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

Tucson, Arizona

- **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: 1807.nnnnn**
  (D. Curtin, KRD & B. Thomas)

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.

IDM 2018 Conference
Brown University, 7/23/2018

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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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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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- 1808.xxxxx (also w/ J. Kumar & P. Stengel)
- 1809.xxxxx (also w/ Y. Buyukdag & T. Gherghetta)
- **… plus ongoing collaborations with others in this room!**

NOVA Next, 5/30/2018:

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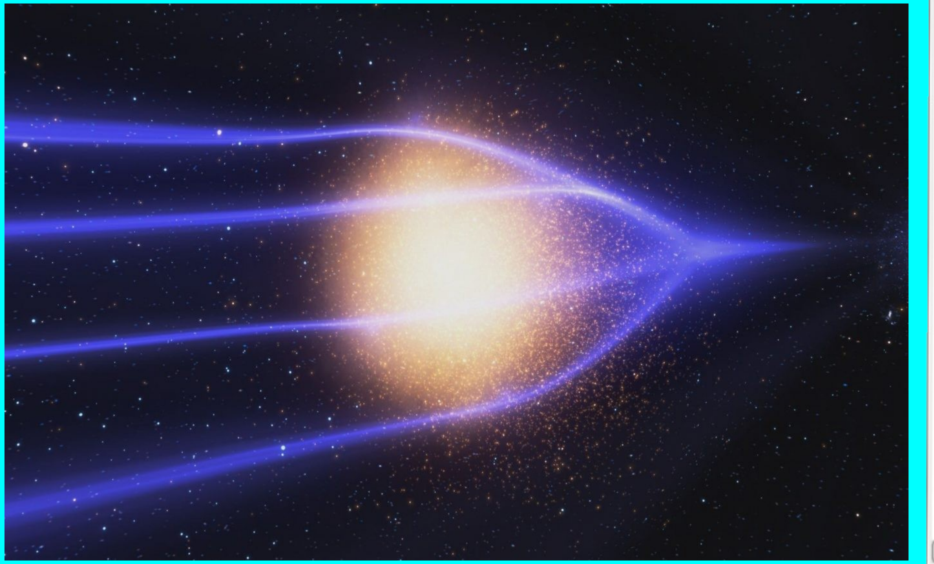
STORYLINE : *Understanding Space and Time*



Does Dark Matter Ever Die?

By Kate Becker on Wed, 30 May 2018

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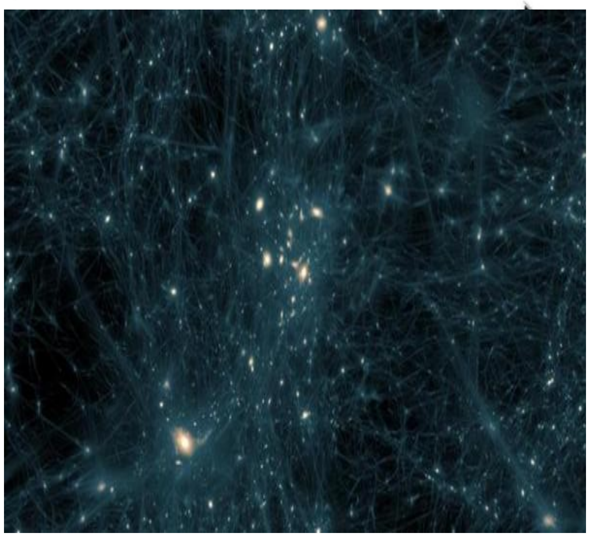


Dark matter is the unseen hand that fashions the universe. It decides where galaxies will form and where they won't. Its gravity binds stars into galaxies and galaxies into galaxy clusters. And when two galaxies merge, dark matter is there, sculpting the product of the merger. But as for what dark matter actually is? No one knows.

Here's the short list of what we do know about dark matter. Number one: There's a lot of it, about five times more than "ordinary" matter. Two: It doesn't give off, reflect, or absorb light, but it does exert gravity, which is what gives it a driver's-seat role in the evolution of galaxies. Three: It's stable, meaning that for almost 13.8 billion years—the current age of the universe—dark matter hasn't decayed into anything else, at least not enough to matter much. In fact, the thinking goes, dark matter will still be around even when the universe is quintillions (that's billions of billions) years old—maybe even forever.

- http://www.pbs.org/wgbh/nova/next/physics/dynamical-dark-matter/
- https://www.realclearscience.com/2018/05/31/does_dark_matter_ever_die_281450.html

This talk…

- Dynamical Dark Matter

  --- a quick overview, 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) χ which carry entire DM abundance: $\Omega_\chi = \Omega_{CDM} = 0.26$ (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": Ω_{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 >>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, 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 ---
<u>a balancing of decay widths against abundances</u>:

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!

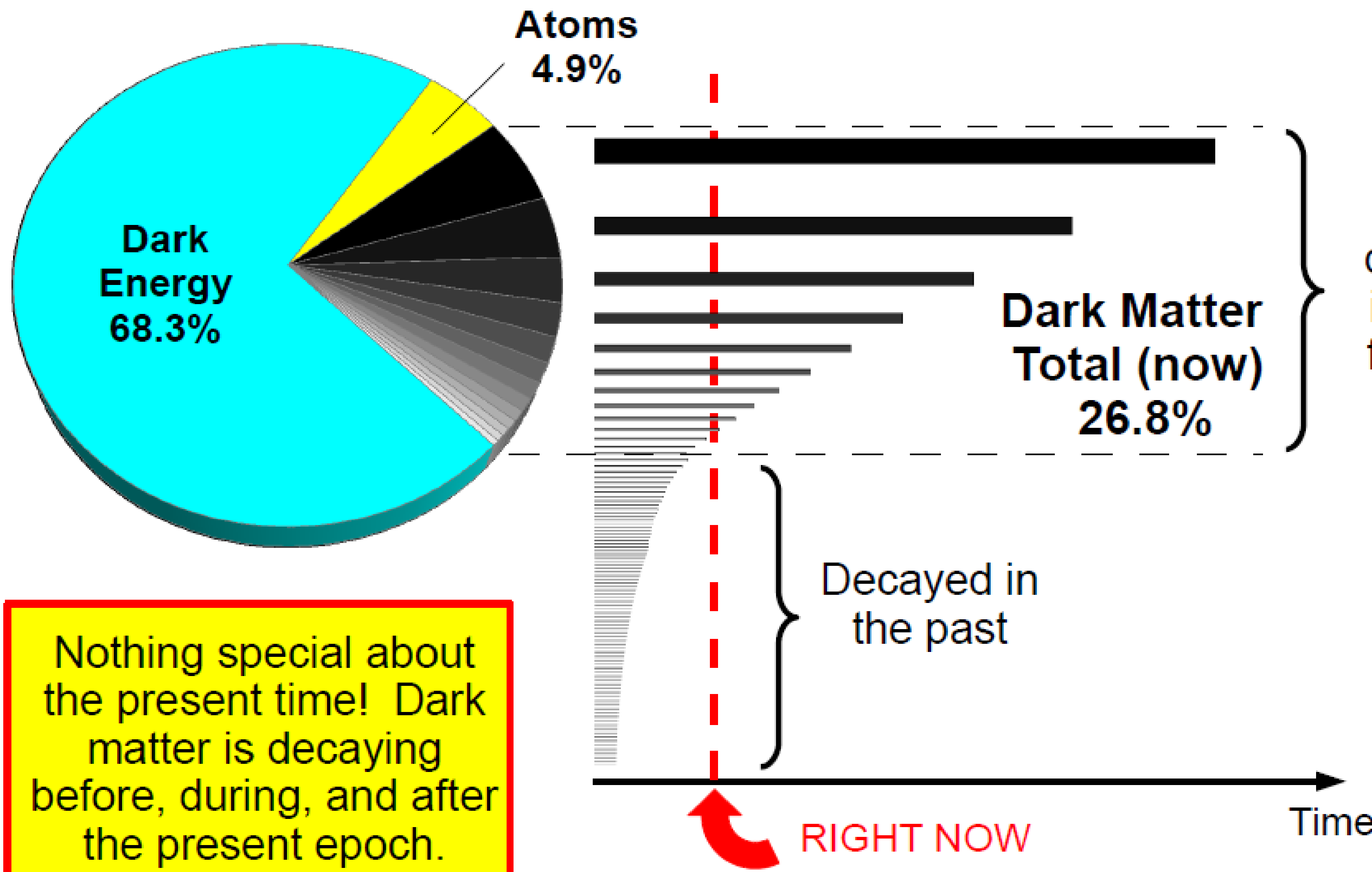
<u>Dynamical Dark Matter (DDM)</u>: an alternative framework for dark-matter physics in which the notion of dark-matter stability is replaced by a balancing of lifetimes against cosmological abundances across an ensemble of individual dark-matter components with different masses, lifetimes, and abundances.

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!***

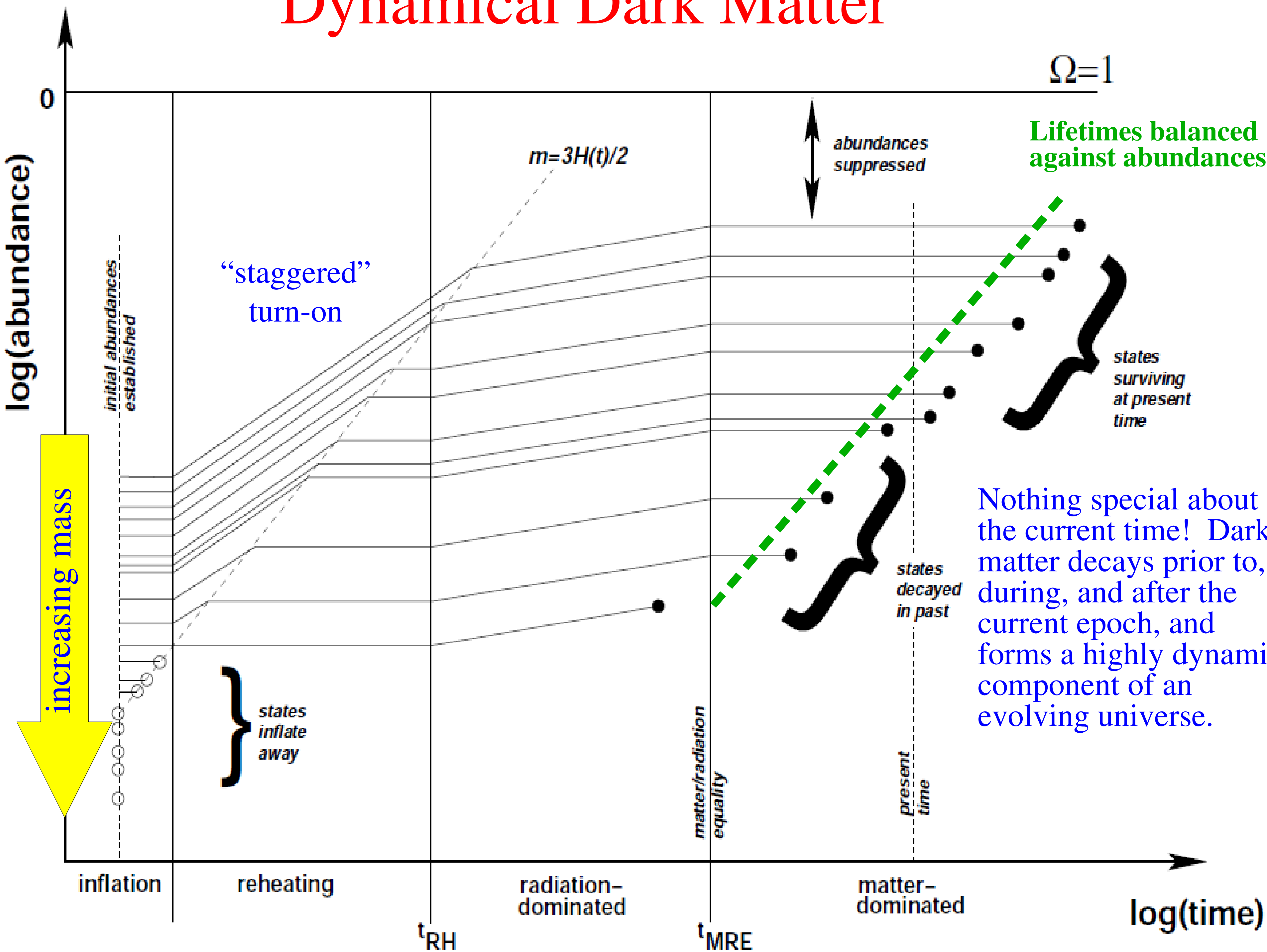
"Dynamical Dark Matter": The Basic Picture:

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



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

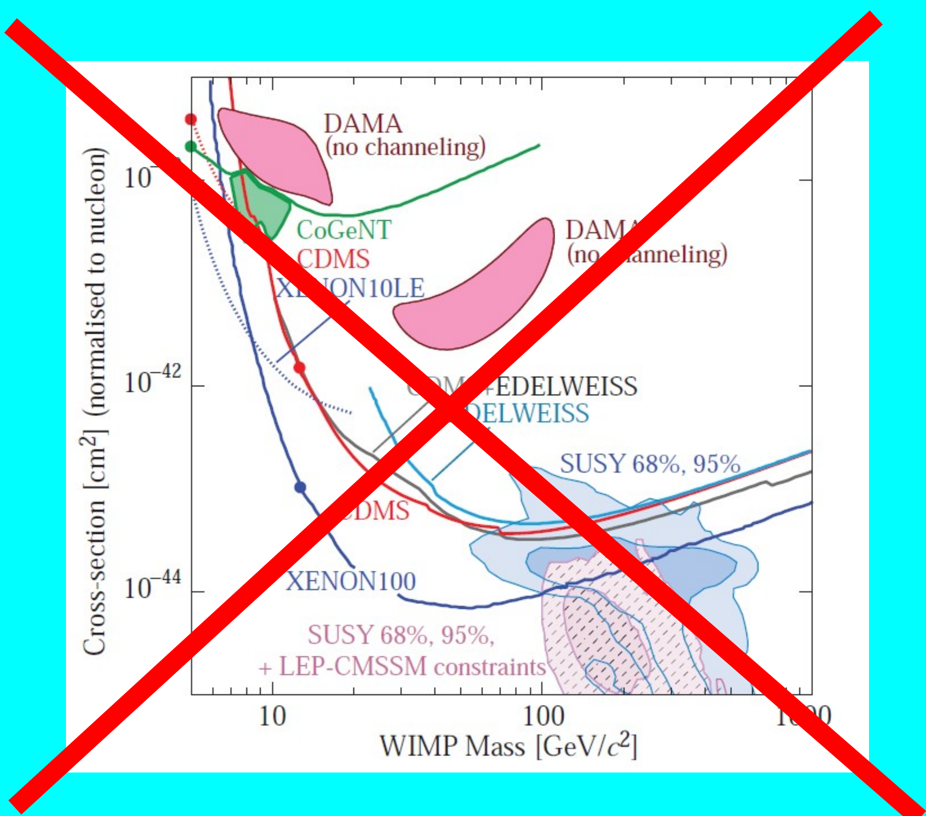
Dynamical Dark Matter



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 evolving universe.

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!

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

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.

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
- KRD, J. Kumar & B. Thomas, 1306.2959
- KRD, J. Kumar, B. Thomas & D. Yaylali, 1406.4868
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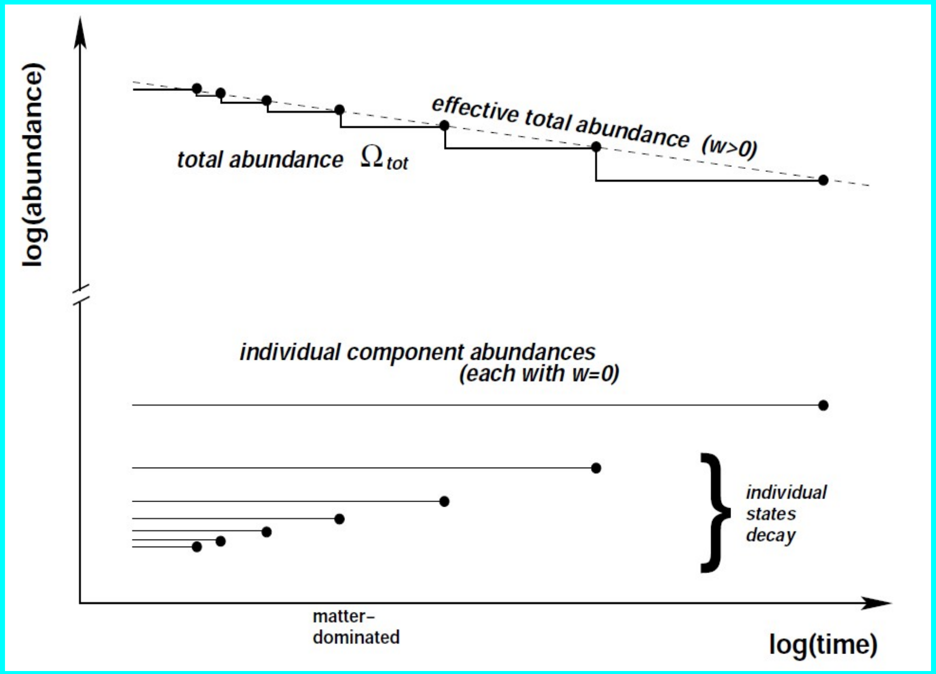
- KRD, J. Kumar, P. Stengel & B. Thomas, 1808.xxxxx
- Y. Buyukdag, KRD, T. Ghergehtta & B. Thomas, 1809.xxxxx

- 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 Ω_{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.,

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

$$\alpha < 0$$

density of states *per unit Γ*

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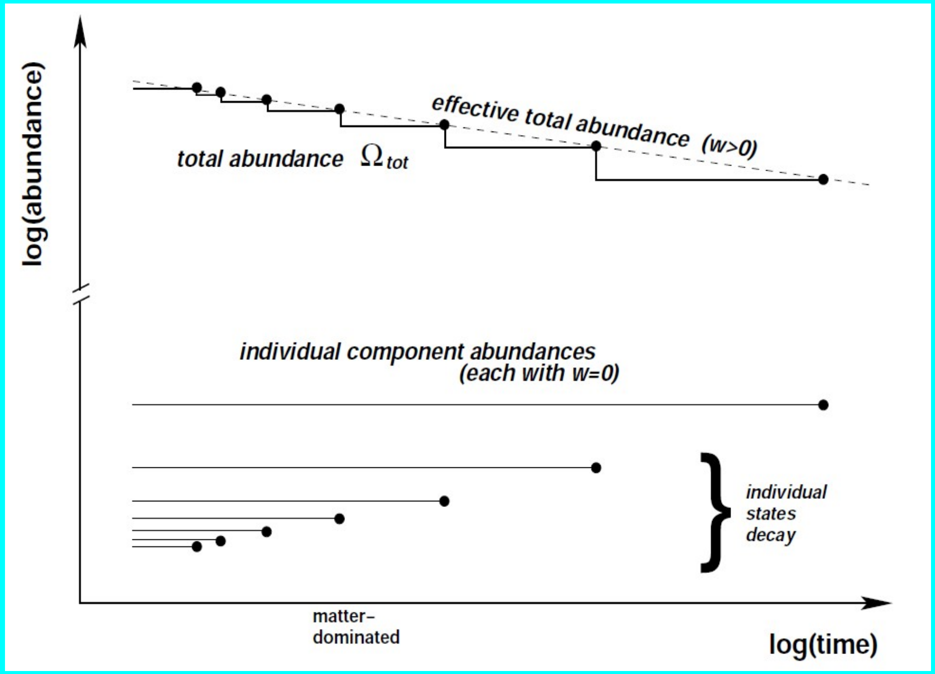


- **For** $x \equiv \alpha + \beta \neq -1$ **:**

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

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

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

- KRD & B. Thomas, arXiv: 1107.0721
- KRD & B. Thomas, arXiv: 1203.1923

<u>Specific DDM models exist which satisfy all known constraints:</u> For example, 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

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

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

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?

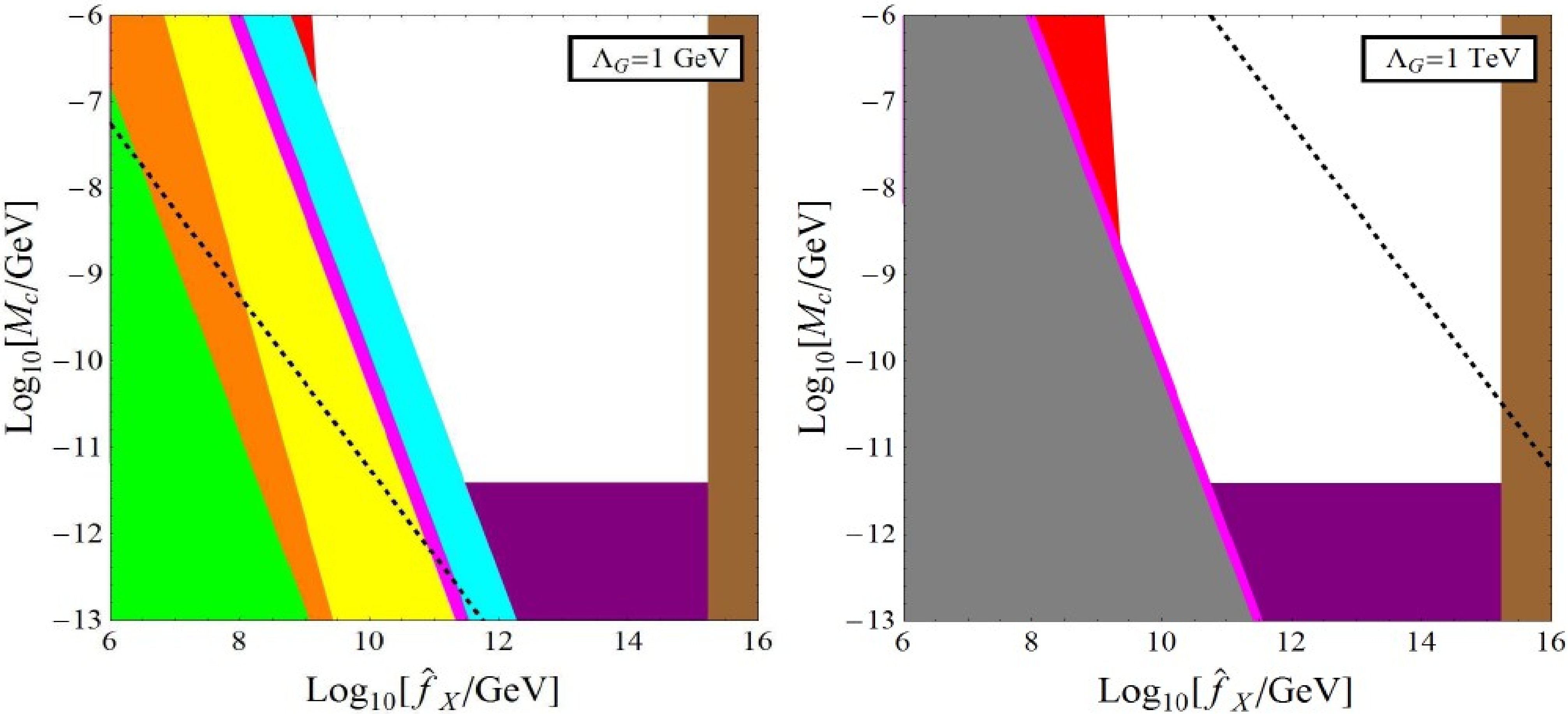
- GC (globular cluster) stars. Axions might carry away energy too efficiently, altering stellar lifetimes. GC stars give most stringent bound.
- SN1987a. Same --- axions would effect energy loss rate.
- Diffuse photon/X-ray backgrounds. Axion decays to photons would leave unobserved imprints.
- Eotvos.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

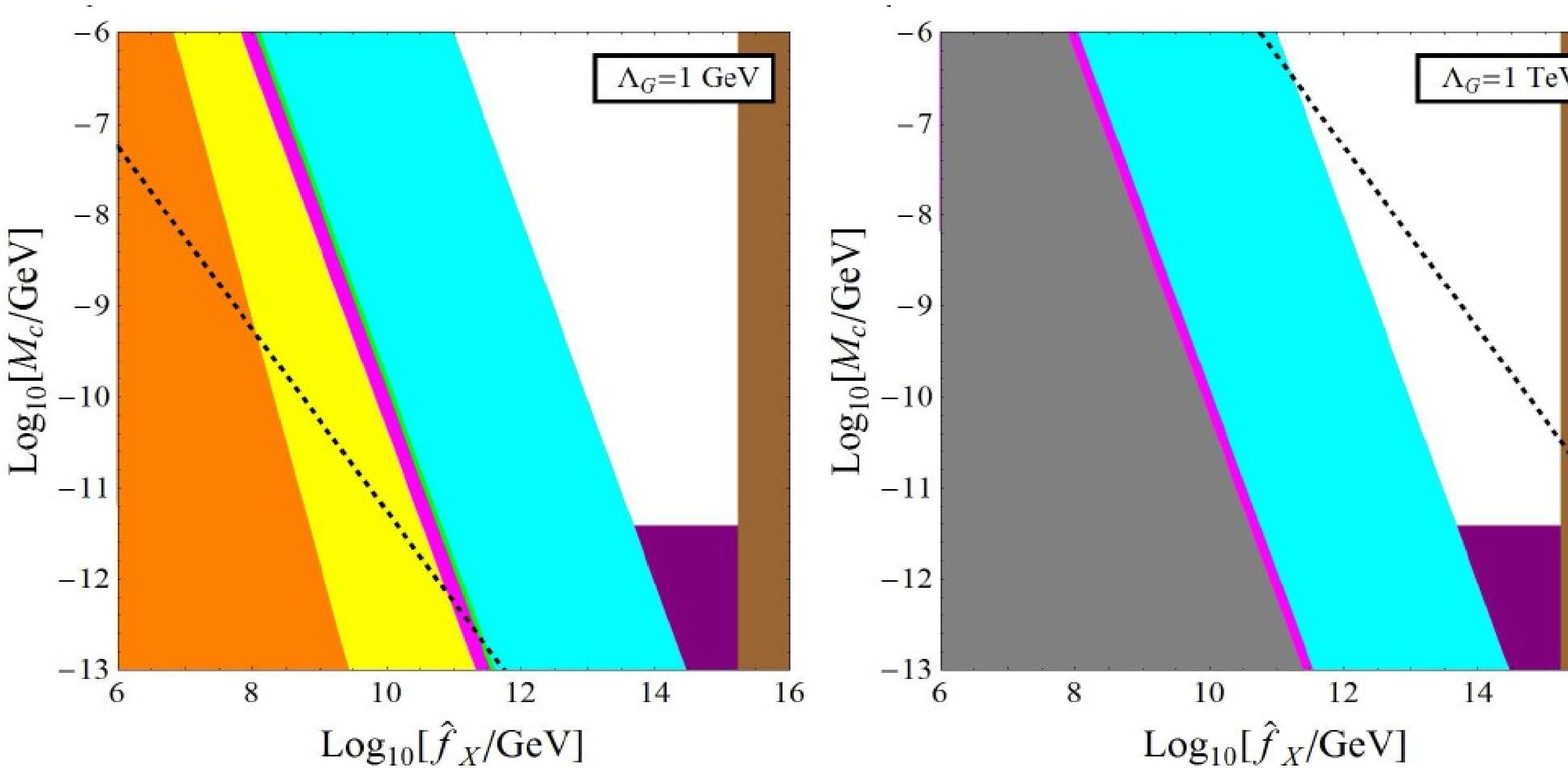


Combined Limits on Dark Towers

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



Experimental signatures of DDM

How can we distinguish DDM...

- at colliders (LHC)
- at the current/next generation of direct-detection experiments
  (e.g., XENON 1T, SuperCDMS, LZ, PANDA-X, DarkSide)
- 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
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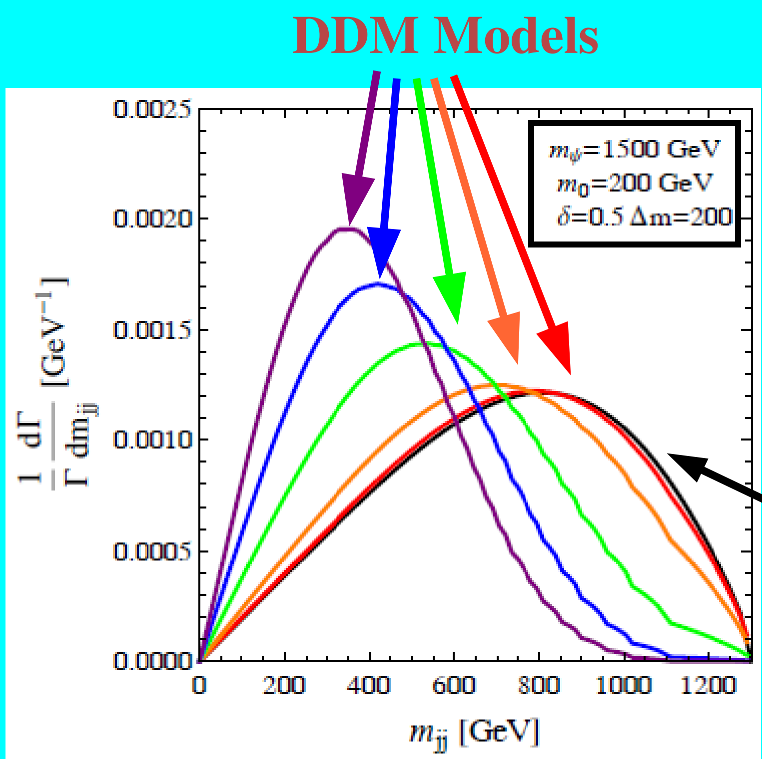
- K. Boddy, KRD, D. Kim, J. Kumar, J.C. Park & B. Thomas, arXiv: 1606.07440
- KRD, J. Kumar, B. Thomas, and D. Yaylali, arXiv: 1708.09698

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



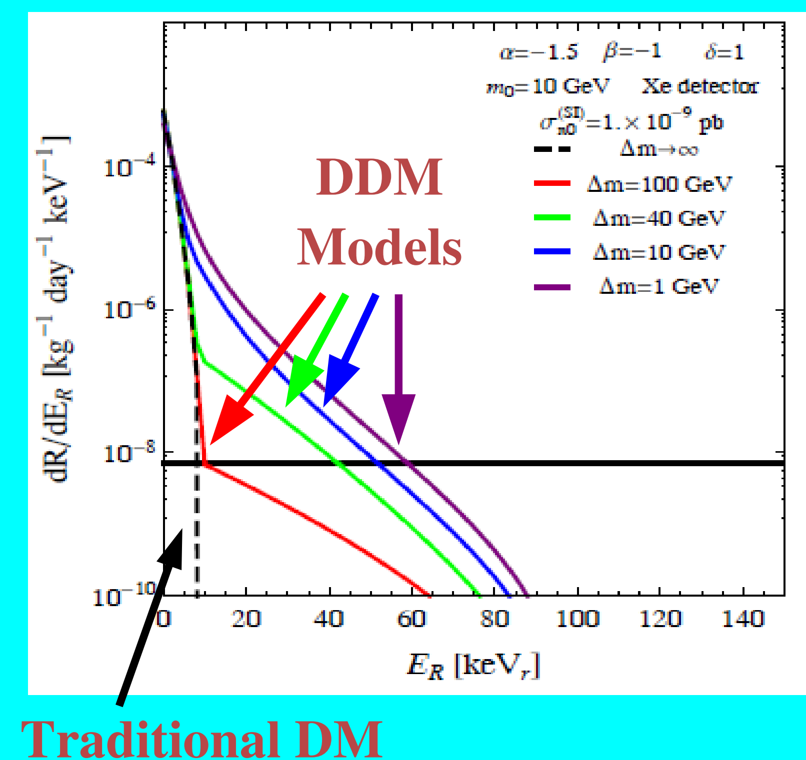
- KRD, S. Su, and B. Thomas, arXiv: 1204.4183
- KRD, S. Su, and B. Thomas, arXiv: 1407.2606

- In many DDM models, constituent fields in the DDM ensemble can be produced alongside SM particles by the decays of additional heavy fields. $\psi \to jj\chi_n$
- 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.

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

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



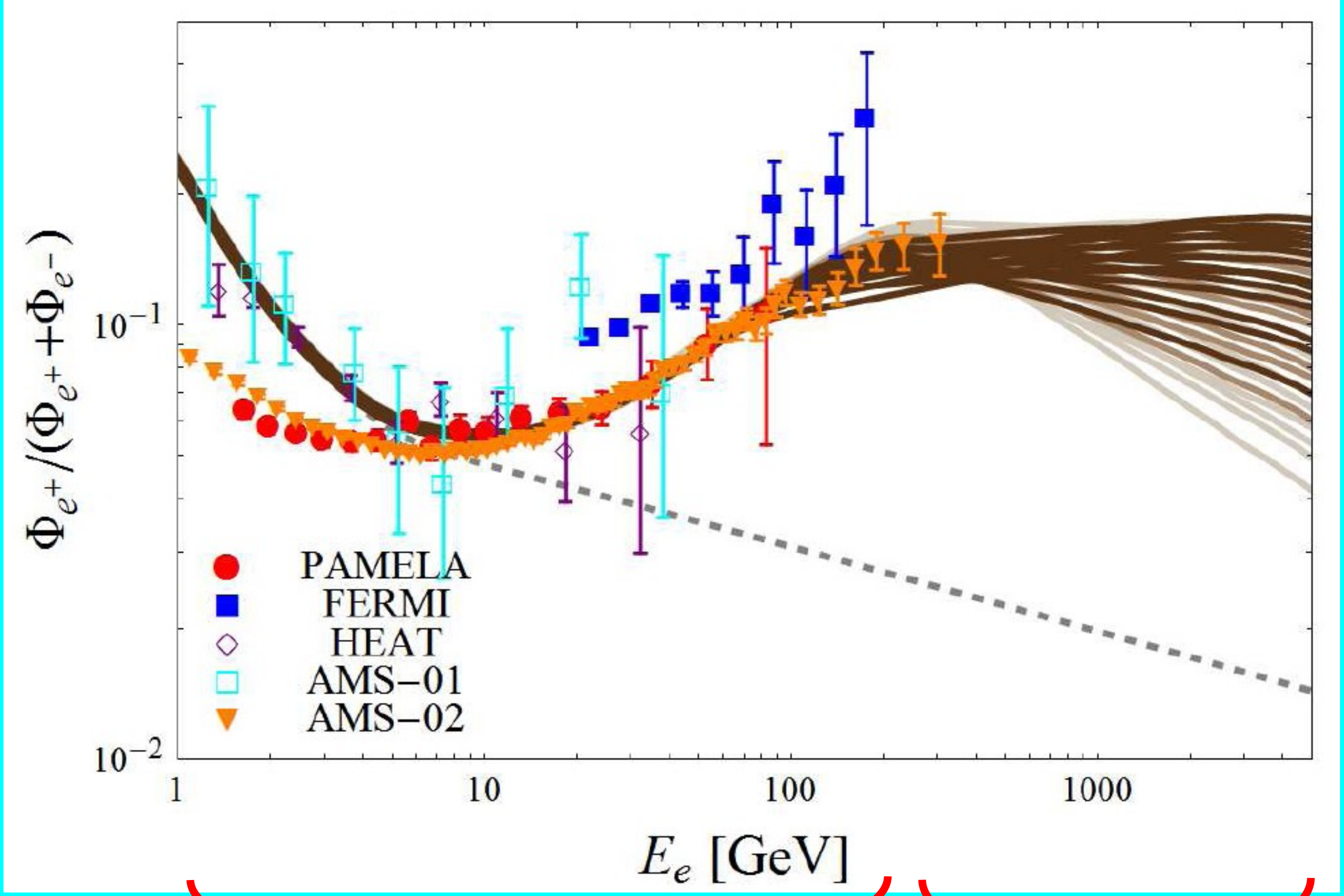
These examples illustrate that DDM ensembles give rise to **observable effects** which can serve to distinguish them from traditional DM candidates.

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)



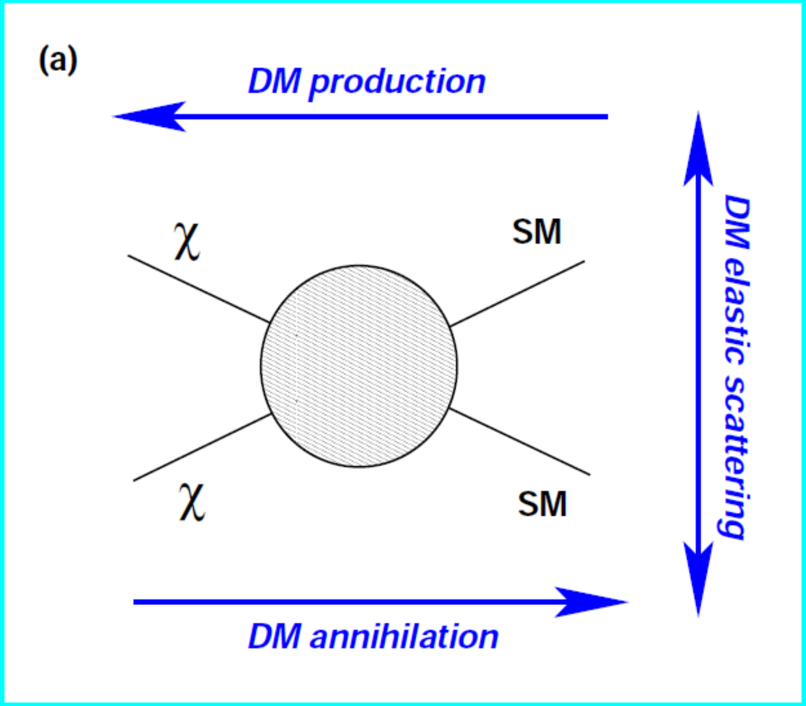
DDM: Fully consistent with positron excess observed thus far [AMS-02]

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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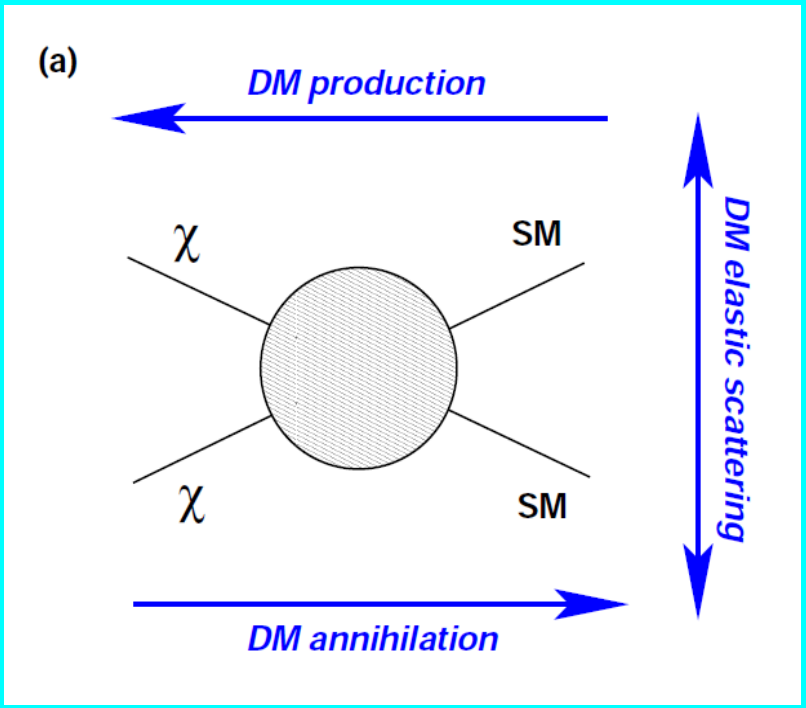
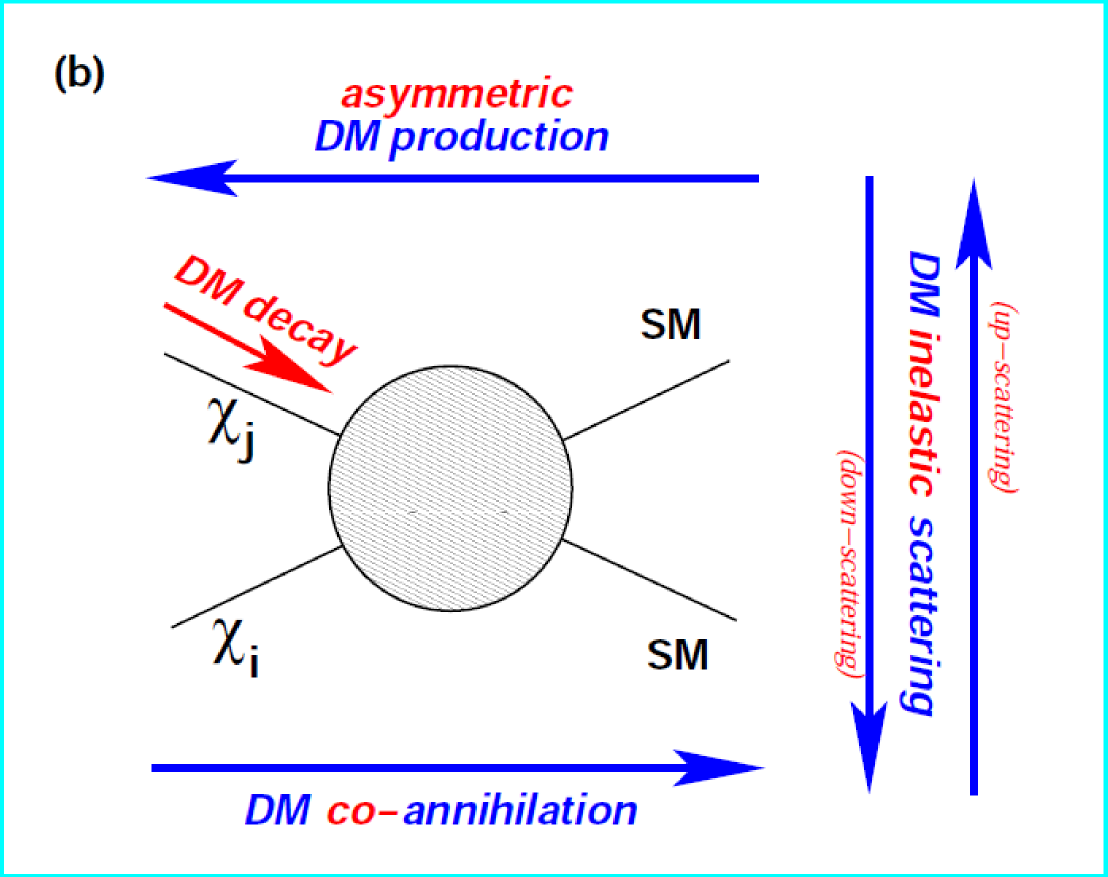


to this...



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!

For example, consider the scalar contact operator

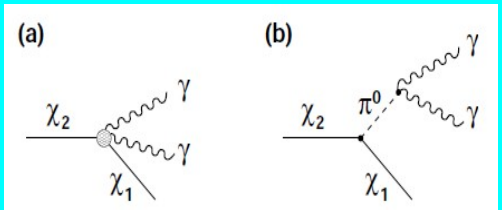
$$\mathcal{L}_{\rm int}^{(S)} = \sum_{q=u,d,s,\ldots} \frac{c_q^{(S)}}{\Lambda^2} (\overline{\chi}_2 \chi_1)(\overline{q} q)$$

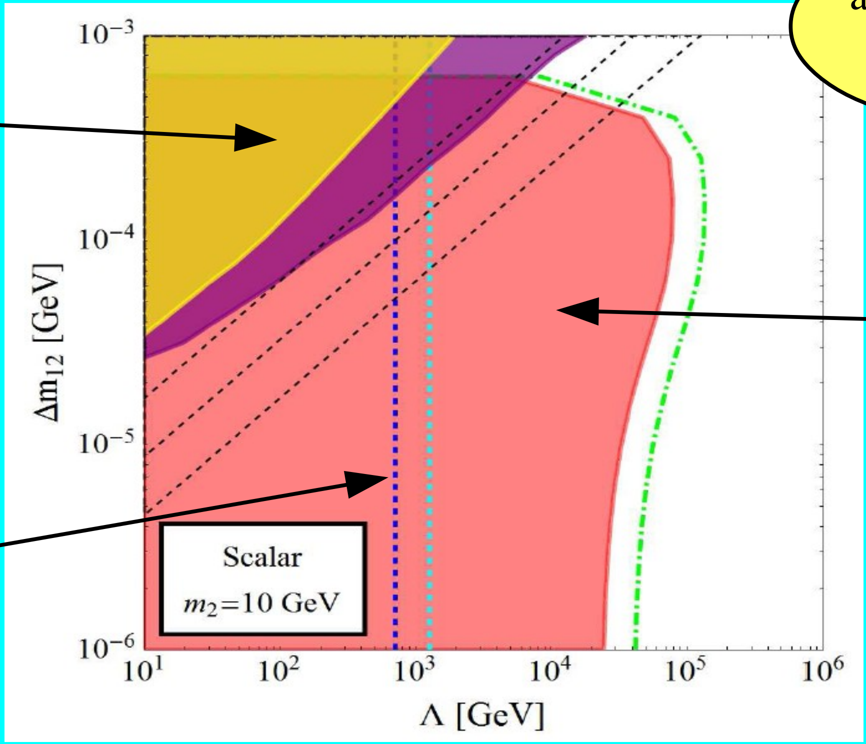
dark/visible coupling

For maximally isospin-violating couplings ($c_u = -c_d$, *etc.*), we can survey the corresponding (Λ, Δm_{12}) parameter space...

assuming $\Omega_1 = \Omega_2$, for simplicity

Limits from DM *decay*





Bounds from direct-detection experiments via *inelastic* scattering

Collider bounds on *asymmetric* DM production

arXiv: 1406.4868

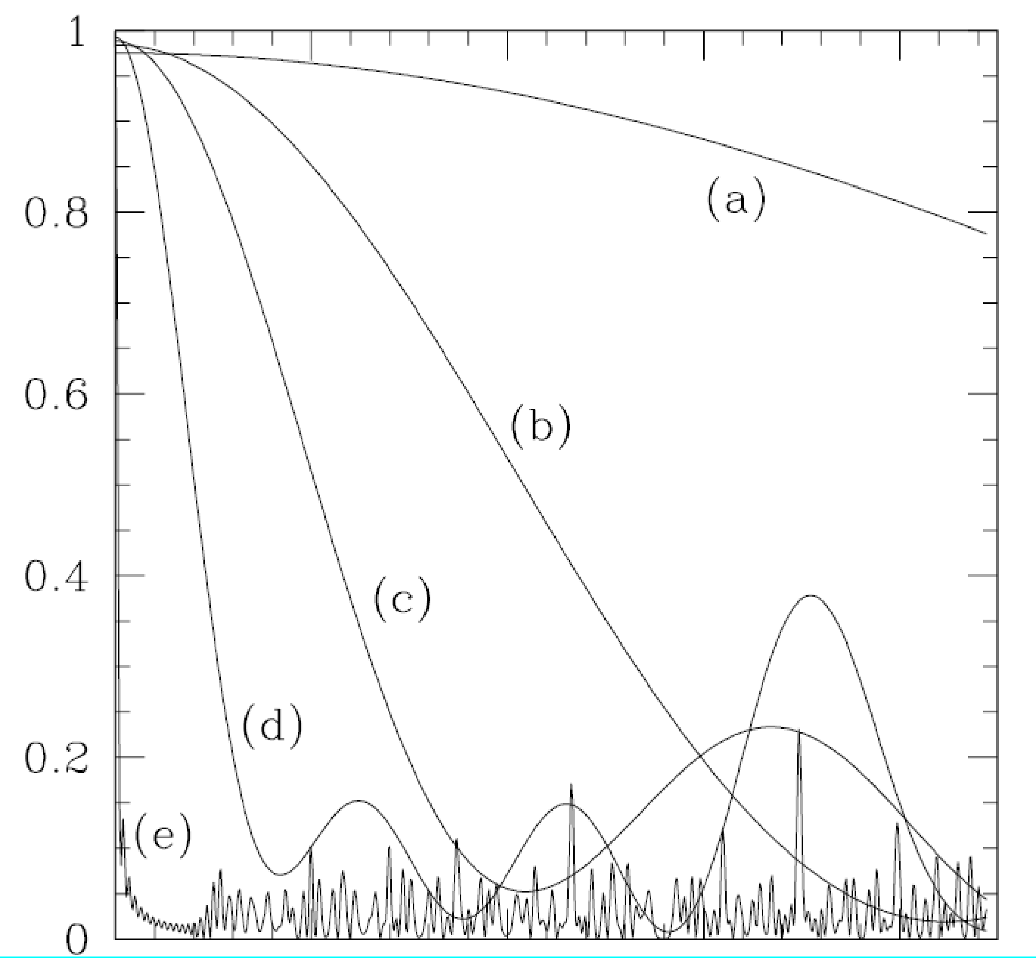
Together, these complementary techniques provide a mixture of both *coverage* and *correlation* within the parameter space of this operator.

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

In many DDM constructions, the SM couples to only one 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);
- KRD, E. Dudas, T. Gherghetta, B. Thomas (2018, in prep)

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.
  - "Random-matrix DDM": ensembles from large hidden-sector gauge groups --- scaling behaviors emerge even from randomness!
- DDM in string theory: not just KK states, but also *oscillator* states!
  - Density of states grows *exponentially*
  - 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.
- General decay constraints on multi-component dark sectors.
- KK towers as DDM ensembles in early-universe cosmology
- The phenomenology of intra-ensemble decays in DDM scenarios
- DDM effects on
  - Structure formation: complex behavior for Jeans instabilities
  - Non-trivial halo structures
- Gravitational back-reactions and applications to inflation
- DDM as a framework for exploring the dark-sector lifetime frontier via MATHUSLA

w/ Barath Coleppa & Shufang Su

w/ Jake Fennick & Jason Kumar, 1601.05094

w/ Fei Huang & Shufang Su, 1610.04112

w/ Jake Fennick & Jason Kumar

w/ Jason Kumar & Pat Stengel

w/ Jeff Kost, 1612.08950

w/ Fei Huang, Jeff Kost & Shufang Su

(just Brooks & me!)

w/ Ethan Garvey

w/ Jeff Kost; w/ Scott Watson

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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 $\Longleftrightarrow$ smaller abundances!

However, increasing mass

$\Rightarrow$ larger phase space for decay, also more possible decay modes

$\Rightarrow$ lifetime generally drops!

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

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

negative scaling exponent!

Misalignment production naturally has this property.
However, this is <u>not</u> what typically emerges in thermal freezeout!

Recall the WIMP miracle ---

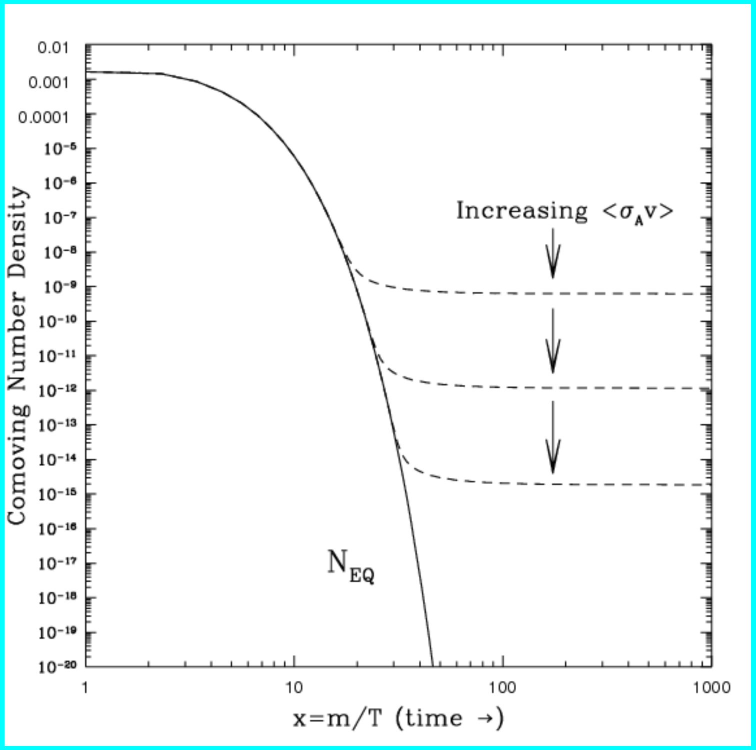
$$\Omega_\chi \sim \frac{m_\chi^2}{g_\chi^4} \quad \Longrightarrow \quad \gamma = +2 \quad \text{(canonical value)}$$

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

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

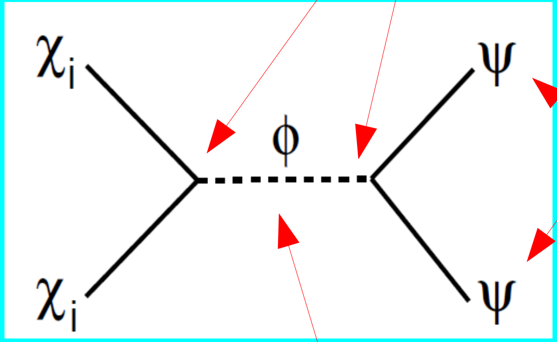
In general, freezeout abundance Ω_χ depends on thermally averaged DM annihilation cross-section:

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



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

g_χ, g_ψ : couplings



SM states

mediator

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

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

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

$\Rightarrow \gamma = 2!$

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_ϕ,
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

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

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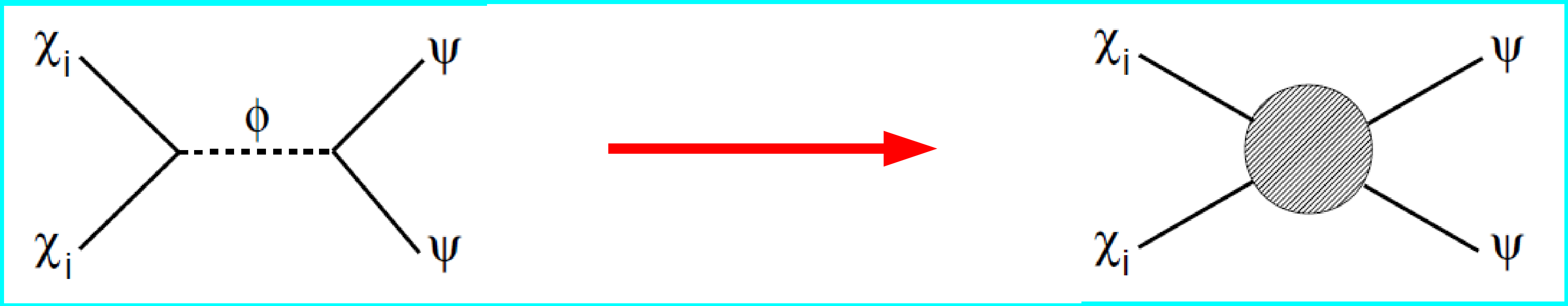
Simply integrate out the mediator!



Integrating Out Before Freezing Out!

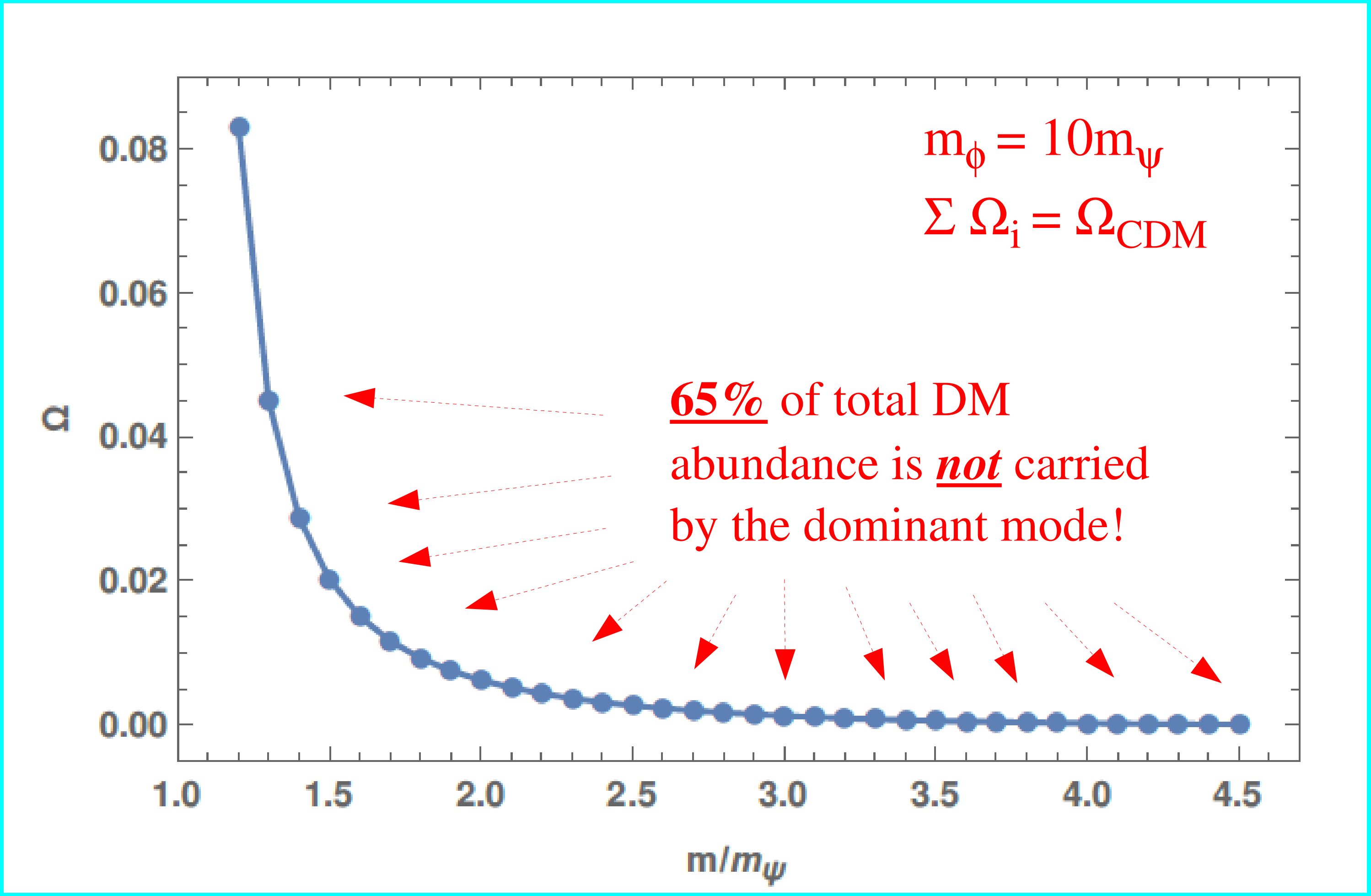
Thus, if we have a DDM ensemble w/ constituent masses m_i ...

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

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!

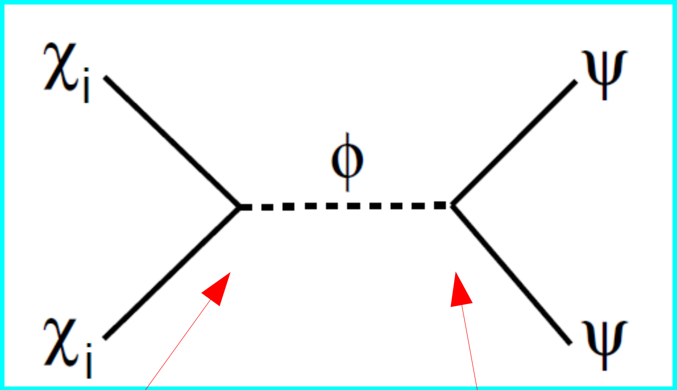
For example, for a Lagrangian coupling of the form $(\bar{\chi}\gamma_5\chi)\,\phi\,(\bar{\psi}\psi)$ where χ,ψ are Dirac fermions and ϕ is a scalar, we obtain...



...precisely the scaling behavior required for DDM!

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

Consider general *s*-channel annihilation processes:



Even within this topology, can consider different spins for χ, ϕ, ψ and different coupling structures at each vertex...

χ_i	ϕ	coupling	ϵ_χ	r
spin-0	spin-0	S: $g_\chi \mu \chi^* \chi \phi$	1	0
spin-1/2	spin-0	S: $g_\chi \overline{\chi} \chi \phi$	0	1
spin-1/2	spin-0	P: $g_\chi \overline{\chi} \gamma_5 \chi \phi$	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: $g_\chi \overline{\chi} \gamma_0 \chi \phi^0$	—	—
spin-1/2	spin-1 (spatial)	V: $g_\chi \overline{\chi} \gamma_i \chi \phi^i$	0	0
spin-1/2	spin-1 (time)	A: $g_\chi \overline{\chi} \gamma_0 \gamma_5 \chi \phi^0$	0	0
spin-1/2	spin-1 (spatial)	A: $g_\chi \overline{\chi} \gamma_i \gamma_5 \chi \phi^i$	0	1

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

Proceeding as before, we then find

contribution from mediator

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

DM mass

canonical contribution

possible super-renormalizable and chirality-suppressed couplings to mediator

final-state kinematic effects

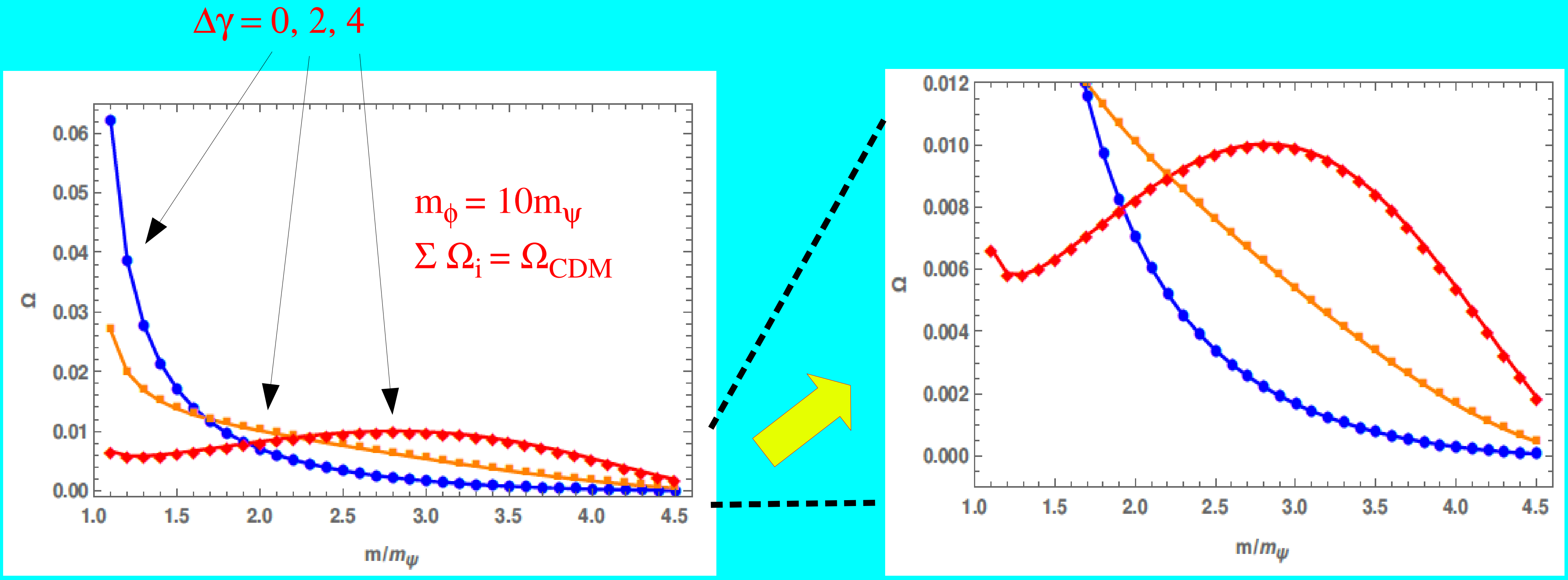
$$\Rightarrow \quad \gamma(m) = 2 + \Delta\gamma + \frac{1}{m^2/m_\phi^2 - 1/4} + \frac{2s+1}{1-m^2/m_\psi^2}$$

where $\Delta\gamma \equiv 2(\epsilon_\chi + \epsilon_\psi + t)$

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.

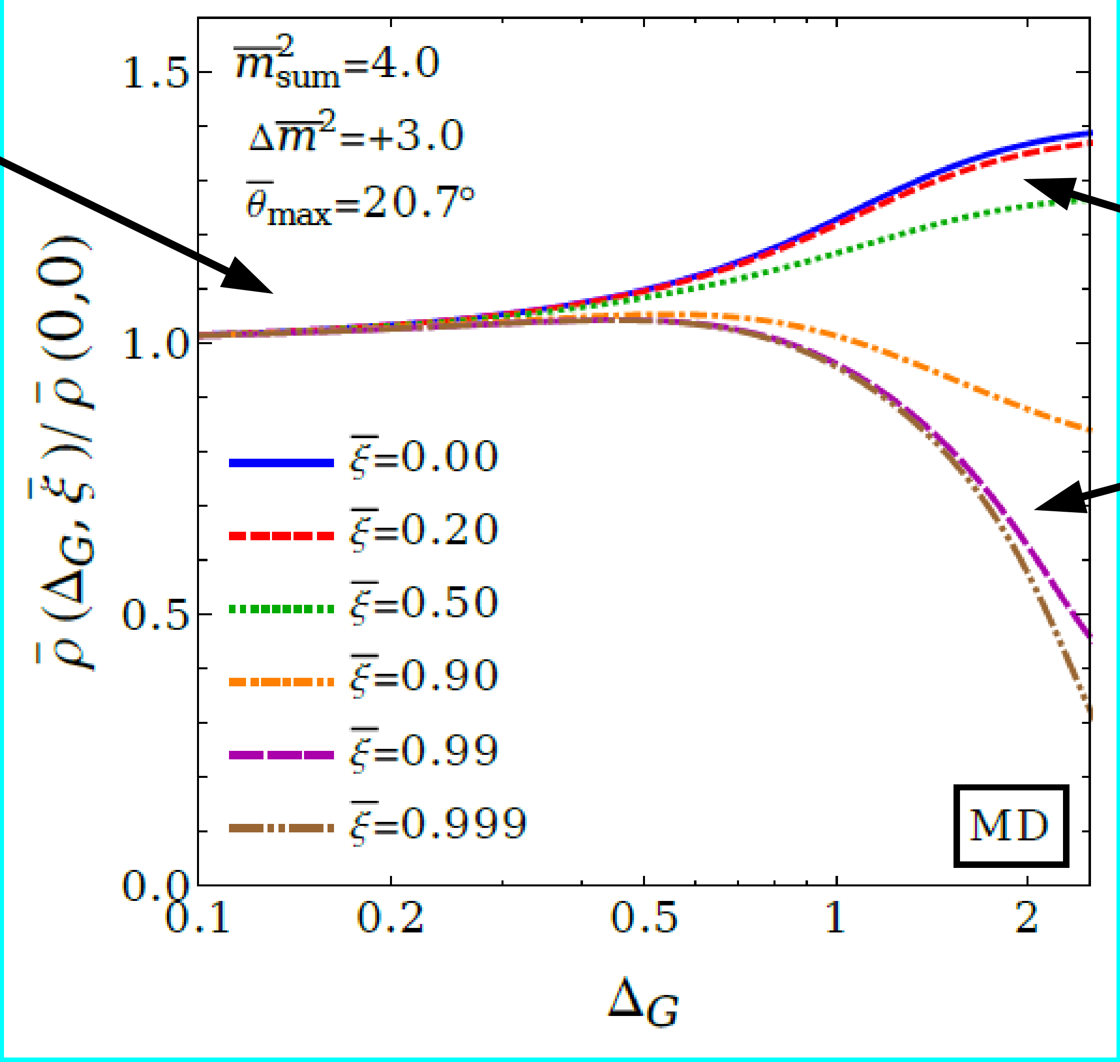
However, in the presence of a cosmological phase transition, these mixings can dramatically alter

- 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)



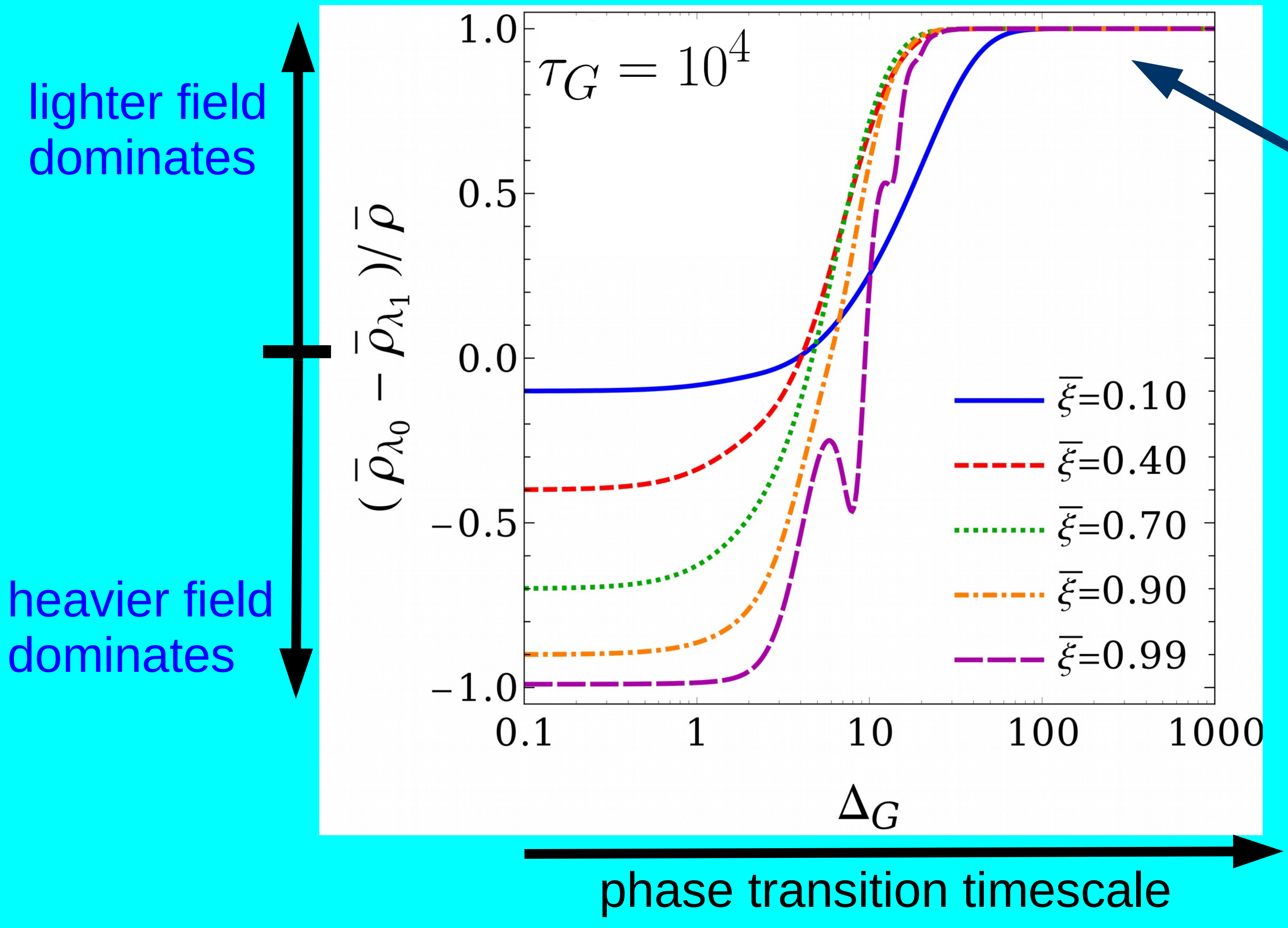
phase transition timescale

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!

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

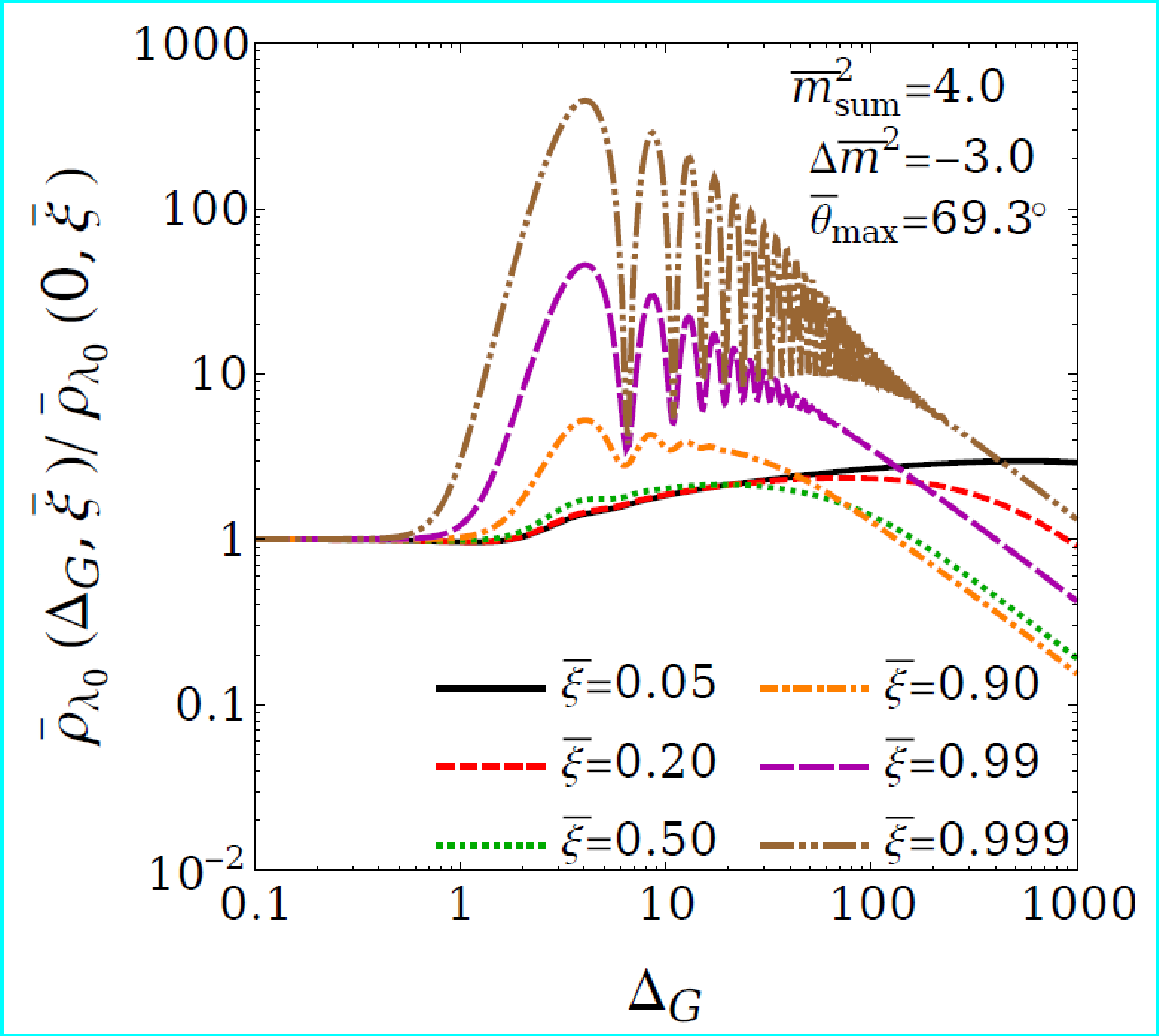
If we compare the *distribution* of the total late-time energy density between the two components, we find



As the width of the phase transition is increased, energy density **shifts completely** to lighter field!

Abundance ratios can be completely inverted!

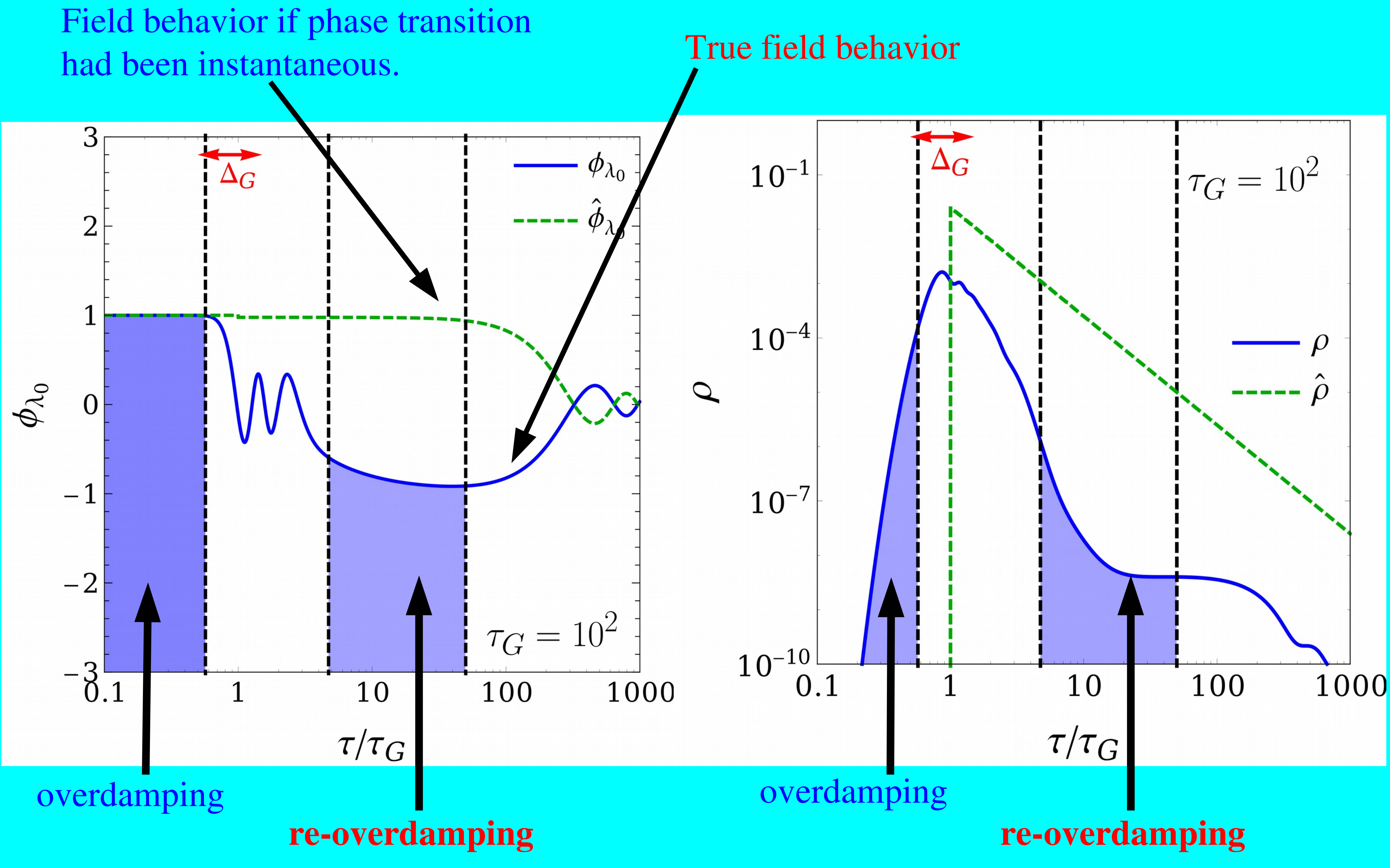
There are also other effects that can emerge which significantly affect the late-time abundances of these scalar fields...



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*!



Dynamical Dark Matter and the Lifetime Frontier

One central characteristic feature of the DDM framework is that the DDM ensemble generically contains states exhibiting a wide variety 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, some of these escaping states will have lifetimes in an ***intermediate*** range. Such states are **relatively long-lived but not infinitely so,** giving rise to **finite but macroscopic displaced vertices on the orders of ~10^2 meters.** From an experimental collider perspective, t***his is an entirely new frontier of parameter space: the lifetime frontier!***

Why is this particularly exciting now?

MATHUSLA

John-Paul Chou
David Curtin
Henry Lubatti
1606.06298

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles

displaced vertex from LLP decay is so spectacular…

… that near-perfect background rejection is possible!

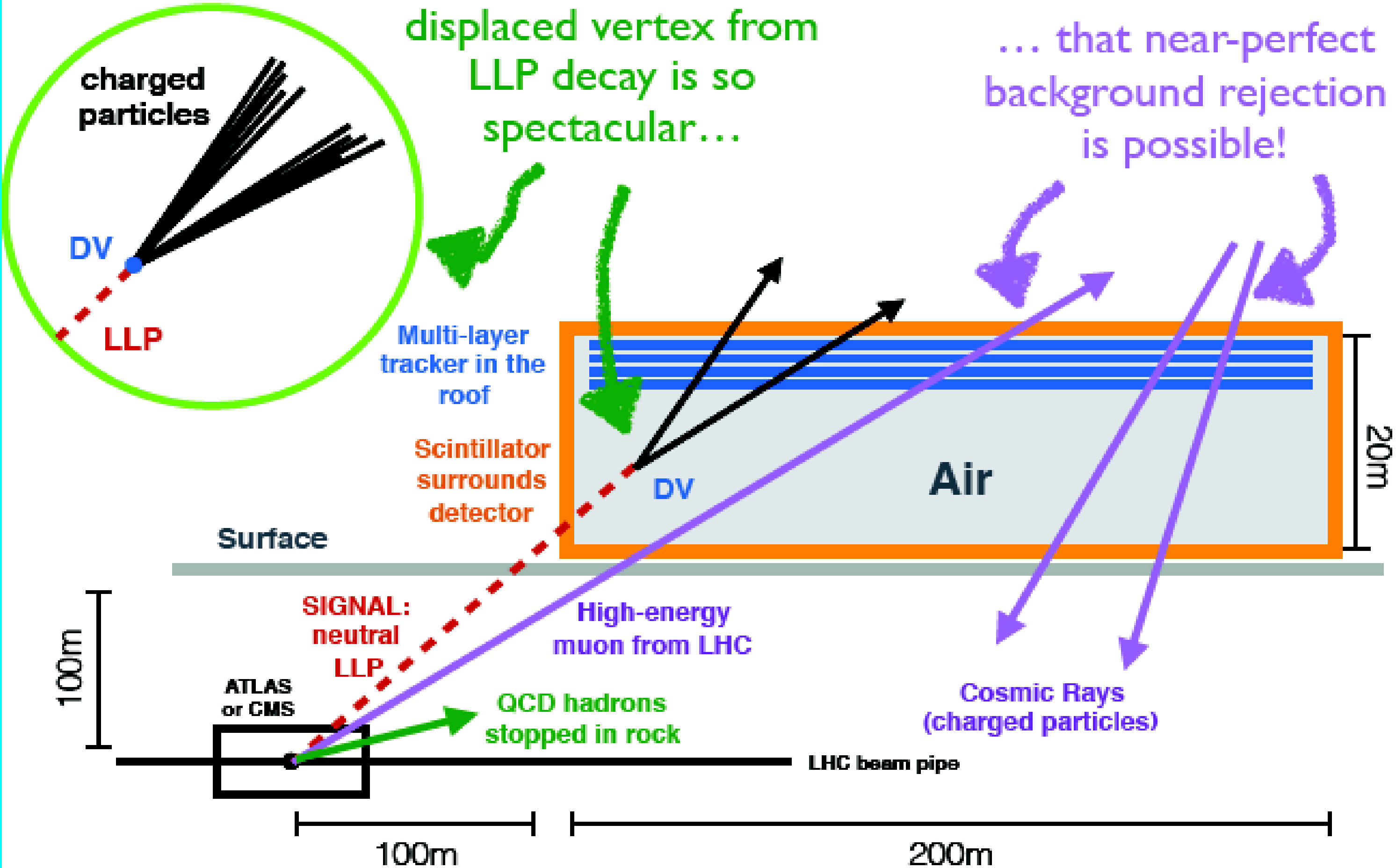


Figure Credit: Curtin, Sundrum, submitted to Physics Today

On schedule for

prototype mid 2017

letter of intent end 2017

Theory White Paper

1806.07396

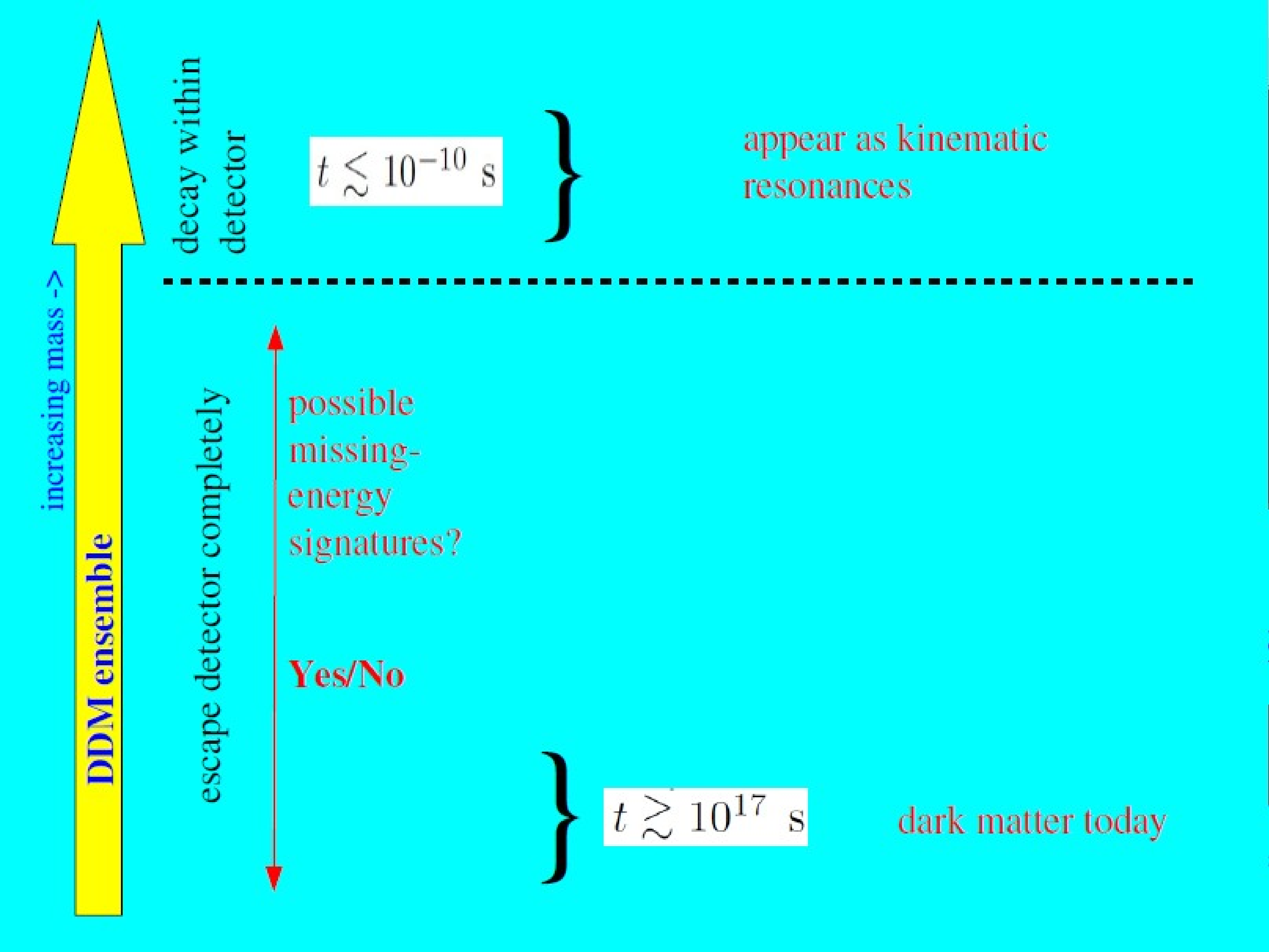
new!!

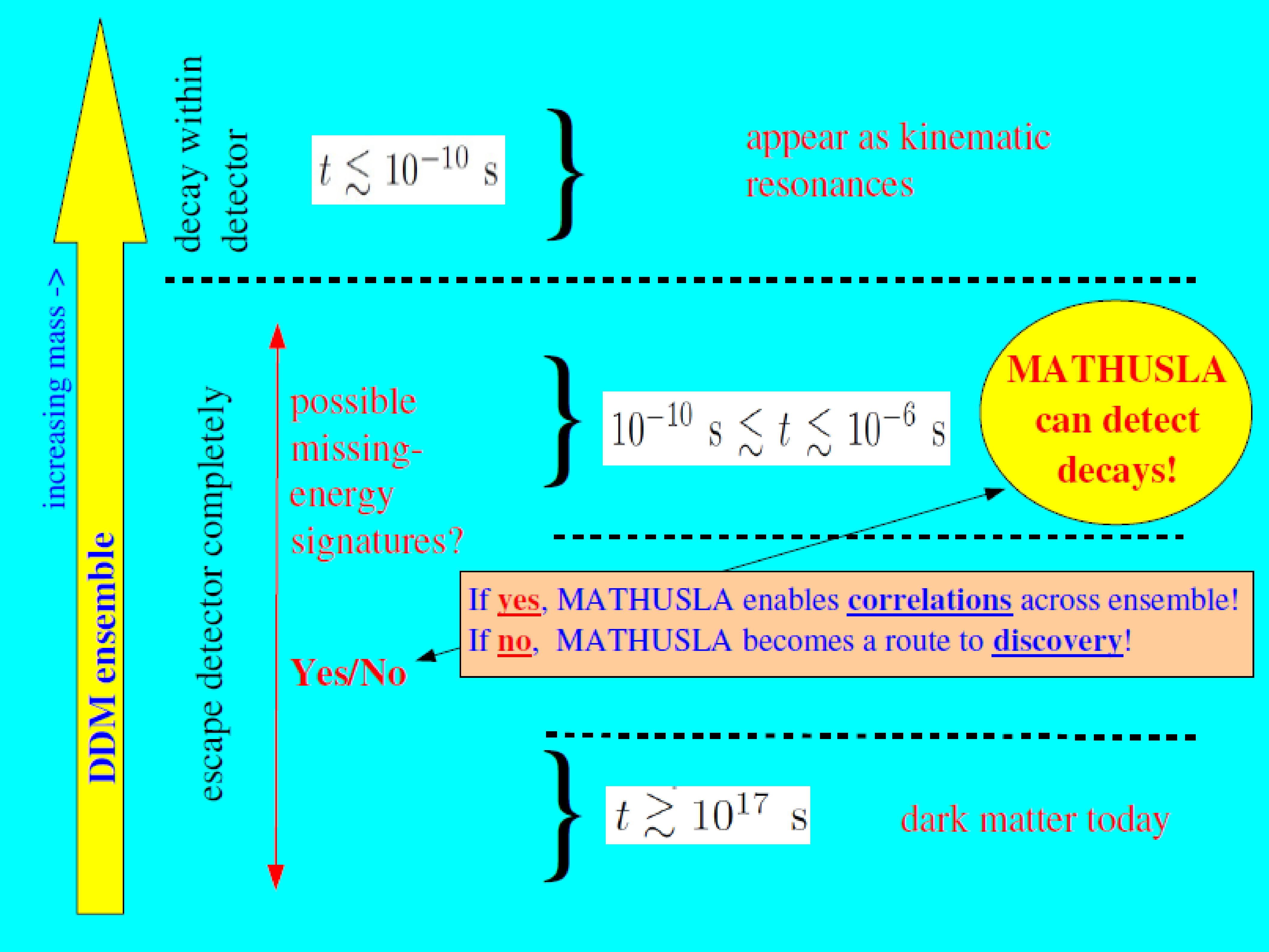
MATHUSLA is a unique instrument for detecting Long-Lived Particles (LLP's) of all sorts. As such, its power extends beyond the specific realm of dark-matter searches.

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, 1807.xxxxx


increasing mass ->
DDM ensemble
decay within detector
$t \lesssim 10^{-10}$ s
appear as kinematic resonances
escape detector completely
possible missing-energy signatures?
Yes/No
$t \gtrsim 10^{17}$ s
dark matter today


increasing mass ->
DDM ensemble
decay within detector
$t \lesssim 10^{-10}$ s
appear as kinematic resonances
escape detector completely
possible missing-energy signatures?
10^{-10} s $\lesssim t \lesssim 10^{-6}$ s
MATHUSLA can detect decays!
If yes, MATHUSLA enables correlations across ensemble!
If no, MATHUSLA becomes a route to discovery!
Yes/No
$t \gtrsim 10^{17}$ s
dark matter today

To quantify the reach of the MATHUSLA detector, assume the DDM ensemble constituents are produced through the decays of a heavy parent ϕ:

$$\phi \to \overline{\chi_n} \chi_n$$

Parametrize our DDM ensemble in the usual way...

Constituent masses:

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

Decay rates to SM states:

$$\Gamma_n = \Gamma_0 \left(\frac{m_n}{m_0}\right)^y$$

assume dominant decay mode

$\phi \overline{\chi_n} \chi_n$ couplings:

$$c_{nn} = c_0 \left(\frac{m_n}{m_0}\right)^\xi$$

helps to determine relative production rates for individual χ_n constituents

not relevant since we only care about *relative* branching ratios

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Choose benchmark values

- $m_\phi = 2\ \text{TeV}$
- $\Gamma_0 = (10^9\, t_\text{now})^{-1}$ where $t_\text{now} = 4.35 \times 10^{17}\ \text{s}$

Remaining DDM parameter space is:

$\{m_0, \Delta m, \delta, y, \xi\}$

For each point within DDM parameter space, we want to know...

- **The reach of MATHUSLA:** What is $\boldsymbol{\sigma_\phi^{min}}$ – the minimum production cross-section of ϕ which enables MATHUSLA to detect at least four events from the decays of χ_n ?

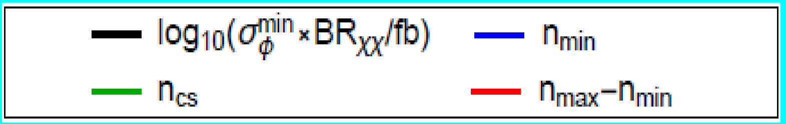
  Note: The reach is actually sensitive to $\boldsymbol{\sigma_\phi^{min}}$ **x** $\mathbf{BR_{\chi\chi}}$ where

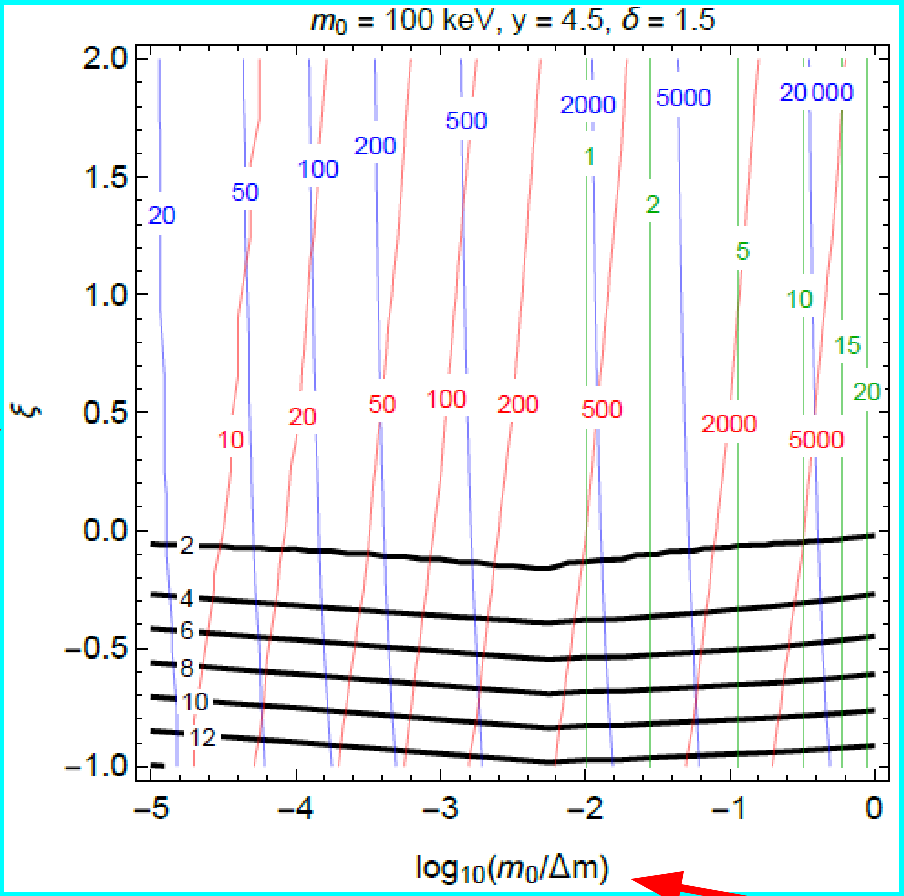
  $$\mathrm{BR}_{\chi\chi} \equiv \sum_{n=0}^{\infty} \mathrm{BR}(\phi \to \chi_n \chi_n)$$

- **DDM ensemble sensitivity:** What is the range $(\mathbf{n_{min}}, \mathbf{n_{max}})$ of ensemble constituents whose decays provide at least 90% of MATHUSLA events?

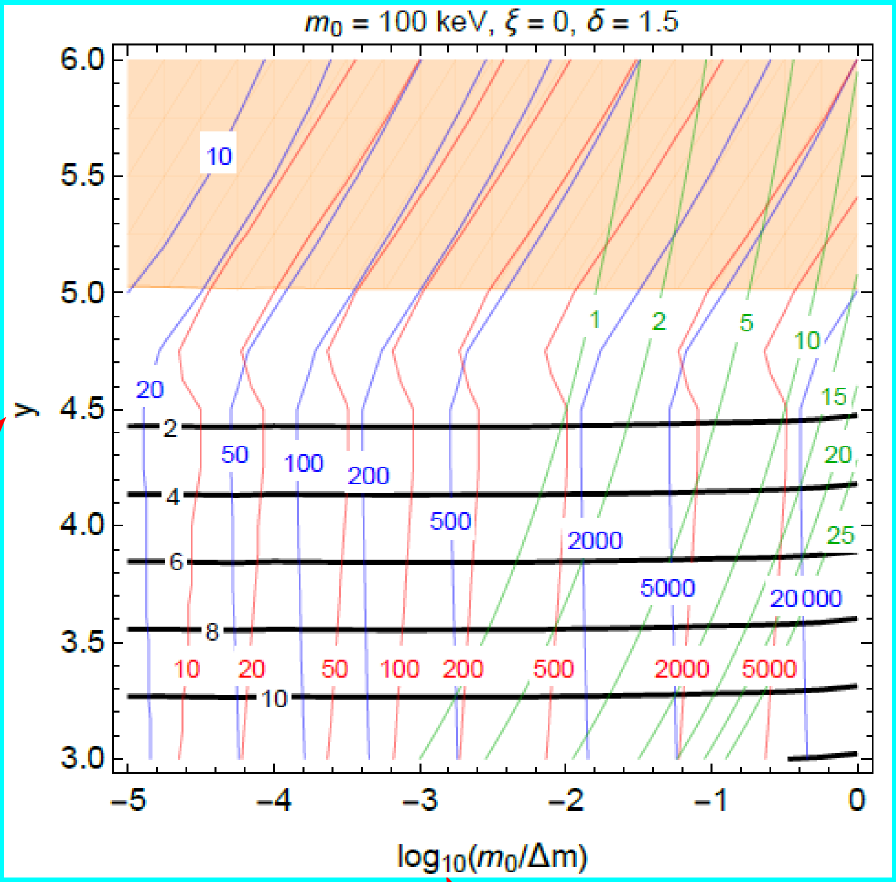
- **DM multiplicity today:** How many ensemble constituents $\mathbf{n_{cs}}$ continue to exist today and contribute to Ω_{CDM} today?

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





Scaling exponent for DDM production



Scaling exponent for DDM decay widths

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

DDM ensemble spectrum

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!

- D. Curtin, KRD & B. Thomas, 1807.xxxxx

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!