Dynamical Dark Matter

A New Framework for Dark-Matter Physics

Keith R. Dienes

National Science Foundation
University of Maryland
University of Arizona

Tucson, Arizona

Work done in collaboration with **Brooks Thomas**

- arXiv: 1106.4546
- arXiv: 1107.0721
- arXiv: 1203.1923
- arXiv: 1204.4183 (also with Shufang Su)
- arXiv: 1208.0336 (also with Jason Kumar)
- arXiv: 1305.nnnn (also with Jason Kumar)

Snowmass on the Pacific
KITP, UCSB, 5/31/2013

This work was supported in part by the National Science Foundation through its employee IR/D program. The opinions and conclusions expressed herein are those of the speaker, and do not necessarily represent the National Science Foundation.

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!

For such an important question, it is important that we not slip into simplistic thinking!

What do we ***really*** know about the dark sector?

Let's reconsider the dark-matter problem from the beginning, without any theoretical prejudices!

Overall issue faced when proposing a dark-matter candidate: must constrain its abundance, its lifetime, or the relation between the two.

Suppose only a single dark-matter particle χ .

- Must carry entire DM abundance: $\Omega_\chi = \Omega_{CDM} = 0.23$ (WMAP).
- Given this large abundance, consistency with BBN, CMB, etc. requires that χ have a lifetime which meets or exceeds the current age of the universe ("minimally stable") ~ 10^{17} s.
- Actually, because of the quantum-mechanical nature of the decay process (not all DM decays at once), the lifetime of χ must *exceed the age of universe* by many orders of magnitude ("hyperstable") ~ 10^{26} s.
- Most DM scenarios take this form.

Hyperstability is the only way in which a single DM candidate can satisfy the competing constraints on abundance and lifetime. Resulting theory is essentially "frozen in time": Ω_{CDM} is constant, etc.

This is the standard paradigm which has dominated our thinking about the entire dark-matter question for many years.

There is nothing wrong with this paradigm, and indeed it dovetails nicely with many of our preconceived notions about physics beyond the Standard Model...

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.

But 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 ... an entire *ensemble* of states!

- 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 share a common lifetime*,** then they must continue to be hyperstable in order to evade problems with BBN, CMB, ...
- We are back to the usual scenario.

However, must these states really have the same lifetimes? (After all, none of them is individually carrying the full dark-matter abundance any longer!)

A fundamental observation:

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

A sufficiently small abundance ensures 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.

Thus we are naturally led to

***a balancing of decay widths against abundances*:**

States with larger abundances must have smaller decay widths,
but states with smaller abundances can have larger decay widths.
As long as decay widths are balanced against abundances across our entire dark-sector ensemble, all phenomenological constraints can be satisfied!

Thus, dark-matter stability is no longer required!

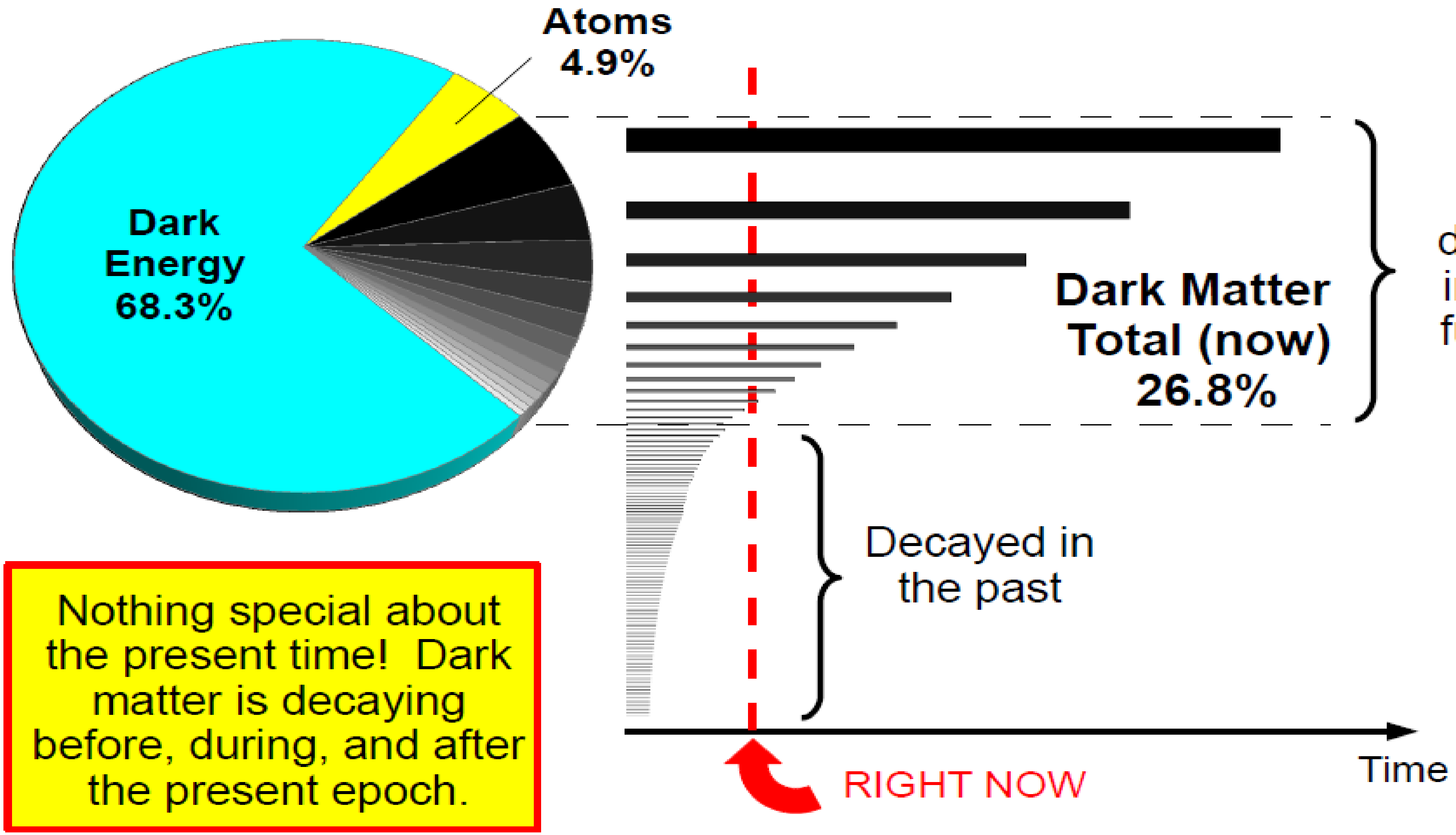
This is **Dynamical Dark Matter (DDM)**: a new framework for dark-matter physics in which the notion of dark-matter stability is replaced by a balancing of lifetimes against cosmological abundances across an ensemble of individual dark-matter components with different masses, lifetimes, and abundances.

This is the most general dark sector that can be contemplated, and reduces to the standard picture of a single stable particle as the number of states in the ensemble is taken to one.

Otherwise, if the number of states is enlarged, ***the notion of dark-matter stability generalizes into something far richer: a balancing of lifetimes against abundances. The dark sector becomes truly dynamical!***

“Dynamical Dark Matter”: The Basic Picture:

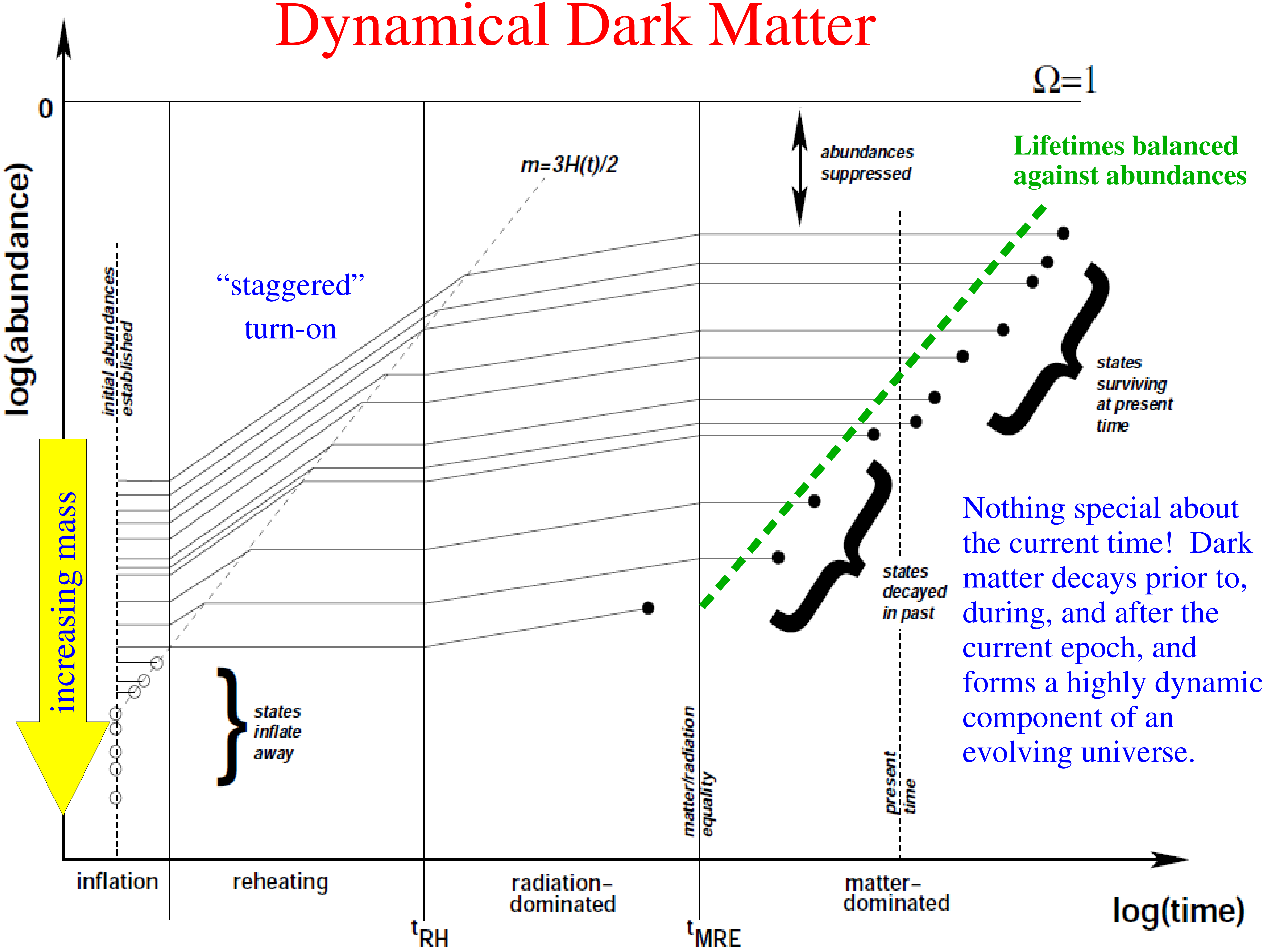
A Snapshot of the Cosmic Pie: Past, Present, and Future



Nothing special about the present time! Dark matter is decaying before, during, and after the present epoch.

Moreover, each of these abundances will generally have its own time-dependence through the evolution of the universe.... e.g.,

Dynamical Dark Matter



“staggered” turn-on

Lifetimes balanced against abundances

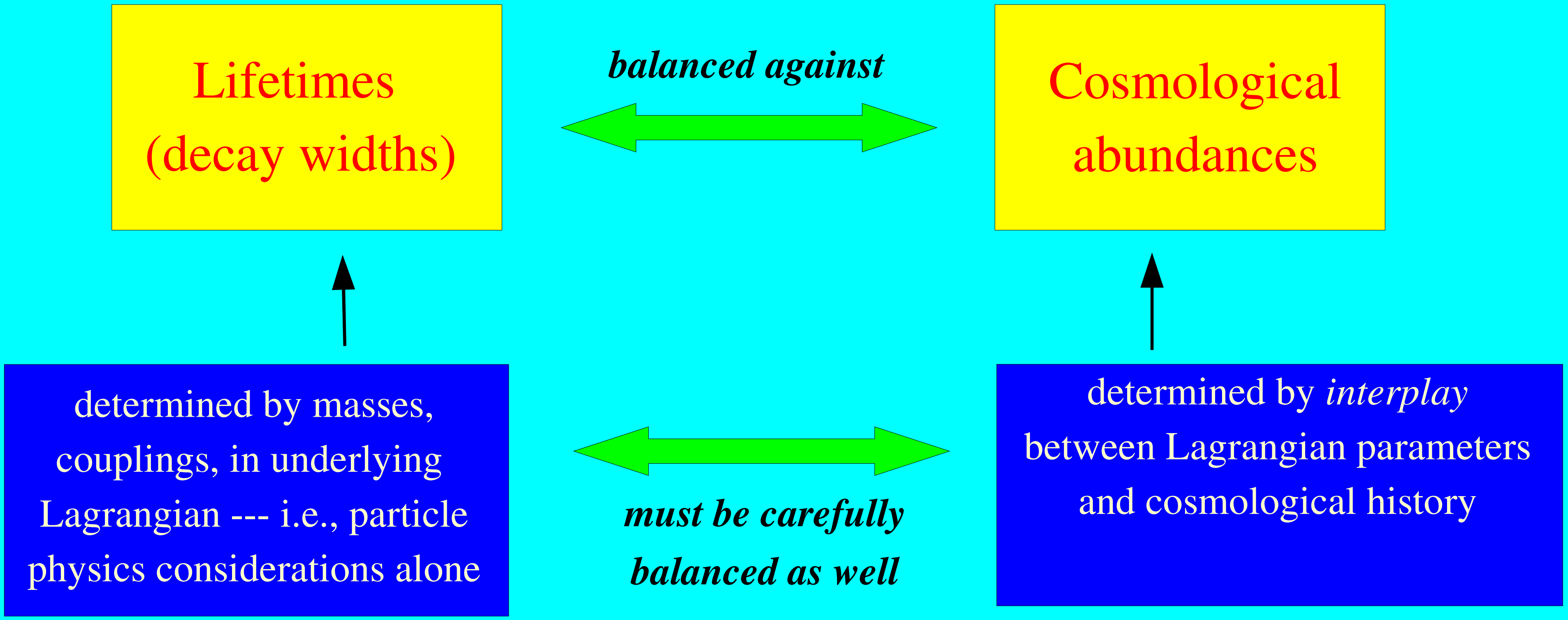
Nothing special about the current time! Dark matter decays prior to, during, and after the current epoch, and forms a highly dynamic component of an evolving universe.

This is clearly a major re-envisioning of the dark sector, and calls for re-thinking and re-evaluating much of what we currently expect of dark matter.

- KRD & B. Thomas, arXiv: 1106.4546
- KRD & B. Thomas, arXiv: 1107.0721
- KRD & B. Thomas, arXiv: 1203.1923
- KRD, S. Su & B. Thomas, arXiv: 1204.4183
- KRD, J. Kumar & B. Thomas, arXiv: 1208.0336
- KRD, J. Kumar & B. Thomas, arXiv: 1305.nnnn
- many more on the way…

- Dark-matter equation of state: do we still have $w=0$? No, much more subtle...
- Are such DDM ensembles of states easy to realize? Yes! (extra dimensions; string theory; axiverse, etc. In fact, DDM is the kind of dark matter string theory gives!)
- Can we make actual explicit models in this framework which really satisfy *every* collider, astrophysical, and cosmological bound currently known for dark matter? Yes! (and phenomenological bounds are satisfied in new, surprising ways)
- Implications for collider searches for dark matter? Unusual and distinctive collider kinematics. Invariant mass spectra, MT2 distributions, ...
- Implications for direct-detection experiments? Distinctive recoil-energy spectra with entirely new shapes and properties!
- Implications for indirect detection? e.g. positron excess easy to accommodate, *with no downturn in positron flux expected...* a “plateau” is actually a smoking gun for DDM!

Unlike traditional dark matter, DDM is not simply a property of the particle physics alone!



Lifetimes (decay widths)

balanced against

Cosmological abundances

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

must be carefully balanced as well

determined by *interplay* between Lagrangian parameters and cosmological history

DDM rests upon a balancing between particle physics and cosmological history! Abundances need not even be set thermally.

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.

⇨ 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 (e.g., scaling relations or other internal correlations or constraints) which describe the behavior of the entire DDM ensemble as a collective entity with its own internal structures and/or symmetries!

Scaling exponents of abundances and density of states relative to widths

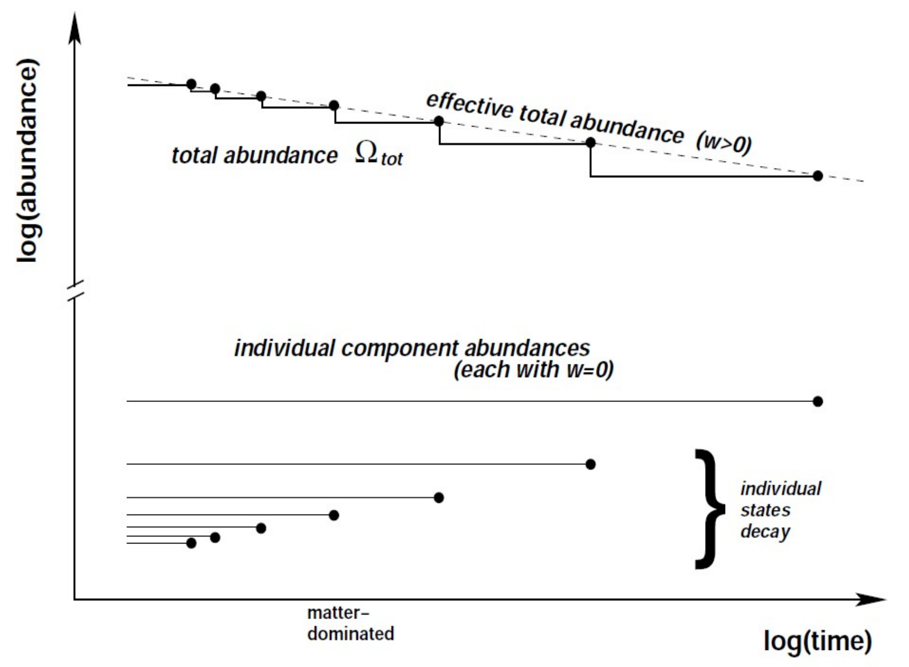
e.g., $\Omega(\Gamma) \sim A\Gamma^{\alpha}$ $\quad$ $\eta_\Gamma(\Gamma) \sim B\Gamma^{\beta}$

$\alpha < 0$

density of states *per unit* Γ

DDM ensembles have a new (effective) equation of state!

- Indeed, one important signature of the dynamical nature of dark matter in this framework is that $\Omega_{\rm tot}$ is a time-evolving quantity ---- *even during the current matter-dominated epoch*! DDM ensemble has a non-trivial effective equation of state!
- Within such a framework, it is therefore only an accident that $\Omega_{\rm tot}$ happens to match the observed $\Omega_{\rm CDM}=0.23$ at the present time.



- **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

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

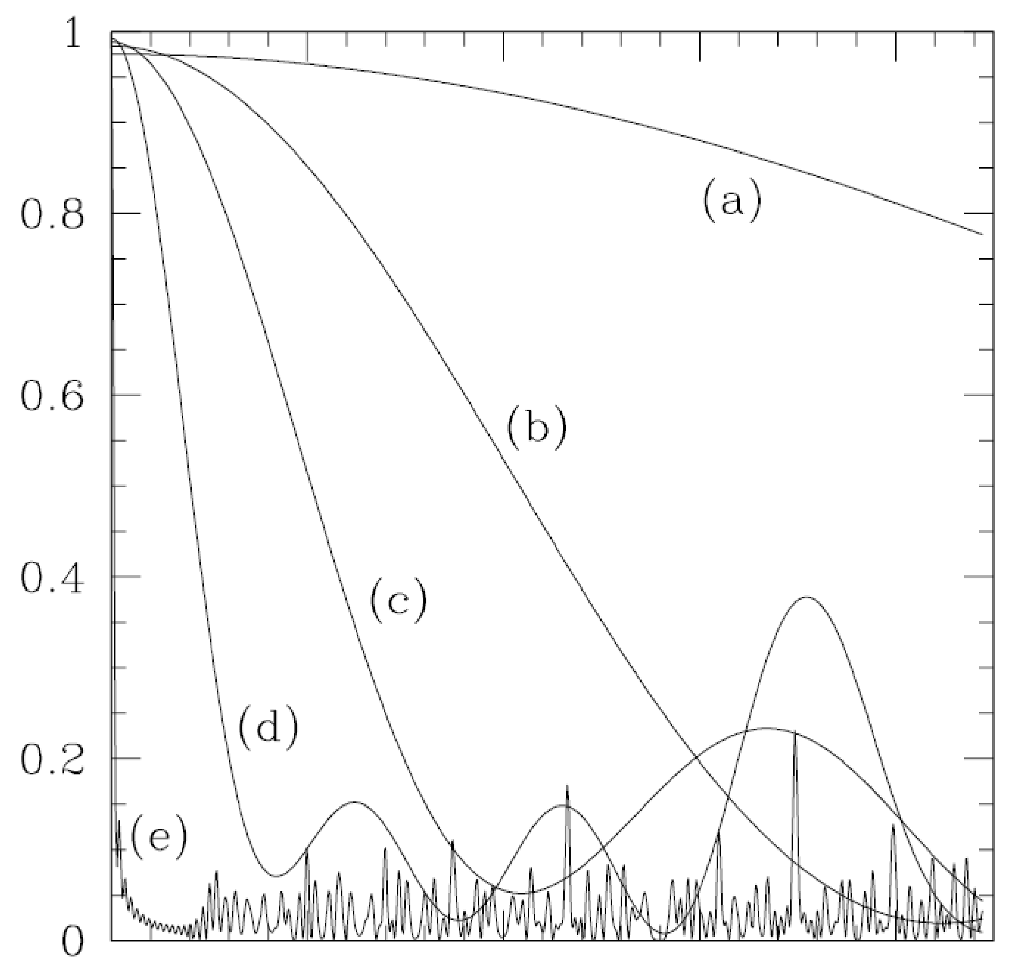
DDM has new ways of helping the dark sector stay dark!

In many constructions, SM couples to only one particular combination of ensemble fields with different masses....

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

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 traditional single-component dark-matter candidates.



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

Specific DDM models exist which satisfy all known constraints: Consider ***5D bulk axion*** with decay constant f_X, corresponding to a general gauge group G with confinement scale Λ_G and coupling g_G

arXiv: 1107.0721
arXiv: 1203.1923

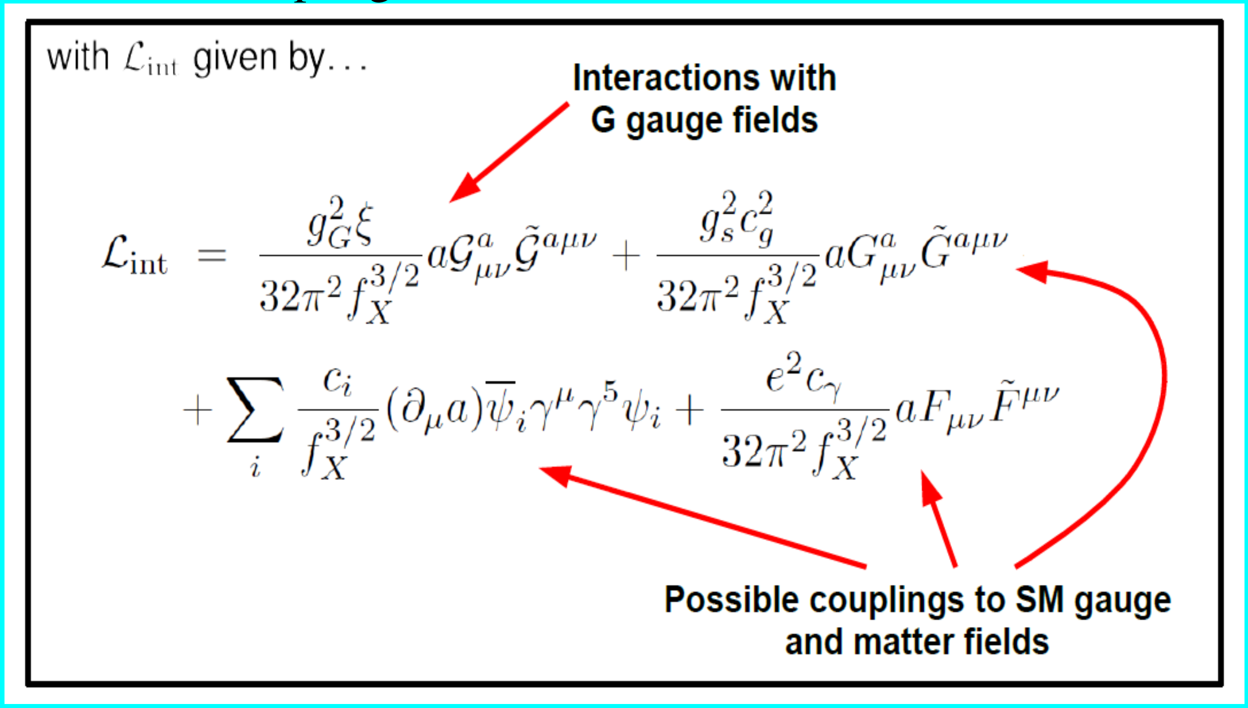
Such a choice is indeed gauge-neutral and well-motivated theoretically, both in field theory and in string theory.

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!)

arXiv: 1203.1923

What are the phenomenological constraints that govern such scenarios?

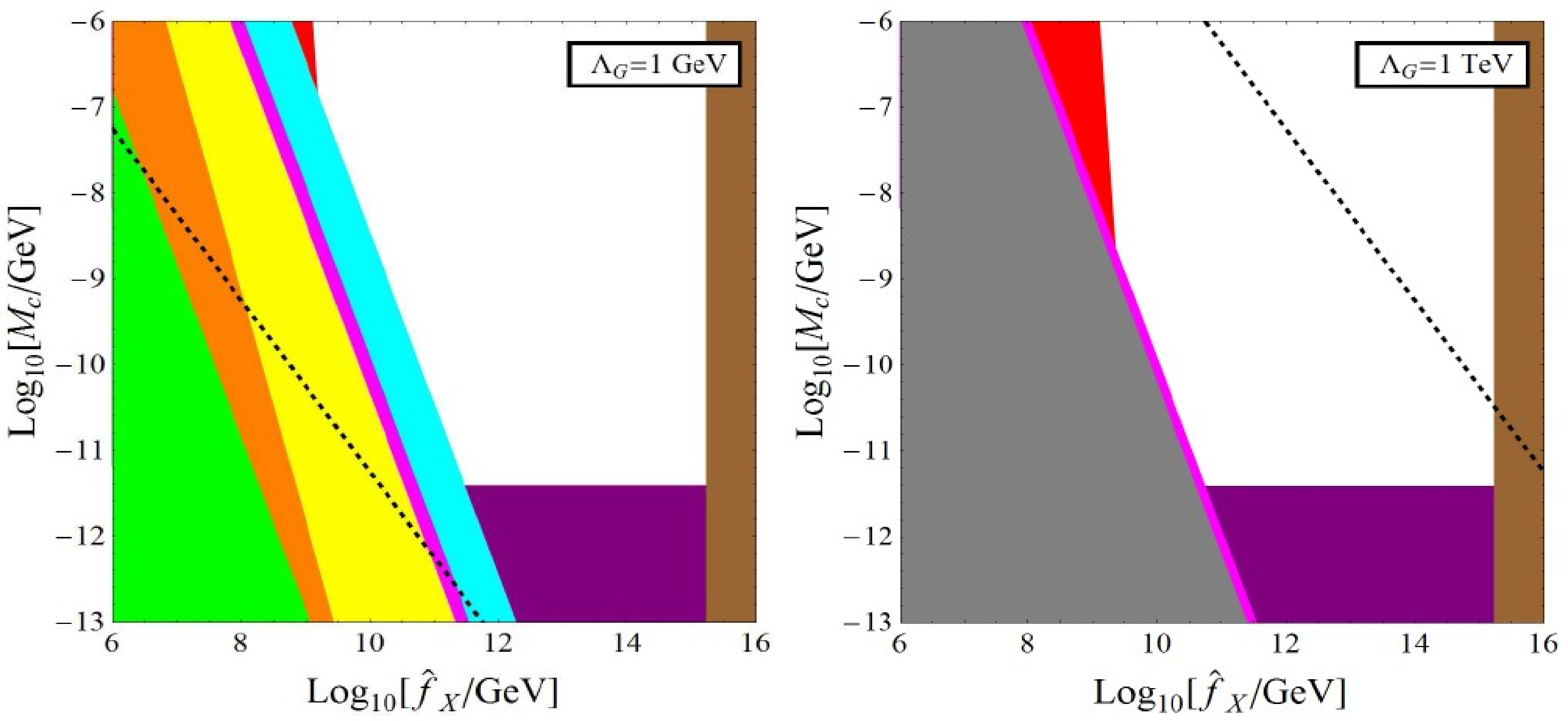
- GC (globular cluster) stars. Axions might carry away energy too efficiently, altering stellar lifetimes. GC stars give most stringent bound.
- SN1987a. Same --- axions would effect energy loss rate.
- Diffuse photon/X-ray backgrounds. Axion decays to photons would leave unobserved imprints.
- Eotvos. 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
- ⬜ Model self-consistency

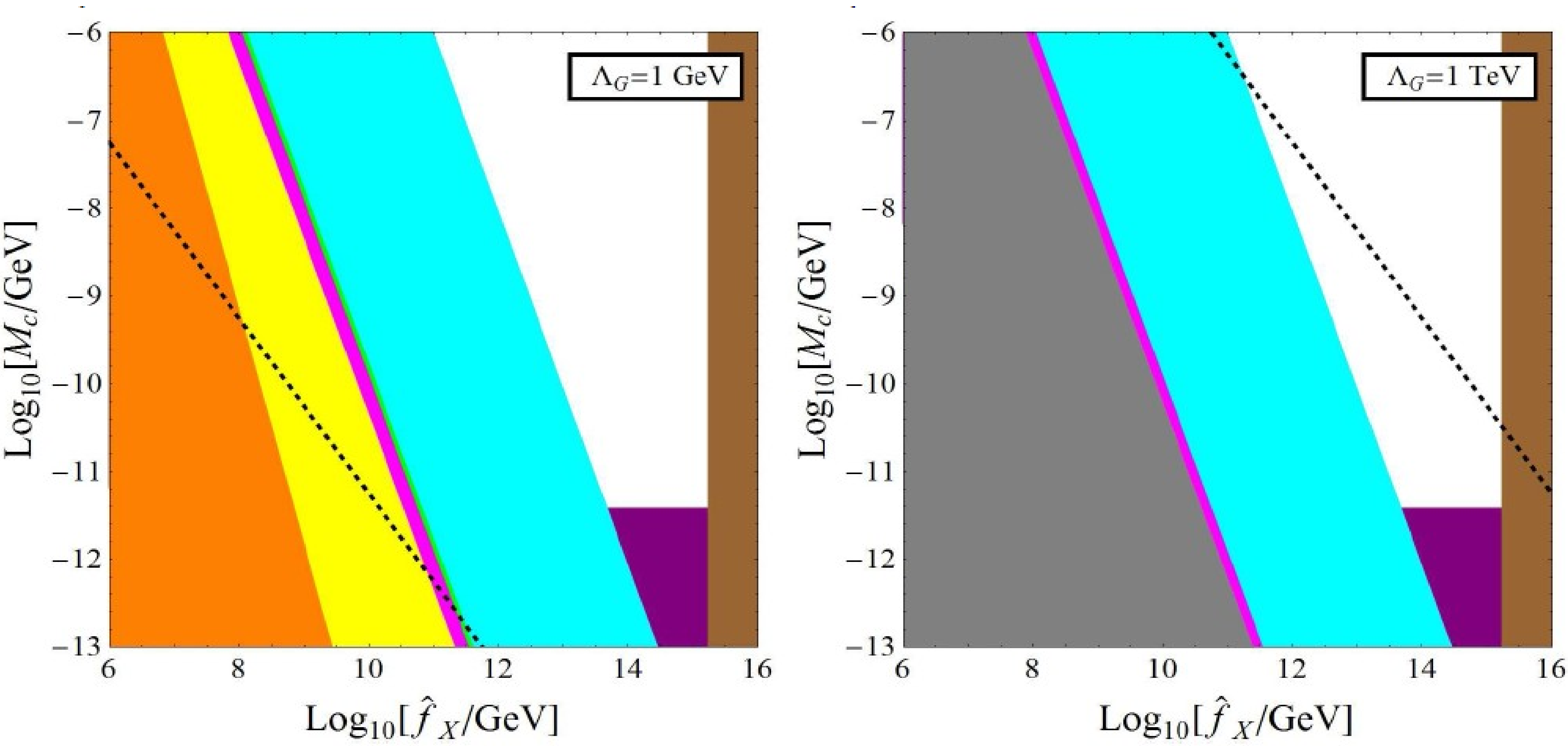


Combined Limits on Dark Towers

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
- ⬜ Model self-consistency



Thus, within open 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...

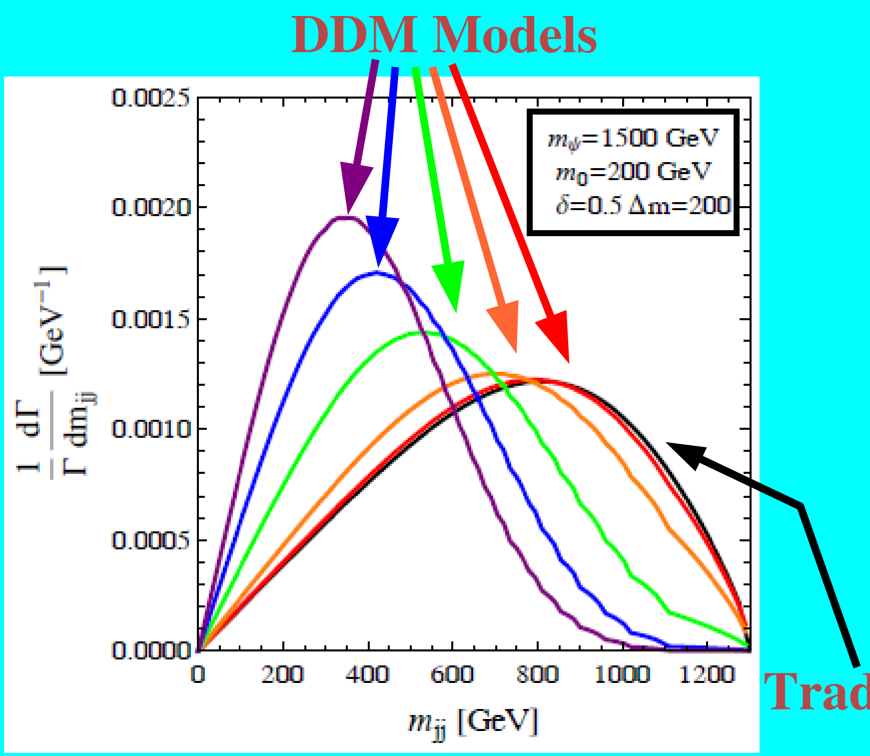
- at colliders (LHC)
- at the next generation of direct-detection experiments

(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: 1208.0336

This can indeed be done --- both at collider experiments...



Traditional DM

- KRD, S. Su, and B. Thomas, arXiv: 1204.4183

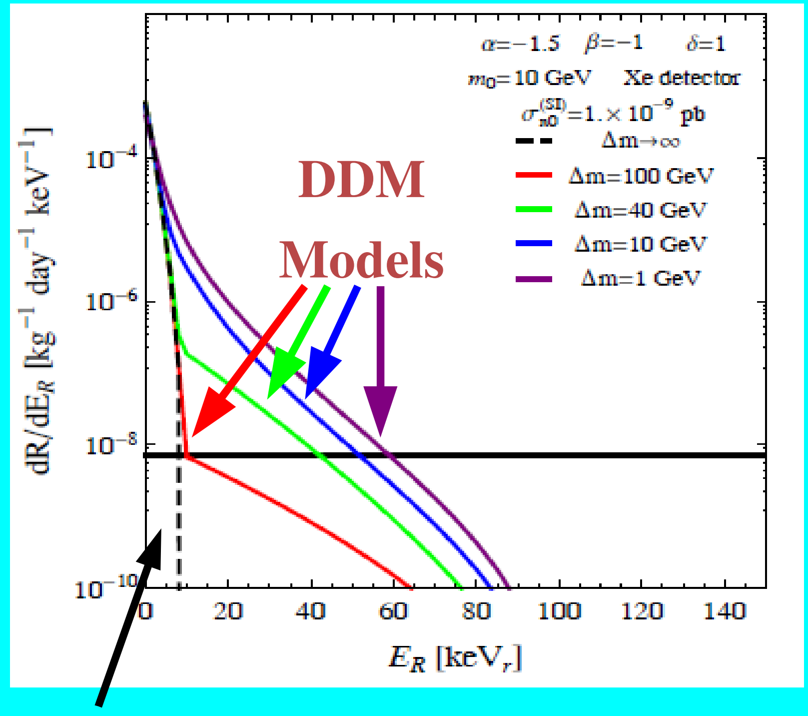
- In many DDM models, constituent fields in the DDM ensemble can be produced alongside SM particles by the decays of additional heavy fields.
- Evidence of a DDM ensemble can be ascertained in characteristic features imprinted on the invariant-mass distributions of these SM particles.

... and at direct-detection experiments.

- KRD, J. Kumar and B. Thomas, arXiv: 1208.0336

- DDM ensembles can also give rise to distinctive features in recoil-energy spectra.

These examples illustrate that DDM ensembles give rise to **<u>observable effects</u>** which can serve to distinguish them from traditional DM candidates.



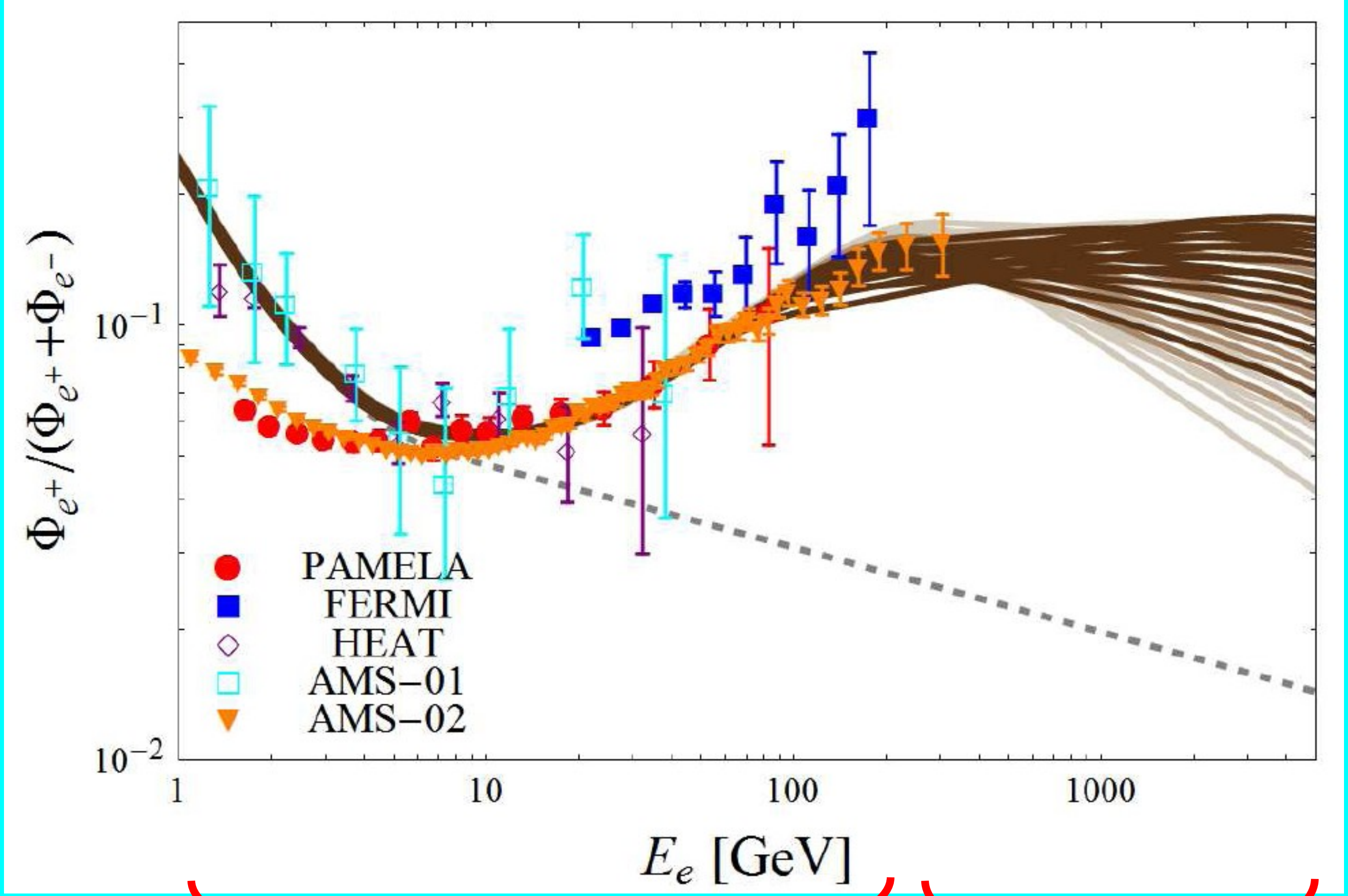
Traditional DM

DDM also makes predictions for indirect-detection experiments…

- KRD, J. Kumar & B. Thomas, arXiv: 1305.nnnn

All curves also satisfy other constraints from...

- Comic-ray antiproton flux (PAMELA)
- Diffuse gamma-ray flux (FERMI-LAT)
- Synchrotron radiation (e+/e- interacting in galactic halo with background magnetic fields)
- CMB ionization history (Planck)
- Combined electron/positron flux (FERMI-LAT)



DDM: Fully consistent with positron excess observed thus far [AMS-02]

DDM prediction: no downturn at higher energies! Flat plateau...

A "smoking gun" for DDM!

We are only at the tip of the iceberg...

Almost every traditional line of investigation in dark-matter physics can be re-evaluated in this context (from structure formation to collider phenomenology, and everything in between).

The Dynamical Dark Matter framework is rich and we have only begun to explore its properties. DDM provides new ways to think about old problems and challenges in dark-matter physics.

But most importantly for a conference such as Snowmass...

The Take-Home Message

Dynamical Dark Matter ***is*** the most general way of thinking about the dark sector...

- Stability is not a fundamental requirement for the dark sector.
- All that is required is a phenomenological balancing of lifetimes against abundances.
- The resulting physics can satisfy all astrophysical, cosmological, and collider constraints on dark matter, and yet simultaneously give rise to new theoretical insights and new experimentally distinct signatures.

It is time we shed our theoretical prejudices and embrace all the possibilities that dark-sector instability allows!