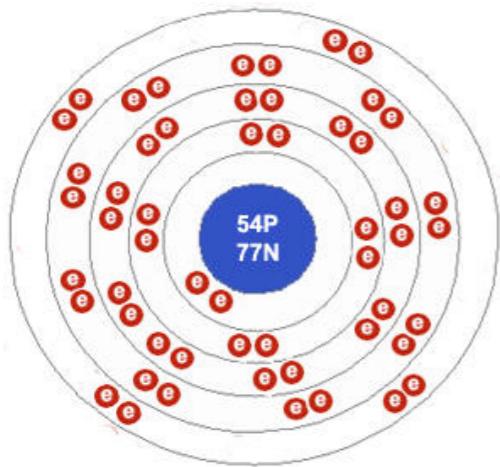


**APCTP Workshop
on Particle Physics
Phenomenology**
Nov 14, 2020

Exothermic self-interacting dark matter



Hyun Min Lee
Chung-Ang University

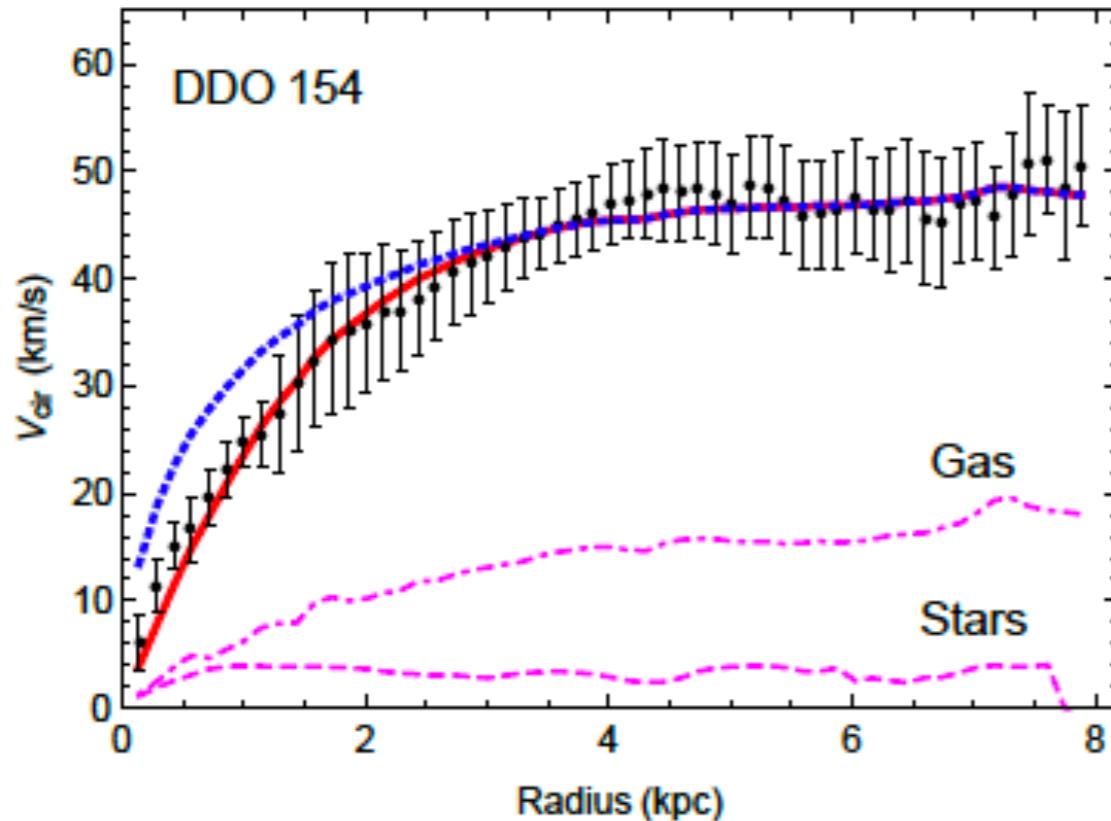


Based on HML, 2006.I3I83 ;
S.-M. Choi, HML, B. Zhu, to appear.

Outline

- Introduction
- Exothermic dark matter
- Microscopic models
- Conclusions

Core-Cusp problem



Circular velocities:

$$v_{\text{cir}} \sim \sqrt{r}, \quad \rho_{\text{dm}} \sim r^{-1} \quad \text{“Cuspy”}$$

$$v_{\text{cir}} \sim r, \quad \rho_{\text{dm}} \sim r^0 \quad \text{“Cored”}$$

Overshoot at < kpc

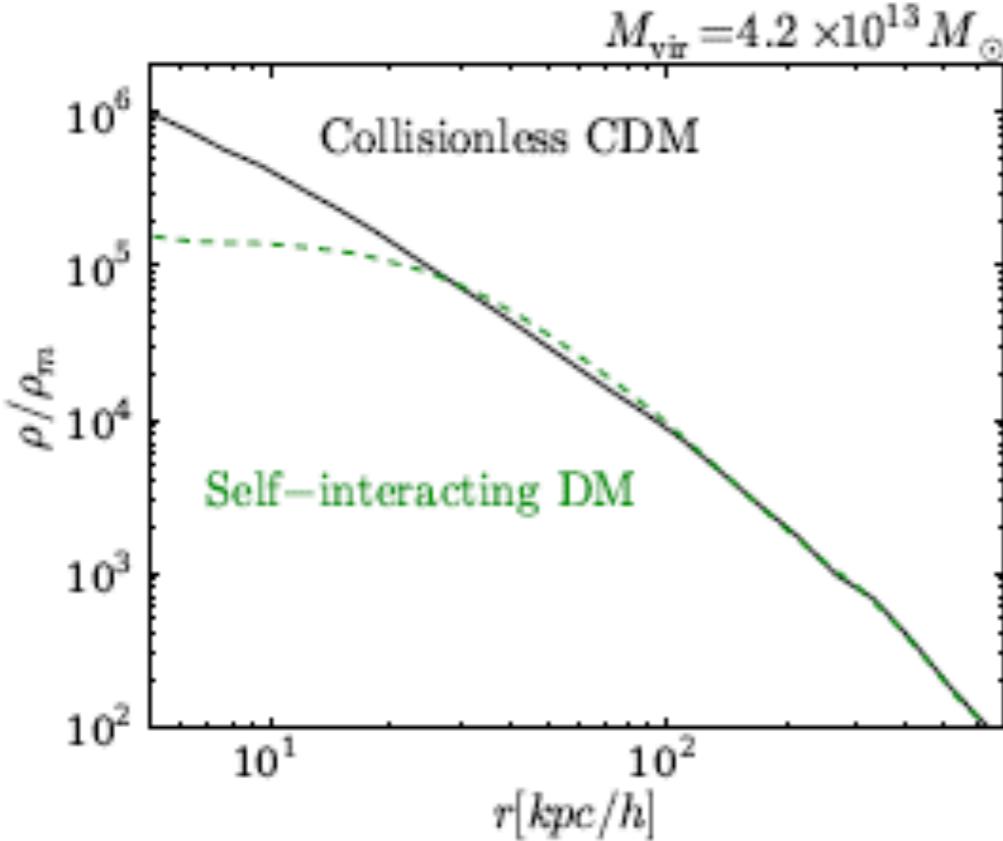
[Spergel, Steinhardt, 2000; Tulin, Yu, 2017]

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

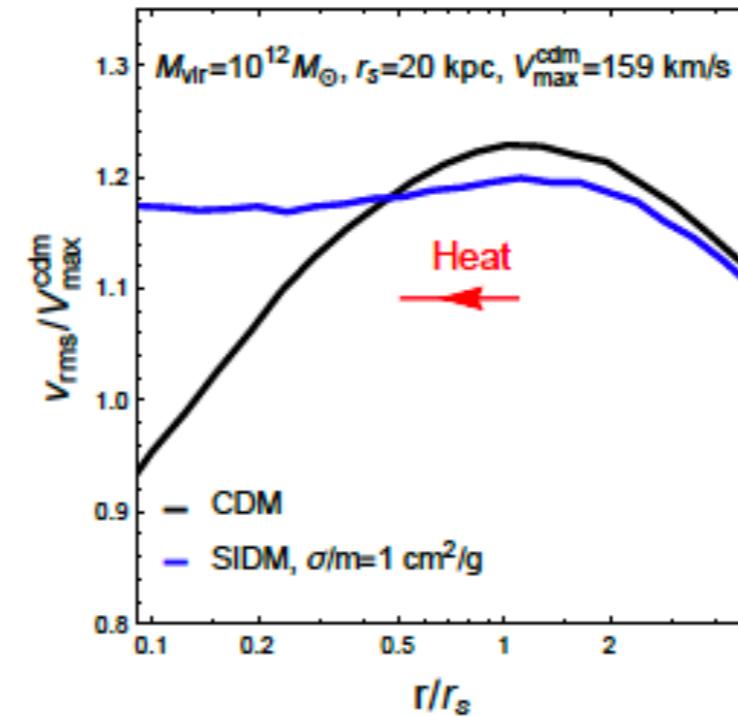
cf. Too-big-to-fail, Diversities for the same halo mass.

Self-Interacting dark matter

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[Weinberg et al, 2013]



[Tulin, Yu, 2017]

Self-interactions transport heat from outside to the core.

→ Flattening the inner DM profile. cf. Baryons (SN feedback).

Self-Interacting cross section:

$$\frac{\sigma_{\text{self}}}{m_{\text{DM}}} \sim 0.1 - 10 \text{ cm}^2/\text{g}$$

→ sub-GeV dark matter favored without a light mediator.

Velocity-dependent SIDM

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Collision rate: $R_{\text{scat}} = \sigma v_{\text{rel}} \rho_{\text{dm}} / m \approx 0.1 \text{ Gyr}^{-1} \times \left(\frac{\rho_{\text{dm}}}{0.1 M_{\odot}/\text{pc}^3} \right) \left(\frac{v_{\text{rel}}}{50 \text{ km/s}} \right) \left(\frac{\sigma/m}{1 \text{ cm}^2/\text{g}} \right)$

- Bullet cluster shows no DM self-interactions. $\sigma/m \lesssim 0.7 \text{ cm}^2/\text{g}$
- DM self-interaction may be velocity-dependent.

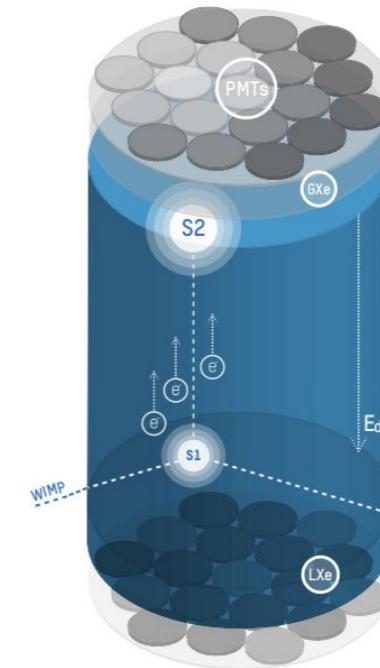
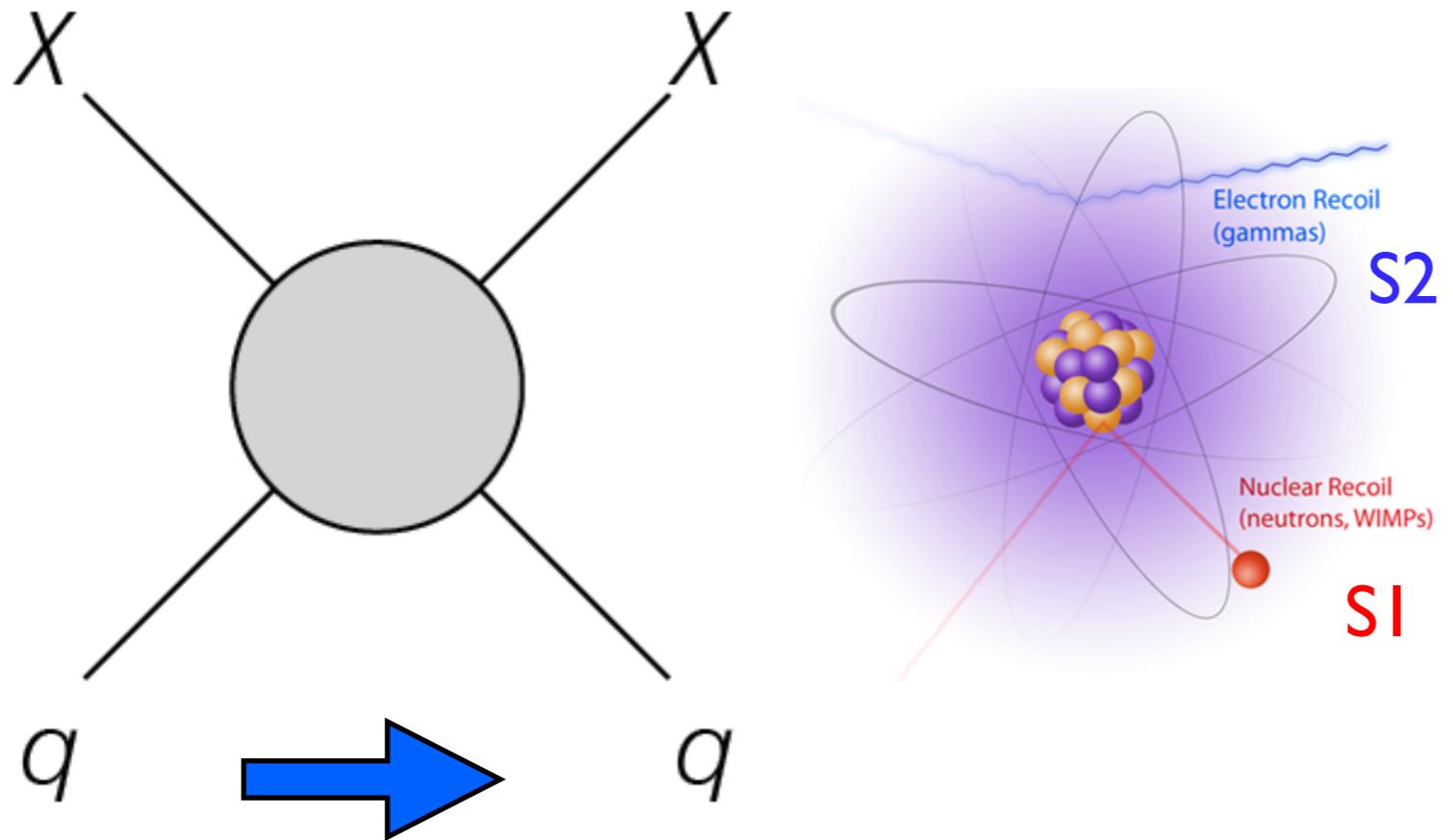
THINGS dwarf galaxies (red), LSB galaxies (blue), and clusters (green).

SIDMN-body simulations, with $\sigma/m = 1 \text{ cm}^2/\text{g}$ (gray)

[M. Kaplinghat et al, 2015]

Dark matter detection

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e.g. XENON1T

SI: Scintillation
(photons)

S2: Ionization
(electrons)

WIMP:

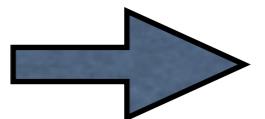
$$SI/S2 \gg (SI/S2)_\gamma$$

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

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

Light dark matter such as SIDM

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



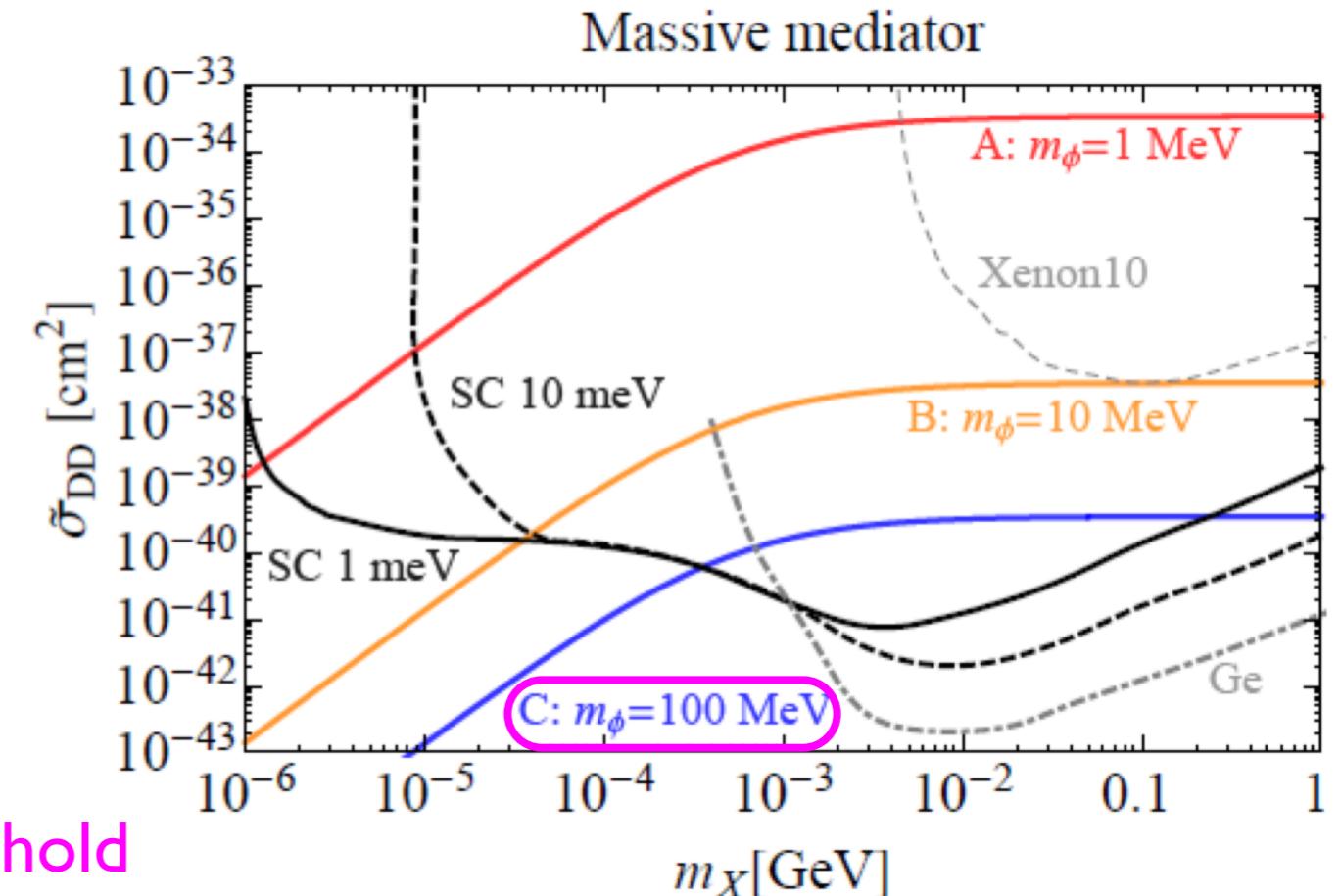
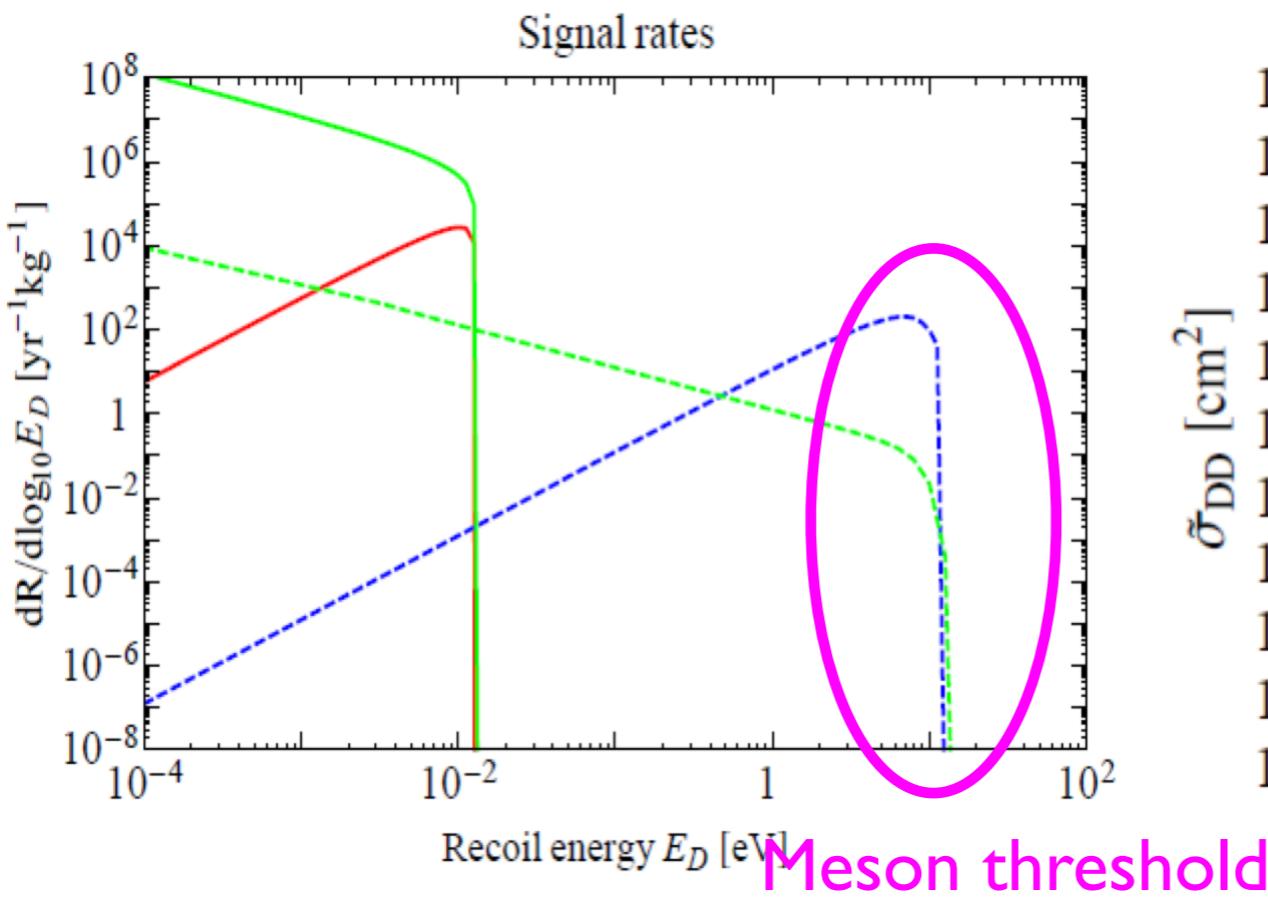
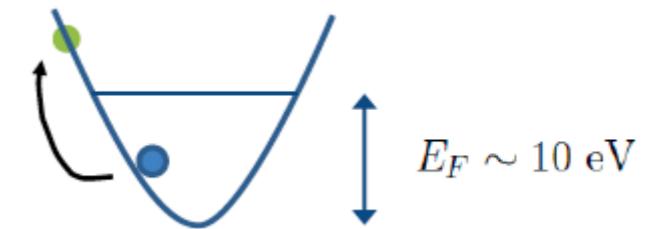
Too small recoil energy below threshold.

Light DM detection

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- DM-nucleon scattering => cryogenic semi-conductors.
e.g. CDMSlite: Ge, $E_{th}=56\text{ eV}$ $\rightarrow m_{\text{DM}} \gtrsim 1.6\text{ GeV}$
- DM-electron scattering (semi-conductor, superconductor)
 $m_{\text{DM}} v^2 \gtrsim \Delta \sim \text{meV}$
 $m_{\text{DM}} \gtrsim m_e : E_R \lesssim 20\text{ eV}$
e.g. Al: $E_F = 11.7\text{ eV}$, $v_{\text{rel}} \sim v_F \sim 10^{-2}$

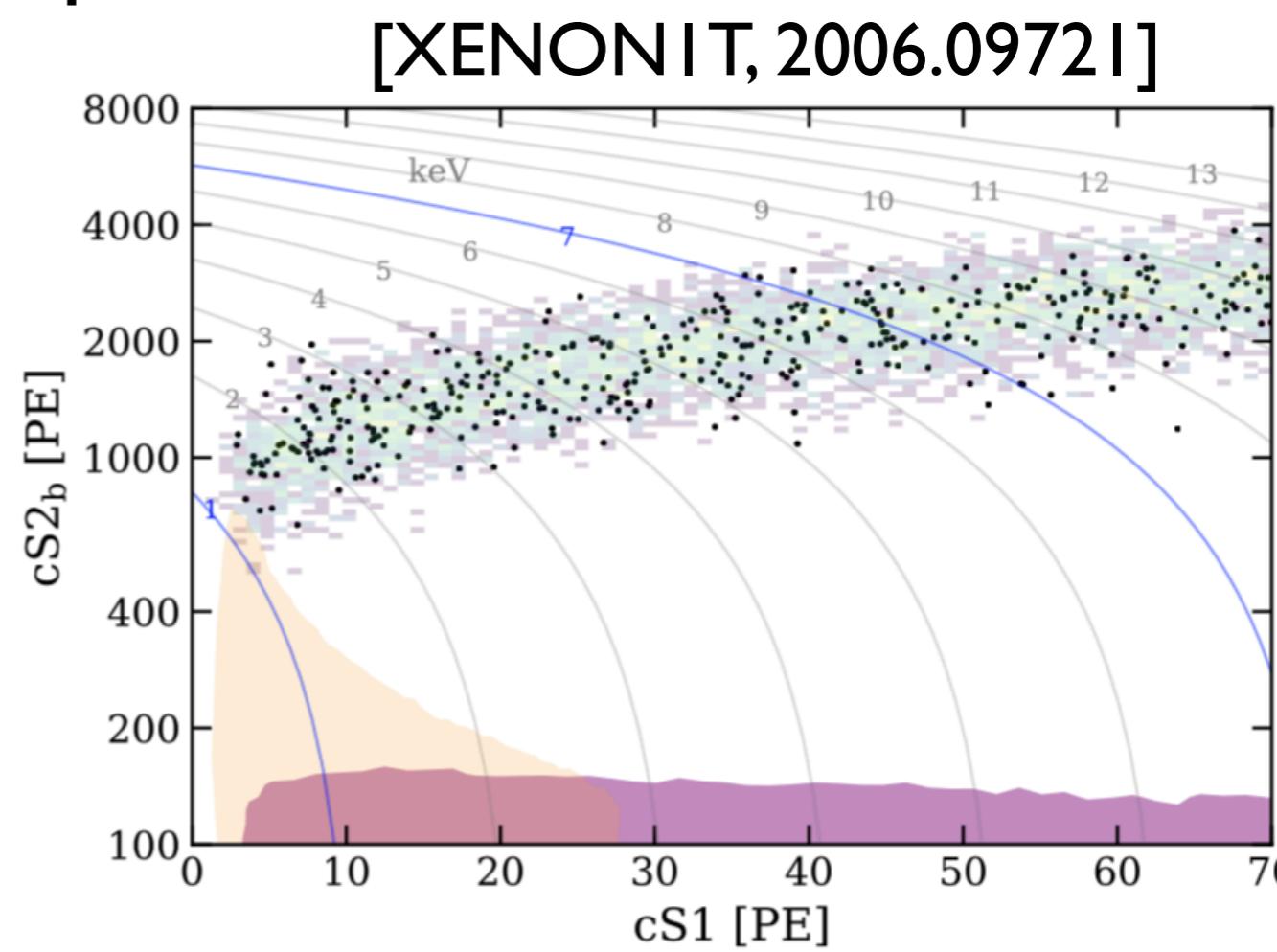
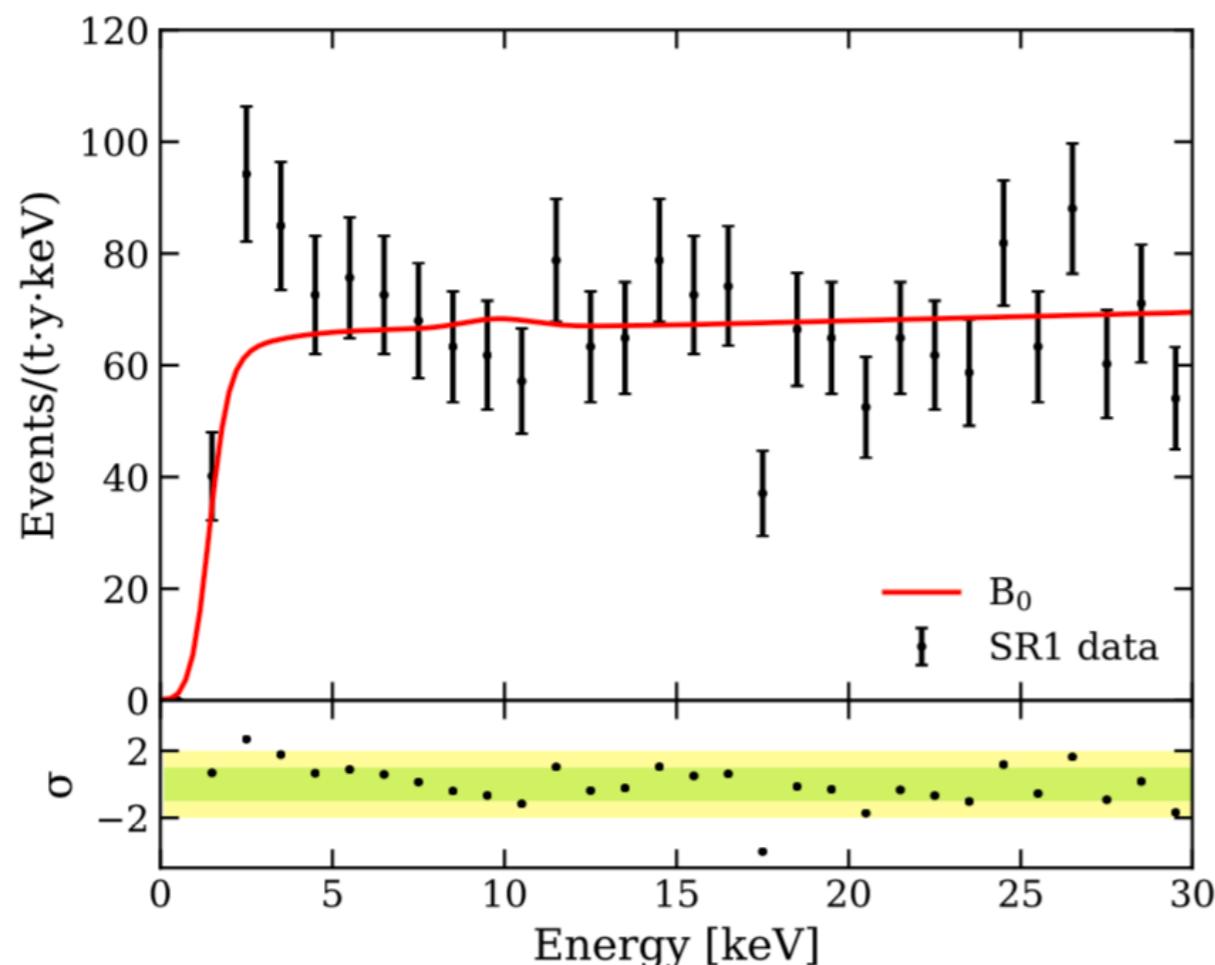
[Hochberg et al (2015)]



XENON1T electron recoil

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- Excess in electron recoil spectrum.



$E_R = 1-7\text{keV}$: 285 events observed,
 232 ± 15 expected



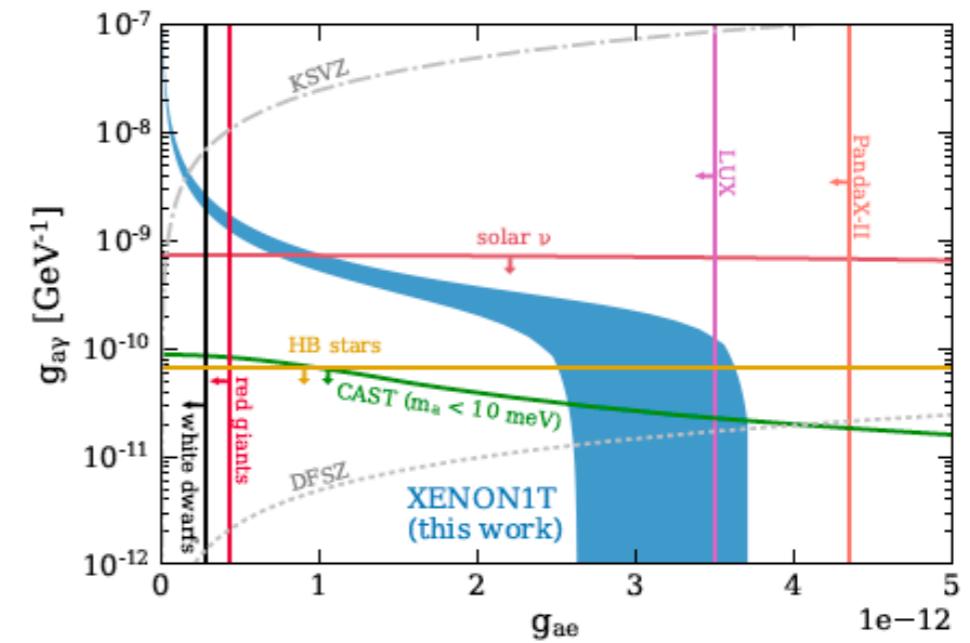
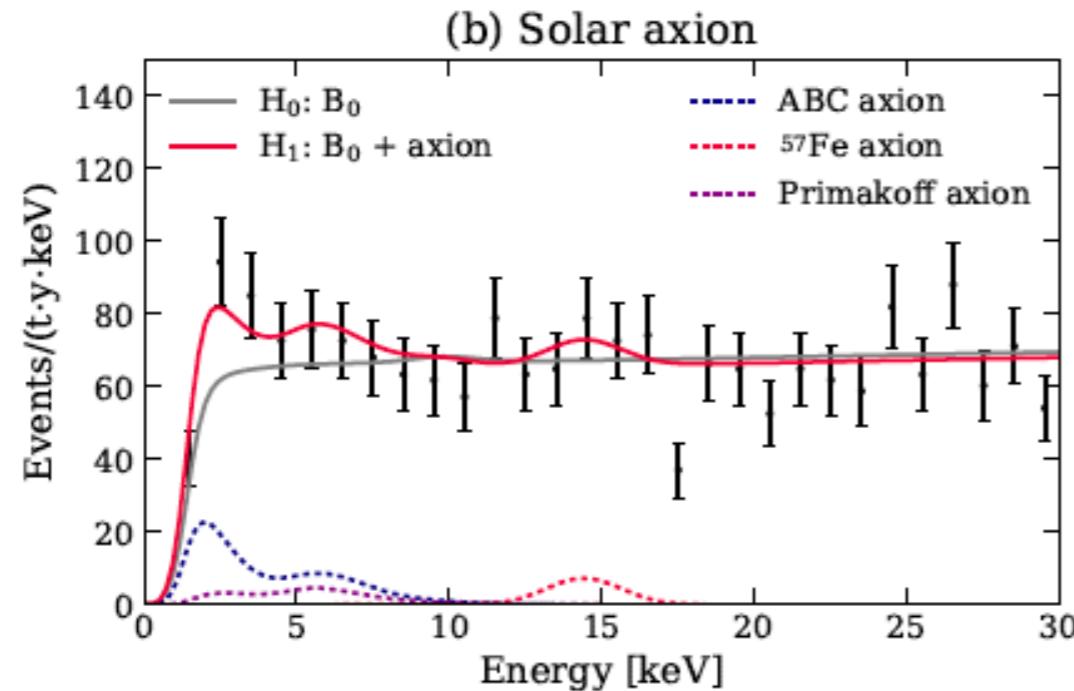
3.3 σ deviation:
most significant at
 $E_R = 2-3\text{keV}$

cf. Other backgrounds: Unknown Tritium, Ar37

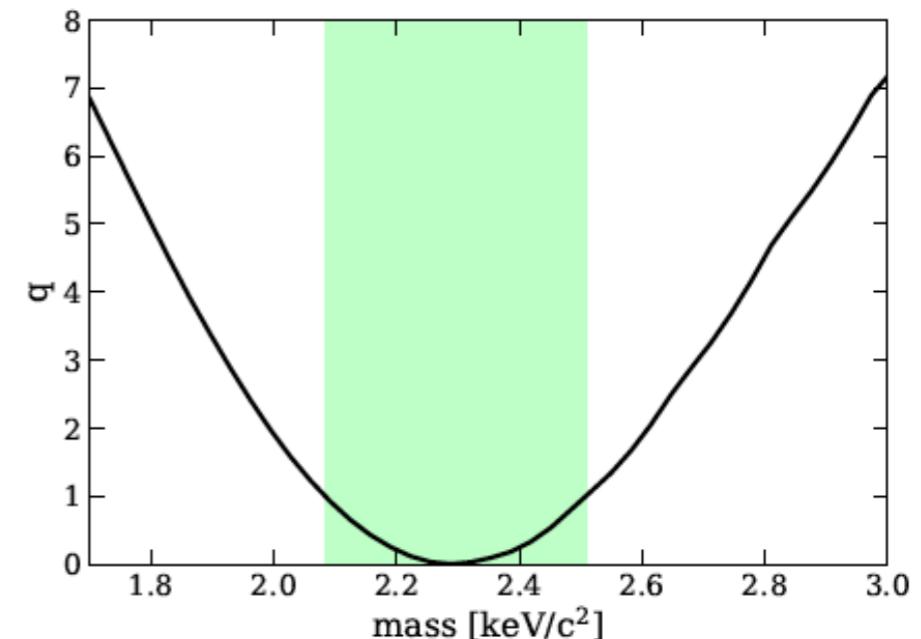
New physics for XeI_T excess

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- Solar axion (or neutrino magnetic dipole moment)
Solar axions produced by ABC, Promakoff, etc, favored at 3.5σ
are absorbed by Xenon atoms.



- keV-scale dark matter
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

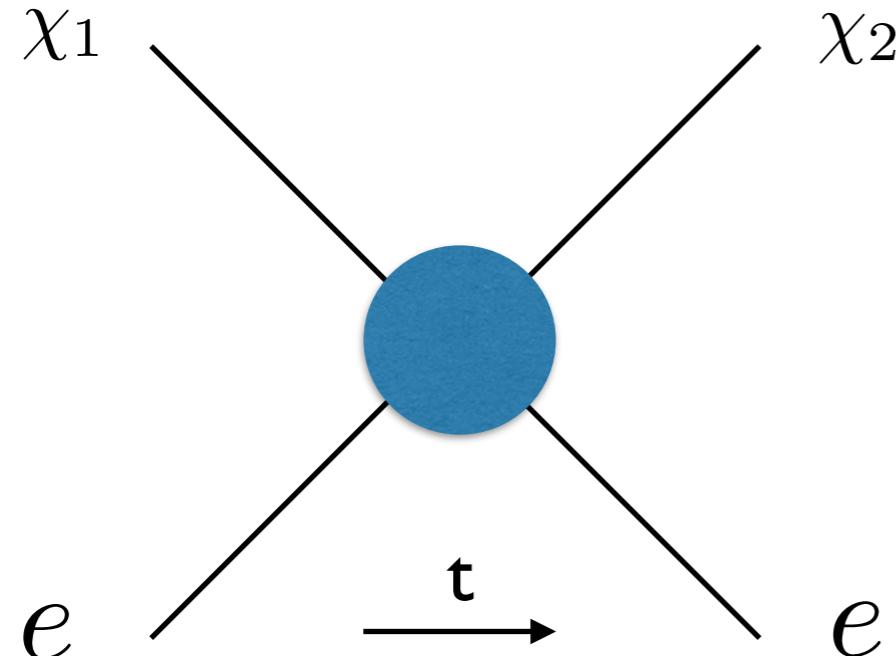
-8-

- Elastic scattering between light DM & electron.

$$E_R \sim \frac{\mu^2 v^2}{m_e} \sim m_e v^2 \sim 0.3 \text{ eV} - 20 \text{ eV} : \text{small recoil energy.}$$
$$m_\chi \gtrsim m_e, \quad v \sim 220 \text{ km/s} - 10^{-2}c$$

- 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:

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

$\rightarrow E_R \sim \Delta m \sim 2.5 \text{ keV}$

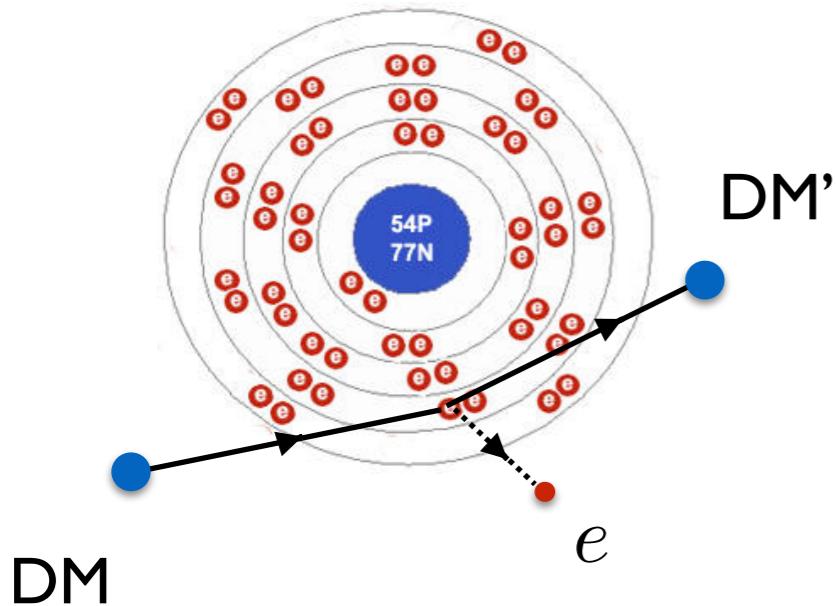
“Exothermic (Exo) dark matter”

Xenon excess is consistent
with standard DM halo model. cf. P. Graham et al; R. Essig et al (2010)

Inside Xenon atoms

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- Electrons are not isolated, bound to Xenon atoms.



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

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

[Essig et al, 2015; HML, 2020]

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

Xenon Binding Energies [eV]				
$n \setminus l$	<i>s</i>	<i>p</i>	<i>d</i>	
<i>O</i>	5	25.7	12.4	–
<i>N</i>	4	213.8	163.5	75.6
<i>M</i>	3	1093.2	958.4	710.7
<i>L</i>	2	5152.19	4837.7	–
<i>K</i>	1	33317.4	–	–

- Nuclear recoil energy:

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

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

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

Exact recoil energy

- Assume no nuclear recoil but electron velocity.

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

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

→ Electron momentum
in CM frame:

$$p_{\text{cm}} = \sqrt{2\mu_2 \left(\Delta m + E_0 + E_e - \frac{p^2}{2M_2} \right)}$$

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:

[HML, 2020]

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

Momentum transfer:

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

Electrons near at rest

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

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

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

$$\Delta m \ll m_e \ll m_{\chi_1},$$

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

Recoil E: $\Delta E_e \simeq \Delta m \left(1 - \frac{2}{\sqrt{\kappa}} \cos \theta \right)$, [HML, 2020]

“Monochromatic”

Momentum transfer:

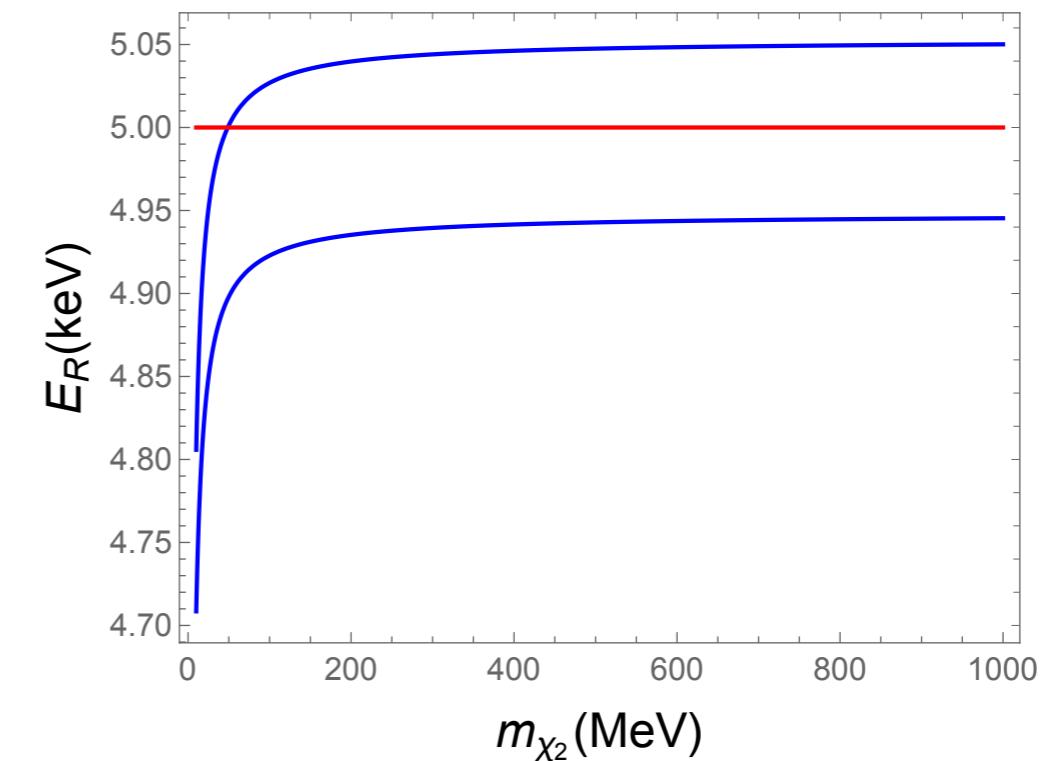
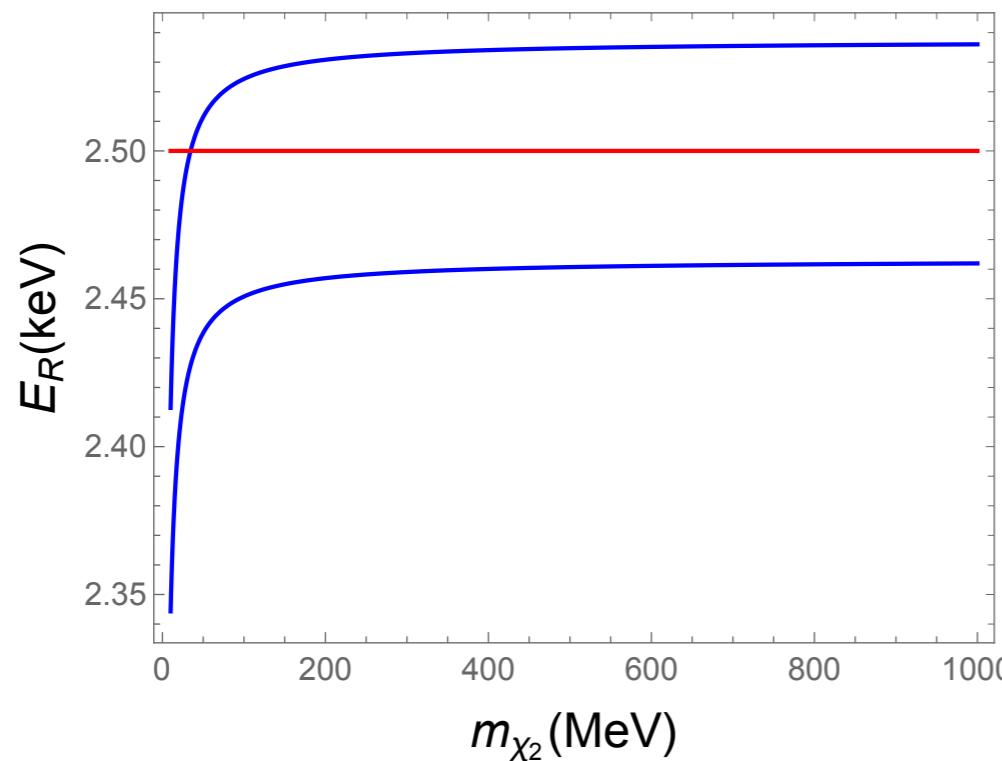
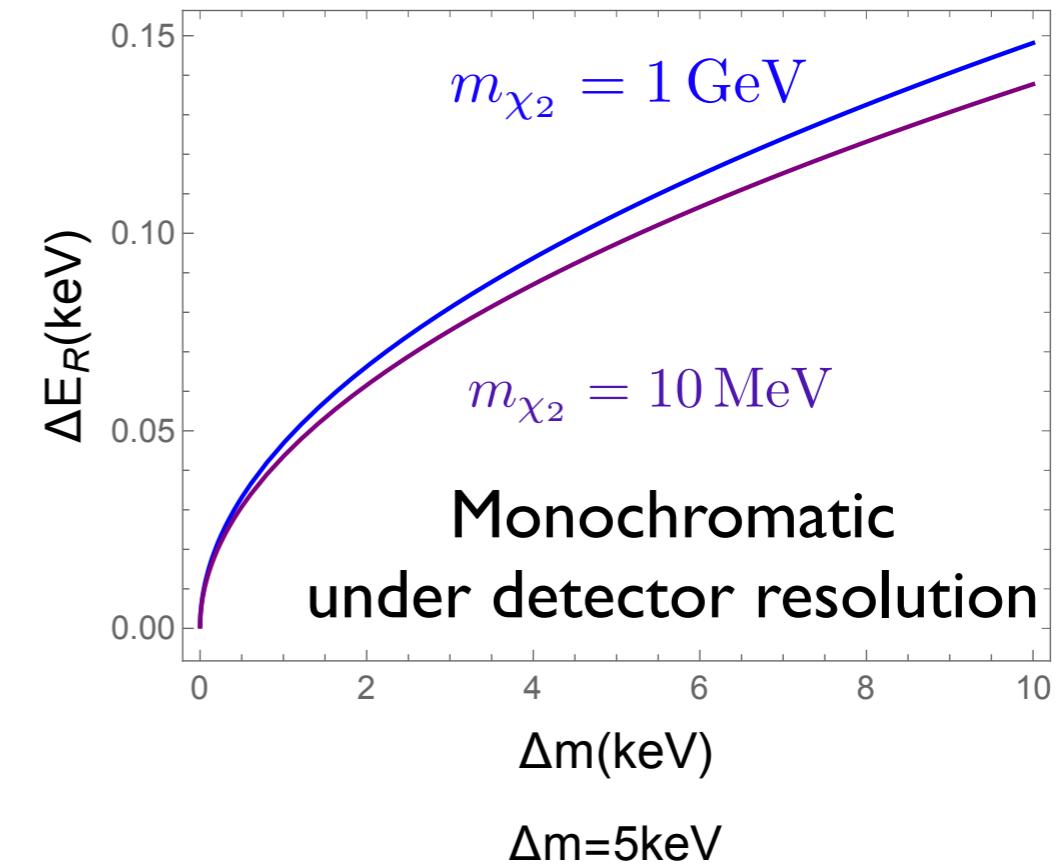
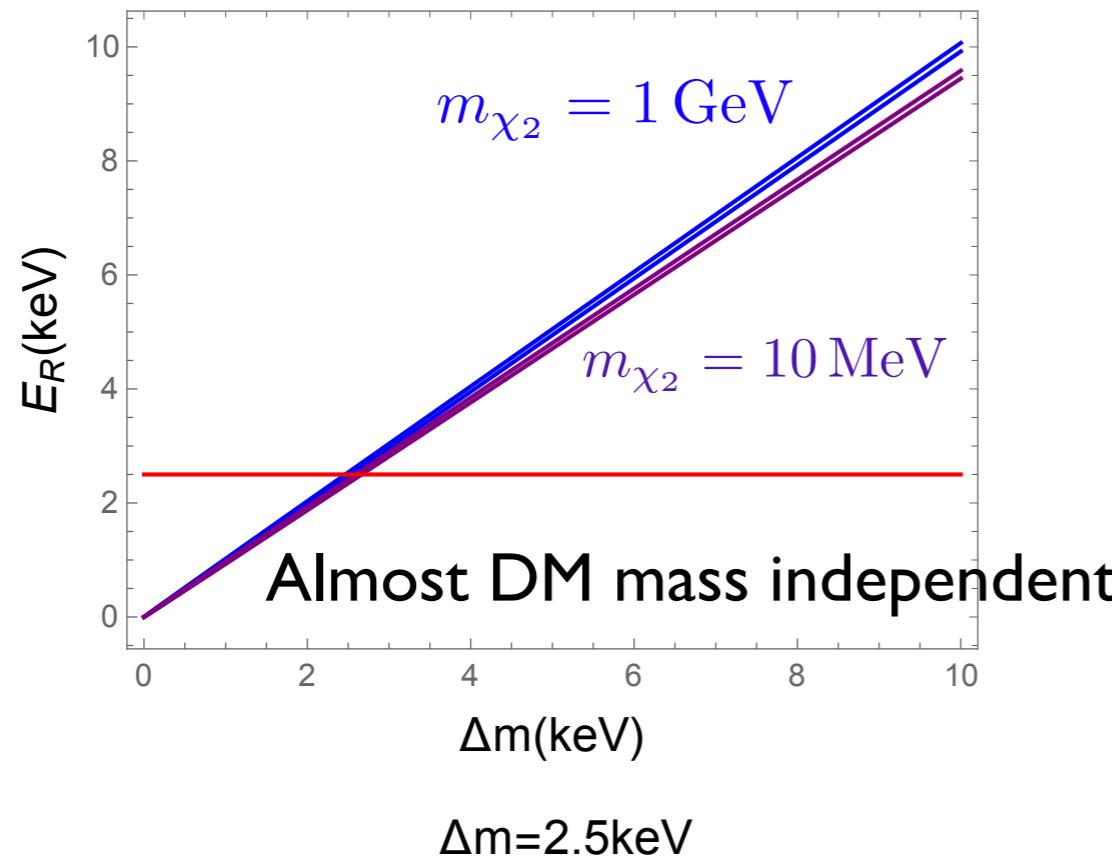
$$q^2 \simeq 2m_e \Delta E_e \simeq 2m_e \Delta m \left(1 - \frac{2}{\sqrt{\kappa}} \cos \theta \right).$$



Mass splitting determines both recoil E & momentum transfer dominantly.

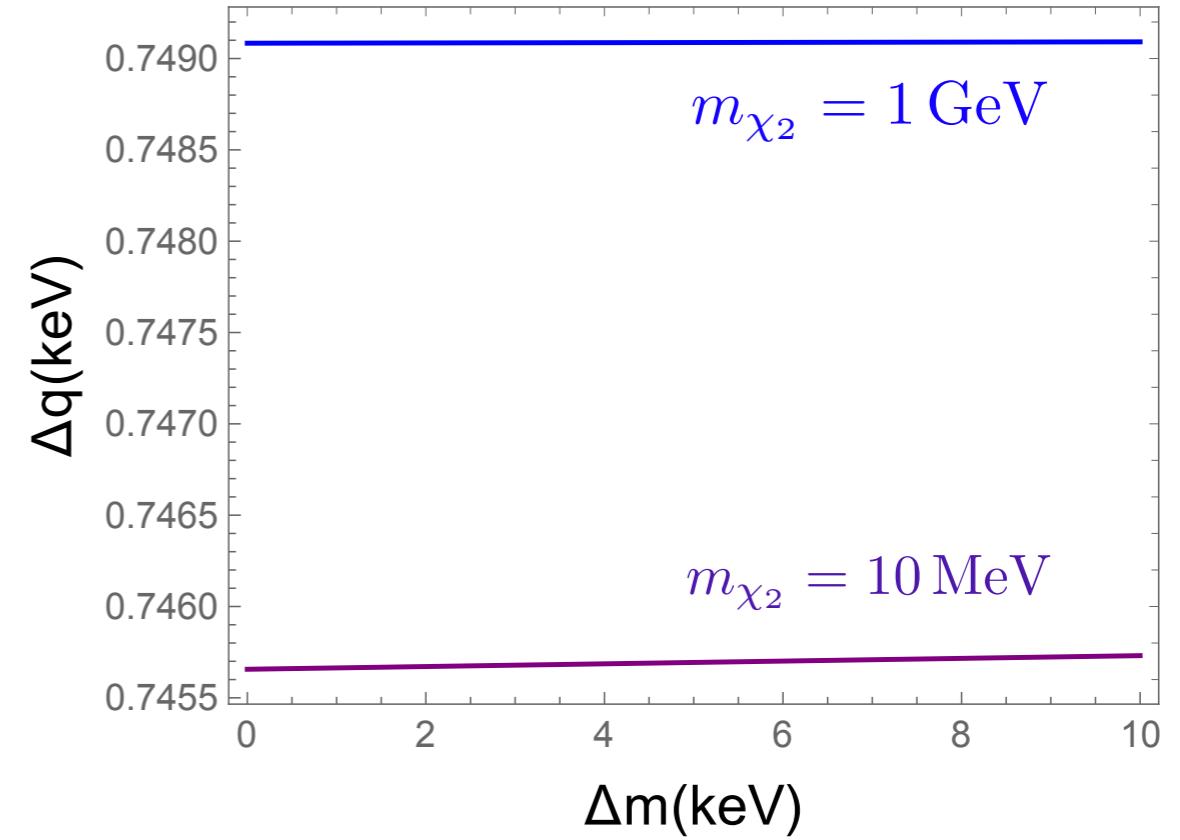
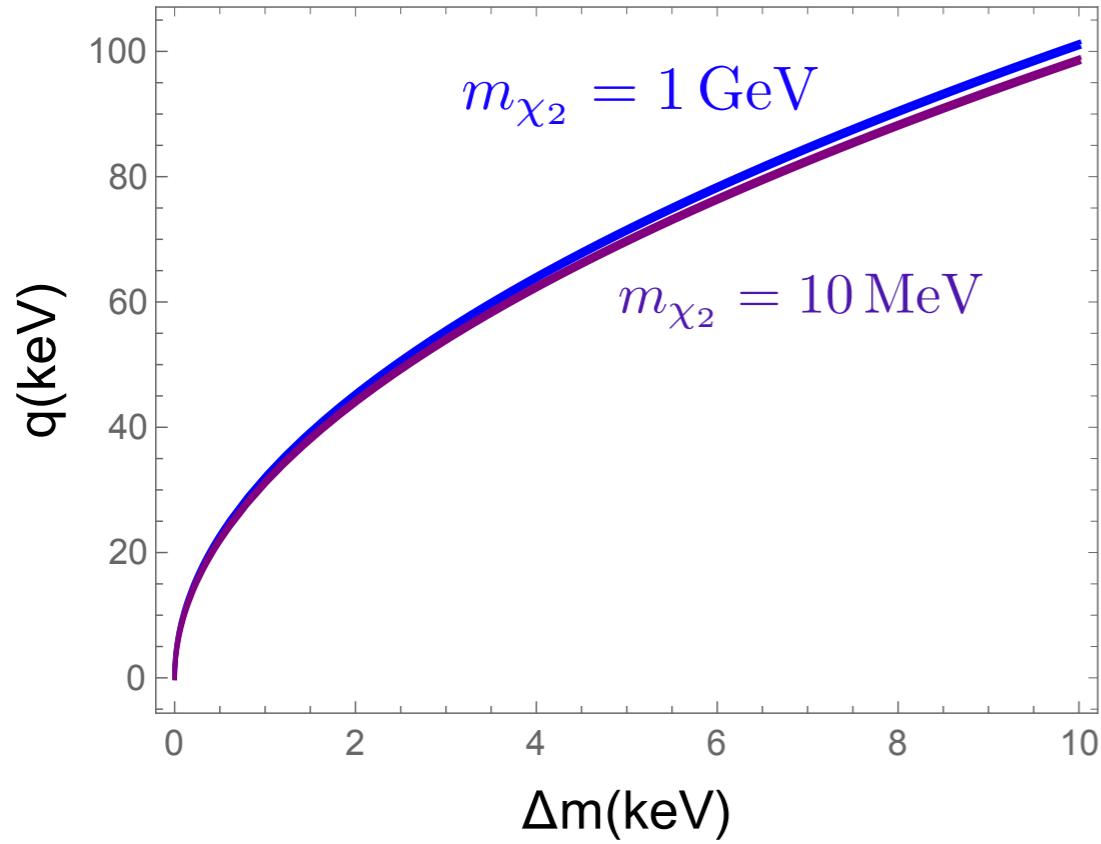
Electron recoil energy

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Momentum transfer

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Momentum transfer is proportional to mass difference with narrow width, being almost independent of DM mass.

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

Moving electrons

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

$$m_{\chi_1} E_0 \lesssim m_e E_e \quad \longrightarrow \quad m_{\chi_1} \lesssim m_e (v_e/v) \sim 10 \text{ MeV}$$

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

$$\Delta m \ll m_e \ll m_{\chi_1},$$

$$\tilde{\kappa} \simeq \frac{\Delta m}{\frac{1}{2} m_e v_e^2} \simeq 10^2 \left(\frac{10^{-2} c}{v_e} \right)^2 \left(\frac{\Delta m}{3 \text{ keV}} \right) \gg 1$$

Recoil E:

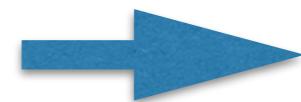
$$\Delta E_e \simeq \Delta m \left(1 - \frac{2m_e}{m_{\chi_1}} \frac{1}{\sqrt{\tilde{\kappa}}} \cos \theta \right)$$

[HML, 2020]

“Monochromatic”

Momentum transfer:

$$q^2 \simeq 2m_e \Delta E_e \simeq 2m_e \Delta m \left(1 - \frac{2m_e}{m_{\chi_1}} \frac{1}{\sqrt{\tilde{\kappa}}} \cos \theta \right)$$



Mass splitting still determines kinematics dominantly

ExoDM event rate

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- The general event rate per target mass is

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

- The total cross section for inelastic scattering:

$$\frac{d\sigma}{dE_R} = \frac{2m_e \bar{\sigma}_e}{q_+^2 - q_-^2} \int_{q_-}^{q_+} a_0^2 q' dq' K(E_R, q') P^2(v), \quad [\text{HML, 2020}]$$

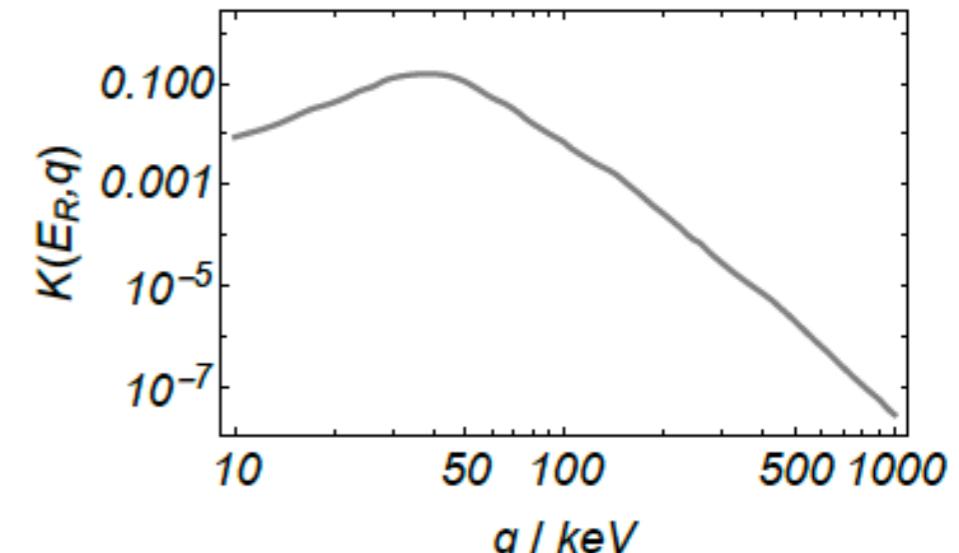
Atomic enhancement factor:

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

Phase space factor:

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

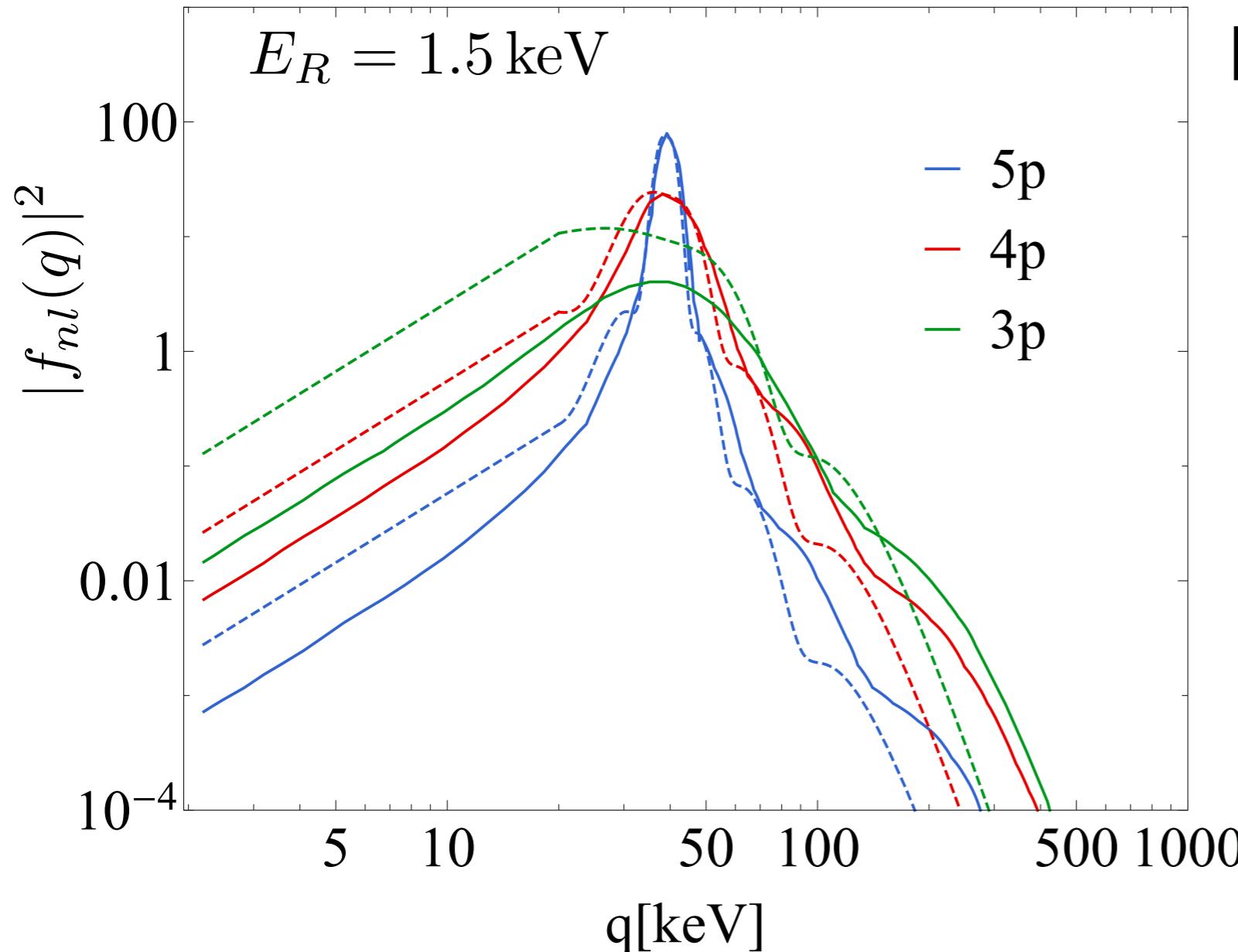
$$E_{\text{cm}} = (m_{\chi_1} + m_e)^2 + m_e m_{\chi_1} v^2$$



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

Atomic form factors

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[Solid: Bloch et al, 2006.I4521;
Dashed: S.Chi, HML, Zhu,
to appear.]

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

Outer-shell electrons are
more easily ionized.

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

ExoDM event rate

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- Differential event rate per target mass:

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

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

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

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

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

$$R_D = M_T \int_{E_T}^{\infty} \frac{dR}{dE_R} dE_R \simeq 50 \left(\frac{M_T}{\text{tonne} - \text{yrs}} \right) \left(\frac{K_{\text{int}}(\Delta m)}{2} \right) \left(\frac{\rho_{\chi_1}}{0.4 \text{ GeV cm}^{-3}} \right)$$

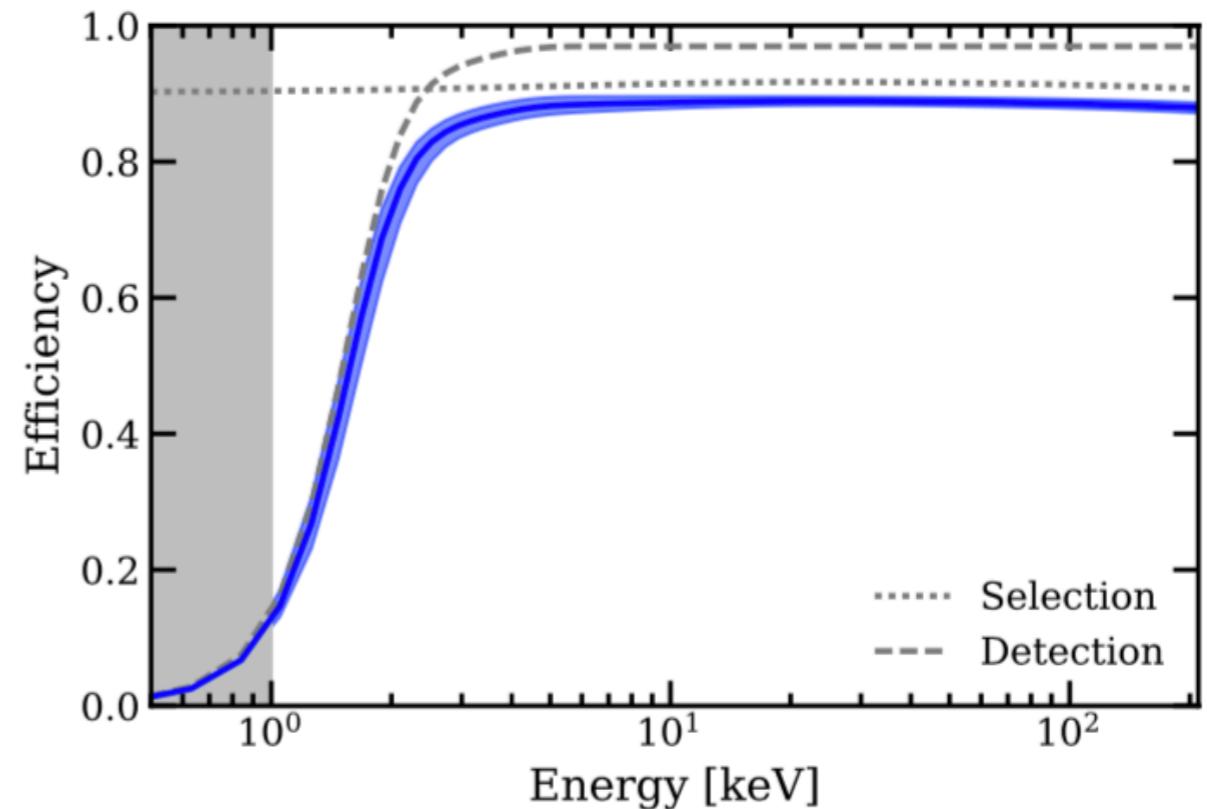
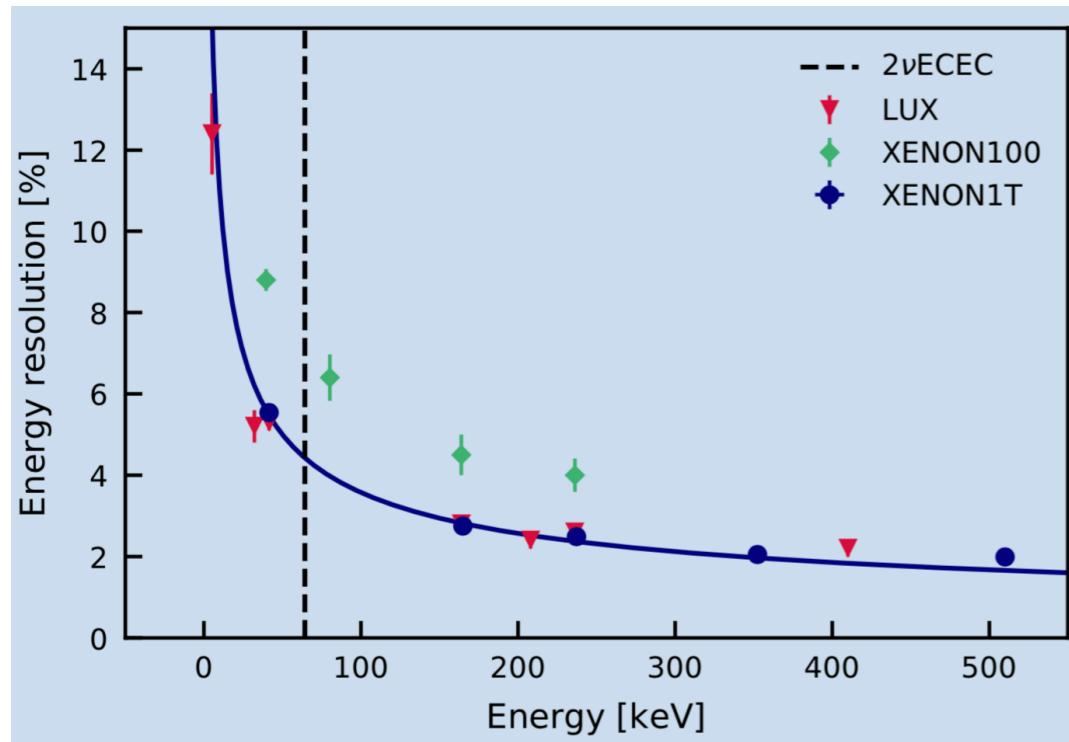
$$\times \left(\frac{\bar{\sigma}_e / m_{\chi_1}}{1.6 \times 10^{-43} \text{ cm}^2/\text{GeV}} \right) \left(\frac{\Delta m}{2.5 \text{ keV}} \right)^{1/2}$$

ExoDM event rate

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- The event is convoluted with detector resolution and efficiency.

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



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

$E_R = 2.5 \text{ keV}$

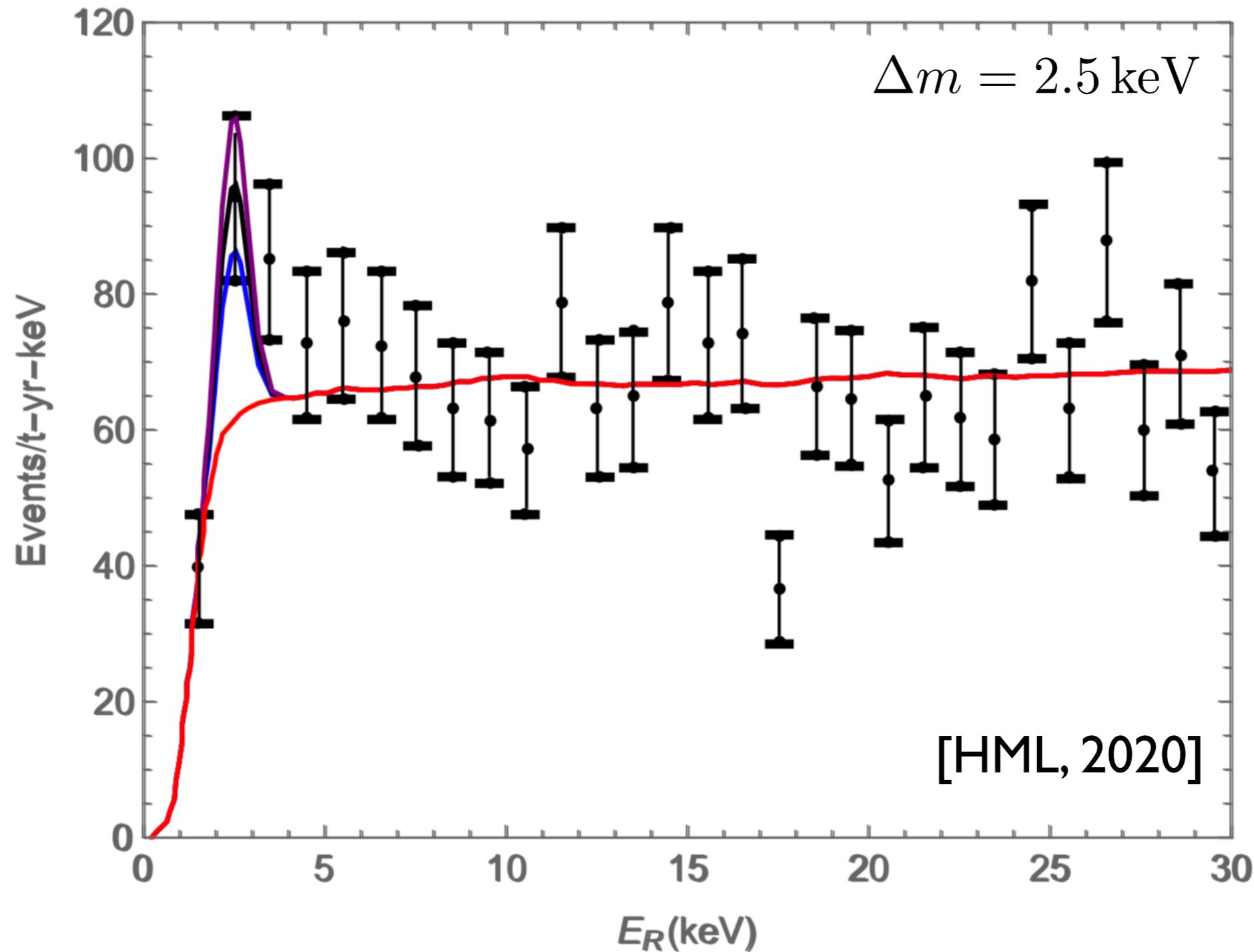
$\alpha(E) = 0.7 - 0.9, E_R = 2 - 10 \text{ keV}$



$\sigma = 0.4 \text{ keV}, \alpha \gtrsim 0.8$

XENON1T electron recoil

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

Red line: Background model

EFT for ExoDM

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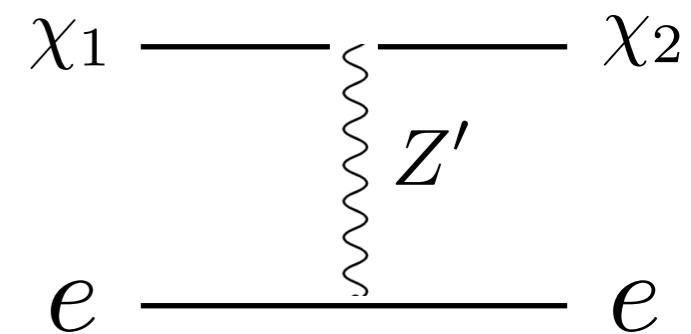
- Effective interactions between EDM and electron with massive Z' mediator: [HML, 2020]

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

- DM-electron inelastic cross section:

$$\bar{\sigma}_e \simeq \frac{v_\chi^2 v_e^2 g_{Z'}^4 \mu_1^2}{\pi m_{Z'}^4}$$

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



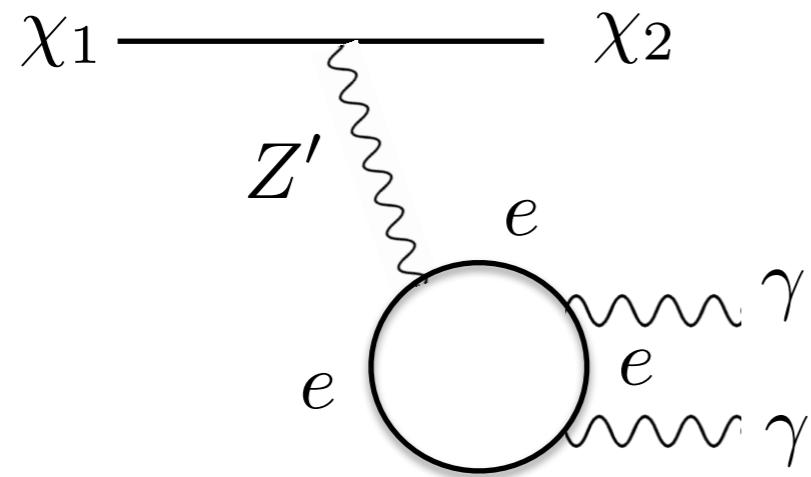
Light dark matter and mediator below GeV scale are favored for XENON1T excess.

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

Bounds on ExoDM

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

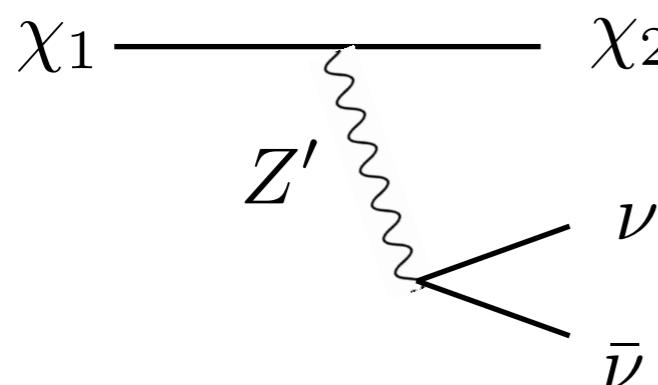


$$\Gamma(\chi_1 \rightarrow \chi_2 \gamma\gamma) \simeq \frac{a_e^2(v_\chi^2 + a_\chi^2)e^4 g_{Z'}^2}{2560\pi^7} \frac{(\Delta m)^5}{m_{Z'}^4}$$

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

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

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



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

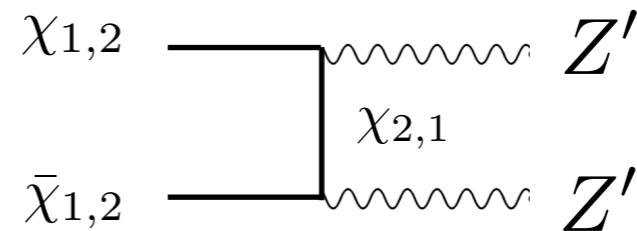
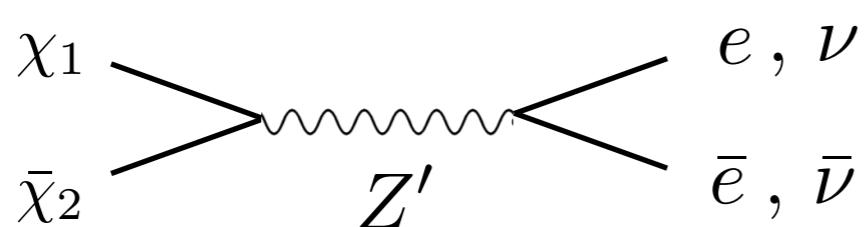
$$\tau_{\chi_1} > t_U : G'_F \sqrt{N_\nu (v_\nu^2 + a_\nu^2)} < 2.4 \times 10^{-6} \text{ GeV}^{-2}$$

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

Dark matter relic density

-22-

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



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

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

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

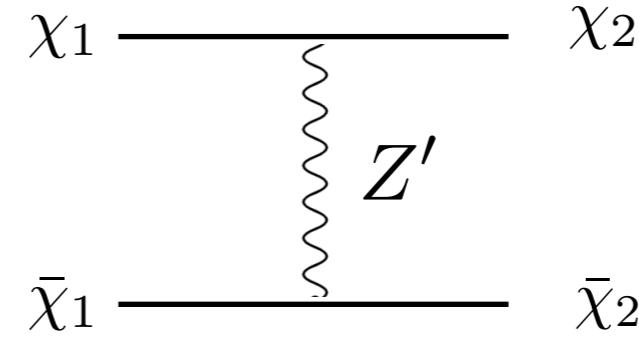
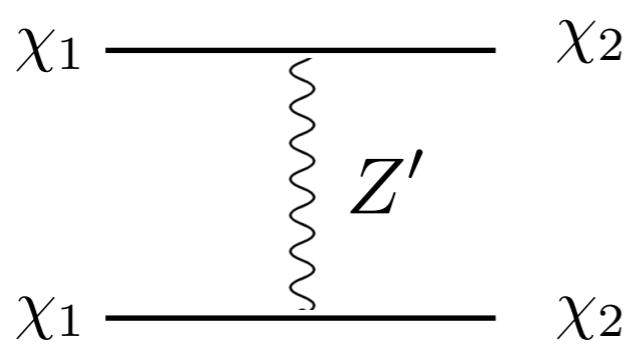
“forbidden channels”

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

Late ExoDM decoupling

-23-

- Heavier DM keeps annihilating into lighter DM.



$$\langle\sigma v\rangle_{\chi_1\chi_1 \rightarrow \chi_2\chi_2} = \frac{\sqrt{2}}{16\pi} \frac{g_{Z'}^4 m_{\chi_1}^2}{m_{Z'}^4} \sqrt{\frac{\Delta m}{m_{\chi_1}}} (v_\chi^4 + 6a_\chi^2 v_\chi^2 + 9a_\chi^4), \quad \langle\sigma v\rangle_{\chi_1\bar{\chi}_1 \rightarrow \chi_2\bar{\chi}_2} = \frac{\sqrt{2}}{8\pi} \frac{g_{Z'}^4 m_{\chi_1}^2}{m_{Z'}^4} \sqrt{\frac{\Delta m}{m_{\chi_1}}} (v_\chi^4 + 3a_\chi^4)$$

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

$$n_{\chi_1} \langle\sigma v\rangle_{\chi_1\bar{\chi}_1 \rightarrow \chi_2\bar{\chi}_2} = H, \quad \text{at } T_\chi > \Delta m$$

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

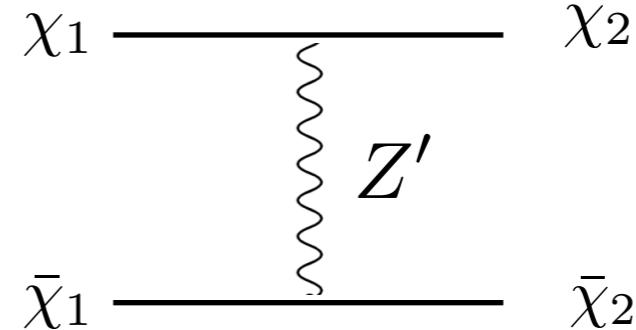
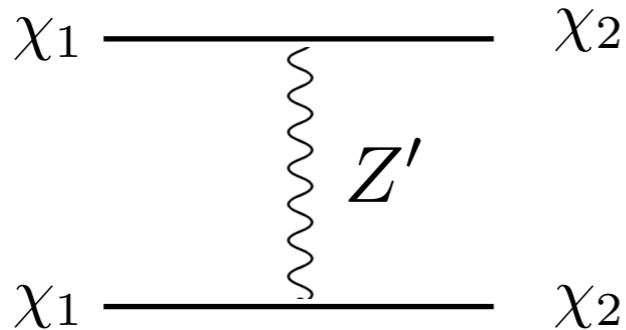
Here, $T_\chi = \frac{T^2}{T_{\text{kd}}}$, $T_{\text{kd}} \sim \text{MeV}$. “Kinetic decoupling temp”

$$T_\chi = \Delta m \left(\frac{1}{2\Omega_{\chi_1}} \right) \left(\frac{5 \times 10^{-3} \text{ GeV}^{-2}}{\langle\sigma v\rangle_0} \right) \left(\frac{m_{\chi_1}/\Delta m}{4 \times 10^4} \right)^{3/2} \left(\frac{\Delta m/2.5 \text{ keV}}{T_{\text{kd}}/1 \text{ MeV}} \right)^{1/2}$$

Dark matter self-scattering

-24-

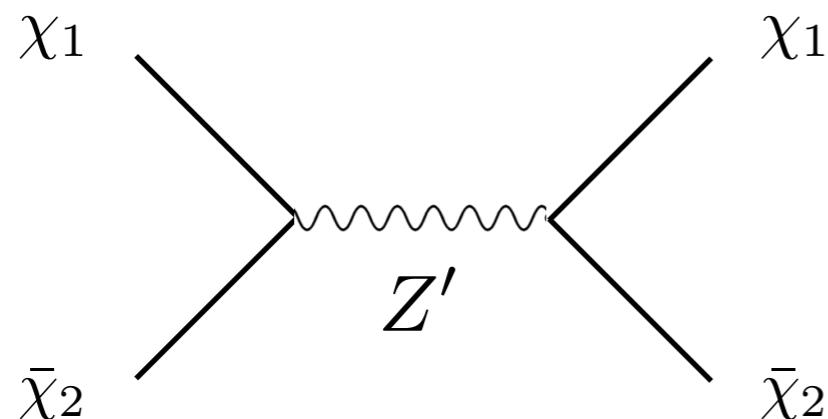
- Inelastic self-scattering.



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

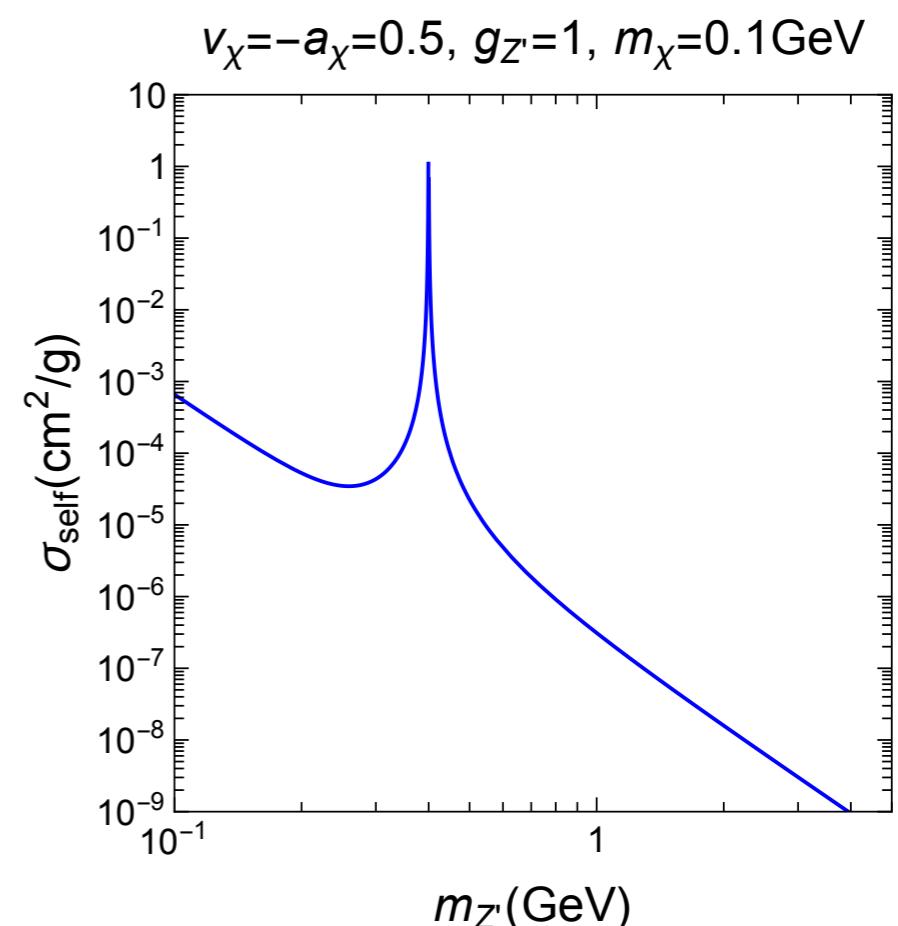
$$\sigma_{\chi_1 \bar{\chi}_1 \rightarrow \chi_2 \bar{\chi}_2} = \frac{1}{8\pi} \frac{g_{Z'}^4 m_{\chi_1}^2}{m_{Z'}^4} (v_\chi^4 + 3a_\chi^4)$$

- Elastic self-scattering.



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

Velocity-dependent self-scattering!



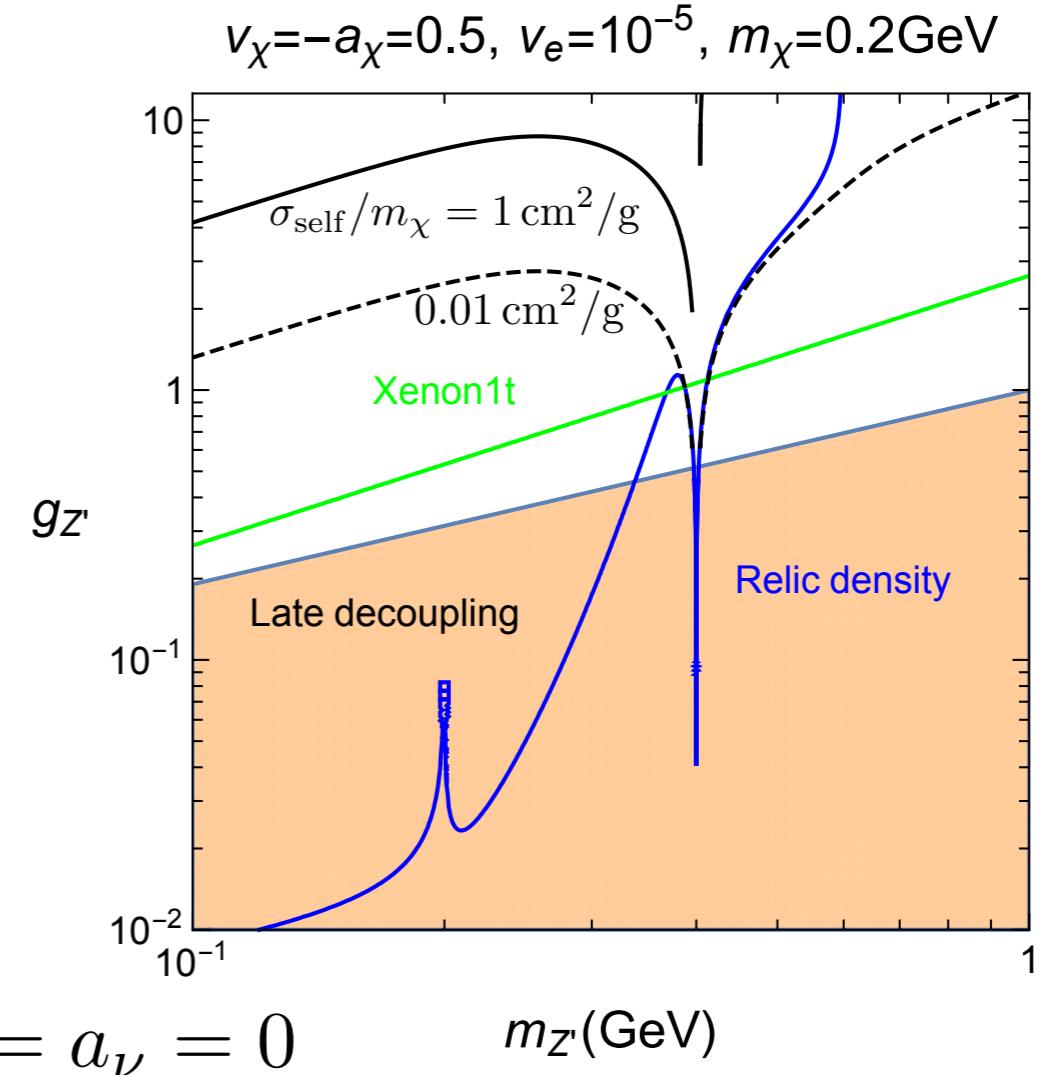
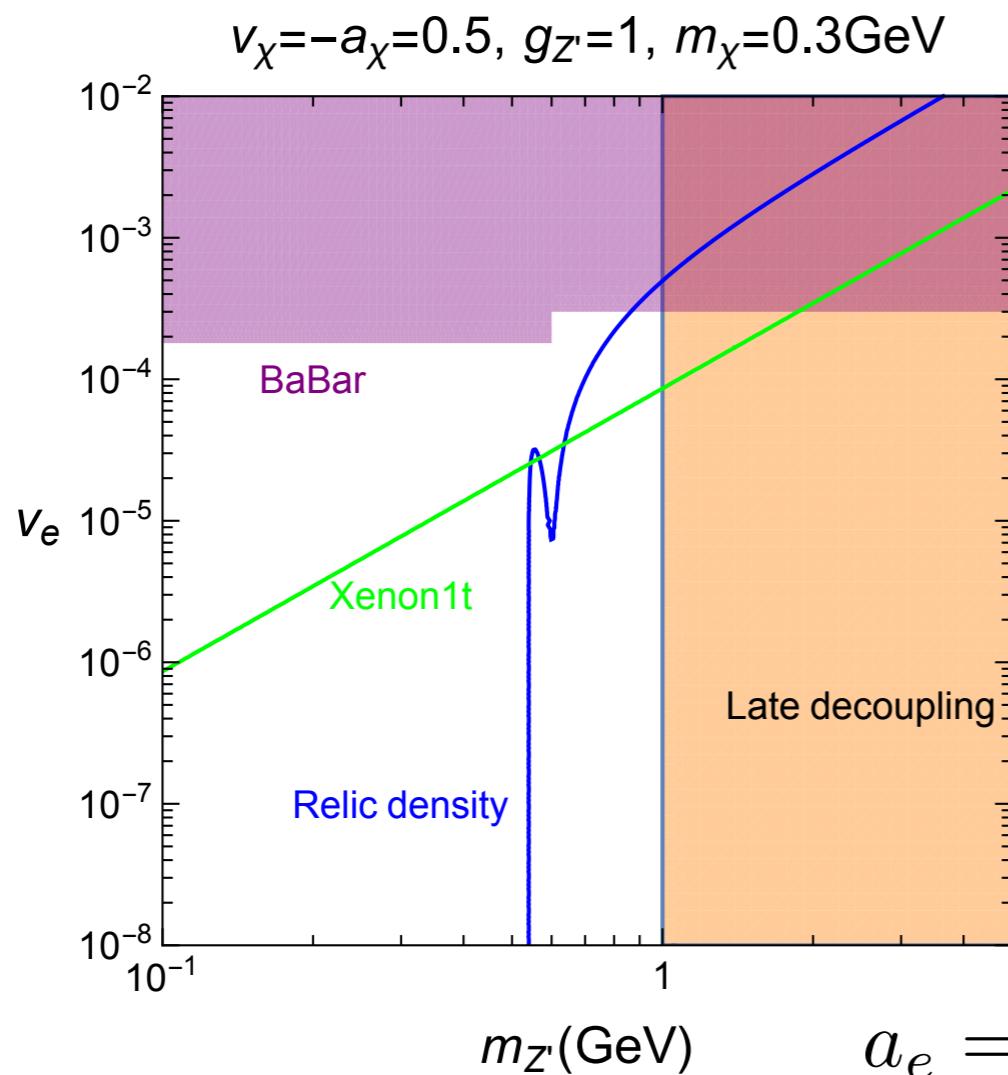
XENON1T + relic

-25-

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

$$m_{Z'} \lesssim 10 \text{ GeV} \quad \xrightarrow{\hspace{1cm}} \quad |v_e| g_{Z'} \lesssim (10^{-4} - 10^{-3}) e$$

- DM relic density & decoupling condition can be satisfied.



Pseudo-Dirac dark matter

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

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

“Dirac mass” “Majorana masses”

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

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

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

“Technically natural splitting” $\Delta m = 4|y_1|v_\phi = 2.5 \text{ keV}$



Z' -DM int:

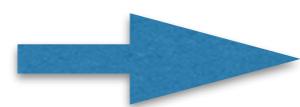
$$\mathcal{L}_{\text{DM}} = g_{Z'} Z'_\mu (\bar{\chi}_1 \gamma^\mu P_L \chi_2 + \bar{\chi}_2 \gamma^\mu P_L \chi_1).$$

Z'-portal for ExoDM

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

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



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

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

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

- Completely safe from diffuse X-ray bounds.
- ExoDM decays dominantly into neutrinos.

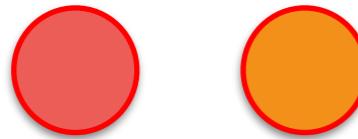
$$\tau_{\chi_1} = \frac{1}{\Gamma(\chi_1 \rightarrow \chi_2 \nu \bar{\nu})} = \left(\frac{10^{-4}e}{\varepsilon g_{Z'}} \right)^2 \left(\frac{2.5 \text{ keV}}{\Delta m} \right)^5 8.9 \times 10^{24} \text{ sec}$$

: Consistent with lifetime bound.

Dark mesons

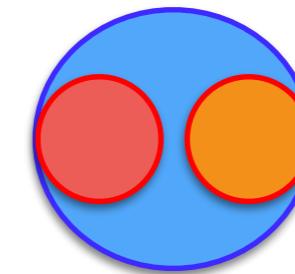
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Dark light fermions
 $G = SU(N_f)_L \times SU(N_f)_R$



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

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



$N_f = 3$:

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

Meson masses:

$$m_{\tilde{\pi}^\pm}^2 = \mu(m'_1 + m'_2),$$

$$m_{\tilde{K}^\pm}^2 = \mu(m'_1 + m'_3),$$

$$m_{\tilde{K}^0}^2 = \mu(m'_2 + m'_3),$$

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

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

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

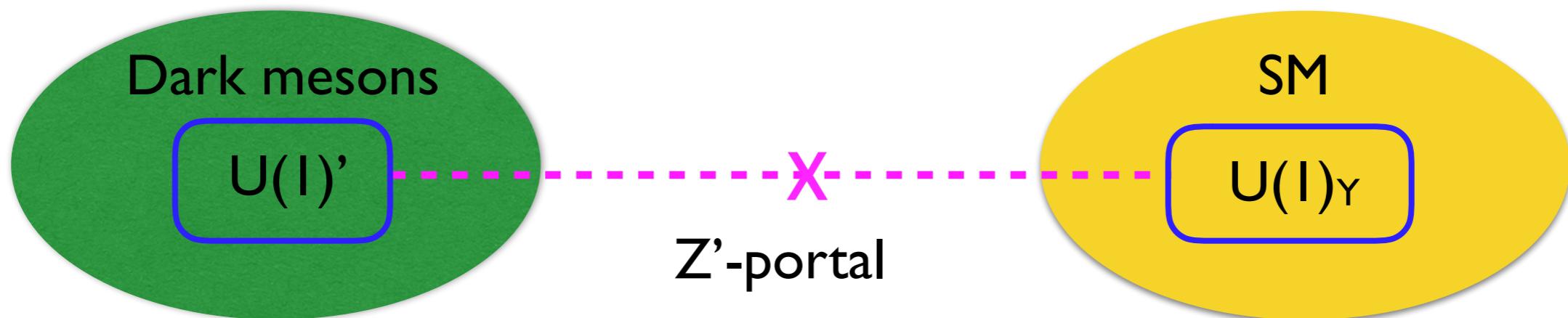
$SU(3)_V$ dark flavor symmetry: $m'_1 = m'_2 = m'_3$



$$\left\{ \begin{array}{l} m_\pi^2 = 2\mu m'_1 : \text{common masses for dark mesons} \\ \text{Stability of dark mesons} \end{array} \right.$$

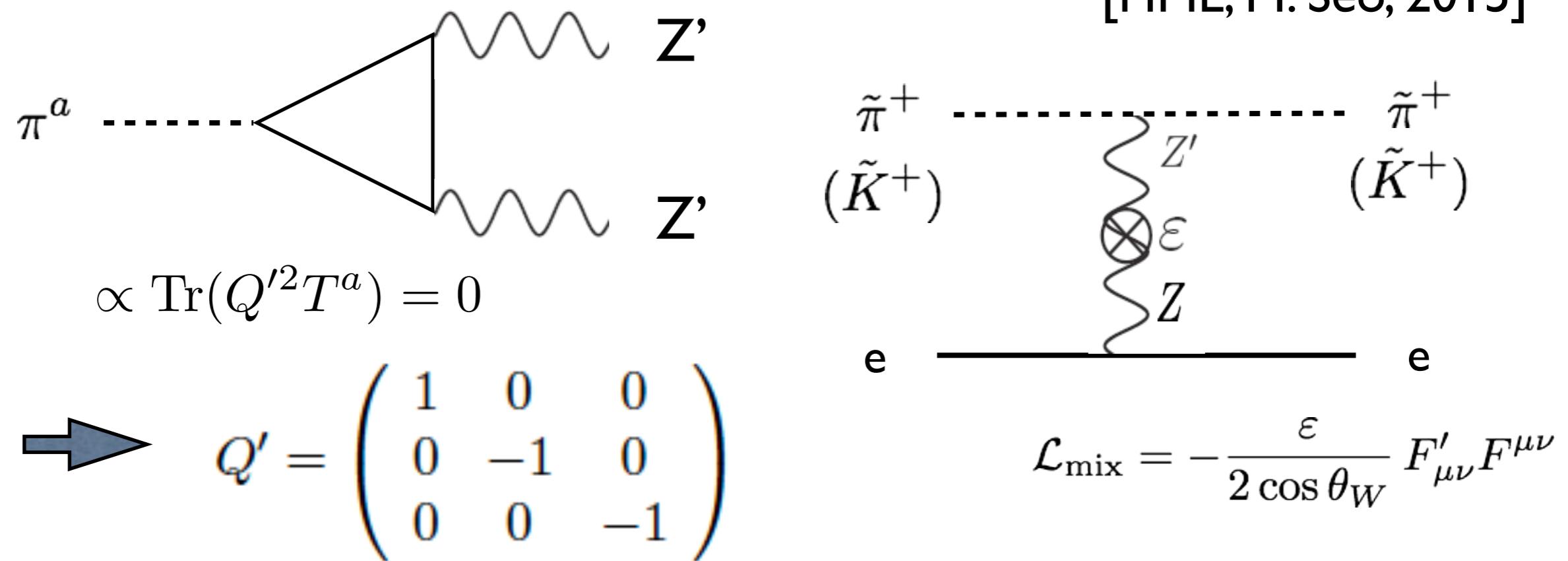
Z'-portal for dark mesons

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

[HML, M. Seo, 2015]



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

Split masses for dark mesons

-30-

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

Mixings due to broken $U(1)'$

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

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

\rightarrow

$$\begin{aligned} m_\pi^2 &\equiv 2\mu m_1 & \left\{ \begin{array}{l} m_{\tilde{\pi}^\pm}^2 = m_\pi^2, \\ m_{\tilde{\pi}^0}^2 = m_\pi^2 \left(1 - \frac{2\Delta m}{\sqrt{3}m_\pi}\right), \end{array} \right. & \begin{array}{l} m_{\tilde{K}^\pm}^2 = m_\pi^2 \left(1 - \frac{\Delta m}{m_\pi}\right), \\ m_{\tilde{K}^0}^2 = m_\pi^2 \left(1 + \frac{\Delta m}{m_\pi}\right), \\ m_{\tilde{\eta}^0}^2 = m_\pi^2 \left(1 + \frac{2\Delta m}{\sqrt{3}m_\pi}\right) \end{array} \\ \Delta m &\equiv \mu \sqrt{\epsilon^2 + \epsilon'^2} / m_\pi \end{aligned}$$

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'

$$(\tilde{K}^0, \tilde{K}^+)$$

$$(\tilde{\pi}^0, \tilde{\pi}^1 = \frac{1}{\sqrt{2}i}(\tilde{\pi}^- - \tilde{\pi}^+), \tilde{\pi}^2 = \frac{1}{\sqrt{2}}(\tilde{\pi}^- + \tilde{\pi}^+))$$

$$M_{\tilde{K}}^2 = \begin{pmatrix} \mu(2m_1 + \epsilon) + \delta & \delta \\ \delta & \mu(2m_1 - \epsilon) + \delta \end{pmatrix}$$

$$M_{\tilde{\pi}}^2 = \begin{pmatrix} 2\mu \left(m_1 - \frac{1}{\sqrt{3}}\epsilon\right) + 2\delta & 0 & 0 \\ 0 & 2\mu m_1 + 2\delta & 0 \\ 0 & 0 & 2\mu m_1 \end{pmatrix}$$

$$m_{K_{1,2}}^2 = 2\mu m_1 + \delta \pm \sqrt{\delta^2 + \mu^2 \epsilon^2}, \quad \delta = c g_{Z'}^2 f_\pi^2, \quad c \sim \frac{1}{16\pi^2} \frac{\mu^2}{m_{Z'}^2},$$

Negligible Z' corrections for $m_{Z'} \gtrsim 1.4\mu (g_{Z'}/0.1)(m_\pi/100 \text{ MeV})^{1/2}$

Exothermic dark mesons

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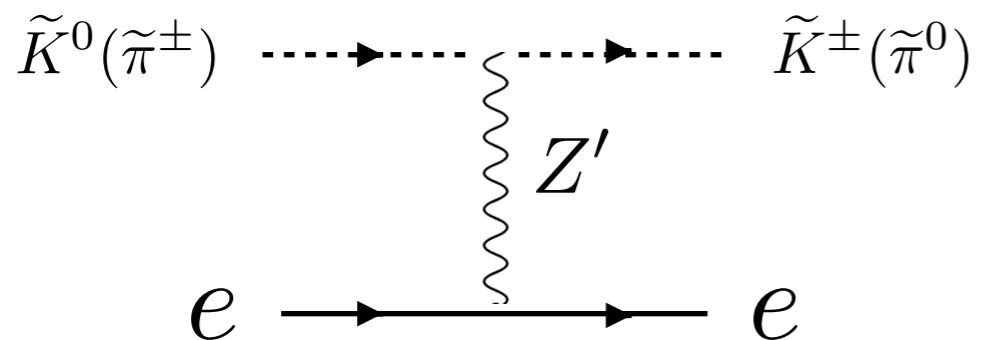
- Non-universal dark $U(1)'$: $[Q', M] \neq 0$

$$\begin{aligned}\mathcal{L}_{Z',2\pi} = & 2ig_{Z'}Z'_\mu \left(K^+ \partial^\mu K^- - K^- \partial^\mu K^+ + \pi^+ \partial^\mu \pi^- - \pi^- \partial^\mu \pi^+ \right) \\ & + 4g_{Z'}^2 Z'_\mu Z'^\mu (K^+ K^- + \pi^+ \pi^-).\end{aligned}$$



Flavor mixing

$$\begin{aligned}\mathcal{L}_{Z',\text{int}} = & ig_{Z'}Z'_\mu \left[(\tilde{K}^0 + \tilde{K}^+) \partial^\mu (\overline{\tilde{K}^0} + \tilde{K}^-) - (\overline{\tilde{K}^0} + \tilde{K}^-) \partial^\mu (\tilde{K}^0 + \tilde{K}^+) \right. \\ & \left. + \sqrt{2}(\tilde{\pi}^- - \tilde{\pi}^+) \partial^\mu \tilde{\pi}^0 - \sqrt{2}\tilde{\pi}^0 \partial^\mu (\tilde{\pi}^- - \tilde{\pi}^+) \right] \\ & + g_{Z'}^2 Z'_\mu Z'^\mu \left[2(\tilde{K}^0 + \tilde{K}^+) (\overline{\tilde{K}^0} + \tilde{K}^-) + 2(\tilde{\pi}^0)^2 - (\tilde{\pi}^- - \tilde{\pi}^+)^2 \right].\end{aligned}$$



Meson-changing Z' interactions



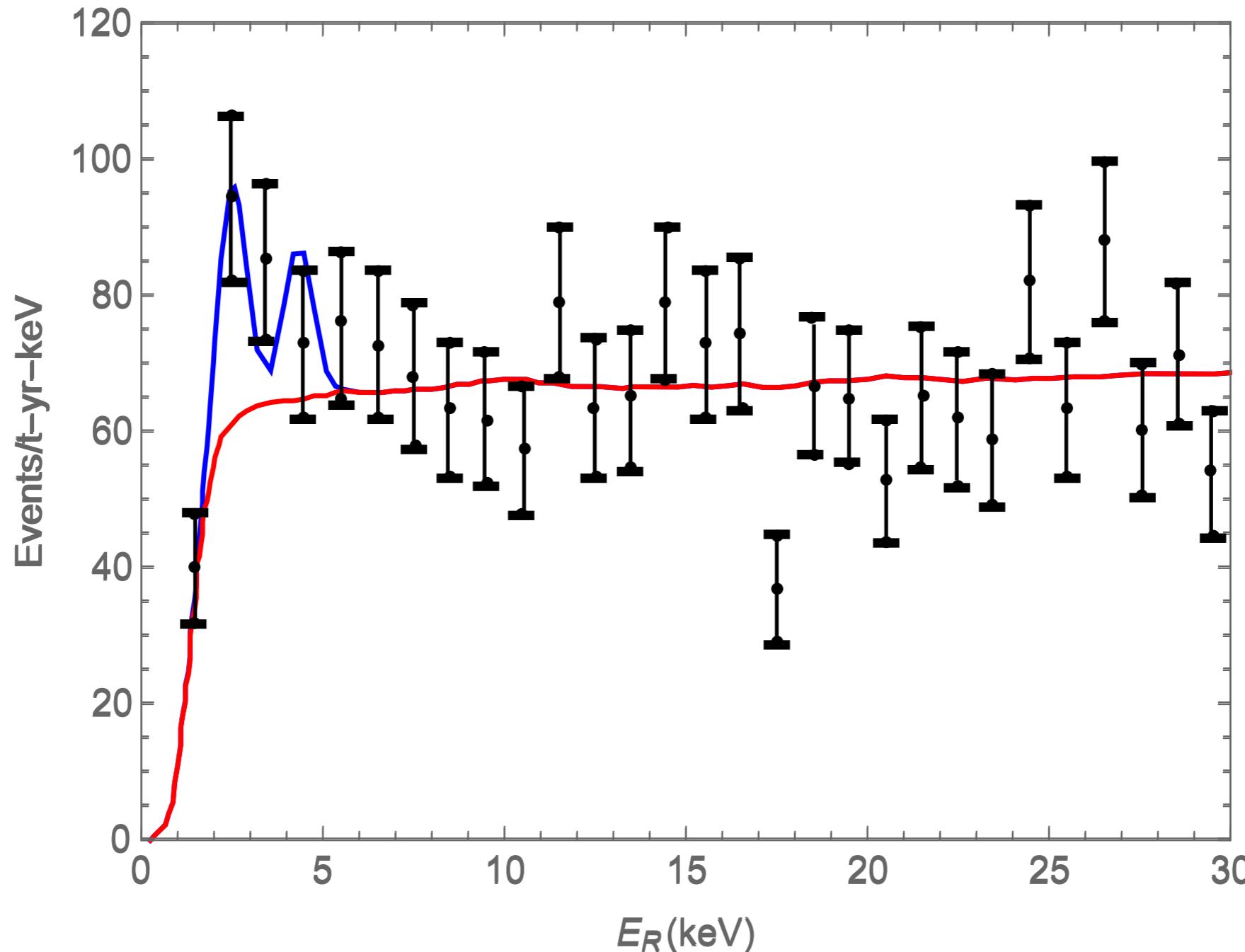
Exothermic DM-e scattering

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

Double peaks in electron E_R

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

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$$m_{\tilde{\pi}^\pm} - m_{\tilde{\pi}^0} = \Delta m = 2.5 \text{ keV}, \quad m_{\tilde{K}^0} - m_{\tilde{K}^\pm} = \sqrt{3}\Delta m = 4.3 \text{ keV}.$$

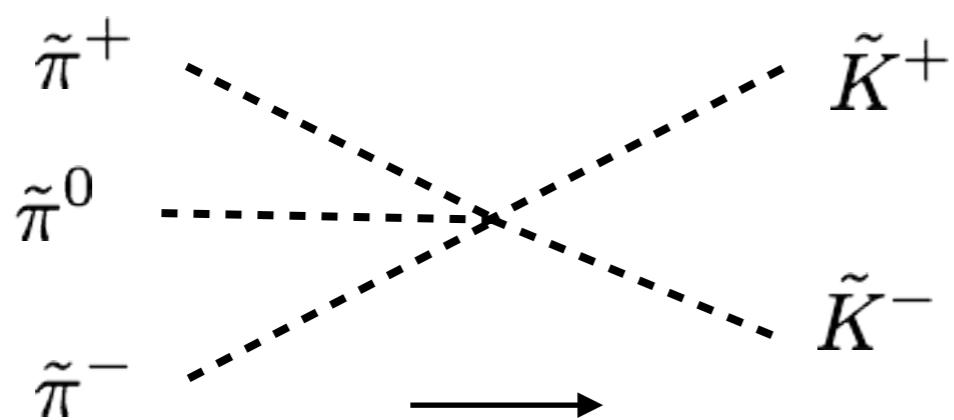
Dark meson self-scattering

- Strongly Interacting Massive Particles from WZW terms

[Wess, Zumino, 1971; Witten, 1983]

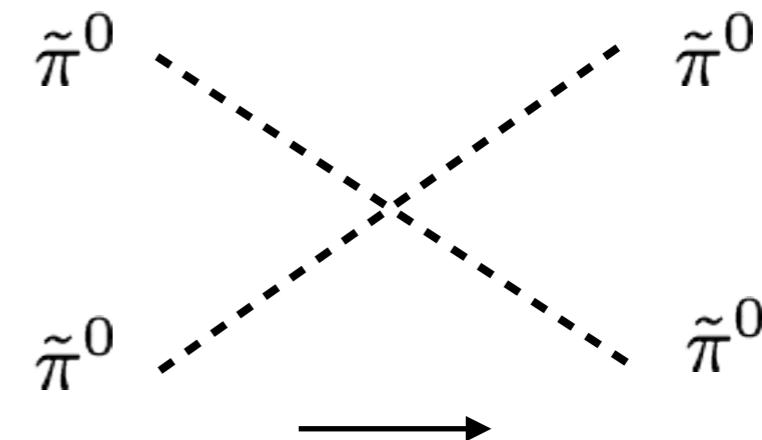
$$\mathcal{L}_{WZW} = \frac{2N_c}{15\pi^2} \epsilon^{\mu\nu\rho\sigma} \text{Tr}[\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi] \quad \text{for } \pi_5(G/H) = \mathbb{Z}$$

[Hochberg et al, 2014; Seo, HML, 2015; S. Choi, P. Ko, HML, A. Natale, 2018; S. Choi, HML, B. Zhu, to appear]



SIMP annihilation
from WZW

$$\langle \sigma v^2 \rangle_{3 \rightarrow 2} = \frac{5\sqrt{5}N_c^2 m_\pi^5}{2\pi^5 F^{10}} \frac{t^2}{N_\pi^3} \left(\frac{T_F}{m_\pi} \right)^2 \sim \frac{1}{N_f}$$



Large self-scattering
in ChpT + Z' interactions

$$\sigma_{\text{self}} = \frac{m_\pi^2}{32\pi F^4} \frac{a^2}{N_\pi^2} \sim \text{const}$$

Conclusions

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- The Xenon electron excess can be explained by **down-scattering of exothermic dark matter** for standard halo model.
- **Light dark matter and mediator** are favored by Xenon excess, thus dark matter can be naturally self-interacting.
- **Pseudo-Dirac dark fermion or dark mesons with flavor mixing** are natural candidates for exothermic dark matter with Z' portals.
- Dark fermion or mesons can be **self-interacting**, being consistent with Xenon excess and Bullet cluster.