Dynamical Dark Matter from Strongly-Coupled Dark Sectors

Keith R. Dienes
University of Arizona

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.

Based on work with...

- Brooks Thomas (DDM framework)
- Fei Huang, Shufang Su, and Brooks Thomas (strongly-coupled DDM)

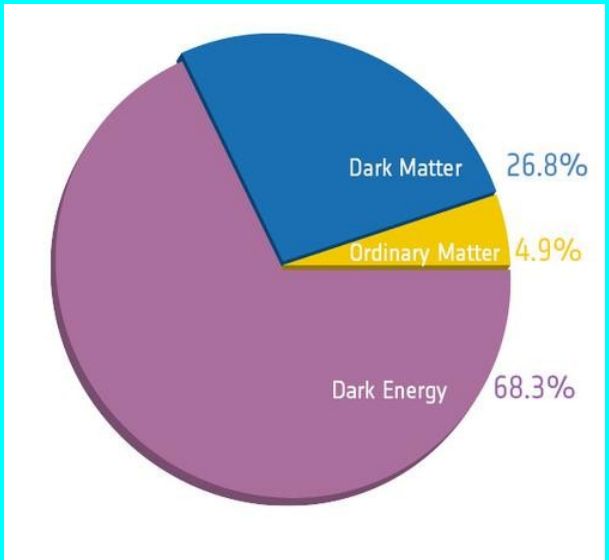
XIII Quark Confinement Conference
Maynooth University, Ireland
August 6, 2018

Dark Matter = ??

- Situated at the nexus of particle physics, astrophysics, and cosmology
- Dynamic interplay between theory and current experiments
- Of fundamental importance: literally 26% of the universe!
- Necessarily involves physics beyond the Standard Model

One of the most compelling mysteries facing physics today!

This is important, since the total energy density of the universe coming from dark matter is **at least five times** that from visible matter!



Physics from **visible sector**

Physics from the **dark sector (dark matter)**

Dark energy

- Indeed, it is primarily the "dark" physics which drives the evolution of the universe through much of cosmological history... cannot be ignored!
- Moreover, thanks to advances in observational cosmology over the past two decades (COBE, Planck, etc.), we are rapidly gaining data concerning the nature and properties of the dark sector!

This is thus a ripe area for study!

Traditional view of dark matter:

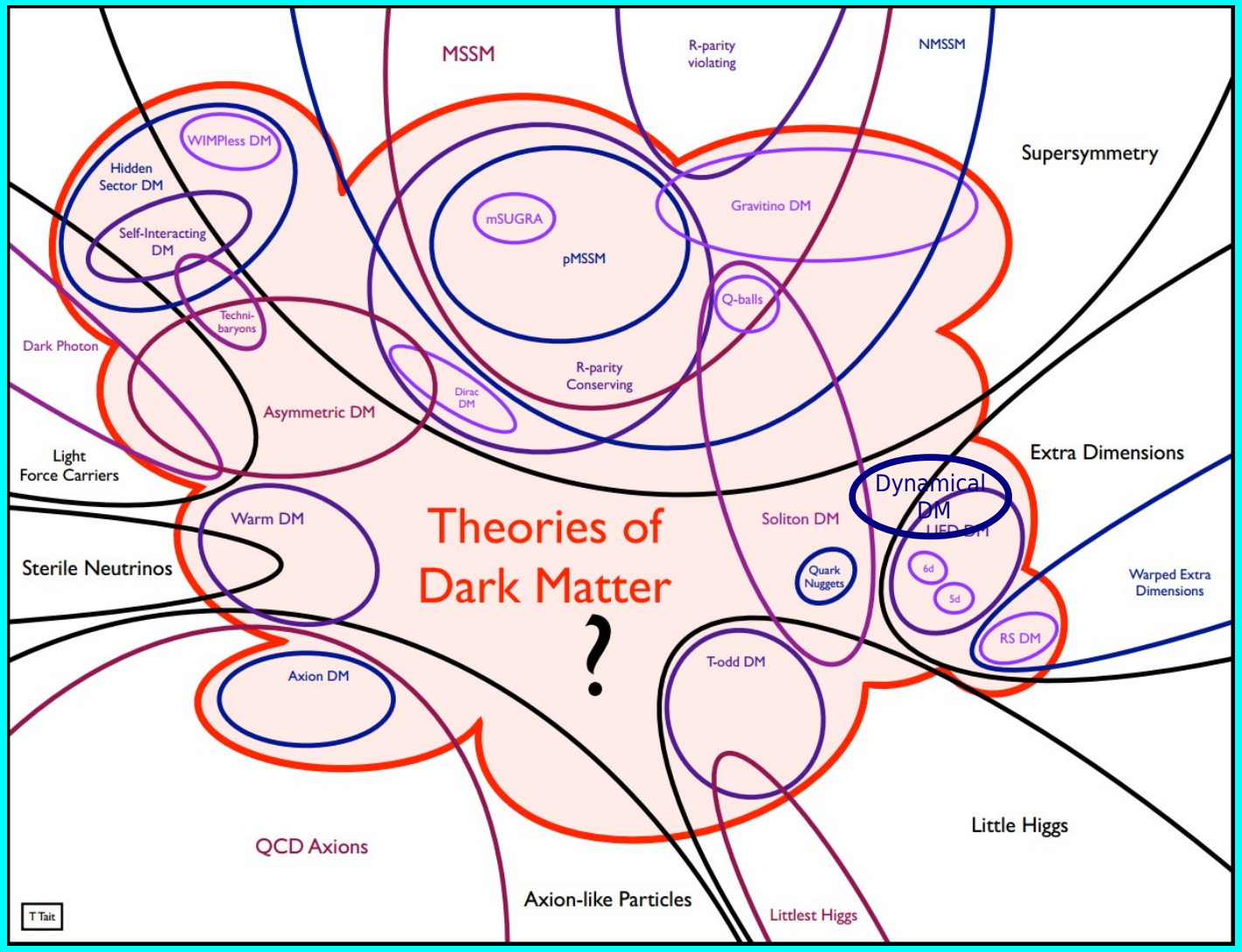
- One or several dark-matter particle(s) χ which carry entire DM abundance: $\Omega_\chi = \Omega_{CDM} = 0.26$ (WMAP).
- Such particle(s) must be hyperstable, with lifetimes exceeding the age of the universe by many orders of magnitude $\sim 10^{26}$ s.
- Most DM scenarios take this form.

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.

But what kind of particle constitutes the dark matter?

Through the years, a huge variety of possible dark-matter candidates have been proposed...



There have also been many dark-matter candidates emerging from **strongly-coupled dark sectors**...

Baryons and baryon-like objects

- Lightest technibaryon in technicolor theories
- Exotic baryon-like composites

Nussinov; Barr, Chivukula, Farhi; Gudnason, Kouvaris, Sannino; Ryttkov, Sannino; Harigaya, Lin, Lou

Appelquist et al. (Lattice Strong Dynamics = LSD Collaboration)

Mesons and meson-like objects

- PNGB's stabilized by analogues of flavor symmetry and/or G-parity
- Heavy/light quark bound states
- Heavy/heavy quark bound states
- More general possibilities

Kribs and Neil; Kilic, Okui, Sundrum; Hur, Ko; Holthausen, Kubo, Lim, Lindner; Hatanaka, Jung, Ko; Ametani, Aoki, Goto, Kubo; Bai, Hill; Buckley, Neil; Bhattacharya, Melic, Wudka; Carmona, Chala; Frigerio, Pomarol, Riva, Urbano; Lewis, Pica, Sannino; Hietanen, Pica, Sannino, Sondergaard

Pure glue

- Glueballs
- From string theory
- From AMSB

Alves, Behbahani, Schuster, Wacker; Lisanti, Wacker; Kribs, Roy, Terning, Zurek; Antipin, Redi, Strumia; Antipin, Redi, Stumia, Vigiani

Okun; Soni, Zhang; Forestell, Morrissey, Sigurdson; Faraggi, Pospelov; Halverson, Nelson, Ruehle; Feng, Shadmi

Bigger objects

- Dark nuclei (can even be generated via dark BBN!)
- Dark atoms / dark molecules
- Exotic *SM-quark* composites?

Detmold, McCullough, Pochinsky; Krnjaic, Sigurdson; Cline, Liu, Moore, Xue; Boddy, Kaplinghat, Kwa, Peter; Hardy, Lasenby, March-Russell, West; Farrar; Bai, Long

In almost all cases, the dark-matter candidate is the **lightest** of these states

⇒ Explains why it is stable!

Moreover, while in some cases the resulting dark-matter candidate is itself only **weakly interacting (WIMP),** in other cases it can be **strongly interacting (SIMP)!**

And these have given rise to new kinds of dark-matter phenomenology...

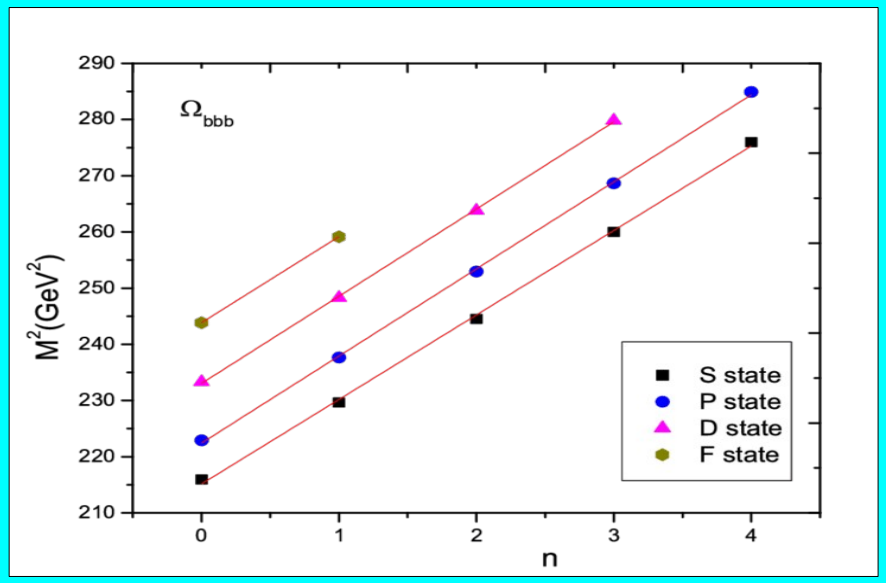
- thermal freezeout through 3->2 (rather than 2->2) processes … leads to different mass scales and couplings than ordinary WIMP's!
- new effects on **structure formation** in the early universe, potentially addressing the "core vs. cusp" and "too big to fail" problems!

Hochberg, Kuflik, Volansky, Wacker; Carlson, Machacek, Hall; de Laix, Scherrer, Schaefer; Hochberg; Kuflik, Murayama, Volansky, Wacker; Hansen, Langaeble, Sannino; Bernal, Chu; Kamada, Yamada, Yanagida, Yonekura

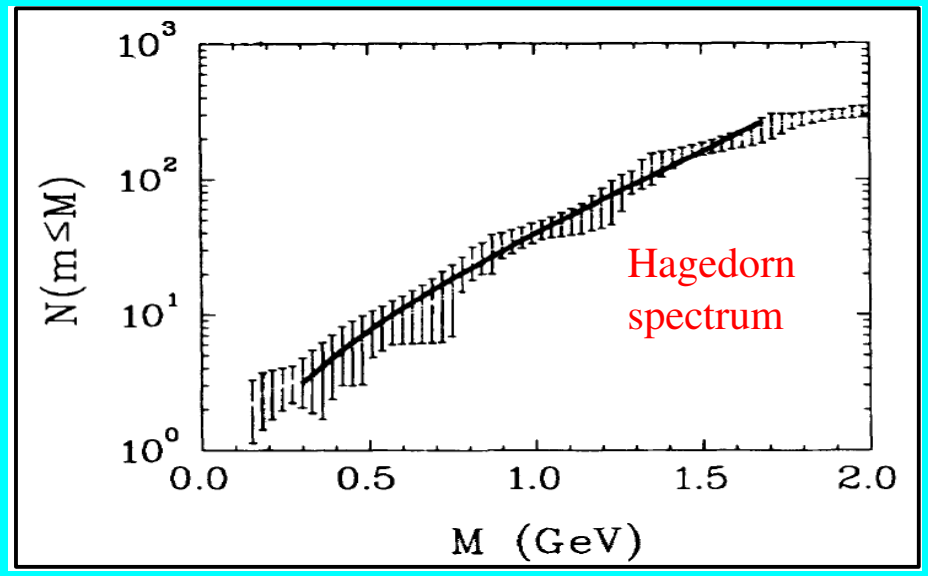
But strongly-coupled theories don't just give rise to these states in isolation...

These states generically arise in conjunction with <u>infinite towers of higher resonances</u>!

For example, for ordinary QCD, these states lie along **Regge trajectories**:



… and the **density of such states grows exponentially with mass:**



The parameters involved in these relations give us vital information about the mass scales and degrees of freedom associated with the underlying flux tubes which represent the strong interaction!

Just as with ordinary QCD,
a strongly-coupled *dark* sector should also
give rise to such infinite towers of resonances!

Can these states also play a role in dark-matter physics??

- In the early universe?
- *In forming the dark-matter today*?

Just as with ordinary QCD,
a strongly-coupled *dark* sector should also
give rise to such infinite towers of resonances!

Can these states also play a role in dark-matter physics??

- In the early universe?
- *In forming the dark-matter today*?

Yes!

… but this goes beyond the traditional dark-matter scenarios which rely on a single, stable dark-matter particle!

Instead, such states are naturally incorporated within an alternate general framework for dark-matter physics known as

Dynamical Dark Matter (DDM).

Instead, such states are naturally incorporated within an alternate general framework for dark-matter physics known as

Dynamical Dark Matter (DDM).

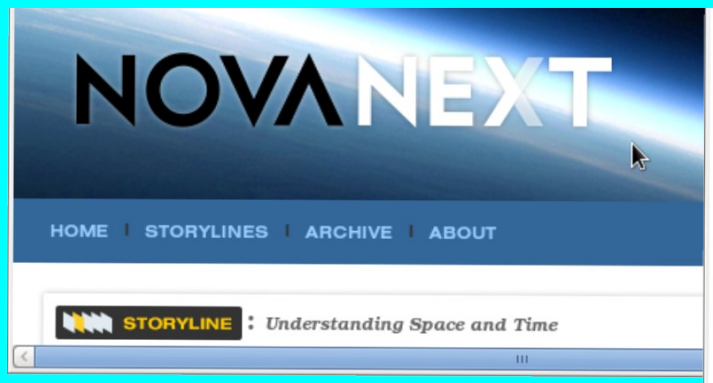
DDM originally proposed in 2011 with **Brooks Thomas...**

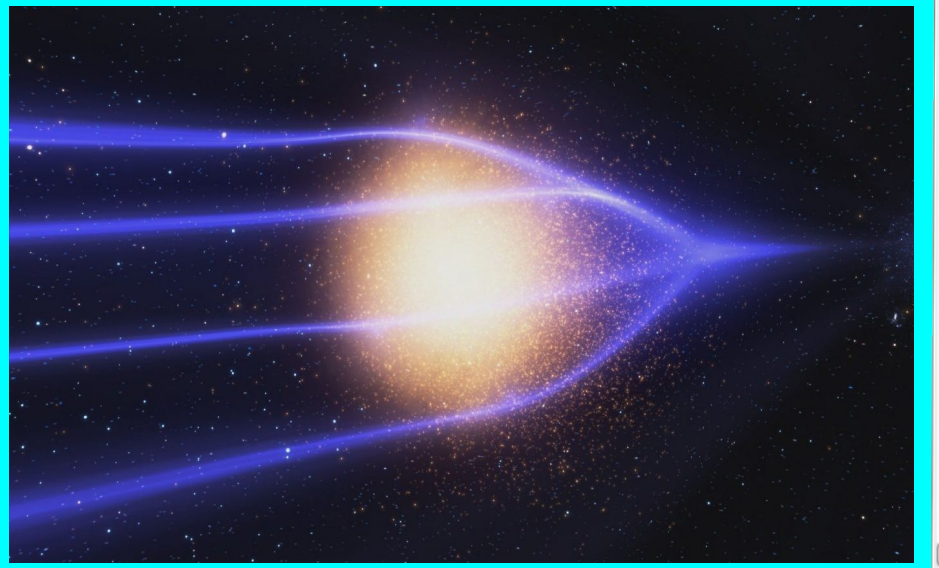
- 1106.4546
- 1107.0721
- 1203.1923

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)
- 1407.2606 (also w/ S. Su)
- 1509.00470 (also w/ J. Kost)
- 1601.05094 (also w/ J. Kumar, J. Fennick)
- 1606.07440 (also w/ K. Boddy, D. Kim, J. Kumar, J.-C. Park)
- 1609.09104 (")
- 1610.04112 (also w/ F. Huang and S. Su)
- 1612.08950 (also w/ J. Kost)
- 1708.09698 (also w/ J. Kumar, D. Yaylali)
- 1712.09919 (also w/ J. Kumar, J. Fennick)
- 1808.xxxxx (also w/ D. Curtin)
- 1808.xxxxx (also w/ F. Huang and S. Su)
- 1808.xxxxx (also w/ J. Kumar & P. Stengel)
- 1809.xxxxx (also w/ Y. Buyukdag & T. Gherghetta)
- ... plus many ongoing projects

NOVA Next, 5/30/2018:

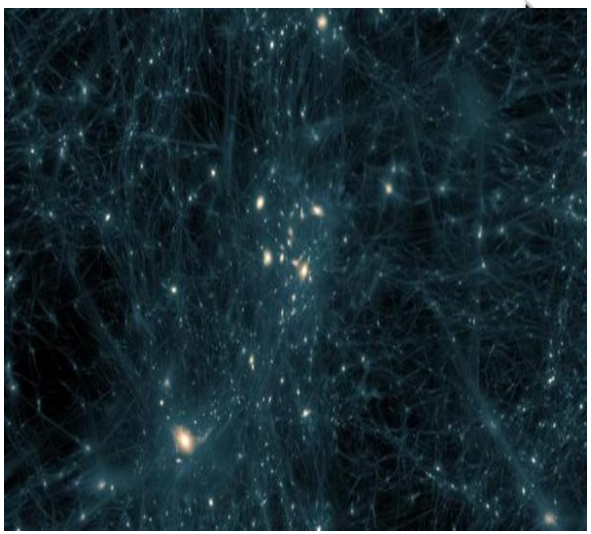




Does Dark Matter Ever Die?

By Kate Becker on Wed, 30 May 2018

Read Later | Like | Tweet



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 (DDM):
  a general alternative framework for dark-matter physics
  --- a quick introduction and overview

- DDM as the natural framework for
  strongly-coupled dark sectors
  --- general formulations, constraints, and results

Recall the 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.

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!

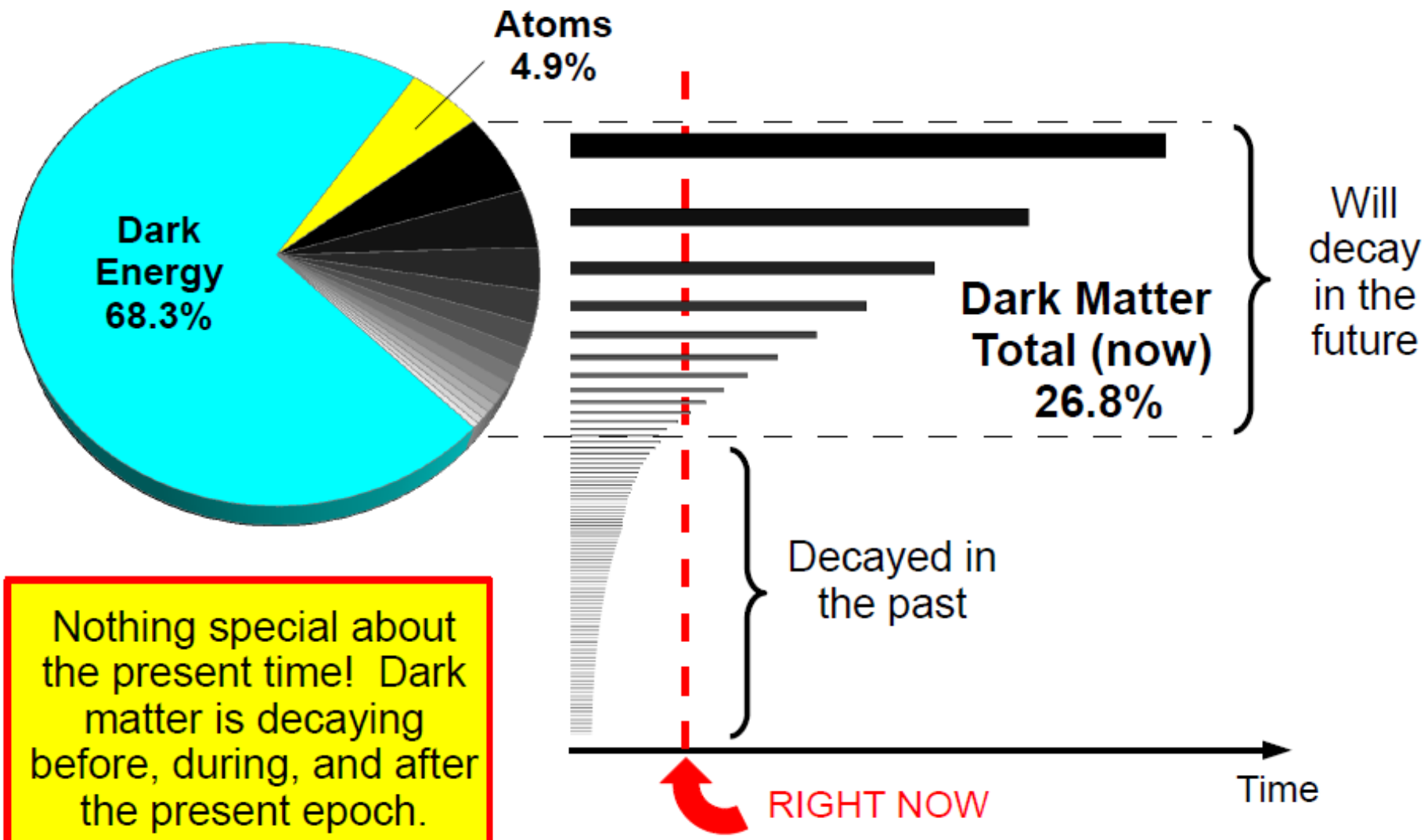
<u>Dynamical Dark Matter (DDM)</u>: an alternative framework for dark-matter physics in which the notion of dark-matter stability is replaced by a balancing of lifetimes against cosmological abundances across an ensemble of individual dark-matter components with different masses, lifetimes, and abundances.

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!***

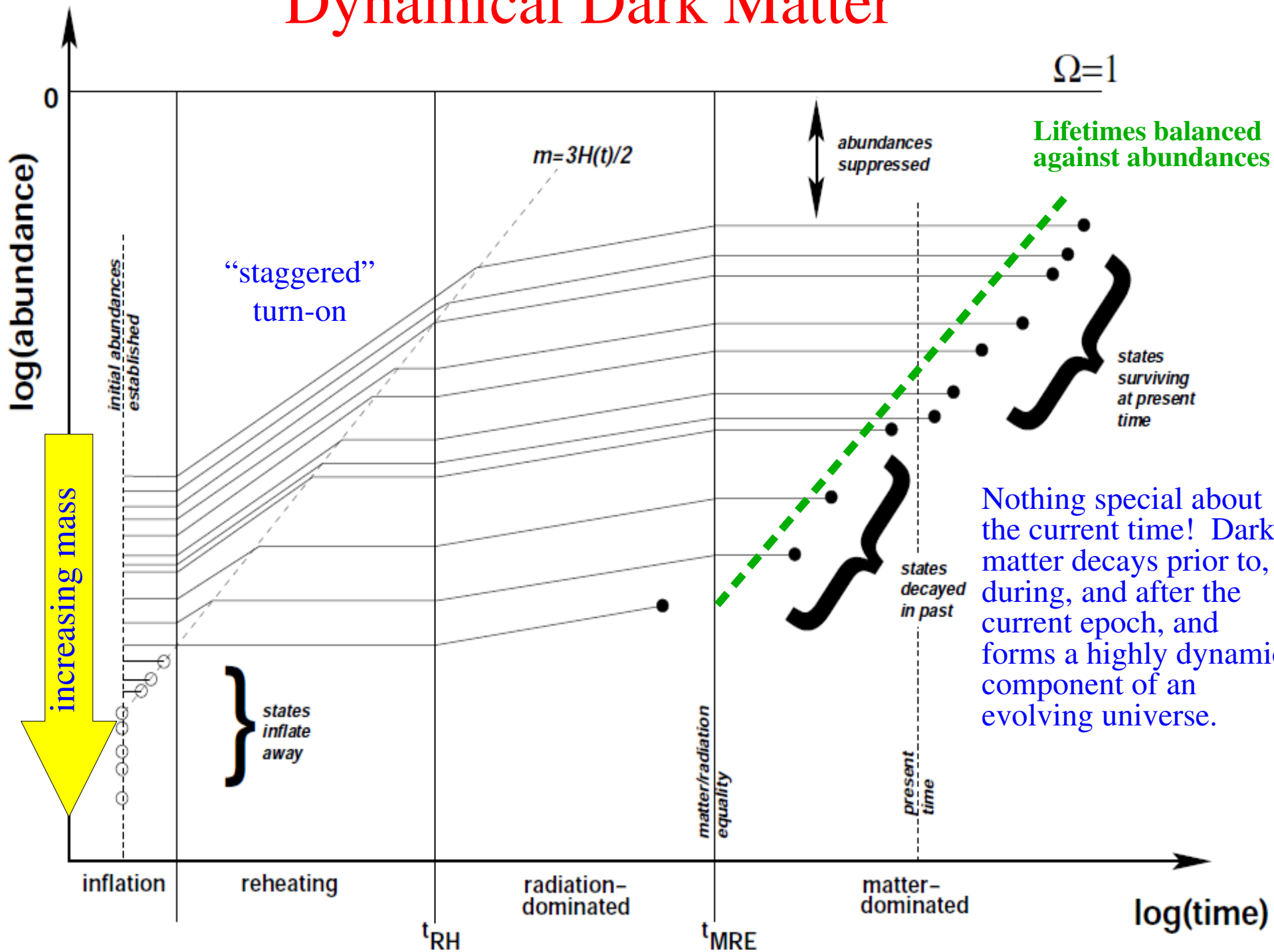
"Dynamical Dark Matter": The Basic Picture:

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.

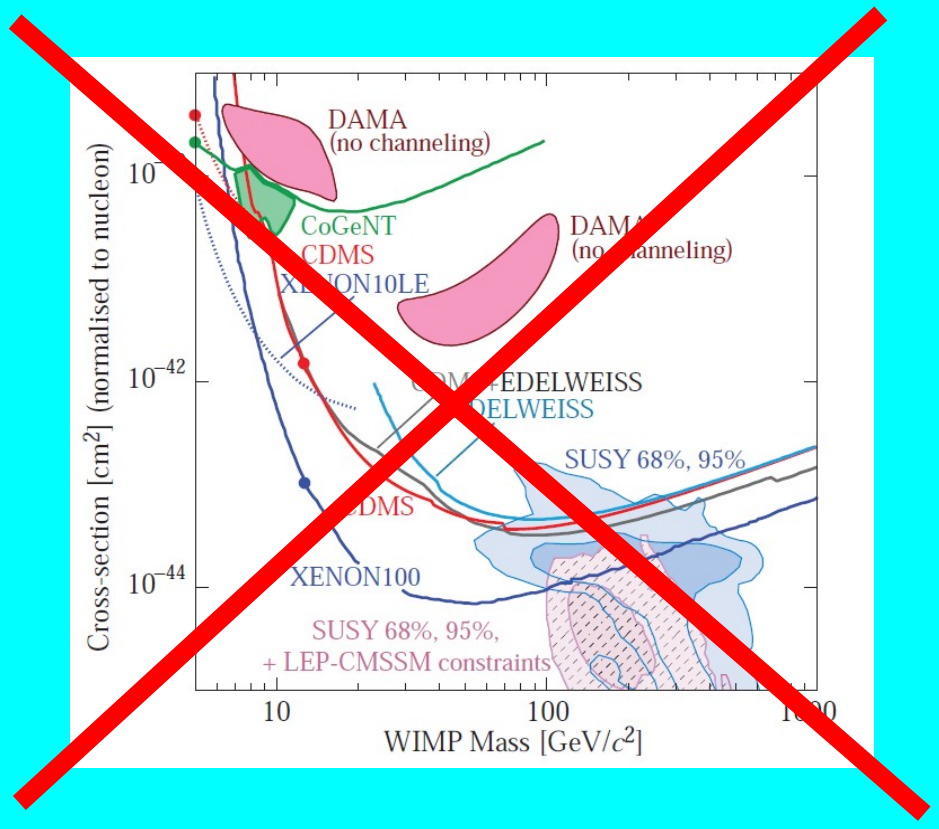
Dynamical Dark Matter



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

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

Lifetimes (decay widths)

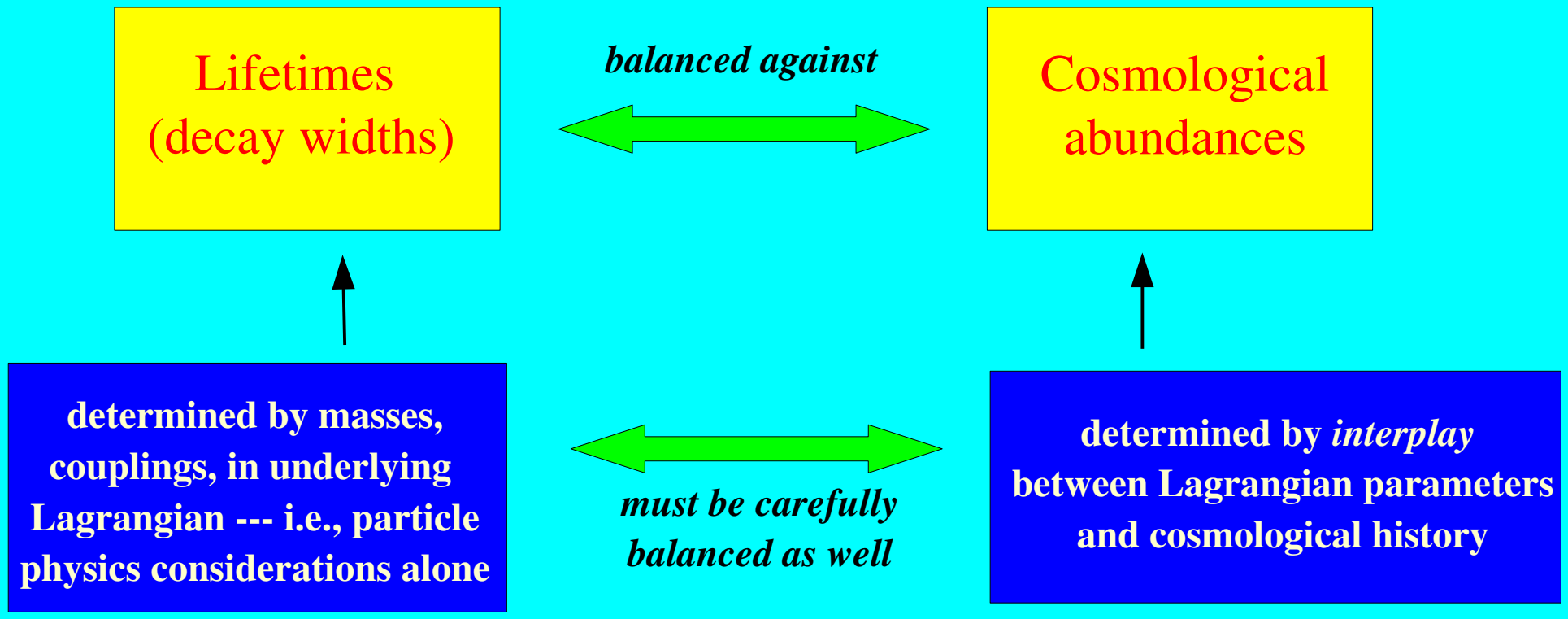
balanced against

Cosmological abundances

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

determined by *interplay* between Lagrangian parameters and cosmological history

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.

In general, at any moment in cosmological history, we can describe the state of the hadronic DDM ensemble by specifying abundances of each state:

$$\Omega_i = \rho_i(t) / \rho_{crit}(t)$$

$3\,[M_{pl}\,H(t)]^2$

Introduce two "complementary" parameters:

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

- *Distribution* of that total abundance: how much is Ω_{tot} shared between a dominant component Ω_0 and all others? Define

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

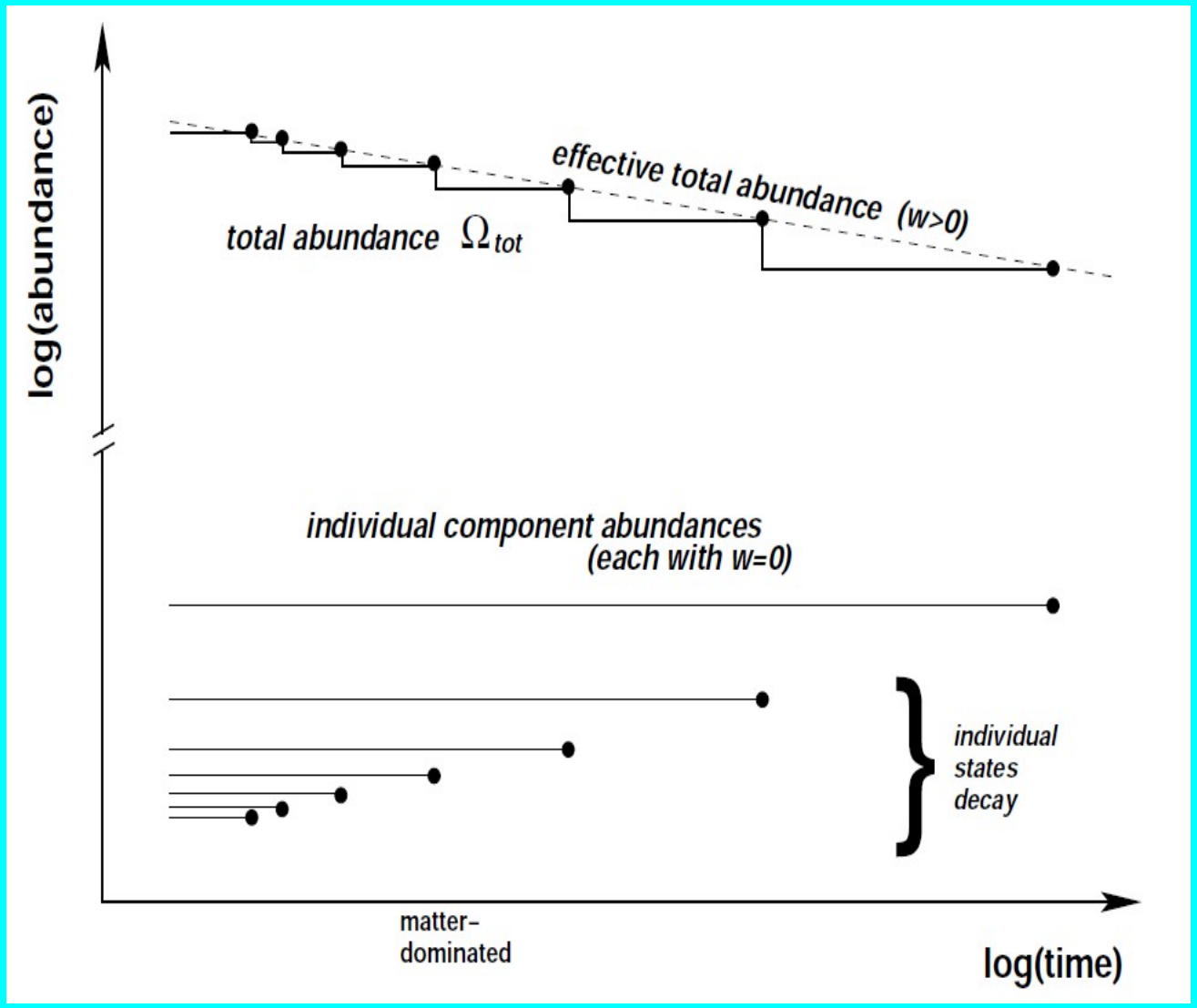
where $\Omega_0 \equiv \max_i\{\Omega_i\}$

Thus

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

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

Because of the decays of the individual constituents of the hadronic DDM ensemble, Ω_{tot} is a time-dependent quantity –- even during the current matter-dominated epoch!



- This time-dependence is an important signature of the dynamical nature of the dark sector!
- As a result, our decaying DDM ensemble of dark-matter states collectively has a non-trivial "effective" equation of state $w_{\mathbf{eff}}(t)$!

In general, we can define...

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

For the purposes of understanding cosmological expansion, this quantity then gives us a measure of how "matter-like" our DDM ensemble is, and the extent to which our DDM ensemble collectively behaves as would a single, stable, dark-matter particle.

In particular, if a given DDM model is to be in rough agreement with cosmological observations, we expect that **w_{eff} today should be fairly small** (since traditional dark matter has $w = 0$). We also expect that **$w_{\rm eff}(t)$ should not have experienced strong variations within the recent past.**

<u>DDM is a general framework for dark-matter physics</u>. However, let us now consider a DDM ensemble consisting of the infinite towers of hadron-like states coming from a strongly-coupled dark sector!

- For such DDM ensembles, the **<u>mass spectrum</u>** of states lies on linear Regge trajectories:

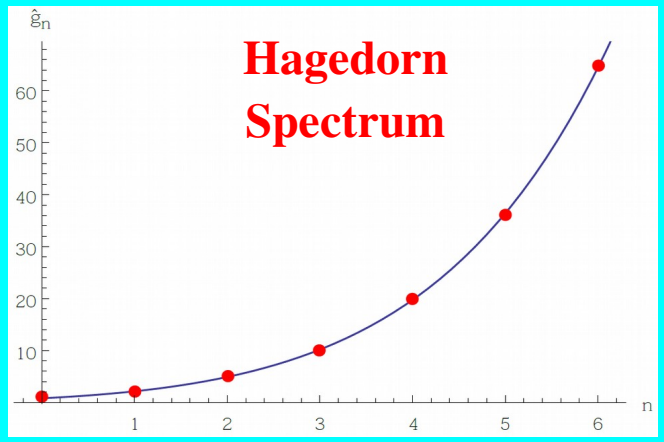
$$M_n^2 = nM_s^2 + M_0^2$$

Note: sensitive to a "string" scale (consider as a free parameter)!

- Likewise, the **<u>degeneracy of states</u>** at each mass level exhibits *exponential* Hagedorn-like growth:

$$g_n \propto 2\pi \left(\frac{16\pi^2 n}{C^2} - 1\right)^{\frac{1}{4}-B} I_{|2B-\frac{1}{2}|}\left(C\sqrt{n - \frac{C^2}{16\pi^2}}\right)$$

$$\approx \frac{1}{\sqrt{2}}\left(\frac{C}{4\pi}\right)^{2B-1} n^{-B} e^{C\sqrt{n}}$$



depends on two free parameters, B and C

- KRD, F. Huang, S. Su, B. Thomas, arXiv: 1610.04112

If we think of these states as corresponding to excitations of a generic flux-tube theory of the form

$$S \sim M_s^2 \int d^2\sigma \sum_{i=1}^{D_\perp} \left(\frac{\partial}{\partial\sigma^\alpha} X^i\right)\left(\frac{\partial}{\partial\sigma_\alpha} X^i\right) + \ldots$$

possible "internal" theory beyond the flux tube itself

Polyakov action

where **$D_\perp$: number of transverse dimensions**
c : total central charge (d.o.f.'s) of theory

then the constants *B* and *C* have physical meaning:

$$\begin{cases} B = \frac{1}{4}(3 + D_\perp) \\ C = \pi\sqrt{2c/3}\ . \end{cases}$$

For example, the corresponding static-quark potential takes the form

$$V(R) = \left(\frac{M_s}{2\pi}\right)\sqrt{(M_s R)^2 - (C/2)^2}$$
$$\approx \frac{M_s^2 R}{2\pi} - \frac{C^2}{16\pi}\frac{1}{R} + \ldots \quad \text{for } R \gg M_s^{-1}$$

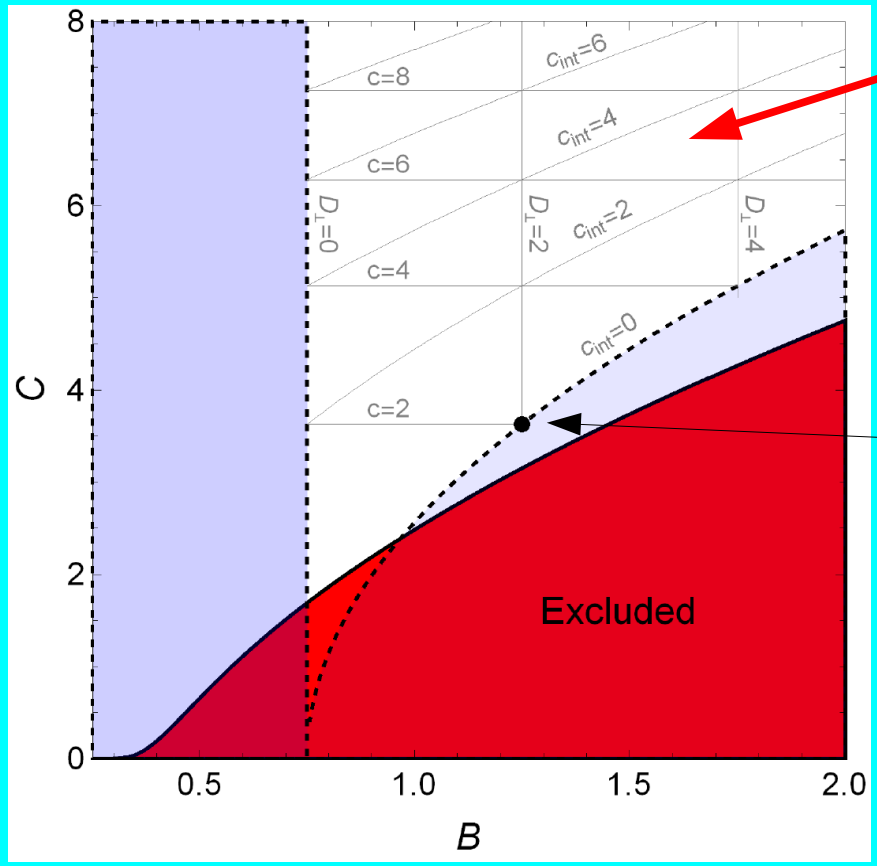
linear confinement

"pseudo-Coulomb" term: attractive universal quantum correction (Casimir energy) from zero-mode vibrations of flux tube...

For consistency, demand

$$\begin{cases} D_\perp \in \mathbb{Z} > 0 \\ c \geq D_\perp \end{cases} \Rightarrow \boxed{C^2 \geq \frac{2\pi^2}{3}(4B-3)}$$

Furthermore, degeneracies g_n should rise monotonically with n.



(B,C) region allowed by consistency constraints

"QCD string" best fit [KRD & Cudell, 1993]

$C^2 < \frac{2\pi^2}{3}(4B-3)$

g_n not monotonic

How are these states <u>produced</u> in the early universe?

Think of flux-tube analogy as model for Hagedorn transition...

- At early times/high temperatures, the theory is the unconfined phase.
- However, when the temperature in the dark sector drops below some **critical temperature** T_C, the dark gauge group G becomes confining.
- Residual G interactions maintain thermal equilibrium among the hadronic states of the confining phase at temperatures just below T_C.

Primordial abundances are **Boltzmann suppressed**:

$$\Omega_n \approx \frac{1}{3\widetilde{M}_P^2 H(T_c)^2} \int \frac{d^3\mathbf{p}}{(2\pi)^3} E_{\mathbf{p}}\, e^{-E_{\mathbf{p}}/T_c}$$

where $T_C \leq T_H$, where $T_H = M_s/C$ is the **Hagedorn temperature**.

In standard dark-matter parlance, this is equivalent to a rapid succession of thermal freeze-out events, *all occurring at the common temperature* T_c associated with deconfinement.

How do these states decay?

There are two possibilities...

- Within the dark sector, to lower dark states

  Depends on dark-sector coupling only. Could lead to highly non-trivial phase-space distributions for lightest remaining dark-matter states, altering structure formation and the resulting matter power spectrum!

  → *currently under study...*

- Out of the dark sector, to SM states on the brane

  Depends on dark/visible coupling. Could cause difficulties with BBN, CMB, and/or leave undesirable imprints in photon/X-ray spectra...

  → *focus on this case for now*

Parametrize the relative decay widths of these states...

$$\Gamma_n = \Gamma_0 \left(\frac{M_n}{M_0}\right)^{\xi}$$

where scaling exponent ξ is an arbitrary parameter

$\Gamma_0 = (10^9\ t_{now})^{-1}$ benchmark value

Impose "zeroth-order" cosmological / astrophysical constraints...

- Total abundance of tower:
  [CMB data, Type Ia supernovae]

$$\Omega_{\rm tot}(t_{\rm now}) \approx 0.26$$

fixes total abundance today

- Equation of state:
  [CMB data, Type Ia supernovae, re-ionization, etc.]

$$w_{\rm eff}(t_{\rm now}) \lesssim 0.05$$

guarantees that total abundance has not changed too significantly since CMB

- Mass of lightest constituent:
  [BBN, small-scale structure]

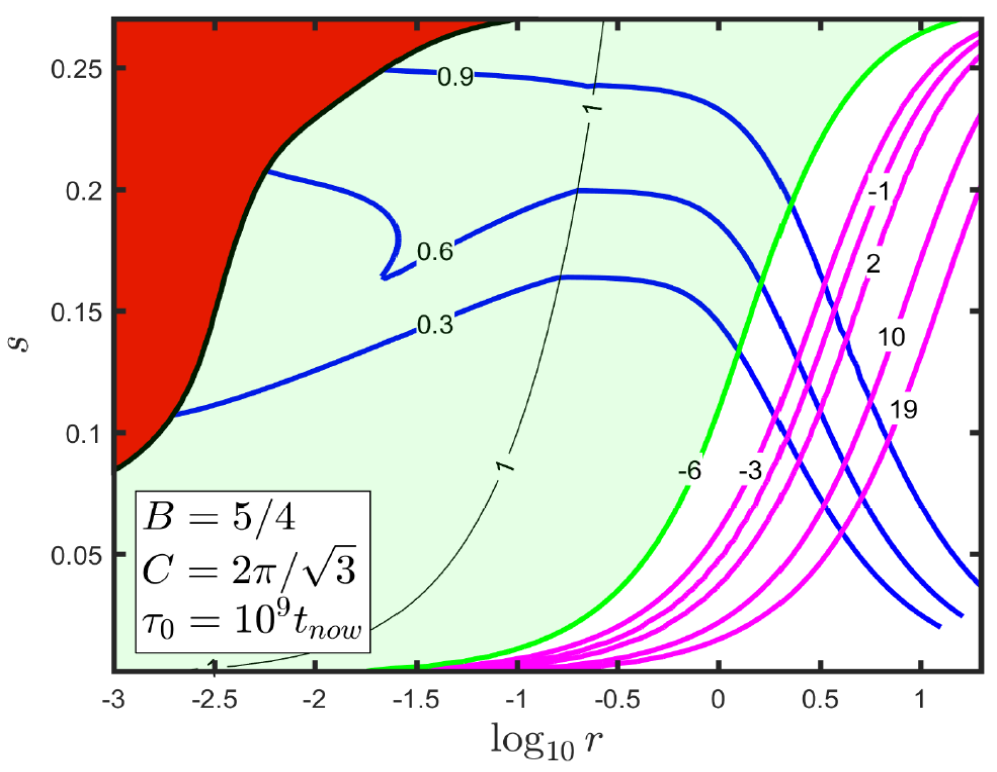
$$M_0 \gtrsim \mathcal{O}(\text{keV})$$

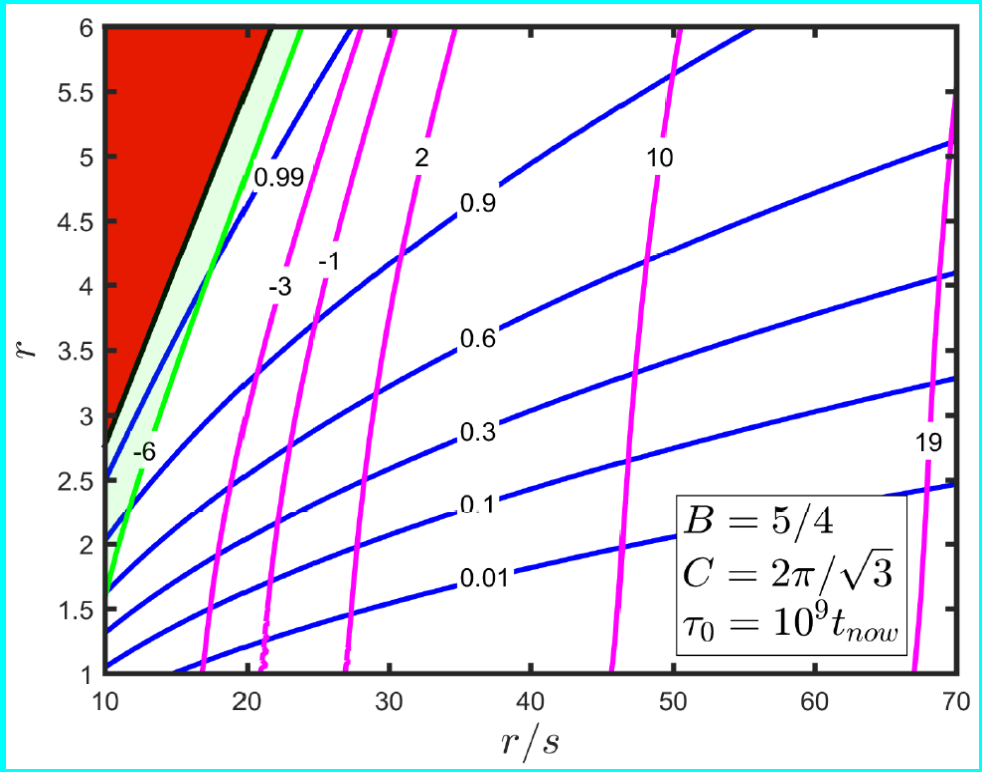
states which are too light can upset BBN and small-scale structure

• KRD, F. Huang, S. Su, B. Thomas, arXiv: 1610.04112

We can then examine the space of viable towers of "dark hadronic" resonances satisfying all three constraints:

$r = M_0/M_s$, $s = T_c/M_s$





Excluded: $M_0 < \mathcal{O}(\text{keV})$

Excluded: $w_{\text{eff}} < 0.05$

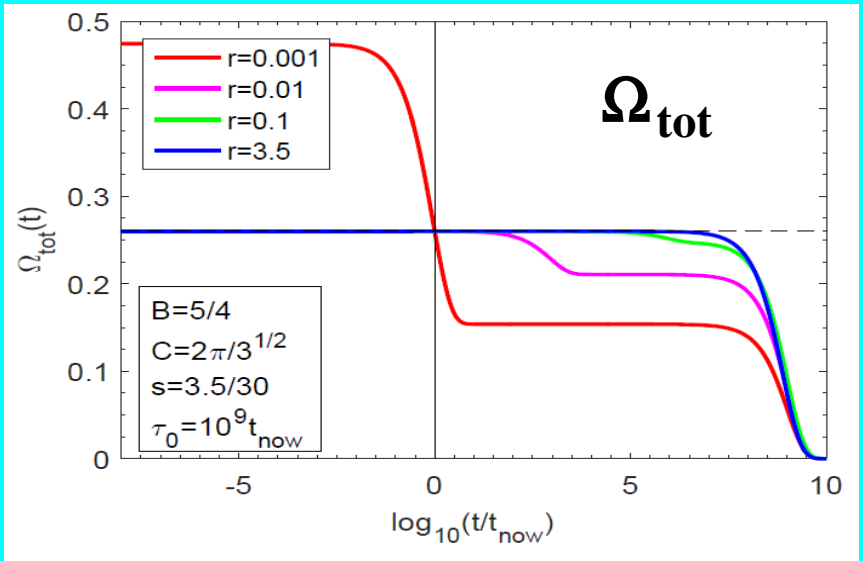
$\eta(t_{\text{now}})$

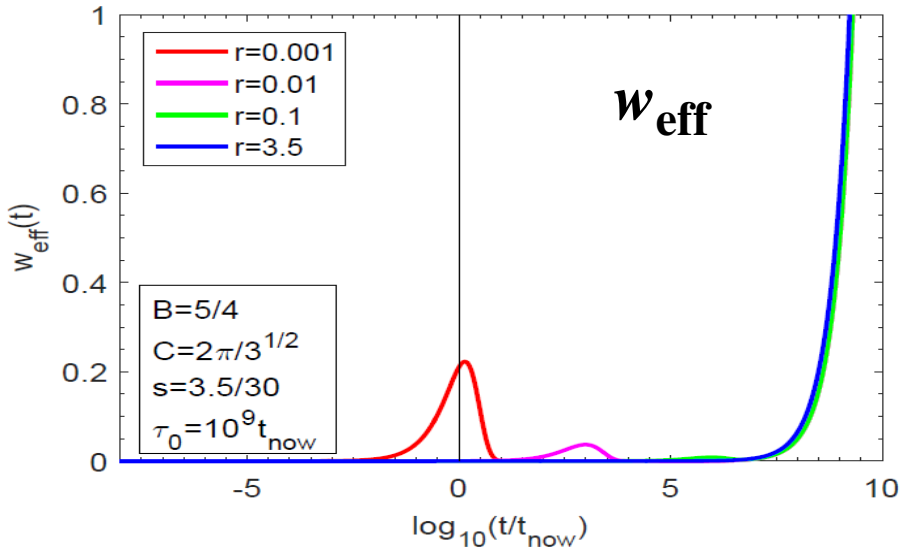
$\log_{10}(M_s/\text{GeV})$

Tower fraction: fraction of Ω_{tot} carried today by all but the lightest constituent

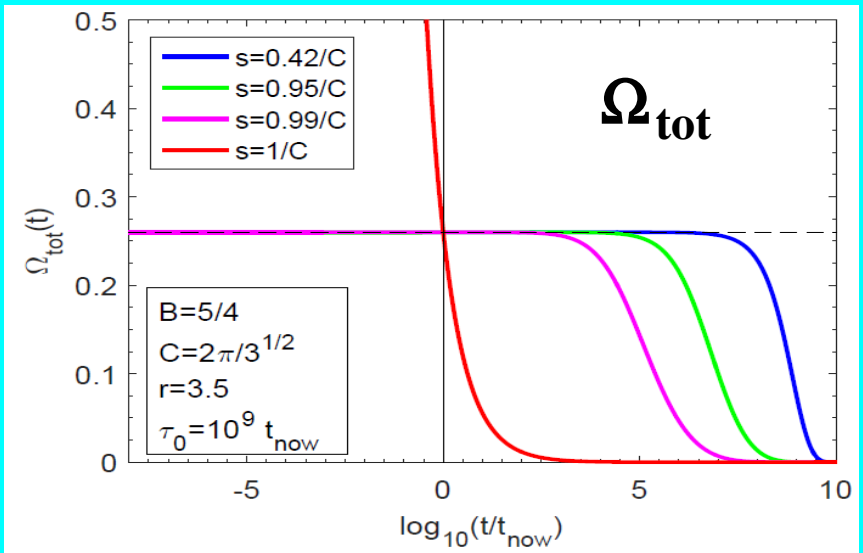
Time evolution of Ω_{tot} and w_{eff}

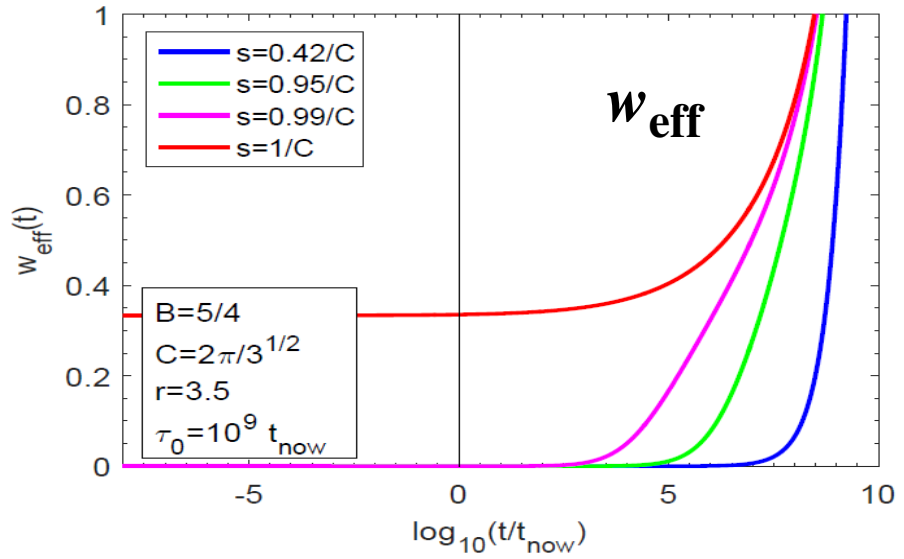
Dependence on $r=M_0/M_s$:



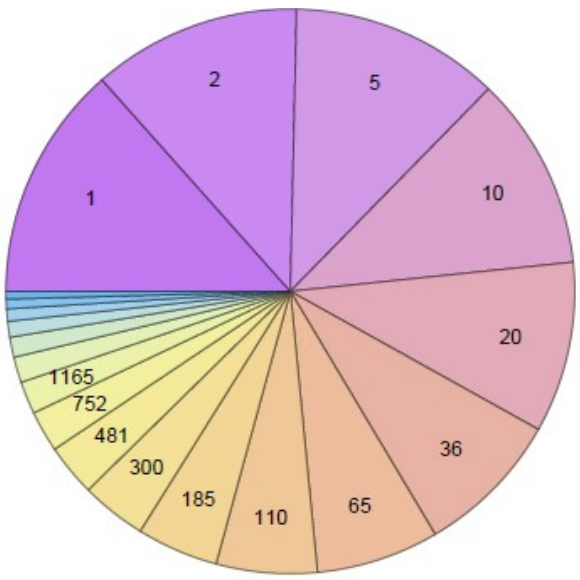


Dependence on $s=T_c/M_s$:





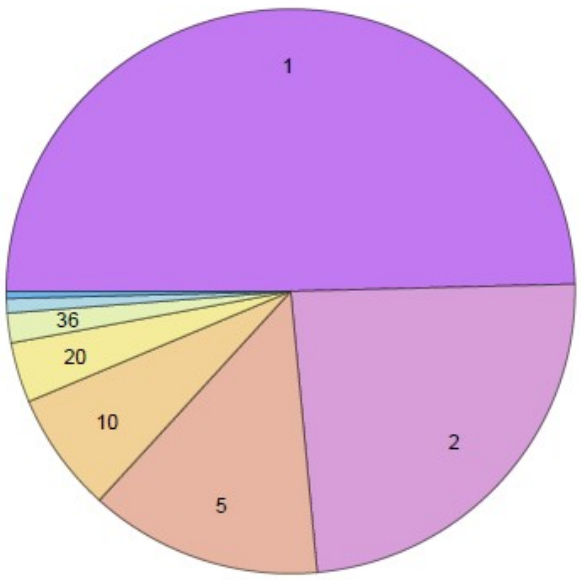
How is the total dark-matter abundance distributed across the hadronic DDM ensemble?



M_0=248.5 GeV

T_C=8.3 GeV

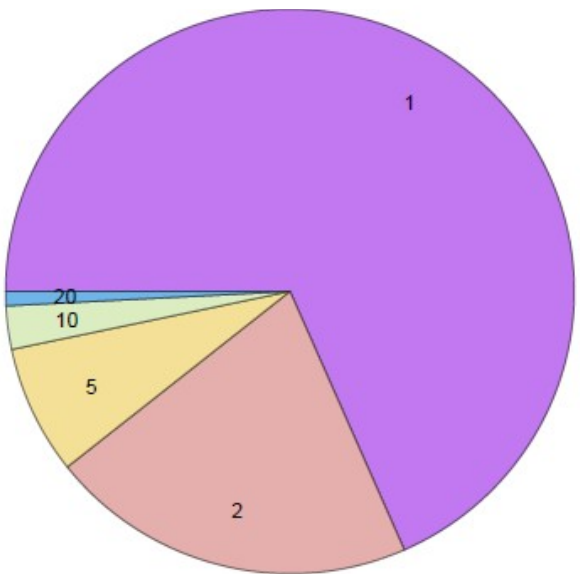
M_s=62.1 GeV



M_0=31.5×10^{10} GeV

T_C=0.6×10^{10} GeV

M_s=7.9×10^{10} GeV



M_0=9.6×10^{17} GeV

T_C=0.2×10^{17} GeV

M_s=2.4×10^{17} GeV

***Unexpected correlation*: The distribution of the total abundance across the hadronic DDM ensemble tends to be <u>more democratic</u> (DDM-like) when the relevant mass scales involved are <u>lower</u>.**

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
- KRD, S. Su & B. Thomas, 1407.2606
- KRD, J. Kost & B Thomas, 1509.00470
- 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
- KRD, F. Huang, S. Su & B. Thomas, 1610.04112
- KRD, J. Kost & B. Thomas, 1612.08950
- KRD, J. Kumar, B. Thomas & D. Yaylali, 1708.09698
- KRD, J. Fennick, J. Kumar & B. Thomas, 1712.09919
- D. Curtin, KRD & B. Thomas, 1808.xxxxx
- KRD, F. Huang, S. Su & B. Thomas, 1808.xxxxx
- 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!

Some highlights for general DDM ensembles...

(even beyond those from strongly-coupled dark sectors!)

- 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

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

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

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

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

Interactions with G gauge fields

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

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

Possible couplings to SM gauge and matter fields

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

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

arXiv: 1203.1923

What are the phenomenological constraints that govern such scenarios?

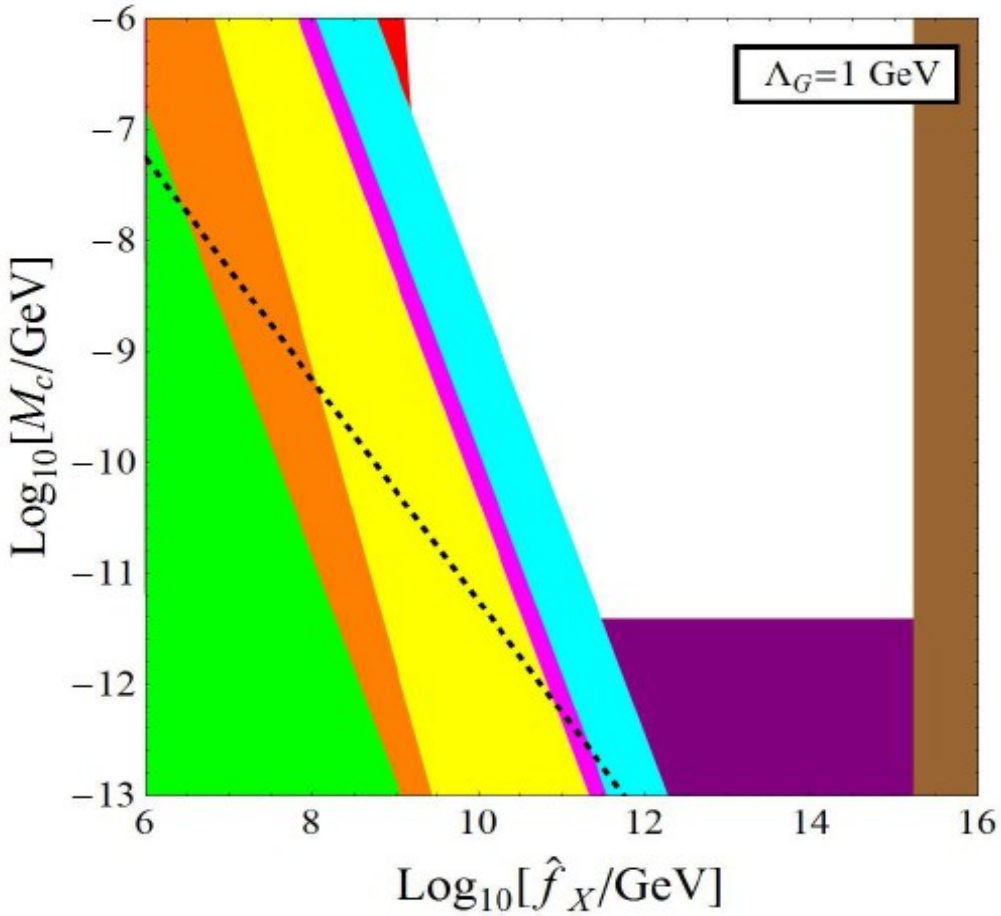
- GC (globular cluster) stars. Axions might carry away energy too efficiently, altering stellar lifetimes. GC stars give most stringent bound.
- SN1987a. Same --- axions would effect energy loss rate.
- Diffuse photon/X-ray backgrounds. Axion decays to photons would leave unobserved imprints.
- Eotvos.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

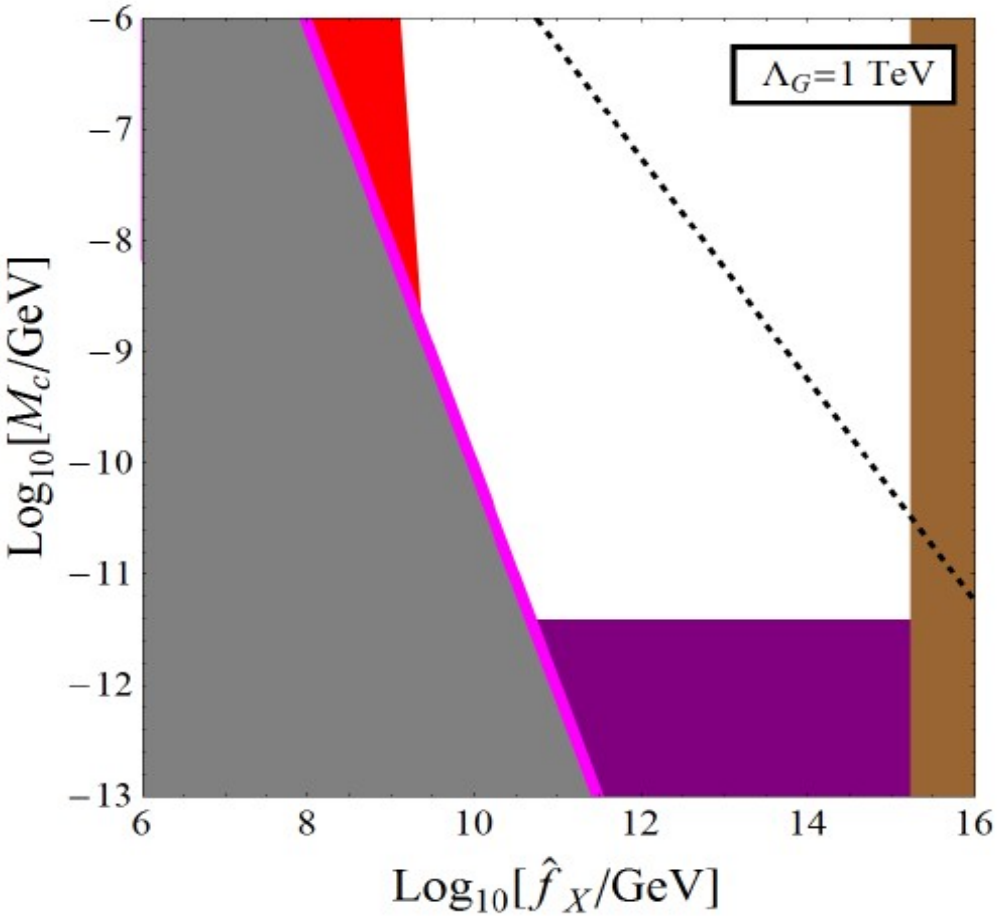
Combined Limits on Dark Towers

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

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

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



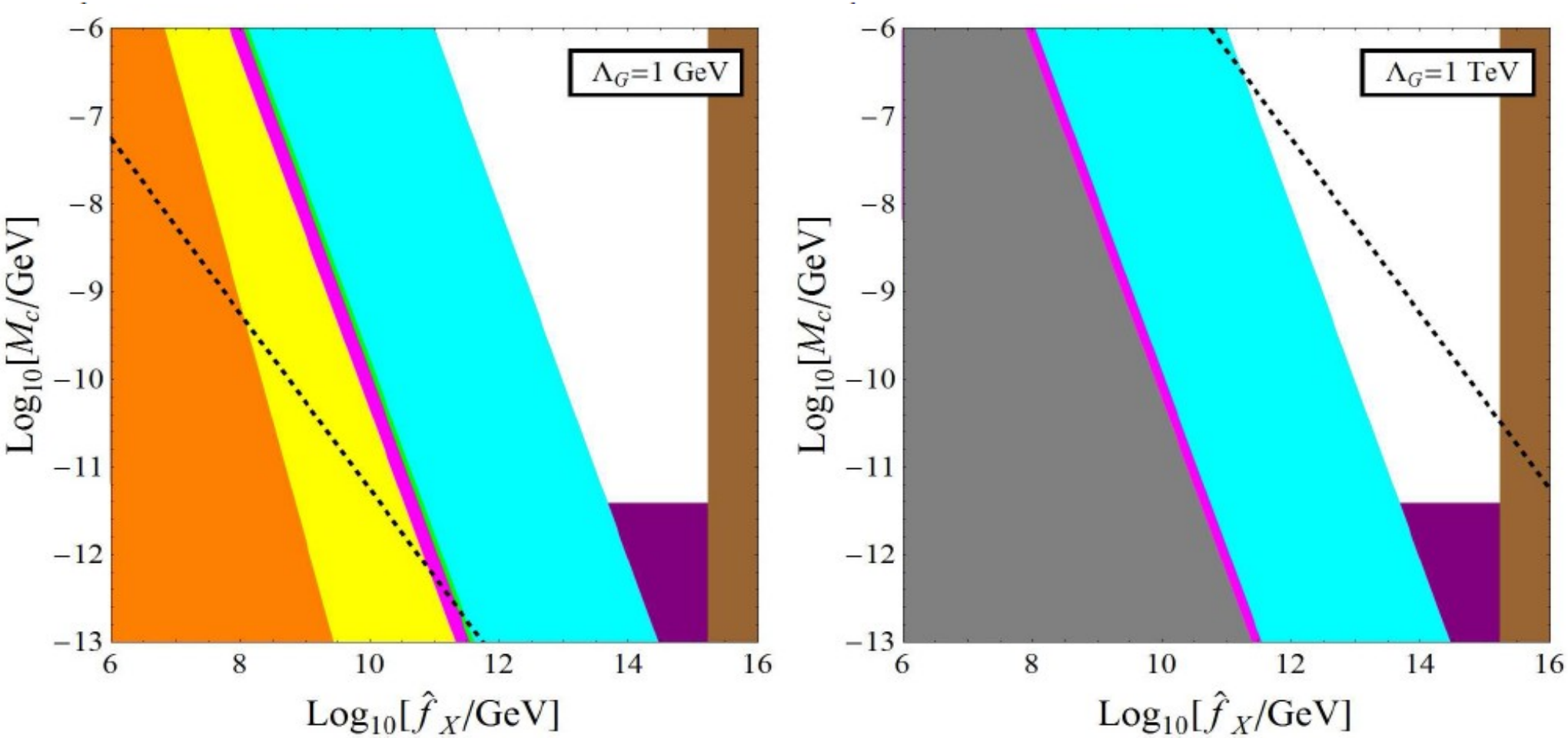


Combined Limits on Dark Towers

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

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

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



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?

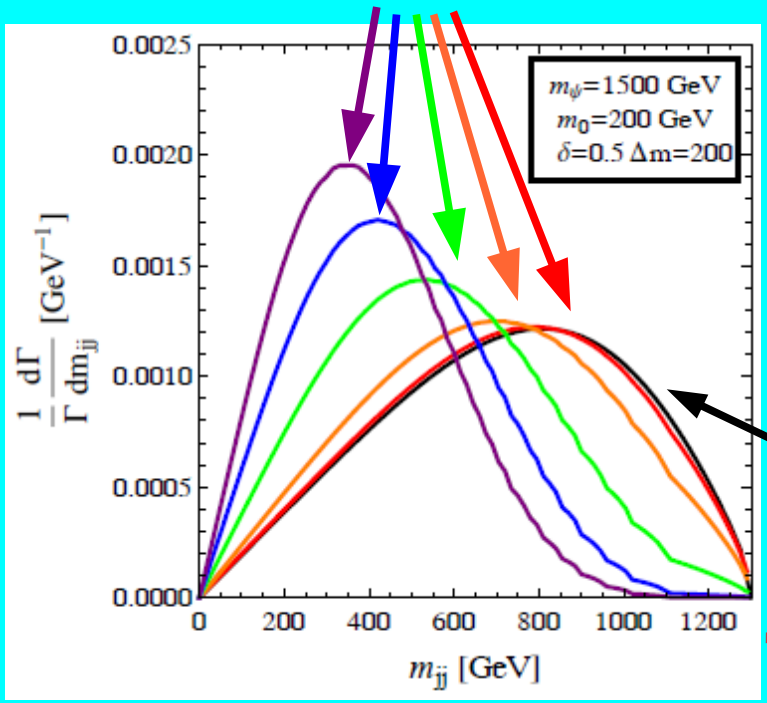
- KRD, S. Su, and B. Thomas, arXiv: 1204.4183
- KRD, J. Kumar, and B. Thomas, arXiv: 1208.0336
- KRD, J. Kumar, and B. Thomas, arXiv: 1306.2959
- KRD, J. Kumar, B. Thomas, and D. Yaylali, arXiv: 1406.4868
- KRD, S. Su, and B. Thomas, arXiv: 1407.2606
- K. Boddy, KRD, D. Kim, J. Kumar, J.C. Park & B. 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

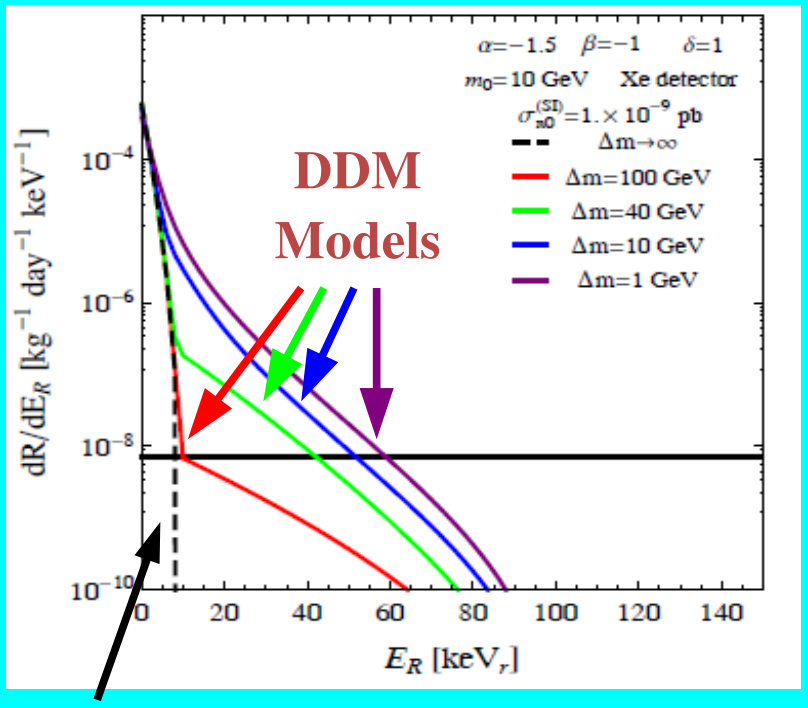
- KRD, S. Su, and B. Thomas, arXiv: 1204.4183
- KRD, S. Su, and B. Thomas, arXiv: 1407.2606

- 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.



Traditional DM

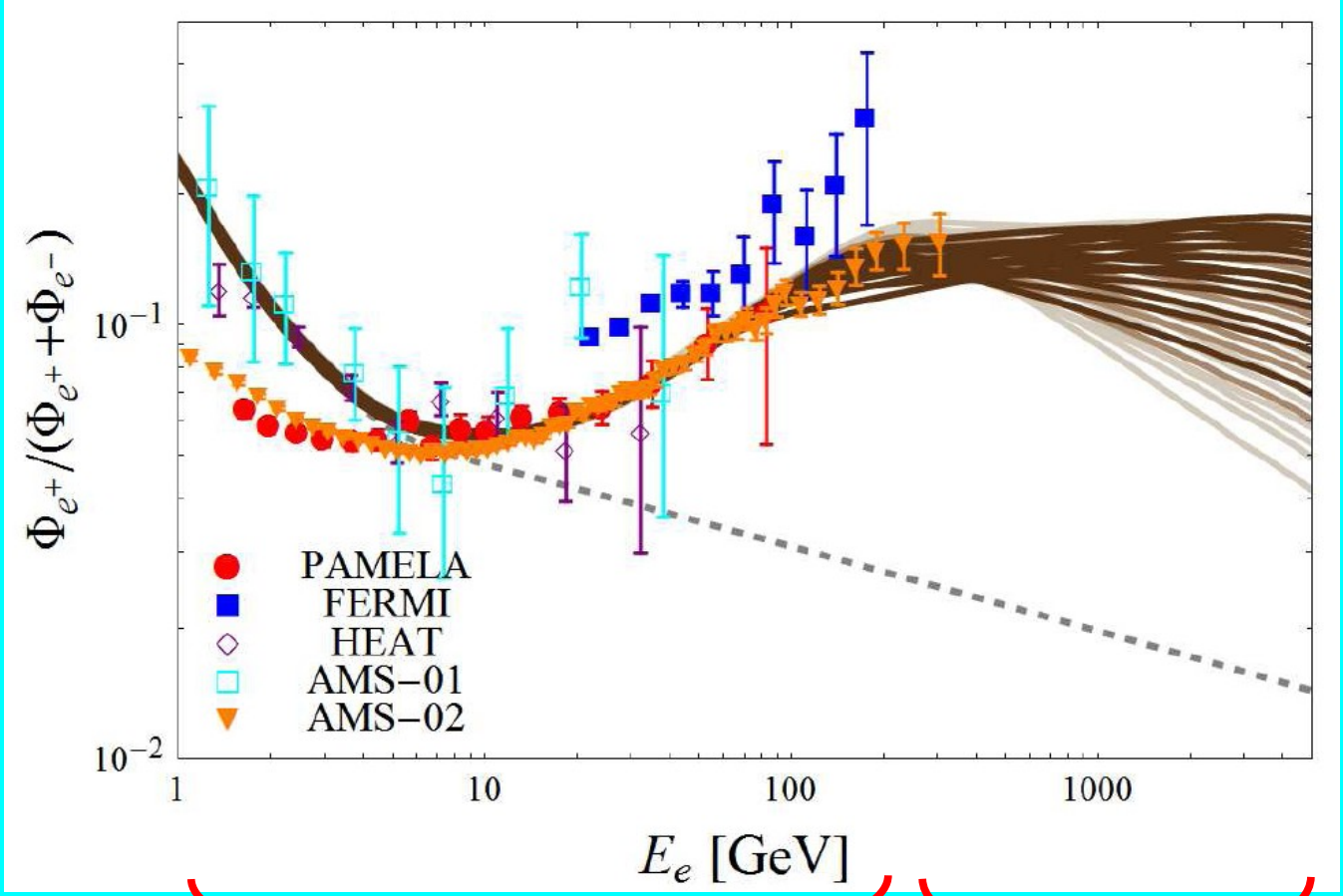
These examples illustrate that DDM ensembles give rise to **observable effects** which can serve to distinguish them from traditional DM candidates.

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)



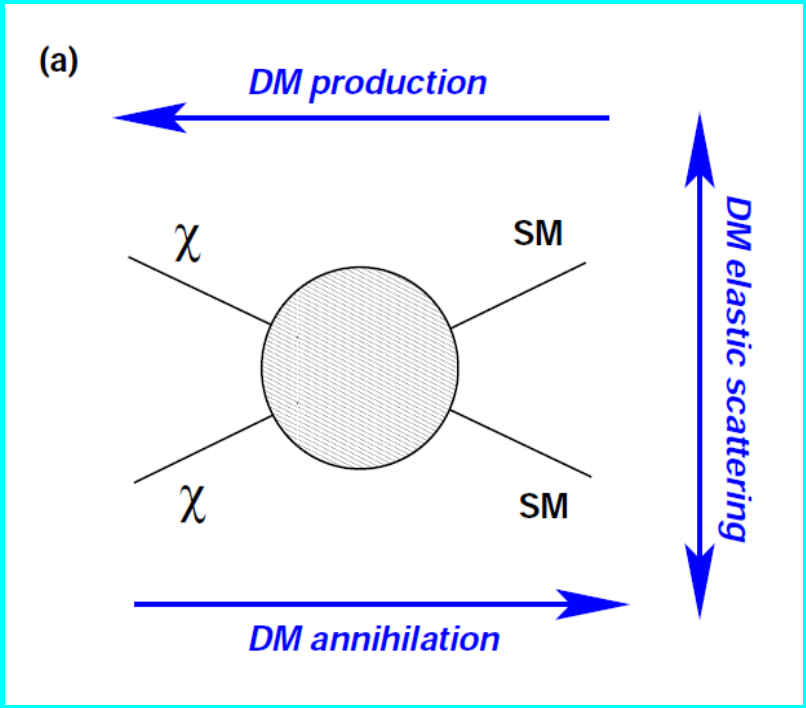
DDM: Fully consistent with positron excess observed thus far [AMS-02]

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...

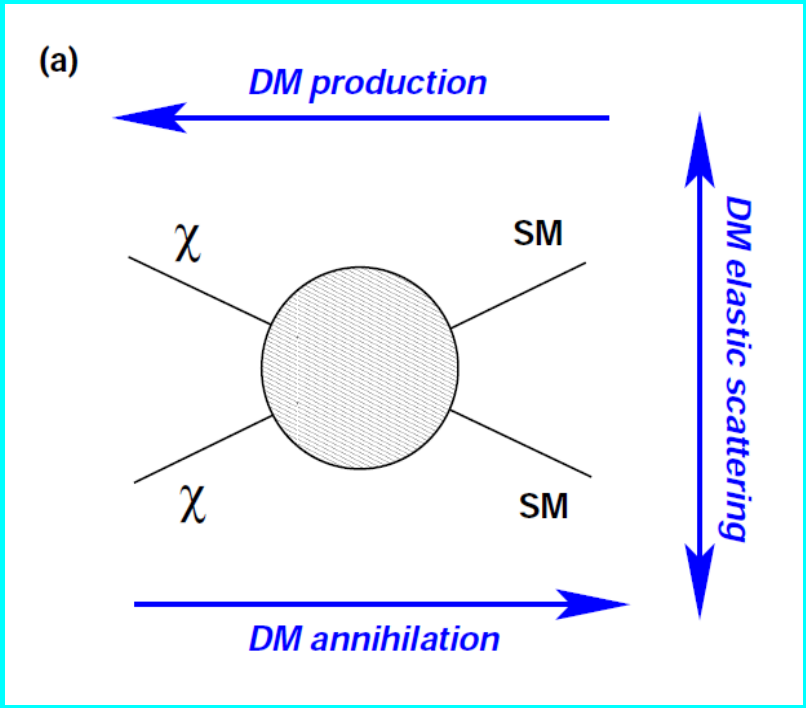


- KRD, J. Kumar, B. Thomas & D. Yaylali, arXiv: 1406.4868
- KRD, J. Kumar, B. Thomas & D. Yaylali, arXiv: 1708.09698

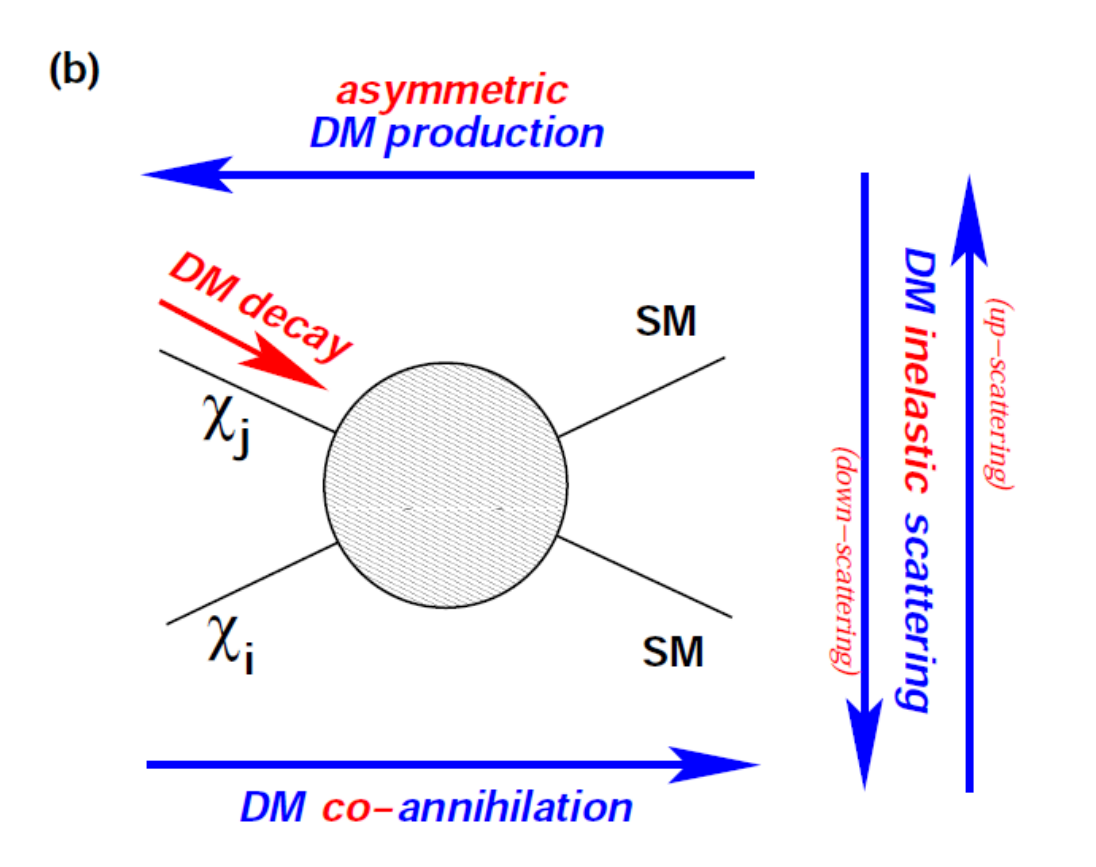
DDM (and more generally, dark-sector non-minimality) even gives rise to entirely new directions for dark-matter complementarity...

From this...

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



to this...



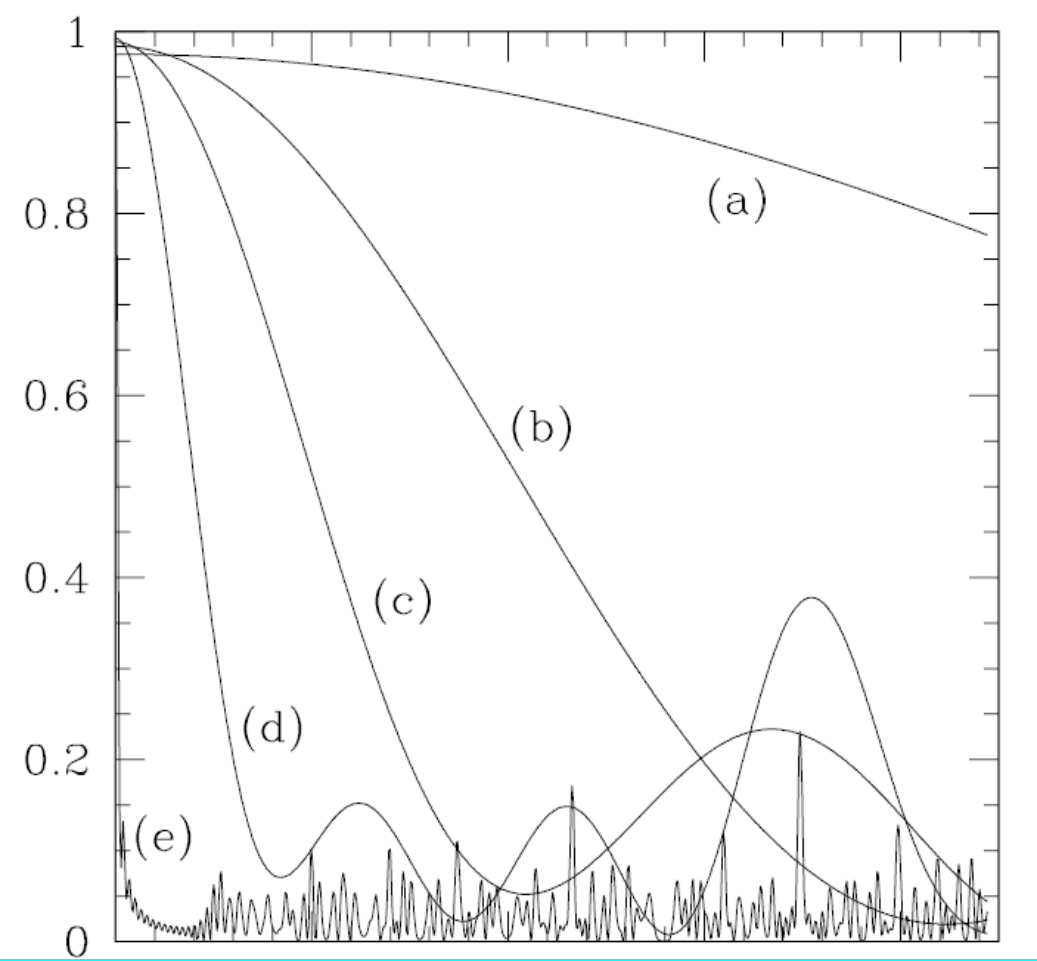
Thus, the traditional DM complementarities are both *augmented* and *extended*. Indeed, in some cases the "off-diagonal" processes may even dominate over the diagonal ones!

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.
- 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!
- DDM implications for MeV-range cosmic-ray data and "energy duality" in the GeV GC cosmic-ray excess.
- Enhanced complementarities for multi-component dark sectors
- 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/ Shufang Su, 1407.2606

w/ Jason Kumar & David Yaylali, 1312.7772

w/ Kim Boddy, Doojin Kim, Jason Kumar & Jong-Chul Park, 1606.07440, 1609.09104

w/ Jason Kumar & David Yaylali, 1406.4869 (PRL), 1708.09698

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

Conclusions

The Dynamical Dark Matter (DDM) framework is ripe with new possibilities for dark-matter physics, **and may be especially relevant when the dark sector is strongly coupled.**

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.

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

Since strongly-coupled dark sectors provide one of the strongest motivations for DDM, they provide an especially compelling laboratory for studying dark matter beyond the WIMP paradigm! Much work remains to be done!