Dynamical Dark Matter

An Alternative Framework for Dark-Matter Physics

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Physics is a subject of great logic, great beauty, and great usefulness.

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But lately, Brooks and I have found a worthy competitor…
another creation of great logic, great beauty, and great usefulness...

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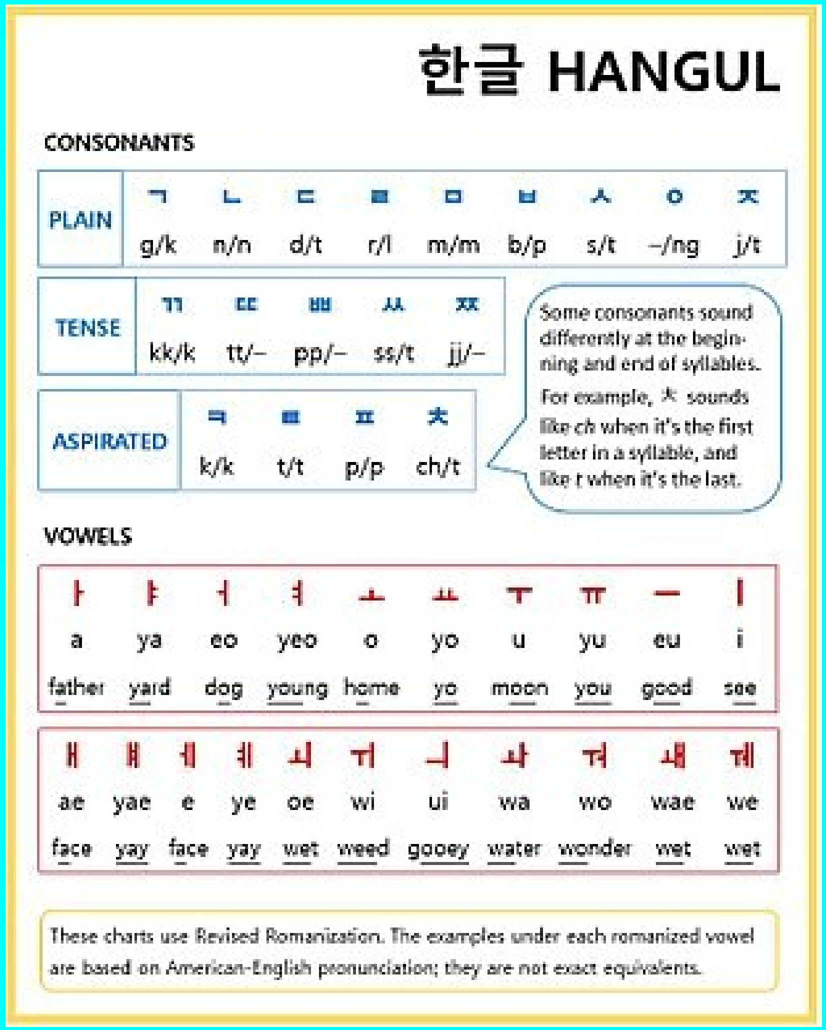

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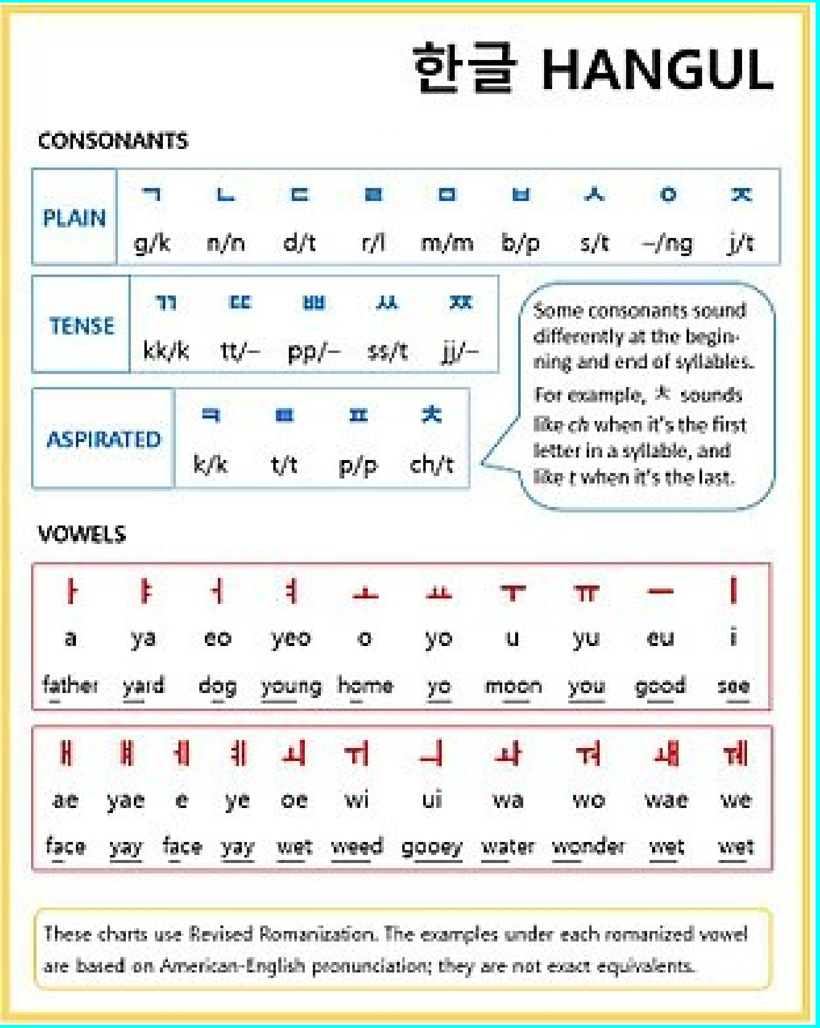

In our opinion, this is the most intelligent orthographic system ever constructed --- built from a true scientific awareness of phonetics and linguistics, combined with a subtle sense of function and style.

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But lately, Brooks and I have found a worthy competitor…
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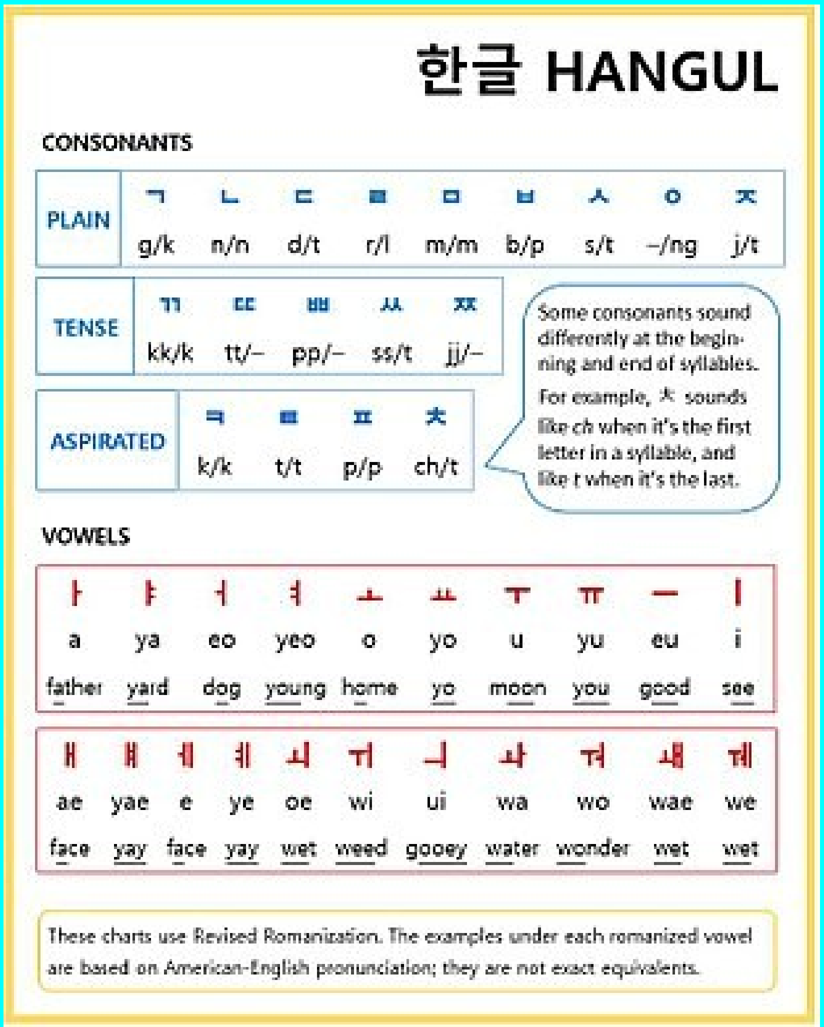

방문을 초대해 주셔서 대단히 감사합니다 .
우리는이 기회를 갖게되어 영광입니다 .

키스 와 브룩스

This series of lectures will focus on

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.

Brooks and I originally proposed DDM in 2011...

- 1106.4546
- 1107.0721
- 1203.1923

and since then this subject has been 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)
- 1407.2606 (also w/ S. Su)
- 1509.00470 (also w/ J. Kost)
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- 1609.09104 (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)
- and many others...

This series of lectures...

- Dynamical Dark Matter

  a quick overview/snapshot, just the basic themes and highlights

- In-depth discussions of specific aspects of DDM

  separate "modules" which can be presented in any order according to ***your*** interests and preferences.

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!

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 $N \gg 1$ ... 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 ---
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!

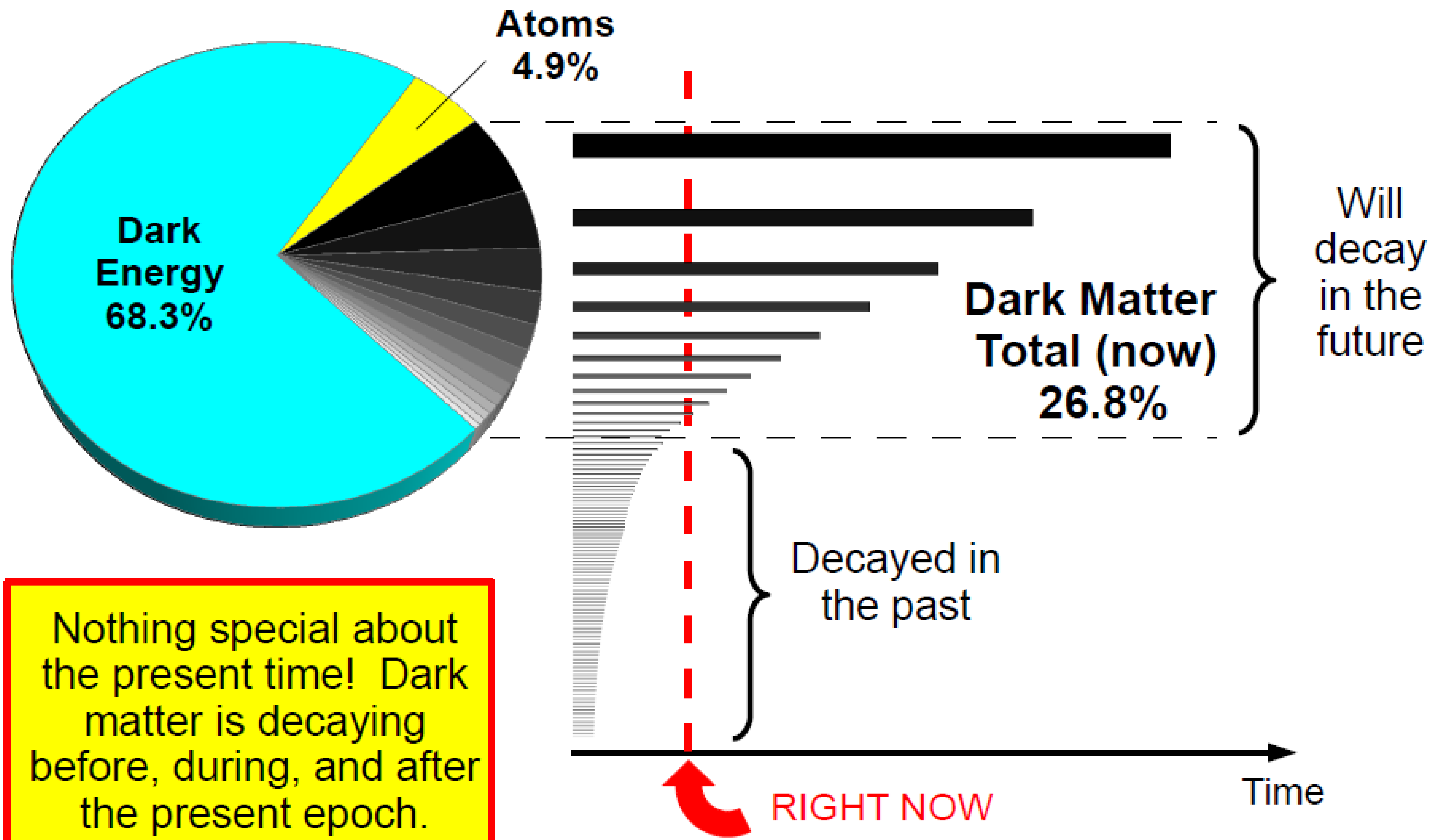
<u>Dynamical Dark Matter (DDM)</u>: an alternative framework for dark-matter physics in which the notion of dark-matter stability is replaced by a balancing of lifetimes against cosmological abundances across an ensemble of individual dark-matter components with different masses, lifetimes, and abundances.

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!***

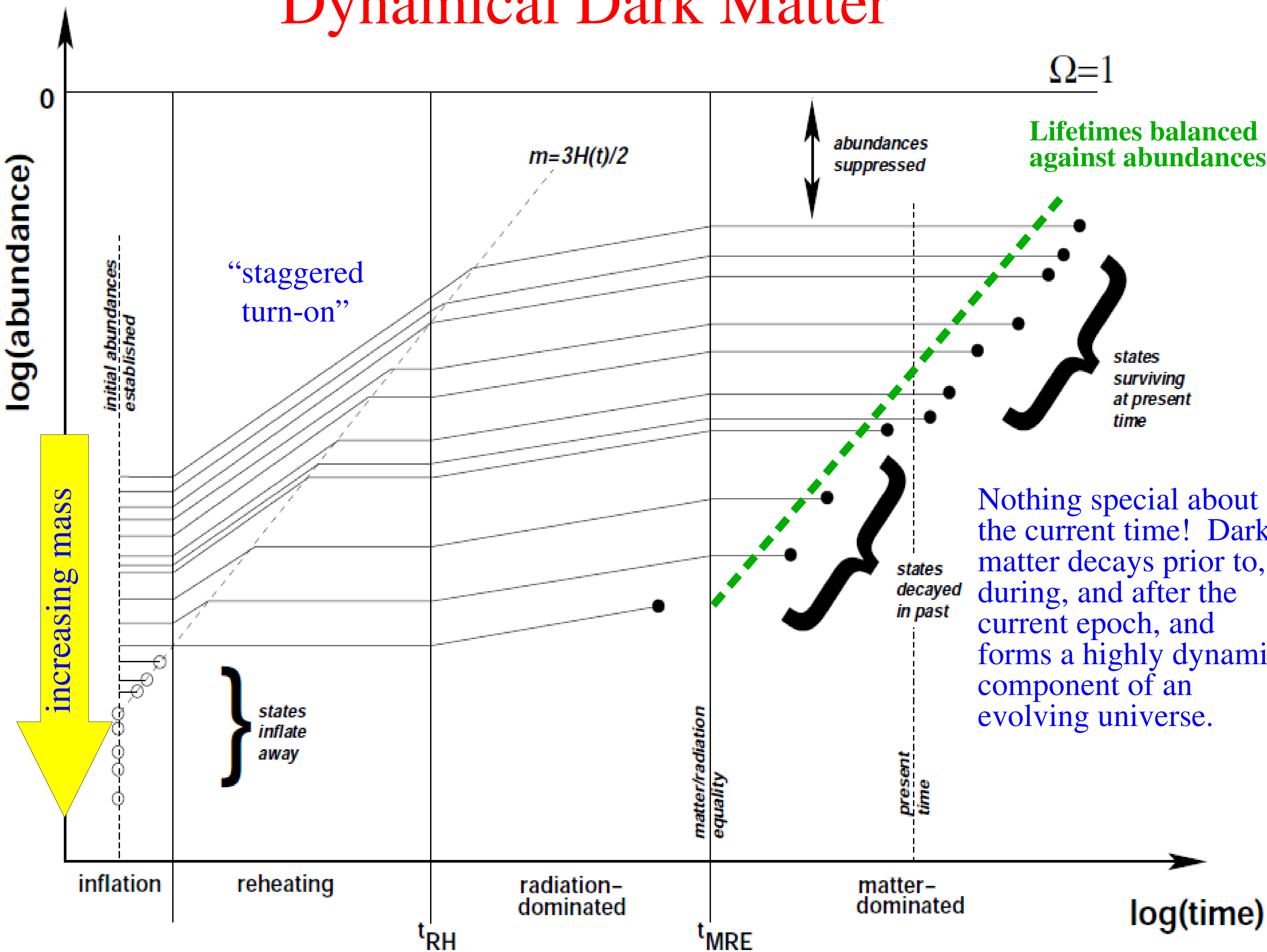
"Dynamical Dark Matter": The Basic Picture:

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.

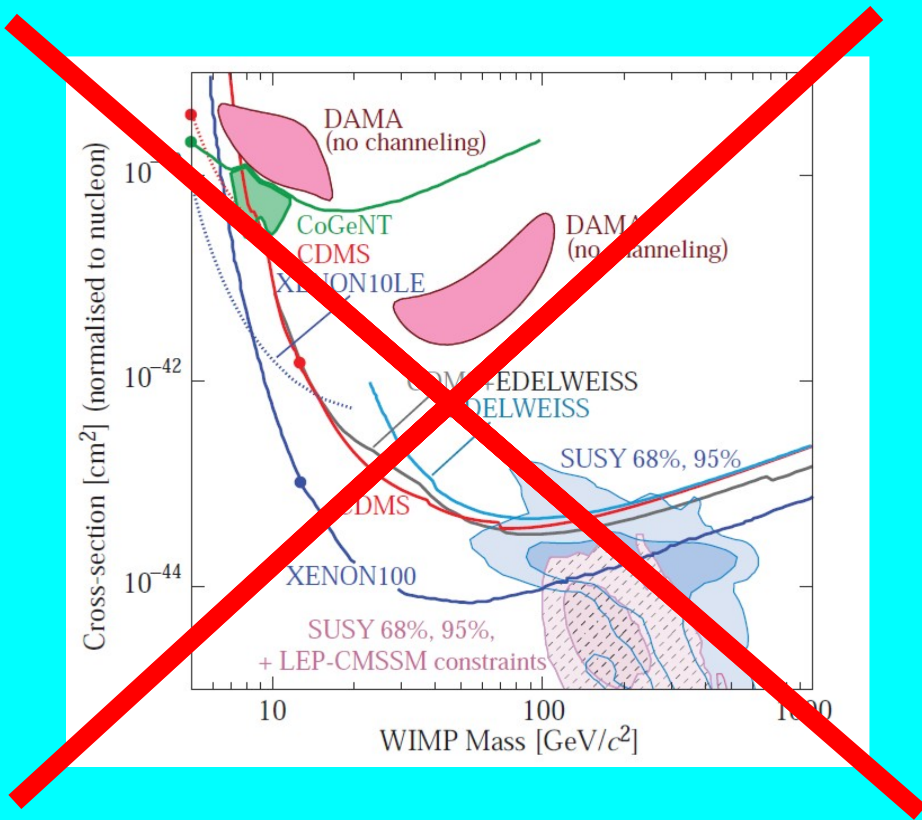
Dynamical Dark Matter



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.

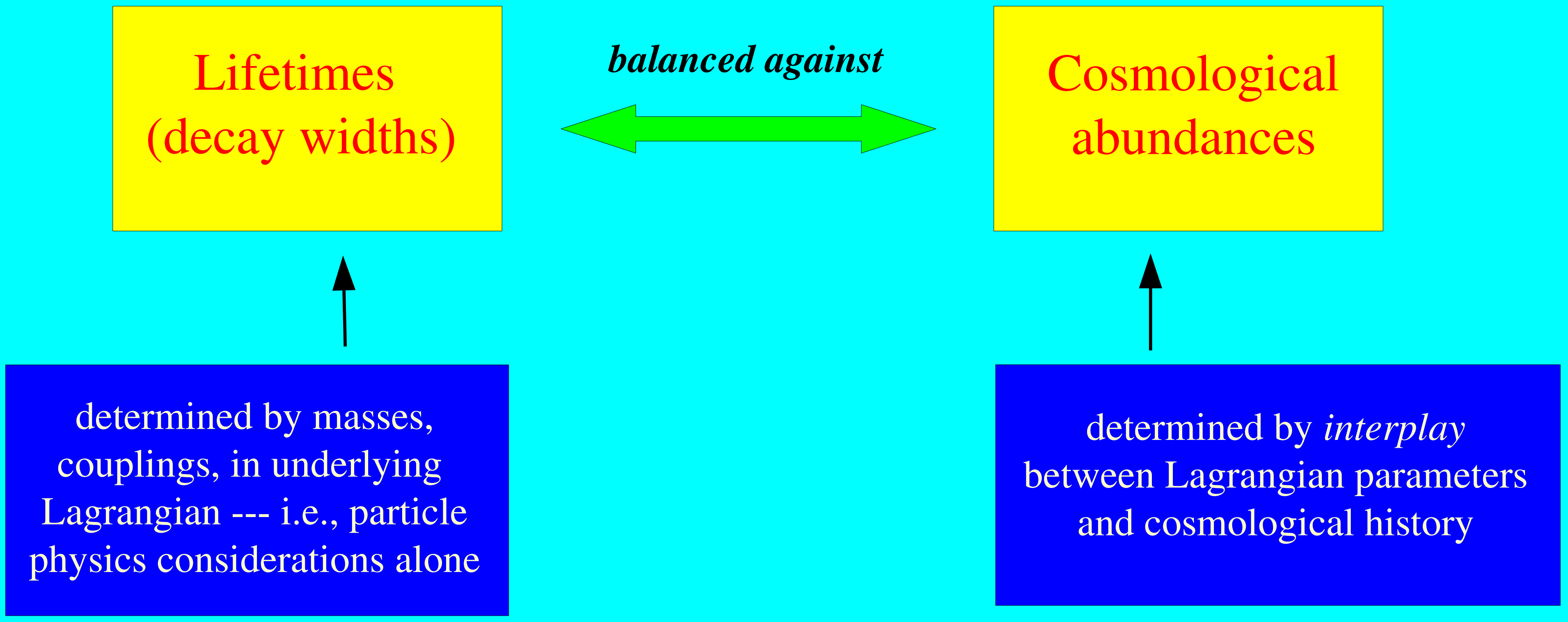
Unlike traditional dark matter, DDM is not simply a property of the particle physics alone!

Lifetimes (decay widths)

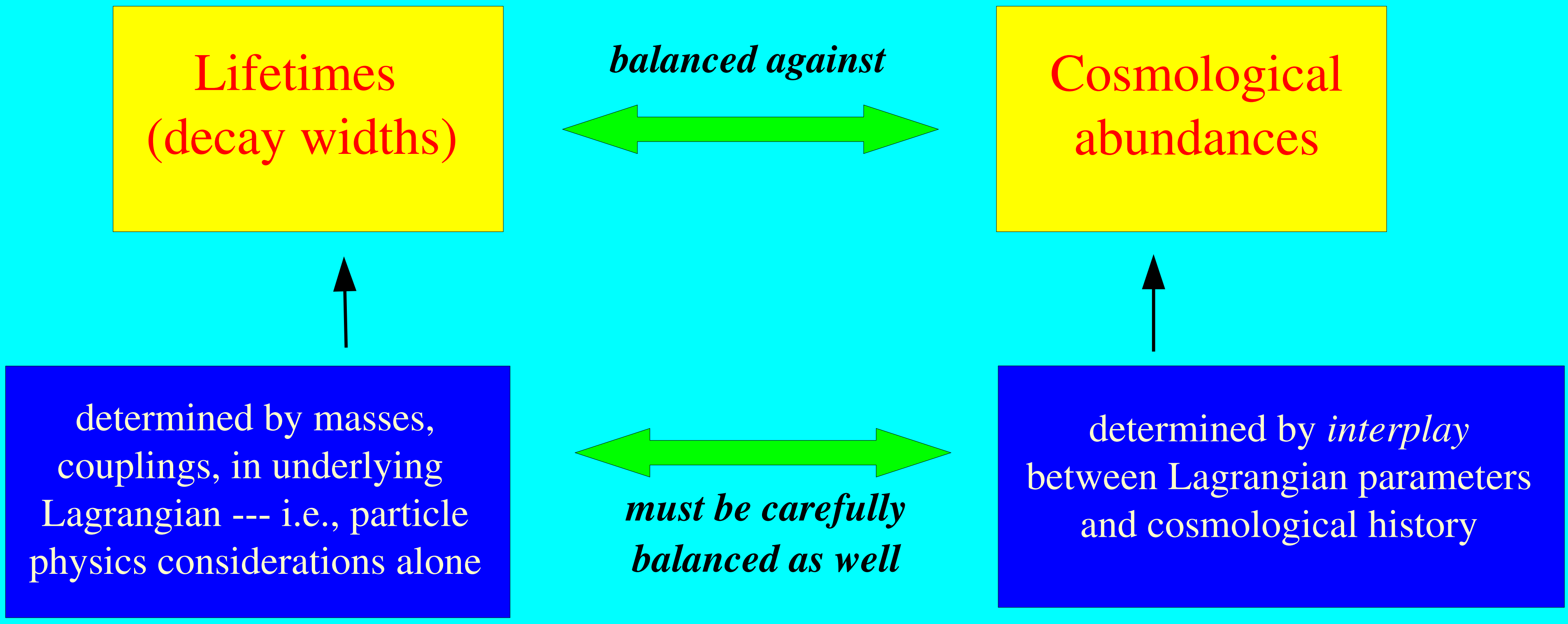
balanced against

Cosmological abundances

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



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
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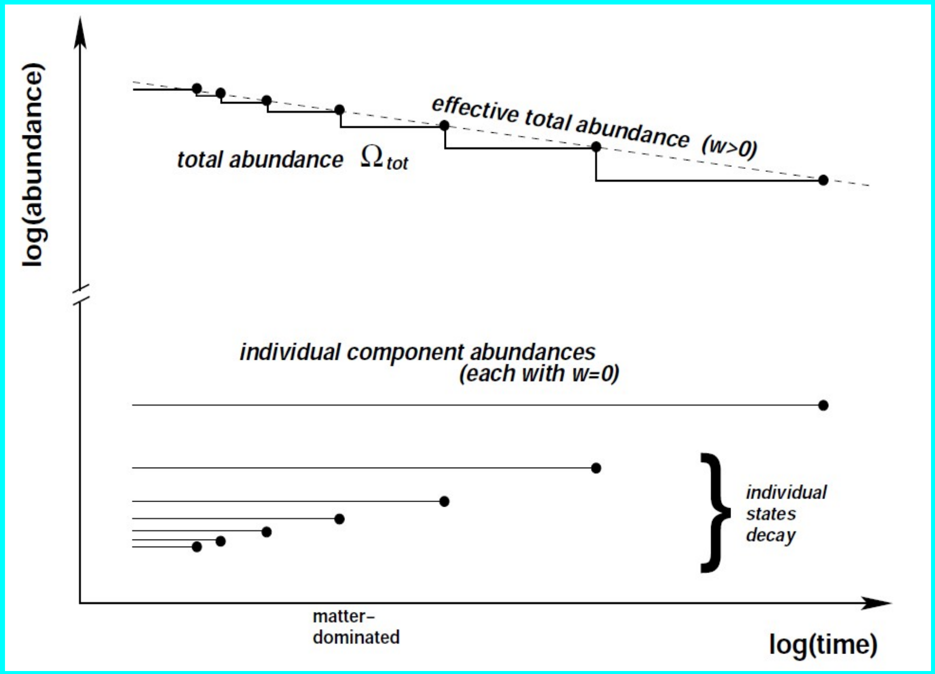
- Y. Buyukdag, KRD, T. Ghergehtta & B. Thomas, 1807.xxxx

- 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 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 $w_{eff}(t)$.



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

Scaling exponents of abundances and density of states relative to widths

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

$\alpha < 0$

density of states *per unit Γ*

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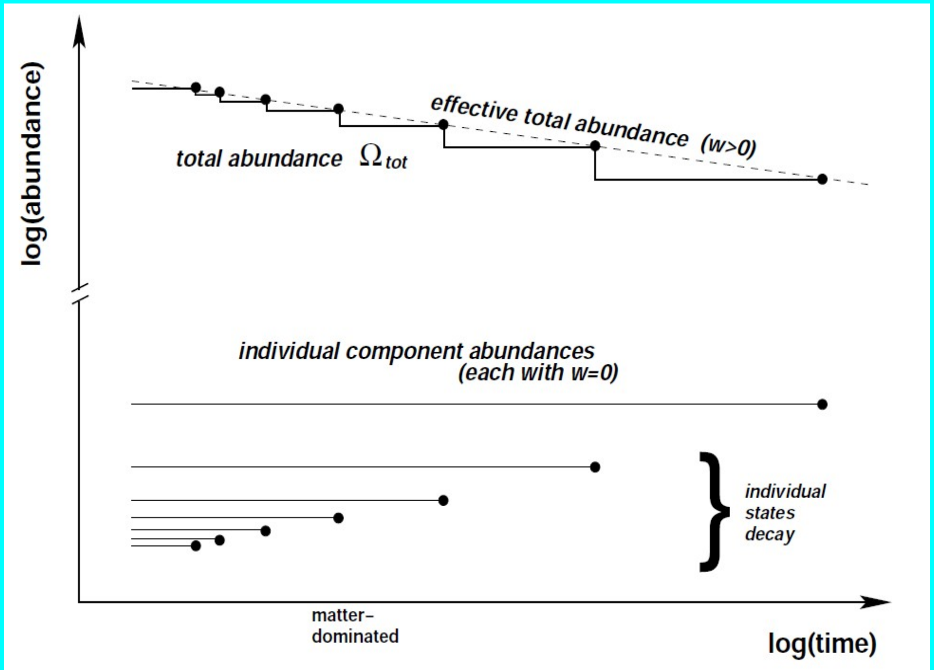


- **For** $x \equiv \alpha + \beta \neq -1$ **:**

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

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

__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 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

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

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?

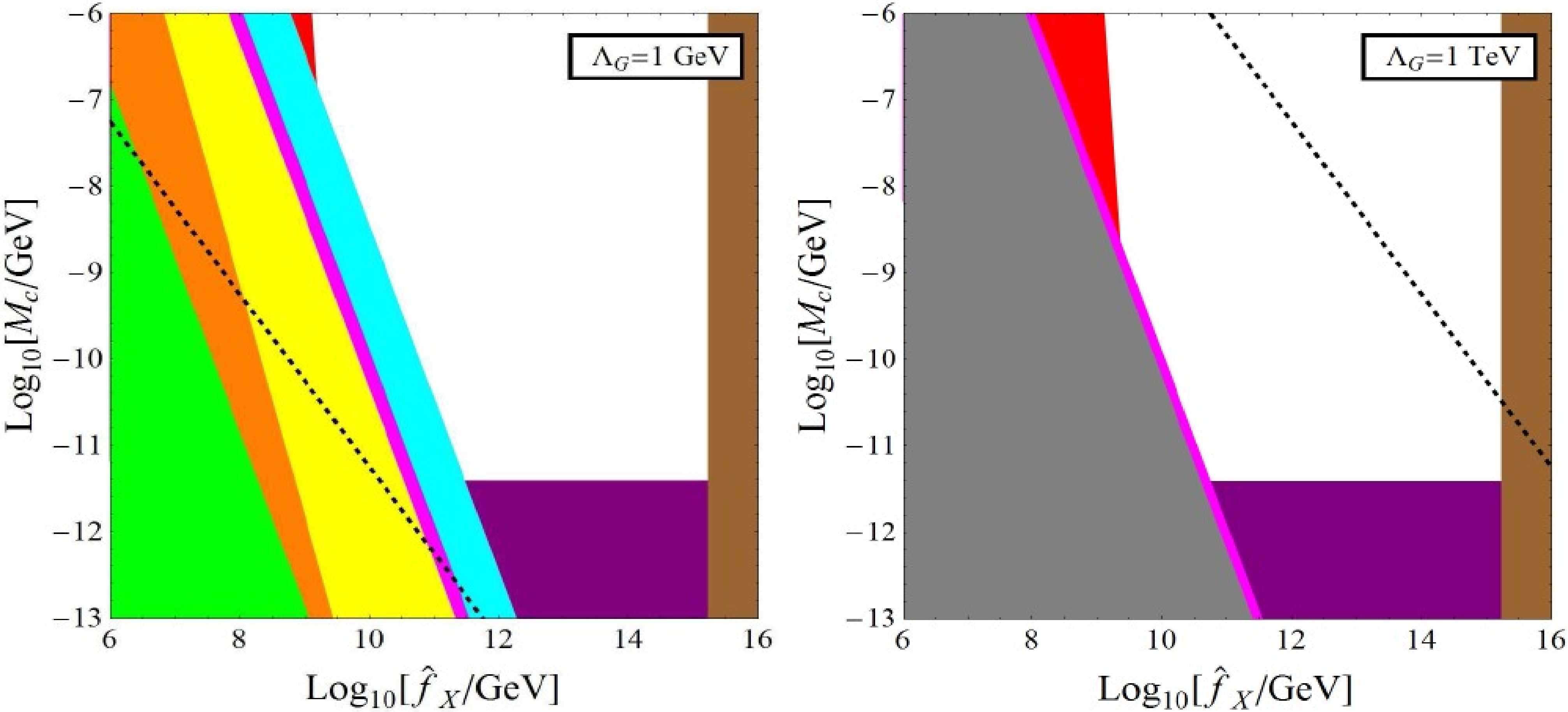
- GC (globular cluster) stars. Axions might carry away energy too efficiently, altering stellar lifetimes. GC stars give most stringent bound.
- SN1987a. Same --- axions would effect energy loss rate.
- Diffuse photon/X-ray backgrounds. Axion decays to photons would leave unobserved imprints.
- Eotvos.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

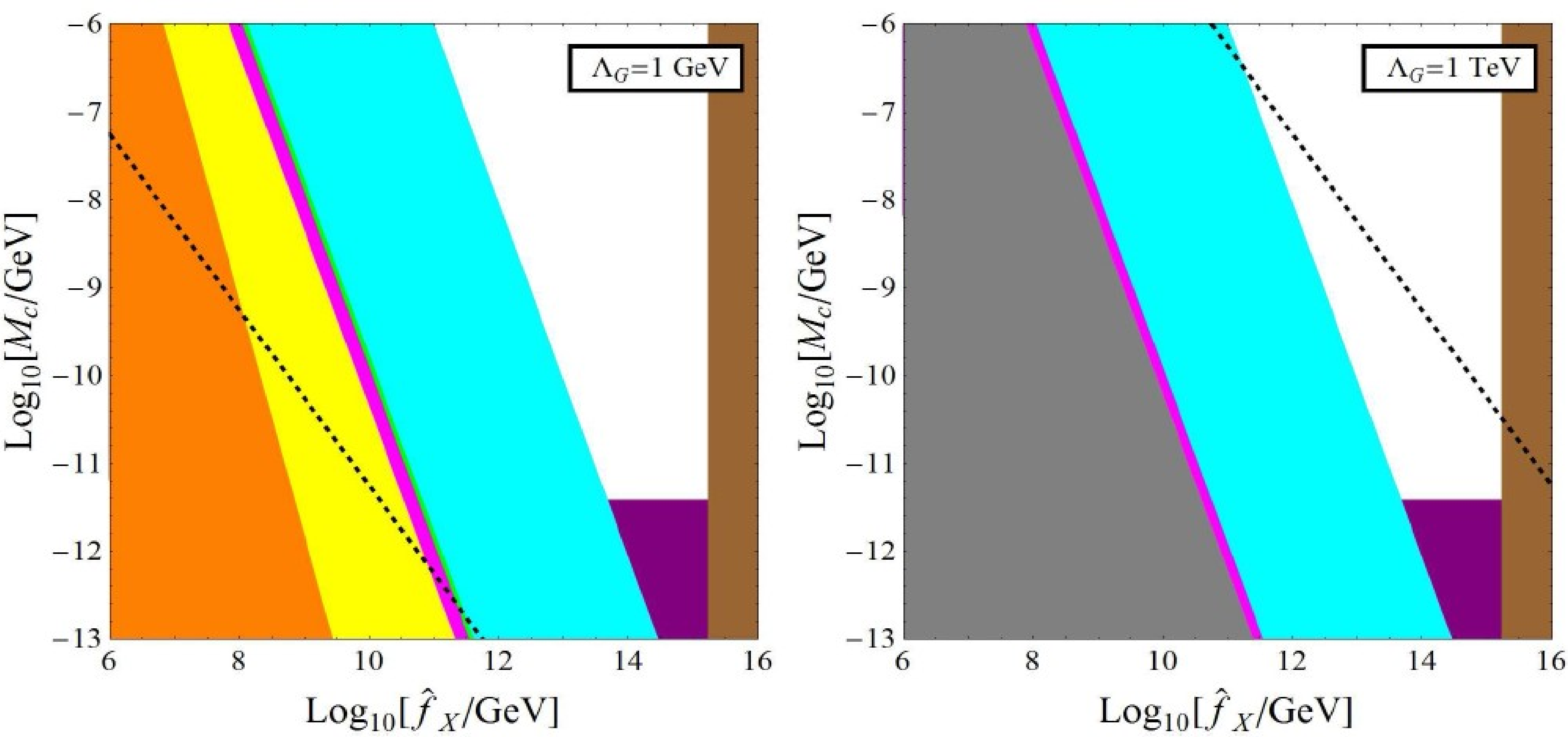


Combined Limits on Dark Towers

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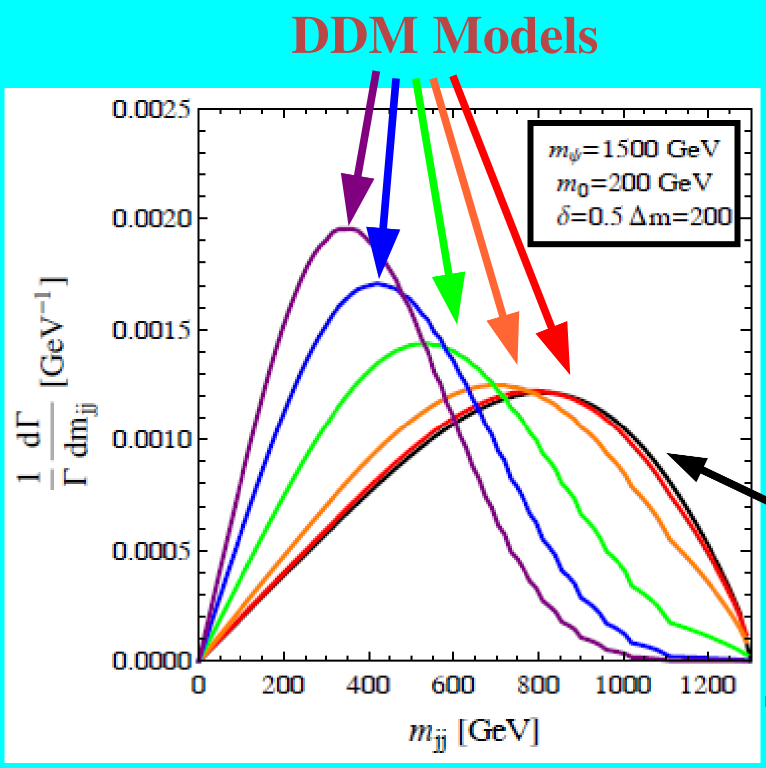
- K. Boddy, KRD, D. Kim, J. Kumar, J.C. Park & B. Thomas, arXiv: 1606.07440
- KRD, J. Kumar, B. Thomas, and D. Yaylali, arXiv: 1708.09698

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



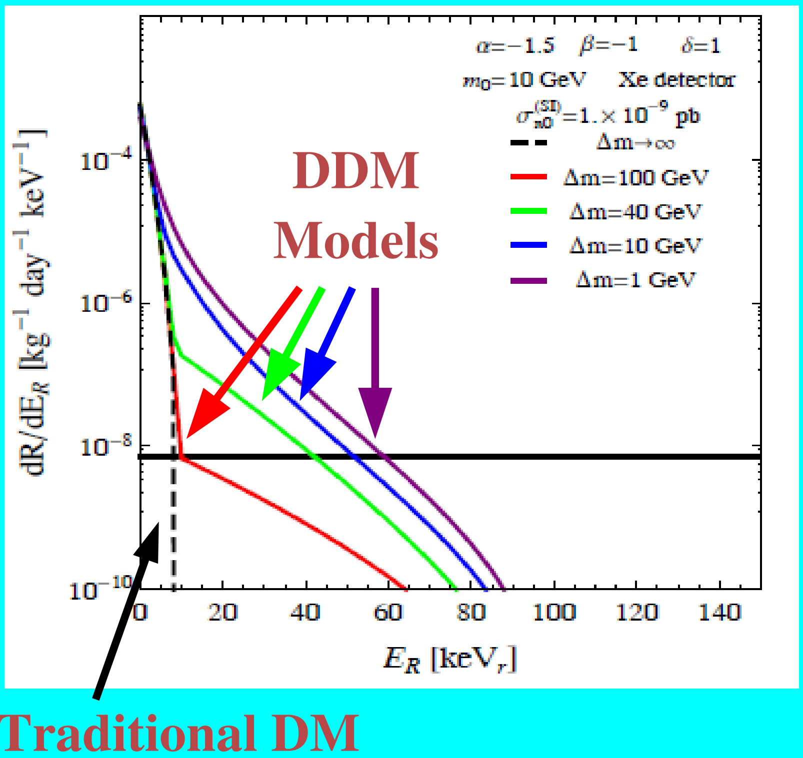
- KRD, S. Su, and B. Thomas, arXiv: 1204.4183
- KRD, S. Su, and B. Thomas, arXiv: 1407.2606

- 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.



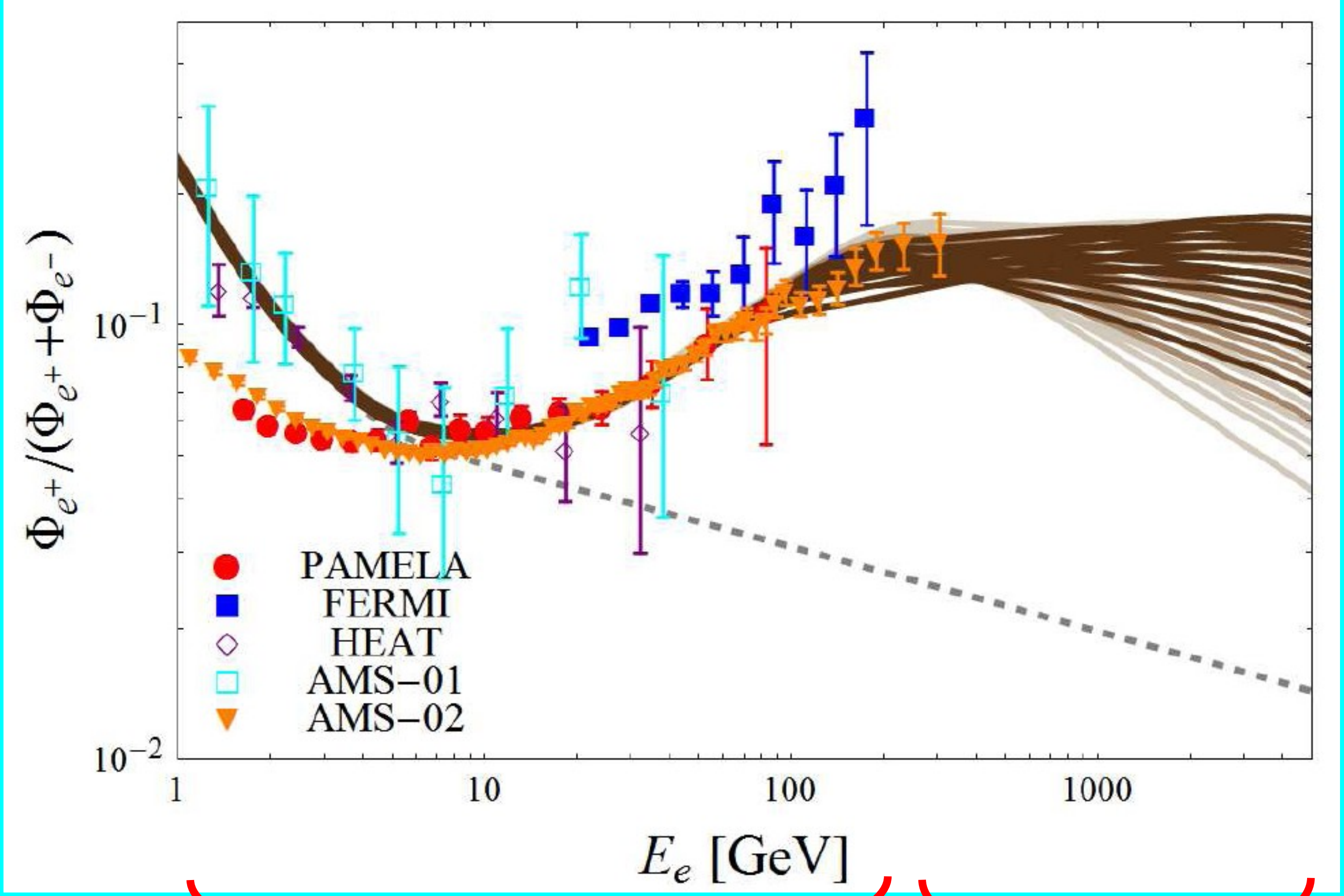
These examples illustrate that DDM ensembles give rise to **observable effects** which can serve to distinguish them from traditional DM candidates.

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...

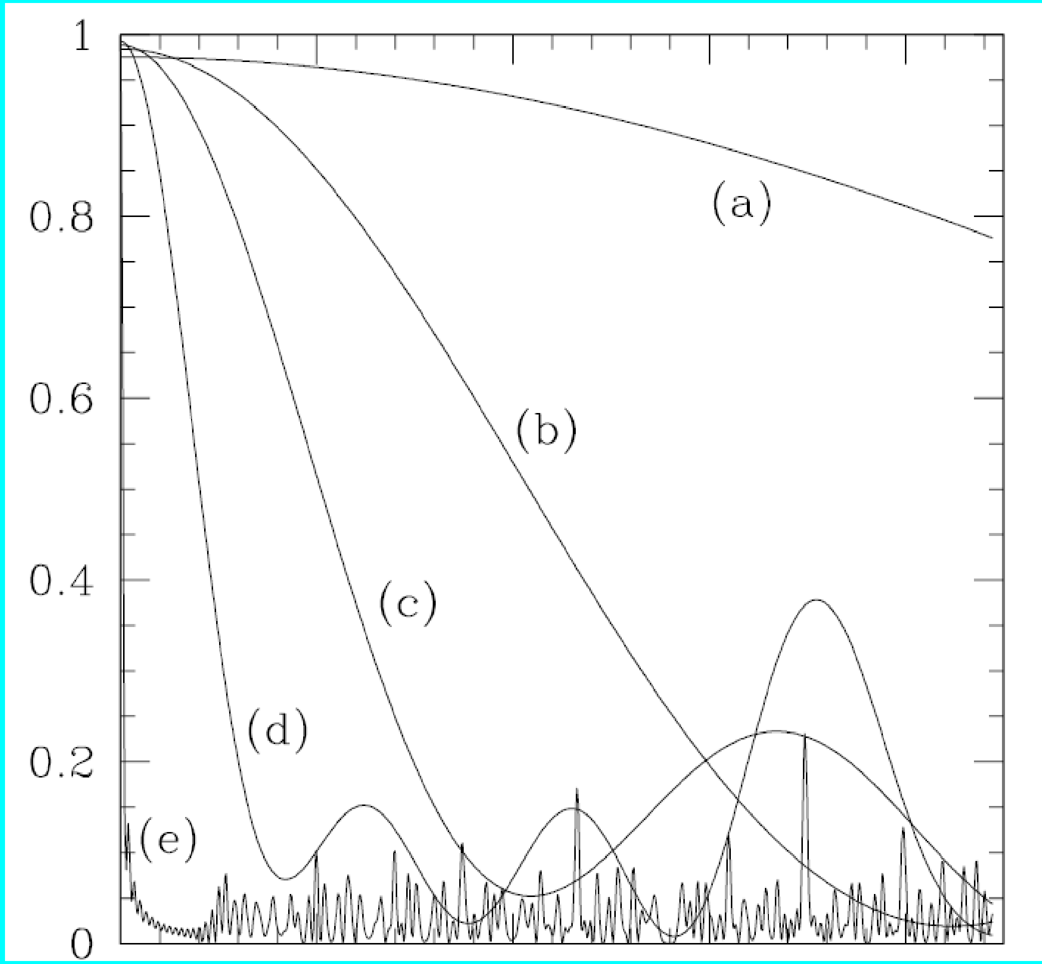
A "smoking gun" for DDM!

DDM also 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...

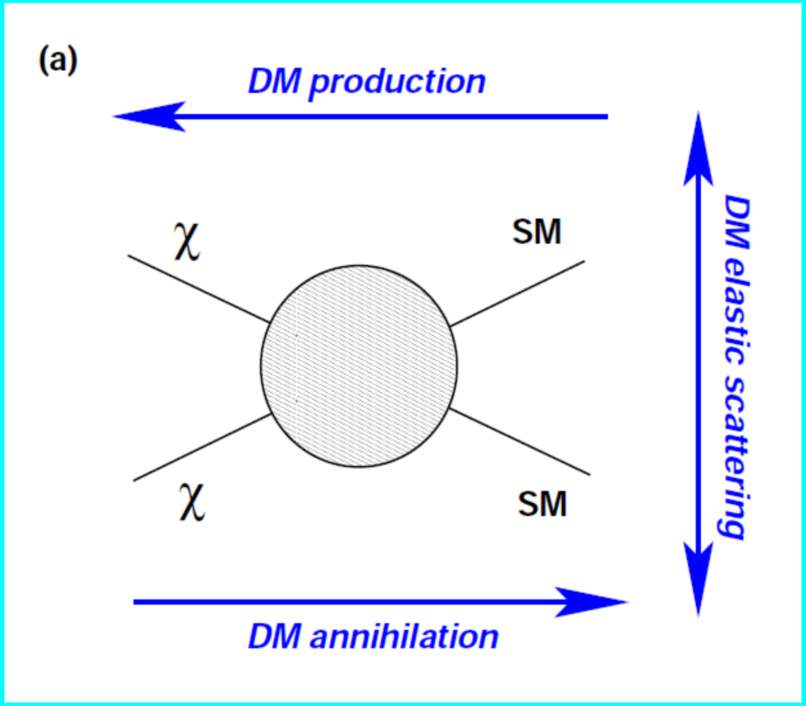


This novel effect provides yet another mechanism which may help dark matter stay dark, and leads to different signature patterns from those which characterize traditional single-component dark-matter candidates.

- KRD, E. Dudas, T. Gherghetta (1999);
- KRD, E. Dudas, T. Gherghetta, B. Thomas (2018, in prep)

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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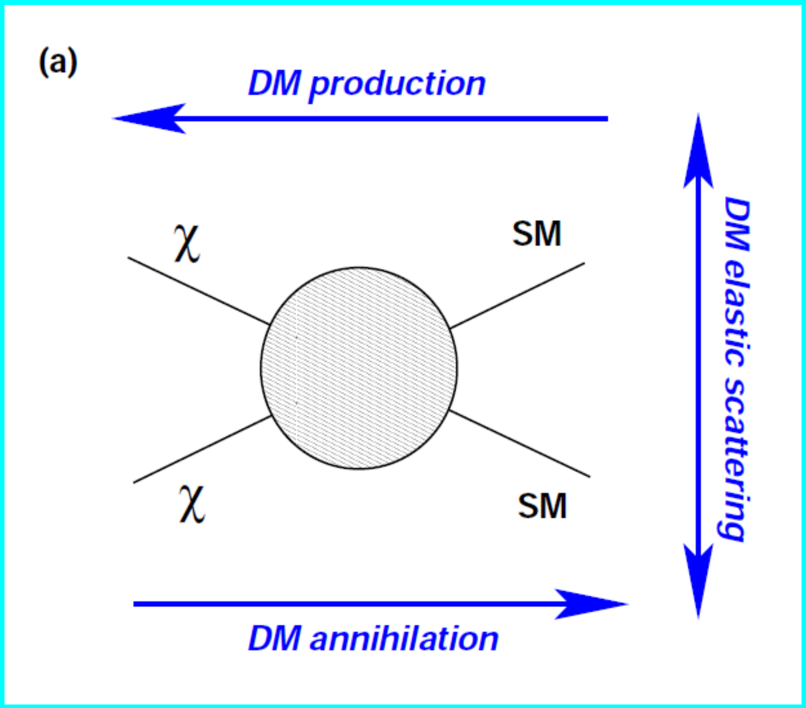
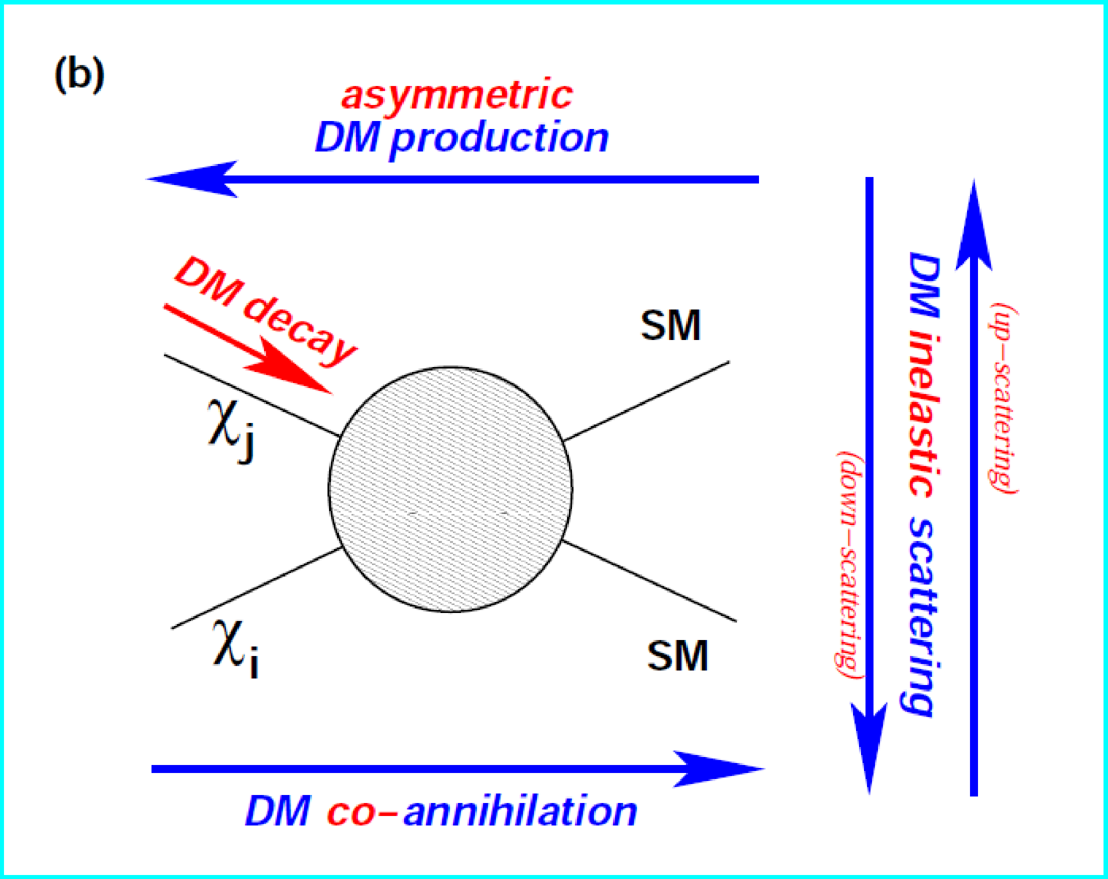


to this...

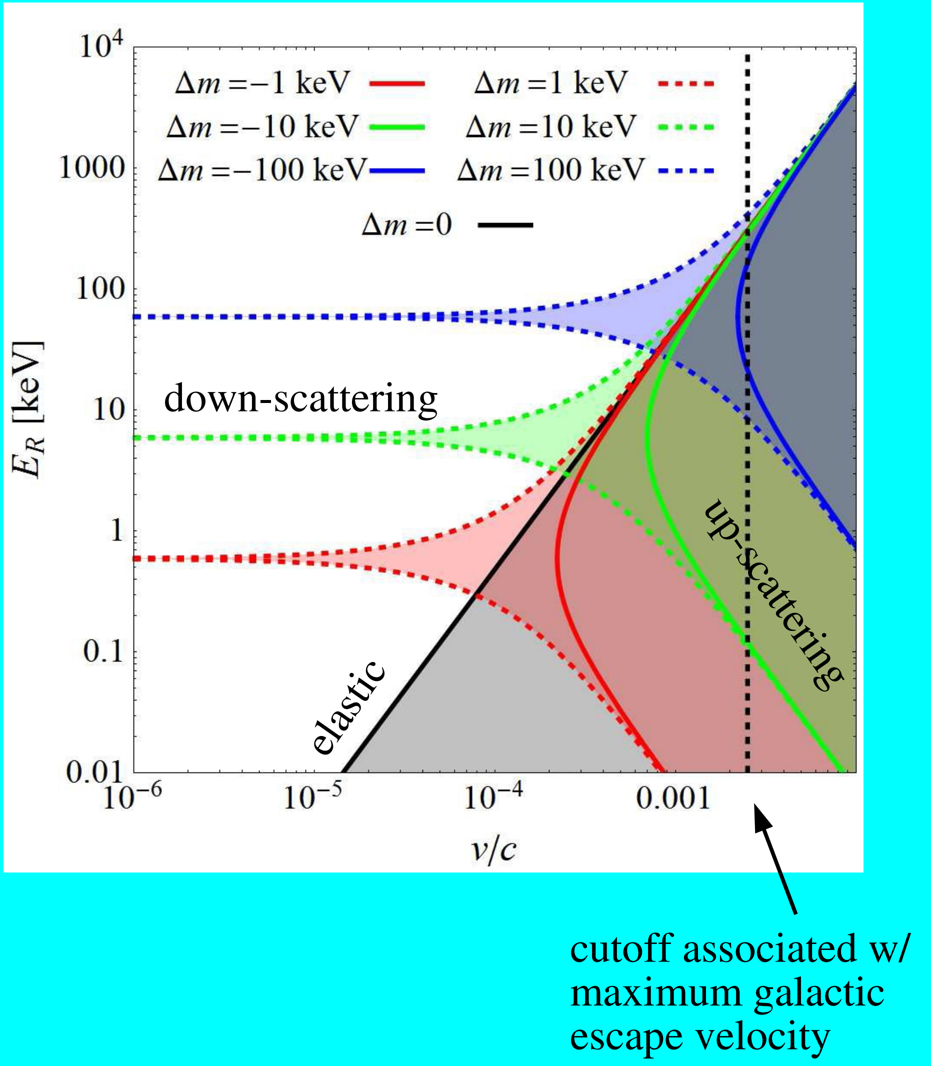


Thus, the traditional DM complementarities are both *augmented* and *extended.* Indeed, in some cases the "off-diagonal" processes may even dominate over the diagonal ones!

In particular, the change in scattering kinematics from *elastic* to *inelastic* can have significant effects...

- For down-scattering with certain recoil energies, the required incoming velocity is essentially *zero*. We thus have **threshold-free scattering with non-zero recoil energy**! (The required input energy comes directly from species conversion within the dark sector.)

- For any incoming DM velocity v, we have not only a finite upper limit on the allowed E_R **but also a non-zero lower limit!** True for both down-scattering and up-scattering. Thus corresponding recoil spectrum is negligible both above a maximum recoil energy and *also below a minimal value*. Indeed, for down-scattering, allowed range of recoil energies becomes exceedingly narrow as the incoming velocity goes to zero!

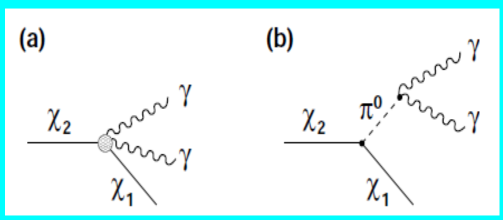


For example, consider the scalar contact operator

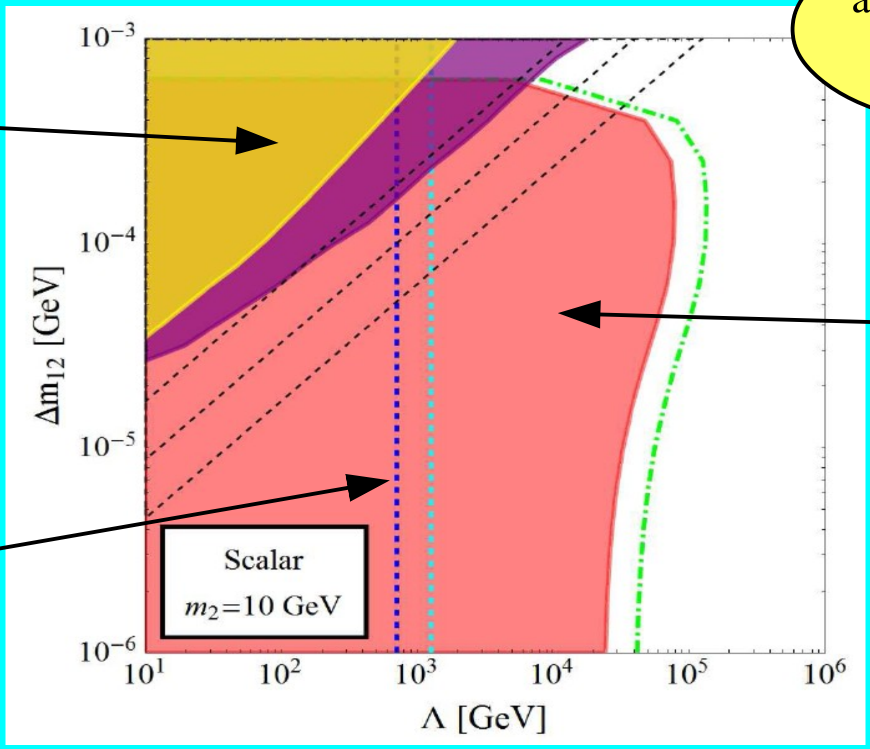
$$\mathcal{L}_{\text{int}}^{(S)} = \sum_{q=u,d,s,\ldots} \frac{c_q^{(S)}}{\Lambda^2} (\overline{\chi}_2 \chi_1)(\overline{q} q)$$

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

Limits from DM *decay*



assuming $\Omega_1=\Omega_2$, for simplicity



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.

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 ← w/ Jeff Kost, 1509.00470, 1612.08950
  - 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.

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

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!

Preliminaries: The DDM ensemble

Characteristics, Parametrizations, Scaling Relations, and Equations of State

Theoretical Realizations of DDM

Types of ensembles

- Kaluza-Klein DDM theories
- DDM from Strongly Coupled Dark Sectors / String Theory
- DDM from Randomness in the Dark Sector

Cosmological production mechanisms

- Misalignment Production of DDM
- Thermal Freezeout of DDM

- Enhanced Complementarities
- Multi-Component Phase Transitions
- Intra-Ensemble Decays & Structure Formation
- Dark-Matter Halo Structure & Dynamics

Experimental Signatures and Bounds on DDM

Direct detection

- Direct Detection of DDM

Indirect detection

- Gamma-Ray Signatures of DDM
- Cosmic-Ray Signatures of DDM

Collider signatures

- DDM at Traditional Detectors
- DDM at the Lifetime Frontier

General constraints

- DDM: Astrophysical / Cosmological Bounds