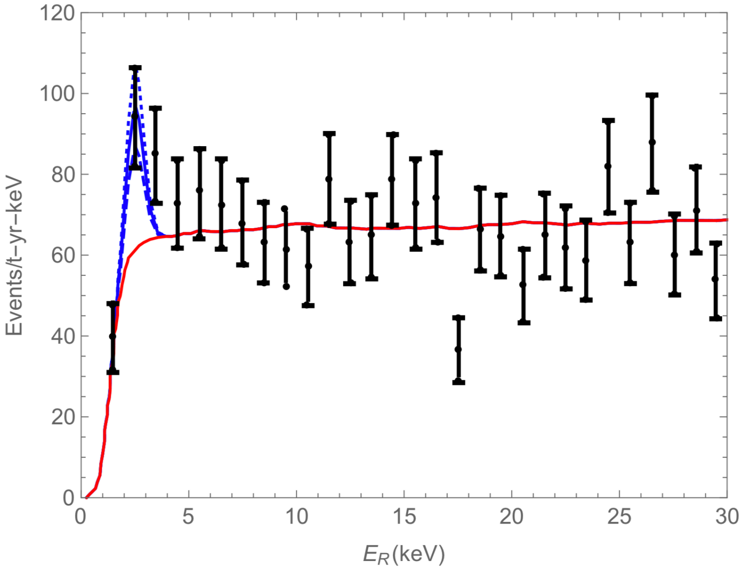

Exothermic dark matter for XENON1T excess

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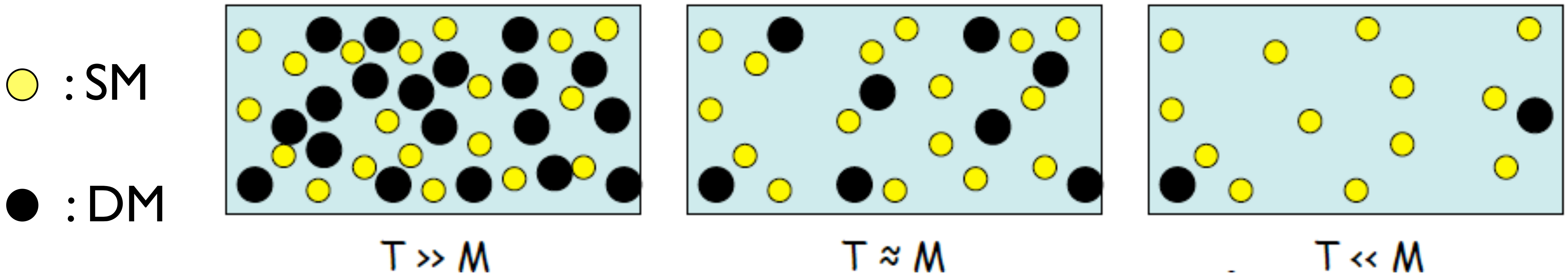
Ref. HML, 2006.13183

6th Korea meeting, KIAS, 17 July 2020

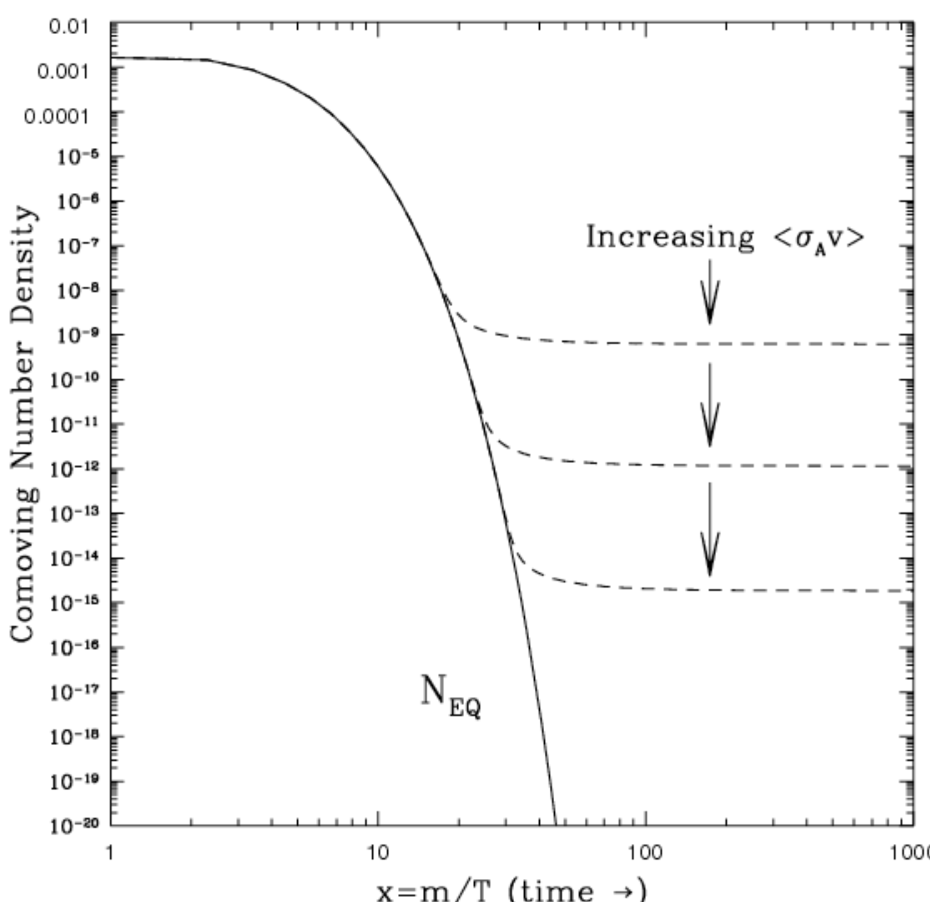
Outline

- XENON1T excess
- Exothermic dark matter
- Effective theory for exothermic DM
- Microscopic models
- Conclusions

WIMP paradigm



DM abundance



time

[Lee,Weinberg(1977)]

Weakly Interacting Massive Particles(WIMP)

Equilibrium: $\chi\chi \leftrightarrow \mathrm{SM\ SM}$

"Freeze-out" process

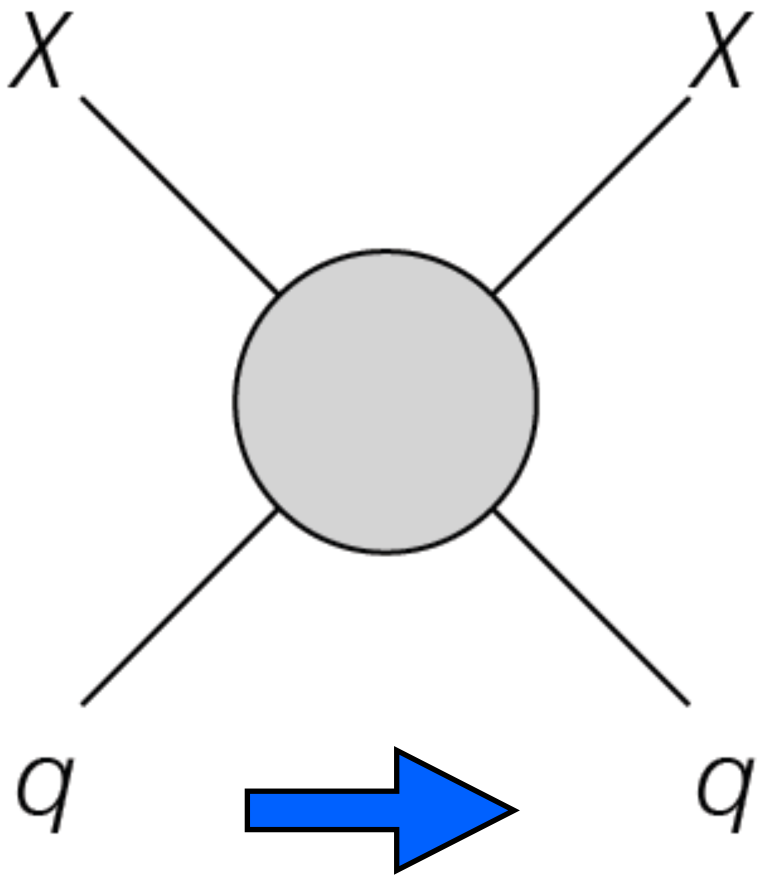
: insensitive to initial history.

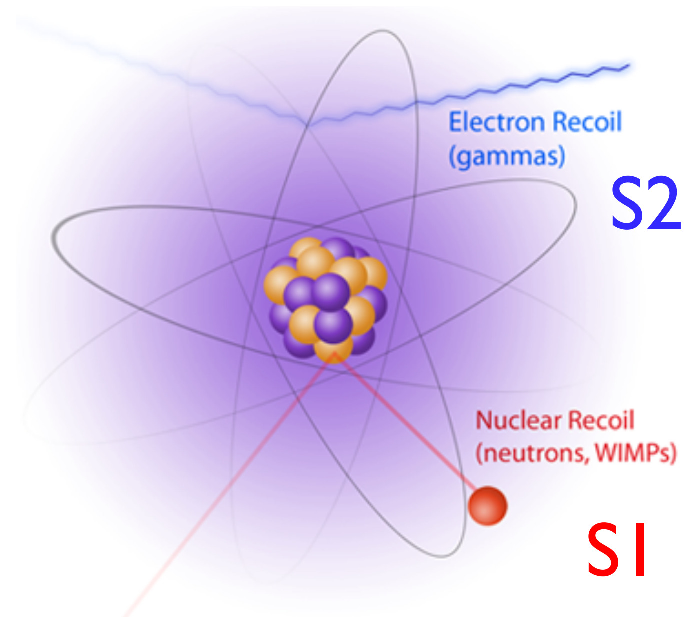
$$t = H^{-1} < t_{\rm int} = (n_{\rm DM}\sigma_A v)^{-1}$$

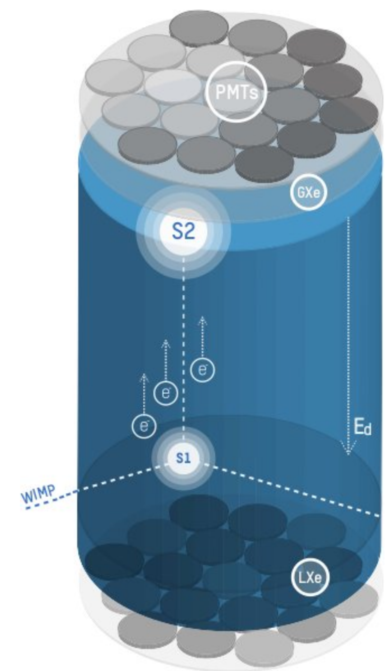
Expansion time   Annihilation time

$$\Rightarrow \quad \Omega_{\rm DM} = 0.3\left(\frac{3\times 10^{-26}{\rm cm}^3/{\rm s}}{\langle \sigma v_A\rangle}\right)$$

WIMP detection







e.g. XENON1T

S1: Scintillation (photons)

S2: Ionization (electrons)

WIMP: S1/S2>>(S1/S2)$_\gamma$

60~600M DM particles per sec go through our body.

Nucleus recoil E: $E_R = \frac{\vec{q}^2}{2m_N} = \frac{(\mu v)^2}{m_N} \lesssim 50\text{keV}$

Event rate: $\frac{dR}{dE_R} = \frac{\rho_\odot}{m_{\rm DM}} \left\langle \frac{d\sigma}{dE_R} v \right\rangle$ ~1 event/kg/day

Astrophysics

$\rho_\odot = 0.3\,\text{GeV/cm}^3$

$v_{\rm ave} = 220\,\text{km/s}$

Particle Physics

DM spin, mass, interactions

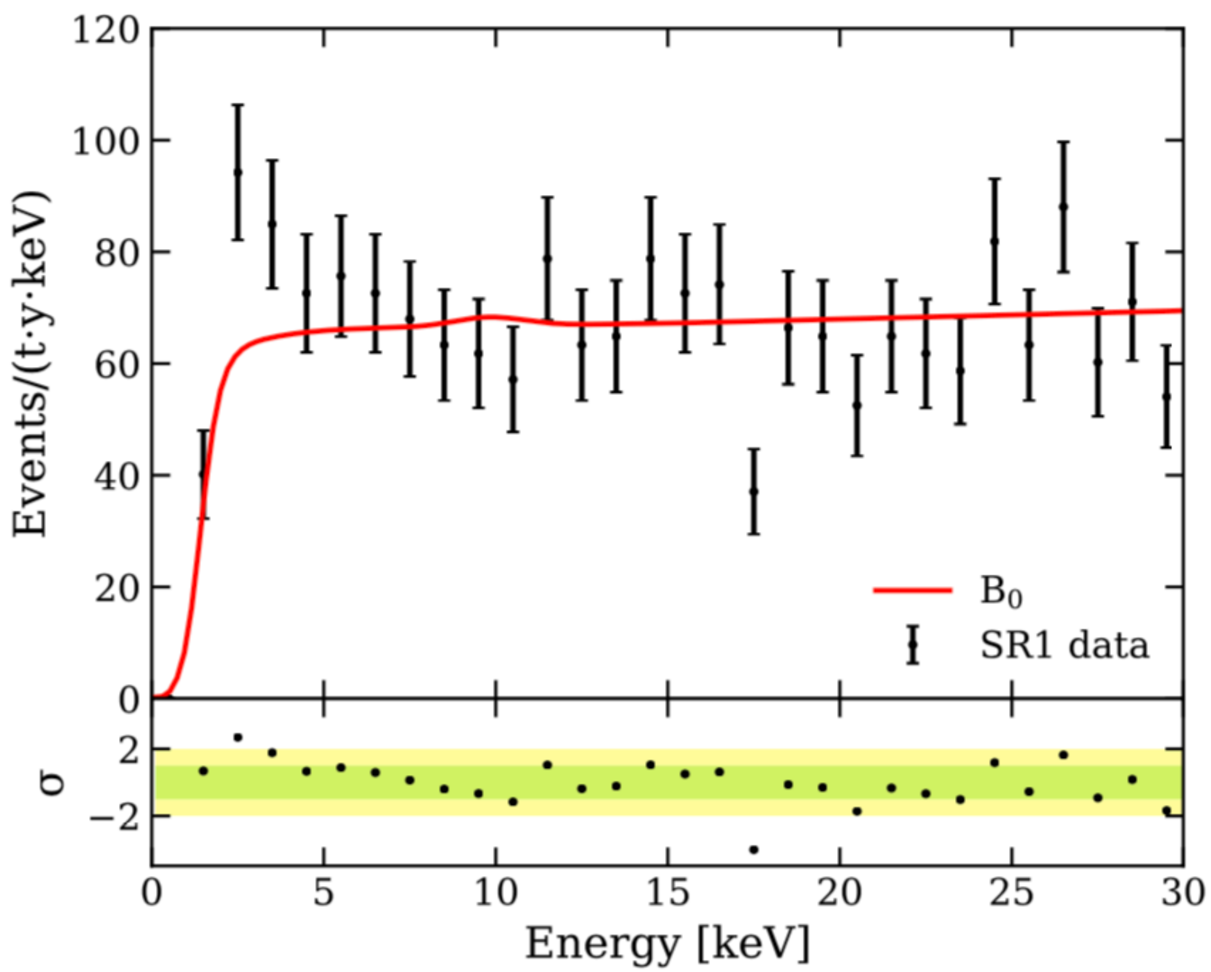
Experiment (Nucleus)	Z	A
LUX (Xe)	54	129
XENON1T (Xe)	54	131
PandaX-II (Xe)	54	136
SuperCDMS (Ge)	32	73
CDMSlite (Ge)	32	73
XENON10 (Xe)	54	131
DarkSide-50 (Ar)	18	39

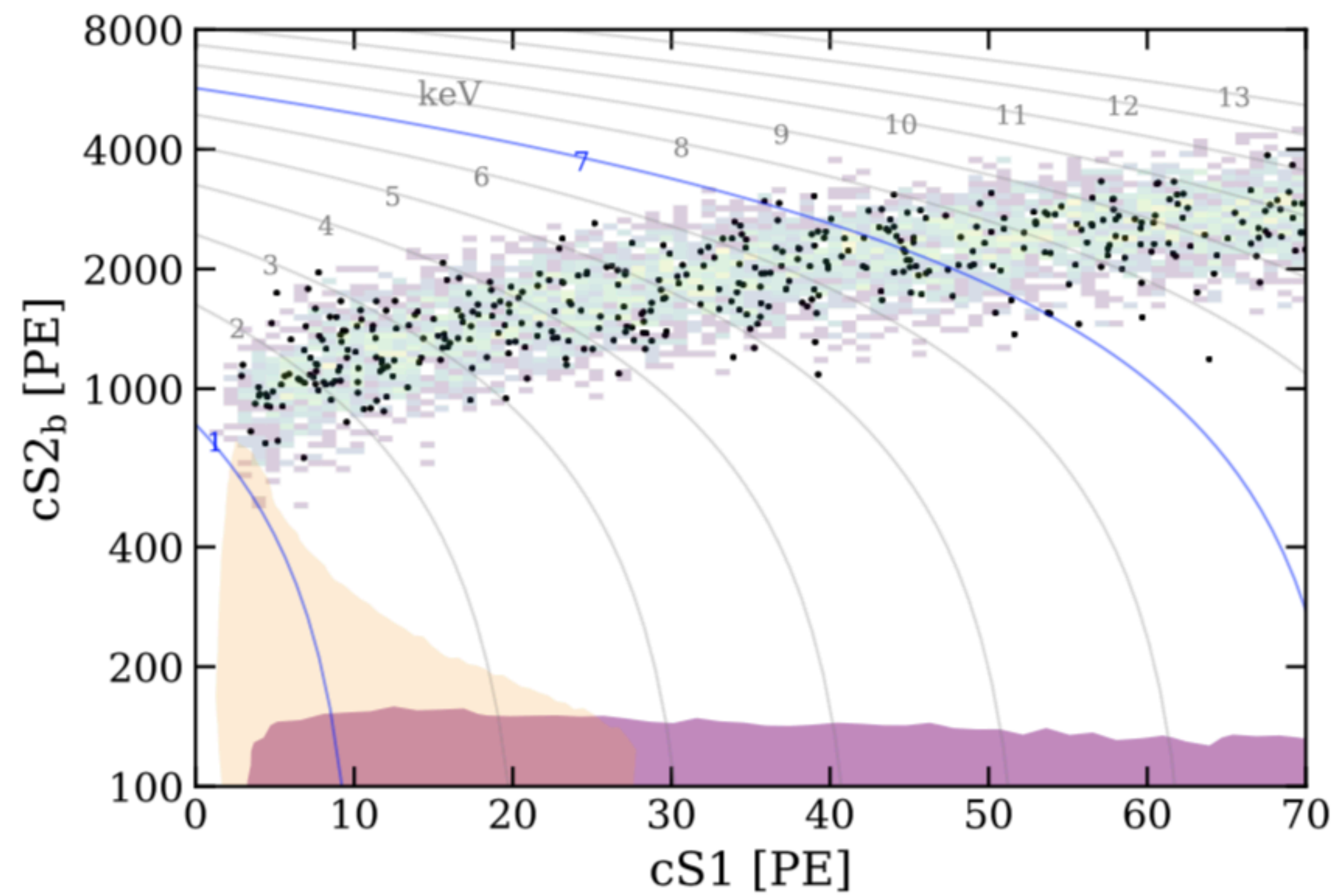
NaI, $CaWO_4$, etc.

^{127}I, ^{29}Si, ^{19}F, ^{23}Na, ^{27}Al

XENON1T electron recoil

- Excess in electron recoil spectrum (SR1)





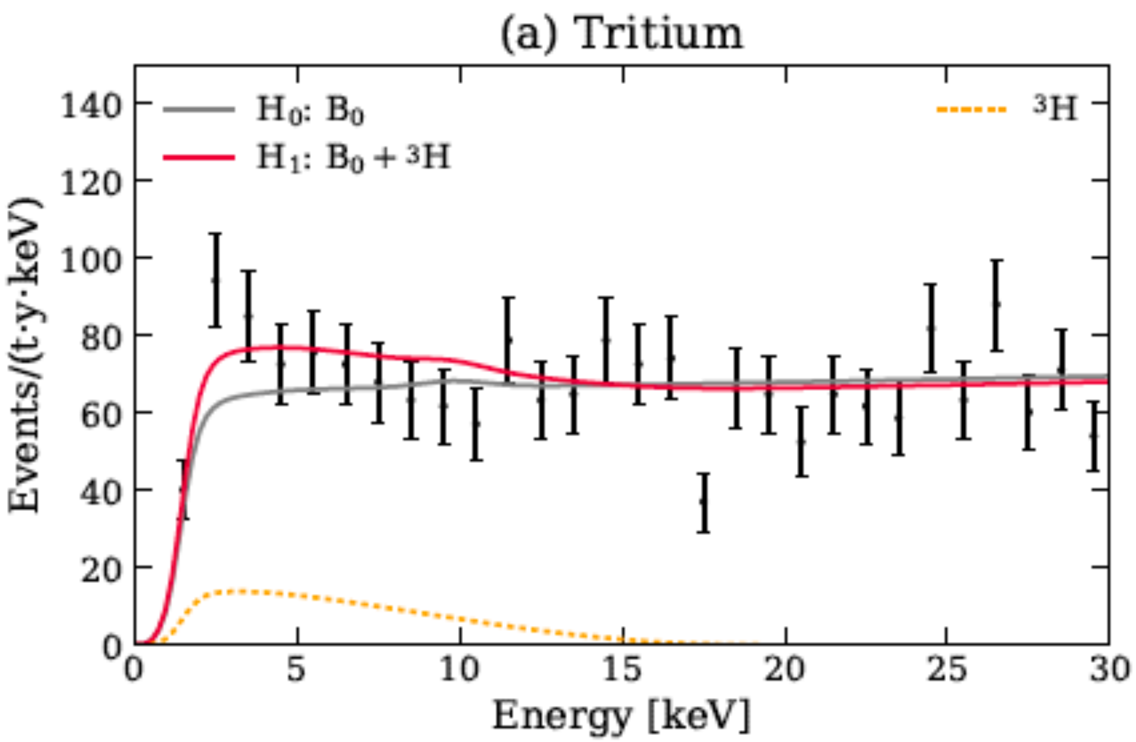
[XENON1T, 2006.09721]

E_R=1-7keV: 285 events observed, 232 ± 15 expected

3.3σ deviation: most significant at E_R=2-3keV

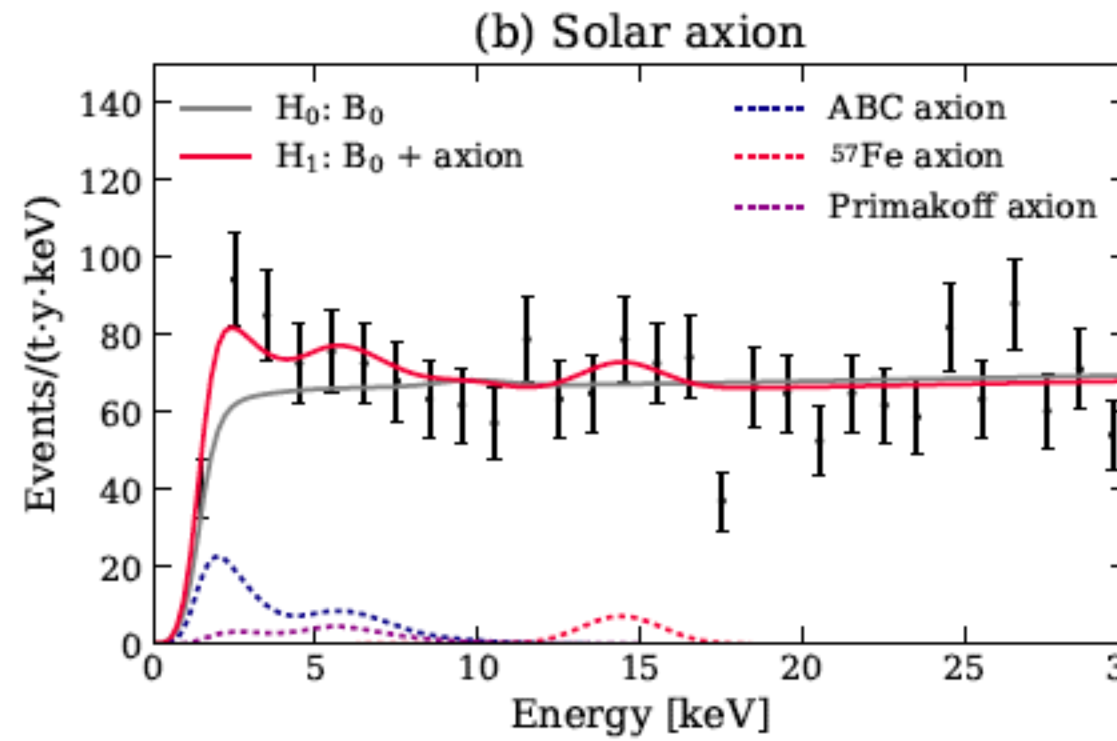
Interpretations

- Tritium background



favored at 3.2σ

- Solar axion, neutrino



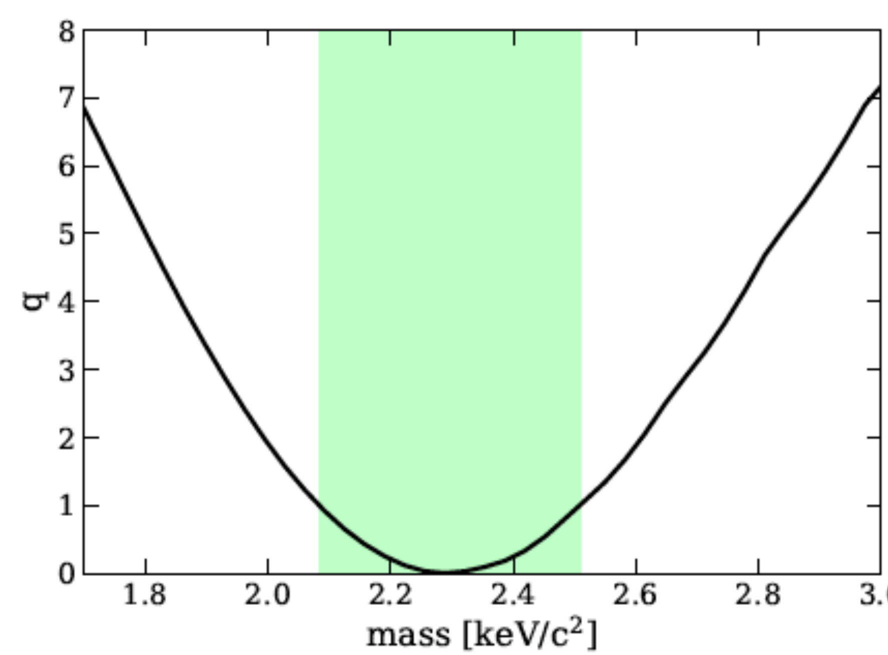
favored at 3.5σ

- keV-scale dark matter

e.g. axion-like particle, dark photon, etc.

mono-chromatic recoil;

global(local) at $3.0(4.0)\sigma$

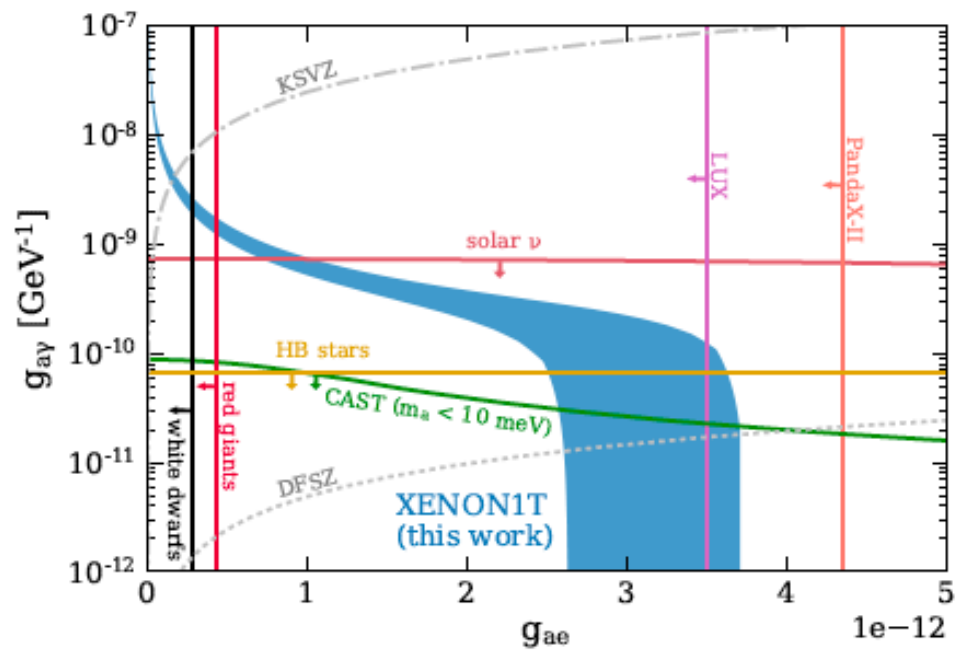


Star cooling bounds

- Electron coupling to light dark matter could affect cooling of white dwarfs, red giant stars, etc.

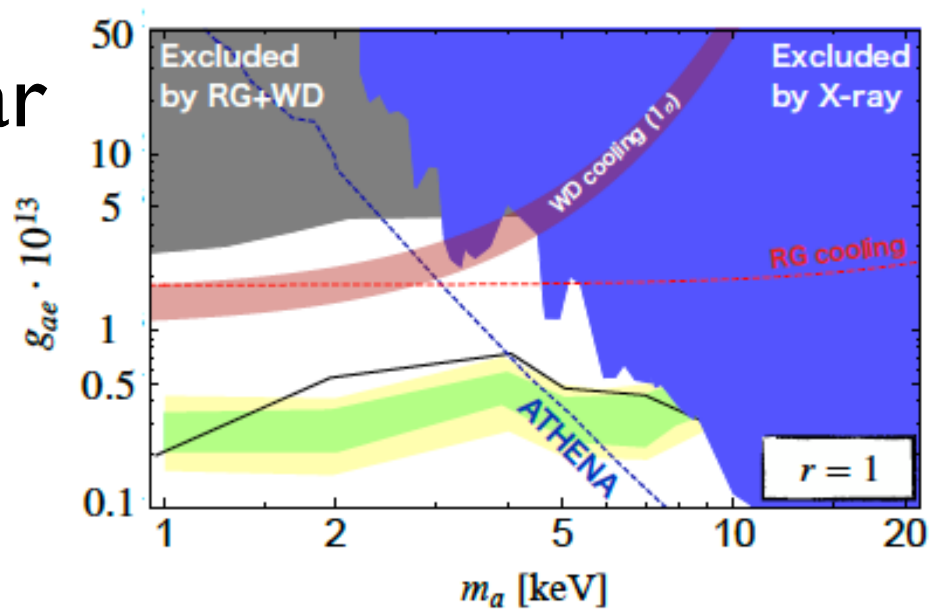
- Solar axion, neutrino

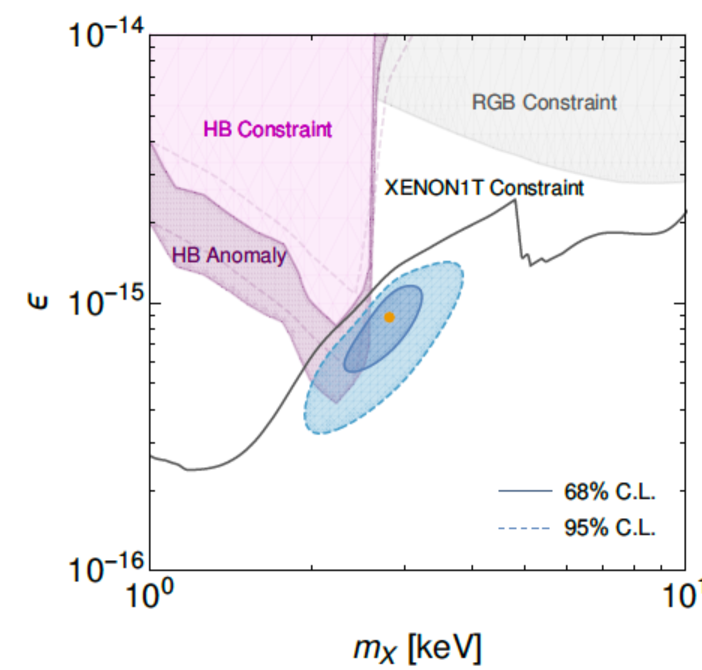
  : Excluded by order of magnitude from star cooling bounds



- keV-scale dark matter

: Consistent with star cooling bounds





[F. Takahashi et al] [J. Jaeckel et al]

Exothermic dark matter

Elastic vs inelastic

- Elastic scattering between dark matter & electron:

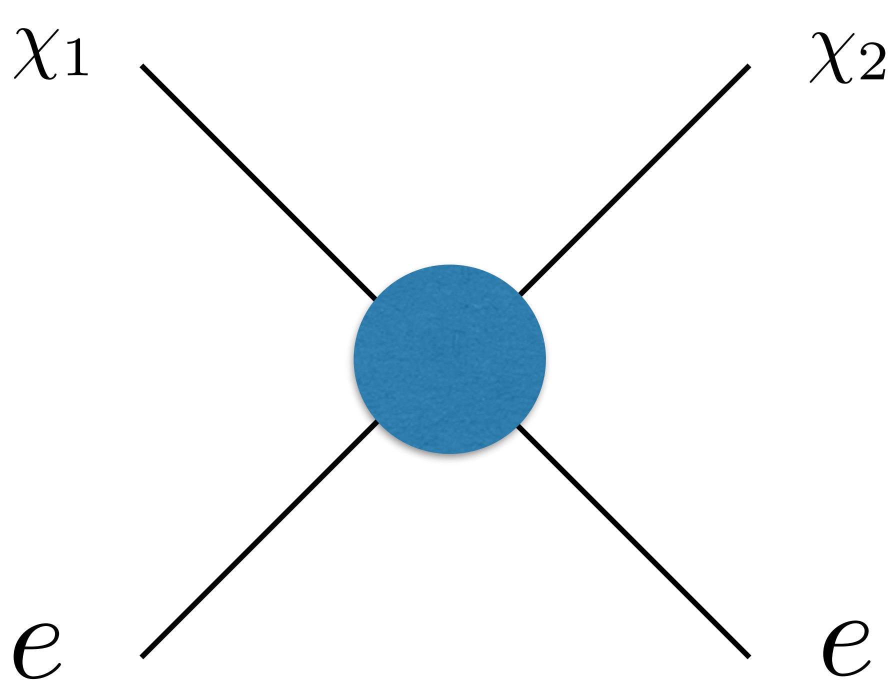
$$E_R \sim \frac{\mu^2 v^2}{m_e} \sim m_e v^2 \sim 0.3\,\mathrm{eV}$$: Too small recoil energy

cf. Boosted dark matter: $\chi\chi \to \chi X$ $\qquad \gamma_\chi = \frac{5m_\chi^2 - m_X^2}{4m_\chi^2}\,, \quad v_\chi < 0.6$

Dark matter profile dependent. [B. Fornal et al]

Large cross section for elastic scattering, $\sigma_e \sim 10^{-28}\,\mathrm{cm}^2$

- Inelastic scattering between dark matter & electron:



"Exothermic dark matter"

$$\Delta m = m_{\chi_1} - m_{\chi_2} \gg \frac{1}{2} m_e v^2$$

→ $E_R \sim \Delta m,$

monochromatic

[K. Harigaya et al; HML; J. Bramante et al]

EDM kinematics

- Both recoil energy and momentum transfer are fixed by the mass splitting.

$$\Delta m \ll m_e \ll m_{\chi_1}, \qquad \kappa \simeq \frac{\Delta m}{\frac{1}{2} m_e v^2} \simeq 2.2 \times 10^4 \left(\frac{220\,\mathrm{km/s}}{v}\right)^2 \left(\frac{\Delta m}{3\,\mathrm{keV}}\right) \gg 1$$

Recoil E:

$$\begin{aligned} E_R &= \Delta m + E_0 \left[1 - \frac{m_{\chi_2}\mu_1^2}{m_{\chi_1}} \left(\frac{\sqrt{1+\kappa}}{m_{\chi_2}} + \frac{1}{m_e}\right)^2\right] \\ &\quad + \frac{\mu_1^2 v^2}{m_e}\sqrt{1+\kappa}\,(1-\cos\theta) \\ &\simeq \Delta m \left(1 - \frac{2}{\sqrt{\kappa}}\cos\theta\right), \end{aligned}$$

[HML, 2020]

"Monochromatic"

Momentum transfer:

$$\begin{aligned} q^2 &= \mu_1^2 v^2 \left[\left(1 + \frac{\Delta m}{m_e}\right)^2 + 1 + \kappa - \frac{2\mu_2}{\mu_1}\left(1 + \frac{\Delta m}{m_e}\right)\sqrt{1+\kappa}\,\cos\theta\right] \\ &\simeq 2 m_e \Delta m \left(1 - \frac{2}{\sqrt{\kappa}}\cos\theta\right). \end{aligned}$$

cf. $\Delta m = 0: \quad E_R = \frac{\mu_1^2 v^2}{m_e}(1 - \cos\theta) = \frac{q^2}{2 m_e}.$

EDM event rate

- The general event rate per target mass is

$$dR = \frac{\rho_{\chi_1} v}{m_{\chi_1} m_T} d\sigma\, f_1(v) dv, \qquad f_1(v) = \frac{4v^2}{v_0^3\sqrt{\pi}} e^{-v^2/v_0^2} \text{ with } v_0 = 220\,\mathrm{km/s}$$

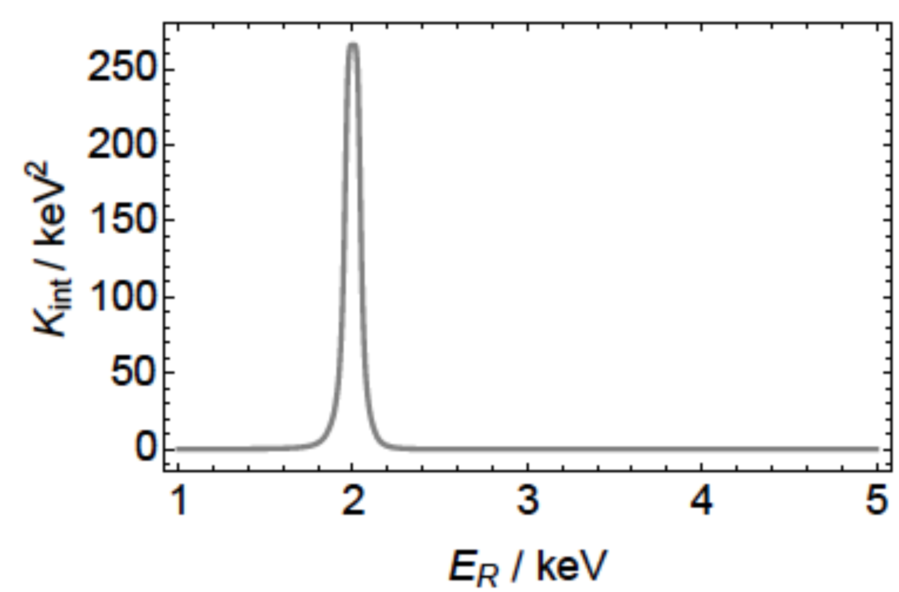
- The total cross section for inelastic scattering:

$$\sigma_e = \int_{q_-^2}^{q_+^2} \frac{d\sigma(q = 1/a_0)}{dq^2} dq^2, \qquad \frac{d\sigma}{dq^2} = \frac{\bar{\sigma}_e}{q_+^2 - q_-^2} K_{\rm int}(E_R) P^2(v)$$

Atomic enhancement factor:

$$K_{\rm int}(E_R) = \int_{q_-}^{q_+} a_0^2\, q'\, dq'\, K(E_R, q')$$

"M-shell electrons dominant"



Phase space factor:

$$P^2(v) = \frac{\left(1 - \frac{(m_{\chi_2}+m_e)^2}{E_{\rm cm}^2}\right)^{1/2}\left(1 - \frac{(m_{\chi_2}-m_e)^2}{E_{\rm cm}^2}\right)^{1/2}}{\left(1 - \frac{(m_{\chi_1}+m_e)^2}{E_{\rm cm}^2}\right)^{1/2}\left(1 - \frac{(m_{\chi_1}-m_e)^2}{E_{\rm cm}^2}\right)^{1/2}} \simeq \sqrt{1 + \frac{2\Delta m}{\mu_1 v^2}}$$

[K. Kannike et al;
K. Harigaya et al]

$$E_{\rm cm} = (m_{\chi_1} + m_e)^2 + m_e m_{\chi_1} v^2$$

[P. Graham et al, 2010]

EDM event rate

- Differential event rate per target mass:

$$q_\pm^2 \simeq 2m_e\Delta m\left(1 \pm \tfrac{2}{\sqrt{\kappa}}\right), \qquad E_- < E_R < E_+ \text{ with } E_\pm = \Delta m\left(1 \pm \tfrac{2}{\sqrt{\kappa}}\right)$$

$$\rightarrow \quad \frac{dR}{dE_R} \simeq \left(\frac{2\Delta m}{m_e}\right)^{1/2} \frac{\bar{\sigma}_e \rho_{\chi_1}}{m_{\chi_1} m_T} K_{\rm int}(E_R)\delta(E_R - \Delta m) \underbrace{\int_0^{v_{\rm max}} f_1(v)dv}_{\simeq 1}$$

- Event rate per detector: [HML, 2020]

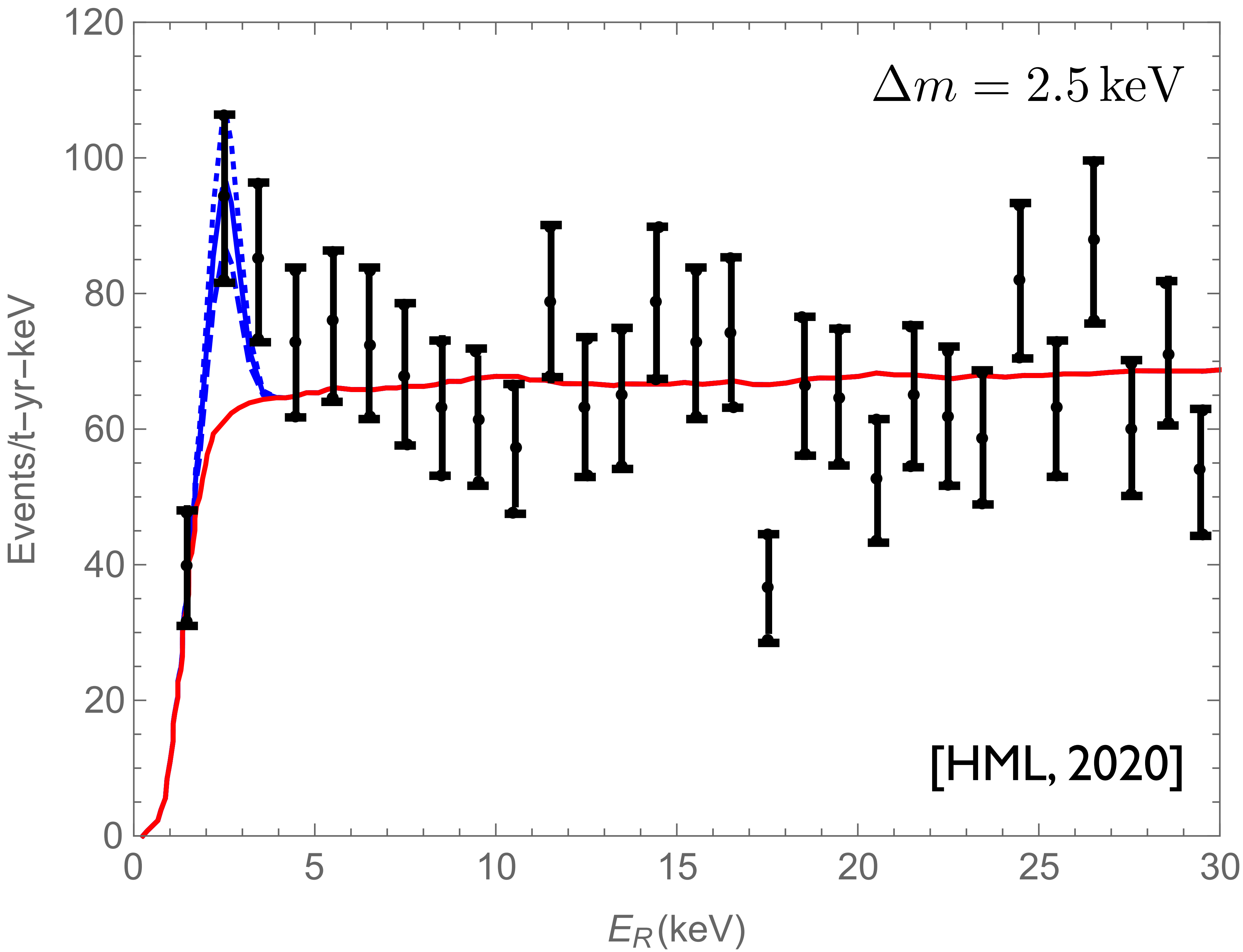
$$R_D = M_T \int_{E_T}^{\infty} \frac{dR}{dE_R} dE_R \simeq 50\left(\frac{M_T}{\rm tonne-yrs}\right)\left(\frac{K_{\rm int}(\Delta m)}{19.4}\right)\left(\frac{\rho_{\chi_1}}{0.4\,{\rm GeV\,cm^{-3}}}\right) \times \left(\frac{\bar{\sigma}_e/m_{\chi_1}}{1.6\times 10^{-44}\,{\rm cm^2/GeV}}\right)\left(\frac{\Delta m}{2.5\,{\rm keV}}\right)^{1/2}$$

- Convoluted with detector resolution & efficiency:

$$\frac{dR_D}{dE_R} = \frac{R_D}{\sqrt{2\pi}\sigma} e^{-(E_R-\Delta m)^2/(2\sigma^2)} \alpha(E)$$

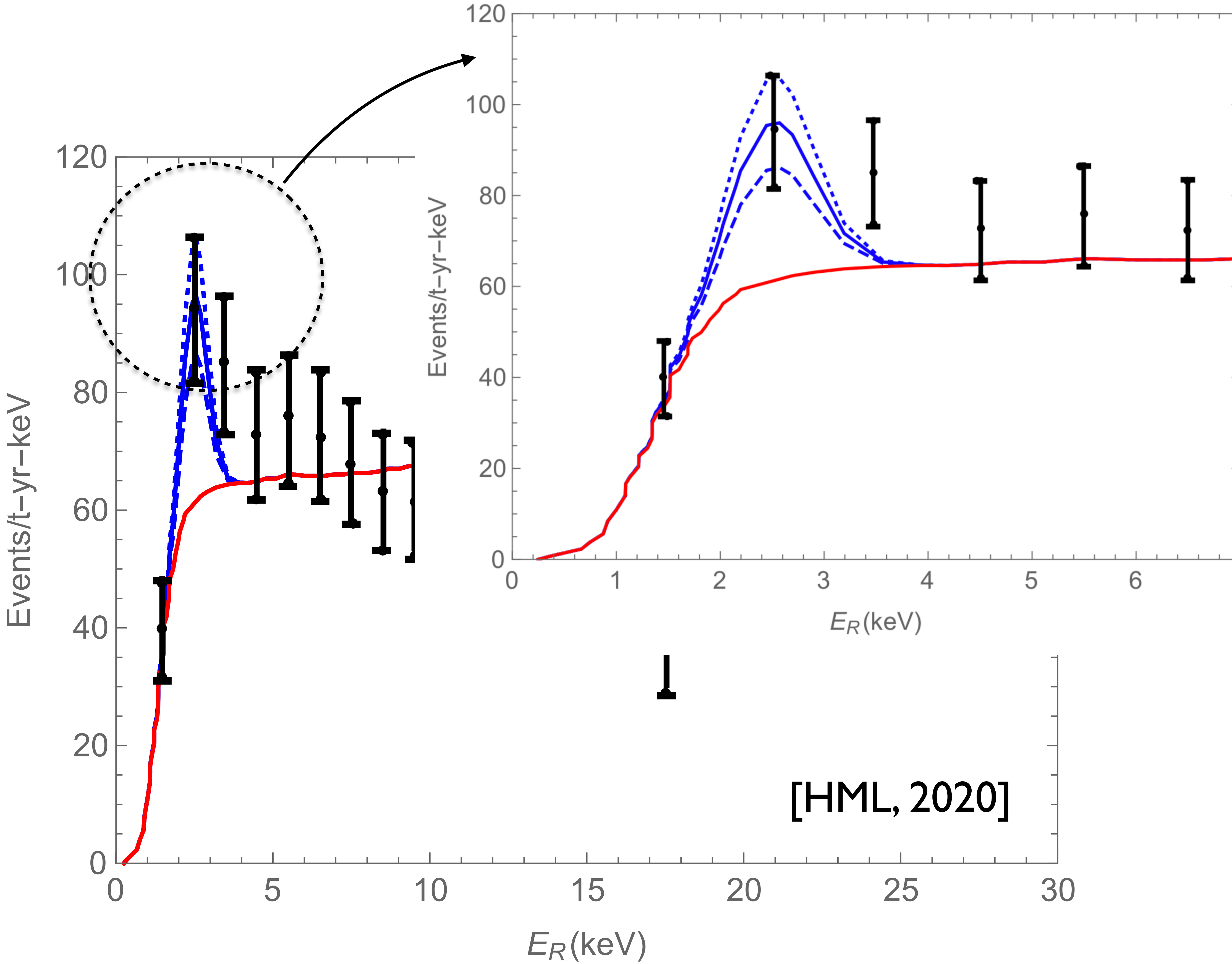
$$\sigma:\ 20\% - 6\%,\ E_R = 2 - 30\,{\rm keV}, \qquad \alpha(E) = 0.7 - 0.9,\ E_R = 2 - 10\,{\rm keV}$$

XENONIT & EDM



Blue lines: $(\bar{\sigma}_e/m_{\chi_1})/(10^{-44}\mathrm{cm}^2\,/\mathrm{GeV}) \simeq 1.0,\ 1.4,\ 1.8$

Red line: Background model


120
100
80
60
40
20
0
Events/t–yr–keV
0
5
10
15
20
25
30
E_R(keV)
120
100
80
60
40
20
0
Events/t–yr–keV
0
1
2
3
4
5
6
7
E_R(keV)
[HML, 2020]

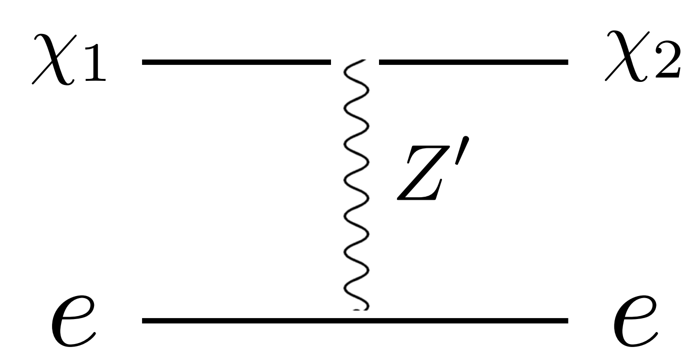
Effective theory for exothermic DM

EFT for EDM

- Effective interactions between EDM and electron with massive Z' mediator: [HML, 2020]

$$\mathcal{L}_{\rm eff} = \left(g_{Z'} Z'_\mu \bar{\chi}_2 \gamma^\mu (v_\chi + a_\chi \gamma^5) \chi_1 + {\rm h.c.}\right) + g_{Z'} Z'_\mu \bar{e}(v_e + a_e \gamma^5) e + g_{Z'} Z'_\mu \bar{\nu} \gamma^\mu (v_\nu + a_\nu \gamma^5) \nu$$

- DM-electron scattering cross section:



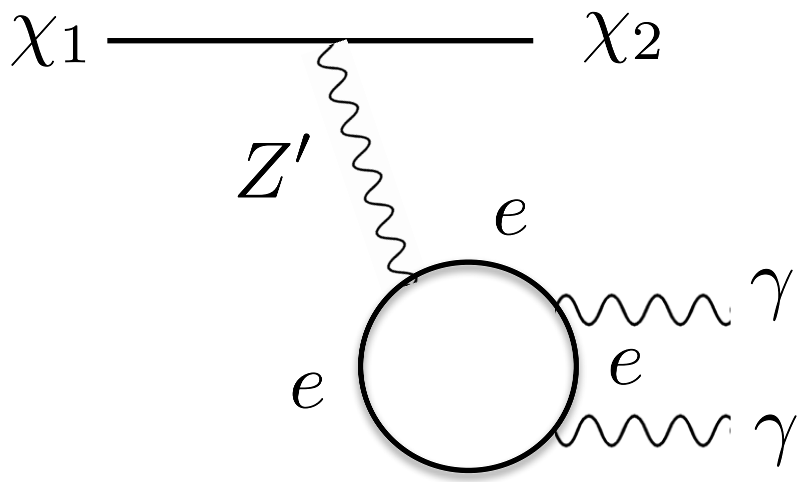
$$\bar{\sigma}_e \simeq \frac{v_\chi^2 v_e^2 g_{Z'}^4 \mu_1^2}{\pi m_{Z'}^4} \simeq \left(\frac{v_\chi g_{Z'}}{0.6}\right)^2 \left(\frac{v_e g_{Z'}}{10^{-4} e}\right)^2 \left(\frac{1\,{\rm GeV}}{m_{Z'}}\right)^4 \left(\frac{\mu_1}{m_e}\right)^2 \times 10^{-44}\,{\rm cm}^2$$

→ Light dark matter below GeV scale is favored for XENON1T excess.

- Constraints on lifetime of heavier state
- Relic abundances, microscopic models

Constraints on decaying EDM

- The axial vector coupling for electron can lead the heavier state to decay into two photons:



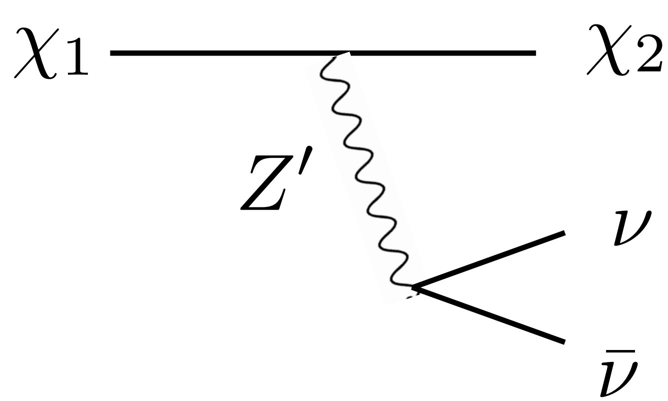
$$\Gamma(\chi_1 \to \chi_2 \gamma\gamma) \simeq \frac{a_e^2 (v_\chi^2 + a_\chi^2) e^4 g_{Z'}^2}{2560\pi^7} \frac{(\Delta m)^5}{m_{Z'}^4}$$

Diffuse X-ray: $\tau_{\chi_1} \gtrsim 10^{24}\,\mathrm{sec}$

$$|a_e| g_{Z'} \sqrt{v_\chi^2 + a_\chi^2} < 2.5 \times 10^{-6} \left(\frac{2.5\,\mathrm{keV}}{\Delta m}\right)^{5/2} \left(\frac{m_{Z'}}{1\,\mathrm{GeV}}\right)^2$$

[HML, v3, to appear]

- Accompanying neutrino coupling opens up neutrino decay channels:



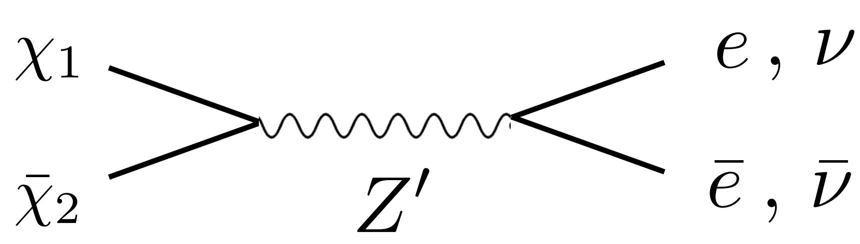
$$\Gamma(\chi_1 \to \chi_2 \nu\bar{\nu}) \simeq \frac{N_\nu G_F'^2 (\Delta m)^5}{30\pi^3} (v_\chi^2 + 3a_\chi^2)(v_\nu^2 + a_\nu^2)$$

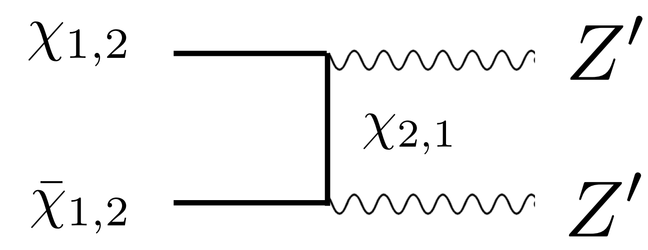
Super-K: $\tau_{\chi_1} \gtrsim 10^{24}\,\mathrm{sec}$

$$\sqrt{(v_\chi^2 + 3a_\chi^2)(v_\nu^2 + a_\nu^2)} < 4.2 \times 10^{-4} \left(\frac{3}{N_\nu}\right)^{1/2} \left(\frac{2.5\,\mathrm{keV}}{\Delta m}\right)^{5/2} \left(\frac{m_{Z'}/g_{Z'}}{0.3\,\mathrm{GeV}}\right)^2$$

Dark matter relic density

- EDM can annihilate into a pair of electrons or neutrinos, and a pair of Z' gauge bosons.





$$\langle\sigma v\rangle = \frac{1}{2}\langle\sigma v\rangle_{\chi_1\bar{\chi}_2\to e\bar{e},\nu\bar{\nu}} + \frac{1}{2}\langle\sigma v\rangle_{\chi_1\bar{\chi}_2\to Z'Z'}$$

$$\langle\sigma v\rangle_{\chi_1\bar{\chi}_2\to e\bar{e},\nu\bar{\nu}} = \frac{g_{Z'}^4 v_\chi^2}{\pi}\left[v_e^2 + a_e^2 + N_\nu(v_\nu^2 + a_\nu^2)\right]\frac{m_{\chi_1}^2}{(m_{Z'}^2 - 4m_{\chi_1}^2)^2 + \Gamma_{Z'}^2 m_{Z'}^2},$$

$$\langle\sigma v\rangle_{\chi_1\bar{\chi}_1,\chi_2\bar{\chi}_2\to Z'Z'} = \begin{cases} \dfrac{g_{Z'}^4}{4\pi}\left[v_\chi^4 + a_\chi^4 + 2v_\chi^2 a_\chi^2\left(4\dfrac{m_{\chi_1}^2}{m_{Z'}^2} - 3\right)\right]\dfrac{m_{\chi_1}^2}{(m_{Z'}^2 - 2m_{\chi_1}^2)^2}\left(1 - \dfrac{m_{Z'}^2}{m_{\chi_1}^2}\right)^{3/2}, & m_{\chi_1} > m_{Z'}, \\ \dfrac{(n_{Z'}^{\rm eq})^2}{n_{\chi_1}^{\rm eq} n_{\chi_2}^{\rm eq}}\langle\sigma v\rangle_{Z'Z'\to\chi_1\bar{\chi}_1,\chi_2\bar{\chi}_2}, & m_{\chi_1} < m_{Z'}. \end{cases}$$

"forbidden channels"

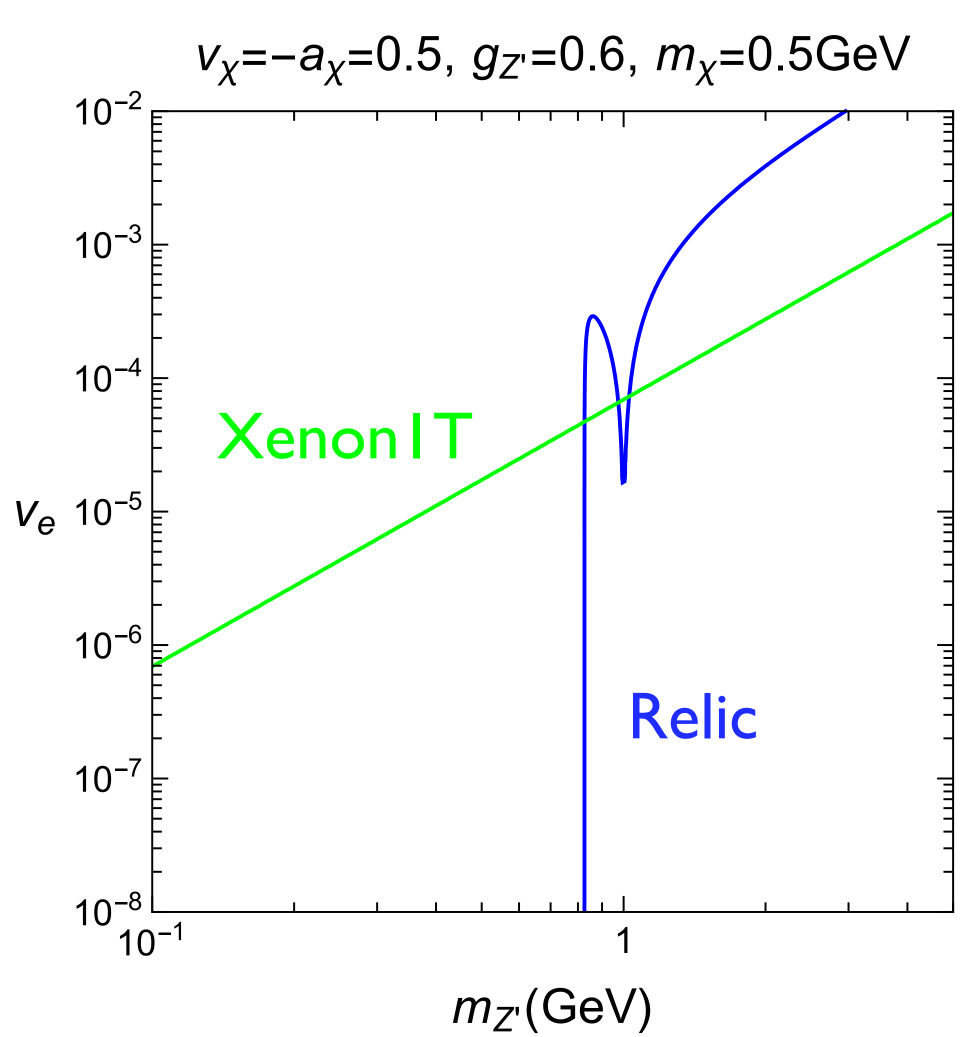
$$\Omega_{\rm DM}h^2 = 0.12\left(\frac{10.75}{g_*(T_f)}\right)^{1/2}\left(\frac{x_f}{20}\right)\left(\frac{4.3\times10^{-9}\,{\rm GeV}^{-2}}{x_f\int_{x_f}^{\infty}x^{-2}\langle\sigma v\rangle}\right) \simeq 2\,\Omega_{\chi_1}h^2$$

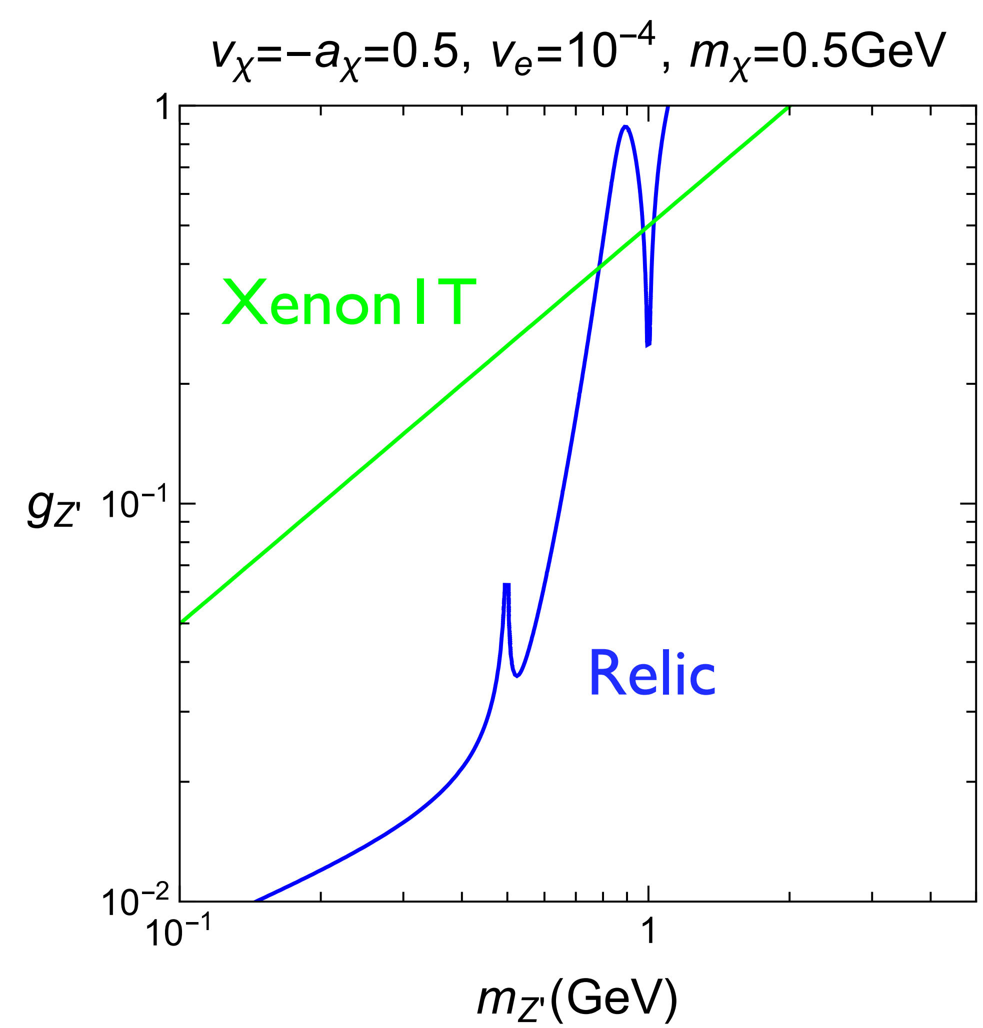
XENON1T + relic

- Electron couplings are constrained by visible/invisible searches at BaBar, beam dump, rare meson decays.

$$m_{Z'} \lesssim 10\,\mathrm{GeV} \quad \Rightarrow \quad |v_e| g_{Z'} \lesssim (10^{-4} - 10^{-3})\, e$$

- Dark matter relic density constrains further.





$$a_e = v_\nu = a_\nu = 0$$

Microscopic models

Pseudo-Dirac dark matter

- Dark matter = singlet Dirac fermion vector-like under Z', which is broken by dark Higgs VEV v_ϕ.

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + |D_\mu\phi|^2 - V(\phi, H) + i\bar{\psi}_{1L}\gamma^\mu D_\mu\psi_{1L} + i\bar{\psi}_{2L}\gamma^\mu D_\mu\psi_{2L} \underbrace{-m_\psi\psi_1\psi_2}_{\text{“Dirac mass”}} - \underbrace{y_1\phi\,\psi_1\psi_1 - y_2\phi^*\psi_2\psi_2}_{\text{“Majorana masses”}} + \text{h.c.}$$

Mass eigenvalues: $m^2_{\chi_{1,2}} = m^2_\psi + 2(y_1^2 + y_2^2)v_\phi^2 \pm 2\sqrt{(y_1^2 - y_2^2)^2 v_\phi^4 + (y_1 + y_2)^2 v_\phi^2 m_\psi^2},$

Mixing angle: $\sin 2\theta = -\frac{4(y_1 + y_2)v_\phi m_\psi}{m^2_{\chi_2} - m^2_{\chi_1}}.$

$y_1 = y_2:\quad m_{\chi_{1,2}} = m_\psi \pm 2y_1 v_\phi\,,\qquad \theta = \frac{\pi}{4}.$

$$\Delta m = 4|y_1|v_\phi = 2.5\,\text{keV}$$

Z'-DM int: $\mathcal{L}_{\rm DM} = g_{Z'}Z'_\mu\left(\bar{\chi}_1\gamma^\mu P_L\chi_2 + \bar{\chi}_2\gamma^\mu P_L\chi_1\right).$

Z'-portal

- Z' mediates to the SM by gauge kinetic mixing,

$$\mathcal{L}_{\rm kin-mix} = -\frac{1}{2}\sin\xi B_{\mu\nu}F'^{\mu\nu}$$

$$\rightarrow \quad \mathcal{L}_{\rm eff,I} = -e\varepsilon\, Z'_\mu\left(\bar{e}\gamma^\mu e + \frac{m_{Z'}^2}{2c_W^2 m_Z^2}\bar{\nu}\gamma^\mu P_L\nu\right) + \cdots$$

$\varepsilon \equiv \xi\cos\theta_W \ll 1$

$$v_e = -\frac{e\varepsilon}{g_{Z'}}, \quad a_e = 0, \qquad v_\nu = -a_\nu = -\frac{e\varepsilon m_{Z'}^2}{4c_W^2 g_{Z'} m_Z^2}.$$

- Completely safe from diffuse X-ray bounds.

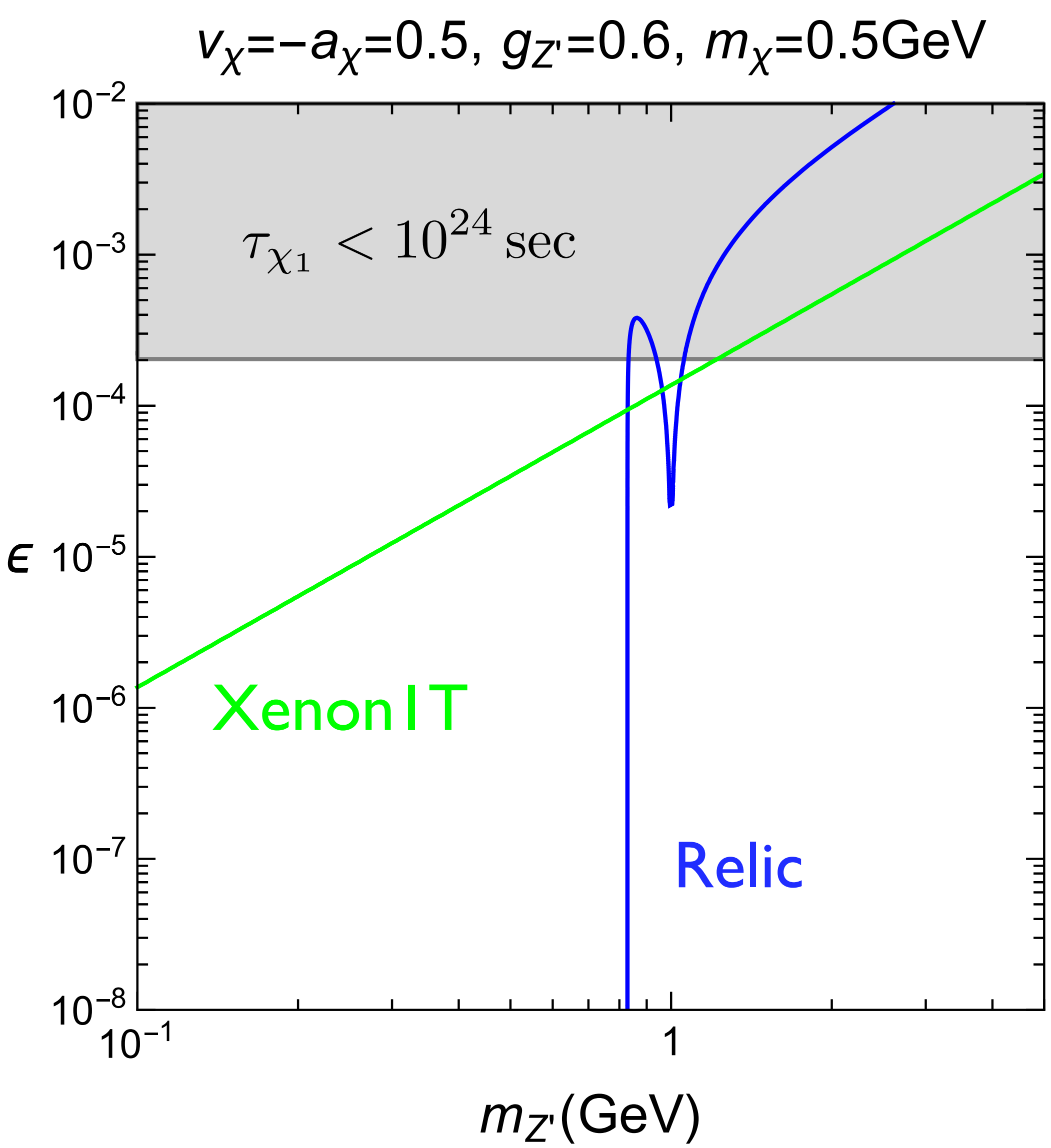
- EDM decays dominantly into neutrinos.

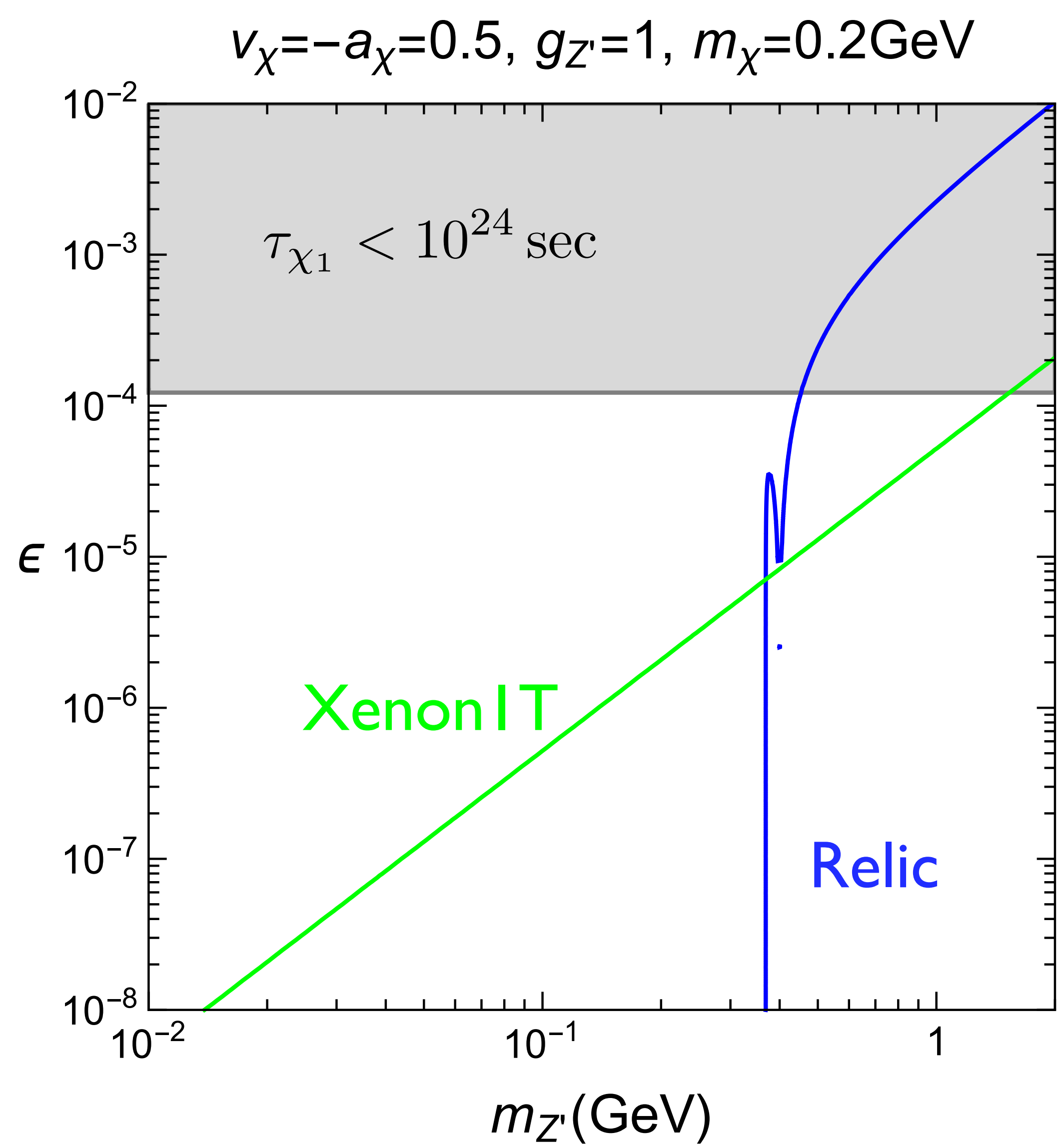
$$\tau_{\chi_1} = \frac{1}{\Gamma(\chi_1\to\chi_2\nu\bar{\nu})} = \left(\frac{10^{-4}e}{\varepsilon g_{Z'}}\right)^2\left(\frac{2.5\,{\rm keV}}{\Delta m}\right)^5 8.9\times 10^{24}\,{\rm sec}$$

: Consistent with neutrino experiments.

Z' portal & XENON1T

- Decay of dark matter into neutrinos constrains the gauge kinetic mixing further.





Vector-like lepton portal

- Vector-like lepton E with nonzero Z' charge.

$$\mathcal{L}_{\rm VL} = -M_E \bar{E}E - (y_E \phi \bar{E} e_R + {\rm h.c.})$$

Mass matrix: $$M_e = \begin{pmatrix} m_e & 0 \\ y_E v_\phi & M_E \end{pmatrix}$$

Mass eigenvalues: $$m^2_{f_{1,2}} = \frac{1}{2}\left(m_e^2 + M_E^2 + y_E^2 v_\phi^2 \mp \sqrt{(m_e^2 + y_E^2 v_\phi^2 - M_E^2)^2 + 4 y_E^2 v_\phi^2 M_E^2}\right)$$

Mixing angles:
$$\sin(2\theta_R) = -\frac{2 y_E v_\phi M_E}{m^2_{f_1} - m^2_{f_2}},$$
$$\sin(2\theta_L) = \frac{m_e^2}{m_{f_1} m_{f_2}} \sin(2\theta_R).$$

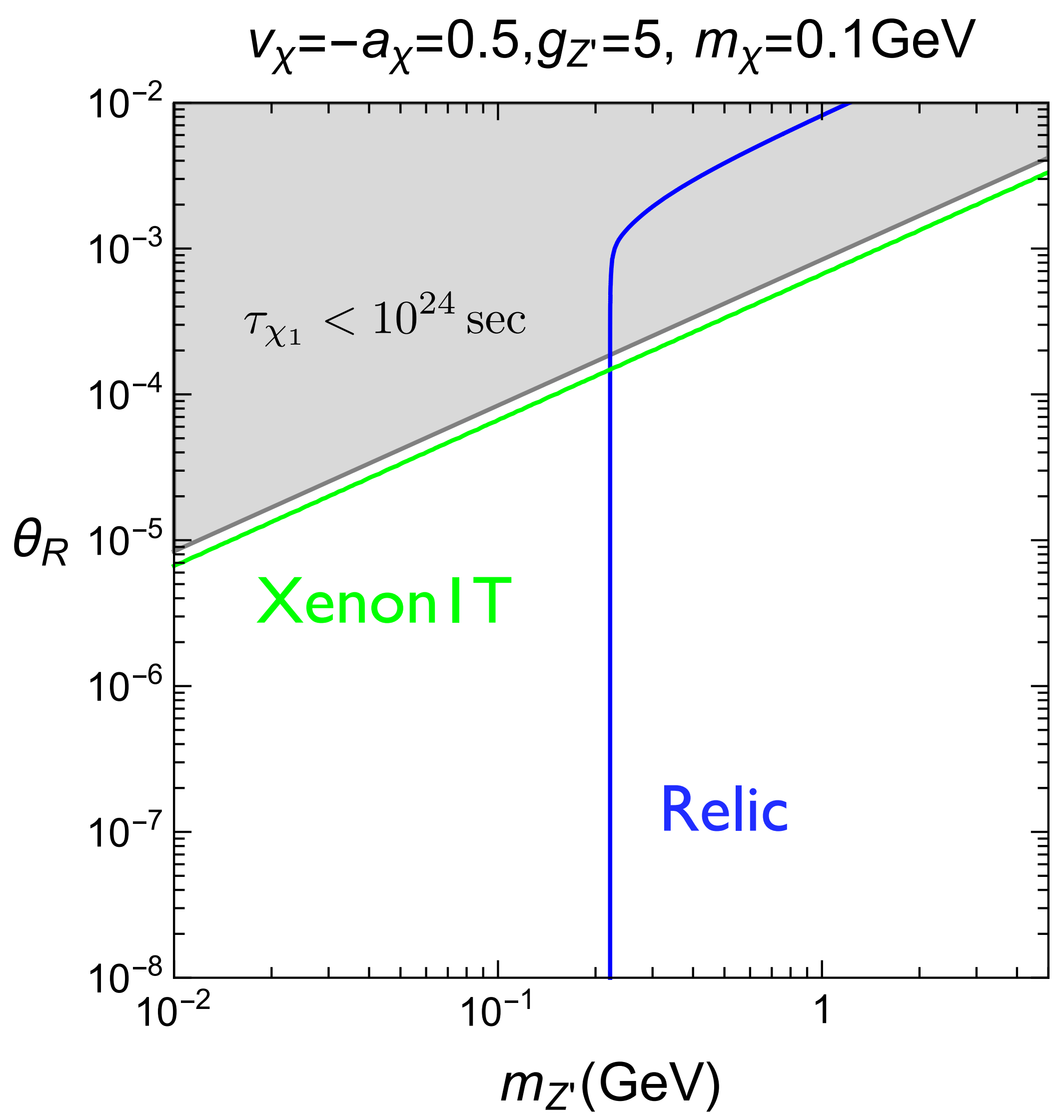
$m_e, y_E v_\phi \ll M_E$: $\quad \theta_R \sim \frac{2 y_E v_\phi}{M_E}, \quad \theta_L \sim \frac{m_e}{M_E}\theta_R$

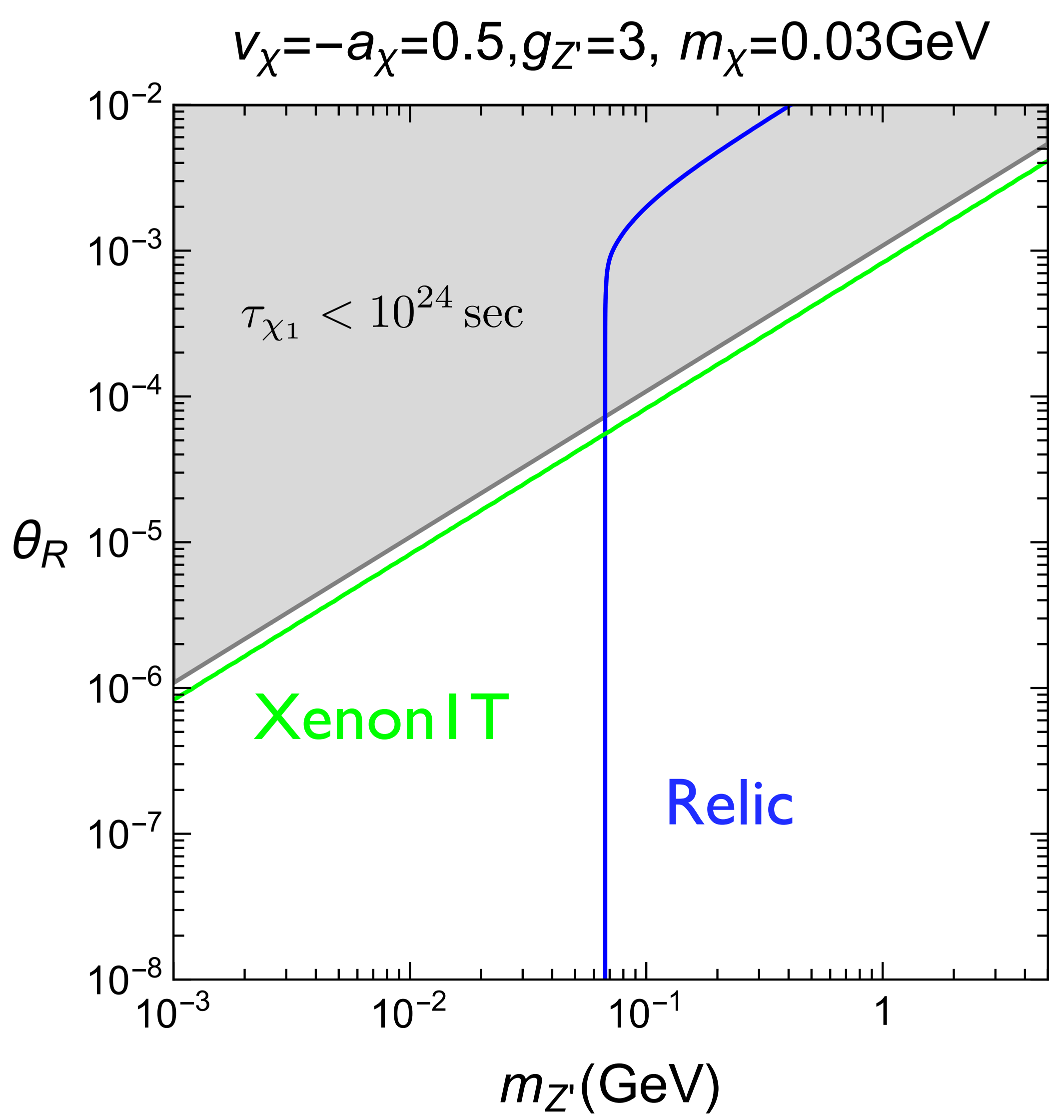
$m_{f_1} \sim m_e$, $\quad M_E \gtrsim 100\,{\rm GeV}$: $\quad \theta_R \lesssim \sqrt{\frac{m_e}{M_E}} \lesssim 2.2 \times 10^{-3}$,

Z'-DM int: $$\boxed{v_e = a_e = -\theta_R^2, \qquad v_\nu = a_\nu = 0.}$$

VL lepton & XENON1T

- Decay of dark matter into two photons constrains the lepton mixing further.





Conclusions

- The Xenon electron excess can be explained by down-scattering of exothermic dark matter for standard halo model.

- The effective theory for exothermic dark matter with Z' mediator was proposed.

- Pseudo-Dirac dark fermion is a candidate for exothermic dark matter with a small mass splitting.

- There are consistent parameter spaces for Xenon excess in Z' portal and vector-like lepton portal.