Search for atmospheric millicharged particles in LZ SR1 data

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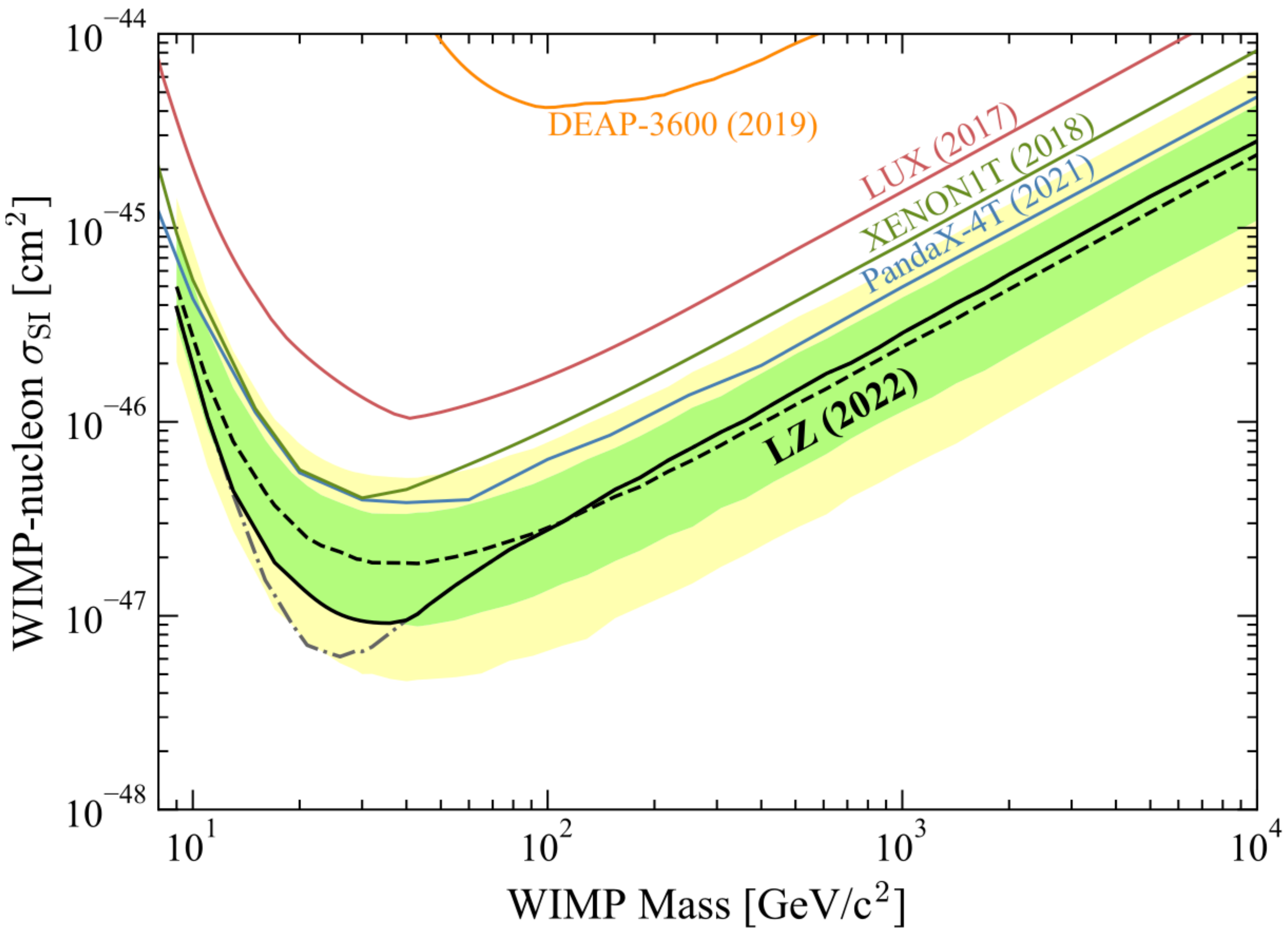
LZ Science Run 1 (SR1)

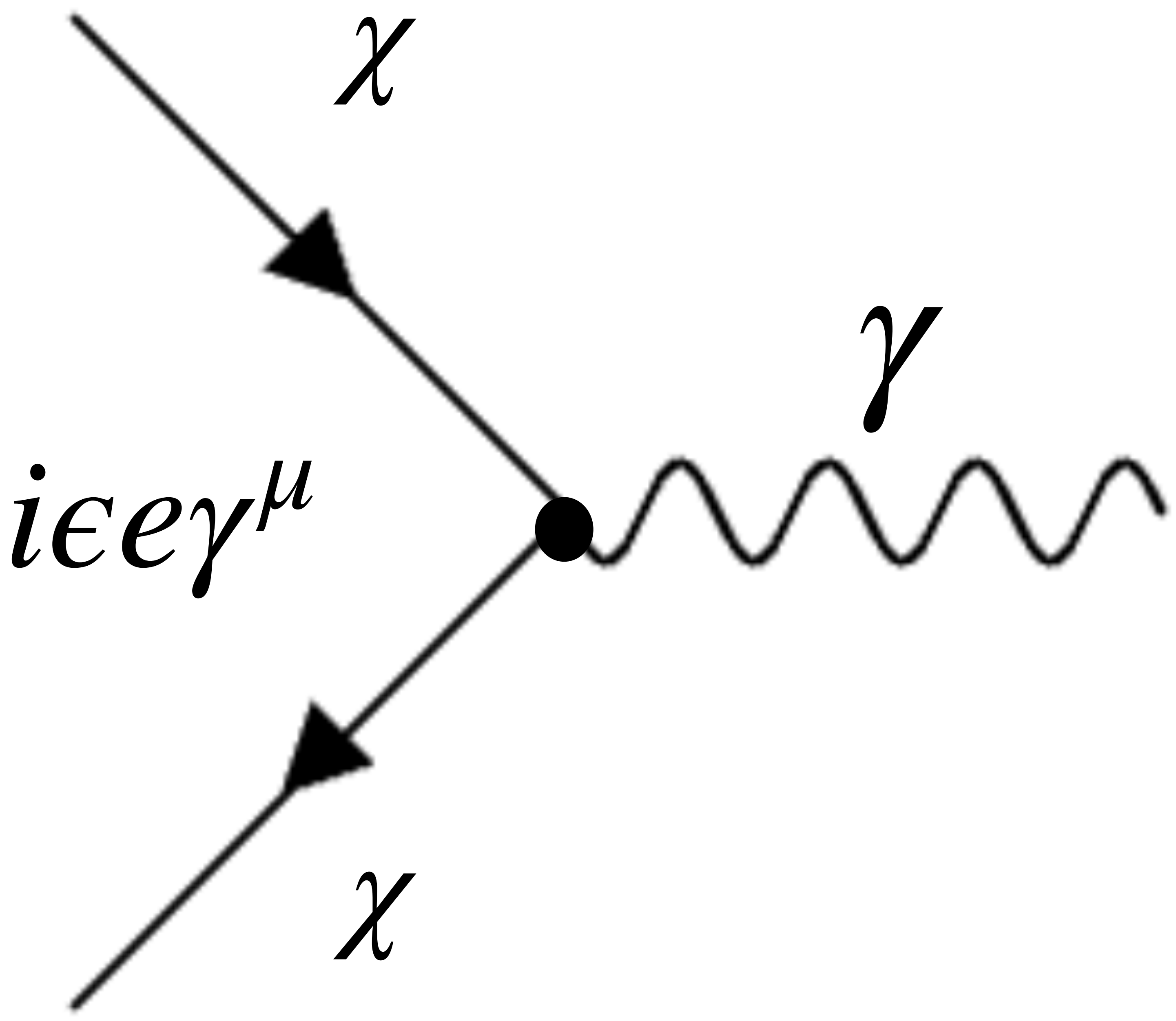
- ***New WIMP result just dropped! Check out talk by Scott Haselschwardt this morning***
- Search for prompt (S1) and delayed (S2) signals of WIMP interaction in a dual-phase liquid Xenon TPC
- 5.5 t fiducial mass, 60 live days
- 192 V/cm electric field
- Excluded 40 GeV WIMPs with a WIMP-neutron spin-independent cross section down to $1 \times 10^{-47}\text{cm}^2$



Basic facts about milliCharged Particle (mCP)

$$\mathscr{L} = \epsilon e A_\mu \bar{\chi} \gamma^\mu \chi$$

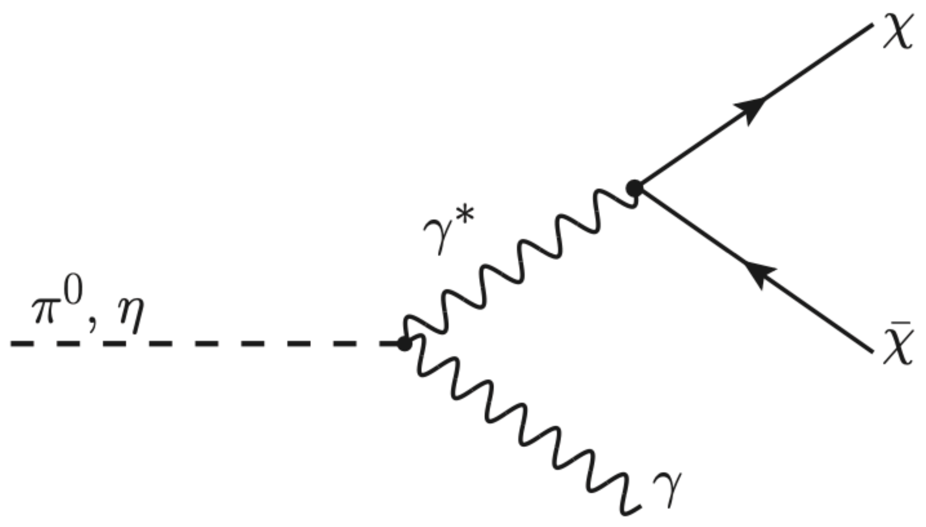
- Also known as fractionally charged particles or lightly ionizing particles
- Carries a small electric charge ϵe, couples to photons at tree-level
- Ionizes atoms like electrons, just less frequently
- Popular non-WIMP DM candidate constituting a small portion of total dark matter mass [1,2,3]
- Plausible solution to the EDGES-21 cm anomaly [4,5,6]

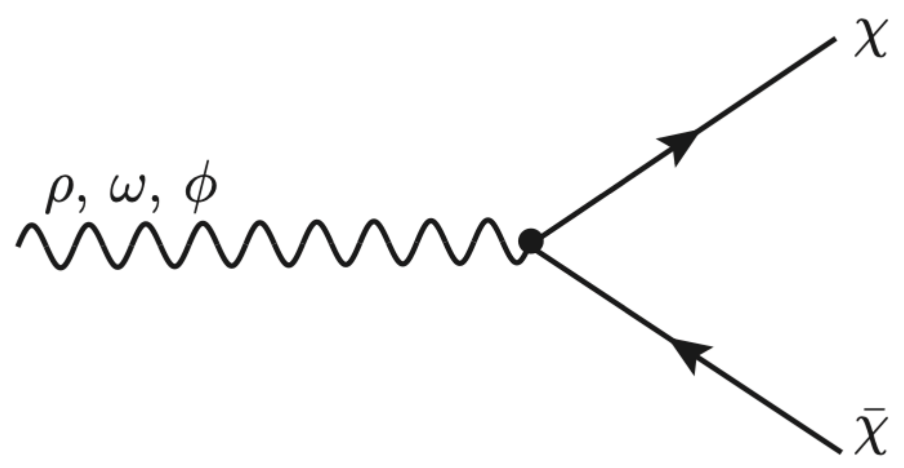


mCP production in cosmic ray atmosphere

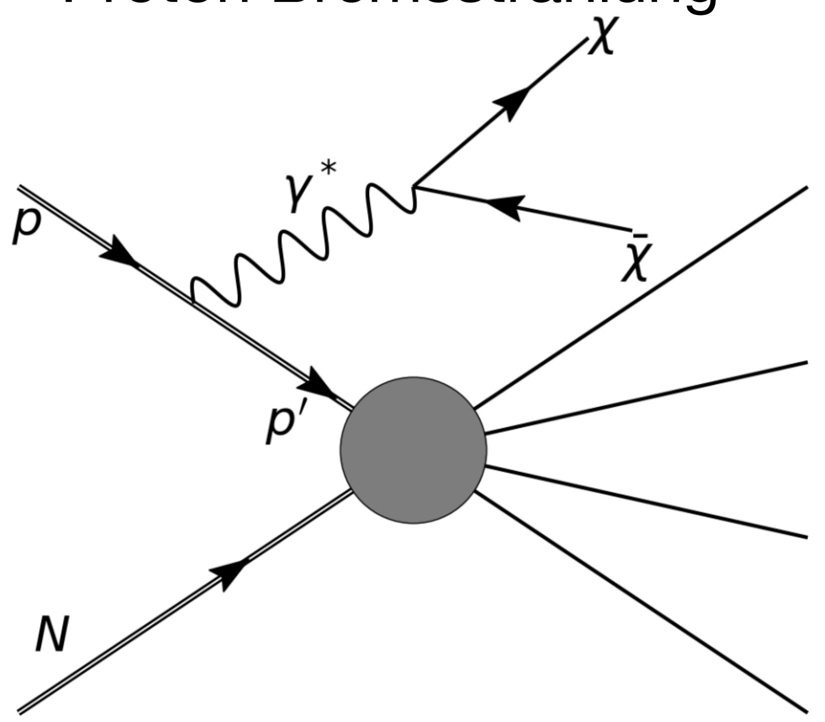
- Two atmospheric production channels considered in this analysis: meson decay (MD) and proton bremsstrahlung (PB)
  - MD: mCP are produced in the decay of a scalar or vector boson [7,8]
  - PB: mCPs are radiated from a proton when it collides with a nucleus in the atmosphere [9, 10]
- The shielding effect of overburden is considered using an energy-loss based analytical method

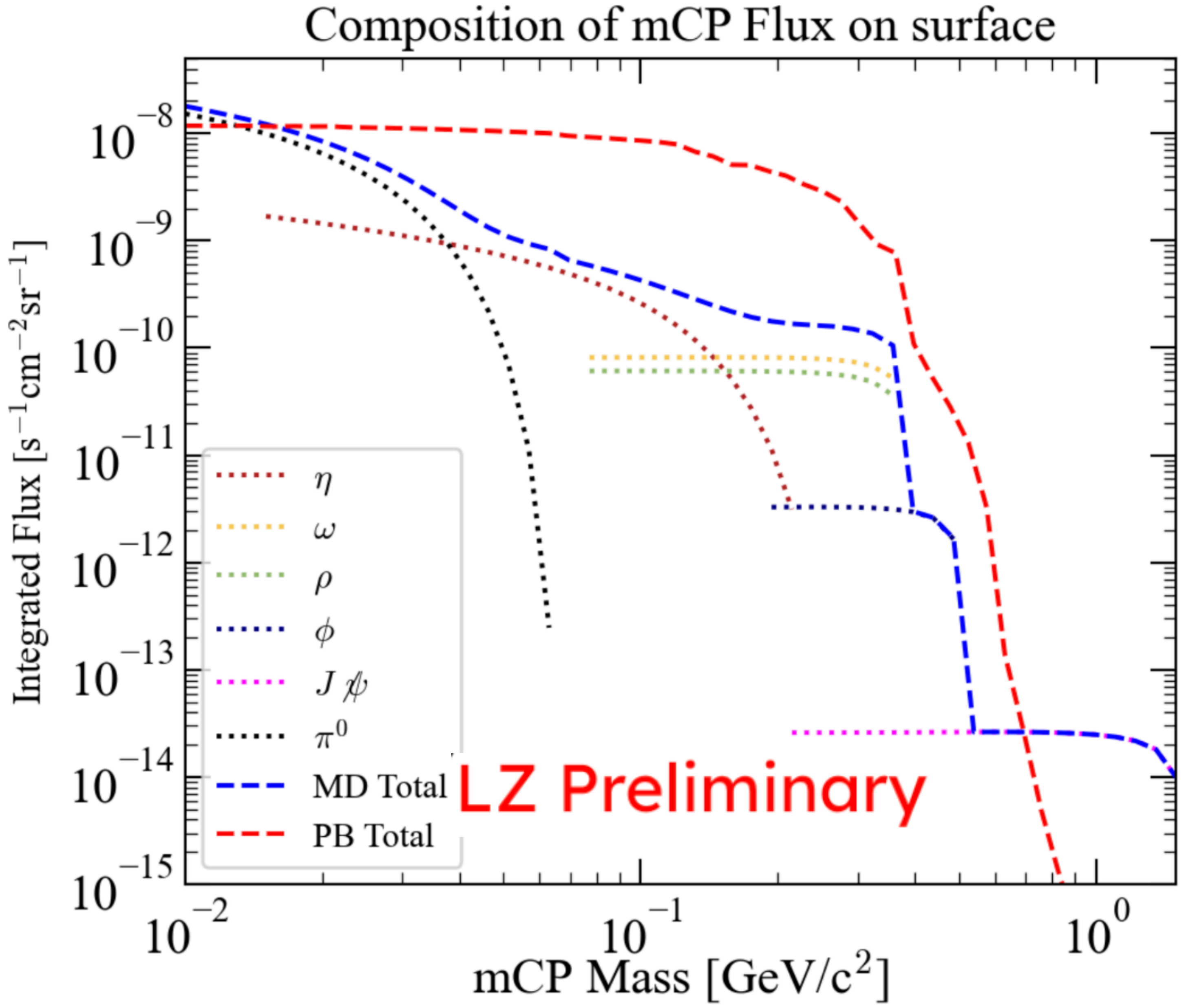
Meson decay

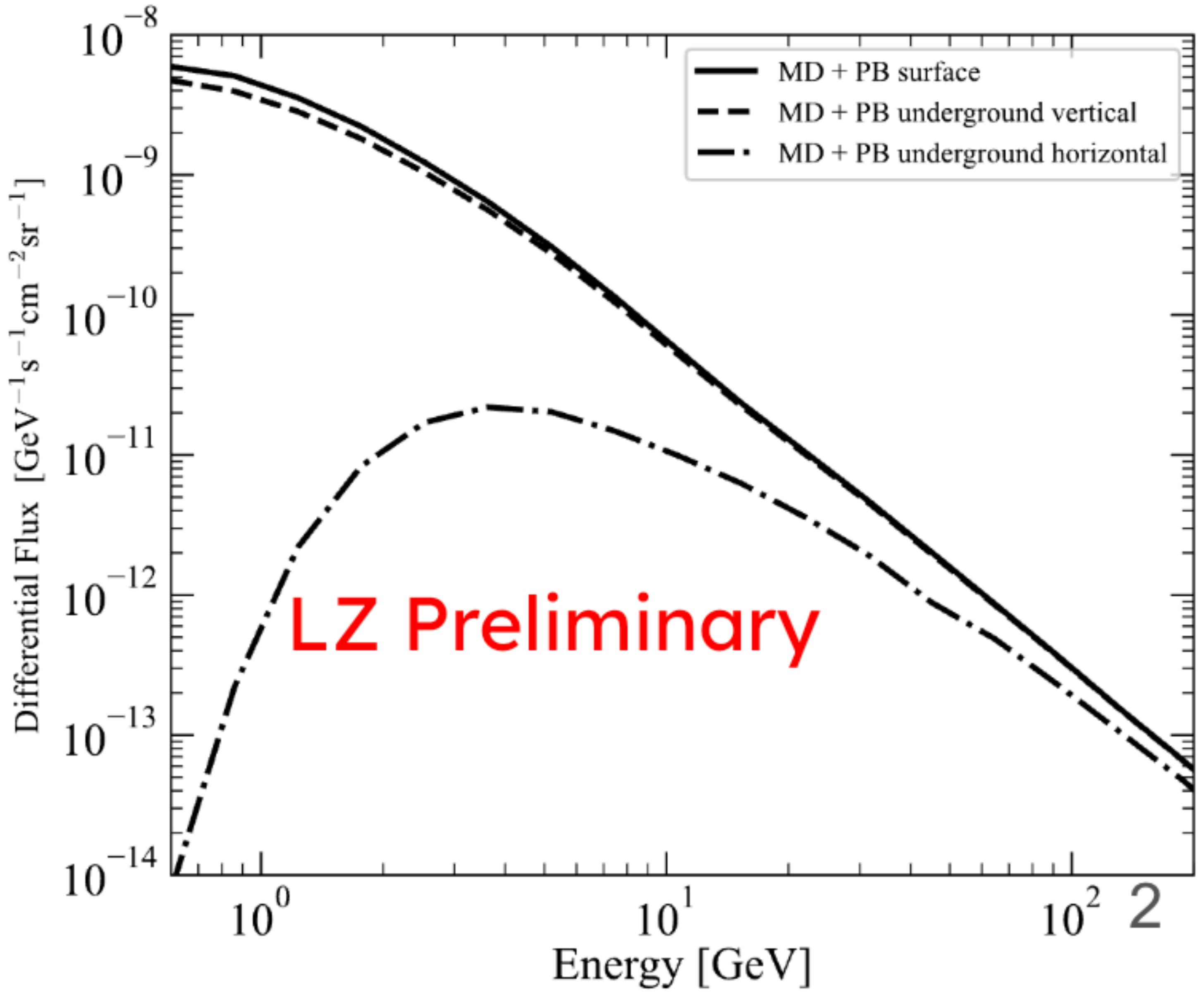




Proton Bremsstrahlung







mCP interaction in liquid xenon

Free electron

- Analogous to QED Møller scattering computed at tree level

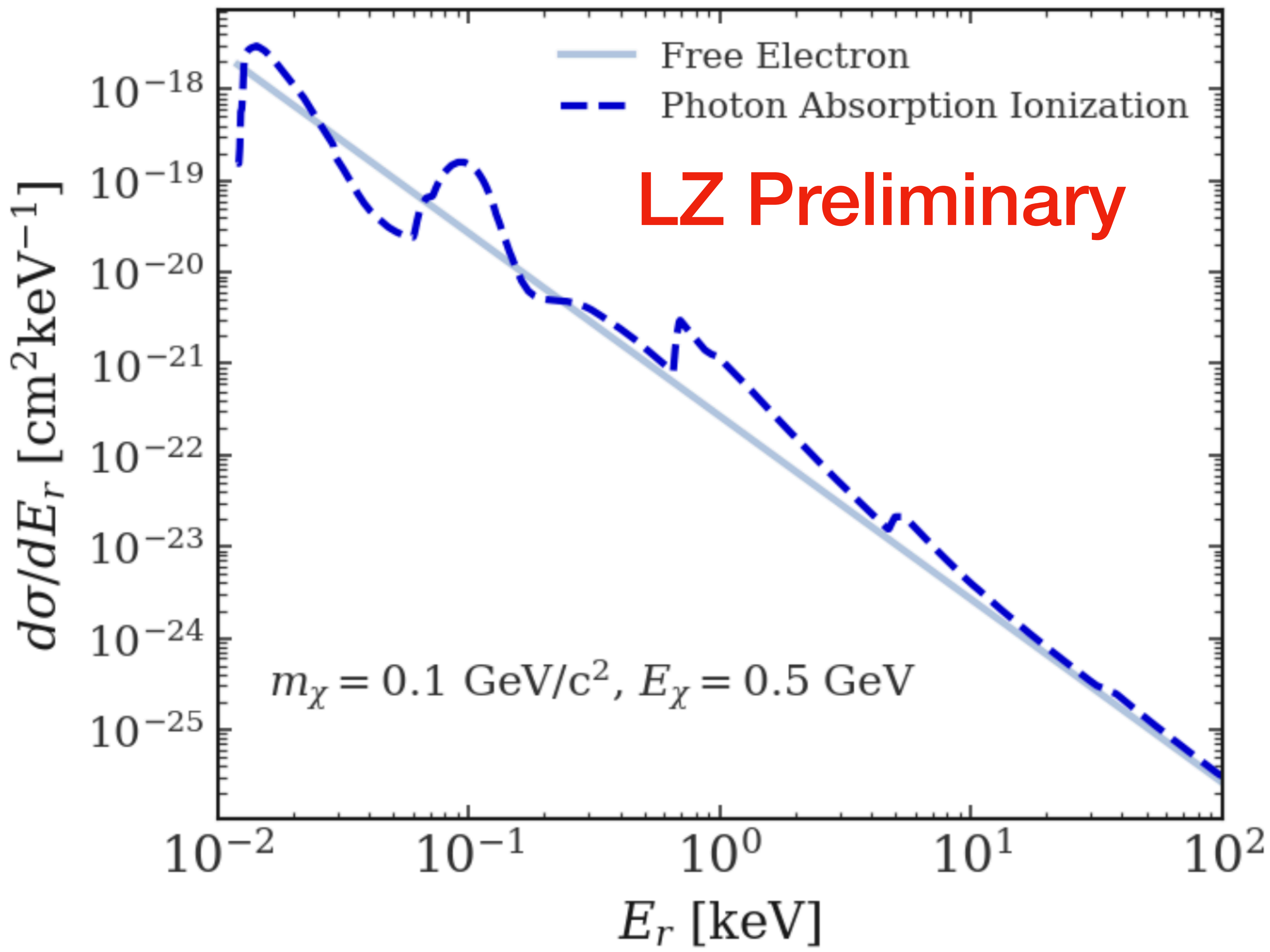
$$\frac{d\sigma}{dE_r} = \varepsilon^2\alpha_{EM}^2\pi\frac{m_e(E_r^2+2E_\chi^2)-E_r(m_e(2E_\chi+m_e)+m_\chi^2))}{E_r^2m_e^2(E_\chi^2-m_\chi^2)},$$

- Does not take into account the effect of electron binding energy

Photon Absorption Ionization (PAI)

- Taking the binding energy of electrons into consideration
- Depends on optical constants, which is derived from x-ray refraction data.

$$\frac{d\sigma_{PAI}(E;\beta)}{dE} = \frac{\alpha}{\beta^2\pi}\frac{\sigma_\gamma(E)}{EZ}\ln[(1-\beta^2\epsilon_1(E))^2+\beta^4\epsilon_2(E)^2]^{-1/2} + \frac{\alpha}{\beta^2\pi}\frac{1}{N\hbar c}\Big(\beta^2-\frac{\epsilon_1(E)}{|\epsilon(E)|^2}\Big)\theta + \frac{\alpha}{\beta^2\pi}\frac{\sigma_\gamma(E)}{EZ}\ln\Big(\frac{2m_ec^2\beta^2}{E}\Big) + \frac{\alpha}{\beta^2\pi}\frac{1}{E^2}\int_0^E\frac{\sigma_\gamma(E')}{Z}dE'$$

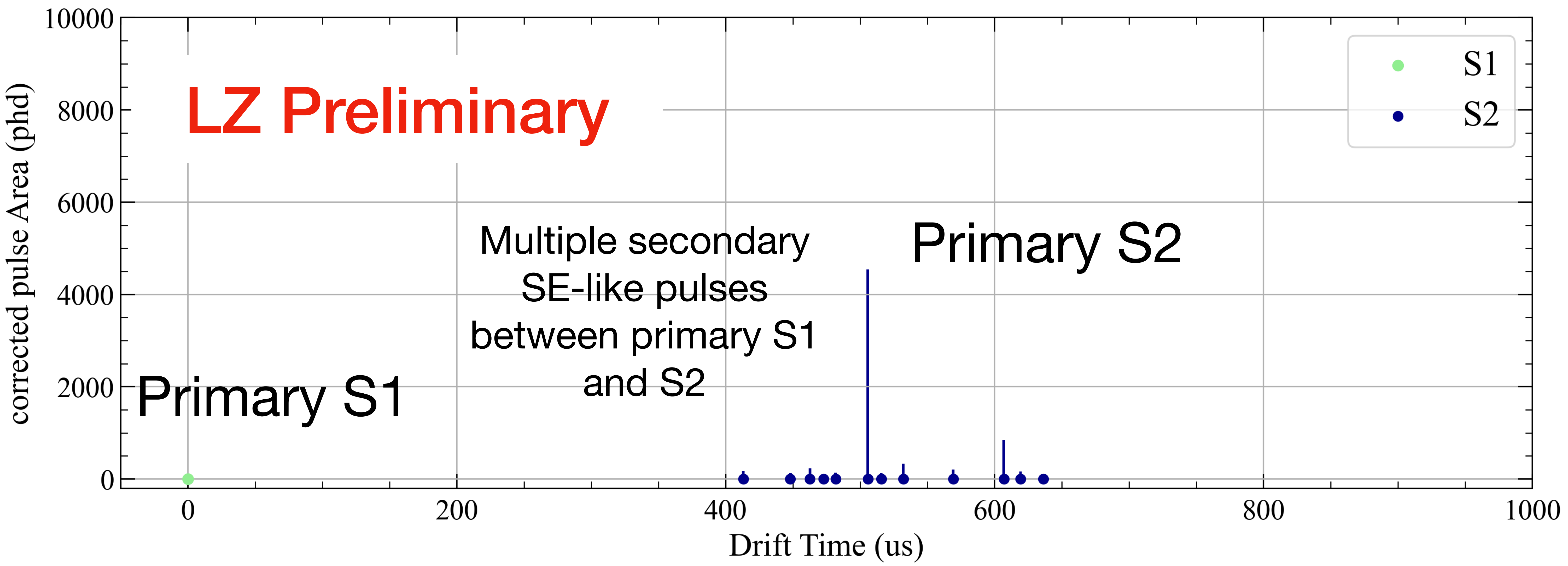


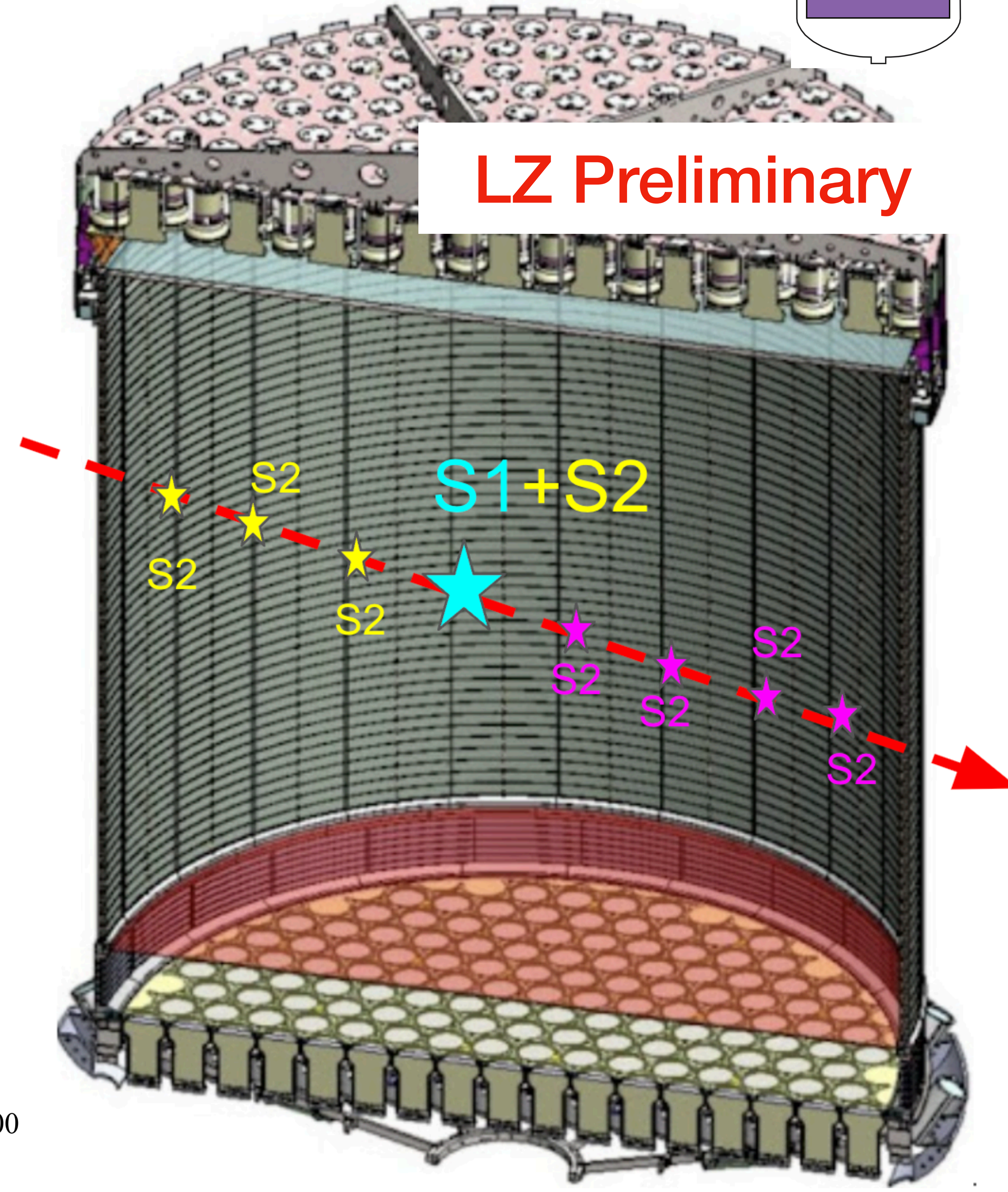
Both cross section are proportional to ϵ^2, and suppressed asymptotically by E_r^{-2}.

A $\mathcal{O}$(keV) hard ER scatter will be accompanied by many sub-keV softer scatters, leading to many small, SE-like S2 pulses!

Search for mCPs in a liquid xenon TPC

- Event signature:
  - An ER-like S1-S2 pair from a single hard scatter (primary S1 and S2), sandwiching multiple sub-threshold S2s (from soft scatters)





Data analysis

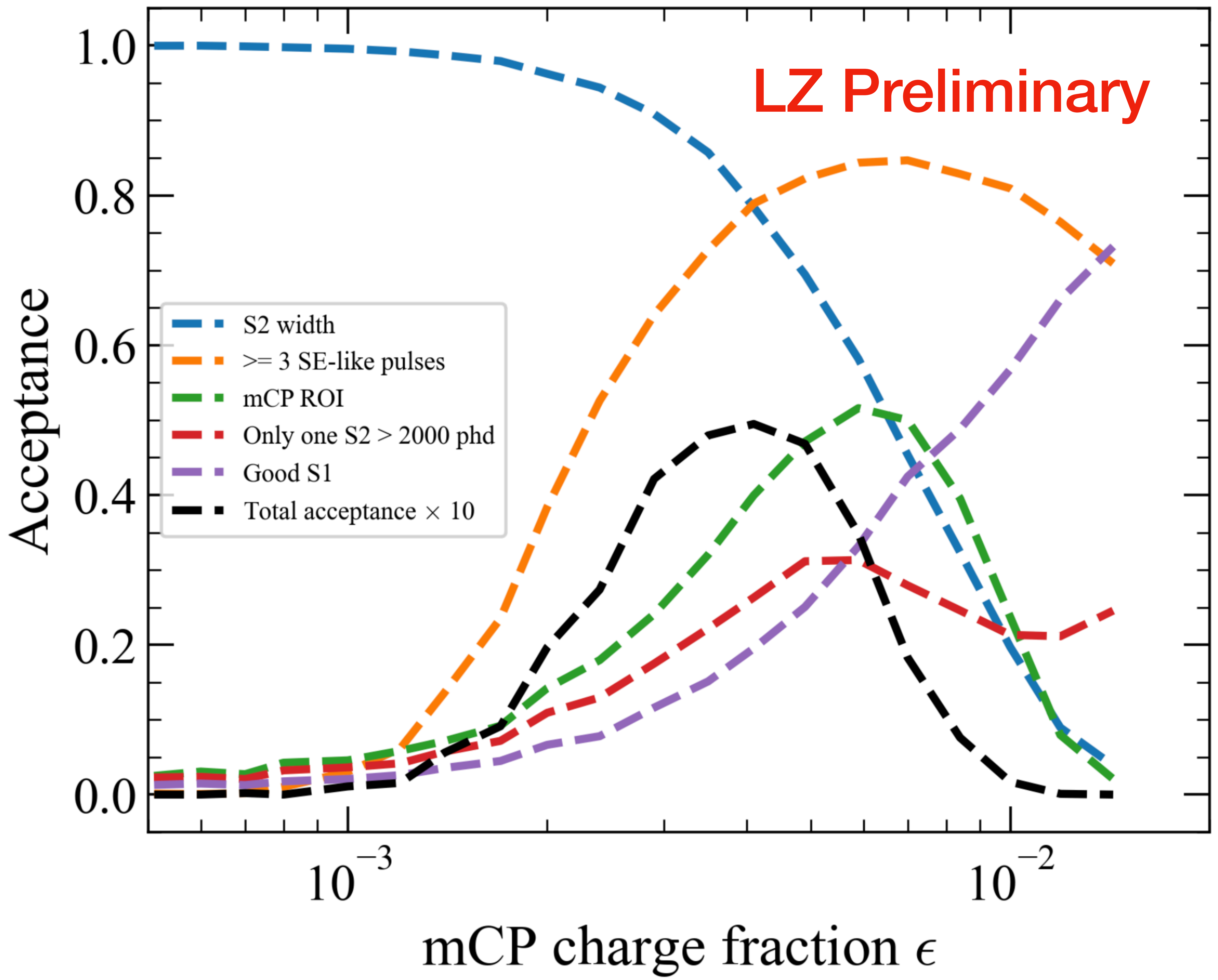
- Dataset: LZ SR1 WIMP serach data set (5.5 t fiducial volume, 60 live days)

Cut name	Descritption
Good S1	Only one S1 pulse that is >= 3 phd in area and satisfies the 3-fold coincidence
Single large S2	Only one S2 pulse > 2000 phd, corresponding to ~1 keV energy deposit
SR1 data quality cuts	The primary S1 and S2 pulse must satisfy all SR1 data quality cuts to mitigate accidental backgrounds
> 2 sub-threshold S2s between primary S1 and S2	There must be at least three S2-like pulses in the event that are smaller than 2000 phd and between the primary S1 and S2
mCP ROI	The primary S1 and S2 area must fall within the 90% CL mCP signal event contour evaluated from simulation

Data analysis

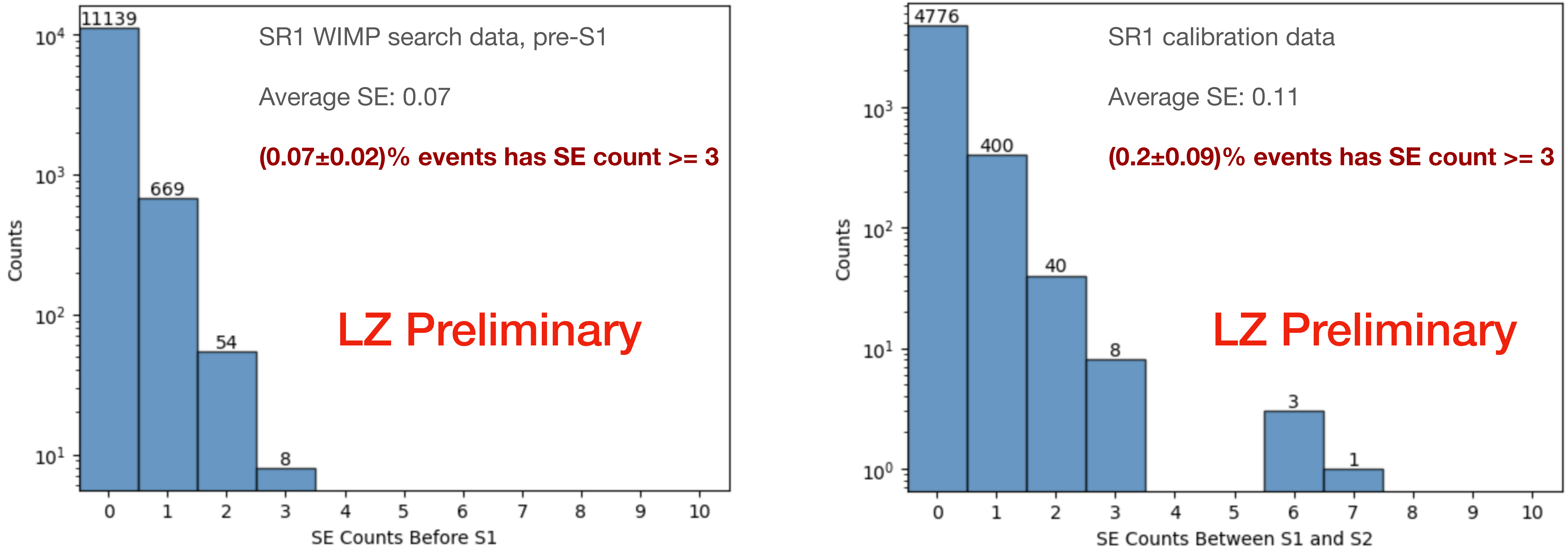
- mCP tracks crossing TPC are simulated using NEST-based LZ internal simulation frame work
- Cut acceptances evaluated on simulated mCP samples
- Efficiency peak when charge is ~0.005
- In small charge region, most signal losses are due to lack of hard scatter
- On the large charge end, most signal losses are from pulse merging and too many large S2s

Cut acceptances evaluated from simulation



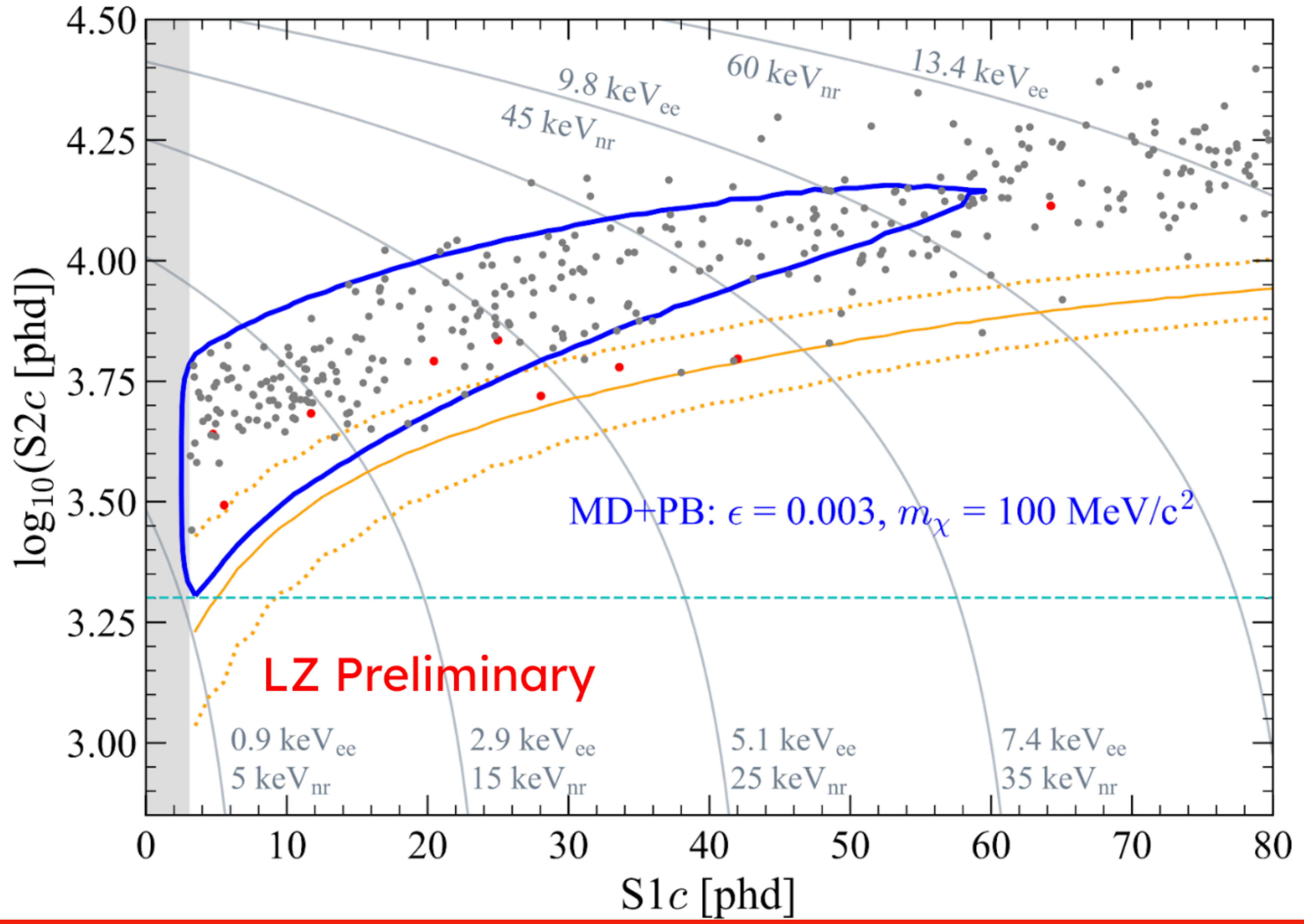
Backgrounds

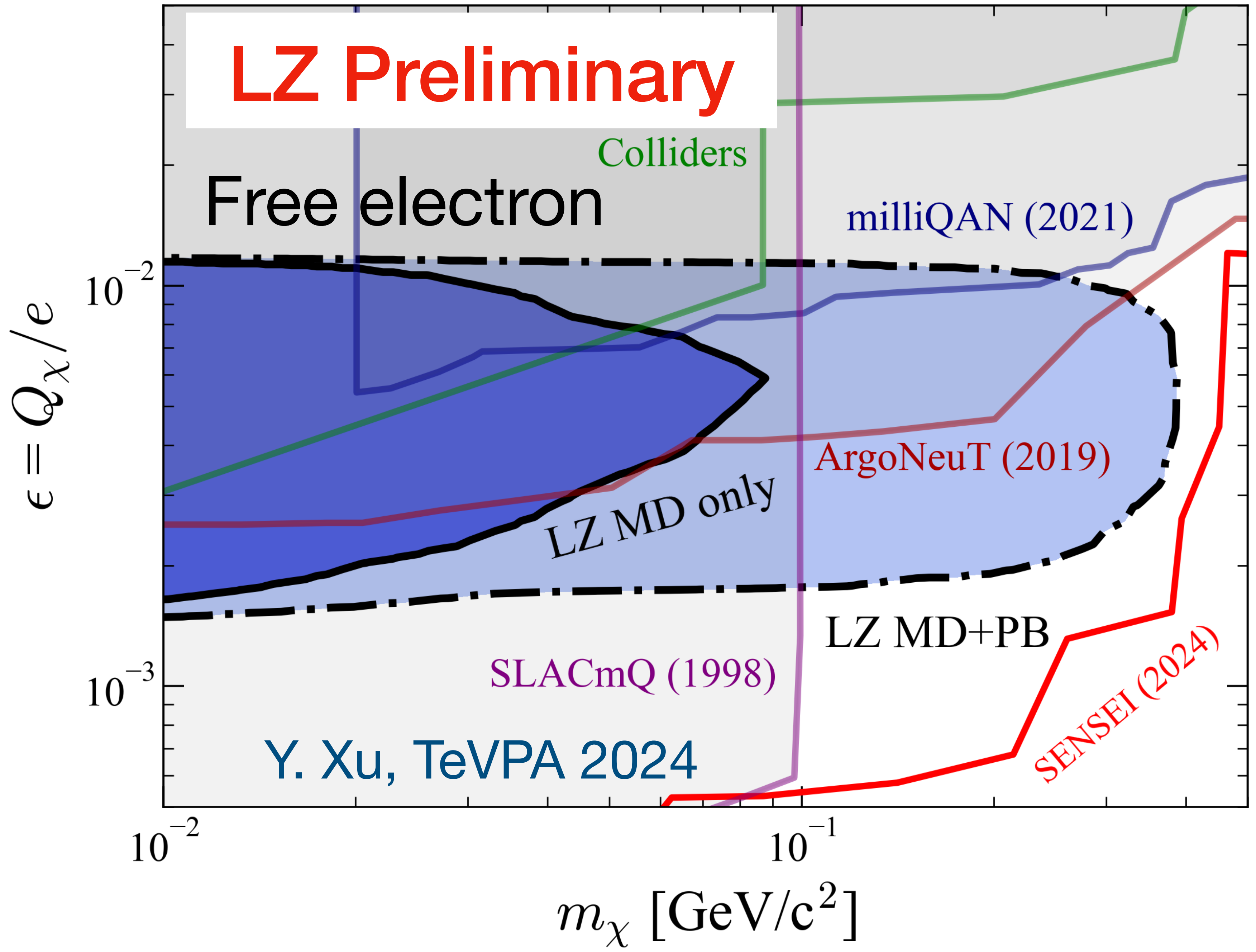
- Two main sources of background considered:
  - Single scatters coincide with >=3 sub-threshold S2s
  - Neutron/γ multiple scatters
- The contribution from first type is quantified using pre-trigger & calibration data and validated using wall events
- The contribution from the second type of events is quantified from simulations to be negligible
- We quote ***0.6*** as the expected number of backgrounds in LZ SR1

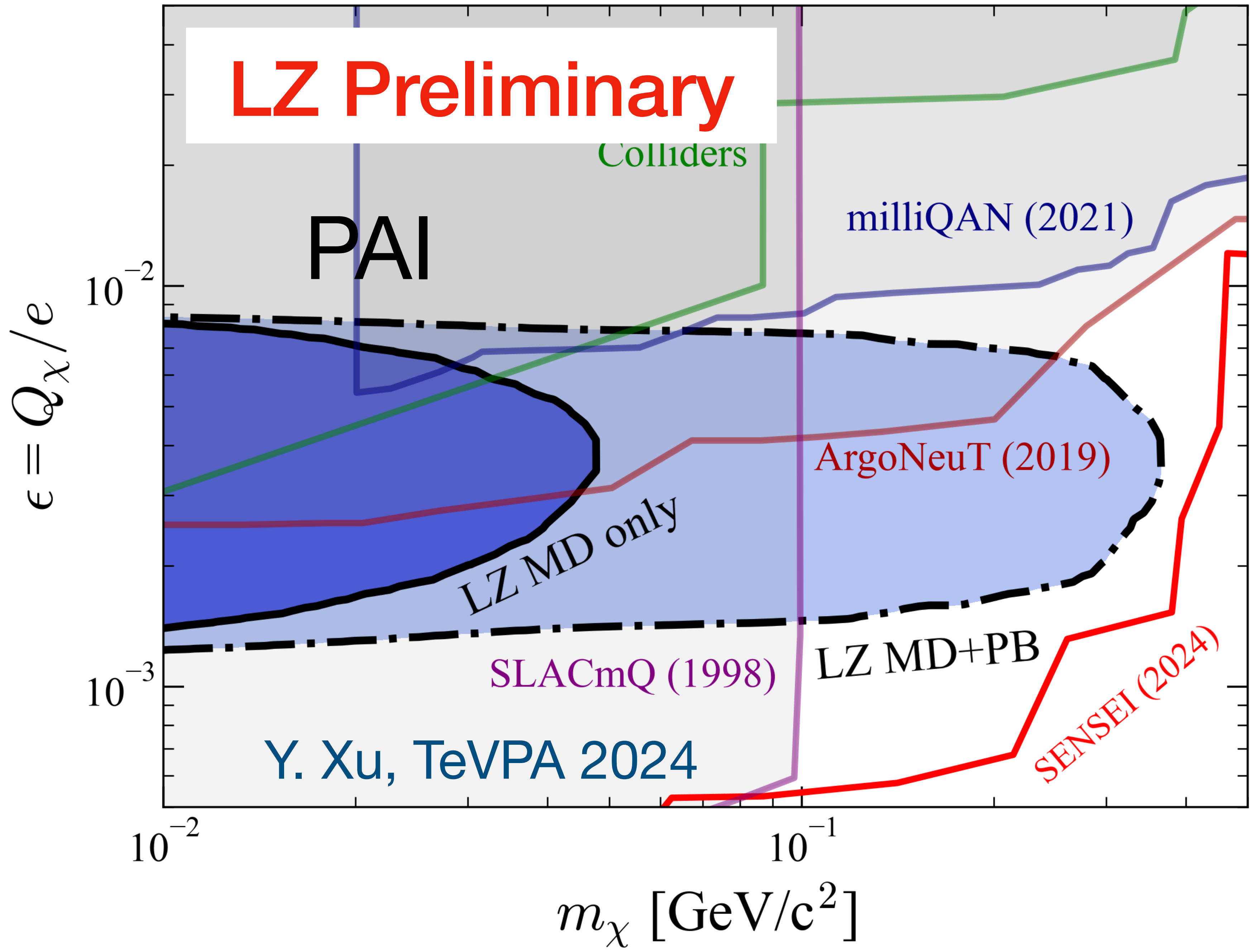


Data analysis

- After applying all cuts, no signal event in SR1 has been observed, consistent with our background model
- We conservatively follow the Feldman-Cousins convention for 0 signal/0 background scenario to set limits on atmospheric mCP models
- New limits are set using contributions from MD and PB channels combined on mCPs with charge ~0.0015 up to mass of ~0.4 GeV







Conclusion

- First experimental search for atmospheric mCPs have been conducted using LZ SR1 data.

- A novel signature has been proposed to search for low charge mCPs in liquid xenon TPCs, and analysis developed accordingly.

- The first limit from underground LXe experiments has been placed on atmospheric mCP models from a quasi-background free search.

- LZ is collecting data and honing analysis tools — expect better sensitivity with our full 1000 day exposure!

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

https://lz.lbl.gov/

250 scientists, engineers, and technical staff

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- 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.
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