Axion Results with &
Future Searches with

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?

• Axions and ALPs can couple with electrons, via the so-called **axio-electric effect**

  • we can measure the coupling between axions/ALPs and electrons ($g_{Ae}$)

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

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)]

- 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
  - \(^{85}\text{Kr}\) and Rn-daughter contaminants undergoing beta decays
  - x-rays emitted following those \(^{127}\text{Xe}\) 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 
  \[ E = (S1c/g1 + S2c/(\varepsilon g2))W \]

  - g1: geometric light collection efficiency and PMT quantum efficiency

  - \( \varepsilon g2 \): 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
solar axions result

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

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

- Local p-value as a function of the ALP mass, with the corresponding number of standard deviations ($\sigma$) away from the null hypothesis
- At 12.5 keV/$c^2$ a local p-value of $7.2 \times 10^{-3}$ (2.4\$\sigma$ deviation) corresponds to a global p-value of $5.2 \times 10^{-2}$ (1.6\$\sigma$ deviation) — applying the Look Elsewhere Effect [E. Gross and O. Vitells, Eur. Phys. J., C70:525 (2010)]
Future Searches with
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
  - $^{85}\text{Kr}$ 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 $g_{\text{Ae}}$, having the BG rates as nuisance parameters and S1 and S2 as observables
most recent solar axions sensitivity projection

- 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

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

LZ sensitivity (1000 live-days, 5.6 ton fiducial mass) excludes $g_{Ae} > 5.9 \times 10^{-14}$ (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!

Phys. Rev. D 93, 072009 (2016)
Back-up slides
Limit conversion: 
\( n_{\text{Sig}} \) to \( g_{\text{Ae}} \)

- Limit on \( g_{\text{Ae}} = g_{\text{Ae}_{\text{sim}}} \times \left( \frac{n_{\text{Sig}}}{n_{\text{PDF}}} \right)^{\text{power}} \)
  
- \( g_{\text{Ae}_{\text{sim}}} \) = arbitrary coupling used to generate the signal model
  
- \( n_{\text{Sig}} \) = limit set by the PLR on the number of events
  
- \( n_{\text{PDF}} \) = integral of the signal PDFs \( \times \) exposure \( \times \) fiducial mass
  
- \( \text{power} \) varies with the axion type
    
    - it is 0.25 for solar axions, as the interaction rate scales with \( g_{\text{Ae}}^4 \)
    
    - it is 0.50 for galactic ALPs, as the interaction rate scales with \( g_{\text{Ae}}^2 \)
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/c²)

- 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 \( \frac{q_W}{W} = \sqrt{\sigma^2(n_{\gamma}) + \sigma^2(n_e)} \). 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 \( \sigma \).

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.

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.

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)

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)

- Resolution and efficiency effects modelled in accordance with the Noble Element Simulation Technique (NEST) package [M. Szydagis et al., JINST 6, P10002 (2011)]

- 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

20 keV/c^2 mass ALP
Why axions? (Particle Physics)

- The Strong CP violation problem

- the QCD Lagrangian acquires a term, proportional to a static parameter $\theta$, 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

- The Peccei and Quinn solution (1977)

- a new global symmetry $U(1)_{\text{PQ}}$ is introduced and spontaneously broken at some large energy scale, and the axion is the Nambu-Goldstone boson generated

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