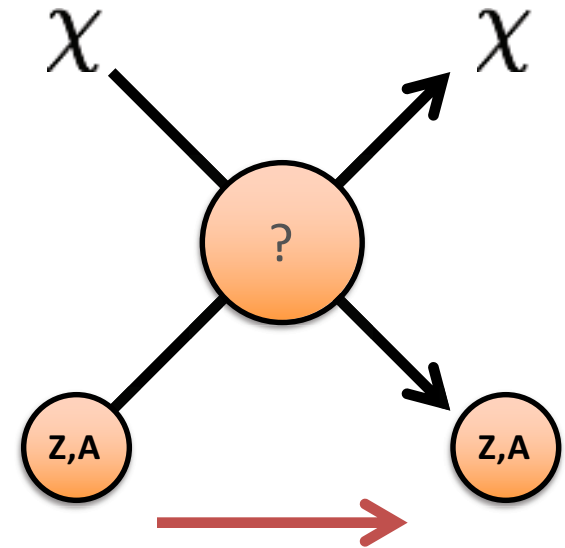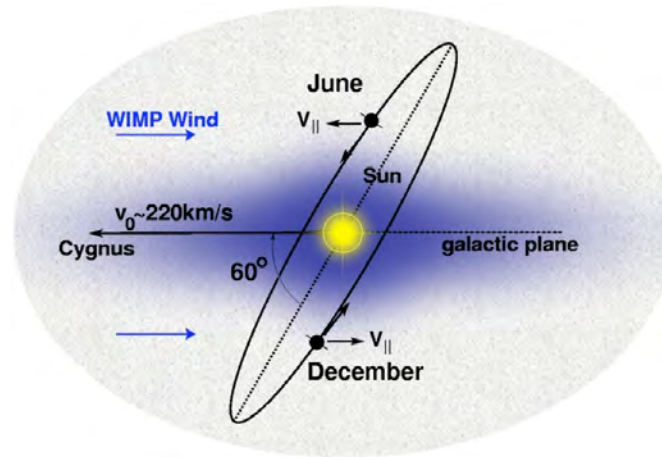# Prospective for low mass dark matter with LUX and LZ

Paolo Beltrame
University of Edinburgh
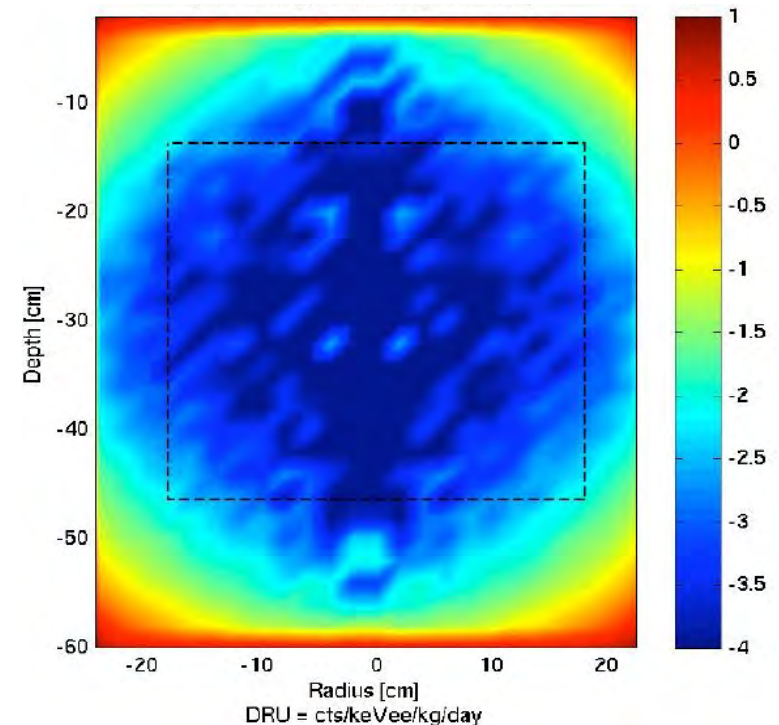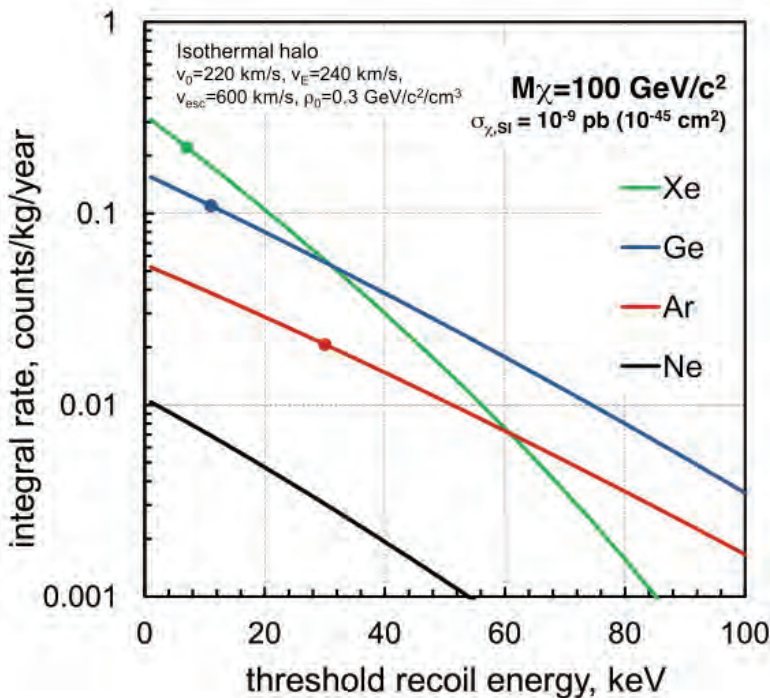
on behalf of the LUX and LZ Collaborations

# Direct detection



- Dark Matter Weakly Interactive Massive Particle (WIMP) in direct search experiments
  - Nuclear Recoil (NR) in the target material, ~ keVnr energy deposit
  - Electron Recoil (ER) giving most of the background (keVee)
- Standard WIMP searches (> 10 GeV/$c^2$ mass)... but not only

# Liquid Xenon



- Radio-pure noble gas
- Scalar WIMP-nucleus: $A^2$ enhancement
- Natural Xe ~50% odd isotopes: spin-dependent interactions

- Liquid detectors easily scalable
- Self shielding from external background sources
- Combining the two => ultra-low-background inner volume

# Dual phase Xe TPC
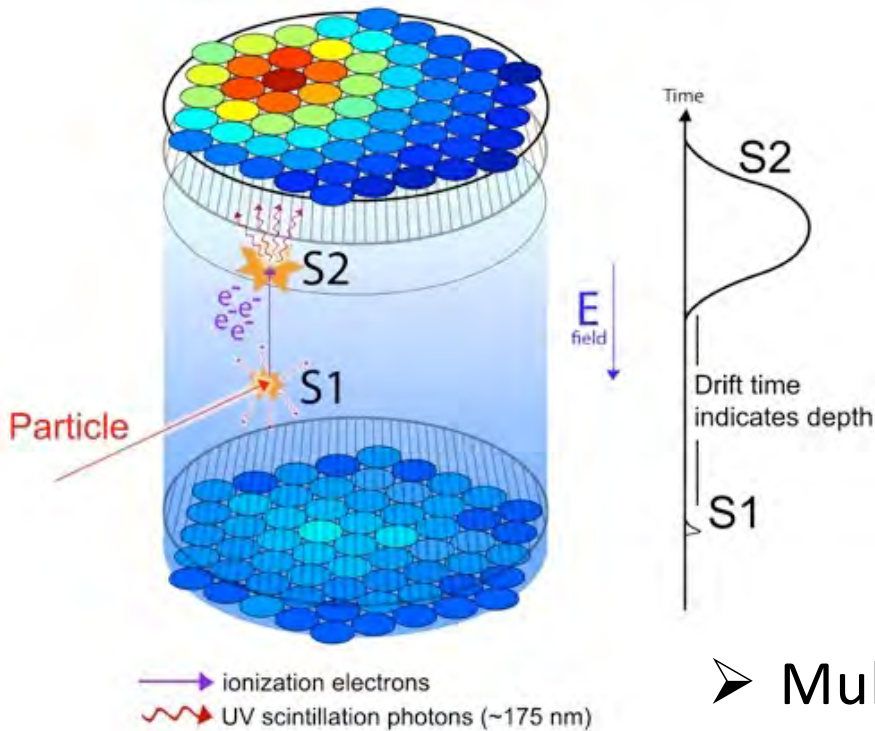


- - **Primary scintillation** light ("S1") at the particle - Liquid Xe interaction vertex
- - Electrons extracted from the interaction drifted by electric field to the surface and into the Gas Xe. **Proportional scintillation** light ("S2")

➢ Multiple scatter event identification (via S2)

➢ 3-D localisation of each vertex (via S1 and S2)

➢ ER/NR discrimination (via S2/S1)

➢ Sensitivity to single electrons (S2)

# Large Underground Xenon experiments

**Brown**

| | |
|---|---|
| Richard Gaitskell | PI, Professor |
| Simon Fiorucci | Research Associate |
| Samuel Chung Chan | Graduate Student |
| Dongqing Huang | Graduate Student |
| Will Taylor | Graduate Student |
| Casey Rhyne | Graduate Student |
| James Verbus | Graduate Student |

**Imperial College London**

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

**Lawrence Berkeley + UC Berkeley**

| | |
|---|---|
| Bob Jacobsen | PI, Professor |
| Murdock Gilchriese | Senior Scientist |
| Kevin Lesko | Senior Scientist |
| Peter Sorensen | Scientist |
| Victor Gehman | Scientist |
| Attila Dobi | Postdoc |
| Daniel Hogan | Graduate Student |
| Mia Ihm | Graduate Student |
| Kate Kamdin | Graduate Student |
| Kelsey Oliver-Mallory | Graduate Student |

**Lawrence Livermore**

| | |
|---|---|
| Adam Bernstein | PI, Leader of Adv. Detectors Grp. |
| Kareem Kazkaz | Staff Physicist |
| Brian Lenardo | Graduate Student |

**LIP Coimbra**

| | |
|---|---|
| Isabel Lopes | PI, Professor |
| Jose Pinto da Cunha | Assistant Professor |
| Vladimir Solovov | Senior Researcher |
| Francisco Neves | Auxiliary Researcher |
| Alexander Lindote | Postdoc |
| Claudio Silva | Postdoc |

**SLAC Nation Accelerator Laboratory**

| | |
|---|---|
| Thomas Shutt | PI, Professor |
| Dan Akerib | PI, Professor |
| Kim Palladino | Project Scientist |
| 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 School of Mines**

| | |
|---|---|
| Xinhua Bai | PI, Professor |
| Doug Tiedt | Graduate Student |

**SDSTA**

| | |
|---|---|
| David Taylor | Project Engineer |
| Mark Hanhardt | Support Scientist |

**SUNY at Albany**

| | |
|---|---|
| Matthew Szydagis | PI, Professor |
| Jeremy Mock | Postdoc |
| Steven Young | Graduate Student |

**Texas A&M**

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

**UC Davis**

| | |
|---|---|
| Mani Tripathi | PI, Professor |
| Britt Hollbrook | Senior Engineer |
| John Thmpson | Development Engineer |
| Dave Herner | Senior Machinist |
| Ray Gerhard | Electronics Engineer |
| Aaron Manalasay | Postdoc |
| Scott Stephenson | Postdoc |
| James Moard | Graduate Student |
| Sergey Uvarov | Graduate Student |
| Jacob Cutter | Graduate Student |

**UC Santa Barbara**

| | |
|---|---|
| Harry Nelson | PI, Professor |
| Mike Witherell | Professor |
| Susanne Kyre | Engineer |
| Dean White | Engineer |
| Carmen Carmona | Postdoc |
| Scott Haselschwardt | Graduate Student |
| Curt Nehrkorn | Graduate Student |
| Melih Solmaz | Graduate Student |
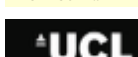
**University College London**

| | |
|---|---|
| Chamkaur Ghag | PI, Lecturer |
| Lea Reichhart | Postdoc |
| Sally Shaw | Graduate Student |

**University of Edinburgh**

| | |
|---|---|
| Alex Murphy | PI, Reader |
| Paolo Beltrame | Research Fellow |
| James Dobson | Postdoc |
| Maria Francesca Marzioni | Graduate Student |
| Tom Davison | Graduate Student |

**University of Maryland**

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

**University of Rochester**

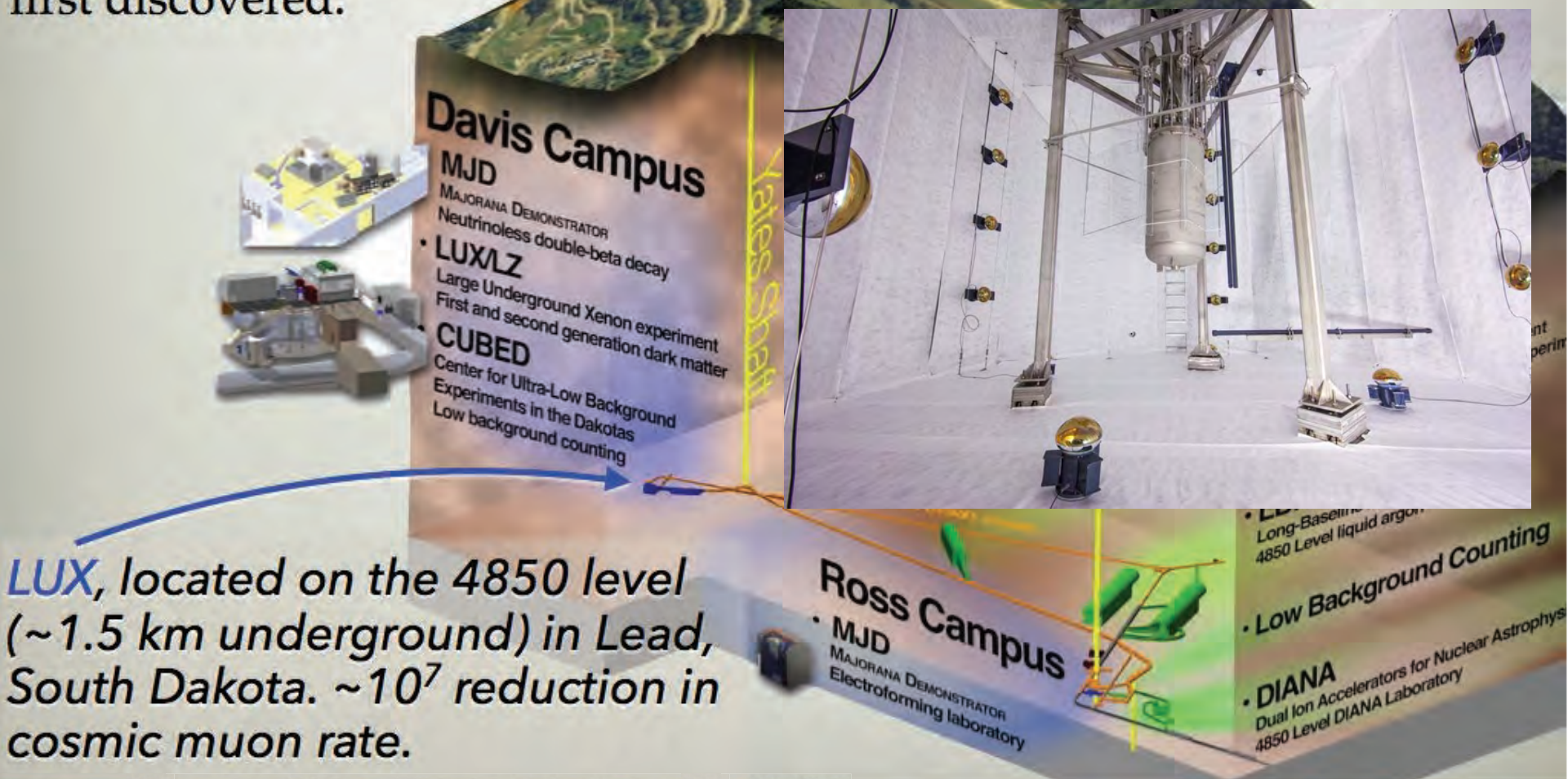| | |
|---|---|
| Frank Wolfs | PI, Professor |
| Wojtek Skutski | Senior Scientist |
| Eryk Druszkiewicz | Graduate Student |
| Dev Ashish Khaitan | Graduate Student |
| Mongkol Moongweluwan | Graduate Student |

**University of South Dakota**

| | |
|---|---|
| Dongming Mei | PI, Professor |
| Chao Zhang | Postdoc |
| Angela Chiller | Graduate Student |
| Chris Chiller | Graduate Student |

**Yale**

| | |
|---|---|
| Daniel McKinsey | PI, Professor |
| Ethan Bernard | Research Scientist |
| Markus Horn | Research Scientist |
| Blair Edwards | Postdoc |
| Scott Hertel | Postdoc |
| Kevin O'Sullivan | Postdoc |
| Elizabeth Boulton | Graduate Student |
| Nicole Larsen | Graduate Student |
| Evan Pease | Graduate Student |
| Brian Tennyson | Graduate Student |
| Lucie Tvrznikova | Graduate Student |

Same cavern where solar neutrinos were first discovered.

**Davis Campus**

MJD
MAJORANA DEMONSTRATOR
Neutrinoless double-beta decay

- **LUX/LZ**
Large Underground Xenon experiment
First and second generation dark matter

- **CUBED**
Center for Ultra-Low Background
Experiments in the Dakotas
Low background counting

*LUX*, located on the 4850 level (~1.5 km underground) in Lead, South Dakota. ~$10^7$ reduction in cosmic muon rate.

**Ross Campus**

- MJD
MAJORANA DEMONSTRATOR
Electroforming laboratory

- Long-Baseline
4850 Level liquid argon

- Low Background Counting

- DIANA
Dual Ion Accelerators for Nuclear Astrophysics
4850 Level DIANA Laboratory

- 47 cm diameter by 48 cm height dodecagonal "cylinder"
- 370 kg LXe total, 250 kg active region
- 61 PMTs on top, 61 on bottom. Low radiogenic BGs and VUV sensitivity
- Xenon pre-purified via chromatographic separation, residual krypton levels to 3.5 ± 1 ppt (g/g)
- Liquid is continuously recirculated (1/4 tonne per day) to maintain chemical purity
- Ultra-low BG titanium cryostat

# WIMP search

# WIMP search

# WIMP search



PRL 112, 091303 (2014)
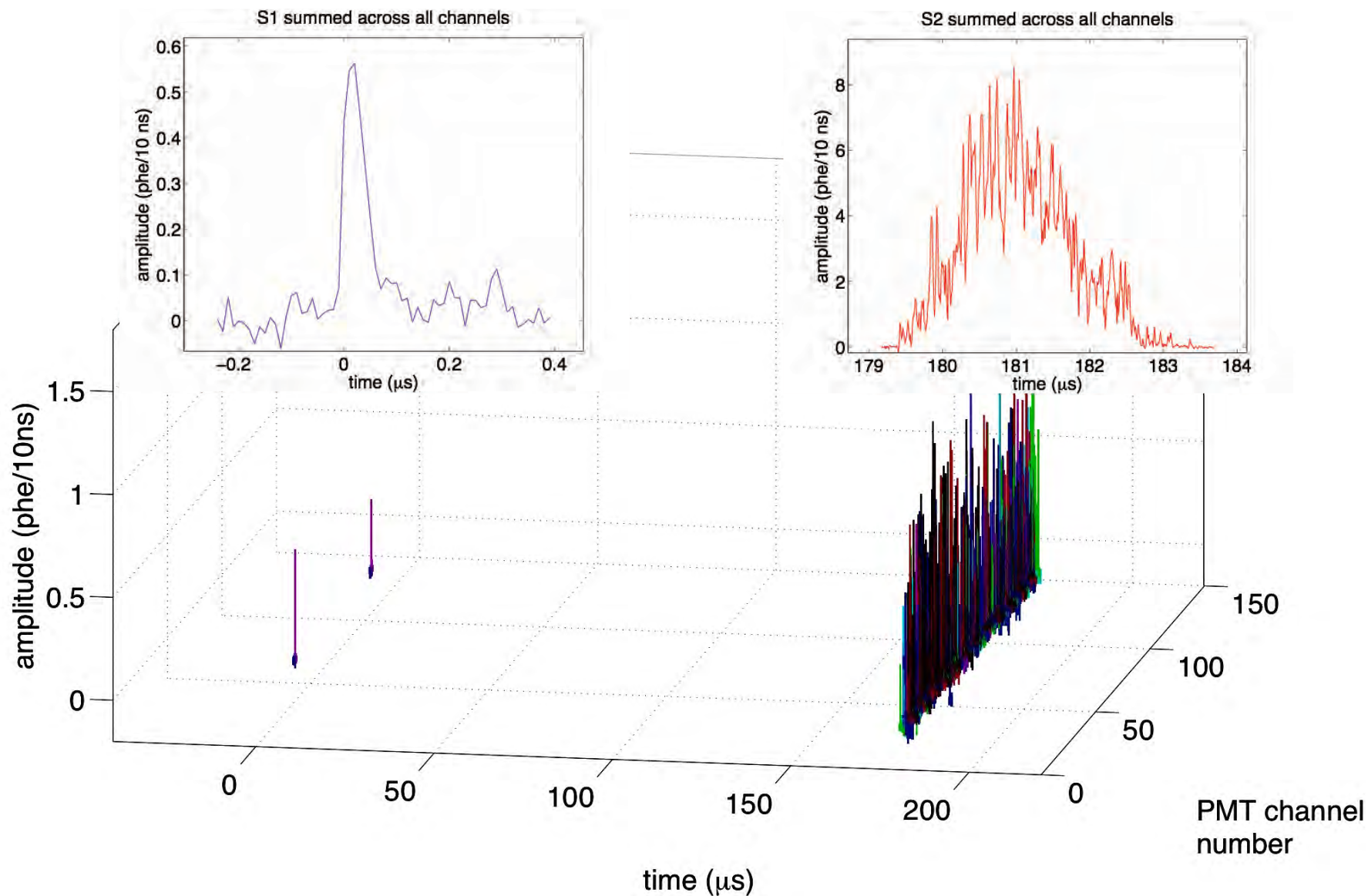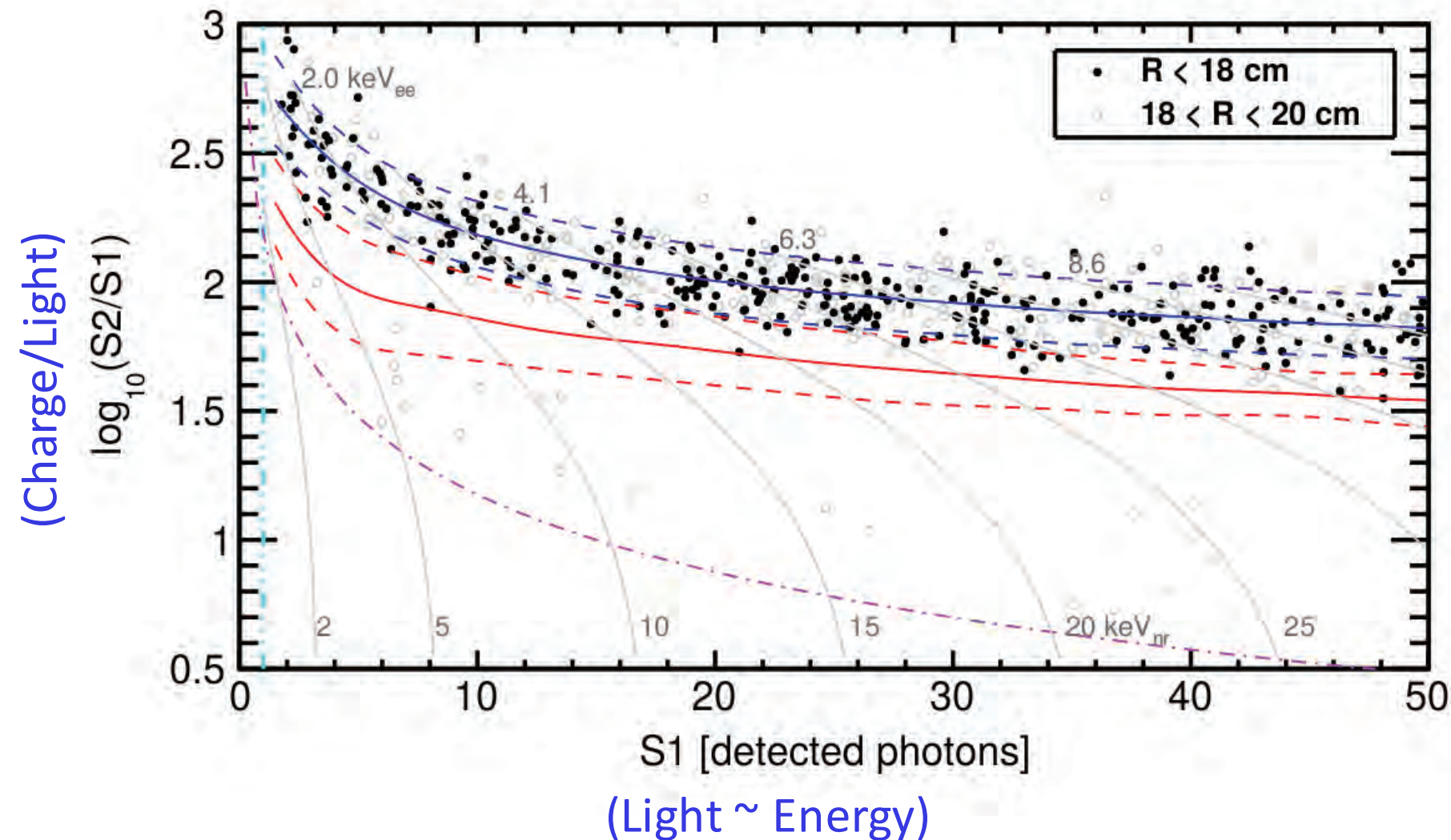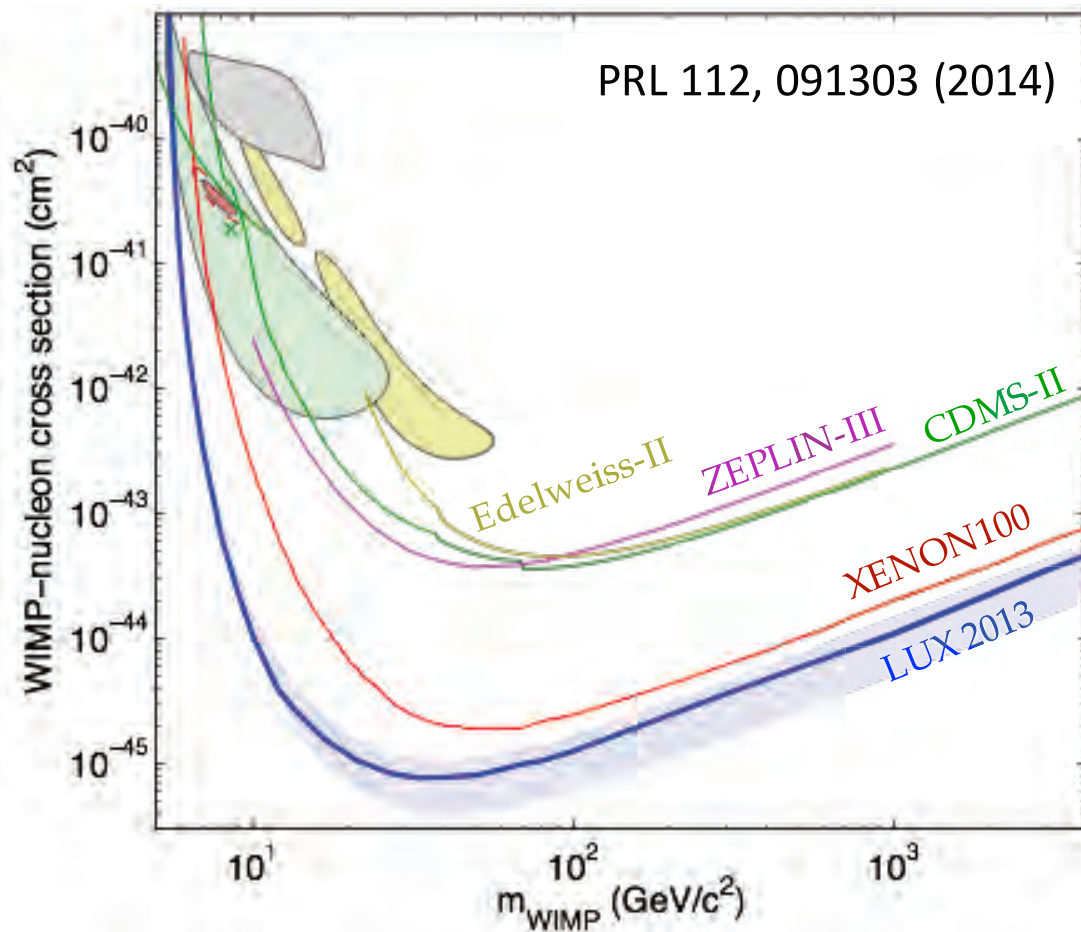
- Exposure: 85.3 live days, 118 kg fiducial mass
- Obs. bkg. events: 160
- Drift field: 181 V/cm
- Analysis 4-parameter profile likelihood, p-value of 35% consistent with backgrounds

$7.6 \times 10^{-46}$ cm$^2$ at 33 GeV/c$^2$

LUX first results conservative assumption of energy cut-off at 3 keVnr: i.e. below 3 keVnr no S1 and no S2

# WIMP sensitivity
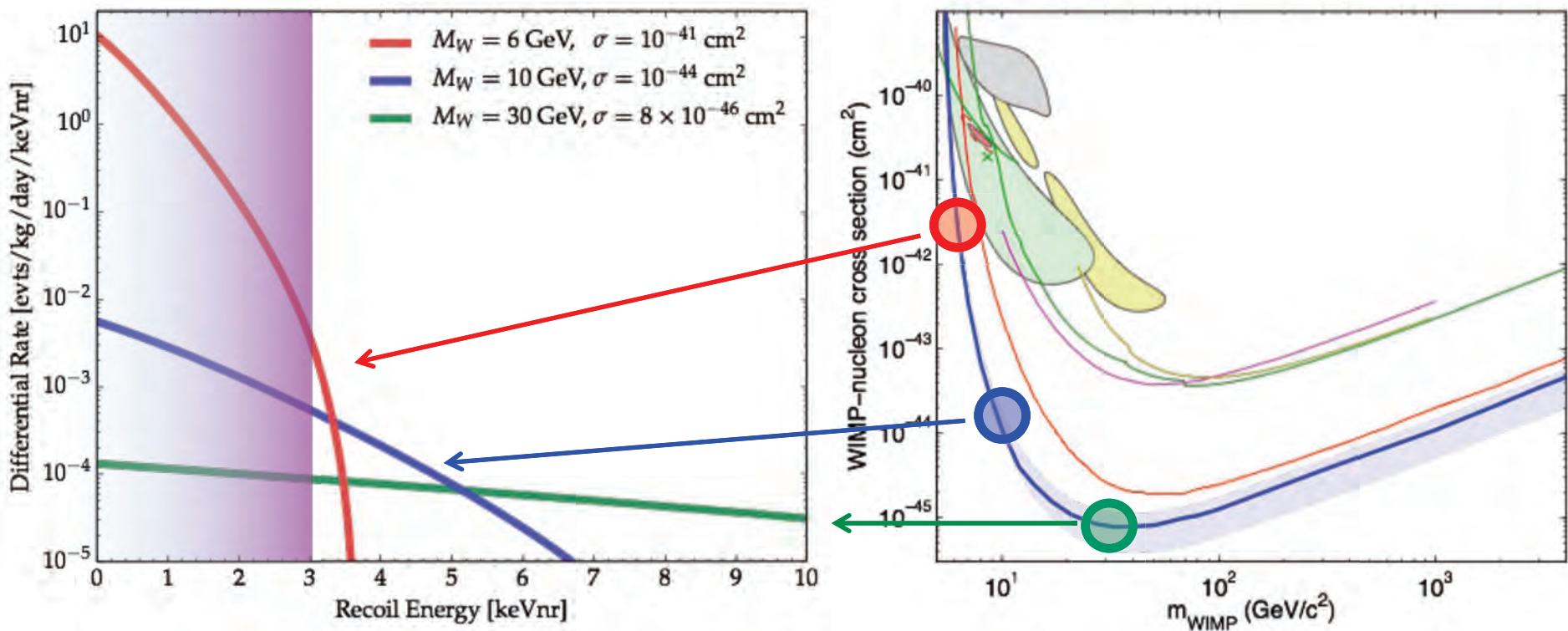
# WIMP sensitivity
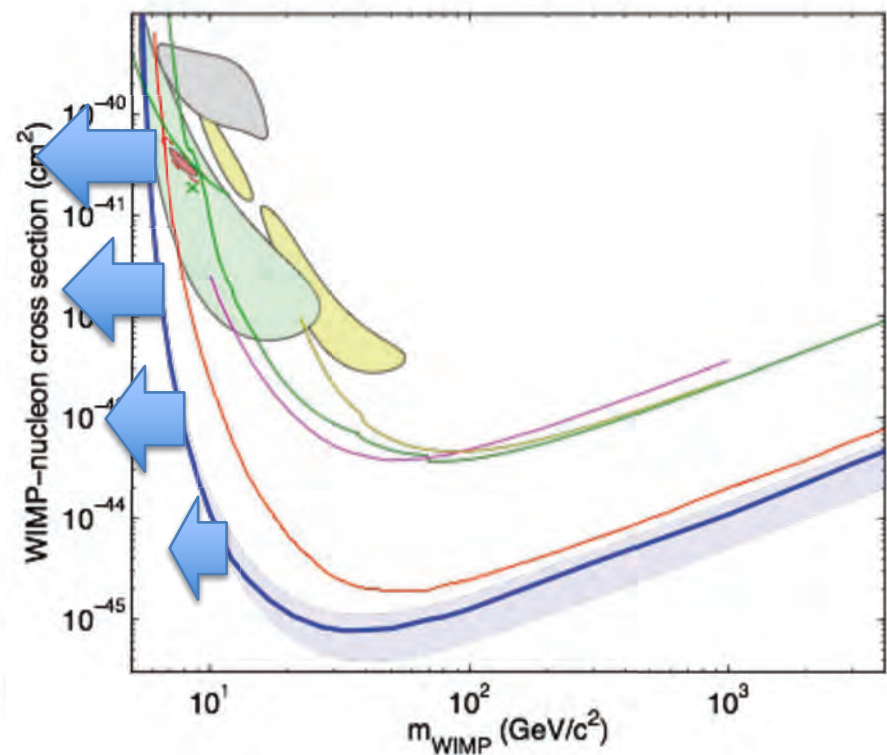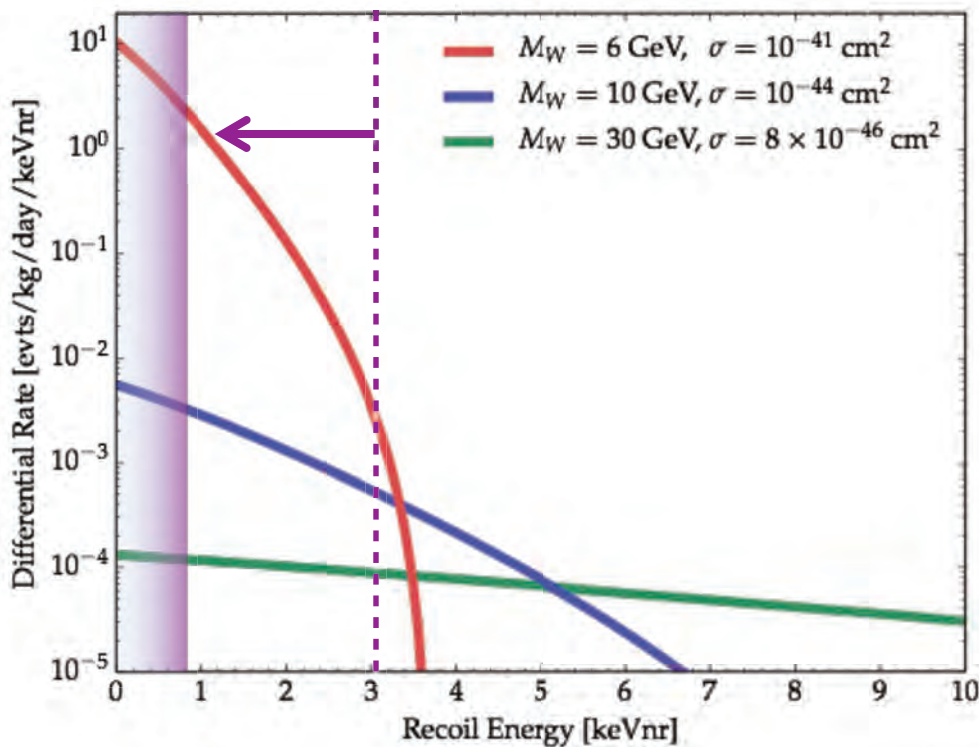
Decreasing this response cutoff from 3 keV to < 1 keV provides access to a factor of 8000 more signal at $M$ = 6 GeV

# Nuclear Recoil events

New detector response calibration for NR: **DD generator**

- Double scatters along beam line inside LUX. Angle gives deposited energy.

=> Absolute calibration of ionisation response: $Q_Y$
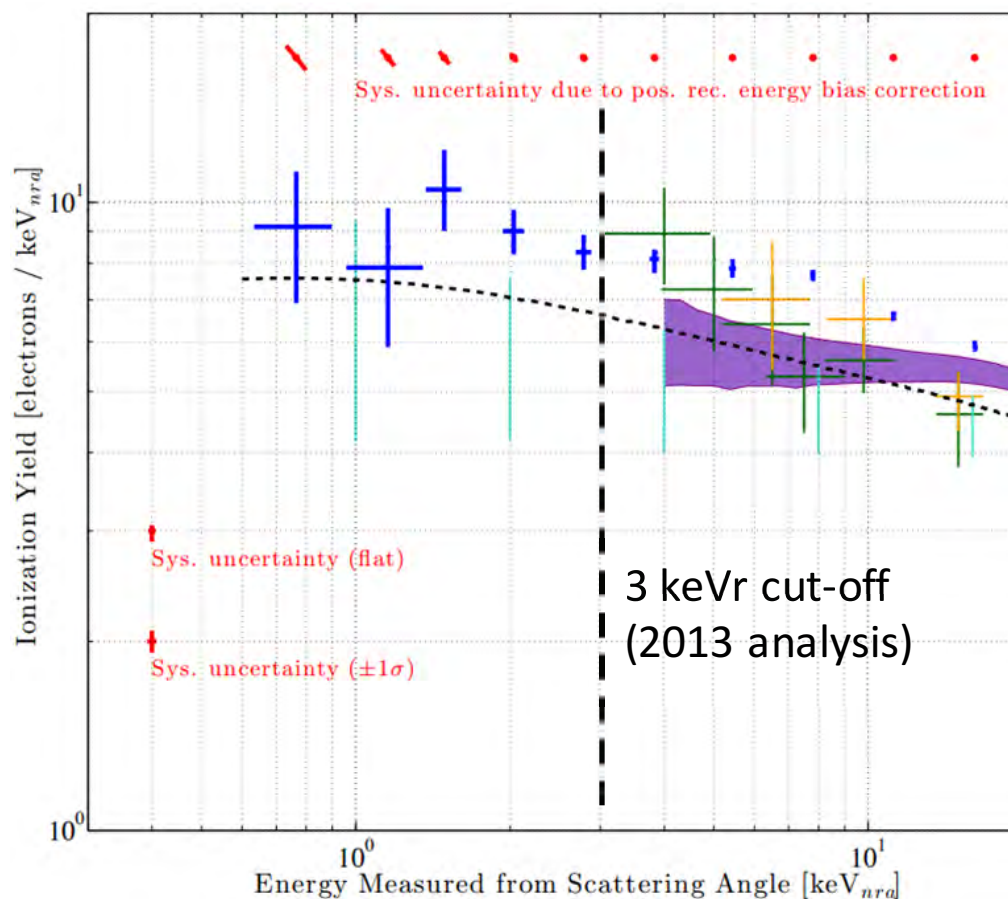
- Apply ionisation scale to single scatter

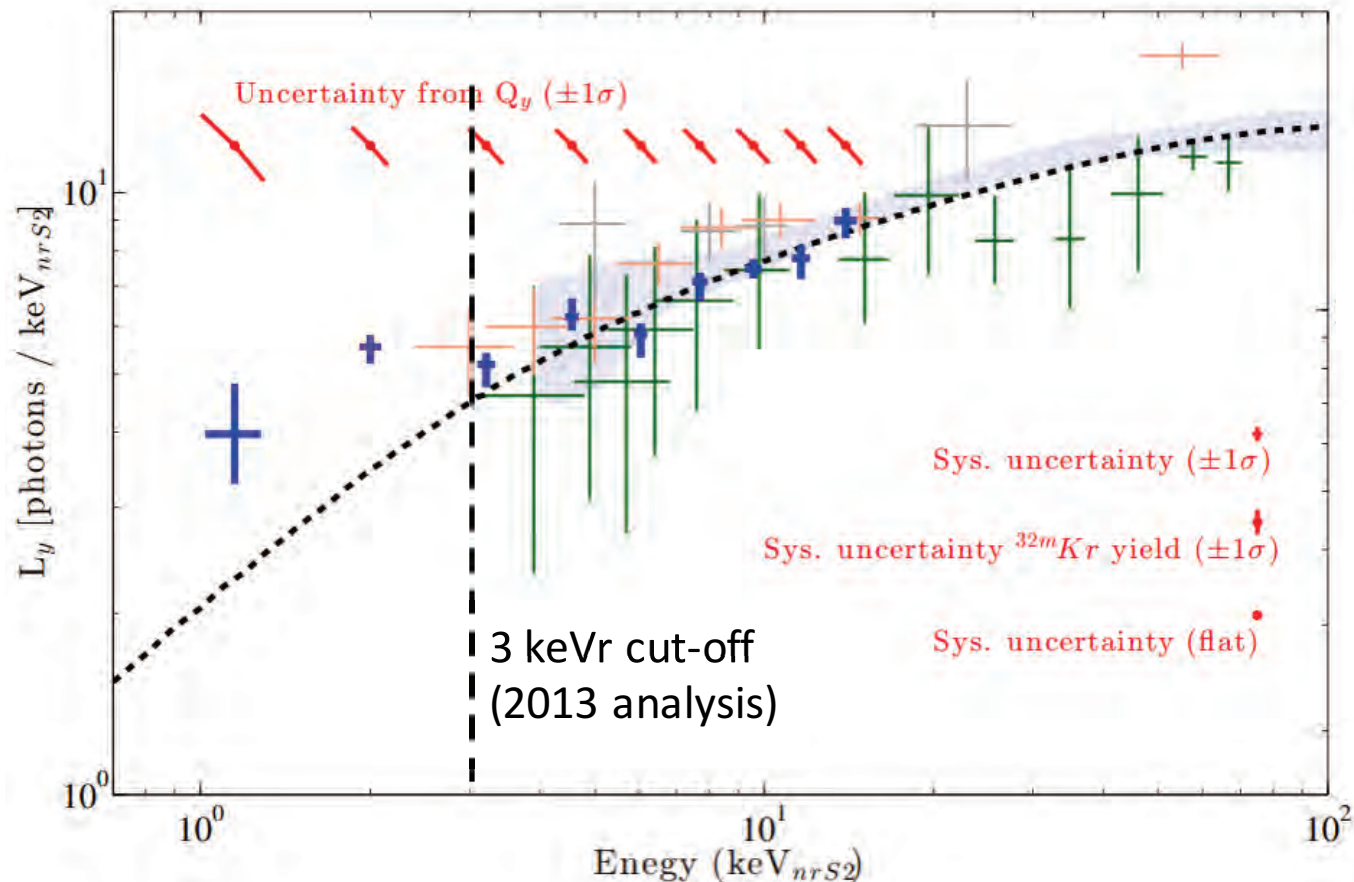=> Absolute calibration of scintillation response: $L_Y$

Monochromatic, collimated 2.45 MeV neutrons
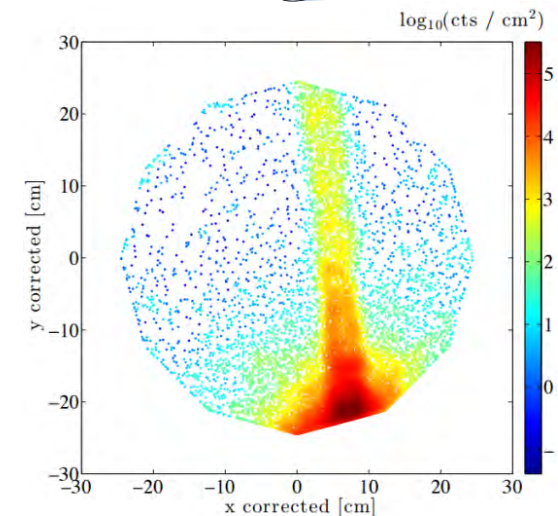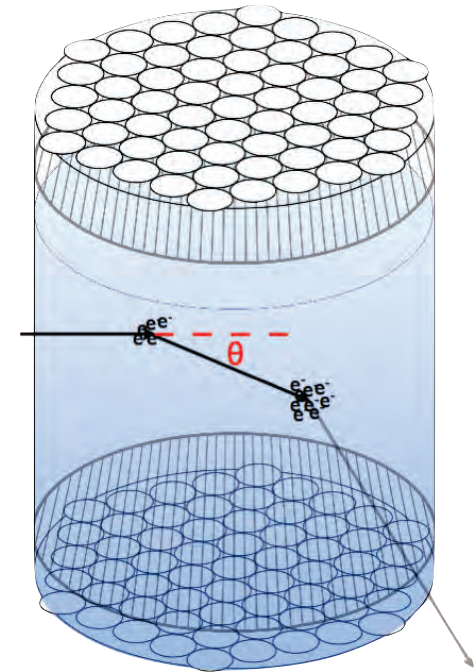
# Charge yield

1.  $Q_y$: linearity between deposited energy and ionisation signal. Measured down to 0.8 keVnr

# Light yield

2.  $L_Y$: linearity between deposited energy and scintillation signal. Measured down to 1.2 keVnr

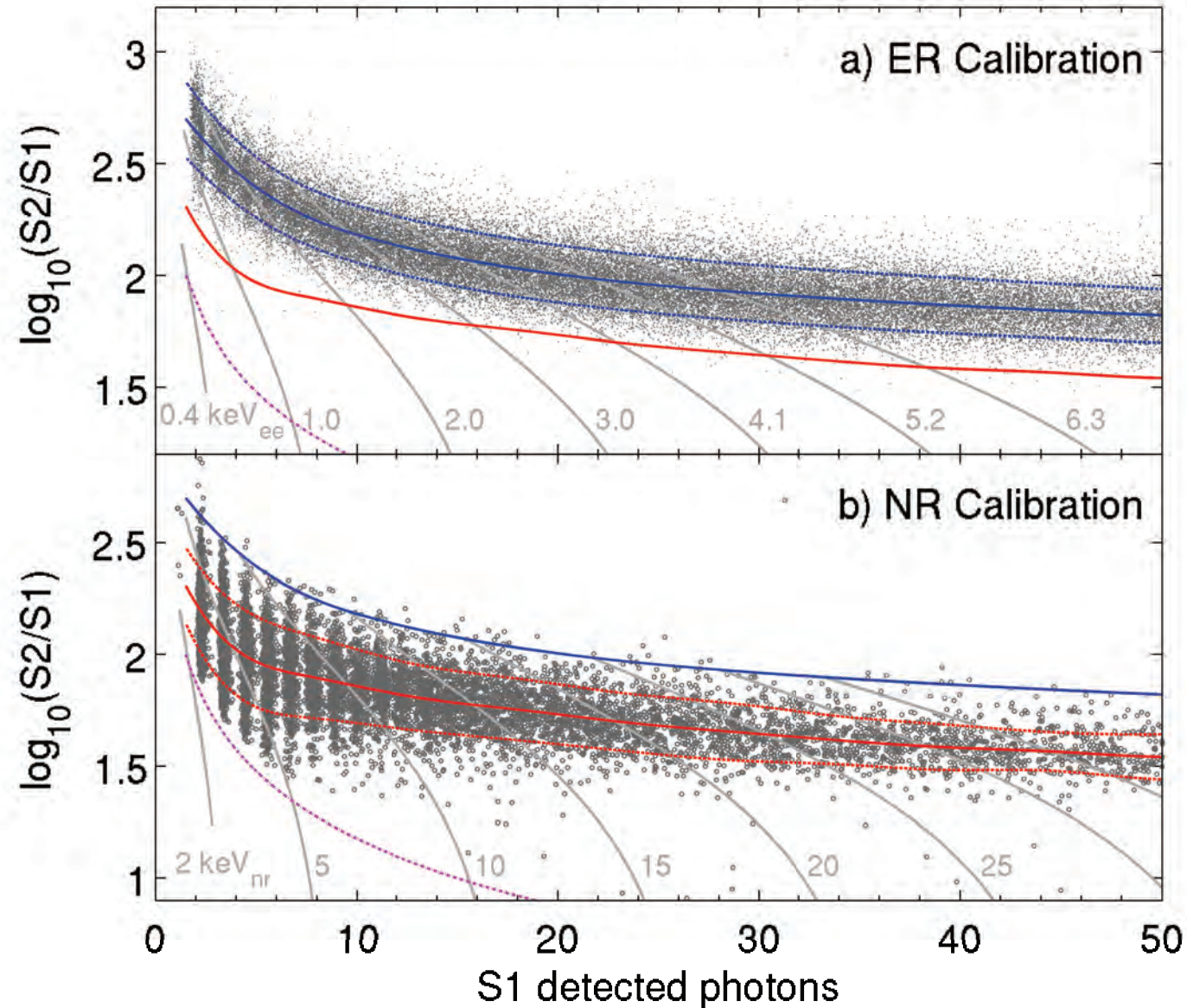# Electron Recoil events

New detector response calibration for ER: **CH₃T injection**

- Light and charge yields to ~1 keVee
- Detection efficiency vs energy
- Informative of the background shape
- "leaks" down into NR S2/S1 region, as a function of S1 from [0.2 - 5] keVee
- Uniformly distributed, used with $^{83m}$Kr for fiducial volume evaluation
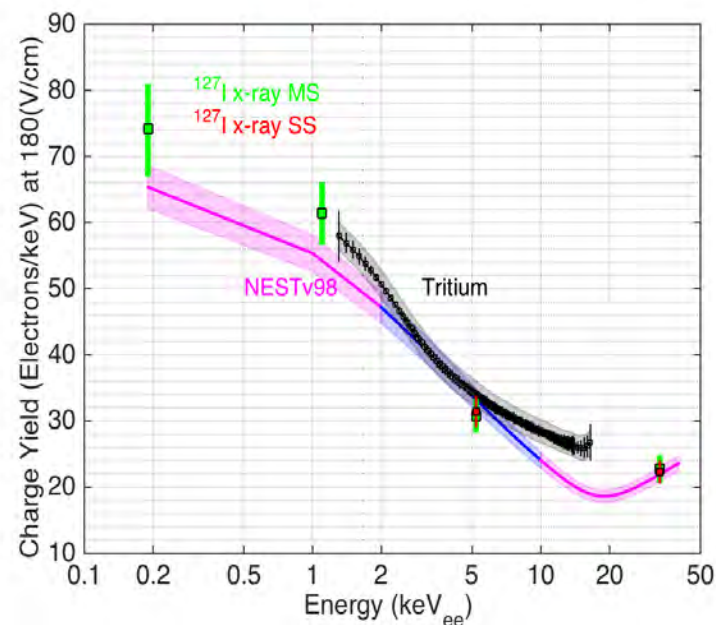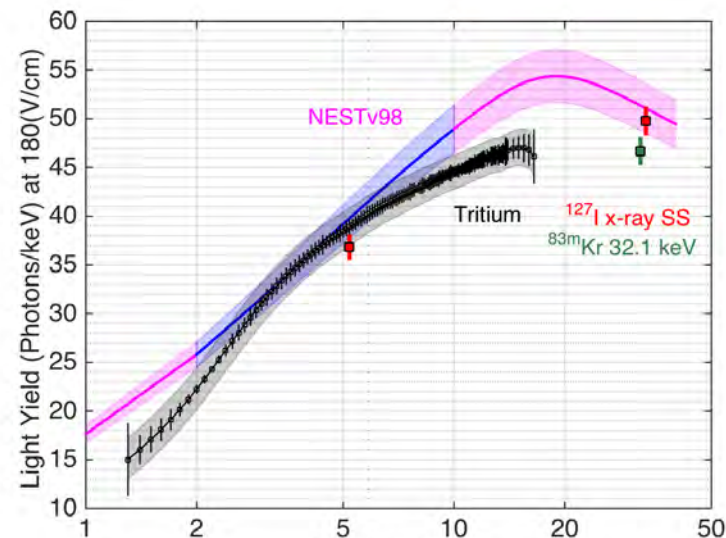
# ER and NR events in S2/S1 space

# Light DM

1. **WIMP search**:
   - S1+S2 exploiting new NR calibration data (i.e. removing hard threshold at 3 keV)
   - S2-only: O(1 GeV/c$^2$) vanilla WIMPs

2. **Axion-like particles** (~keV):
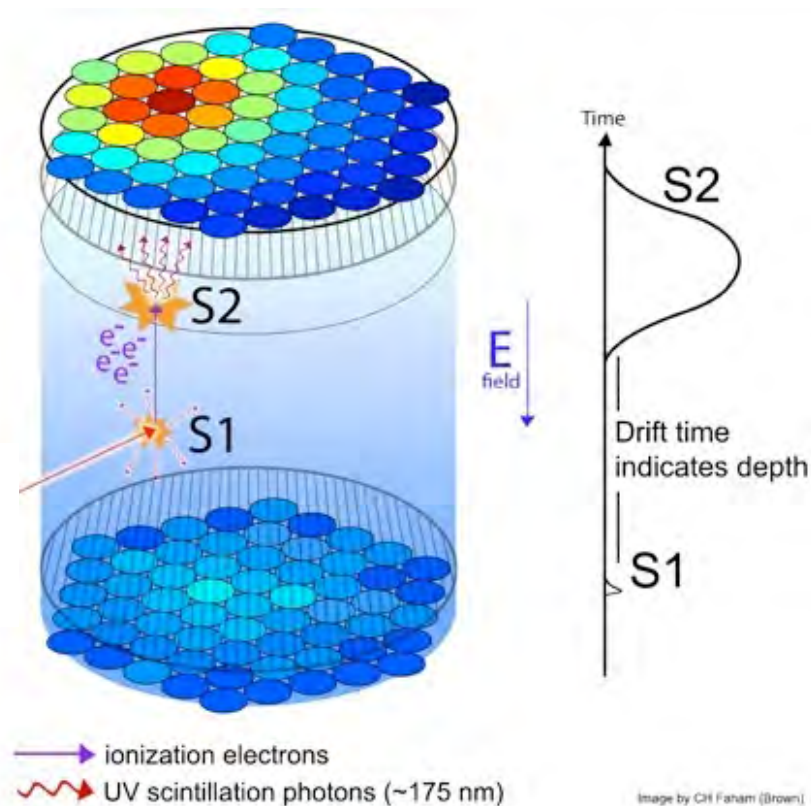   - S1+S2 exploiting new ER calibration data

3. **Hidden-sector U(1)' models***:
   - S2-only exploiting new ER calibration data

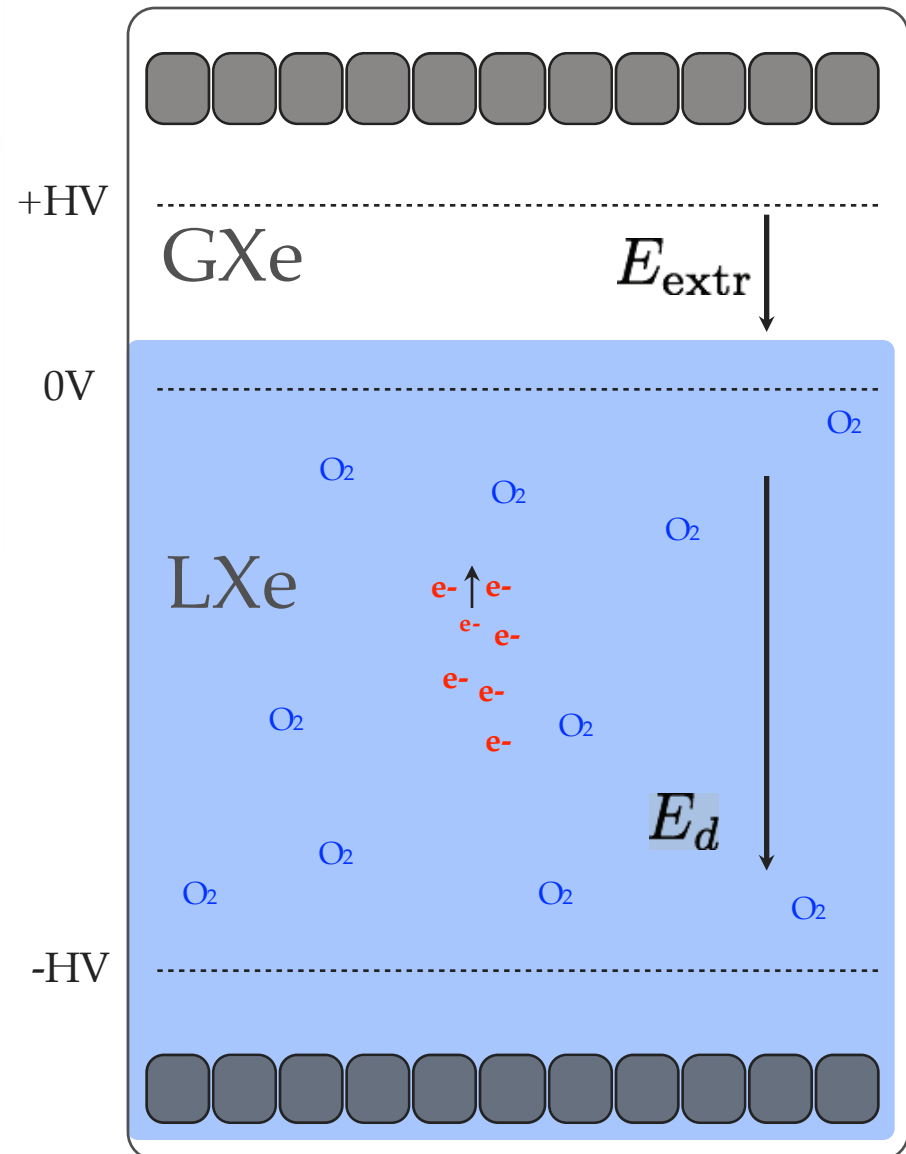\* PRL 109, 021301 (2012), PRD 85, 076007 (2012)

# S2-only

- S2 signal sensitive to smaller energy depositions: NR thresholds (<1 keV) too feeble for a detectable S1

- Ionisation channel sensitivity to individual electrons. Threshold for analysis at > 2 $e^-$

- Interaction point localization: S2 (x, y) and longitudinal spread for z-coordinate.



Time

S2

E field

S1

Drift time indicates depth

→ ionization electrons
↝ UV scintillation photons (~175 nm)

Image by CH Faham (Brown)

# Charge lost in the LXe

| Experiment | Max. charge loss to impurities |
|------------|-------------------------------|
| XENON10 | ~0% |
| XENON100 | ~40% |
| LUX | ~30% |

+HV

GXe

$E_{extr}$

0V

$O_2$

$O_2$

$O_2$

$O_2$

LXe

e- ↑ e-

e-  e-

e-  e-

e-

$O_2$      $O_2$

$E_d$

$O_2$

$O_2$      $O_2$      $O_2$

-HV

# Charge lost in the extraction

| Experiment | Electron extraction efficiency |
|---|---|
| XENON10 | ~100% |
| XENON100 | ~100% |
| LUX | ~50% |



+HV

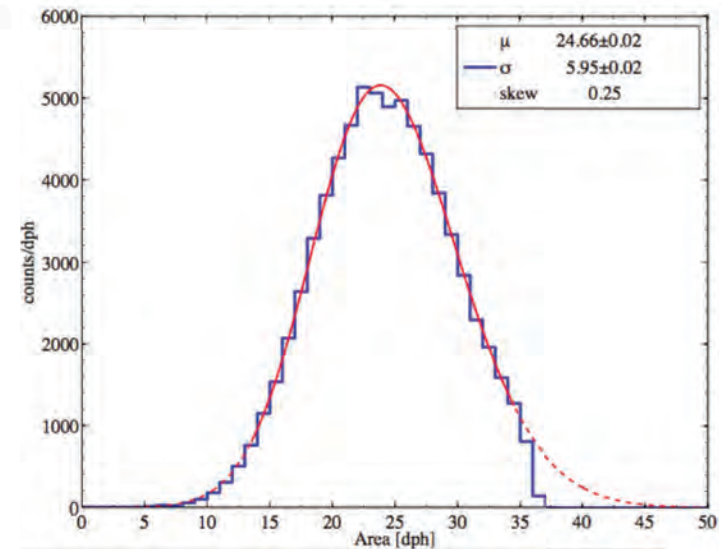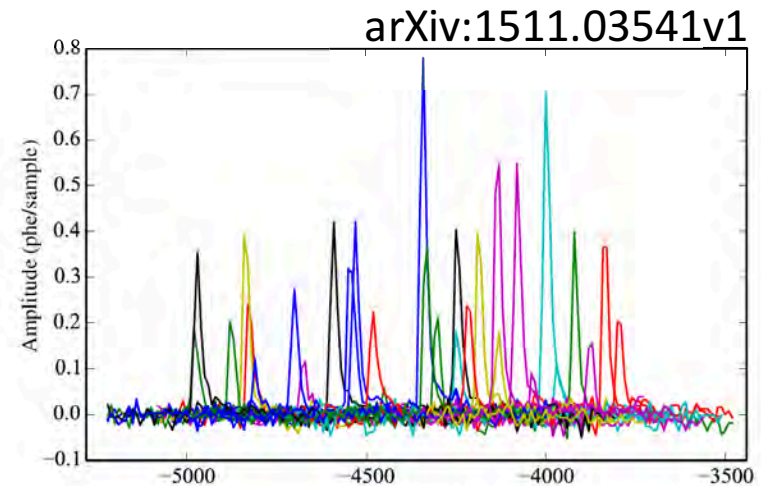GXe $\qquad$ e- e- $\qquad$ $E_{\text{extr}}$
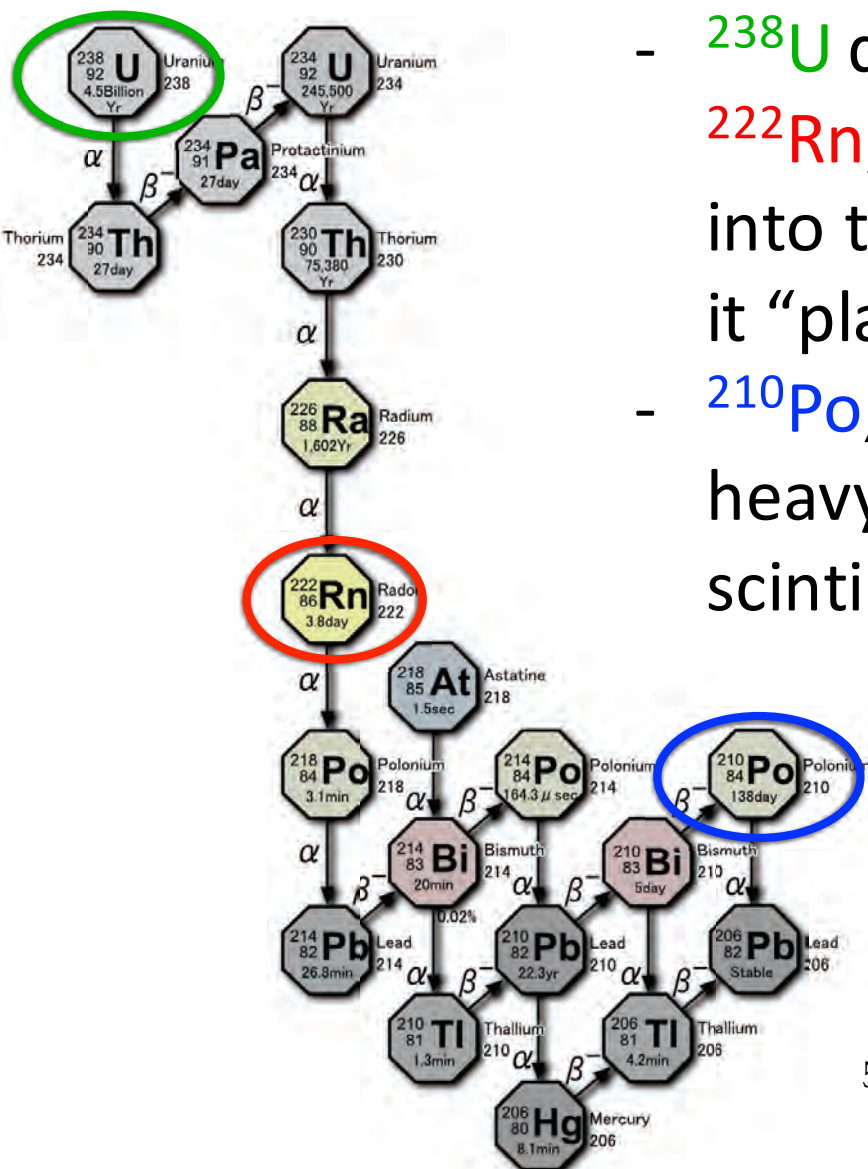
0V

LXe

$E_d$

-HV
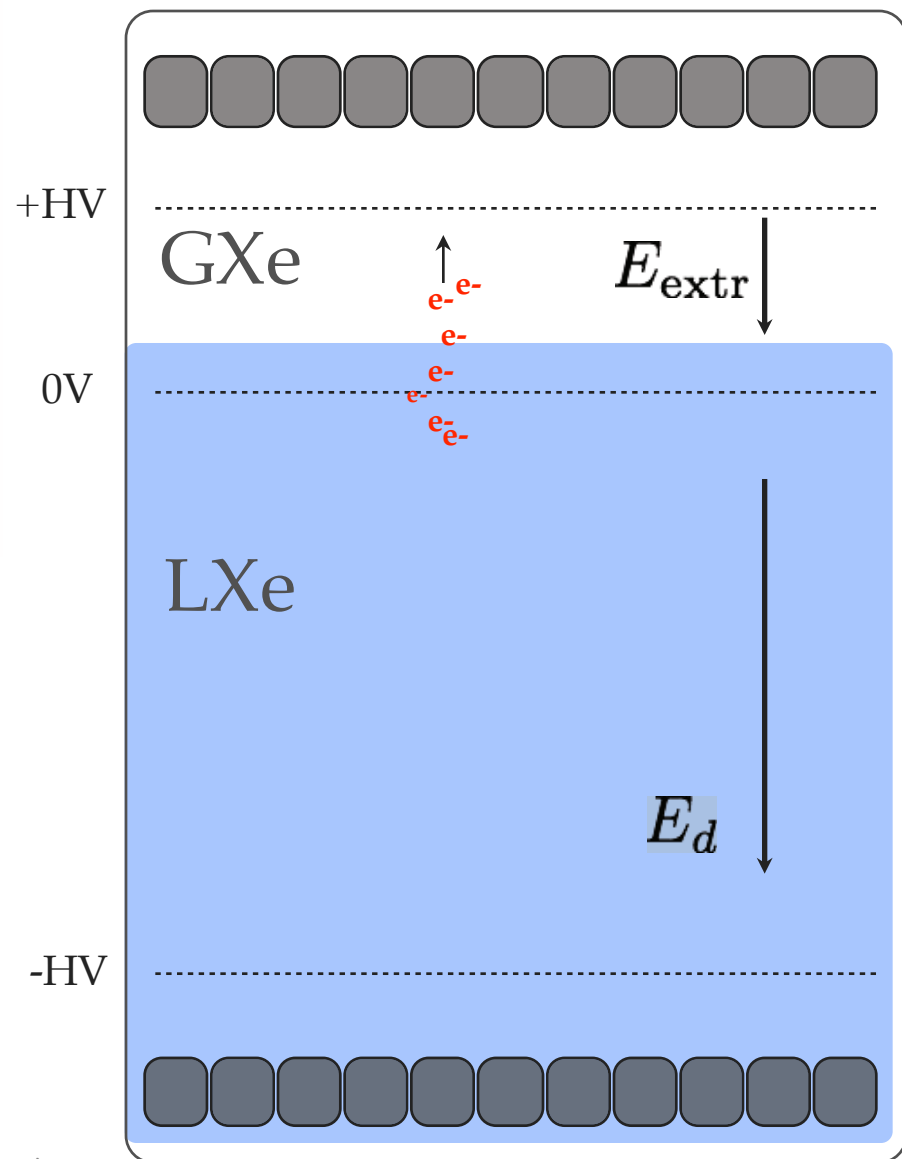
# Single electron events

LUX trigger system is capable of triggering on signals from single extracted electrons

Single-e process very difficult to model

- Photoionization after S1/S2: grids ionization, bulk ionization…

- Trapped S2 electrons (e-trains)

- Field emission single-e

arXiv:1511.03541v1

# Surface background



- $^{238}$U decay chain takes it through $^{222}$Rn, which is a noble gas, can diffuse into the air and get everywhere. Then it "plate out" once it decays
- $^{210}$Po, is problematic: low energy, heavy projectile, gives small scintillation and ionisation signals



$^{210}$Po

$\alpha$

5.3 MeV

$^{206}$Pb

103 keV
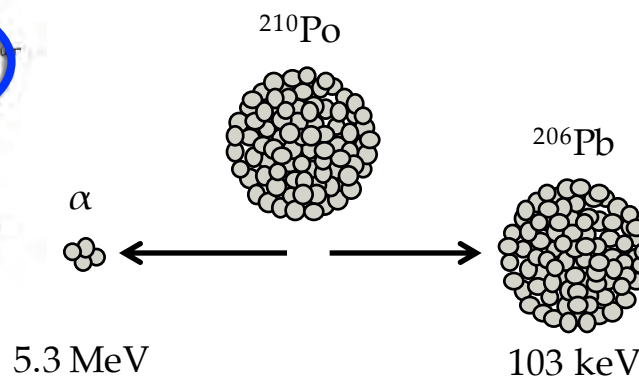
# Electronic Recoil DM

- Axion-Like particles as one of the best candidate

- Experimentally detectable in the Xe exploiting the axion-electron effect (proportional to the photo-electric effect)
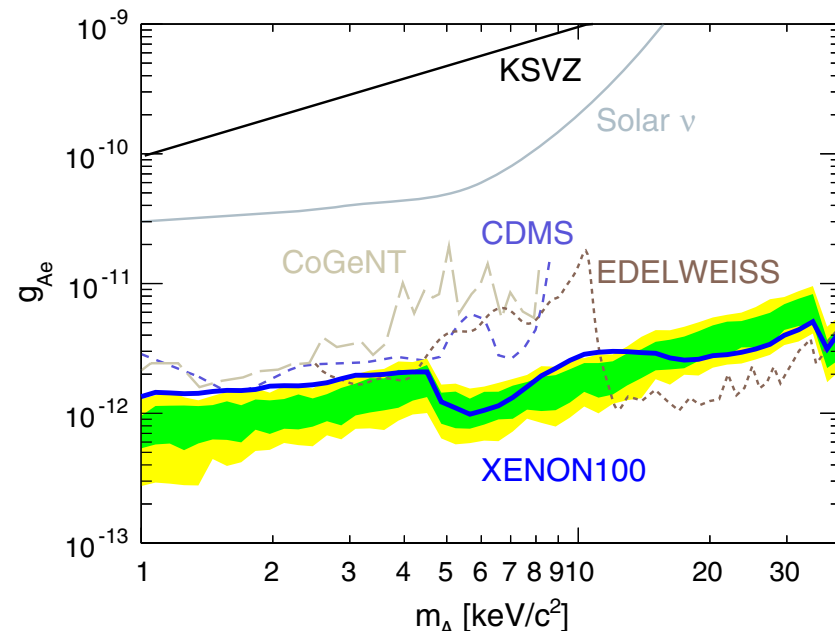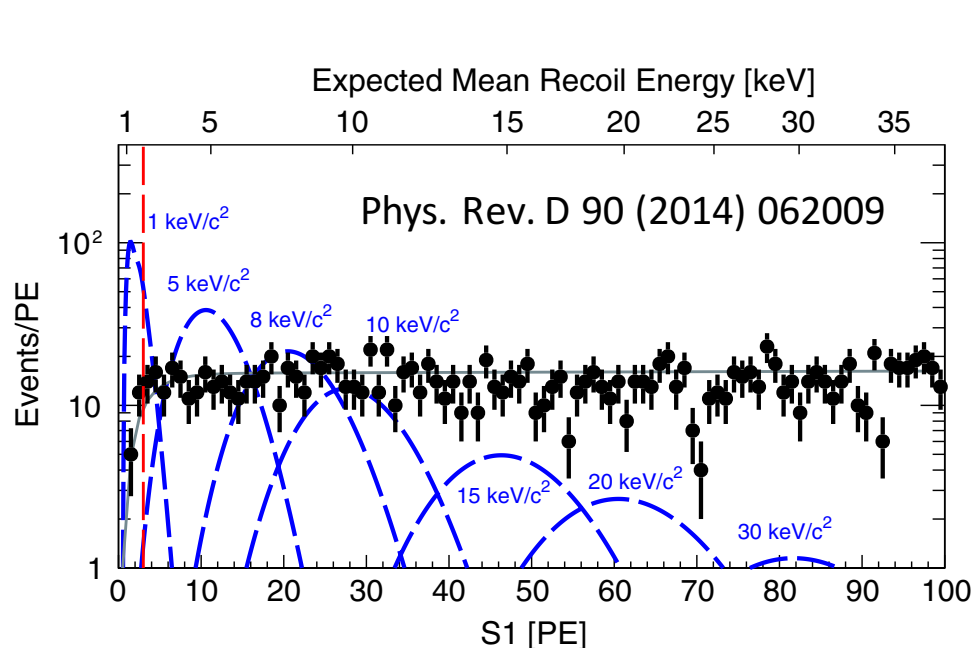
$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{{g_{Ae}}^2}{\beta_A}\frac{3{E_A}^2}{16\pi\,\alpha_{em}\,{m_e}^2}\left(1 - \frac{\beta_A^{2/3}}{3}\right)$$
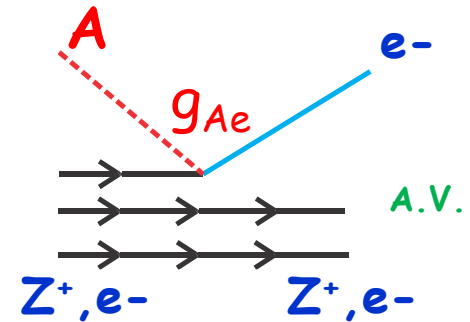


- Invisible axions, could solve the the QCD Charge-Parity Violation problem

- Axion-Like Particles from extension of the Standard Model, could also be Dark Matter particle candidate
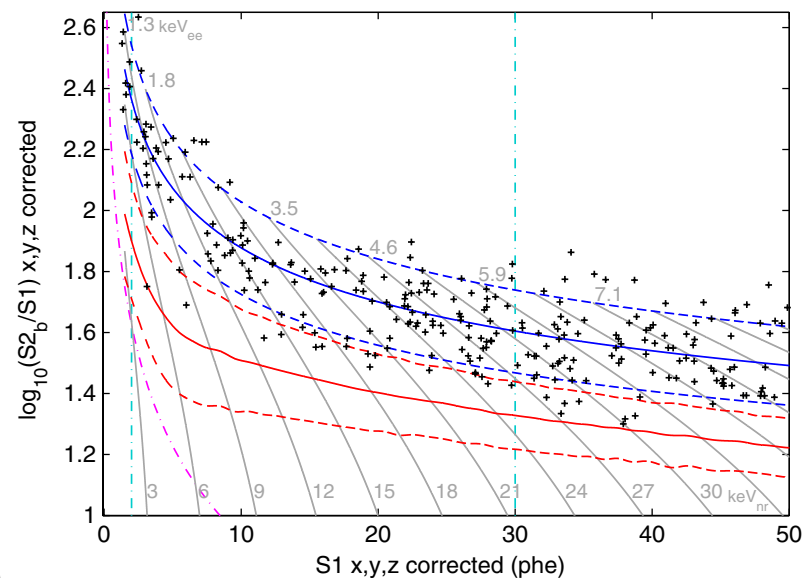
Phys. Rev. D 35, 2752 (1987),
Nucl. Rev. D 78, 115012 (2008), Phys. Rev. D 82, 065006 (2010).

# keV axion-like particles



Phys. Rev. D 90 (2014) 062009



With the current LUX WIMP search:

- 118 kg fiducial x 85.3 days

- 160 events between 1 - 5 keVee

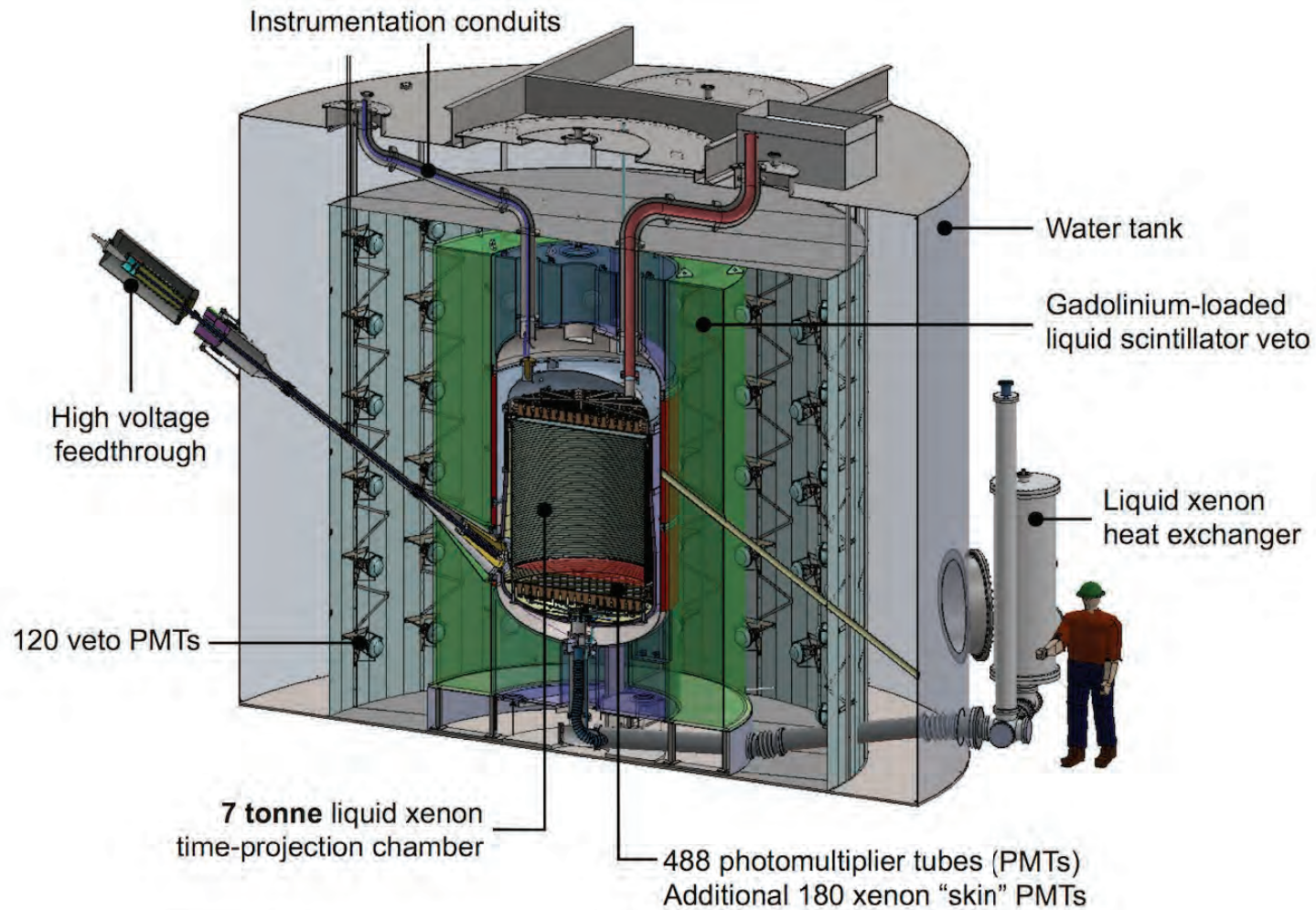- Lower background than XENON100 => improved sensitivity

# Summary on LUX

- LUX re-analysis coming out soon. Currently collecting data for the 300-day run

- Several DM papers in the pipeline

- Ionisation-only searches and/or electronic recoil events are good at targeting light DM candidates

- Key advantage of LUX:

  - low background

  - great energy resolution

- Several groups working to detailed understanding of the detector response and background description

# LUX-ZEPLIN

- Next generation, LUX-ZEPLIN (LZ) experiment, selected as one of three "G2" DM projects
- 32 international institutions (~ 200 members)
- Conceptual Design Report: arXiv:1509.02910

| Year | Month | Activity |
|------|-------|----------|
| 2012 | March | LZ (LUX-ZEPLIN) collaboration formed |
| | May | First Collaboration Meeting |
| | September | DOE CD-0 for G2 dark matter experiments |
| 2013 | November | LZ R&D report submitted |
| 2014 | July | LZ Project selected in US and UK |
| 2015 | April | DOE CD-1/3a approval, similar in UK<br>Begin long-lead procurements (Xe, PMT, cryostat) |
| 2016 | April | DOE CD-2/3b approval, baseline, all fab starts |
| 2017 | June | Begin preparations for surface assembly @ SURF |
| 2018 | July | Begin underground installation |
| 2019 | Feb | Begin commissioning |

# LUX-ZEPLIN instruments



Instrumentation conduits

Water tank

Gadolinium-loaded
liquid scintillator veto

High voltage
feedthrough

Liquid xenon
heat exchanger

120 veto PMTs

**7 tonne** liquid xenon
time-projection chamber

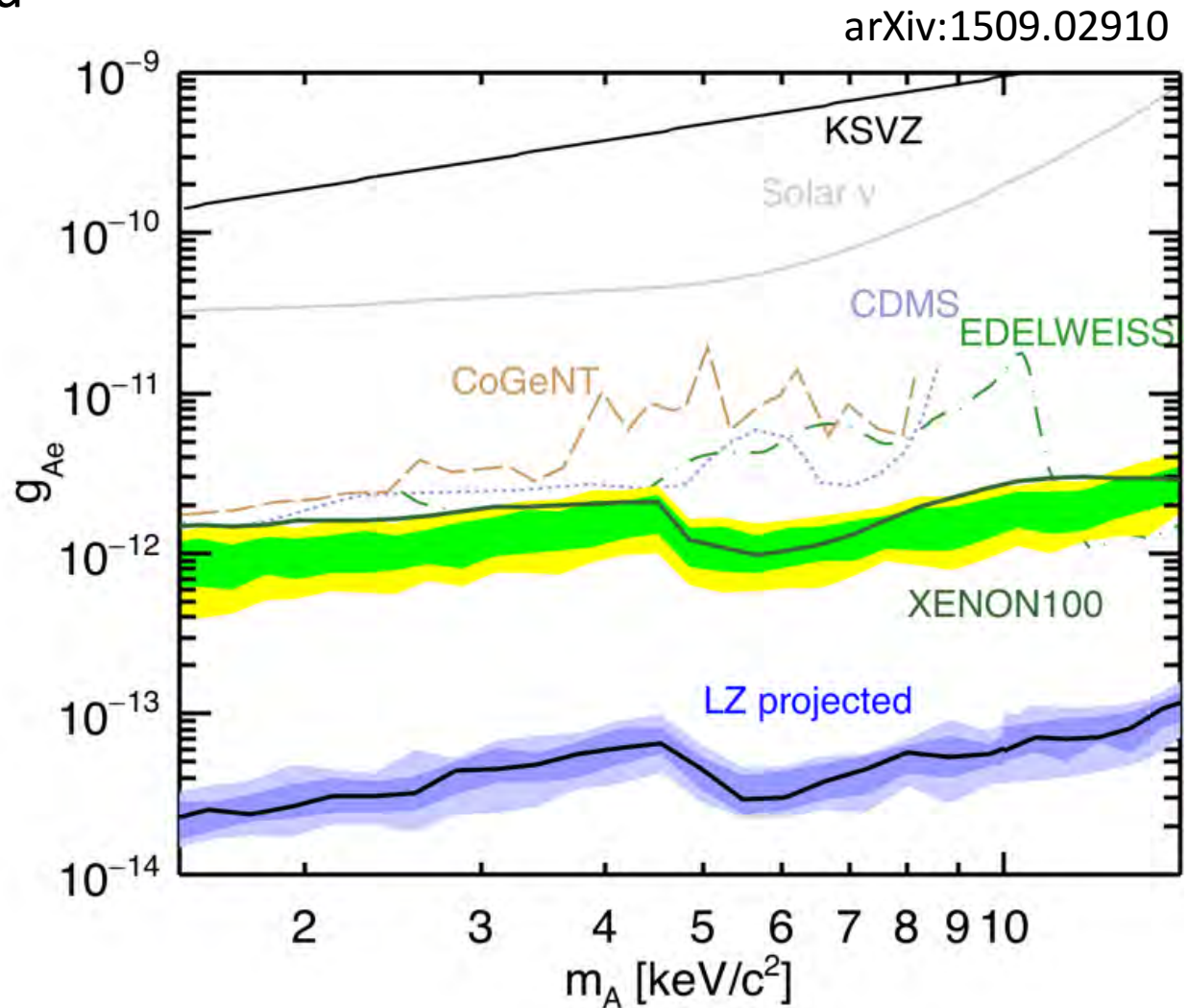488 photomultiplier tubes (PMTs)
Additional 180 xenon "skin" PMTs

# WIMP

- S1+S2 WIMP SI sensitivity: $2 \times 10^{-48}$ cm$^2$: 5.6t x 1000d
- Lower energy threshold: 1 keV
- S2-only: 2.5 e$^-$ (100 photons detected), 1t x 1000d



**$2\times10^{-48}$ cm$^2$**
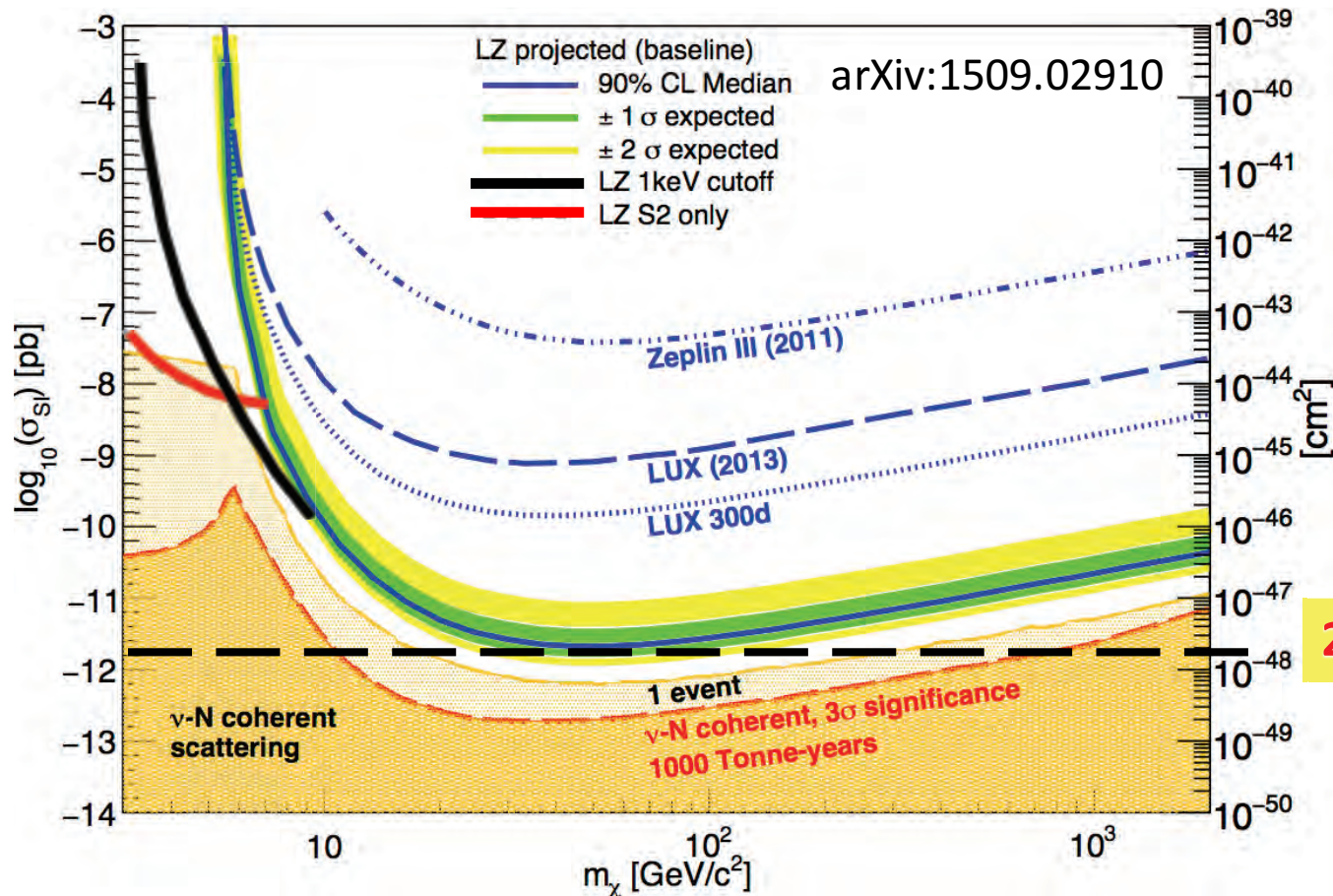
# Axion-like particles

- Assumed background form pp Solar neutrinos
- 5.6t x 1000d
- S1-based Profile Likelihood analysis

arXiv:1509.02910

# Summary on LUX-ZEPLIN

- Extensive prototyping program underway

- Benefits from LUX calibrations and understanding of backgrounds

- LZ science run to start in 2019

  - spin-independent sensitivity: $2 \times 10^{-48}$ cm$^2$. Limited by neutrino-induced backgrounds

- Dedicated studies on light DM detection

  - S2-only analysis, Electrophilic DM, exploiting the presence of Outer Detector system

# Original from Led Zeppelin

# BACKUP

# ER calibration

## New detector response calibration for ER: $CH_3T$ injection

- Homogeneous $\beta$ source with Q = 18 keV
- Removal with $\tau$ < 12h

- Light and charge yields to ~1 keVee
- Detection efficiency vs energy
- Informative of the background shape
- Precise determination of ER event
- "leaks" down into NR S2/S1 region, as a function of S1 from [0.2 - 5] keVee
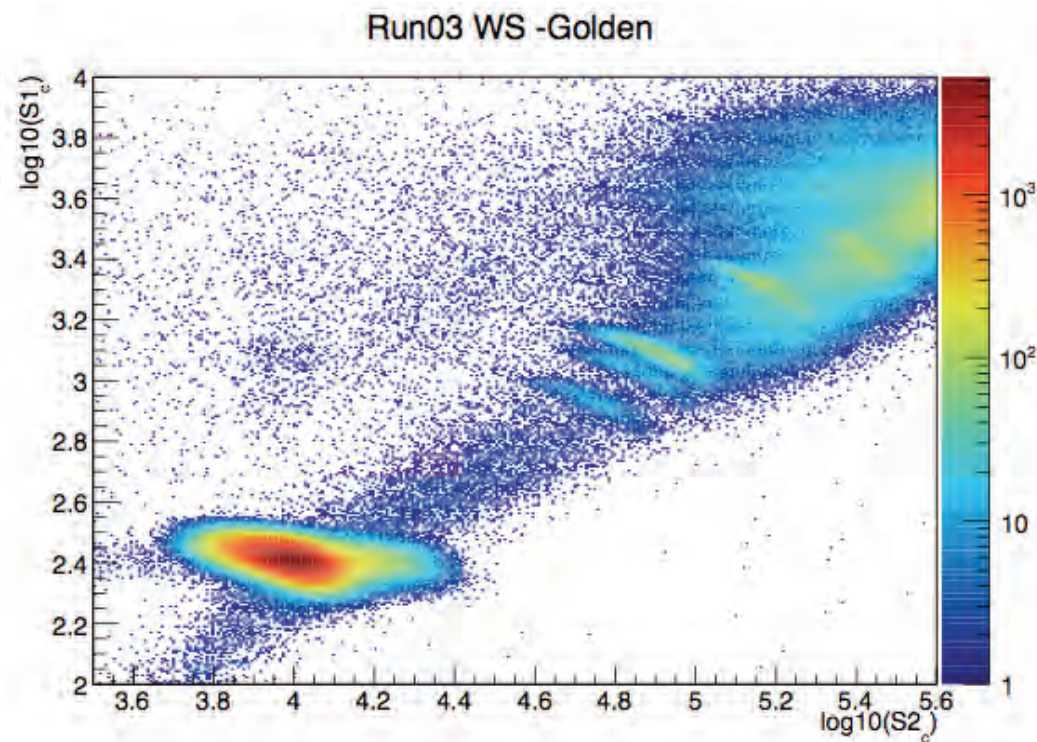- Uniformly distributed, used with $^{83m}Kr$ for fiducial volume evaluation
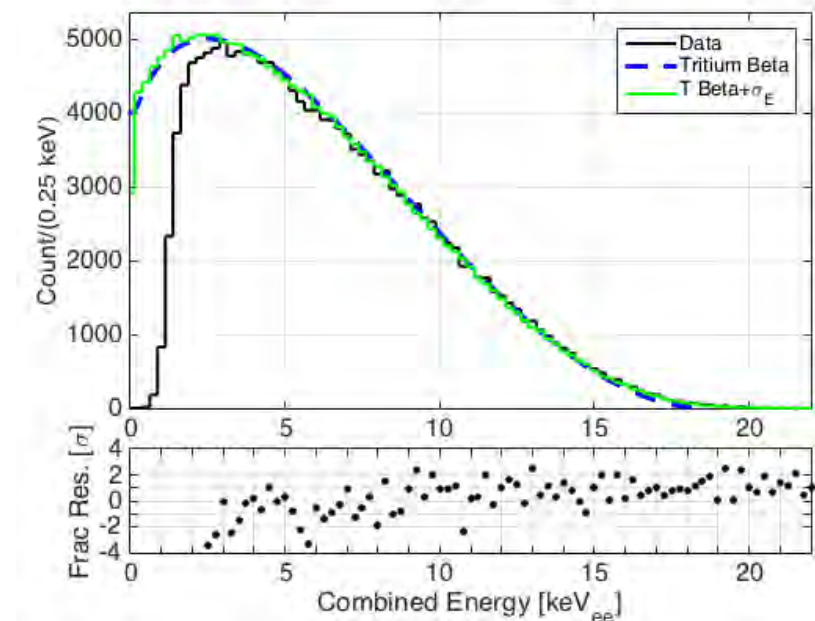
# Event Reconstruction

$$\frac{E}{W} = n_\gamma + n_e = \frac{S1}{g_1} + \frac{S2}{g_2}$$

$W = 13.7 \times 10^{-3}$ keVee

- $g_1$: accounts for both geometric light collection and the QEs of the PMTs

  Defined for the center, with position variation, +/− ~20% between top and bot, mapped out with Kr83m

- $g_2$: accounts for electron extraction efficiency and number of photons detected per extracted electron

- NR has factor $L < 1$ accounting for fewer overall quanta (not just S1 photons) being generated due to NR being more effective making more NR (i.e. heat)
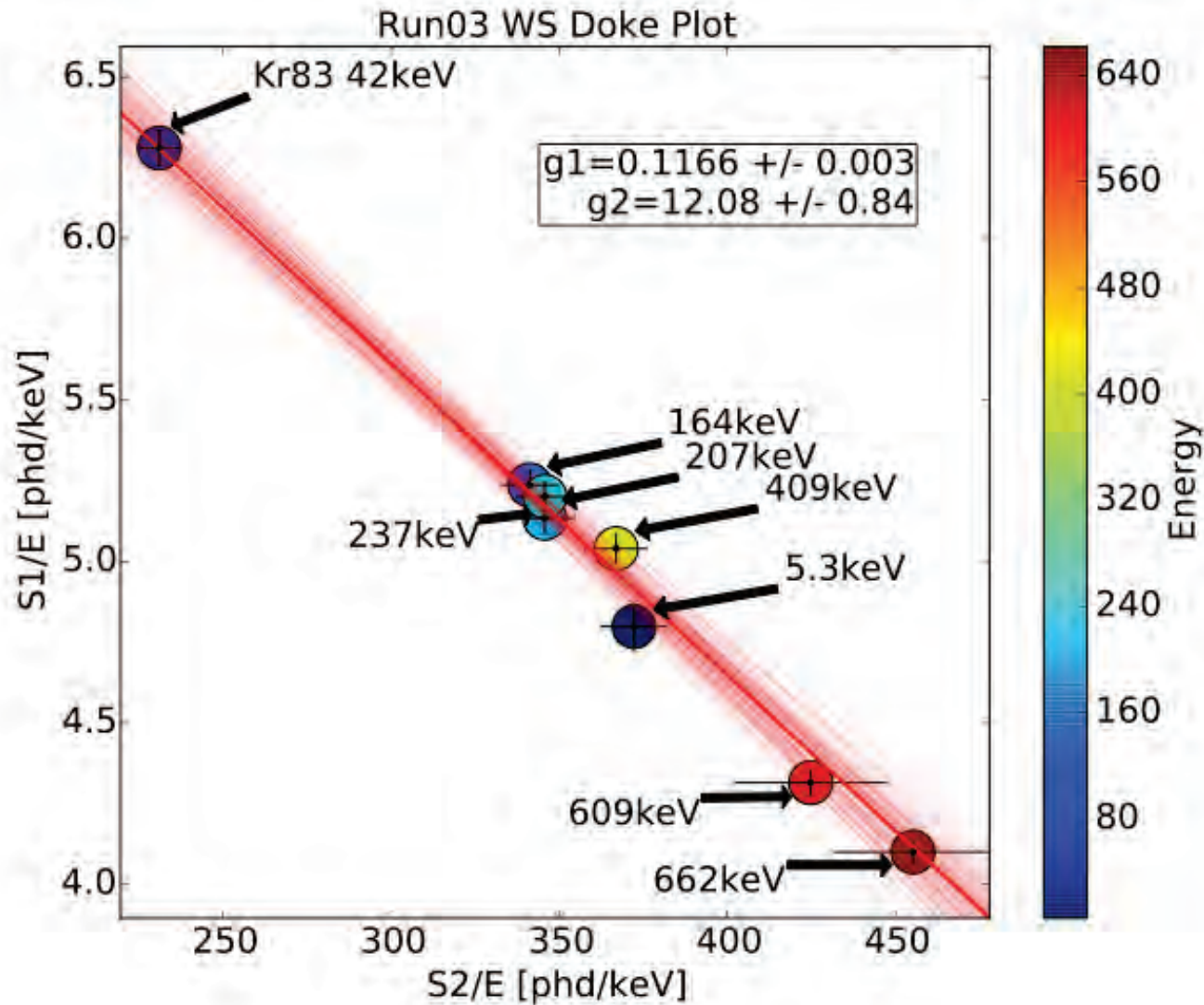
# Doke Plot

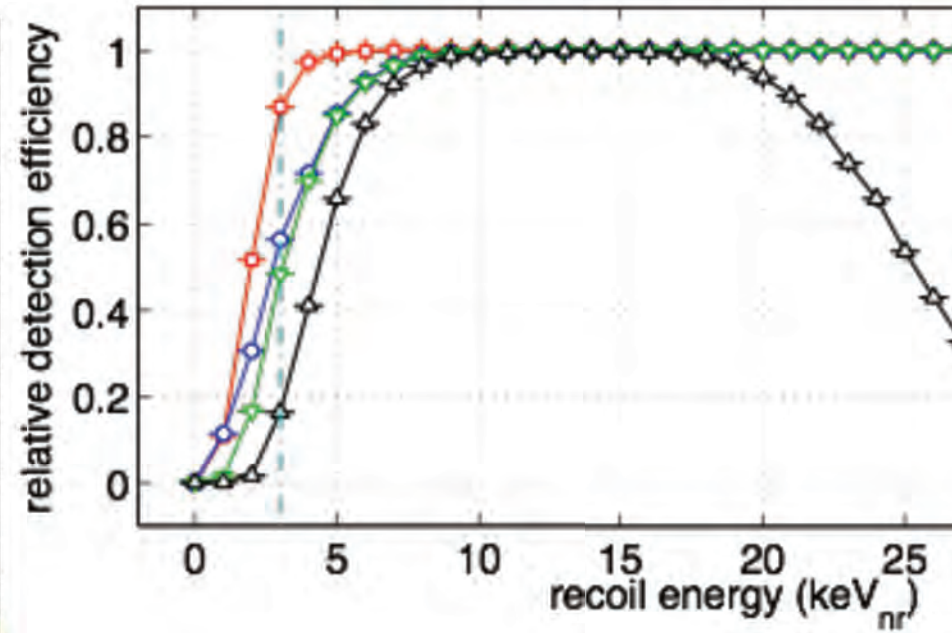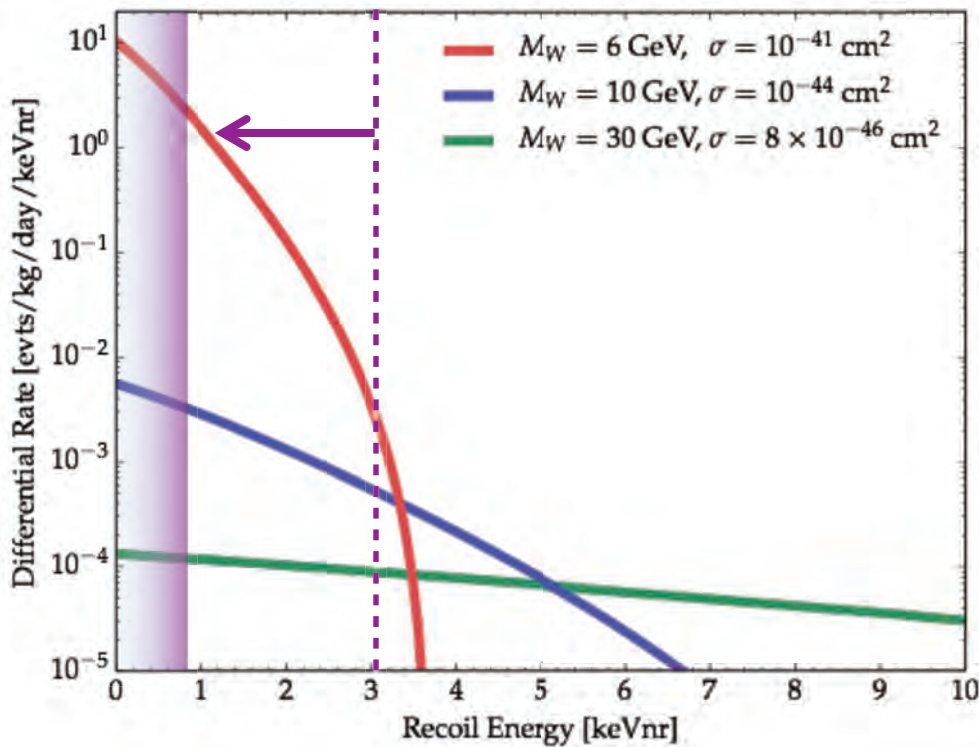| Source | Energy [keV] | Decay Type |
|--------|--------------|------------|
| *Xe K shell* | *29.7, 34* | *X-ray* |
| *83m Kr* | *41.55* | *Internal Conversion* |
| *131 Xe* | *163.9* | *Internal Conversion* |
| *127 Xe* | *203 or 375* | *γ -emission* |
| *127 Xe* | *33.8* | *Kb shell X-ray* |
| *127 Xe* | *5.3* | *L shell X-ray* |
| *129m Xe* | *236.1* | *Internal Conversion* |
| *214 Bi* | *609* | *γ -emission* |
| *137 Cs* | *661.6* | *γ -emission* |



Run03 WS -Golden

$$\langle n_\gamma \rangle = \frac{\langle S1 \rangle}{g_1} \qquad S1/E = \frac{n_\gamma}{(n_\gamma + n_e)} \times \frac{g_1}{W}$$

$$\langle n_e \rangle = \frac{\langle S2 \rangle}{g_2} \qquad S2/E = \frac{n_e}{(n_\gamma + n_e)} \times \frac{g_2}{W}$$

# Doke Plot



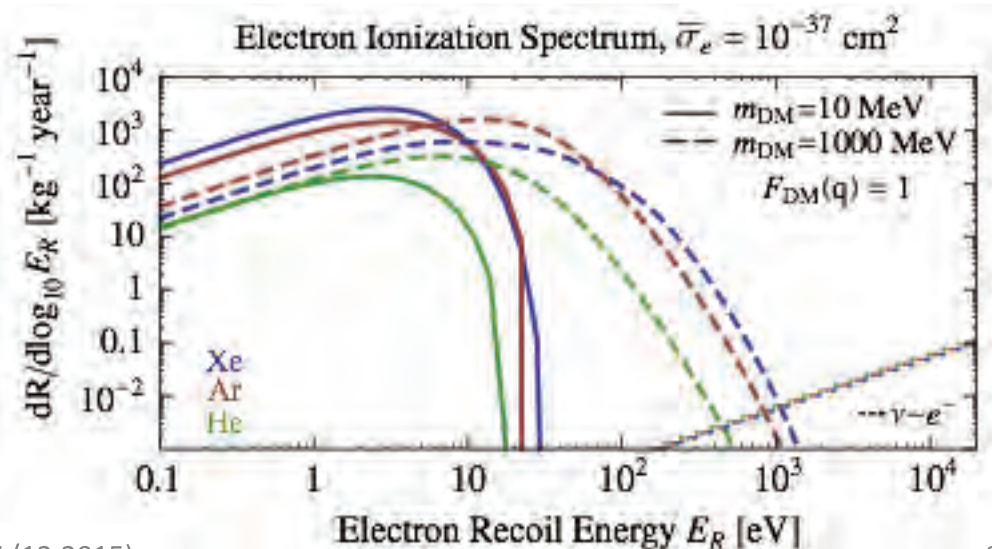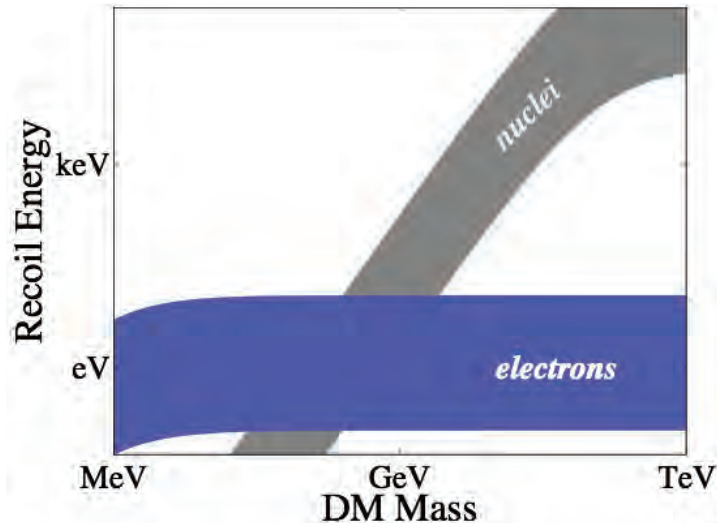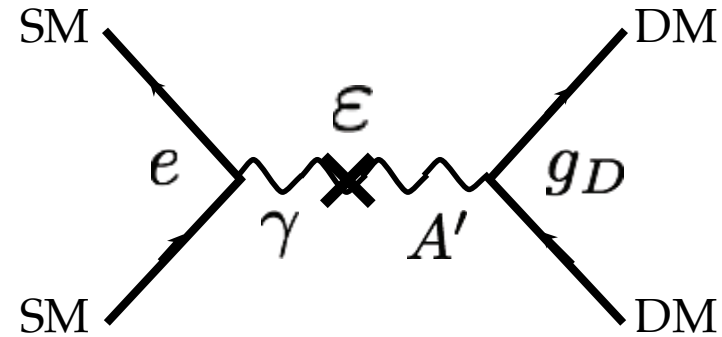Run03 WS Doke Plot

g1=0.1166 +/- 0.003
g2=12.08 +/- 0.84

# Impact on WIMP



Ionization efficiency, assuming ~4-electron threshold

# Light DM hidden sector

- Hidden sector with its own U(1)' gauge symmetry.

- The hidden gauge boson, A', kinetically mixes with our photon.

- DM masses O(1-1000 MeV)

- Kinematics precludes looking for this as nuclear recoils: we look instead for electronic recoils.

# Single electron processes

- The electrons see a potential barrier at the surface and can get trapped there, to later "evaporate" off

- $O_2$ impurities that have captured an electron can be ionised by a Xe scintillation photon

- A Xe scintillation photon (7 eV) can eject an electron from the surface of a metal (i.e. one of the electrodes)
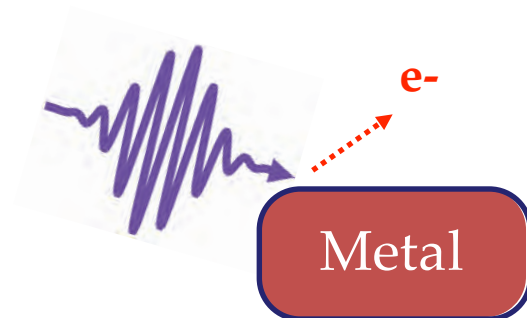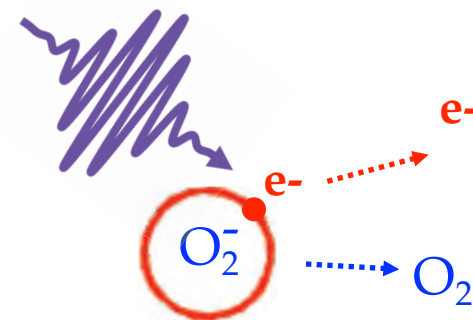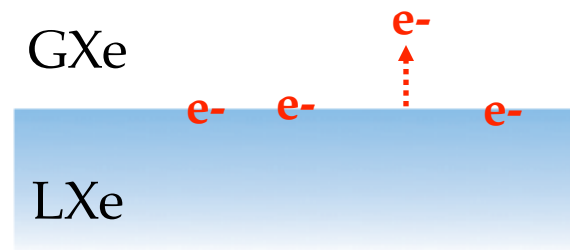
# LZ Background table

## Expected backgrounds for 5.6 tonnes fiducial in 1000 days run

| Item | Mass kg | U mBq/kg | Th mBq/kg | $^{60}$Co mBq/kg | $^{40}$K mBq/kg | n/yr | ER cts | NR cts |
|---|---|---|---|---|---|---|---|---|
| R11410 PMTs | 93.7 | 2.7 | 2.0 | 3.9 | 62.1 | 373 | 1.24 | 0.20 |
| R11410 bases | 2.7 | 74.6 | 29.1 | 3.6 | 109.2 | 77 | 0.17 | 0.03 |
| Cryostat vessels | 2,140 | 0.09 | 0.23 | ≈0 | 0.54 | 213 | 0.86 | 0.02 |
| OD PMTs | 122 | 1,507 | 1,065 | ≈0 | 3,900 | 20,850 | 0.08 | 0.02 |
| Other components | - | - | - | - | - | 602 | 9.5 | 0.05 |
| Total components | | | | | | | 11.9 | 0.32 |
| Dispersed radionuclides (Rn, Kr, Ar) | | | | | | | 54.8 | - |
| $^{136}$Xe 2νββ | | | | | | | 53.8 | - |
| Neutrinos (ν-e, ν-A) | | | | | | | 271 | 0.5 |
| Total events | | | | | | | 391.5 | 0.82 |
| WIMP background events (99.5% ER discrimination, 50% NR acceptance) | | | | | | | 1.96 | 0.41 |
| Total ER+NR background events | | | | | | | 2.37 | |

# Using Outer Detector

- Exotic DM models (excitations)
- NR scattering in LXe and consequent photon emission detected in the Liquid Scintillator of the outer detector
- It is expected for the photon to be monochromatic
- Given the scattering is in LXe no special trigger is required

arXiv:1312.1363