XENON1T Interpretation

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Outline

- Boost Interpretation of XENON1T anomaly。
  B. Fornal, P. Sandick, J. Shu, M. Su, Y. Zhao, [arxiv: 2006.11264 [hep-ph.CO]].
- Boost from the scattering in the Sun the "reflection"。
  Y. Chen, J. Shu, X. Xue, G. Yuan, Q. Yuan, [arxiv: 2006.12447 [hep-ph.CO]].
- Some comments

Boosted DM Interpretation

Boosted DM

Semi-annihilation (Z_3)

F. D'Eramo, J. Thaler, JHEP 06, 109 (2010)

$$\chi + \chi \to \bar{\chi} + X. \qquad \gamma_\chi = (5m_\chi^2 - m_X^2)/4m_\chi^2.$$

Two component

K. Agashe, Y.Cui, L. Necib, J. Thaler, JCAP, 10 062 (2014)

$$\psi_A + \bar{\psi}_A \to \psi_B + \bar{\psi}_B. \qquad \gamma_B = m_A/m_B.$$

Boosted DM flux

Thermal annihilation at the Galactic Center (GC)

$$\Phi_{\rm gal}^{\rm BDM} = 1.6 \times 10^{-6}\,{\rm cm}^{-2}{\rm s}^{-1} \times \left(\frac{\langle\sigma_{\rm ann} v\rangle}{5\times10^{-26}\,{\rm cm}^3{\rm s}^{-1}}\right)\left(\frac{10\,{\rm GeV}}{m_{\rm DM}}\right)^2,$$

Solar capture rate at the Sun

$$C(m_{\rm DM},\sigma_{\rm nucl}) \simeq 2\times10^{22}\,{\rm s}^{-1} \times \left(\frac{\sigma_{\rm nucl}}{10^{-42}\,{\rm cm}^2}\right)\left(\frac{10\,{\rm GeV}}{m_{\rm DM}}\right)^2.$$

BDM flux

$$\Phi_{\rm Sun}^{\rm BDM} = \frac{C(m_{\rm DM},\sigma_{\rm nucl})}{4\pi\,{\rm AU}^2} = 7.2\times10^{-6}\,{\rm cm}^{-2}{\rm s}^{-1}\left(\frac{\sigma_{\rm nucl}}{10^{-42}\,{\rm cm}^2}\right)\left(\frac{10\,{\rm GeV}}{m_{\rm DM}}\right)^2, \quad (5)$$

Signal Rate and Recoil Spectrum

The signal events for a given BDM flux

$$N_{\rm sig} = Z' \, n_{\rm Xe} \, V \, T \, \sigma_{\rm elec} \, \Phi^{\rm BDM} = Z' \, \frac{M_{\rm det} T}{m_{\rm Xe}} \times \sigma_{\rm elec} \times \Phi^{\rm BDM} \, .$$

BDM-electron cross section versus event number

$$\sigma_{\rm elec} = 3 \times 10^{-29} \, {\rm cm}^2 \left(\frac{10^{-6} \, {\rm cm}^{-2} {\rm s}^{-1}}{\Phi^{\rm BDM}} \right) \left(\frac{N_{\rm sig}}{100} \right).$$

Benchmark

$$\sigma_{\rm elec} = \frac{g_{\rm BDM}^2 g_e^2 m_e^2}{\pi \, m_{\rm med}^4} \, ,$$

mark, consider $g_{\rm BDM} = 1.1$, $g_e = 10^{-5}$, $m_{\rm BDM} = 10$ GeV, and $m_{\rm med} = 0.1$ MeV, which results in $\sigma_{\rm elec} = 4 \times 10^{-29}\,{\rm cm}^2$. Thus, for reasonable parameter values, a cross section as large as $\sigma_{\rm elec} = \mathcal{O}(10^{-29} - 10^{-28})\,{\rm cm}^2$ is

Penetration Length

Sun core: 150g/cm^3

$$L_{fs,S} \simeq 1\,\mathrm{m} \times \left(\frac{10^{-28}\,\mathrm{cm}^2}{\sigma_{\mathrm{elec}}}\right),$$

can not coming from the sun

Similarly for BDM captured through DM-electron (not nucleus) interactions

Earth core: 5.5g/cm^3

XENON1T: 1600m

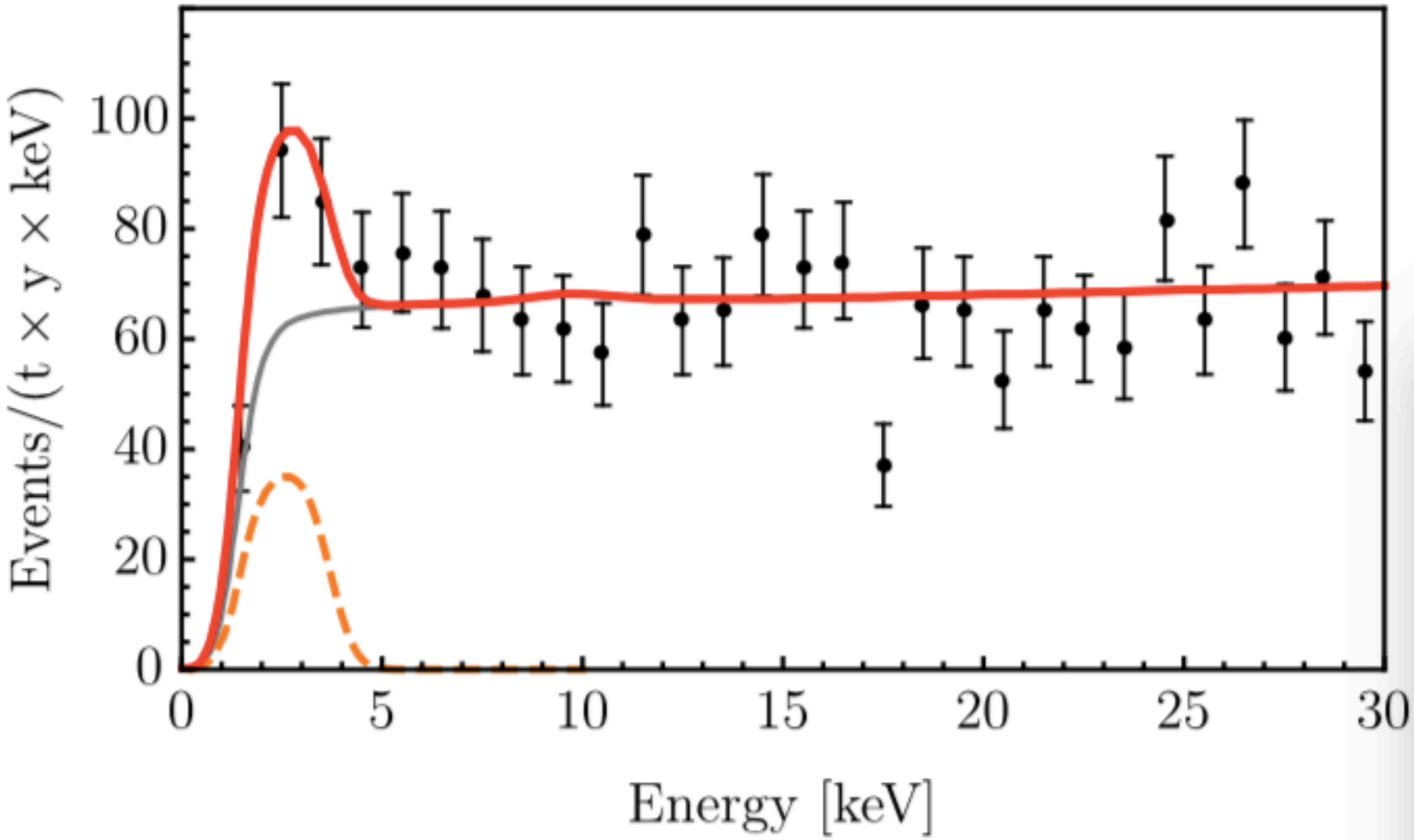
$$L_{fs,E} \simeq 60\,\mathrm{m} \times \left(\frac{10^{-28}\,\mathrm{cm}^2}{\sigma_{\mathrm{elec}}}\right).$$

Earth is semi-opaque: daily modulation.

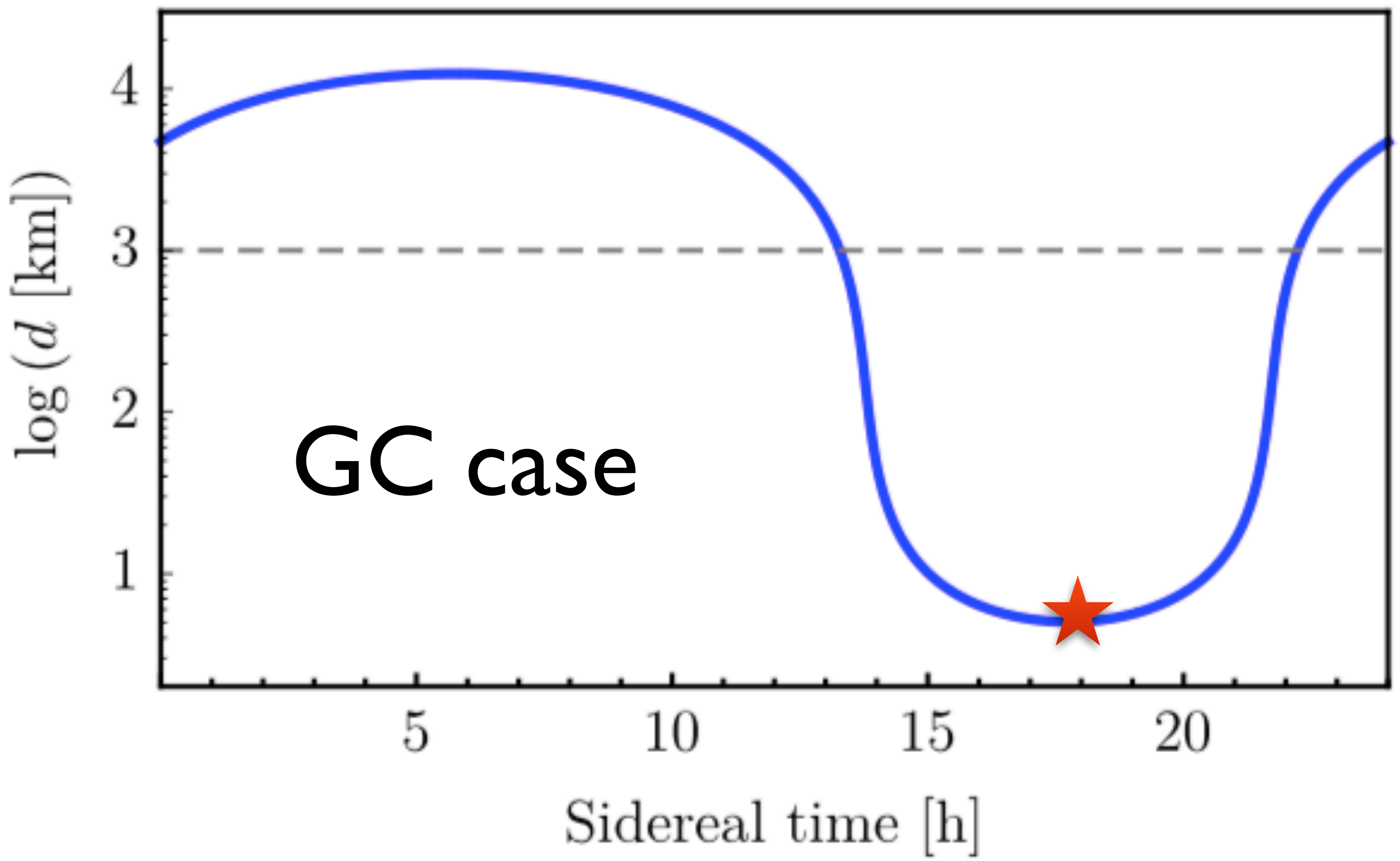
Recoil energy spectrum

In the limit $m_{\rm BDM} \gg m_e$ $\qquad E_e \leq 2 m_e v_{\rm BDM}^2$

$$\frac{d\sigma_{\rm elec}}{dE_e} = {\rm const} \times \Theta(2 m_e v_{\rm DM}^2 - E_e)\ ,$$



Daily modulation



Must use sidereal time

$$d_e \gtrsim 1000\ \text{km} \left(\frac{10^{-28}\ \text{cm}^2}{\sigma_{\text{elec}}}\right)\left(\frac{m_{\text{BDM}}}{10\ \text{GeV}}\right)\left(\frac{v_{\text{BDM}}}{0.1\ c}\right)^2.$$

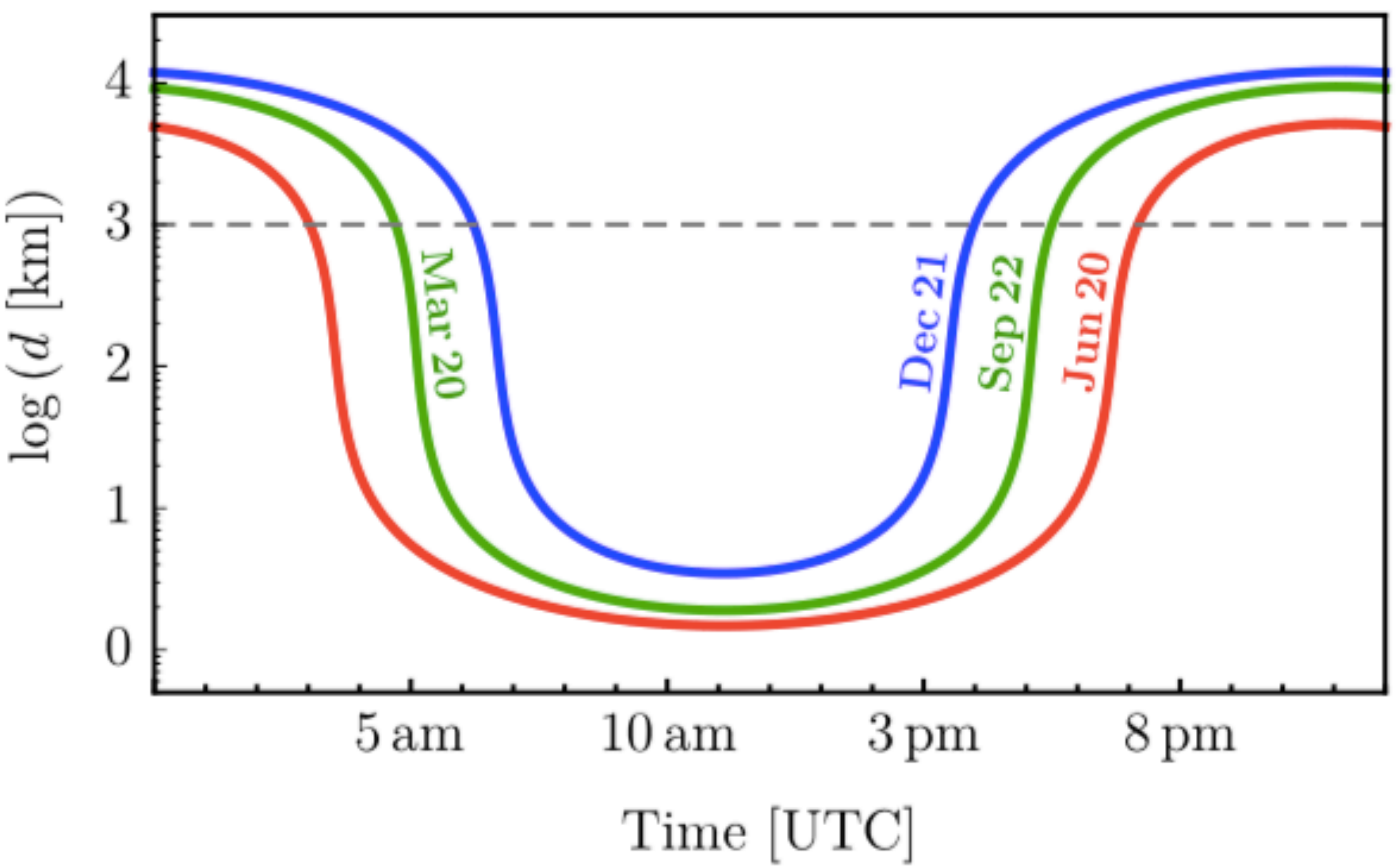
Stopped distance

- The minimal d (star position) tells you the direction of the BDM

Non-directional XENON experiment tells you the direction of BDM flux, is it COOL?

If not GC direction, maybe from nearby DM sub-halo or mini-cluster

Daily modulation



Sun modulation changes seasonally

summer/winter: longest/ shortest daily exposures

Imagine intermediate \phi help escape from the Sun

$$\psi_A + \bar{\psi}_A \to \phi + \phi^* \to 2\psi_B + 2\bar{\psi}_B,$$

Needs more analysis for the real modulation

More details in the future

We have considered the full possibilities for daily modulation: GC, Sun, nearby sub-halo/mini-cluster

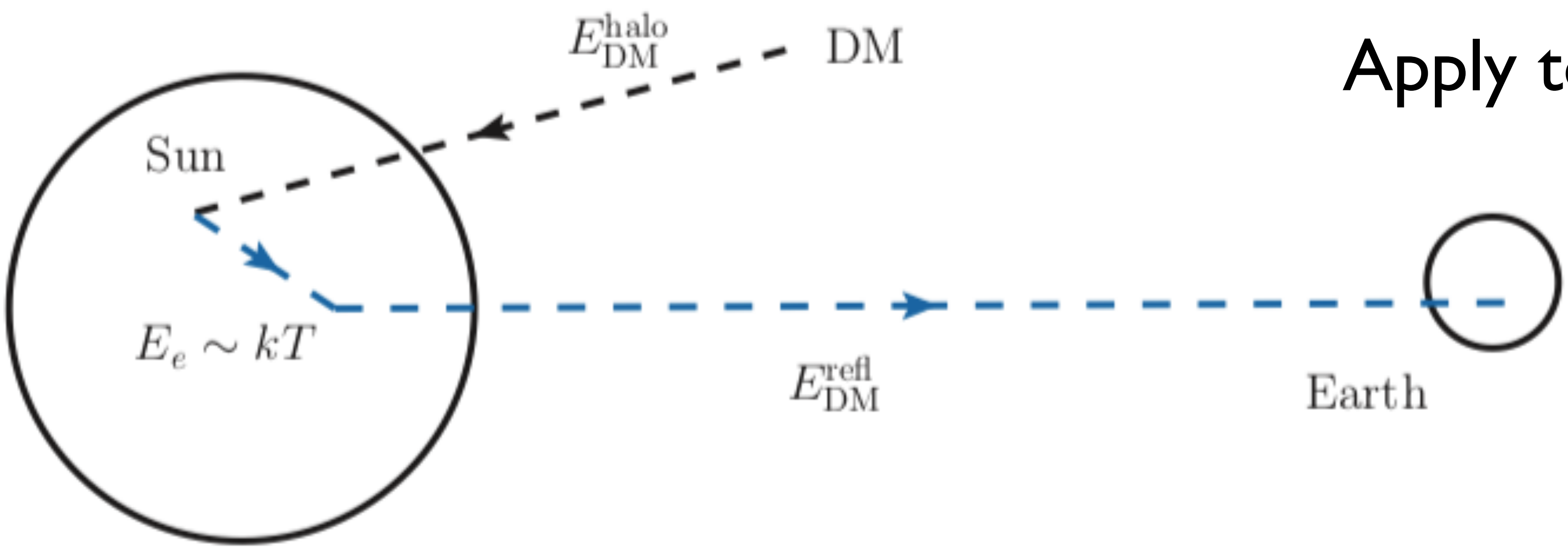
- The rock density above Gran Sasso < average of earth

- The electron energy loss spectrum inside Earth。 Workout the real survival probability.

- Other experiments like LZ, PandaX, etc.

Sun-heated DM Interpretation

Sun reflected/heated DM



Apply to any DM in halo

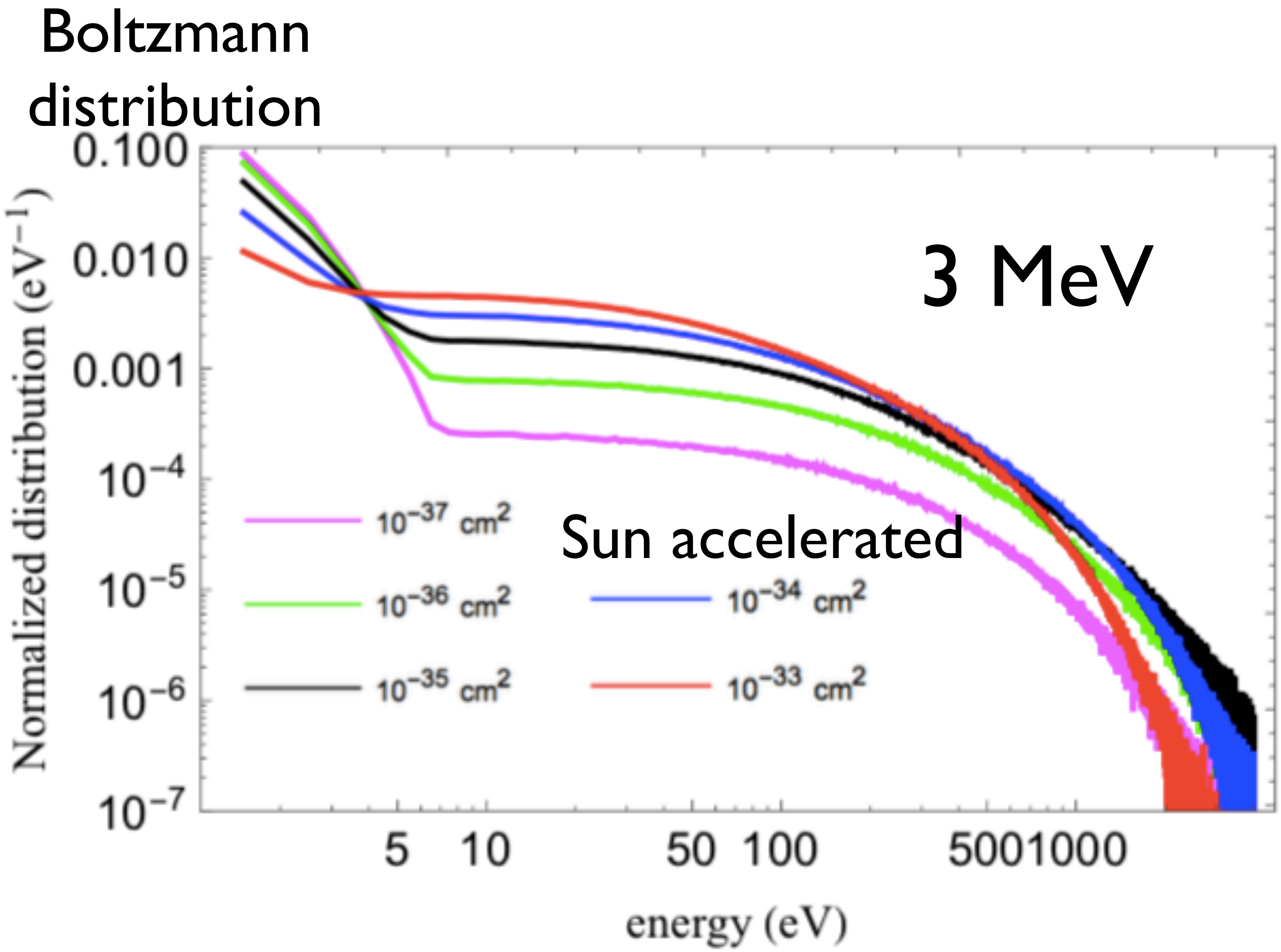
H-p. An, M. Pospelov, J. Pradler, A. Ritz, Phy.Rev.Lett. 120 14, 141801 (2018)

"heated": the halo DM v < reflected v, not really symmetrically reflect.

Benchmark: maximal momentum transfer. m_{DM} = m_e = 0.5 MeV

How we rescale the distribution?

$F_{A_\rho = 16\pi R_\odot^2}(E)$



smaller DM-e cross section, E increase as reflection in the Sun core (higher T)

$$\Phi_{\rm refl} \sim \frac{\Phi^{\rm halo}}{4} \times \begin{cases} \frac{4S_g}{3}\left(\frac{R_{\rm core}}{1\,{\rm A.U.}}\right)^2 \sigma_e n_e^{\rm core} R_{\rm core}, & \sigma_e \ll 1\,{\rm pb}, \\ S_g \left(\frac{R_{\rm scatt}}{1\,{\rm A.U.}}\right)^2, & \sigma_e \gg 1\,{\rm pb}. \end{cases}$$

The energy spectrum is almost the same, change the normalization

How we rescale the distribution?

- The normalization $$\frac{d\Phi_{\rm refl}}{dE} = \Phi_{\rm halo} \times \frac{A_\rho F_{A_\rho}(E)}{4\pi(1\,{\rm A.U.})^2}.$$

- 3 MeV —> 0.5 MeV Use the "endpoint" as a handle

the dark matter mass and scattering cross section the average energy of the reflected DM, the endpoint of the reflected DM spectrum (defined as the upper limit of the energy interval containing 95% of the reflected flux), and the total

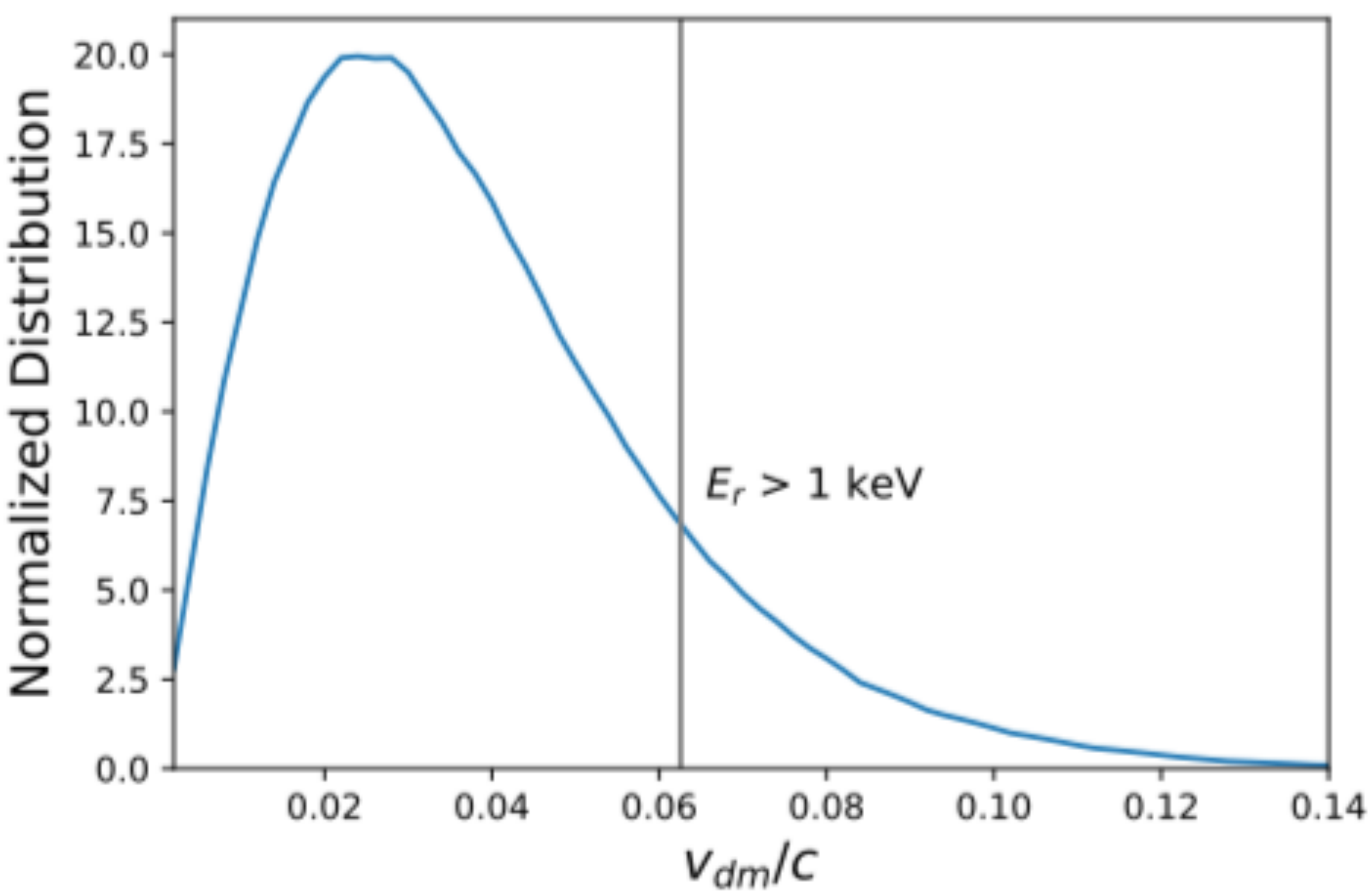
Endpoint: 95% (not the cutoff), it is actually these 5% that gives u the signal.

0.5 MeV	527 eV	510 eV	437 eV	339 eV	236 eV
	1796 eV	1725 eV	1466 eV	1165 eV	819 eV
	12 $\rm cm^{-2}sec^{-1}$	84 $\rm cm^{-2}sec^{-1}$	256 $\rm cm^{-2}sec^{-1}$	472 $\rm cm^{-2}sec^{-1}$	645 $\rm cm^{-2}sec^{-1}$
2 MeV	364 eV	373 eV	370 eV	319 eV	243 eV
	1223 eV	1245 eV	1271 eV	16071152 eV	871 eV
	2.9 $\rm cm^{-2}sec^{-1}$	21 $\rm cm^{-2}sec^{-1}$	63 $\rm cm^{-2}sec^{-1}$	116 $\rm cm^{-2}sec^{-1}$	157 $\rm cm^{-2}sec^{-1}$
4 MeV	248 eV	270 eV	314 eV	306 eV	255 eV
	810 eV	883 eV	1108 eV	1158 eV	934 eV
	1.3 $\rm cm^{-2}sec^{-1}$	9.6 $\rm cm^{-2}sec^{-1}$	30 $\rm cm^{-2}sec^{-1}$	55 $\rm cm^{-2}sec^{-1}$	74 $\rm cm^{-2}sec^{-1}$

Unfortunately we have to average the 2MeV and 4MeV to get the 3MeV…….

Spectrum

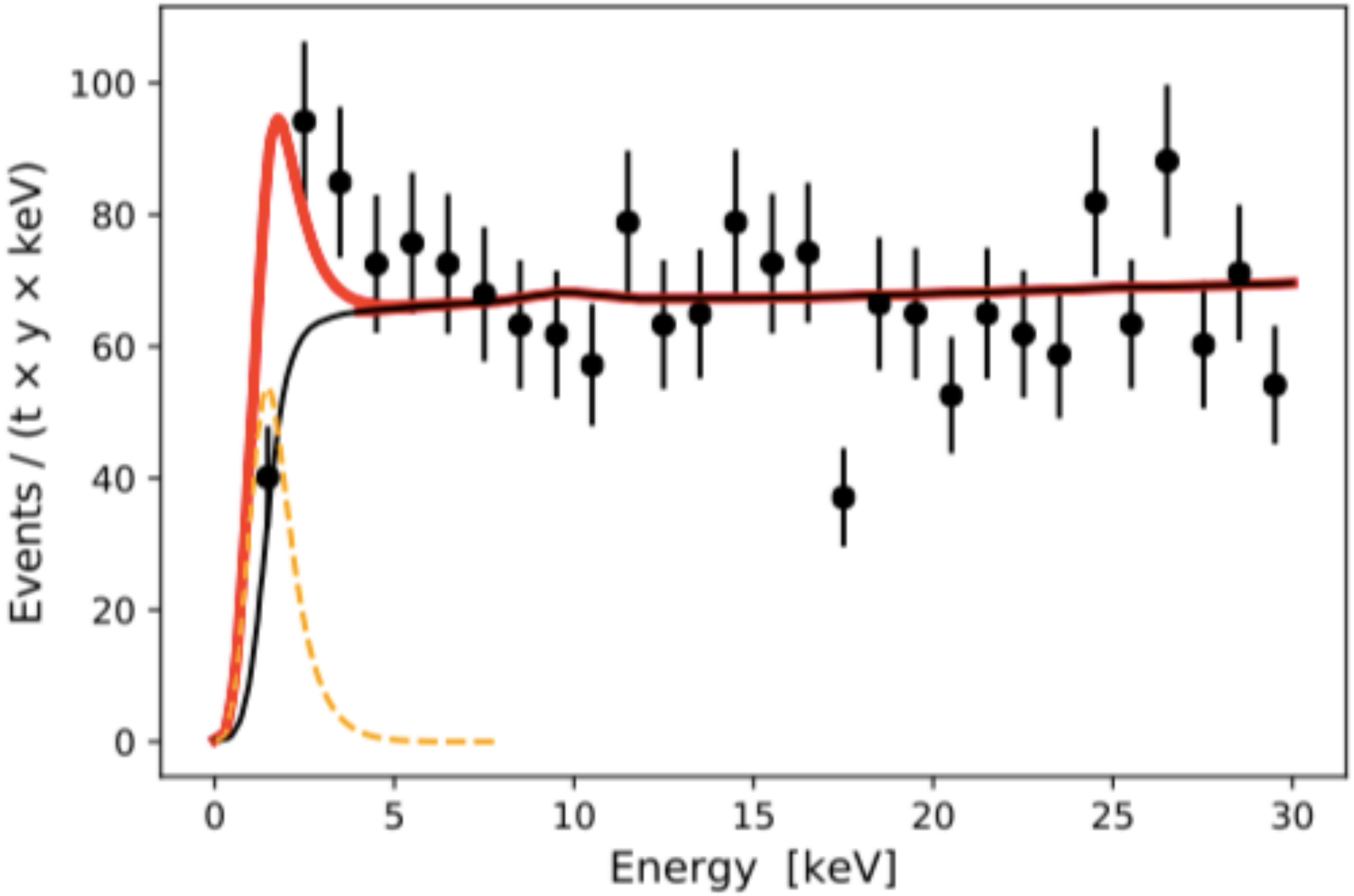
- Final distribution (not logplot)



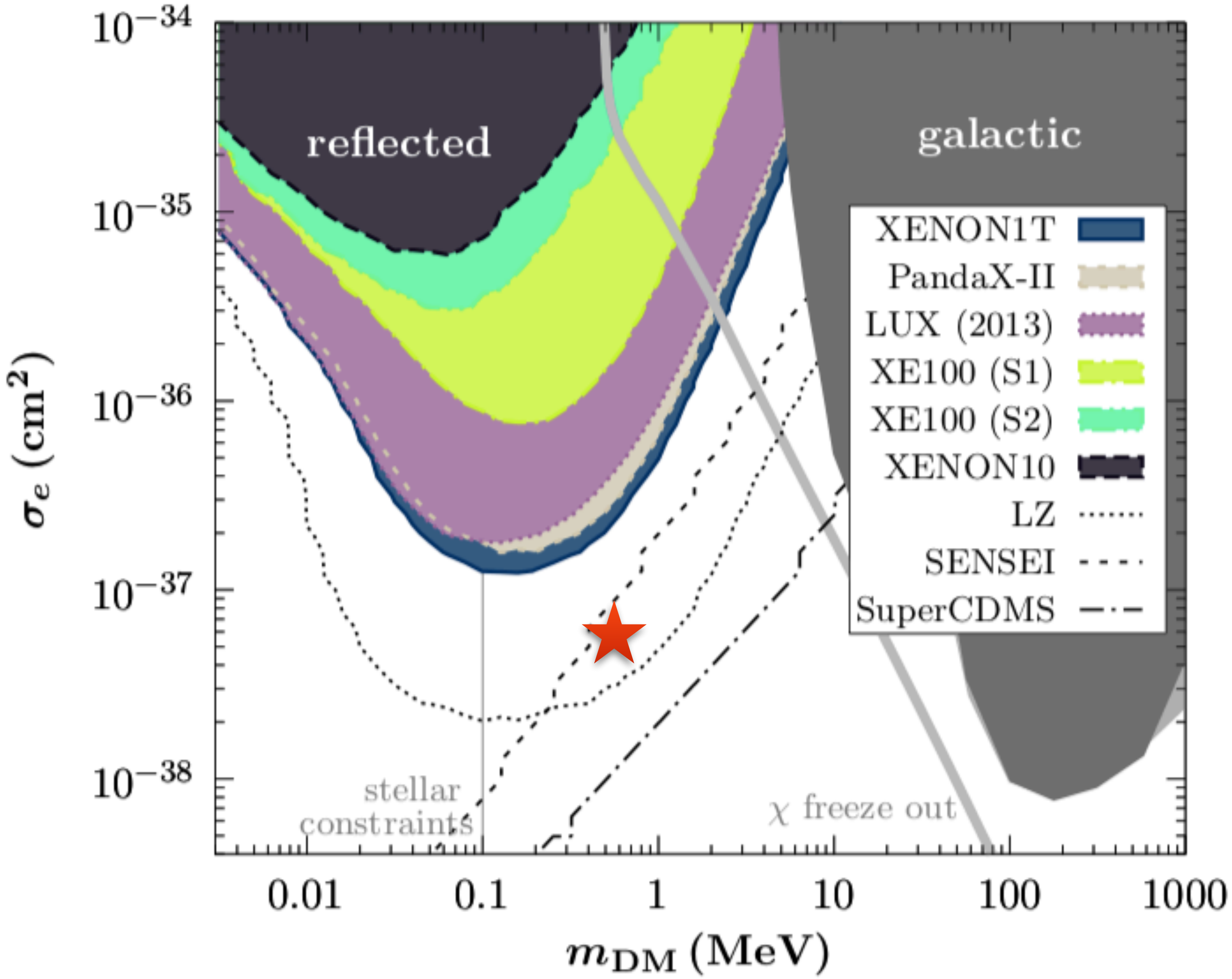
The event spectrum

$$\frac{\mathrm{d}N}{\mathrm{d}E_\mathrm{r}} = N_d \times \int \frac{\mathrm{d}\sigma}{\mathrm{d}E_\mathrm{r}}(v_\mathrm{dm}, E_\mathrm{r}) \, \frac{\mathrm{d}\Phi_\mathrm{heat}}{\mathrm{d}v_\mathrm{dm}} \, \mathrm{d}v_\mathrm{dm},$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_\mathrm{r}}(v_\mathrm{dm}, E_\mathrm{r}) = \frac{\sigma_e}{2m_\mathrm{e}v_\mathrm{dm}^2} \int_{q_-}^{q_+} a_0^2 \, q \, \mathrm{d}q \, \left|F(q)\right|^2 K(E_\mathrm{r}, q),$$



Low threshold DM experiment



H-p. An, M. Pospelov, J. Pradler, A. Ritz, Phy.Rev.Lett. 120 14, 141801 (2018)

First pointed out in

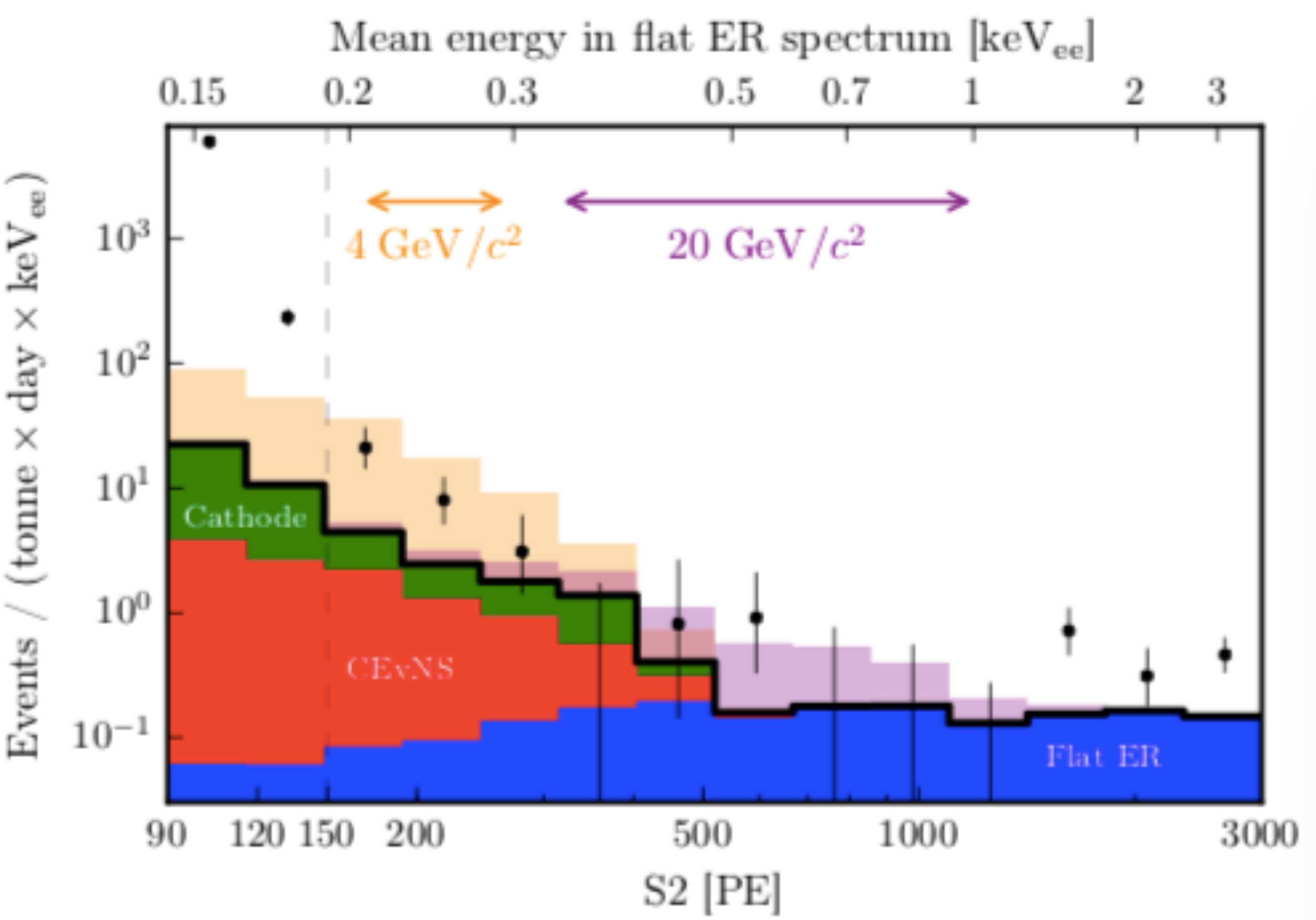
R. Essig, A. Manalaysay, J. Mardon, P. Sorensen and T. Volansky, Phy.Rev.Lett. 109 021301 (2012)

Cosmology bounds (BBN, N_eff, etc) prefer relative light mediators

B. Lehmann, S. Profumo, [arxiv: 2002.07809 [hep-ph.CO]].

Low threshold DM experiment

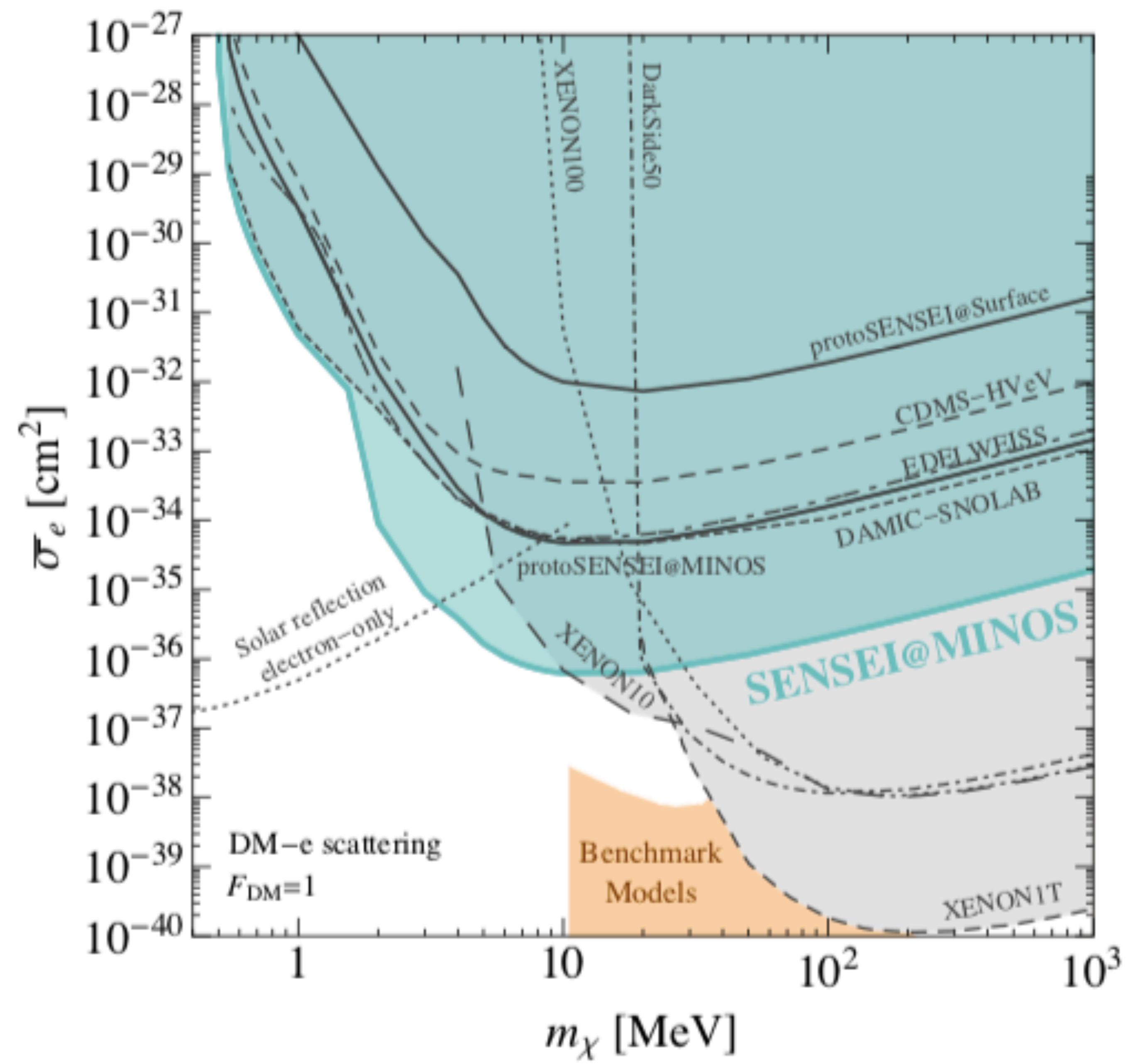
XENON1T SR2 only



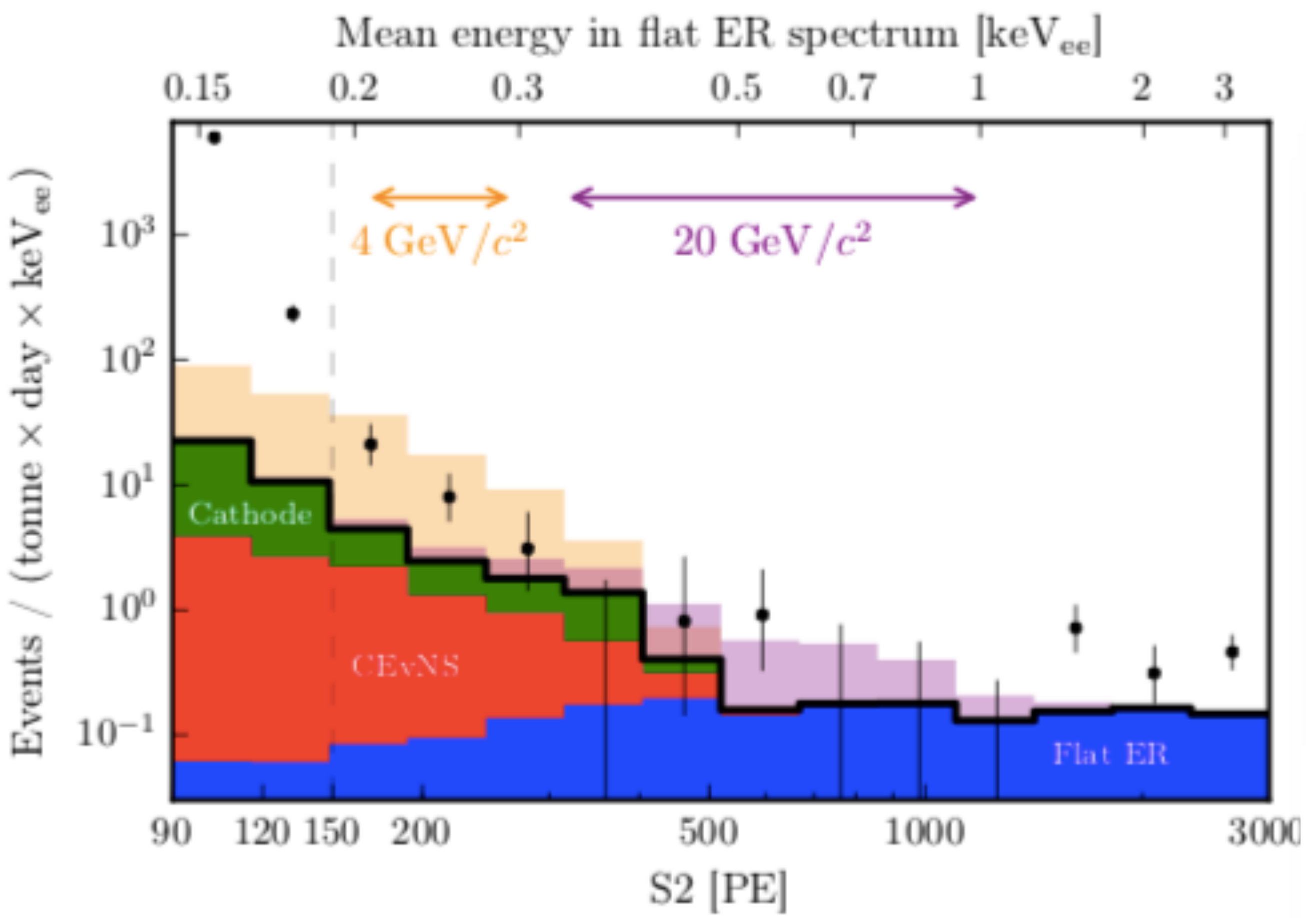
E. Aprile et al. [XENON], Phy.Rev.Lett. 123 25 251801 (2019)

SENSEI

L. Barak et al. [SENSEI], [arxiv: 2004.11378 [atro-ph.CO]].

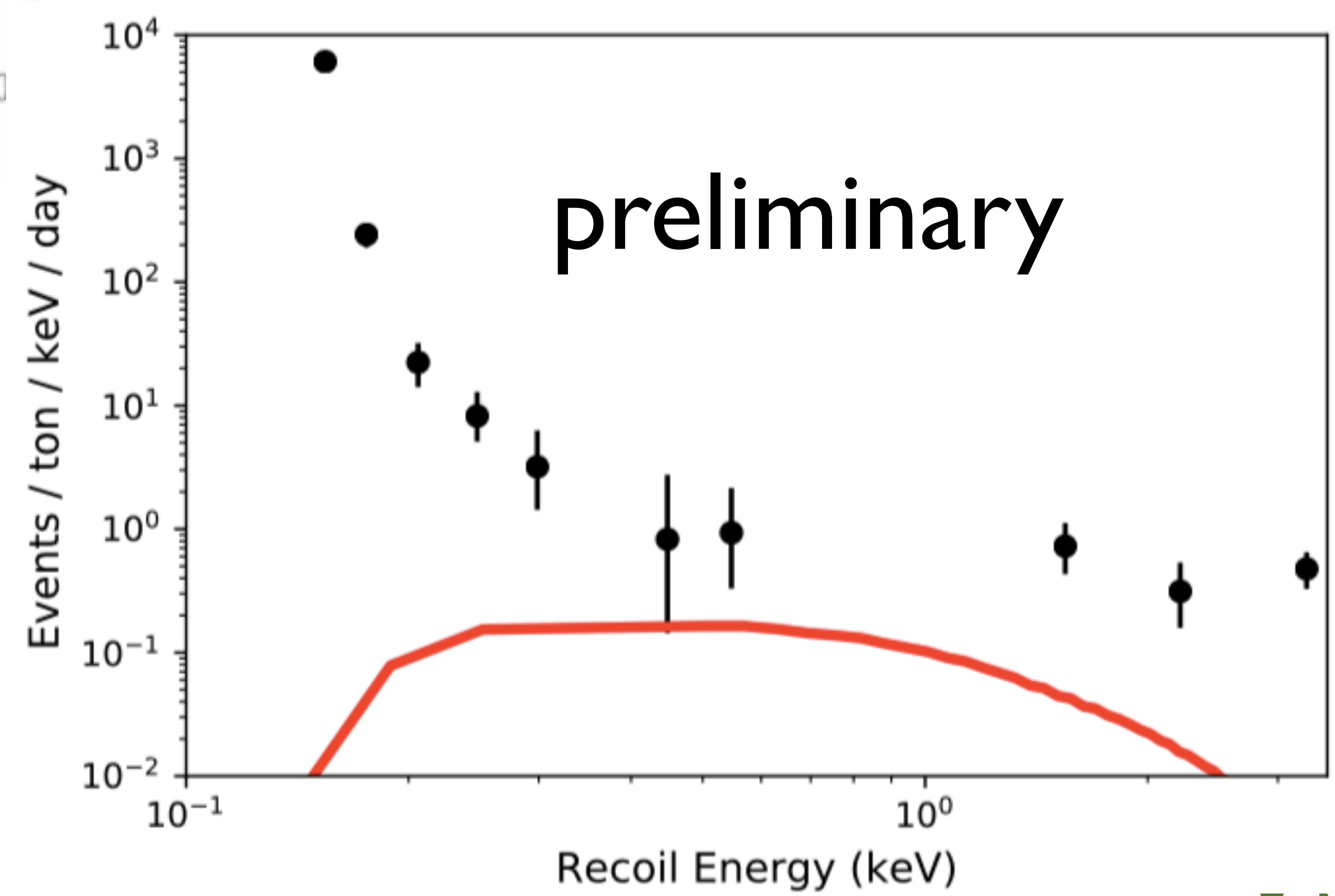


Low threshold DM experiment



The current SENSEI is not expected to be as strong as XENON1T SR2 only

Sun reflection heated benchmark



Summary and comments

- Boost Interpretation (works fine)。
- BDM flux naturally from GC. The flux from the Sun is not realized in the simplest scenario.
- Striking daily modulation signals. Can even know the direction of the signal source. Expected to check that in the future.

Better theorists guide experimentalists what to look next.

- Clean model, no specific assumption on DM models.
- Can help the fit for the spectrum。
- Consistent with the current low threshold experiment. (future results probe the explanation.)

Back up slices

Signal Rate and Recoil Spectrum

The signal events for a given BDM flux

$$N_{\rm sig} = Z' \, n_{\rm Xe} \, V \, T \, \sigma_{\rm elec} \, \Phi^{\rm BDM}$$
$$= Z' \, \frac{M_{\rm det} T}{m_{\rm Xe}} \times \sigma_{\rm elec} \times \Phi^{\rm BDM} \, .$$

Z' is the effective number of electrons in xenon that undergo recoils. ~ 40

N, O, M can be kicked out to free electrons