Dynamical Dark Matter

A New Framework for Dark-Matter Physics

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Based on work done in collaboration with Keith Dienes

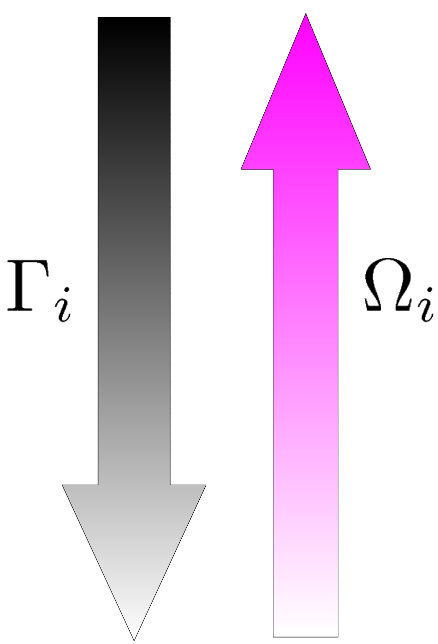
[arXiv:1106.4546, arXiv:1107.0721, arXiv:1110.xxxx]

A New Framework for Dark Matter Physics

- The dominant paradigm in dark-matter phenomenology has been to consider scenarios in which Ω_{DM} is made up by one stable particle (or maybe two or three), but maybe nature isn't quite so simple.

- It could be that many particles – maybe even a **vast** number – contribute nontrivially to that abundance, with each providing only a minute fraction of the total.

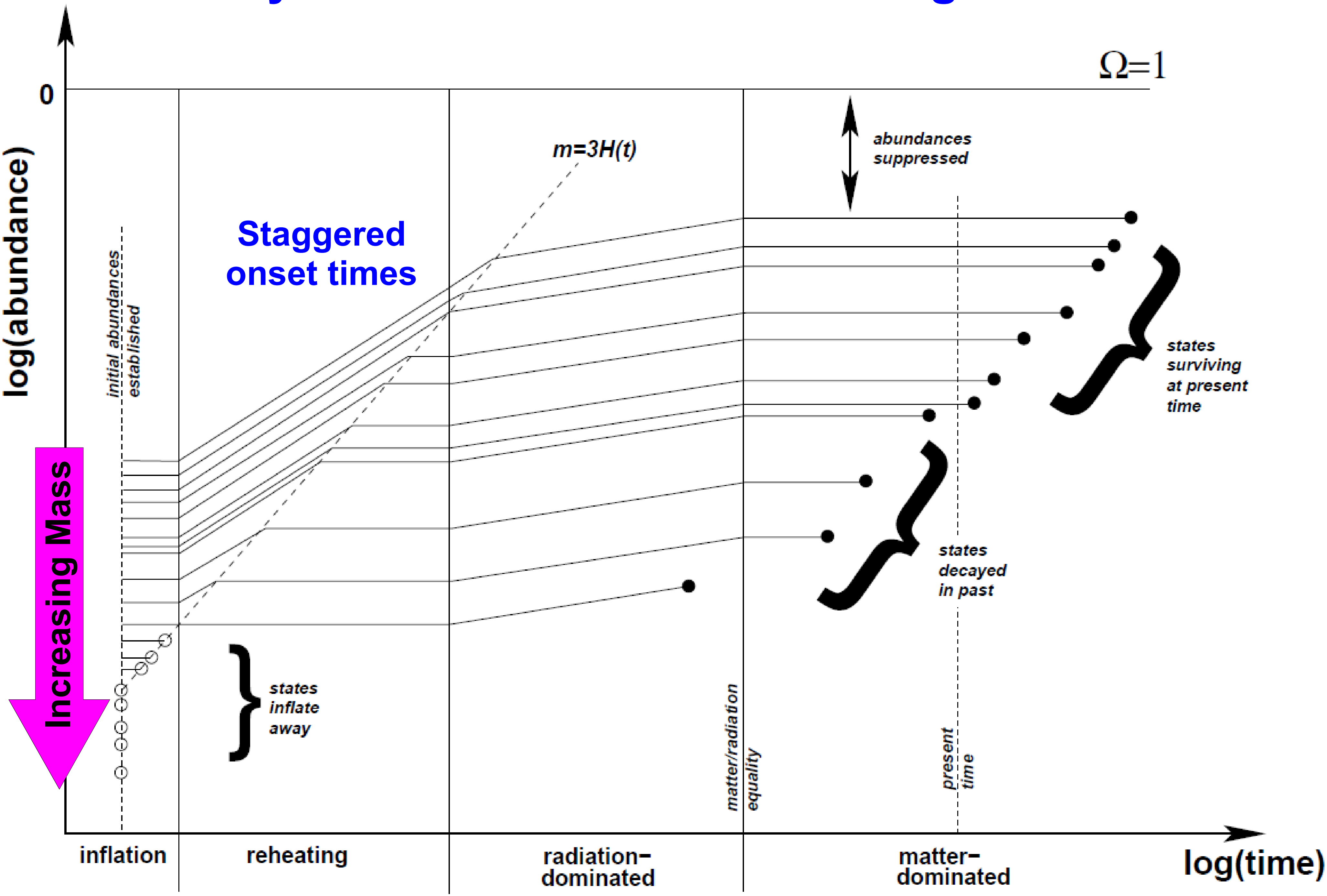
$$\boxed{\Omega_{\mathrm{DM}} = \sum_i \Omega_i}$$



- Some of these states may be only quasi-stable, but as long as the individual abundances are **balanced against decay rates** in just the right way, this can be a viable dark-matter scenario!

$\Rightarrow$ **“Dynamical Dark Matter”**

Dynamical Dark Matter: The Big Picture



Contrived?

Non-minimal?

Ridiculously fine-tuned?

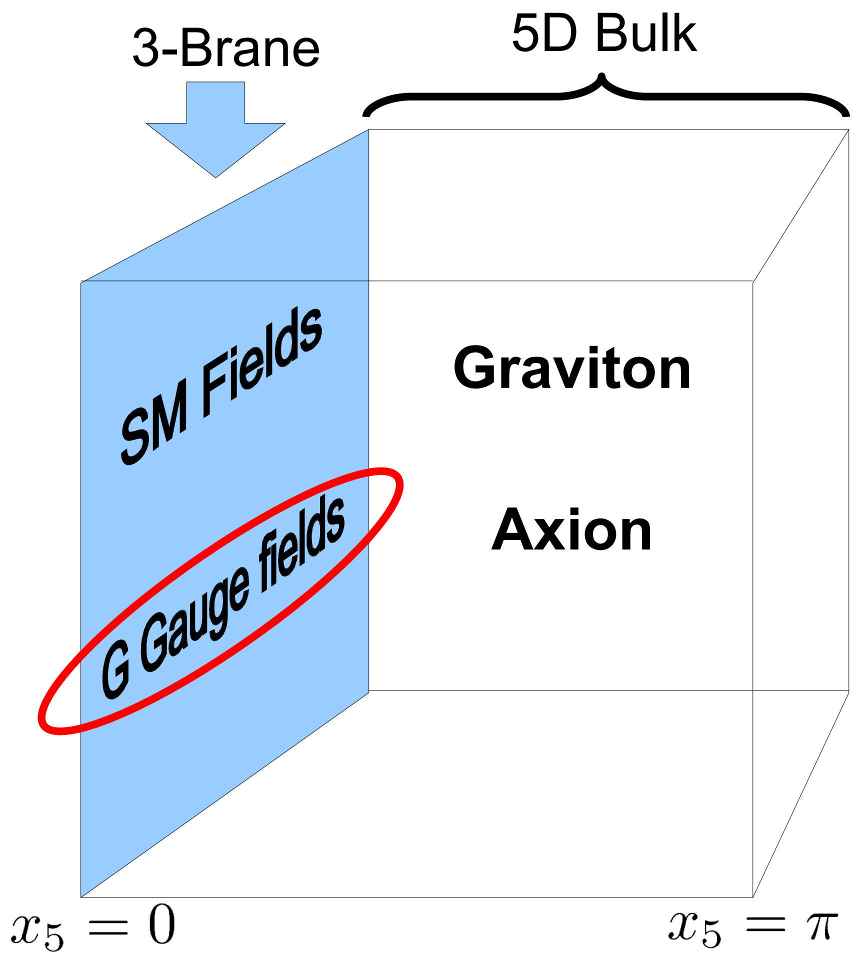
<u>Not at all</u>!

Over the course of this talk, I'll demonstrate how such scenarios arise **naturally** in the context of large extra dimensions.

Moreover, I'll provide a concrete example of a viable model of dynamical dark matter, in which all applicable constraints are satisfied, and a large number of states contribute significantly toward Ω_{DM}.

This example demonstrates that dynamical dark matter is a viable framework for addressing the dark-matter question.

(General) Axions in Large Extra Dimensions



- Consider a 5D theory with the extra dimension compactified on S_1/Z_2 with radius $R = 1/M_c$.
- Global $U(1)_X$ symmetry broken at scale f_X by a bulk scalar → bulk axion is PNGB.
- SM and an **additional gauge group** G are restricted to the brane. G confines at a scale Λ_G. Instanton effects lead to a **brane-mass** term m_X for the axion.

Axion mass matrix:

$$\begin{pmatrix} m_X^2 & \sqrt{2}m_X^2 & \sqrt{2}m_X^2 & \cdots \\ \sqrt{2}m_X^2 & 2m_X^2 + M_c^2 & 2m_X^2 & \cdots \\ \sqrt{2}m_X^2 & 2m_X^2 & 2m_X^2 + 4M_c^2 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

When $y \equiv M_c/m_X$ is small, substantial **mixing** occurs:

Mass eigenstates $(\widetilde{\lambda} \equiv \lambda/m_X)$

$$a_\lambda = \sum_{n=0}^{\infty} U_{\lambda n} a_n \equiv \sum_{n=0}^{\infty} \left(\frac{r_n \widetilde{\lambda}^2}{\widetilde{\lambda}^2 - n^2 y^2} \right) A_\lambda a_n$$

"Mixing Factor"

$$A_\lambda = \frac{\sqrt{2}}{\widetilde{\lambda}} \left[1 + \widetilde{\lambda}^2 + \pi^2/y^2 \right]^{-1/2}$$

The Three Fundamental Questions:

1. "Does the relic abundance come out right?"

$$\Omega_{\rm tot} \equiv \sum_\lambda \Omega_\lambda$$

must match

$$\Omega_{\rm DM}^{\rm WMAP} h^2 = 0.1131 \pm 0.0034$$

[Komatsu et al.; '09]

2. "Do a large number of modes contribute to that abundance, or does the lightest one make up essentially all of $\Omega_{\rm DM}$?"

Define: $$\eta \equiv 1 - \frac{\Omega_{\lambda_0}}{\Omega_{\rm tot}}$$ "Tower Fraction"

If η is $\mathcal{O}(1)$, the full tower contributes nontrivially to $\Omega_{\rm DM}$.

3. "Is the model consistent with all of the applicable experimental, astrophysical, and cosmological constraints?"

Thanks to the properties of the mixing factor A_λ, the answer to all three questions can indeed (simultaneously) be in the affirmative!

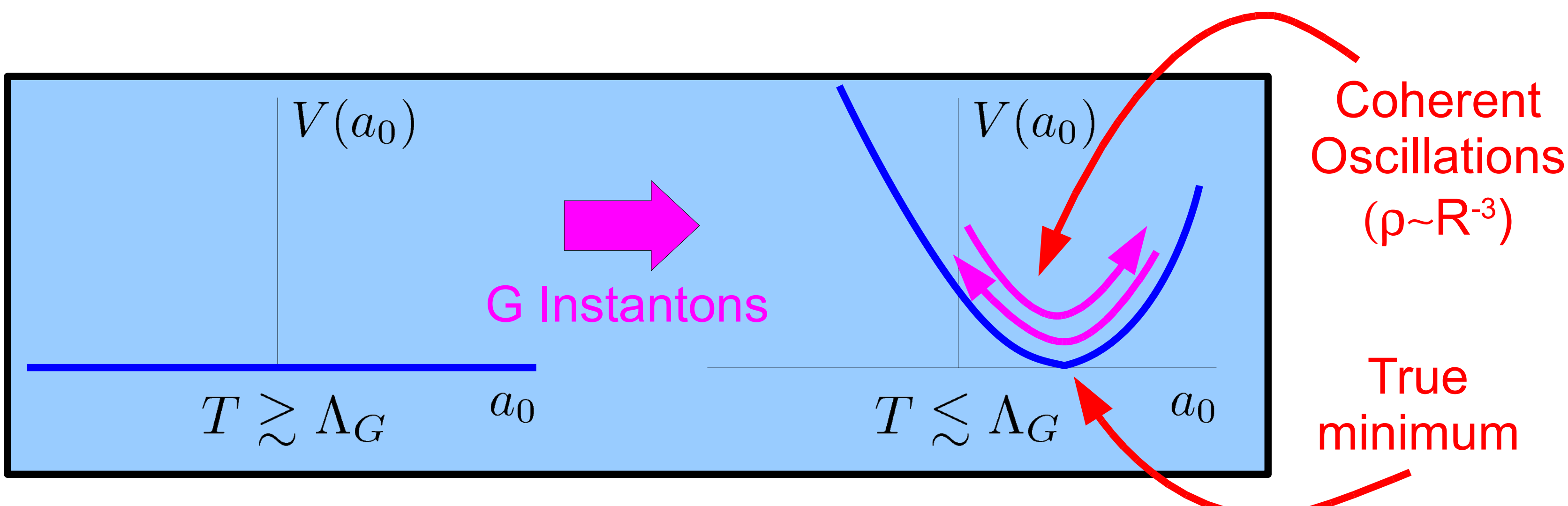
Mixing and Relic Abundances:

- At temperatures $T \gg \Lambda_G$, $m_X \approx 0$. At such temperatures, mixing is negligible, and the potential for a_0 effectively vanishes.
- The expectation value of a_0 at such temperatures is therefore undetermined:

$$\boxed{\langle a_0 \rangle_{\rm init} = \theta \hat{f}_X}$$

"Misalignment Angle"
(parameterizes initial displacement)

- However, at $T \sim \Lambda_G$, instanton effects turn on:
  - m_X becomes nonzero, so KK eigenstates are no longer mass eigenstates.
  - The zero-mode potential now has a well-defined minimum.



- The a_λ are initially populated (at t_G) according to their overlap with a_0:

Initial Overlap

$$\boxed{\langle a_\lambda(t_G)\rangle = \theta \hat{f}_X A_\lambda}$$

Energy Densities

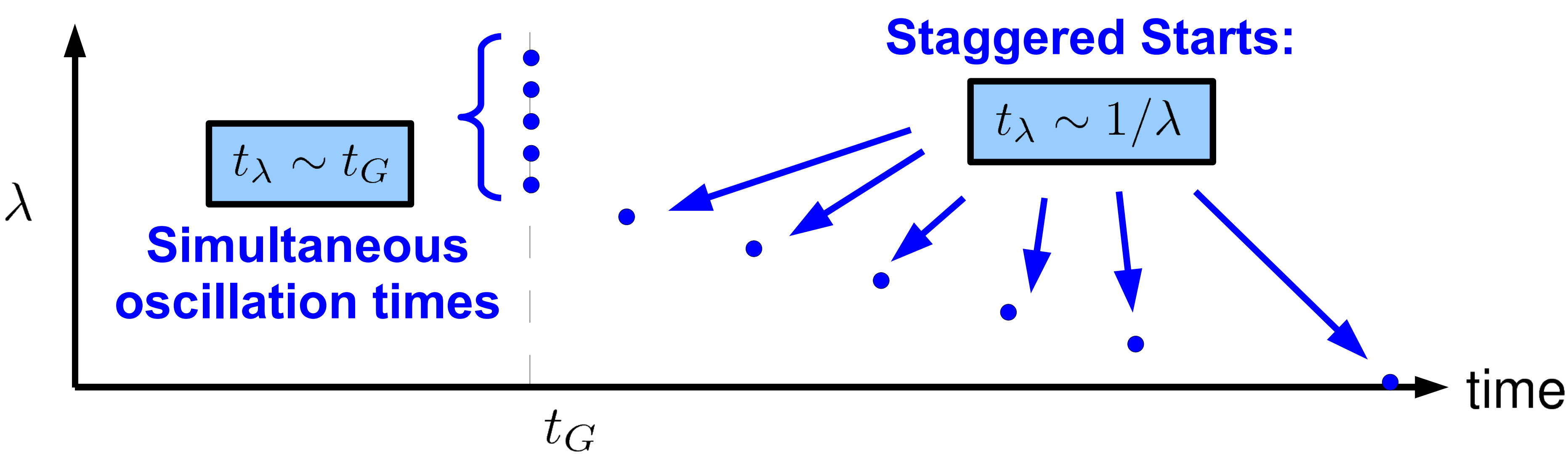
$$\boxed{\rho_\lambda(t_G) = \frac{1}{2}\theta^2 \hat{f}_X^2 \lambda^2 A_\lambda^2}$$

- Each field begins to oscillate at a time t_λ, when **two** conditions are met:

  1. ρ_λ is nonzero (so $t \gtrsim t_G$).

  2. Mass has become comparable to Hubble Parameter: $\lambda \sim 3H(t)$.

- In the approximation that the instanton potential turns on rapidly, we have two regimes:



The Contribution from Each Field

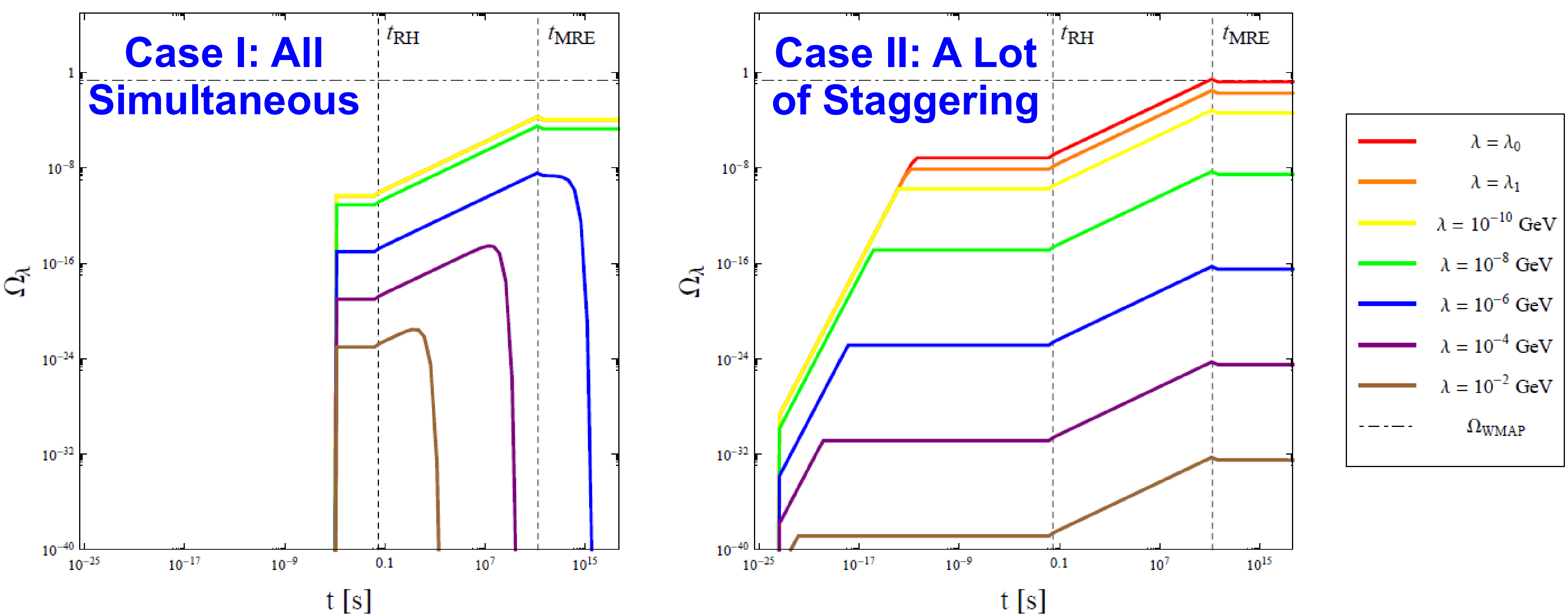
Time-evolution factor (for t_λ during reheating)

Mixing factor from A_λ^2

Decay suppression

$$\Omega_\lambda = 3\left(\frac{\theta \hat{f}_X m_X}{M_P}\right)^2 t_\lambda^2 \left[1 + \frac{\lambda^2}{m_X^2} + \frac{\pi^2 m_X^2}{M_c^2}\right]^{-1} e^{-\Gamma_\lambda (t - t_G)} \begin{cases} \frac{1}{4} & 2/\lambda \lesssim t \lesssim t_{\rm RH} \\ \frac{4}{9}\left(\frac{t}{t_{\rm RH}}\right)^{1/2} & t_{\rm RH} \lesssim t \lesssim t_{\rm MRE} \\ \frac{1}{4}\left(\frac{t_{\rm MRE}}{t_{\rm RH}}\right)^{1/2} & t \gtrsim t_{\rm MRE} \end{cases}$$

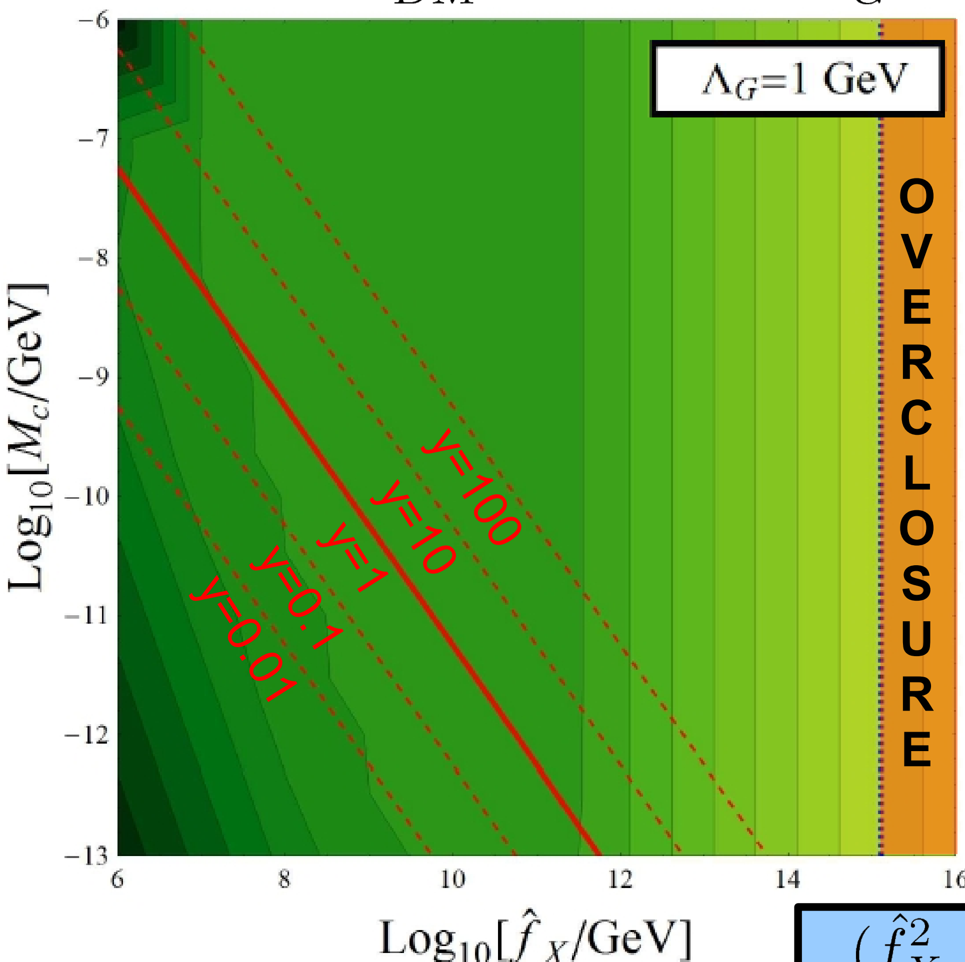
t_G^2 (simultaneous) or $4/\lambda^2$ (staggered)



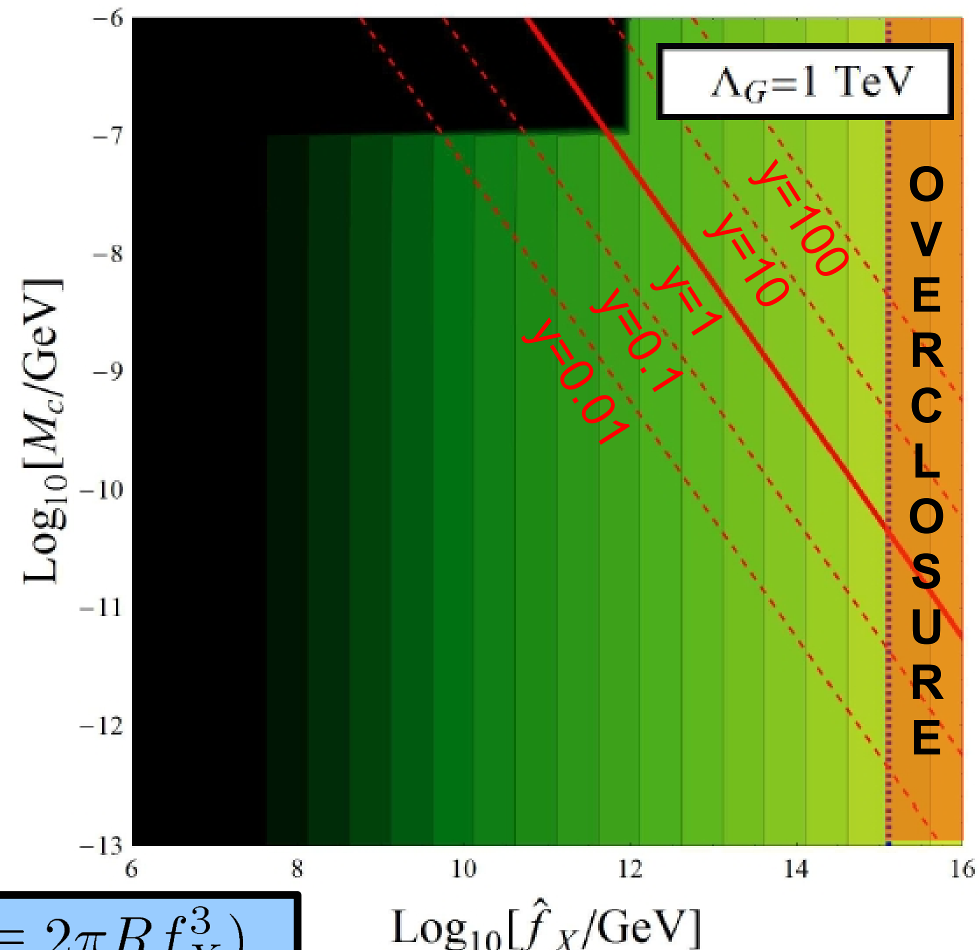
E Pluribus Unum: Ω_{tot} from Ω_λ

The total relic abundance at present time is obtained by summing over these individual contributions.

Total $\Omega_{\rm DM}$ with Small Λ_G



Total $\Omega_{\rm DM}$ with Large Λ_G

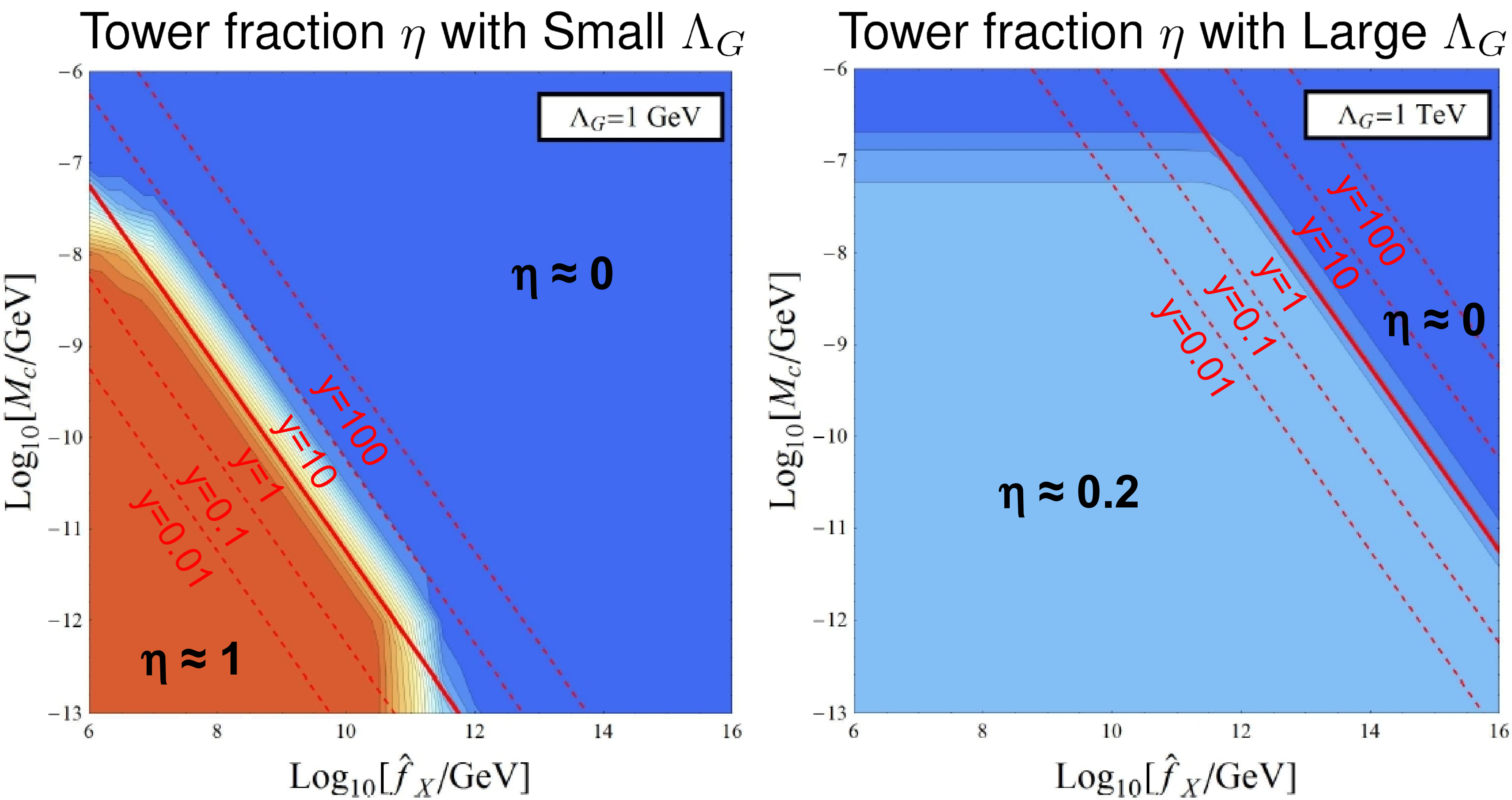


$(\hat{f}_X^2 \equiv 2\pi R f_X^3)$

The upshot: $\Omega_{\rm DM}$ consistent with WMAP results for $\hat{f}_X \sim 10^{14} - 10^{15}$ GeV.

Tower Fractions

- When Λ_G is small and t_G occursvery late, all modes begin oscillating **simultaneously** at t_G and contribute "democratically" to $\Omega_{\rm DM}$.
- When Λ_G is large and t_G occurs early, t_λ for the relevant modes are staggered in time. Lighter modes contribute proportionally **more** to $\Omega_{\rm DM}$.



Mixing and stability:

- Couplings between SM fields and the a_λ are propoptional to $\widetilde{\lambda}^2 A_\lambda$.
- This results in a decay-width suppression for modes with $\lambda \lesssim m_X^2/M_c$

$$\boxed{\Gamma_\lambda \propto \frac{\lambda^3}{\hat{f}_X^2}\left(\widetilde{\lambda}^2 A_\lambda\right)^2}$$

$\mathcal{O}(1)$ for $\lambda \gg \frac{m_X^2}{M_c}$

Tiny for $\lambda \ll \frac{m_X^2}{M_c}$

- Comparing to the relic-abundance results, above we find that the a_λ with large Γ_λ **automatically** have suppressed Ω_λ!

This balance between Ω_λ and Γ_λ rates relaxes constraints related to:

- Distortions to the CMB
- Features in the diffuse X-ray and gamma-ray background
- Disruptions of BBN
- Late entropy production

Mixing and axion production:

Without mixing:
(e.g. KK-graviton production)

$$\sigma_{\rm prod} \propto \frac{1}{M_P^2}\left(\frac{E}{M_c}\right)$$

With mixing:

$$\sigma_{\rm prod} \propto \frac{1}{\hat{f}_X^2}\aleph^2(E)$$

where

$$\boxed{\aleph^2(E) \equiv \sum_{\lambda}^{E} (\widetilde{\lambda}^2 A_\lambda)^2}$$

Suppression significantly relaxes limits from processes in which axions are produced, but not detected directly, including those from:

- Supernova energy-loss rates
- Stellar evolution
- Collider production ($j+E_T$, $\gamma+E_T$,...)

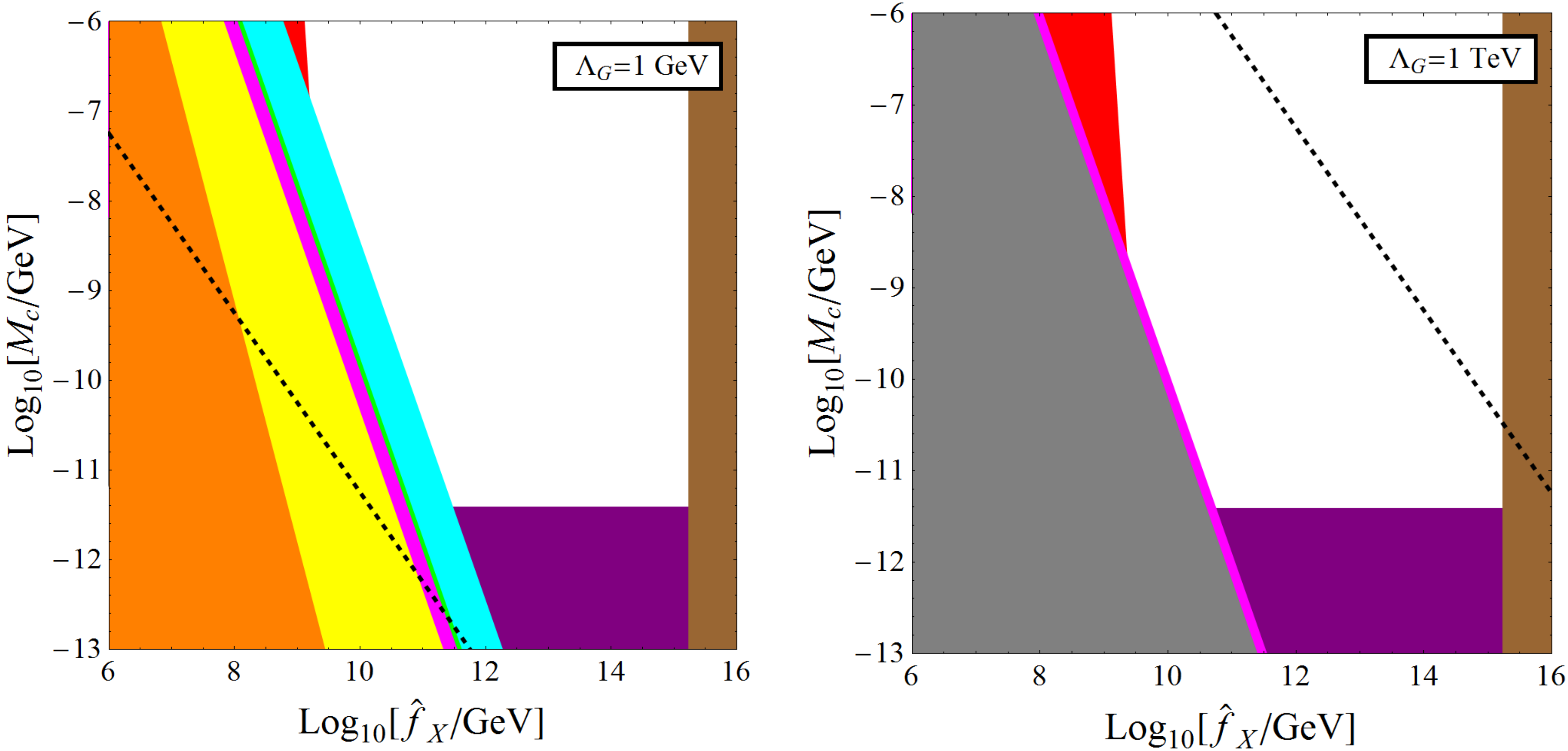
Decoherence phenomena (also related to axion mixing) suppress detection rates from: [Dienes, Dudas, Gherghetta; '99]

- Microwave-cavity experiments
- Helioscopes
- "Light-shining-through-walls" (LSW) experiments, etc.

Constraints on Dark Towers

- Therefore, while a great many considerations constrain scenarios involving light bulk axions, they can all be simultaneously satisfied.

GC stars
SN1987A
Diffuse photon spectra
Eötvös experiments
Helioscopes (CAST)
Collider limits
DM overabundant
Thermal production
5D Theory Inconsistent



Summary

- There's no reason to assume that a single, stable particle accounts for all of the non-baryonic dark matter in our universe.
- Indeed, there are simple, well-motivated BSM scenarios in which a large number of particles contribute non-trivially toward $\Omega_{DM.}$
- Production mechanisms (e.g. misalignment production) exist which naturally generate relic abundances for the contributing fields in such a way that an inverse correlation exists between Ω_λ. and Γ_λ.
- The same mass-mixing which gives rise to this correlation automatically suppresses the interactions between the lighter modes and the SM fields, making these particles less dangerous from a phenomenological perspective.

The Take-Home Message:

Dynamical dark matter is as viable a framework in which to address the dark matter question as any other.