On-shell mediator DM models and the Xenon1T excess

Zuowei Liu (Nanjing University)

in collaboration with Mingxuan Du, Jinhan Liang, Van Que Tran, Yilun Xue, arXiv:2006.11949

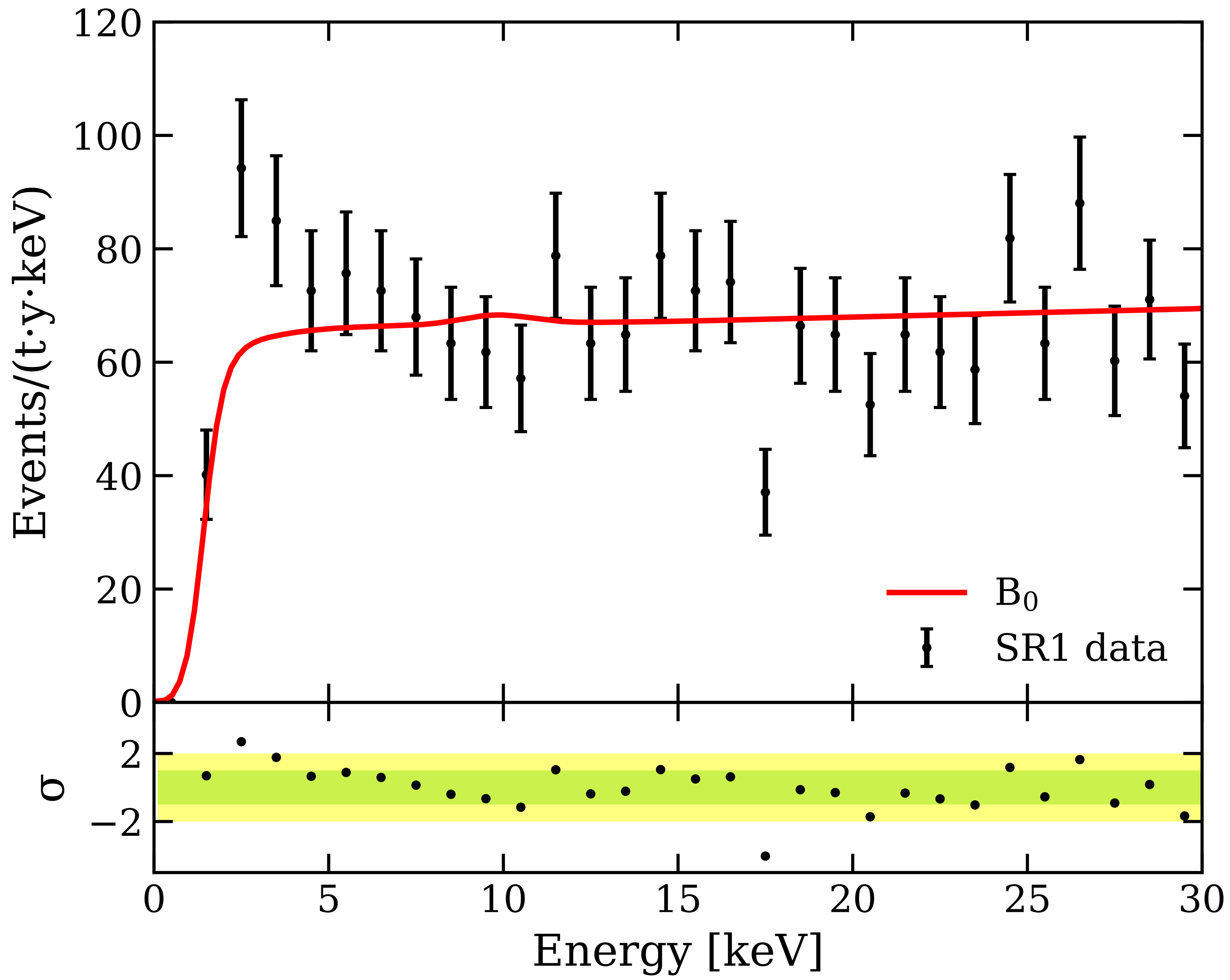
Mini-workshop: Low Energy Recoils from Deep Underground

CHEP, PKU, 2020-09-26

Outline

- Xenon1T electron recoil excess
- On-shell mediator dark matter models
- Velocity distribution
- Particle flux and xsec
- Constraints
- Conclusion

Xenon1T electron recoil excess

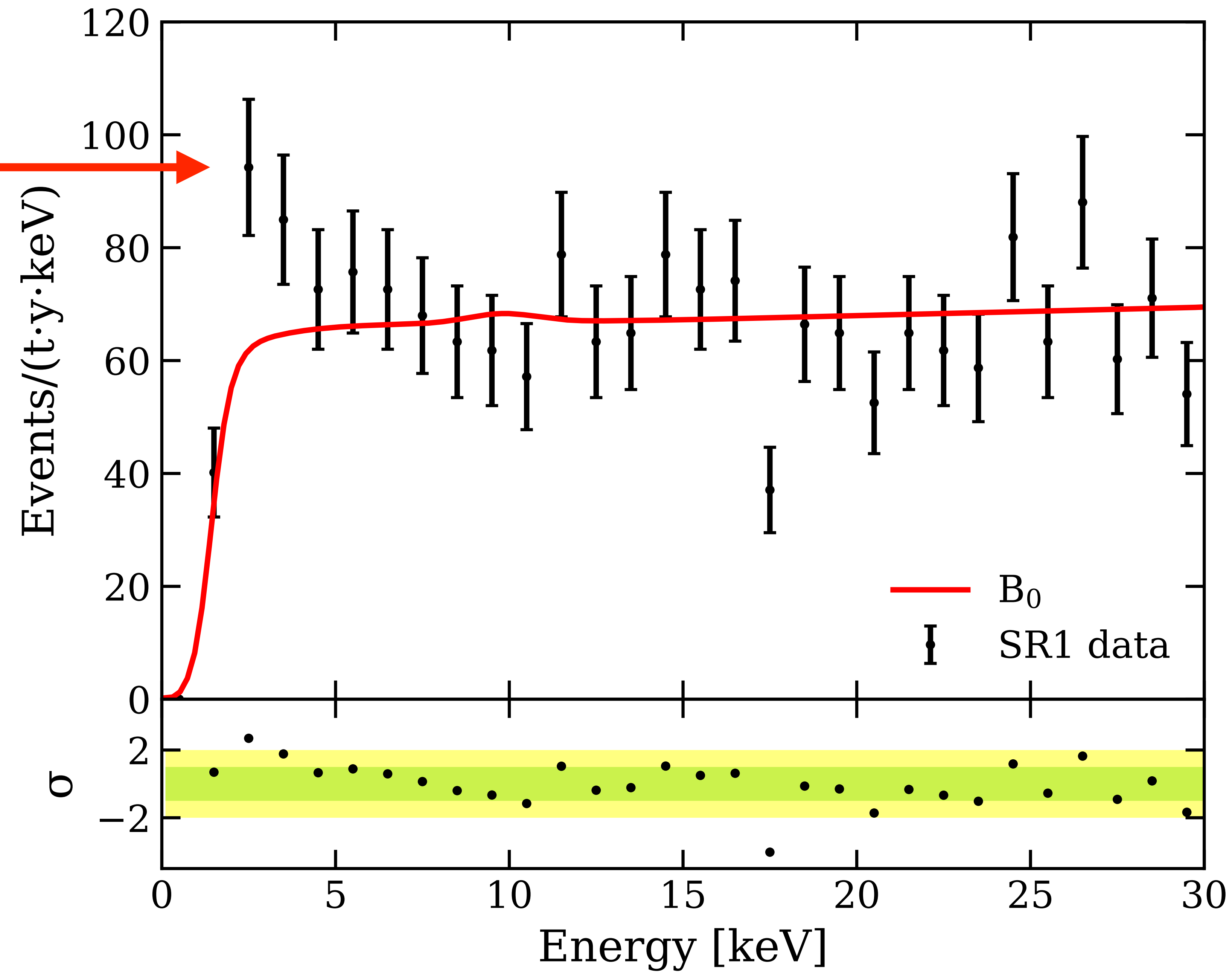


[XENON Collaboration, 2006.09721]

Xenon1T electron recoil excess

low energy electron recoil excess

2-5 keVer



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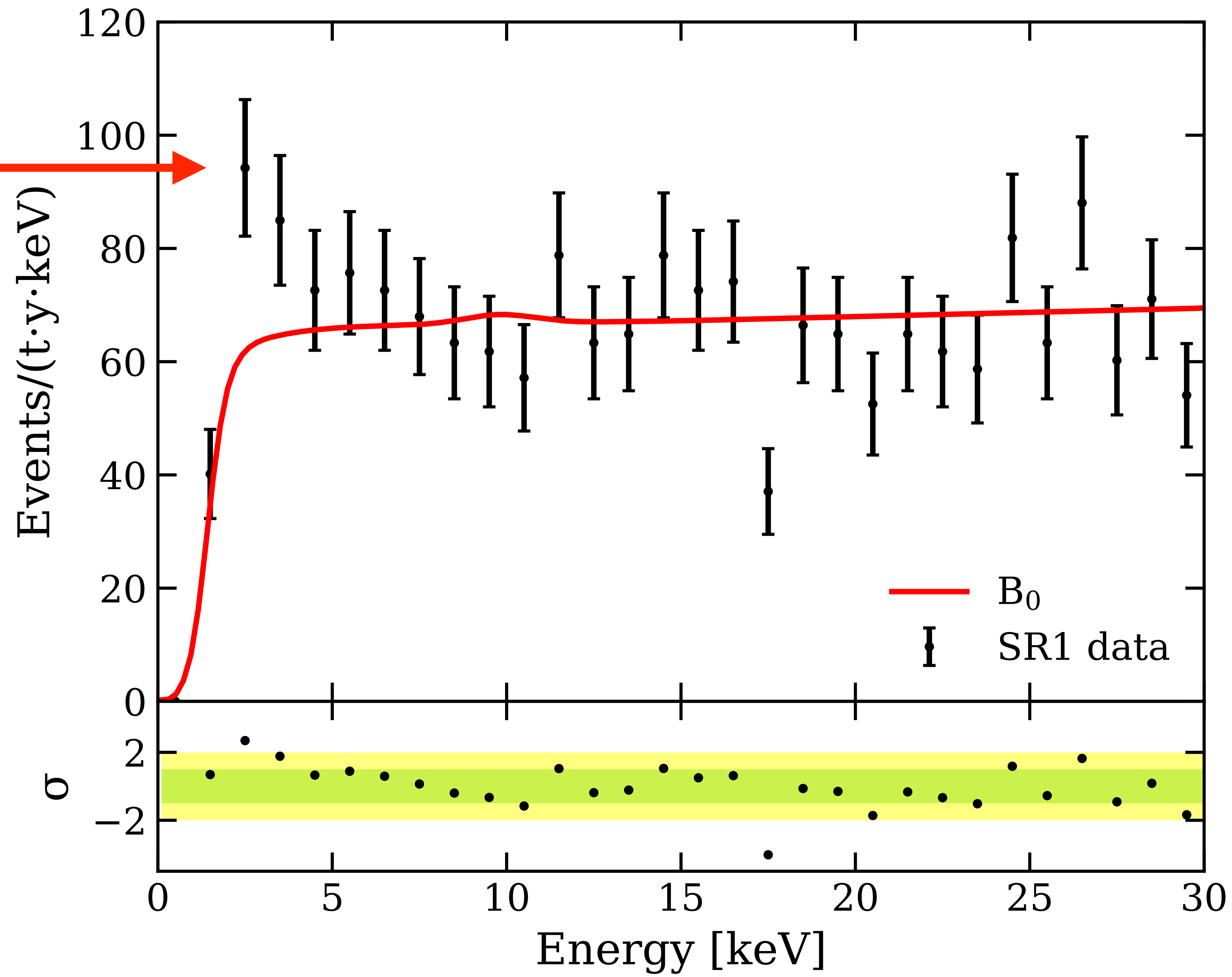
solar axion?



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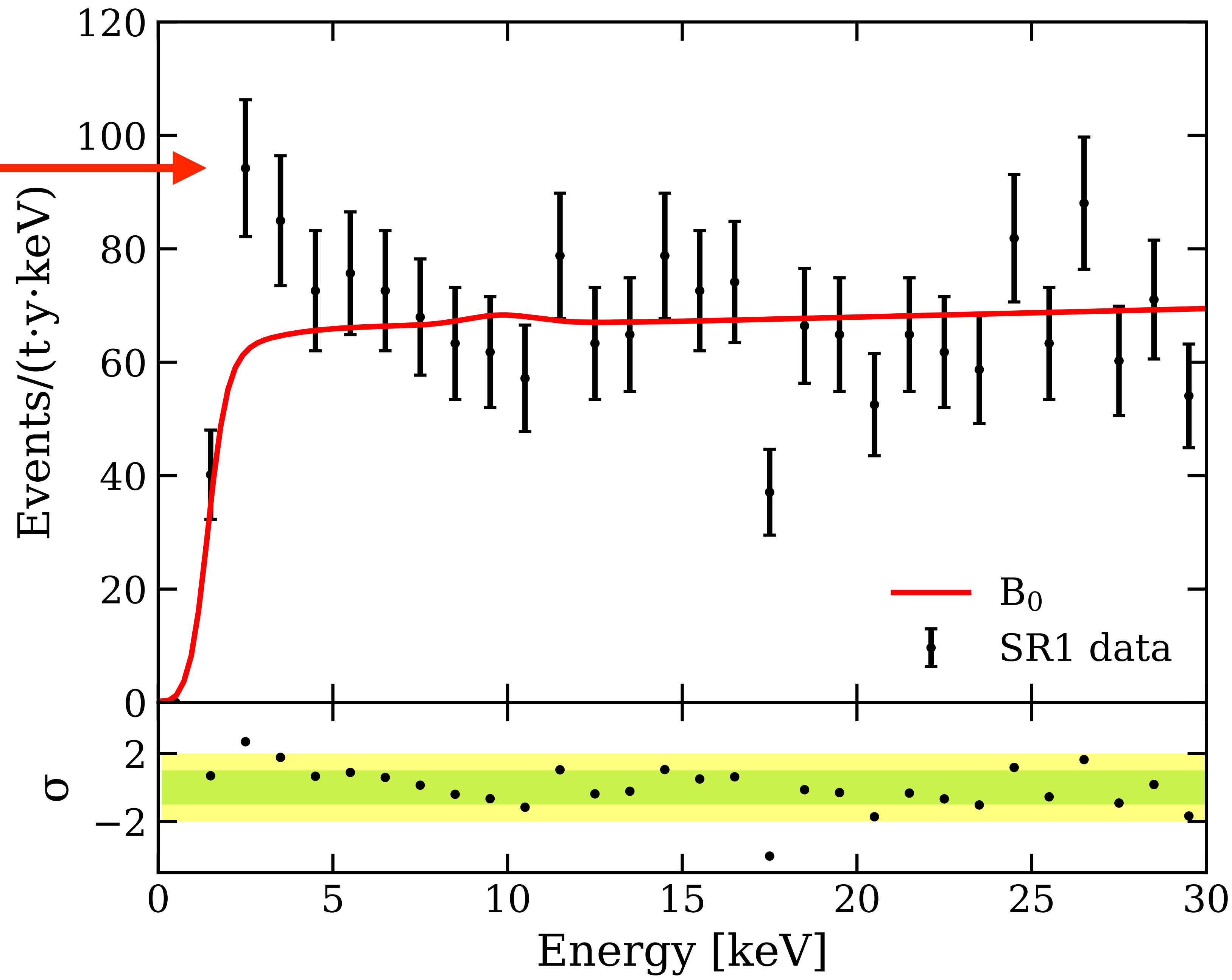
DM?



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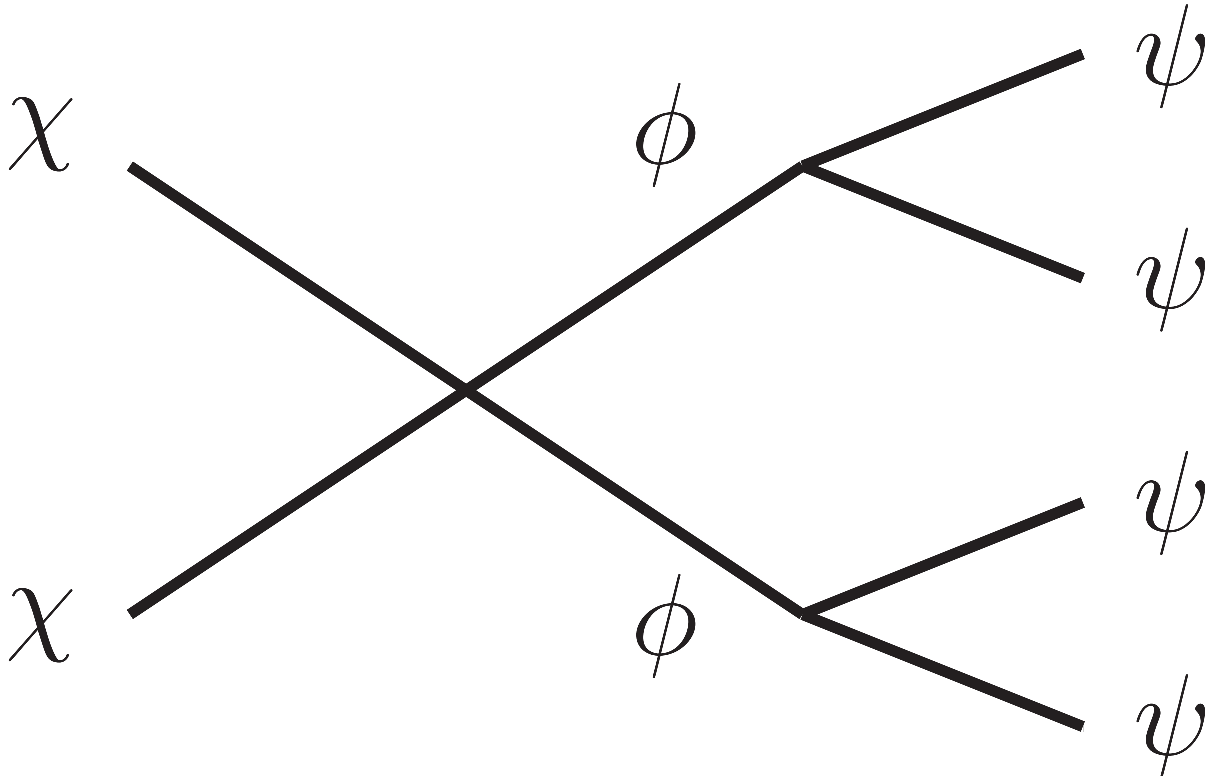
on-shell mediator DM models

$$m_\chi > m_\phi > 2m_\psi$$



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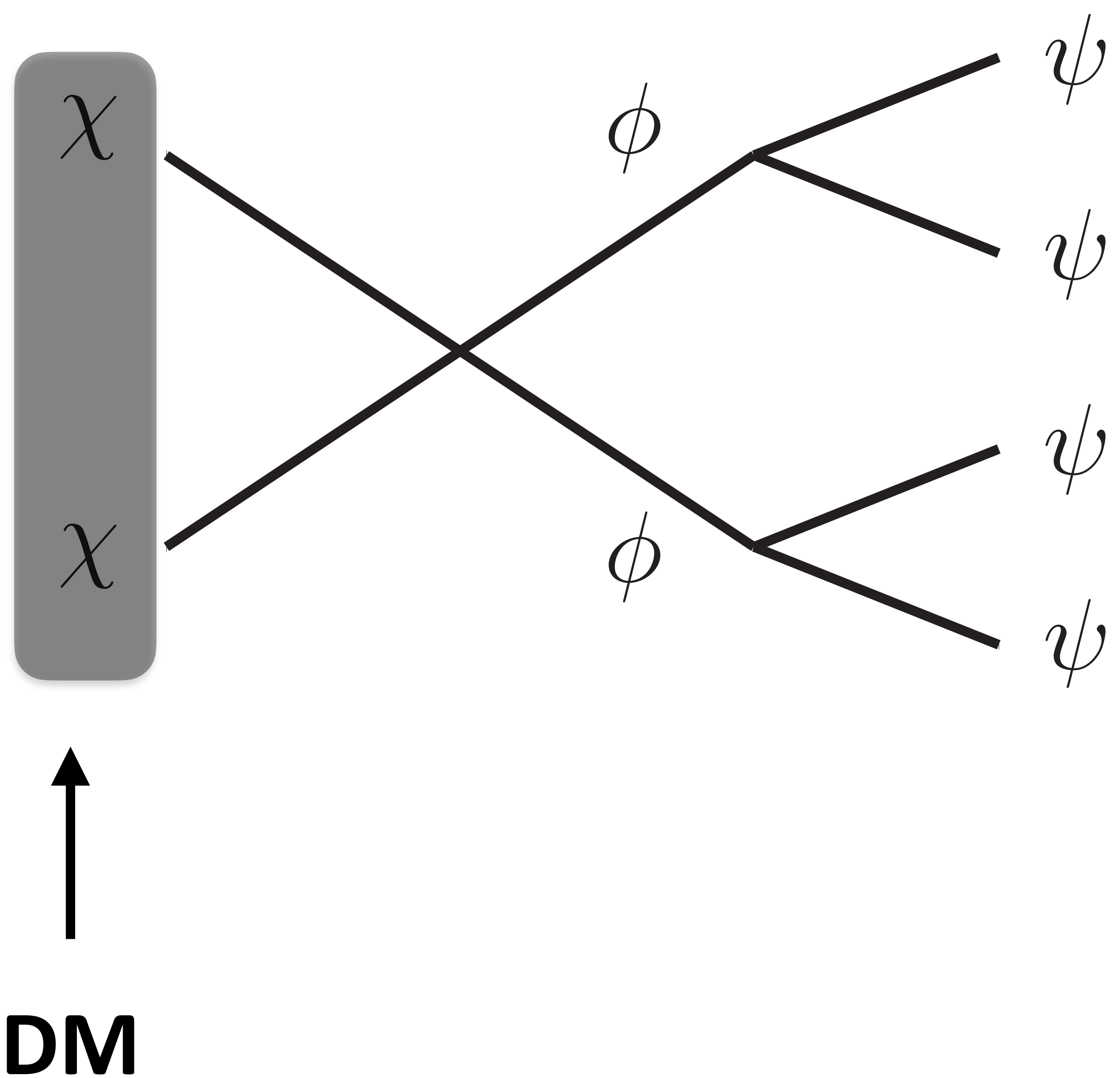

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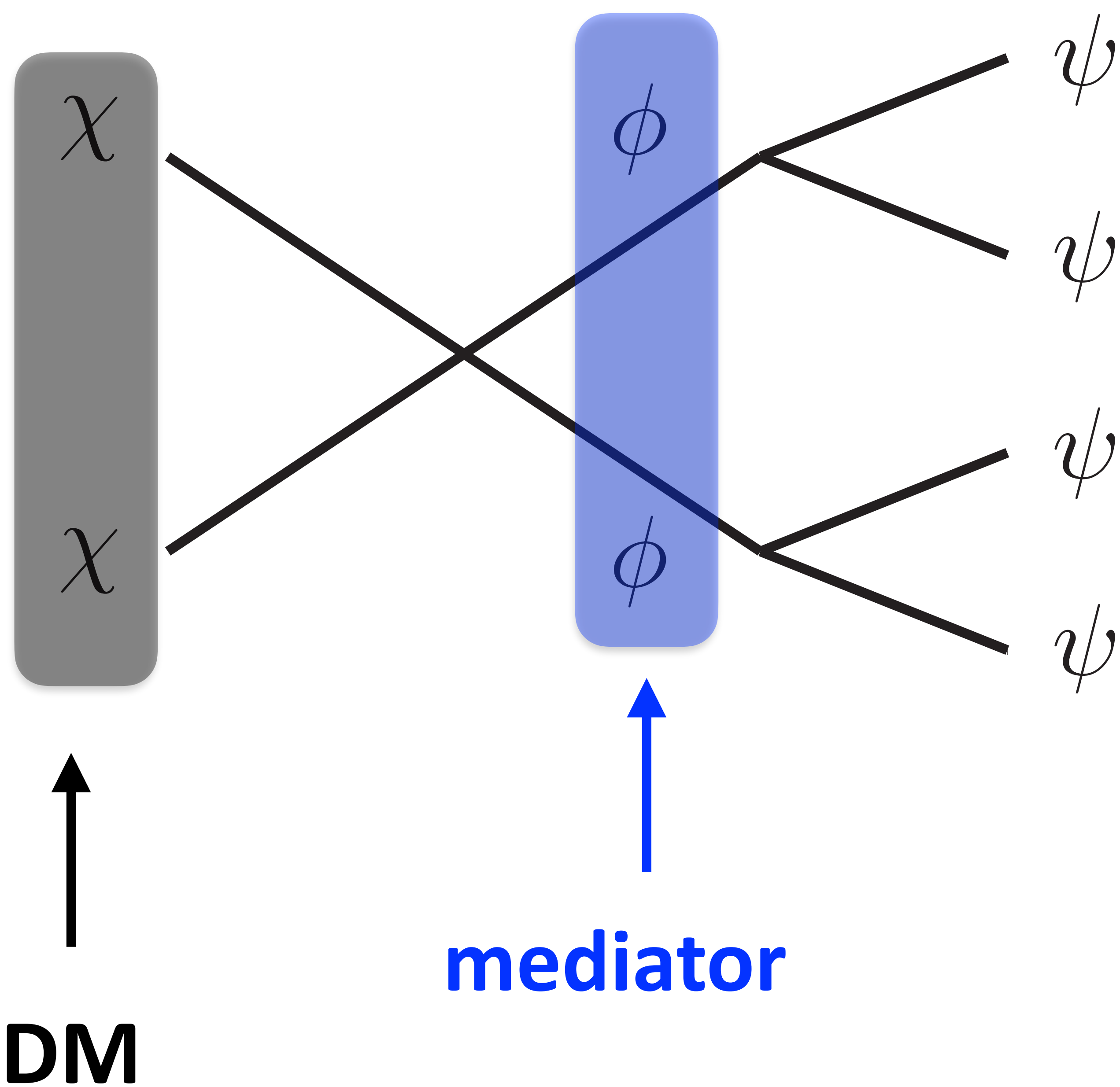

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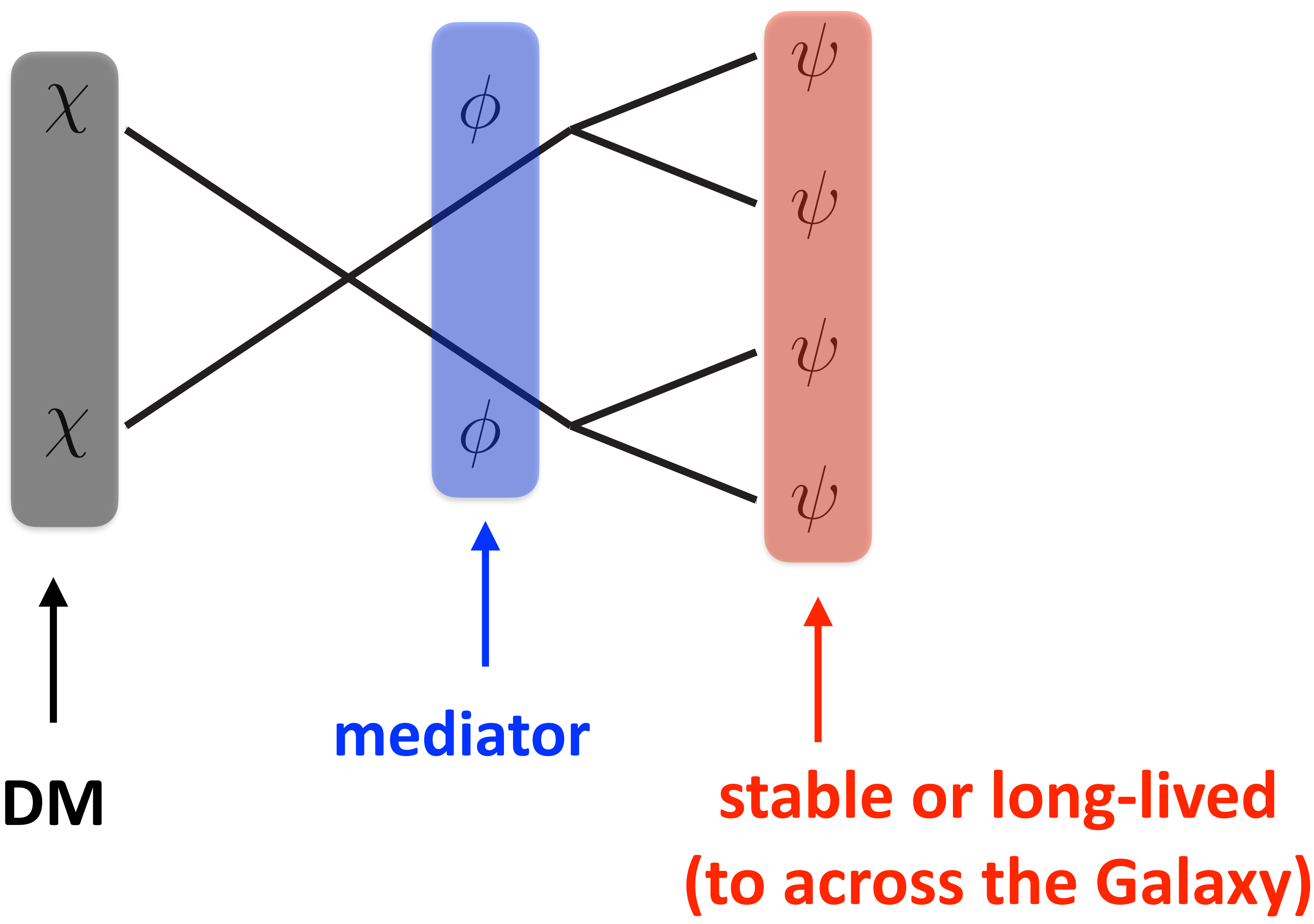

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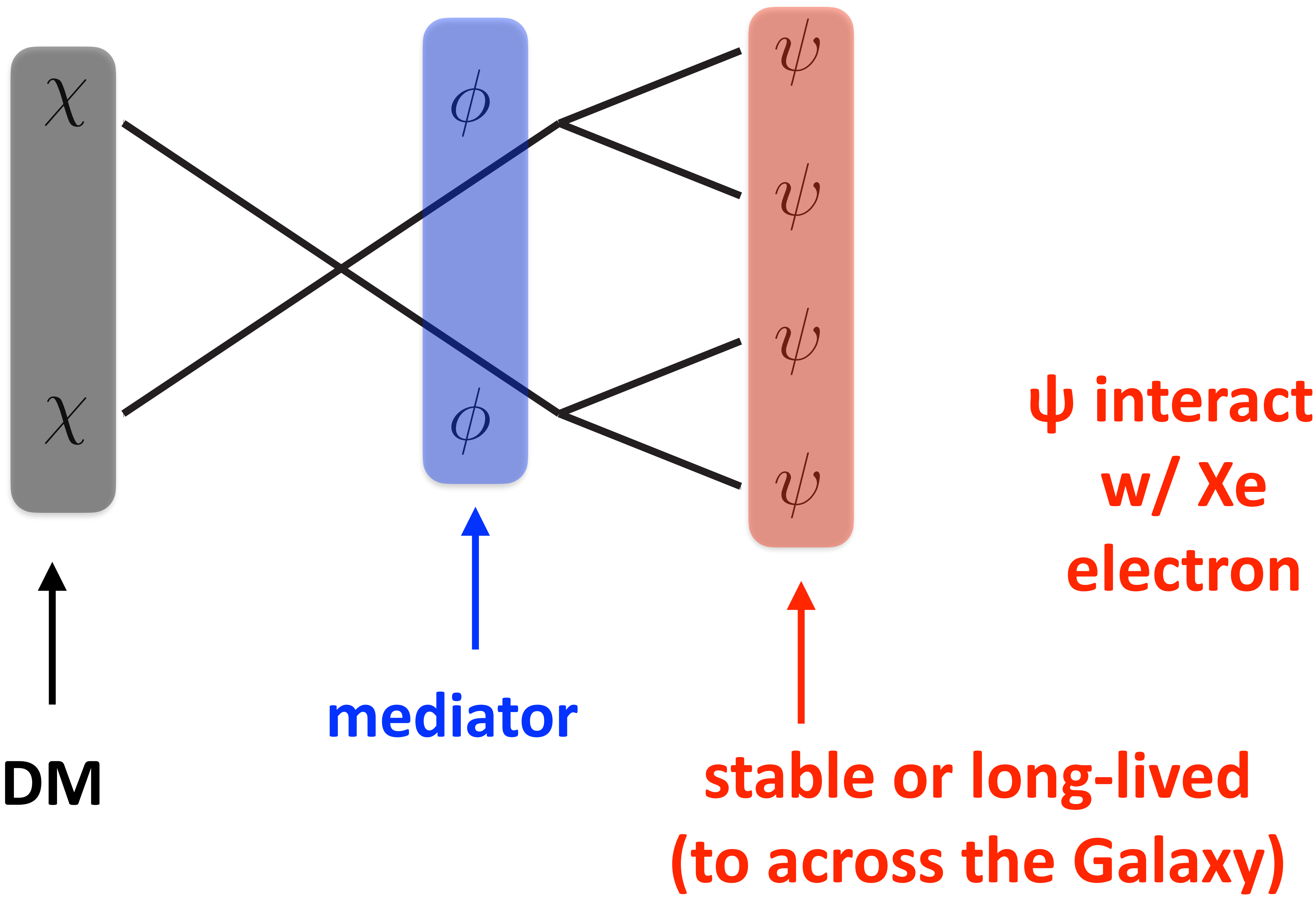

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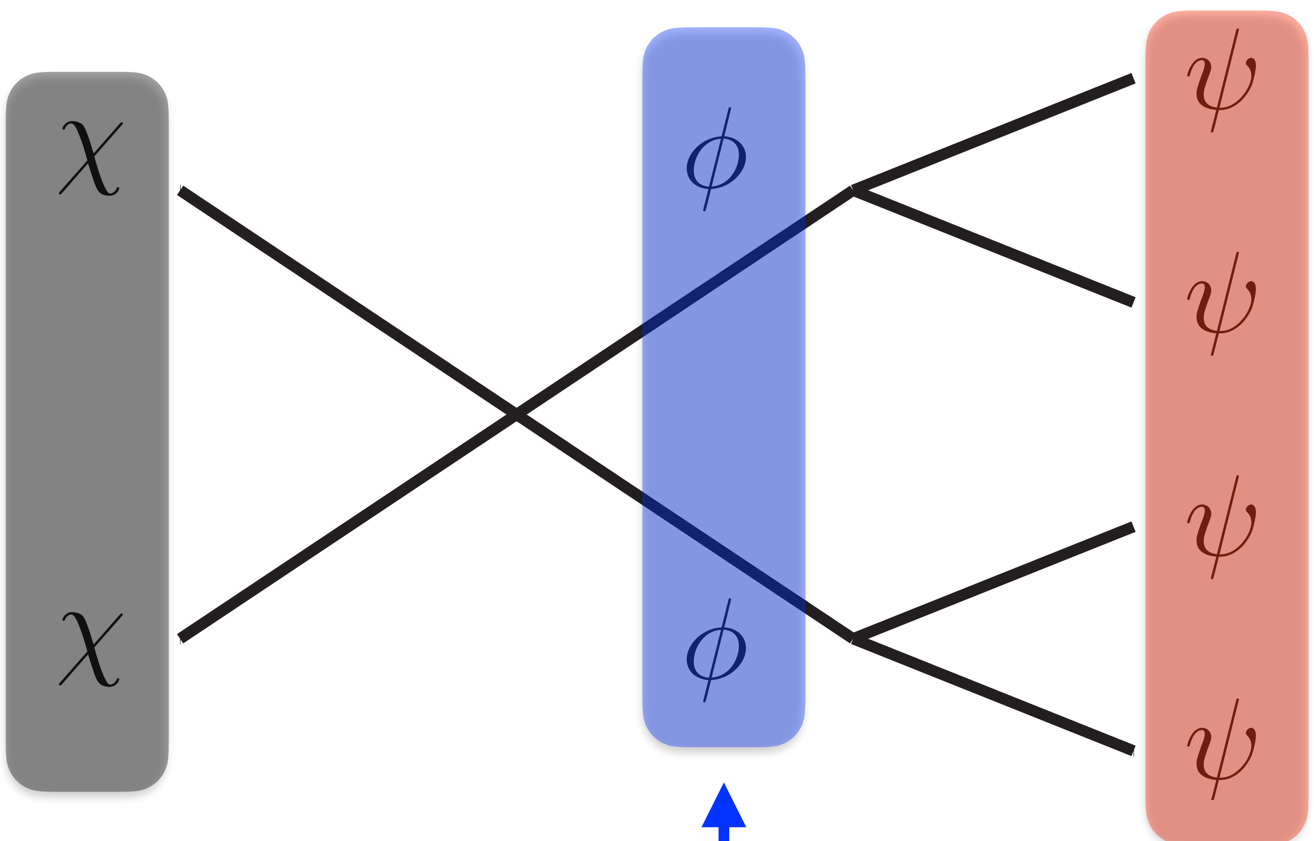

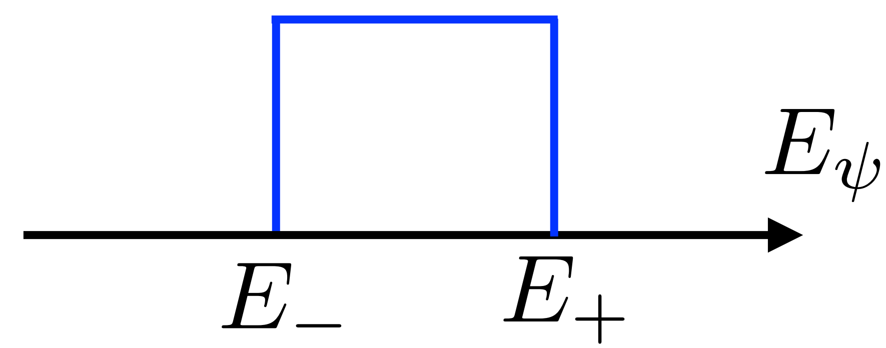

ψ interacts w/ Xe electron

DM

mediator

stable or long-lived (to across the Galaxy)

energy spectrum

energy spectrum

$$m_\chi > m_\phi > m_\psi$$

2 parameters

$$x = \sqrt{1 - m_\phi^2/m_\chi^2}$$

$$y = \sqrt{1 - 4m_\psi^2/m_\phi^2}$$

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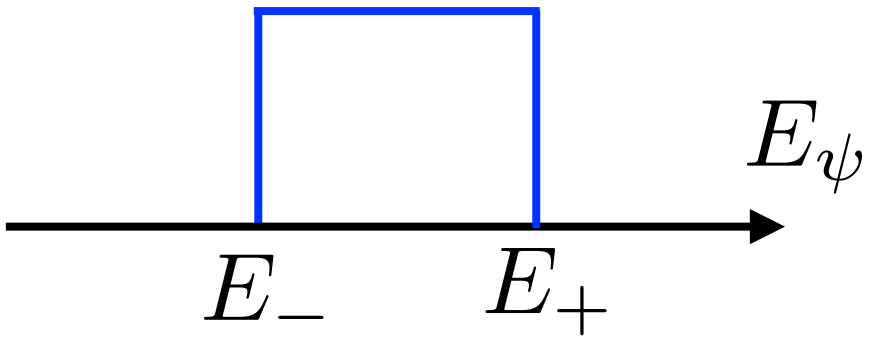
energy of ψ

box-shape

$$E_- < E_\psi < E_+$$

$$E_\pm = \frac{m_\chi}{2}(1 \pm xy)$$



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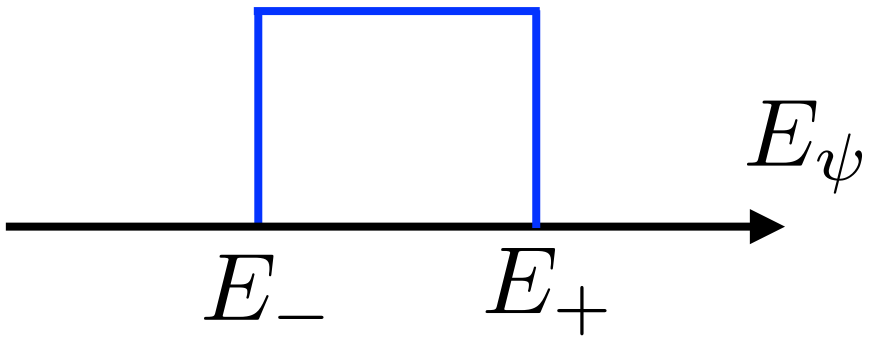


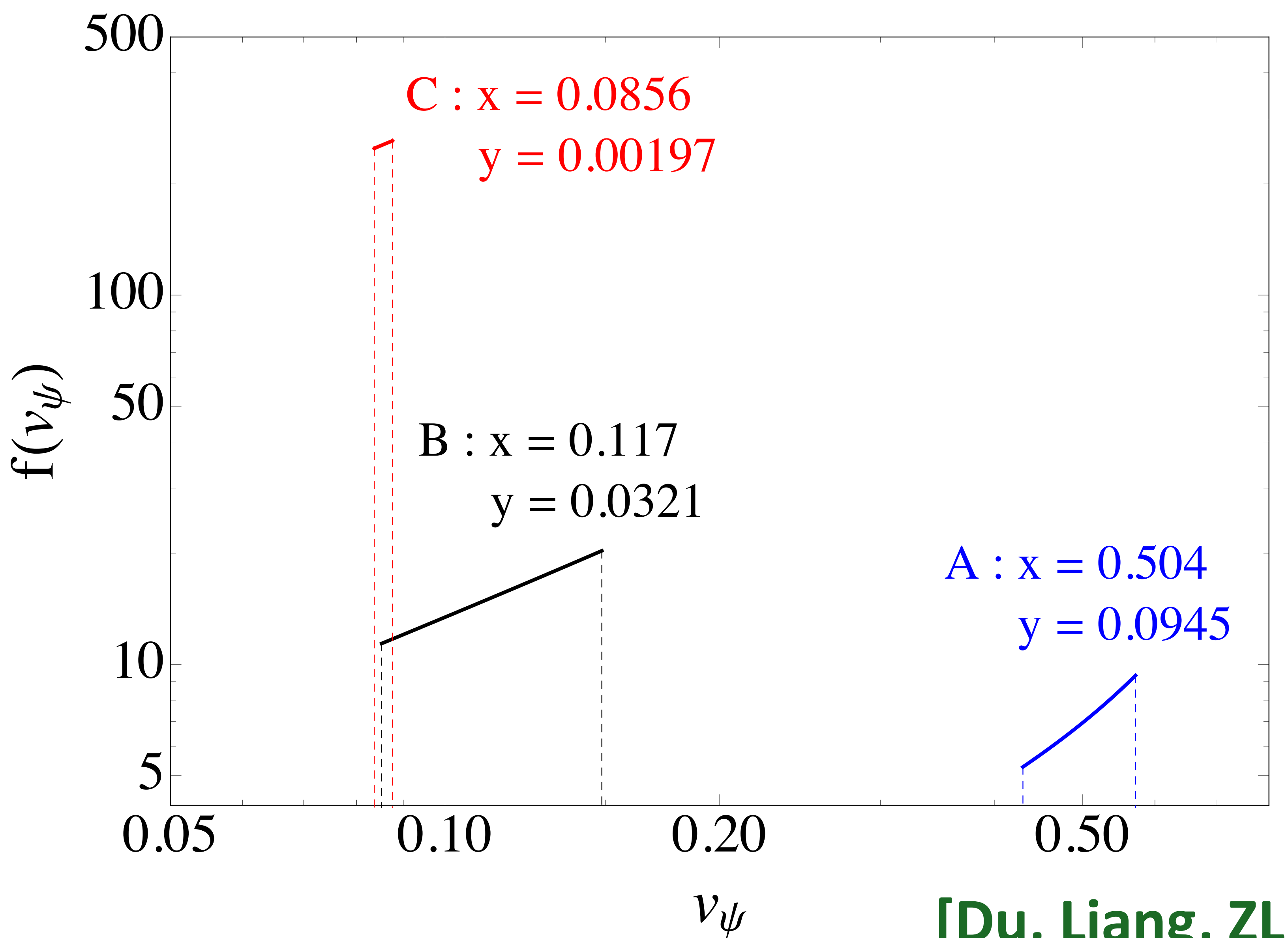
velocity of ψ

$$v_\psi(E_\psi) = \sqrt{1 - m_\psi^2/E_\psi^2}$$

$$v_\pm = \frac{|x \pm y|}{1 \pm xy}$$

velocity distribution

$$\int_{v_-}^{v_+} dv_\psi f(v_\psi) = \int_{v_-}^{v_+} dv_\psi \frac{v_\psi \sqrt{1-x^2}\sqrt{1-y^2}}{2\,(1-v_\psi^2)^{3/2}\,x\,y}$$



velocity depends on x & y , but not on any mass scale

[Du, Liang, ZL, Tran, Xue, 2006.11949]

ER spectrum

[see e.g. Essig+ 1108.5383, Roberts+ 1904.07127]

$$\frac{d\langle \sigma v_\psi \rangle}{dE_R} = \frac{\bar{\sigma}_{e\psi}}{2m_e} \int \frac{dv_\psi f(v_\psi)}{v_\psi} \int_{q_-}^{q_+} a_0^2 q dq |F(q)|^2 K(E_R, q),$$

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$$q_{\pm} = m_{\psi} v_{\psi} \pm \sqrt{m_{\psi}^2 v_{\psi}^2 - 2 m_{\psi} E_R}$$

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atomic function

[Roberts+ 1604.04559, 1904.07127, 1509.09044]

ER Events

differential event rate

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# of Xe atoms

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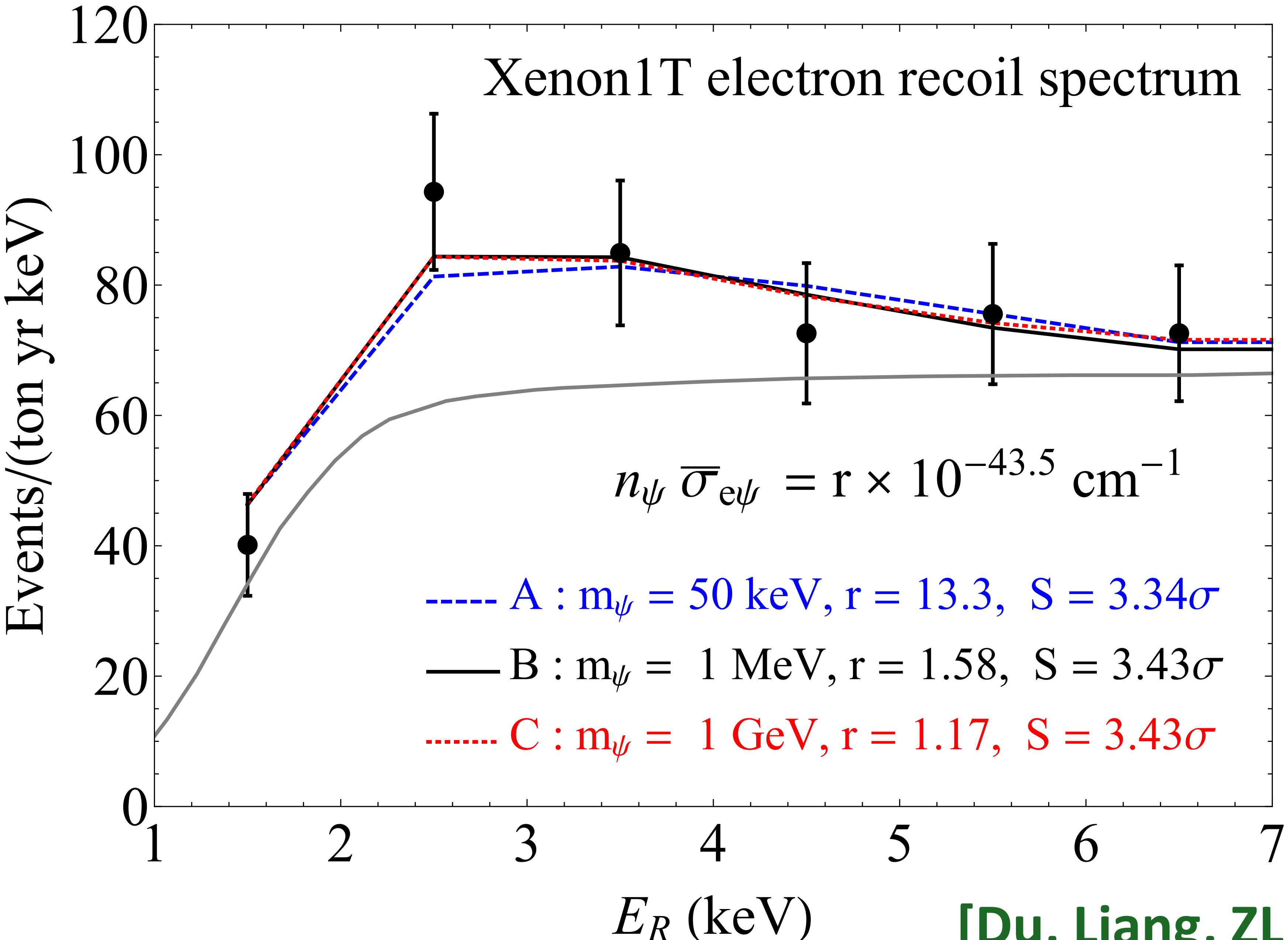
efficiency

ER spectrum from DM

Model	m_ψ (keV)	x	y	$n_\psi \bar{\sigma}_{e\psi}$ (cm^{-1})
A	50	0.504	0.0945	$13.3 \times 10^{-43.5}$
B	10^3	0.117	0.0321	$1.58 \times 10^{-43.5}$
C	10^6	0.0856	0.00197	$1.17 \times 10^{-43.5}$



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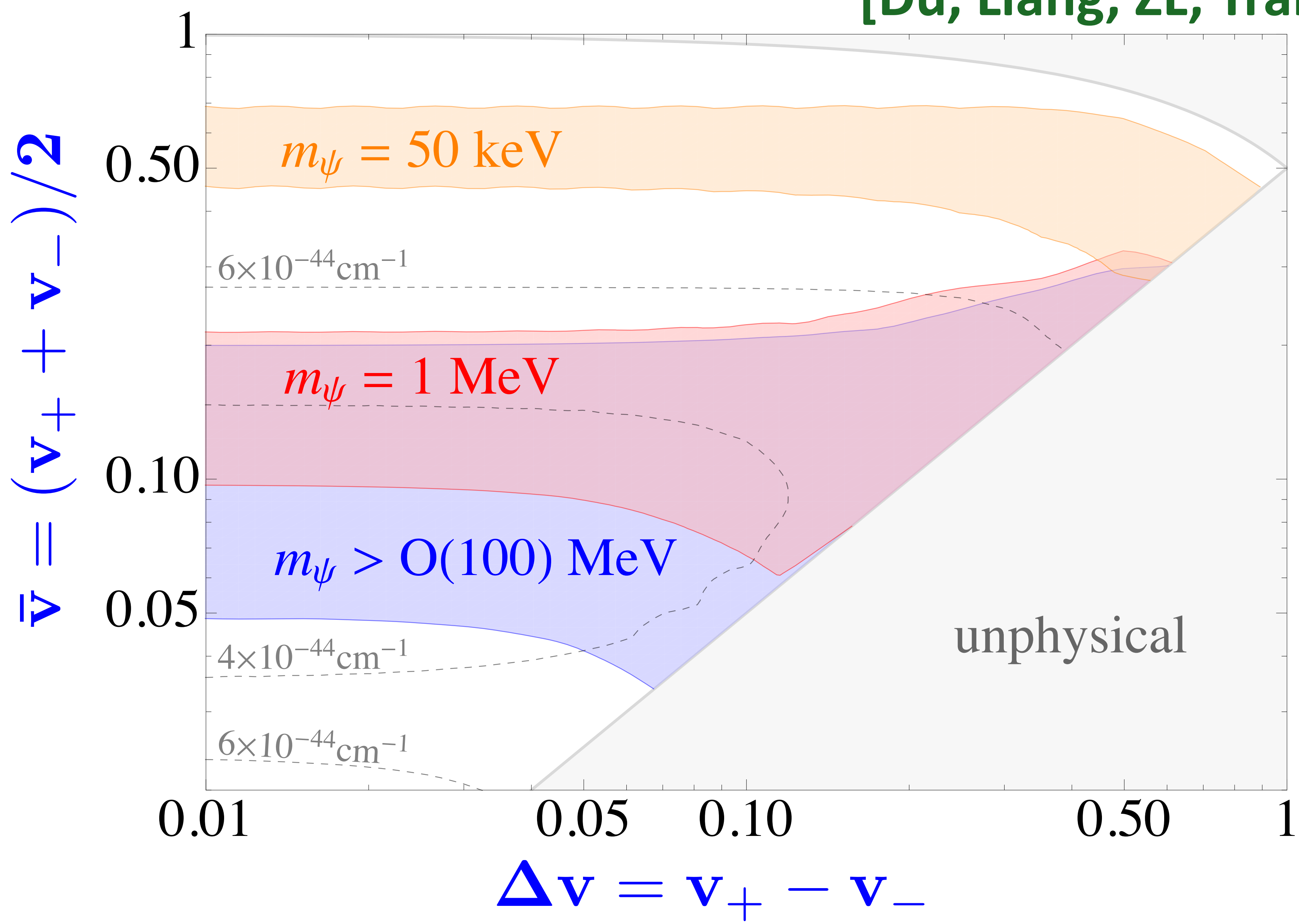
1σ region in the parameter space

[Du, Liang, ZL, Tran, Xue, 2006.11949]



$\Delta\chi^2 \leq 2.3$

$$\chi^2_{\rm min} = 1.656 \text{ w/ } (m_\psi,\, \bar{v},\, \Delta v) = (117.5 \text{ MeV},\, 0.086,\, 0.011)$$

$$n_\psi \bar{\sigma}_{e\psi} = 3.73 \times 10^{-44} \text{ cm}^{-1}$$

Particle flux

particle flux

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↑

4 FS

Particle flux

DM
annihilation
xsec

particle
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NFW profile

$$\rho_\chi(r) = \rho_s \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}$$

$$\gamma = 1$$

$$\rho_s = 0.31 \text{ GeV/cm}^3$$

$$r_s = 21 \text{ kpc}$$

$$J \simeq 10^{23} \text{ GeV}^2/\text{cm}^5$$

DM annihilation xsec (galaxy vs RD)

current xsec versus early universe

$$R \equiv \frac{\langle \sigma v \rangle_{\mathrm{freeze-out}}}{\langle \sigma v \rangle_{\mathrm{galaxy}}}$$

phase space

$$\sigma v_\chi \propto v_\chi \frac{|\mathbf{p}_\phi|}{|\mathbf{p}_\chi|} = \sqrt{x^2 + v_\chi^2 - x^2 v_\chi^2}$$

assuming all the particles are scalars

$$\mathrm{R} \simeq 1.1,\ 2.7,\ 3.6 \text{ for A, B, C}$$

DM-electron interaction xsec

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much larger than DMDD

stopped by rock (2 km)

$$\sigma_{e\psi} \gtrsim 10^{-24}\ \mathrm{cm}^2 \text{ for } m_\psi \simeq \mathcal{O}(\mathrm{MeV})$$

larger xsec for higher mass

[Emken+, 1905.06348]

One possible realization

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2 Dirac fermions couple to a U(1) gauge boson

$$g_h \phi_\mu (\bar{\chi}\gamma^\mu \chi + \bar{\psi}\gamma^\mu \psi)$$

both fermions are stable

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LEP constraints monophoton+MET

$$\frac{1}{\Lambda^2}\bar{\psi}\psi\bar{e}e \qquad \Lambda \gtrsim 440 \text{ GeV}$$

[Fox+, 1103.0240]

↓

$$\bar{\sigma}_{e\psi} \lesssim 1 \times 10^{-45}\,\text{cm}^2$$

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$m_\psi > 100$ GeV? → $\bar{\sigma}_{e\psi} \sim \mathcal{O}(10^{-24})\ \text{cm}^2$ **Xenon1T**

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$$m_\psi > 100 \text{ GeV?} \longrightarrow \bar{\sigma}_{e\psi} \sim \mathcal{O}(10^{-24}) \text{ cm}^2$$

Xenon1T

increase DM ann xsec for a larger flux?

Summary

- “Non-standard” velocity distributions of ‘DM’ particles can be obtained in the on-shell mediator models

- The new velocity distribution can explain the Xenon1T excess events in electron recoils

- Required particle flux and direct detection cross section are consistent with the canonical thermal annihilation cross section and the stopping effects of rock

- “Challenging” LEP constraints?