Axion and axion-like particle searches in LUX and LZ

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Outline

- Why are we interested in axions
- How can we detect axions with a xenon TPC
- Axion signal
- Relevant background
- LUX axion analysis and preliminary results
- LZ axion case study
- Summary

Why are we interested in 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

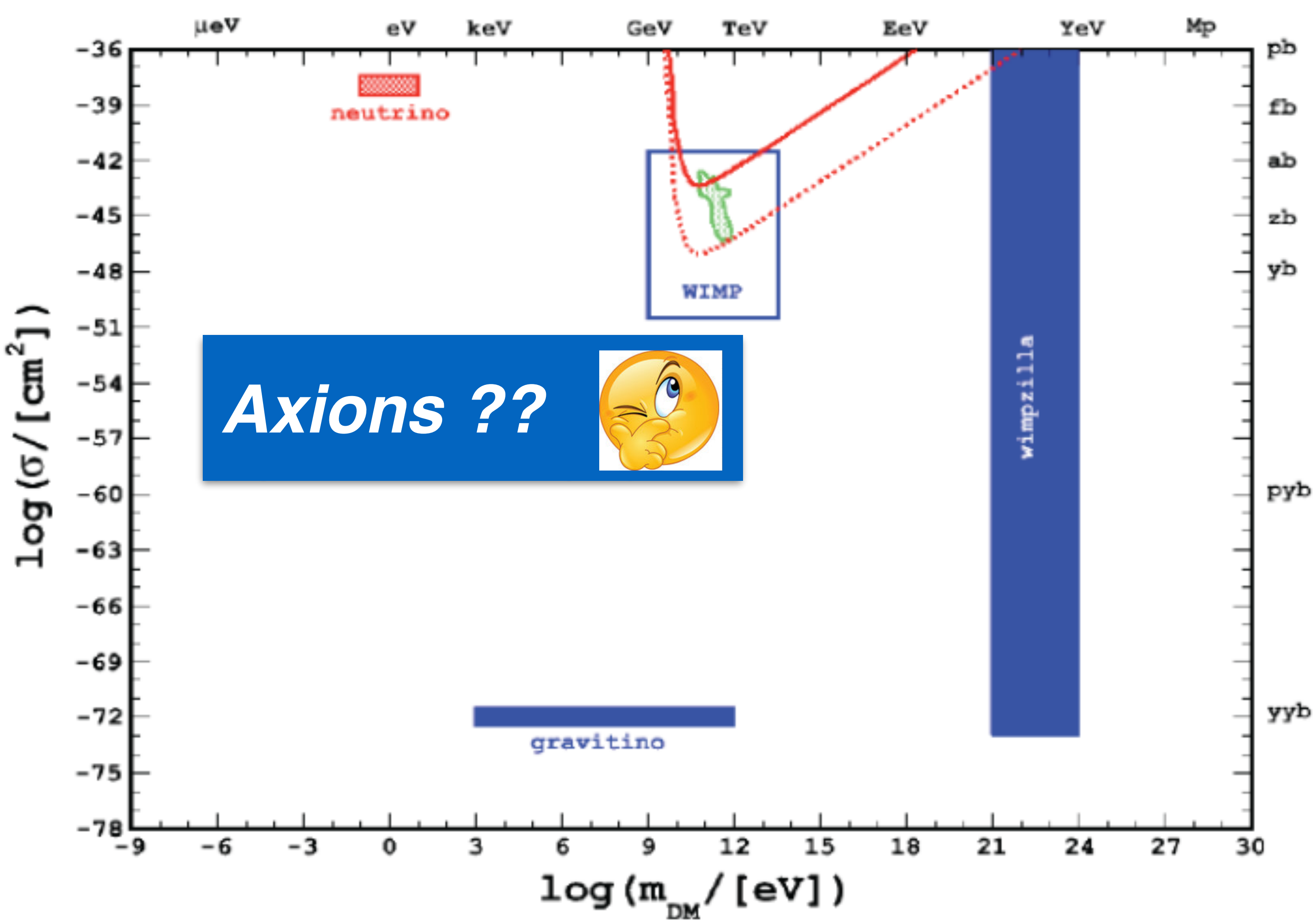
$$L_{QCD} = \overline{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} + \frac{\alpha_S\overline{\theta}}{8\pi}G^a_{\mu\nu}\widehat{G}^{a\mu\nu}$$

- 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

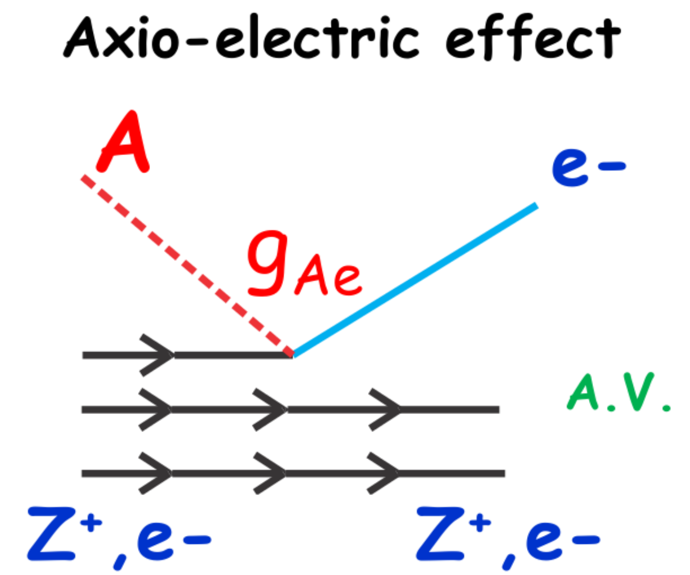
Why are we interested in axions (Dark Matter)



- 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

How can we detect axions with a xenon TPC

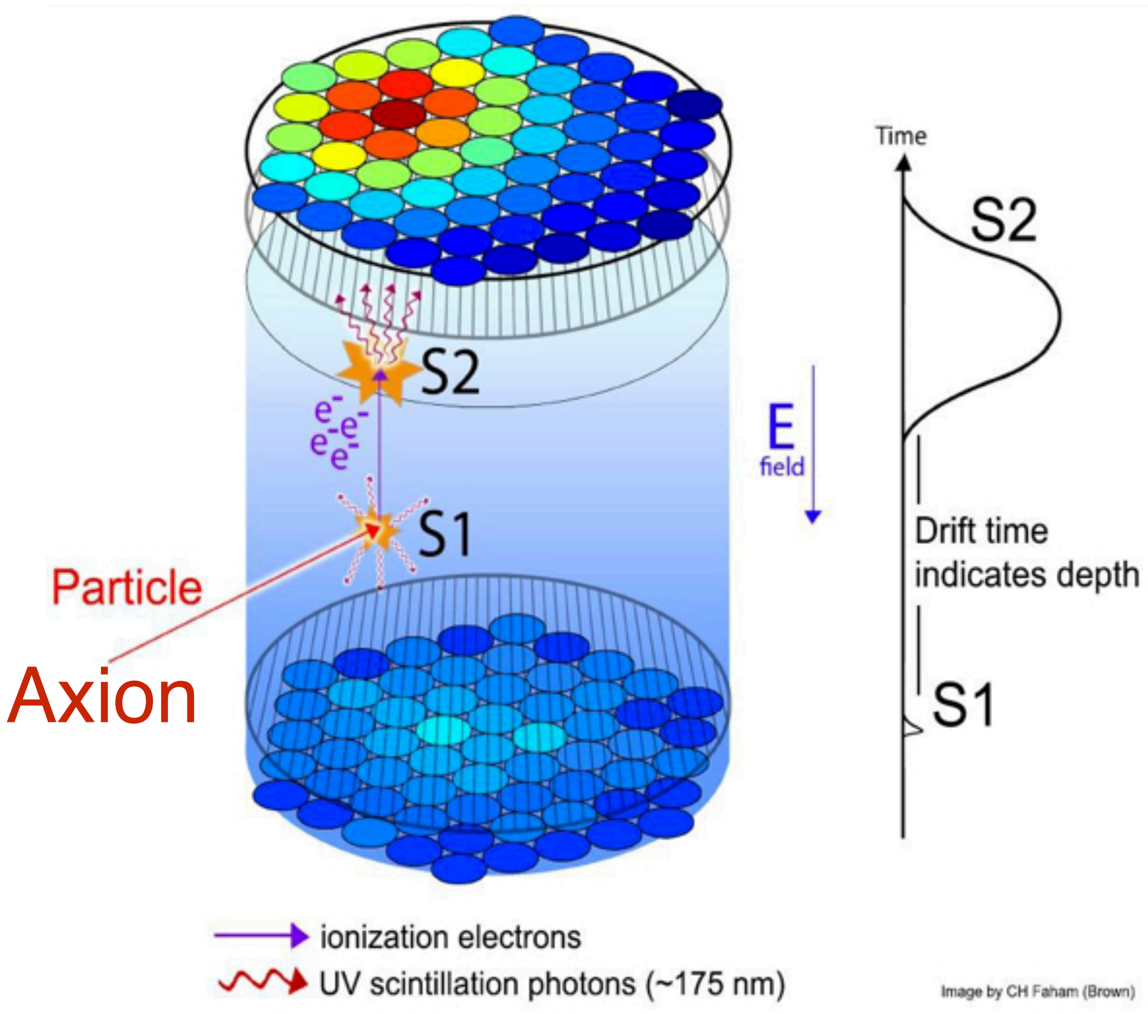
- Axions and ALPs can couple with electrons, via the so called axio-electric effect
  - measure the coupling between axions/ALPs and electrons (gAe)
- Potential sources of axions:
  - axions come from the Sun
  - ALPs slowly move within our Galaxy



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

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)

How can we detect axions 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)

How can we detect axions with a xenon TPC

- WIMP signal: nuclear recoil (NR) scattering
- Axion signal: electronic recoil (ER) scattering
- Most of the background: electronic recoil (ER) scattering

A good discrimination of NR and ER is possible thanks to the S2 info;
this is a powerful discrimination in the standard WIMP search, but does not help in the axion search

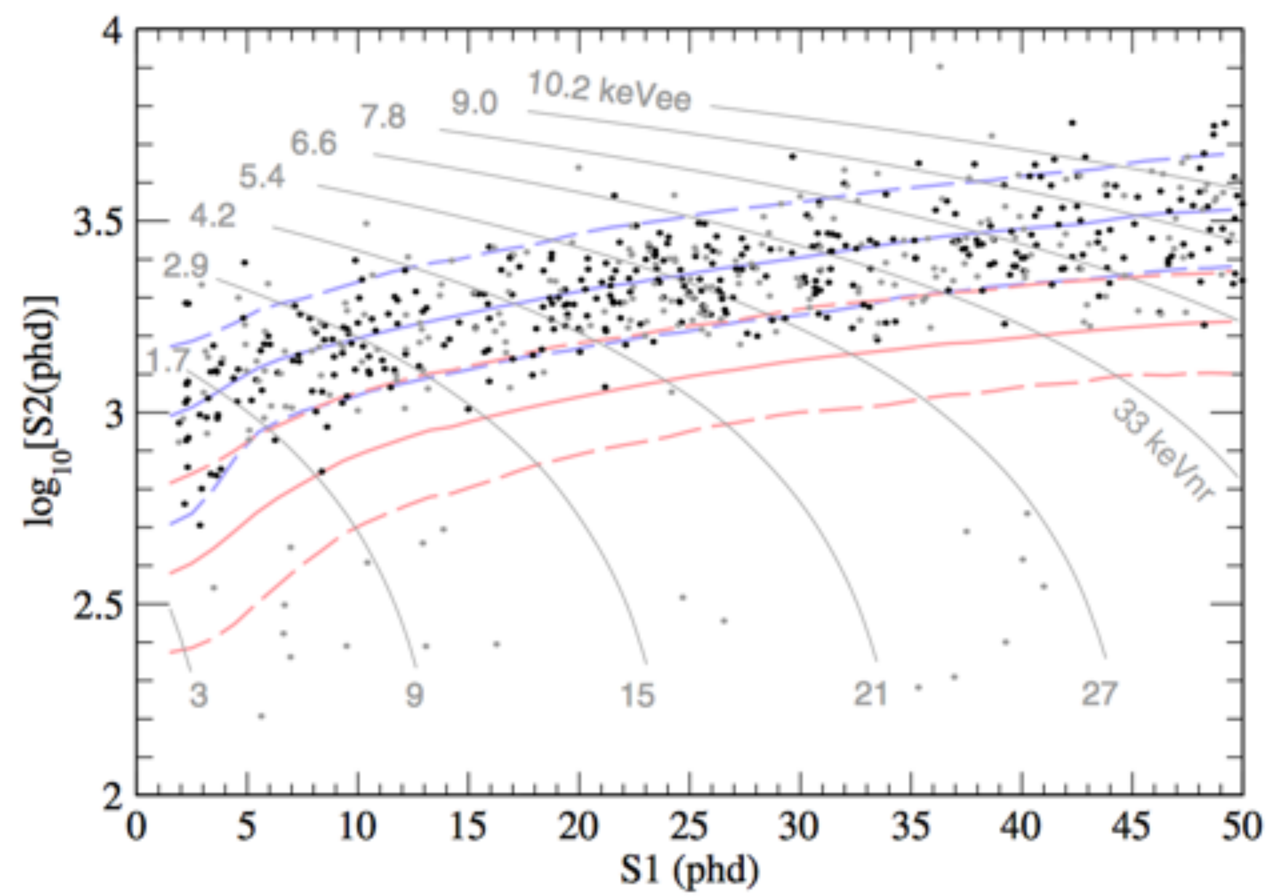


FIG. 2. Observed events in the 2013 LUX exposure of 95 live days and 145 kg fiducial mass. Points at <18 cm radius are black; those at 18–20 cm are gray. Distributions of uniform-in-energy electron recoils (blue) and an example 50 GeV c^{-2} WIMP signal (red) are indicated by 50th (solid), 10th, and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

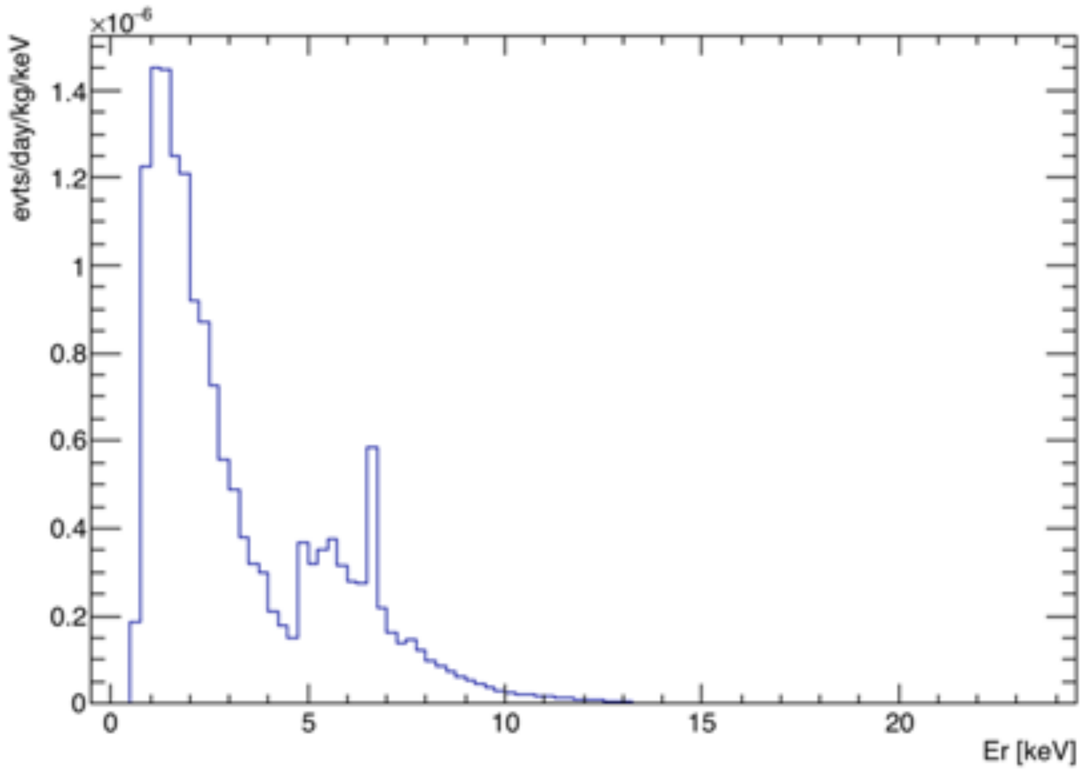
Solar axion signal

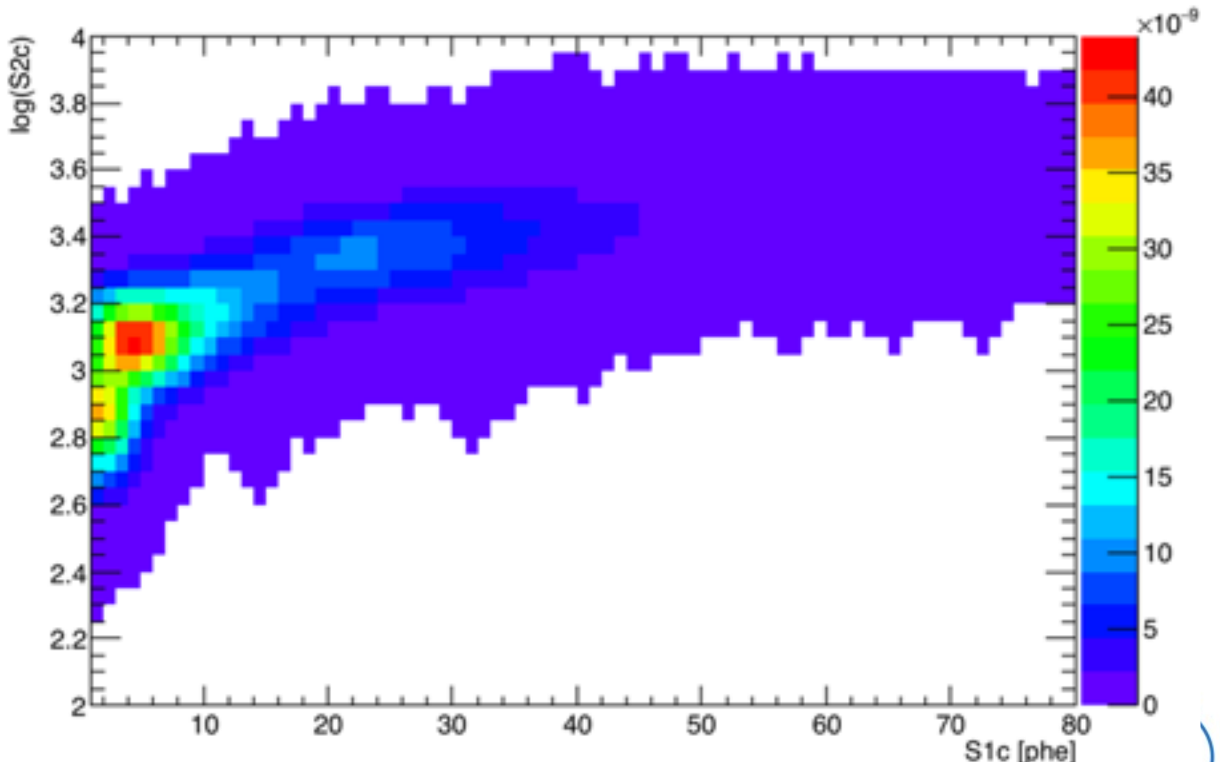
- Theoretical spectrum

J. Redondo, JCAP 1312, 008 (2013)

  - product of solar axion flux and axio-electric cross section
  - solar axion assumed to be massless

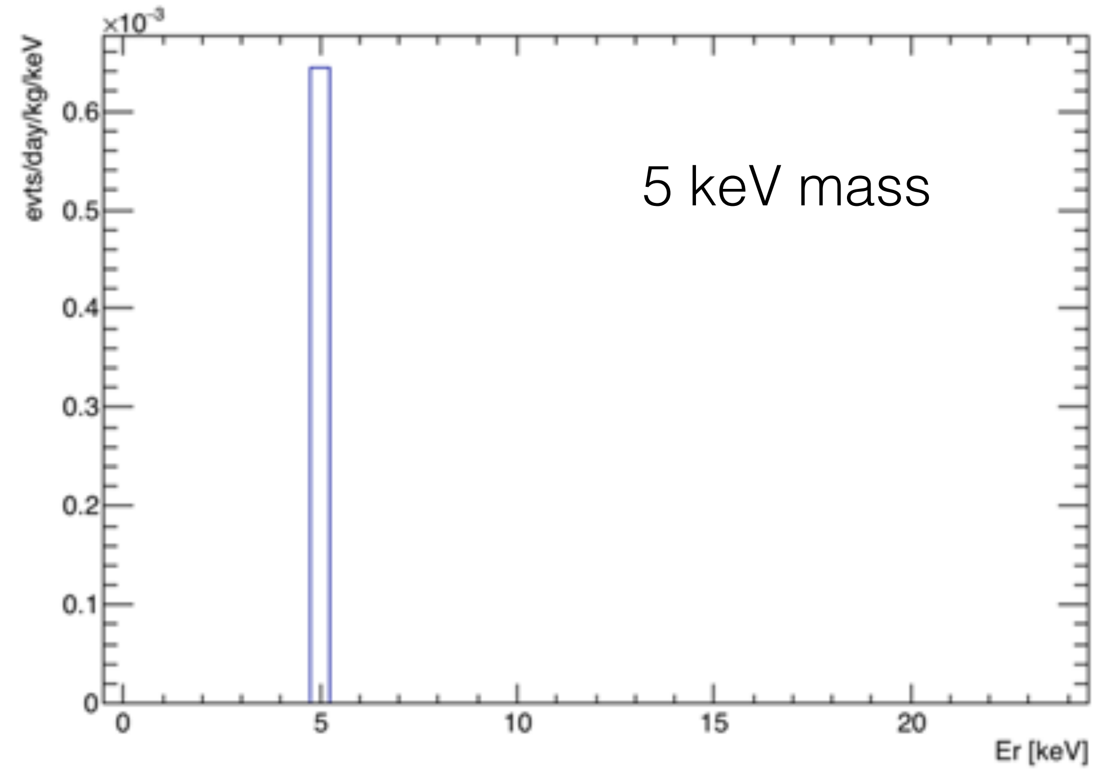
- Axion signal PDFs in the standard LUX phase space

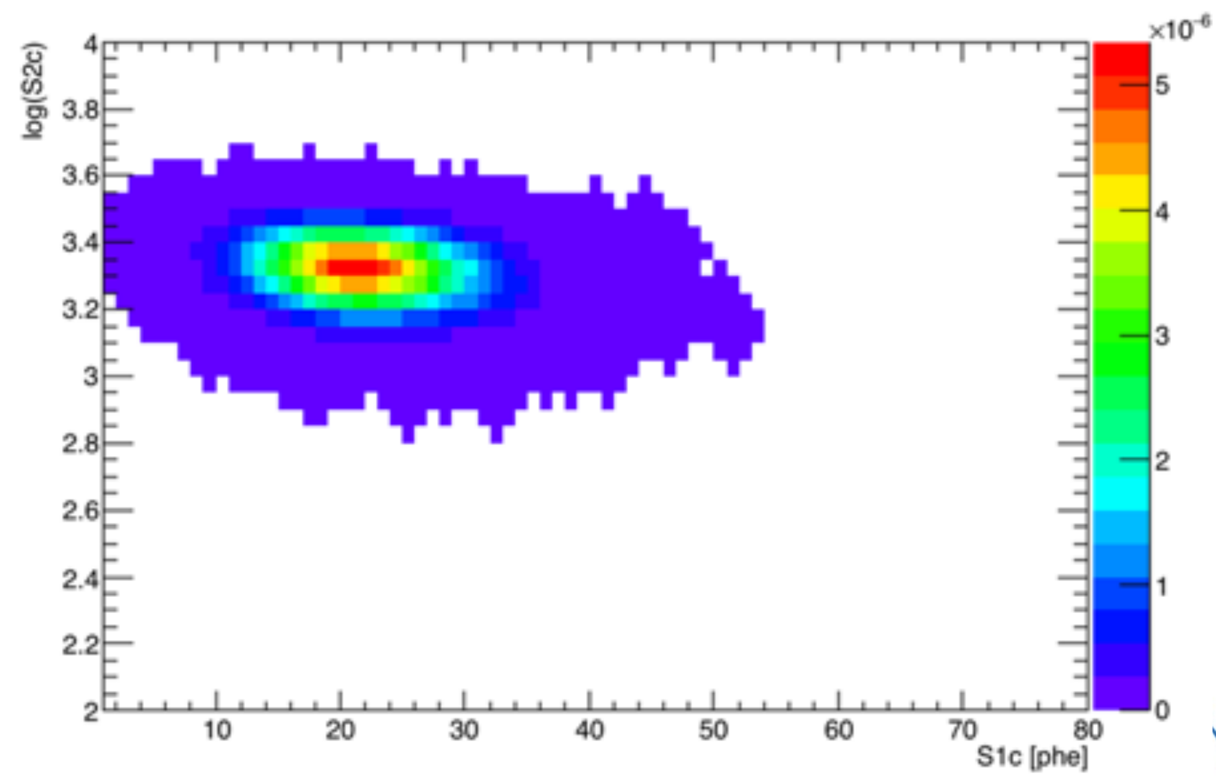




Galactic ALPs signal

- Theoretical spectrum
  - spike at the ALPs mass
  - width due to experimental resolution (note: in this plot, the width has no physical meaning — only for visualisation)
- Axion signal PDFs in the standard LUX phase space





Relevant background

- The majority of the background for LUX and LZ sits in the ER band
- This is helpful in the standard WIMP search, as the signal is in the NR band and we are able to discriminate the background and the signal thanks to the S2 information
- For ER band searches, such as the axion/ALPs search, we do expect the signal to be in the same band as the background

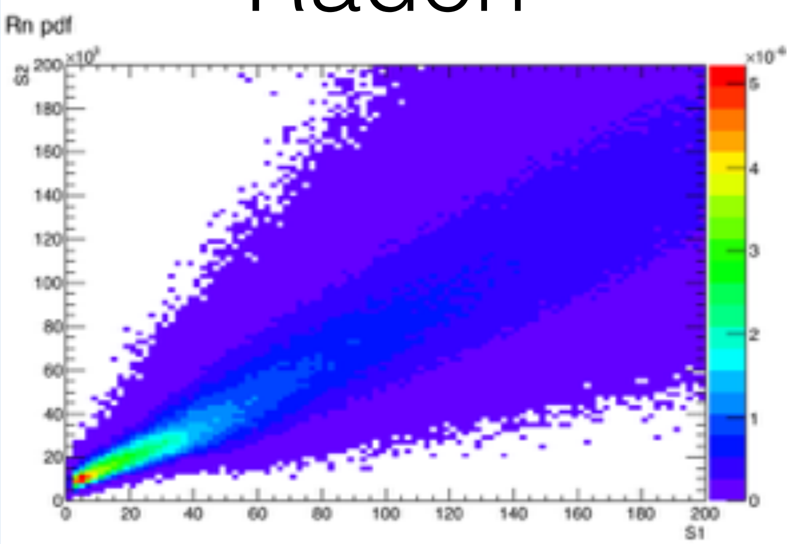
1. Intrinsic radioactivity (Rn, Kr85, Ar37)
2. Lab and cosmogenic (Compton, Xe127)
3. Surface contamination
4. Xe136 double beta decay
5. Neutrinos

a good description of the background is essential to perform ER band searches

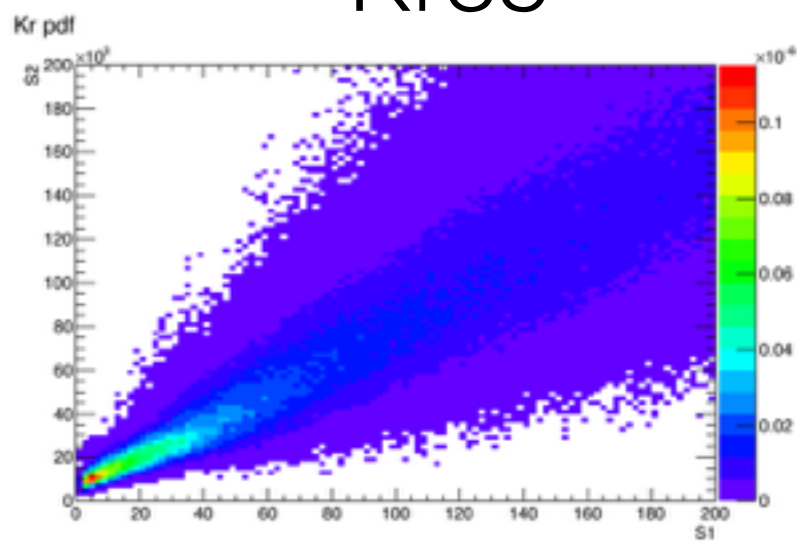
Relevant background

Intrinsic radioactivity

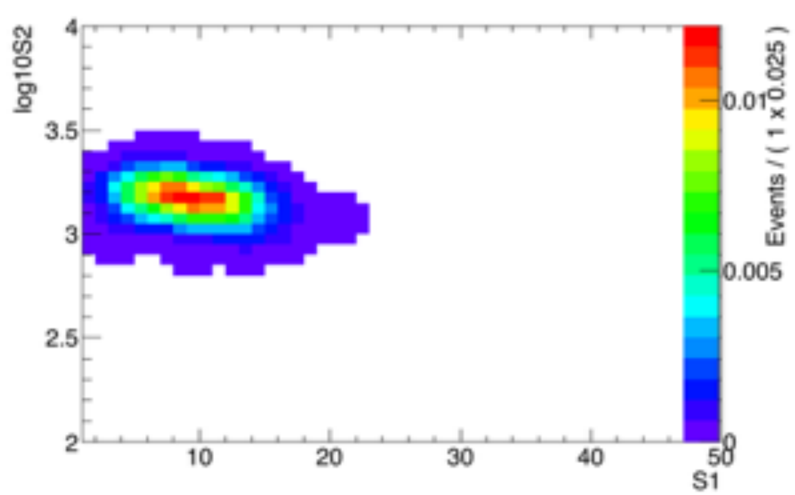
Radon



Kr85

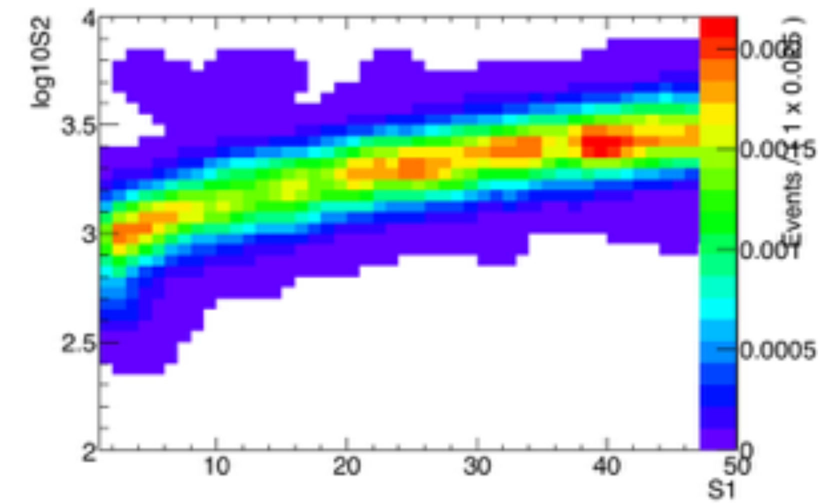


Ar37

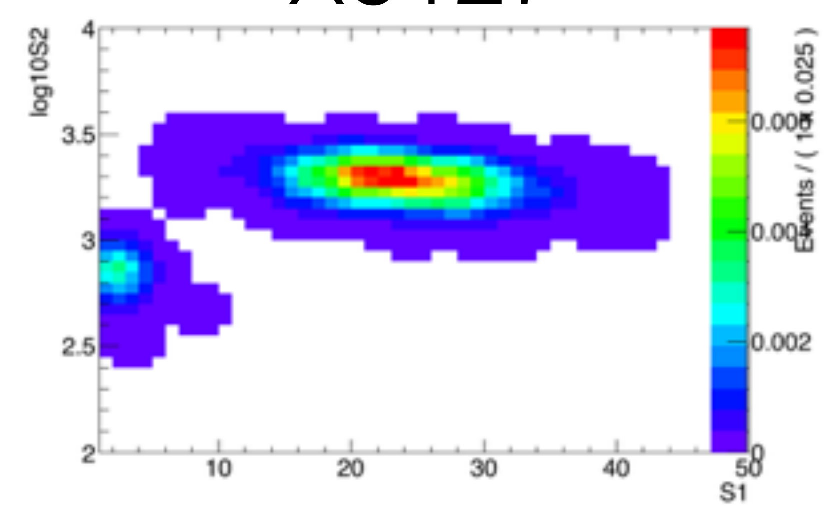


lab & cosmogenic

Compton +

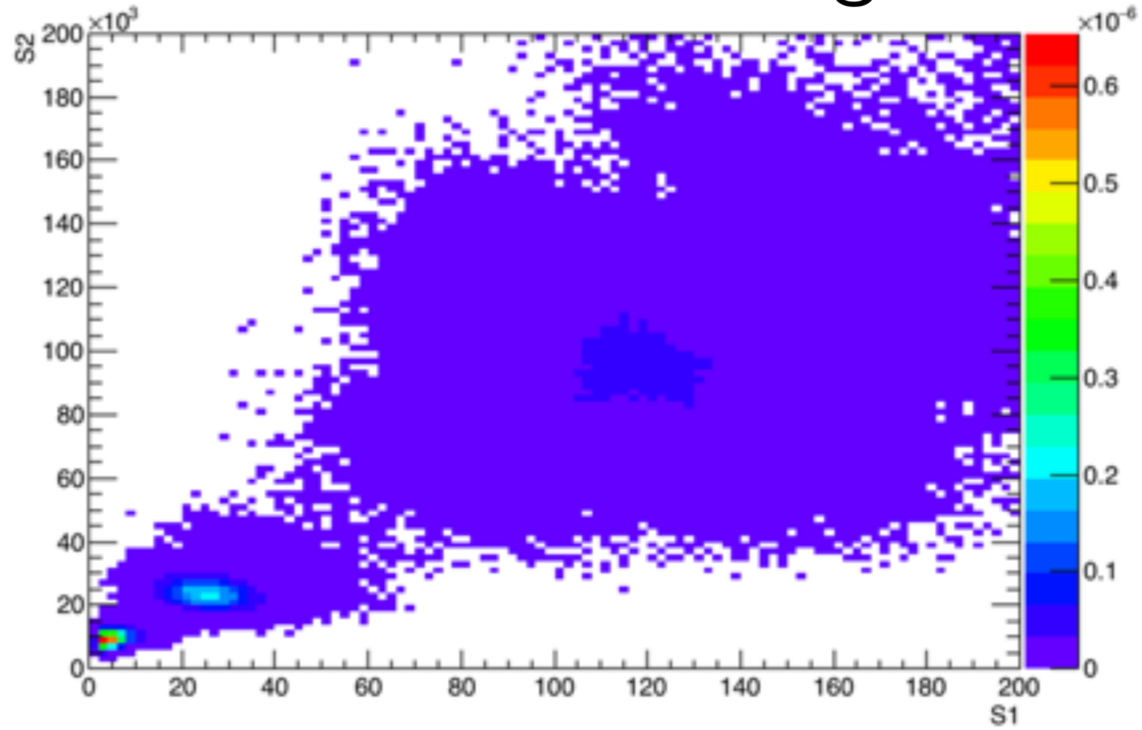


Xe127

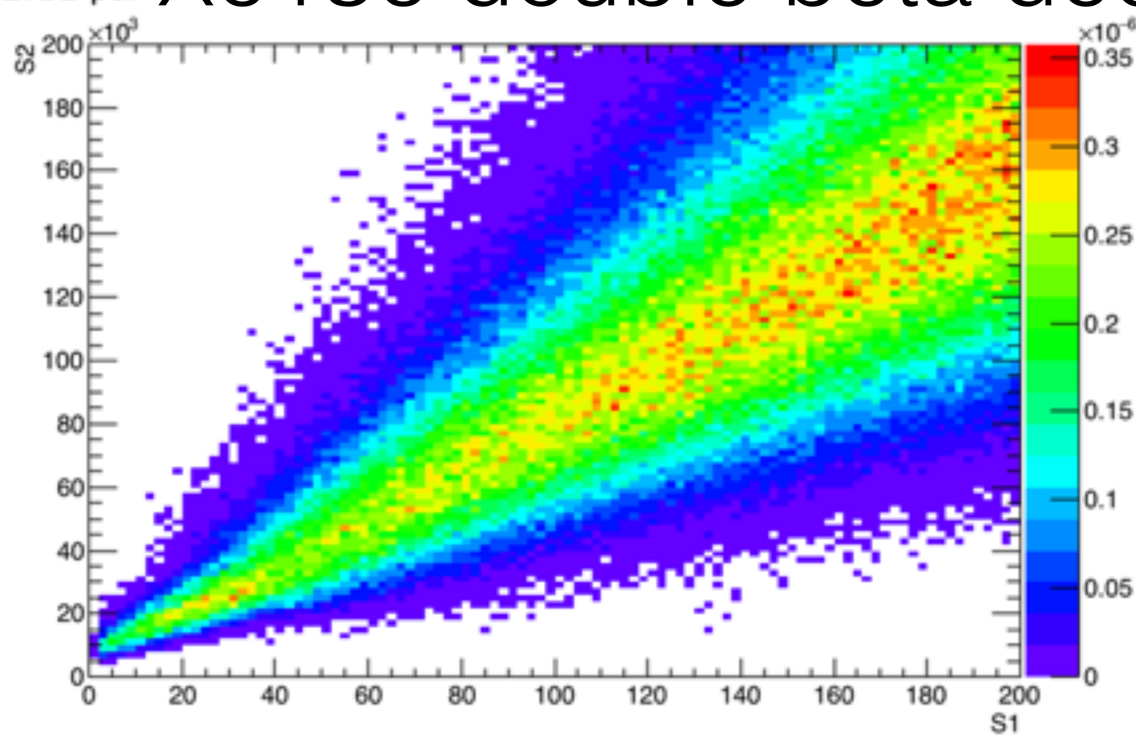


Relevant background

Detector ER bg

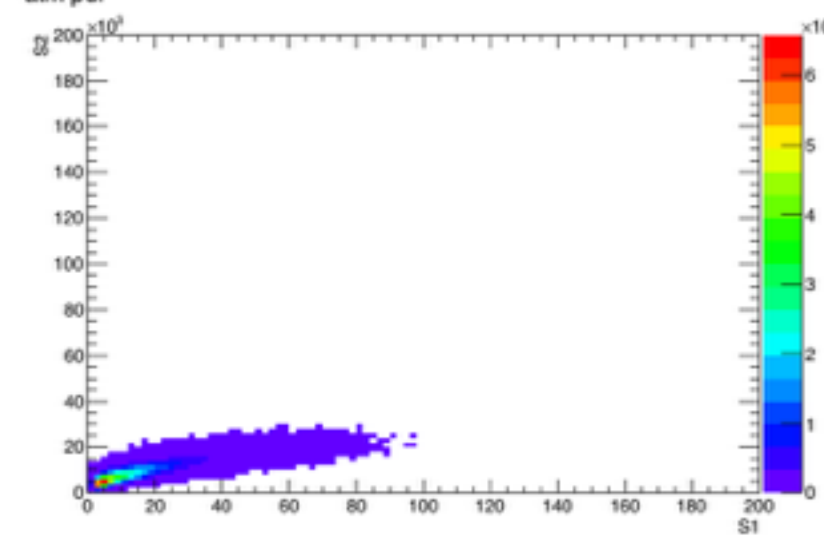


Xe136 double beta decay

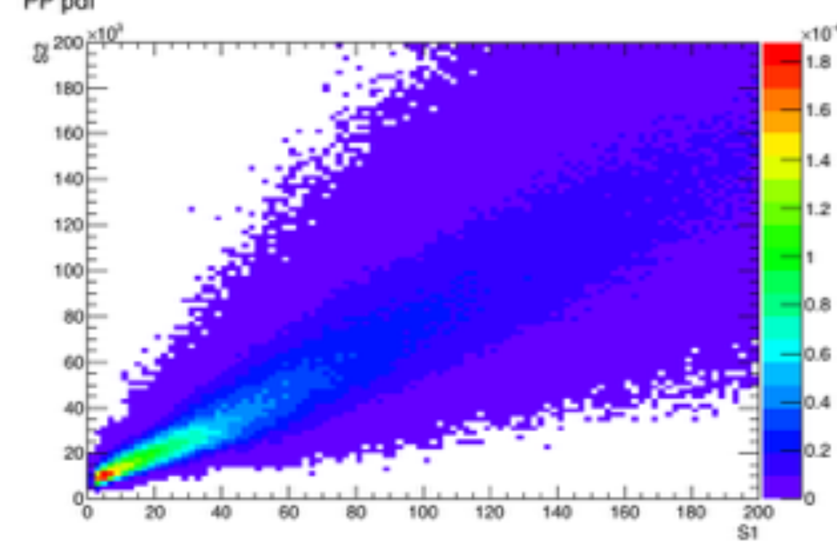


neutrinos

Atmospheric nu



PP solar nu



LUX axion analysis

- We test the axion signal model against LUX Run03 data [95 live days x 145 kg]
- We use a PLR (Profile Likelihood Ratio) analysis to set a limit on the coupling gAe, with test statistic: $q(g_{Ae}) = -2\log[\lambda(g_{Ae})] = -2\log[L(g_{Ae},\hat{\hat{\theta}})/L(\hat{g}_{Ae},\hat{\theta})]$
- Observables: S1 (primary scintillation), log10S2 (secondary ionisation), r (TPC radius), z (TPC vertical coordinate)
- Parameter of interest: number of signal events
  - converted in to gAe

- Solar axions:
  - $g_{Ae} = g_{Ae}$_sim * (nSig/nPDF)^0.25
- Galactic ALPs:
  - $g_{Ae} = g_{Ae}$_sim * (nSig/nPDF)^0.50

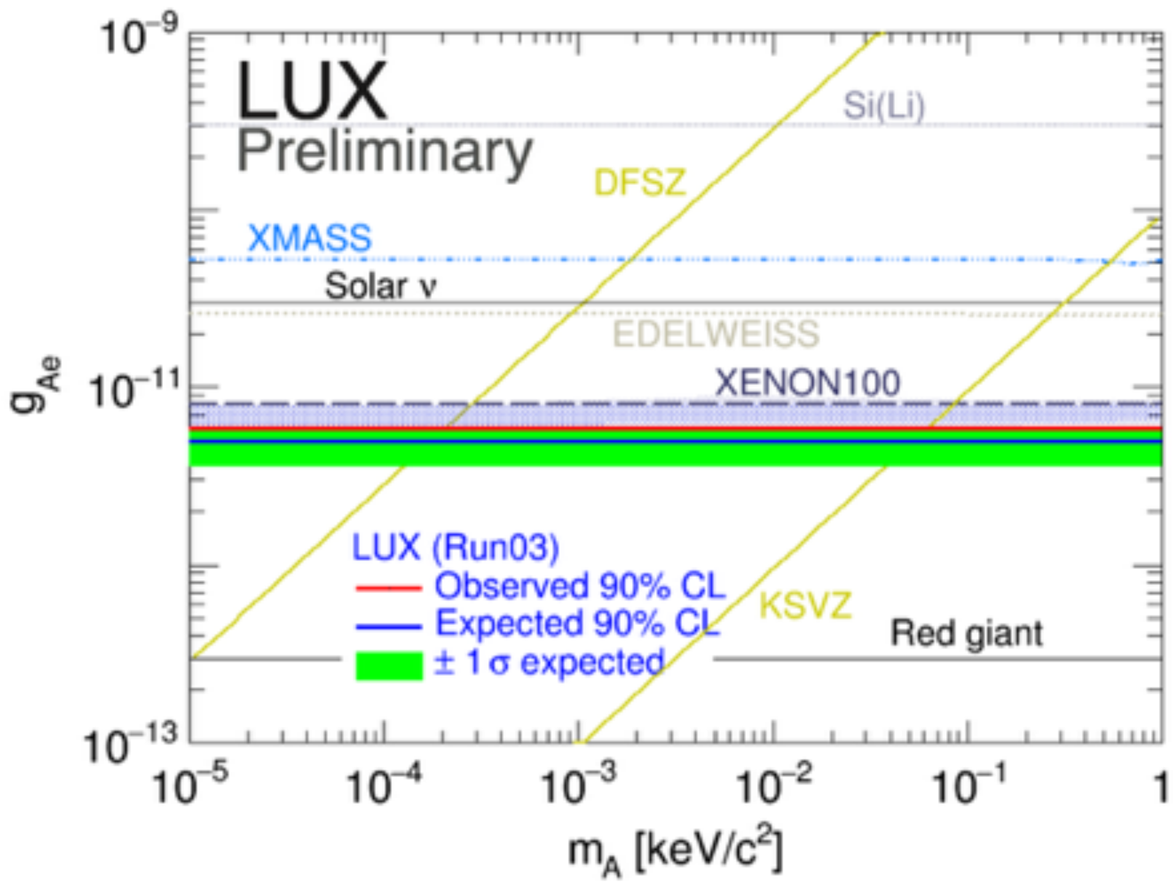
The power depends on the interaction rate scaling, proportional to:
- g_{Ae}^4 for solar axions
- g_{Ae}^2 for galactic ALPs

- **g_{Ae}_sim** is the coupling assumed in the generation
- **nSig** is the limit set by the PLR (when POI=nSig)
- **nPDF** is the integral of the signal PDFs

- Nuisance parameters: background components rates

LUX preliminary axion results

Solar axions



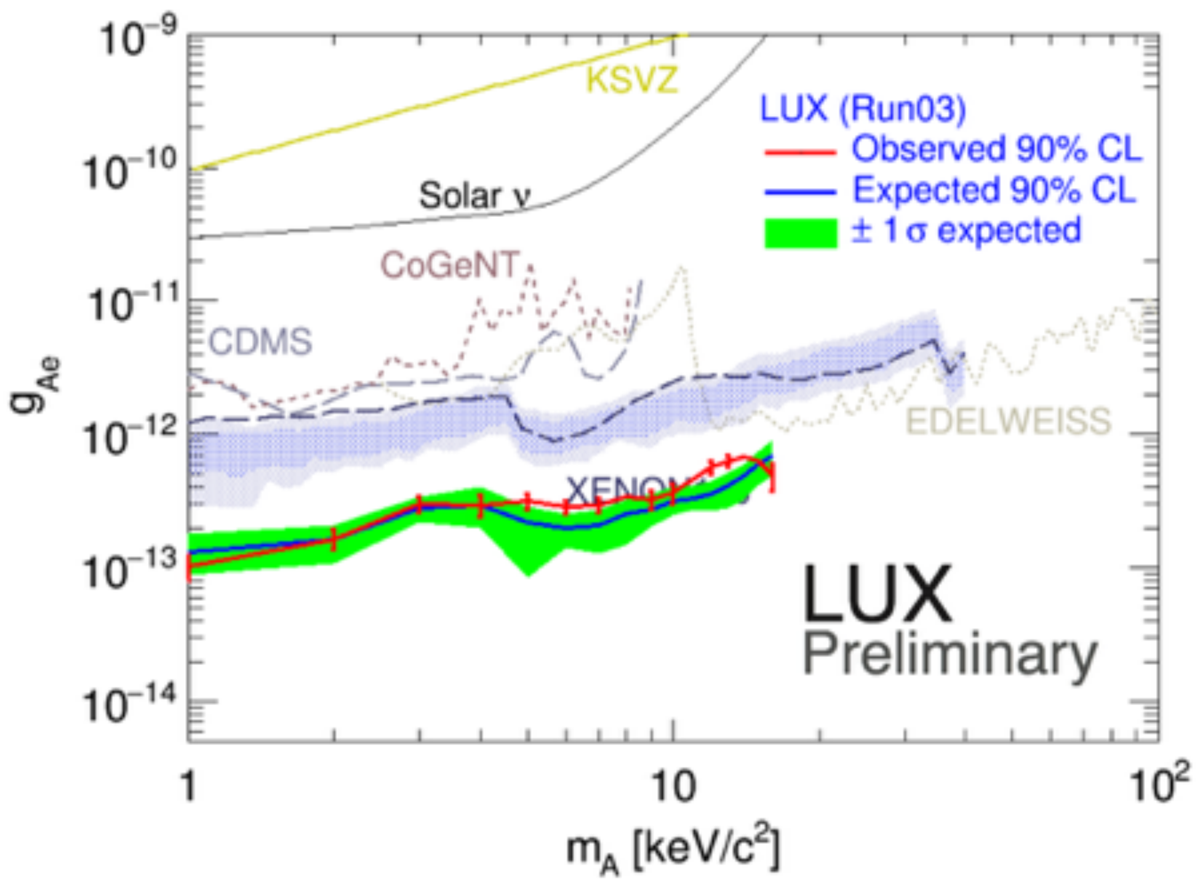
QCD axion theoretical models

- DFSZ: axion is the phase of a new electroweak singlet scalar field and couples to a new heavy quark, not to 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 essentially 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 preliminary axion results

Galactic ALPs



- Plan: extend the galactic axion-like particles search up to higher energies (~40 keV minimum)
- Background model is limited at 20 keV, so we need to extend it

LZ axion case study

- Differences with respect to the LUX analysis:
  - fake data generated on the LZ background model instead of real data
  - larger exposure: 1000 live days x 5.6 ton

Status and plan for the LUX analysis

- Preliminary results are in good shape, but we need to cross check a few items in the Profile Likelihood
- Background model is limited at 20 keV, and we would like to extend it up to ~100 keV
- We also need data which are free from Kr (work in progress…)
- Target: have a robust preliminary result by IDM 2016

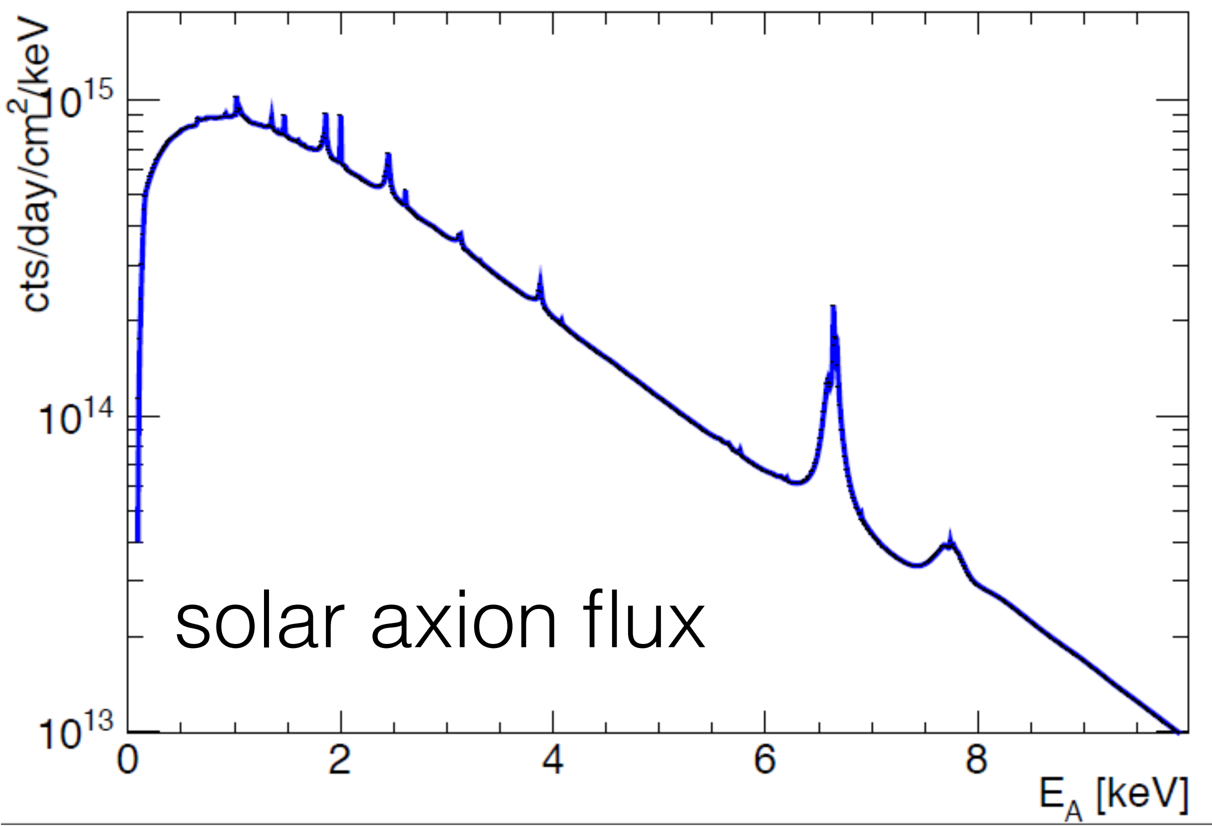
Summary

- 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 are also suitable Dark Matter candidates
- The majority of the background for LUX and LZ sits in the ER band, making a good description of the background essential to perform axion searches
- A Profile Likelihood Ratio approach has been chosen as statistical strategy, using the most meaningful experimental quantities as observables

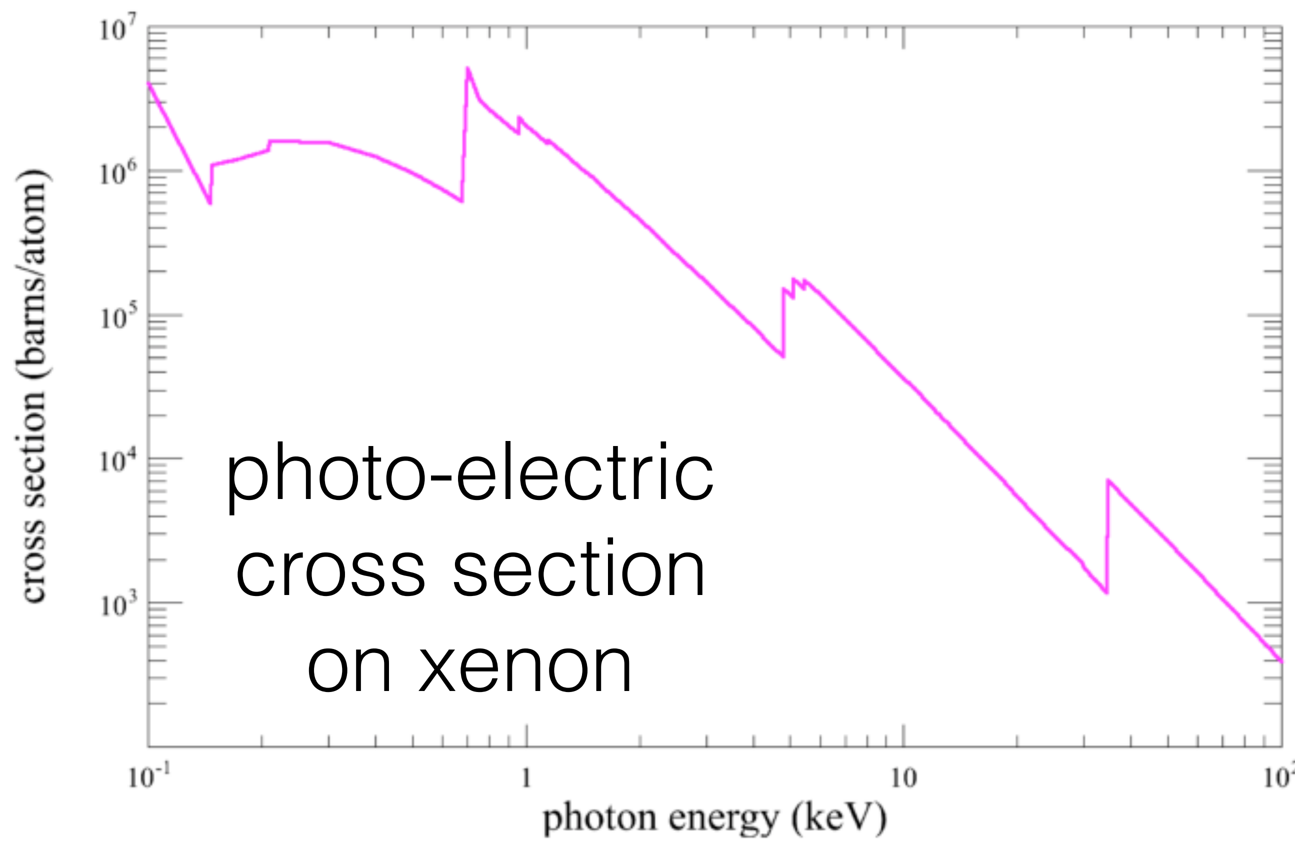
Backup

Solar axion theoretical spectrum

- The solar axion theoretical spectrum is the product of the solar axion flux and the axio-electric cross section



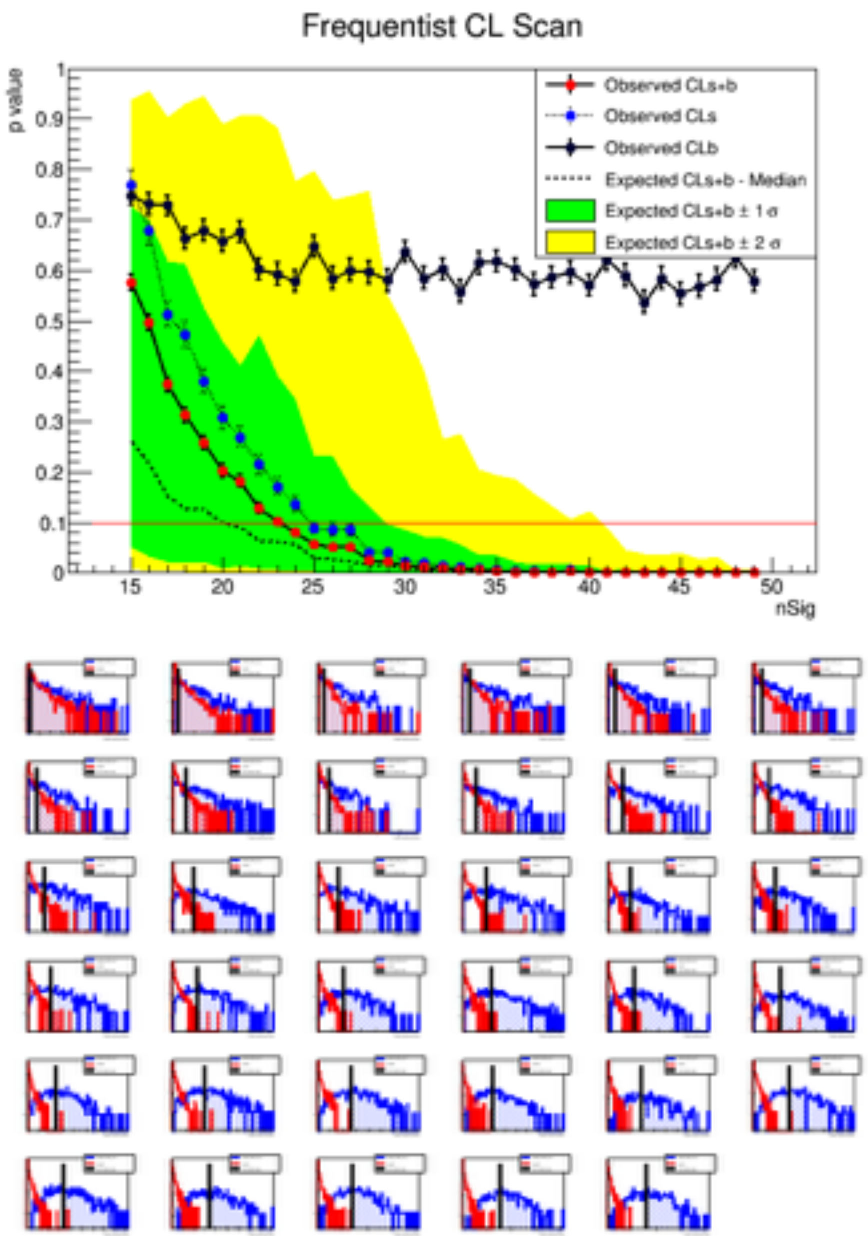
J. Redondo, JCAP 1312, 008 (2013)



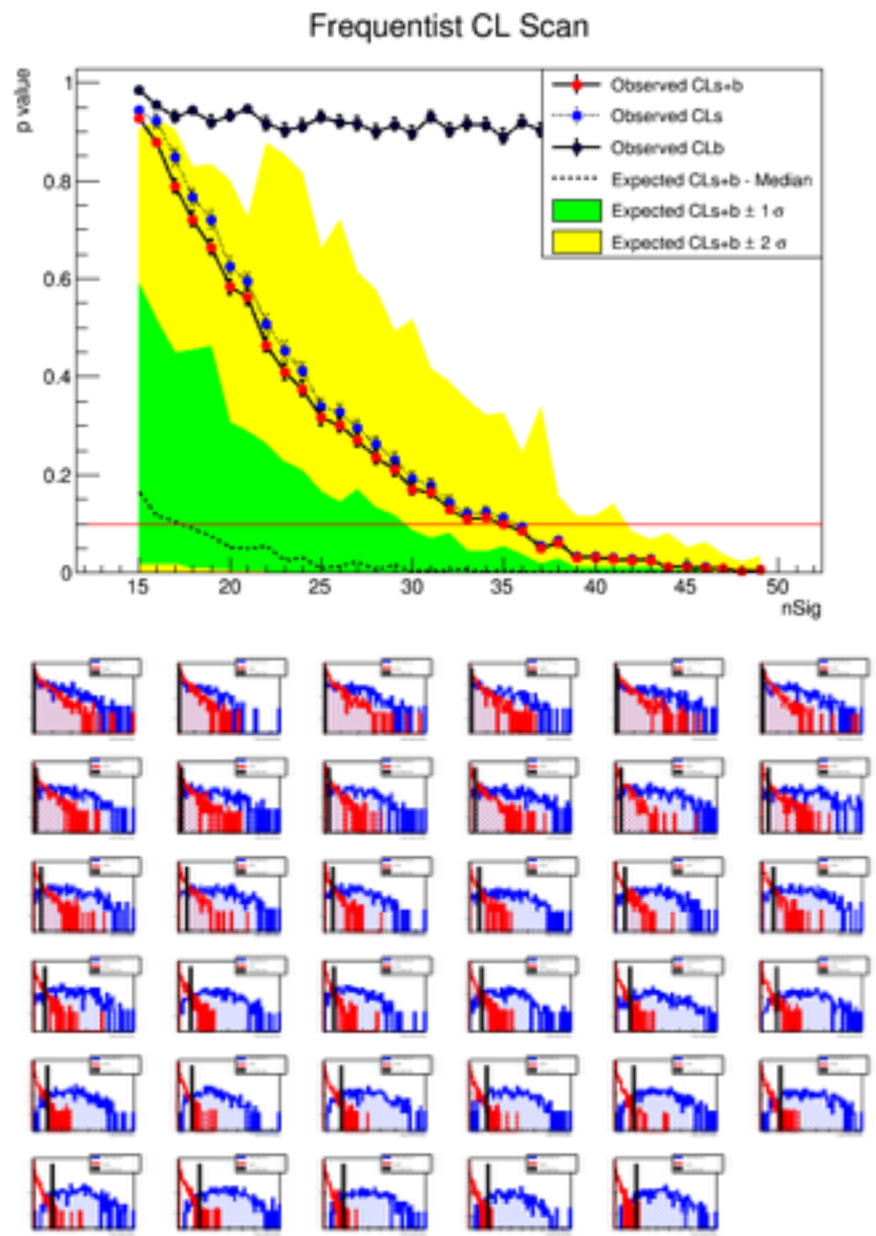
How does the LUX PLR work

Galactic ALPs analysis

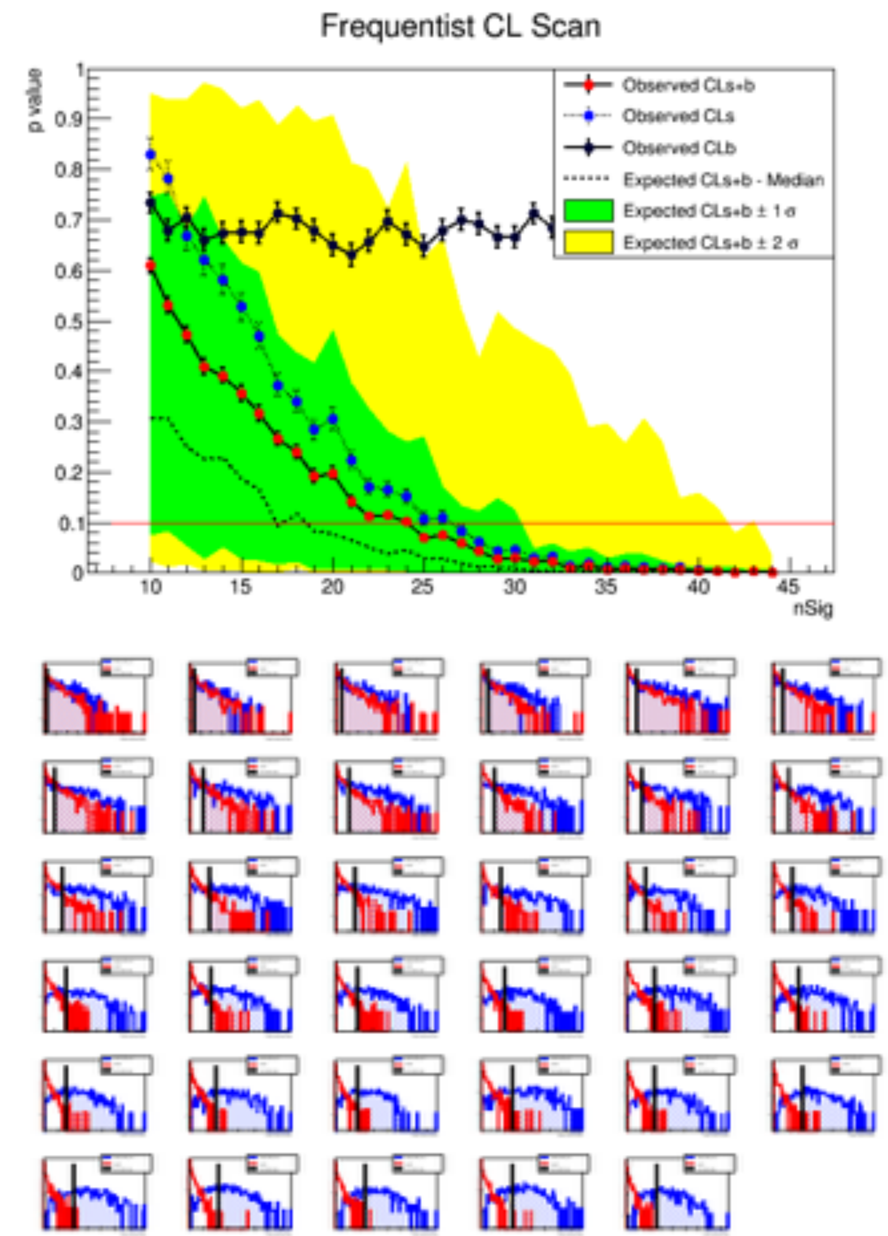
mA = 3 keV



mA = 5 keV



mA = 10 keV



How does the LUX PLR work

Solar axions analysis