Status and Results from the LUX-ZEPLIN Experiment

Joe McLaughlin
University College London
On behalf of the LZ Collaboration
Lake Louise Winter Institute 2024

The LZ Collaboration

LUX-ZEPLIN (LZ) is…

- 250 scientists, engineers, and technical staff
  37 institutions
  5 countries (US, UK, Portugal, Korea, Australia)
- Follow us! ***@lzdarkmatter***
- Our website: https://lz.lbl.gov/

Science and Technology Facilities Council

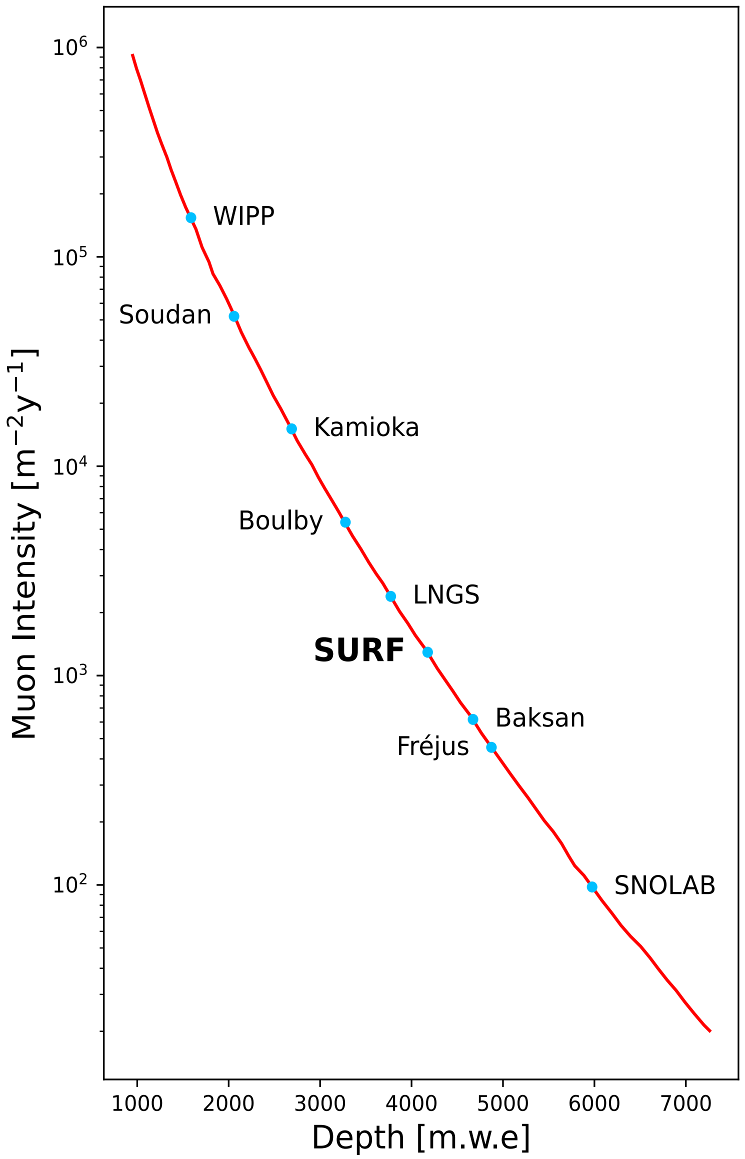
FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

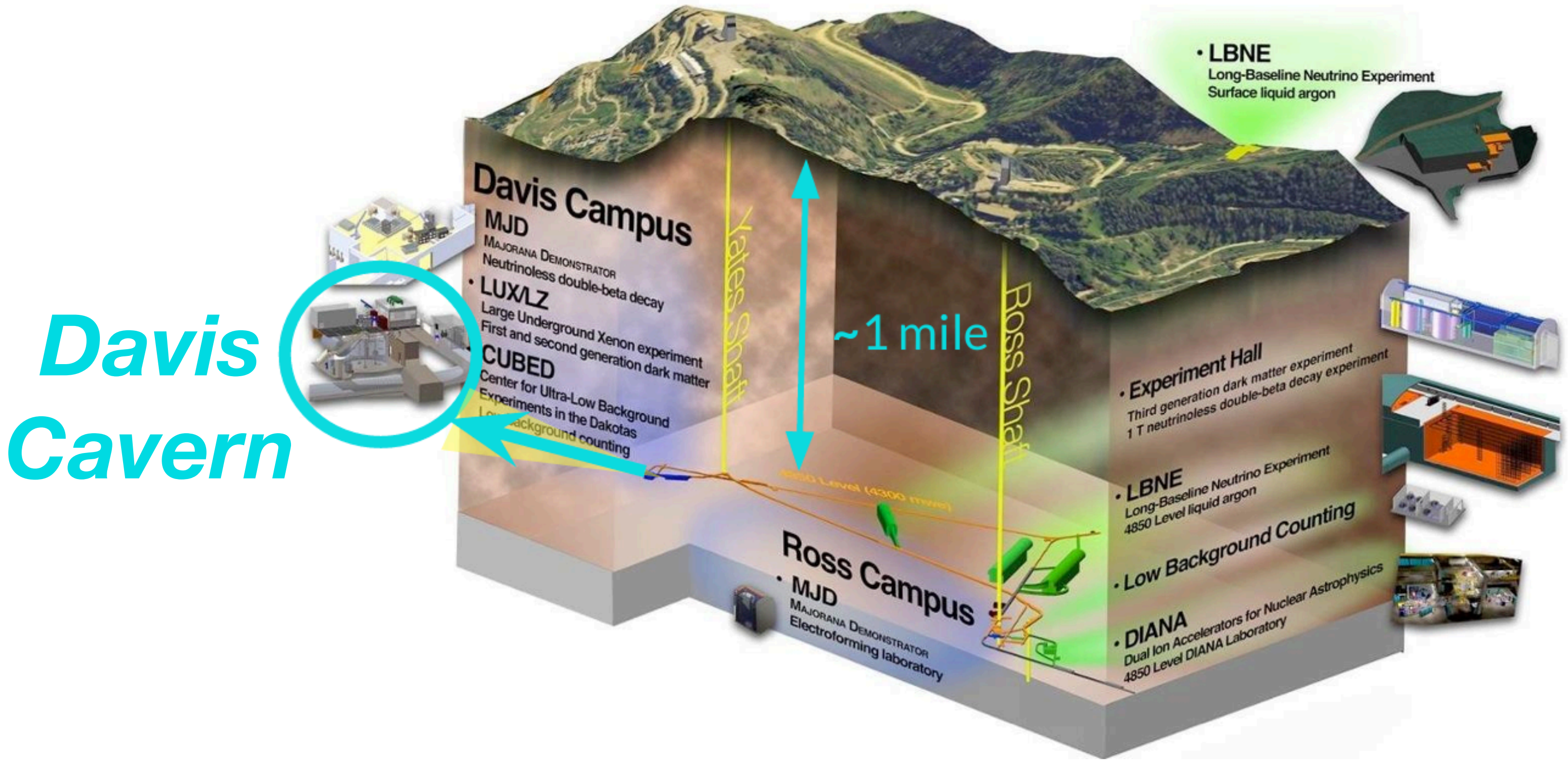
Sanford Underground Research Facility
South Dakota Science and Technology Authority

Institute for Basic Science

The LZ Experiment

1 mile under the Black Hills of South Dakota



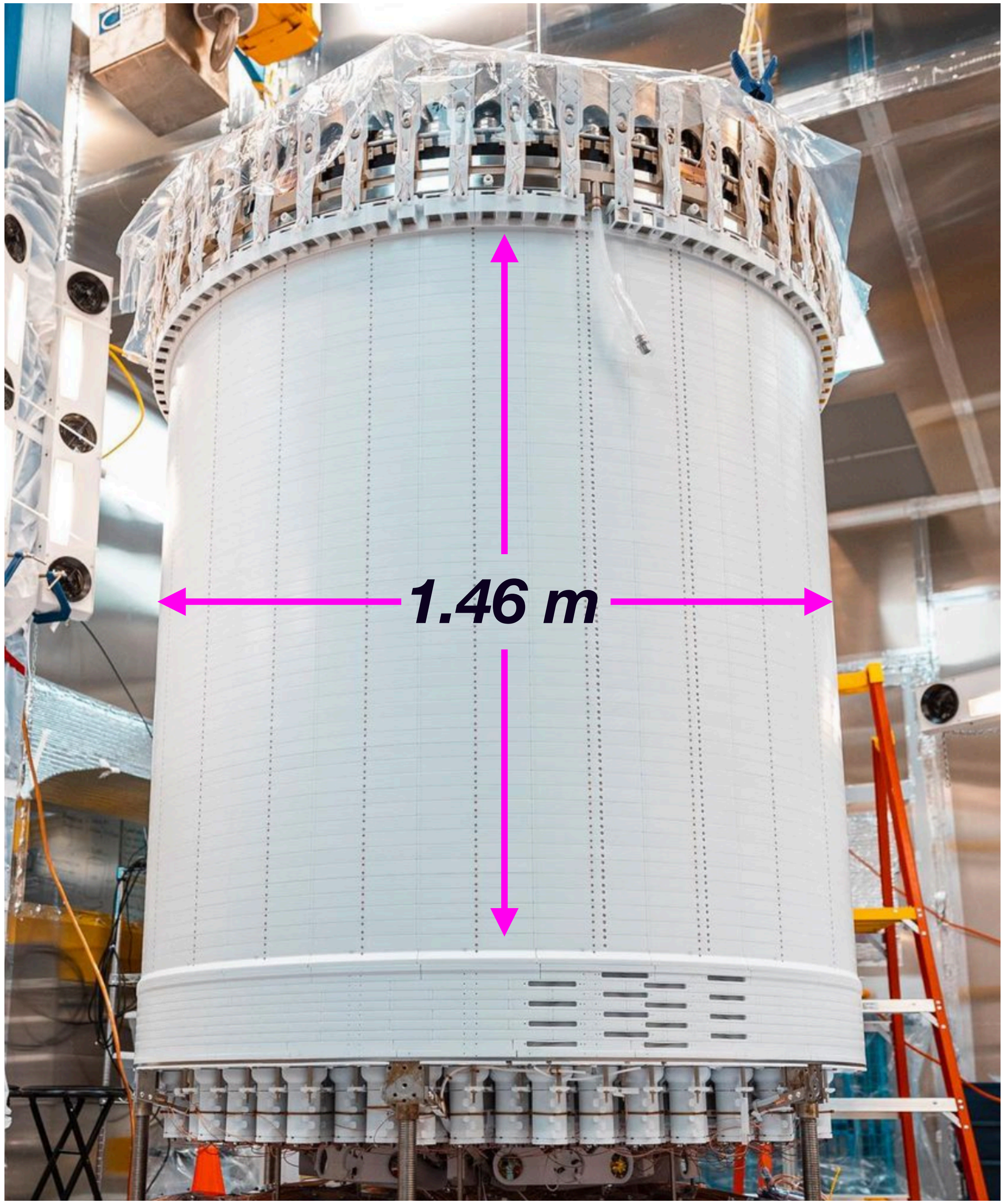


Sanford Underground Research Facility
South Dakota Science and Technology Authority

The LZ Experiment

Dual-phase liquid xenon (LXe) time projection chamber (TPC)

- 10 tonnes total mass
- 7 tonnes active mass
- 5.5 tonnes fiducial mass



The LZ Experiment

Dual-phase liquid xenon (LXe) time projection chamber (TPC)

- 10 tonnes total mass
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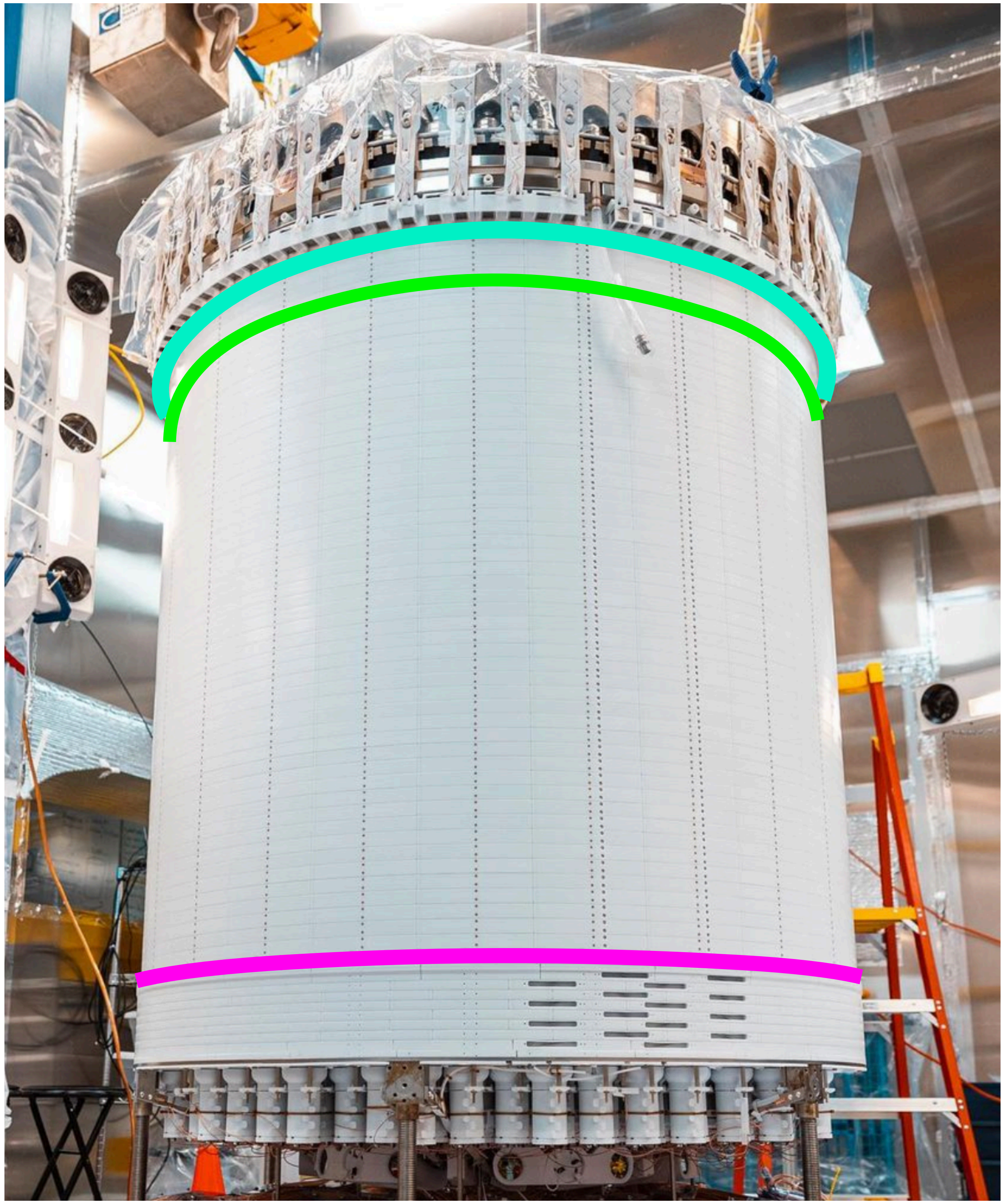
Mesh wire grid electrodes

- GXe extraction region between ***gate*** and ***anode***— ***7.3 kV/cm***
- LXe drift region between ***cathode*** and ***gate***— ***193 V/cm***



The LZ Experiment

Dual-phase liquid xenon (LXe) time projection chamber (TPC)

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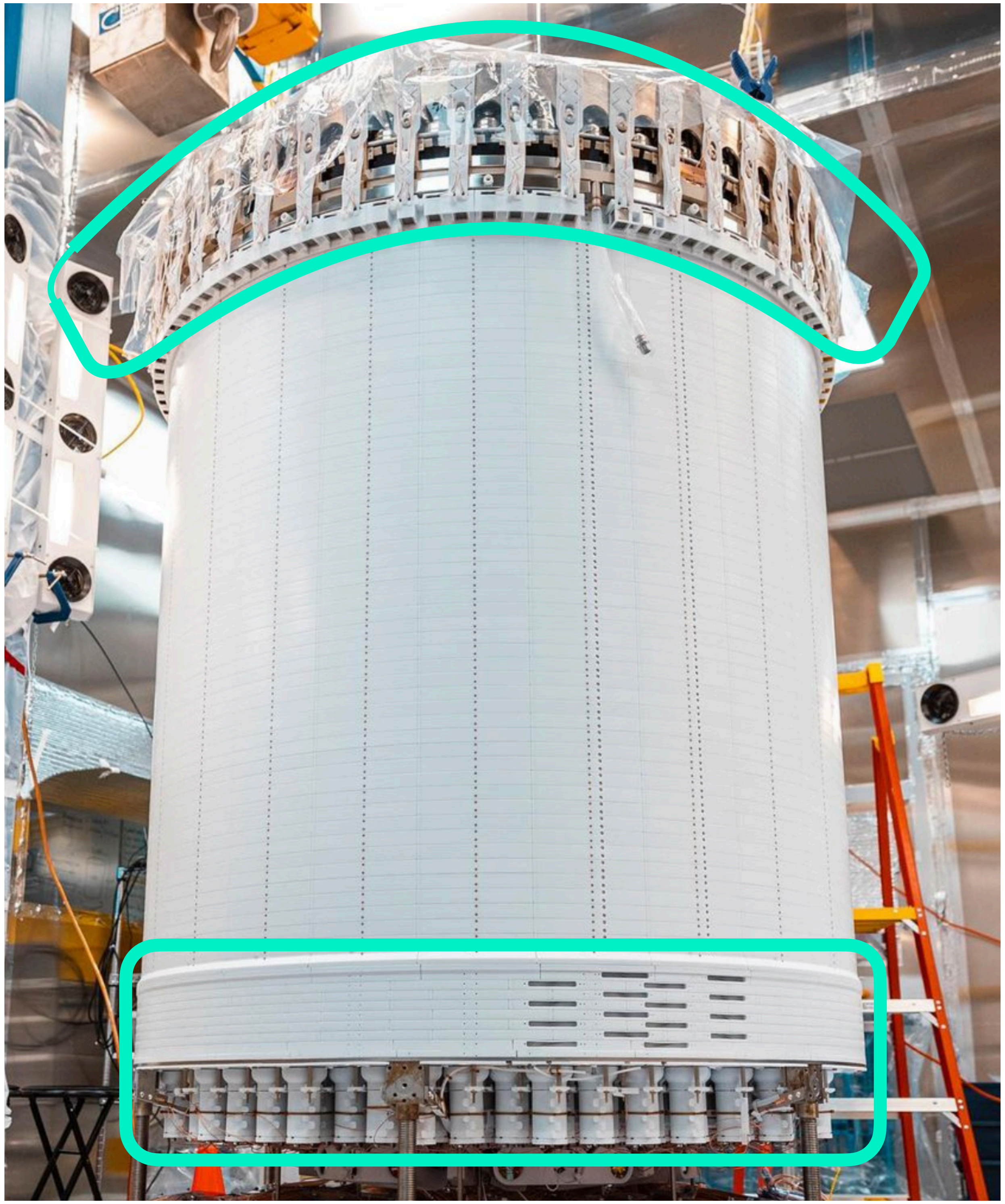
Mesh wire grid electrodes

GXe extraction region between ***gate*** and ***anode***— ***7.3 kV/cm***
LXe drift region between ***cathode*** and ***gate***— ***193 V/cm***

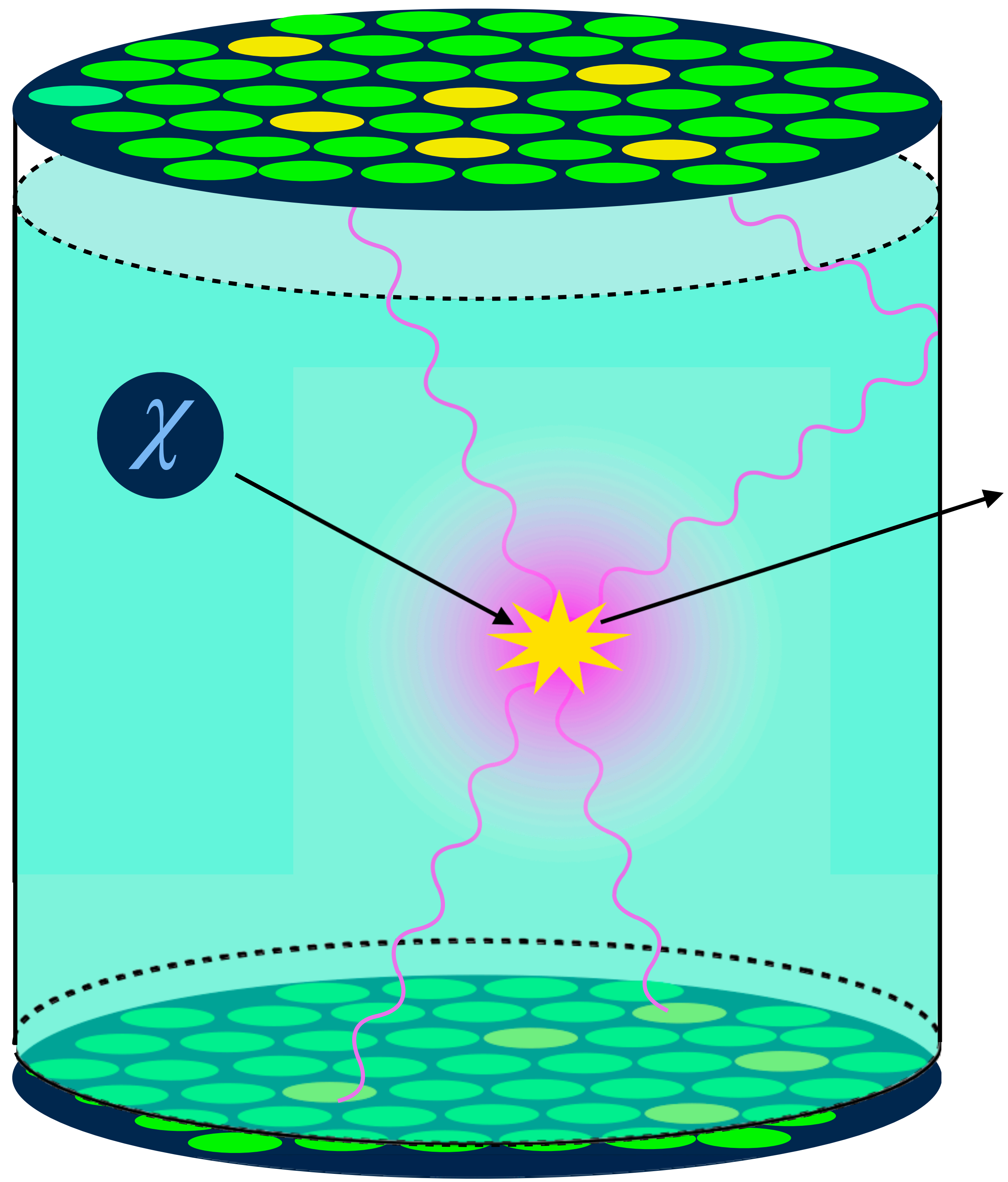
Instrumented with 494 Hamamatsu R11410-22 3" PMTs

253 PMTs in top array
241 PMTs in bottom array



Event Reconstruction

A typical signal



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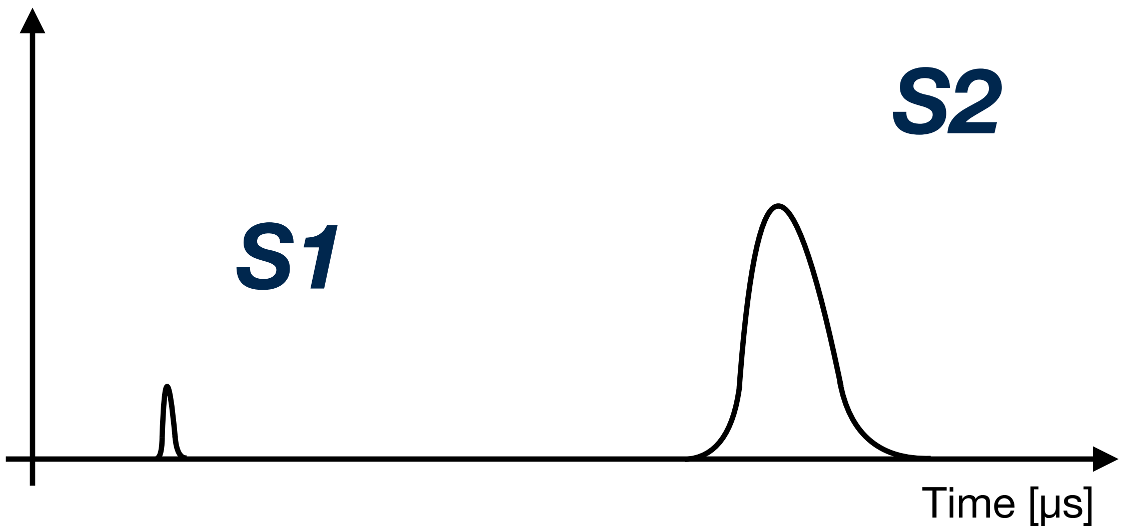

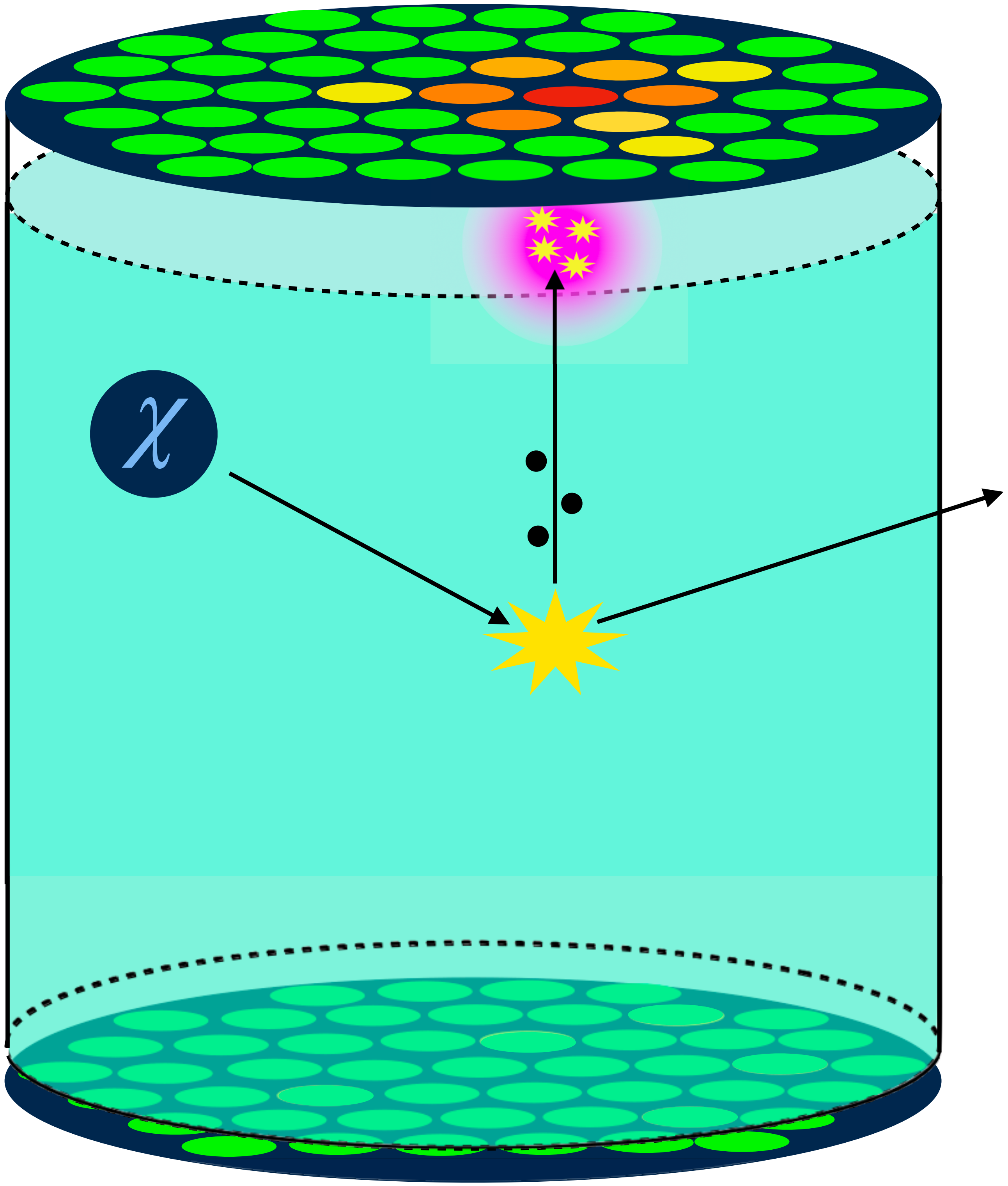

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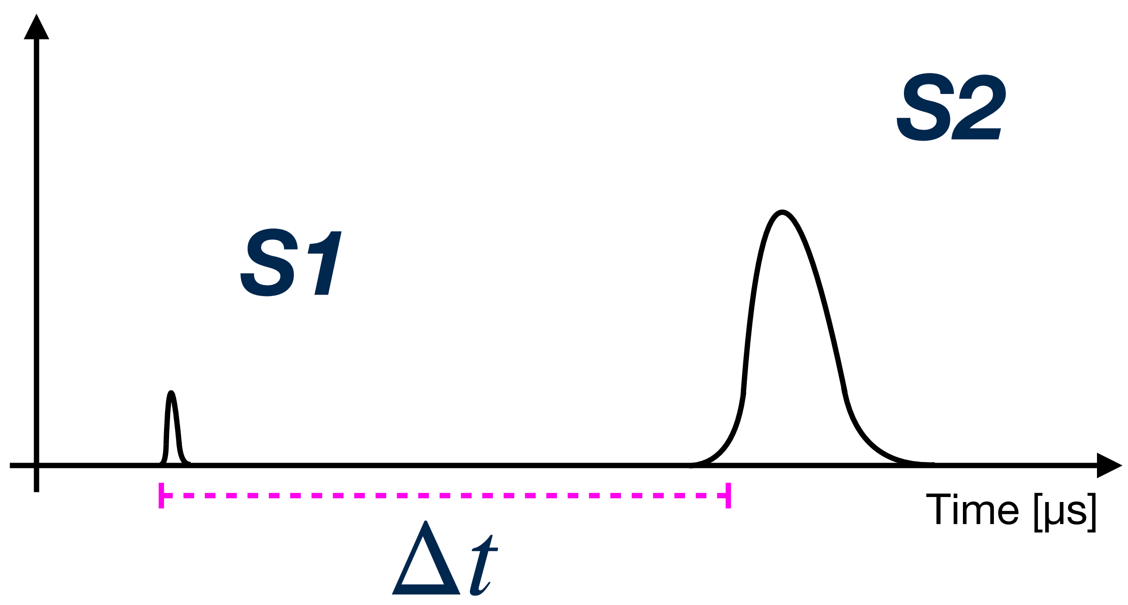
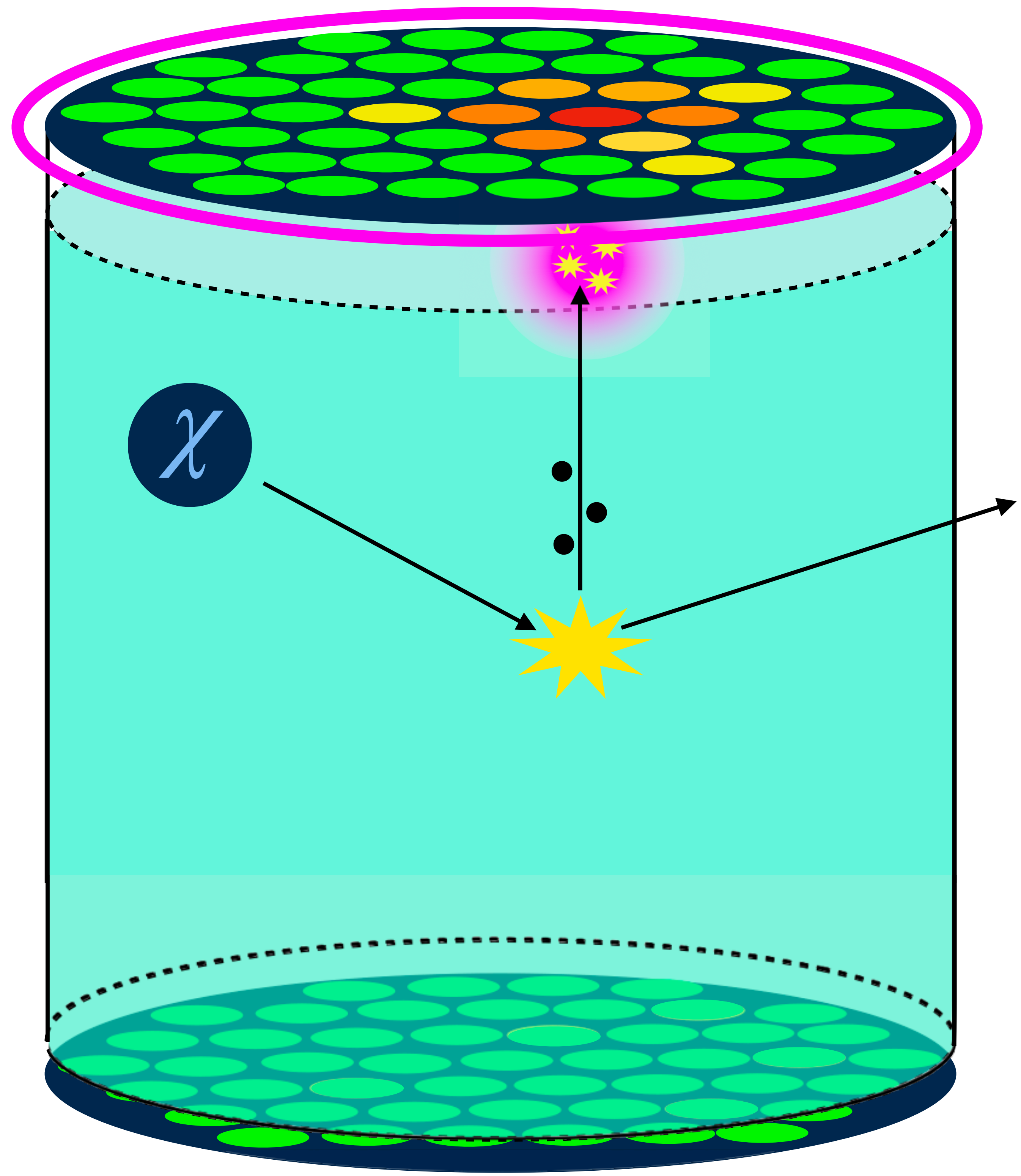


3D Position Reconstruction

- **Hit pattern** gives radial position
- Δt gives vertical position



Event Reconstruction

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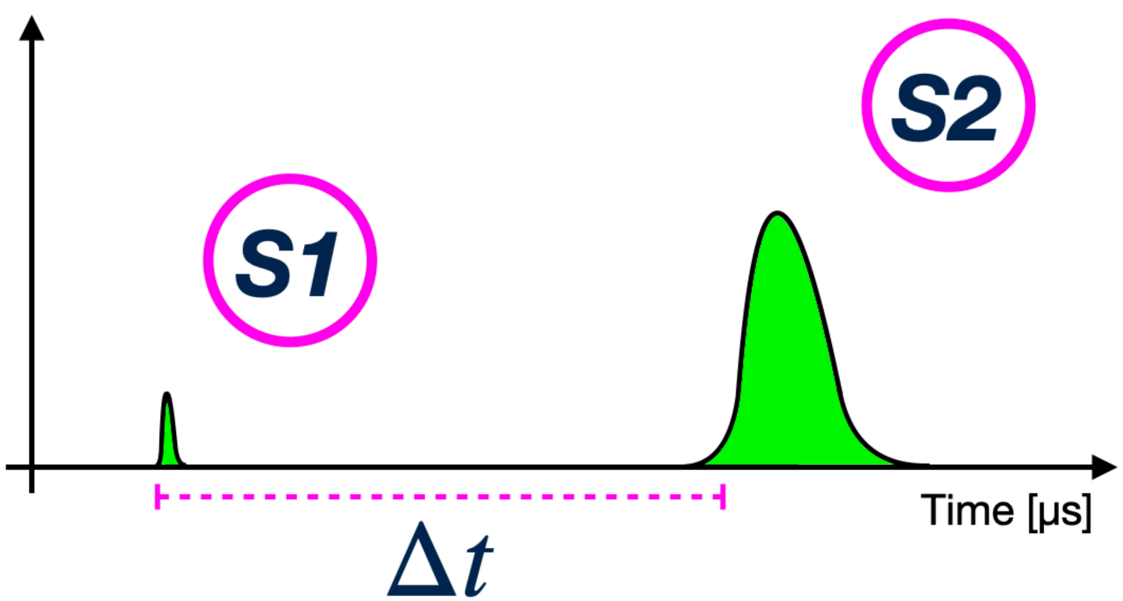
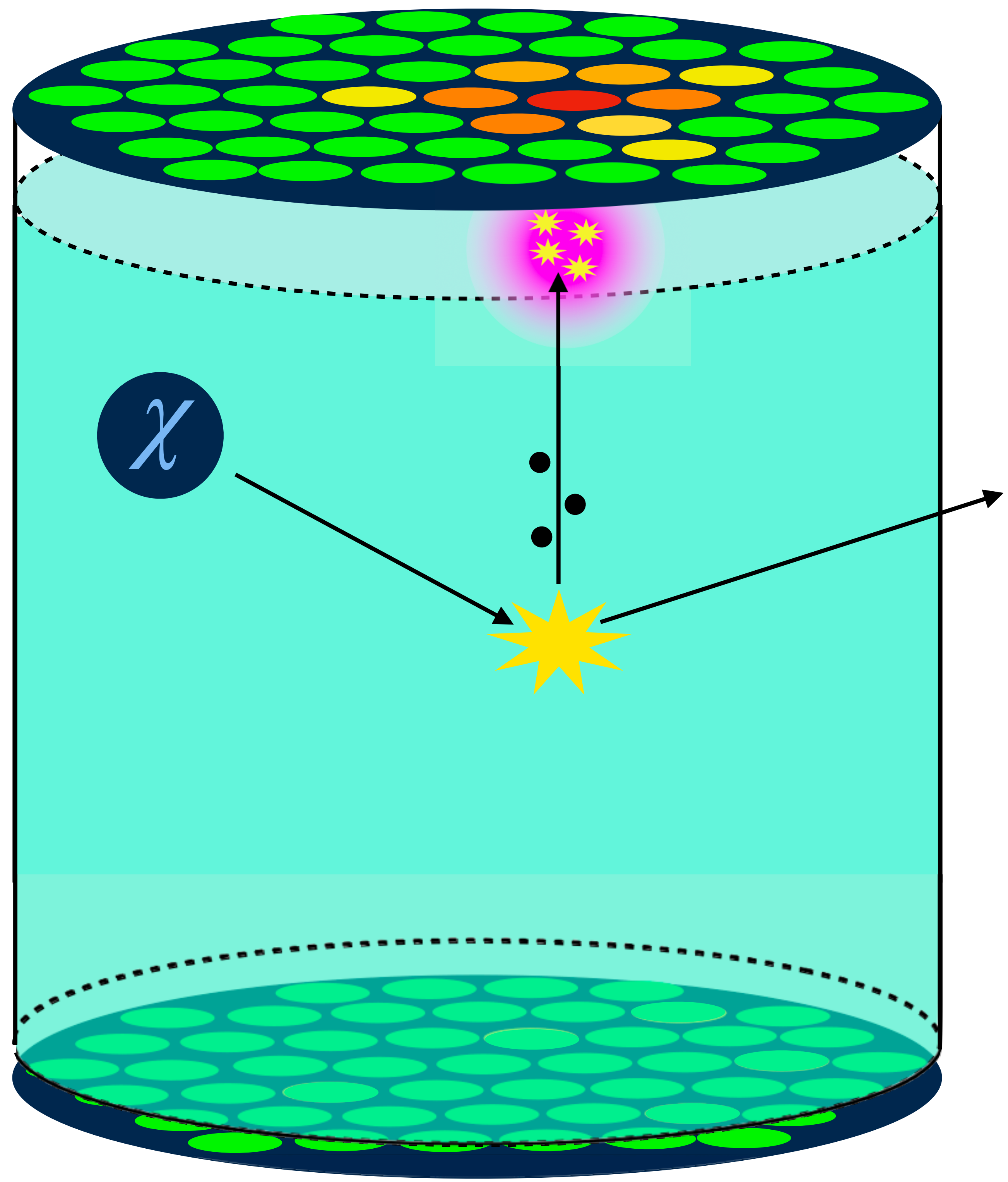


Energy Reconstruction

$$E = 13.5\,\mathrm{eV}\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$

- $g_1 \equiv$ S1 photons detected (phd) per scintillation photon
- $g_2 \equiv$ S2 phd per ionization electron



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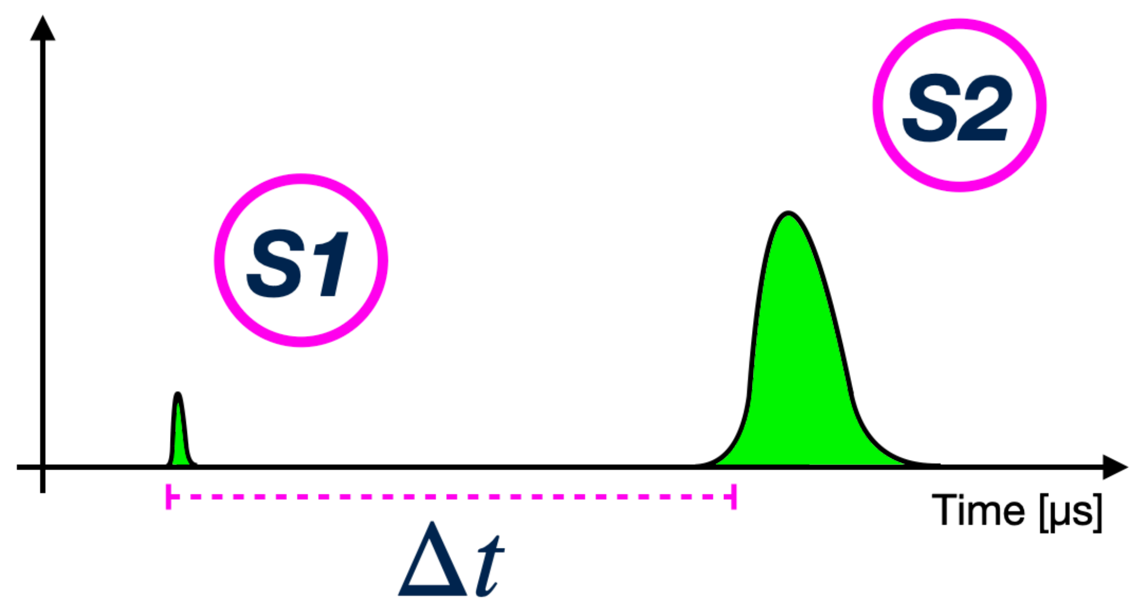
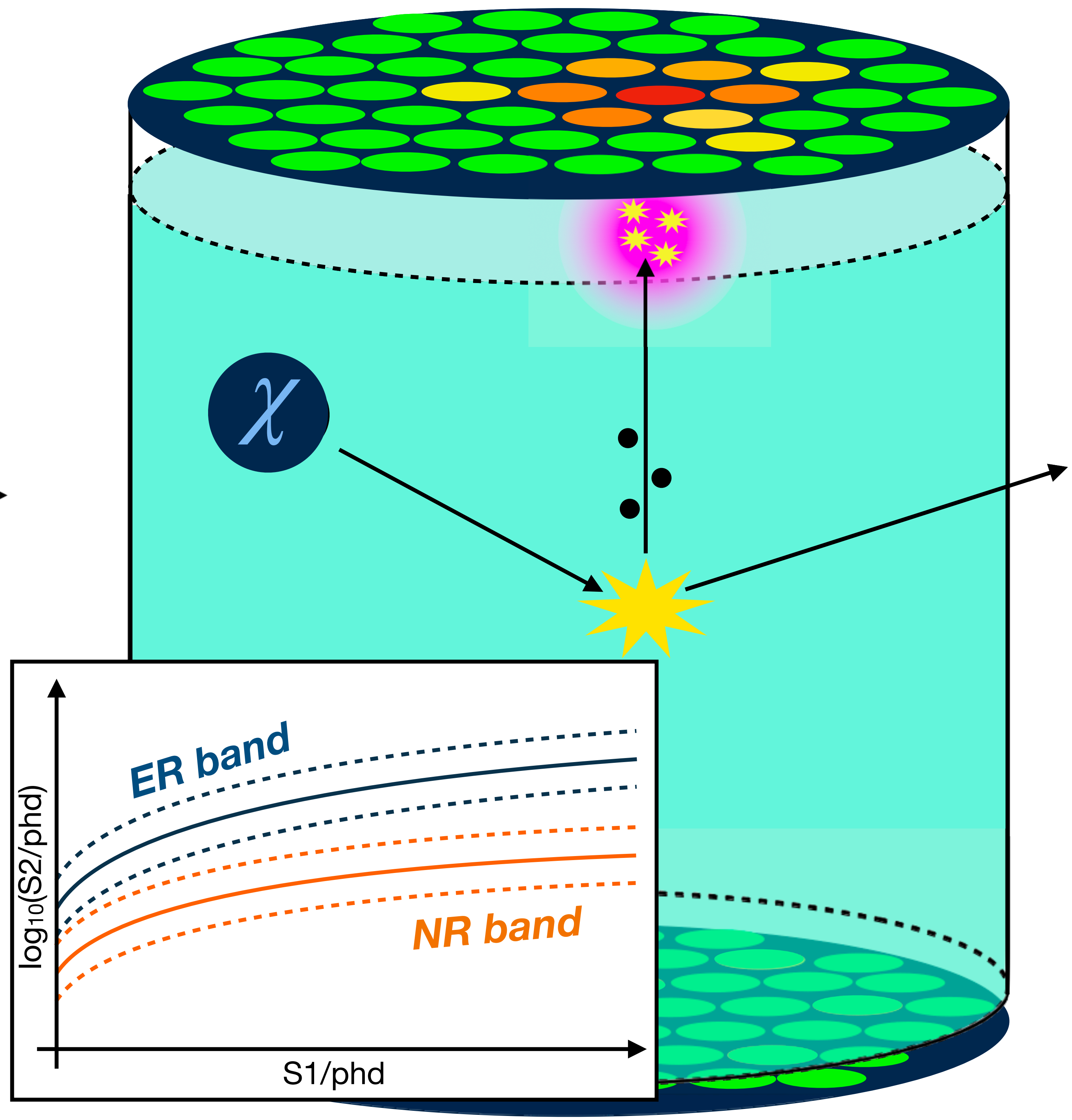
Event Reconstruction

A typical signal





Particle Identification

- Electronic Recoils (ERs) have exciton:ion ratio ~0.06

  ➡ ***Favours ionization***

- Nuclear Recoils (NRs) have exciton:ion ratio ~1

  ➡ ***Favours scintillation***

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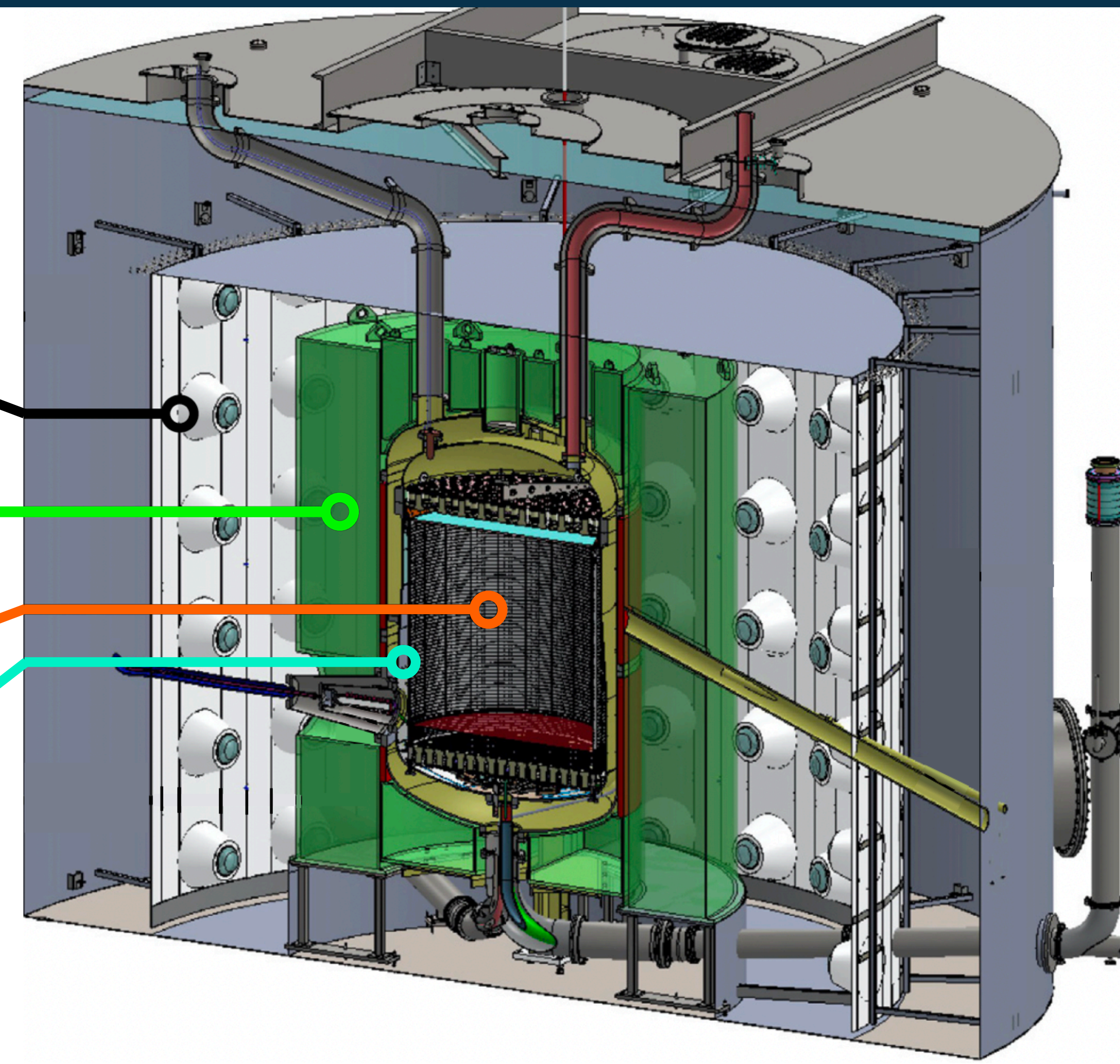
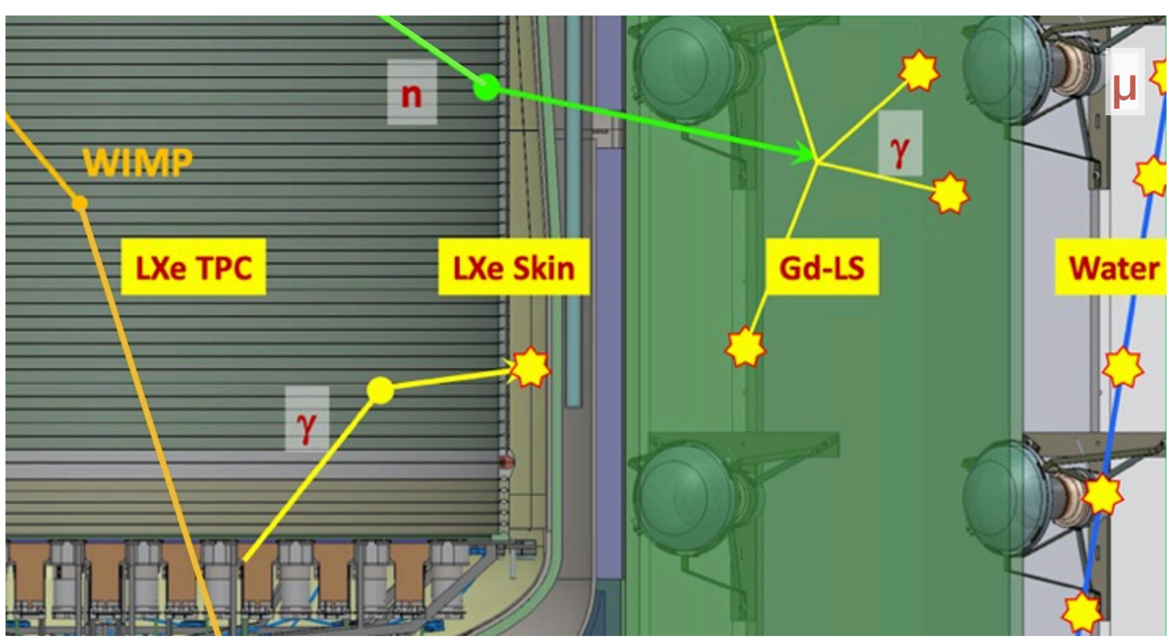
Outside the TPC

Anti-Coincidence Veto System





- 17 tonnes **Gd-loaded scintillator** in OD
  - High thermal neutron capture cross-section
  - Release of ~8 MeV γ-rays from neutron capture
- **LXe Skin** detector 78±5% efficient at tagging γ-rays from internal TPC decays

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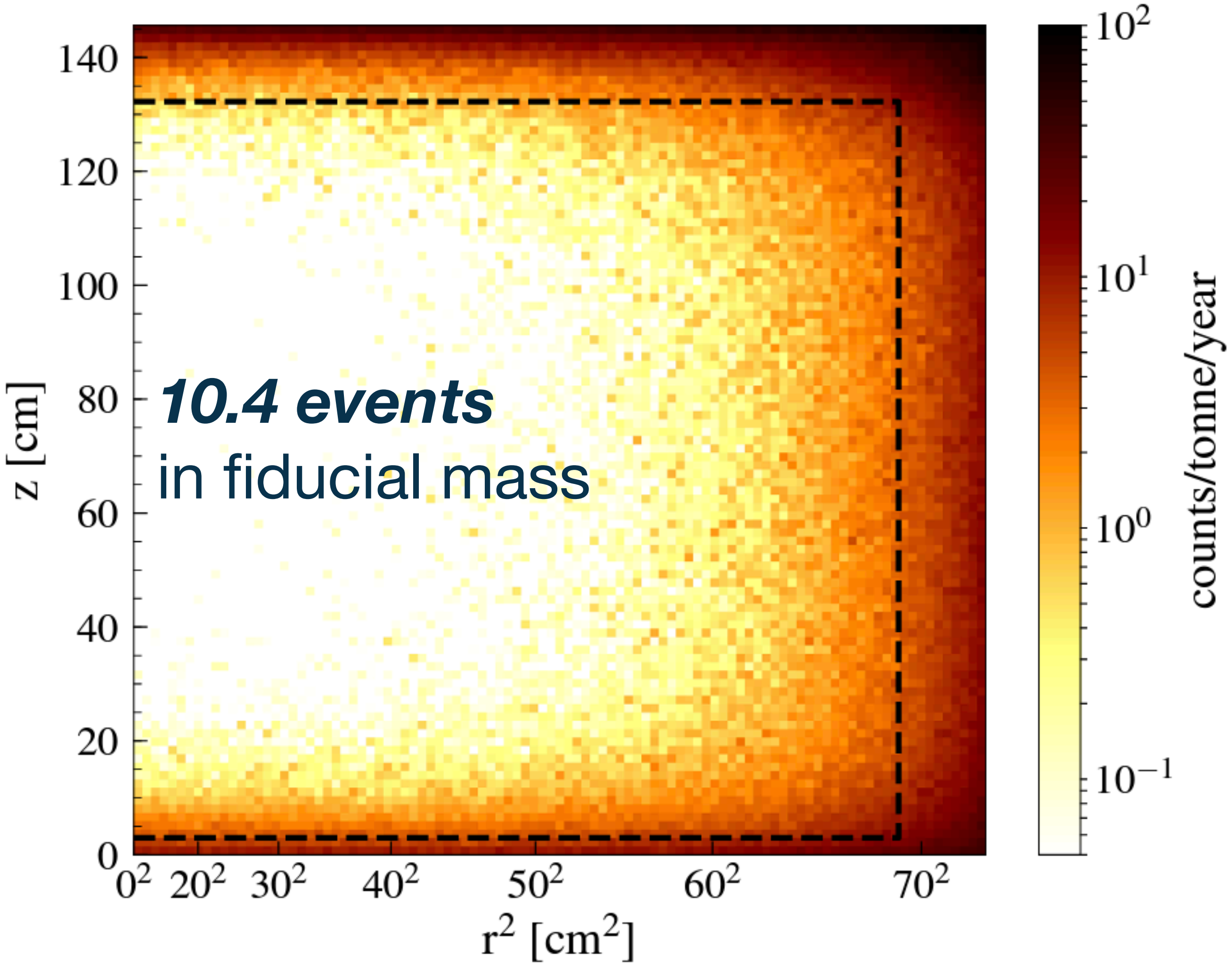
Outside the TPC

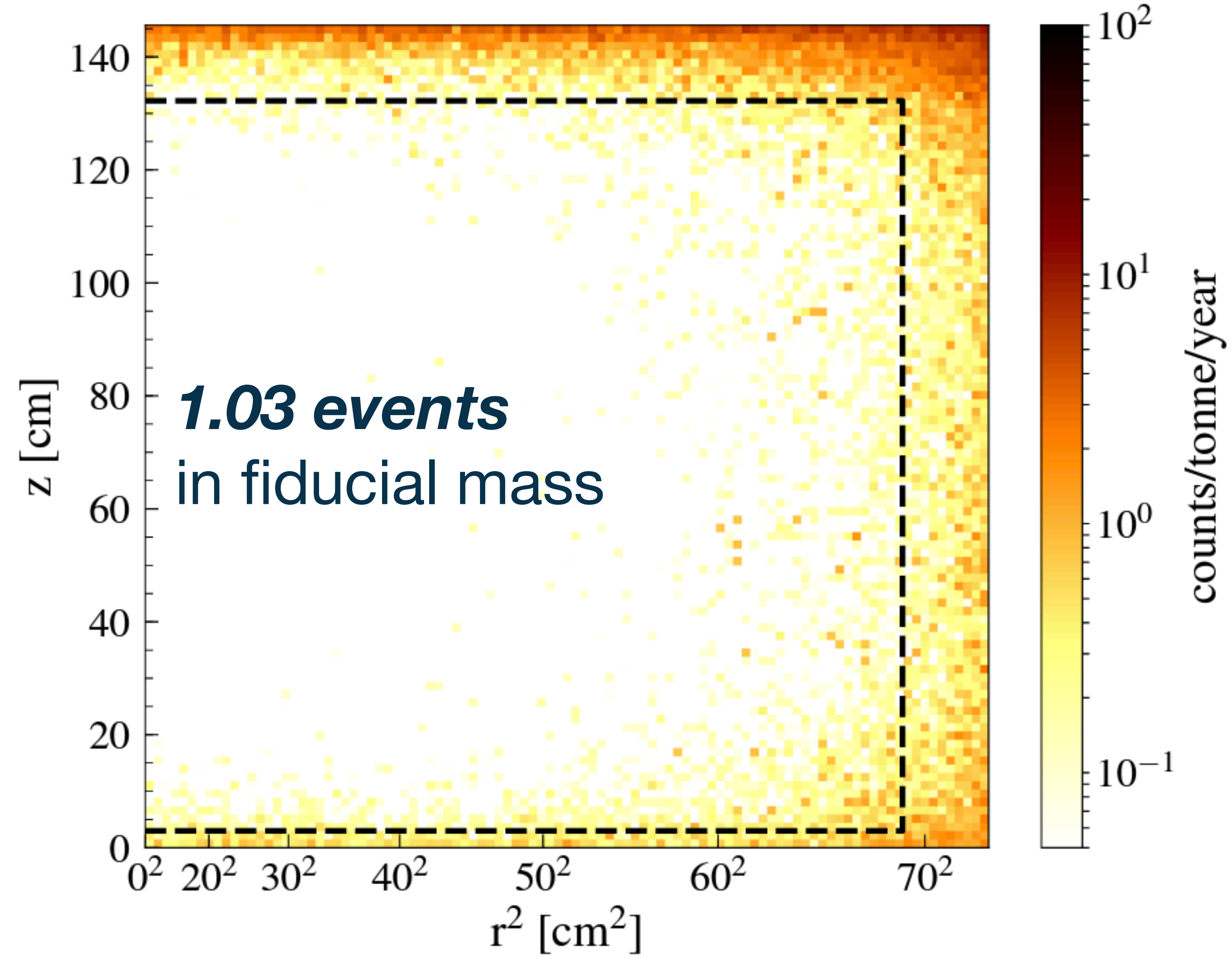
Anti-Coincidence Veto System

- Simulations show anti-coincidence veto reduces NR backgrounds in 1000 day run by factor of 10

6-30 keV nuclear recoils
before anti-coincidence veto



6-30 keV nuclear recoils
after anti-coincidence veto



First Results (SR1)

PHYSICAL REVIEW LETTERS **131,** 041002 (2023)

Editors' Suggestion **Featured in Physics**

First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment

J. Aalbers,[1,2] D. S. Akerib,[1,2] C. W. Akerlof,[3] A. K. Al Musalhi,[4] F. Alder,[5] A. Alqahtani,[6] S. K. Alsum,[7] C. S. Amarasinghe,[3] A. Ames,[1,2] T. J. Anderson,[1,2] N. Angelides,[5,8] H. M. Araújo,[8] J. E. Armstrong,[9] M. Arthurs,[3] S. Azadi,[10] A. J. Bailey,[8] A. Baker,[8] J. Balajthy,[11] S. Balashov,[12] J. Bang,[6] J. W. Bargemann,[10] M. J. Barry,[13] J. Barthel,[14] D. Bauer,[8] A. Baxter,[15] K. Beattie,[13] J. Belle,[16] P. Beltrame,[5,17] J. Bensinger,[18] T. Benson,[7] E. P. Bernard,[13,19] A. Bhatti,[9]

(Received 18 July 2022; revised 6 March 2023; accepted 7 June 2023; published 28 July 2023)

The LUX-ZEPLIN experiment is a dark matter detector centered on a dual-phase xenon time projection chamber operating at the Sanford Underground Research Facility in Lead, South Dakota, USA. This Letter reports results from LUX-ZEPLIN's first search for weakly interacting massive particles (WIMPs) with an exposure of 60 live days using a fiducial mass of 5.5 t. A profile-likelihood ratio analysis shows the data to be consistent with a background-only hypothesis, setting new limits on spin-independent WIMP-nucleon, spin-dependent WIMP-neutron, and spin-dependent WIMP-proton cross sections for WIMP masses above 9 GeV/c^2. The most stringent limit is set for spin-independent scattering at 36 GeV/c^2, rejecting cross sections above 9.2×10^{-48} cm^2 at the 90% confidence level.

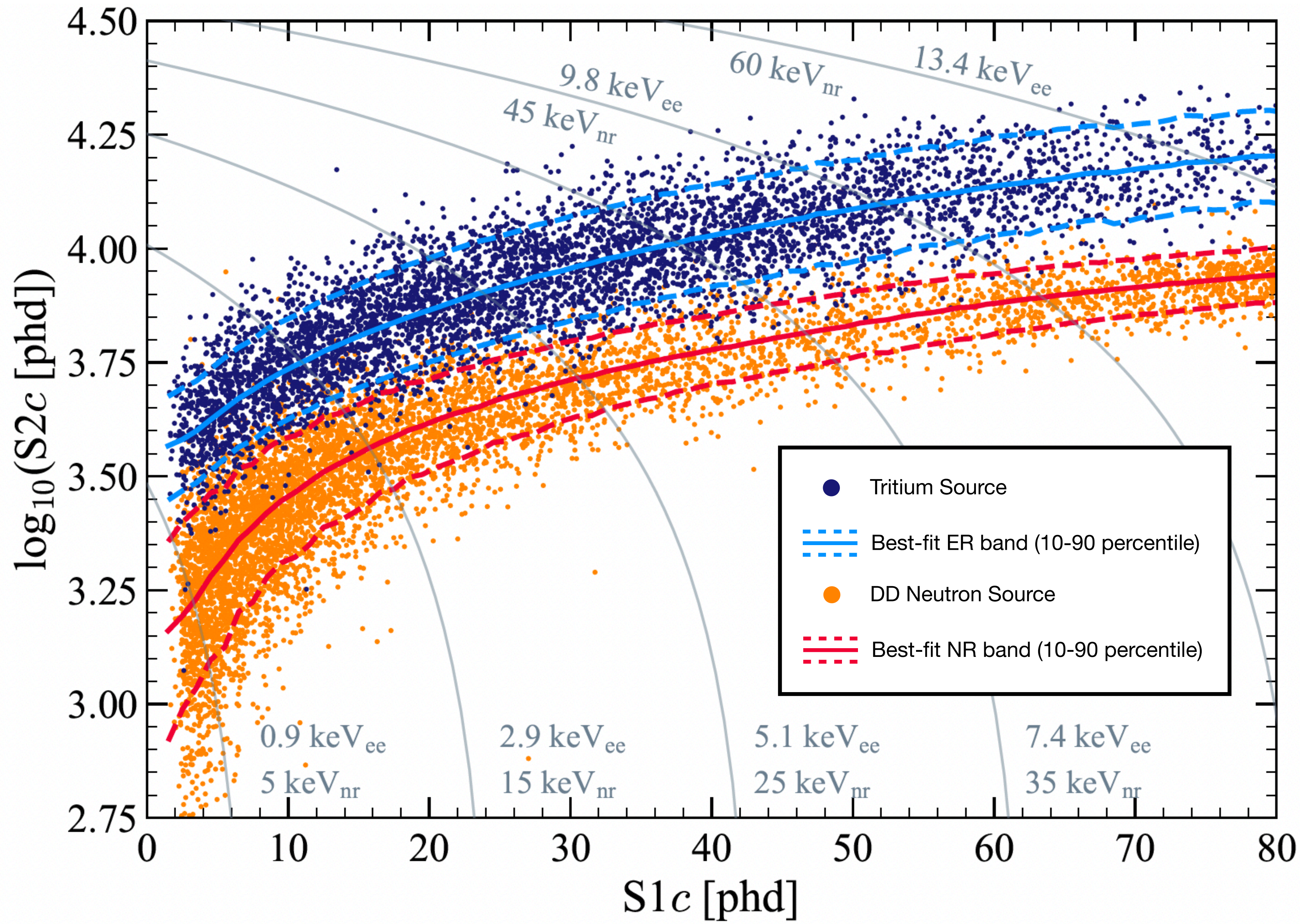
DOI: 10.1103/PhysRevLett.131.041002

SR1 Calibration

***Tritiated methane** (CH_3T) used to calibrate ER band*
- spatially homogenous
- β spectrum with 18 keV endpoint energy

***DD fusion neutrons** used to calibrate NR band*
- Monoenergetic neutron source; 2.45 MeV

ER and NR bands fit using NESTv2.3.7
- GitHub link



99.9% of ER events fall above NR band mean

$$g_1 = 0.114 \pm 0.002 \ phd/\gamma$$

$$g_2 = 47.1 \pm 1.1 \ phd/e^-$$

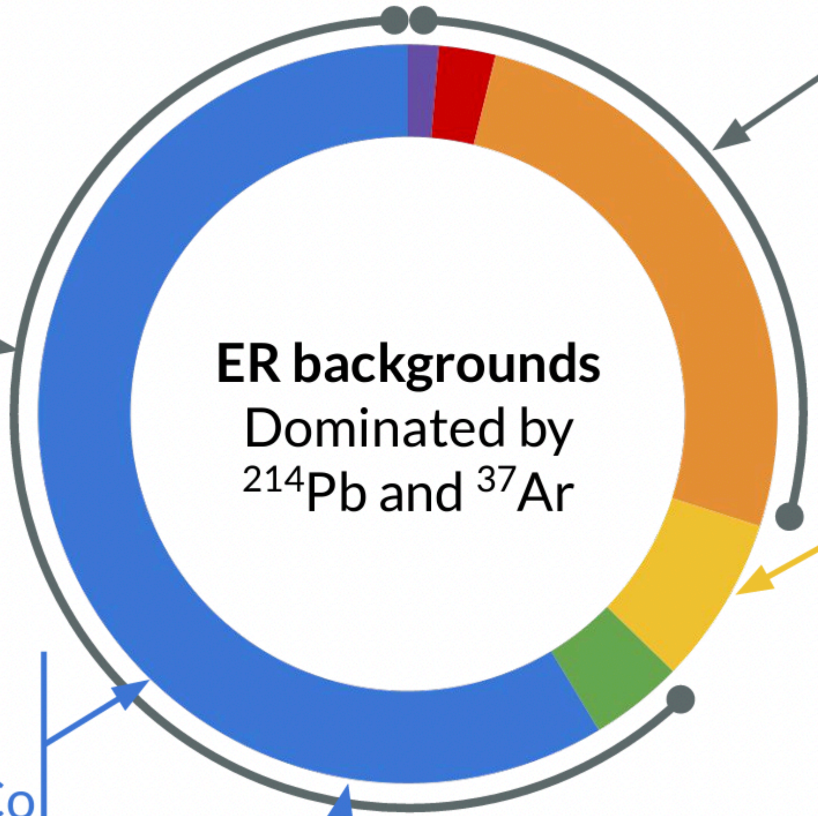
SR1 Backgrounds

ER Band Backgrounds

Total expected **ER** counts in ROI in first run: **276** + [0, 291] from ^{37}Ar

Total expected **NR** counts in ROI in first run: **0.15**

Dissolved β-emitters
- ^{214}Pb (^{222}Rn daughter)
- ^{212}Pb (^{220}Rn daughter)
- ^{85}Kr
- ^{136}Xe ($2\nu\beta\beta$)



Dissolved e-captures (mono-energetic x-ray/Auger cascades):
- ^{37}Ar
- ^{127}Xe
- ^{124}Xe (double e-capture)

Solar neutrinos (ER)
- pp + ^{7}Be + ^{13}N

Includes γ-emitters in detector materials
- ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co

Flat-spectrum (in ROI) ERs

NR backgrounds
- Neutron emission from spontaneous fission and (α,n)
- ^{8}B solar neutrinos

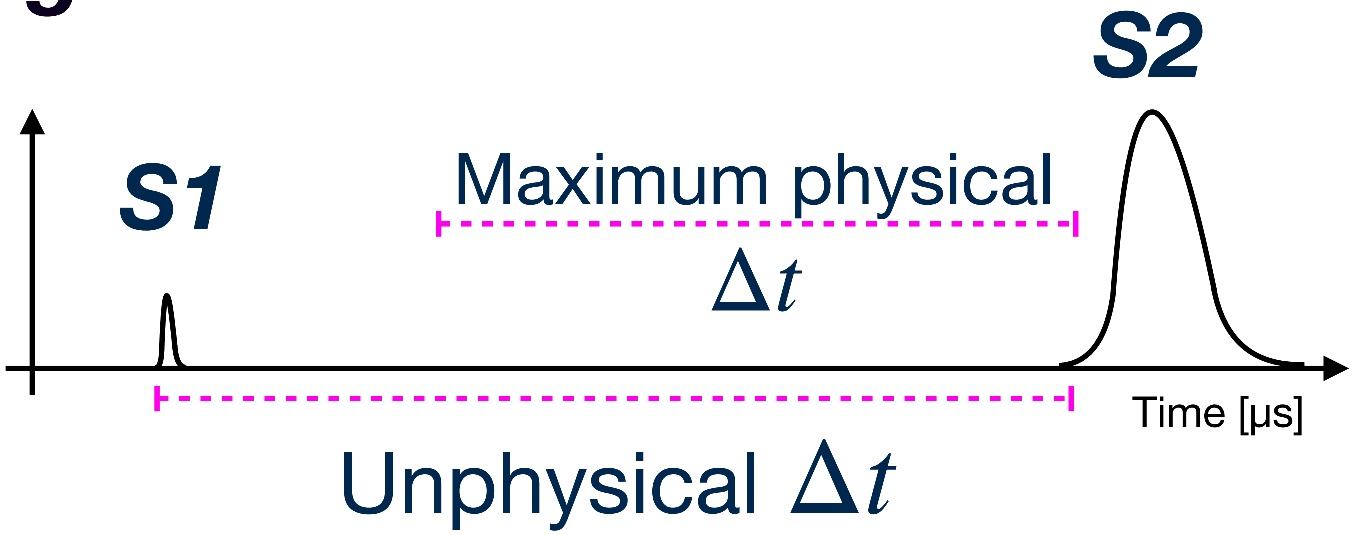
Accidental coincidence backgrounds
- 1.2 events expected

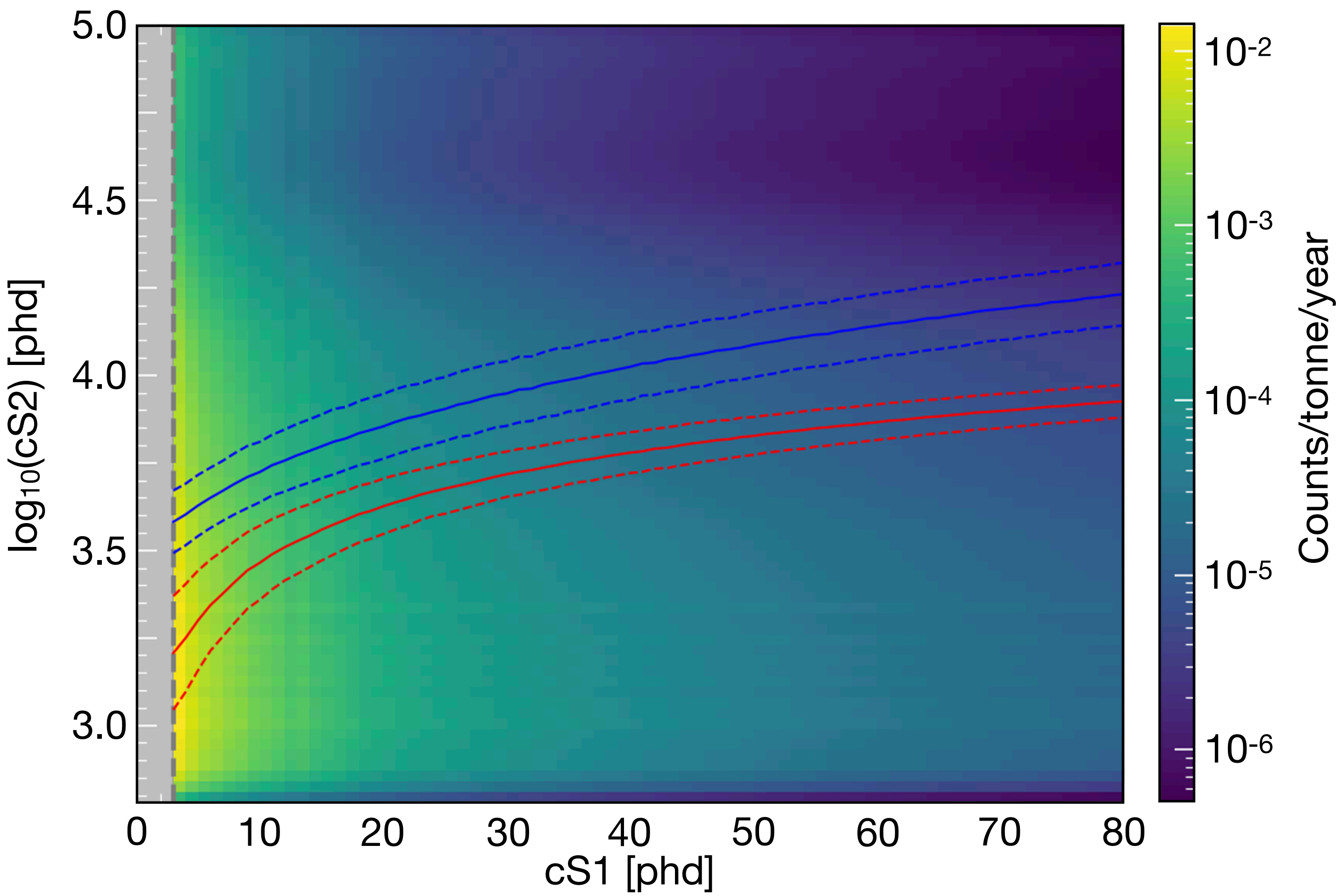
LZ backgrounds: Phys. Rev. D 108, 012010

SR1 Backgrounds

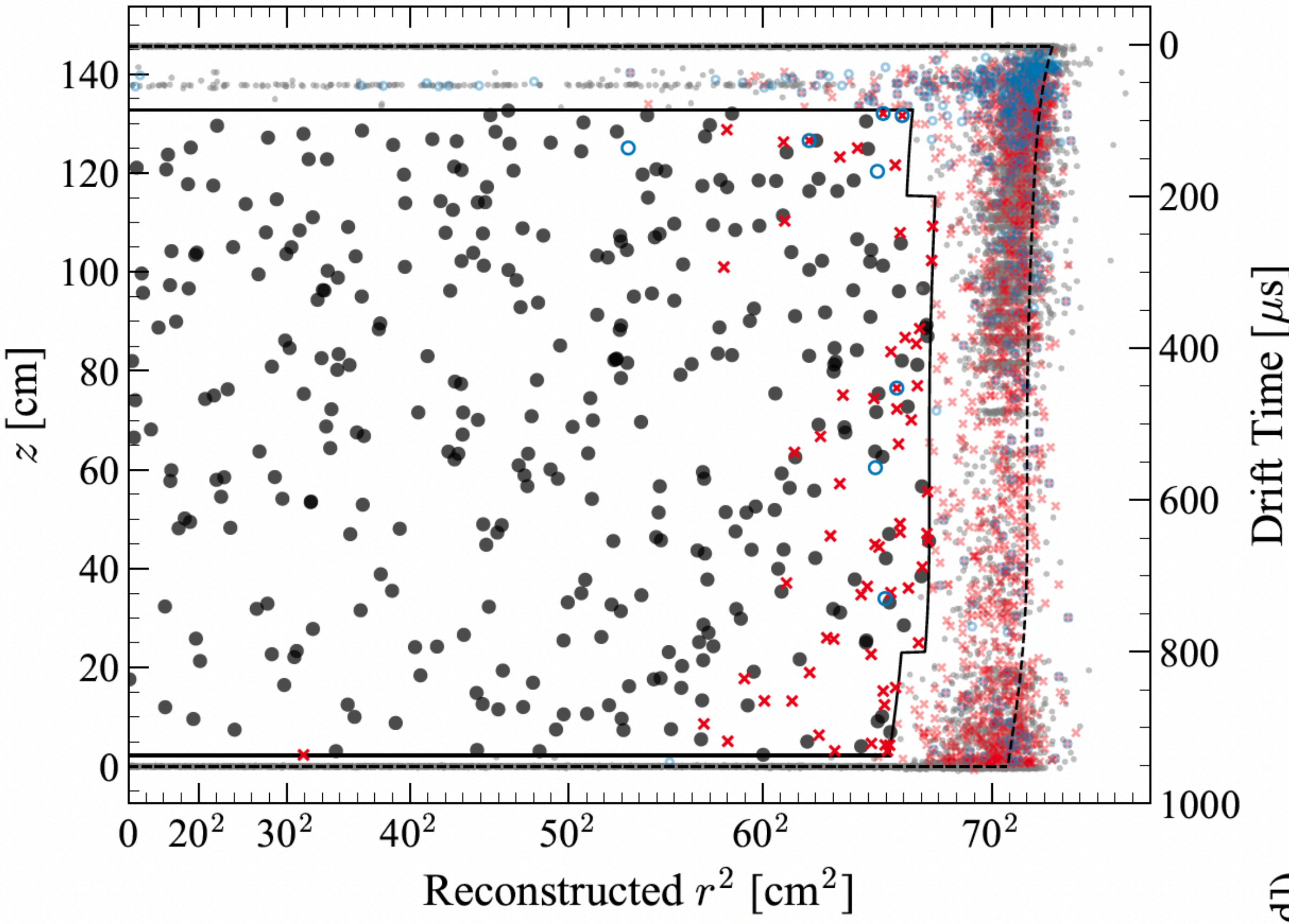
Accidental Coincidence Background

- Unrelated S1s & S2s can accidentally combine to produce single scatter events
- ***Rate***: population of definite accidental events with drift time >1 ms
- ***Distribution***: fake events constructed from lone S1 & S2 pulse waveforms
- Analysis cuts developed to combat observed pulse/event pathologies
    - >99.5% efficiency in removing accidentals
    - SR1 WIMP search counts: 1.2 ± 0.3

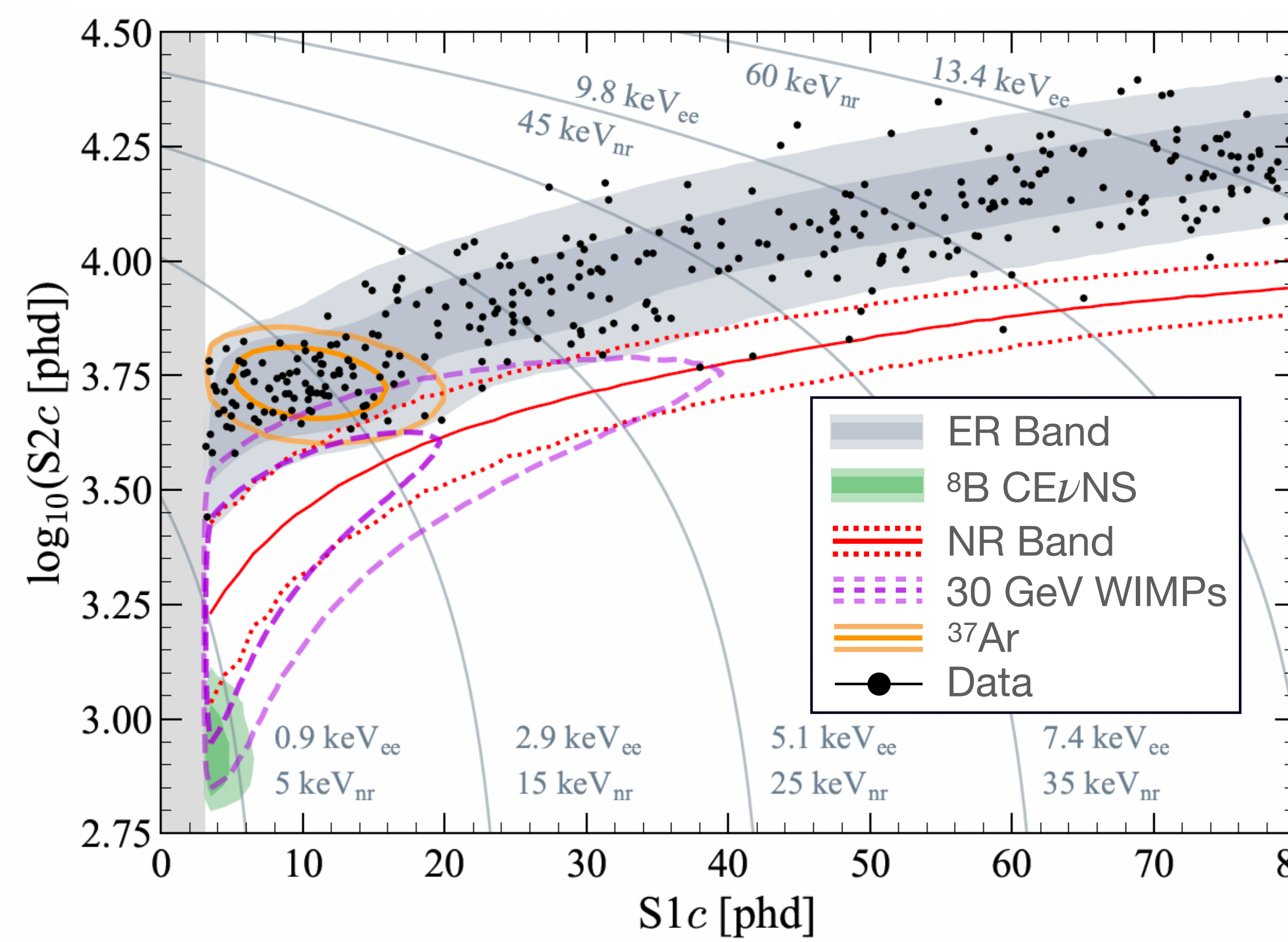




SR1 Results



- ● *Inside Fiducial Volume*
- ● *Outside Fiducial Volume*
- ✕ *Tagged by LXe Skin*
- ○ *Tagged by OD PMTs*



- 335 events remaining after analysis cuts
- Statistical inference with Profile Likelihood Ratio (PLR) method

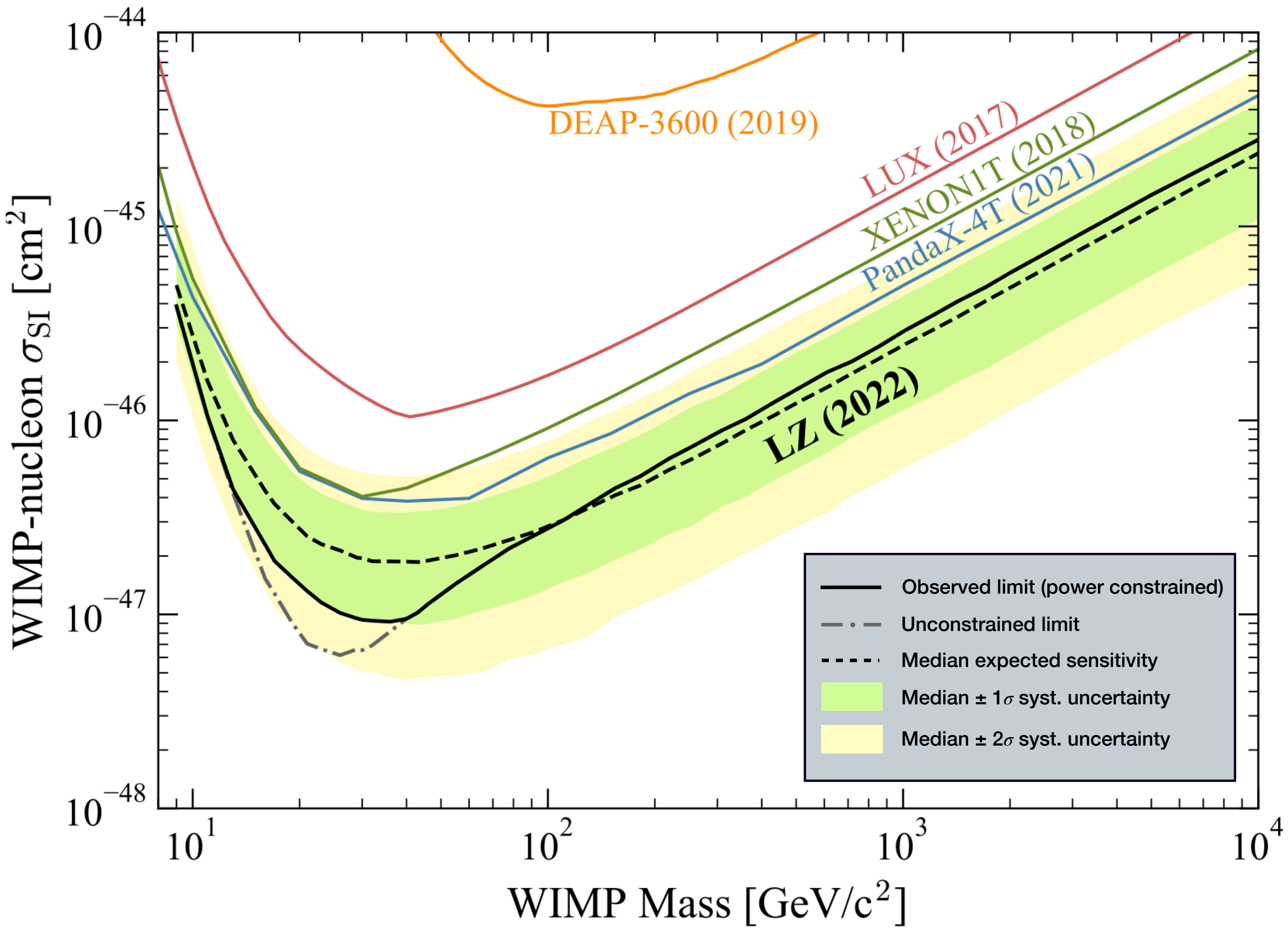
SR1 Results

Source	Expected Events	Fit Result
β decays + Det ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	273 ± 36	280 ± 16
^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	...	$0.0^{+0.6}$
Total	...	333 ± 17
Total Observed Events		335

Data are consistent with background-only hypothesis

World leading sensitivity

- WIMP masses > 9 GeV
- Highest sensitivity at 36 GeV
- Power constrained at -1σ



Low Energy ERs

A search for new physics in low-energy electron recoils from the first LZ exposure

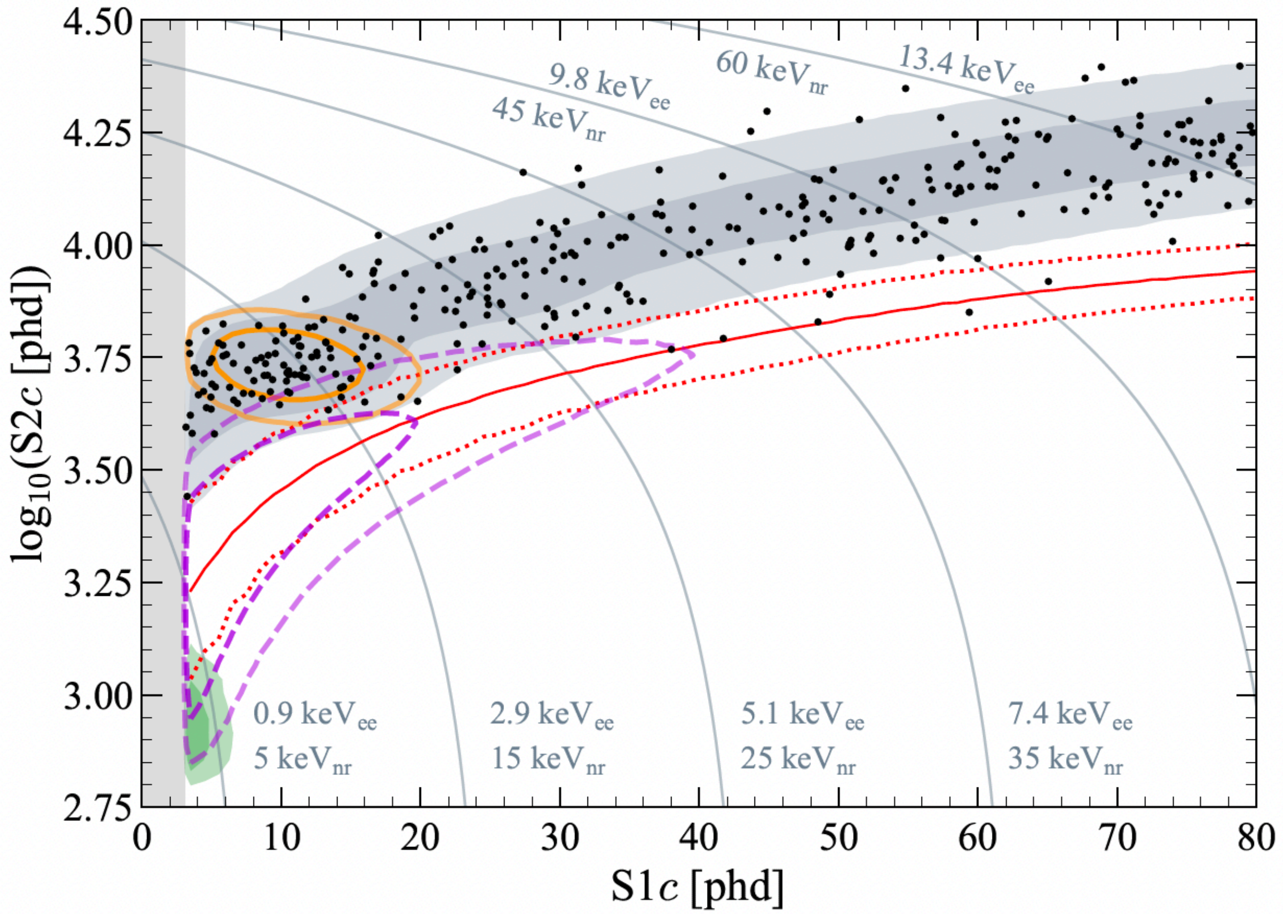
J. Aalbers,[1,2] D.S. Akerib,[1,2] A.K. Al Musalhi,[3] F. Alder,[4] C.S. Amarasinghe,[5] A. Ames,[1,2] T.J. Anderson,[1,2] N. Angelides,[6] H.M. Araújo,[6] J.E. Armstrong,[7] M. Arthurs,[1,2] A. Baker,[6] S. Balashov,[8] J. Bang,[9] J.W. Bargemann,[10] A. Baxter,[11] K. Beattie,[12] P. Beltrame,[4] T. Benson,[13] A. Bhatti,[7] A. Biekert,[12,14] T.P. Biesiadzinski,[1,2] H.J. Birch,[5] G.M. Blockinger,[15] B. Boxer,[16] C.A.J. Brew,[8] P. Brás,[17] S. Burdin,[11] M. Buuck,[1,2] M.C. Carmona-Benitez,[18] C. Chan,[9] A. Chawla,[19] H. Chen,[12] J.J. Cherwinka,[13] N.I. Chott,[20] M.V. Converse,[21] A. Cottle,[3,22] G. Cox,[18,23] D. Curran,[23] C.E. Dahl,[22,24] A. David,[4] J. Delgaudio,[23] S. Dey,[3]

(Received 28 July 2023; accepted 12 September 2023; published 9 October 2023)

The LUX-ZEPLIN (LZ) experiment is a dark matter detector centered on a dual-phase xenon time projection chamber. We report searches for new physics appearing through few-keV-scale electron recoils, using the experiment's first exposure of 60 live days and a fiducial mass of 5.5 t. The data are found to be consistent with a background-only hypothesis, and limits are set on models for new physics including solar axion electron coupling, solar neutrino magnetic moment and millicharge, and electron couplings to galactic axionlike particles and hidden photons. Similar limits are set on weakly interacting massive particle (WIMP) dark matter producing signals through ionized atomic states from the Migdal effect.

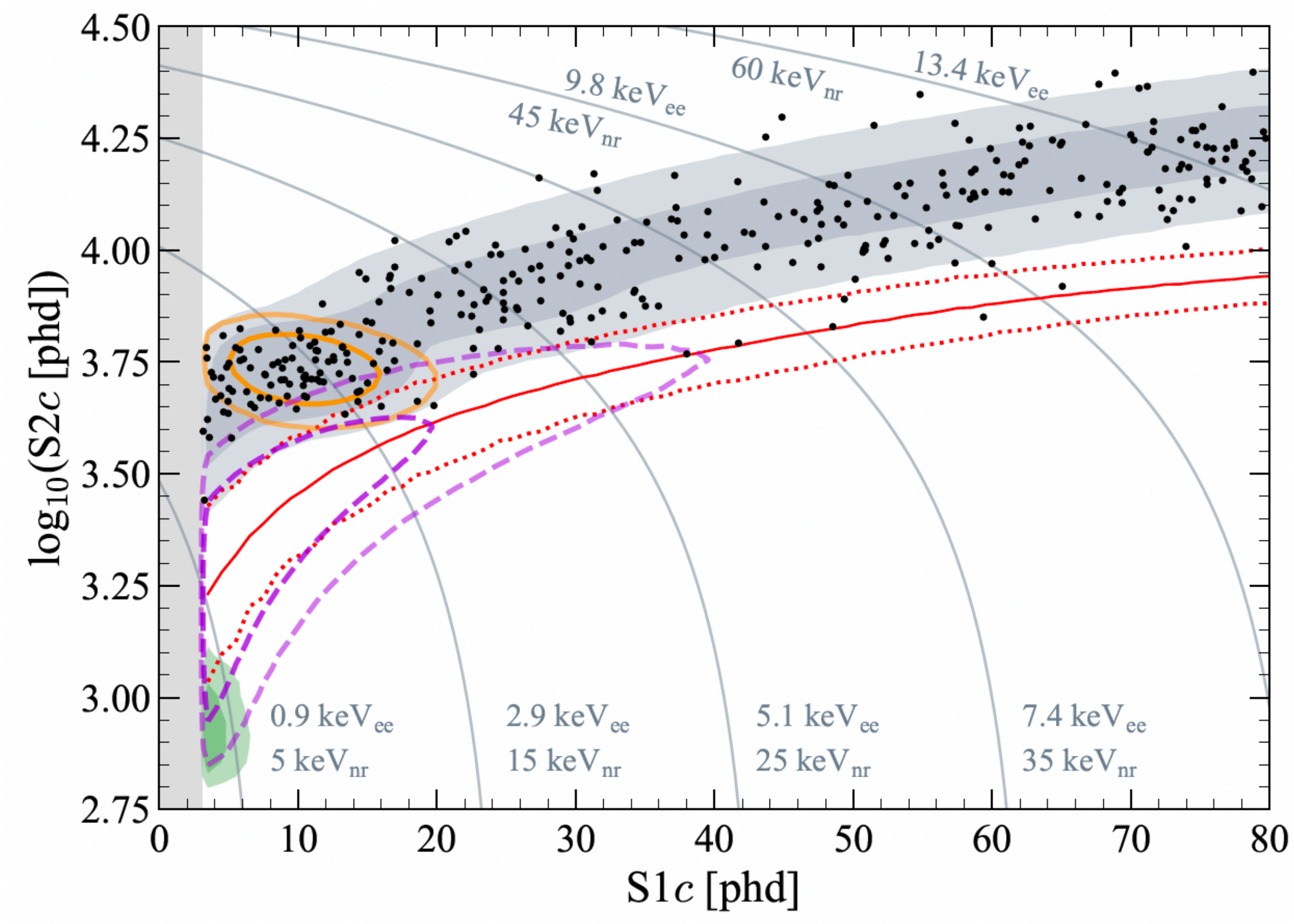
DOI: 10.1103/PhysRevD.108.072006

Low Energy ERs

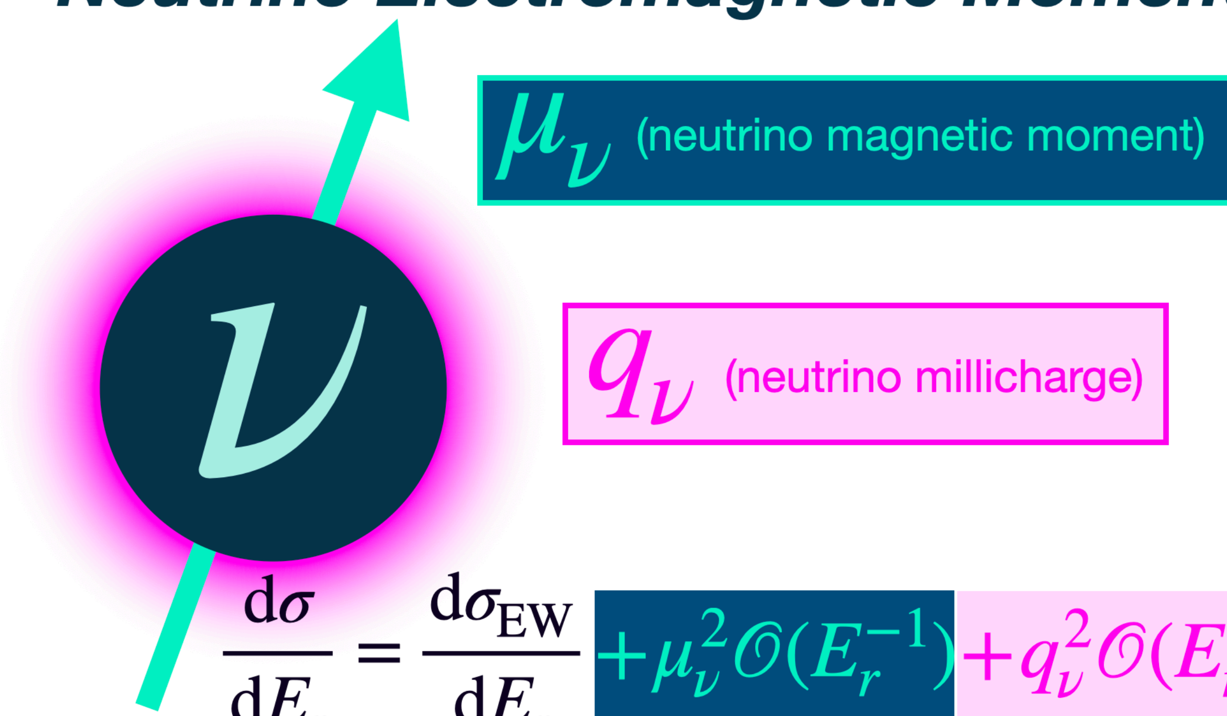


Anything interesting happening here?

Low Energy ERs

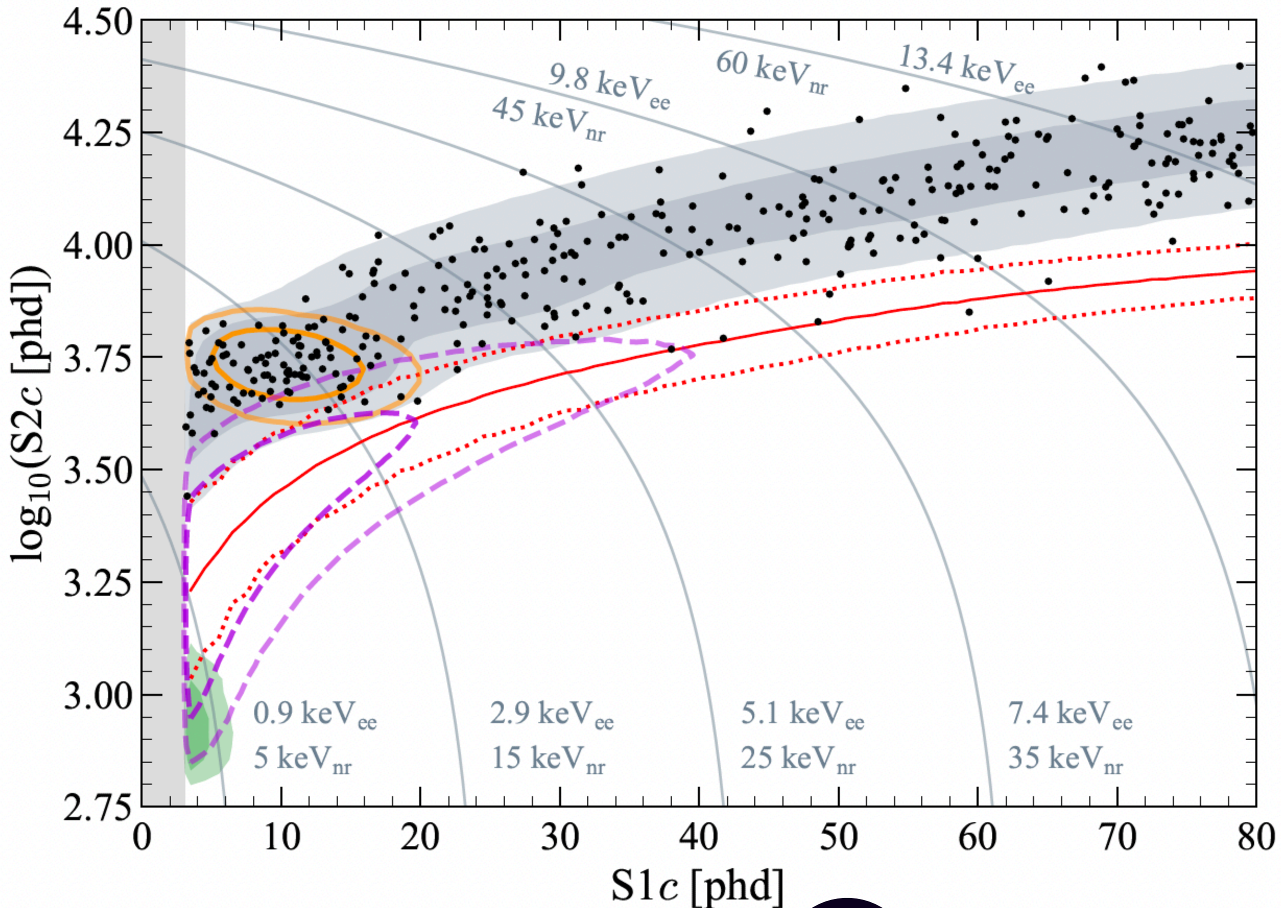


Neutrino Electromagnetic Moments



$$\frac{d\sigma}{dE_r} = \frac{d\sigma_{EW}}{dE_r} + \mu_\nu^2 \mathcal{O}(E_r^{-1}) + q_\nu^2 \mathcal{O}(E_r^{-2})$$

Low Energy ERs



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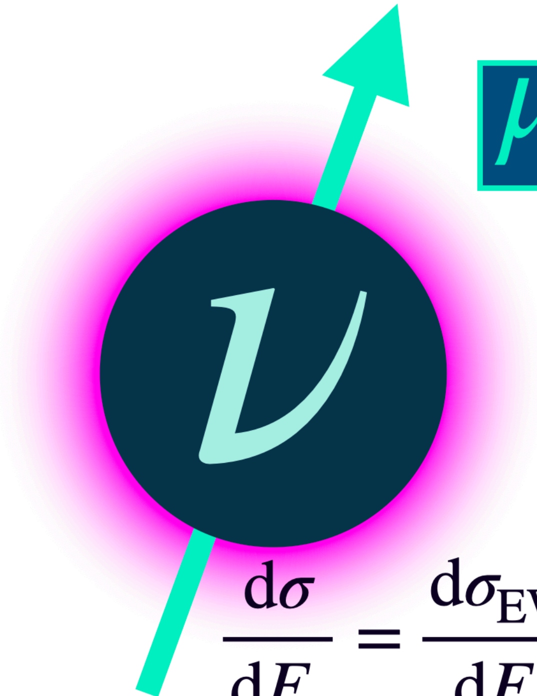
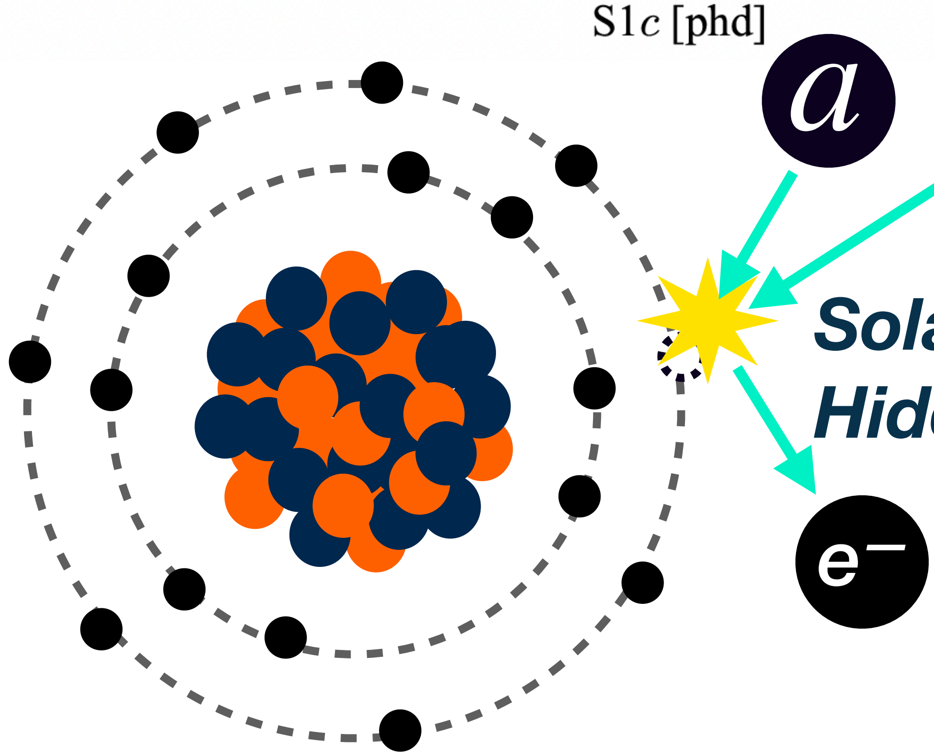


μ_ν (neutrino magnetic moment)

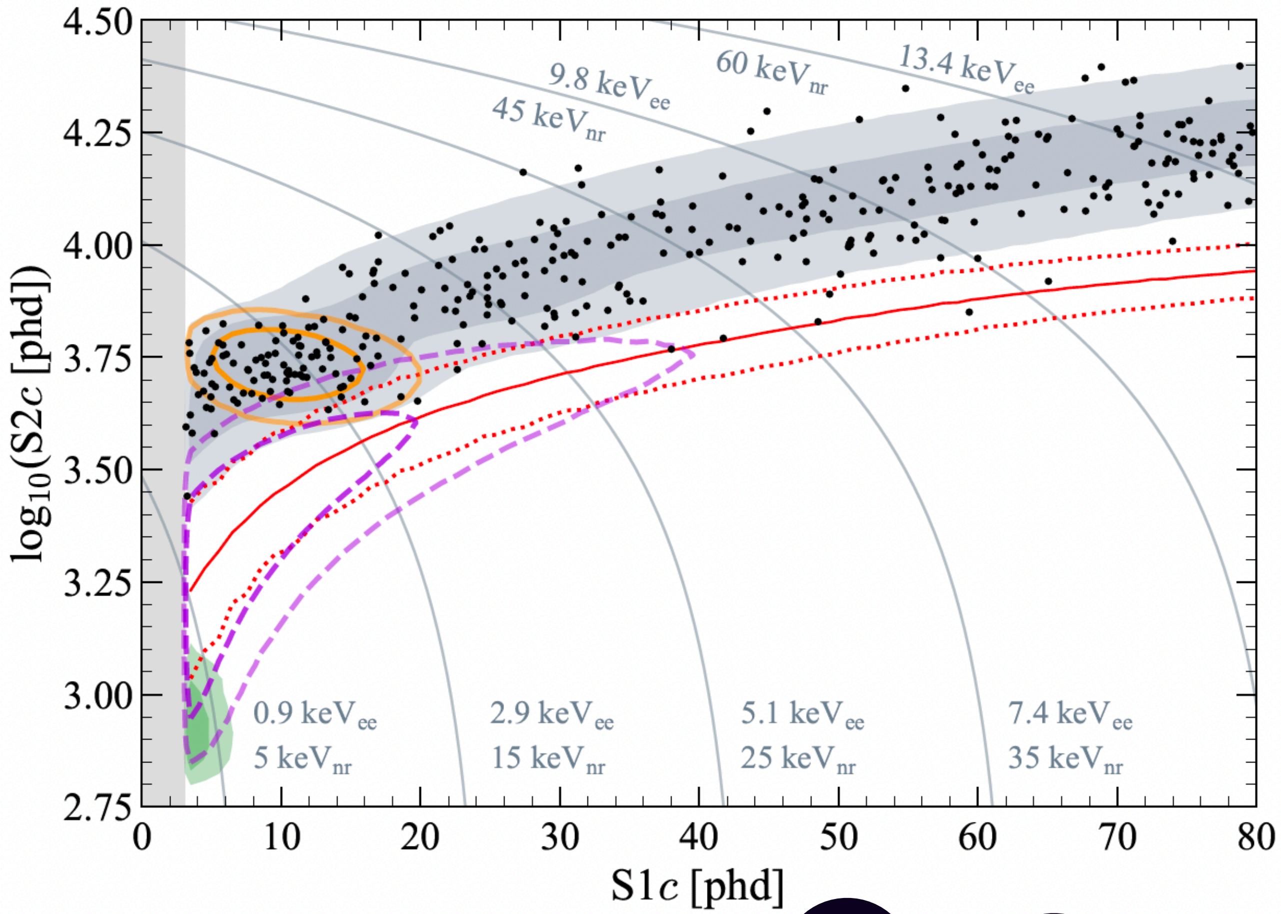
q_ν (neutrino millicharge)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} = \frac{\mathrm{d}\sigma_{\mathrm{EW}}}{\mathrm{d}E_r} + \mu_\nu^2 \mathcal{O}(E_r^{-1}) + q_\nu^2 \mathcal{O}(E_r^{-2})$$

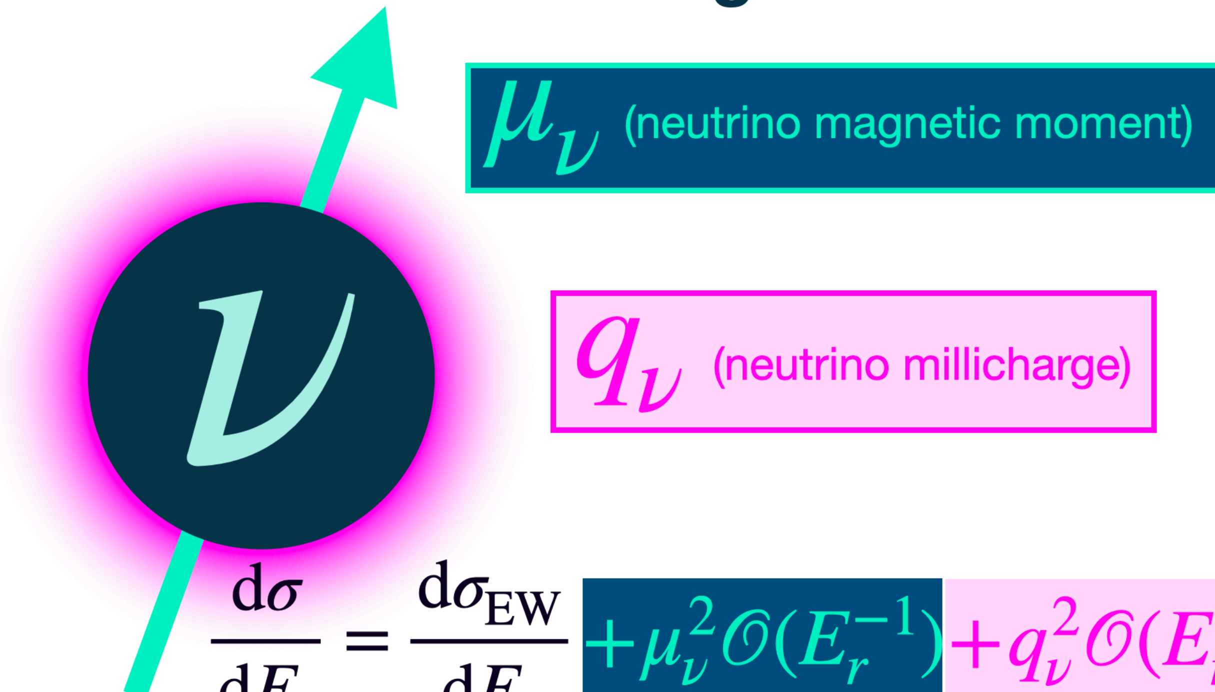


Solar axions/ALPs
Hidden photons

Low Energy ERs



Neutrino Electromagnetic Moments



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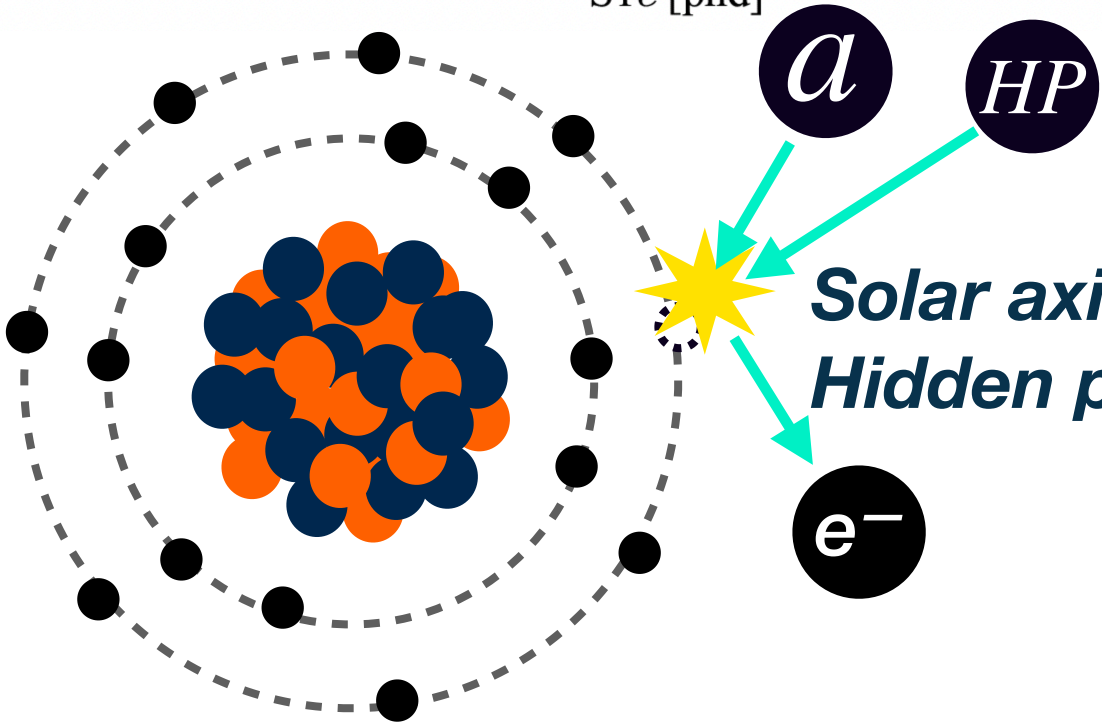

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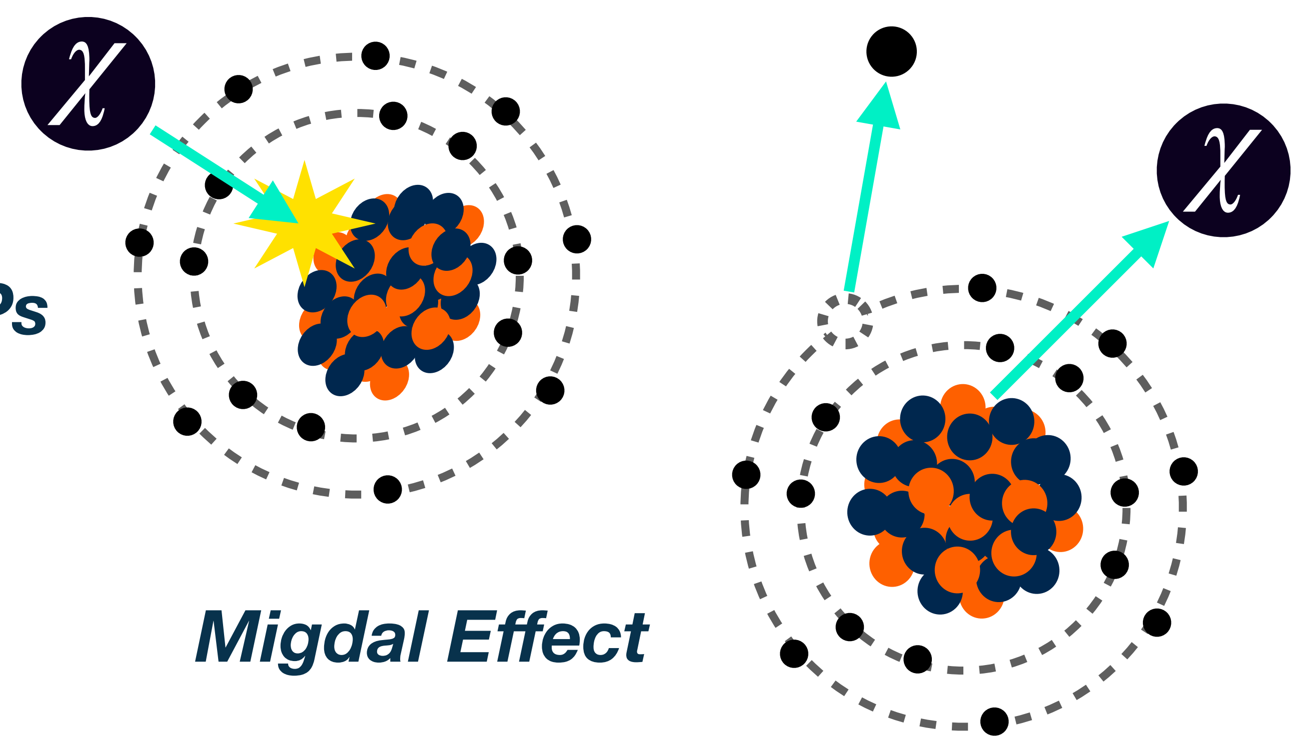
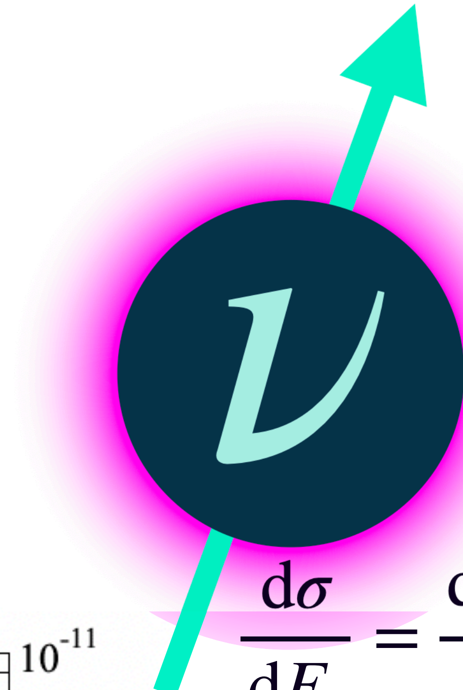


Migdal Effect

Low Energy ERs

Neutrino Electromagnetic Moments



μ_ν (neutrino magnetic moment)

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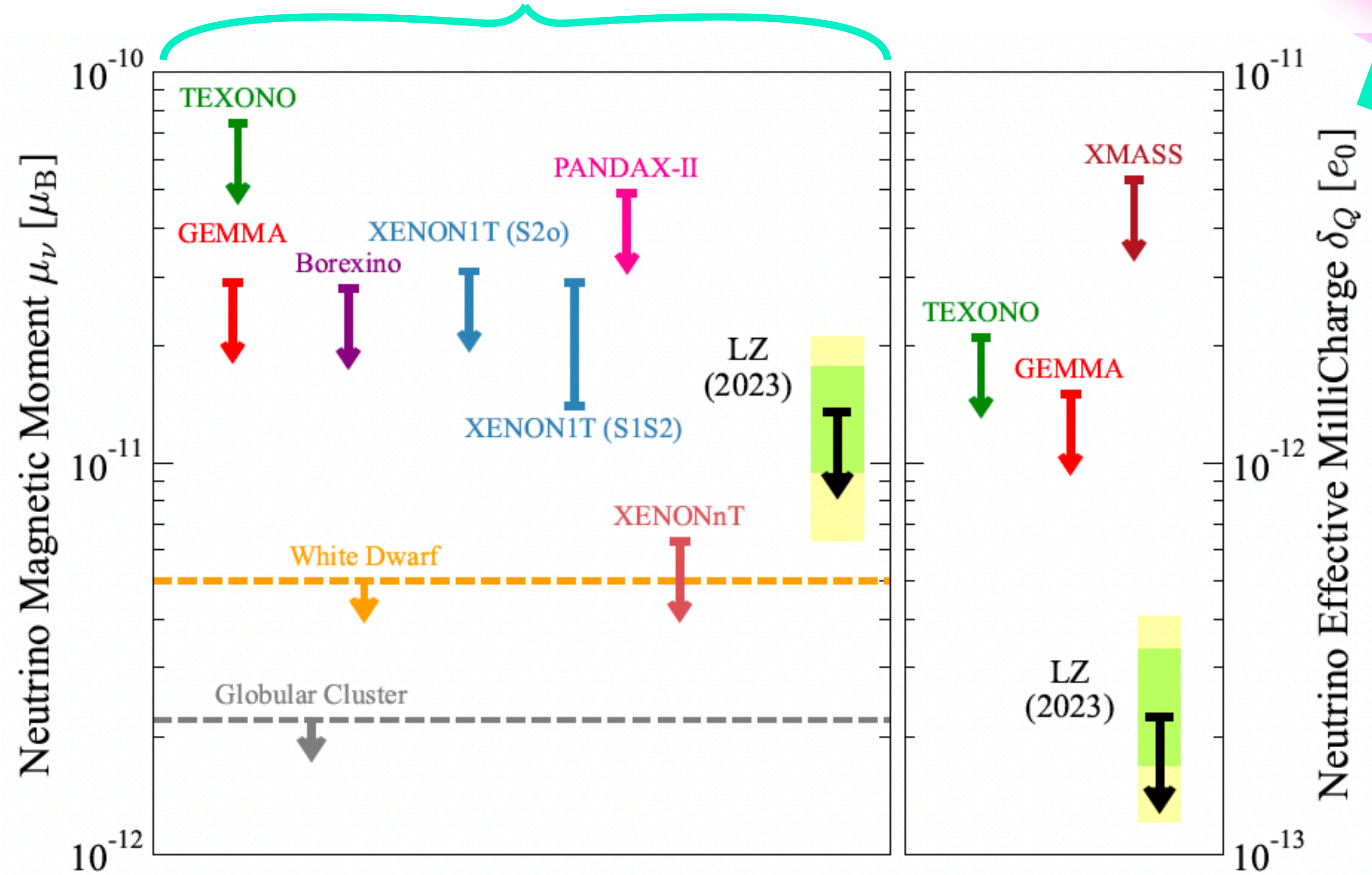
Neutrino magnetic moment most stringently constrained by astrophysical observations

LZ upper limit: 1.36 × 10^{-11} μ_B



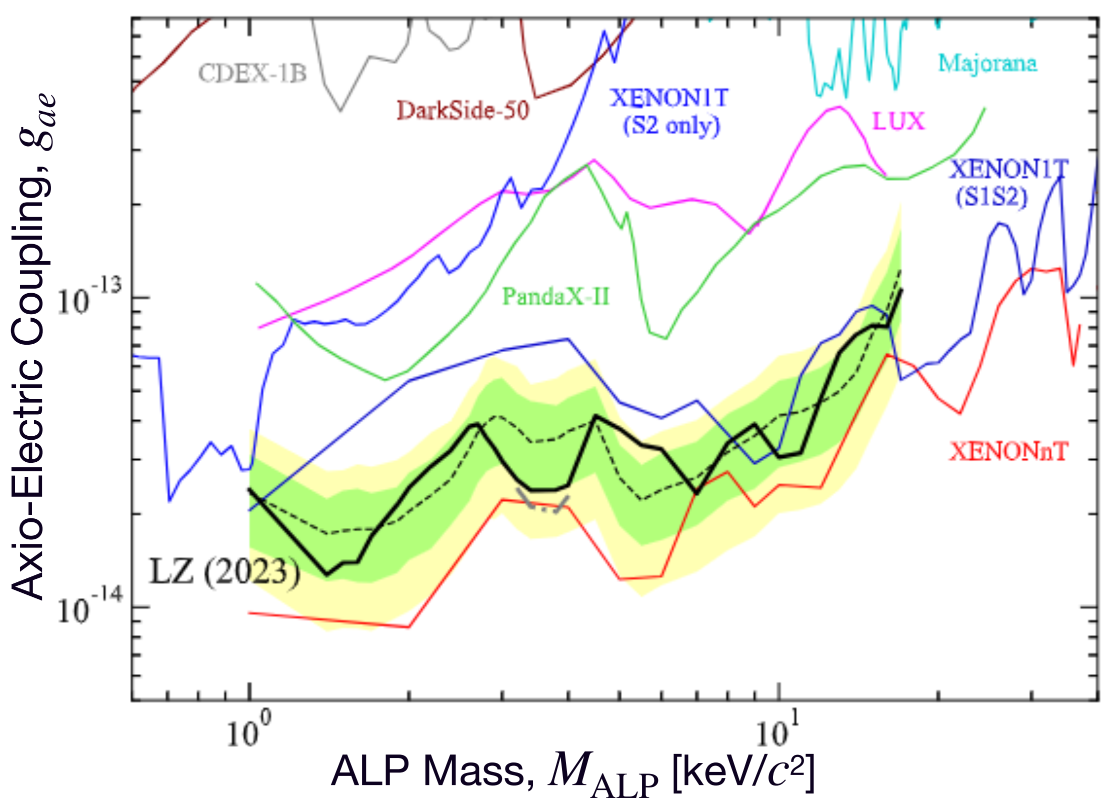
Leading neutrino millicharge observed

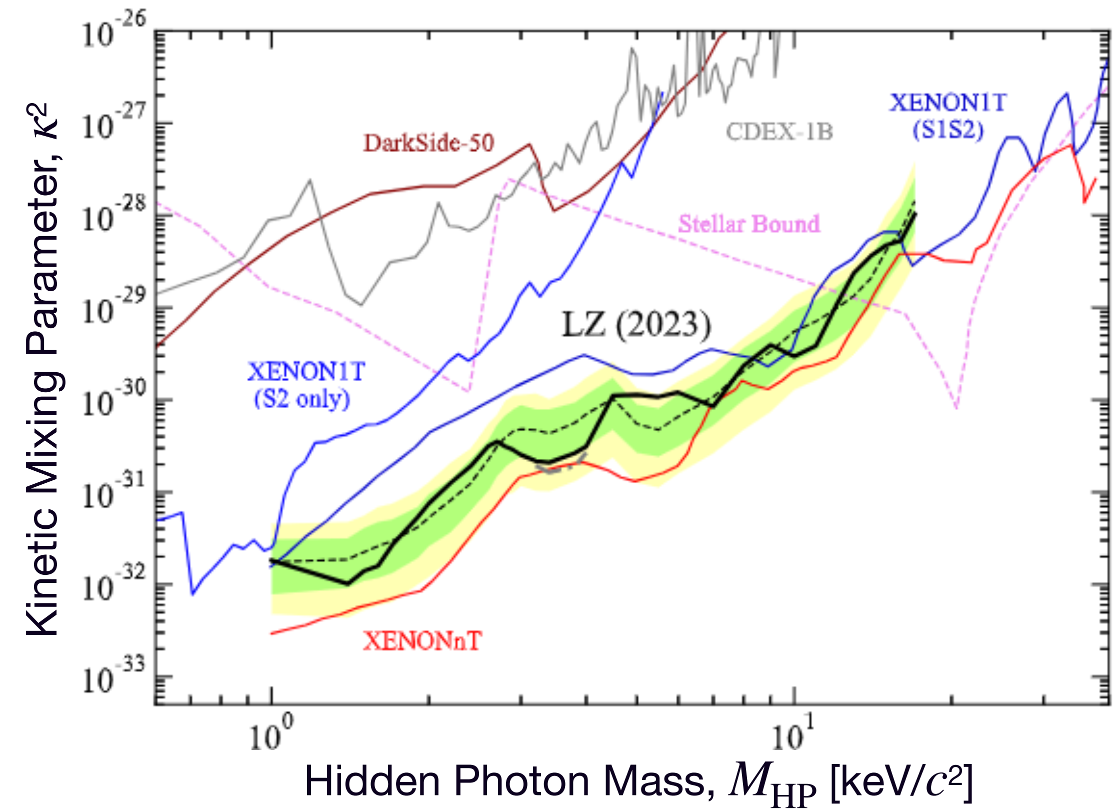
LZ upper limit: 2.24 × 10^{-13} e_0

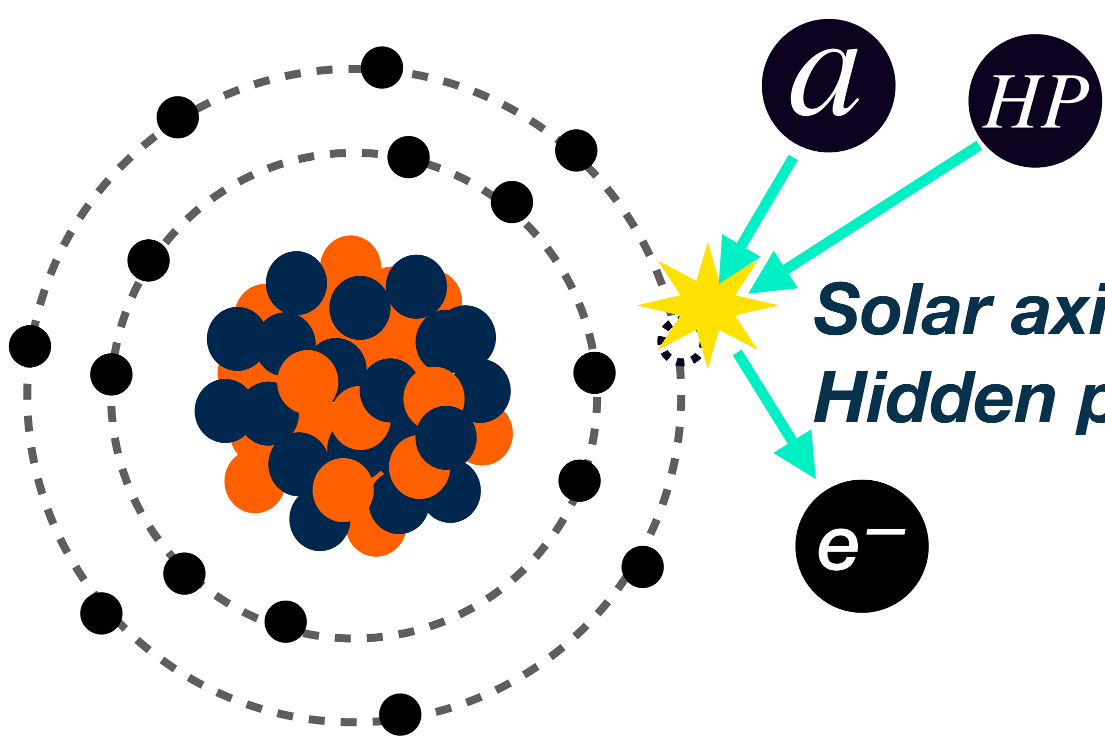
$e_0 \equiv$ ***electron charge***

$\mu_B \equiv$ ***Bohr magneton***

Low Energy ERs







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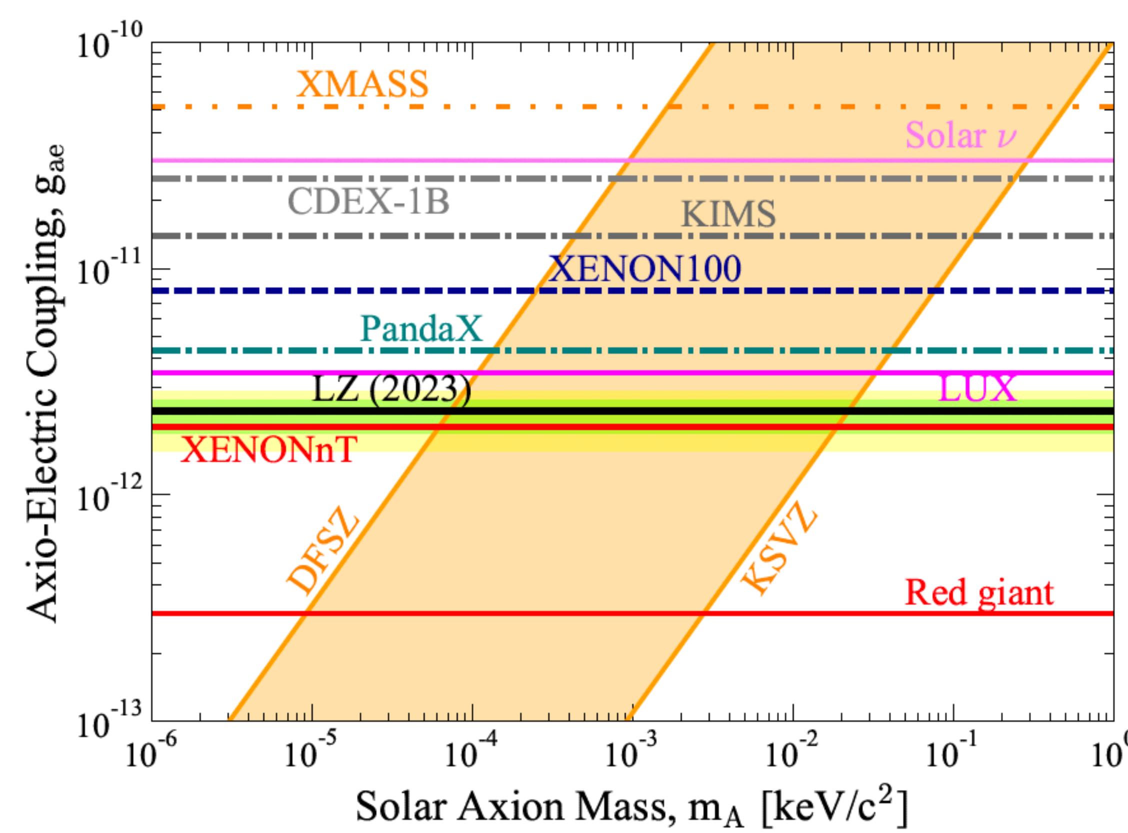

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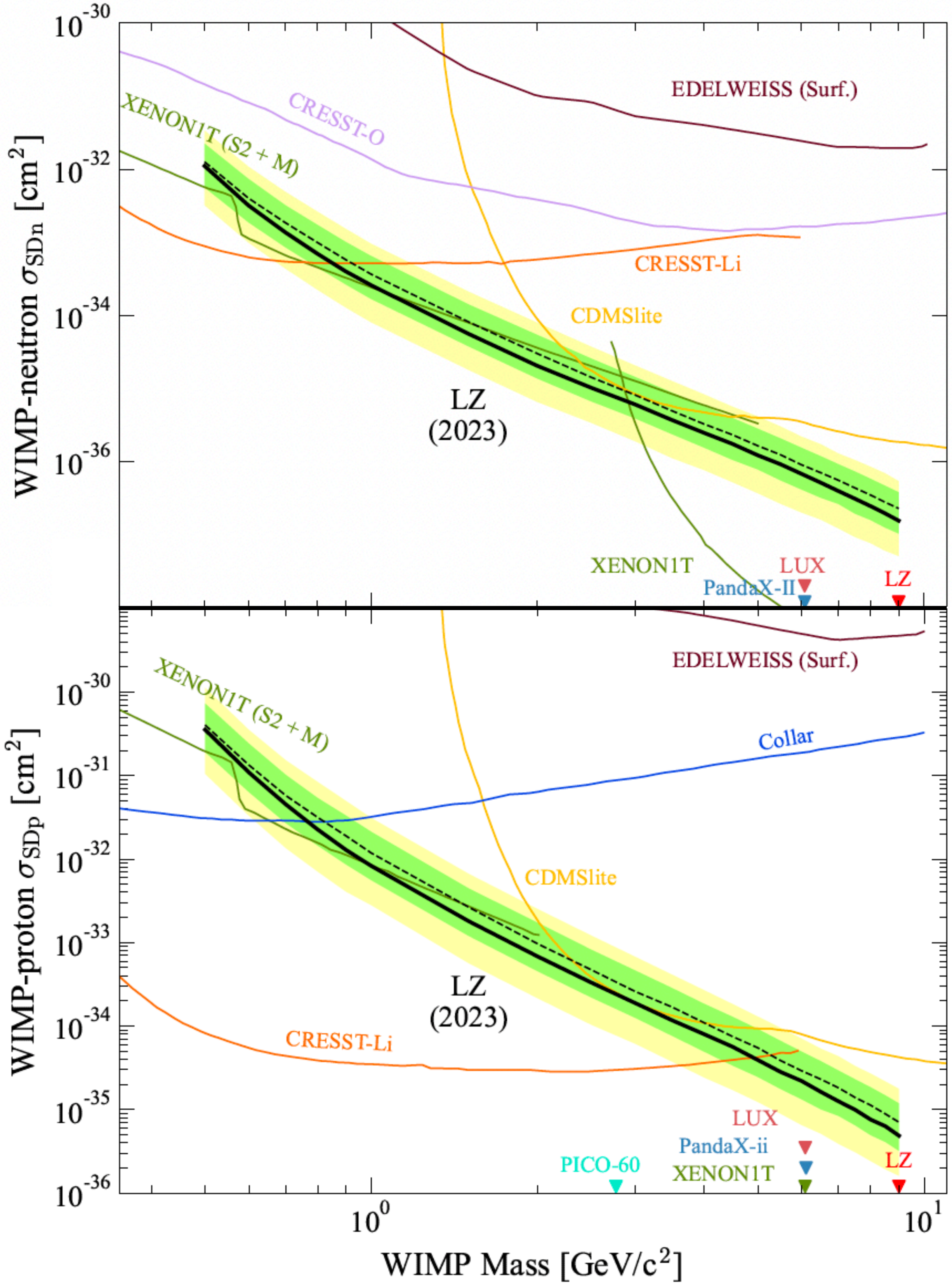
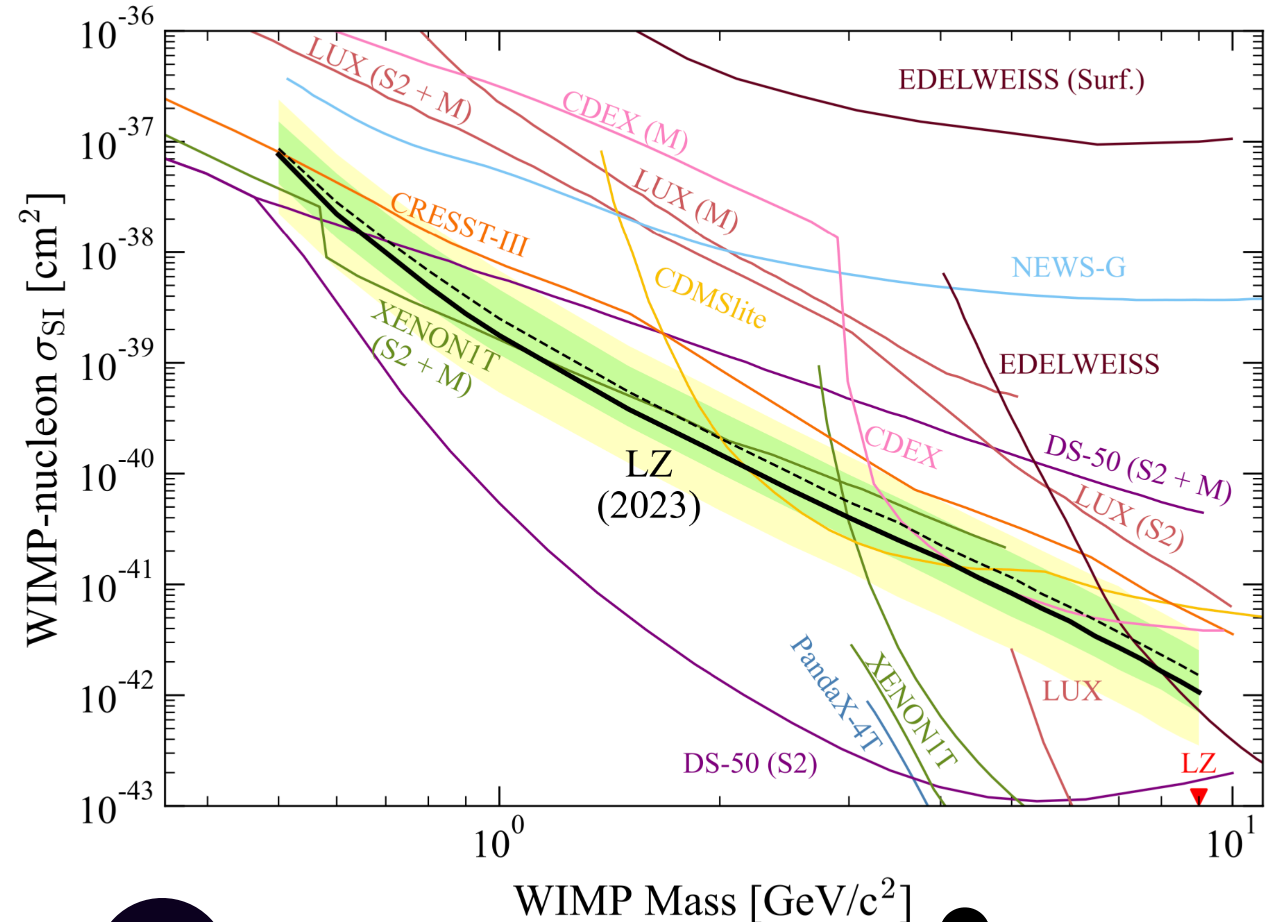
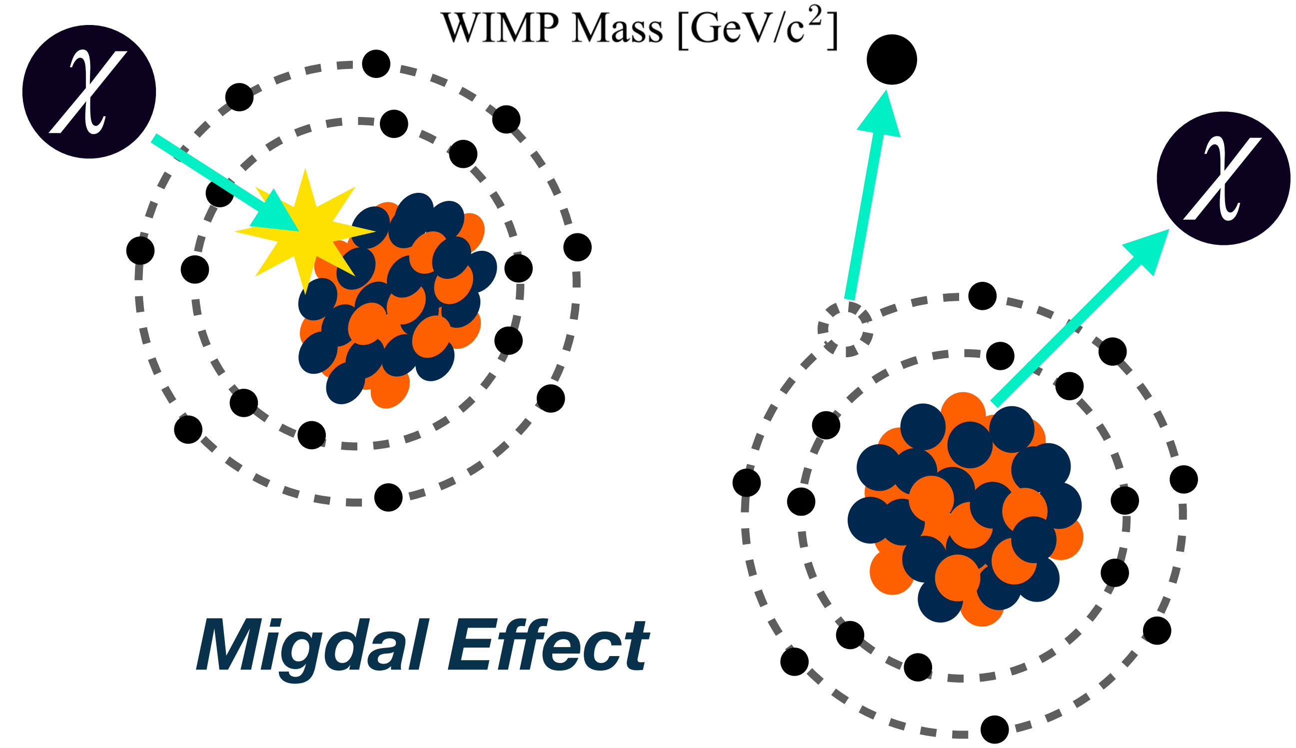






Conclusion

In Summary

LZ first results set world-leading upper limits for WIMPs

Competitive searches for physics in low energy ERs

Continuing to take data for future WIMP searches

In the pipeline

Nonrelativistic Effective Field Theory

See Sam Eriksen's talk next!

Ultra Heavy Dark Matter Search

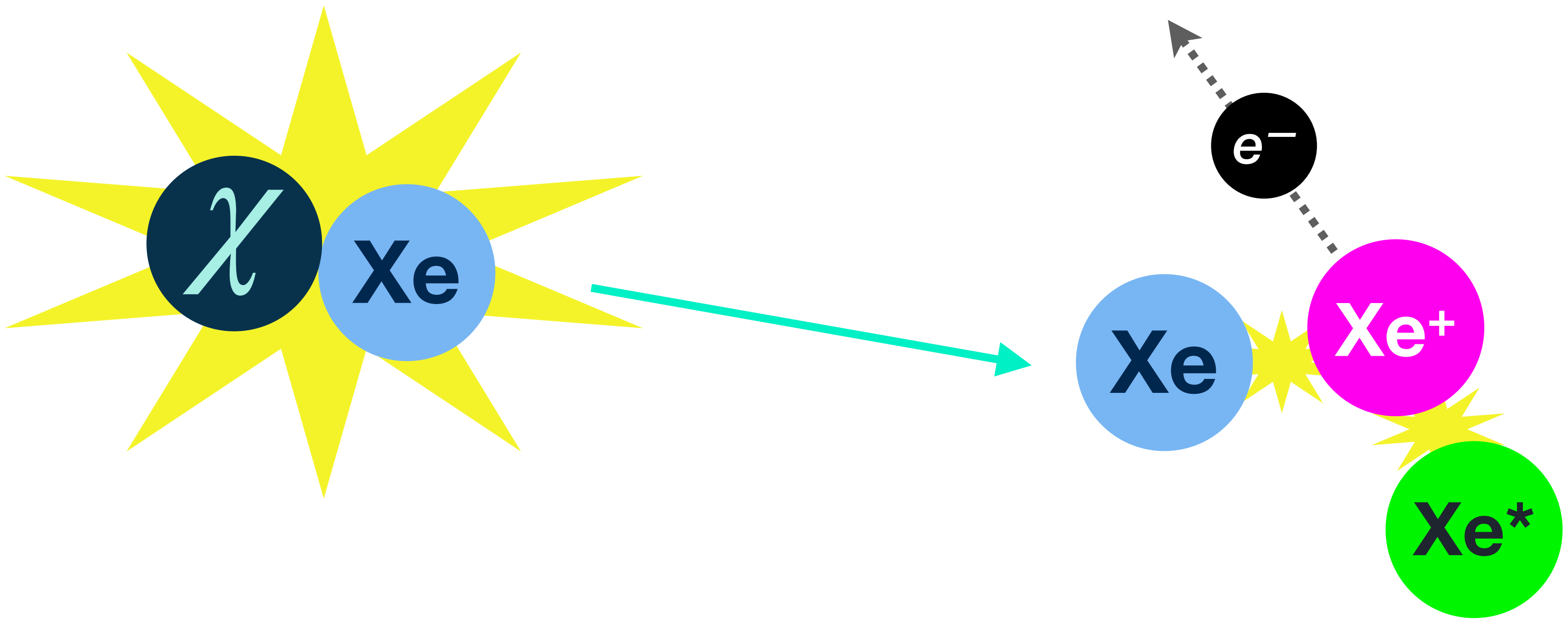
Radon Tagging Veto

Muon Flux Measurements

Thank you!

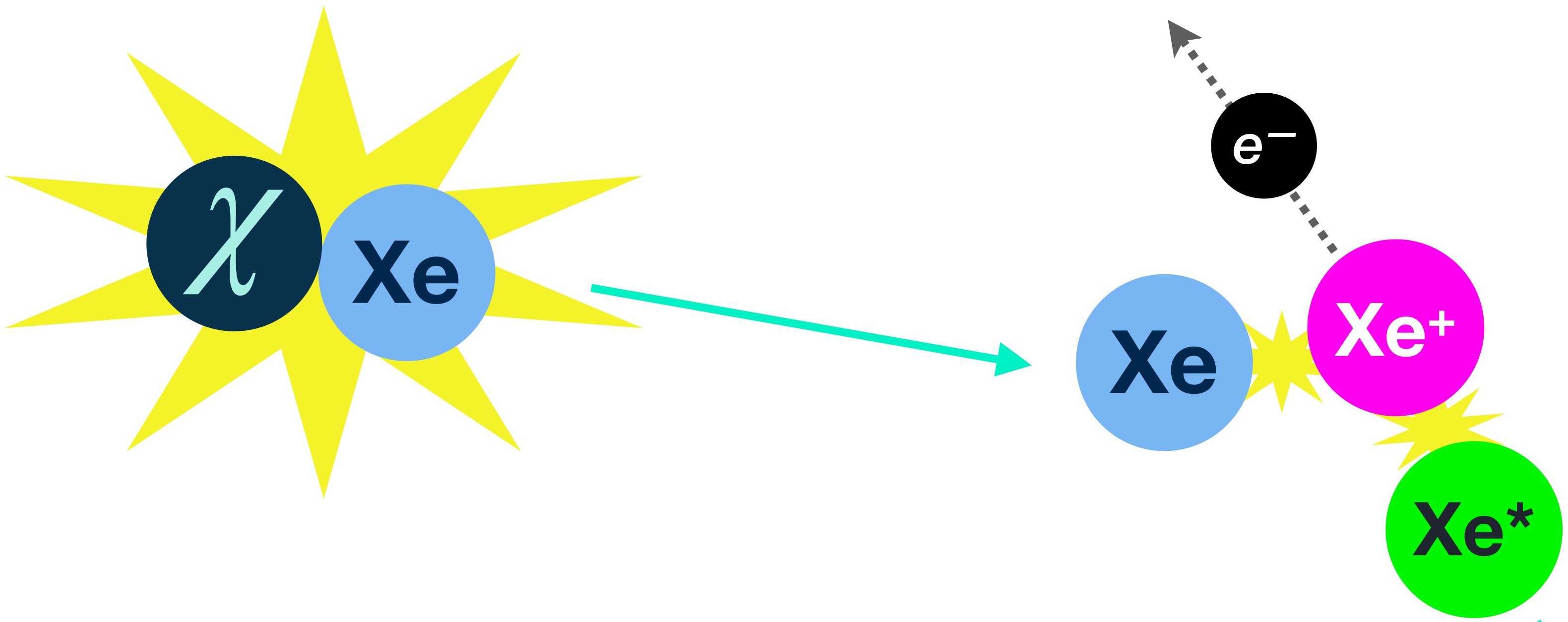
Backup Slides

Liquid Xenon Microphysics

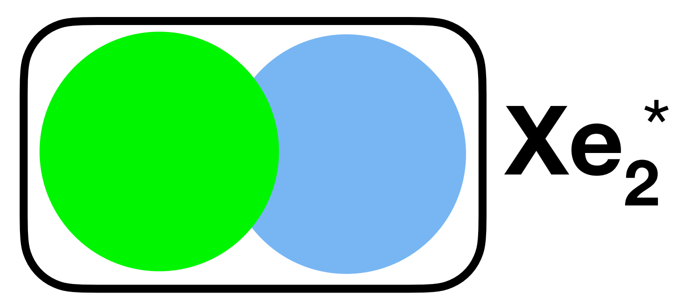


Atoms in the track of a recoiling nucleus become ***excitons*** or ***ions***

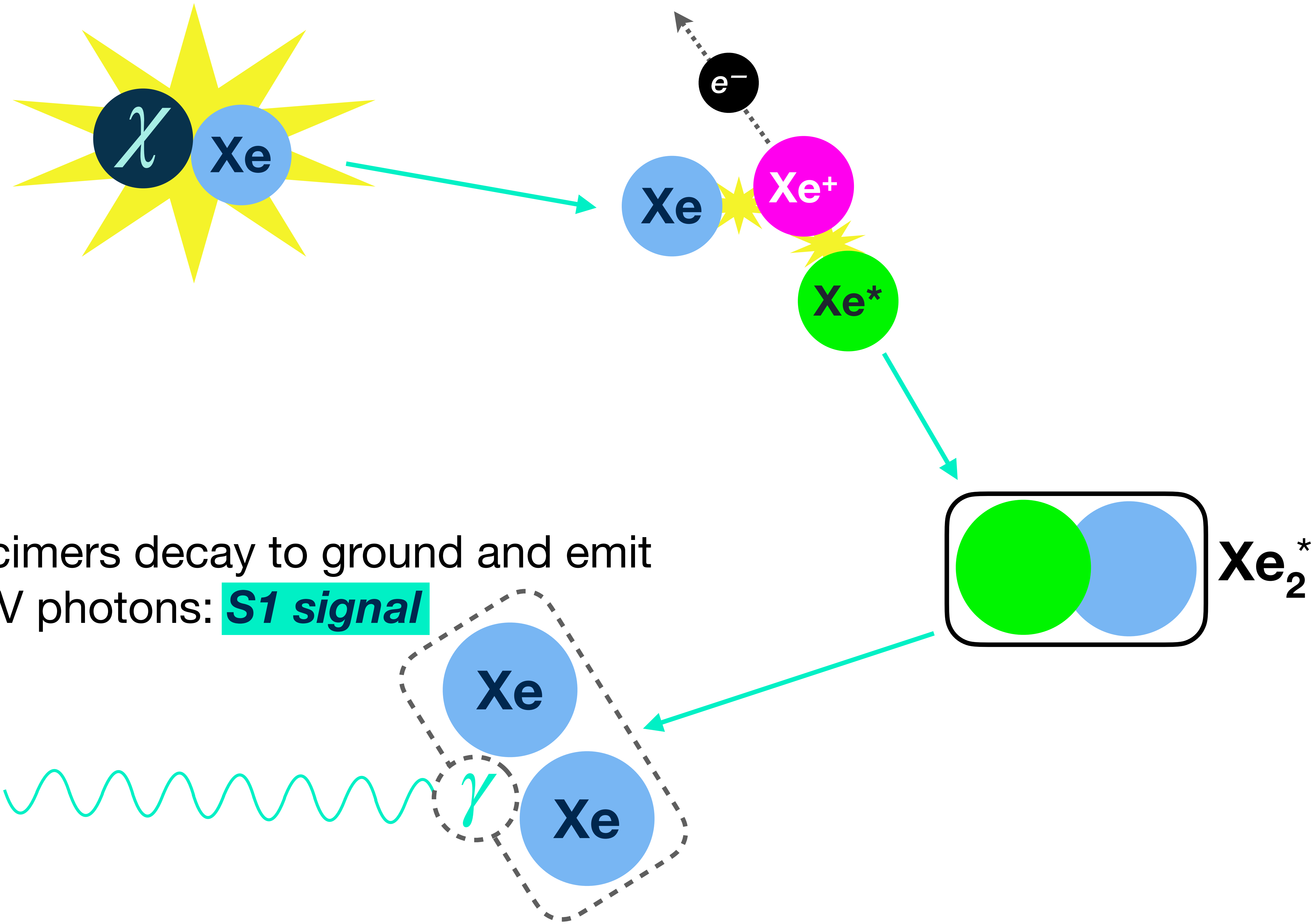
Liquid Xenon Microphysics



Excitons form excited dimers *(excimers)* with ground-state atoms

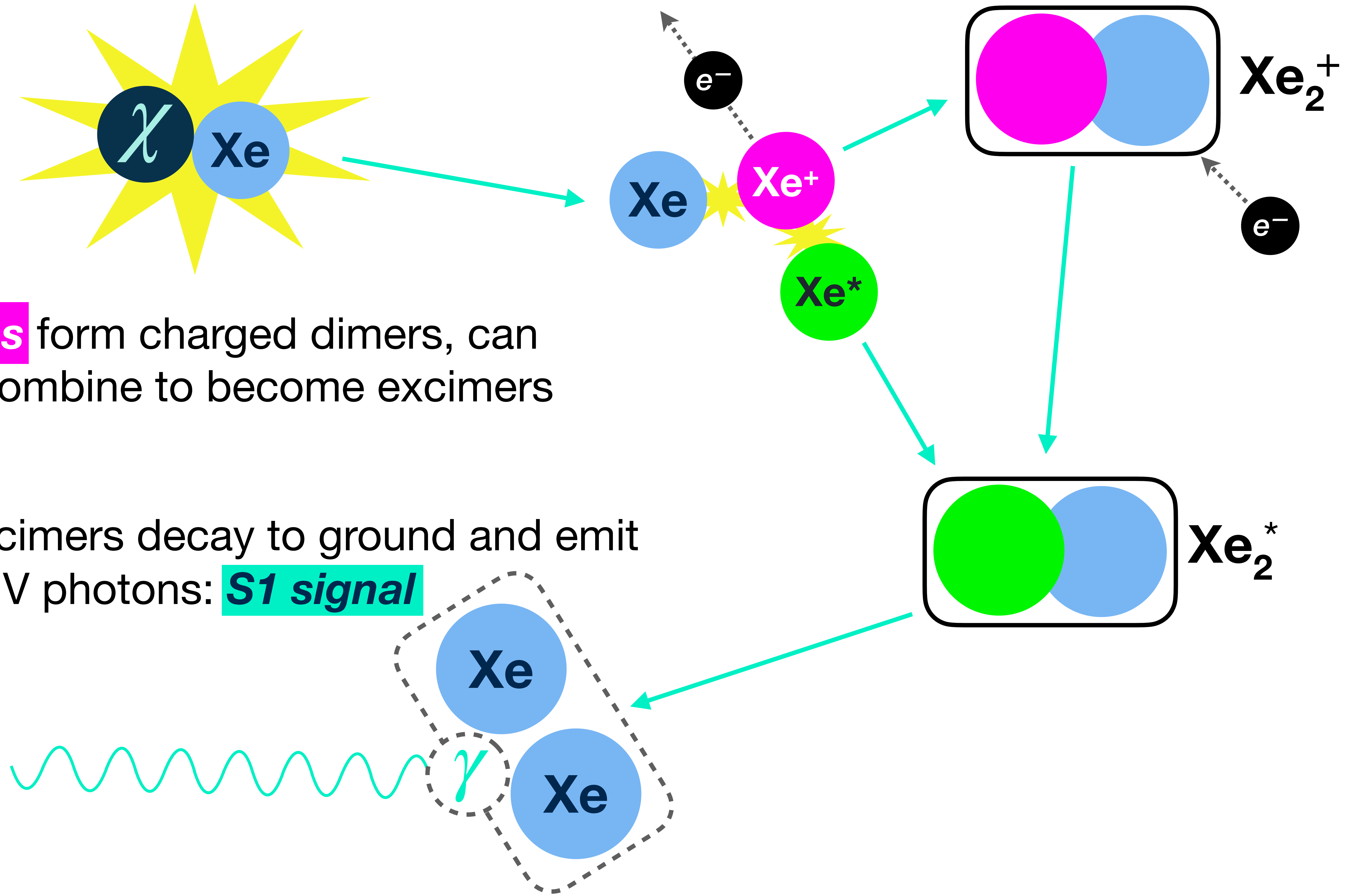


Liquid Xenon Microphysics



Excimers decay to ground and emit VUV photons: ***S1 signal***

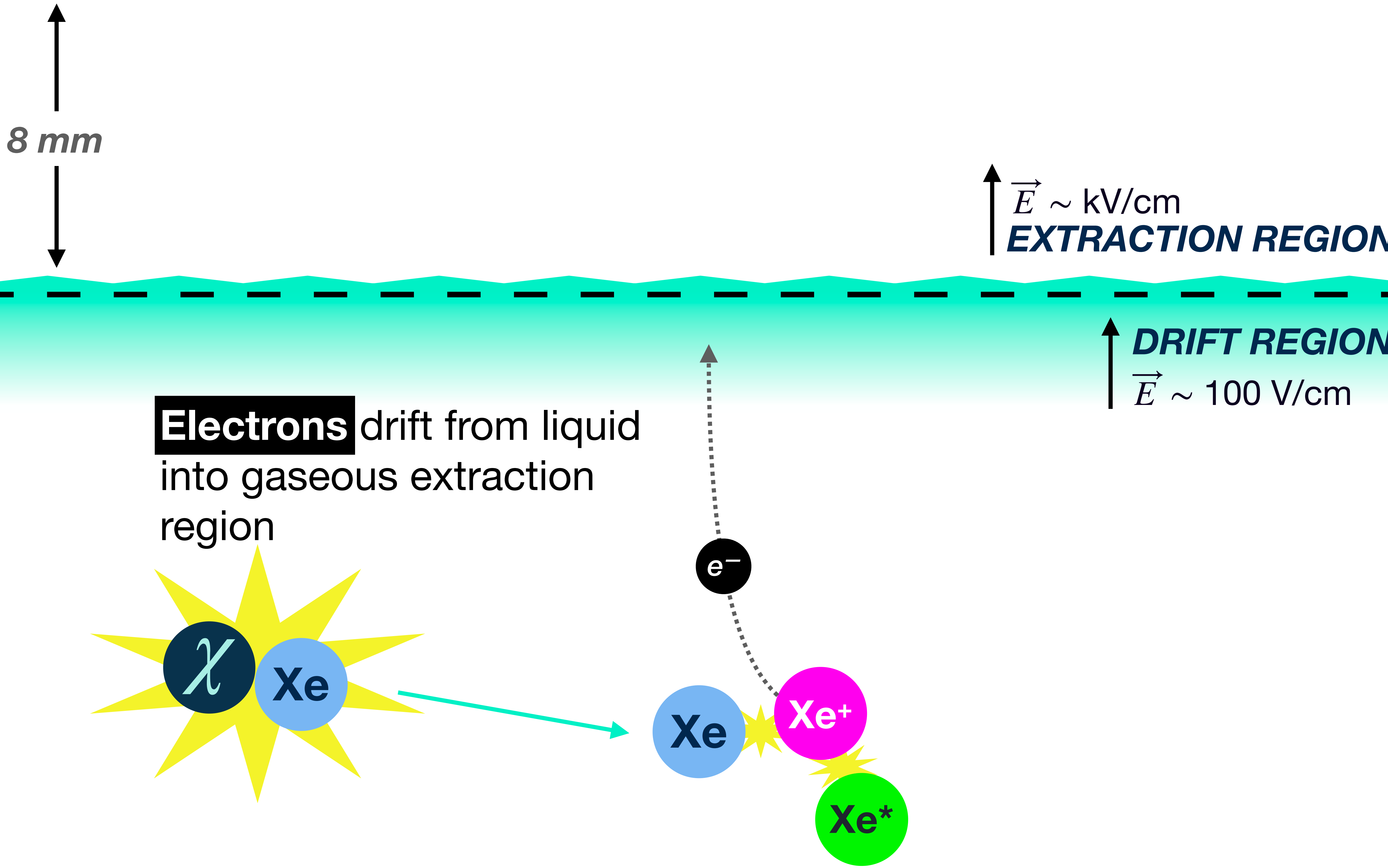
Liquid Xenon Microphysics



Ions form charged dimers, can recombine to become excimers

Excimers decay to ground and emit VUV photons: ***S1 signal***

Liquid Xenon Microphysics



Liquid Xenon Microphysics