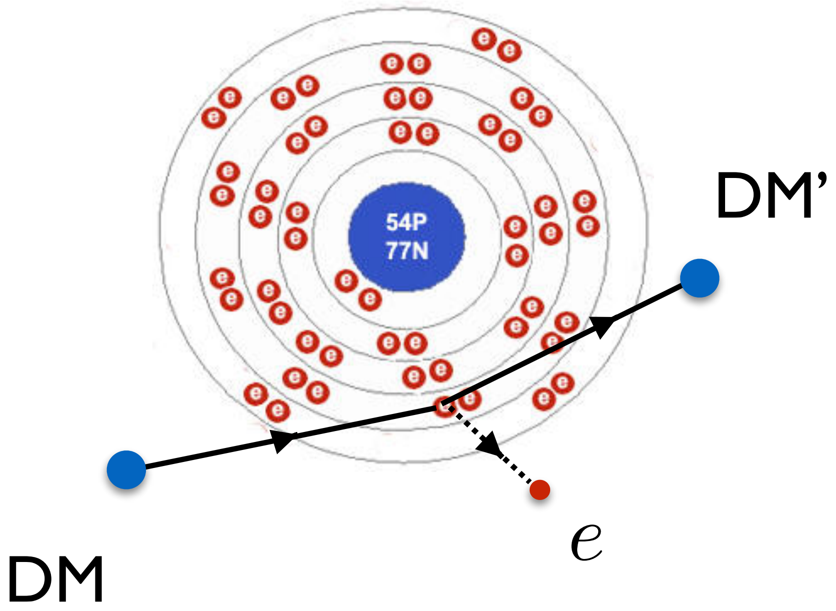



# Exothermic self-interacting dark matter

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Based on  HML,  2006.13183 ;

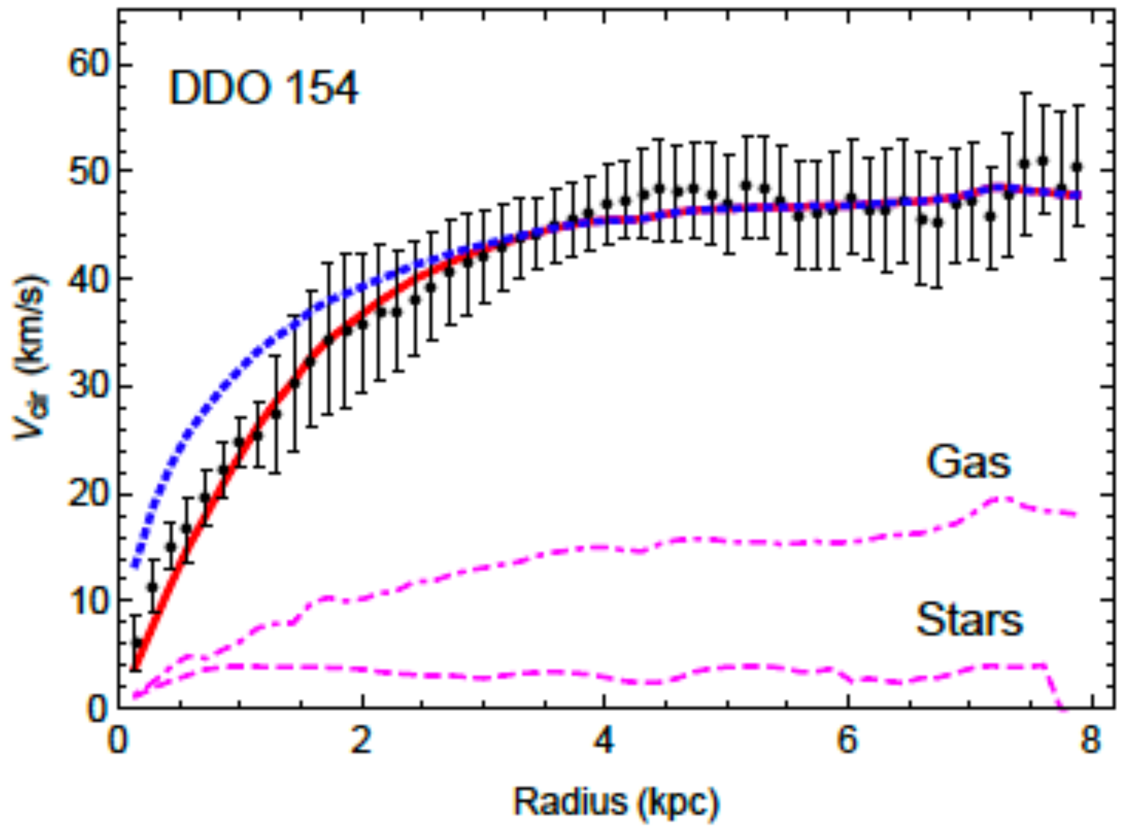
S.-M. Choi, HML, B. Zhu, to appear.

# Outline

- Introduction
- Exothermic dark matter
- Microscopic models
- Conclusions

# Core-Cusp problem






Circular velocities:

$v_{\rm cir} \sim \sqrt{r}, \quad \rho_{\rm dm} \sim r^{-1}$ "Cuspy"

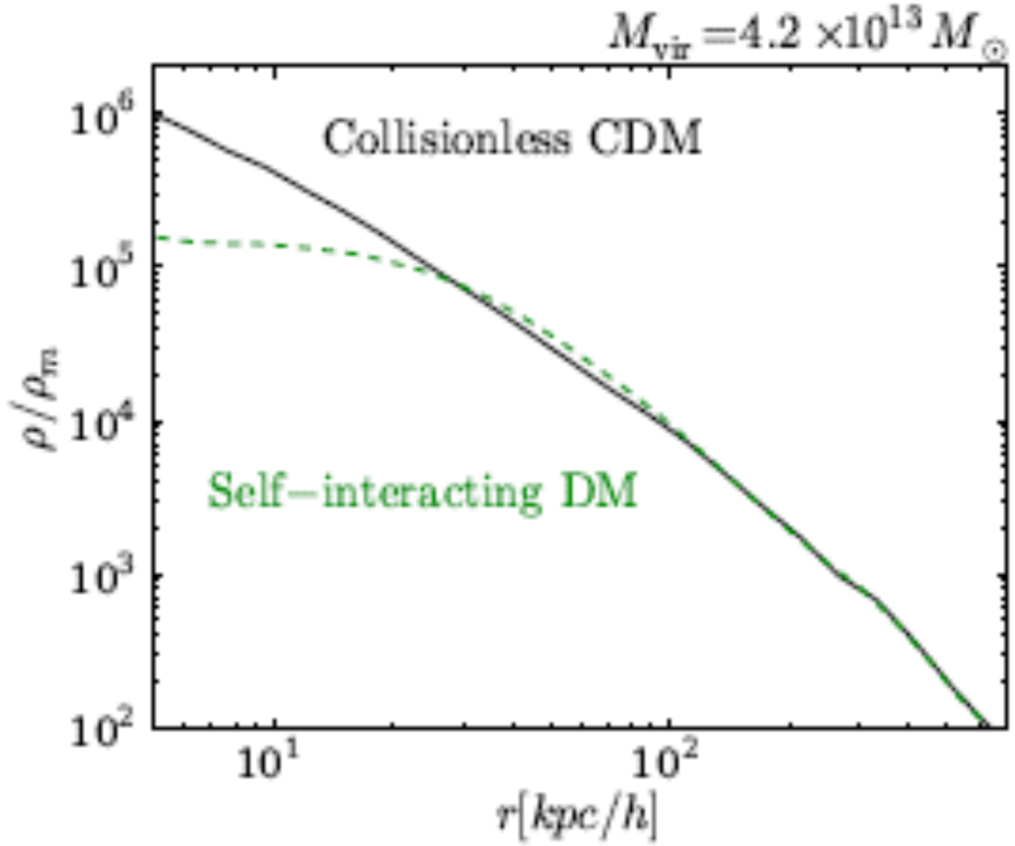
$v_{\rm cir} \sim r, \quad \rho_{\rm dm} \sim r^{0}$ "Cored"

Overshoot at <kpc [Spergel, Steinhardt, 2000; Tulin, Yu, 2017]

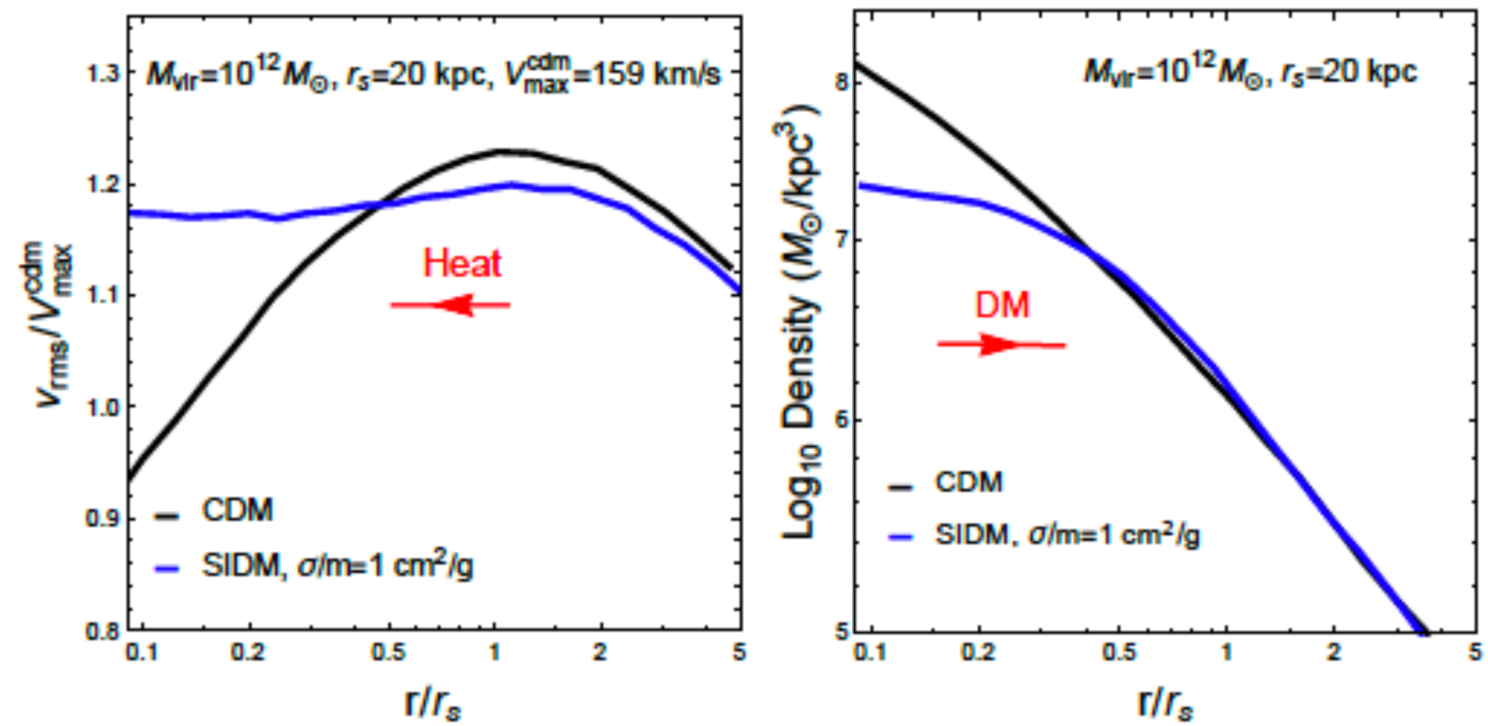
- Core-Cusp problem: CDM N-body simulation predicts cuspy DM profile (NFW), rendering rotation velocities larger at small scales (→cored DM profile favored).

cf. Too-big-to-fail, Diversities for the same halo mass.

# Self-Interacting dark matter $_{\text{-2-}}$




[Weinberg et al, 2013]




[Tulin, Yu, 2017]

Transport heat from outside makes DM profile cored.

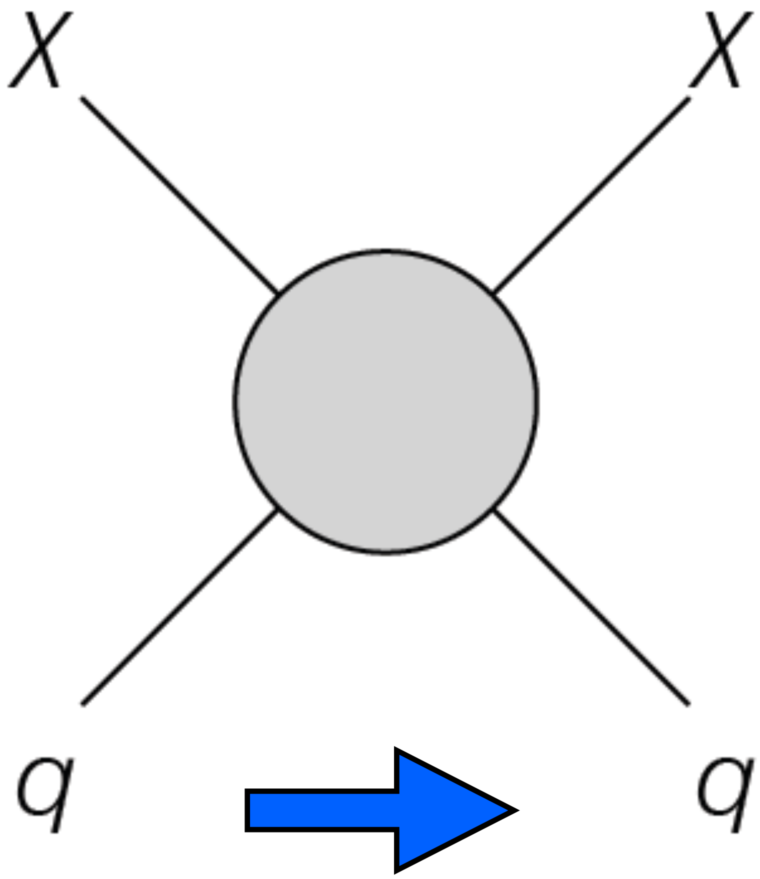
Self-Interacting cross section: $\frac{\sigma_{\rm self}}{m_{\rm DM}} \sim 0.1 - 10 {\rm cm}^2/{\rm g}$

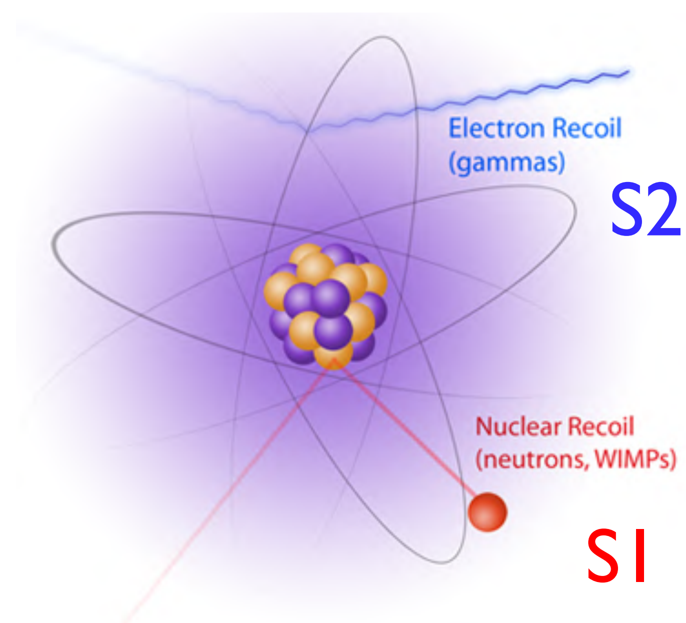
cf. Baryons (SN feedback).

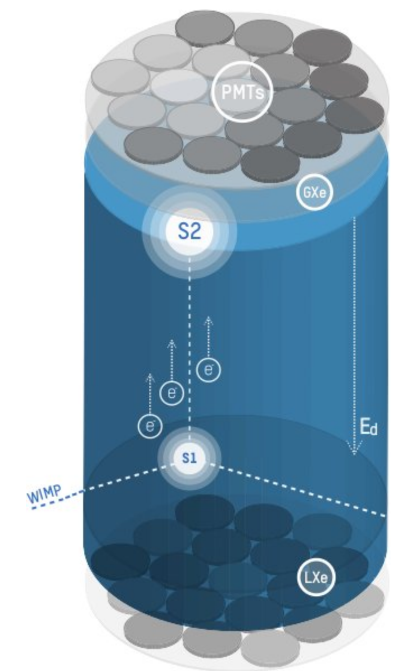
But, Bullet cluster bounds DM self-scattering. $\sigma/m \lesssim 0.7\,{\rm cm}^2/{\rm g}$

# Dark matter detection






e.g. XENON1T

S1: Scintillation (photons)

S2: Ionization (electrons)

WIMP:

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

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

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

| 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 |

Light dark matter such as SIDM

→ Too small recoil energy below threshold.

# Light DM detection



- DM-nucleon scattering => cryogenic semi-conductors.

  e.g. CDMSlite: Ge, $E_{th}$=56eV ⟹ $m_{\rm DM} \gtrsim 1.6\,{\rm GeV}$

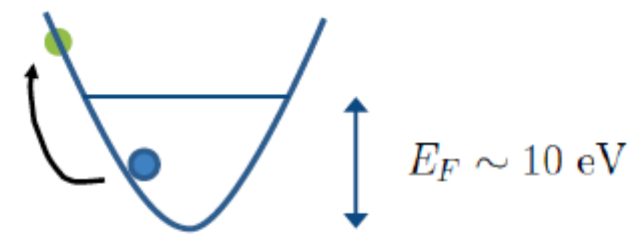
- DM-electron scattering (semi-conductor, superconductor)

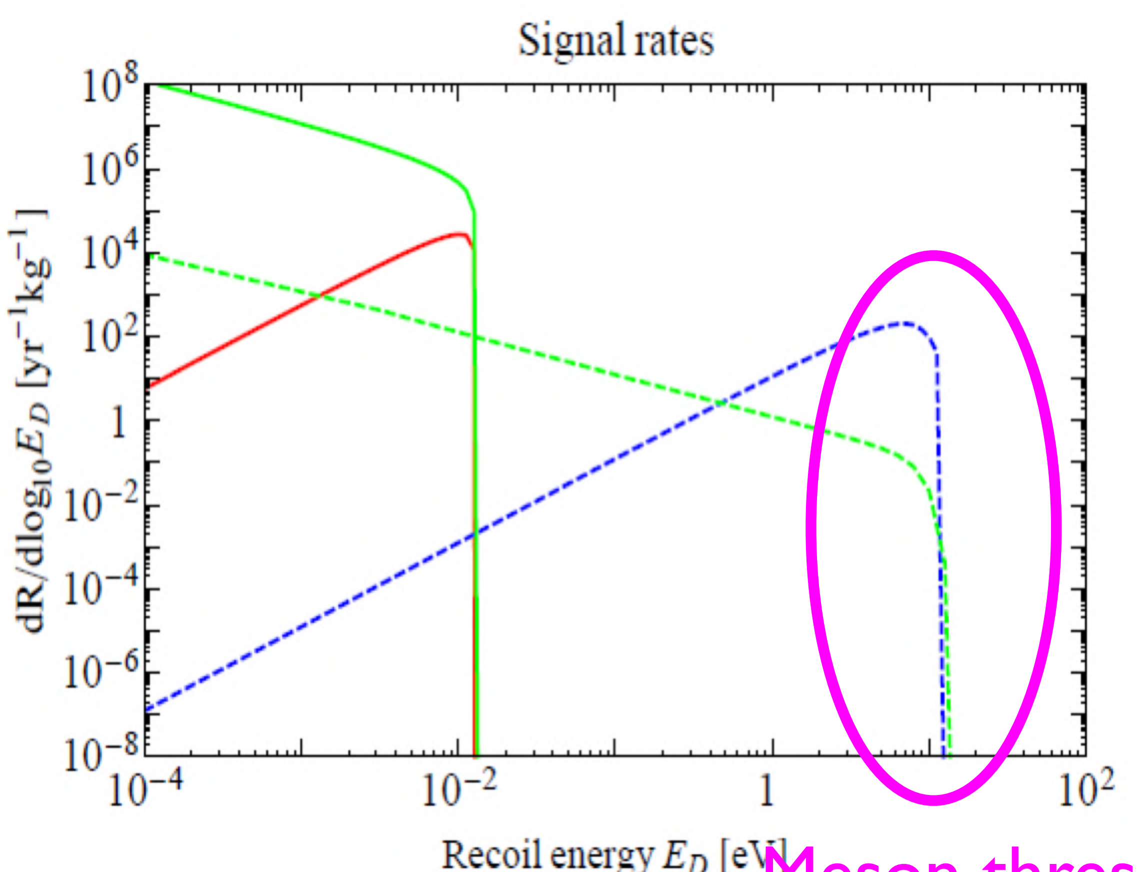
  $m_{\rm DM} v^2 \gtrsim \Delta \sim {\rm meV}$

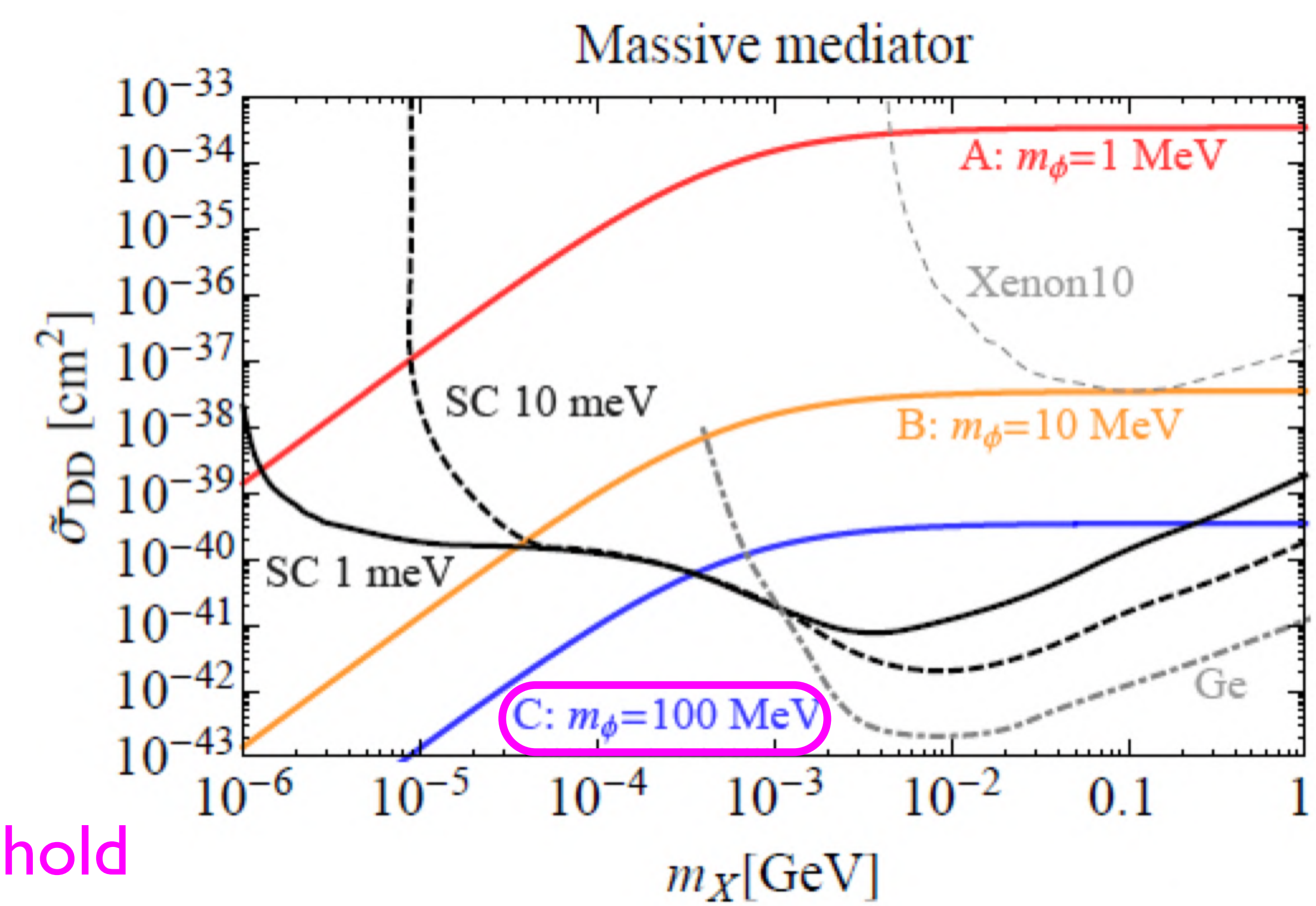
  $m_{\rm DM} \gtrsim m_e : \quad E_R \lesssim 20\,{\rm eV}$

  e.g. Al: $E_F = 11.7\,{\rm eV},\ v_{\rm rel} \sim v_F \sim 10^{-2}$

[Hochberg et al (2015)]



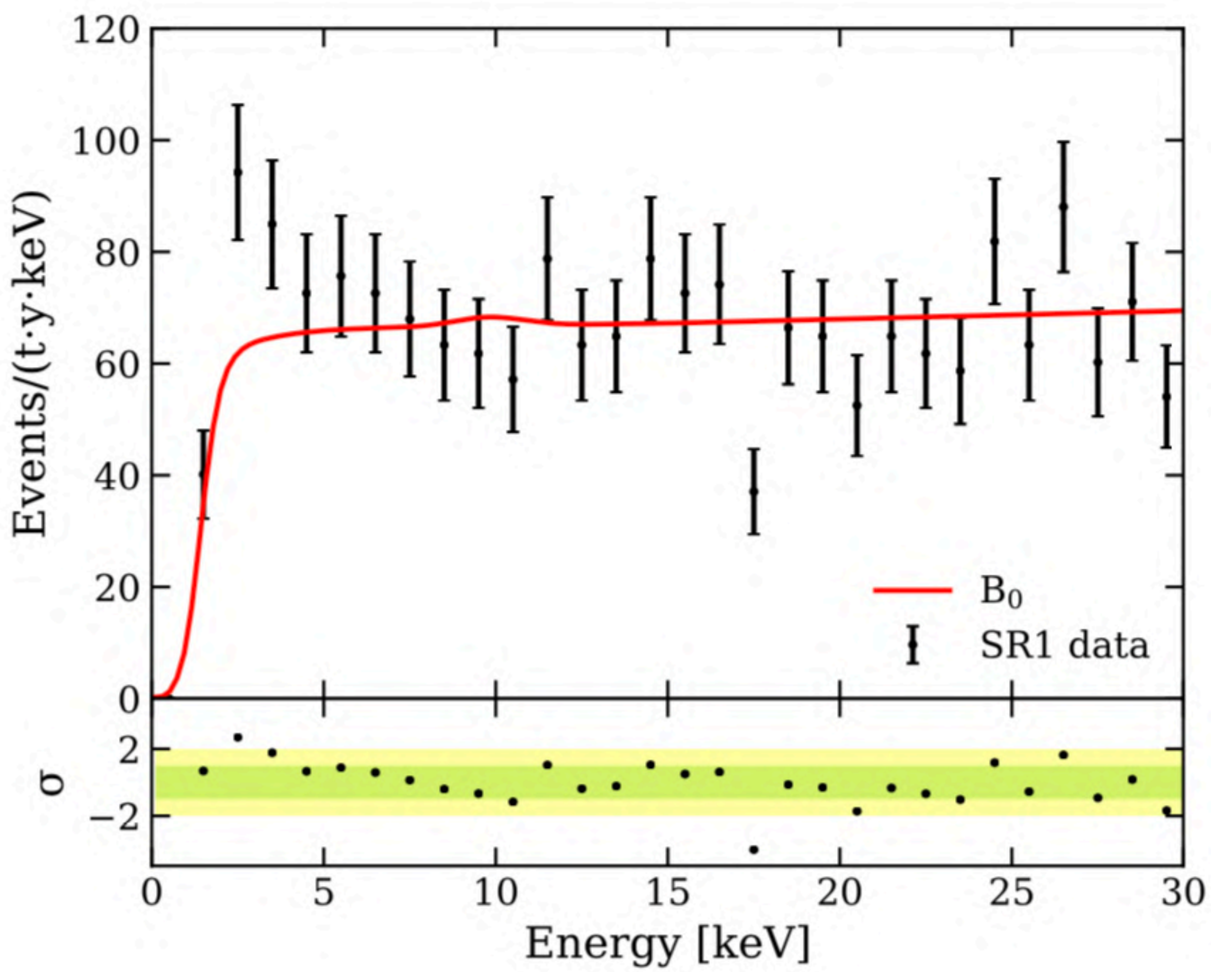



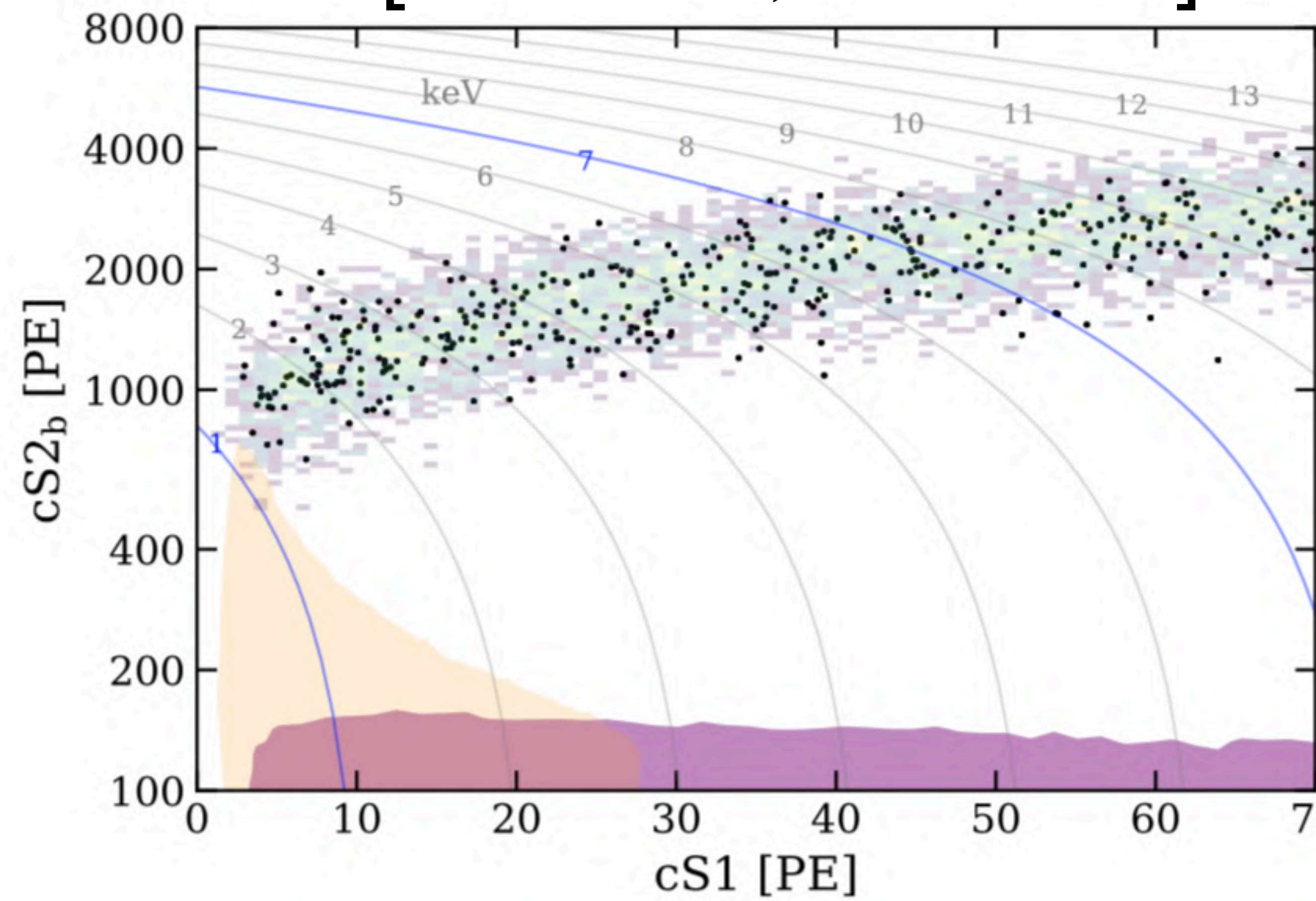
# XENON1T electron recoil



- Excess in electron recoil spectrum.

[XENON1T, 2006.09721]




$E_R$=1-7keV: 285 events observed,

$232 \pm 15$ expected

$3.3\sigma$ deviation:

most significant at $E_R$=2-3keV

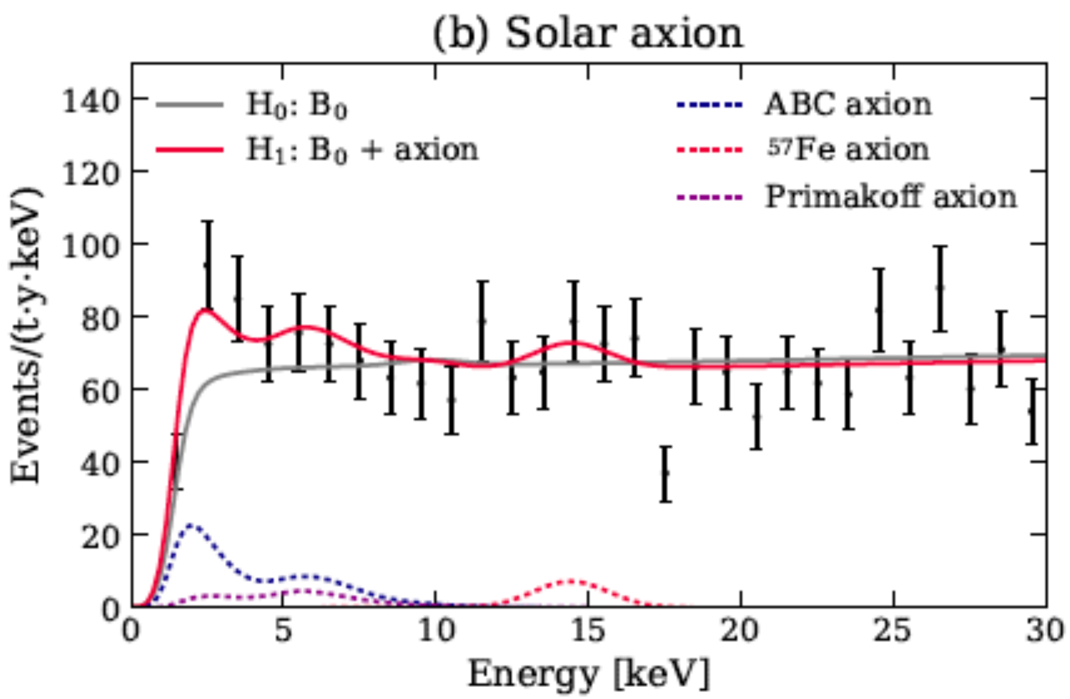
cf. Other backgrounds: Unknown Tritium, Ar37

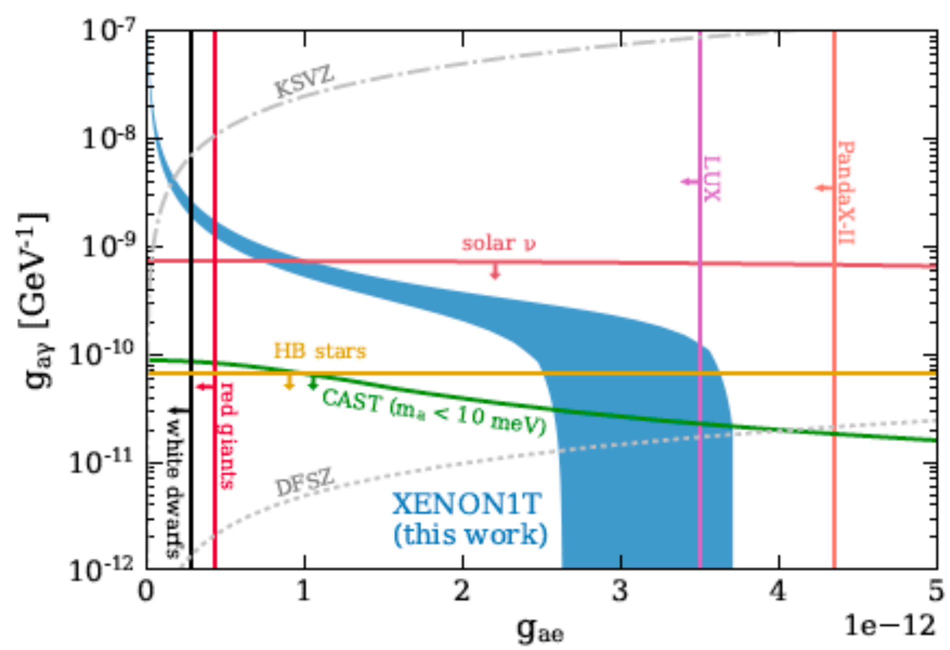
# New physics for Xe1t excess



- <u>Solar axion</u> (or neutrino magnetic dipole moment)

Solar axions produced by ABC, Promakoff, etc, are absorbed by Xenon atoms. favored at $3.5\sigma$

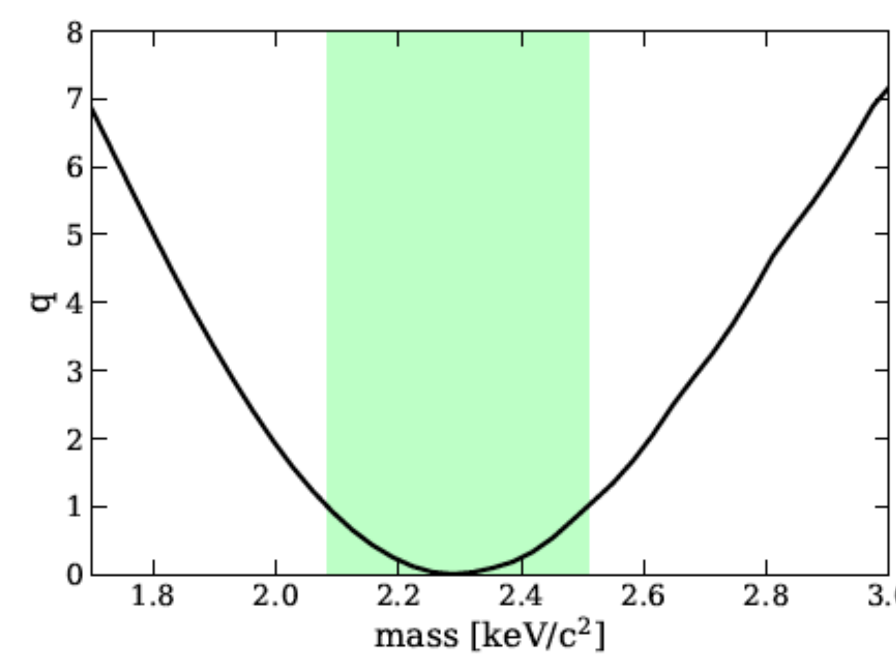



- <u>keV-scale dark matter</u>

Axio-electric process for "cold axion-like particle", dark photon, etc.

mono-chromatic recoil; global(local) at $3.0(4.0)\sigma$



# Elastic vs inelastic light DM



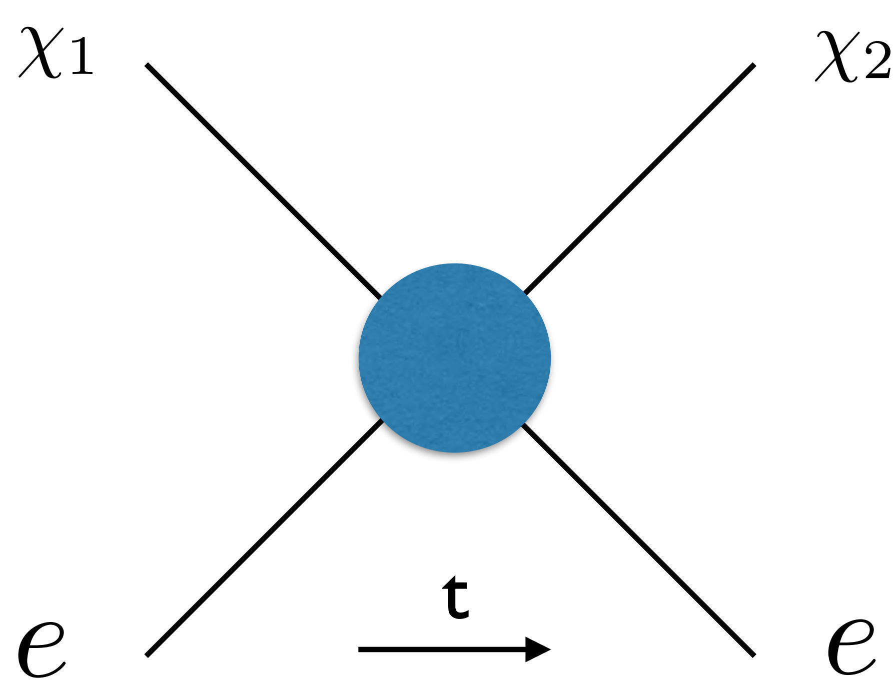
- Elastic scattering between light DM & electron.

$$E_R \sim \frac{\mu^2 v^2}{m_e} \sim m_e v^2 \sim 0.3\,\mathrm{eV} - 20\,\mathrm{eV}$$ : small recoil energy.

$$m_\chi \gtrsim m_e, \quad v \sim 220\,\mathrm{km/s} - 10^{-2}c$$

- Inelastic scattering between dark matter & electron.

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




Down scattering with electron for small mass splitting:

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

$$E_R \sim \Delta m \sim 2.5\,\mathrm{keV}$$

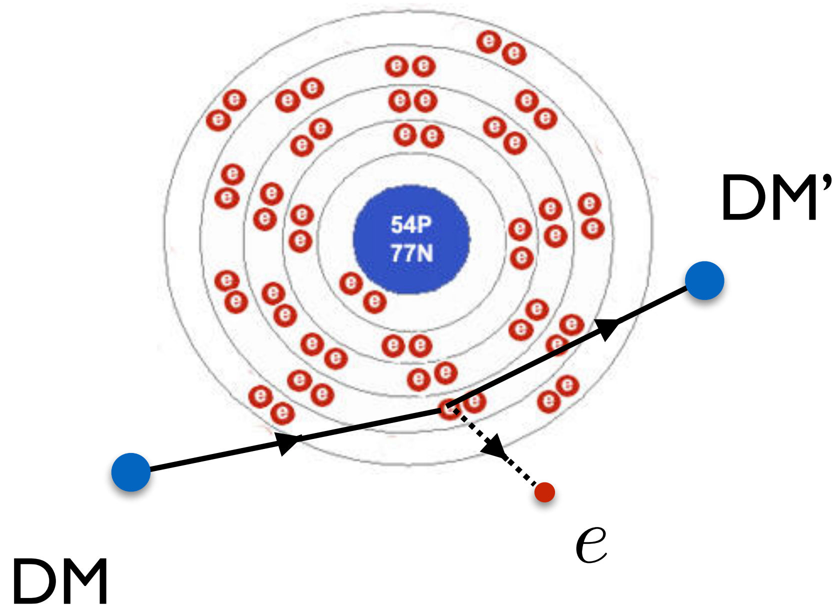
"Exothermic (Exo) dark matter"

Xenon excess is consistent with standard DM halo model.

cf. P. Graham et al; R. Essig et al (2010)

# Inside Xenon atoms

- Electrons are not isolated, bound to Xenon atoms.




- Electron velocity $v_e \sim Z_{\text{eff}}\alpha \sim 10^{-2}$
- Nuclear recoil $\Delta E_{\text{N}} \sim \frac{1}{2}\mu_N v_{\text{DM}}^2$
- Ionization energy $E_{\text{bound}} \lesssim 1\,\text{keV}$

$$E_R = \Delta E_e - E_{\text{bound}}$$

[Essig et al, 2015; HML, 2020]

$$\Delta E_e = -\Delta E_{\text{DM}} - \Delta E_N$$
$$= \Delta m\left(1 - \frac{1}{2}\left(\frac{m_{\chi_1}}{m_{\chi_2}}\right)v^2\right) + \frac{m_{\chi_1}}{m_{\chi_2}}\vec{q}\cdot\vec{v} - \frac{\vec{q}^2}{2\mu_{\chi_2 N}}$$

Xenon Binding Energies [eV]

| | $n \backslash l$ | $s$ | $p$ | $d$ |
|---|---|---|---|---|
| $O$ | 5 | 25.7 | 12.4 | – |
| $N$ | 4 | 213.8 | 163.5 | 75.6 |
| $M$ | 3 | 1093.2 | 958.4 | 710.7 |
| $L$ | 2 | 5152.19 | 4837.7 | – |
| $K$ | 1 | 33317.4 | – | – |

[Bunge et al, 1993;Dror et al, 2020]

- Nuclear recoil energy:

$$q^2 \sim m_e \Delta m \gg q_{\text{typ}}^2 \sim m_e^2 v_e^2$$

$$\Delta E_N = \frac{\vec{q}^2}{2\mu_{\chi_2 N}} \sim \frac{m_e}{m_{\chi_2}}(\Delta m) \ll \Delta m \quad \text{for } m_e \ll m_{\chi_2} < m_N$$

# Electron recoil energy



- Assume no nuclear recoil but electron velocity.

Initial energies: $E_e = \frac{1}{2} m_e v_e^2 \quad , \qquad E_0 = \frac{1}{2} m_{\chi_1} v^2$

Energy conservation: $m_{\chi_2} + \frac{p^2}{2M_2} + \frac{p_{\rm cm}^2}{2\mu_2} = m_{\chi_1} + E_0 + E_e$

⟶ Electron momentum in CM frame: $p_{\rm cm} = \sqrt{2\mu_2\Big(\Delta m + E_0 + E_e - \frac{p^2}{2M_2}\Big)}$

Total 3-momentum: $p^2 = 2m_{\chi_1} E_0 + 2m_e E_e + 4\cos\alpha\sqrt{m_e m_{\chi_1} E_0 E_e}$

Electron recoil E:

$$\begin{aligned}\Delta E_e &= \frac{1}{2m_e}\left(\frac{m_e}{M_2}\vec{p} - \vec{p}_{\rm cm}\right)^2 - E_e \\ &= \frac{m_e}{2M_2^2}p^2 + \frac{\mu_2}{m_e}\Big(\Delta m + E_0 + E_e\Big) - \frac{\mu_2}{2m_e M_2}p^2 - E_e \\ &\quad - \frac{p}{M_2}\cos\theta\sqrt{2\mu_2(\Delta m + E_0 + E_e) - \frac{\mu_2}{M_2}p^2}.\end{aligned}$$

[HML, 2020]

Momentum transfer: $q^2 = 2m_e\Delta E_e + m_e^2 v_e^2 - 2m_e v_e \cos\psi\sqrt{m_e \Delta E_e}$

# Electron recoil energy



- Initial electron momentum can be ignored for relatively heavy dark matter.

$$m_{\chi_1} E_0 \gtrsim m_e E_e \longrightarrow m_{\chi_1} \gtrsim m_e (v_e/v) \sim 10\,\mathrm{MeV}$$

➡ Total 3-momentum: $p^2 \simeq 2 m_{\chi_1} E_0$ due to DM energy.

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

Recoil E: $$\Delta E_e \simeq \Delta m \left(1 - \frac{2}{\sqrt{\kappa}} \cos\theta\right),$$

[HML, 2020]

"Monochromatic"

Momentum transfer: $$q^2 \simeq 2 m_e \Delta E_e \simeq 2 m_e \Delta m \left(1 - \frac{2}{\sqrt{\kappa}} \cos\theta\right).$$

➡ Mass splitting determines both recoil E & momentum transfer dominantly.

# Moving electrons



- Width of recoil energy depends on electron velocity for light dark matter.

$$m_{\chi 1} E_0 \lesssim m_e E_e \longrightarrow m_{\chi 1} \lesssim m_e (v_e/v) \sim 10\,\mathrm{MeV}$$

➡ Total 3-momentum: $p^2 \simeq 2 m_e E_e$ due to electron energy.

$$\Delta m \ll m_e \ll m_{\chi 1}\,, \quad \boxed{\tilde{\kappa} \simeq \frac{\Delta m}{\frac{1}{2} m_e v_e^2}} \simeq 10^2 \left(\frac{10^{-2} c}{v_e}\right)^2 \left(\frac{\Delta m}{3\,\mathrm{keV}}\right) \gg 1$$

Recoil E:

$$\Delta E_e \simeq \Delta m \left(1 - \frac{2 m_e}{m_{\chi 1}} \frac{1}{\sqrt{\tilde{\kappa}}} \cos\theta\right)$$

[HML, 2020]
"Monochromatic"

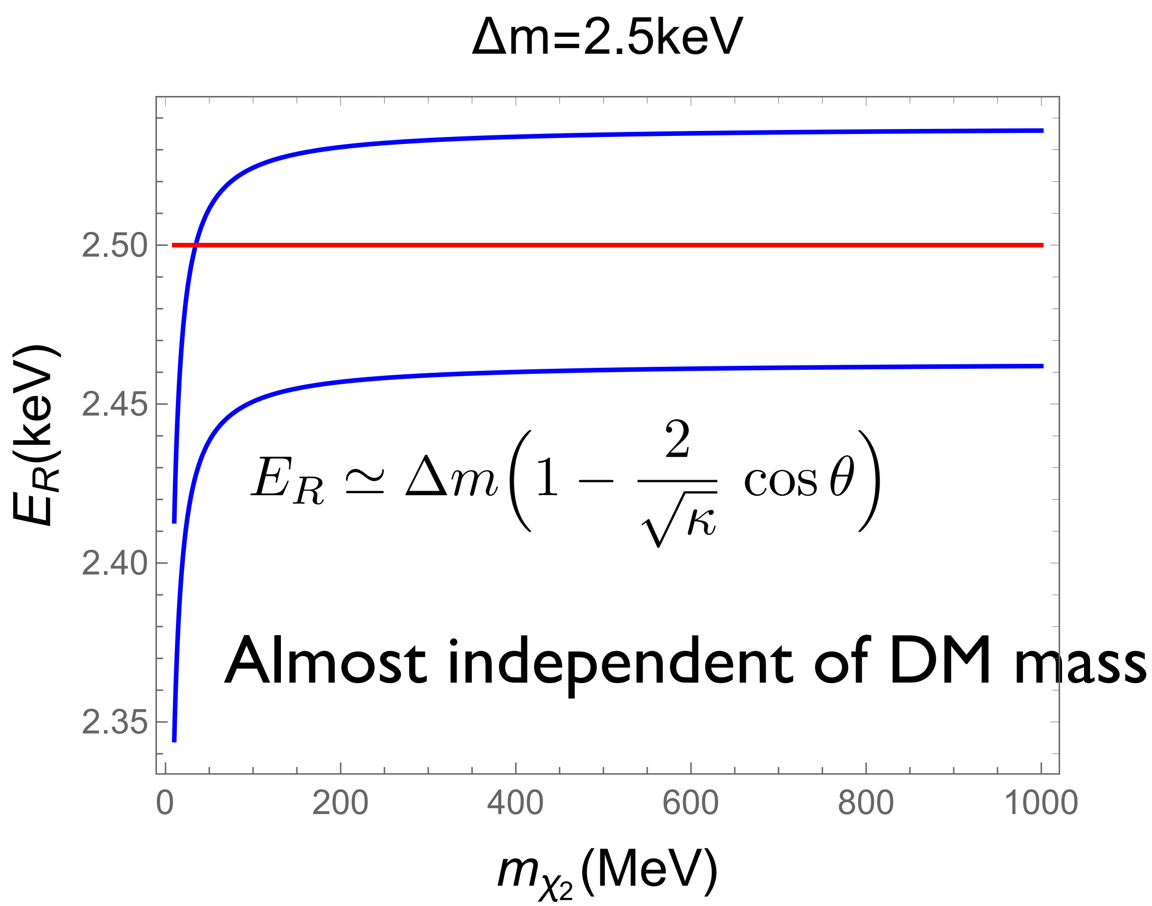
Momentum transfer:

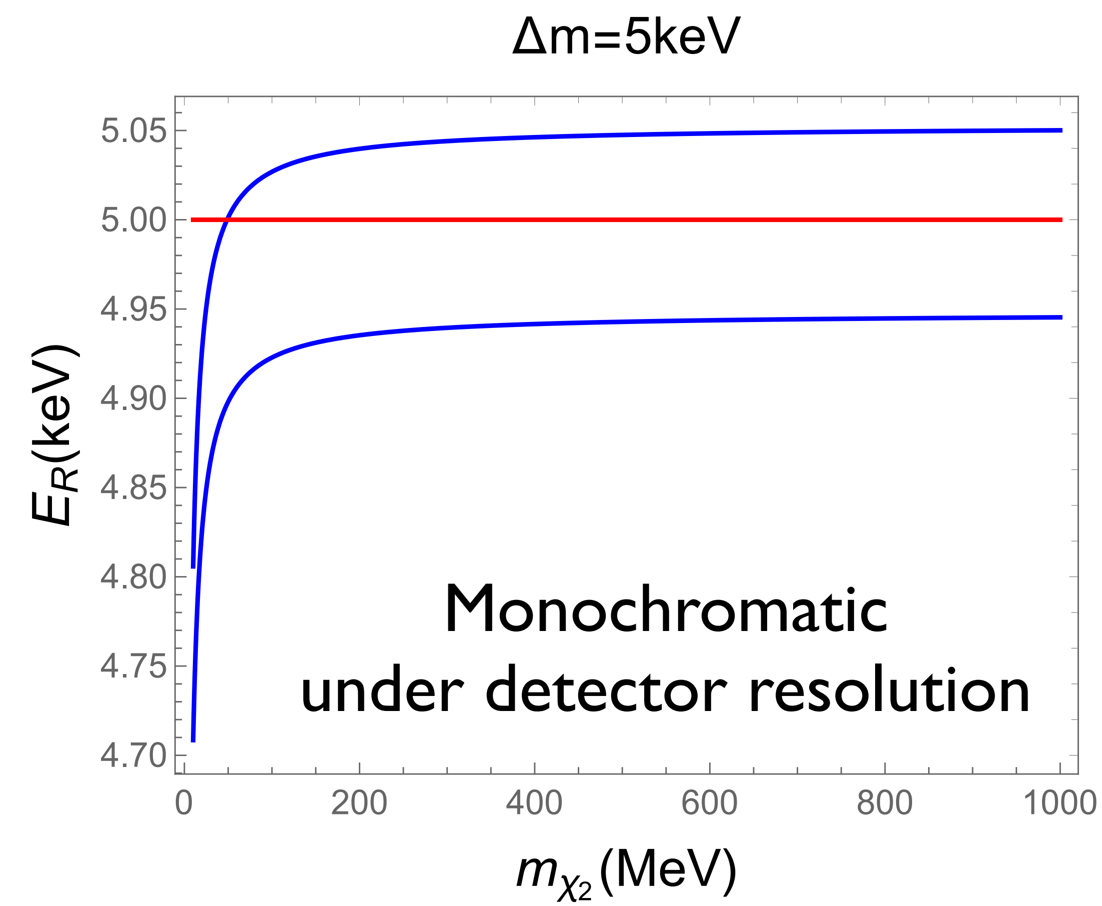
$$q^2 \simeq 2 m_e \Delta E_e \simeq 2 m_e \Delta m \left(1 - \frac{2 m_e}{m_{\chi 1}} \frac{1}{\sqrt{\tilde{\kappa}}} \cos\theta\right)$$

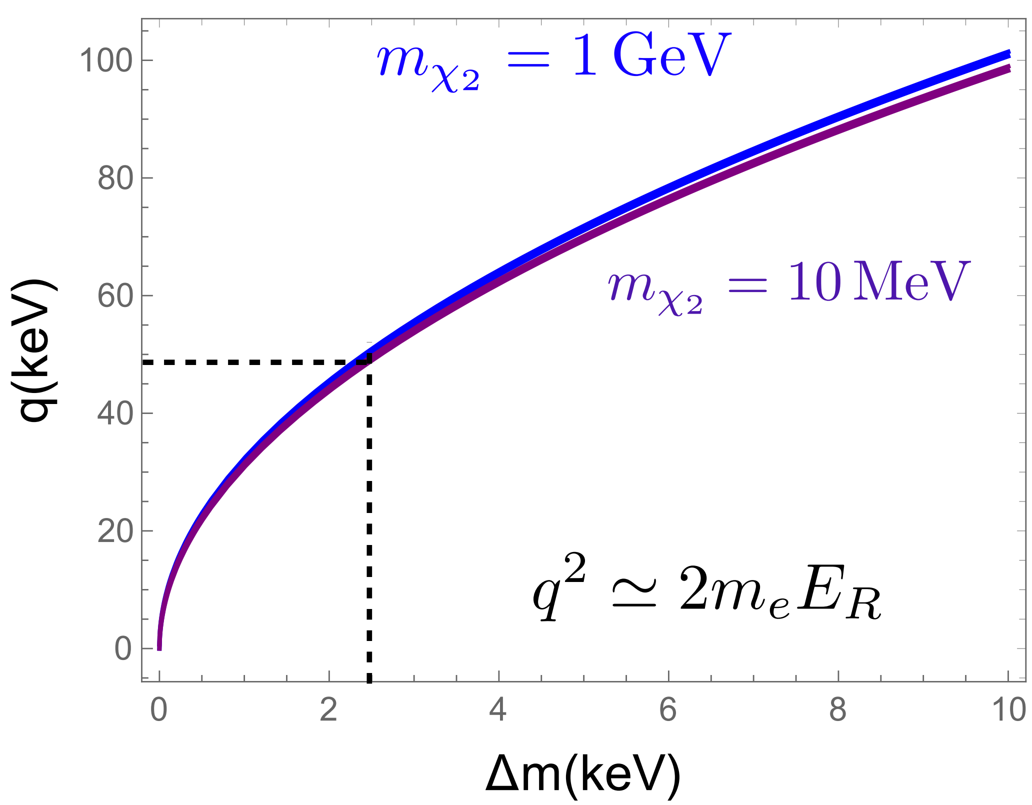
➡ <u>Mass splitting still determines kinematics dominantly</u>

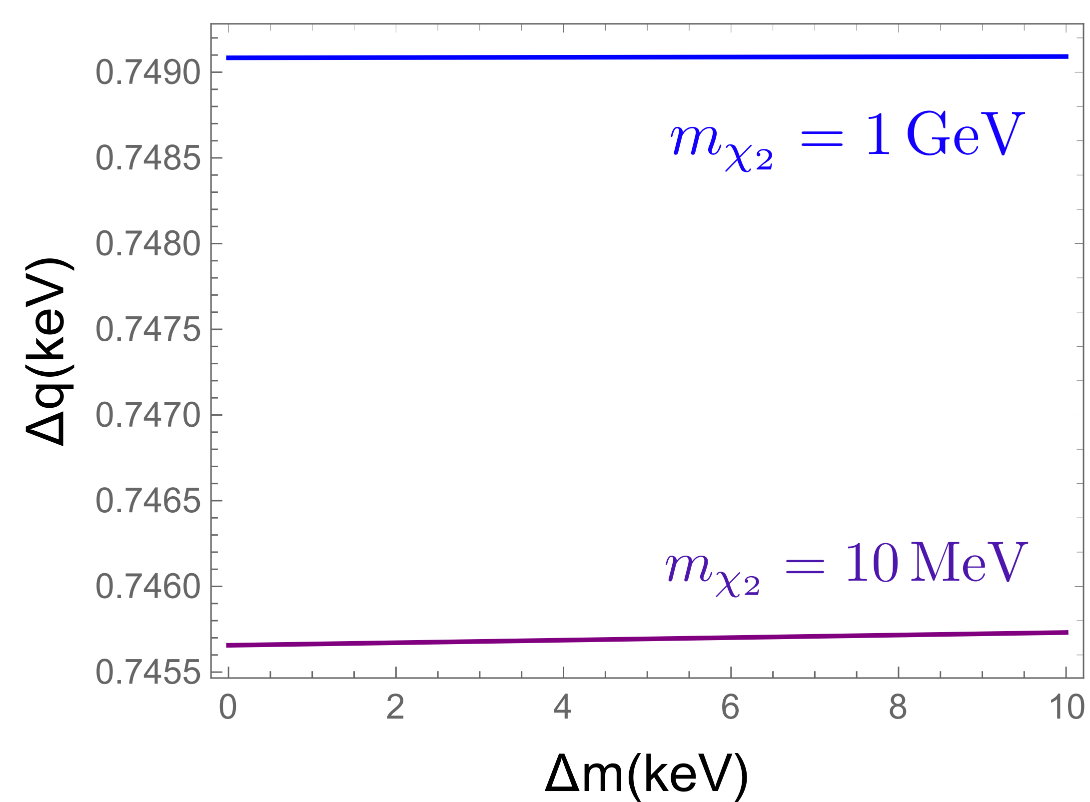
# Energy/momentum transfer





# ExoDM event rate



- The general event rate per target mass is

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

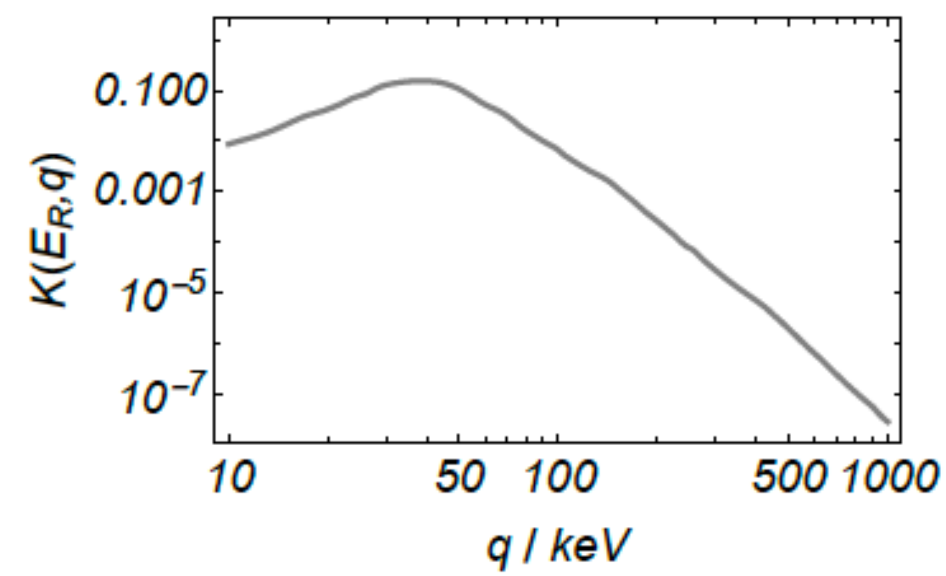
- The total cross section for inelastic scattering:

$$\frac{d\sigma}{dE_R} = \frac{2m_e\bar{\sigma}_e}{q_+^2 - q_-^2}\int_{q_-}^{q_+} a_0^2\, q'\, dq'\, K(E_R, q')\, P^2(v).$$

[HML, 2020]

<u>Atomic enhancement factor:</u>

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




<u>Phase space factor:</u>

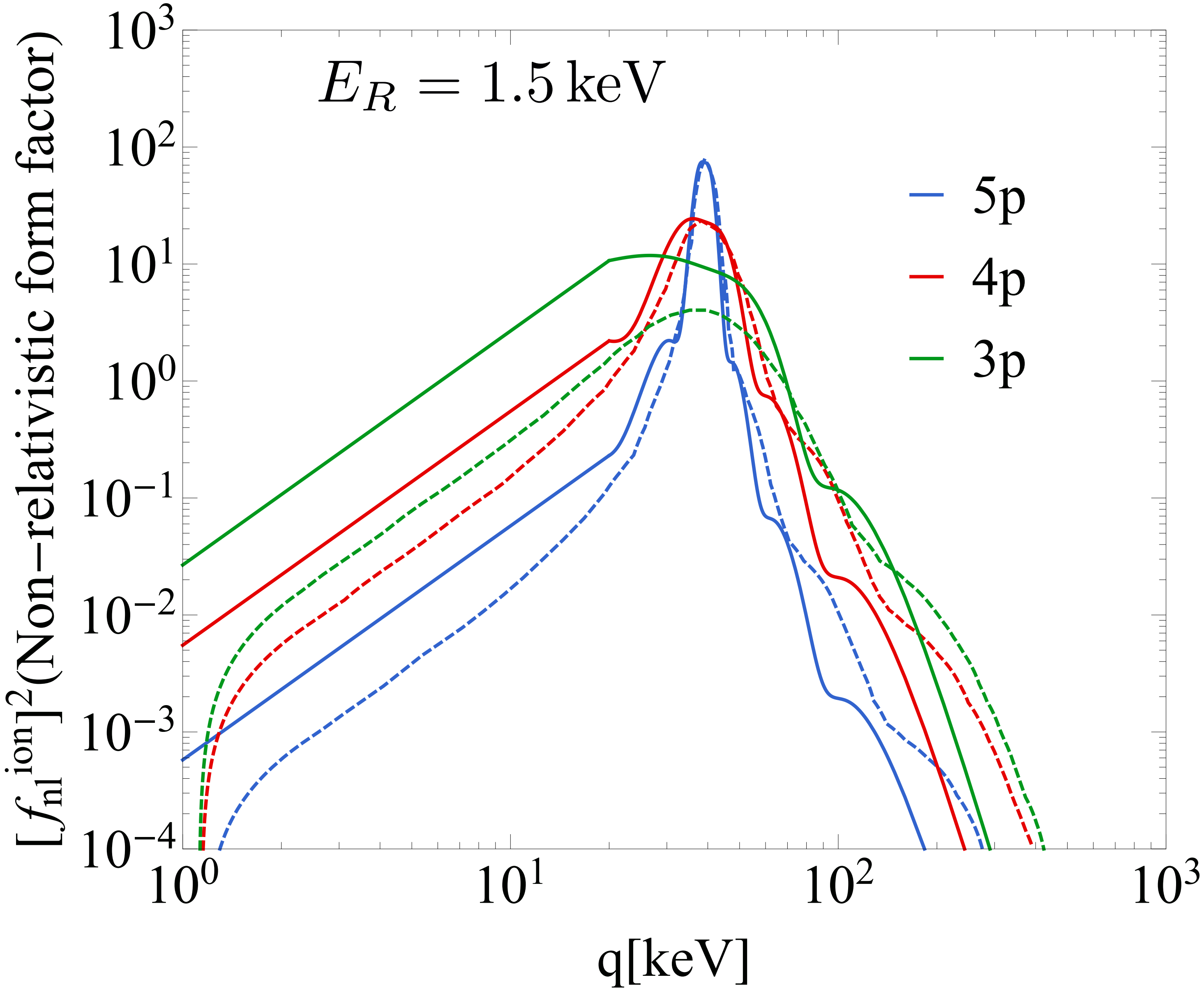
$$P^2(v) = \frac{\left(1 - \frac{(m_{\chi_2}+m_e)^2}{E_{\text{cm}}^2}\right)^{1/2}\left(1 - \frac{(m_{\chi_2}-m_e)^2}{E_{\text{cm}}^2}\right)^{1/2}}{\left(1 - \frac{(m_{\chi_1}+m_e)^2}{E_{\text{cm}}^2}\right)^{1/2}\left(1 - \frac{(m_{\chi_1}-m_e)^2}{E_{\text{cm}}^2}\right)^{1/2}} \simeq \sqrt{1 + \frac{2\Delta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

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

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

# Atomic form factors






Solid: S.Choi, HML, Zhu, to appear.

cf. Dashed: Bloch et al, 2006.14521

Both results are consistent, in particular, near the peak.

Outer-shell electrons are more easily ionized.

$$K(E_R, q) = \frac{\alpha^2 m_e (m_e + m_{\chi_1})^2}{4 E_R m_{\chi_1}^2} \sum_{n,l} |f_{nl}(p_e, q)|^2, \qquad p_e = \sqrt{2 m_e E_R}$$

# ExoDM event rate



- Differential event rate per target mass:

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

Peaked at $q \simeq \sqrt{2m_e\Delta m} \simeq 50\,\mathrm{keV},\ E_R \simeq \Delta m = 2.5\,\mathrm{keV}.$

$$\frac{dR}{dE_R} = \frac{2m_e\bar{\sigma}_e\rho_{\chi_1}}{m_{\chi_1}m_T}K_{\rm int}(E_R)\int_{v_{\rm min}}^{\infty}\frac{vP^2(v)}{q_+^2 - q_-^2}f_1(v)\,dv \quad \theta(E_R - E_-)\theta(E_+ - E_R),$$

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

- Total event rate per detector: [HML, 2020]

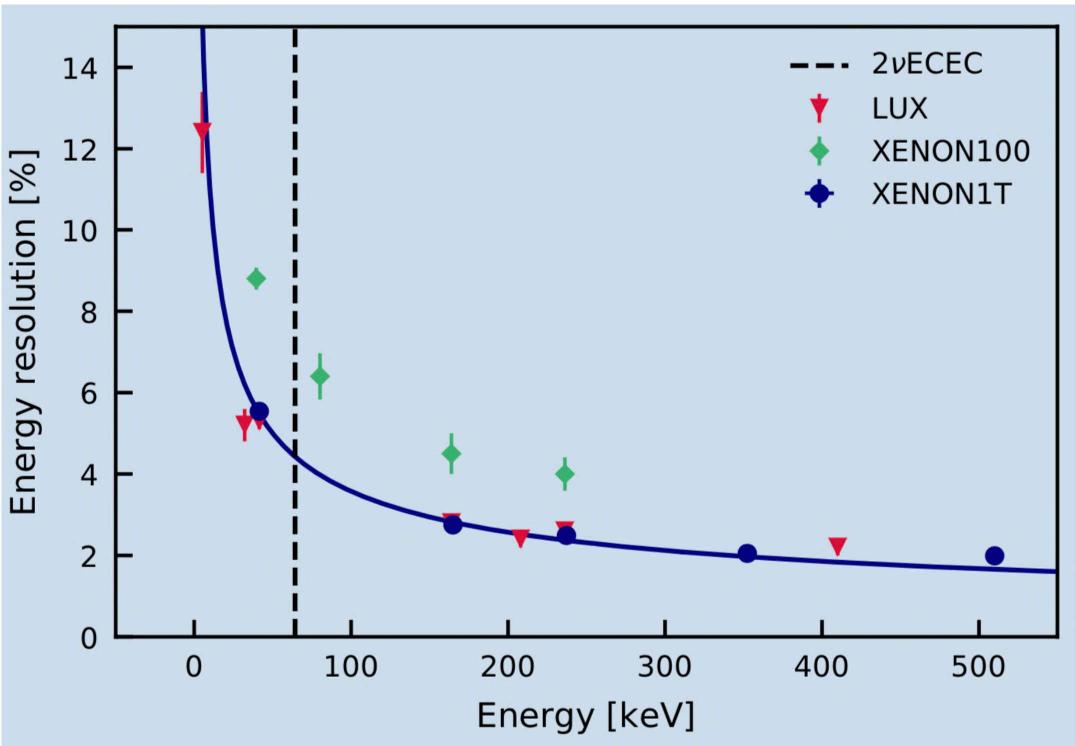
$$R_D = M_T\int_{E_T}^{\infty}\frac{dR}{dE_R}dE_R \simeq 50\left(\frac{M_T}{\rm tonne - yrs}\right)\left(\frac{K_{\rm int}(\Delta m)}{2.6}\right)\left(\frac{\rho_{\chi_1}}{0.4\,\mathrm{GeV\,cm^{-3}}}\right) \times\left(\frac{\bar{\sigma}_e/m_{\chi_1}}{1.2\times 10^{-43}\,\mathrm{cm^2/GeV}}\right)\left(\frac{\Delta m}{2.5\,\mathrm{keV}}\right)^{1/2}$$

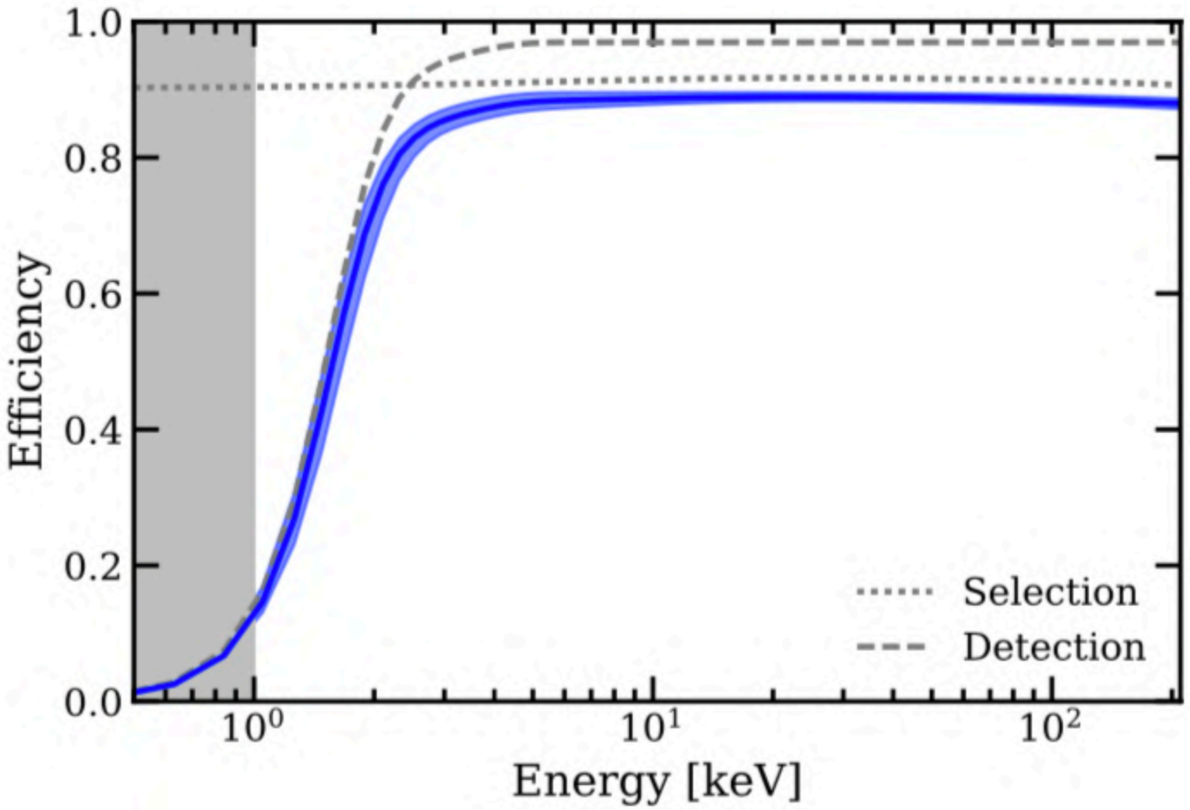
# ExoDM event rate



- The event is convoluted with detector resolution and efficiency.

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



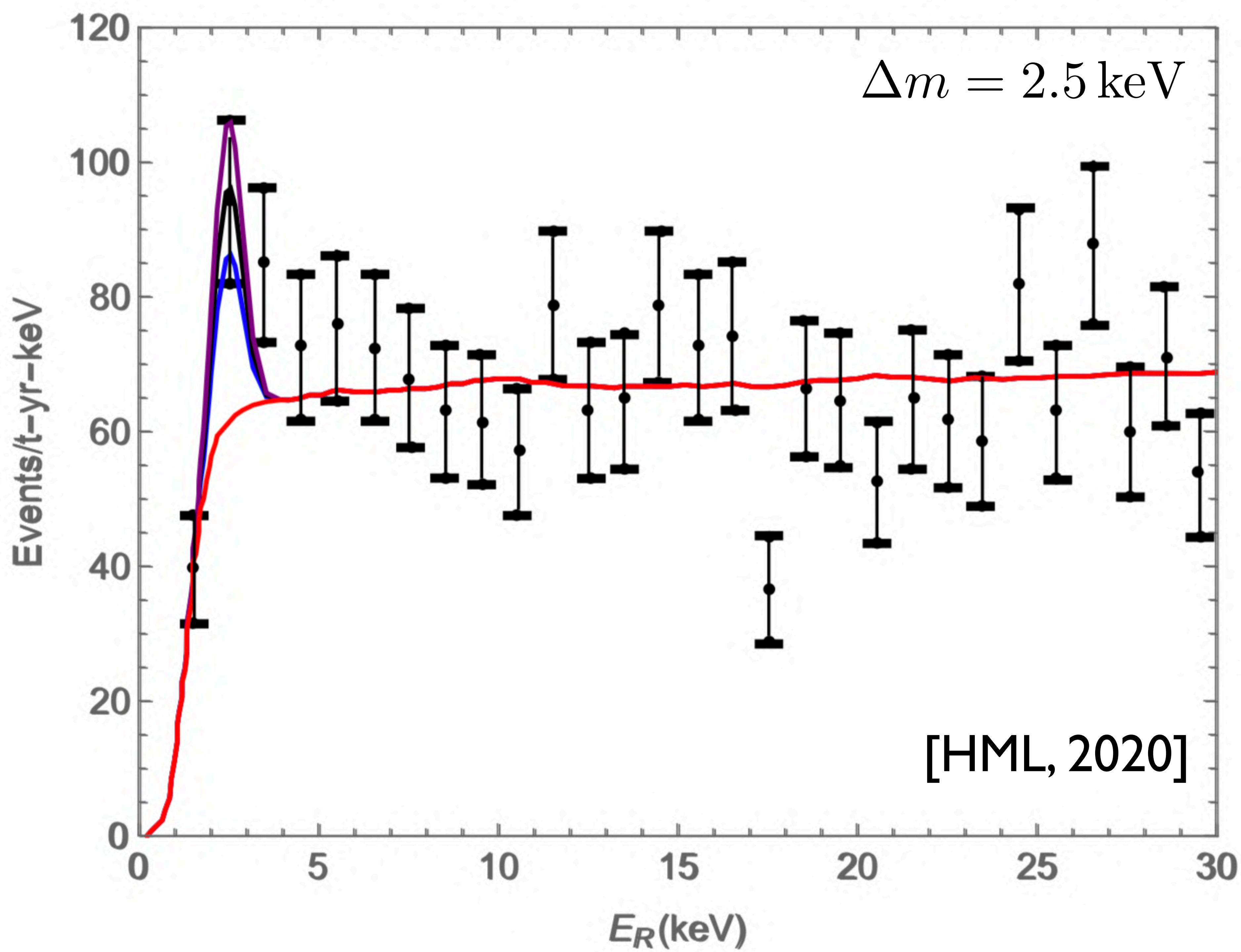

$\sigma : 20\% - 6\%,\ E_R = 2 - 30\,\mathrm{keV},$

$\alpha(E) = 0.7 - 0.9,\ E_R = 2 - 10\,\mathrm{keV}$

$E_R = 2.5\,\mathrm{keV}$ → $\sigma = 0.4\,\mathrm{keV},\ \alpha \gtrsim 0.8$

# XENON1T electron recoil






Bottom to top: $(\bar{\sigma}_e/m_{\chi_1})/(10^{-43}\mathrm{cm}^2\,/\mathrm{GeV}) \simeq 1.0,\ 1.4,\ 1.8$

Red line: Background model

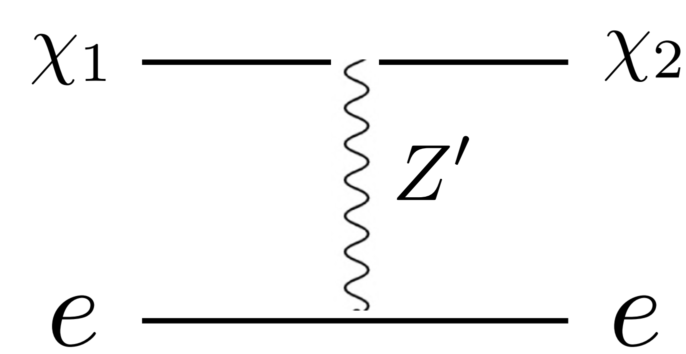
# EFT for ExoDM



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

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

- DM-electron inelastic cross section:




$$\bar{\sigma}_e \simeq \frac{v_\chi^2 v_e^2 g_{Z'}^4 \mu_1^2}{\pi m_{Z'}^4} \simeq \left(\frac{v_\chi g_{Z'}}{0.6}\right)^2 \left(\frac{v_e g_{Z'}}{10^{-4} e}\right)^2 \left(\frac{600\,{\rm MeV}}{m_{Z'}}\right)^4 \left(\frac{\mu_1}{m_e}\right)^2 \times 10^{-43}\,{\rm cm}^2$$

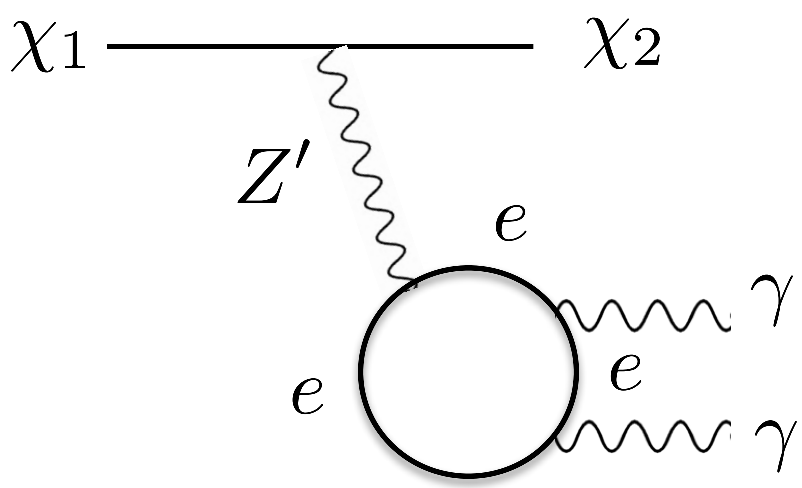
→ Light dark matter and mediator below GeV scale are favored for XENON1T excess.

- Astrophysics bounds on lifetime of heavier state.
- DM relic abundances & terrestrial bounds.

# Bounds on ExoDM



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

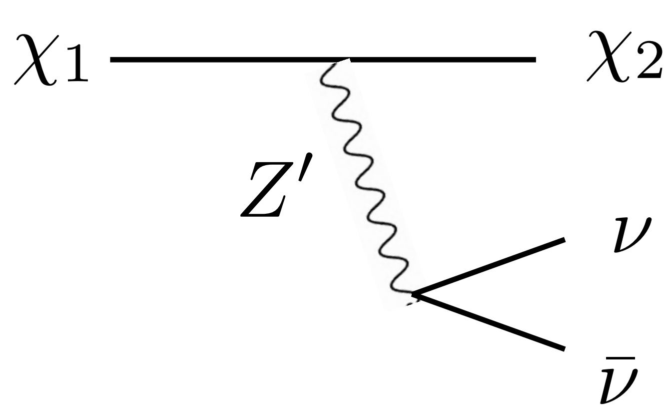



$$\Gamma(\chi_1 \to \chi_2\gamma\gamma) \simeq \frac{a_e^2(v_\chi^2 + a_\chi^2)e^4 g_{Z'}^2}{2560\pi^7}\frac{(\Delta m)^5}{m_{Z'}^4}$$

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

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

- Accompanying neutrino coupling opens up neutrino decay channels: $E_\nu \sim \mathrm{keV}$




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

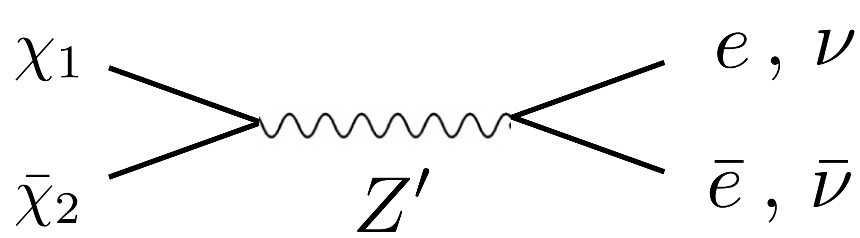
$\tau_{\chi_1} > t_U$ : $G_F'\sqrt{N_\nu(v_\nu^2 + a_\nu^2)} < 2.4\times 10^{-6}\,\mathrm{GeV}^{-2}$

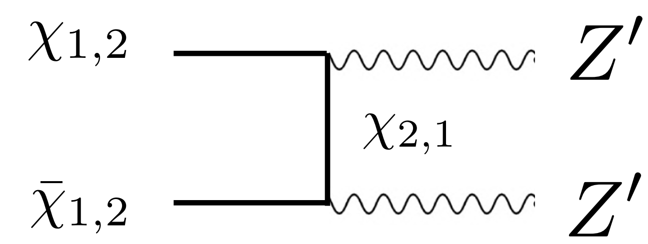
cf. Super-K: $\tau_{\chi_1} \gtrsim 10^{24}\,\mathrm{sec}\,,\ E_\nu \gtrsim 0.1\,\mathrm{GeV}$

# Dark matter relic density



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




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

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

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

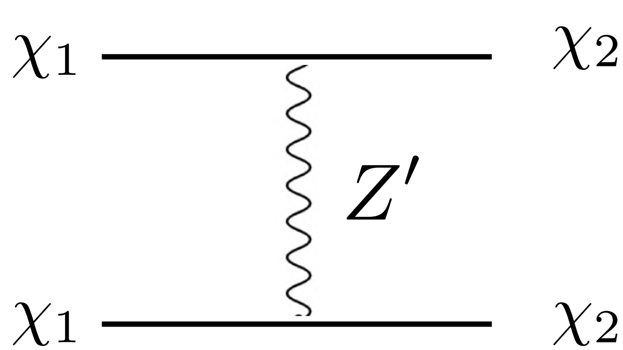
"forbidden channels"

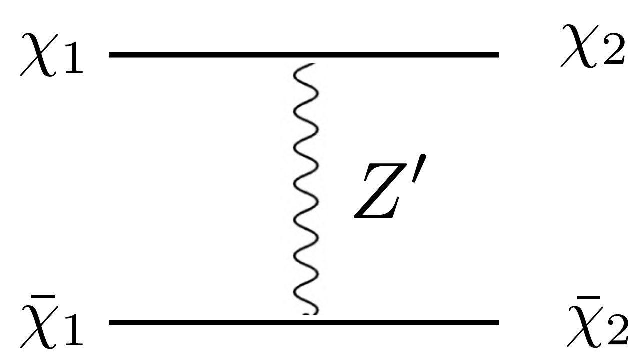
$$\Omega_{\rm DM}h^2 = 0.12\left(\frac{10.75}{g_*(T_f)}\right)^{1/2}\left(\frac{x_f}{20}\right)\left(\frac{4.3\times 10^{-9}\,{\rm GeV}^{-2}}{x_f\int_{x_f}^{\infty} x^{-2}\langle\sigma v\rangle}\right) \simeq 2\,\Omega_{\chi_1}h^2$$

# Late chemical decoupling



- Heavier DM keeps annihilating into lighter DM.




$$\langle\sigma v\rangle_{\chi_1\chi_1\to\chi_2\chi_2} = \frac{\sqrt{2}}{16\pi}\frac{g_{Z'}^4 m_{\chi_1}^2}{m_{Z'}^4}\sqrt{\frac{\Delta m}{m_{\chi_1}}}\,(v_\chi^4 + 6a_\chi^2 v_\chi^2 + 9a_\chi^4),\qquad \langle\sigma v\rangle_{\chi_1\bar\chi_1\to\chi_2\bar\chi_2} = \frac{\sqrt{2}}{8\pi}\frac{g_{Z'}^4 m_{\chi_1}^2}{m_{Z'}^4}\sqrt{\frac{\Delta m}{m_{\chi_1}}}\,(v_\chi^4 + 3a_\chi^4)$$

Heavier component must be decoupled at $T_\chi \gtrsim \Delta m.$

$$n_{\chi_1}\langle\sigma v\rangle_{\chi_1\bar\chi_1\to\chi_2\bar\chi_2} = H, \qquad \text{at } T_\chi > \Delta m$$

Otherwise, Boltzmann suppressed: $n_{\chi_1} = e^{-\Delta m/T_\chi}\, n_{\chi_2}$

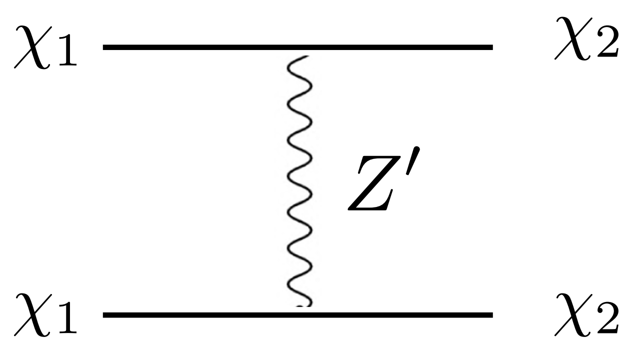
Here, $T_\chi = \dfrac{T^2}{T_{\rm kd}},\quad T_{\rm kd} \sim {\rm MeV}.$ "Kinetic decoupling temp"

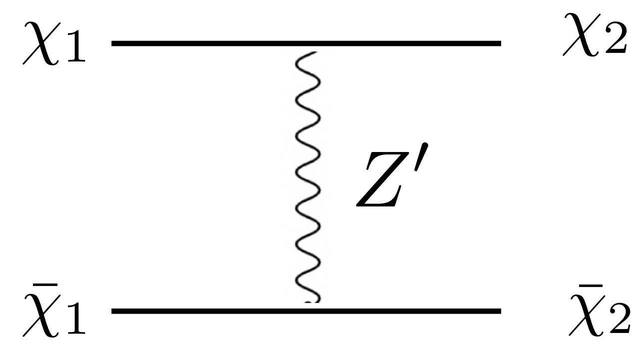
$$\frac{|v_\chi| g_{Z'} m_{\chi_1}}{m_{Z'}} \lesssim 0.035\left(\frac{\Omega_{\rm DM}/2}{\Omega_{\chi_1}}\right)^{1/4}\left(\frac{m_{\chi_1}}{100\,{\rm MeV}}\right)^{1/2}\left(\frac{m_{\chi_1}/\Delta m}{4\times 10^4}\right)^{3/8}\left(\frac{\Delta m/(2.5\,{\rm keV})}{T_{\rm kd}/(10\,{\rm MeV})}\right)^{1/8}$$

# Dark matter self-scattering



- Inelastic self-scattering.

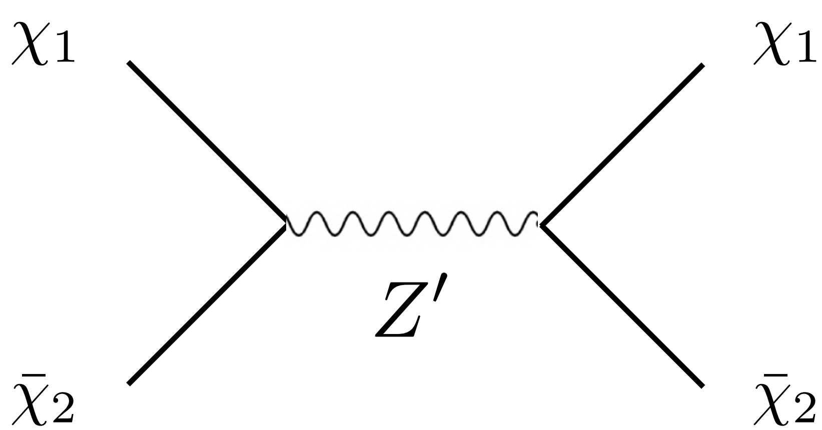



$$\sigma_{\chi_1\chi_1\to\chi_2\chi_2} = \frac{1}{16\pi}\frac{g_{Z'}^4 m_{\chi_1}^2}{m_{Z'}^4}\left(v_\chi^4 + 6a_\chi^2 v_\chi^2 + 9a_\chi^4\right),$$

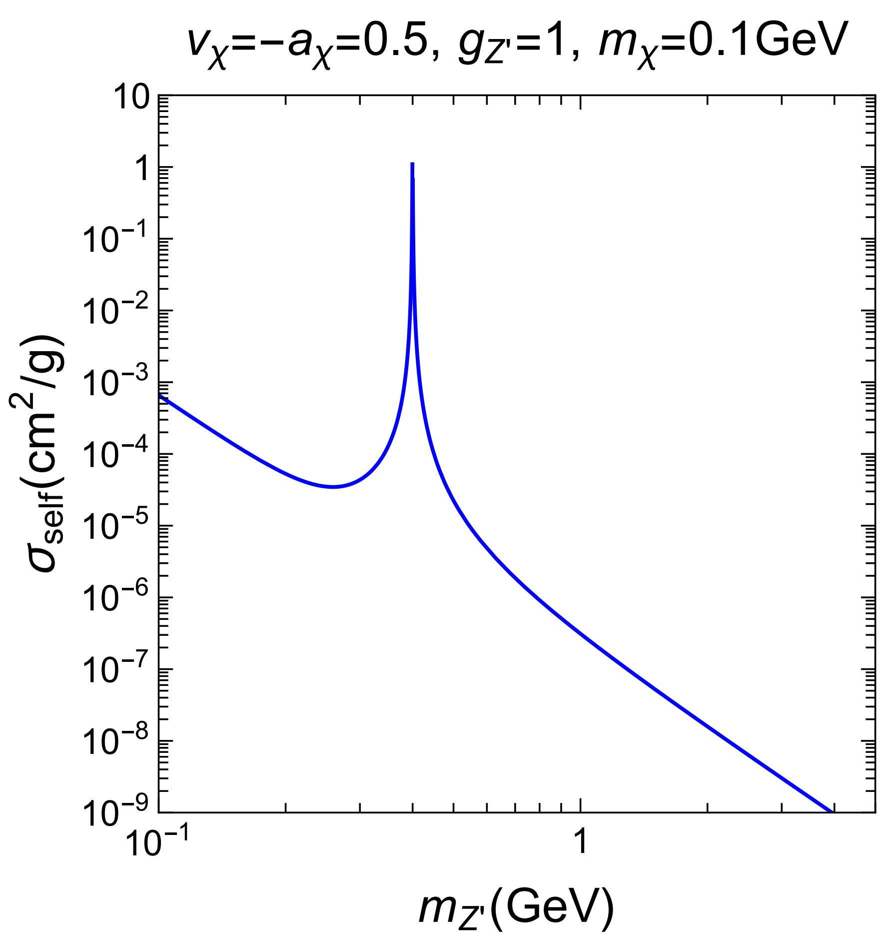
$$\sigma_{\chi_1\bar{\chi}_1\to\chi_2\bar{\chi}_2} = \frac{1}{8\pi}\frac{g_{Z'}^4 m_{\chi_1}^2}{m_{Z'}^4}\left(v_\chi^4 + 3a_\chi^4\right)$$

- Elastic self-scattering.




$$\sigma_{\chi_1\bar{\chi}_2\to\chi_1\bar{\chi}_2} = \frac{g_{Z'}^4 v_\chi^2(v_\chi^2 + a_\chi^2)}{\pi}\frac{m_{\chi_1}^2}{(m_{Z'}^2 - 4m_{\chi_1}^2(1+v^2/4))^2 + \Gamma_{Z'}^2 m_{Z'}^2}$$

Velocity-dependent self-scattering!



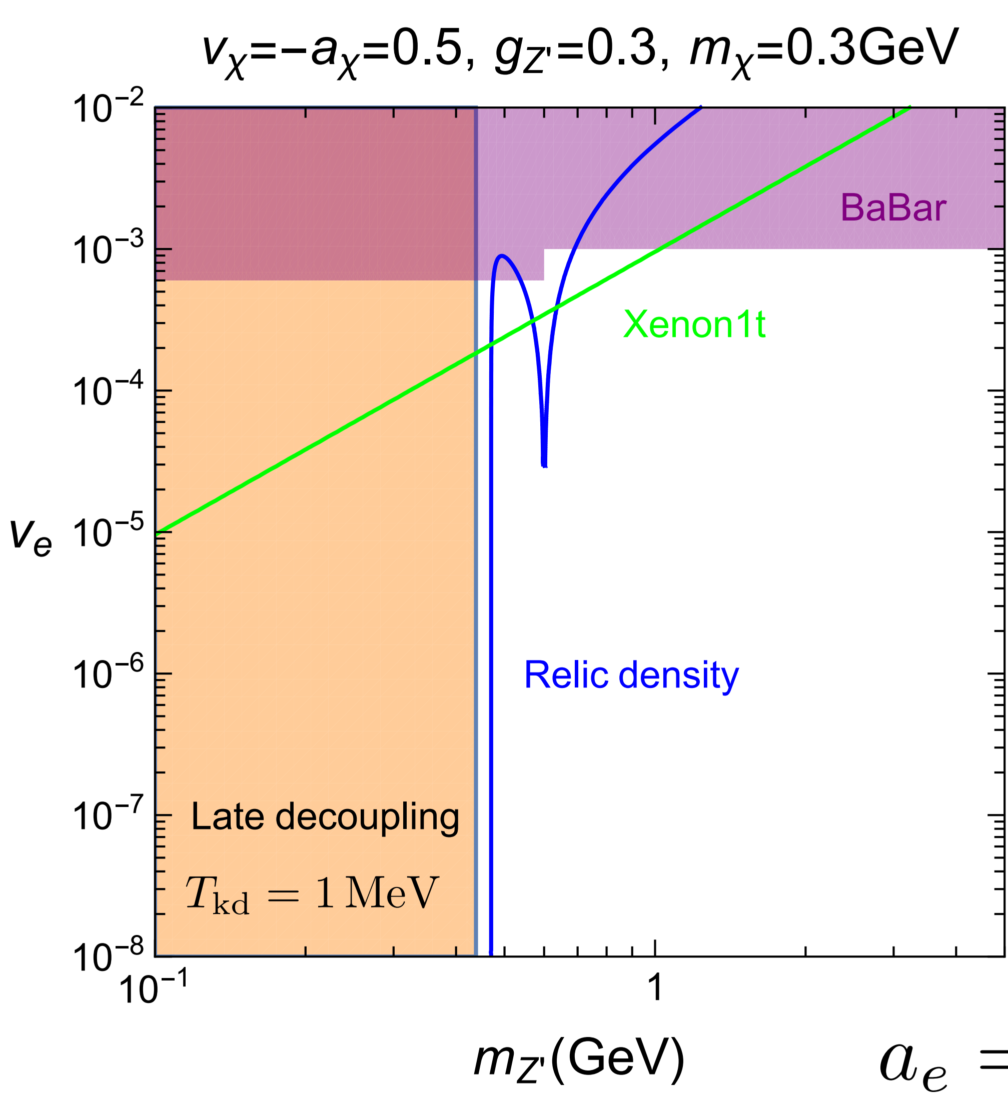
# XENON1T + relic

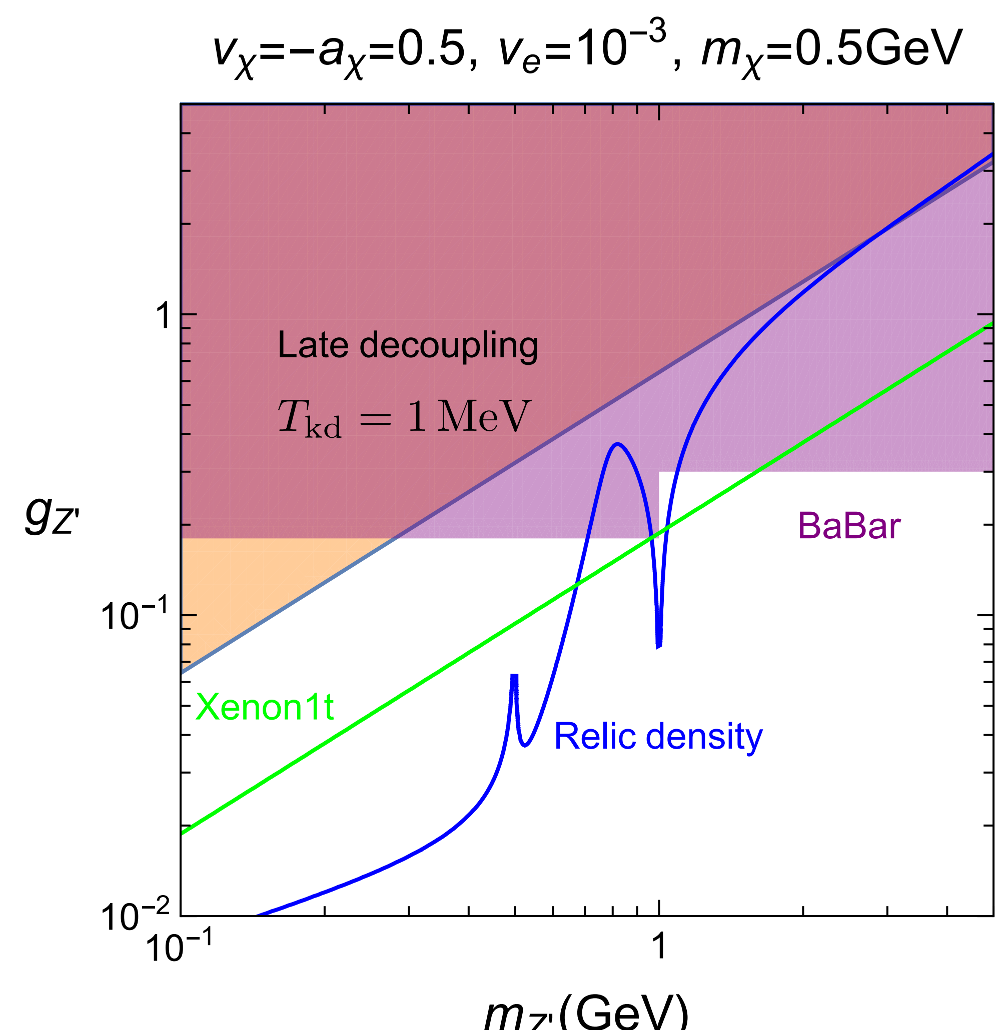


- Electron couplings are constrained by visible/invisible searches at BaBar, beam dump, meson decays, Belle-2.

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

- DM relic density & decoupling condition can be satisfied.




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

# Pseudo-Dirac dark matter



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

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

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

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

"Technically natural splitting" $\quad \Delta m = 4|y_1|v_\phi = 2.5\,\mathrm{keV}$

→ 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 for ExoDM



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

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

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

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

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

- Completely safe from diffuse X-ray bounds.

- ExoDM 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 lifetime bound.

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

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

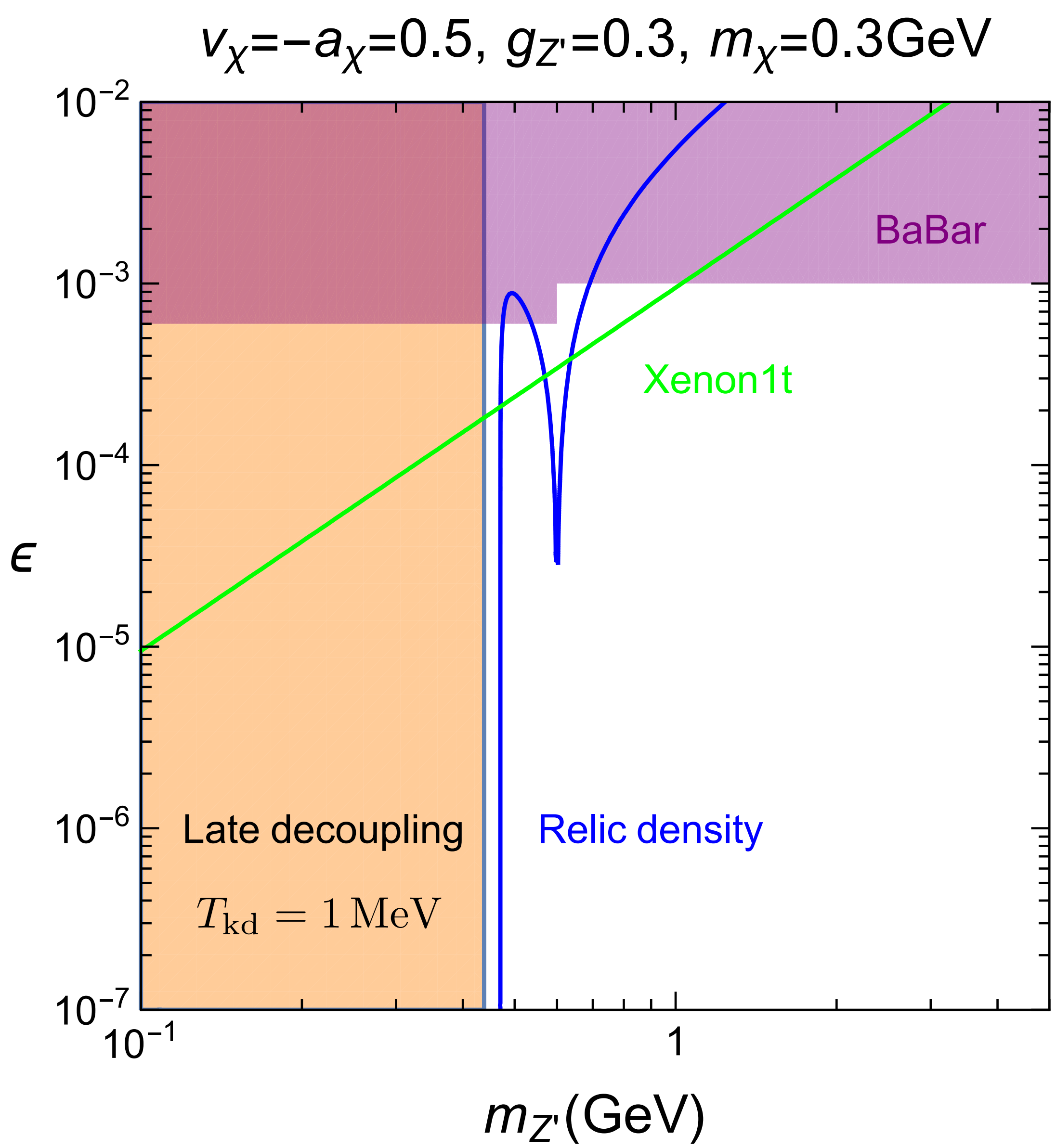
$m_{f_1} \sim m_e$, $M_E \gtrsim 100\,{\rm GeV}$ : $\theta_R \lesssim \sqrt{\frac{m_e}{M_E}} \lesssim 2.2 \times 10^{-3}$,

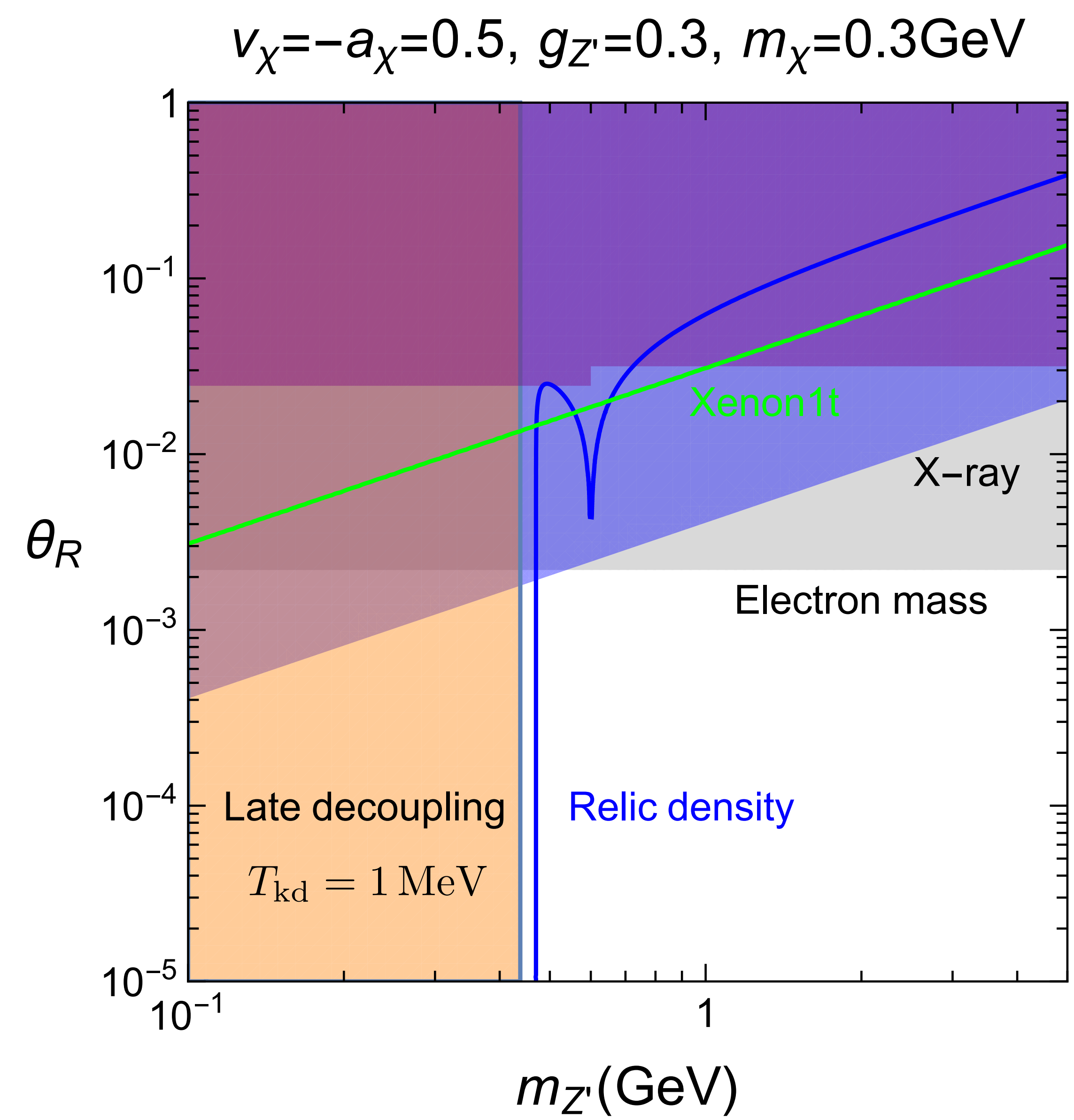
Z'-DM int: $v_e = a_e = -\theta_R^2, \quad v_\nu = a_\nu = 0.$

# Portals & XENON1T



- Z' portal is consistent with Xenon1t excess; VL portal is highly constrained by X-ray bounds.



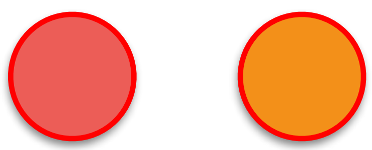
# Dark mesons

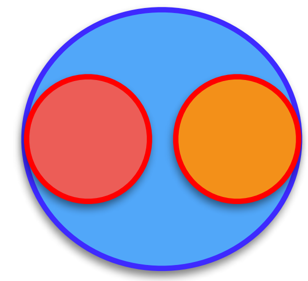


Dark light fermions
$G = SU(N_f)_L \times SU(N_f)_R$

→ Condensate in dark QCD $\langle \bar{q} q \rangle = \mu^3 \neq 0$ →

Dark mesons
$H = SU(N_f)_V$ flavor sym.





$N_f = 3:$

$$M_{\rm diag} = {\rm diag}(m'_1, m'_2, m'_3)$$

$$\pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta^0 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta^0 & K^0 \\ K^- & \overline{K^0} & -\frac{2}{\sqrt{6}}\eta^0 \end{pmatrix}$$

Meson masses:

$$\begin{aligned} m^2_{\tilde{\pi}^\pm} &= \mu(m'_1 + m'_2), \\ m^2_{\tilde{K}^\pm} &= \mu(m'_1 + m'_3), \\ m^2_{\tilde{K}^0} &= \mu(m'_2 + m'_3), \end{aligned}$$

$$M_0^2 = \mu \begin{pmatrix} m'_1 + m'_2 & \frac{1}{\sqrt{3}}(m'_1 - m'_2) \\ \frac{1}{\sqrt{3}}(m'_1 - m'_2) & \frac{1}{3}(m'_1 + m'_2 + 4m'_3) \end{pmatrix}$$

$\tilde{\pi}^0, \tilde{\eta}^0$ mix

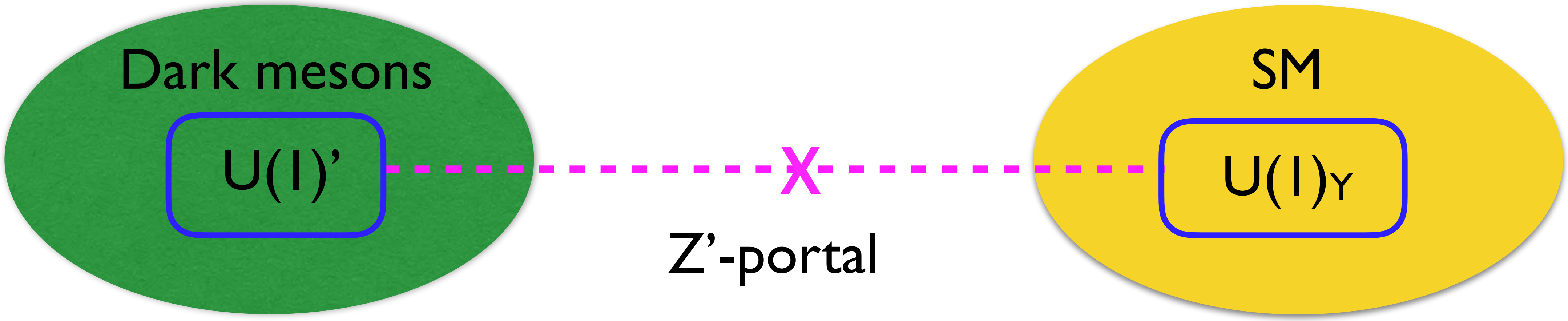
$SU(3)_V$ dark flavor symmetry: $m'_1 = m'_2 = m'_3$

→ $m^2_\pi = 2\mu m'_1$ : common masses for dark mesons

Stability of dark mesons

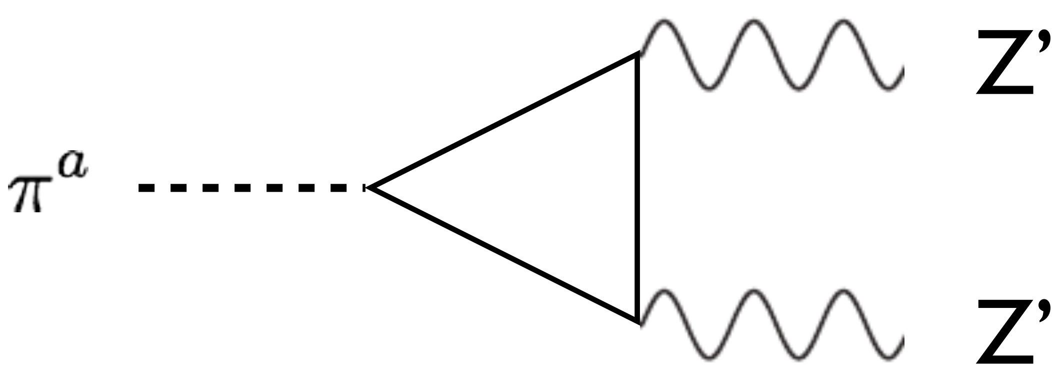
# Z'-portal for dark mesons





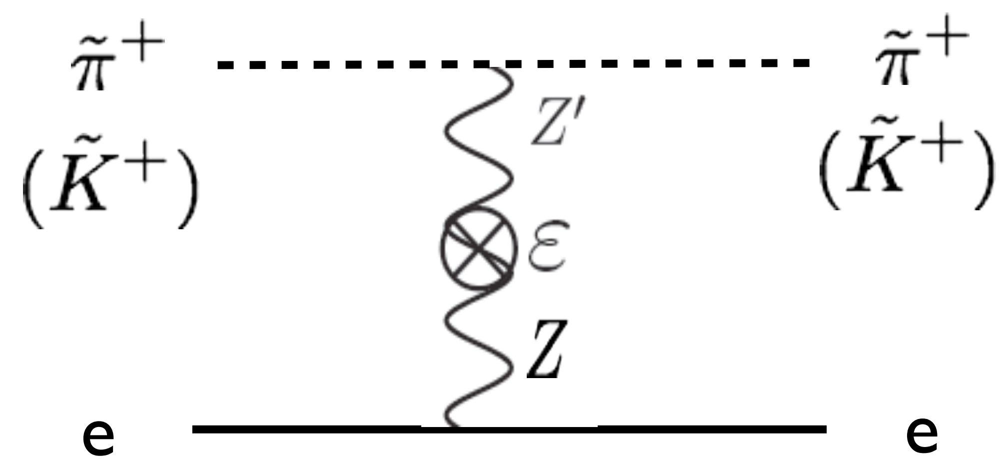

- Z' with no dark chiral anomalies ensure stable mesons.

[HML, M. Seo, 2015]




$$\propto \mathrm{Tr}(Q'^2 T^a) = 0$$

$$Q' = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$




$$\mathcal{L}_{\rm mix} = -\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} F^{\mu\nu}$$

- Kinetic equilibrium: $|\varepsilon| g_{Z'} \gtrsim 1.1 \times 10^{-8} \left(\frac{m_{Z'}}{1\,{\rm GeV}}\right)^2 \left(\frac{x_f}{15}\right)^3 \left(\frac{300\,{\rm MeV}}{m_\pi}\right)^{3/2}$

# Split masses for dark mesons



- Mass splitting due to flavor mixing [S.Choi, HML, B. Zhu, to appear]

Mixings due to broken U(1)'

$$\mathcal{L}_{\rm mix} = -y_{12}\,\phi\,\bar{u}'d' - y_{13}\,\phi\,\bar{u}'s' - {\rm h.c.}$$

$$\longrightarrow \quad M = \begin{pmatrix} m_1 & \epsilon & \epsilon' \\ \epsilon & m_1 & 0 \\ \epsilon' & 0 & m_1 \end{pmatrix}$$

$$m_\pi^2 \equiv 2\mu m_1$$

$$\Delta m \equiv \mu\sqrt{\epsilon^2+\epsilon'^2}/m_\pi$$

$$\left\{ \begin{array}{lcl} m^2_{\tilde{\pi}^\pm} & = & m_\pi^2, \\ m^2_{\tilde{\pi}^0} & = & m_\pi^2\Big(1-\frac{2\Delta m}{\sqrt{3}m_\pi}\Big), \end{array} \right.$$

$$m^2_{\tilde{K}^\pm} = m_\pi^2\Big(1-\frac{\Delta m}{m_\pi}\Big), \quad m^2_{\tilde{K}^0} = m_\pi^2\Big(1+\frac{\Delta m}{m_\pi}\Big), \quad m^2_{\tilde{\eta}^0} = m_\pi^2\Big(1+\frac{2\Delta m}{\sqrt{3}m_\pi}\Big)$$

**Meson mass splitting:** $m_{\tilde{K}^0} - m_{\tilde{K}^\pm} \simeq \Delta m\,, \quad m_{\tilde{\pi}^\pm} - m_{\tilde{\pi}^0} \simeq \frac{1}{\sqrt{3}}\,\Delta m.$

- Mass corrections due to Z'

$$m^2_{K_{1,2}} = m^2_{\tilde{\pi}} - \delta \pm \sqrt{\delta^2 + m^2_{\tilde{\pi}}(\Delta m)^2}$$

$$\delta = c\, g^2_{Z'} f^2_\pi \quad , \; c \sim \frac{1}{16\pi^2}\,\frac{\mu^2}{m^2_{Z'}}$$

$$\begin{array}{lcl} m^2_{\tilde{\pi}^0} & = & m^2_{\tilde{\pi}}\Big(1-\frac{2\Delta m}{\sqrt{3}m_{\tilde{\pi}}}\Big) - 2\delta, \\ m^2_{\tilde{\pi}^1} & = & m^2_{\tilde{\pi}}, \\ m^2_{\tilde{\pi}^2} & = & m^2_{\tilde{\pi}} - 2\delta. \end{array}$$

Negligible Z' corrections for $m_{Z'} \gtrsim 0.6\mu\left(\frac{g_{Z'}}{0.01}\right)\left(\frac{0.2}{m_{\tilde{\pi}}/f_\pi}\right)\left(\frac{m_{\tilde{\pi}}/100\,{\rm MeV}}{\Delta m/4\,{\rm keV}}\right)^{1/2}$

# Exothermic dark mesons

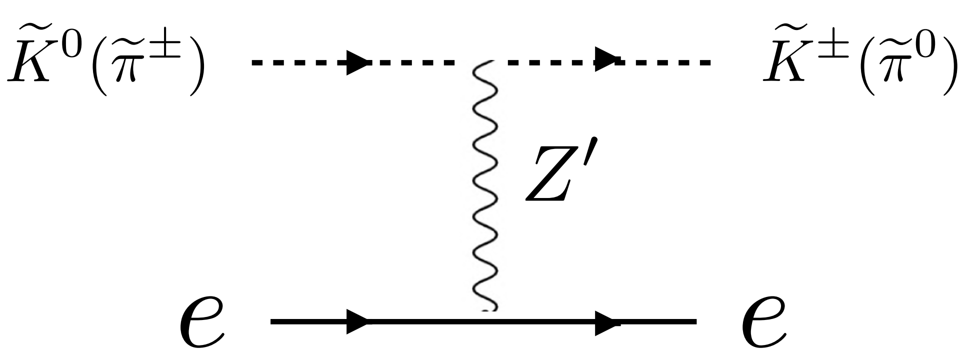


- Non-universal dark U(1)': $[Q', M] \neq 0$

$$\mathcal{L}_{Z',2\pi} = 2ig_{Z'}Z'_\mu\Big(K^+\partial^\mu K^- - K^-\partial^\mu K^+ + \pi^+\partial^\mu\pi^- - \pi^-\partial^\mu\pi^+\Big) + 4g_{Z'}^2 Z'_\mu Z'^\mu(K^+K^- + \pi^+\pi^-).$$

Flavor mixing

$$\mathcal{L}_{Z',\mathrm{int}} = ig_{Z'}Z'_\mu\Big[(\widetilde{K}^0+\widetilde{K}^+)\partial^\mu(\overline{\widetilde{K}^0}+\widetilde{K}^-) - (\overline{\widetilde{K}^0}+\widetilde{K}^-)\partial^\mu(\widetilde{K}^0+\widetilde{K}^+) + \sqrt{2}(\widetilde{\pi}^- - \widetilde{\pi}^+)\partial^\mu\widetilde{\pi}^0 - \sqrt{2}\widetilde{\pi}^0\partial^\mu(\widetilde{\pi}^- - \widetilde{\pi}^+)\Big] + g_{Z'}^2 Z'_\mu Z'^\mu\Big[2(\widetilde{K}^0+\widetilde{K}^+)(\overline{\widetilde{K}^0}+\widetilde{K}^-) + 2(\widetilde{\pi}^0)^2 - (\widetilde{\pi}^- - \widetilde{\pi}^+)^2\Big]$$




Meson-changing Z' interactions

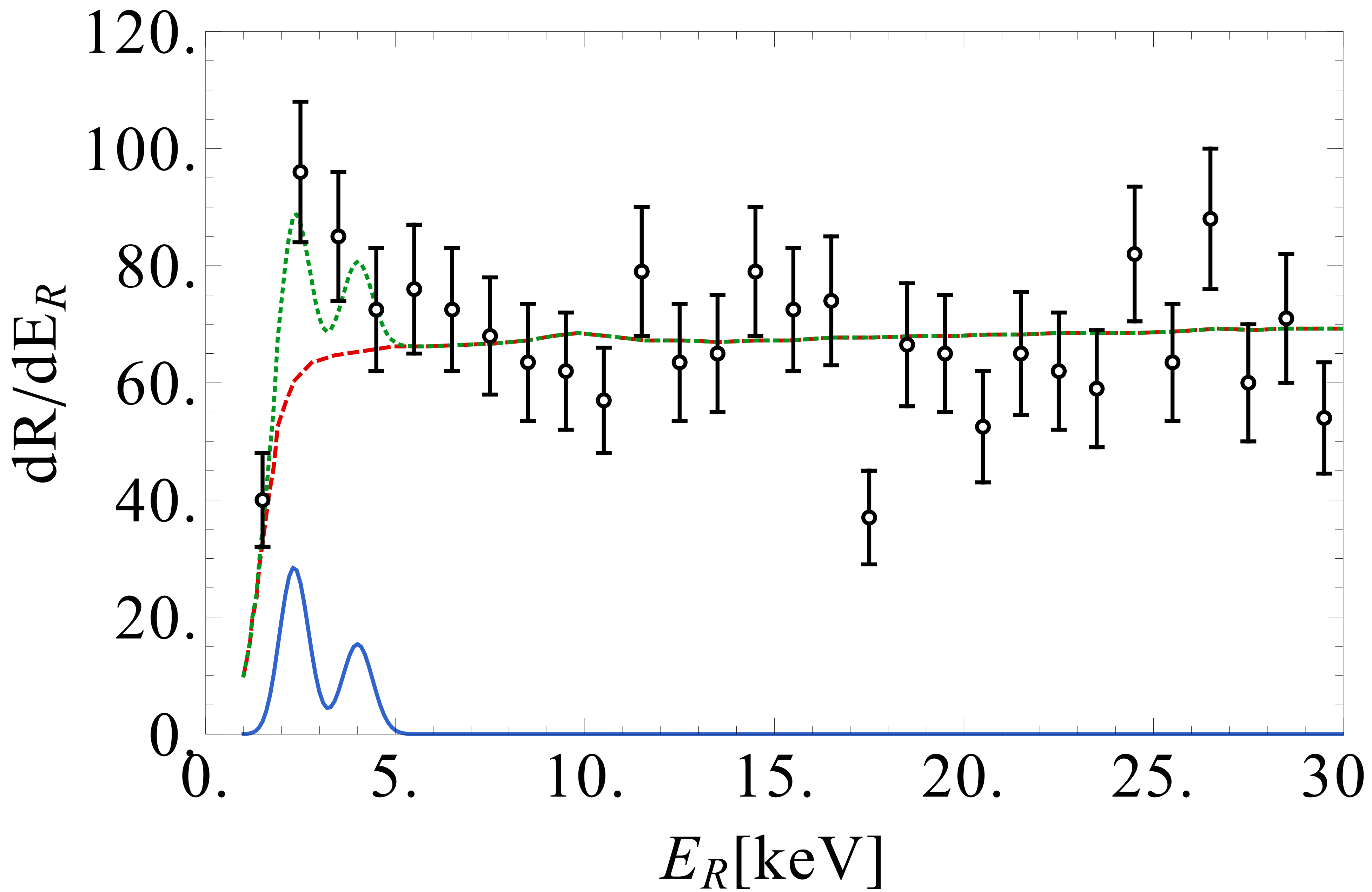
Exothermic DM-e scattering

[S.Choi, HML, B. Zhu, to appear]

# Double peaks in electron $E_R$

[S.Choi, HML, B. Zhu, to appear]

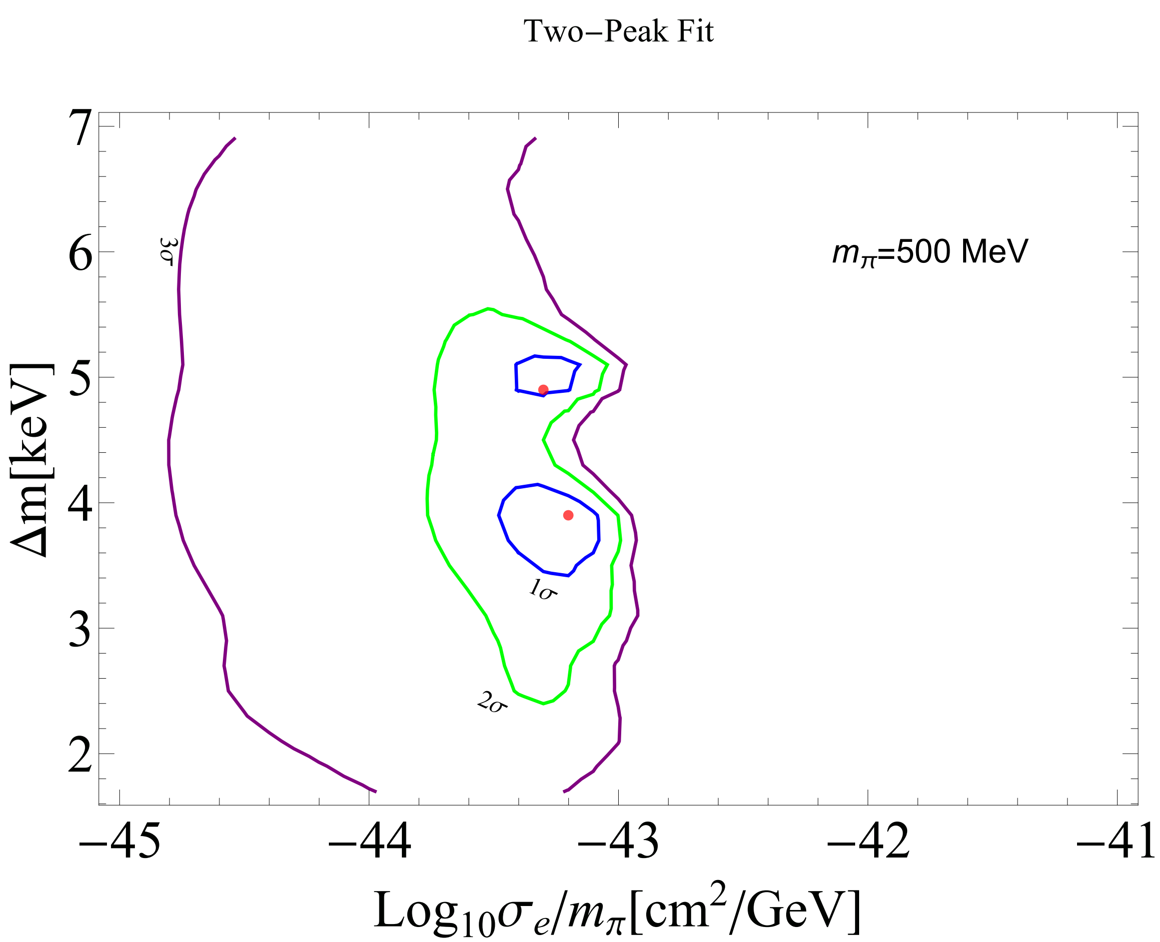


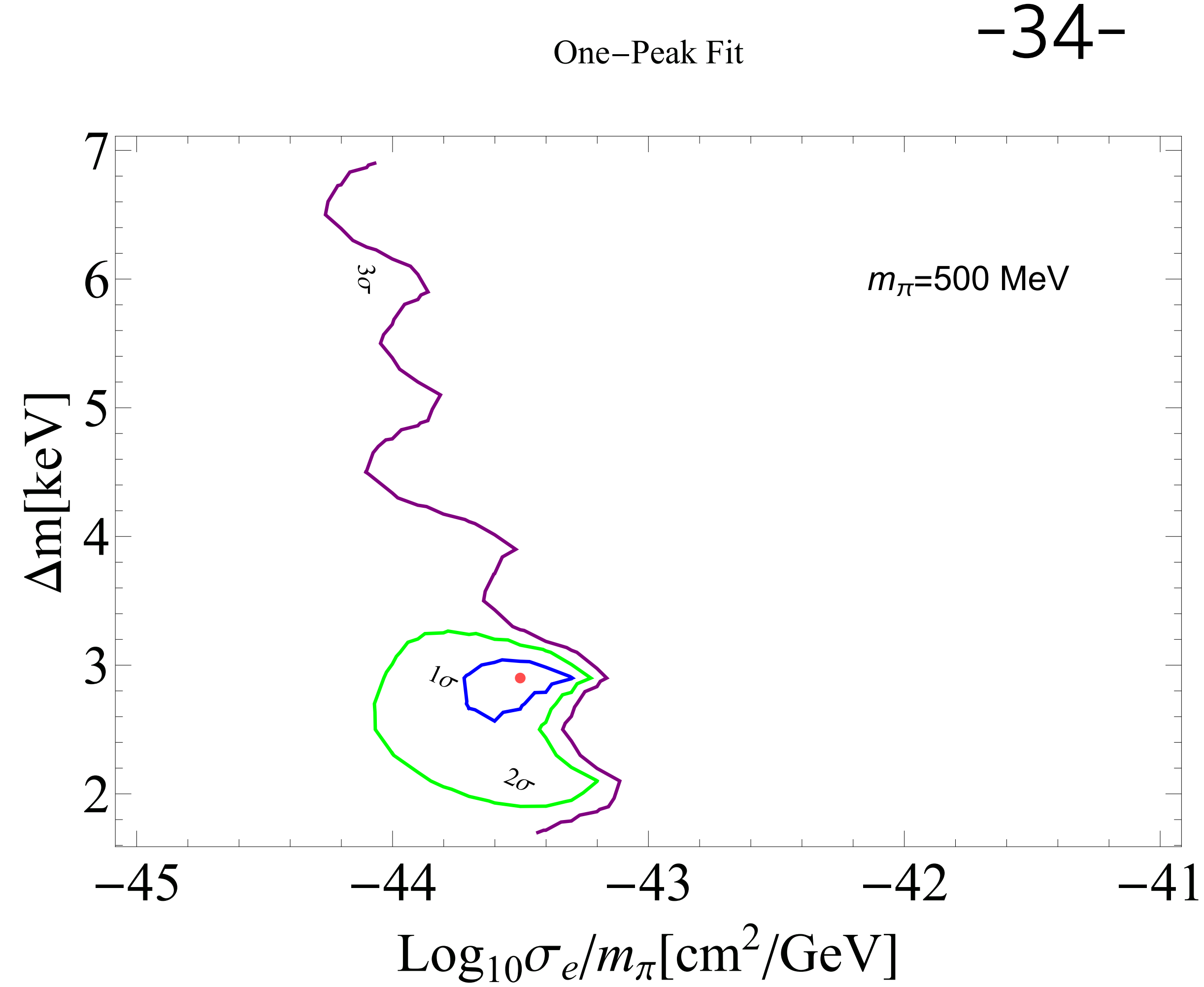



$$m_{\widetilde{\pi}^{\pm}} - m_{\widetilde{\pi}^{0}} = \Delta m = 2.3\,\mathrm{keV}, \qquad m_{\widetilde{K}^{0}} - m_{\widetilde{K}^{\pm}} = \sqrt{3}\Delta m = 4.0\,\mathrm{keV}.$$

# Double peaks vs single peak






[S.Choi, HML, B. Zhu, to appear]

Double-peak best-fit:

$$[\Delta m = 3.9\,\mathrm{keV},\ \bar{\sigma}_e/m_{\tilde{\pi}} = 2\times 10^{-43}\,\mathrm{cm}^2/\mathrm{GeV}],$$

$$\chi^2_{\rm min} = 1.48$$

One-peak best-fit:

$$[\Delta m = 2.9\,\mathrm{keV}, \bar{\sigma}_e/m_{\tilde{\pi}} = 1.3\times 10^{-43}\,\mathrm{cm}^2/\mathrm{GeV}]$$

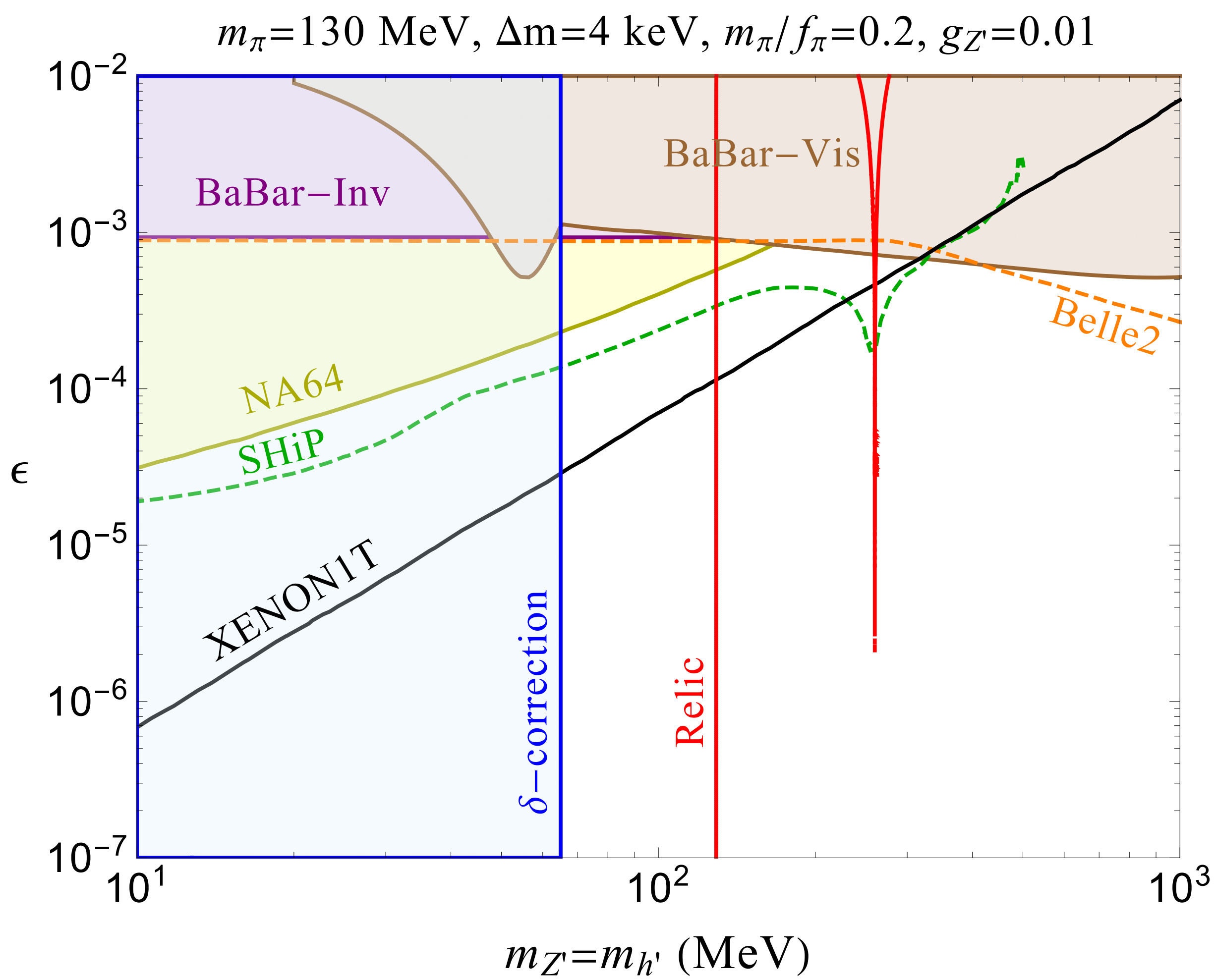
$$\chi^2_{\rm min} = 2.43$$

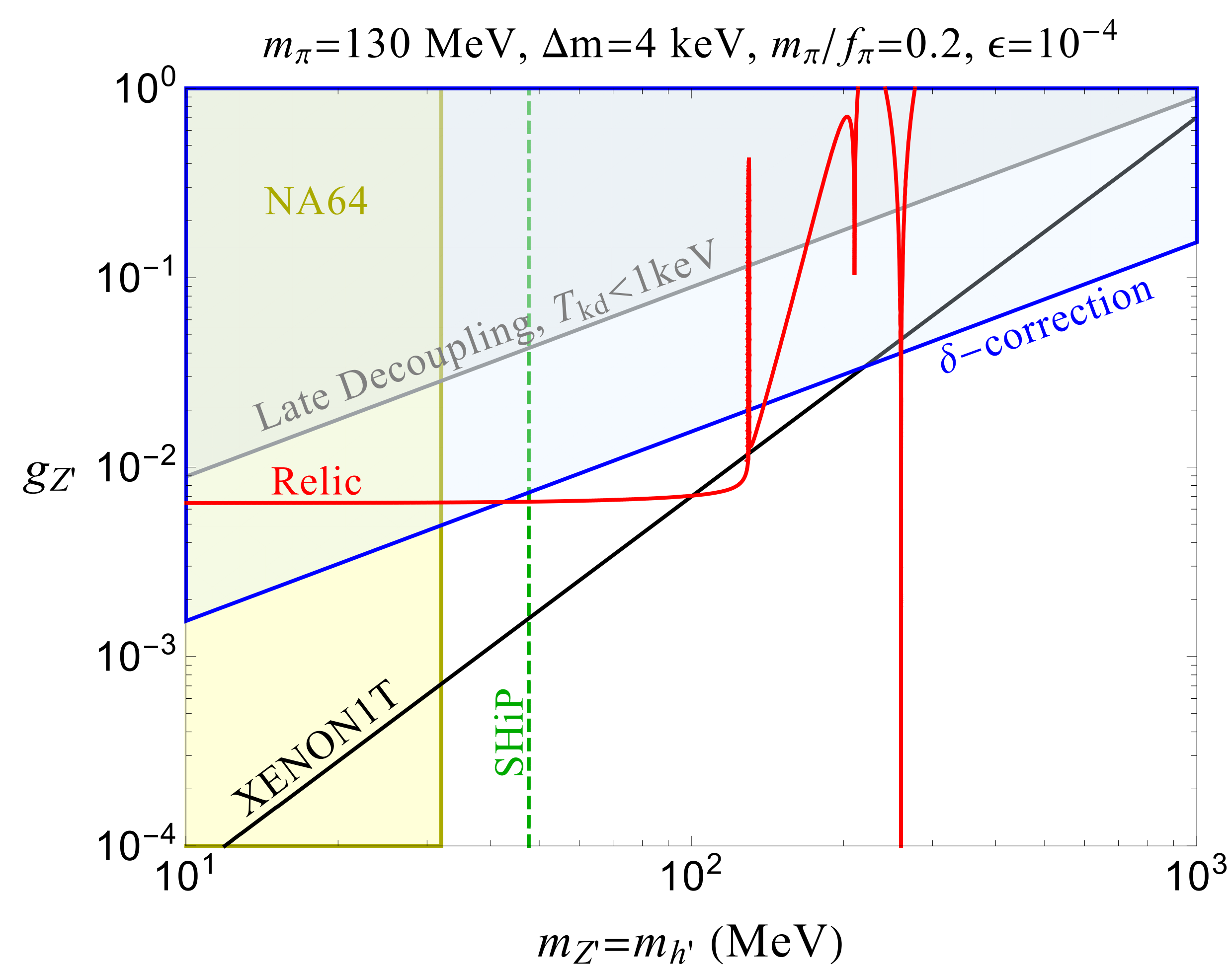
→ Double-peak case fits better than one-peak case.

# Dark mesons & XENON1T



- Strong bounds from late decoupling & Z' mass corrections => new light fermions, protection symmetry?
- Resonance and forbidden regions can be searched for in intensity & beam dump experiments.



# Conclusions



- The Xenon electron excess can be explained by down-scattering of exothermic dark matter for standard halo model.
- Light dark matter and mediator favored by Xenon excess can have large self-scattering cross section to solve small-scale problems.
- Pseudo-Dirac dark fermion are natural candidates for exothermic dark matter with Z' portal and self-interacting with velocity dependence.
- Dark mesons with approximate flavor symmetry lead to testable signatures with two peaks in electron recoil energy and fit better to Xenon excess.