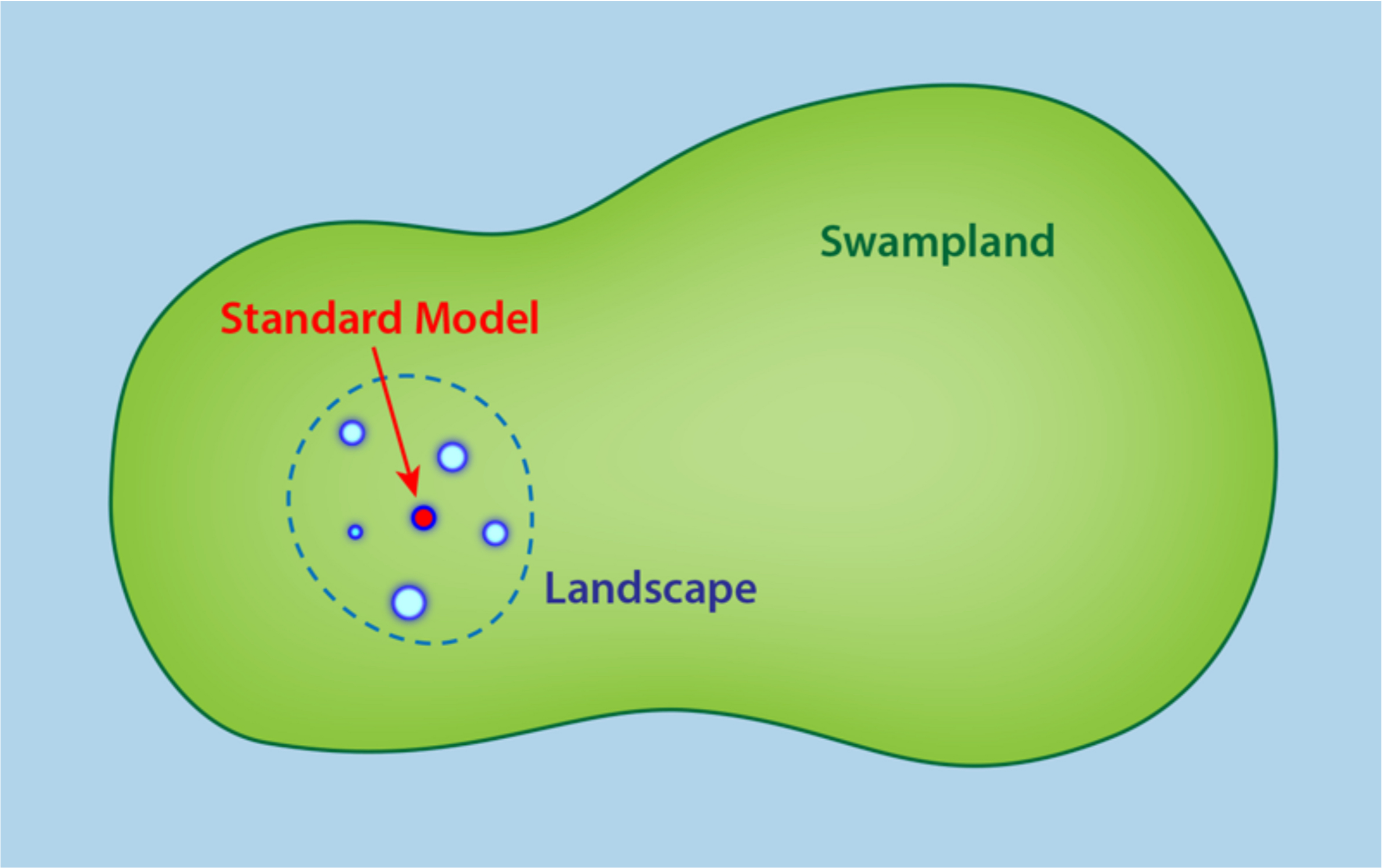
Swampland Program: Summarizes lessons about QG we have learned from string theory.

It turns out these general lessons lead to insights into these questions.

What we have learned from string theory is that quantum gravitational theories are far more restrictive than previously imagined.

Very few effective field theories emerge in the IR limit of UV complete quantum gravitational theories.

These restrictions lead to predictions;
Features of effective field theories that emerge from gravity are correlated. One feature can be observed, and using that another feature can be predicted.



APS/Alan Stonebraker

For example:

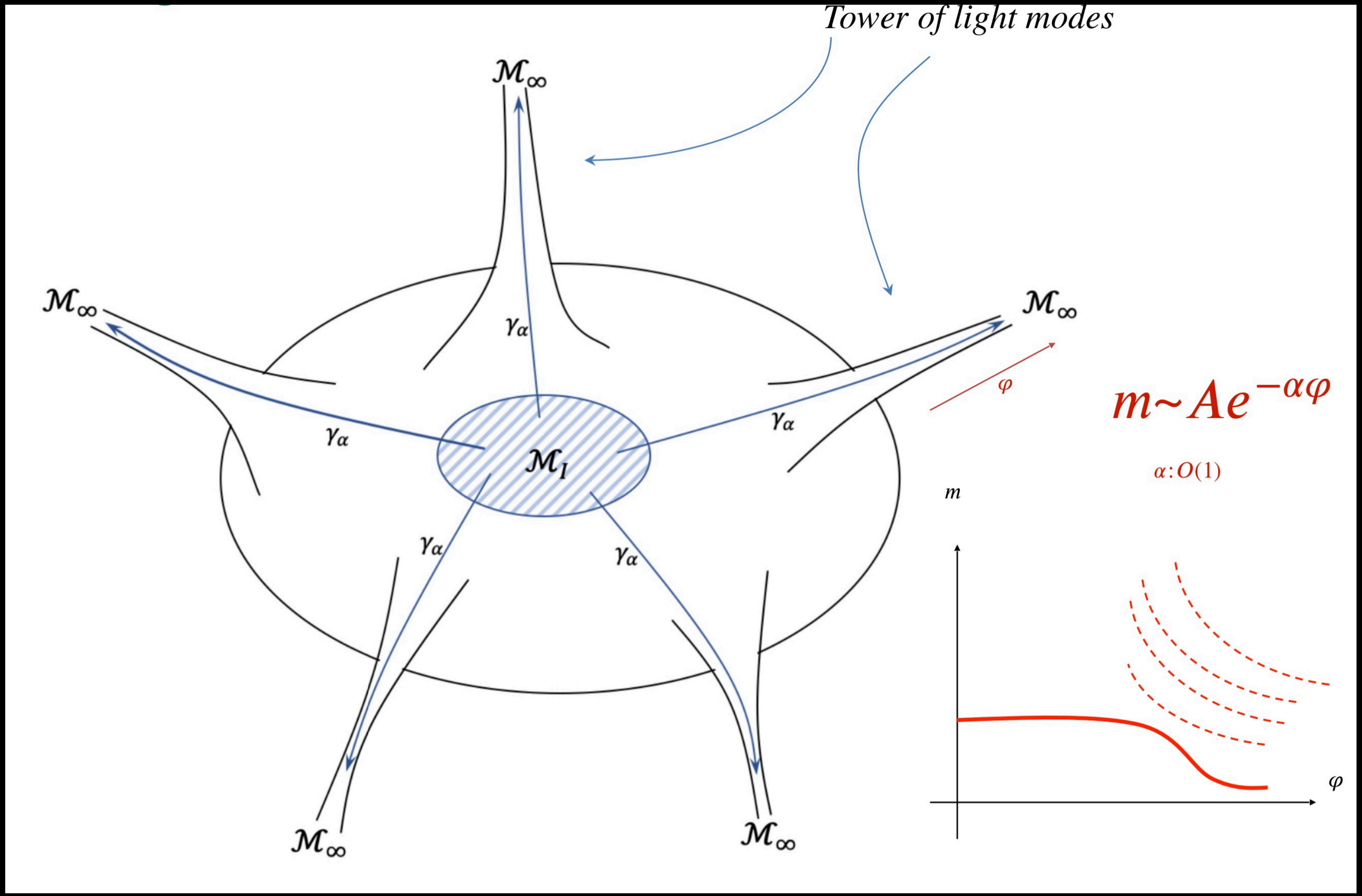
Gravity is the weakest force in any quantum theory of gravity, more specifically in our universe we can explain the following feature:

$$m_\nu < m_e < M_{pl}$$

For any QG rank of gauge groups are bounded. For example if we consider N=4 supersymmetric theories in 4 dimensions, only gauge groups with rank less than 23 can appear if coupled to gravity.

$SU(N)$ for $N \geq 24$ are in the Swampland.

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

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

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 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. 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

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

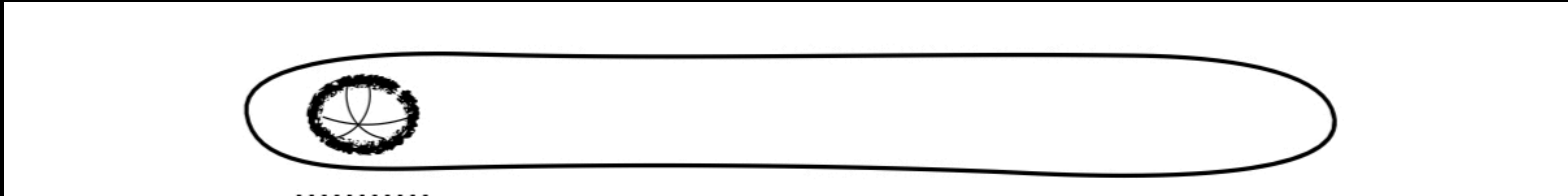
The Dark Dimension: One extra mesoscopic dimension of length 1-10 microns!
This leads to a fundamental Planck scale in higher dimension

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

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 $10^{10} GeV$.

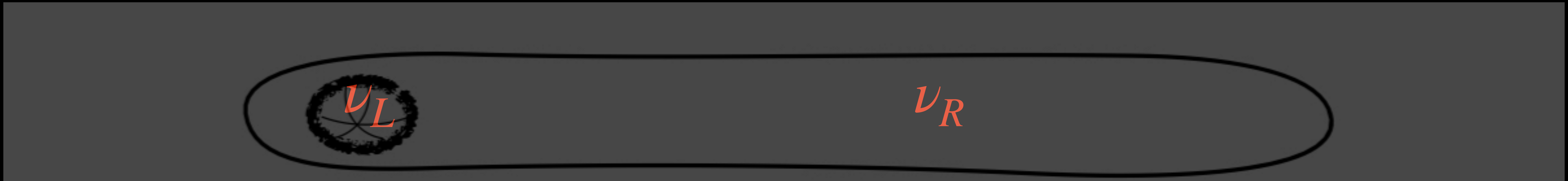
2) Neutrino physics: 5d bulk fermions coupled to ν_L on the brane can act as right-handed neutrinos [DDG,ADDM, 98]; the couplings to SM neutrinos give the active neutrinos the expected mass thanks to dark dimension parameters.

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

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

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

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

Together with experimental bounds leads to

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

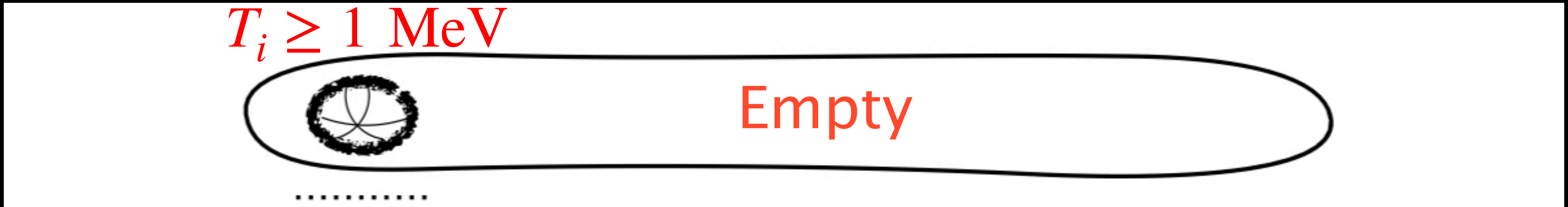
$$m_a \sim \frac{\Lambda_{QCD}^2}{f_a} \sim \frac{\Lambda^{\frac{2}{6}}}{\Lambda^{\frac{1}{12}}} \sim \Lambda^{\frac{3}{12}} \sim 10^{-1} eV \sim m_\nu \sim m_{tower}$$

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 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:



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

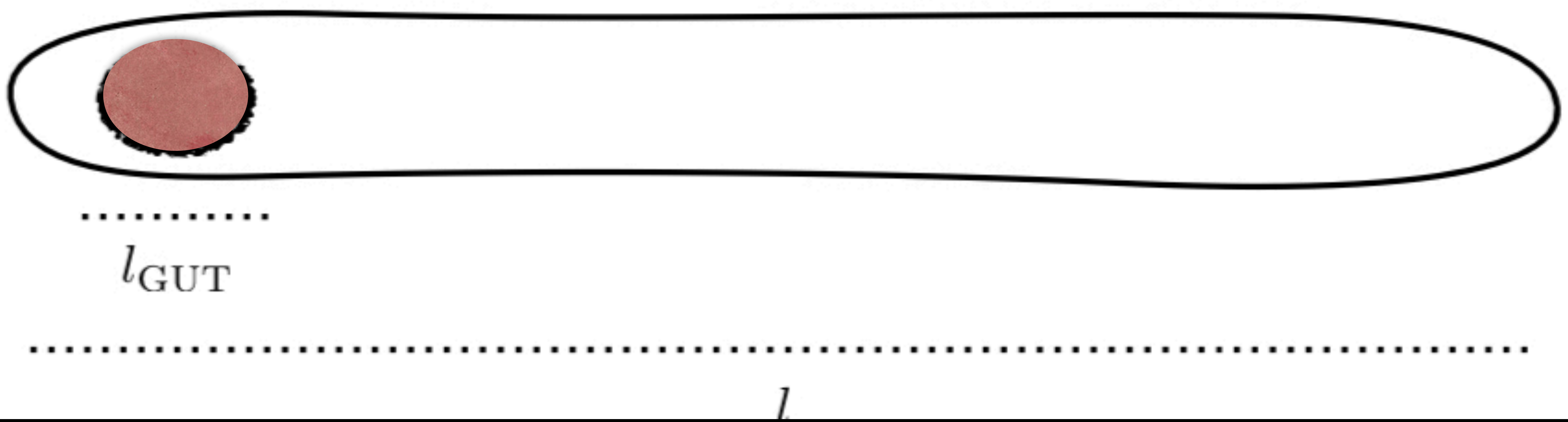
$$\frac{1}{\hat{M}_p^{3/2}} \int d^4x \, h_{\mu\nu}(x,z) \Big|_{z=0} T^{\mu\nu}(x)$$

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

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

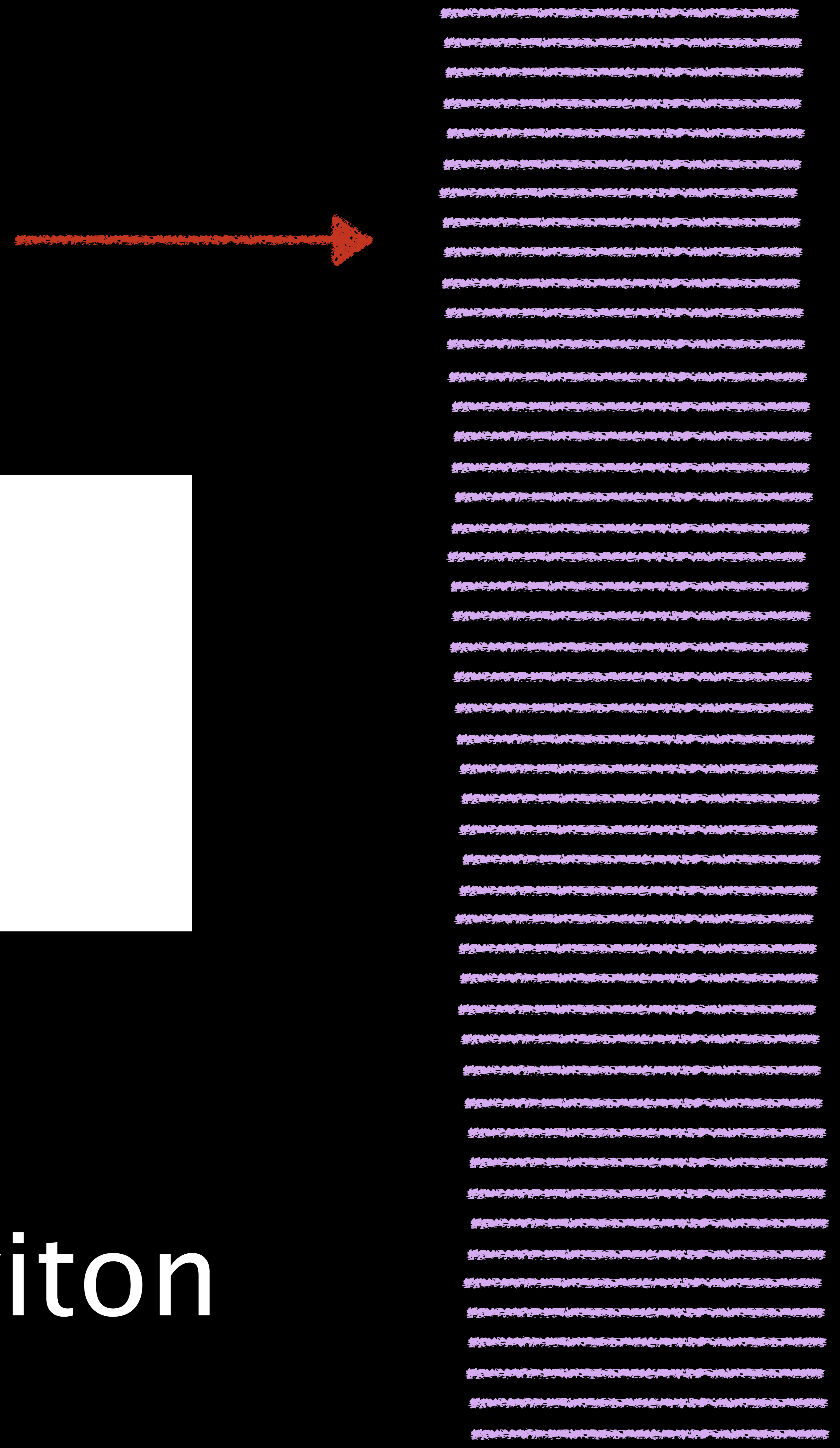
$$m_n \sim n \cdot m_{KK} \sim \frac{n}{l}$$

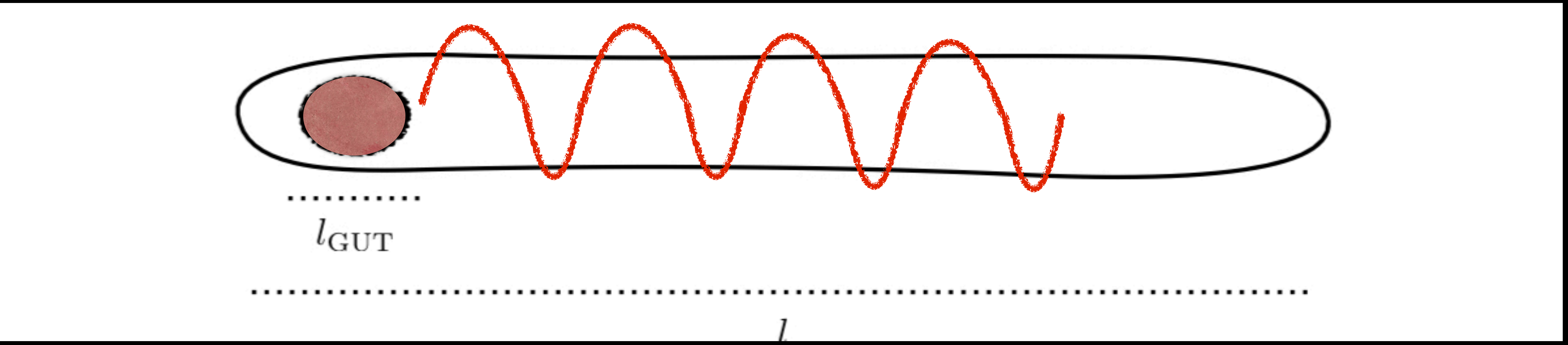
$$\sim \frac{1}{M_p} \sum_n \int d^4x \, h^n_{\mu\nu}(x) T^{\mu\nu}(x)$$



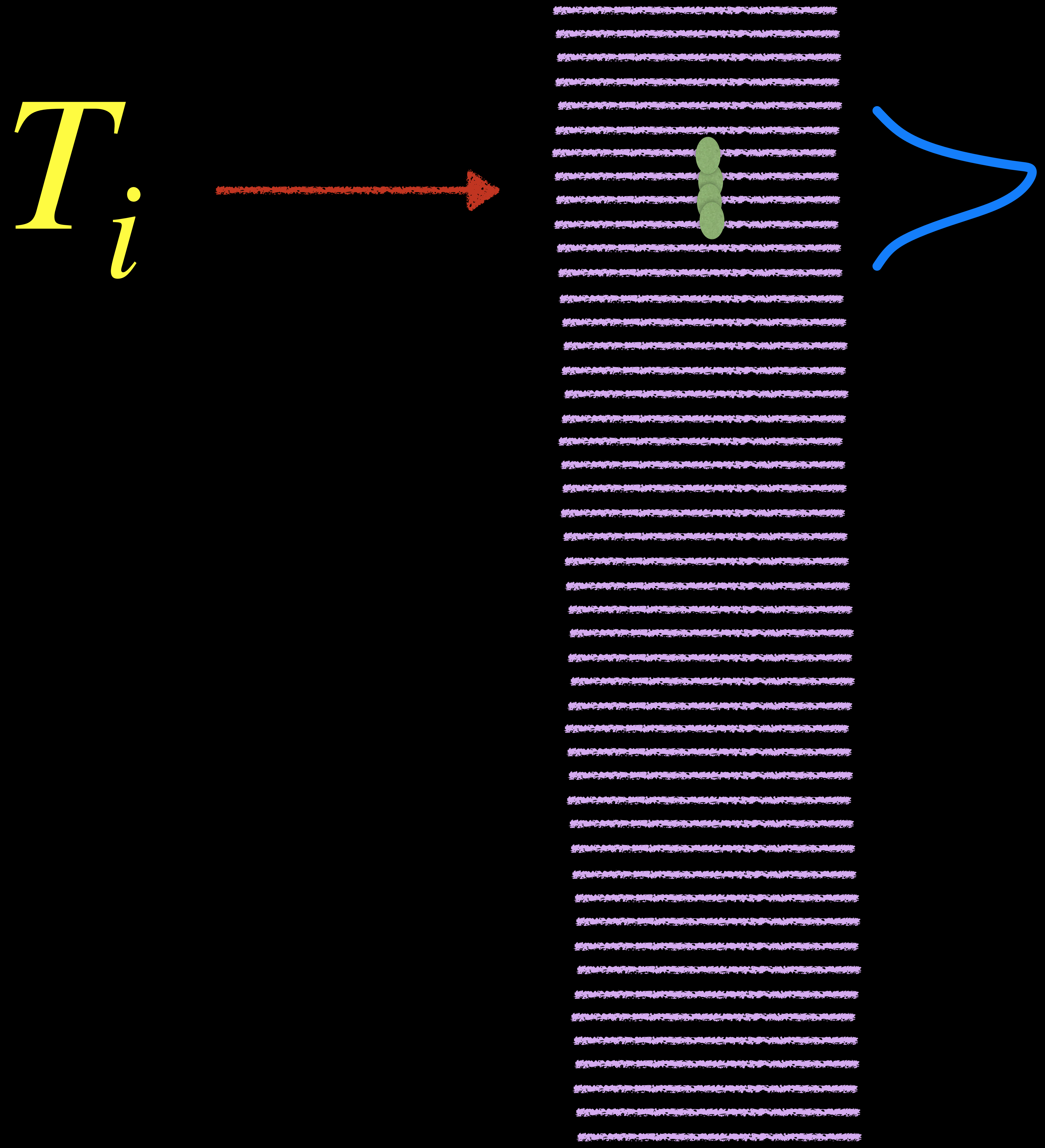
$l_{\rm GUT}$

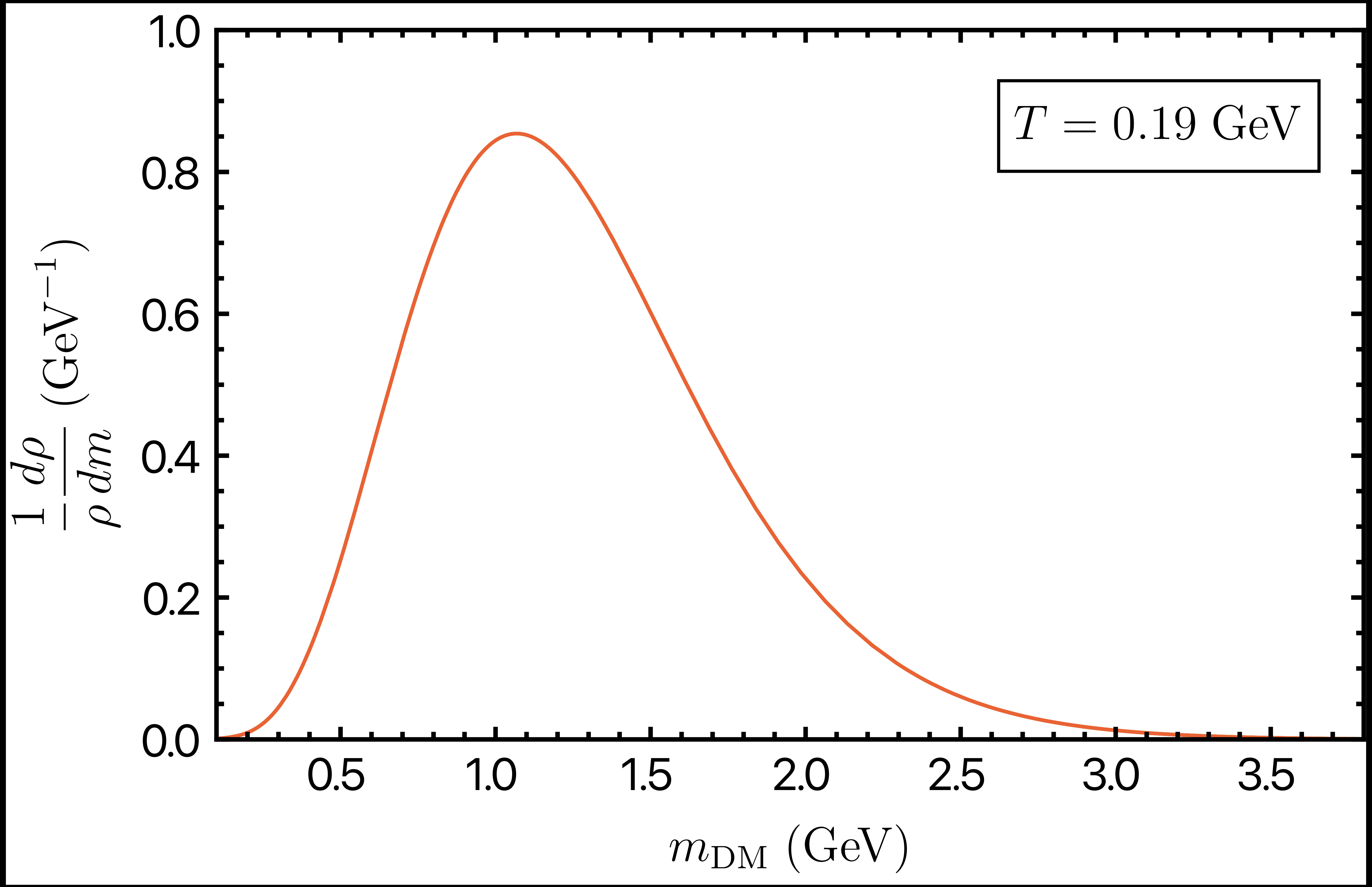
T_i



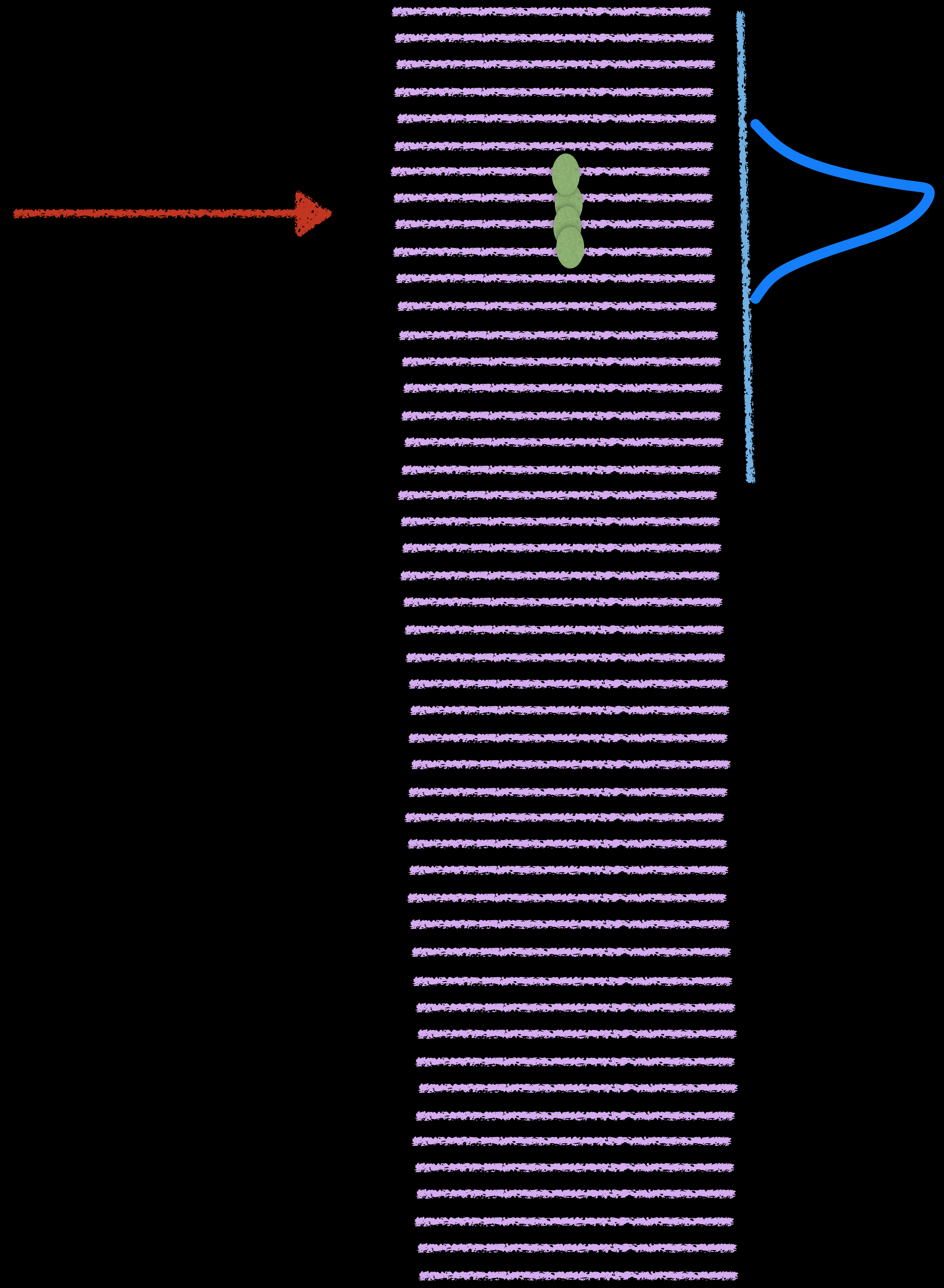


Dark matter is excitation of graviton in the dark dimension!


T_i

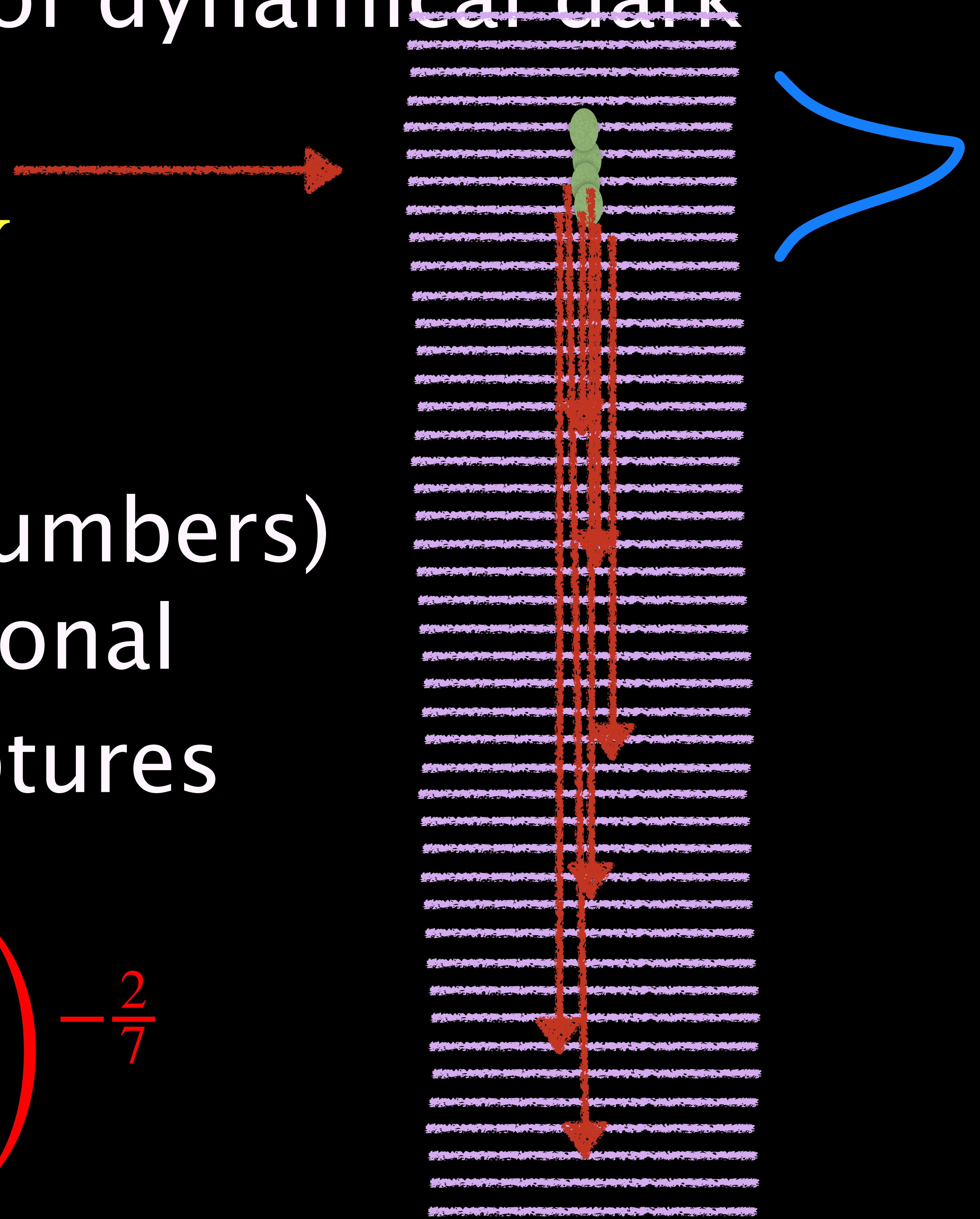

1.0
0.8
0.6
0.4
0.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
$T = 0.19$ GeV
$\frac{1}{\rho}\frac{d\rho}{dm}$ (GeV^{-1})
m_{DM} (GeV)

T_i



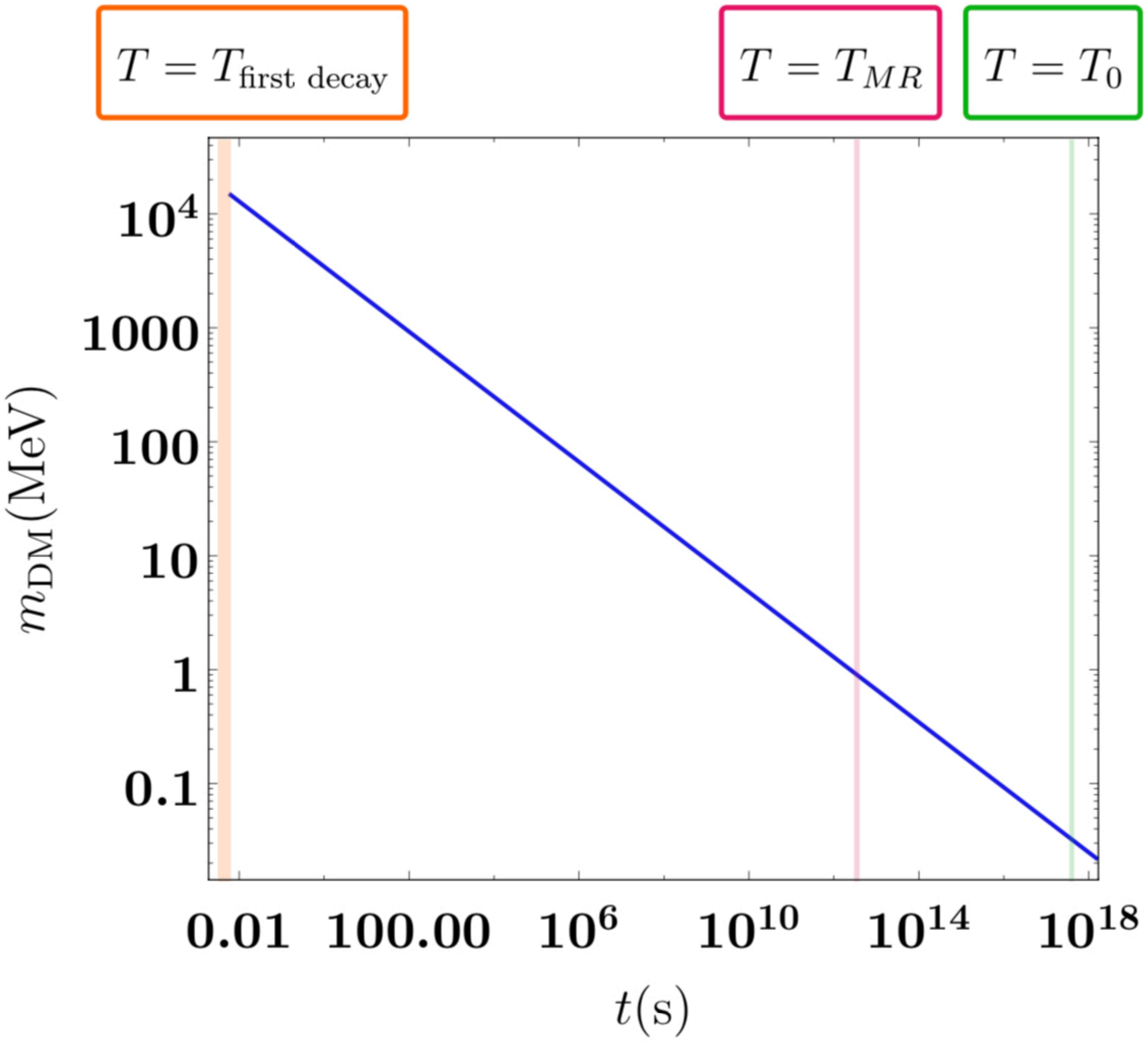
Once produced they lower their mass by decaying mostly to lower KK modes by gravitational interactions (and in the process the total energy density of dark matter does not change appreciably)—A special case of dynamical dark matter scenario [DT,11]

$$T_i \sim GeV$$



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

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

Using

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

we learn

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

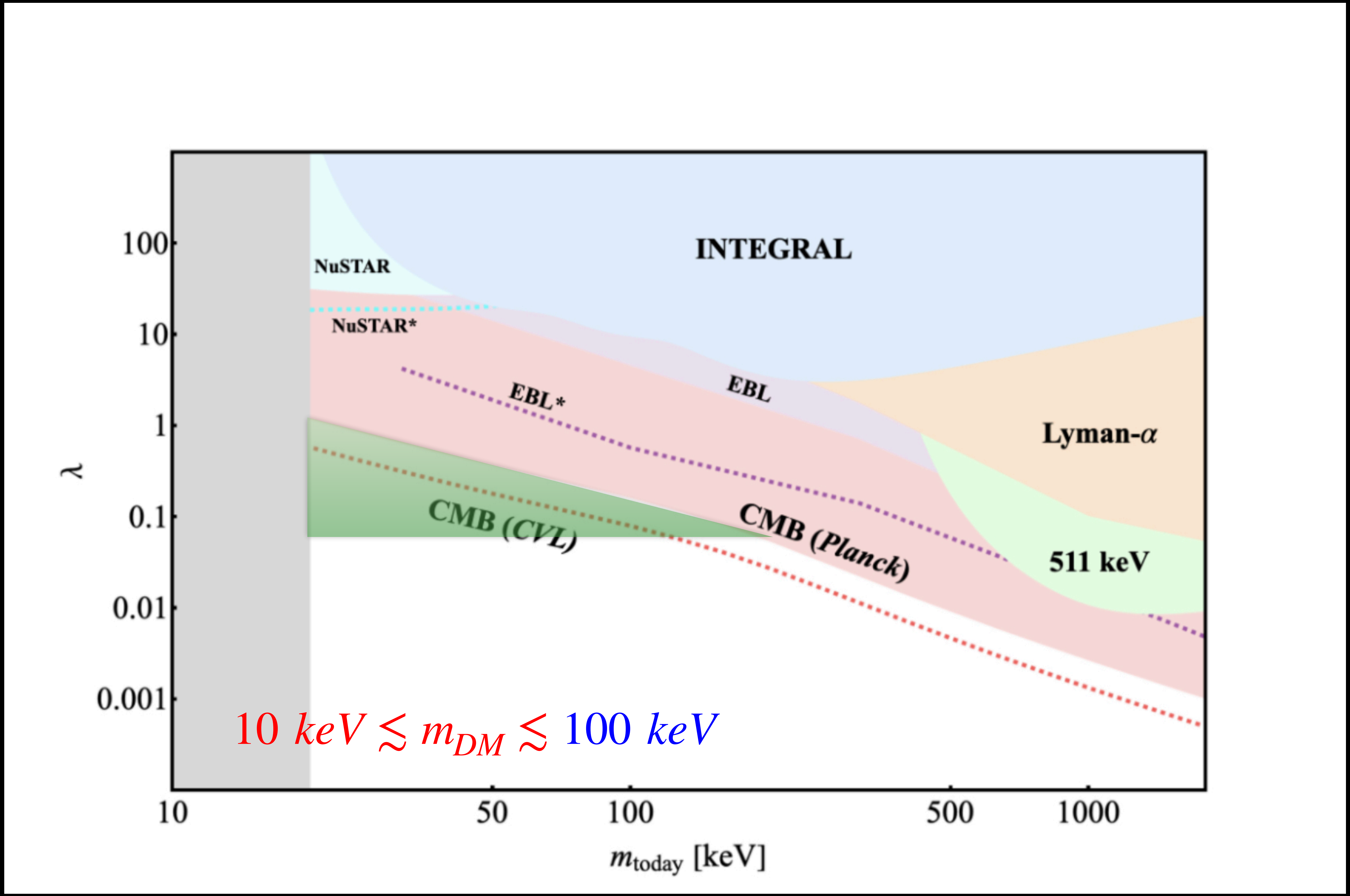
Could impact structure formation.

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

but decaying DM mass cannot be too large due to

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

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

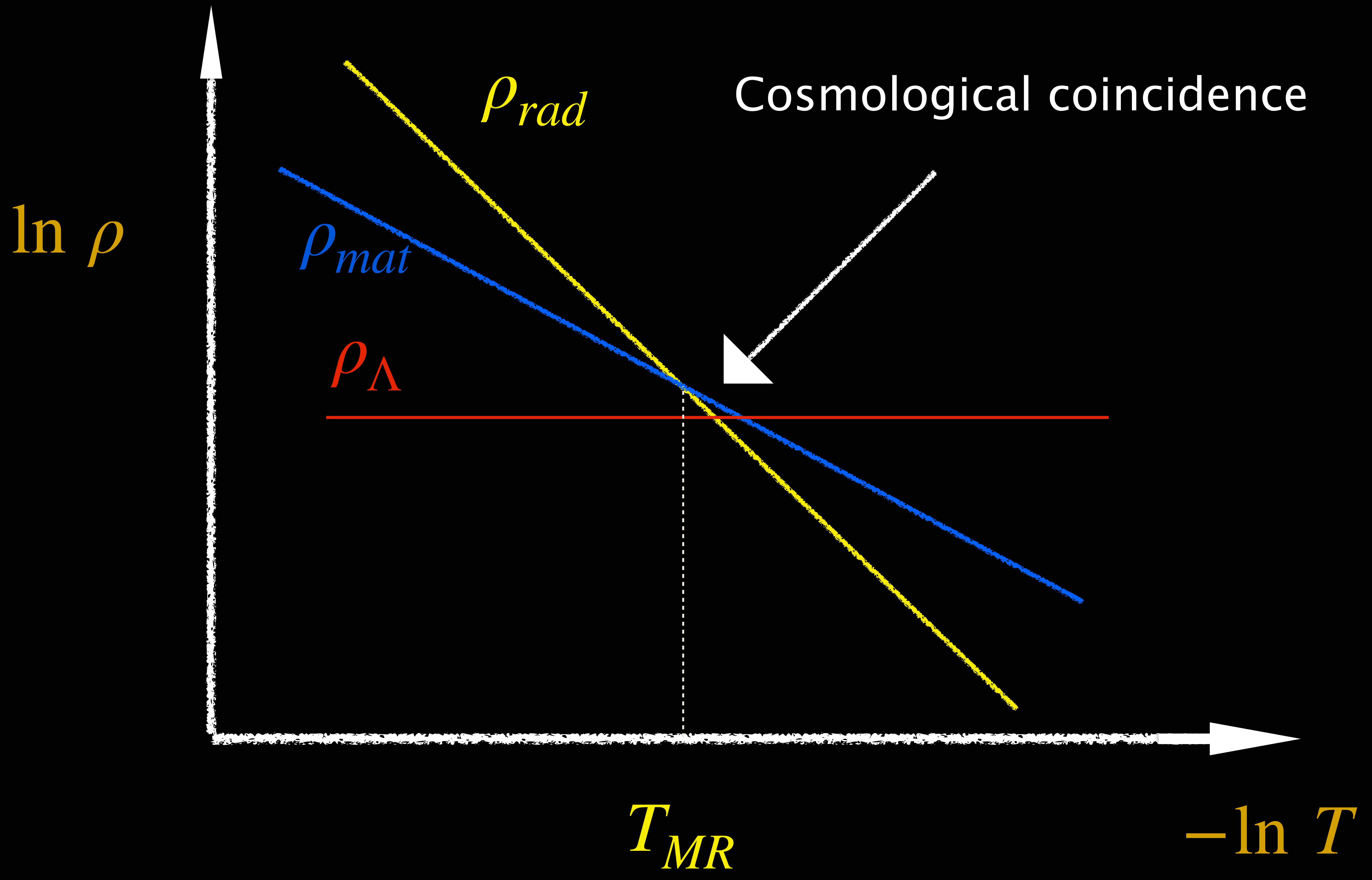


Additional Puzzles of Cosmology

Why do we live now?

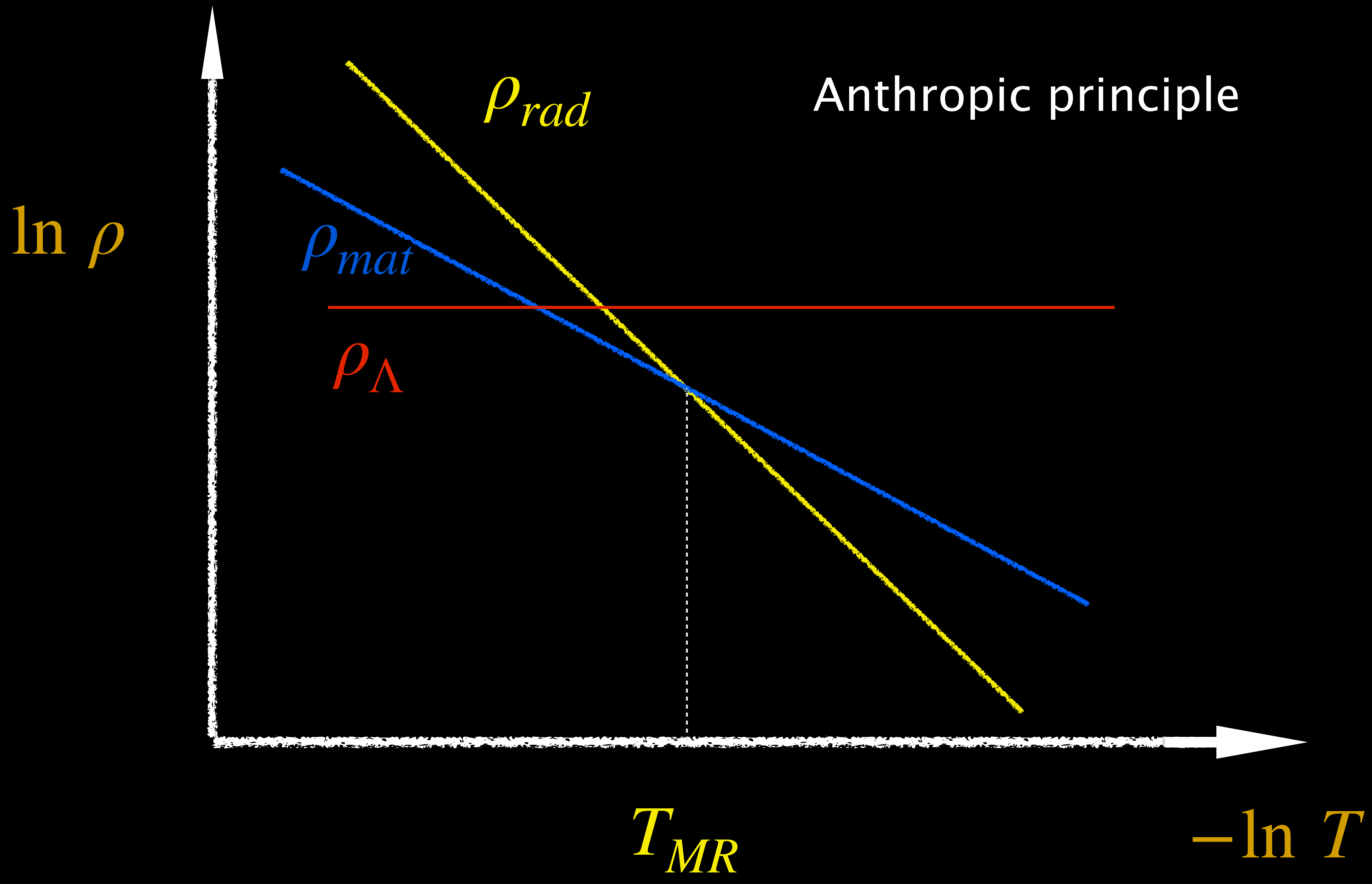
$$\tau_{now} \sim \frac{1}{\sqrt{\Lambda}}$$

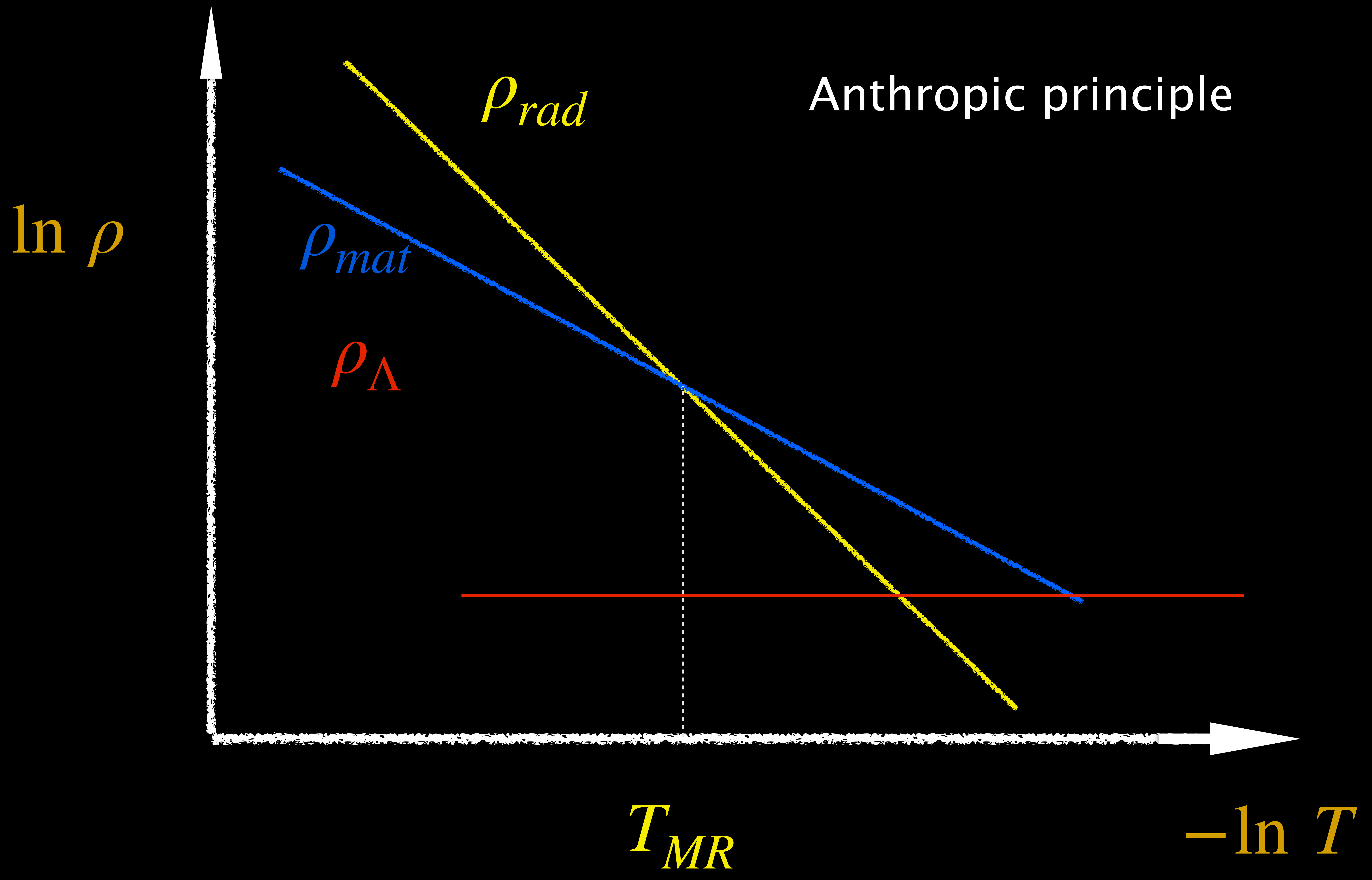
Is Dark energy stable?



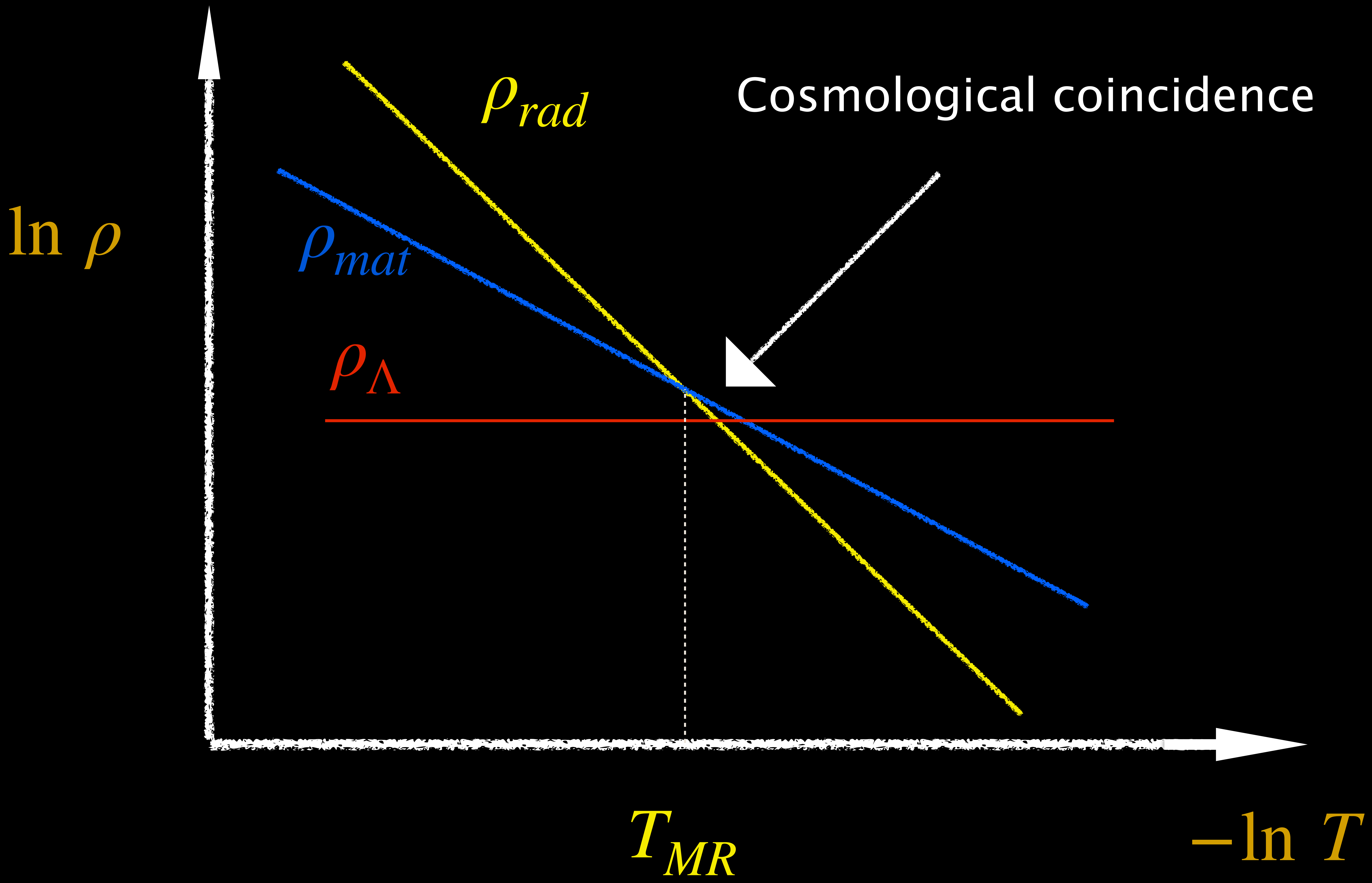
ρ_{rad}
Cosmological coincidence
$\ln \rho$
ρ_{mat}
ρ_{Λ}
T_{MR}
$-\ln T$

Anthropic principle





Anthropic principle
$\ln \rho$
ρ_{rad}
ρ_{mat}
ρ_{Λ}
T_{MR}
$-\ln T$



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

Transplanckian Censorship Conjecture
[BV, 19]

In an expanding universe subplanckian regions cannot exit the horizon of a dS space.
Motivation: Subplanckian modes cannot freeze to become visible, as they are unphysical.

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

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

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!

3 Applications of TCC:

1) 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: $\exp(\tau_{max} H).1 < \frac{1}{H} \rightarrow \tau_{max} < \frac{1}{H}\log(\frac{1}{H}) \sim 2 \text{ trillion years}$

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

2) Dark Energy should evolve in Hubble time! (DESI?)

3) What fixes the initial temperature on the brane?

$$T_i \lesssim m_\phi$$

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]):

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

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

Dark dimension:

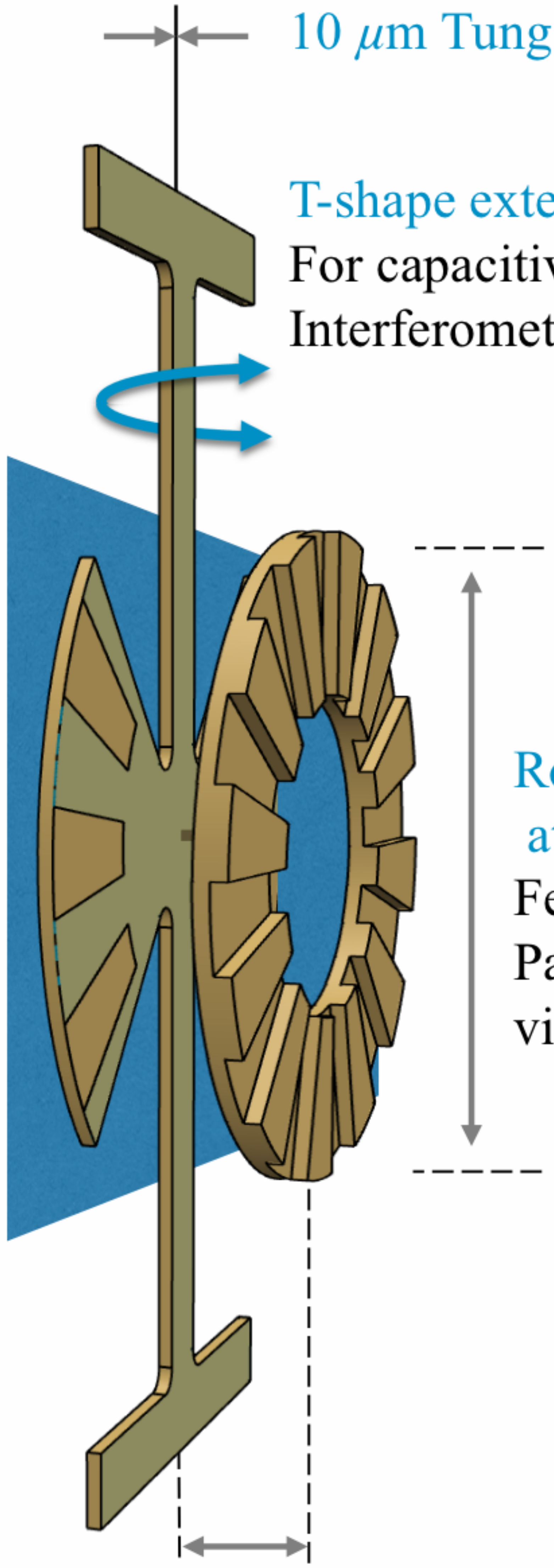
Easily falsifiable (verifiable)! Improving precision measurement of deviation from Newton's law by a factor of 10

$$\frac{1}{r^2} \to \frac{1}{r^3} \qquad r \ll 1\mu m$$

If we can test Newton's theory down to a few microns, with a leading correction of the form

$$\alpha \frac{exp(\frac{-r}{l})}{r^2} \qquad \alpha \sim O(1); l \sim 1 - 10\mu m$$

New ISLE at the Conrad Observatory



ISLE core team

Markus Aspelmeyer
IQOQI Vienna & University of Vienna

Eric Adelberger
University of Washington

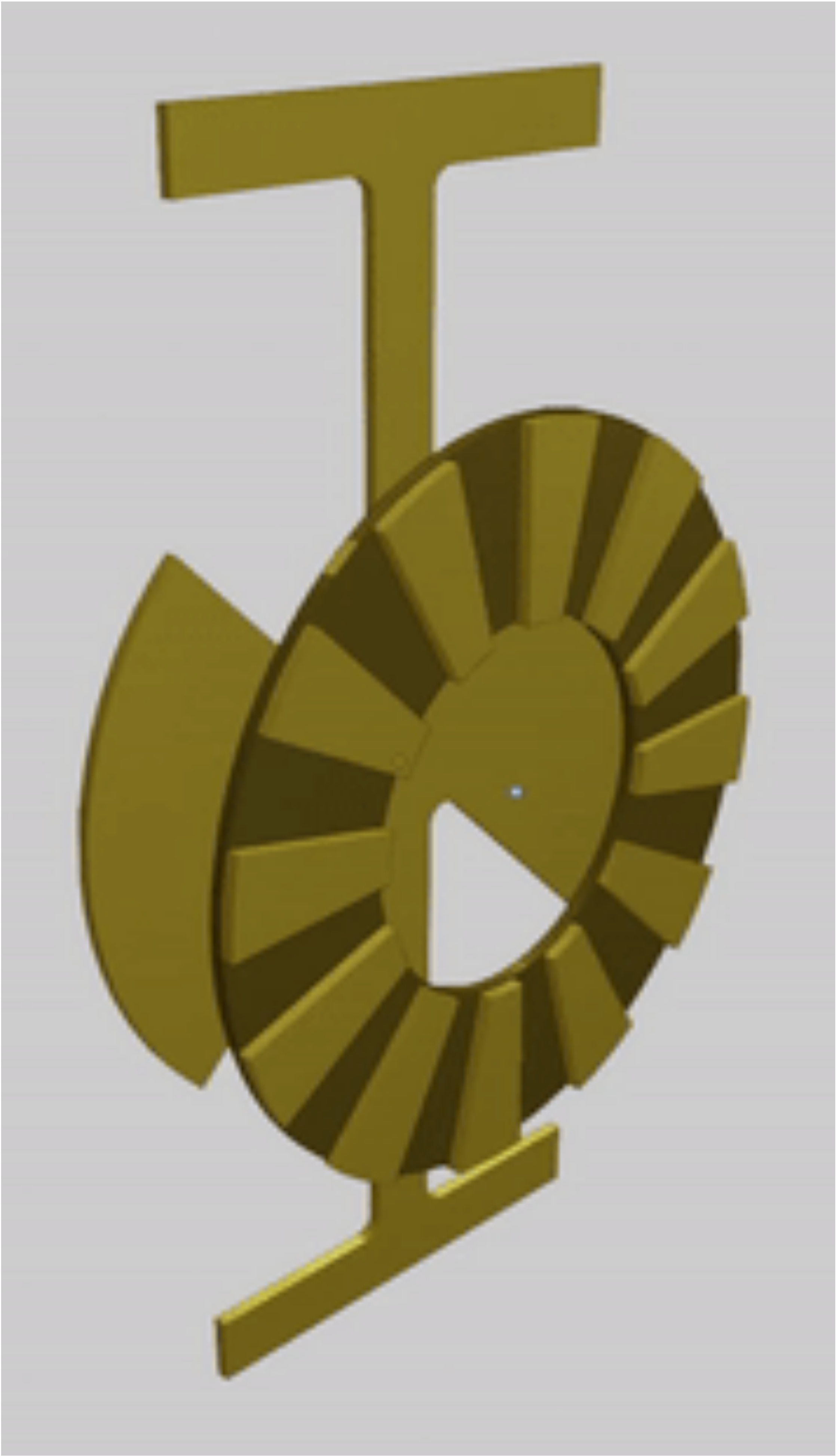
Armin Shayeghi
IQOQI Vienna

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…

New ISLE at the Conrad Observatory



Conrad Observatory

Main challenges for ISLE at separations ≲ 10 μm

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IQI

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

$\downarrow$

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):

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

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

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

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

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