Low energy electron recoil searches within LZ and using FlameNEST for future work

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3rd year PhD Astroparticle student
University of Edinburgh
11/04/24 IOP Joint APP, HEPP and NP Conference

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

- 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
- Royal Holloway University of London
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- South Dakota Science & Technology Authority
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- University of Oxford
- University of Rochester
- University of Sheffield
- University of Sydney
- University of Texas at Austin
- University of Wisconsin, Madison
- University of Zürich

US Europe Asia Oceania

250 scientists, engineers, and technical staff

@lzdarkmatter

https://lz.lbl.gov/

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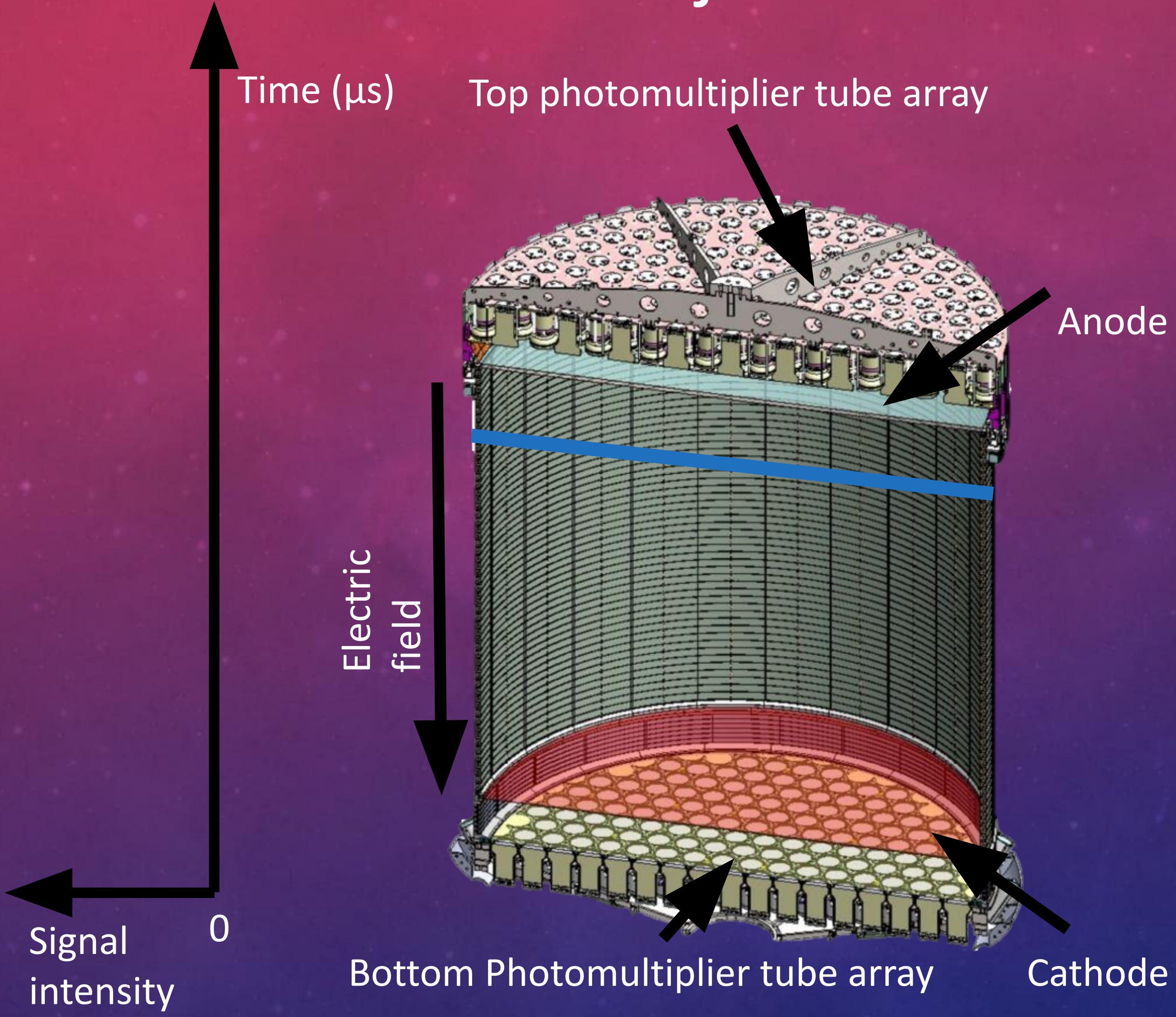
LZ - 7 Tonne Xenon Time Projection Chamber (TPC)



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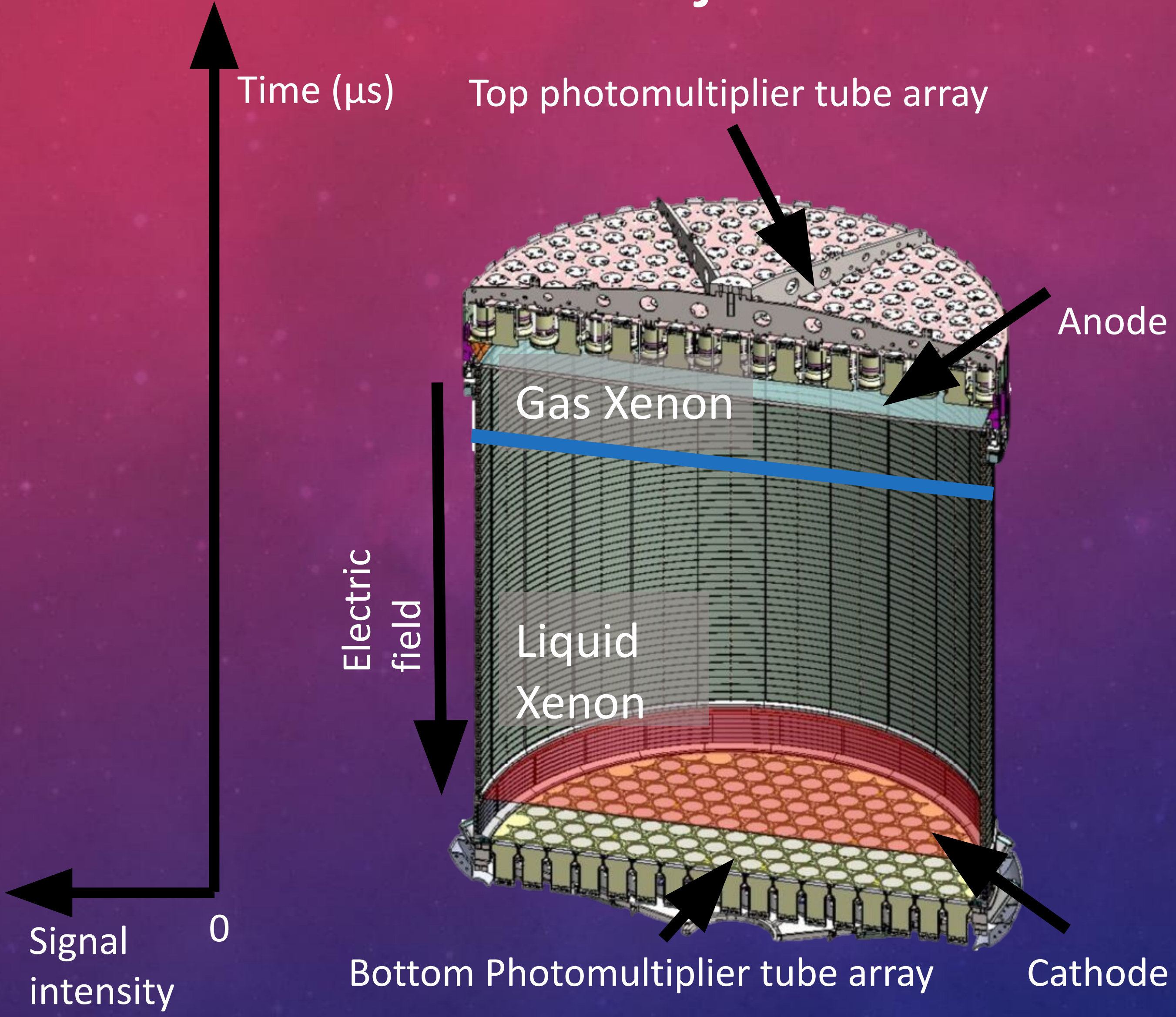

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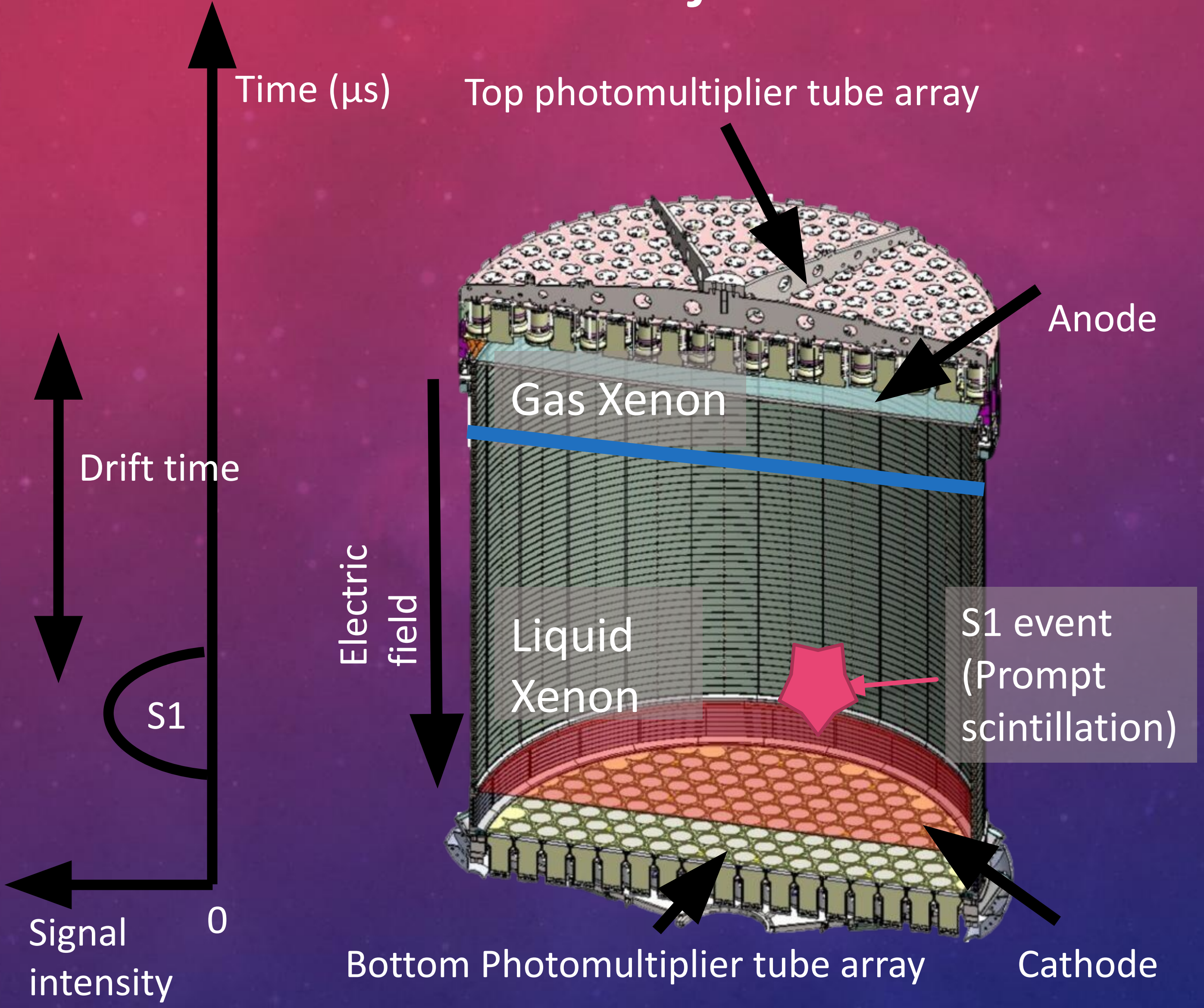

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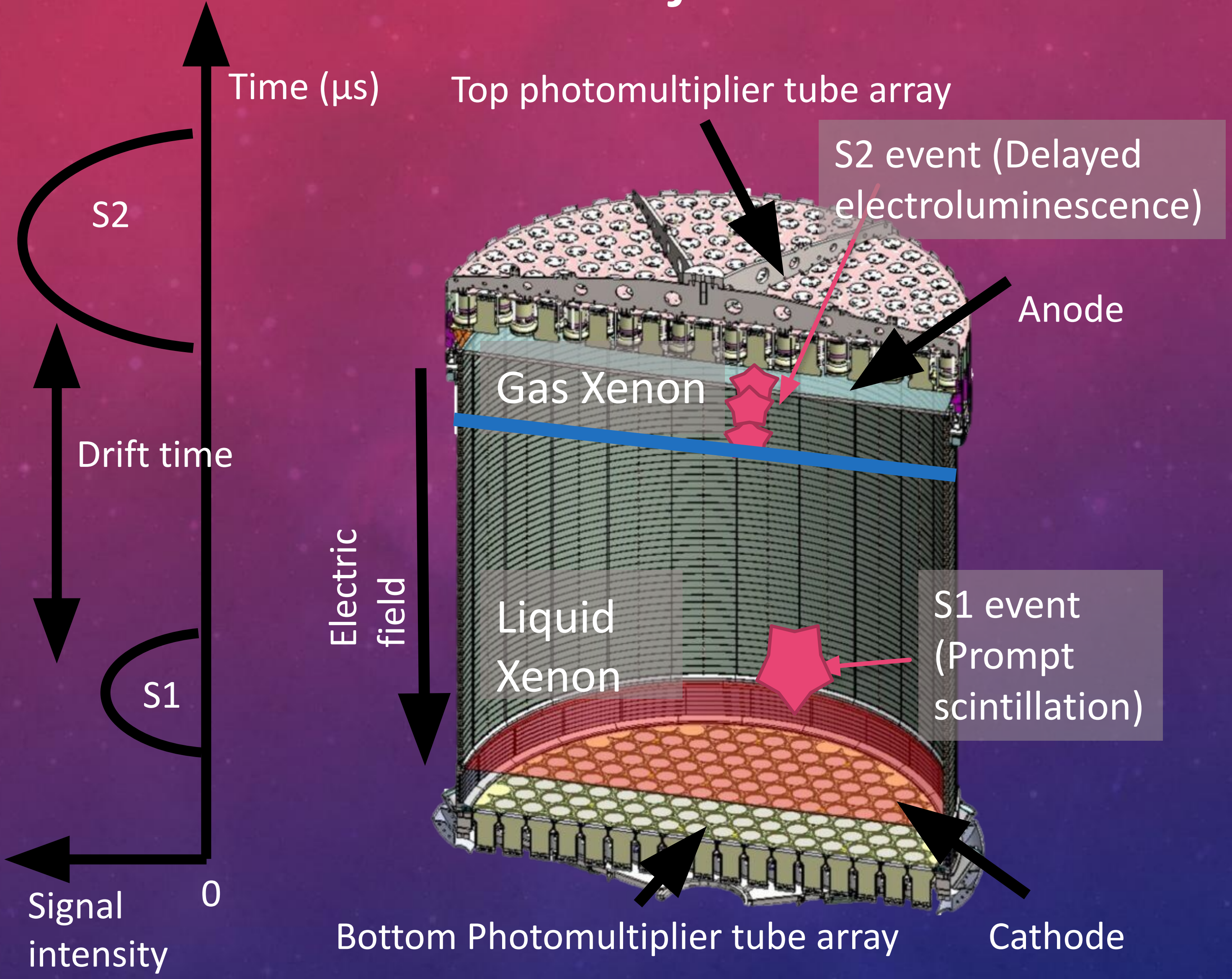
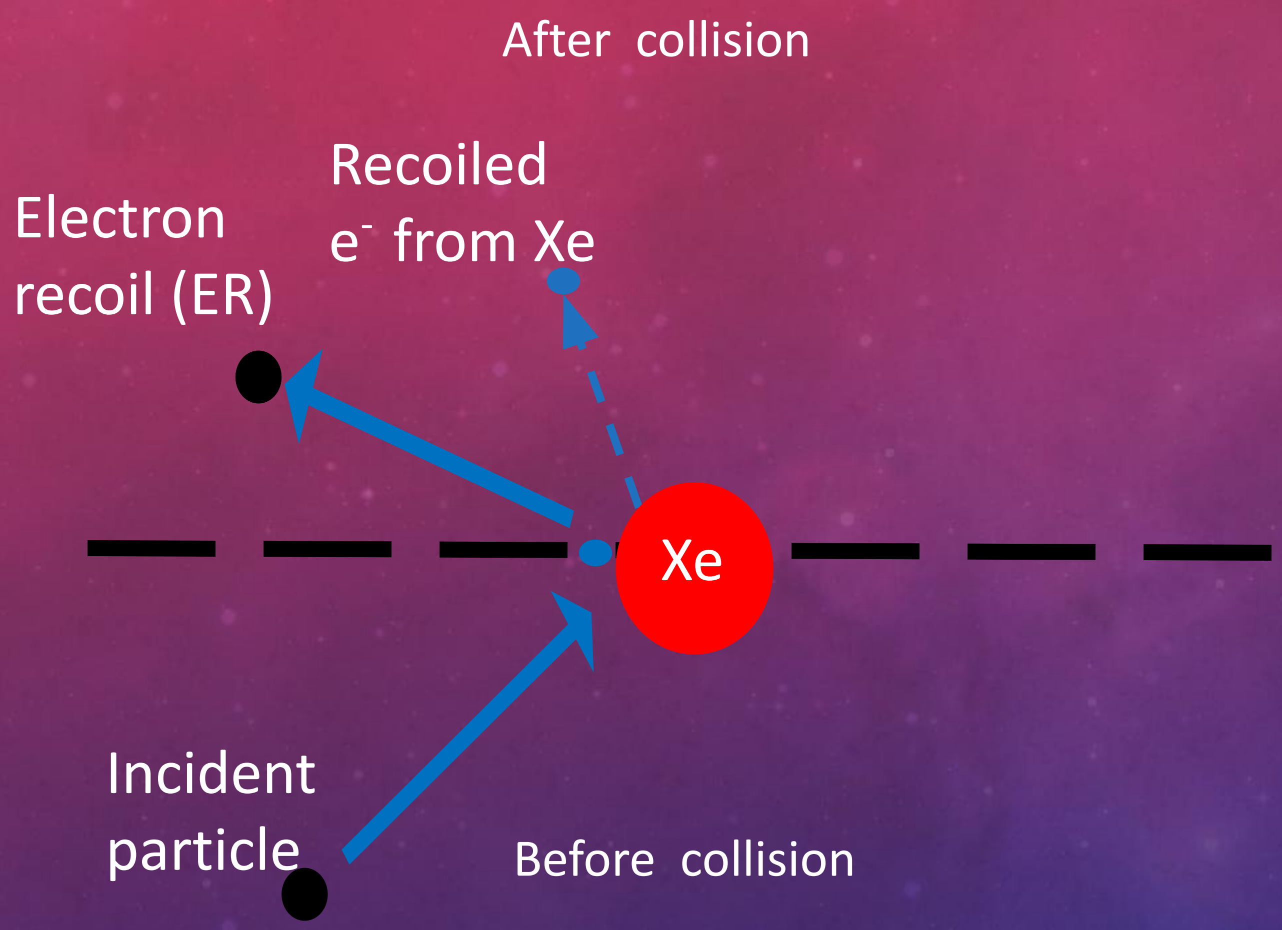


Nuclear Recoils (NR) and Electron Recoils (ER)



- S1 can occur via Nuclear Recoil (NR) or Electron Recoil (ER) event
- S2/S1 light ratio distinguish ER and NR events
- WIMPs and neutrons produce NRs
- γ, β and exotic models produce ERs

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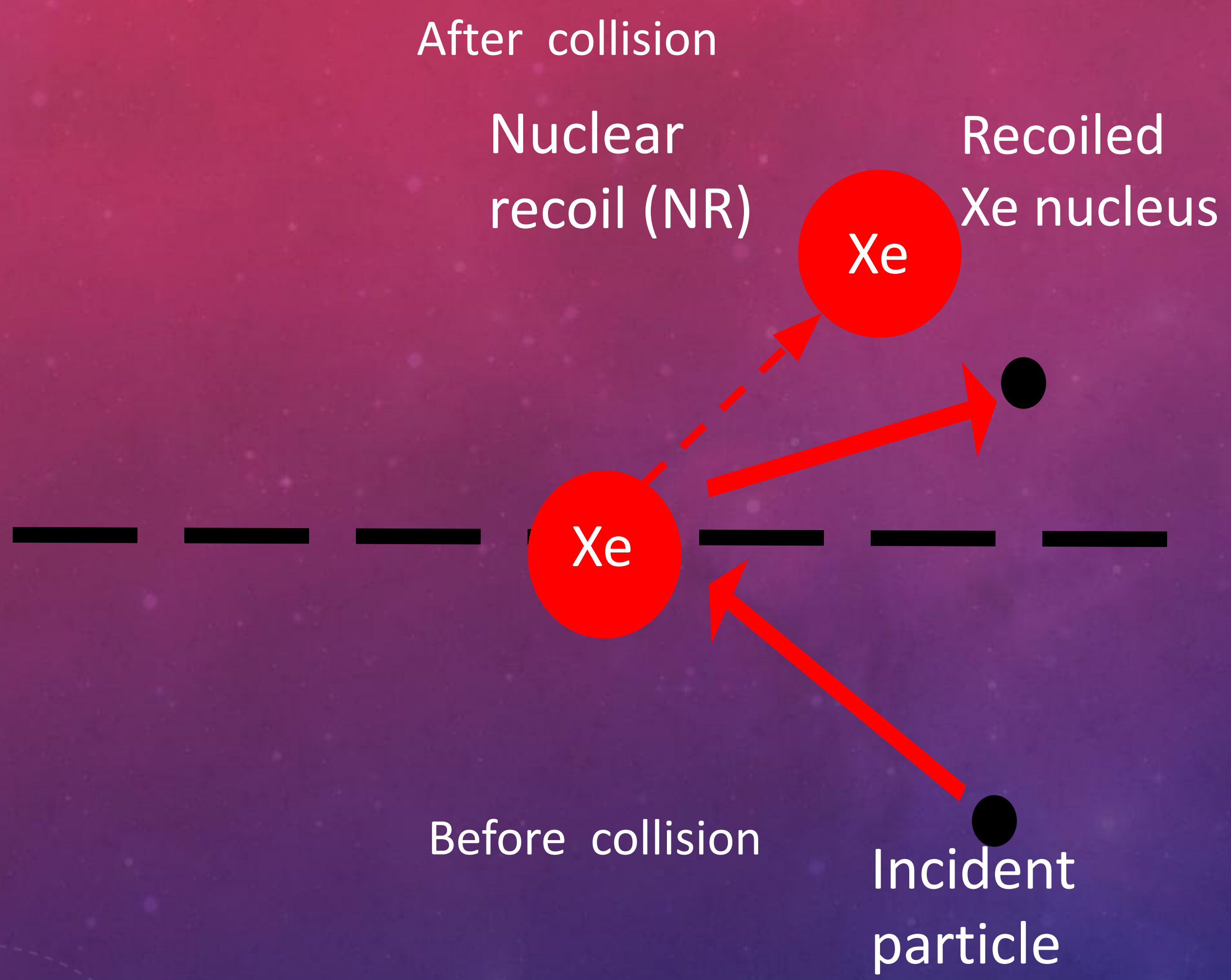

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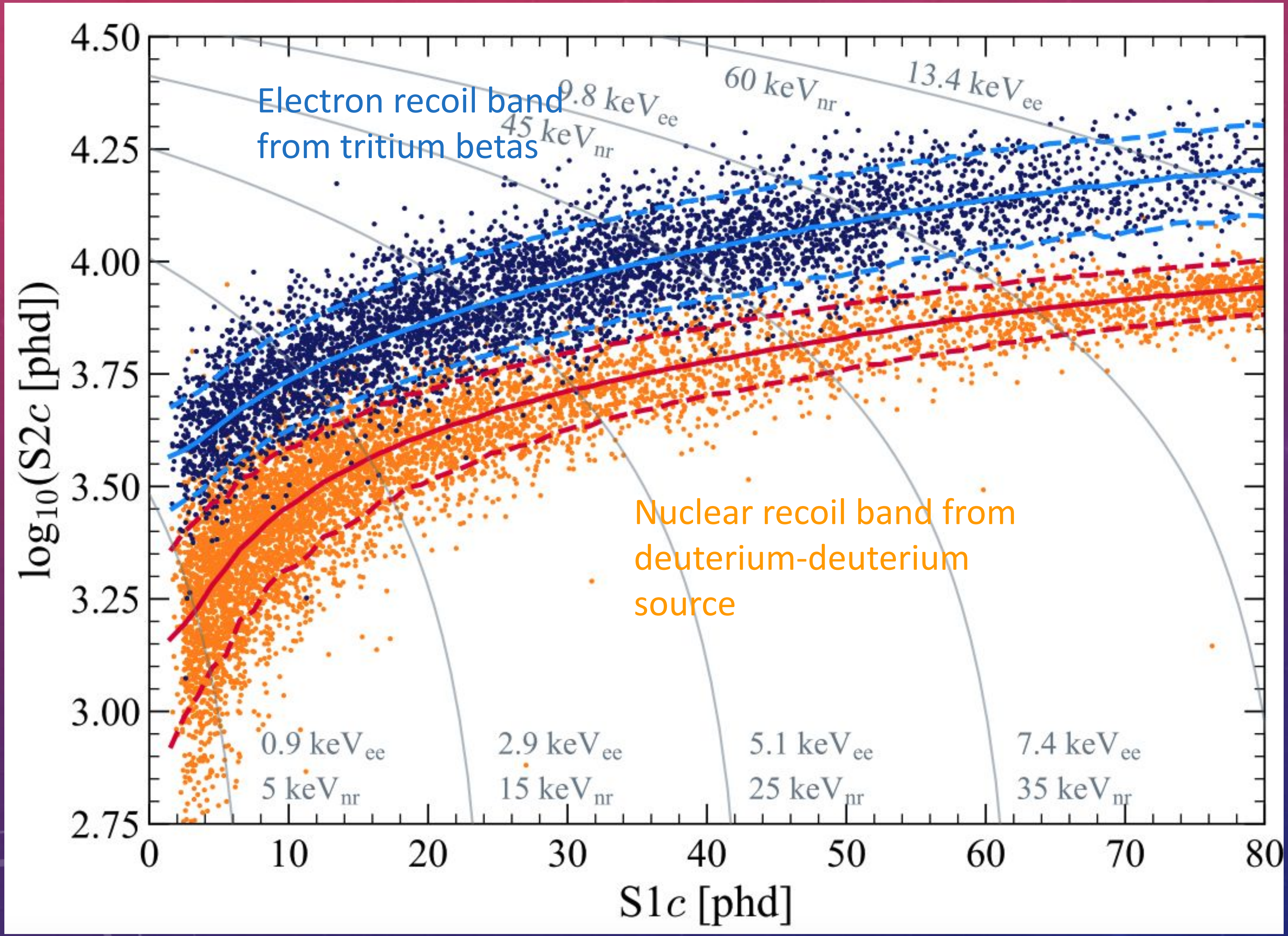
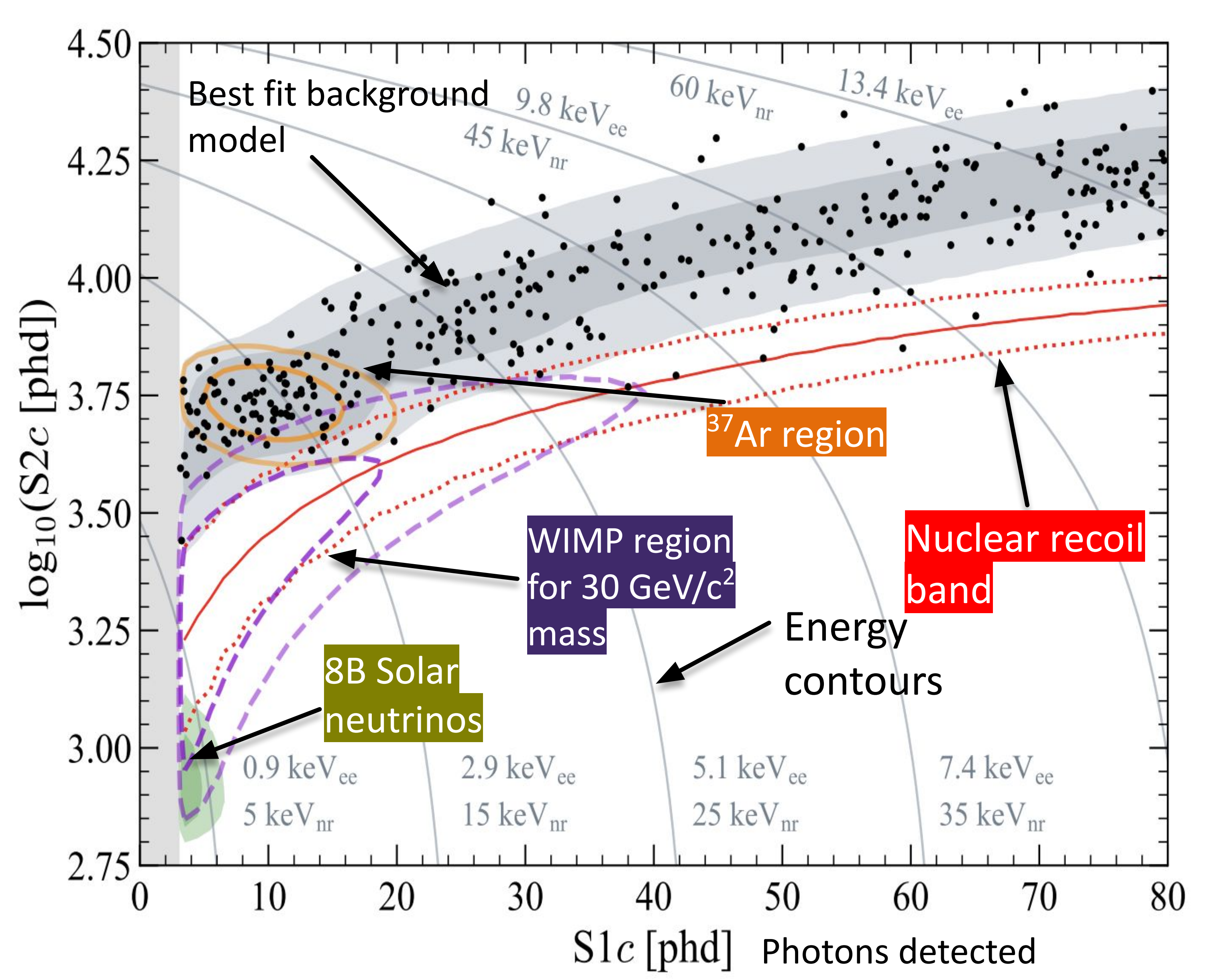
Band Making



Phys. Rev. Lett. 131, 041002

LZ Science Run 1 result



- Results taken over 60 live days of WIMP search data runs
- 335 events after cuts applied
- Best fit to data is zero WIMP events

Phys. Rev. Lett. 131, 041002

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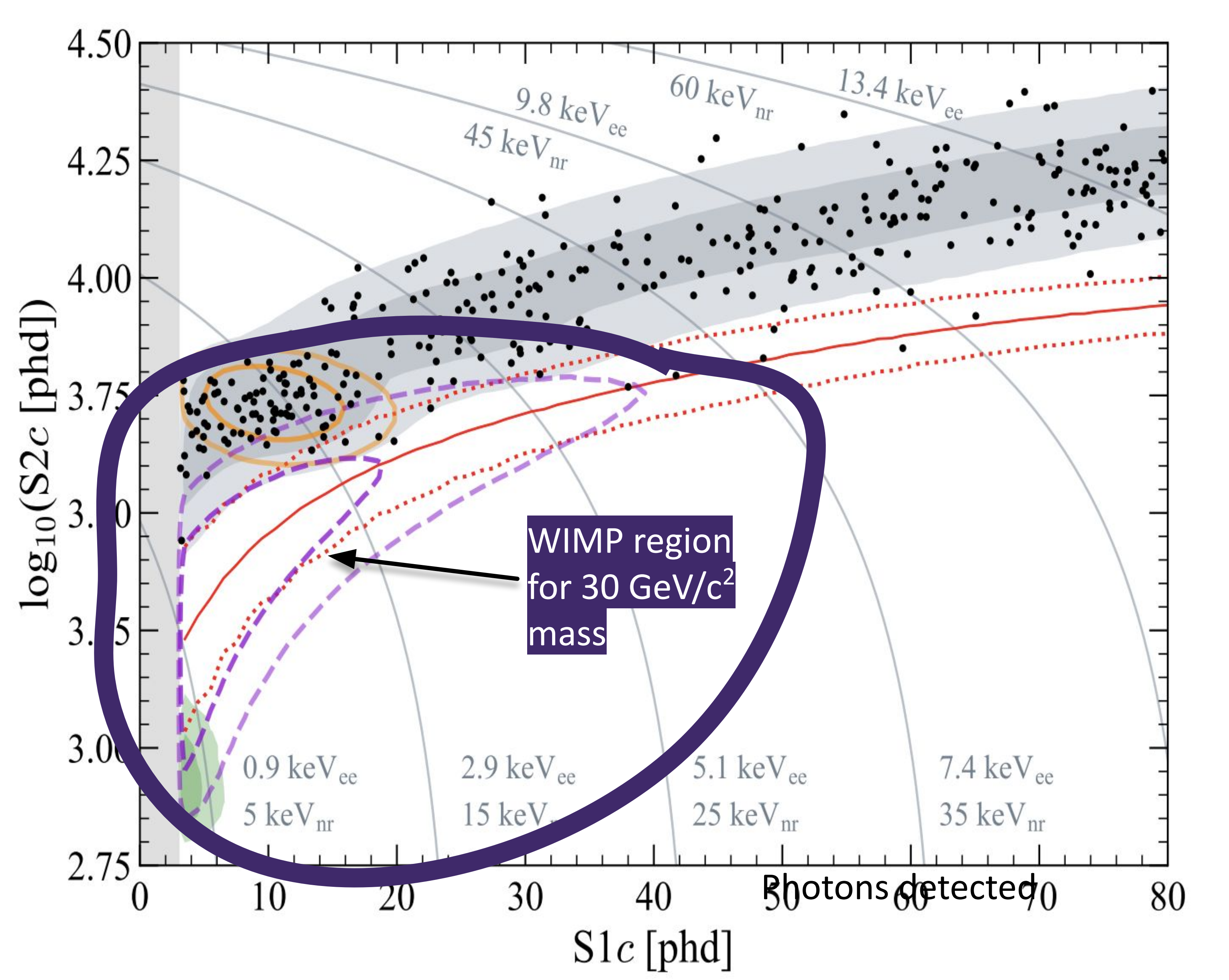

Phys. Rev. Lett. 131, 041002

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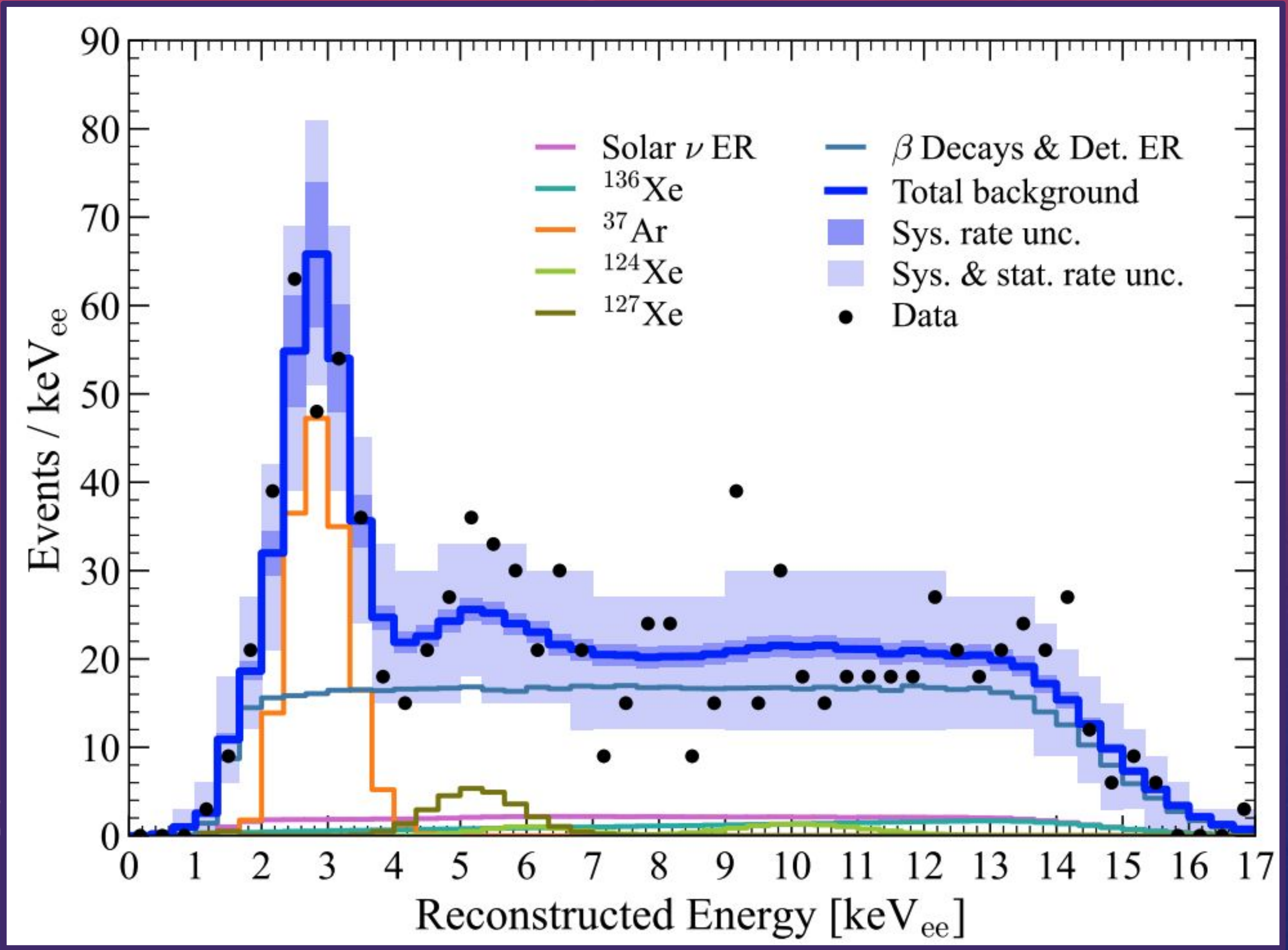
LZ Science Run 1 model - Counting with energy



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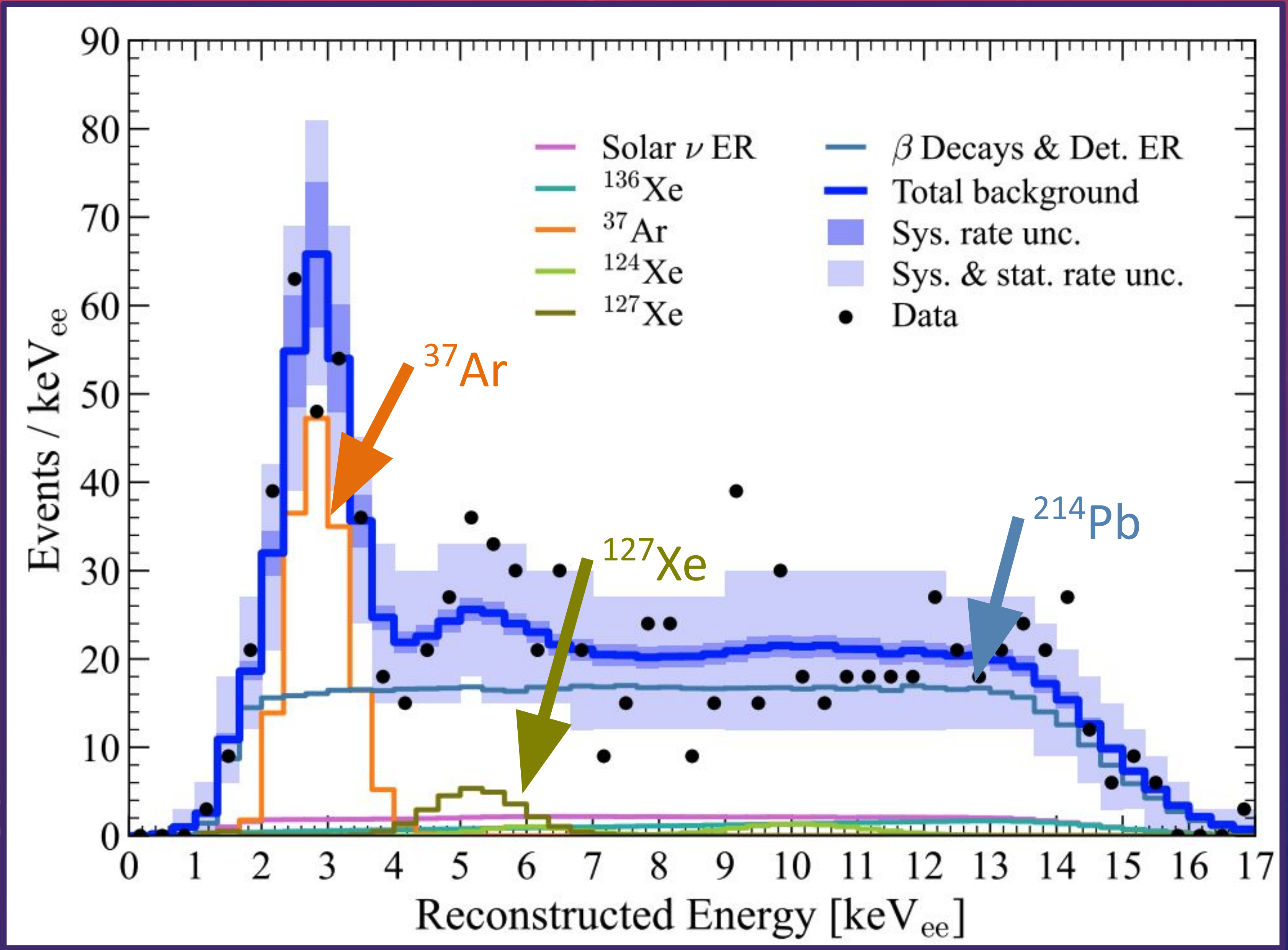
LZ Science Run 1 model - Counting with energy



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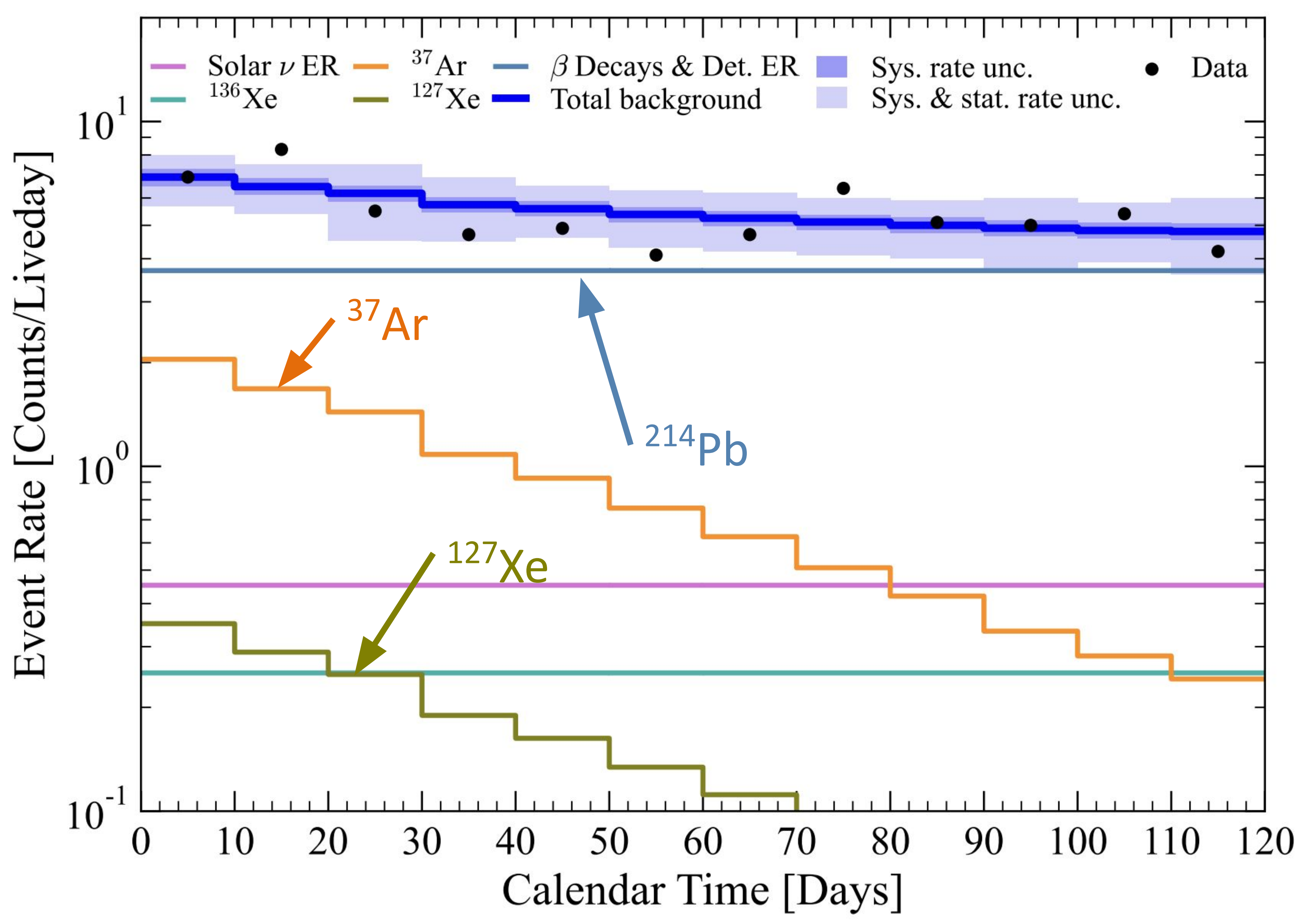
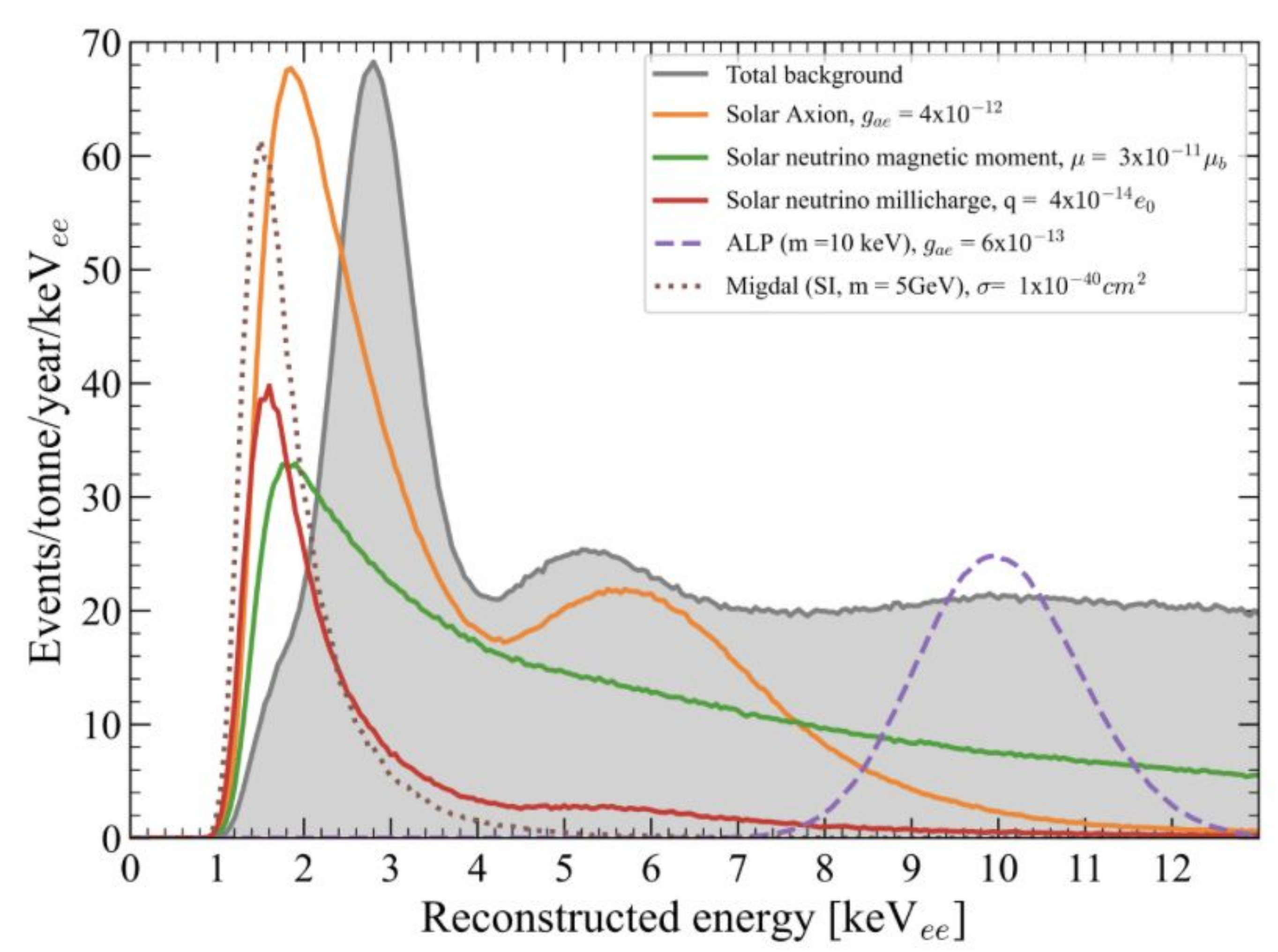
LZ Science Run 1 (SR1) model - Counting with time



Phys. Rev. D 108, 072006

Low energy electron recoil searches

Signal Model	Origin	Interaction methods
Solar Axion (Mine)	Sun	Axion-electron coupling JCAP12(2013)008
Neutrino magnetic moment	Sun	Neutrino-electron scattering Phys. Rev. D 100, 073001
Neutrino millicharge	Sun	Neutrino-electron scattering Phys. Rev. D 100, 073001
Migdal effect sensitivity to WIMPs	Galactic Halo	Migdal effect - electron recoil enhancement of nuclear recoils JHEP03(2018)194
Axion-like Particles (ALP)	Galactic Halo	ALP absorption via axio-electric effect Phys. Rev. D 78, 115012
Hidden Photon (HP)	Galactic Halo	Kinetic mixing Phys. Rev. D 78, 115012



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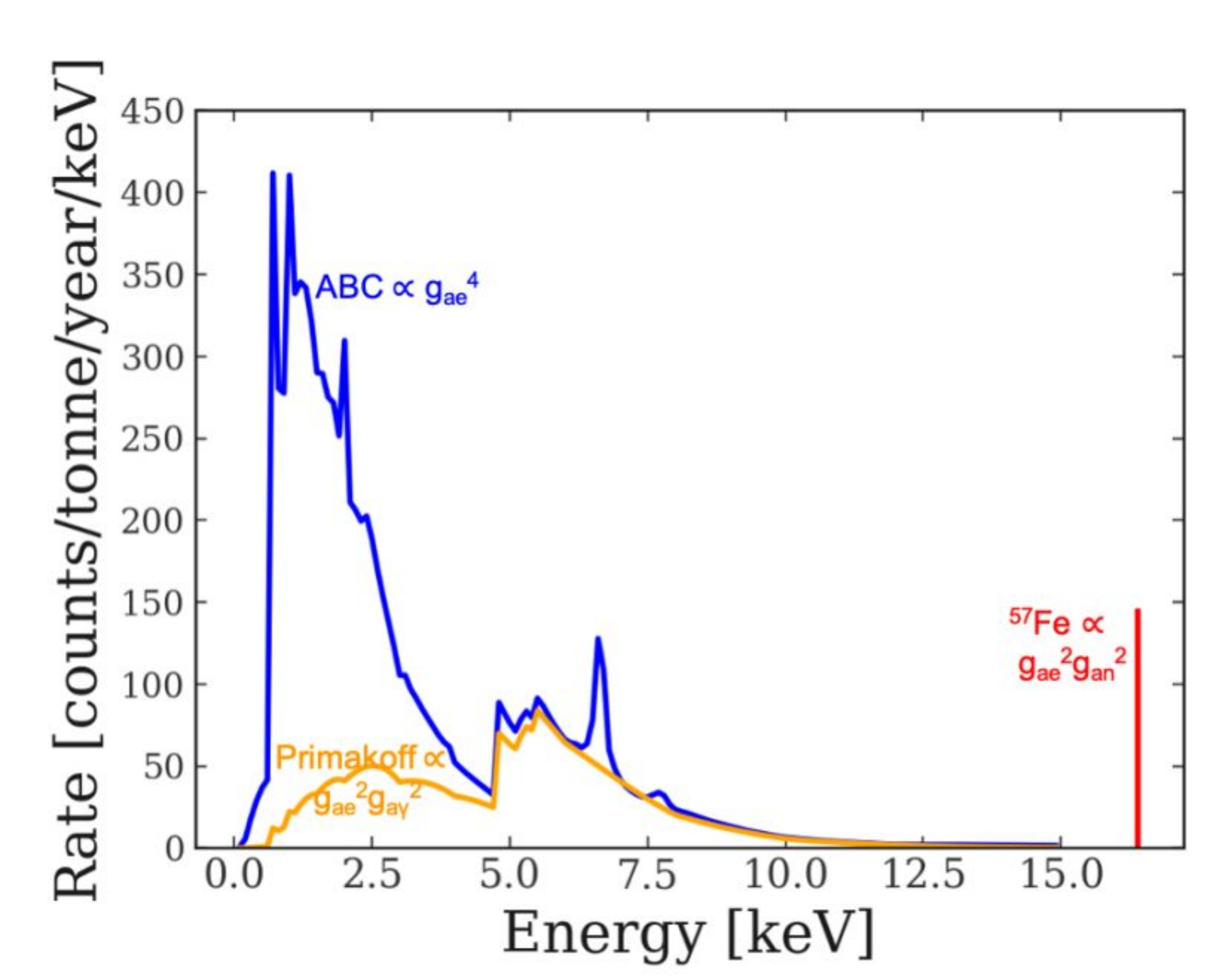
Solar Axions



- Axion: pseudo-scalar Nambu-Goldstone boson: solution to the strong CP problem
- Produced in the sun through thermal processes:
  - ABC (Atomic deexcitation and recombination, Bremsstrahlung, Compton scattering)
  - Primakoff effect
  - M1 transitions of ^{57}Fe
- Only ABC contribution considered
- Axions couple to e^- via axio-electric effect (**g_{ae}**)

Building the model

Generate Probability Distribution Function (PDF) of detector response to signal

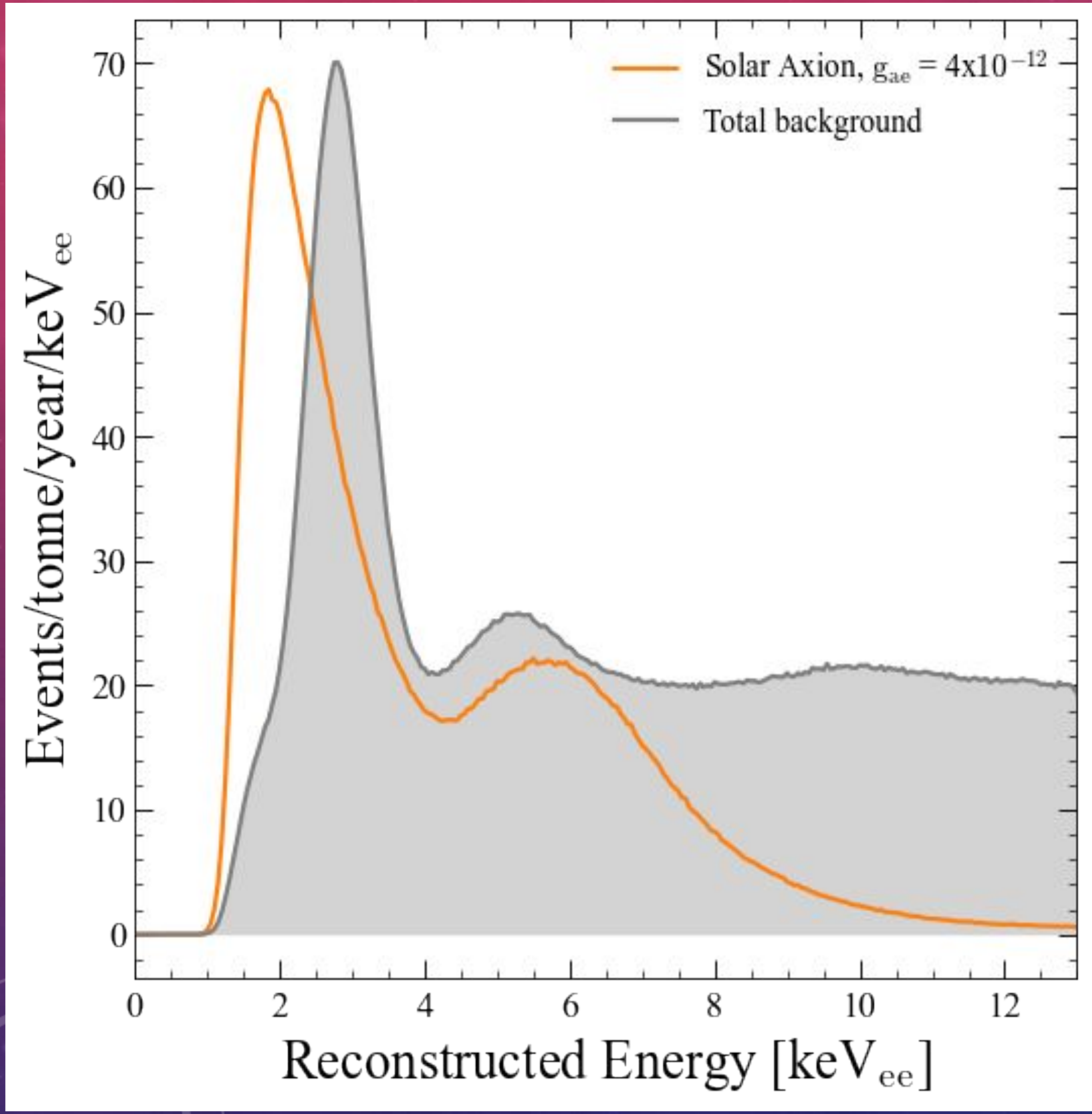
Building the model

Generate Probability Distribution Function (PDF) of detector response to signal

↓

Generate PDFs of detector response to backgrounds

Building the model



Generate Probability Distribution Function (PDF) of detector response to signal

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Generate PDFs of detector response to backgrounds

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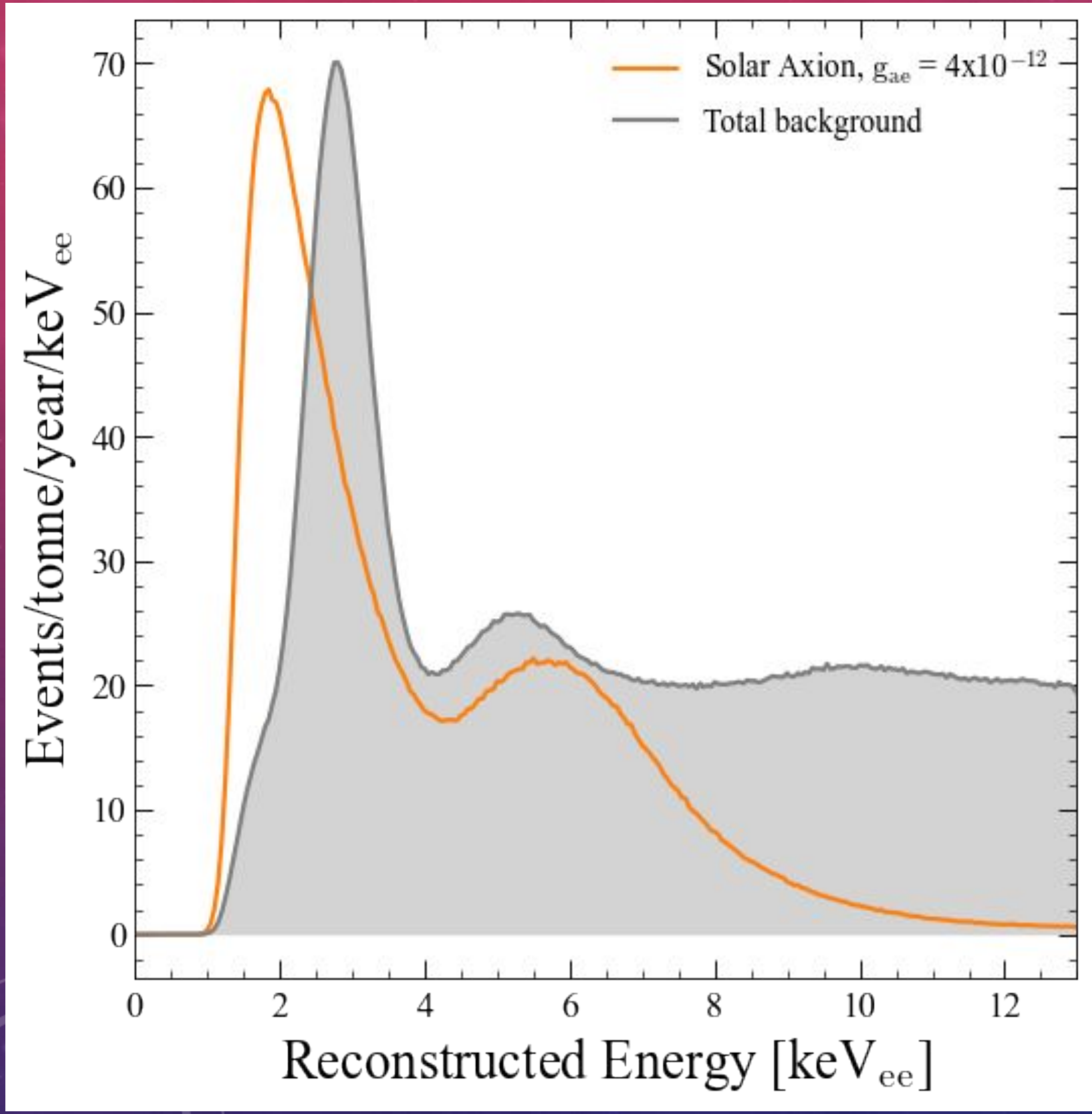
Apply WIMP search corrections and data cuts to PDFs

Building the model



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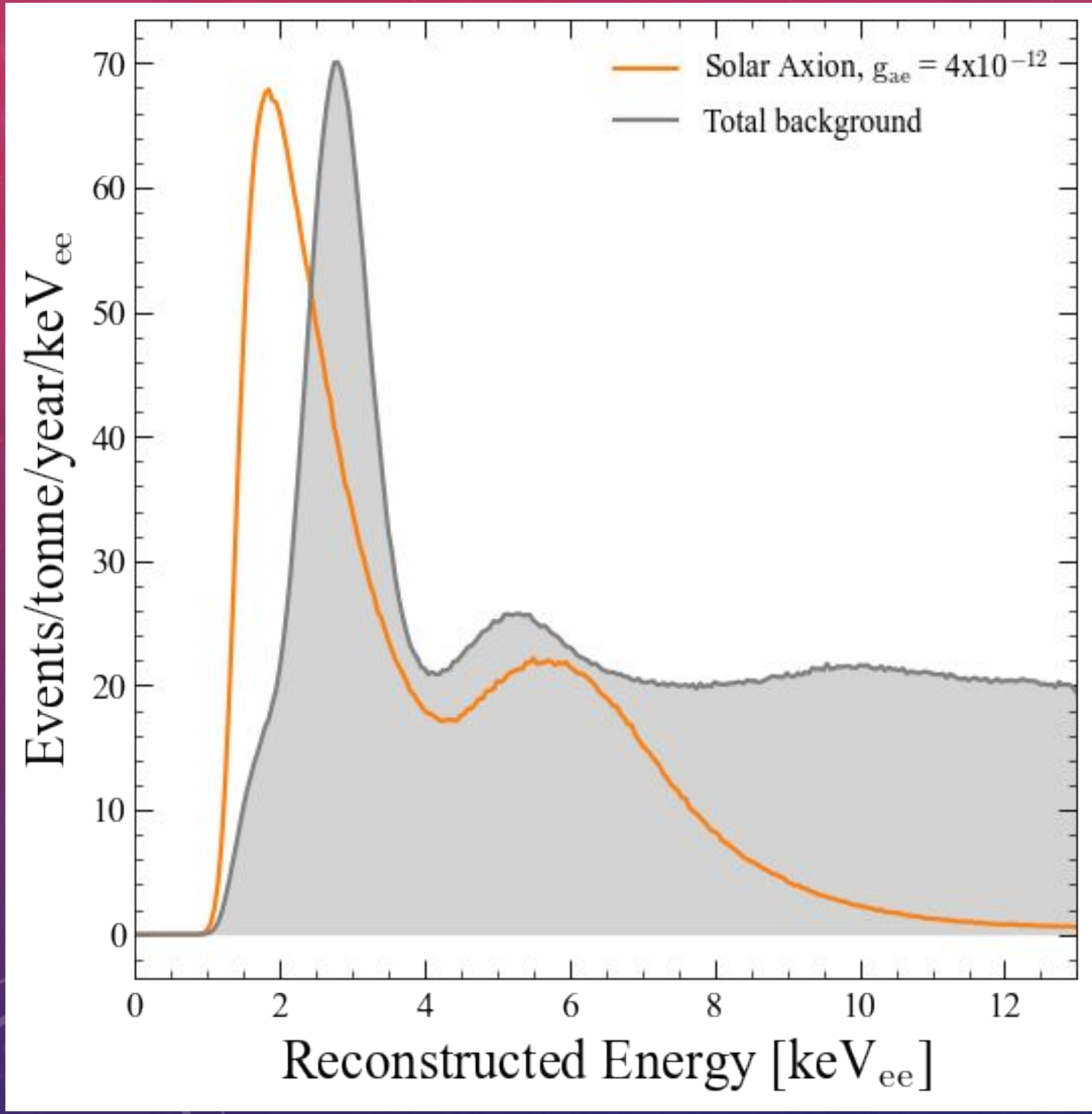
Combine PDFs and analysis parameters to create the model

Building the model



Generate Probability Distribution Function (PDF) of detector response to signal

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Generate PDFs of detector response to backgrounds

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Apply WIMP search corrections and data cuts to PDFs

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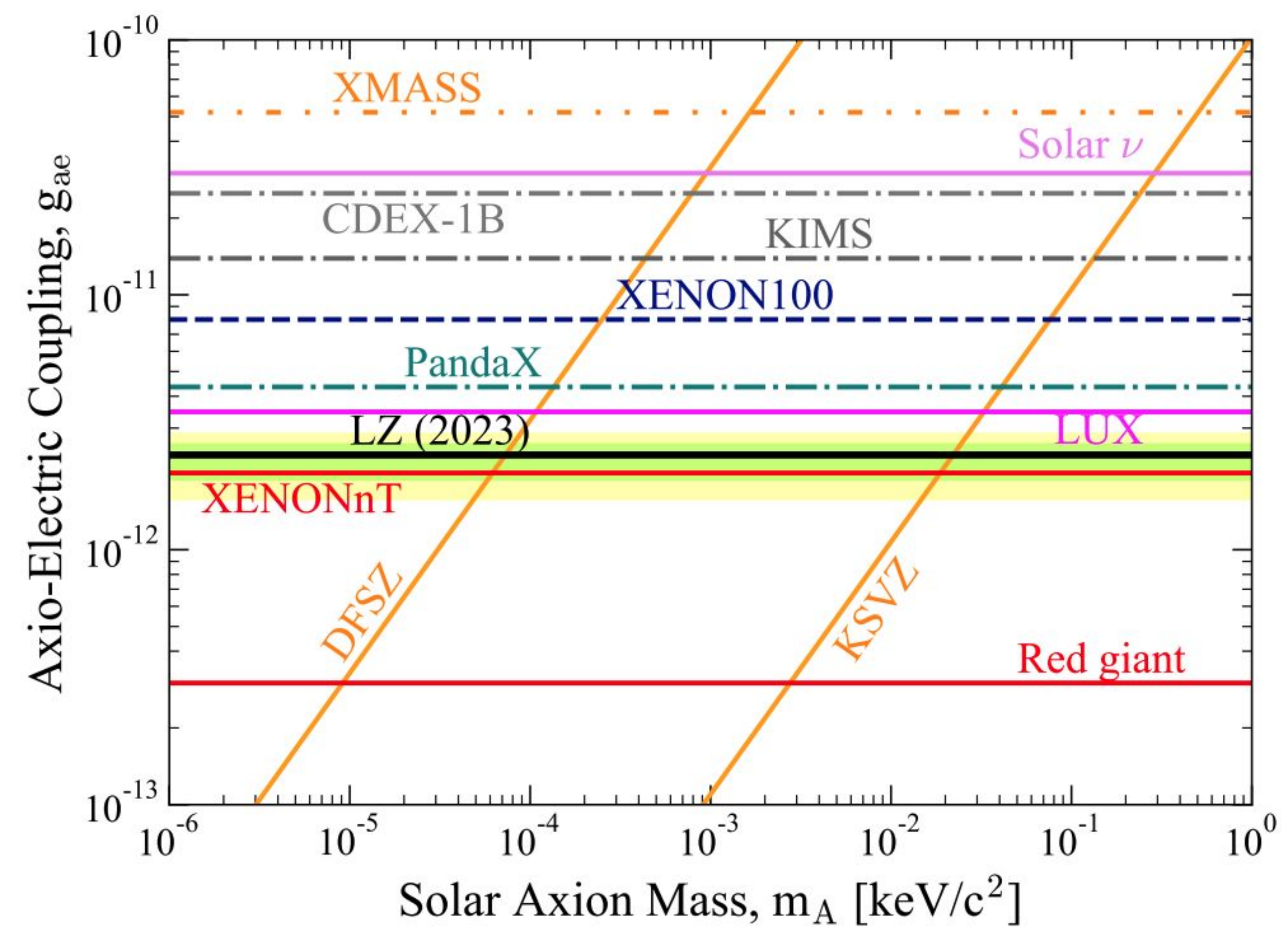
Combine PDFs and analysis parameters to create the model

↓

Use Profile Likelihood Ratio test to set upper limits on signal and background counts

Solar Axions



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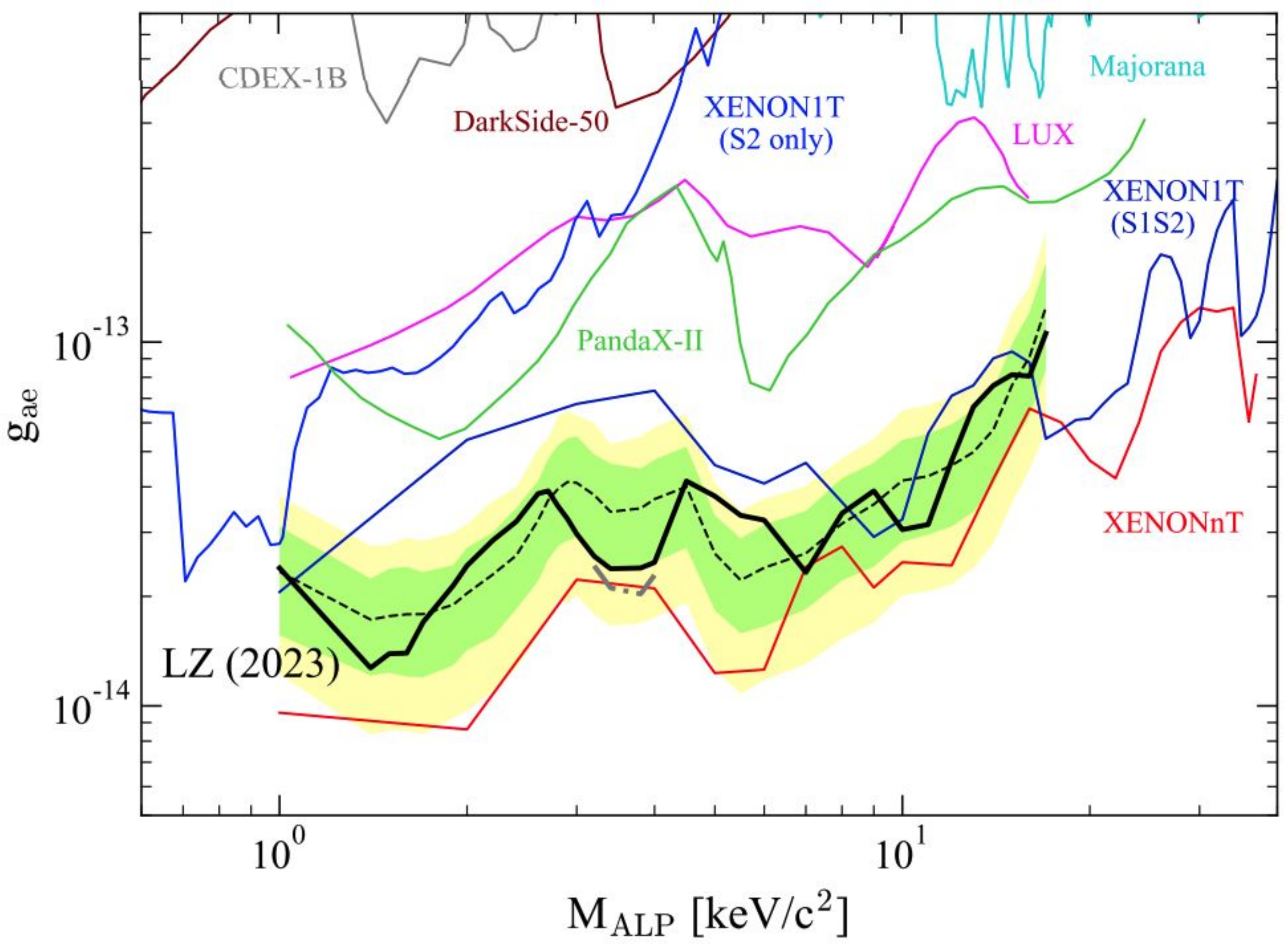
Axion Like Particles (ALP)



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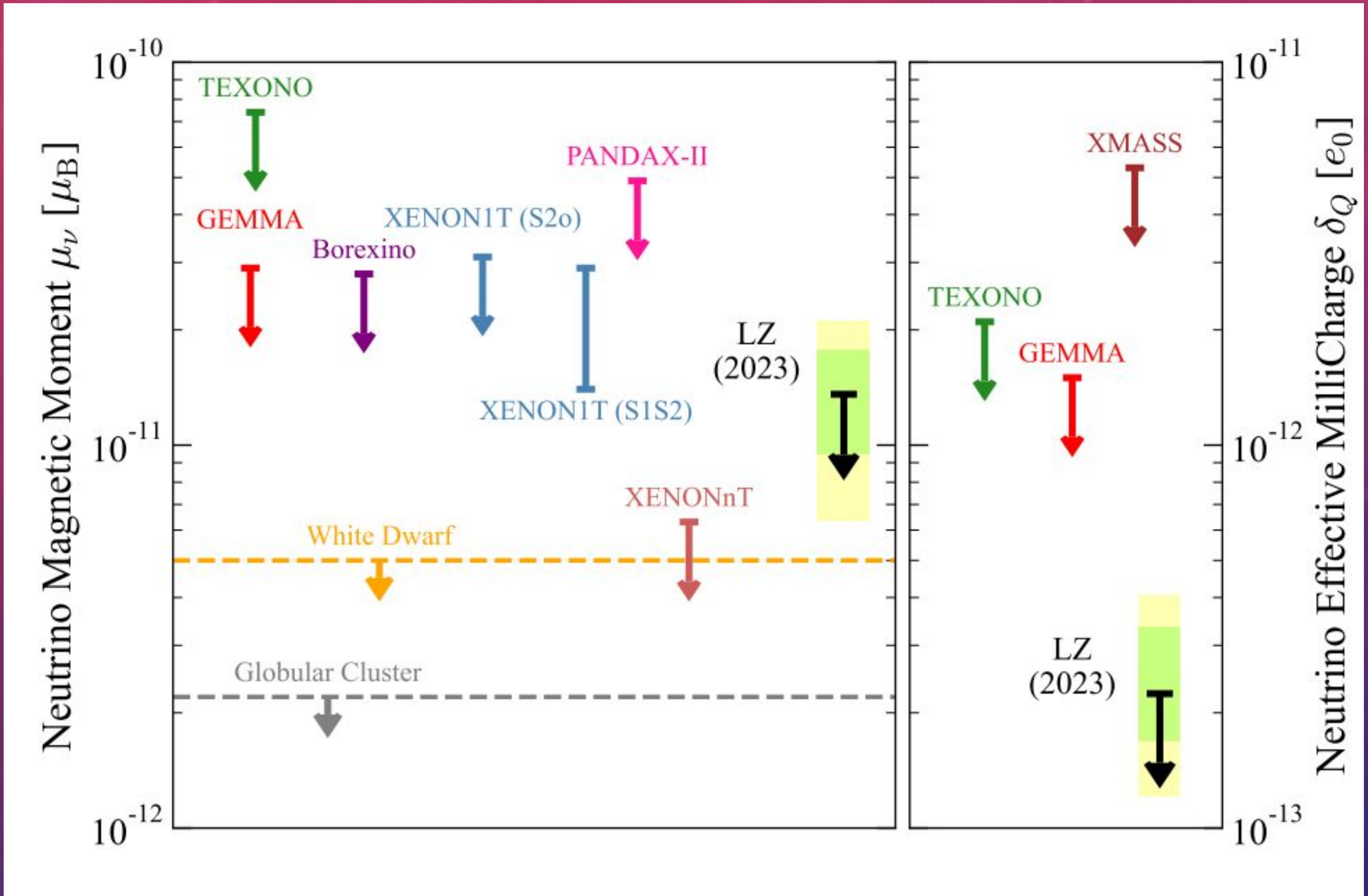
- General type of pseudo Nambu-Goldstone boson
- Similar to axions, but more general type of particles
- Full ALP mass absorbed during scattering process
- Monoenergetic signal that is dependent on ALP mass

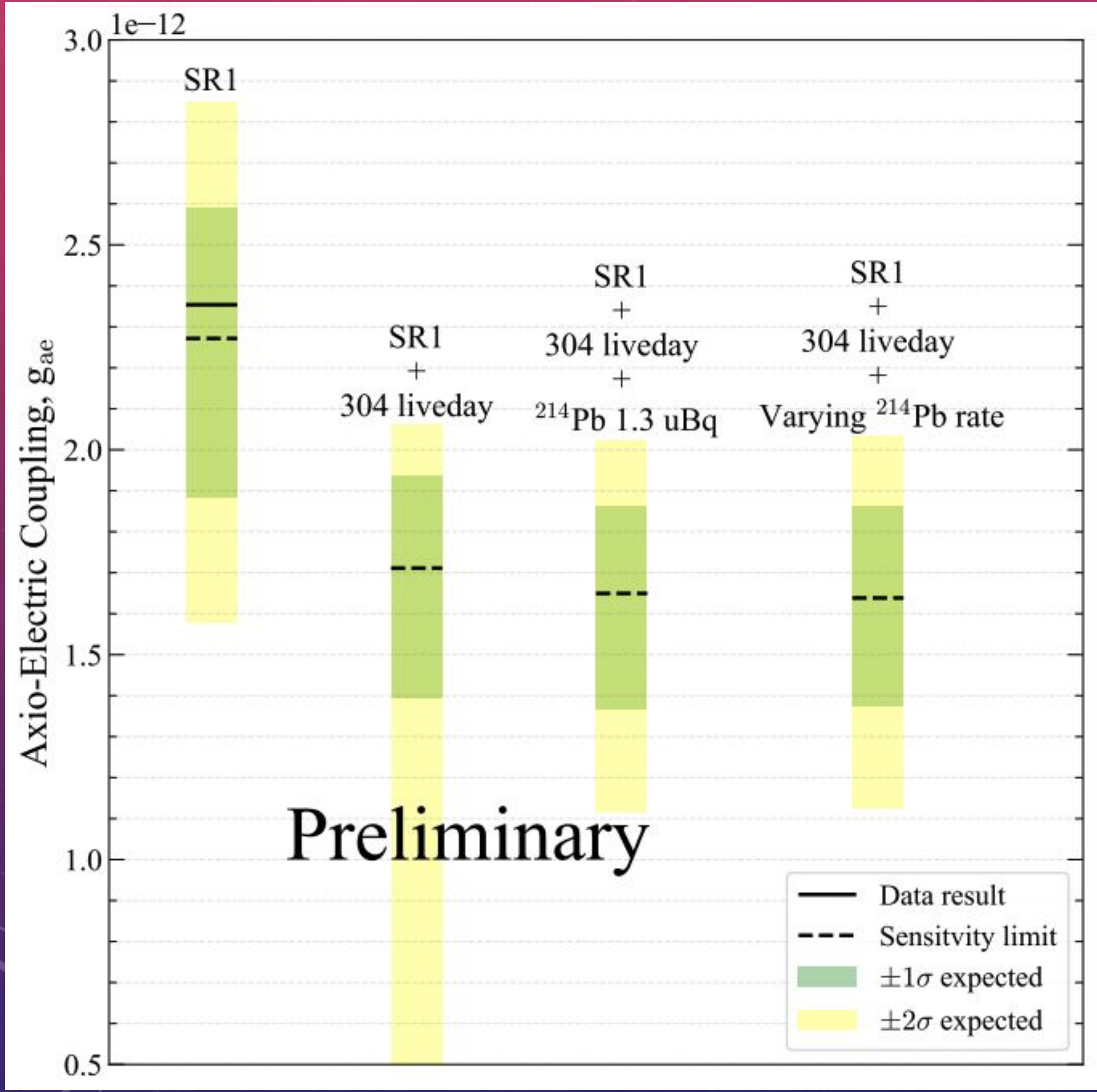
Solar neutrinos' millicharge & magnetic moment



[Phys. Rev. D 108, 072006]

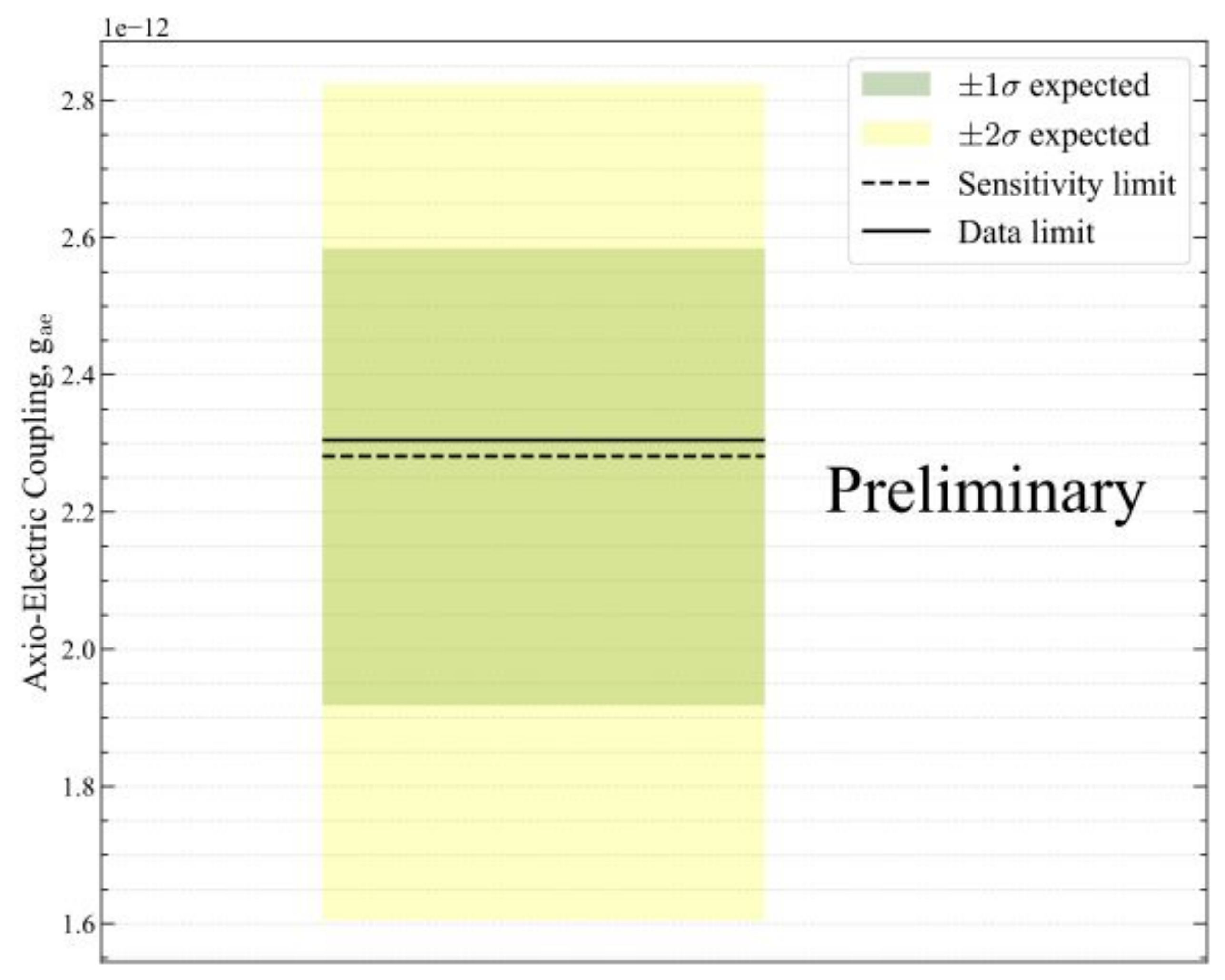
- Neutrinos show small EM coupling via loop corrections
- EM properties are: effective neutrino millicharge (q_ν) and magnetic moment (μ_ν)
- Couple to e^-, give additional neutrino events
- Search for excesses of neutrino events

Solar Axions – future projections



- Increasing lifetime increase significant sensitivity
- ^{37}Ar ,^{127}Xe have decayed away fully
- Change ^{214}Pb rate does give a shift in limit obtained

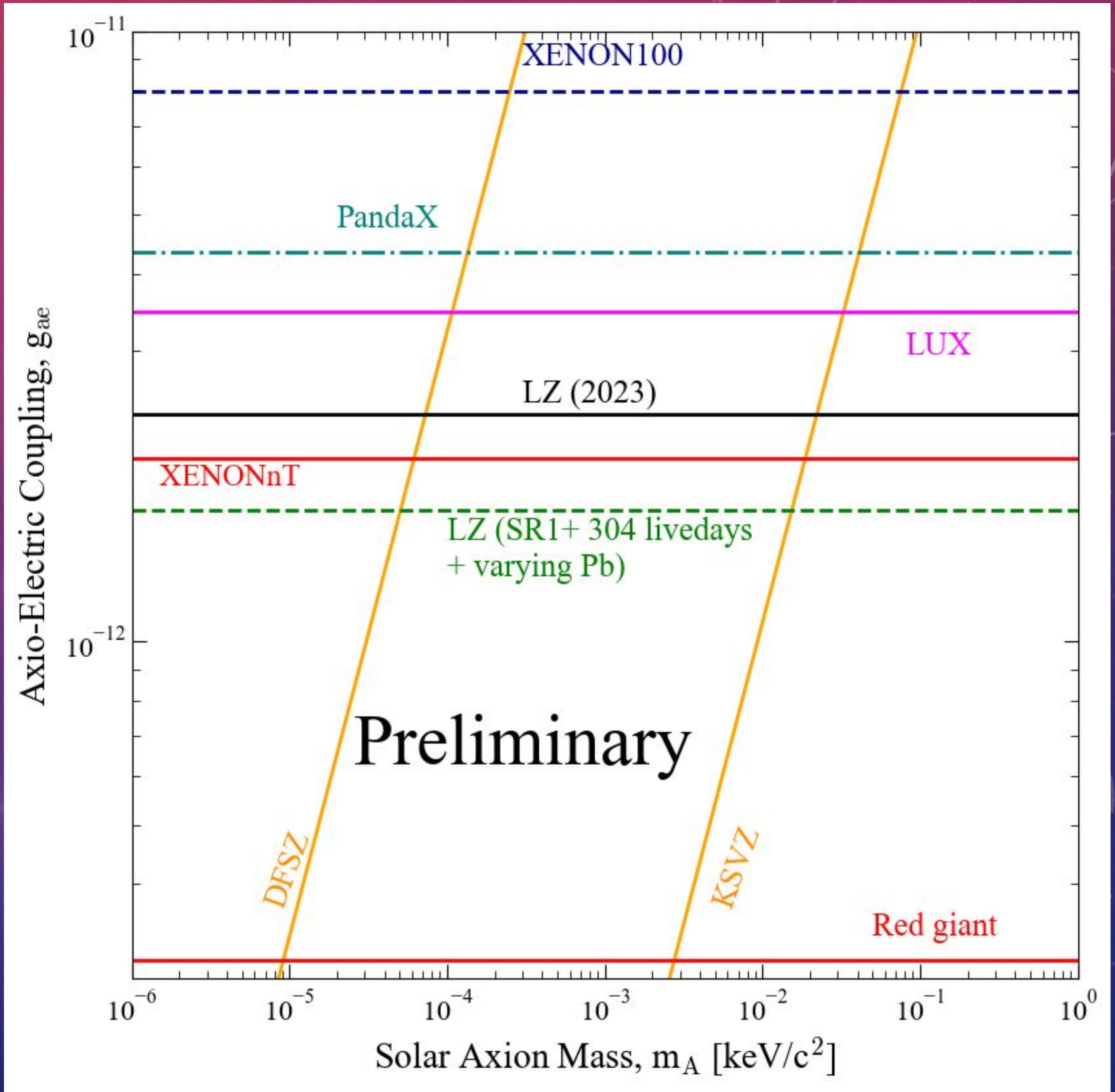
Solar Axions – FlameNest future applications



- FlameNEST - method for multidimensional models
- Has inference tools for traditional monte carlo and FlameNEST models
- Tested the inference code on SR1 solar axion monte carlo models
- Plan to extend to full flameNEST analysis chain in the future
- Read more at R.S. James et al 2022 JINST 17 P08012

Conclusion

- No WIMPs found during first science run, 335 events are left to understand
- New physics could be hiding behind background results
- Searches for signals ongoing
- New analysis tools will help look behind the curtain and understand more



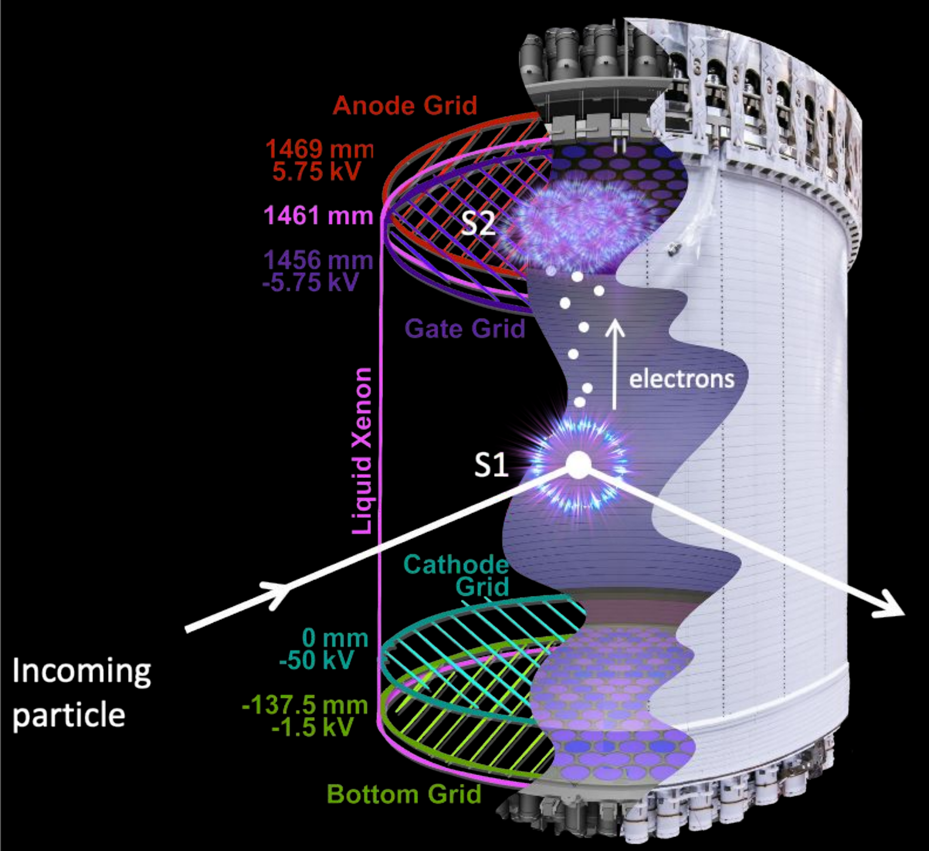


Image by Nicolas A. (Imperial College London)

Thank you!

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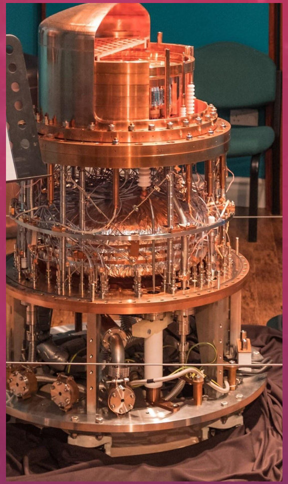
Any questions?

HOW IT CAME TO BE



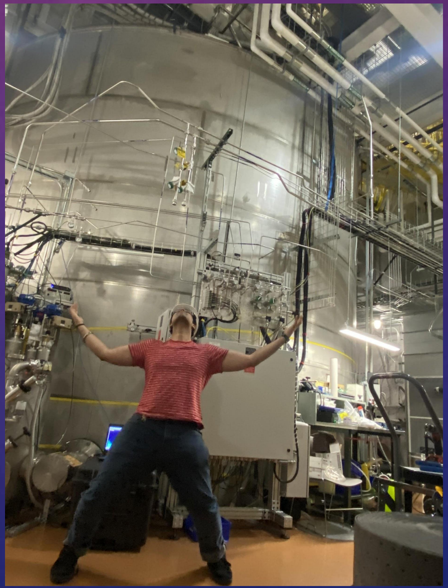
Zeplin (UK) experiment concluded, joining LUX (US) experiment. Creating LUX-Zeplin

LZ detectors starts construction

Results of Science run 1 (SR1) published

2012 2016 2019 2021 2022 Now

LUX finishes and decommissioned



The detector is installed underground, filled with LXe and begins taking data

Currently planning for next set of data taking and beyond

TIME PROJECTION CHAMBER (TPC)

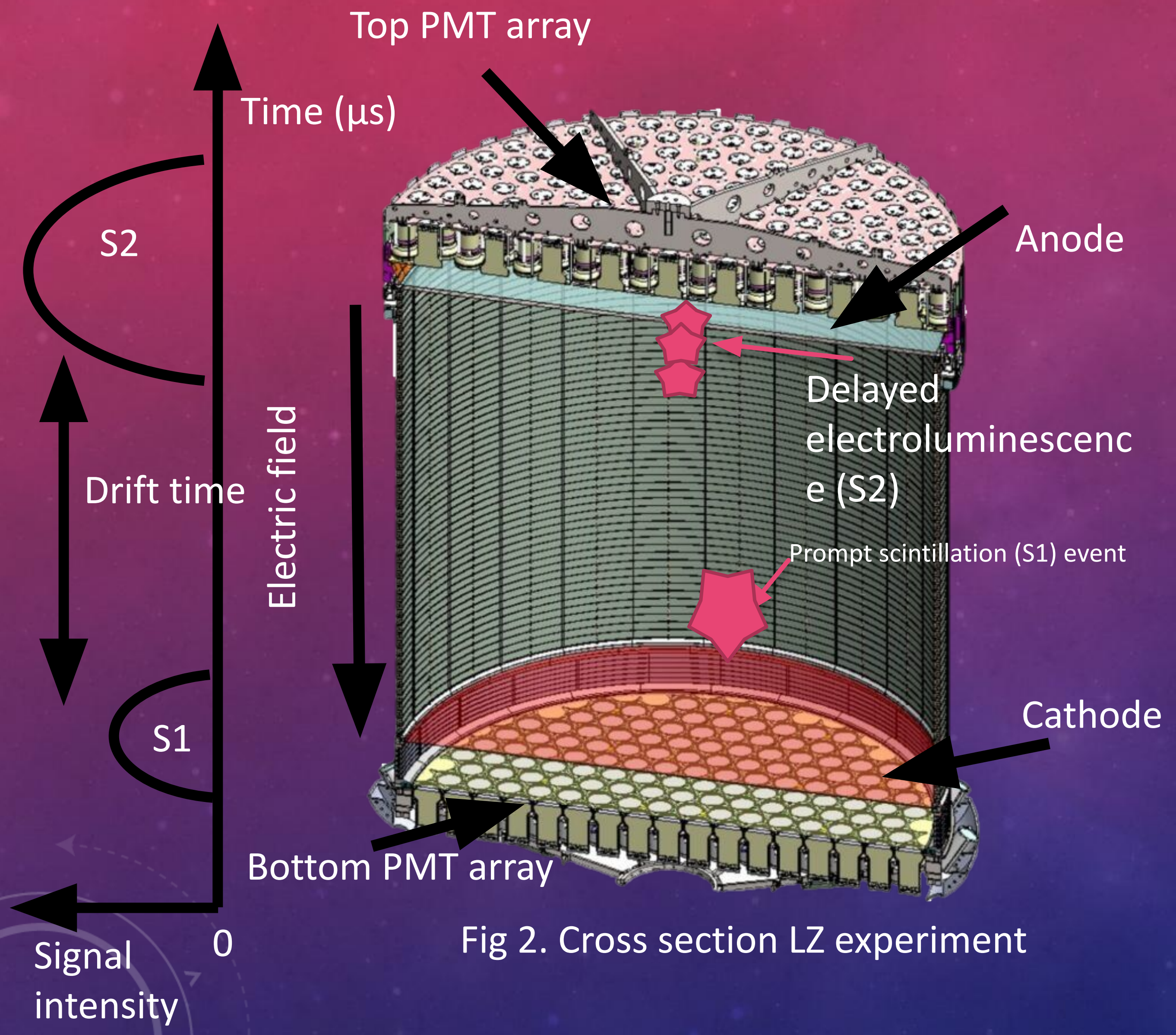


Fig 2. Cross section LZ experiment

- TPC is the key aspect of direct dark matter detection experiments
- LZ uses a two phase TPC with 7 tonnes of LXe. 5.5 tonnes as a fiducial volume below a gas layer of Xe, remaining LXe surrounds TPC as skin detector
- Electric field goes vertically through TPC, anode on top, cathode on bottom
- Particles scatter with LXe, producing scintillation light (called 'S1') and e^- via ionization
- e^- drifts upwards to anode. When in gas phase Xe, e^- causes electroluminescent event called S2
- Light produced from S1 and S2 events are detected by PMT arrays on top and bottom of TPC

LAYERS TO THE ONION

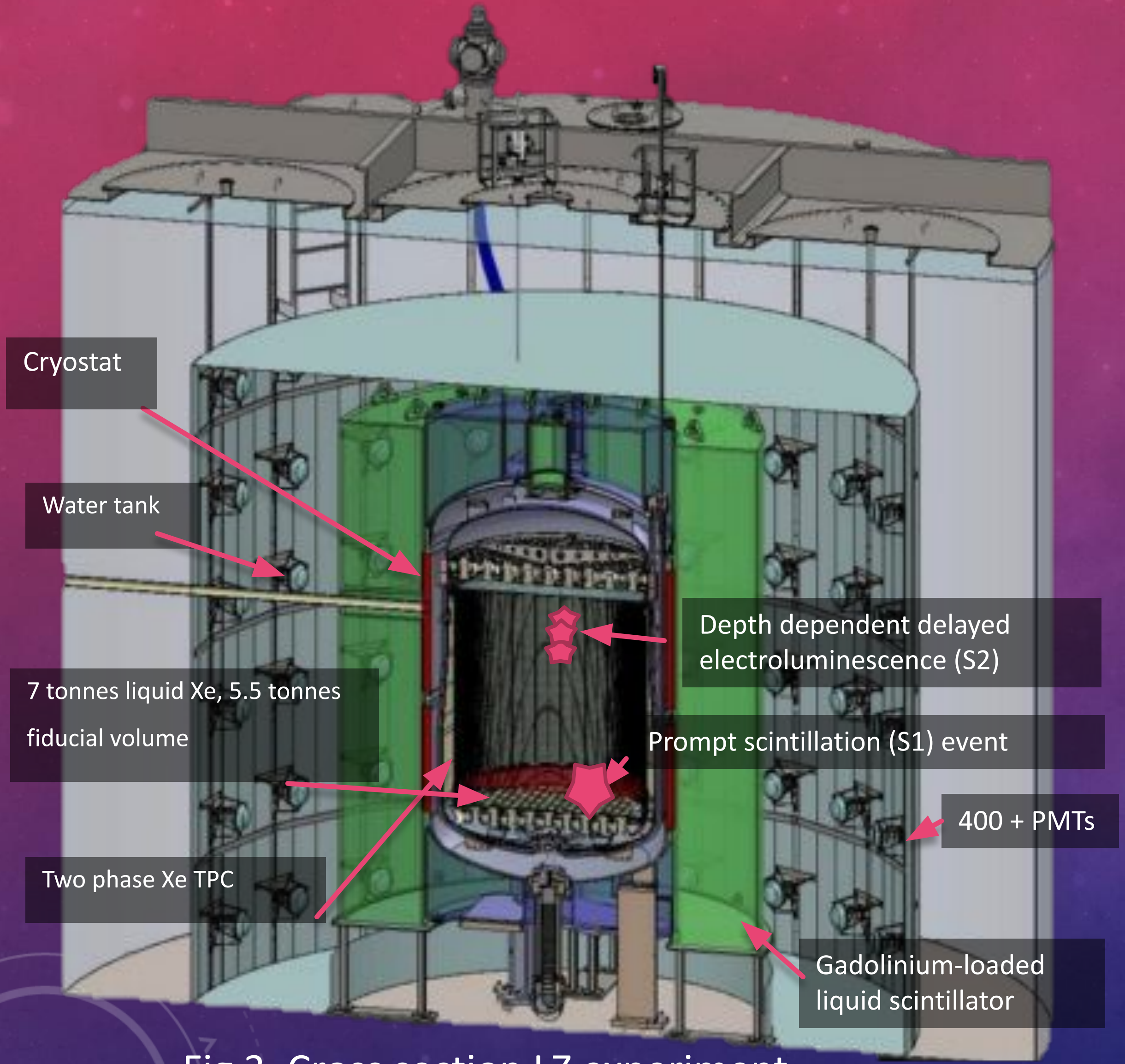
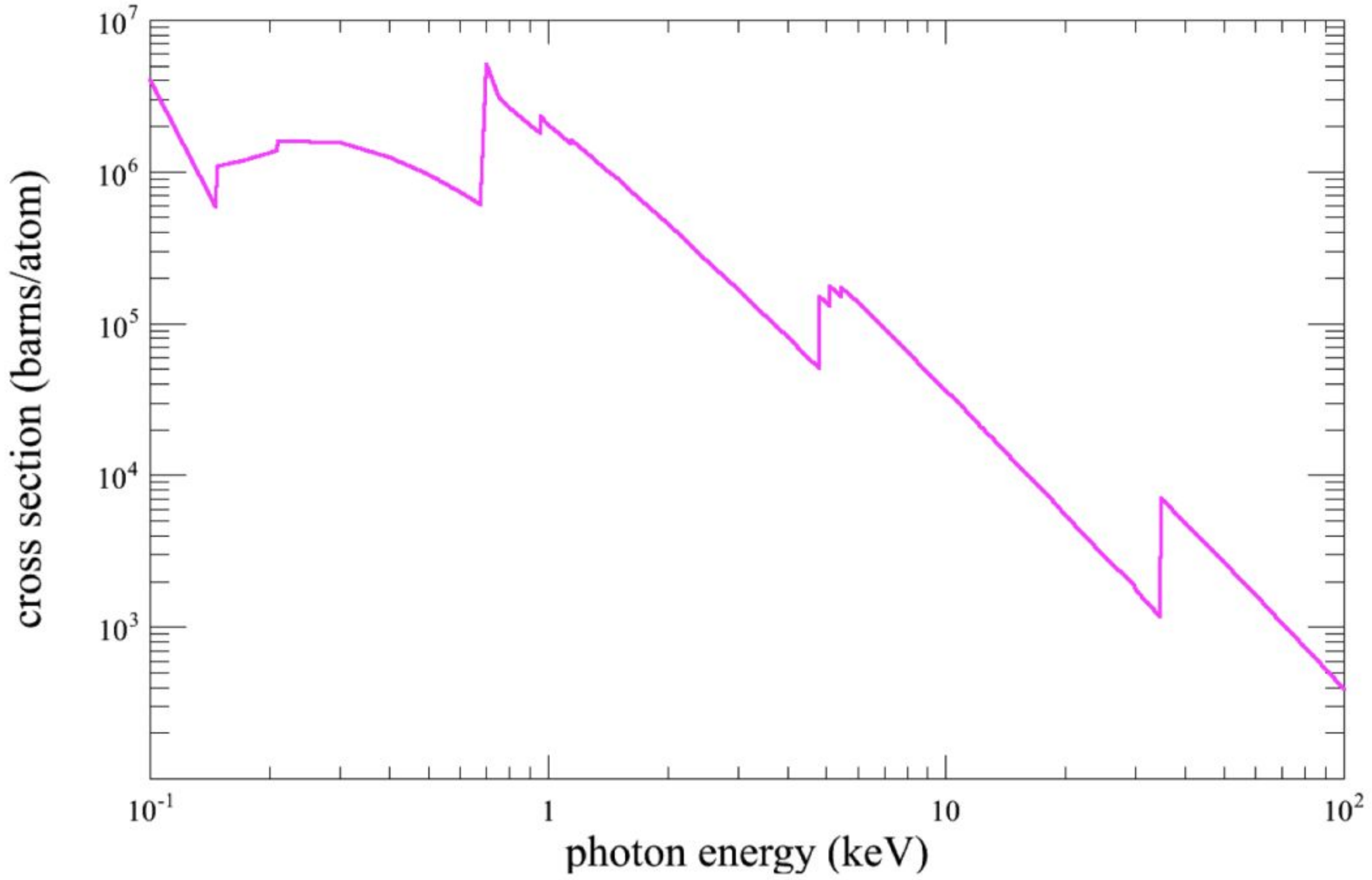


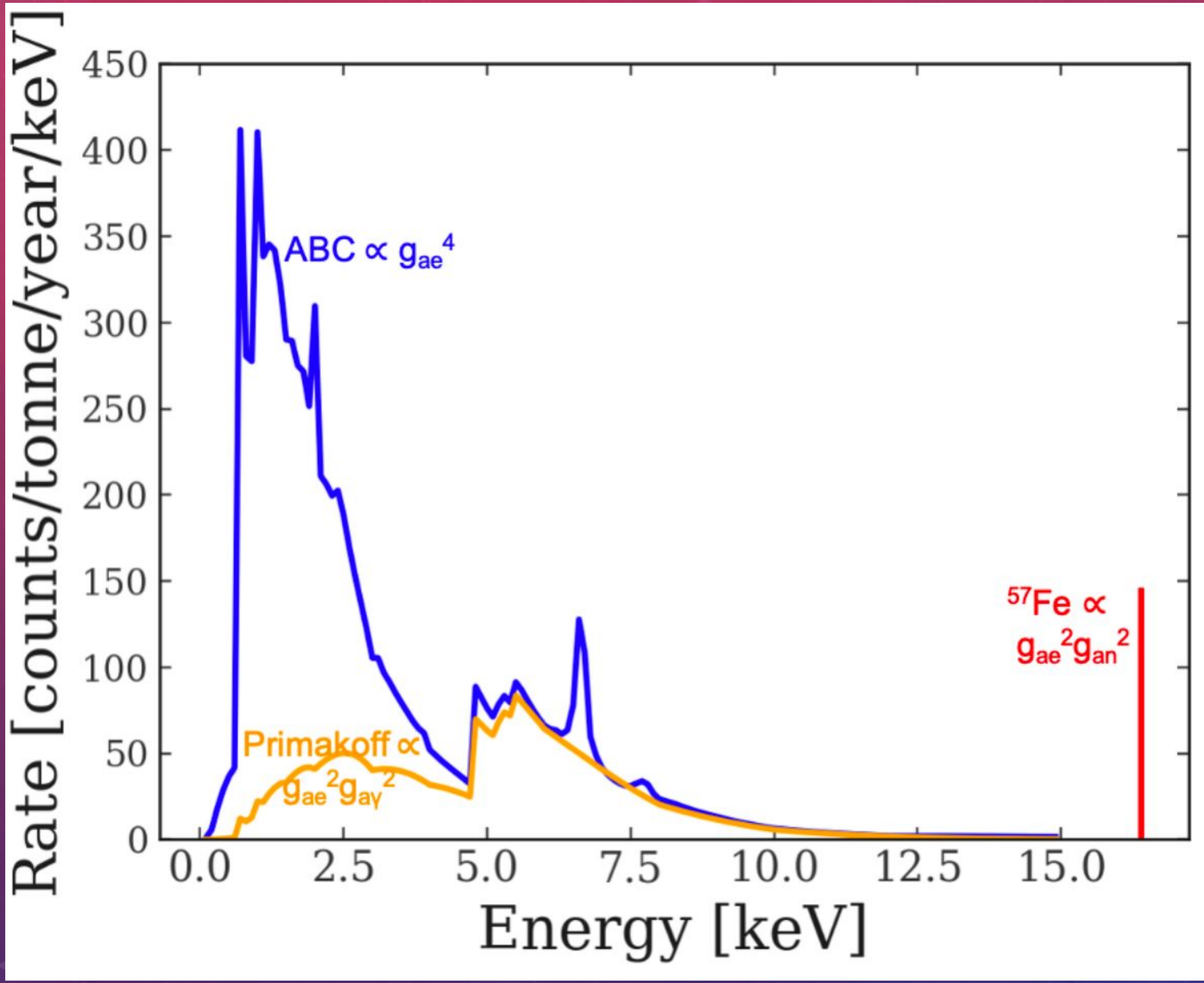
Fig 3. Cross section LZ experiment

- The TPC is surrounded by layers of equipment for best function of the detector:
  - Skin layer detector
  - Cryostat
  - Gadolinium-loaded scintillator
  - Water tank
  - PMTs
  - Steel casing
- Skin detector and gadolinium –loaded scintillator used to attempt to tag incoming particles and remove them from final results



cross section (barns/atom)
10^7
10^6
10^5
10^4
10^3
10^{-1}
1
10
10^2
photon energy (keV)

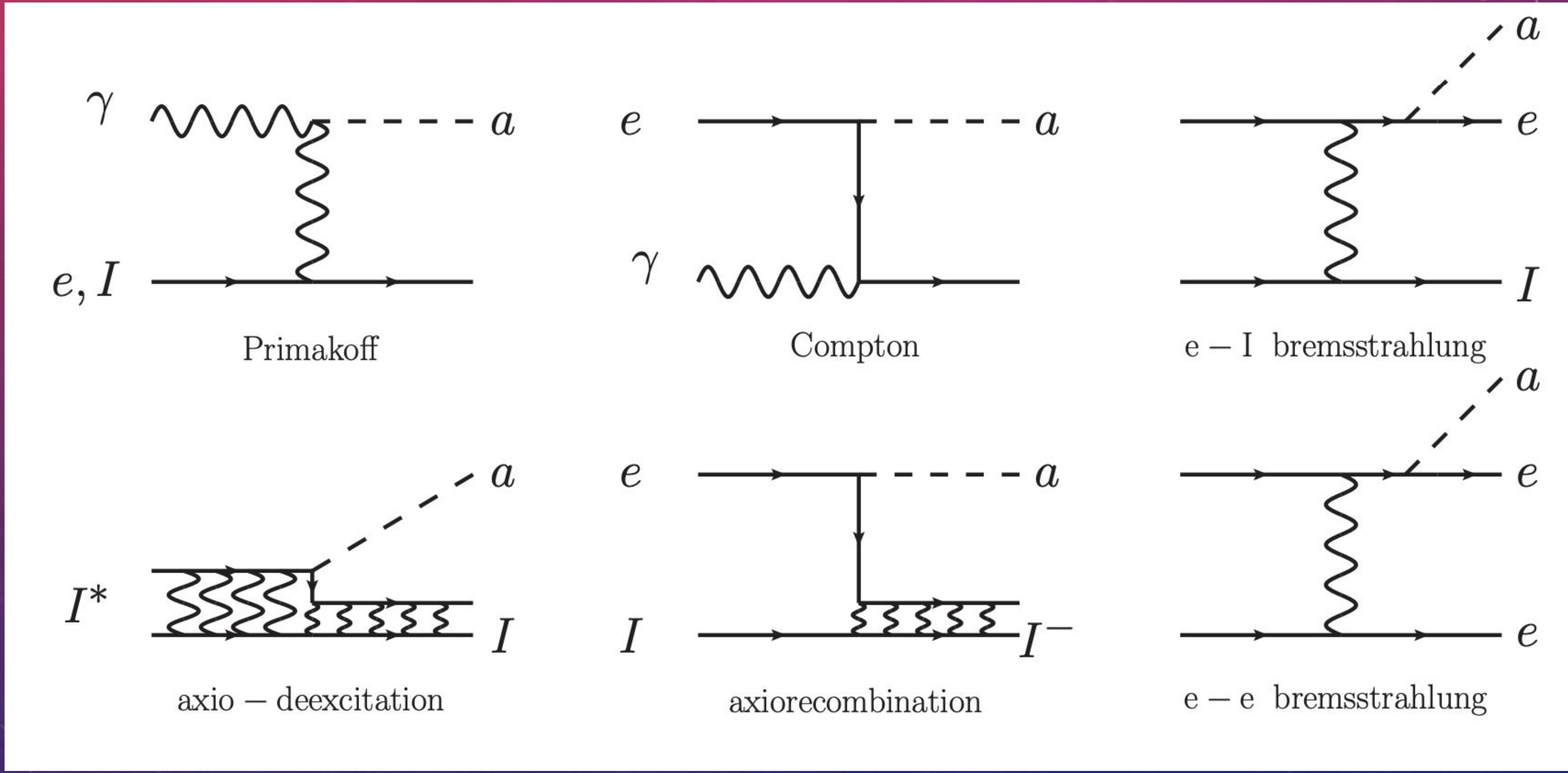
Solar Axions



- Axion: pseudo-scalar Nambu-Goldstone boson: solution to the strong CP problem
- Axions couple to e^- via axio-electric effect
- Produced in the sun through thermal processes:
- Only ABC contribution considered
- Axion-electron cross section has a direct dependence on axion-e^- coupling constant (**g_{ae}**) :

$$\sigma_A = \sigma_{\mathrm{PE}}(E_A)\frac{g_{ae}{}^2}{\beta_A}\frac{3E_A{}^2}{16\pi\alpha m_e{}^2}\left(1-\frac{\beta_A^{2/3}}{3}\right)$$

Solar axion ABC processes



Hidden Photons

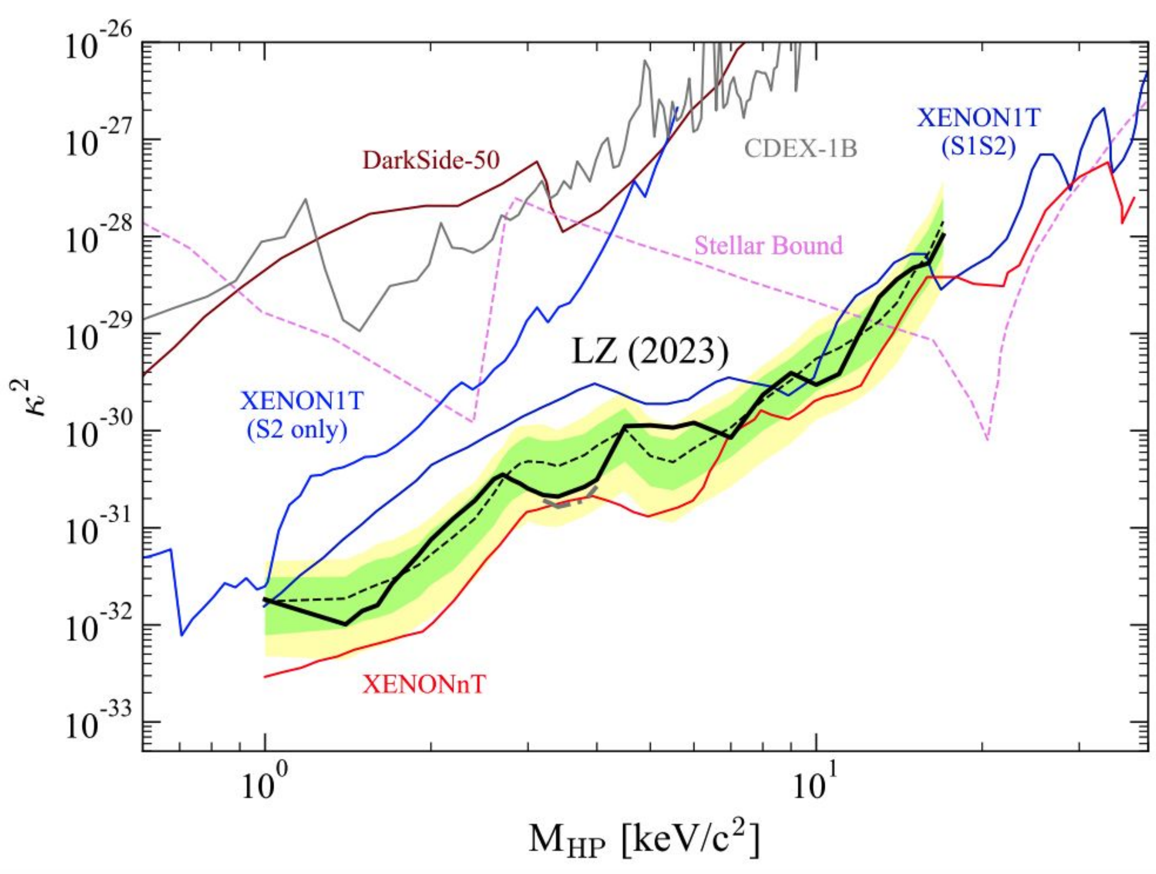


Fig 8. 90% confidence limit sensitivity for hidden photon kinetic mixing parameter (κ^2) for LZ and other experiments Phys. Rev. D 108, 072006

- Hypothetical U(1)′ gauge boson from the hidden sector
- Able to obtain mass through the Hidden Higgs or a Stueckelberg mechanism
- Absorption of hidden photon to bound electron is analogous to photo-electric.

$$\frac{\sigma_{\mathrm{HP}} v}{\sigma_{\mathrm{PE}}(\omega = m_{\mathrm{HP}})c} \approx \frac{\alpha'}{\alpha}$$

- Similar to ALPs, hidden photons produce a monoenergetic signal

Migdal effect

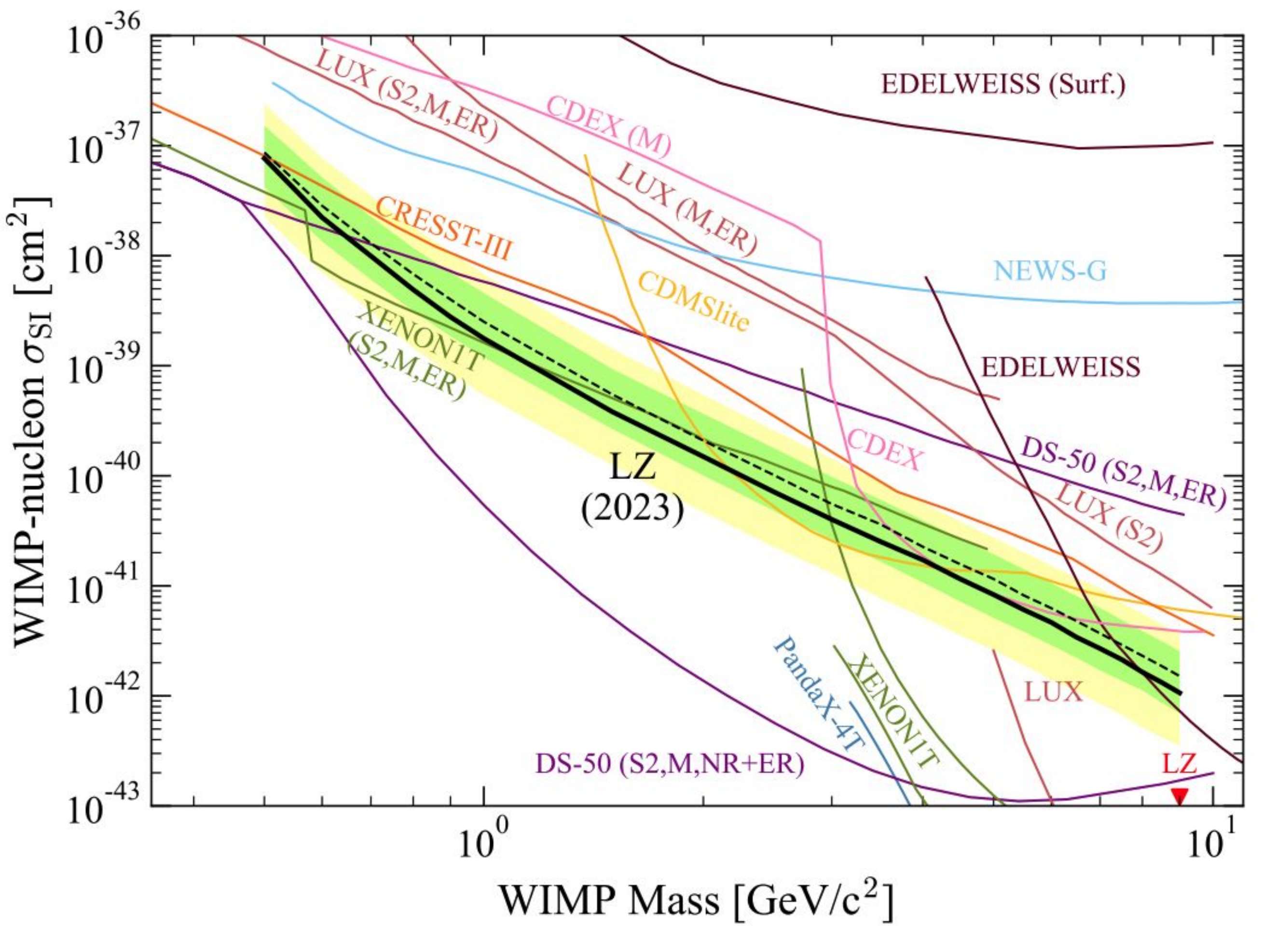


Fig 10. Reconstructed energy spectra for a spin independent Migdal effect from a 5 GeV WIMP Phys. Rev. D 108, 072006

- Electronic ionization when WIMPs scatter off atomic nuclei
- Many variants: spin independent, proton spin dependent, neutron spin dependent
- Allows searches for lighter WIMP masses
- Only ER contributions of Migdal is considered for this work

LZ Science Run 1 (SR1) RESULTS

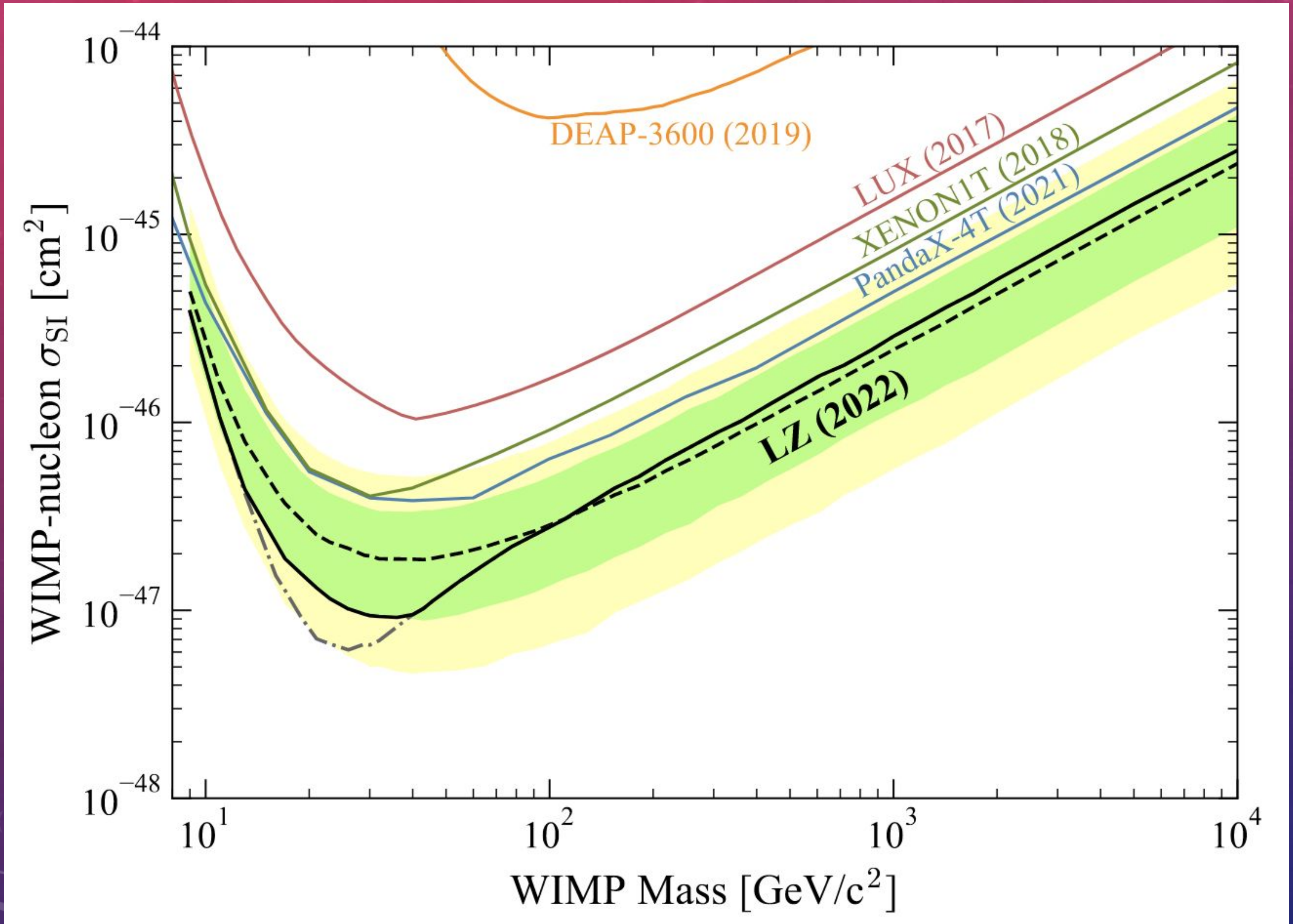


Fig 3. 90% confidence limit black line for SI WIMP-nucleon cross section Phys. Rev. Lett. 131, 041002

- New constraint on the WIMP-nucleon cross-section obtained from SR1
- Obtained highly competitive cross-section for WIMP masses above 30 GeV/c^2