

# Analyzing the Cosmology & Signals of pseudo-Dirac DM

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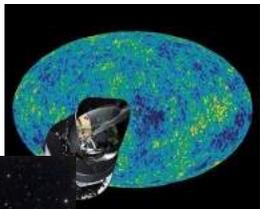
## **DM + $\nu$ Forum**

Based on arxiv: 2108.13422 w. Natalia Toro

Imperial College  
London

# DM evidence

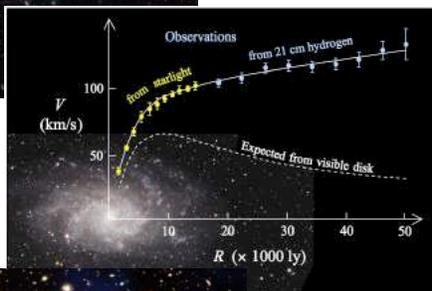
Galaxy clusters



CMB



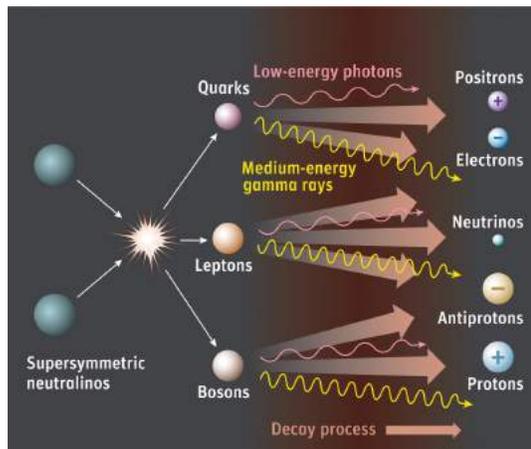
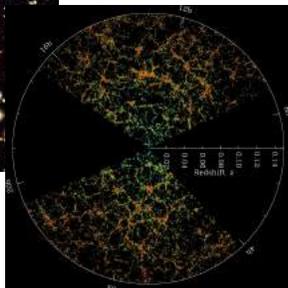
Rotation curves



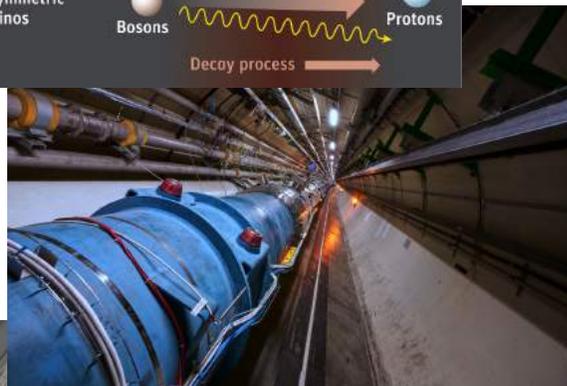
Bullet cluster



LSS



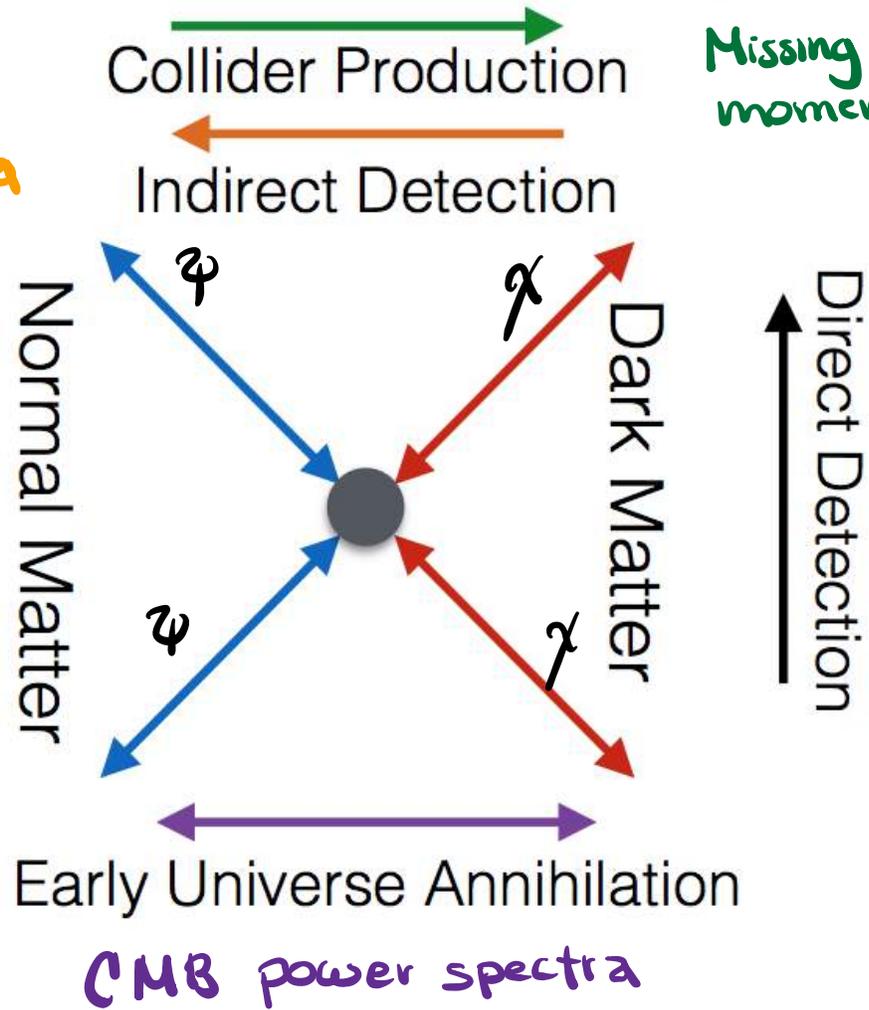
SEARCHES



# In this talk:

CMB  
power  
spectra

Beam dump  
Missing mass, energy,  
momentum



Nuclear recoils

Electron recoils

# DM PARTICLE

M:

Bounds from QM

$\lambda < 1 \text{ kpc}$  structures

\* fermions:  
T.G. bound  $m \geq 18 \text{ eV}$

$10^{-22} \text{ eV}$

axions

MeV DM

WIMPS

$m \sim 10^{10} \text{ eV}$

EW scale

Bound from  $N_{\text{eff}}$

Thermal relic

Q balls

Bound from tidal disruption

$70$   
 $10 \text{ eV}$

Wave DM

interparticle separation  $< \lambda$

$m \leq 30 \text{ eV}$

PBH

asteroid mass

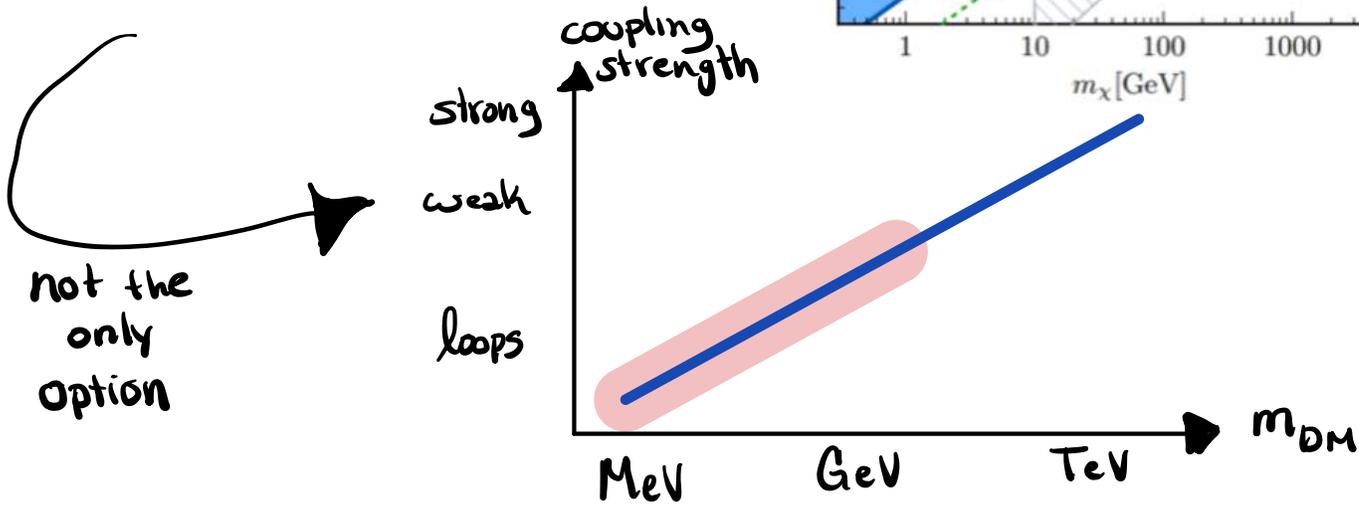
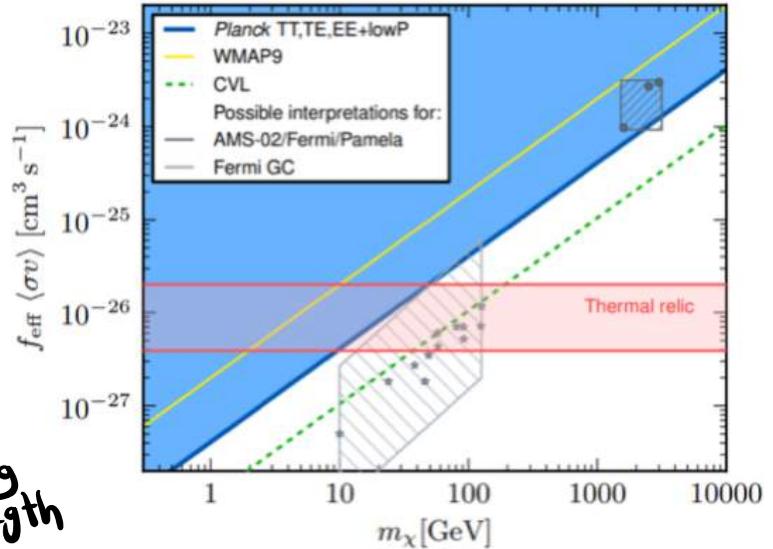
stellar mass

S:

Spin  $0, \frac{1}{2}, 1, \frac{3}{2}$

# What happened to WIMPs?

- thermal relic
- $\langle \sigma v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$
- elastic scattering
- weakly interacting
  - $m_{\text{DM}} \sim \text{GeV}$



# Thermal Relic DM

Interacts with thermal bath of SM particles

## DM PORTALS

Higgs portal

$$\epsilon_h |H|^2 |\phi|^2$$

Vector Portal

$$\epsilon_\gamma F'_{\mu\nu} F^{\mu\nu}$$

↑

kinetic mixing

Neutrino portal

$$\epsilon_\nu h L \not{\partial} \nu$$

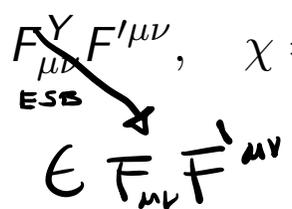
Can arise at loop level in unification scenarios

Generically small  $\epsilon_\gamma$



Simplest technically natural scenario

$$\mathcal{L} \supset \bar{\chi}(i\not{D} - m_\chi)\chi + \frac{1}{2}m_A'^2 A'^2 + \frac{1}{2}\epsilon_Y F_{\mu\nu}^Y F'^{\mu\nu}, \quad \chi = (\eta \ \xi^\dagger)$$



No symmetry forbids Majorana masses  $m_\eta, m_\xi \ll m_\chi$

→ nearly degenerate mass eigenstates with mass splitting

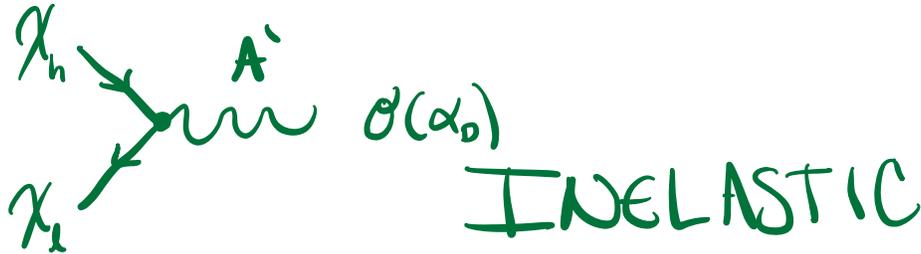
$$\delta = m_\eta + m_\xi$$

$$\chi_l \simeq \frac{1}{\sqrt{2}}(\eta + \xi), \quad \chi_h \simeq \frac{1}{\sqrt{2}}(\eta - \xi),$$

Also  
 $m_{A'} > m_\chi$

$$m_{\chi_l} \simeq m_\chi - \delta/2, \quad m_{\chi_h} \simeq m_\chi + \delta/2$$

$$\alpha_0 \equiv \frac{g_0^2}{4\pi}$$



$$\mathcal{L} \supset -igD \frac{m_\chi}{\sqrt{m_\chi^2 + (m_\eta - m_\xi)^2/4}} \left( \chi_l^\dagger \bar{\sigma}^\mu A'_\mu \chi_h - \chi_h^\dagger \bar{\sigma}^\mu A'_\mu \chi_l \right)$$

$$-igD \frac{m_\eta - m_\xi \equiv 0}{\sqrt{m_\chi^2 + (m_\eta - m_\xi)^2/4}} \left( \chi_h^\dagger \bar{\sigma}^\mu A'_\mu \chi_h - \chi_l^\dagger \bar{\sigma}^\mu A'_\mu \chi_l \right)$$

ELASTIC



Large changes in thermal history of DM

# Interactions with SM

- Diagonalize gauge fields kinetic terms

$\Rightarrow$

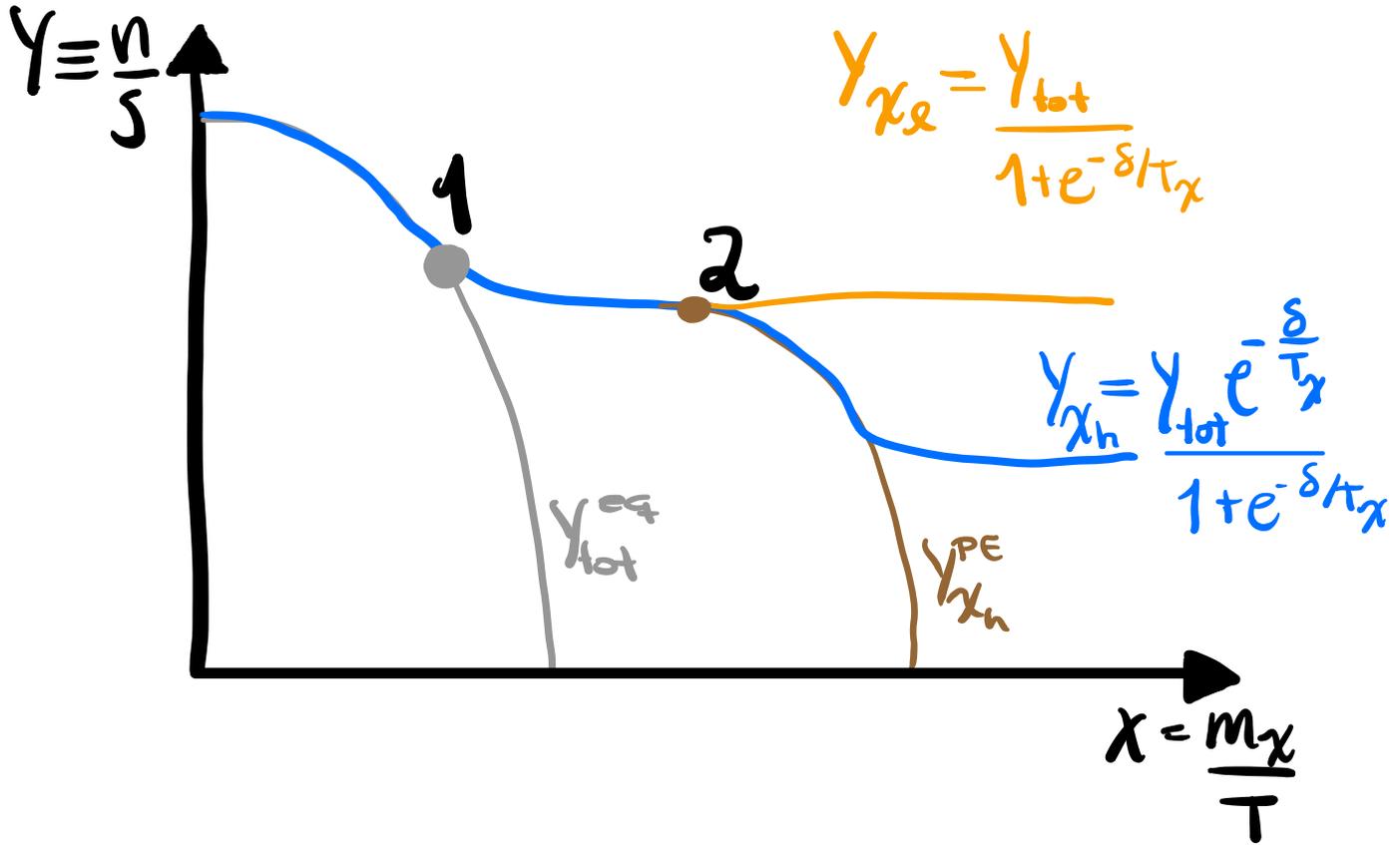
$$U(1)^{\text{QED}} \qquad U(1)^{\text{D}}$$
$$q \longrightarrow \epsilon q$$



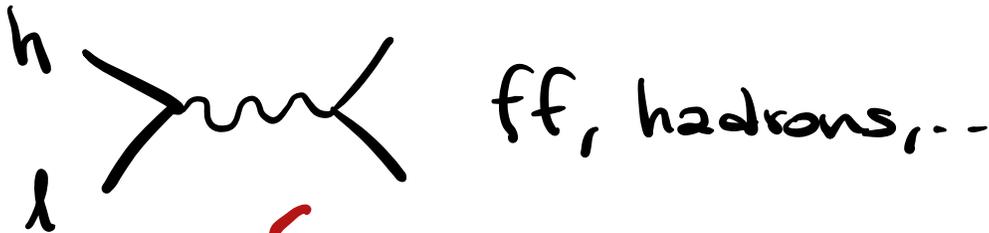
SM matter acquires  
small  $U(1)^{\text{D}}$  charge

# Evolution of DM abundance

# Thermal History



# 1st freeze-out:



$$\langle \sigma_{\text{ann}} v \rangle (m_{\chi_e}, \delta, \alpha_D, m_{A'}, \epsilon) \Big|_{T=T_{\text{f.o.}}} = \langle \sigma_{\text{ann}} v \rangle^{\text{thermal relic}} (m_{\chi_e}, \delta)$$

**BENCHMARK**

$$m_{A'} = 3m_{\chi_e}$$

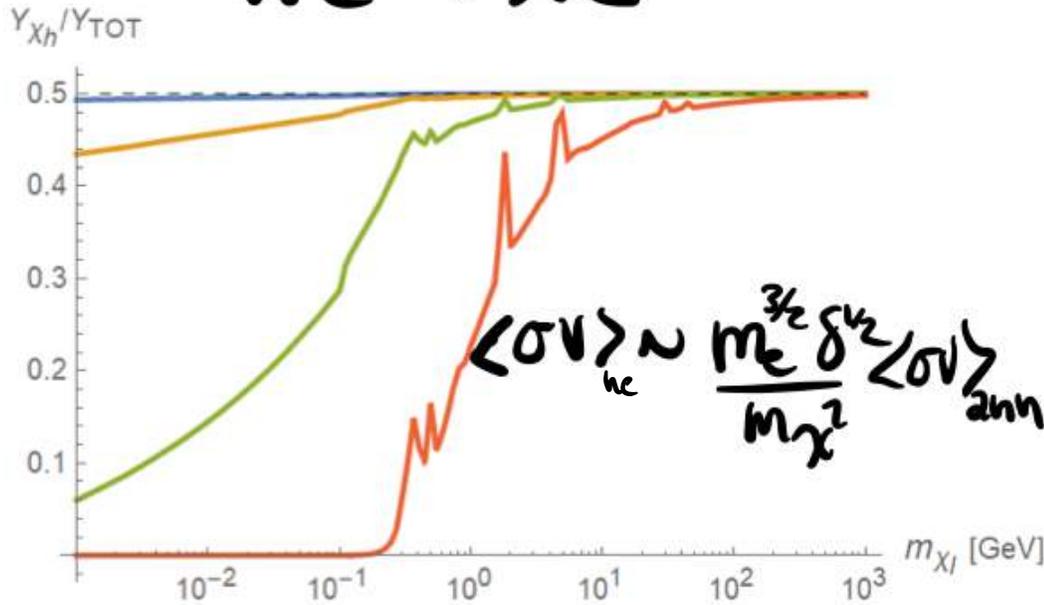
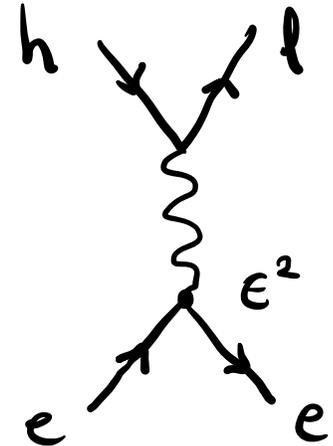
$$\alpha_D = 0.5$$

Required from  $\Omega_{\text{DM}}^{\circ}$

# 2nd freeze-out

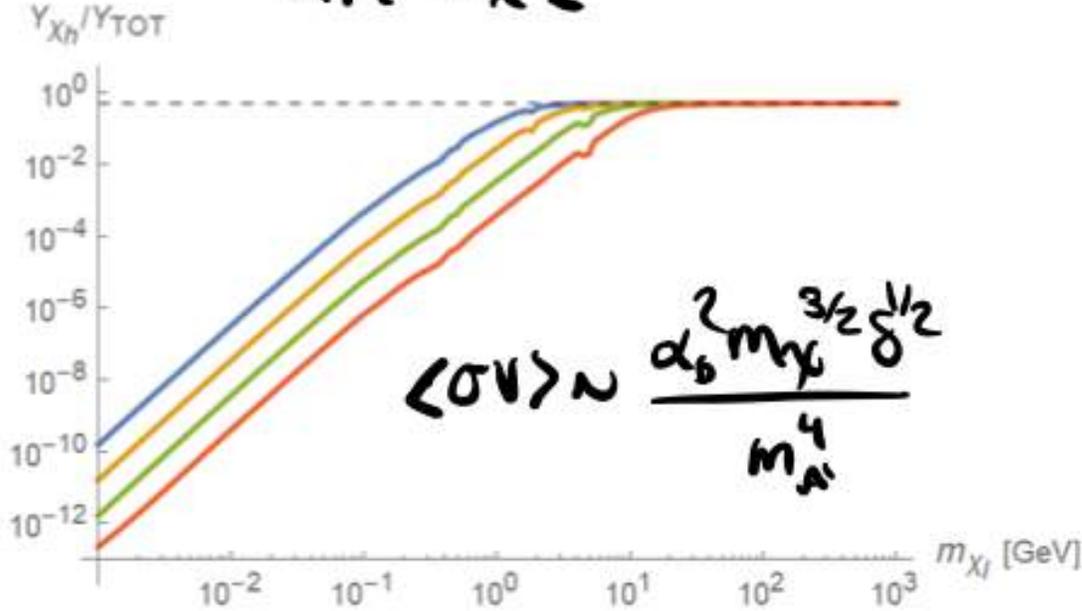
$he \rightarrow le$

Kinetic decoupling

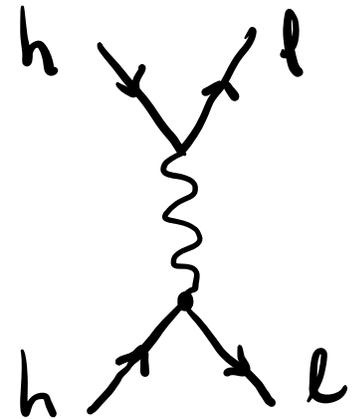


- $\delta=10^{-6}$  GeV
- $\delta=10^{-5}$  GeV
- $\delta=10^{-4}$  GeV
- $\delta=10^{-3}$  GeV

$hh \rightarrow ll$



- $\delta=10^{-6}$  GeV
- $\delta=10^{-5}$  GeV
- $\delta=10^{-4}$  GeV
- $\delta=10^{-3}$  GeV



- After kinetic decoupling

$$T_\chi \sim T_{Xe} \left( \frac{T^{SM}}{T_{Xe}} \right)^2$$

# Depopulation via decays

$$Y_{\chi_h} = Y_{\text{tot}} e^{-\Gamma t}$$

$$h \rightarrow l + 2e$$

$$\Gamma \sim \frac{\alpha_0 \epsilon^2 \delta^5}{m_{\tilde{A}'}^4}$$

Only for  
 $\delta > 2m_e$

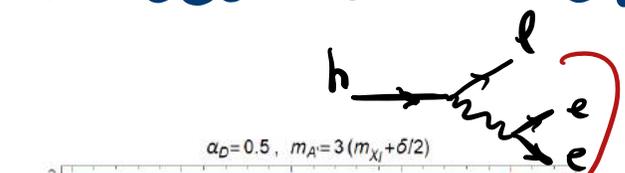
$$h \rightarrow l + 3\pi$$

$$\Gamma \sim \frac{\alpha_0 \epsilon^2 \delta^5}{m_{\tilde{A}'}^4} \frac{\delta^8}{m_e^8}$$

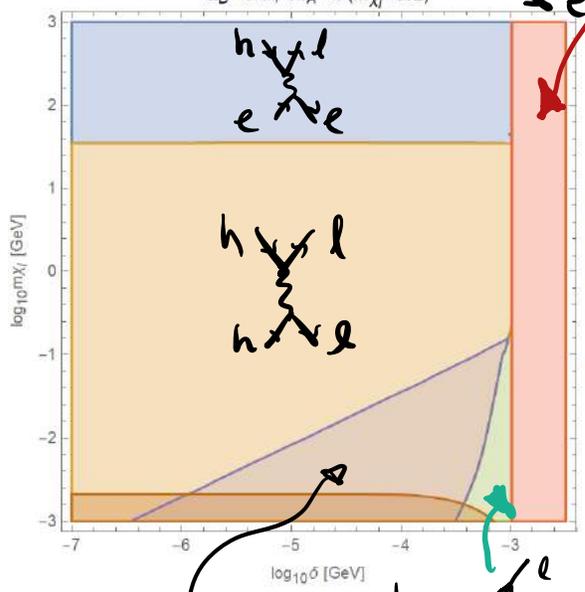
$$h \rightarrow l + 2\nu$$

$$\Gamma \sim \frac{\alpha_0 \epsilon^2 \delta^5}{m_{\tilde{A}'}^4} G_{\text{eff}}^2 \delta^4$$

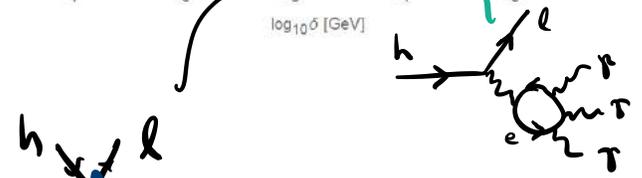
# At recombination:



$\alpha_D = 0.5, m_A = 3(m_{X_l} + \delta/2)$



- $X_h e \rightarrow X_l e$  dominant
- $X_h X_h \rightarrow X_l X_l$  dominant
- $X_h \rightarrow X_l + 3\gamma$  dominant
- $X_h \rightarrow X_l + 2e$  dominant
- $X_h X_l \rightarrow X_l X_l$  potentially relevant
- $T_{X_l X_h \rightarrow \gamma\gamma} < 3 T_{X_h e \rightarrow X_l e}$

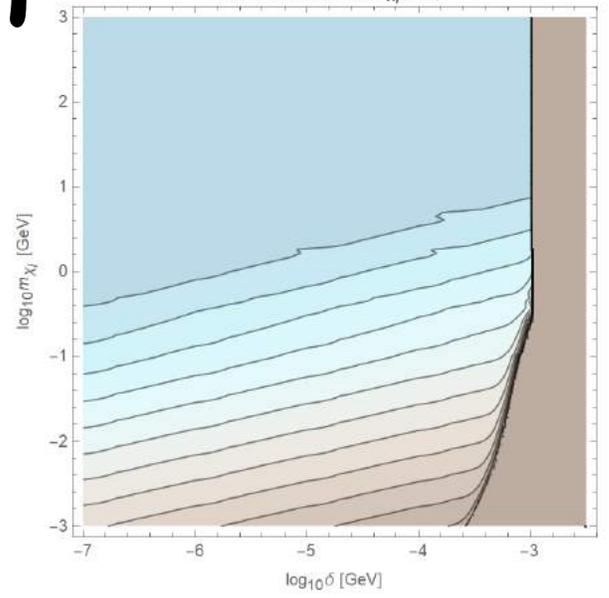


$\frac{\delta}{m_X} v^2$  suppressed  
 semi-elastic scattering

$m_X$

$$f_{X_h} \equiv \frac{Y_{X_h}}{Y_{tot}}$$

$\alpha_D = 0.5, m_A = 3(m_{X_l} + \delta/2)$



$\frac{Y_{X_h}}{Y_{X_h} + Y_{X_l}}$

10<sup>-1</sup>  
 10<sup>-2</sup>  
 10<sup>-3</sup>  
 10<sup>-4</sup>  
 10<sup>-5</sup>  
 10<sup>-6</sup>  
 10<sup>-7</sup>  
 10<sup>-8</sup>  
 10<sup>-9</sup>  
 10<sup>-10</sup>  
 10<sup>-11</sup>  
 10<sup>-12</sup>  
 10<sup>-13</sup>

$\delta$

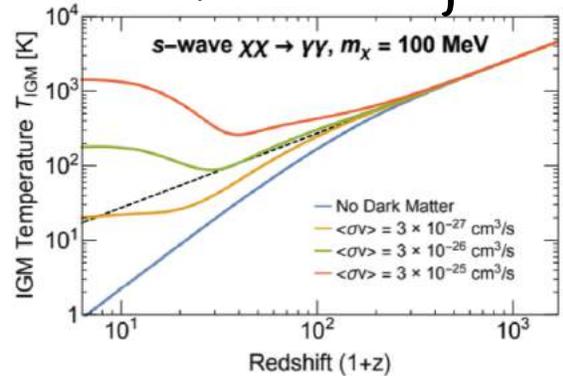
# Primordial constraints

# Residual Annihilation & Decay

Change of IGM ionization near recombination

Change CMB temperature and polarization spectra

Li, Slatyer, Zavala, 2016



annihilating DM

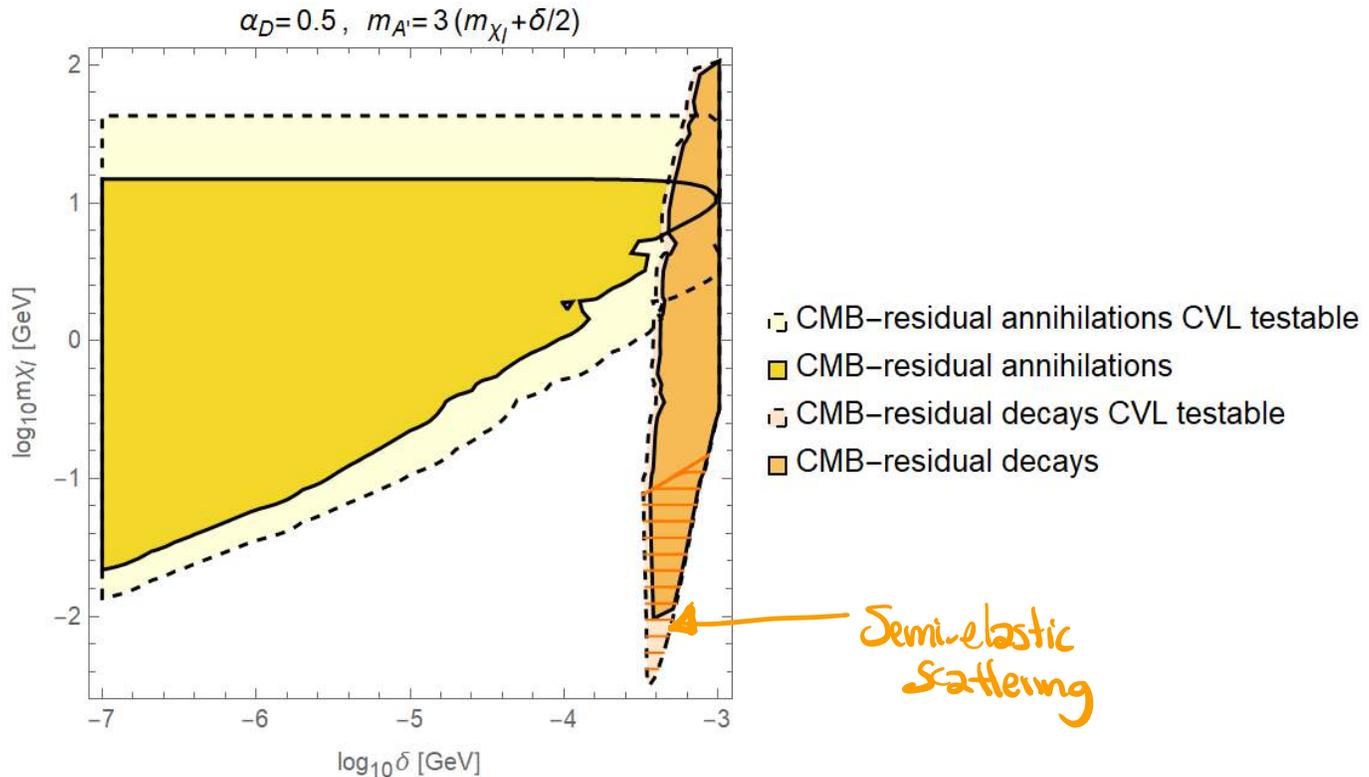
$$\frac{dE}{dt dV} = \rho_{\alpha}^2 \Omega_{\text{CDM}}^2 (1+z)^6 \frac{2 Y_{\chi_n} Y_{\chi_e}}{Y_{\text{tot}}^2} \frac{\langle\sigma_{\text{ann}} v\rangle}{m_{\chi}} f_a(z) \equiv P_{\text{ann}}$$

decaying DM

$$\frac{dE}{dt dV} = \rho_{\alpha} \Omega_{\text{CDM}} (1+z)^3 \frac{Y_{\chi_n}}{Y_{\text{tot}}} \frac{\delta}{m_{\chi}} \frac{f_{\text{dec}}}{\tau_{\chi_n}} \equiv P_{\text{dec}}$$

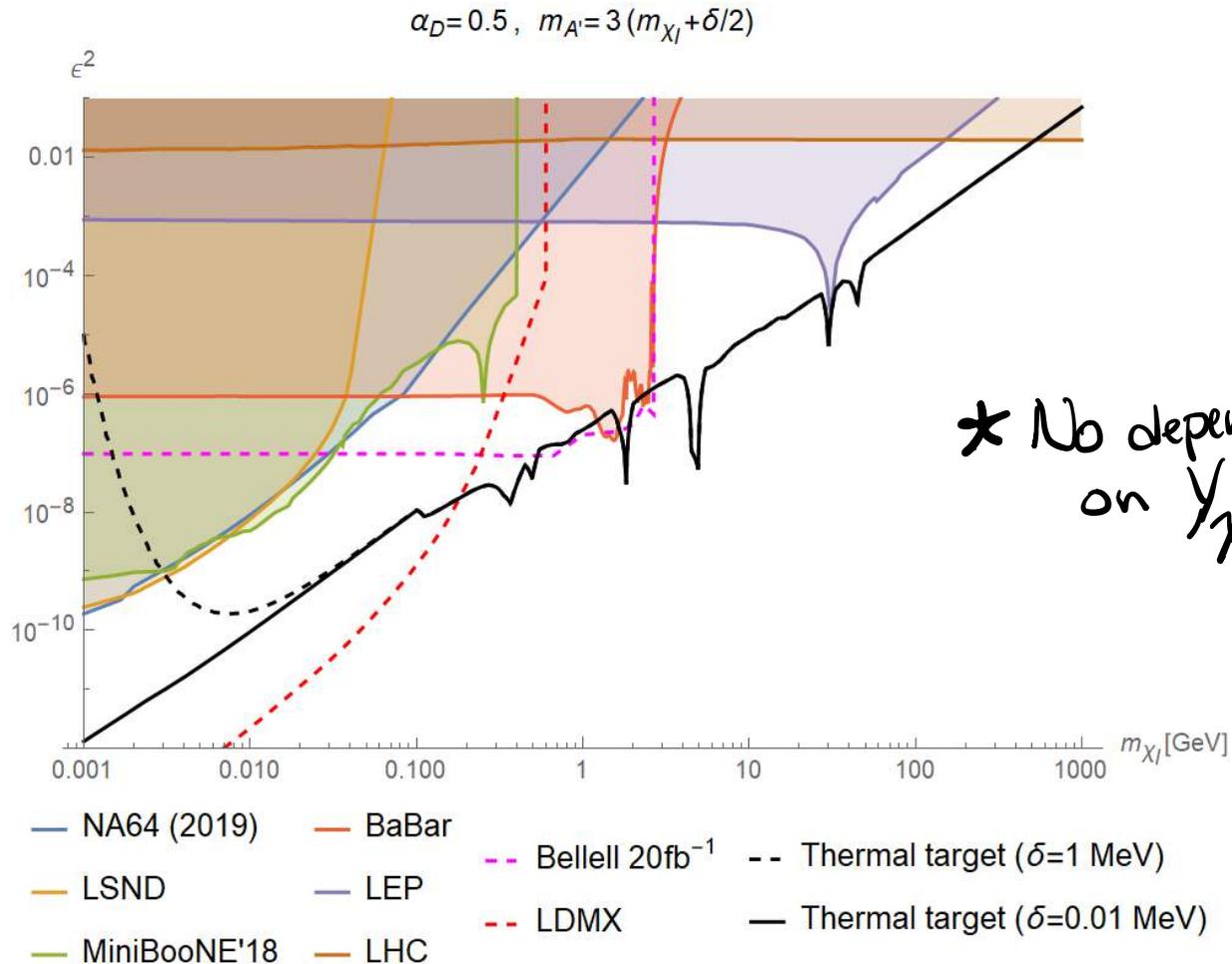
$$P_{\text{ann}} \lesssim 10^{-2} \frac{\text{cm}^3}{\text{s GeV}} \sim 10^{-11} \text{ GeV}^{-3}$$

$$P_{\text{dec}} \lesssim \frac{1}{10^{24} \text{ s}}$$

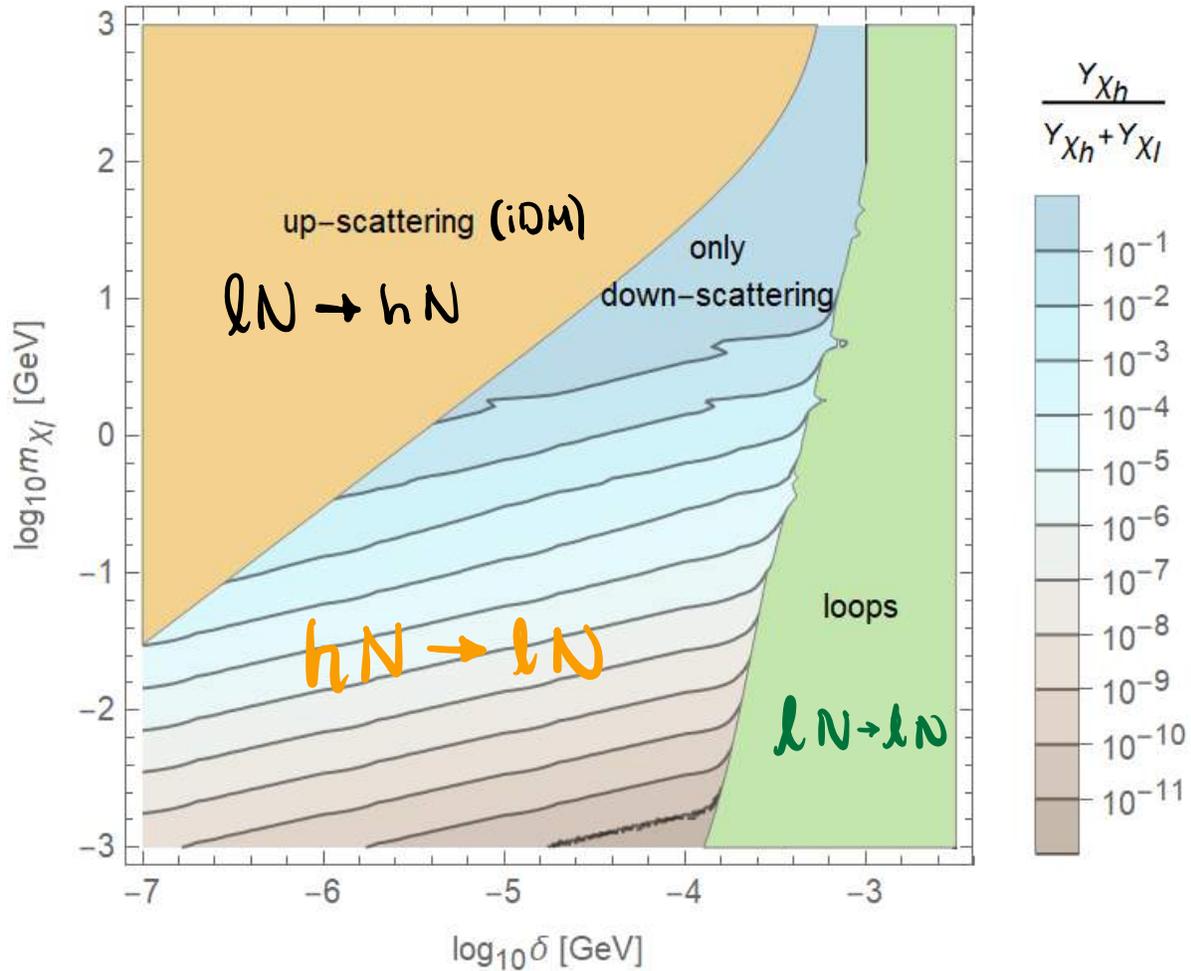


# Accelerator- based Production

# Accelerator-Based DM Production



Direct detection  
of a  
thermal target



# DM-nucleon Down-scattering

Mono-energetic recoil energy

$$E_R \sim \frac{M_{\chi N}}{m_N} \delta \quad \text{with} \quad \delta \gtrsim M_{\chi N} v^2$$

Expected Rate

$$R_N \sim E_{\text{det}} f_{\chi_h}^{\text{det}} \frac{\rho_{\chi}}{m_{\chi}} \frac{N_A}{A_N} \sigma_{\chi N} v$$

Not good  
at  
small  $m_{\chi}$

Earth's shadow suppression

$$f_{\chi_h}^{\text{det}} = E_{\text{det}} \frac{v_{\chi_h}}{v_{\text{tot}}}$$
$$\rightarrow = \int_0^{\pi} d\theta \frac{1}{2} e^{-\frac{L_{\text{earth}}}{\lambda_{\chi_h}}}$$

→ sidereal-day modulation

$$\sigma_{\chi N} v \sim \frac{\alpha \alpha_D E^2 M_{\chi N}^{3/2} \delta^{1/2}}{m_N^4} |F|^2$$

# CRESST-II & III

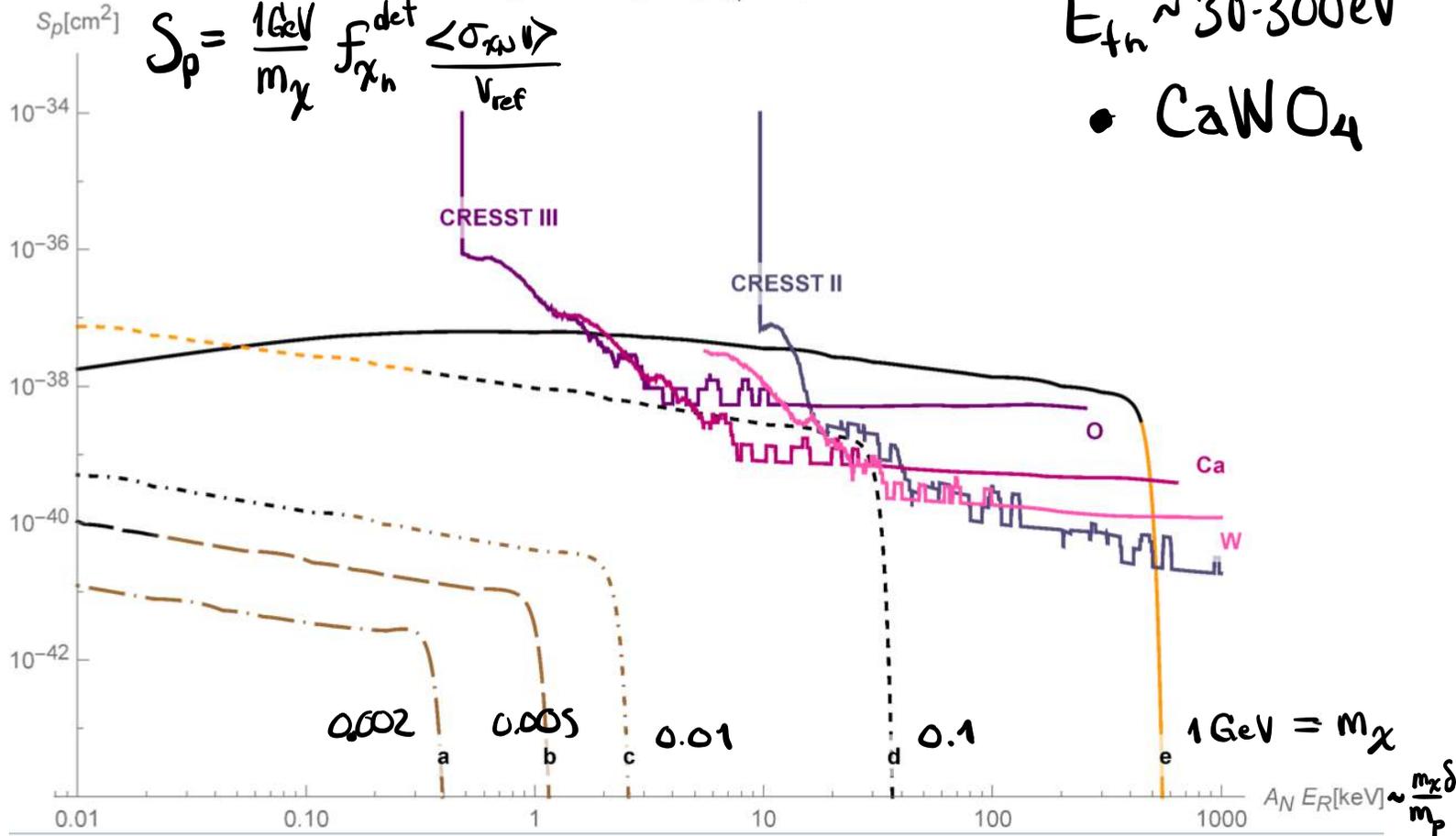
Signal Strength

$$\alpha_D = 0.5, \quad m_{A'} = 3(m_{\chi_l} + \delta/2)$$

$$E_{th} \sim 30-300 \text{ eV}$$

- $\text{CaWO}_4$

$$S_p = \frac{1 \text{ GeV}}{m_\chi} f_{\chi_n}^{\text{det}} \frac{\langle \sigma_{\chi_n \nu} \rangle}{v_{\text{ref}}}$$



# DM-electron Down-scattering

Mono-energetic recoil energy  $E_R = \frac{A_{Xe}}{m_e} \delta_u \delta$

Expected Rate

$$R_e \sim E_{\text{det}} f_{\chi_n}^{\text{det}} \frac{\rho_{\chi}}{m_{\chi}} \frac{NA}{A_N} \tau_{\text{exc}} \sigma_{Xe} V$$

# excited electrons

$$\sigma_{Xe} \sim \frac{\alpha \alpha_0 E^2 \mu_{Xe}^{3/2} \delta^{1/2}}{m_{A'}^4} \sim \frac{m_e^{3/2} \delta^{1/2}}{m_{\chi}^2} \langle \sigma_{ann} v \rangle$$

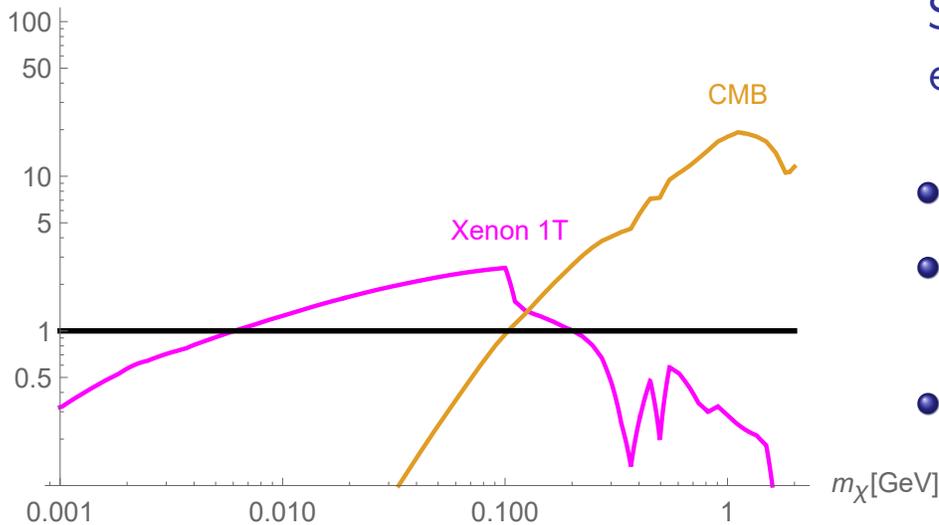
Good at small  $m_{\chi}$





$\delta=3$  keV

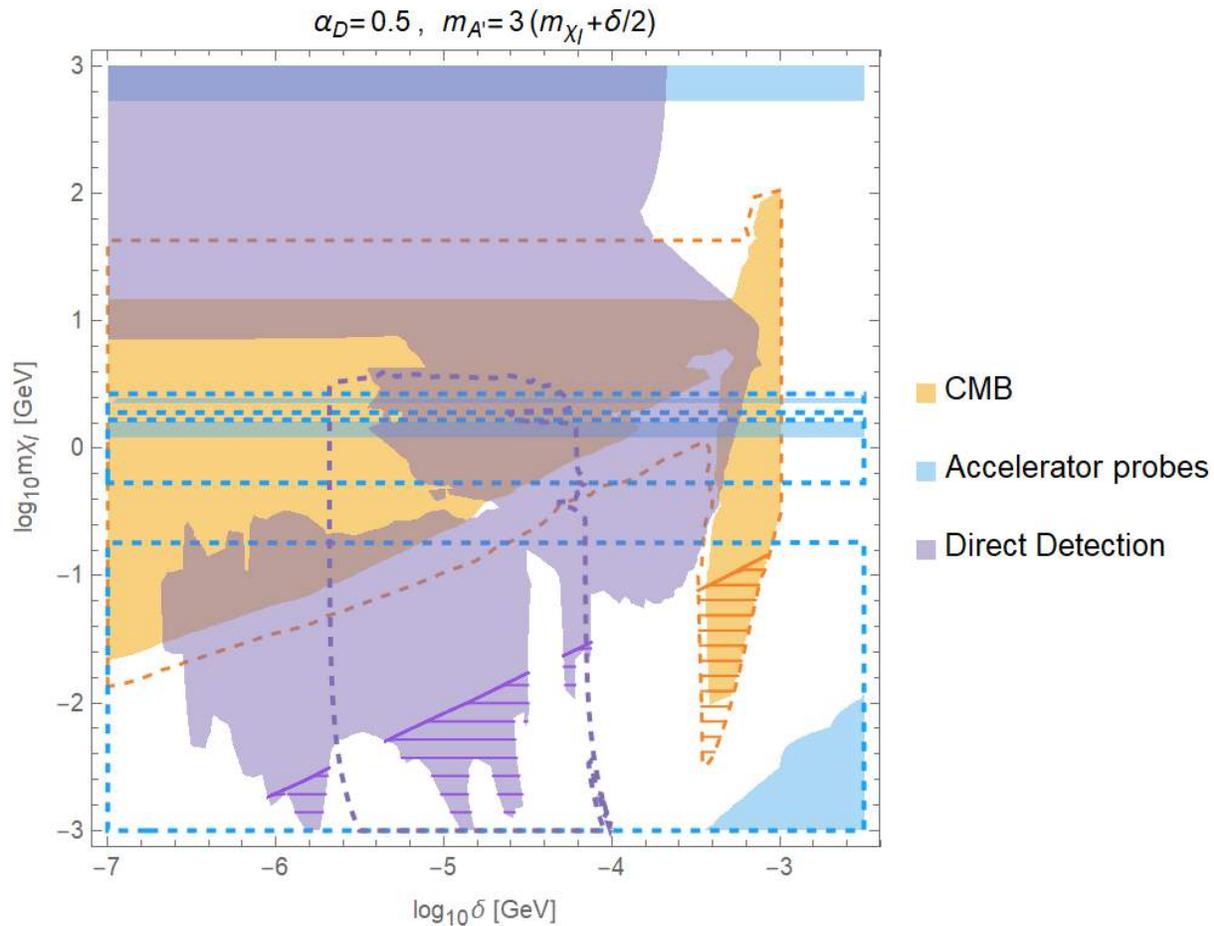
Exclusion factor



Small DM masses could explain Xenon1T excess

- Not strongly ruled-out
- Sensitive to cosmological history  $Y_{\chi h}$
- Sensitive to semi-elastic scatterings  $h\ell \rightarrow \ell\ell$

# Projections for CMB, accelerator and DD probes



# THANK YOU!

