Dynamical Dark Matter

An Explicit Model from Extra Dimensions

Brooks Thomas
(University of Hawaii)

[arXiv:1106.4546, 1107.0721, 1203.1923] with Keith Dienes
[arXiv:1204.4183] with Keith Dienes and Shufang Su
[arXiv:1205.xxxx] with Keith Dienes and Jason Kumar

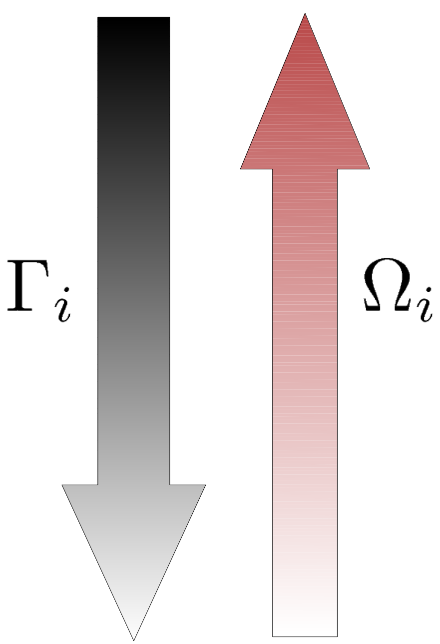
The DDM Framework: A Brief Review

(see also: talk given in this afternoon's DM session)

- 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.

- Alternatively, it could be that many particles – maybe even a **vast** number – make up that abundance **collectively**, with each providing only a minute fraction of the total.

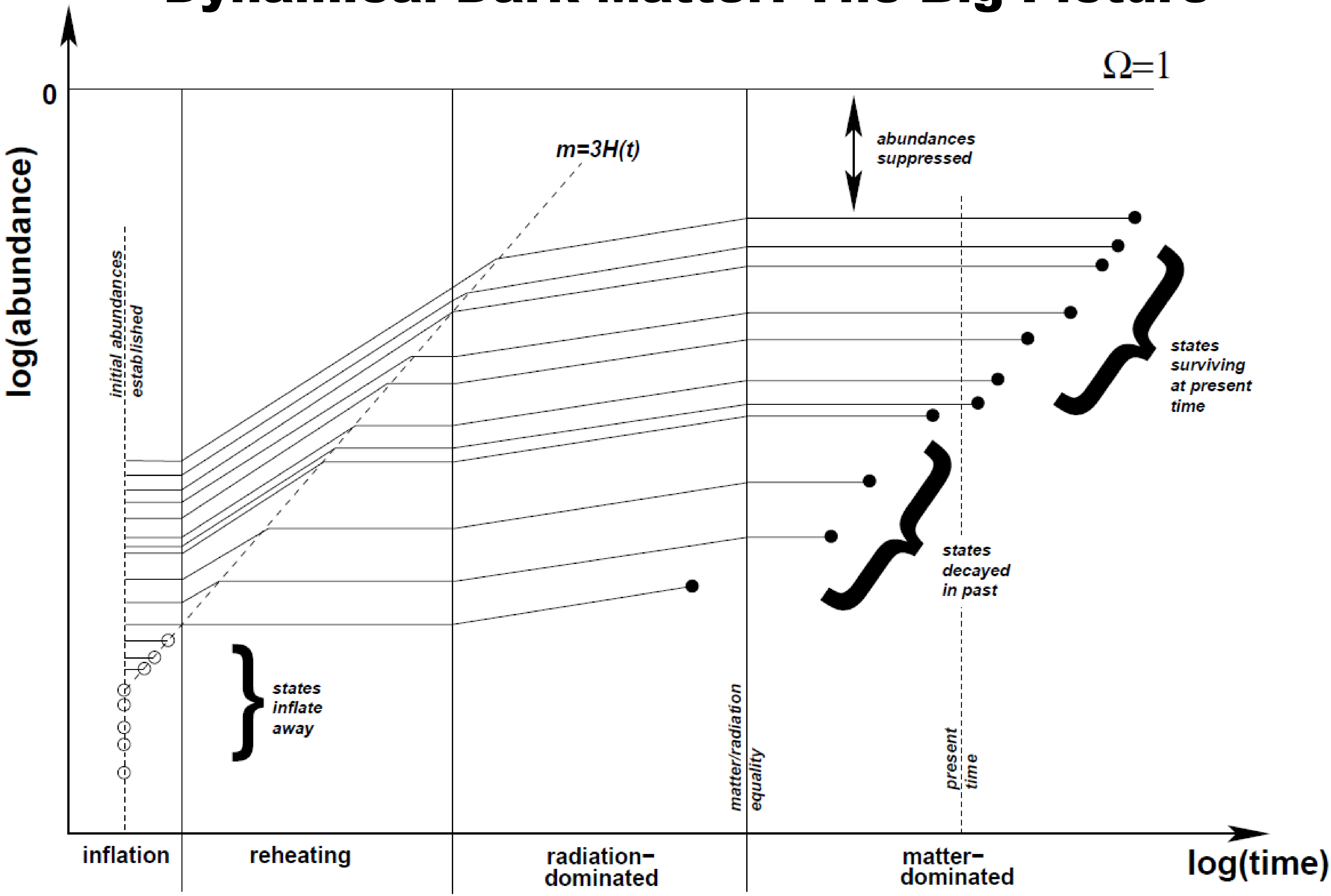
$$\Omega_{\mathrm{DM}} = \sum_i \Omega_i$$



- Some of the states in this **DM ensemble** 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?

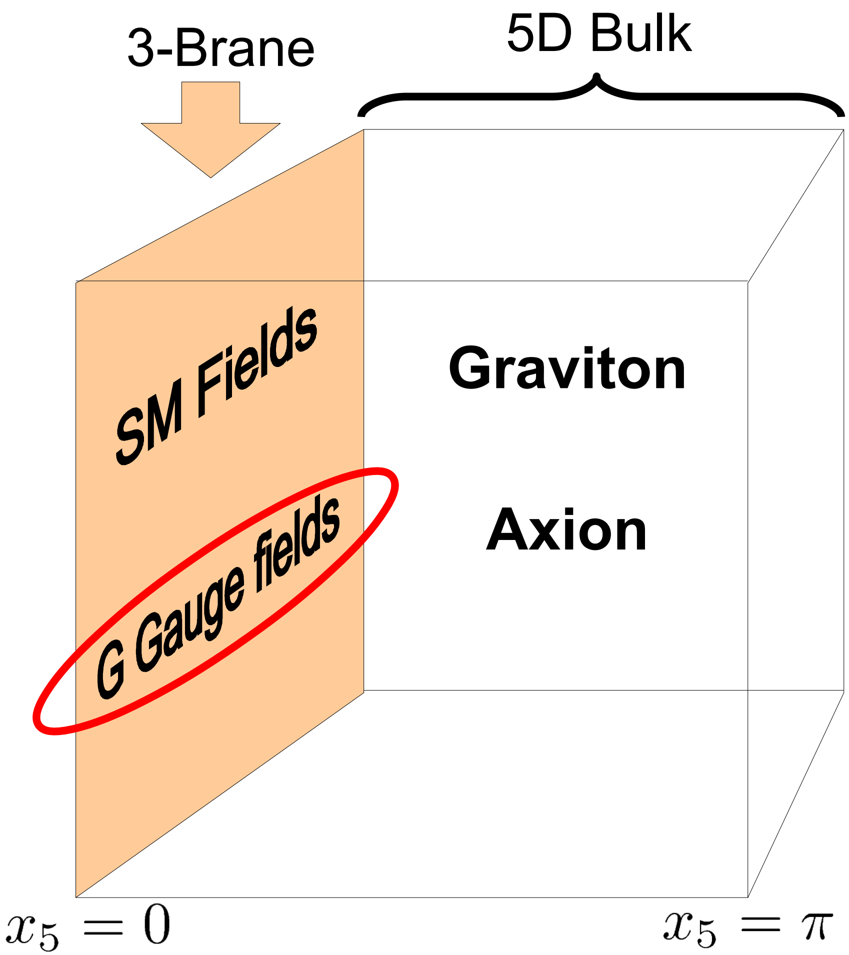
Not at all!

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 an **explicit model** of DDM, in which all applicable constraints are satisfied, and the full ensemble of states contributes significatly toward Ω_{DM}.

This example demonstrates that DDM 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!

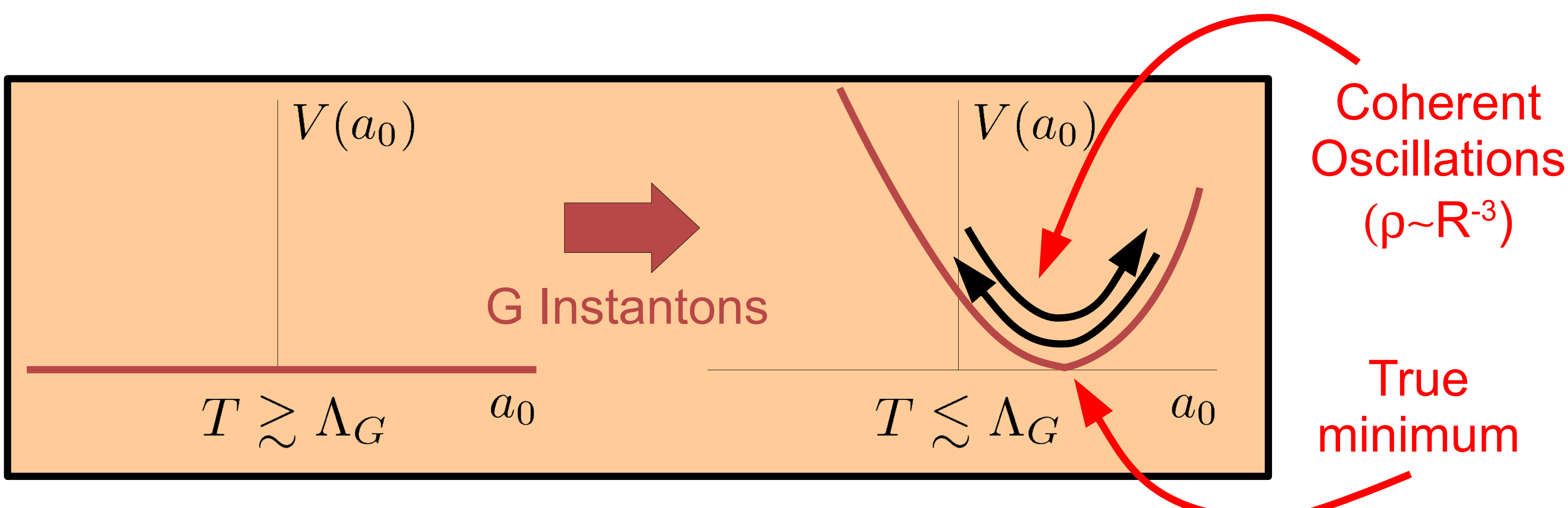
Mixing and Relic Abundances:

- 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:

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

"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

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

→

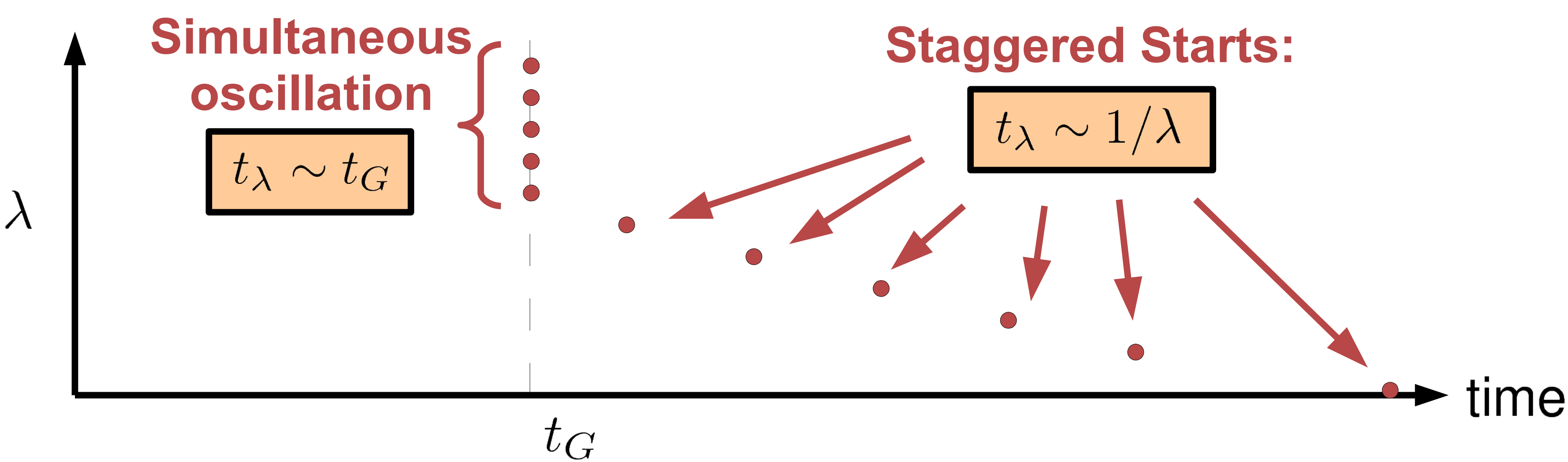
Energy Densities

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

- 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

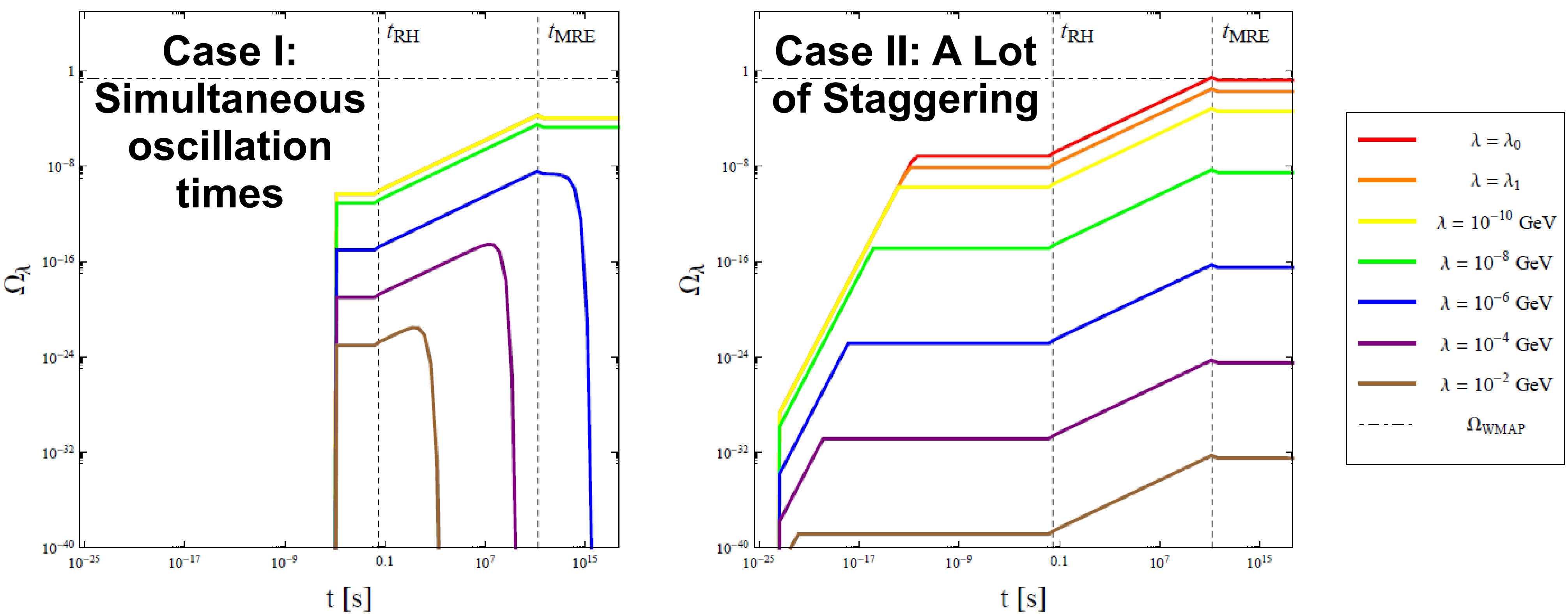
Mixing factor from A_λ^2

Decay suppression

Time-evolution factor (for t_λ during reheating)

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

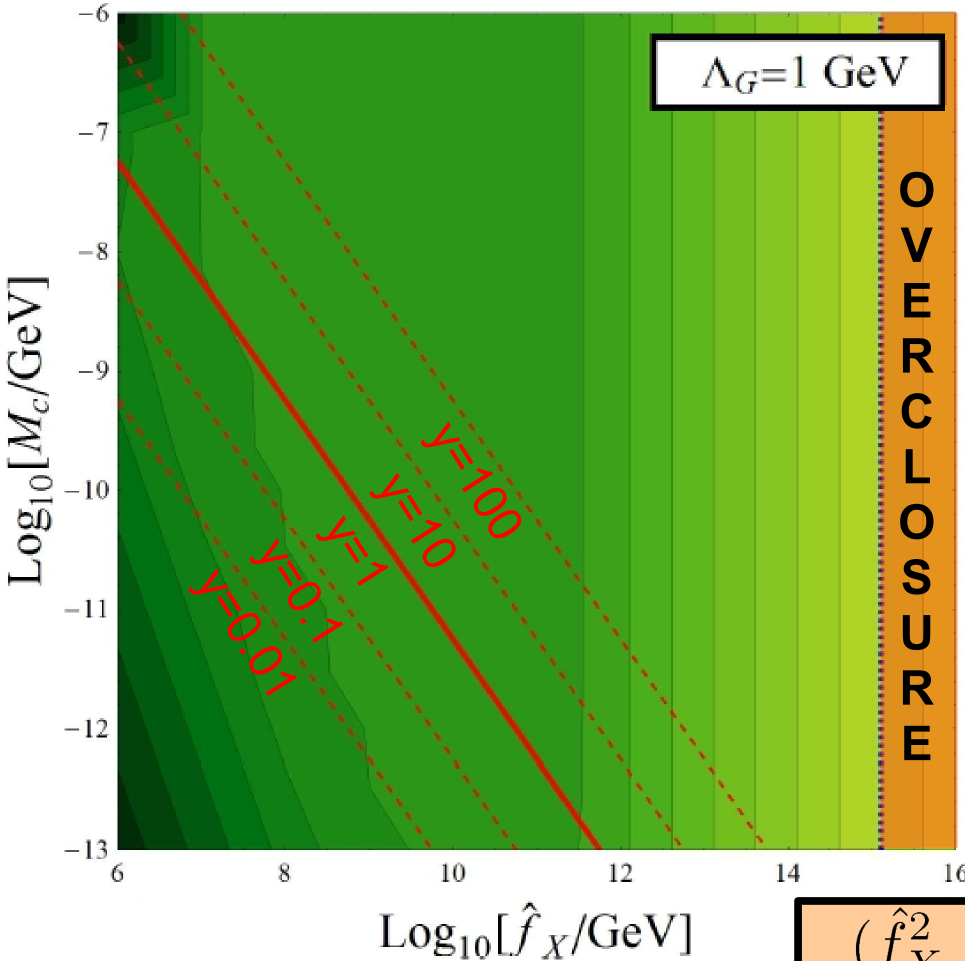
t_G^2 (simultaneous) or $4/\lambda^2$ (staggered)



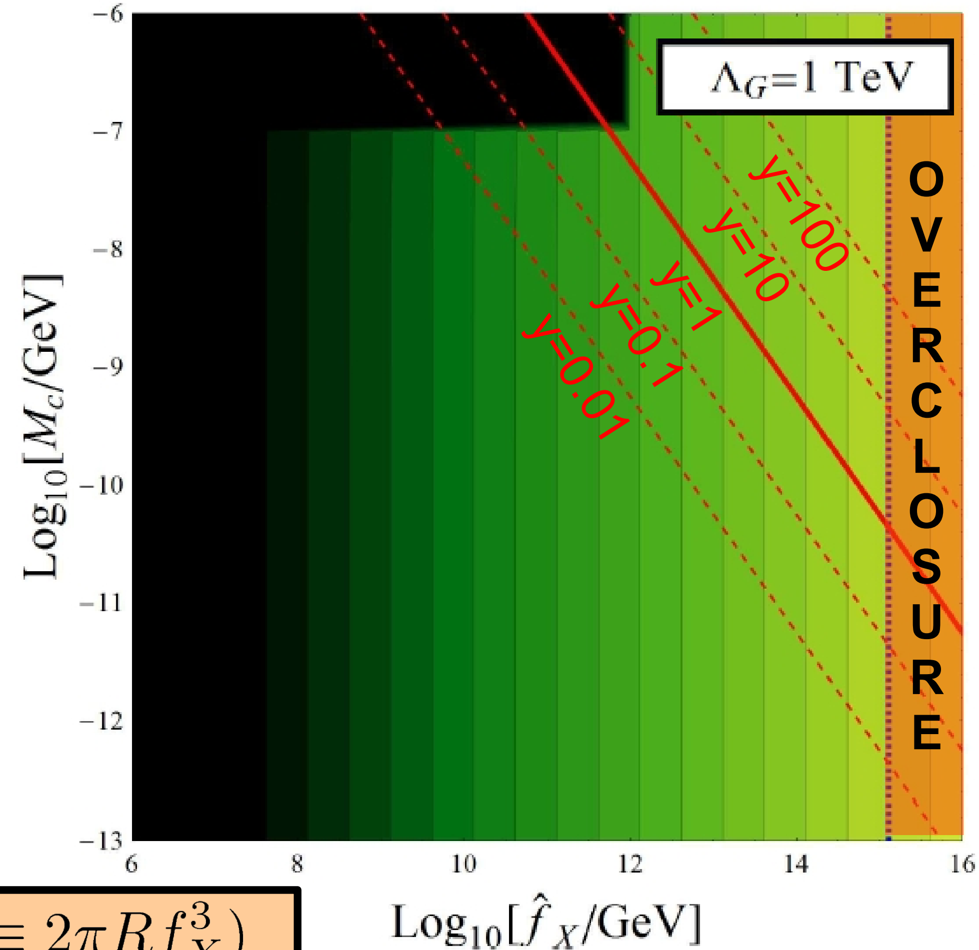
E Pluribus Unum: Ω_{tot} from Ω_λ

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



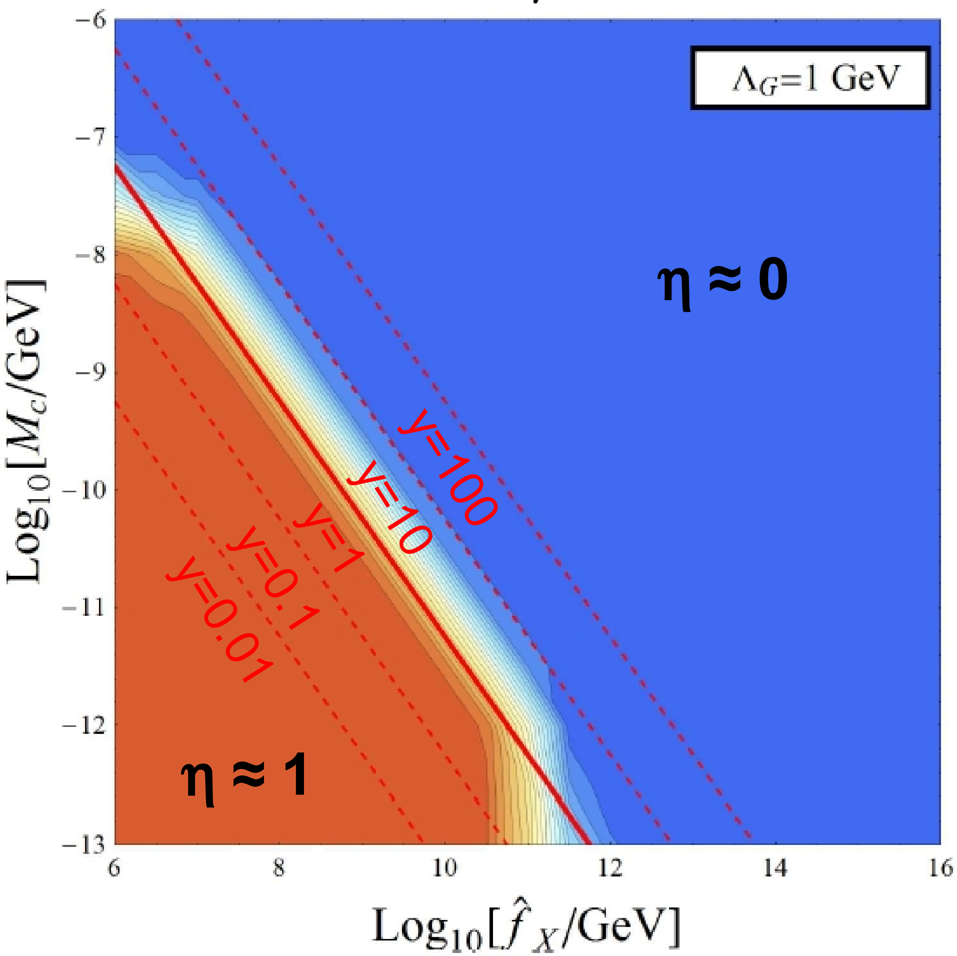
$(\hat{f}_X^2 \equiv 2\pi R f_X^3)$

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

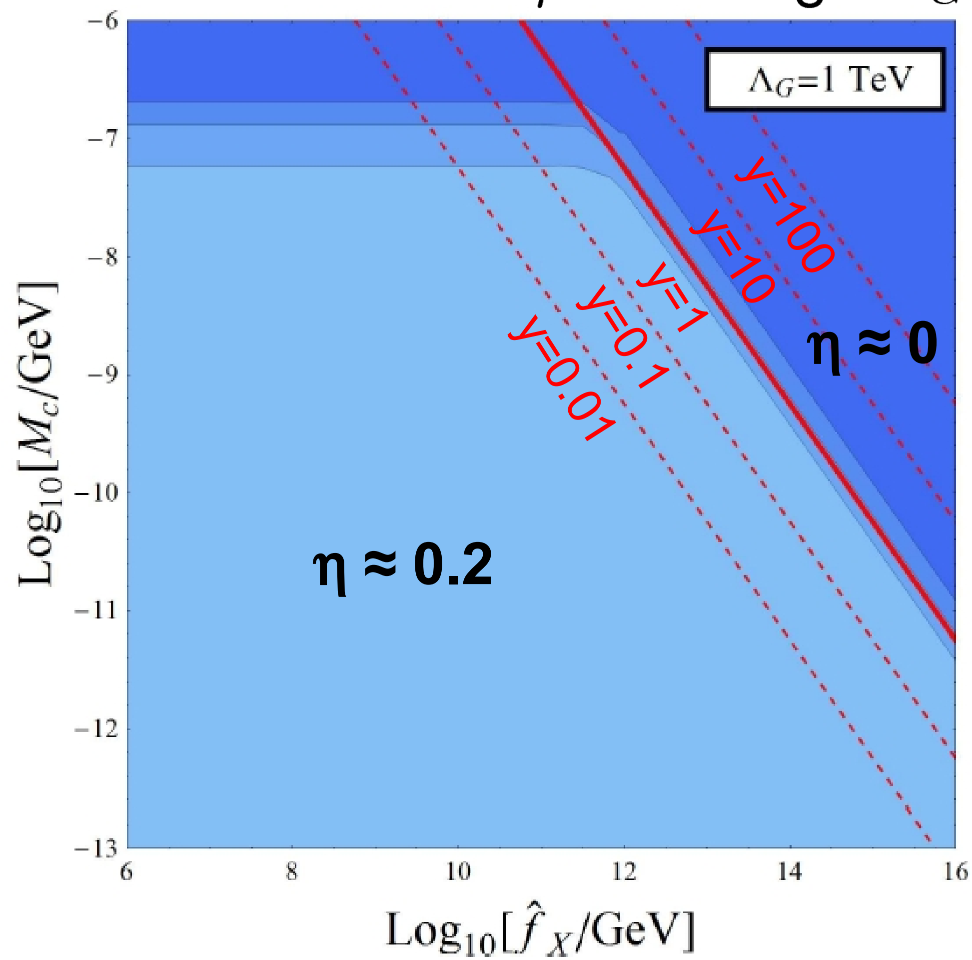
Tower Fractions

- 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 $\Omega_{\rm DM}$.

Tower fraction η with Small Λ_G



Tower fraction η with Large Λ_G



Mixing and stability:

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

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

$\mathcal{O}(1)$ 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

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

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

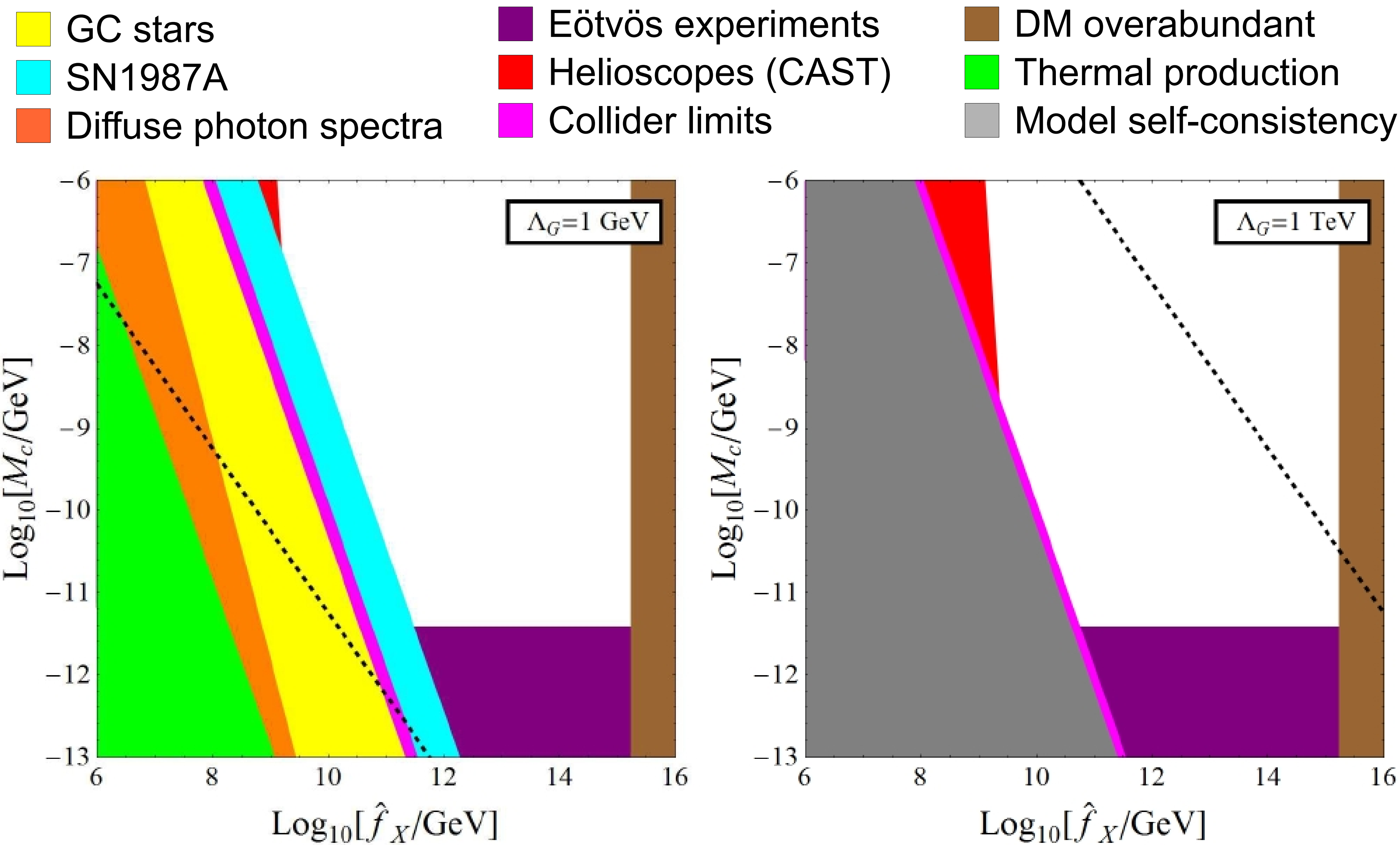
- Supernova energy-loss rates
- Stellar evolution
- Collider production ($j+E_T$, $\gamma+E_T$,...)

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

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

Constraints on Axion Models of DDM

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



Constraints on Axion Models of DDM

- 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

...and of course, there's also:

- Isocurvature perturbations
- Exotic hadron decays
- Light-shining-through-walls experiments
- Microwave-cavity detectors (ADMX)
- Light-element abundances (BBN)
- Late entropy production
- Inflation and primordial gravitational waves

Within the region of parameter space in which $\Omega_{tot} \sim \Omega_{CDM}$, these are satisfied too!

Summary

- There's no reason to assume that a single, stable particle accounts for all of the non-baryonic dark matter in our universe.

- There are simple, well-motivated BSM scenarios in which a DDM ensemble with the correct internal structure arises naturally.

- Indeed, 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:

DDM ensembles are just as viable – and just as natural and minimal – as traditional DM candidates.