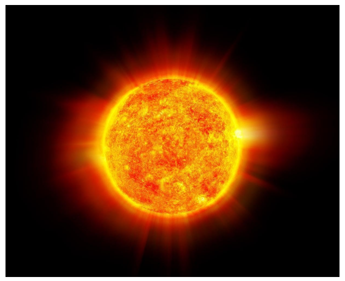
arXiv:1704.02297 (2017),
PRL accepted

Axion Results with LUX & Future Searches with LZ

Maria Francesca Marzioni
on behalf of the LUX and LZ Collaborations

Invisibles17 Workshop, University of Zurich, 13/06/2017

Axions: why, where, how?



- Potential sources of axions we can look at with LUX and LZ:
  - **the Sun** —> QCD **axions** (Peccei-Quinn solution for the strong CPV problem)
  - **our Galaxy** —> Axion-Like Particles (ALPs) introduced by extensions of the Standard Model, suitable (cold) dark matter candidates

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Axions: why, where, how?

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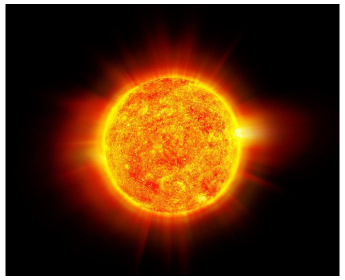

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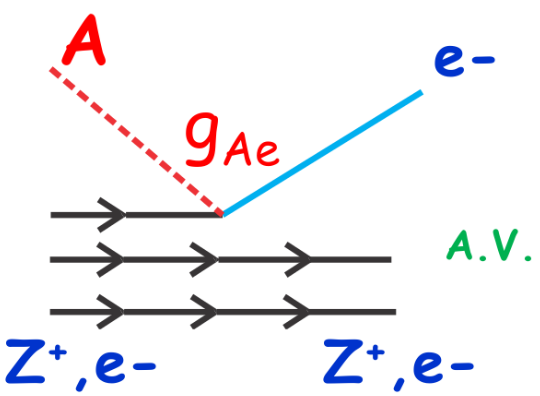
Axio-electric effect



- 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})

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

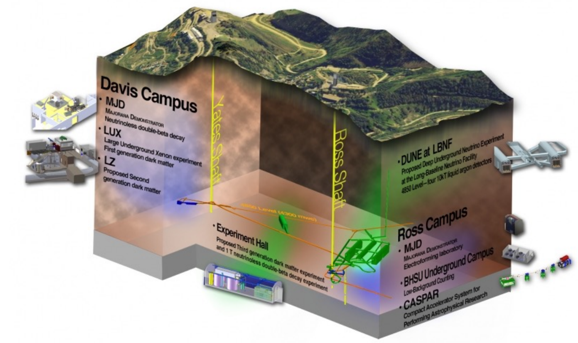
F. T. Avignone et al., Phys. Rev. D 35, 2752 (1987);

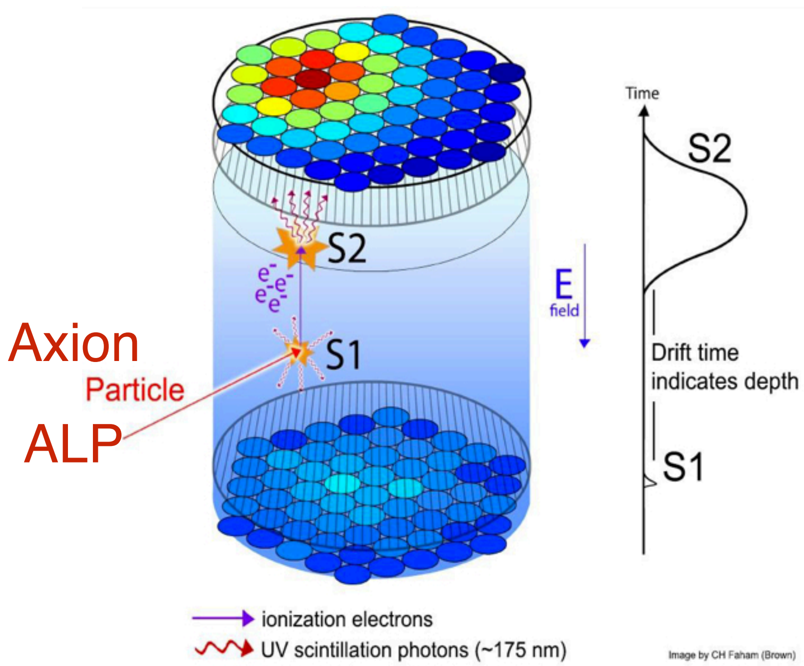
M. Pospelov et al., Nucl. Rev. D 78, 115012 (2008);

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

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

- LUX has operated **4850 feet underground**, in Davis Carven of the Sanford Underground Research Facility (South Dakota, USA)





- LUX is a **dual phase xenon TPC** (250 kg active mass)
  - scintillation (S1) + ionisation (S2) signal
  - NR vs ER discrimination thanks to S2/S1

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

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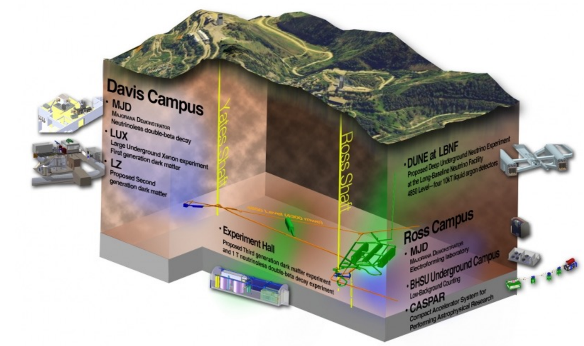

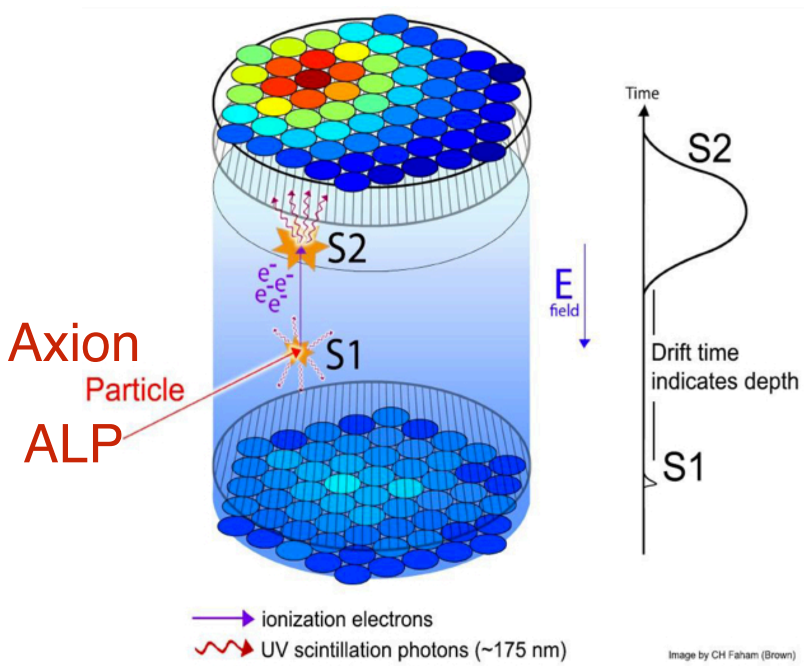

D. S. Akerib et al., Phys. Rev. Lett. 116, 161301 (2016)

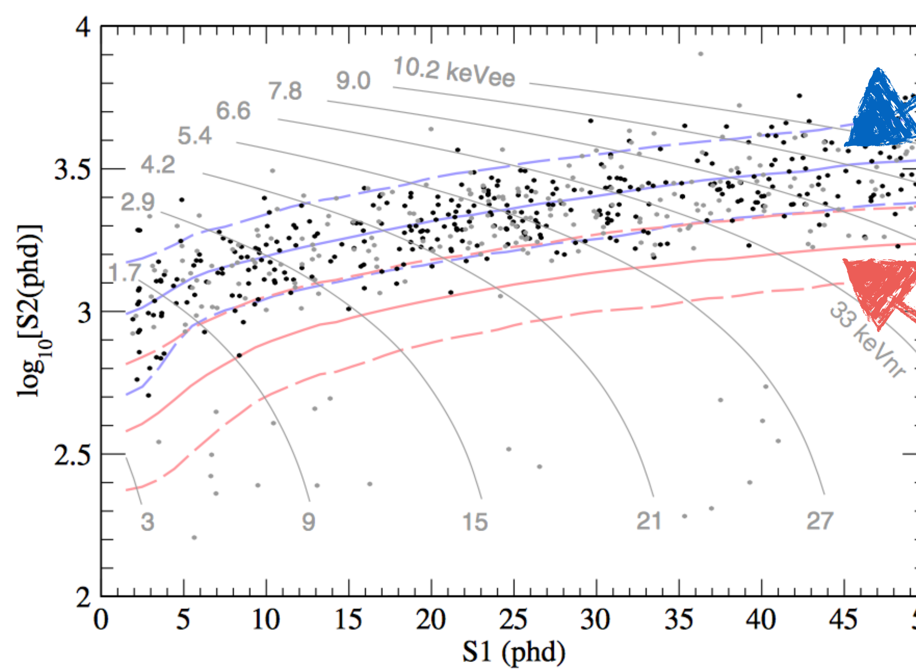

FIG. 2. Observed events in the 2013 LUX exposure of 95 live days and 145 kg fiducial mass. Points at <18 cm radius are black; those at 18–20 cm are gray. Distributions of uniform-in-energy electron recoils (blue) and an example 50 GeV c^{-2} WIMP signal (red) are indicated by 50th (solid), 10th, and 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].

ER band: most of the background + potential axion signal

NR band: few background events + potential WIMP signal

- LUX is a **dual phase xenon TPC** (250 kg active mass)
  - scintillation (S1) + ionisation (S2) signal
  - NR vs ER discrimination thanks to S2/S1

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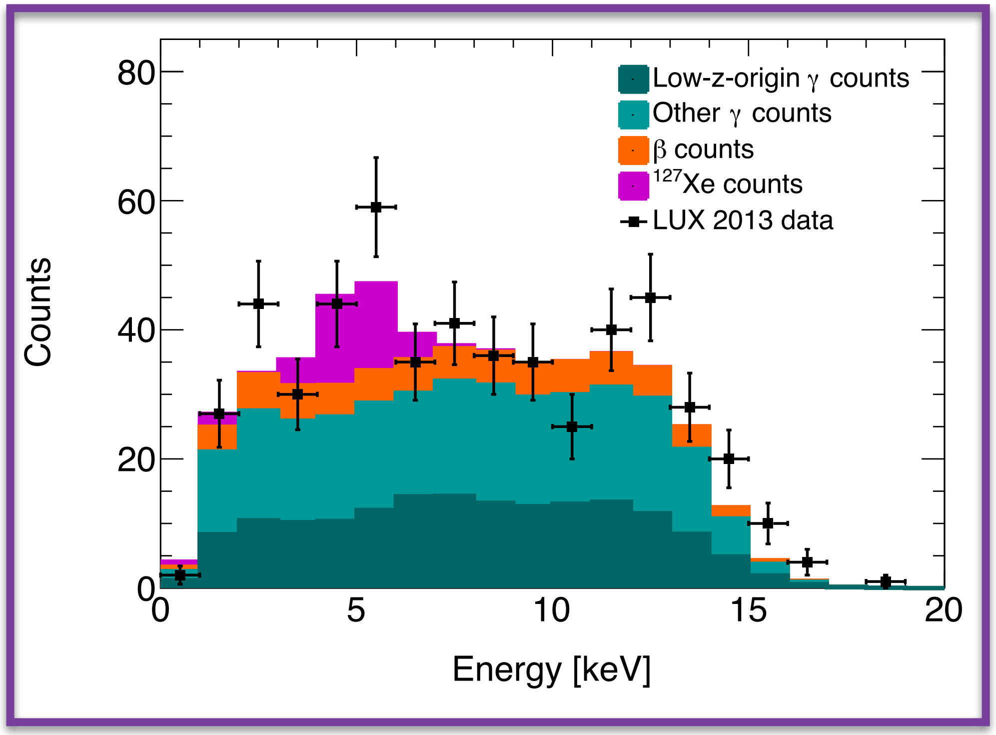
LUX 2013 data analysis

- Test LUX 2013 data (95 live days x118 kg fiducial mass) against **background** + **signal** model



LUX 2013 data analysis

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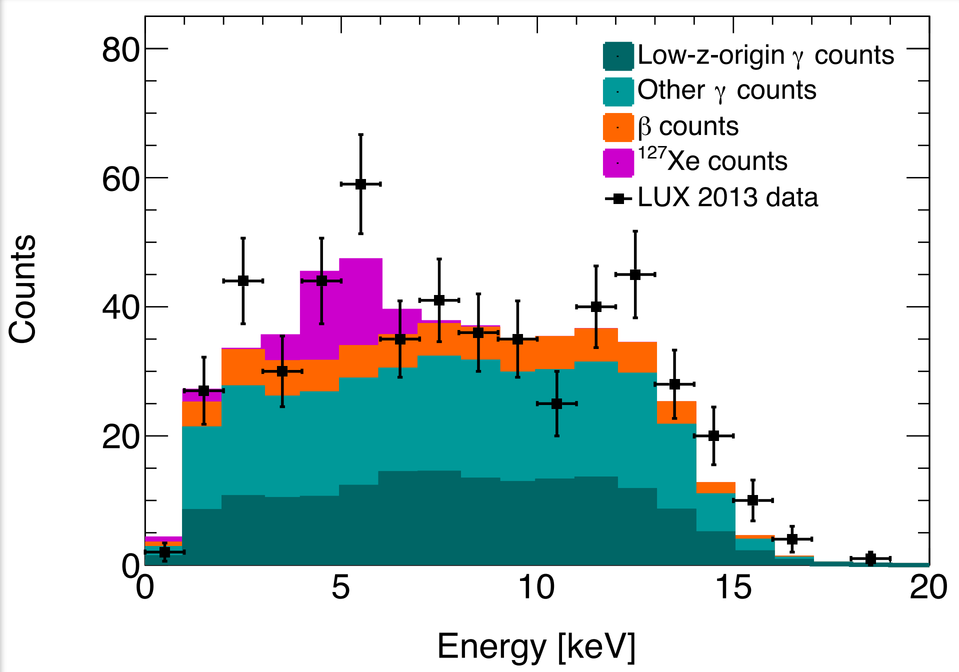
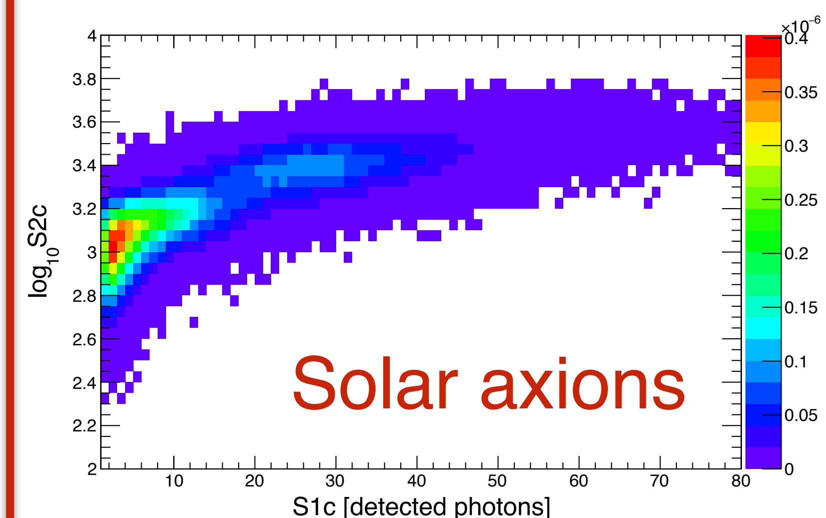
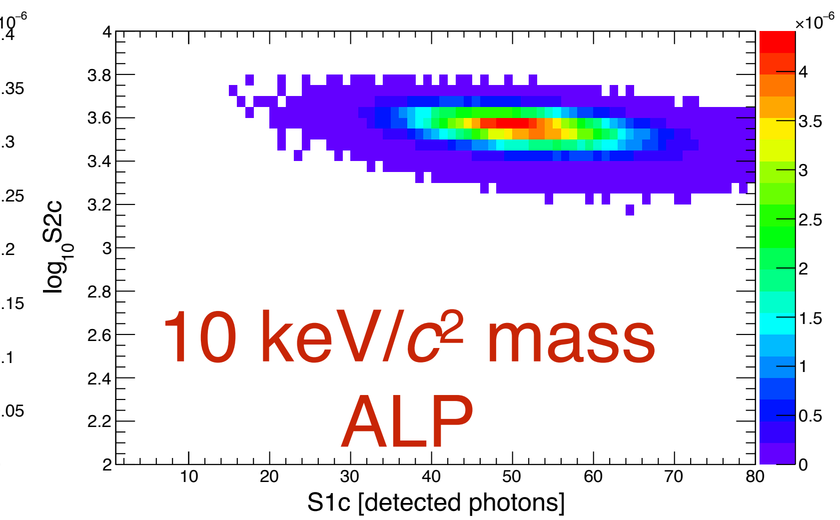


- Solar axion flux [J. Redondo, JCAP 12, 008 (2013)] times photo-electric cross section
- Sharp spectral feature as at rest within the galaxy (ER recoil energy = ALP mass)
- Resolution and efficiency effects modelled in accordance with NEST [M. Szydagis et al., JINST 6, P10002 (2011)]





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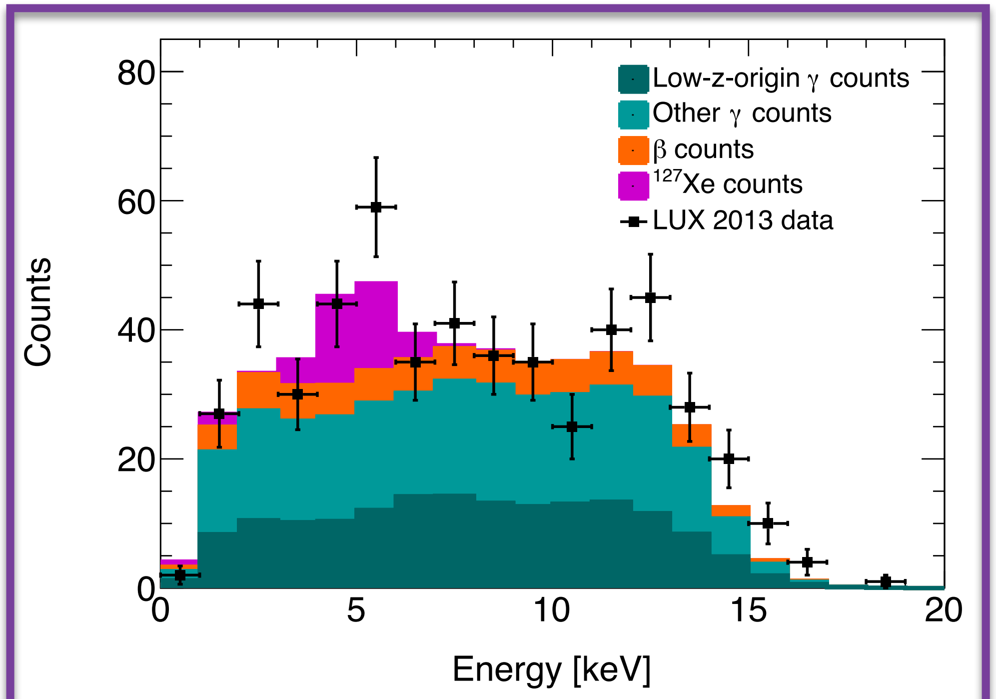
LUX 2013 data analysis

- Test LUX 2013 data (95 live days x118 kg fiducial mass) against **background** + **signal** model



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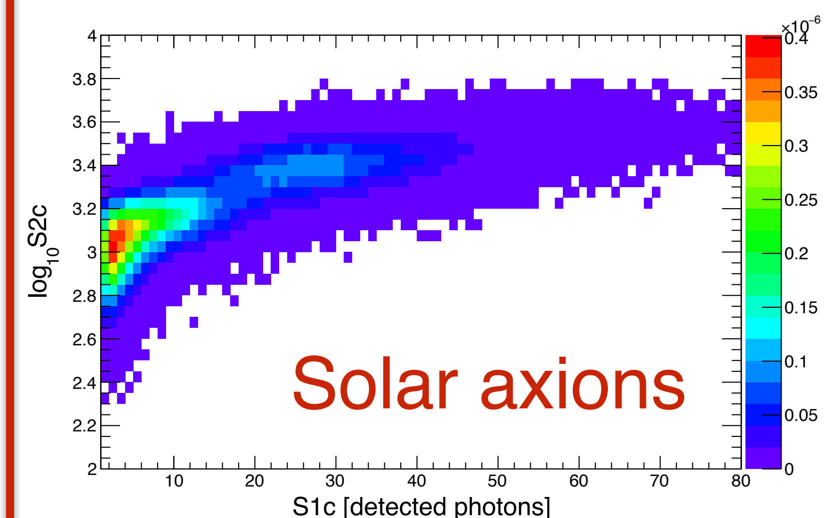

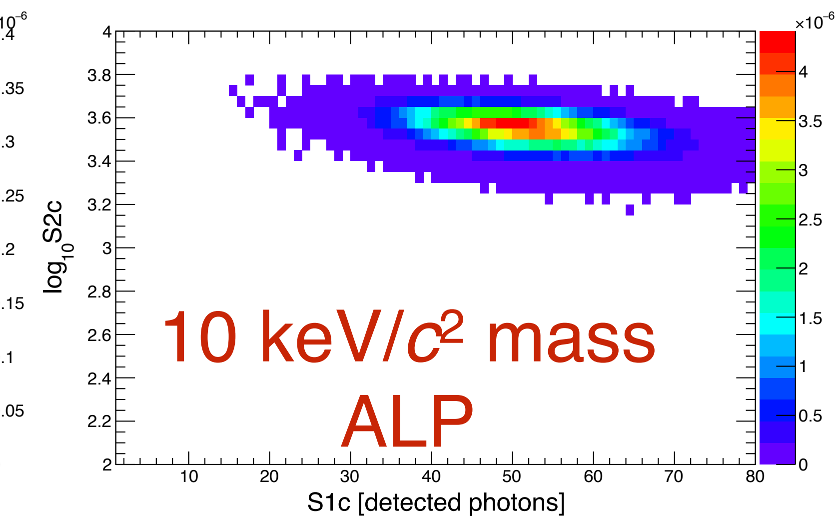

- Set a two-sided limit on the coupling g_{Ae} with a **Profile Likelihood Ratio analysis**, having the BG rates as nuisance parameters and [S1,S2,r and z] as observables

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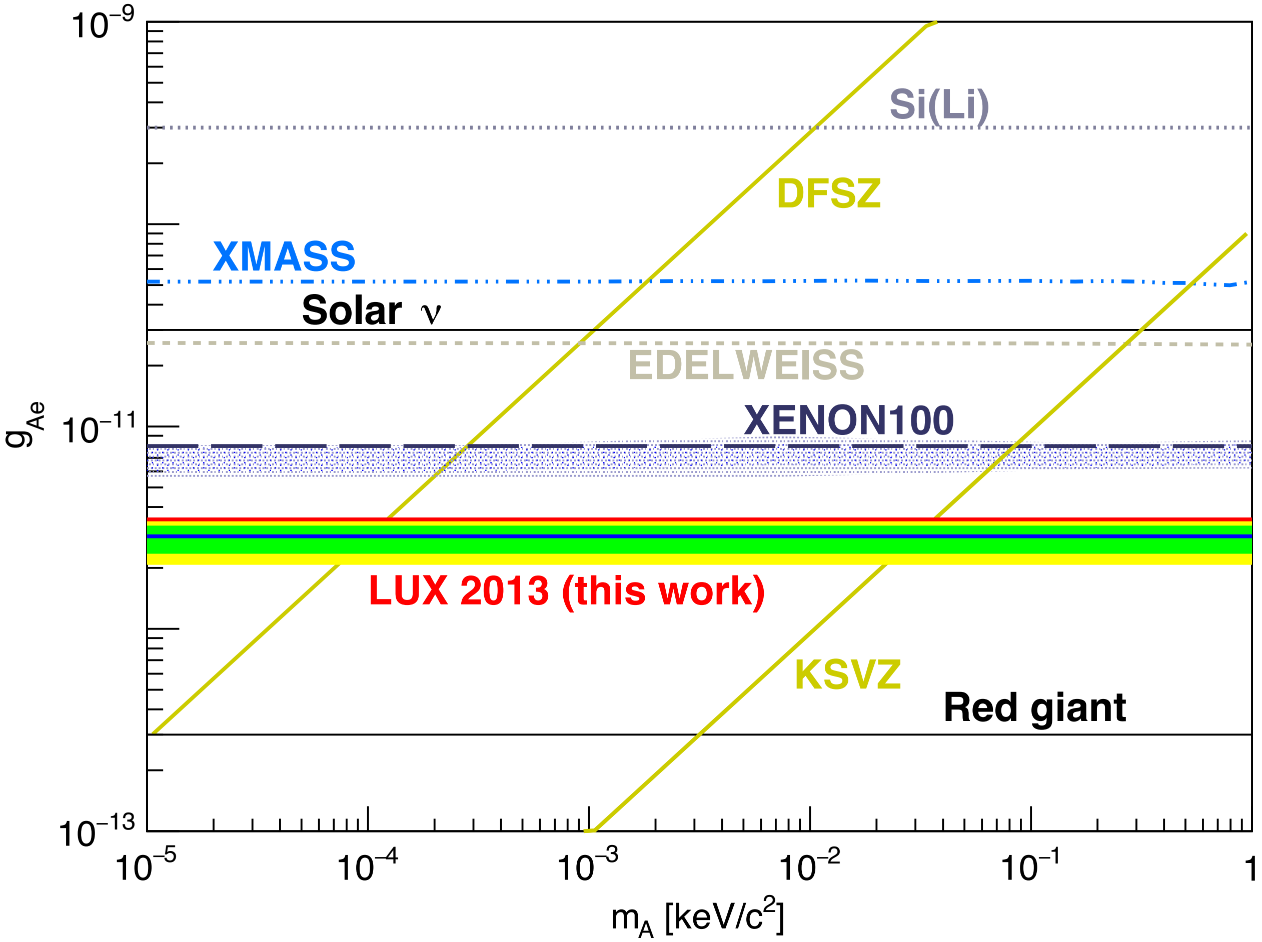
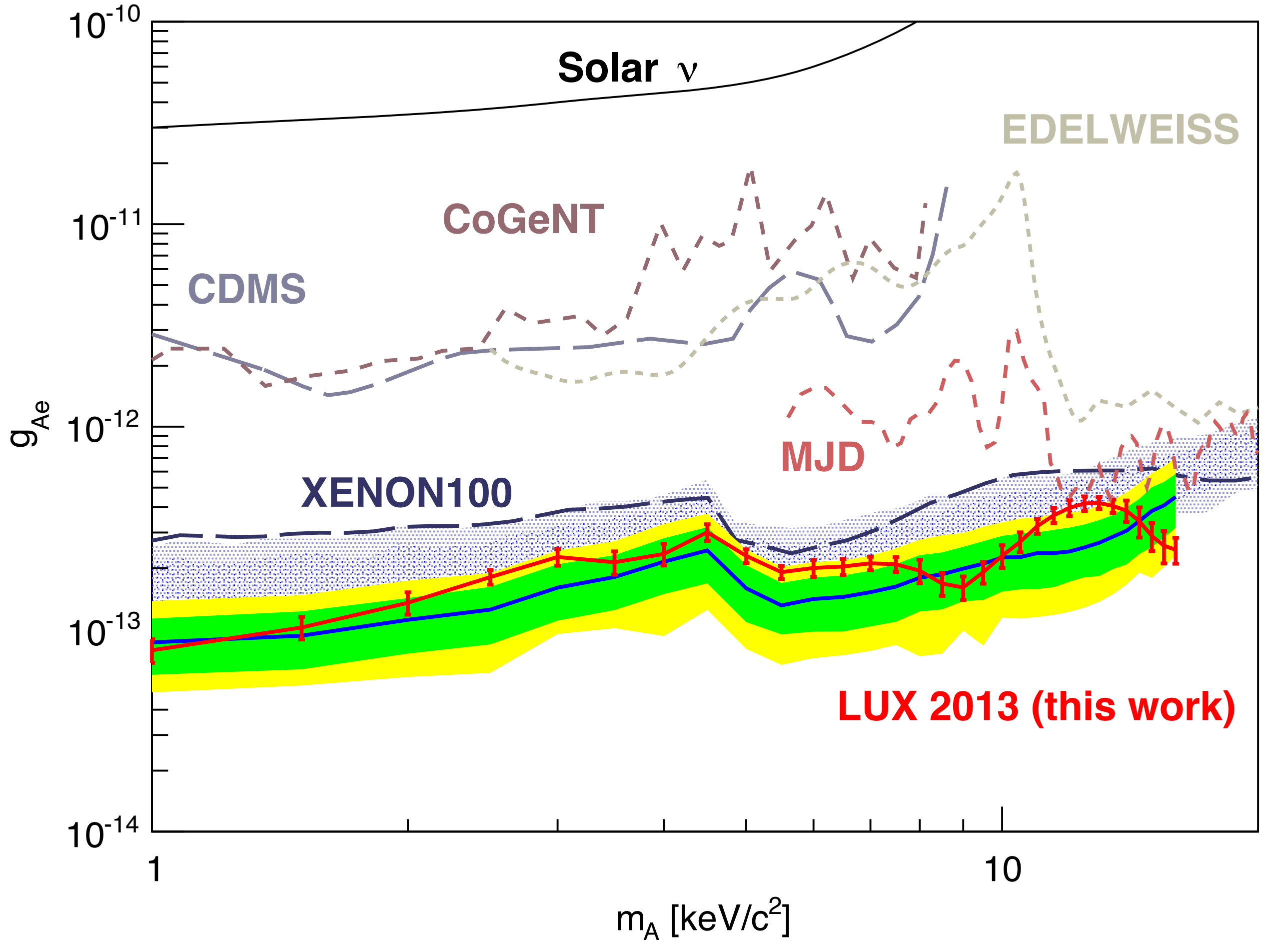
LUX 2013 results

arXiv:1704.02297 (2017), PRL accepted

Solar axions



Galactic ALPs



LUX 2013 excludes $g_{Ae} > 3.5\times10^{-12}$ (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)

LUX 2013 excludes $g_{Ae} > 4.2\times10^{-13}$ (90% CL) across the range 1-16 keV/c^2 in ALP mass

- Analysis of the complete LUX exposure for axion and ALP searches is planned

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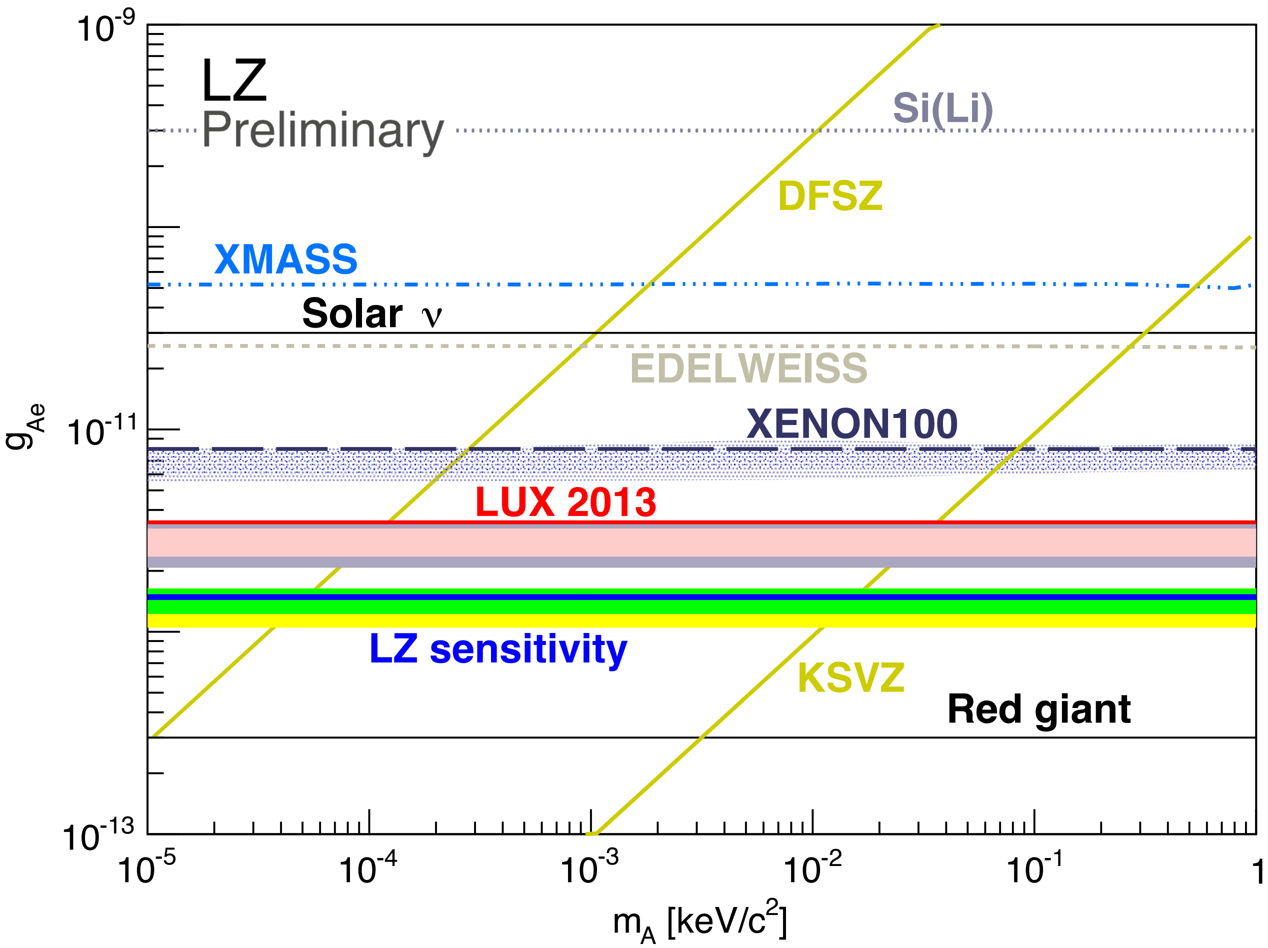
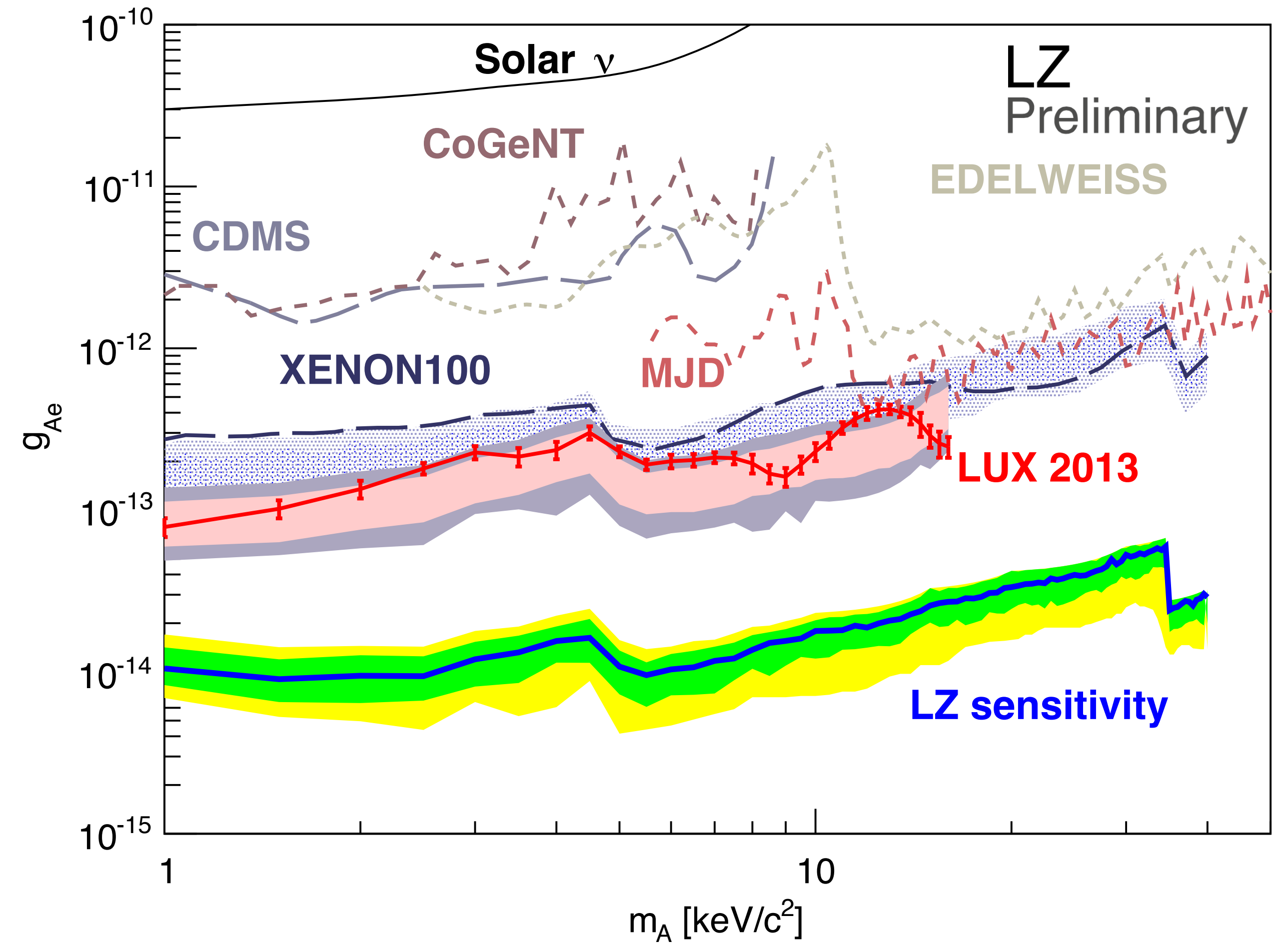
sensitivity projections

Solar axions



LZ sensitivity excludes $g_{Ae} > 1.5 \times 10^{-12}$ (90% CL)

Galactic ALPs



LZ sensitivity excludes $g_{Ae} > 5.9 \times 10^{-14}$ (90% CL) across the range 1-40 keV/c^2 in ALP mass

- Next generation experiment, which will take LUX's place in the Davis Cavern at the Sanford Underground Research Facility (South Dakota, USA) and is expected to run for 1000 live days x 5.6 ton fiducial mass
- Profile Likelihood Ratio analysis to extract the sensitivity, using fake data generated according to the LZ background model

Thank you!

It's been a very interesting year for LUX!
arXiv:1705.03380 (2017), PRL accepted
arXiv:1704.02297 (2017), PRL accepted
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)

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Dongqing Huang	Graduate Student
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James Morad	Graduate Student
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Scott Haselschwardt	Graduate Student
Curt Nehrkorn	Graduate Student
Melih Solmaz	Graduate Student

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M. Moongweluwan	Graduate Student
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Kimberly Palladino	PI, Asst Professor
Shaun Alsum	Graduate Student

The LZ collaboration

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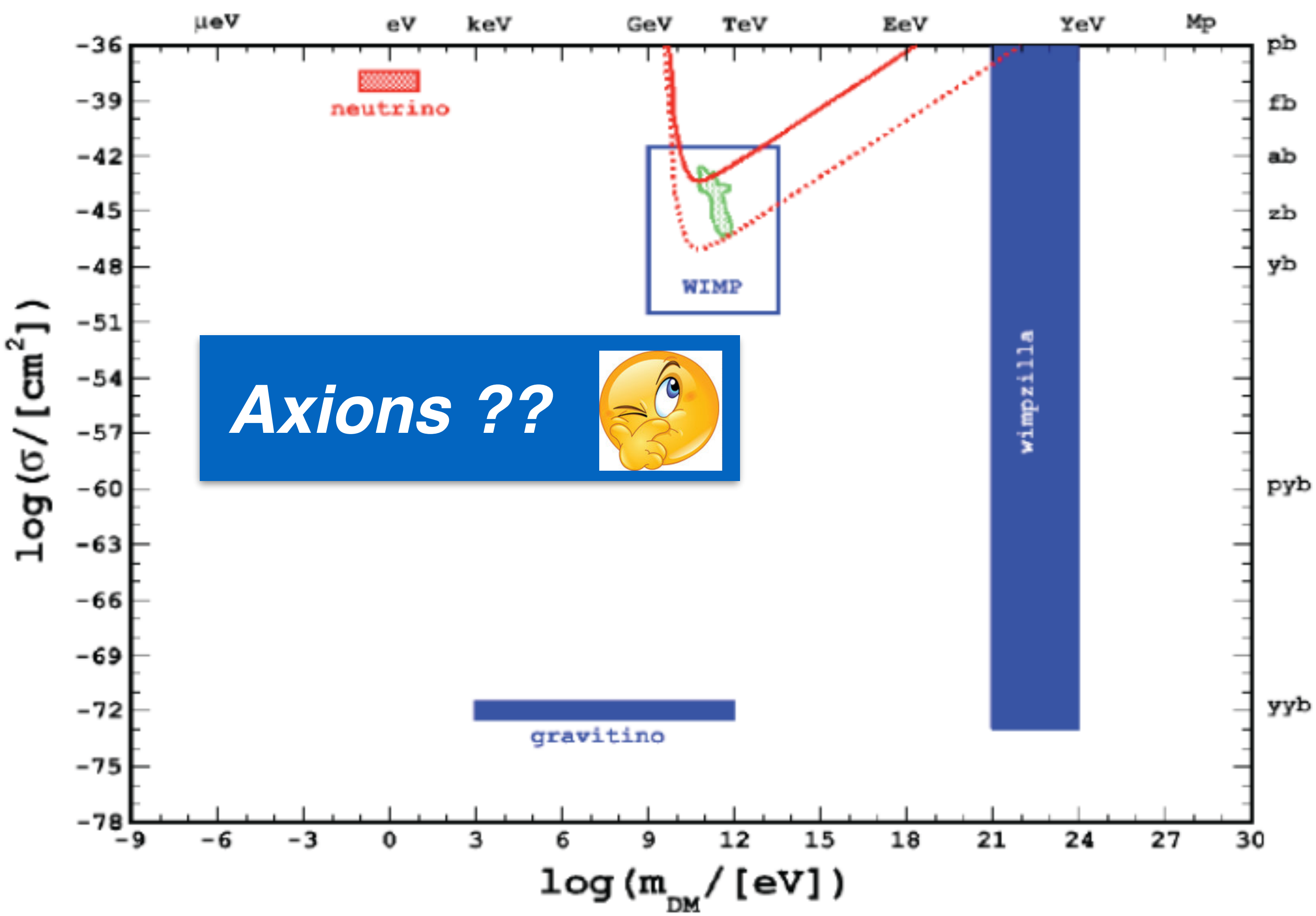
MEPhI (Russia)
Edinburgh University (UK)
University of Liverpool (UK)
Imperial College London (UK)
University College London (UK)
University of Oxford (UK)
STFC Rutherford Appleton Laboratories (UK)
University of Sheffield (UK)

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

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

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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

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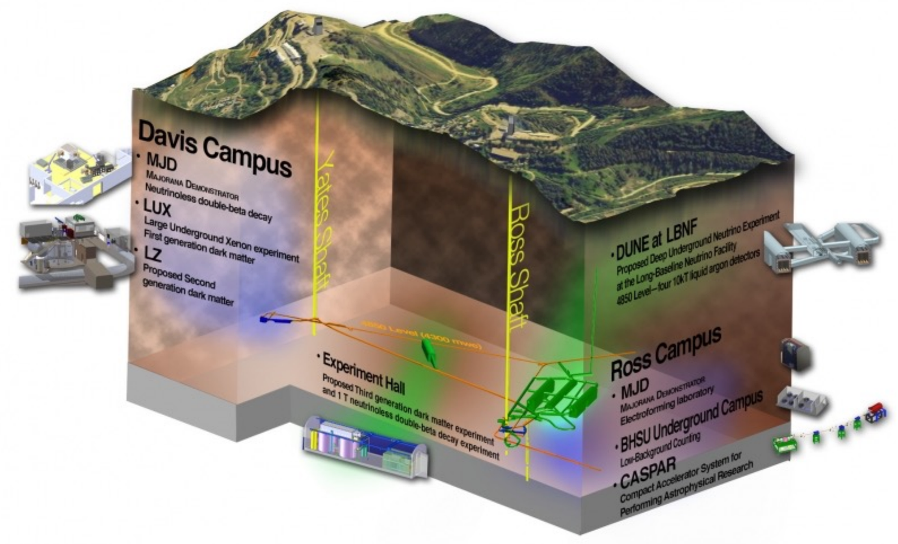
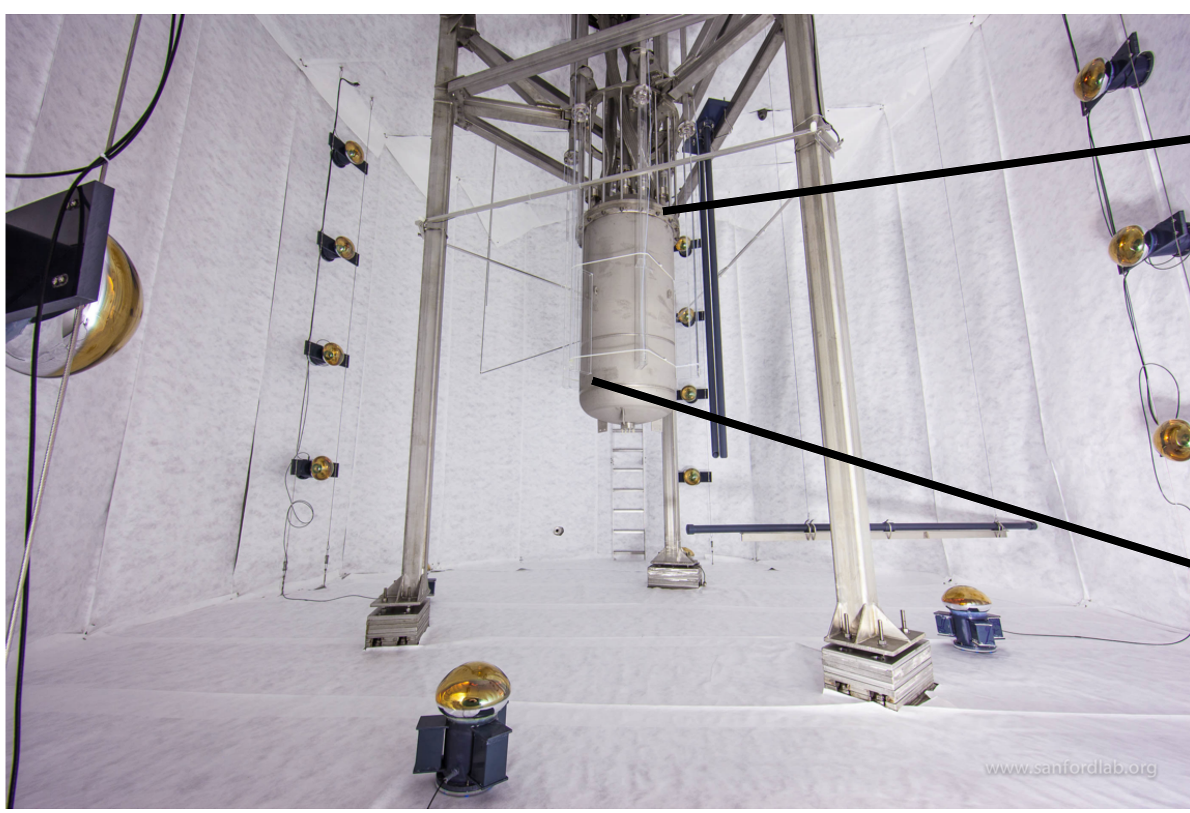
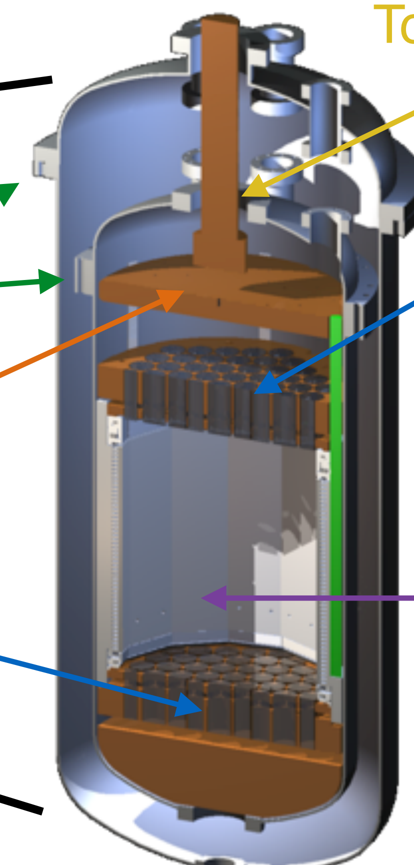
The Large Underground Xenon experiment



- 370 kg of liquid xenon, 250 kg of active mass
    - with a layer of gaseous xenon maintained above the liquid xenon (**dual phase TPC**)
- LUX has operated **4850 feet underground**, in Davis Carven of the Sanford Underground Research Facility (South Dakota, USA)
- Vertical electric field applied (181 V/cm)
- 61 top + 61 bottom **PMTs** to detect signals





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

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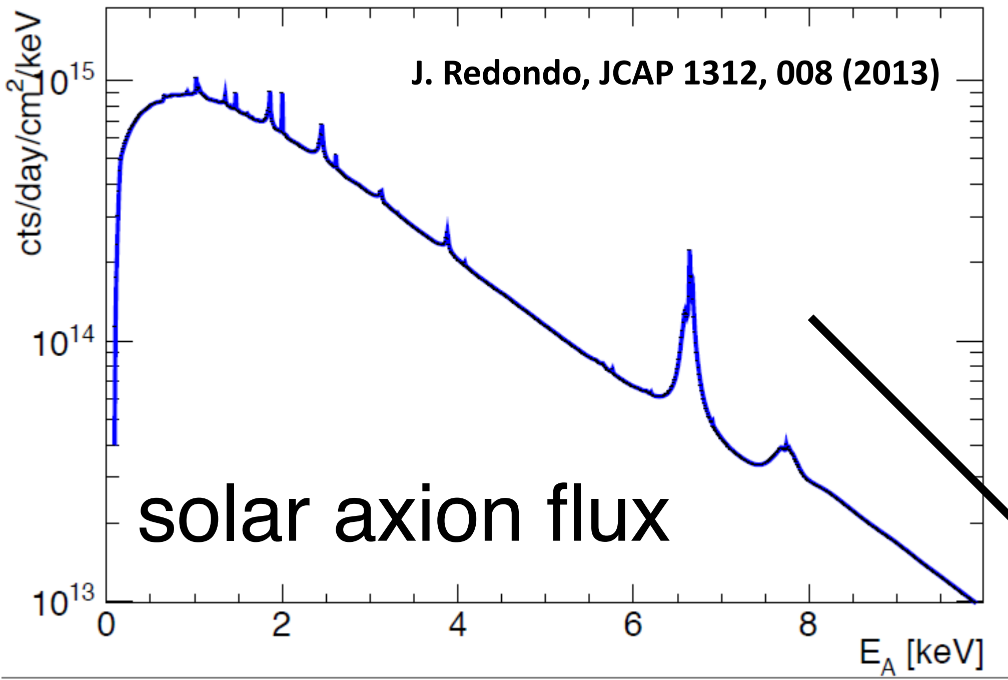
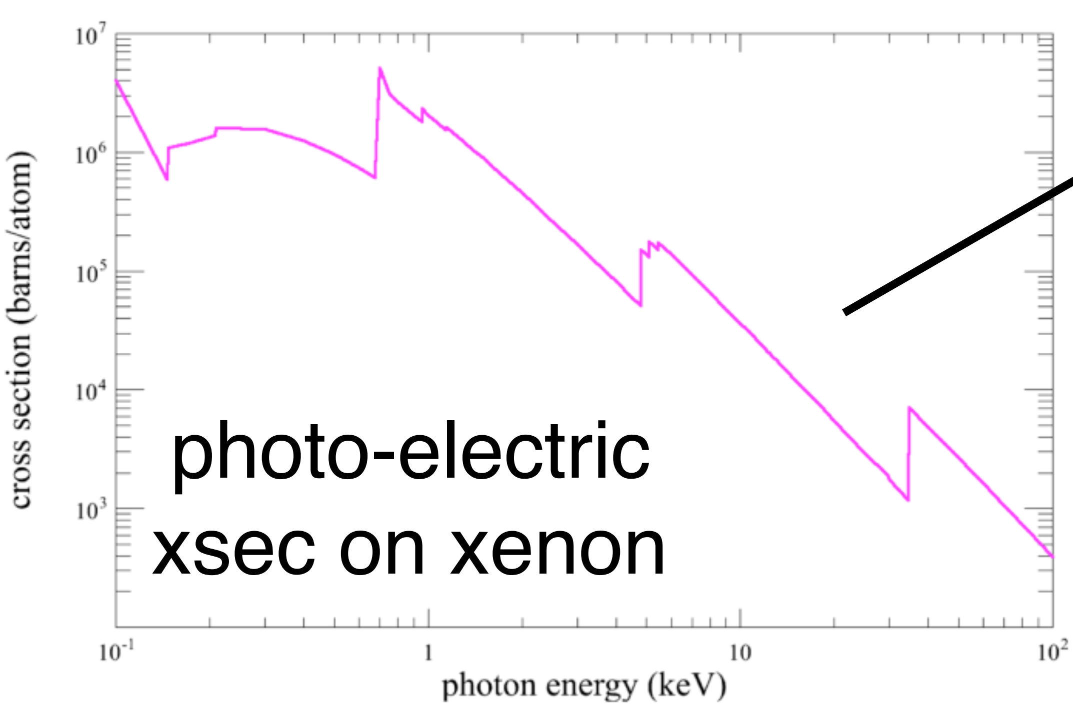
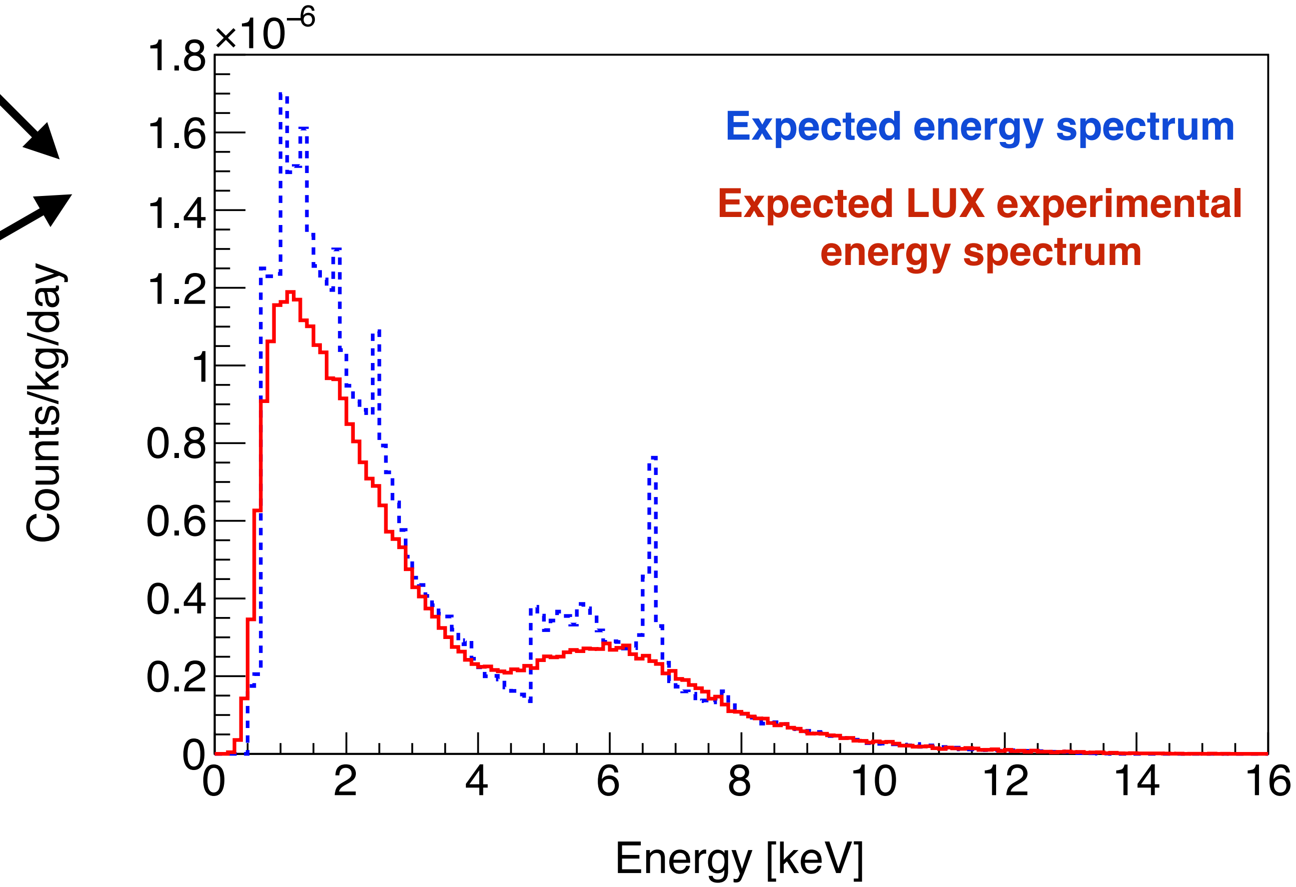
The solar axions spectral shape



- 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 2013 search data & the background model

- LUX 2013 data exposure: 95 live days x118 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 γ rays from detector component radioactivity
    - additional γ-ray contribution from heavily down-scattered emission from decays in the center of a large copper block below the PMTs
  - ^{85}Kr and Rn-daughter contaminants in the liquid xenon undergoing beta decays with no accompanying γ rays detected
  - x rays emitted following those ^{127}Xe electron-capture decays where the coincident γ ray escapes the xenon

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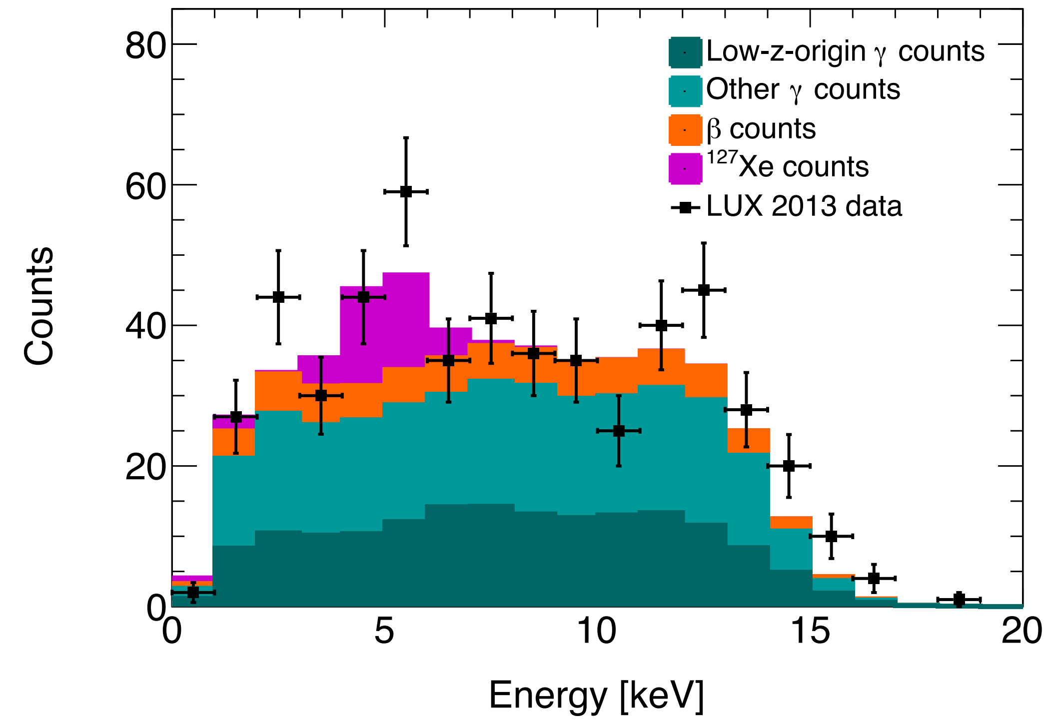
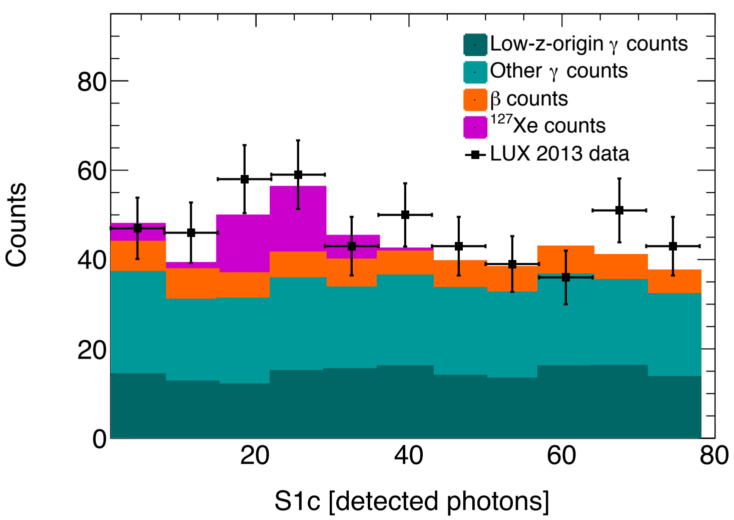
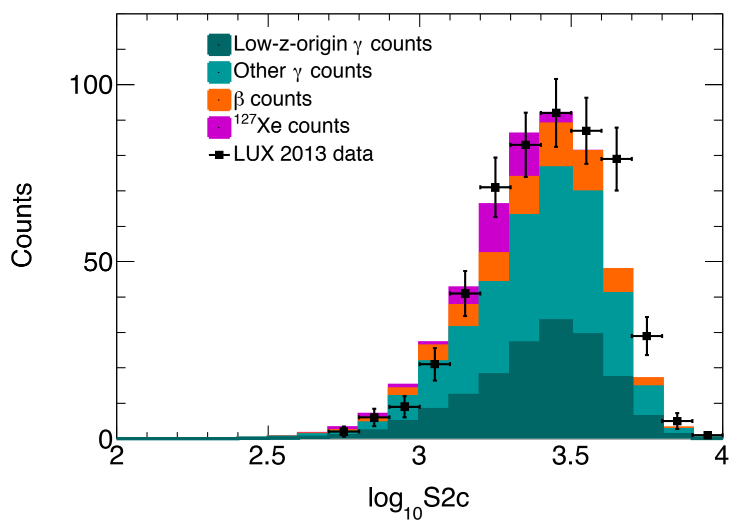
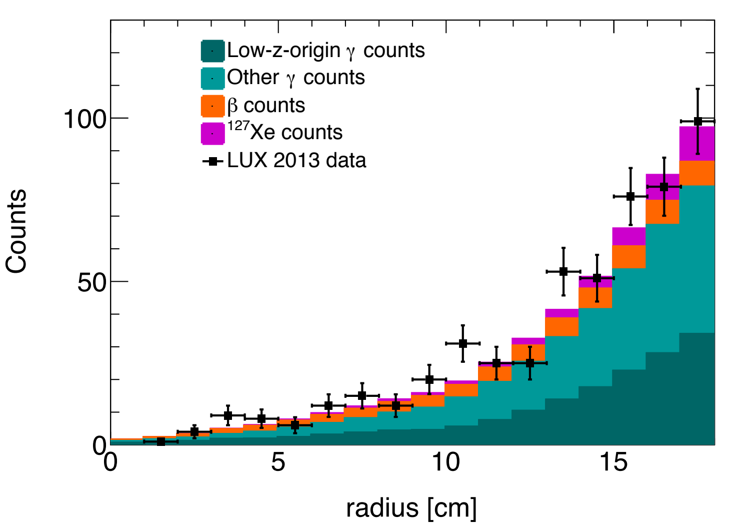
- LUX 2013 data and background model as a function of recoil energy, with the energy reconstructed as
  E = [S1c/g1+ S2c/(εg2)] W
  - g1: geometric light collection efficiency and PMT quantum efficiency
  - εg2: electron extraction efficiency and number of photons detected per electron extracted

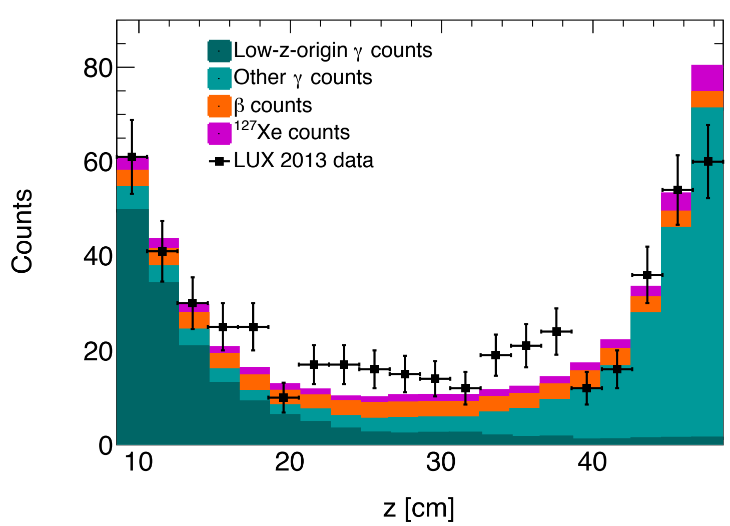






- Backgrounds modelled on the **four observables** used in the statistical analysis: the prompt scintillation (S1) and the logarithm in base 10 of the proportional (S2) signal, and the radius (r) and depth (z) of the event location





- Statistical **Profile Likelihood Ratio analysis**, aimed at setting a two-sided limit on the coupling between axions/ALPs and electrons $\mathbf{g_{Ae}}$, having the BG rates as nuisance parameters

LUX efficiency for electronic recoils

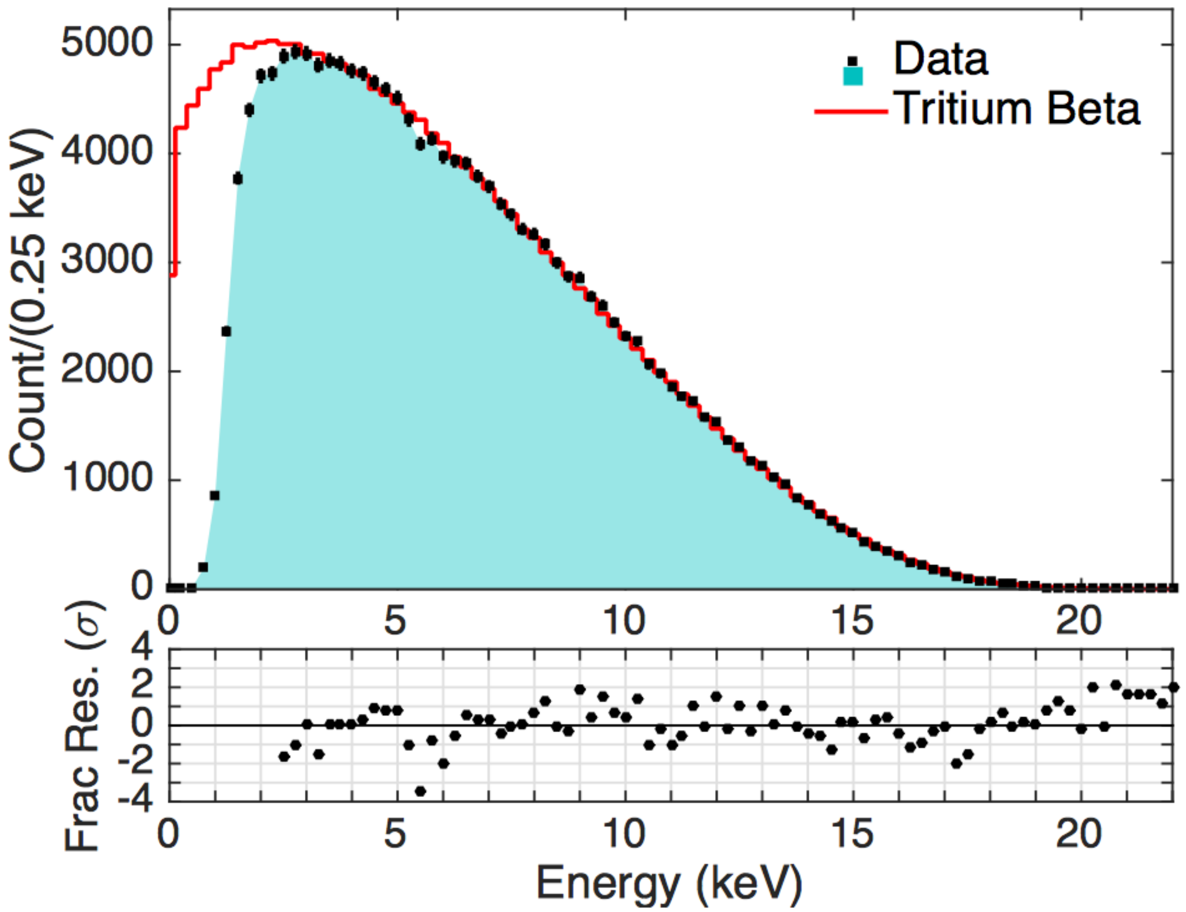


FIG. 5: Top: The tritium energy spectrum measured by LUX with the combined energy model (black) compared to a tritium spectrum convolved with detector resolution ($\frac{\sigma_E}{W} = \sqrt{\sigma^2(n_\gamma) + \sigma^2(n_e)}$.) The p-value between data and model from 3 to 18 keV is 0.70. Bottom: Bin-by-bin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

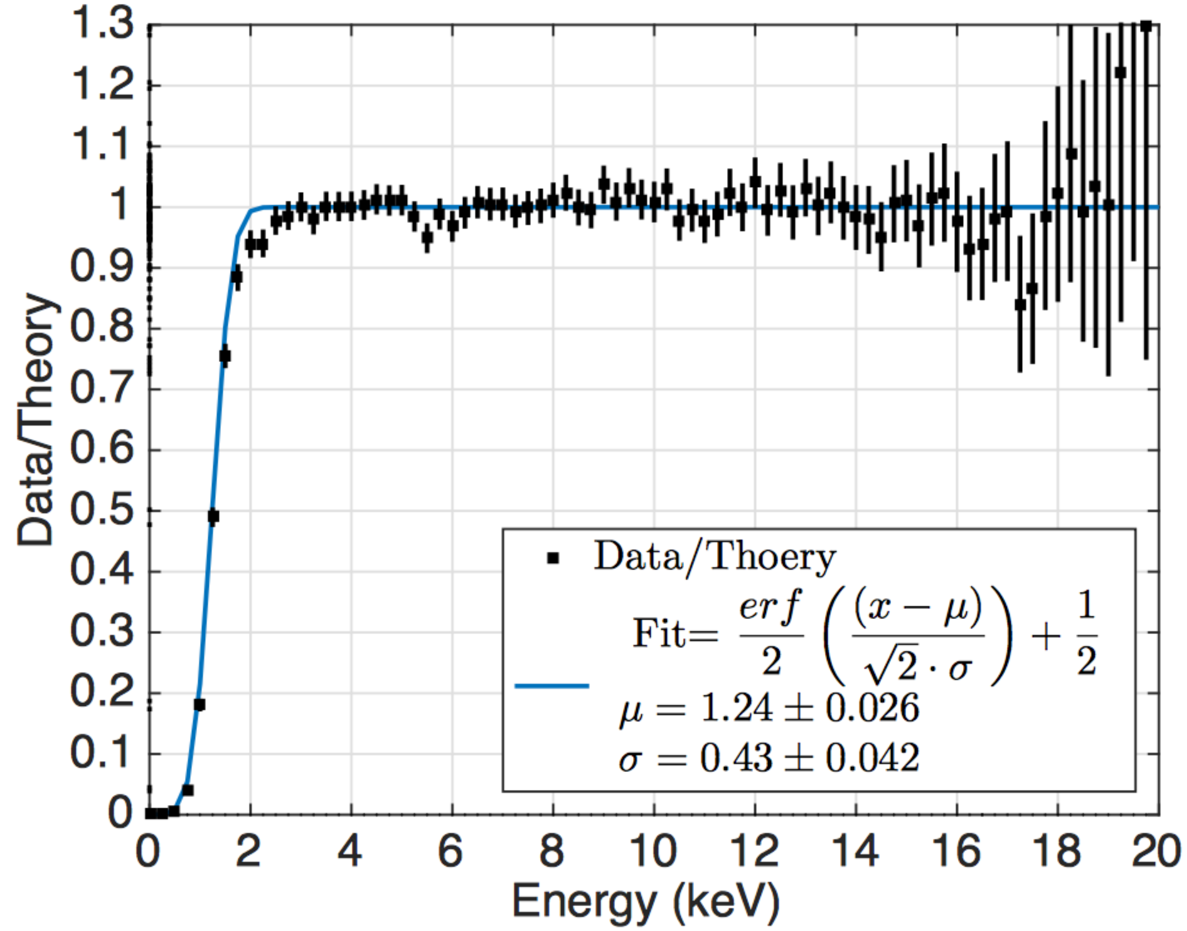


FIG. 6: Ratio of the measured tritium energy spectrum and the true one convolved with the detector resolution. A fit to an error function is shown.

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

LUX energy resolution for electronic recoils

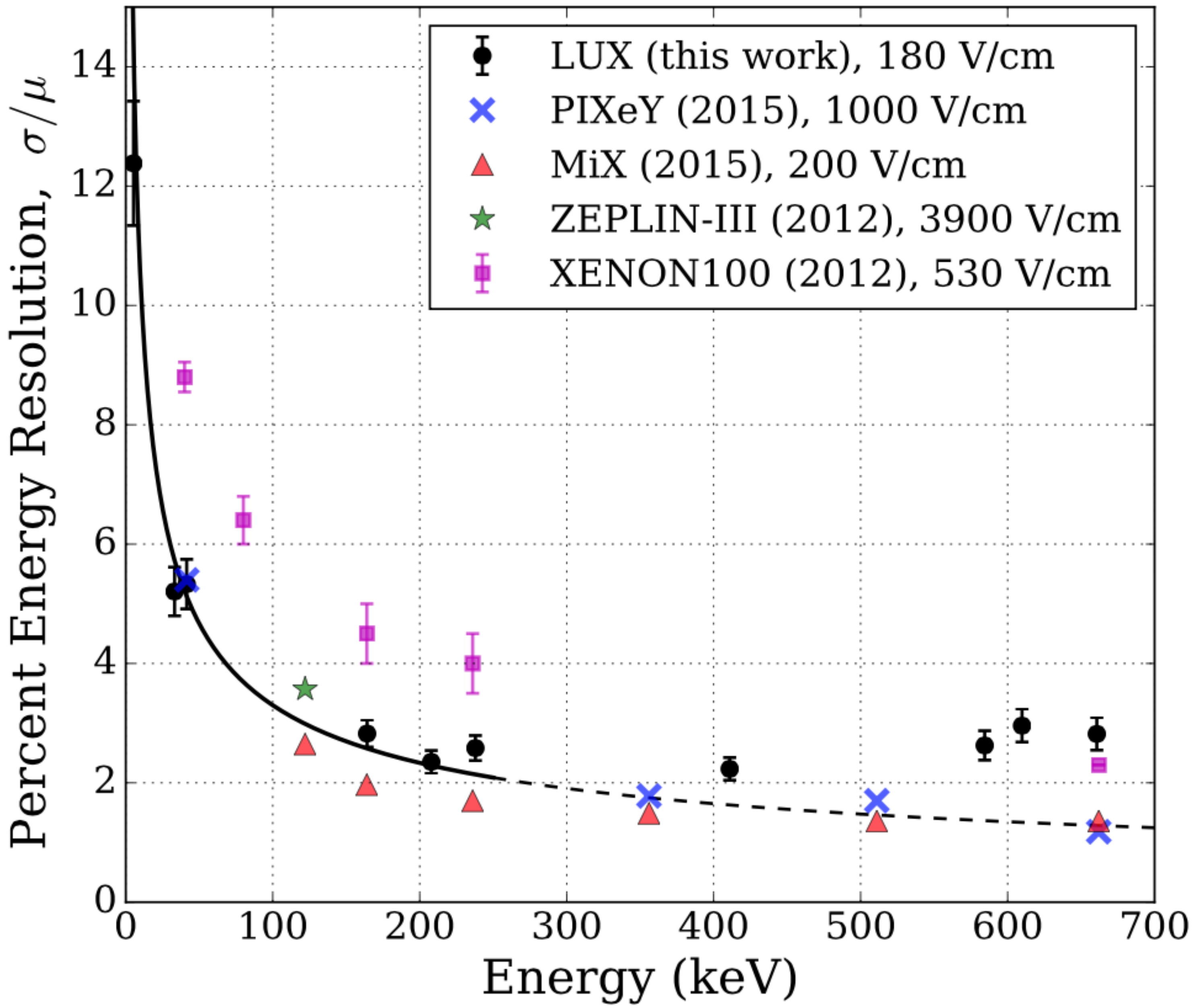


FIG. 8. The measured energy resolution at known energy peaks in the LUX ER backgrounds. The detector is optimized for low energy sensitivity, and variable amounts of PMT saturation and single-electron contributions affect S2 pulses and hamper the energy resolution at high energy, as discussed in the 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)

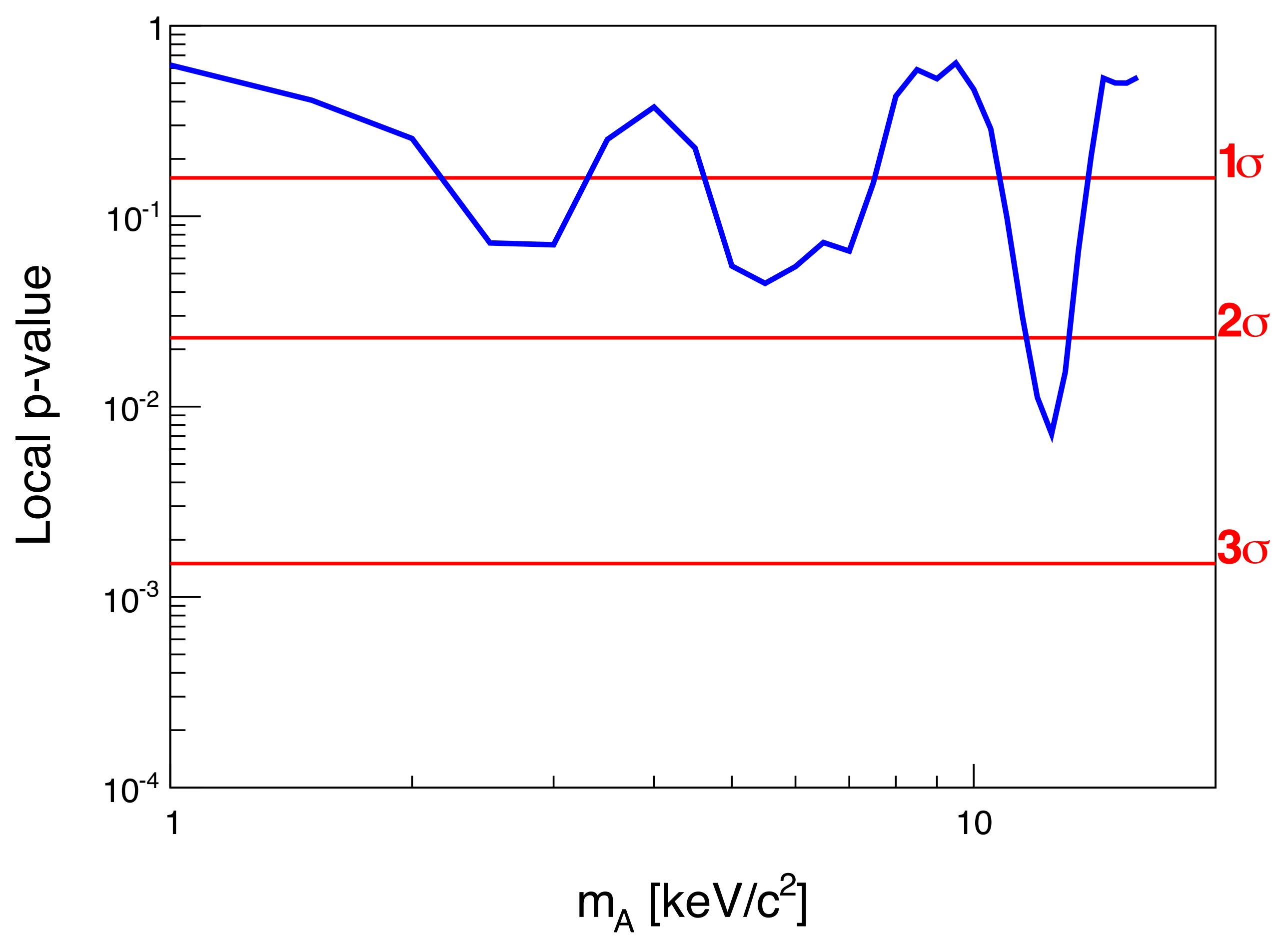
Limit conversion: nSig to gAe

- Limit on **$gAe = gAe_{sim} * (nSig/nPDF)^{power}$**
  - gAe_{sim} = arbitrary coupling, used to generate the signal model
  - nSig = limit on the number of events, as set by the PLR
  - nPDF = integral of the signal PDFs * exposure
  - 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

What can we compare the limit on g_{Ae} with, in the case of solar axions ?

- 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 Standard Model ones
  - **KSVZ**: axion does not couple directly to quarks and leptons, but via its interaction with two Higgs doublets
- Assuming one of these two models, it would be possible to extract a limit on the axion mass, which makes a (model dependent) comparison between g_{Ae} and $g_{A\gamma}$ feasible
- **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

Look Elsewhere Effect in the LUX 2013 ALPs analysis



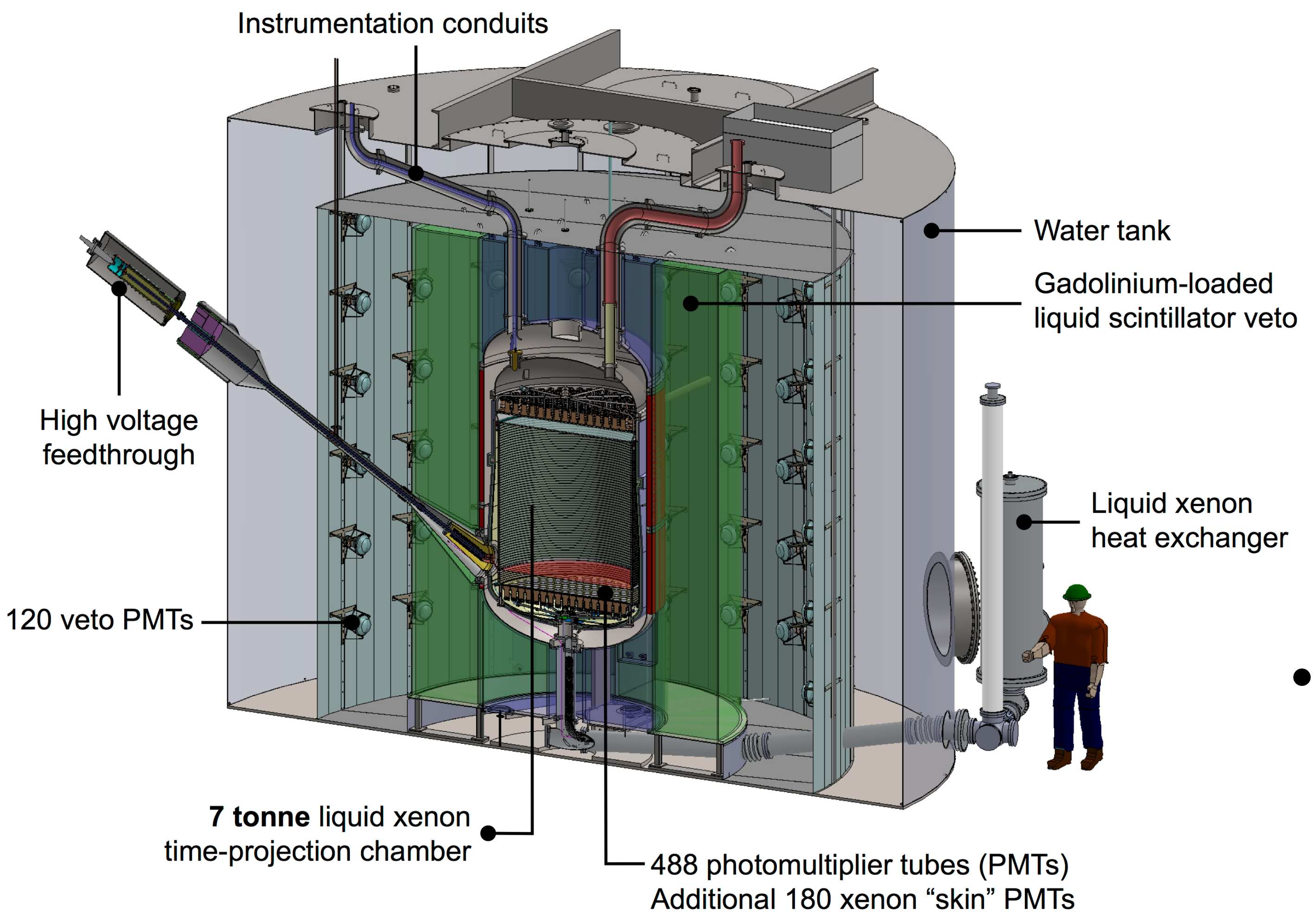
- Local p-value as a function of the ALP mass, with the corresponding number of standard deviations (σ) away from the null hypothesis
- At 12.5 keV/c^2 a local p-value of 7.2×10^{-3} (2.4σ deviation) corresponds to a global p-value of 5.2×10^{-2} (1.6σ deviation) — applying the Look Elsewhere Effect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

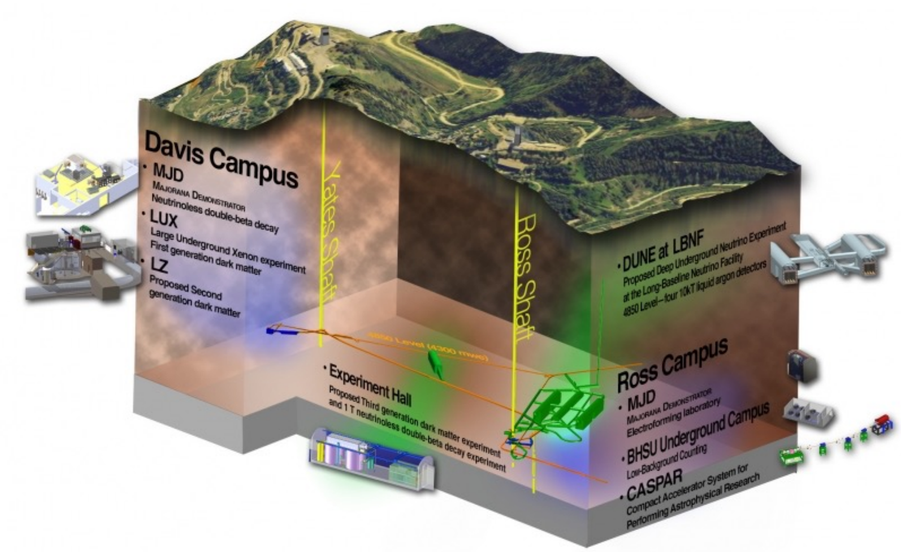
Maria Francesca Marzioni

The LZ (LUX+ZEPLIN) experiment

- Dual-phase xenon TPC: 10 ton total mass, 7 ton active LXe mass, **5.6 ton fiducial mass**
- Expected to run for 1000 live days

The LZ Dark Matter Experiment





- Will be installed at SURF, taking LUX's place — onsite improvements in infrastructure for LZ