Darkness from the Bulk:

An Alternative Approach to Dark-Matter Physics

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Based in part on work done in collaboration with
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During most of its existence as a field over the past third century (!), string model-building (and string phenomenology more generally) have tended to focus on a number of critical "architectural" questions...

- Gauge groups?
  - Standard Model?
  - Pati-Salam?
  - GUT's of various types (SU_5, E_6, ...)?
- Particle representations
  - Chirality?
  - Complete sets of quarks and leptons?
  - Numbers of generations?
- Weak-scale SUSY:
  - breaking to N=1?
  - residual N=1 broken or unbroken?
  - SUSY-breaking scale?
  - Non-SUSY at string scale?
- Couplings, masses and mixings
  - Gauge coupling unification?
  - Mass matrices?
  - Yukawa couplings, etc.?

In most (open-string, Type I) string constructions, this is <u>physics on the brane</u>.

But just as important is <u>physics in the bulk</u>.
The bulk is a rich and important place, and may have properties that are even more "stringy" and therefore more universal (model-independent) than physics on the brane!

Gauge-neutral states

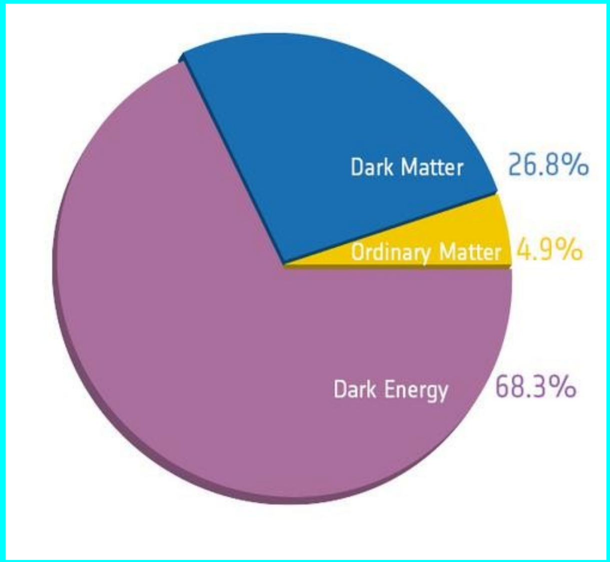
- gravity multiplet
- string moduli
- axions
- RH neutrinos, ...

all can live in the bulk.

Because these states are neutral under all SM gauge symmetries, they cannot be probed directly through SM interactions. They therefore interact with the SM only gravitationally or through other kinds of higher-order effective interactions...

They are part of the **<u>dark sector</u>**.

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



Physics from the (SM) **brane**

Physics from the **bulk**

Potentially even more physics from the **bulk**

?

- 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 then leads to new kinds of phenomenological constraints on string model-building and string phenomenology!

Thus, the time is ripe for a serious phenomenological / cosmological examination of the physics of the bulk.

Of course, there have already been many detailed examinations along these lines...

In this conference alone, see cosmological talks by...

- Davis
- Antoniadis
- Cicoli
- Zavala
- Danielsson
- Lewicki

- Sasaki
- Van Riet
- Brandenberger
- Mukohyama
- Shiu

- Guidetti
- Obikhod
- Shukla
- Duch
- Mehta
- Diaz
- Pedro

- Ashoorioon
- Mori
- Bonnefoy
- Domenech
- Artymowski
- Kim
- Wieczorek

But most of these analyses focus on the cosmological implications of the *lightest* states in the bulk (moduli, axions, etc.) or on the dynamics of the branes themselves...

However, string-theoretic dark sectors contain
infinite towers of dark string states!

- **Kaluza-Klein (KK) states**
  - **Intrinsic** to the bulk, which is necessarily higher-dimensional
  - Density of KK states is constant or rises *polynomially* with mass:

    $\rho(m) \sim m^{\delta}$ for some δ
- **String oscillator states**
  - Density of states rises *exponentially* with mass

    (Hagedorn behavior): $\rho(m) \sim A\, m^{B} \exp(Cm)$
  - The resonances of strongly coupled CFT's in the bulk also have this behavior (via AdS/CFT correspondence to warped KK theories)

Cannot integrate these states out ⇒ their physics can be very important and may contribute to the full richness of the dark sector!

Thus, we must consider the physics of *non-minimal* dark sectors -- the types of dark sectors which string theory naturally gives!

For all of these states, there are two critical questions that must be addressed at the outset...

1 **How are these states produced in the early universe?**

- Thermally (e.g., freeze-out)?
  Non-thermally (e.g., misalignment production)?
- What energy densities do they carry as the universe evolves?
- How do these energy densities scale as functions of their masses?

These issues determine the properties of the resulting cosmological expansion if these energy densities dominate... could even potentially overclose the universe!

2 **How do these states decay?**

- Are they stable?   If not...
- Do they primarily decay **out of the dark sector**, to SM states on the brane?

  Depends on brane/bulk couplings! Could cause difficulties with BBN, CMB, and/or leave undesirable imprints in photon/X-ray spectra...

- Or do they primarily decay **within the dark sector**, to lighter dark states?

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

All of these issues lead to **new constraints on string model-building!**

In this talk, I will describe some preliminary work investigating issues along these lines.

- Our work is a general study of non-minimal dark sectors, without focusing on any type of specific string-theoretic origin *per se*.
- However, as we shall see, our results nevertheless have immediate implications for string theory and string model-building.

So our fundamental questions are:

- **What if the dark sector is non-minimal, with lots of degrees of freedom, as suggested in string theory?**
- **Can this be consistent? What general principles can we formulate for this kind of dark matter? What bounds and constraints --- both phenomenological and cosmological --- necessarily apply? How could we detect such a dark sector experimentally?**

It turns out that the dark sector in string theory naturally gives rise to an entirely new way of thinking about dark matter...

Dynamical Dark Matter (DDM)

An Alternative Framework for Dark-Matter Physics

Brooks Thomas and I originally proposed DDM in 2011...

- 1106.4546
- 1107.0721
- 1203.1923

and since then we have further developed this subject 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 (also w/ K. Boddy, D. Kim, J. Kumar, J.-C. Park)
- 1610.04112 (also w/ F. Huang, S. Su)
- 1612.08950 (also w/ J. Kost)
- 1708.09698 (also w/ J. Kumar, D. Yaylali)
- 1712.09919 (also w/ J. Kumar, J. Fennick)
- 1807.xxxxx (also w/ D. Curtin)
- 1807.xxxxx (also w/ J. Kumar, P. Stengel)
- 1808.xxxxx (also w/ F. Huang, J. Kost, S. Su)
- 1808.xxxxx (also w/ Y. Buyukdag, T. Gherghetta)
- and many others...

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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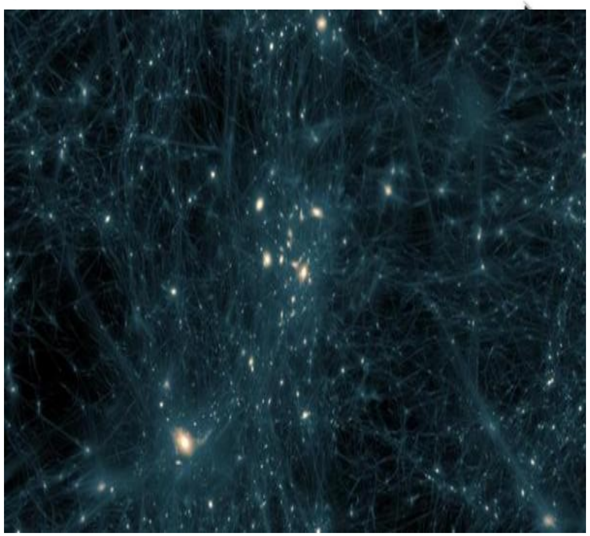


Dark matter is the unseen hand that fashions the universe. It decides where galaxies will form and where they won't. Its gravity binds stars into galaxies and galaxies into galaxy clusters. And when two galaxies merge, dark matter is there, sculpting the product of the merger. But as for what dark matter 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

The rest of this talk...

- Dynamical Dark Matter:
  the kind of dark matter that string theory naturally gives
  – a quick introduction, just the basic ideas

- Basic cosmological constraints on DDM realized through...
  - Bulk KK states
  - String oscillator states

- Beyond the basics:
  An overview of the work already done in the field, current status

So let's begin...

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!
Just as in the N=1 case, assume these states decay primarily to visible states.

e.g., a KK tower or a tower of string oscillator modes...

- 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:

This is the physics of the bulk!
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, absolute dark-matter stability is no longer required!

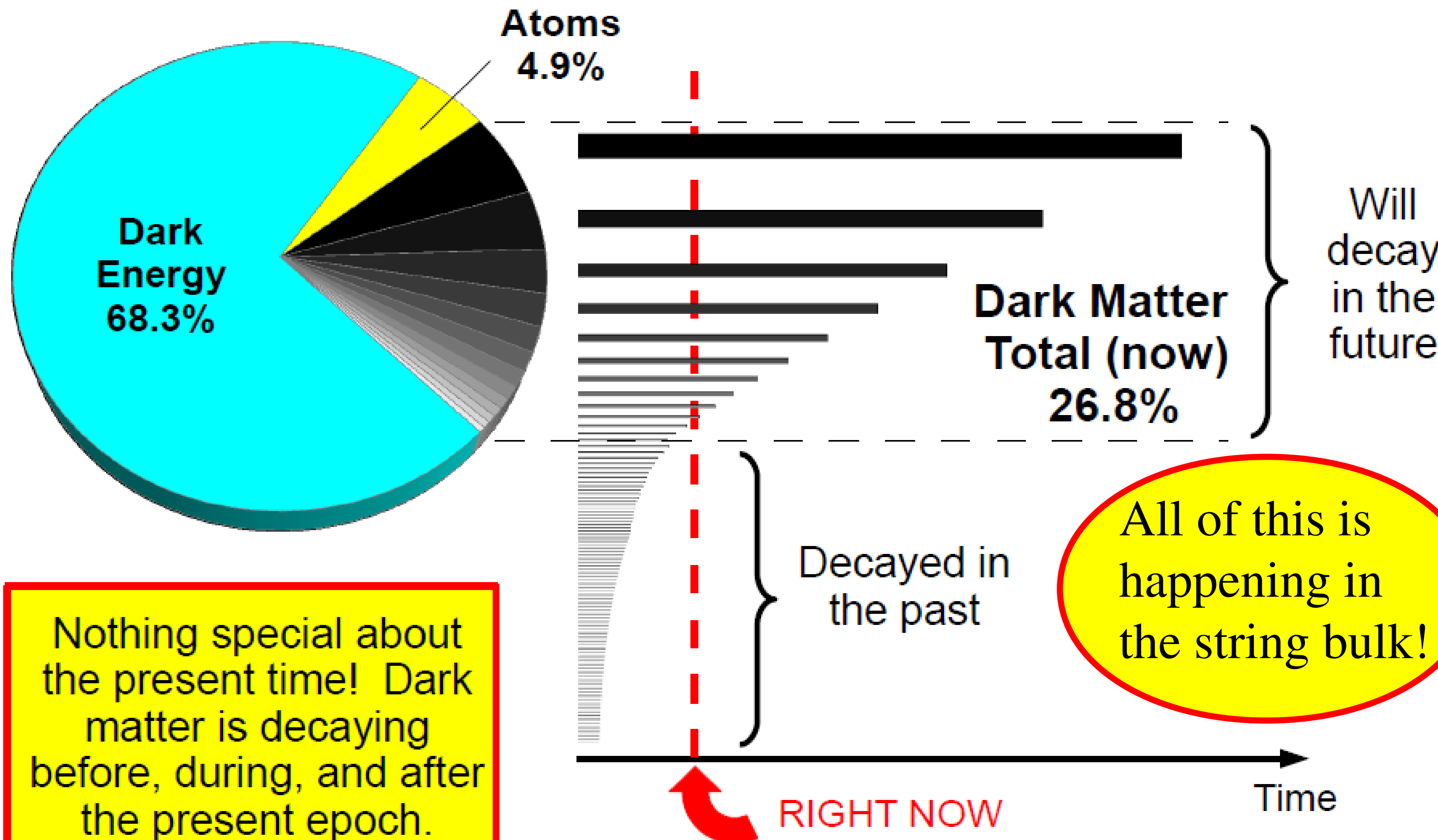
Dynamical Dark Matter (DDM): an alternative framework for dark-matter physics in which the notion of dark-matter stability is replaced by a balancing of lifetimes against cosmological abundances across an ensemble of individual dark-matter components with different masses, lifetimes, and abundances.

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

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

"Dynamical Dark Matter": The Basic Picture:

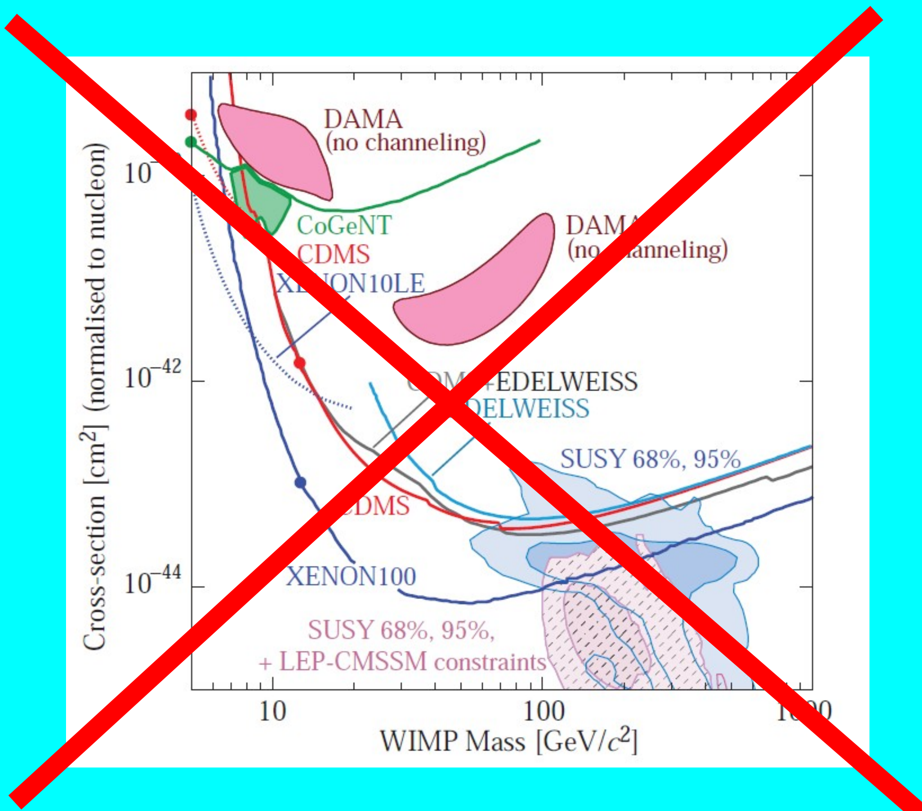
A Snapshot of the Cosmic Pie: Past, Present, and Future



All of this is happening in the string bulk!

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

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.



Phenomenological bounds on dark matter in the DDM framework must be phrased and analyzed in terms of ***a new set of variables (e.g., scaling relations or other internal correlations)*** which describe the behavior of the DDM ensemble as a ***collective bulk entity*** with its own internal structures and/or symmetries.

String theory compels us to move beyond the standard WIMP paradigm.

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

Lifetimes (decay widths) ⟷ ***balanced against*** ⟷ Cosmological abundances

Note: 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 string model --- i.e., particle physics considerations alone

determined by *interplay* between the particle physics of the string model and the cosmological history in which it is embedded

Note: 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 string model --- i.e., particle physics considerations alone

must be carefully balanced as well

determined by *interplay* between the particle physics of the string model and the cosmological history in which it is embedded

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 bulk by specifying abundances of each state in the ensemble:

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

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

Introduce two "complementary" parameters:

- Total abundance at any moment: $\Omega_{\rm tot}(t) \equiv \sum_i \Omega_i(t)$
- *Distribution* of that total abundance: how much is Ω_{tot} shared between a dominant component Ω_0 and all others? Define

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

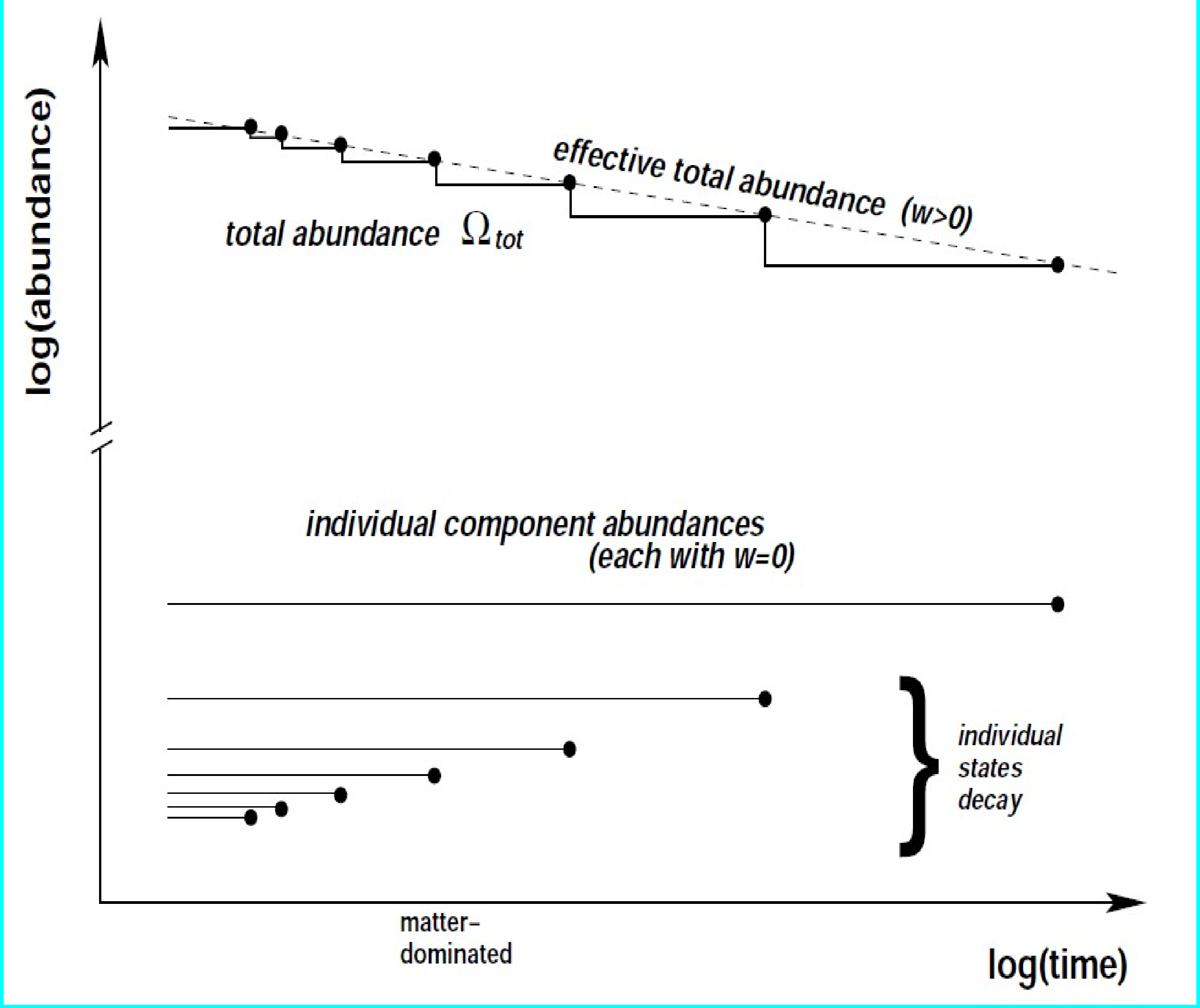
where $\Omega_0 \equiv \max_i\{\Omega_i\}$

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 bulk towers, 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 physics in the bulk!
- It further implies that our decaying DDM ensemble of dark-matter states has a non-trivial "effective" equation of state $w_{\mathrm{eff}}(t)$!

In general, we can define...

$$w_{\rm eff}(t) \equiv -\left(\frac{1}{3H}\frac{d\log\rho_{\rm tot}}{dt}+1\right)$$

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

Let us further assume that our tower of states obeys general scaling relations of the form...

Scaling relations of this form hold for a wide variety of specific DDM realizations...

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

$$\alpha < 0$$

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

abundance of any state with decay width Γ

inverse balancing of lifetimes against abundances, as required for DDM consistency

density of states with decay width Γ per unit Γ

• KRD & B. Thomas, arXiv: 1106.4546

We then find the results

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

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

where

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

- **For** $x = -1$ **:**

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

where

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

These are "effective" equations of state for the entire DDM ensemble in the string bulk!

If the DDM model in question is to be in rough agreement with cosmological observations, we expect that w_* today should be fairly small (since traditional dark "matter" has $w = 0$).

We also expect that the function $w_{\rm eff}(t)$ should not have experienced strong variations within the recent past.

Given the previous functional forms for $w_{\rm eff}(t)$, this implies that the situations which are likely to be phenomenologically preferred are those with

$$\boxed{x \equiv \alpha + \beta \lesssim -1}$$

This is therefore a general constraint on all cosmologically viable towers of states in the bulk!

Not all KK towers in the string bulk will satisfy this constraint.
This therefore becomes a constraint on string model-building!

Are there any KK towers which can satisfy this constraint in a natural way?

YES!

(Moreover, we find that successful scenarios satisfy these constraints as a consequence of the non-trivial interplay between physics in the bulk and physics on the brane.)

For example, let us consider a very simple "bare-bones" setup:

Universe has a single, flat extra dimension of length R, one massless bulk field Φ, and SM lives on a brane located at y=0...

SM fields

$$S \;=\; \int d^4x dy \left[\mathcal{L}_{\rm bulk}(\Phi) + \delta(y)\mathcal{L}_{\rm brane}(\psi_i, \Phi)\right]$$

where

$$\mathcal{L}_{\rm bulk} \;=\; \tfrac{1}{2}\,\partial_M \Phi^* \partial^M \Phi$$

no mass term in bulk

$$\mathcal{L}_{\rm int} \;\supset\; -\tfrac{1}{2} m^2 |\Phi|^2$$

effective mass term induced by SM dynamics on brane

Now do KK reduction for Z_2 orbifold (line segment) of radius R:

$$\Phi(x^\mu, y) \;=\; \frac{1}{\sqrt{2\pi R}} \sum_{k=0}^{\infty} r_k\, \phi_k(x^\mu) \cos\left(\frac{ny}{R}\right)$$

$$r_k \;\equiv\; \begin{cases} 1 & \text{for } k=0 \\ \sqrt{2} & \text{for } k>0 \end{cases}$$

These are the individual constituents of our ensemble!

- KRD & B. Thomas, arXiv: 1106.4546

The masses of these states are the eigenvalues λ_k of the KK mass matrix.

Further assume…

- Standard misalignment production in the bulk for 5D bulk field Φ

  ⇒ sets **initial abundance Ω_k** for each KK mode ϕ_k

- **Decay width Γ_k** for decay $\phi_k \to$ SM as determined through standard leading-order brane/bulk interactions

e.g.,

$$\frac{1}{\hat{f}}(\partial_\mu \phi')\,\overline{\psi}\gamma^\mu\psi\ , \qquad \frac{1}{\hat{f}}\phi' F_{\mu\nu}F^{\mu\nu}$$

if Φ is CP-even

e.g., moduli...

$$\frac{1}{\hat{f}}(\partial_\mu \phi')\,\overline{\psi}\gamma^\mu\gamma^5\psi\ , \qquad \frac{1}{\hat{f}}\phi' F_{\mu\nu}\tilde{F}^{\mu\nu}$$

if Φ is CP-odd

e.g., axions...

where ϕ' is projection of Φ onto brane:

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

$$\Rightarrow \quad \Gamma_\lambda \sim \frac{\lambda^3}{\hat{f}^2}(\tilde{\lambda}^2 A_\lambda)^2 \sim \frac{\lambda^3}{\hat{f}^2}$$

• KRD & B. Thomas, arXiv: 1106.4546

Combining our results for Ω_λ and Γ_λ,
we obtain the following *product relations*
across our KK towers:

Different possibilities depending on the cosmological conditions under which abundances were established

$$\begin{aligned} \text{instantaneous}: &\quad \Omega_\lambda \Gamma_\lambda^{2/3} \sim \text{constant} \\ \text{staggered (RD era)}: &\quad \Omega_\lambda \Gamma_\lambda^{7/6} \sim \text{constant} \\ \text{staggered (reheating/MD era)}: &\quad \Omega_\lambda \Gamma_\lambda^{4/3} \sim \text{constant} \end{aligned}$$

In all cases, decay widths are balanced against abundances, as promised!
This is a universal feature for such KK towers.

Indeed, for a generic KK tower,
we find the following values of $x = \alpha + \beta$:

	large $\tilde{\lambda}$	small $\tilde{\lambda}$
instantaneous	$-4/3$	$-4/5$
staggered (RD era)	$-11/6$	$-11/10$
staggered (RH/MD eras)	-2	$-6/5$

TABLE I: Values of the equation-of-state parameter $x \equiv \alpha+\beta$ for different portions of a general KK tower with different "turn-on" phenomenologies. We observe that KK towers naturally give rise to values $x \lesssim -1$, which is precisely the range favored phenomenologically.

... precisely in the phenomenologically preferred range!!

Thus, such KK towers provide particularly compelling realizations of DDM ensembles!

One can also formulate an analogous immediate set of constraints for DDM towers of *oscillator* states...

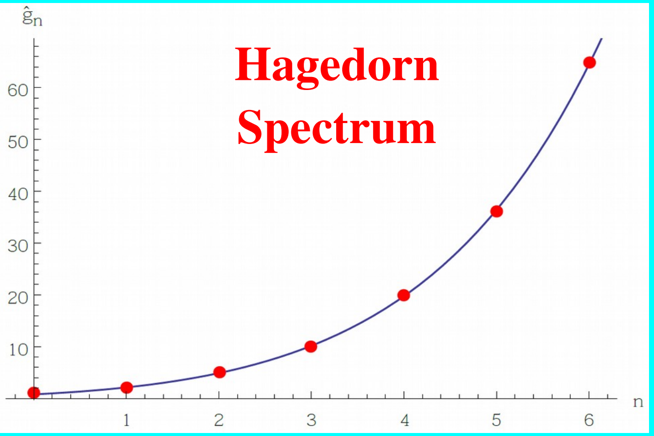
- For such DDM towers, the **mass spectrum** of states lies on linear Regge trajectories:

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

unlike KK towers, now sensitive to string scale (consider as a free parameter)!

- Likewise, the **degeneracy of states** 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

If we think of the oscillator tower 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

Polyakov action

where **$D_\perp$: number of transverse dimensions**

c : total central charge of theory

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

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

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

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

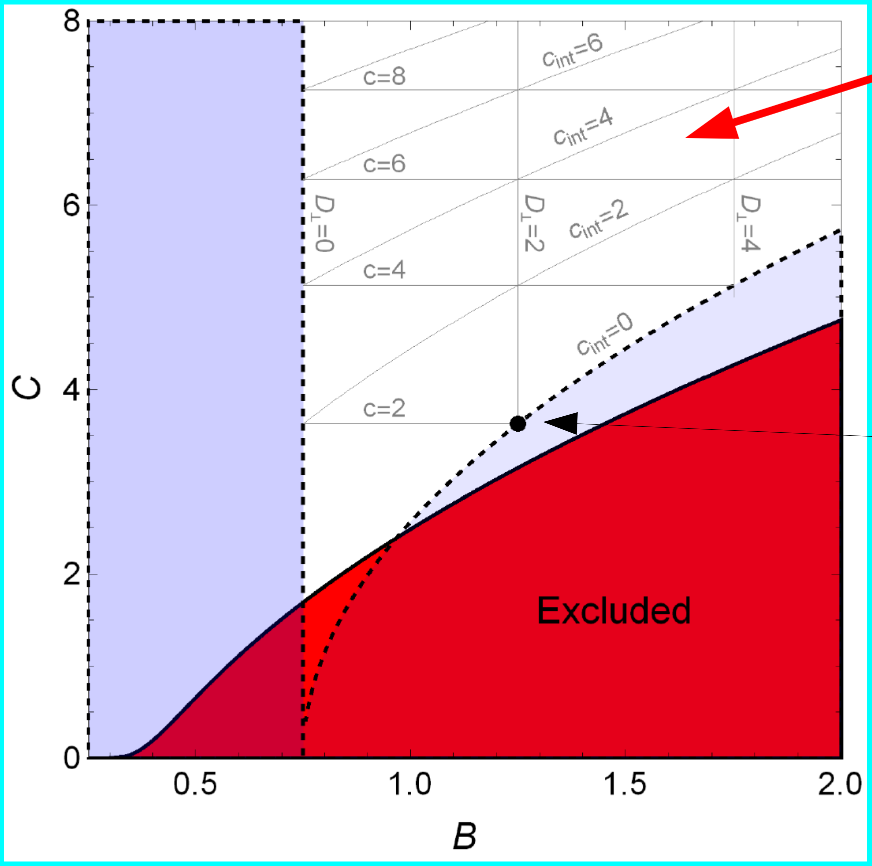
linear confinement

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

For consistency, demand

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

Furthermore, degeneracies g_n should rise monotonically with n.



(B,C) region allowed by string 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 **produced** 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**:

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

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

***Important Note**:* This is equivalent to a rapid succession of thermal freeze-out events, *all occurring at the common temperature T_c.* Unlike the situation for KK towers, **this is the only self-consistent production mechanism for string oscillator states, as standard freeze-out or non-thermal mechanisms would inject an infinite energy density into the oscillator towers!**

How do these states decay?

Recall two possibilities...

- Within the dark sector, to lower dark states

  Depends on bulk/bulk coupling only (g_s). 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 brane/bulk 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]

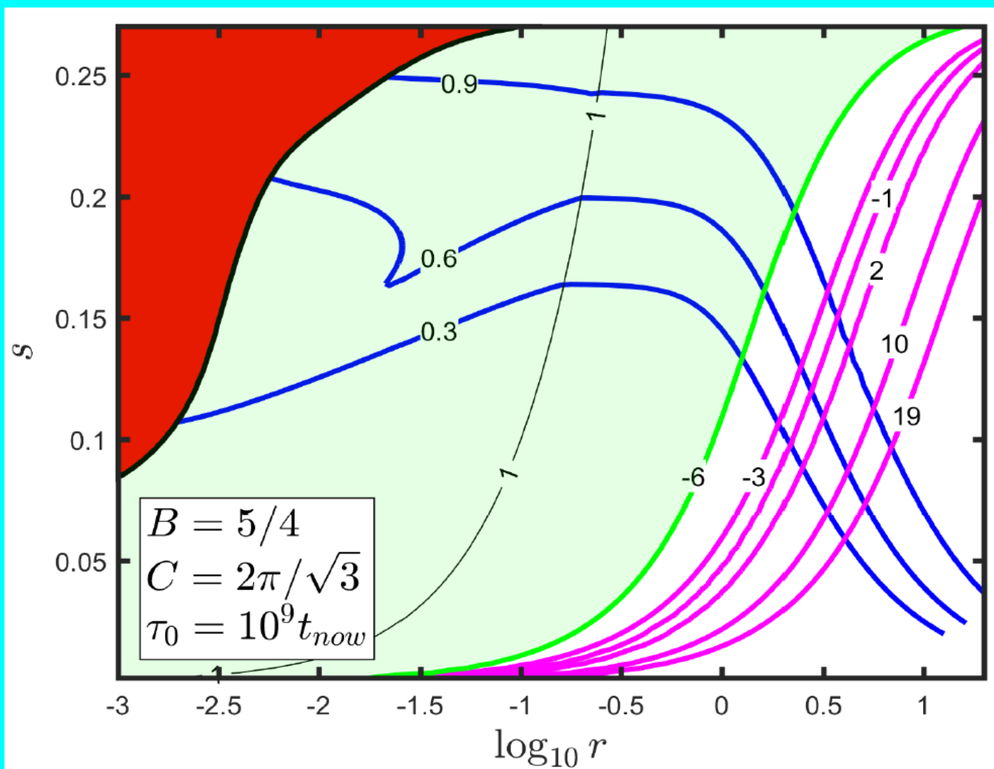
$$M_0 \gtrsim \mathcal{O}({\rm keV})$$

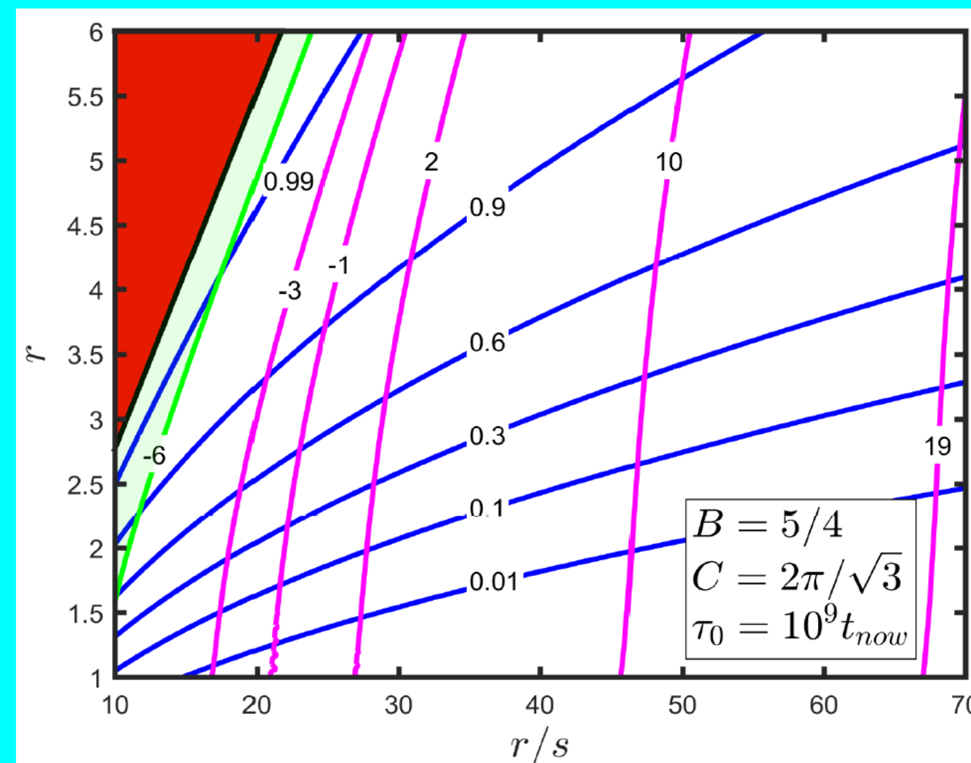
states which are too light can upset BBN and small-scale structure

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

We can then examine the space of viable oscillator towers satisfying all three constraints:

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





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

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

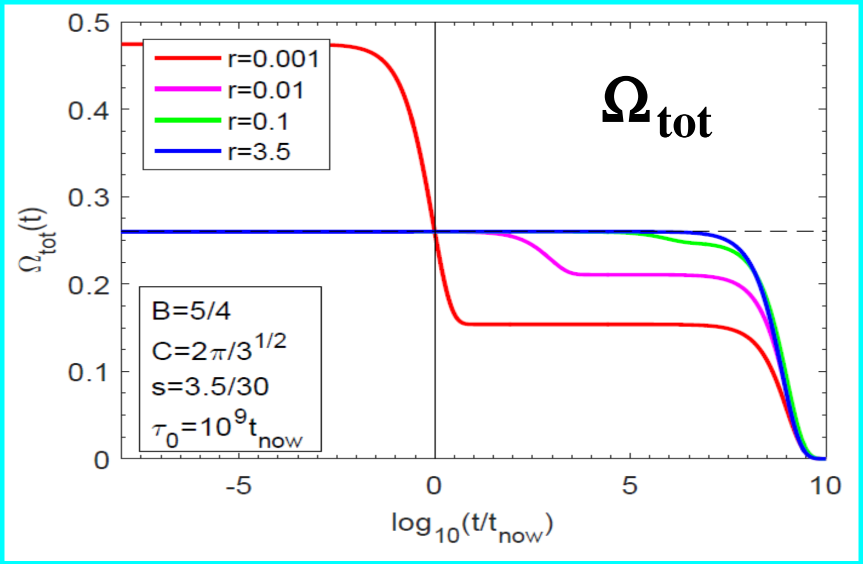
$\eta(t_{\text{now}})$

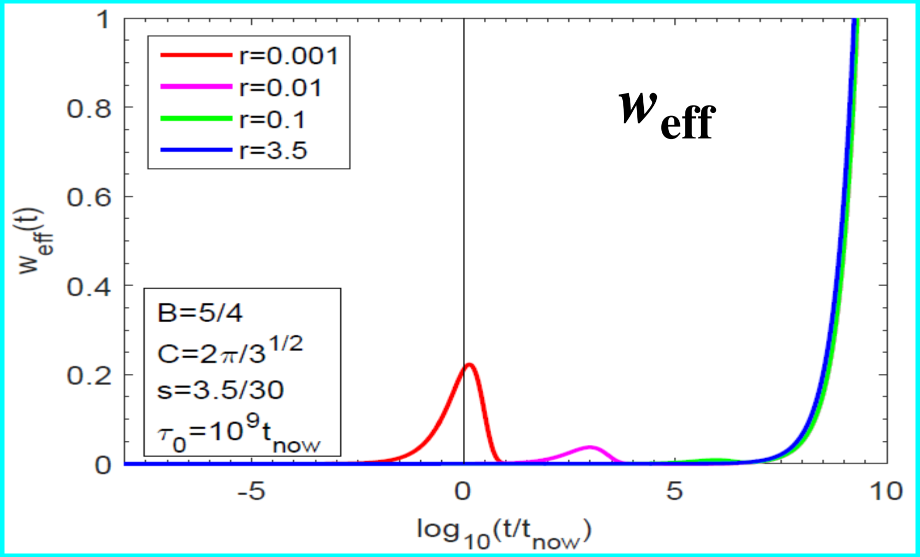
$\log_{10}(M_s/\text{GeV})$

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

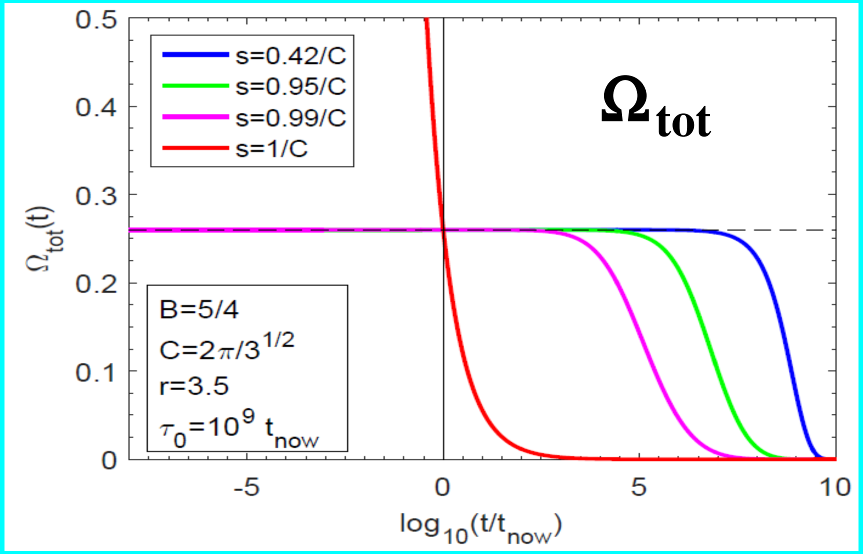
Time evolution of Ω_{tot} and w_{eff}

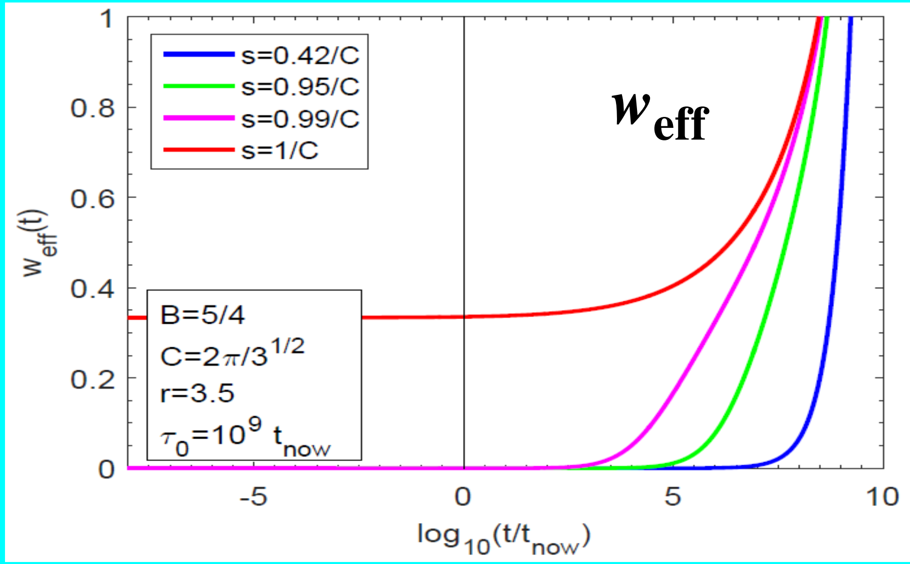
Dependence on $r=M_0/M_s$:



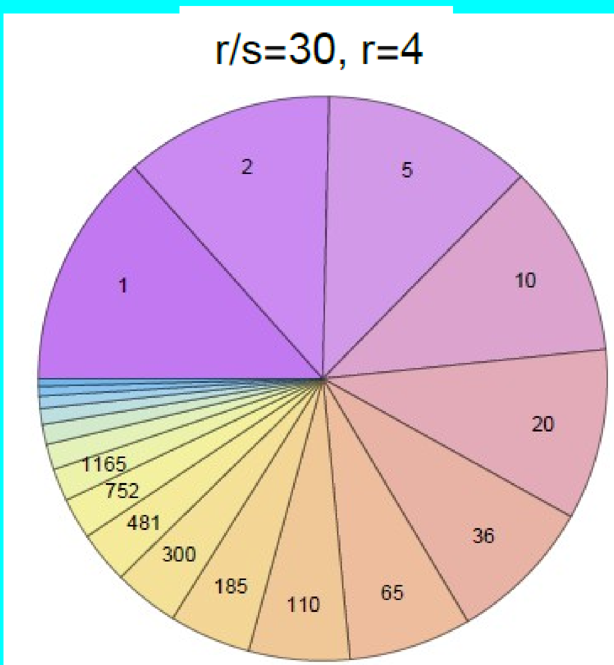


Dependence on $s=T_c/M_s$:





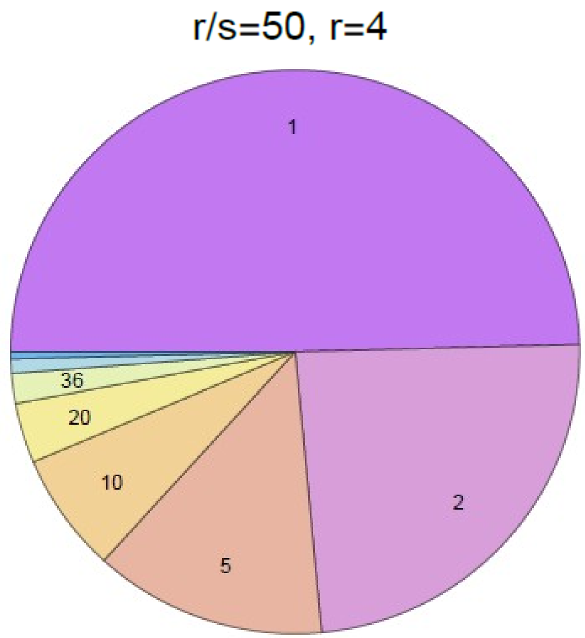
How is the total dark-matter abundance distributed across the DDM oscillator ensemble?



M_0=248.5 GeV

T_C=8.3 GeV

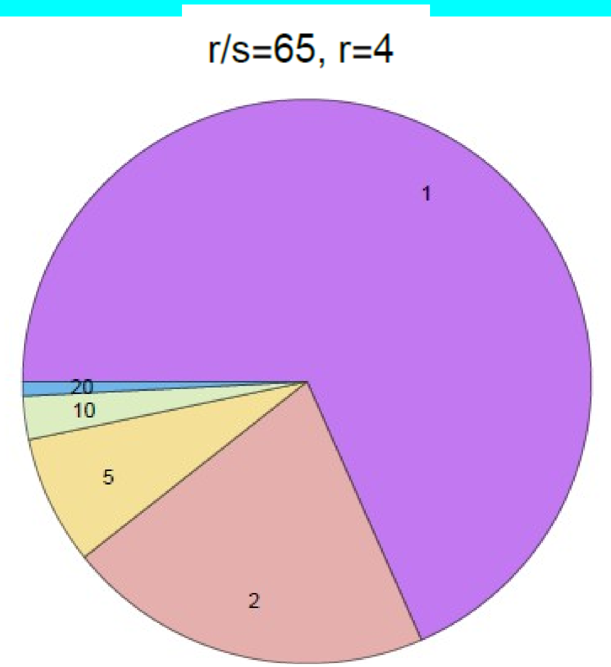
M_s=62.1 GeV



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 DDM oscillator ensemble tends to be <u>more democratic</u> (DDM-like) when the relevant mass scales involved are <u>lower</u>.**

This is only the tip of the iceberg. DDM clearly represents 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, 1807.xxxxx
- KRD, F. Huang, J. Kost, S. Su & B. Thomas, 1807.xxxxx
- KRD, J. Kumar, P. Stengel & B. Thomas, 1807.xxxxx
- Y. Buyukdag, KRD, T. Ghergehtta & B. Thomas, 1807.xxxx

- Bulk 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 (particle-physics) models** in this framework which satisfy *every* collider, astrophysical, and cosmological bound 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!

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

Specific bulk 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

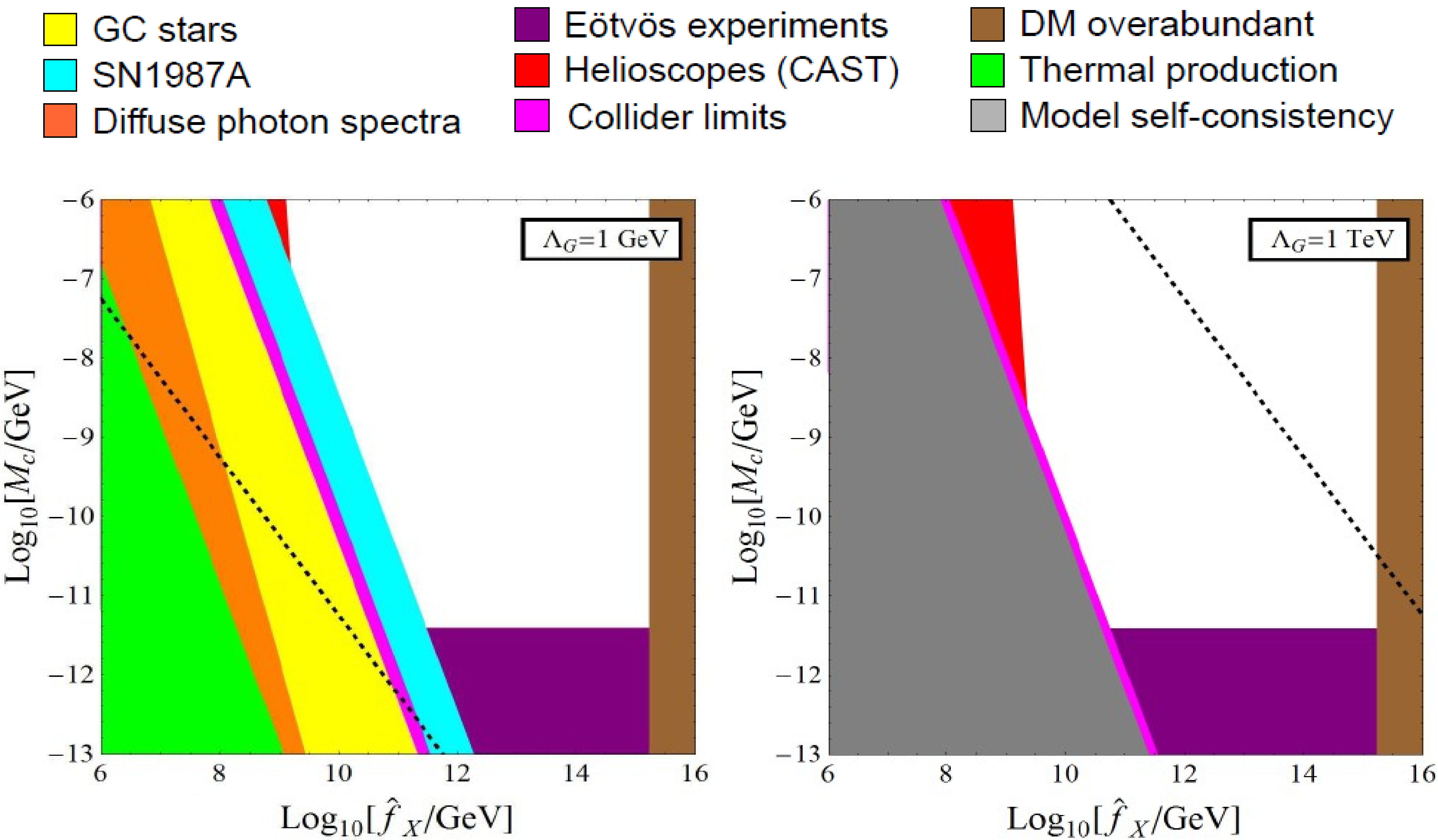
What are the phenomenological constraints that govern such scenarios?

- 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)

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

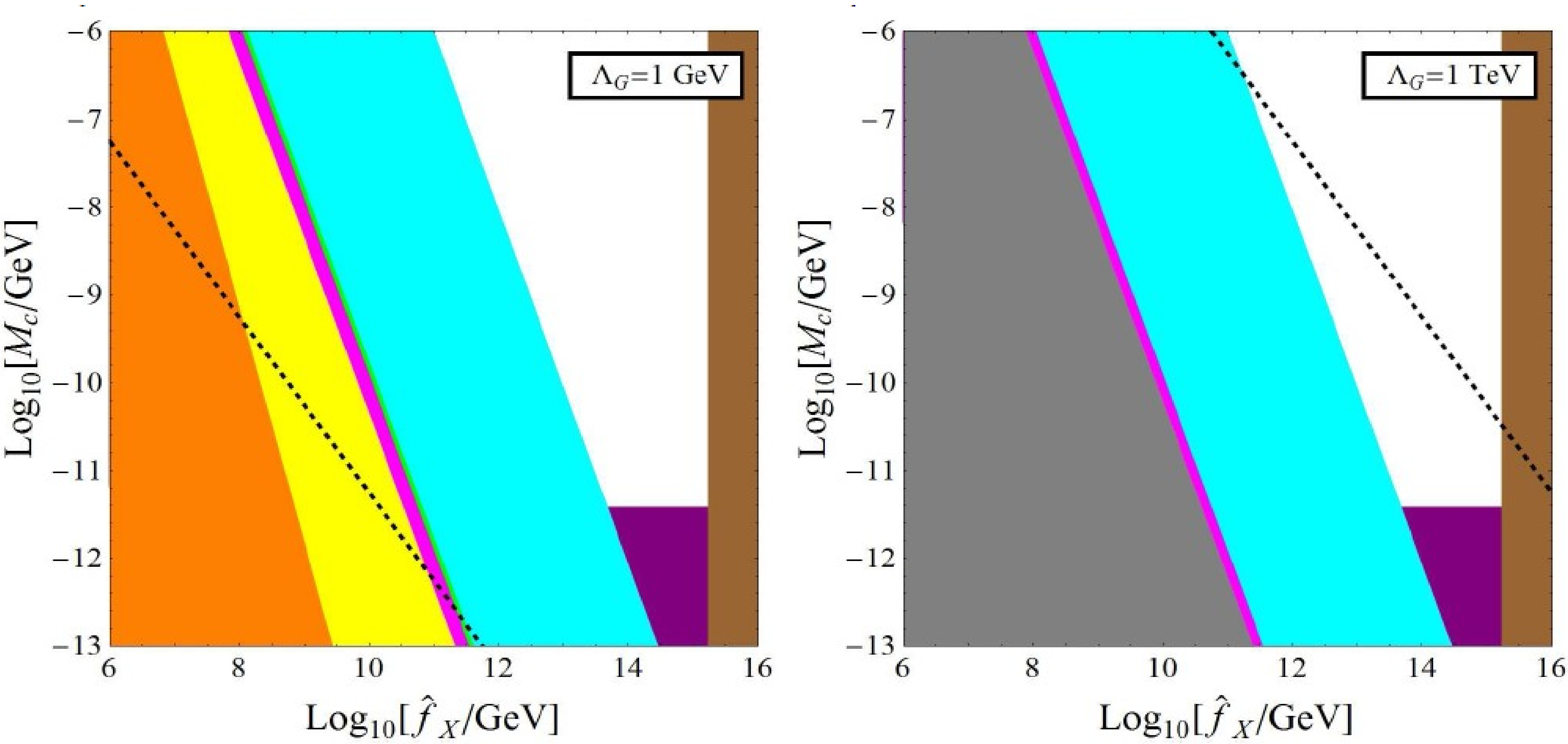


Combined Limits on Dark Towers

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

If the bulk contains sufficiently large extra dimensions,
it is even possible to distinguish DDM...

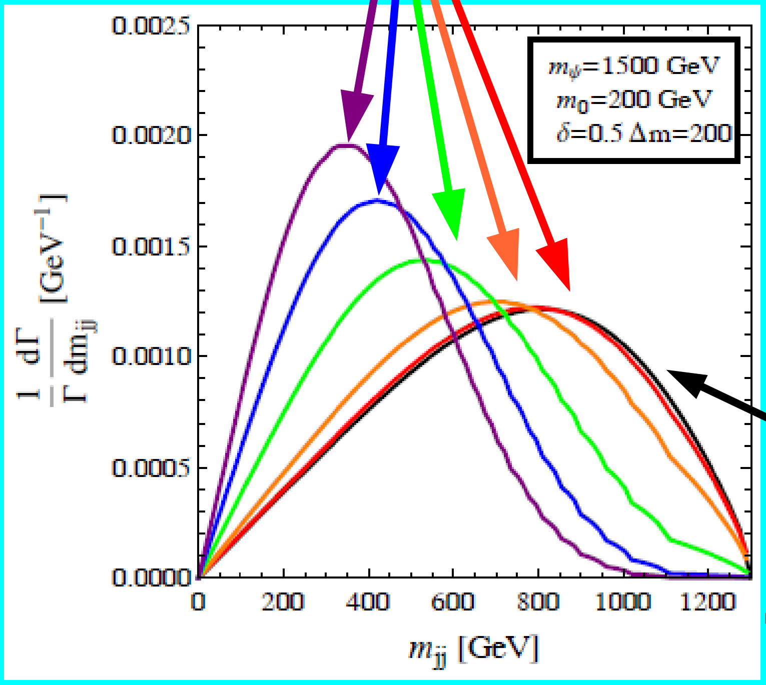
- at colliders (LHC)
- at the next generation of direct-detection experiments
  (e.g., XENON 100/1T, SuperCMS, LUX, PANDA-X)
- at indirect-detection experiments (e.g., AMS-02, ...)

... relative to more traditional dark-matter candidates!

- KRD, S. Su, and B. Thomas, arXiv: 1204.4183
- KRD, J. Kumar, and B. Thomas, arXiv: 1208.0336
- KRD, J. Kumar, and B. Thomas, arXiv: 1306.2959
- KRD, J. Kumar, B. Thomas, and D. Yaylali, arXiv: 1406.4868
- KRD, S. Su, and B. Thomas, arXiv: 1407.2606
- K. Boddy, KRD, D. Kim, J. Kumar, J.C. Park & B. Thomas, arXiv: 1606.07440
- K. Boddy, KRD, D. Kim, J. Kumar, J.C. Park & B. Thomas, arXiv: 1606.07440
- KRD, J. Kumar, B. Thomas, and D. Yaylali, arXiv: 1708.09698

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

DDM Models



Traditional DM

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

- In many bulk DDM models, constituent fields in the DDM ensemble can be produced alongside SM particles by the decays of additional heavy fields.

$$\psi \to jj\chi_n$$

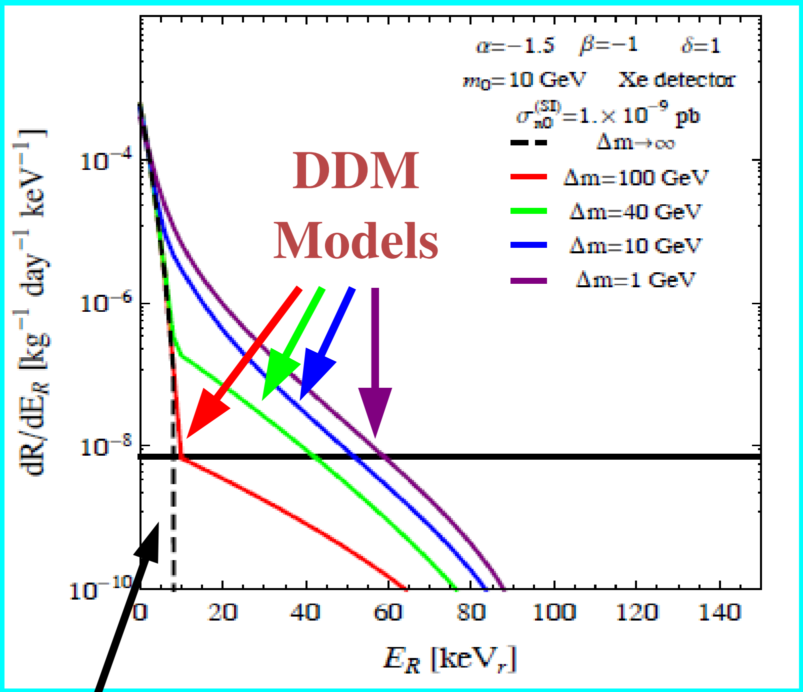
- Evidence of a DDM ensemble can be ascertained in characteristic features imprinted on the invariant-mass distributions of these SM particles.

... and at direct-detection experiments.

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

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

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



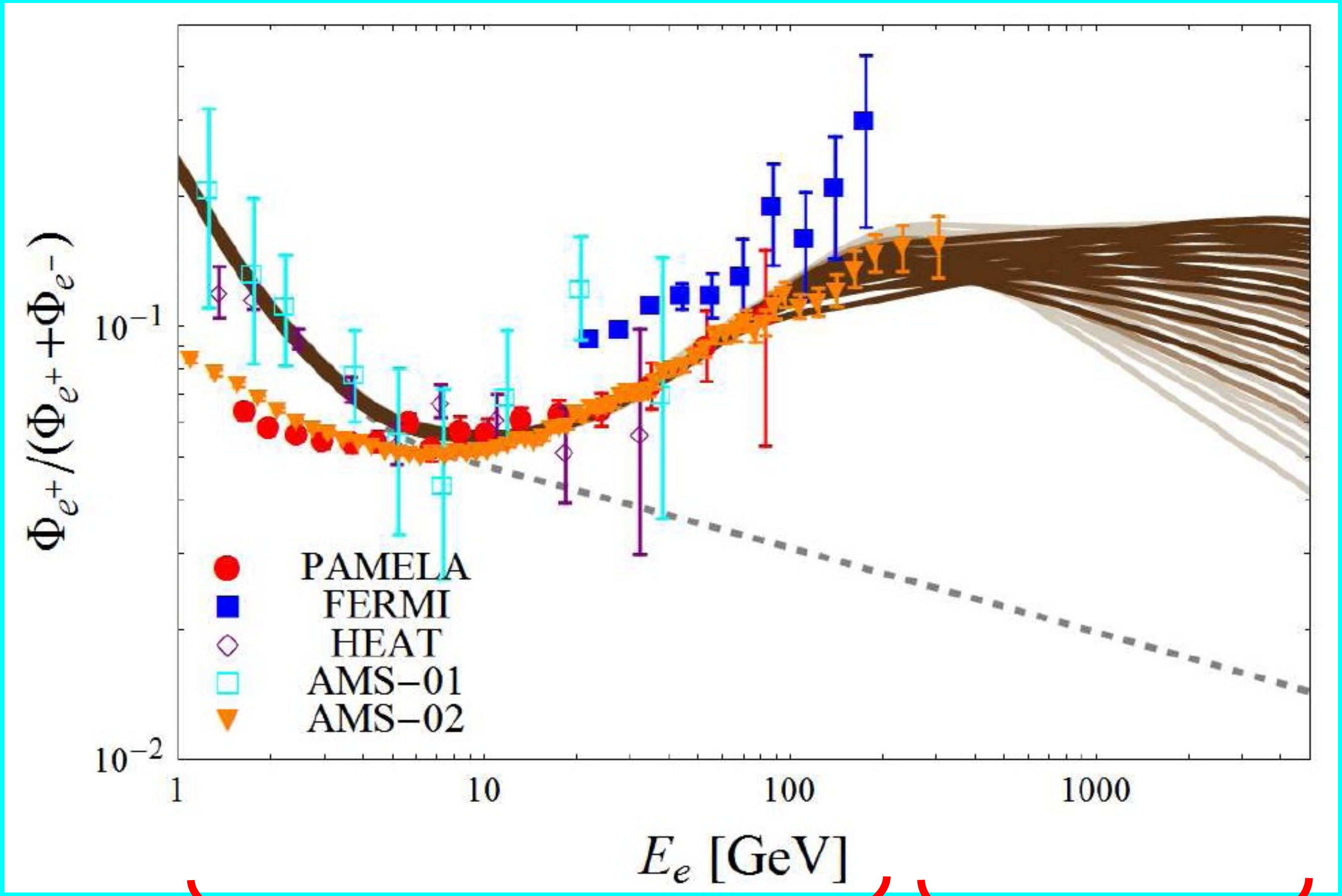
Traditional DM

Bulk DDM also can make 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!

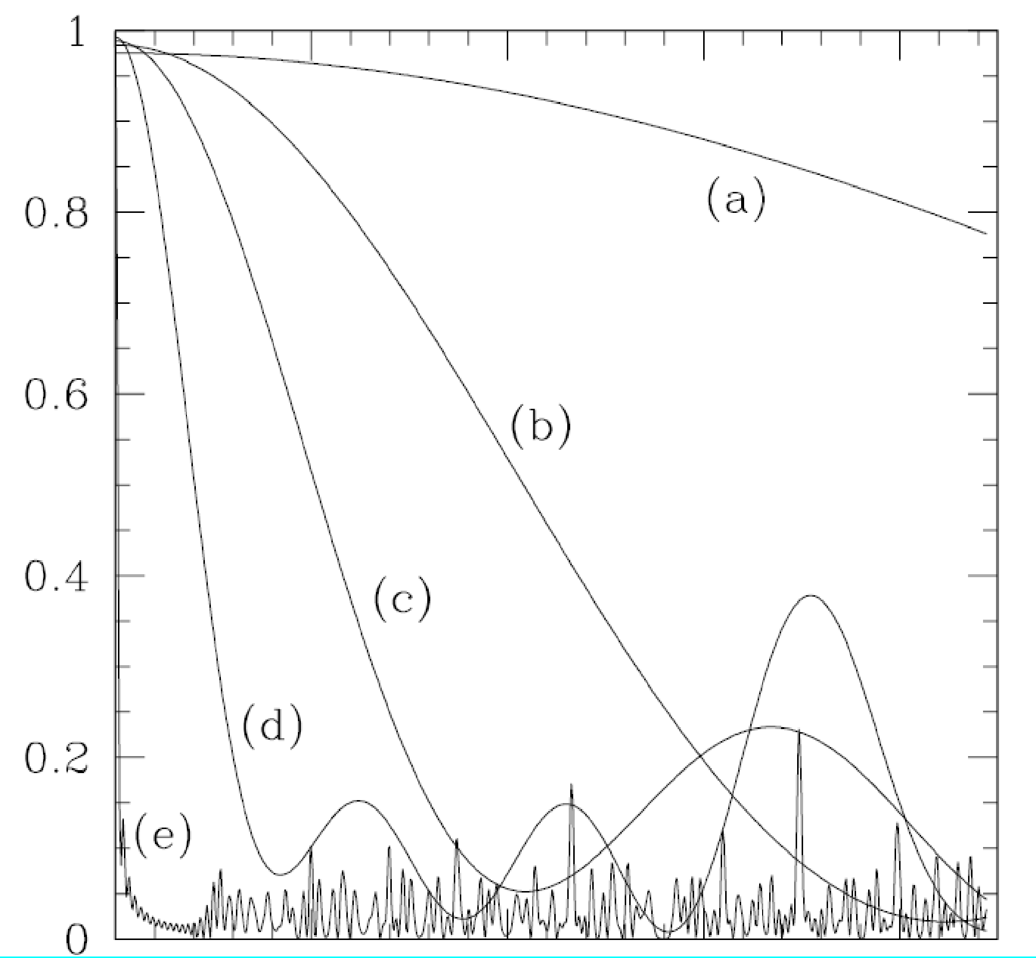
DDM also has new ways of helping the dark sector stay dark!

For bulk DDM, the SM couples to only one combination of ensemble fields with different masses...

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

Projection of bulk field onto SM brane!

However, once ϕ' is produced (in laboratory, in distant astrophysical sources, etc.), it rapidly ***decoheres*** and does not reconstitute in finite time...

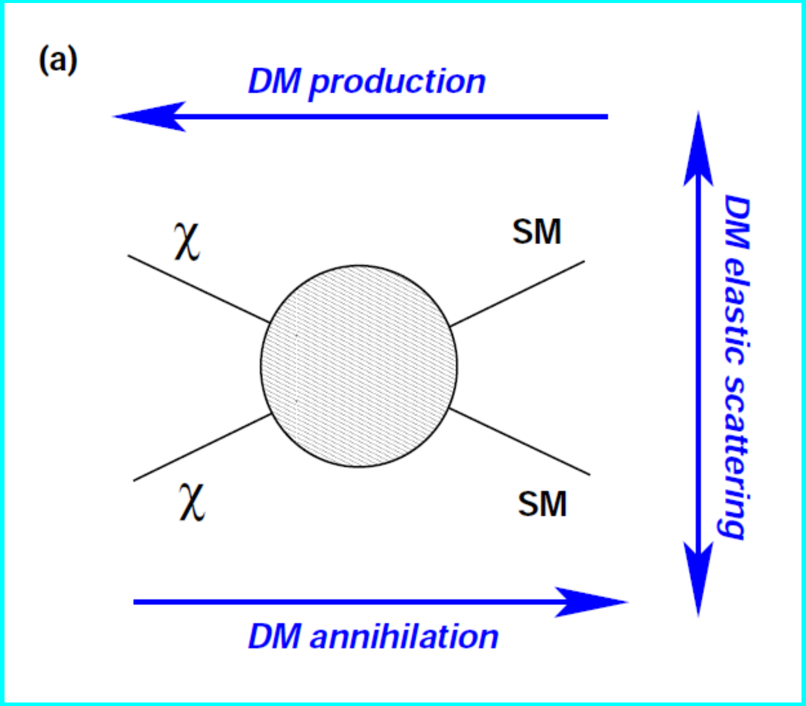


This novel effect provides yet another mechanism which may help dark matter stay dark, and leads to different signature patterns from those which characterize traditional single-component dark-matter candidates.

- 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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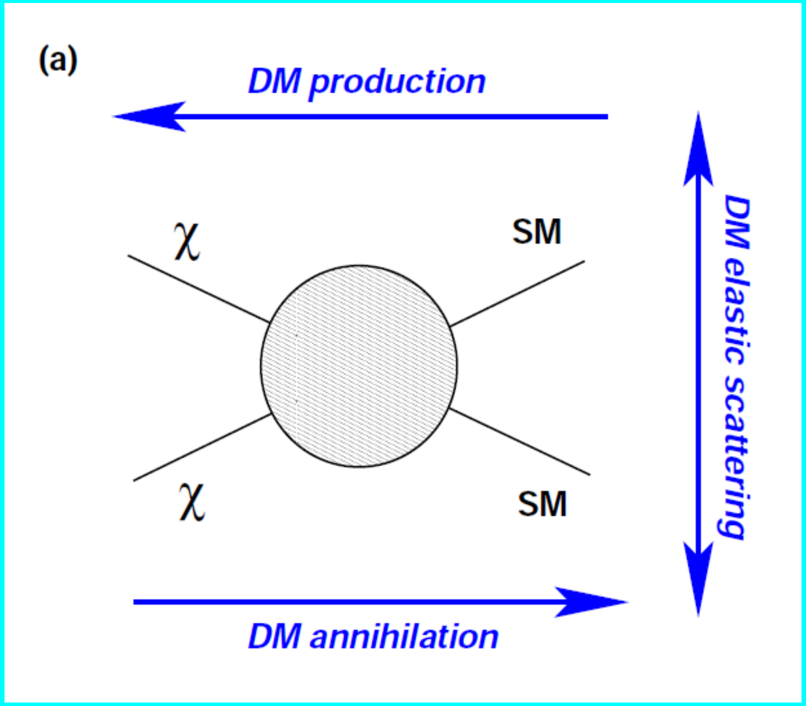
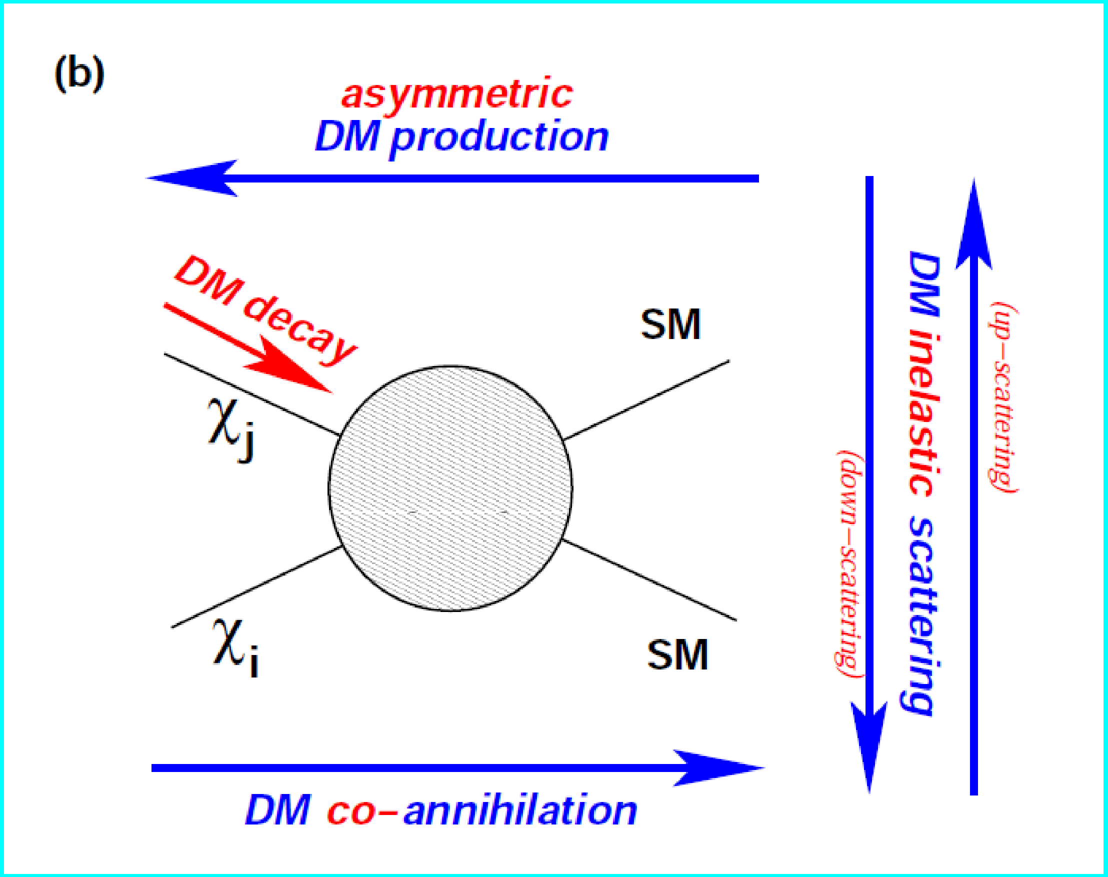


to this...



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!

For example, consider the scalar contact operator

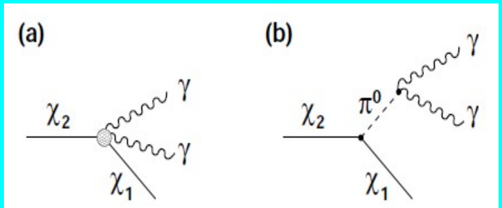
$$\mathcal{L}_{\text{int}}^{(S)} = \sum_{q=u,d,s,\ldots} \frac{c_q^{(S)}}{\Lambda^2} (\overline{\chi}_2 \chi_1)(\overline{q} q)$$

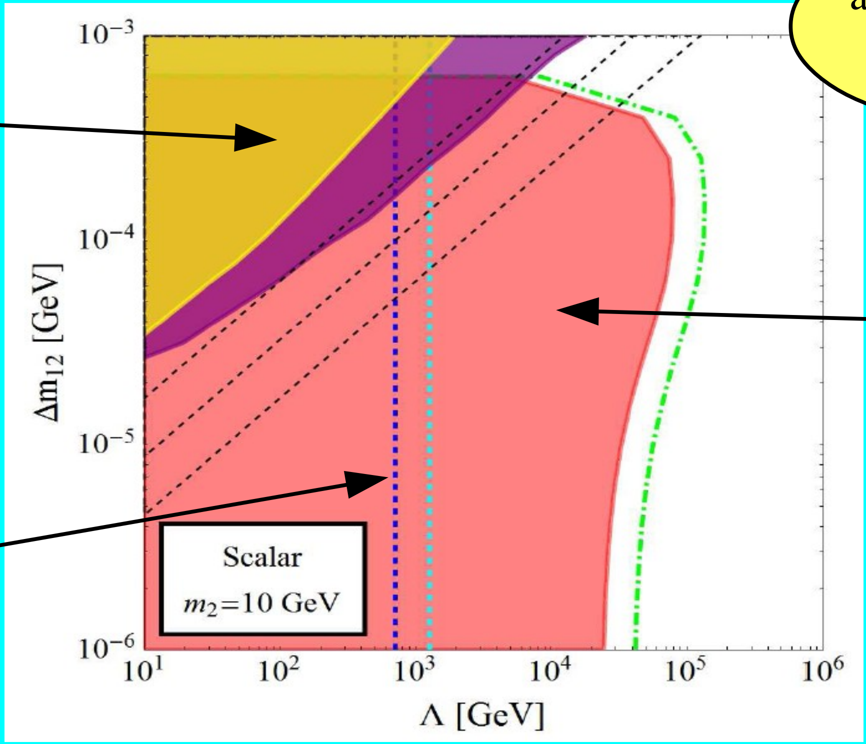
brane/bulk coupling

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 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.

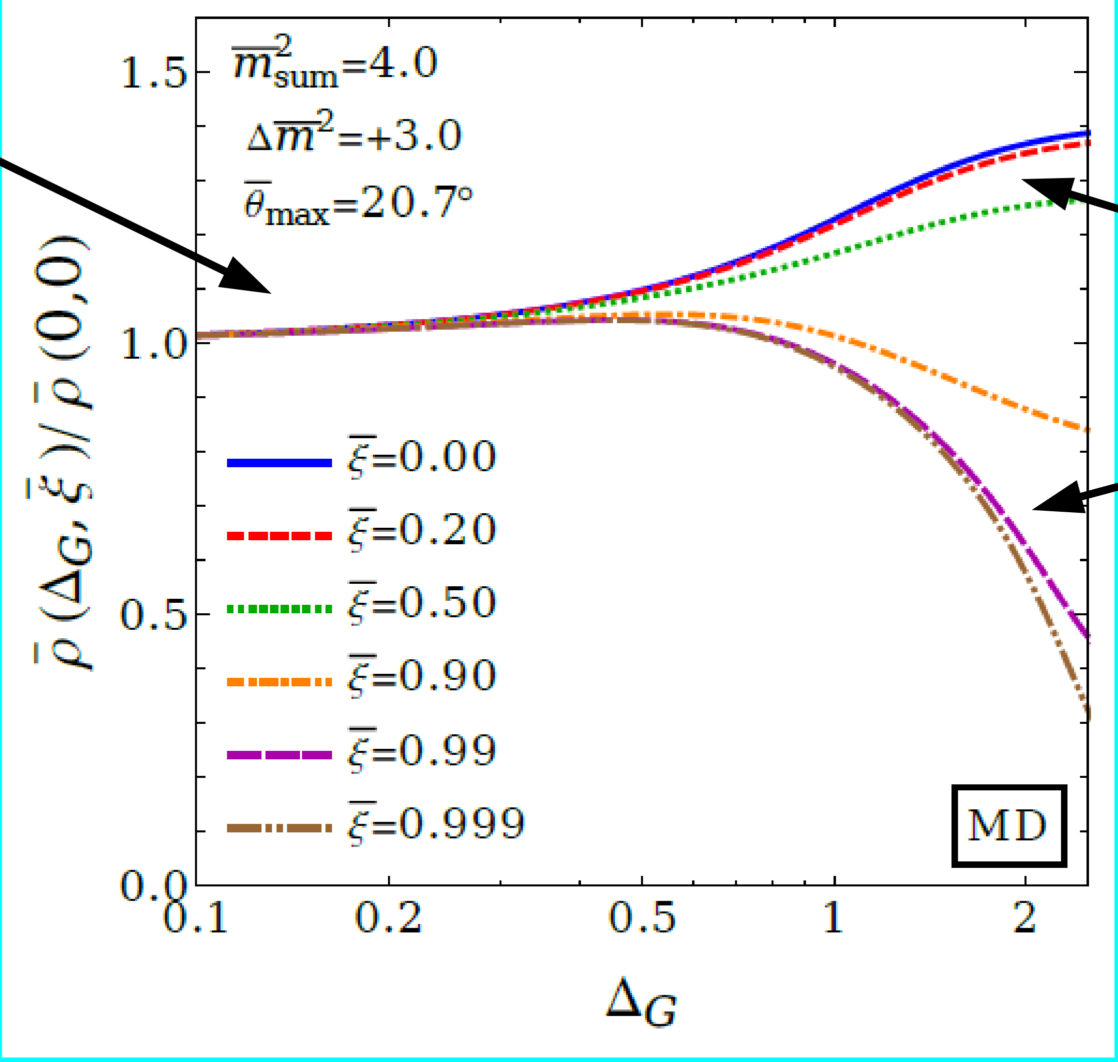
However, in the presence of a cosmological phase transition, these mixings can dramatically alter

- 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!

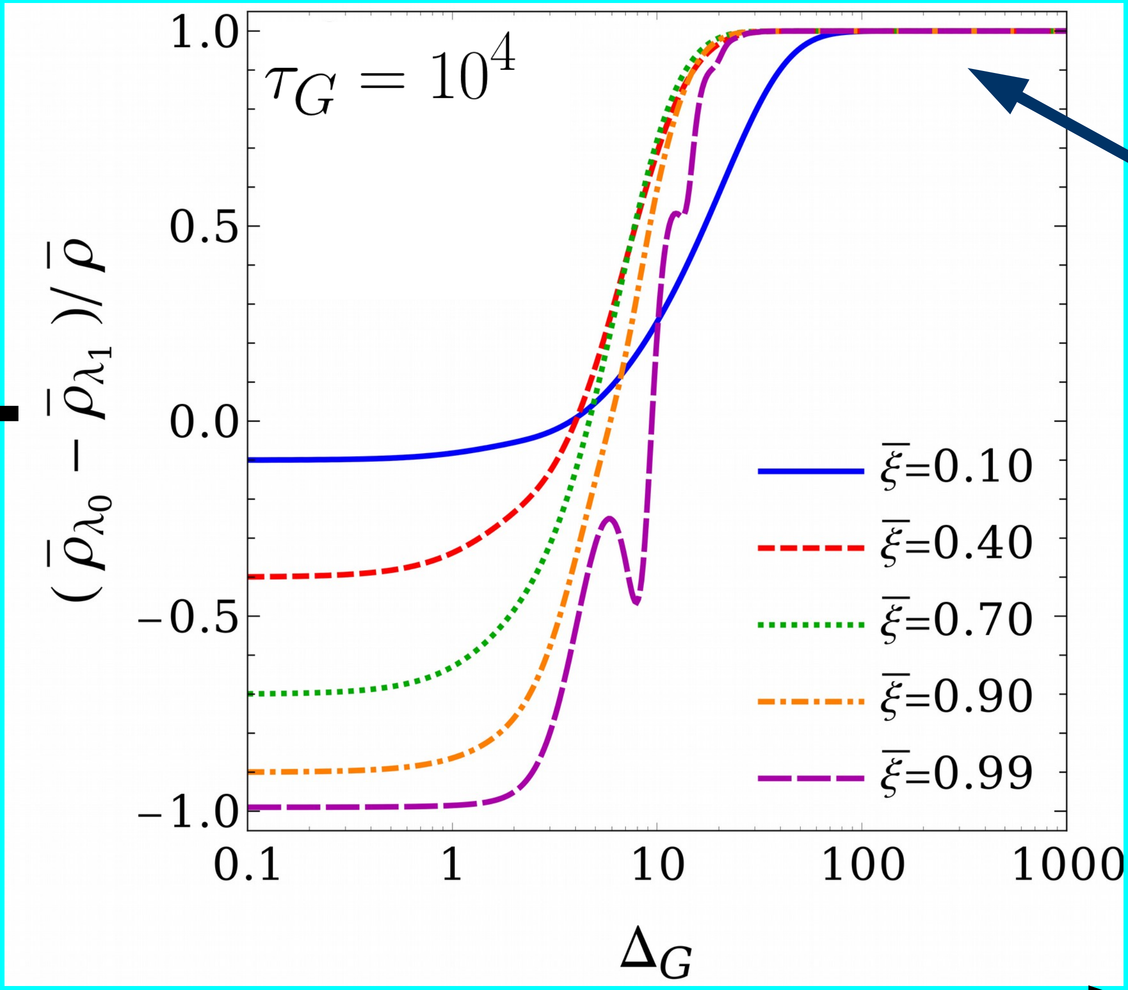
Can be relevant for theories with multiple axions, even if only weakly mixed!

- 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

lighter field dominates

heavier field dominates

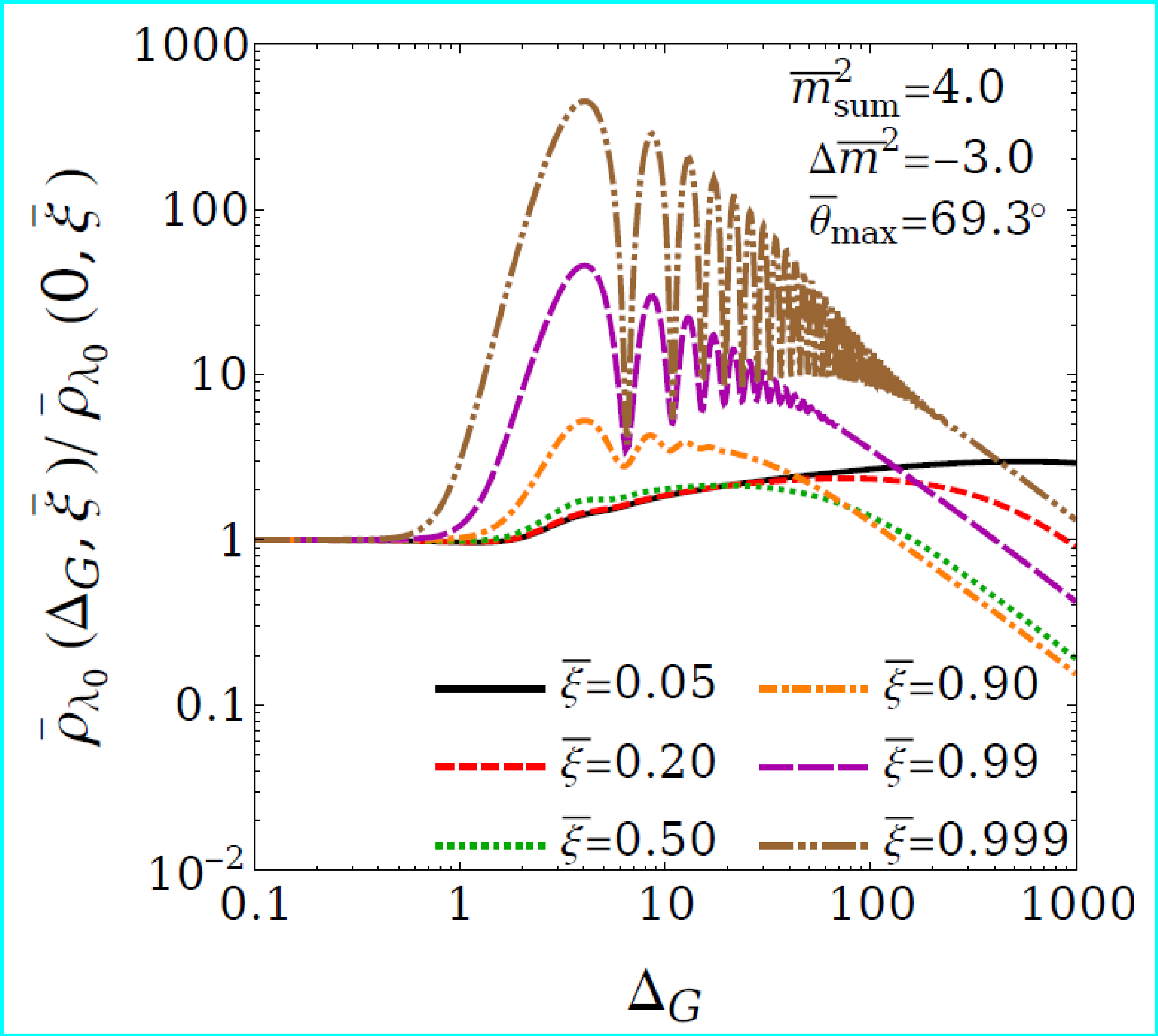


phase transition timescale

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...



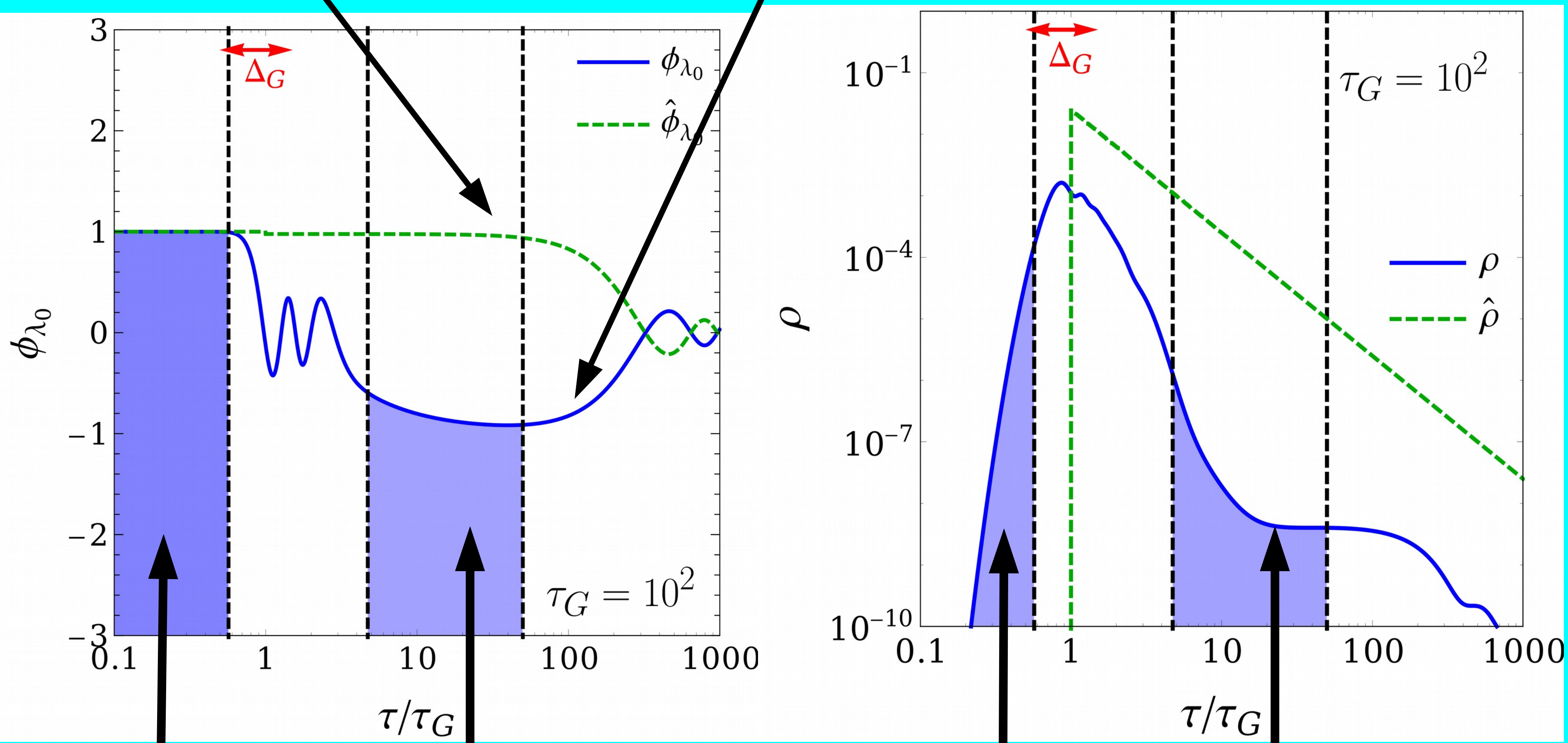
e.g., ***parametric resonances*** that arise due to the non-trivial interplay between the mixing and non-zero timescale (width) associated with the mass-generating phase transition!

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*!

Field behavior if phase transition had been instantaneous.

True field behavior



overdamping

re-overdamping

overdamping

re-overdamping

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! — w/ Fei Huang & Shufang Su, 1610.04112
  - 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. — 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 physics of the string-theoretic bulk is important for dark-matter physics and for cosmology in general, and predicts the existence of a non-minimal dark sector.
  ⇒ String theory requires that we move beyond the WIMP paradigm!

- As we have seen, fairly elementary observations can be used to place rather significant cosmological constraints on viable string models and their bulk sectors!

- **Dynamical Dark Matter (DDM)** is the framework that captures this complexity, and is ripe with new possibilities for dark-matter physics! Almost every traditional line of investigation in dark-matter physics must be re-evaluated in this context.
  - ***Stability is not a fundamental property of the dark sector!***
  - All that is required is a phenomenological balancing of lifetimes against abundances. A much richer ***dynamical*** dark sector is possible, with new theoretical possibilities 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!