Dynamical Dark Matter from Thermal Freeze-Out

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Based on work done in collaboration with:

- **Keith Dienes, Jacob Fennick, and Jason Kumar [arXiv:1712.09919]**

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Dynamical Dark Matter

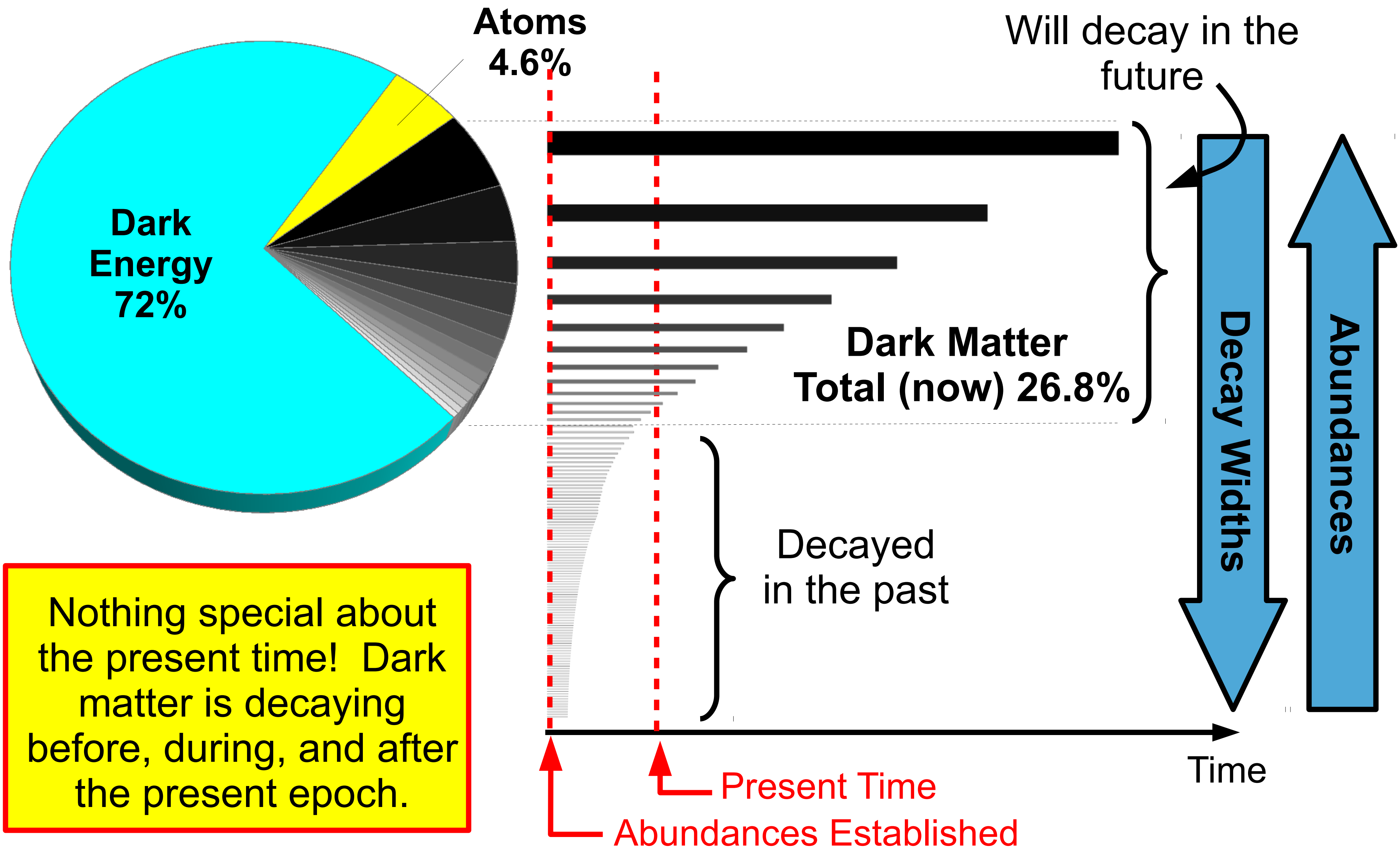
[Dienes, BT: 1106.4546]

Dynamical Dark Matter (DDM) is a theoretical framework in which constraints on dark matter can be satisfied **without the hyperstability criterion** ($\tau_\chi \gtrsim 10^{26}$ s) typically required of traditional DM candidates.

In particular, in DDM scenarios...

- The dark-matter candidate is an **ensemble** consisting of a potentially vast number of constituent particle species.
- The individual abundances of the ensemble constituents are **balanced against decay rates** across the ensemble such that constraints are satisfied.
- The DM abundance and equation of state also exhibit a **non-trivial time-dependence** beyond that associated with Hubble expansion.

DDM Cosmology: The Big Picture



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

DDM Model Building

- The viablitiy of a DDM ensemble hinges on three fundamental **scaling relations** which describe how masses, abundances, and decay widths scale in relation to each other across the ensemble:

1. Abundance $\Omega(m)$ as a function of mass
2. Decay width $\Gamma(m)$ as a function of mass
3. Density of states $n(m)$ as a function of mass

(1, 2): Depend on cosmology, couplings to external fields, etc.

(3): Reflects the internal structure of the ensemble itself

One crucial ingredient is an **abundance-generation mechanism** which can provide an appropriate abundance spectrum $\Omega(m)$.

- Realizations of DDM have typically relied on non-thermal mechanisms for abundance generation (e.g., misalignment production).

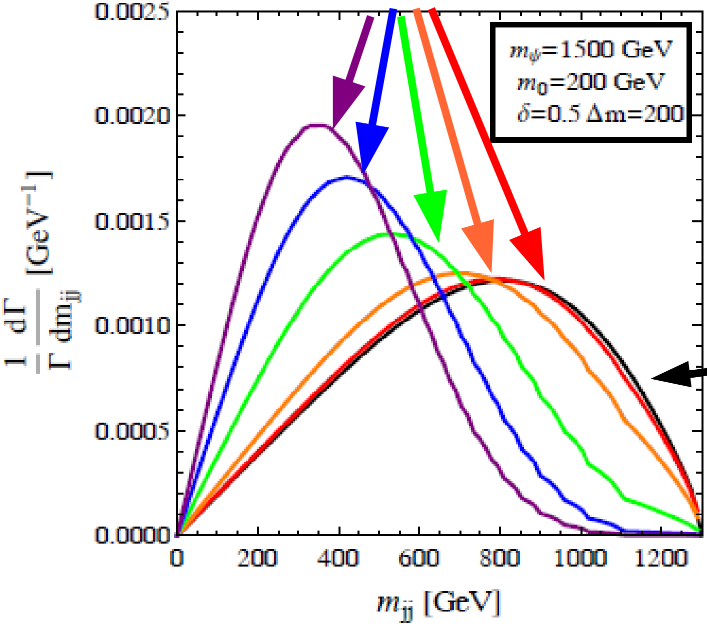
⇒ $m_i \ll \mathcal{O}(\text{keV})$, highly suppressed couplings

- In this talk, however I will demonstrate that a viable set of scaling relations can also be achieved through **thermal freeze-out**.

⇒ $\mathcal{O}(\text{keV}) \lesssim m_i \lesssim \mathcal{O}(\text{TeV})$, $\mathcal{O}(1)$ couplings

DDM ensembles with masses and couplings in this regime can give rise to variety of **distinctive and characteristic experimental signatures**:

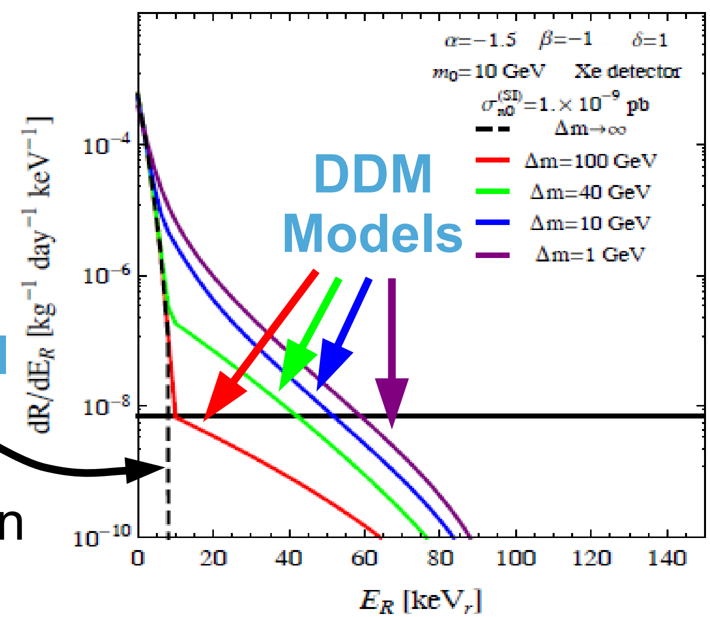
DDM Models



Traditional DM

At Colliders

- Characteristic features in kinematic distributions of SM particles produced alongside the ensemble consitituents. Dienes, Su, BT [1204.4183, 1407.2606]



Traditional DM

At Direct-detection experiments

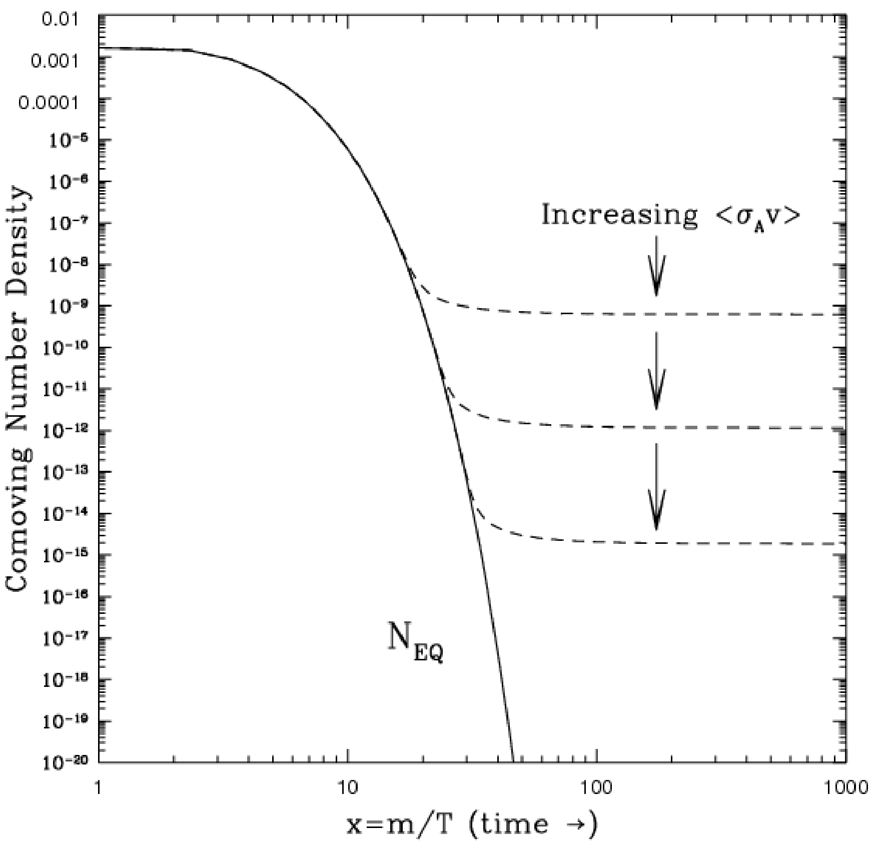
- DDM ensembles also give rise to distinctive features in recoil-energy spectra. Dienes, Kumar, BT [1208.0336]

And at Indirect-Detection Experiments

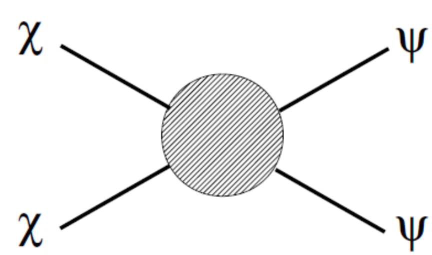
- In the shape of the differential flux spectra of cosmic-ray particles produced from dark-matter annihilation or decay. Dienes, Kumar, BT [1306.2959]
- In characteristic features in the gamma-ray spectra of dwarf galaxies, the Galactic Center, etc. Boddy, Dienes, Kim, Kumar, Park, BT [1606.07440, 1609.09104]

Thermal Freeze-Out

- As an abundance-generation mechanism for dark matter, **thermal freeze-out** has a number of phenomenological advantages:
  - Insensitivity to initial conditions
  - Applicable to particles χ with weak-scale masses and couplings sufficiently large (compared to, say, axions) as to be relevant for collider physics, direct detection, etc.



- Characteristic dependence of the abundance when χ annihilates (e.g., through light mediators or t-channel diagrams) into light fields ψ:

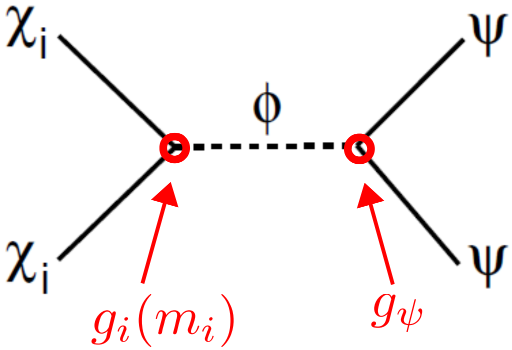


$$\langle \sigma v \rangle \sim \frac{g_\chi^2 g_\psi^2}{m_\chi^2} \Rightarrow \Omega_\chi \sim \frac{m_\chi^2}{g_\chi^2 g_\psi^2}$$

Thermal DDM?

The Question: Can thermal freezeout naturally provide the balancing of decay widths against abundances required for DDM?

- Typically, Γ_i scales with m_i to some positive power. For a viable ensemble, Ω_i must scale with m_i to a sufficient **inverse power**.
- Consider an ensemble of dark-matter constituents χ_i which all couple to a **common mediator** ϕ which also couples to a light fields ψ.
- In the regime in which $m_\phi > m_i$ for all χ_i, all constituents annihilate primarily to ψ pairs via an s-channel ϕ.



- Scaling of $g(m_i)$ with m_i can depend on underlying theory structure, renormalization, etc. For simplicity we take $g_i \equiv g_\chi$ to be **universal**.

Annihilation Cross-Sections

- The way in which the annihilation cross-section scales with m_i, m_ϕ, and m_ψ is dictated by the structure of the pertinent Lagrangian operators:

$$\sigma_i \sim \frac{g_\chi^2 g_\psi^2}{m_i^2} v^{2r-1} \left(\frac{\mu}{m_i}\right)^{2(n_\chi+n_\psi)} \frac{(1-m_\psi^2/m_i^2)^{s+1/2}}{(1-m_\phi^2/4m_i^2)^2} \left(\frac{m_\psi}{m_i}\right)^t$$

Operators (On the Dark-Matter Side)

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

n_χ: mass dimension of operator coefficient

r: whether initial state can be L=0 ($r = 0$) or only L=1 ($r = 1$)

Annihilation Cross-Sections

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Operators (On the Light-Particle Side)

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

n_χ: mass dimension of operator coefficient

s: whether final state can be L=0 ($s = 0$) or only L=1 ($s = 1$)

t: whether coupling is chirality-suppressed ($t = 1$) or not ($t = 0$)

Abundance Spectrum

- The corresponding spectrum of abundances Ω_i for the ensemble is

$$\Omega_i \sim \frac{m_i^2}{g_\chi^2 g_\psi^2} m_i^{2(n_\chi+n_\psi)+t} \frac{(1-m_\phi^2/4m_i^2)^2}{(1-m_\psi^2/m_i^2)^{s+1/2}}$$

- Equivalently, we can parametrize this spectrum of abundances in terms of an (m_i-dependent) **scaling exponent** $\gamma(m_i)$:

$$\Omega_i \sim m_i^{\gamma(m_i)}$$

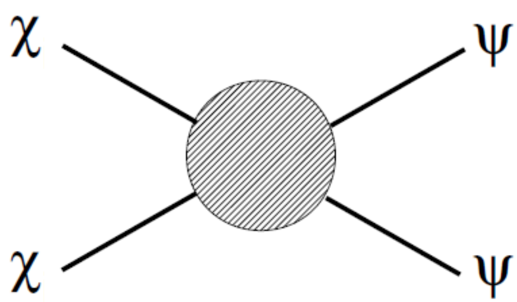
$$\gamma(m_i) \equiv \frac{d\ln\Omega(m_i)}{d\ln m_i} = 2 + \Delta\gamma + \frac{1}{m_i^2/m_\phi^2 - 1/4} + \frac{2s+1}{1-m_i^2/m_\psi^2}$$

where we have defined $\quad \Delta\gamma \equiv 2(n_\chi + n_\psi) + t$

Integrating Out Before Freezing Out

- Decay widths typically scale as a positive power of m_i. Thus, DDM prefers $\gamma < 0$.
- This naturally occurs in the regime in which $m_\psi \ll m_i \ll m_\phi$

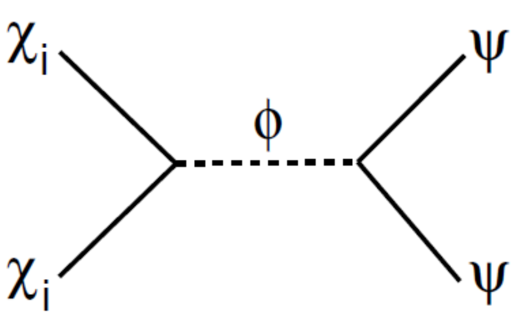
Standard WIMP



$\gamma \approx 2$

Heavy Mediator

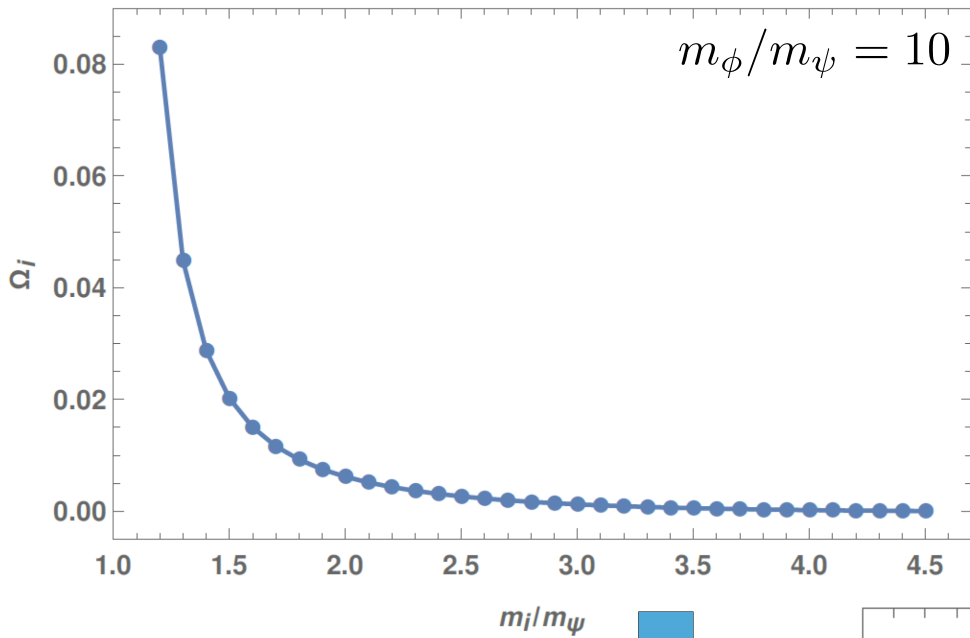
$m_\psi \ll m_i \ll m_\phi$



$\gamma \approx -2 + \Delta\gamma$

Ideal for DDM

Abundance Spectrum



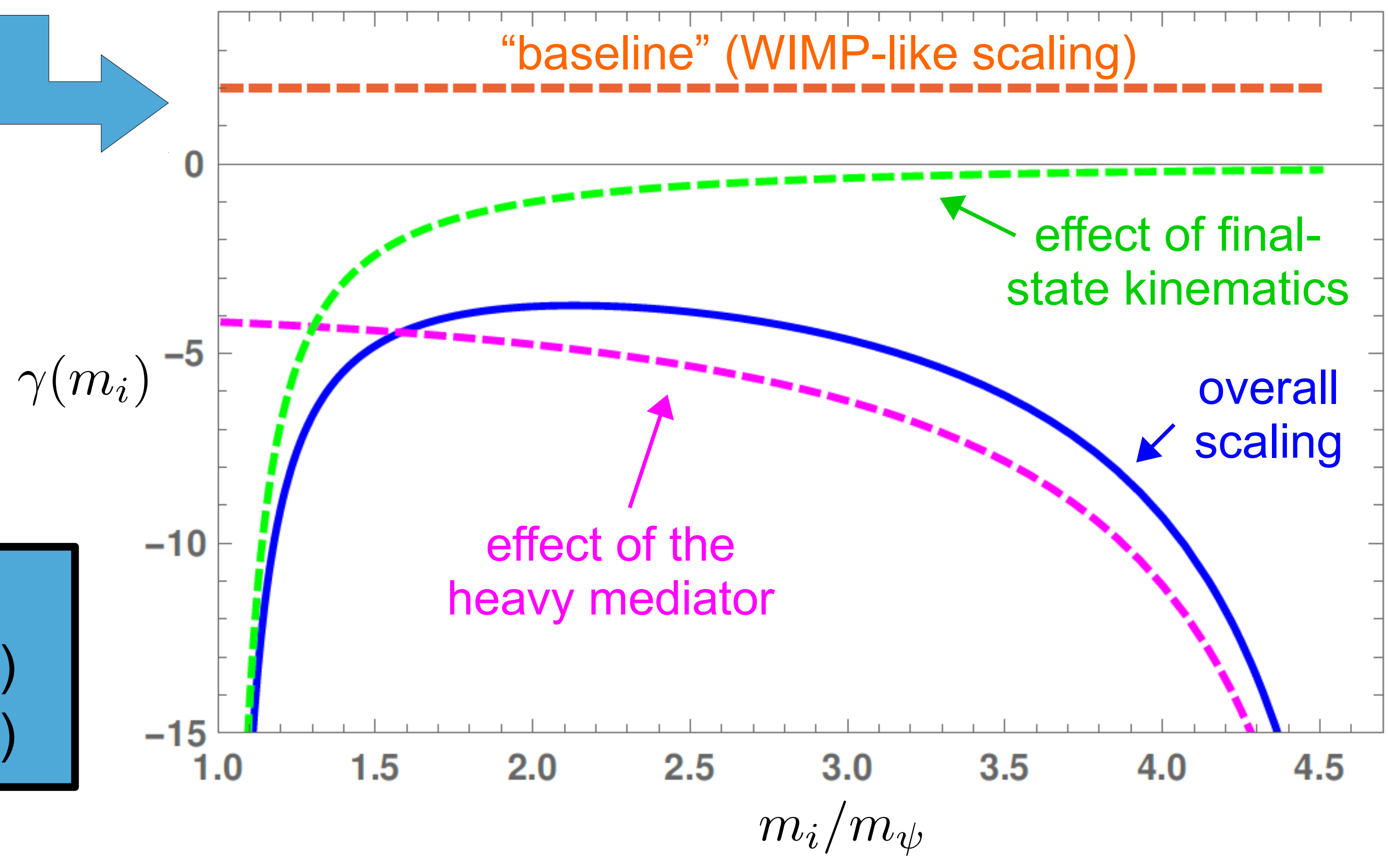
- Spectrum of Ω_i shown here for

ϕ:	scalar
χ_i:	fermion (S coupling)
ψ:	fermion (A coupling)

- Corresponds to the parameters:

$$n_\chi = n_\psi = t = r = 0 \qquad s = 1$$

Scaling Exponent

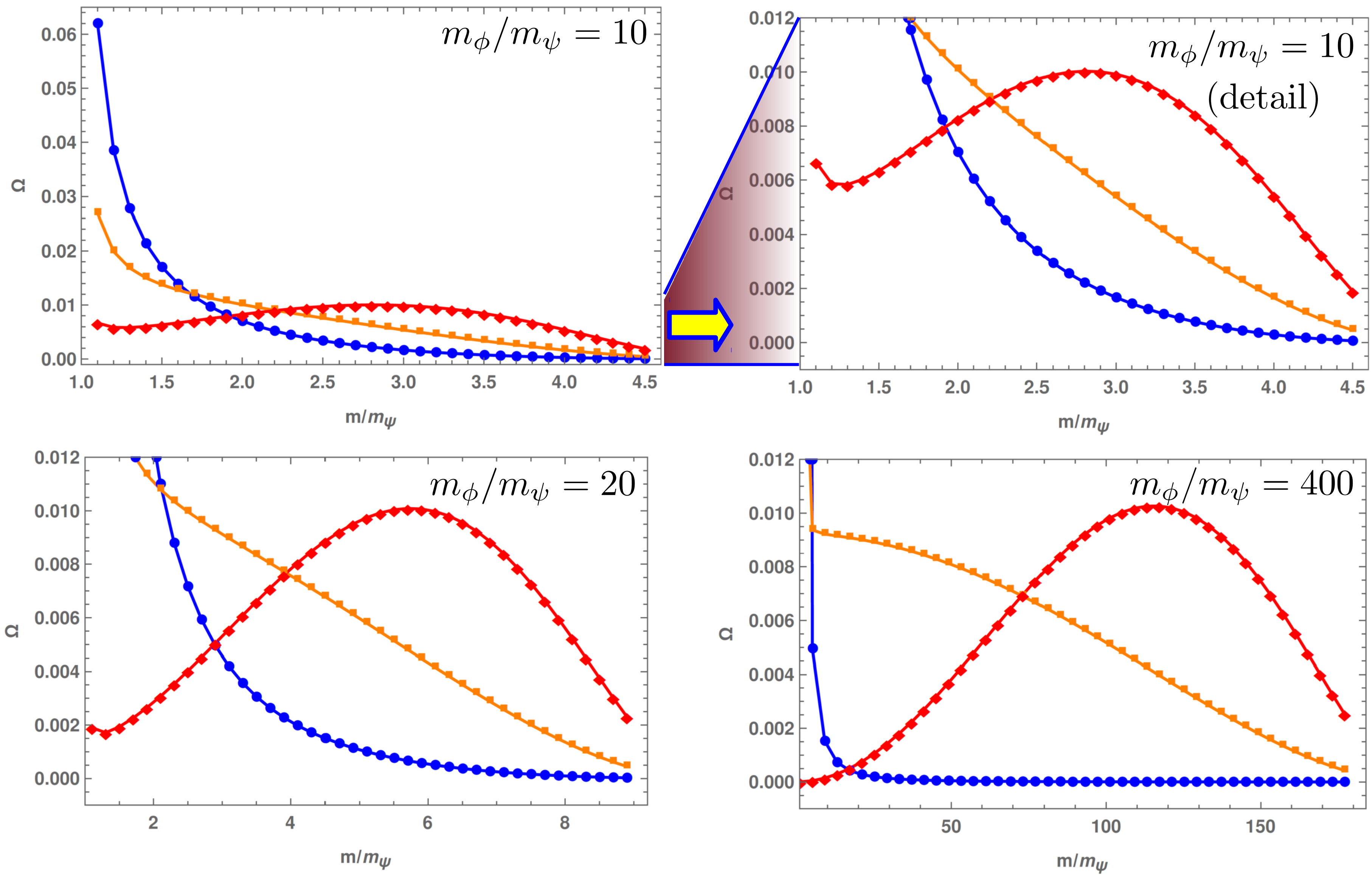


- Not a strong dependence on s, so curves basically the same for a simple Z' scenario where:

ϕ:	vector
χ_i:	fermion (V coupling)
ψ:	fermion (V coupling)

Abundance Spectra

$\Delta\gamma = 0$ $\Delta\gamma = 2$ $\Delta\gamma = 4$



Balancing Widths Against Abundances

- DDM requires a balancing of decay widths Γ_i against abundances Ω_i.

Balancing Criterion

Abundance (function of Γ): $\Omega(\Gamma) \sim \Gamma^{\alpha}$

Density of states (per unit Γ): $n_{\Gamma}(\Gamma) \sim \Gamma^{\beta}$

$$x \equiv \alpha + \beta \lesssim -1$$

Dienes, BT [1106.4546]

- Assuming typical scaling behavior for Γ_i and a typical mass spectrum

$$\Gamma \sim m^{y} \qquad\qquad m \sim k^{\delta}$$

...we find that:

$$\frac{1}{y}\left(\gamma + \frac{1}{\delta}\right) \lesssim 0$$

i.e.,

$$\delta \gtrsim \delta_{\text{min}} \equiv -\frac{1}{\gamma}$$

holds regardless of the value (or sign) of y

The Upshot: Easy to achieve the correct balancing!

For example: fermionic χ_i, ψ; vector ϕ with $m_\psi \ll m_i \ll m_\phi$ $\Rightarrow$ $\gamma \approx -2$

Regimes of Interest

- For a standard WIMP: $\Omega_\chi \propto \frac{1}{\langle \sigma_\chi v \rangle} \sim \frac{m_\chi^2}{g_\chi^4}$

weak-force coupling

- Likewise, for a DDM ensemble: $\Omega_{\rm tot} \propto \sum_i \frac{1}{\langle \sigma_i v \rangle} \sim \sum_i \frac{m_\phi^2}{16 g_\chi^2 g_\phi^2 m_i^2}$

  (χ_i, ψ both fermions, vector ϕ)

$$\sum_i \left(\frac{m_\phi}{m_i}\right)^2 \lesssim g_\chi^2 g_\psi^2 \left(\frac{2.37 \text{ TeV}}{m_\phi}\right)^2$$

- g_ψ and g_χ must remain perturbative.
- $m_i \gtrsim \mathcal{O}(\text{keV})$ for all χ_i (structure formation, etc.)
- Thus, our regime of interest for thermal DDM is one in which the ***χ_i are light***, the couplings are large, the mediator is below the TeV scale, and the annihilation products are primarily **dark-sector states**.

$$\mathcal{O}(\text{keV}) \lesssim m_i \ll m_\phi \ll \mathcal{O}(\text{TeV})$$

Summary

- In this talk, I have shown the appropriate scaling relations for DDM can arise in scenarios in which the dark-matter abundance is generated via **thermal freeze-out**.
- A **broad range of scaling behaviors** can be achieved, depending on the masses, spins, *etc*. of the particles involved.
- Straightforward to arrange a balancing between decay widths and abundances.
- A regime of interest emerges in which the ensemble constituents are light, couplings are large, and the mediator is at the TeV-scale – a regime ripe with phenomenological possibilities!