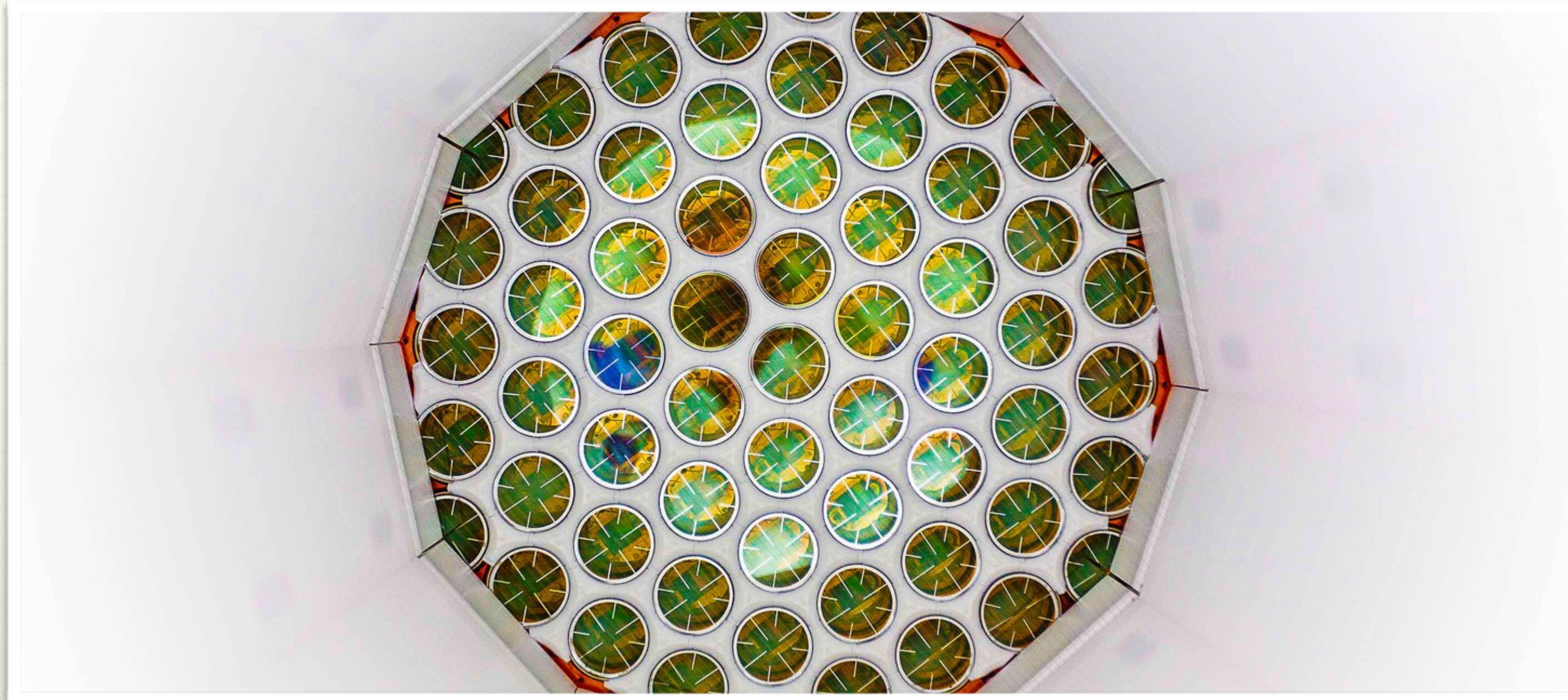


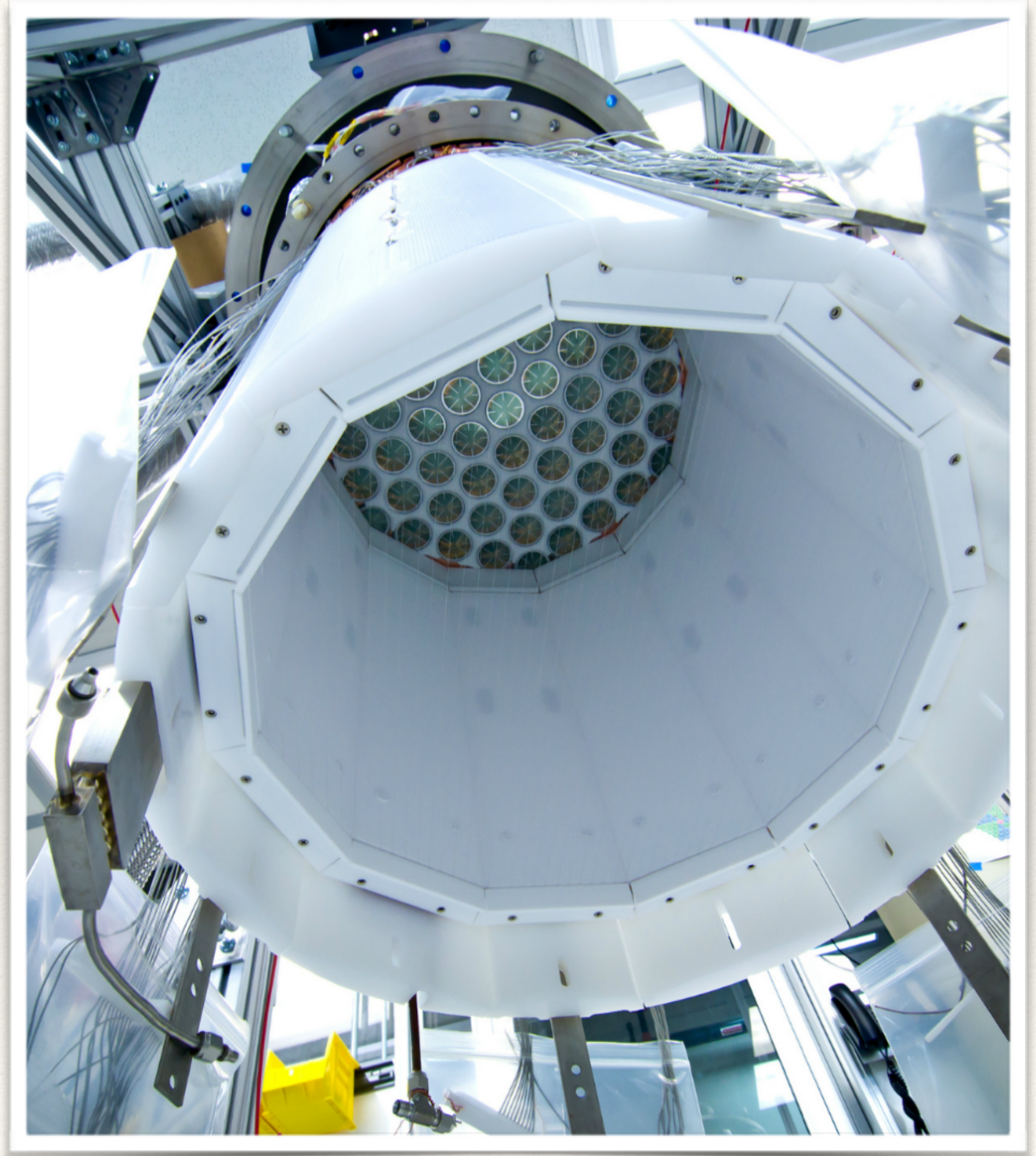
HEP 2017, 6th of July 2017

New Results from LUX

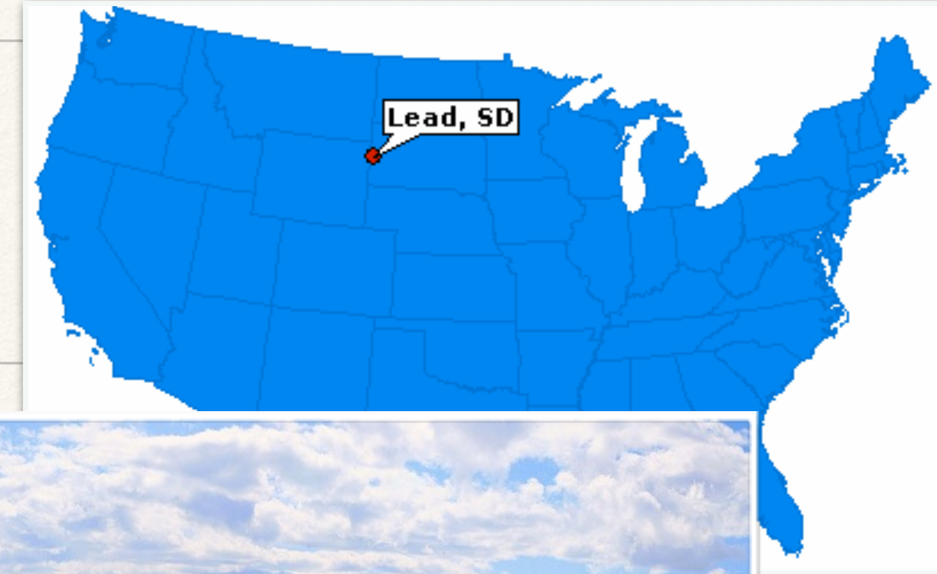
Alex Lindote
LIP and University of Coimbra
on behalf of the LUX collaboration

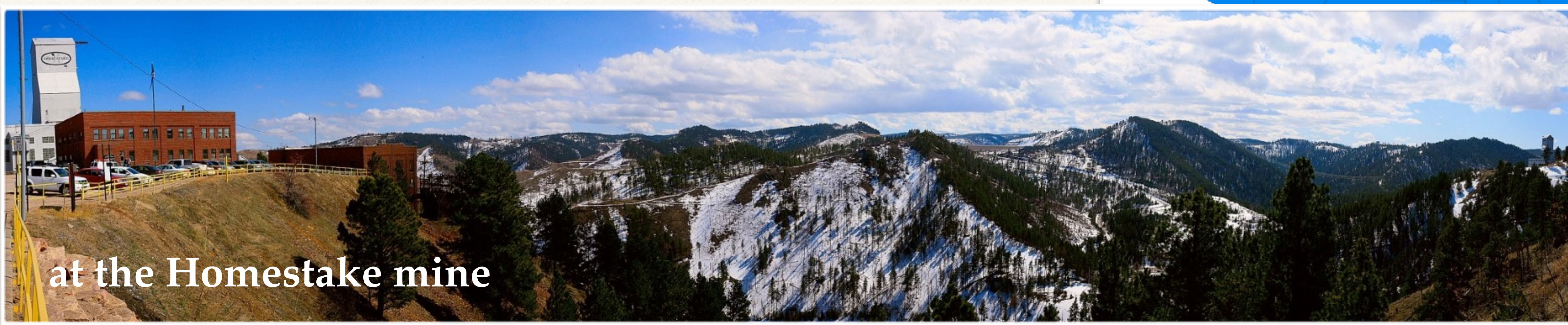
LUX Details

- 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 cryostat
- 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

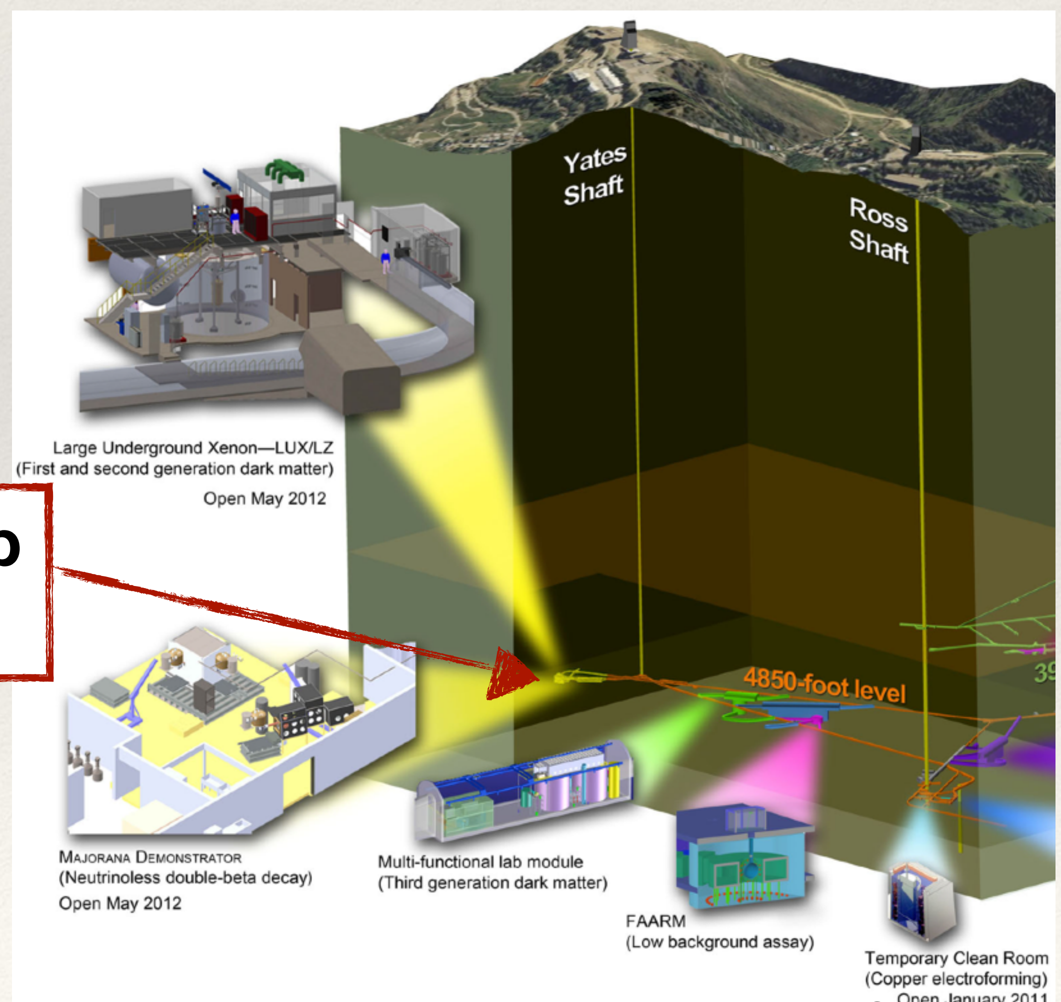


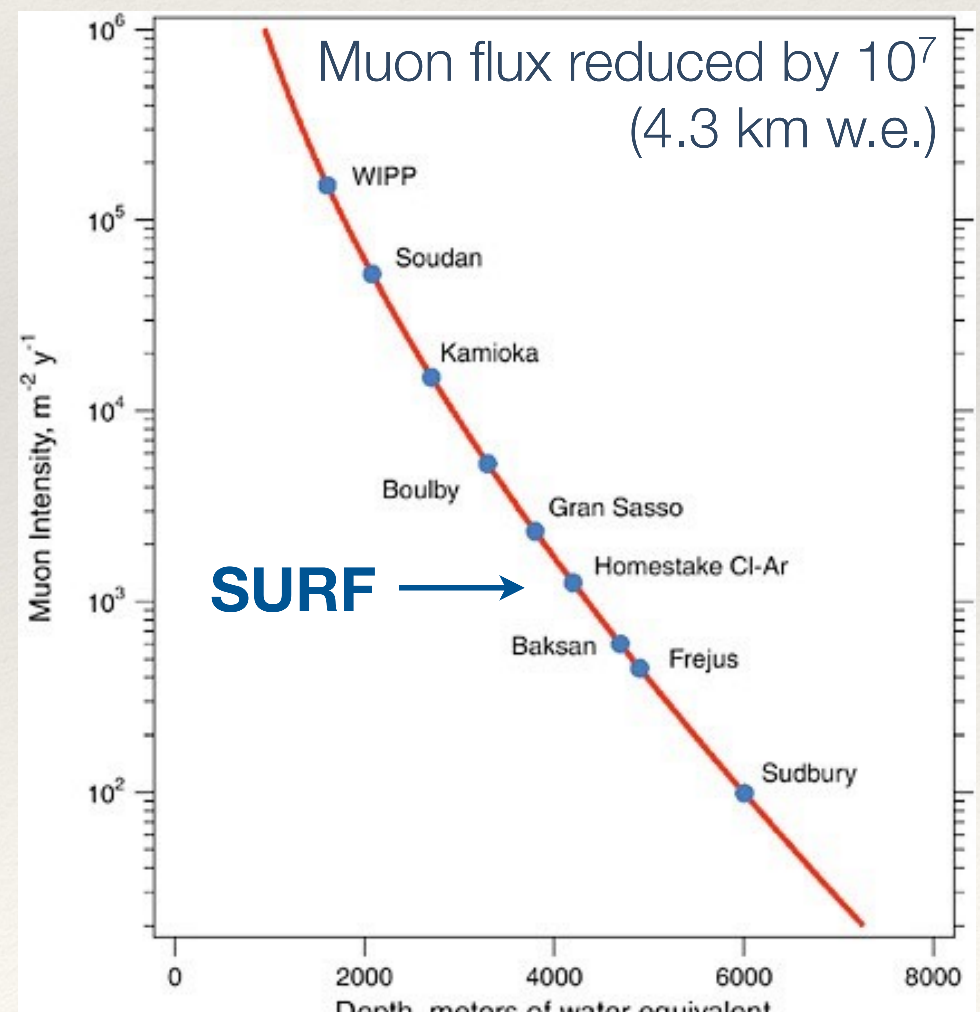
Sanford UG Research Lab





4850 feet deep (1478 m)





LUX Timeline

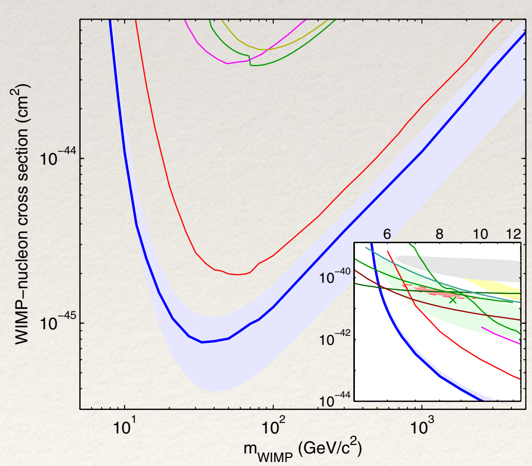
2006: LUX collab. formed

2008: LUX funded (DOE+NSF)

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

2013 (Apr): First science run starts

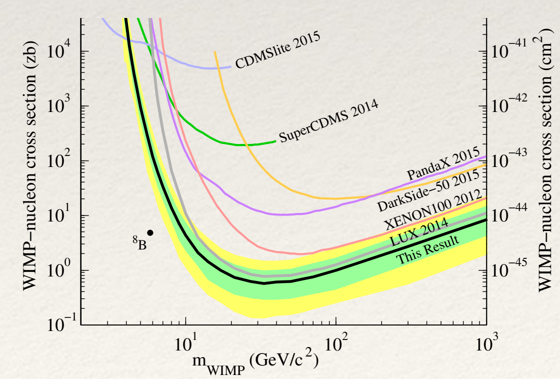
2013 (Nov): First results (3 months) reported



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

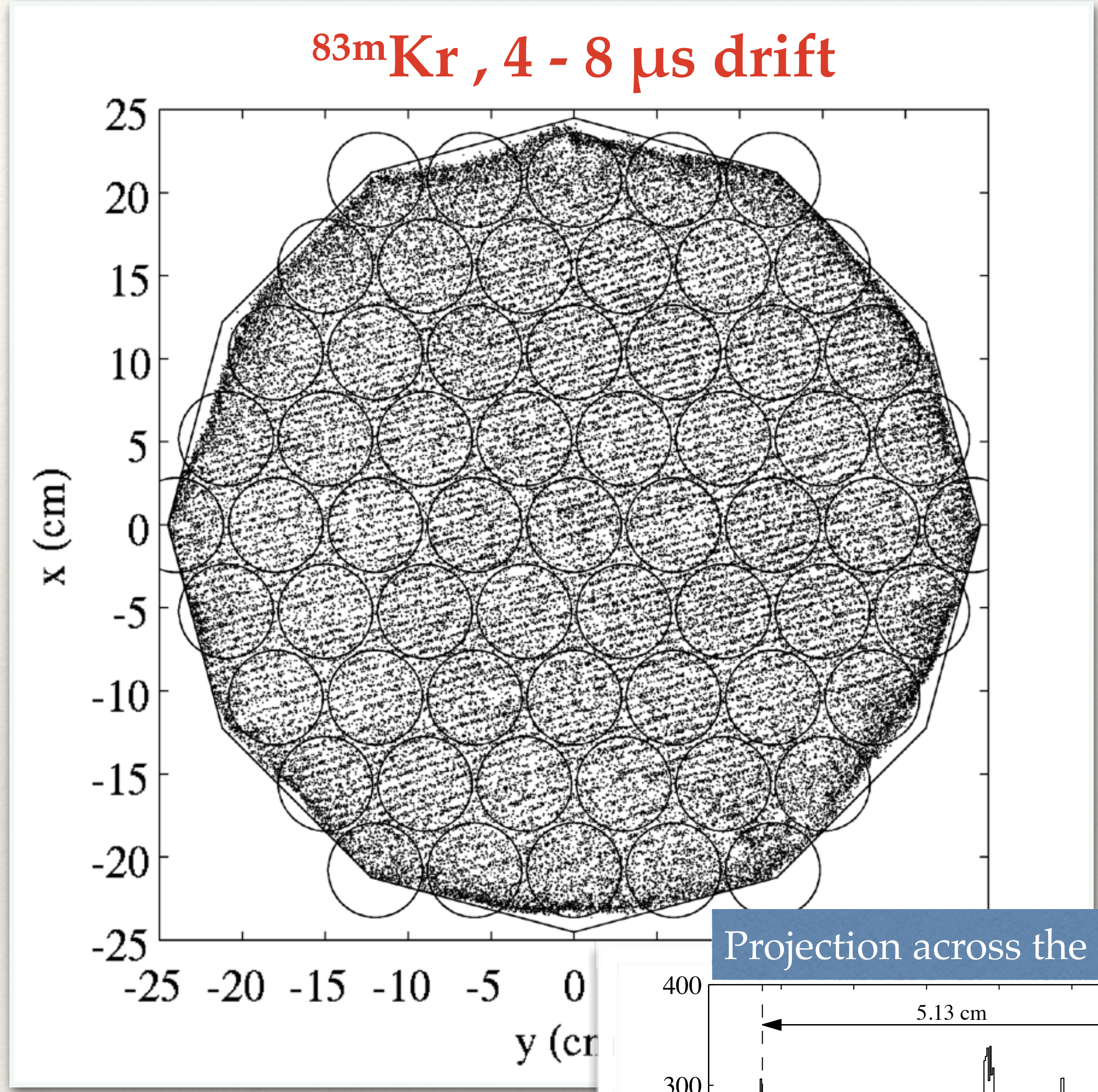
2016 (May): Run finished

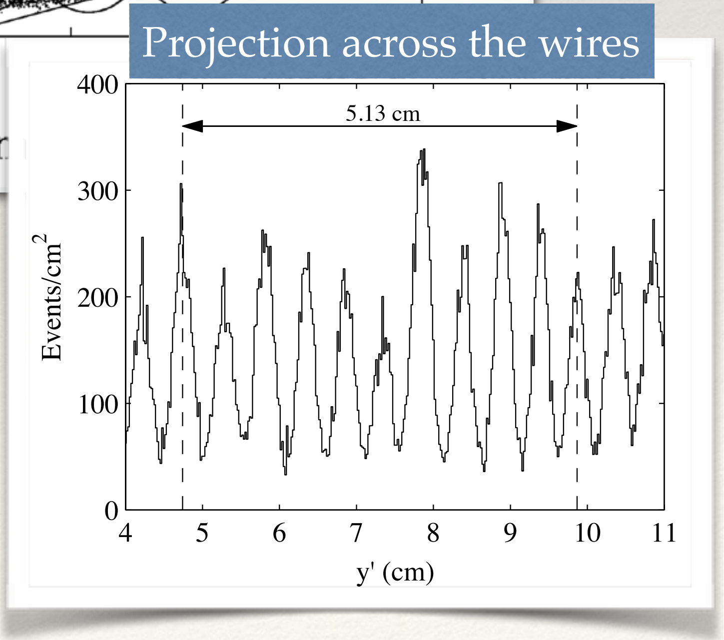
2016 (July): 332 day results announced

2016 (Sep): Decommis. starts

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

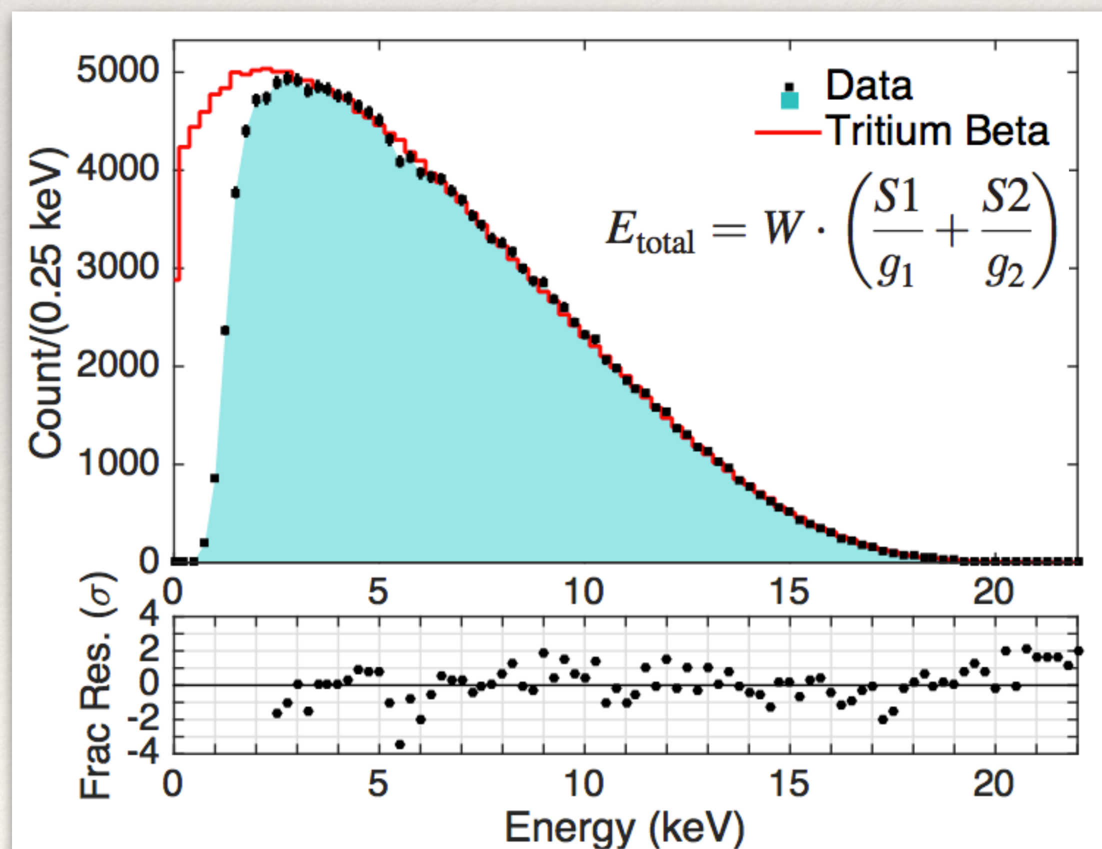


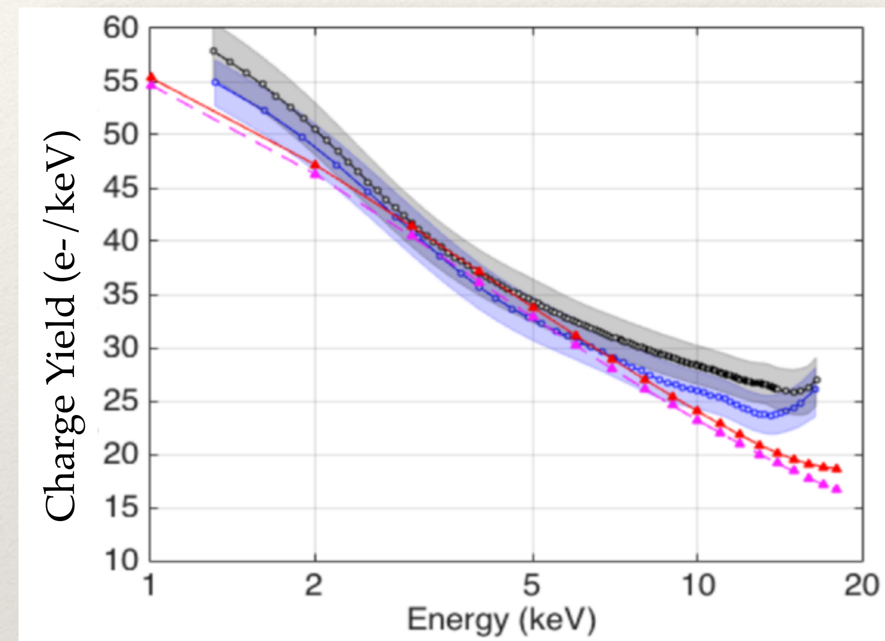


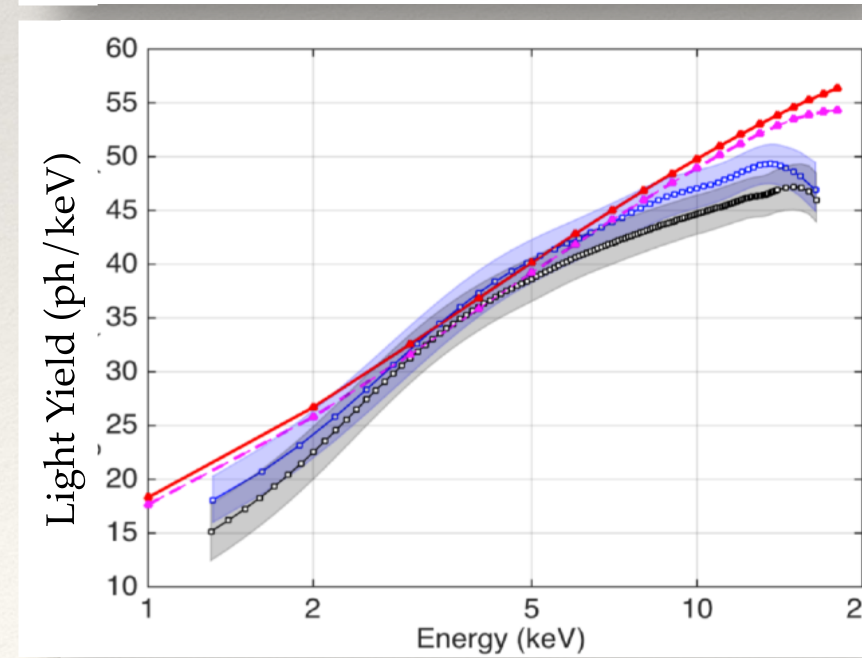
Calibrations - Electron Recoils

- 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)

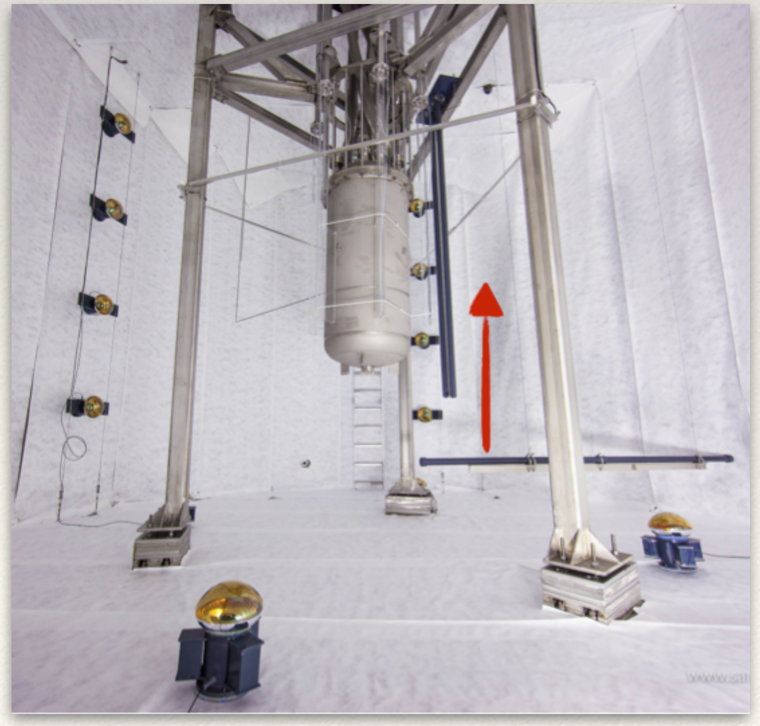


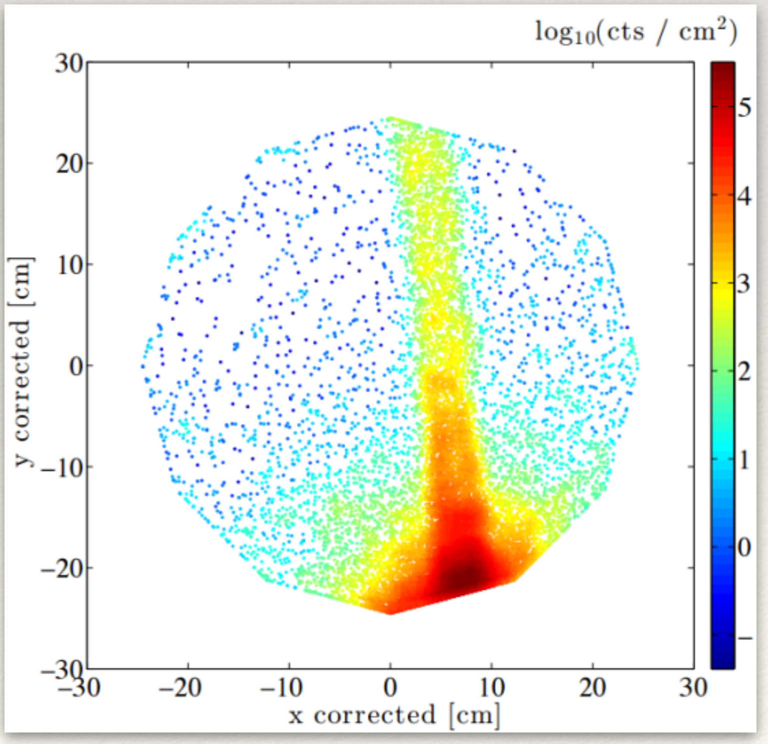


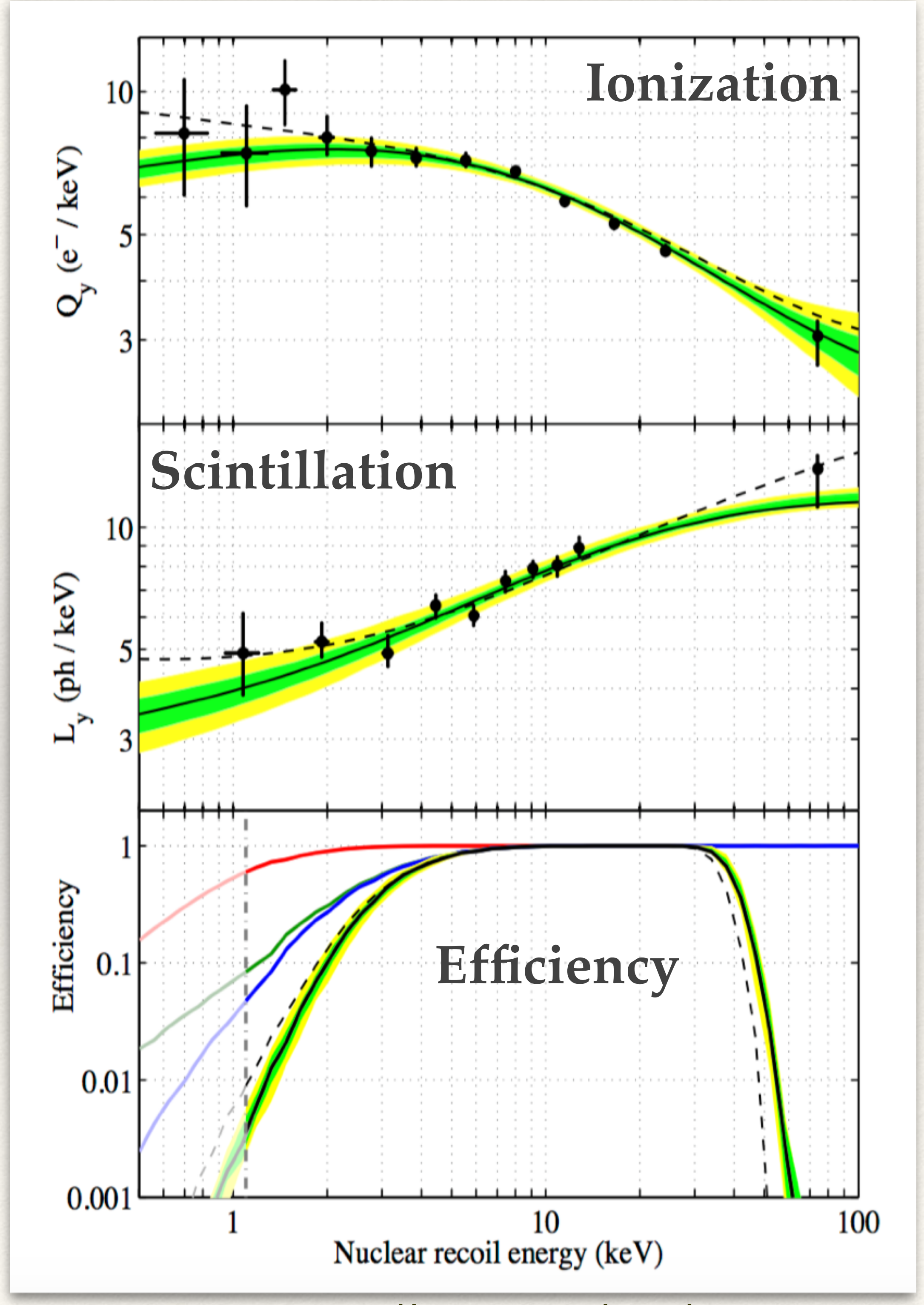


Calibrations — Nuclear Recoils

- DD neutron generator outside water tank (2.45 MeV neutrons)
- NR calibrations every 3 months and at different heights
- 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)

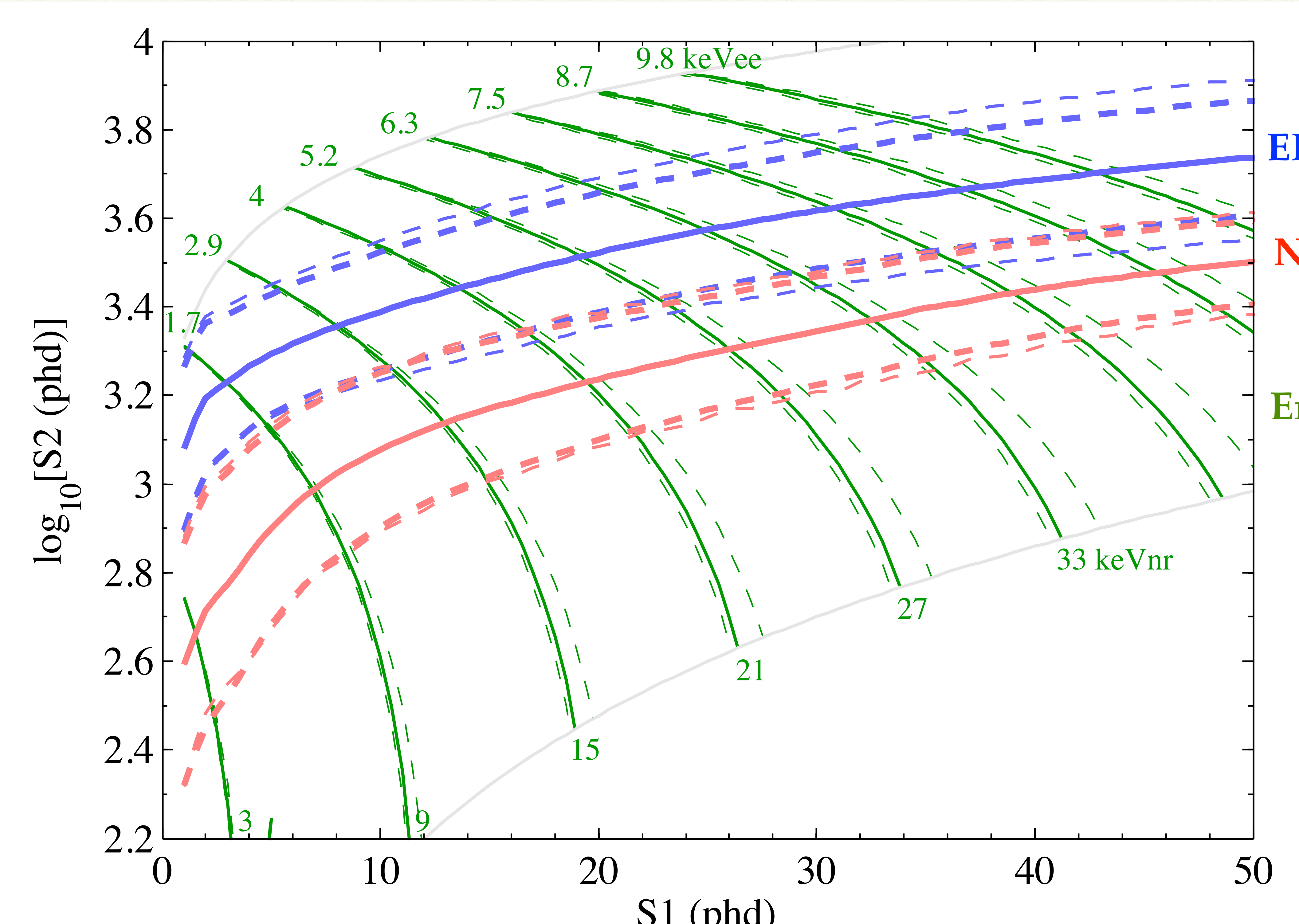






https://arxiv.org/abs/1608.05381

Parameter Space



ER band mean

NR band mean

Energy contours

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 (S1, log(S2), R, z, ϕ)

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

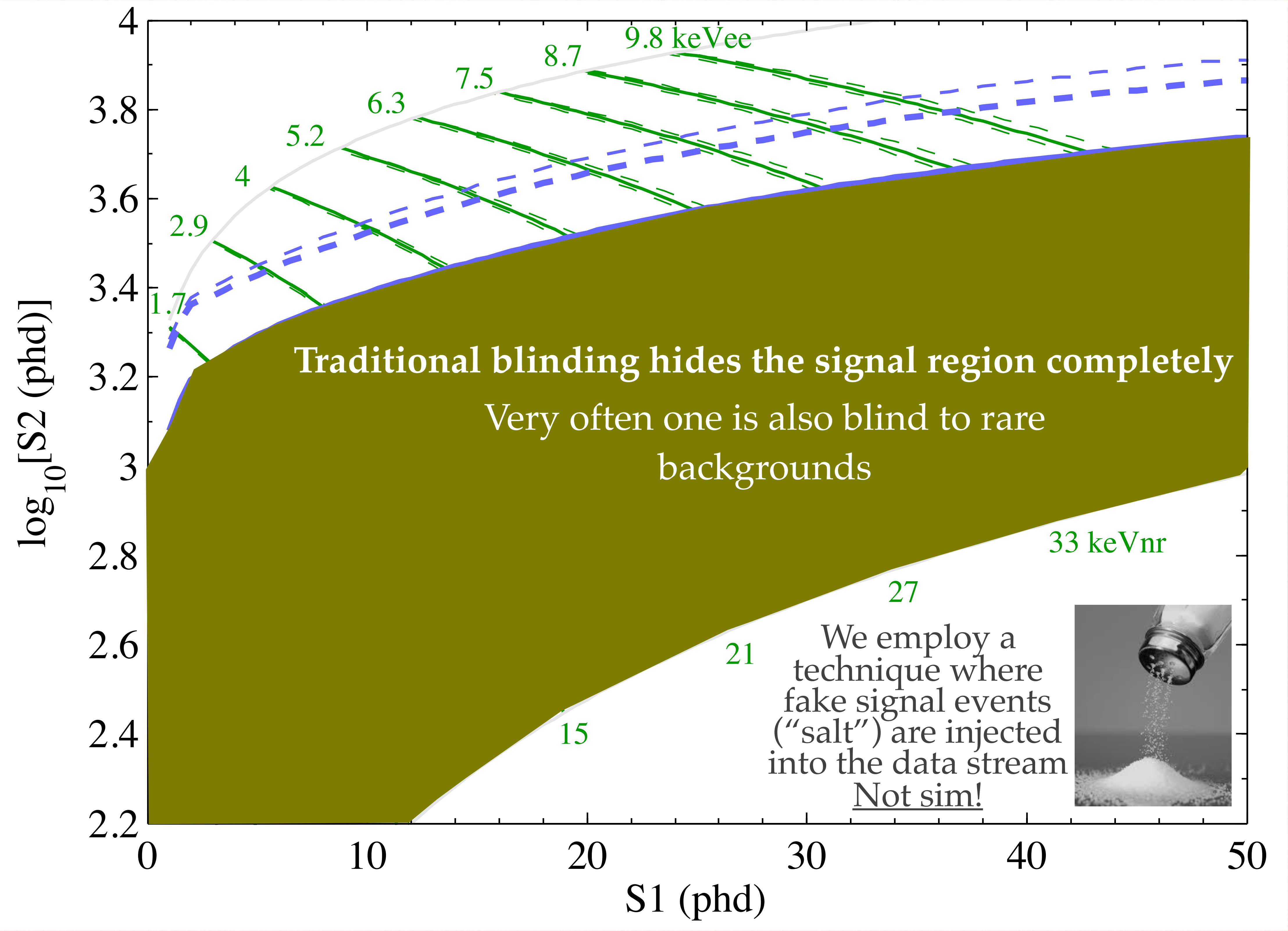
Rn plate out: Low energy, but limited to the edge of the detector*

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

~ 0.3 single scatter neutrons, not included in PLR

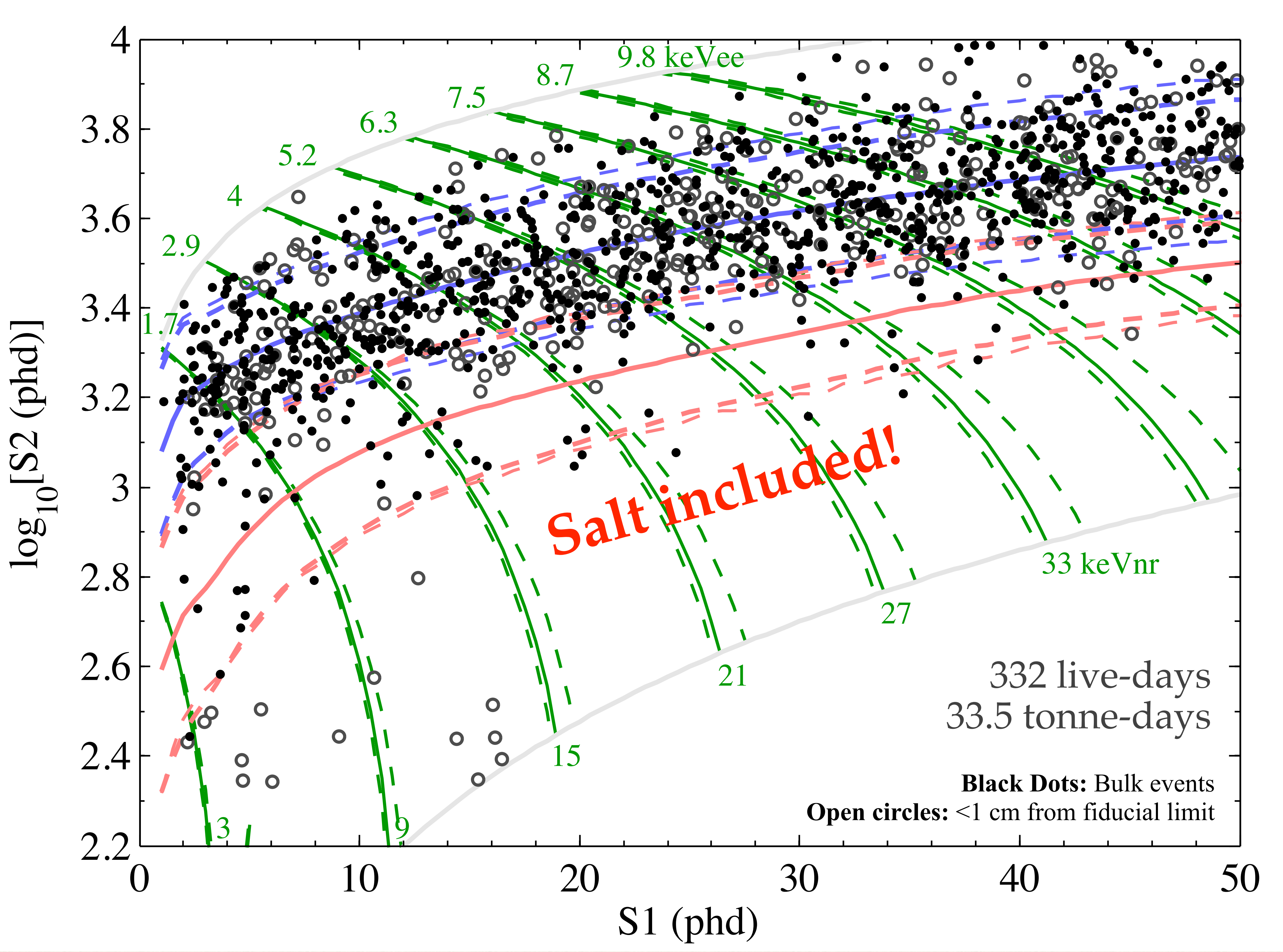
* - Our likelihood analysis includes position information, so these have a low likelihood as signal

Salting

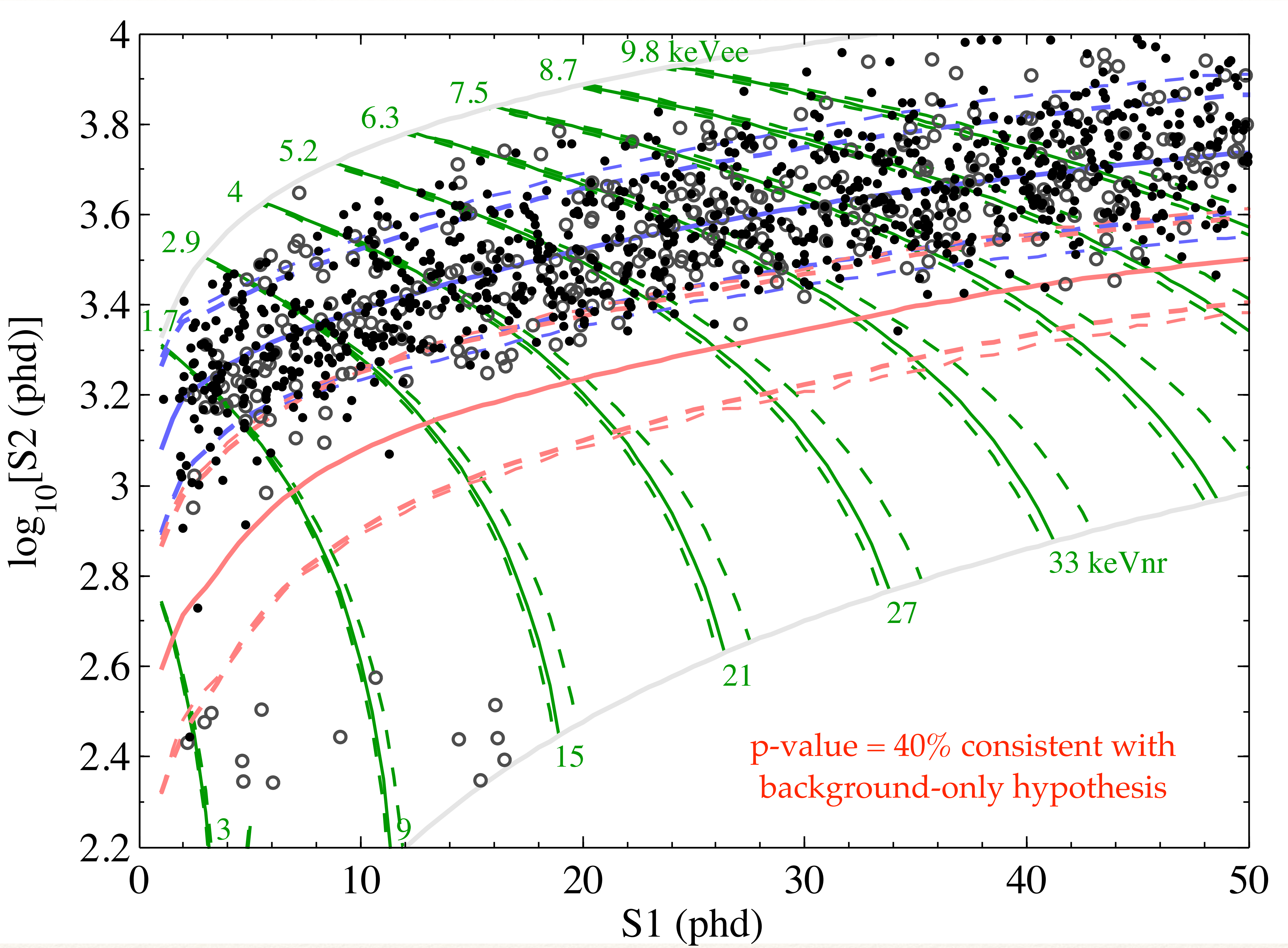


Traditional blinding hides the signal region completely
Very often one is also blind to rare backgrounds
We employ a technique where fake signal events ("salt") are injected into the data stream
Not sim!
9.8 keVee
8.7
7.5
6.3
5.2
4
2.9
1.7
33 keVnr
27
21
15
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
0
10
20
30
40
50
S1 (phd)
log10[S2 (phd)]

WIMP-Search Data

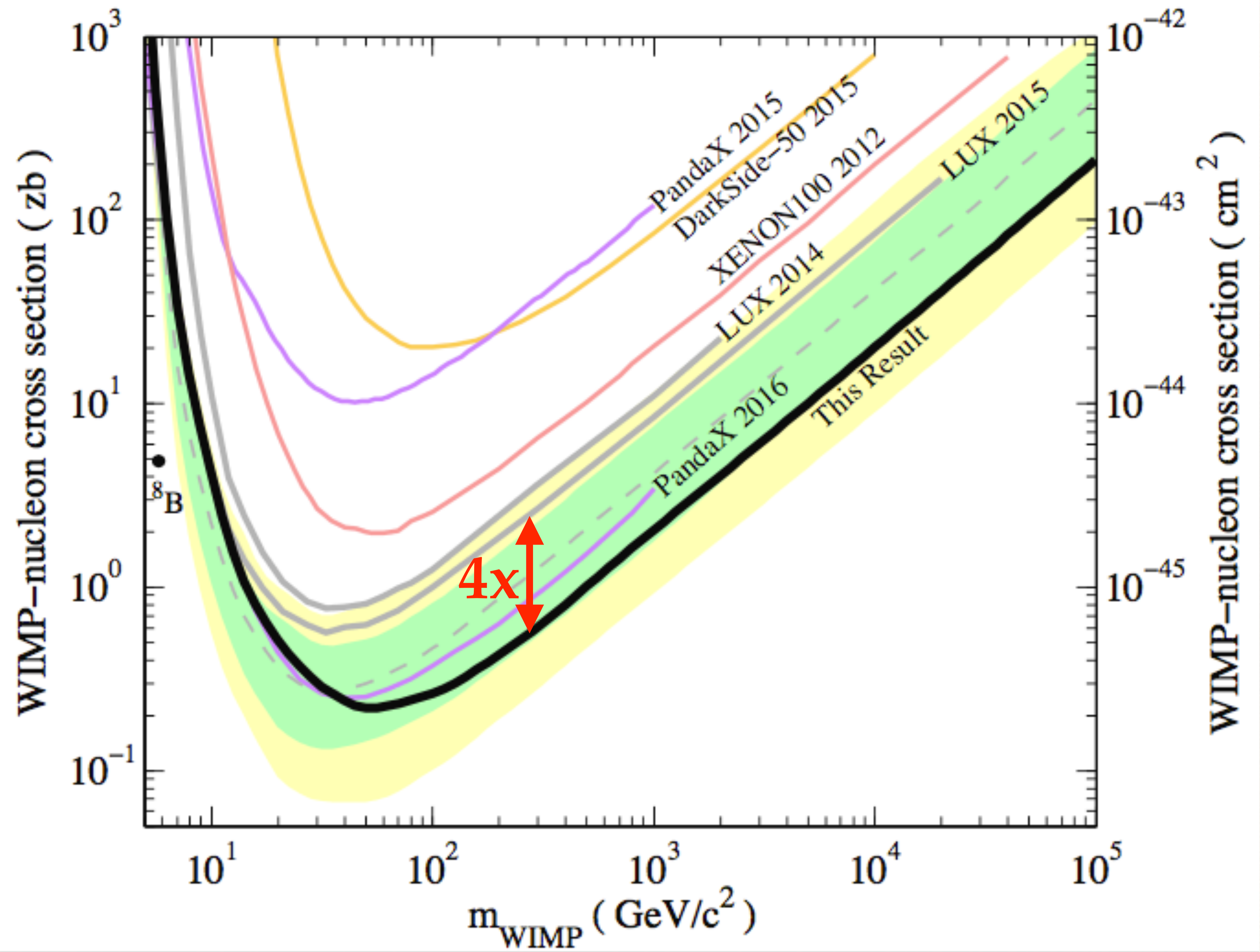


Final WS Data – 332 live-days

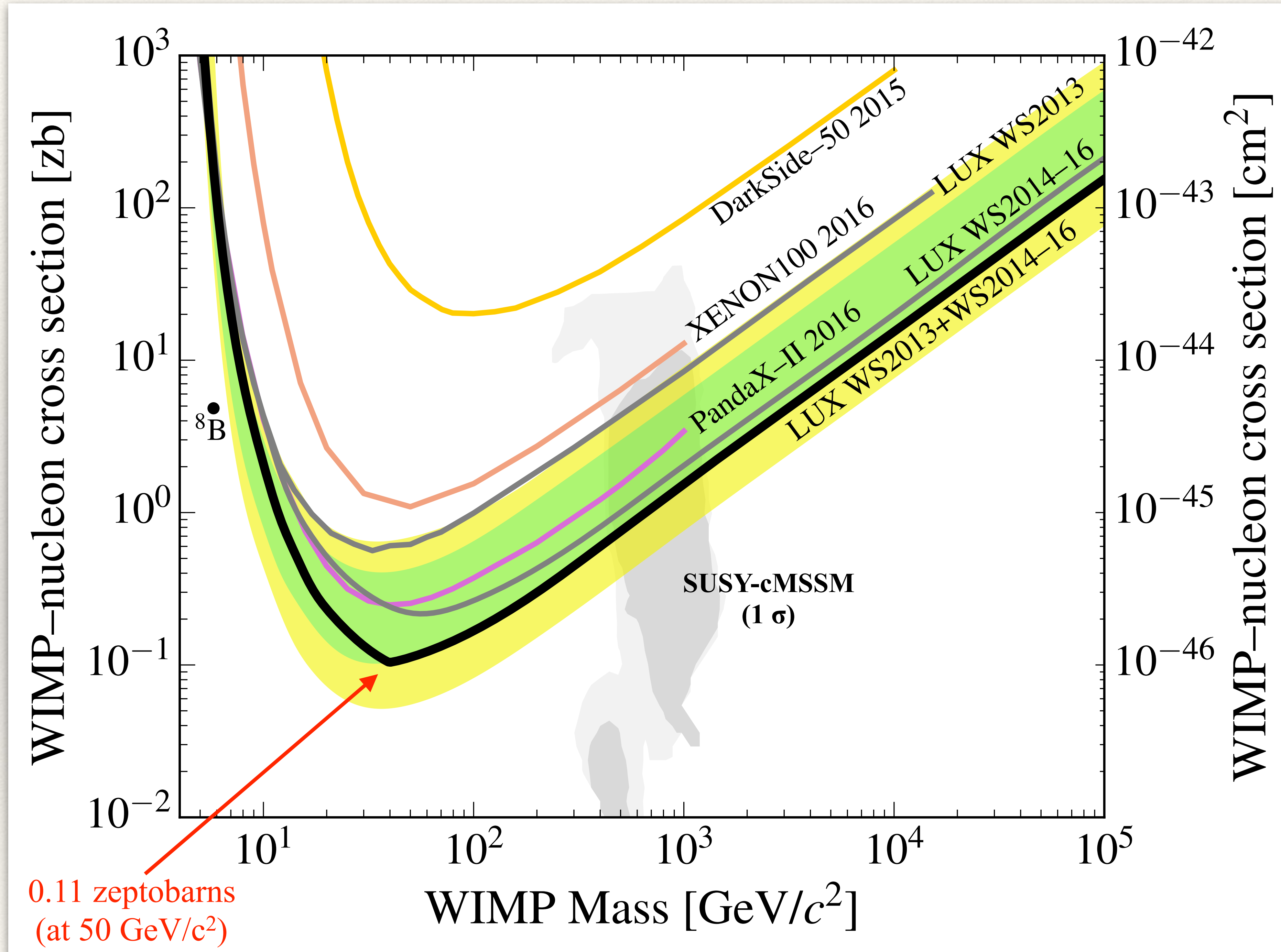


SI Exclusion Limit – 332 live-days

- 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

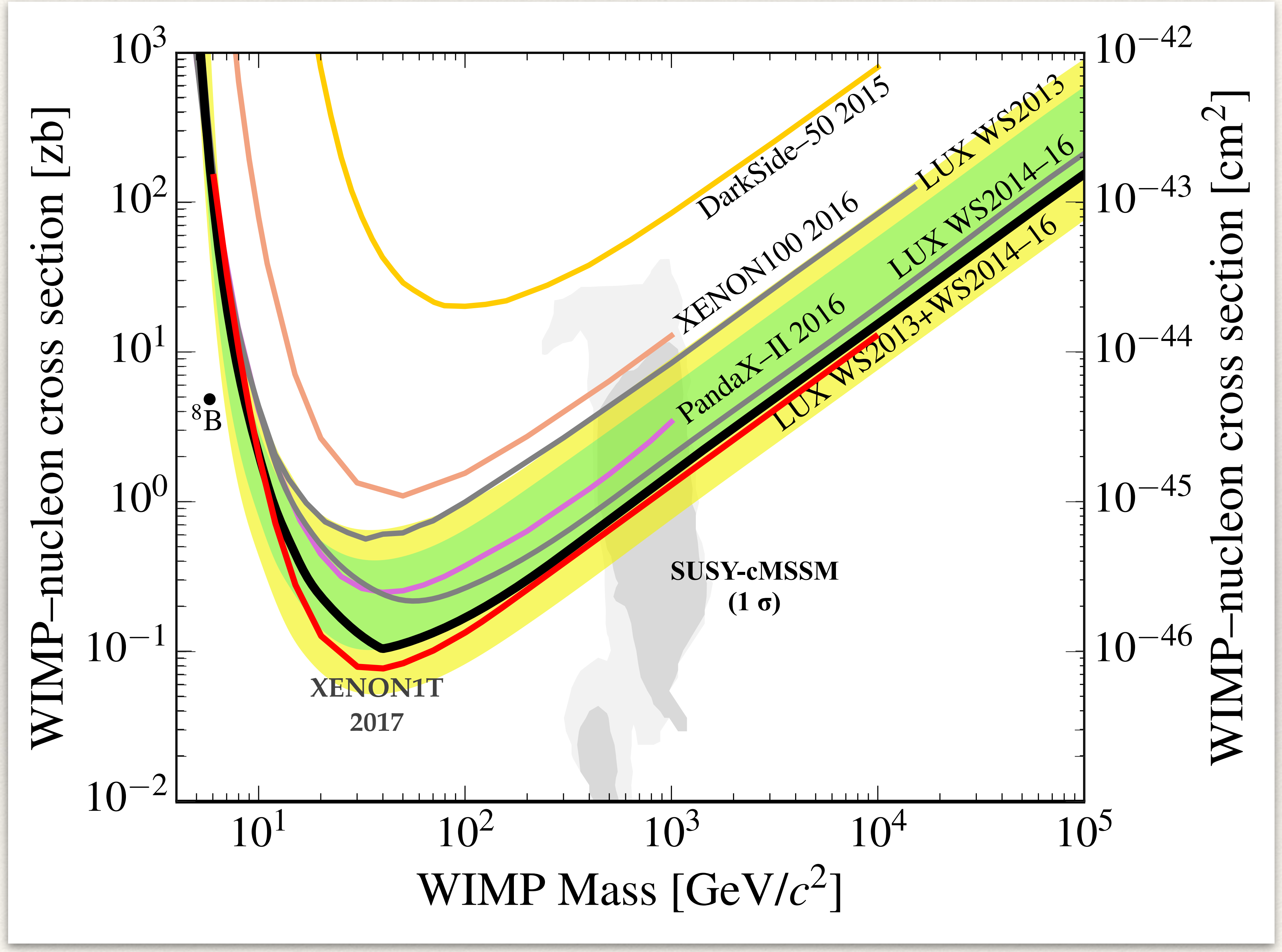


SI Exclusion limit – 95+332 live-days



PRL, 118, 21303 (2017)

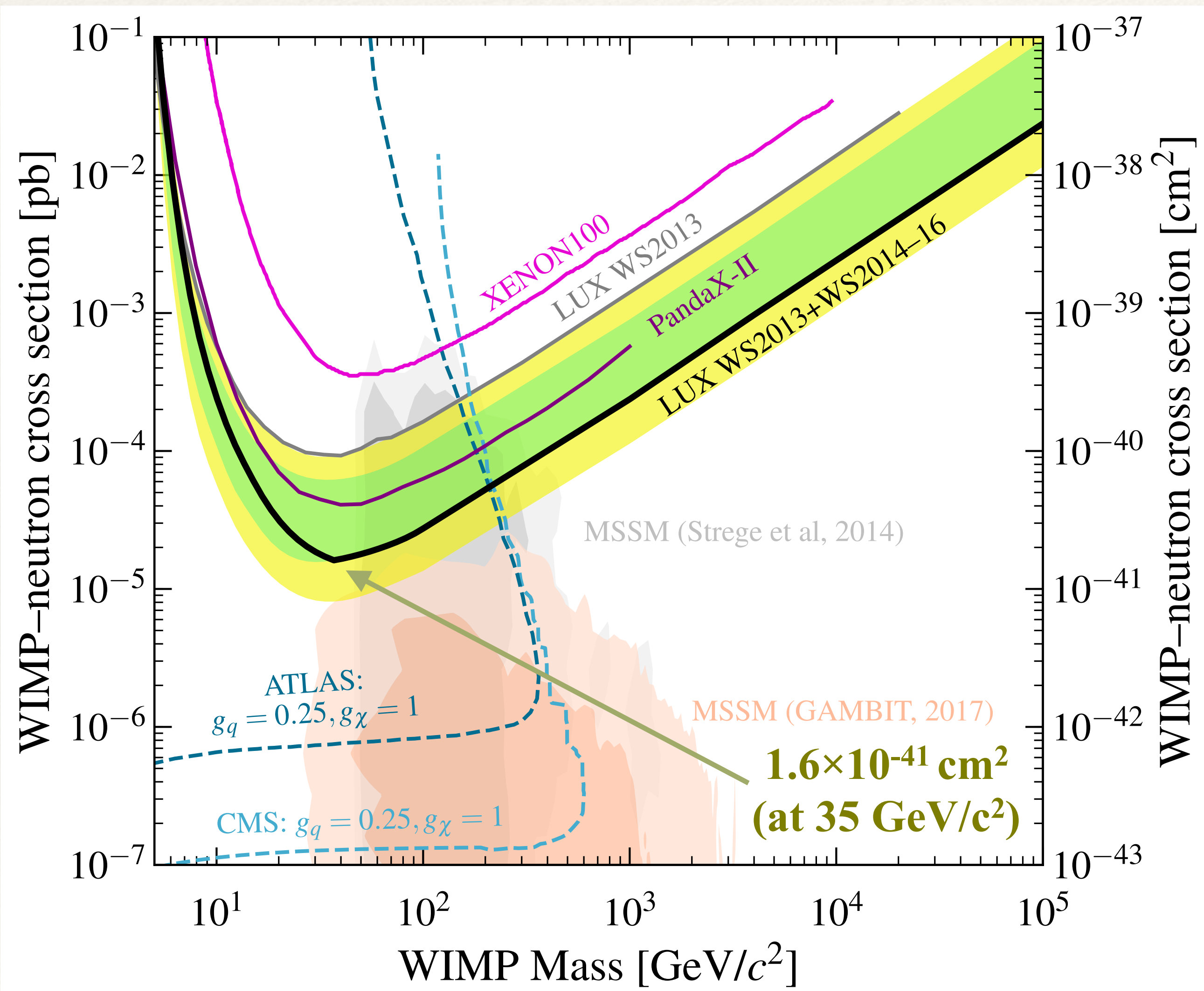
SI Exclusion limit – 95+332 live-days



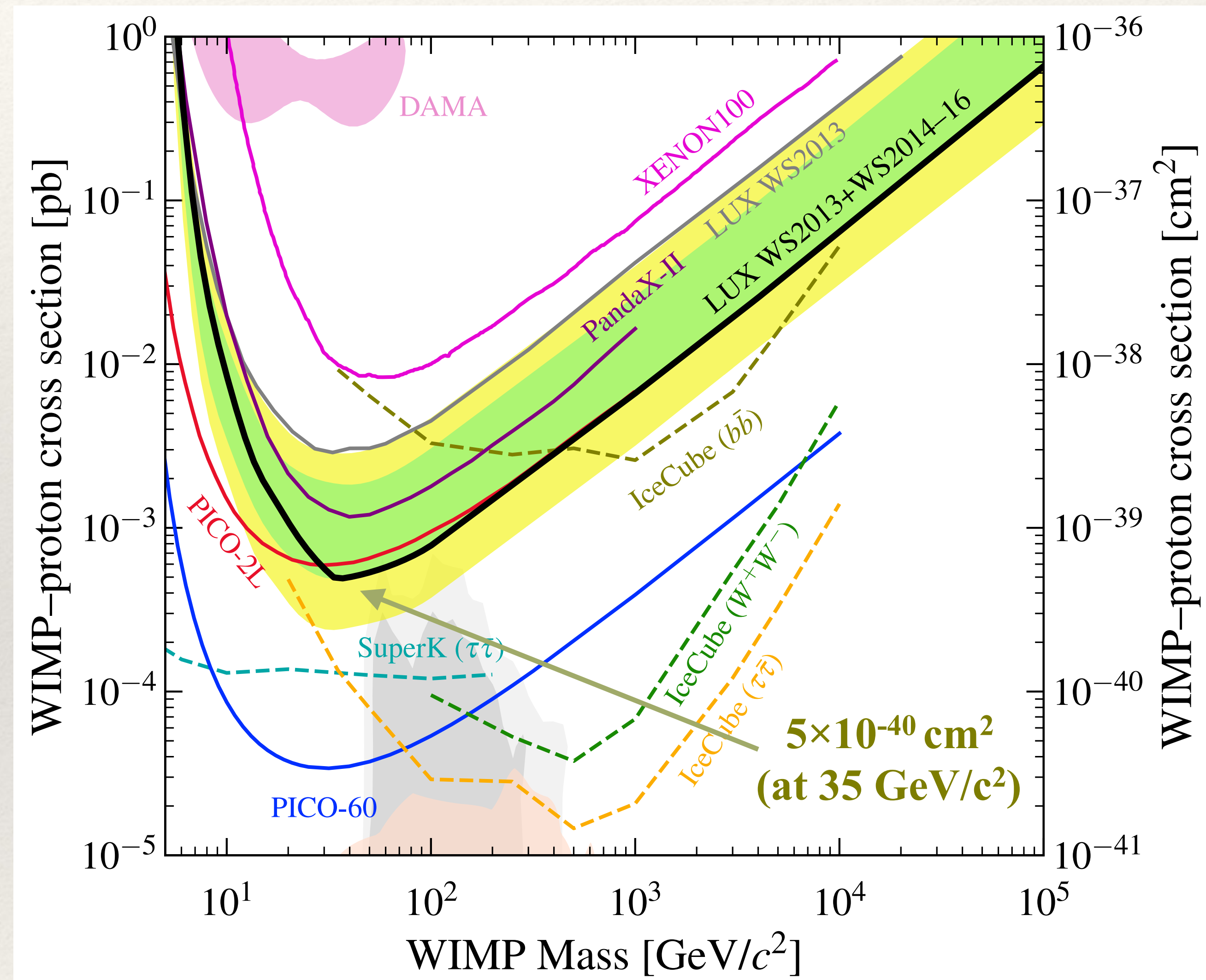
PRL, 118, 21303 (2017)

SD Exclusion Limits – 95+332 live-days

WIMP-neutron



WIMP-proton

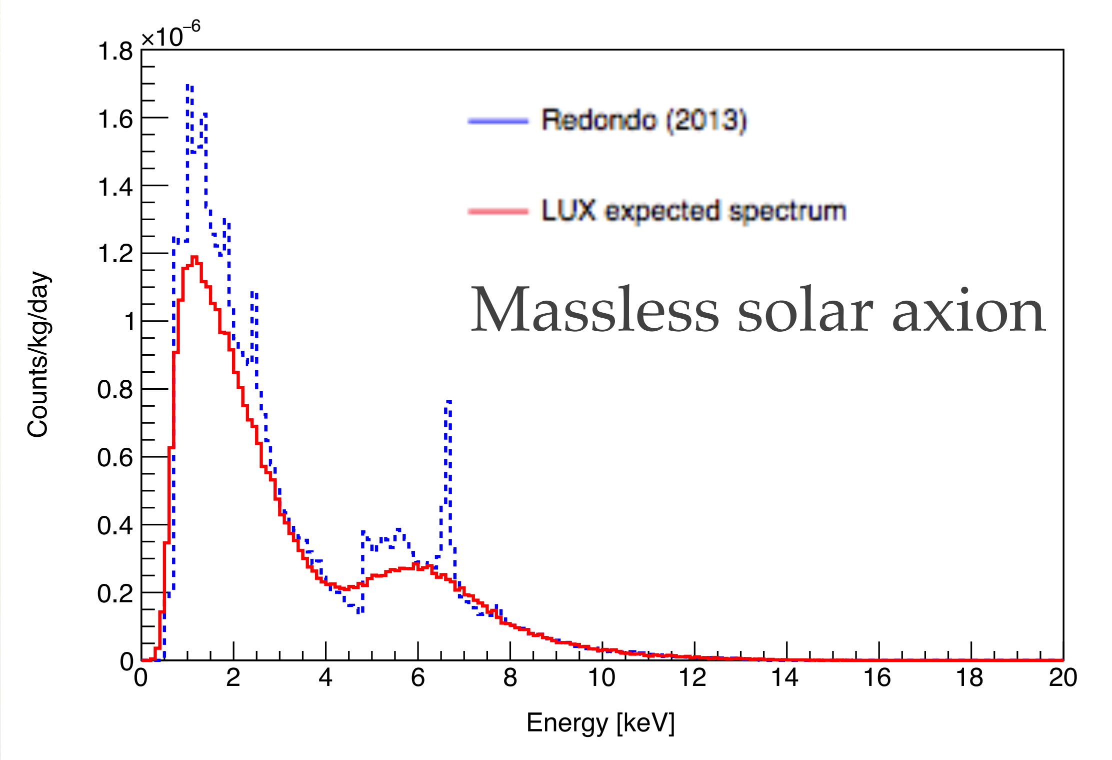


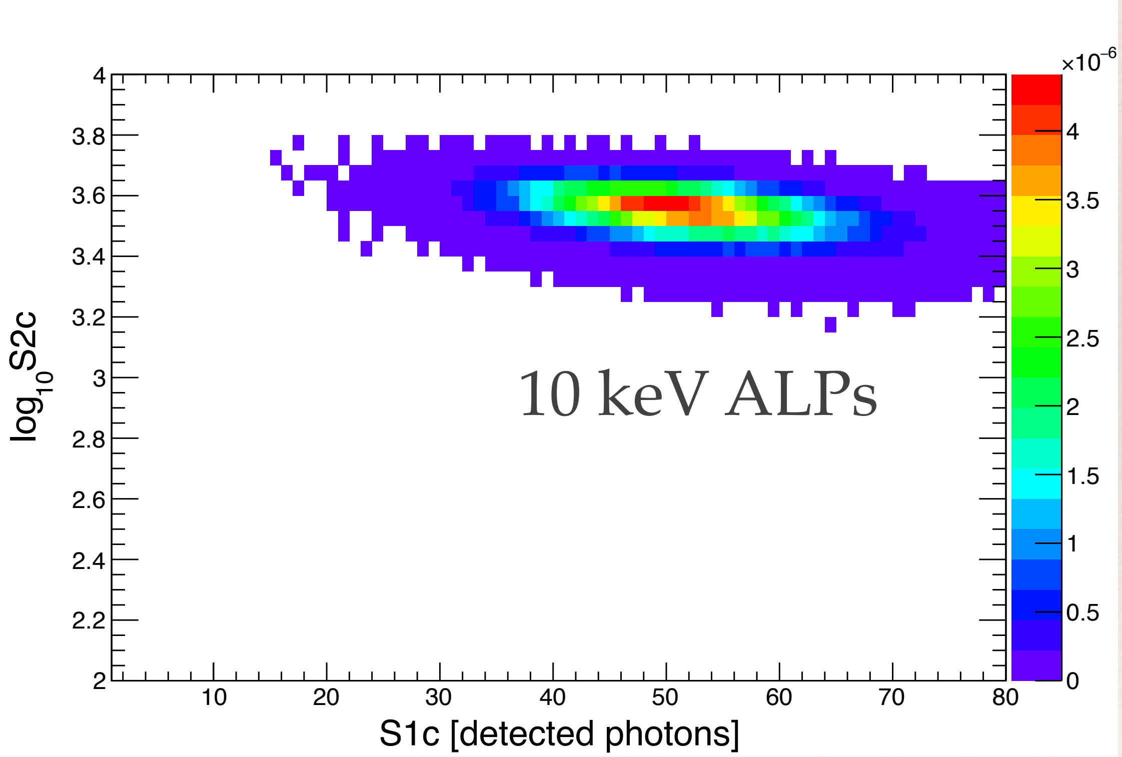
An improvement of a factor of six compared with the results from the 2013 run

PRL 118, 251302 (2017)
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





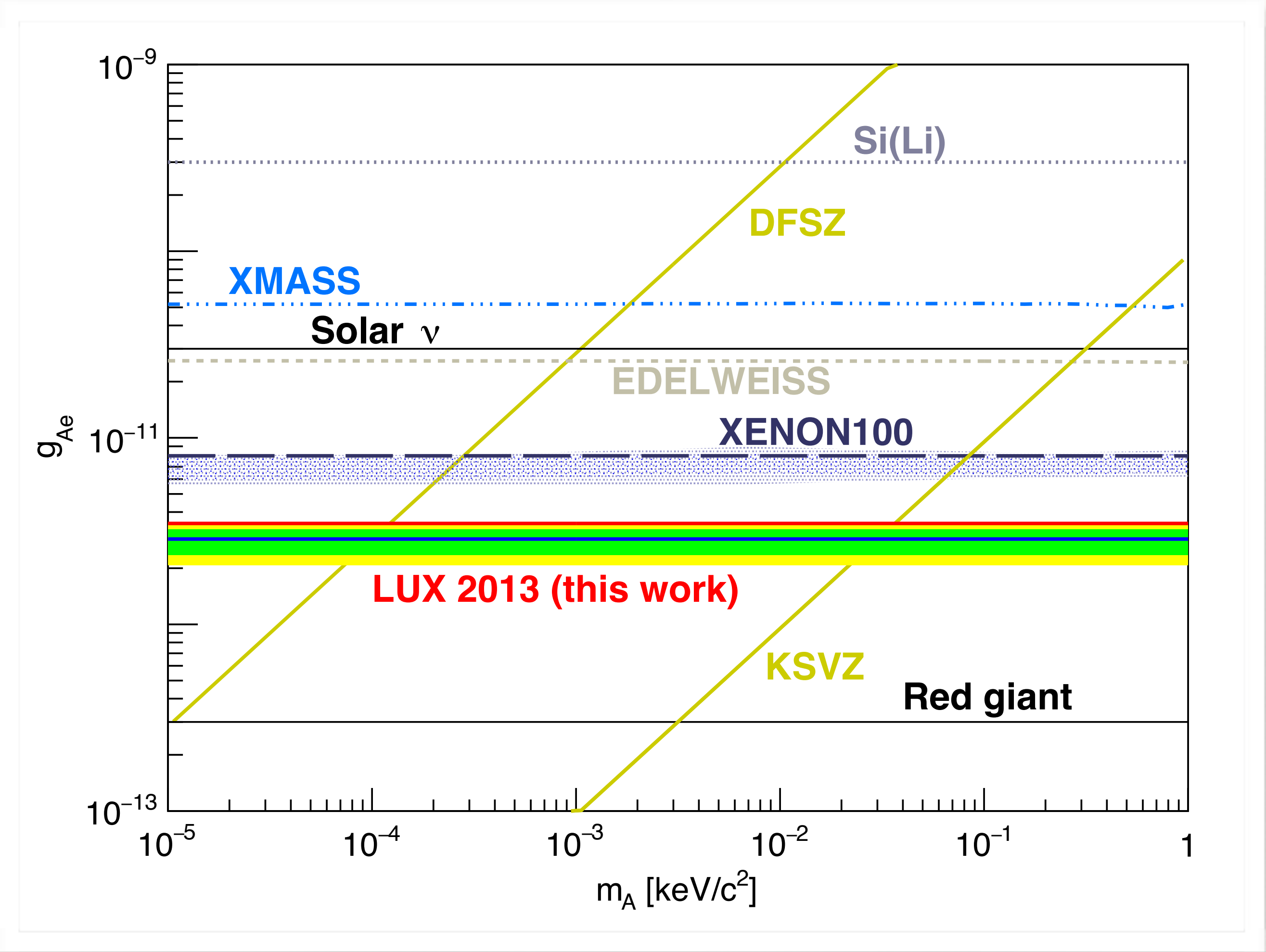
- ALPs expected to be at rest within the galaxy
- Axio-electric absorption leads to ERs with kinetic energy of the ALP mass: sharp feature, smeared by detector resolution

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

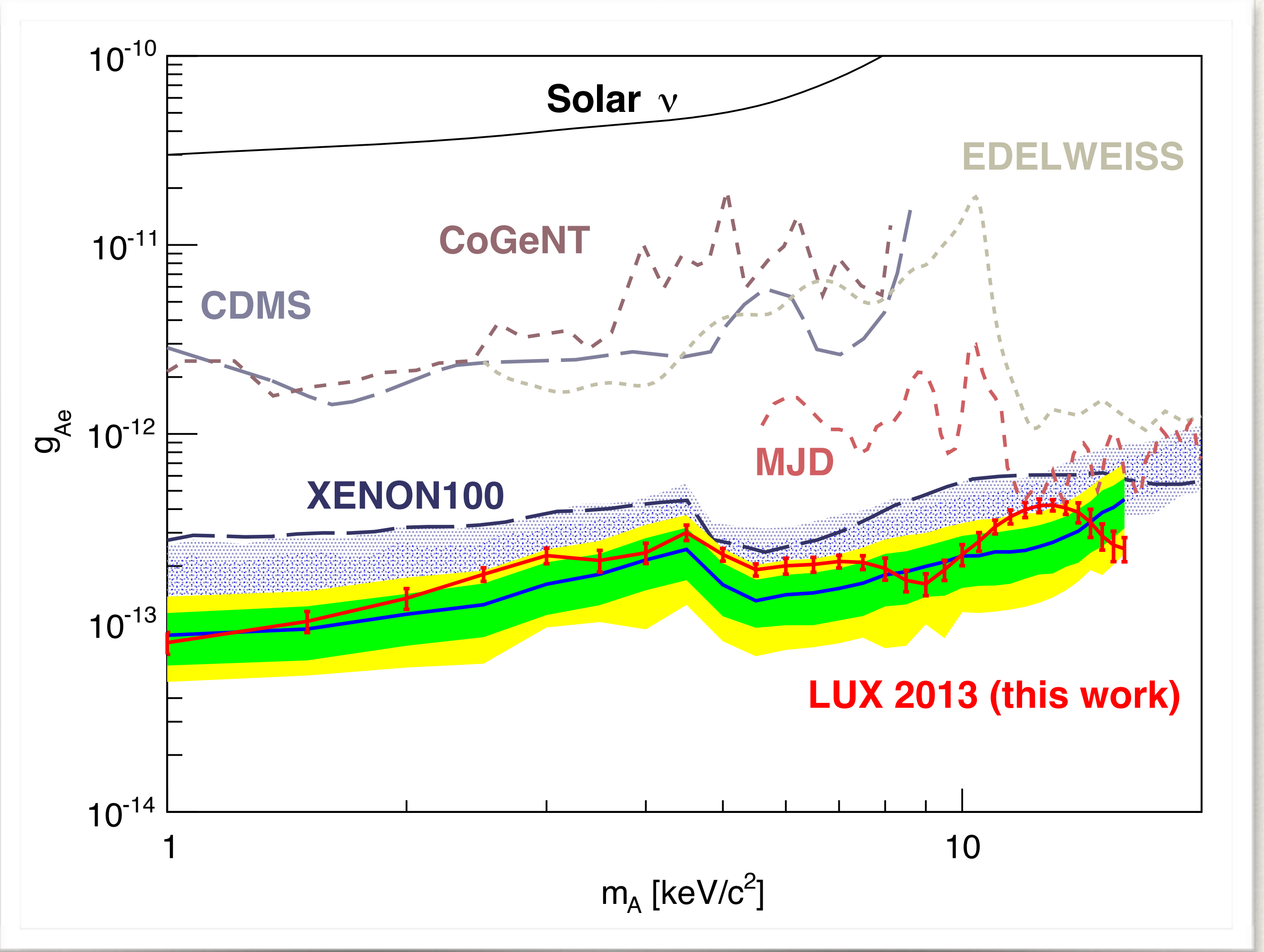
Axions



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)

ALPs



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

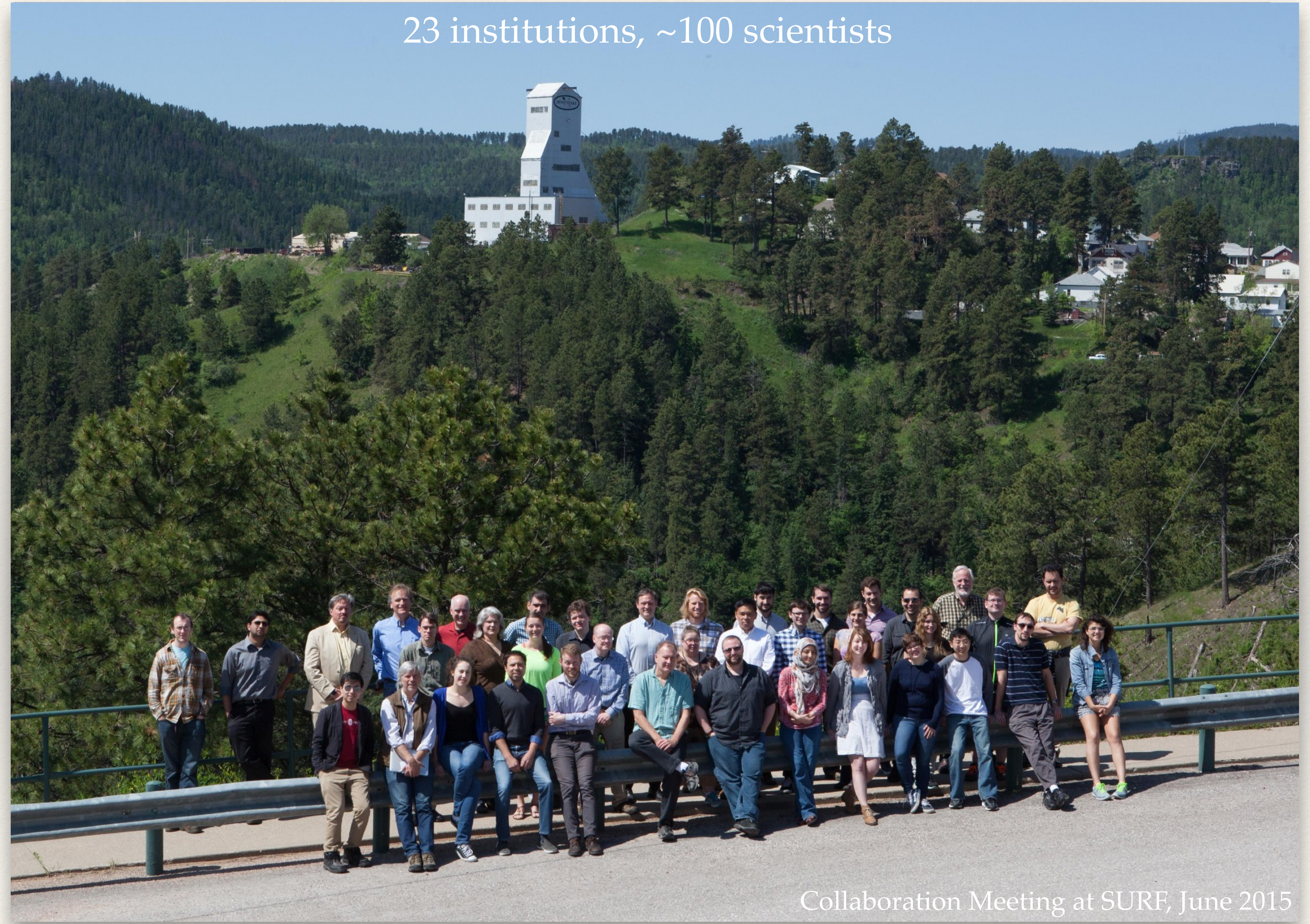
arXiv:1704.02297

PRL 118, 261301 (2017)

Summary

- LUX had 4 extremely productive years, and is still producing new physics results
  - 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
  - EFT, annual modulation, inelastic DM, etc.
- Accumulated expertise used in the design of LZ
  - Next talk by W. Lorenzon

LUX on display at the SURF visitors center



luxdarkmatter.org

The LUX collaboration

Berkeley Lab / UC Berkeley

Bob Jacobsen	PI, Professor
Murdock Gilcrease	Senior Scientist
Kevin Lesko	Senior Scientist
Michael Witherell	Lab Director
Peter Sorensen	Divisional Fellow
Simon Fiorucci	Project Scientist
Evan Pease	Postdoc
Daniel Hogan	Graduate Student
Kelsey Oliver-Mallory	Graduate Student
Kate Kamdin	Graduate Student

Brown University

Richard Gaitskell	PI, Professor
Junhui Liao	Postdoc
Samuel Chan	Graduate Student
Dongqing Huang	Graduate Student
Casey Rhyne	Graduate Student
Will Taylor	Graduate Student
James Verbus	Ex-Postdoc

University of Edinburgh

Alexander Murphy	PI, Professor
Paolo Beltrame	Ex-Research Fellow
Maria F. Marzioni	Graduate Student
Tom Davison	Graduate Student

Lawrence Livermore National Laboratory

Adam Bernstein	PI, RED group leader
Kareem Kazkaz	Physicist
Jingke Xu	Postdoc
Brian Lenardo	Graduate Student

Stanislaus State

Wing To	PI, Assistant Professor

Imperial College London

Henrique Araujo	PI, Professor
Tim Sumner	Professor
Alastair Currie	Ex-Postdoc
Adam Bailey	Ex-Graduate Student
Khadeeja Yazdani	Ex-Graduate Student
Nellie Marangou	Graduate Student

SLAC National Accelerator Laboratory

Dan Akerib	PI, Professor
Thomas Shutt	PI, Professor
Tomasz Biesiadzinski	Research Associate
Christina Ignarra	Research Associate
Alden Fan	Research Associate
Wei Ji	Graduate Student
TJ Whitis	Graduate Student

LIP Coimbra

Isabel Lopes	PI, Professor
José Pinto de Cunha	Assistant Professor
Vladimir Solovov	Senior Researcher
Alexandre Lindote	Postdoc
Francisco Neves	Auxiliary Researcher
Claudio Silva	Research Fellow
Paulo Bras	Graduate Student

PennState

Carmen Carmona	PI, Assistant Professor
Emily Grace	Postdoc

SD Mines

Xinhua Bai	PI, Professor
Douglas Tiedt	Graduate Student

SDSTA / Sanford Lab

David Taylor	Senior Engineer
Markus Horn	Research Scientist

University at Albany, State University of New York

Matthew Szydagis	PI, Assistant Professor
Cecilia Levy	Postdoc
Jack Genovesi	Research Assistant

Texas A&M University

Robert Webb	PI, Professor
Paul Terman	Graduate Student

Berkeley

Daniel Mckinsey	PI, Professor
Ethan Bernard	Project Scientist
Elizabeth Boulton	Graduate Student
Junsong Lin	Postdoc
Brian Tennyson	Graduate Student
Lucie Tvrznikova	Graduate Student
Vetri Velan	Graduate Student

UC Davis, University of California

Mani Tripathi	PI, Professor
Aaron Manalaysay	Project Scientist
James Morad	Ex-Graduate Student
Sergey Uvarov	Ex-Graduate Student
Jacob Cutter	Graduate Student
Dave Hemer	Senior Machinist

Wisconsin, University of Wisconsin-Madison

Kimberly Palladino	PI, Assistant Professor
Shaun Alsum	Graduate Student
Rachel Mannino	Postdoc

UC Santa Barbara

Harry Nelson	PI, Professor
Sally Shaw	Postdoc
Scott Haselschwardt	Graduate Student
Curt Nehrkorn	Graduate Student
Melih Solmaz	Graduate Student
Dean White	Engineer
Susanne Kyre	Engineer

UCL University College London

Chamkaur Ghag	PI, Professor
Jim Dobson	Postdoc
Umit Utku	Graduate Student

University of Maryland

Carter Hall	PI, Professor
Jon Balajthy	Graduate Student

UMass Amherst

Scott Hertel	PI, Assistant Professor
Christ Nedlik	Graduate Student

University of Rochester

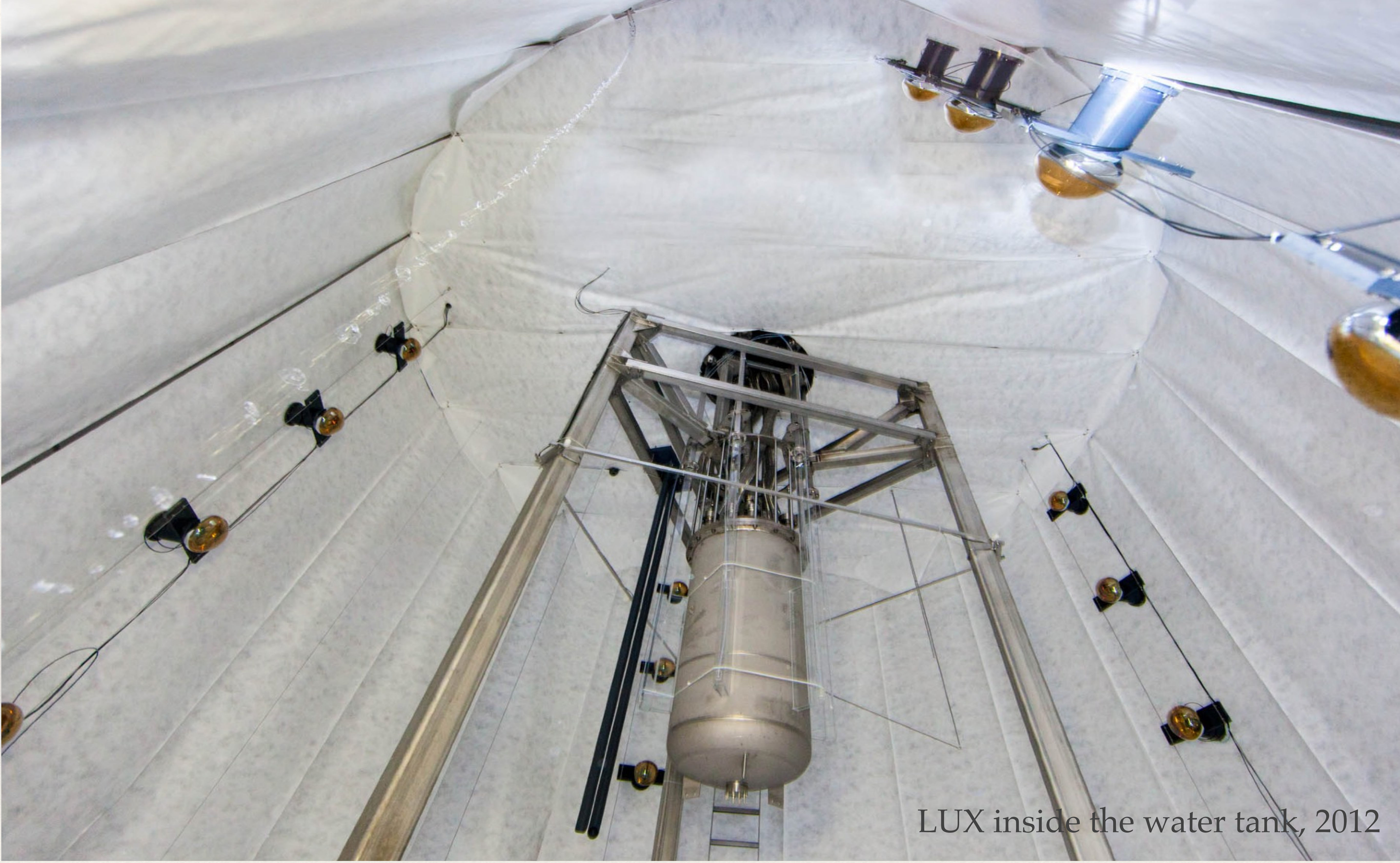
Frank Wolfs	PI, Professor
Wojtek Skulski	Senior Scientist
Eryk Druszkiewicz	Electrical Engineer
Dev Aashish Khaitan	Graduate Student
Mongkol Moongweluwan	Graduate Student

University of Sheffield

Vitaly Kudryavtsev	Reader, Particle Physics
Elena Korolkova	Research Associate
David Woodward	Research Associate
Peter Rossiter	Graduate Student

University of South Dakota

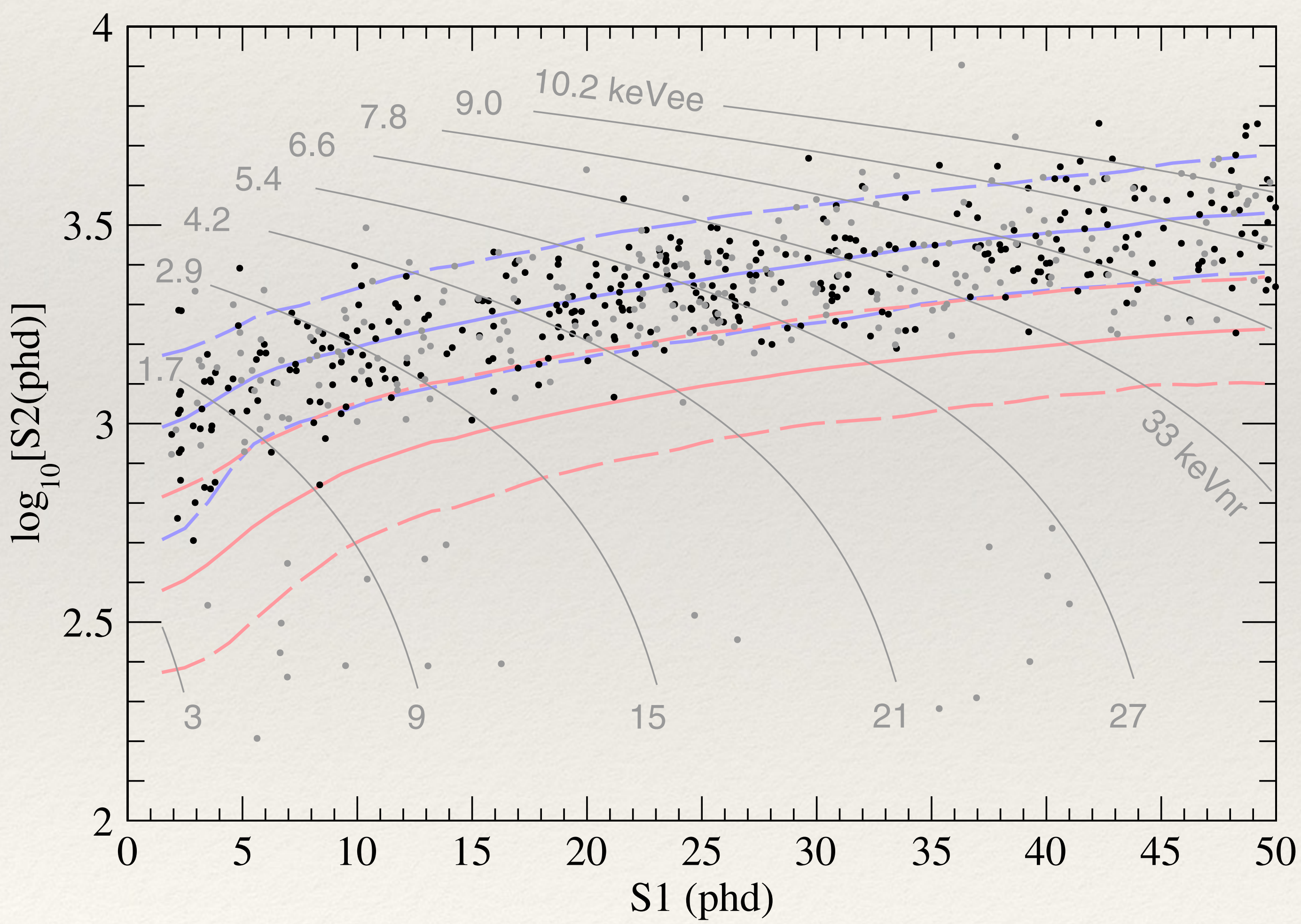
Dongming Mei	PI, Professor

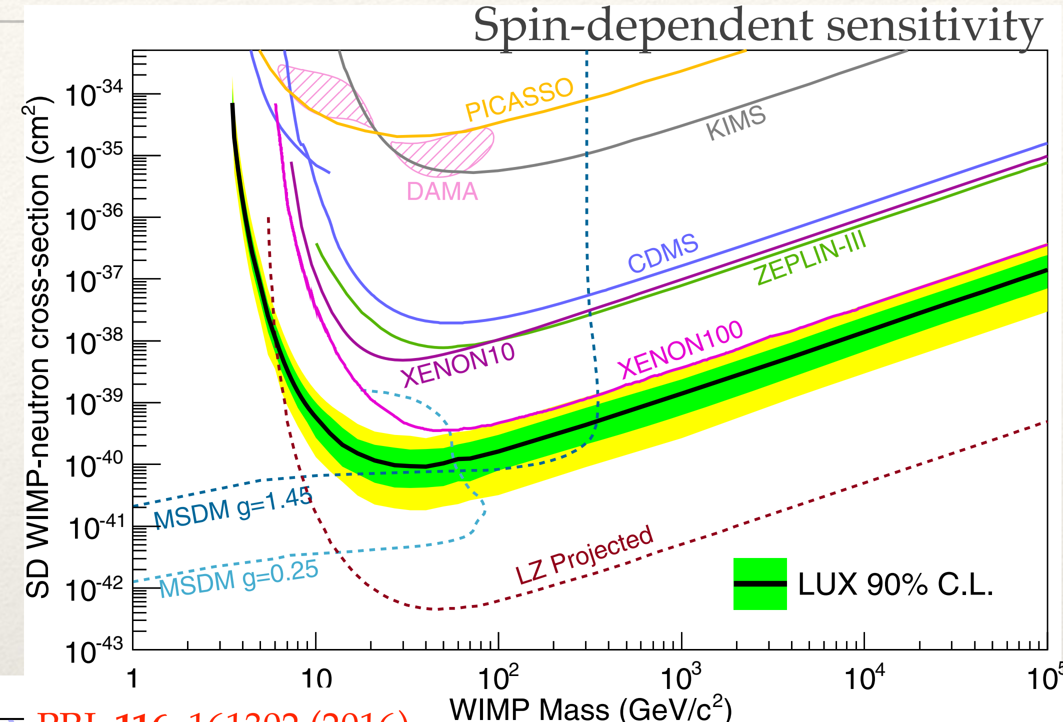


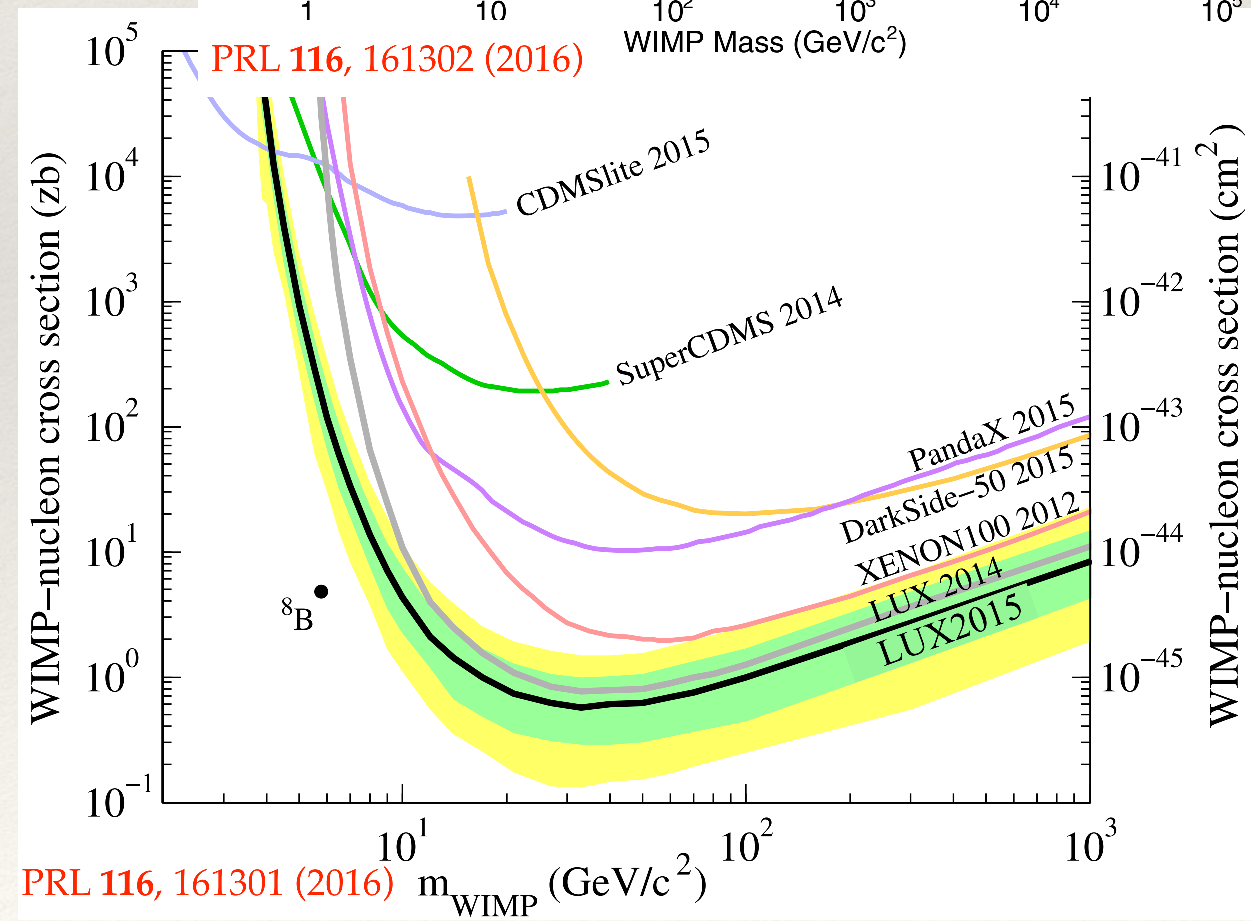
Backup

First Run Reanalysis

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

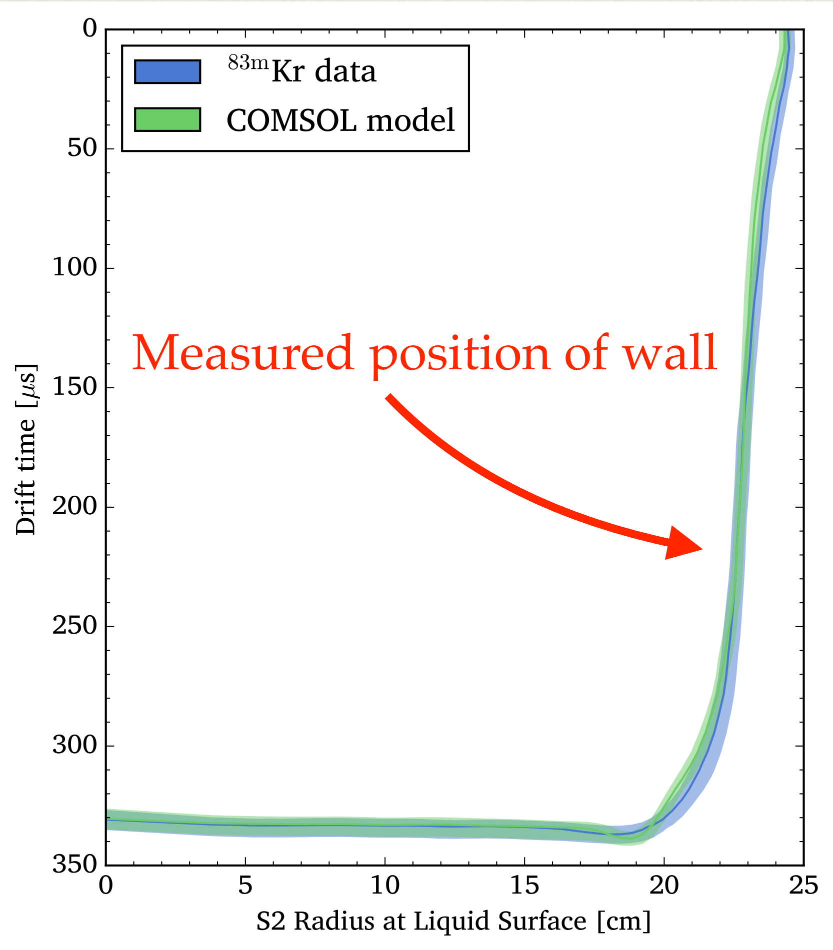




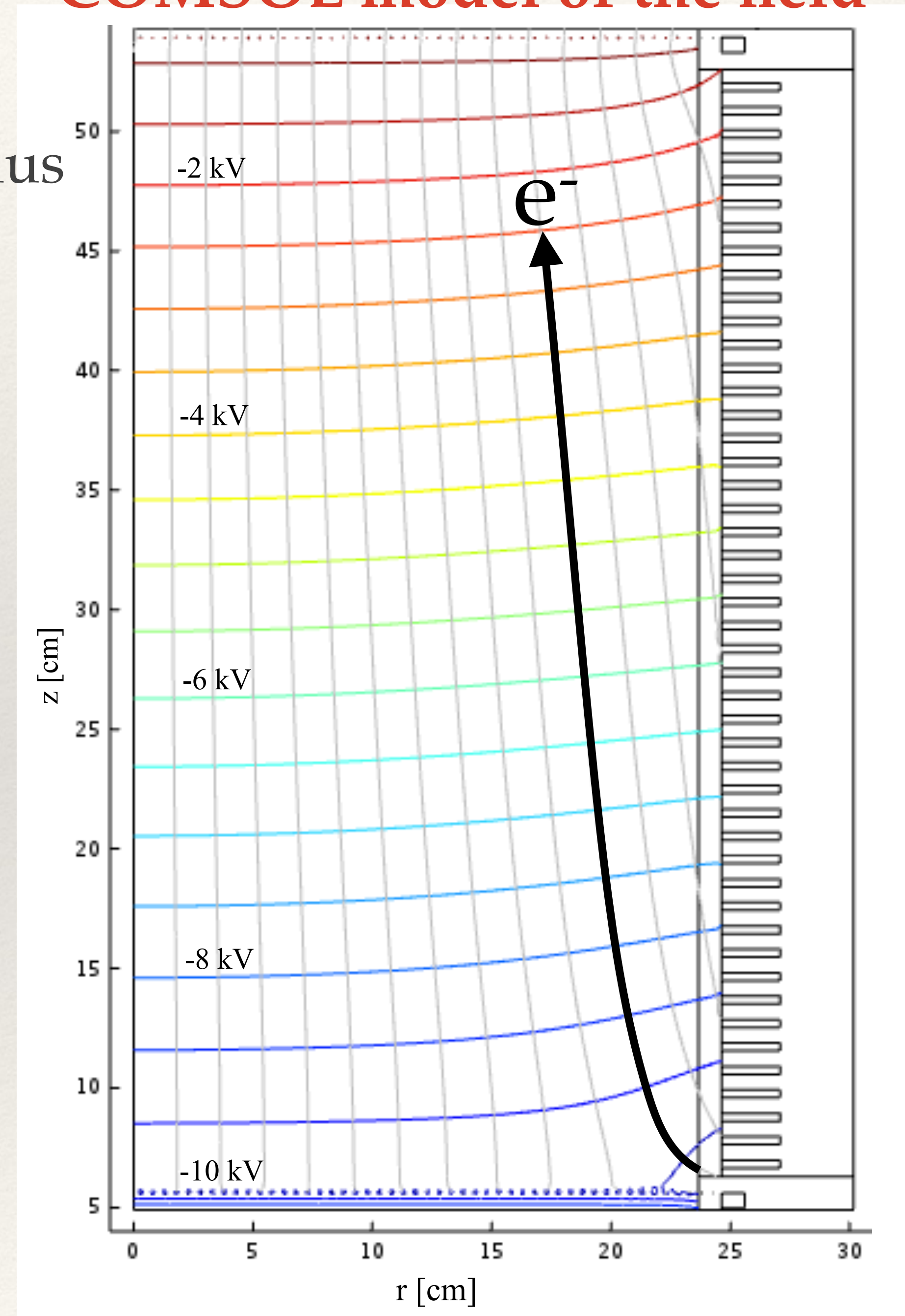


S2 Coordinates

- 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



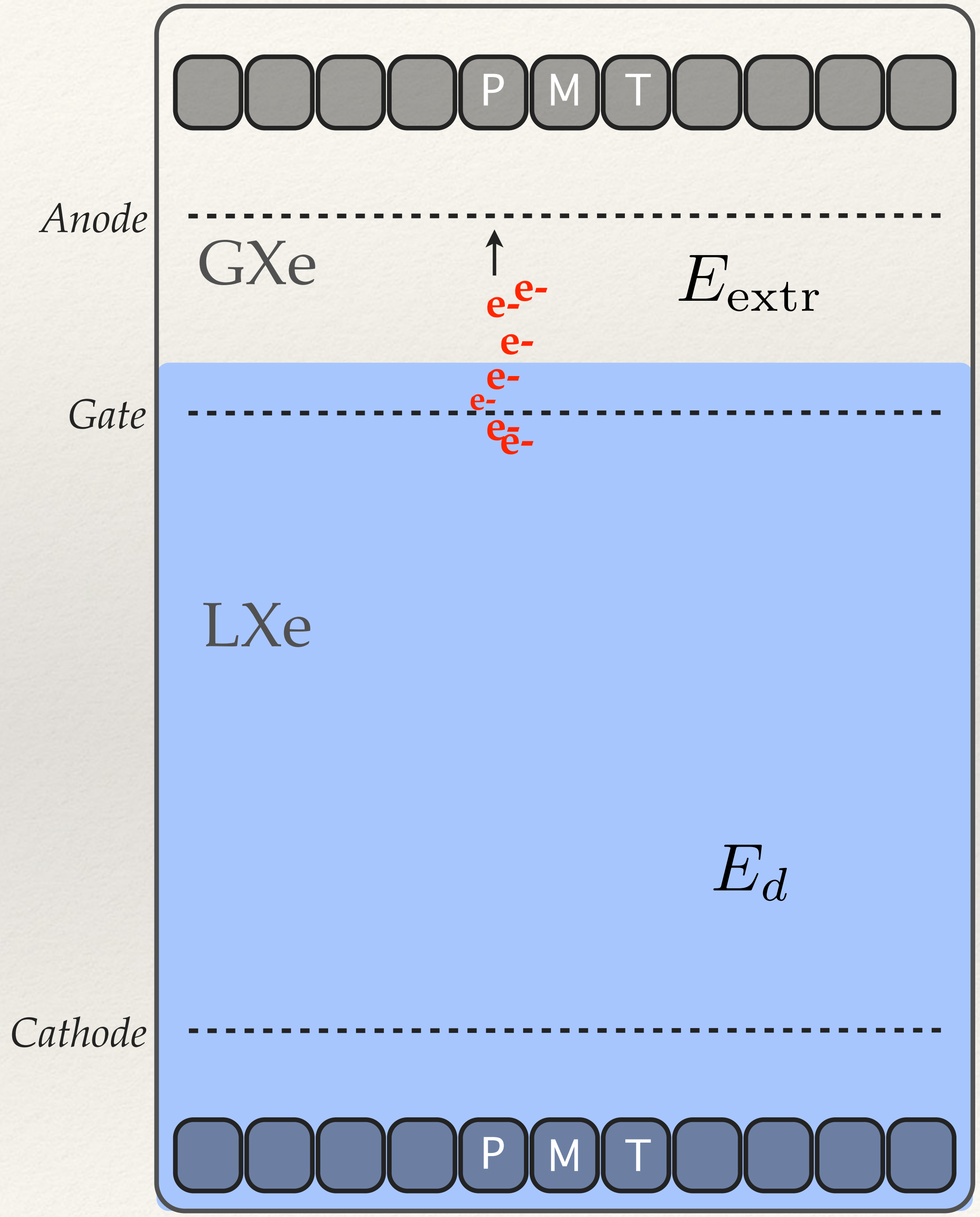
COMSOL model of the field



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:

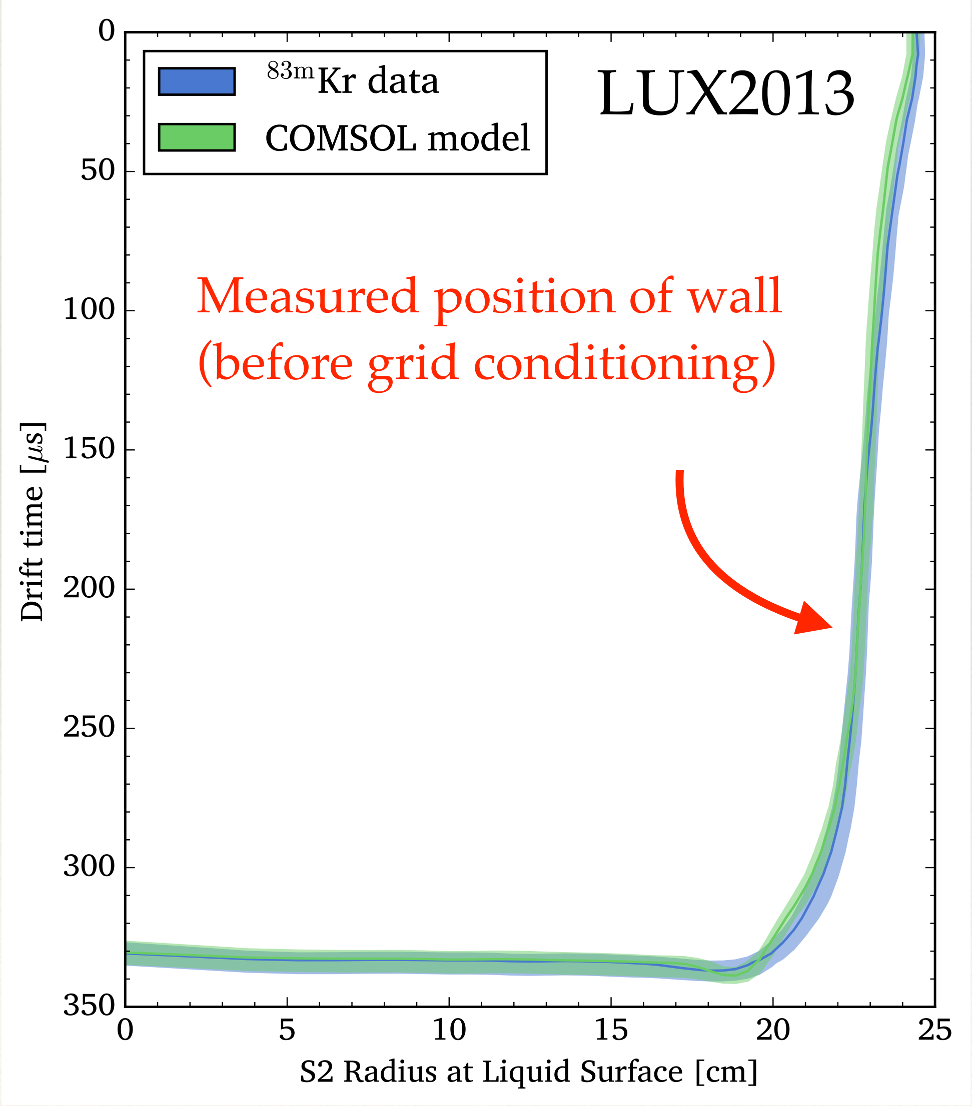
  extraction efficiency raised to 75%

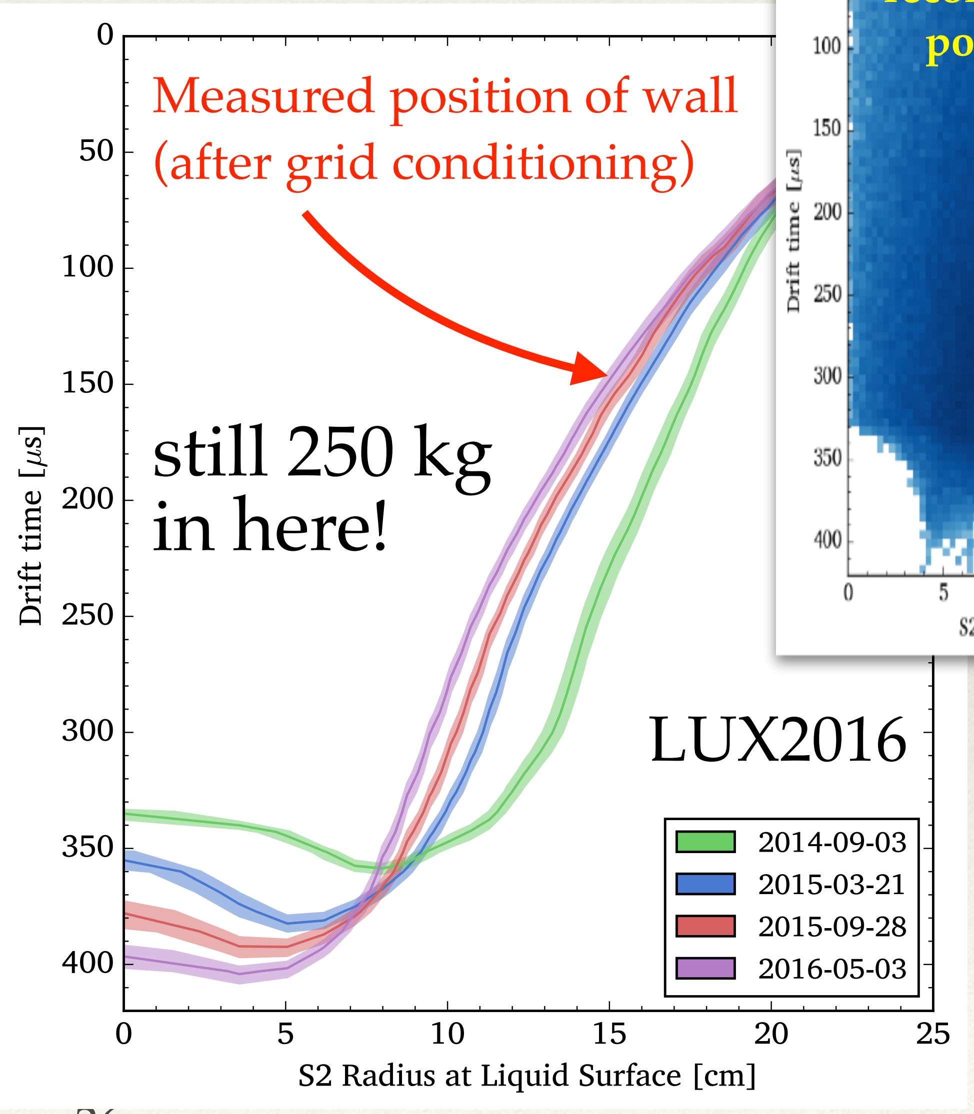


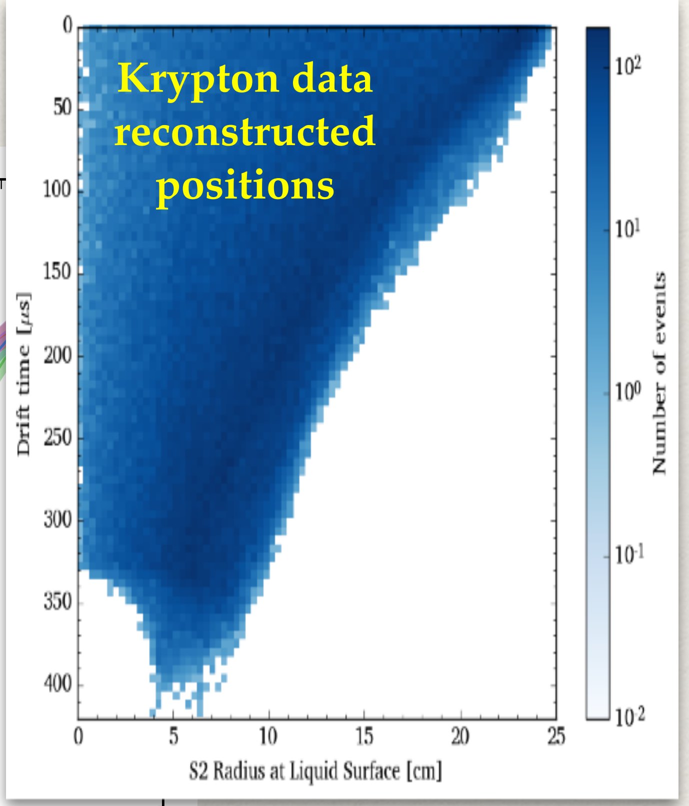
Grid Conditioning – Side Effects

- 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

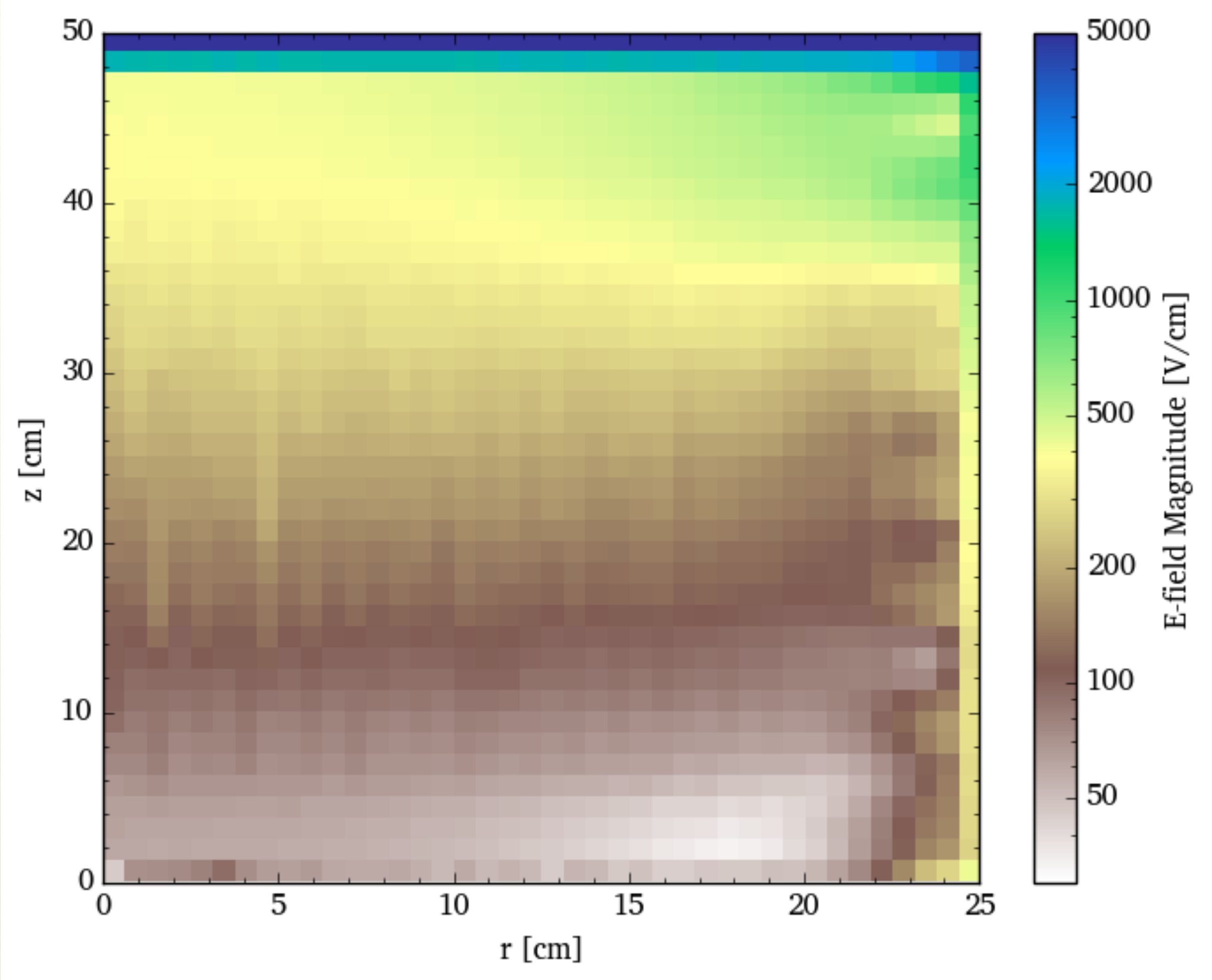






Modelling the Field

- 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

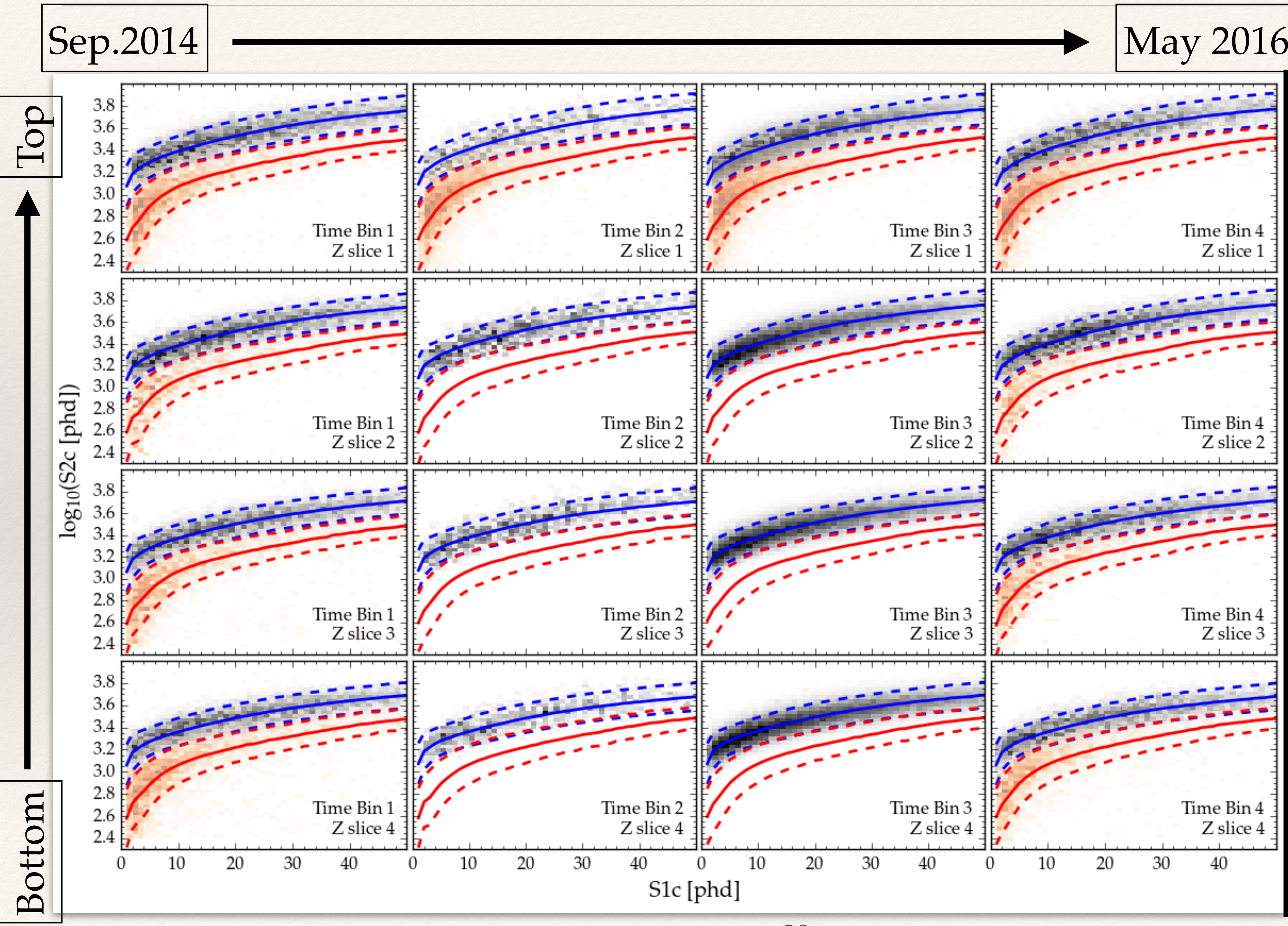
$$\text{Fiducial Mass} = 251\,\text{kg} \times \frac{\text{Num. evts. passing fiducial cut}}{\text{Num. evts. total}}$$

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



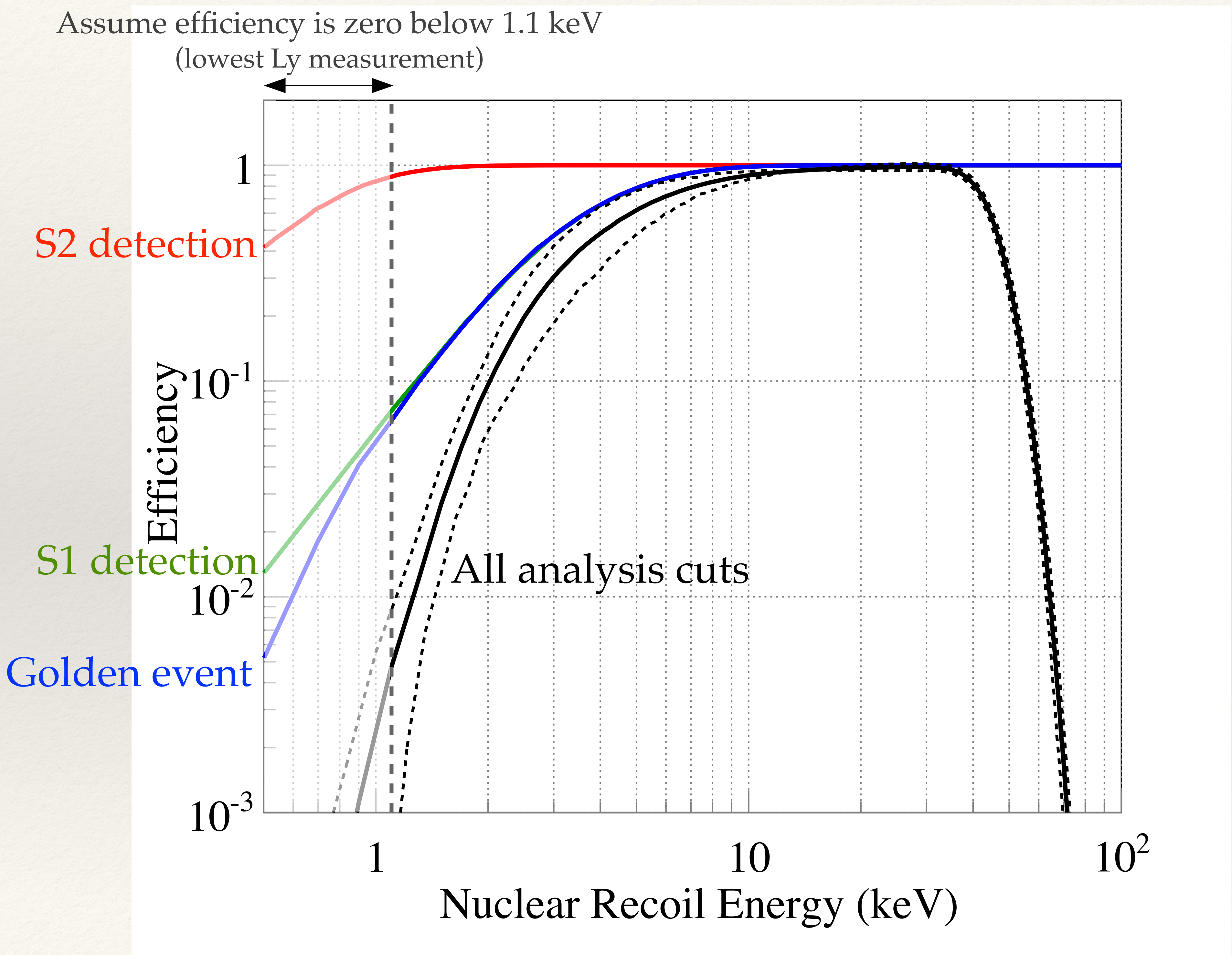
Gray density: CH_3T calibration (ER)

Orange density: DD calibration (NR)

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

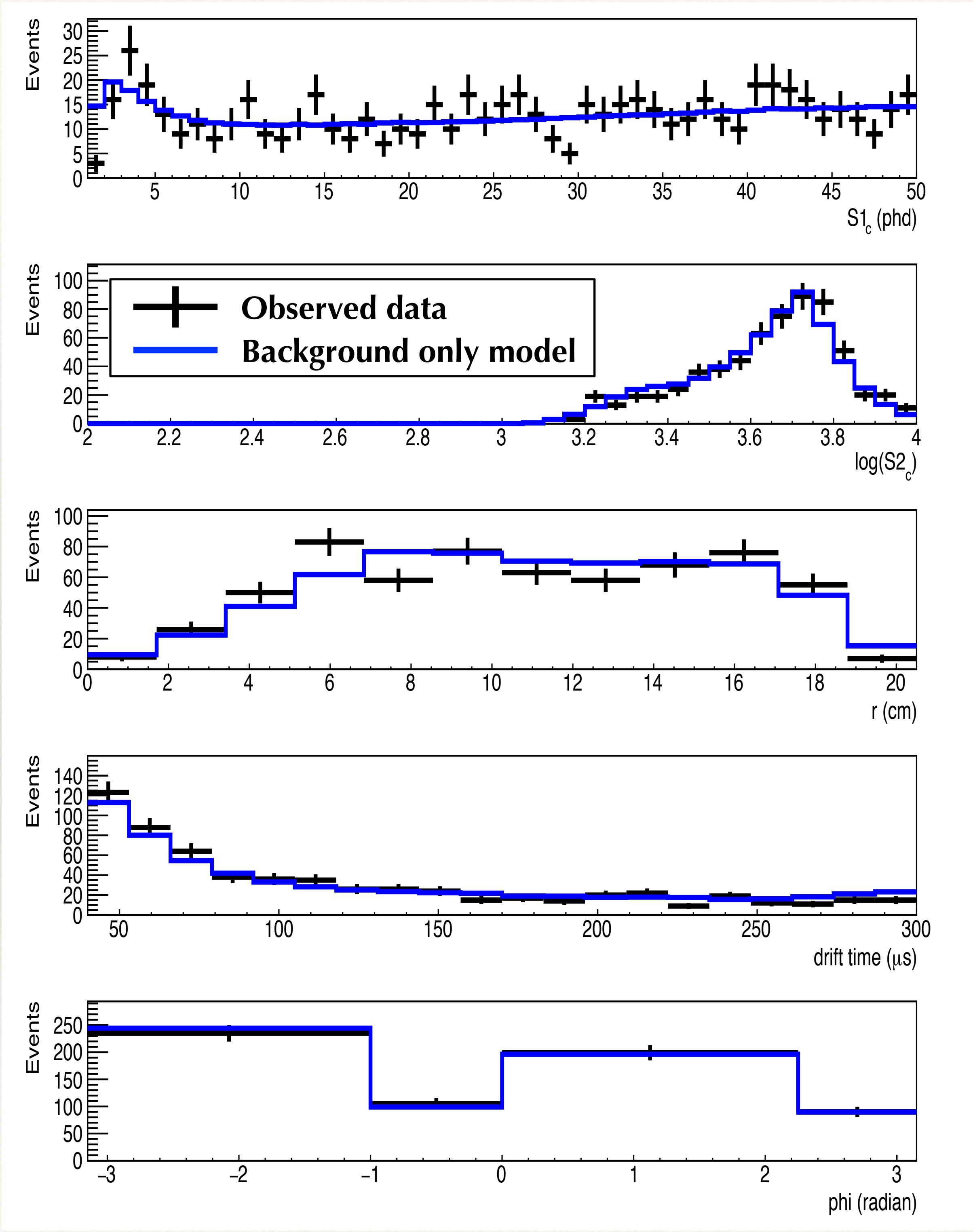
Dashed lines: NEST model, 10-90 percentile.

Efficiency for NR Events



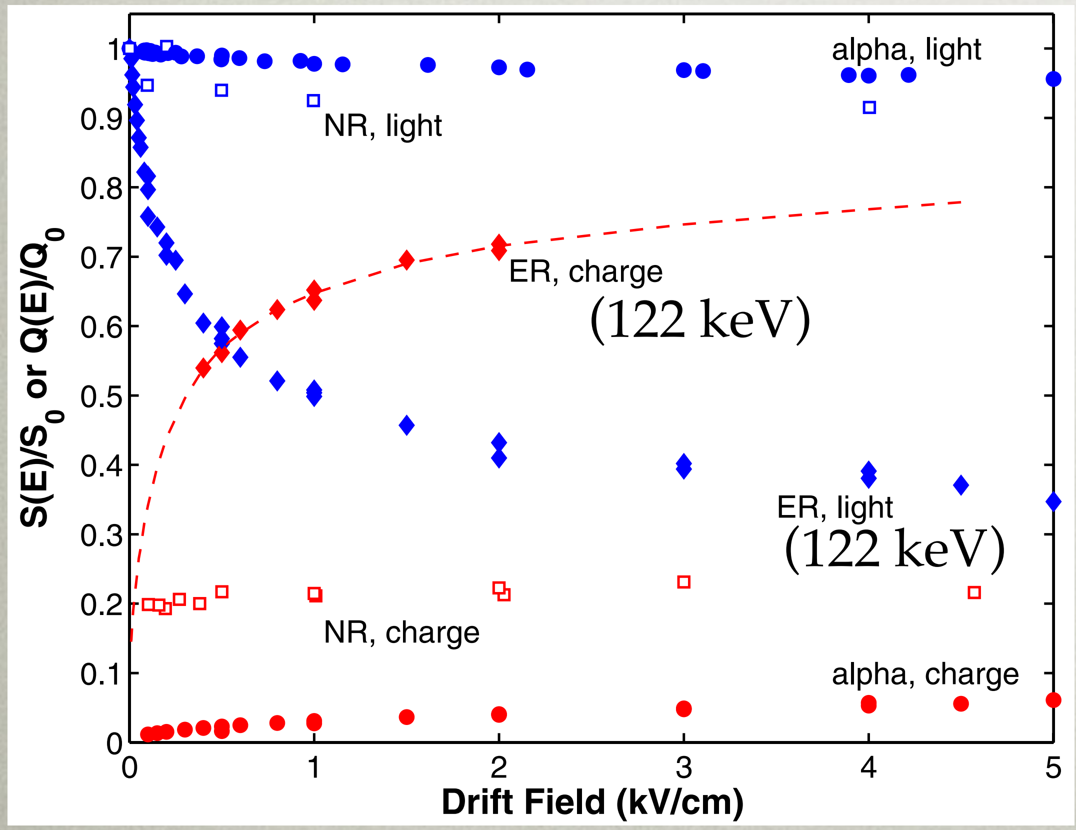
Profile Likelihood Ratio Analysis

- 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

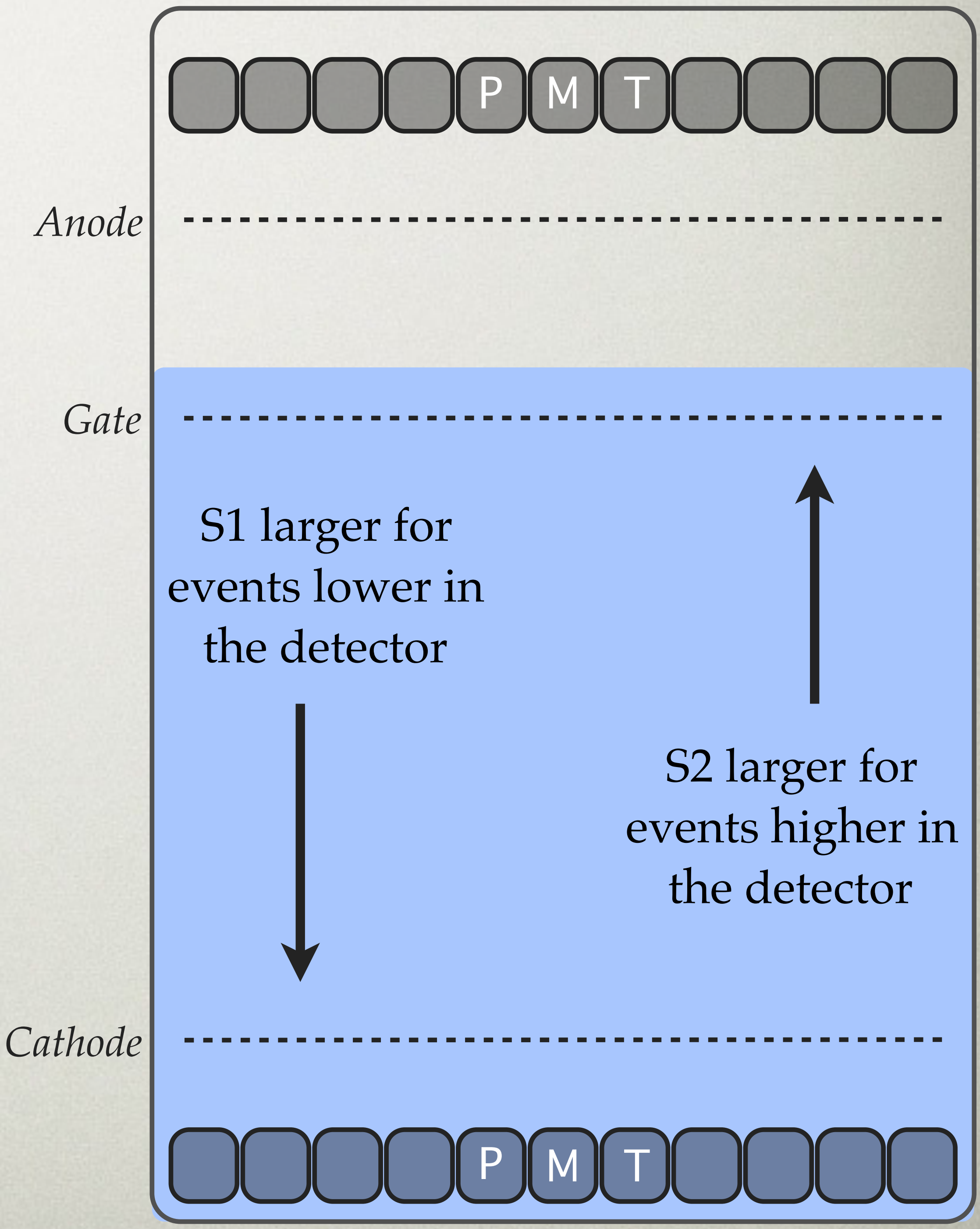


Position corrections

- 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.

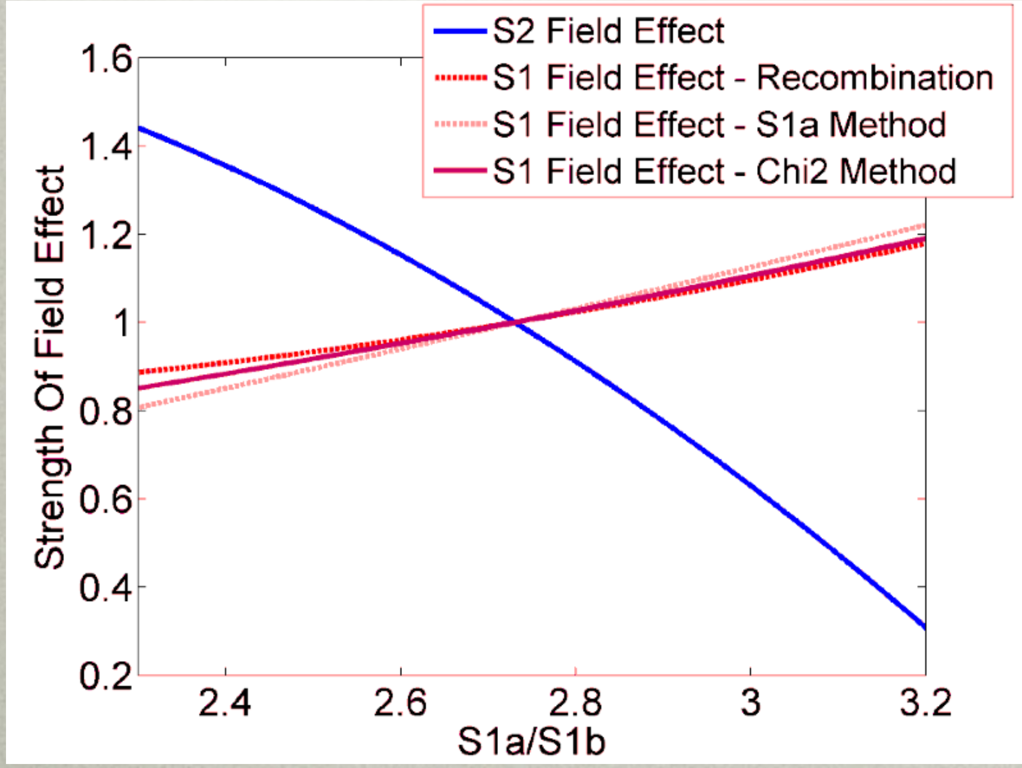


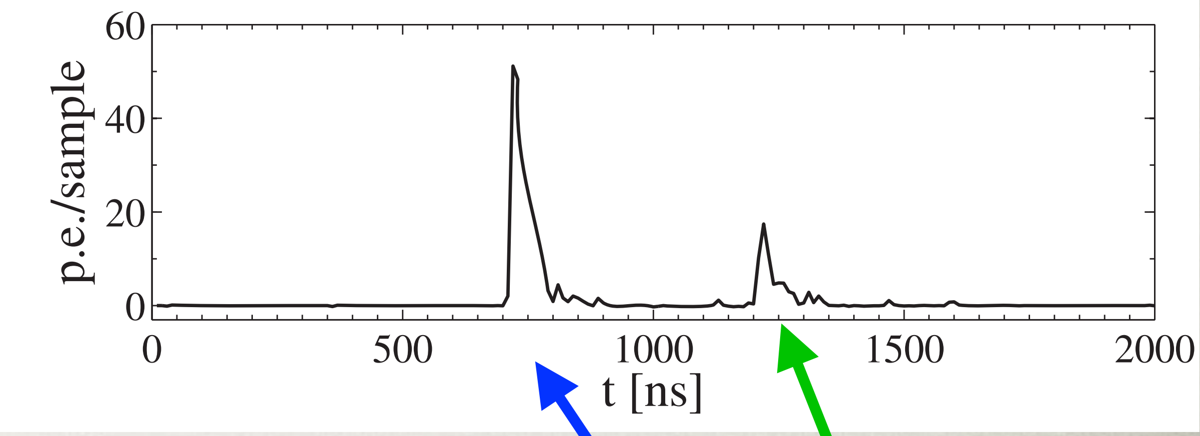
E. Aprile *et al*. PRL **97** (2006) 081302, astro-ph/0601552

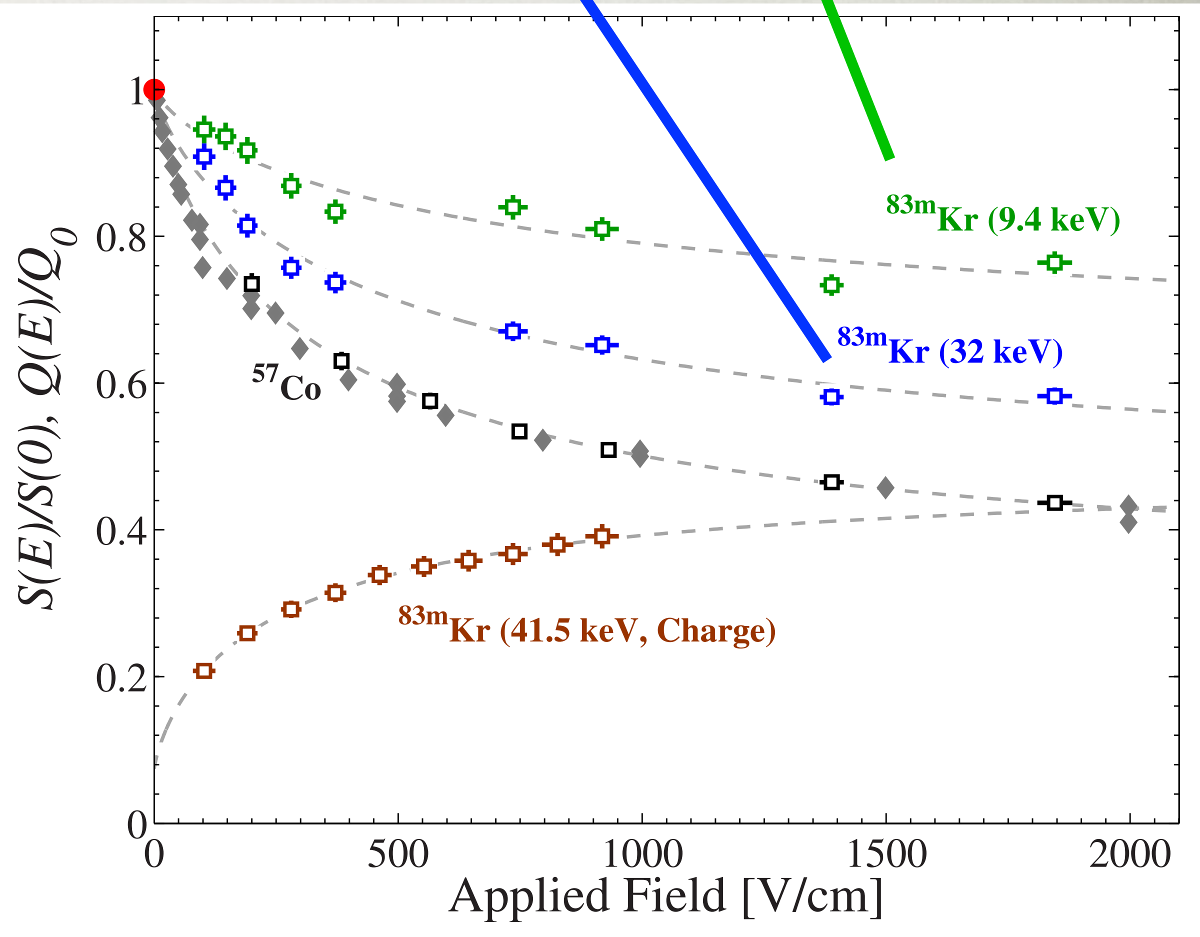


Position corrections

- 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.

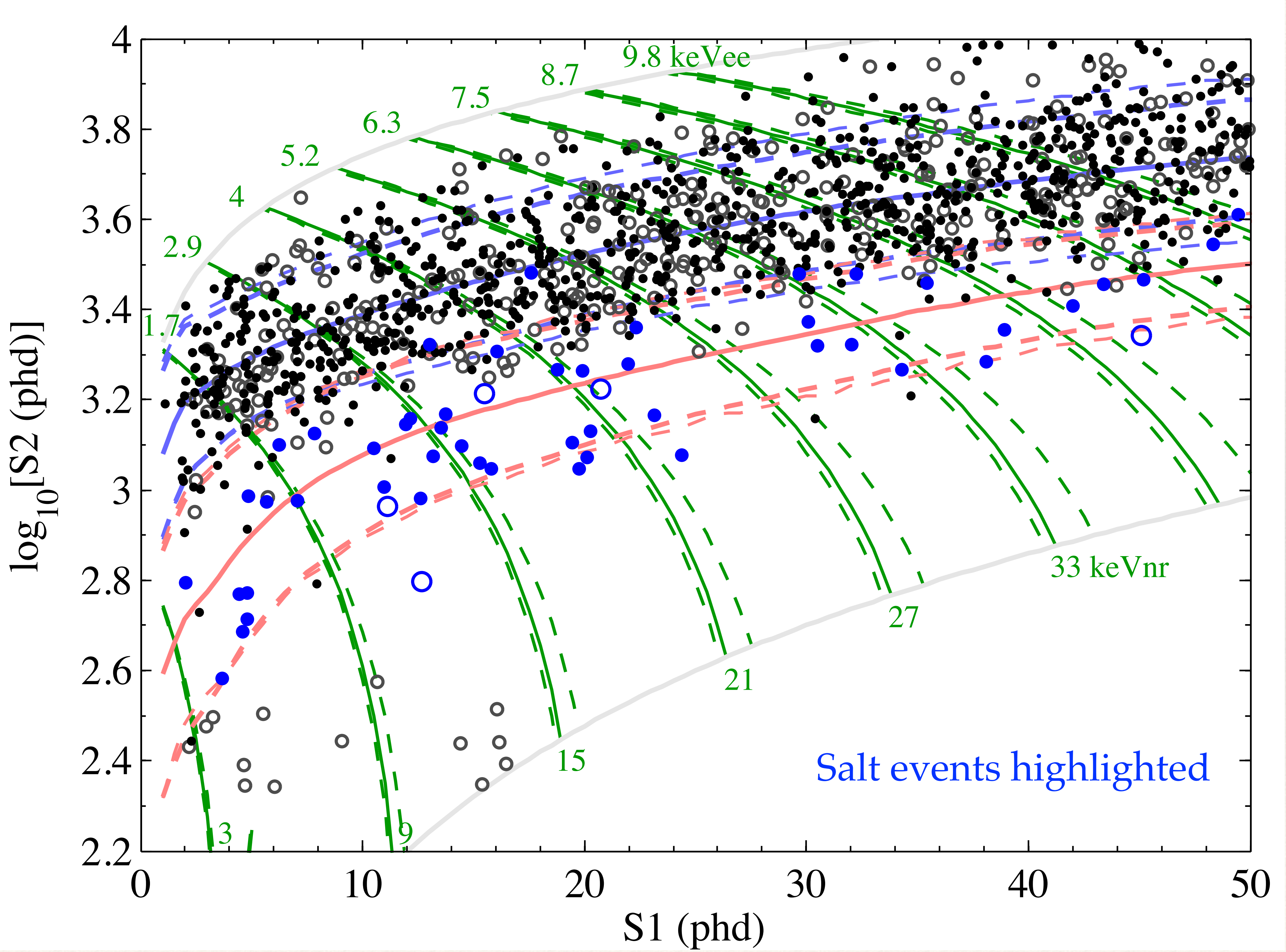




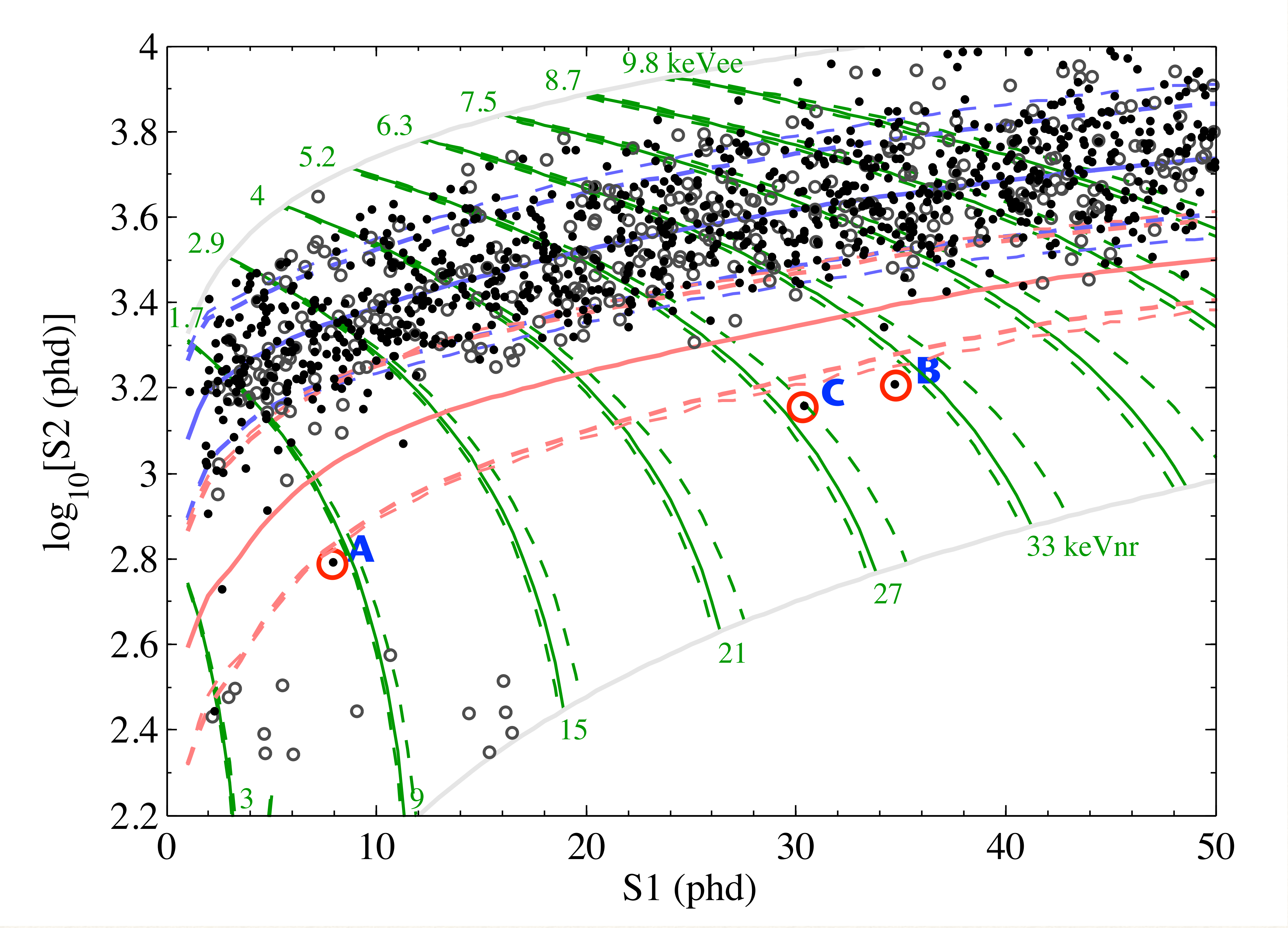


A.Manalaysay *et al.*, Rev.Sci.Instrum. **81** (2010) 073303, 0908.0616

WIMP-Search Data

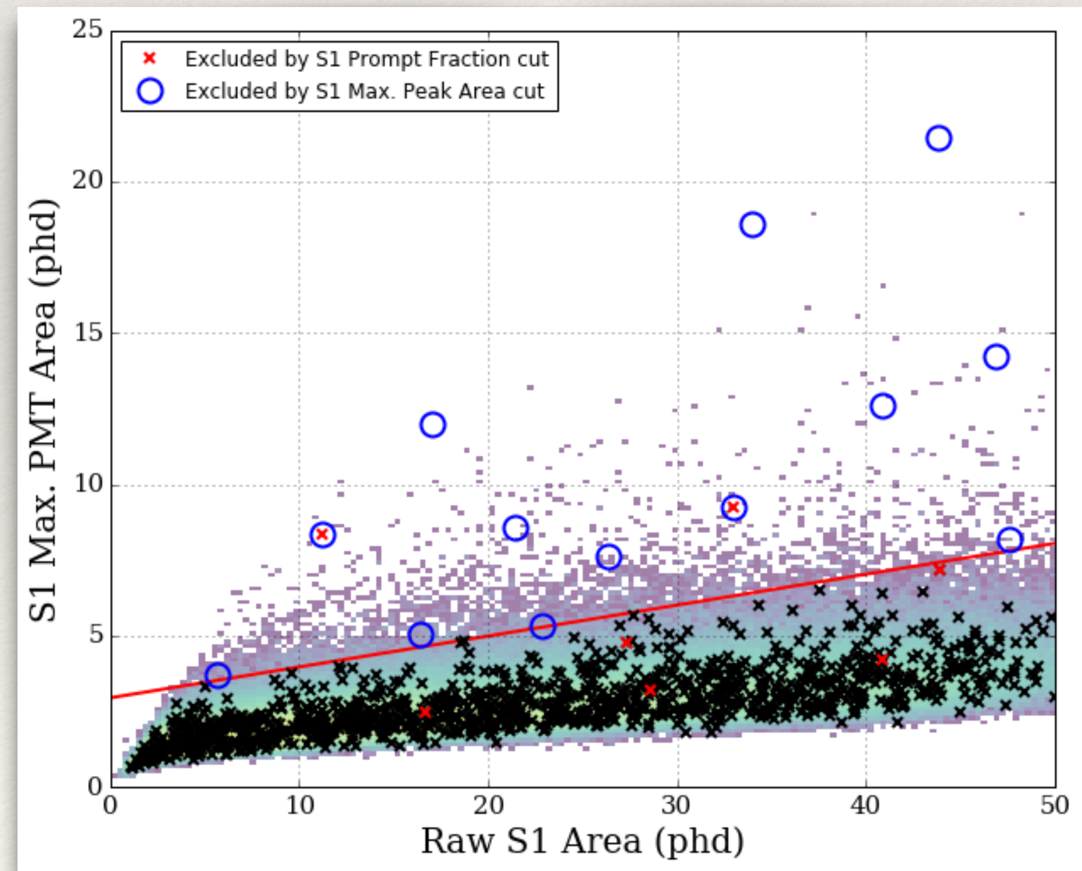


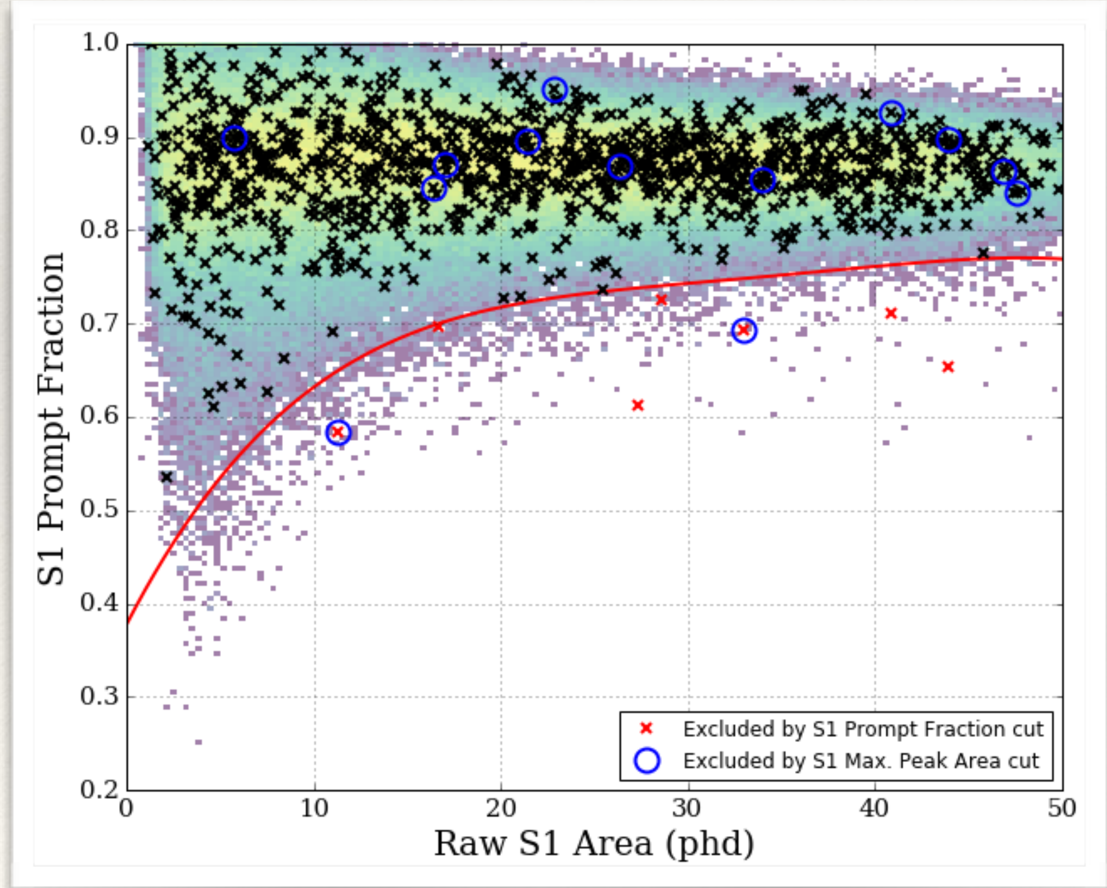
WS Data – Pathological Events



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.