Secluded Dark Sector and Muon $(g-2)$ in the Light of Modified Cosmology

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Based on
i) JCAP 05(2022)019
ii) JCAP 02(2023)044
in collaboration with Ananya Tapadar and Sourov Roy

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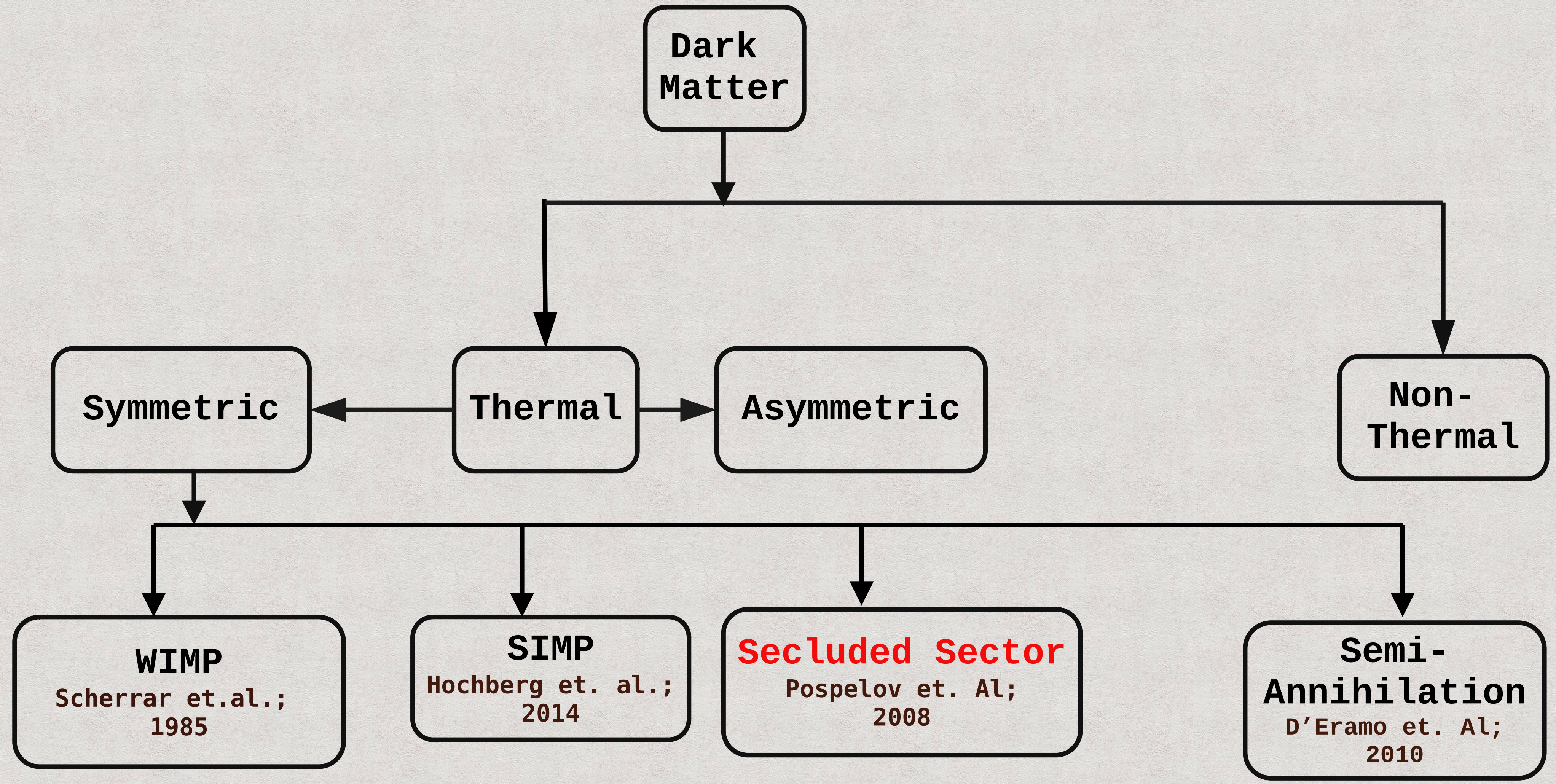
Classifications of particle dark matter: A schematic picture



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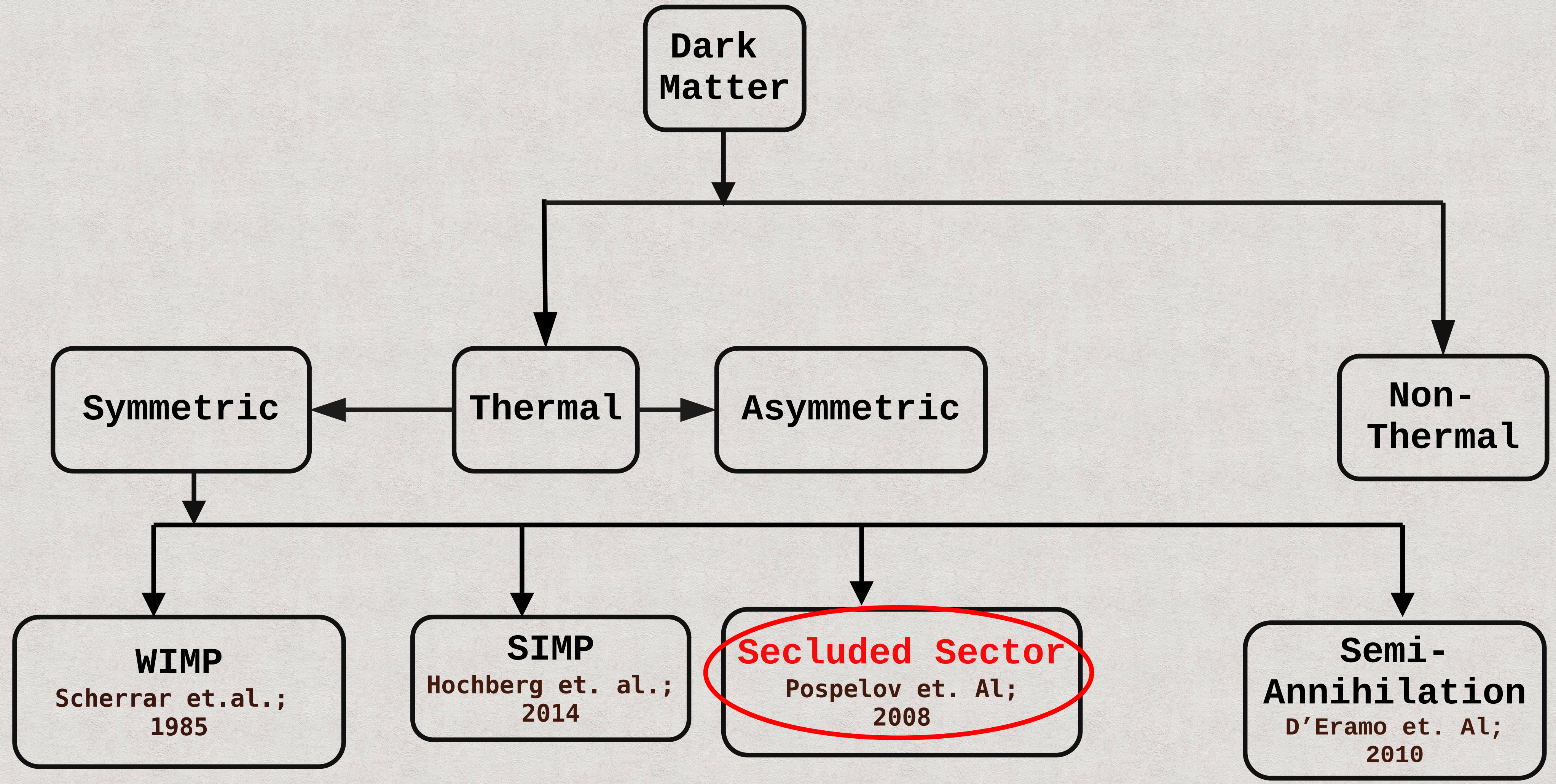

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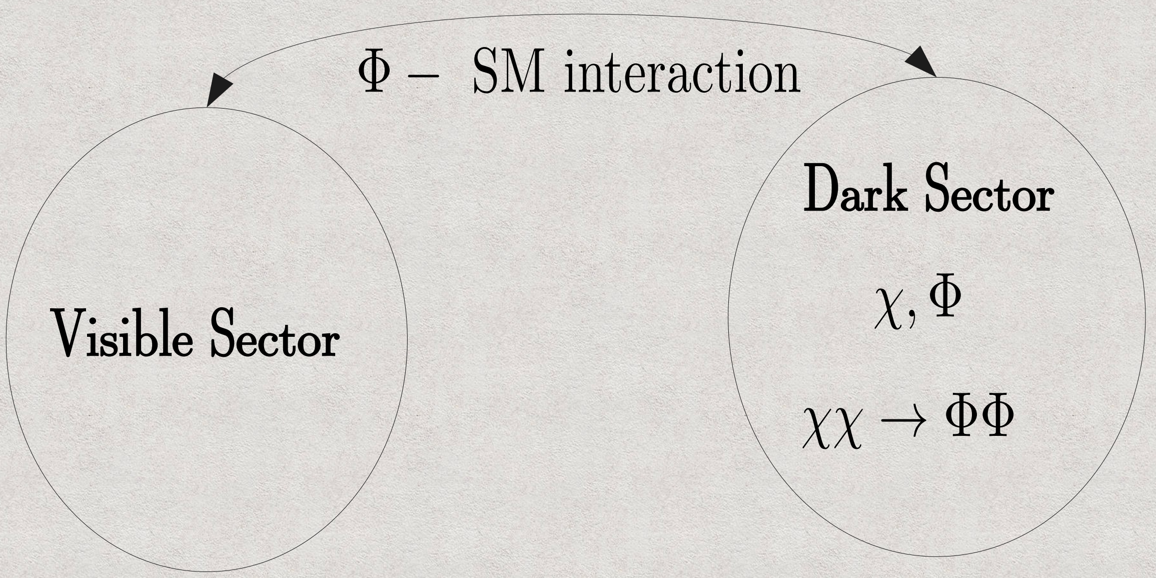

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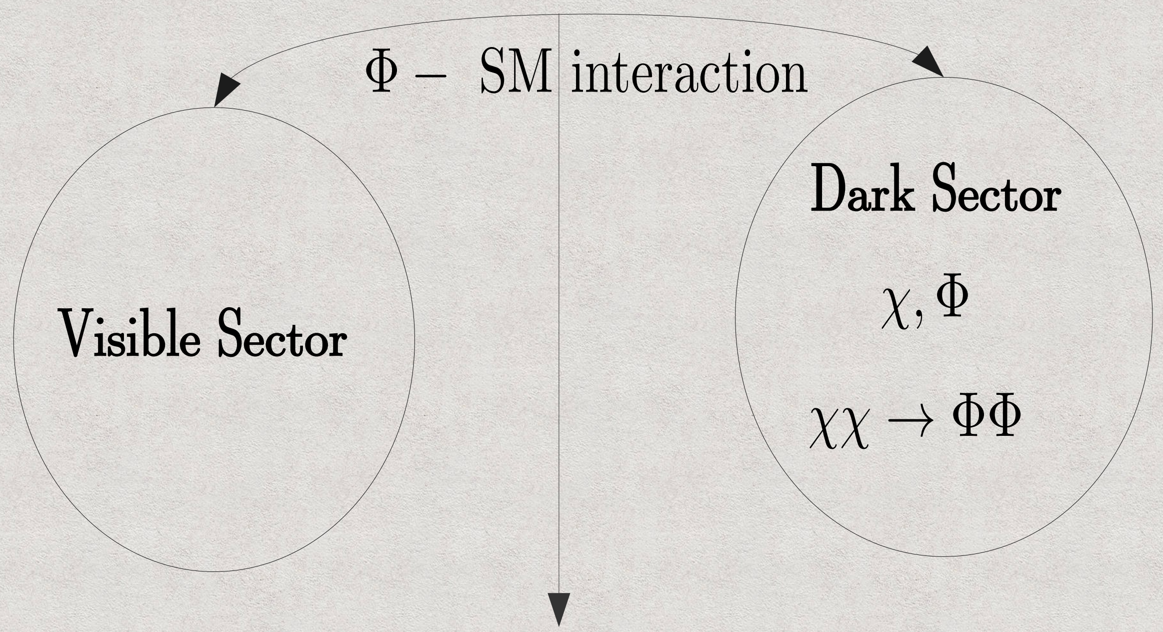

- Constraints from direct searches can be evaded easily
- Determines the thermal properties of the dark sector

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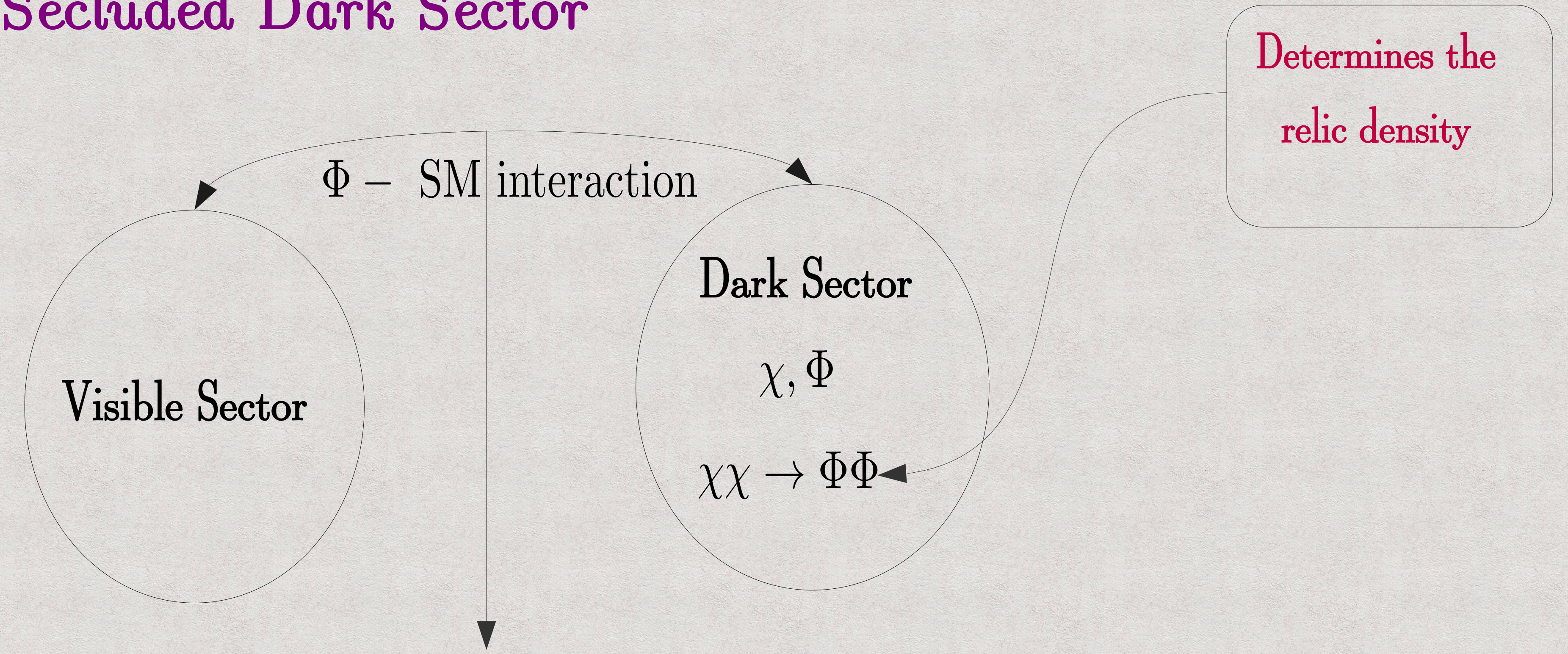

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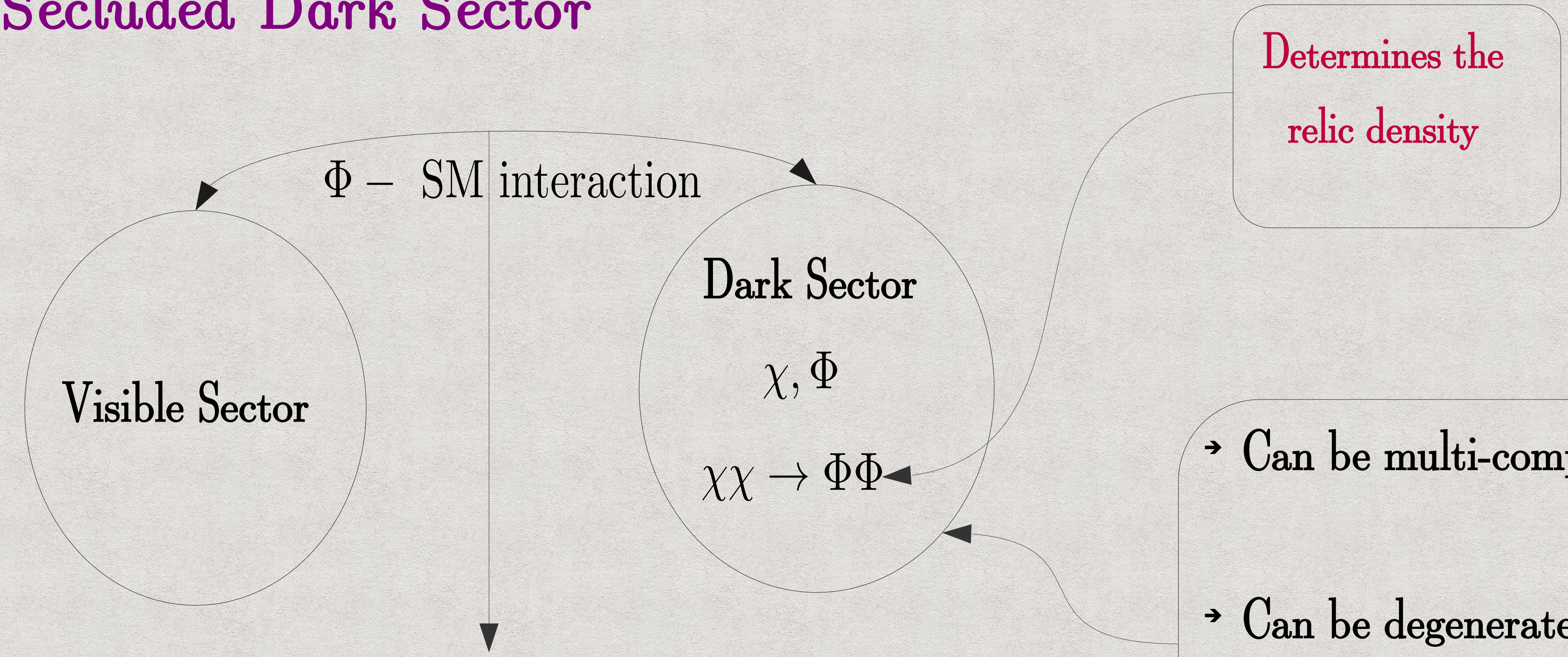

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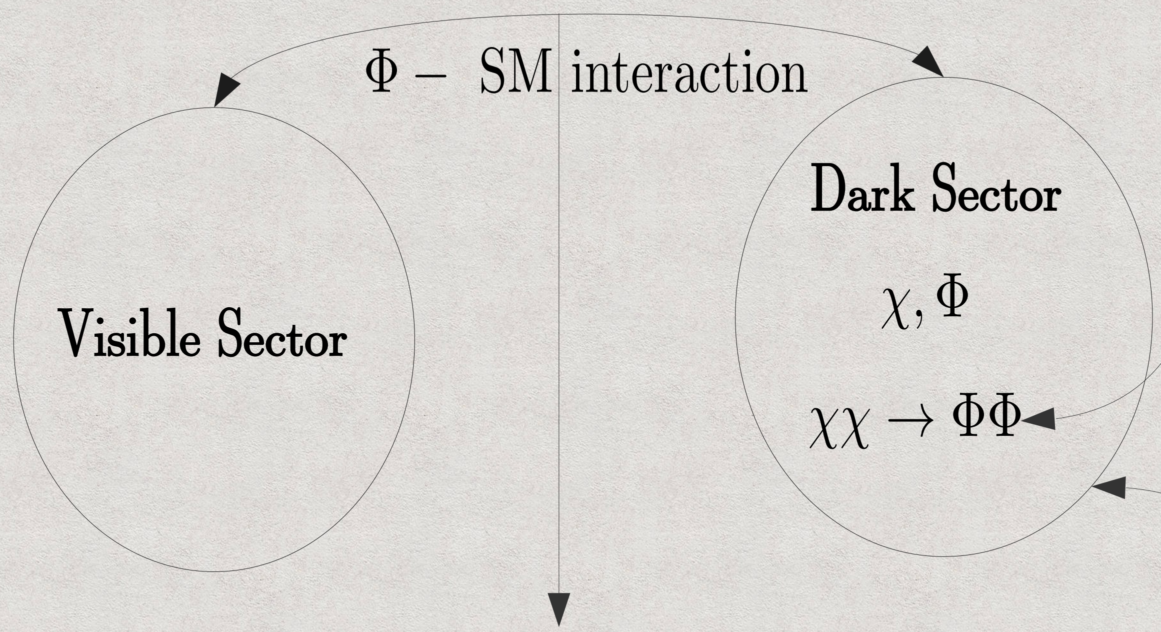
- Determines the thermal properties of the dark sector

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

Secluded Dark Sector

Determines the relic density



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Assuming the dark sector is internally thermalised

$$\rho' = \frac{\pi^2}{30} g'_\rho T'^4$$

Define

$$\xi(T) = \frac{T'}{T} \ll 1$$

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$$\xi(T) \simeq \left[\int_T^{T_0} \frac{30\mathcal{C}_{SM\to DS}(\bar{T})}{g'_\rho \pi^2 \bar{T}^5 H(\bar{T})} d\bar{T}\right]^{1/4}$$

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Dark sector only couples with the SM fields which are charged under $U(1)_{L_\mu - L_\tau}$ gauge symmetry.

Dark Matter phenomenology is less constrained since it is not coupled with the first generation of leptons and quarks at tree level.

The Model

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$$
\begin{aligned}
\mathcal{L} \quad = \quad & \mathcal{L}_{\mathrm{SM}} + \bar{\chi}\left(i\partial\!\!\!/ - m\right)\chi - \frac{1}{4}\hat{X}^{\rho\sigma}\hat{X}_{\rho\sigma} - \frac{1}{4}\hat{F}^{\rho\sigma}_{\mu\tau}\hat{F}_{\mu\tau_{\rho\sigma}} \\
& - g_X\bar{\chi}\gamma^{\rho}\chi\hat{Z}'_{\rho} - g_{\mu\tau}\left(\bar{\mu}\gamma_{\rho}\mu + \bar{\nu}_{\mu}\gamma_{\rho}P_L\nu_{\mu} - \bar{\tau}\gamma_{\rho}\tau - \bar{\nu}_{\tau}\gamma_{\rho}P_L\nu_{\tau}\right)\hat{Z}^{\rho}_{\mu\tau} \\
& + \frac{1}{2}\hat{m}^2_{\mu\tau}\hat{Z}^{\rho}_{\mu\tau}\hat{Z}_{\rho} + \frac{1}{2}\hat{m}'^2\hat{Z}'^{\rho}\hat{Z}'_{\rho} + \frac{\sin\delta}{2}\hat{F}^{\rho\sigma}_{\mu\tau}\hat{X}_{\rho\sigma}
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Kinetic mixing

The Model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar\chi \left(i\partial\!\!\!/ - m\right)\chi - \frac{1}{4}\hat X^{\rho\sigma}\hat X_{\rho\sigma} - \frac{1}{4}\hat F^{\rho\sigma}_{\mu\tau}\hat F_{\mu\tau_{\rho\sigma}}$$
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Kinetic mixing

Mass basis

$$\mathcal{L} \supset -g_X\bar\chi\gamma^\rho\chi Z'_\rho + \epsilon\left(\bar\mu\gamma^\rho\mu + \bar\nu_\mu\gamma^\rho P_L\nu_\mu - \bar\tau\gamma^\rho\tau - \bar\nu_\tau\gamma^\rho P_L\nu_\tau\right)Z'_\rho$$

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Determines the dark sector

freeze-out

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Determines the dark sector freeze-out

$$\epsilon = g_{\mu\tau}\frac{m'^2}{m^2_{\mu\tau}}\tan\delta$$

Determines the temperature evolution of the dark sector as well as the population of dark sector particles

Dark Matter Number Density

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$$\frac{dY_{\rm tot}}{dx} = \frac{h_{\rm eff}(x)}{2}\frac{s(x)}{xH(x)}\langle\sigma v\rangle^{T'}_{\bar\chi\chi\to Z'Z'}\left(Y_{{\rm eq}_{\rm tot}}(T',T)^2 - Y^2_{\rm tot}\right)$$

Dark Sector Freeze-out, depends on the

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Production of DM from the SM bath

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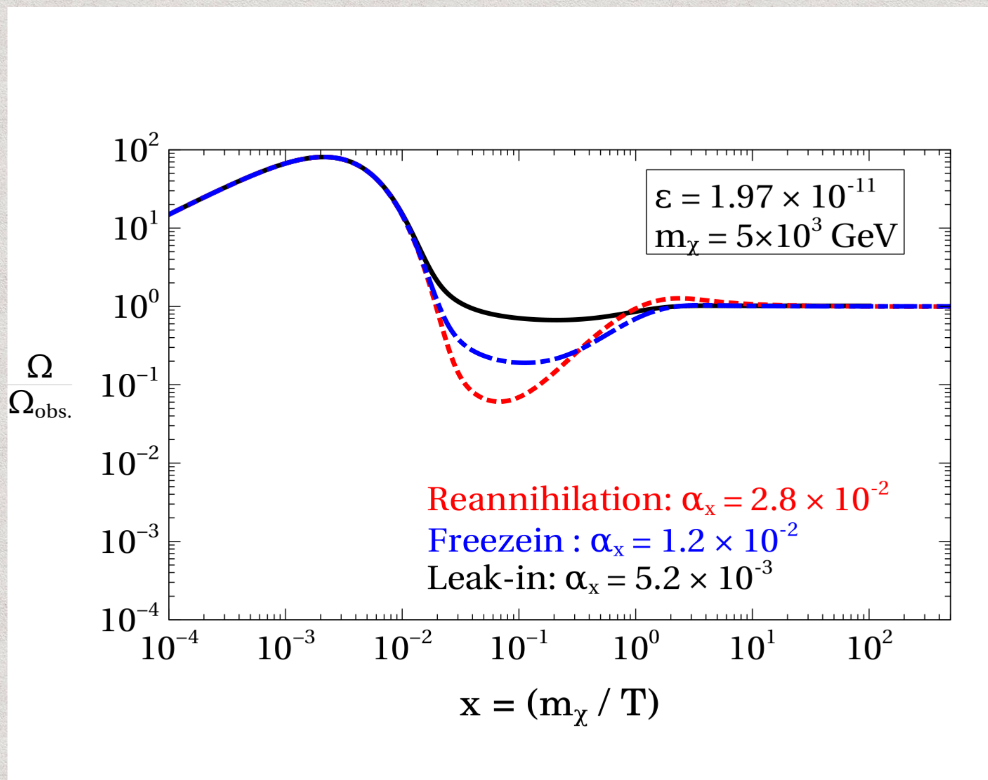
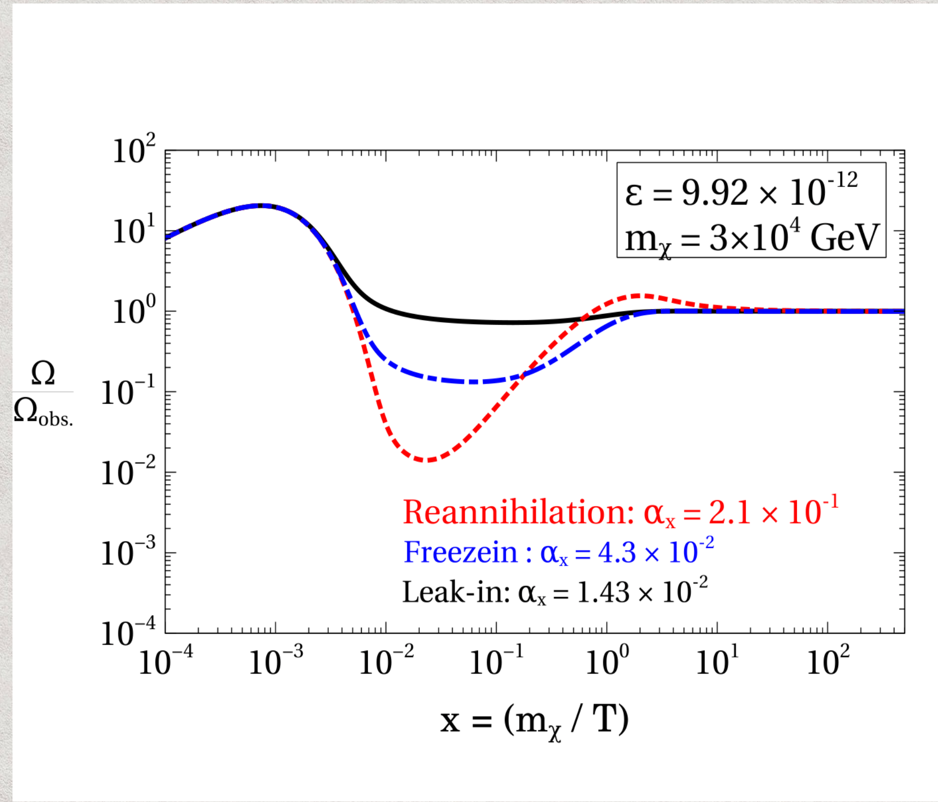
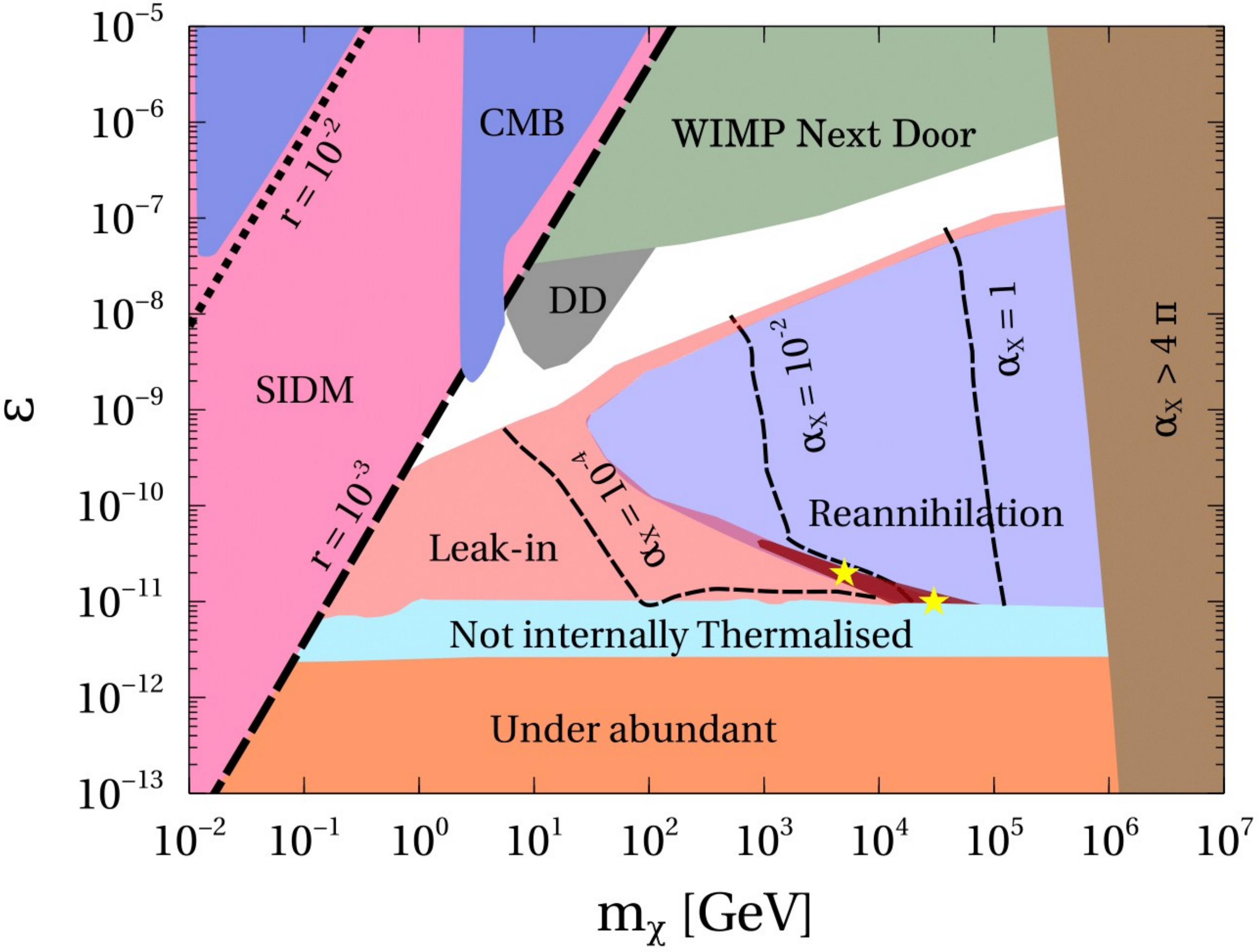




DM parameter space in $m_\chi - \epsilon$ plane



DM parameter space in $m_\chi - \epsilon$ plane

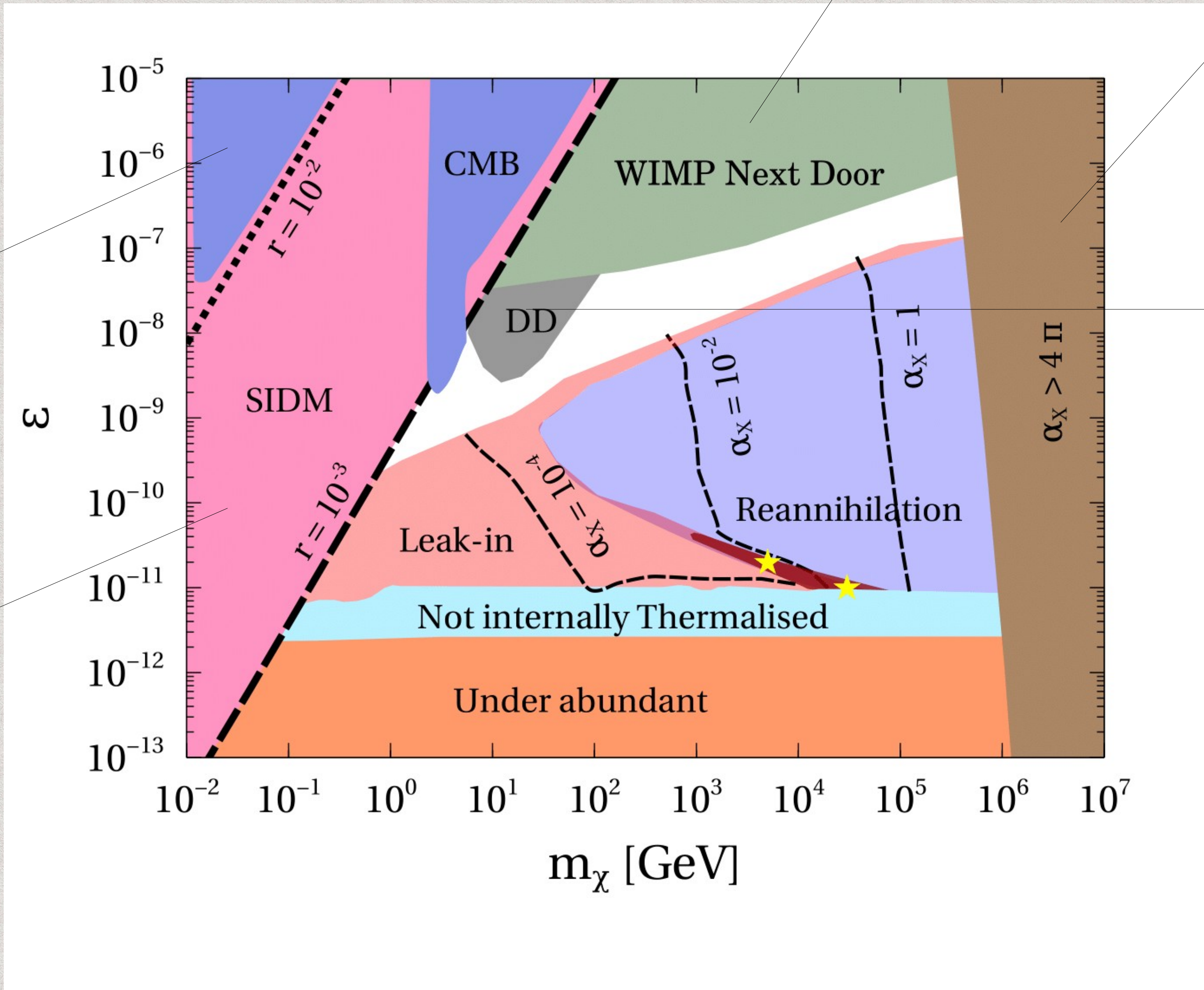
Dark sector in thermal equilibrium with the SM bath

Relic satisfied region with $g_X \geq 4\pi$

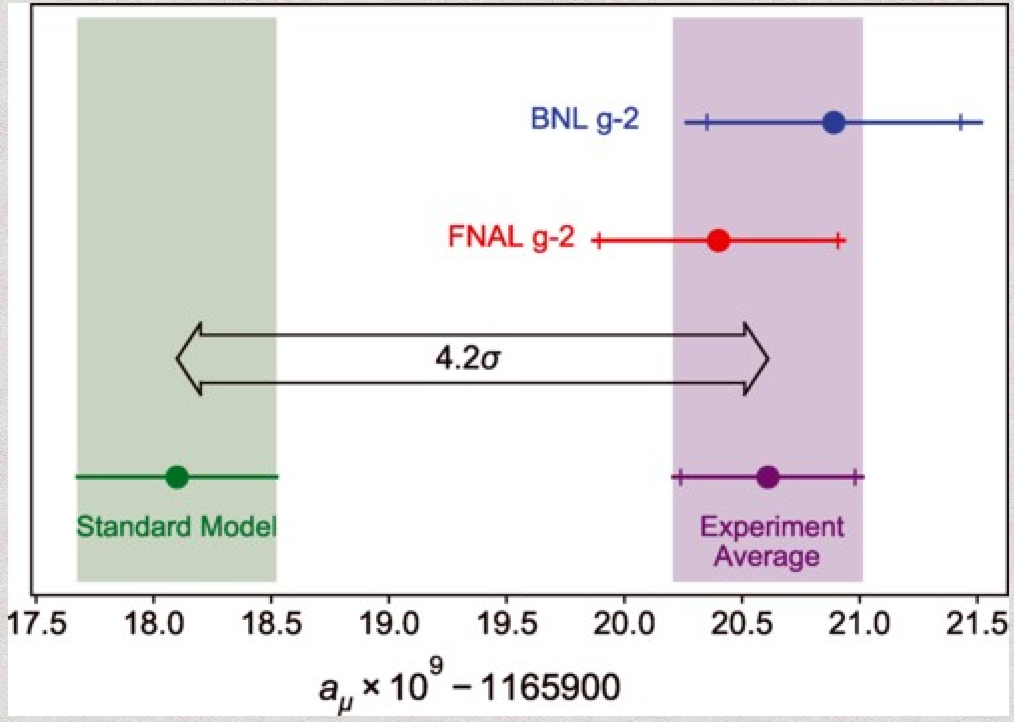
CMB constraint on s-wave DM annihilation cross section into SM particles

Direct detection, effect of $\gamma - Z'$ mixing at loop level

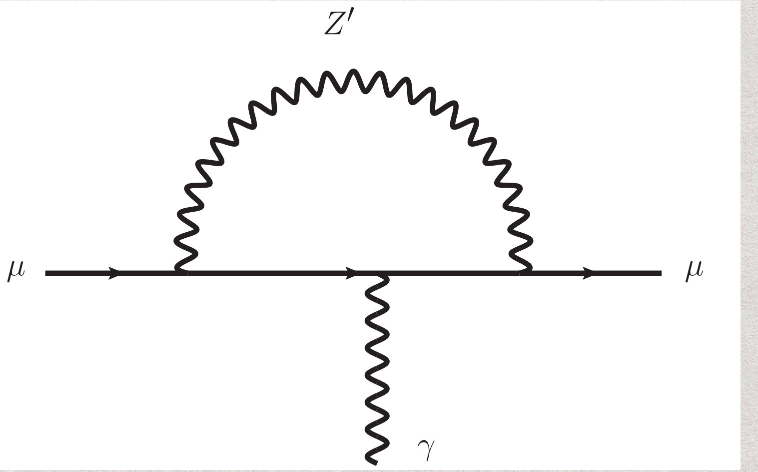
$\frac{\sigma_{\rm self-int}}{m_\chi} \geq 1 cm^2 g^{-1}$



$(g-2)_\mu$ anomaly



PRL 126 (2021) 141801



Only source in our model

to explain the anomaly

Is it possible to expain $(g-2)_\mu$ anomaly and DM relic density even if dark and visible sectors are thermally decoupled?

Modified Cosmology: Effect of a fast expanding component

Consider a new field ϕ whose energy density redshifts as $\rho_\phi \propto a^{-(4+n)}$ where $n > 0$

We define a temperature T_r at which

$$\rho_\phi(T_r) = \rho_{\rm rad}(T_r)$$

Using entropy conservation one can write

$$\rho_\phi(T) = \rho_r(T)\left(\frac{g_\rho(T_r)}{g_\rho(T)}\right)\left(\frac{g_{*s}(T)}{g_{*s}(T_r)}\right)^{\frac{4+n}{3}}\left(\frac{T}{T_r}\right)$$

The total energy density of the Universe will be

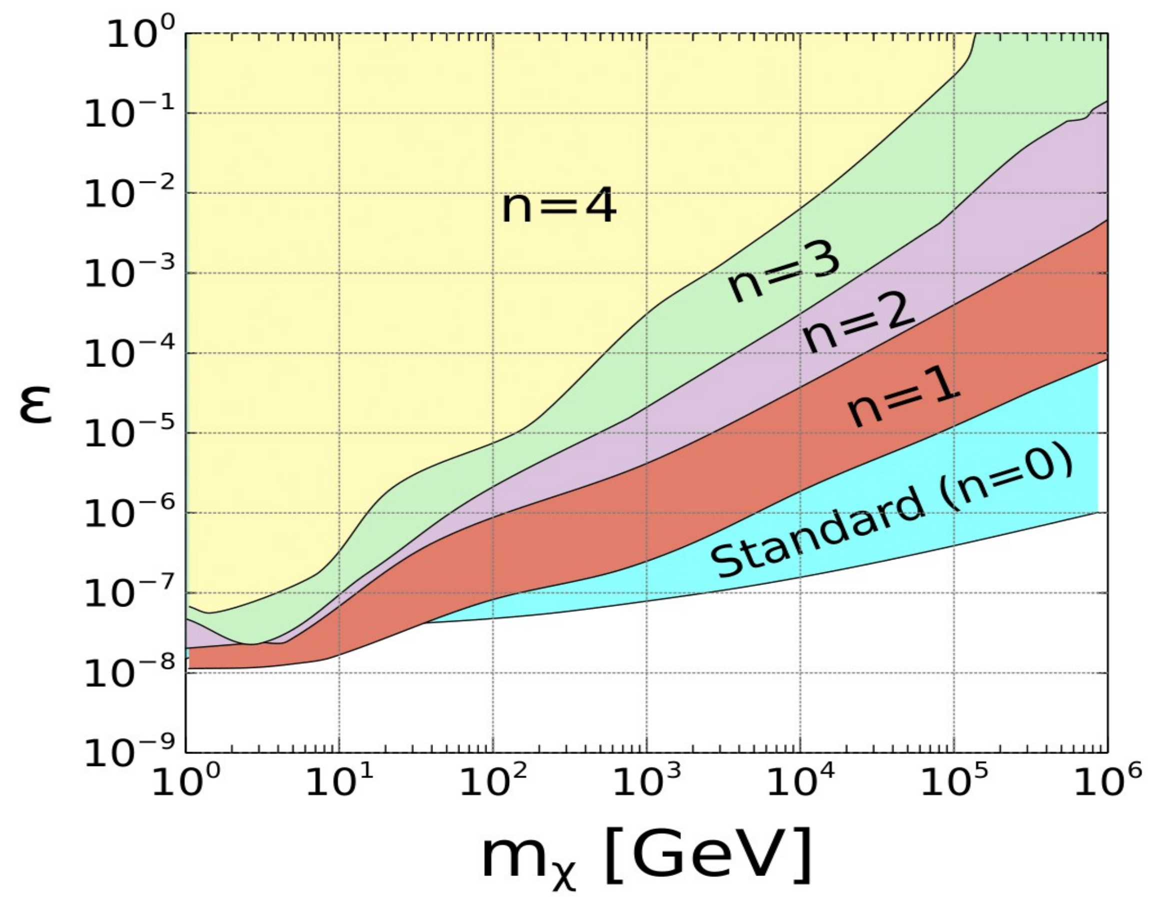
$$\rho(T) = \rho_r(T)\left[1 + \left(\frac{g_\rho(T_r)}{g_\rho(T)}\right)\left(\frac{g_{*s}(T)}{g_{*s}(T_r)}\right)^{\frac{4+n}{3}}\left(\frac{T}{T_r}\right)^n\right]$$

At $T \gg T_r$ the Hubble parameter is

$$H(T) \simeq \frac{\pi}{3M_{\rm Pl}}\sqrt{\frac{4\pi}{5}}\sqrt{g_\rho(T)}T^2\left(\frac{T}{T_r}\right)^{n/2}$$

F. D'Eramo et.al, JCAP 05 (2017)012

Equilibration floor



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Modified Hubble

Dark Sector Freeze-out, depends on the DS temperature

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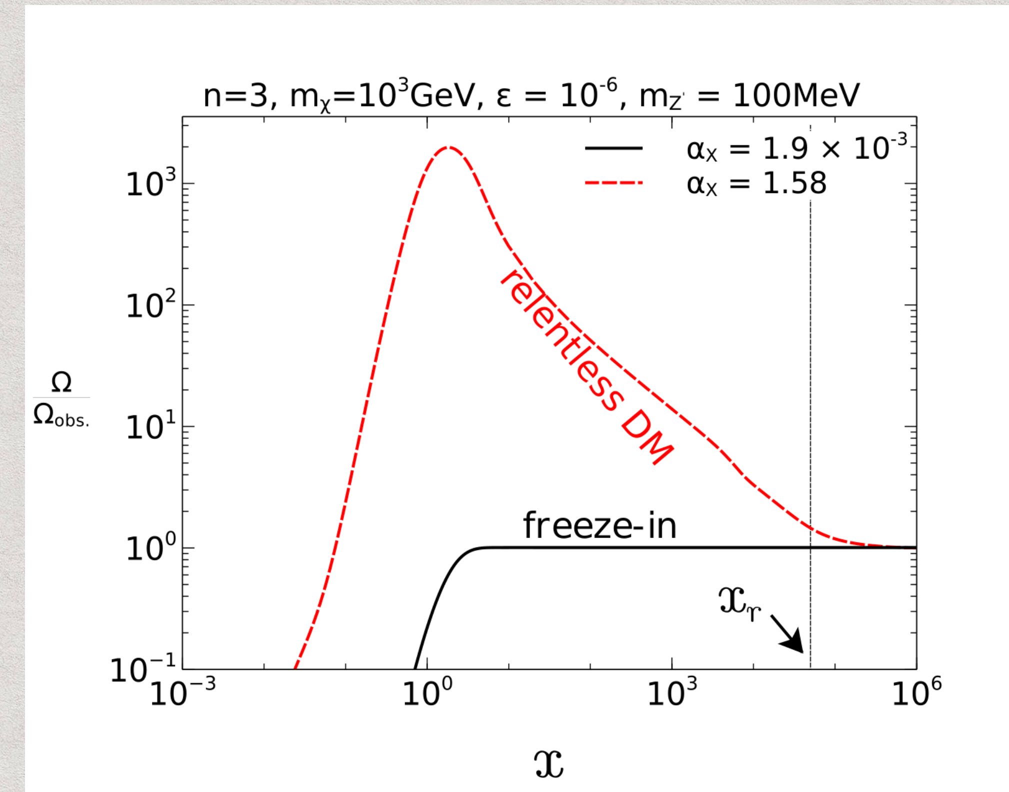

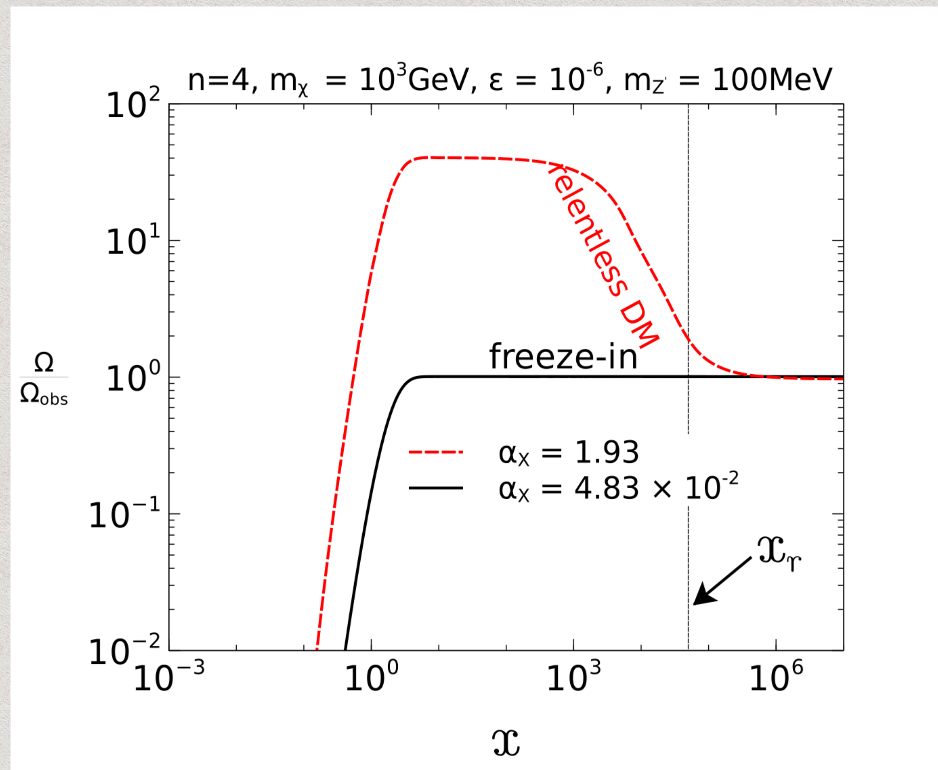

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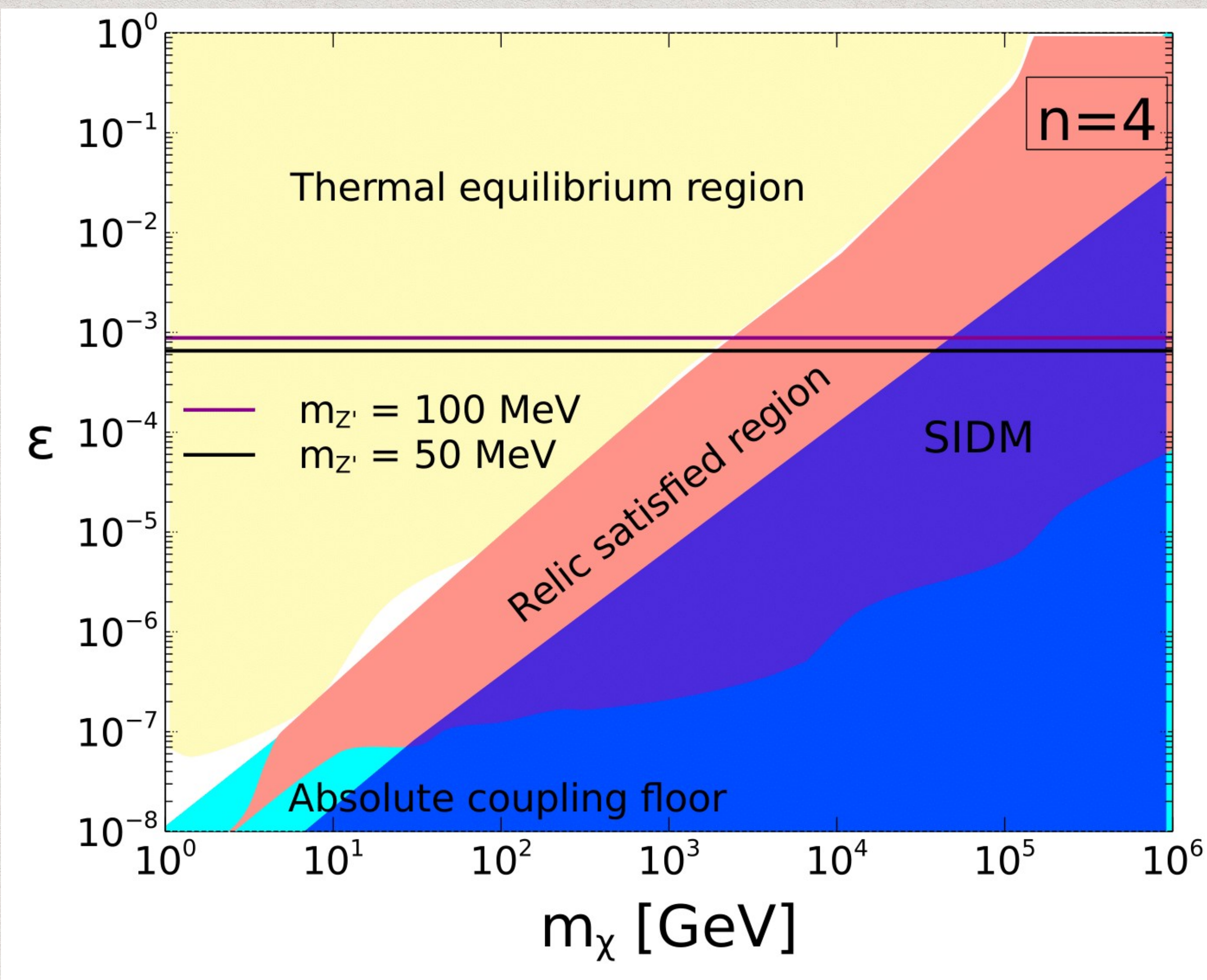
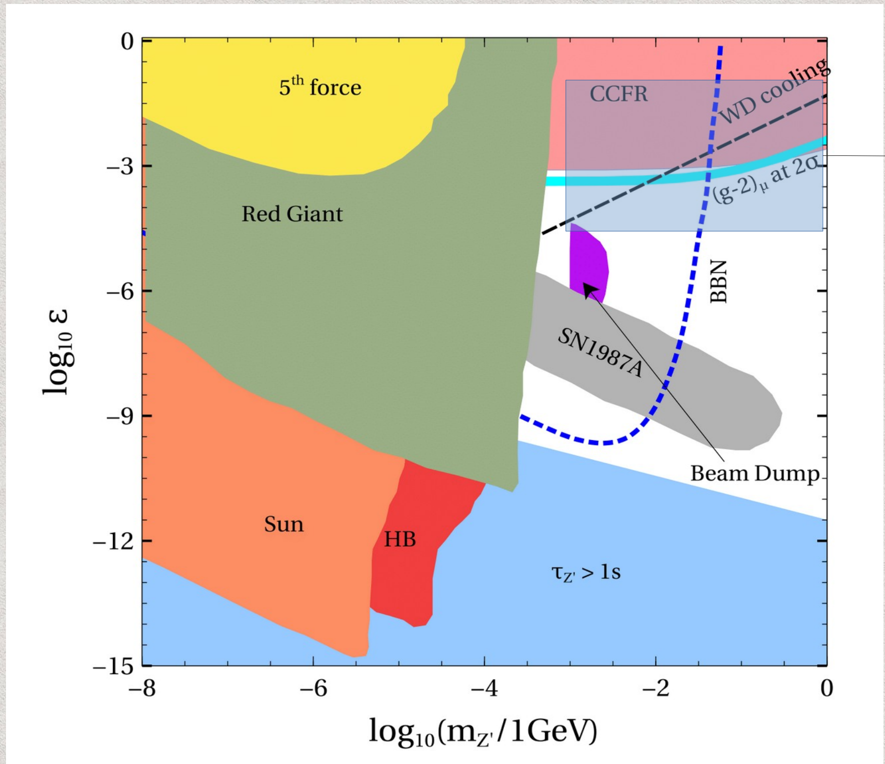
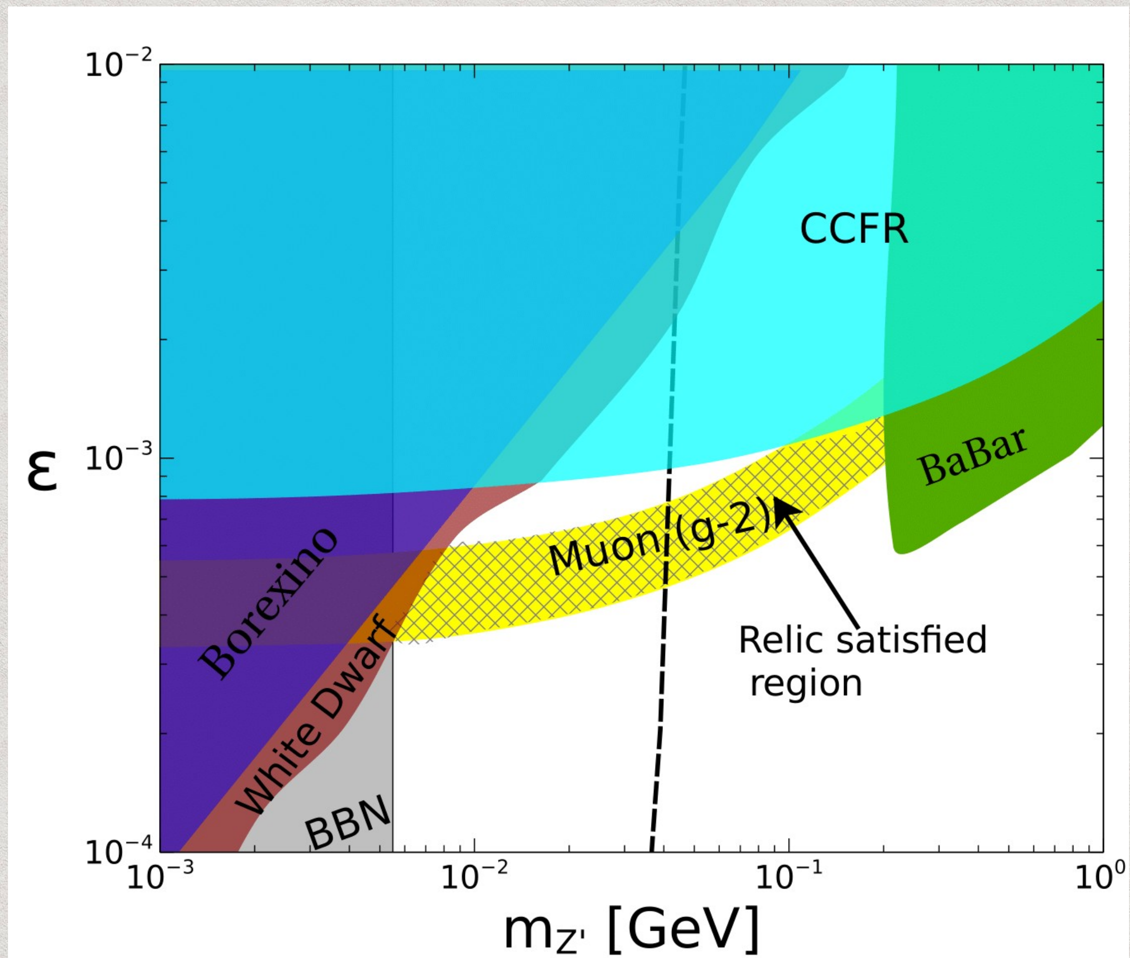


Constraints on the $U(1)_{L_\mu - L_\tau}$ portal



Modified Cosmology



Summary

- We have considered a $U(1)_X \otimes U(1)_{L_\mu - L_\tau}$ gauge extension of the SM where the dark sector is only charged under $U(1)_X$ gauge symmetry.

- Due to the presence of tree level kinetic mixing between Z' and $Z_{\mu\tau}$, the dark sector is only populated through the annihilation of muon and tau involving annihilation channels.

- Since the dark sector do not couple with the first generation of quarks and leptons, the parameter space of the dark sector phenomenology will be less constarined as compared to the gauged B-L scenario.

- The presence of the $L_\mu - L_\tau$ portal opens up the possibility of non-adiabatic evolution of the dark sector.

- For standard radiation dominated Universe, we have shown that for a thermally decoupled dark sector, simultaneous explanations of dark matter relic density and muon (g-2) anomaly are not possible while satisfying the other laboratory, cosmolgical, and astrophysical constraints.

- We have shown that reconcilation of dark matter relic density and muon (g-2) anomaly are possible if the energy budget of the early Universe is dominated by a fast expanidng component in the early Universe.

Thank You