

Light thermal relic Dark Matter

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Center for Cosmology and Particle Physics

In collaboration with:

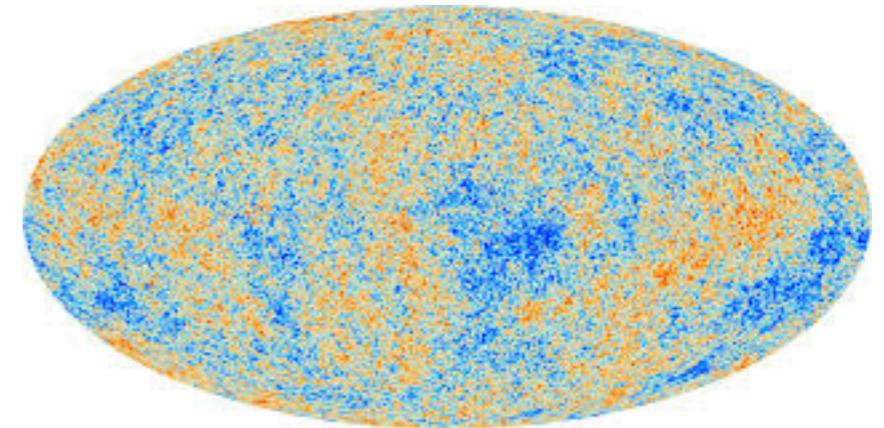
Raffaele D'Agnolo, Joshua Ruderman, Po-Jen Wang,
Maxim Pospelov, and Oren Slone



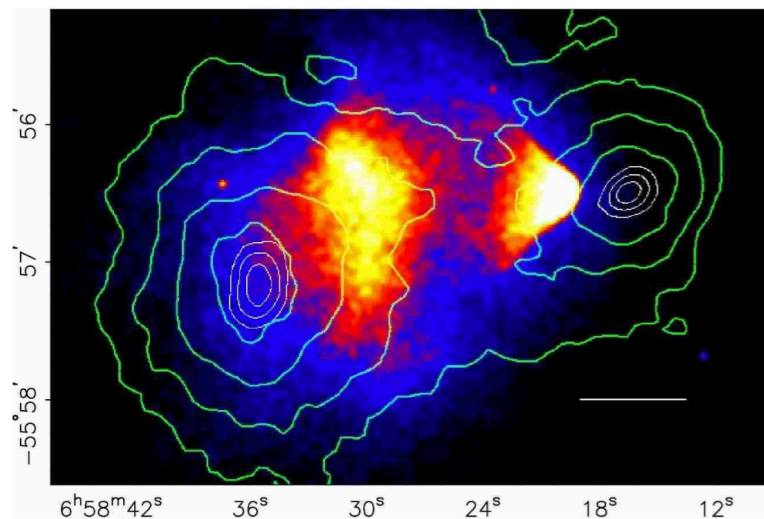
What we know about DM

- Gravitational interaction
- Stable (cosmologically)
- Electrically neutral
- Cold, pressureless fluid

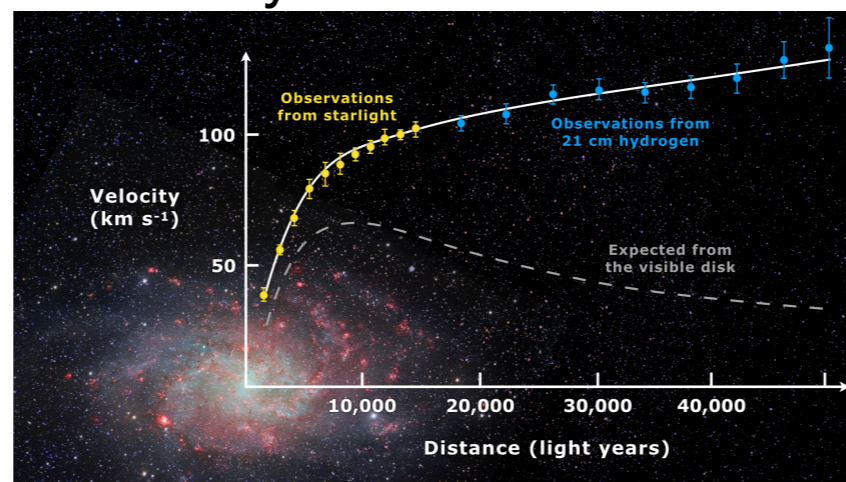
CMB



Galaxy mergers



Galaxy rotation curves



What we know about DM

- Gravitational interaction
- Stable (cosmologically)
- Electrically neutral
- Cold, pressureless fluid

The SM does not provide a DM candidate

What we DON'T know about DM

- Fundamental/composite
- Cosmological origin
- Mass
- Other interactions?

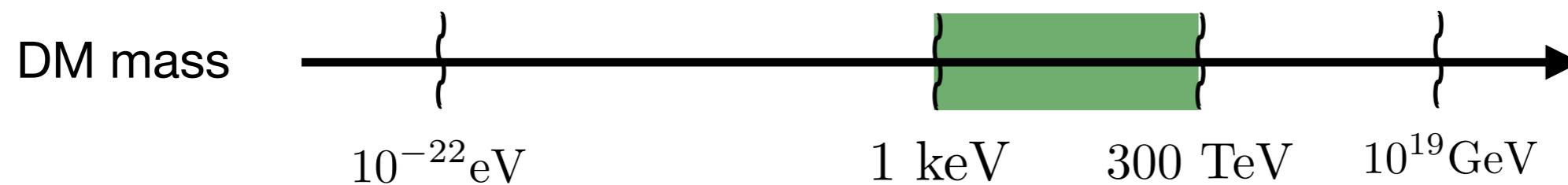
What we DON'T know about DM

- Fundamental/composite → **Fundamental particle**
- Cosmological origin
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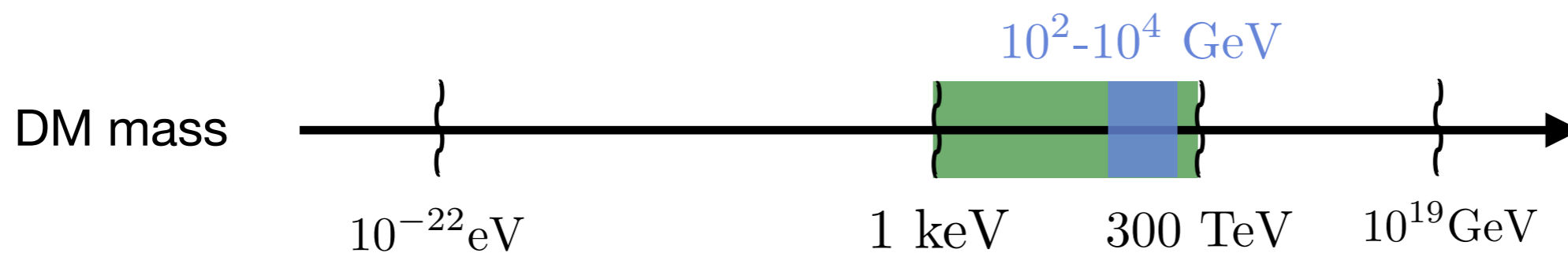
What we DON'T know about DM

- Fundamental/composite → **Fundamental particle**
- Cosmological origin → **Thermally produced**
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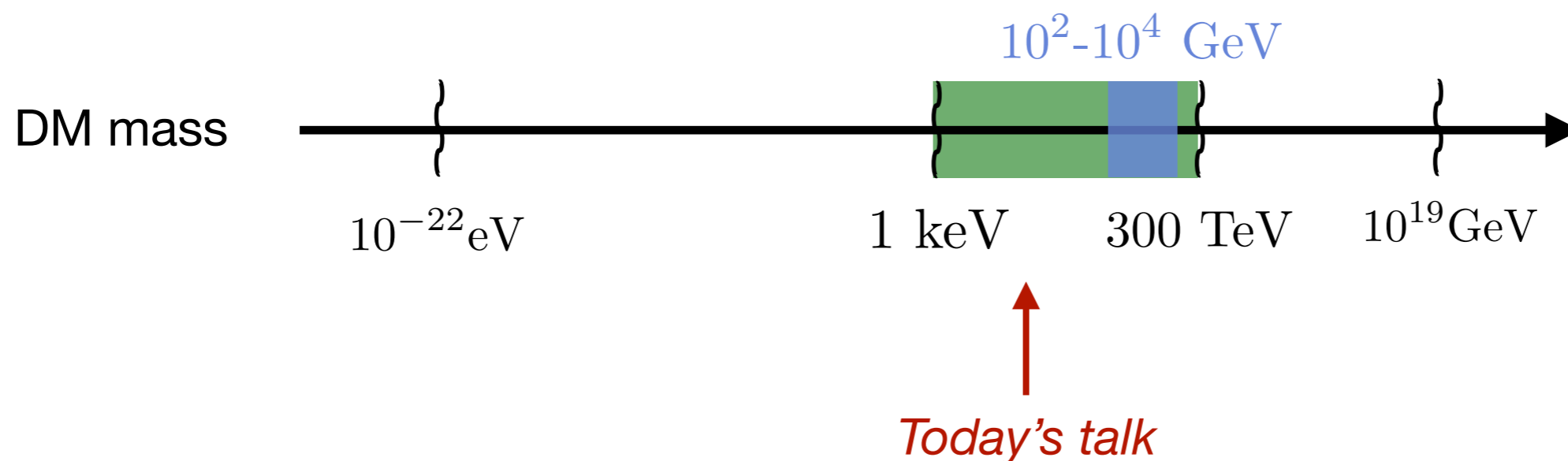
What we DON'T know about DM

- Fundamental/composite → **Fundamental particle**
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What we DON'T know about DM

- Fundamental/composite → **Fundamental particle**
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- Mass → **WIMP**
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Outline

- Thermal relics
- Exceptions: coannihilation
- Dark Higgs

Thermal relics

Early Universe: hot plasma in **thermal equilibrium**



Interaction rates \gg Expansion rate

$$n\langle\sigma v\rangle \gg H$$

Thermal relics

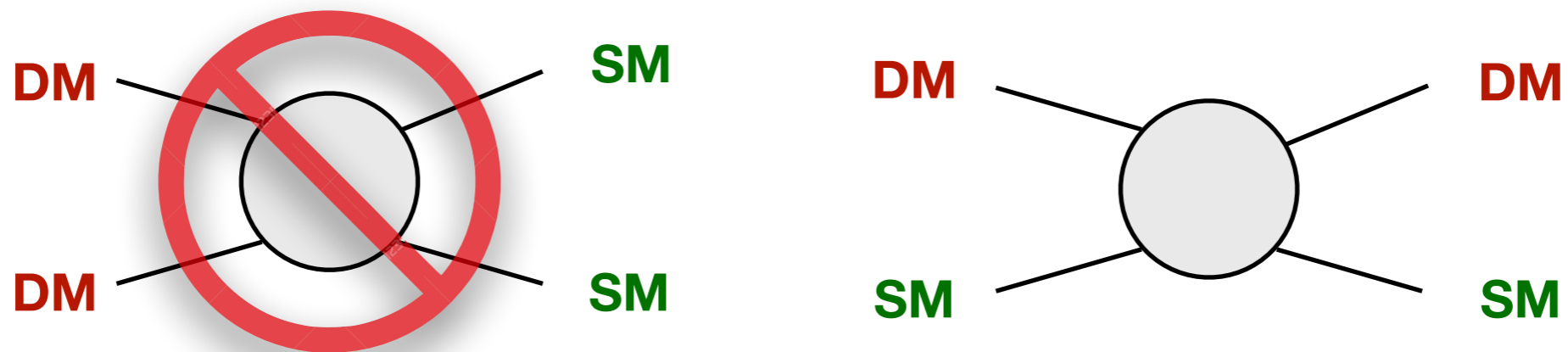
Early Universe: hot plasma in thermal equilibrium



$$T \lesssim m_{\text{DM}} \Rightarrow n_{\text{DM}} \sim e^{-m_{\text{DM}}/T}$$

Thermal relics

Early Universe: hot plasma in thermal equilibrium



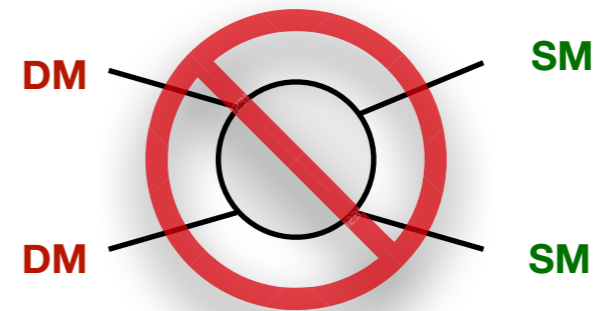
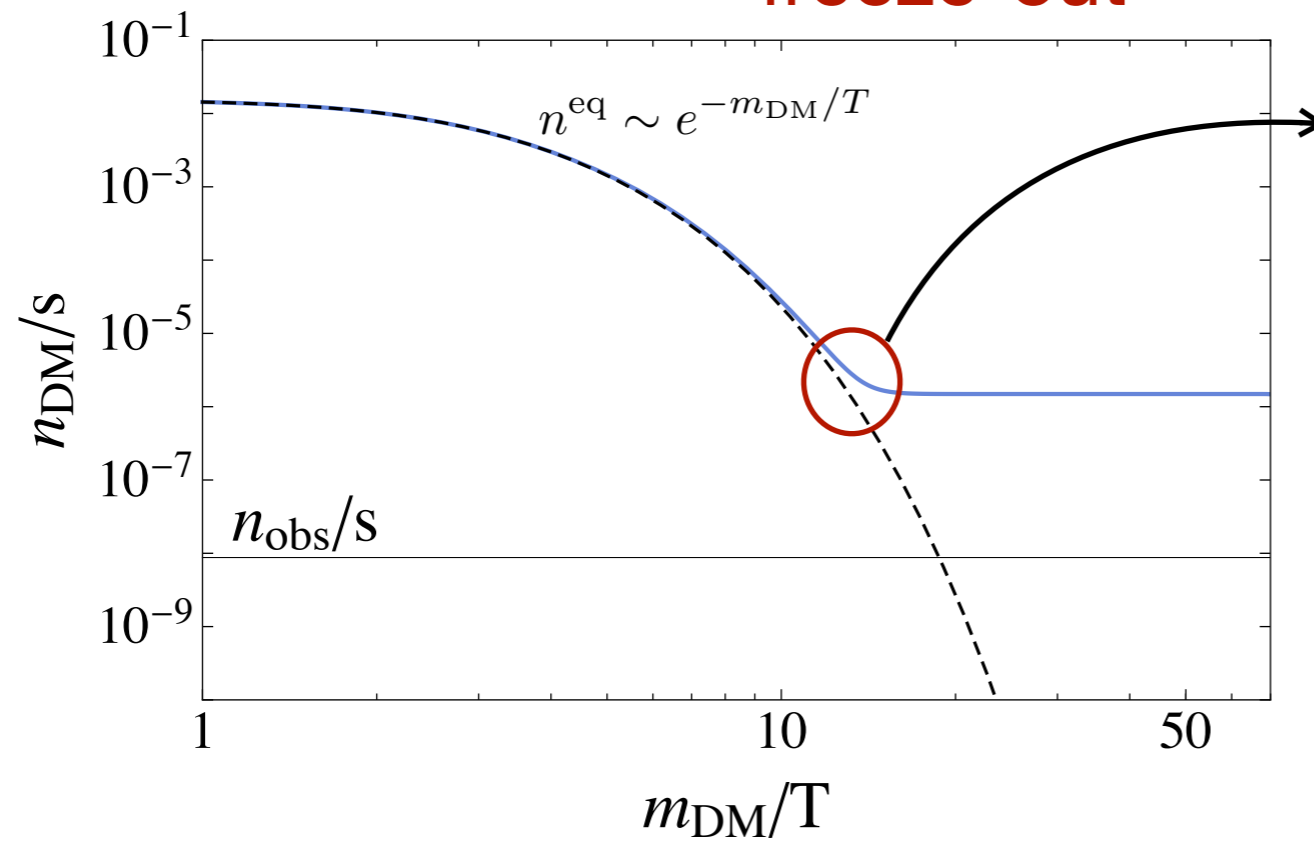
$$T \lesssim m_{\text{DM}} \Rightarrow n_{\text{DM}} \sim e^{-m_{\text{DM}}/T}$$

DM annihilation
freeze-out

$$n_{\text{DM}} a^3 = \text{const}$$

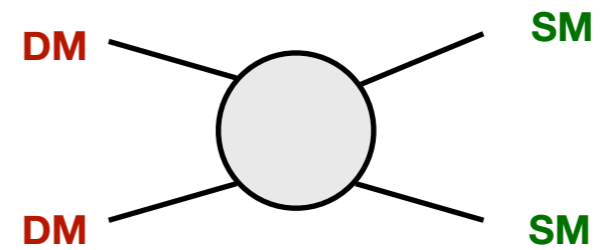
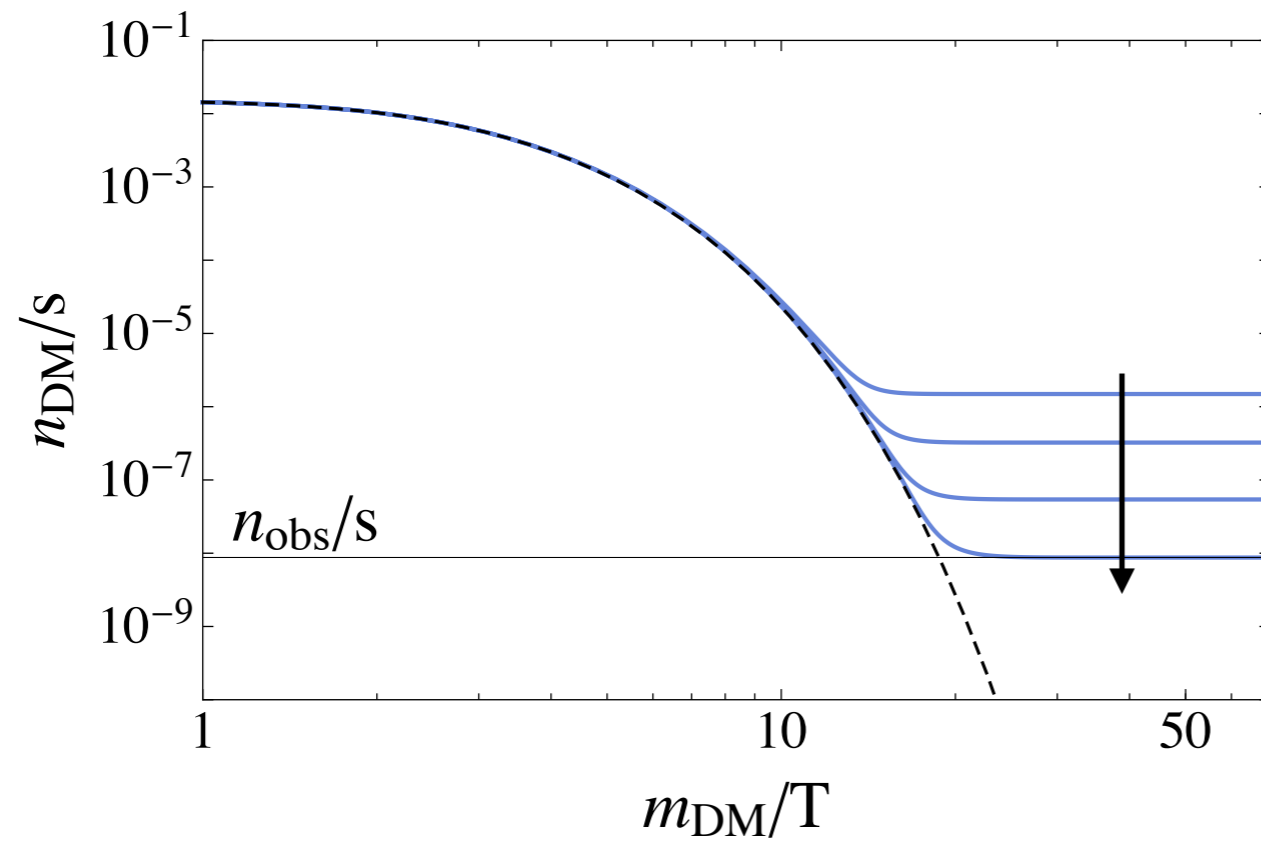
Relic abundance

DM annihilation
freeze-out



$$n \langle \sigma v \rangle |_{T_f} \simeq H(T_f)$$

Relic abundance



Increasing $\langle\sigma v\rangle$

WIMP miracle

DM relic
abundance

$$\Omega_{\text{DM}} h^2 \simeq \frac{m n}{T_{\text{EQ}} s}$$

WIMP miracle

Sudden freeze-out
approximation

$$n\langle\sigma v\rangle \simeq H$$

DM relic
abundance

$$\Omega_{\text{DM}} h^2 \simeq \frac{m n}{T_{\text{EQ}} s} \simeq \frac{m H}{T_{\text{EQ}} \langle\sigma v\rangle s}$$

WIMP miracle

Sudden freeze-out approximation

$$n\langle\sigma v\rangle \simeq H$$

DM relic abundance

$$\Omega_{\text{DM}} h^2 \simeq \frac{m n}{T_{\text{EQ}} s} \simeq \frac{m H}{T_{\text{EQ}} \langle\sigma v\rangle s} \simeq \frac{1}{T_{\text{EQ}} M_{\text{Pl}} \langle\sigma v\rangle}$$

$$H \simeq T^2 / M_{\text{Pl}}$$

$$s \simeq T^3$$

$$T \simeq m$$

WIMP miracle

DM relic abundance

$$\Omega_{\text{DM}} h^2 \simeq \frac{m n}{T_{\text{EQ}} s} \simeq \frac{m H}{T_{\text{EQ}} \langle \sigma v \rangle s} \simeq \frac{1}{T_{\text{EQ}} M_{\text{Pl}} \langle \sigma v \rangle}$$

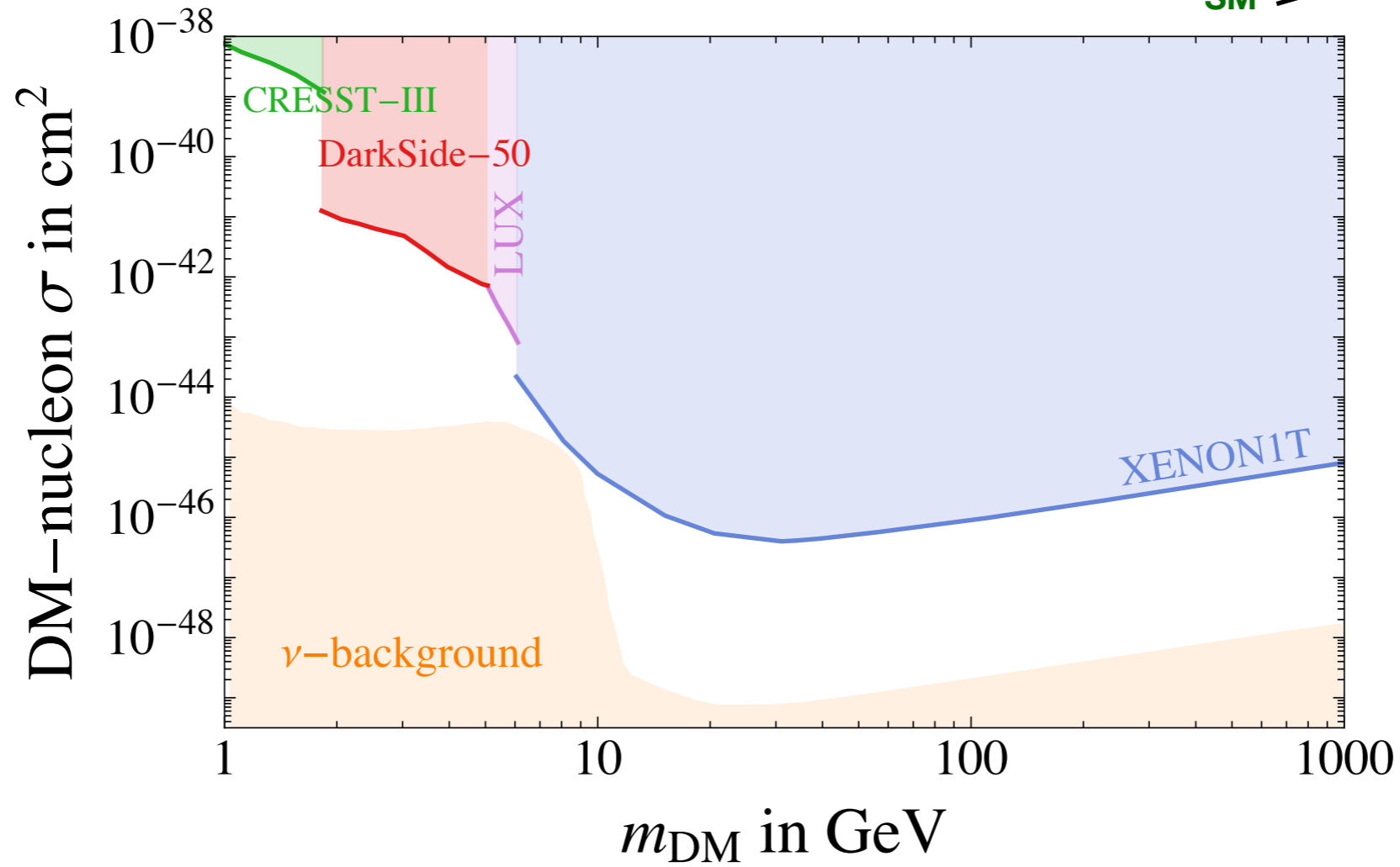
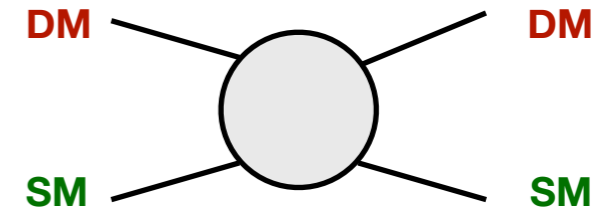
$$\Rightarrow \langle \sigma v \rangle \sim \frac{1}{T_{\text{EQ}} M_{\text{Pl}}}$$

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m^2} \Rightarrow m \sim \alpha \sqrt{T_{\text{EQ}} M_{\text{Pl}}} \sim \text{TeV}$$

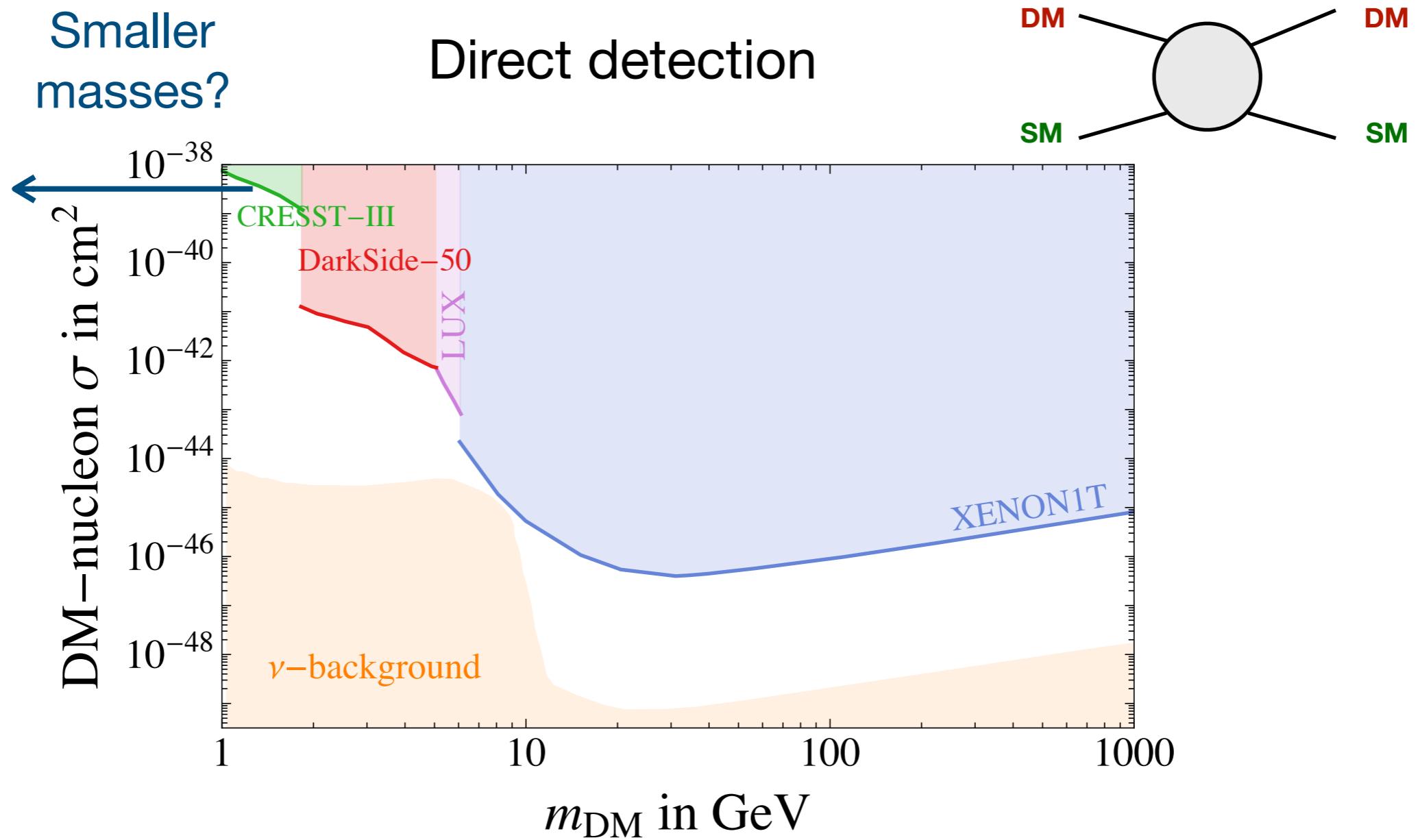
WIMP miracle

WIMP searches

Direct detection



WIMP searches

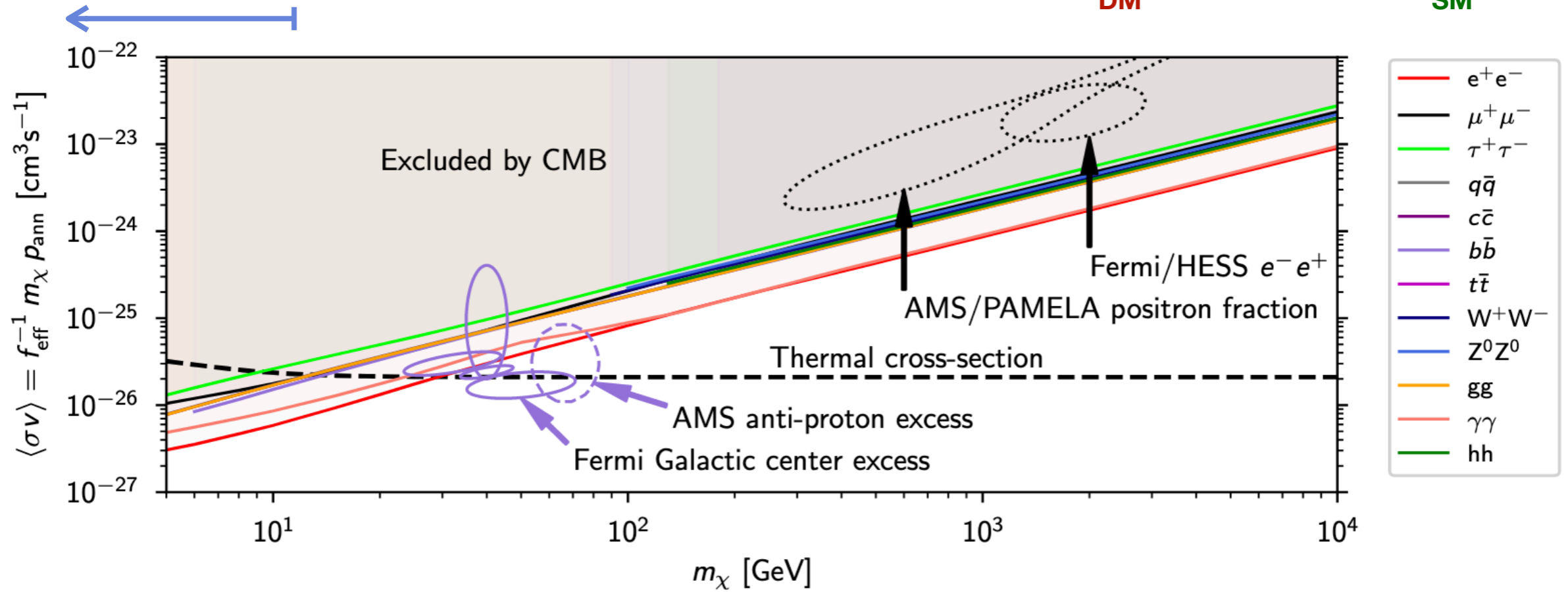
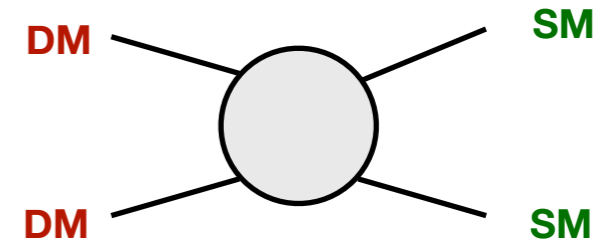


WIMP searches

$$m_{\text{DM}} \lesssim 10 \text{ GeV}$$

excluded

Indirect detection



Planck collaboration, 2018

Outline




- Thermal relics
- Exceptions: coannihilation
- Dark Higgs

Standard assumptions

- $\langle \sigma v \rangle \sim \text{const. during freeze-out}$ ✓
- $\text{DM DM} \longrightarrow \text{SM SM}$ dominates ✓
- Thermal equilibrium with SM bath ✓




$$T_{\text{DM}} = T_{\text{SM}} \quad \mu_{\text{DM}} = 0$$

Standard assumptions




- $\langle \sigma v \rangle \sim \text{const. during freeze-out}$  resonance*, forbidden annihilation*,
- $\text{DM DM} \longrightarrow \text{SM SM}$ dominates 
- Thermal equilibrium with SM bath 

$$T_{\text{DM}} = T_{\text{SM}} \quad \mu_{\text{DM}} = 0$$




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- $\text{DM DM} \longrightarrow \text{SM SM}$ dominates  coannihilation*,
 $\text{DM DM DM} \longrightarrow \text{DM DM}$,
coscattering
- Thermal equilibrium with SM bath 
$$T_{\text{DM}} = T_{\text{SM}} \quad \mu_{\text{DM}} = 0$$

Standard assumptions

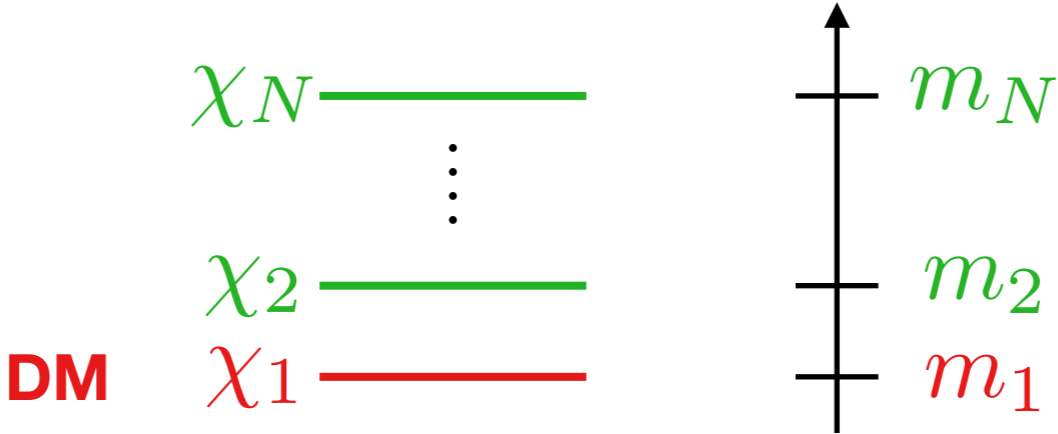
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 - Thermal equilibrium with SM bath  asymmetric,
 $T_{\text{DM}} \neq T_{\text{SM}}$
- $$T_{\text{DM}} = T_{\text{SM}} \quad \mu_{\text{DM}} = 0$$

Standard assumptions

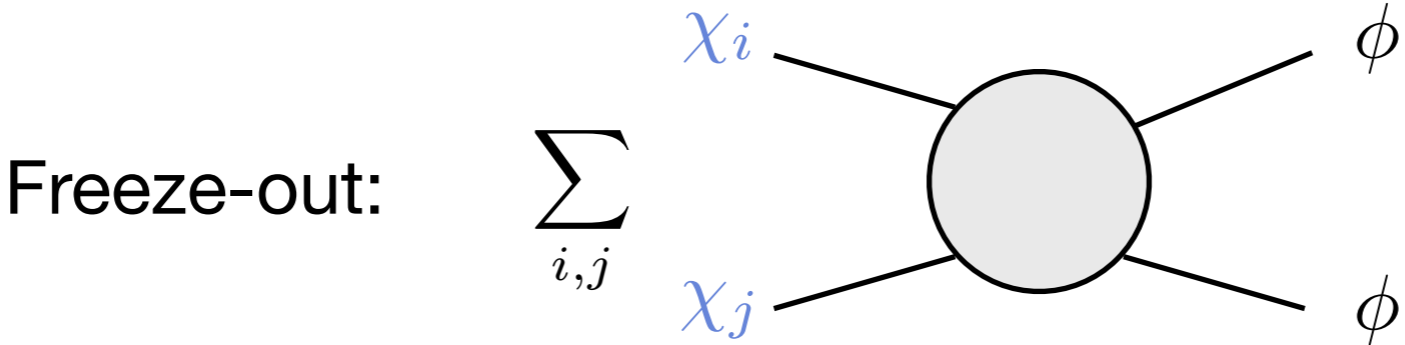
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DM properties can be very different from WIMP!

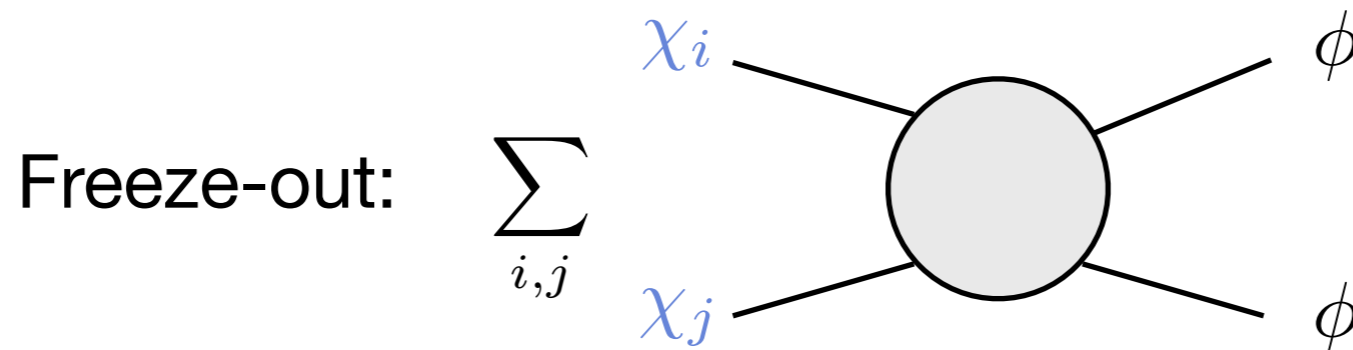
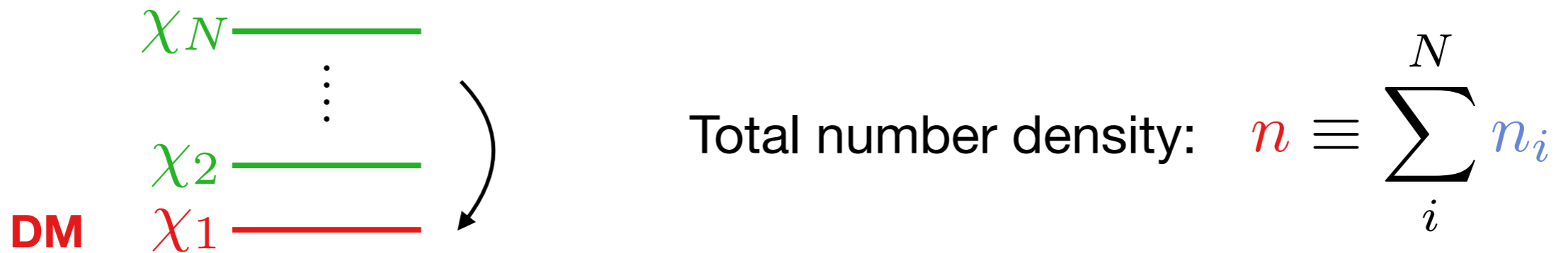
Coannihilation relic density



Rapid $\chi_i \leftrightarrow \chi_j$



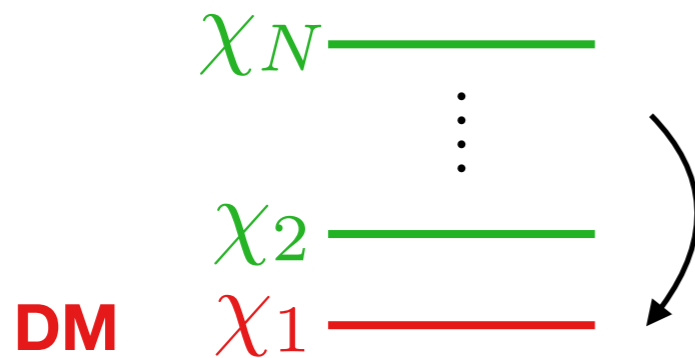
Coannihilation relic density



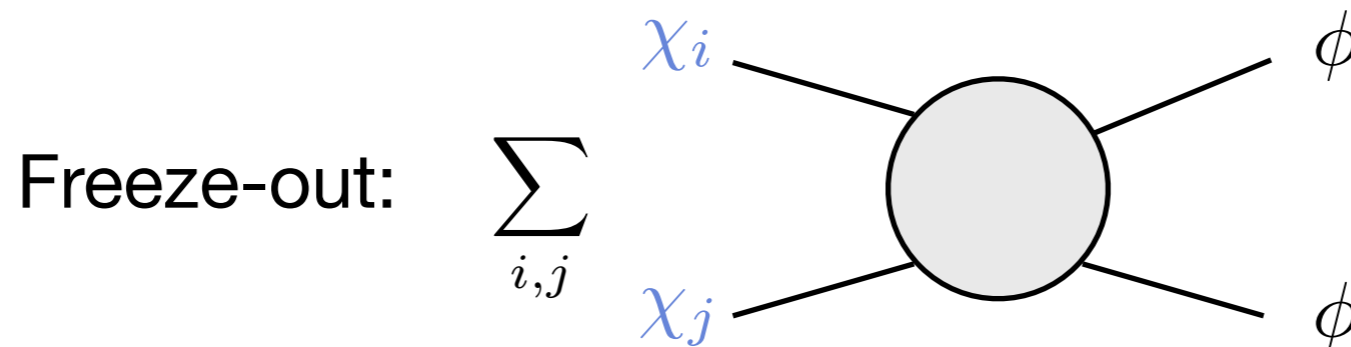
$$\langle \sigma_{\text{eff}} v \rangle \equiv \sum_{i,j} \frac{n_i^{\text{eq}} n_j^{\text{eq}}}{(n^{\text{eq}})^2} \sigma_{ij}$$

$$\frac{dn}{dt} + 3Hn = -\langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)$$

Coannihilation relic density



Total number density: $n \equiv \sum_i^N n_i$



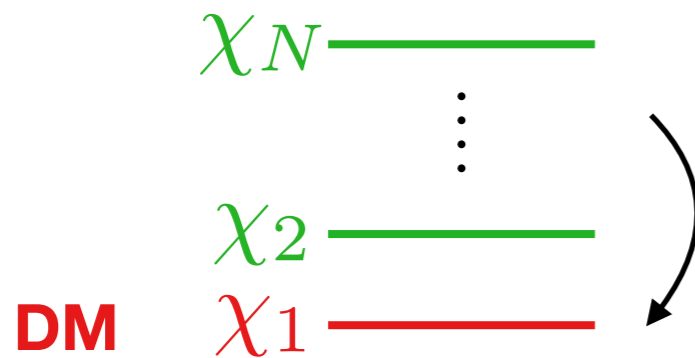
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Degenerate mass states

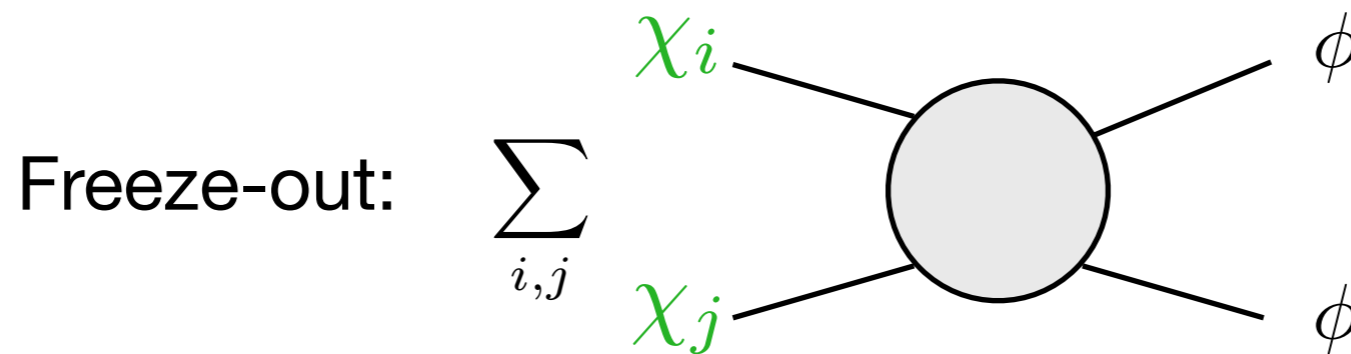
Griest and Seckel, 1991
Arkani-Hamed, Delgado, and Giudice, 2006

$$\frac{dn}{dt} + 3Hn = -\langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)$$

Sterile coannihilation



Total number density: $n \equiv \sum_i^N n_i$



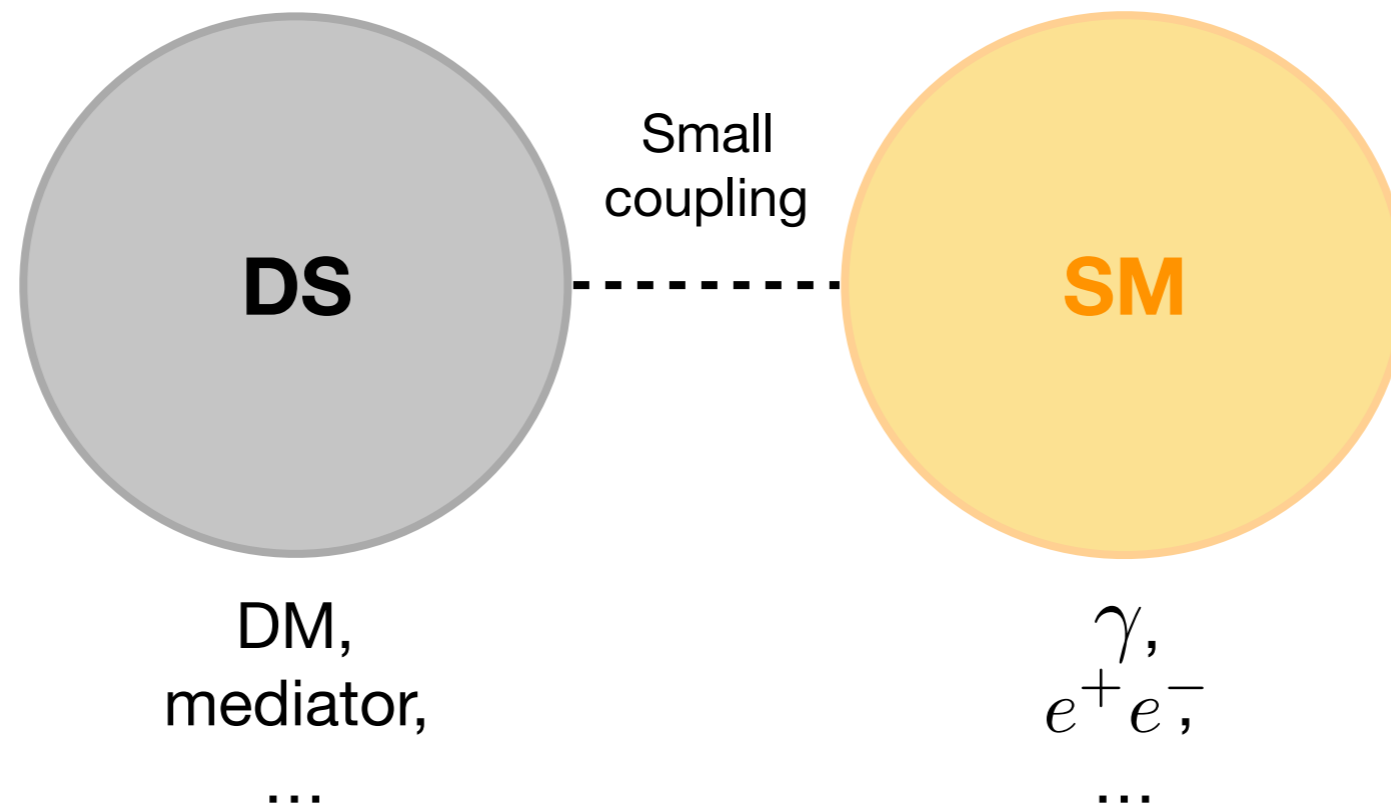
$$\langle \sigma_{\text{eff}} v \rangle \simeq \sum_{i,j} \frac{n_i^{\text{eq}} n_j^{\text{eq}}}{(n^{\text{eq}})^2} \sigma_{ij}$$

- Split masses
- $\sigma_{11} \ll \sigma_{\text{eff}}$

$$\Rightarrow \langle \sigma_{\text{eff}} v \rangle \sim \sum_{i,j} e^{-\frac{m_i + m_j - 2m_1}{T}} \sigma_{ij}$$

D'Agnolo, CM, Ruderman, and Wang, 2018

“Secluded” dark sector (DS)



Boehm and Fayet, 2003

Finkbeiner and Weiner, 2007

Pospelov, Ritz, and Voloshin, 2007

Feng and Kumar, 2009

...

A simple model

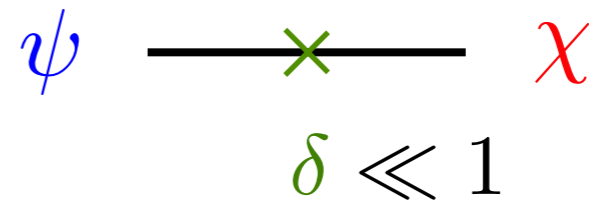
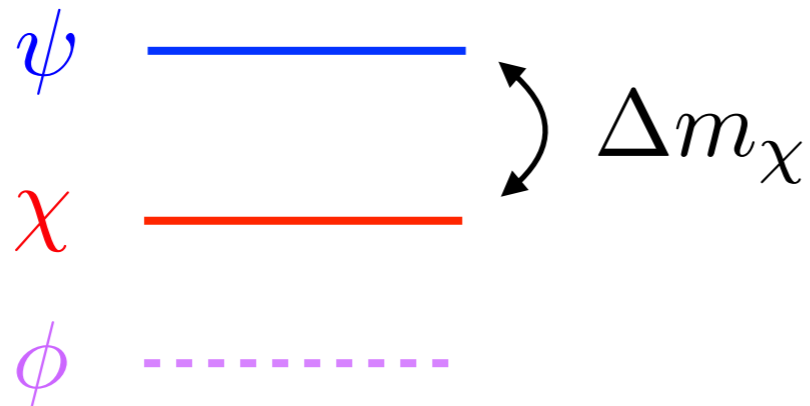
$$\mathcal{L} \supset -\frac{m_\phi^2}{2} \phi^2 - \frac{m_\psi}{2} \psi^2 - \frac{y}{2} \phi \psi^2$$

ψ —————

ϕ - - - - -

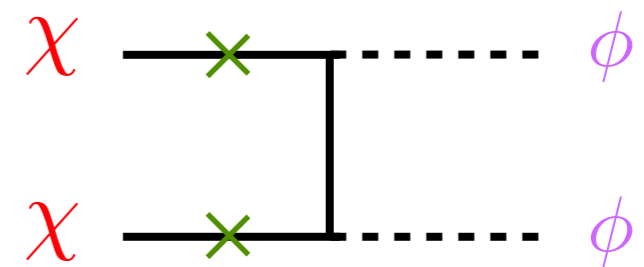
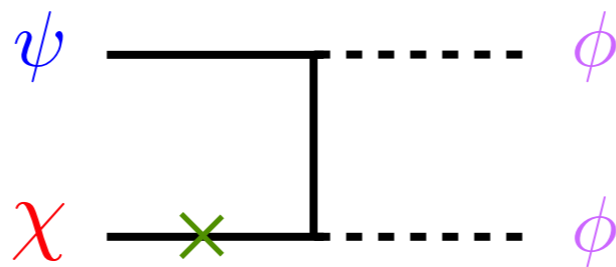
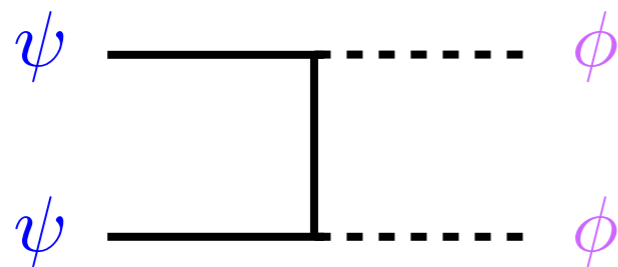
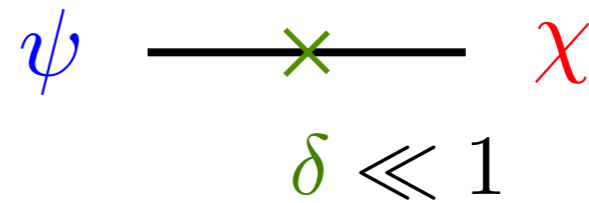
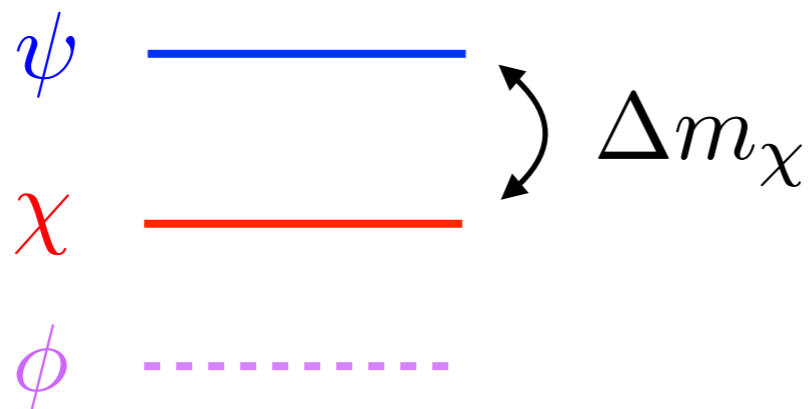
A simple model

$$\mathcal{L} \supset -\frac{m_\phi^2}{2} \phi^2 - \frac{m_\psi}{2} \psi^2 - \frac{y}{2} \phi \psi^2 - \frac{m_\chi}{2} \chi^2 - \delta m_\chi \chi \psi$$



A simple model

$$\mathcal{L} \supset -\frac{m_\phi^2}{2} \phi^2 - \frac{m_\psi}{2} \psi^2 - \frac{y}{2} \phi \psi^2 - \frac{m_\chi}{2} \chi^2 - \delta m_\chi \chi \psi$$



$$\langle \sigma_{\text{eff}} v \rangle \propto e^{-2\Delta x_f}$$

$$\delta^2 e^{-\Delta x_f}$$

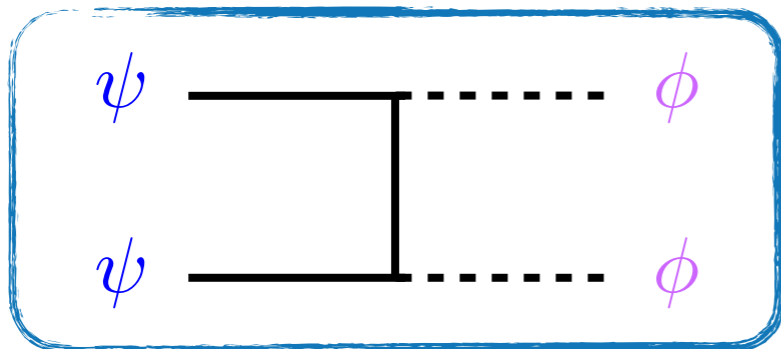
$$\delta^4$$

A simple model

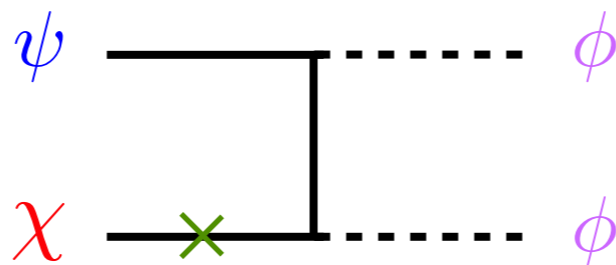
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Sterile coannihilation:

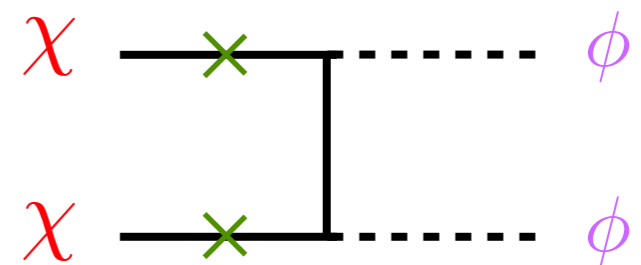
$$\delta^2 \ll e^{-\Delta x_f}$$



$$\langle \sigma_{\text{eff}} v \rangle \propto e^{-2\Delta x_f}$$



$$\delta^2 e^{-\Delta x_f}$$

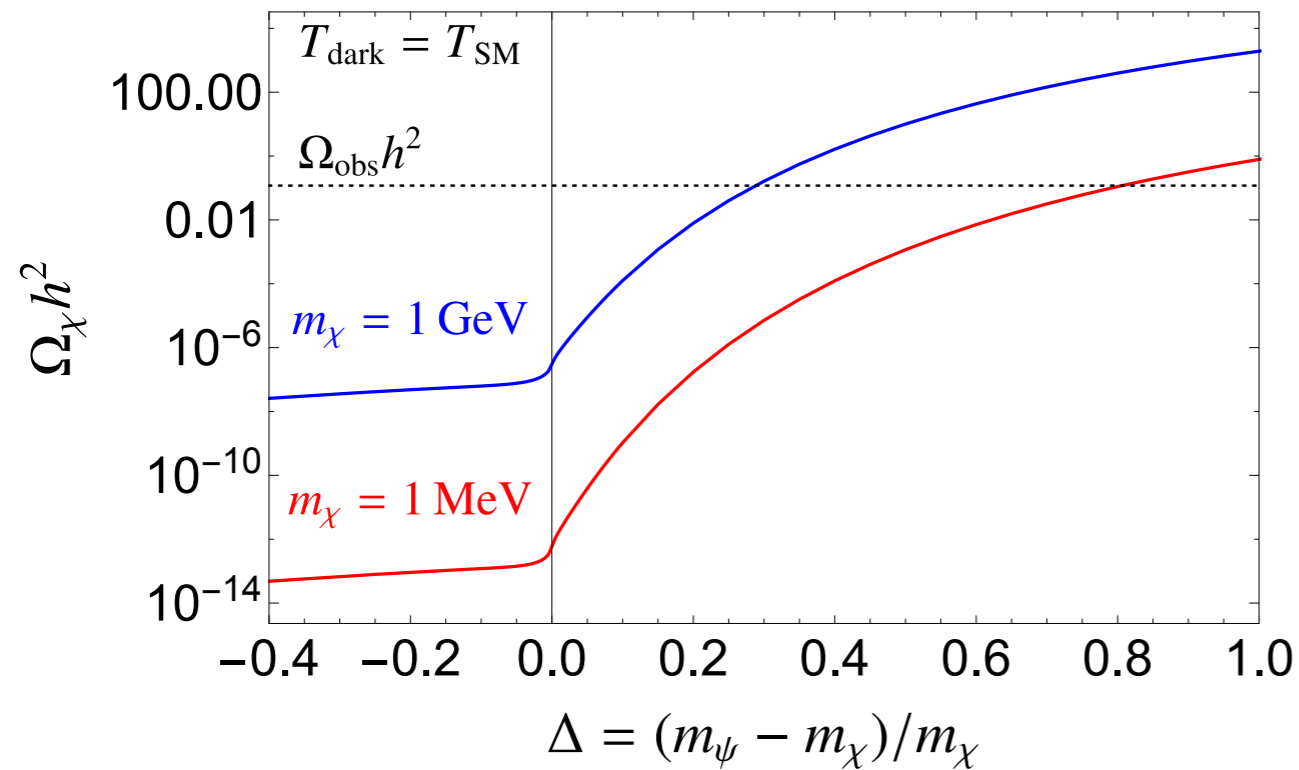


$$\delta^4$$

Sterile coannihilation:

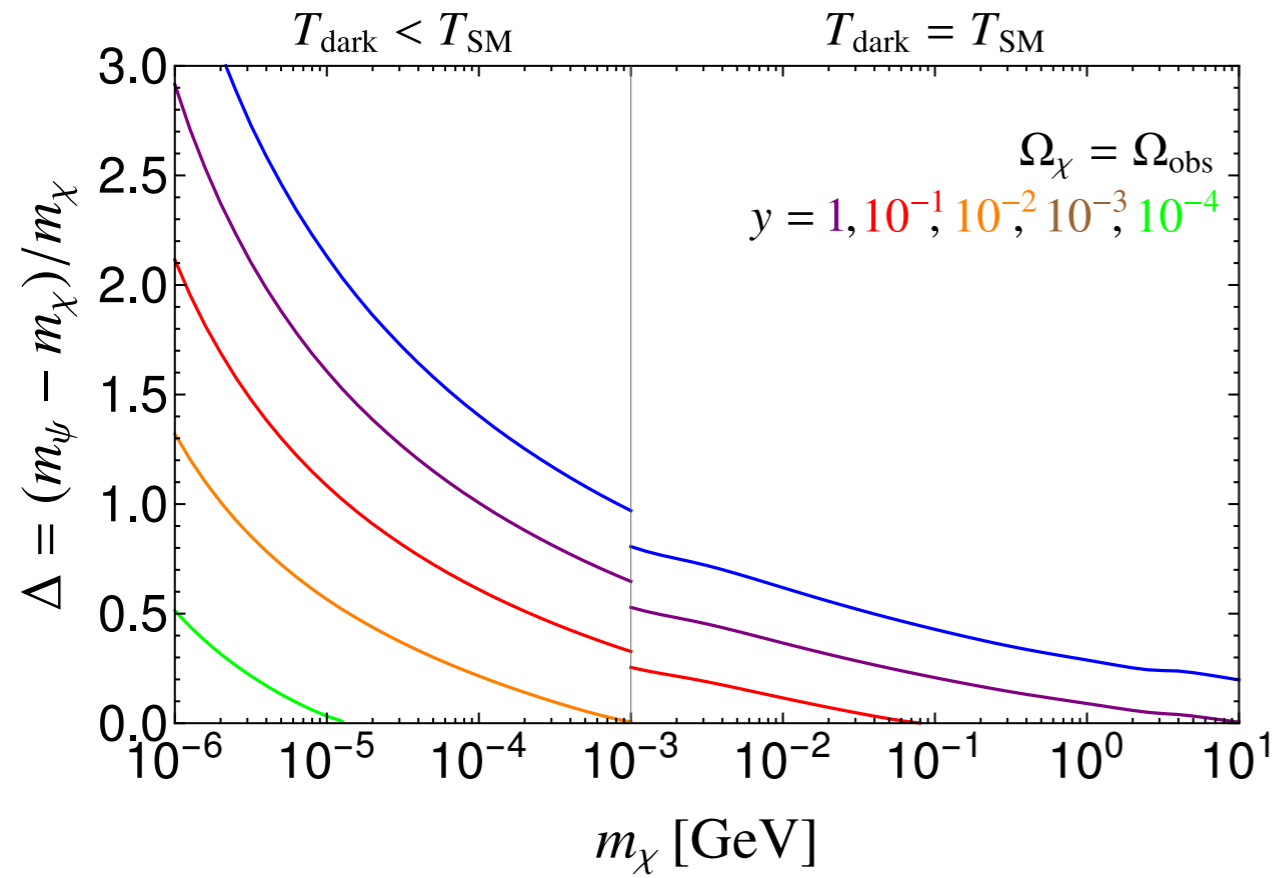
$$\Omega_{\text{DM}} h^2 \sim \frac{1}{T_{\text{EQ}} M_{\text{Pl}} \langle \sigma_{\text{eff}} v \rangle} \sim \frac{1}{T_{\text{EQ}} M_{\text{Pl}}} \frac{e^{2\Delta x_f}}{\sigma_{\psi\psi}}$$

Relic Density vs Mass Splitting

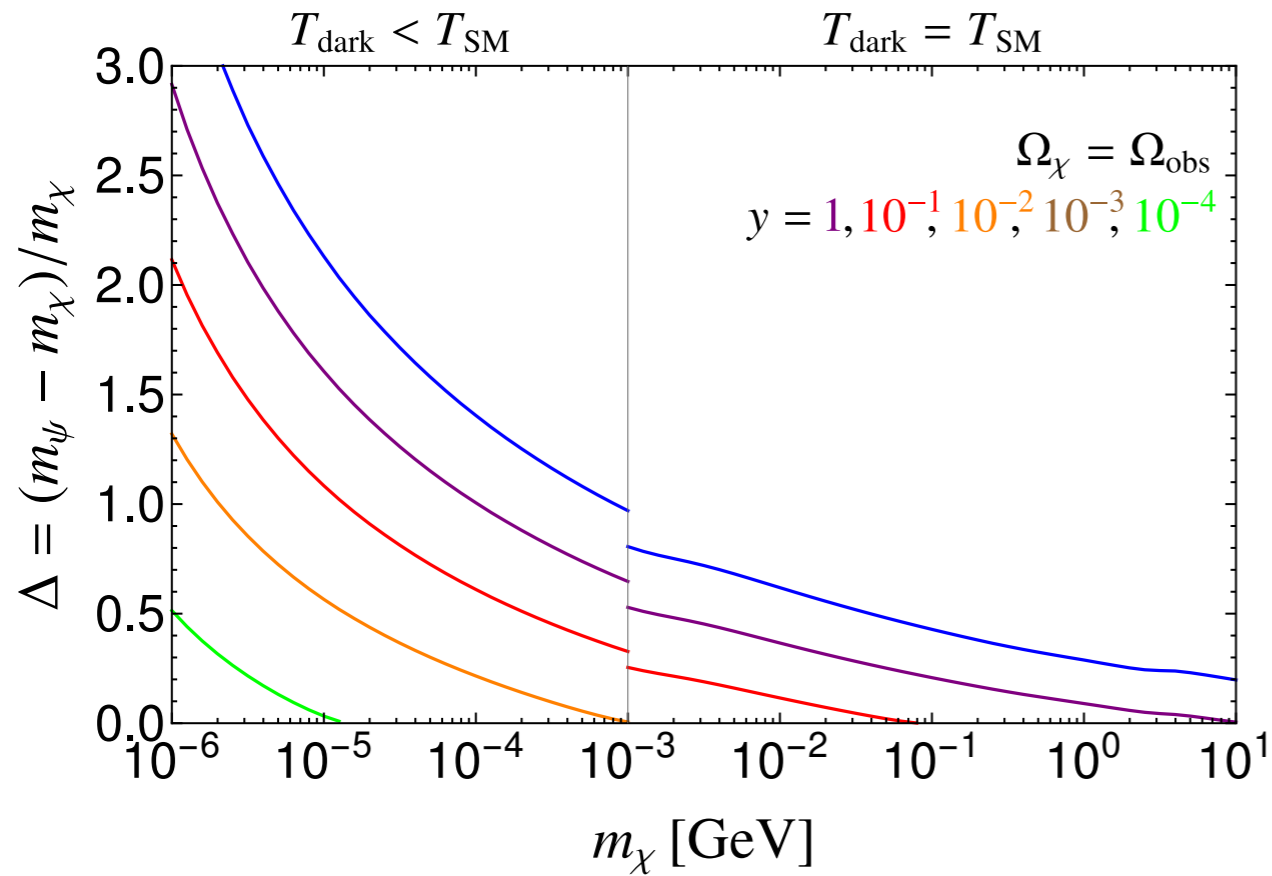


$$m_\chi \sim e^{-\Delta x_f} \sqrt{T_{\text{EQ}} M_{\text{Pl}}}$$

**Exponentially lighter
than the weak scale**

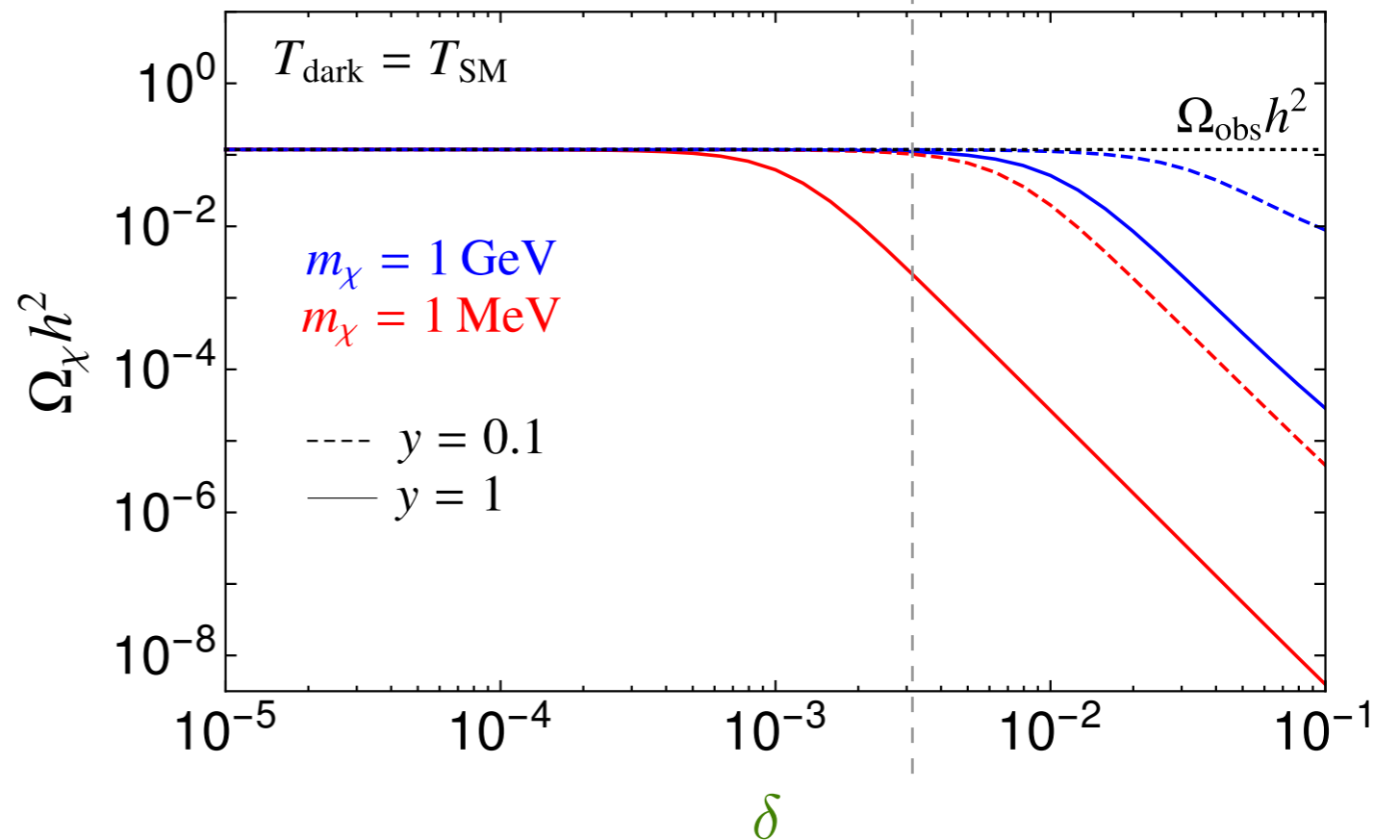
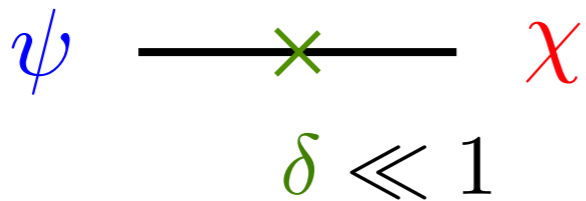


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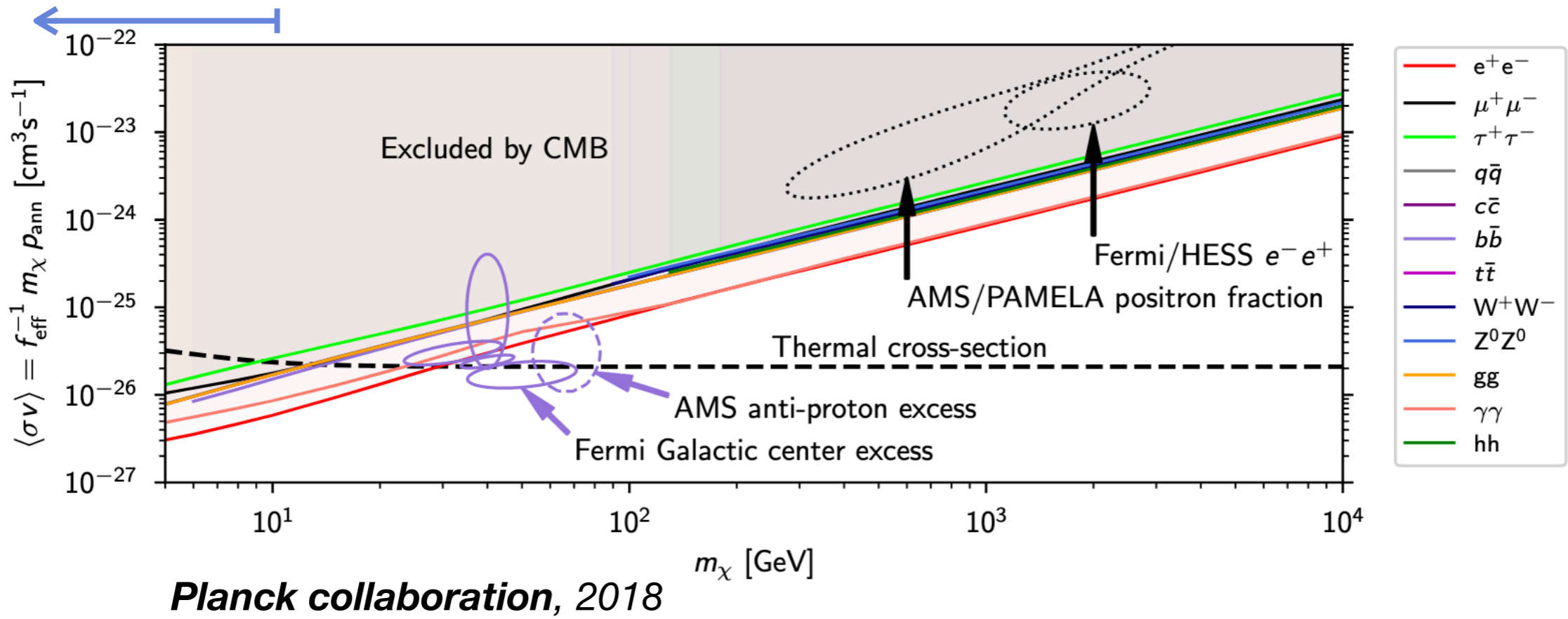
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Sterile
 coannihilation



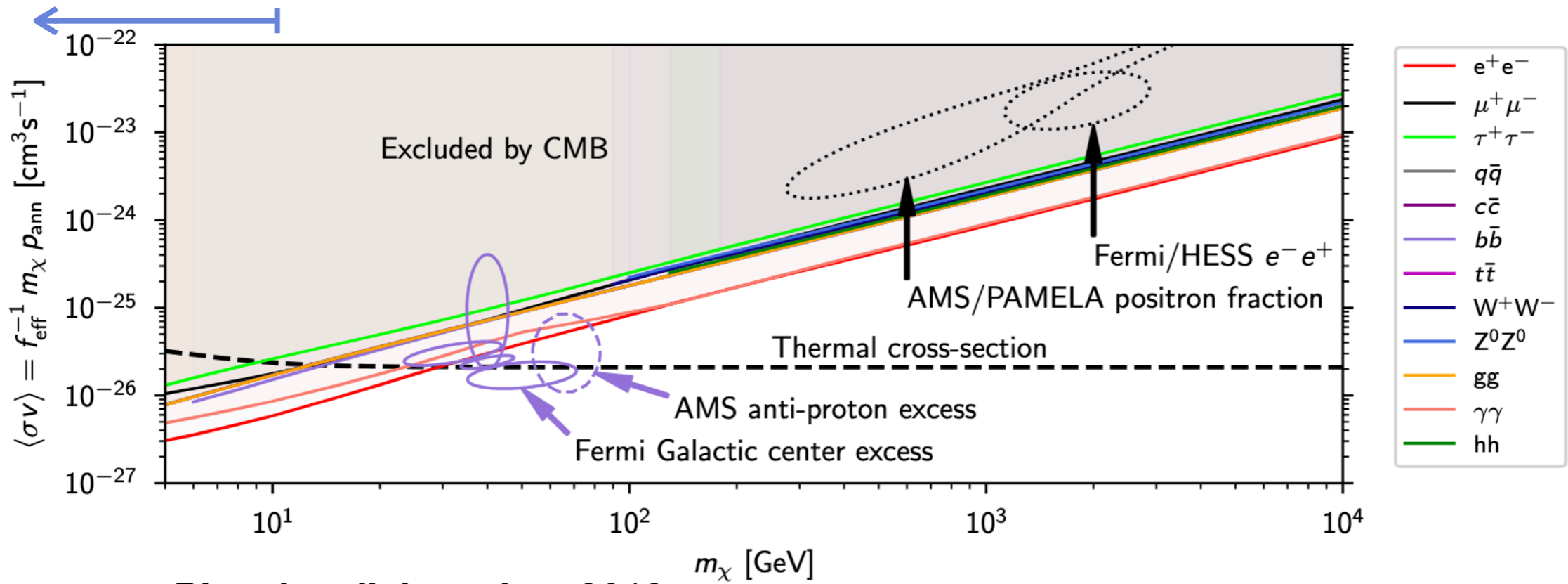
$m_{\text{DM}} \lesssim 10 \text{ GeV}$

excluded



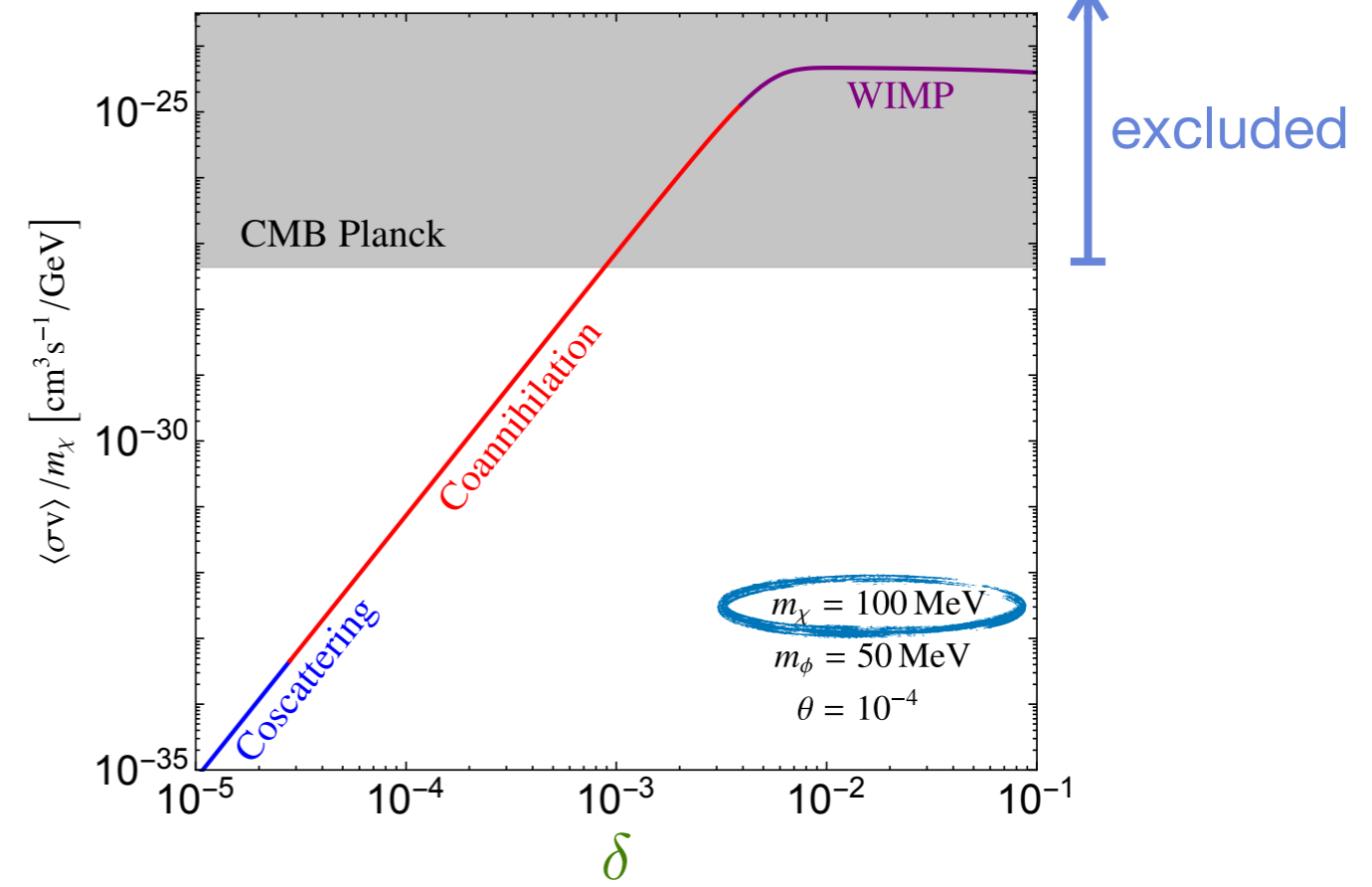
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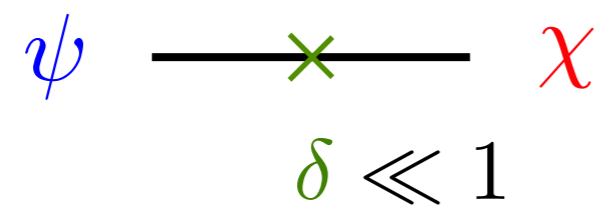


Planck collaboration, 2018

DM annihilation cross-section



Sterile coannihilation
naturally avoids the CMB
bound on sub-GeV DM



Dark sector temperature

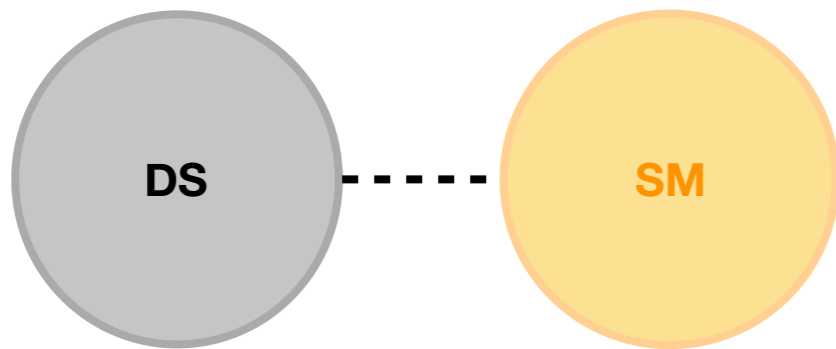
$$T_{\text{dark}} \sim a^{-1}$$

Coupling to the SM

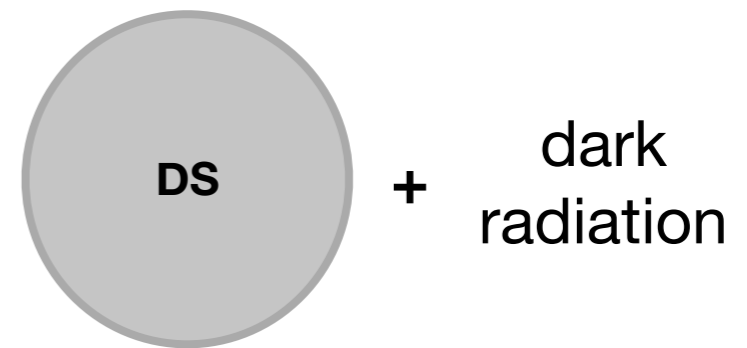
Coupling to radiation

$$T_{\text{dark}} = T_{\text{SM}}$$

$$T_{\text{dark}} \neq T_{\text{SM}}$$



$$m_{\text{DM}} \gtrsim 10 \text{ MeV}$$



$$m_{\text{DM}} \gtrsim \text{keV}$$

Dark sector temperature

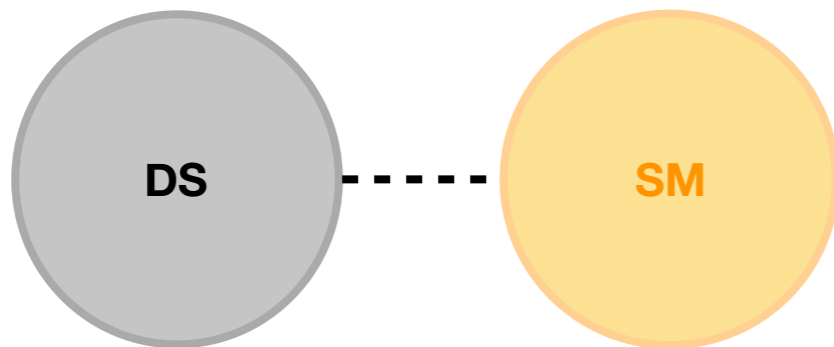
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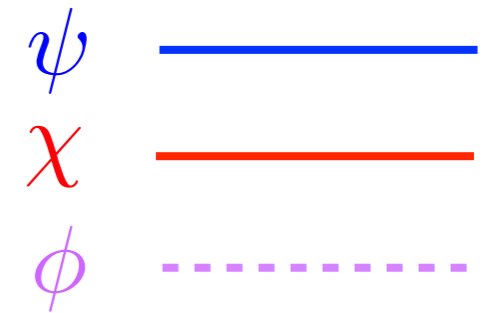
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$$m_{\text{DM}} \gtrsim \text{keV}$$

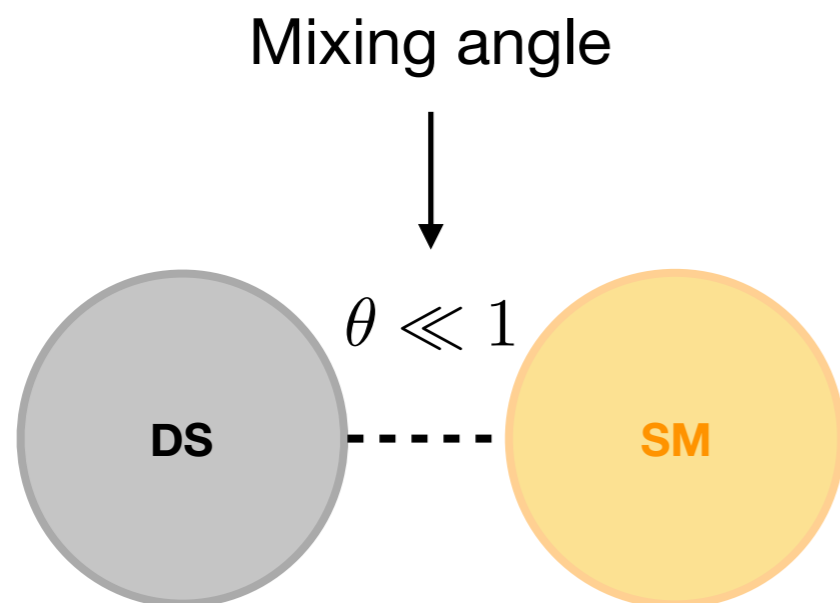
Coupling to the SM: Higgs portal

$$\mathcal{L} \supset -\frac{m_\phi^2}{2} \phi^2 - \frac{m_\psi}{2} \psi^2 - \frac{y}{2} \phi \psi^2 - \frac{m_\chi}{2} \chi^2 - \delta m_\chi \chi \psi$$



Mass mixing
with SM Higgs

$$\mathcal{L} \supset a \phi |H|^2 + \dots$$



- Large enough that $T_{\text{dark}} = T_{\text{SM}}$

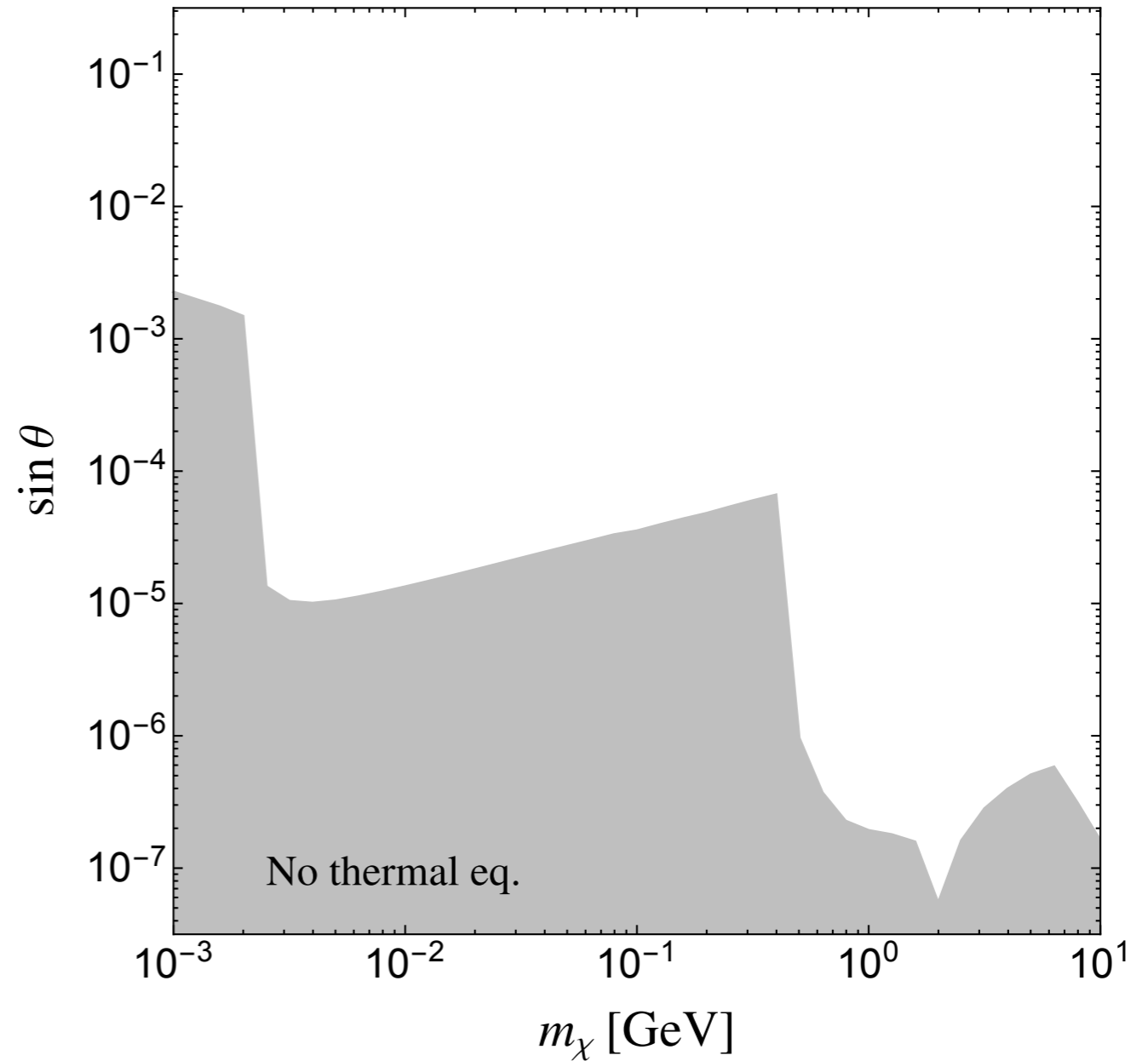
- Small enough that

$$\psi\psi \rightarrow \text{SM SM} \ll \psi\psi \rightarrow \phi\phi$$

Higgs portal phenomenology

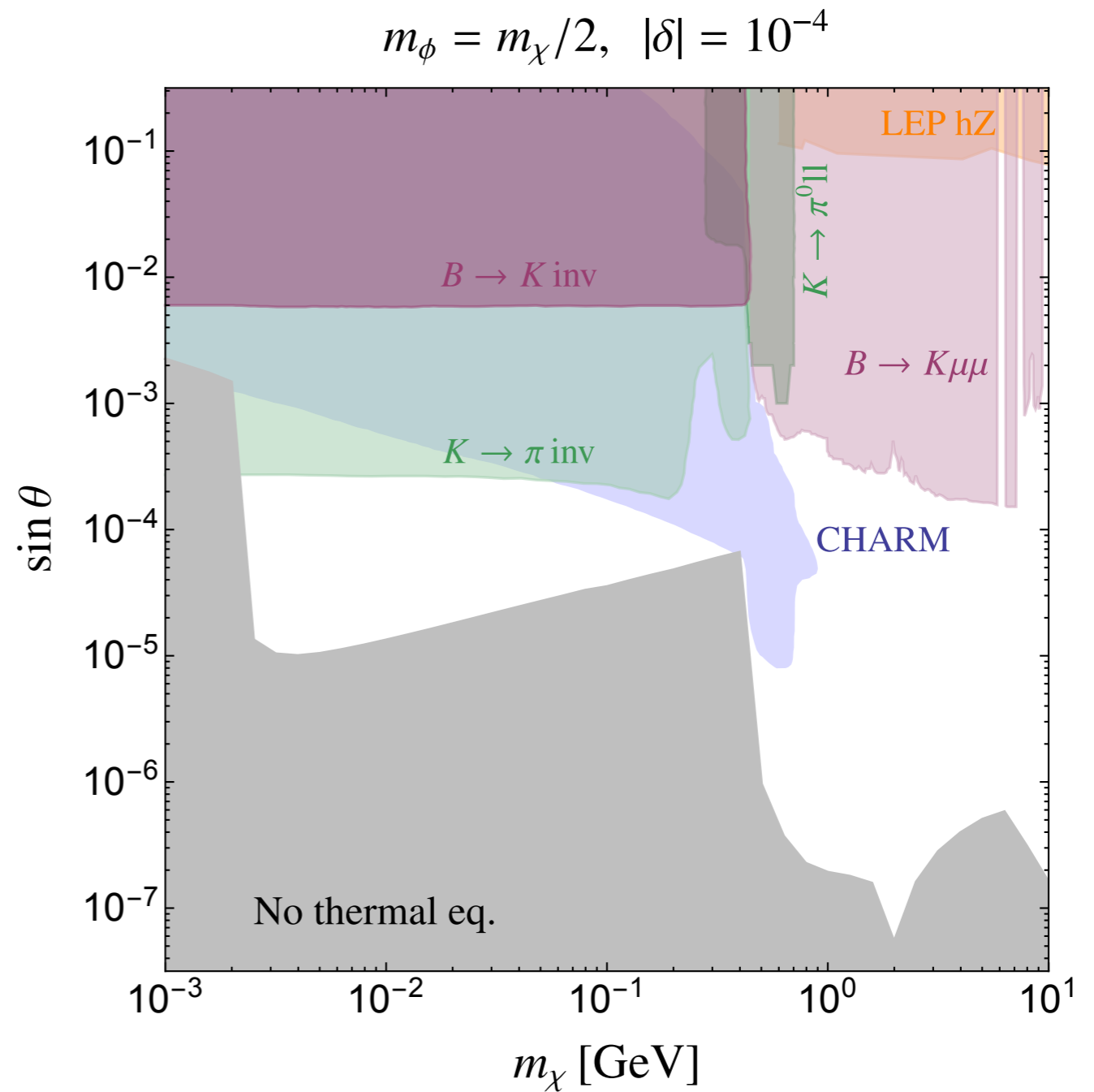
$$m_\phi = m_\chi/2, \quad |\delta| = 10^{-4}$$

- $T_{\text{dark}} = T_{\text{SM}}$
@ DM freeze-out



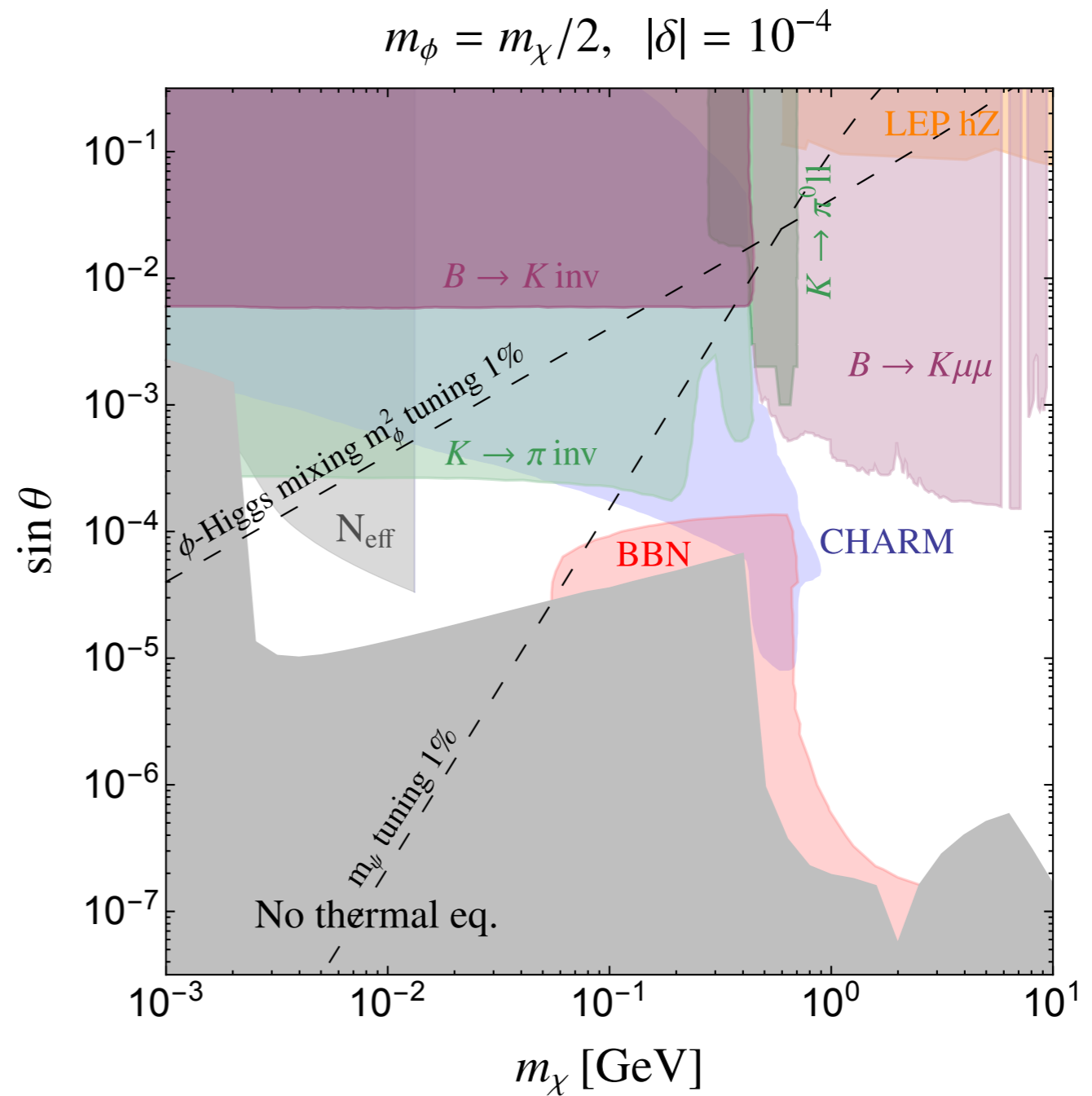
Higgs portal phenomenology

- $T_{\text{dark}} = T_{\text{SM}}$
@ DM freeze-out
- ϕ contributes to meson decays



Higgs portal phenomenology

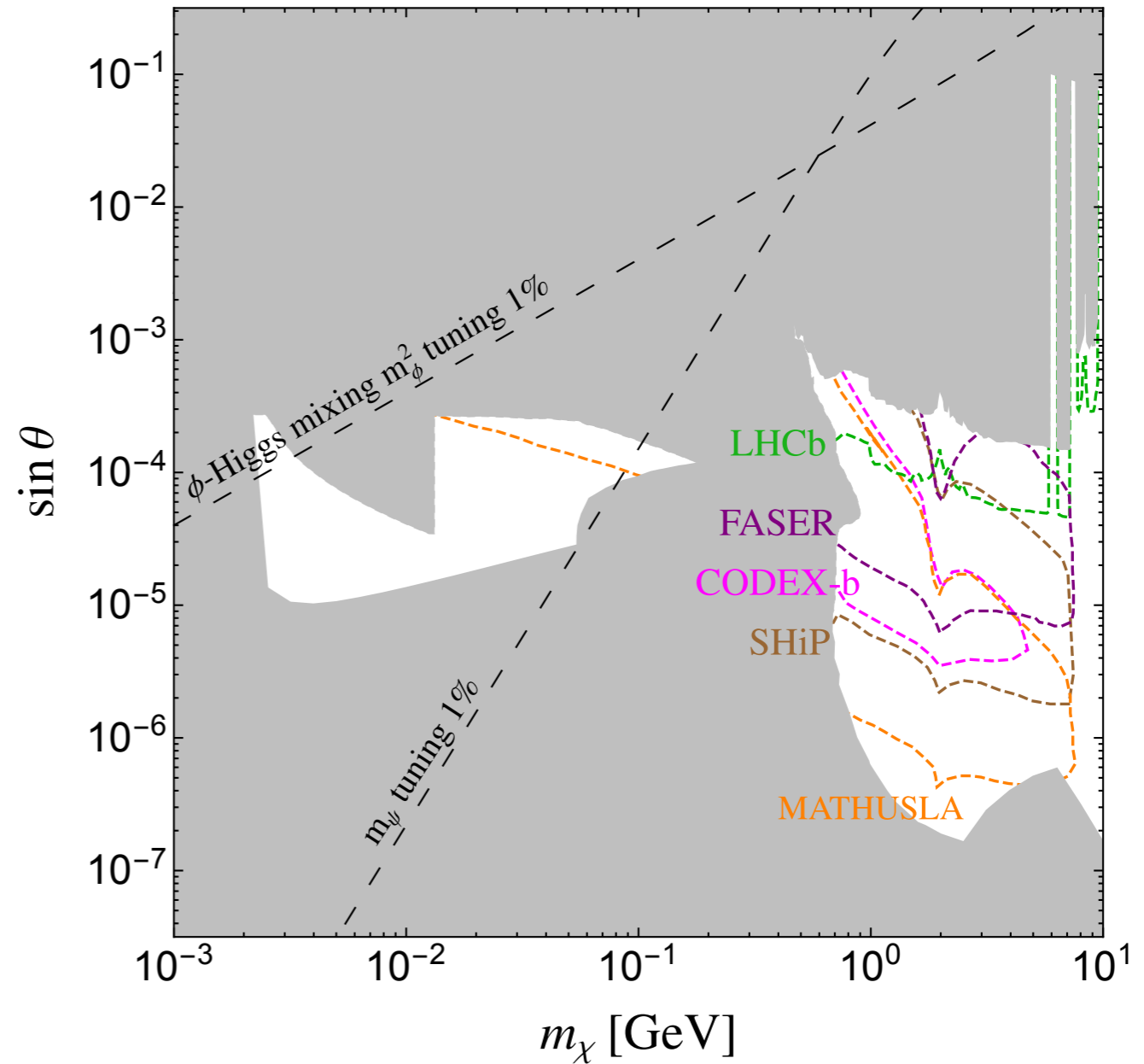
- $T_{\text{dark}} = T_{\text{SM}}$
@ DM freeze-out
- ϕ contributes to meson decays
- Number of light degrees of freedom (CMB)
- Late ψ decay (BBN)



Higgs portal phenomenology

$$m_\phi = m_\chi/2, \quad |\delta| = 10^{-4}$$

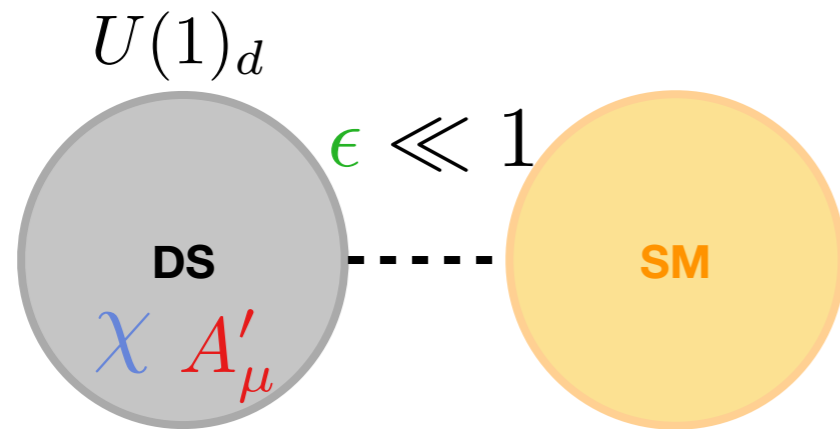
- LLP experiments can detect ϕ



Outline

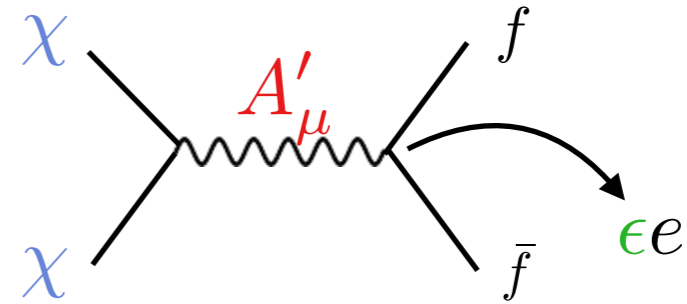
- Thermal relics
- Exceptions: coannihilation
- **Dark Higgs**

Dark Photon

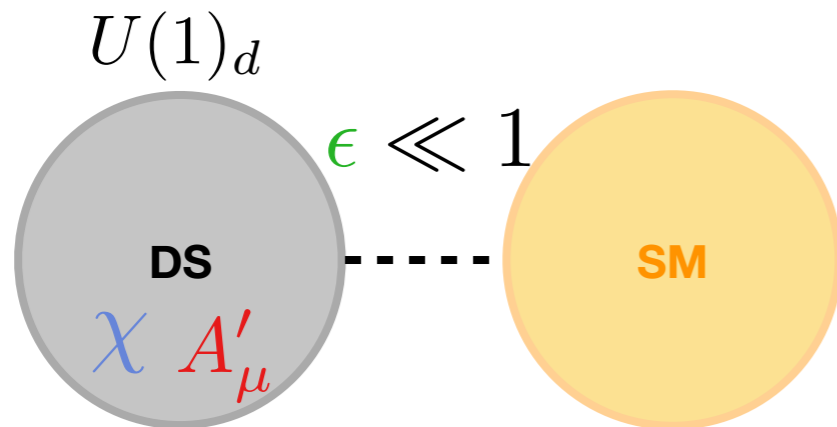


$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu$$

$$\Rightarrow \mathcal{L} \supset \epsilon e A'_\mu J_{\text{EM}}^\mu$$

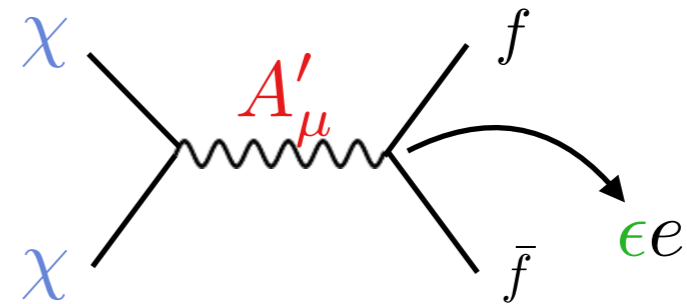
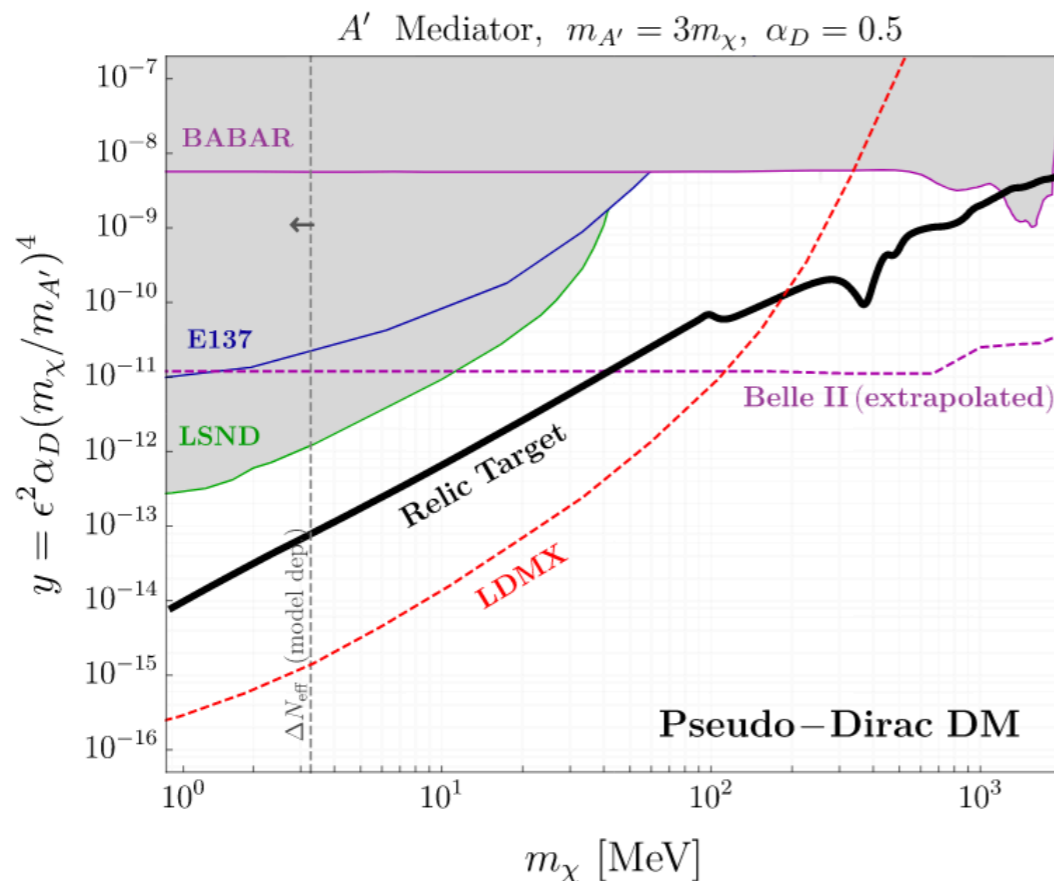


Dark Photon



$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu$$

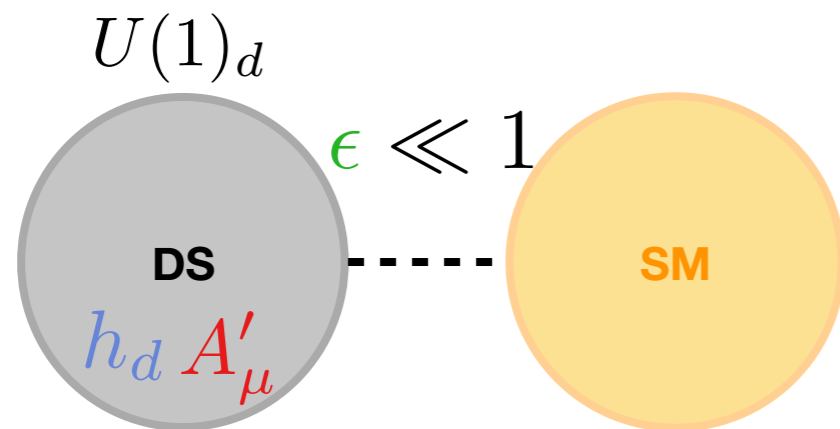
$$\Rightarrow \mathcal{L} \supset \epsilon e A'_\mu J_{EM}^\mu$$



$$\langle \sigma v \rangle \propto \frac{\epsilon^2 \alpha_d m_{\text{DM}}^2}{m_{A'}^4}$$

$$\epsilon_{\text{relic}} \sim 10^{-5} \frac{m_{\text{DM}}}{1 \text{ MeV}}$$

Dark Photon mass



$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu$$

- Stueckelberg mechanism

- Higgs mechanism \longrightarrow Associated scalar

Dark Higgs

$$\mathcal{L} \supset \frac{1}{2} (\partial_\mu h_d)^2 - \frac{1}{2} m_{h_d}^2 h_d^2 - \frac{\lambda_d}{4} h_d^4$$

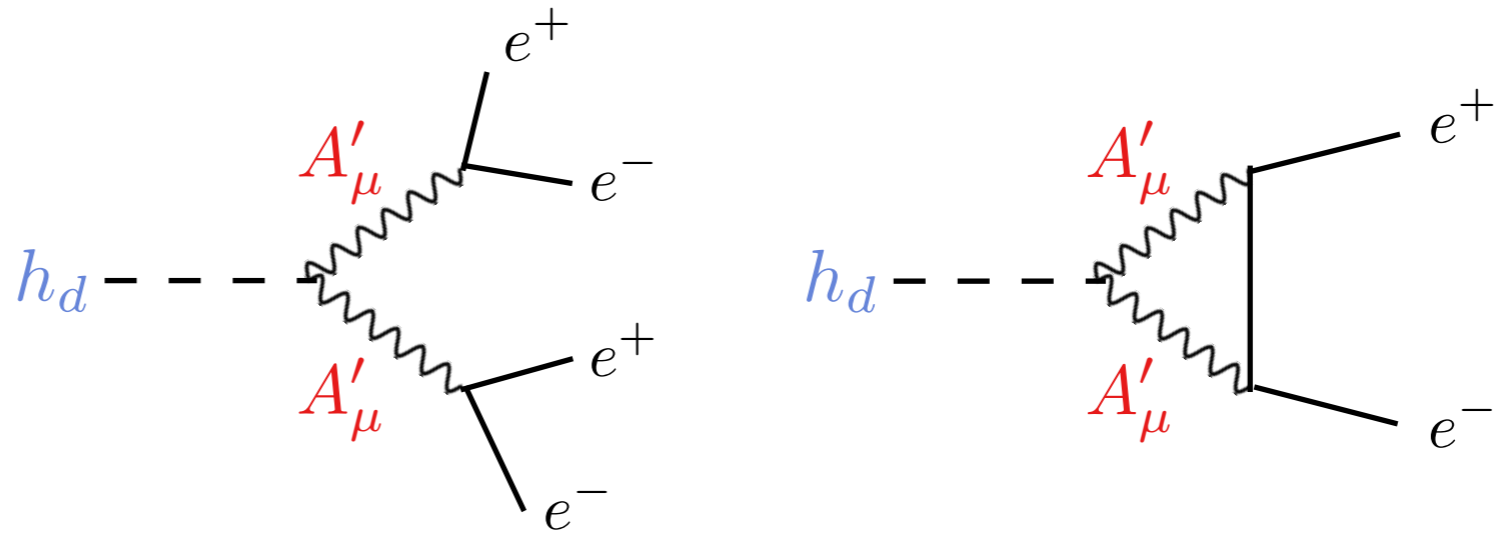
$$m_{h_d} = \lambda_d v_d$$

$$m_{A'} = g_d v_d$$

$$\Rightarrow m_{h_d} \sim m_{A'}$$

Dark Higgs decay

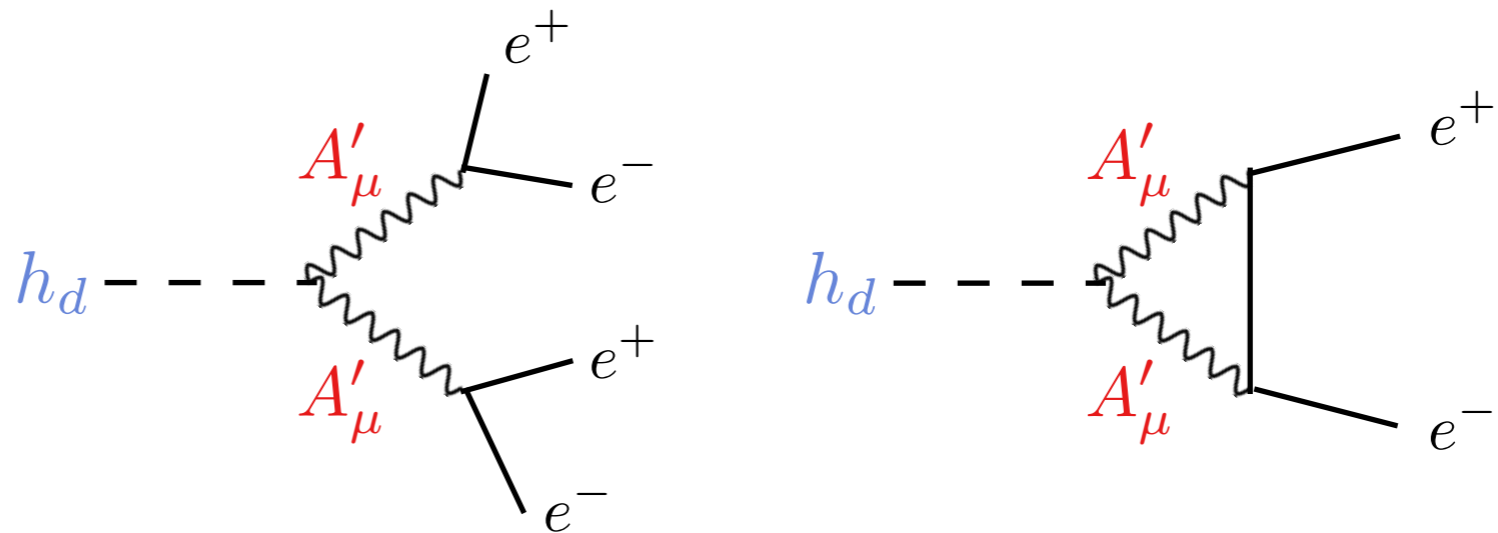
$$m_{h_d} < m_{A'}$$



$$\Gamma_{h_d} \propto \epsilon^4 \alpha^2 \alpha_d \longrightarrow \text{Cosmologically stable}$$

Dark Higgs decay

$$m_{h_d} < m_{A'}$$

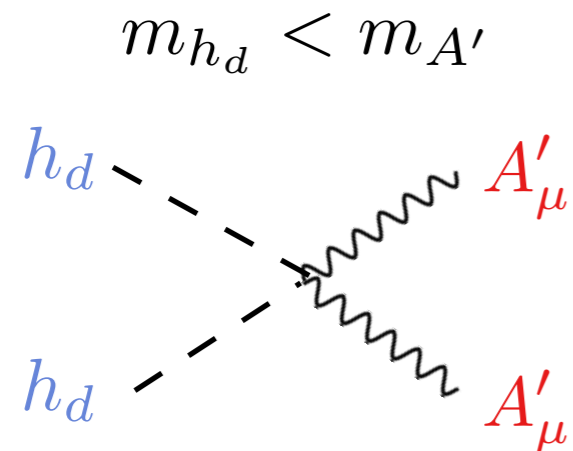


$$\Gamma_{h_d} \propto \epsilon^4 \alpha^2 \alpha_d \longrightarrow \text{Cosmologically stable}$$

$$\tau_{h_d} \sim 10^{19} \text{ s} \left(\frac{50 \text{ MeV}}{m_{h_d}} \right) \left(\frac{0.01}{\alpha_d} \right) \left(\frac{10^{-8}}{\epsilon} \right)^4$$

Can the dark Higgs account for total DM abundance?

Dark Higgs freeze-out

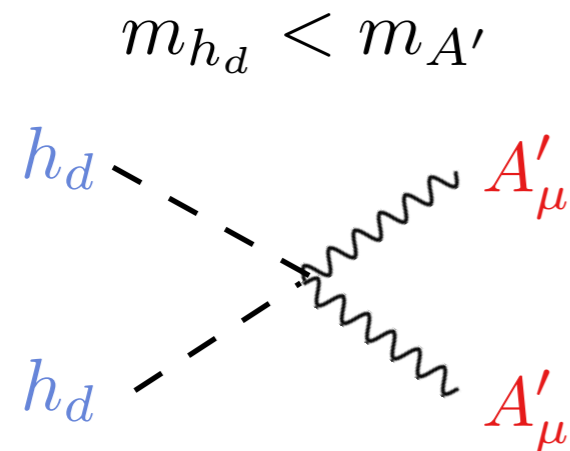


Kinematically forbidden annihilation

$$(n_{h_d}^{eq})^2 \langle \sigma v \rangle_{h_d h_d} = (n_{A'}^{eq})^2 \langle \sigma v \rangle_{A'_\mu A'_\mu}$$

$$\langle \sigma v \rangle_{h_d h_d} \simeq \left(\frac{n_{A'}^{eq}}{n_{h_d}^{eq}} \right)^2 \frac{\alpha_d^2}{m_{A'}^2}$$

Dark Higgs freeze-out



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$$\langle \sigma v \rangle_{h_d h_d} \simeq e^{-2 \frac{m_{A'} - m_{h_d}}{T}} \frac{\alpha_d^2}{m_{A'}^2}$$

Exponentially lighter
than the weak scale

Bounds on dark Higgs decay

- Electromagnetic energy injections in the CMB

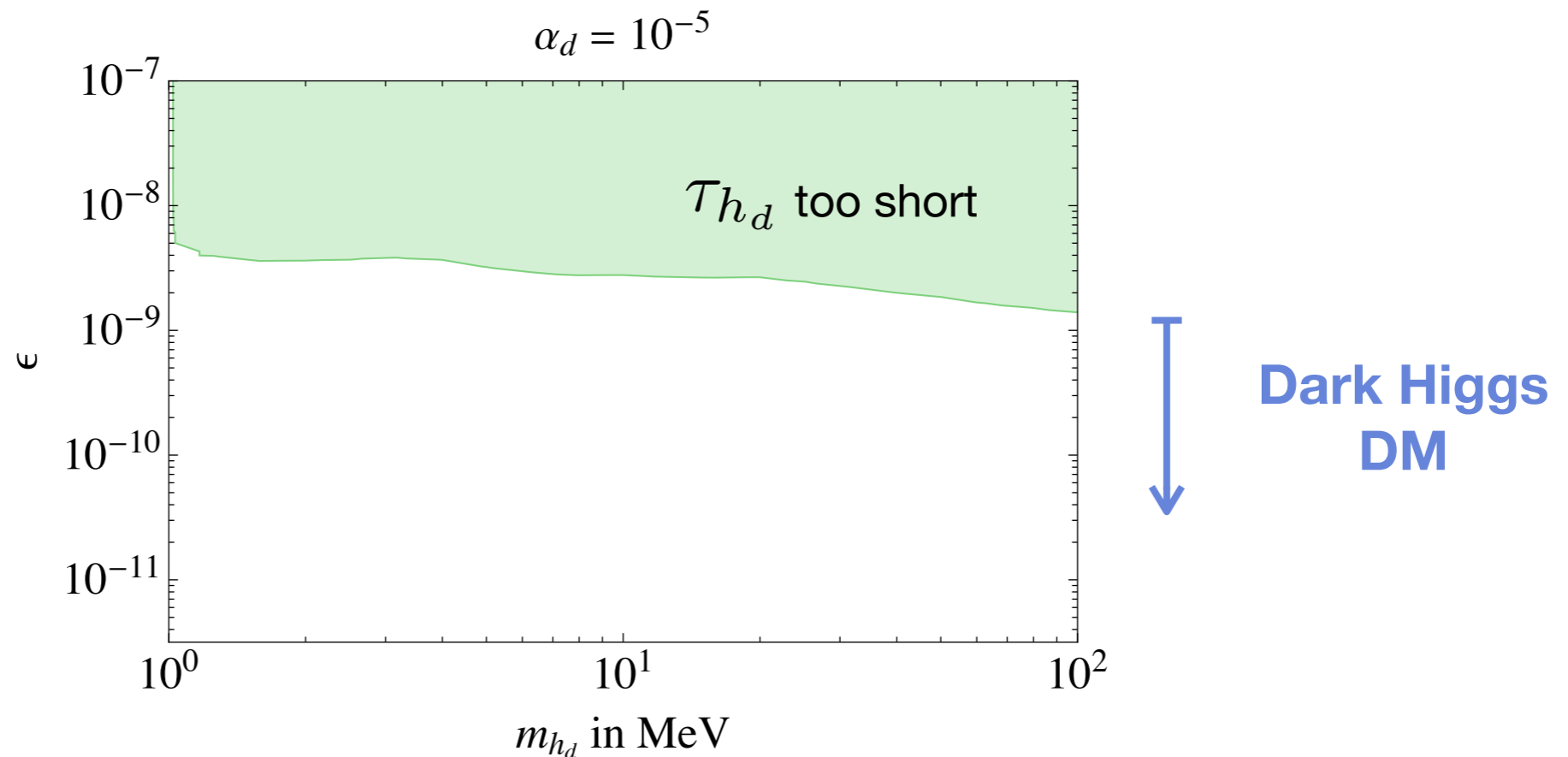
Poulin, Lesgourgues, and Serpico, 2016

Slatyer and Wu, 2016

$$\Rightarrow \tau_{h_d} \gtrsim 10^{25} \text{ s}$$

- Diffuse photon spectra (FSR)

Essig, Kuflik, McDermott, Volansky, and Zurek, 2013



Thermal equilibrium

$$\epsilon \lesssim 10^{-8}$$

During DM freeze-out: DS \leftrightarrow SM $>$ Hubble ?

$$T_d = T_{\text{SM}} \quad ?$$

$$\mu_d = 0 \quad ?$$

Thermal equilibrium

$$\epsilon \lesssim 10^{-8}$$

During DM freeze-out:

$$\text{DS} \leftrightarrow \text{SM} > \text{Hubble} \quad ?$$

$$T_d = T_{\text{SM}} \quad ?$$

$$\mu_d = 0 \quad ?$$

Dark sector processes:

- 2-to-2 $h_d h_d \leftrightarrow A' A'$
- 2-to-3 $h_d h_d h_d \leftrightarrow A' A'$
- 1-to-2 $A' \leftrightarrow e^+ e^-$

Thermal equilibrium

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During DM freeze-out:

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Dark sector processes:

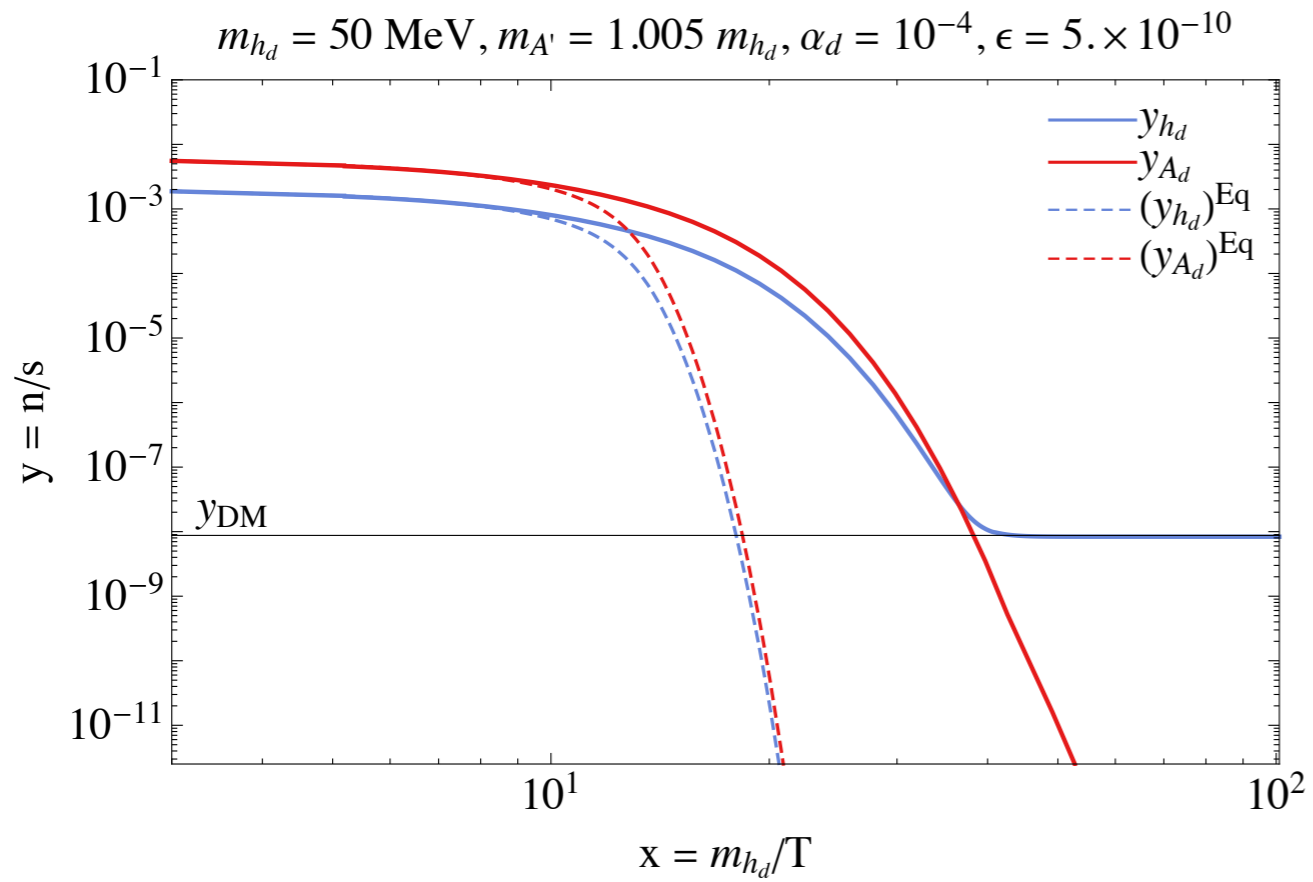
- 2-to-2 $h_d h_d \leftrightarrow A' A'$

- 2-to-3 $h_d h_d h_d \leftrightarrow A' A'$

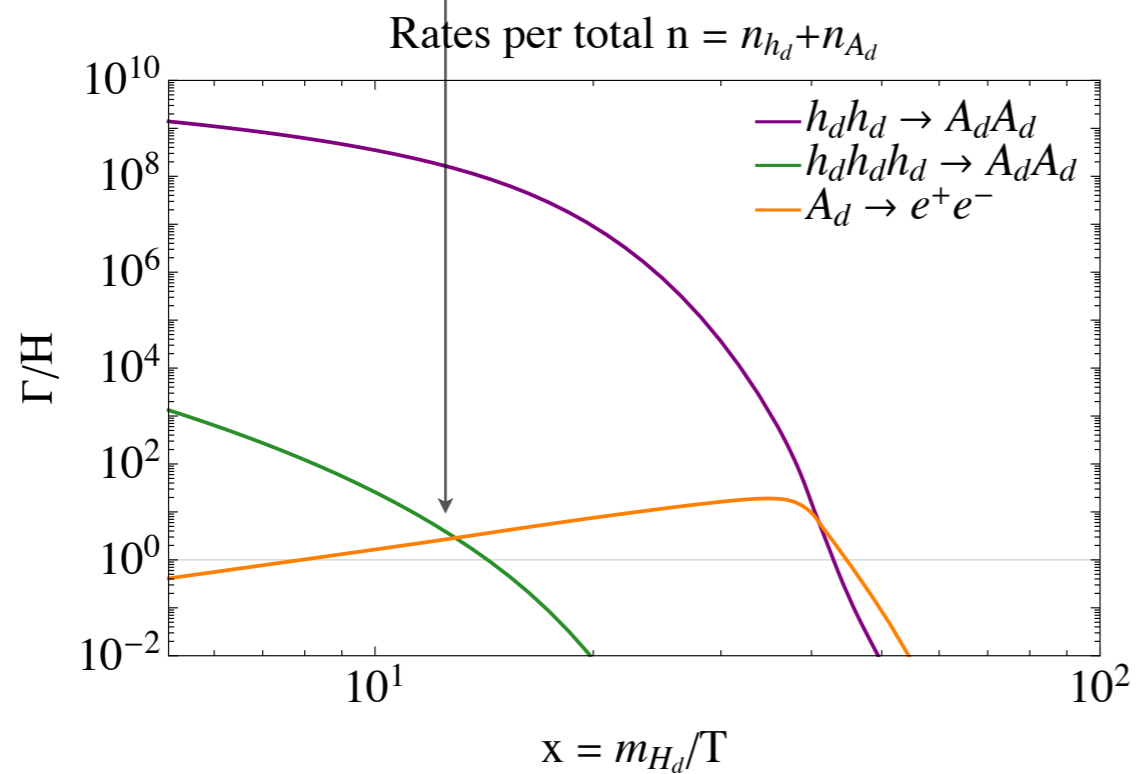
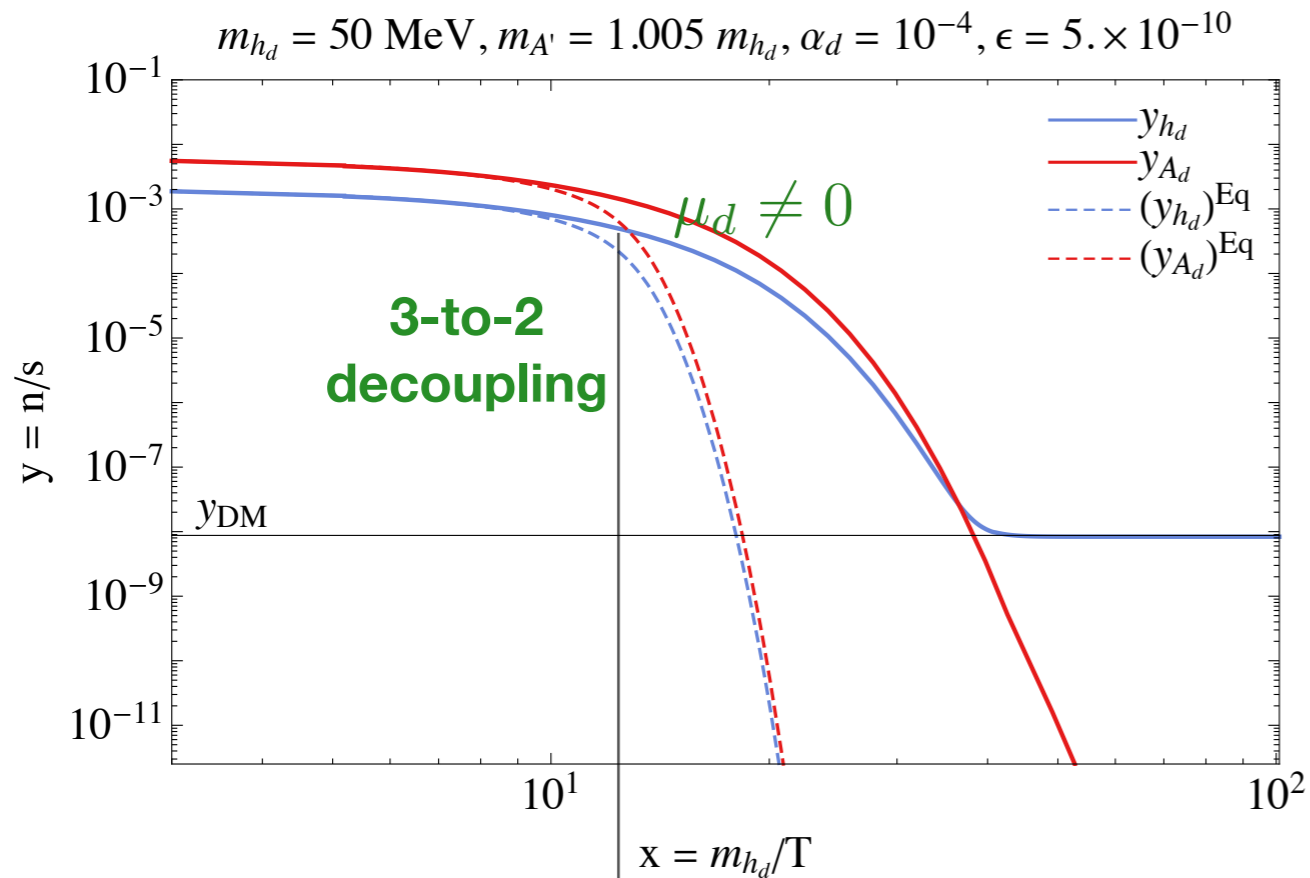
- 1-to-2 $A' \leftrightarrow e^+ e^-$

Need 1st and 2nd moment of the Boltzmann equation

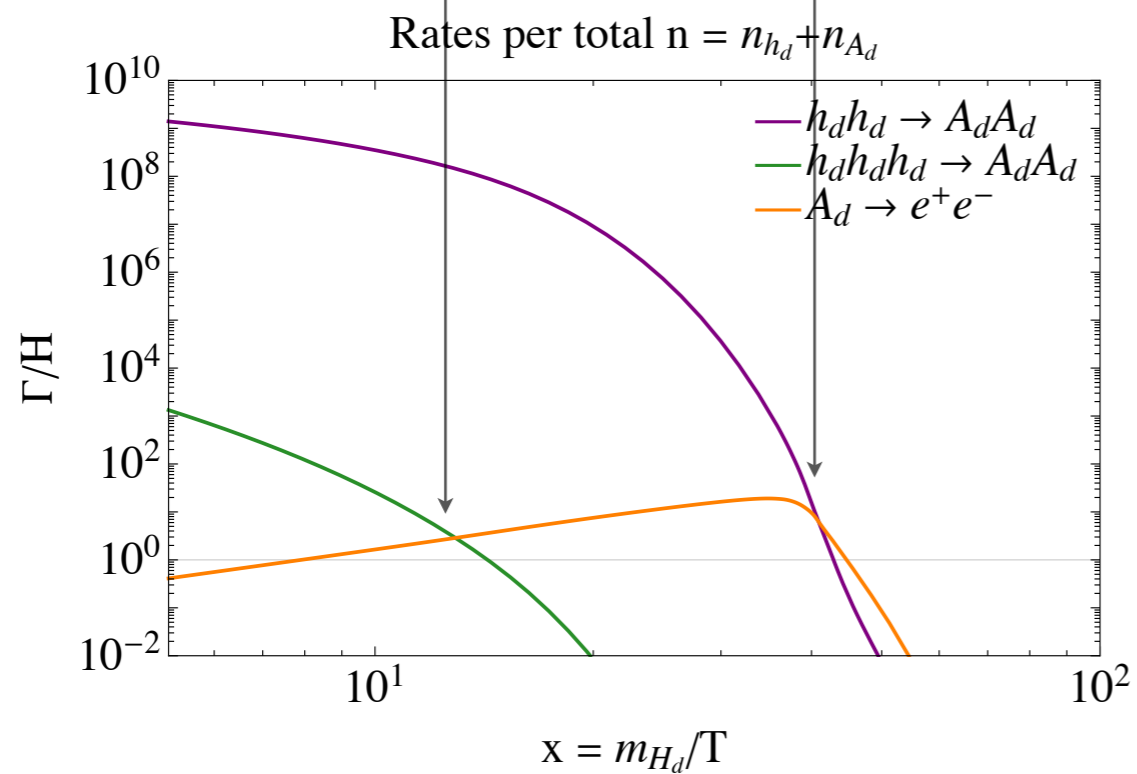
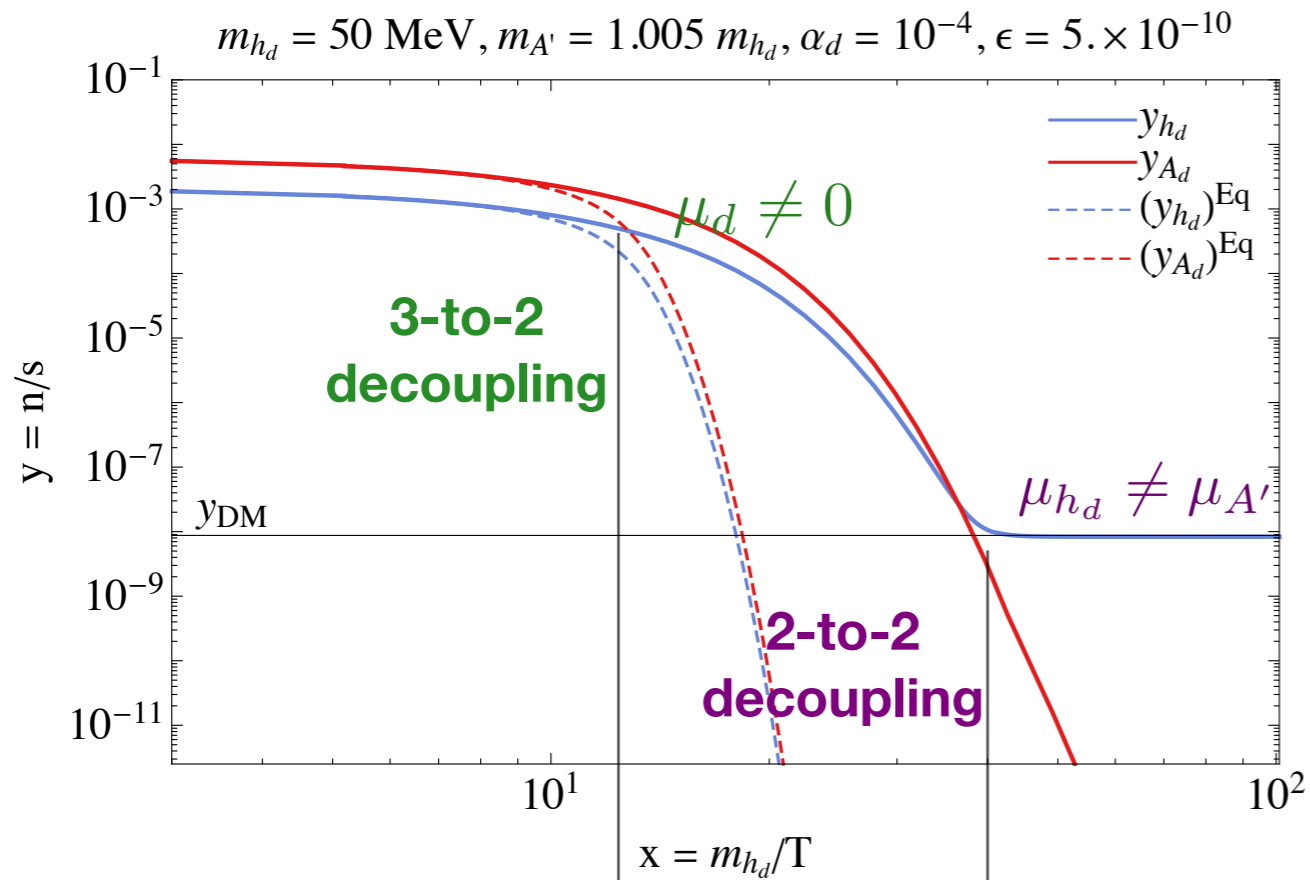
Dark sector evolution



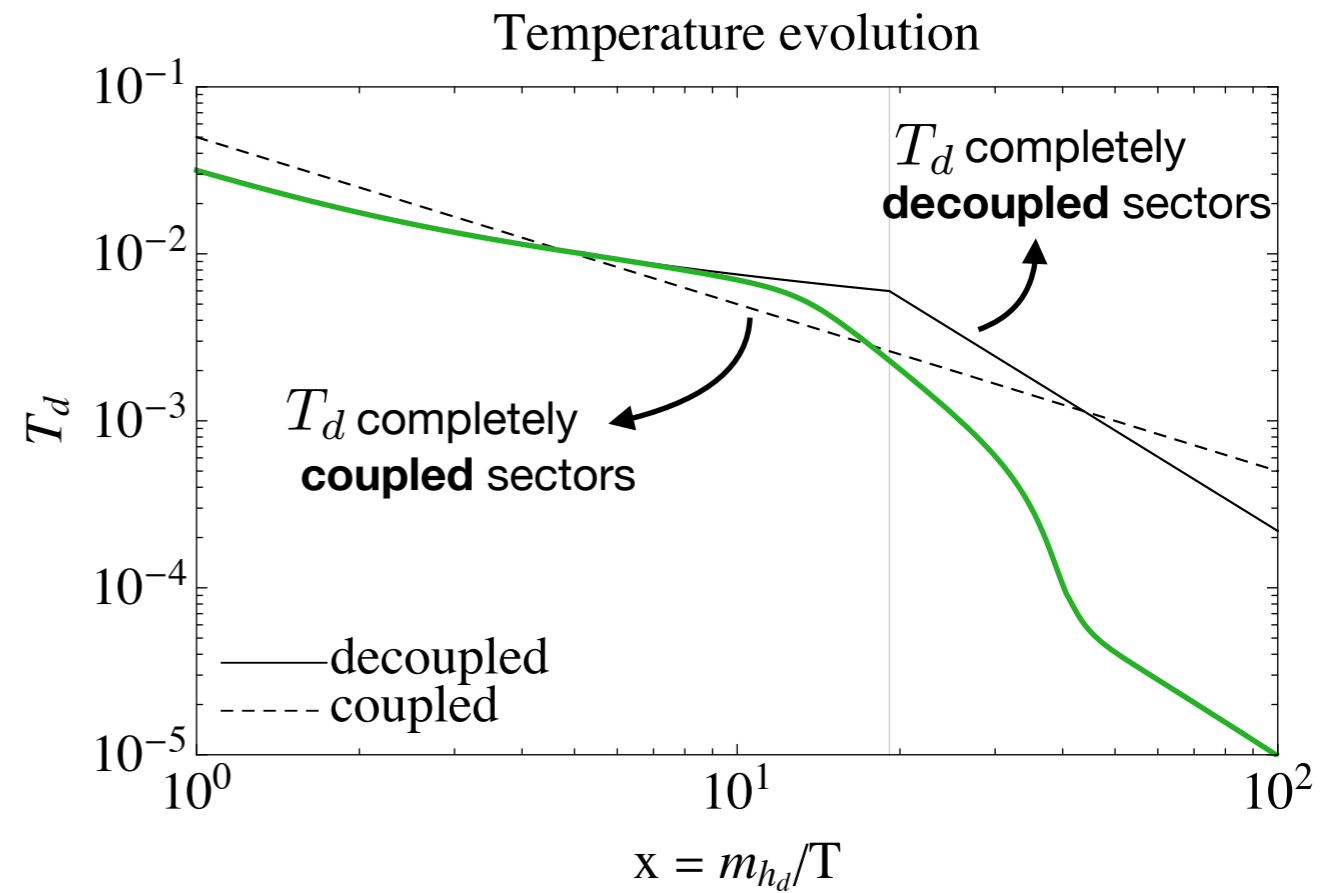
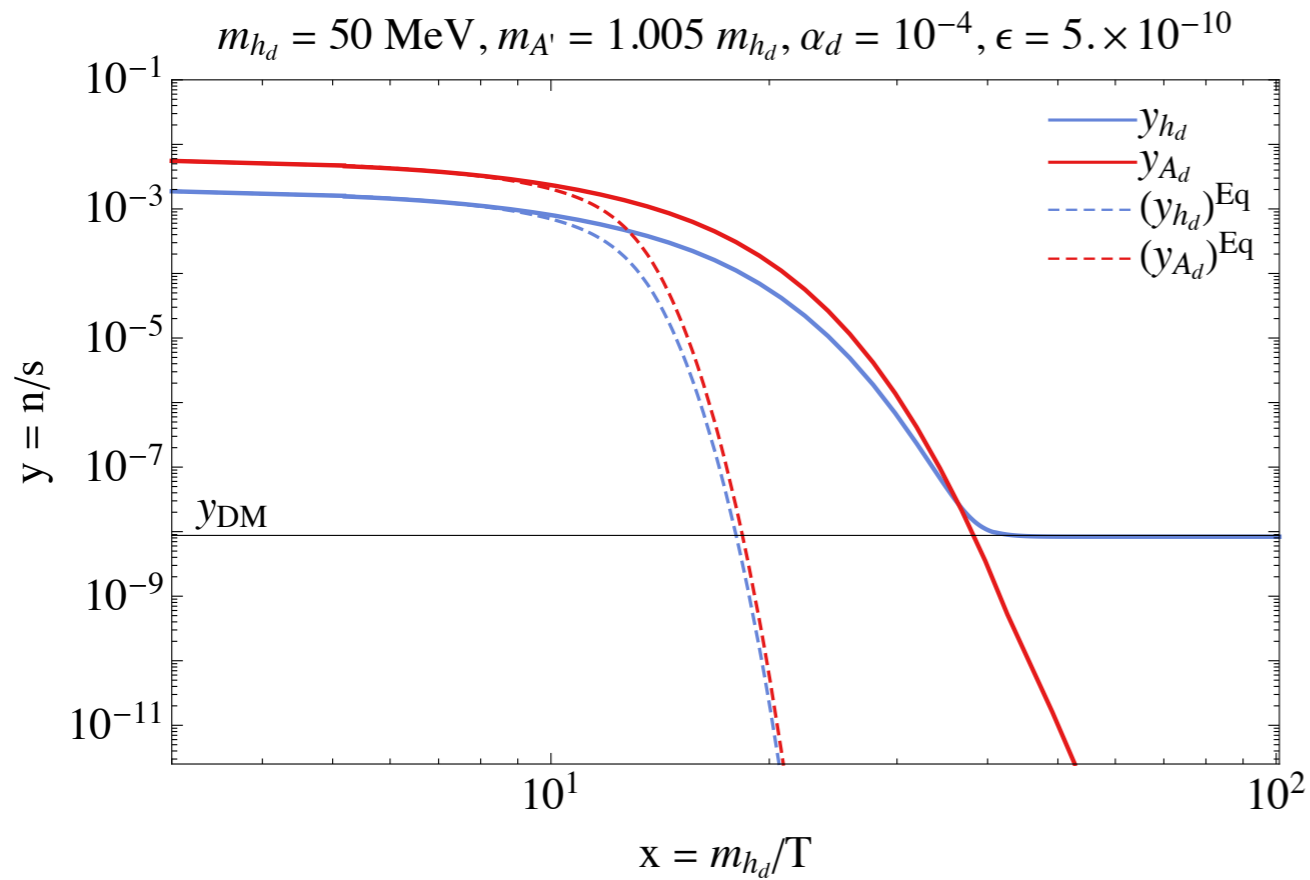
Dark sector evolution



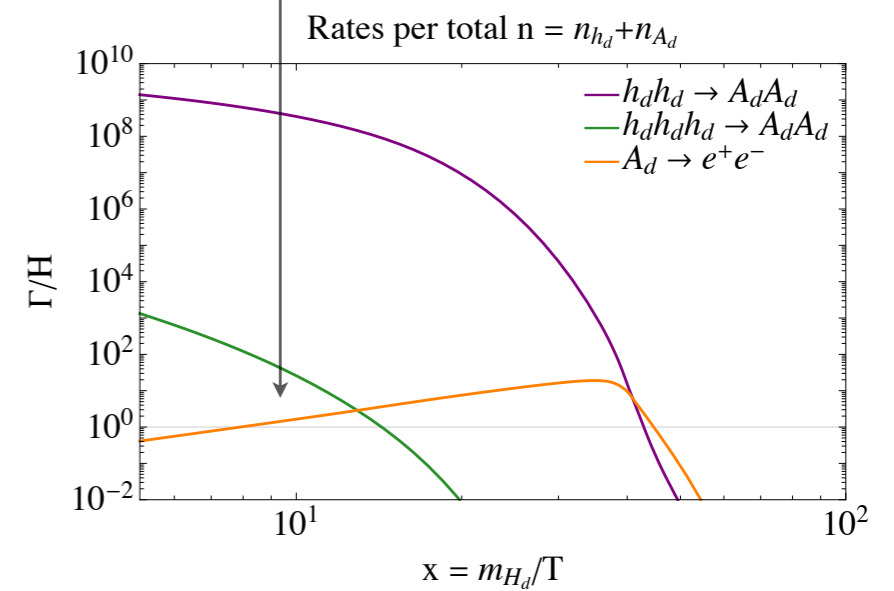
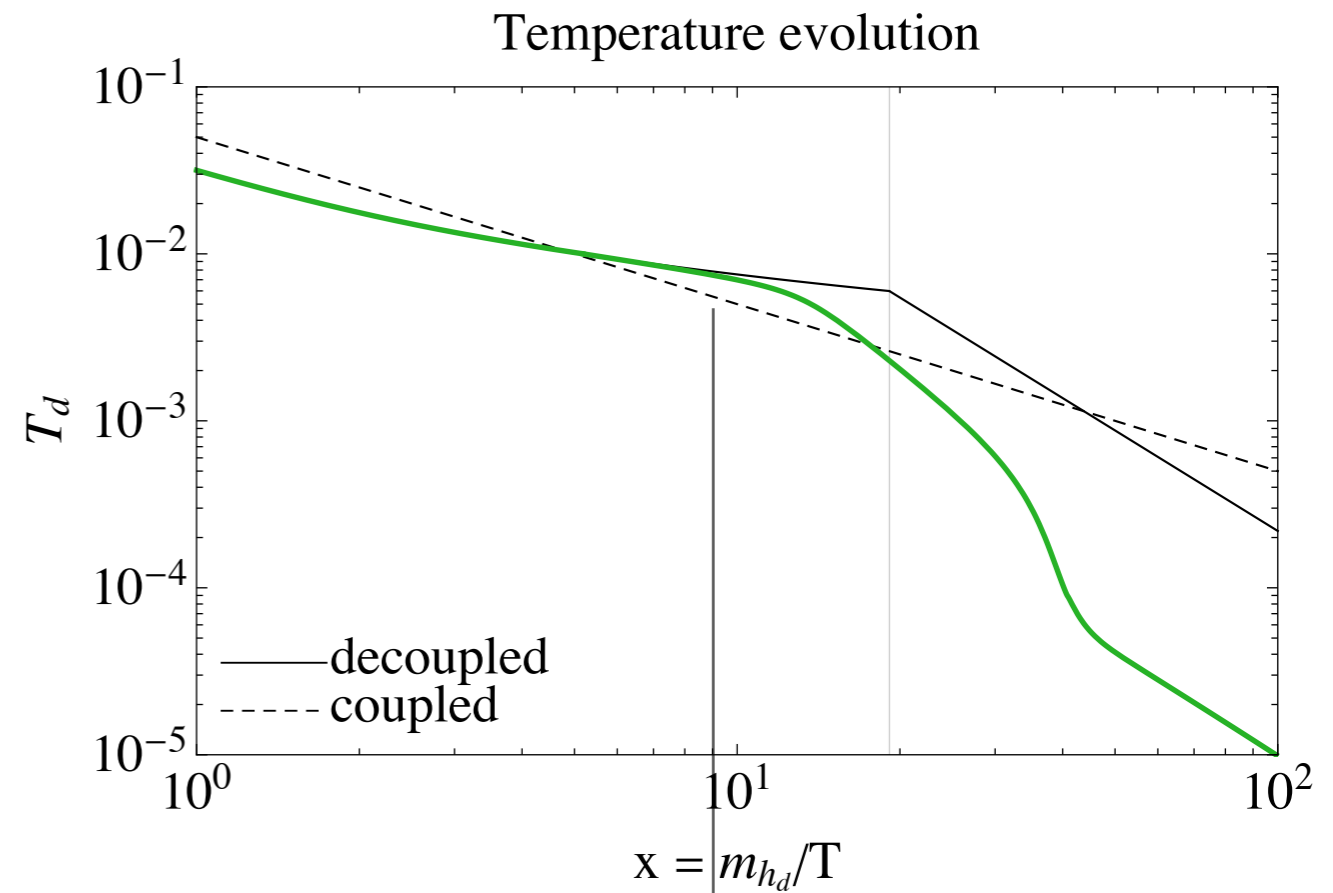
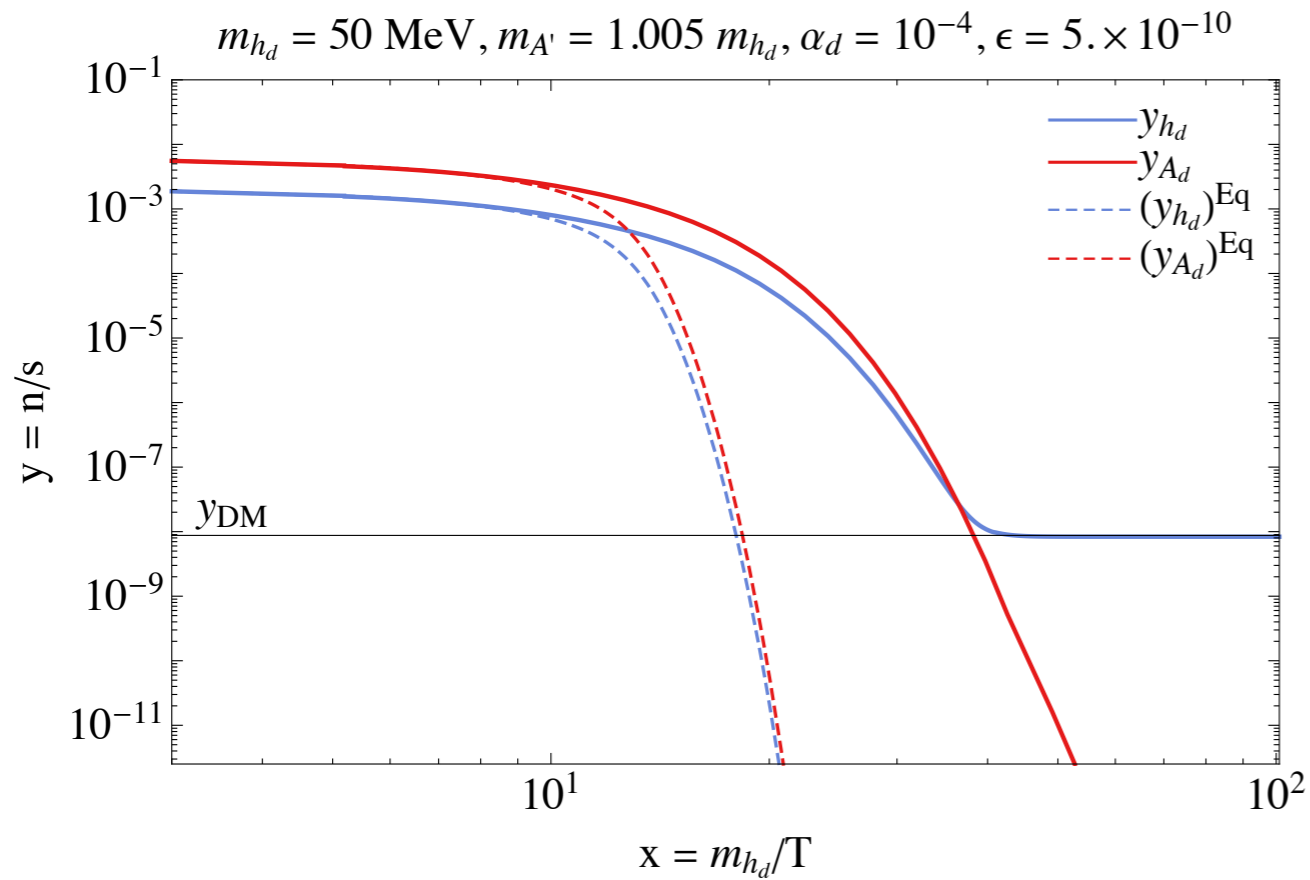
Dark sector evolution



Dark sector evolution



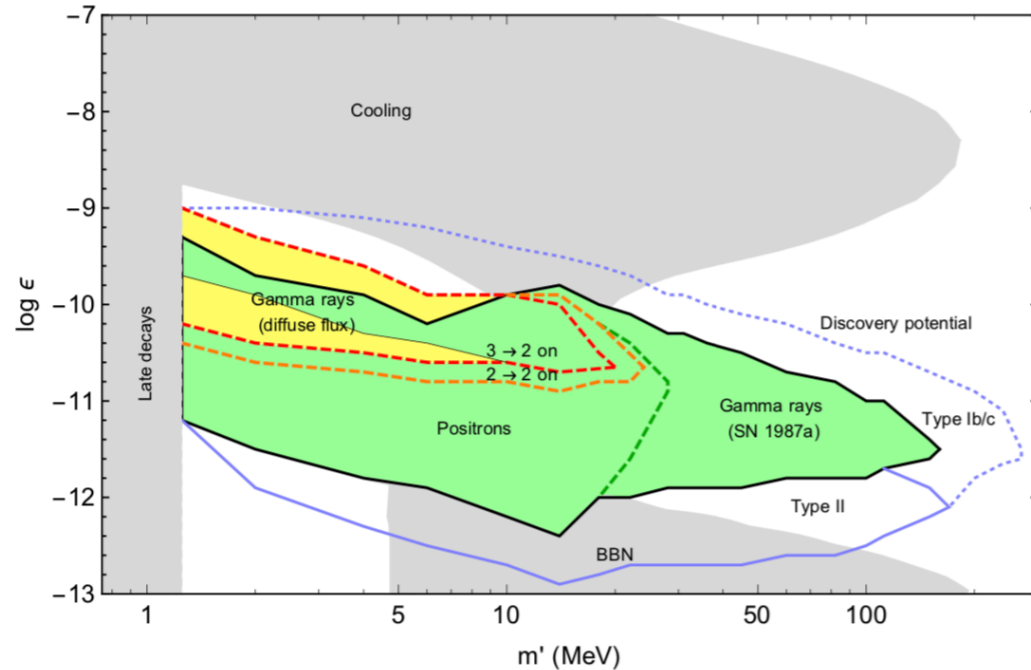
Dark sector evolution



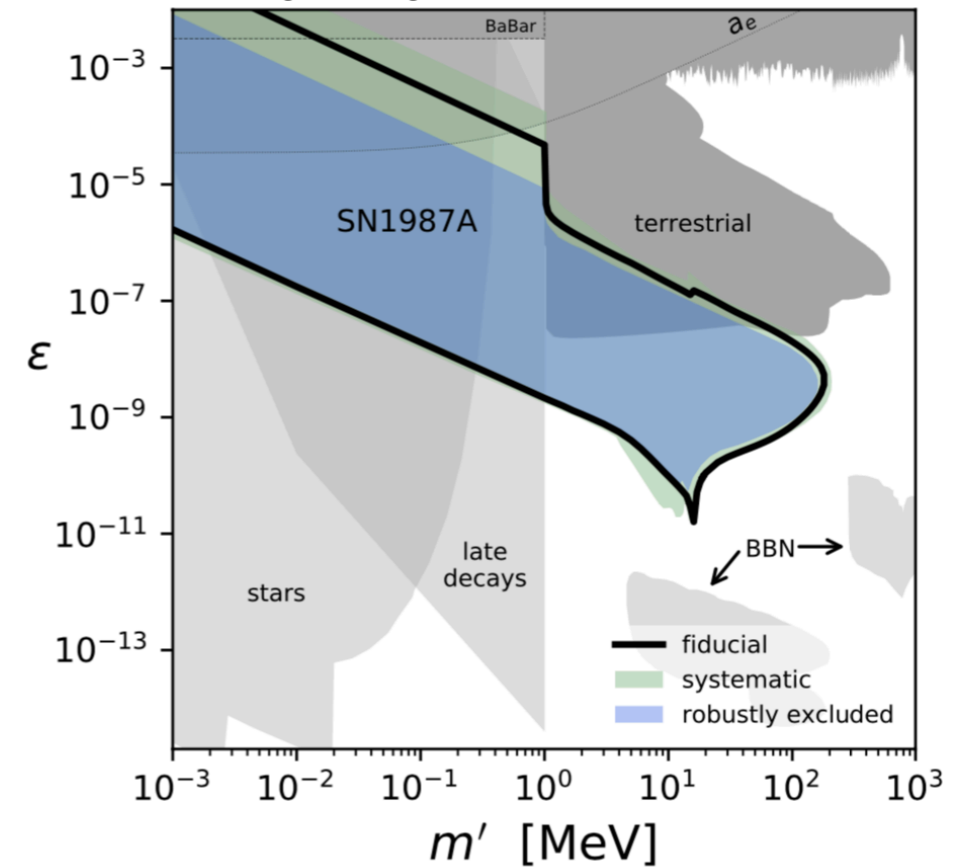
Experimental signatures

- A' in supernovae

DeRocco, Graham, Kasen, Marques-Tavares, and Rajendran, 2019



Chang, Essig, and McDermott, 2016



Is there a supernova bound on axions?

Bar, Blum, and D'Amico, 2019

Summary

- Thermal relic DM could be \neq WIMP \longrightarrow Need for multiple experimental searches
- Coannihilating DM with $\mathcal{O}(1)$ mass splittings \longrightarrow sub-GeV DM that evades CMB bounds
 \searrow DM abundance insensitive to DM coupling

The dark Higgs can be DM:

- Simple model, complicated thermal history!
- Very small ϵ , large α_d \longrightarrow freeze-in DM with self-interaction?