A Hunt for Hidden Photons with the LZ Experiment

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- LZ Collaboration
- Detector Working Principle

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- Sensitivity Projection: HPs
- Sensitivity Projection: ALPs

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LZ Collaboration

LUX-ZEPLIN

- Dark Matter Direct Detection Experiment
- Detector Located at Sanford Underground Research Facility (SURF), South Dakota, USA
- 37 institutions, 250 scientists, engineers, and technicians

Collaboration Meeting @ SLAC, March 2017

LZ Detector

- liquid xenon Time Projection Chamber (LXe-TPC)
- 7 tonnes of LXe
- Gd loaded outer detector
- 494 PMTs
- (Additional veto) 131 xenon “skin” PMTs
- science run to start in 2020
- 1000 live days * 5.6 tonnes planned exposure

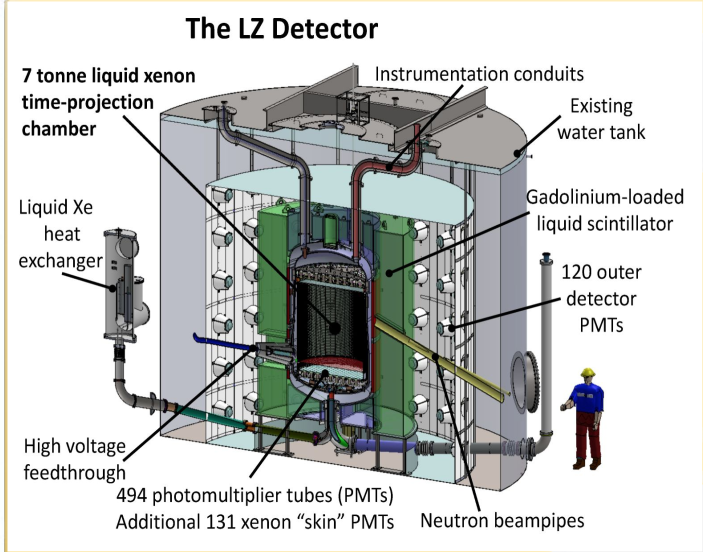


Fig.1 . LZ Detector

Detail overview and status: See Benjamin Krikler ‘s *slides* from yesterday!!

Detector Principle

- Signals due to particle interactions:
  - S1 : Primary Scintillation Signal (prompt photons, directly measured by PMTs)
  - S2: Secondary Ionisation Signal (from electroluminescence of electrons extracted in gaseous phase)
- Energy and Position Reconstruction by S1-S2 Signals

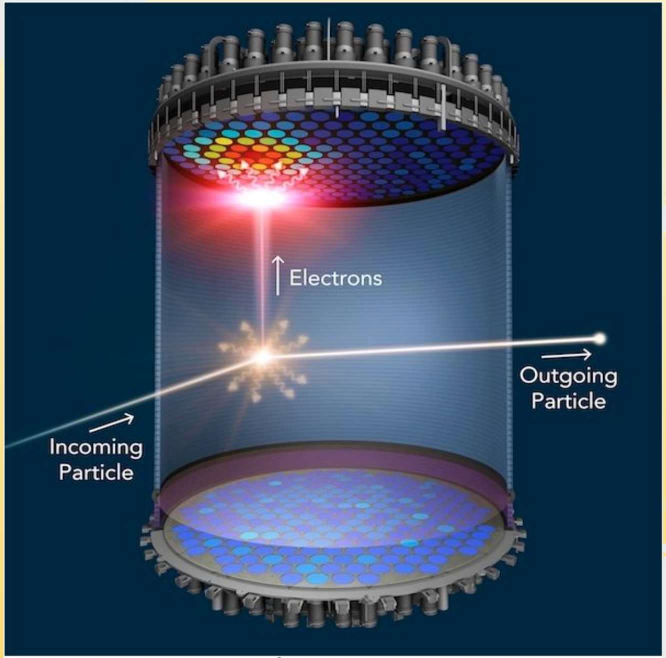


Fig.2 .Working Principle

Projected Sensitivity: WIMPs

- Weakly Interacting Massive Particles (WIMPs): An well-motivated Dark Matter candidate
- What LZ mainly Looks For: WIMP- Nuclear Recoils
- for 1000~live days and a 5.6~tonne fiducial mass.
- The best sensitivity of 1.6 x 10^{-48} cm^2 is achieved at a WIMP mass of 40 GeV/c^2.
- The -2σ expected region is omitted based on the expectation that the limit will be power constrained [8]

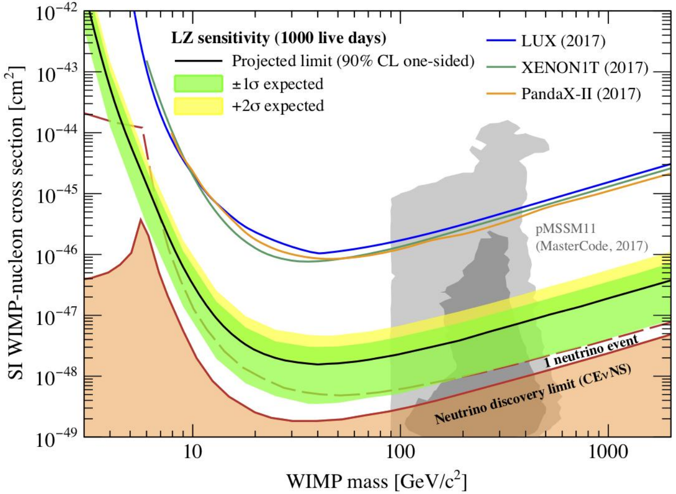


Fig.3 . LZ projected sensitivity to SI WIMP-nucleon elastic scattering for 1000~live days and a 5.6~tonne fiducial mass [9]

But….What if Dark Matter is not a WIMP?

- A vast possible scenario…..
- Hence a vast possible searches….

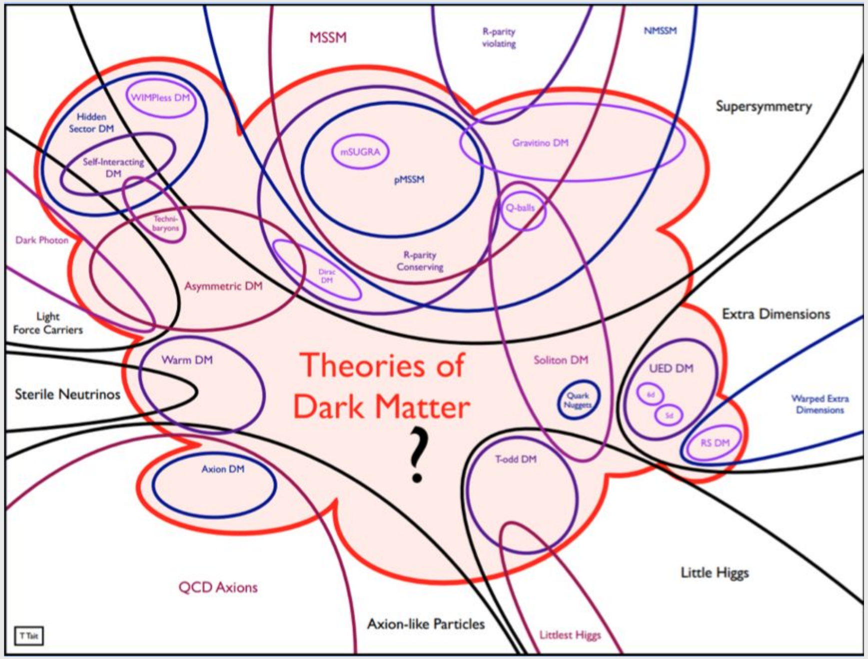


Fig.4. A Vast Possible Theories

Standard Model

U(1) × **SU(2)** × **SU(3)**

Gauge group of EM interaction:

- *1 charge (e.g. electron)**
- *1 gauge boson (photon)*

Gauge group of Weak interaction:

- *2 charge types (2 weak isospin charges)*
- *3 Gauge bosons (W^+,W^-,Z)*

Gauge group of Strong interaction:

- *3 charge types (colour charges)*
- *8 gauge bosons (gluons)*

Is this structure that Obvious?

No!

Then….Can there be any **additional gauge forces**?

** positrons treated as electrons going back in time*

Hidden Photons

$U(1) \times SU(2) \times SU(3) \times U'(1)$

STANDARD MODEL

EXTENSION

- Dark Matter (DM) is secluded from SM
- extra ***U′(1)*** gauge boson as a mediator of SM-DM interactions: **Hidden Photons**
- Minimal Model: broken U(1) symmetry and a massive hidden photon
- Coupling through the mechanism of kinetic mixing
- Correct DM relic abundance can be obtained automatically (M. Pospelov et al. [6])
- Several Other models incorporating U(1) extensions also exist

Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{D} + \mathcal{L}_{mediator}$$

SM Lagrangian

Dynamics in the Hidden Sector

Interaction between SM and hidden sector

Direct Detection

Hidden Photoelectric Effect

$$\frac{\sigma_{abs} v}{\sigma_{pe}(\omega = m_{HP}) c} = \frac{\alpha'}{\alpha}$$

v= velocity of the HP,
Є = $(\alpha'/\alpha)^{1/2}$= Kinetic mixing

σ_{abs} = Hidden p.e. cross-section

σ_{pe}= (ordinary) p.e. cross-section

Electromagnetic Fine Structure Constant $\alpha = \frac{e^2}{4\pi}$

Hidden Fine Structure Constant $\alpha' = \frac{g_D^2}{4\pi}$

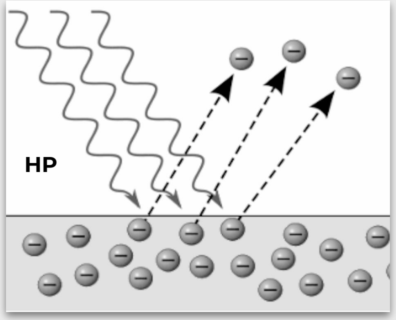


Fig.5. Hidden Photoelectric Effect

- Analogous to the photoelectric effect in SM
- HP completely absorbed
- Line Spectra

Event Rate:(in LXe)

$$R_{HP}[1/\text{kg/day}] = \frac{4 \times 10^{23}}{A} \frac{\alpha'}{\alpha} \frac{\sigma_{pe}[\text{barn}]}{m_{HP}[\text{keV}]}$$

A = 131.3 is an atomic mass of xenon of natural composition

Connection to Axion Like Particle (ALP) Searches

Hidden Photoelectric Effect for HPs

$$R_{HP}[1/\text{kg/day}] = \frac{4\times 10^{23}}{A}\frac{\alpha'}{\alpha}\frac{\sigma_{pe}[\text{barn}]}{m_{HP}[\text{keV}]}$$

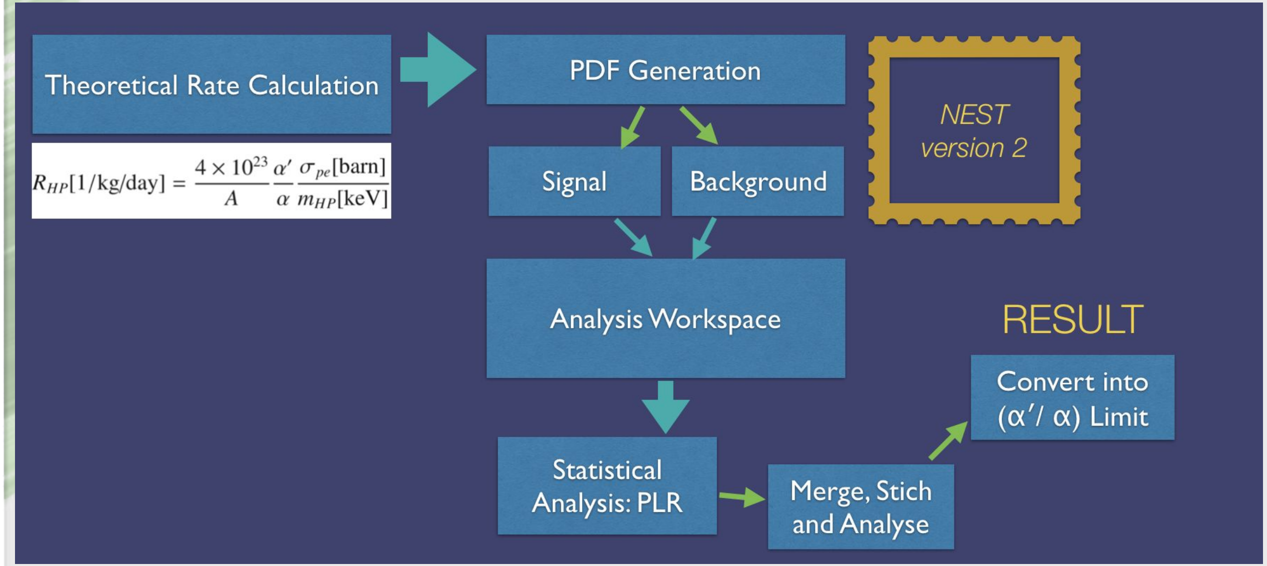
Axio-electric effect for ALPs

$$R_{ALP}[1/\text{kg/day}] = \frac{1.2\times 10^{19}}{A} g_{Ae}^2 \sigma_{pe}[\text{barn}]\cdot m_{ALP}[\text{keV}]$$

$$R_{HP}/R_{ALP} = 3.3 \times 10^4 \times (\alpha'/\alpha) \times (g_{Ae})^{-2} \times (1/m_{HP}\, m_{ALP})$$

Once we have a constraint on (α′/ α) for HP
we can convert that to a constraint on g_{Ae} for ALPs

Analysis Framework



Background Model

- Vast Majority of of Backgrounds in ER band
- This Analysis: Used the same Background Models as in WIMP search
- ER Background Model upto 100 keV

Table 1. ER Background Components

Background	Components
ER	Solar pp+Be7 Neutrinos
	Xe136 2vBB Decay
	Kr85
	Rn-222
	Rn-220
	Detector ERs

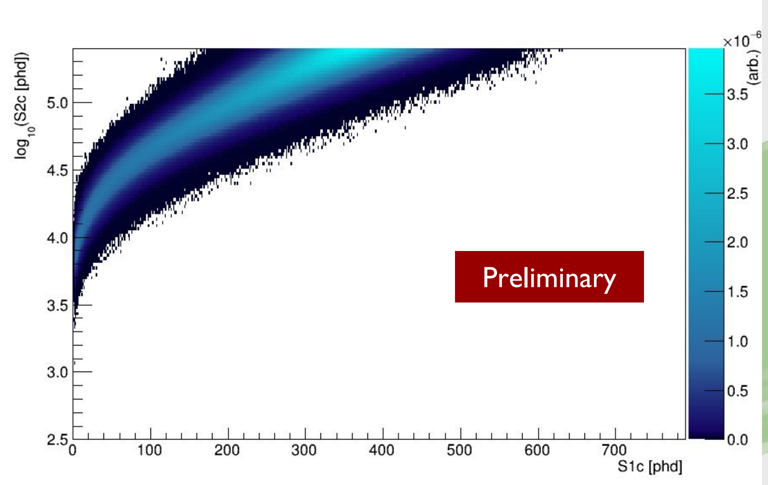


Fig.6. ER Background Model

HP Signal Model

- Investigated Hidden Photon Masses from 2 keV to 85 keV
- Theoretical event rates calculated according to Slide 13
- Signal Models generated using NEST (Nobel Element Simulation Technique) version 2

Energy Reconstruction

$$E_R = W \cdot \left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$

For Projected Detector:

***g_1=0.118735** phd/photon,*
***g_2=79.2291** phd/electron*

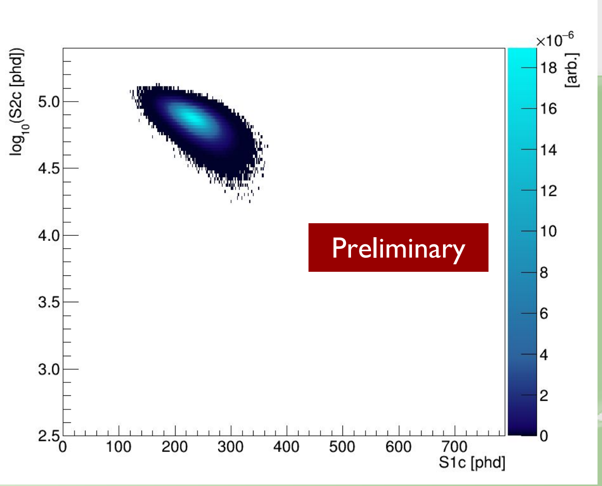


Fig.7. Hidden Photon Signal Model (40 keV)

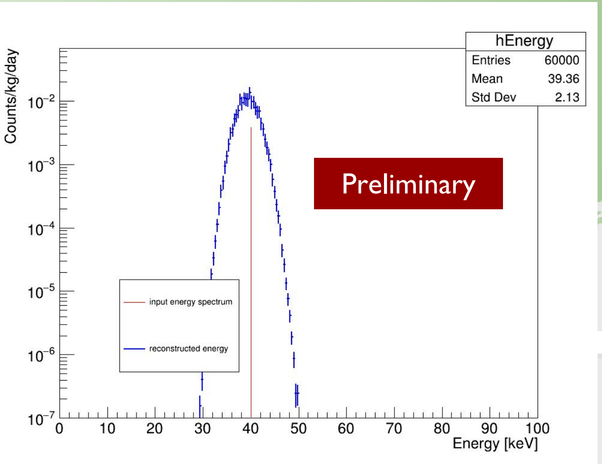


Fig.8. Reconstructed Energy

LZ Projected Sensitivity: Hidden Photons

- Sensitivity Estimation: Hidden Photons
- Statistical Analysis: Profile Likelihood Ratio (PLR) Method
- Hidden Photon Mass (This Work) 2-85 keV
- Experimental limits taken from XMASS 2018 paper [3]

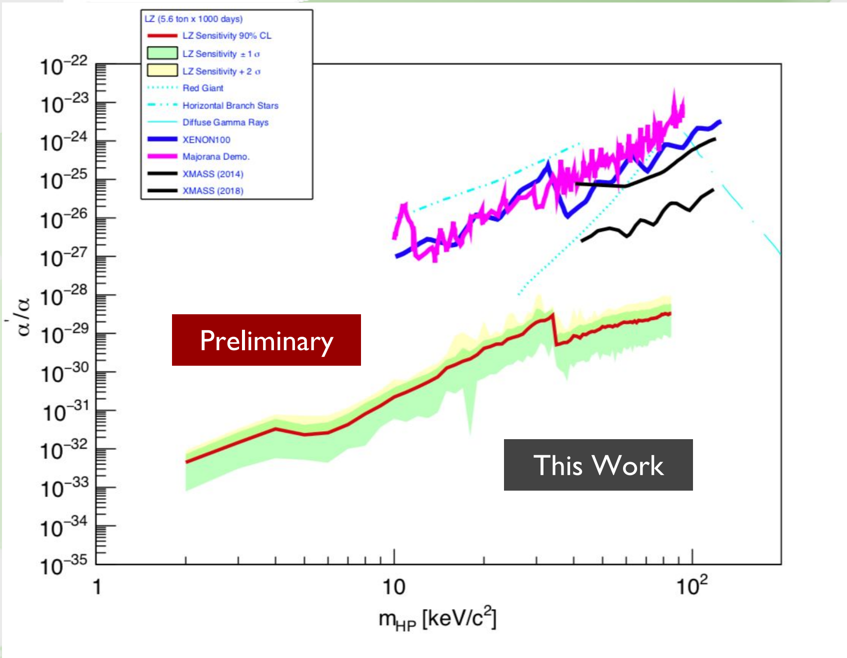


Fig.9. Sensitivity Projection: HPs

LZ Projected Sensitivity: ALPs

- Sensitivity Estimation: ALPs
- Statistical Analysis: Profile Likelihood Ratio (PLR) Method
- ALP Mass (This Work) 2-85 keV

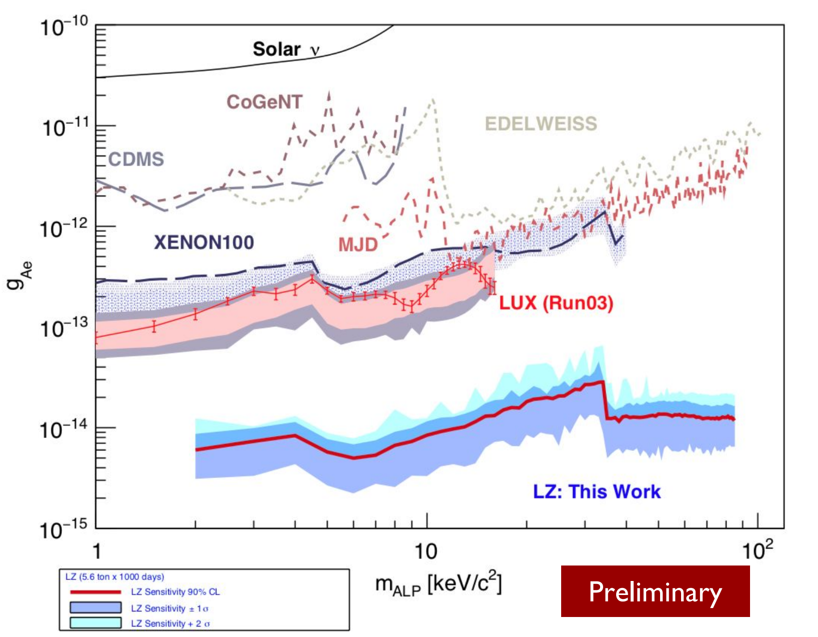


Fig.10. Sensitivity Projection: ALPs

Results/ Discussions

- Hidden Photon Sensitivity: (over the mass 2-85 keV/c^2)
  - we expect more than ~2 order of magnitude improved sensitivity for (α'/α)
  - (α'/α) no larger than 2.9×10^{-29} (Highest value at 34 keV, atomic binding effect)
- ALP sensitivity: (over the mass 2-85 keV/c^2)
  - g_{Ae} no larger than 2.8×10^{-14} (Highest value at 34 keV, atomic binding effect)
  - ~2 order of magnitude improvement

Questions?

References

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Backup Slides

HP Minimal Model

- Minimal Model: single new broken U(1) gauge symmetry
- models with unbroken U(1) gauge symmetry result in a massless dark photon carrying a long-range interaction.
- A massless dark photon, however, will experimentally be hard to distinguish from the Standard Model photon.

$$\mathcal{L} \supset -\frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m^2_{A'} A'^{\mu} A'_{\mu} + \epsilon e A'^{\mu} J^{EM}_{\mu}$$

$F'_{\mu\nu}$ dark photon field

$m_{A'}$ dark photon mass, generated by the Higgs or Stueckelberg mechanism

J^{EM}_{μ} EM current with coupling e

ϵ Kinetic Mixing Factor

Kinetic Mixing

- Tree level SM photon γ- hidden photon γ′ interaction is forbidden
- Simplest Case : by a loop of non-SM charged heavy particles, ψ′
- γ and γ′ couple to them with strengths e and g_D
- Properties of ψ′ particles :
  - they are charged; hence sensitive to EM interaction
  - have not been detected yet in experiments like LHC: mass scale should be above the weak scale
  - this mass scale constrains the coupling strength of γ′ to γ
  - At Lower Energies < Weak Scale: ψ′ can be integrated out.

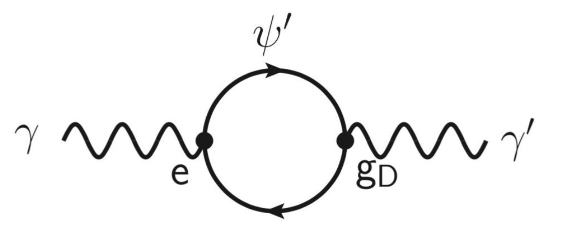

Fig.5. Feynman diagram of kinetic mixing

Below Electroweak Scale

$$L_{\text{mediator}} = \varepsilon e \, j^{\mu}_{A} A'_{\mu}$$

kinetic mixing factor — EM Current — hidden photon field

LZ Projected Sensitivity: ALPs

- Sensitivity Estimation: ALPs
- Statistical Analysis: Profile Likelihood Ratio (PLR) Method
- ALP Mass (This Work):
  - 2-85 keV
  - g_{Ae} no larger than 2.8 x 10^{-14}
- Previous Work by LZ:
  - 1-40 keV
  - g_{Ae} no larger than 5.9 x 10^{-14}

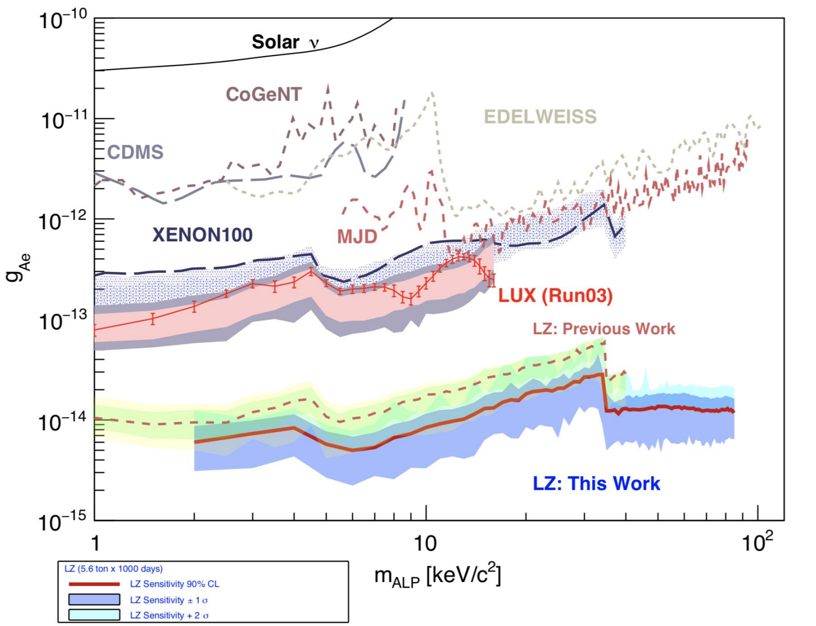

Fig.10. Sensitivity Projection: ALPs