Dark matter searches with the LUX experiment

PATRAS 2015
Zaragoza, 22June 2015

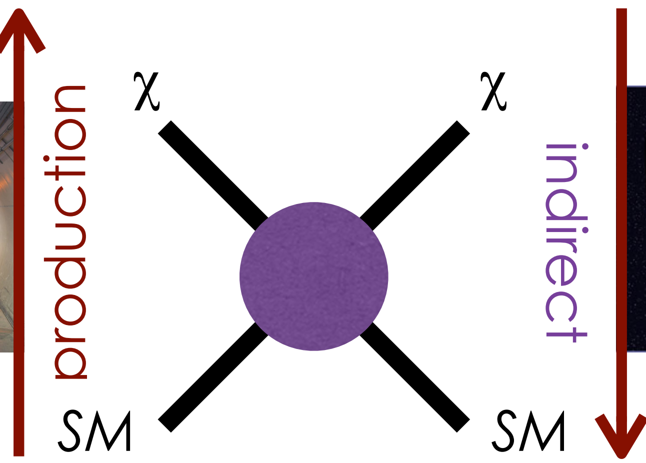
Paolo Beltrame
(on behalf of the LUX collaboration)

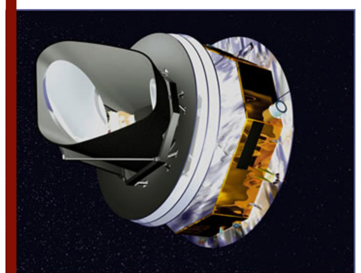
Direct DM search with LUX (a "reminder")

Status and preparation of new results

A taste of wider searches in LUX

Dark Matter detection





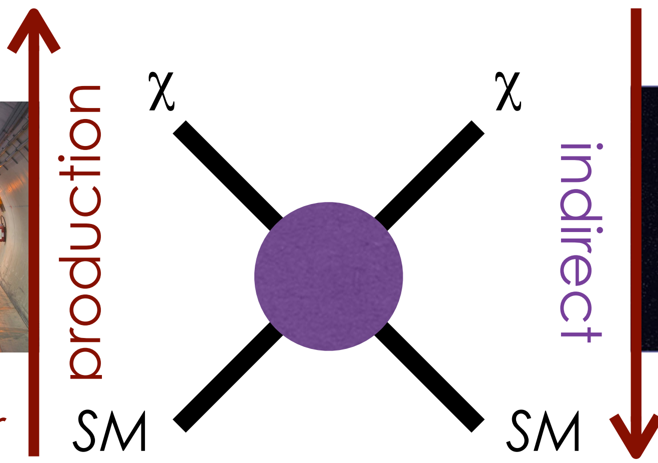
Indirect Detection
(DM annihilation)

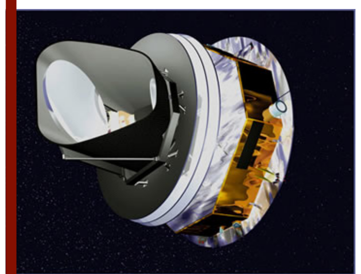
PAMELA, ANTARES, Fermi, IceCube, MAGIC, CTA, AMS, HESS

Accelerator Searches
(DM production)

LHC, ILC

Dark Matter detection





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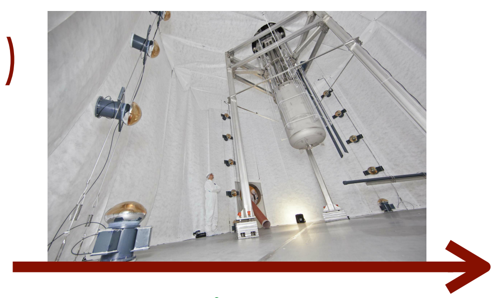
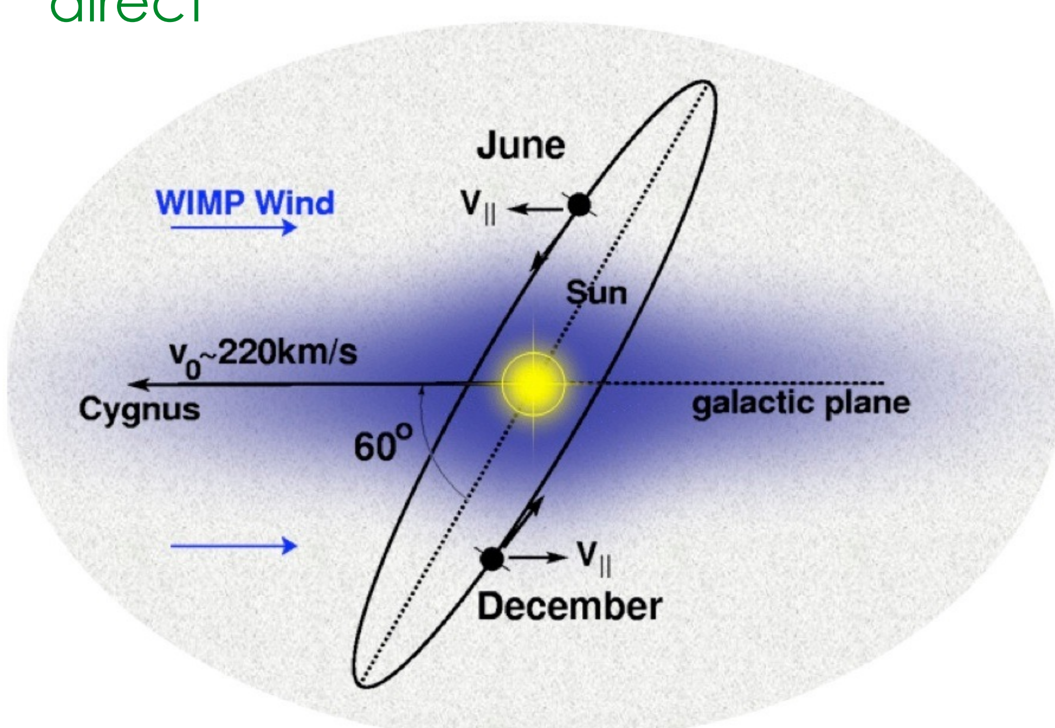


direct



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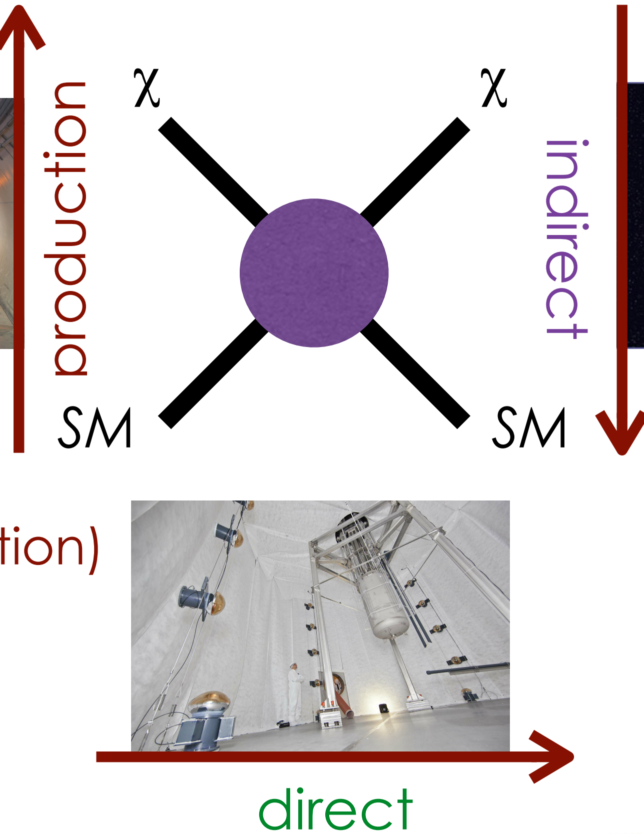

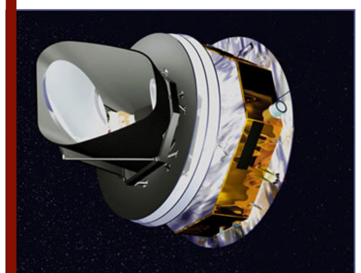

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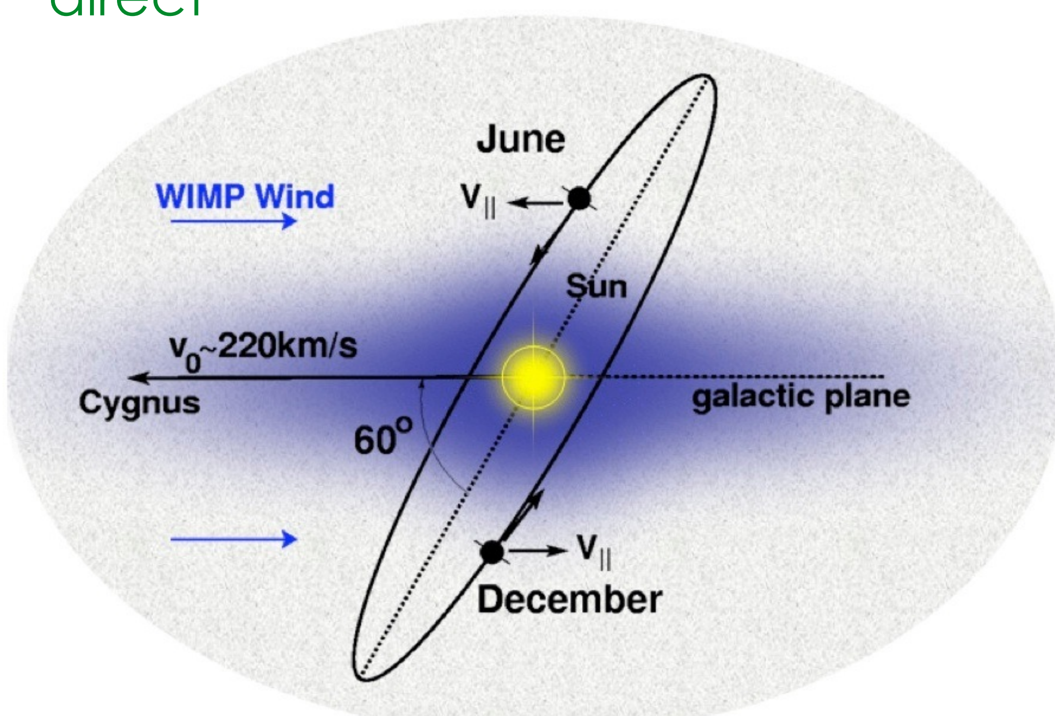
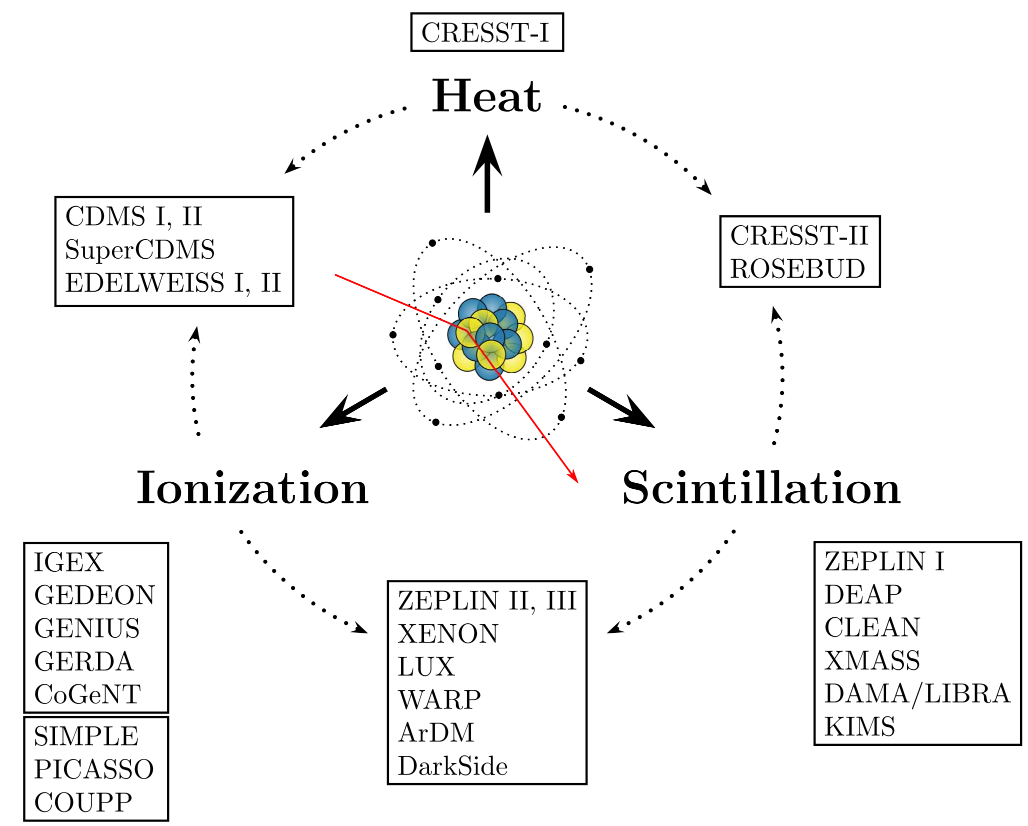


Signal in direct searches



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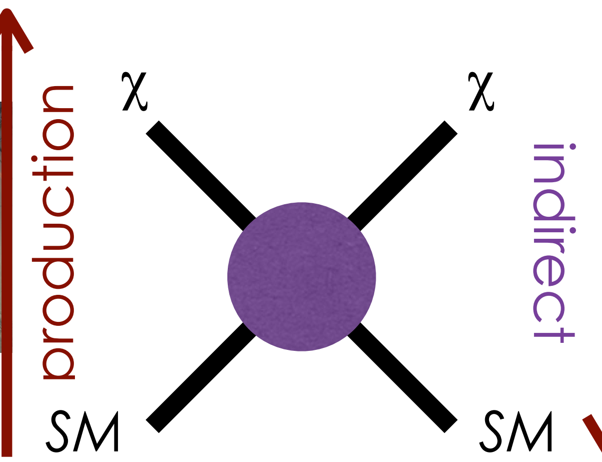

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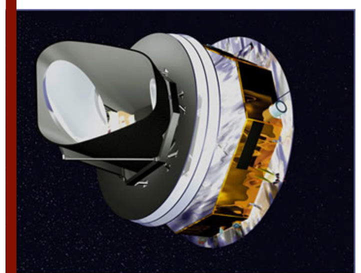

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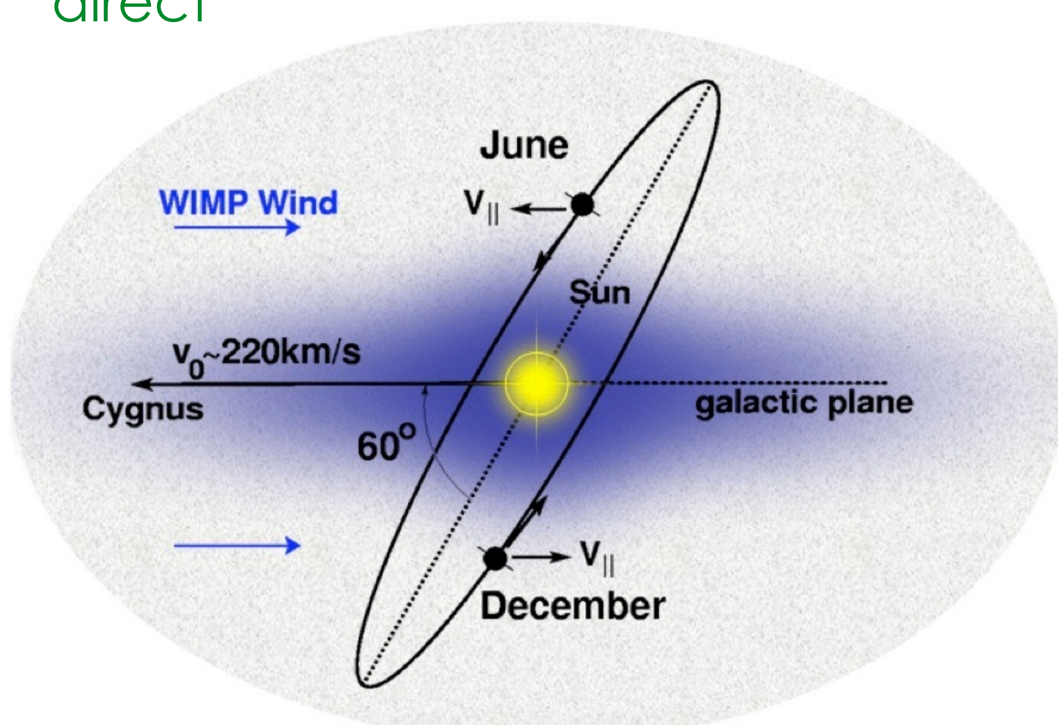

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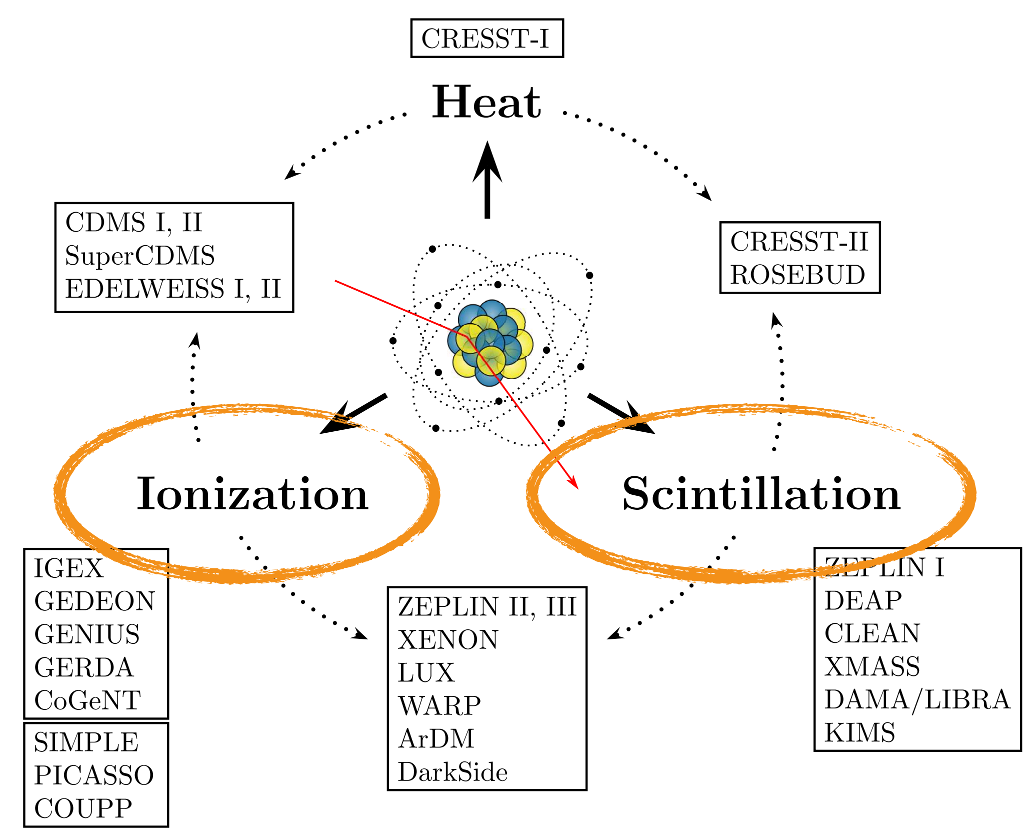


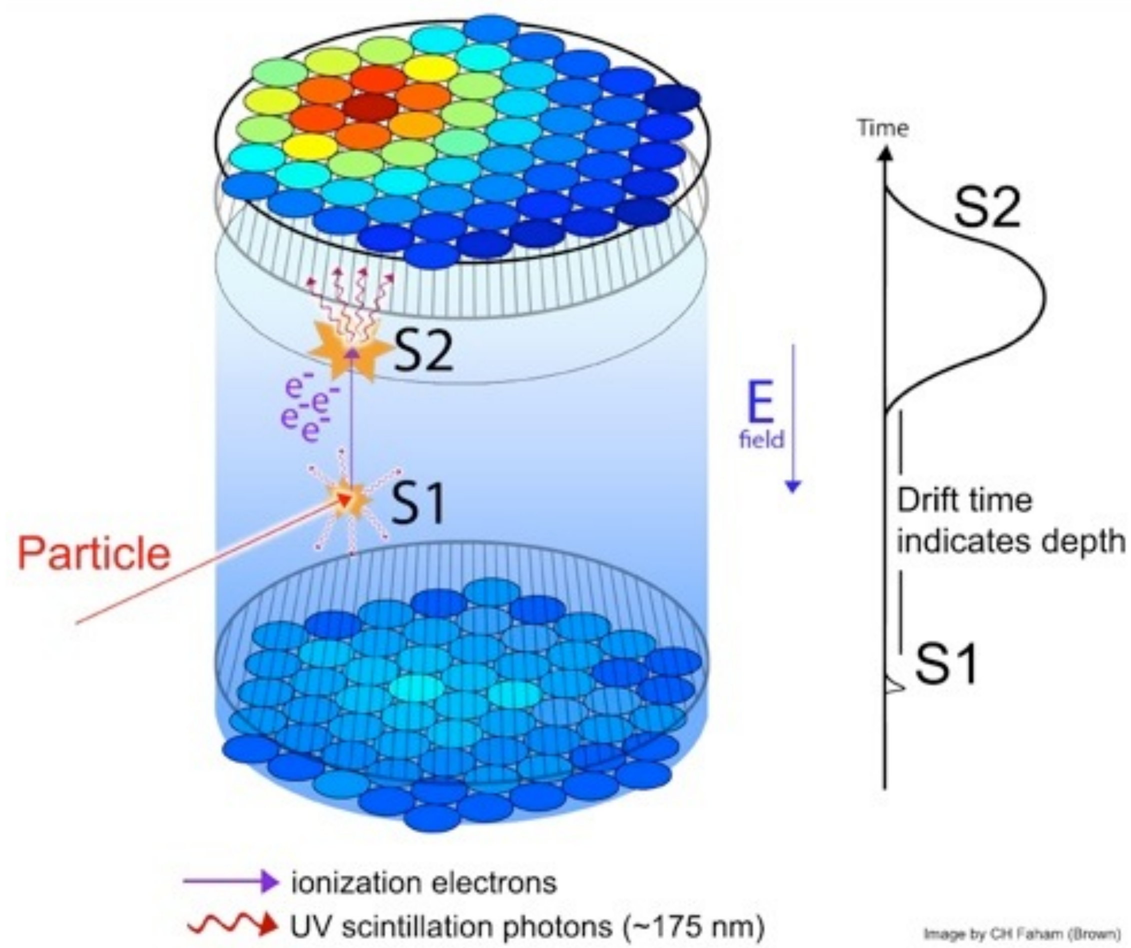
Dual-phase Xenon Time Projection Chamber

(Scintillation) **S1**: LXe is an excellent scintillator

- Density: 3 g/cm^3
- light yield: > 60 ph/keV (zero field)
- scintillator light: 178 nm
- nuclear recoil threshold: ~ 2 keV

(Ionisation) **S2**: LXe excellent ionisation detector

- S1 + S2 allows mm vertex reconstruction
- single ionisation electron capability
- nuclear recoil threshold: < 1 keV



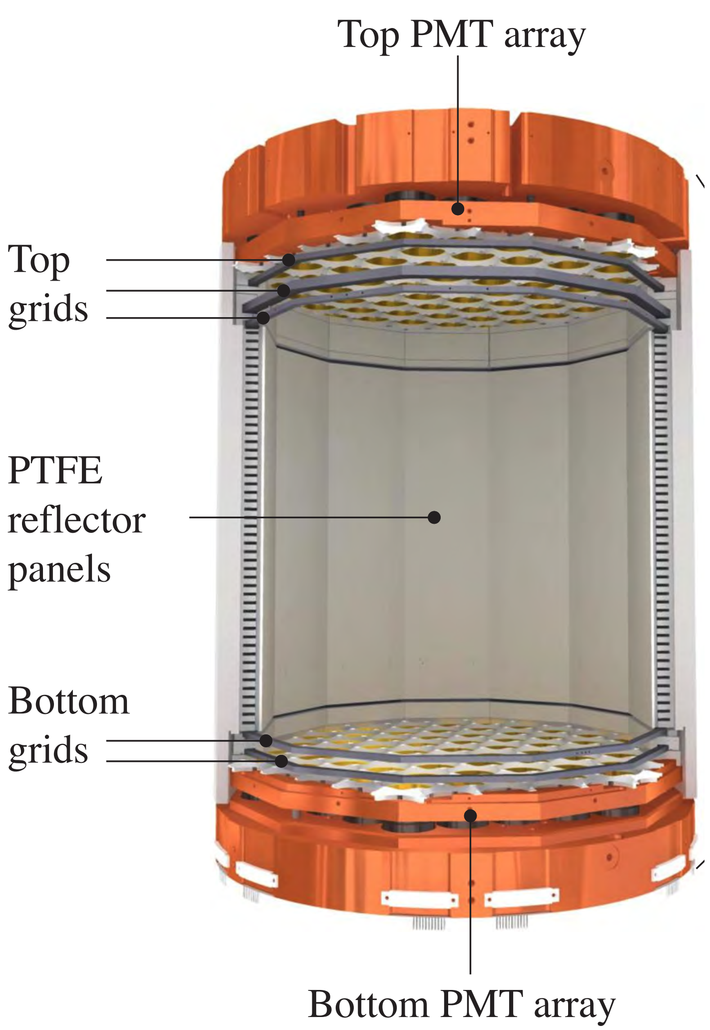
WIMP target:

- scalar WIMP-nucleon scattering $dR/dE \sim A^2$
- odd-neutron isotopes (^{129}Xe, ^{131}Xe) enable spin-dependent
- no damaging intrinsic background (^{127}Xe,$^{129m/131m}$Xe, ^{136}Xe, ^{85}Kr)
- light WIMP search search with low S2 threshold
- alternative searches

The LUX instrument

LUX (**L**arge **U**nderground **X**enon detector) is a dual-phase Xe TPC

- 250 kg of active LXe, 47 x 49 cm^2 TPC
- S1 and S2 read out by two arrays each of 61 ultra-pure PMTs
- Low background (Xe self shielding, low background materials, external water tank - Cherenkov μ detector)



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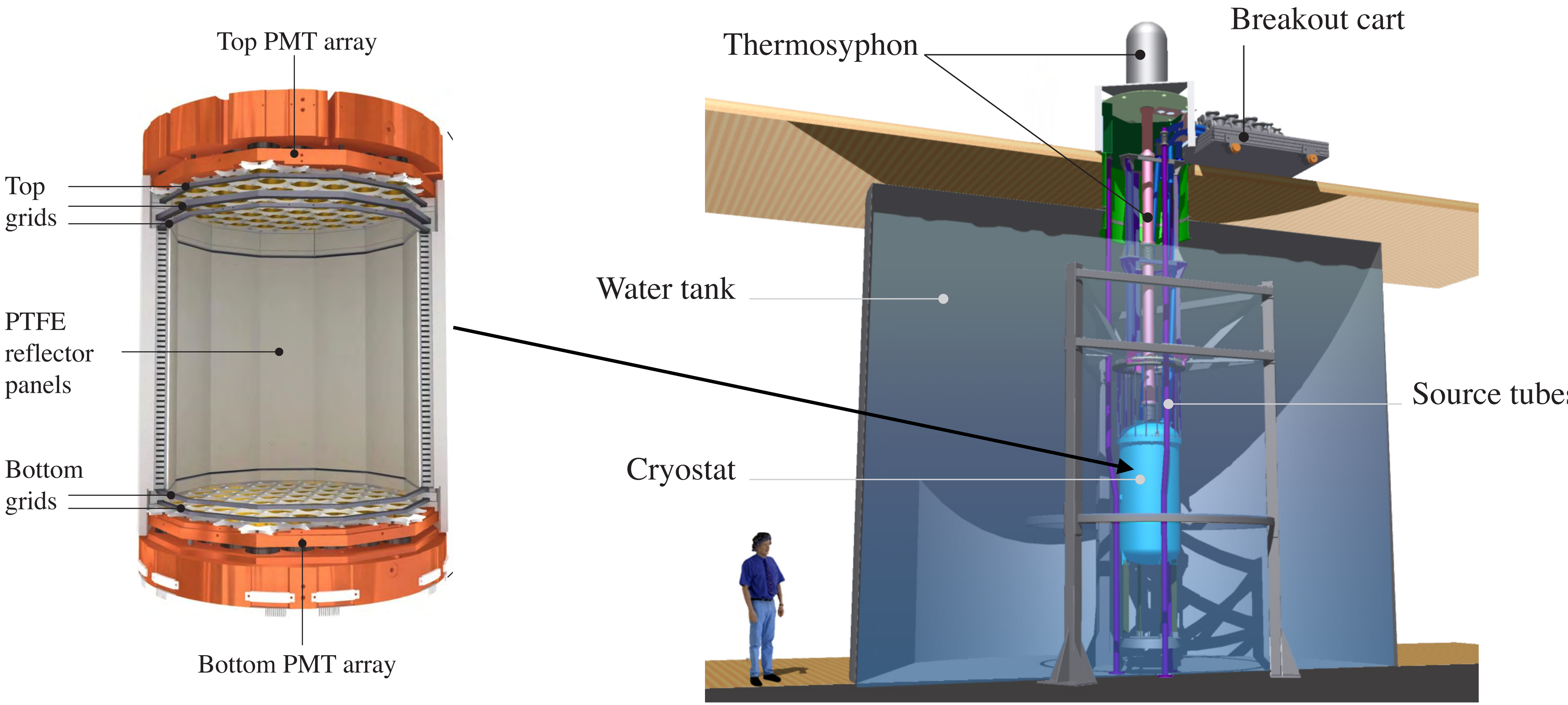

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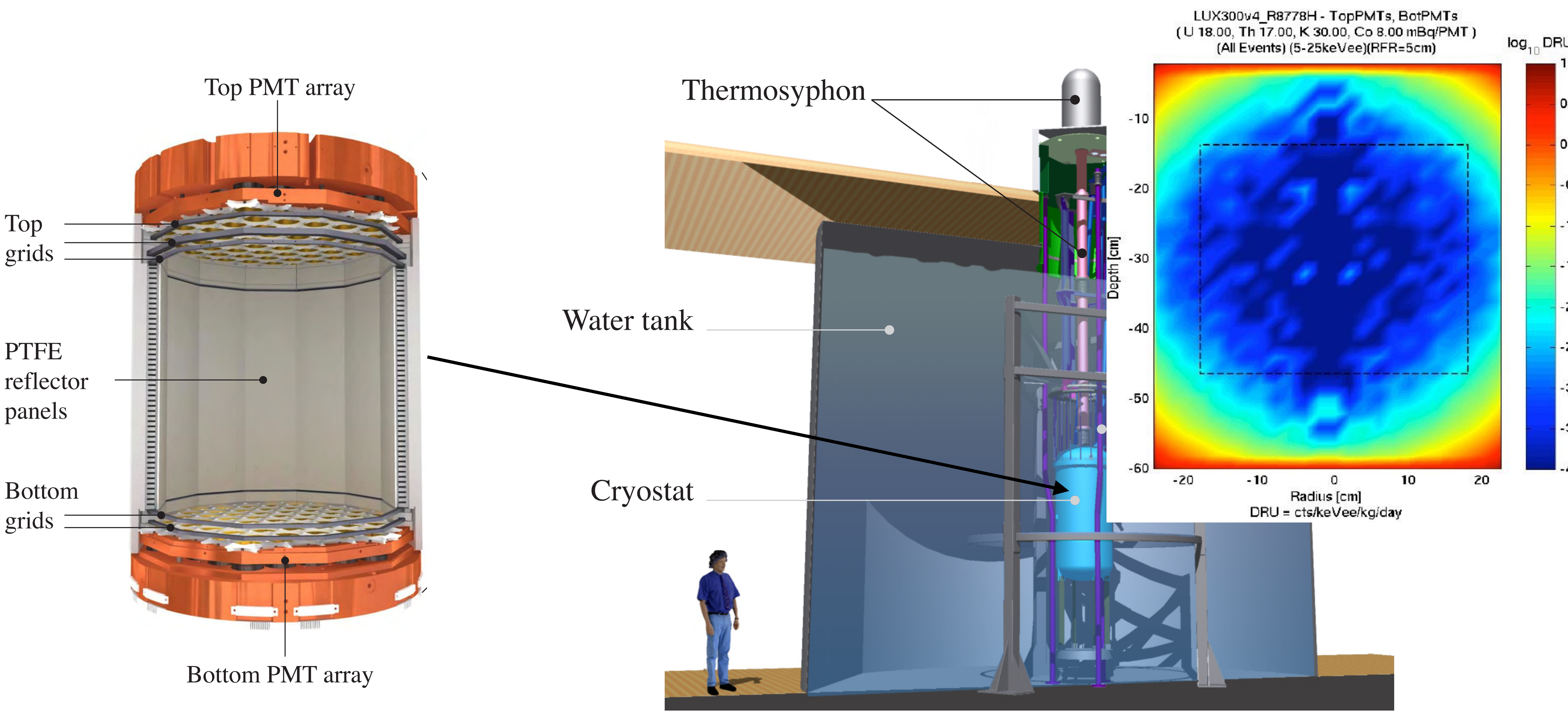
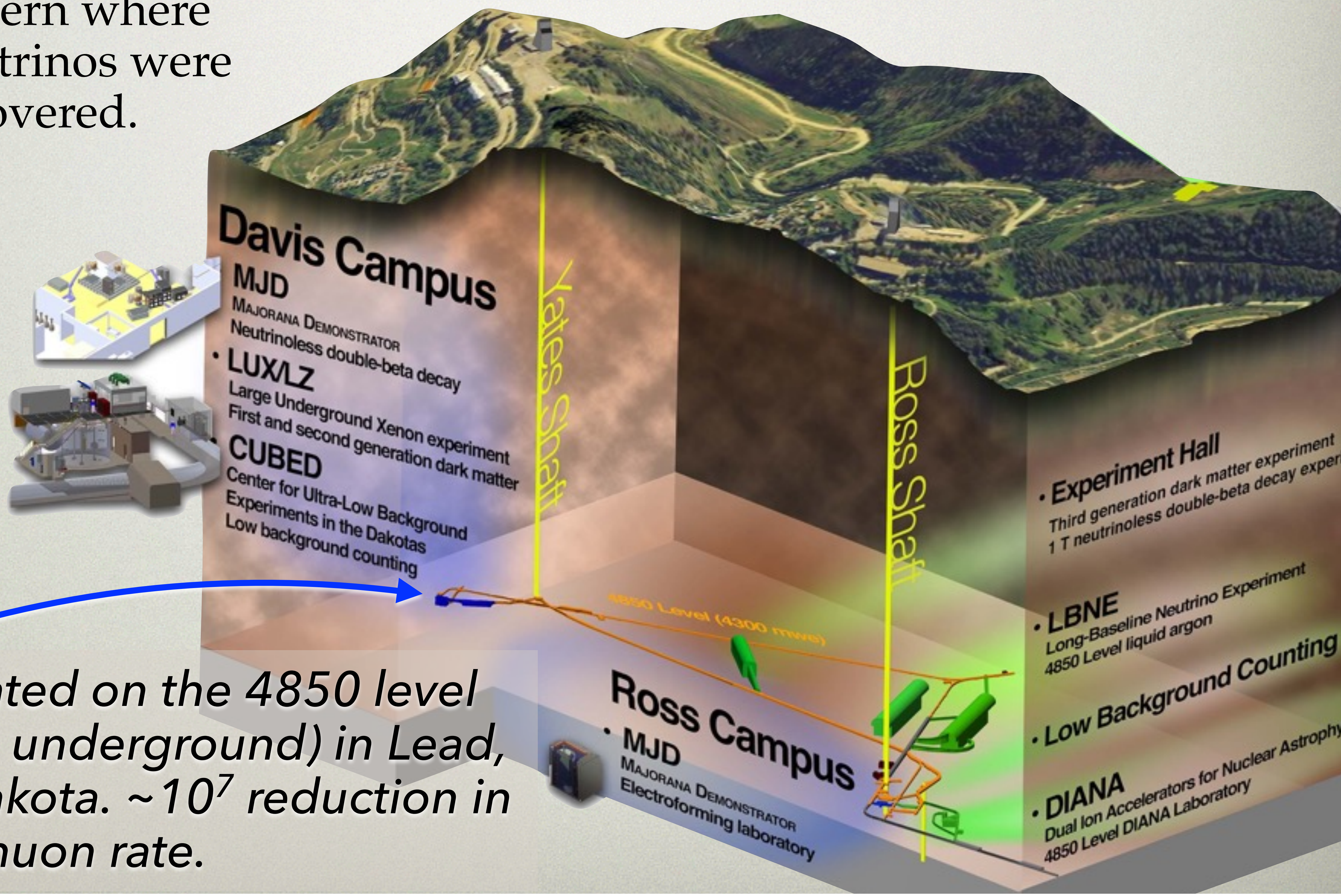


Same cavern where solar neutrinos were first discovered.



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

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

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Alastair Currie	Postdoc
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Khadeeja Yazdani	Graduate Student

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Kelsey Oliver-Mallory	Graduate Student

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Christina Ignarra	Research Associate
Wing To	Research Associate
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Wei Ji	Graduate Student
T.J. Whitis	Graduate Student

SD School of Mines

Xinhua Bai	PI, Professor
Doug Tiedt	Graduate Student

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Texas A&M

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Paul Terman	Graduate Student

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John Thmpson	Development Engineer
Dave Herner	Senior Machinist
Ray Gerhard	Electronics Engineer
Aaron Manalasay	Postdoc
Scott Stephenson	Postdoc
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Mike Witherell	Professor
Susanne Kyre	Engineer
Dean White	Engineer
Carmen Carmona	Postdoc
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Chris Chiller	Graduate Student

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Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
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Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
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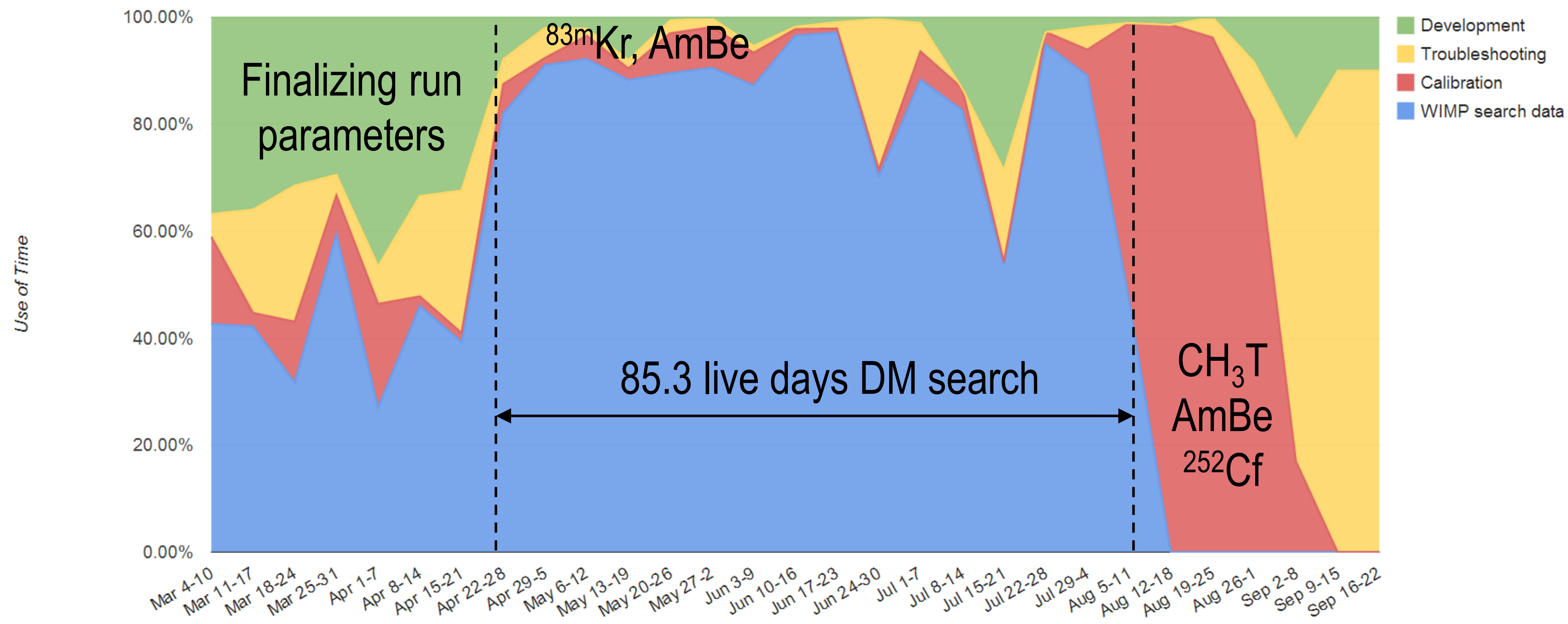


The LUX ‘Run 3’ results

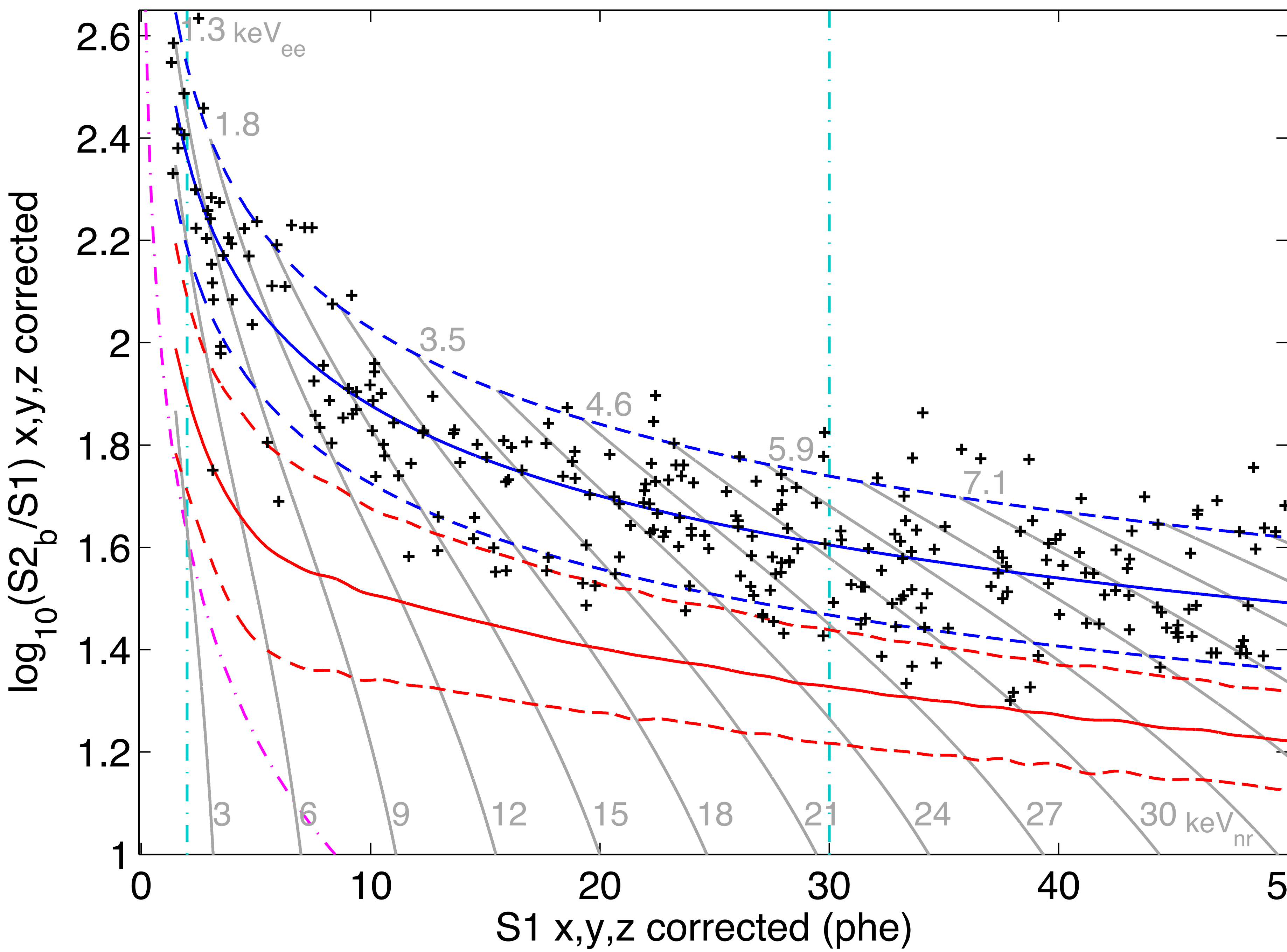
LUX underground in July 2012

Cooling down in January 2013, Xe condensed in February 2013

Kr and AmBe calibrations throughout, CH3T after WIMP searches

WIMP searches: 85.3 days - 118 kg

Events recorded in the Run 3 WIMP search data



(Light ~ Energy)

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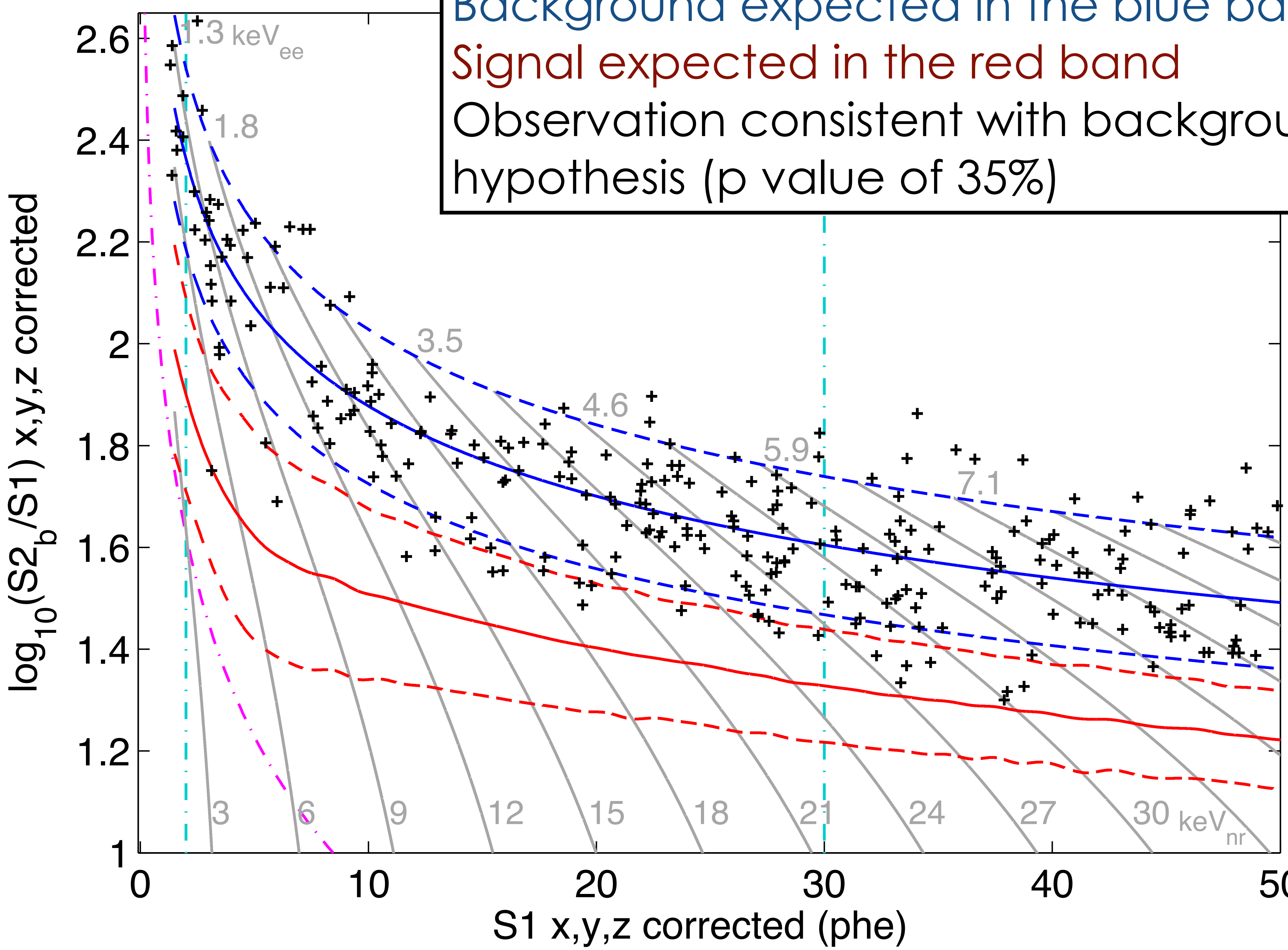


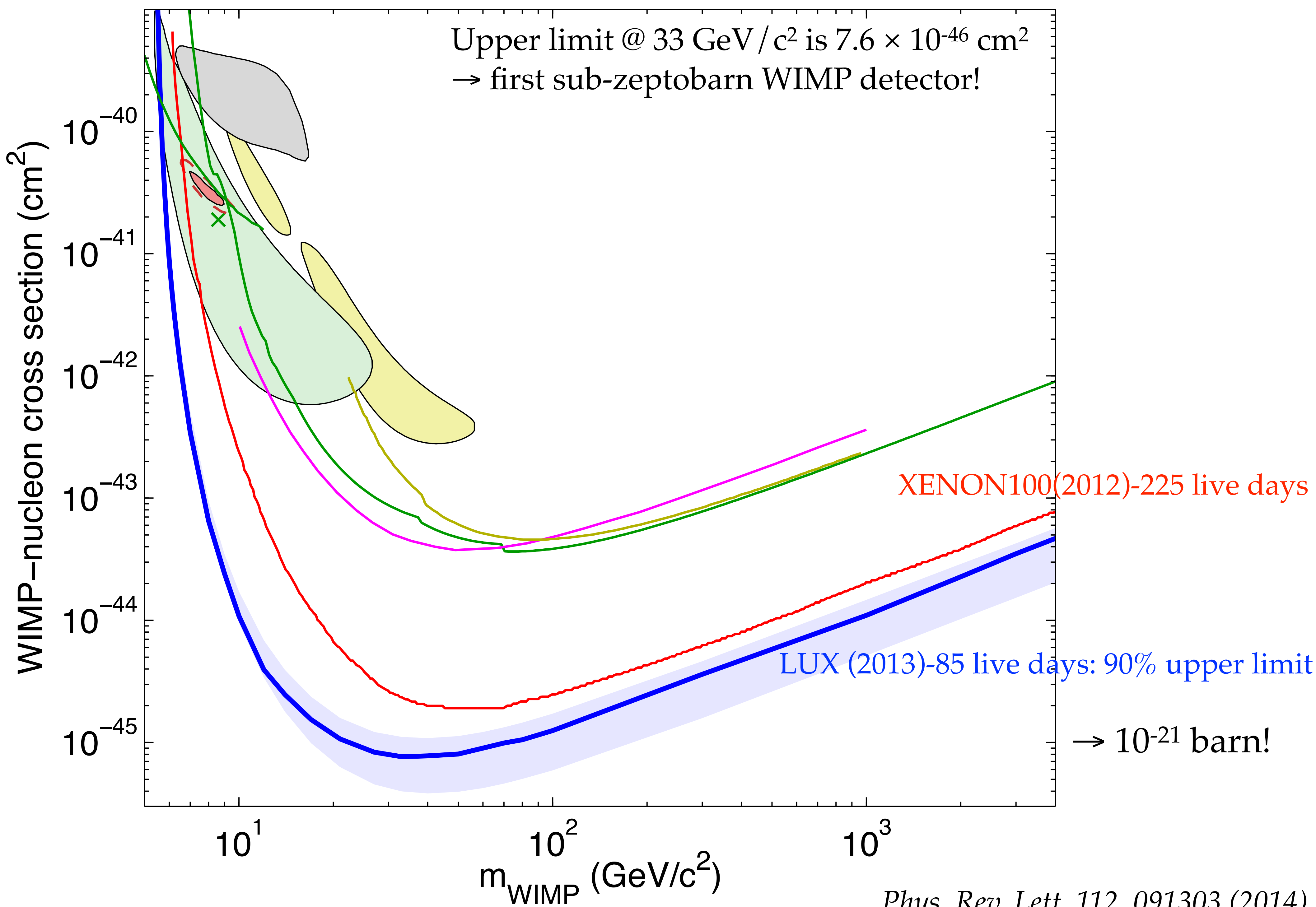
Background expected in the blue band
Signal expected in the red band
Observation consistent with background only hypothesis (p value of 35%)

(Charge/Light)

(Light ~ Energy)

WIMP searches Run 3 limit

WIMP nuclear Spin Independent (SI) cross section



Phys. Rev. Lett. 112, 091303 (2014)

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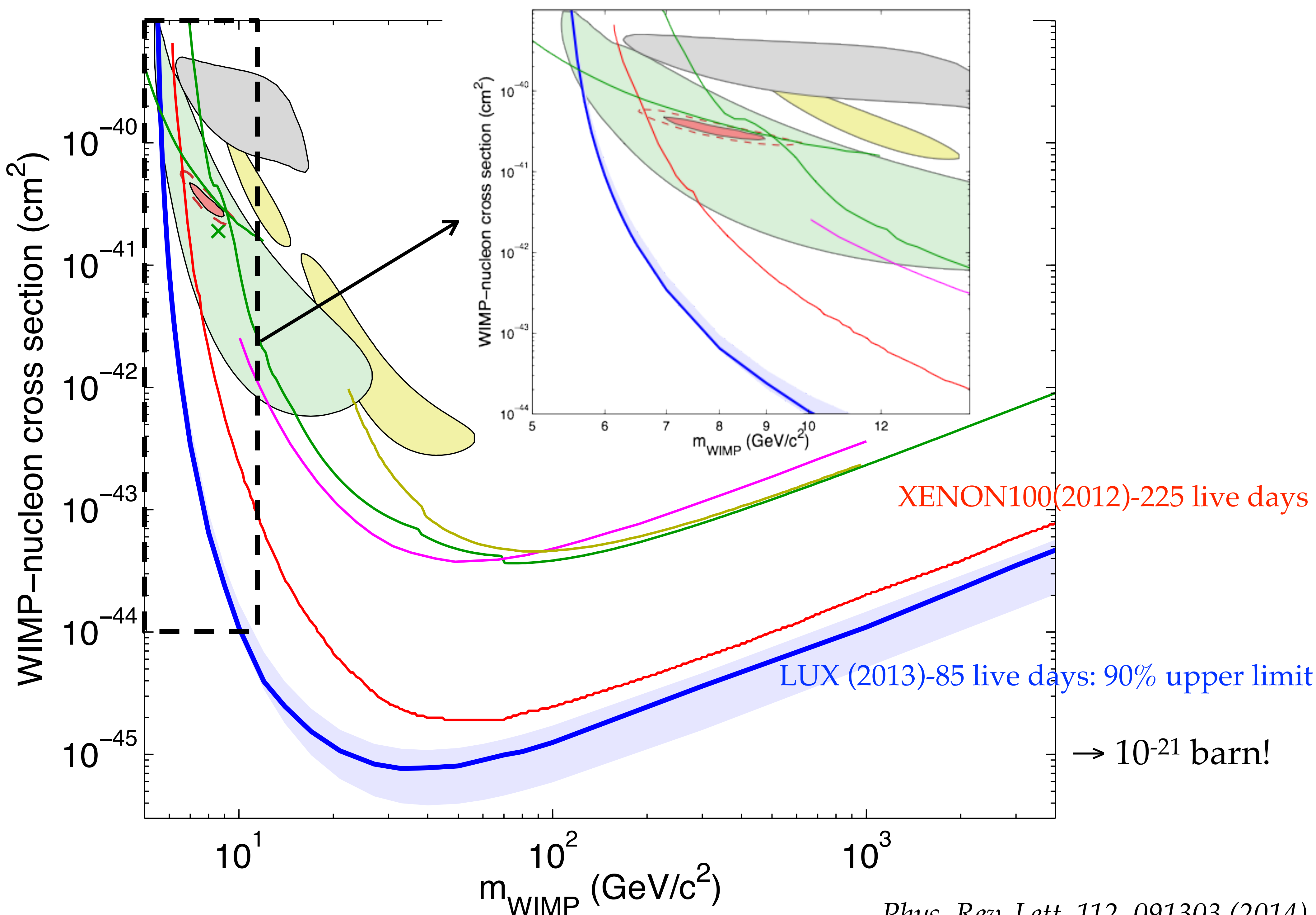

Phys. Rev. Lett. 112, 091303 (2014)

Status and preparation for new results

LUX towards 'Run 4' WIMP searches and re-analysis

LUX 'Run4'

Before Run 4

- End of 2013: high-stats calibration with CH_3T and DD neutron, for Run 3
- First half of 2014: optimising grids HV. Increased extraction field by 17%

Run 4 started in Sep 2014 after finalising new stable run parameters

- 4 weeks of DD neutron data + 5 days of CH_3T data
- So far ~100 live-days of WIMP search data
- March-April: second set of DD + CH_3T calibrations
- Aiming for 300 live-days WIMP search (+ calibrations) before June 2016

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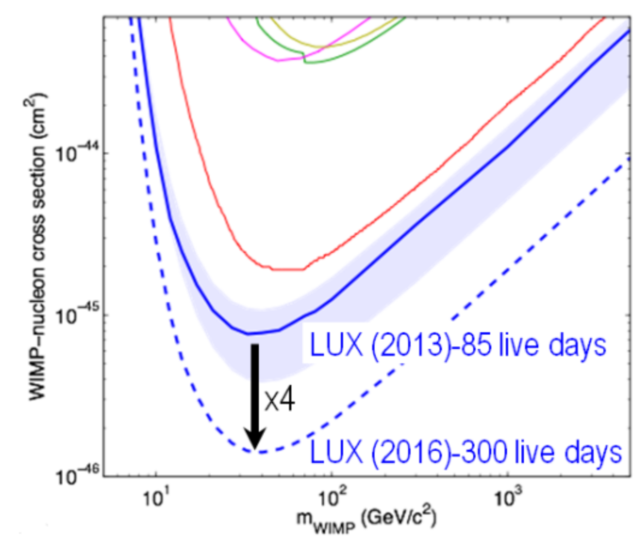
- Expected improvement of a factor of 2 - 4
  - ^{127}Xe has disappeared
  - Better background modelling for Profile Likelihood Ratio (PLR) analysis
  - Improved detector response calibration at very low energy



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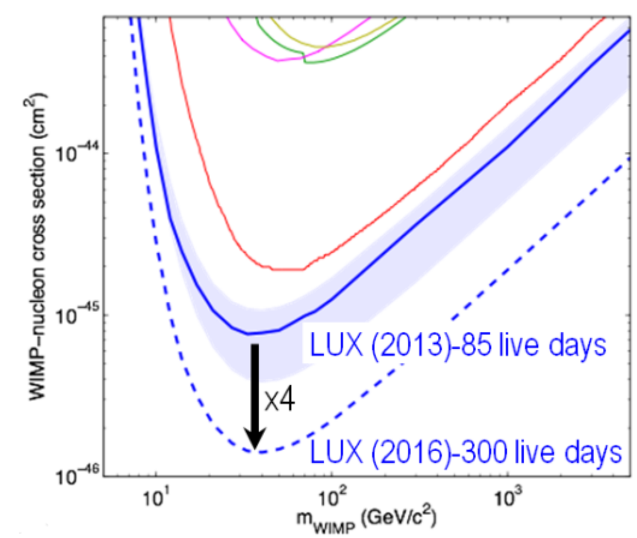
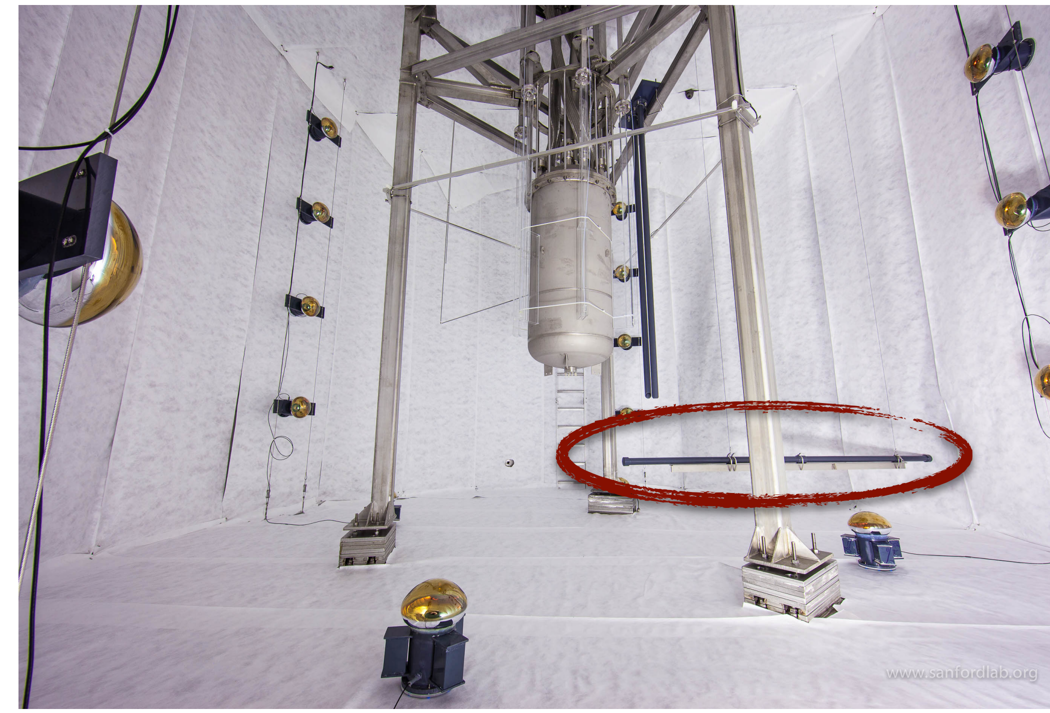


The last two last can also be applied to Run 3 data.

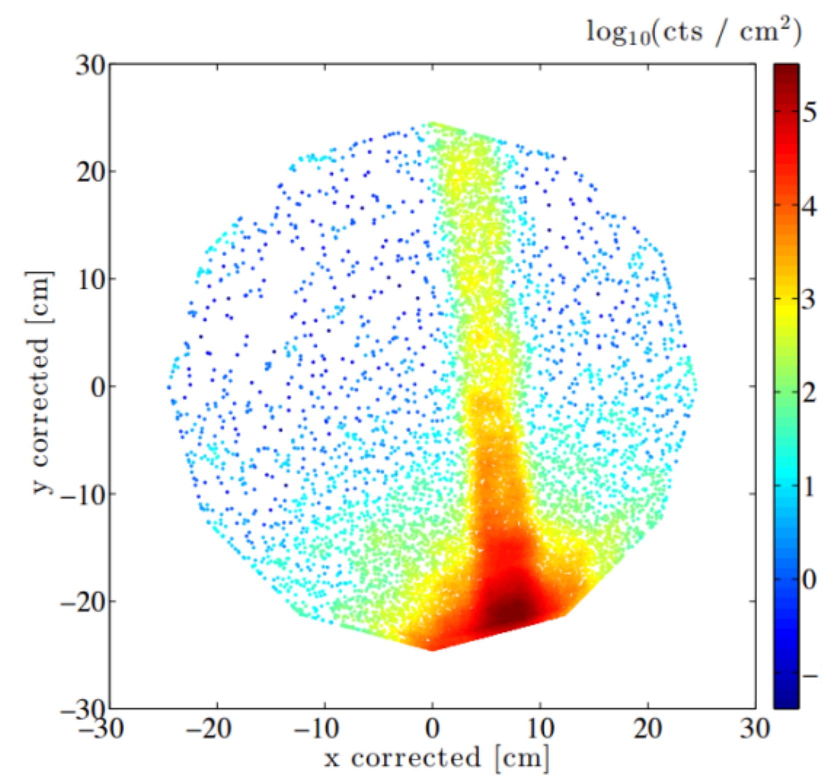
Calibration data: Nuclear Recoil

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



- Q_Y measured down to 0.8 keVnr
- L_Y measured down to 1.2 keVnr



Dedicated papers in preparation

For the Run 3 re-analysis used modified LUX Monte Carlo simulation (LUXSim and NEST) with new Q_Y and L_Y

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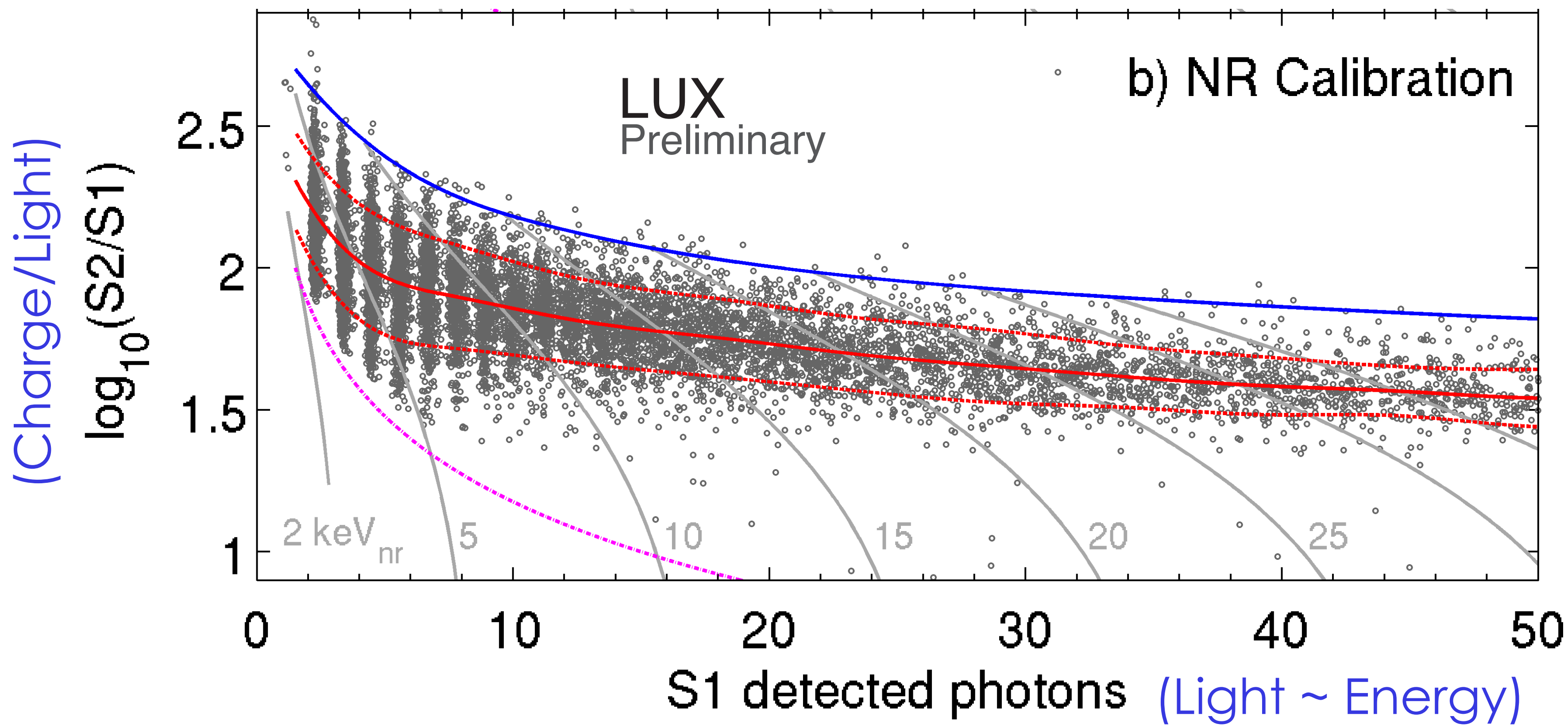
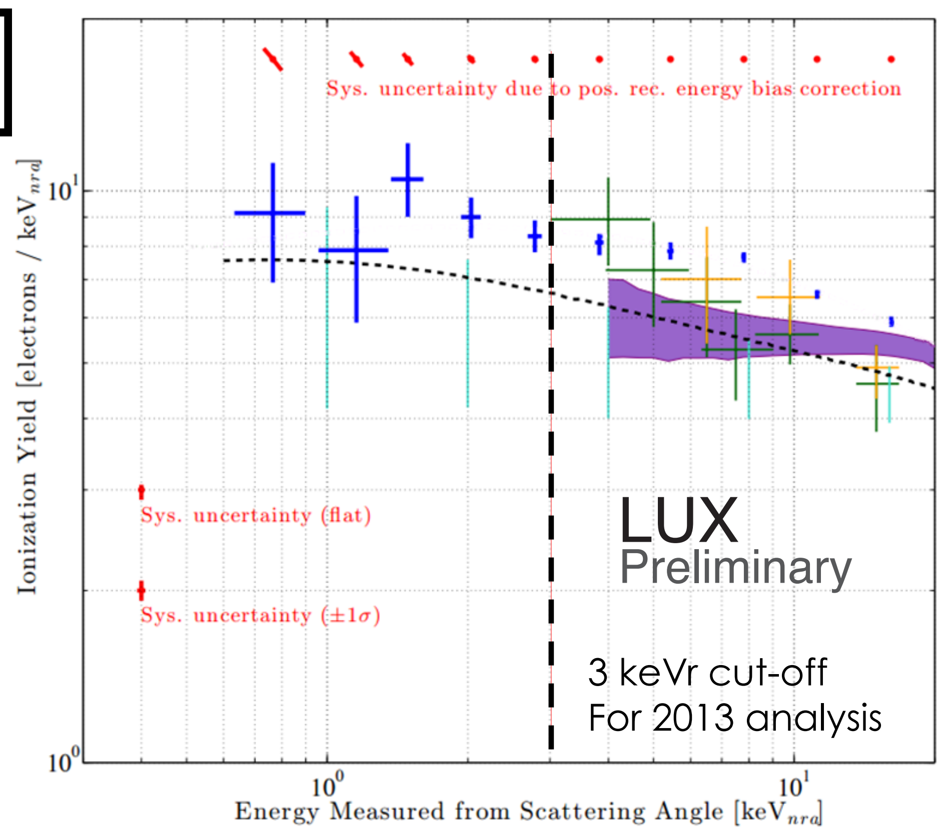
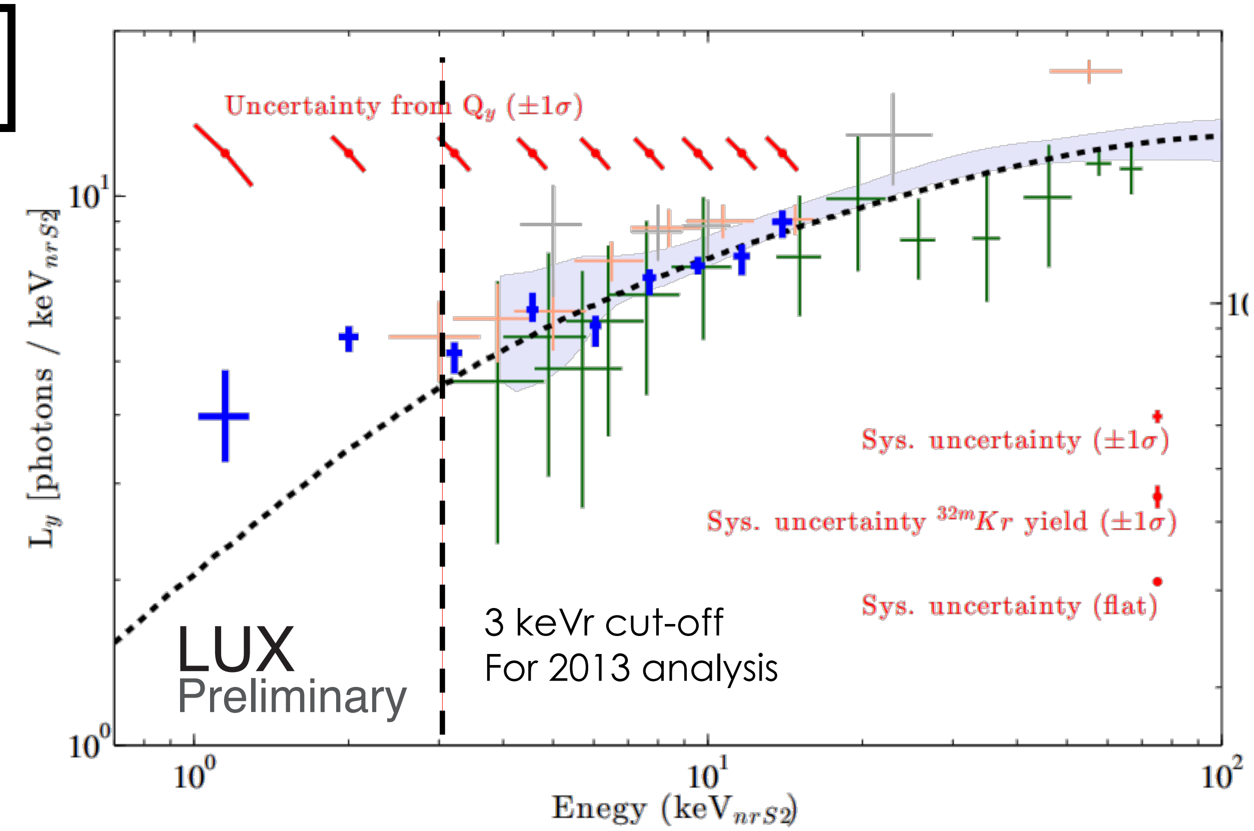


Qy



Ly



Calibration data: Electron Recoil

Injection of of CH_3T

- Homogeneous β source with Q = 18 keV
- Removal with τ < 12h
- Safe WIMP search data 5 days after 3 Bq injection

- ER light and charge yields vs energy down 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

Dedicated papers in preparation

Highly relevant for low mass and alternative searches

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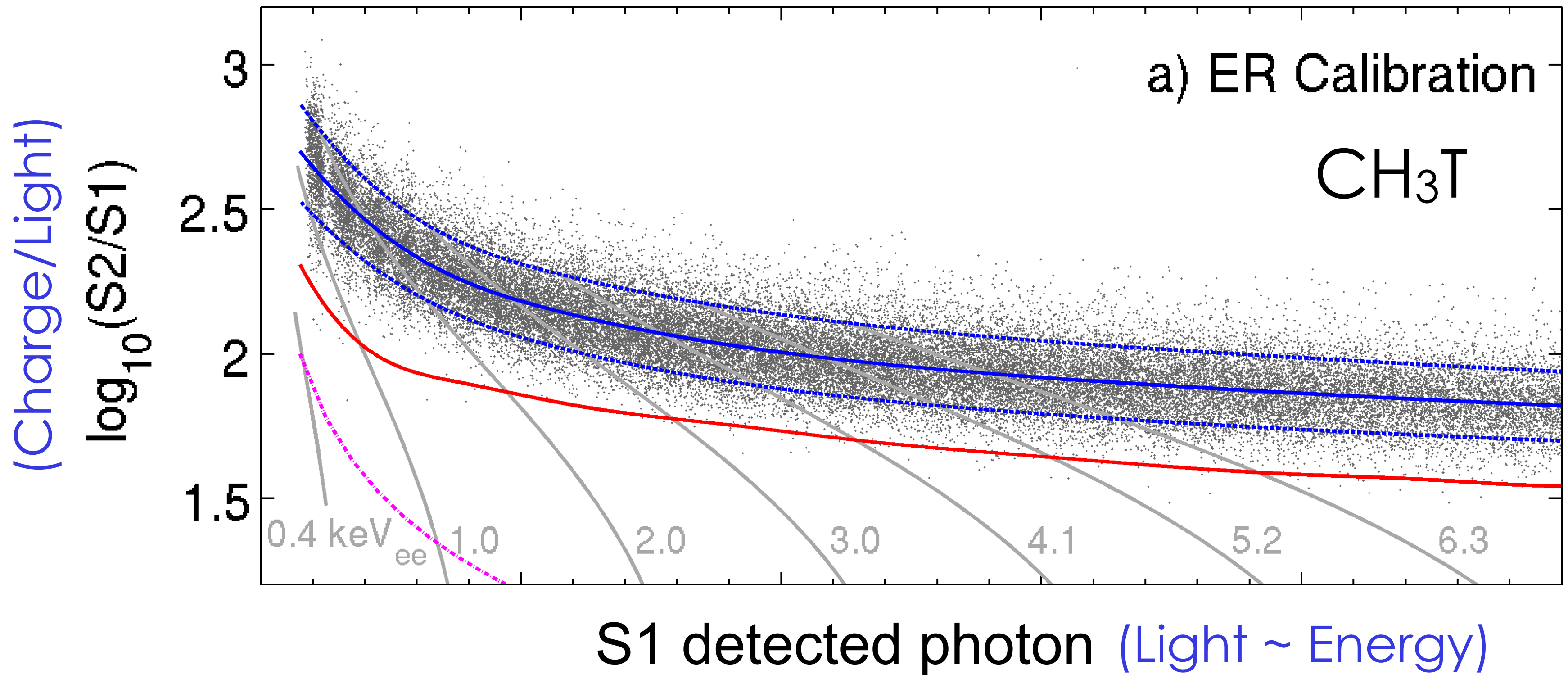
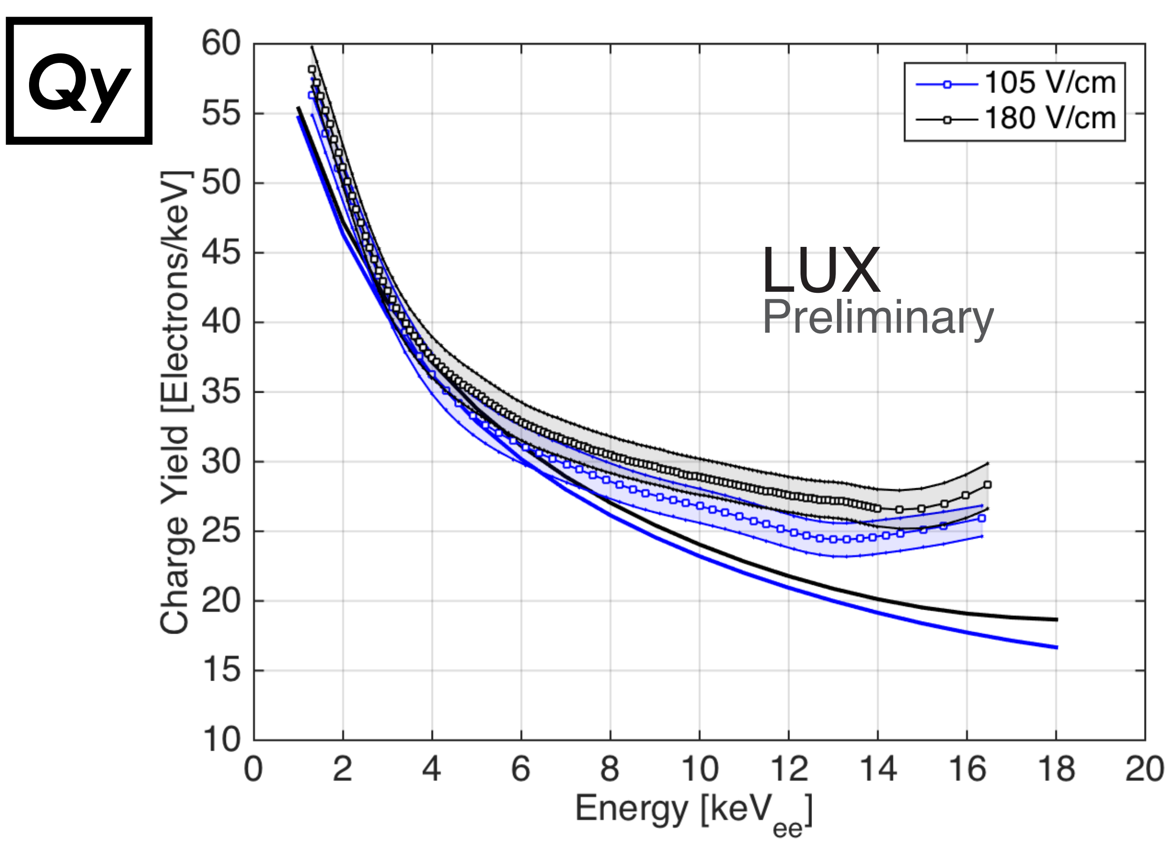
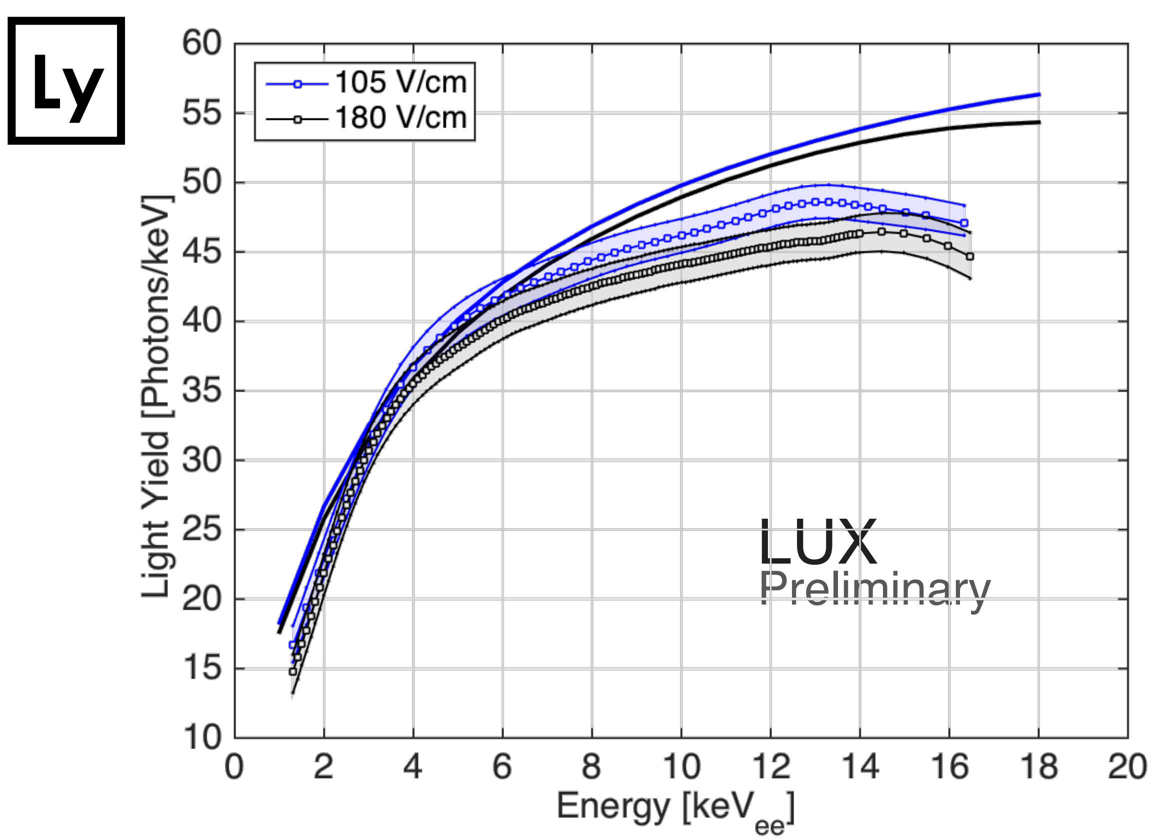






Additional improvements

Small increase to statistics with higher datasets acceptance

Updates to pulse finding algorithm

Updates to position reconstruction algorithm

- Use of photon counting at very low energy
- Update to fiducial volume definition (with CH_3T data)

Non-uniformity of electric field highly studied

Improved fit to calibration data for energy scales S1 (g1) and S2 (g2)

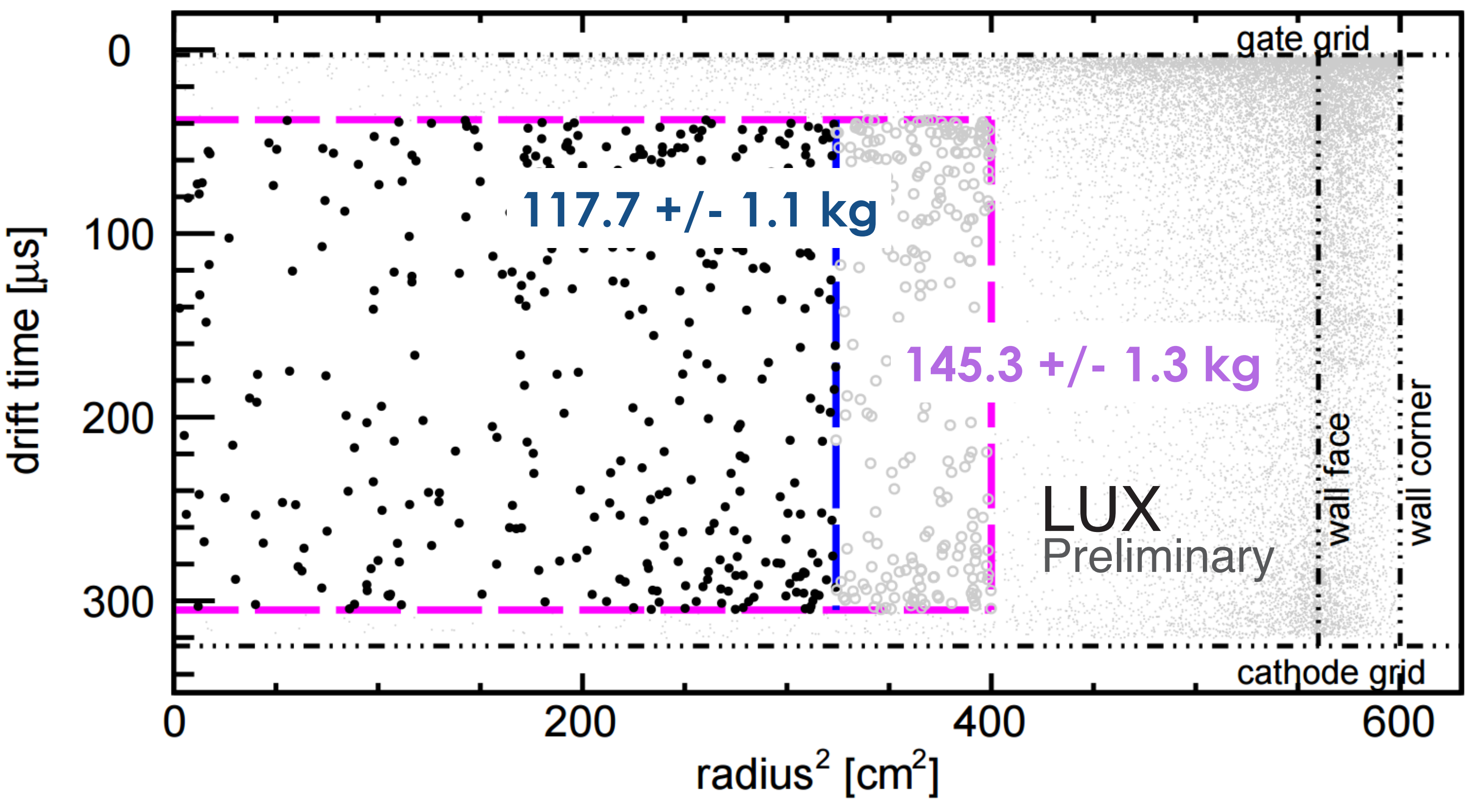
- Updated best-fit light collection and extraction efficiency

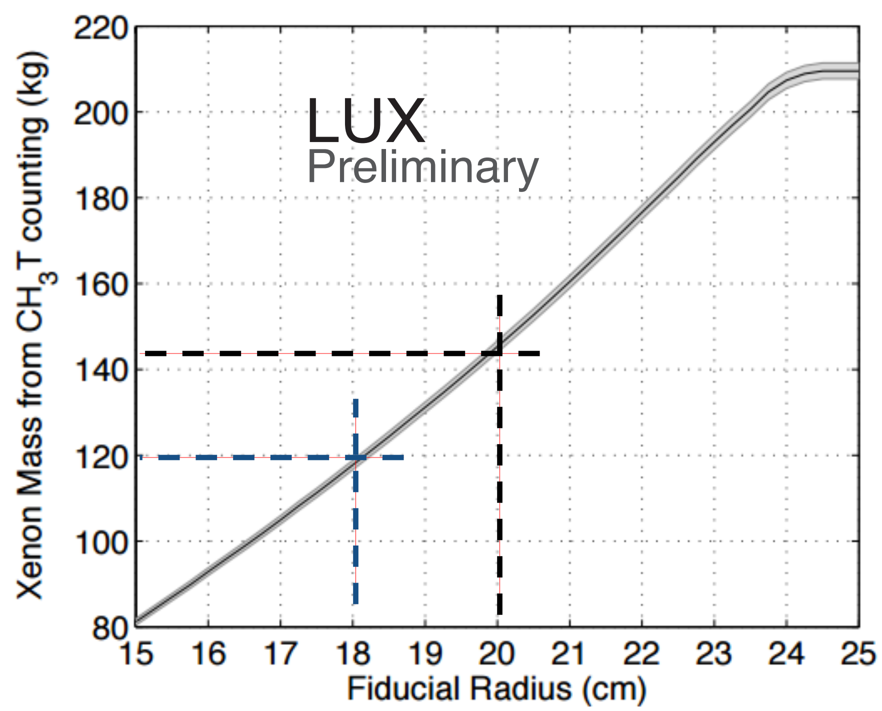
Update to Background Model

- More systematic use of sidebands
- Addition of "Wall Events" – mis-reconstructed alphas
- Increased granularity in sources of background
- Improved rejection of noisy events ("bad area")

Improved statistical analysis method: **Profile Likelihood Ratio** with S1, $\log_{10}$S2, r, z as input parameters, g1 and g2 as nuisance parameters

Fiducial Volume





Because of PLR:

- no need of NR vs. ER discrimination
- larger fiducial volume range with an improved background

Background rate of 3.6 +/- 0.3 x 10^{-3} single scatters/(keV-kg-day) in low-energy regime

- Kr at 3.5 ppt with RGA. PMT gamma-rays is the biggest background
- Cosmogenics from surface decayed away (^{131m}Xe, ^{129m}Xe)

Potential fiducial mass increase

… so

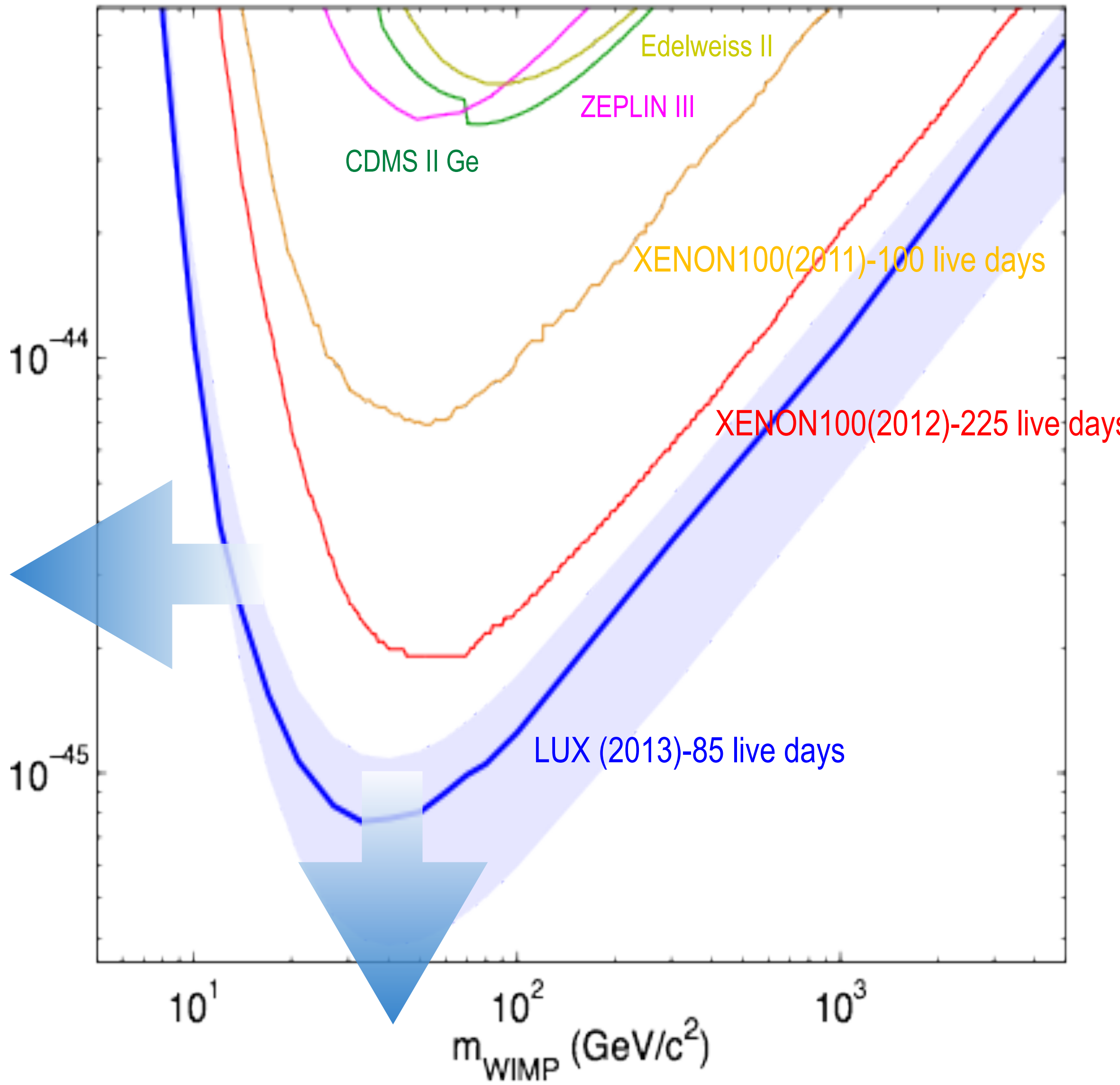
… preprint coming really soon!

Improved Background Model understanding

- Potential gain in fiducial mass, absolute sensitivity at all χ masses

Energy threshold reduced from 3 keVnr (previous Run 3) to 1.2 keVnr

- Guaranteed progress at very low masses



A taste of wider searches in LUX

LUX wide dark matter searches, beyond the WIMP spin-independent and spin-dependent interactions

Light O(1 GeV) vanilla WIMPs

not looking at the scintillation signal

Axion and Axion-like-particles

looking at electron recoil

SubGeV hidden-sector U(1)' models

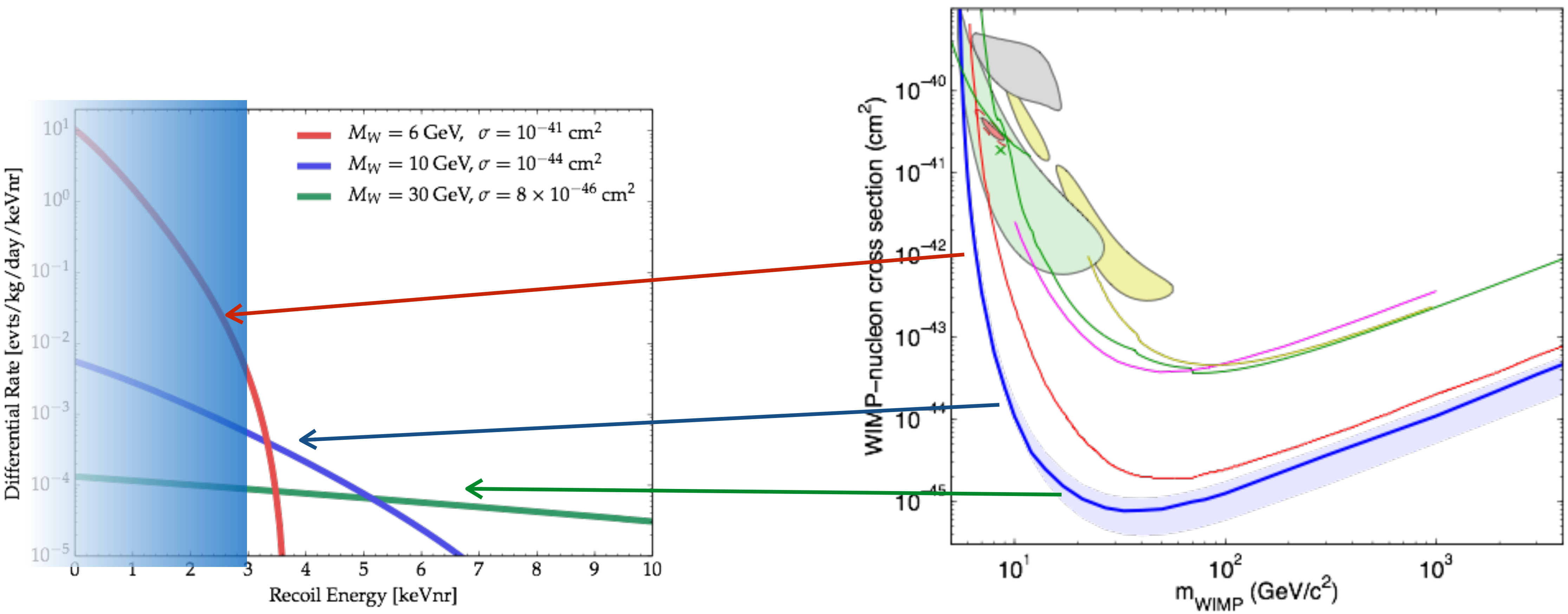
not looking at at the scintillation signal and looking at electron recoil

Effective Filed Theory approach

new WIMP-Nucleon Interactions

Light WIMP search

The LUX Run 3 results hard cut-off at 3 keVnr (assuming LXe to be blind for energy deposit below that)



Now measurement of LXe ionisation down to 0.75 keV

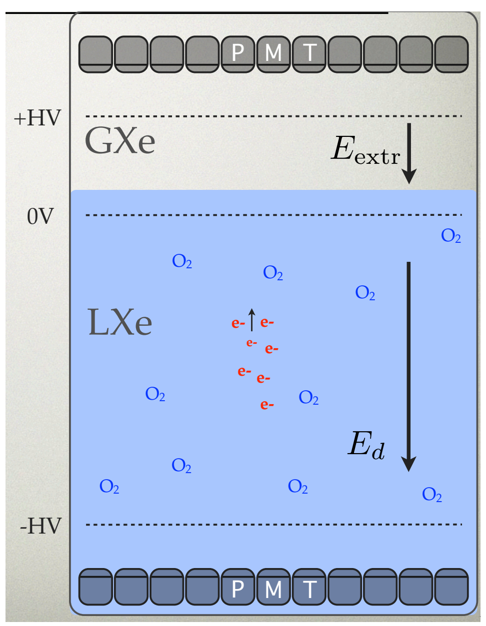
Decreasing the cut-off to 1 keV provides access to a factor of 1000 (before detector effect) more signal at 6 GeV/c^2

Challenge 1: Detector “details”

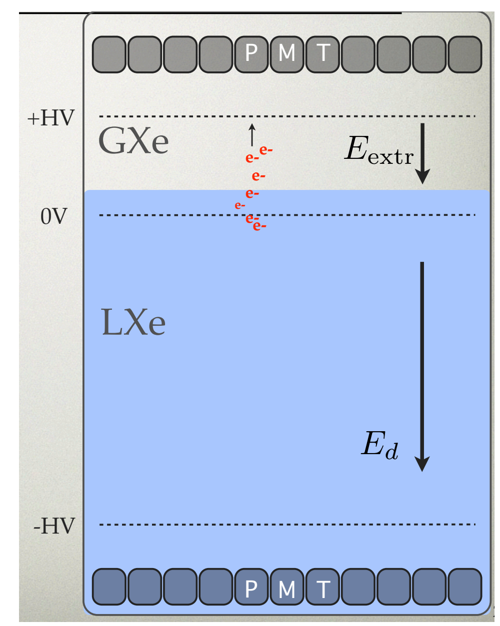
Using ionisation-only searches

Detector “features” lead to difficulties.

Large detectors are harder to build than small detectors



Experiment	Charge loss to impurities*
XENON10	~0%
XENON100	~40%
LUX	~30%

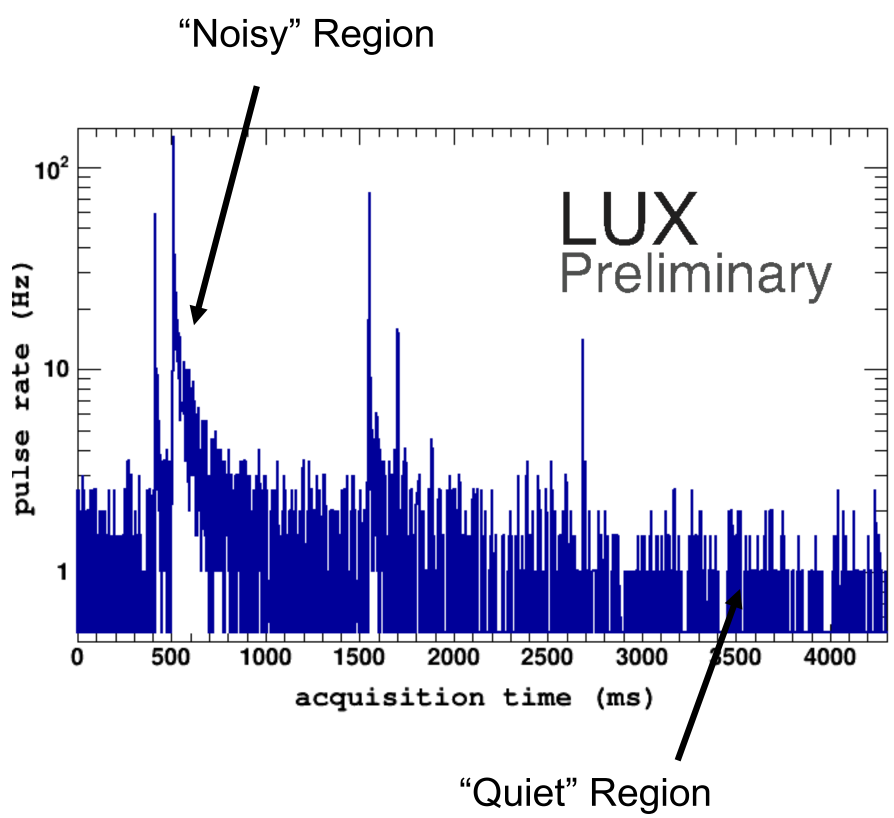


Experiment	Liquid-gas electron extraction efficiency
XENON10	~100%
XENON100	~100%
LUX	~50%

Challenge 2: Background

In normal mode (S1 and S2), more handles for background identification and rejection: particle ID, or vertex position. This is not possible with ionisation-only.

Single electrons: all dual phase LXe DM experiments have observed single e- background. Very difficult to model.



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

O2 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).

Surface Background: 222Rn diffuse into the air and get everywhere. It will then "plate out" once it decays. The 210Po daughter is problematic: low energy, heavy projectile, gives small ionisation and scintillation signals (for which we don't yet have measurements).

Why are we interested in axions?

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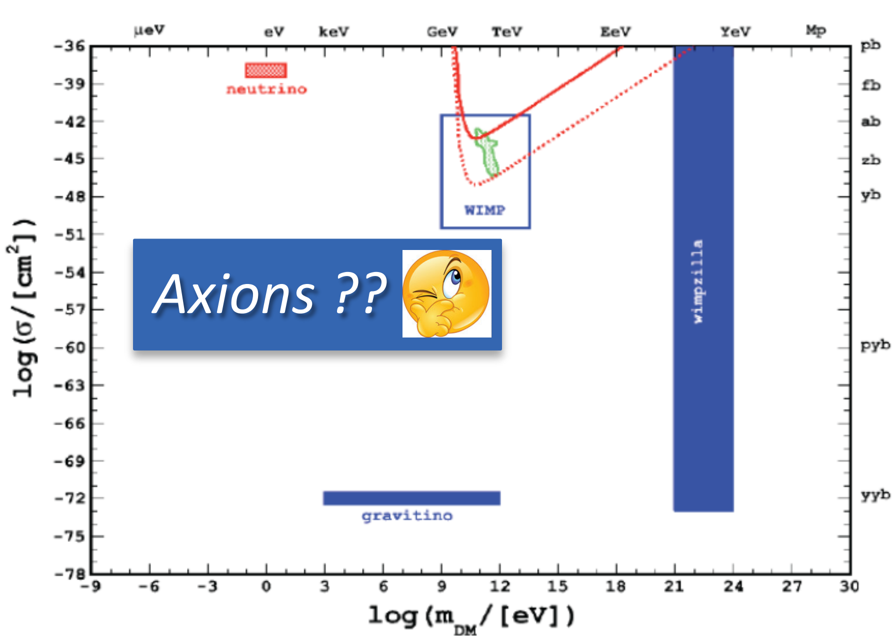
Why are we interested in axions?

Theory

- "Invisible" axions could be **QCD axions** solving the strong CPV problem
- **ALPs** (axion-like particles), introduced from extensions of the SM, could be dark matter particles

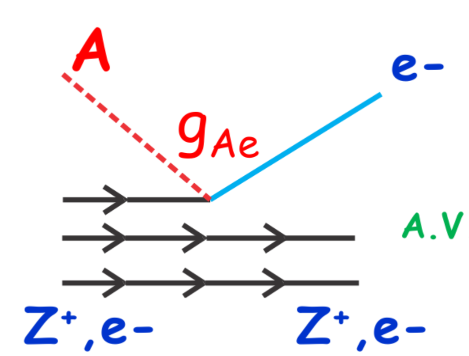
Experimental detection with xenon

- Axions and ALPs can couple with electrons ($\mathbf{g_{Ae}}$)
- Potential sources:
  - Axions come from **the *Sun***
  - ALPs slowly move within **our *Galaxy***



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

Axio-electric effect



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)

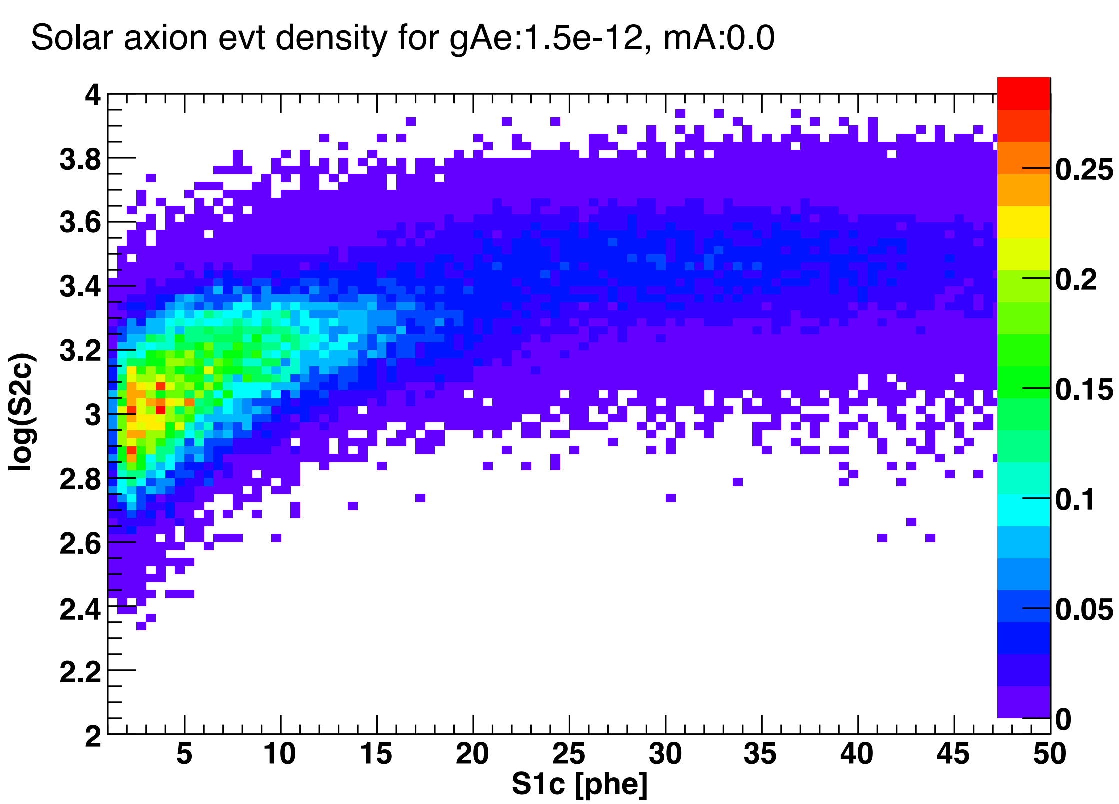
Axion analyses: Solar

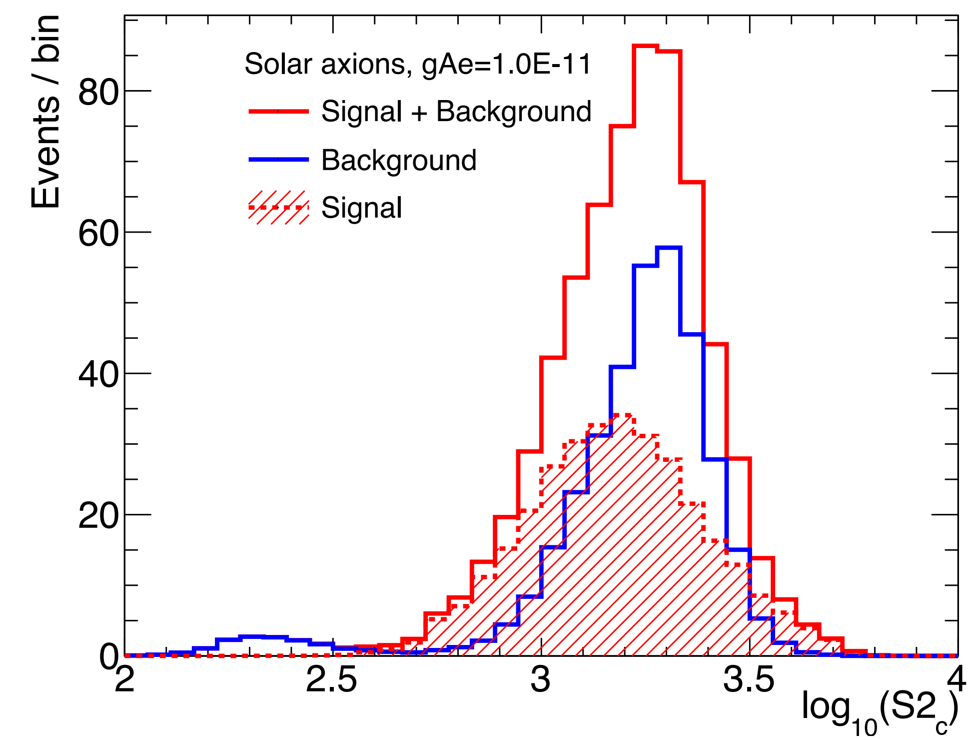
Solar flux from J. Redondo JCAP12, 008 (2013)

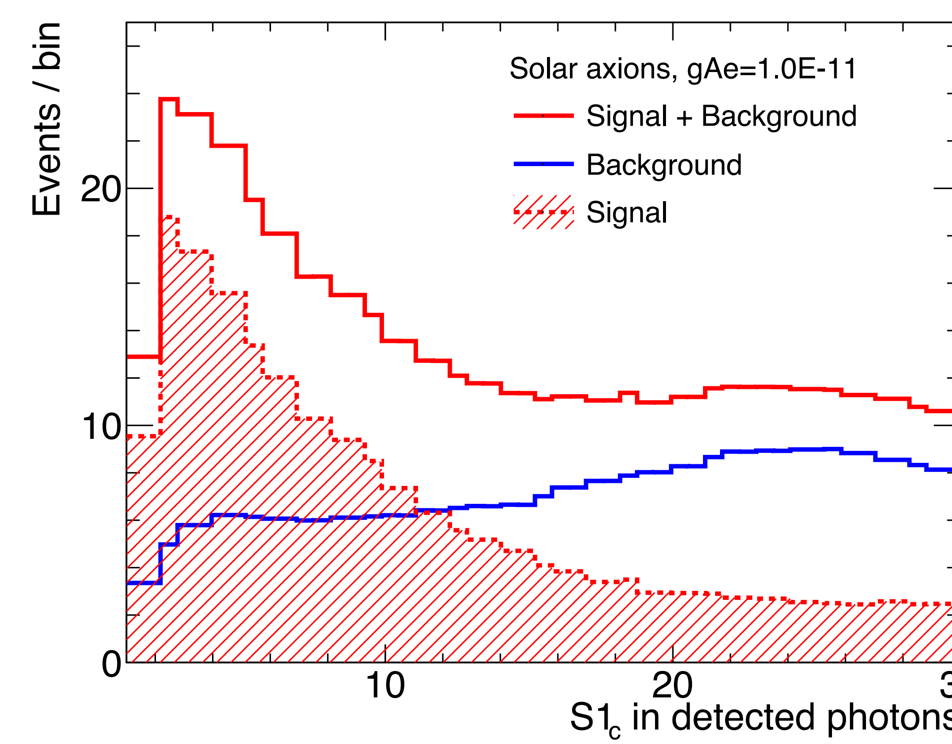
Implemented in the LUX analysis.

Exploiting NEST and LUXSim software packages

Generating the variables for the Profile Likelihood statistical.







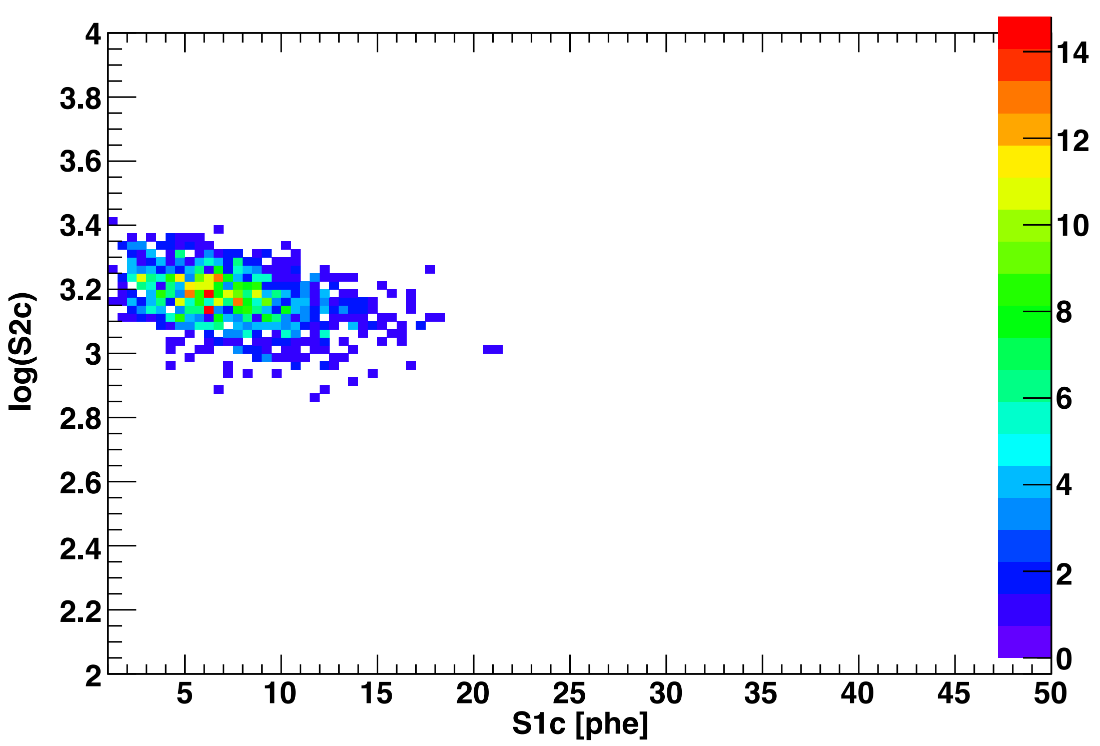
Challenge: precise background model at lowest energy possible

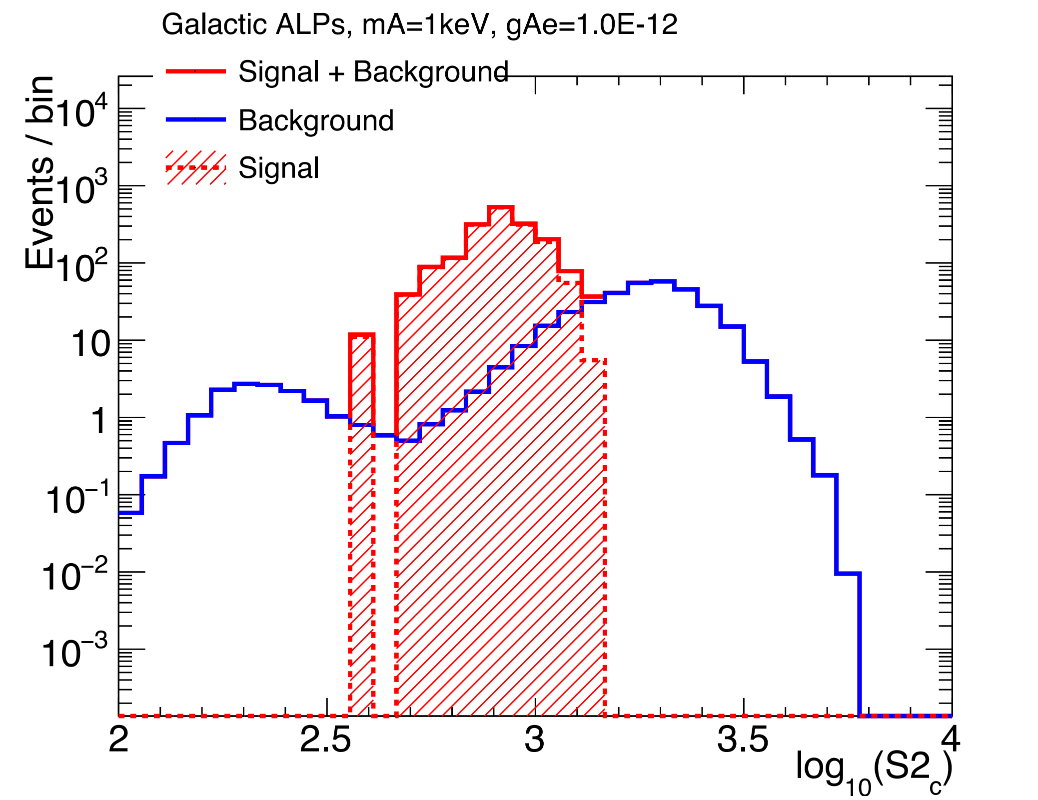
Axion analyses: Galactic

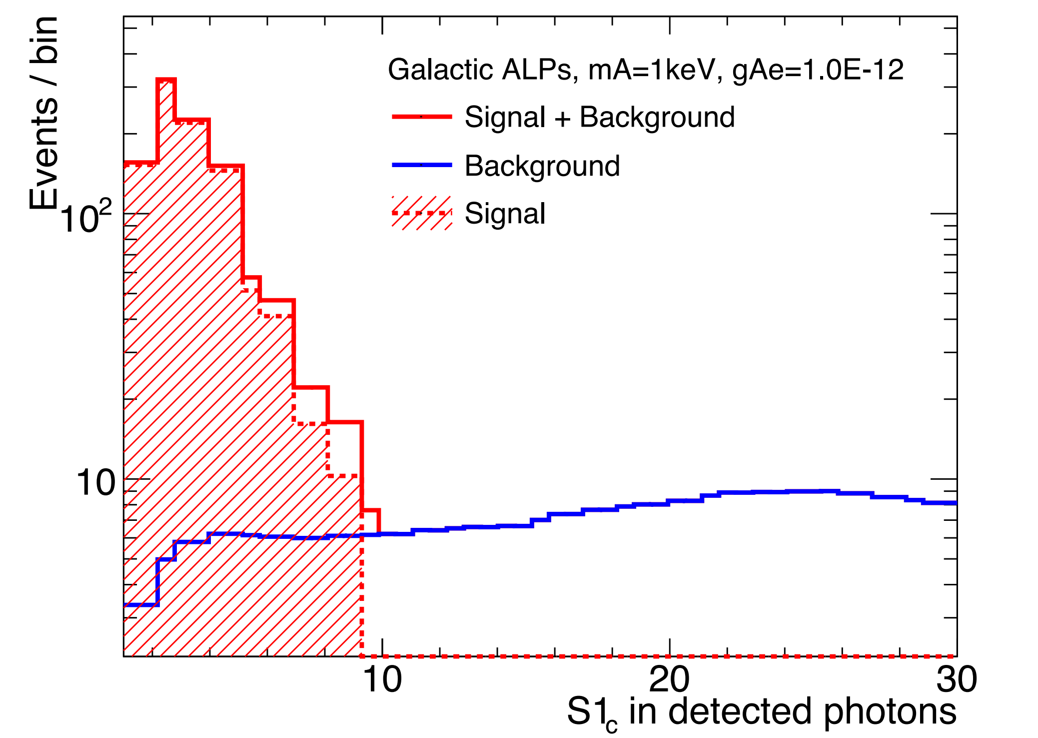
Implemented in the LUX analysis.

Exploiting NEST and LUXSim software packages

Generating the variables for the Profile Likelihood statistical.







To be done: precise detector response and background model above 5 keVee

Summary

Re-analysis of original exposure underway. Results soon!

Dedicated DD and tritium papers in preparation,

Widening the DM searches, new analyses of the initial data set
- Spin-dependent neutron and proton
- Solar and galactic axion searches
- S2-only limit for low-mass
- Effective field theory scattering

Working on next, 300-day run. New type of analysis: blind, via salting. Pushing sensitivity down by factor of 4.

G2 WIMP experiment LUX-ZEPLIN coming (passed DOE CD-1 review)

LUX *still* strictest limit on WIMP-nucleon spin-independent interaction cross section across widest range of WIMP masses.

Thank you

‘We’ can now rejoice even in the falsification of a cherished theory, because even this is a scientific success.

– Sir John Carew Eccles
In K. R. Popper, Conjectures and Refutations.

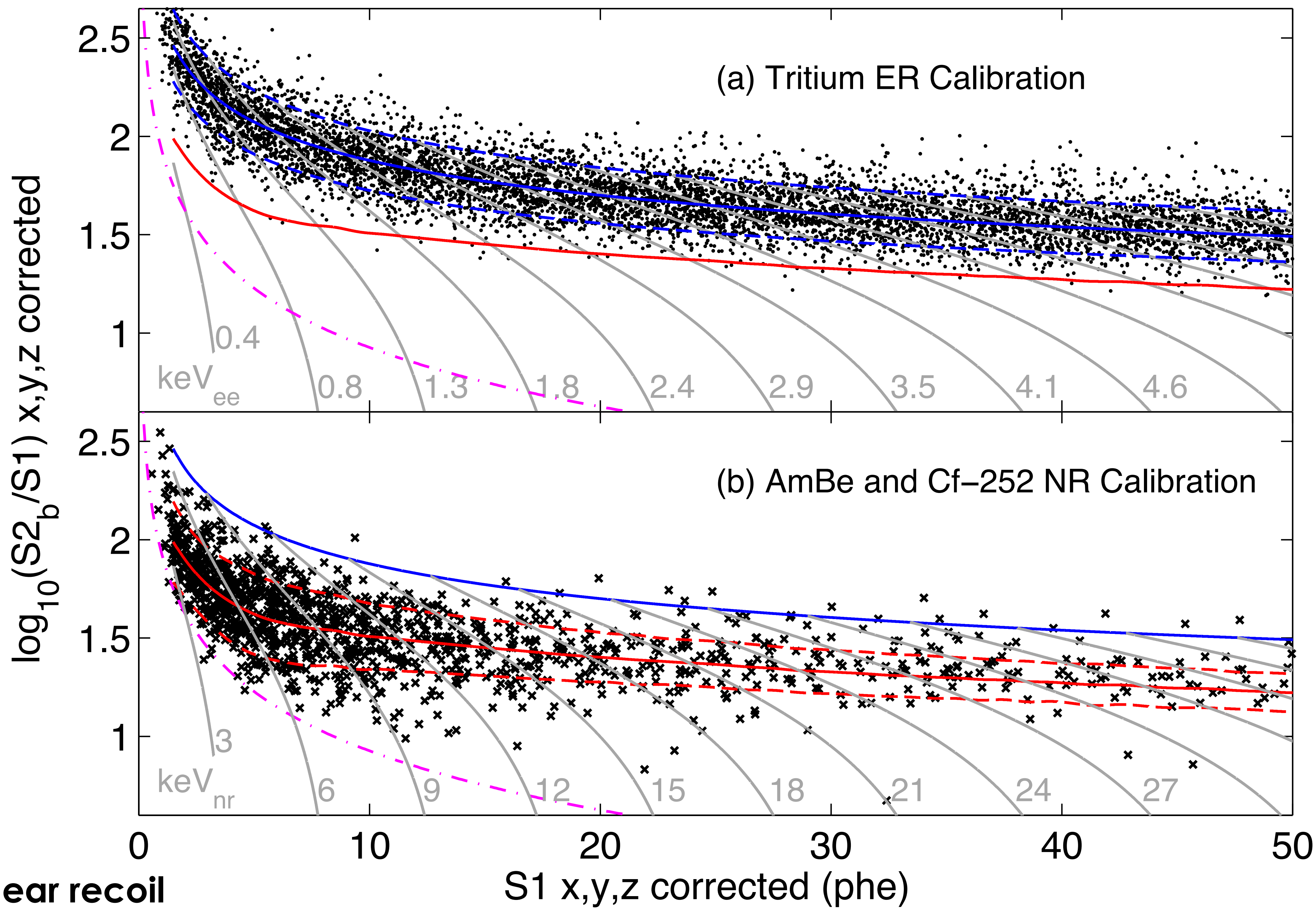
But that is not enough…

Thank you

Backup slides

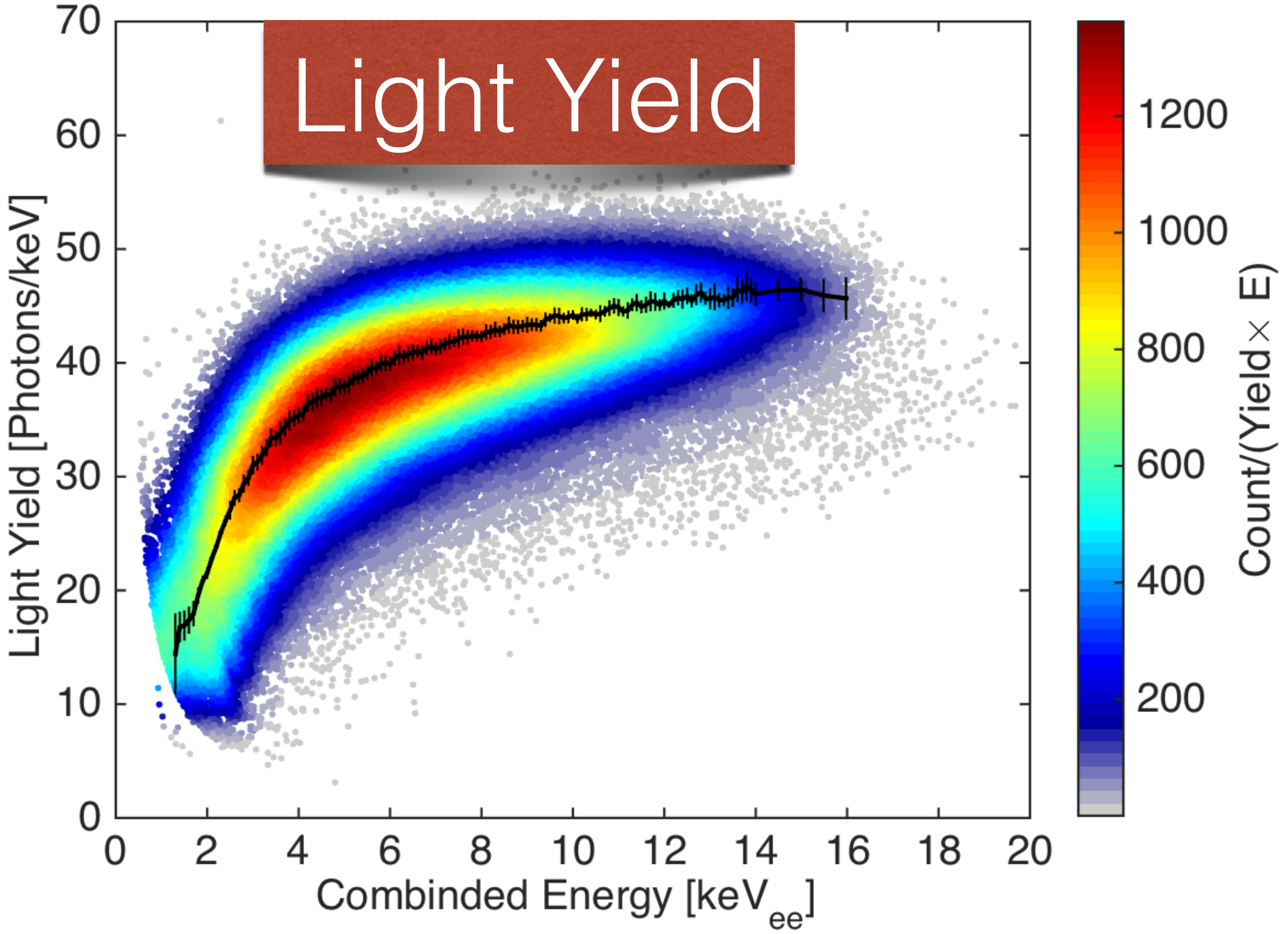
WIMP searches: 85.3 days - 118 kg

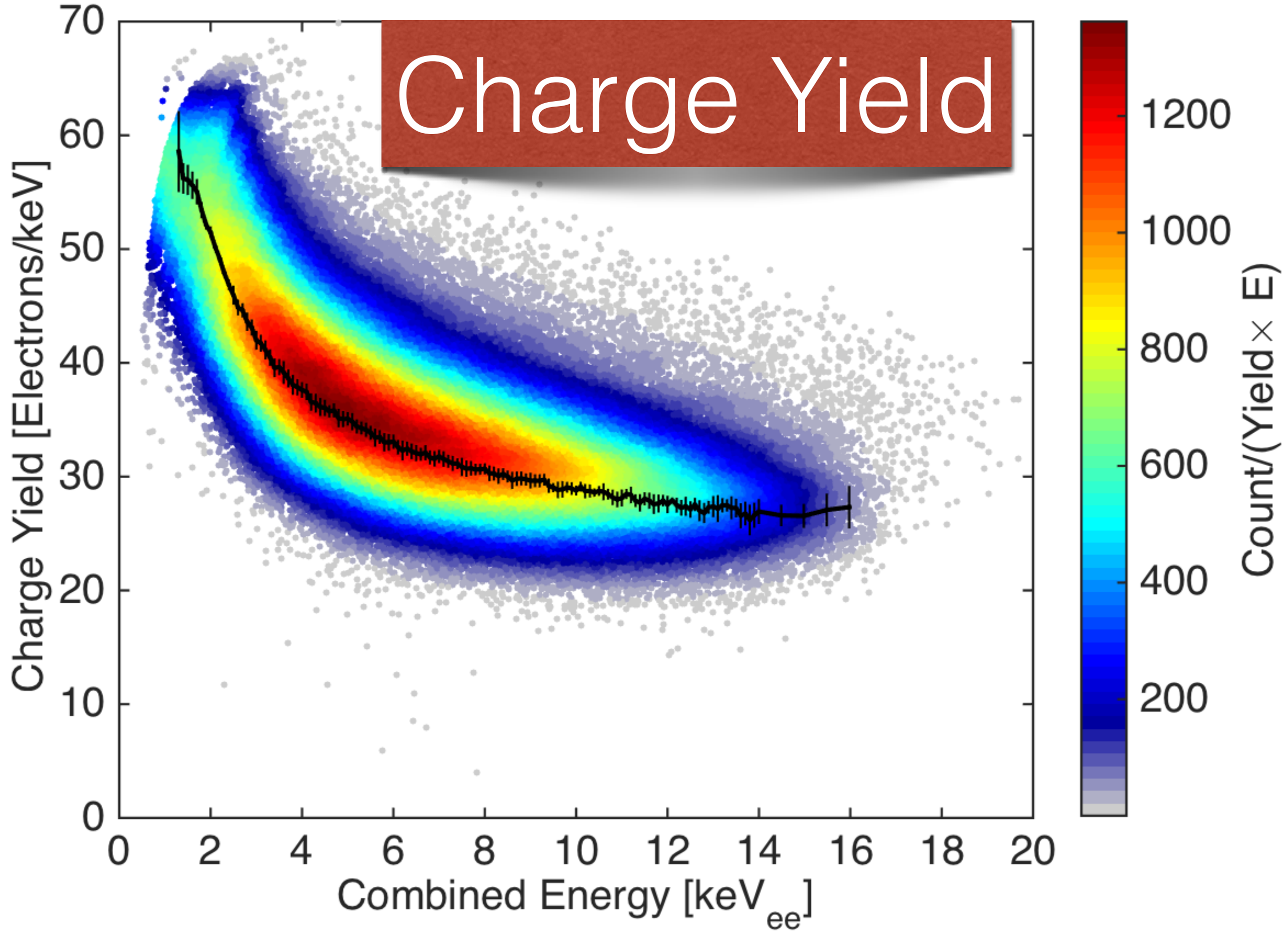
Calibration data for
Electron Recoil (ER) and Nuclear Recoil (NR) events

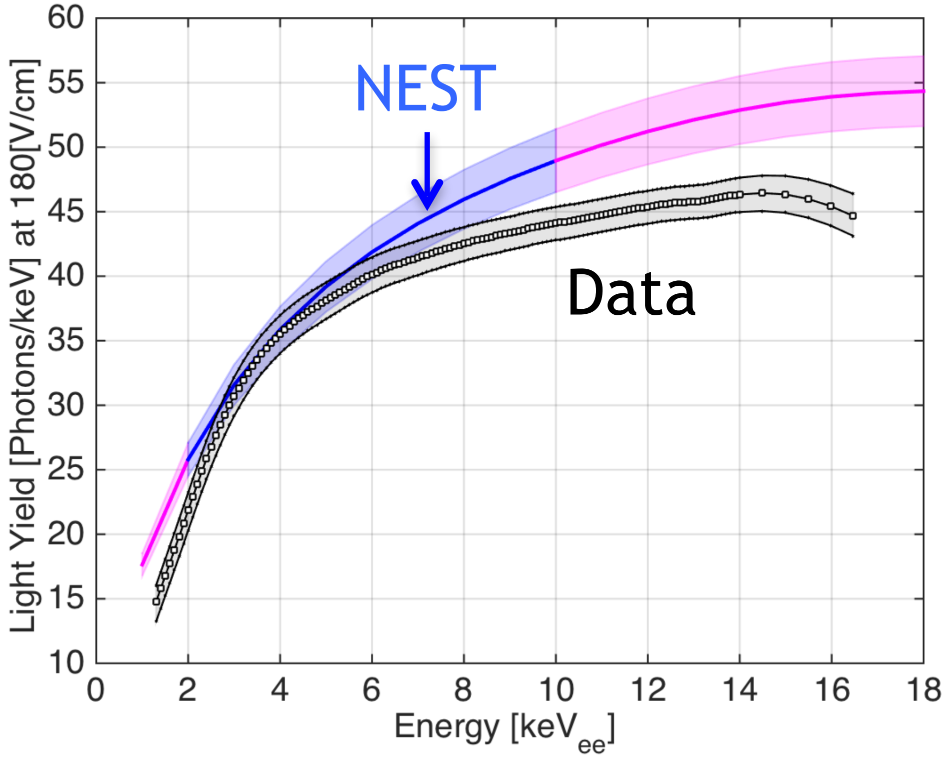


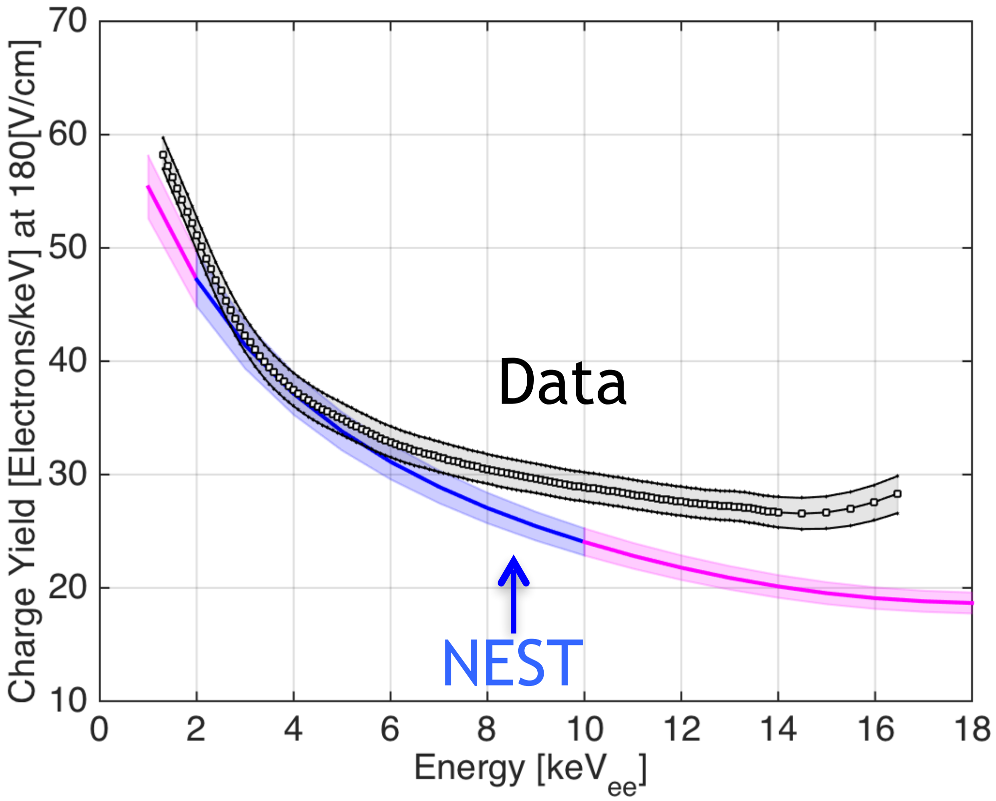
keVnr: nuclear recoil
keVee: electron equivalent

Yields Measured in LUX Fiducial Volume







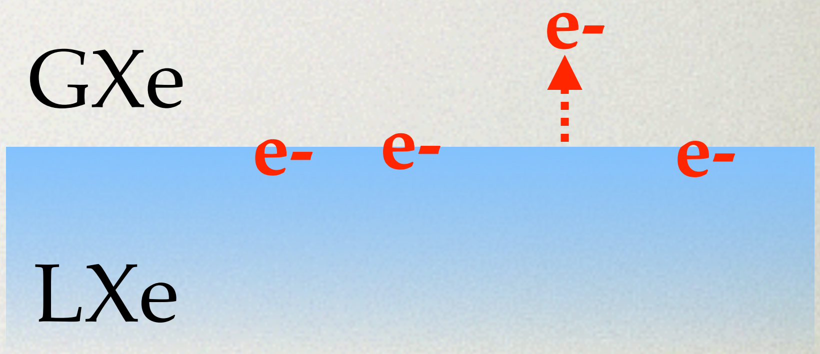


Single electrons

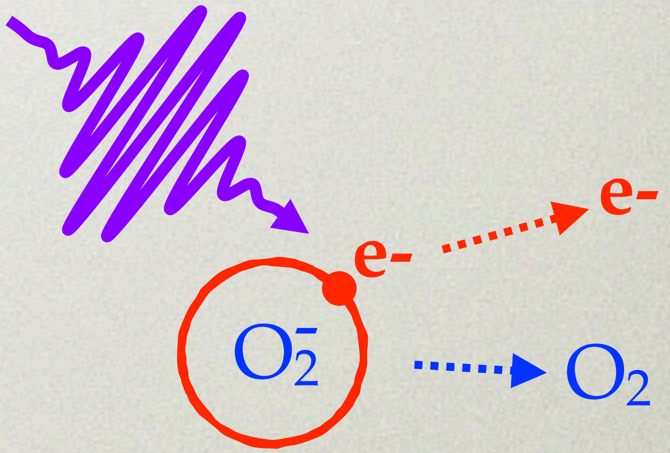
from A. Manalaysay

These observations teach us that multiple mechanisms contribute to single-electron background signals.

- 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 ionized by a Xe scintillation photon.

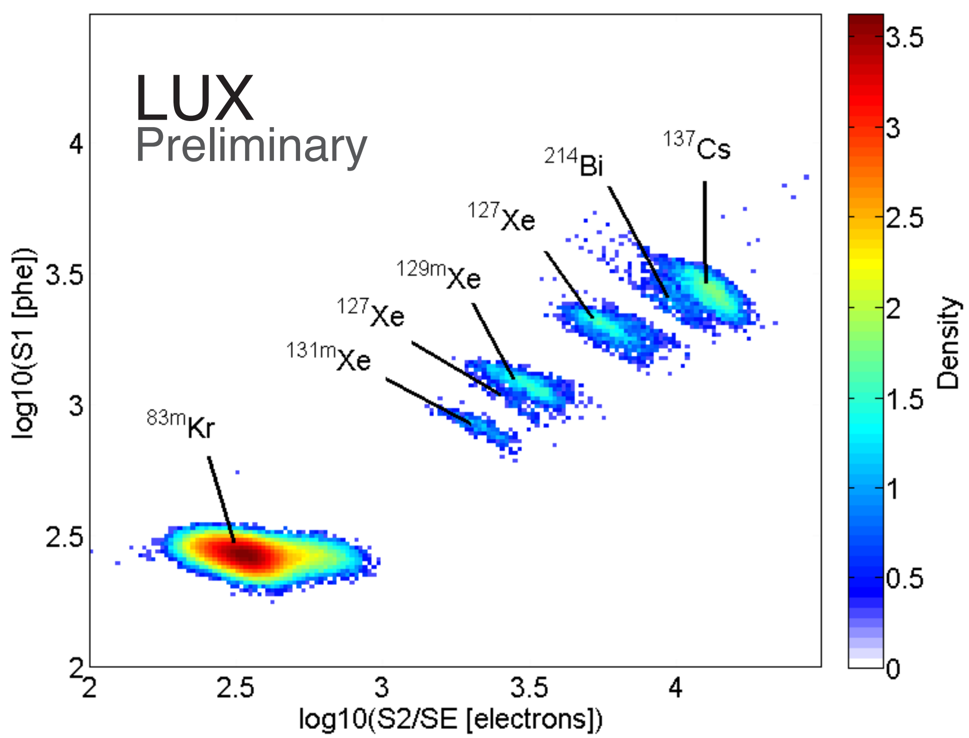


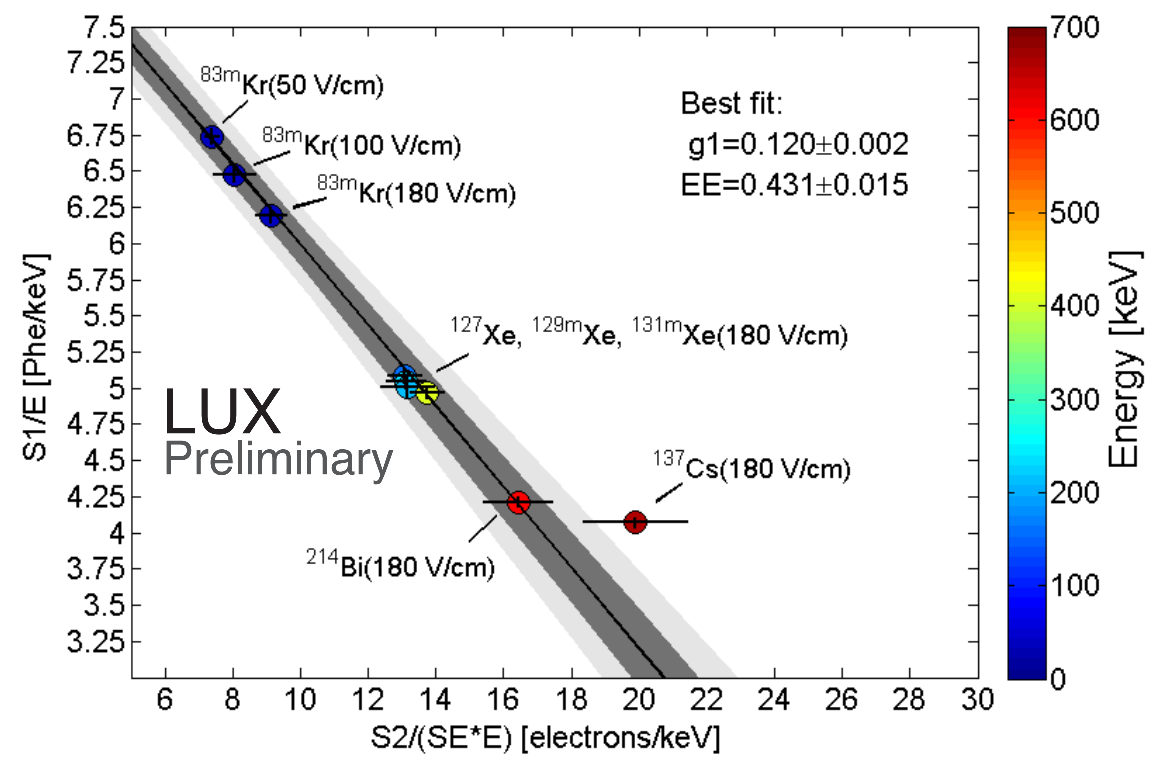
Event energy reconstruction

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

For electronic recoils in xenon W = 13.7 eV

Measure *S1* and *S2*; convert to photons and electrons with gains *g1* and *g2*





12% efficiency for the detection of a primary scintillation photon

43% extraction, coupled with ~25 detected photons per single electron to make g_2

Event energy reconstruction

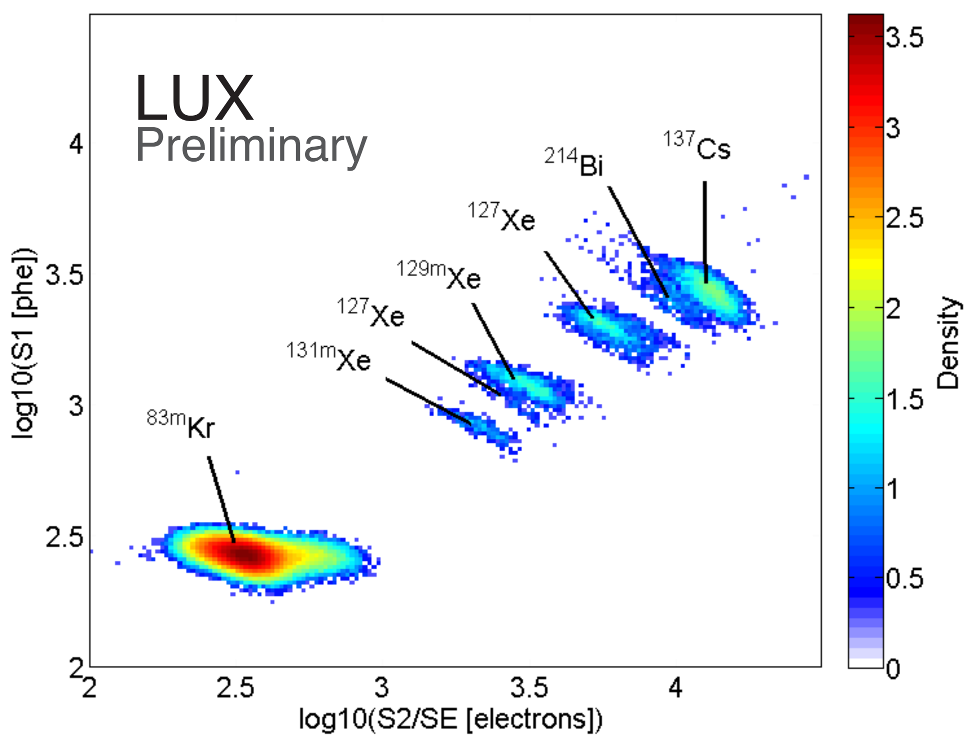
$$\frac{E}{W} = n_\gamma + n_e = \frac{S1}{g_1} + \frac{S2}{g_2}$$

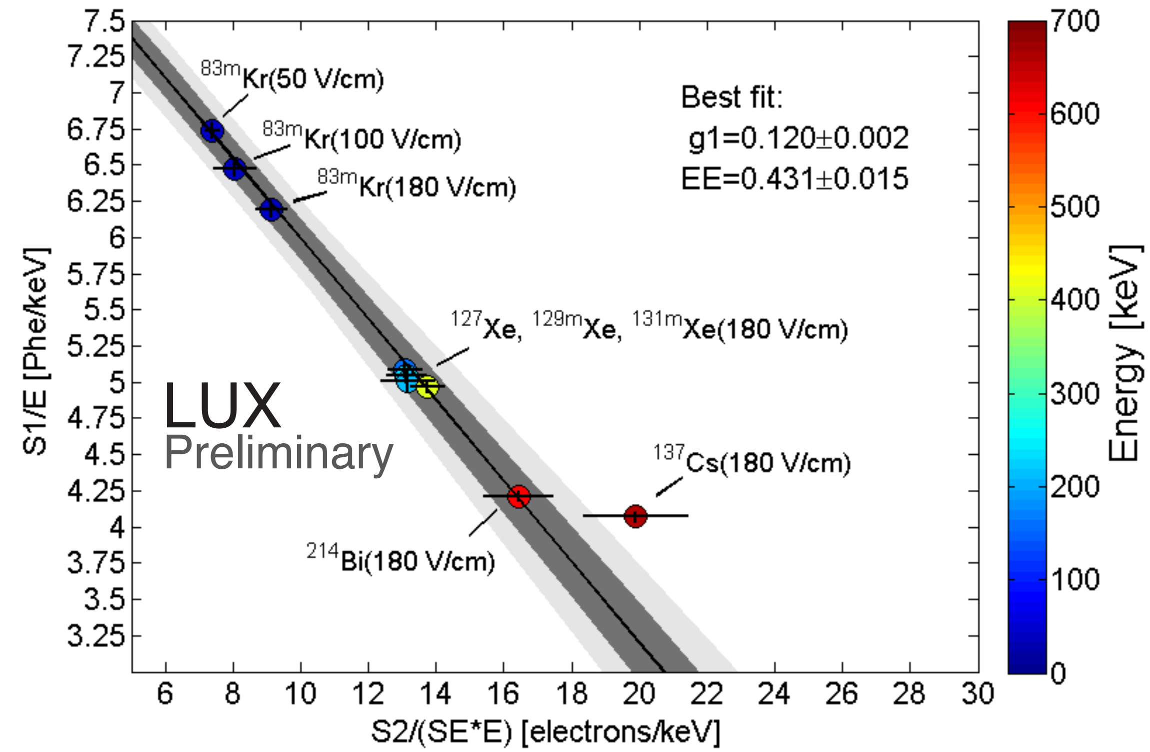
$$\langle n_\gamma \rangle = \frac{\langle S1 \rangle}{g_1} \qquad S1/E = \frac{n_\gamma}{(n_\gamma + n_e)} \times \frac{g1}{W}$$

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

For electronic recoils in xenon W = 13.7 eV

Measure *S1* and *S2*; convert to photons and electrons with gains *g1* and *g2*

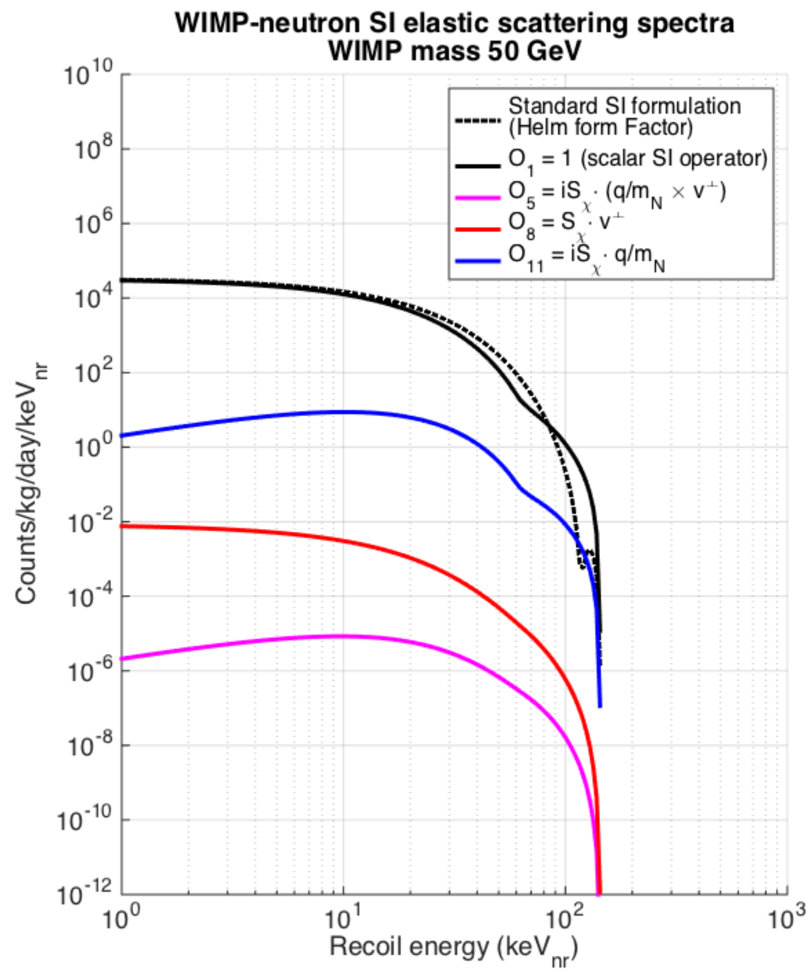


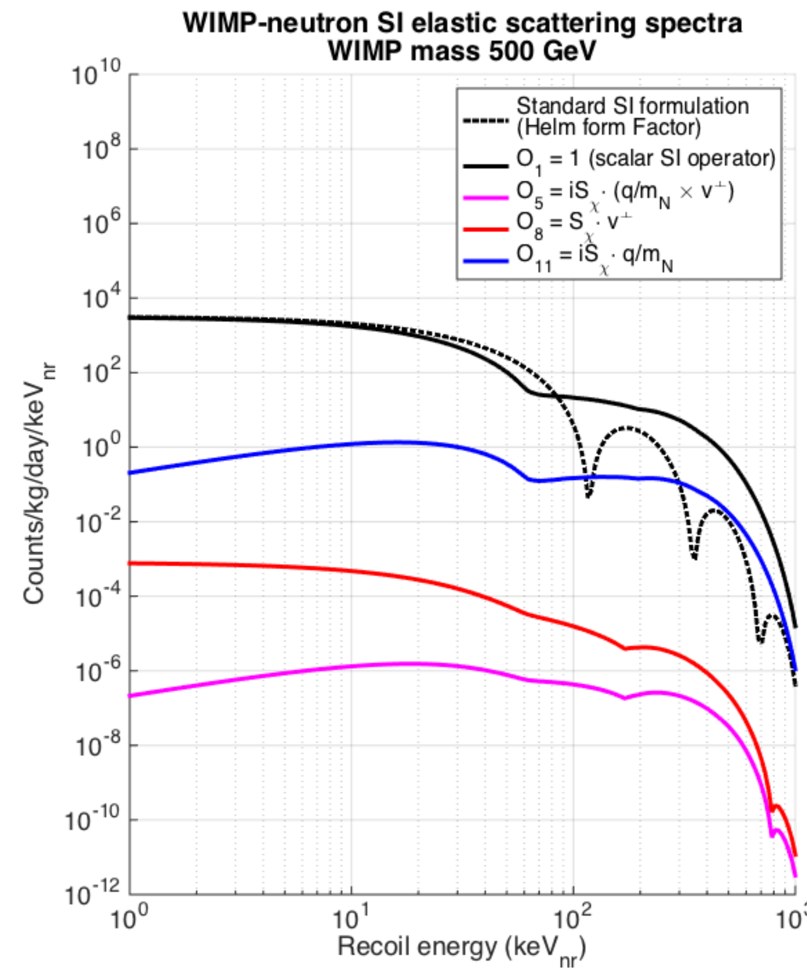


12% efficiency for the detection of a primary scintillation photon

43% extraction, coupled with ~25 detected photons per single electron to make g_2

Spin-independent and LD



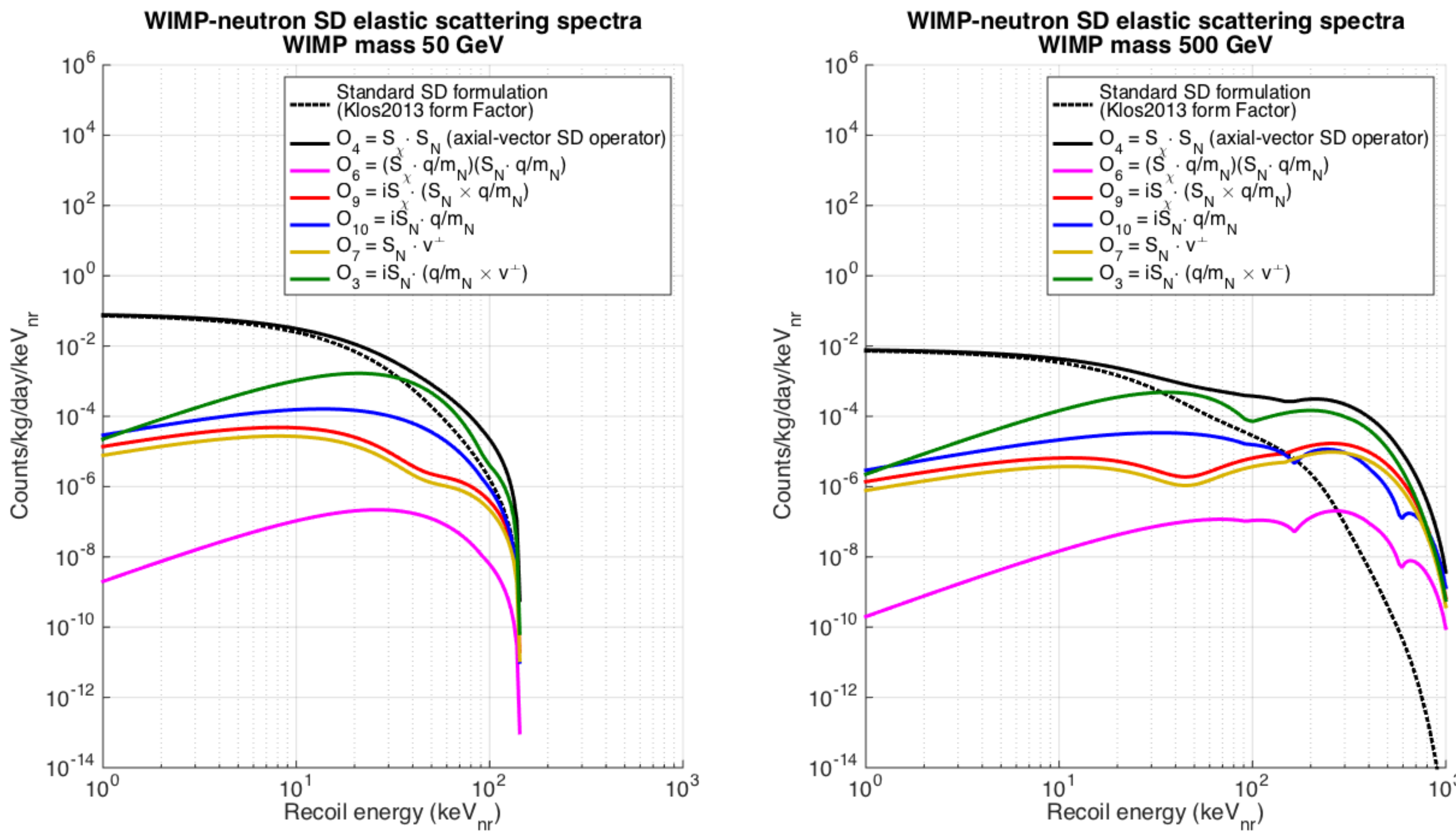


O_1 (the usual SI interaction) and O_{11} both produce an SI response, but the spectra have different slopes due to different *q*-dependence.

O_5 and O_8 each produce both an LD and an SI response, again with different *q*-dependence.

For m_{WIMP} large, the EFT spectra stay relatively flat out to ~few hundred keV.

Spin-dependent and LSD



The two types of SD response (transverse and longitudinal to the momentum transfer *q*) exhibit distinctly different behaviors.

Again the slope of the spectrum depends on the *q*-dependence of the operator.

O_3 (green) is the only LSD operator. Its spectrum increases sharply to around 50 keV and does not begin to decrease until ~300 keV for heavy WIMPs.

Constraints on Representative Operators