GeV-scale dark matter : resonant annihilation

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LAPTh, Annecy-le-Vieux

Based on GB, S. Chakraborti, Y. Genolini, P. Salati, arXiv:2401.02513

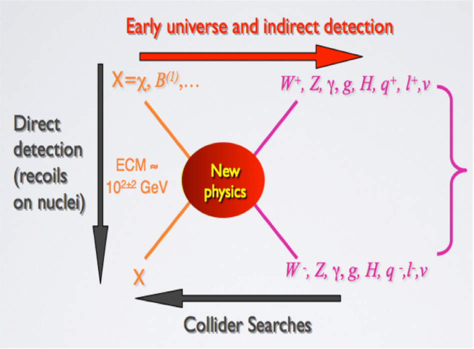
Corfou, 13/09/2024

Introduction

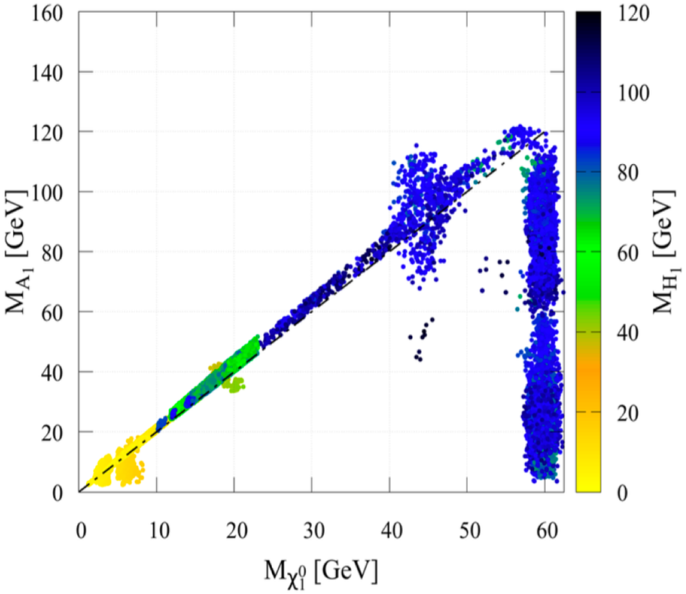
- Strong evidence for dark matter from many scales : galaxy, clusters, cosmology
- Is DM a new particle : what are its properties? cold, neutral (or very small charge), stable, non-baryonic, weak interactions with SM (or feeble)
- Relic density of DM known precisely (PLANCK)

$$\Omega_{\rm DM} h^2 = 0.1188 \pm 0.0010\,,$$

- Leaves lots of possibilities for DM of different mass and interaction strength – especially since well-motivated New Physics model has yet to be singled out
- A new stable WIMP is most studied candidate - despite strong experimental programs – no signs of WIMPs but the searches continue

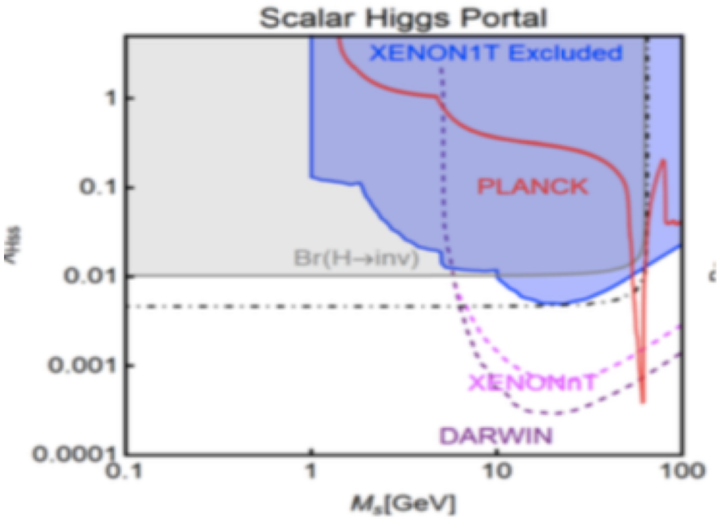


- Assume DM a new stable neutral weakly interacting particle : which scale?
  - Here interest in DM at GeV-scale – in principle a particle physics candidate that should be accessible in many different experiments – yet escapes many of the direct detection limits since below the threshold of large detectors
- Lee-Weinberg bound: DM below ~2 GeV-scale cannot reach the correct relic density only with interactions with SM
- Can introduce new particles (mediator) at GeV scale, eg. NMSSM where annihilation near a light singlet resonance allows GeV scale neutralino



Barman, GB, Bhattacherjee,
Godbole, Sengupta, Tata, 2005.05874

- Note : annihilation near a resonance is common in WIMP models as it requires smaller couplings hence avoids many constraints



Arcadi et al, 2101.02507

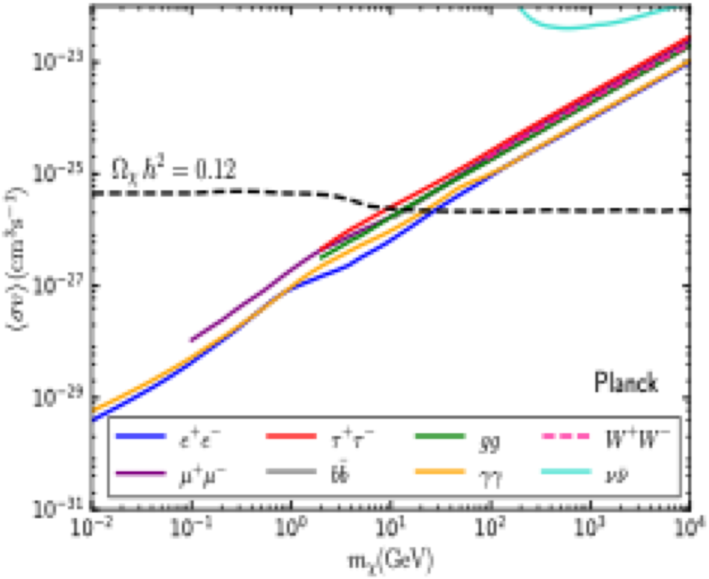
- Other possibility : add other processes, e.g. co-annihilation, semi-annihilation.. or go to TeV scale where annihilation in gauge bosons is efficient
- DM around or below GeV scale is easily achievable in freeze-in scenarios where DM is so feebly coupled that cannot reach thermal equilibrium in the early Universe, produced through decays or scattering of SM-like particles. Couplings are very small – not too many signatures (with notable exceptions – DD with light mediator, decaying DM (L. Covi's talk), LLPs…)

- Light DM (below few GeVs)
  - Strong constraints from CMB and Indirect detection
    - Ionizing particles (e^+ e^- γ) from DM annihilation change the ionization history of hydrogen gas-> perturbation of CMB anisotropies
    - Constrain the annihilation parameter $f_{\rm eff}\langle\sigma v\rangle/m_\chi$.

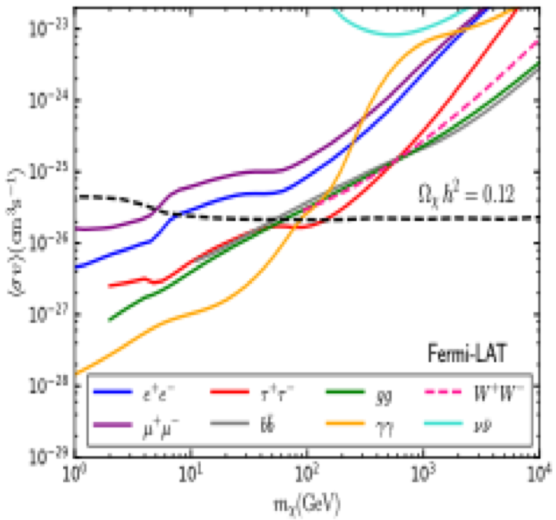
$$f_{\rm eff}(m_\chi) = \frac{\int_0^{m_\chi} E dE \left[2 f_{\rm eff}^{e^+e^-}(E)\left(\frac{dN}{dE}\right)_{e^+} + f_{\rm eff}^{\gamma}(E)\left(\frac{dN}{dE}\right)_{\gamma}\right]}{2 m_\chi}$$

    - Stringent limits on light DM assuming s-wave annihilation and 100%BR in given SM (neutrino annihilation channel escapes constraints)

Slatyer, 1506.03811



- Indirect detection
  - Fermi-LAT searches for photons from DM annihilation in dSPhs also put strong constraints
  - Xray constraints from XMM-Newton (and others) : DM annihilation into e+e- pairs e+- scatter on low-energy photons in Galaxy and generate X-rays (keV energies)



Dutta et al, 2212.09795

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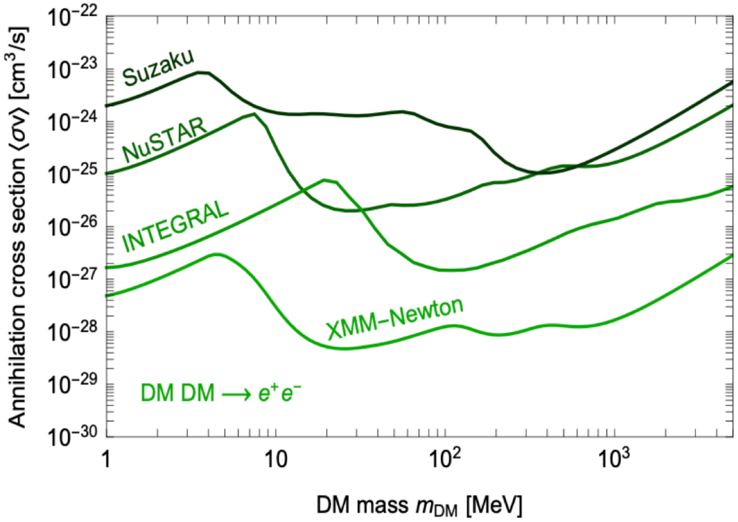
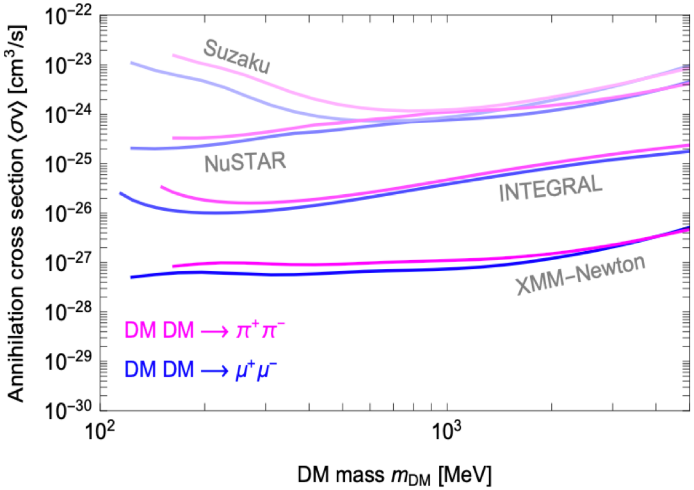
  - Constrain canonical annihilation cross-section for m_DM<5GeV





Cirelli, Fornengo, Koechler, Pinetti, Roach 2303.08854

- Escaping constraints for GeV-scale DM:
  - p-wave – Boehm, Fayet, NPB683 (2004) 219
    - Suppresses CMB constraint (v/c ~10^{-8}) and ID (v/c~10^{-3})
  - Resonant annihilation (Diamanti et al, JCAP 02 (2014); Bernreuther, Heeba, Kahlhofer, 2010.14522; Binder et al, 2205.10149; Croon et al, PRD105(2022) ; Brahma, Heeba, Schutz, 2308.01960; Balan et al, 2405.17458; GB, Chakraborti, Delaunay, Jomain, in preparation)
  - Asymmetric dark matter (Lin, Yu, Zurek, PRD85 (2012); Hara et al PRD 105 (2022); Balan et al, 2405.17458)

- Light DM (below few GeVs)
  - Example : complex scalar DM coupled to dark photon - kinetic mixing (ε), Z2 symmetry

$$\mathcal{L}_{\text{int}} = -\, i g_x A'^{\mu} \left(\phi^\dagger \partial_\mu \phi - \partial_\mu \phi^\dagger \phi\right)\Big\} - \epsilon e Q_f \bar{f} \not{A}' f$$

  - Pair annihilation into fermions – p-wave

$$\sigma_{\text{ann}} v = \frac{g_x^2 \epsilon^2 e^2 \tilde{Q}^2}{6\pi} \left\{ \frac{m_\phi^2 v^2}{(4m_\phi^2 - m_x^2 + m_\phi^2 v^2)^2 + m_x^2 \Gamma_x^2} \right\},$$

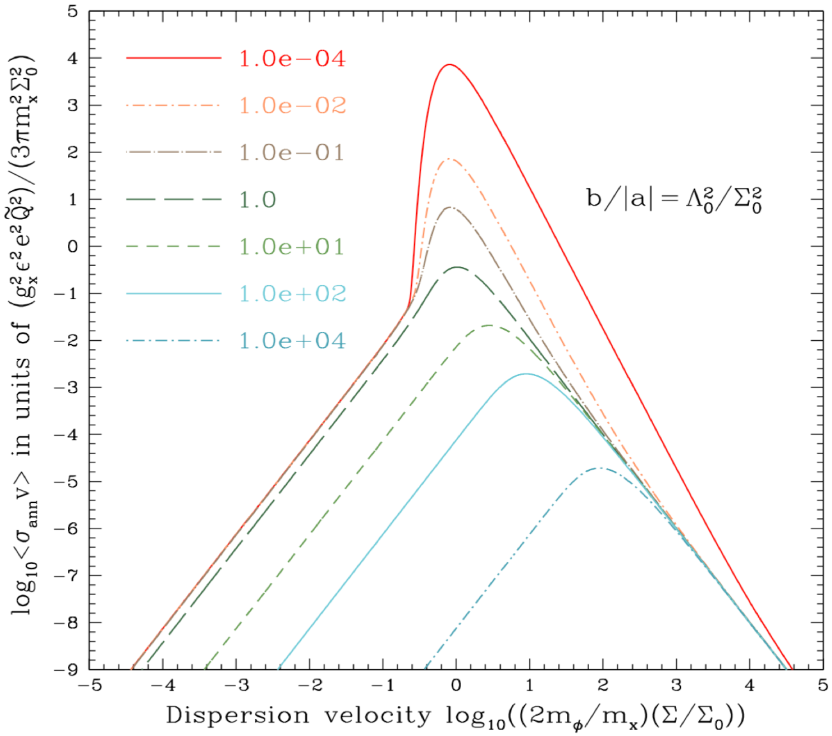
  - Strongly enhanced at v-> 0 when $2m_\phi \sim m_x$ and Γ_x small
  - Dark photon decays in DM or fermions

$$\Gamma_x = \frac{m_x}{12\pi} \left\{ \frac{g_x^2}{4} \Sigma_0^3 + \epsilon^2 e^2 Q'^2 \right\}.$$

  - Thermally average

$$\langle \sigma_{\text{ann}} v \rangle = \frac{g_x^2 \epsilon^2 e^2 \tilde{Q}^2}{12\pi} \left\{ \frac{J(a,b)}{m_\phi^2 \Sigma^2} \right\}$$

  - Consider $m_x > 2\, m_\phi$

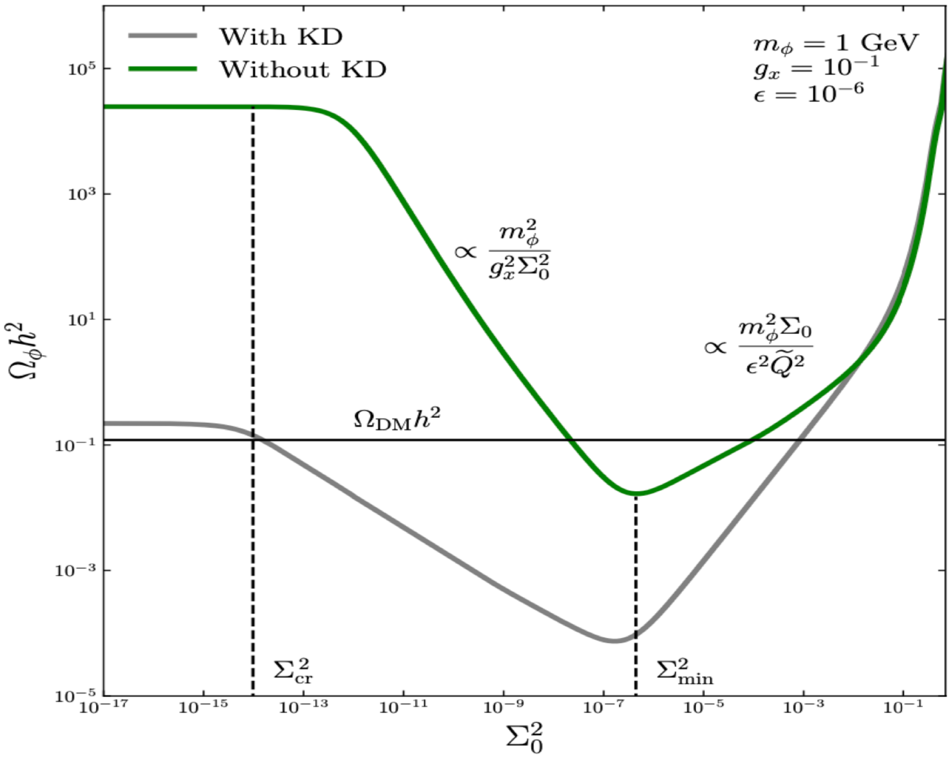


$$\Sigma_0^2 \equiv 1 - 4m_\phi^2/m_x^2$$

$$\Lambda_0^2 \equiv \Gamma_x/m_x \, .$$

- When width is large – no enhancement
- When width is small – peak around Σ_0
- annihilation near resonance – Breit-Wigner enhancement and possible that σv (MW) >> σv (FO) (Ibe, Murayama, Yanagida, 0812.0072)
- process is p-wave avoid strongest constraints from CMB ($v \sim 10^{-8}$)

- Assuming thermal equilibrium



$$\Sigma_0^2 \equiv 1 - 4m_\phi^2/m_x^2$$

- Two values of the mass splitting that lead the wanted relic density
- Important to take into account kinetic decoupling (Binder et al, 1706.07433; Binder et al. 2103.01944; Abe, 2106.01956; Hryczuk, Laletin 2204.07078; Duan, Ramos, Tsai 2404.12019; Hryczuk, LHEP 344 2023;)

- Generalization of Boltzmann equations

$$E\left(\frac{\partial}{\partial t} - H\vec{p}\cdot\frac{\partial}{\partial \vec{p}}\right) f_\chi(t,\vec{p}) = \underset{\underset{\text{DM,DM-> SM,SM}}{\uparrow}}{C_{ann.}}[f_\chi] + C_{el.}\underset{\underset{\text{DM,SM-> DM,SM}}{\uparrow}}{[f_\chi]},$$

- If DM and SM have same T, usual Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle\sigma_{\rm ann}v\rangle n^2 + \langle\sigma_{\rm ann}v\rangle n_{\rm eq}^2\,,$$

- Otherwise need to follow evolution of temperature
- Assume that DM has strong enough interactions – temperature T_{ϕ}.

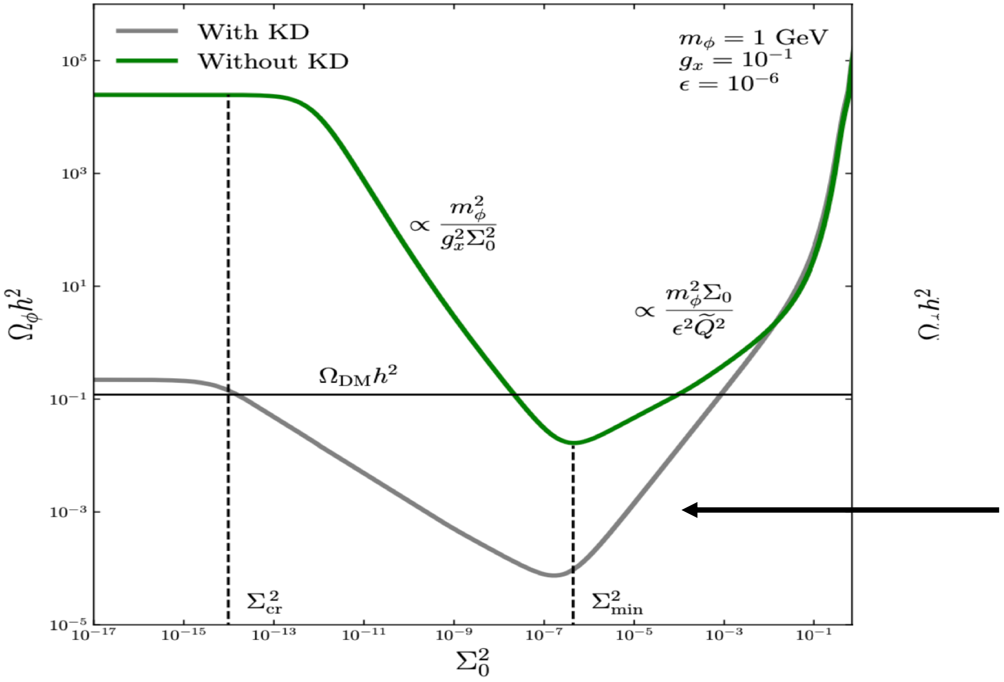
$$T_\chi = \frac{g_\chi}{n_\chi}\int\frac{d^3p}{(2\pi)^3}\frac{\vec{p}^2}{3E}f_\chi(\vec{p}).$$

$$\frac{dT_\phi}{dt} = -2HT_\phi - \left\{\langle\sigma_{\rm ann}v\rangle_T\frac{n_{\rm eq}^2}{n} + \mathcal{C}_{\rm col}T^6\right\}(T_\phi - T)\,.$$

$$\frac{dn}{dt} = -3Hn - \langle\sigma_{\rm ann}v\rangle_{T_\phi}n^2 + \langle\sigma_{\rm ann}v\rangle_T n_{\rm eq}^2\,.$$

- With kinetic decoupling

K



$$\Sigma_0^2 \equiv 1 - 4m_\phi^2/m_x^2$$

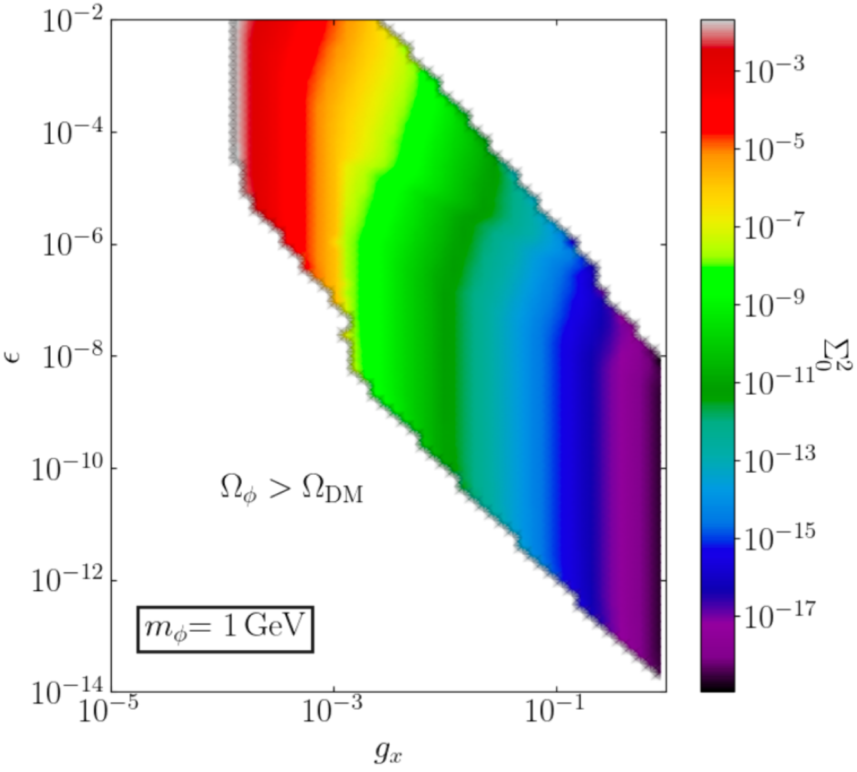
- In standard FO DM annihilation stops around FO time x~20 . Here peak of annihilation when T ~mx-2mϕ, can be much larger x
- Strong reduction of relic abundance

Results

- Allowed parameter space – m_{DM}, Σ0 (mass splitting), gx, ε
- Constraints
  - Relic density
  - CMB anisotropies
  - CMB distorsions
  - Indirect detection (XMM and/or Fermi)
  - Direct detection
  - Colliders

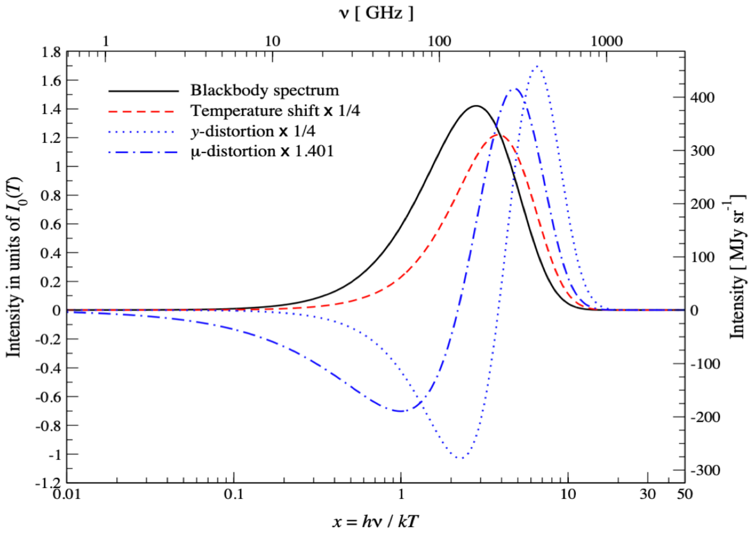
- Allowed parameter space – $m_{DM} = 1\text{GeV}$
- First case : $\Sigma_0^2 < \bar{\Sigma}_{\min}^2$

Relic density



CMB distorsions

- DM annihilation injects energy in primordial plasma and generate distorsions – frozen after recombination -> deviations of CMB from pure black body (J. Chluba, arXiv:1806.02915)
- Injection before $z_{DC}=1.8\ 10^6$ - energy redistribution efficient via Compton scattering and number of photons modified by photons non-conserving processes: double Compton and thermal bremstrahlung -> temperature shift
- Injection before $z_C = 5.8\ 10^4$ – number of photons unchanged – Compton scattering ensures efficient energy redistribution amongst photons-> energy per photon increases and leads to non-zero chemical potential (μ distorsion)
- Injection after z_C – energy redistribution inefficient – y distorsion



CMB distorsions

- Limits from FIRAS - Fixsen et al, APJ73 (1996) 576; with reanalysis Bianchini, Fabbian, arXiv:2206.02762
  - $|\mu|<4.7\mathrm{X}10^{-5}$ $|y|< 1.5\mathrm{X}10^{-5}$
- Energy released in the photon bath

$$d\rho_\gamma = f_{\rm em} \times \langle\sigma_{\rm ann} v\rangle n_\phi^2 dt \times 2m_\phi$$

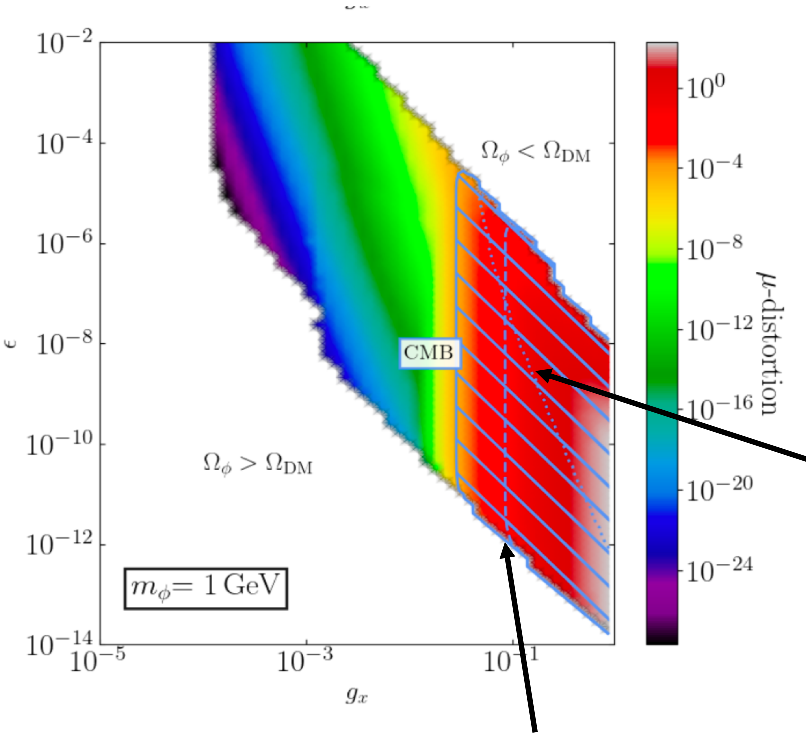
$$\mu = \int d\mu \approx 1.4 \int_0^\infty \mathcal{J}_\mu(z) \frac{d\rho_\gamma}{\rho_\gamma}$$

$$y = \int d\mu \approx \frac{1}{4} \int_0^\infty \mathcal{J}_y(z) \frac{d\rho_\gamma}{\rho_\gamma} \ ,$$

$$\mathcal{J}_\mu(z) = \left(1 - \exp\left[-\left(\frac{1+z}{z_C}\right)^{1.88}\right]\right) \times \exp\left[-\left(\frac{z}{z_{DC}}\right)^{5/2}\right] ,$$

$$\mathcal{J}_y(z) = \left(1 + \left(\frac{1+z}{6.0 \times 10^4}\right)^{2.58}\right)^{-1} .$$

- Allowed parameter space – mDM=1 GeV
- First case : $\Sigma_0^2 < \bar{\Sigma}_{\min}^2$



DM annihilation injects energy in plasma generate distortions from pure black body spectrum – constraints from FIRAS

- Note future missions (PIXIE,PRISM) sensitivity 10^{-8} ou μ and y

Anisotropies of the CMB computed at z~600

$$p_{\rm ann} = \frac{R^2}{2} f_{\rm em} \frac{\langle \sigma_{\rm ann} v \rangle_{\rm CMB}}{m_\phi} ,$$

y -distorsions

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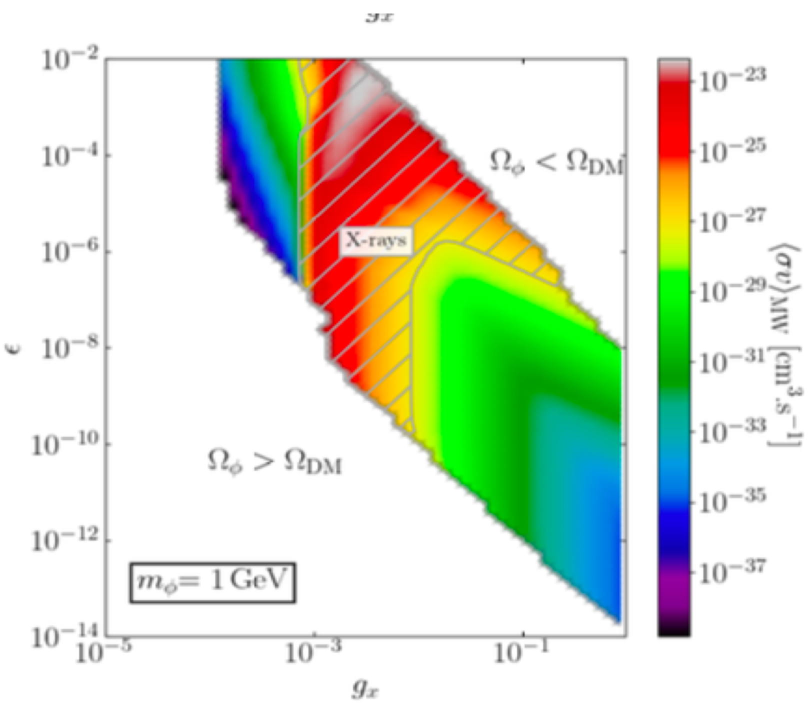


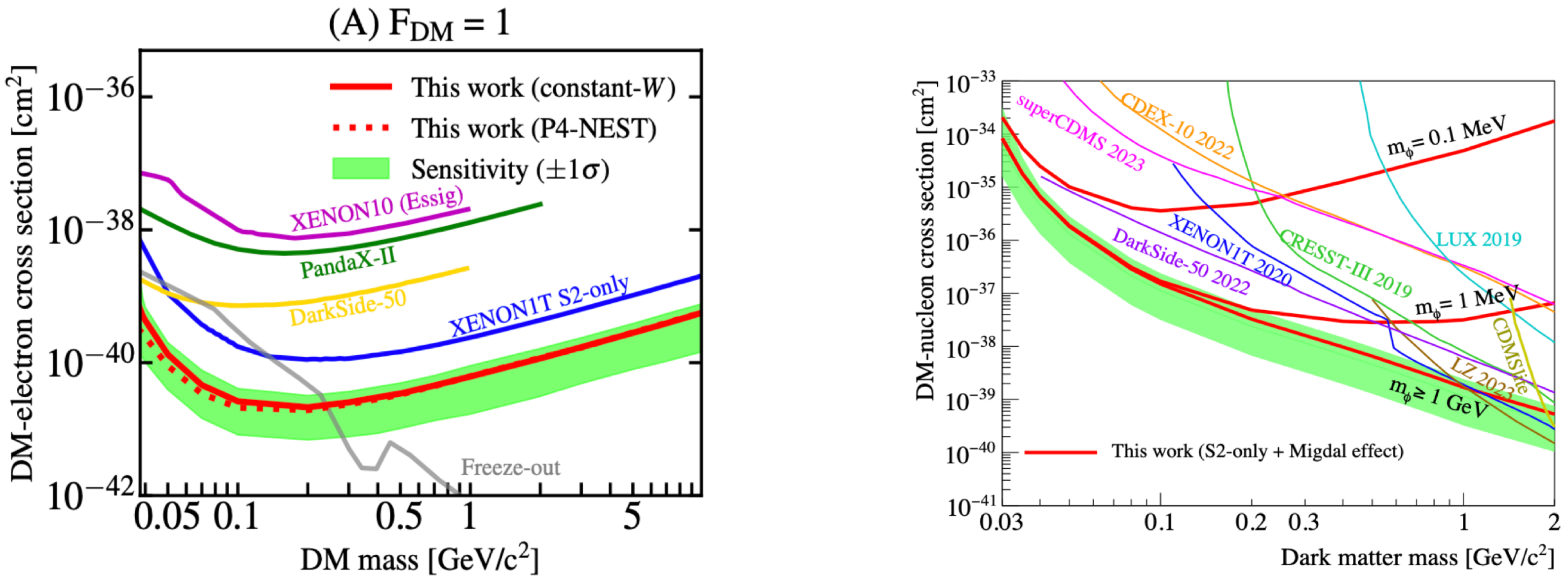
Xray Constraints from XMM Newton, Cirelli et al 2303.08854

GB, Chakraborti, Genolini, Salati, 2401.02513 ($M_{med} \sim 2M_\chi$)

- Adding Constraints from direct detection and colliders
- Direct detection :

$$\sigma^{\rm SI}_{\phi T} \approx \frac{1}{\pi}\,\frac{q_T^2\, e^2\, \epsilon^2\, g_x^2}{m_x^4}\,\mu_T^2\, .$$

  - Electrons : PANDAX-4T (arXiv:2212.10067)
  - Nucleon : PandaX-4T (arXiv:2308.0540) projections DARKSPHERE, SBC



PandaX-4T

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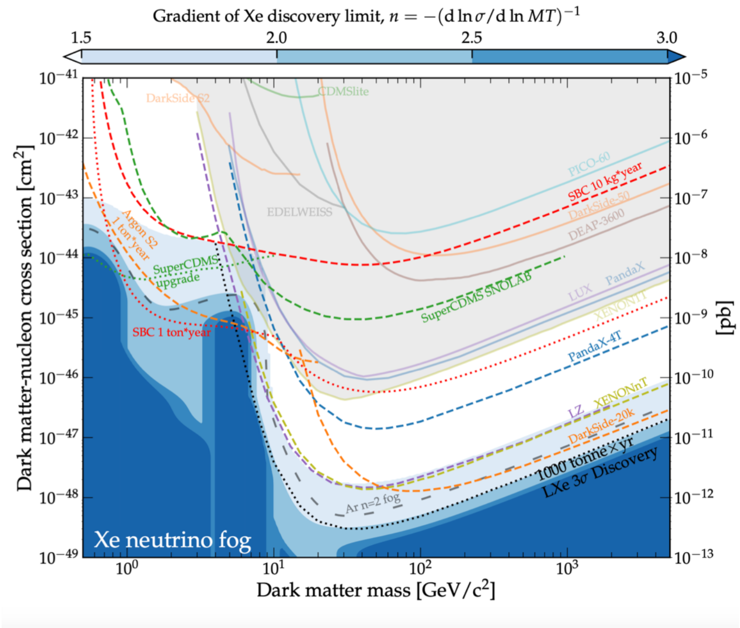
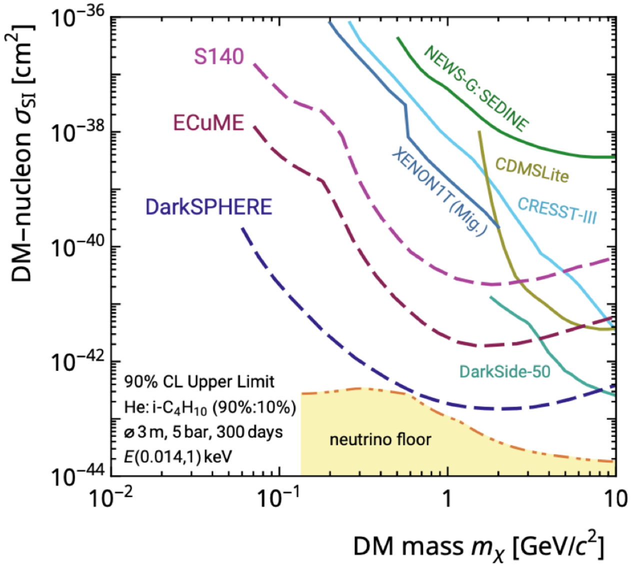
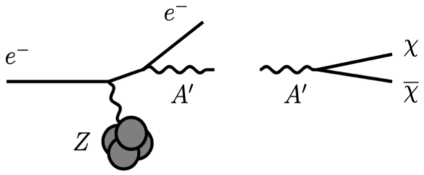
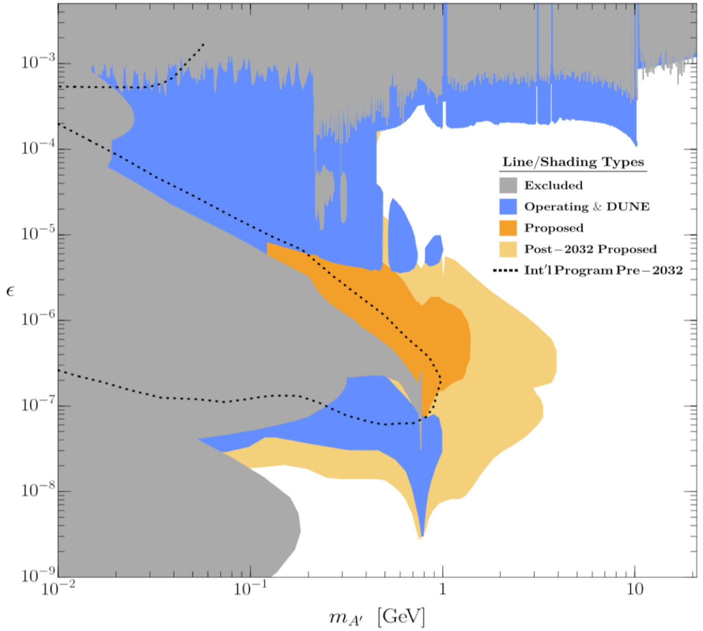




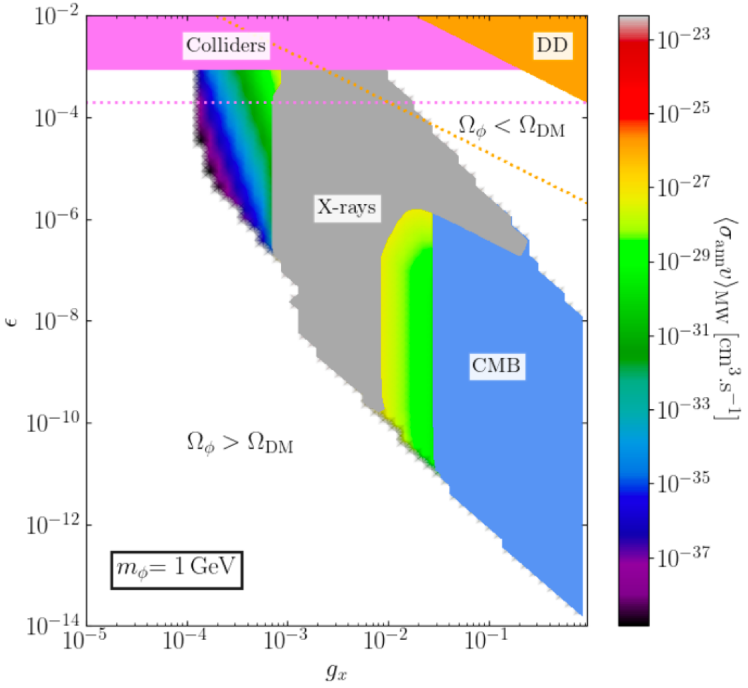
- Colliders : Searches for dark photons in both visible and invisible mode
  - Visible:
    - BABAR $e^+e^- \to \gamma A'$, $A' \to e^+e^-, \mu^-\mu^+$. ---- $1\ \text{GeV} \lesssim m_x \lesssim 10\ \text{GeV}$.
    - LHCb : $\pi^0 \to A'\gamma$, $\eta \to A'\gamma$; $A' \to \mu^-\mu^+$ ---- $2\,m_\mu \lesssim m_x \lesssim 0.5\ \text{GeV}$
    - and CMS : di-muon searches for $m_{A'} > 10\text{GeV}$
    - Beam dumps (ν-CAL, CHARM) - $\eta \to A'\gamma$ and A'decays into displaced muons
      - Relevant for $m_{A'} <$ few hundred MeV's
  - Invisible : BABAR ($m_{A'} < 8$ GeV) and LEP ($m_{A'} > 8$ GeV) , $e^+e^- \to \gamma A' \to$ invisible
  - Future: visible : DUNE, BELLE-II (dileptons)
    - Invisible : LDMX – electron beam dump

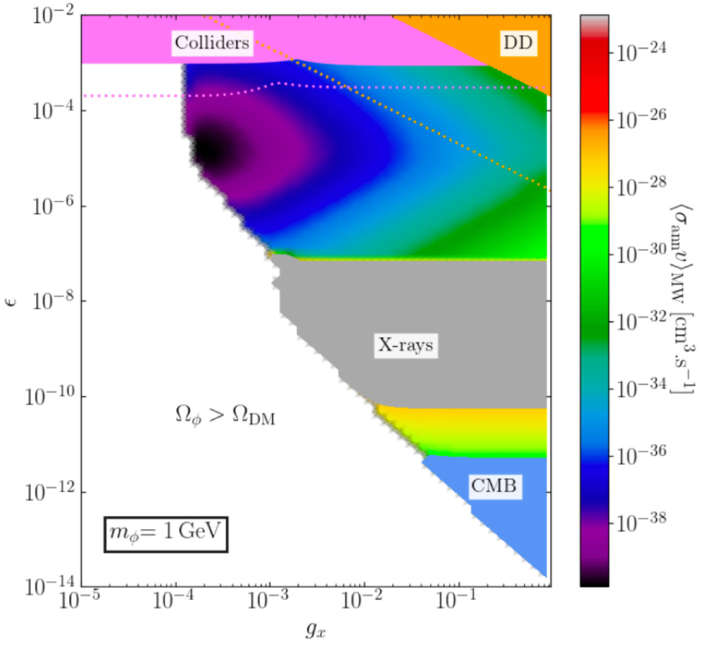




Snowmass, Gori et al, 2209.04671

- Allowed parameter space – 1GeV
  - strong constraints from ID (Xray) and CMB,
  - Collider constraints (here BABAR e+e--> γA’ both visible/invisible decays)
  - Mostly below threshold for DD on nucleons - (PandaX and projections for DarkSPhere/SBC)

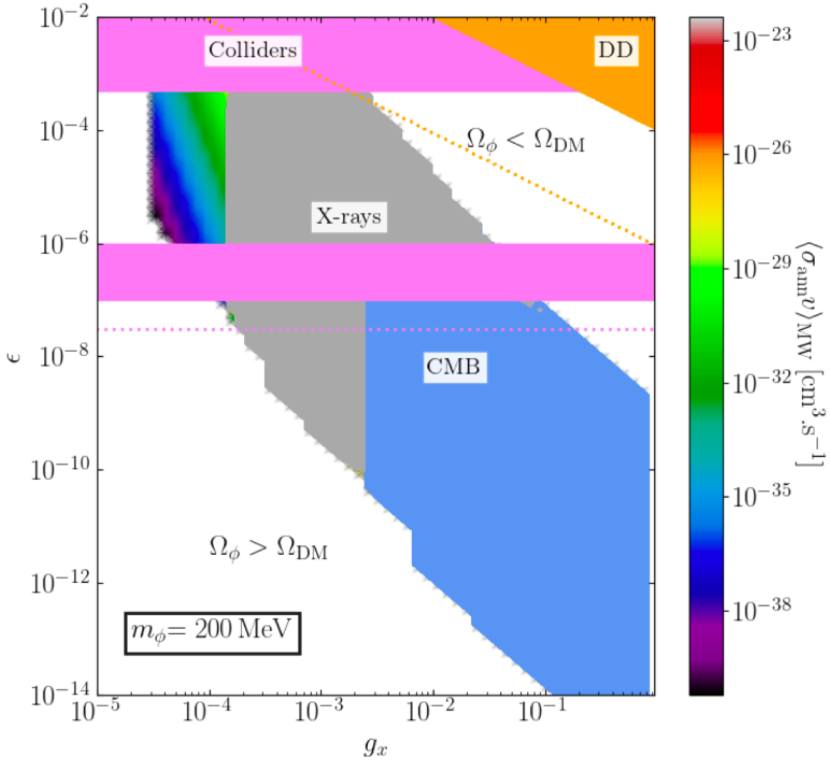


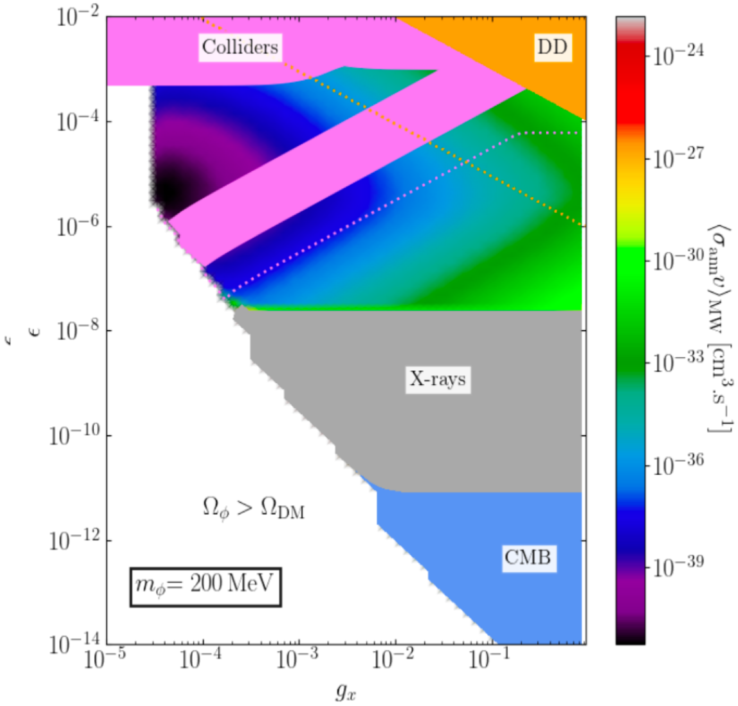


$$\Sigma_0^2 > \bar{\Sigma}^2_{\rm min}$$

- Allowed parameter space – lighter DM (200MeV)
    - Collider constraints – LHCb + beam dumps +BABAR
    - DD on nucleons or electrons (PandaX and projections for DarkSPhere)

νCAL
CHARM



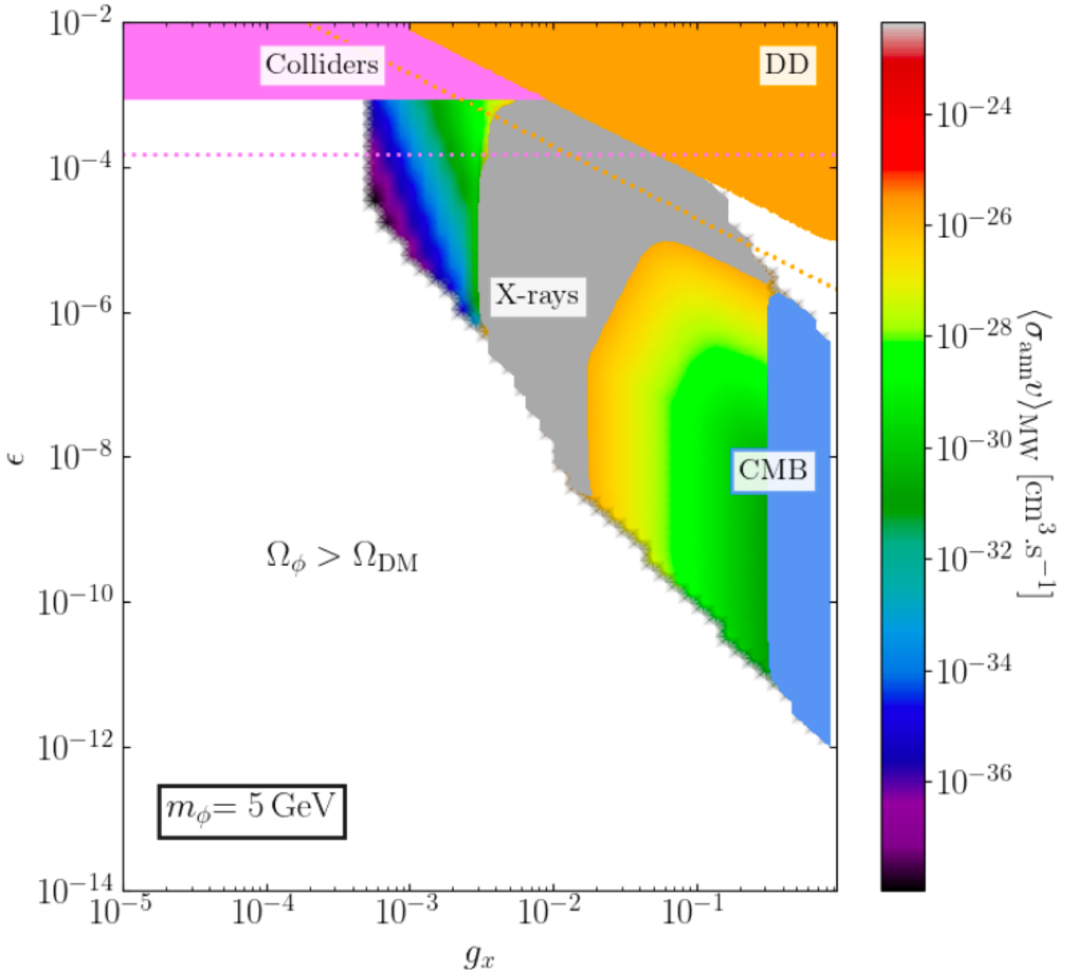


$\Sigma_0^2 > \bar{\Sigma}_{\rm min}^2$

Summary

- DM annihilation mostly occurs when its temperature is of the order of the mass gap (much after FO), taking into account kinetic decoupling can lower relic abundance by orders of magnitude
- In dark photon model, when kinetic mixing is small – peak of DM annihilation occurs when CMB spectrum is most sensitive to energy injection – μ distorsions put strong constraints,
- X ray, collider and DD are complementary
- Potential to further probe the allowed parameter space with future CMB missions (PIXIE or PRISM) future DD and searches for dark photons.
- GeV-scale DM still allowed – potential signature in cosmology/ ID/DD/Collider

- Allowed parameter space – heavier DM (5GeV)



$\tilde{\Sigma}_0 > \tilde{\Sigma}_{\rm min}$