Axion Results with LUX & Future Searches with LZ

Maria Francesca Marzioni
on behalf of the LUX and LZ Collaborations

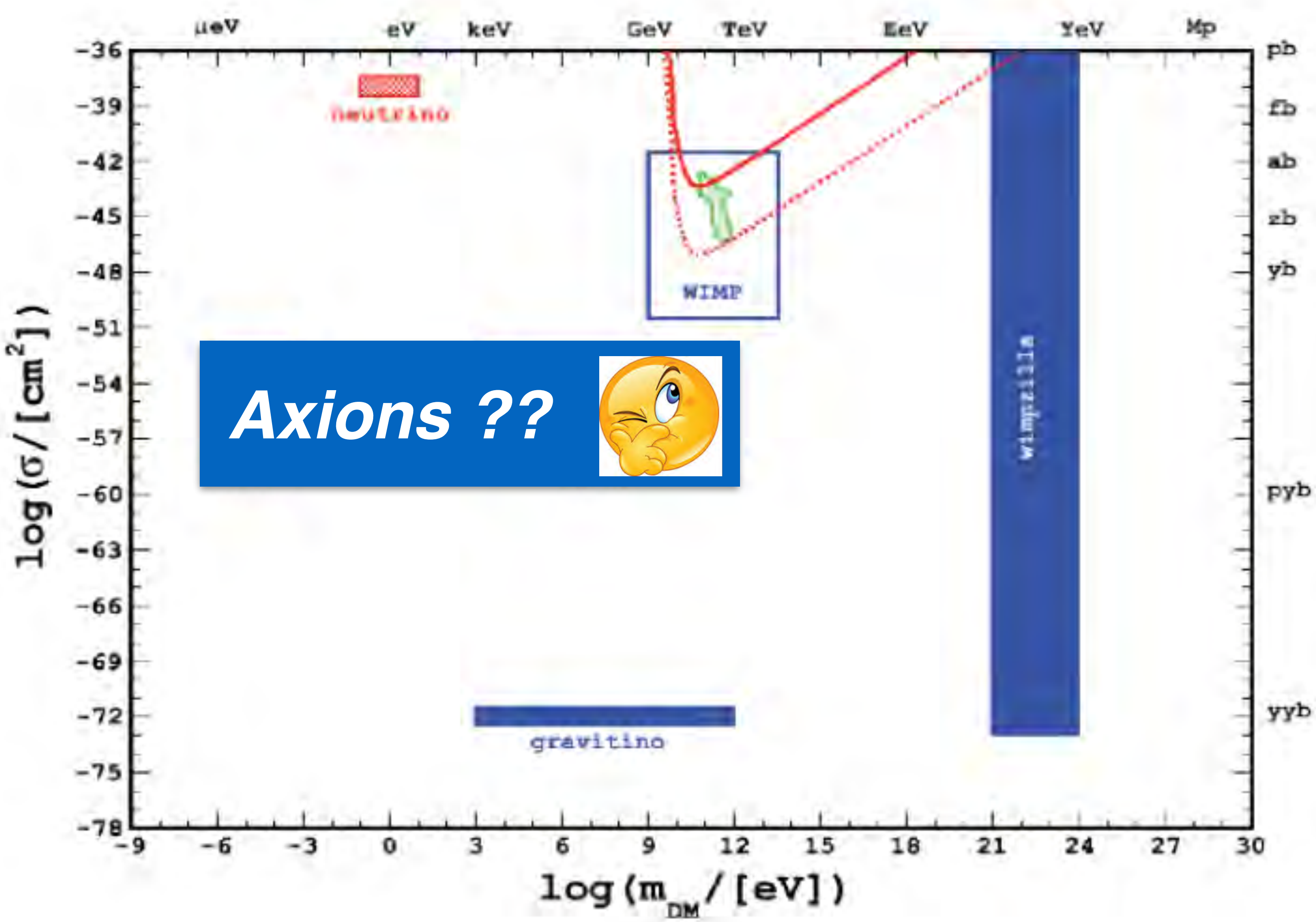
Institute of Physics Joint APP and HEPP Annual Conference, University of Sheffield, 11/04/2017

Outline

- Axions: why, where, how
- Axion searches with xenon time projection chambers
- First axion results with LUX
- Sensitivity for axion searches with LUX-ZEPLIN
- Summary

Why axions ?

- In Particle Physics, the axion field provides a dynamical solution to the strong CP violation problem (Peccei-Quinn solution)

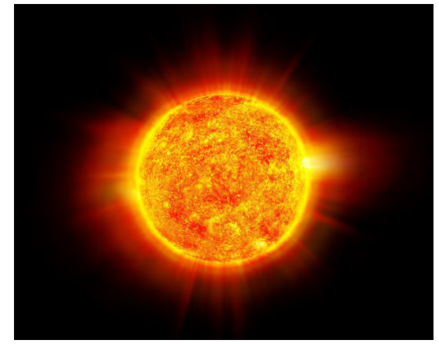


- Axions do have the main DM characteristics: nearly collision-less, neutral, non baryonic, present within the Universe in sufficient quantities to provide the DM density

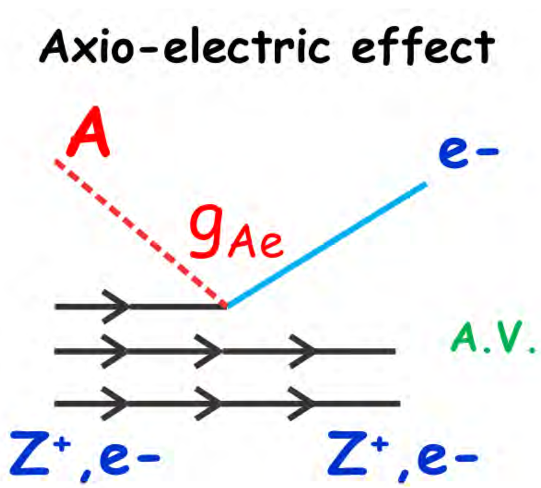
- Extensions of the Standard Model of Particle Physics introduce the so called axion-like particles (ALPs), which could be dark matter candidates
    - The scenario of Dark Matter searches can be wider than just WIMPs

Where do axions come from?

- Potential sources of axions:
  - **axions come from the Sun**
  - **ALPs slowly move within our Galaxy**



How do axions/ALPs couple?



F. T. Avignone et al., Phys. Rev. D 35, 2752 (1987);

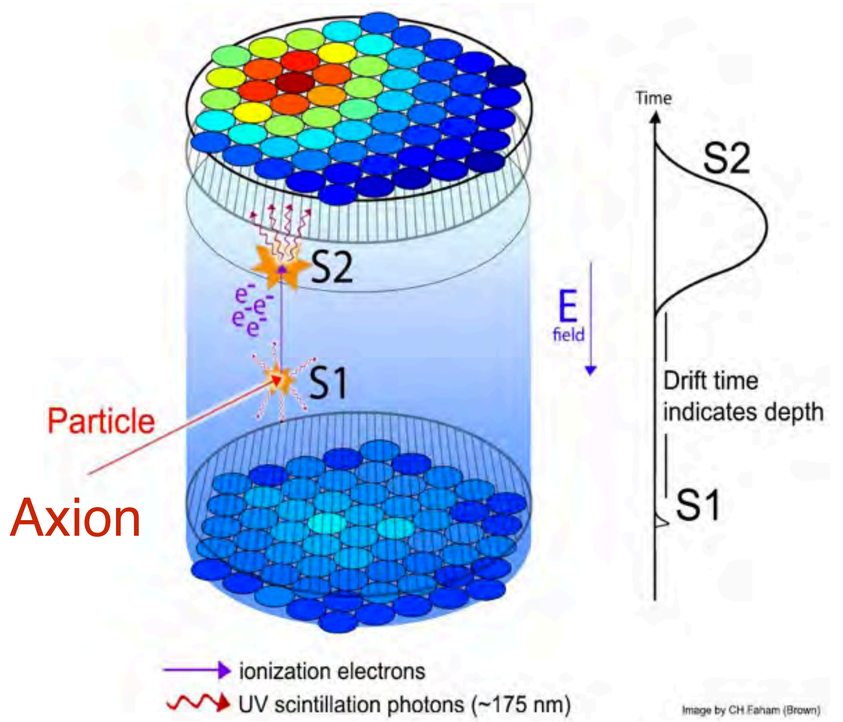
M. Pospelov et al., Nucl. Rev. D 78, 115012 (2008);

A. Derevianko et al., Phys. Rev. D 82, 065006 (2010)

- Axions and ALPs can couple with electrons, via the so called **axio-electric effect**
  - we can measure the coupling between axions/ALPs and electrons (g_{Ae})

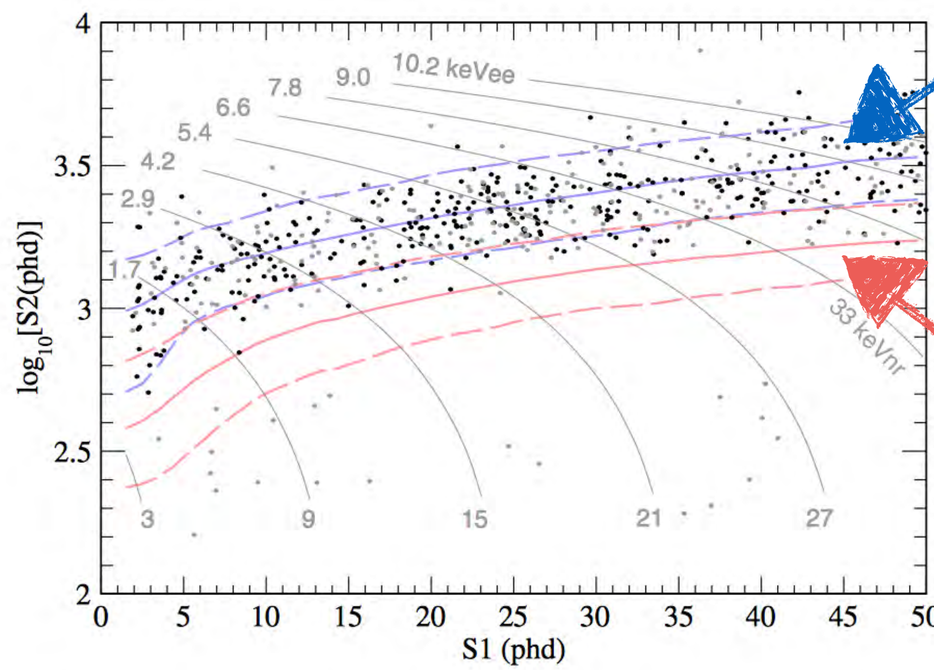
$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta_A}\frac{3E_A^2}{16\pi\alpha_{em}m_e^2}\left(1-\frac{\beta_A^{2/3}}{3}\right)$$

The use of axio-electric effect to detect axions/ALPs with a xenon TPC



- Detection principle for a TPC: the particle, interacting within the detector, produces photons and electrons
    - S1 is the primary scintillation signal (prompt photons)
    - S2 is the secondary ionisation signal from electroluminescence (electrons drift thanks to the applied field)

A good discrimination of nuclear (NR) vs electronic recoil (ER) is possible thanks to the ratio S2/S1: powerful in standard WIMP search, not in axion search



ER band: most of the background + potential axion signal

NR band: few background events + potential WIMP signal

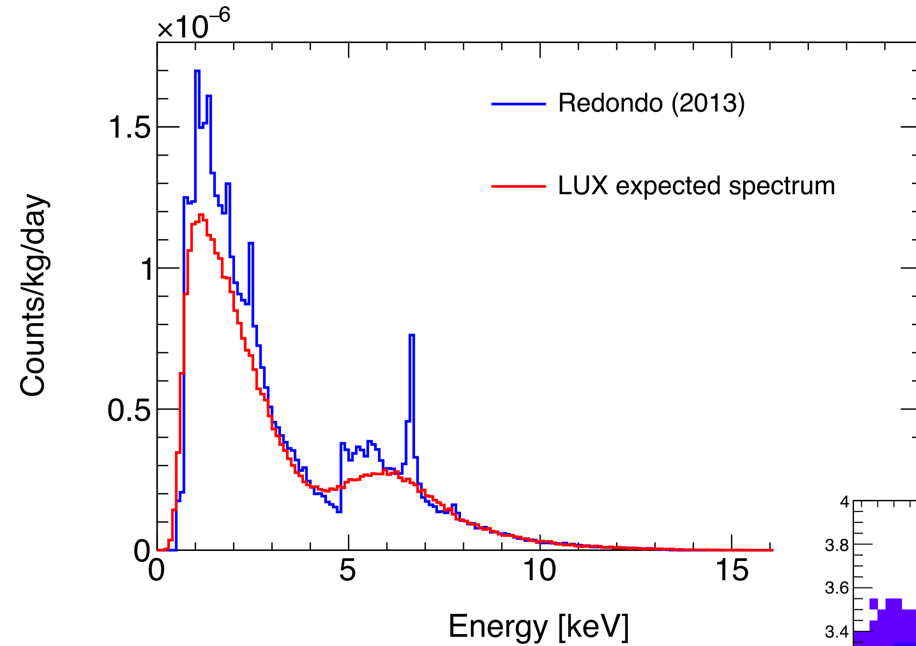
FIG. 2. Observed events in the 2013 LUX exposure of 95 live days and 145 kg fiducial mass. Points at <18 cm radius are black; those at 18–20 cm are gray. Distributions of uniform-in-energy electron recoils (blue) and an example 50 GeV c^{-2} WIMP signal (red) are indicated by 50th (solid), 10th, and 90th (dashed) percentiles of $S2$ at given $S1$. Gray lines, with ER scale of keVee at top and Lindhard-model NR scale of keVnr at bottom, are contours of the linear combined $S1$-and-$S2$ energy estimator [19].

D. S. Akerib et al., Phys. Rev. Lett. 116, 161301 (2016)

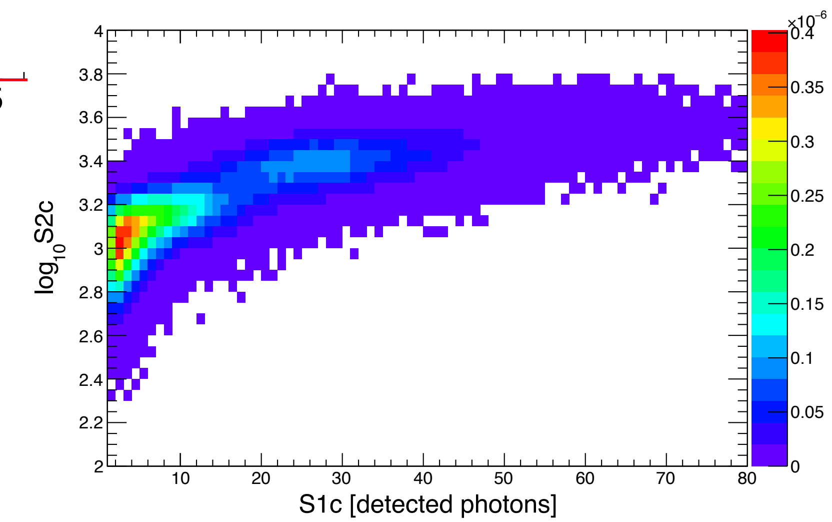
Axion Results with LUX

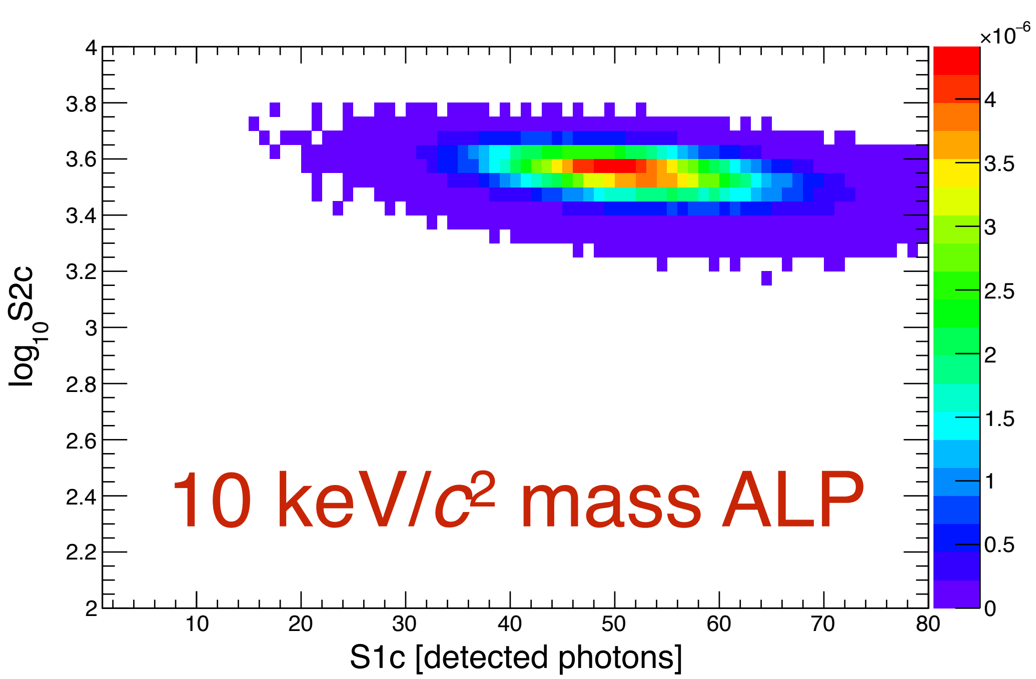
The signal model

- Solar axion spectral shape: product of solar axion flux [J. Redondo, JCAP 12, 008 (2013)] and photo-electric cross section on xenon, assuming massless axions (still valid for masses smaller than 1 keV/c^2)
- Resolution and efficiency effects modelled in accordance with the Noble Element Simulation Technique (NEST) package [M. Szydagis et al., JINST 6, P10002 (2011)]



Solar axions



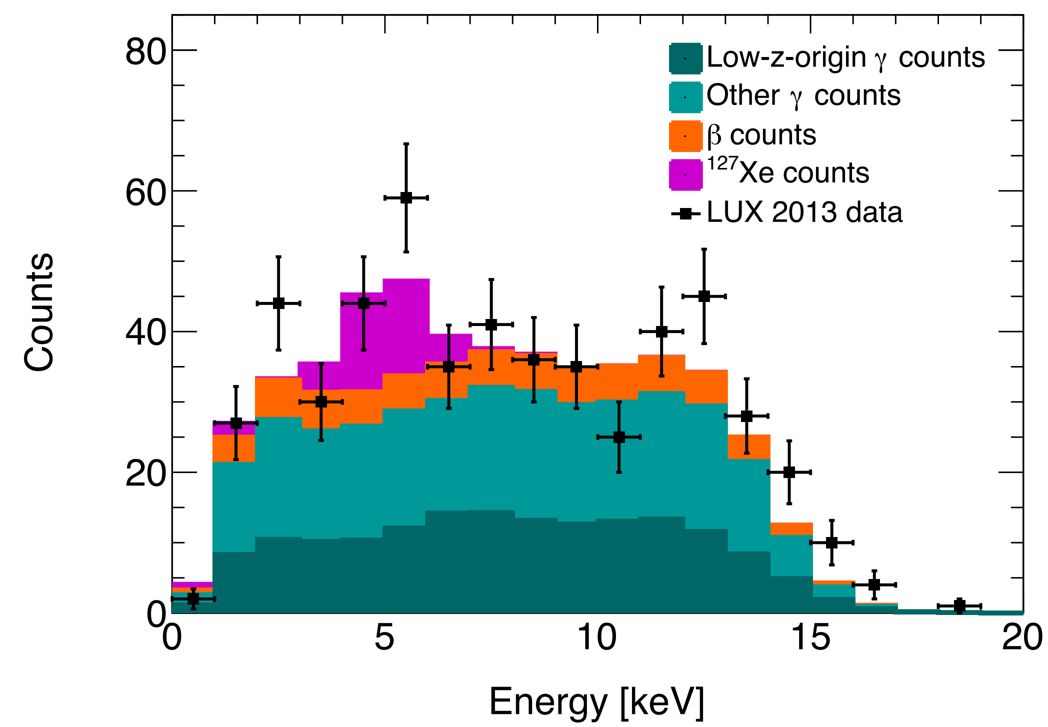


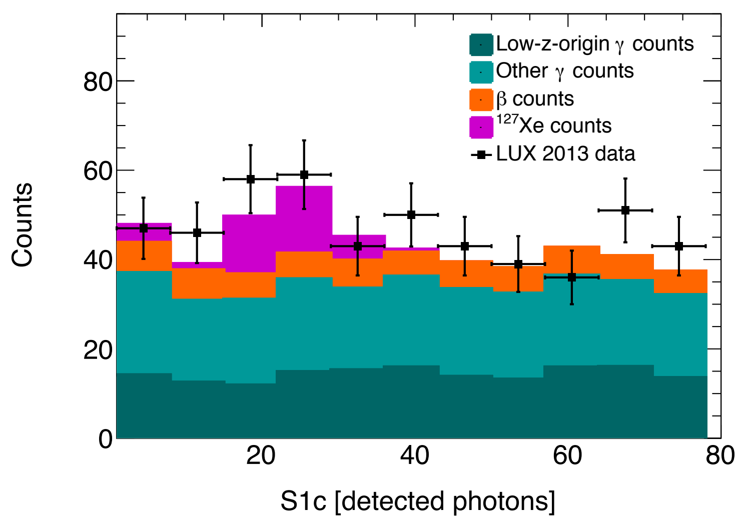
- ALPs expected to be essentially at rest within the galaxy
- Axio-electric absorption leads to electron recoils with kinetic energy equal to the ALP mass: sharp spectral feature, smeared by energy resolution

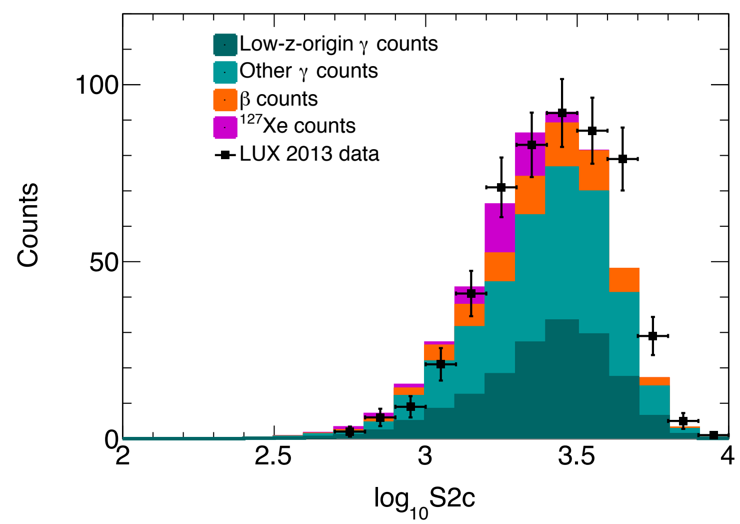
LUX 2013 search data & the background model

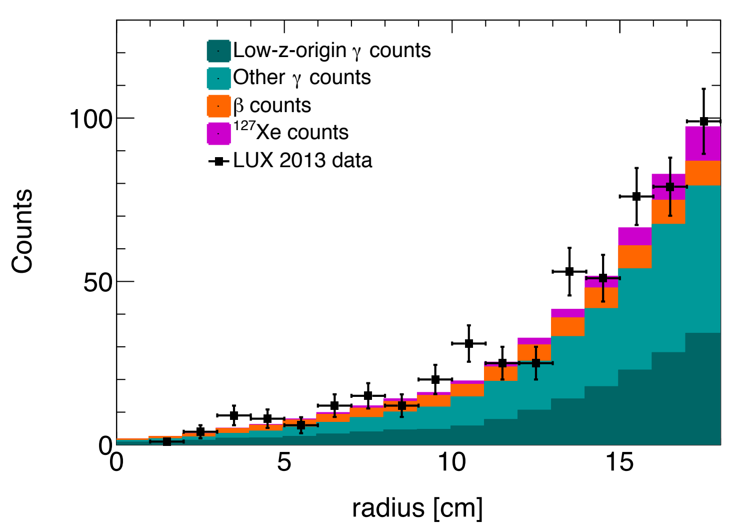
- LUX 2013 data: 95 live-days,118 kg fiducial mass
- Low rate of background radioactivity thanks to detector design, location deep underground, construction materials, xenon self-shielding, active circulation and purification
- Different contributions to the background:
  - Compton scattering of gamma rays from detector component radioactivity
  - ^{85}Kr and Rn-daughter contaminants undergoing beta decays
  - x-rays emitted following those ^{127}Xe electron-capture decays where the coincident gamma escapes the xenon

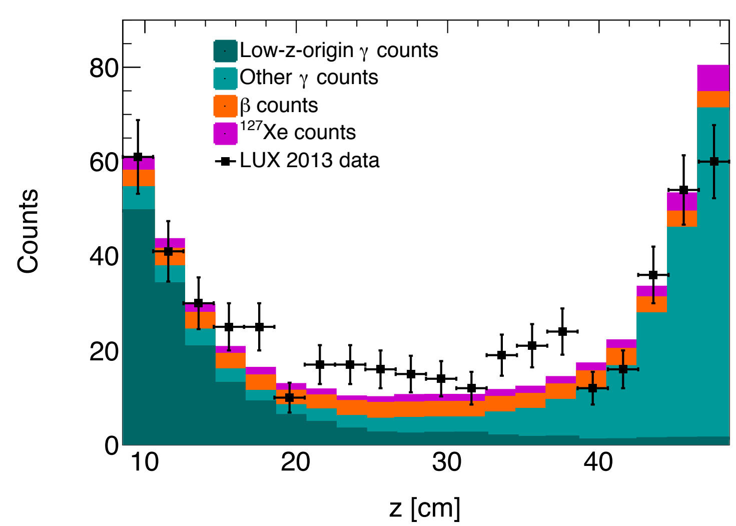
- LUX 2013 data and background model as a function of recoil energy, with the energy reconstructed as E = (S1c/g1+ S2c/(εg2))W
  - g1: geometric light collection efficiency and PMT quantum efficiency
  - εg2: electron extraction efficiency and number of photons detected per electron extracted







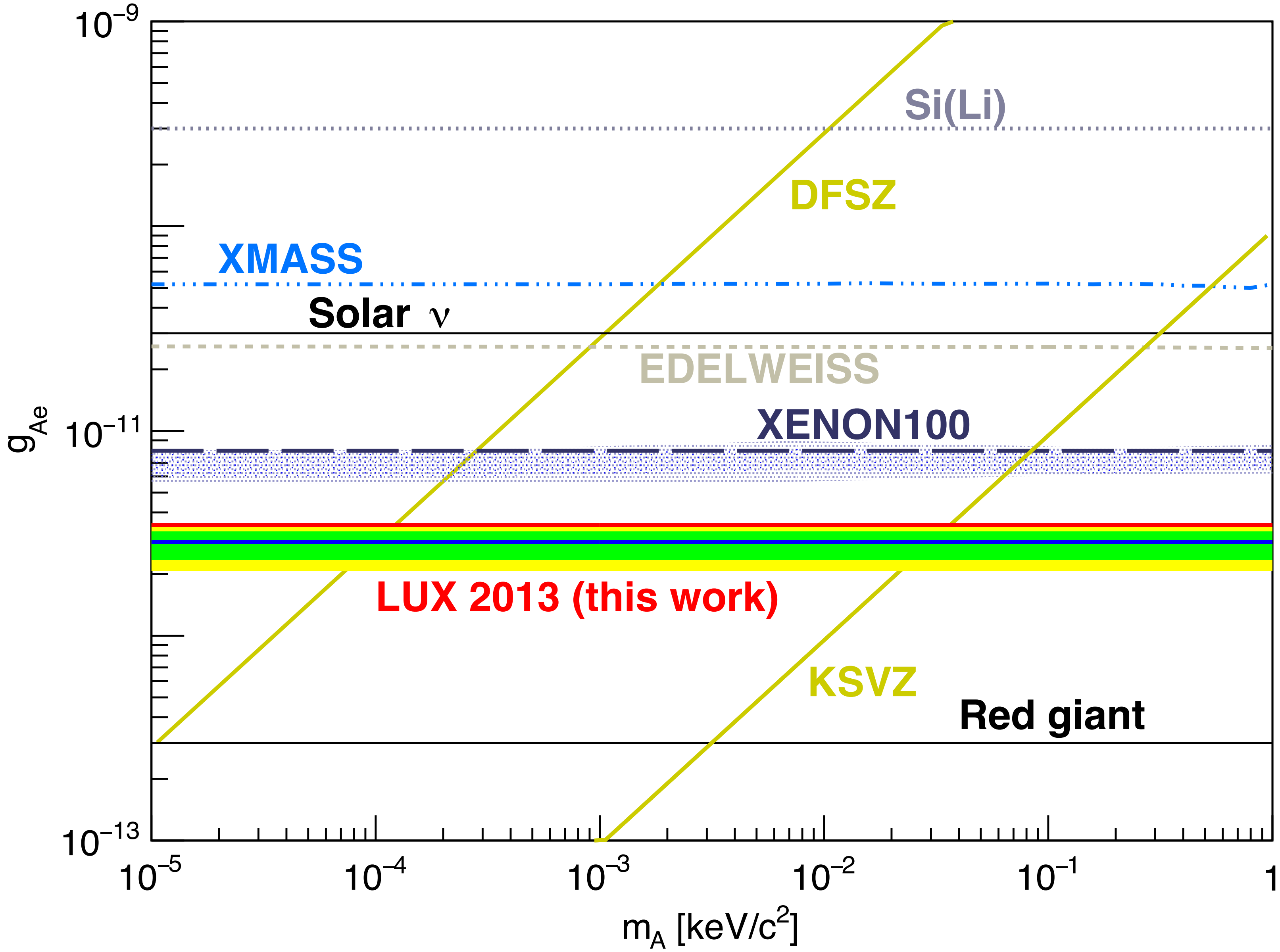




- Backgrounds modelled on the four observables used in the statistical analysis: the prompt scintillation (S1) and the logarithm in base 10 of the proportional (S2) signal, and the radius (r) and depth (z) of the event location
- Statistical PLR (Profile Likelihood Ratio) analysis, aimed at setting a two-sided limit on the coupling between axions/ALPs and electrons g_{Ae}, having the BG rates as nuisance parameters

LUX solar axions result

arXiv:1704.02297 [astro-ph.CO] (2017)

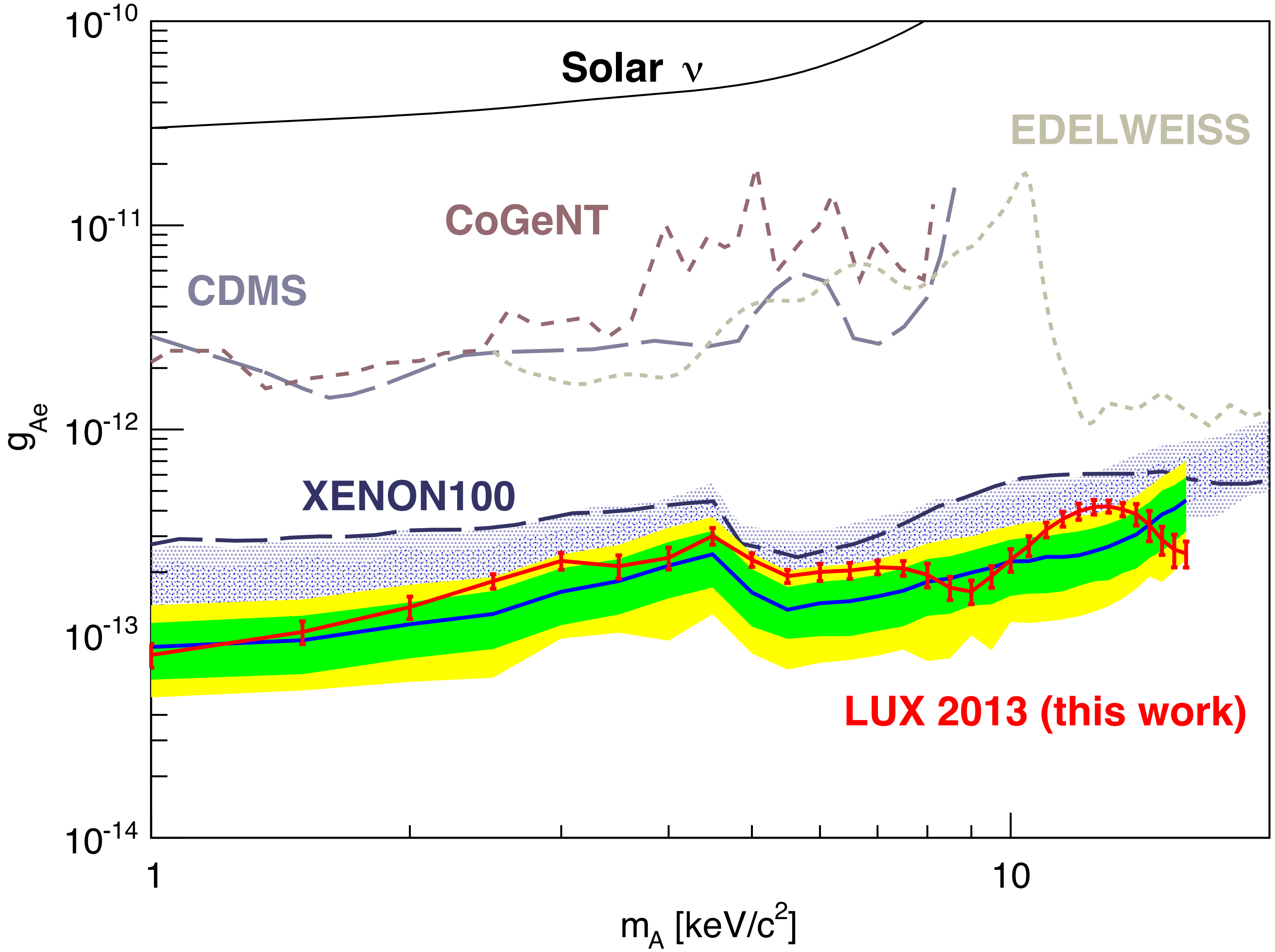


- QCD axion theoretical models:
  - **DFSZ**: axion is the phase of a new electroweak singlet scalar field and couples to a new heavy quark, not to SM ones
  - **KSVZ**: axion does not couple directly to quarks and leptons, but via its interaction with two Higgs doublets
- **Red Giant** limit: the degenerate core of a low-mass red giant before helium ignition is a helium white dwarf; the observed white-dwarf luminosity function reveals that their cooling speed agrees with expectations, constraining new cooling agents such as axion emission

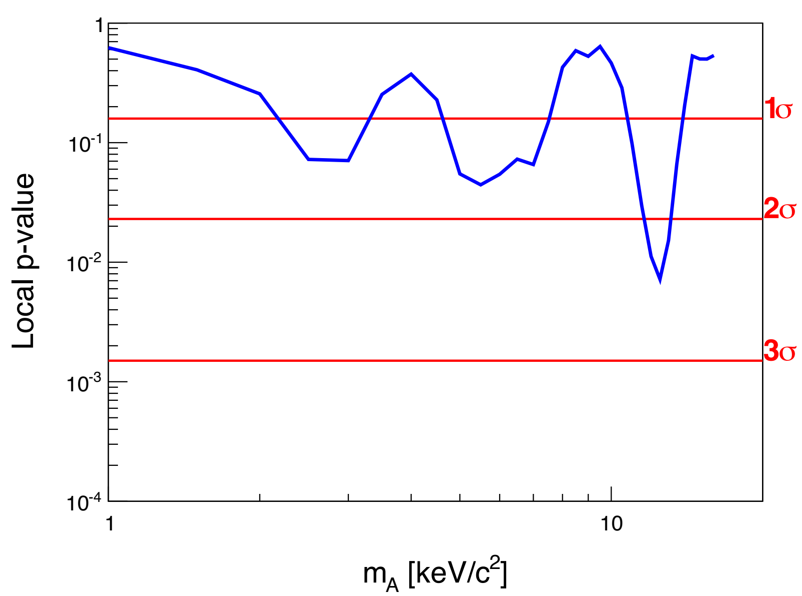
LUX 2013 excludes $g_{Ae} > 3.5 \times 10^{-12}$ (90% CL)
LUX 2013 excludes $m_A > 0.12$ eV/c^2 (DFSZ model)
LUX 2013 excludes $m_A > 36.6$ eV/c^2 (KSVZ model)

galactic ALPs result

arXiv:1704.02297 [astro-ph.CO] (2017)



- Local p-value as a function of the ALP mass, with the corresponding number of standard deviations (σ) away from the null hypothesis
- At 12.5 keV/c^2 a local p-value of 7.2×10^{-3} (2.4σ deviation) corresponds to a global p-value of 5.2×10^{-2} (1.6σ deviation) — applying the Look Elsewhere Effect [E. Gross and O. Vitells, Eur. Phys. J., C70:525 (2010)]



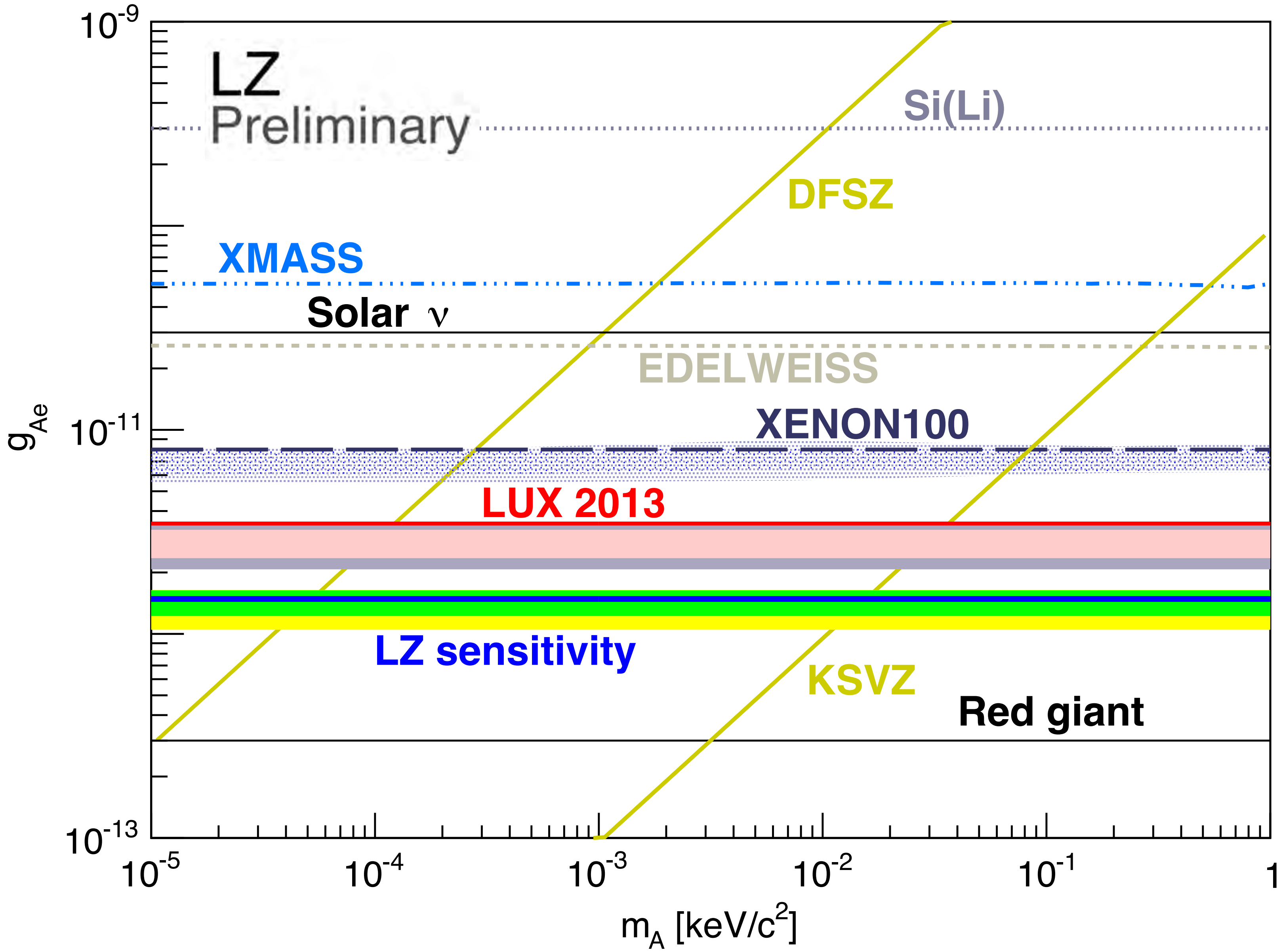
LUX 2013 excludes $g_{Ae} > 4.2\text{x}10^{-13}$ (90% CL) across the range 1-16 keV/c^2 in ALP mass

Future Searches with LZ

Sensitivity for axion searches with LZ

- LZ expected exposure: 1000 live-days, 5.6 ton fiducial mass
- Low rate of background radioactivity thanks to detector design, location deep underground, construction materials and xenon self-shielding
- Different contributions to the background:
  - Compton scattering of gamma rays from detector component radioactivity
  - ^{85}Kr and Rn-daughter contaminants undergoing beta decays
  - neutrinos (atmospheric, PP solar)
- Statistical PLR (Profile Likelihood Ratio) analysis, aimed at setting a two-sided limit on the coupling between axions/ALPs and electrons g_{Ae}, having the BG rates as nuisance parameters and S1 and S2 as observables

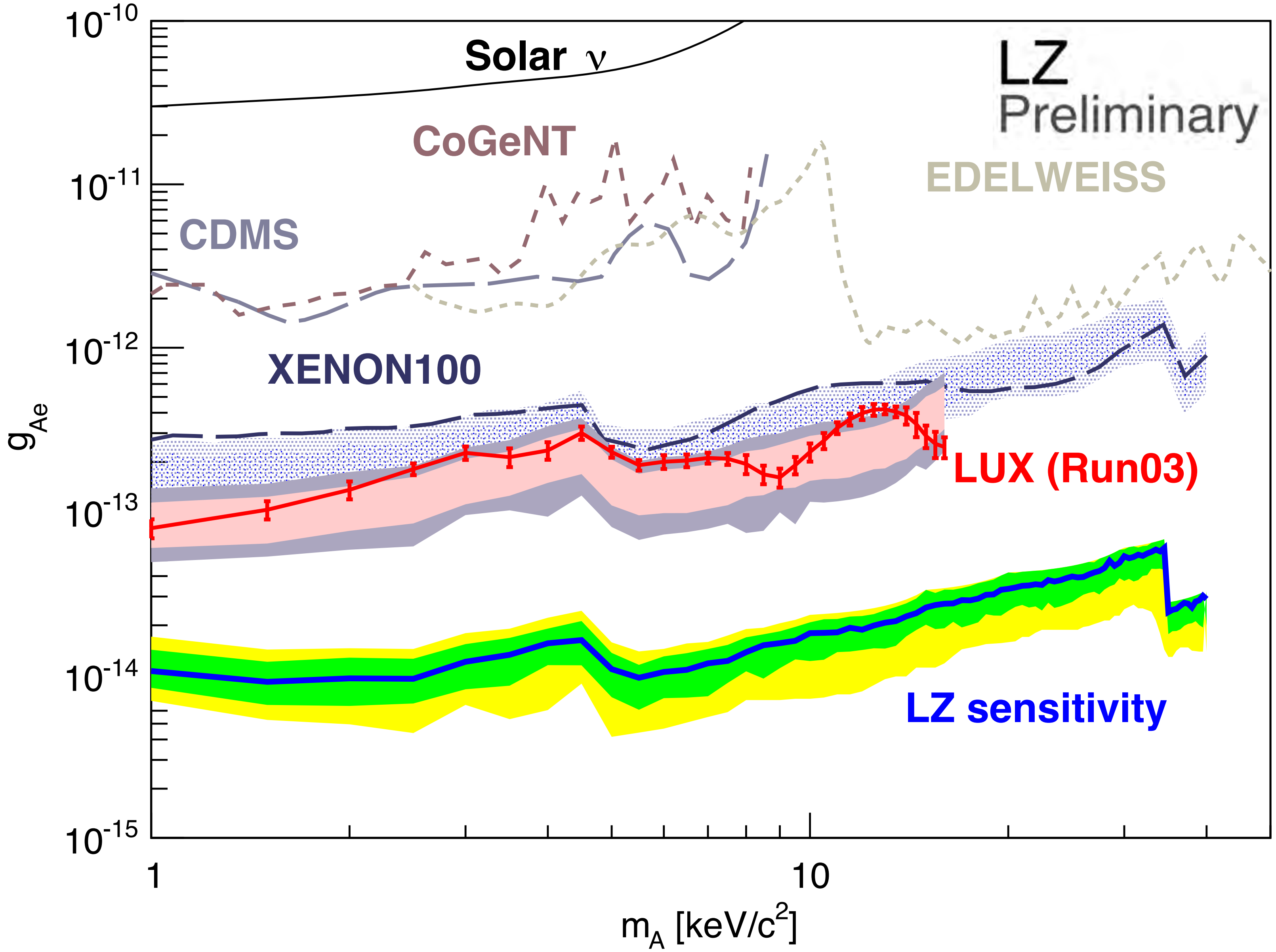
most recent solar axions sensitivity projection



LZ sensitivity (1000 live-days, 5.6 ton fiducial mass) excludes $g_{Ae} > 1.5 \times 10^{-12}$ (90% CL)

- QCD axion theoretical models:
  - **DFSZ**: axion is the phase of a new electroweak singlet scalar field and couples to a new heavy quark, not to SM ones
  - **KSVZ**: axion does not couple directly to quarks and leptons, but via its interaction with two Higgs doublets
- **Red Giant** limit: the degenerate core of a low-mass red giant before helium ignition is a helium white dwarf; the observed white-dwarf luminosity function reveals that their cooling speed agrees with expectations, constraining new cooling agents such as axion emission

most recent galactic ALPs sensitivity projection



LZ sensitivity (1000 live-days, 5.6 ton fiducial mass) excludes $g_{Ae} > 5.9\times10^{-14}$ (90% CL) across the range 1-40 keV/c^2 in ALP mass

Summary

- Xenon detectors (such as LUX and LZ) present suitable characteristics to test models beyond the standard WIMP scenario
- QCD axions can solve the strong CPV problem
- Some classes of axions/axion-like particles are also suitable Dark Matter candidates
- Axion signal in a xenon TPC is expected in the ER band, where also most of the backgrounds sit
- A Profile Likelihood Ratio statistical strategy is used to set an upper limit on the coupling g_{Ae}, using the most meaningful experimental quantities as observables
- LUX 2013 delivers the most stringent constraints to date for these interactions (**yesterday on arXiv:1704.02297**) and the analysis of the full LUX exposure is planned
- LZ will be able to probe a wider phase space thanks to its sensitivity

Thank you!

It's been a very interesting year for LUX!
arXiv:1704.02297 (2017)
Phys. Rev. D 95, 012008 (2017)
Phys. Rev. Lett. 118, 021303 (2017)
Phys. Rev. Lett. 116, 161302 (2016)
Phys. Rev. Lett. 116, 161301 (2016)
Phys. Rev. D 93, 072009 (2016)

The LUX collaboration

Berkeley Lab / UC Berkeley

Bob Jacobsen	PI, Professor
Murdock Gilchriese	Senior Scientist
Kevin Lesko	Senior Scientist
Michael Witherell	Lab Director
Peter Sorensen	Scientist
Simon Fiorucci	Project Scientist
Attila Dobi	Postdoc
Daniel Hogan	Graduate Student
Kate Kamdin	Graduate Student
Kelsey Oliver-Mallory	Graduate Student

Brown University

Richard Gaitskell	PI, Professor
Samuel Chung	Graduate Student
Dongqing Huang	Graduate Student
Casey Rhyne	Graduate Student
Will Taylor	Graduate Student
James Verbus	Graduate Student

University of Edinburgh, UK

Alex Murphy	PI, Professor
Paolo Beltrame	Research Fellow
Tom Davison	Graduate Student
Maria F. Marzioni	Graduate Student

Imperial College London, UK

Henrique Araujo	PI, Reader
Tim Sumner	Professor
Alastair Currie	Postdoc
Adam Bailey	Graduate Student
Khadeeja Yazdani	Graduate Student

Lawrence Livermore

Adam Bernstein	PI, Leader of Adv. Detectors Grp.
Kareem Kazkaz	Staff Physicist
Jingke Xu	Postdoc
Brian Lenardo	Graduate Student

LIP Coimbra, Portugal

Isabel Lopes	PI, Professor
Jose Pinto da	Assistant Professor
Vladimir Solovov	Senior Researcher
Francisco Neves	Auxiliary Researcher
Alexander Lindote	Postdoc
Claudio Silva	Postdoc
Paulo Bras	Graduate Student

SLAC Stanford (CWRU)

Dan Akerib	PI, Professor
Thomas Shutt	PI, Professor
Tomasz Biesiadzinski	Research Associate
Christina Ignarra	Research Associate
Wing To	Research Associate
Rosie Bramante	Graduate Student
Wei Ji	Graduate Student
T.J. Whitis	Graduate Student

SD Mines

Xinhua Bai	PI, Professor
Doug Tiedt	Graduate Student

SDSTA / Sanford Lab

David Taylor	Project Engineer
Markus Horn	Research Scientist
Dana Byram	Support Scientist

University at Albany

Matthew Szydagis	PI, Professor
Jeremy Mock	Postdoc
Sean Fallon	Graduate Student
Steven Young	Graduate Student

Texas A&M University

James White †	PI, Professor
Robert Webb	PI, Professor
Rachel Mannino	Graduate Student
Paul Terman	Graduate Student

UC Berkeley (Yale)

Daniel McKinsey	PI, Professor
Ethan Bernard	Project Scientist
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Elizabeth Boulton	Graduate Student
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Lucie Tvrznikova	Graduate Student
Nicole Larsen	Graduate Student

UC Davis

Mani Tripathi	PI, Professor
Britt Hollbrook	Senior Engineer
John Thomson	Development
Dave Hemer	Senior Machinist
Ray Gerhard	Electronics Engineer
Aaron Manalaysay	Project Scientist
Jacob Cutter	Graduate Student
James Morad	Graduate Student
Sergey Uvarov	Graduate Student

UC Santa Barbara

Harry Nelson	PI, Professor
Susanne Kyre	Engineer
Dean White	Engineer
Carmen Carmona	Postdoc
Scott Haselschwardt	Graduate Student
Curt Nehrkorn	Graduate Student
Melih Solmaz	Graduate Student

University College London, UK

Chamkaur Ghag	PI, Lecturer
James Dobson	Postdoc
Sally Shaw	Graduate Student

University of Maryland

Carter Hall	PI, Professor
Jon Balajthy	Graduate Student
Richard Knoche	Graduate Student

University of Rochester

Frank Wolfs	PI, Professor
Wojtek Skutski	Senior Scientist
Eryk Druszkiewicz	Graduate Student
Dev Ashish Khaitan	Graduate Student
Diktat Koyuncu	Graduate Student
M. Moongweluwan	Graduate Student
Jun Yin	Graduate Student

University of South Dakota

Dongming Mei	PI, Professor
Chao Zhang	Postdoc

University of Wisconsin

Kimberly Palladino	PI, Asst Professor
Shaun Alsum	Graduate Student

The LZ collaboration

- LIP Coimbra (Portugal)
- Center for Underground Physics (Korea)
- MEPhI (Russia)
- Edinburgh University (UK)
- University of Liverpool (UK)
- Imperial College London (UK)
- University College London (UK)
- University of Oxford (UK)
- STFC Rutherford Appleton Laboratories (UK)
- University of Sheffield (UK)
- University of Alabama
- University at Albany SUNY
- Berkeley Lab (LBNL)
- University of California, Berkeley
- Brookhaven National Laboratory
- Brown University
- University of California, Davis
- Fermi National Accelerator Laboratory
- Lawrence Livermore National Laboratory
- University of Maryland
- University of Michigan
- Northwestern University
- University of Rochester
- University of California, Santa Barbara
- University of South Dakota
- South Dakota School of Mines & Technology
- South Dakota Science and Technology Authority
- SLAC National Accelerator Laboratory
- Texas A&M
- Washington University
- University of Wisconsin

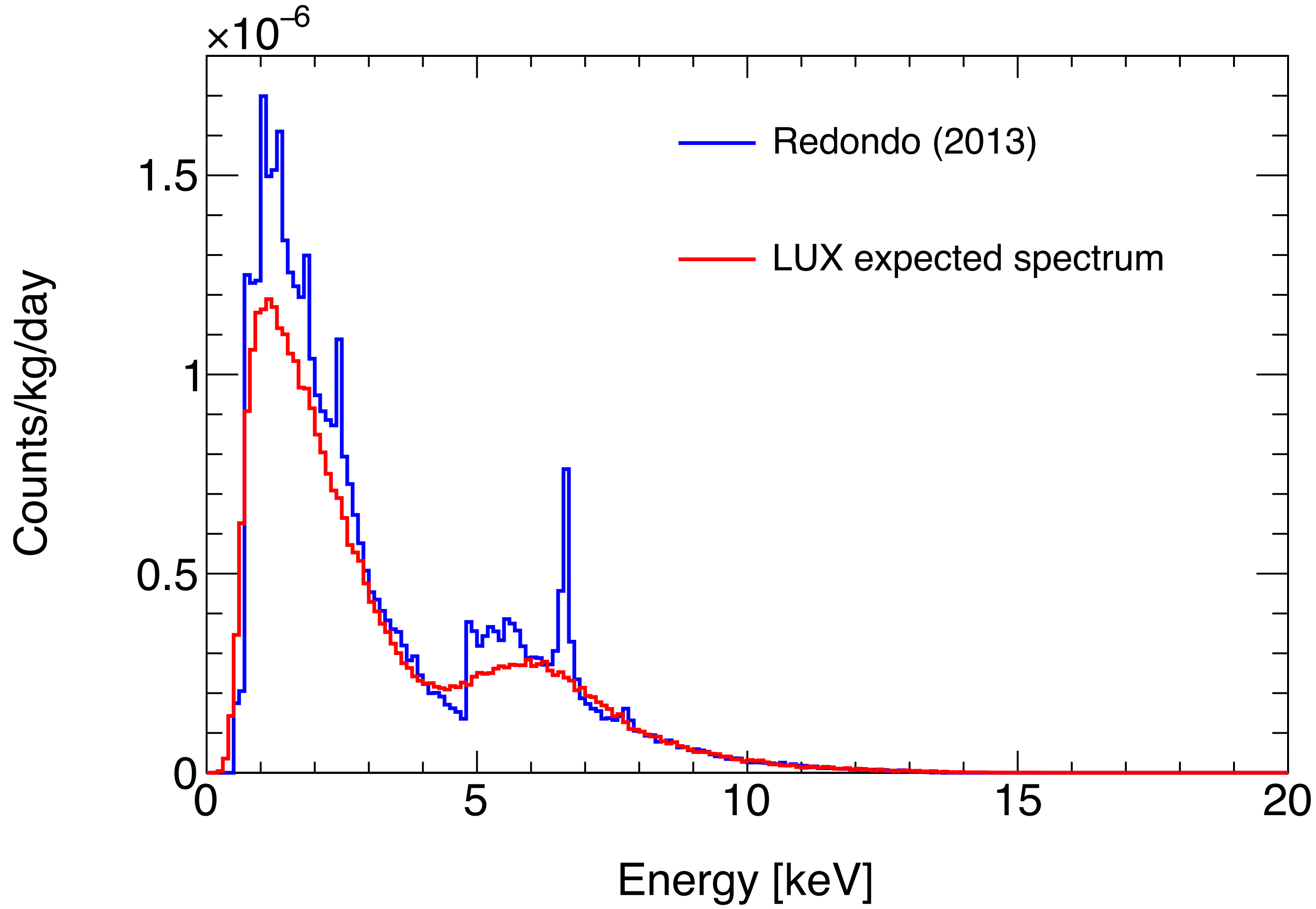
Back-up slides

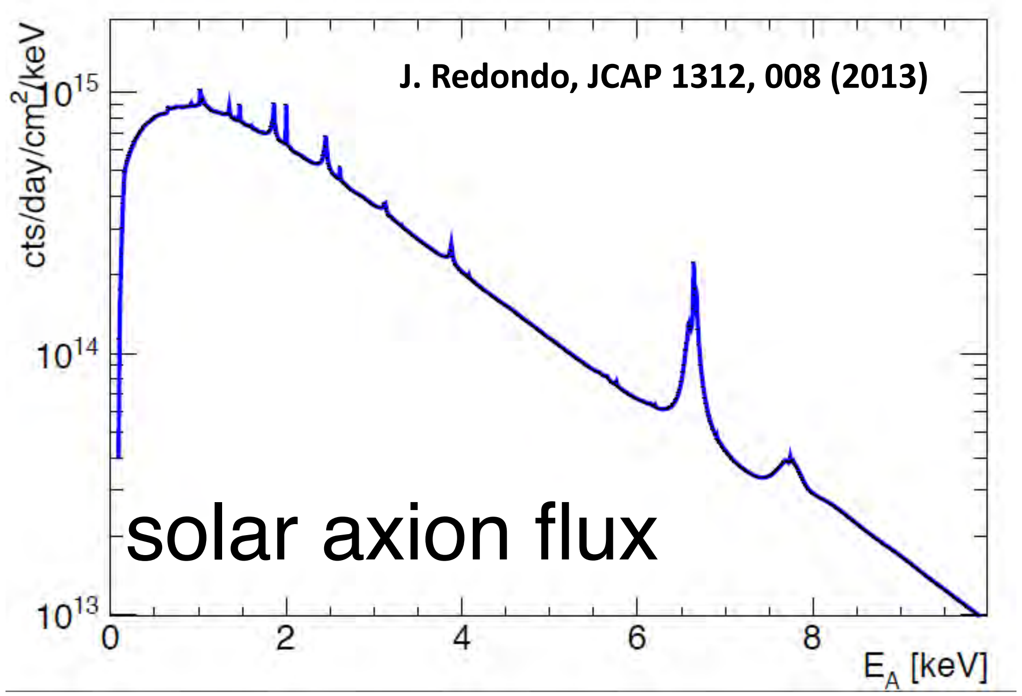
Limit conversion: nSig to gAe

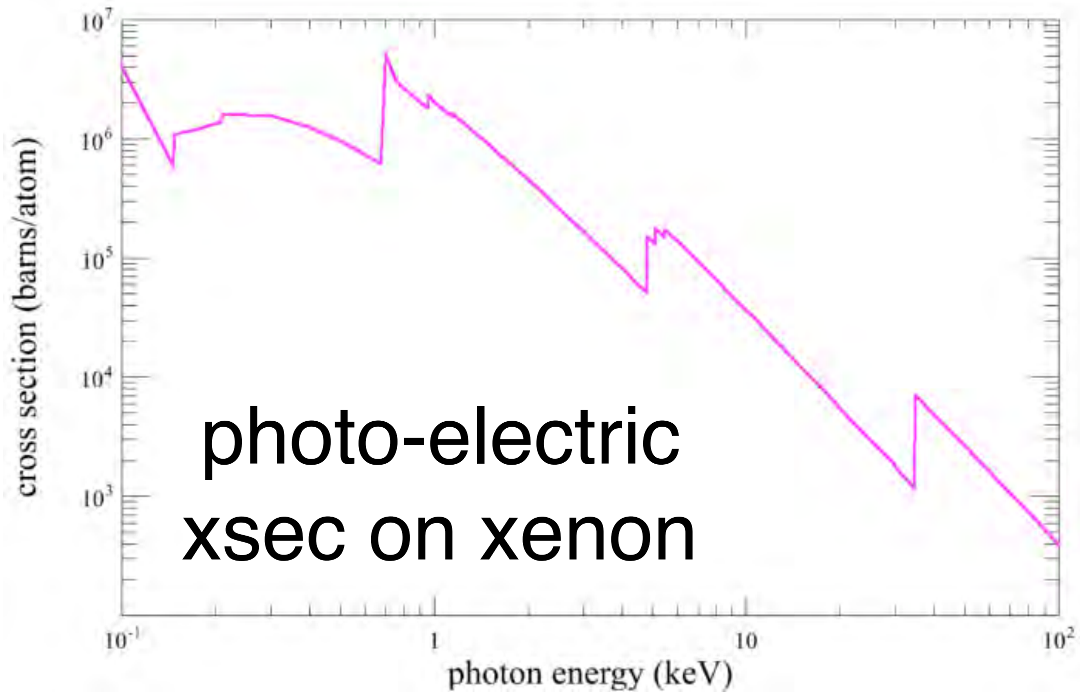
- Limit on **$gAe = gAe_{sim} * (nSig/nPDF)^{power}$**
  - gAe_{sim} = arbitrary coupling used to generate the signal model
  - nSig = limit set by the PLR on the number of events
  - nPDF = integral of the signal PDFs * exposure * fiducial mass
  - power varies with the axion type
    - it is 0.25 for solar axions, as the interaction rate scales with gAe^4
    - it is 0.50 for galactic ALPs, as the interaction rate scales with gAe^2

The solar axions signal model

- Solar axion spectral shape: product of solar axion flux [J. Redondo, JCAP 12, 008 (2013)] and photo-electric cross section on xenon, assuming massless axions (still valid for masses smaller than 1 keV/c^2)
- Resolution and efficiency effects modelled in accordance with the Noble Element Simulation Technique (NEST) package [M. Szydagis et al., JINST 6, P10002 (2011)]







LUX efficiency for electronic recoils

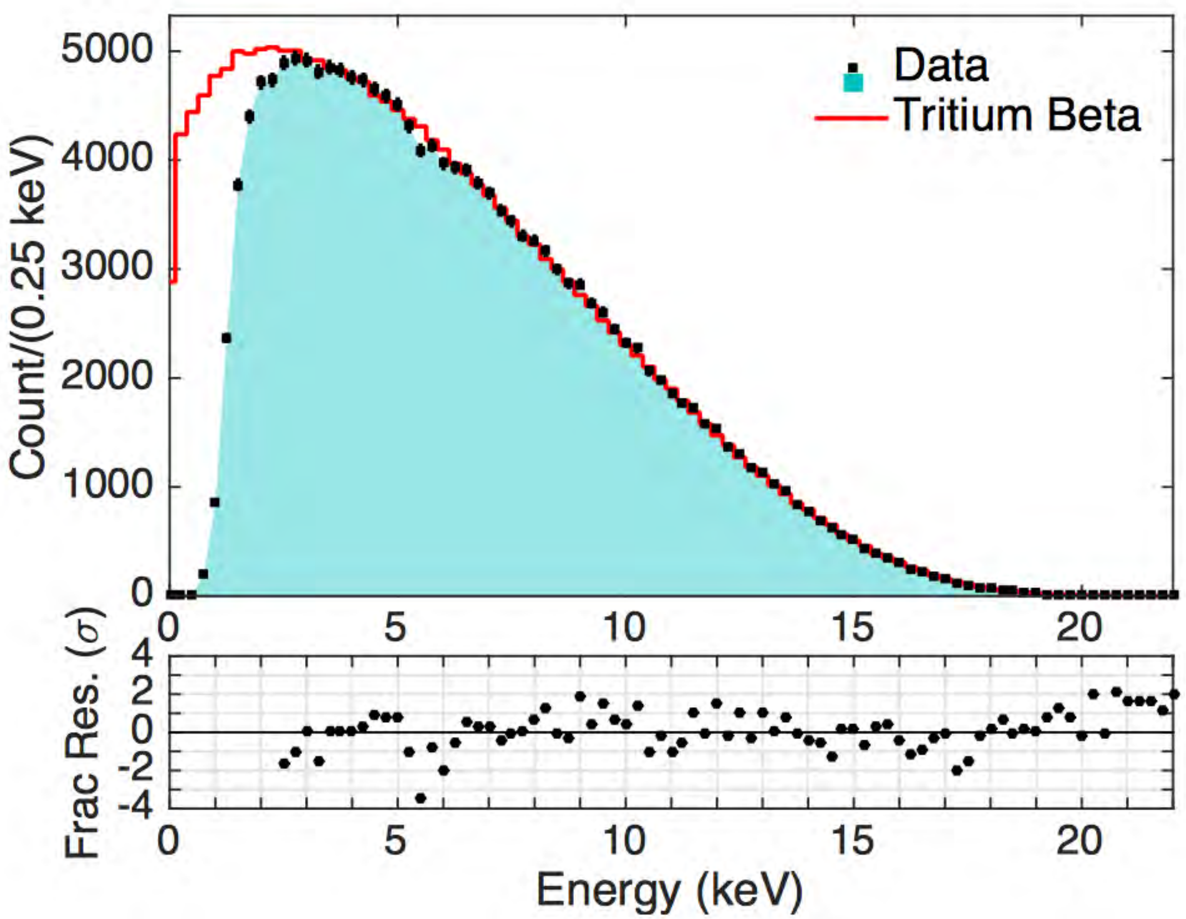


FIG. 5: Top: The tritium energy spectrum measured by LUX with the combined energy model (black) compared to a tritium spectrum convolved with detector resolution ($\frac{\sigma_E}{W} = \sqrt{\sigma^2(n_\gamma) + \sigma^2(n_e)}$.) The p-value between data and model from 3 to 18 keV is 0.70. Bottom: Bin-by-bin fit residuals between data and theory, in units of σ.

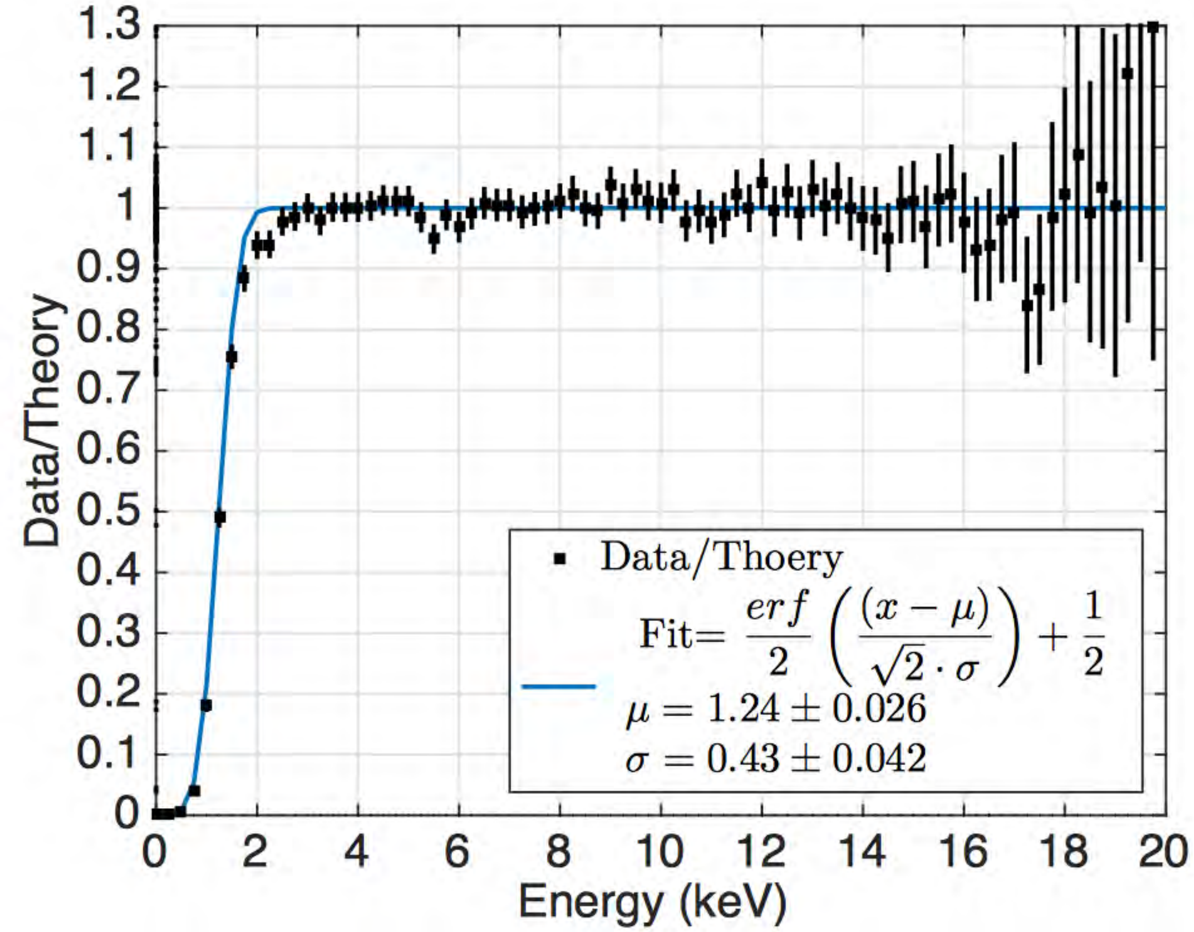


FIG. 6: Ratio of the measured tritium energy spectrum and the true one convolved with the detector resolution. A fit to an error function is shown.

D. S. Akerib et al., Phys. Rev. D93, 072009 (2016)

LUX energy resolution for electronic recoils

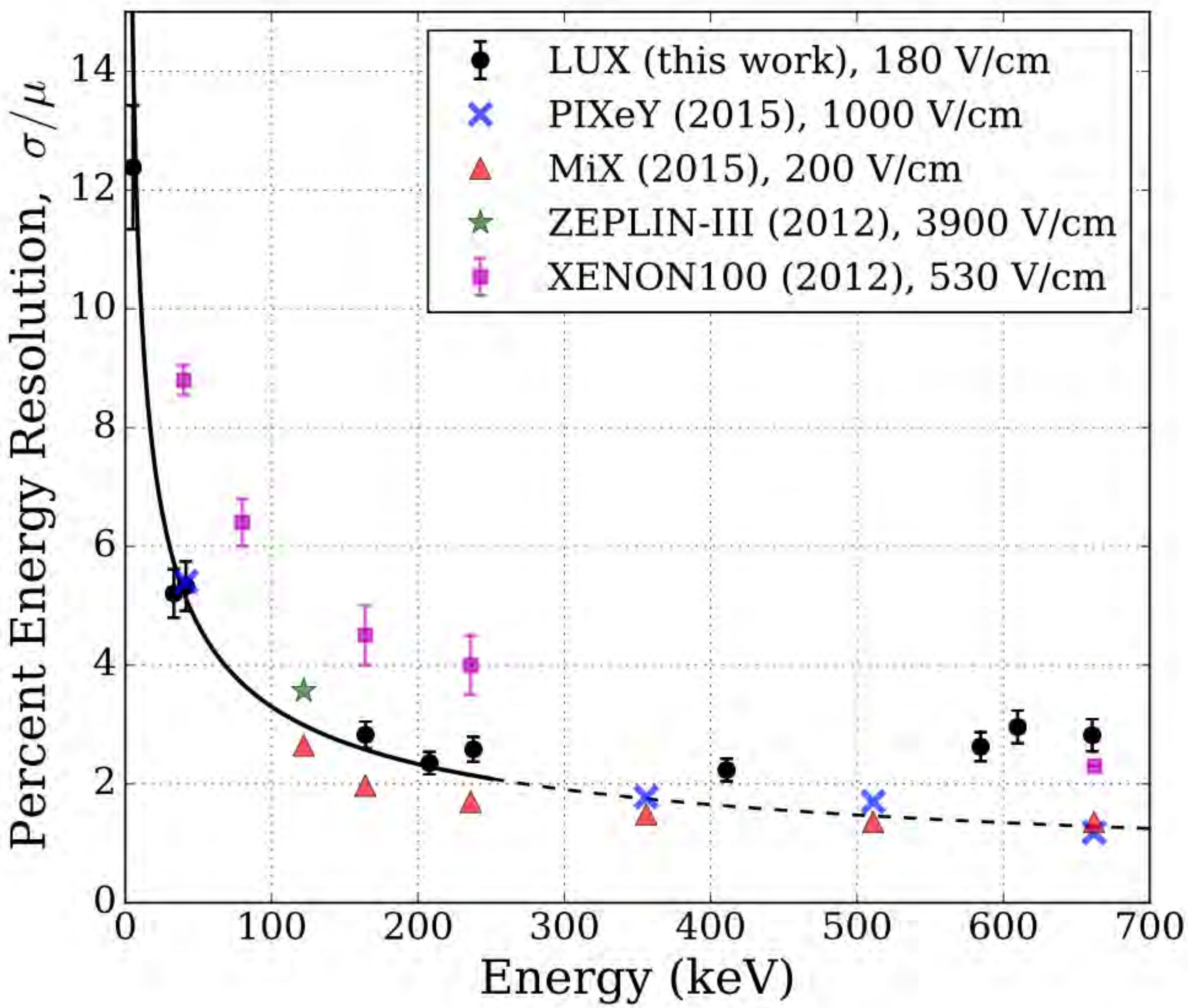
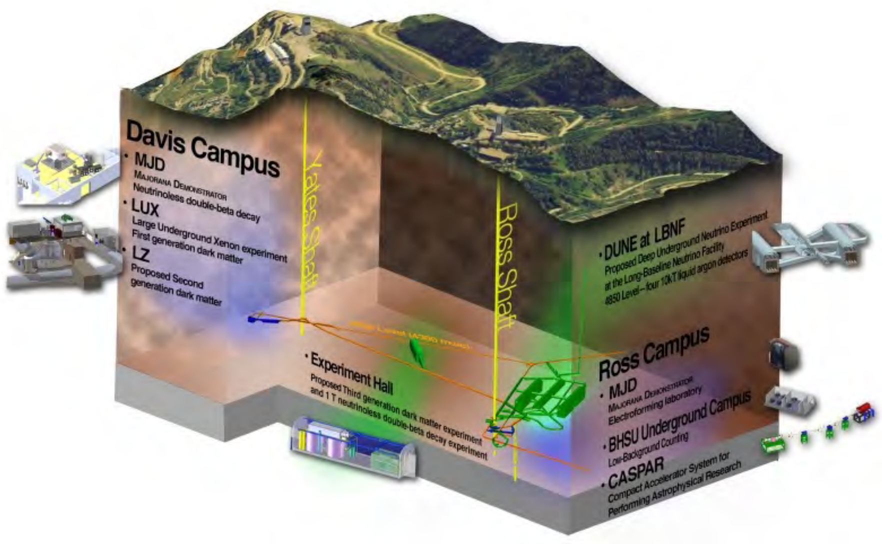


FIG. 8. The measured energy resolution at known energy peaks in the LUX ER backgrounds. The detector is optimized for low energy sensitivity, and variable amounts of PMT saturation and single-electron contributions affect S2 pulses and hamper the energy resolution at high energy, as discussed in the text. Data from the PIXeY (blue x; [26, 27]), MiX (red triangle; [28]), ZEPLIN-III (green star; [29]), and XENON100 (magenta square; [30]) are shown for comparison.

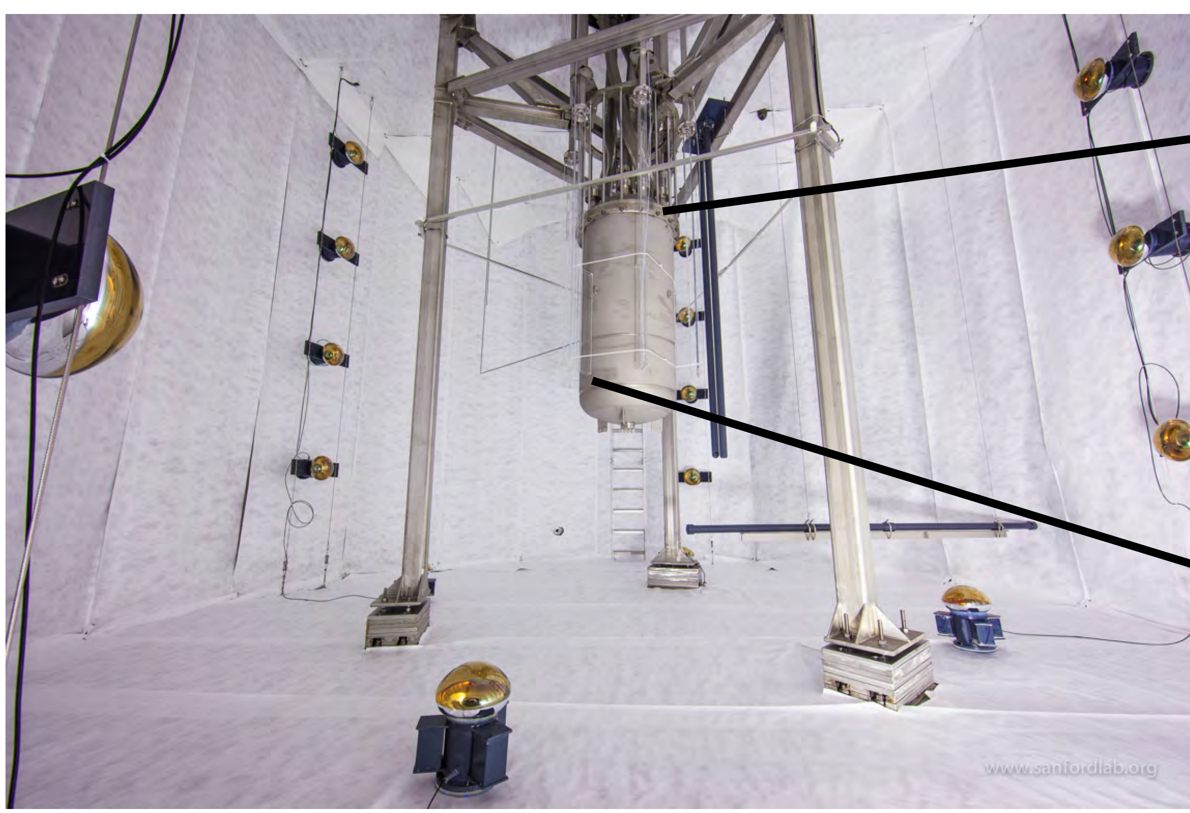
D. S. Akerib et al., Phys. Rev. D95, 012008 (2017)

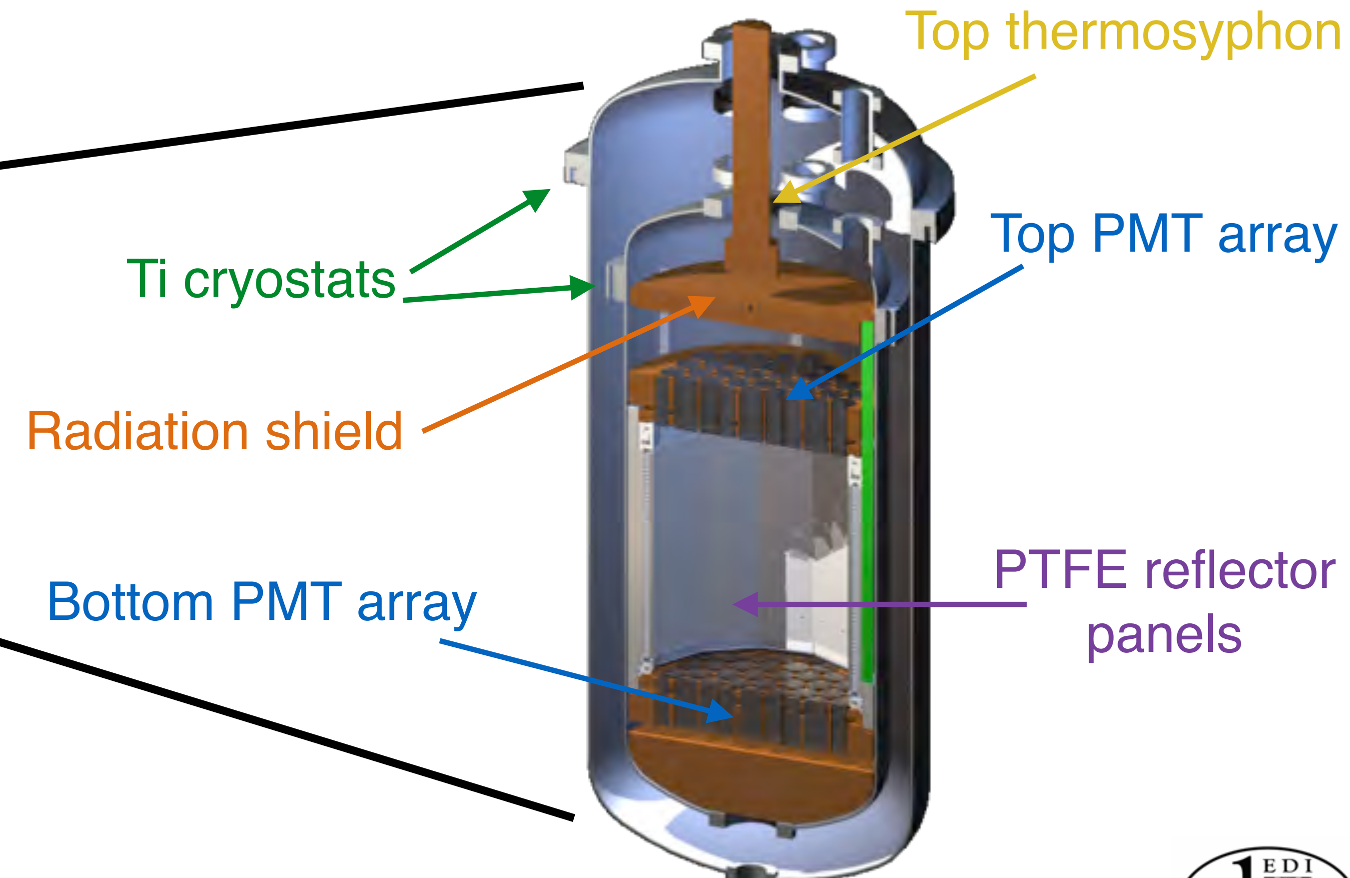
The Large Underground Xenon experiment



- 370 kg of liquid xenon, 250 kg of active mass
  - with a layer of gaseous xenon maintained above the liquid xenon (dual phase TPC)
- Vertical electric field applied (181 V/cm)
- 61 top + 61 bottom PMTs to detect signals

- LUX used to operate 4850 feet underground, in Davis Carven of the Sanford Underground Research Facility (South Dakota, USA)

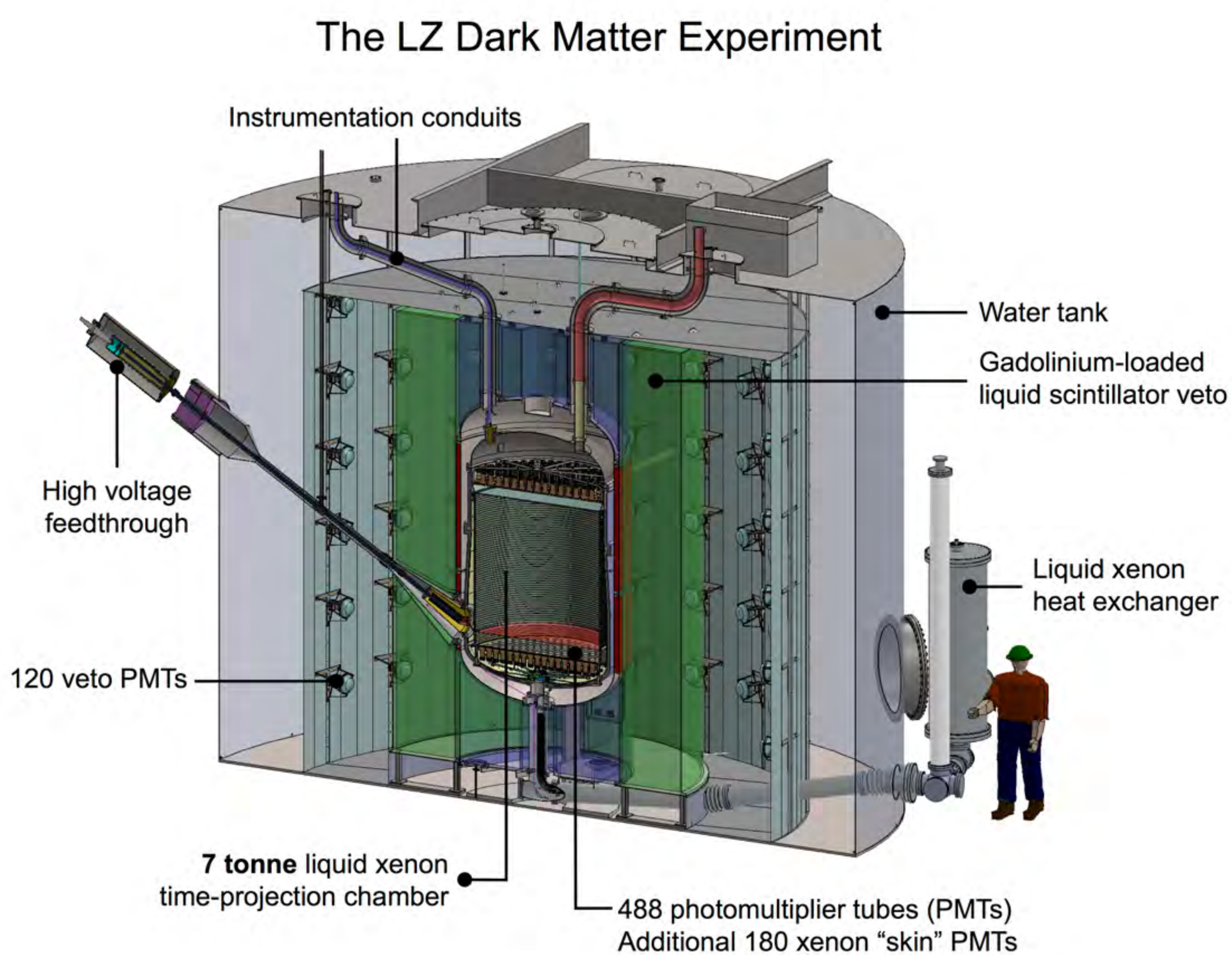


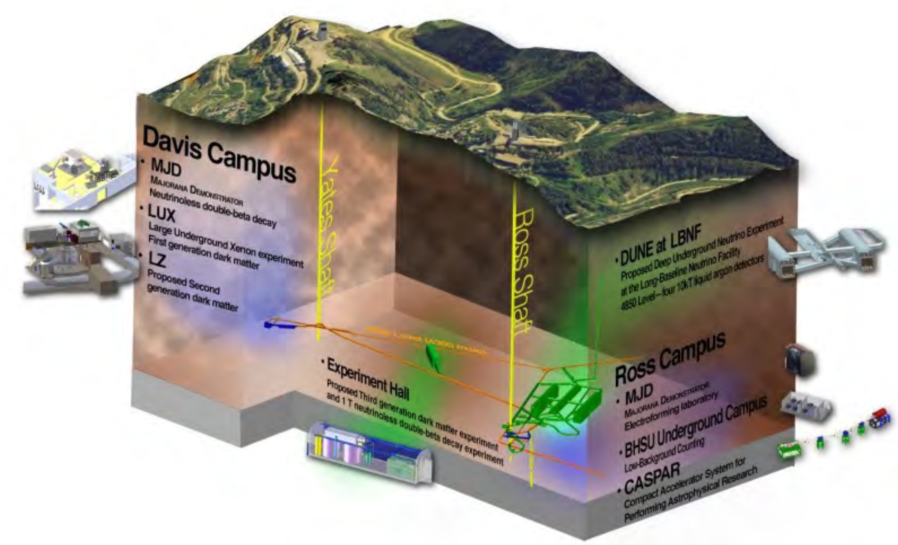


D. S. Akerib et al., Nucl. Instrum. Methods. A704, 111 (2013)

The LZ (LUX+ZEPLIN) experiment

- Dual-phase xenon TPC: 10 ton total mass, 7 ton active LXe mass, 5.6 ton fiducial mass





- Will be installed at SURF, where LUX used to work — onsite improvements in infrastructure for LZ

The signal model

- Solar axion spectral shape: product of solar axion flux [J. Redondo, JCAP 12, 008 (2013)] and photo-electric cross section on xenon, assuming massless axions (still valid for masses smaller than 1 keV/c^2)
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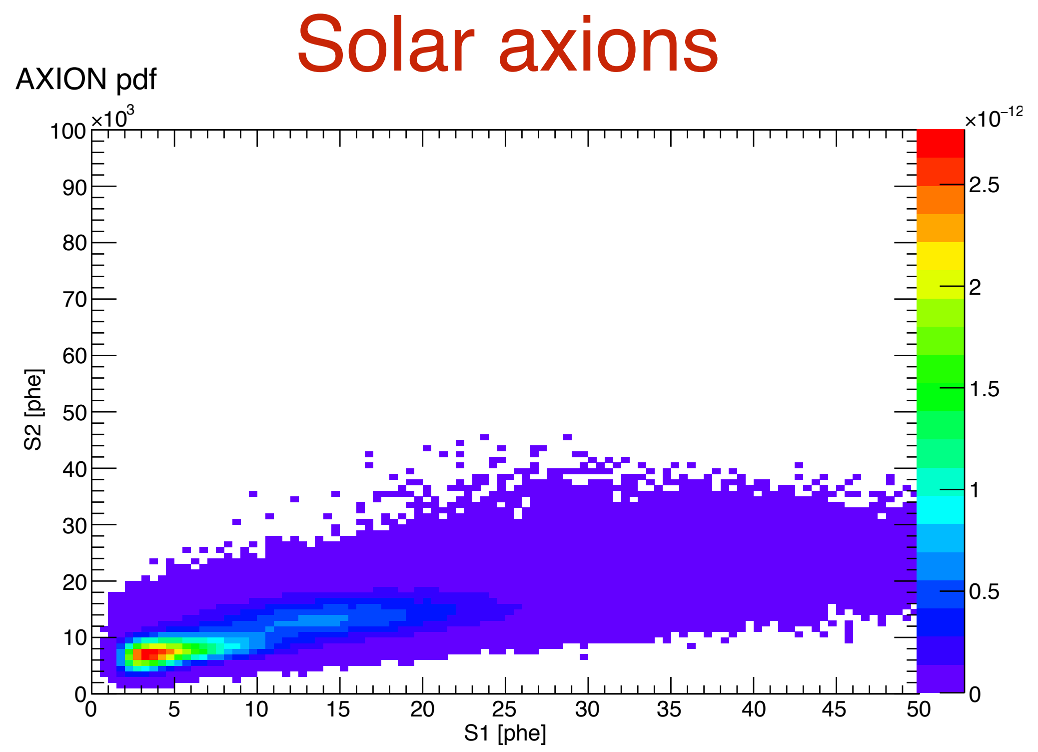

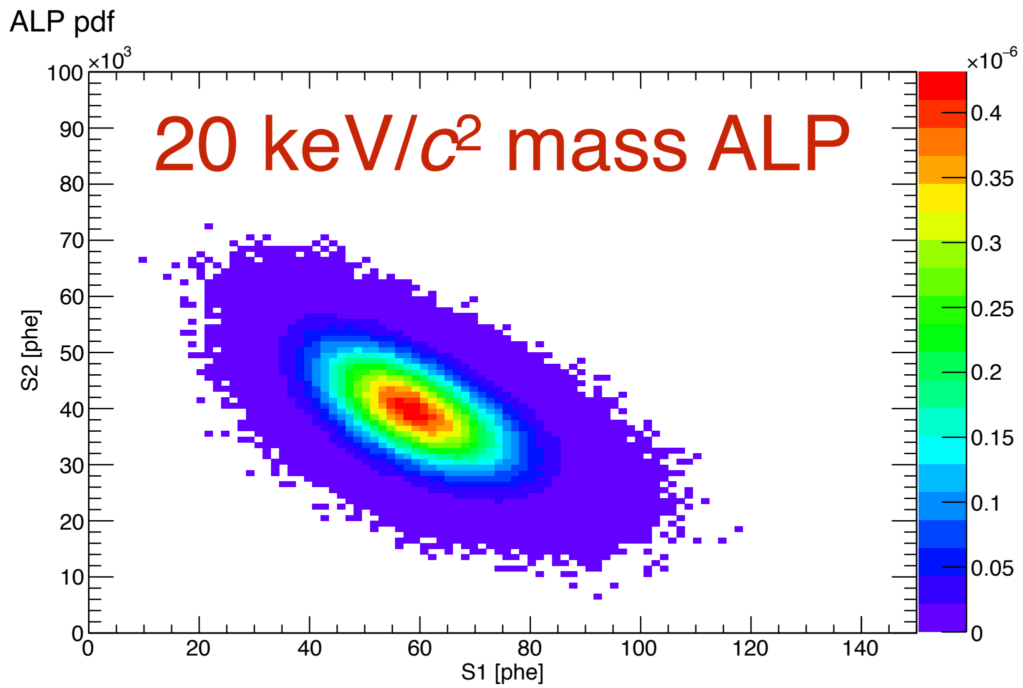

- ALPs expected to be essentially at rest within the galaxy
- Axio-electric absorption leads to electron recoils with kinetic energy equal to the ALP mass: sharp spectral feature, smeared by energy resolution

Why axions ? (Particle Physics)

- The Strong CP violation problem
  - the QCD Lagrangian acquires a term, proportional to a static parameter θ, because of the non zero divergence of the axial current
  - this term is CP violating, but we do not observe any CP violation in strong interactions

$$L_{QCD} = \overline{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} + \frac{\alpha_S\overline{\theta}}{8\pi}G^a_{\mu\nu}\widehat{G}^{a\mu\nu}$$

- The Peccei and Quinn solution (1977)
  - a new global symmetry U(1)_PQ is introduced and spontaneously broken at some large energy scale, and the axion is the Nambu-Goldstone boson generated

$$L = \overline{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} - \frac{1}{2}\partial_\mu a_{phys}\partial^\mu a_{phys} + L_{int}[\partial^\mu a_{phys}/f, \psi] + \frac{a_{phys}}{f_a}\xi\frac{\alpha_S}{8\pi}G^a_{\mu\nu}\widehat{G}^{a\mu\nu}$$

  - the axion field terms introduced in the QCD Lagrangian, cancel out the term proportional to θ, providing a dynamical solution to the strong CP problem