Prospective for low mass dark matter with LUX and LZ

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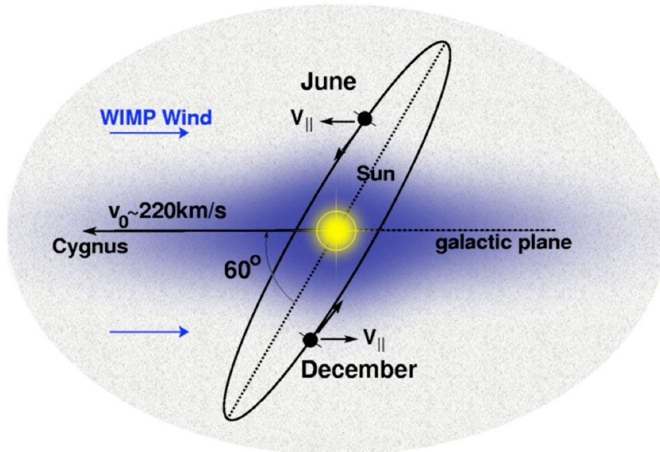
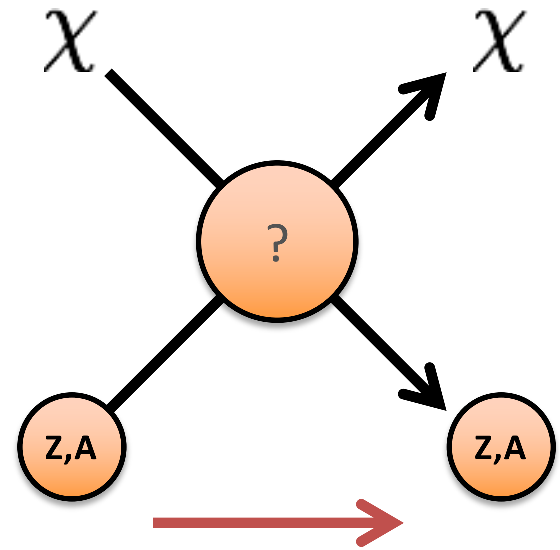
on behalf of the LUX and LZ Collaborations

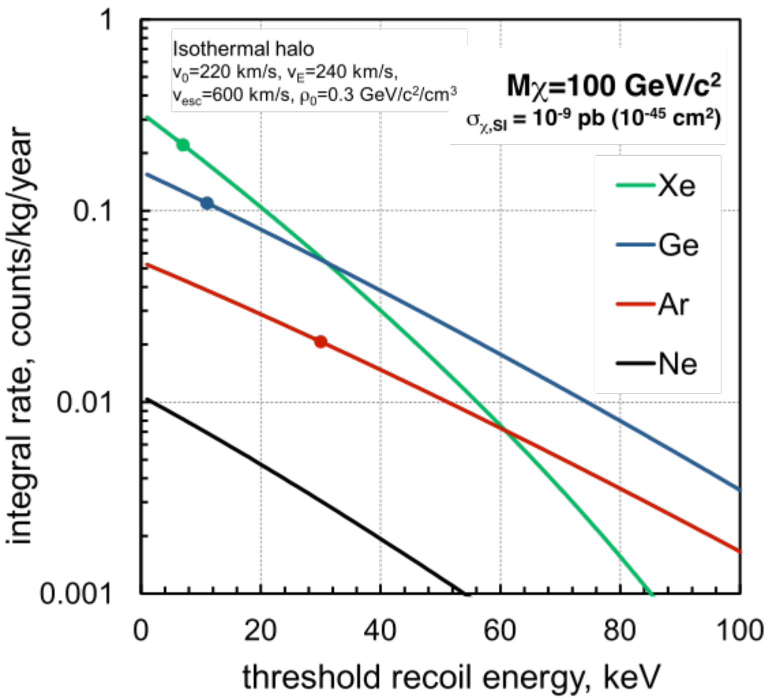
Direct detection

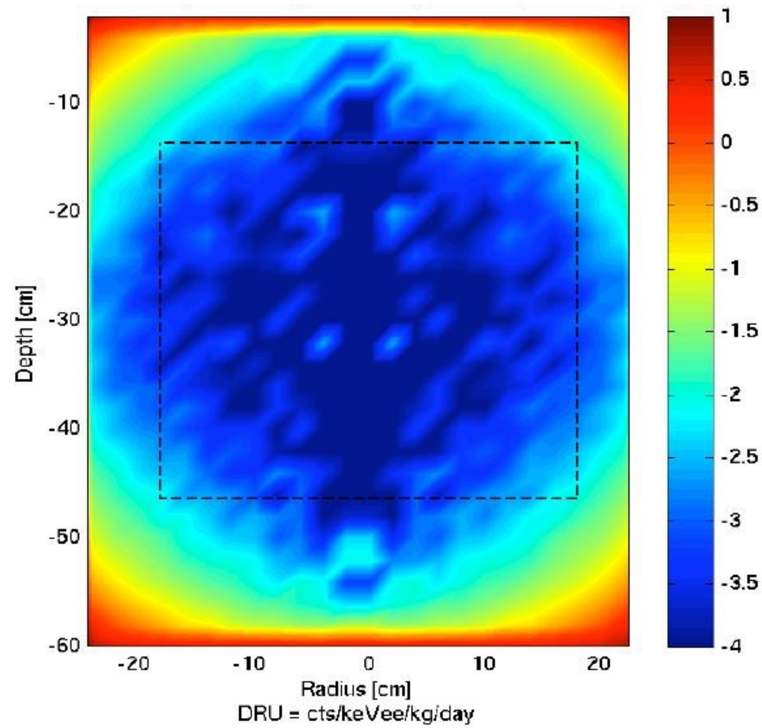




- Dark Matter Weakly Interactive Massive Particle (WIMP) in direct search experiments
  - Nuclear Recoil (NR) in the target material, ~ keVnr energy deposit
  - Electron Recoil (ER) giving most of the background (keVee)
- Standard WIMP searches (> 10 GeV/c^2 mass)… but not only

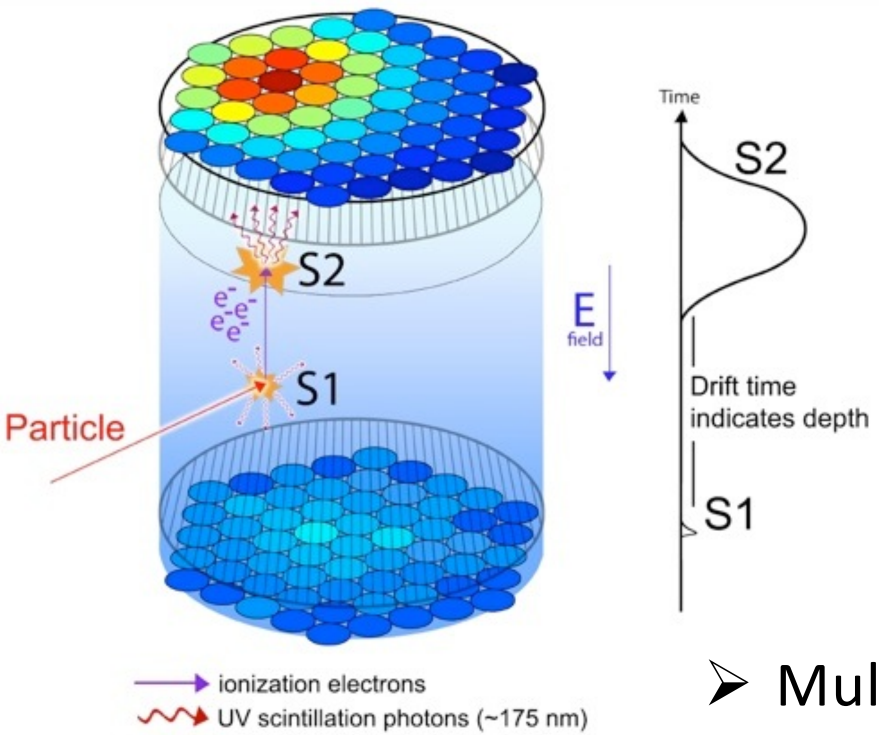
Liquid Xenon





- 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

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Dongqing Huang	Graduate Student
Will Taylor	Graduate Student
Casey Rhyne	Graduate Student
James Verbus	Graduate Student

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Tim Sumner	Professor
Alastair Currie	Postdoc
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Khadeeja Yazdani	Graduate Student

Lawrence Berkeley + UC Berkeley

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Kevin Lesko	Senior Scientist
Peter Sorensen	Scientist
Victor Gehman	Scientist
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Mia Ihm	Graduate Student
Kate Kamdin	Graduate Student
Kelsey Oliver-Mallory	Graduate Student

Lawrence Livermore

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Kareem Kazkaz	Staff Physicist
Brian Lenardo	Graduate Student

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Vladimir Solovov	Senior Researcher
Francisco Neves	Auxiliary Researcher
Alexander Lindote	Postdoc
Claudio Silva	Postdoc

SLAC Nation Accelerator Laboratory

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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

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Doug Tiedt	Graduate Student

SDSTA

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Mark Hanhardt	Support Scientist

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Jeremy Mock	Postdoc
Steven Young	Graduate Student

Texas A&M

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Robert Webb	PI, Professor
Rachel Mannino	Graduate Student
Paul Terman	Graduate Student

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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

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Mike Witherell	Professor
Susanne Kyre	Engineer
Dean White	Engineer
Carmen Carmona	Postdoc
Scott Haselschwardt	Graduate Student
Curt Nehrkorn	Graduate Student
Melih Solmaz	Graduate Student

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Paolo Beltrame	Research Fellow
James Dobson	Postdoc
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Tom Davison	Graduate Student

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Richard Knoche	Graduate Student
Jon Balajthy	Graduate Student

University of Rochester

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Wojtek Skutski	Senior Scientist
Eryk Druszkiewicz	Graduate Student
Dev Ashish Khaitan	Graduate Student
Mongkol Moongweluwan	Graduate Student

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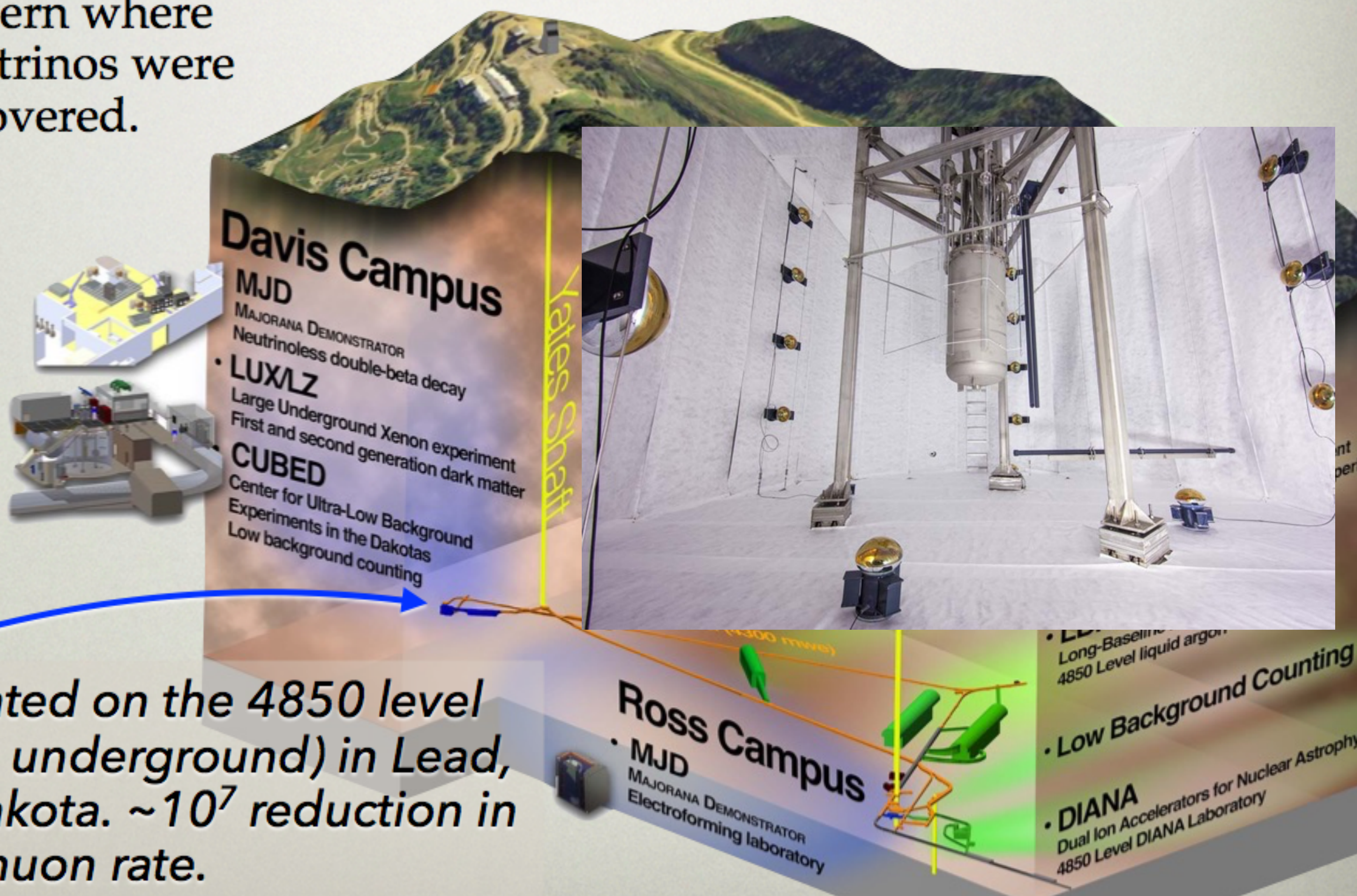
Chao Zhang	Postdoc
Angela Chiller	Graduate Student
Chris Chiller	Graduate Student

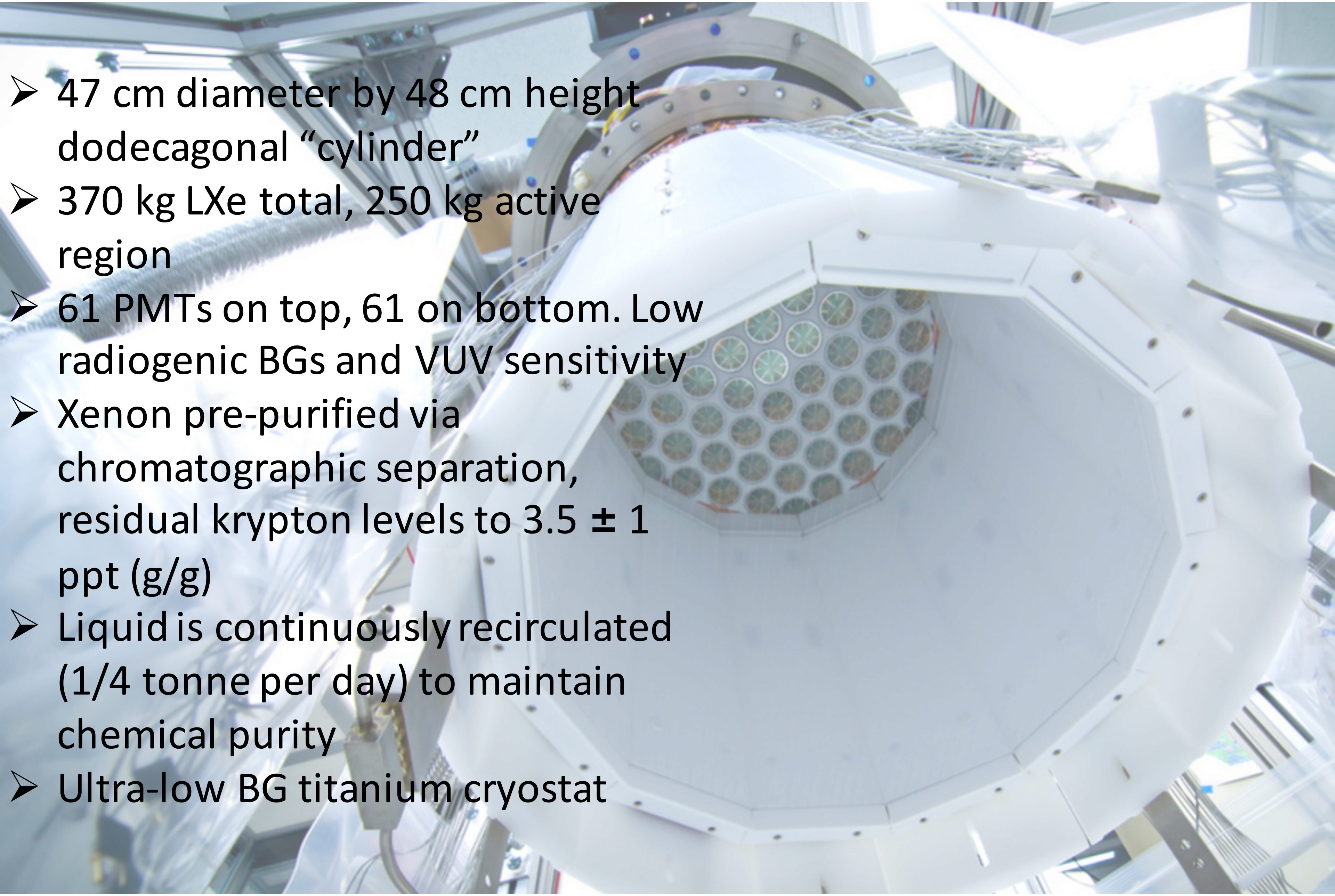
Yale

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.

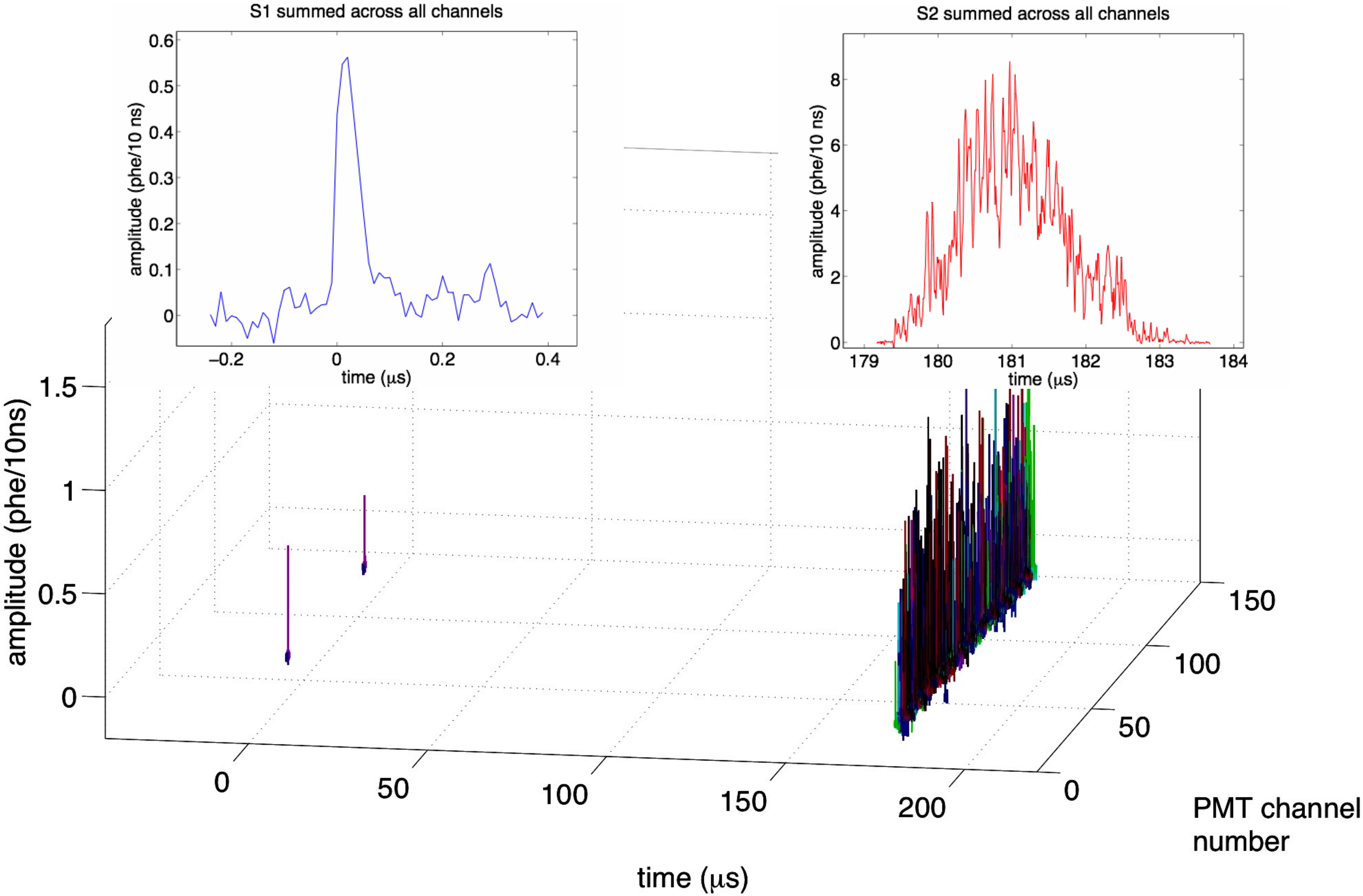


LUX, located on the 4850 level (~1.5 km underground) in Lead, South Dakota. ~10^7 reduction in cosmic muon rate.

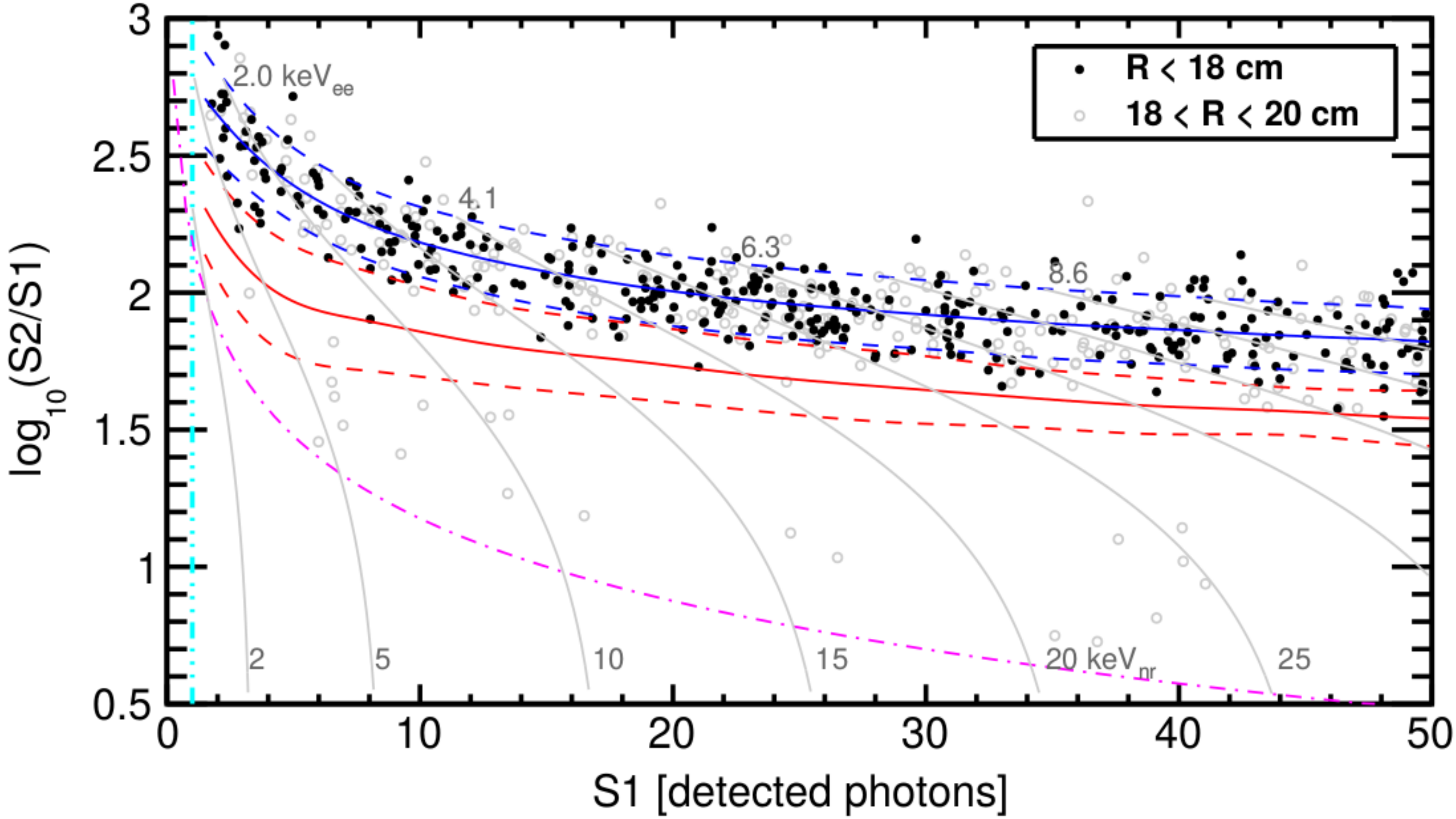


- 47 cm diameter by 48 cm height dodecagonal “cylinder”
- 370 kg LXe total, 250 kg active region
- 61 PMTs on top, 61 on bottom. Low radiogenic BGs and VUV sensitivity
- Xenon pre-purified via chromatographic separation, residual krypton levels to 3.5 ± 1 ppt (g/g)
- Liquid is continuously recirculated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

WIMP search


S1 summed across all channels
amplitude (phe/10 ns)
time (µs)
S2 summed across all channels
amplitude (phe/10 ns)
time (µs)
amplitude (phe/10ns)
time (µs)
PMT channel number

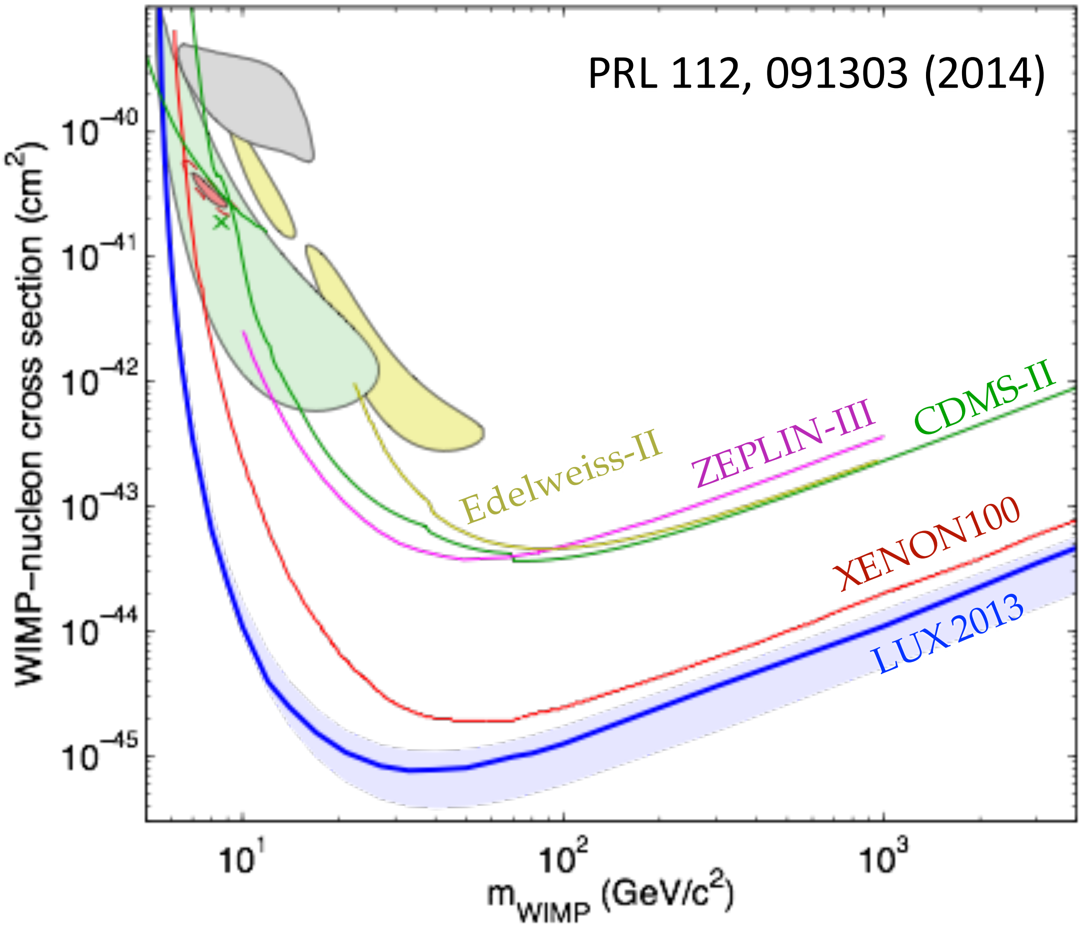
WIMP search



(Charge/Light)

(Light ~ Energy)

WIMP search



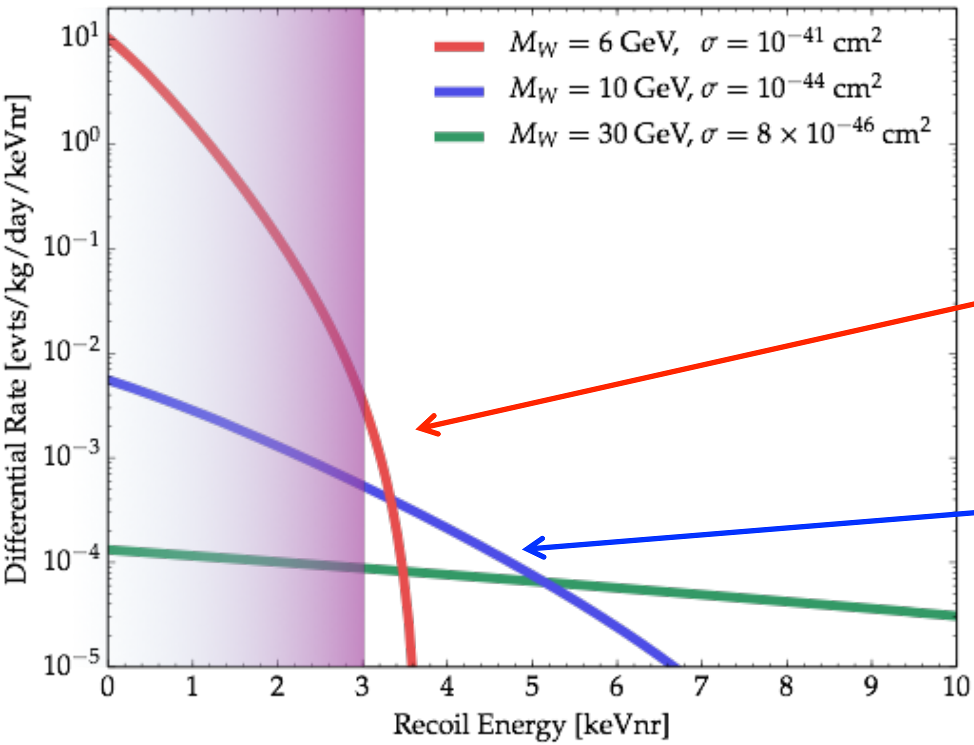
- Exposure: 85.3 live days, 118 kg fiducial mass
- Obs. bkg. events: 160
- Drift field: 181 V/cm
- Analysis 4-parameter profile likelihood, p-value of 35% consistent with backgrounds

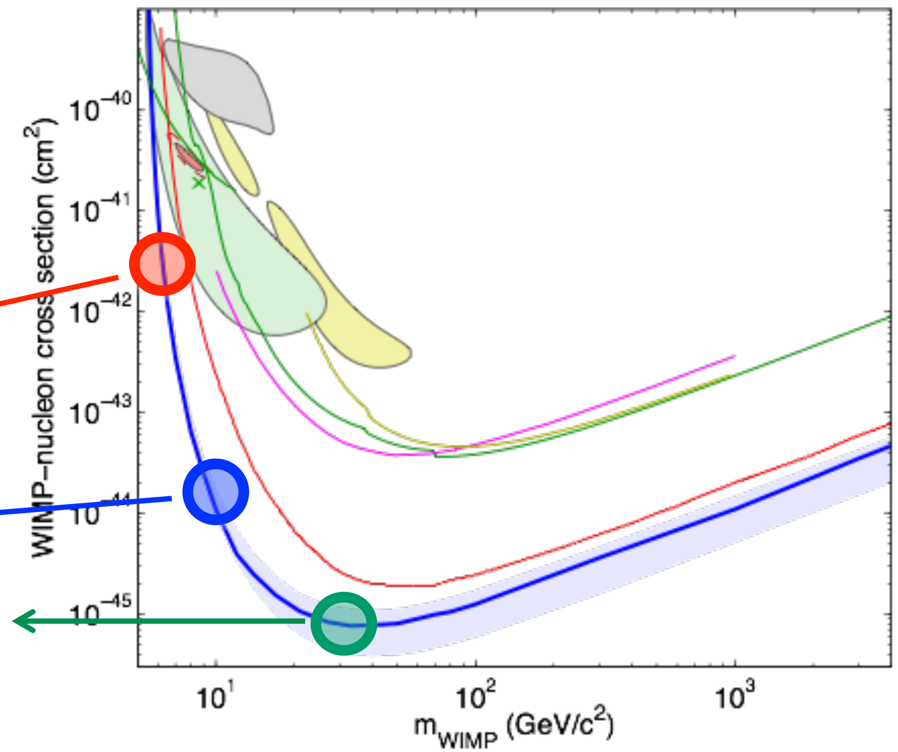
7.6×10^{-46} cm^2 at 33 GeV/c^2

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

WIMP sensitivity

http://indico.hep.manchester.ac.uk/contributionDisplay.py?contribId=133&sessionId=17&confId=4221





WIMP sensitivity

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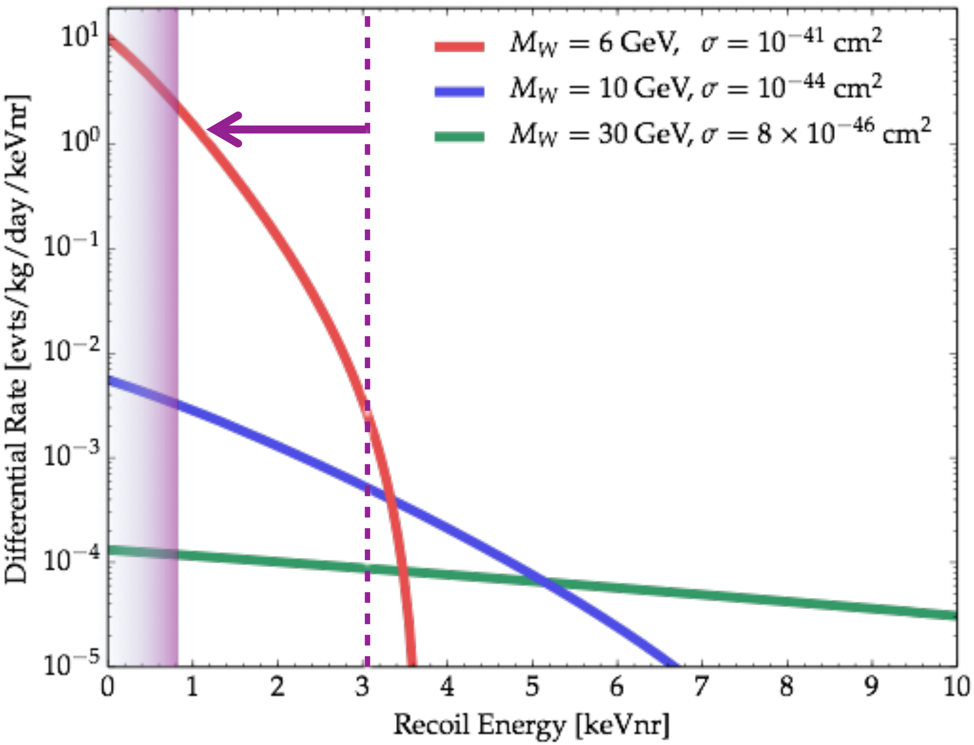
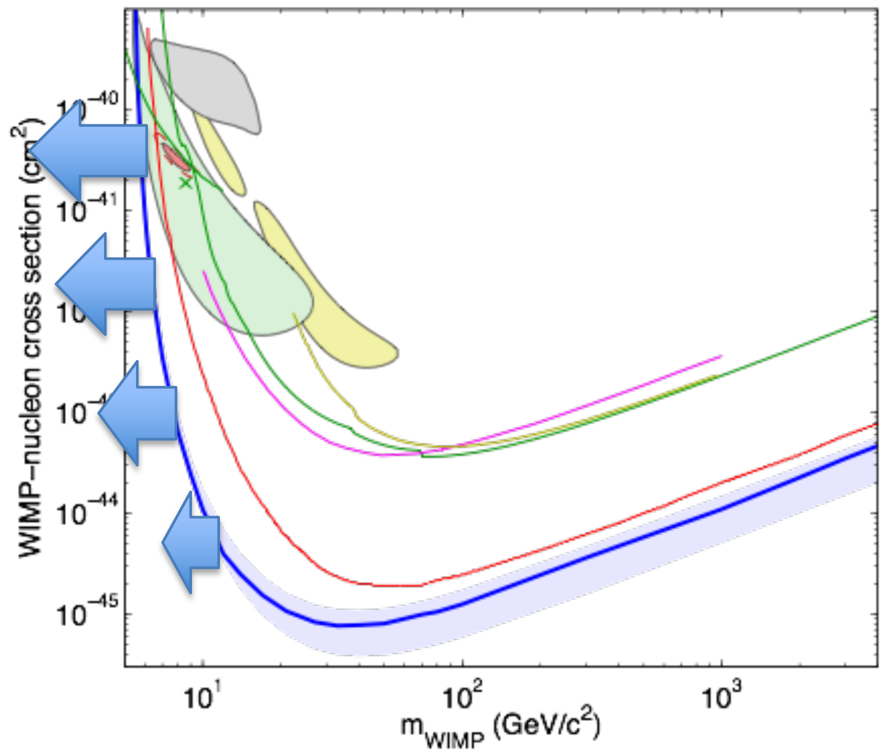




Decreasing this response cutoff from 3 keV to < 1 keV provides access to a factor of 8000 more signal at *M* = 6 GeV

Nuclear Recoil events

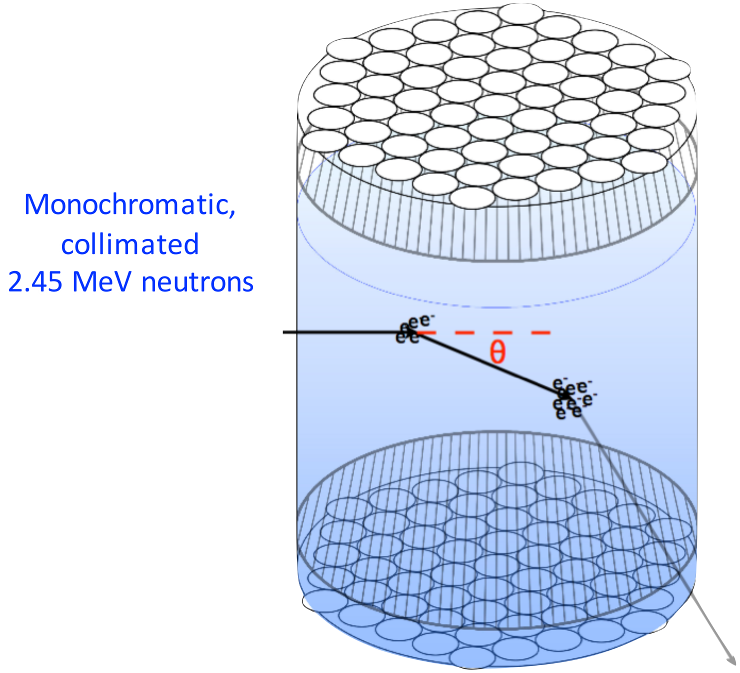
New detector response calibration for NR: **DD generator**

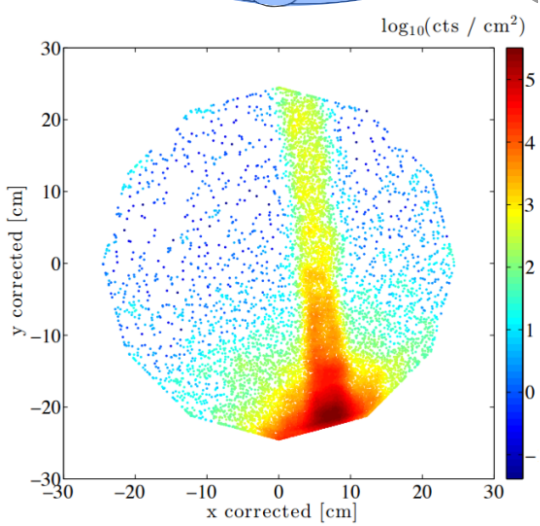
- Double scatters along beam line inside LUX. Angle gives deposited energy.

=> Absolute calibration of ionisation response: Q_Y

- Apply ionisation scale to single scatter

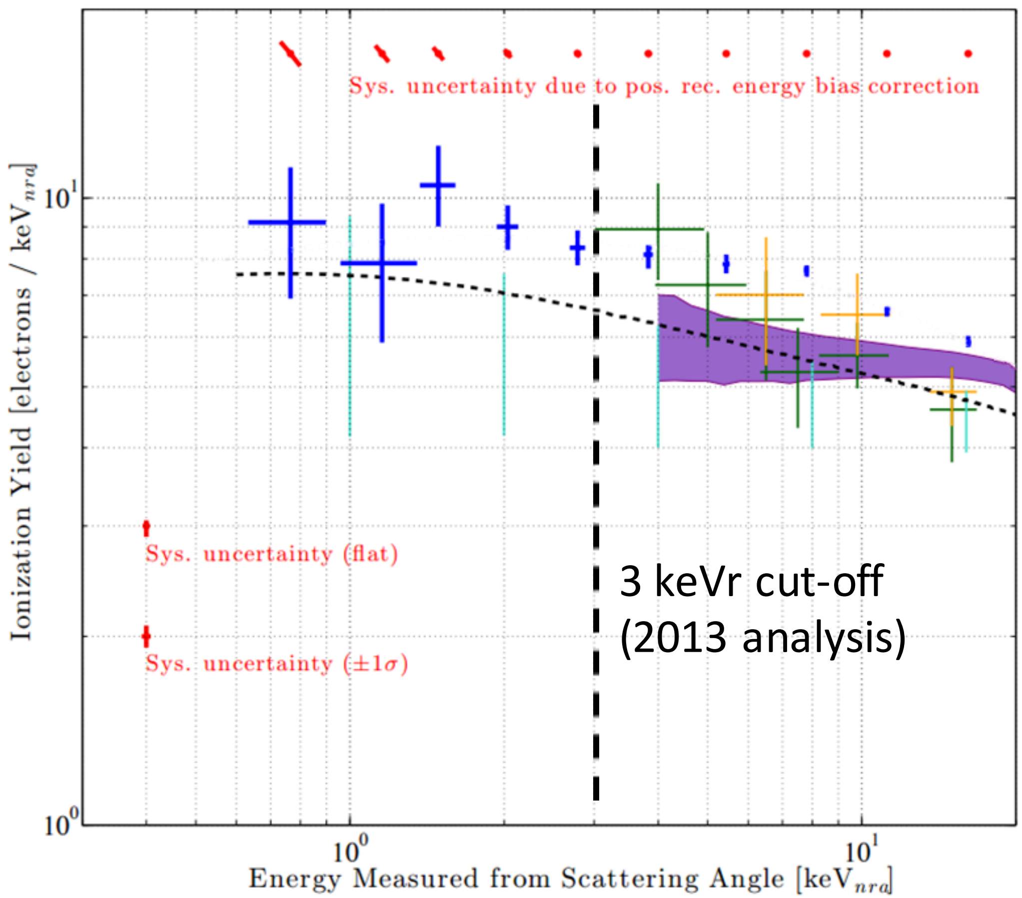
=> Absolute calibration of scintillation response: L_Y





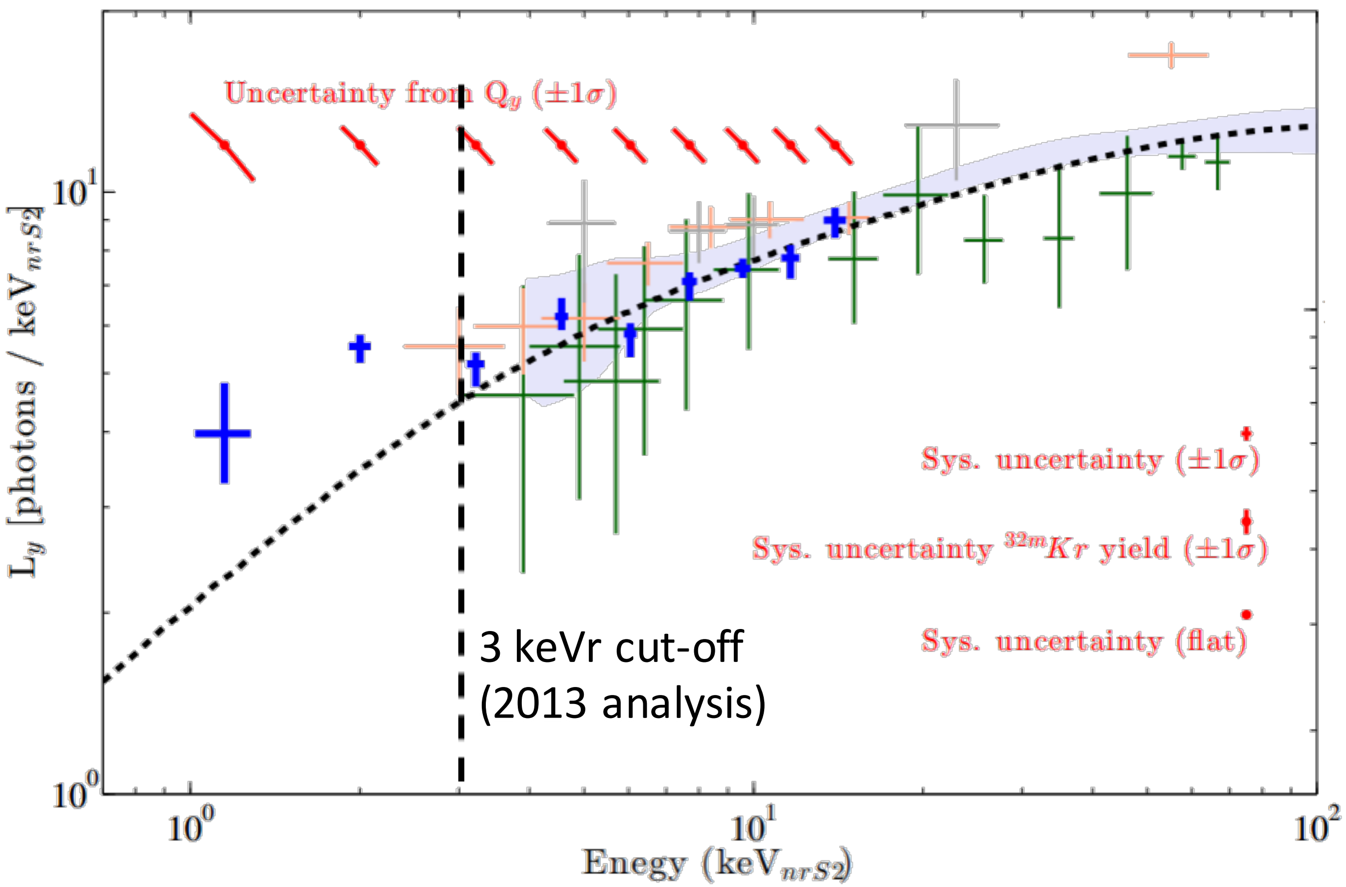
Charge yield

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



Light yield

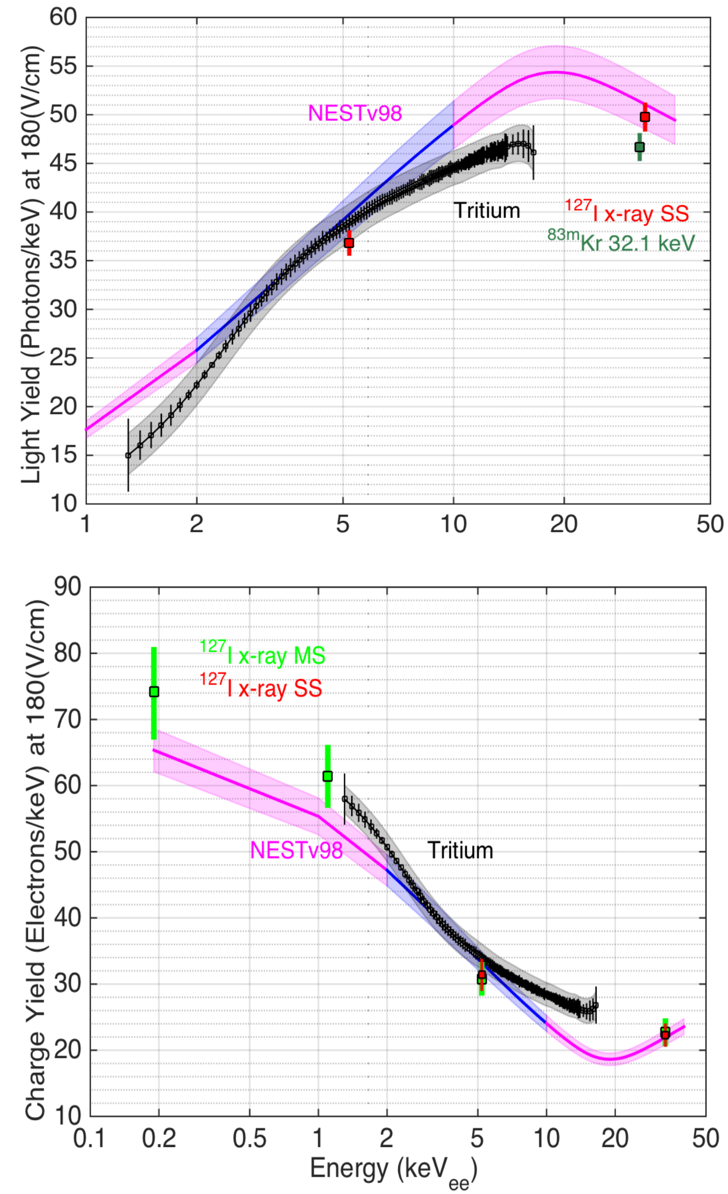
2. L_Y: linearity between deposited energy and scintillation signal. Measured down to 1.2 keVnr



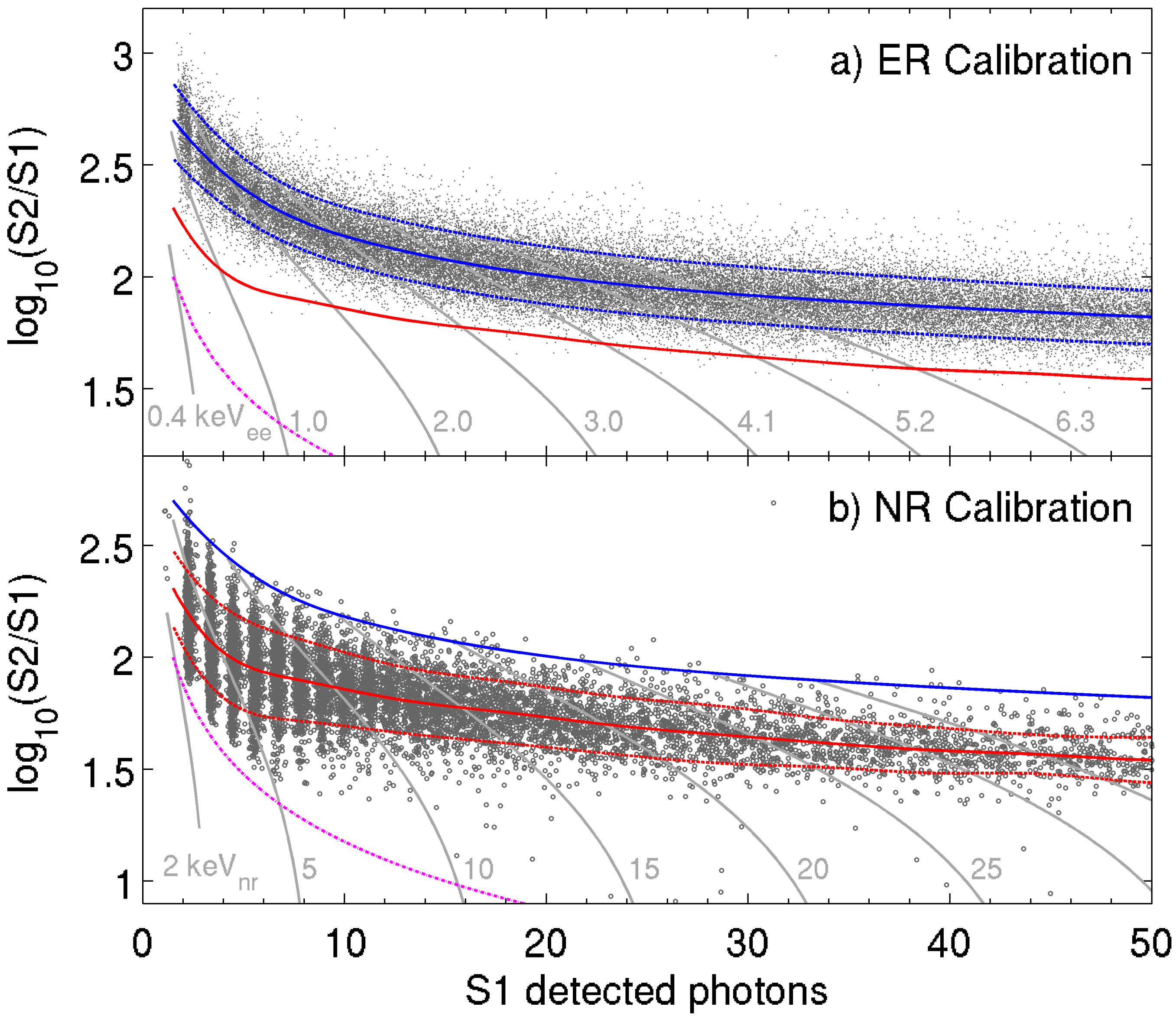
Electron Recoil events

New detector response calibration for ER: **CH_3T 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

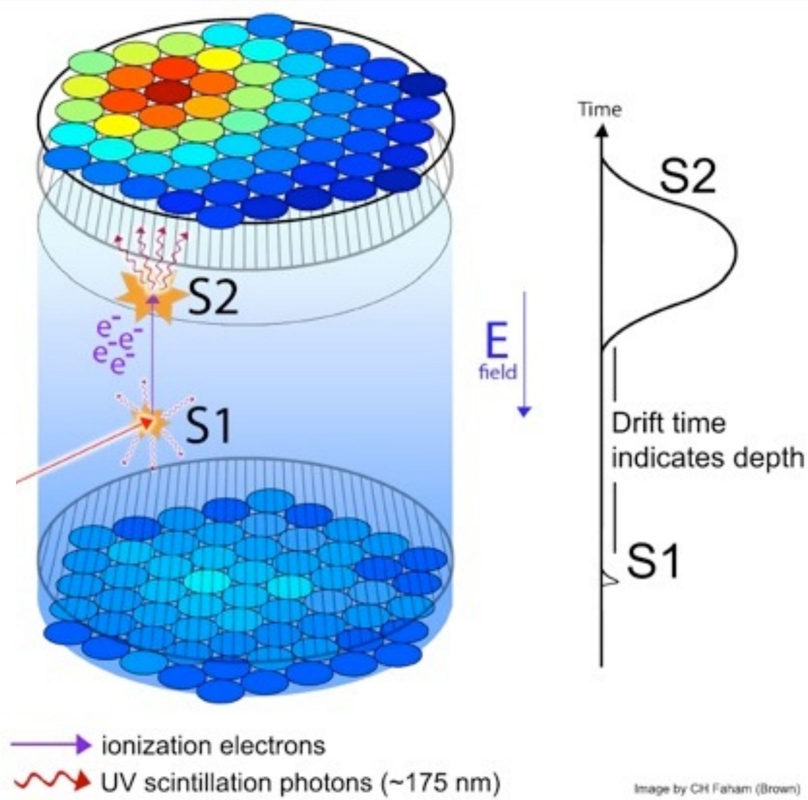
2. **Axion-like particles** (~keV):
   - S1+S2 exploiting new ER calibration data

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

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

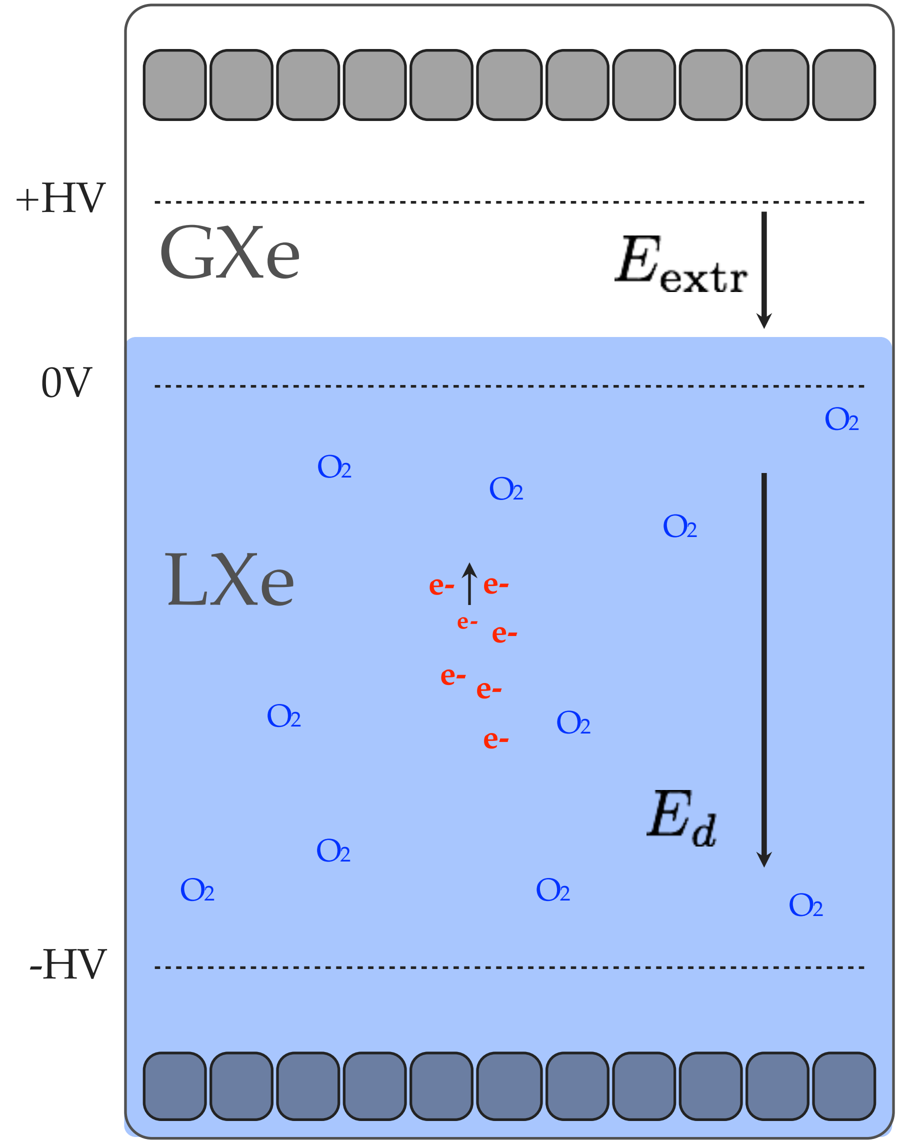
S2-only

- 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.



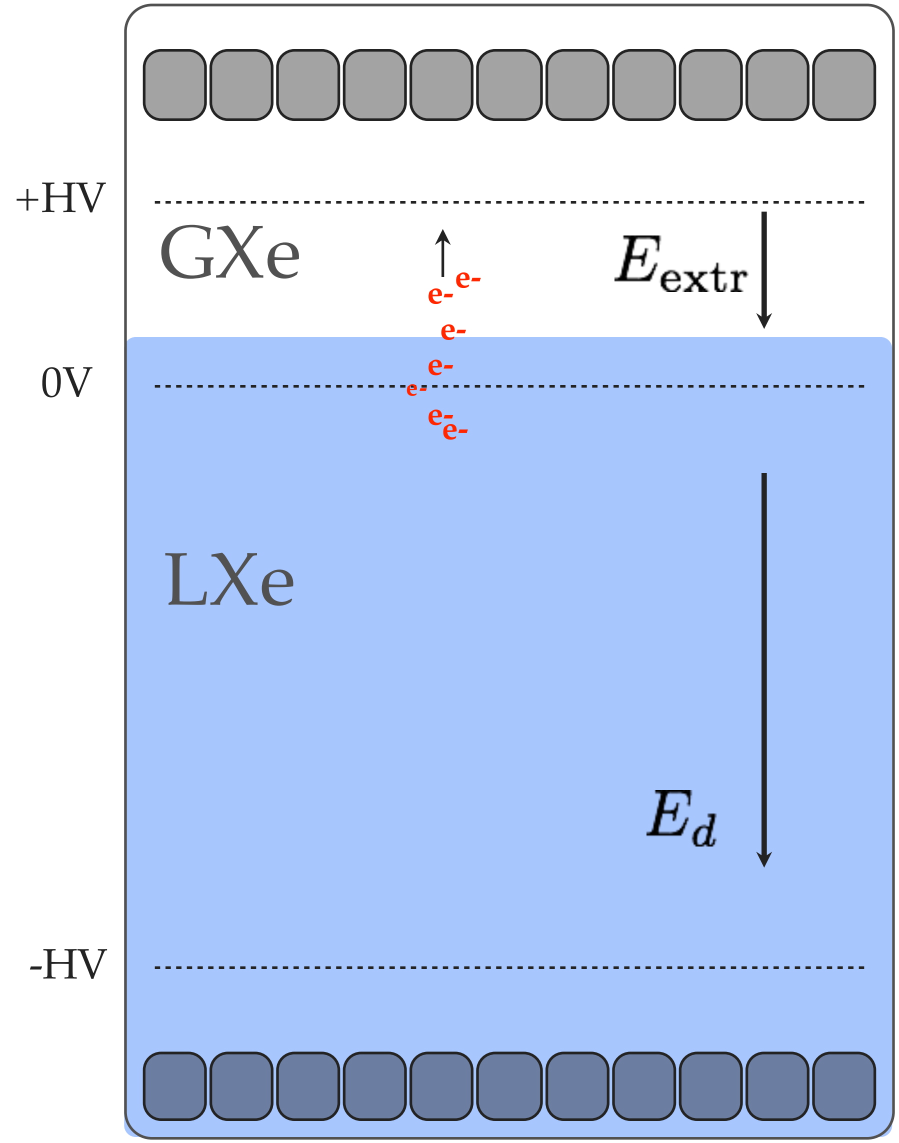
Charge lost in the LXe

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



Charge lost in the extraction

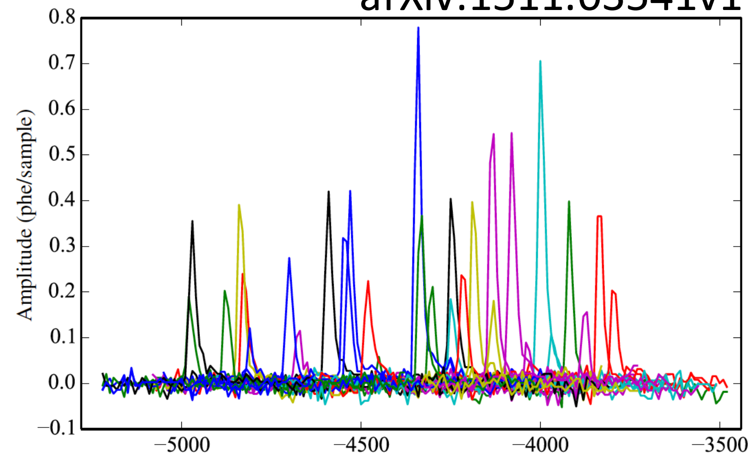
Experiment	Electron extraction efficiency
XENON10	~100%
XENON100	~100%
LUX	~50%

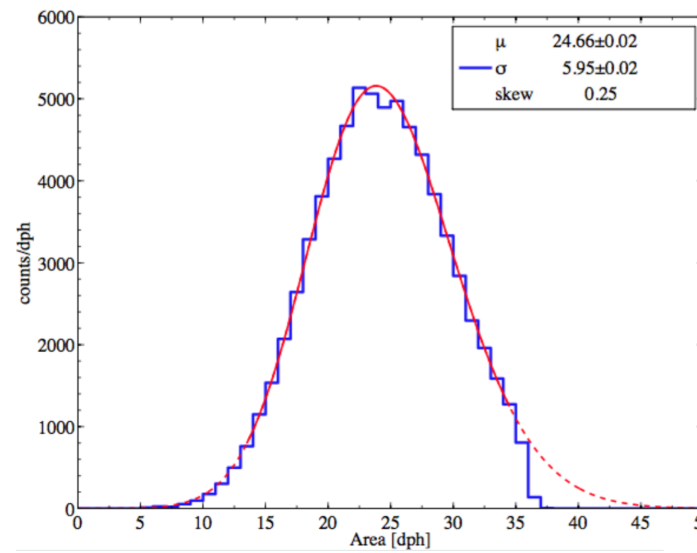


Single electron events

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

arXiv:1511.03541v1

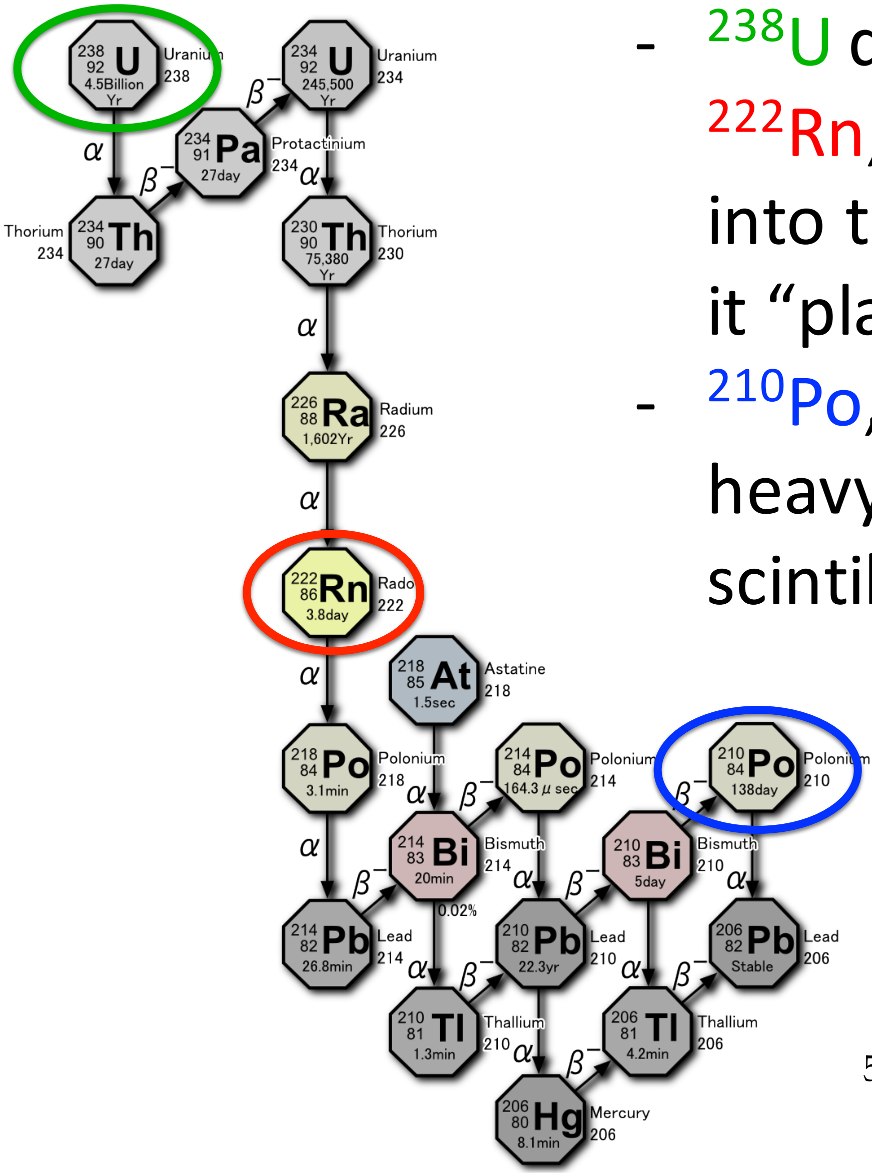




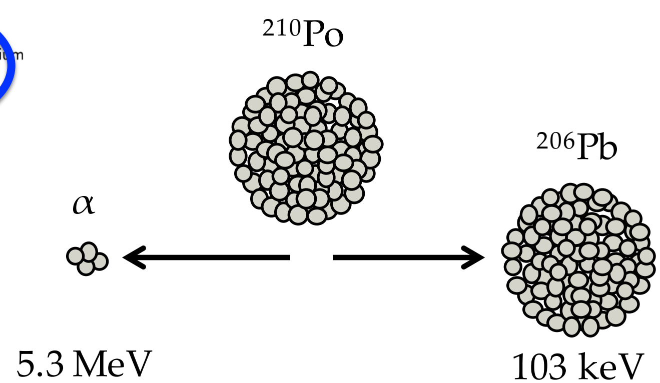
Single-e process very difficult to model

- Photoionization after S1/S2: grids ionization, bulk ionization…
- Trapped S2 electrons (e- trains)
- Field emission single-e

Surface background



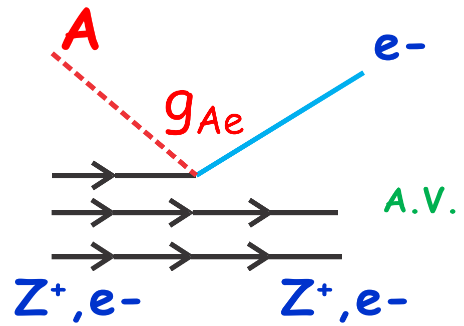
- ^{238}U decay chain takes it through ^{222}Rn, which is a noble gas, can diffuse into the air and get everywhere. Then it "plate out" once it decays
- ^{210}Po, is problematic: low energy, heavy projectile, gives small scintillation and ionisation signals



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)

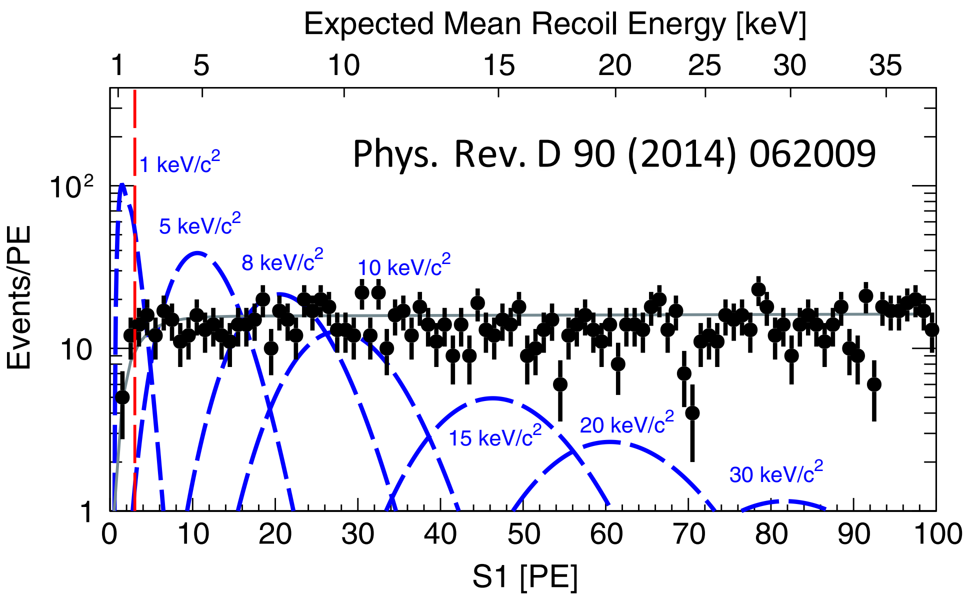
$$\sigma_{Ae} = \sigma_{pe}(E_A) \frac{{g_{Ae}}^2}{\beta_A} \frac{3{E_A}^2}{16\pi\,\alpha_{em}\,{m_e}^2}\left(1 - \frac{\beta_A^{2/3}}{3}\right)$$

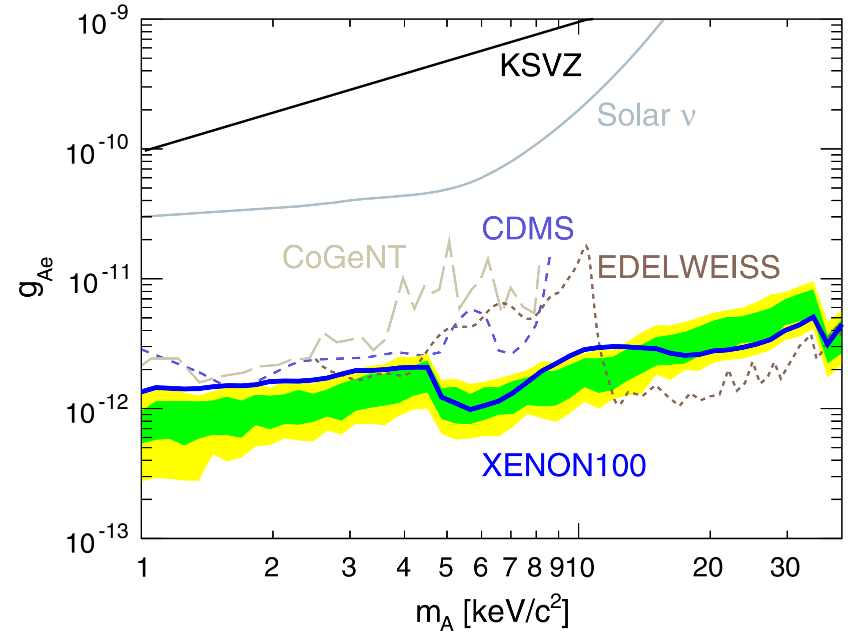


- Invisible axions, could solve the the QCD Charge-Parity Violation problem
- Axion-Like Particles from extension of the Standard Model, could also be Dark Matter particle candidate

Phys. Rev. D 35, 2752 (1987),
Nucl. Rev. D 78, 115012 (2008), Phys. Rev. D 82, 065006 (2010).

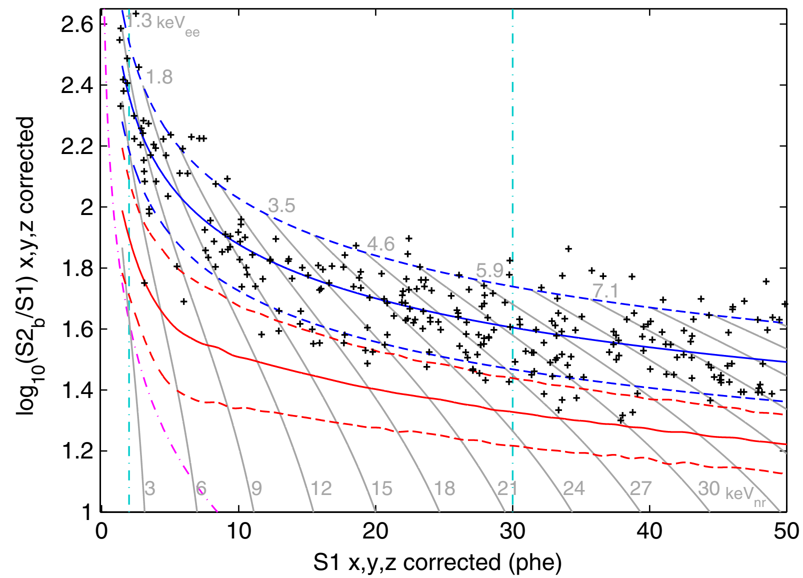
keV axion-like particles





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

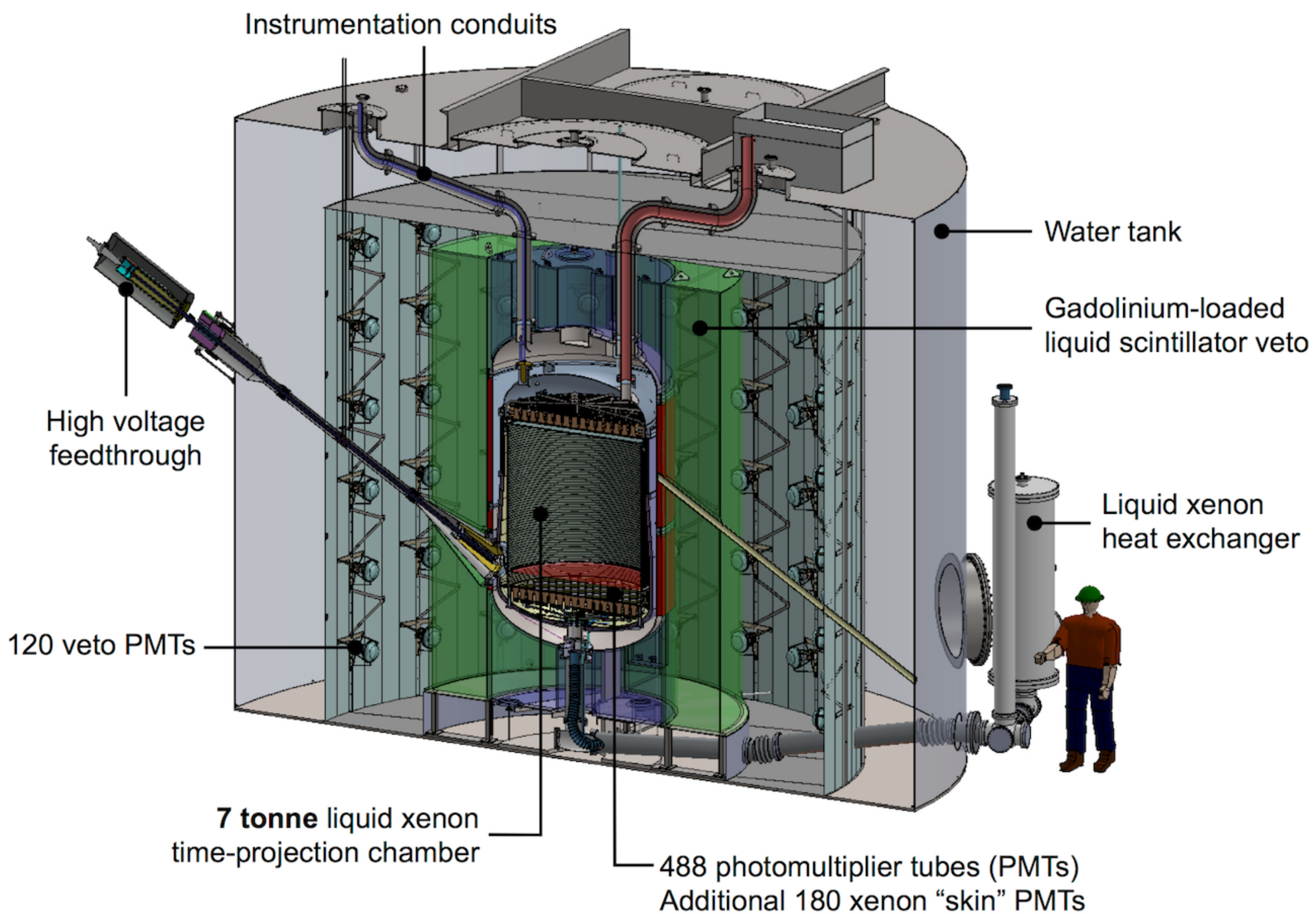
- LUX re-analysis coming out soon. Currently collecting data for the 300-day run
- Several DM papers in the pipeline
- Ionisation-only searches and/or electronic recoil events are good at targeting light DM candidates
- Key advantage of LUX:
  - low background
  - great energy resolution
- Several groups 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

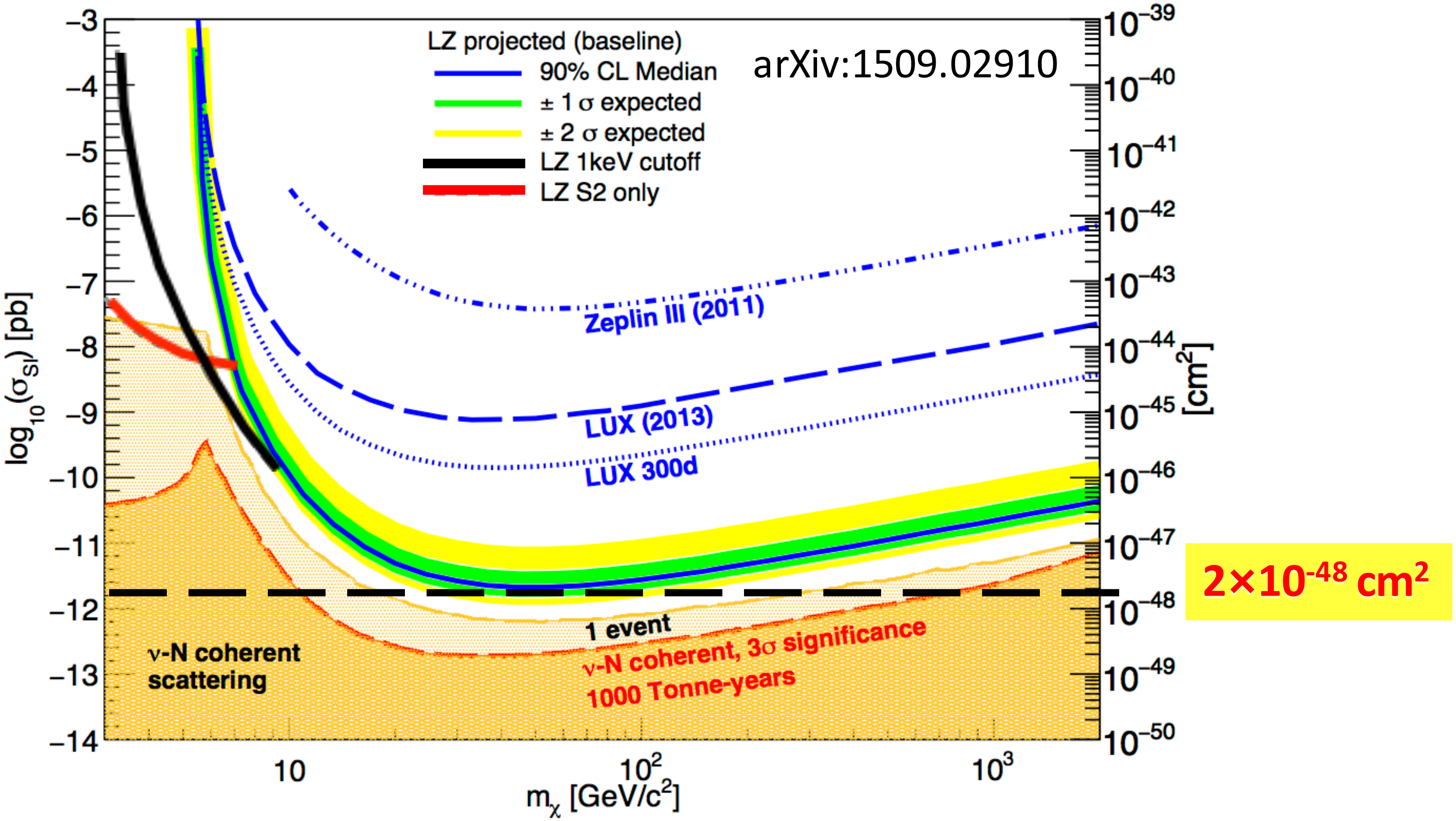
Year	Month	Activity
2012	March	LZ (LUX-ZEPLIN) collaboration formed
	May	First Collaboration Meeting
	September	DOE CD-0 for G2 dark matter experiments
2013	November	LZ R&D report submitted
2014	July	LZ Project selected in US and UK
2015	April	DOE CD-1/3a approval, similar in UK Begin long-lead procurements (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



WIMP

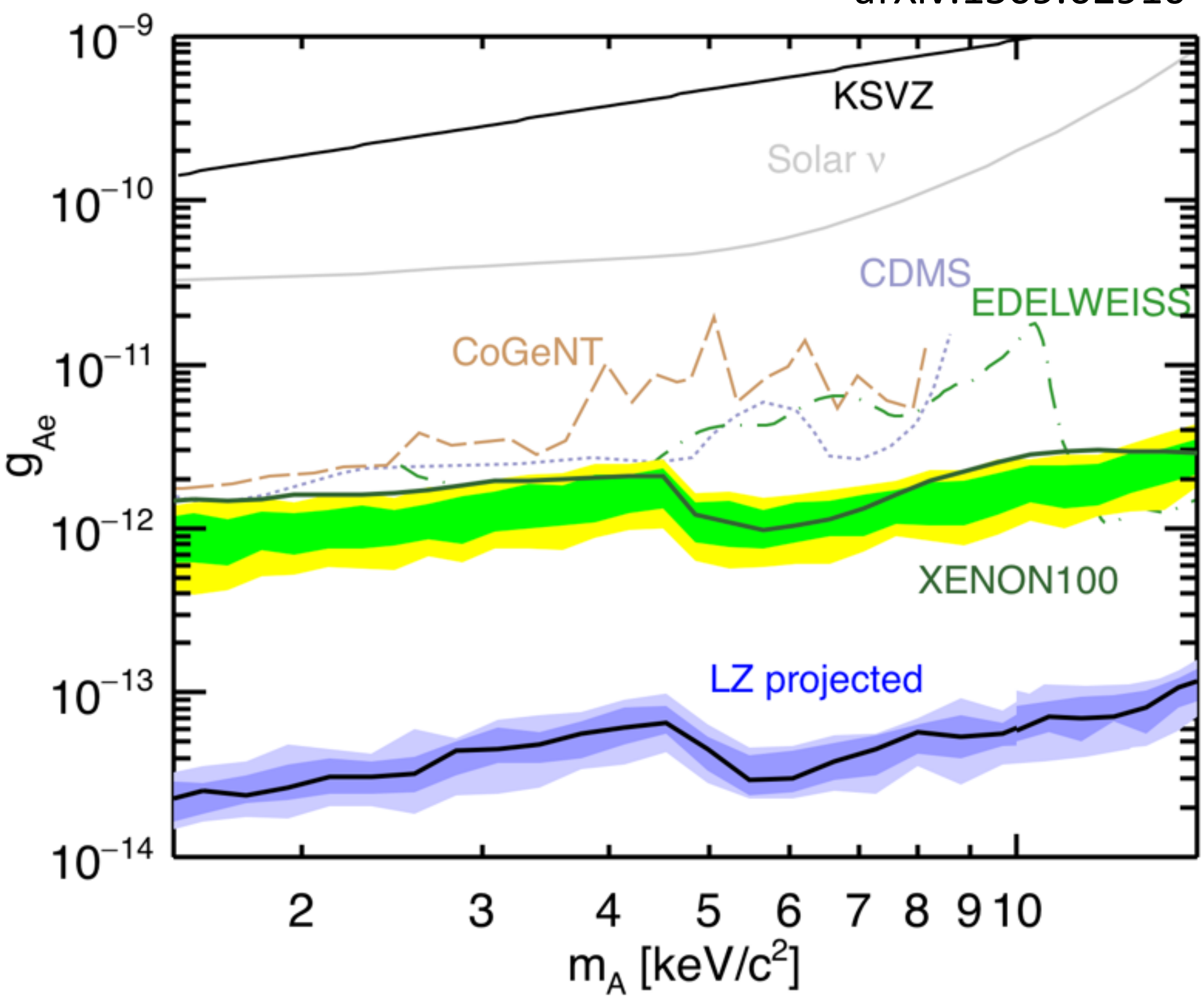
- S1+S2 WIMP SI sensitivity: 2×10^{-48} cm^2: 5.6t x 1000d
- Lower energy threshold: 1 keV
- S2-only: 2.5 e^- (100 photons detected), 1t x 1000d



Axion-like particles

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

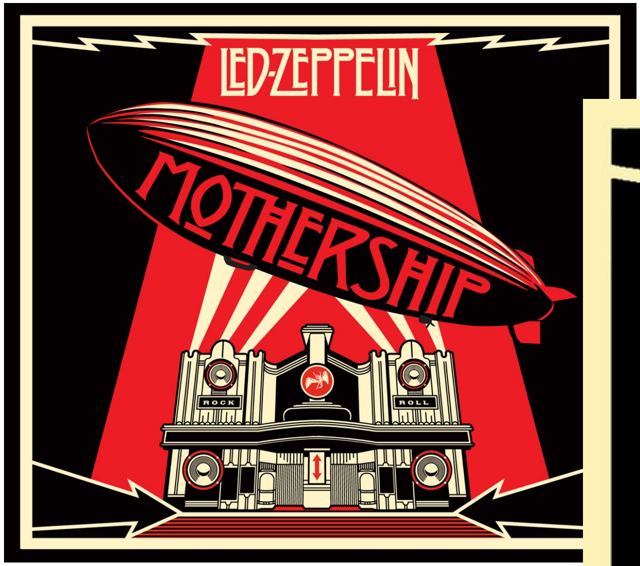
arXiv:1509.02910



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: 2×10^{-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



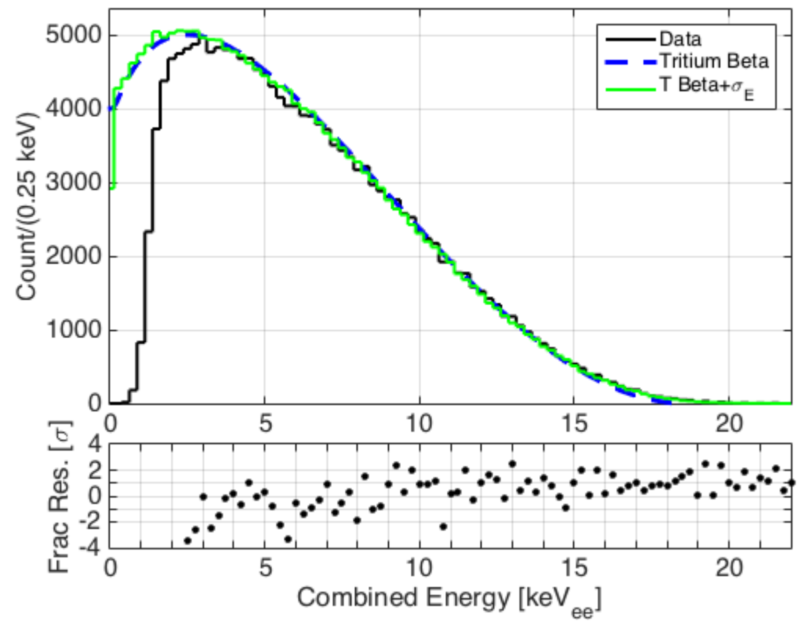
BACKUP

ER calibration

New detector response calibration for ER: CH_3T injection

- Homogeneous β source with Q = 18 keV
- Removal with τ < 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

$$\frac{\mathrm{E}}{\mathrm{W}} = \mathrm{n}_\gamma + \mathrm{n}_\mathrm{e} = \frac{\mathrm{S1}}{\mathrm{g_1}} + \frac{\mathrm{S2}}{\mathrm{g_2}}$$

W = 13.7 x 10^{-3} keVee

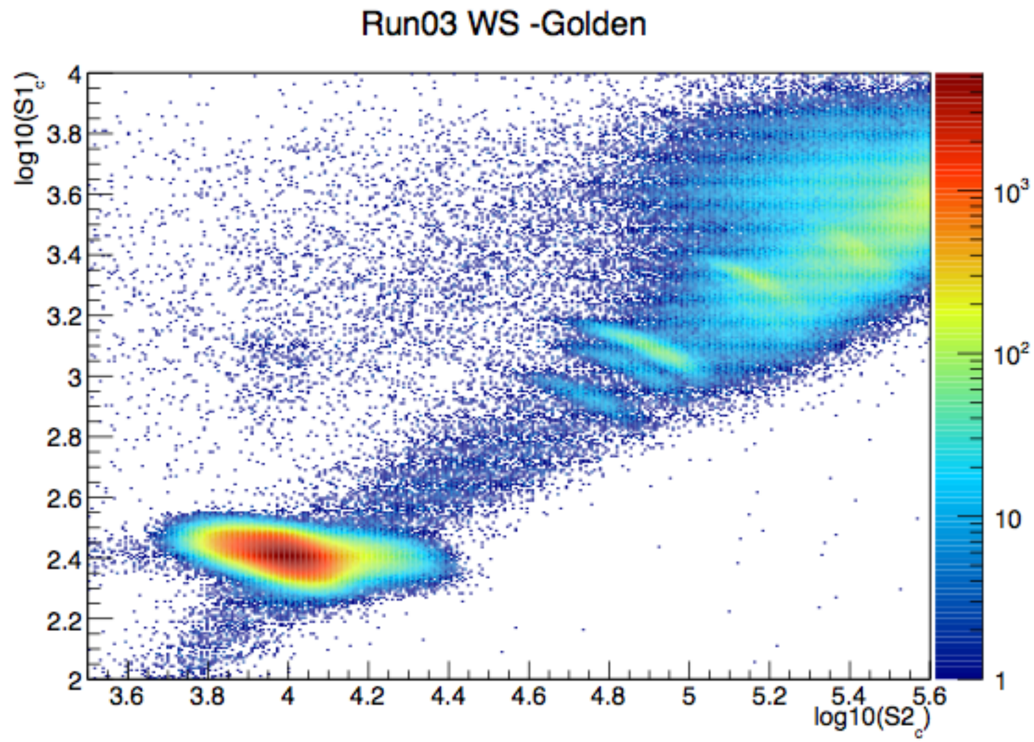
- g_1: accounts for both geometric light collection and the QEs of the PMTs

  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

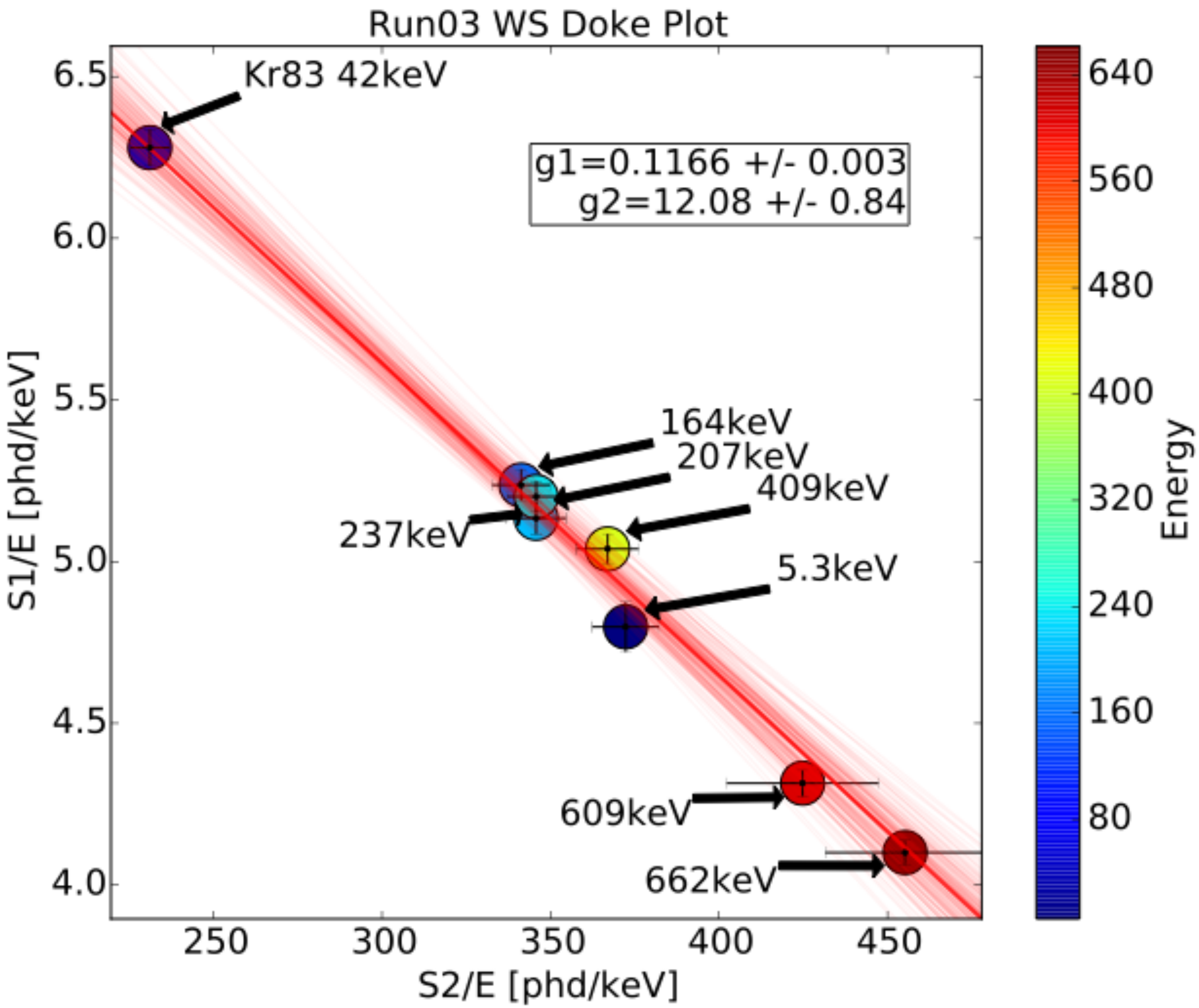
Source	Energy [keV]	Decay Type
Xe K shell	*29.7, 34*	*X-ray*
83m Kr	*41.55*	*Internal Conversion*
131 Xe	*163.9*	*Internal Conversion*
127 Xe	*203 or 375*	*γ -emission*
127 Xe	*33.8*	*Kb shell X-ray*
127 Xe	*5.3*	*L shell X-ray*
129m Xe	*236.1*	*Internal Conversion*
214 Bi	*609*	*γ -emission*
137 Cs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



$$\langle n_\gamma \rangle = \frac{\langle S1 \rangle}{g_1} \quad S1/E = \frac{n_\gamma}{(n_\gamma + n_e)} \times \frac{g1}{W}$$

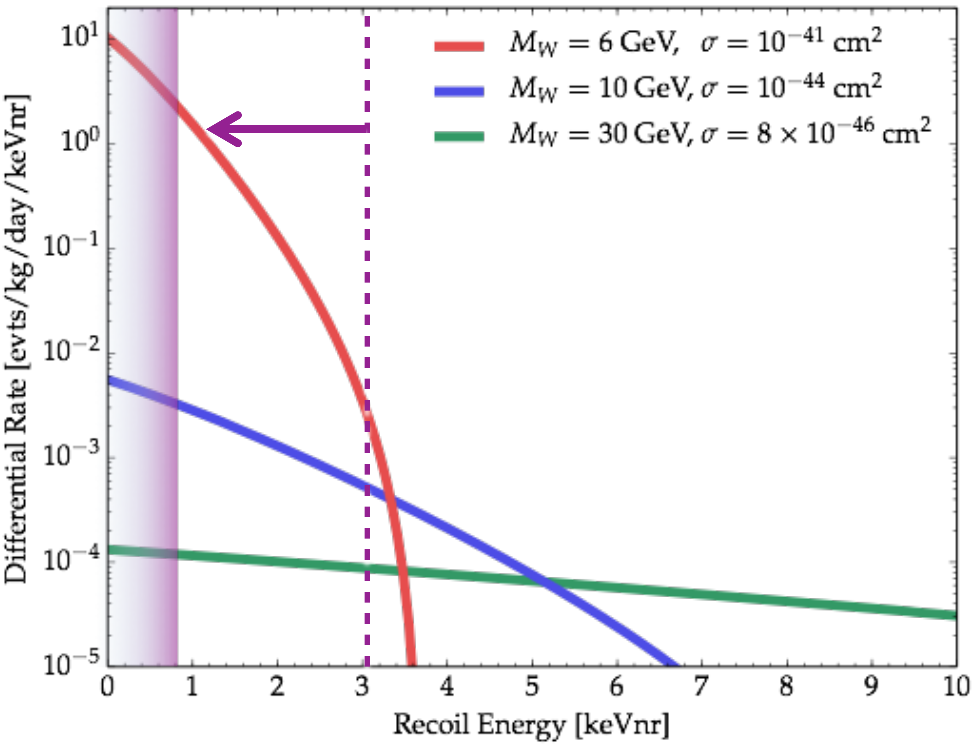
$$\langle n_e \rangle = \frac{\langle S2 \rangle}{g_2} \quad S2/E = \frac{n_e}{(n_\gamma + n_e)} \times \frac{g2}{W}$$

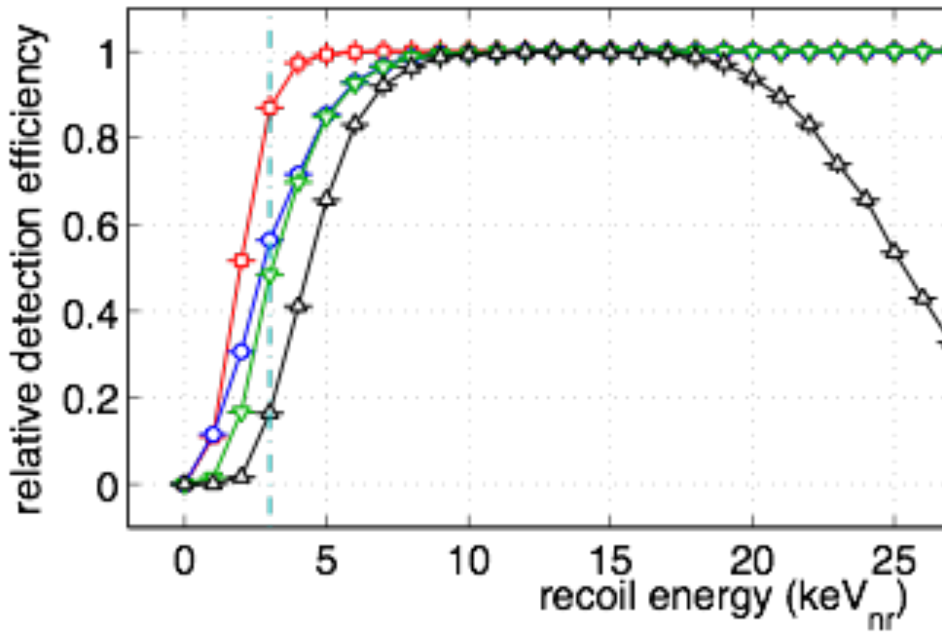
Doke Plot



Run03 WS Doke Plot
g1=0.1166 +/- 0.003
g2=12.08 +/- 0.84
Kr83 42keV
164keV
207keV
409keV
237keV
5.3keV
609keV
662keV
S1/E [phd/keV]
S2/E [phd/keV]
6.5
6.0
5.5
5.0
4.5
4.0
250
300
350
400
450
Energy
640
560
480
400
320
240
160
80

Impact on WIMP

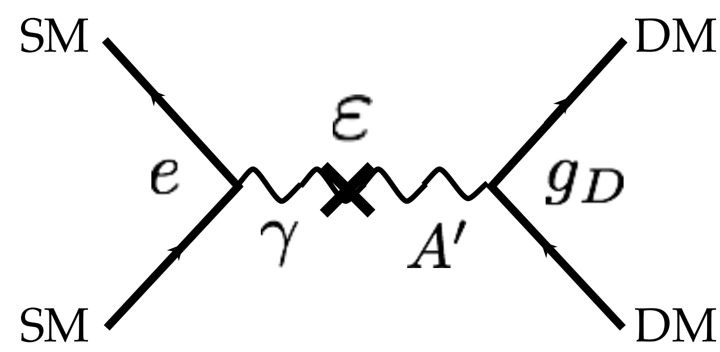


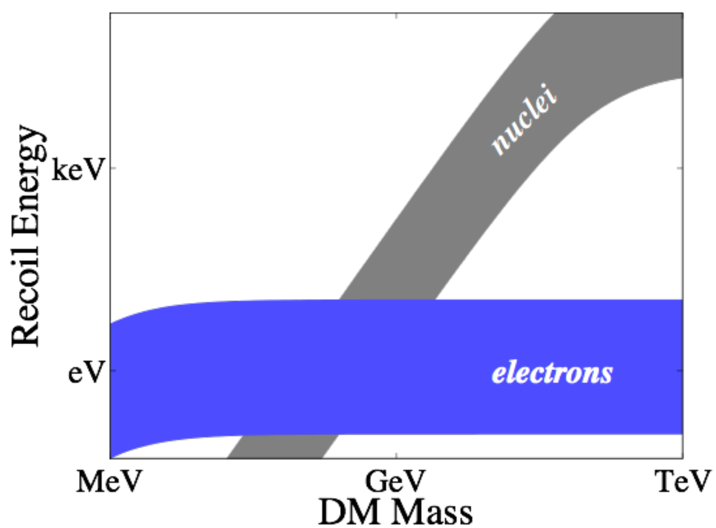


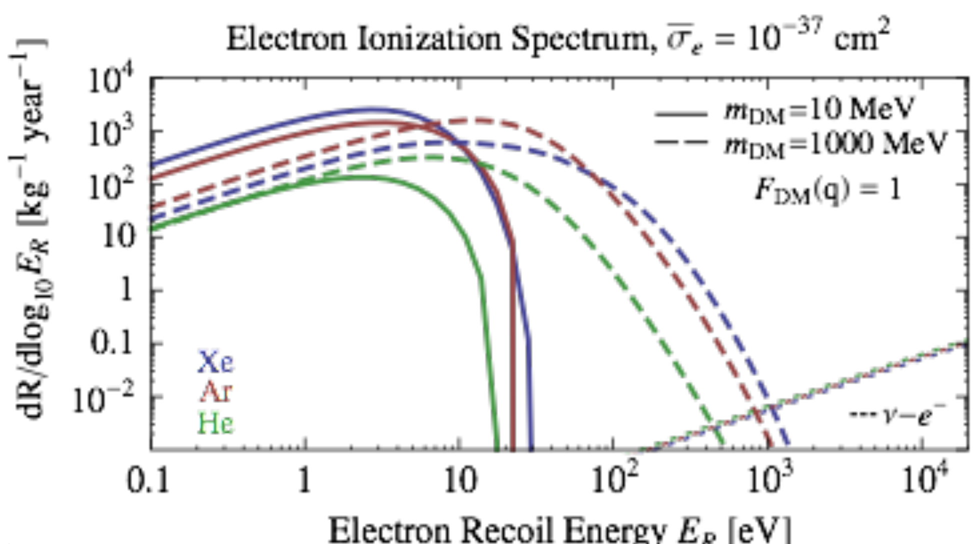
Ionization efficiency, assuming ~4-electron threshold

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.

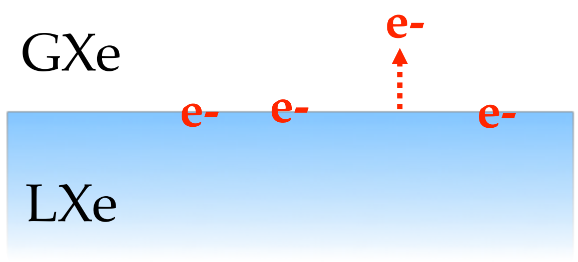




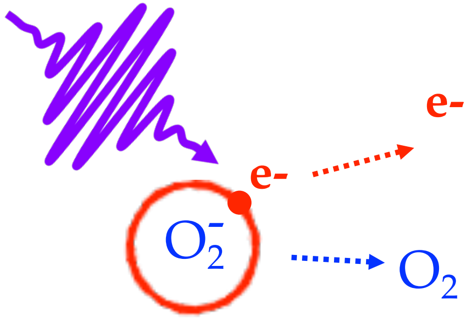


Single electron processes

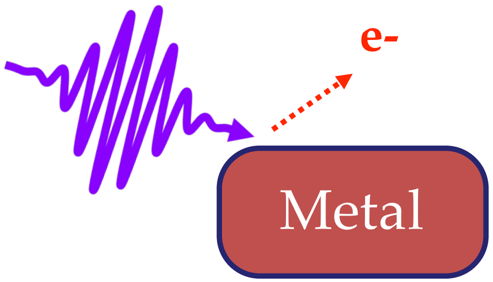
- The electrons see a potential barrier at the surface and can get trapped there, to later “evaporate” off



- 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

arXiv:1509.02910

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