Constraining boosted dark matter-electron interactions with LUX-ZEPLIN

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for the LZ collaboration

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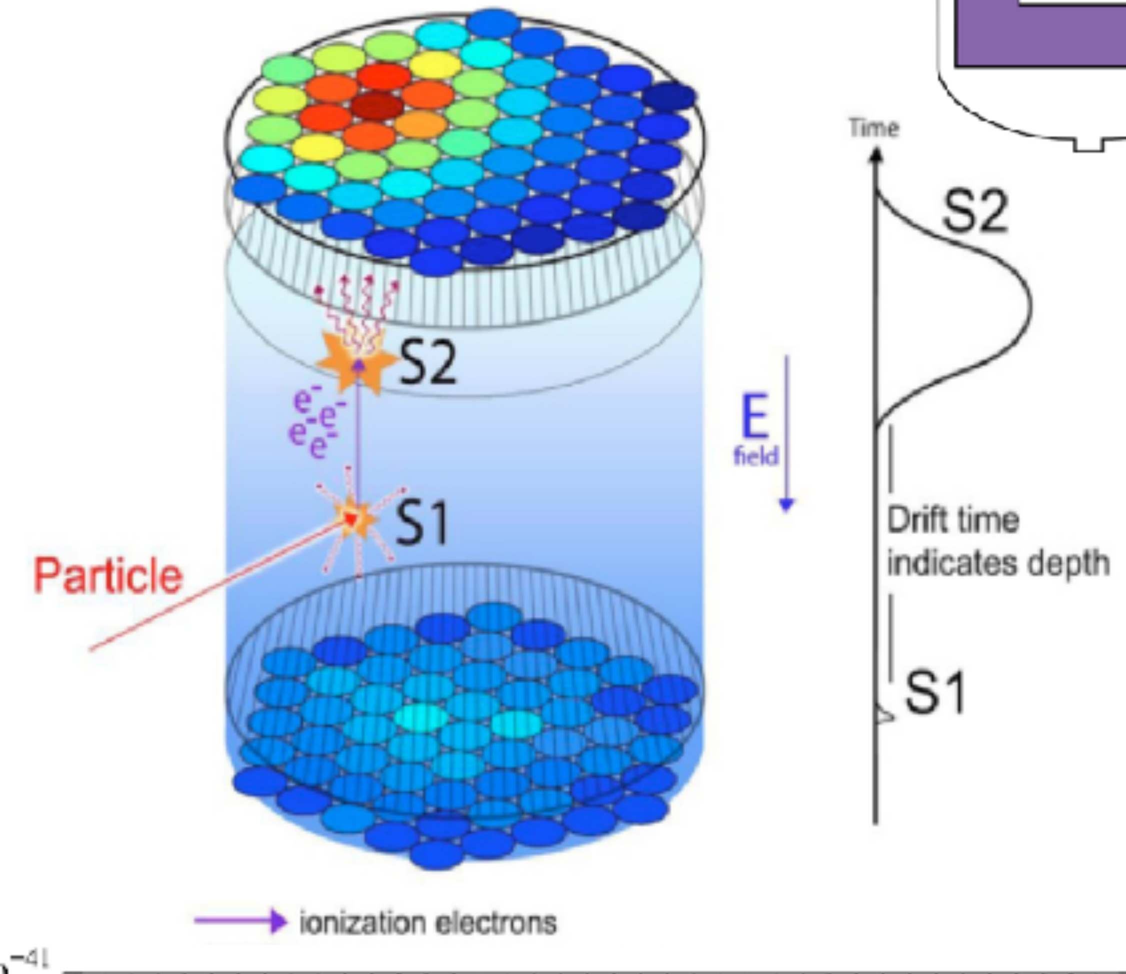
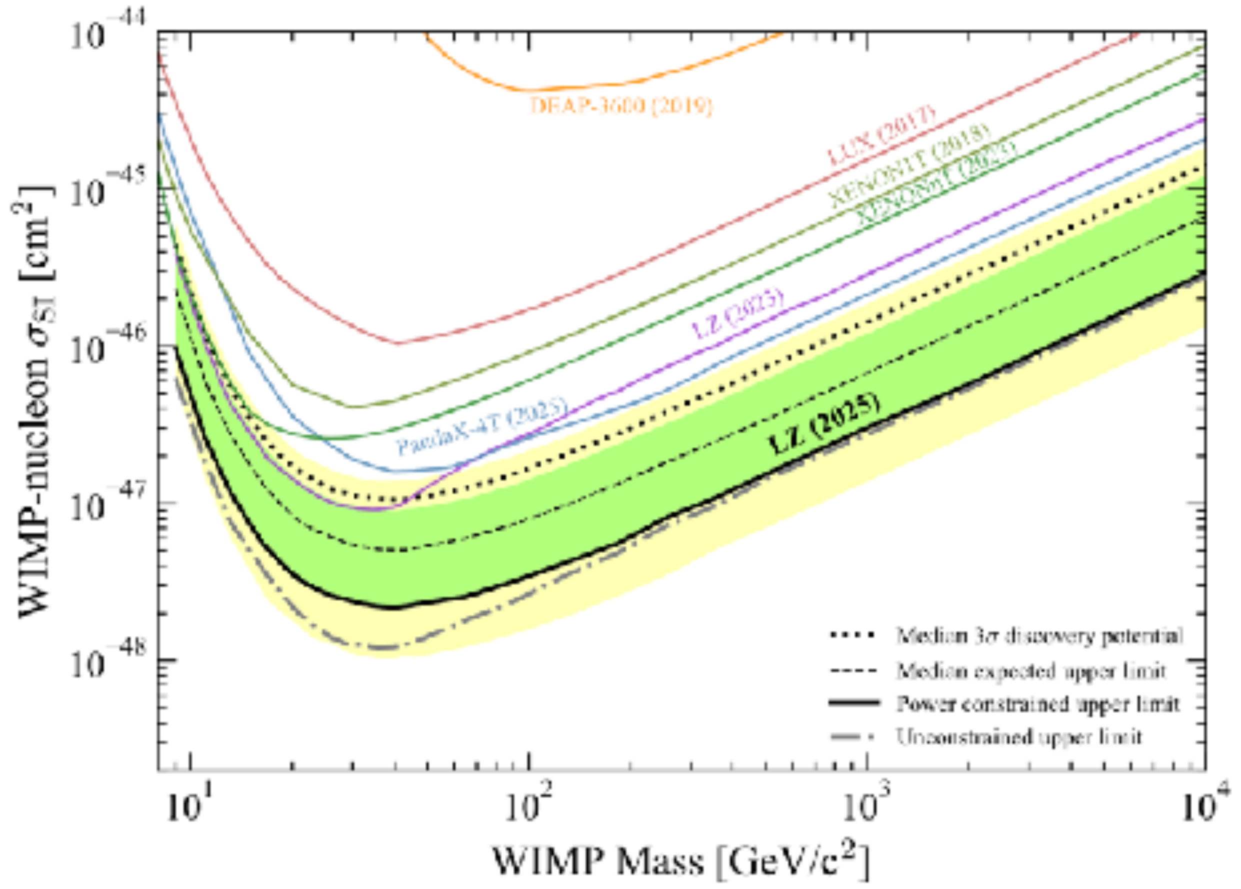
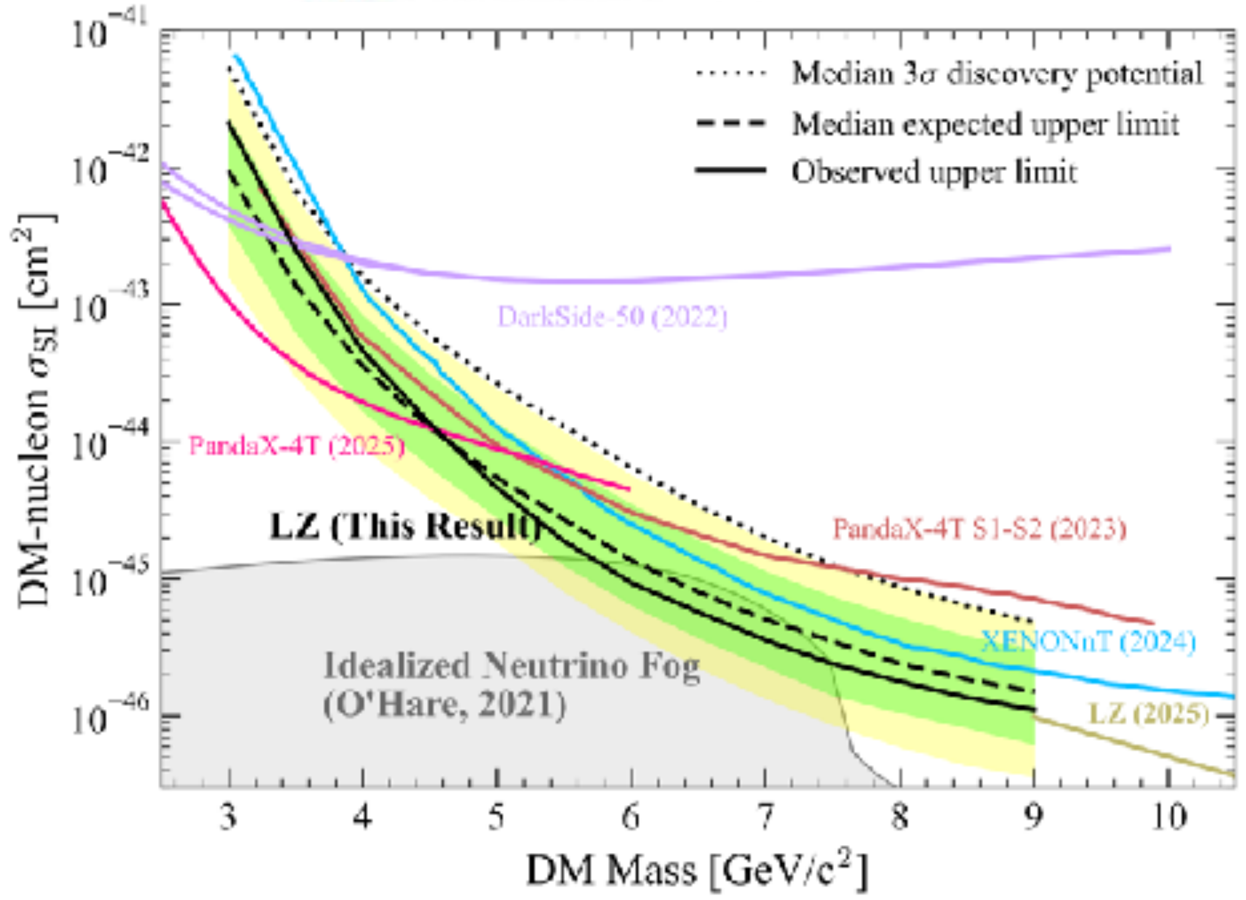
The LZ Dark Matter Experiment

- 7-tonne dual-phase xenon TPC with a broad rare-event physics program at SD, USA
- Primarily searches for prompt scintillation (S1) and ionization (S2) signals from WIMP-nucleon interactions
- The most sensitive experiment for WIMPs with masses above 5 GeV/c^2
- See also the other LZ talks by Daniel Kodroff, Aiham Al Musalhi, and Sam Eriksen





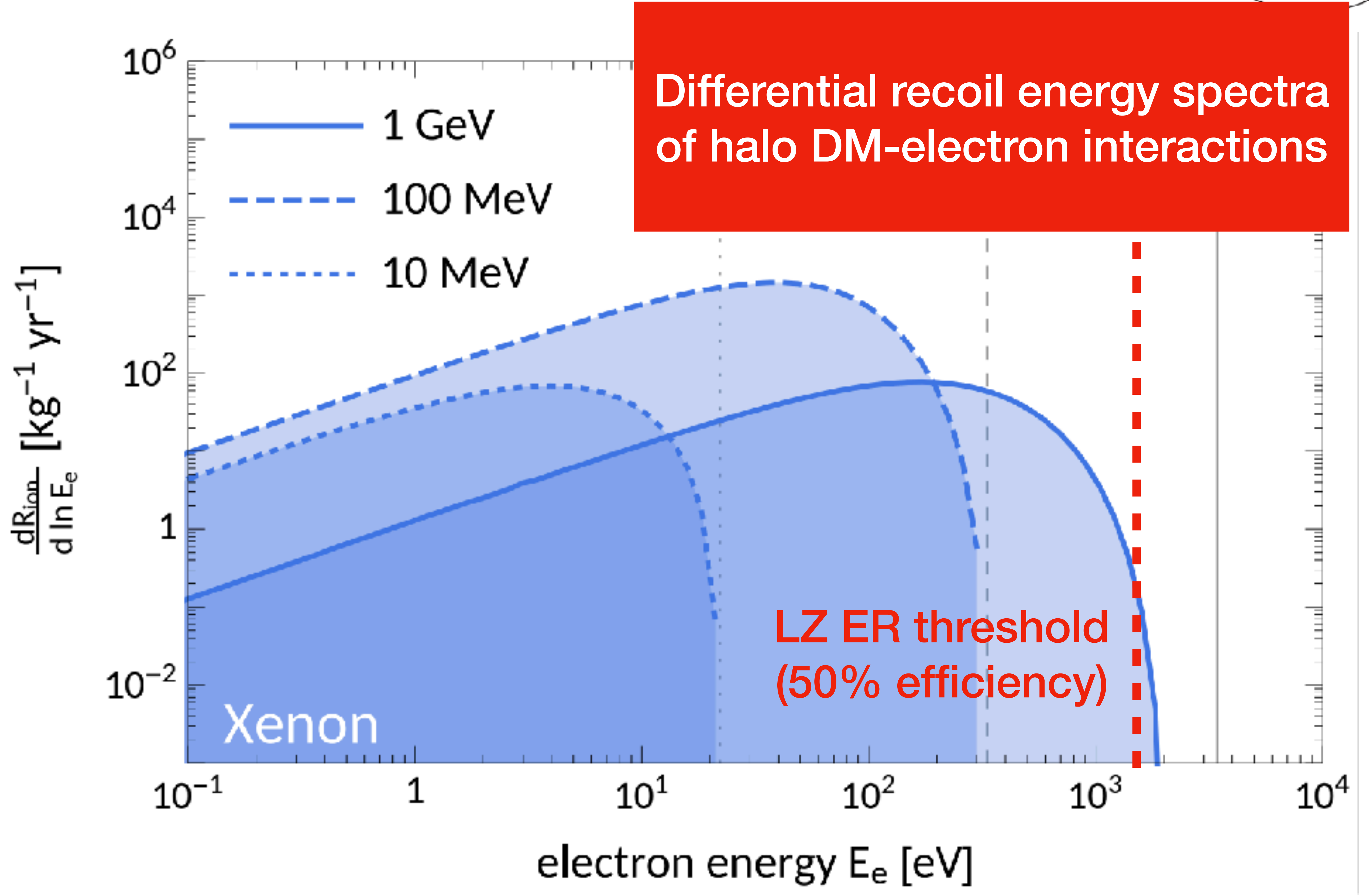
Heavy WIMPs [LZ collaboration, Phys. Rev. Lett. 135 (2025) 011802]



Light WIMP and ^{8}B neutrino CEνNS [LZ collaboration arXiv:2512.08065, accepted by PRL]

Experimental Search for DM-electron Interactions

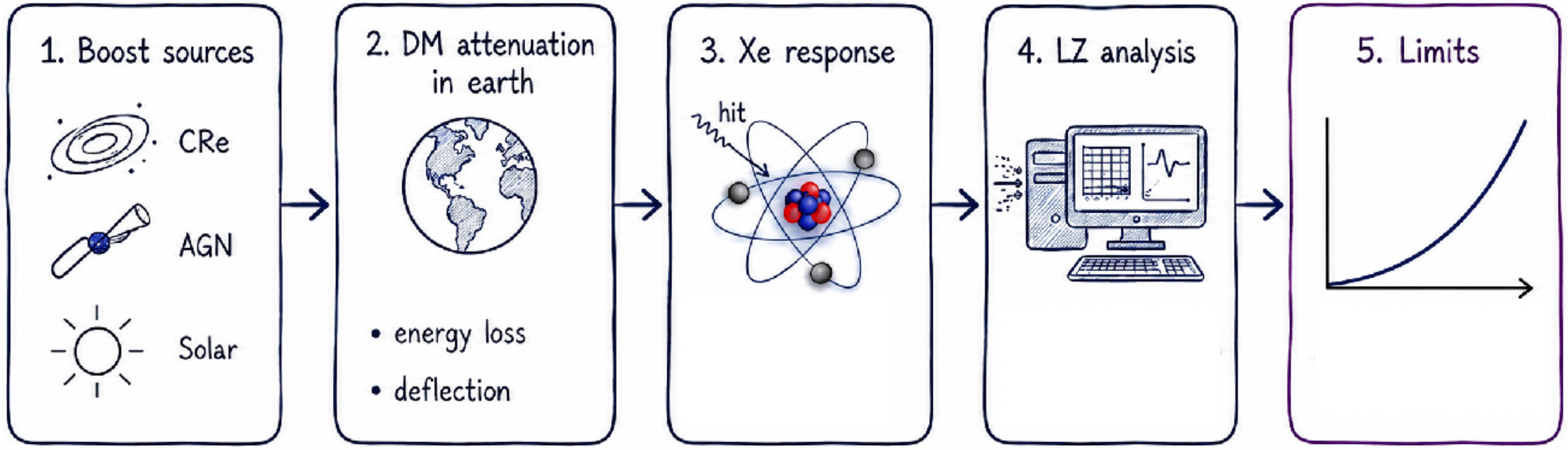
- Typically, because of kinematic limitations, dark matter-electron interactions in liquid xenon are only detectable in the ionization-only channel
- ***Boosted DM overcomes this limitation!***
- Boosting turns otherwise S2-only DM–electron scattering into detectable S1+S2 ER signatures in LZ



[Catena et al., Phys. Rev. Res. 2 (2020) 033195]

Boosting Dark Matter (DM) With Electrons

- Three boosting mechanisms explored
  - Cosmic-ray electrons (CRe)
  - Active galactic nuclei jets (AGN)
  - Solar thermal electron reflection
- Accounting for
  - Lorentz structure of the χ-e^- interaction
  - Mediator mass limits
  - Earth propagation



Flow chart created by ChatGPT

Cosmic ray electron upscattering

- Galactic cosmic-ray electrons (CRe) are ubiquitous throughout the Milky Way
  - Convolve the CRe distribution with the dark matter profile then integrate along the line of sight for the flux of boosted DM near Earth
  - Differential cross section from tree-level DM-electron elastic scattering
- CRe produces a broad boosted flux over keV–MeV DM in kinetic energies

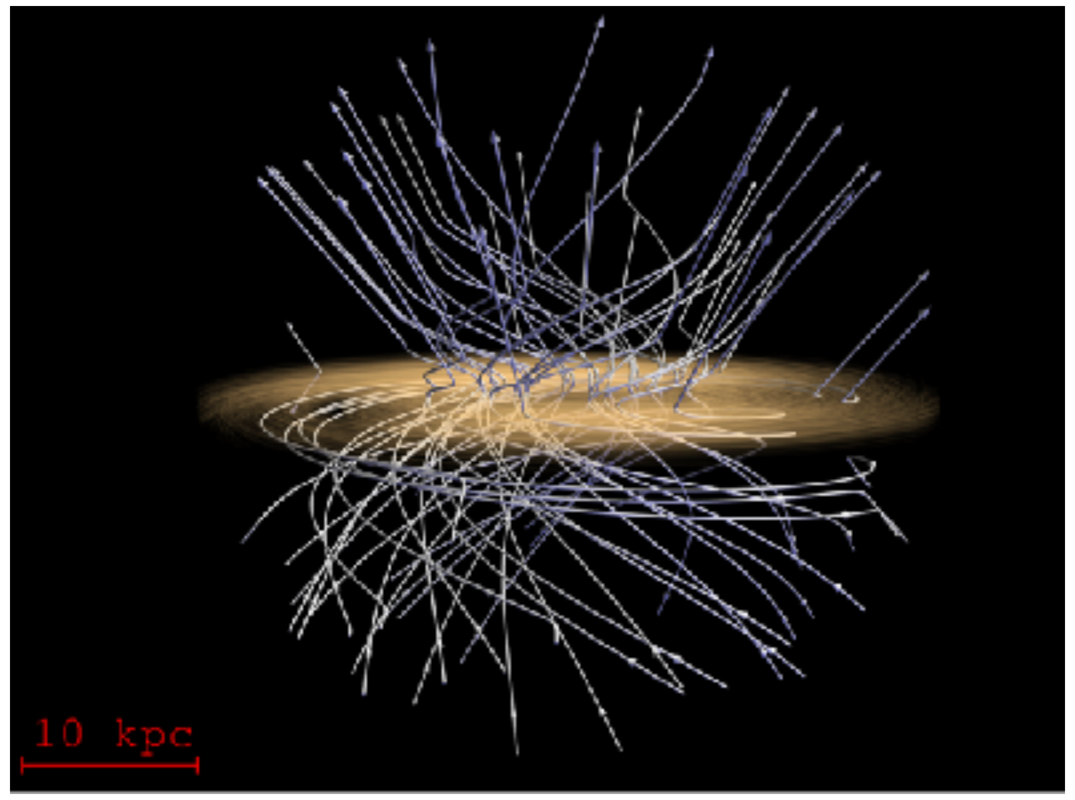
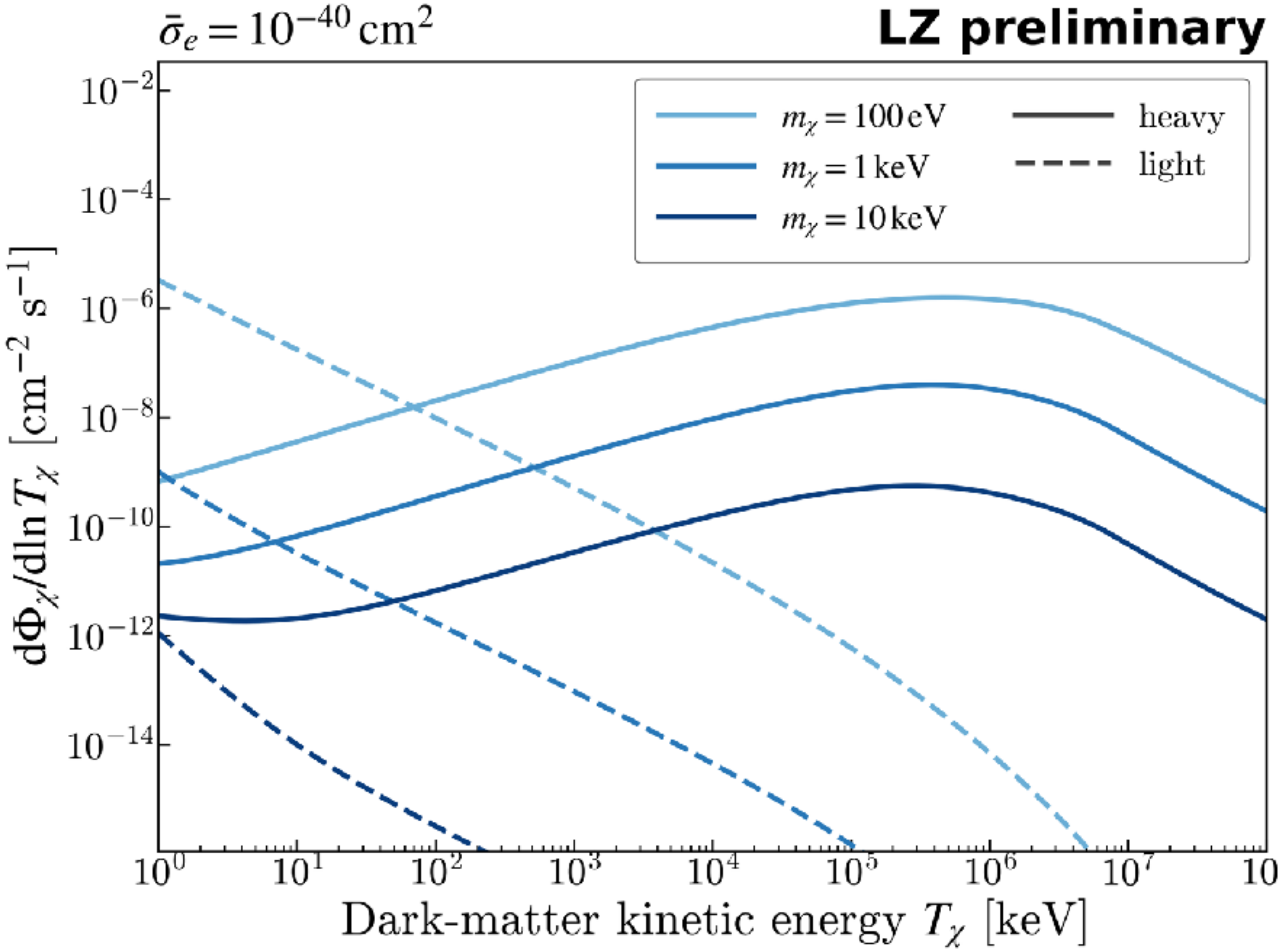


Illustration credit: NASA



*Heavy: mediator mass $m_{\text{med}} \gg$ momentum transfer q

Light: $m_{\text{med}} \ll q$

AGN jets

- Active galactic nuclei (AGN) can launch powerful jets of SM particles, including electrons, from the vicinity of central supermassive black holes
- As the jet traverses the DM cusp, $e^- - \chi$ scatterings produce a flux of boosted DM
- Boosted DM flux spectrum generally harder than CRe-induced

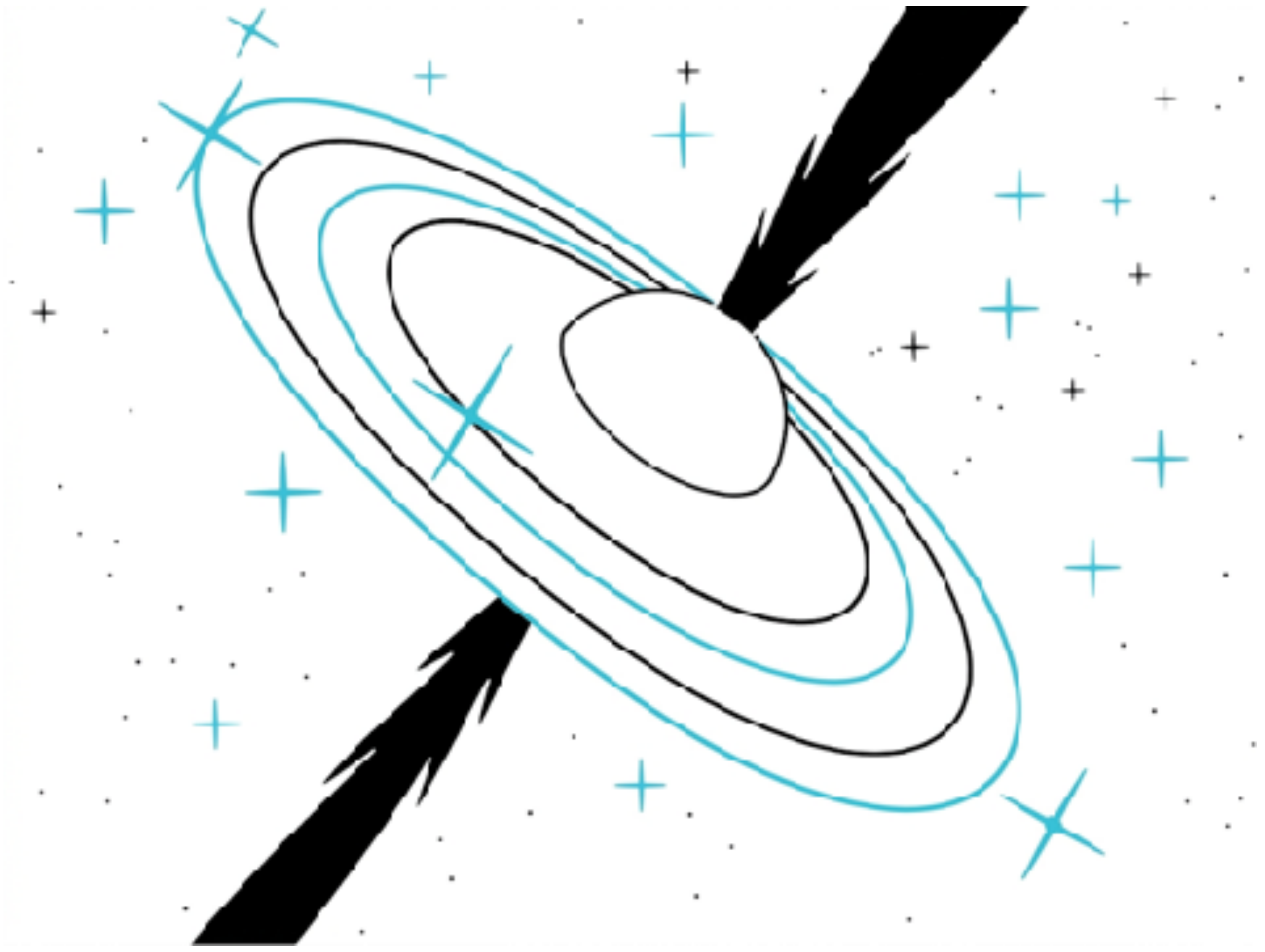
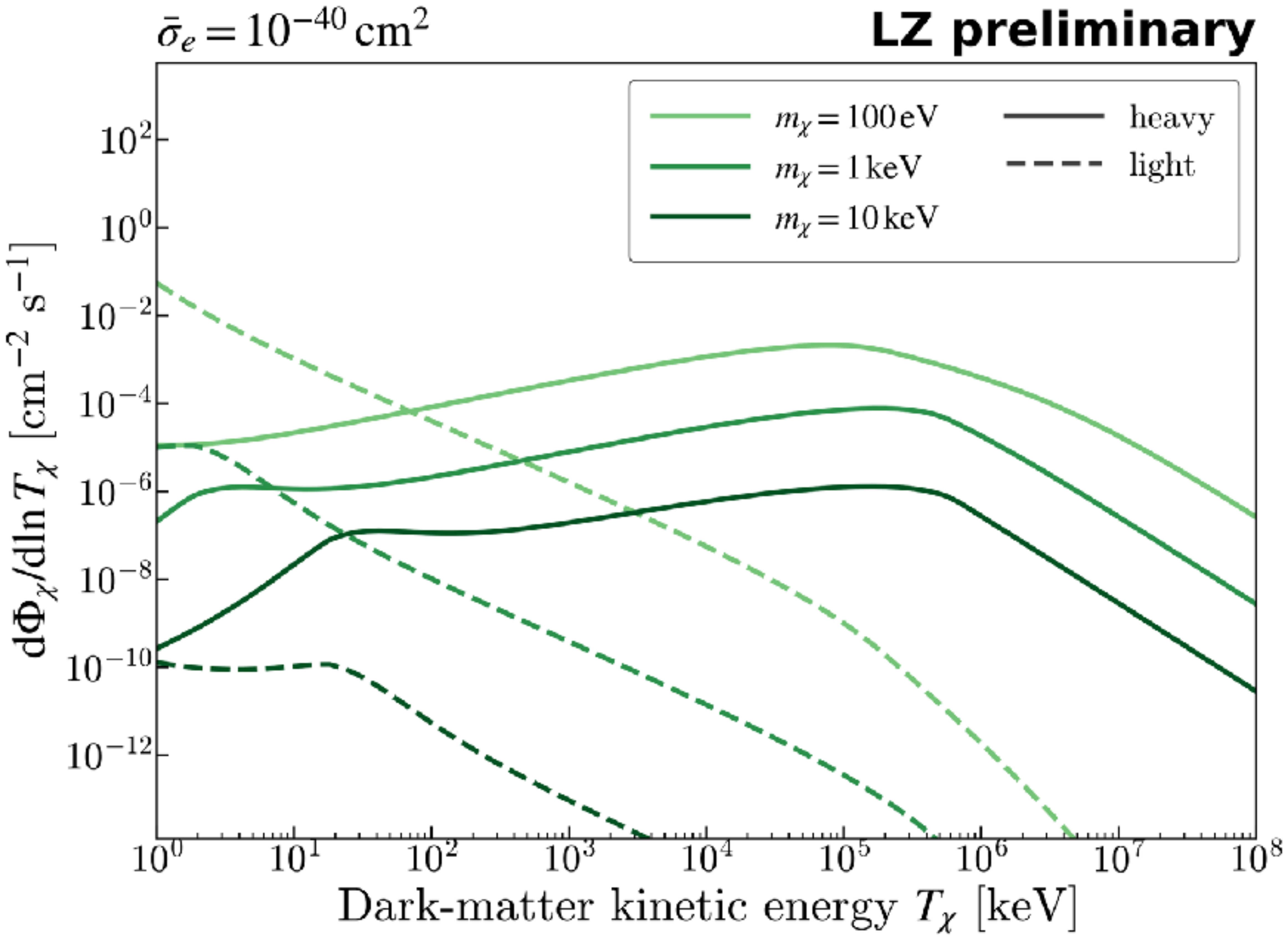


Illustration credit: ChatGPT



Solar reflected dark matter

- Electrons in the solar core are abundant and thermally energetic, with kinetic energies of $\mathcal{O}$(keV).
  - With electron coupling, DM entering the Sun can scatter off thermal electrons and be reflected, producing an energetic outgoing flux.
  - Flux at Earth calculated with `Damascus-SUN` [Github release]
  - The DM flux kinetic-energy spectra are softer than in the CRe- or AGN-boosted scenarios

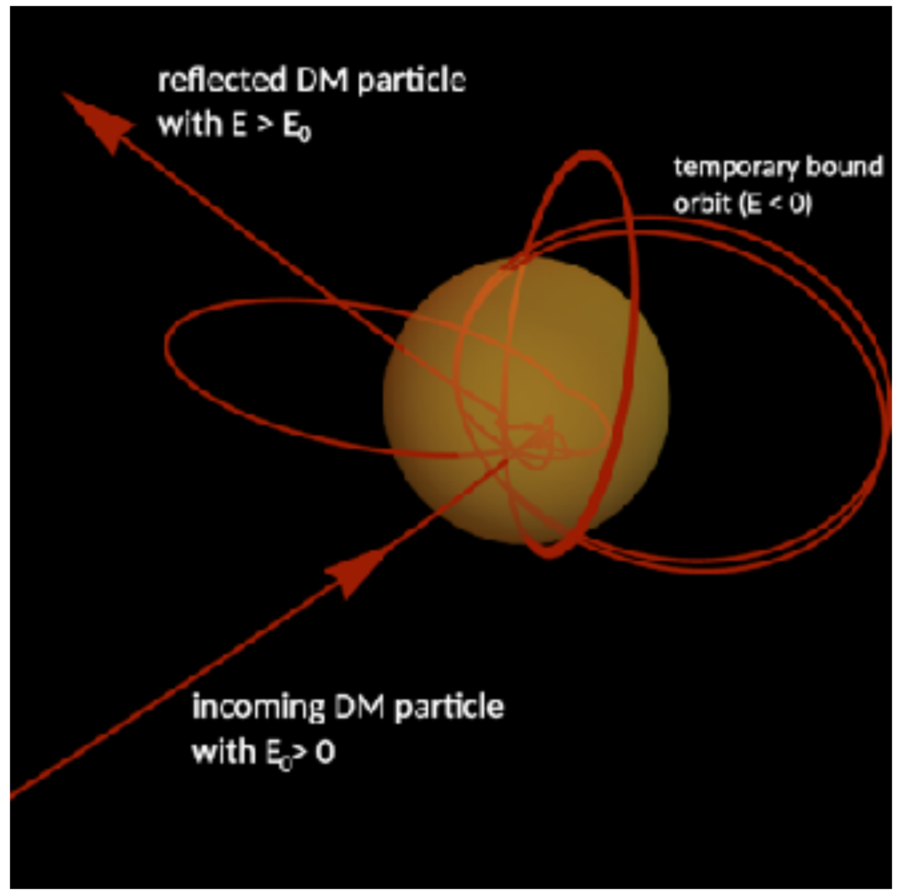
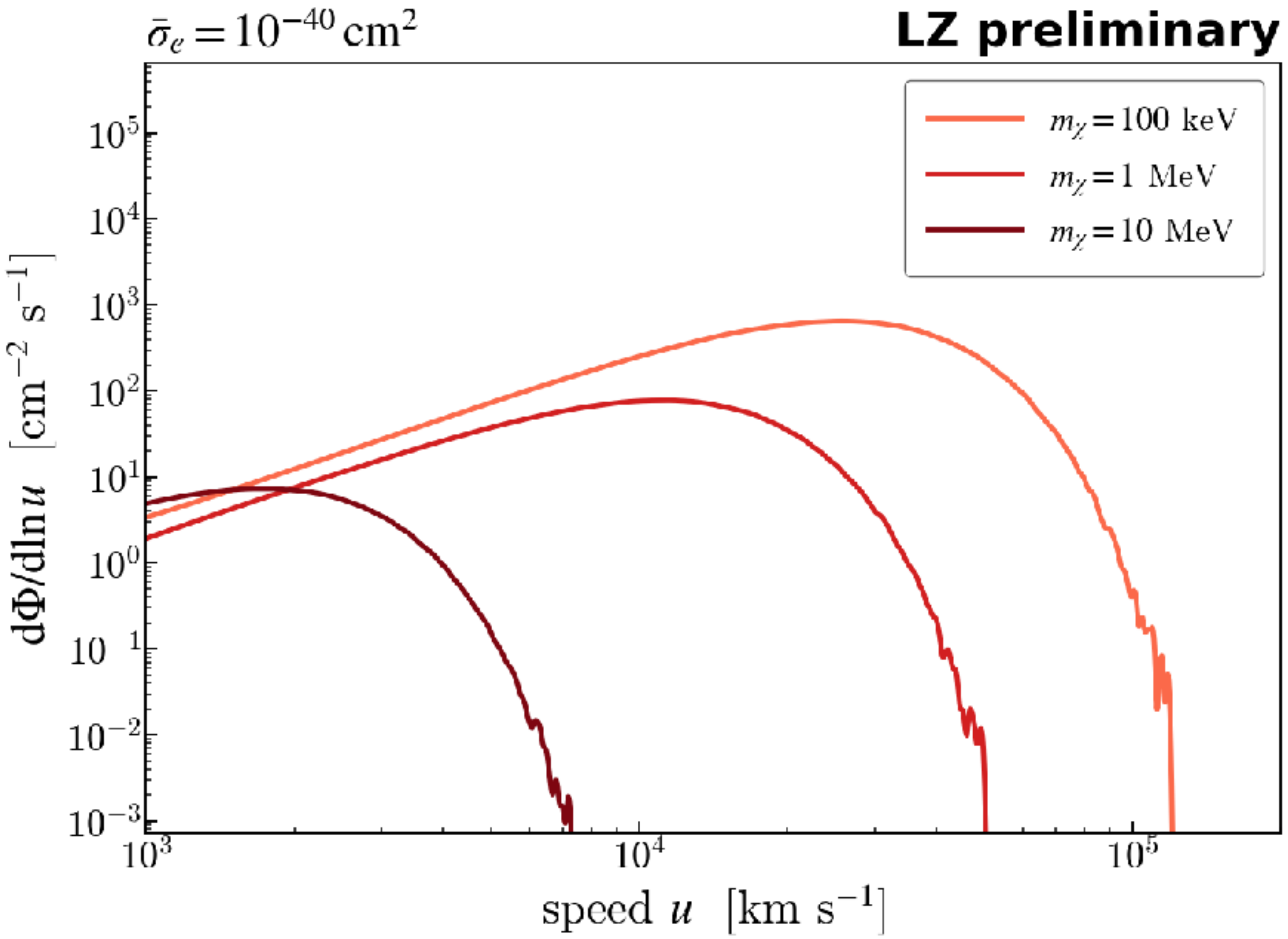
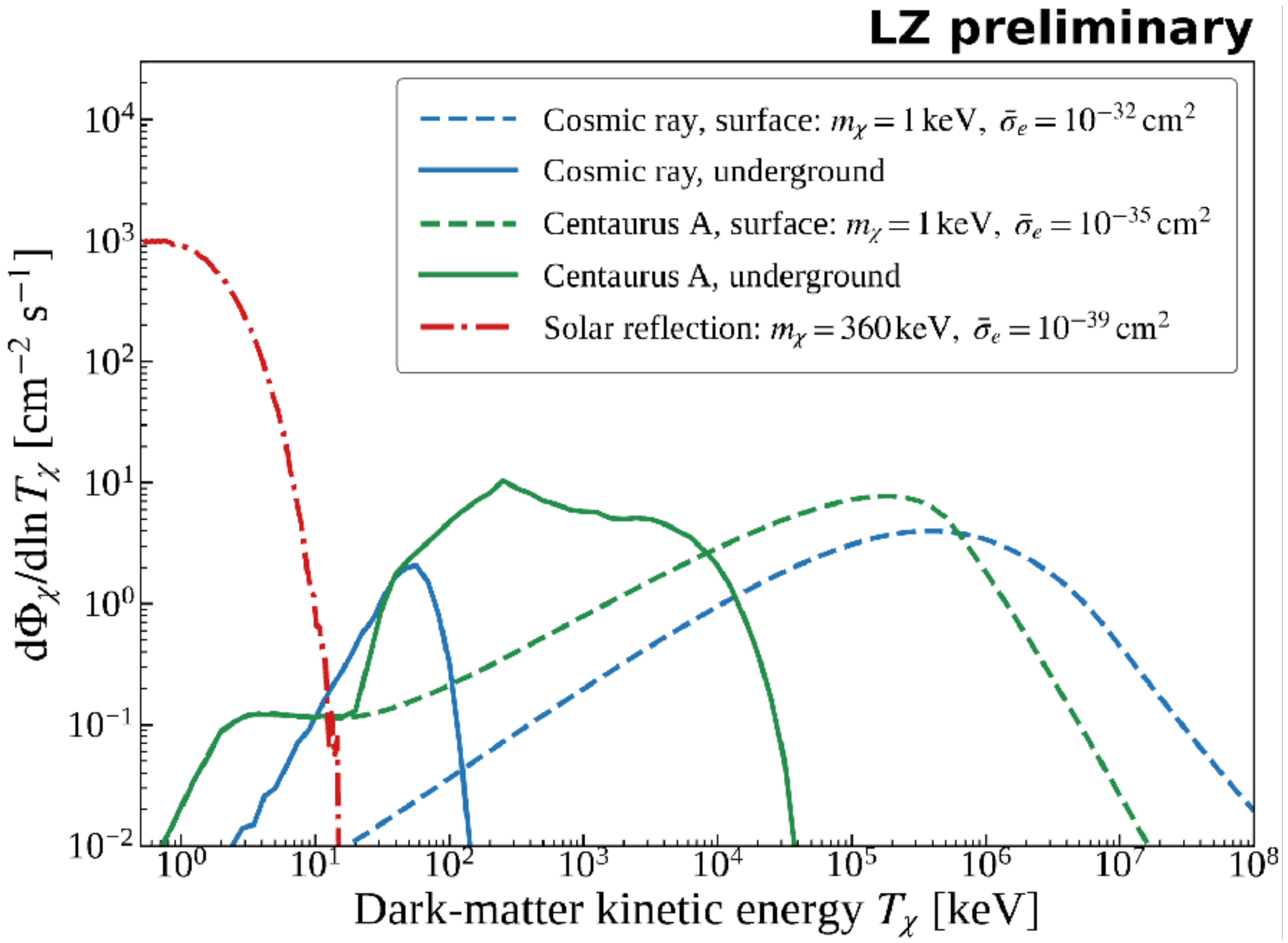


Illustration credit: Timon Emken



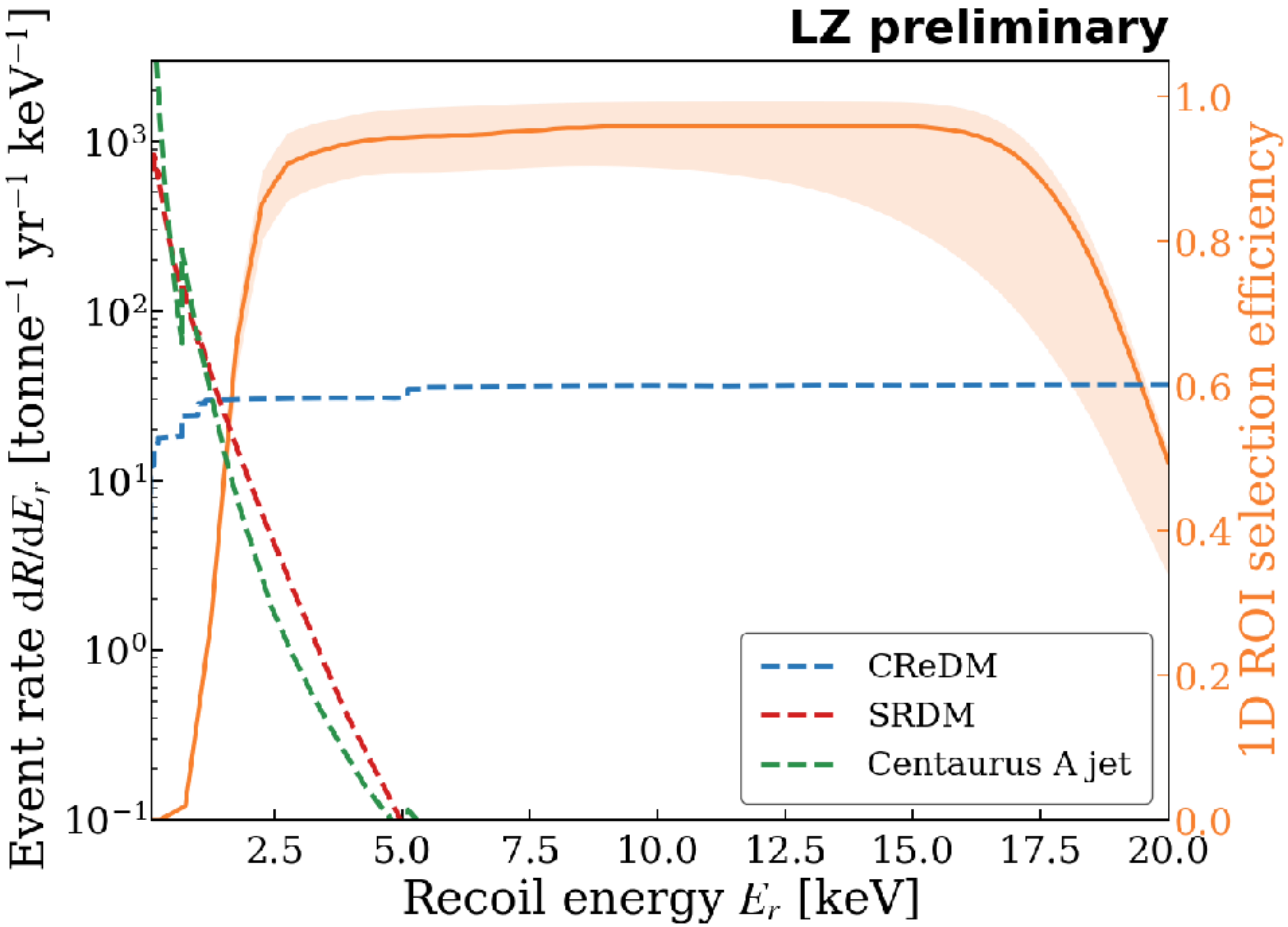
Earth attenuation

- DM–electron scattering in the Earth's crust attenuates the incoming flux
- Earth propagation modeled with DarkProp MC [Xia et al., JCAP 02 (2022) 028]
- Attenuation increases with
  - Cross sections $\bar{\sigma}_e$ ↑
    - For $\bar{\sigma}_e$ very small the attenuation vanishes, see SRDM case
  - Kinetic energies T_χ ↑
  - DM masses m_χ ↓



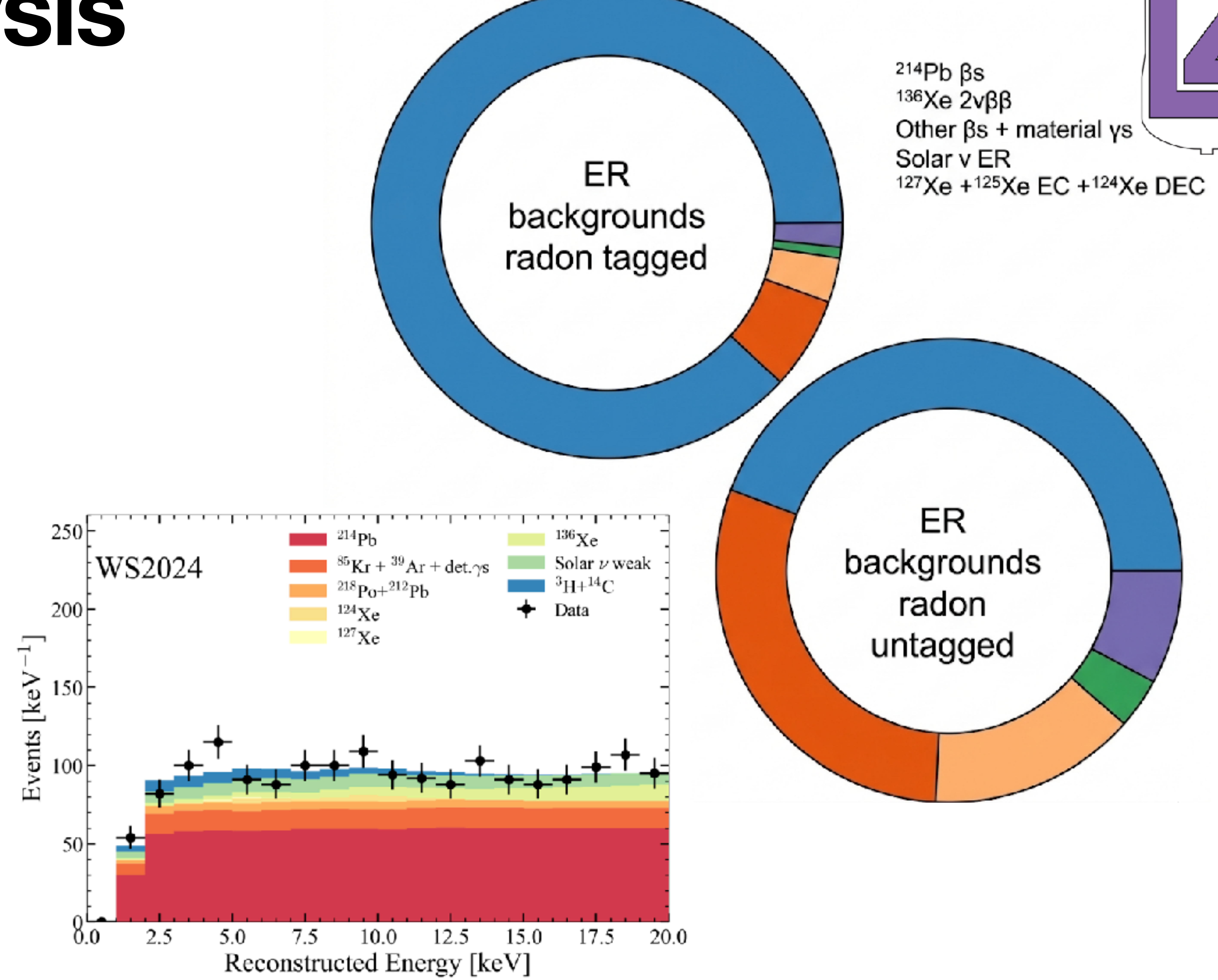
DM-atomic electron interaction

- Electrons in the detector are bound in atomic shells
- Atomic binding effects are incorporated through an ionization form factor calculated with DarkART [Catena et al., Phys.Rev.Res. 2 (2020) 033195].
- Lorentz structures and mediator mass limits enter through the kinematic kernel, as formulated in [Cao et al., Chin. Phys. C 45 (2021) 045002]



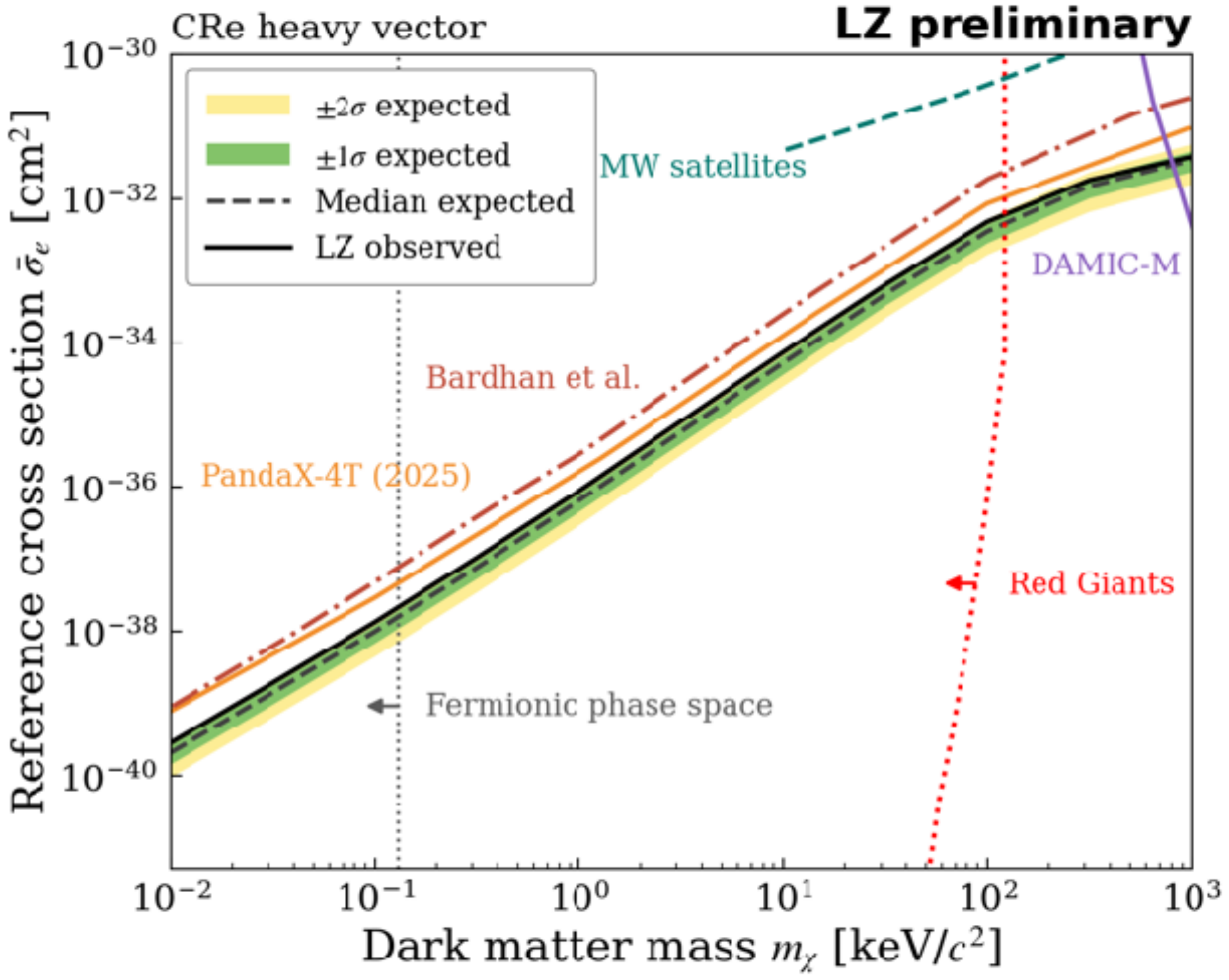
Dataset and Analysis

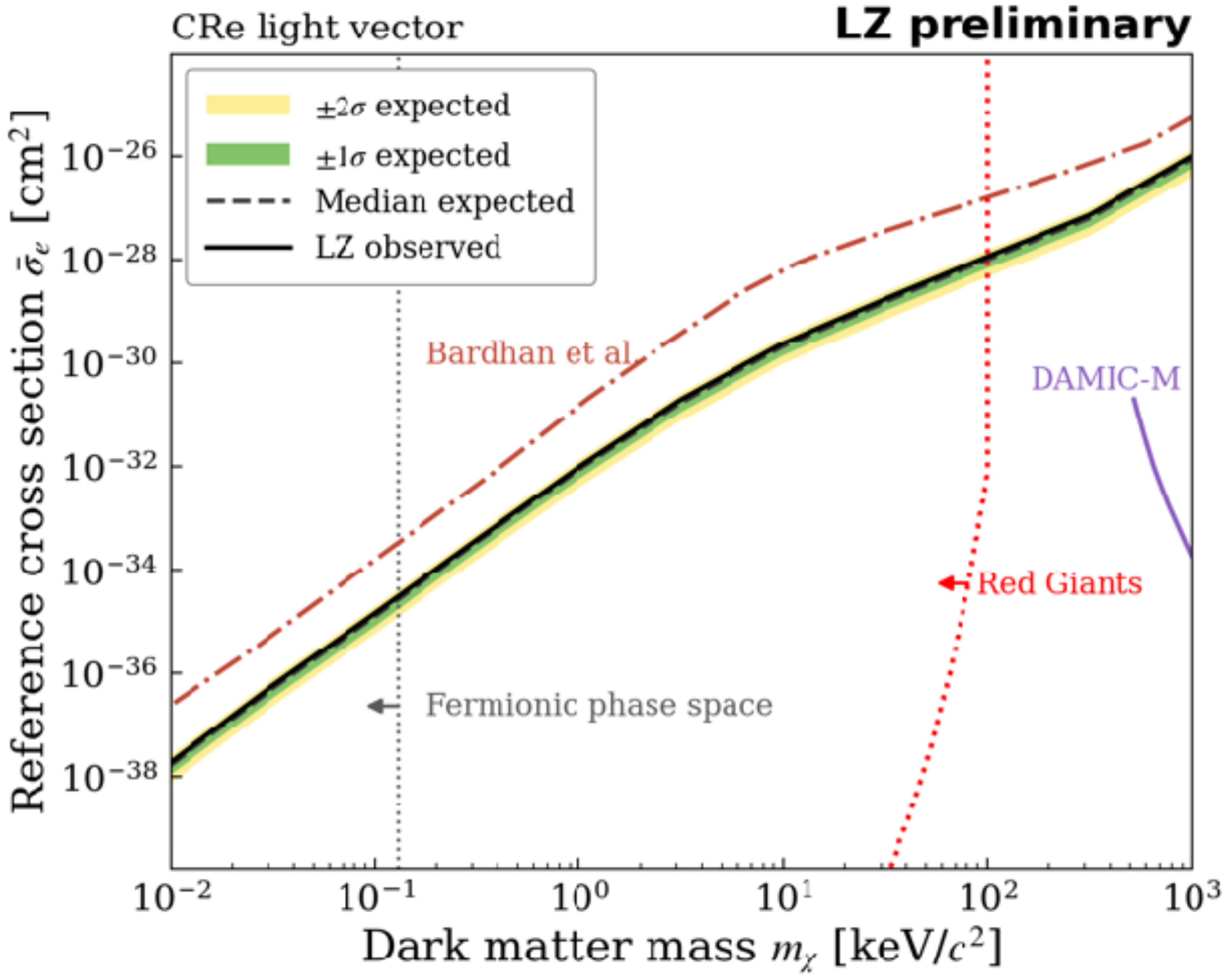
- A total of 4.2 tonne × year exposure used
    - 0.9 tonne × year were collected at 192 V/cm, 3.3 at 97 V/cm
- Background modeling follows the WIMP analysis
- The main background from ^{214}Pb suppressed by flow-based Rn tagging
- Profiled likelihood ratio test performed in 1D E_{rec} only



CReDM Results

- We set the **most stringent experimental constraints** for both heavy- and light-mediator scenarios.
- Most sensitive region disfavored by astrophysical bounds





*Regions the arrows pointing into are disfavored

Other representative constraints

[Nguyen et al., Phys. Rev. D 104 (2021) 103521]

[DAMIC-M Collaboration, Phys. Rev. Lett. 135 (2025) 071002]

[Chang et al., JHEP 03 (2021) 141]

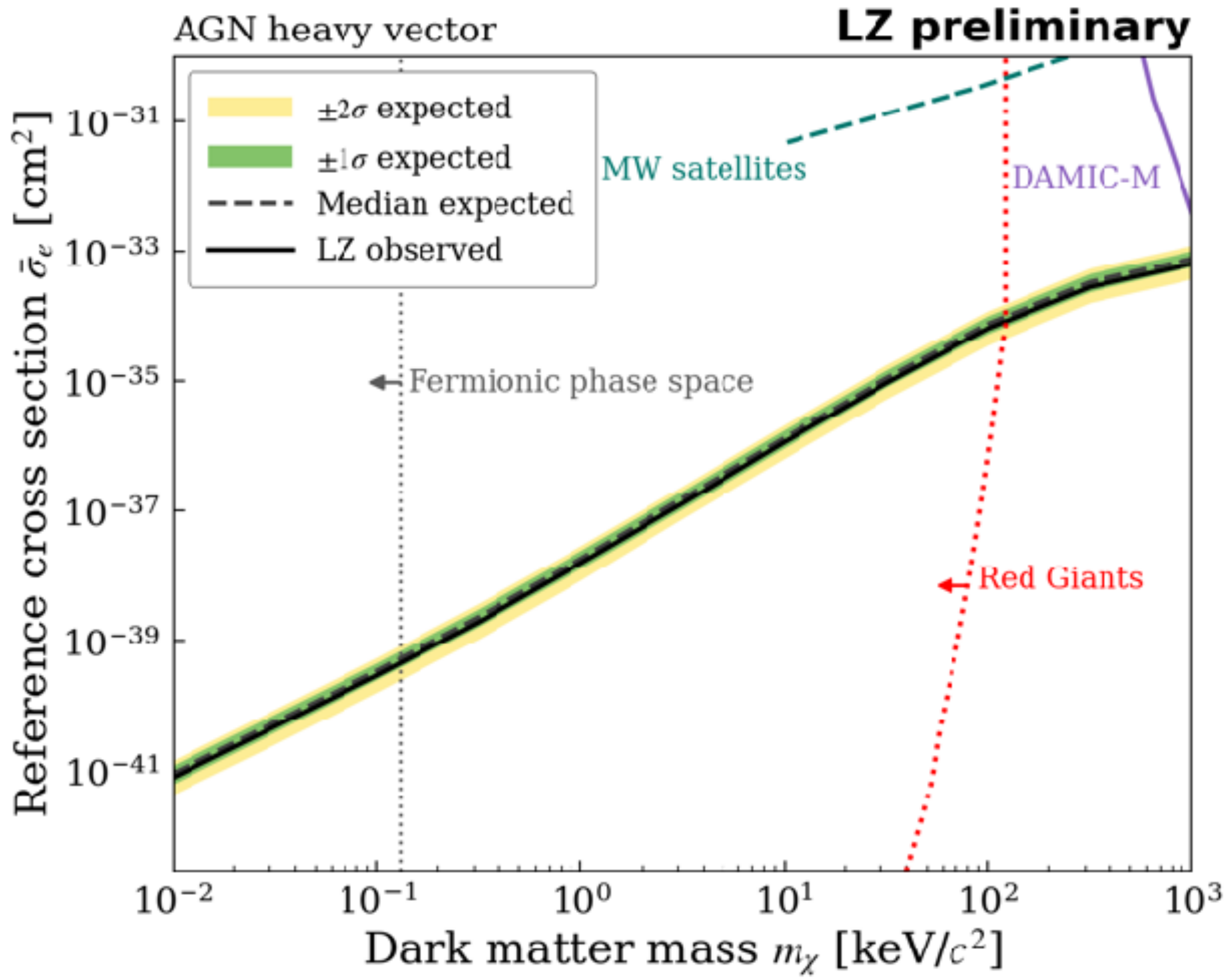
[Alvey et al., Mon. Not. R. Astron. Soc. 501 (2021) 1188–1201]

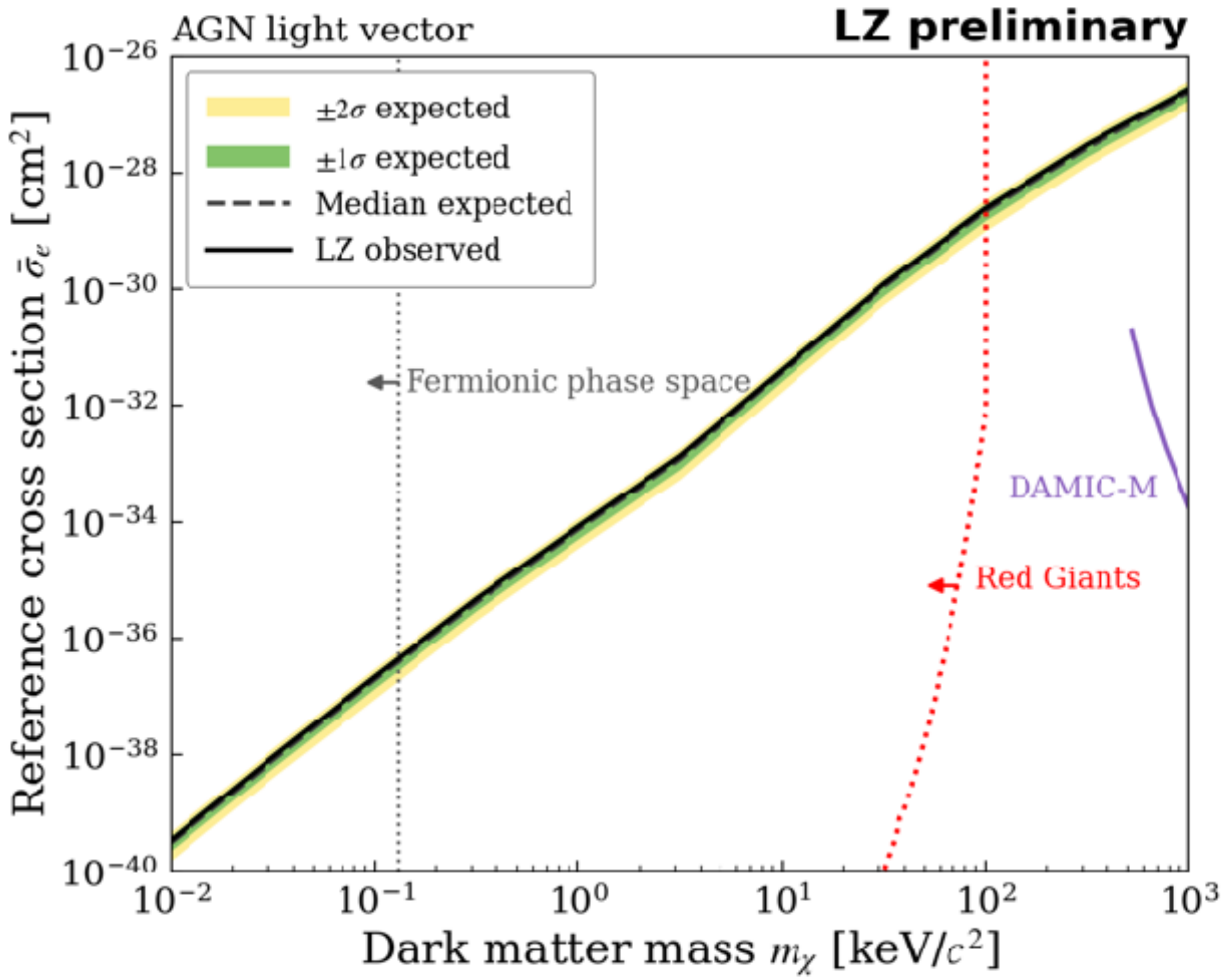
[PandaX Collaboration, Phys. Rev. Lett. 133 (2024) 101805]

[(XENONnT recast) Bardhan et al., Phys. Rev. D 107 (2023) 015010]

AGN jet boosted DM

- **New constraints** set on DM boosted by AGN jets using a benchmark AGN model
- Stronger than CRe constraints due to larger flux





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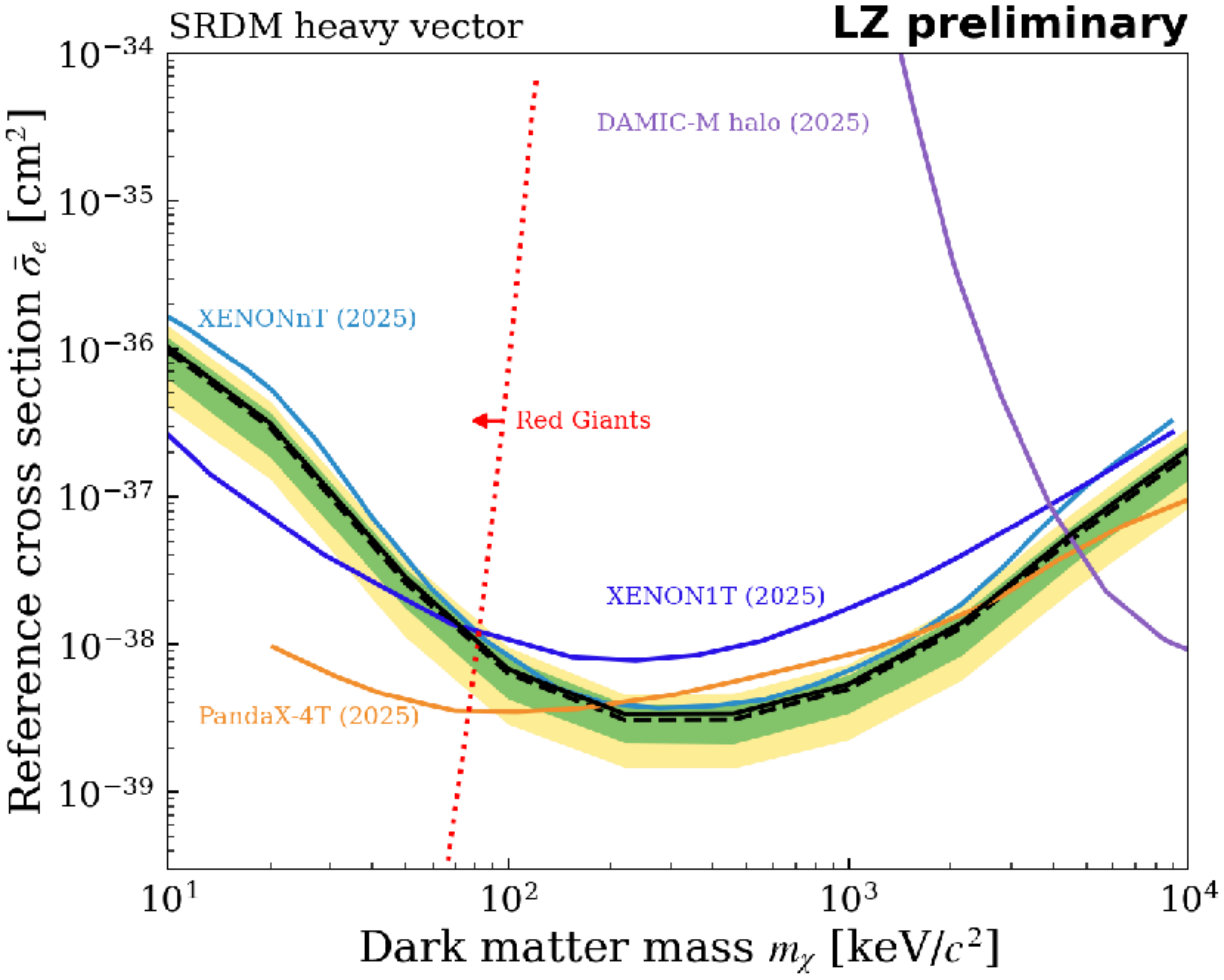
[Chang et al., JHEP 03 (2021) 141]

[Alvey et al., Mon. Not. R. Astron. Soc. 501 (2021) 1188–1201]

*Regions the arrows pointing into are disfavored

Solar reflection

- **Most stringent experimental constraints** set on SRDM from 200 keV to ~3 MeV



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Other representative constraints

[DAMIC-M Collaboration, Phys. Rev. Lett. 135 (2025) 071002]

[Chang et al., JHEP 03 (2021) 141]

[PandaX Collaboration, Phys. Rev. Lett. 134 (2025) 161003]

[XENON Collaboration, arXiv:2512.19592]

[XENON Collaboration, arXiv:2512.19592]

Conclusion

- We searched for signatures of sub-MeV electron coupling DM boosted by several astrophysical processes in LZ's WS2022+2024 dataset
- With no excess over the background model observed, limits are set on boosting channels studied
  - CRe-DM: **Most stringent terrestrial experimental constraints**
  - AGN-jet DM: **New constraints** set from Centaurus A, slightly stronger than CReDM
  - Solar reflected DM: **Most stringent constraints** for masses in the range 0.2 MeV $< m_\chi <$ 3 MeV
- These constraints rely only on the current universe and are highly complementary to existing astrophysical bounds

LZ (LUX-ZEPLIN) Collaboration, 39 Institutions

@lzdarkmatter

https://lz.lbl.gov/

250 scientists, engineers, and technical staff

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King's College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Purdue University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
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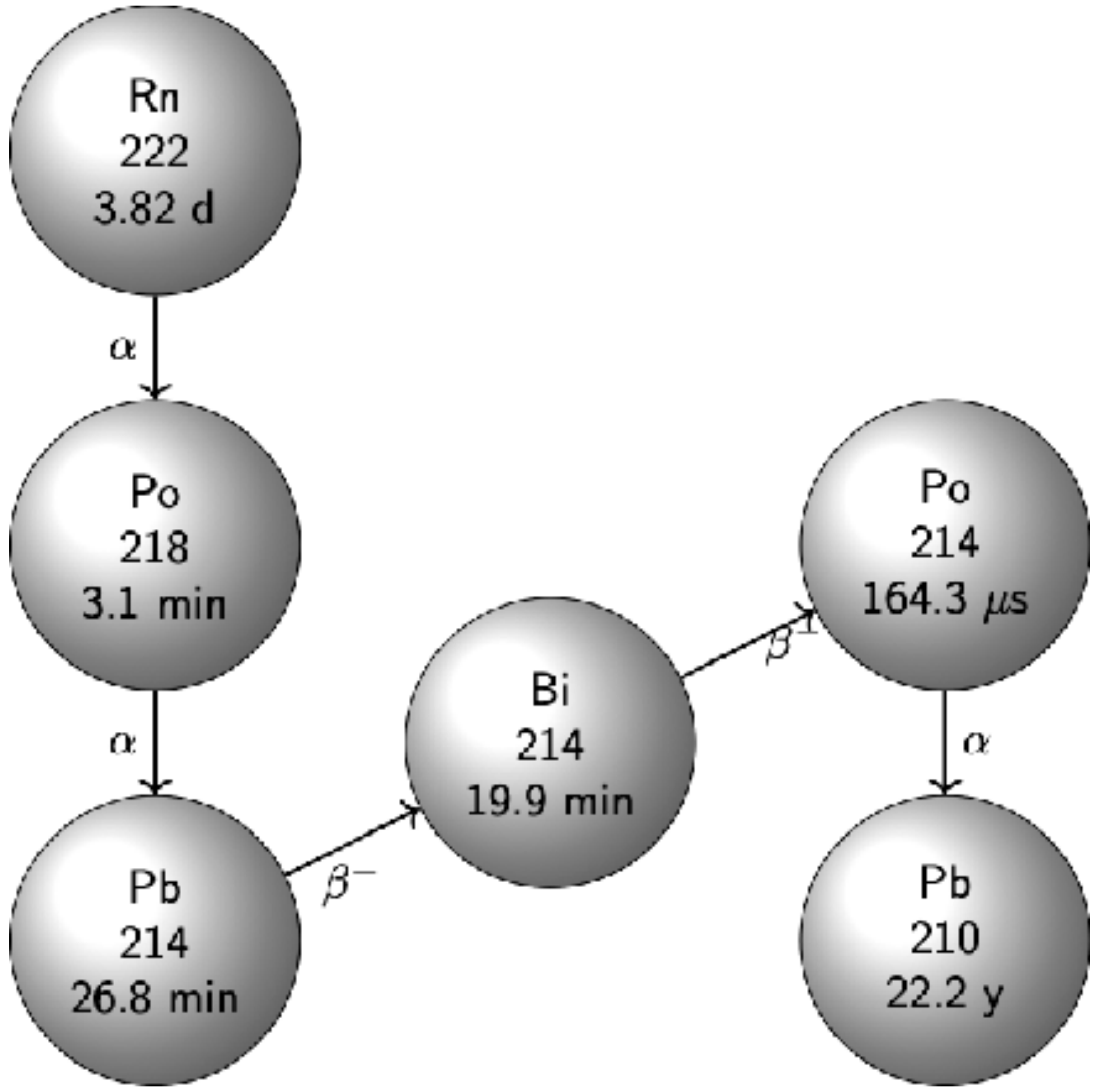
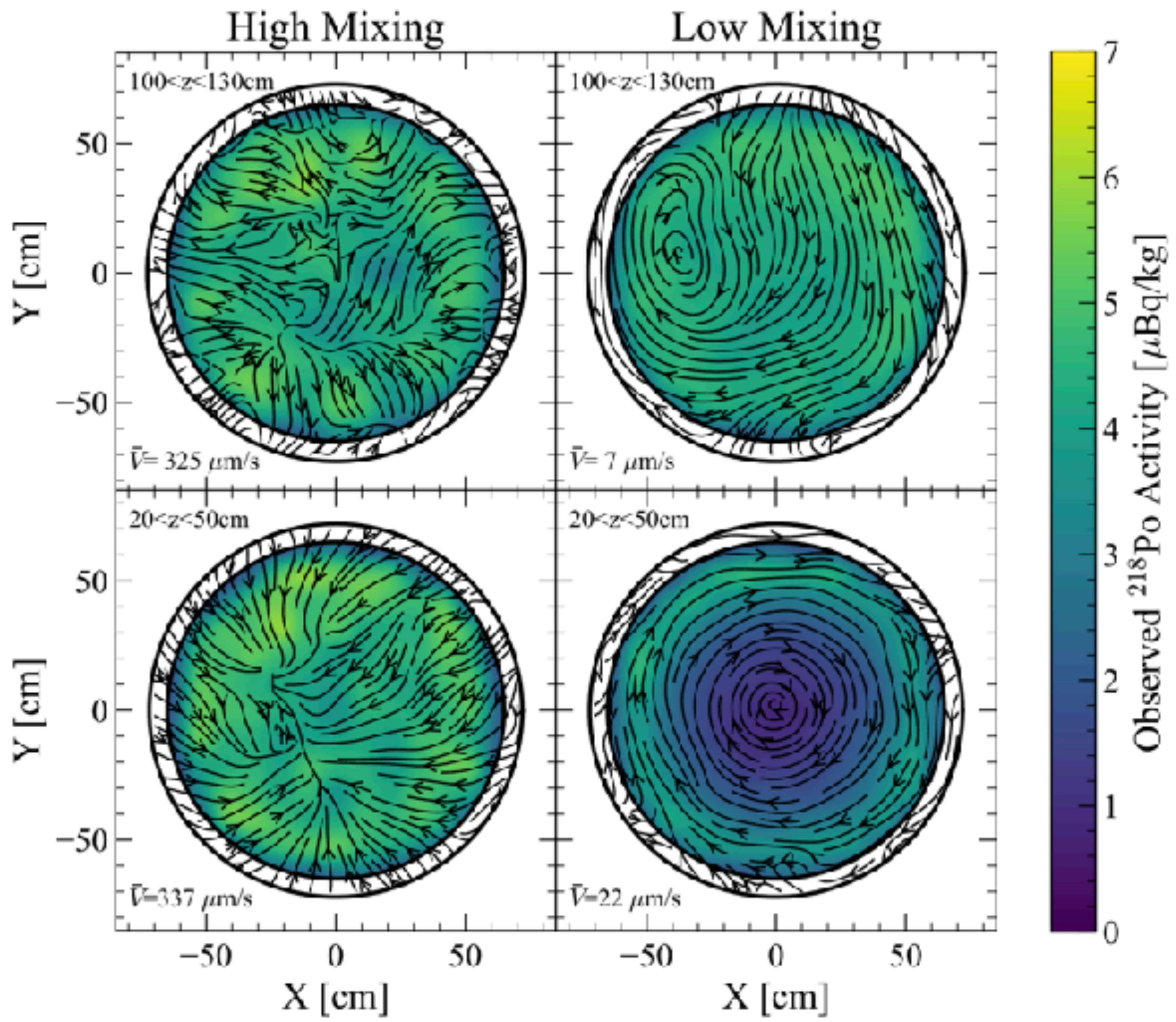
Backup

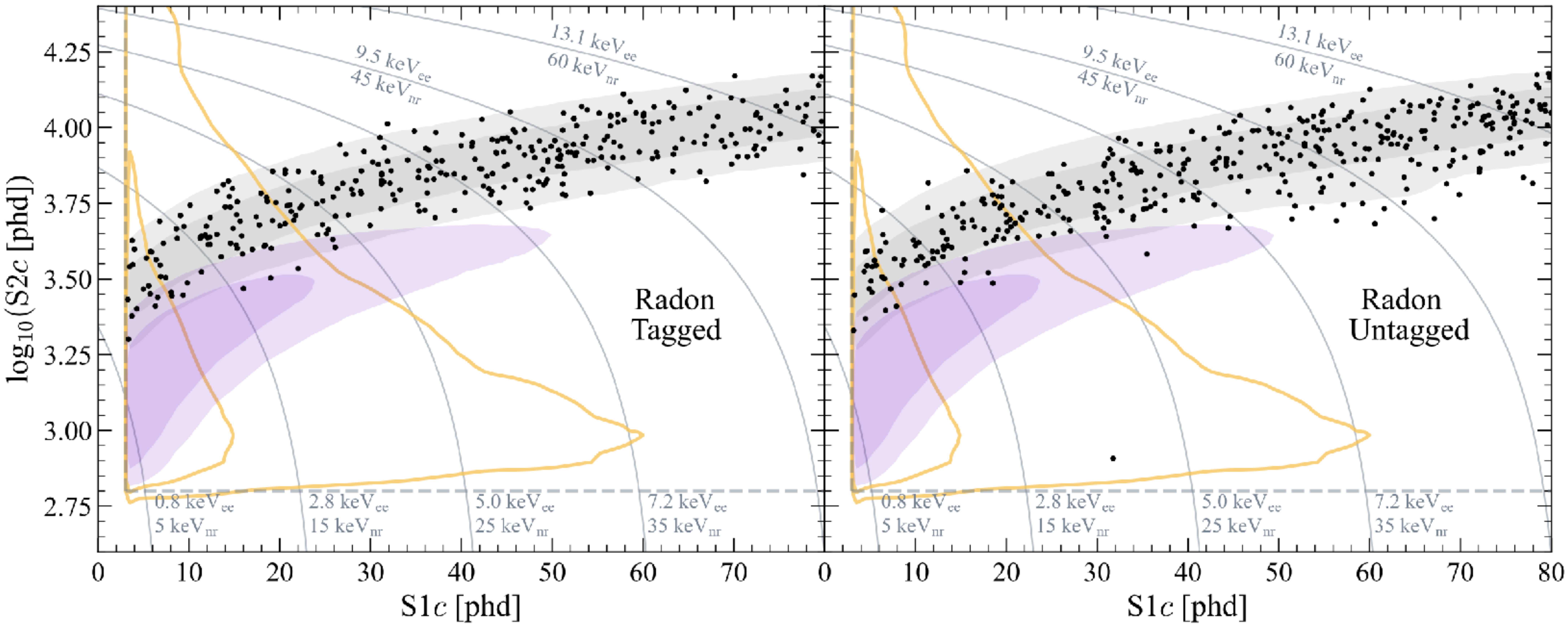
Tagging ^{214}Pb β using xenon flow model

- Tag ^{214}Pb naked decays using flow maps and parent/daughter decays
- Controlling the xenon flow state enables mapping of fluid flow using alpha events
- The Rn tagged dataset contains about 60% of the full FV activity of ^{214}Pb
- Tagged data also included in statistical inference
- See [LZ collaboration, arXiv: 2508.19117] for more details





WS2024 data: tagged vs untagged



[LZ collaboration, Phys. Rev. Lett. 135 (2025), 011802]

Free electron-DM scattering cross section

- Used in upscattering in CRe and AGN scenarios
- Tree-level t-channel scattering

$$\frac{\mathrm{d}\sigma_V}{\mathrm{d}T_\chi} = \frac{\overline{\sigma}_e}{4\mu_{\chi e}^2 T_e(T_e+2m_e)} \left(\frac{m_{\text{med}}^2+q_{\text{ref}}^2}{m_{\text{med}}^2+Q^2}\right)^2 \times \Big[2m_\chi(m_e+T_e)^2 - \{2m_\chi T_e + (m_\chi+m_e)^2\}T_\chi + m_\chi T_\chi^2\Big]$$

Vector

$$\frac{\mathrm{d}\sigma_S}{\mathrm{d}T_\chi} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2 T_e(T_e+2m_e)} \left(\frac{m_{\text{med}}^2+q_{\text{ref}}^2}{m_{\text{med}}^2+Q^2}\right)^2 \times (2m_\chi+T_\chi)(2m_e^2+m_\chi T_\chi).$$

Scalar

$$\frac{\mathrm{d}\sigma_A}{\mathrm{d}T_\chi} = \frac{\overline{\sigma}_e}{12\mu_{\chi e}^2 T_e(T_e+2m_e)} \left(\frac{m_{\text{med}}^2+q_{\text{ref}}^2}{m_{\text{med}}^2+Q^2}\right)^2 \times \Big[2m_\chi(T_e^2+2m_eT_e+3m_e^2) + \{(m_e-m_\chi)^2 - 2m_\chi T_e\}T_\chi + m_\chi T_\chi^2\Big]$$

Axial-vector

- Mediator mass limits

$$\left(\frac{m_{\text{med}}^2+q_{\text{ref}}^2}{m_{\text{med}}^2+Q^2}\right)^2 \longrightarrow \begin{cases} 1, & m_{\text{med}}^2 \gg q_{\text{ref}}^2,\ Q^2, \\ \dfrac{q_{\text{ref}}^4}{Q^4}, & m_{\text{med}}^2 \ll q_{\text{ref}}^2,\ Q^2. \end{cases}$$

Heavy

Light

- *For axial-vectors, the longitudinal mode in the numerator of the propagator complicates the taking of the light mediator limit

CRe boosted DM flux at earth

- Convolving CRe flux with energy-dependent differential cross section
- Milky Way information encoded in D_{eff} (8.02 kpc as suggested in Cao et al, 2021 Chin.Phys.C 45 045002)

$$\frac{\mathrm{d}\Phi_\chi^{\mathrm{CReDM}}}{\mathrm{d}T_\chi} = D_{\mathrm{eff}} \frac{\rho_{\chi,\odot}}{m_\chi} \int_{T_e^{\min}(T_\chi)}^{\infty} \mathrm{d}T_e \, \frac{\mathrm{d}\Phi_e^{\mathrm{LIS}}}{\mathrm{d}T_e} \frac{\mathrm{d}\sigma_i}{\mathrm{d}T_\chi}(T_e, T_\chi)$$

AGN-boosted DM flux at each

- Electron spectrum in the blob (jet) frame

$$\frac{d^2 n_e}{dE_e\, d\Omega_e} = \frac{\beta_e}{4\pi\sqrt{X}} \frac{dn'_e}{dE'_e},$$
$$X = (1 - \beta_B \beta_e u_e)^2 - (1 - \beta_B^2)(1 - \beta_e^2).$$

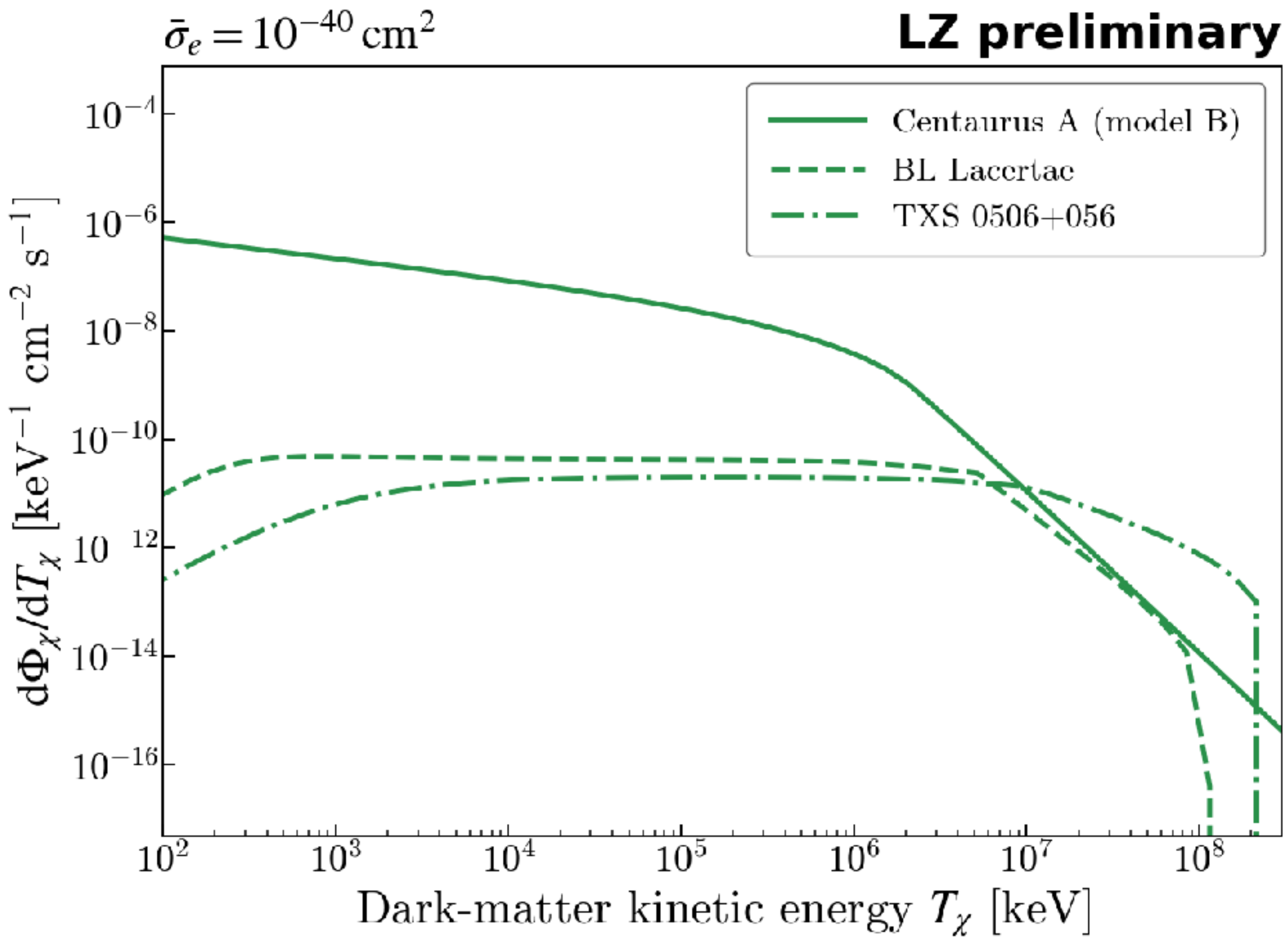
- Convolving the differential cross section and the electron spectrum evaluated at the contributing angle to find the boosted DM flux at earth

$$\frac{d\Phi_\chi^{\rm AGN}}{dT_\chi} = \frac{\pi R'^{\,2}_B c}{d_L^2} \mathcal{N}_\chi \times \int_{E_e^{\rm min}(T_\chi)}^{\infty} dE_e \int_0^{2\pi} \frac{d\phi_{\rm sc}}{2\pi} \times \beta_e \frac{d^2 n_{e,\rm eff}}{dE_e\, d\Omega_e} \frac{d\sigma_i}{dT_\chi}.$$

AGNs in the universe

- Many AGNs exist throughout the universe
- Some level of model-dependence
- We use Centaurus A as our benchmark because it yields the largest boosted-DM flux among the AGNs considered

Source	d_L (Mpc)	$M_{\rm BH}$ ($M_\odot$)	Γ_B	$\theta_{\rm LOS}$ (deg)	γ'_e range
TXS 0506+056	1835.4	3.09×10^8	20	0	500–1.3×10^4
BL Lacertae	322.7	8.65×10^7	15	3.82	700–1.5×10^4
Centaurus A	3.7	5×10^7	3	42	1–10^6



Atomic electron DM-interaction

- Convolving the flux with the cross section

- The cross section given by the kinematic kernel multiplied by ionization form factor

$$\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{dep}}} = \frac{N_{\mathrm{Xe}}\overline{\sigma}_e}{8\mu_{\chi e}^2} \sum_{nl} \frac{1}{T_e} \int_{T_{\chi,\mathrm{min}}}^{\infty} \mathrm{d}T_\chi \, \frac{1}{\beta_\chi^2} \frac{\mathrm{d}\Phi_\chi}{\mathrm{d}T_\chi} \times \int^{q_{\max}} \mathrm{d}q \, q \, \left|F_{\mathrm{DM}}(q, T_\chi, E_{\mathrm{dep}})\right|^2 W_1^{nl}(T_e, q)$$

- Kinematic kernels

Vector

$$\left|F_{\mathrm{DM}}^{V}\right|^2 = \frac{L_V^{00}}{4E_\chi^2} = 1 - \frac{\Delta E}{E_\chi} - \frac{q^2 - \Delta E^2}{4E_\chi^2},$$

Scalar

$$\left|F_{\mathrm{DM}}^{S}\right|^2 = \frac{L_S}{4E_\chi^2} = \frac{m_\chi^2}{E_\chi^2} + \frac{q^2 - \Delta E^2}{4E_\chi^2},$$

Axial vector

$$\left|F_{\mathrm{DM}}^{A}\right|^2 = \frac{\sum_j L_A^{jj}}{12E_\chi^2} = \frac{1}{3}\left[1 - \frac{\Delta E}{E_\chi} + \frac{q^2 - \Delta E^2}{4E_\chi^2} + \frac{2m_\chi^2}{E_\chi^2}\right]$$

Extra factor for light mediator

$$\left|F_{\mathrm{DM}}^{i,\mathrm{L}}\right|^2 = \frac{q_{\mathrm{ref}}^4}{(q^2 - \Delta E^2)^2} \left|F_{\mathrm{DM}}^{i}\right|^2, \quad i = V, S.$$