Non-adiabatic evolution of a secluded dark sector in the presence of $U(1)_{L_\mu - L_\tau}$ gauge symmetry

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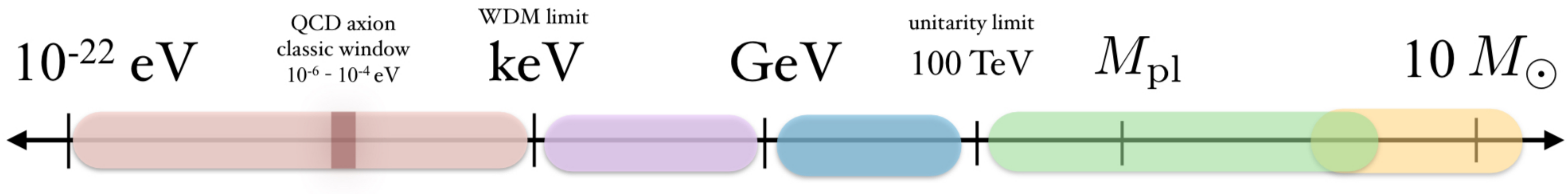
PPC 2023
Institute for Basic Science
Daejeon, South Korea
June 15, 2023

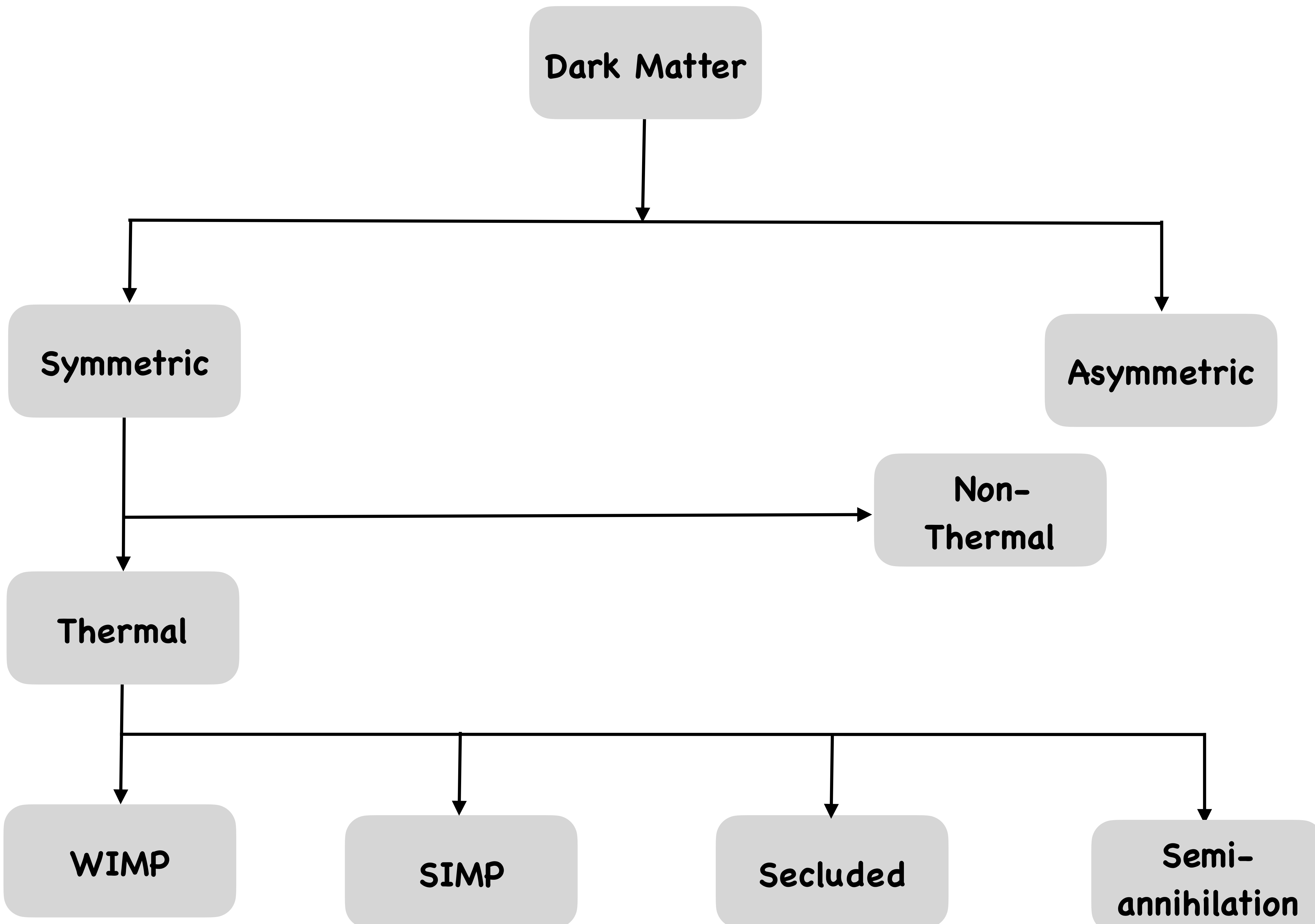
Based on:
JCAP 05 (2022) 019, JCAP 02 (2023) 044
in collaboration with Ananya Tapadar and Sourov Roy (IACS, India)

Possible mass range



Lin 1904.07915

Classifications of Particle Dark Matter



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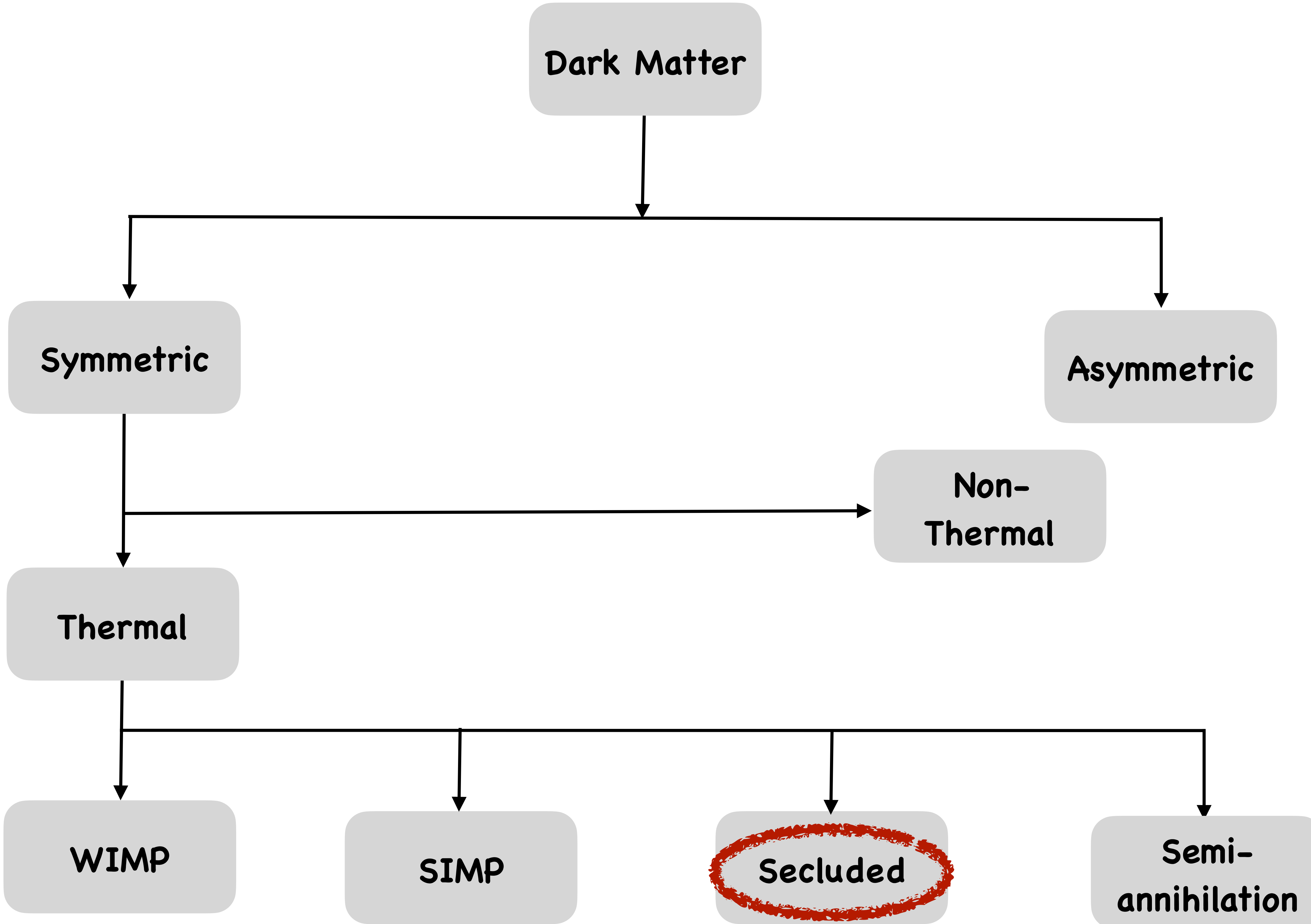

Secluded dark sector

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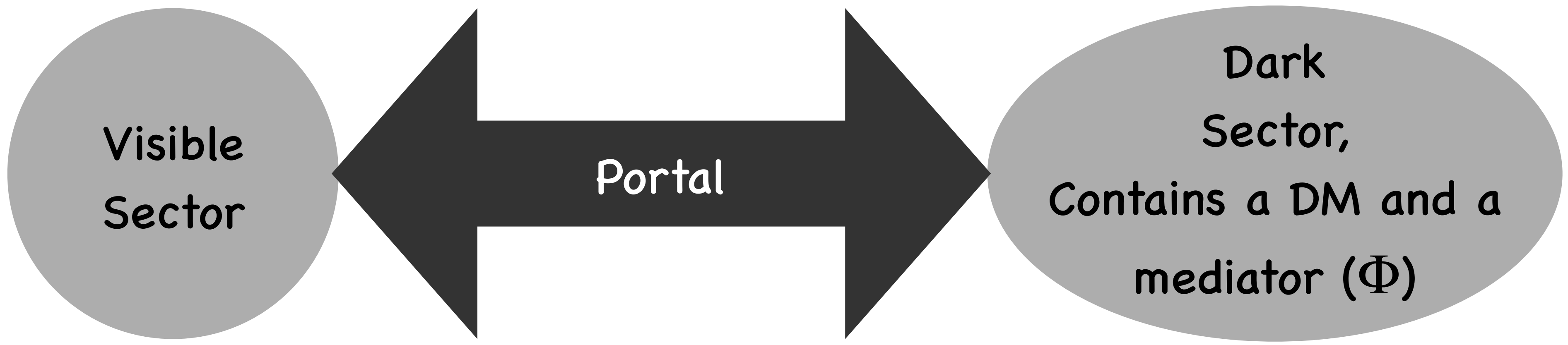

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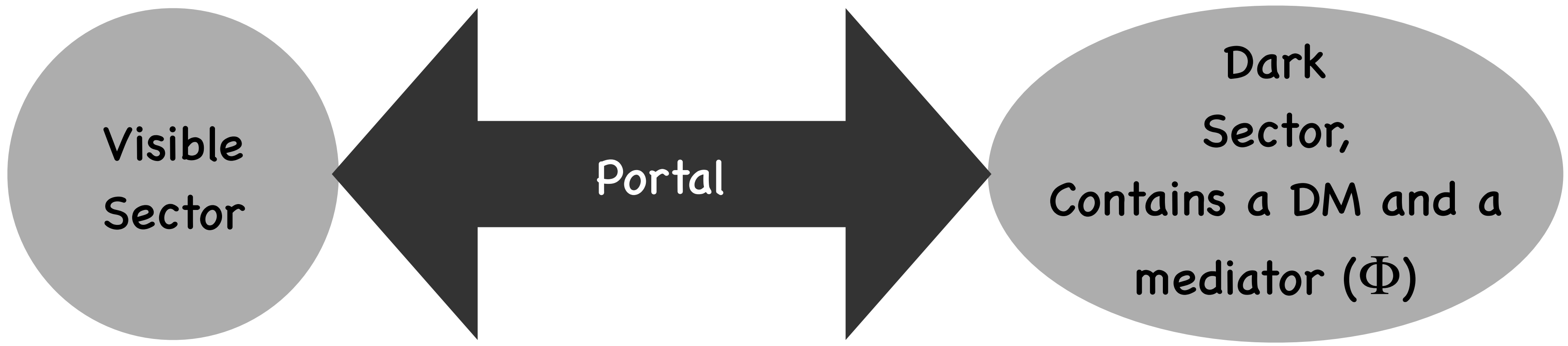

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- Thermal properties of the dark sector may have different properties.
- It is possible that the dark sector evolves non-adiabatically.

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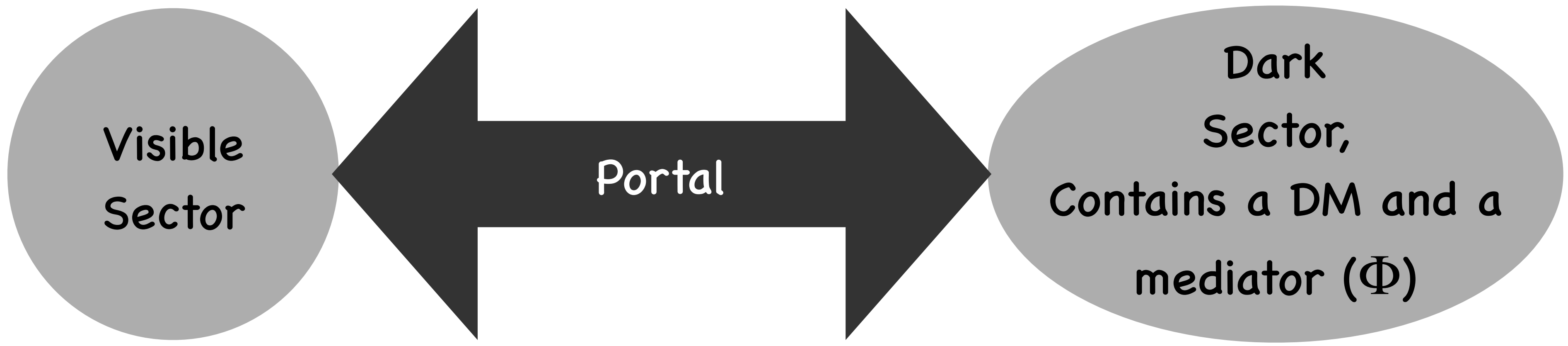

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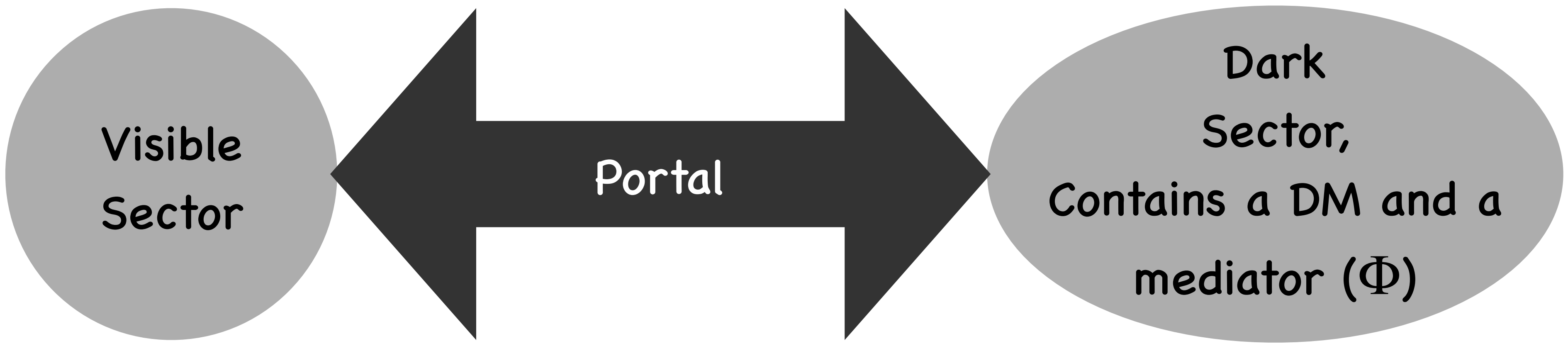

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and defining $\xi = \frac{T'}{T}$

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

Temperature evolution of dark sector: Continue……

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Renormalisable interaction

Non-Renormalisable interaction

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Sensitive to IR physics		Sensitive to UV physics

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- Considered $U(1)_{L_\mu - L_\tau} \otimes U(1)_X$ extension of SM.

Well motivated in the context of muon anomalous magnetic moment and neutrino mass-mixings

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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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$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\chi}(i\gamma^\mu\partial_\mu - m)\chi - \frac{1}{4}\hat{X}^{\rho\sigma}\hat{X}_{\rho\sigma} - \frac{1}{4}\hat{F}^{\rho\sigma}_{\mu\tau}\hat{F}_{\mu\tau\rho\sigma} - g_x\bar{\chi}\gamma^\mu\chi\hat{Z}_\mu$$
$$-g_{\mu\tau}(\bar{\mu}\gamma_\rho\mu + \bar{\nu}_\mu\gamma_\rho P_L\nu_\mu - \bar{\tau}\gamma_\rho\tau - \bar{\nu}_\tau\gamma_\rho P_L\nu_\mu)\,\hat{Z}^\rho_{\mu\tau}$$
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Tree level kinetic mixing

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Mass basis

Tree level kinetic mixing

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

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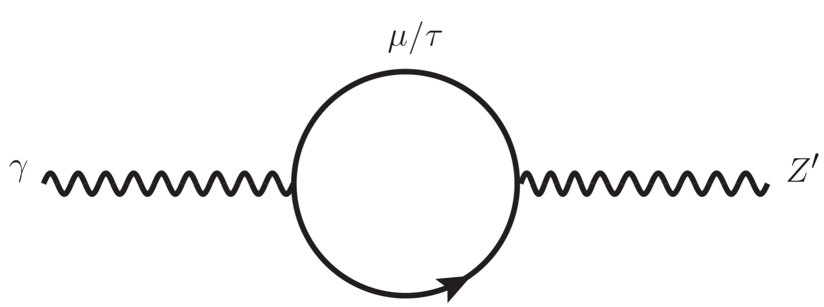
Kinetic mixing between γ and Z' can be generated at one loop level which is proportional to ϵ.



$$i\Pi(q^2) = -\frac{ie\epsilon}{2\pi^2}\int_0^1 x(1-x)\log\left(\frac{m_\mu^2 - q^2x(1-x)}{m_\tau^2 - q^2x(1-x)}\right)dx$$

Relic density estimation

Using sudden freeze-out approximation

$$\Omega h^2 \simeq 0.12 \left(\frac{\xi}{10^{-5}}\right)\left(\frac{x_f'}{10}\right)\left(\frac{7\times 10^{-15}\,\mathrm{GeV}}{\langle\sigma v\rangle}\right)\left(\frac{\sqrt{g_\rho(T_f)}}{10}\right)\left(\frac{100}{g_{*s}(T_f)}\right)$$

From S-matrix Unitarity

$$\langle\sigma v\rangle_{\mathrm{Max}} \simeq \frac{4\pi}{m_\chi^2}\sqrt{\frac{x_f'}{\pi}}$$

Relic density + Unitarity gives

$$m_\chi \leq \frac{127\mathrm{TeV}}{\sqrt{\xi}}$$

Unitarity limit of DM mass can be relaxed if the dark sector is colder

Boltzmann equation for DM relic density

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

Dark sector freeze-out, depends on dark sector temperature

Production of DM from SM bath: freeze-in

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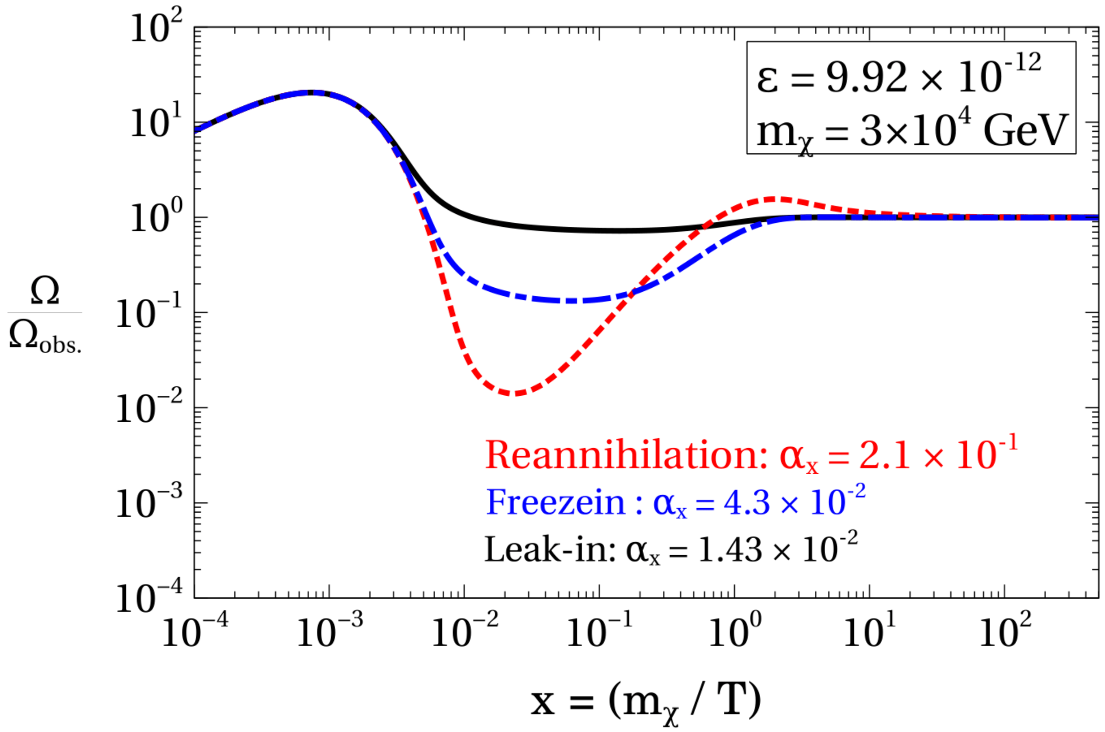
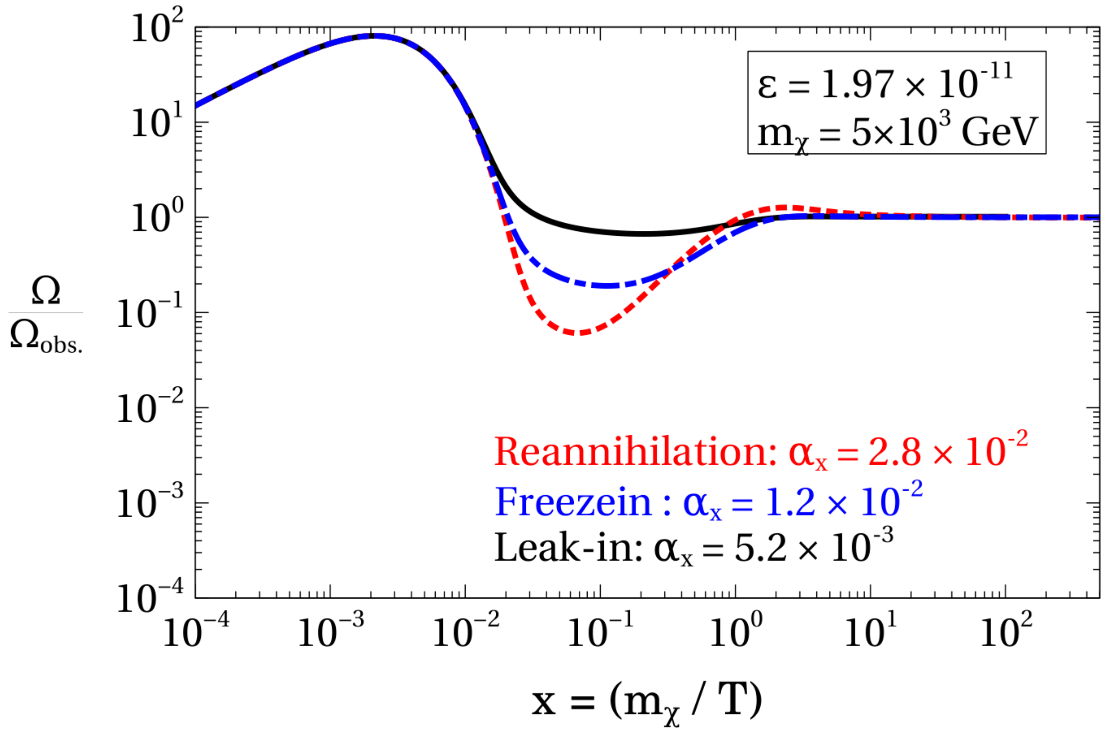
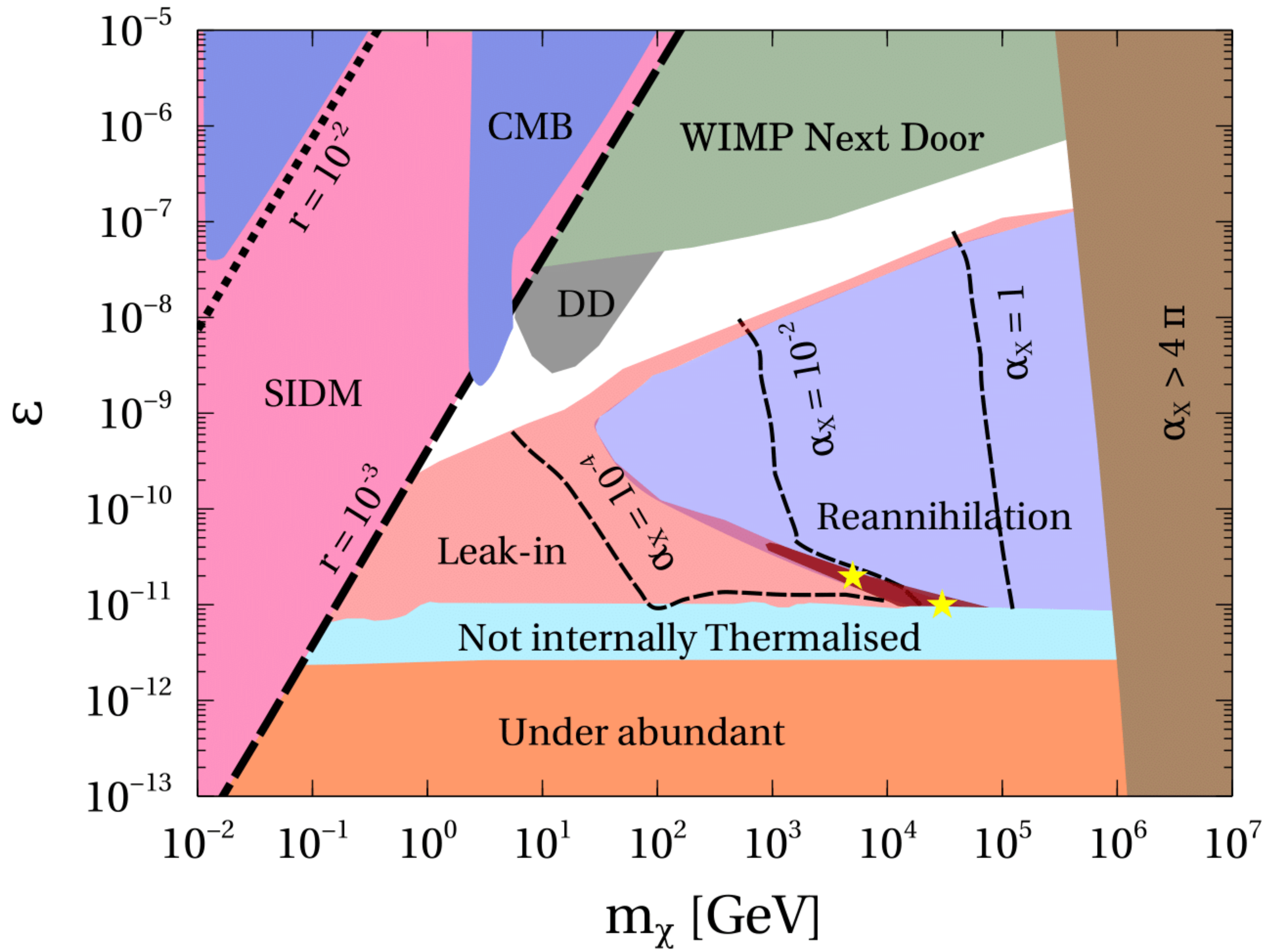
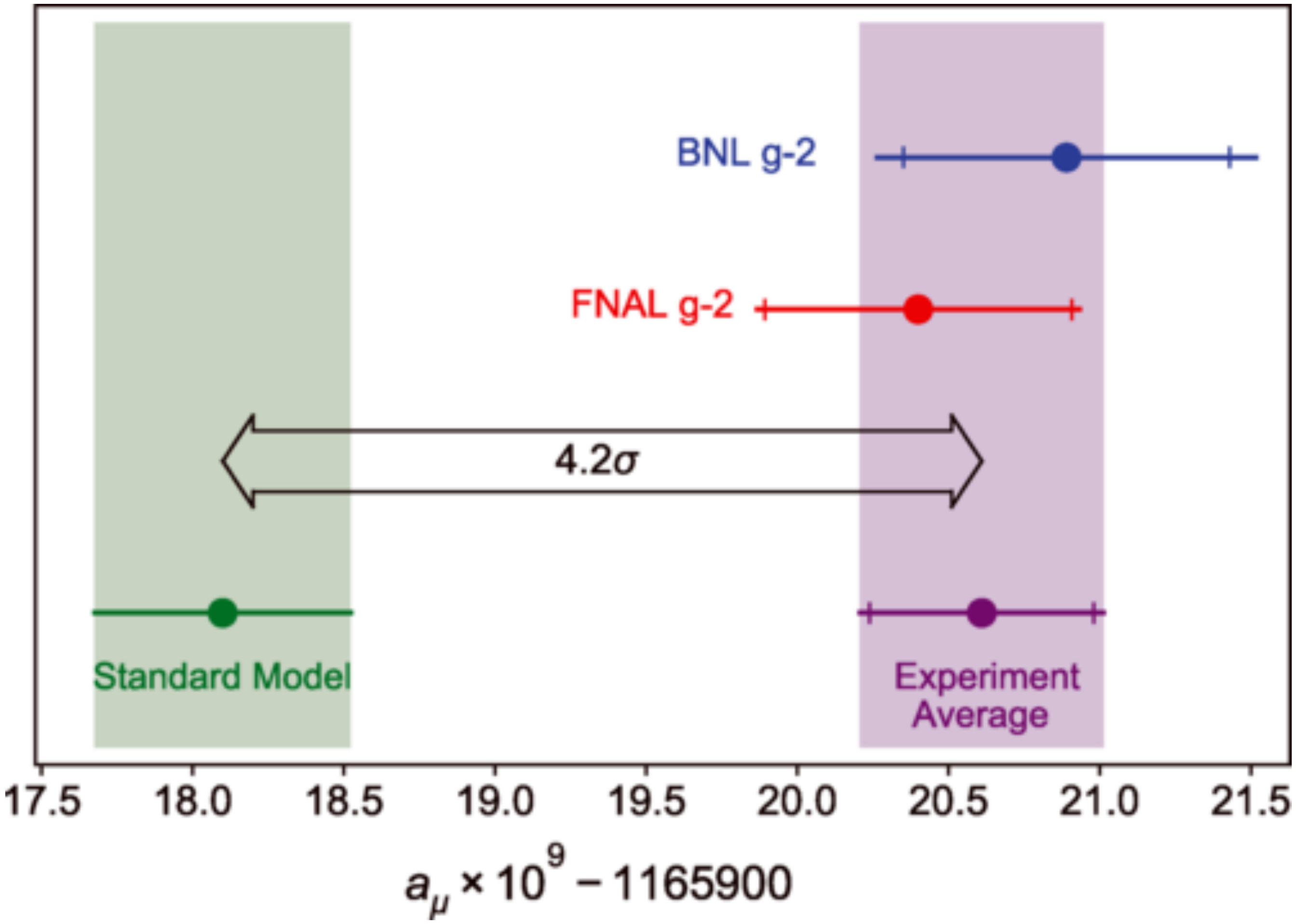




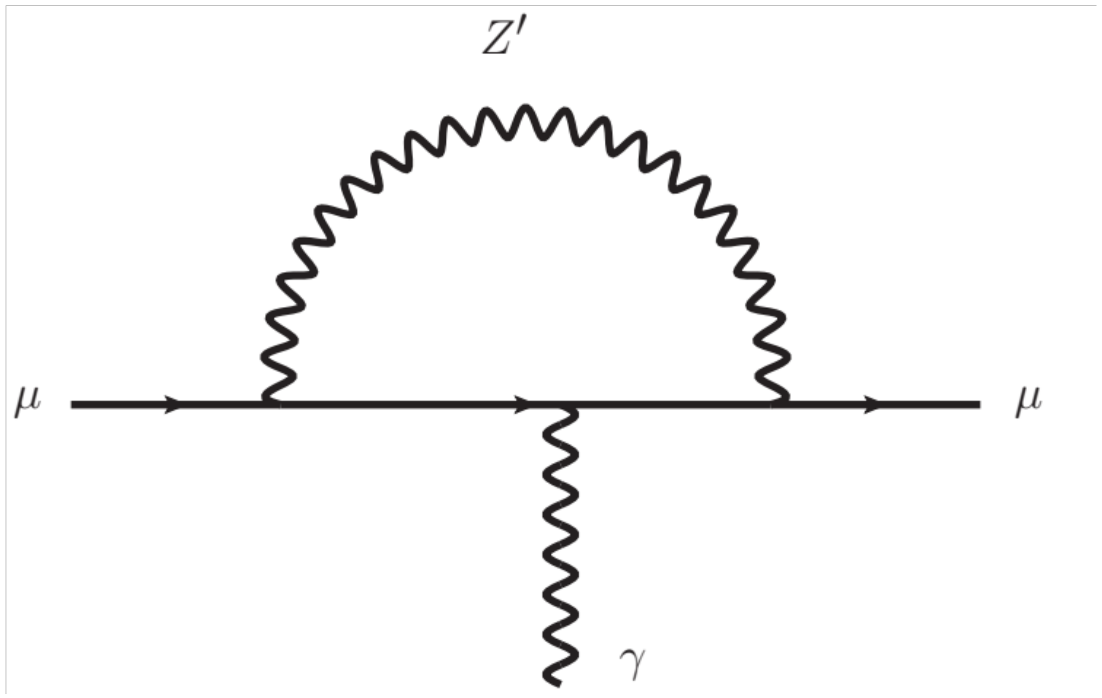
DM parameter space in $m_\chi - \epsilon$ plane



Muon (g-2) anomaly

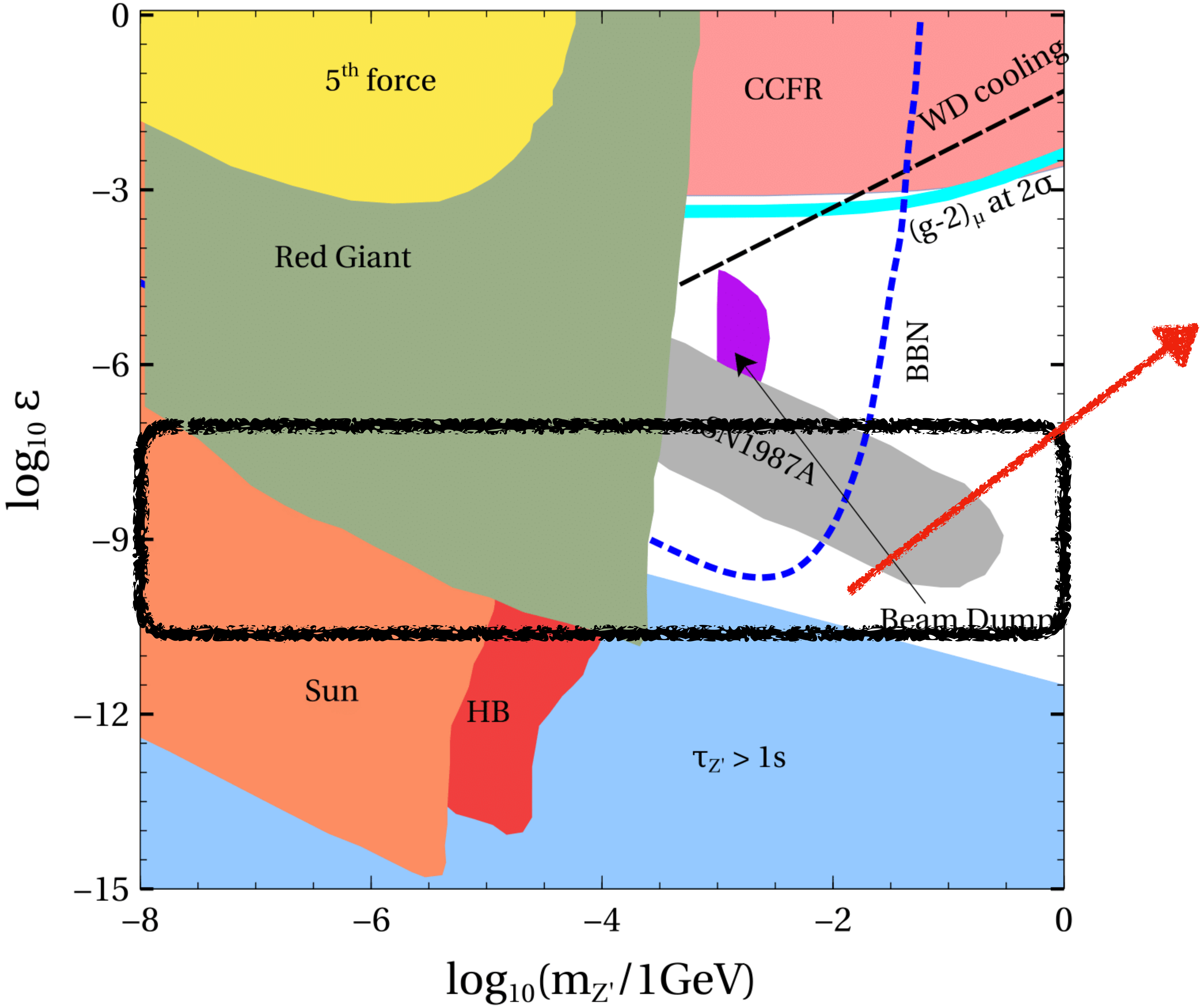


PRL 126 (2021) 141801



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

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



Relic satisfied region

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, we can write

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

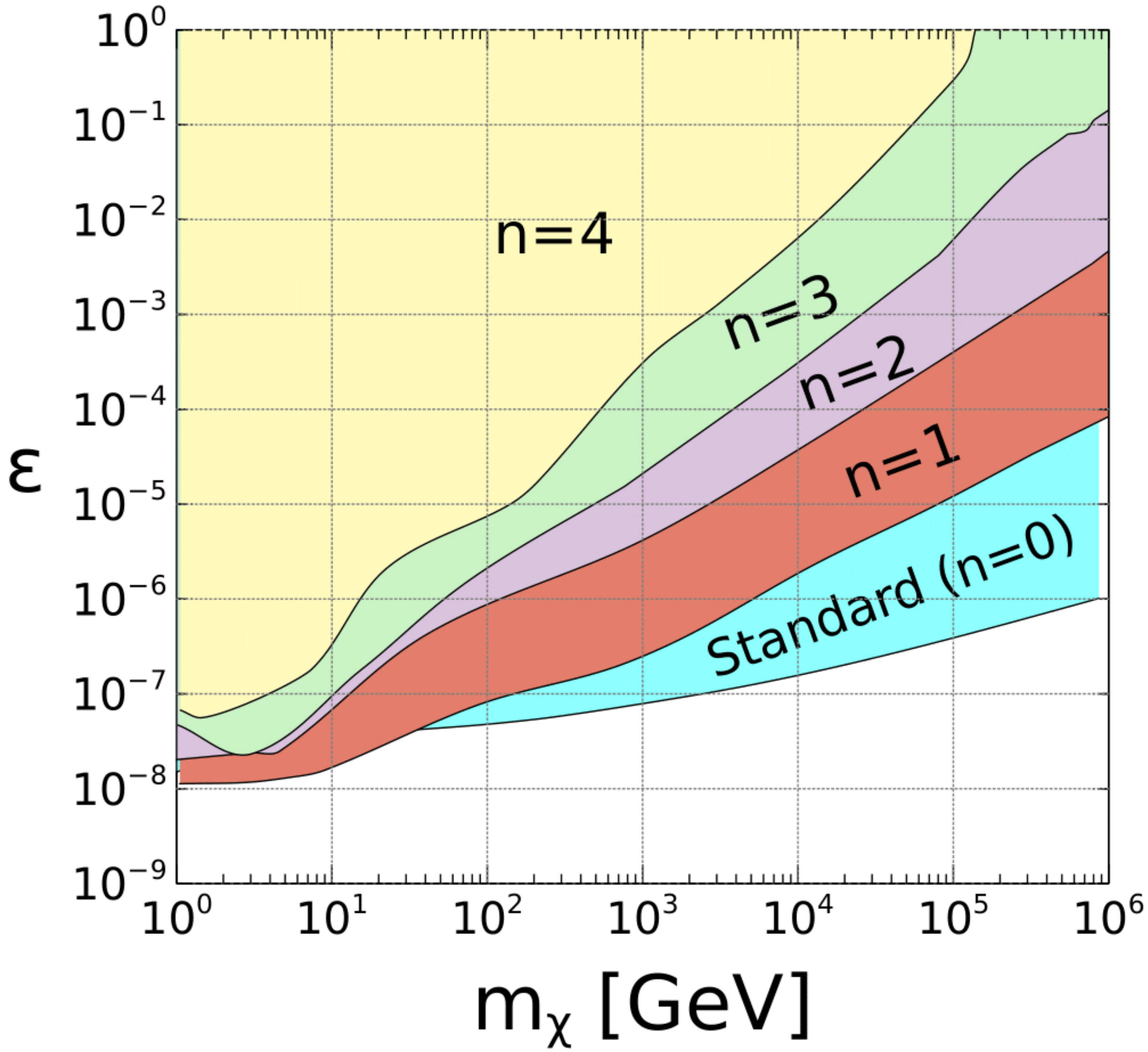
- Total energy of the Universe will be

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

- For $T \gg T_r$, the Hubble parameter is

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

Equilibration floor



DM number density in modified cosmology

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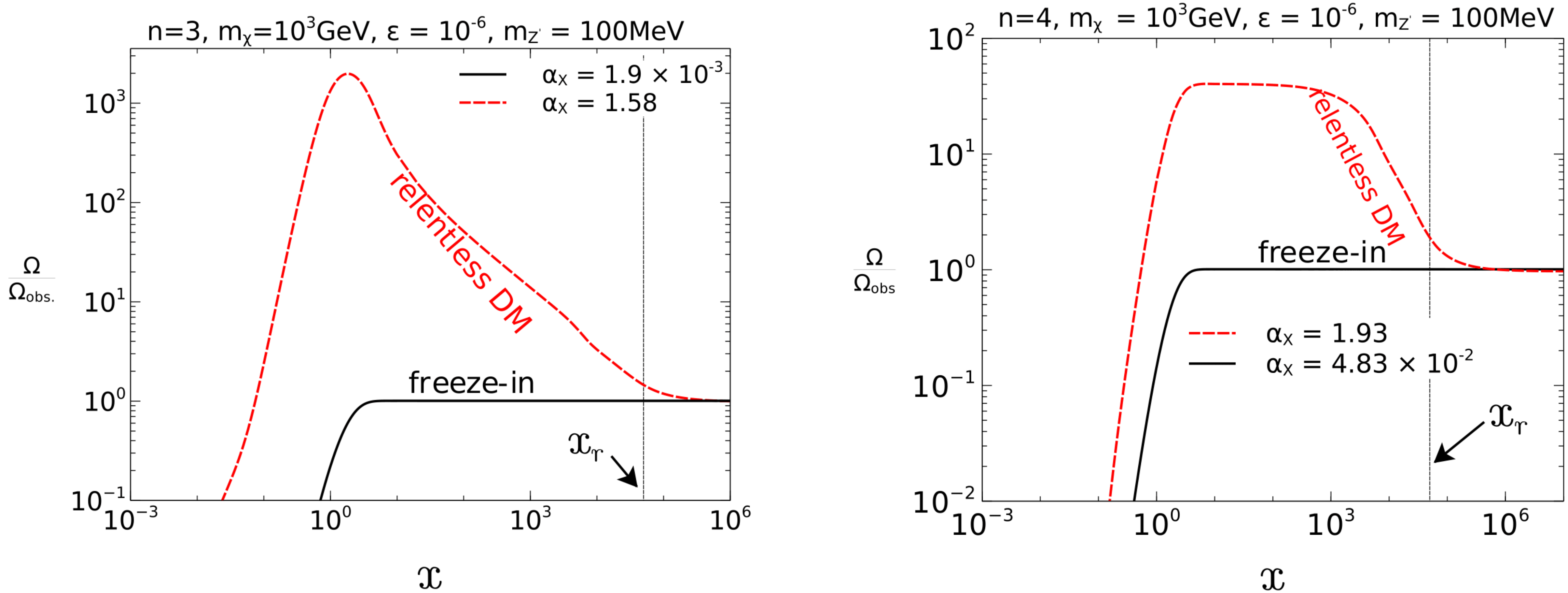
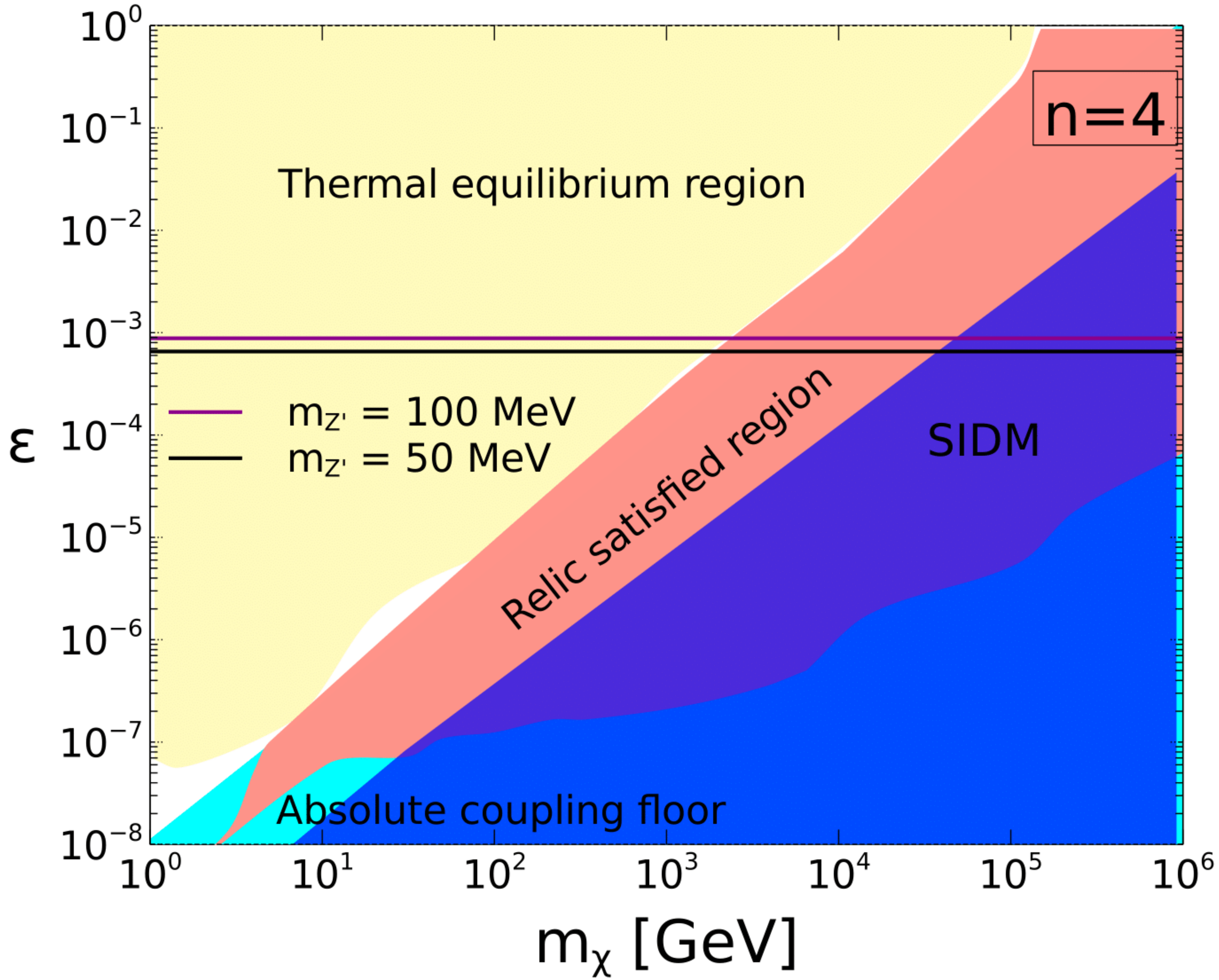
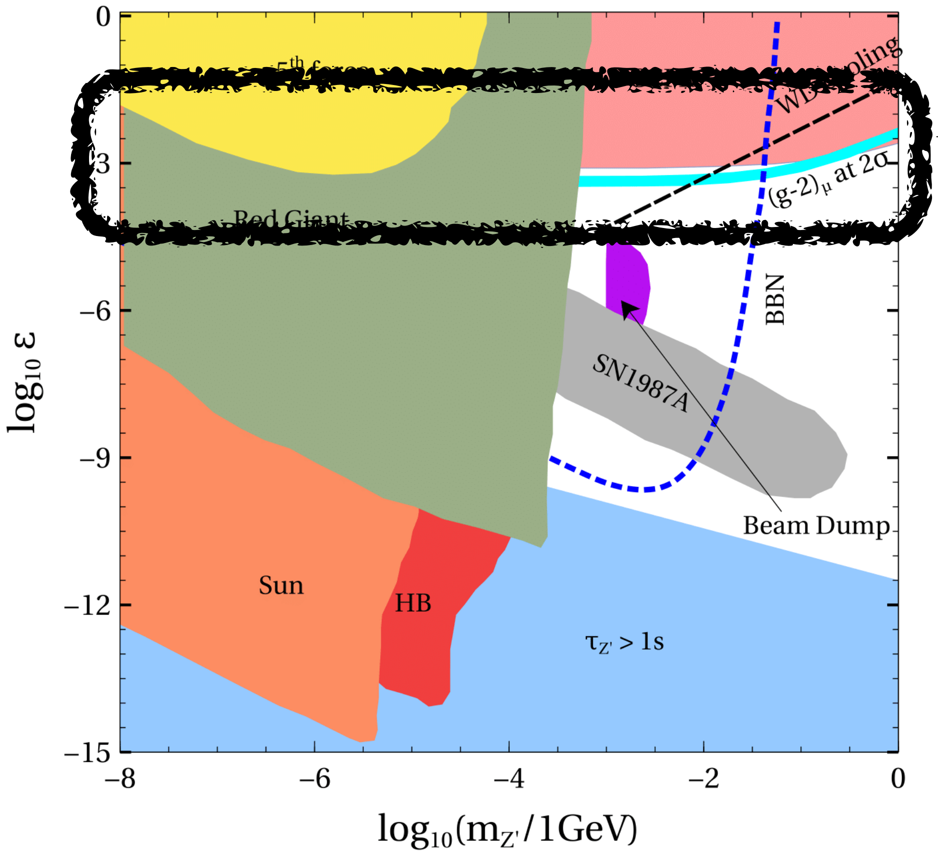
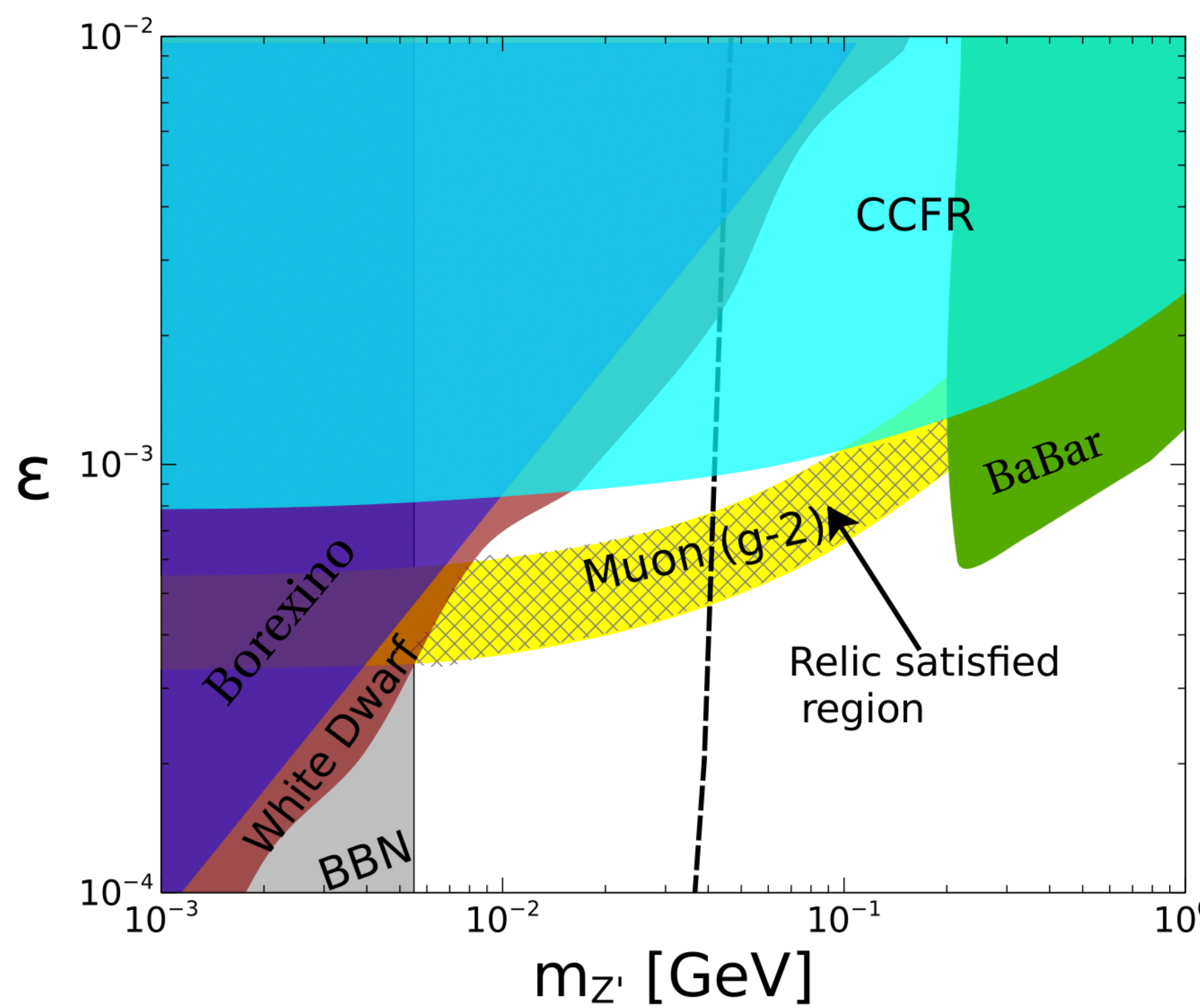


DM parameter space in $m_\chi - \epsilon$ plane in modified cosmology



$m_{Z'} - \epsilon$ plane





Summary

We have considered a $U(1)_{L_\mu - L_\tau} \otimes U(1)_X$ 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 second and third generation of SM leptons.

The parameter space is less constrained as compared to the gauged $B-L$ scenario.

For standard cosmology, we have shown that for a thermally decoupled dark sector, simultaneous explanations of DM relic and $(g-2)_\mu$ anomaly are not possible.

Reconciliation of DM relic and $(g-2)_\mu$ are possible if the total energy of the Universe in at early epoch is dominated by a fast expanding component.

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Thank You for your attention !!!!!!