

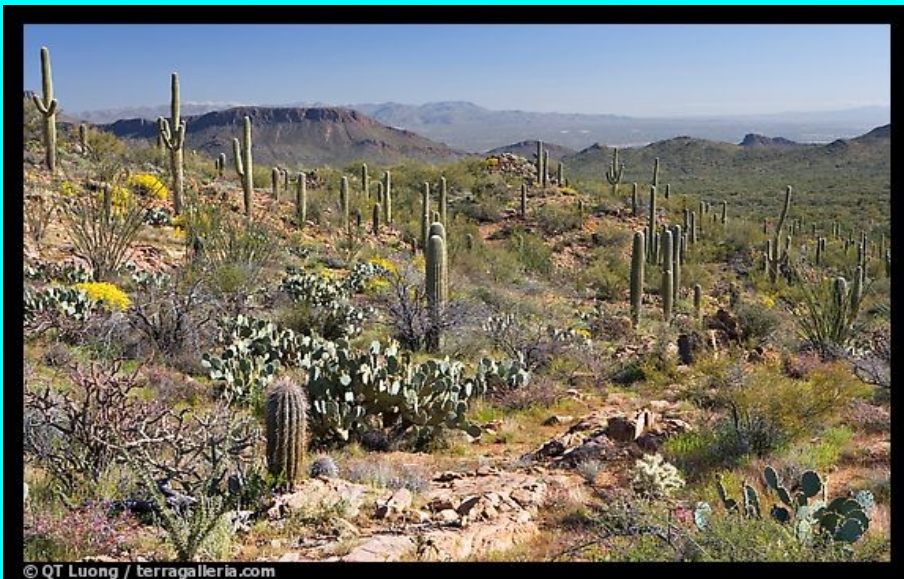
# Reaching Beyond the Standard Scenarios

From Strongly Coupled Dark Sectors and Thermal Freezeout  
to Cosmological Phase Transitions and the Lifetime Frontier

**Keith R. Dienes**

University of Arizona

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Tucson, Arizona

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.

- **arXiv: 1610.04112**  
(KRD, F. Huang, S. Su & B. Thomas)
- **arXiv: 1712.09919**  
(KRD, J. Fennick, J. Kumar & B. Thomas)
- **arXiv: 1509.00470, 1612.08950**  
(KRD, J. Kost & B. Thomas)
- **arXiv: 1805.nnnnn**  
(D. Curtin, KRD & B. Thomas)

**Mitchell Conference,  
Texas A&M, 5/22/2018**

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What our work on these diverse topics has in common is that our results are all inspired by -- and relevant for ---

**Dynamical Dark Matter (DDM),**  
an alternative framework for thinking about the dark-matter problem.

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## Dynamical Dark Matter (DDM),

an alternative framework for thinking about the dark-matter problem.

DDM originally proposed in 2011 with **Brooks Thomas...**

- 1106.4546
- 1107.0721
- 1203.1923

and then further developed in many different directions with many additional collaborators...

- 1204.4183 (also w/ S. Su)
- 1208.0336 (also w/ J. Kumar)
- 1306.2959 (also w/ J. Kumar)
- 1406.4868 (also w/ J. Kumar, D. Yaylali)
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- 1601.05094 (also w/ J. Kumar, J. Fennick)
- 1606.07440 (also w/ K. Boddy, D. Kim, J. Kumar, J.-C. Park)
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- 1807.xxxxx (also w/ J. Kumar & P. Stengel)
- 1807.xxxxx (also w/ Y. Buyukdag & T. Gherghetta)
- **... plus ongoing collaborations with others in this room!**

This talk...

- **Dynamical Dark Matter**

  - a quick review, just the relevant basics

- **Beyond the Standard DM Scenarios:**

  - New approaches inspired by DDM...

    - Non-standard phenomenologies from thermal freezeout
    - Dark matter from strongly coupled dark sectors
    - Surprises from phase transitions in the early universe
    - A new collider-based approach to dark-matter detection:  
DDM, MATHUSLA, and the lifetime frontier

# Traditional view of dark matter:

- One or several dark-matter particle(s)  $\chi$  which carry entire DM abundance:  $\Omega_\chi = \Omega_{\text{CDM}} = 0.26$  (WMAP).
- Such particle(s) must be hyperstable, with lifetimes exceeding the age of the universe by many orders of magnitude  $\sim 10^{26}$  s.
- Most DM scenarios take this form.

**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 gamma-ray/X-ray backgrounds.**

Stability is thus critical for traditional dark matter. The resulting theory is essentially “frozen in time”:  $\Omega_{\text{CDM}}$  is constant, etc.

# Dynamical Dark Matter (DDM):

**Why assume the dark sector has only one species of particle?**

Certainly not true of *visible* sector! So let's suppose the dark sector consists of  $N$  states, where  $N \gg 1$  ... an entire *ensemble* of states!

- No state individually needs to carry the full  $\Omega_{\text{CDM}}$  so long as the sum of their abundances matches  $\Omega_{\text{CDM}}$ .
- In particular, individual components can have a wide variety of abundances, some large *but some small*.

**But 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 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.

**We are thus naturally led to an alternative concept ---  
*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!**



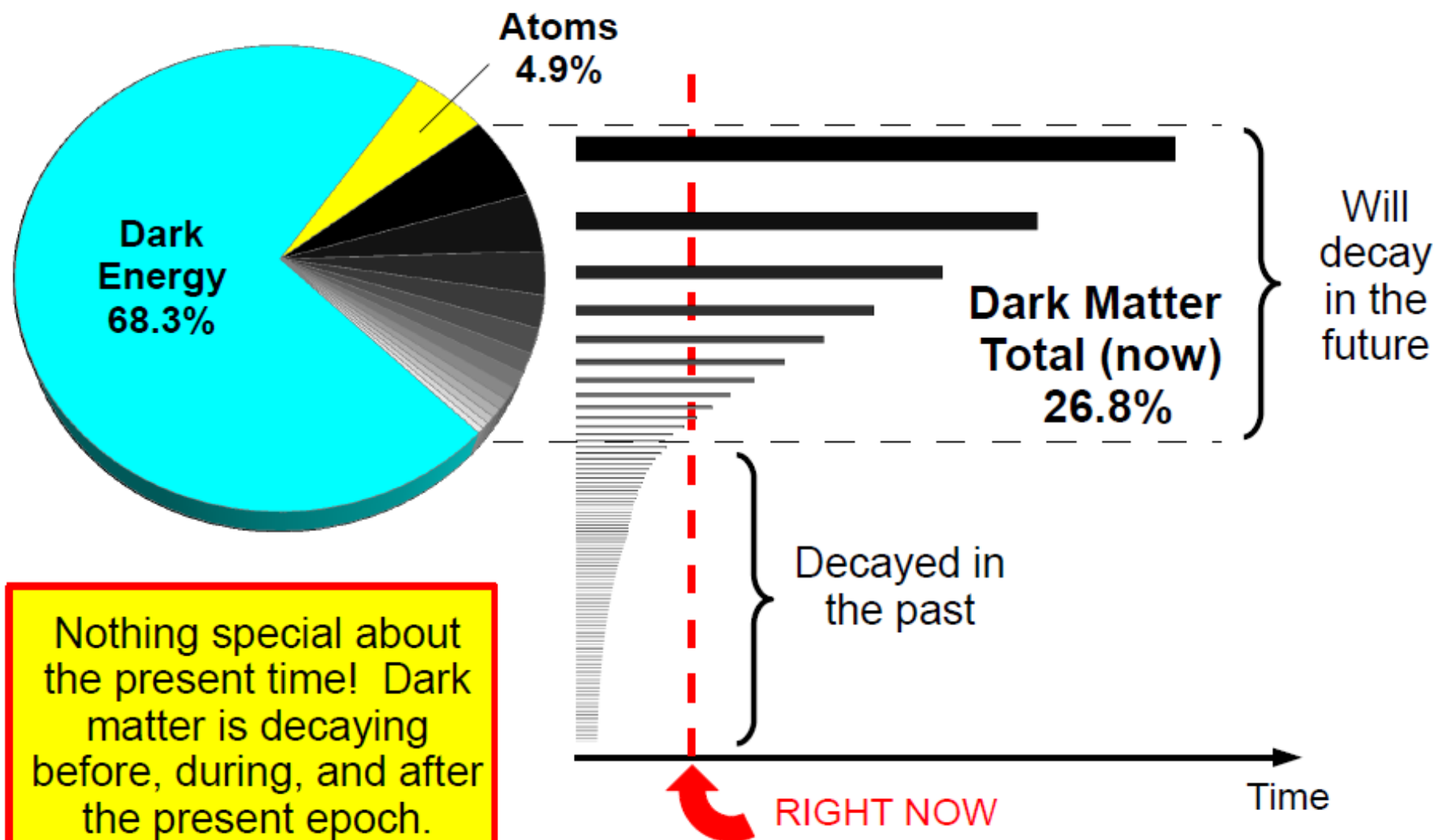
**Dynamical Dark Matter (DDM)**: an alternative framework for dark-matter physics in which the notion of dark-matter stability is replaced by a balancing of lifetimes against cosmological abundances across an ensemble of individual dark-matter components with different masses, lifetimes, and abundances.

*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.

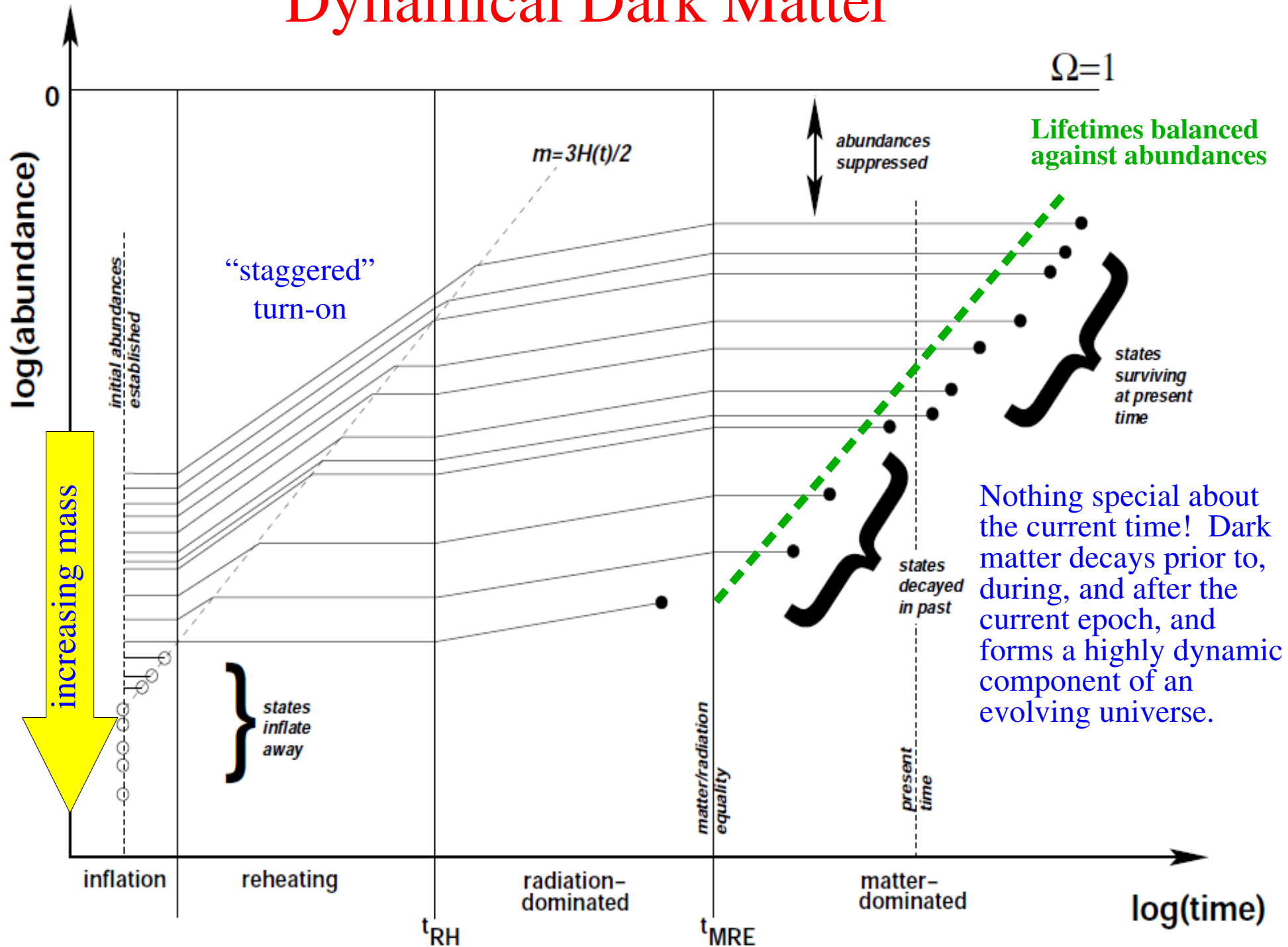
Otherwise, if the number of states is enlarged, *the notion of dark-matter stability generalizes into something far richer: a balancing of lifetimes against abundances. The dark sector becomes truly dynamical!*

# “Dynamical Dark Matter”: The Basic Picture:

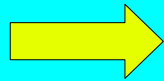
A Snapshot of the Cosmic Pie: Past, Present, and Future



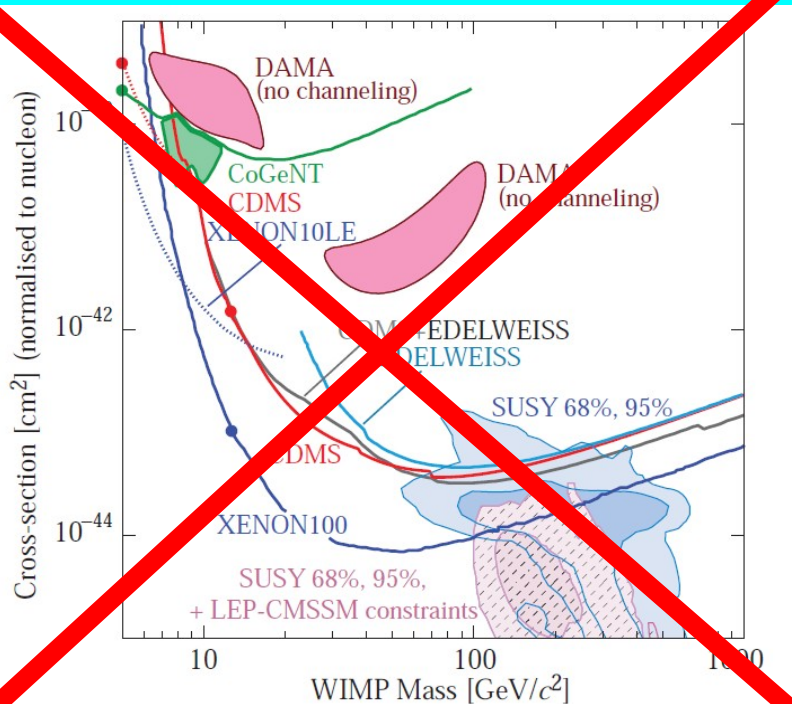
# Dynamical Dark Matter



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.



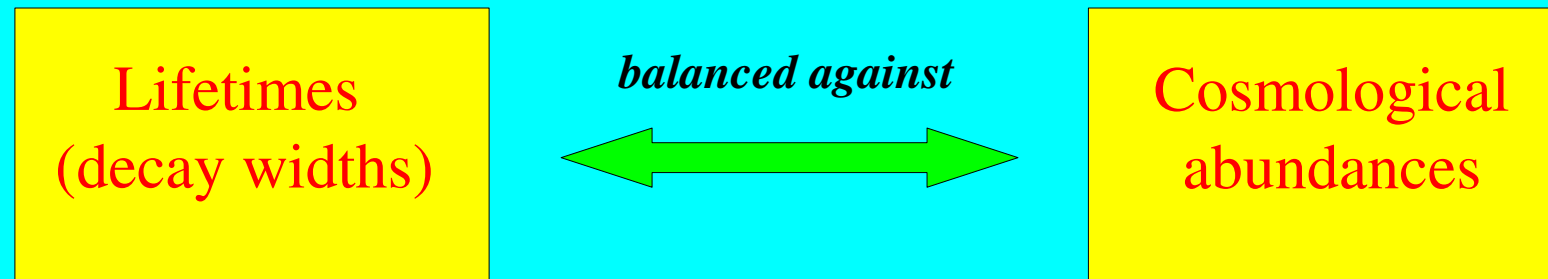
The DDM ensemble must therefore be characterized in terms of parameters (e.g., scaling relations or other internal correlations and constraints) which describe the behavior of its constituents as a whole.



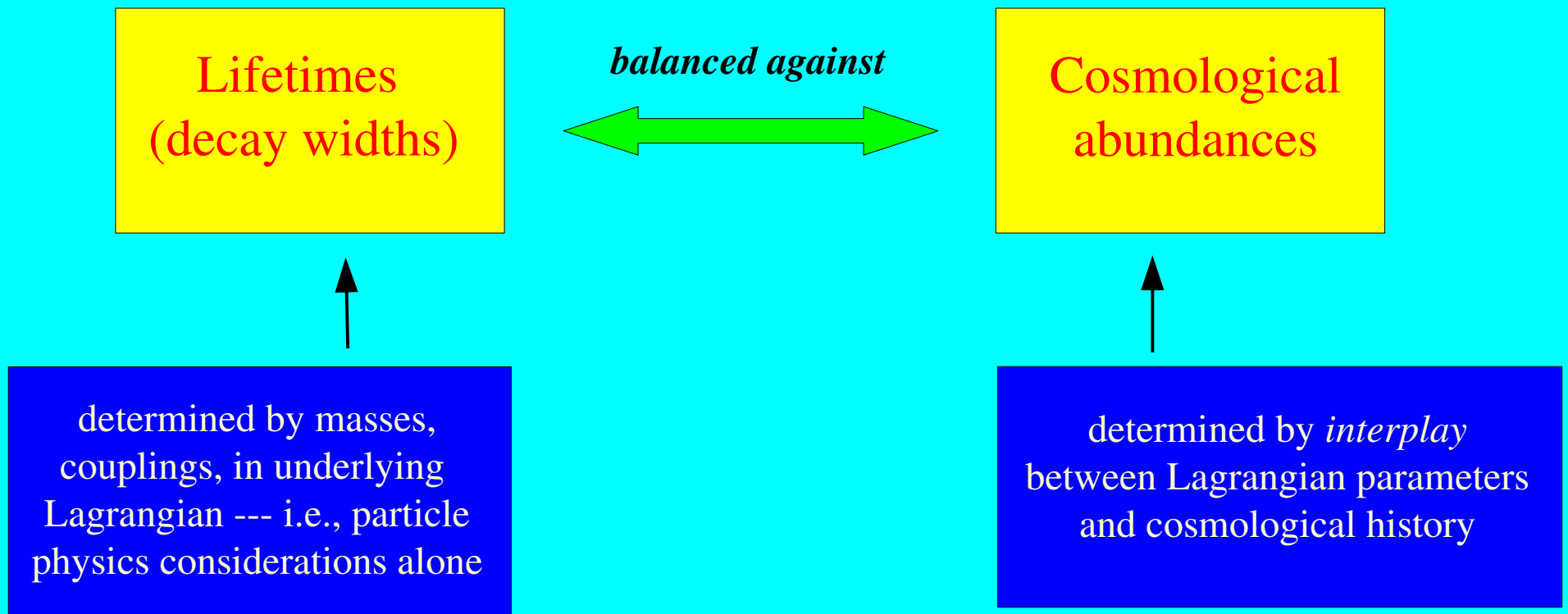
As a consequence, phenomenological bounds on dark matter in the DDM framework must be phrased and analyzed in terms of *a new set of variables* which describe the behavior of the entire DDM ensemble as a collective entity with its own internal structures and/or symmetries.

*We must move beyond the standard WIMP paradigm.*

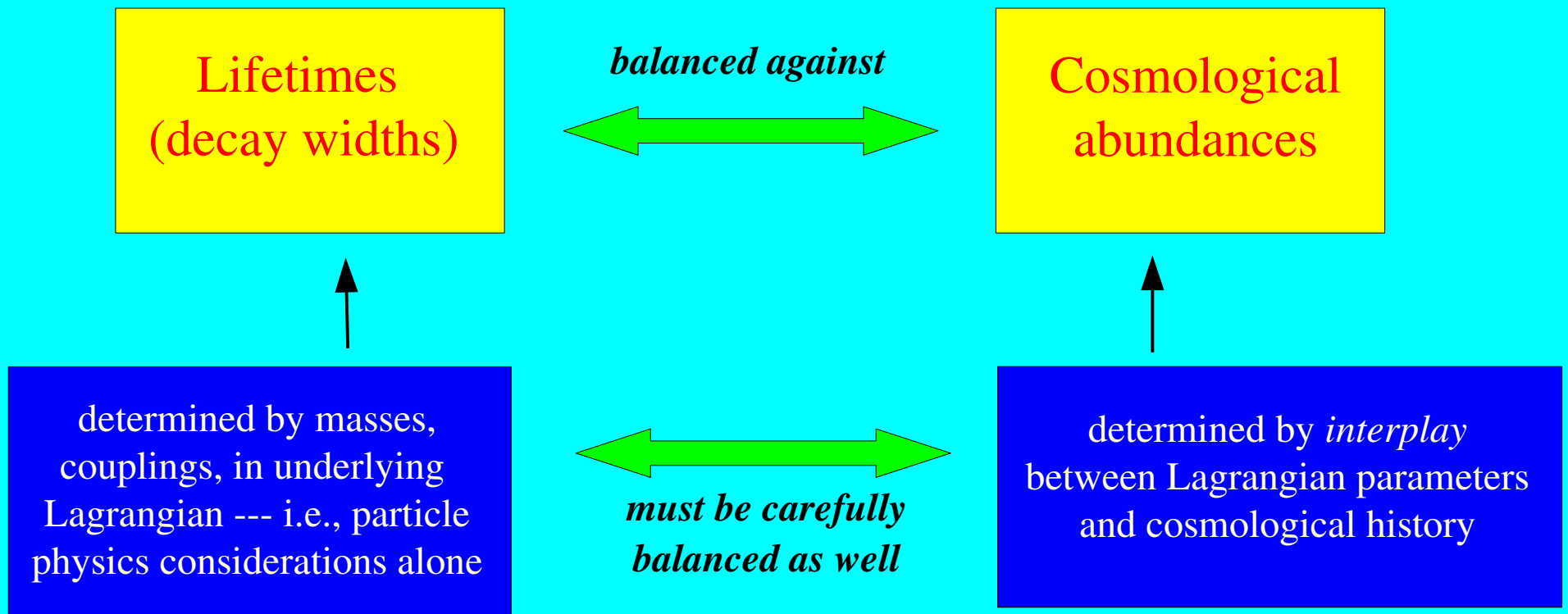
Unlike traditional dark matter, DDM is not simply a property of the particle physics alone!



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



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

# 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, 1106.4546
- KRD & B. Thomas, 1107.0721
- KRD & B. Thomas, 1203.1923
- KRD, S. Su, & B. Thomas, 1204.4183
- KRD, J. Kumar & B. Thomas, 1208.0336
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- KRD, J. Fennick, J. Kumar & B. Thomas, 1601.05094

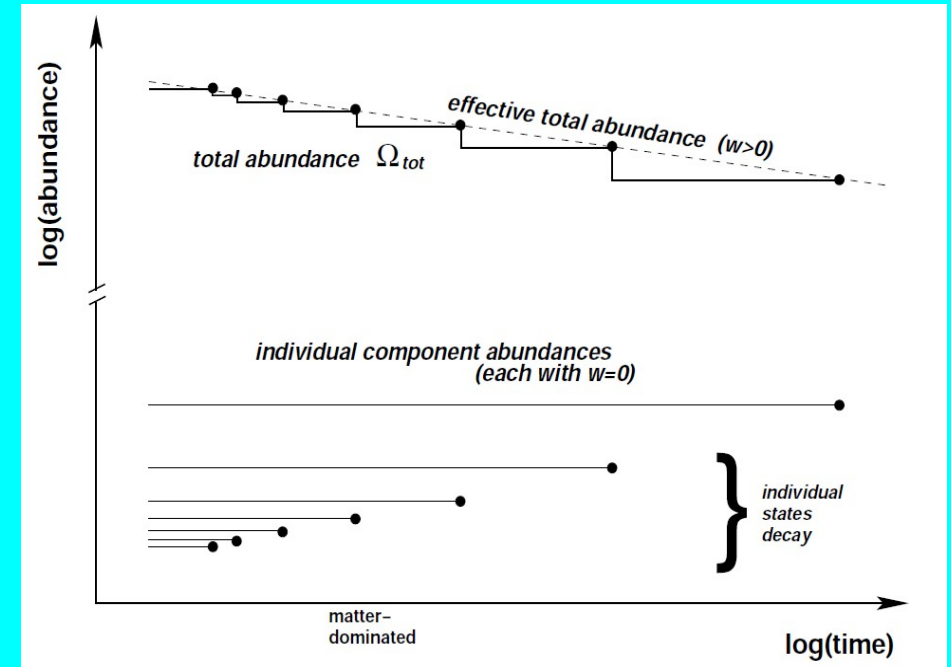
- K. Boddy, KRD, D. Kim, J. Kumar, J.C. Park & B. Thomas, 1606.07440
- K. Boddy, KRD, D. Kim, J. Kumar, J.C. Park & B. Thomas, 1609.09104
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- KRD, J. Kumar, B. Thomas & D. Yaylali, 1708.09698
- KRD, J. Fennick, J. Kumar & B. Thomas, 1712.09919
- D. Curtin, KRD & B. Thomas, 1805.xxxxx
- KRD, F. Huang, S. Su & B. Thomas, 1806.xxxxx
- KRD, J. Kumar, P. Stengel & B. Thomas, 1807.xxxxx
- Y. Buyukdag, KRD, T. Gherghetta & B. Thomas, 1807.xxxx

- **Dark-matter equation of state:** do we still have  $w=0$  ? **No, much more subtle...**
- **Are such DDM ensembles easy to realize? Yes!** (extra dimensions; string theory; axiverse, etc. **In fact, DDM is the kind of dark matter string theory naturally 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... a “plateau” is actually a smoking gun for DDM!**
- **New kinds of complementarities** involving DM decay!
- **New experimental probes of DDM ensemble at *lifetime* frontier!**



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

- In the DDM framework, the total dark-sector abundance  $\Omega_{\text{tot}}$  is a time-evolving quantity ---- *even during the current matter-dominated epoch!* Thus, the DDM ensemble has a non-trivial time-dependent effective equation of state parameter  $w_{\text{eff}}(t)$ .



Assume the DDM ensemble is parametrized through certain *scaling* exponents...

*Scaling exponents of abundances and density of states relative to widths*

e.g.,

$$\Omega(\Gamma) \sim A\Gamma^\alpha$$

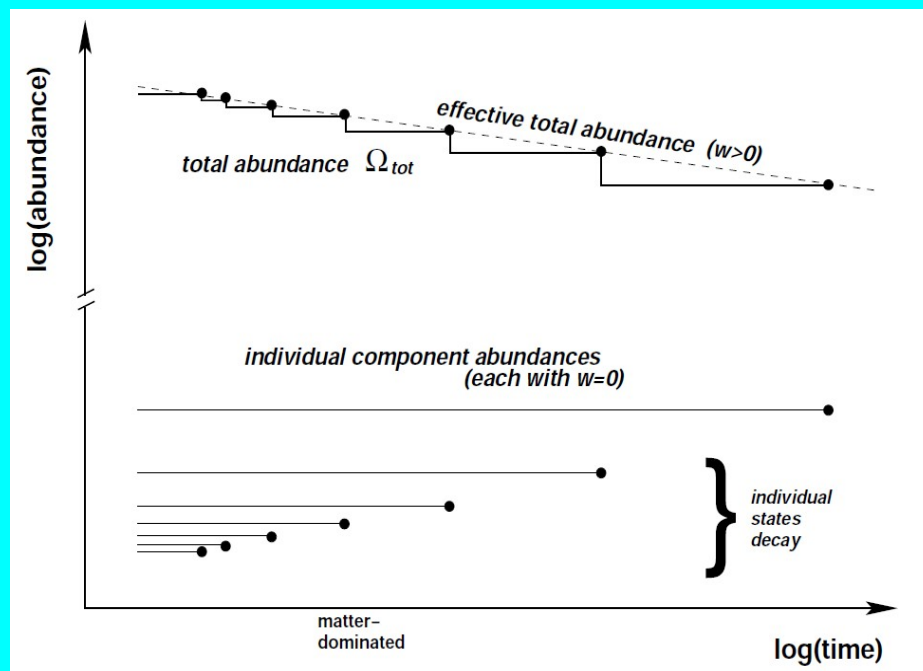
$$\alpha < 0$$

$$\eta_\Gamma(\Gamma) \sim B\Gamma^\beta$$

density of states *per unit*  $\Gamma$

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

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

where

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

- For**  $x = -1$  :

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

where

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

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

- KRD & B. Thomas, arXiv: 1107.0721
- KRD & B. Thomas, 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

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

← brane mass comes from axion potential induced by instanton dynamics associated with group  $G$  at scale  $\Lambda_G$

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

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

$$\begin{aligned} \mathcal{L}_{\text{int}} = & \frac{g_G^2 \xi}{32\pi^2 f_X^{3/2}} a G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{g_s^2 c_g^2}{32\pi^2 f_X^{3/2}} a G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \\ & + \sum_i \frac{c_i}{f_X^{3/2}} (\partial_\mu a) \bar{\psi}_i \gamma^\mu \gamma^5 \psi_i + \frac{e^2 c_\gamma}{32\pi^2 f_X^{3/2}} a F_{\mu\nu} \tilde{F}^{\mu\nu} \end{aligned}$$

Interactions with  $G$  gauge fields

Possible couplings to SM gauge and matter fields

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

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

# What are the phenomenological constraints that govern such scenarios?

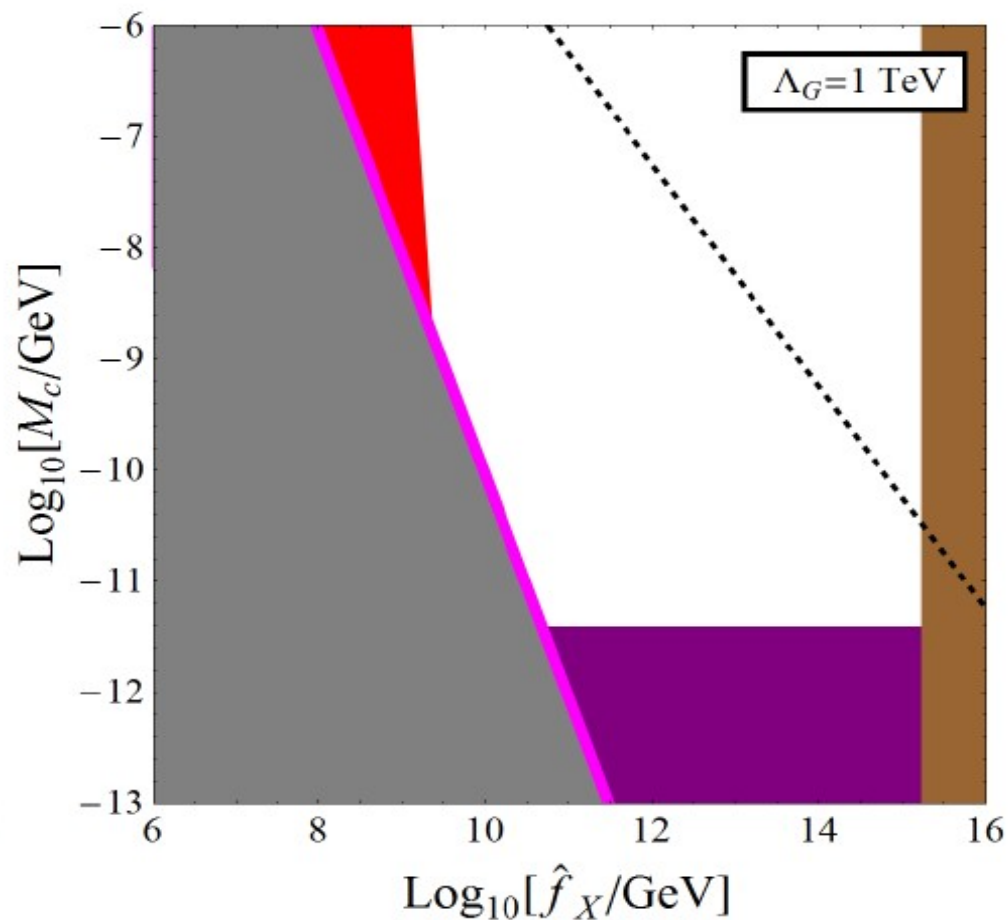
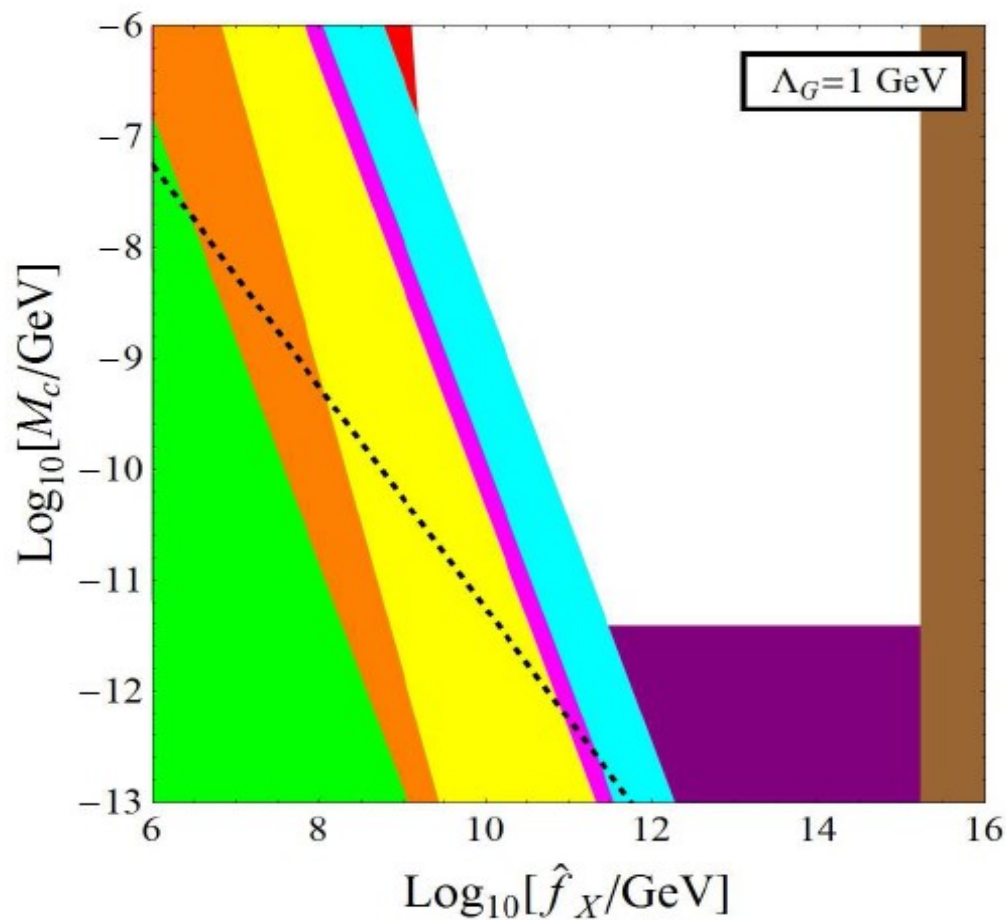
- GC (globular cluster) stars. Axions might carry away energy too efficiently, altering stellar lifetimes. GC stars give most stringent bound.
- SN1987a. Same --- axions would effect energy loss rate.
- Diffuse photon/X-ray backgrounds. Axion decays to photons would leave unobserved imprints.
- Eotvos. Cavendish-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               | Eötvös experiments | DM overabundant        |
| SN1987A                | Helioscopes (CAST) | Thermal production     |
| Diffuse photon spectra | Collider limits    | Model self-consistency |

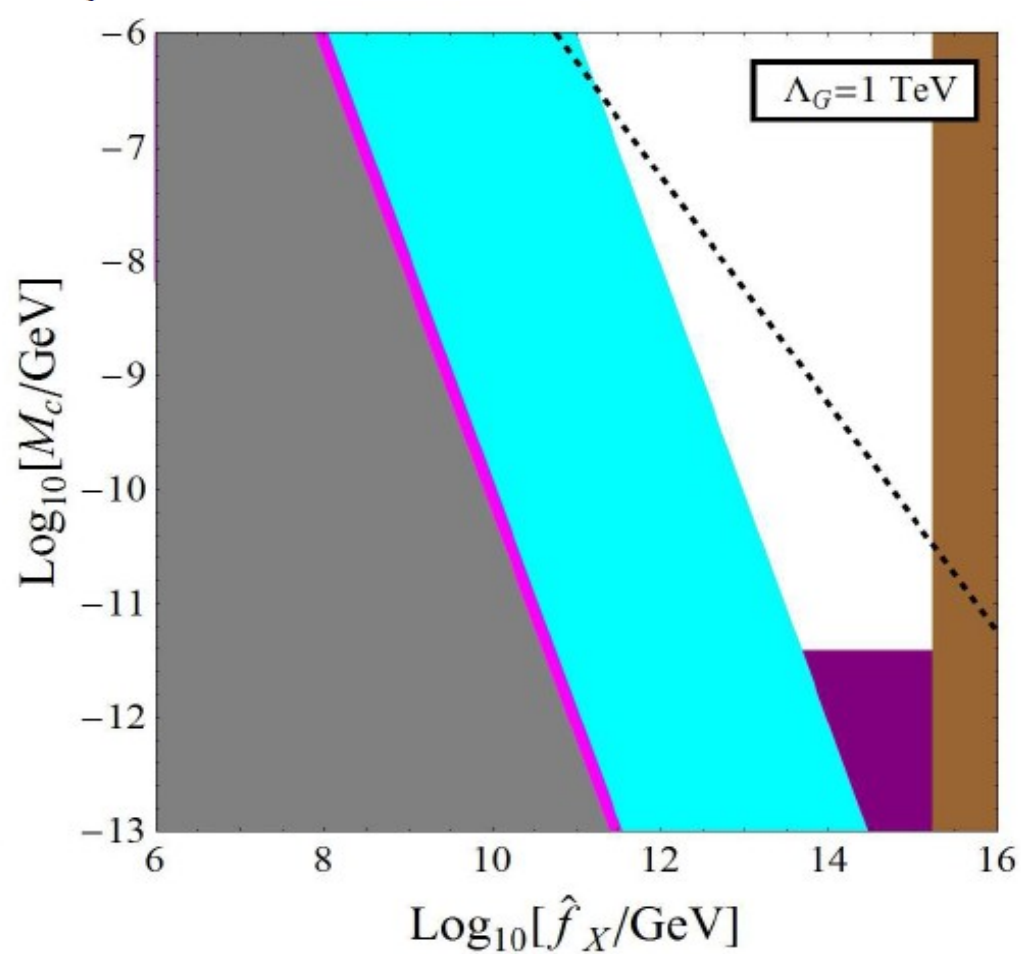
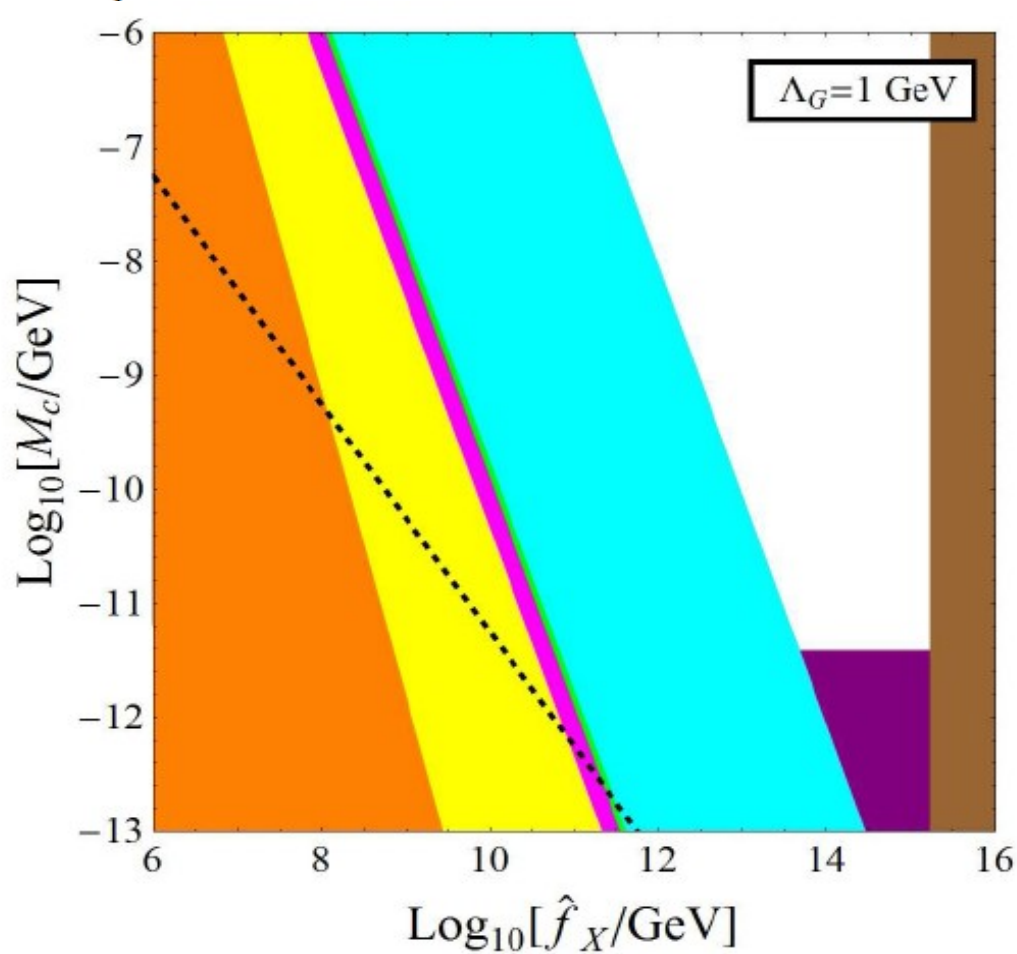


# Combined Limits on Dark Towers

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

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

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





# Experimental signatures of DDM

How can we distinguish DDM...

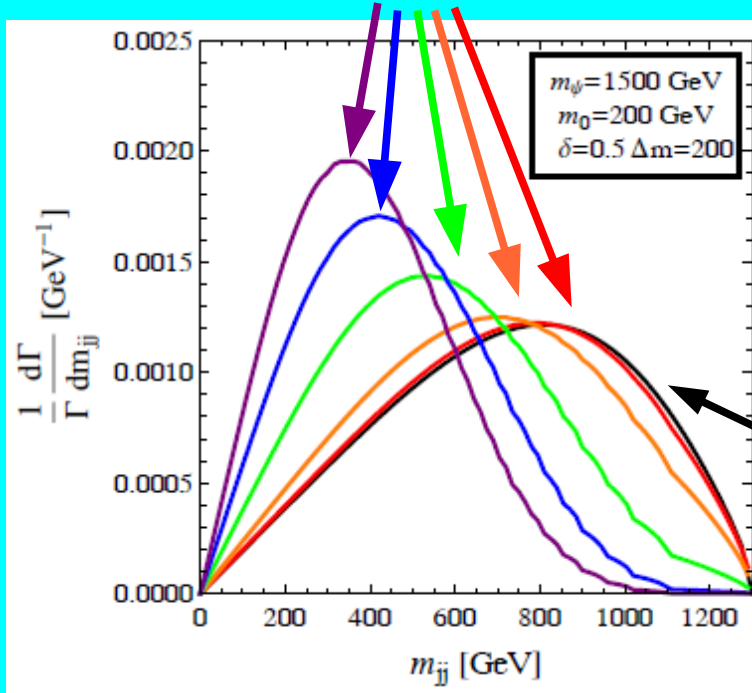
- at colliders (LHC)
- at the next generation of direct-detection experiments  
(e.g., XENON 100/1T, SuperCMS, LUX, PANDA-X)
- at indirect-detection experiments (e.g., AMS-02, ...)

... 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
- KRD, J. Kumar, and B. Thomas, arXiv: 1306.2959
- KRD, J. Kumar, B. Thomas, and D. Yaylali, arXiv: 1406.4868
  - KRD, S. Su, and B. Thomas, arXiv: 1407.2606
- K. Boddy, KRD, D. Kim, J. Kumar, J.C. Park & B. Thomas, arXiv: 1606.07440
- K. Boddy, KRD, D. Kim, J. Kumar, J.C. Park & B. Thomas, arXiv: 1606.07440
  - KRD, J. Kumar, B. Thomas, and D. Yaylali, arXiv: 1708.09698

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

## DDM Models



## Traditional DM

- KR, S. Su, and B. Thomas, arXiv: 1204.4183
- KR, S. Su, and B. Thomas, arXiv: 1407.2606

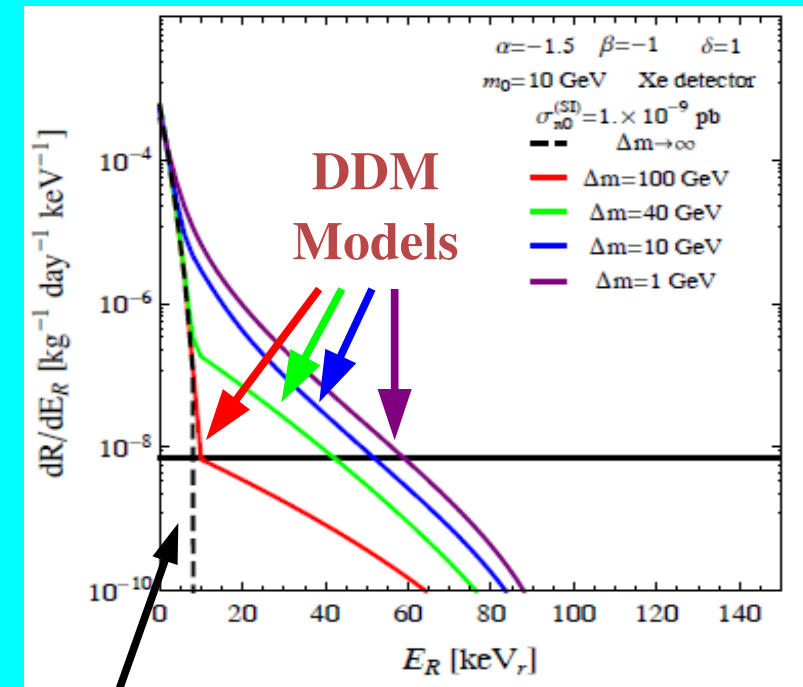
- In many DDM models, constituent fields in the DDM ensemble can be produced alongside SM particles by the decays of additional heavy fields.  
 $\psi \rightarrow jj\chi_n$
- Evidence of a DDM ensemble can be ascertained in characteristic features imprinted on the invariant-mass distributions of these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

# ... and at direct-detection experiments.

- KR, 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 **observable effects** which can serve to distinguish them from traditional DM candidates.



## Traditional DM

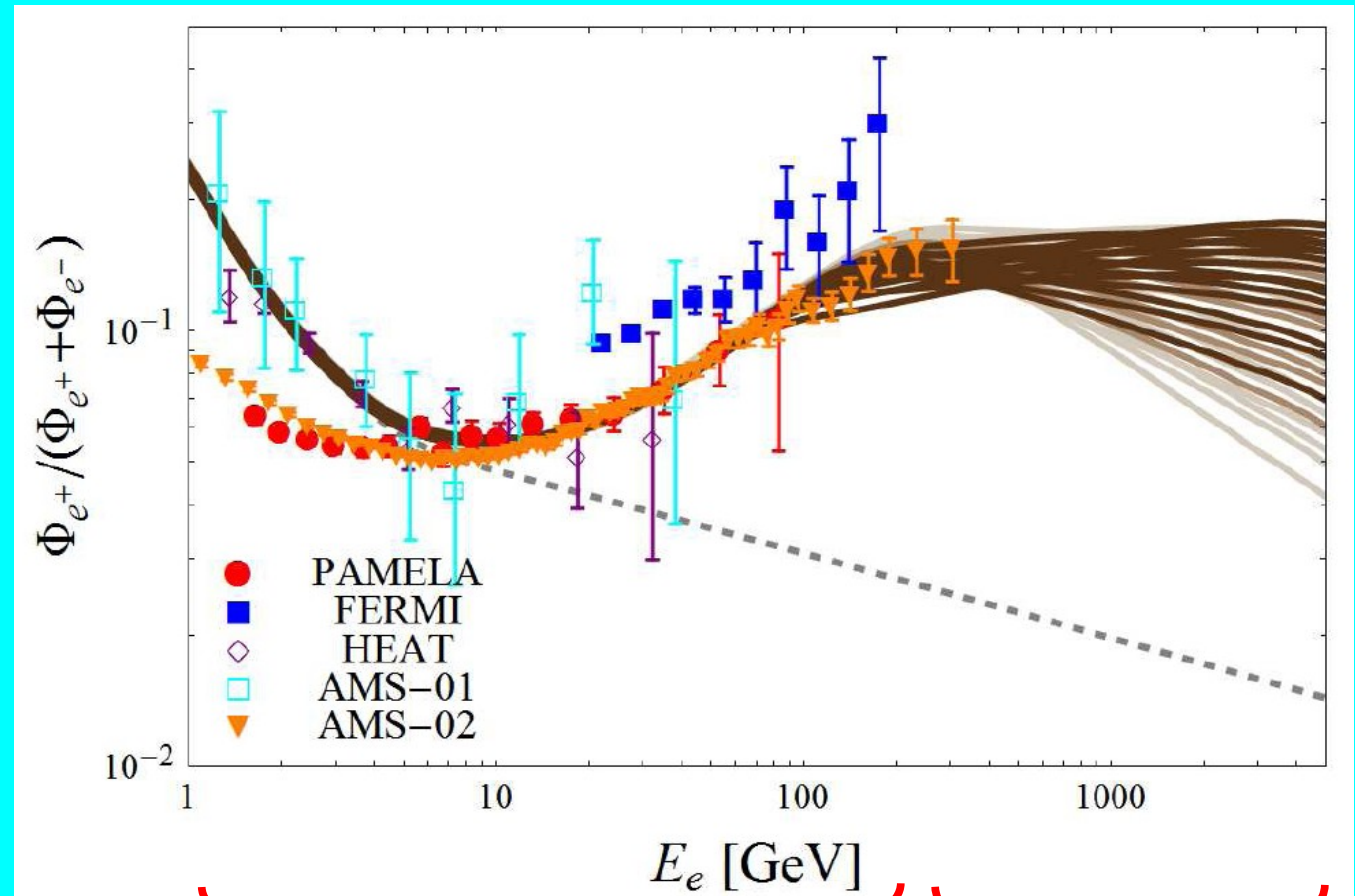


# DDM also makes predictions for indirect-detection experiments...

•KRD, J. Kumar & B. Thomas,  
arXiv: 1306.2959

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)



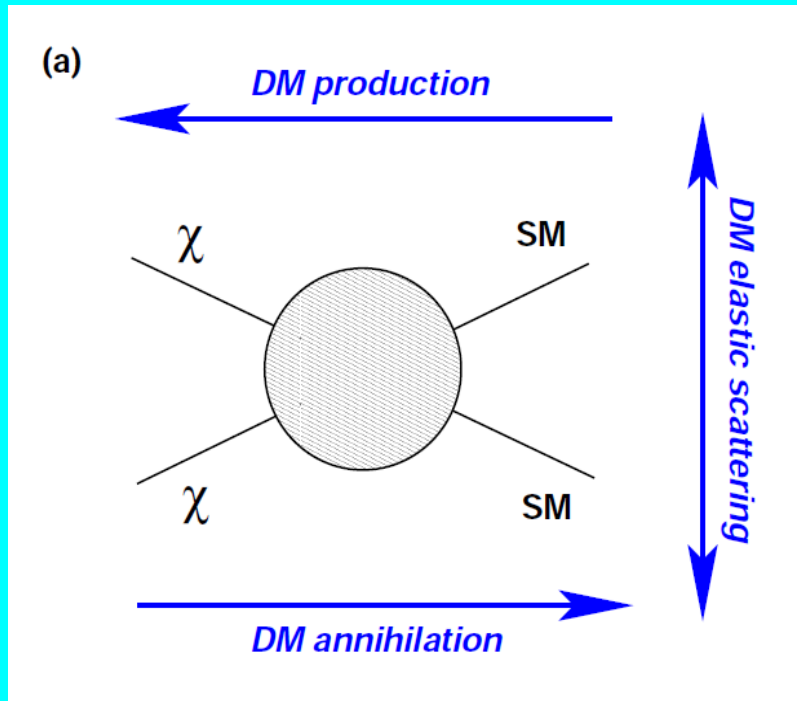
**DDM:** Fully consistent with positron excess observed thus far [AMS-02]

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

A “smoking gun” for DDM!

# DDM (and more generally, dark-sector non-minimality) even gives rise to entirely new directions for dark-matter complementarity...

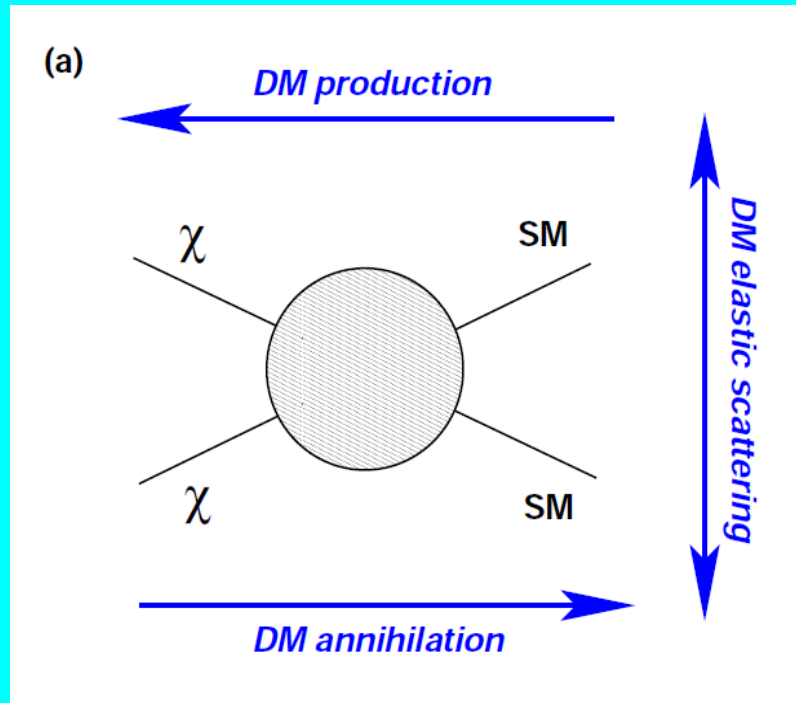
*From this...*



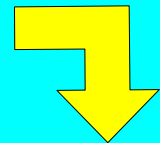
- KRD, J. Kumar, B. Thomas & D. Yaylali, arXiv: 1406.4868
- KRD, J. Kumar, B. Thomas & D. Yaylali, arXiv: 1708.09698

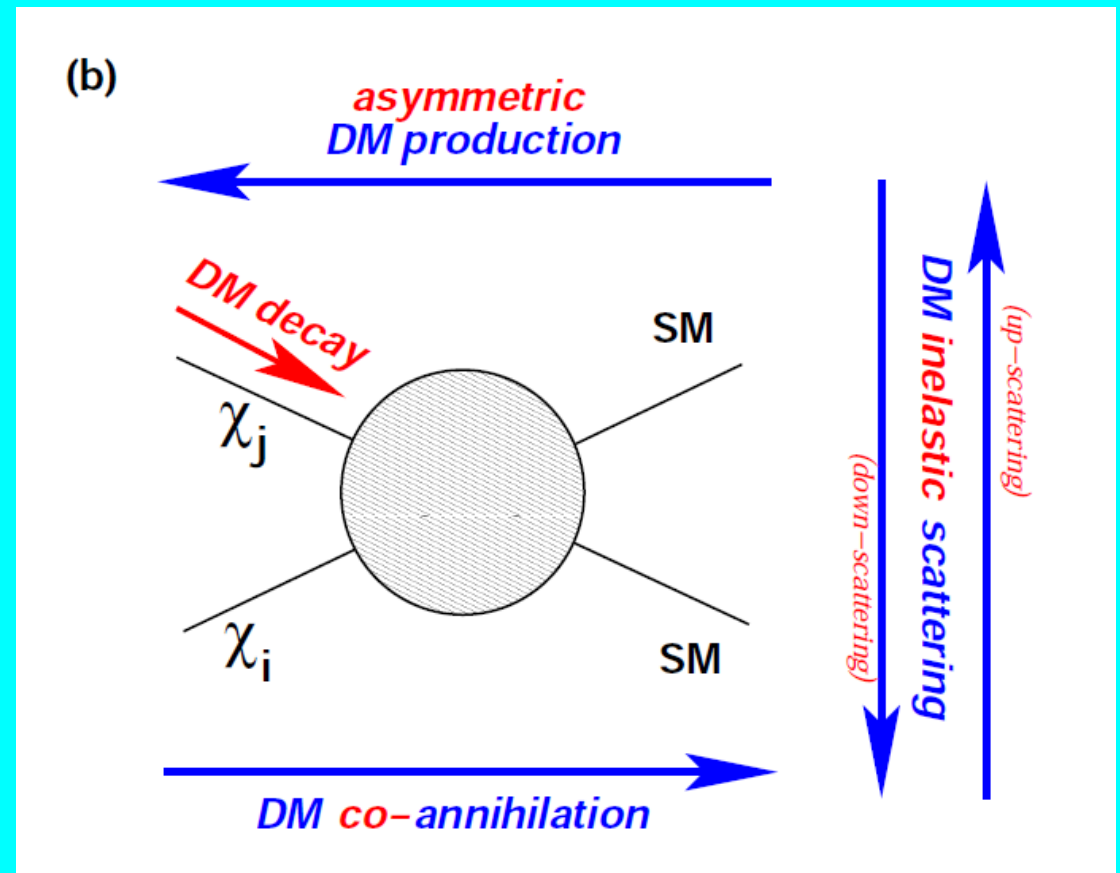
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*From this...*



- KR D, J. Kumar, B. Thomas & D. Yaylali, arXiv: 1406.4868
- KR D, J. Kumar, B. Thomas & D. Yaylali, arXiv: 1708.09698

 *to this...*



**Thus, the traditional DM complementarities are both *augmented and extended*.**

**Indeed, in some cases the “off-diagonal” processes may even dominate over the diagonal ones!**

# Over the past few years, many other DDM projects have been completed, or are actively in progress...

all with  
Brooks Thomas  
and ...

- New strategies for probing non-minimal dark sectors at colliders: beyond the standard “bump-hunt”: interplay/ correlations between different kinematic variables, their distributions, and potential cuts. ← w/ Shufang Su, 1407.2606
- New effects in direct detection: velocity suppression --- normally believed to render pseudoscalar couplings irrelevant --- can be overcome through special nuclear-physics effects. Thus direct-detection experiments can be sensitive to pseudoscalar DM/SM couplings, especially if isospin-violating effects are included! ← w/ Jason Kumar & David Yaylali, 1312.7772
- DDM implications for MeV-range cosmic-ray data and “energy duality” in the GeV GC cosmic-ray excess. ← w/ Kim Boddy, Doojin Kim, Jason Kumar & Jong-Chul Park, 1606.07440, 1609.09104
- Enhanced complementarities for multi-component dark sectors ← w/ Jason Kumar & David Yaylali, 1406.4869 (PRL), 1708.09698
- Cosmology with multiple scalar fields: Mixing, mass generation, and phase transitions in the early universe
  - Mixing effects can enhance and/or suppress dissipation of total energy density and alter distribution across different modes
  - Parametric resonances and other non-monotonicities emerge
  - *Re-overdamping:* new behaviors beyond pure vacuum energy or matter. ← w/ Jeff Kost, 1509.00470, 1612.08950

# And also...

all with  
**Brooks Thomas**  
and ...

- Other realizations of DDM ensembles

- “Deconstructed DDM”: resembles KK towers but with numerous unexpected discretization effects with new phenomenologies. ← w/ Barath Coleppa & Shufang Su
- “Random-matrix DDM”: ensembles from large hidden-sector gauge groups --- scaling behaviors emerge even from randomness! ← w/ Jake Fennick & Jason Kumar, 1601.05094

- DDM in string theory: not just KK states, but also *oscillator* states!

- Density of states grows *exponentially* ← w/ Fei Huang & Shufang Su, 1610.04112
- Hagedorn behavior, phase transitions, etc.

Moreover, this is mathematically equivalent to a strongly coupled dark sector with DM ensemble = hadron-like bound-state spectrum.

- Designing DDM ensembles via new *thermal* freezeout mechanisms. ← w/ Jake Fennick & Jason Kumar

- General decay constraints on multi-component dark sectors. ← w/ Jason Kumar & Pat Stengel

- KK towers as DDM ensembles in early-universe cosmology ← w/ Jeff Kost, 1612.08950

- The phenomenology of intra-ensemble decays in DDM scenarios ← w/ Fei Huang, Jeff Kost & Shufang Su

- DDM effects on

- Structure formation: complex behavior for Jeans instabilities ← (just Brooks & me!)
- Non-trivial halo structures ← w/ Ethan Garvey

- Gravitational back-reactions and applications to inflation ← w/ Jeff Kost; w/ Scott Watson

- DDM as a framework for exploring the dark-sector lifetime frontier via MATHUSLA ← w/ David Curtin

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w/ Barath Coleppa & Shufang Su

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- KK towers as DDM ensembles in early-universe cosmology

- The phenomenology of intra-ensemble decays in DDM scenarios

w/ Jeff Kost, 1612.08950

- DDM effects on

- Structure formation: complex behavior for Jeans instabilities
- Non-trivial halo structures

w/ Fei Huang, Jeff Kost & Shufang Su

(just Brooks & me!)

w/ Ethan Garvey

- Gravitational back-reactions and applications to inflation

w/ Jeff Kost; w/ Scott Watson

- DDM as a framework for exploring the dark-sector lifetime frontier via MATHUSLA

w/ David Curtin

# New Dark-Matter Phenomenologies from Thermal Freezeout

- KRD, J. Fennick, J. Kumar, B. Thomas, 1712.09919

Until recently, almost all work on DDM has assumed that the dark matter is produced in the early universe through **non-thermal** mechanisms such as misalignment production.


- Very natural if the DDM ensemble consists of the KK states of a massless gauge-neutral field propagating in extra dimensions.
- Indeed, DDM models in this class have been shown to have successful phenomenologies that satisfy all known constraints on dark matter!

*But what about thermal mechanisms such as freezeout?*


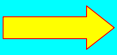
- This is the most widely discussed and exploited method of dark-matter abundance generation in the literature!
- This is even the underpinning of the WIMP miracle!
- Also leads to appropriate abundances for a broad range of dark-matter masses and couplings (WIMP-less miracle, other scenarios...)

**At first glance, it may appear that thermal freezeout is unsuitable as an abundance-generating mechanism for DDM...**

*Recall the fundamental feature of DDM: a balancing of abundances against lifetimes across the dark-matter ensemble.*

Shorter lifetimes  smaller abundances!

However, increasing mass

-  larger phase space for decay, also more possible decay modes
-  lifetime generally drops!

**Thus, DDM tends to require abundance-generating mechanisms for which larger masses lead to smaller abundances...**

$$\Omega_i \sim m_i^\gamma \quad \text{where } \gamma < 0$$

 negative scaling exponent!



Misalignment production naturally has this property.

**However, this is not what typically emerges in thermal freezeout!**

Recall the WIMP miracle ---

$$\Omega_\chi \sim \frac{m_\chi^2}{g_\chi^4} \quad \longrightarrow \quad \gamma = +2 \quad (\text{canonical value})$$

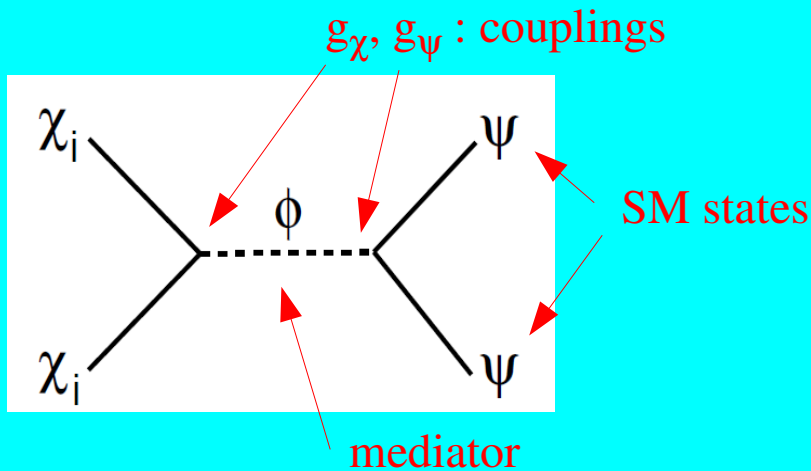
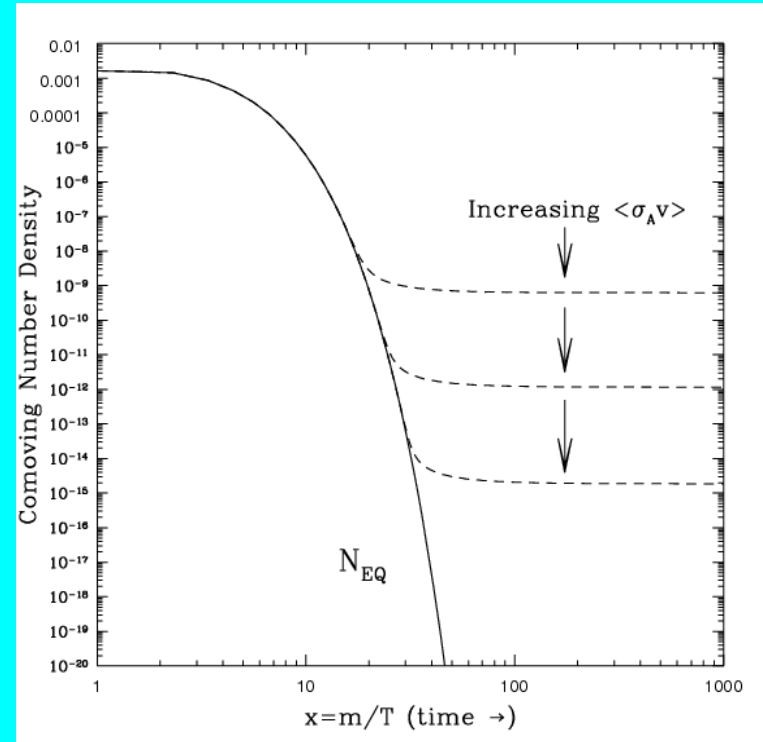
Short of adjusting the couplings in a mass-dependent way,  
how then can we obtain  $\gamma < 0$  ?

# To see how to proceed, let's first recall how this result is derived...

In general, freezeout abundance  $\Omega_\chi$  depends on thermally averaged DM annihilation cross-section:

$$\Omega_\chi \sim \langle \sigma_\chi v \rangle^{-1}$$

For simplicity, let's assume an annihilation process of the form



For heavy dark matter  $m_\chi \gg m_\phi, m_\psi$ :

$$\langle \sigma v \rangle \sim \frac{g_\chi^2 g_\psi^2}{m_\chi^2}$$

(non-rel:  $E_\chi \sim m_\chi$ )

$$\Omega_\chi \sim \frac{m_\chi^2}{g_\chi^2 g_\psi^2}$$

$$\gamma = 2!$$

# How then can we “flip” the abundance spectrum?

Need to flip the power of energy in the denominator of the cross-section.

**Fortunately, there is an easy way to do this!**

If we imagine the mediator has a mass  $m_\phi$ ,

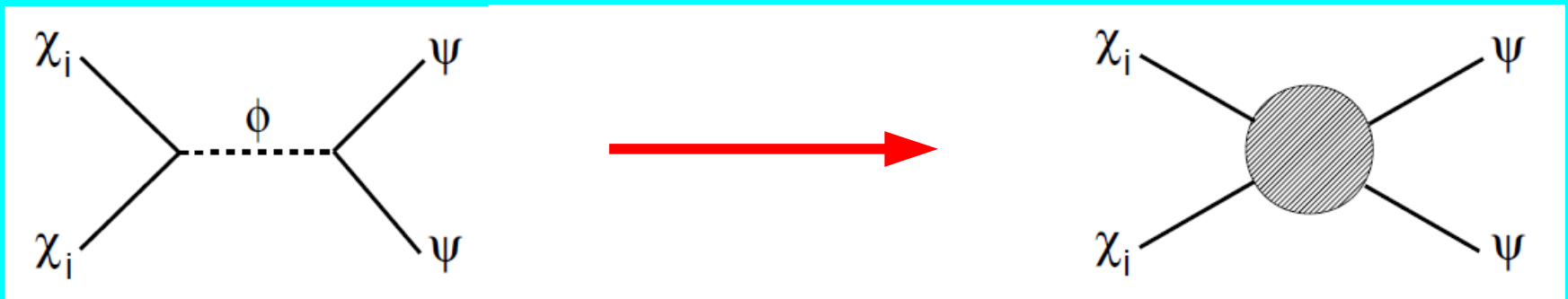
then there is a natural process which amounts to replacing

$$\frac{g_\chi^2 g_\psi^2}{E^2} \longrightarrow G^2 E^2$$

with dimensionful coupling

$$G \equiv g_\chi g_\psi / m_\phi^2$$

**Simply integrate out the mediator!**



**Integrating Out Before Freezing Out!**

**Thus, if we have a DDM ensemble w/ constituent masses  $m_i$  ...**

$$\begin{aligned} m_i \gg m_\phi : \quad \Omega_i &\sim m_i^2 & \implies \gamma = +2 , \\ m_i \ll m_\phi : \quad \Omega_i &\sim m_i^{-2} & \implies \gamma = -2 . \end{aligned}$$

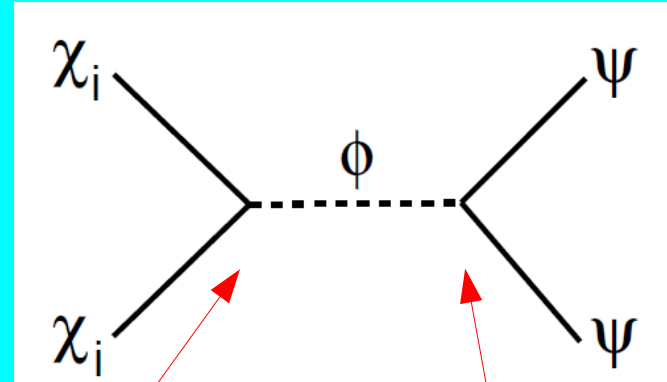
As long as the mediator is chosen to be heavier than all relevant ensemble constituents, thermal freezeout can produce a spectrum of abundances of the form that DDM requires!



**The DDM framework can be successfully extended into the thermal domain!**

# In fact, even richer possibilities exist for model-building...

Consider general  $s$ -channel annihilation processes:



Even within this topology, can consider different spins for  $\chi$ ,  $\phi$ ,  $\psi$  and different coupling structures at each vertex...

$\chi_i$	$\phi$	coupling	$\epsilon_\chi$	$r$
spin-0	spin-0	S: $g_\chi \mu \chi^* \chi \phi$	1	0
spin-1/2	spin-0	S: $g_\chi \bar{\chi} \chi \phi$	0	1
spin-1/2	spin-0	P: $g_\chi \bar{\chi} \gamma_5 \chi \phi$	0	0
spin-0	spin-1 (time)	V: $g_\chi (\chi^* \partial_0 \chi) \phi^0$	—	—
spin-0	spin-1 (spatial)	V: $g_\chi (\chi^* \partial_i \chi) \phi^i$	0	1
spin-1/2	spin-1 (time)	V: $g_\chi \bar{\chi} \gamma_0 \chi \phi^0$	—	—
spin-1/2	spin-1 (spatial)	V: $g_\chi \bar{\chi} \gamma_i \chi \phi^i$	0	0
spin-1/2	spin-1 (time)	A: $g_\chi \bar{\chi} \gamma_0 \gamma_5 \chi \phi^0$	0	0
spin-1/2	spin-1 (spatial)	A: $g_\chi \bar{\chi} \gamma_i \gamma_5 \chi \phi^i$	0	1

$\phi$	$\psi$	coupling	$\epsilon_\psi$	$s$	$t$
spin-0	spin-0	S: $g_\psi \mu \phi \psi^* \psi$	1	0	0
spin-0	spin-1/2	S: $g_\psi \phi \bar{\psi} \psi$	0	1	0
spin-0	spin-1/2	P: $g_\psi \phi \bar{\psi} \gamma_5 \psi$	0	0	0
spin-1 (time)	spin-0	V: $g_\psi \phi^0 (\psi^* \partial_0 \psi)$	—	—	—
spin-1 (spatial)	spin-0	V: $g_\psi \phi^i (\psi^* \partial_i \psi)$	0	1	0
spin-1 (time)	spin-1/2	V: $g_\psi \phi^0 \bar{\psi} \gamma_0 \psi$	—	—	—
spin-1 (spatial)	spin-1/2	V: $g_\psi \phi^i \bar{\psi} \gamma_i \psi$	0	0	0
spin-1 (time)	spin-1/2	A: $g_\psi \phi^0 \bar{\psi} \gamma_0 \gamma_5 \psi$	0	0	1
spin-1 (spatial)	spin-1/2	A: $g_\psi \phi^i \bar{\psi} \gamma_i \gamma_5 \psi$	0	1	0

Proceeding as before, we then find

$$\Omega(m) \sim \frac{m^2}{g_\chi^2 g_\psi^2} m^{2(\epsilon_\chi + \epsilon_\psi + t)} \frac{(1 - m_\phi^2/4m^2)^2}{(1 - m_\psi^2/m^2)^{s+1/2}}$$

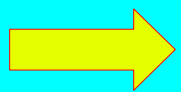
contribution  
from mediator

DM mass

canonical  
contribution

possible  
super-renormalizable  
and chirality-suppressed  
couplings to mediator

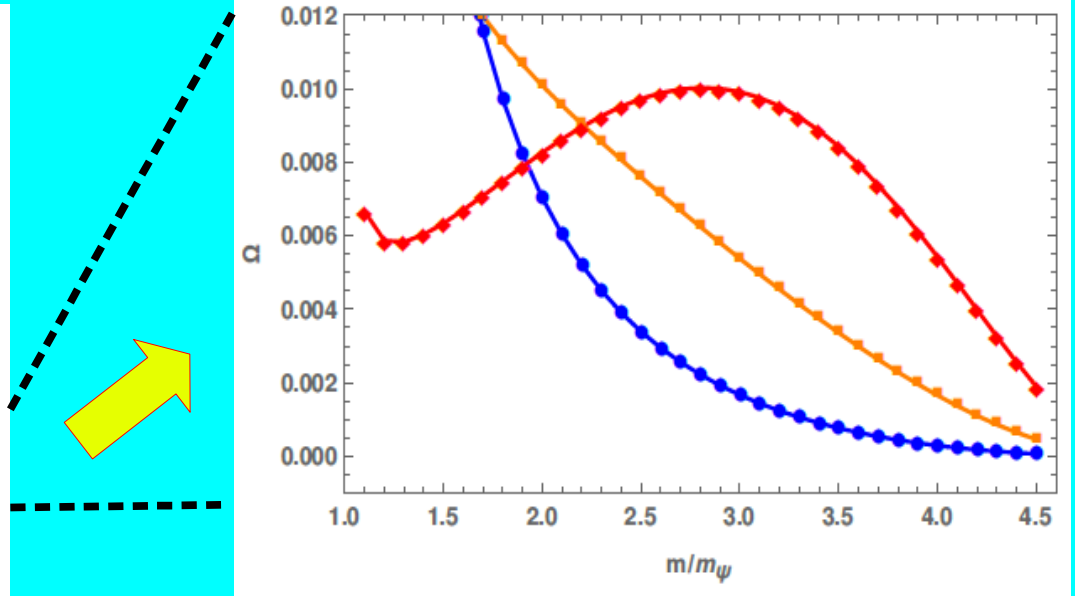
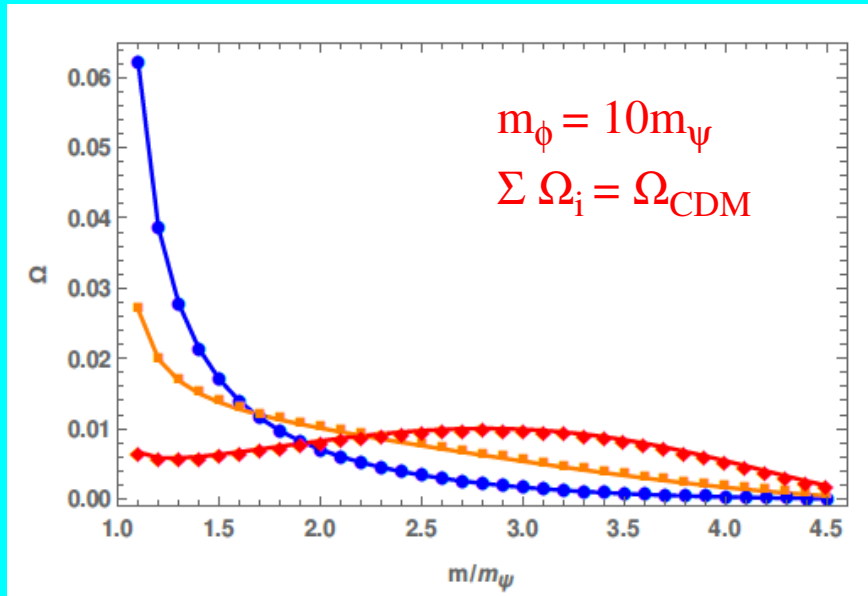
final-state  
kinematic effects



$$\gamma(m) = 2 + \Delta\gamma + \frac{1}{m^2/m_\phi^2 - 1/4} + \frac{2s + 1}{1 - m^2/m_\psi^2}$$

Highly non-trivial scaling exponents as functions of mass!

Many behaviors are possible, all resulting from thermal freezeout!  
For example...



- In some parts of the ensemble, abundances can fall while in other parts abundances can rise – *all within a standard cosmology!*
- One can even have special states receiving abundances which are local maxima or local minima!
- Possibilities for model-building are rich and barely explored...

# DDM and Cosmological Phase Transitions

- KRD, J. Kost, B. Thomas, 1509.00470
- KRD, J. Kost, B. Thomas, 1612.08950

As we have seen, within the DDM framework the dark sector comprises an ensemble of different states.

In general, these states not only have different masses, but can also have different mixings.

However, in the presence of a cosmological phase transition, these mixings can dramatically alter

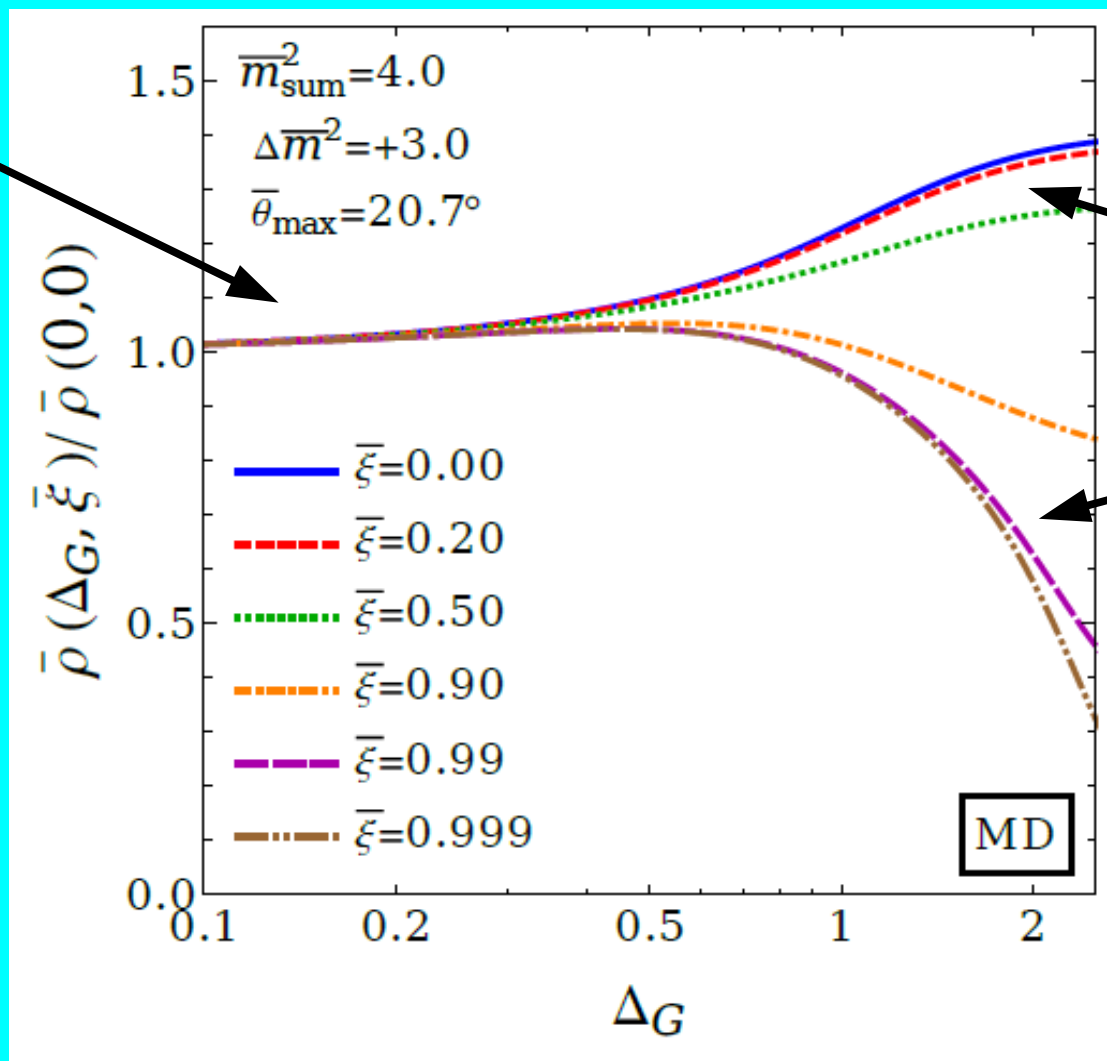
- not only the total late-time energy density of the ensemble
- but also the distribution of the energy densities across the different constituents!

Moreover, these effects depend extremely sensitively on the length of time over which the phase transition unfolds...!



E.g., consider only two scalars which mix and receive masses through a cosmological phase transition...

mixing has **no effect** with rapid phase transition (in this regime)



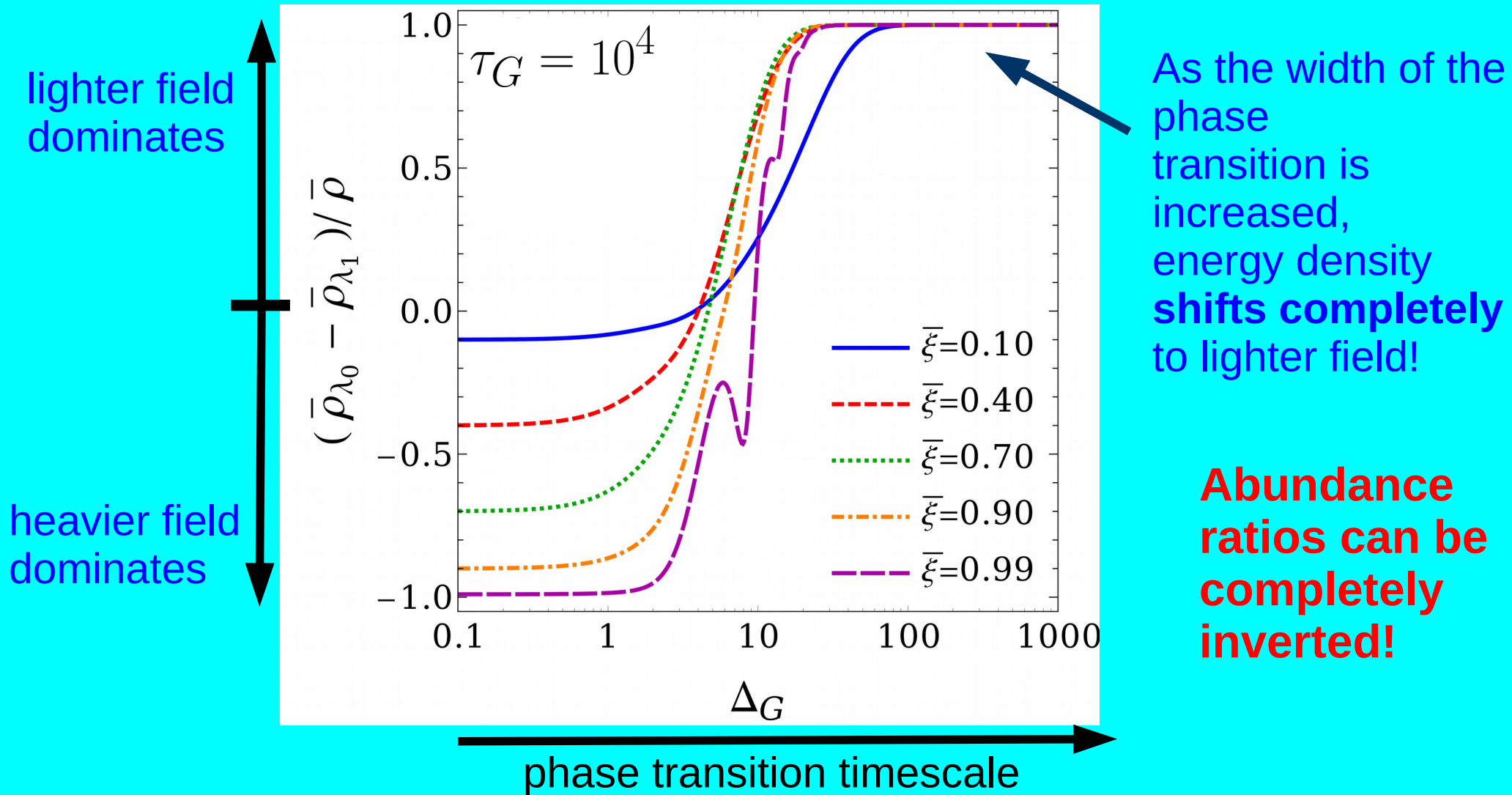
an **enhancement** develops for small mixing, while a **suppression** develops when mixing is highly saturated!

Can be relevant for theories with multiple axions, even if only weakly mixed!

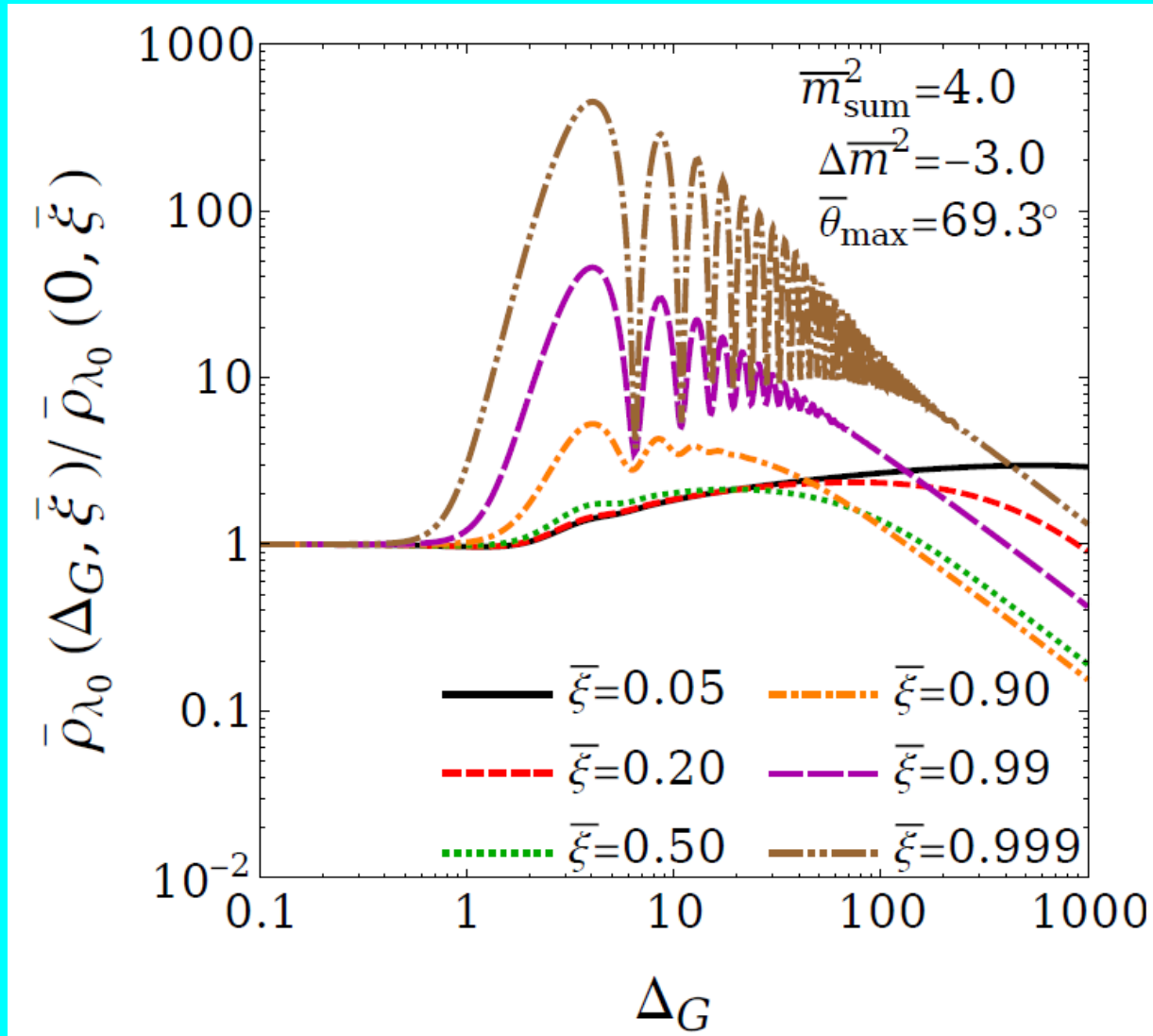
phase transition timescale

- KRD, J. Kost, B. Thomas, 1509.00470, 1612.08950

If we compare the distribution of the total late-time energy density between the two components, we find



There are also other effects that can emerge which significantly affect the late-time abundances of these scalar fields...



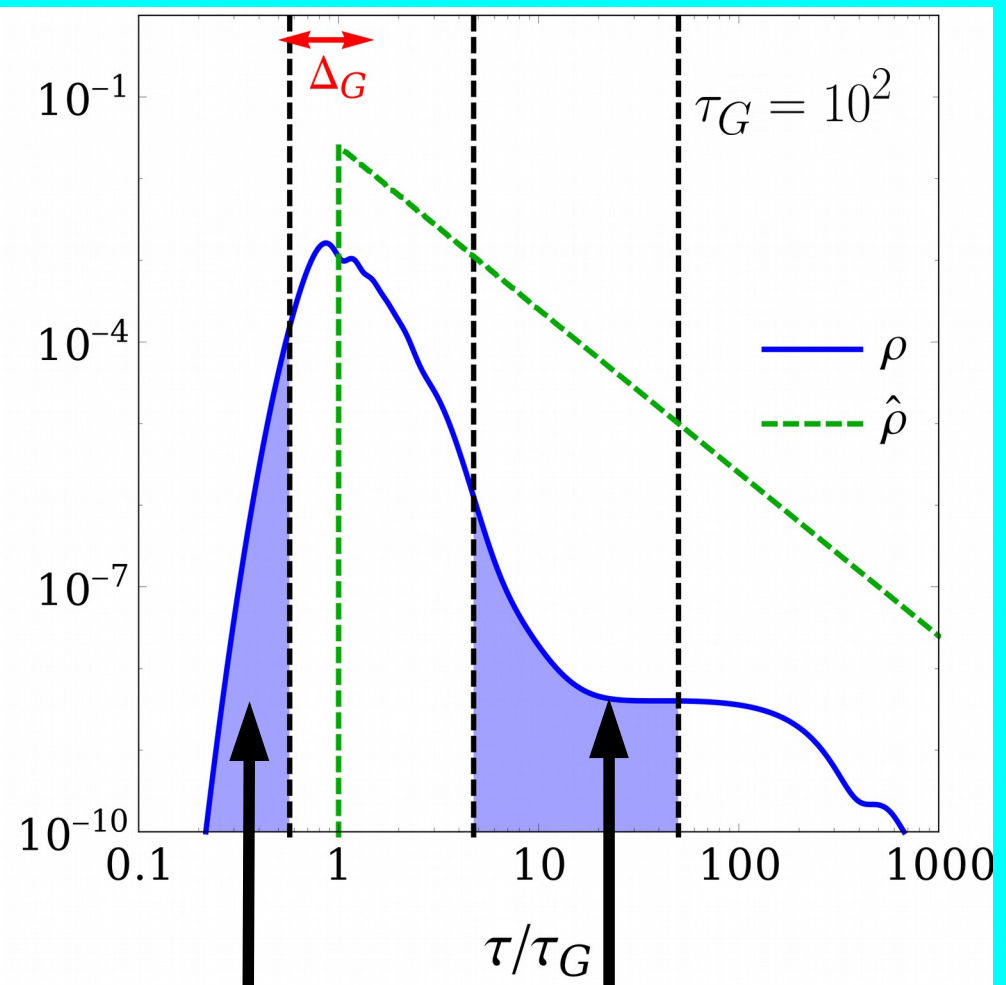
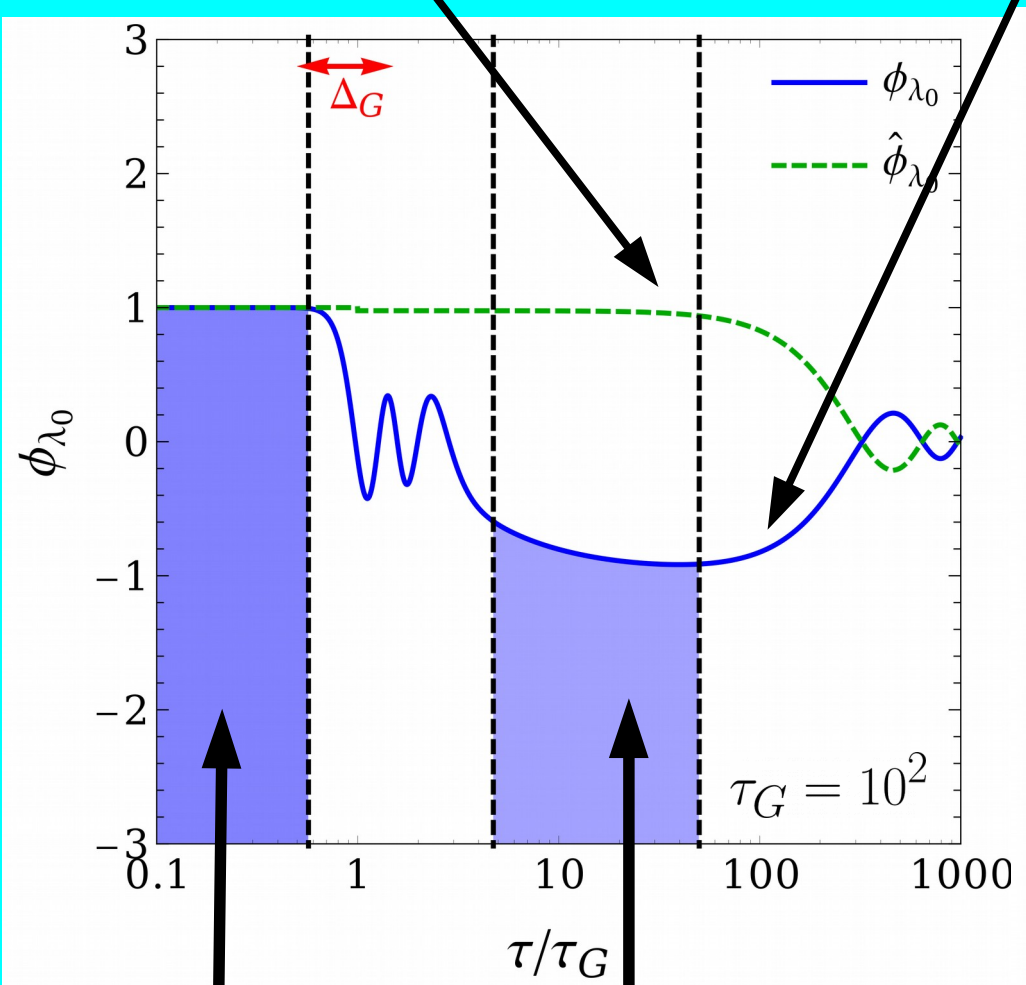
e.g., parametric resonances that arise due to the non-trivial interplay between the **mixing** and non-zero timescale (**width**) associated with the mass-generating phase transition!

**Can enhance the resulting late-time energy densities by many orders of magnitude!**

# In fact, in some cases, an entirely new field behavior (“re-overdamping”) emerges... *not vacuum energy and not matter!*

Field behavior if phase transition had been instantaneous.

True field behavior



overdamping

re-overdamping

overdamping

re-overdamping

## DDM, MATHUSLA, and the Lifetime Frontier

One central characteristic feature of the DDM framework is that the DDM ensemble generically contains states exhibiting an entire spectrum of lifetimes.

As a result, if the DDM ensemble is produced in a collider, certain states within the ensemble may decay promptly while others may escape as missing energy.

Most excitingly, however, there will also be states in an *intermediate* range which are relatively long-lived but not infinitely so, giving rise to finite but macroscopic displaced vertices on the orders of  $\sim 10^2$  meters. *This is an entirely new frontier of parameter space: the lifetime frontier!*

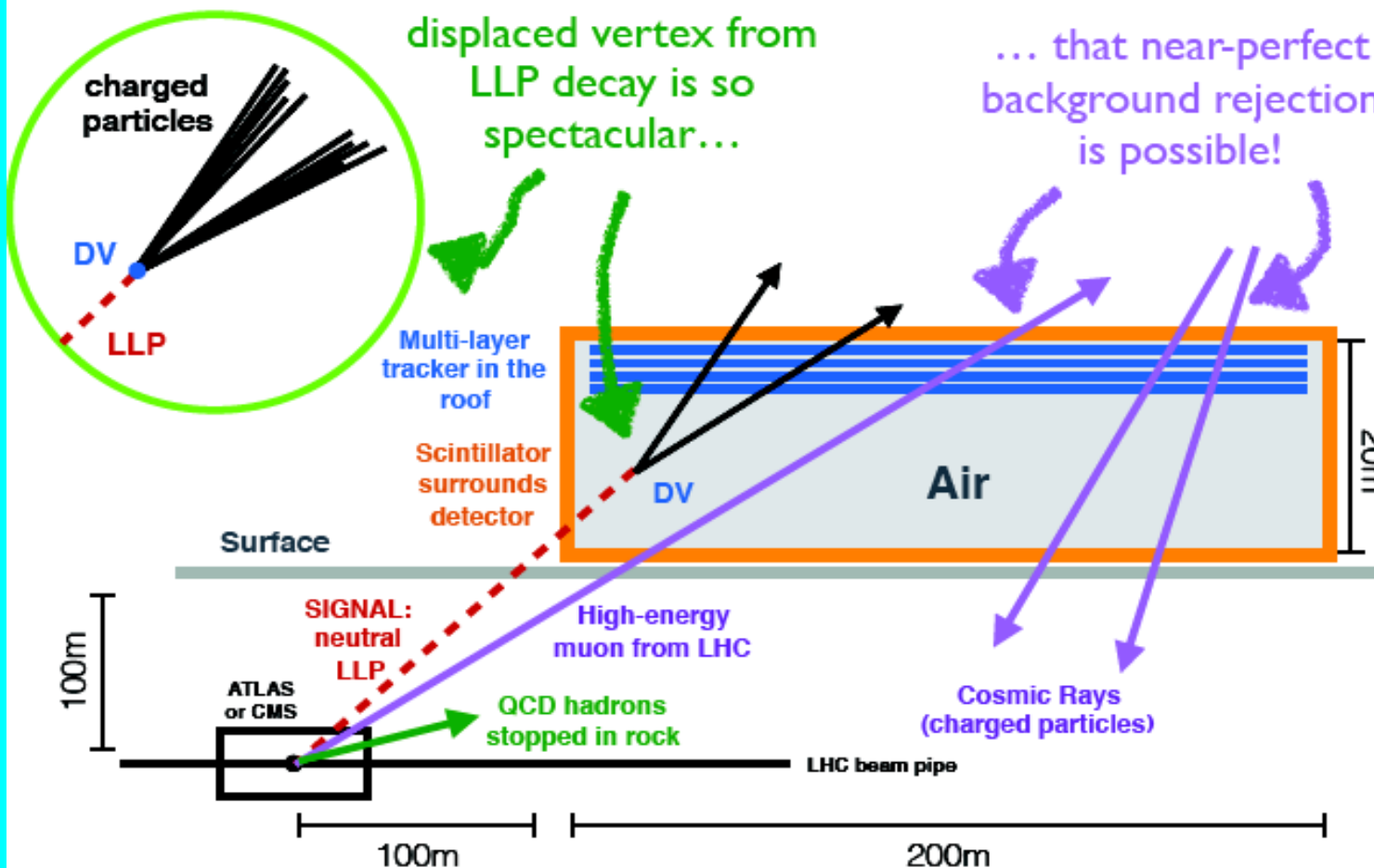
Why is this particularly exciting now?

# MATHUSA

John-Paul Chou  
David Curtin  
Henry Lubatti  
1606.06298



## MASSIVE Timing Hodoscope for ULtra-Stable NeutraL PArticles



On schedule for

prototype  
mid 2017  
letter of intent  
end 2017

Theory  
White Paper  
May 2016  
May 2018

new!!

MATHUSLA is a unique instrument for detecting Long-Lived Particles (LLP's) of all sorts. As such, its power extends beyond the specific realm of dark-matter searches.

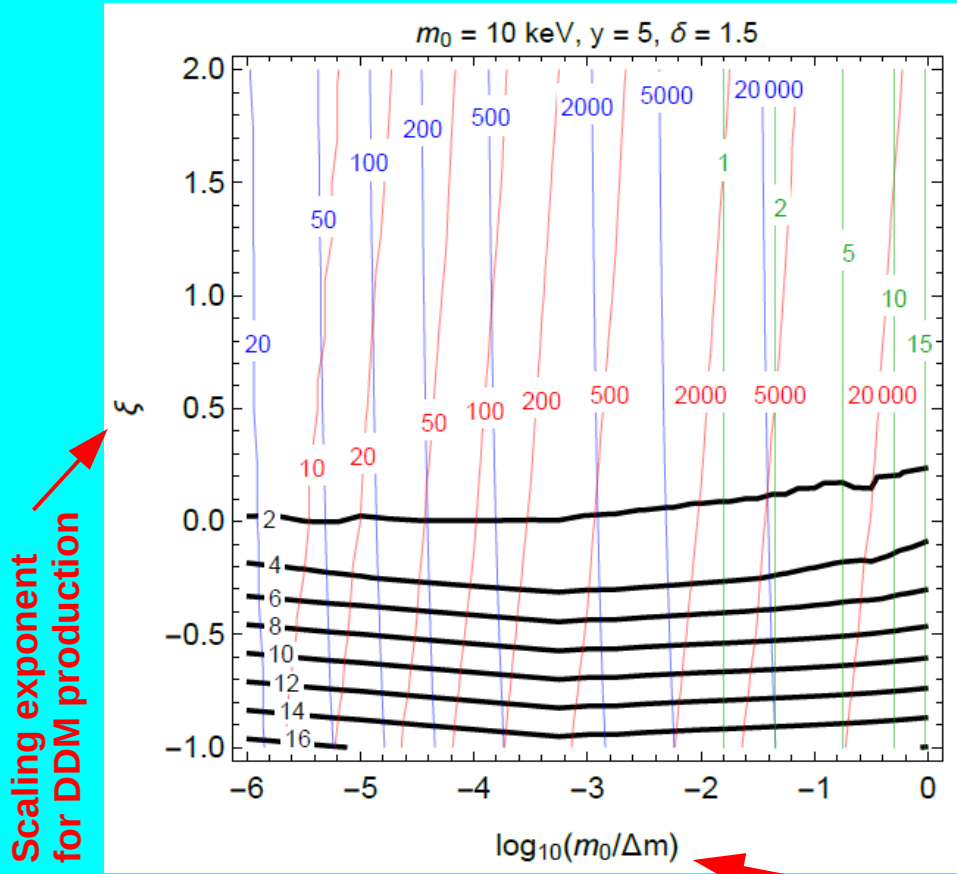
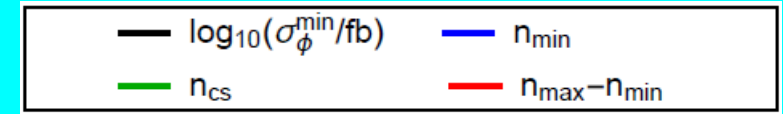
However, for dark matter, MATHUSLA is ideally capable of probing portions of the DDM ensemble (and thus regions of DDM parameter space) which may be beyond those accessible through other means!

**MATHUSLA may thus eventually play an important role in probing (and thereby helping to confirm) the DDM nature of the dark sector.**

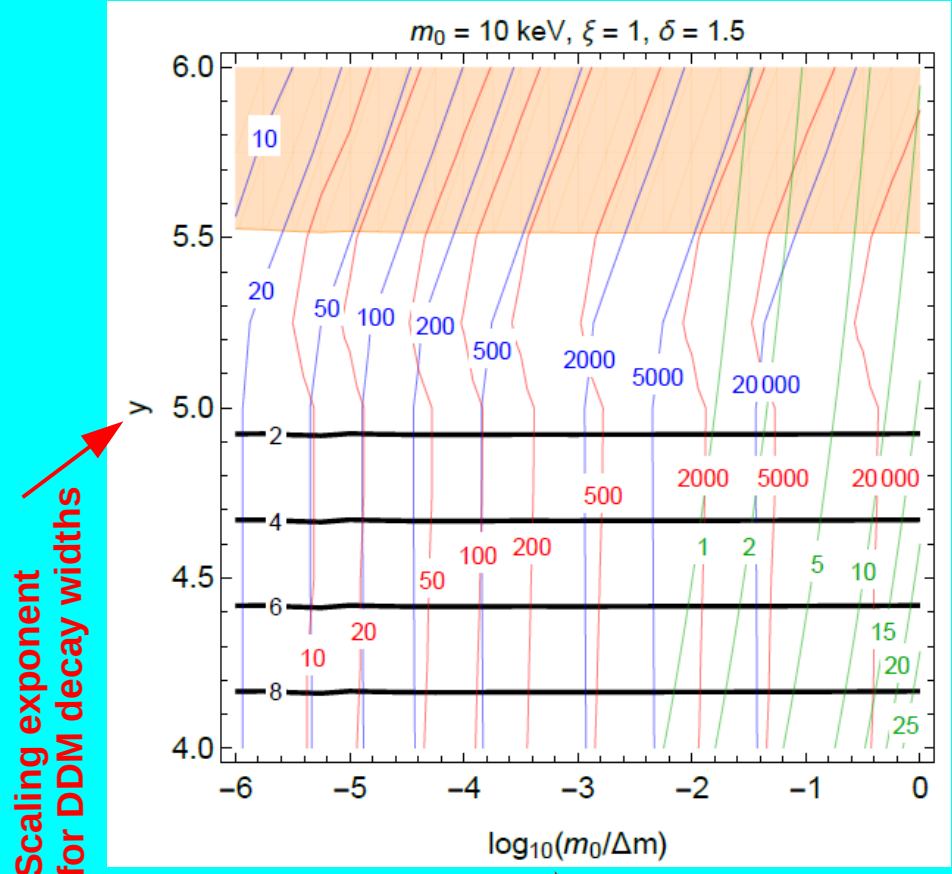
- D. Curtin, KRD & B. Thomas, 1805.xxxxx



# The reach of the MATHUSLA detector within the DDM parameter space...



Scaling exponent for DDM production



Scaling exponent for DDM decay widths

There exist large “sweet spots” in which multiple light DDM states comprise the present-day dark matter, while heavier states in the same DDM ensemble lead to an observable signal at MATHUSLA!

$$m_n = m_0 + (\Delta m) n^\delta$$

DDM ensemble spectrum



# Conclusions

The Dynamical Dark Matter (DDM) framework is ripe with new possibilities for dark-matter physics.

*Although the internal structure of the DDM ensemble is generally organized and governed by very specific scaling relations, this framework reaches far beyond the WIMP paradigm and extends into almost every corner of dark-matter parameter space in an organized and controlled way.*

Indeed, as we have seen, even the standard variables that are traditionally used for characterizing the dark-matter parameter space (mass, cross section, etc.) no longer apply!

Thus, almost every traditional line of investigation in dark-matter physics must be re-analyzed and re-evaluated in this context.

But perhaps most importantly...

# The Take-Home Message

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

- *Stability and minimality are not fundamental properties of the dark sector!*
- *All that is required is a phenomenological balancing of lifetimes against abundances. A much richer **dynamical** dark sector is possible!*
- *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 non-minimality and instability allow!