Dark sector freeze-out due to a non-Boltzmann suppression

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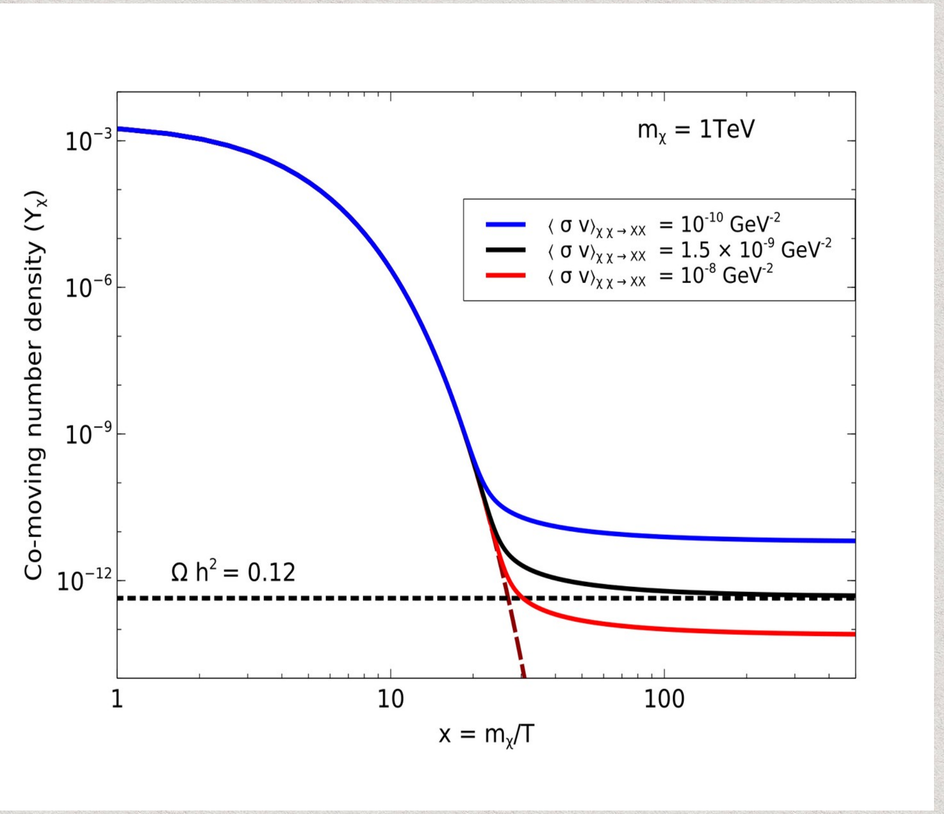
Thermal dark matter: Idea of WIMP

Assumptions:

- **DM is in thermal equilibrium with the SM particles in the early Universe.**
- **DM interacts with the SM particles with weak scale couplings.**



WIMP annihilation cross section considering m_{DM}= 1TeV

$$\langle\sigma v\rangle_{\mathrm{DMDM}\to\mathrm{SMSM}} \simeq \frac{g_2^4}{32\pi m_{\mathrm{DM}}^2} = 1.46\times 10^{-9}\mathrm{GeV}^{-2}$$

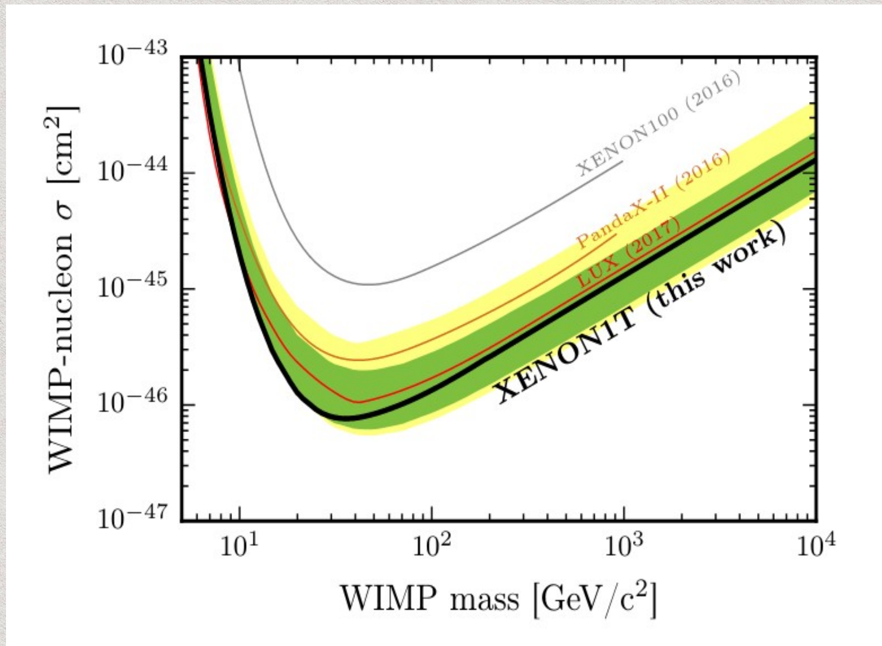
DM of mass 1TeV satisfies the relic density constraint if it couples with the SM particles with weak scale coupling

WIMP Miracle

WIMP Searches

- **Spin-independent DM-nucleon cross-section put stringent constraint on the DM mass and its couplings with the SM particles.**

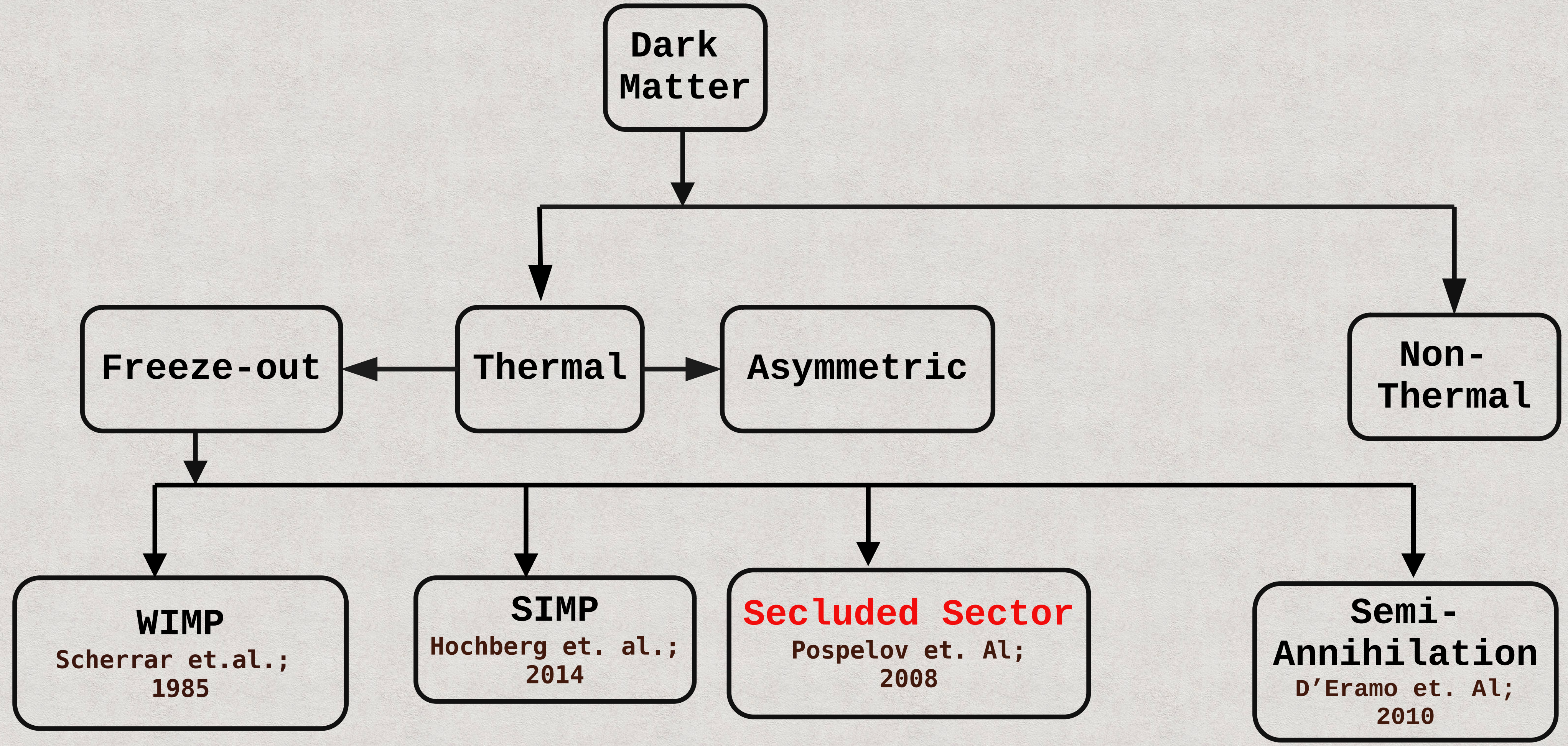
- **In colliders, produce WIMP in association with the SM particles and calculate the missing energy to predict the mass of the WIMP.**



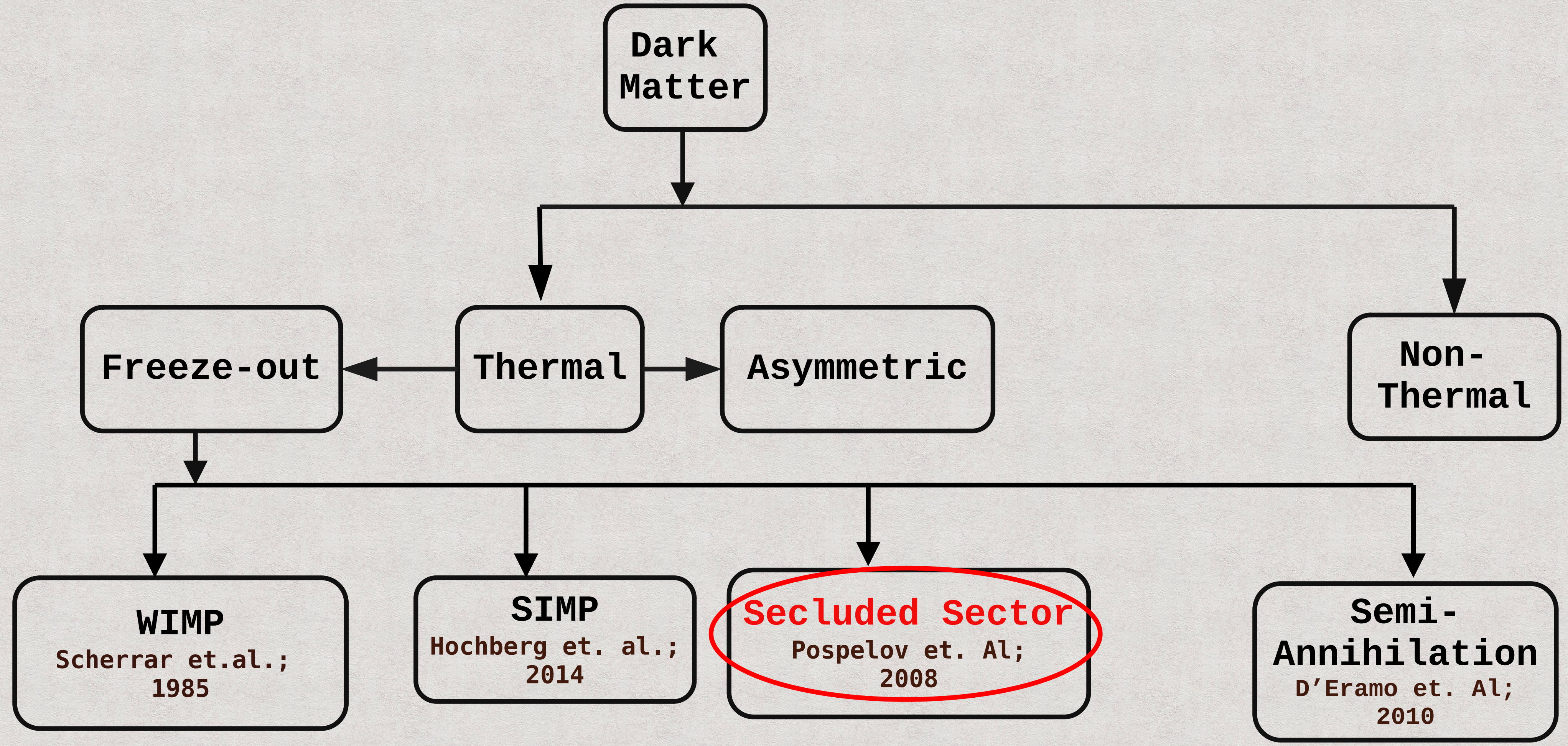
Need to go beyond WIMP

Phys. Rev. Lett. 121 (2018) 111302

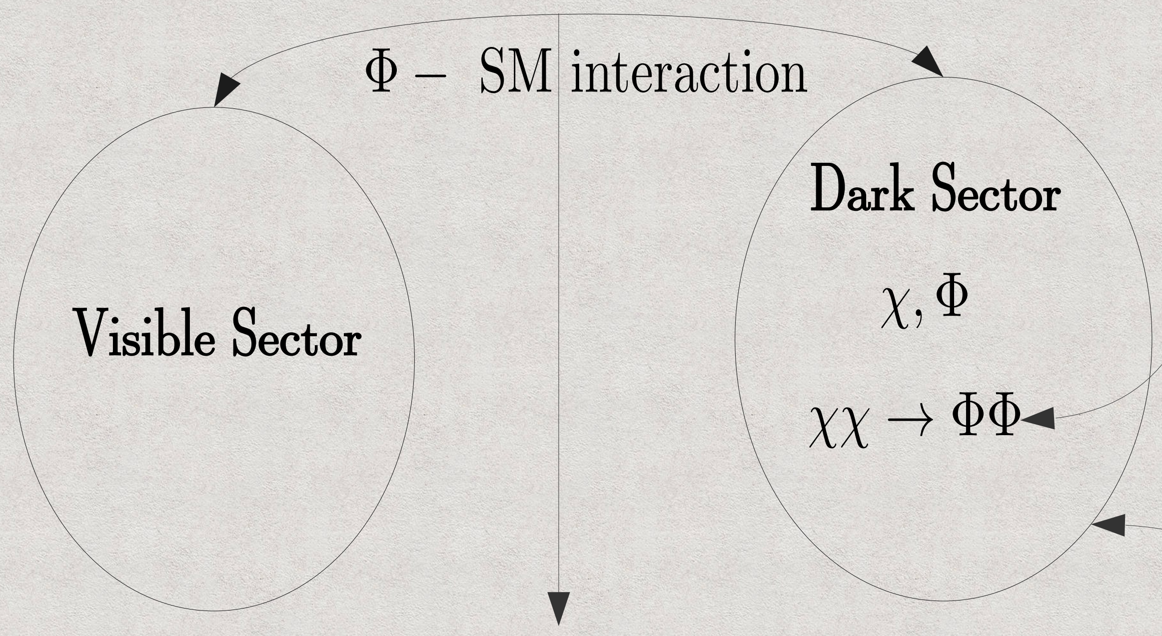
Classifications of particle dark matter: A schematic picture



Classifications of particle dark matter: A schematic picture



Secluded Dark Sector



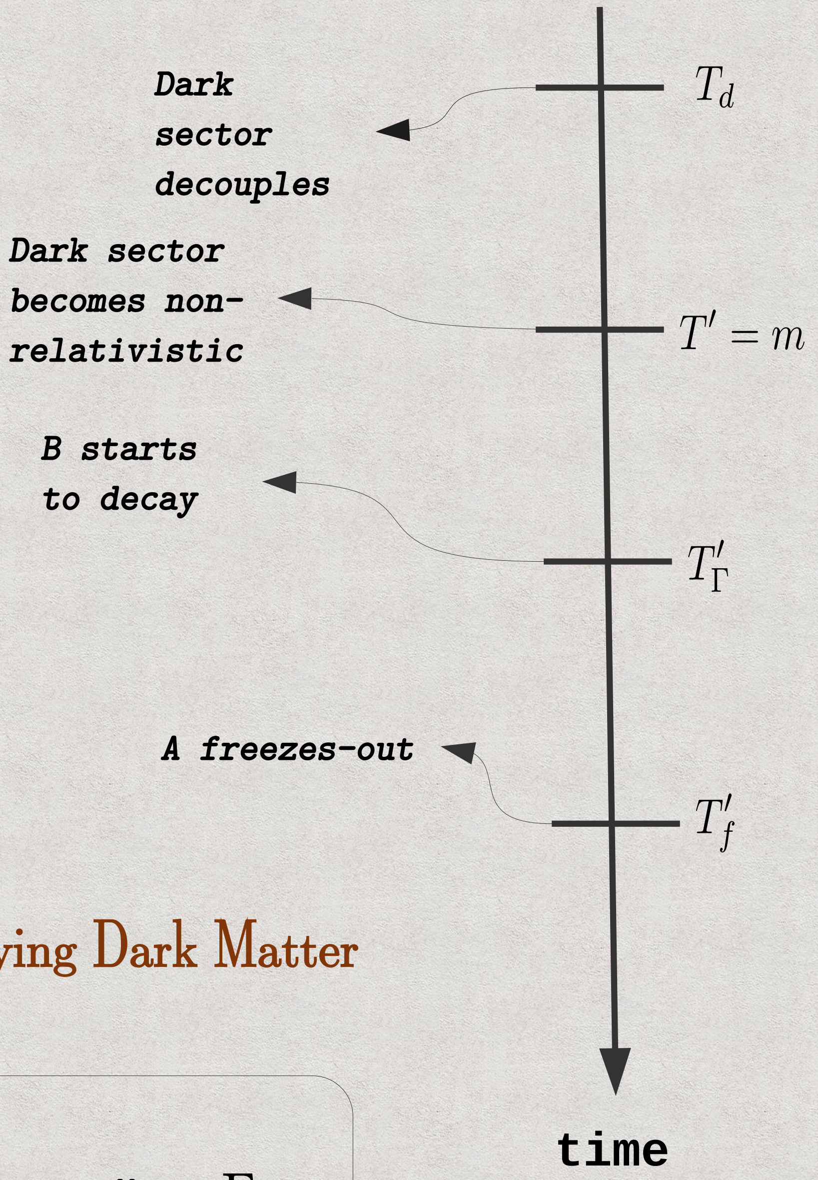
Determines the relic density

- Can be multi-component.
- Can be degenerate.
- Can be thermally decoupled.

- **Constraints from direct searches can be evaded easily**
- **Determines the thermal properties of the dark sector**
- Φ **should decay before BBN**

Degenerate Dark Sector

- *The dark sector contains two particles A and B and they are degenerate i.e. $m_A = m_B = m$*
- *B can decay out-of-equilibrium into the SM particles.*
- *Number density of A starts to decrease when B starts to decay into the SM particles.*



Co-Decaying Dark Matter

Final abundance of A depends on $\langle \sigma v \rangle_{AA \to BB}$ as well as Γ_B

Dror et. al., Phys. Rev. Lett. 117, 211801

Dynamics of a multicomponent degenerate dark sector

- ***We need a DM candidate.***
- ***We need a massive mediator particle, which can decay into SM particles.***

A natural choice $U(1)_X$ extension of SM.

- ***Contains*** ξ_{1L} and ξ_{2L} ***with U(1)$_X$ charges +1 and -1 respectively*** → ***Anomaly free***
- ***A gauge boson*** Z' ***corresponding to the U(1)$_X$ gauge symmetry and it kinetically mixes with SM Z boson.***
- ***A complex scalar*** η ***to break U(1)$_X$ gauge symmetry*** → ***Massive*** Z'

The dark sector contains

- Two Majorana fermions χ_1 and χ_2
- Two mediator particles Z' and h_d

→ *Two component dark matter*

→ γ ***and*** ν ***signals from DM annihilation via one step cascade processes***

A multi-component dark sector

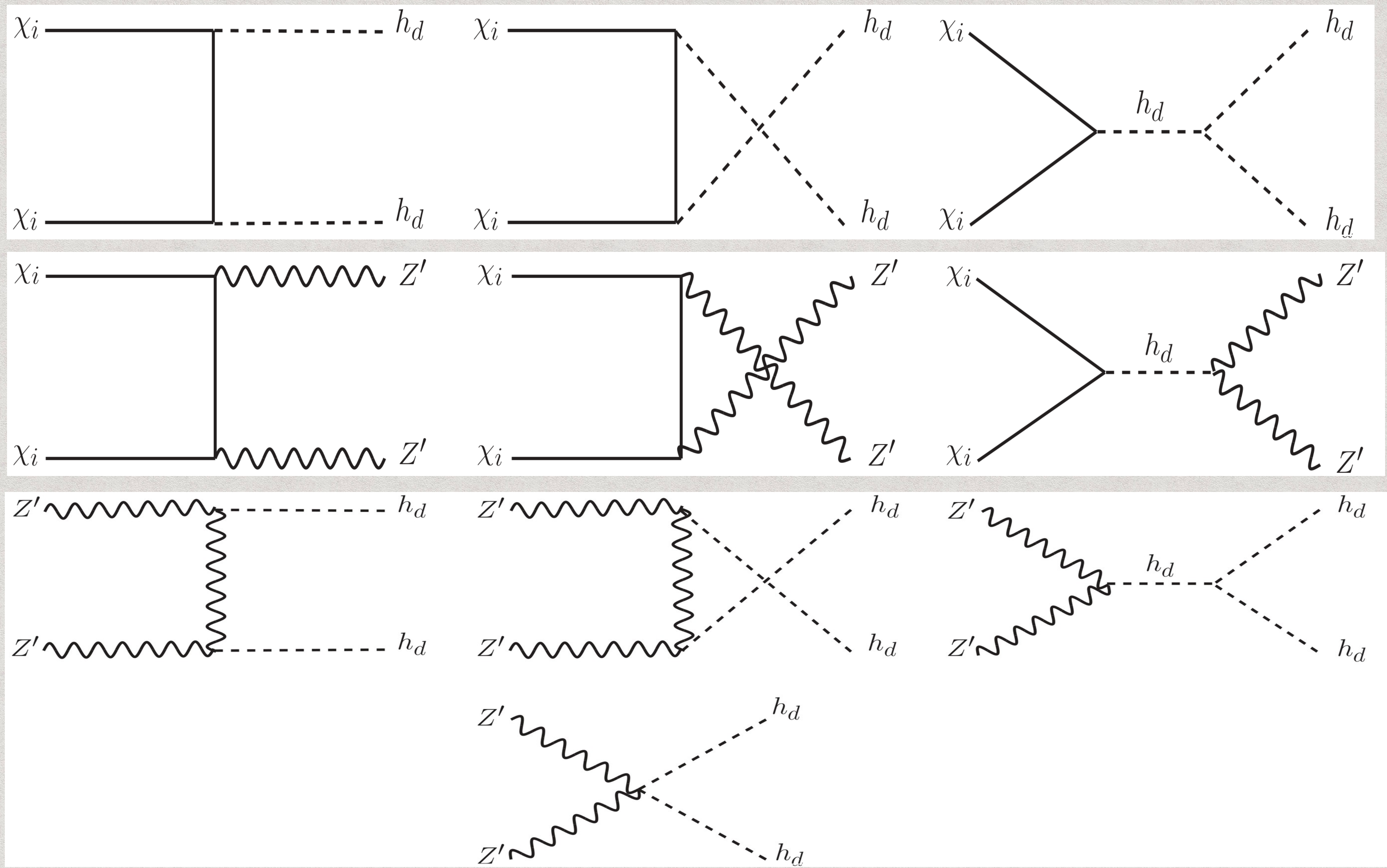
Lagrangian

$$\mathcal{L} \quad = \quad \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm DM-gauge} + \mathcal{L}_{\rm DM-Yukawa} + \mathcal{L}_{\rm scalar} \ ,$$

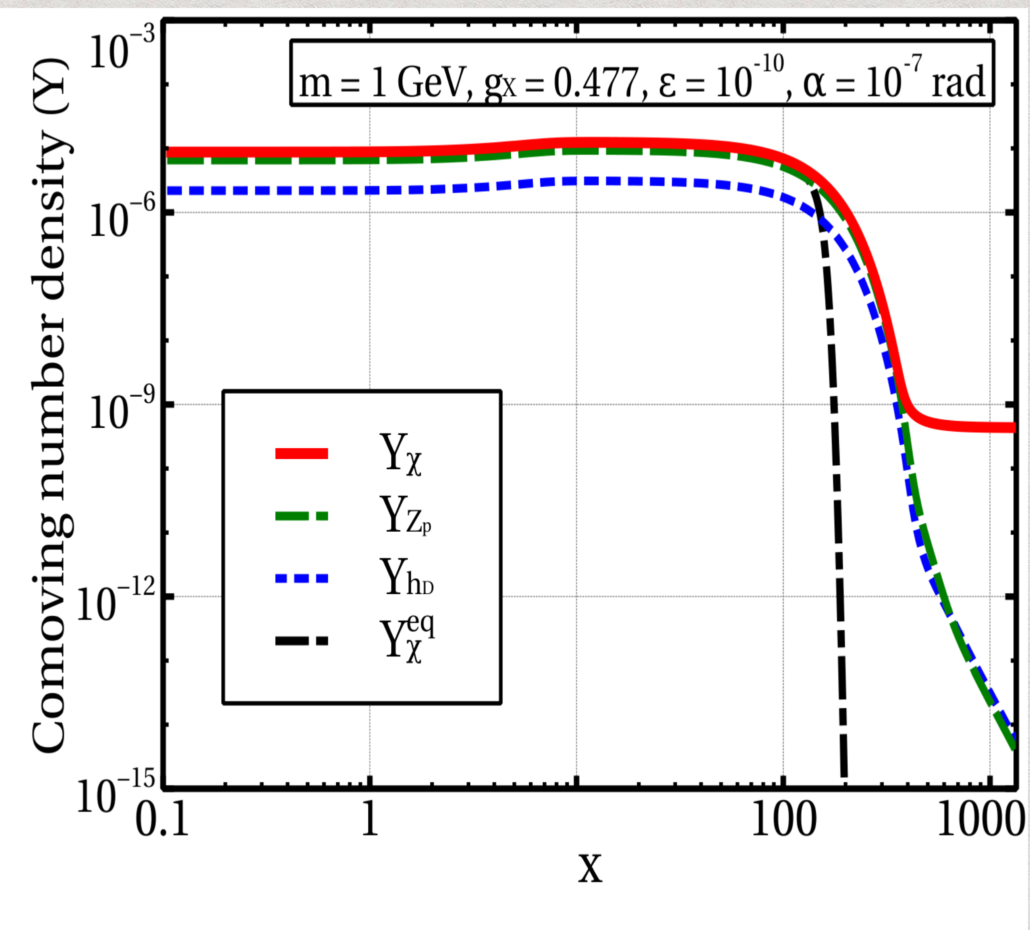
where

$$\begin{aligned}
\mathcal{L}_{\rm gauge} &= -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\epsilon}{2} B_{\mu\nu} X^{\mu\nu} \ , \\
\mathcal{L}_{\rm DM-gauge} &= i\,\overline{\xi_{1L}} \not{D} \xi_{1L} + i\,\overline{\xi_{2L}} \not{D} \xi_{2L} \ , \\
\mathcal{L}_{\rm DM-Yukawa} &= -\left(\frac{y}{2} \overline{\xi_{1L}^c} \xi_{1L} \eta + \frac{y}{2} \overline{\xi_{2L}^c} \xi_{2L} \eta^\dagger + h.c \right) \ , \\
\mathcal{L}_{\rm scalar} &= (D_\mu \eta^\dagger)(D^\mu \eta) + \mu_X^2 (\eta^\dagger \eta) - \lambda_X (\eta^\dagger \eta)^2 - \lambda' (\eta^\dagger \eta)(\Phi^\dagger \Phi) \ .
\end{aligned}$$

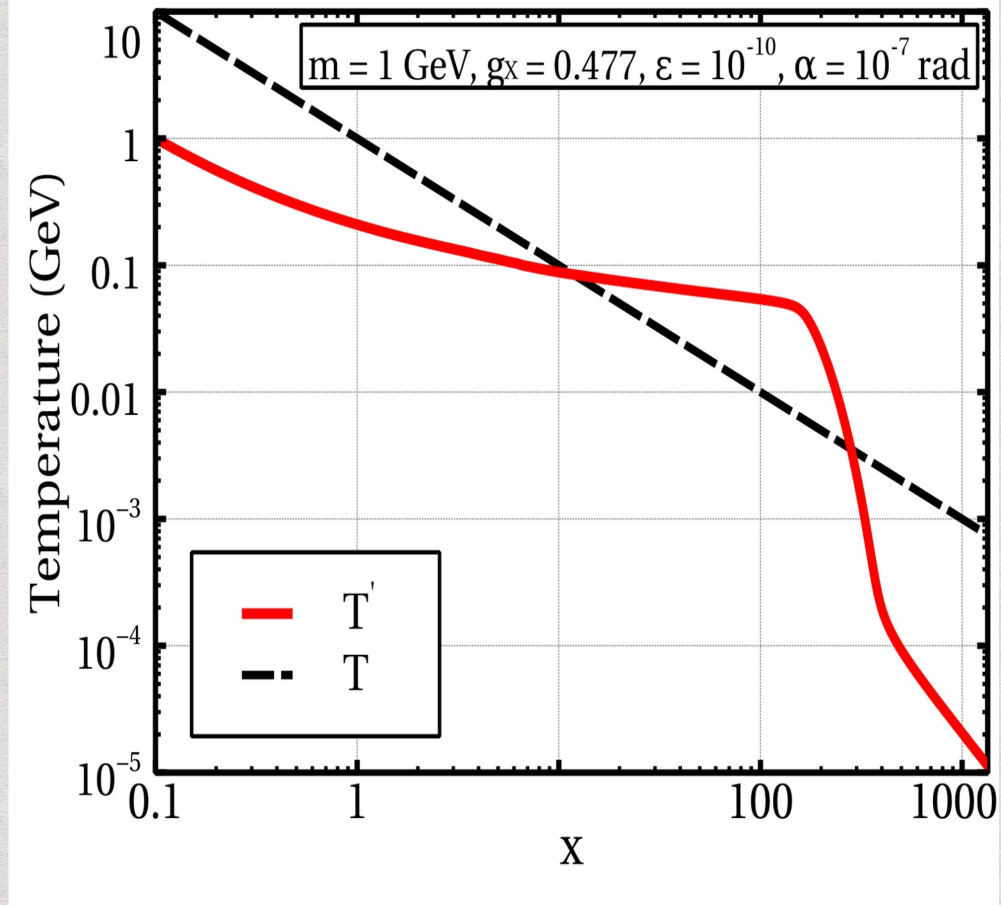
DM annihilation channels



Results

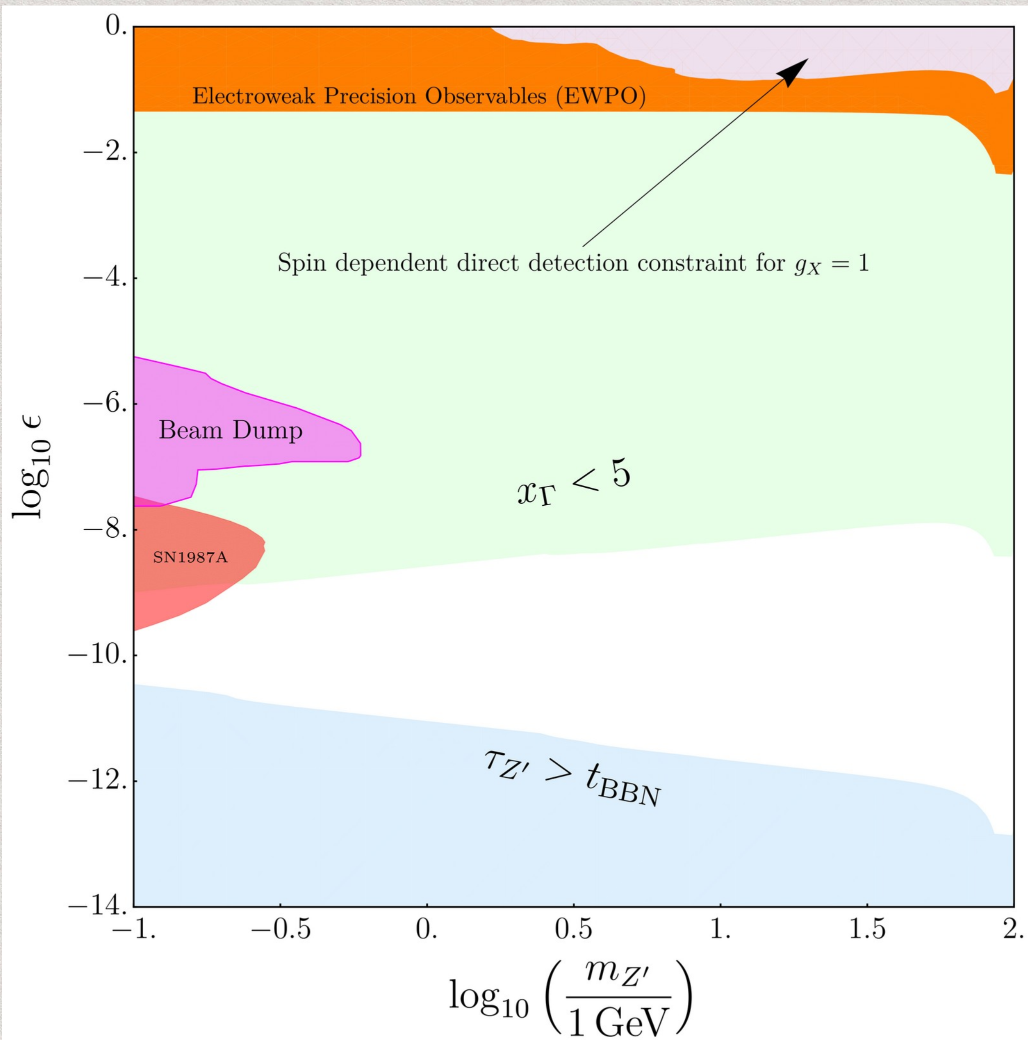


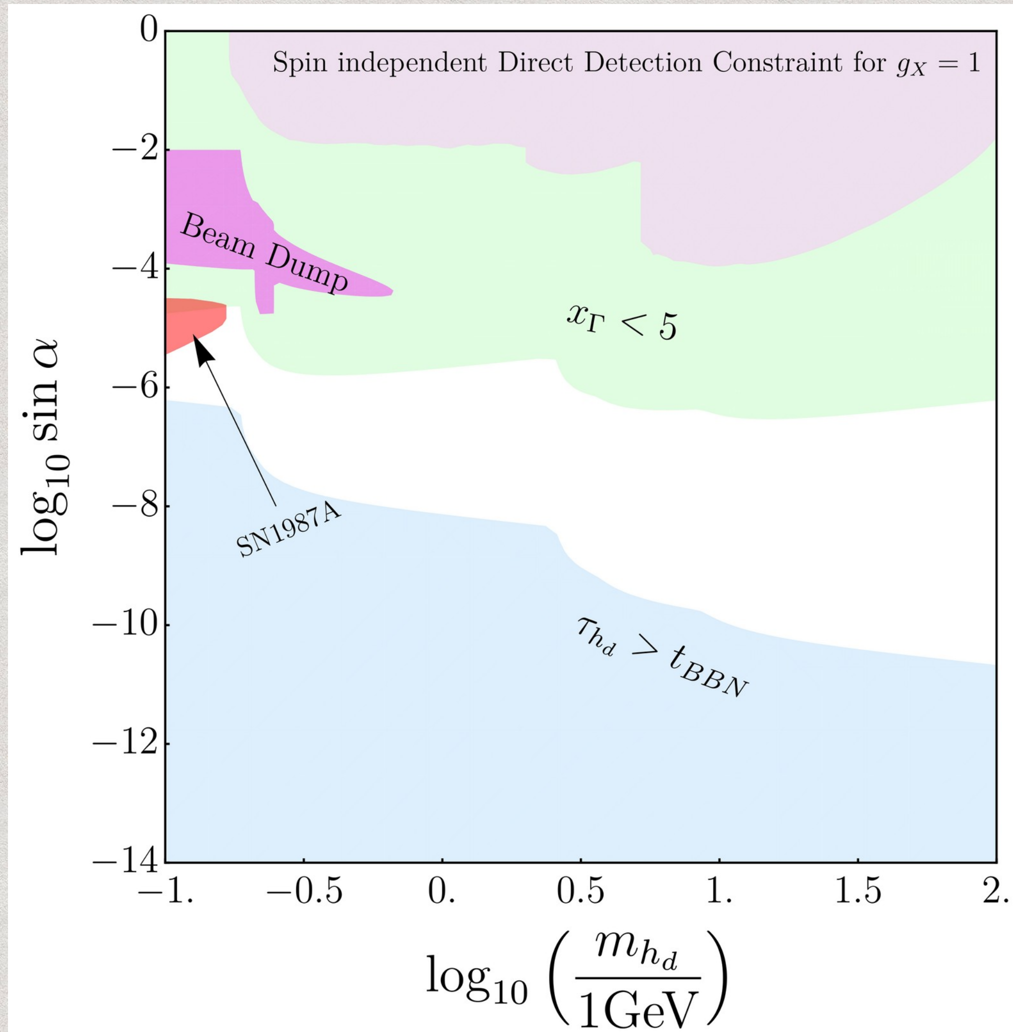
m = 1 GeV, gX = 0.477, ε = 10^-10, α = 10^-7 rad
Comoving number density (Y)
10^-3
10^-6
10^-9
10^-12
10^-15
0.1
1
100
1000
x
Yχ
YZp
YhD
Yχ^eq



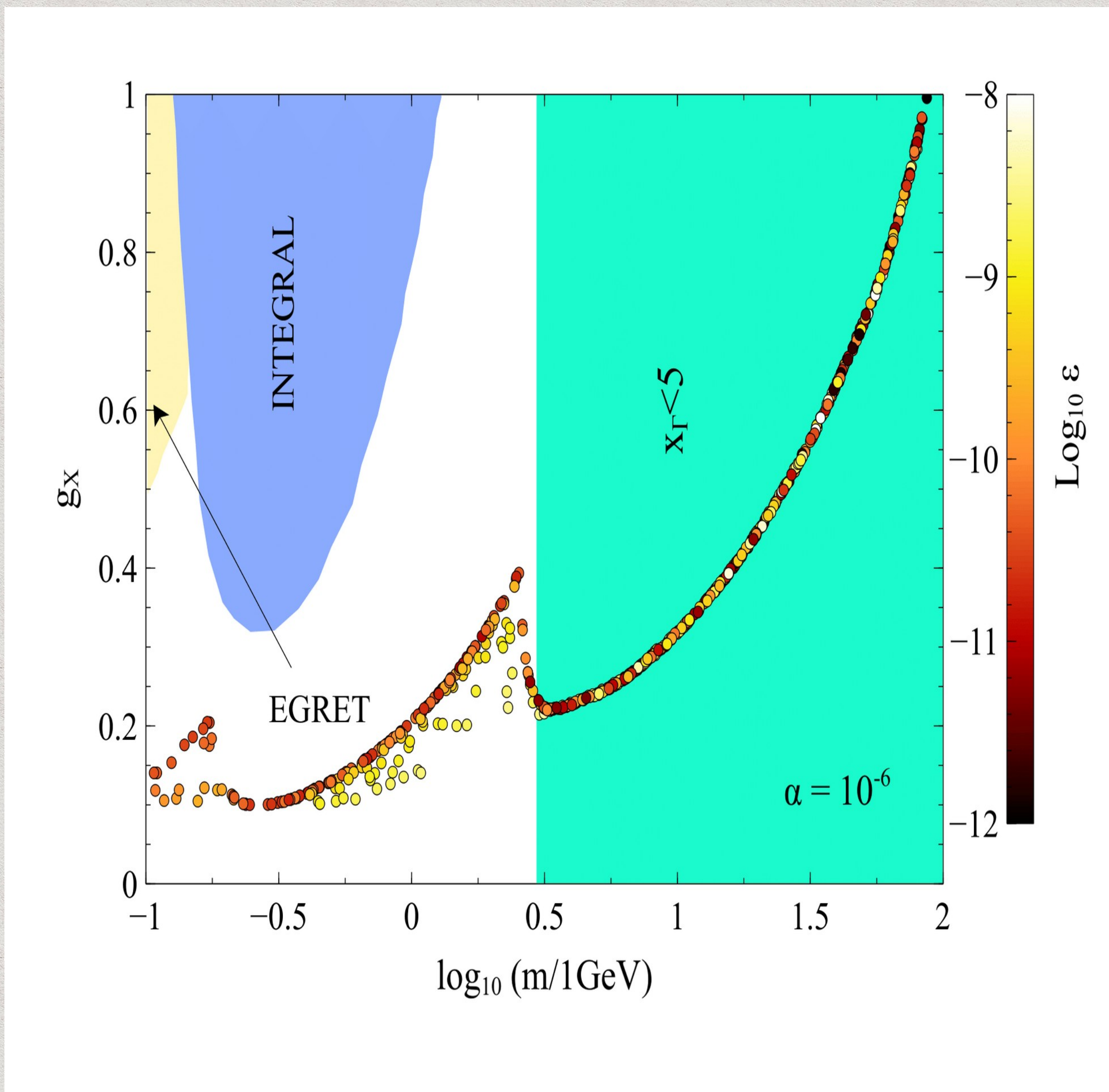
m = 1 GeV, gX = 0.477, ε = 10^-10, α = 10^-7 rad
Temperature (GeV)
10
1
0.1
0.01
10^-3
10^-4
10^-5
0.1
1
100
1000
x
T'
T

Constraints on the mediator particles





m-g_X plane



INTEGRAL
EGRET
$x_\Gamma<5$
$\alpha = 10^{-6}$
g_X
$\log_{10}$ (m/1GeV)
$\mathrm{Log}_{10}\ \varepsilon$

Summary

The out-of-equilibrium decay of long-lived mediator particle such as Z' and h_d leading to delayed freeze-out of Dark Matter and this is known as "Co-Decaying Dark Matter".

The dark sector enters into the "Cannibal" phase due to the presence of $3 \to 2$ processes and during this phase the temperature evolution changes significantly.

We have investigated the allowed region of parameter space from ν and γ ray signals from DM annihilation via one step cascade process.

The bounds from direct, indirect, laboratory and astrophysical searches can be easily evaded in case of degenerate dark sector. However for non-degenerate dark sector, a certain region of the parameter space is significantly constrained from the measurement of diffuse γ ray flux by INTEGRAL, CMB anisotropy, and positron flux by AMS-02 experiment.

Thank You

Back-up slides