Dynamical Dark Matter

A New Framework for Dark-Matter Physics

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Work done in collaboration with **Brooks Thomas**

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arXiv: 1204.4183 (also with Shufang Su)
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Dark Matter = ??

- Situated at the nexus of particle physics, astrophysics, and cosmology
- Dynamic interplay between theory and current experiments
- Of fundamental importance: literally 23% of the universe!
- Necessarily involves physics beyond the Standard Model

One of the most compelling
mysteries facing physics today!

Many theoretical proposals for physics beyond the SM give rise to suitable dark-matter candidates --- e.g.,

- LSP in supersymmetric theories
- LKP in (universal) higher-dimensional theories in which the SM propagates in the extra dimensions

In all cases, the ability of these particles to serve as dark-matter candidates rests squarely on their stability. This in turn is usually the consequence of a stabilizing symmetry --- e.g.,

- R-parity in supersymmetric theories
- "KK parity" in higher-dimensional theories

Indeed, any particle which decays too rapidly into SM states is likely to upset BBN and light-element abundances, and also leave undesirable imprints in the CMB and diffuse photon/X-ray backgrounds.

There is, of course, one important exception to this argument:

A given dark-matter candidate need not be stable if its abundance at the time of its decay is sufficiently small.

A sufficiently small abundance assures that the disruptive effects of the decay of such a particle will be minimal, and that all constraints from BBN, CMB, etc. will continue to be satisfied.

In this talk, we will consider a new framework for dark-matter physics which takes advantage of this possibility.

- *Multi-component framework*: dark matter comprises a vast ensemble of interacting fields with varying masses, mixings, and abundances.
- Rather than impose stability for each field individually (or even for the collection of fields as a whole), we ensure the phenomenological viability of this scenario by requiring that states with larger masses and SM decay widths have correspondingly smaller abundances, and vice versa.
- *In other words, stability is not an absolute requirement in such a scenario: stability is balanced against abundance!*
- As we shall see, this leads to a highly dynamical scenario in which cosmological quantities such as Ω_{CDM} experience non-trivial time-dependences beyond those associated with the expansion of the universe.

→ **"Dynamical Dark Matter" (DDM)**

Thus, in the DDM framework, the DM "candidate" is actually a ***DDM ensemble***: an ensemble of individual dark component states in which

Lifetimes (decay widths)

balanced against

Cosmological abundances

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Lifetimes (decay widths)

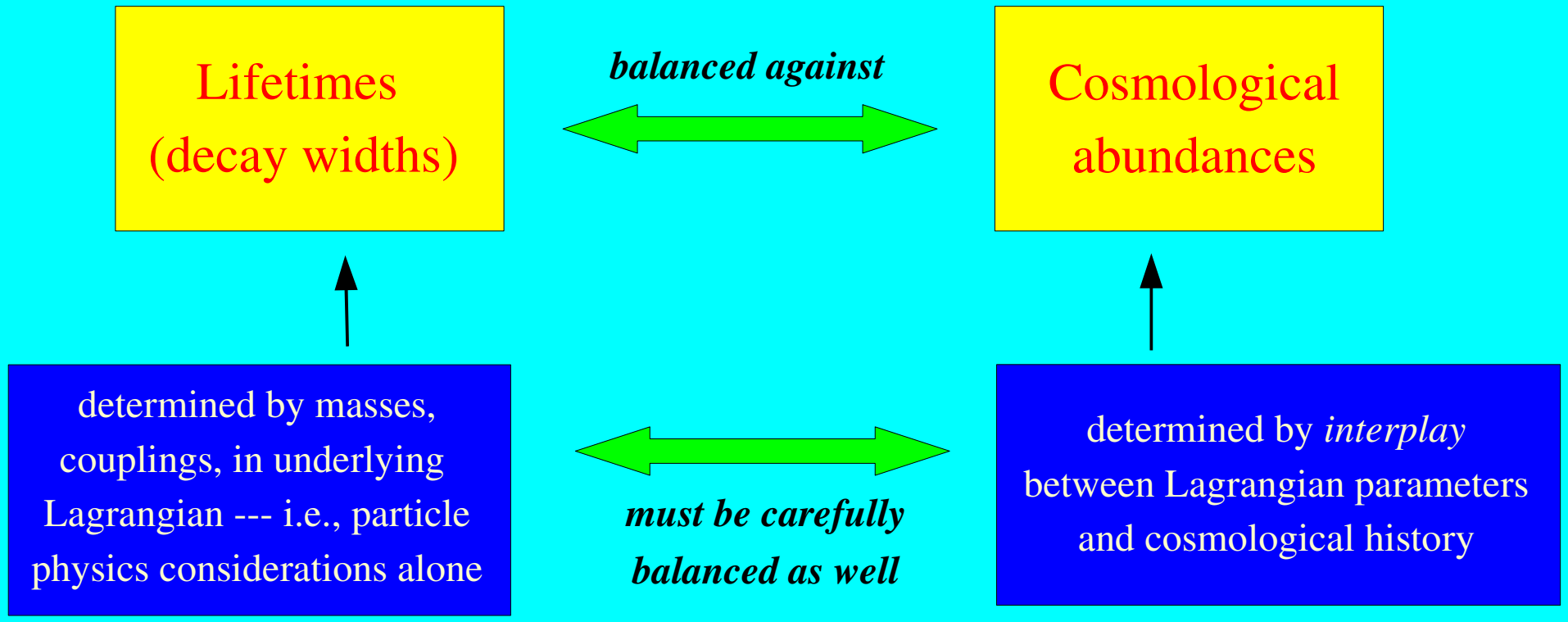
balanced against

Cosmological abundances

determined by masses, couplings, in underlying Lagrangian --- i.e., particle physics considerations alone

determined by *interplay* between Lagrangian parameters and cosmological history

Thus, in the DDM framework, the DM "candidate" is actually a ***DDM ensemble***: an ensemble of individual dark component states in which



This is the "magic" of the DDM ensemble --- the "core" which underlies the DDM framework and which collectively conspires to produce distinctive signatures (astrophysical, cosmological, and collider) that transcend those usually associated with dark matter.

Because of its non-trivial structure, the DDM ensemble --- unlike most traditional dark-matter candidates --- cannot be characterized in terms of a single mass, decay width, or set of scattering amplitudes.

➡ The DDM ensemble must therefore be characterized in terms of parameters (e.g., scaling relations or other correlations and constraints) which describe the behavior of its constituents as a whole.

As a consequence, phenomenological bounds on dark matter in the DDM framework must be phrased and analyzed in terms of a new set of variables which describe the behavior of the entire DDM ensemble as a collective entity with its own internal structures and/or symmetries.

At first glance, it might seem difficult (or at best fine-tuned) to arrange a collection of states which are not only suitable candidates for dark matter but in which the abundances and SM decay widths are precisely balanced in this manner...

However, it turns out that there is one group of states for which such a balancing act can occur naturally:

An infinite tower of Kaluza-Klein (KK) states living in the bulk of large extra spacetime dimensions!

- SM restricted to brane ⇒ all bulk states can interact with the SM only gravitationally ⇒ natural candidates for dark matter!
- From 4D perspective, this "dark matter" appears as infinite tower of KK states.
- As we shall see, a suitable balancing of abundances and lifetimes can occur --- *even if the stability of the KK tower itself is entirely unprotected*!

Thus, a KK tower is a natural example of a DDM ensemble!

Outline

- Dynamical Dark Matter: General framework
- DDM meets the incredible bulk: KK towers as DDM ensemble
- New collider/astrophysics phenomenon:
  "decoherence" --- a new way to help dark matter stay dark

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Thus far, merely a broad, theoretical overview of the general DDM framework. We will not specify any particular dark-matter fields, neither restricting ourselves to specific numbers nor subjecting ourselves to specific phenomenological bounds.

- ***A concrete example:*** An explicit model within the DDM framework, and a demonstration that this model indeed satisfies all known collider, astrophysical, and cosmological constraints.

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An "existence proof" that DDM is a viable dark-matter framework, and must be considered alongside other approaches in the overall dark-matter discussion.

- ***Experimental signatures:*** Distinguishing DDM at the LHC and at direct-detection experiments via new signatures that transcend those traditionally associated with dark matter!

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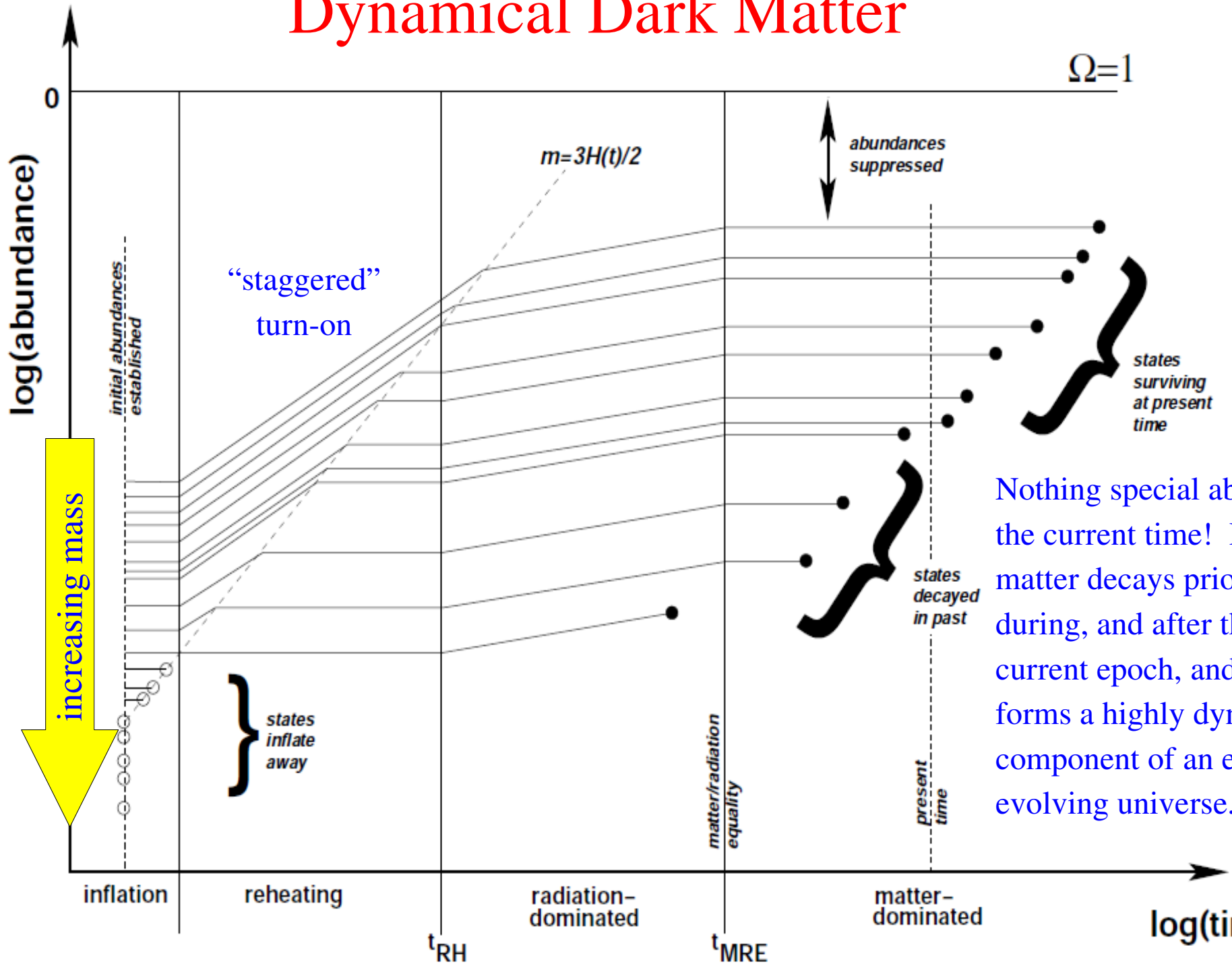
Why should dark matter consist of only one particle?
After all, the *visible* matter has much smaller abundance, yet is teeming with a diversity and complexity known as the Standard Model.

Let's suppose the dark matter of the universe consists of N states, with N>>1.

- No state individually needs to carry the full Ω_{CDM} so long as the sum of their abundances matches Ω_{CDM}.
- In particular, each state can have a very small abundance.
- If all states have the same lifetime, then they must continue to be hyperstable in order to evade problems with BBN, CMB, ...
- However, states can carry different lifetimes! As long as those with larger abundances have larger lifetimes (and vice versa), phenomenological constraints can be satisfied.

Usual dark-matter scenarios are nothing but a limiting N=1 case of this more general framework. However, taking N>>1 leaves room for our states to exhibit a whole spectrum of decay widths (lifetimes) without running afoul of phenomenological and cosmological constraints.

Dynamical Dark Matter



Nothing special about the current time! Dark matter decays prior to, during, and after the current epoch, and forms a highly dynamic component of an ever-evolving universe.

How to characterize a particular DDM configuration?

Introduce two "complementary" parameters:

- Total abundance at any moment: $\Omega_{\rm tot}(t) \equiv \sum_i \Omega_i(t)$

- *Distribution* of that total abundance: how much is $\Omega_{\rm tot}$ shared between a dominant component and all others?

  Define

$$\eta \equiv 1 - \frac{\Omega_0}{\Omega_{\rm tot}}$$

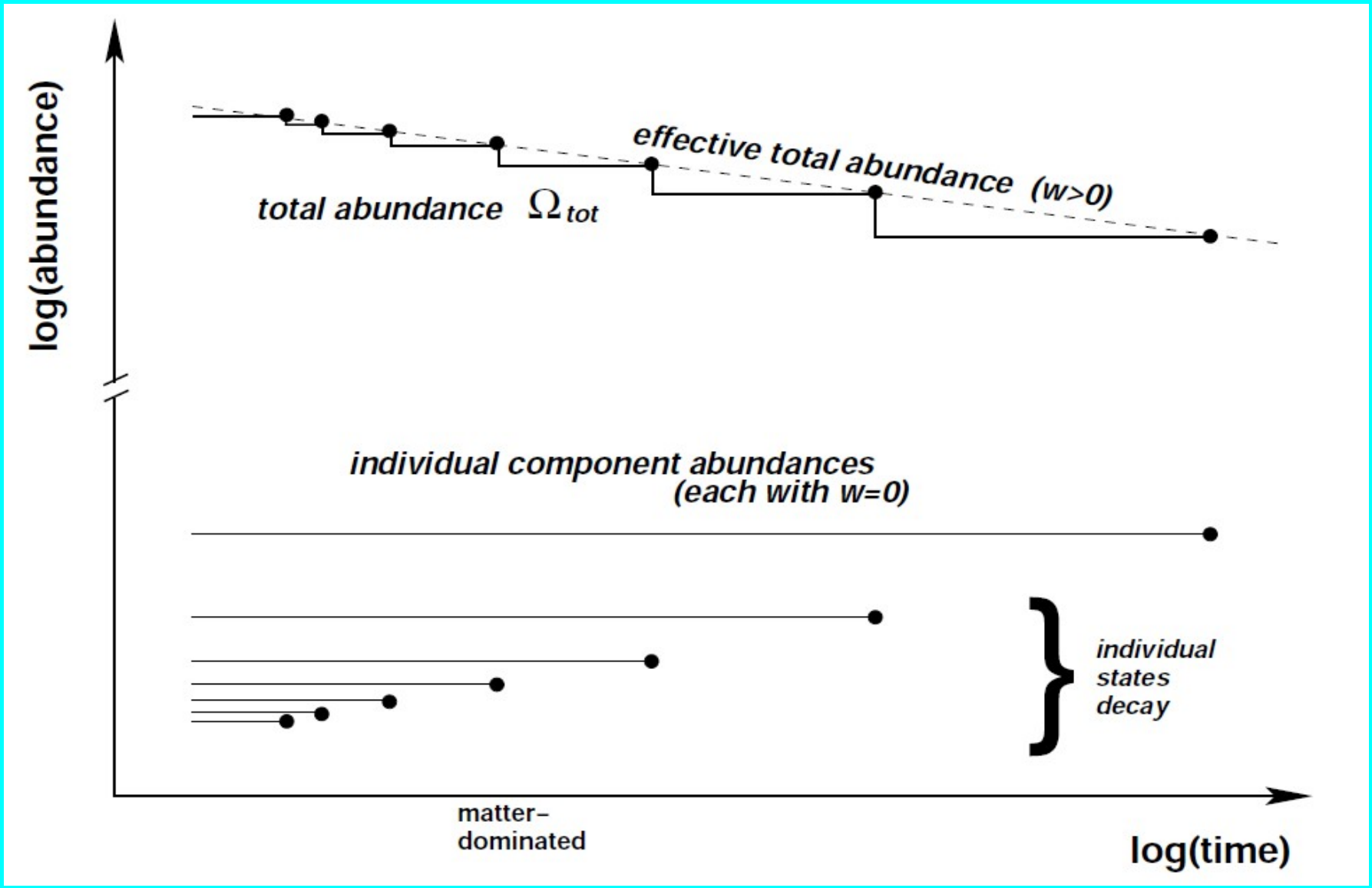
where $\Omega_0 \equiv \max_i\{\Omega_i\}$

Thus

$$0 \leq \eta \leq 1$$

- $\eta=0$ signifies one dominant component (standard picture)
- $\eta>0$ quantifies departure from standard picture

Each of these quantities will have a unique time-dependence in the DDM framework.



Sketch shown for $\alpha + \beta > -1$, with $\alpha < 0$ and $\beta > 0$

This means that the DDM ensemble as a whole has a non-zero "effective" equation-of-state parameter $w_{\rm eff}(t)$. In general, we can define...

$$
\begin{aligned}
w_{\rm eff}(t) &\equiv -\left(\frac{1}{3H}\frac{d\log\rho_{\rm tot}}{dt}+1\right) \\
&= \begin{cases} -\dfrac{1}{2}\left(\dfrac{d\log\Omega_{\rm tot}}{d\log t}\right) & \text{for RH/MD eras} \\ -\dfrac{2}{3}\left(\dfrac{d\log\Omega_{\rm tot}}{d\log t}\right)+\dfrac{1}{3} & \text{for RD era} \quad . \end{cases}
\end{aligned}
$$

Let us also parametrize the spectrum of DDM ensemble components in terms of their ***scaling behavior as function of decay width*** ---

$$\Omega(\Gamma) \sim A\Gamma^{\alpha} \qquad \eta_{\Gamma}(\Gamma) \sim B\Gamma^{\beta}$$

$$\alpha < 0$$

density of states *per unit* Γ

We then find the results

- **For** $x \equiv \alpha + \beta \neq -1$ **:**

$$w_{\rm eff}(t) = \frac{(1+x)w_*}{2w_* + (1+x-2w_*)(t/t_{\rm now})^{1+x}}$$

where

$$w_* \equiv w_{\rm eff}(t_{\rm now}) = \frac{AB}{2\Omega_{\rm CDM} t_{\rm now}^{1+x}}$$

- **For** $x = -1$ **:**

$$w_{\rm eff}(t) = \frac{w_*}{1 - 2w_* \log(t/t_{\rm now})}$$

where

$$w_* \equiv w_{\rm eff}(t_{\rm now}) = \frac{AB}{2\Omega_{\rm CDM}}$$

These are "effective" equations of state for the entire DDM ensemble!

If the DDM model in question is to be in rough agreement with cosmological observations, we expect that w_* today should be fairly small (since traditional dark "matter" has $w = 0$).

We also expect that the function $w_{\rm eff}(t)$ should not have experienced strong variations within the recent past.

Given the previous functional forms for $w_{\rm eff}(t)$, this implies that the situations which are likely to be phenomenologically preferred are those with

$$x \equiv \alpha + \beta \lesssim -1$$

However, depending on the detailed properties of the particular DDM scenario under study, values of x slightly above -1 may also be acceptable.

Thus far, we have only presented a general framework. In particular, we have not yet demonstrated that such "DDM ensembles" of dark-matter states can be easily assembled in which the individual component abundances are balanced against lifetimes in a well-motivated way.

However, it turns out that an infinite tower of KK states propagating in the bulk of large extra dimensions has exactly the desired properties!

As we shall see, this feature ultimately emerges as the consequence of the non-trivial interplay between physics in the bulk and physics on the brane.

To see this, let us consider a very simple "bare-bones" setup:

Universe has a single, flat extra dimension of length R, one bulk field Φ, and SM lives on a brane located at y=0...

SM fields

$$S = \int d^4x dy \, [\mathcal{L}_{\rm bulk}(\Phi) + \delta(y)\mathcal{L}_{\rm brane}(\psi_i, \Phi)]$$

where

$$\mathcal{L}_{\rm bulk} = \frac{1}{2}\partial_M \Phi^* \partial^M \Phi - \frac{1}{2}M^2|\Phi|^2$$

$$\mathcal{L}_{\rm int} \supset -\frac{1}{2}m^2|\Phi|^2$$

M = bulk mass
m = brane mass

All by itself, this simple setup naturally leads to a DDM ensemble with phenomenologically attractive properties!

For example,

Let us define

$$\phi' \equiv \Phi(y)\big|_{y=0} = \sum_{k=0}^{\infty} r_k \phi_k$$

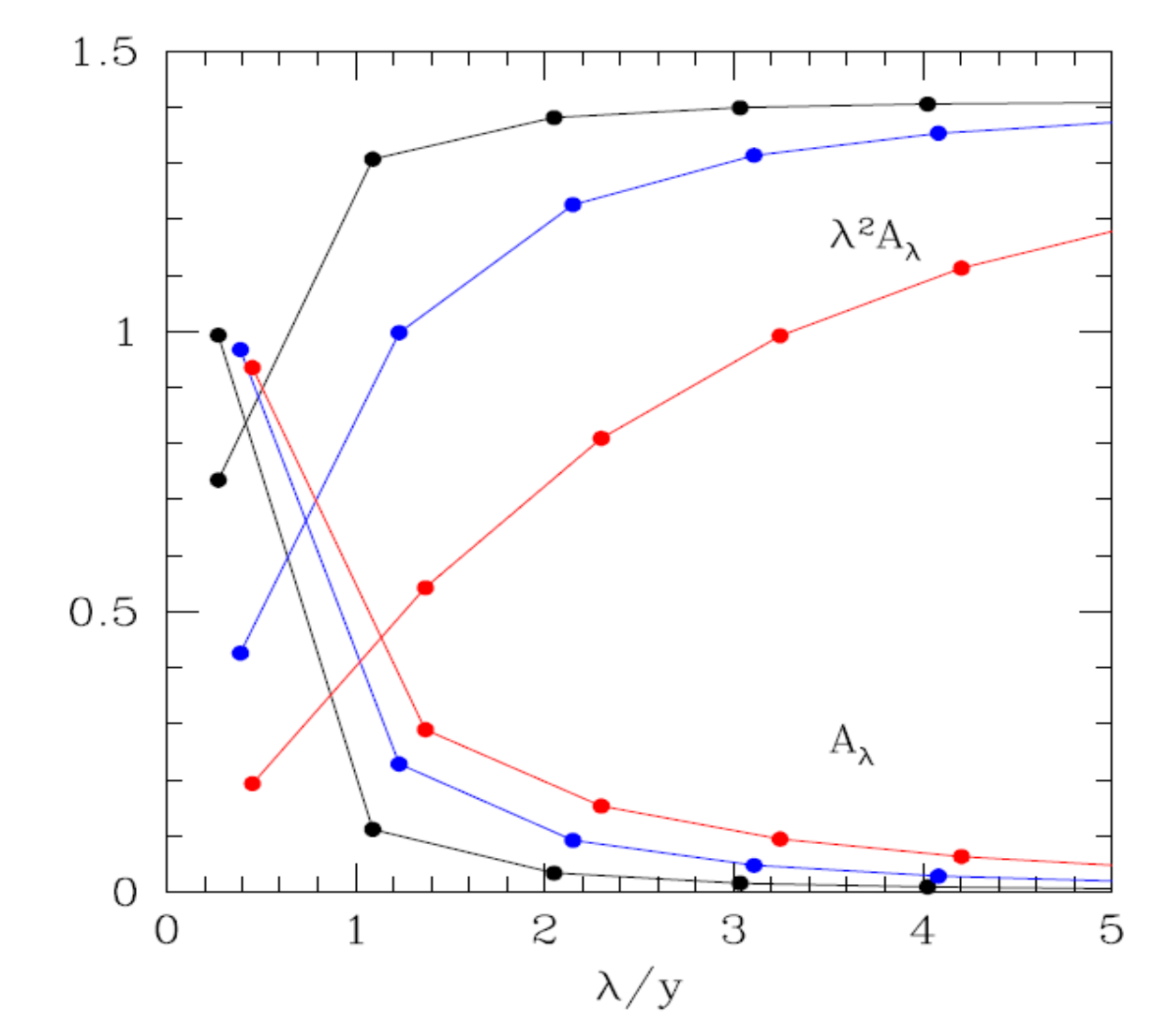
projection of bulk field onto SM brane

Then

$$\langle \phi_\lambda | \phi' \rangle = A_\lambda \sum_{k=0}^{\infty} \frac{r_k^2 \tilde{\lambda}^2}{\tilde{\lambda}^2 - k^2 y^2}$$

$$= \frac{\pi \tilde{\lambda}^2}{y} \cot\left(\frac{\pi \tilde{\lambda}}{y}\right) A_\lambda = \tilde{\lambda}^2 A_\lambda$$

governs couplings between the KK modes and the SM brane



Non-trivial interplay between brane and bulk physics induces a natural suppression of the couplings between the SM and the lightest, most-dangerous KK modes!

Can also look at cosmological abundances and decay widths of different KK modes.

Assuming a misalignment-production mechanism and lowest-order dimension-five couplings to the SM, we find the following *product relations* across our KK towers:

$$\begin{aligned} \text{instantaneous}: &\quad \Omega_\lambda \Gamma_\lambda^{2/3} \sim \text{constant} \\ \text{staggered (RD era)}: &\quad \Omega_\lambda \Gamma_\lambda^{7/6} \sim \text{constant} \\ \text{staggered (reheating/MD era)}: &\quad \Omega_\lambda \Gamma_\lambda^{4/3} \sim \text{constant} \end{aligned}$$

Decay widths are always balanced against abundances, as promised! This is a universal feature for such KK towers.

Indeed, for a generic KK tower,

we find the following values of $x = \alpha + \beta$:

	large $\tilde{\lambda}$	small $\tilde{\lambda}$
instantaneous	$-4/3$	$-4/5$
staggered (RD era)	$-11/6$	$-11/10$
staggered (RH/MD eras)	-2	$-6/5$

TABLE I: Values of the equation-of-state parameter $x \equiv \alpha+\beta$ for different portions of a general KK tower with different "turn-on" phenomenologies. We observe that KK towers naturally give rise to values $x \lesssim -1$, which is precisely the range favored phenomenologically.

... precisely in the phenomenologically preferred range!!

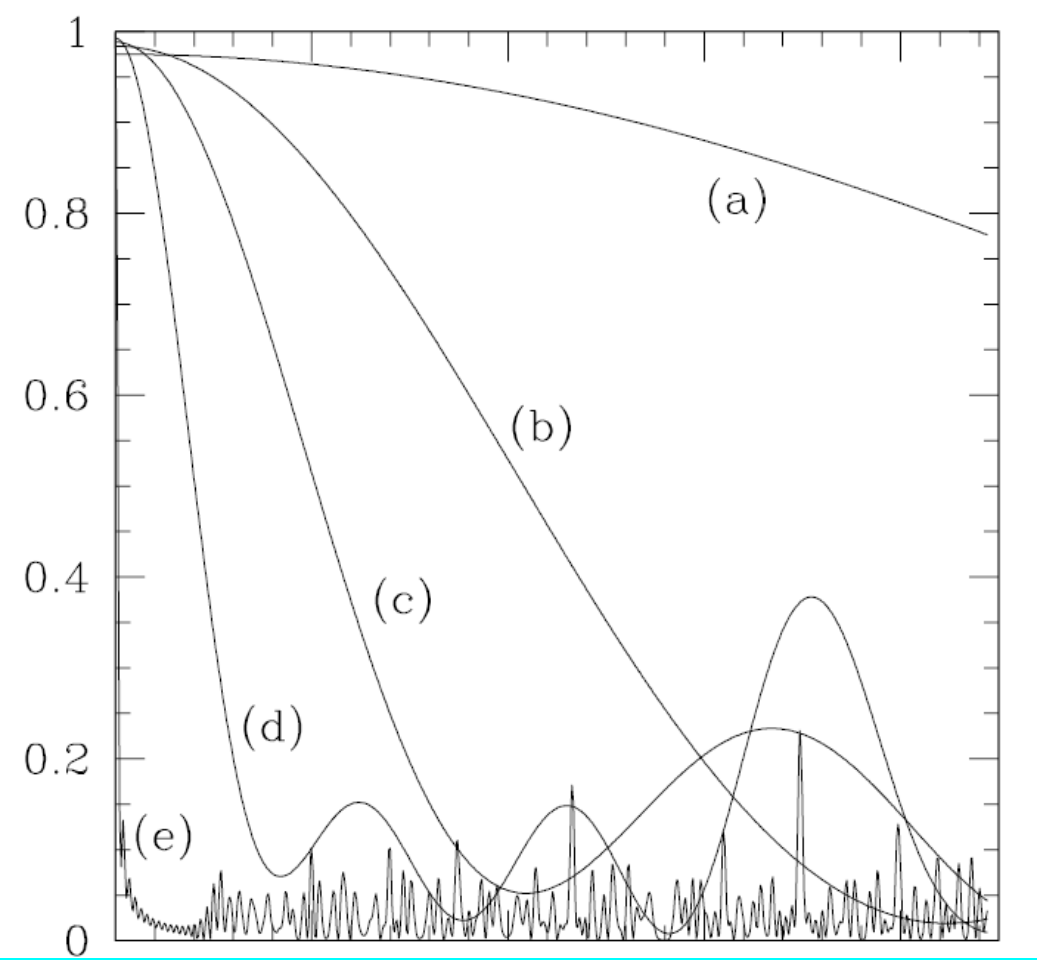
Finally, another feature which helps the dark matter stay dark!

Recall that the bulk field only couples to brane through its brane projection:

$$\phi' \equiv \Phi(y)\big|_{y=0} = \sum_{k=0}^{\infty} r_k \phi_k$$

However, once ϕ' is produced (in laboratory, in distant astrophysical sources, etc.), it rapidly ***decoheres*** and does not reconstitute in finite time...

This novel effect provides yet another mechanism which may help dark matter stay dark, and leads to different signature patterns from those which characterize purely 4D scalars and traditional single-component dark-matter candidates.



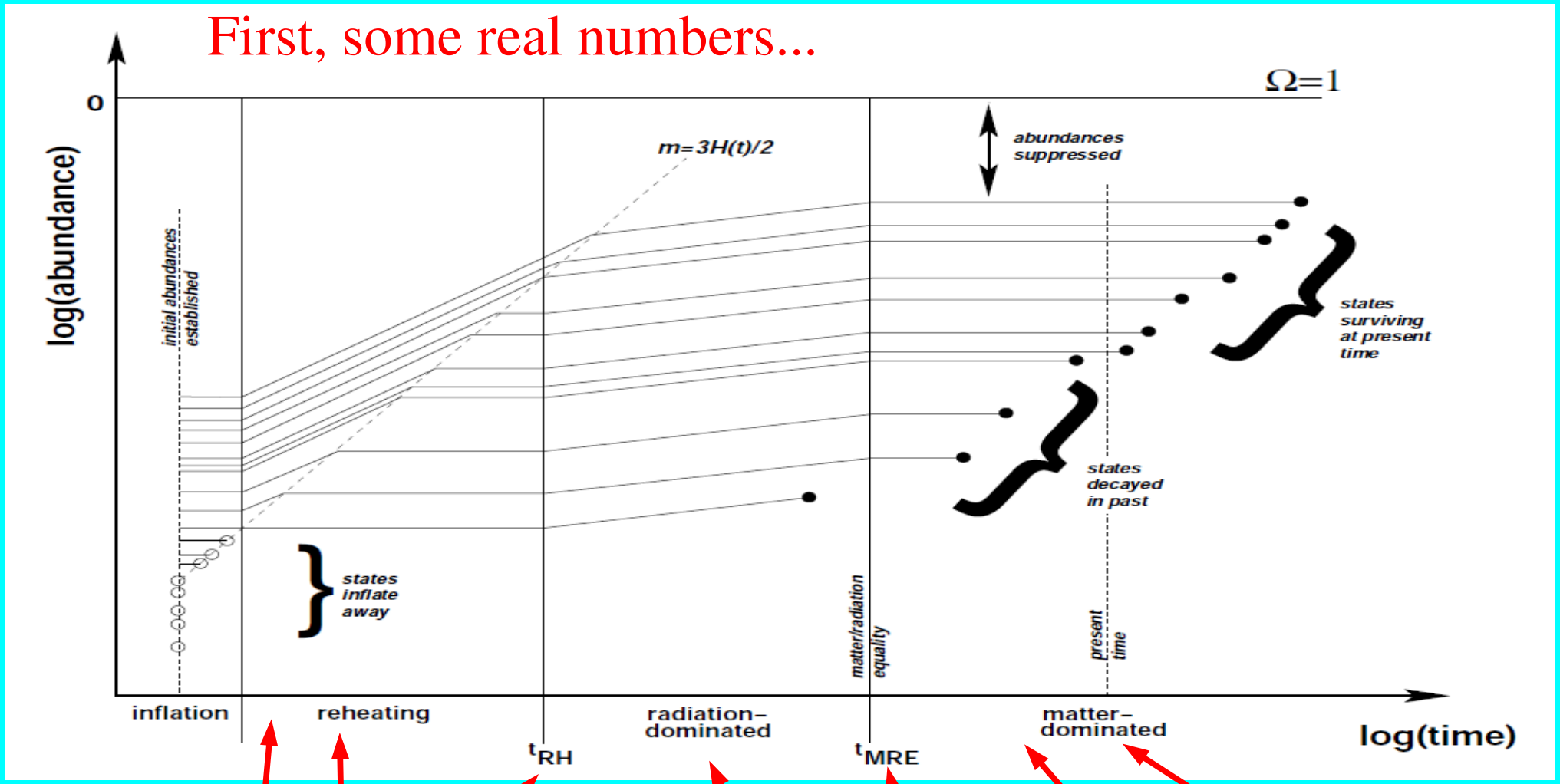
KRD, E. Dudas, T. Gherghetta (1999)

OK, enough general formalism!

Let's now present a concrete example of this entire framework, along with real numbers and experimental bounds and constraints!

This will therefore serve as a “proof of concept” for the entire DDM framework.

First, some real numbers...



choose...

T_{max}~150 GeV
(H_{inf} ~1 MeV)

T_{QCD}~250 MeV

t_{RH}~10^{-1} sec
T_{RH}~5 MeV
(LTR cosmology!)

t_{BBN}~1 sec
T_{BBN}~MeV

t_{MRE}~10^{11} sec
T_{MRE}~keV

$t_{last\ scatt}$ ~10^{13} sec
$T_{last\ scatt}$ ~eV

t_{now}~10^{17} sec
T_{now}~3 K

arXiv: 1107.0721
arXiv: 1203.1923

Furthermore, let us consider the case where Φ = ***axion*** with decay constant f_X, corresponding to a general gauge group G with confinement scale Λ_G and coupling g_G

Such a choice is indeed gauge-neutral and well-motivated theoretically, both in field theory and in string theory.

Our analysis then follows exactly as before, with the specific values

$$\begin{cases} M & \rightarrow & 0 \\ m & \rightarrow & \dfrac{g_G \xi \Lambda_G^2}{4\sqrt{2}\pi \hat{f}_X} \end{cases}$$

brane mass comes from axion potential induced by instanton dynamics associated with group G at scale Λ_G

Likewise, couplings to brane fields take the form...

with $\mathcal{L}_{\rm int}$ given by...

Interactions with G gauge fields

$$\mathcal{L}_{\rm int} = \frac{g_G^2 \xi}{32\pi^2 f_X^{3/2}} a \mathcal{G}^a_{\mu\nu} \tilde{\mathcal{G}}^{a\mu\nu} + \frac{g_s^2 c_g^2}{32\pi^2 f_X^{3/2}} a G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

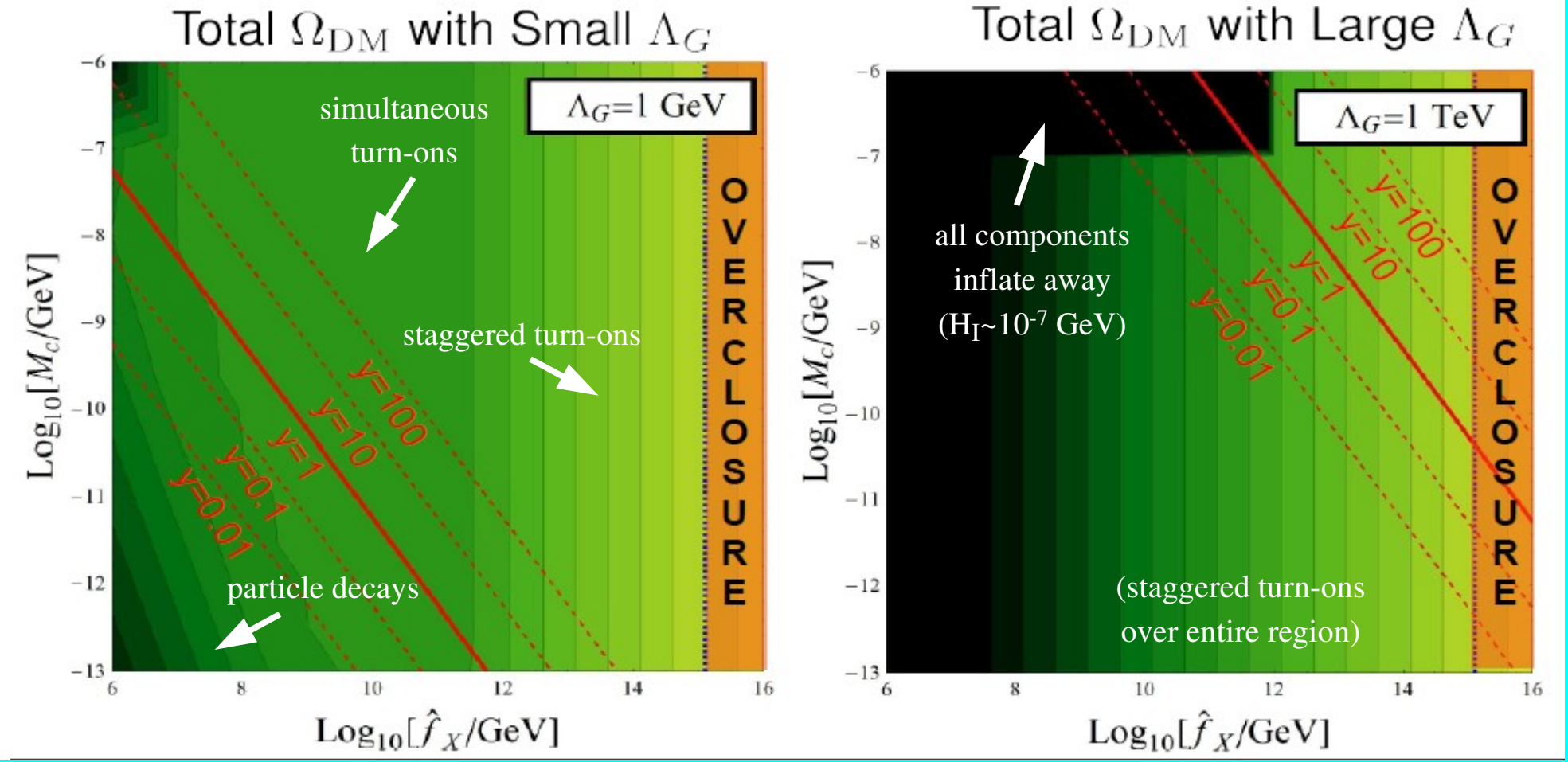
$$+ \sum_i \frac{c_i}{f_X^{3/2}} (\partial_\mu a) \overline{\psi}_i \gamma^\mu \gamma^5 \psi_i + \frac{e^2 c_\gamma}{32\pi^2 f_X^{3/2}} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Possible couplings to SM gauge and matter fields

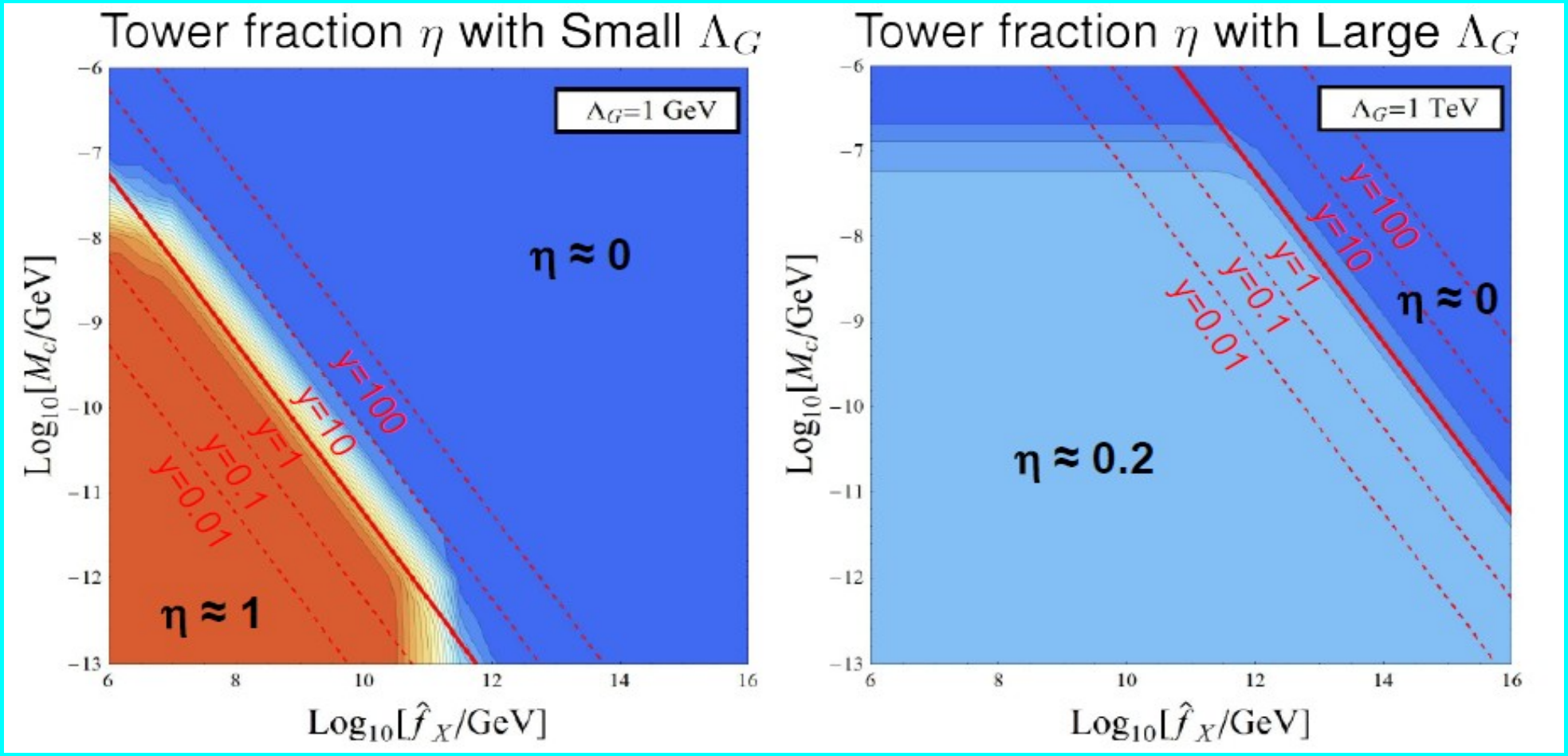
We can then vary the free parameters (R, f_X, Λ_G) ***to survey different outcomes...***

(Indeed, only three parameters govern the entire KK tower!)

How does Ω_{tot} depend on f_X and $M_c = 1/R$?



How does η depend on f_X and $M_c = 1/R$?



arXiv: 1203.1923

What are the phenomenological constraints that govern such scenarios?

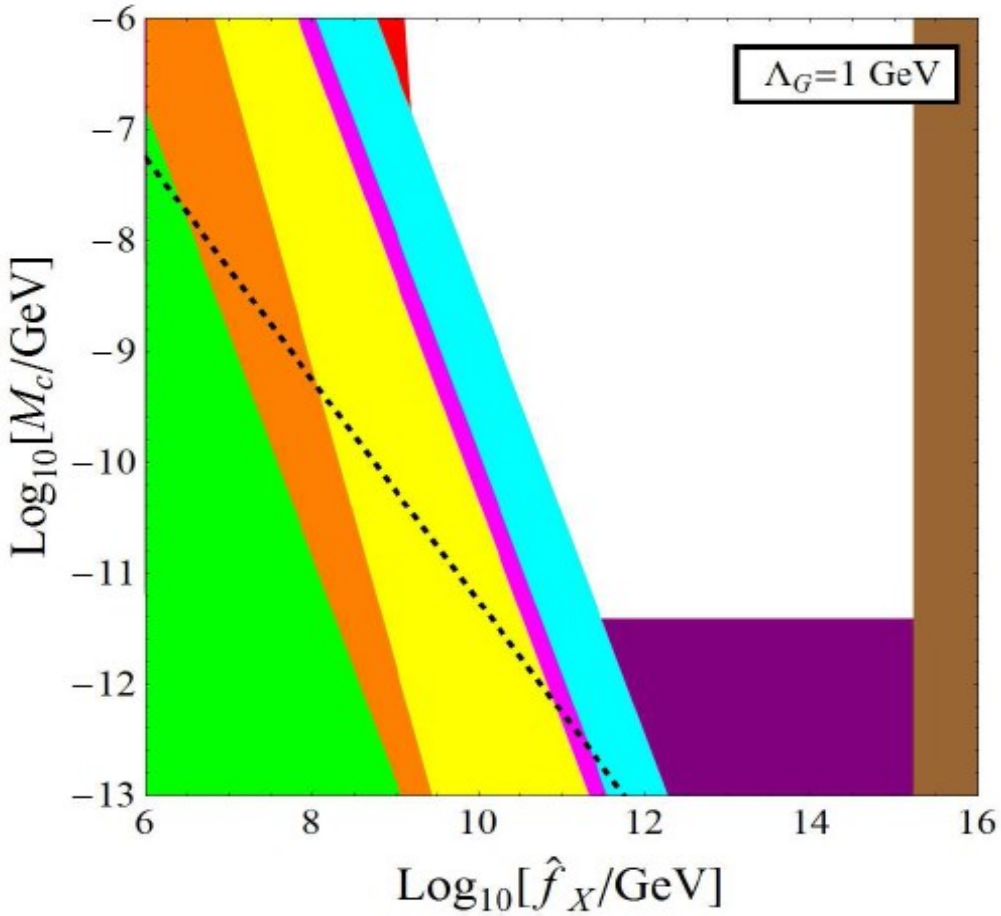
- GC (globular cluster) stars. Axions might carry away energy too efficiently, altering stellar lifetimes. GC stars give most stringent bound.
- SN1987a. Same --- axions would effect energy loss rate.
- Diffuse photon/X-ray backgrounds. Axion decays to photons would leave unobserved imprints.
- Eotvos. Cavenish-type "fifth force" experiments place bounds on sizes of extra spacetime dimensions.
- Helioscopes. Detectors on earth measure axion fluxes from sun.
- Collider limits. Constraints on missing energies, etc.
- Overclosure. Too great a DDM abundance can overclose universe.
- Thermal / cosmic-string production. Need to ensure that other production mechanisms not contribute significantly to relic abundances (so that misalignment production dominates).
- CMB and BBN constraints must be satisfied. No significant distortions.
- Isocurvature fluctuations must be suppressed. Critical issue for DDM *ensembles*.
- Quantum fluctuations during inflation must not wash out DDM scaling structure.
- Late entropy production. Must not exceed bounds.

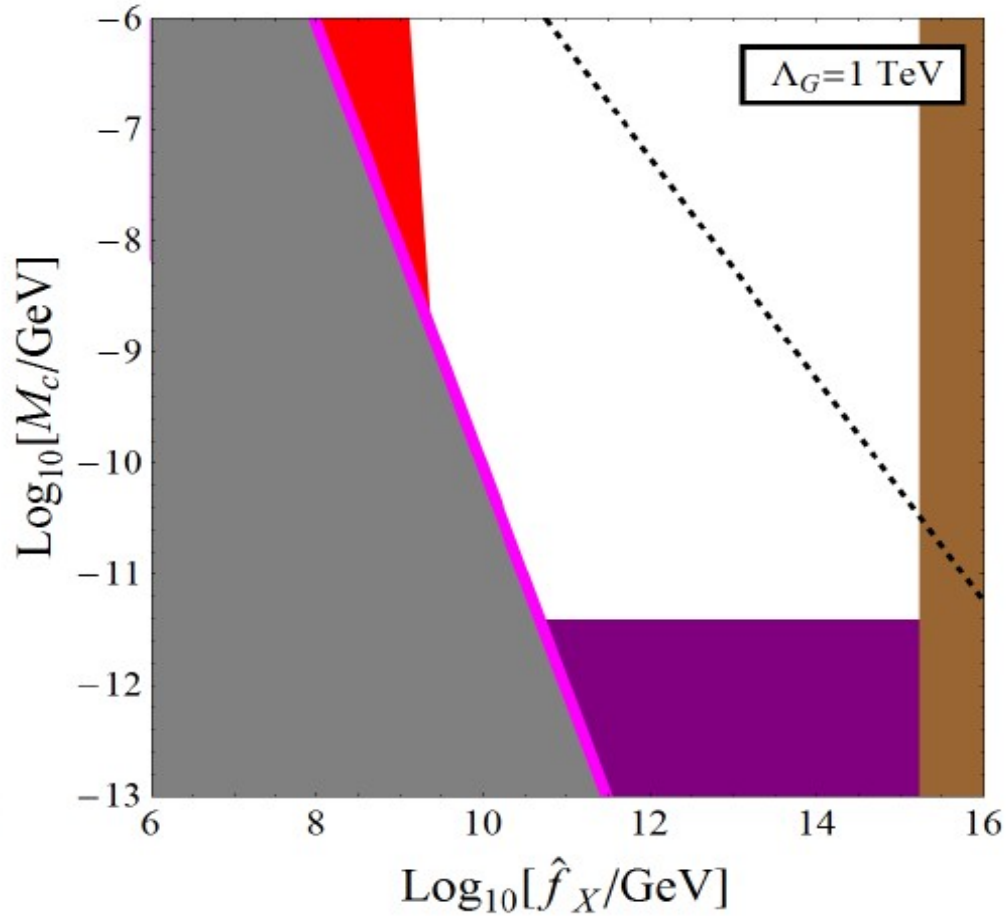
Combined Limits on Dark Towers

Case I: "Photonic" Axion (couples only to photon field)

$(g_\gamma = 1, \xi = \theta = 1)$

- GC stars
- SN1987A
- Diffuse photon spectra
- Eötvös experiments
- Helioscopes (CAST)
- Collider limits
- DM overabundant
- Thermal production



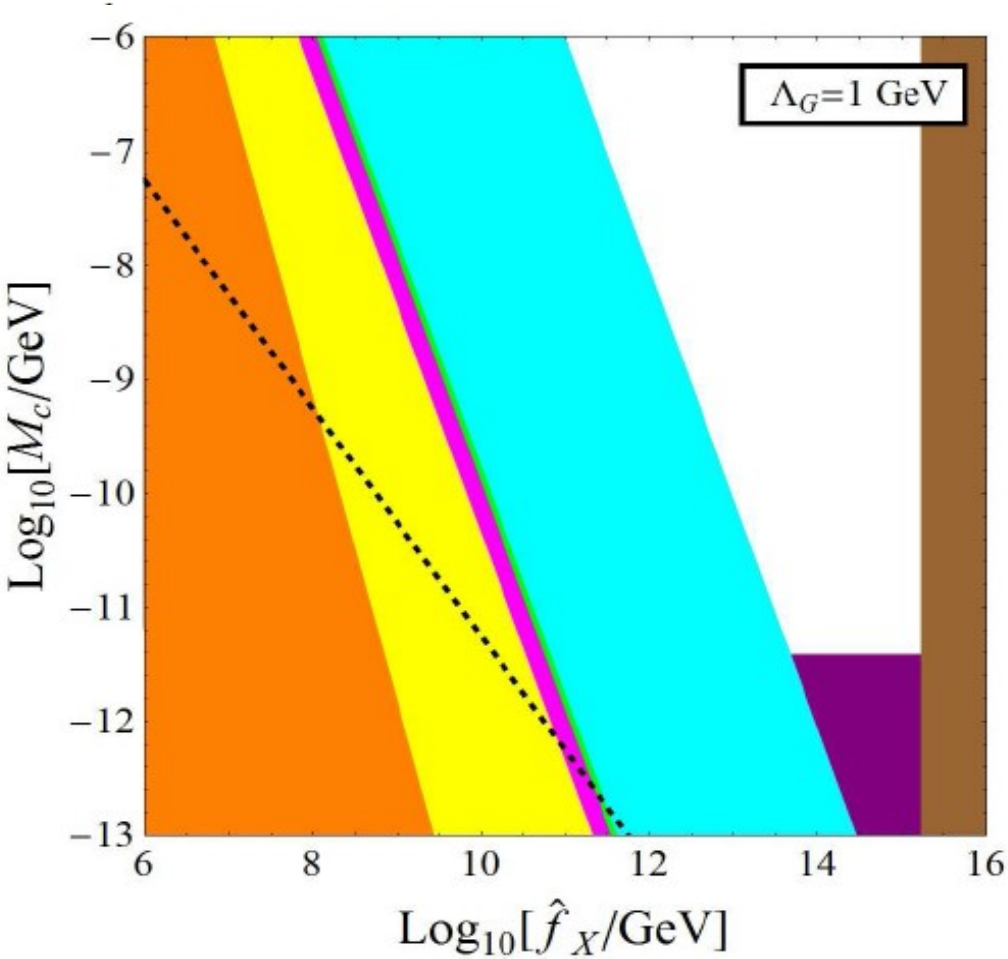


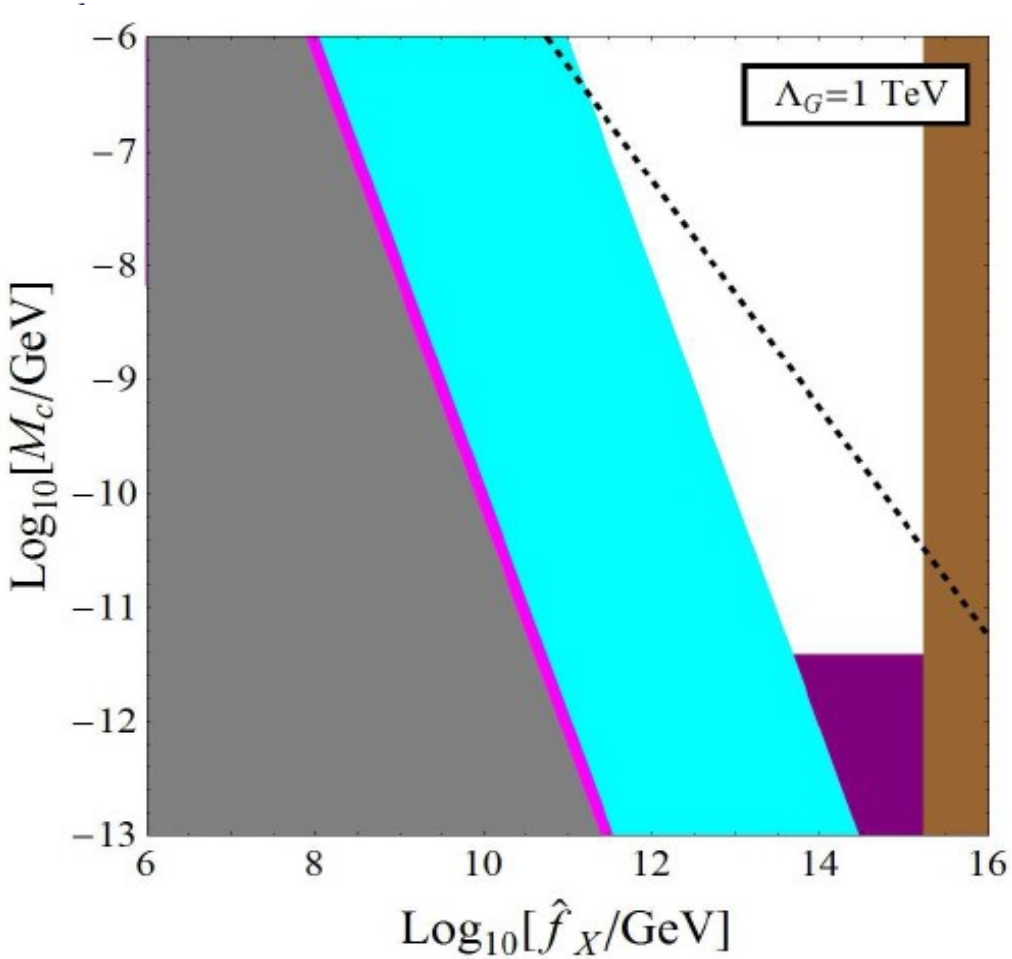
Combined Limits on Dark Towers

Case II: "Hadronic" Axion (couples to photon, gluon fields)

$(g_\gamma = g_g = 1, \xi = \theta = 1)$

- GC stars
- SN1987A
- Diffuse photon spectra
- Eötvös experiments
- Helioscopes (CAST)
- Collider limits
- DM overabundant
- Thermal production





Morever, as we have seen, these allowed regions of parameter space include precisely the regions where...

- The tower fraction η is significantly different from zero.
- The KK tower "mixing" is nearly maximal (i.e., y very close to zero)! Almost all KK states are participating in the physics!

These are precisely the conditions which uniquely characterize the DDM framework.

Thus, within these regions of parameter space, this DDM model satisfies all known phenomenological constraints. This is therefore an "existence proof" for the phenomenological viability of the overall DDM framework.

Experimental signatures of DDM

How can we distinguish DDM...

- at colliders (LHC)
- at the next generation of direct-detection experiments
  (e.g., XENON 100/1T, SuperCMS, LUX, PANDA-X)

... relative to more traditional dark-matter candidates?

KRD, S. Su, and B. Thomas, arXiv: 1204.4183
KRD, J. Kumar, and B. Thomas, arXiv: 1207.nnnn

Experimental signatures of DDM

Talk from Brooks Thomas (next!)

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Conclusions

"Dynamical dark matter": a new framework for dark-matter physics

- Stability is replaced by a delicate balancing between abundances and lifetimes across a vast collection of dark-matter components which collectively produce a time-varying Ω_{CDM}. Dark-matter decays occur throughout current epoch!
- This scenario is well-motivated in field theory and string theory, and can even be used to constrain the phenomenological and cosmological viability of certain limits of string theory.
- Specific examples of "dynamical dark matter" satisfy all known collider, astrophysical, and cosmological constraints, and potentially yield new signatures and features (e.g., decoherence) that transcend those usually associated with dark matter. Many extensions/generalizations are possible!

Dynamical dark matter is therefore a viable alternative to the standard paradigm of a single, stable, dark-matter particle, and must be considered alongside other approaches in future discussions of the dark-matter problem.

Generalizations and Extensions

For the general scenario (not specifically involving extra dimensions), many generalizations and extensions are possible.

- Not all components need to be scalars. Higher-spin fields may also be OK.
- Need not always have simple dimension-five couplings to SM. More complicated coupling structures can also be considered.
- Indeed, the DDM ensemble need not be SM-neutral. Can carry weak charge.
- The components of the DDM ensemble may experience *intra-ensemble* decays in addition to SM decays. Decay patterns can be highly complex!
- While misalignment production leads to desired inverse balancing relations between lifetimes and abundances, other production mechanisms (thermal, topological, etc.) can also be investigated.
- Effects of non-zero cosmological constant today? FRW $\longrightarrow$ ΛCDM ! Effects?

Likewise, for the specific DDM realization involving extra dimensions, many generalizations and extensions are also possible.

- Extra dimensions need not be flat. Warped extra dimensions will give rise to a completely different KK spectroscopy.
- There can be multiple extra spacetime dimensions.
- There can be multiple species of bulk fields: gravitons, gravitini, axions, other axion-like particles, string-theory moduli, right-handed neutrinos, etc. All of these fields are singlets with respect to SM symmetries and thus in principle are "dark"! What are the effects of having multiple species of KK towers in the bulk?

Finally, the DDM approach itself can potentially be generalized to address numerous broader issues.

- Since DDM leads to a time-varying Ω_{CDM}, this approach might serve as a useful starting point towards addressing the cosmic coincidence problem.
- Indeed, even the cosmological constant might be addressed in a dynamical fashion --- after all, recall that the energy stored in our scalar components *prior* to turn-on acts as vacuum energy.
- The DDM framework might provide a new means of placing phenomenological bounds on candidate string models --- after all, string theory in general is rife with bulk fields whose contributions to cosmological dark-matter and dark-energy abundances need to be taken into account.
- General phenomenon of decoherence --- applications in other contexts?
- A central cornerstone of the overall DDM framework is the phenomenon whereby decaying "stuff" with one equation of state collectively simulates "stuff" with a *different* equation of state!
    - Generalize our scenario to simulate dark "matter" with non-matter components?
    - Might dark energy and dark matter actually be composed of the same thing??

Clearly, much remains to be explored!