Dark Matter Freeze-out via **Catalyzed Annihilation**

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The DM+nu forum @TDLI/SJTU

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1 Dark Matter Overview

2 Thermal Freeze-out

3 Catalyzed Annihilation

4 Summary

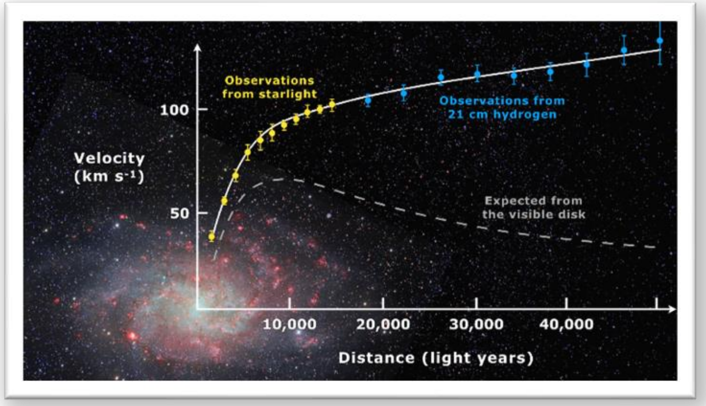
PART 01

Dark Matter Overview

Existence of Dark Matter

Lots of evidence:

1. Galaxy rotation curves.



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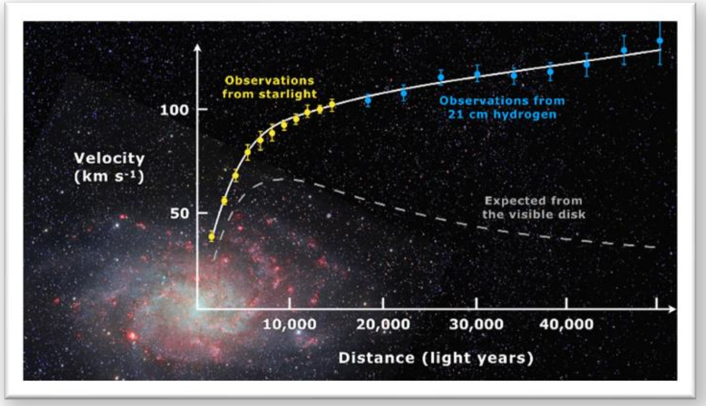
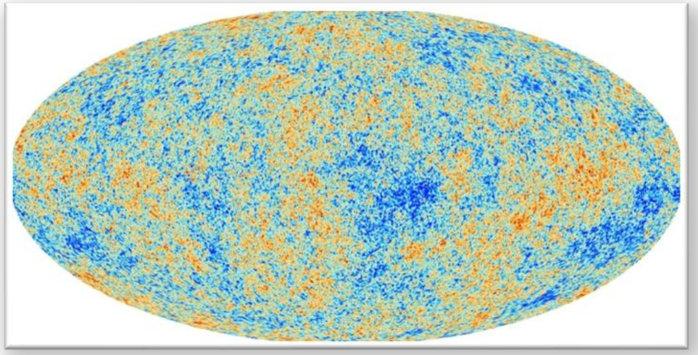
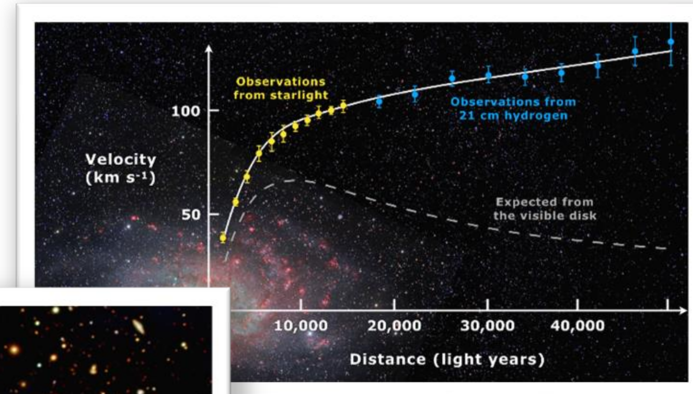




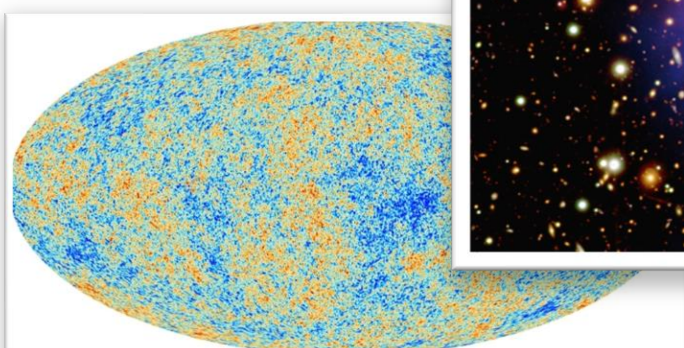
Lots of evidence:

1. Galaxy rotation curves.
2. CMB.
3. Bullet cluster.
4. …



Pink: X-ray image;
Blue: gravitational lensing

arXiv:astro-ph/0608407



What do we know about DM?

1/ Stable.

- If DM decays, its lifetime is longer than the age of the Universe.
  $\tau \gtrsim 10^{17}\text{s}.$
- Much more stringent bound from CMB.
  $\tau \gtrsim 10^{25}\text{s}.$

arXiv:1308.2578

What do we know about DM?

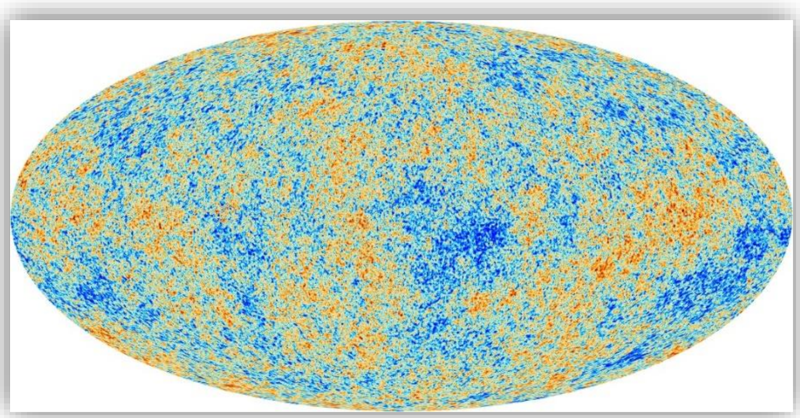
1. Stable.

2. Dark.

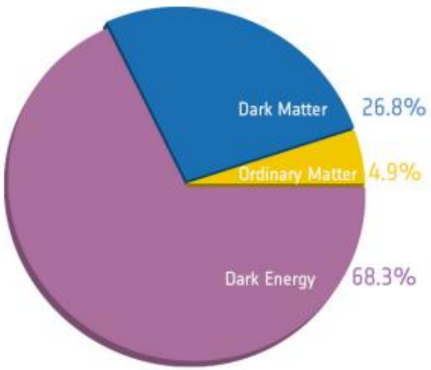
   - DM is neutral.
   - Or its electric charge is tiny.

⏩ What do we know about DM?

1. Stable.
2. Dark.
3. DM abundance. $\Omega h^2 = 0.12$



Planck Collaboration.



What do we know about DM?

1. Stable.
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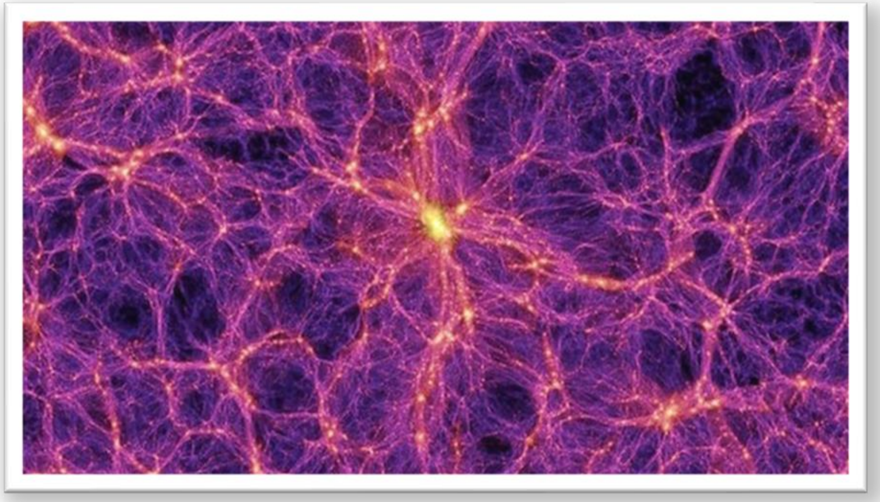
4. Seed structures in the universe.

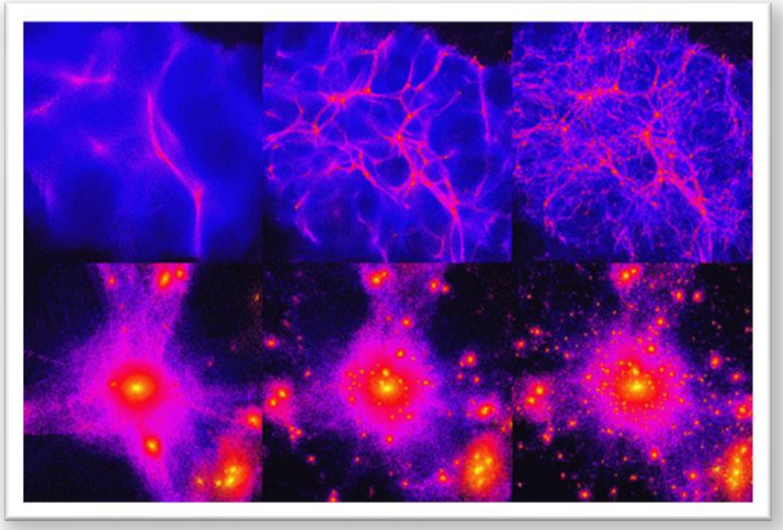


⏩ What do we know about DM?

1. Stable.
2. Dark.
3. DM abundance. $\Omega h^2 = 0.12$
4. Seed structures in the universe.
5. Cold.

   Non-relativistic: kinetic energy << mass.

hot warm cold



What do we know about DM?

1. Stable.
2. Dark.
3. DM abundance. $\Omega h^2 = 0.12$
4. Seed structures in the universe.
5. Cold.

Question of the day:

What does it tell us?

PART 02

Thermal Freeze-out

⏩ What is thermal freeze-out

Thermal freeze-out:

- In the early universe, DM keeps in **thermal equilibrium with SM particles**.

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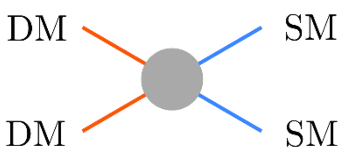
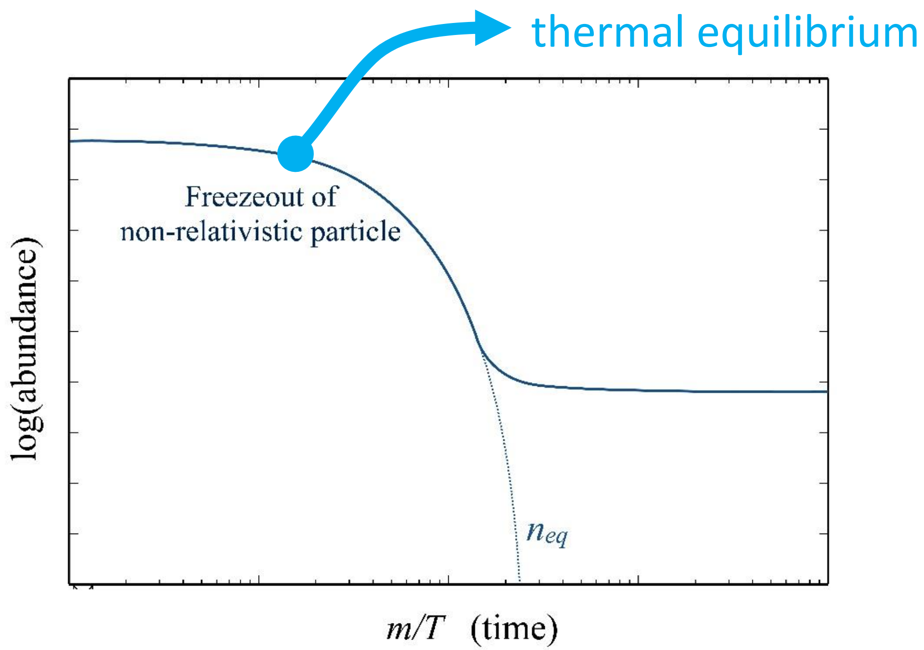
Example:

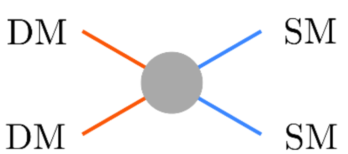


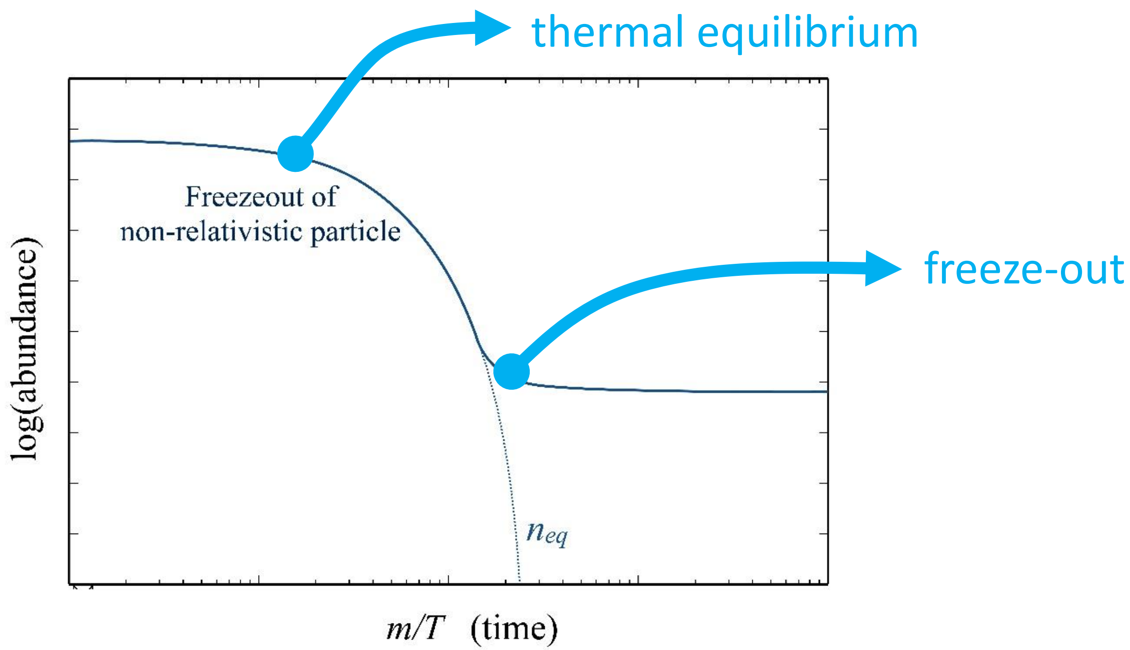


Thermal freeze-out:

- In the early universe, DM keeps in **thermal equilibrium with SM particles**.
- As the universe expands, DM **drops out of equilibrium** to its observed abundance.

Example:





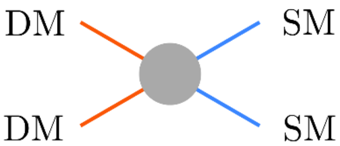
⏩ Why thermal freeze-out

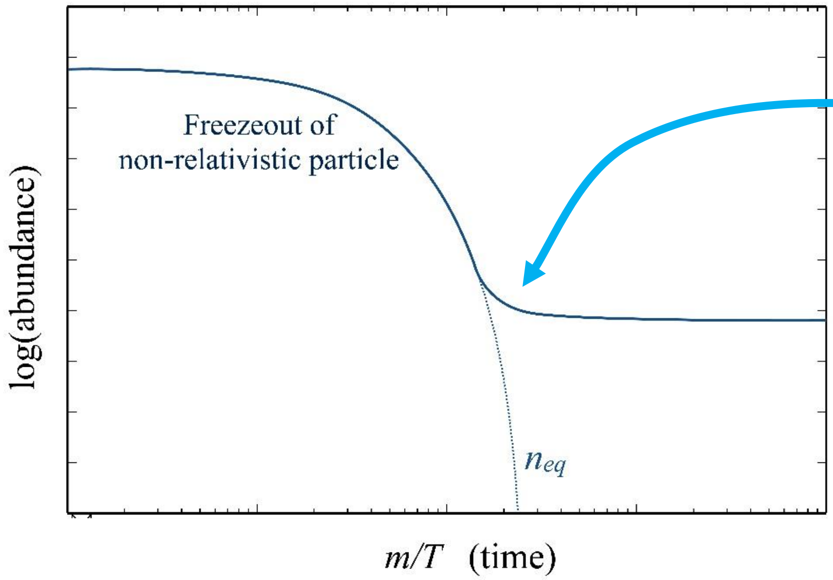
Why is thermal freeze-out appealing:

- **Reasonable!**
  SM relics (photons, neutrinos, nuclei) are determined by this mechanism.
- **Testable!**
  Thermal equilibrium implies interaction between DM and SM.
- **Insensitive to initial conditions!**
  What happens before freeze-out is not related.

⏩ To determine DM abundance

Condition for freeze-out and DM abundance:





$\Gamma_{\mathrm{DM}\to\mathrm{SM}} \simeq H.$

Γ: annihilation rate;
H: Hubble constant.

To determine DM abundance

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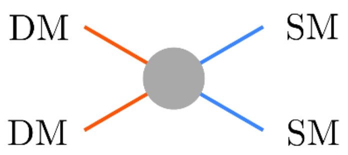

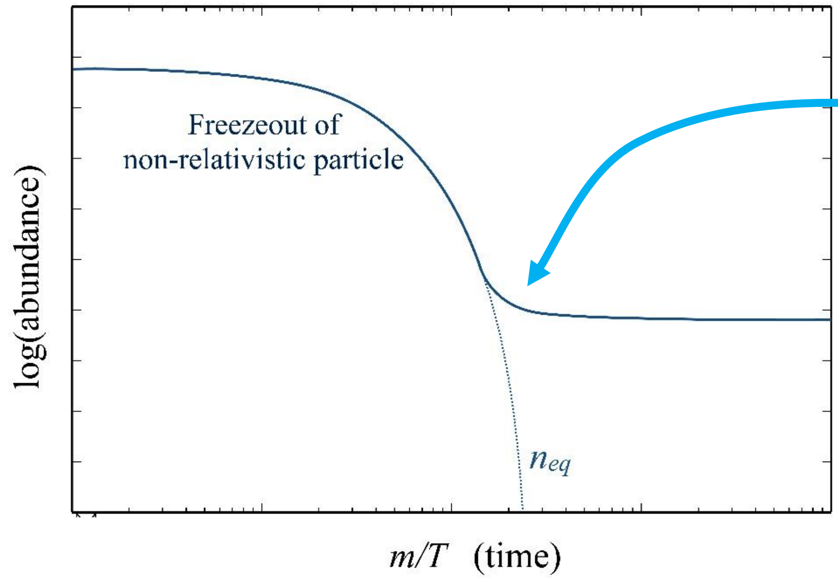

$\Gamma_{\mathrm{DM}\to\mathrm{SM}} \simeq H.$

$\Omega h^2 = 0.12$

$\langle \sigma v \rangle \approx 2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$

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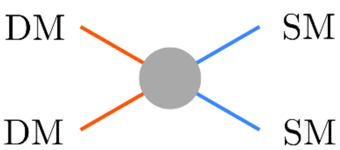

$$\langle \sigma v \rangle \approx 2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

1. $O(1)$ coupling. (Weakly interacting)

2. $100\mathrm{GeV}$ mass. (massive particles)

WIMPs

WIMPs

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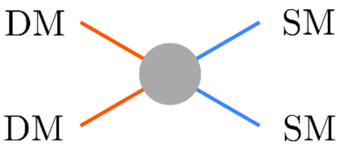

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WIMPs ⟷ **Electroweak**

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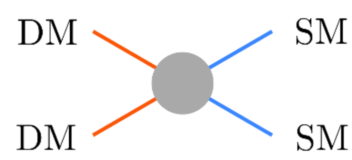

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"WIMP Miracle"

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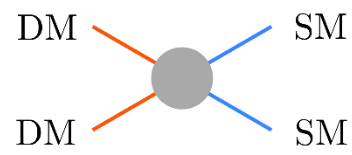

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SUSY DM
composite DM
…

<u>“WIMP Miracle”</u>

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2. 100GeV mass. (massive particles)

WIMPs

1. $O(1)$ coupling.
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Electroweak

Boltzmann equation

Quantitatively, we should solve for the Boltzmann equations to get DM abundance.

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle_{\chi\bar{\chi}\to\phi\phi}\left[n_\chi^2 - n_\chi^{\mathrm{eq}\,2}\right]$$

⏩ Boltzmann equation

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- The expansion of the Universe.
- Radiation dominated.

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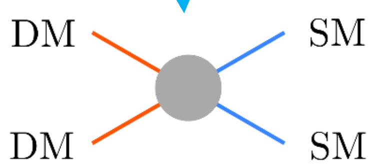

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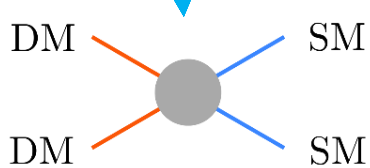

- The expansion of the Universe.
- Radiation dominated.

- Annihilation and inverse annihilation
- Squared for 2 particle interaction

▶▶ Boltzmann equation

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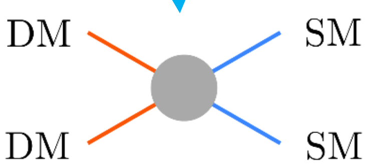

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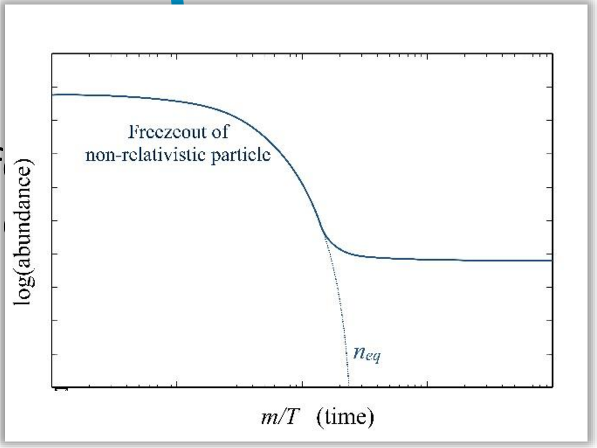
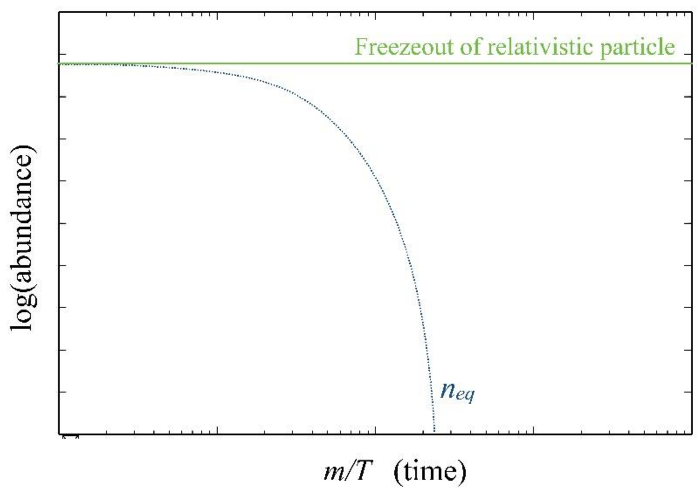


The Boltzmann equation can be solved numerically.

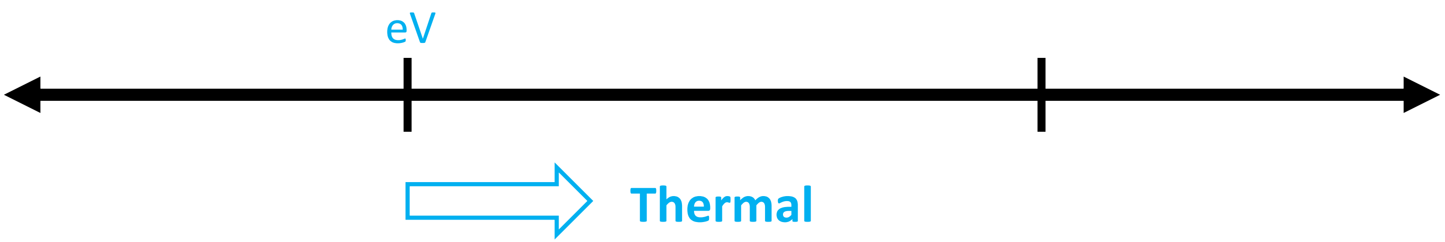
⏩ Mass range

Lower bound:

Since $\rho \simeq m_{DM} \cdot n$, small DM mass indicates large number density.



$$\Omega_\chi h^2 \simeq 0.12 \times \frac{g}{g_{*,S}(T_{\rm fo})} \left(\frac{m_\chi}{2\,\rm eV}\right).$$



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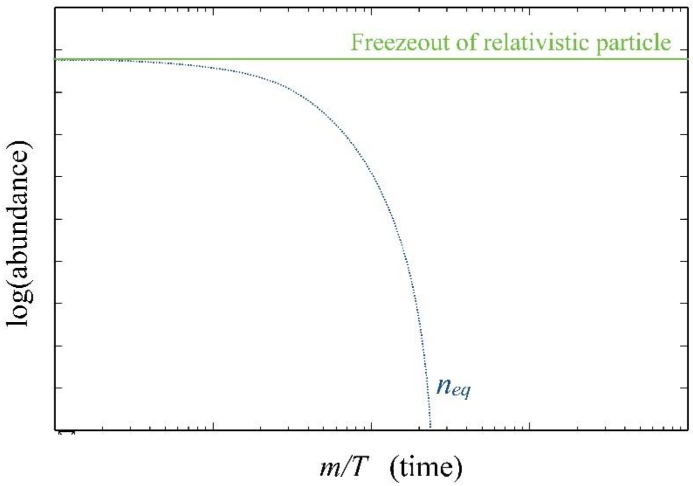
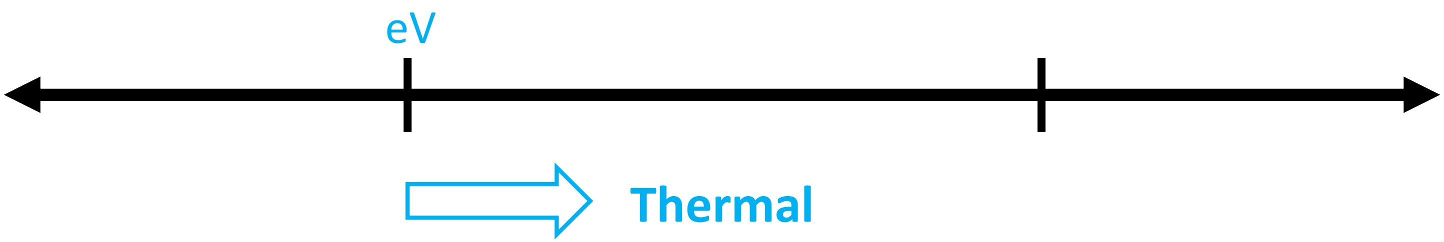


$$\Omega_\chi h^2 \simeq 0.12 \times \frac{g}{g_{*,S}(T_{\rm fo})} \left(\frac{m_\chi}{2\,{\rm eV}}\right).$$

$$m_{DM} \gtrsim 1\mathrm{eV}$$

Mass range



Upper bound:

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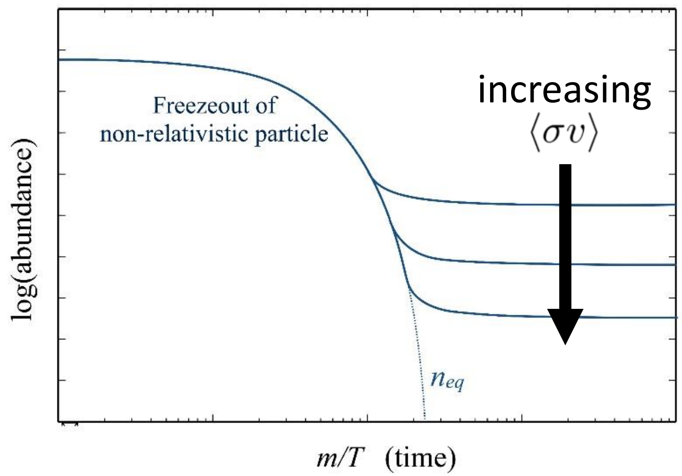
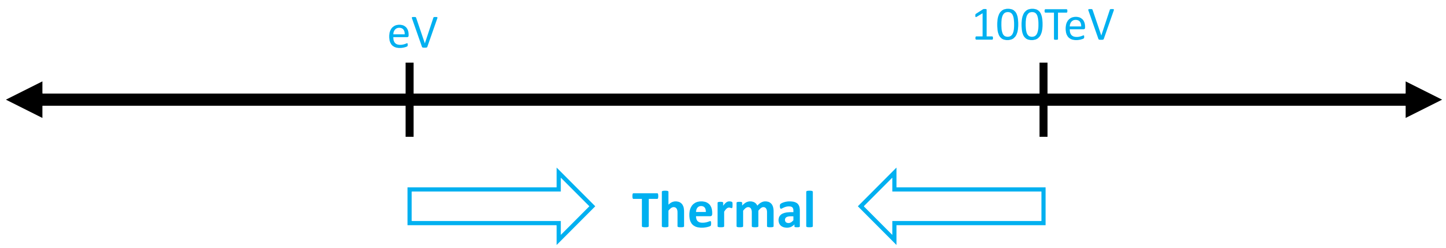


Mass range



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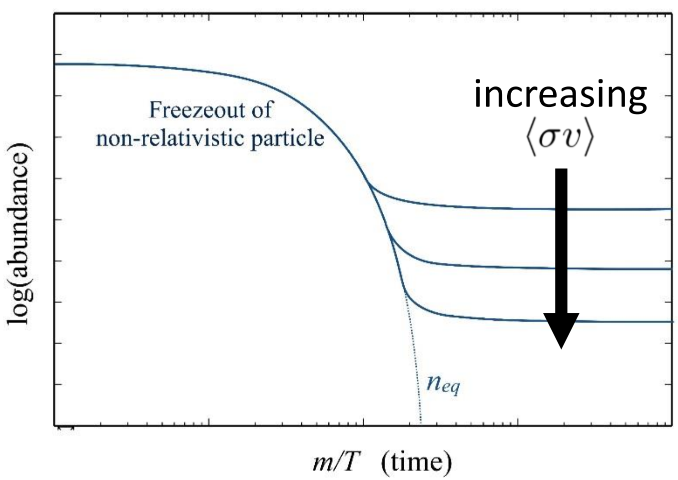


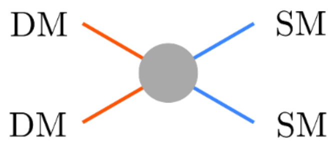
Unitarity limit for 2 DM annihilation:

$$\sigma v \leq \frac{4\pi}{m_{\rm DM}^2 v}$$

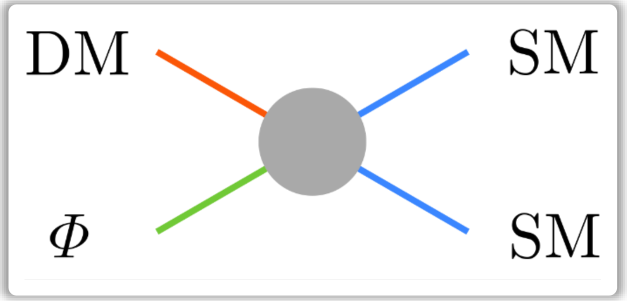
$$\boldsymbol{m_{DM} \lesssim 100\mathrm{TeV}}$$

The WIMP neighborhood

Beyond self-annihilation:



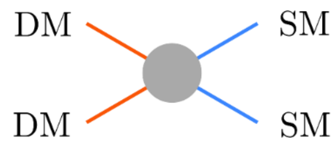
- Co-annihilation.



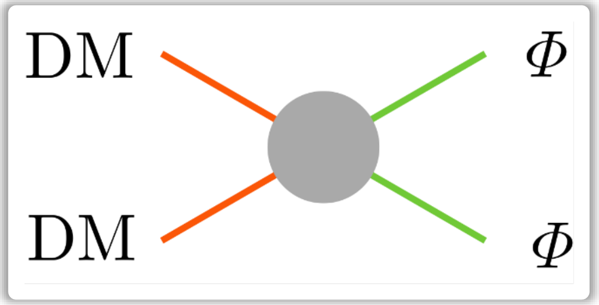
- DM and Φ are both odd under dark $U(1)$ or Z_2.
- $m_\Phi > m_{DM}$ to ensure DM stability.

⏩ The WIMP neighborhood

Beyond self-annihilation:



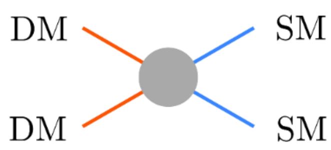
- Co-annihilation.
- Forbidden annihilation.



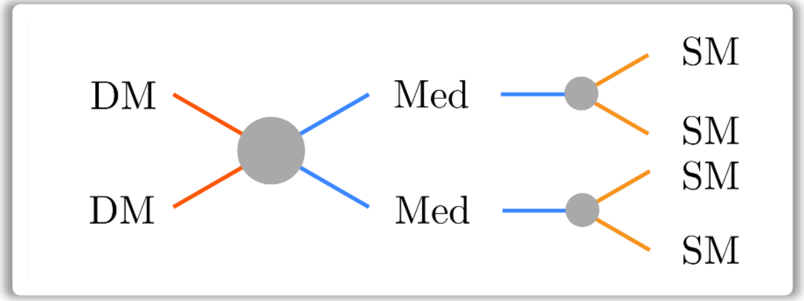
- DM annihilation to heavier states dominated. $m_{\Phi} > m_{DM}$.
- The channel is forbidden at low temperature.
- The mass gap should be small.

⏩ The WIMP neighborhood

Beyond self-annihilation:



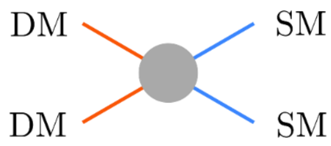
- Co-annihilation.
- Forbidden annihilation.
- Secluded annihilation.



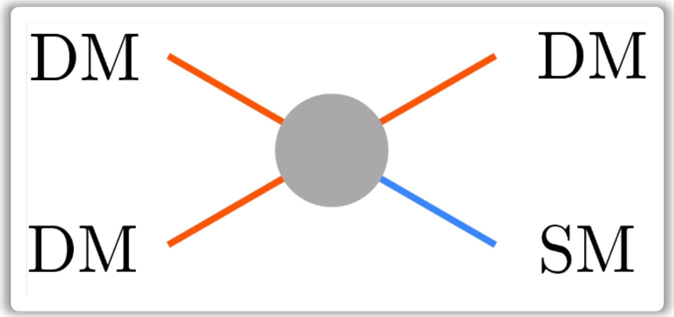
- DM annihilates to mediator particles instead of SM.
- Mediator particles decays to SM.
- Mediator particles is in equilibrium with SM.

⏩ The WIMP neighborhood

Beyond self-annihilation:



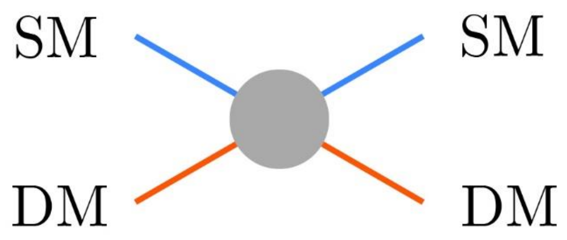
- Co-annihilation.
- Forbidden annihilation.
- Secluded annihilation.
- Semi-annihilation.
- …



- Only one DM particle consumed.
- Z_3-odd to ensure stability instead of $U(1)$ or Z_2.

⏩ Direct Detection

- Theoretically, great achievements in thermal freeze-out.
- Experimentally, direct detection (DD) experiments to search for DM.



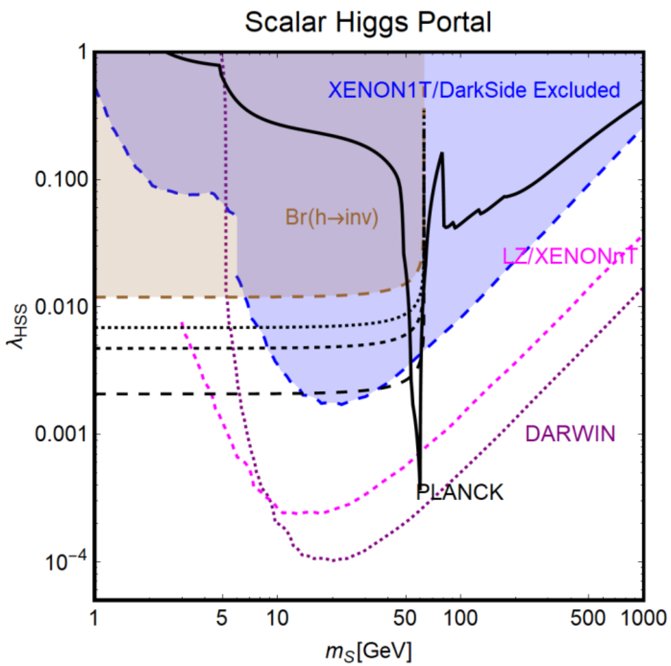
PandaX

- DM is still not found.
- Stringent constraints on WIMP models.

⏩ The WIMP Crisis

A simple Higgs portal model:

$$\Delta\mathcal{L} = -\frac{1}{4}\lambda H^\dagger H \chi^2$$



arXiv:1903.03616

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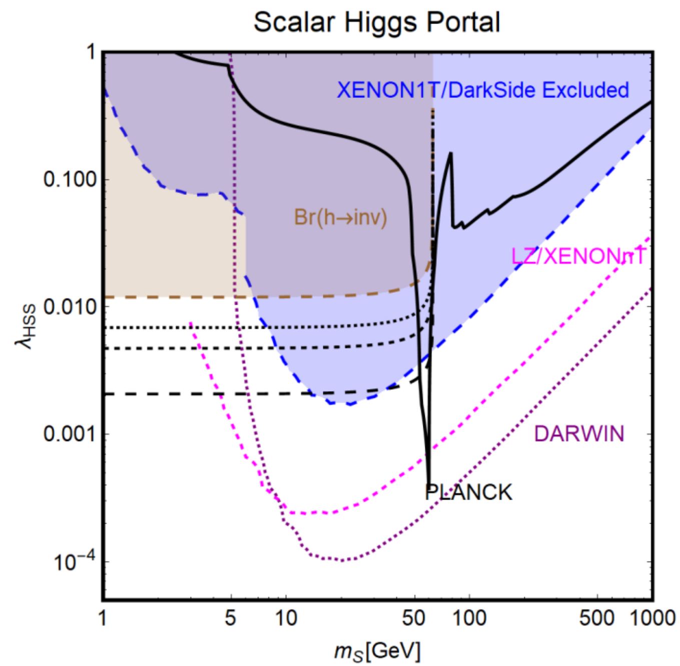

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Relic Abundance

Strongly coupled?

⟷

Direct Detection

Weakly coupled?

A simple Higgs portal model:

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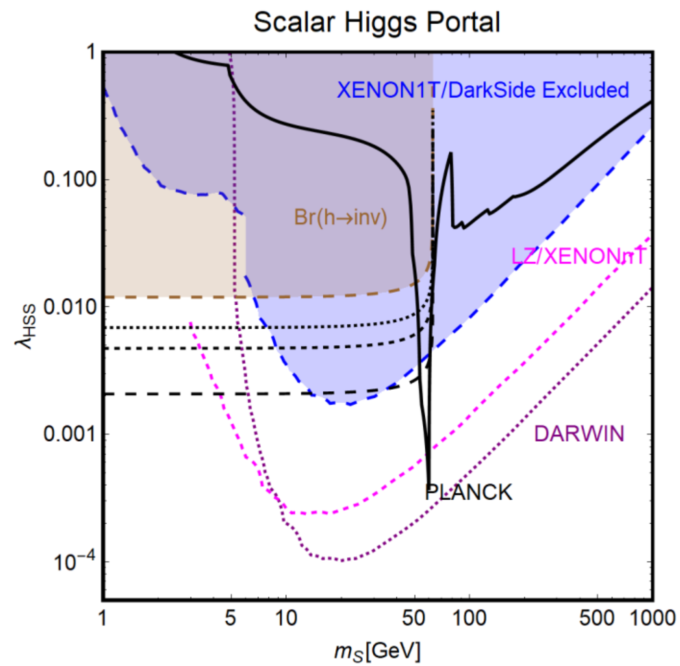

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The WIMP Crisis

Relic Abundance

Strongly coupled?

Direct Detection

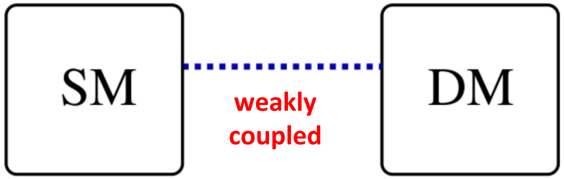
Weakly coupled?

PART 03

Catalyzed Annihilation

⏩ DM in a Secluded Sector

Can we reproduce correct abundance in a weakly coupled sector?



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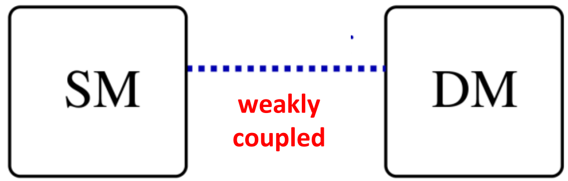
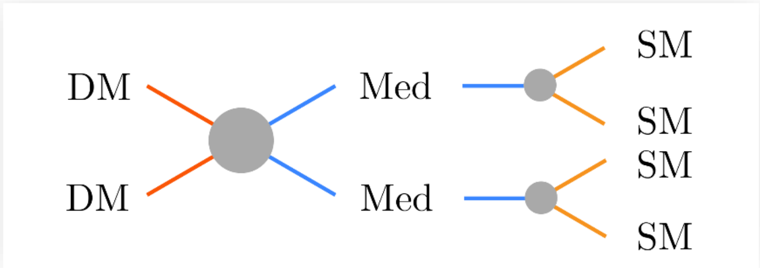


1 **Secluded DM.**



arXiv:0711.4866

- Direct detection bounds are invaded.
- Mediator is short-lived to stay in equilibrium.

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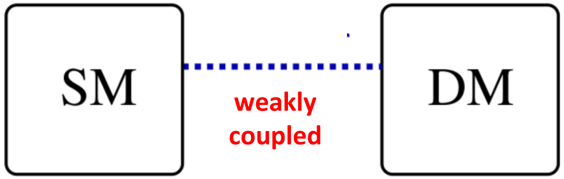
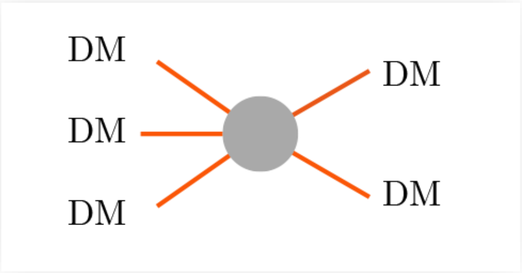


1 **Secluded DM.**

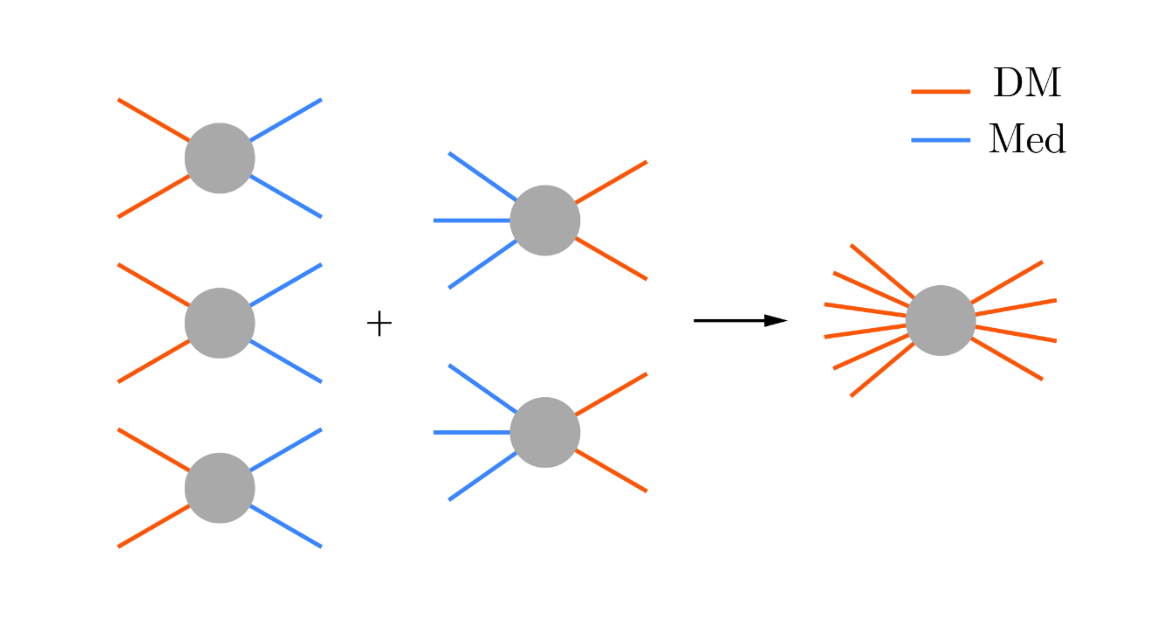
2 **Strongly Interacting Massive Particles (SIMPs).**



arXiv:1402.5143

- Number-changing annihilation dominated.
- DM-SM coupling is unrelated. Suppressed DD signals.
- Z_3 or Z_5 odd to ensure stability instead of $U(1)$ or Z_2.
- $\mathrm{MeV} - \mathrm{GeV}$ DM.

The Catalyzed Annihilation



- Two processes included: $2\mathrm{DM} \to 2\mathrm{Med}$ & $3\mathrm{Med} \to 2\mathrm{DM}$.
- 2 DM particles consumed.
- Mediator is not consumed, like a catalyst.

Boltzmann Equation

The coupled Boltzmann equations for DM (χ) and Med (A').

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma_2 v\rangle\left(n_\chi^2 - \bar{n}_\chi^2\frac{n_{A'}^2}{\bar{n}_{A'}^2}\right) + \langle\sigma_3 v^2\rangle\left(n_{A'}^3 - \bar{n}_{A'}^3\frac{n_\chi^2}{\bar{n}_\chi^2}\right),$$

$$\dot{n}_{A'} + 3Hn_{A'} = +\langle\sigma_2 v\rangle\left(n_\chi^2 - \bar{n}_\chi^2\frac{n_{A'}^2}{\bar{n}_{A'}^2}\right) - \frac{3}{2}\langle\sigma_3 v^2\rangle\left(n_{A'}^3 - \bar{n}_{A'}^3\frac{n_\chi^2}{\bar{n}_\chi^2}\right) - \langle\Gamma_{A'}\rangle(n_{A'} - \bar{n}_{A'}).$$

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Hubble expansion

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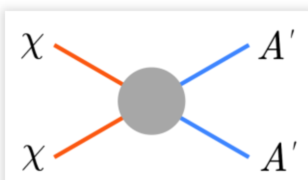
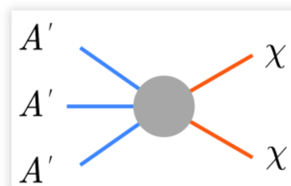
Hubble expansion





Note: The coefficients and the signs are different!

The coupled Boltzmann equations for DM (χ) and Med (A').

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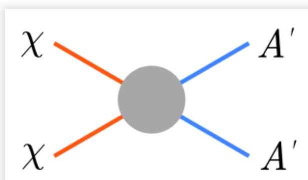
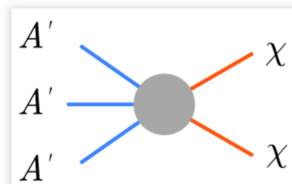
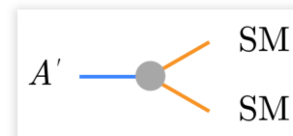
Hubble expansion

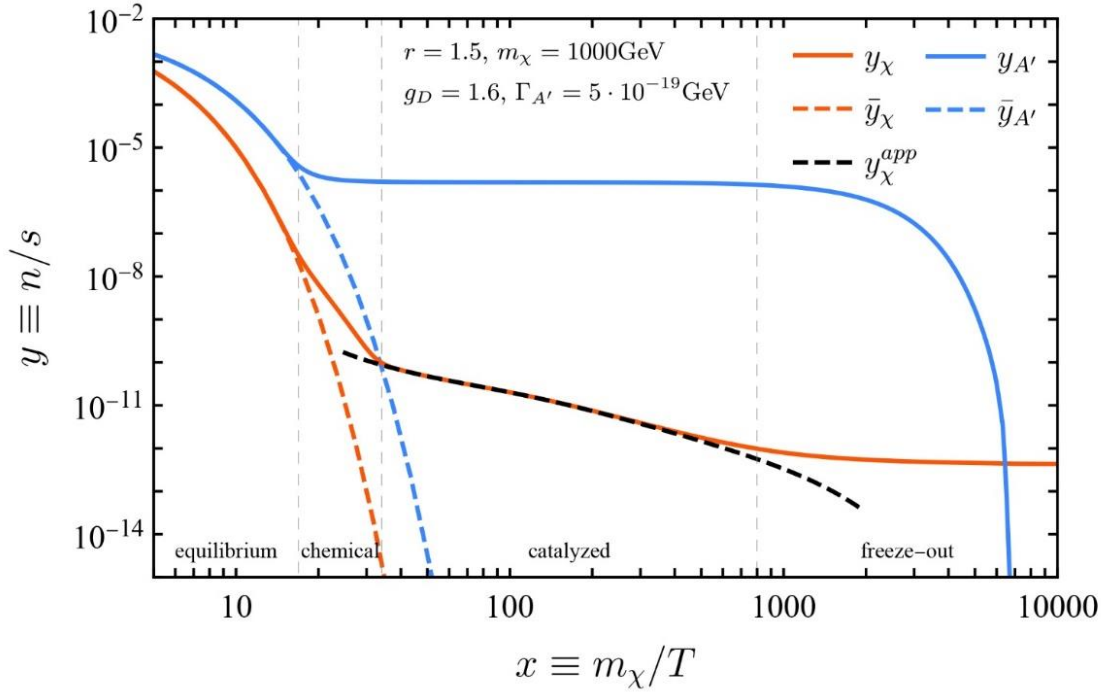






Note: The coefficients and the signs are different!

Thermal evolution of DM/Med



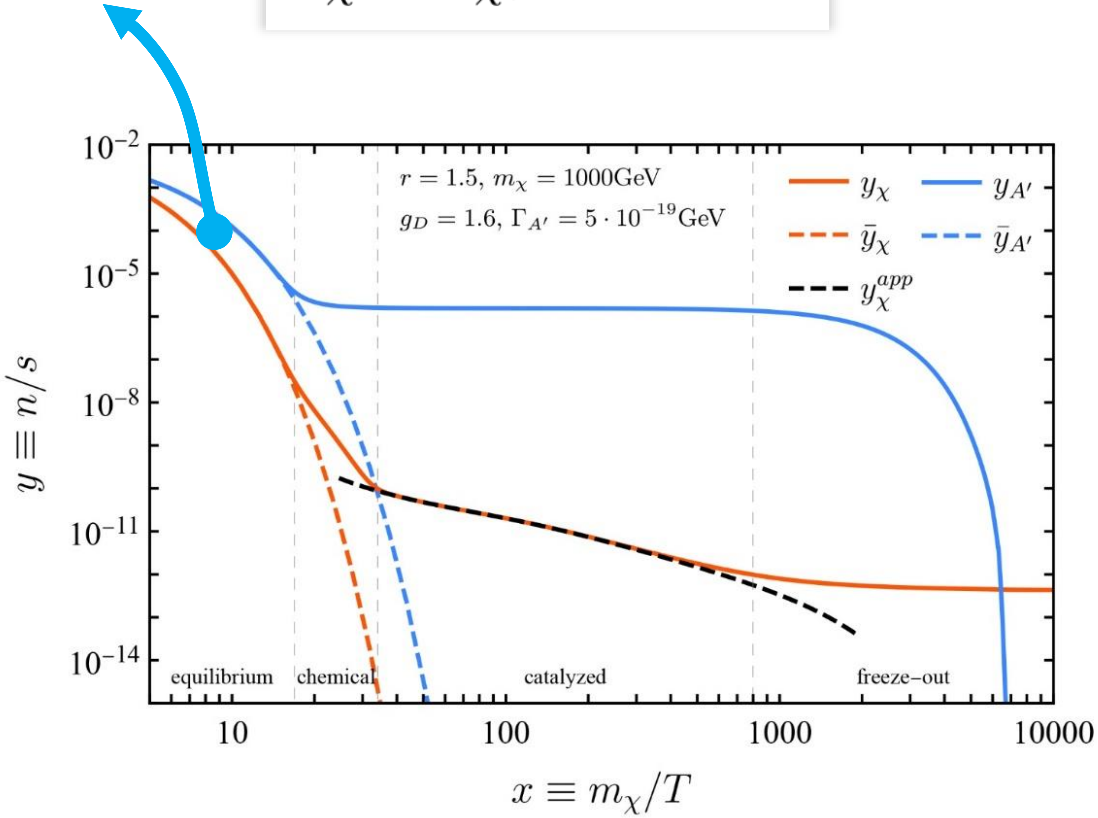
Blue Curve: Med

Red Curve: DM

Thermal evolution of DM/Med

1) Equilibrium

$$n_\chi \simeq \bar{n}_\chi, n_{A'} \simeq \bar{n}_{A'}.$$

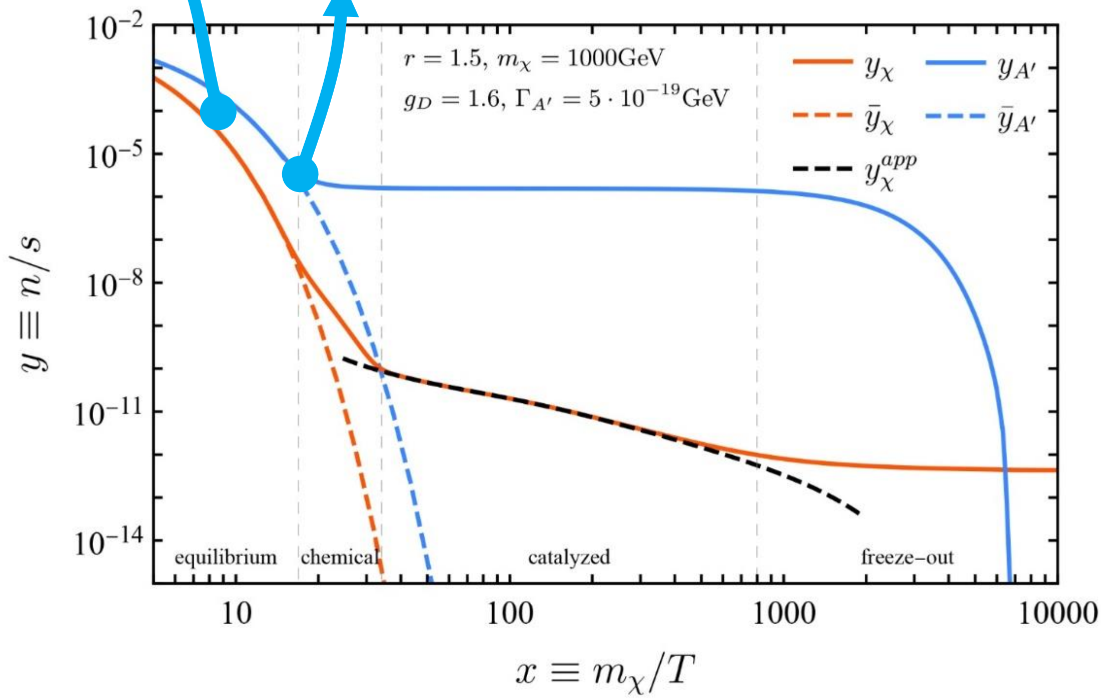


Thermal evolution of DM/Med

1) Equilibrium

2) Med decouple

$\langle \sigma_3 v^2 \rangle \bar{n}_{A'}^2 \simeq H$

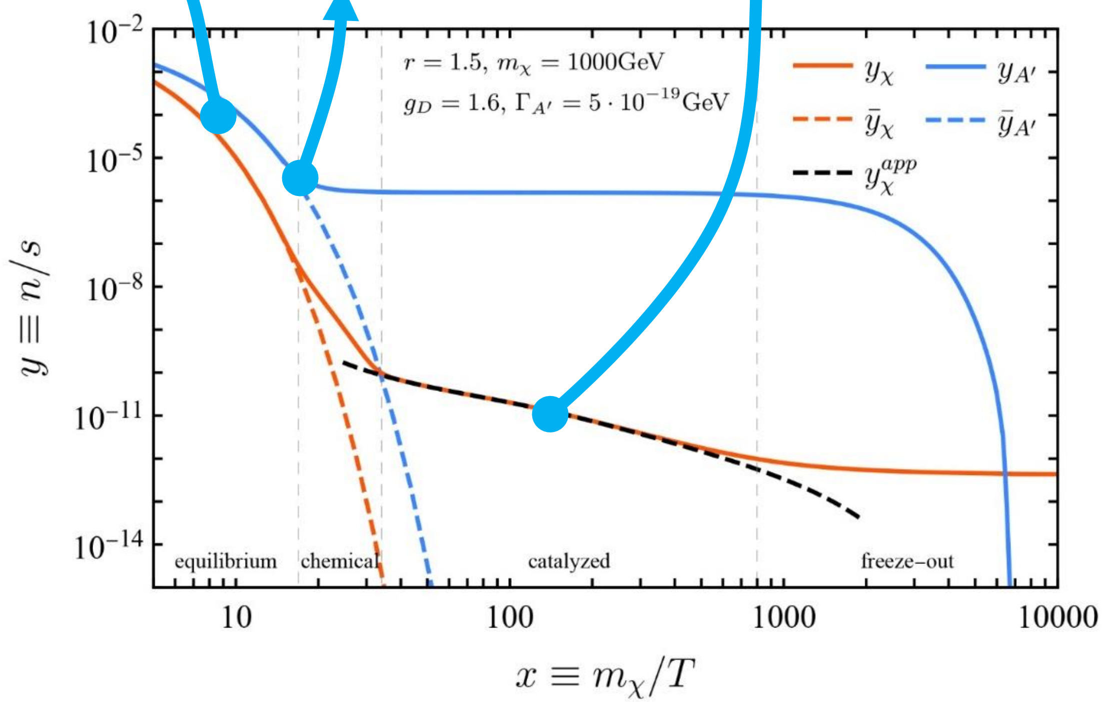


Thermal evolution of DM/Med

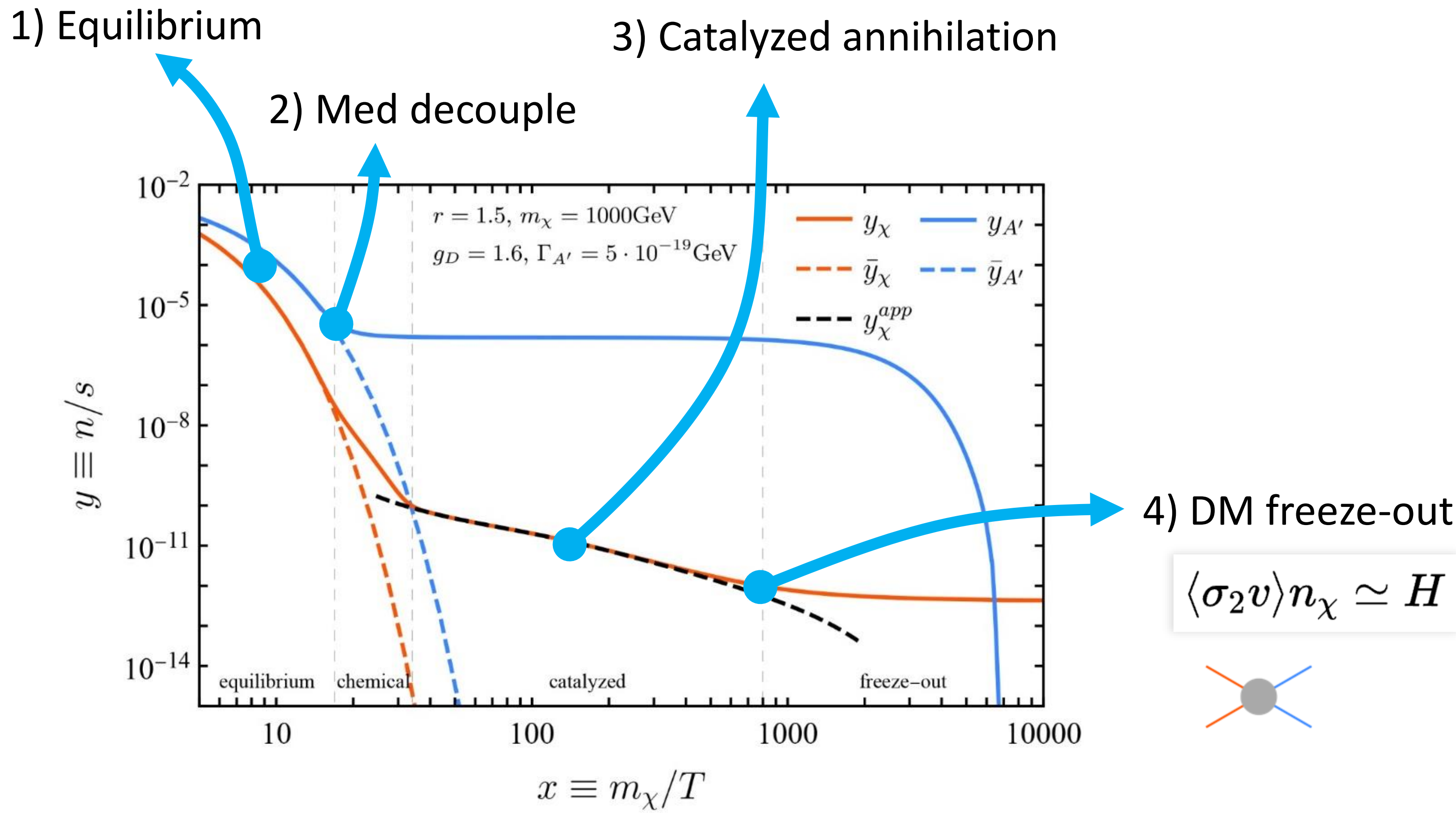
1) Equilibrium

2) Med decouple

3) Catalyzed annihilation $\langle\sigma_2 v\rangle\, n_\chi^2 \simeq \langle\sigma_3 v^2\rangle\, n_{A'}^3$



Thermal evolution of DM/Med



$$\langle \sigma_2 v \rangle n_\chi \simeq H$$

Thermal evolution of DM/Med

1) Equilibrium

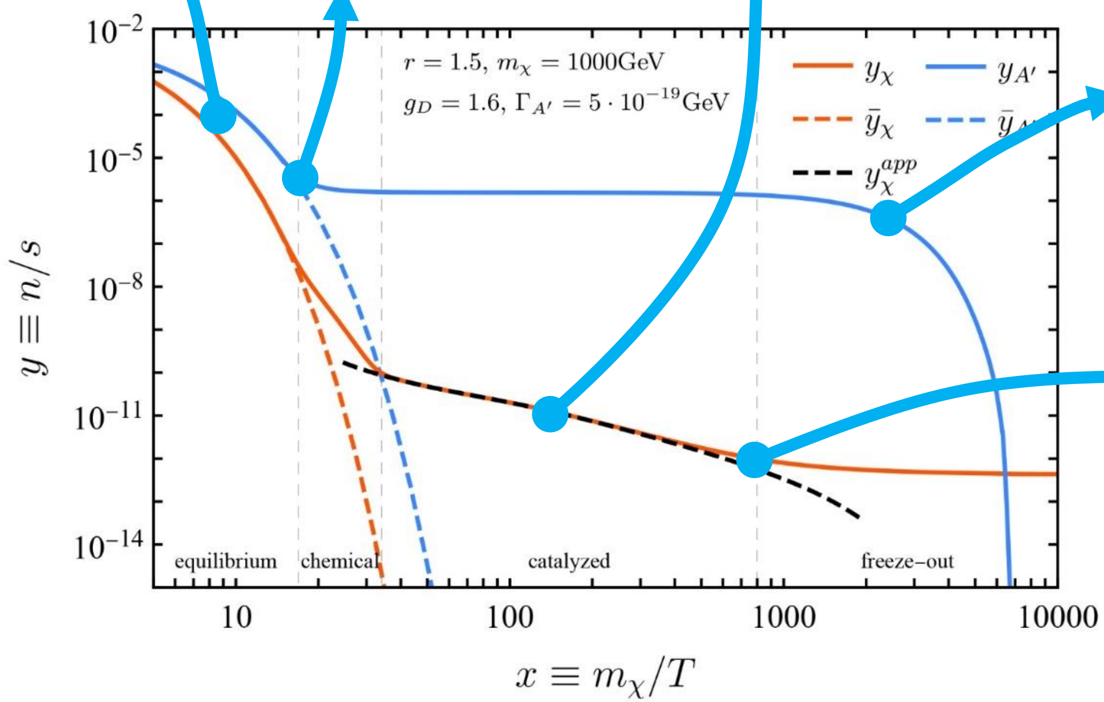
2) Med decouple

3) Catalyzed annihilation

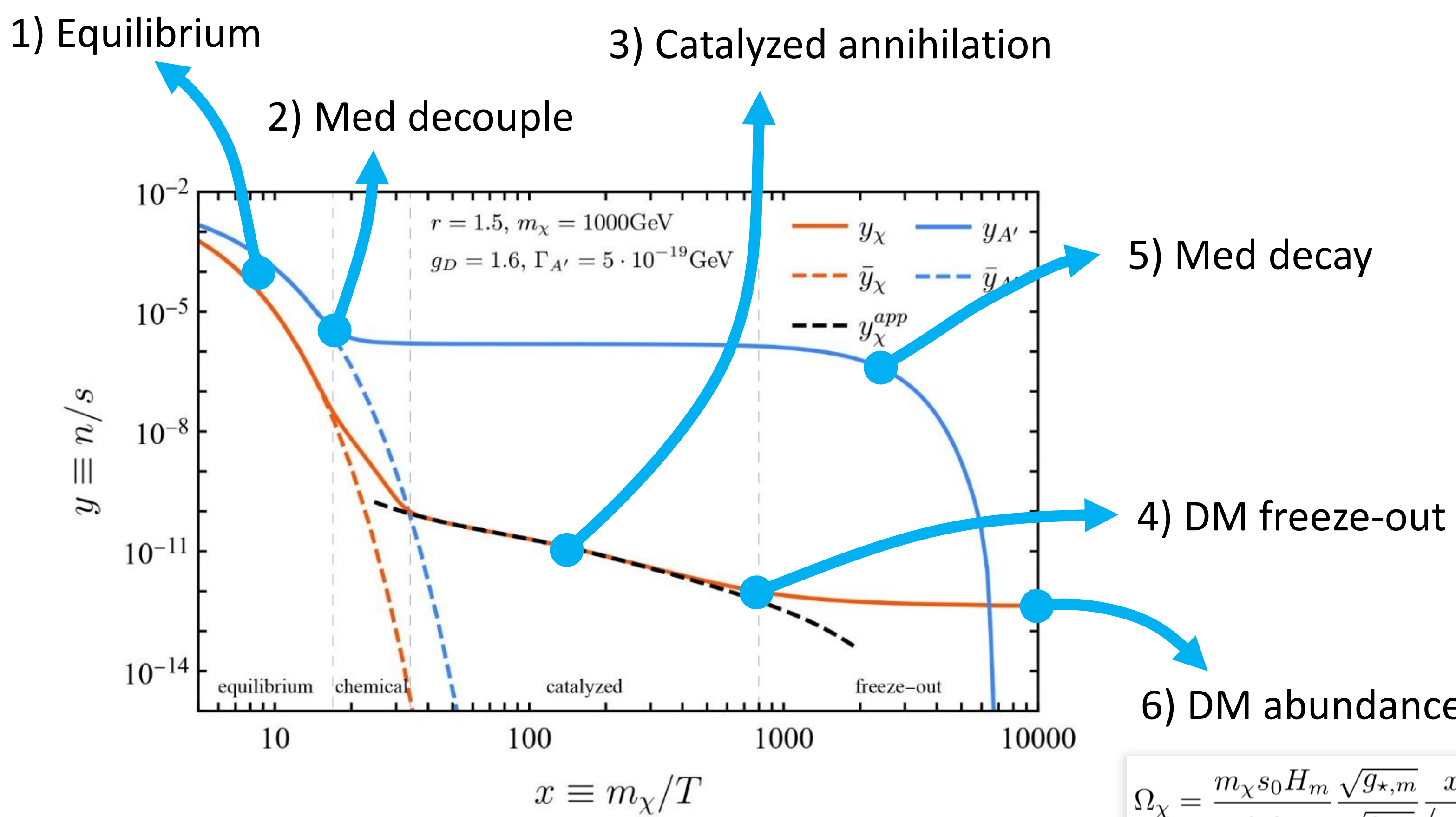
5) Med decay

$\Gamma_{A'} \simeq H$

4) DM freeze-out



Thermal evolution of DM/Med



$$\Omega_\chi = \frac{m_\chi s_0 H_m}{\rho_c s_m} \frac{\sqrt{g_{\star,m}}}{\sqrt{g_{\star,f}}} \frac{x_f}{\langle \sigma_2 v \rangle}.$$

Requirements

Requirements:

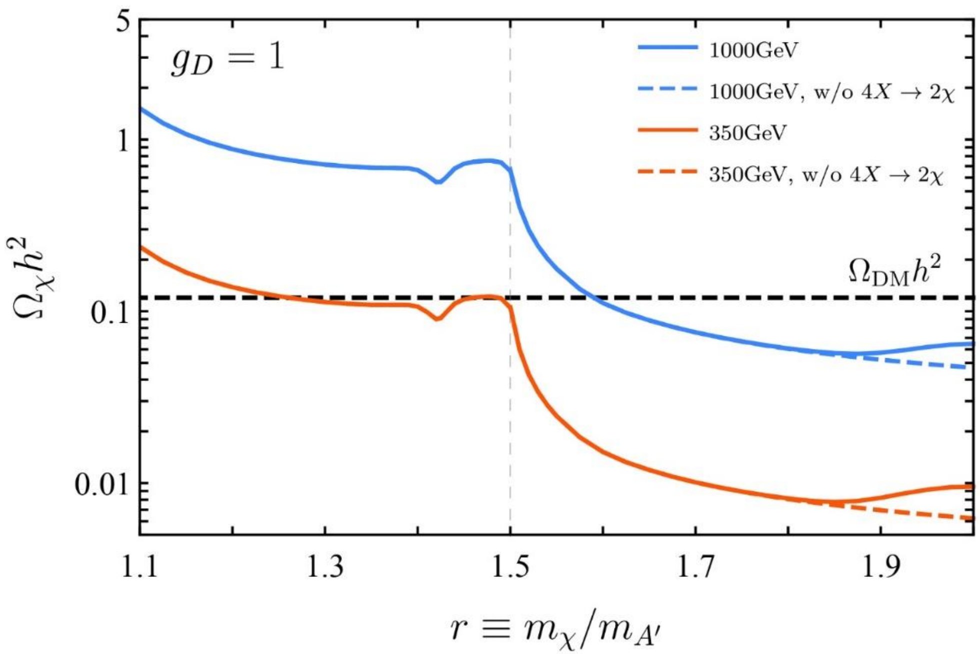
1. Secluded sector.
   - DM annihilates to SM is subdominant.
2. Long-lived mediator.
   - Mediator is out of equilibrium at early time.
   - If mediator short-lived, back to the secluded DM.
3. DM is slightly heavier than Med.
   - Mediator is more abundant than DM.
   - $3\mathrm{Med} \to 2\mathrm{DM}$ is not suppressed.
4. Annihilation channels.

Features:

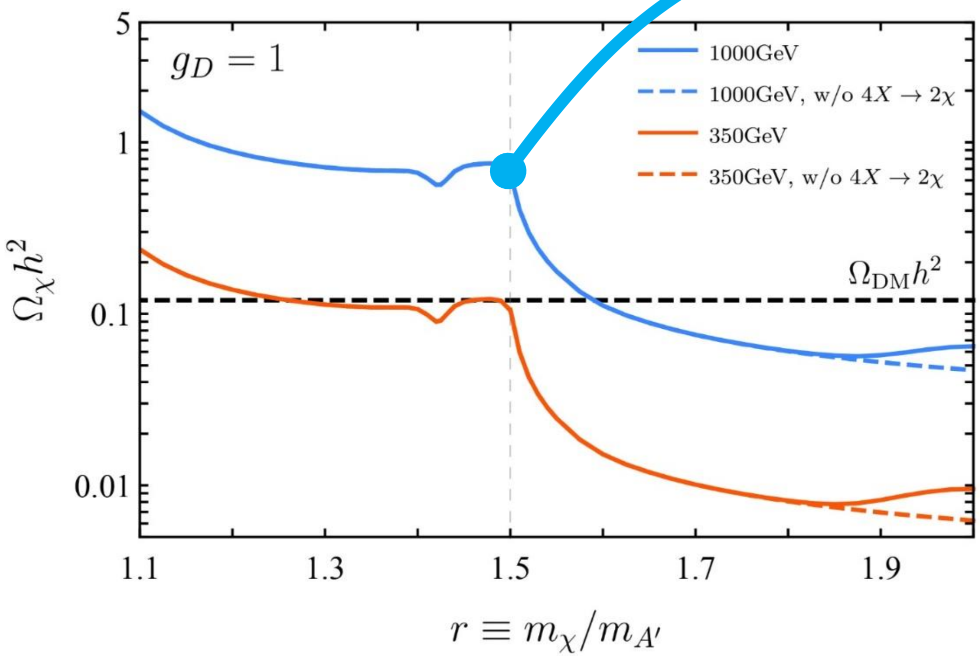
1. Polynomially suppressed n_χ . $n_\chi \propto T^{9/2}$
   - For WIMPs/SIMPs, it is exponentially suppressed.
2. $\mathrm{MeV} - \mathrm{TeV}$ DM mass.
3. The freeze-out is late. $x_f \simeq 800$.
   - Since the polynomially suppression, DM are consumed slowly.
   - The catalyzed annihilation lasts long.
4. Enhanced indirect detection signals.
   - Since $\Omega_\chi \propto \frac{x_f}{\langle \sigma_2 v \rangle}$, late freeze-out means large annihilation.

⏩ Catalyzed Freeze-out

Varying Mass Ratio $r \equiv m_\chi / m_{A'}$



Varying Mass Ratio $r \equiv m_\chi / m_{A'}$

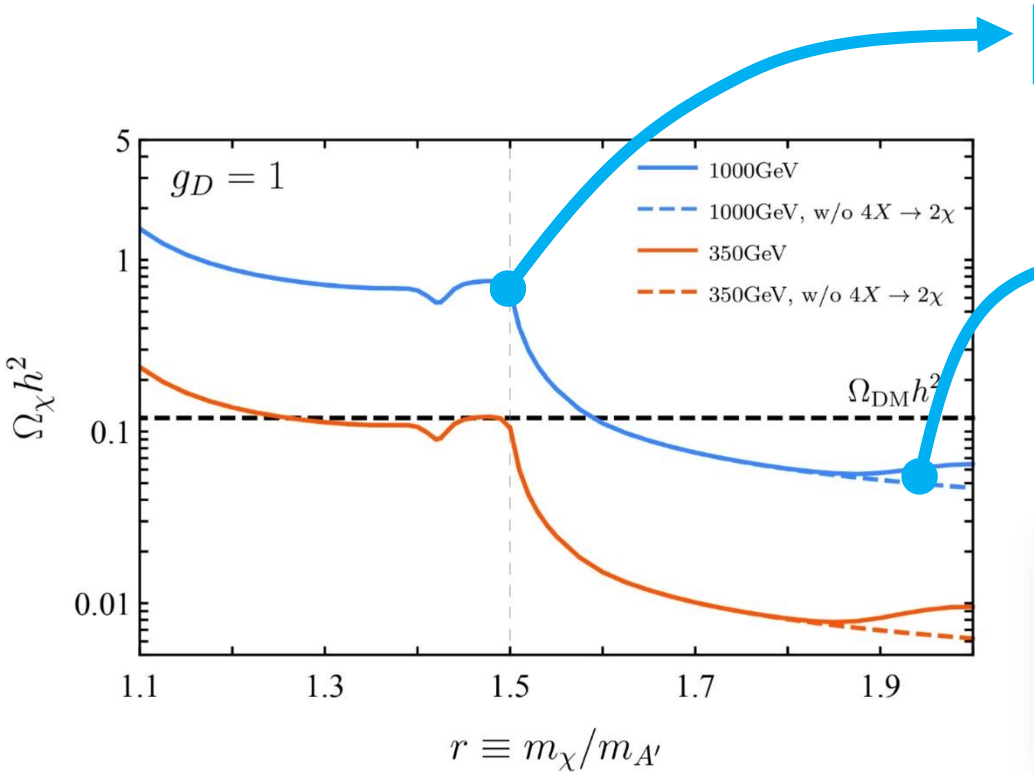


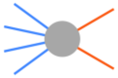
$r = 1.5$ threshold

When $3m_{A'} < 2m_\chi$,  is exponentially suppressed at low temperature.

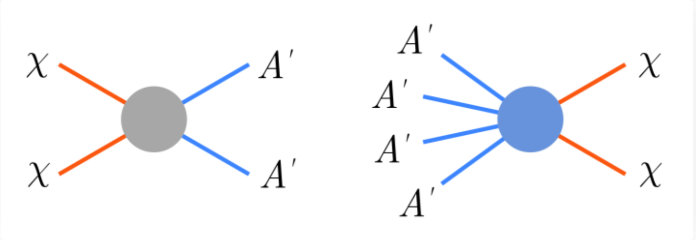
$$\langle \sigma_3 v^2 \rangle \propto e^{-(2r-3)x/r}$$

Varying Mass Ratio $r \equiv m_\chi / m_{A'}$



When $4m_{A'} \simeq 2m_{\chi}$,  turn dominant, since it is not exponentially suppressed.

The catalyzed annihilation here:



Model & Phenomenology

Dark Photon Model:

$$\mathcal{L}_{\rm DS} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu + \bar{\chi}(i\not{D} - m_\chi)\chi,$$

$$\mathcal{L}_{\rm mix} = -\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}.$$

χ: DM
A': Mediator

Model & Phenomenology

Dark Photon Model:

$$\mathcal{L}_{\rm DS} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + \bar{\chi}(i\not{D} - m_\chi)\chi,$$

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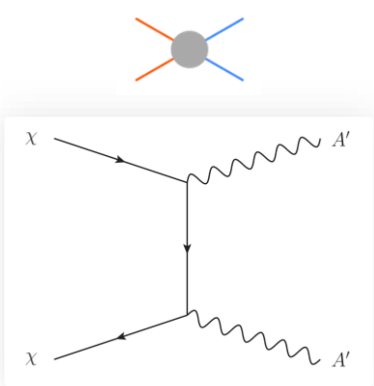
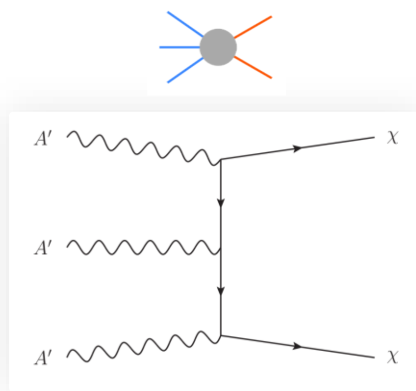
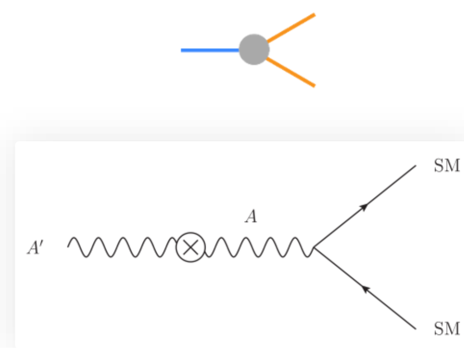
Feynman diagrams:







Model & Phenomenology

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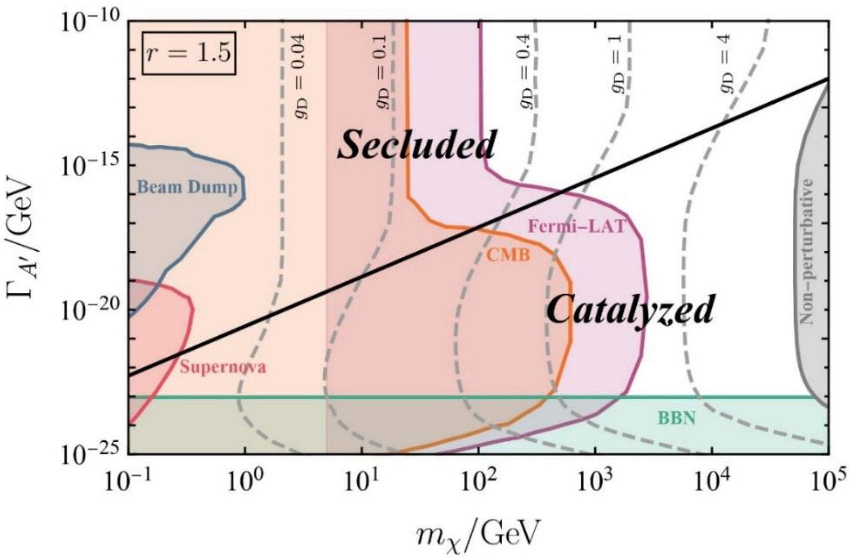
$$\mathcal{L}_{\rm mix} = -\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}.$$

χ: DM
A': Mediator

Phase diagram and bounds:



⏩ Model & Phenomenology

Dark Photon Model:

$$\mathcal{L}_{\rm DS} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + \bar{\chi}(i\not{D} - m_\chi)\chi,$$

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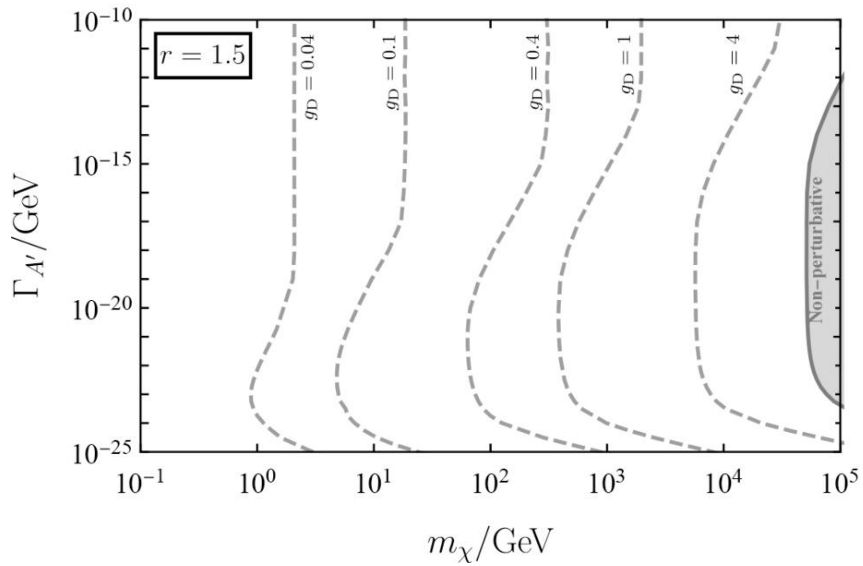

- Only four parameters.
- Mass ratio: $r = 1.5$.
- Every point gives correct abundance with different coupling g_D.
- Five curves with constant g_D shown.
- Heavy DM require strong coupling.
- Non-perturbative: $g_D < 4\pi$.

Model & Phenomenology

Dark Photon Model:

$$\mathcal{L}_{\rm DS} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu + \bar{\chi}(i\not{D} - m_\chi)\chi,$$

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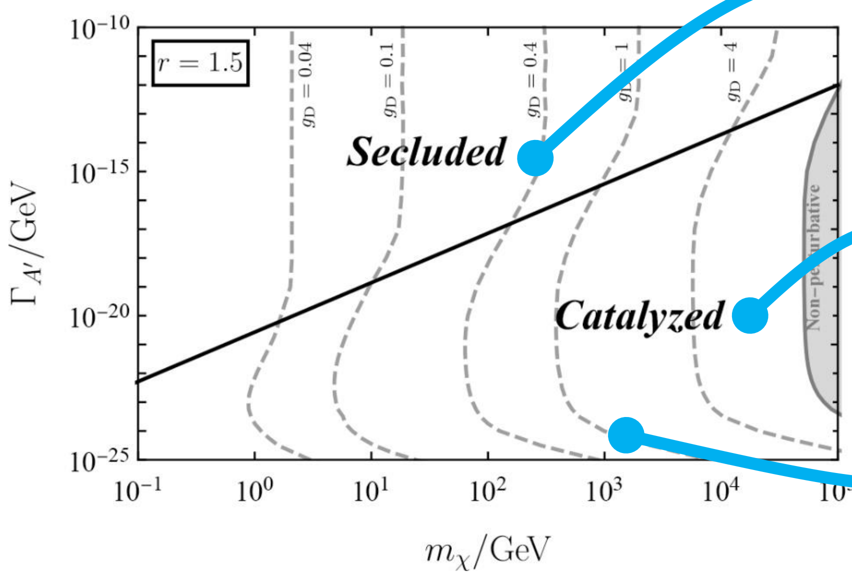
χ: DM
A': Mediator



Secluded Phase

- Short-lived mediator, secluded DM.
- Mediator stays in equilibrium.

Catalyzed Phase

- Long-lived mediator, catalyzed annihilation.
- Mediator is out-of-equilibrium before freeze-out.

Long-lived mediator decay injects entropy and dilute DM abundance.

⏩ Model & Phenomenology

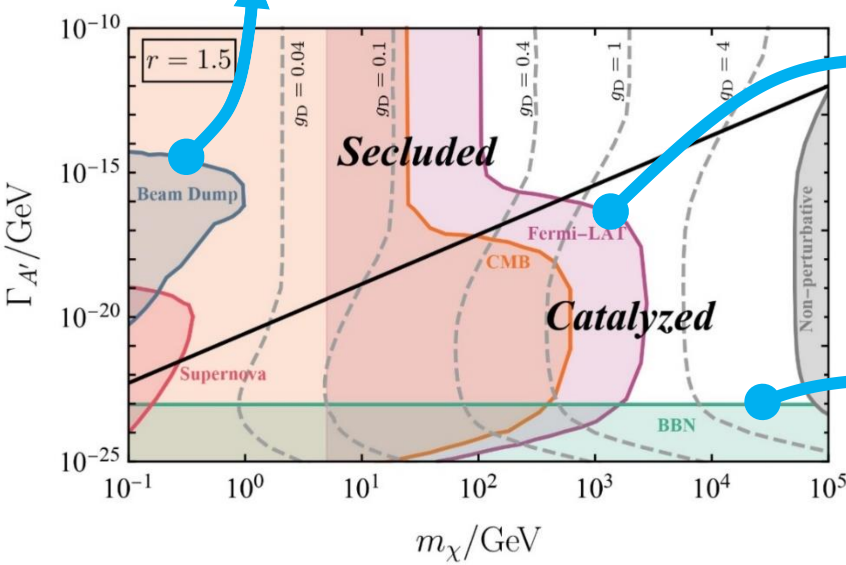
Dark Photon Model:

$$\mathcal{L}_{\rm DS} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + \bar{\chi}(i\not{D} - m_\chi)\chi,$$

$$\mathcal{L}_{\rm mix} = -\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}.$$

χ: DM
A': Mediator

1) Beam dump & supernova bounds on dark photon lifetime.



2) CMB & indirect detection bounds on DM annihilation.

- more stringent for catalyzed phase.
- DM below 3TeV is not favored.

3) BBN limit on dark photon lifetime.

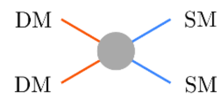
- Late decay of A' will fail BBN.

Discussion

Thermal decoupling vs. Chemical decoupling

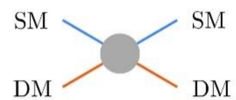
1 WIMPs:

chemical decoupling:



$\langle \sigma_2 v \rangle n_{\rm DM} \simeq H$

thermal decoupling:



$\langle \sigma_{\rm el} v \rangle n_{\rm SM} \simeq H$

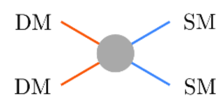
- Since $n_{\rm SM} \gg n_{\rm DM}$, thermal decoupling happens later.
- $T_{\rm DM} = T_{\rm SM}$ before freeze-out.

Discussion

Thermal decoupling vs. Chemical decoupling

1 WIMPs:

chemical decoupling:



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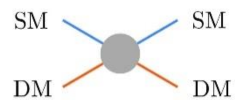
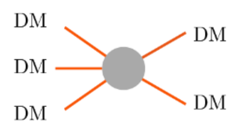
thermal decoupling:



$\langle \sigma_{\rm el} v \rangle n_{\rm SM} \simeq H$

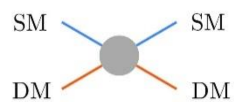
2 SIMPs:

chemical decoupling:



$\langle \sigma_3 v \rangle n_{\rm DM}^2 \simeq H$

thermal decoupling:



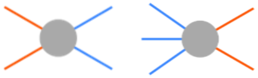
$\langle \sigma_{\rm el} v \rangle n_{\rm SM} \simeq H$

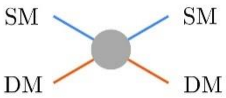
- Thermal decoupling can happen before chemical decoupling.
- $T_{\rm DM} \neq T_{\rm SM}$ at freeze-out.
- DM abundance determined by thermal decoupling. arXiv:1512.04545

Discussion

Thermal decoupling vs. Chemical decoupling

Catalyzed annihilation:

chemical decoupling: 

thermal decoupling: 

- The work is based on the assumption: $T_{\rm DM} = T_{\rm SM}$.
- Thermal decoupling can happen before freeze-out.
- DM abundance is modified with thermal decoupling considered.
- Further works are required!

Summary:

1. WIMP is stringently constrained by direct detections (the WIMP crisis).
2. We proposed novel catalyzed freeze-out paradigm.
3. The paradigm is realized in the dark photon model.
4. The thermal decoupling of the paradigm should be discussed.

Thanks.

Chuan-Yang Xing