



Dynamical Dark Matter

A New Framework for Dark-Matter Physics

Brooks Thomas

(University of Hawaii)

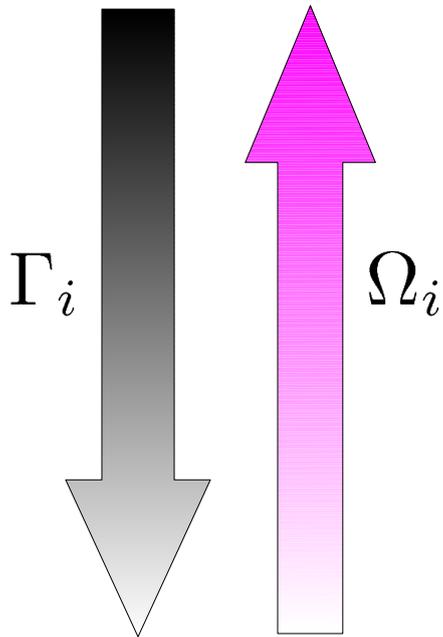
Based on work done in collaboration with Keith Dienes

[arXiv:1105.xxxx, arXiv:1105.yyyy, arXiv:1105.zzzz]

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.

$$\Omega_{\text{DM}} = \sum_i \Omega_i$$

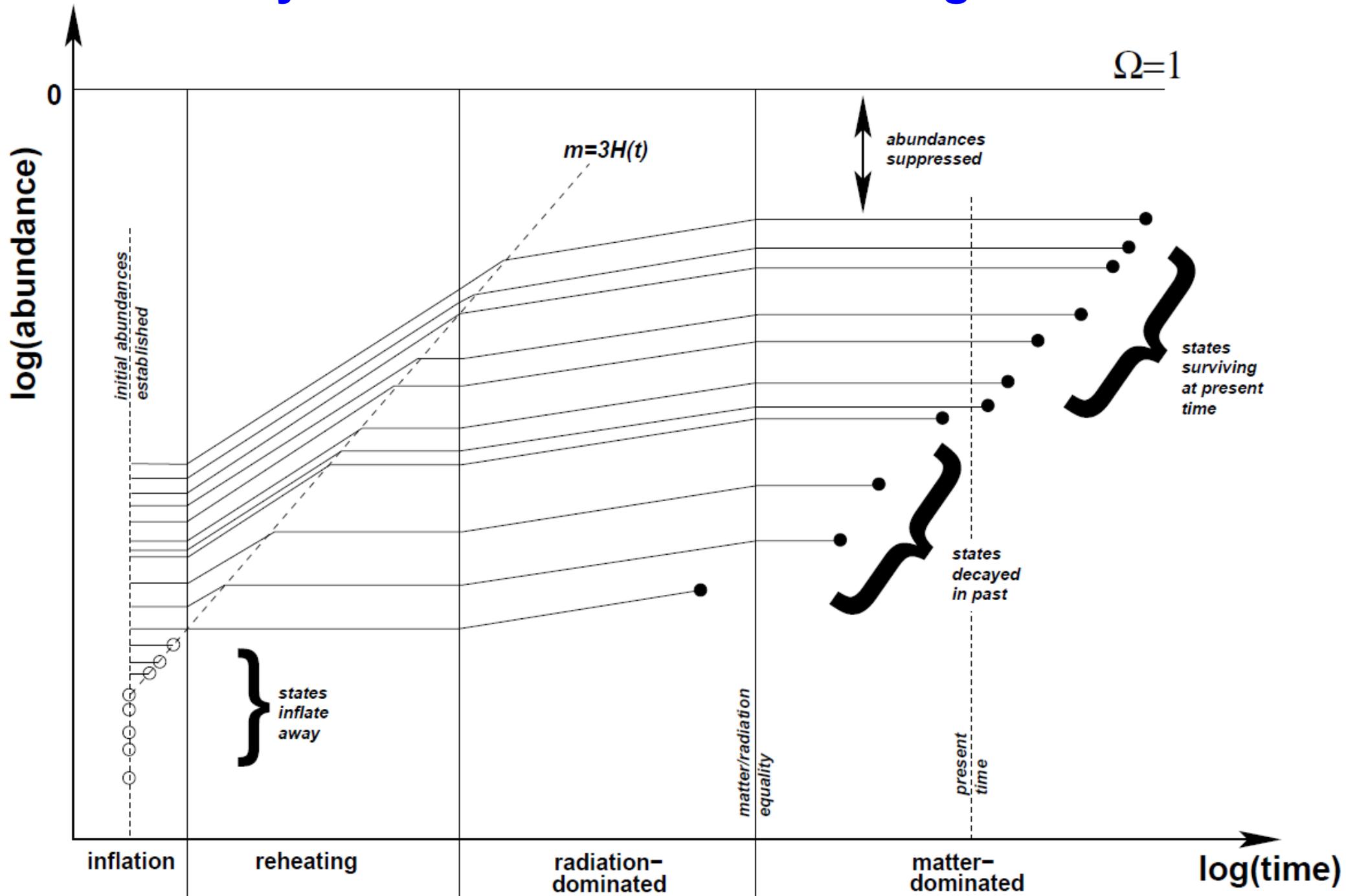


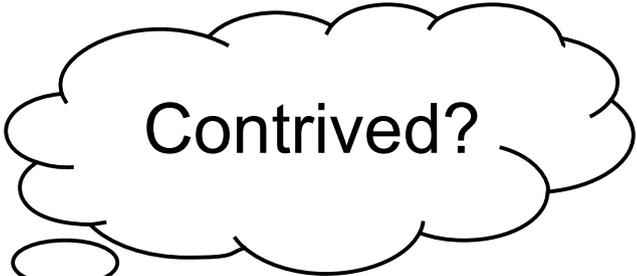
- Some of these states may be only quasi-stable, but as long as the individual abundances are **balanced against decay rates** in just the right way, this can be a viable dark-matter scenario!



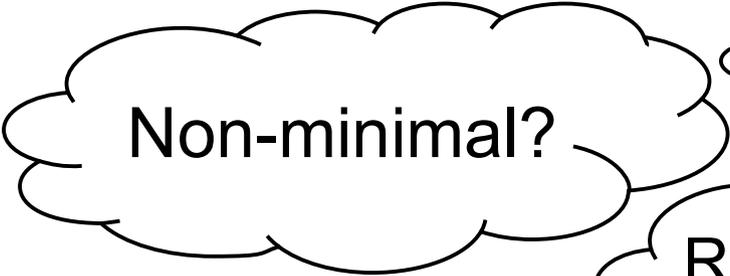
“Dynamical Dark Matter”

Dynamical Dark Matter: The Big Picture

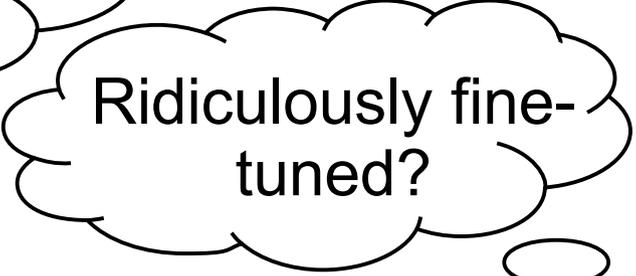




Contrived?



Non-minimal?



Ridiculously fine-tuned?

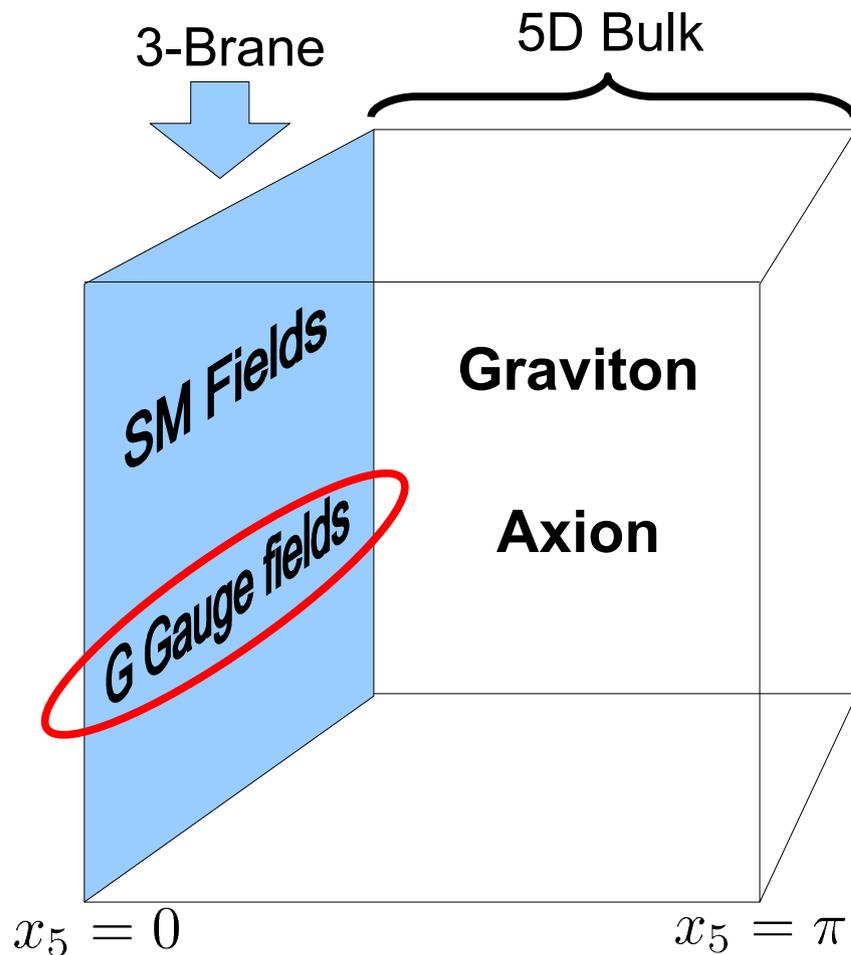
Not at all!

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 legitimate 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 \rightarrow 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:

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

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

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

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

“Mixing Factor”

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

The Three Fundamental Questions:

1. “Does the relic abundance come out right?”

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

must match

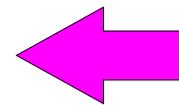
$$\Omega_{\text{DM}}^{\text{WMAP}} h^2 = 0.1131 \pm 0.0034$$

[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 Ω_{DM} ?”

Define:

$$\eta \equiv 1 - \frac{\Omega_{\lambda_0}}{\Omega_{\text{tot}}}$$



“Tower Fraction”

If η is $\mathcal{O}(1)$, the full tower contributes nontrivially to Ω_{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!

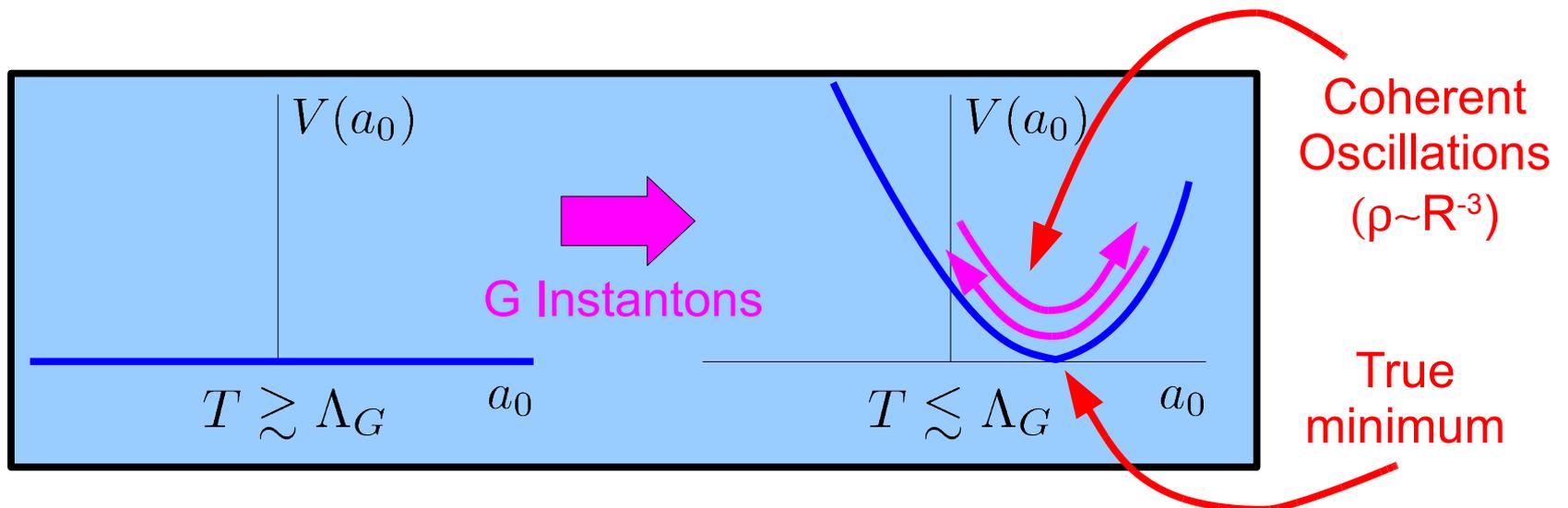
Mixing and Relic Abundances:

- 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:

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

“Misalignment Angle”
(parameterizes initial displacement)

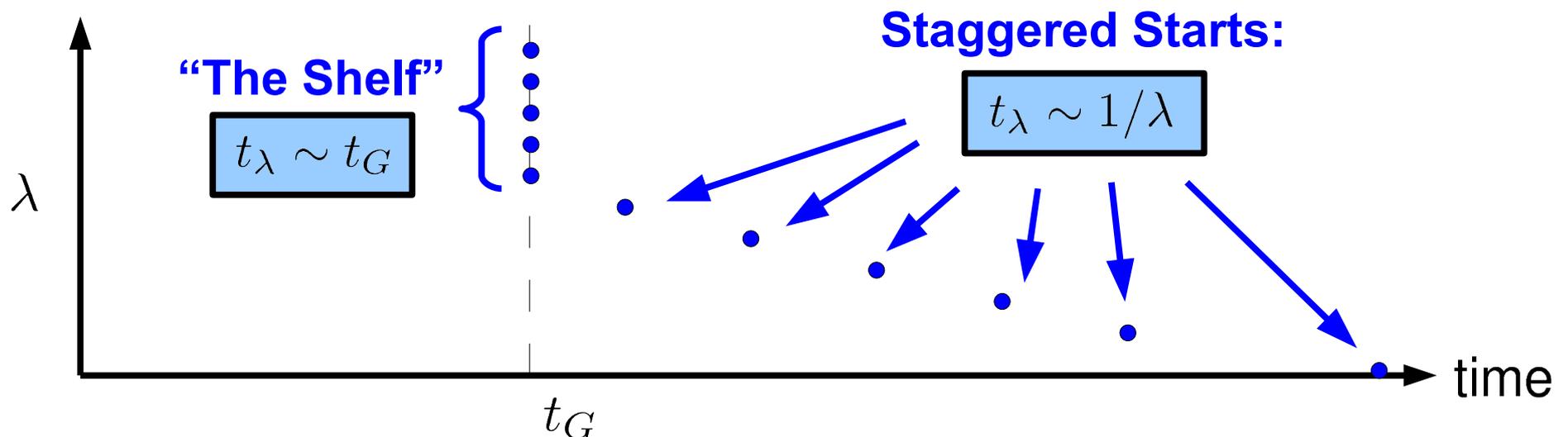
- However, at $T \sim \Lambda_G$, instanton effects turn on:
 - m_X becomes nonzero, so KK eigenstates are no longer mass eigenstates.
 - The zero-mode potential now has a well-defined minimum.



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

Initial Overlap		Energy Densities
$\langle a_\lambda(t_G) \rangle = \theta \hat{f}_X A_\lambda$	➔	$\rho_\lambda(t_G) = \frac{1}{2} \theta^2 \hat{f}_X^2 \lambda^2 A_\lambda^2$

- 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

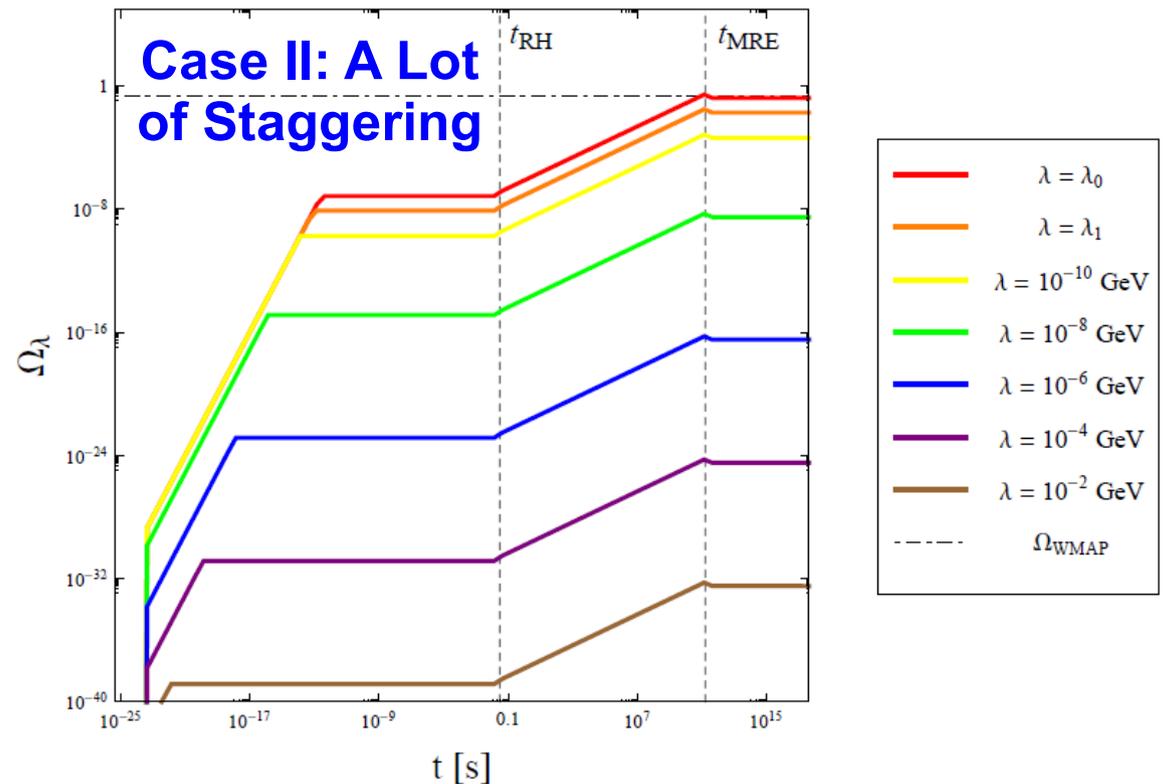
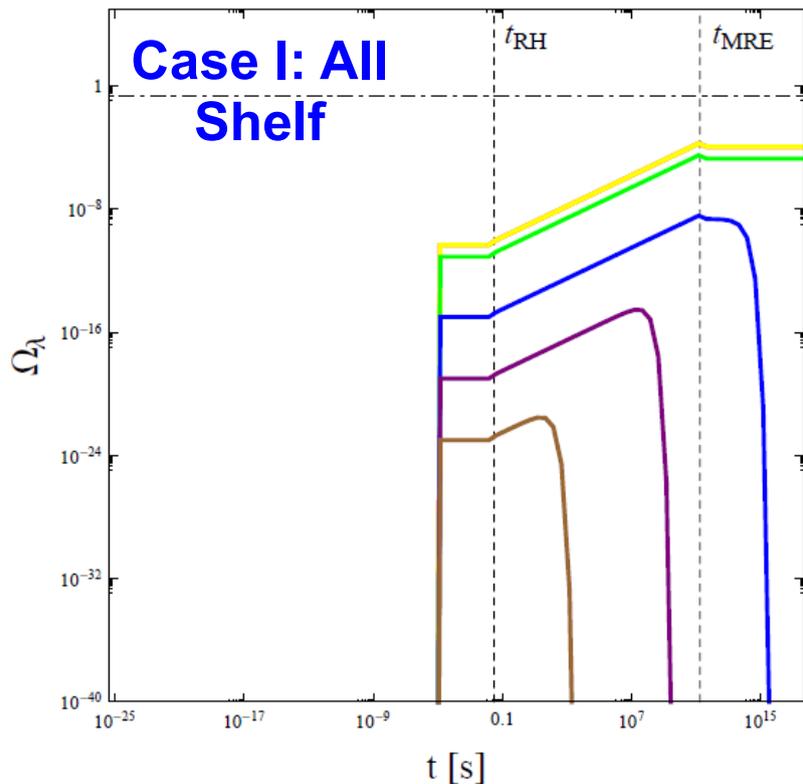
Time-evolution factor
(for t_λ during reheating)

Mixing factor from A_λ^2

Decay suppression

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

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



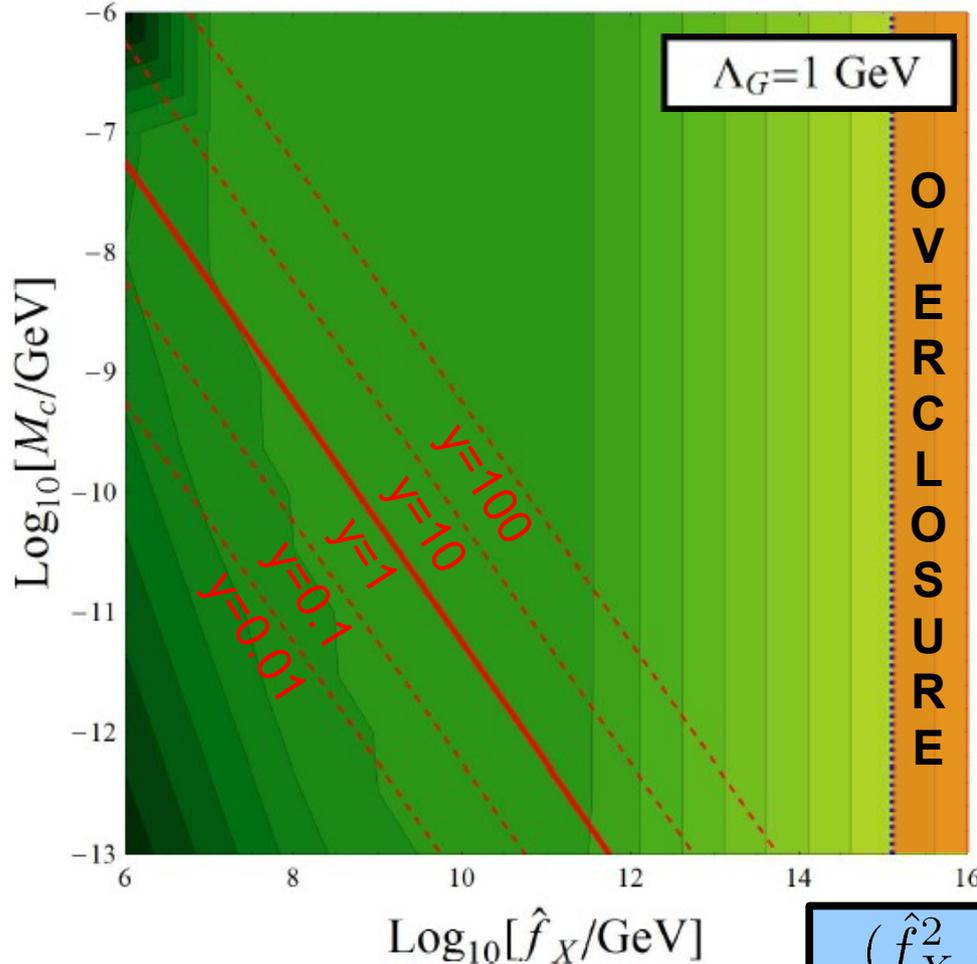


E Pluribus Unum: Ω_{tot} from Ω_λ

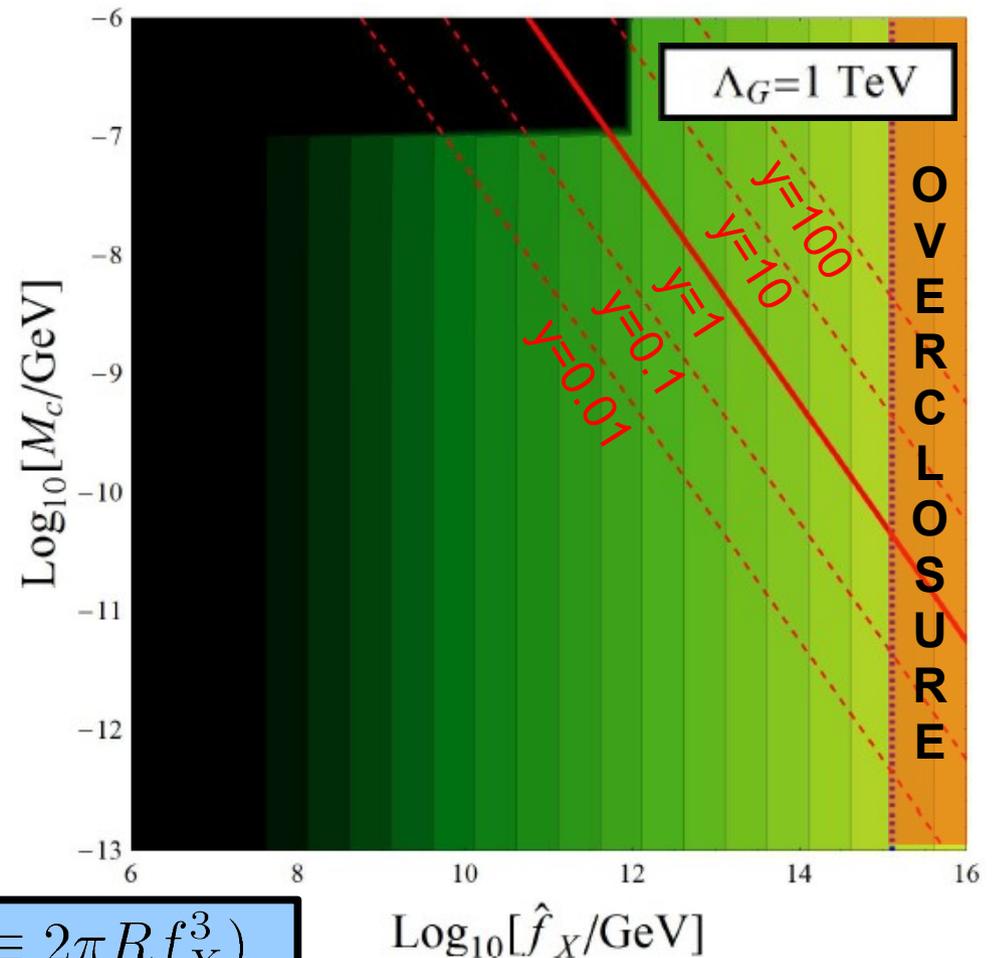


The total relic abundance at present time is obtained by summing over these individual contributions.

Total Ω_{DM} with Small Λ_G



Total Ω_{DM} with Large Λ_G

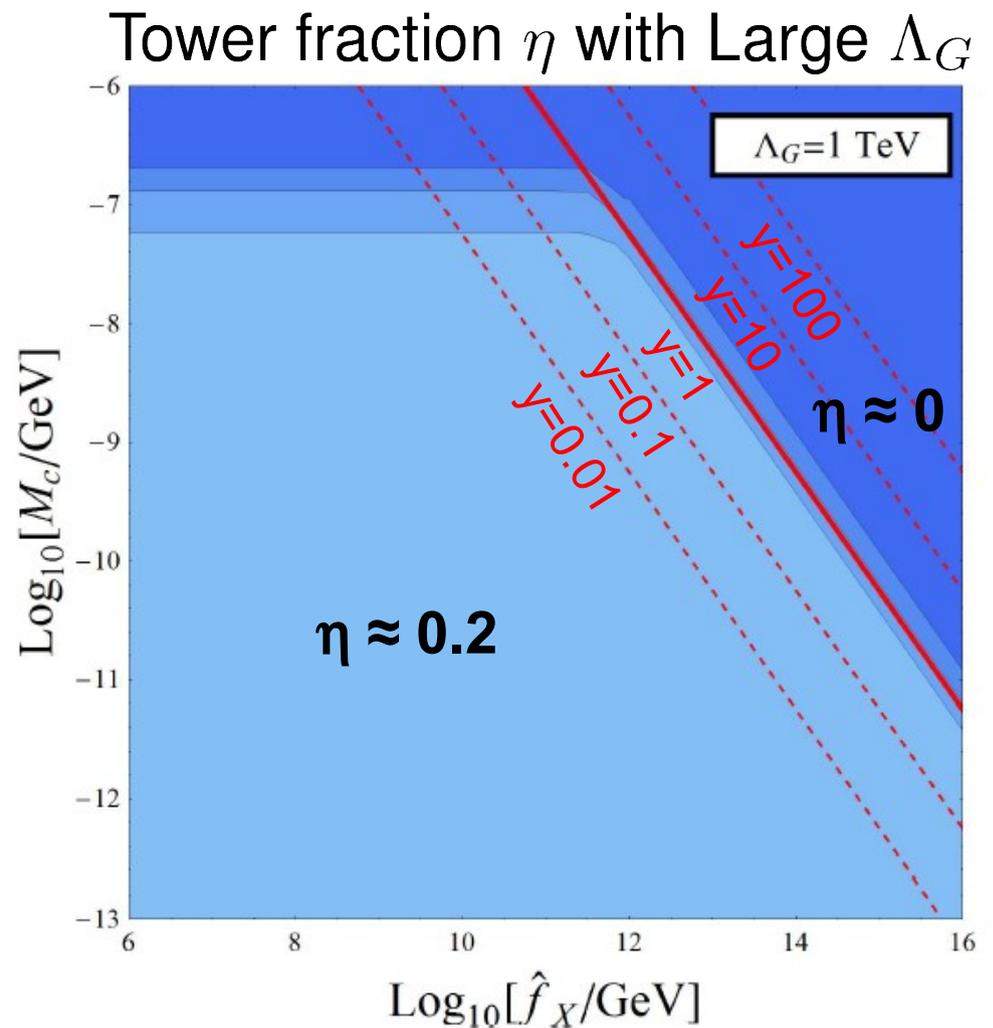
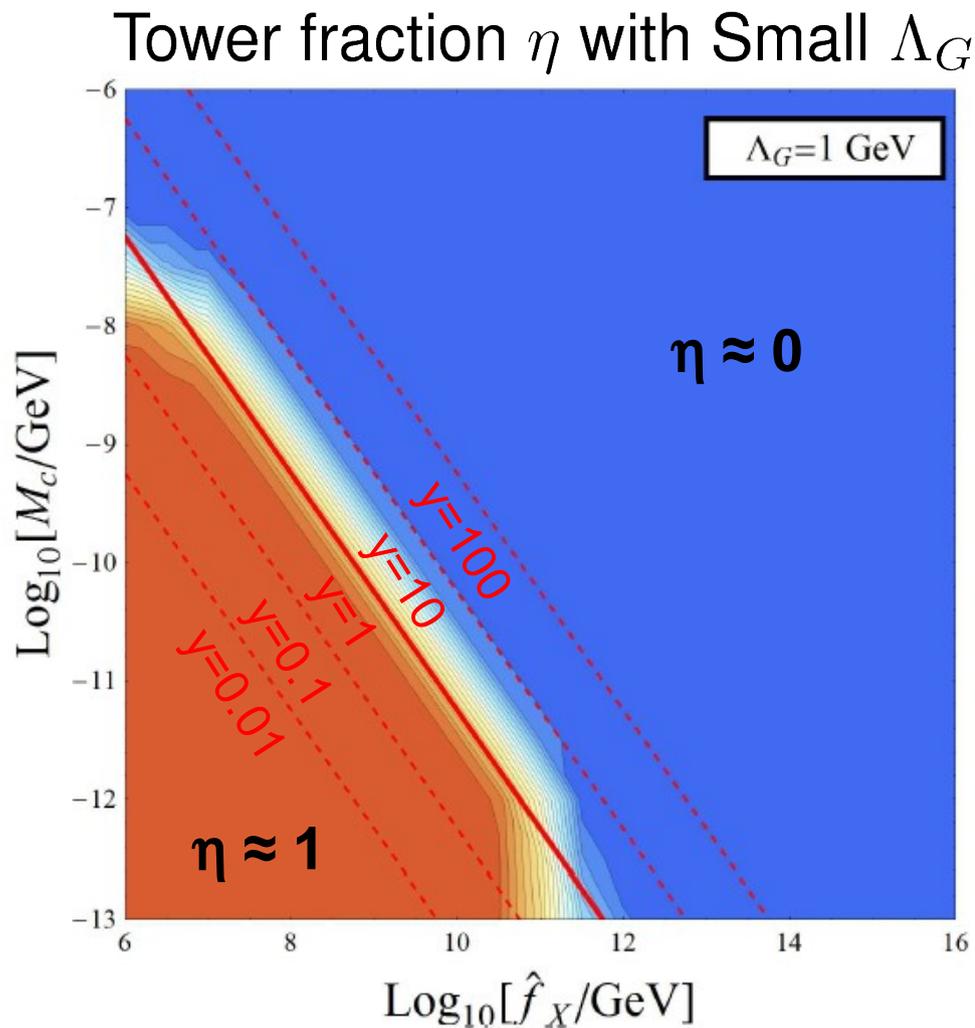


$$(\hat{f}_X^2 \equiv 2\pi R f_X^3)$$

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

Tower Fractions

- When Λ_G is small and t_G occurs very late, all modes begin oscillating **simultaneously** at t_G and contribute “democratically” to Ω_{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 Ω_{DM} .



Mixing and stability:

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

$$\Gamma_\lambda \propto \frac{\lambda^3}{\hat{f}_X^2} (\tilde{\lambda}^2 A_\lambda)^2$$

$\mathcal{O}(1)$ 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:

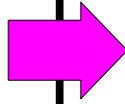
- Distortions to the CMB
- Features in the diffuse X-ray and gamma-ray background
- Disruptions of BBN
- Late entropy production

Mixing and axion production:

Without mixing:

(e.g. KK-graviton production)

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



With mixing:

$$\sigma_{\text{prod}} \propto \frac{1}{\hat{f}_X^2} \mathcal{N}^2(E)$$

where

$$\mathcal{N}^2(E) \equiv \sum_{\lambda}^E (\tilde{\lambda}^2 A_{\lambda})^2$$

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

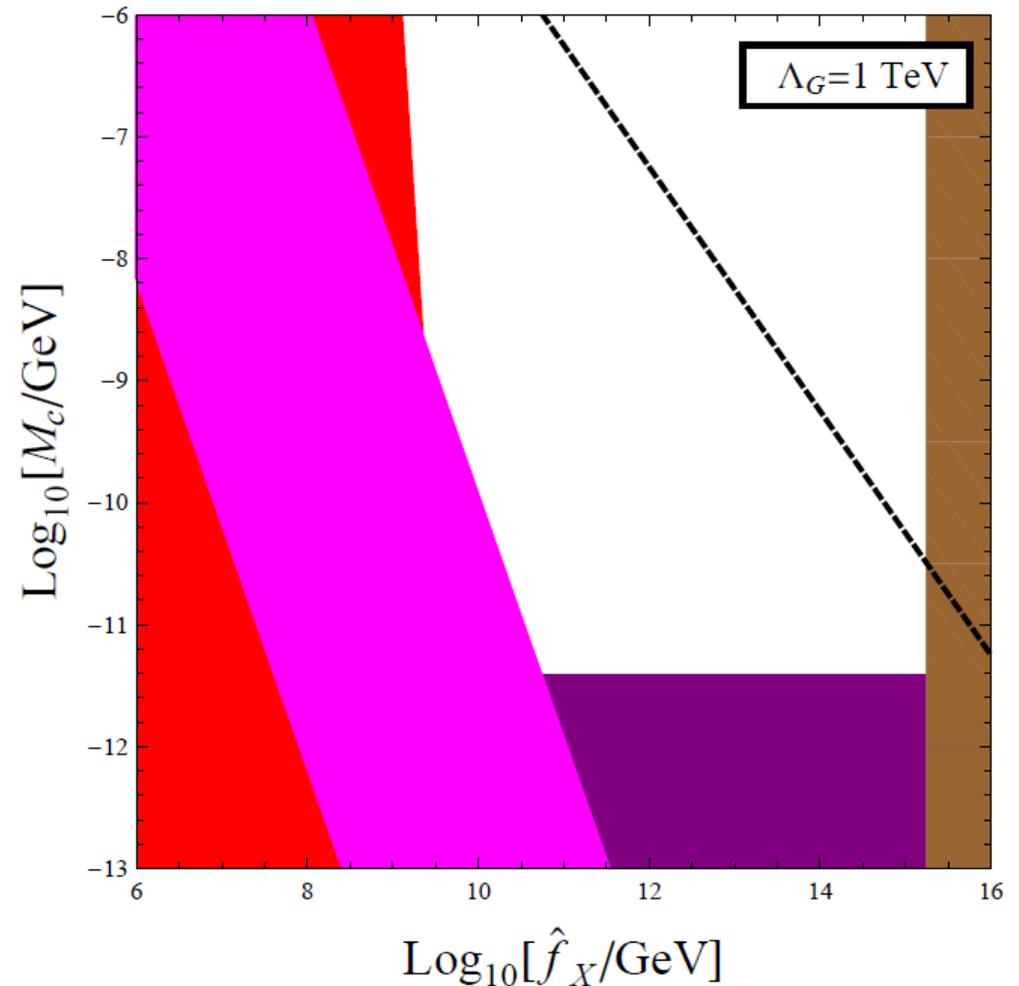
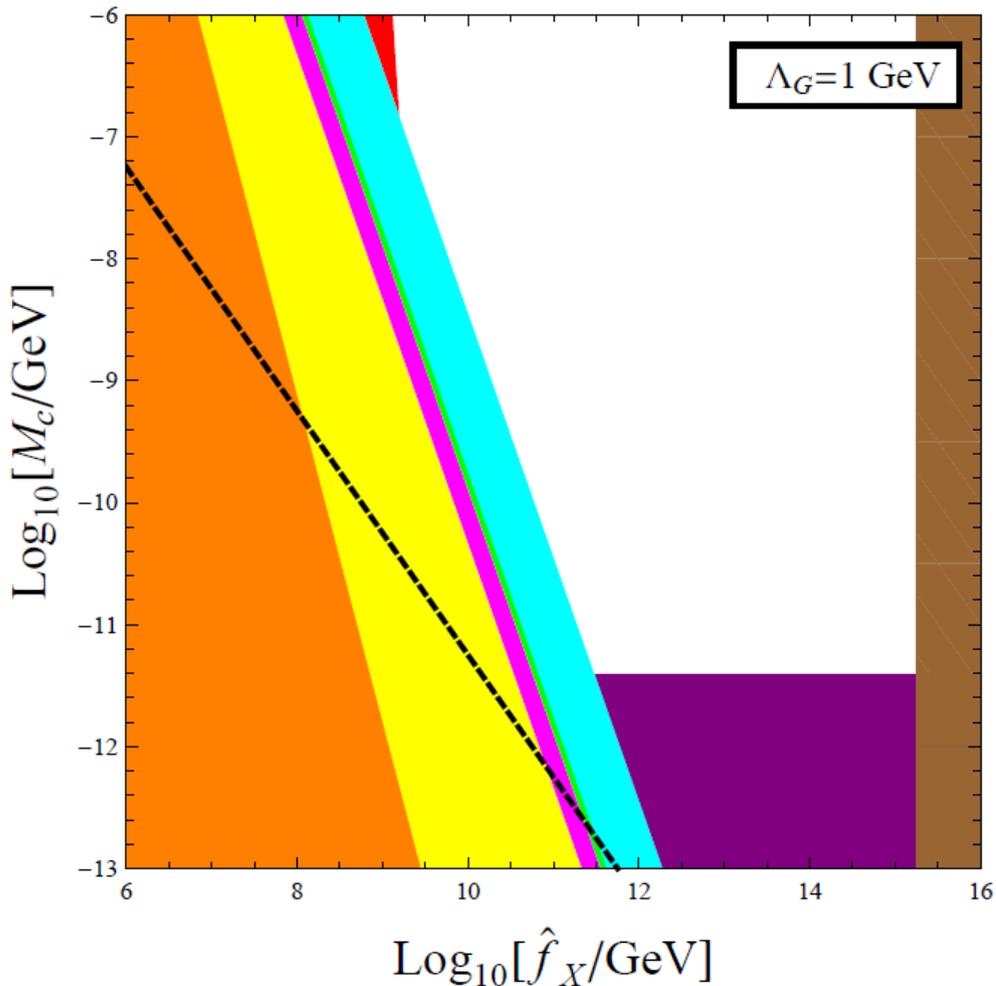
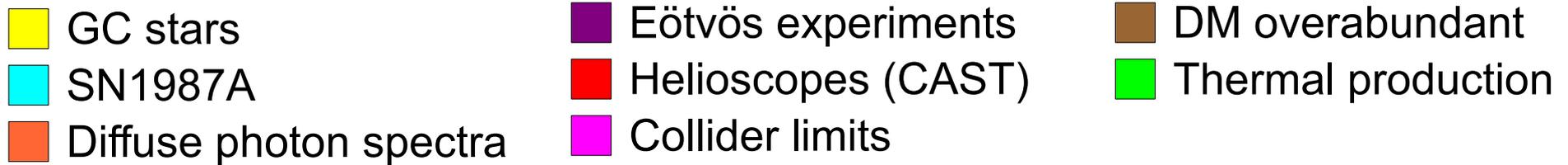
- Supernova energy-loss rates
- Stellar evolution
- Collider production ($j+E_T$, $\gamma+E_T, \dots$)

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.



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 Ω_{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 a viable framework in which to address the dark matter question.