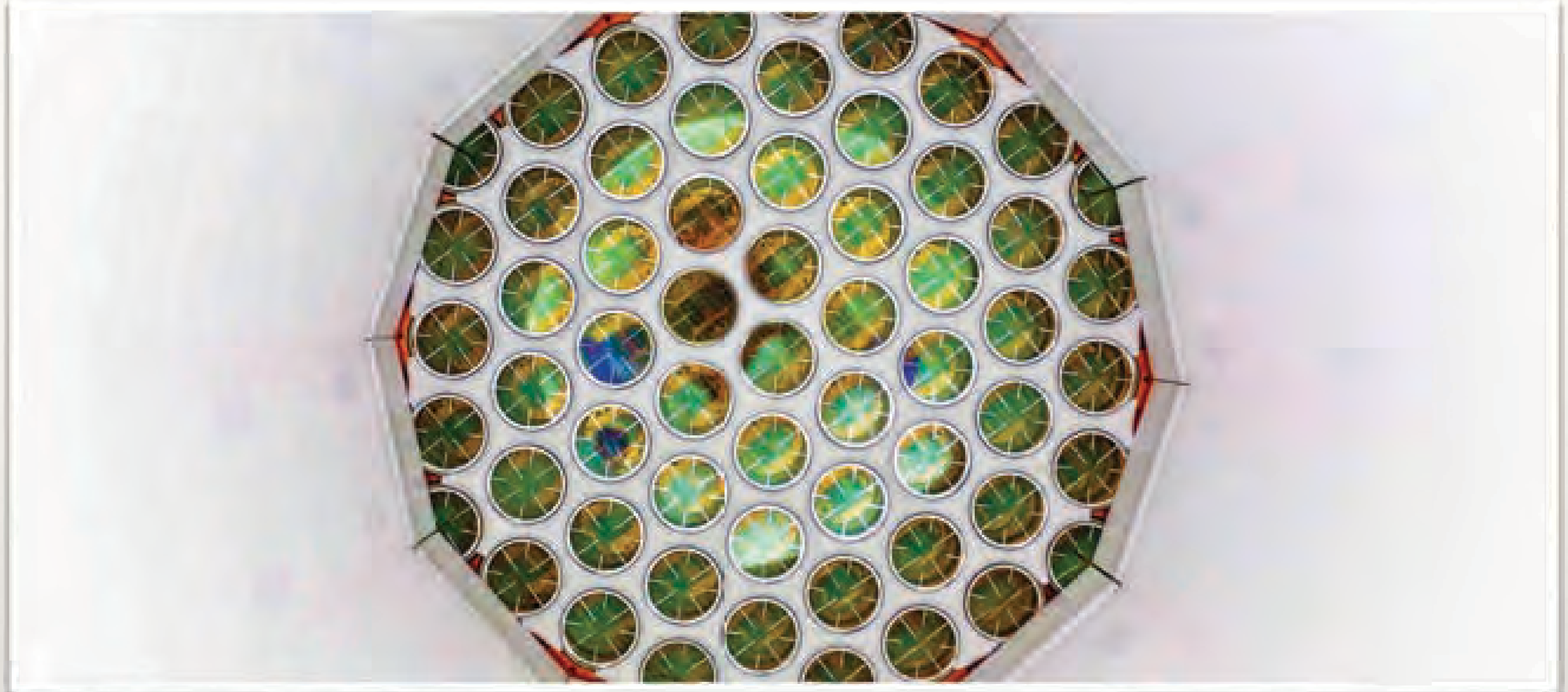


PATRAS 2017 workshop, 16th of May 2017

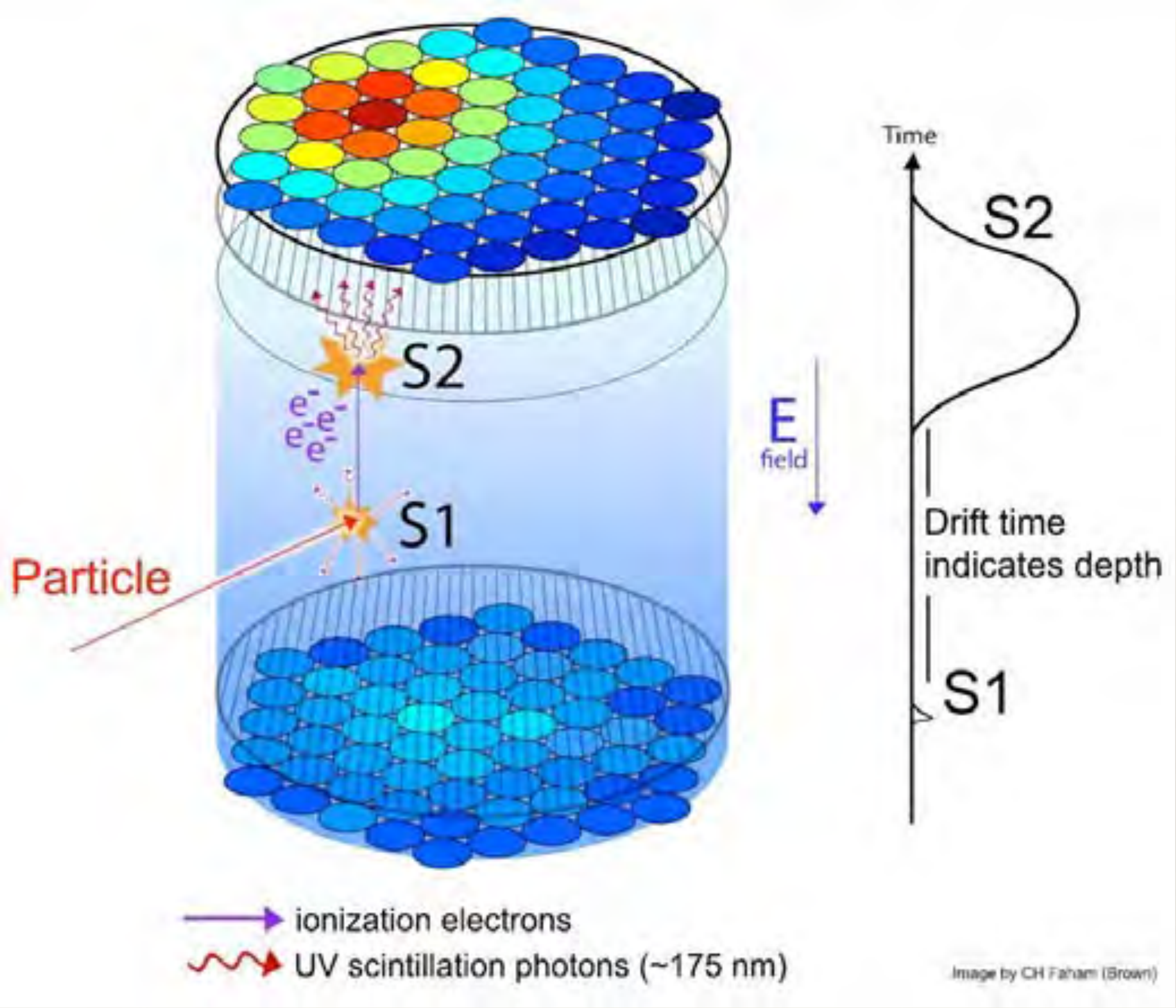
Direct Dark Matter Searches with LUX and LZ

Alex Lindote

LIP and University of Coimbra

on behalf of the LUX and LZ collaborations

2-phase xenon TPC – working principle

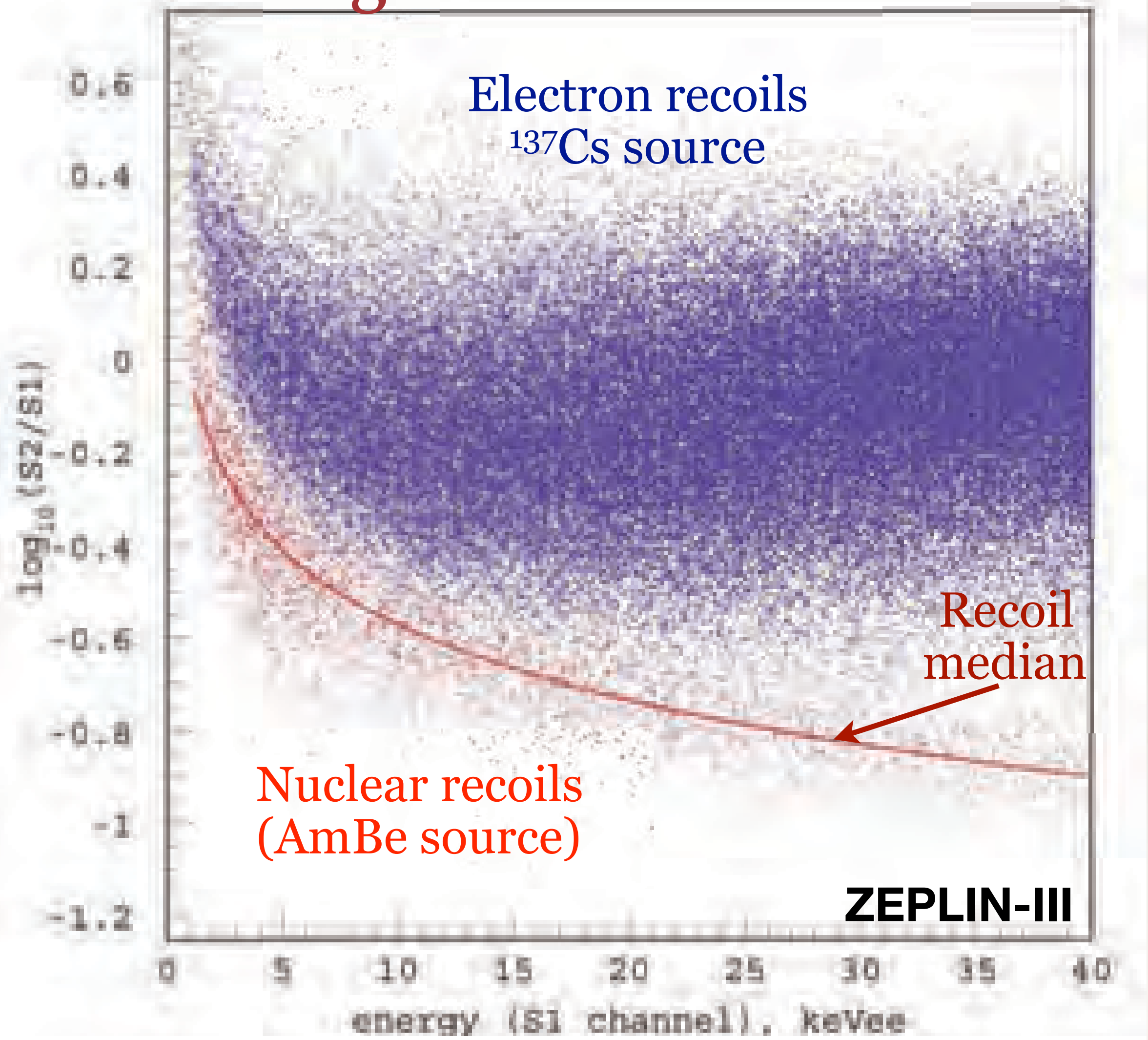


3D Position Reconstruction

- Z from time difference between S1 and S2 (1.5 mm/μs @ 180 V/cm)
- XY reconstructed from light pattern (resolution of a few mm in WIMP search region)

- WIMPs and neutrons → nuclear recoils **short, dense tracks**
- γs and e$^-$ → electron recoils **longer, less dense tracks**

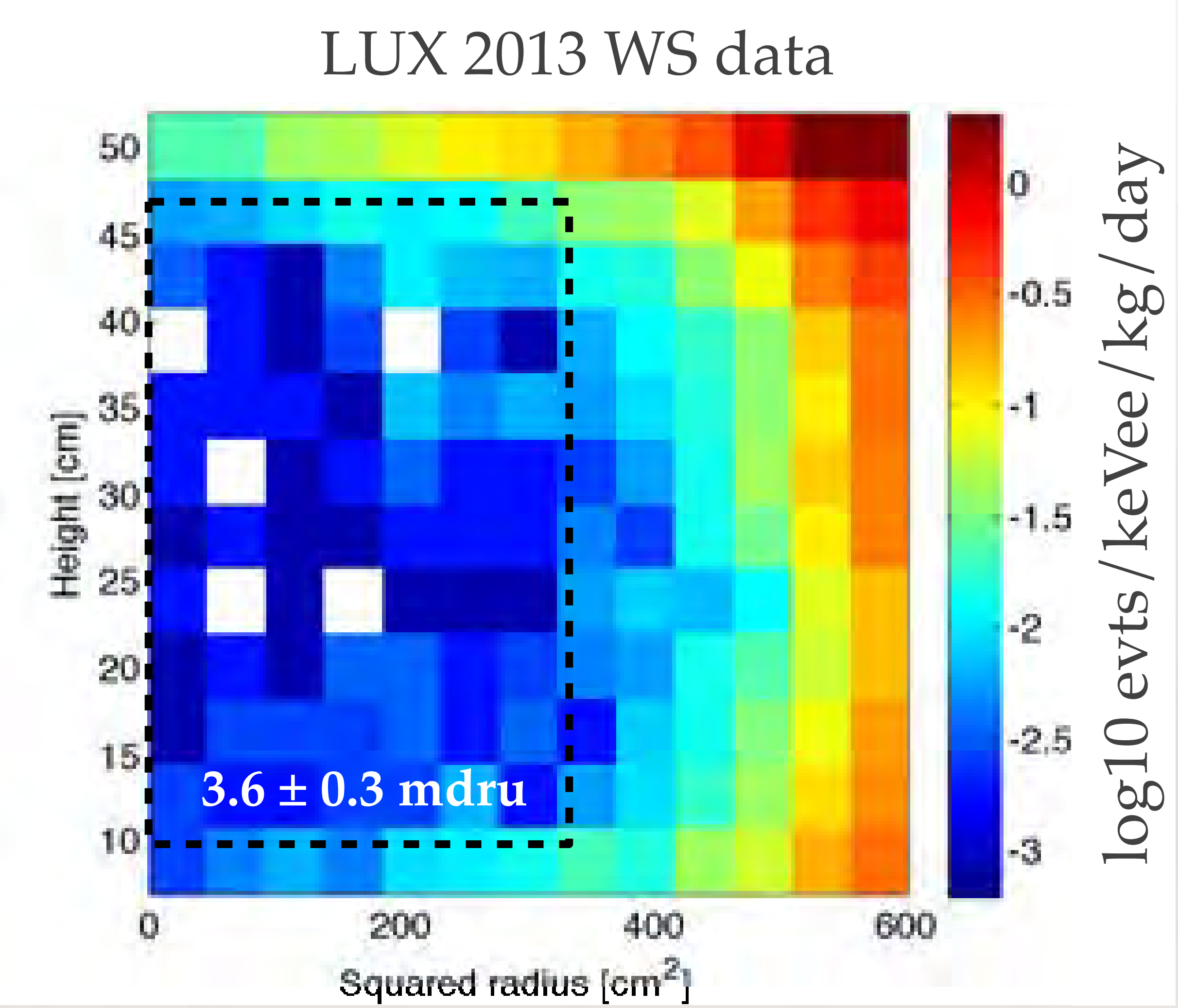
Background discrimination



S2/S1 used for discrimination (>99.5% @ 50% NR acceptance)

Xenon as a WIMP target

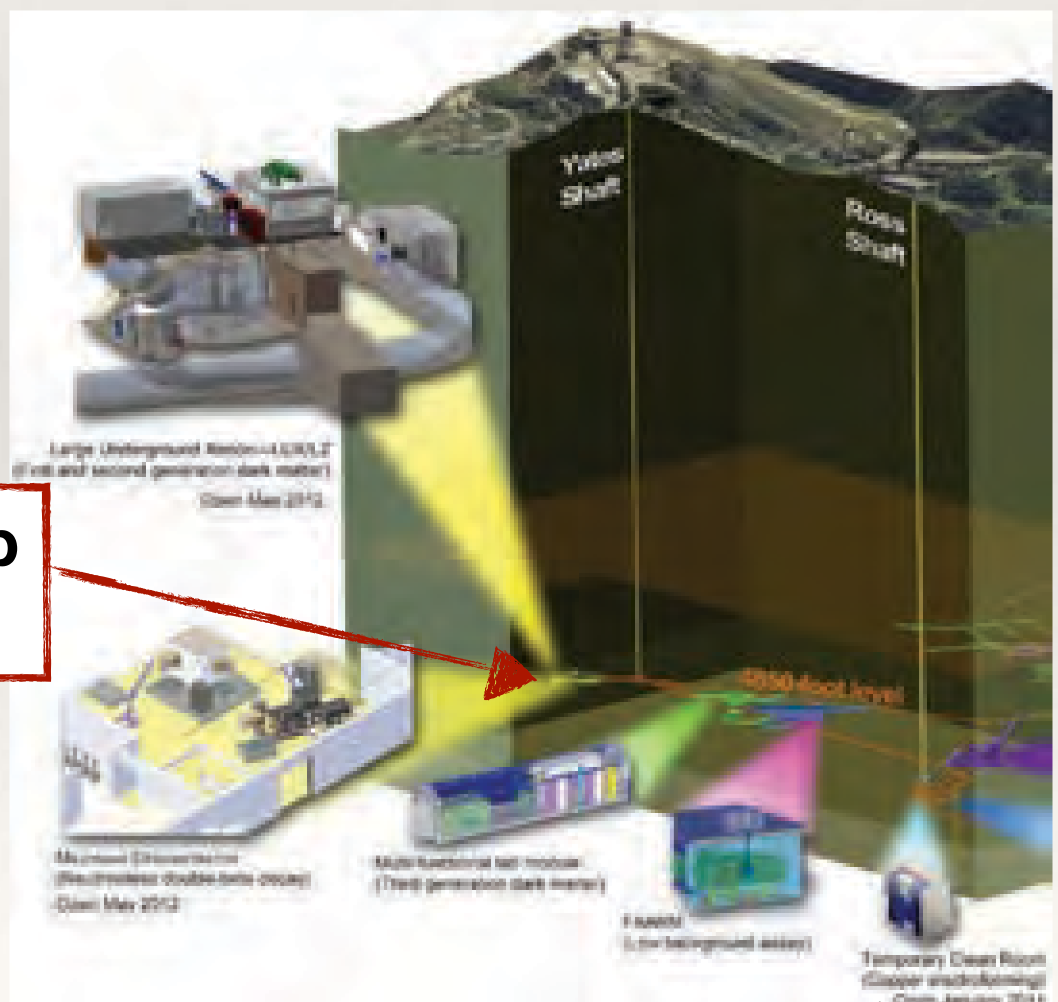
- Relatively high density (2.9 g/cm3)
- Self-shielding (using 3D pos. recons.)
- High atomic mass (A=131 g/mol)
- Spin-dependent sensitive isotopes
- Long electron drift lengths (~1 m)
- Excellent ionisation threshold
- No intrinsic backgrounds
- Scalable to multi-ton size

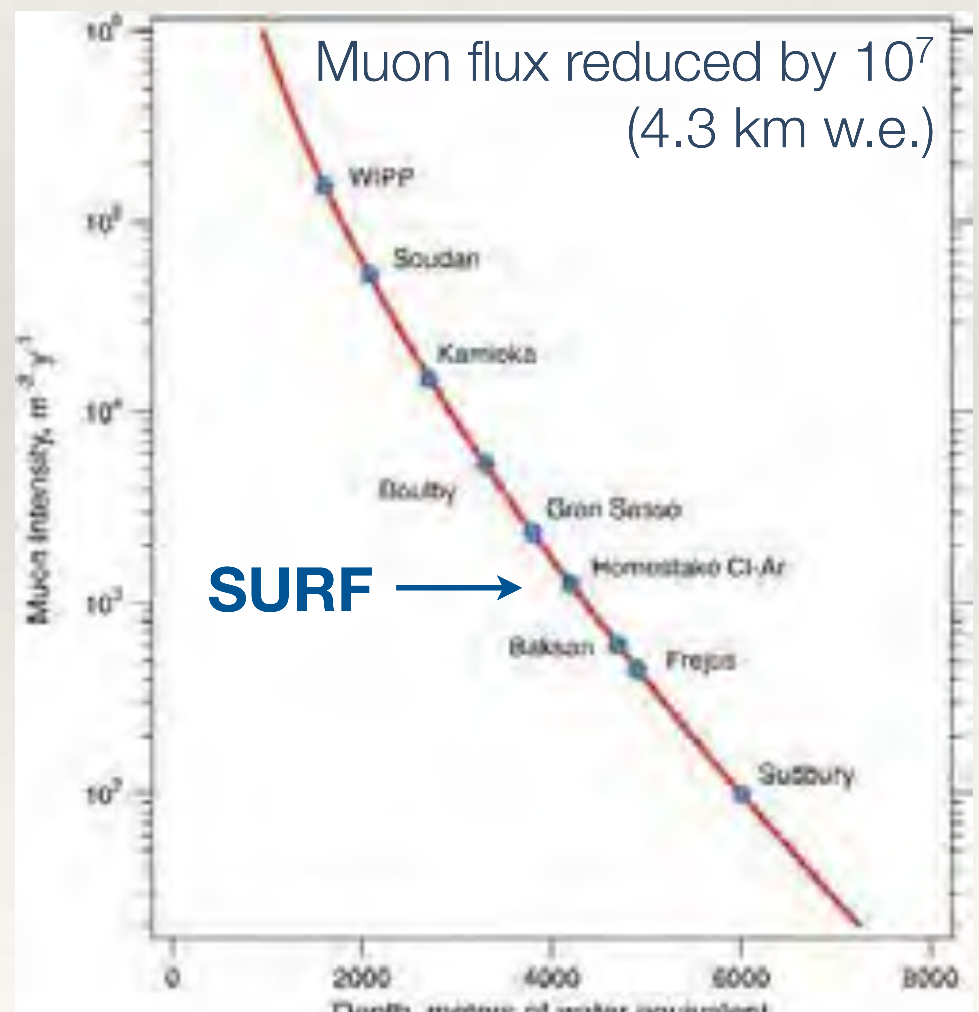


1 mdru = 1 evt/keV/ton/day

Sanford UG Research Lab

4850 feet deep (1478 m)





LUX Timeline

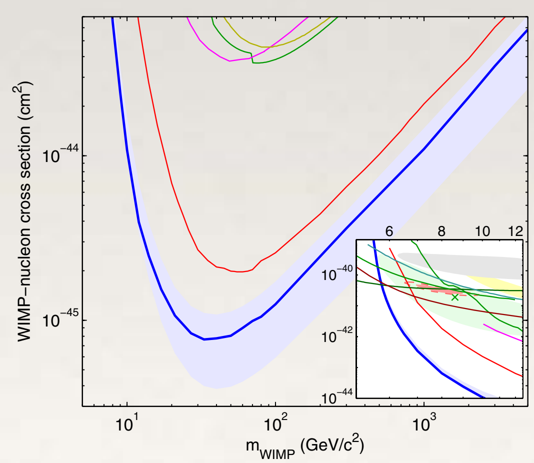
2006: LUX collab. formed

2008: LUX funded (DOE+NSF)

2012 (Jul): UG lab complete, LUX moves UG

2013 (Apr): First science run starts

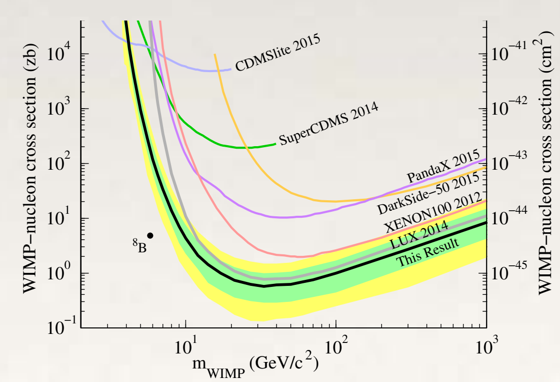
2013 (Nov): First results (3 months) reported



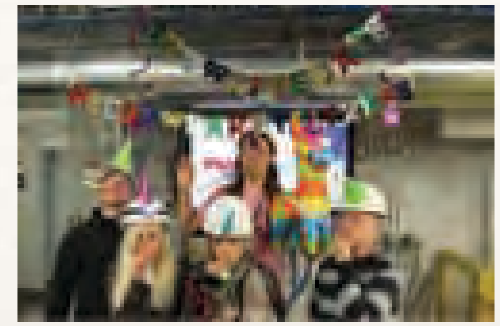
PRL, 112, 091303 2014

2014 (Sep): 332-day run started!

2015 (Dec.) 3-month run reanalysis posted



PRL, 116, 161301 2016
PRL, 116, 161302 2016



2016 (May): Run finished

2016 (July): 332 day results announced

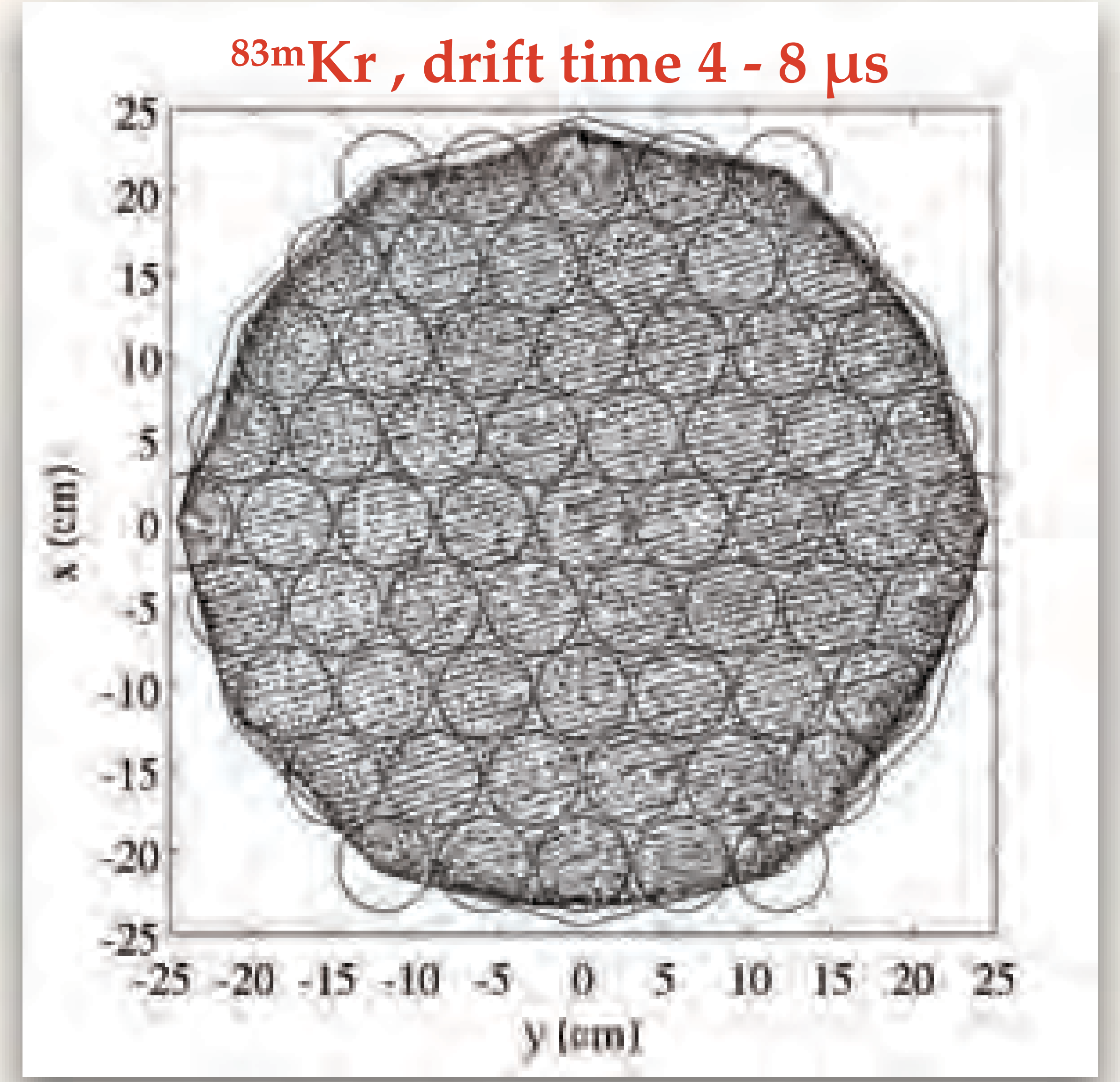
2016 (Sep): Decommis. starts

LUX Details

- 49 cm diameter by 59 cm height dodecagonal chamber
  - PTFE walls to maximize light collection
  - 48 cm drift length
- 370 kg of liquid xenon
  - 250 kg in the active region
- 122 Hamamatsu R8778 PMTs
  - in two arrays
- Ultra-low background Ti cryostats
- Xenon continuously recirculated to maintain purity (~250 kg/day)
- Chromatographic separation reduced Kr content to ~4 ppt
- Inside 300 tonne water tank
  - all external backgrounds subdominant

Calibrations – ^{83m}Kr

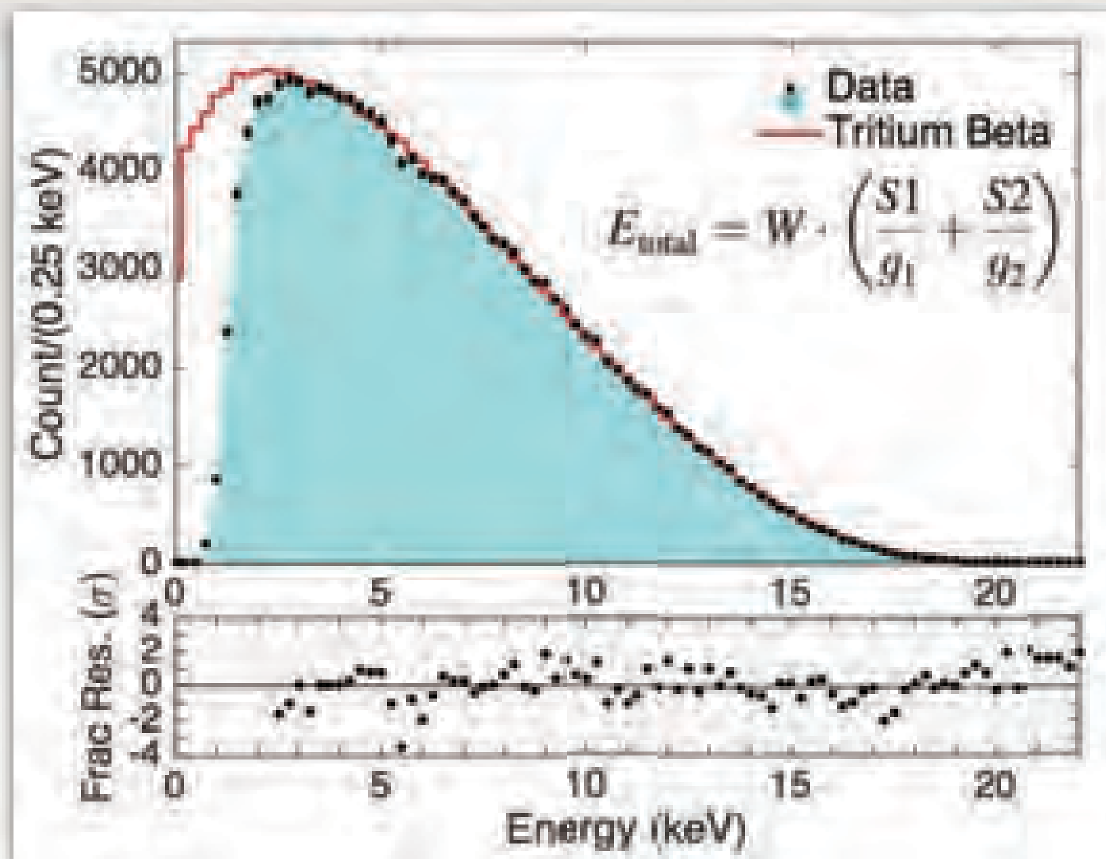
- Injected ~weekly in the gas system
- Quickly mixes in the xenon, uniform distribution
- 2 IT electrons in quick succession
  - 32.2 keV + 9.4 keV ($T_{1/2}$ = 154 ns)
  - Mono energetic for our standard analysis
- 1.8 hours half-life
  - Clears the system in a few hours
- Used for:
  - Position reconstruction
  - Electron lifetime
  - S1 and S2 position corrections

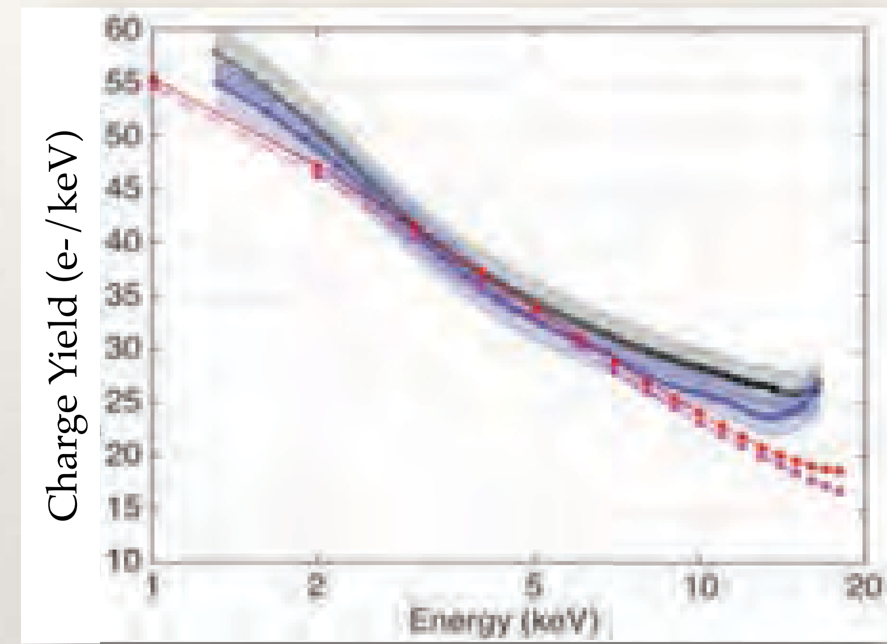


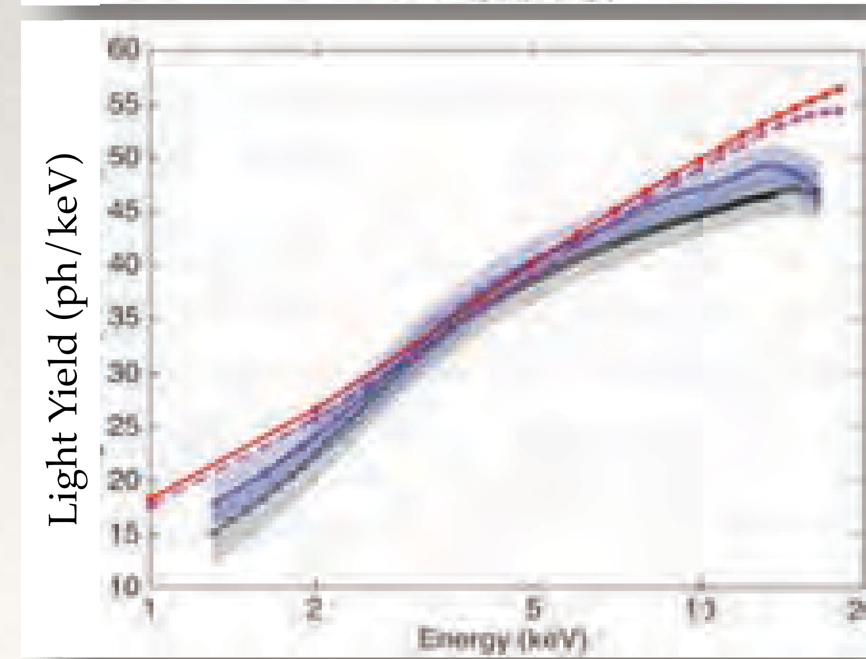
Calibrations - Electron Recoils

- Tritium has a low energy β decay (Q = 18.6 keV, <E> = 5.9 keV)
  - ideal to study the response of the detector to electron recoils
  - used to determine the ER band
- Long half-life (12.3 yr)
  - CH_3T removed by purity system ($T_{1/2}$ ~6 hours)
- Injected every three months

Phys. Rev. D 93, 072009 (2016)

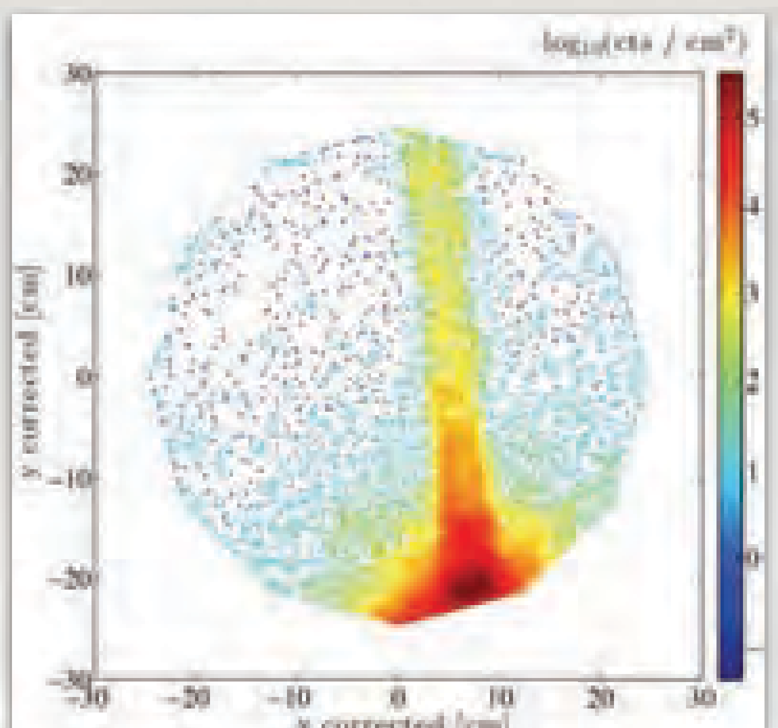


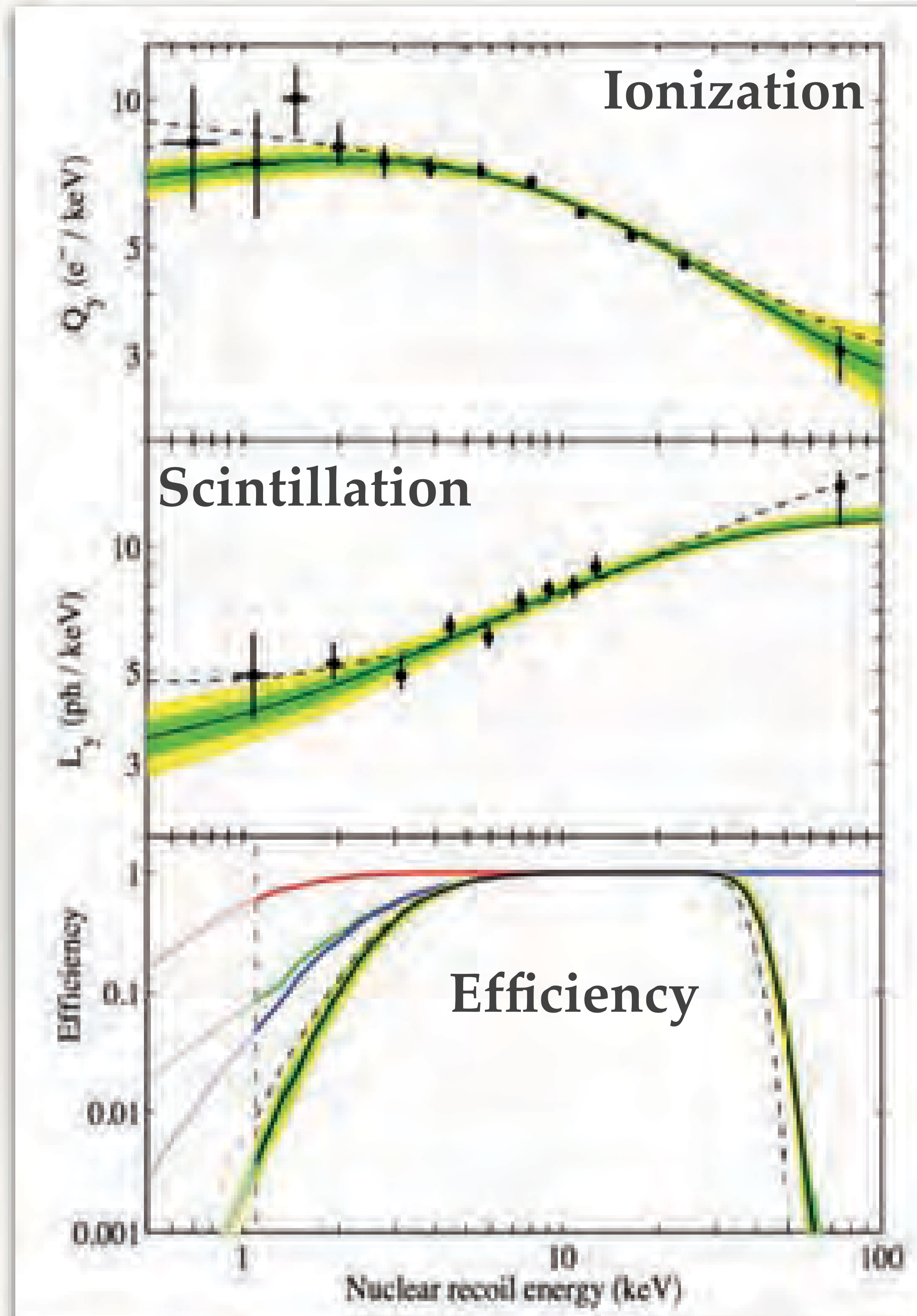




Calibrations – Nuclear Recoils

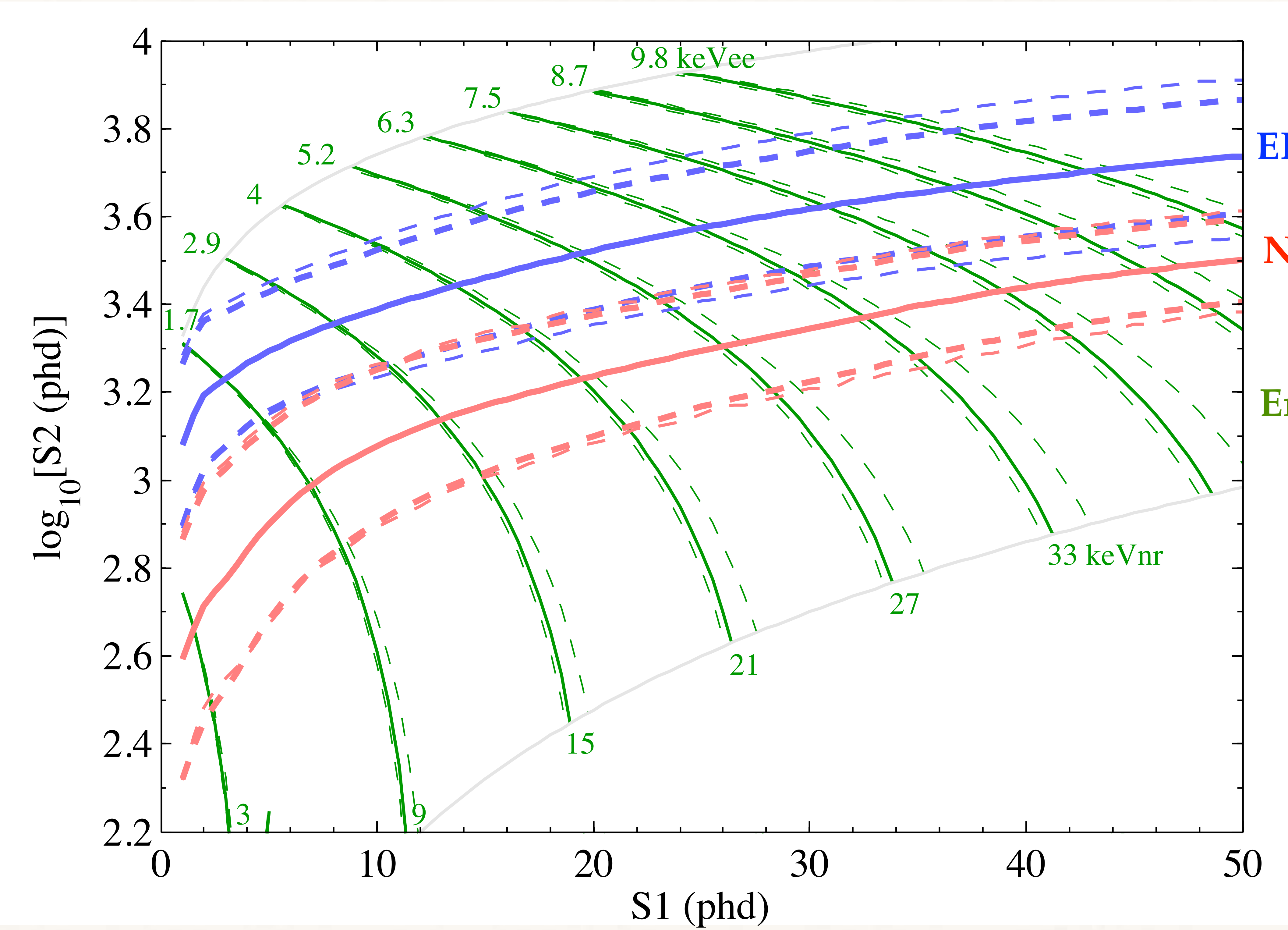
- DD neutron generator outside water tank (2.45 MeV neutrons)
- NR calibrations every 3 months and at different levels
- Double scatters used for Q_y analysis (0.7 - 74 keV)
- Single scatters used for L_y analysis and NR band (1.1 - 74 keV)





https://arxiv.org/abs/1608.05381

Parameter Space



Dashed lines are 10%-90%-iles

Backgrounds in 2014-16 Run

- LUX is a low-background detector
  - Furthermore, we already understand the backgrounds from the previous run
  - Unlike the 2013 run, ^{127}Xe is no longer present

Background source	Expected number below NR median
External gamma rays	1.51 ± 0.19
Internal betas	1.2 ± 0.06
Rn plate out (wall background)	8.7 ± 3.5
Accidental S1-S2 coincidences	0.34 ± 0.10
Solar ^{8}B neutrinos (CNNS)	0.15 ± 0.02

These are figures of merit only, we do a 5D likelihood analysis!

External gamma rays and internal betas: In the bulk, leakage at all energies

Rn plate out: Low energy, but limited to the edge of the detector*

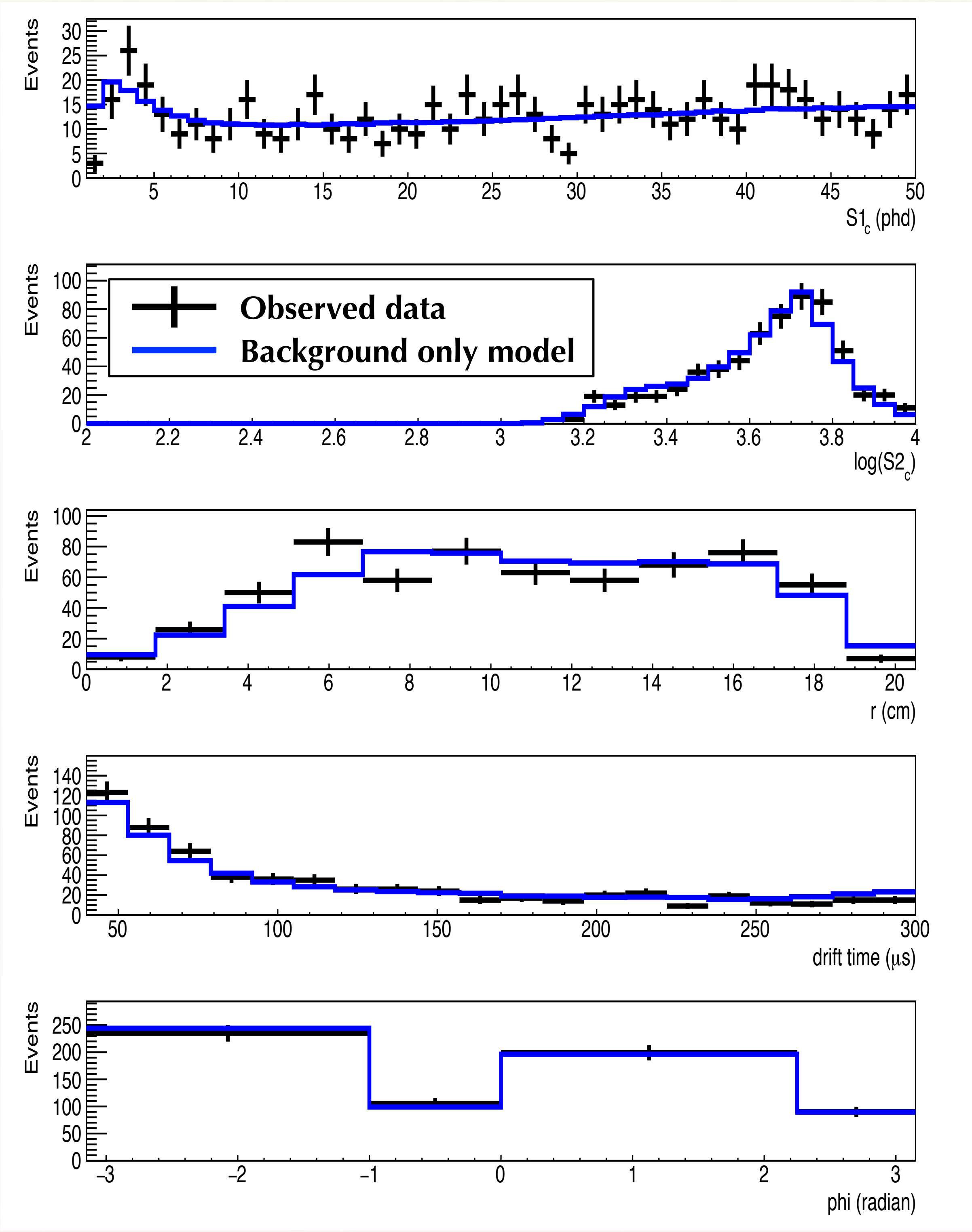
Accidental S1-S2 coincidences and solar ^{8}B neutrinos: In the bulk, at low energy in the NR band

~ 0.3 single scatter neutrons, not included in PLR

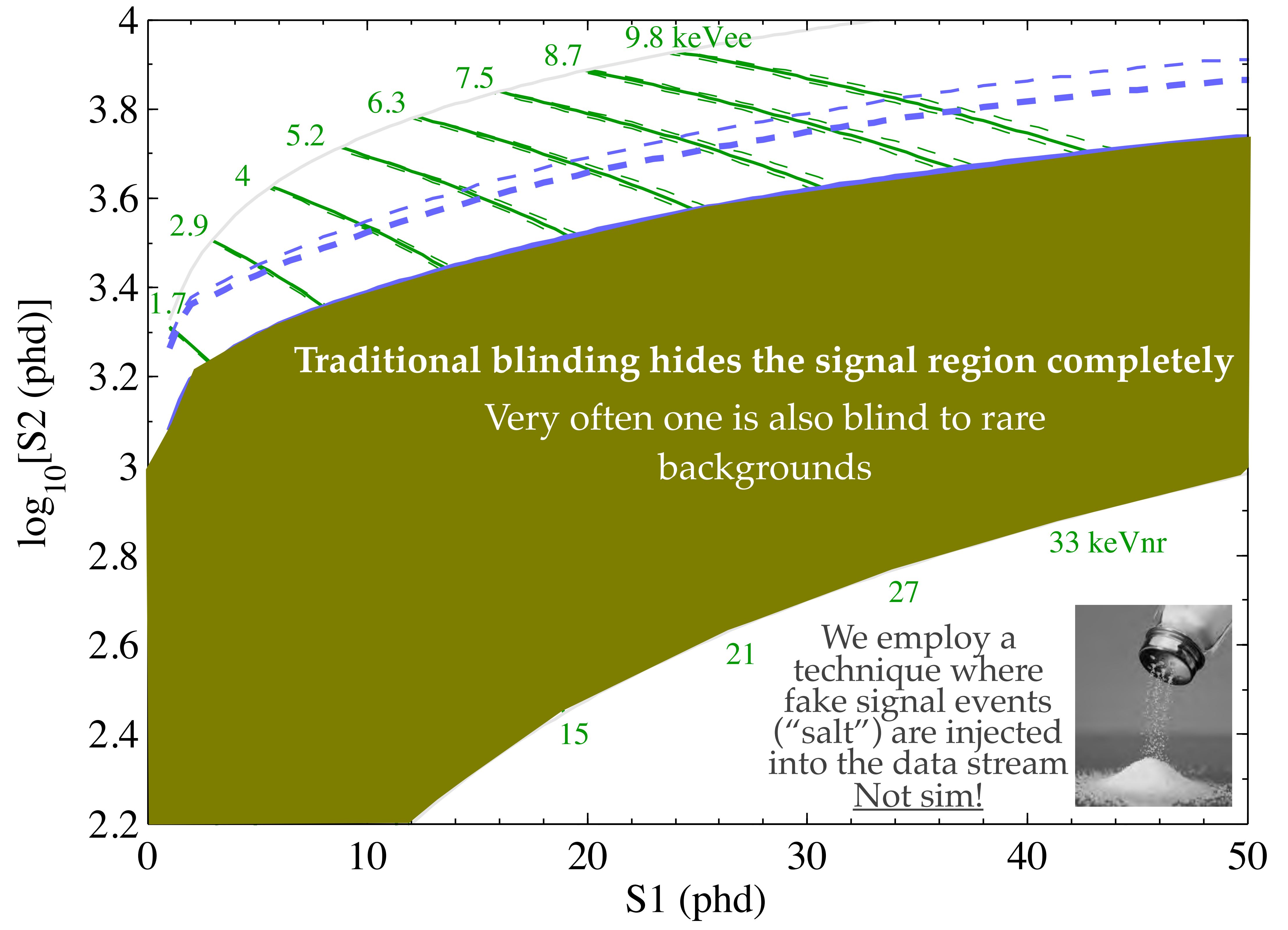
* - Our likelihood analysis includes position information, so these have a low likelihood as signal

Profile Likelihood Ratio Analysis

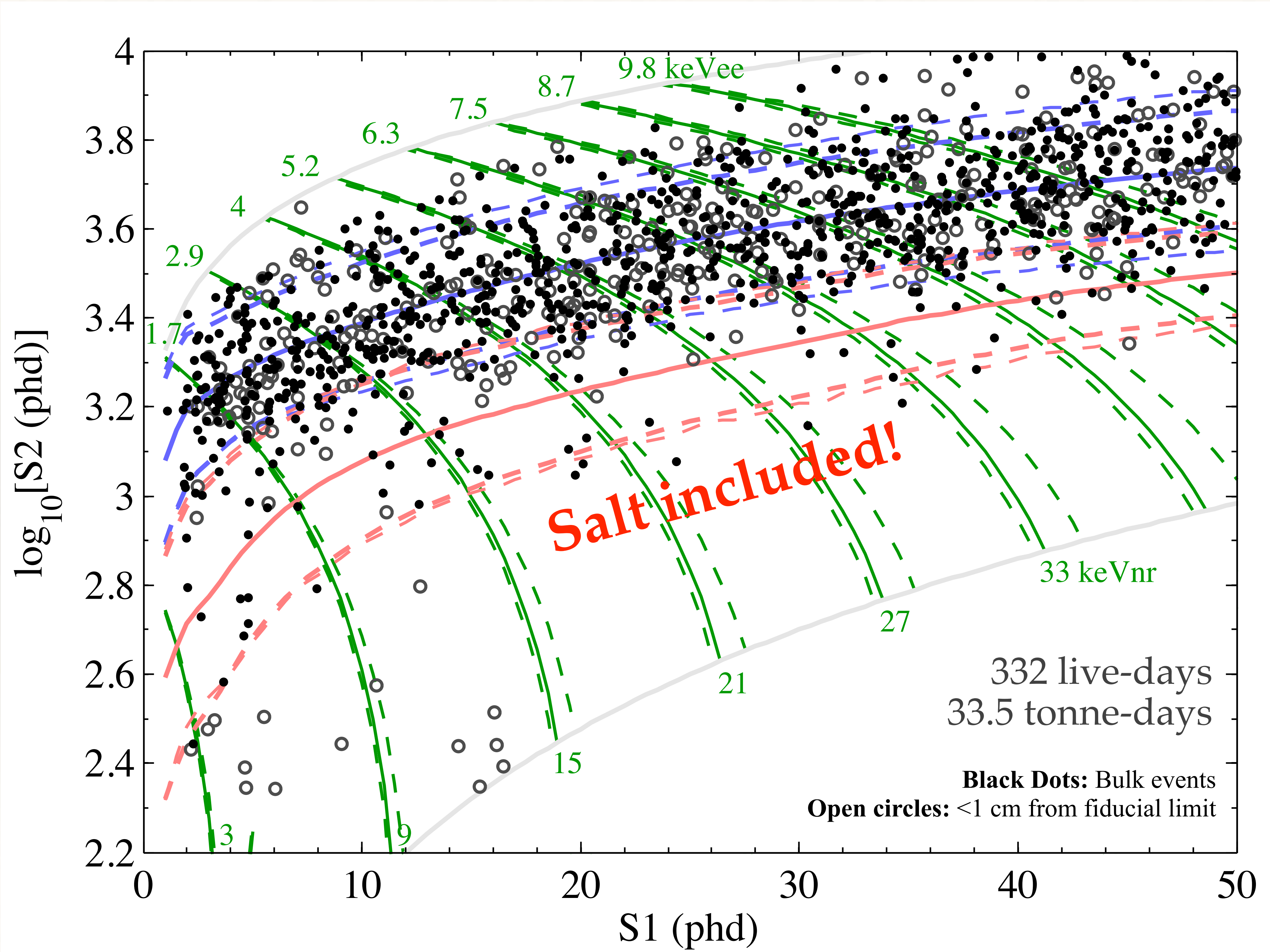
- The data in the upper-half of the ER band were compared to the model (plot at right) to assess goodness of fit.
- Data are compared to models in an un-binned, 2-sided profile-likelihood-ratio (PLR) test.
- 5 un-binned PLR dimensions:
  - Spatial: r, ϕ, drift-time (raw-measured coordinates)
  - Energy: S1 and log10(S2)
- 1 binned PLR dimension:
  - Event date



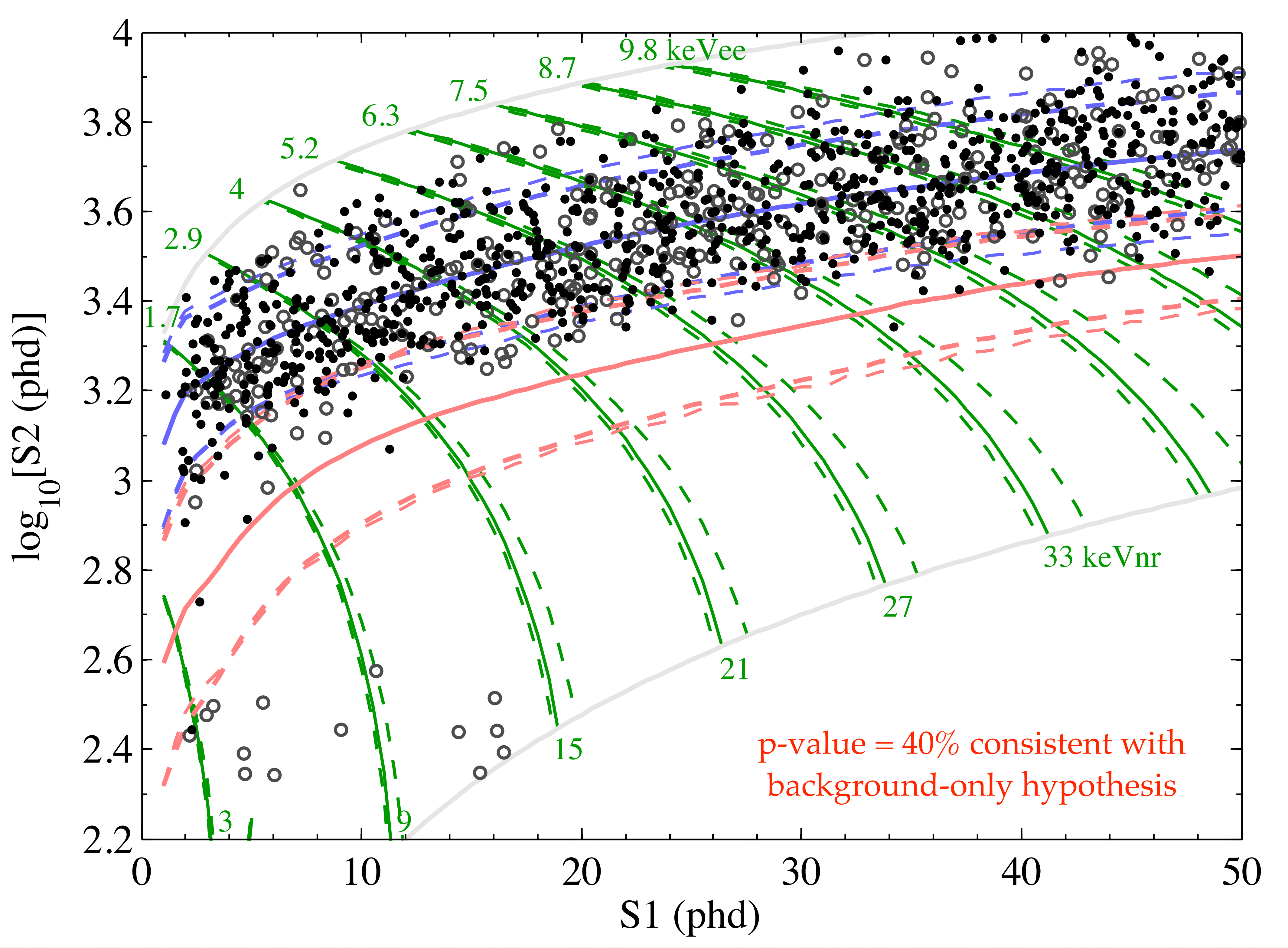
Salting


9.8 keVee
8.7
7.5
6.3
5.2
4
2.9
1.7
33 keVnr
27
21
15
Traditional blinding hides the signal region completely
Very often one is also blind to rare backgrounds
We employ a technique where fake signal events ("salt") are injected into the data stream
Not sim!
$\log_{10}$[S2 (phd)]
S1 (phd)
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
0
10
20
30
40
50

WIMP-Search Data

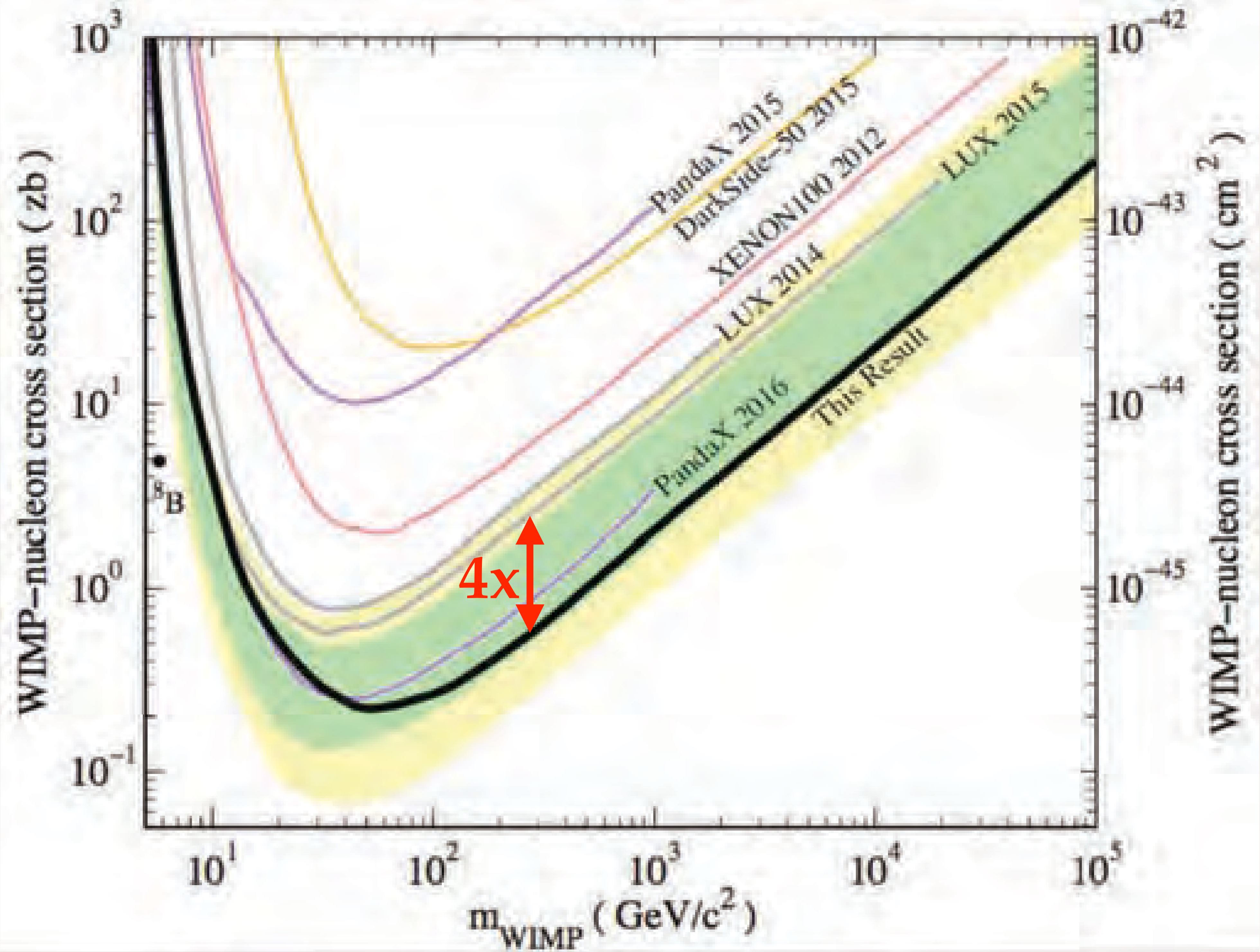


WS Data – 332 live-days

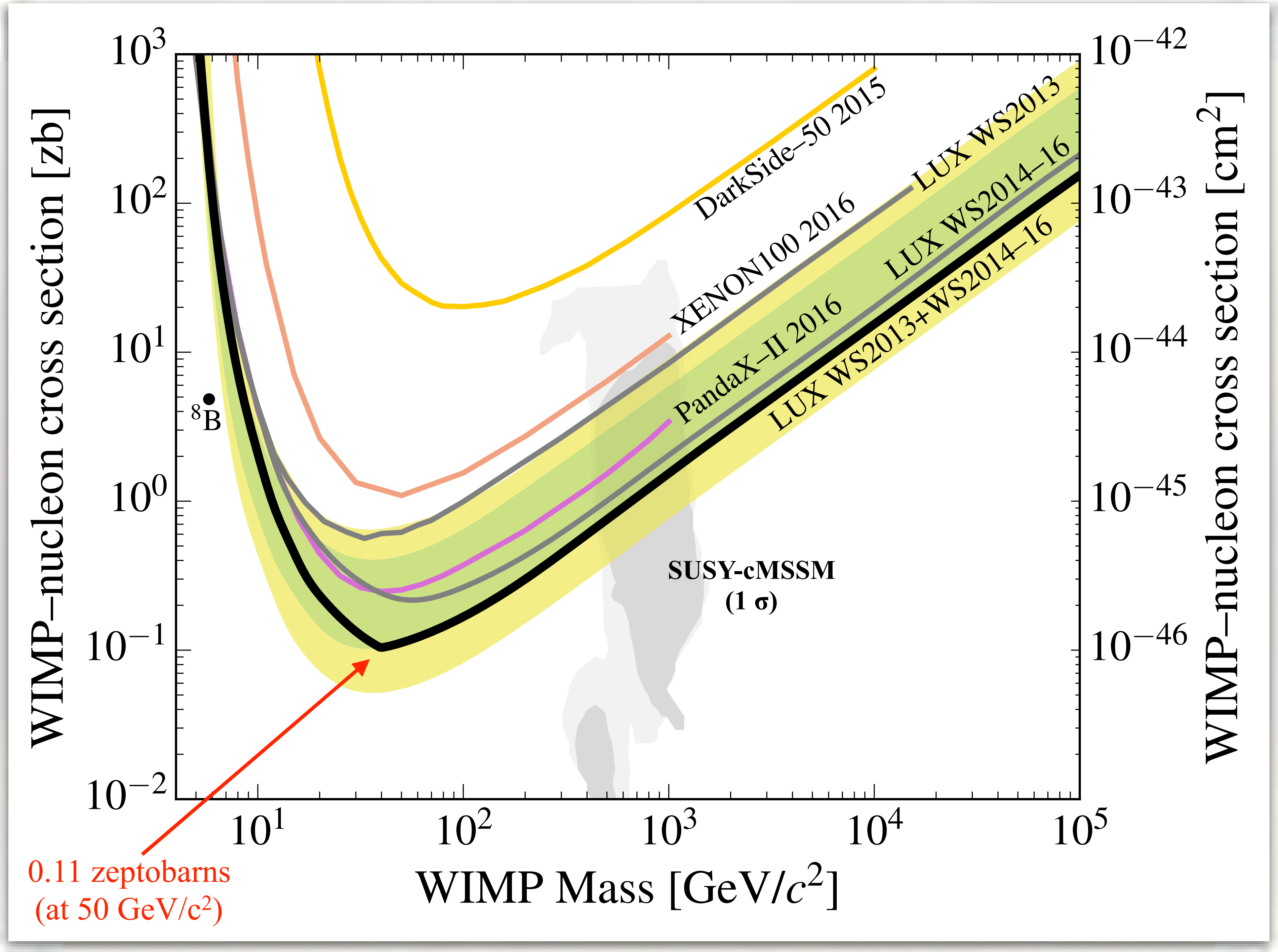


SI Exclusion Limit – 332 live-days

- 4x improvement at high mass
- Minimum of 0.22 zb @ 50 GeV
- Brazil bands show 1- and 2-sigma range of sensitivities, based on random BG-only experiments

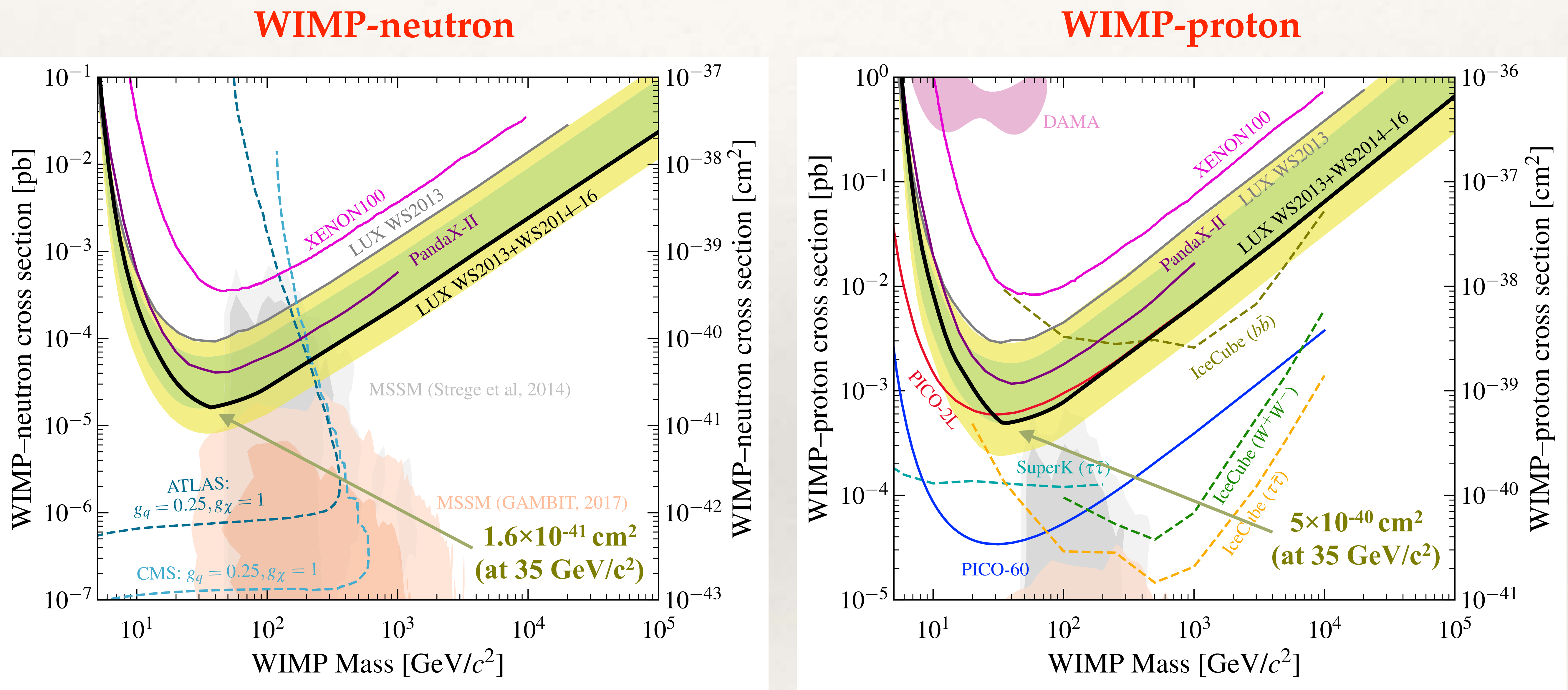


SI Exclusion limit – 95+332 live-days



PRL, 118, 21303 (2017)

SD Exclusion Limits – 95+332 live-days

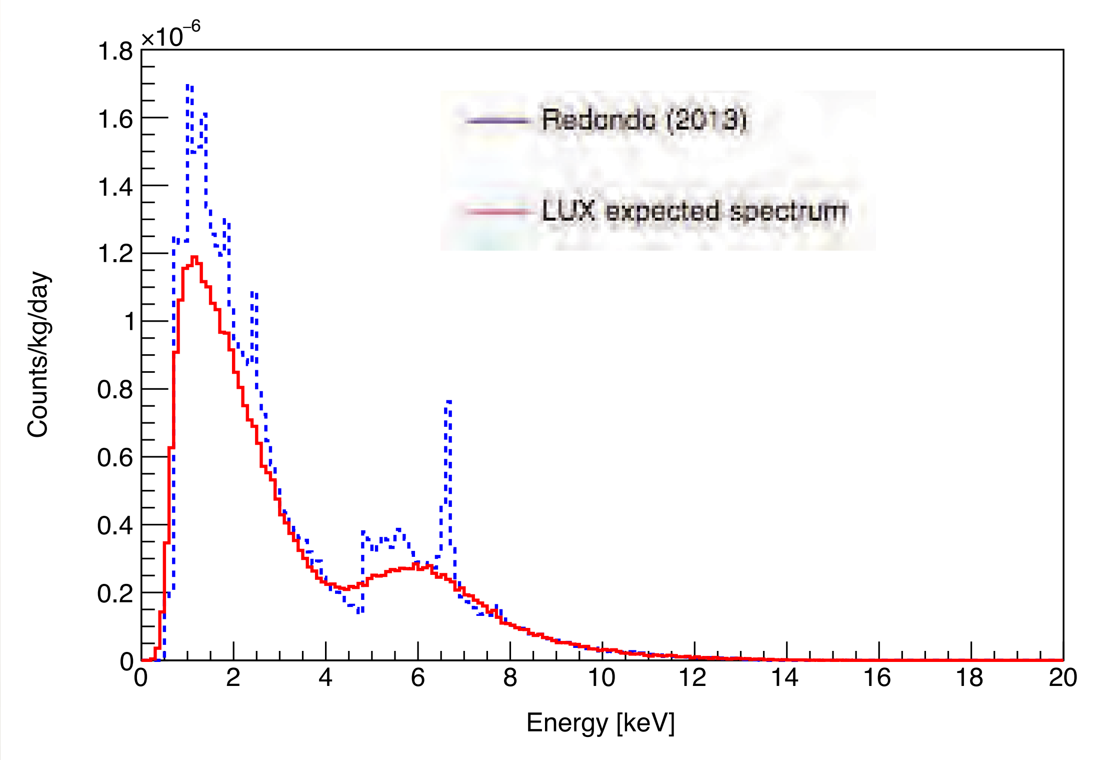


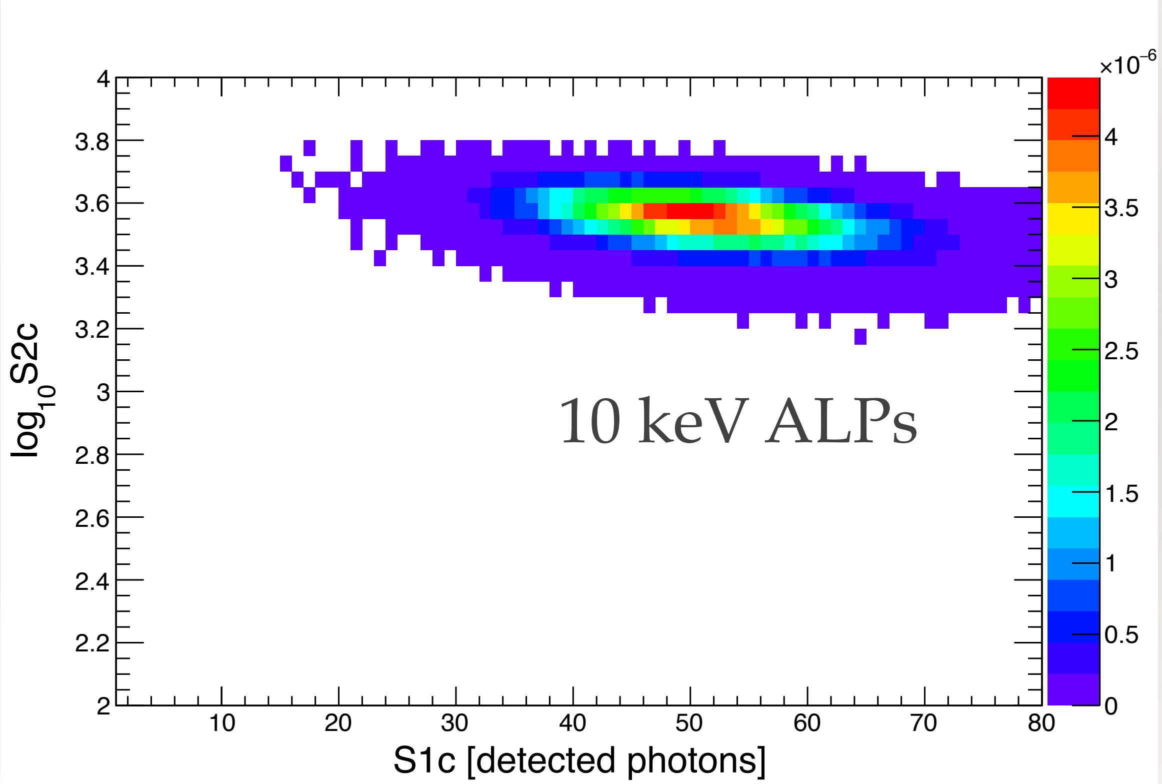
An improvement of a factor of six compared with the results from the 2013 run

arXiv:1705.03380

Axions and ALPs in the 2013 Data

- Solar axion spectral shape: convolution of solar axion flux (JCAP 12, 008 (2013), $g_{Ae} = 10^{-12}$) with axio-electric cross-section on xenon
- Resolution and efficiency modelled with NEST





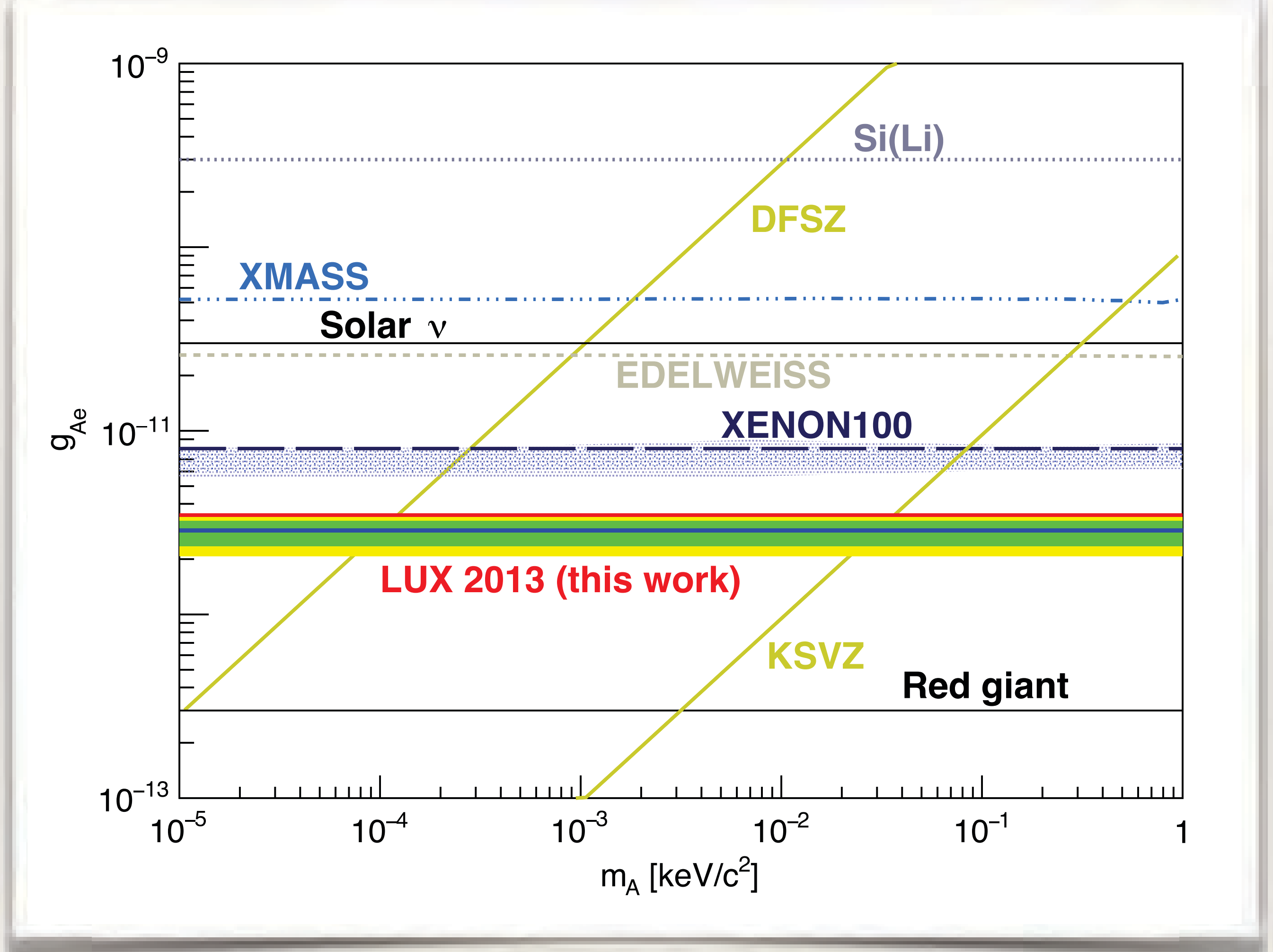
- ALPs expected to be at rest within the galaxy
- Axio-electric absorption leads to ERs with kinetic energy of the ALP mass: sharp feature, smeared by detector resolution

Backgrounds from 2013 data thoroughly studied and well understood

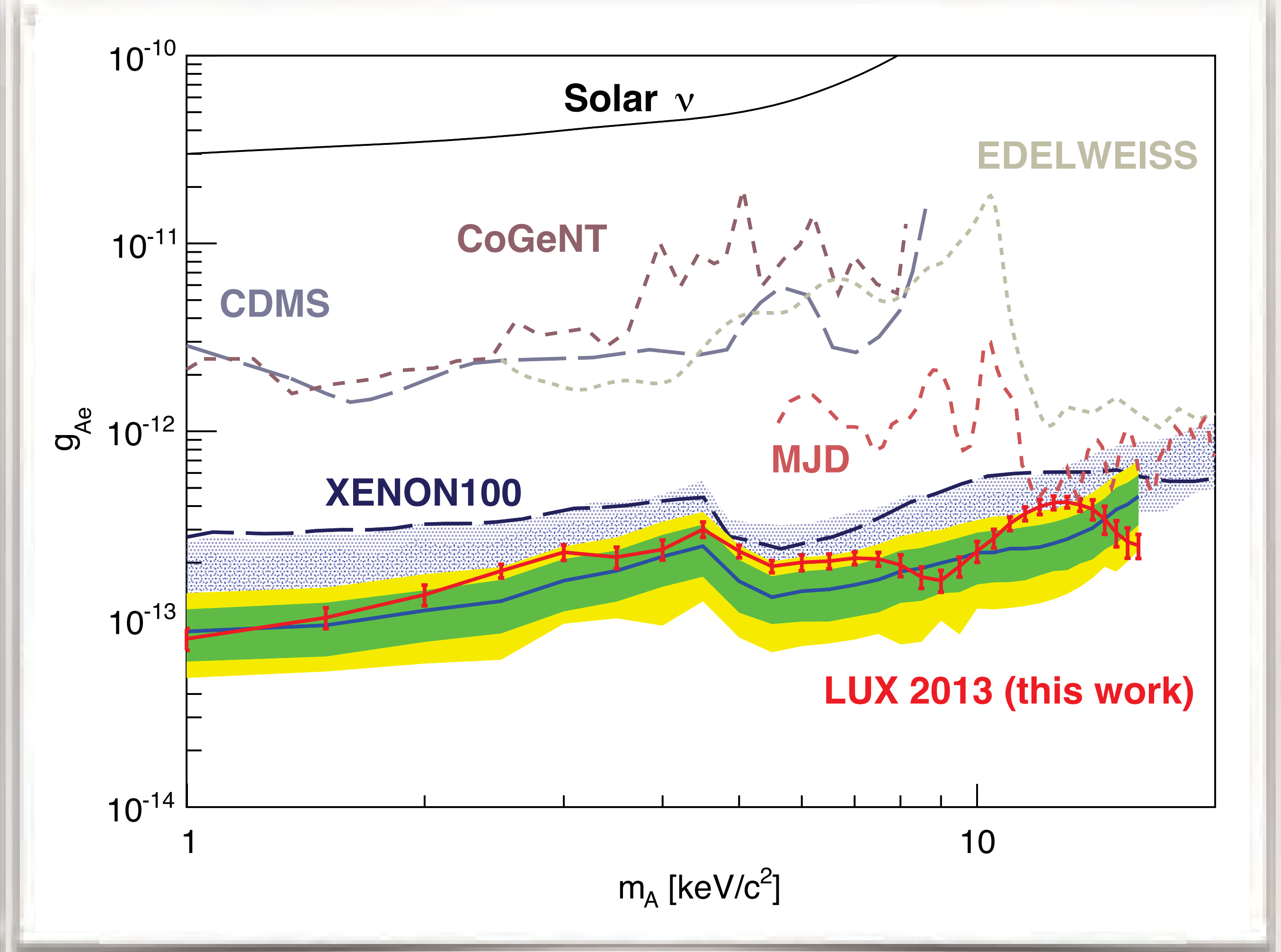
PLR analysis with 4 observables: *S1*, *log_{10}(S2)*, *r* and *z*

Limits for Axions and ALPs

Axions



ALPs



LUX 2013 excludes $g_{Ae} > 3.5 \times 10^{-12}$ (90% CL)

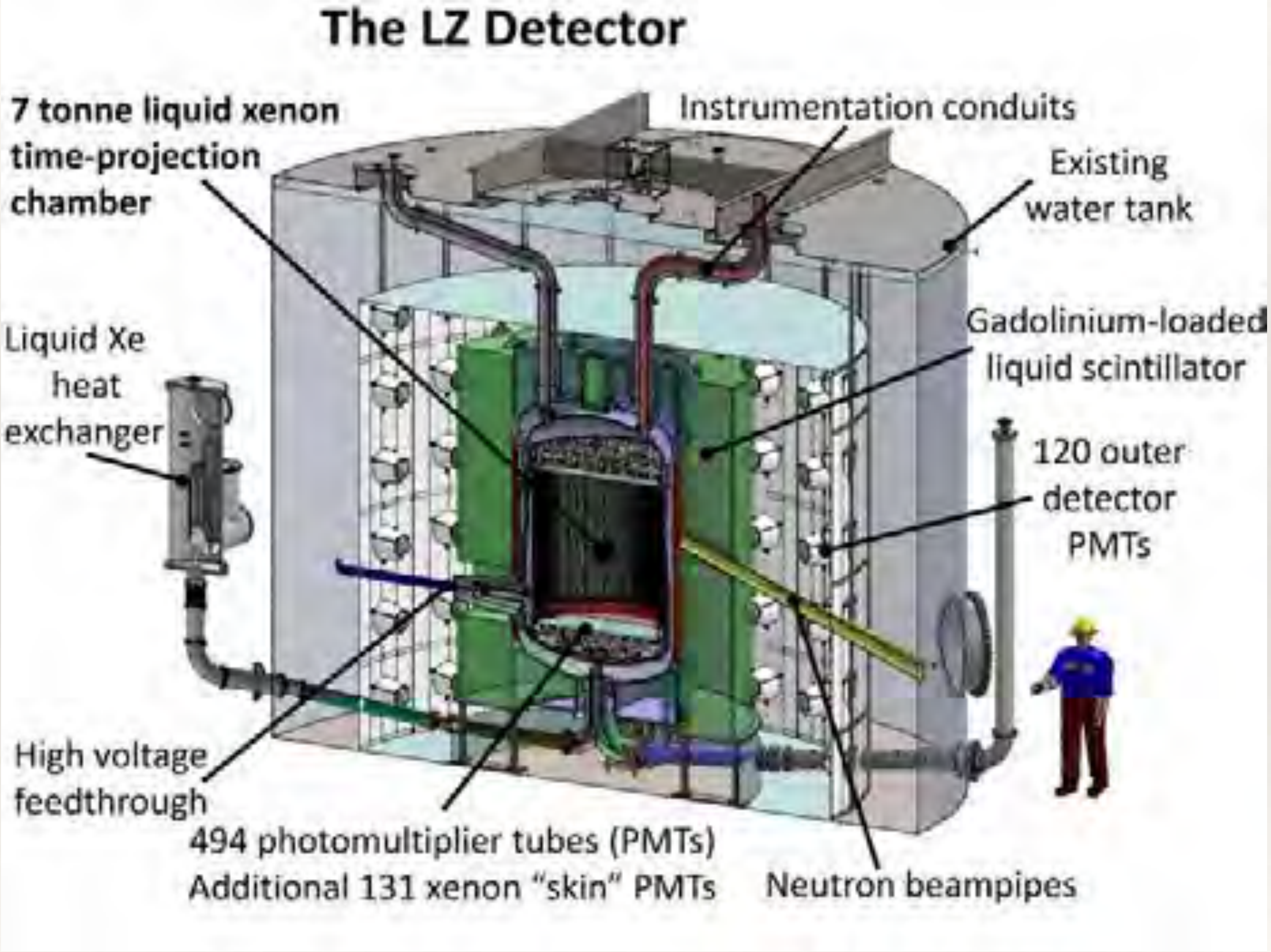
- $m_A > 0.12$ eV/c^2 (DFSZ model)
- $m_A > 36.6$ eV/c^2 (KSVZ model)

LUX 2013 excludes $g_{Ae} > 4.2 \times 10^{-13}$ (90% CL) across the range 1-16 keV/c^2 in ALP mass

arXiv:1704.02297

LUX-ZEPLIN

- 10 tonnes of LXe
  - 7 ton active
  - ~5.6 ton fiducial
- Will be installed in the laboratory used for LUX and use same water tank
- Liquid scintillator veto
- Instrumented skin region (additional veto)
- Commissioning starts in 2020, 1000 live-days run

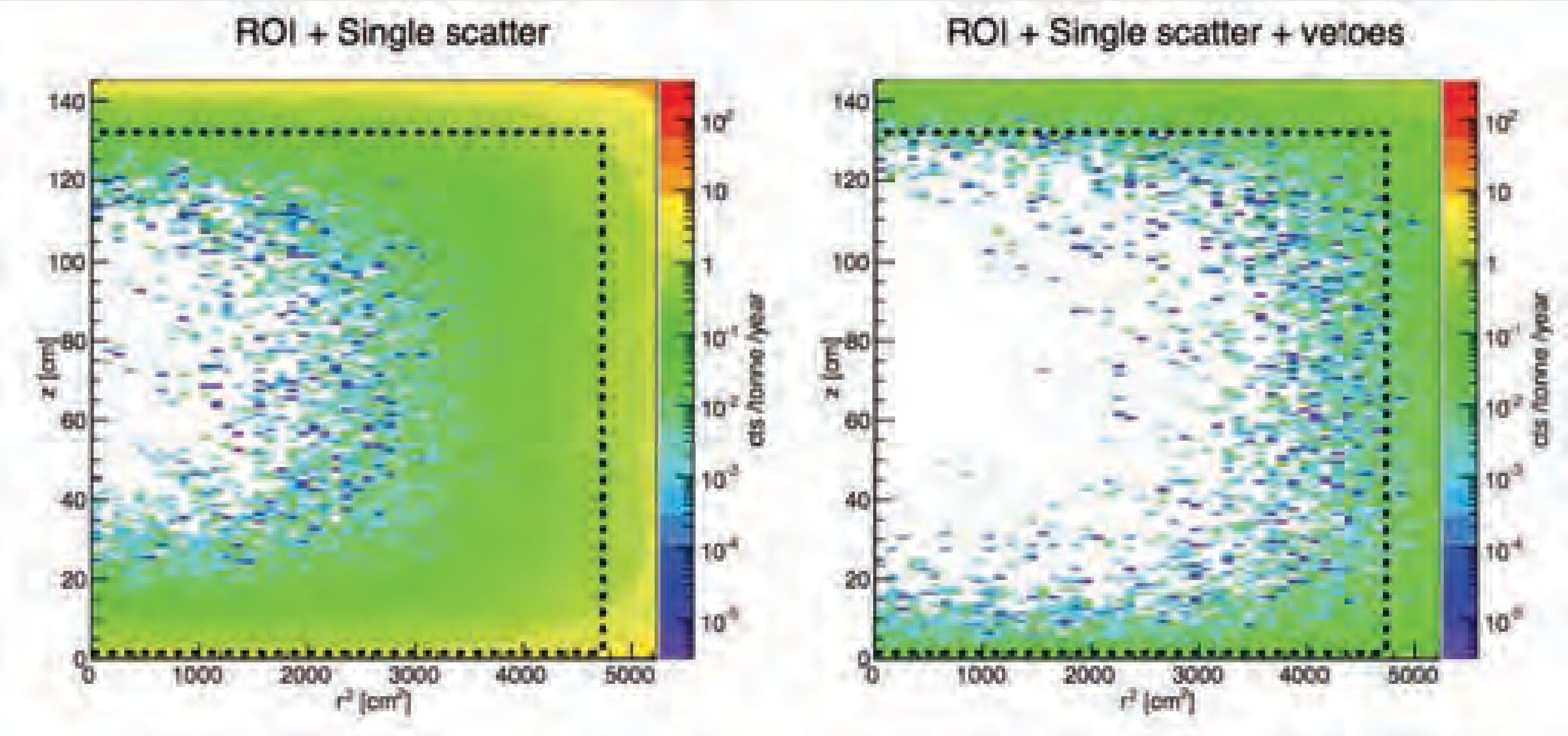


LZ TDR (arXiv:1703.09144)

Backgrounds in LZ

- <7 signal-like background events in 1000 live-days
  - Cut-and-count method, considering 99.5% ER discrimination and 50% NR acceptance
  - PLR used for sensitivity estimate
- Largest contribution comes from Rn
  - Followed by ν-e solar neutrino scattering and atmospheric CNN scattering

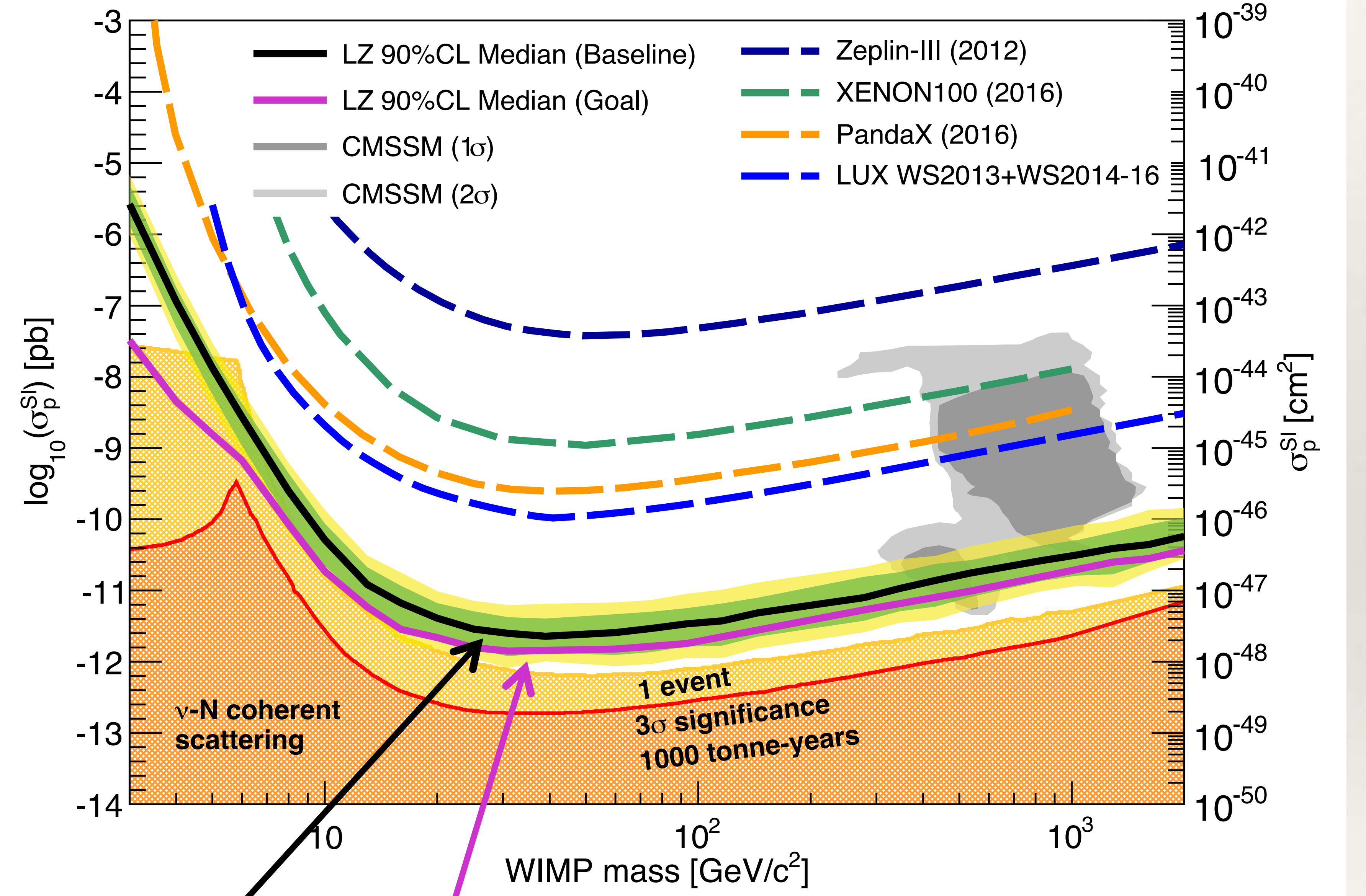
NR events from all detector components



LZ Sensitivity to WIMPs

Detector Parameter	Baseline	Goal
Light collection	7.5%	12%
Extraction efficiency	95%	99%
Electron lifetime (μs)	850	2800
N-fold trigger	3	2
^{222}Rn (mBq in 7 ton)	13.4	0.67

PLR is used to estimate the sensitivity



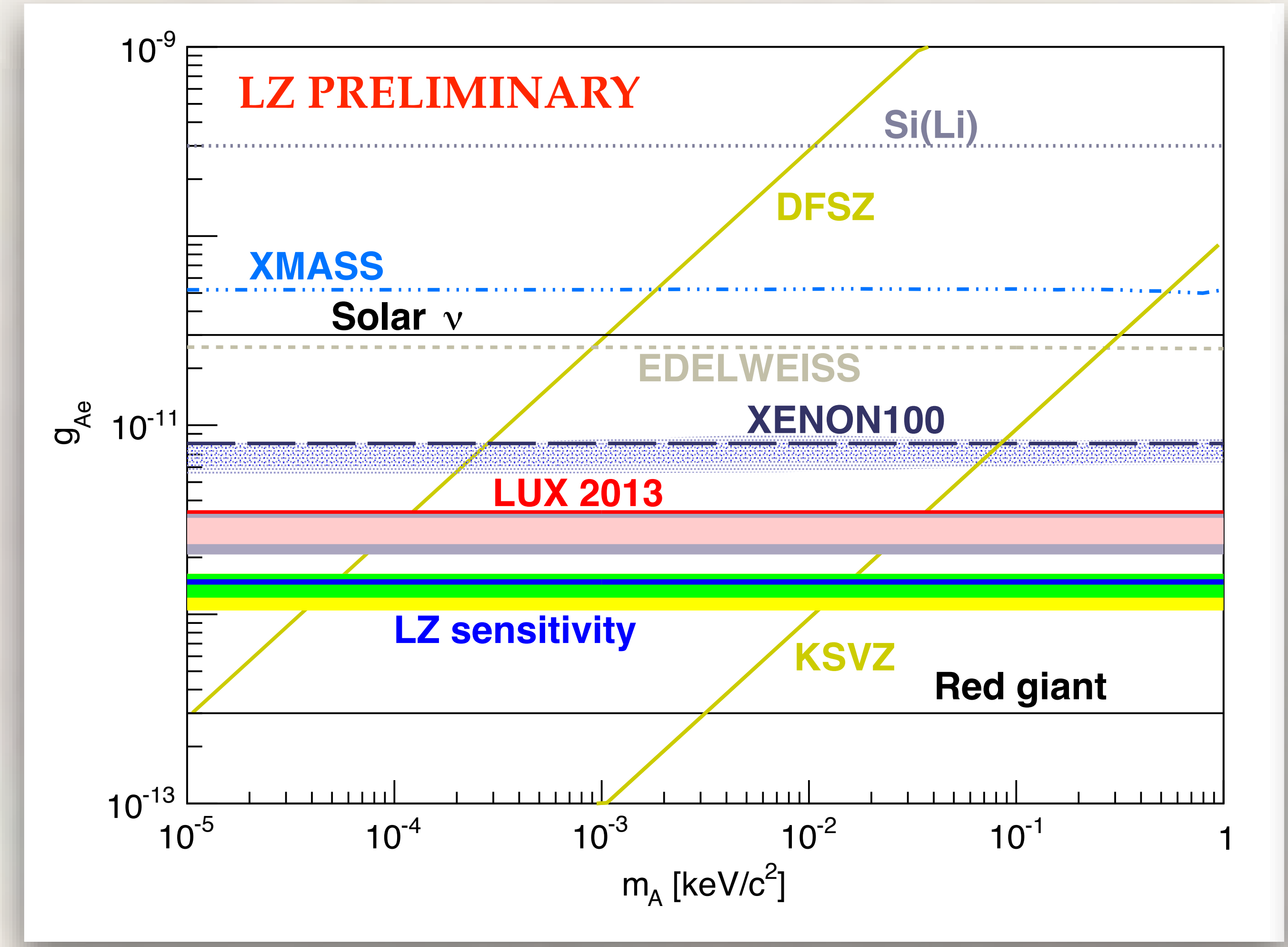
Baseline: 2.3×10^{-48} cm^2
(40 GeV WIMP)

Goal: 1.1×10^{-48} cm^2

LZ Sensitivity to Axions and ALPs

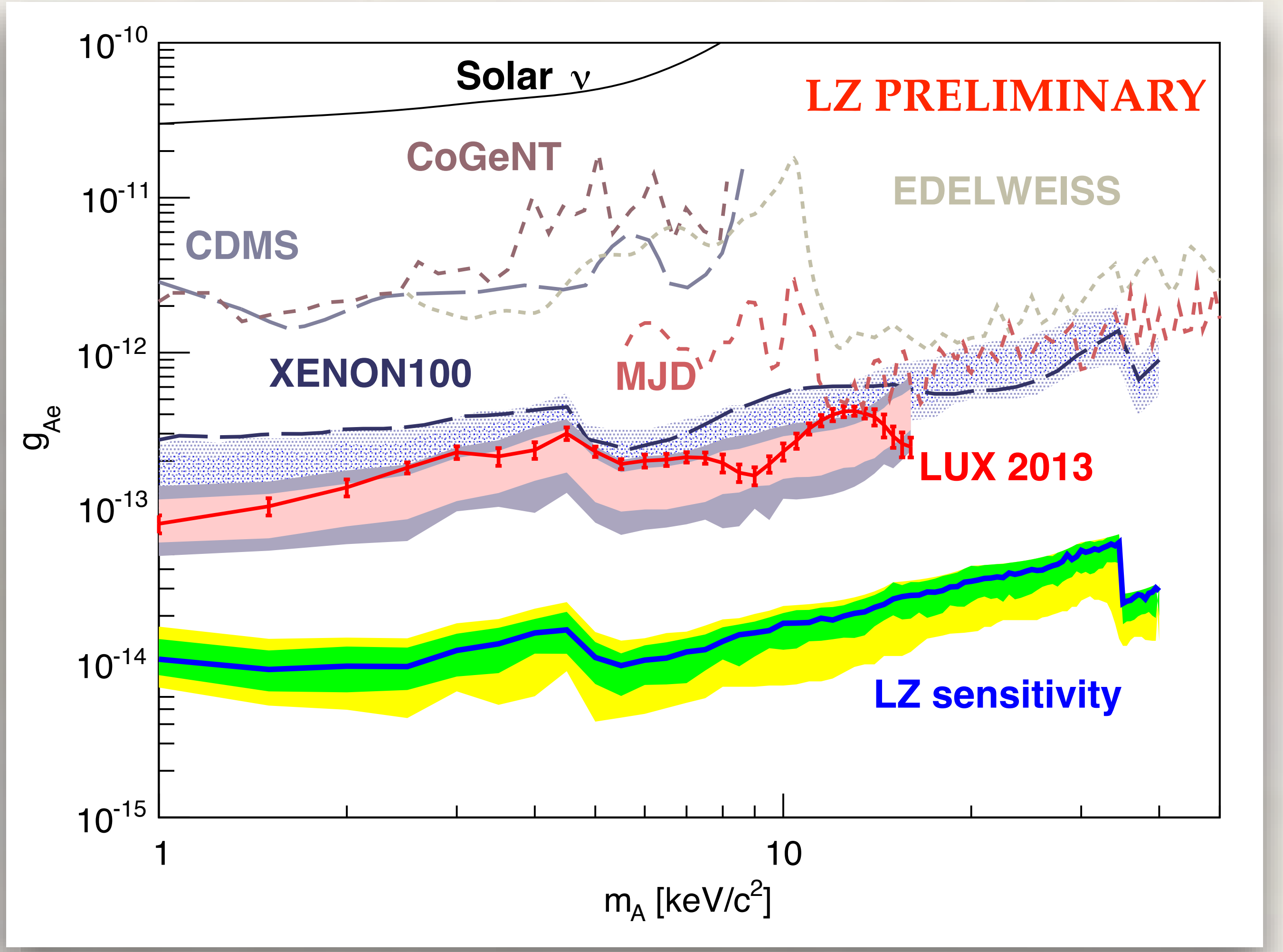
1000 live-days, 5.6 ton fiducial mass

Axions



excludes $g_{Ae} > 1.5\times10^{-12}$ (90% CL)

ALPs



excludes $g_{Ae} > 5.9\times10^{-14}$ (90% CL) across the mass range 1-40 keV / c^2

Summary

- LUX had 4 extremely productive years, and is still producing new physics results
  - It is the world leading WIMP-search experiment since 2013
  - Made significant improvements in the calibration of xenon detectors
  - Various additional analyses on-going, to explore the full physics potential
    - Annual modulation
    - Inelastic DM
    - Etc.
- The LZ collaboration is working to ensure a successful follow-up detector is deployed on or ahead of time

LUX & LZ Collaborations

LUX

20 institutions

~100 scientists

luxdarkmatter.org

LZ

36 institutions

~250 scientists, engineers, and technicians

lzdarkmatter.org

LUX inside the water tank, 2012

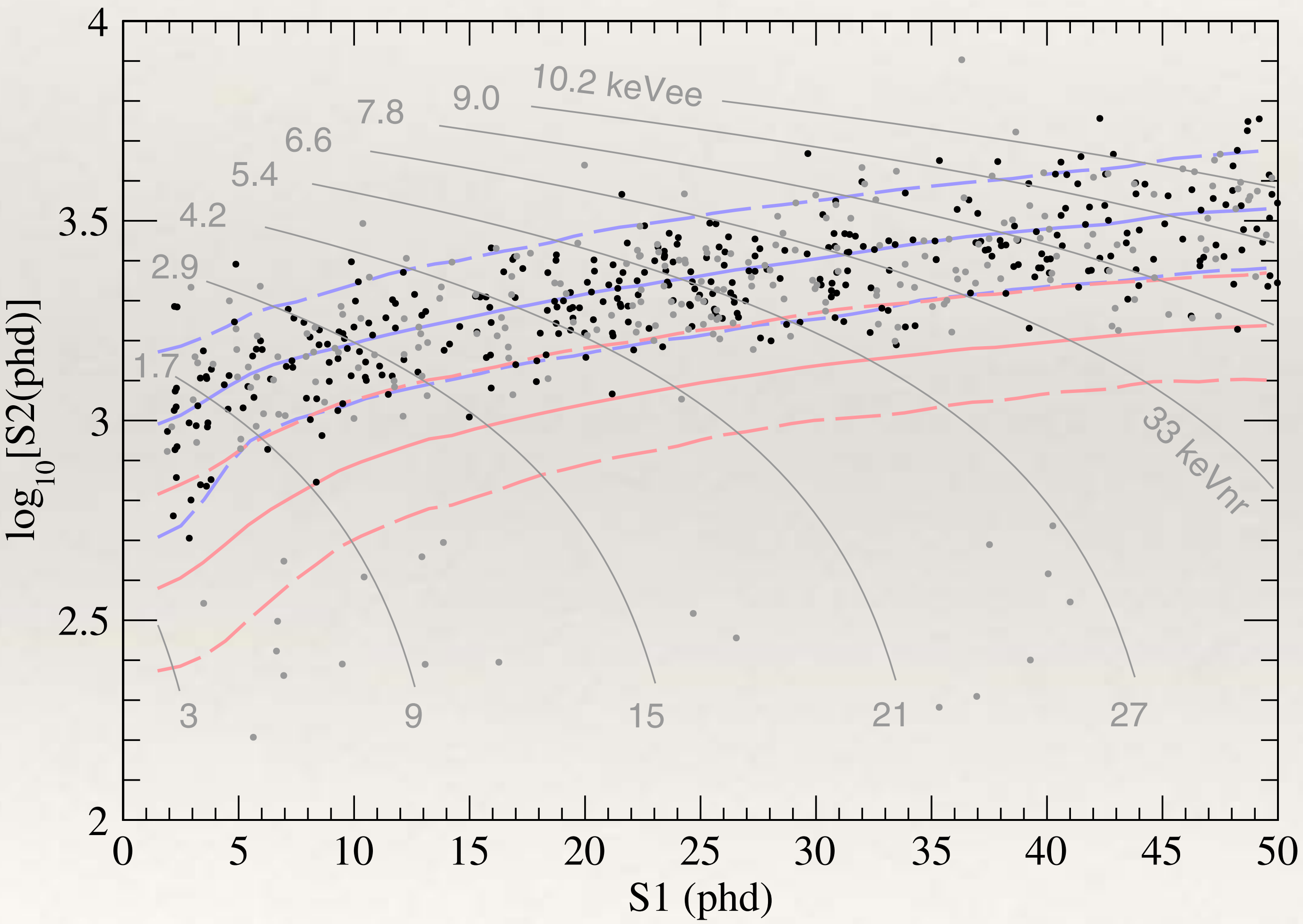
Backup

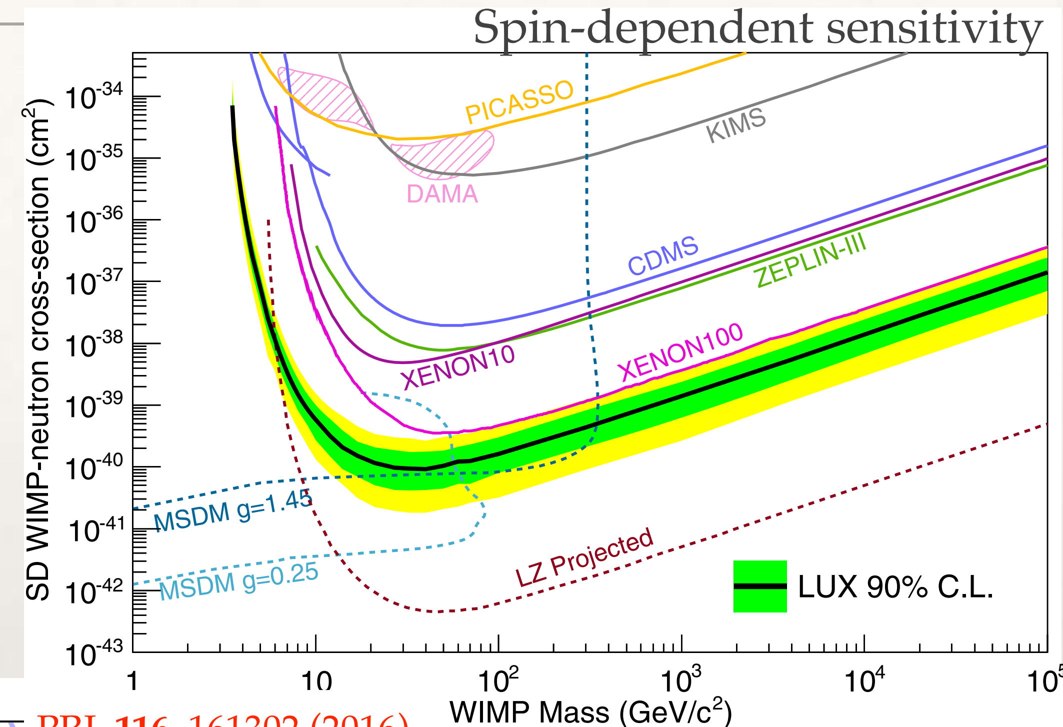
LUX Status

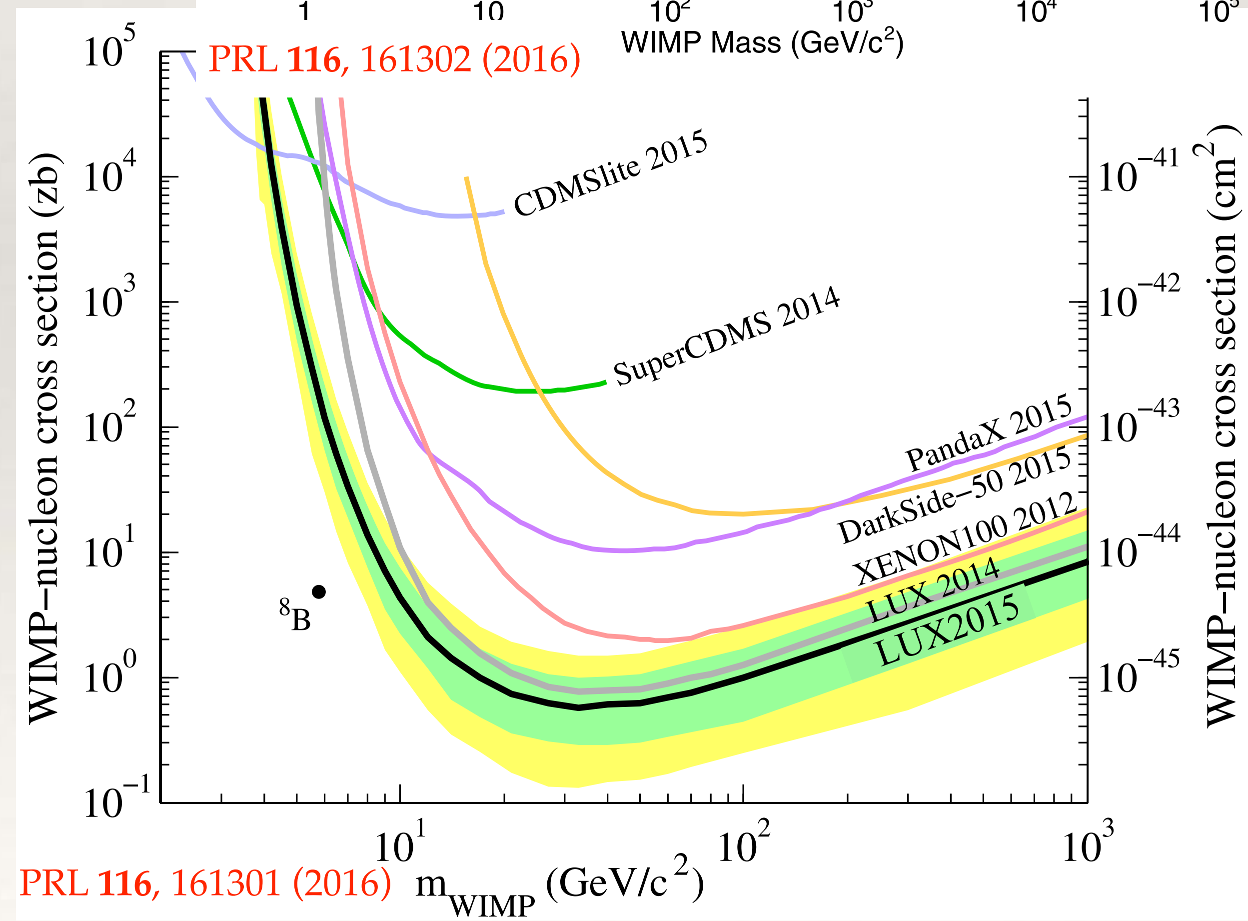
- Detector removed from the water tank in Oct '16, after 3+ years
- Results for the full 95+332 live days exposure published last January in PRL, 118, 021303, 2017
- LUX currently has the most stringent SI WIMP-nucleon exclusion limits
- Various analyses on-going, to explore the full physics potential
  - Annual modulation
  - Inelastic DM
  - Etc.

First Run Reanalysis

- Reanalysis of 2013 data (95 live-days)
- Using calibration results, improved low mass sensitivity

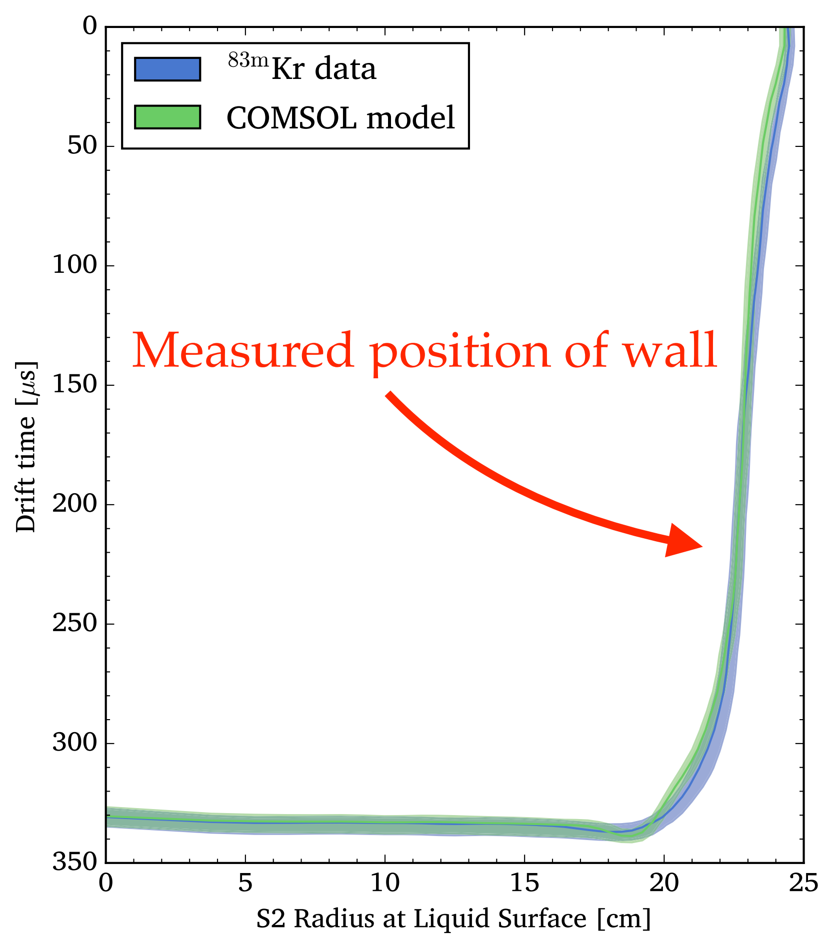




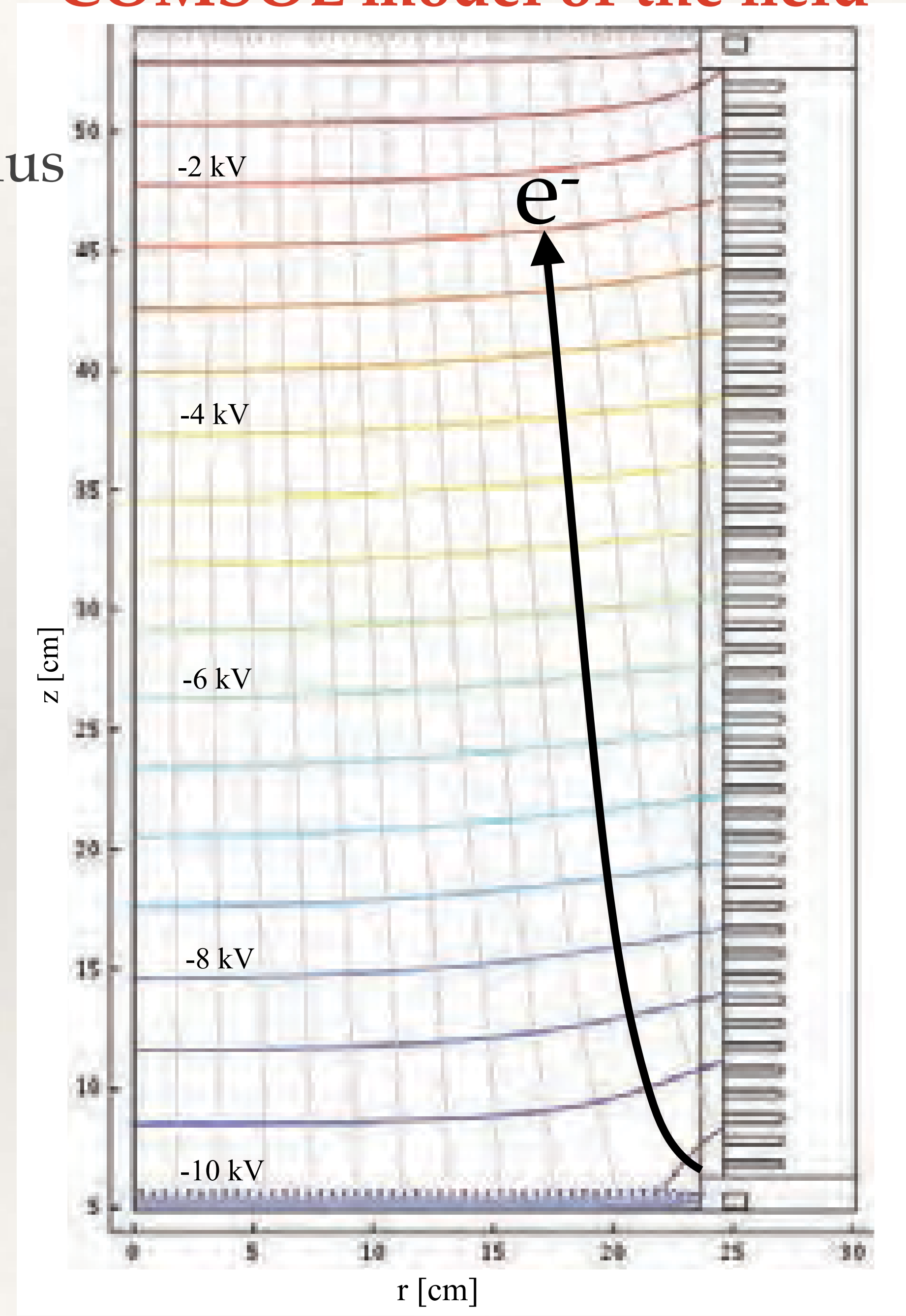


S2 Coordinates

- Field shaping rings help ensure the uniformity of the field
- A small radial component pushes electrons inwards
- Reconstructed radius at the surface is smaller than real radius
- S2 coordinates are squeezed relatively to real coordinates
- ^{83m}Kr is uniform and can be used to estimate this effect

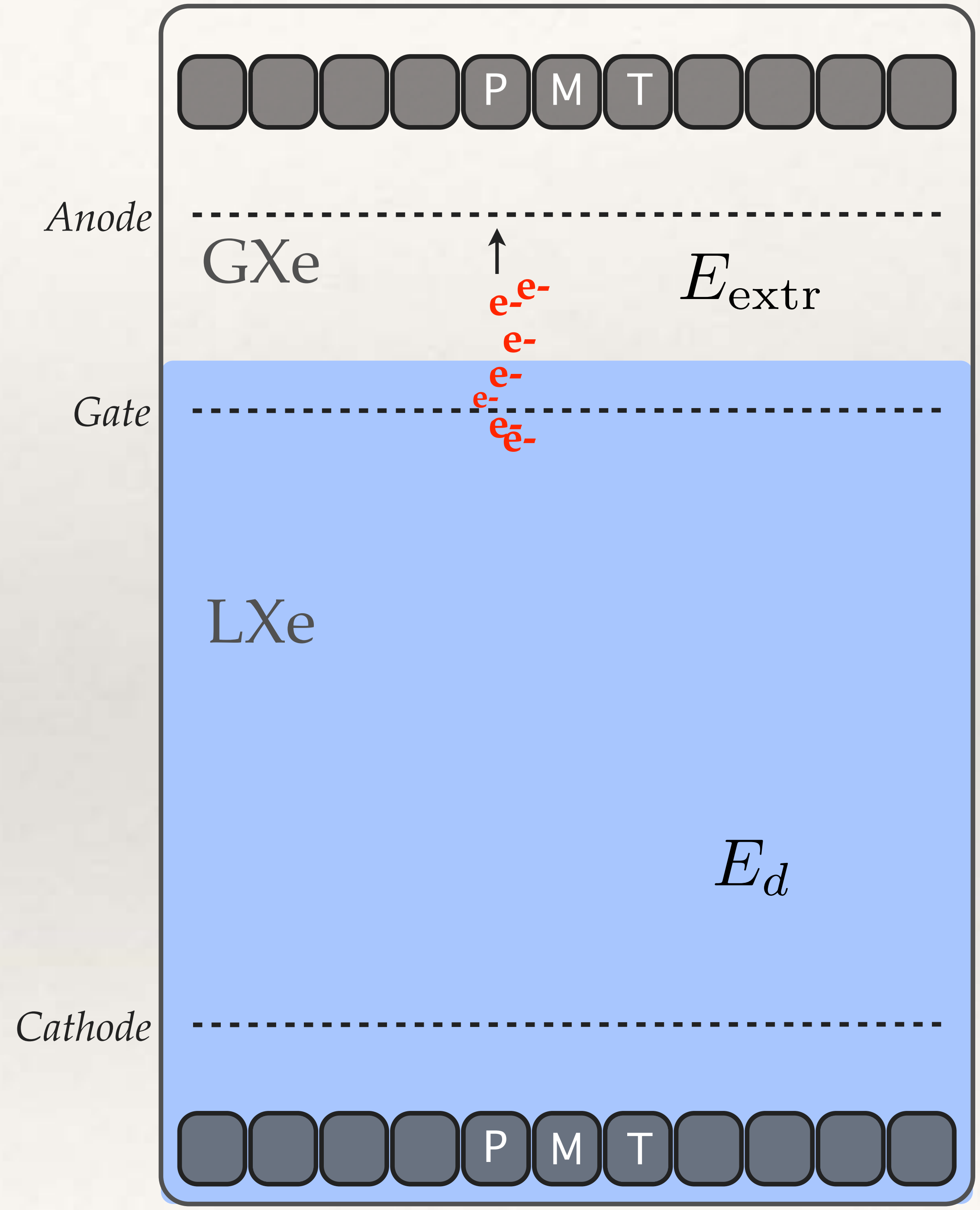


COMSOL model of the field



Grid conditioning

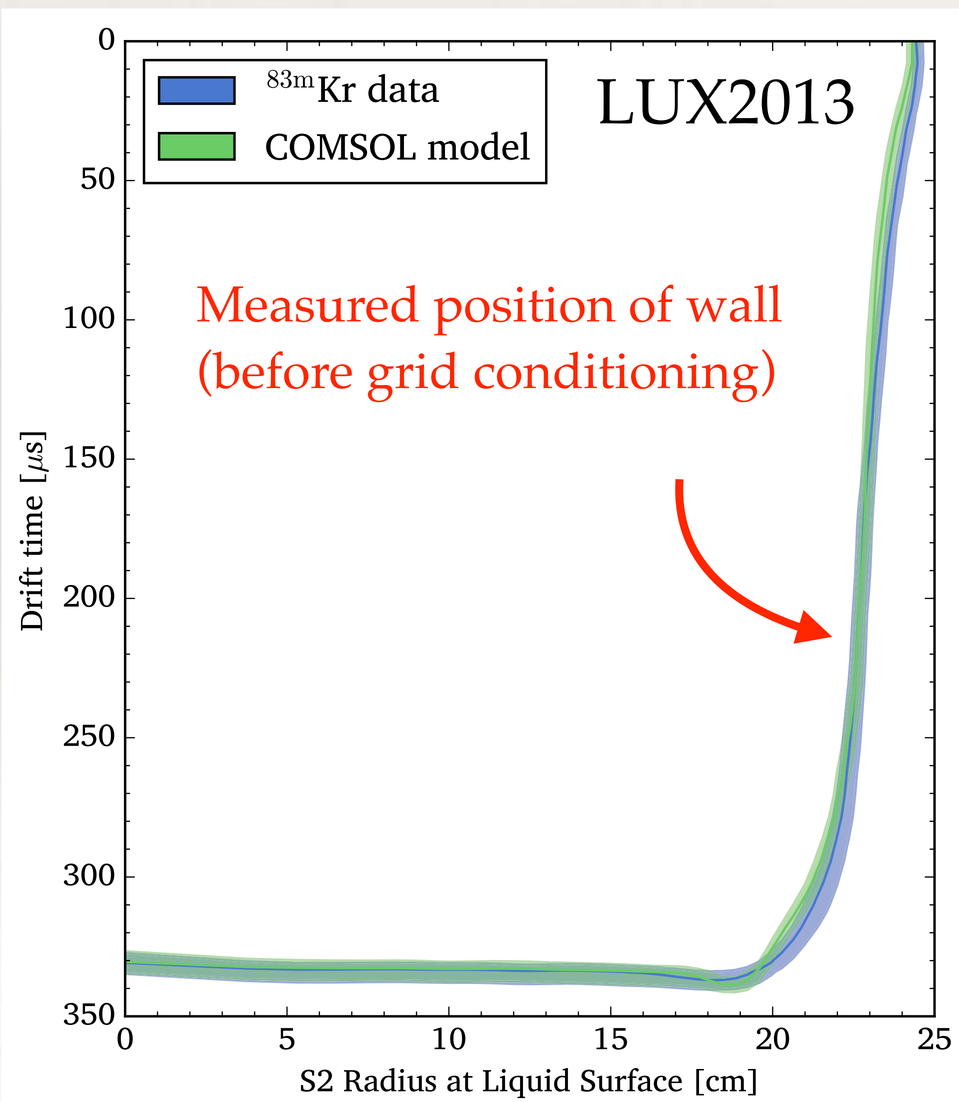
- In the 2013 run, extraction field efficiency was 50%
- Voltages were limited due to light production from the grids
  - thought to be from small sharp defects in the wires
- Grid conditioning: raising voltage above threshold for discharges and allow current to be drawn for long periods
  - ablates features on the wire surfaces
- Result:
  extraction efficiency raised to 75%

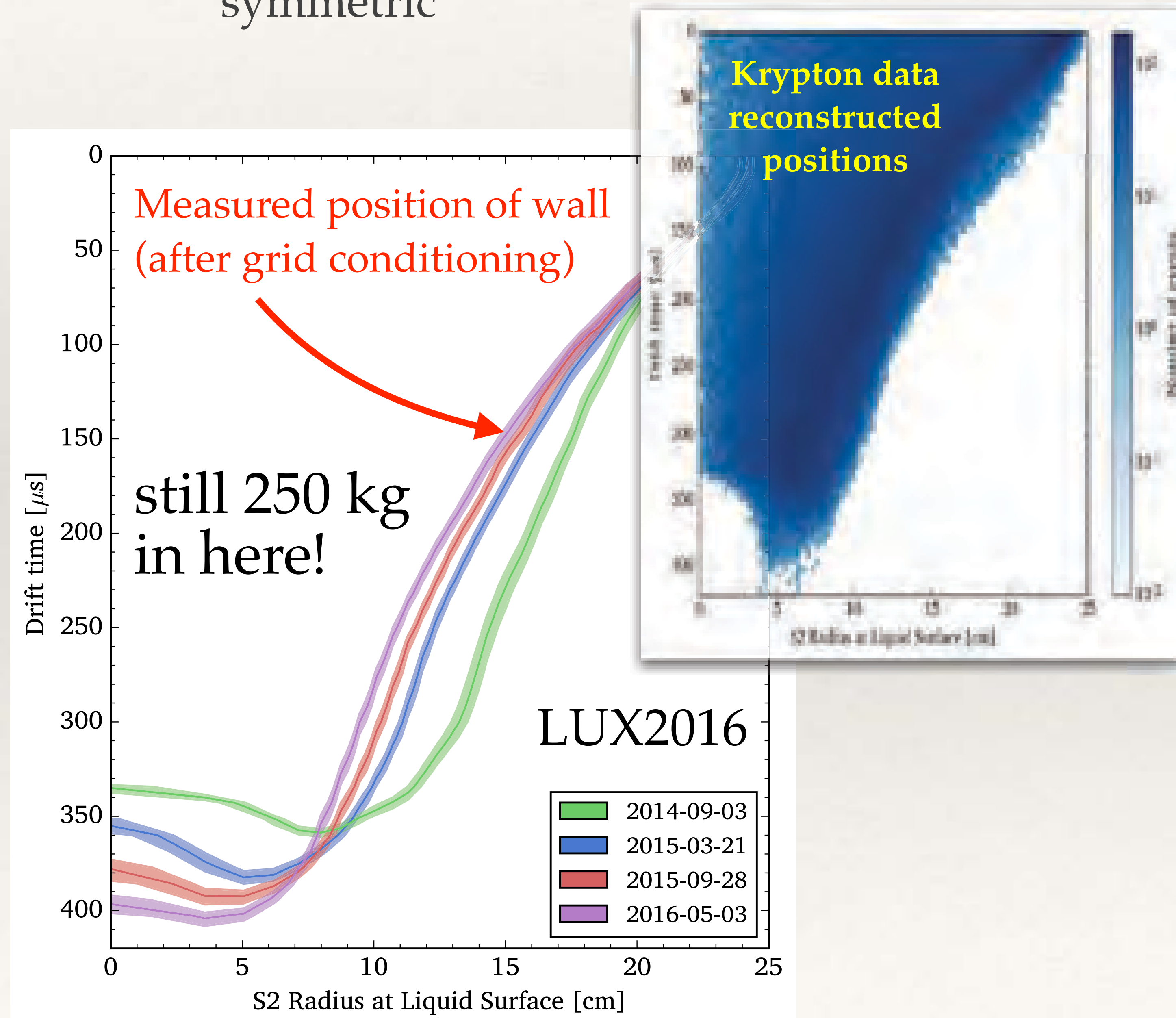


Grid Conditioning – Side Effects

- Significant increase in the radial field component
- Consistent with charging up of the PTFE walls

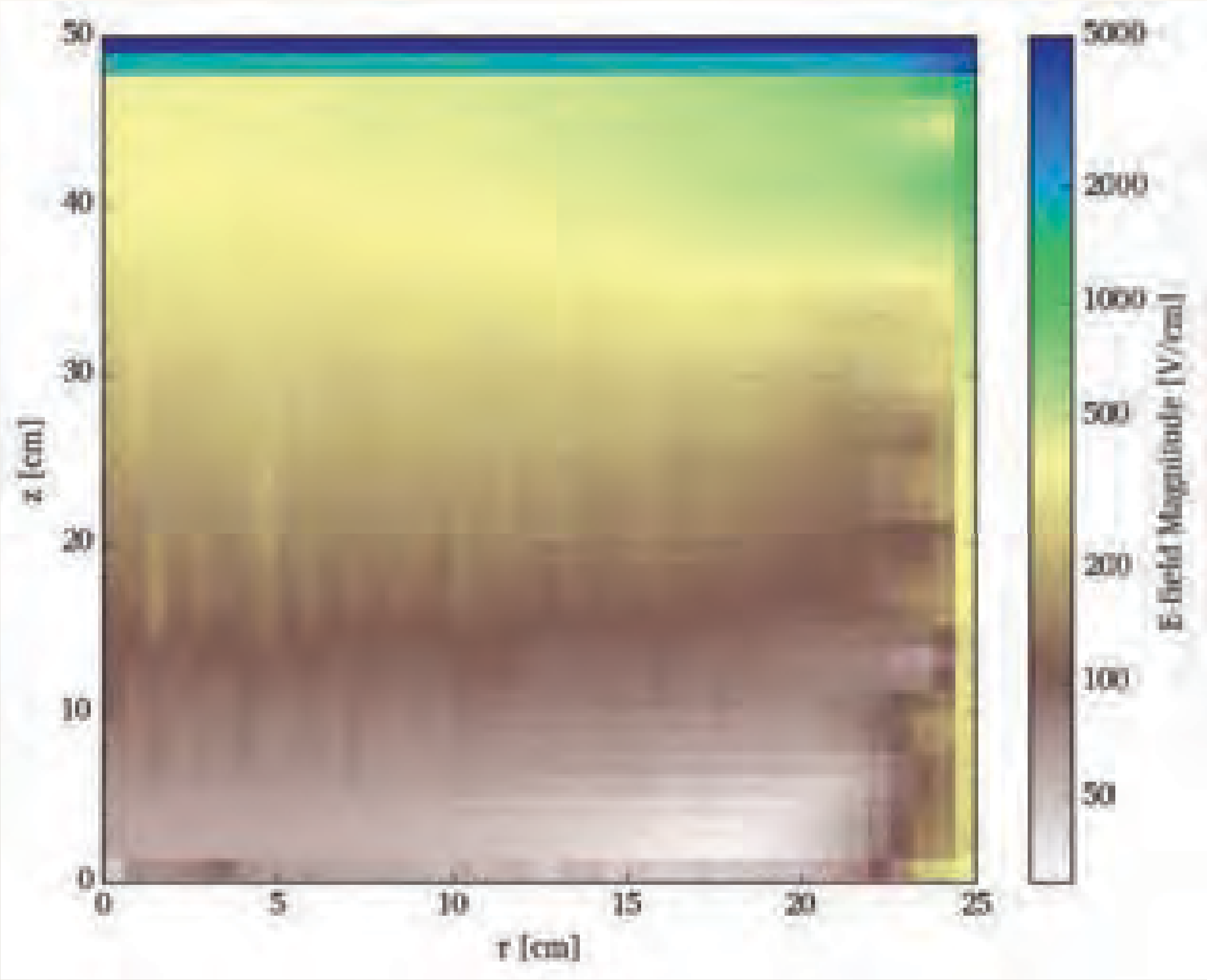
- Wall position slowly varies with time
- The measured wall radius is not axially symmetric





Modelling the Field

- 3-D model constructed in the COMSOL Multiphysics® FEM simulation software.
- Charges are added (non-uniformly) to the walls and the 3-D field is calculated.
- The 3D field map is combined with the known field dependence on the electron drift speed to obtain a mapping between "real space" and "S2 space" coordinates.
- Results are compared to the observed ^{83m}Kr distribution, and the charge densities are iterated until a best-fit is obtained.
- Charge is concentrated in the upper portion of the PTFE walls



Calibration data allows for robust calculation of fiducial volume

$$\text{Fiducial Mass} = 251\,\text{kg} \times \frac{\text{Num. evts. passing fiducial cut}}{\text{Num. evts. total}}$$

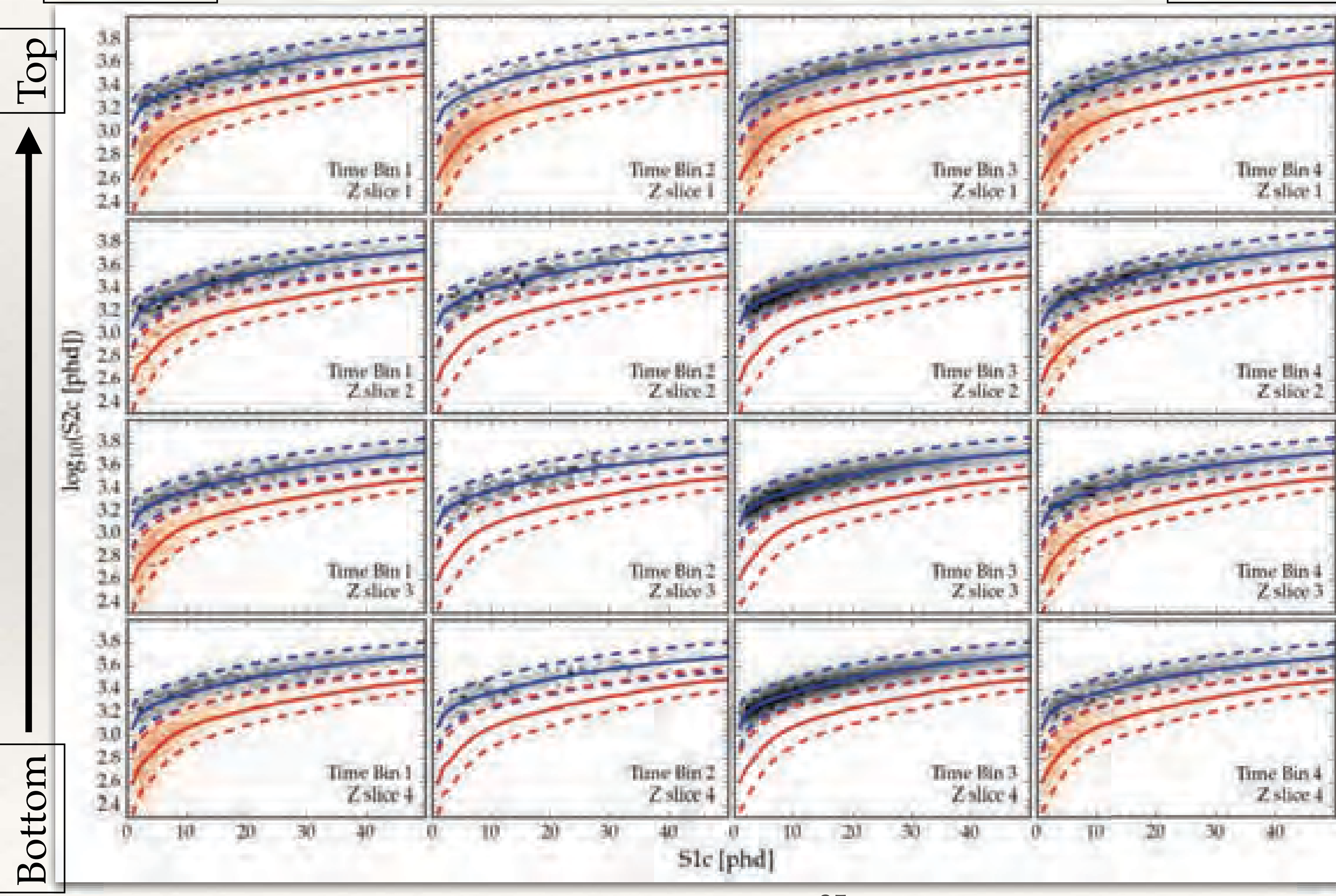
Dealing with a Varying Field

- How to deal with a field that varies in **space** and **time**?
  - Divide the run in *M* time bins
  - Divide the detector in *N* vertical sections
  - In each of the *M*x*N* segments, consider a uniform detector model for ER and NR response (*i.e.* constant applied field and other detector parameters)
  - In the end, 4x4 segments were used — **16 independent detectors** (a compromise between field uniformity and calibration data statistics)
  - NEST used to model the S1 and S2 response in each of the 16 detectors

http://nest.physics.ucdavis.edu

Detector Calibrations

Sep.2014 → May 2016



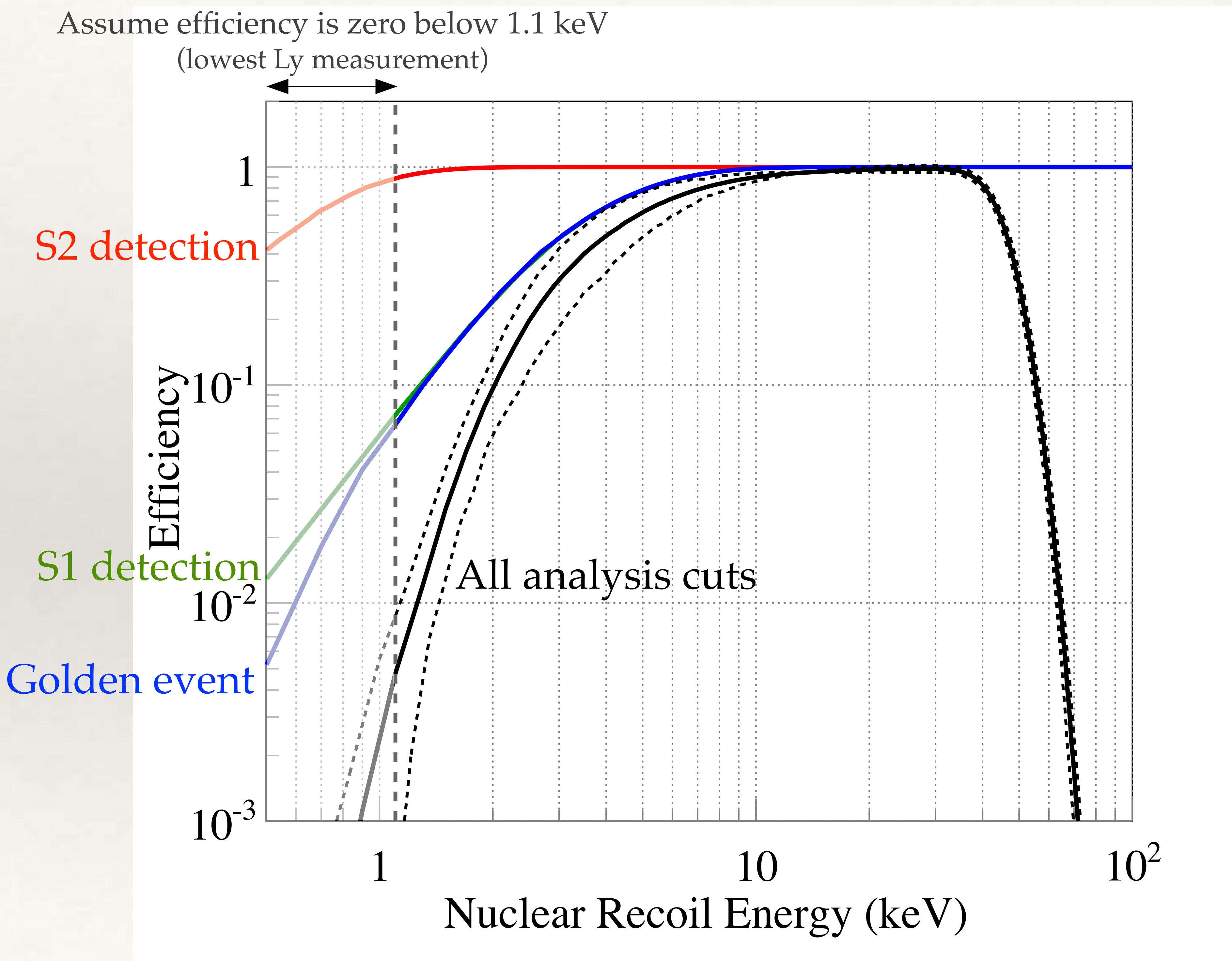
Gray density: CH_3T calibration (ER)

Orange density: DD calibration (NR)

Solid lines: NEST model, ER, NR band mean.

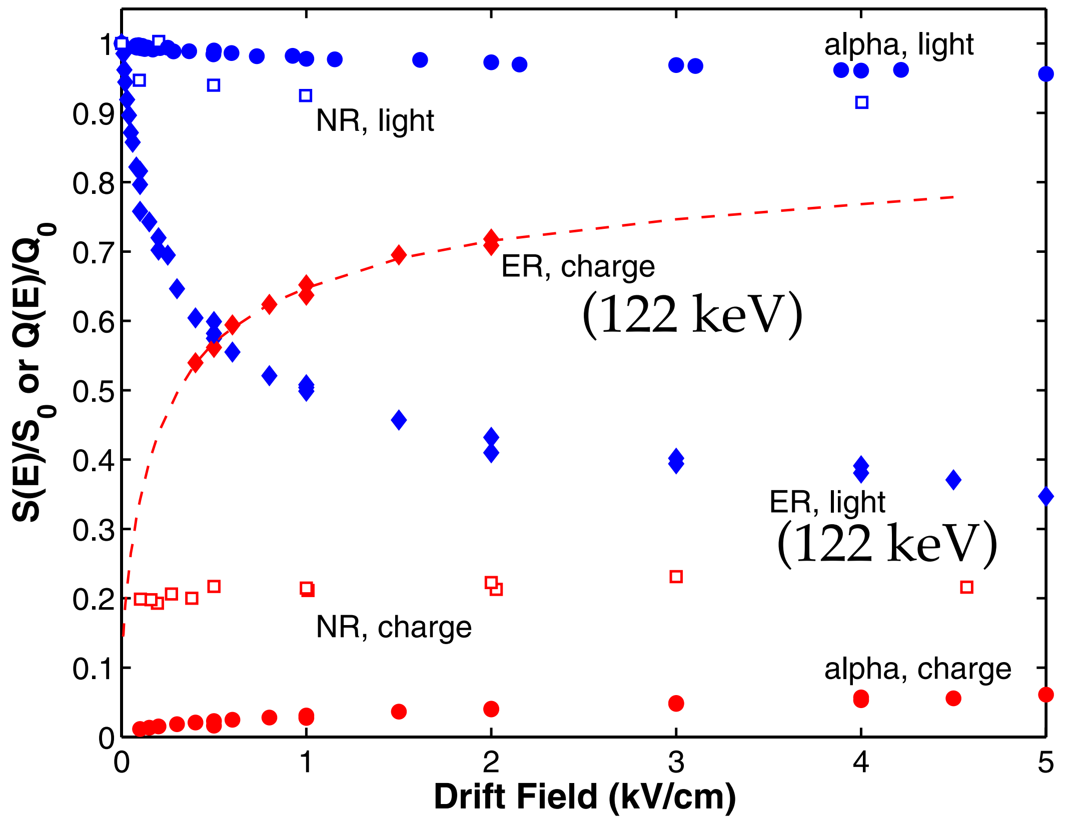
Dashed lines: NEST model, 10-90 percentile.

Efficiency for NR Events

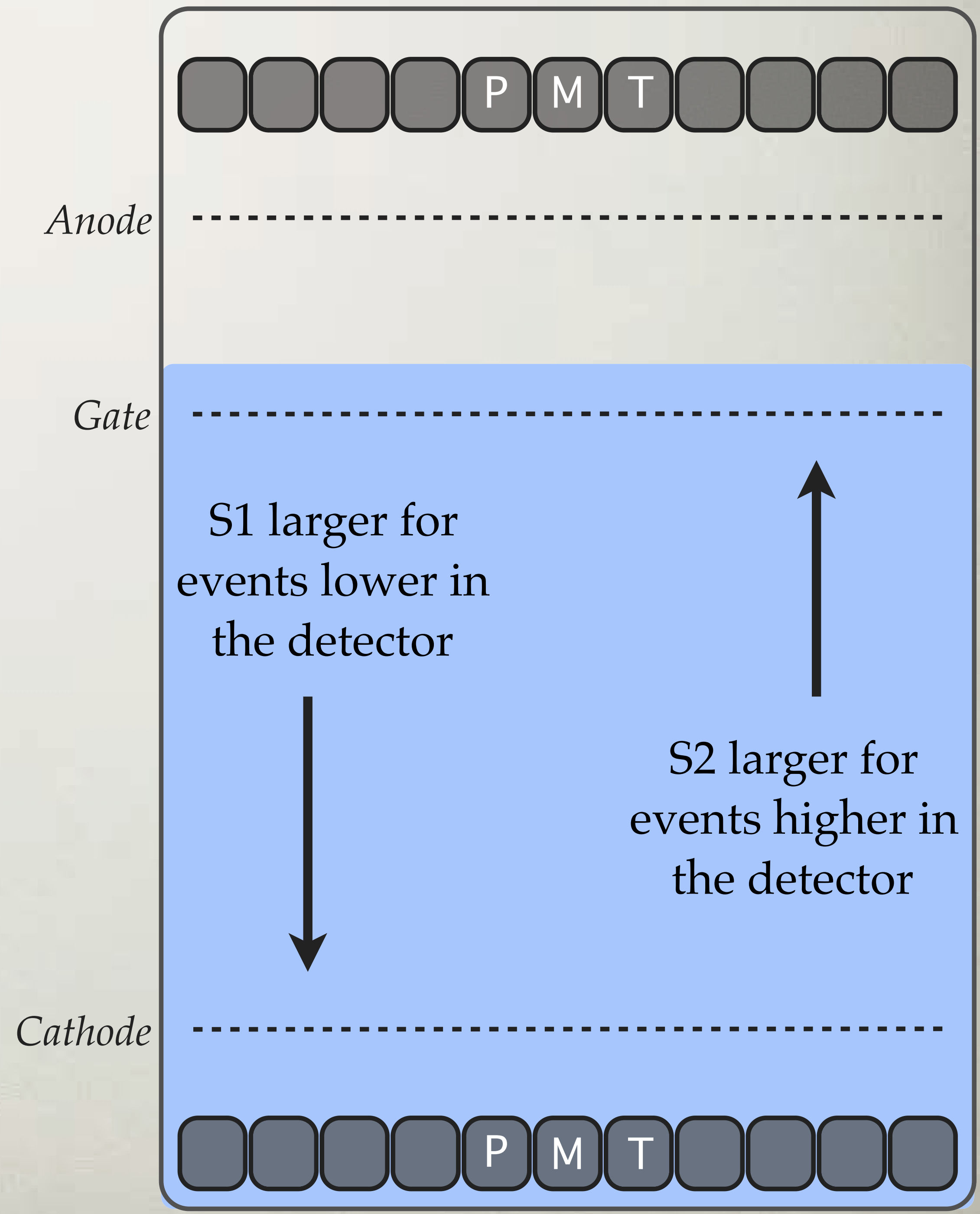


Position corrections

- Size of the S1 depends on the location of the event (due to geometrical light collection), and S2 (due to electronegative impurities)
- Normally, one develops a geometrical correction factor by flat fielding a mono-energetic source.
- However, a spatially varying E-field ALSO affects S1 and S2 sizes, but differently for every particle type and energy.

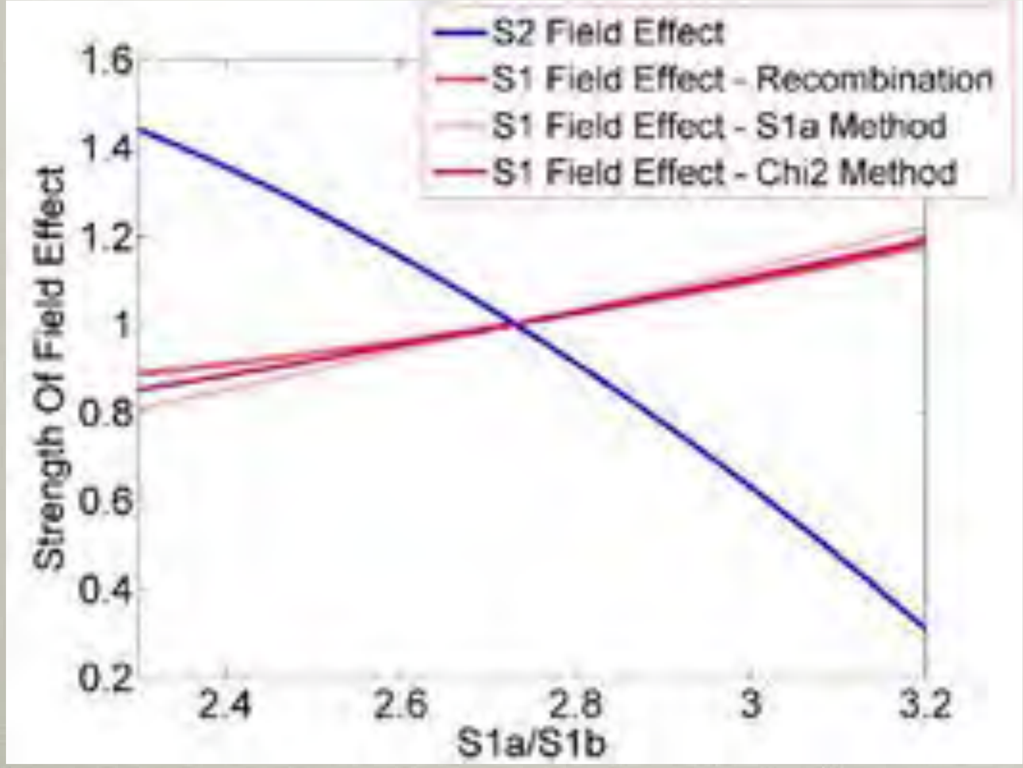


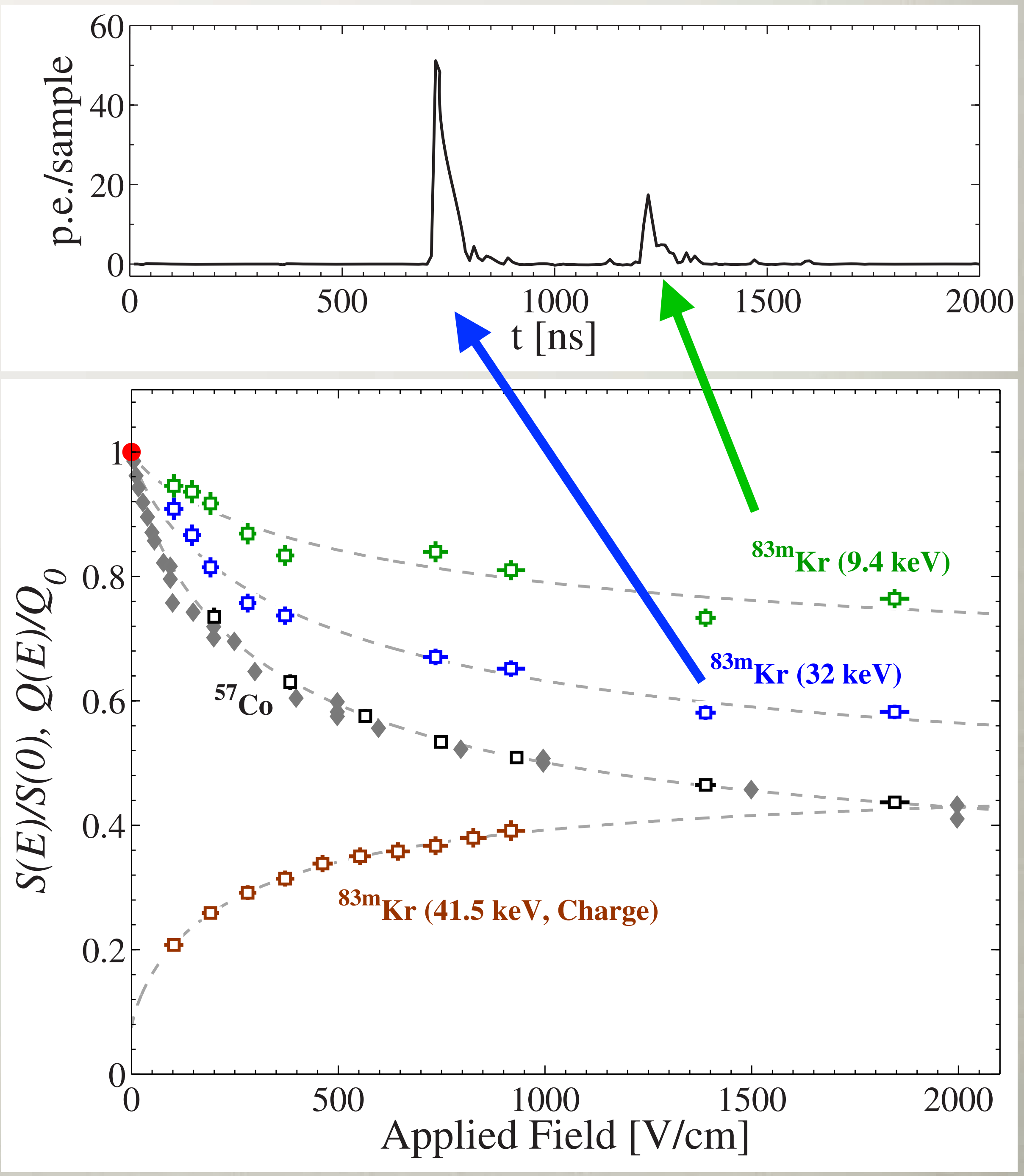
E. Aprile *et al*. PRL **97** (2006) 081302, astro-ph/0601552



Position corrections

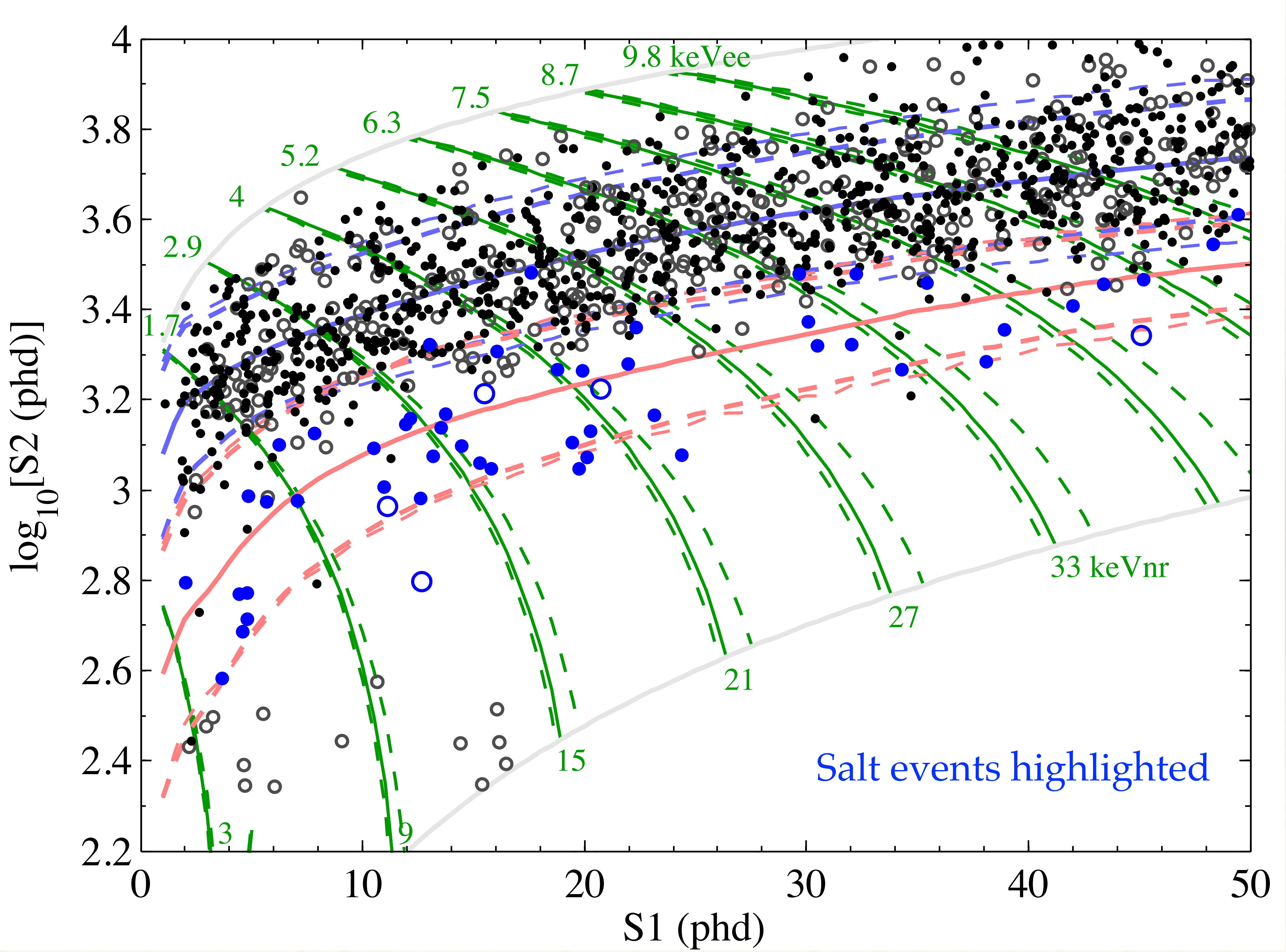
- Our strategy is:
  - Disentangle position effects from field effects.
  - Apply a correction to account for position effects only.
- ^{83m}Kr has two decays close in time. The ratio of the first-to-second S1 pulse area depends on field alone. This allows us to measure the component of variation due to applied field alone.



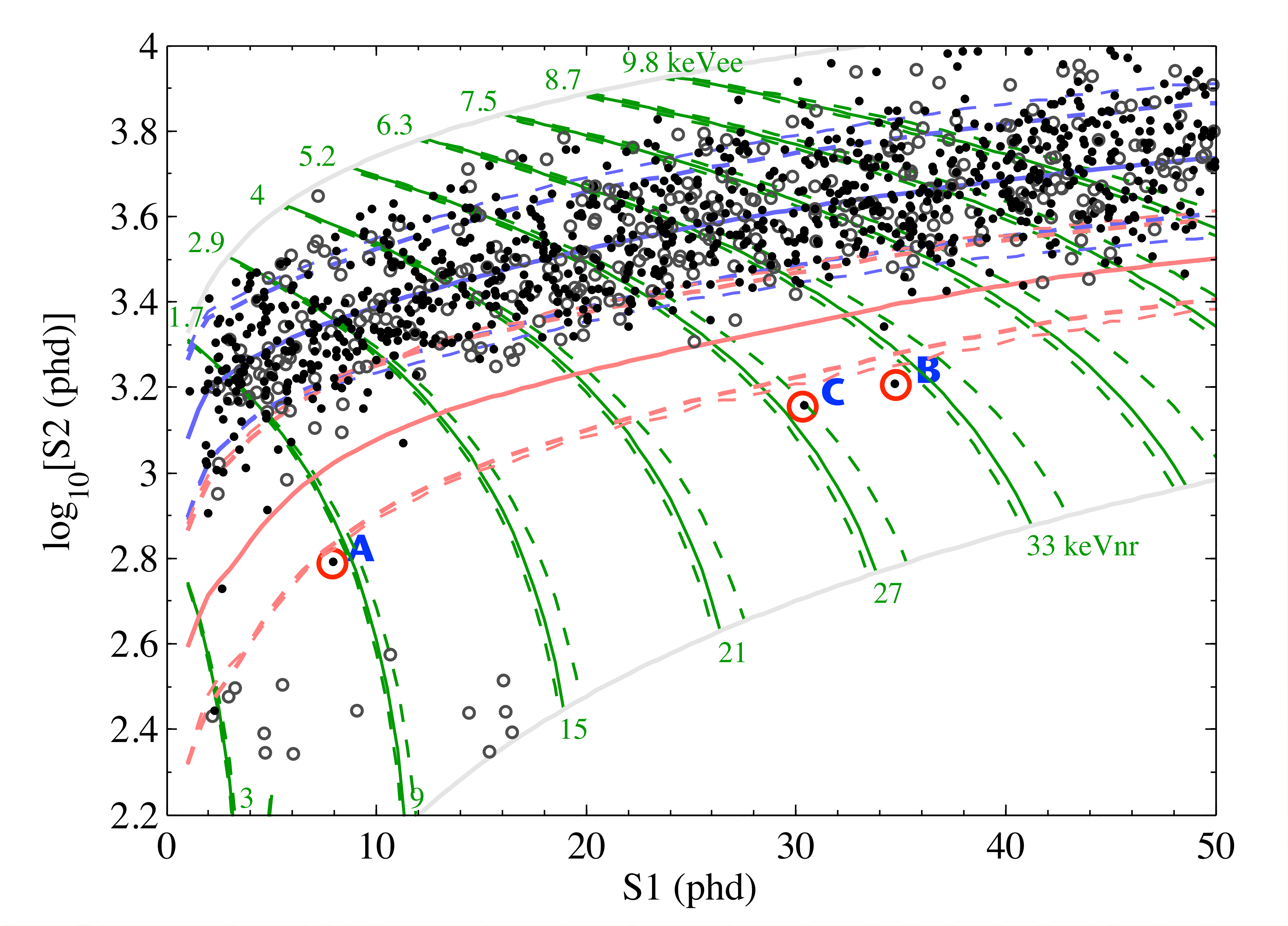


A.Manalaysay *et al.*, Rev.Sci.Instrum. **81** (2010) 073303, 0908.0616

WIMP-Search Data

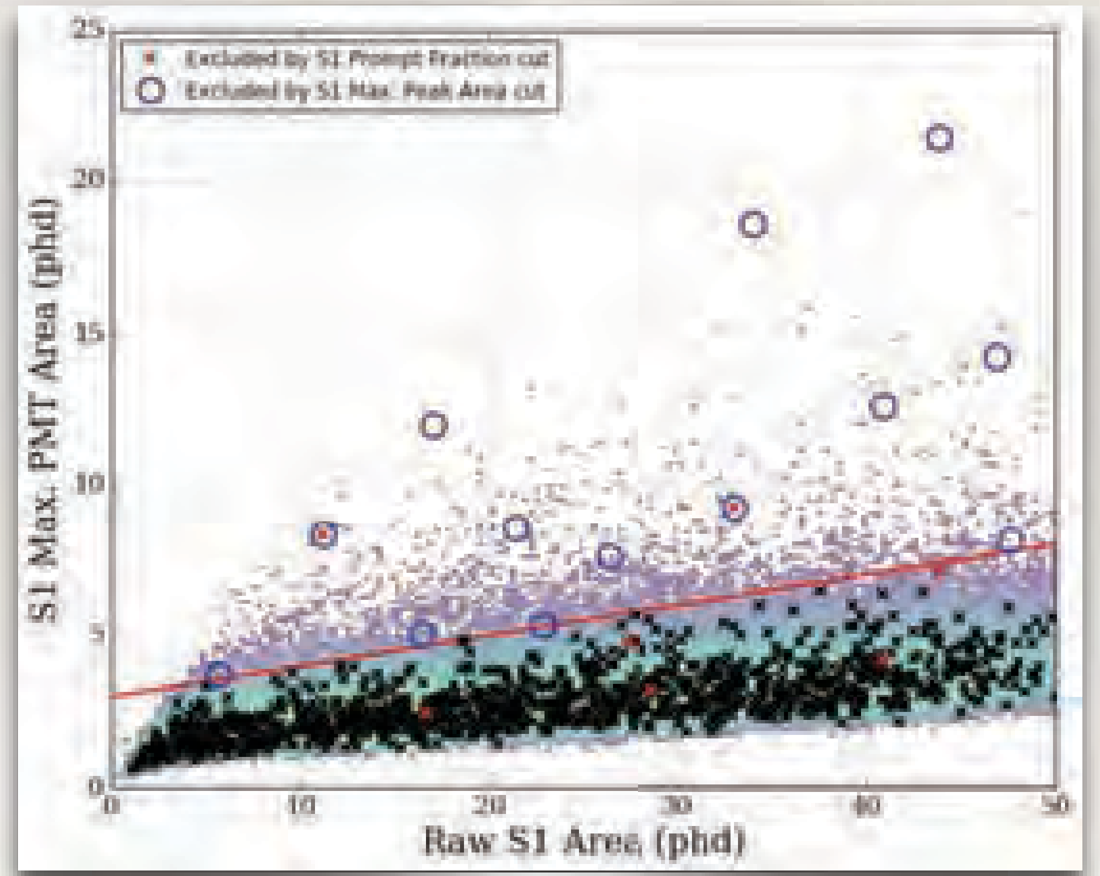


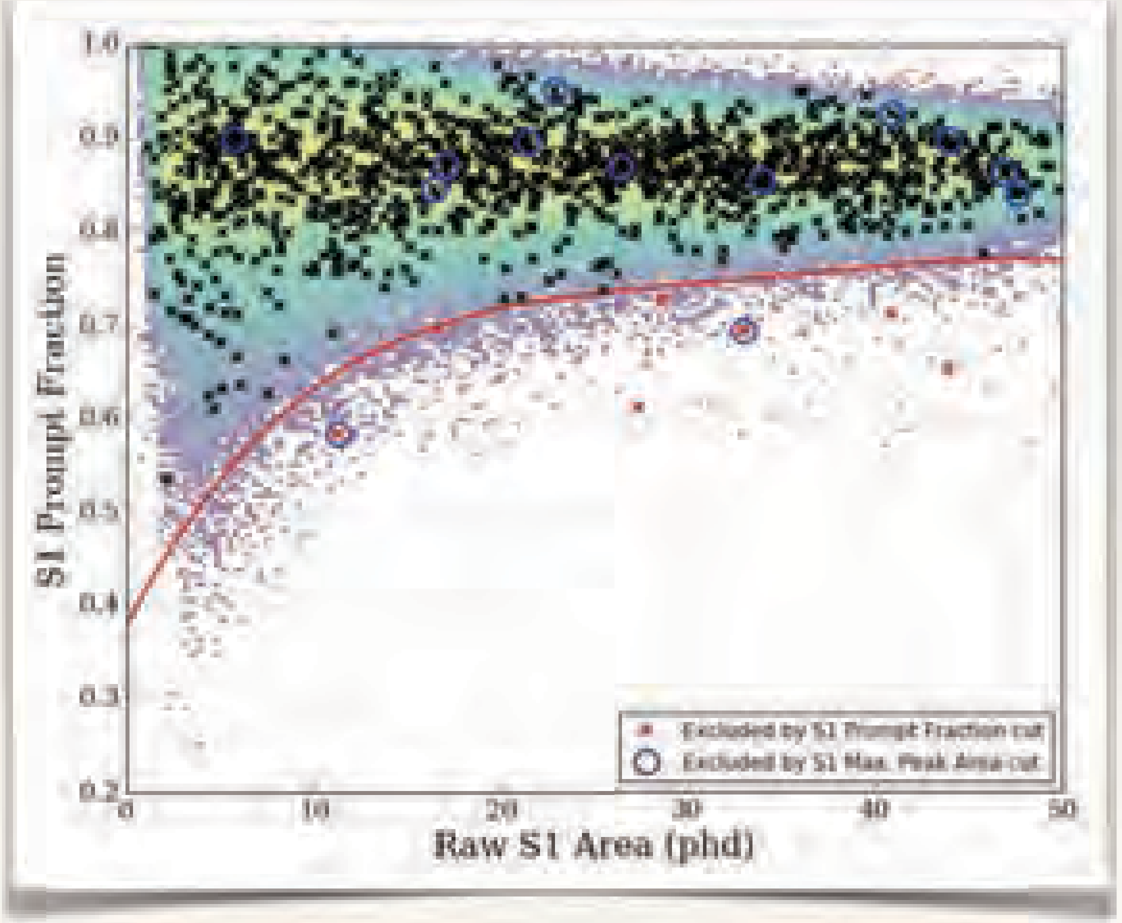
WS Data – Pathological Events



Post-Unsalting Quality Cuts

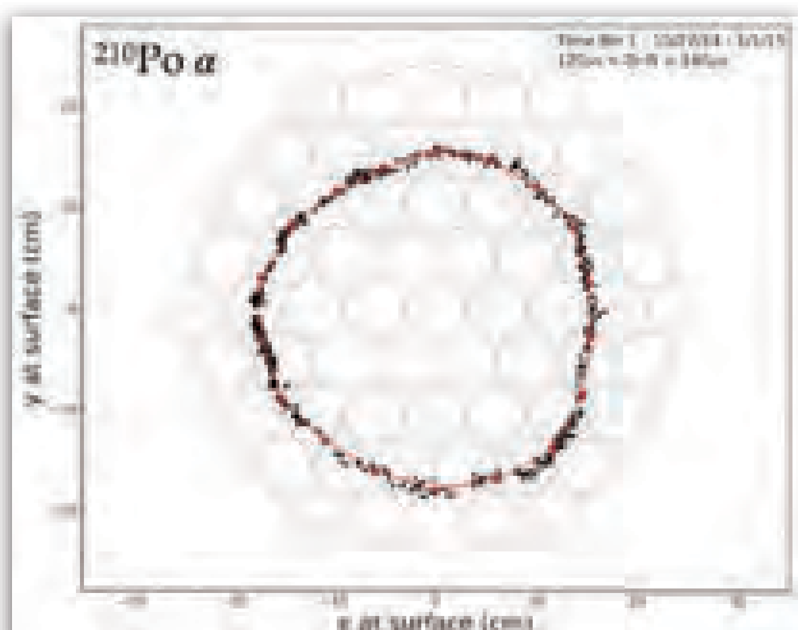
- After unsalting the data, we revisited all the events below the ER band
- Two populations of rare pathological events were identified
  - Events A and B have 80% of their S1 light in a single top edge PMT
  - Event C has time structure consistent with a gas scintillation event
- Cuts for these pathologies were developed on DD and CH3T calibration data.
- Flat signal acceptance of 98.5% with both cuts applied

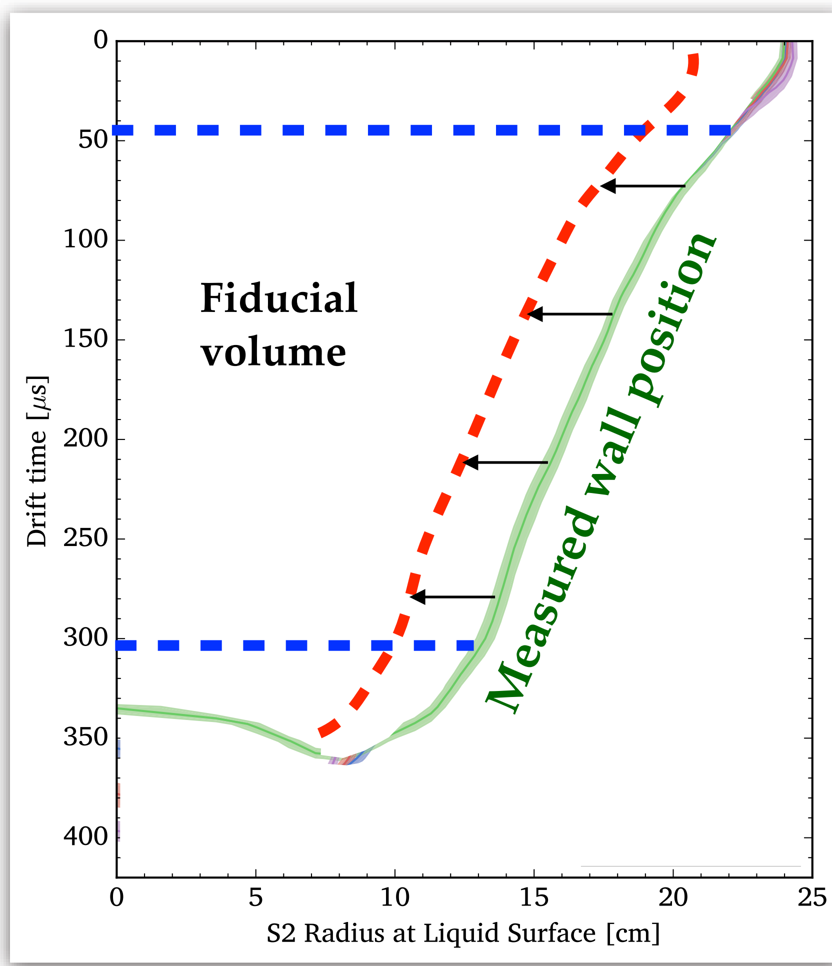


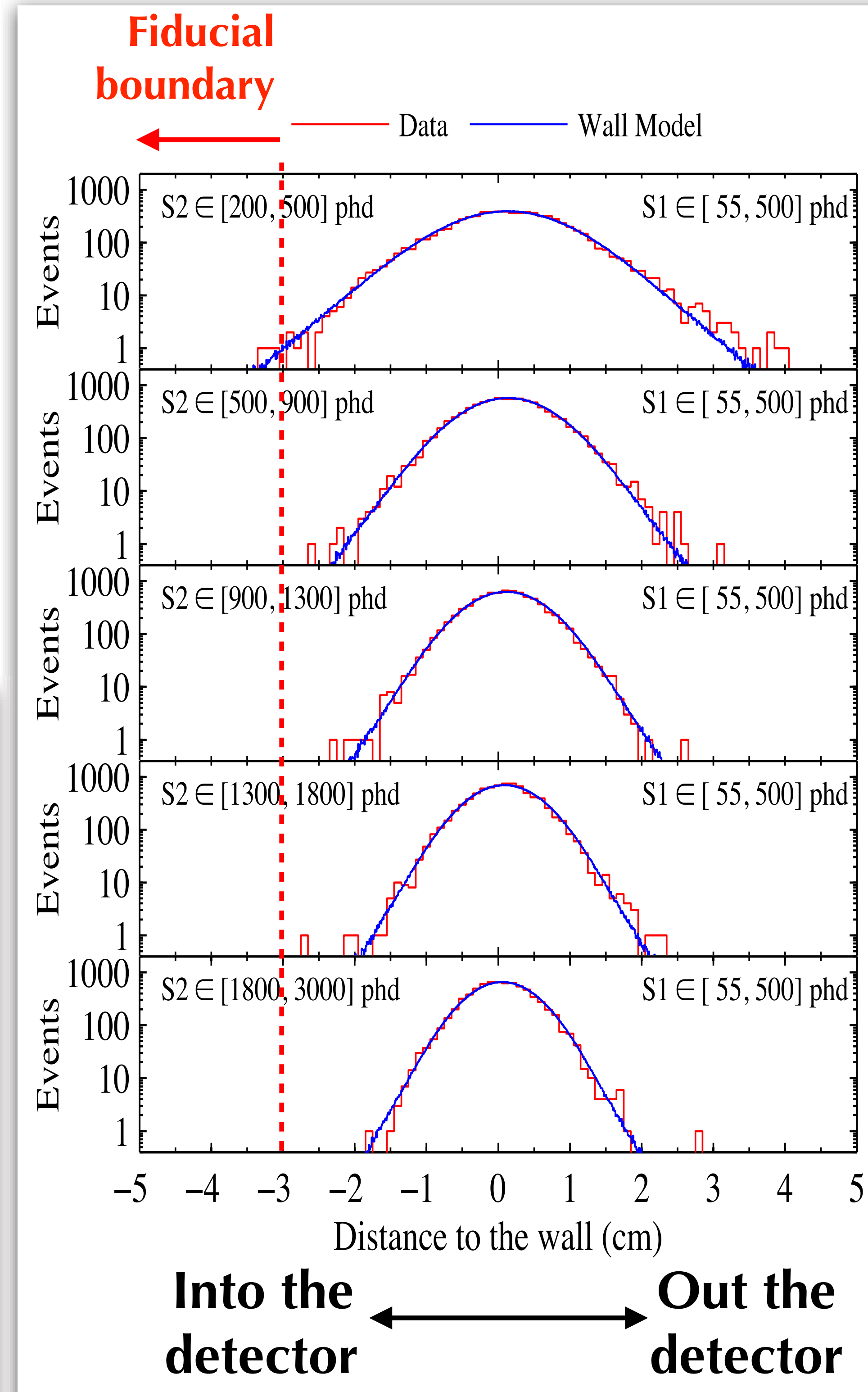


Wall-surface backgrounds

- ^{238}U late chain plate-out on PTFE surfaces survives as ^{210}Pb and its daughters (mainly ^{210}Bi and ^{210}Po).
- Betas and ^{206}Pb recoils travel negligible distance, but they can be reconstructed some distance from the wall as a result of position resolution (especially for small S2s).
- These sources can be used to define the position of the wall in measured coordinates, for the 4 data bins and any combination of drift-time and ϕ.
- The boundary of the fiducial volume is defined at 3 cm from the observed wall in S2 space and for a drift time between 50 and 300 μs.







Backgrounds in LZ

5.6 ton fiducial, 1000 live-days

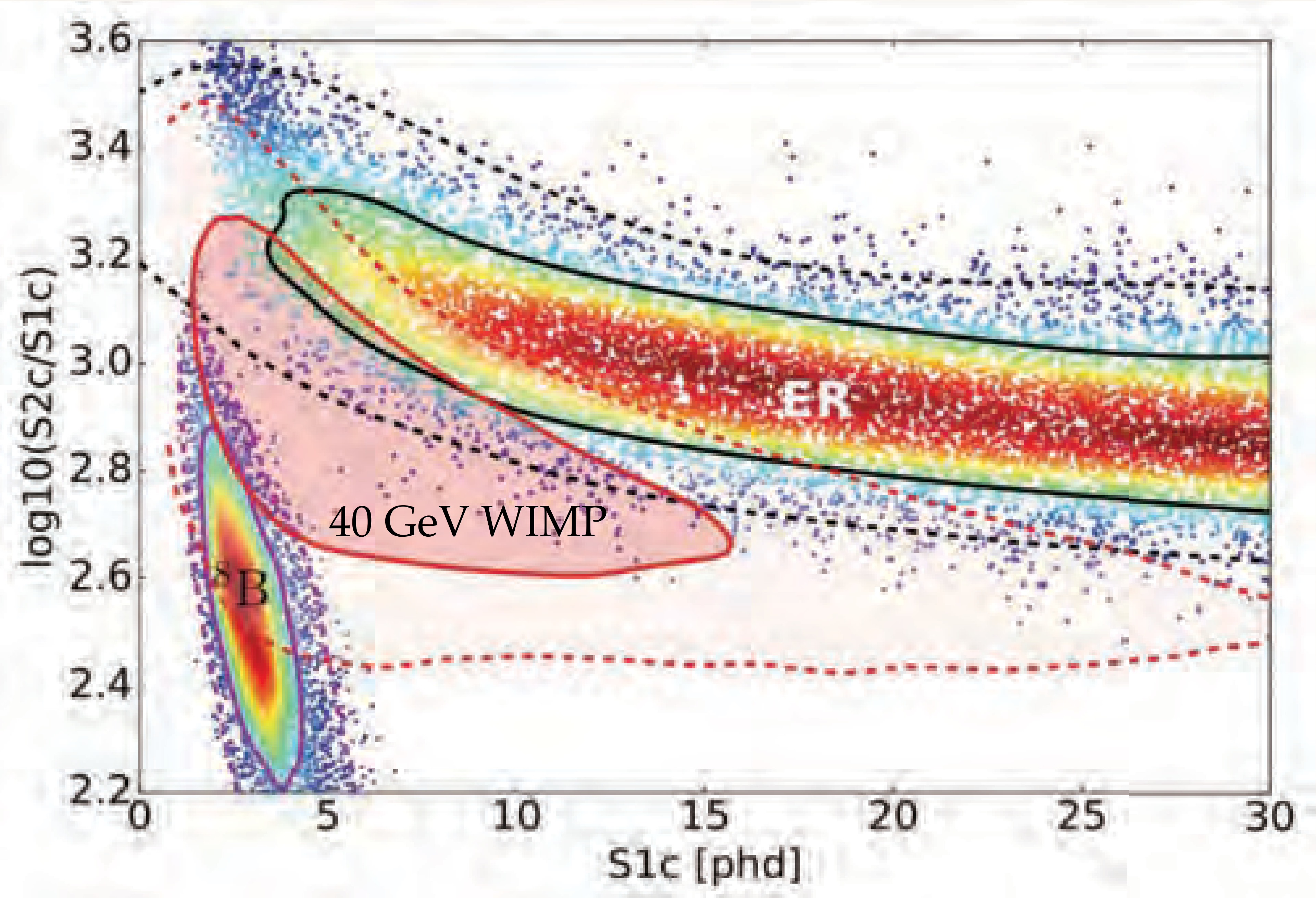
~1.5 - 6.5 keV, single scatters, no coincident veto

Background Source	ERs	NRs
Detector Components	6.2	0.07
Dispersed Radionuclides — Rn, Kr, Ar	911	—
Laboratory and Cosmogenics	4.3	0.06
Surface Contamination and Dust	0.19	0.37
Physics Backgrounds — 2ß decay, neutrinos*	322	0.72
Total (after 99.5% discrimination and 50% NR efficiency)	**6.83**	

* not including ^{8}B

^{8}B Background in LZ

With PLR, background from ^{8}B affects low-mass WIMPs only



The LUX collaboration

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Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Lucie Tvrznikova	Graduate Student
Nicole Larsen	Graduate Student

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LZ Collaboration

March 2017

36 institutions — 250 scientists, engineers, and technicians

1) Center for Underground Physics (South Korea)
2) LIP Coimbra (Portugal)
3) MEPhI (Russia)
4) Imperial College London (UK)
5) STFC Rutherford Appleton Lab (UK)
6) University College London (UK)
7) University of Bristol (UK)
8) University of Edinburgh (UK)
9) University of Liverpool (UK)
10) University of Oxford (UK)
11) University of Sheffield (UK)
12) Black Hill State University (US)
13) Brookhaven National Lab (US)
14) Brown University (US)
15) Fermi National Accelerator Lab (US)
16) Lawrence Berkeley National Lab (US)
17) Lawrence Livermore National Lab (US)
18) Northwestern University (US)
19) Pennsylvania State University (US)
20) SLAC National Accelerator Lab (US)
21) South Dakota School of Mines and Technology (US)
22) South Dakota Science and Technology Authority (US)
23) Texas A&M University (US)
24) University at Albany (US)
25) University of Alabama (US)
26) University of California, Berkeley (US)
27) University of California, Davis (US)
28) University of California, Santa Barbara (US)
29) University of Maryland (US)
30) University of Massachusetts (US)
31) University of Michigan (US)
32) University of Rochester (US)
33) University of South Dakota (US)
34) University of Wisconsin – Madison (US)
35) Washington University in St. Louis (US)
36) Yale University (US)