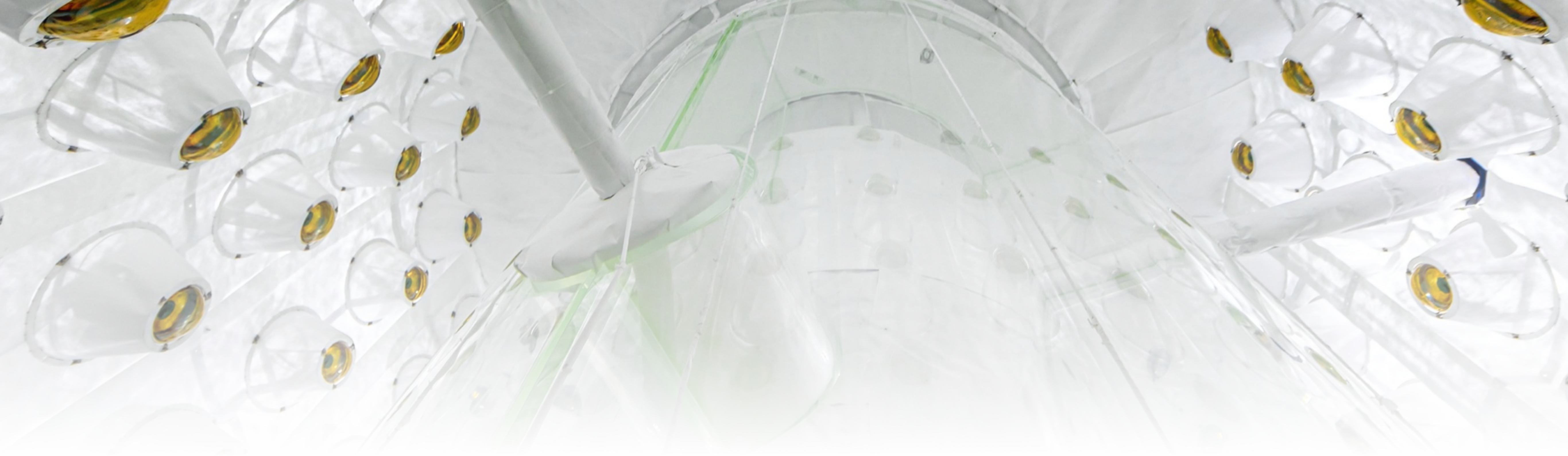
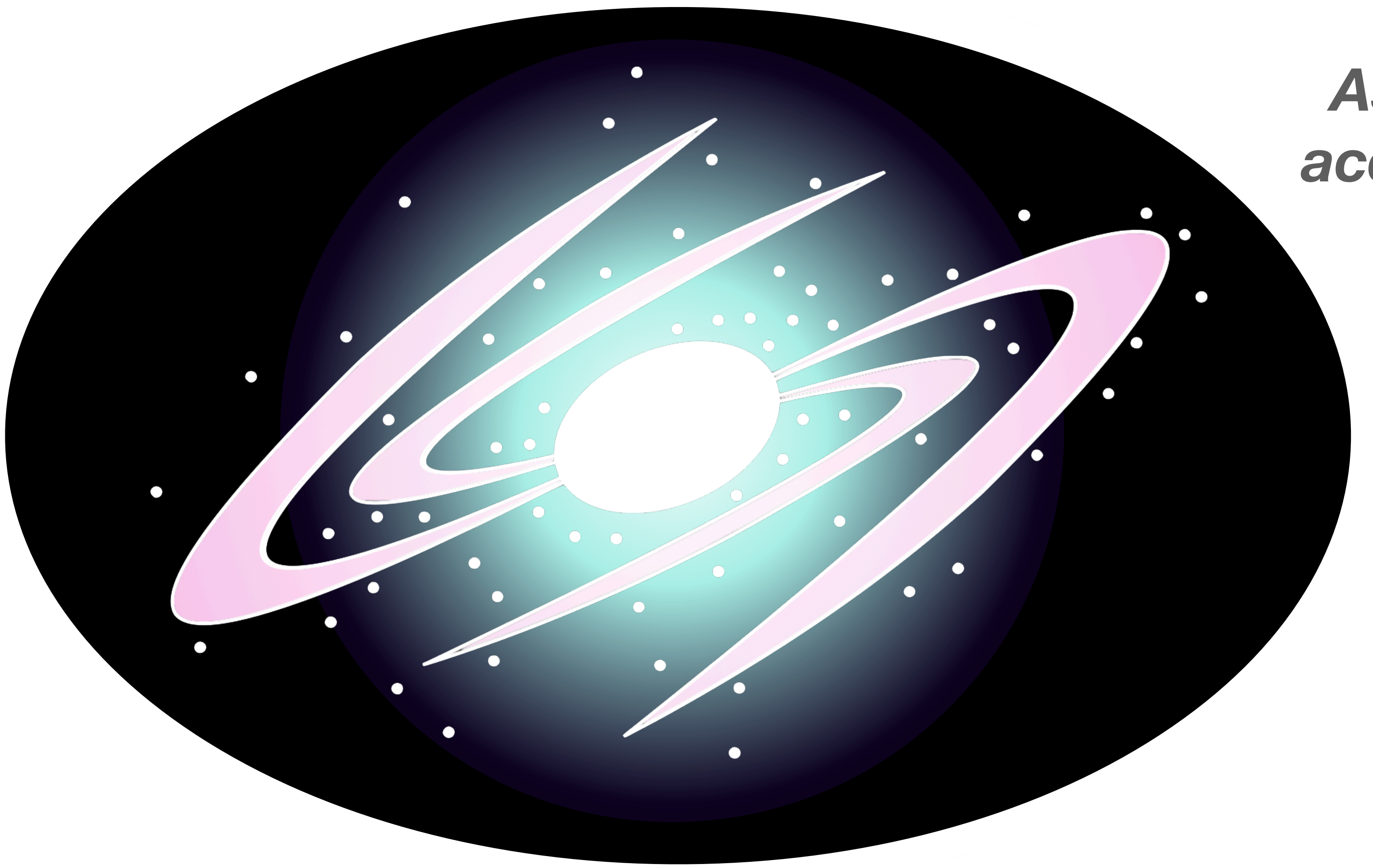


Status and Results from the LUX-ZEPLIN Experiment

Joe McLaughlin
University College London
On behalf of the LZ Collaboration
Cosmology 2023

Contents

Some Context



Assuming dark matter is distributed according to the Standard Halo Model

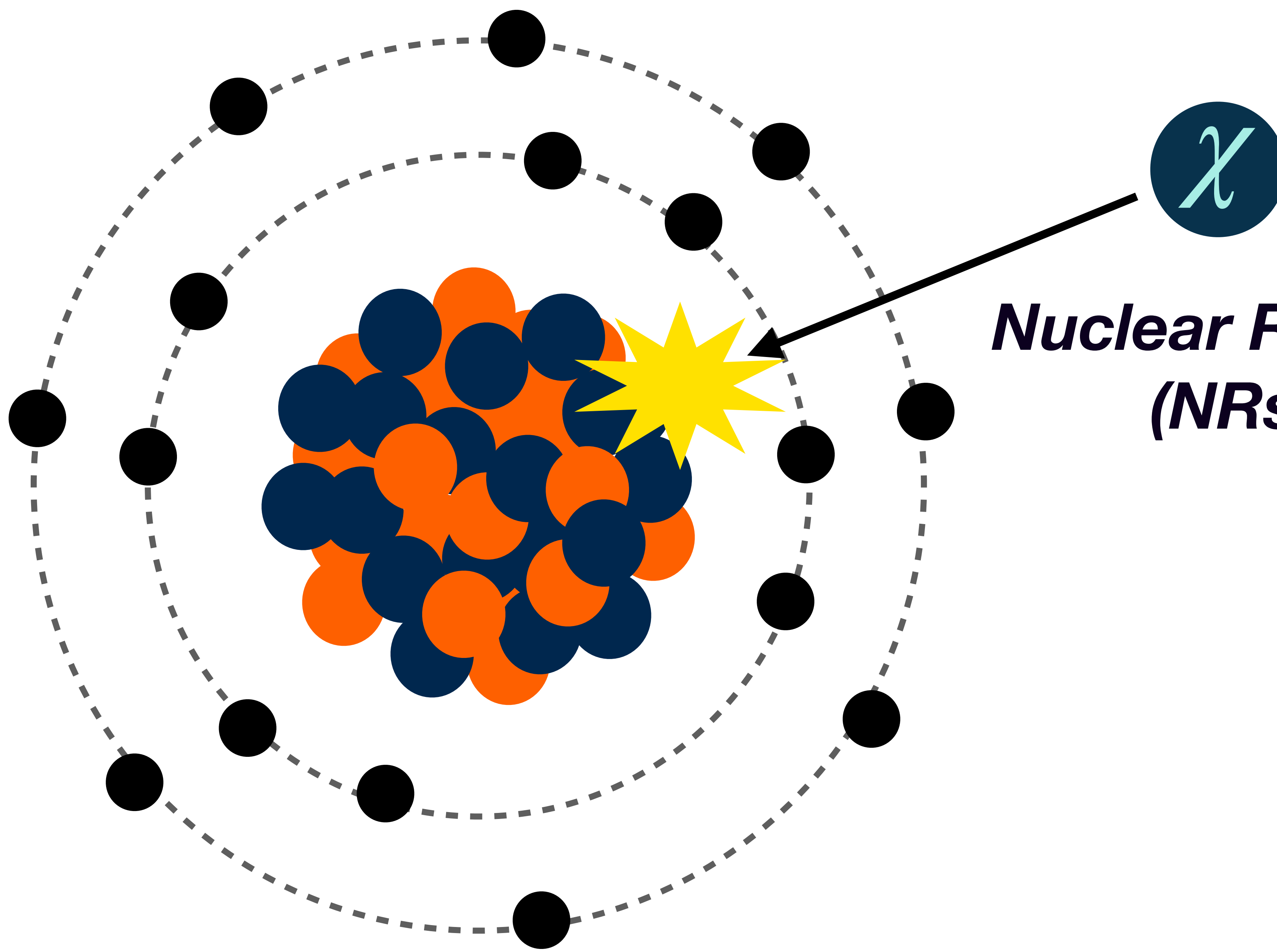
- Isothermal sphere of DM, $\rho \propto r^{-2}$
- Local density $\rho_0 \sim 0.3$ GeV/cm^3
- Truncated Maxwell-Boltzmann velocity distribution
- Characteristic velocity $v_0 = 220$ km/s $\rightarrow$ non-relativistic!

Assuming dark matter made up of Weakly Interacting Massive Particles (WIMPs)

- GeV–TeV mass scale
- Extremely weak coupling to baryonic matter
- e.g. SUSY neutralino, Kaluza-Klein dark matter

Some Context

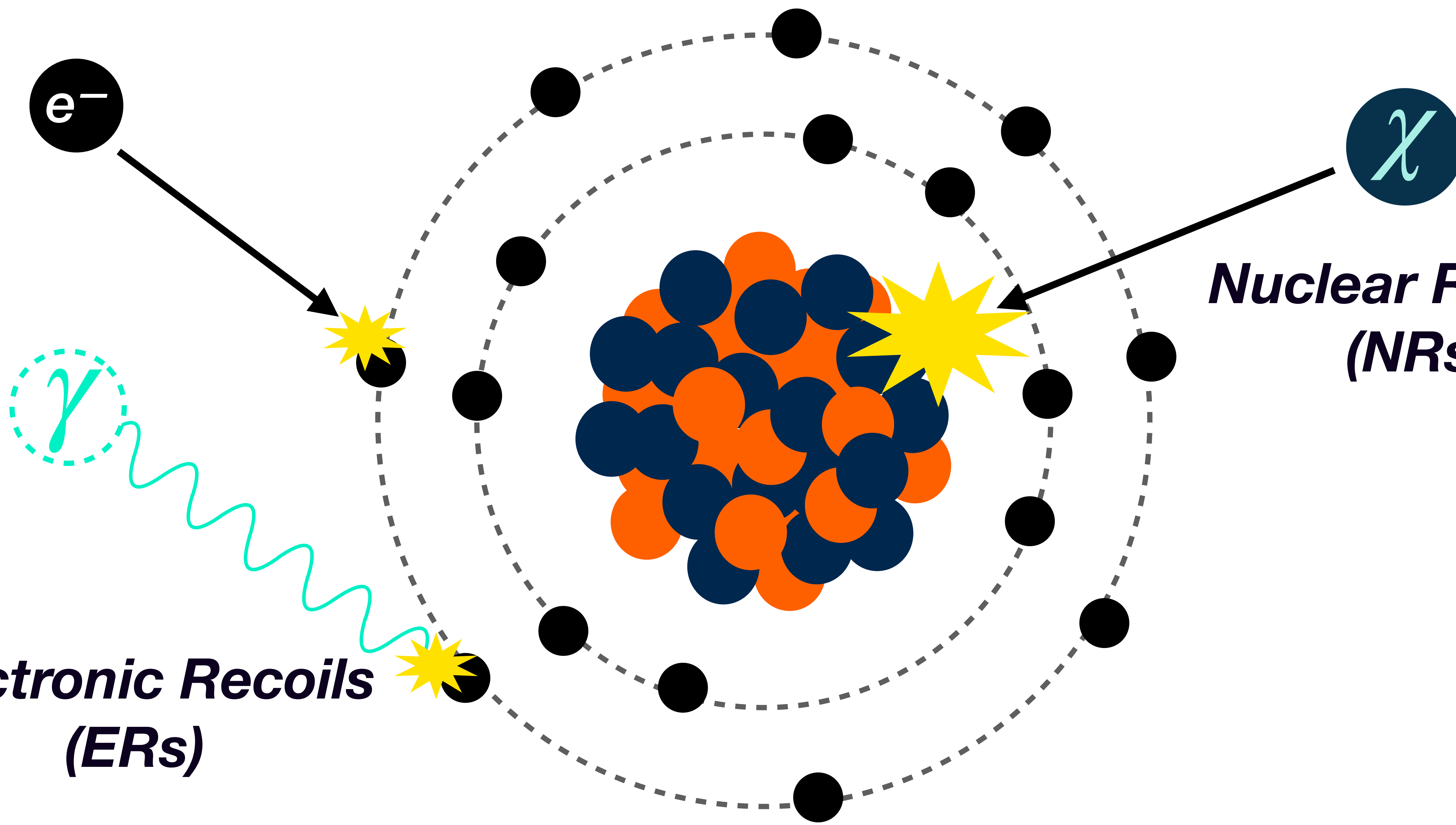
Assuming* dark matter *can interact with baryonic matter, virtually always via elastic collisions with nuclei



Nuclear Recoils (NRs)

Some Context

*Assuming **dark matter** can interact with baryonic matter, virtually always via elastic collisions with nuclei*



Nuclear Recoils (NRs)

Electronic Recoils (ERs)

Lighter particles, such as electrons or photons, kinematically limited to scatter with atomic electrons

The LZ Experiment

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/

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

UKRI 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

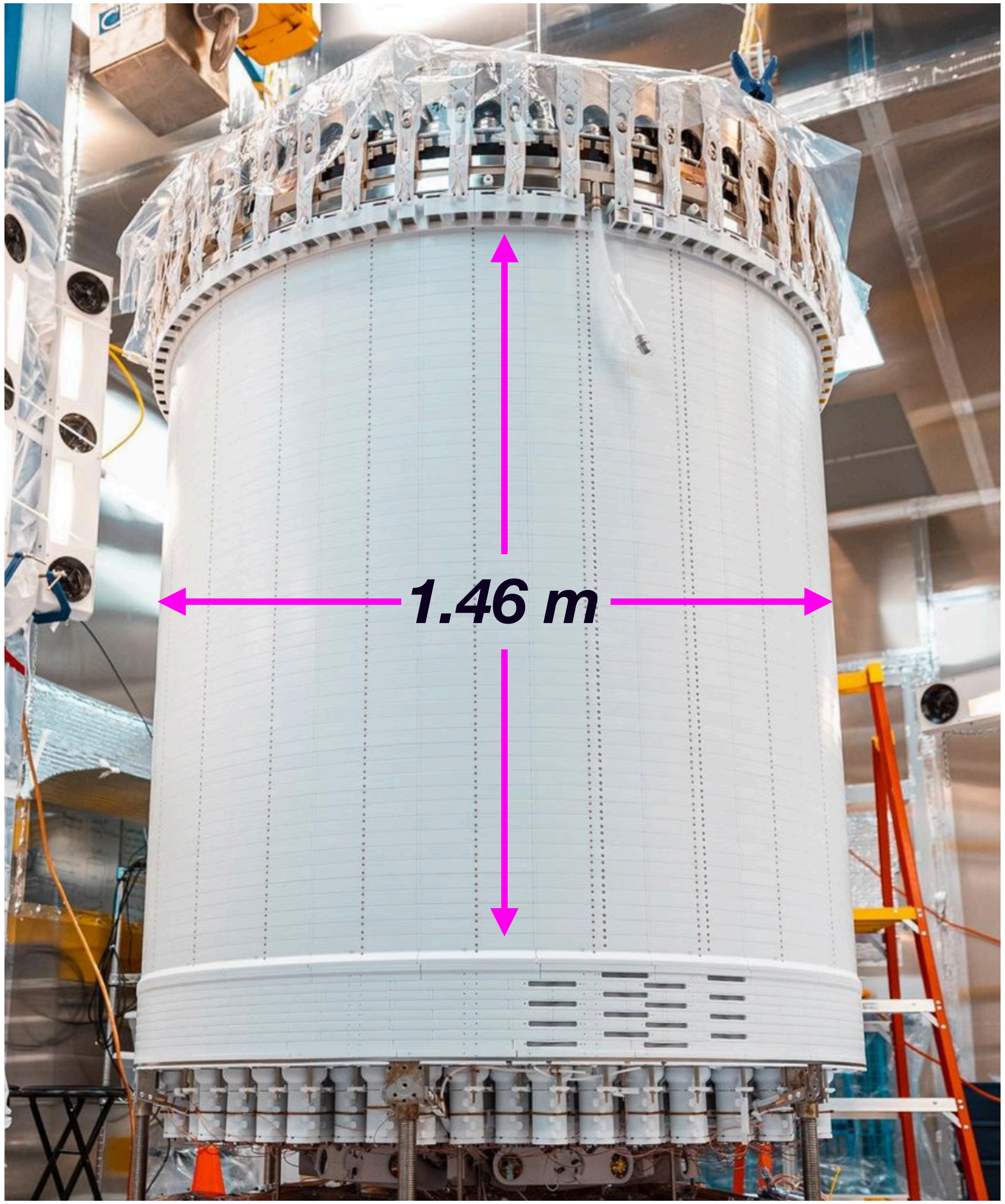
ibs Institute for Basic Science

The LZ Experiment

LUX-ZEPLIN (LZ) is…

A dual-phase time projection chamber (TPC) filled with liquid xenon (LXe) as a WIMP scattering target

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



The LZ Experiment

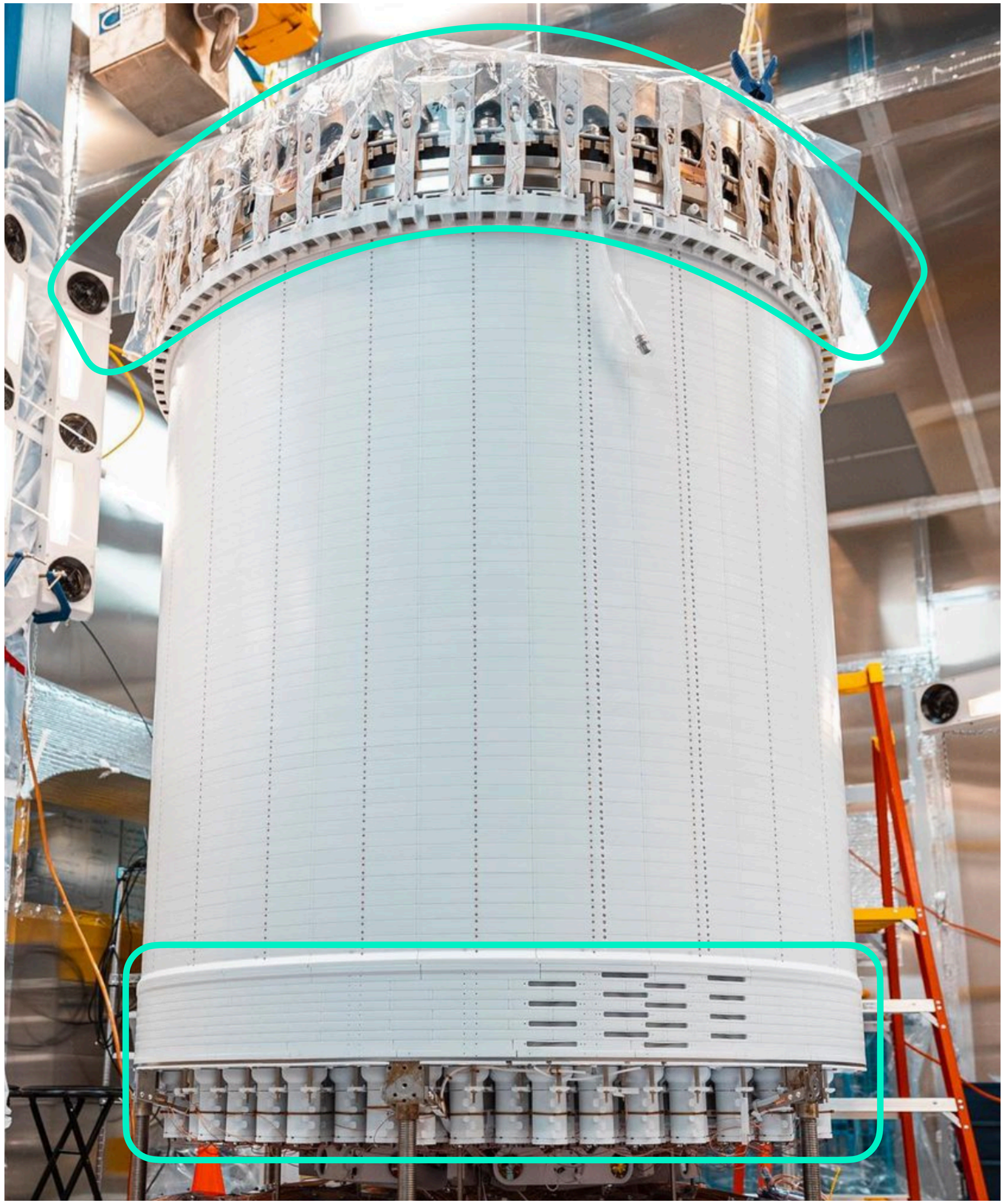
LUX-ZEPLIN (LZ) is…

A dual-phase time projection chamber (TPC) filled with liquid xenon (LXe) as a WIMP scattering target

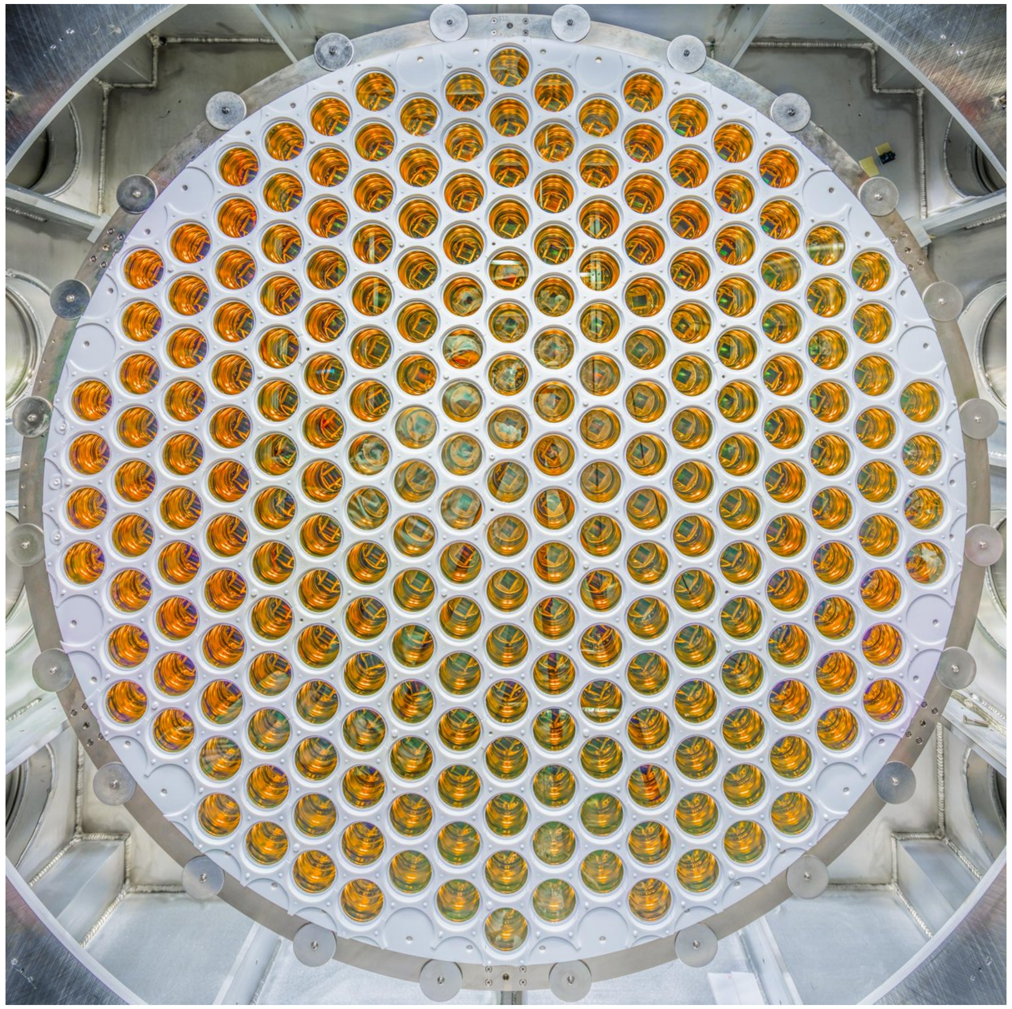
- ***10 tonnes total mass***
- ***7 tonnes active mass***
- ***5.5 tonnes fiducial mass***

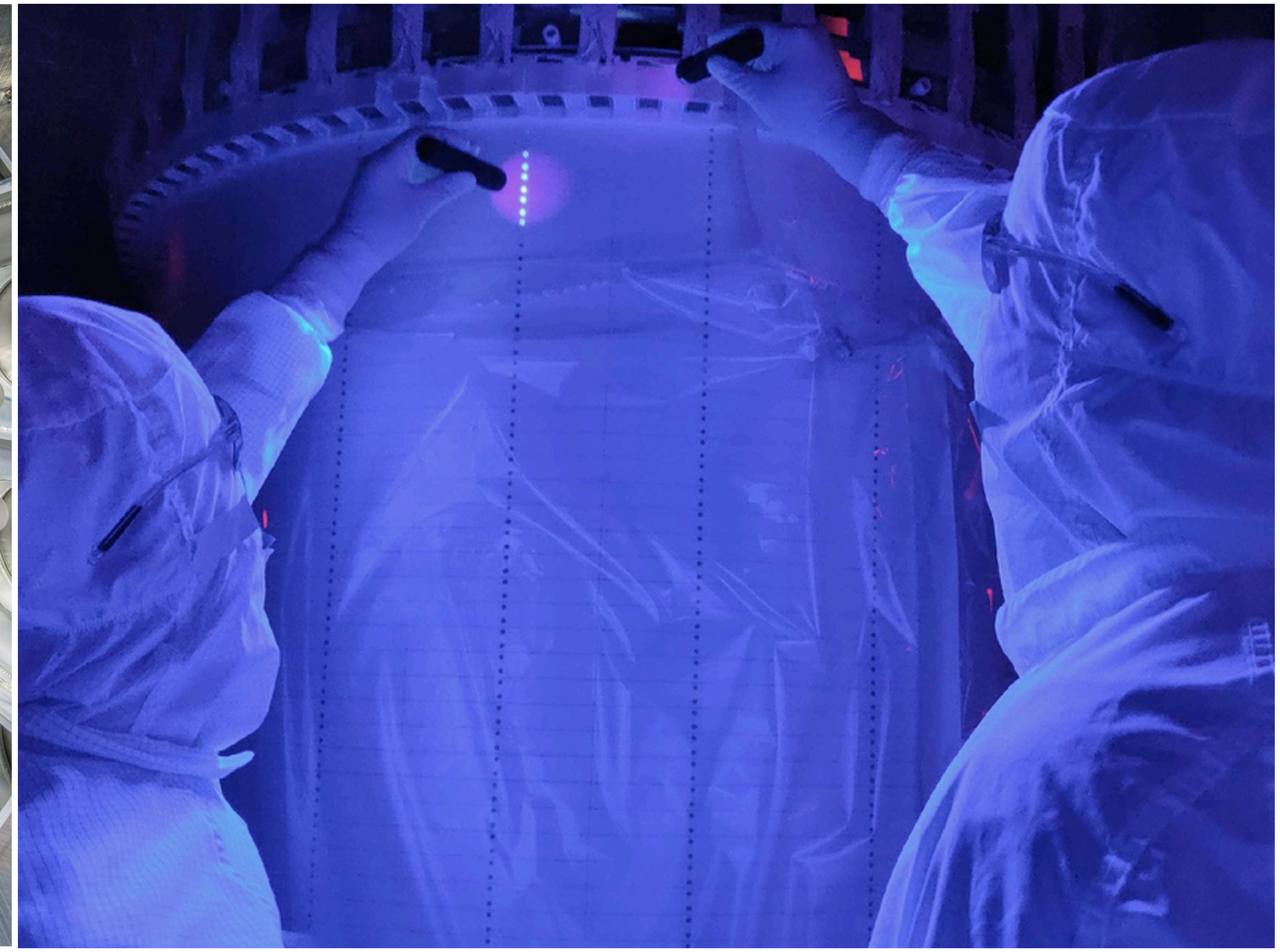
Instrumented with Hamamatsu R11410-22 3" Photomultiplier Tubes (PMTs) on top and bottom arrays and high reflectivity PTFE walls

- ***Sensitivity in VUV range***
- ***494 PMTs in total***



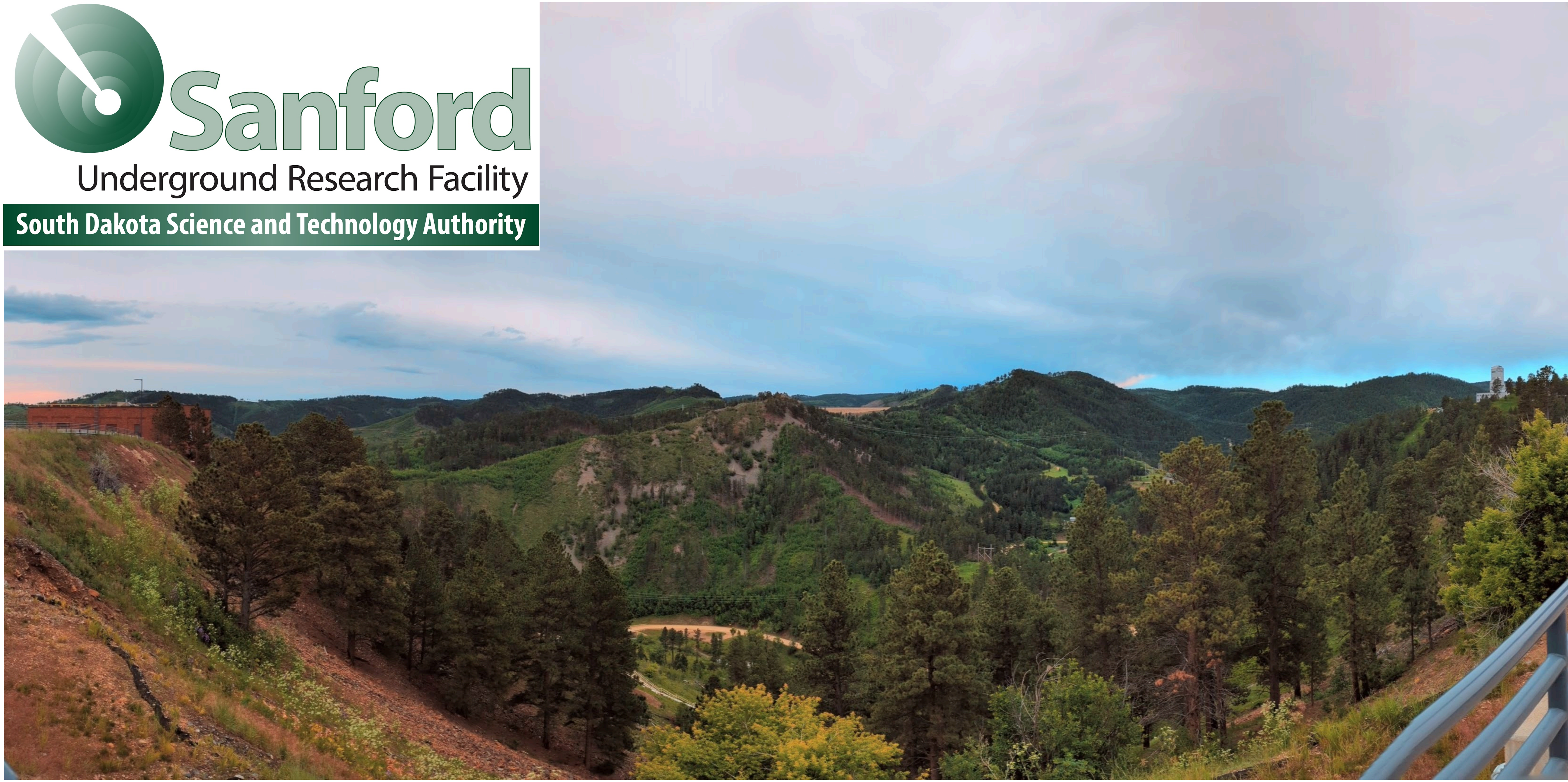
The LZ Experiment





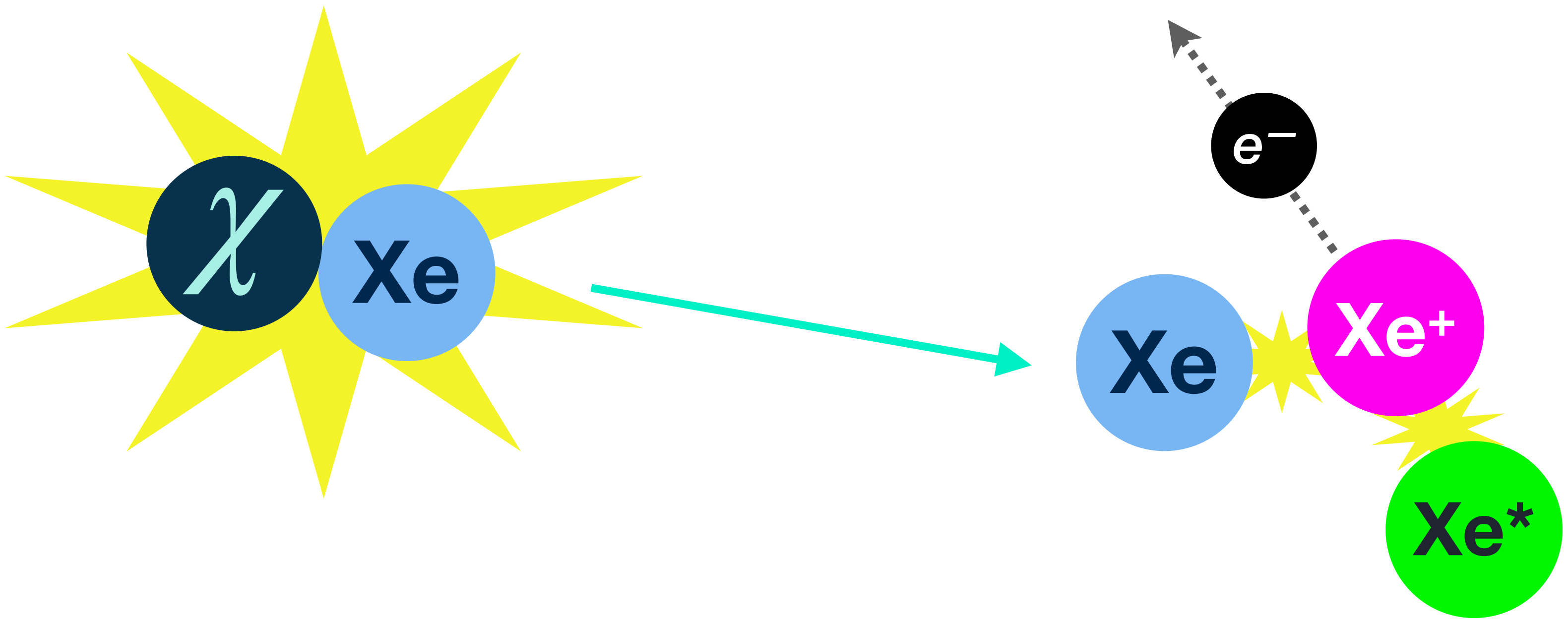
The LZ Experiment

Sanford
Underground Research Facility
South Dakota Science and Technology Authority



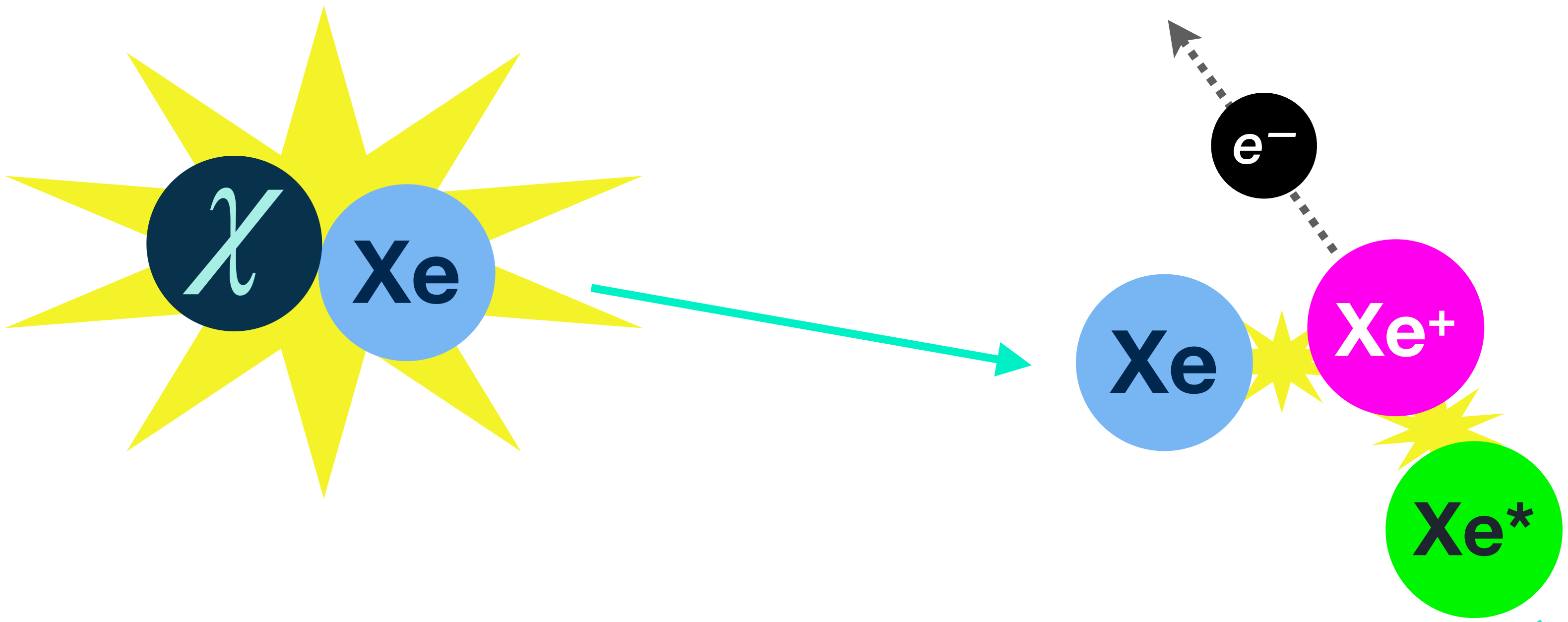
1 mile under the Black Hills of South Dakota

The LZ Experiment

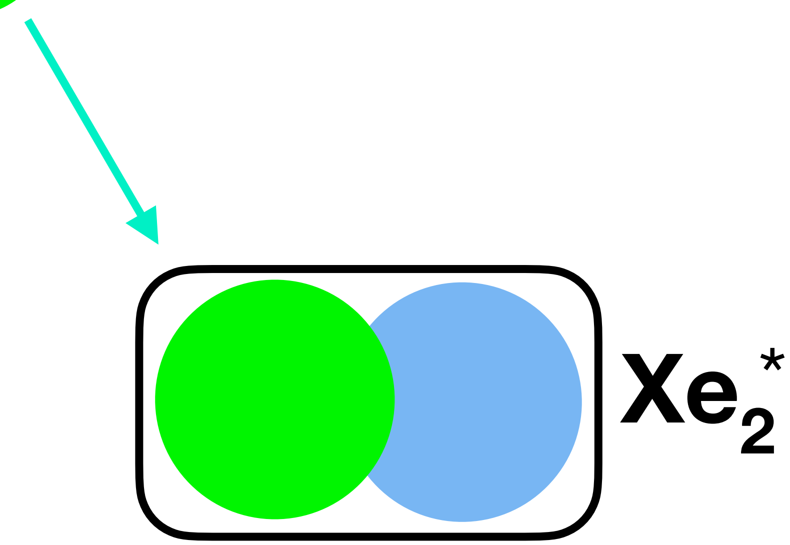


Atoms in the track of a recoiling nucleus become ***excitons*** or ***ions***

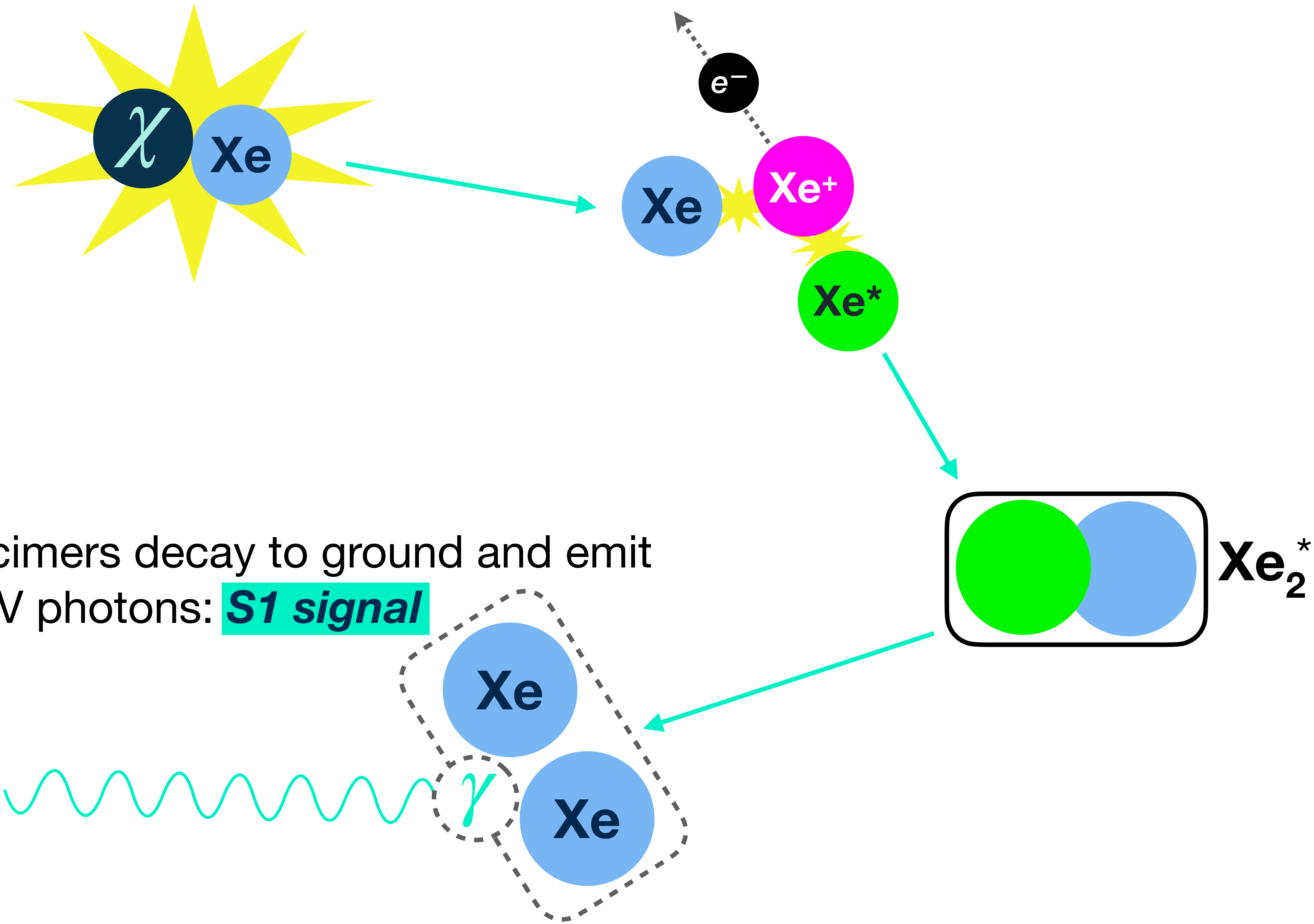
The LZ Experiment



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

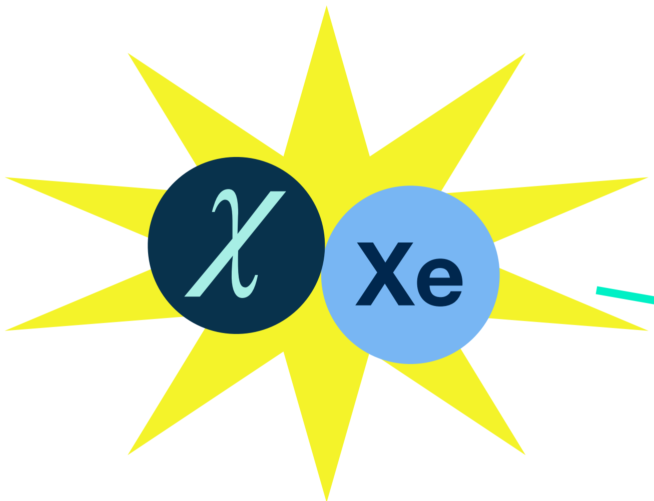


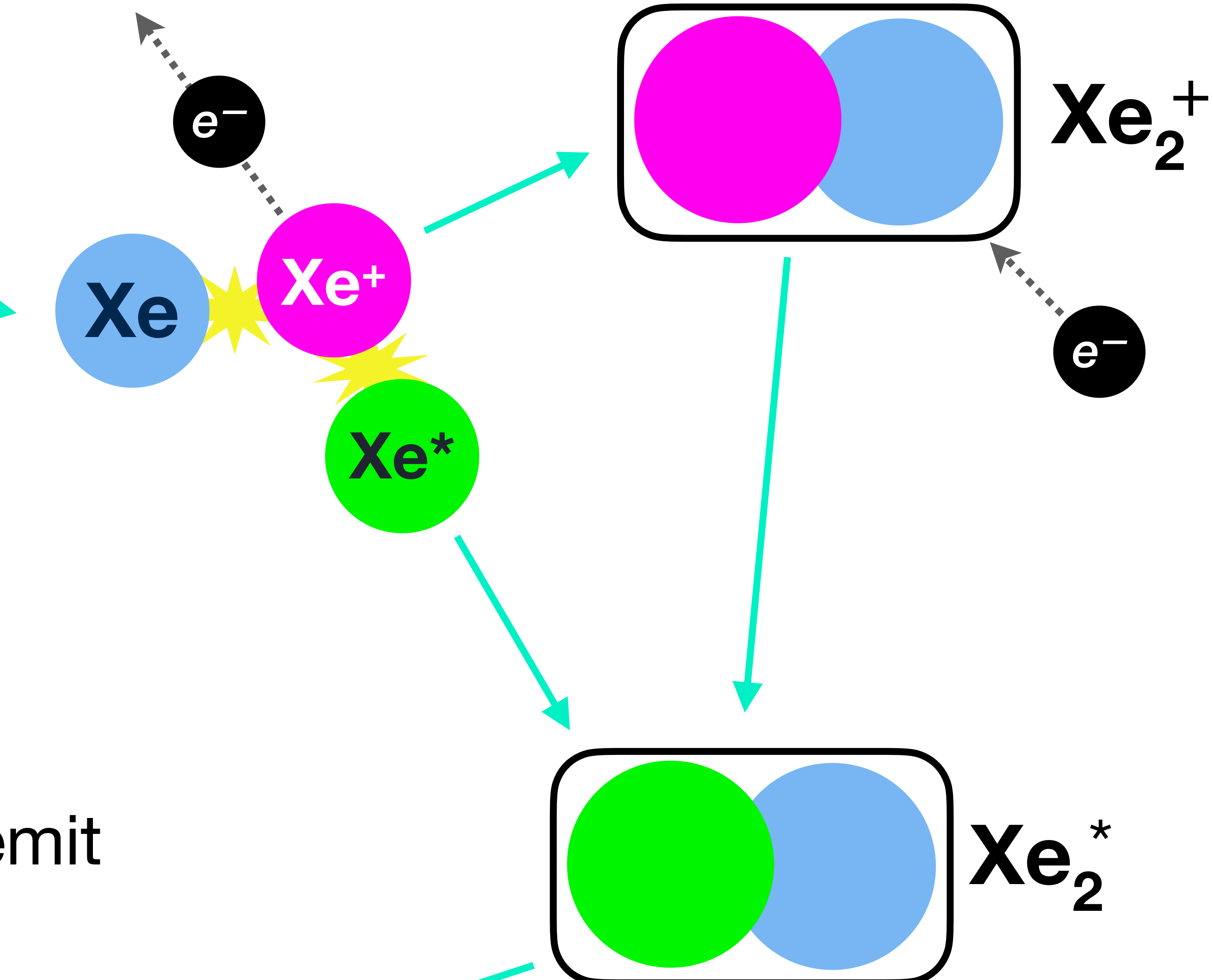
The LZ Experiment



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

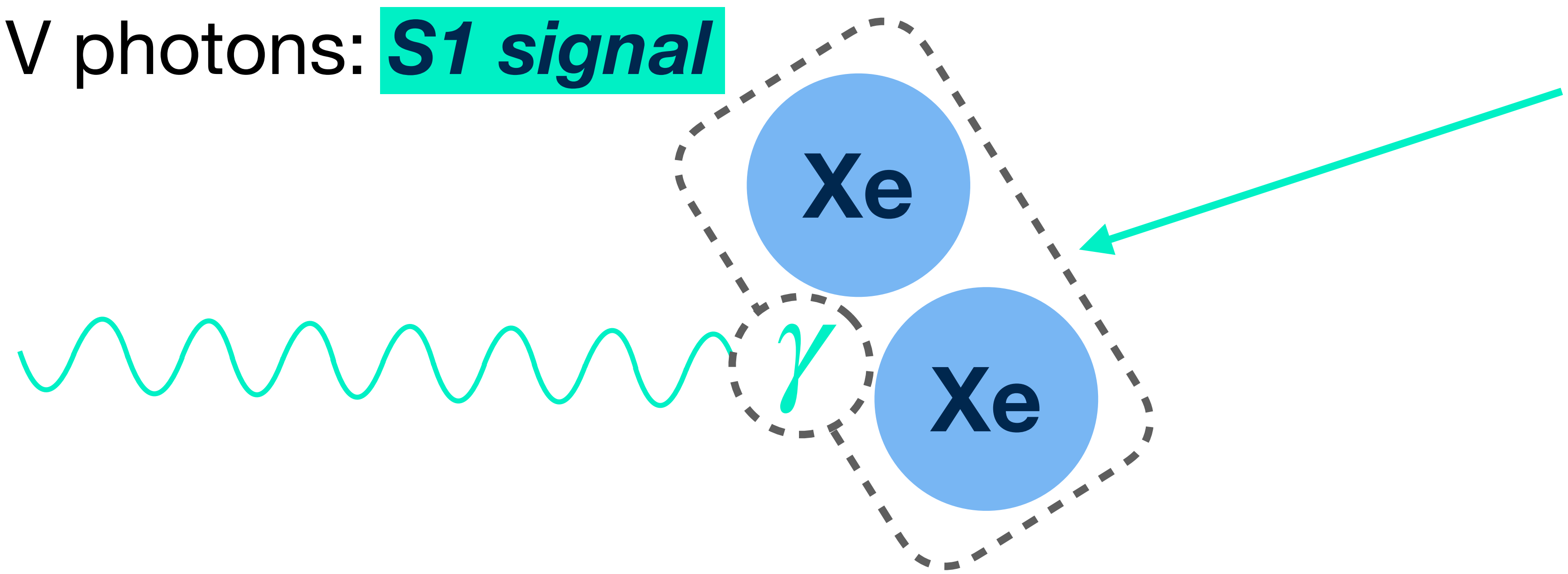
The LZ Experiment



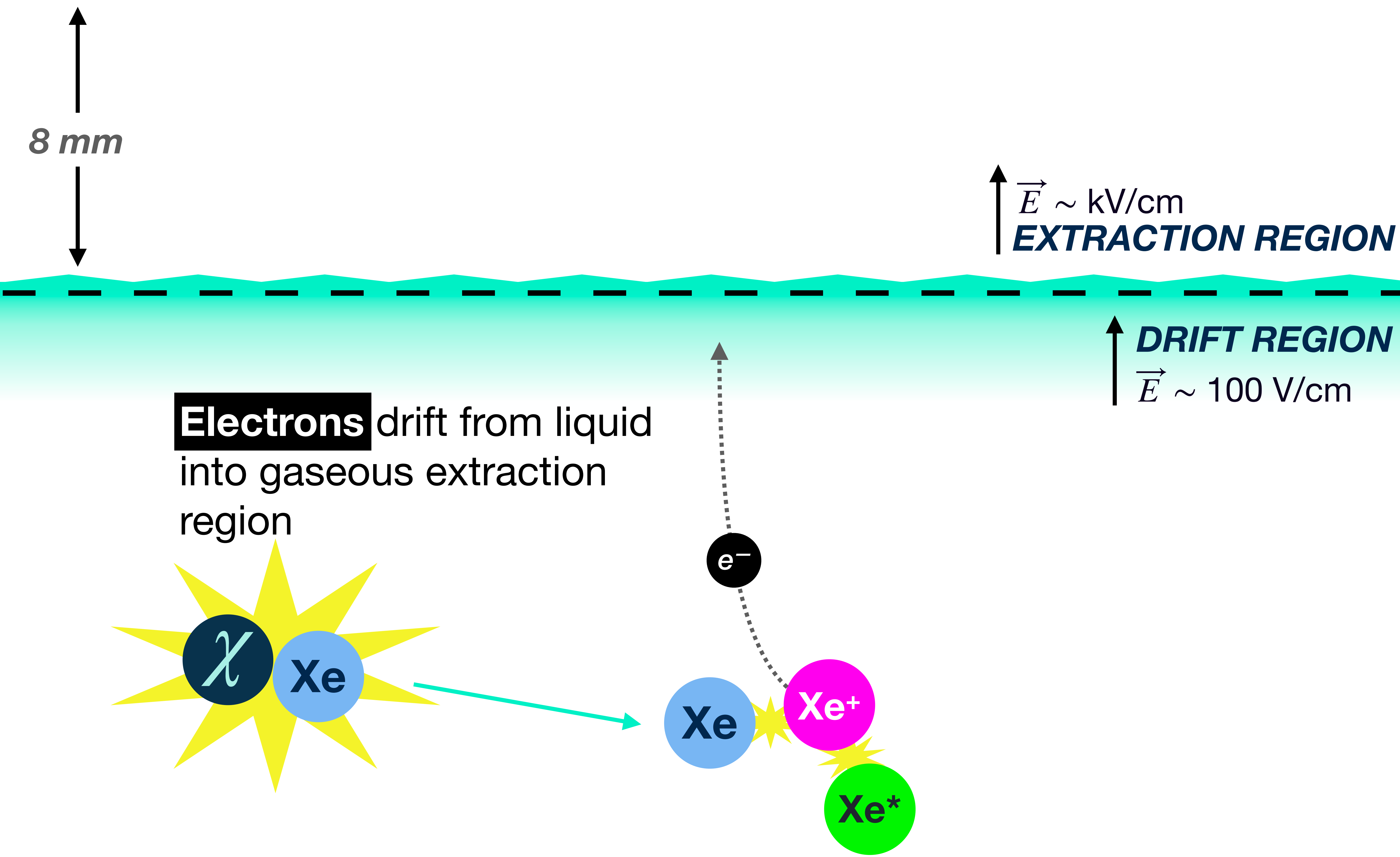


Ions form charged dimers, can recombine to become excimers

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

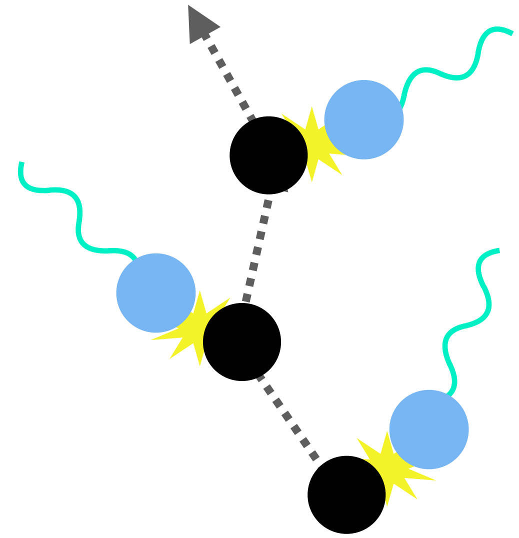


The LZ Experiment

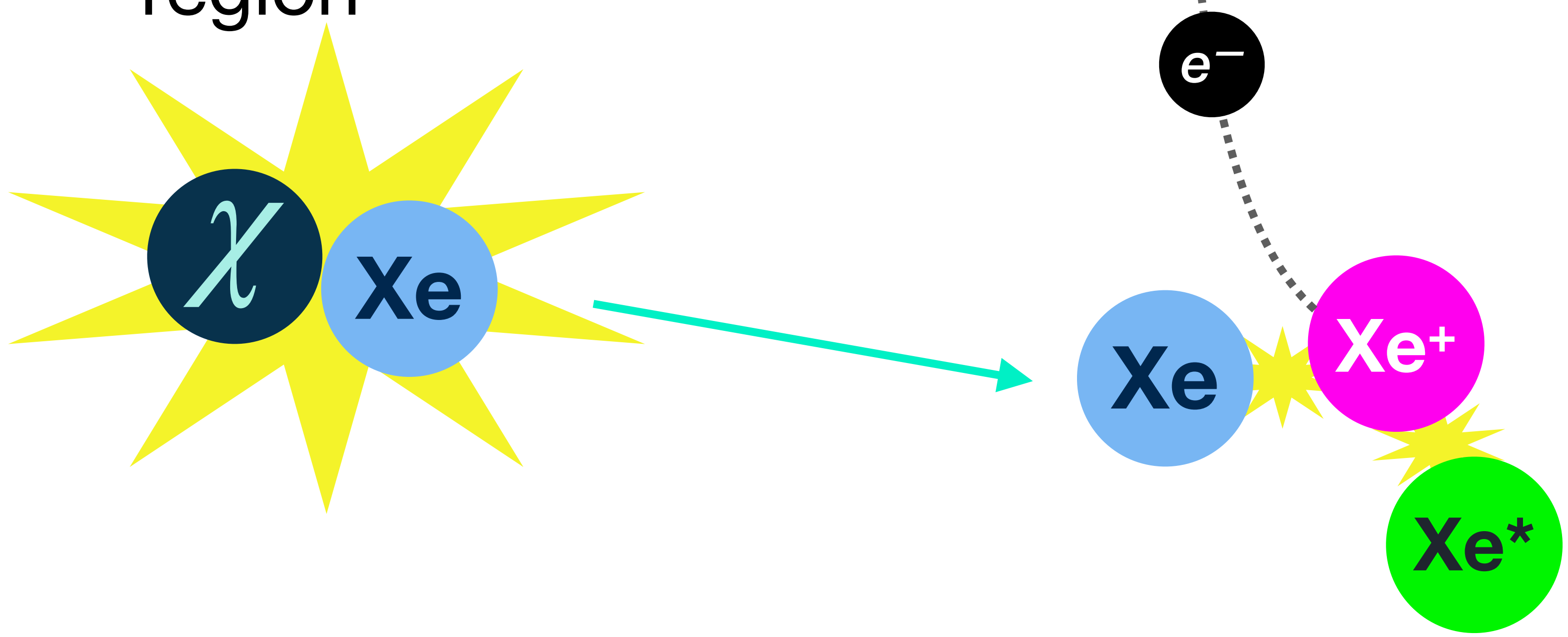


The LZ Experiment

Electroluminescence makes secondary VUV photons in gas phase: ***S2 signal***

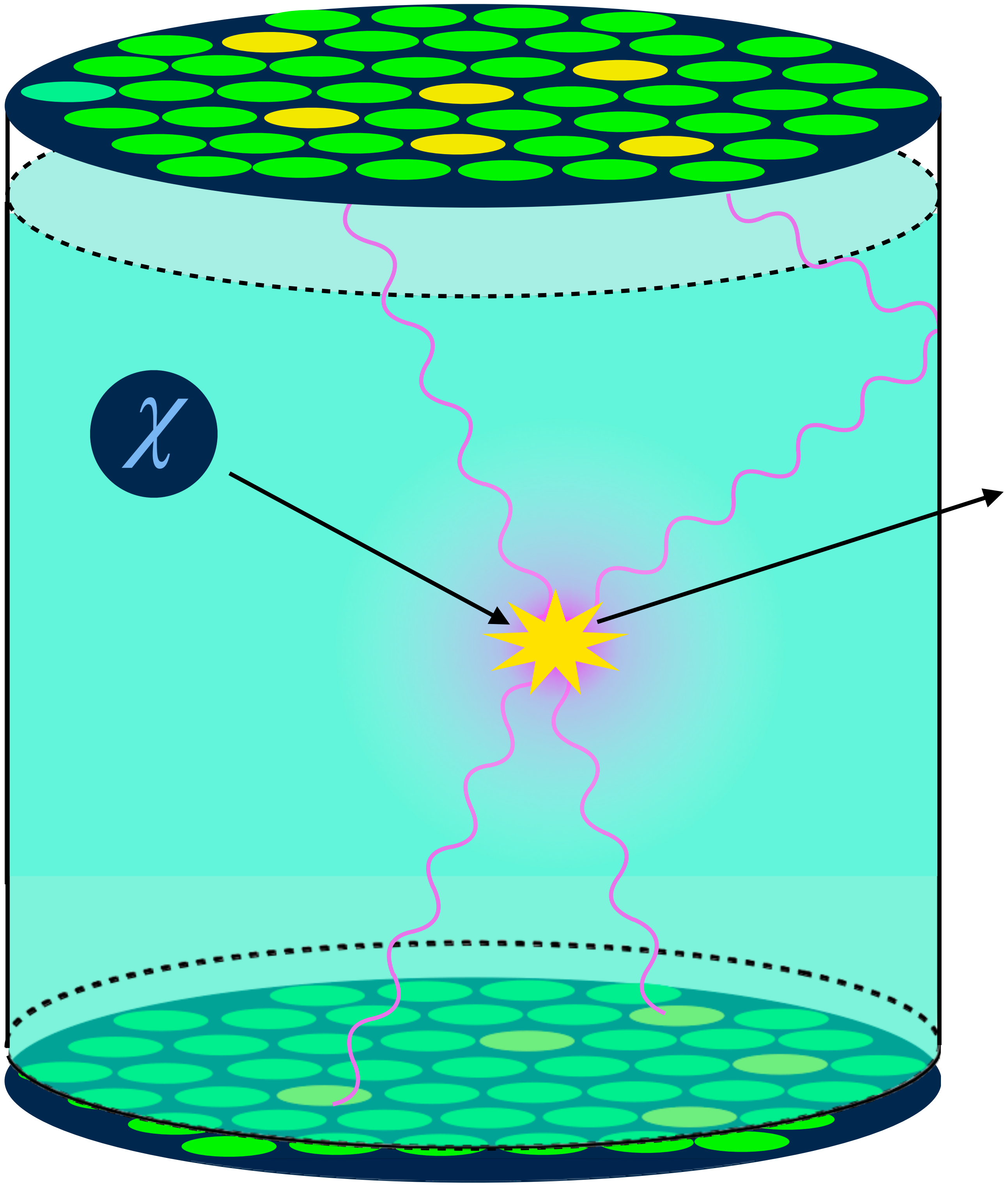


Electrons drift from liquid into gaseous extraction region



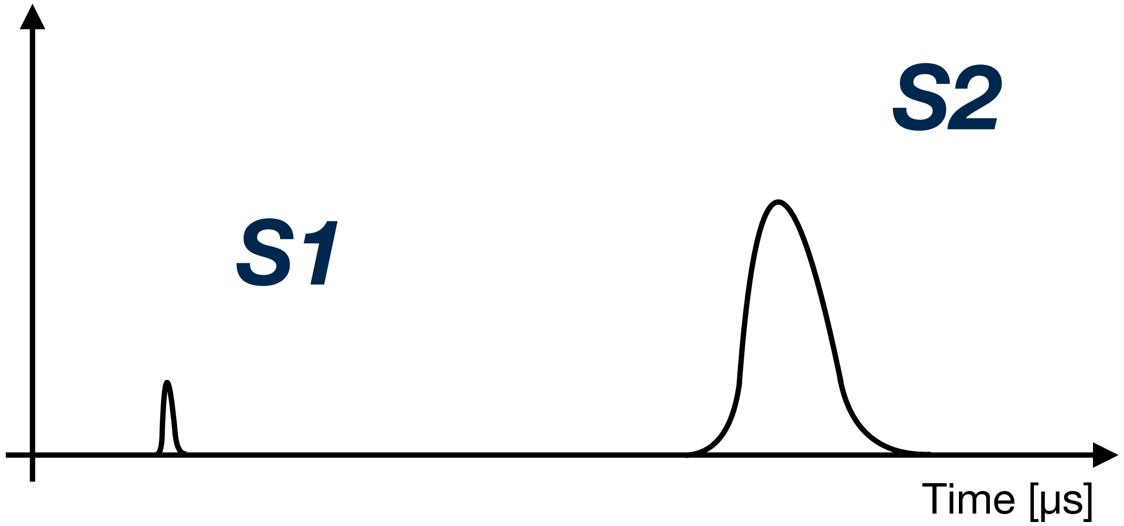
The LZ Experiment

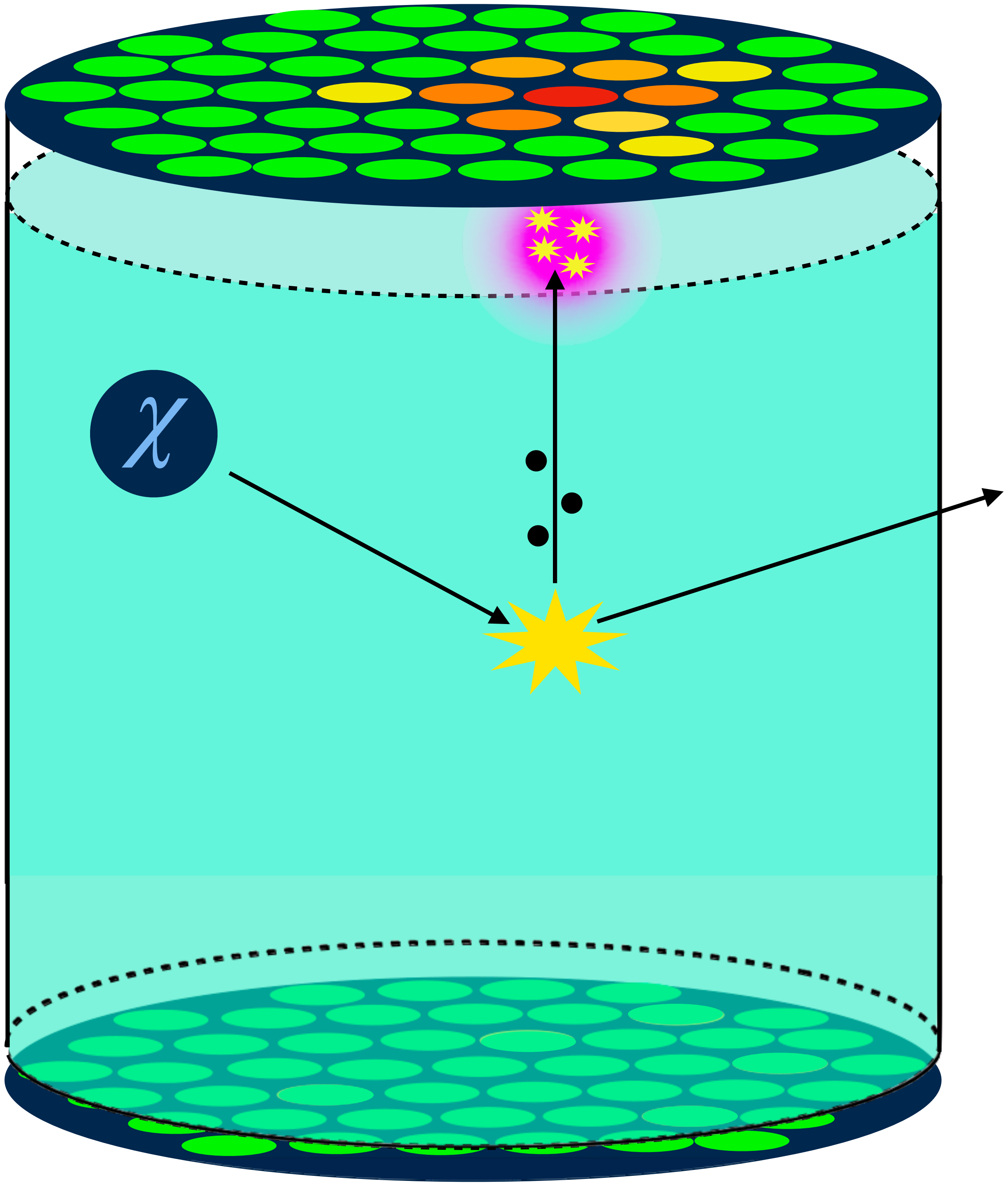
A typical signal



The LZ Experiment

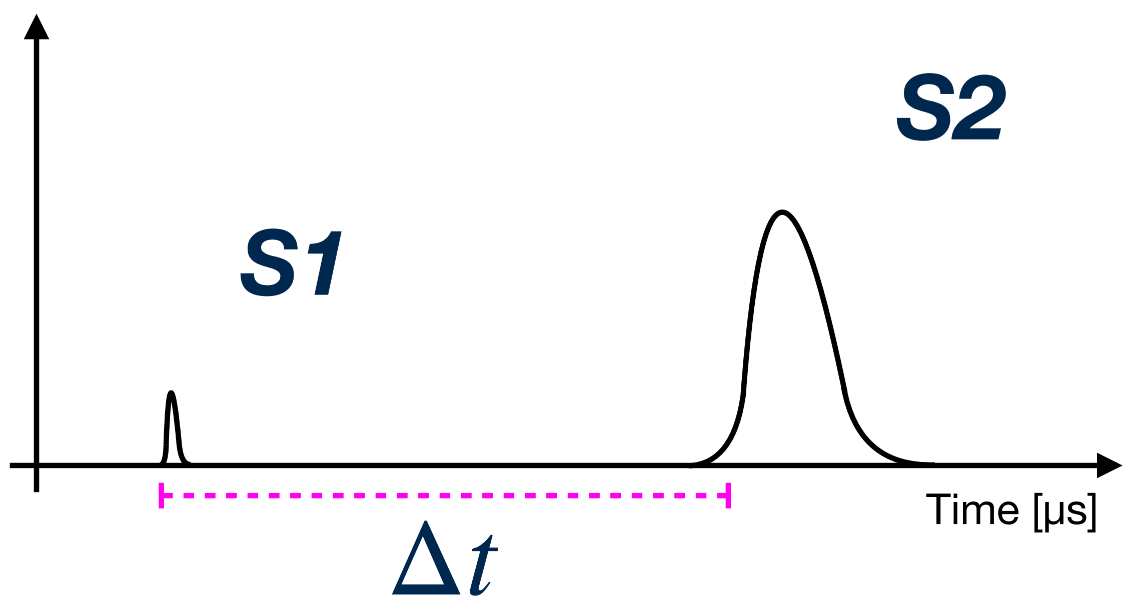
A typical signal





The LZ Experiment

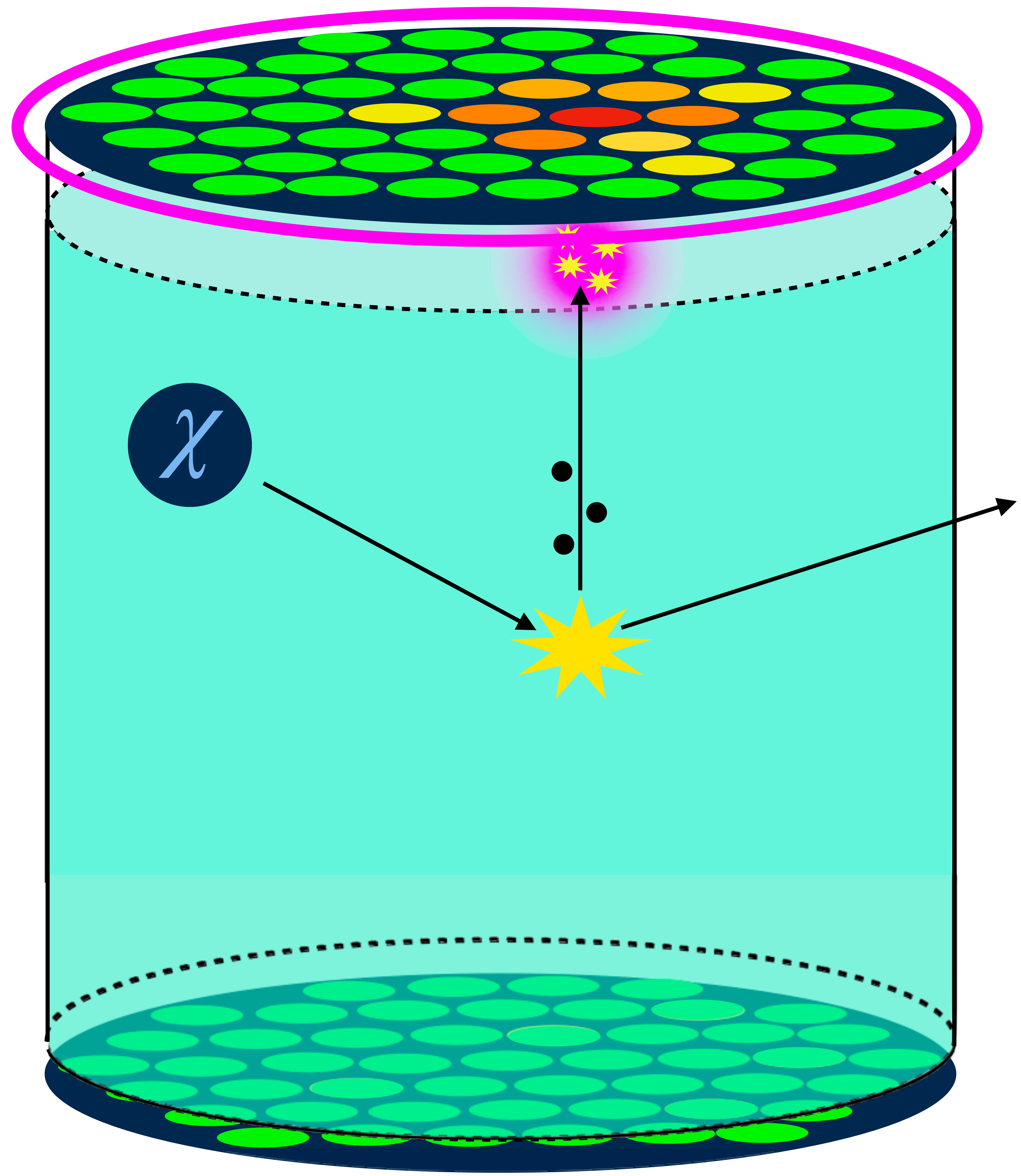
A typical signal



Hit pattern tells us radial position

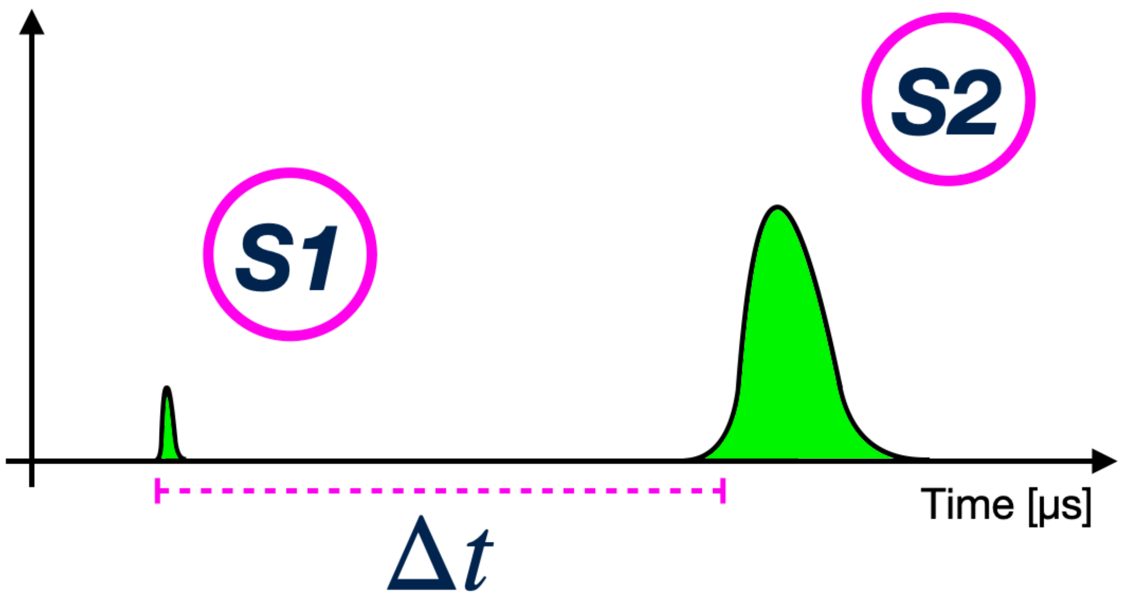
Δt tells us vertical position

> ***Resolution ~ mm***
> ***Critical for fiducialization!***



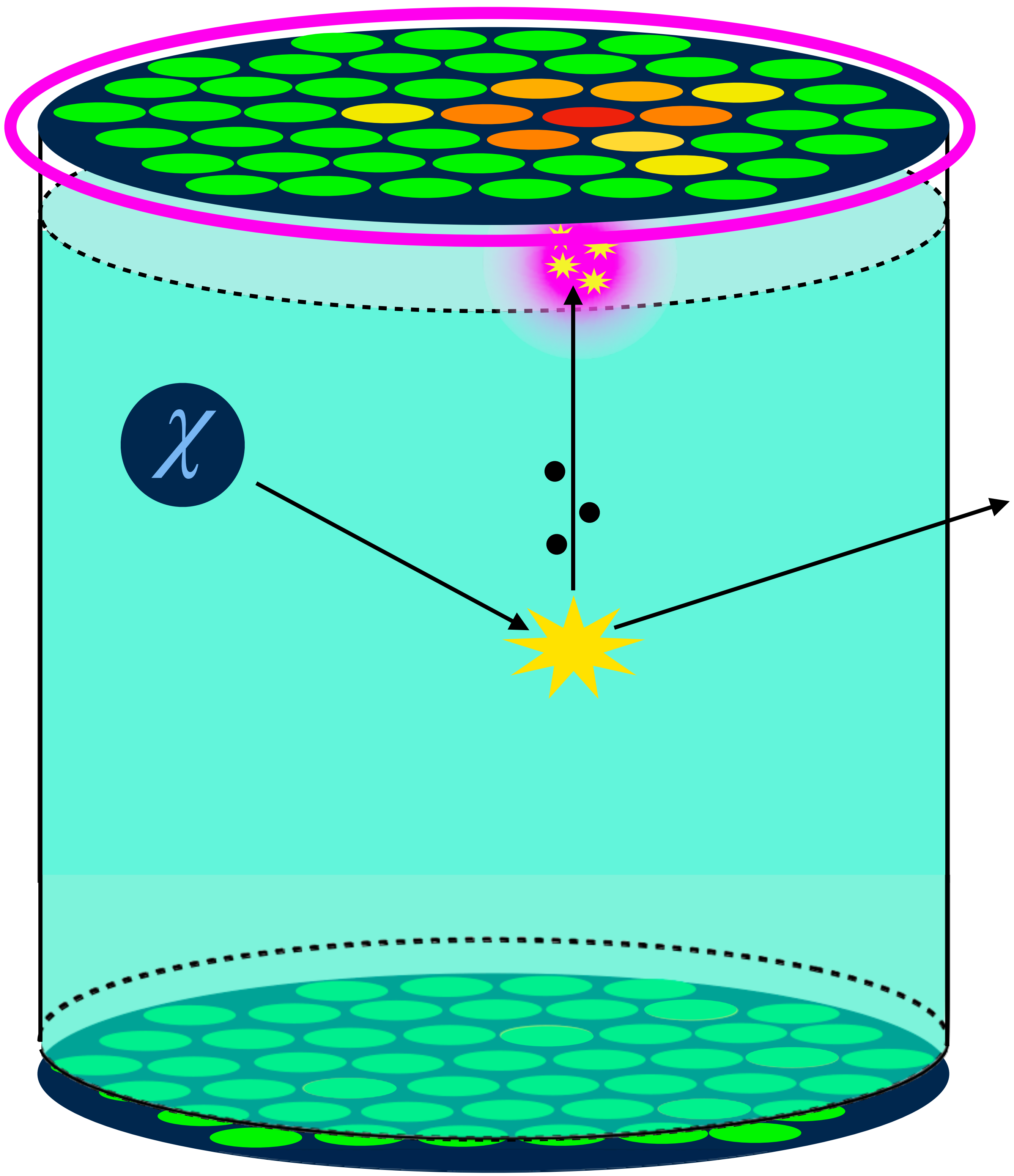
The LZ Experiment

A typical signal



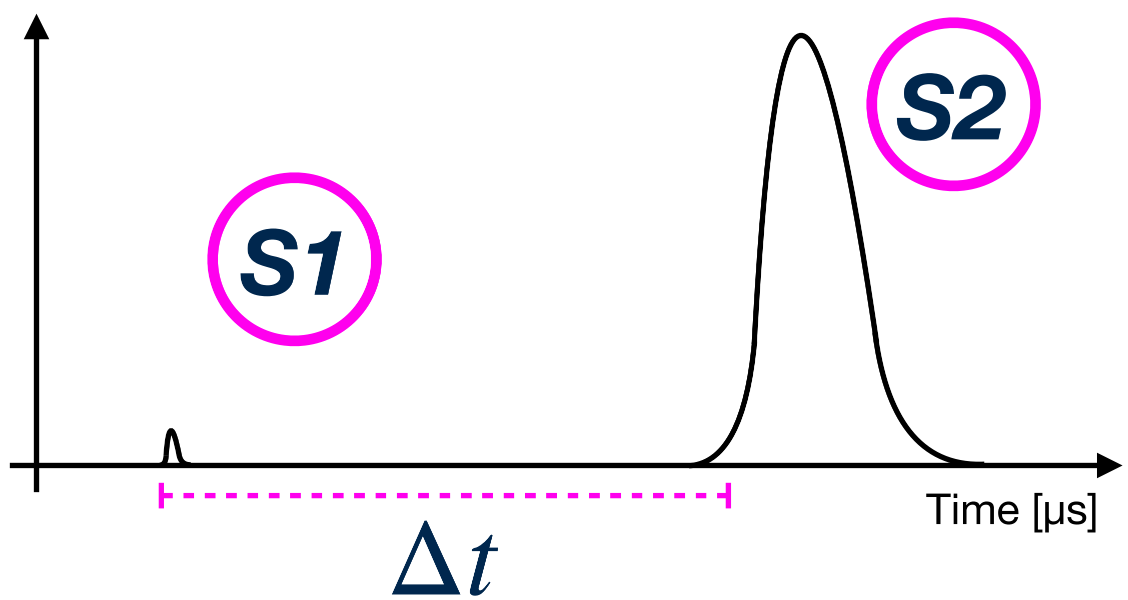
Hit pattern tells us radial position
Δt tells us vertical position
S1+S2 tells us the collision energy

Expressed in 'photons detected' (phd)



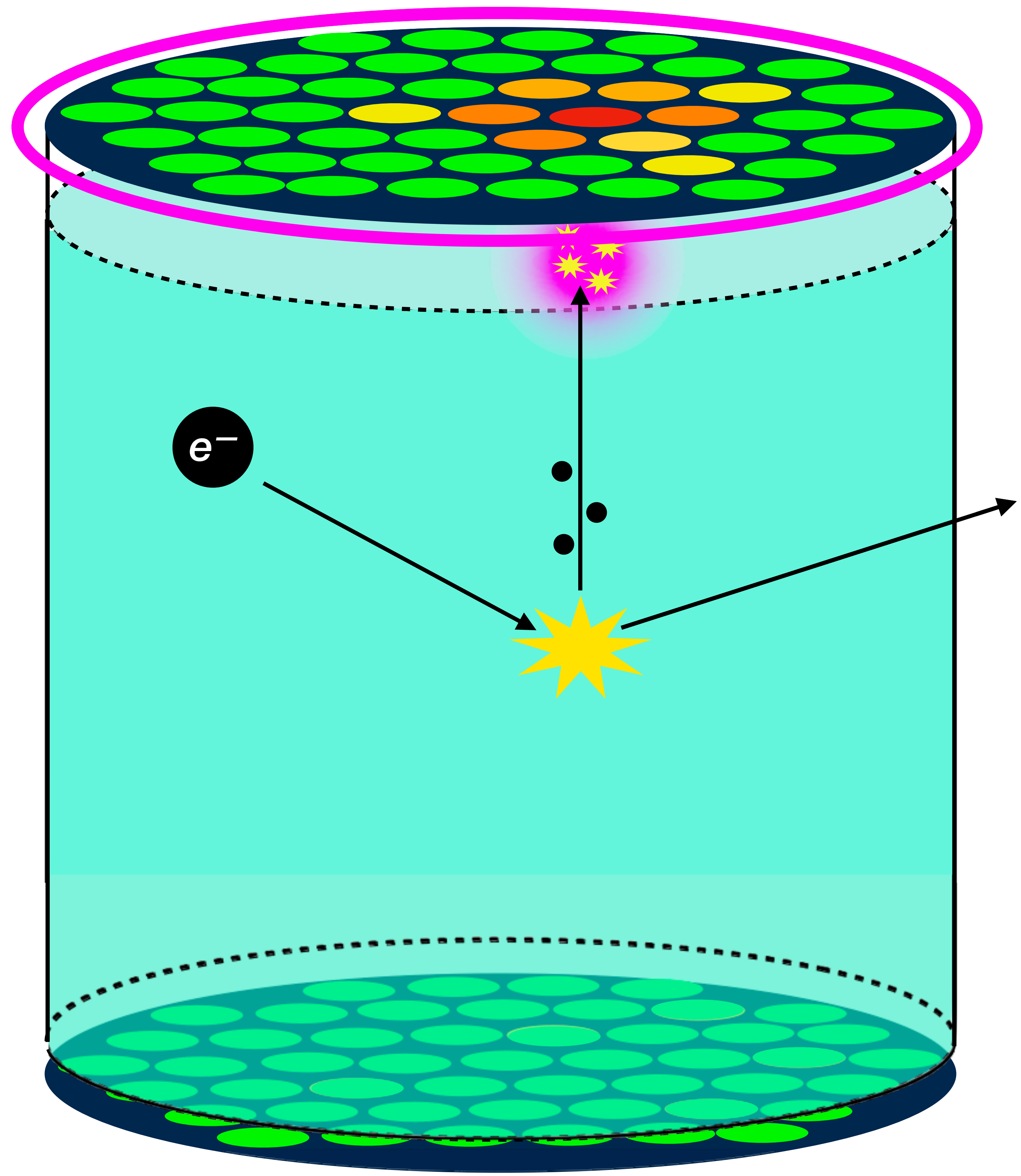
The LZ Experiment

A typical signal

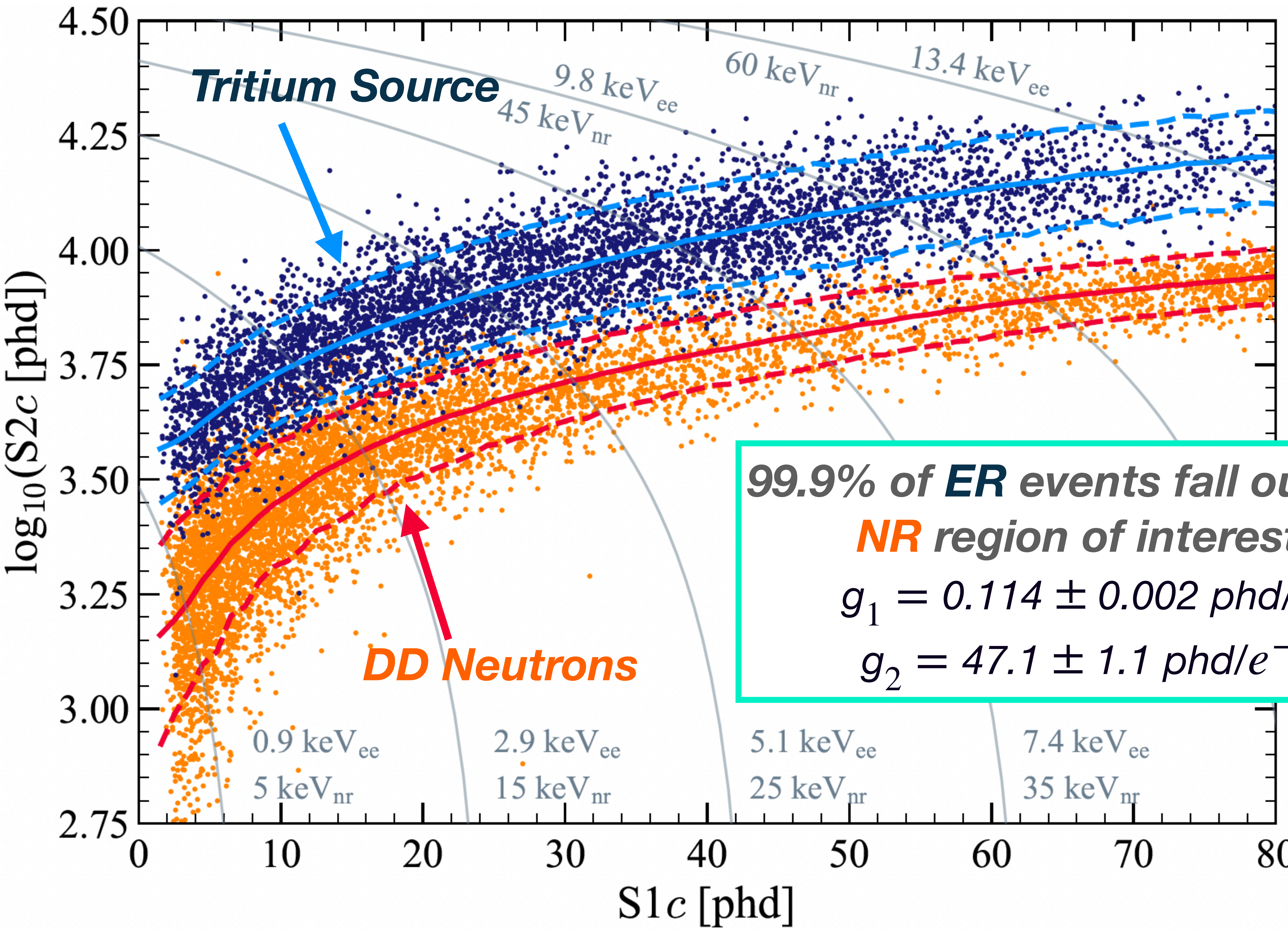


Hit pattern tells us radial position
Δt tells us vertical position
S1+S2 tells us the collision energy

S1:S2 ratio tells us the interaction type



The LZ Experiment



99.9% of ER events fall outside NR region of interest

$g_1 = 0.114 \pm 0.002$ phd/γ

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

The LZ Experiment

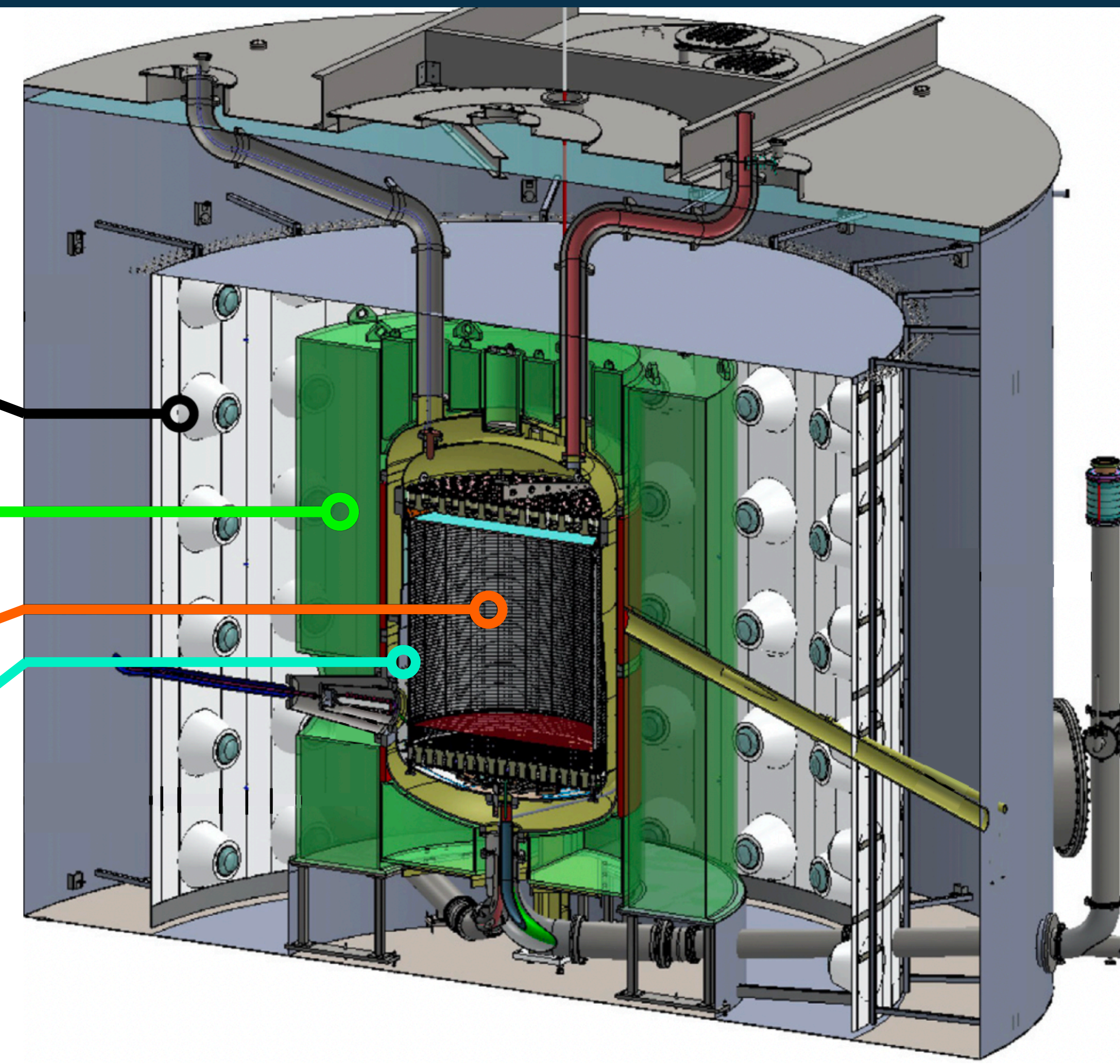
Anti-Coincidence Veto System

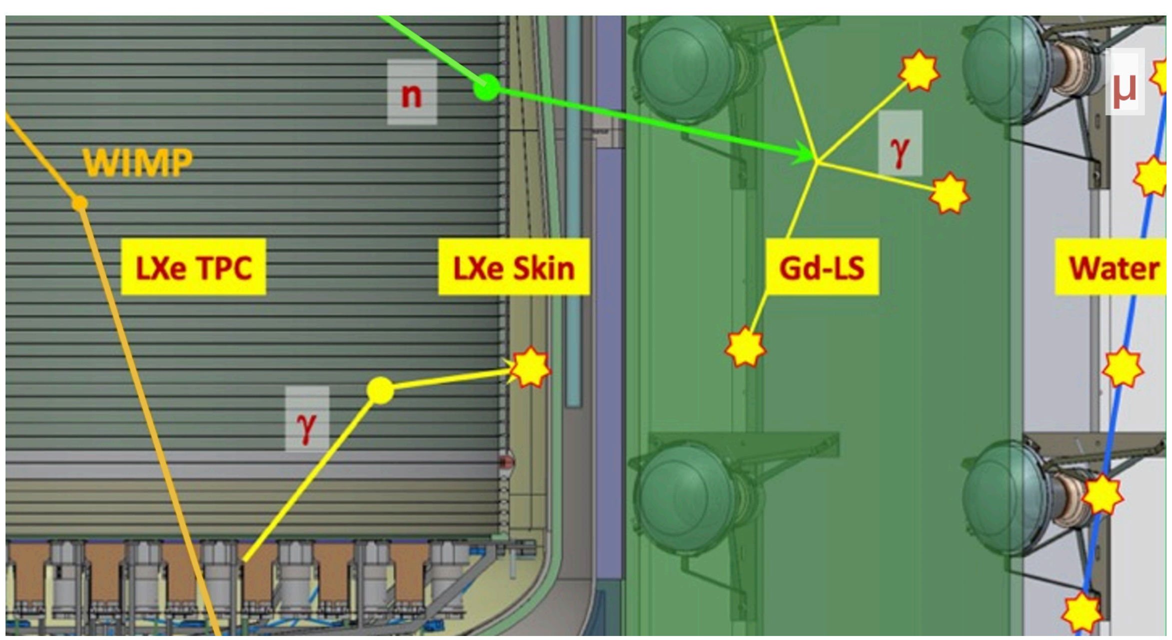
Outer Detector (OD) PMTs

Gadolinium loaded Liquid Scintillator

Active TPC Region

LXe Skin





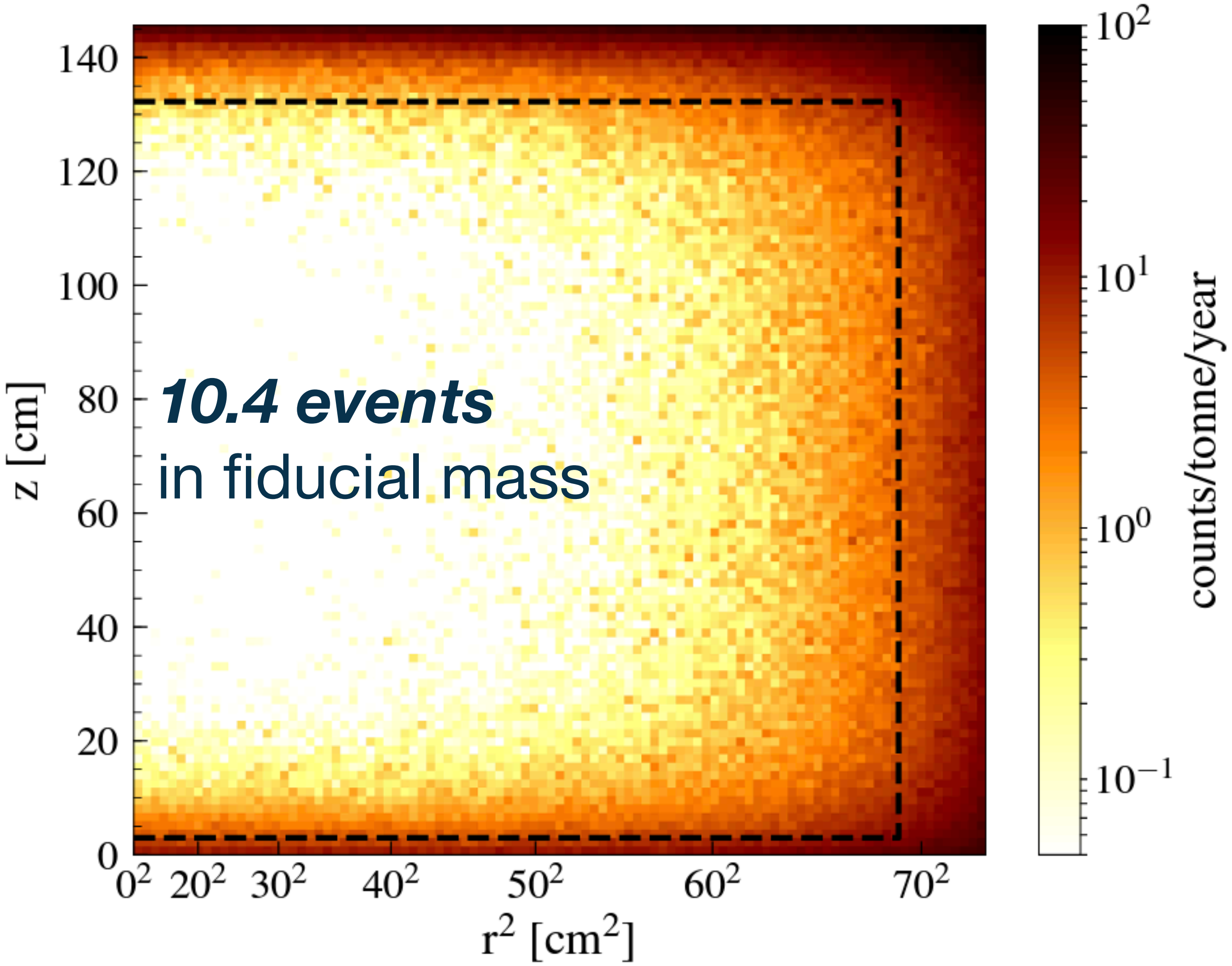
- 17 tonnes ***Gd-loaded scintillator*** in OD
  - High thermal neutron capture cross-section
  - Release of ~8 MeV γ-rays from neutron capture
- ***LXe Skin*** detector effective at tagging γ-rays from internal TPC decays, OD neutron captures

The LZ Experiment

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
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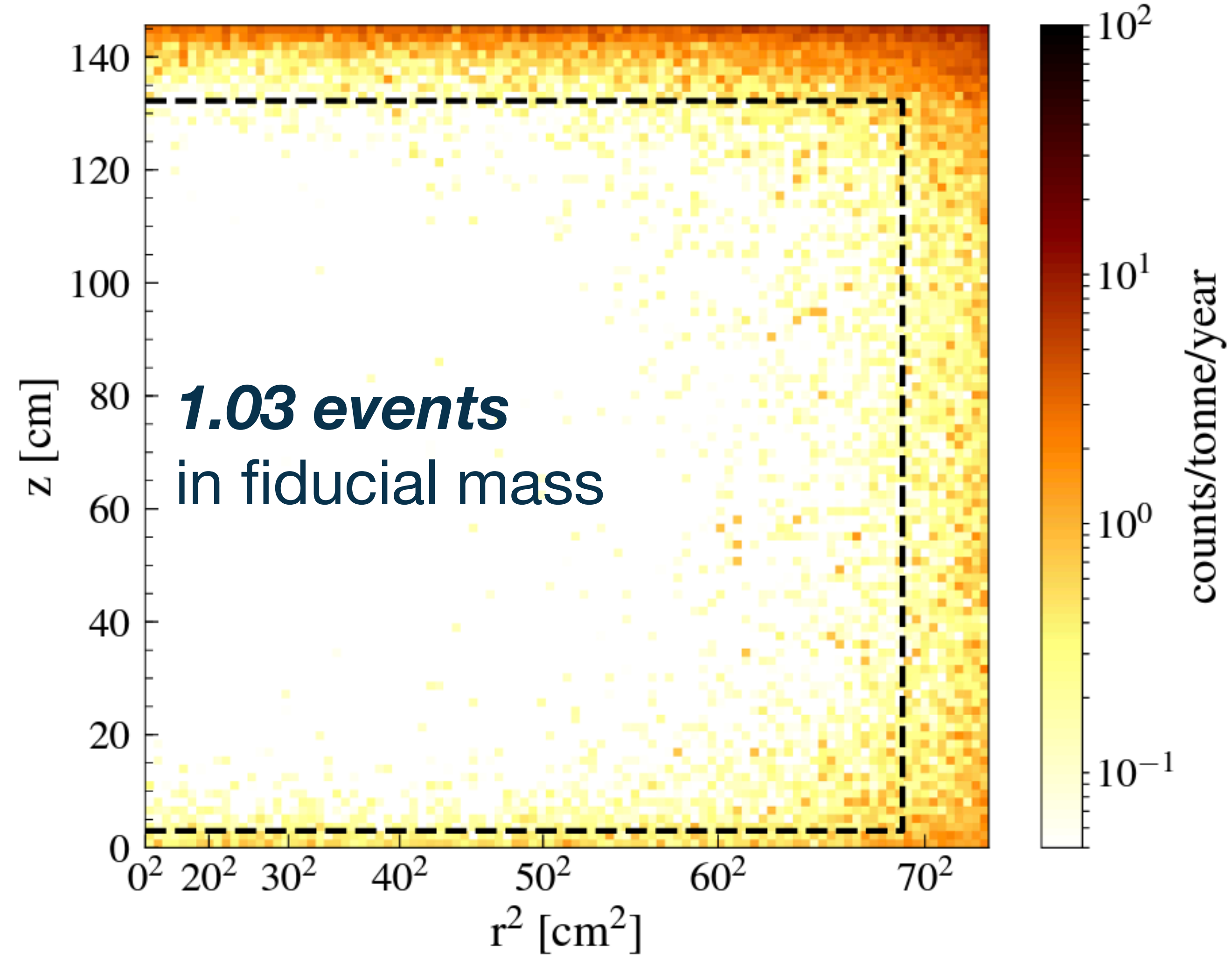


First Results (SR1)

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)

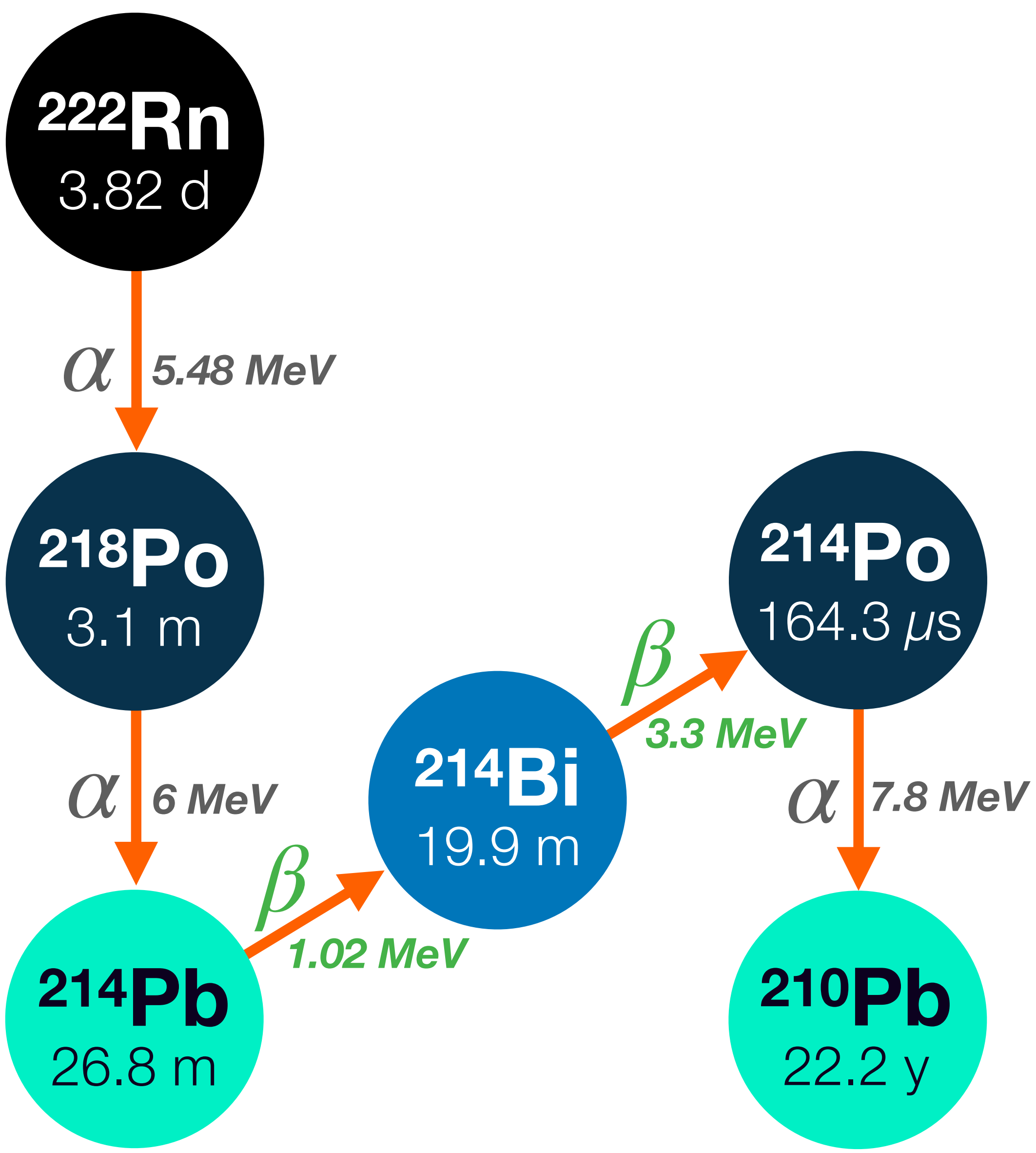
The LUX-ZEPLIN experiment is a dark matter detector centered on a dual-phase xenon time projection chamber operating at the Sanford Underground Research Facility in Lead, South Dakota, USA. This Letter reports results from LUX-ZEPLIN's first search for weakly interacting massive particles (WIMPs) with 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.

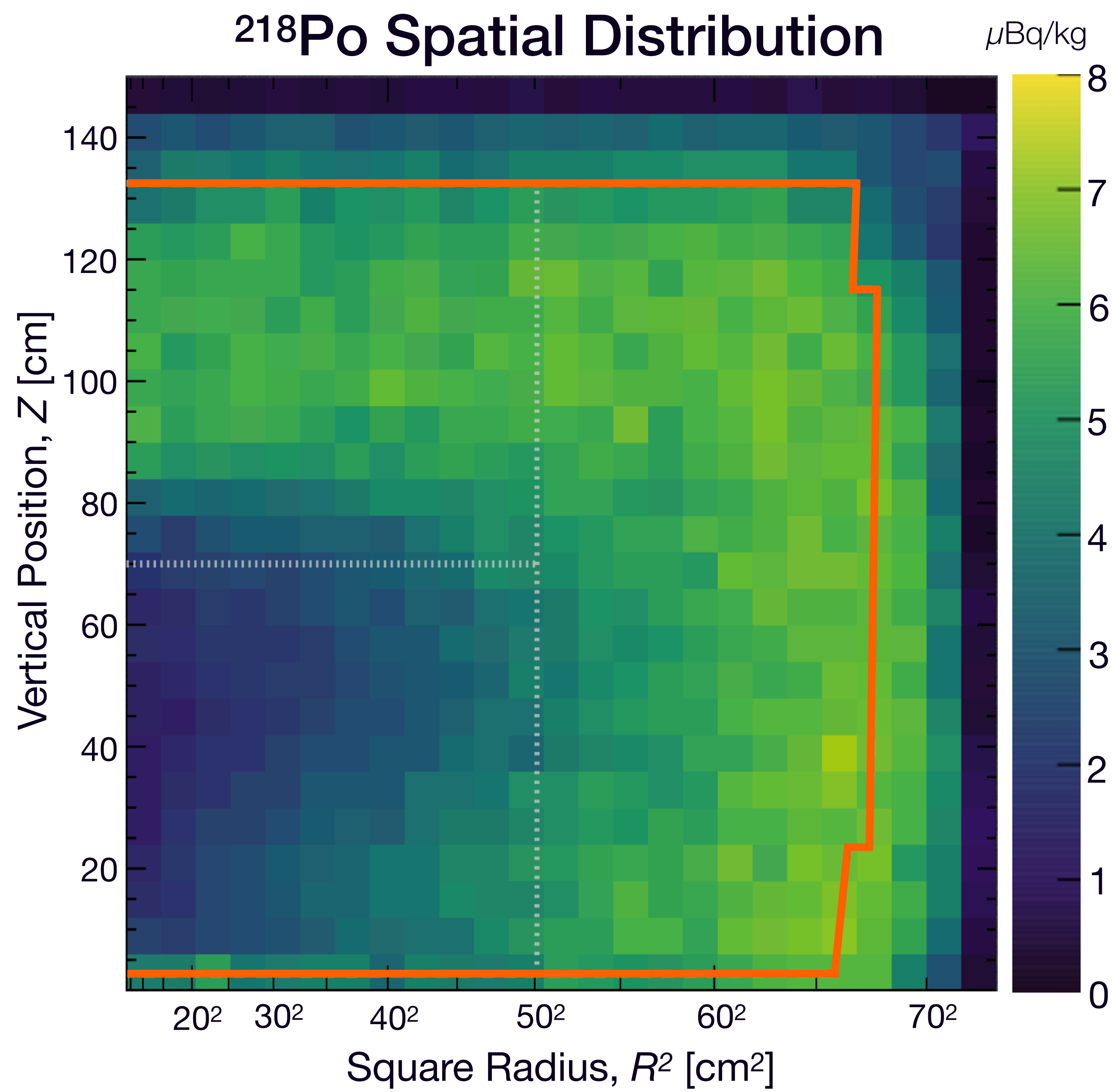
DOI: 10.1103/PhysRevLett.131.041002

SR1: Backgrounds

Radon emanates from detector materials into the xenon

Non-uniform position distribution due to xenon flow and charged ion movement





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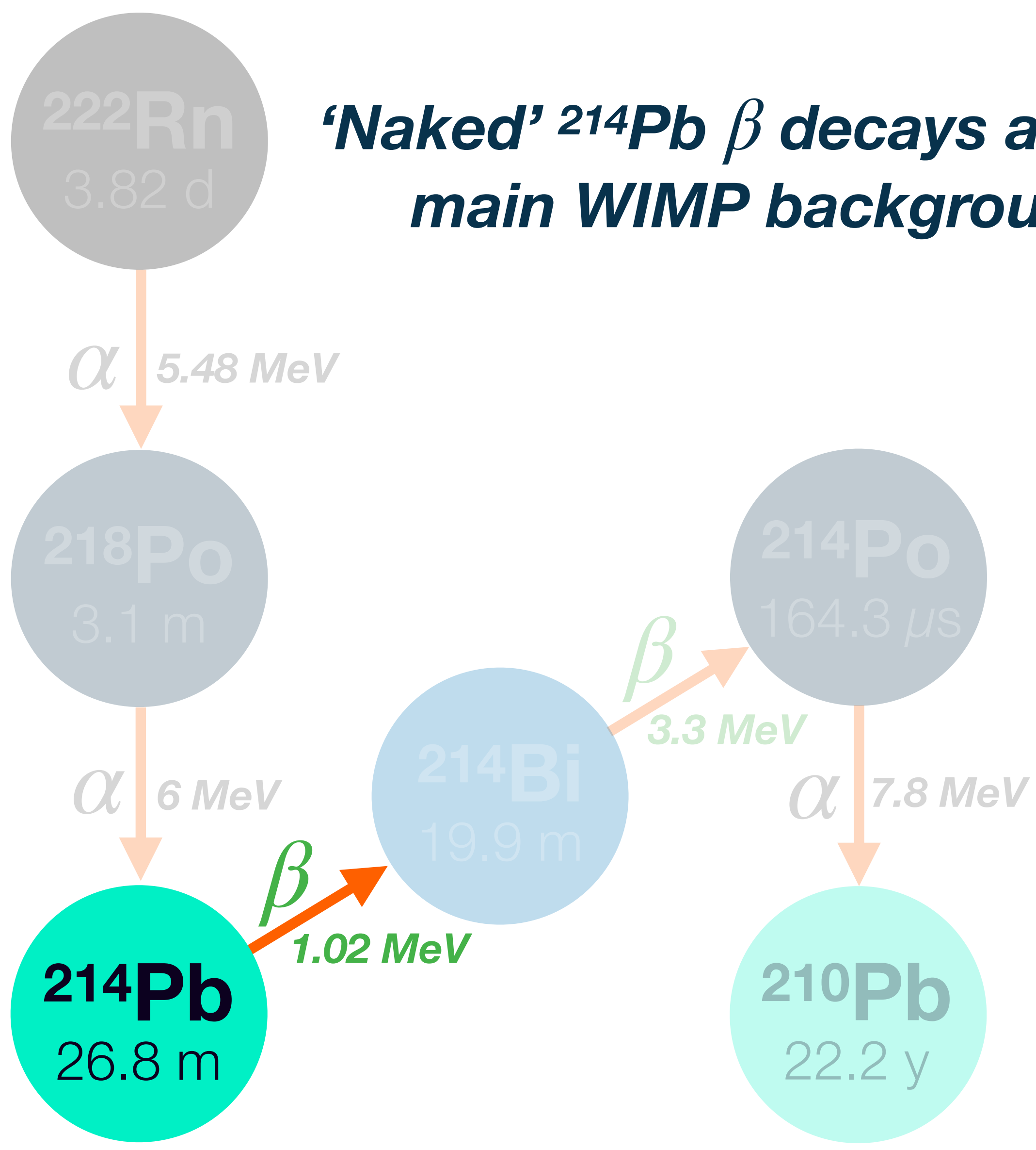
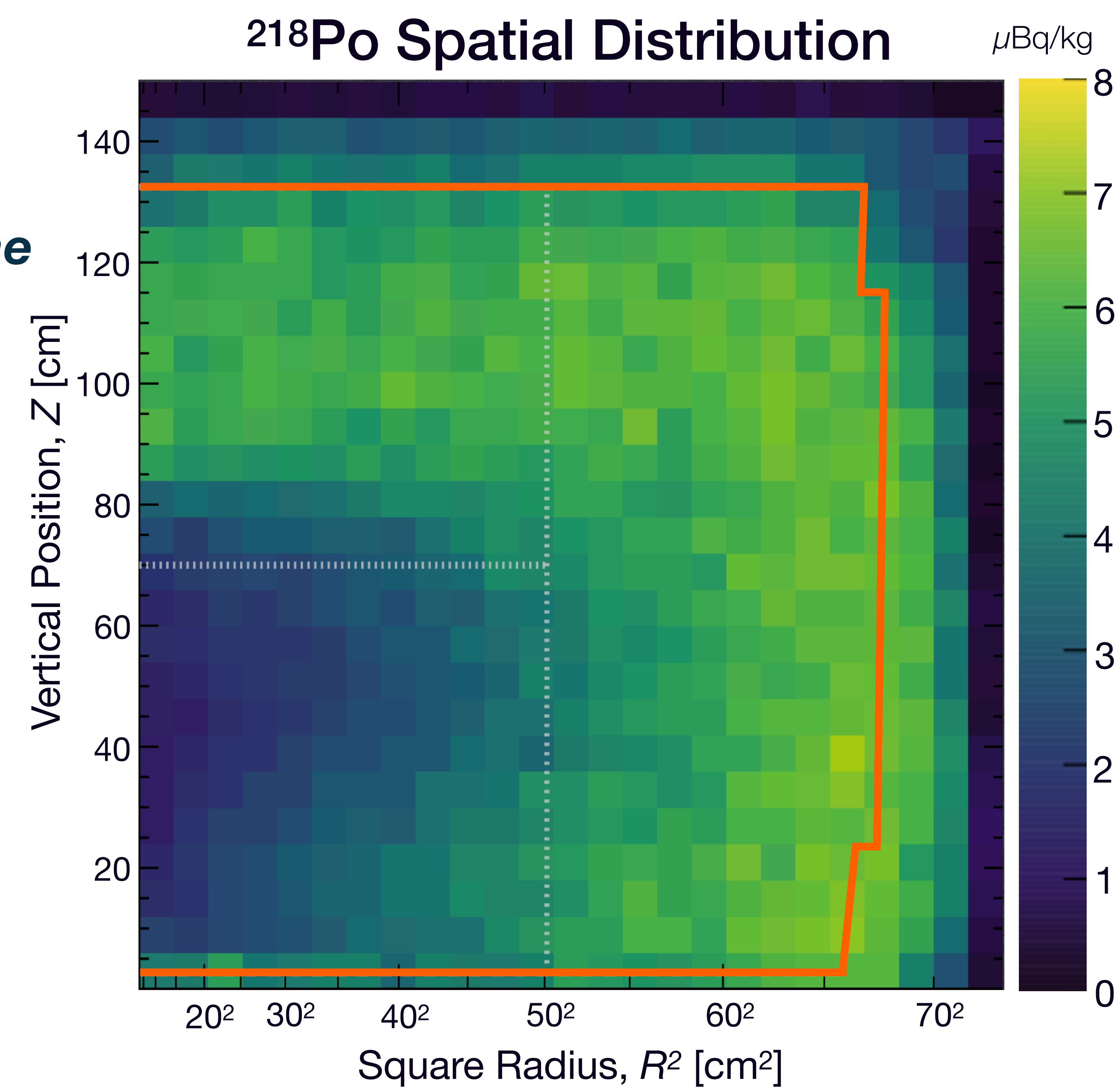
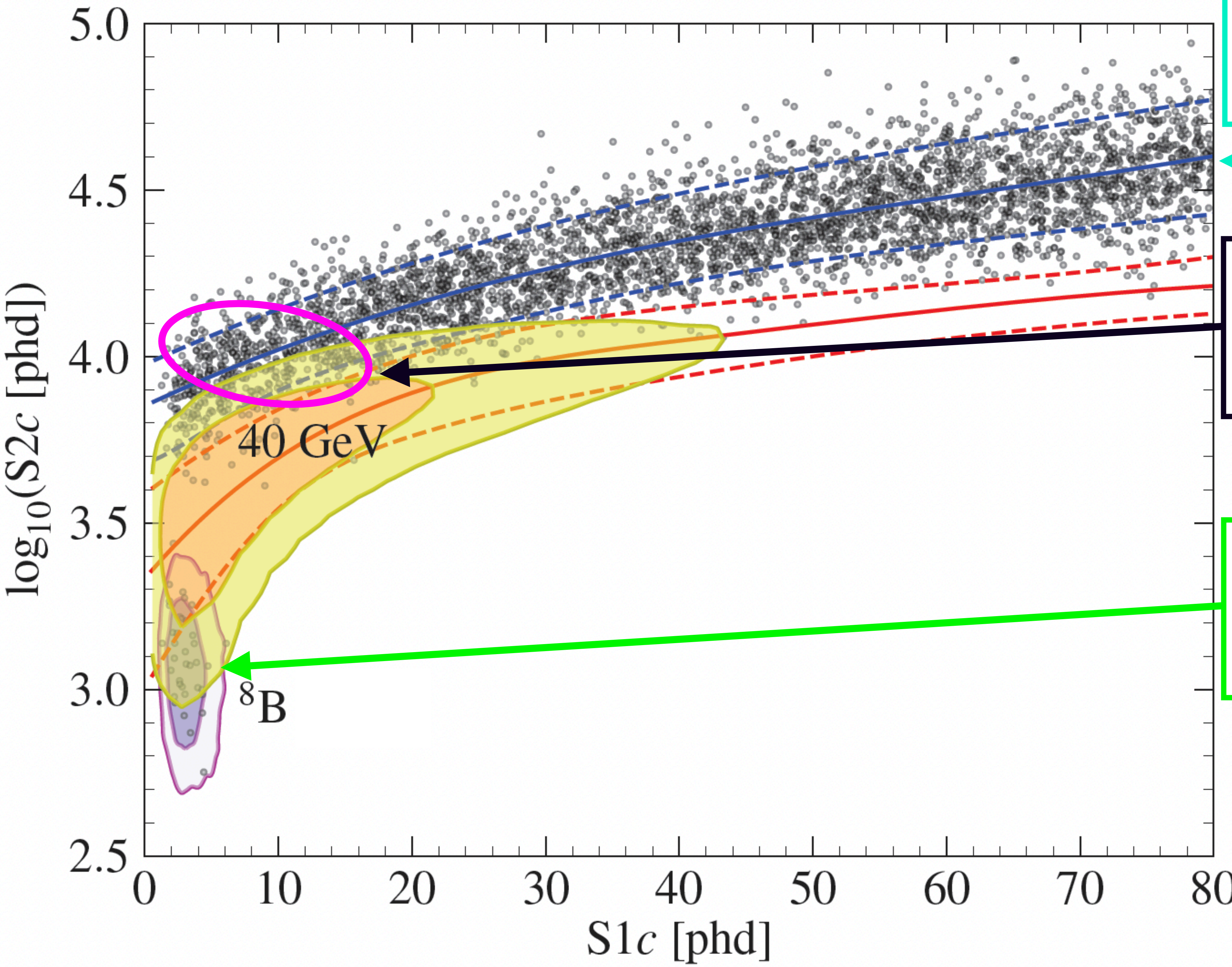


'Naked' ^{214}Pb β decays are the main WIMP background



SR1: Backgrounds

Other backgrounds considered:



^{212}Pb (β), ^{85}Kr (β), ^{124}Xe ($\varepsilon\varepsilon$), ^{136}Xe ($\beta\beta$), ^{127}Xe (ε), CC solar neutrinos…

Cosmogenically activated ^{37}Ar (ε) should live around here

Coherent elastic neutrino-neutron scattering (CEνNS) from ^{8}B solar neutrinos

SR1: Backgrounds

Accidental Coincidence Background

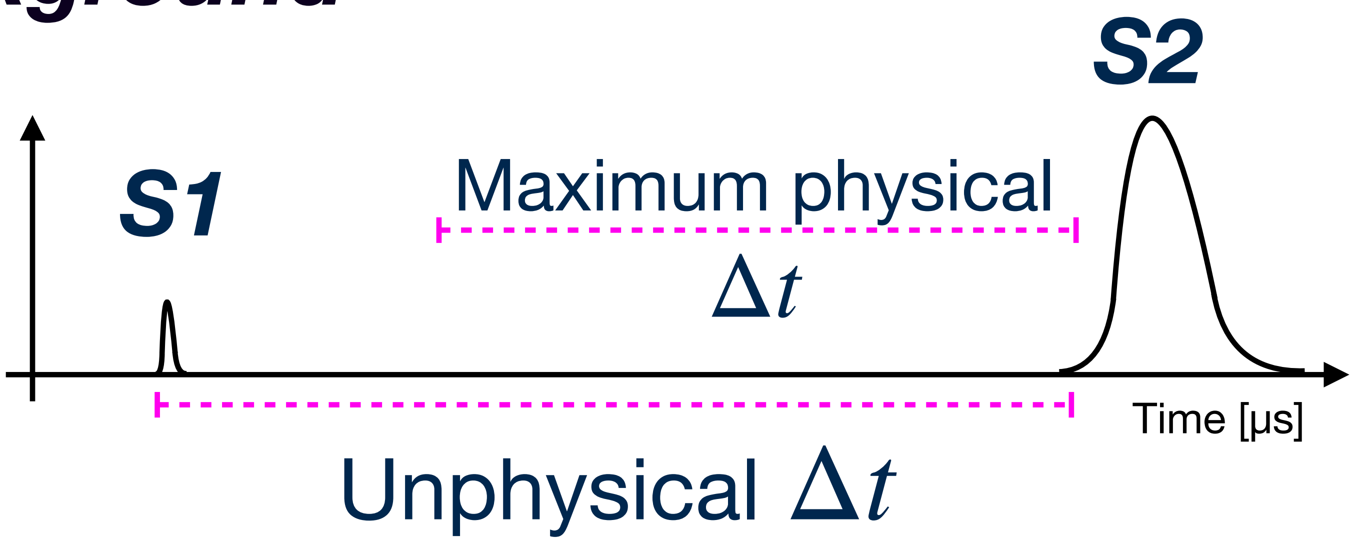
- Unrelated S1s & S2s can accidentally combine to produce single scatter events

SR1: Backgrounds

Accidental Coincidence Background

- Unrelated S1s & S2s can accidentally combine to produce single scatter events

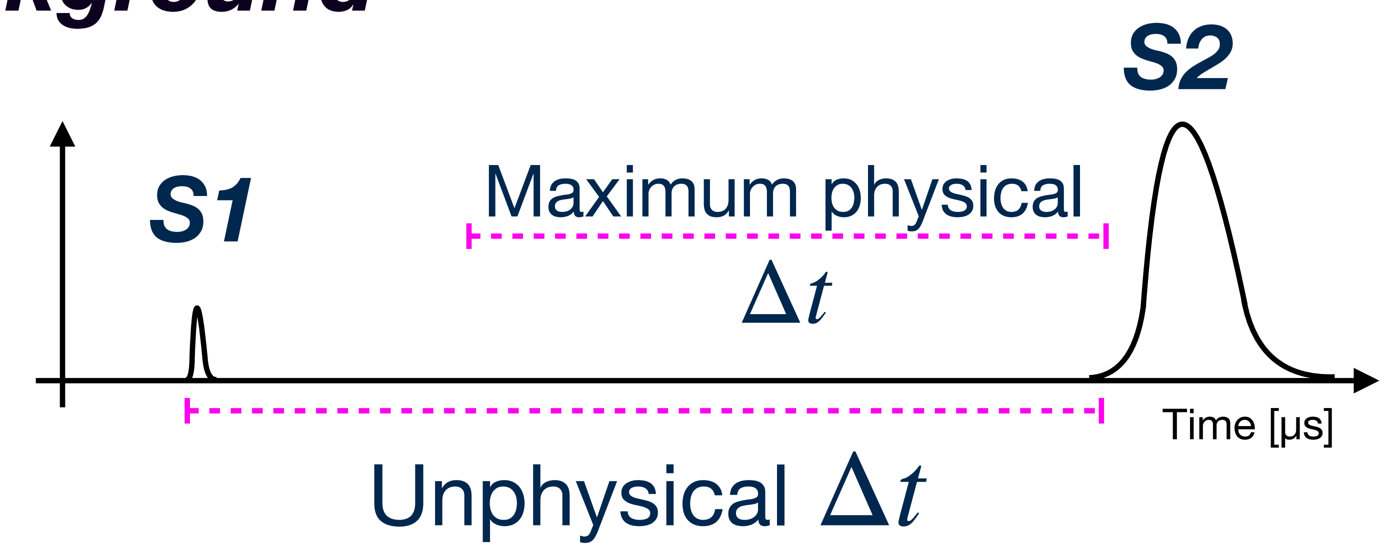
- ***Rate***: population of definite accidental events with drift time >1 ms

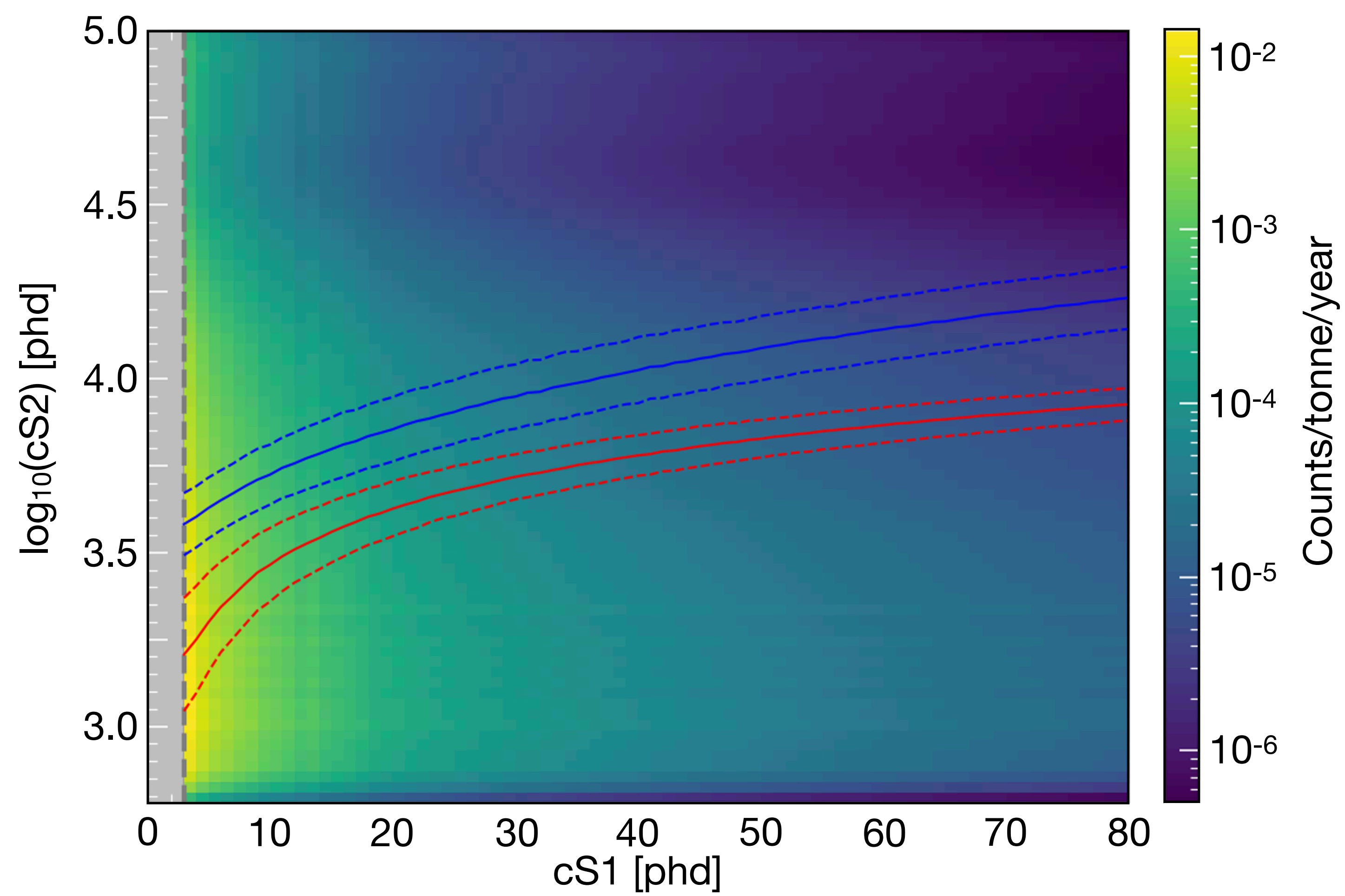


SR1: Backgrounds

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

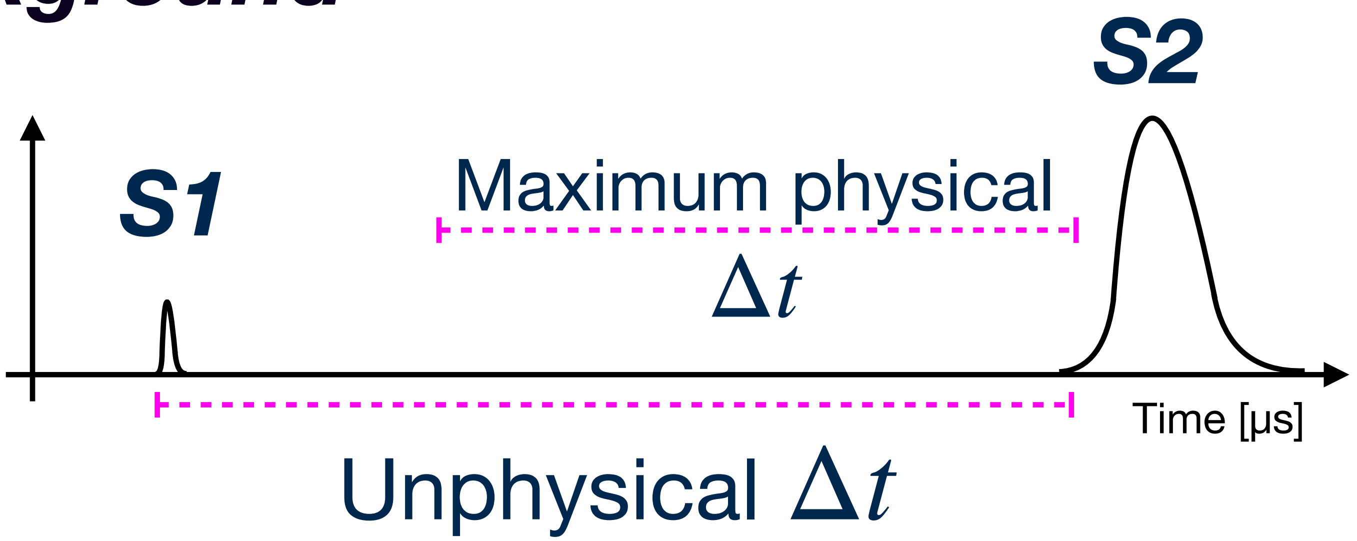


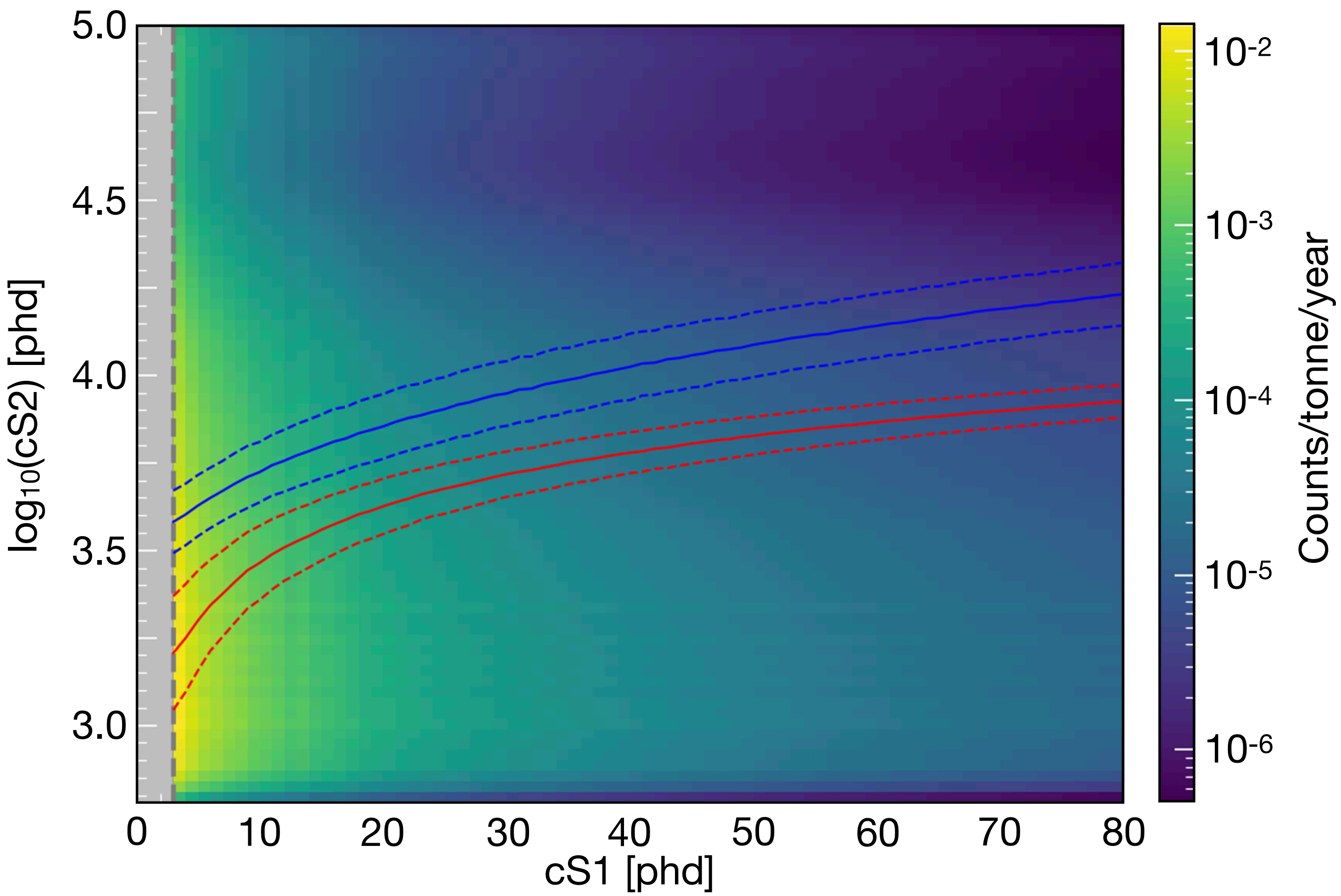


SR1: Backgrounds

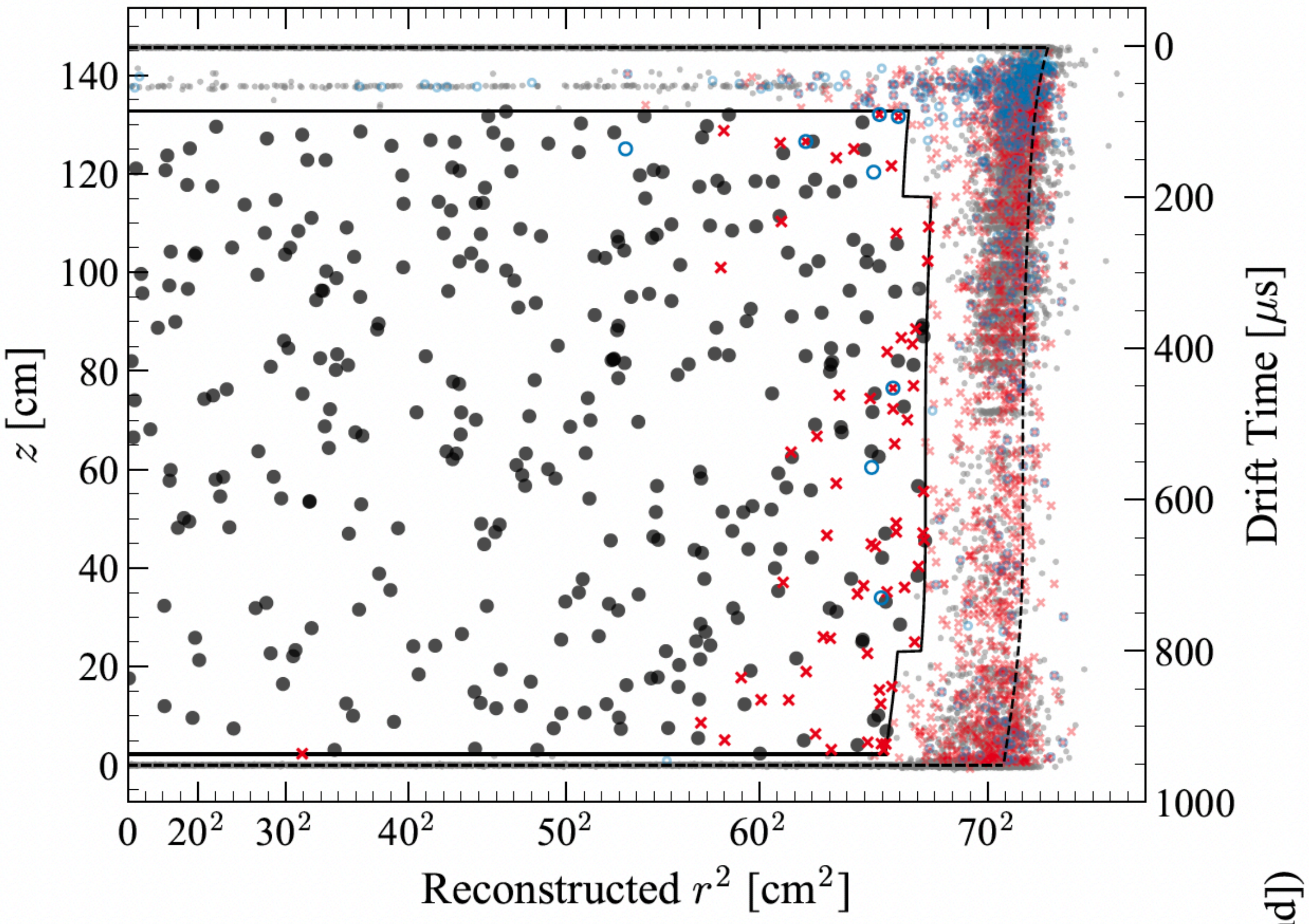
Accidental Coincidence Background

- 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

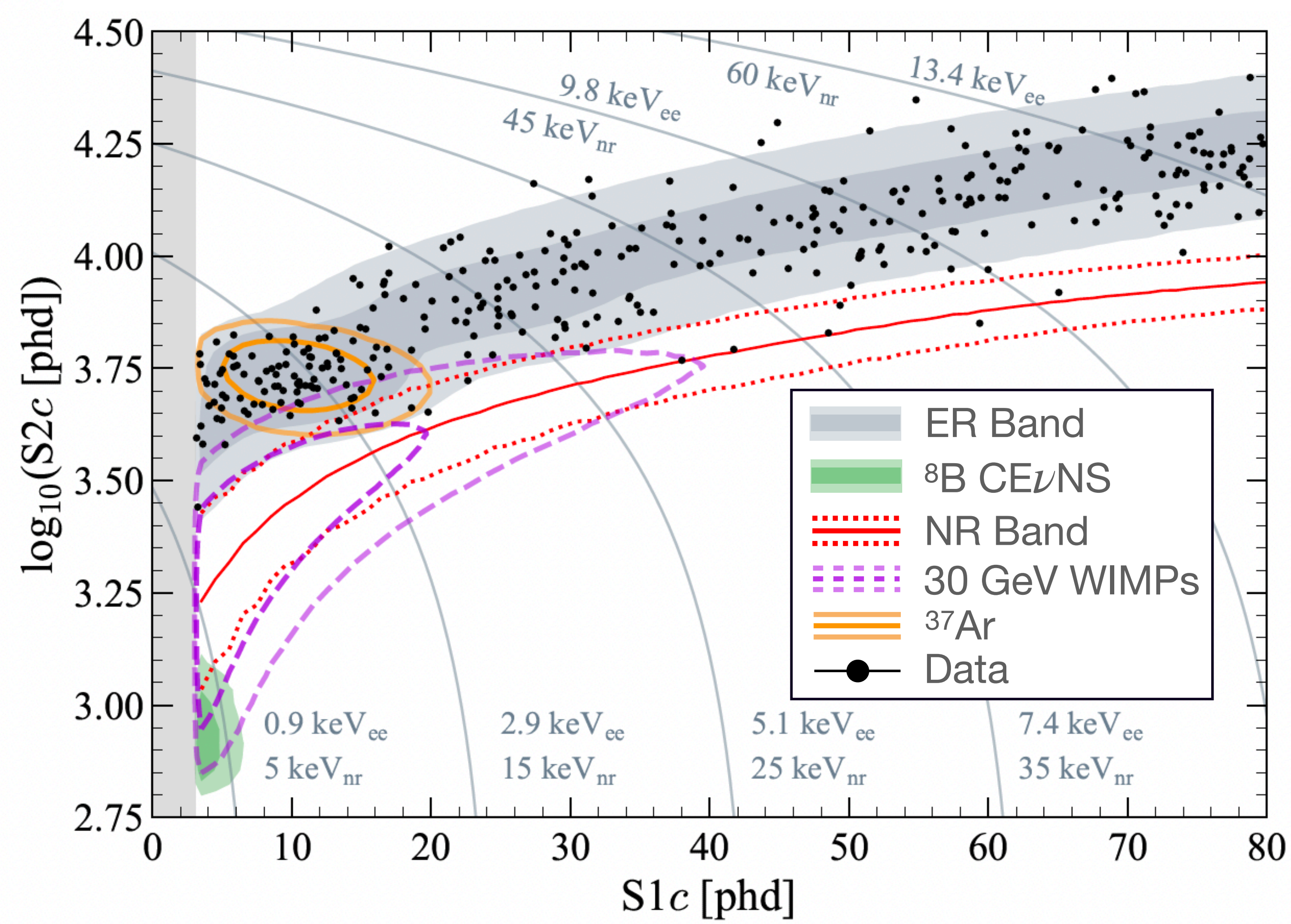




SR1: Results



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

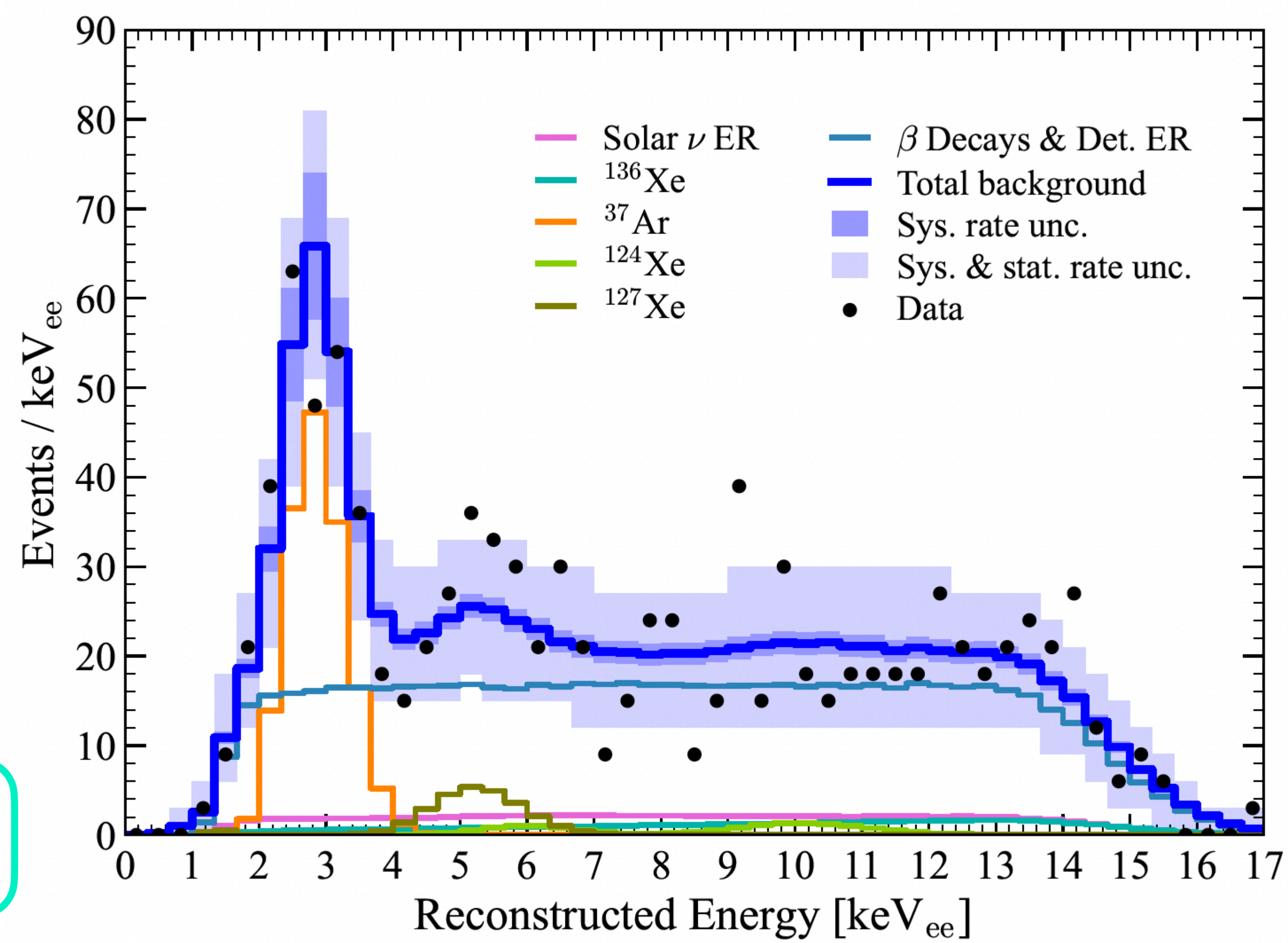


- 335 events remaining after analysis cuts
- Statistical inference with Profile Likelihood Ratio (PLR) method

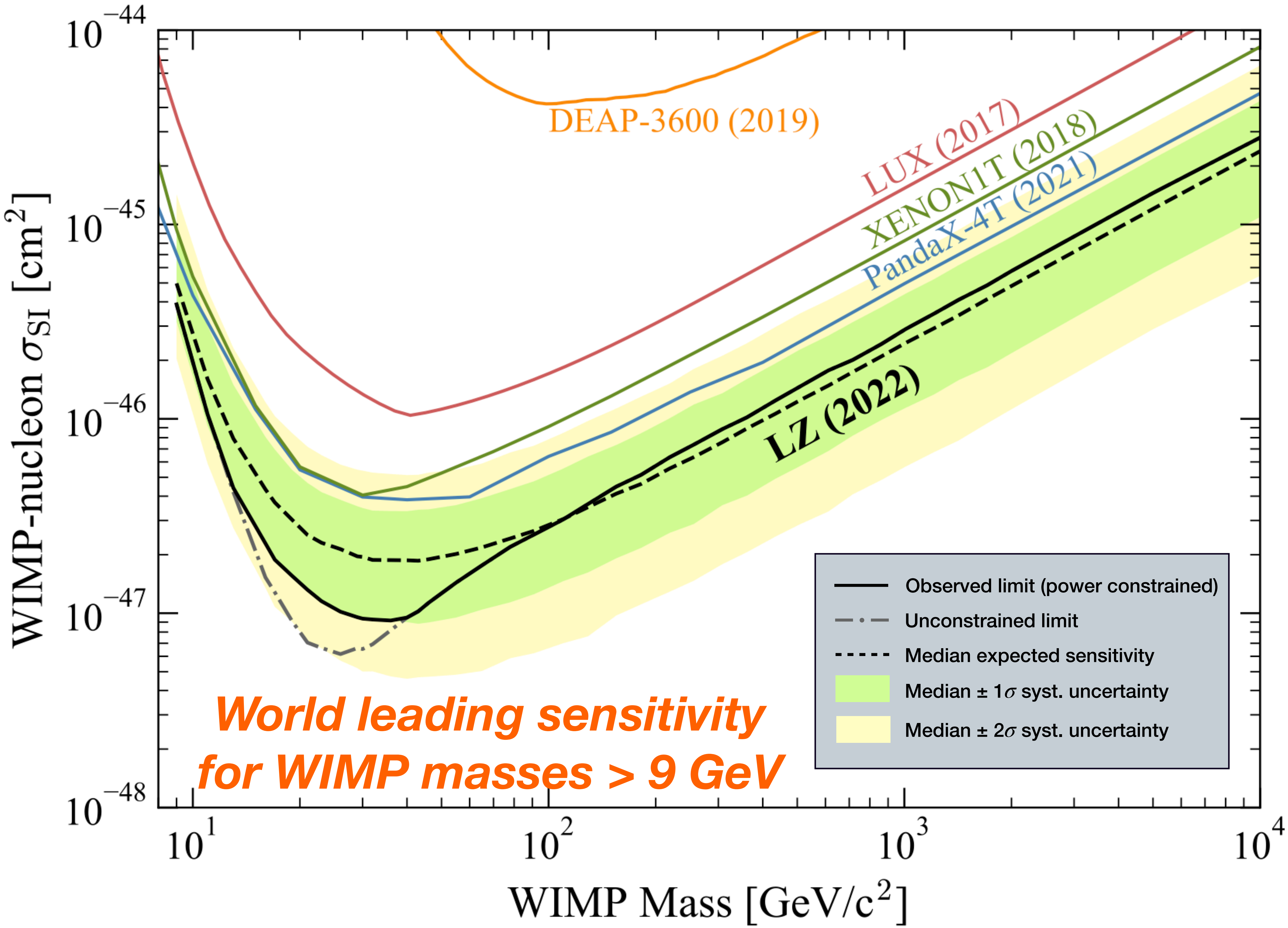
SR1: Results

Data are consistent with background-only hypothesis

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



SR1: Results



World leading sensitivity for WIMP masses > 9 GeV

joe.mclaughlin@ucl.ac.uk

Low Energy ERs

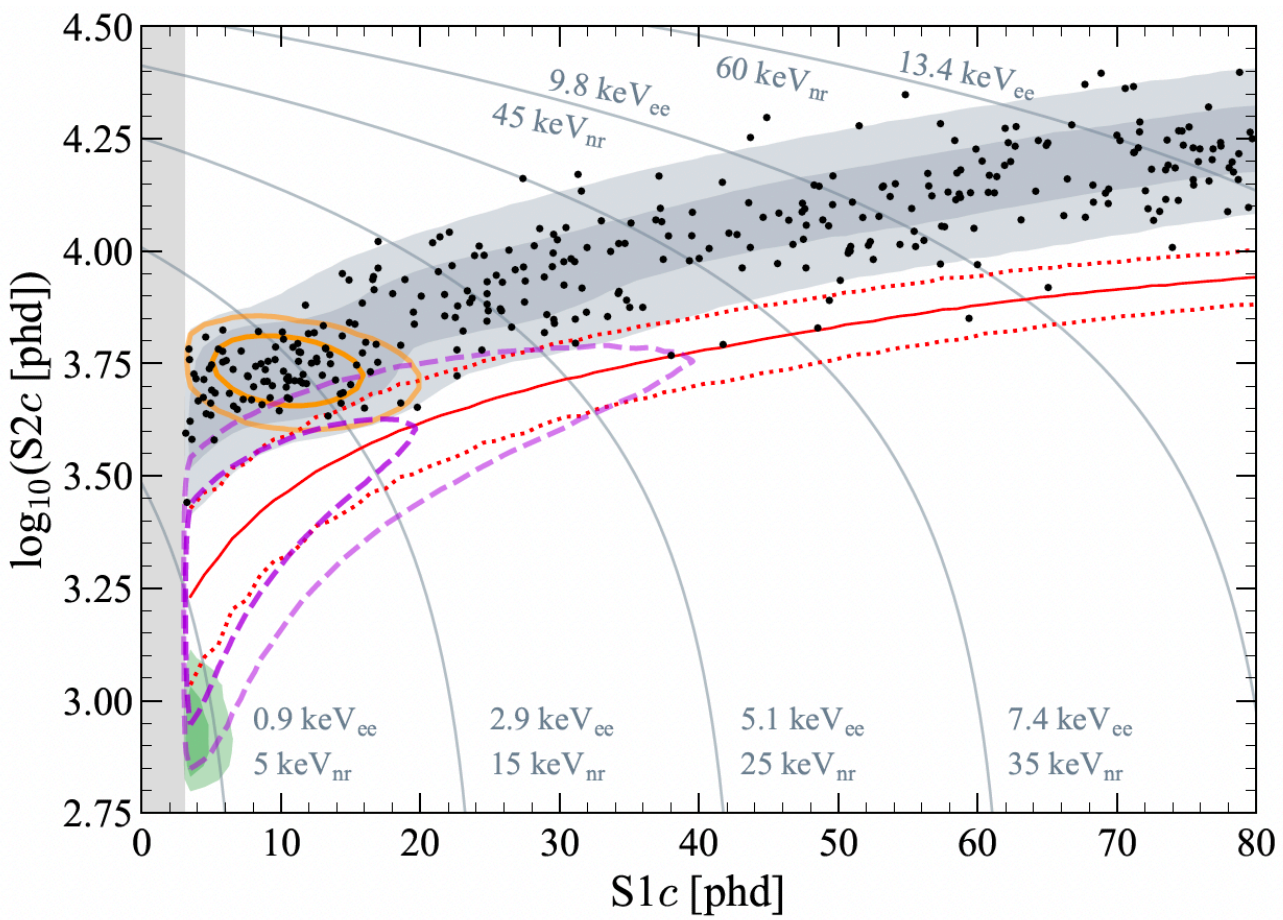
A search for new physics in low-energy electron recoils from the first LZ exposure

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]

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 axion-like 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.

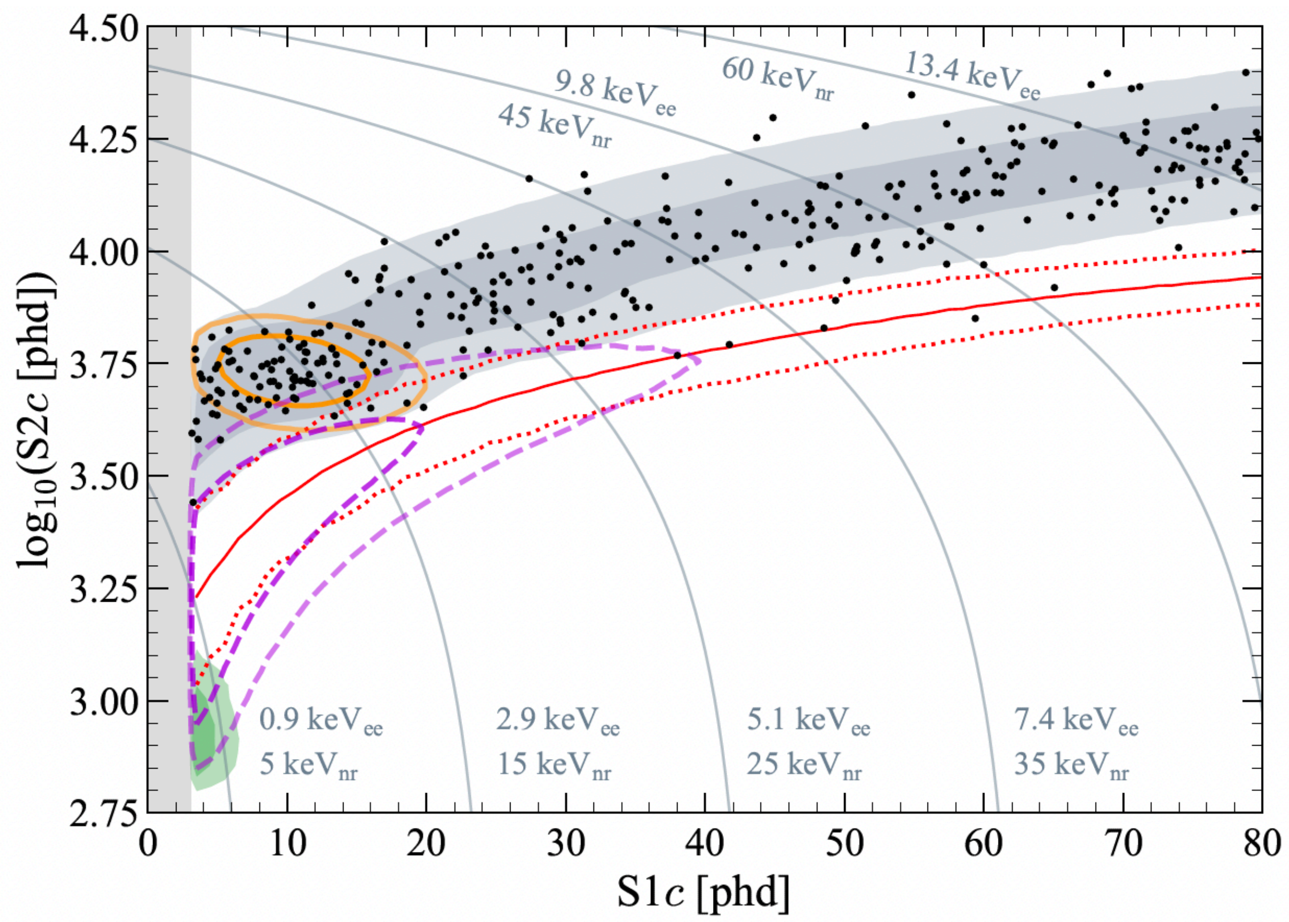
arXiv preprint: 2307.15753

Low Energy ERs

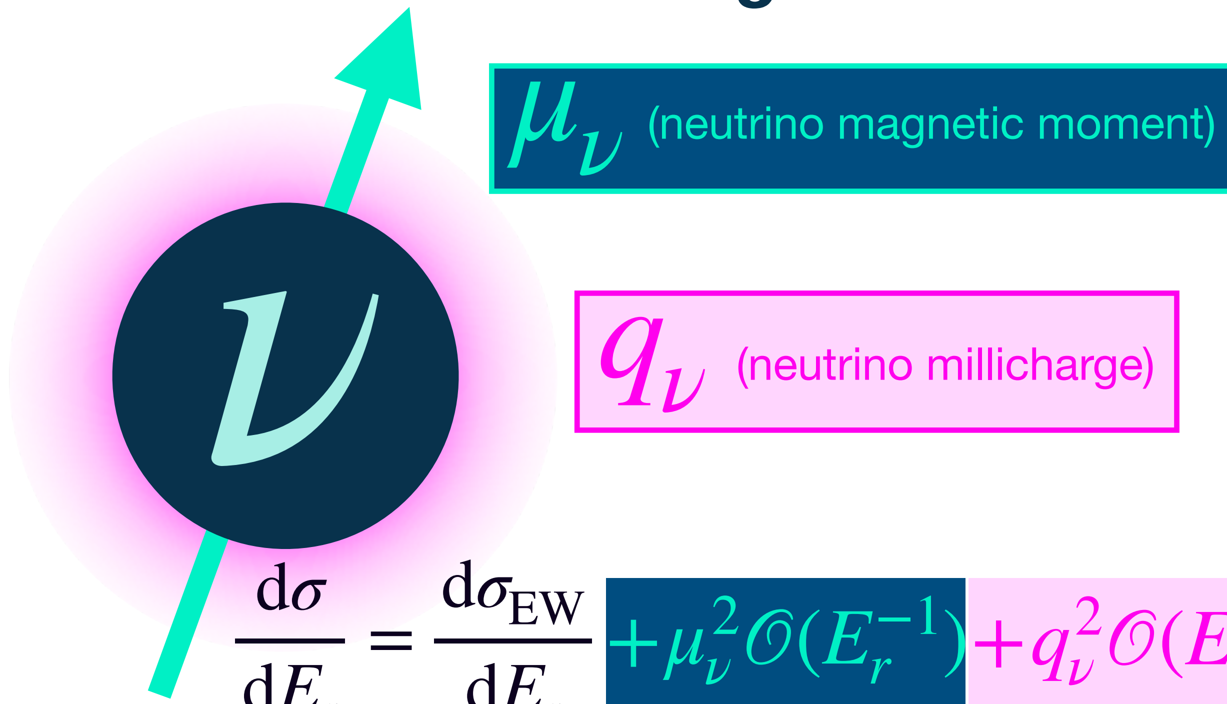


Anything interesting happening here?

Low Energy ERs

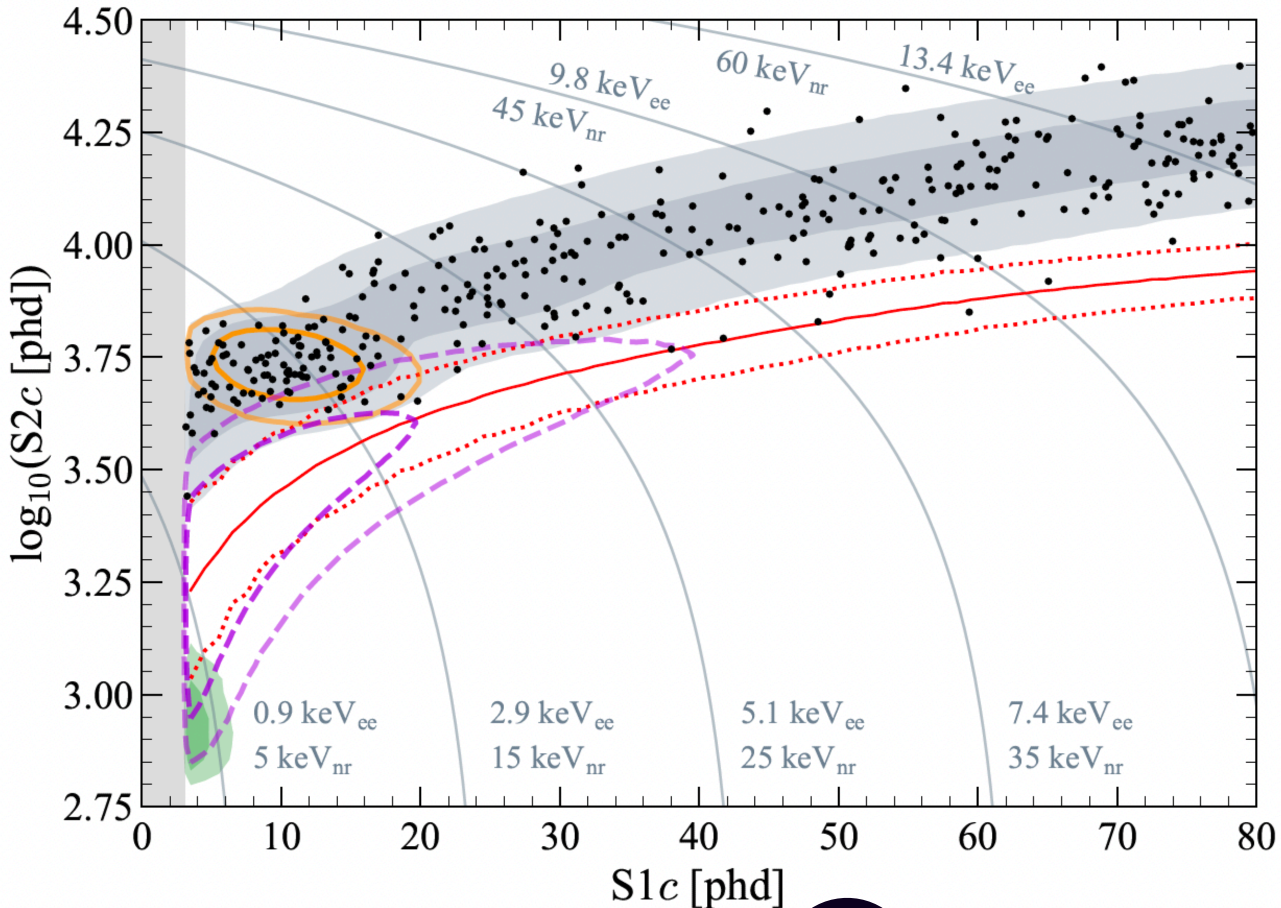


Neutrino Electromagnetic Moments

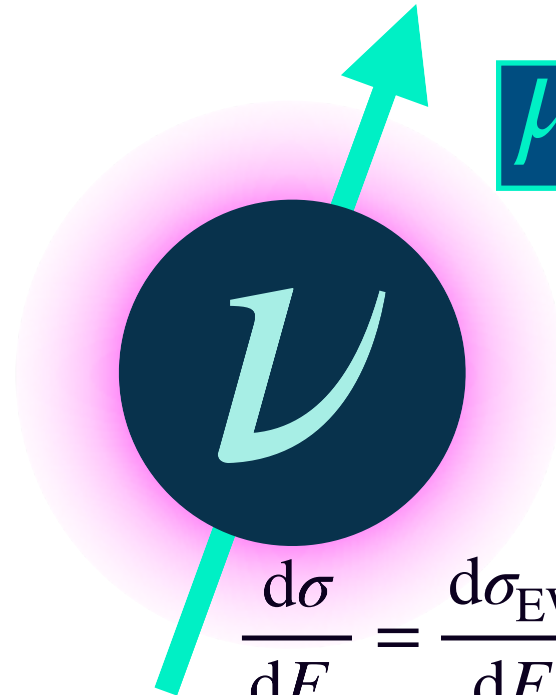


$$\frac{d\sigma}{dE_r} = \frac{d\sigma_{EW}}{dE_r} + \mu_\nu^2 \mathcal{O}(E_r^{-1}) + q_\nu^2 \mathcal{O}(E_r^{-2})$$

Low Energy ERs



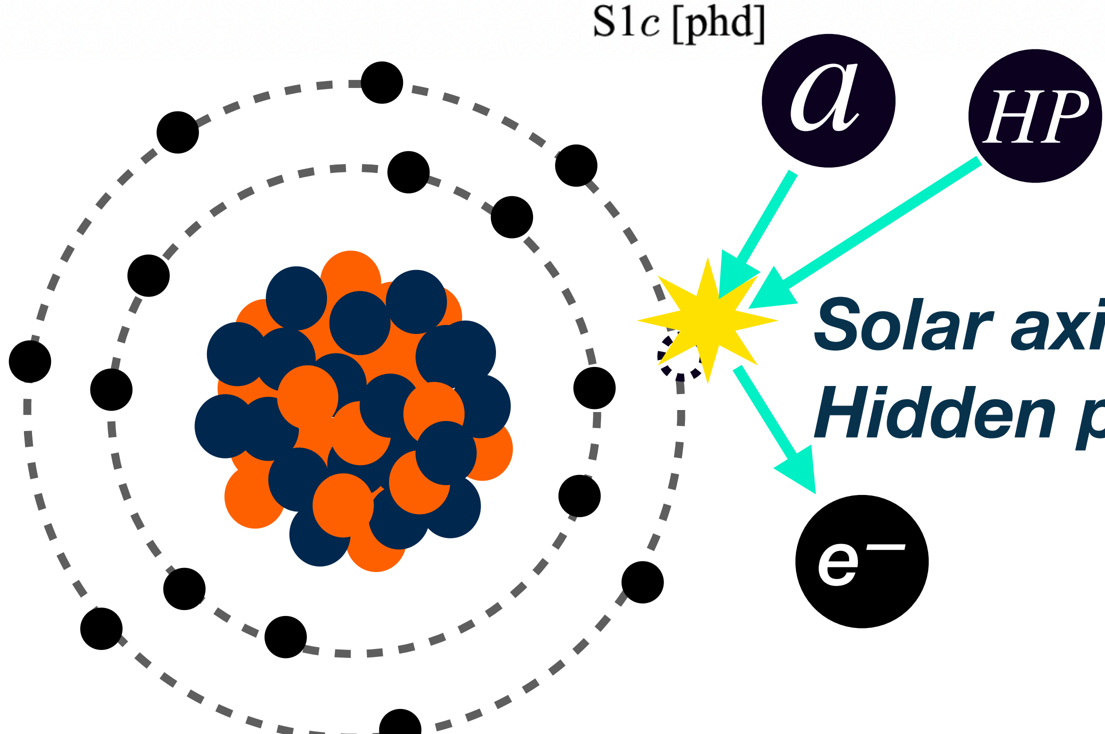
Neutrino Electromagnetic Moments



μ_ν (neutrino magnetic moment)

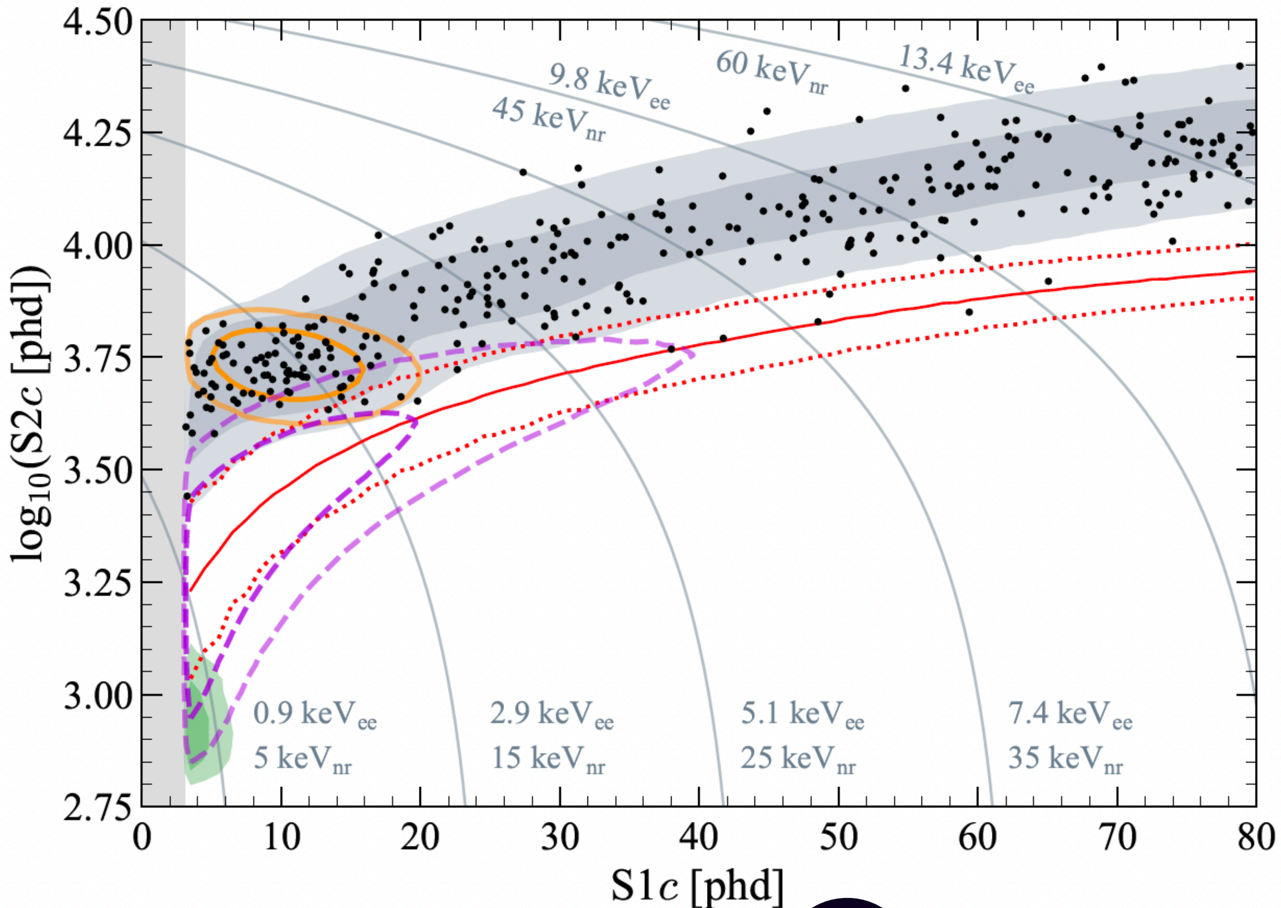
q_ν (neutrino millicharge)

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

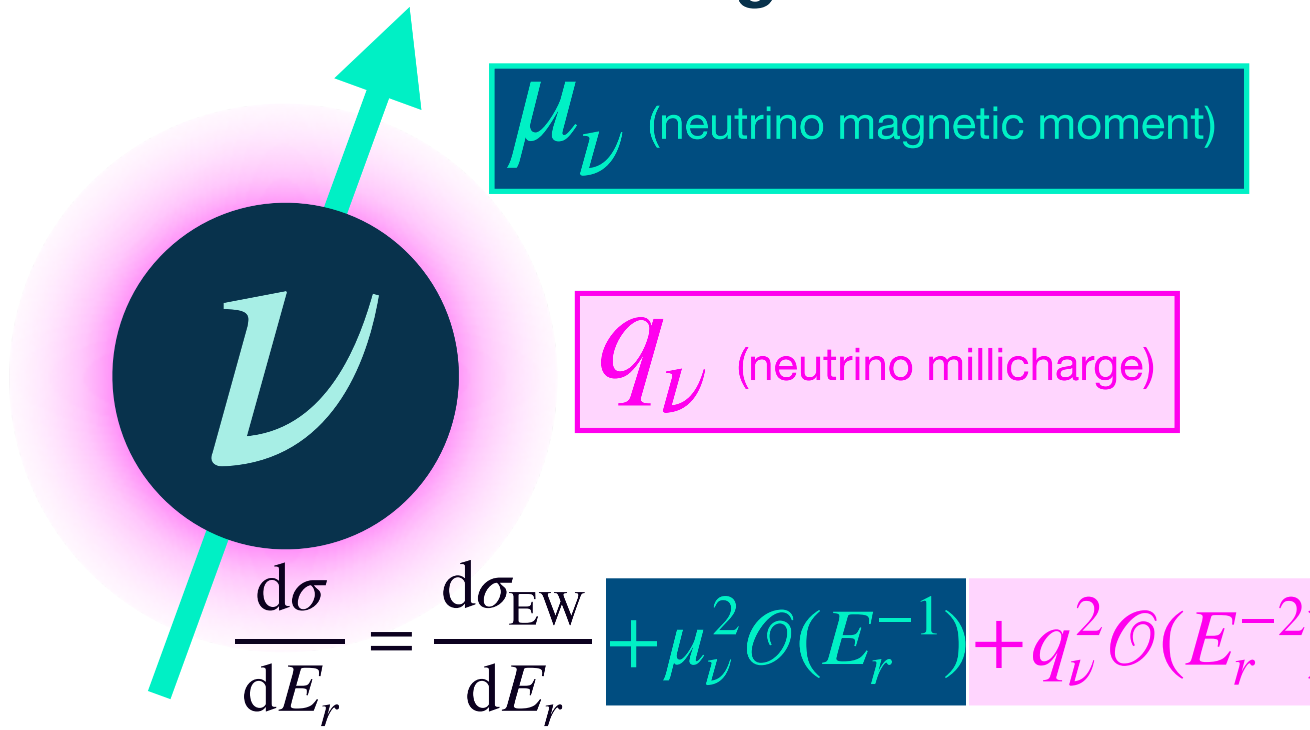


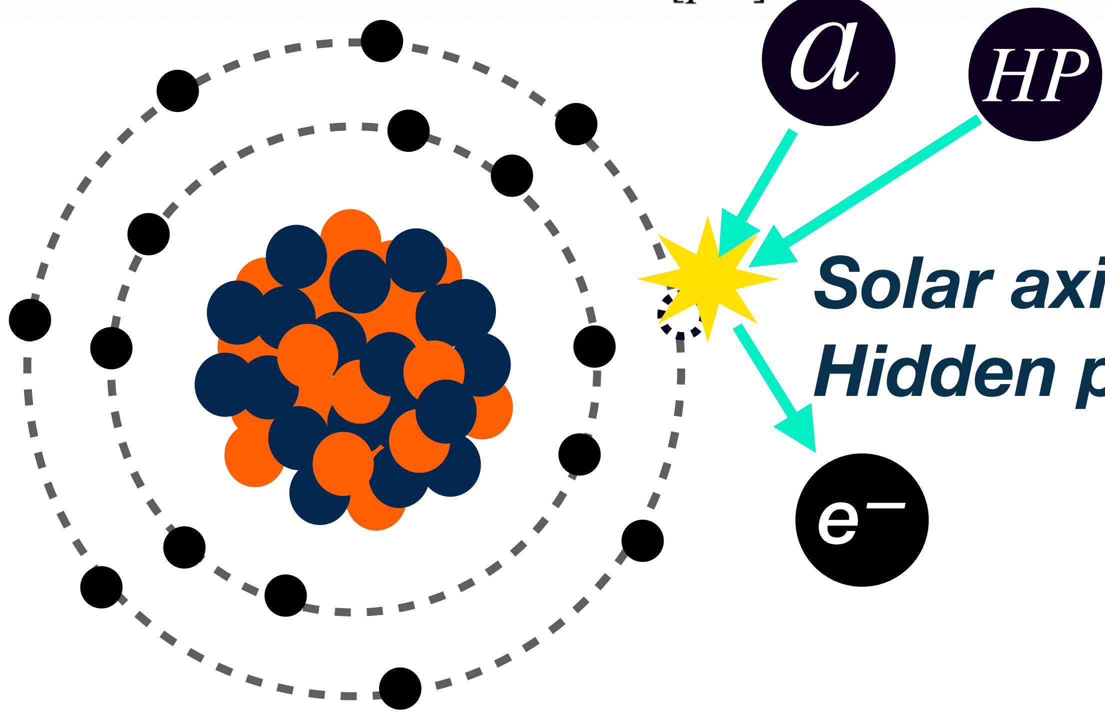
Solar axions/ALPs
Hidden photons

Low Energy ERs



Neutrino Electromagnetic Moments





Solar axions/ALPs
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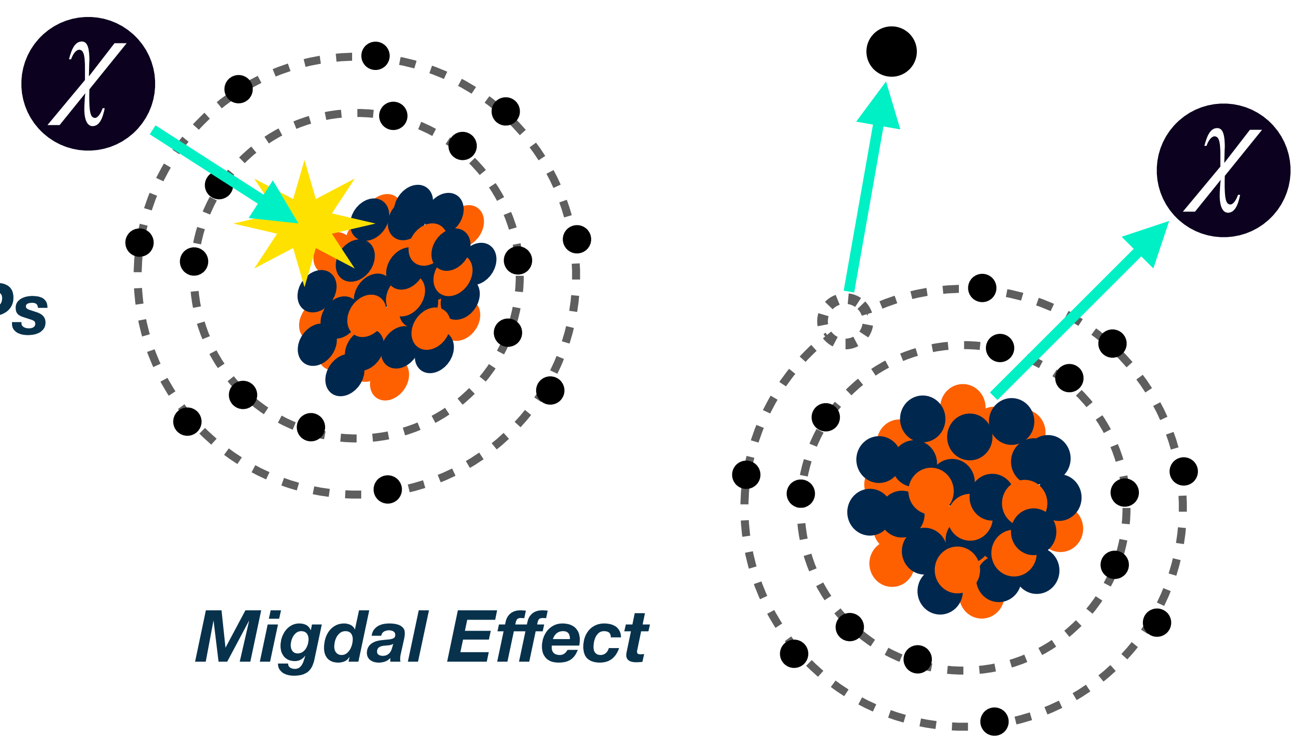
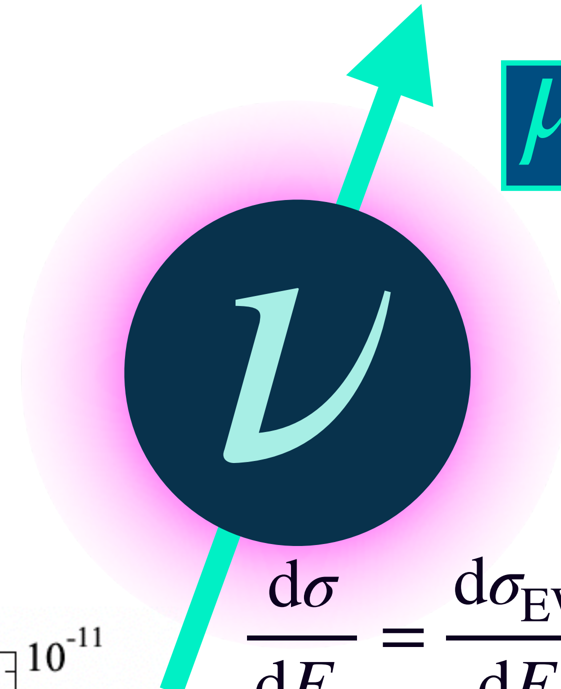


Migdal Effect

Low Energy ERs

Neutrino Electromagnetic Moments



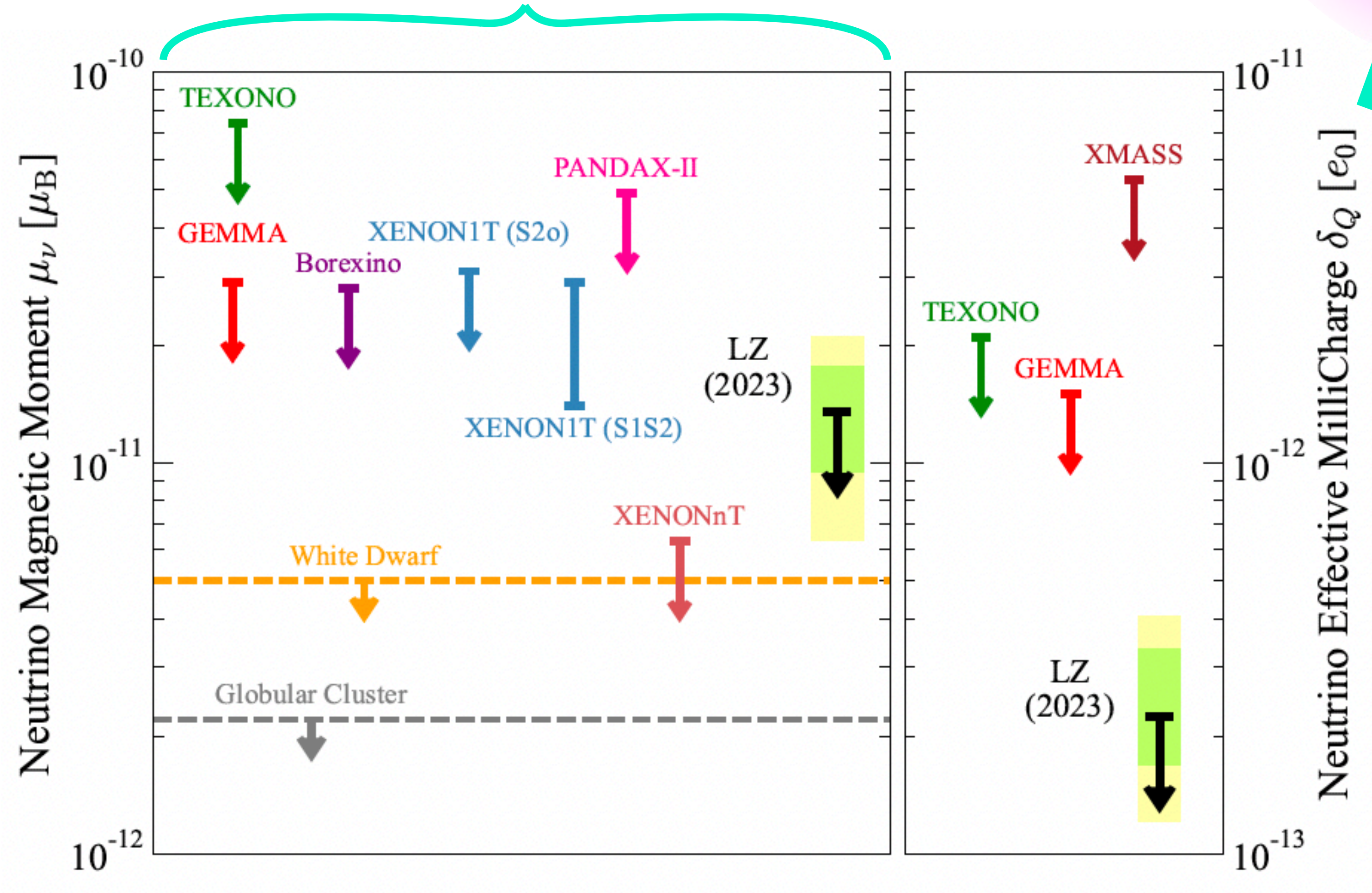
μ_ν (neutrino magnetic moment)

q_ν (neutrino millicharge)

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

Neutrino magnetic moment most stringently constrained by astrophysical observations

LZ upper limit: 1.36 × 10^{-11} μ_B



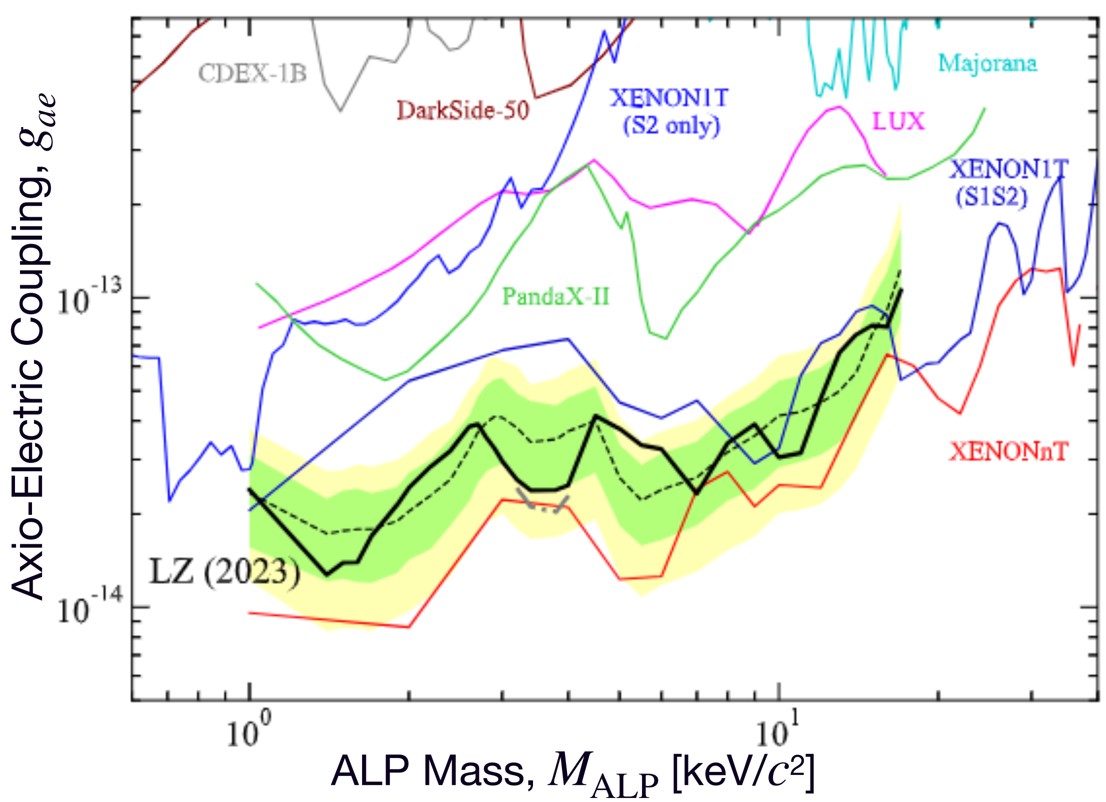
Leading neutrino millicharge observed

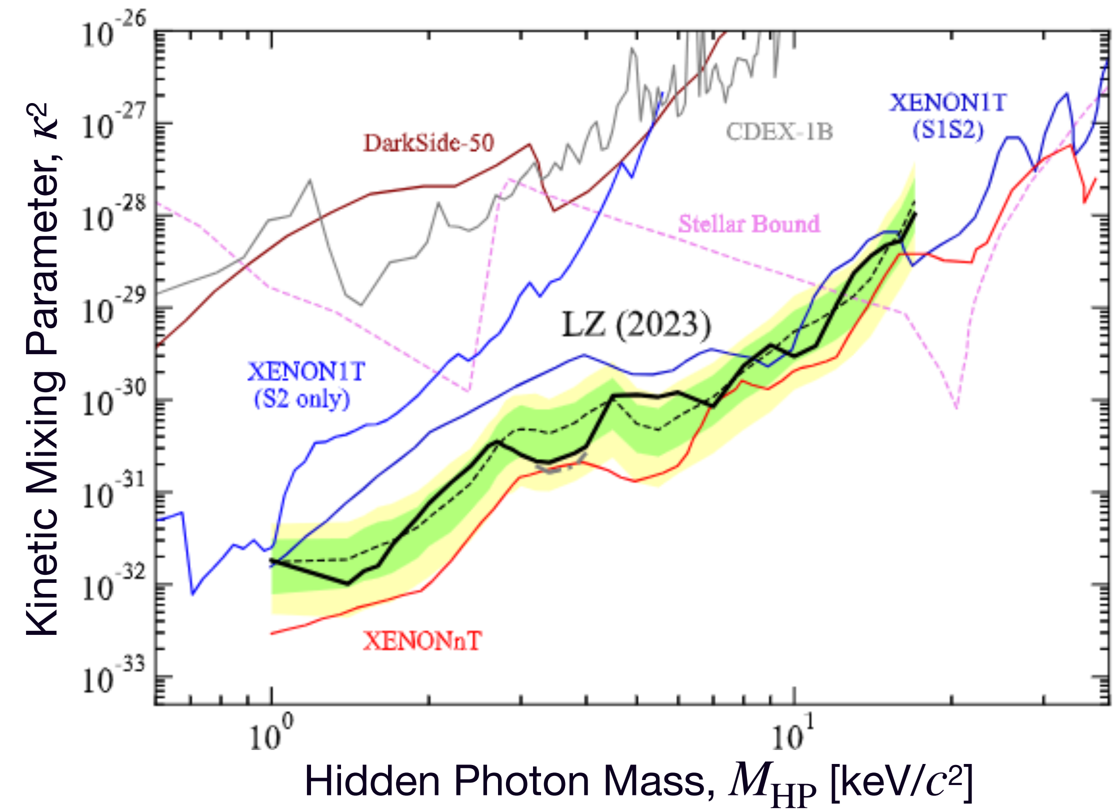
LZ upper limit: 2.24 × 10^{-13} e_0

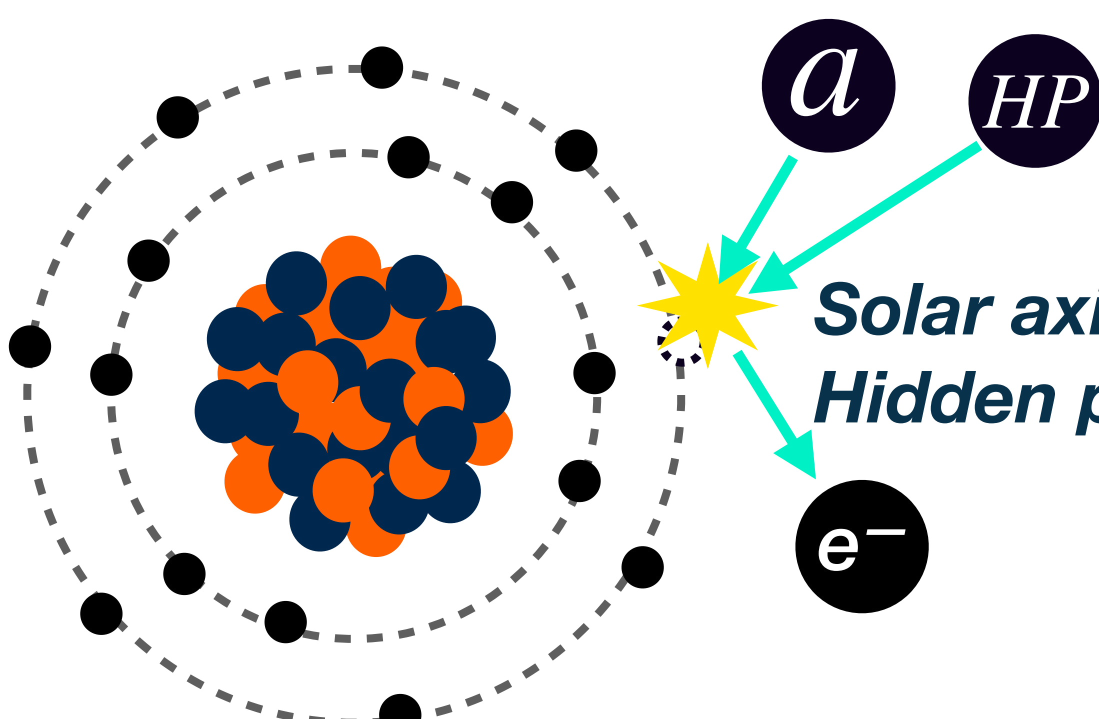
e_0 ≡ ***electron charge***

μ_B ≡ ***Bohr magneton***

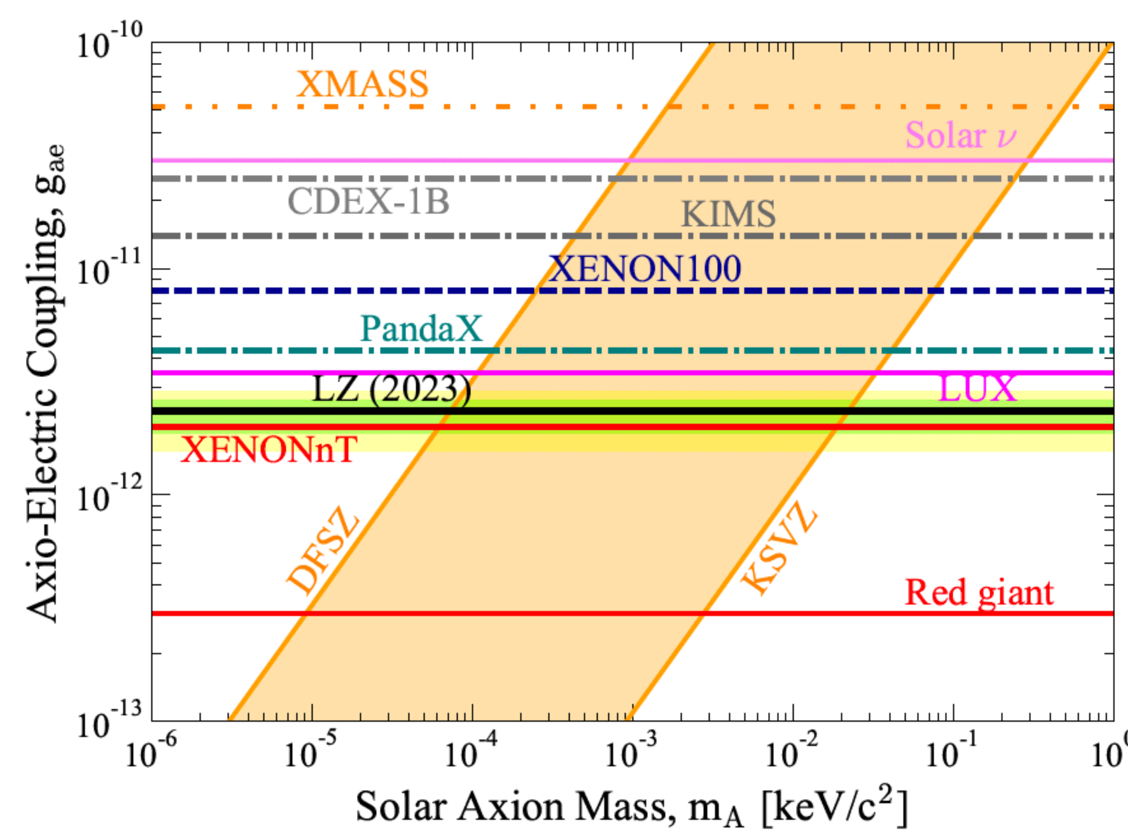
Low Energy ERs



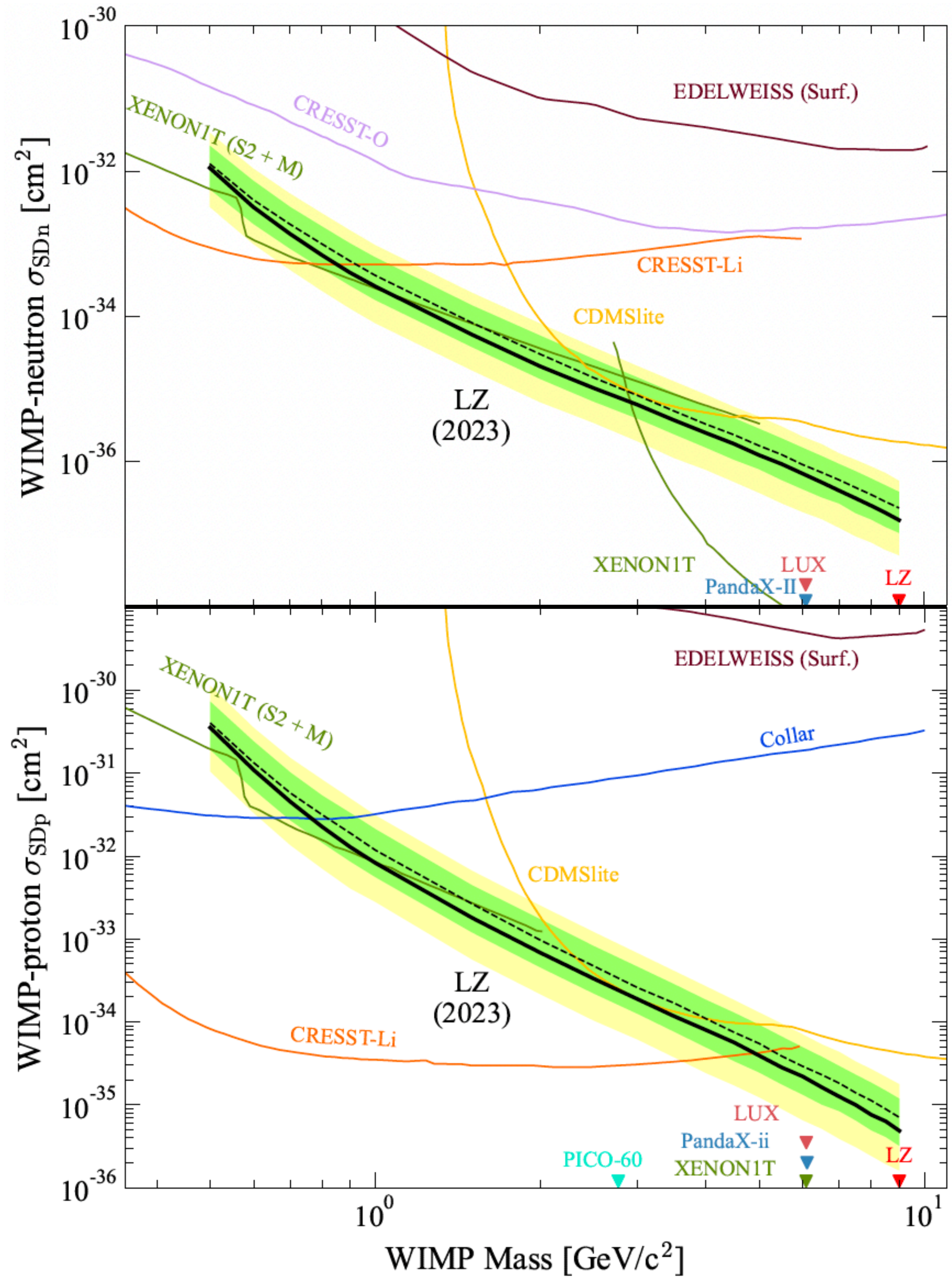


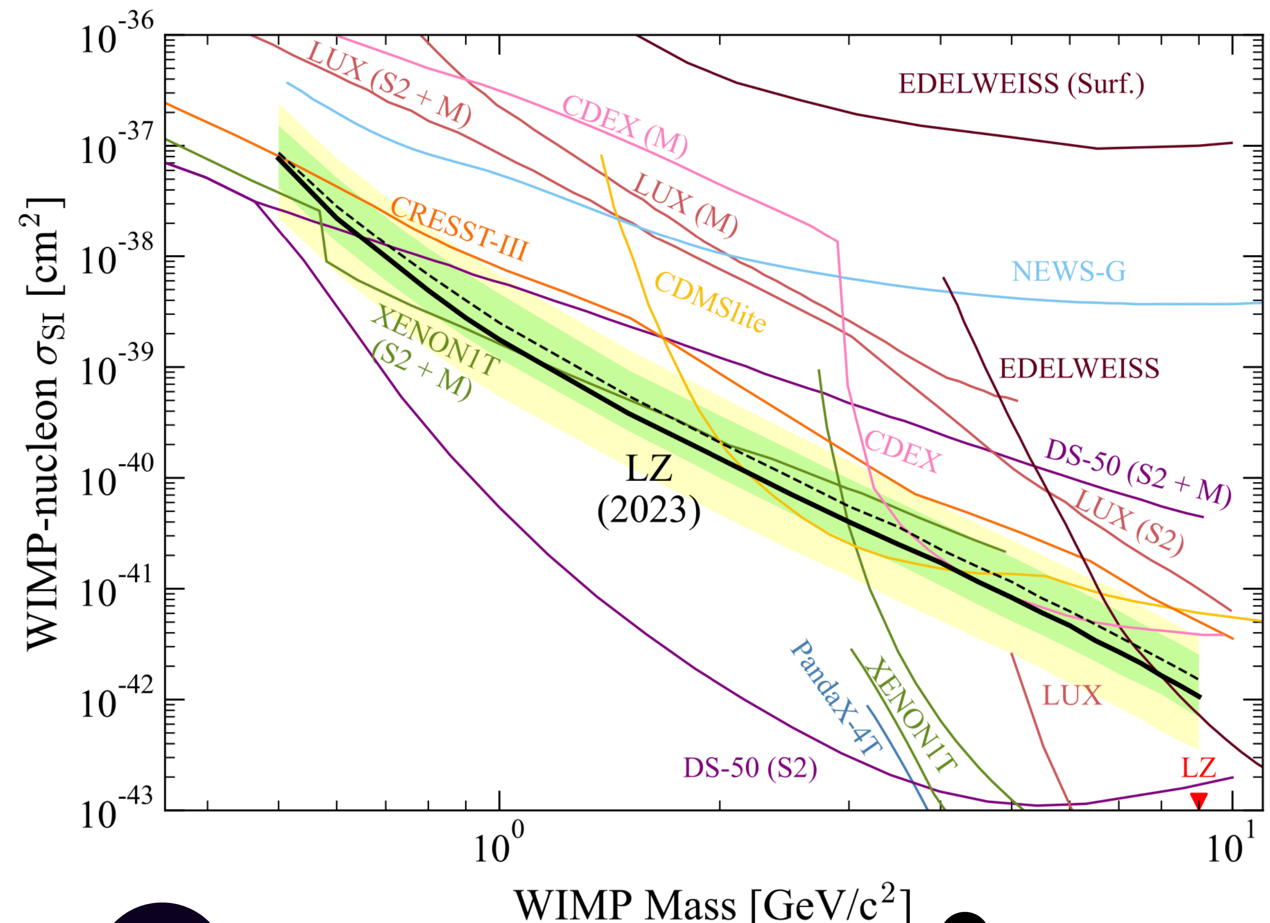


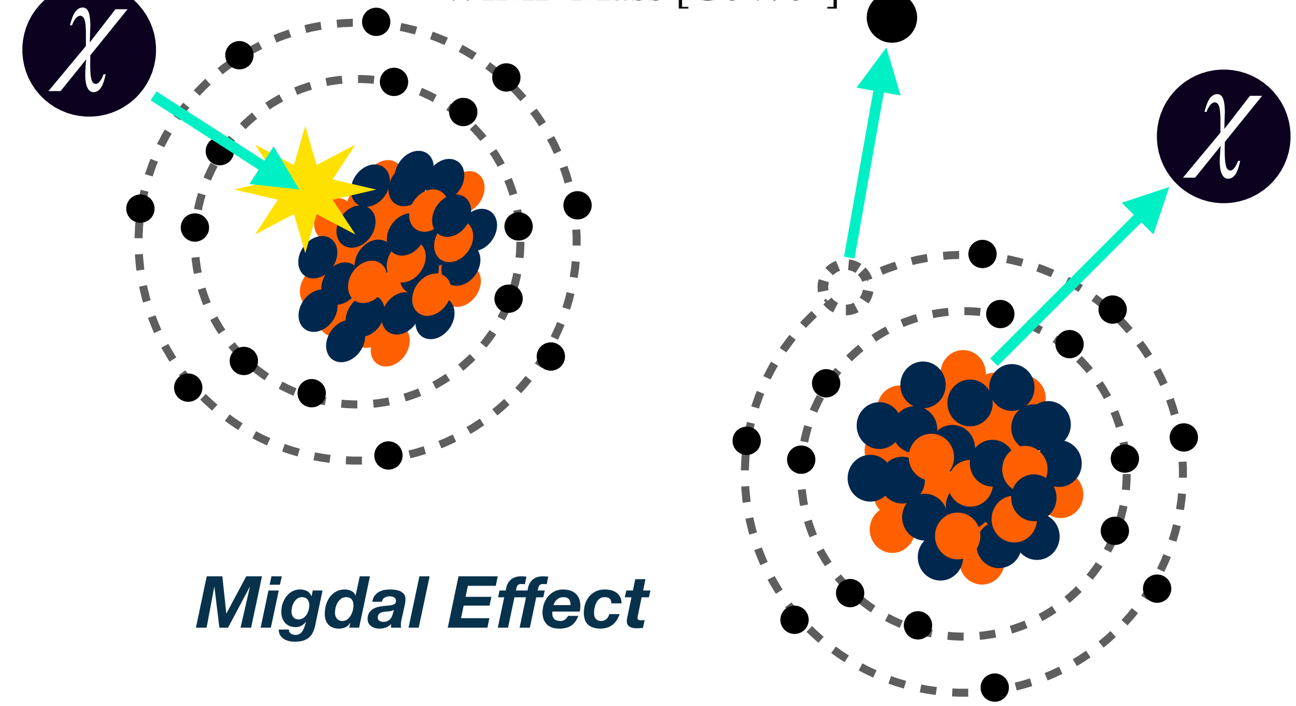
Solar axions/ALPs
Hidden photons



Low Energy ERs







In The Pipeline

Nonrelativistic Effective Field Theory

Searches utilizing a model-agnostic framework for WIMP-nucleon interactions in an extended energy region

Ultra Heavy Dark Matter Search

Search for Planck scale ($M \sim 10^6$ GeV) high multiplicity interactions in LZ detector. Multiply Interacting Massive Particles—MIMPs

Radon Tagging Veto

An investigation into mitigating the ^{214}Pb background using a tagged coincidence veto with ^{222}Rn alpha decays

Muon Flux Measurements

Characterization of the muon rate during SR1, with comparison to current simulation models

Conclusion

First results leading the way for WIMPs

Most stringent cross-section upper limits for SI scatters for m > 9 GeV. 6% of total planned exposure

Low energy ER searches

LZ sets world leading upper limits in parts of SD-neutron Migdal parameter space, as well as for neutrino millicharge

Onward to 1000 live days

LZ continues to take data for a planned exposure of 1000 live days, pushing into discovery territory for WIMPs and with significantly improved expected sensitivity for ER physics signals

Thank you!