Searching for Dark Matter with LUX and LZ

Presenting combined results from 427 LUX livedays

Matthew Szydagis

for the LUX and LZ collaborations

UNIVERSITY AT ALBANY
State University of New York

2nd Int'l. Conf. on Particle Physics and Astrophysics
Milan Hotel, Moscow, Russia, October 13, 2016

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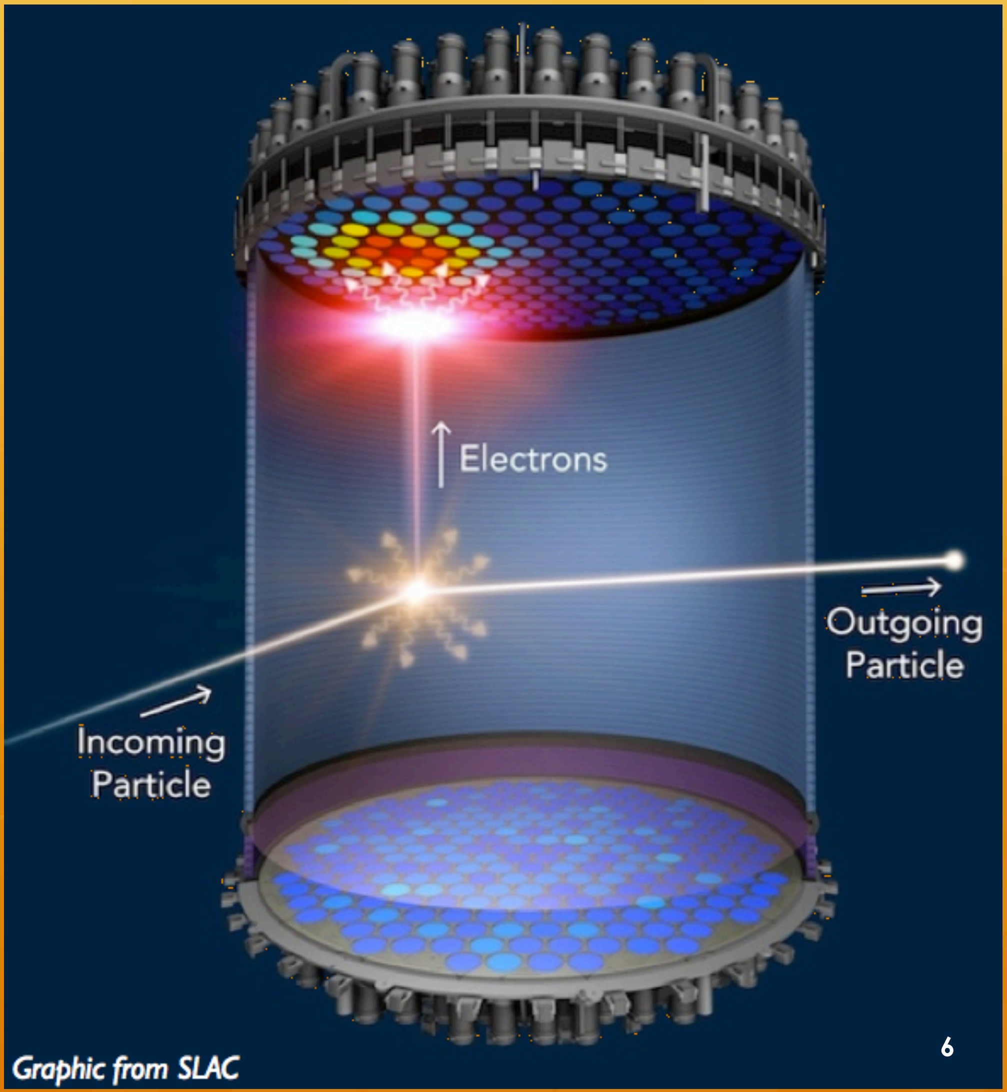
University of South Dakota
South Dakota School of Mines & Technology
South Dakota Science and Technology Authority
SLAC National Accelerator Laboratory
Texas A&M
Washington University
University of Wisconsin


LUX

A Brief Outline

- A review of the LUX experiment, a two-phase Xe TPC
- The first LUX result (2013-4) and its re-analysis (2014-5)
- Details of internal electric field post grid conditioning
- ***332 live-day WIMP search run*** (300 live-days salted)
- Salting of data with NR events as a form of blinding
- Latest LUX sensitivity to WIMP-nucleon SI cross-section
- First-run SD sensitivity, and preliminary axion/ALP limits
- A bright future: more LUX, plus ton-scale LZ detector

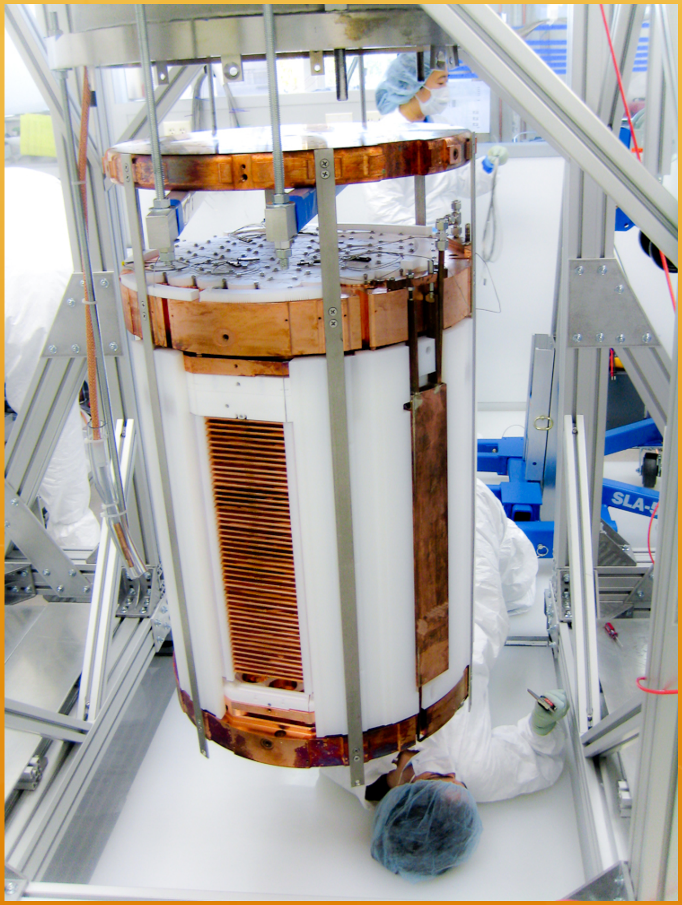
The Detection Method



- Xe-based TPCs have been leading pack for 10 years
  - XENON10, ZEPLIN-II/III, XENON100, now LUX/LZ
- PMTs convert single photons into single photo-electrons (phe)
  - phd = photons detected, term coined by LUX (better-resolution counting method)
- Time between S1 and S2 gives you depth (Z), and S2 top hit pattern is radial position (X and Y)
- LUX is @Sanford Lab, Lead

Large Underground Xenon

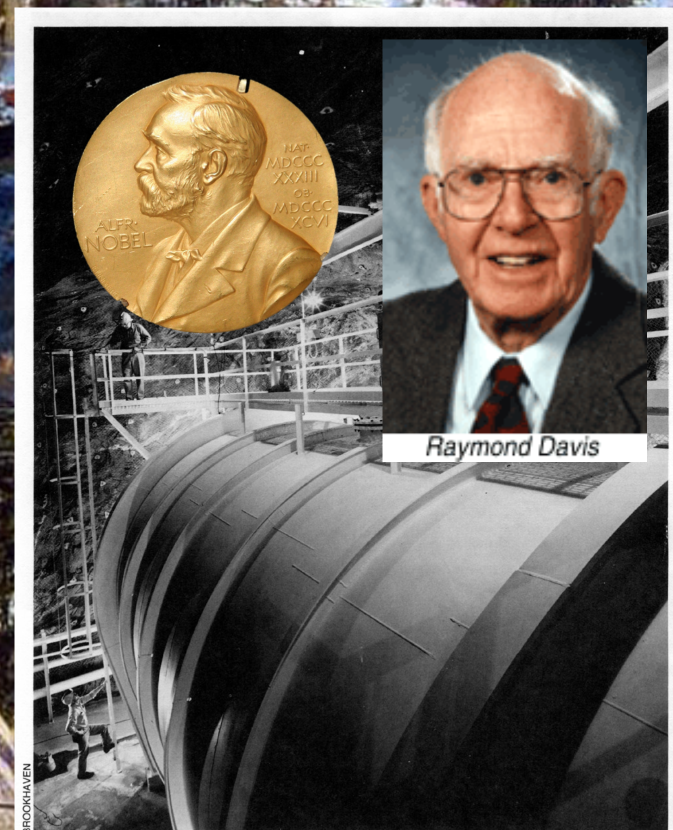
- ~1:1 ratio: 50 x 50 cm dodecagonal cylinder of highly reflective PTFE
- 370 kg LXe in total (within all crevices)
  - 250 kg in active region (with field)
  - 118, 145, 100 kg fiducial across different analyses (depends on BG)
- 122 phototubes (2 x 61, top and bot)
  - Low BG, sensitive to 175 nm VUV
- Xe pre-purified of Kr-85, plus re-circulated during run for impurities
- Ultra-low BG Ti cryostat, big thermos!
- ~3-4 keV NR threshold (point of 50% efficiency pre-discrimination of ER)
- 0.2% ER leak for ~50% NR accepted (approximate, as PLR used)



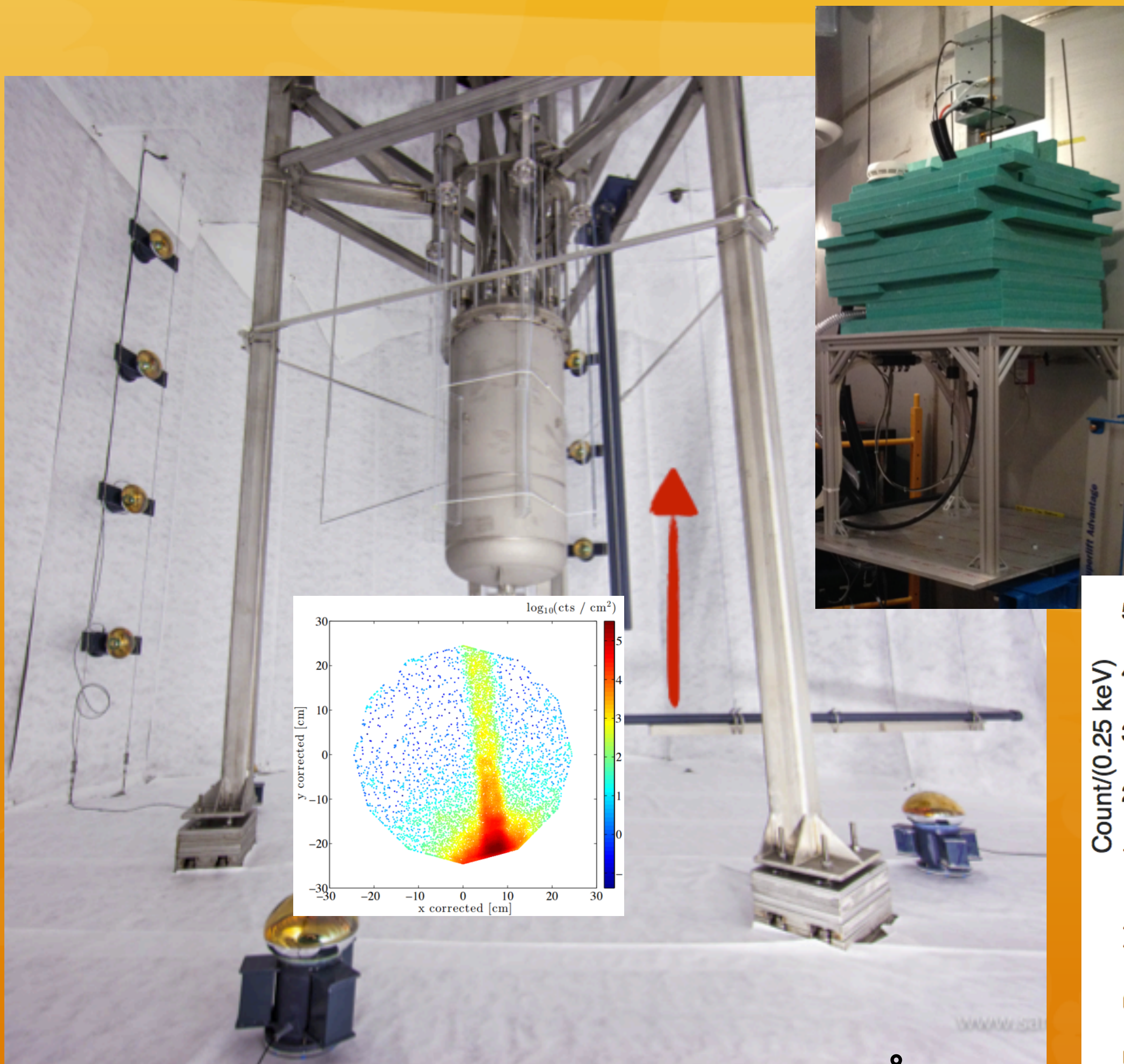
SURF (Sanford Underground Research Facility)

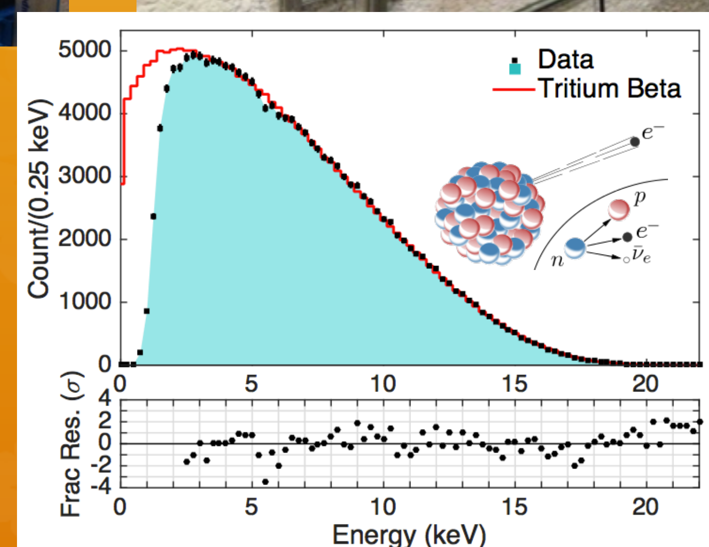
4850 ft. below Lead, SD.
The former site of the Homestake gold mine

LUX is installed in the Davis cavern, once home to the Nobel prize-winning Ray Davis neutrino experiment

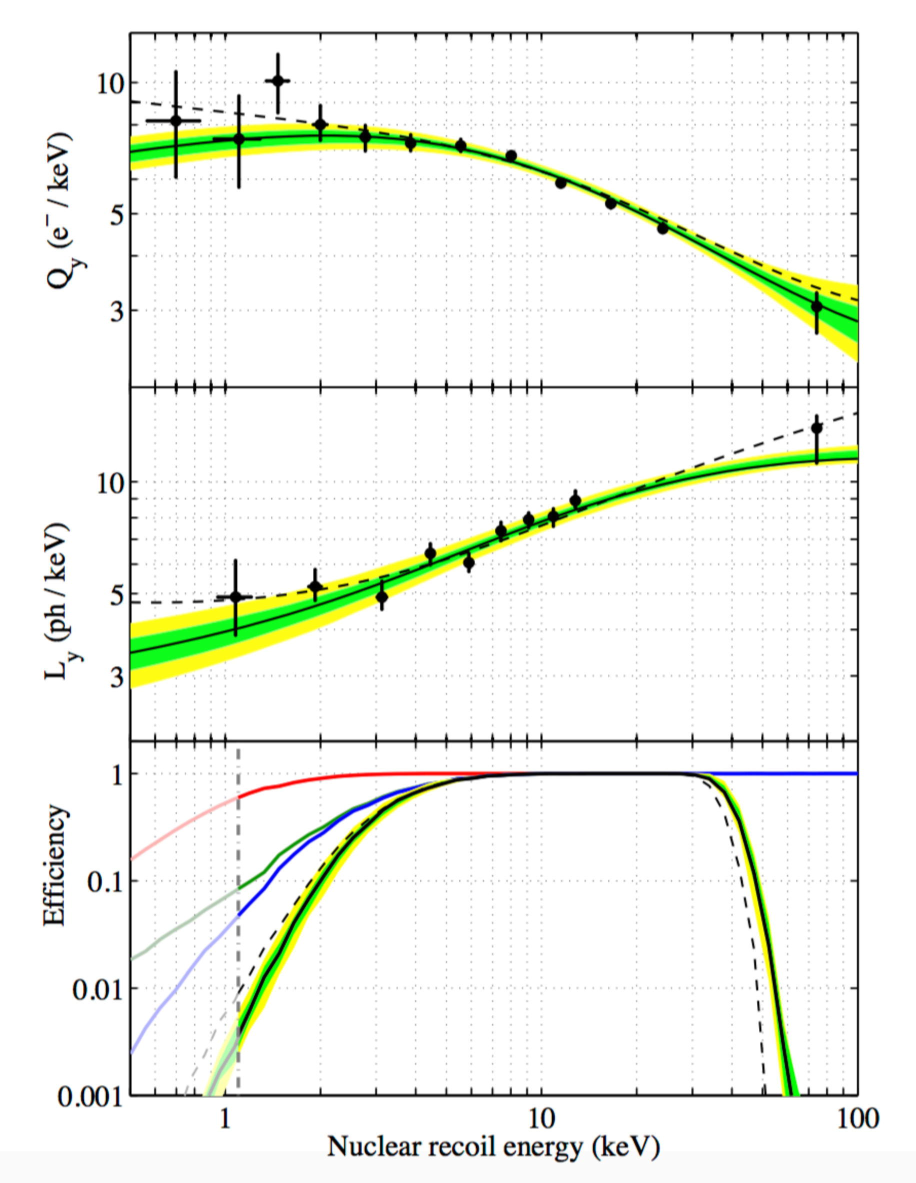


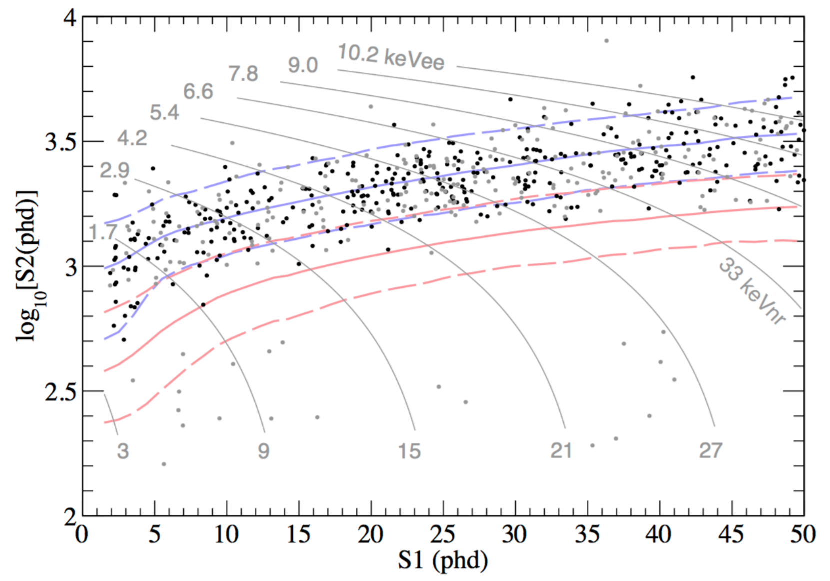
NR / ER Calibrations

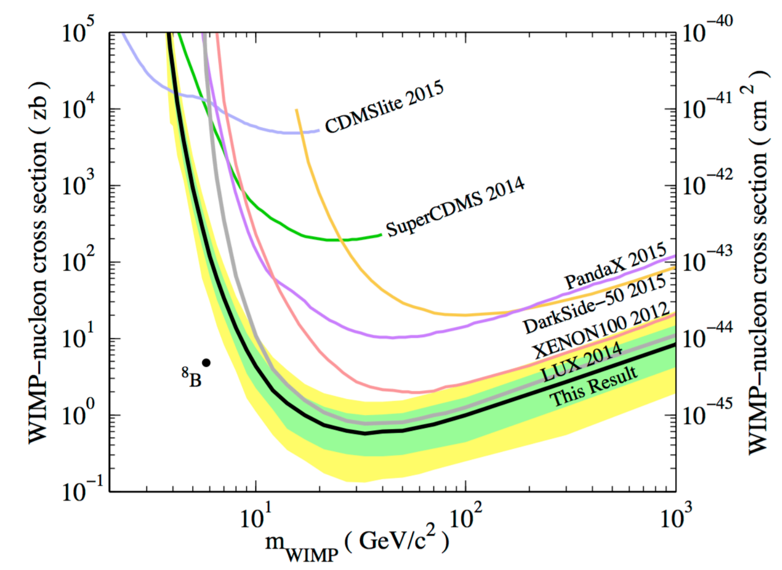




LUX 2013, '14 works: 95 days

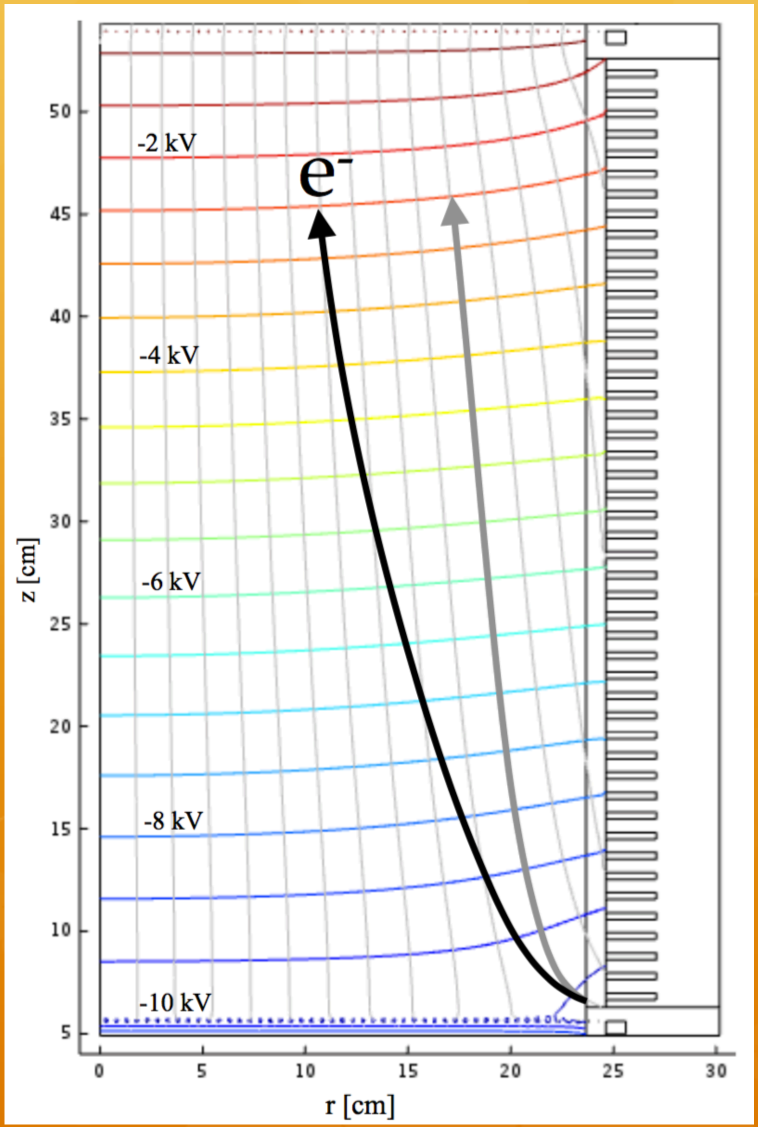






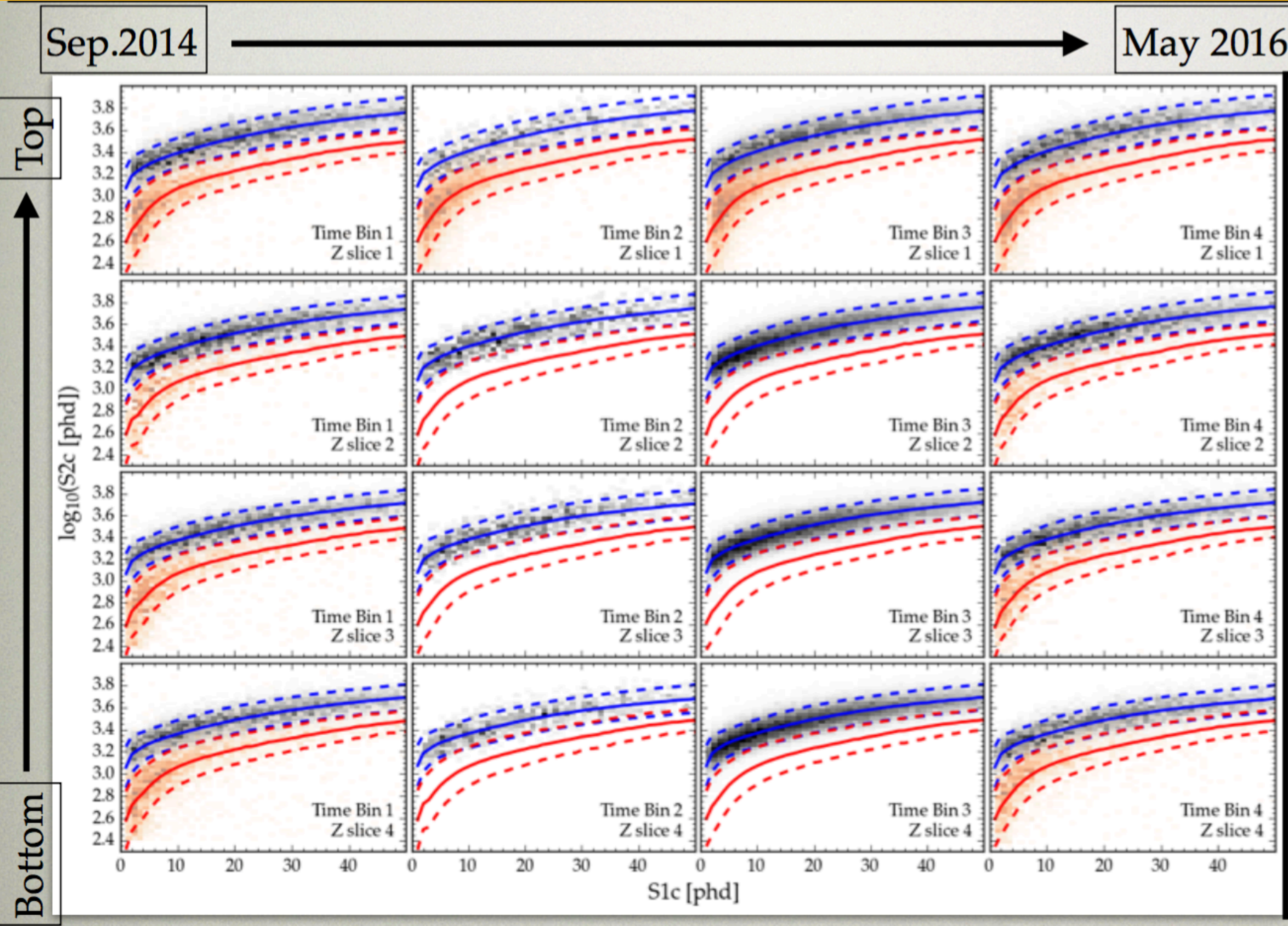
Effects of Grid "Conditioning"

~LHC baguette??



- Attempted to raise 180 V/cm drift and 6 kV/cm extraction after science run; succeeded
  - Motivated by alleged higher discrimination (turned out light collection more important)
  - Also to seek lower S2 threshold
- Successful on both counts
  - Electron extraction efficiency raised from 48.9% to >70%
- However, drift electric field became distorted, both in magnitude and in direction

Solution: Time / Space Bins



Gray density: CH_3T calibration (ER)

Orange density: DD calibration (NR)

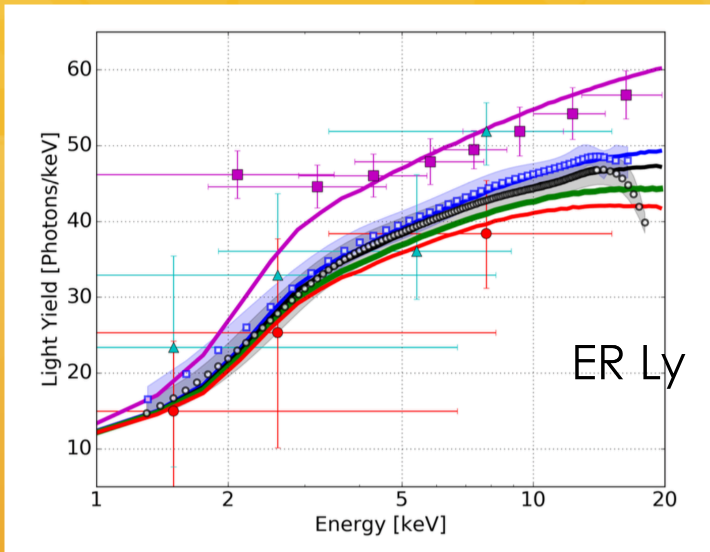
Solid lines: NEST model, band mean.

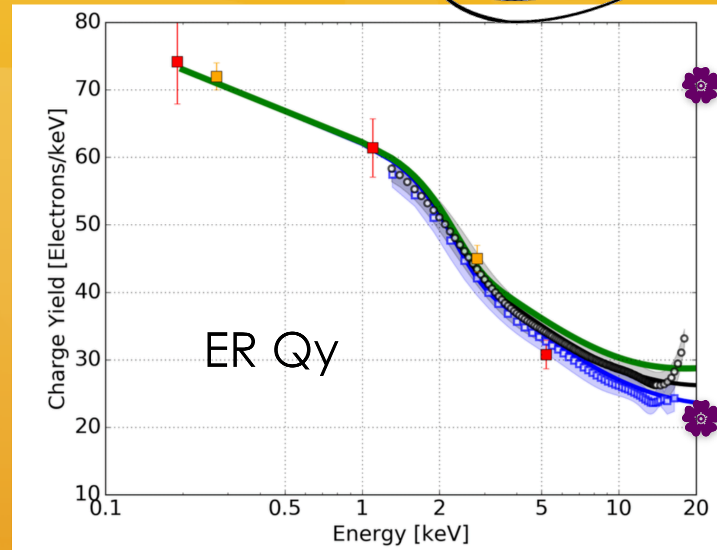
Dashed lines: NEST model, 10-90 percentile.

4 event date bins X 4 z-slices = 16 ‘segments’

What is NEST?

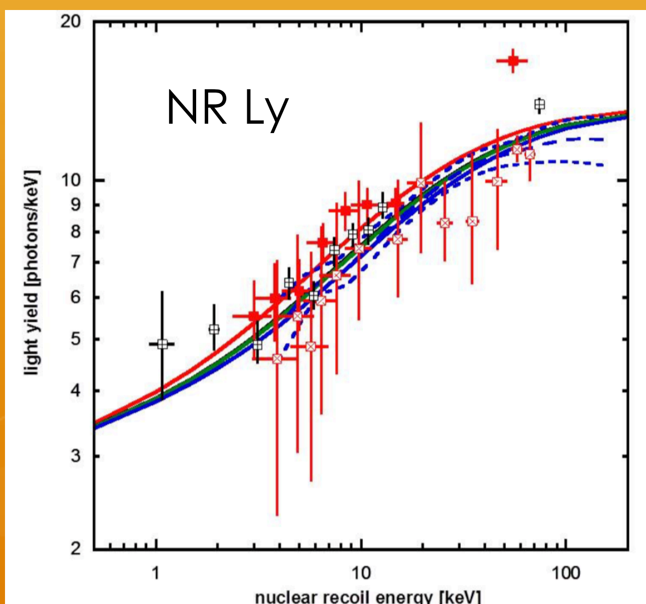
See my parallel session talk on NEST from Monday

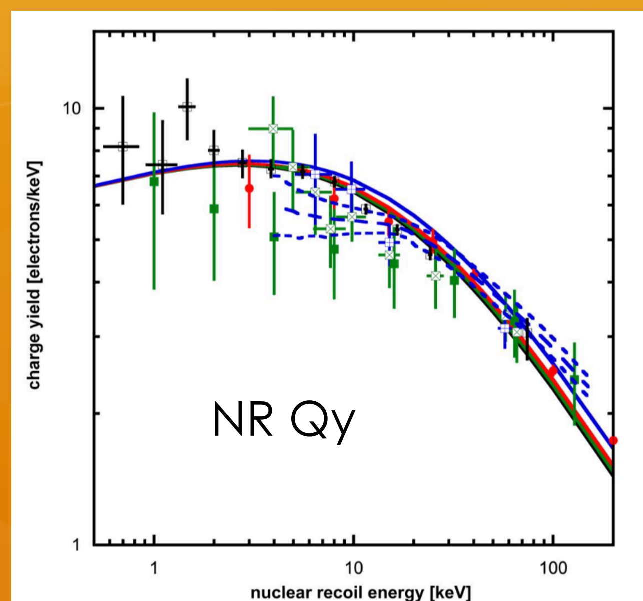




The Noble Element Simulation Technique

MC model/ framework





- Best-fit electric fields agreed within uncertainty with COMSOL out of the box
- Semi-empirical, absorbing existing data

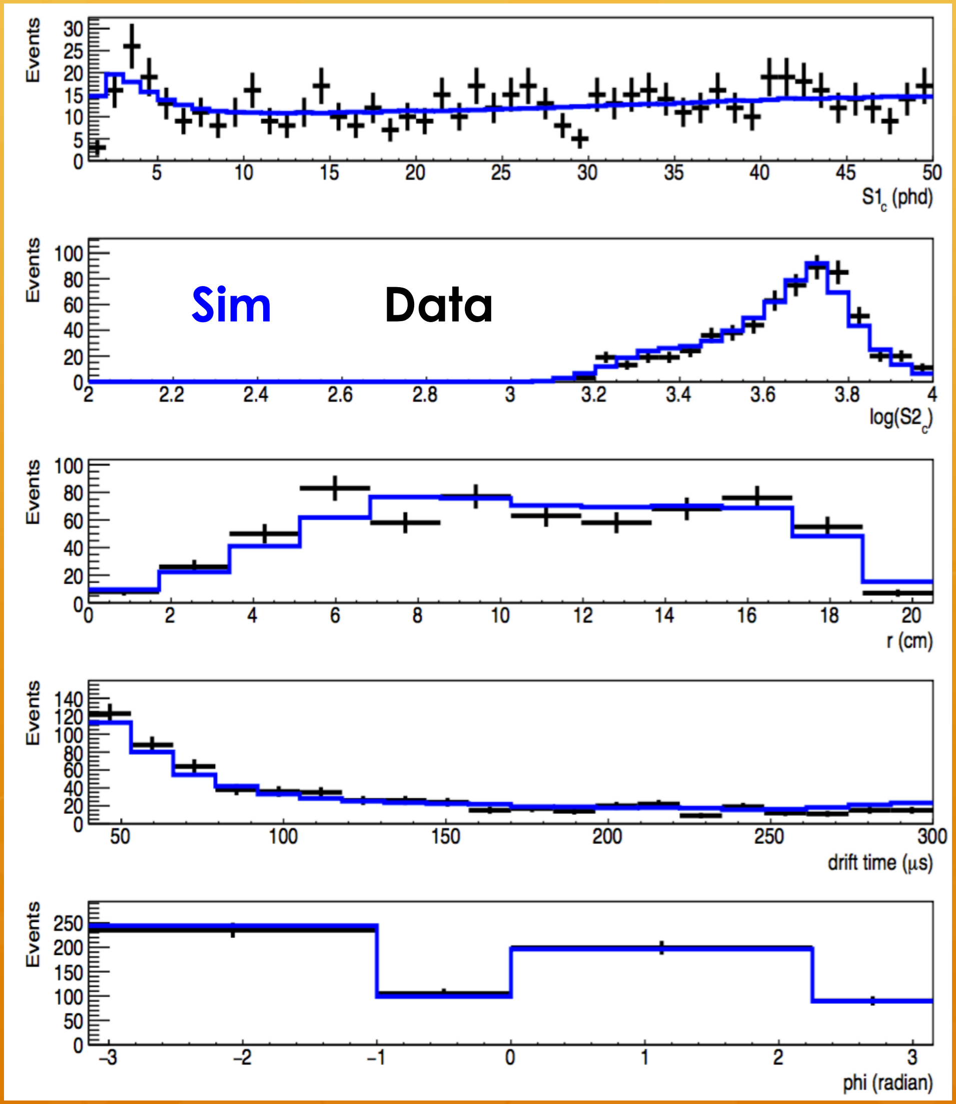
(plots for LZ planning)

Estimation of Backgrounds

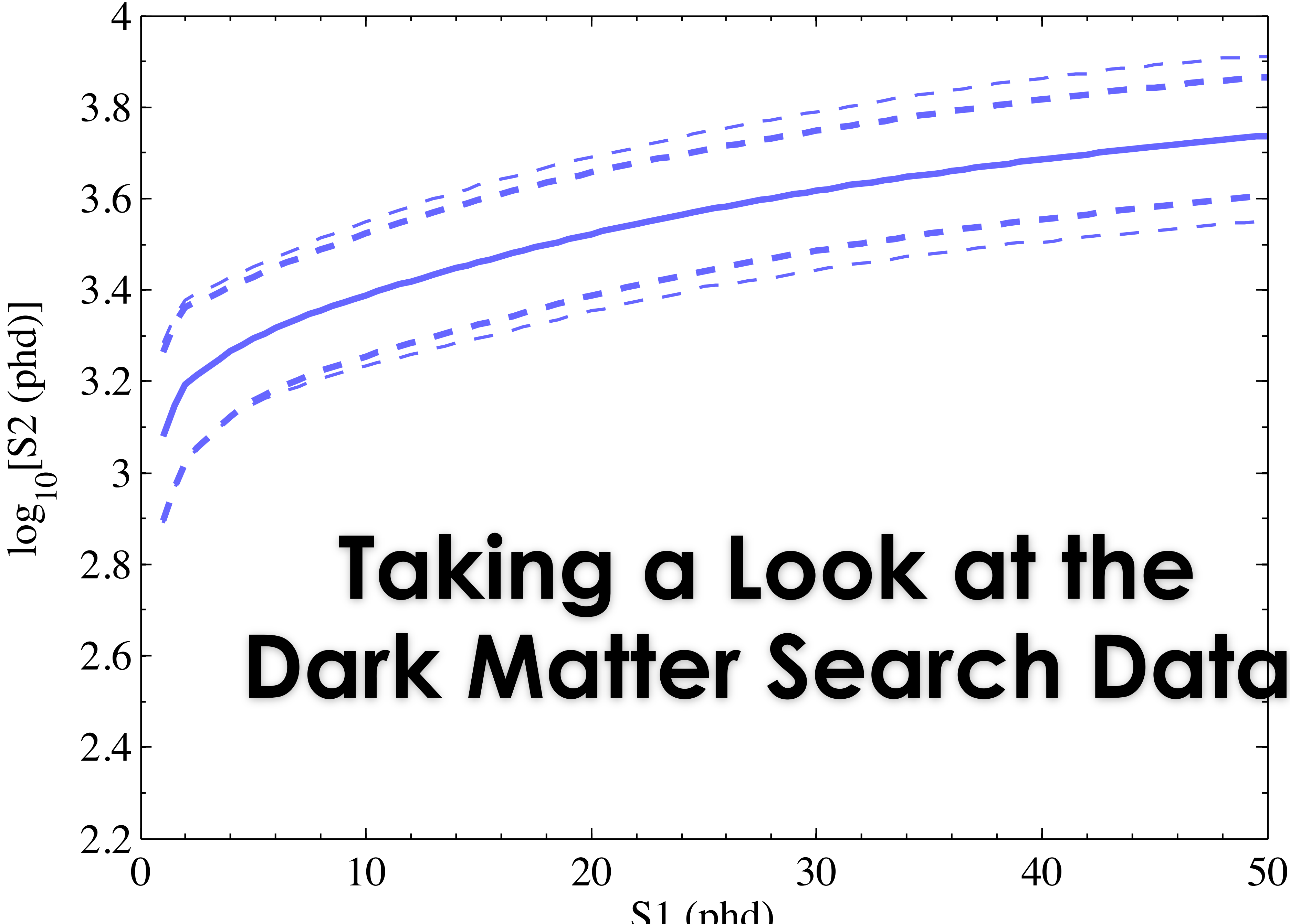
- Figure of merit only (we do a likelihood analysis)
- Bulk volume, but leakage at all energies
- Low-energy, but confined to the edge of our fiducial volume
  - Our likelihood analysis includes position information, so these events have low $\mathcal{L}$(signal) likelihood
- In the bulk volume, low-energy, in the NR band

Background	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
Neutrons	0.3 ± 0.03

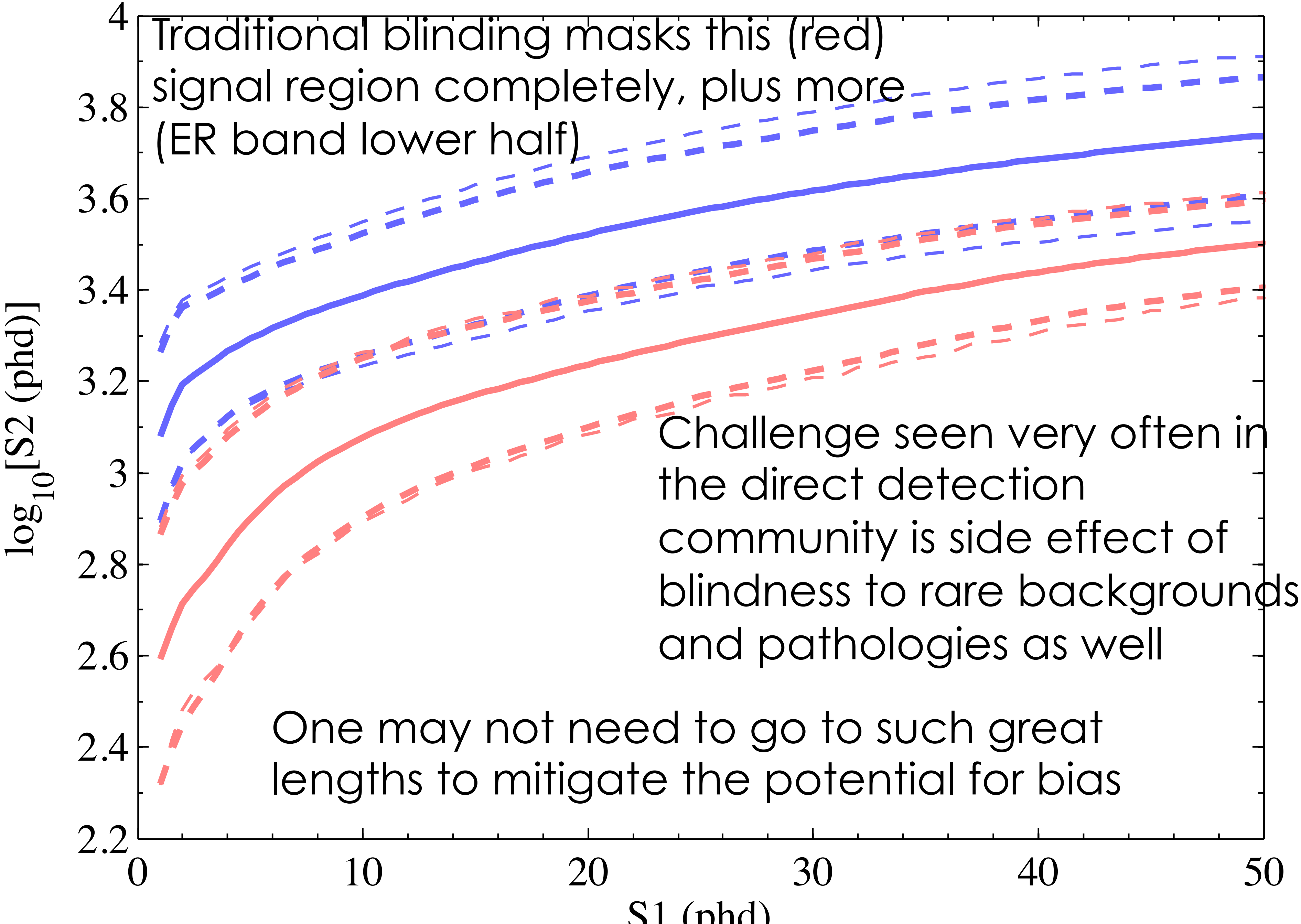
Pre-Unsalting Verification

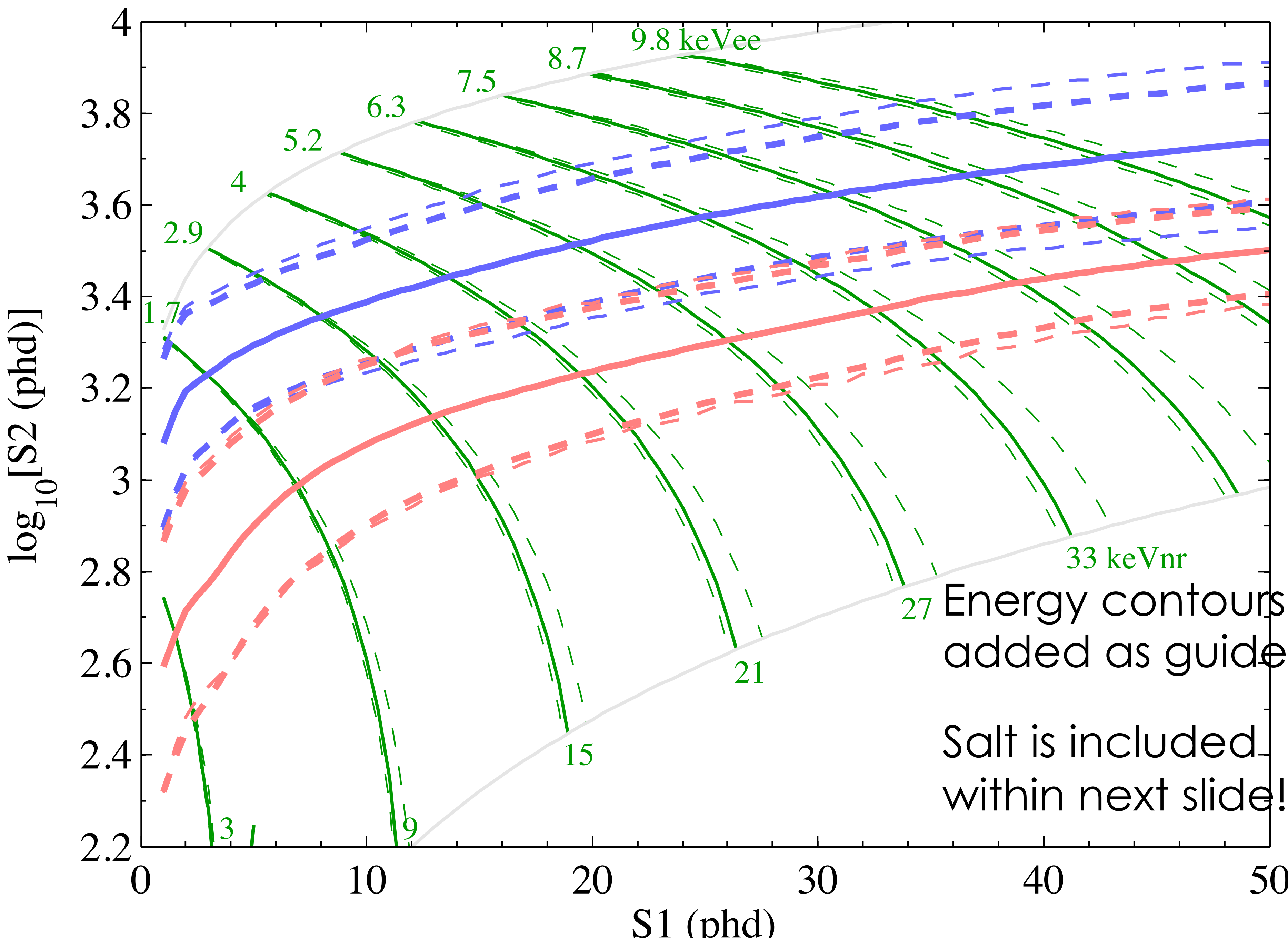


- Data are compared with models in an un-binned, 2-sided Profile Likelihood Ratio (PLR)
- Six dimensions
  - Spatial (raw): radius, polar angle, drift time
  - Energy: S1 and S2
  - Temporal (date bins)
- Side-band: upper ER
- Outstanding p-values >>10%, outstripping last run's great BG model



Taking a Look at the Dark Matter Search Data

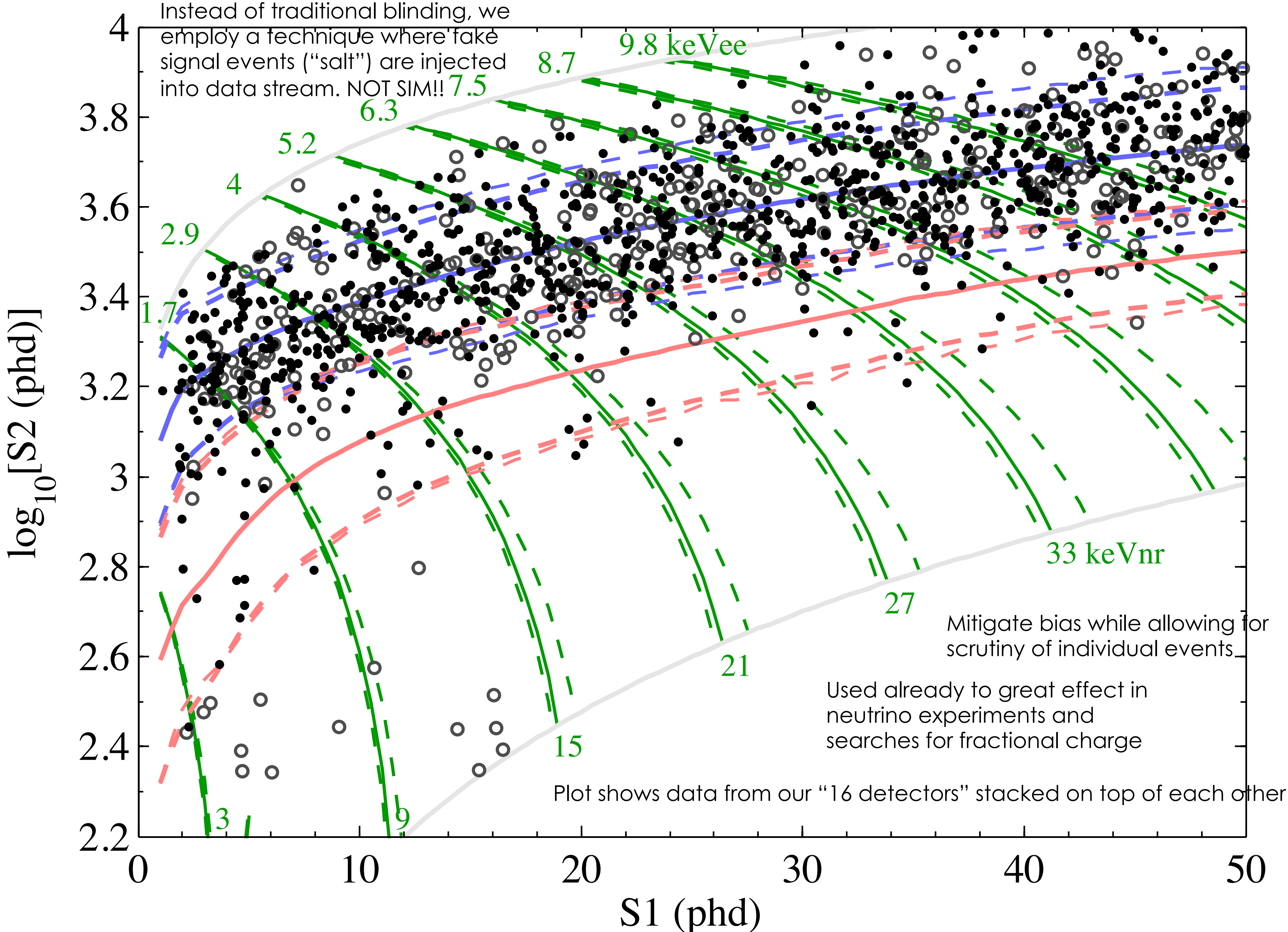

Traditional blinding masks this (red) signal region completely, plus more (ER band lower half)
Challenge seen very often in the direct detection community is side effect of blindness to rare backgrounds and pathologies as well
One may not need to go to such great lengths to mitigate the potential for bias
$\log_{10}$[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



Energy contours added as guides

Salt is included within next slide!

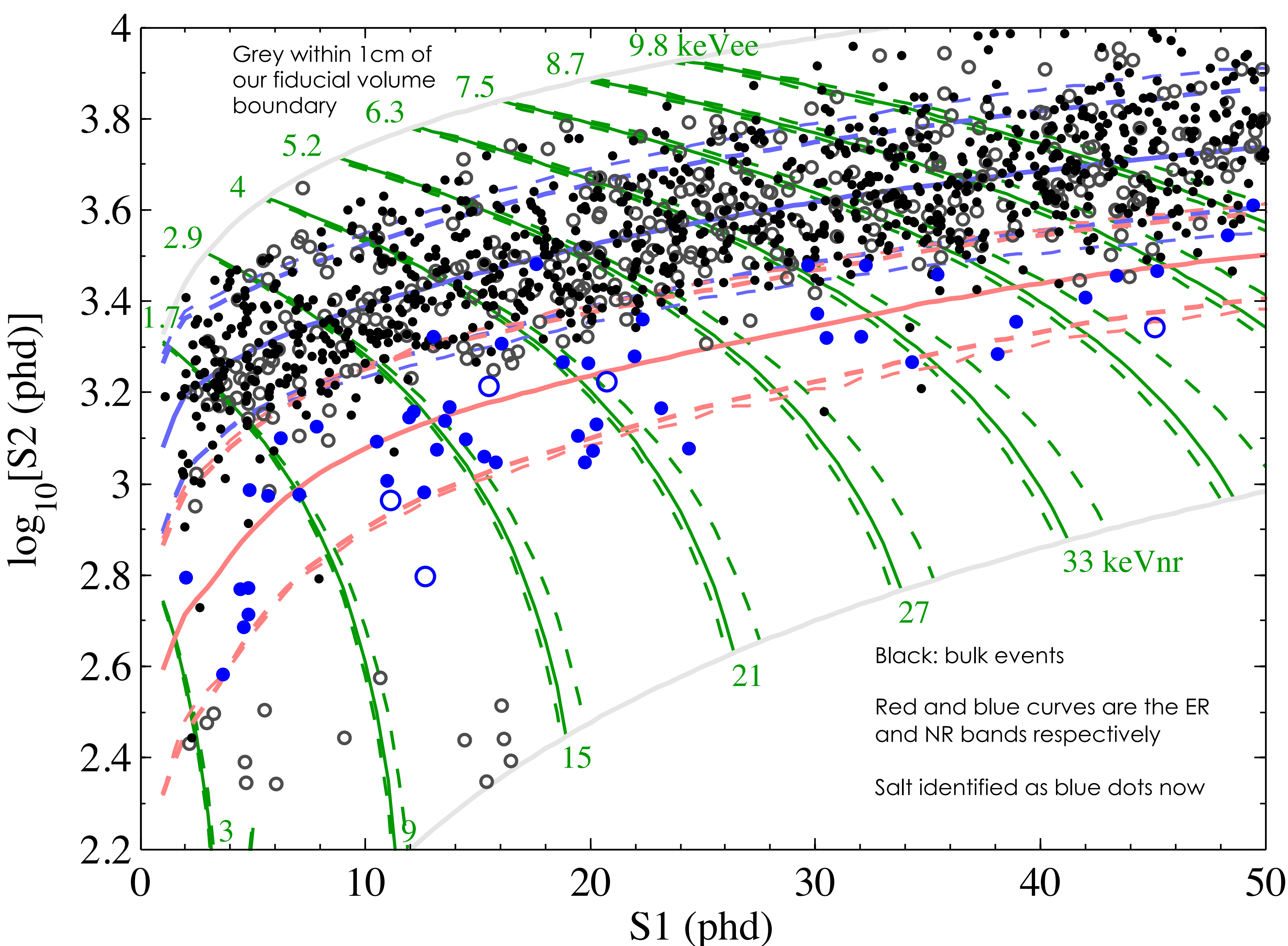
Instead of traditional blinding, we employ a technique where fake signal events ("salt") are injected into data stream. NOT SIM!!

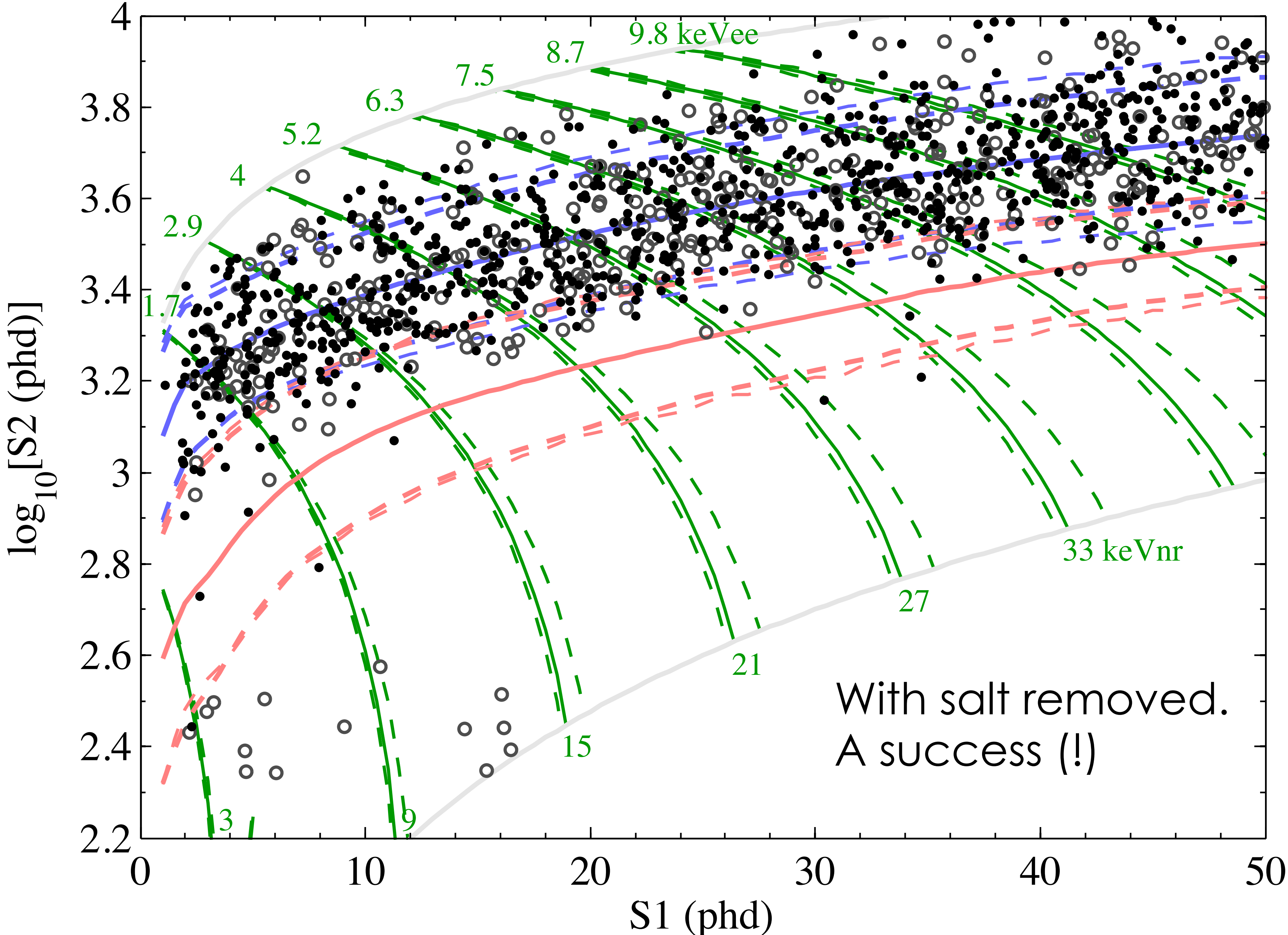


Mitigate bias while allowing for scrutiny of individual events

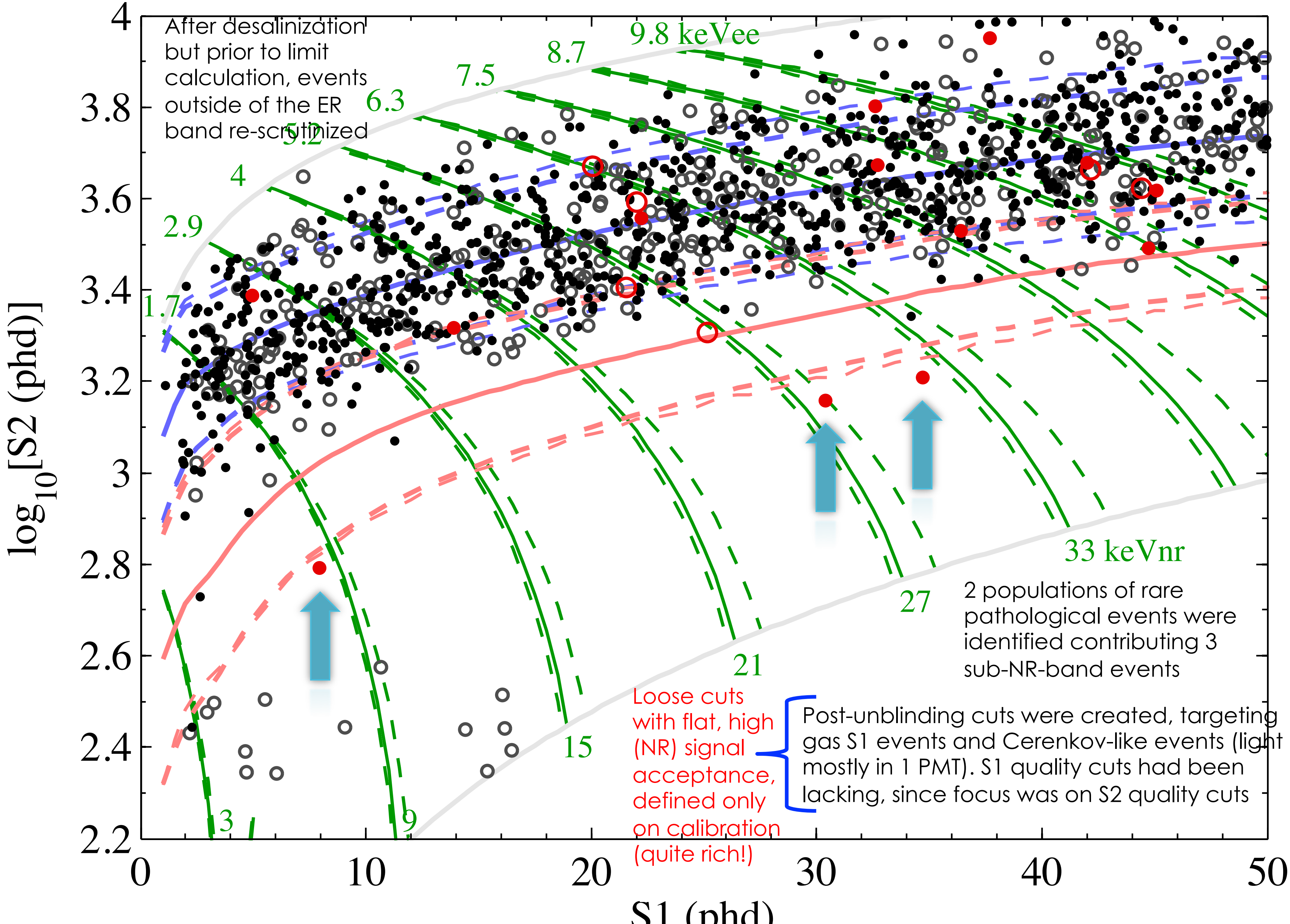
Used already to great effect in neutrino experiments and searches for fractional charge

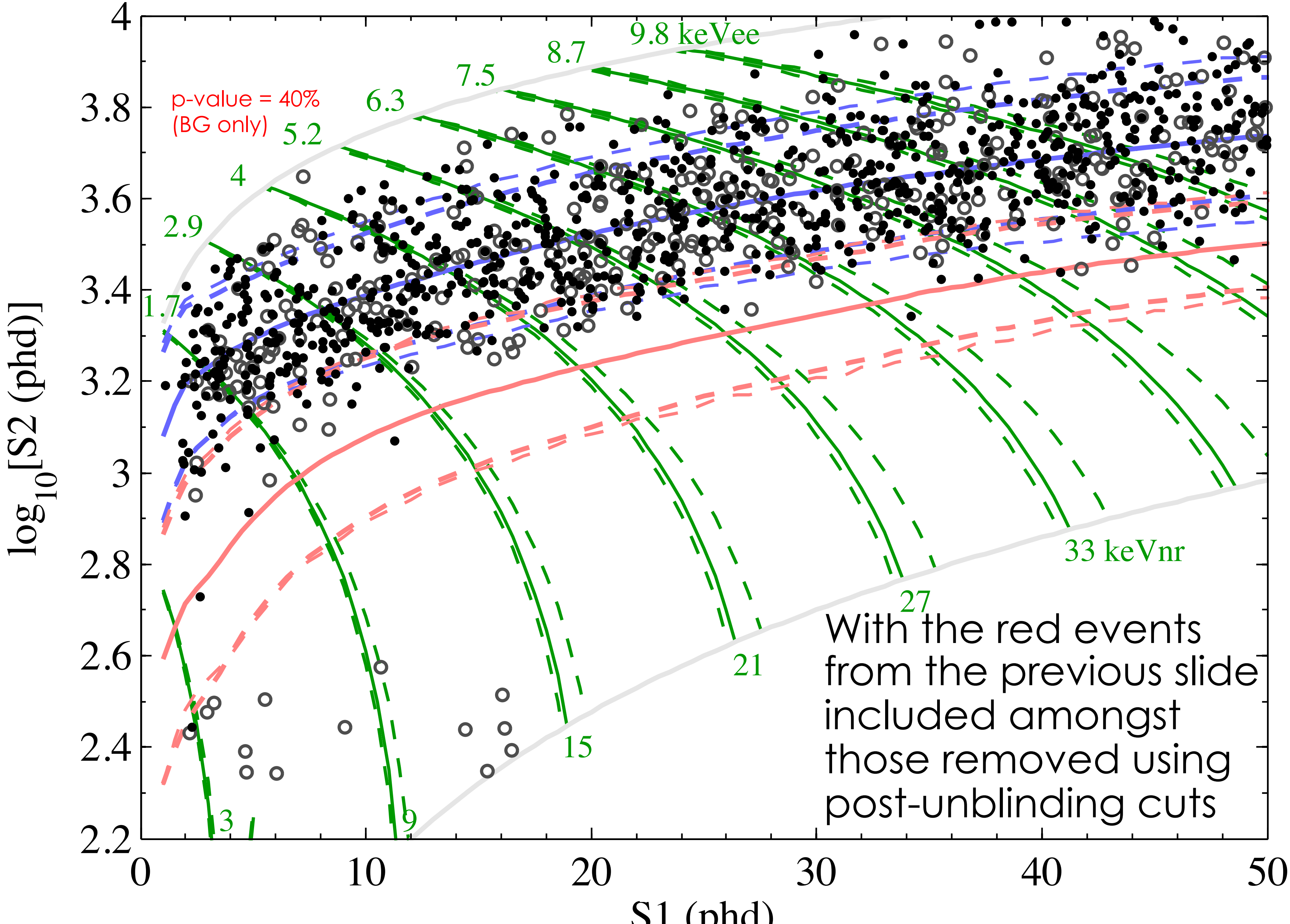
Plot shows data from our "16 detectors" stacked on top of each other


Grey within 1cm of our fiducial volume boundary
9.8 keVee
8.7
7.5
6.3
5.2
4
2.9
1.7
33 keVnr
27
21
15
9
3
Black: bulk events
Red and blue curves are the ER and NR bands respectively
Salt identified as blue dots now
log10[S2 (phd)]
S1 (phd)



9.8 keVee
8.7
7.5
6.3
5.2
4
2.9
1.7
3
9
15
21
27
33 keVnr
With salt removed.
A success (!)
log10[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

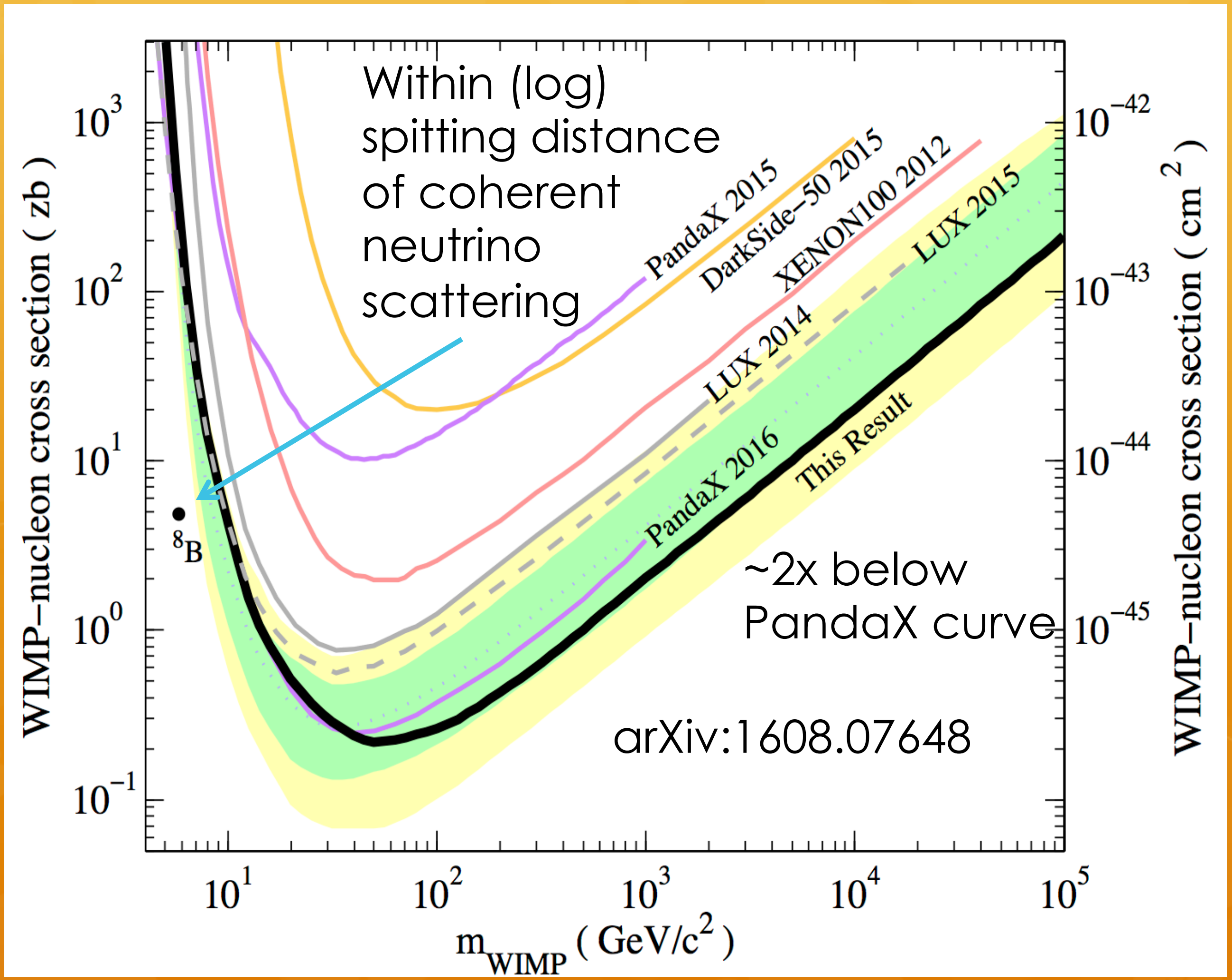

After desalinization but prior to limit calculation, events outside of the ER band re-scrutinized
9.8 keVee
8.7
7.5
6.3
5.2
4
2.9
1.7
33 keVnr
27
21
15
9
3
2 populations of rare pathological events were identified contributing 3 sub-NR-band events
Loose cuts with flat, high (NR) signal acceptance, defined only on calibration (quite rich!)
Post-unblinding cuts were created, targeting gas S1 events and Cerenkov-like events (light mostly in 1 PMT). S1 quality cuts had been lacking, since focus was on S2 quality cuts
$\log_{10}$[S2 (phd)]
S1 (phd)


p-value = 40%
(BG only)
9.8 keVee
8.7
7.5
6.3
5.2
4
2.9
1.7
3
9
15
21
27
33 keVnr
log10[S2 (phd)]
S1 (phd)
With the red events
from the previous slide
included amongst
those removed using
post-unblinding cuts

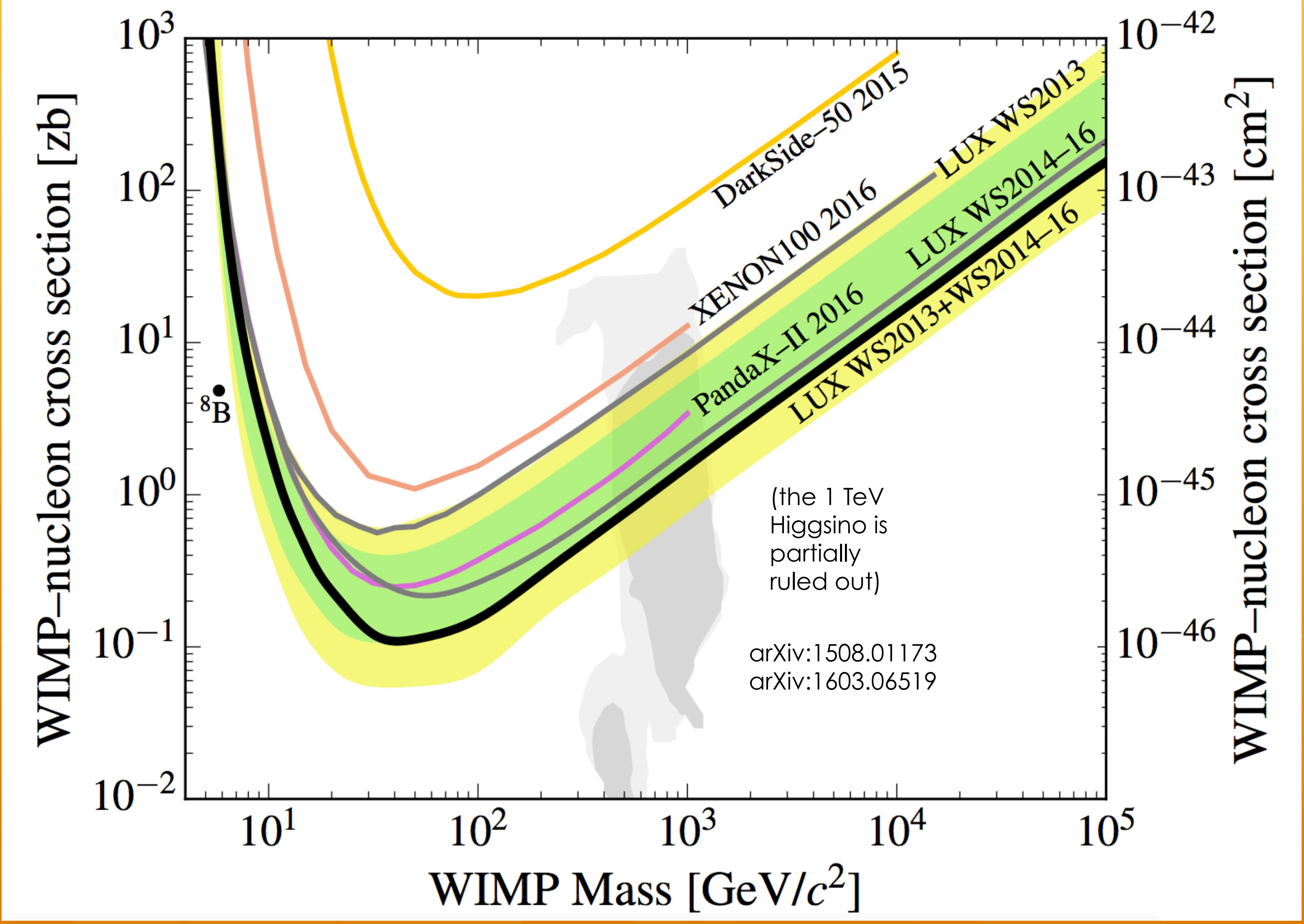
WIMP-nucleon SI Exclusion

- Our best, lowest exclusion is at 50 GeV: 2.2×10^{-46} cm^2 (That's 0.22 zeptobarns in σ!)
  - 1 order of magnitude off XENON1T
  - Within < 2 orders of LZ projection
- Comparable to LUX 2015 re-analysis of 3 months' worth of data at low mass but FOUR TIMES better at high mass. (Final G1?)

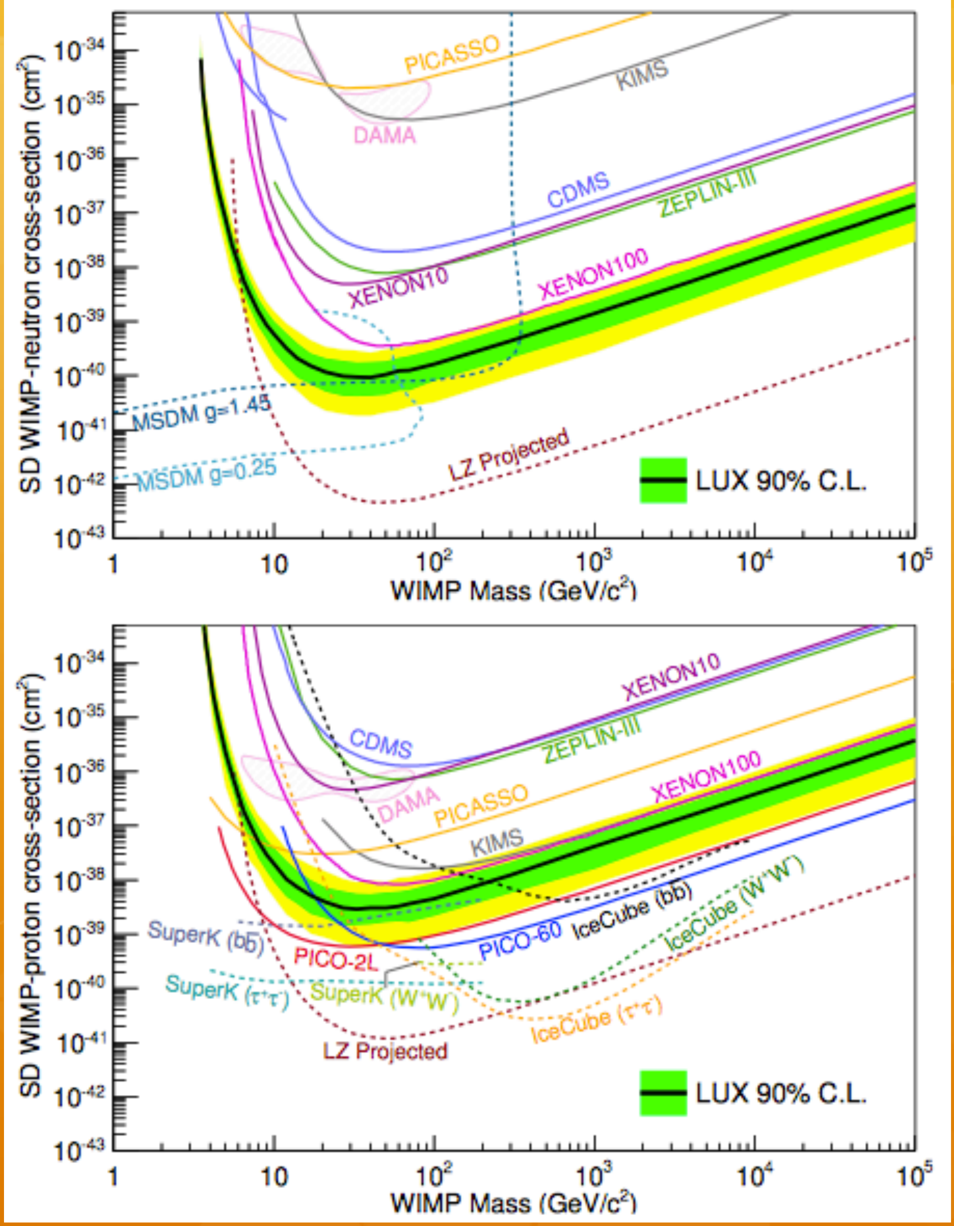
(NOT preliminary. Analysis / limit is final. Paper is being submitted to PRL.)



Both LUX Runs Combined

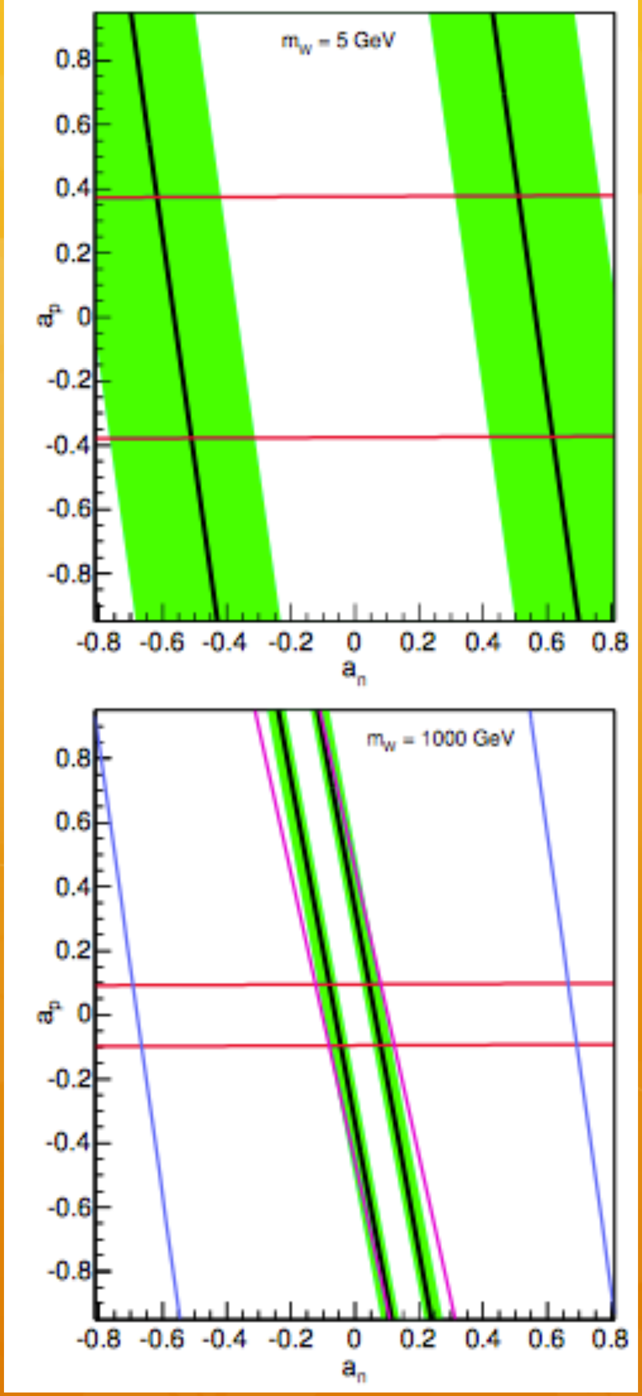


SD Exclusion

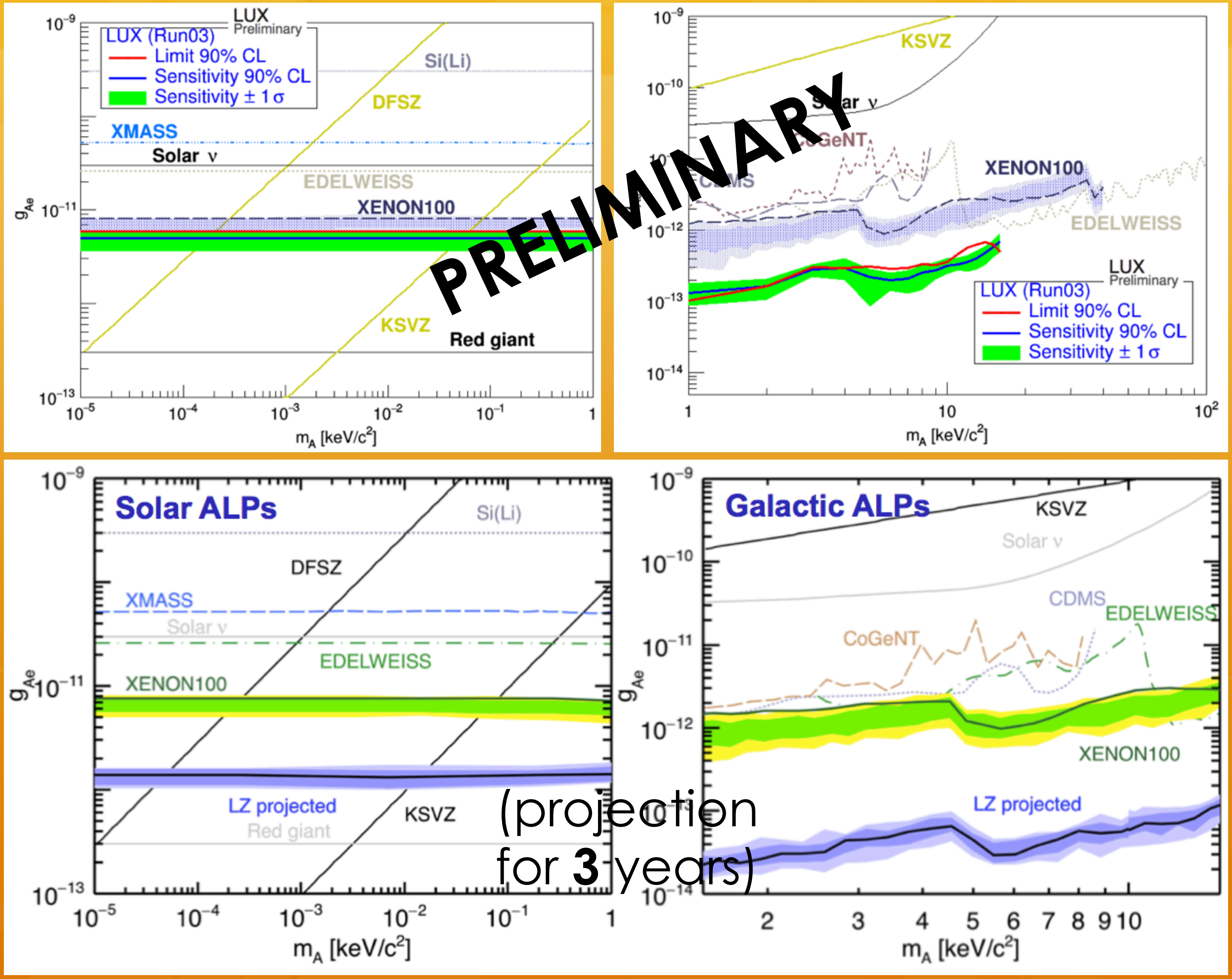


NOTE: This is still the old run. Still needs to be updated with the 1 year's worth of new data

Xenon is the *best* element for neutron coupling (while fluorine is best for protons)



Axions (LUX 95 days, and LZ)



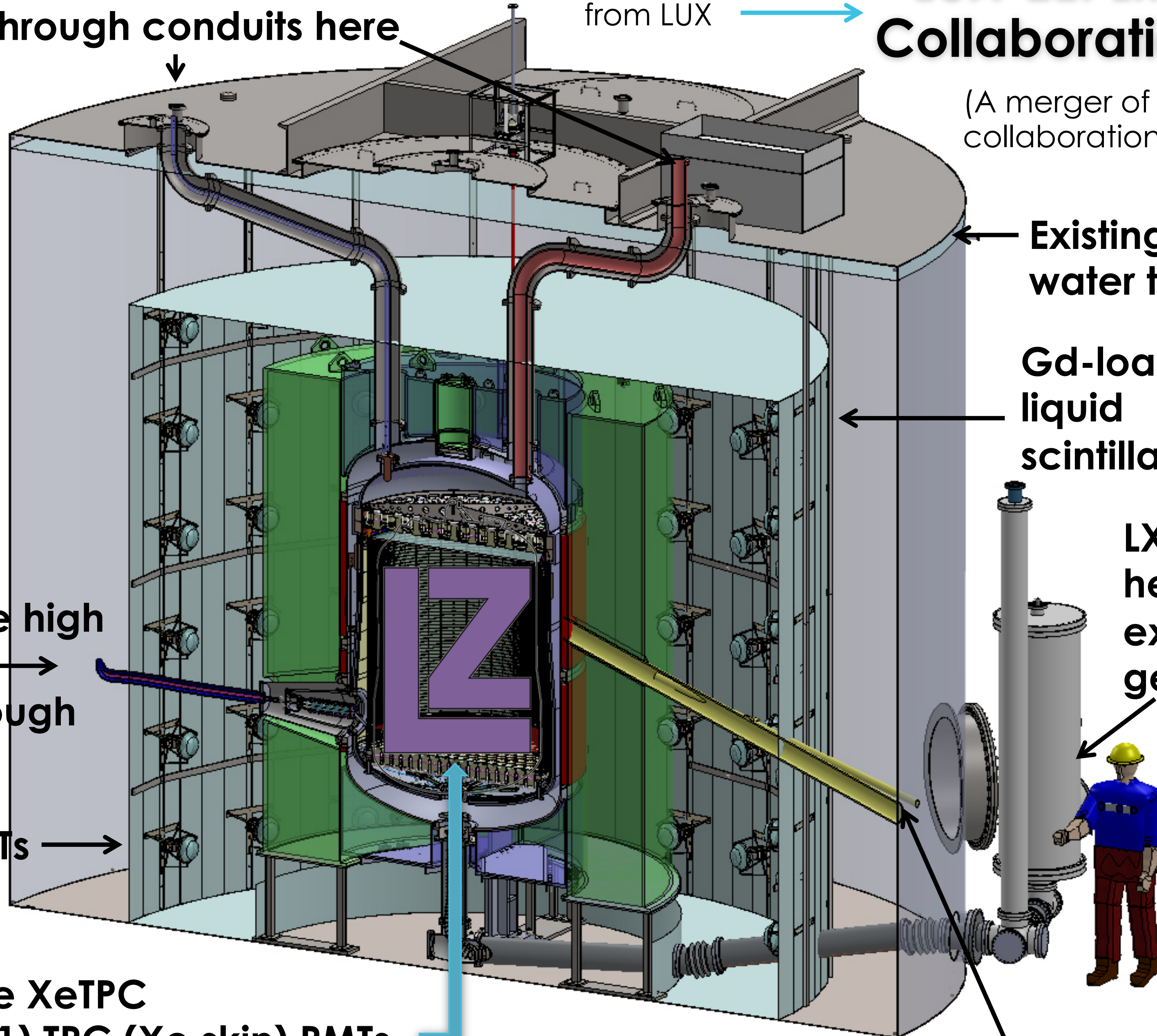
LUX-ZEPLIN Collaboration

(A merger of 2 collaborations)

Separate project from LUX

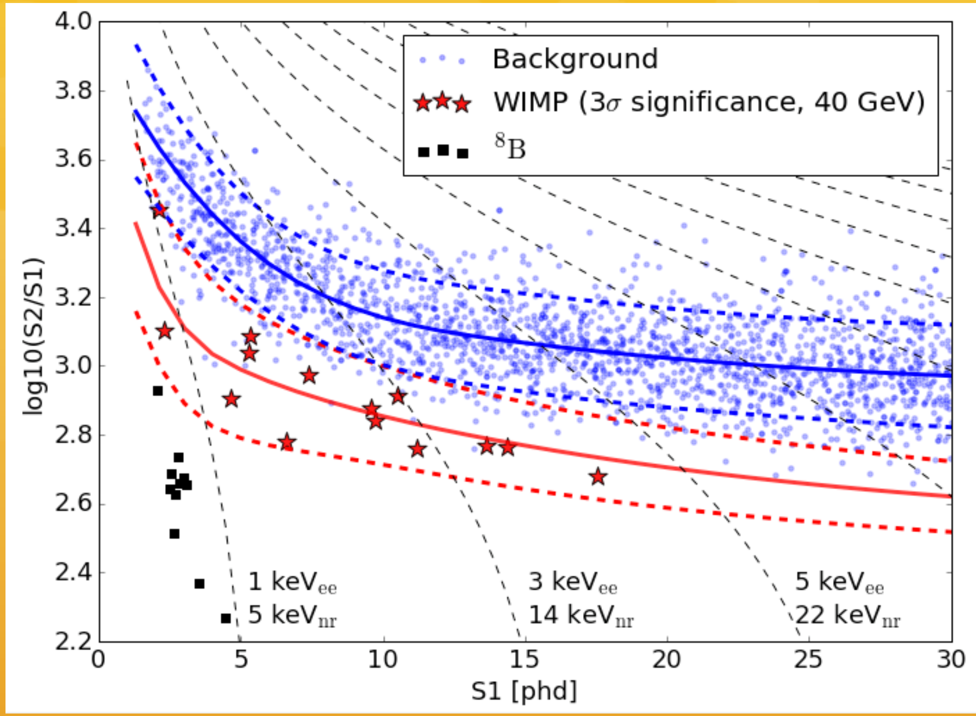
A bigger and *better* version of LUX. Funded!

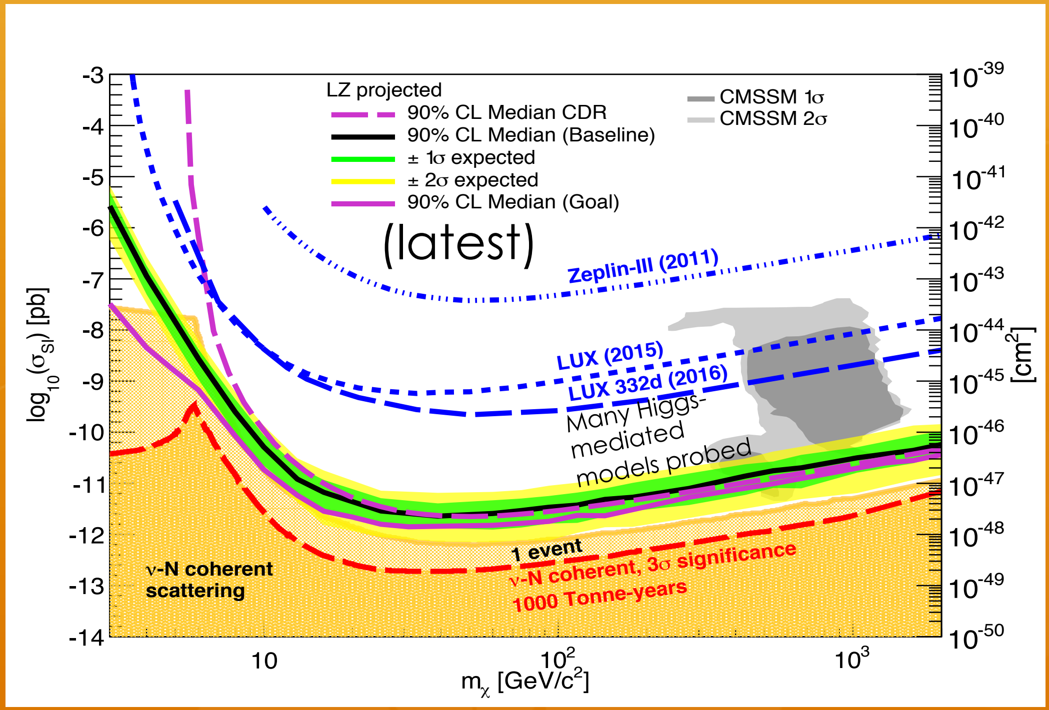
LZ has just passed its DOE CD-2/3b review. (Was already past CD-1/3a last year.)



LZ's Reach

- Turning on by 2020 with 1,000 initial live-days plan
- 10 tons total, 7 tons active, ~5.6 ton fiducial mass
  - Due to unique triple veto
- GOALS: < 3 x 10^{-48} cm^2, at 40 GeV. Clip ν shoulder





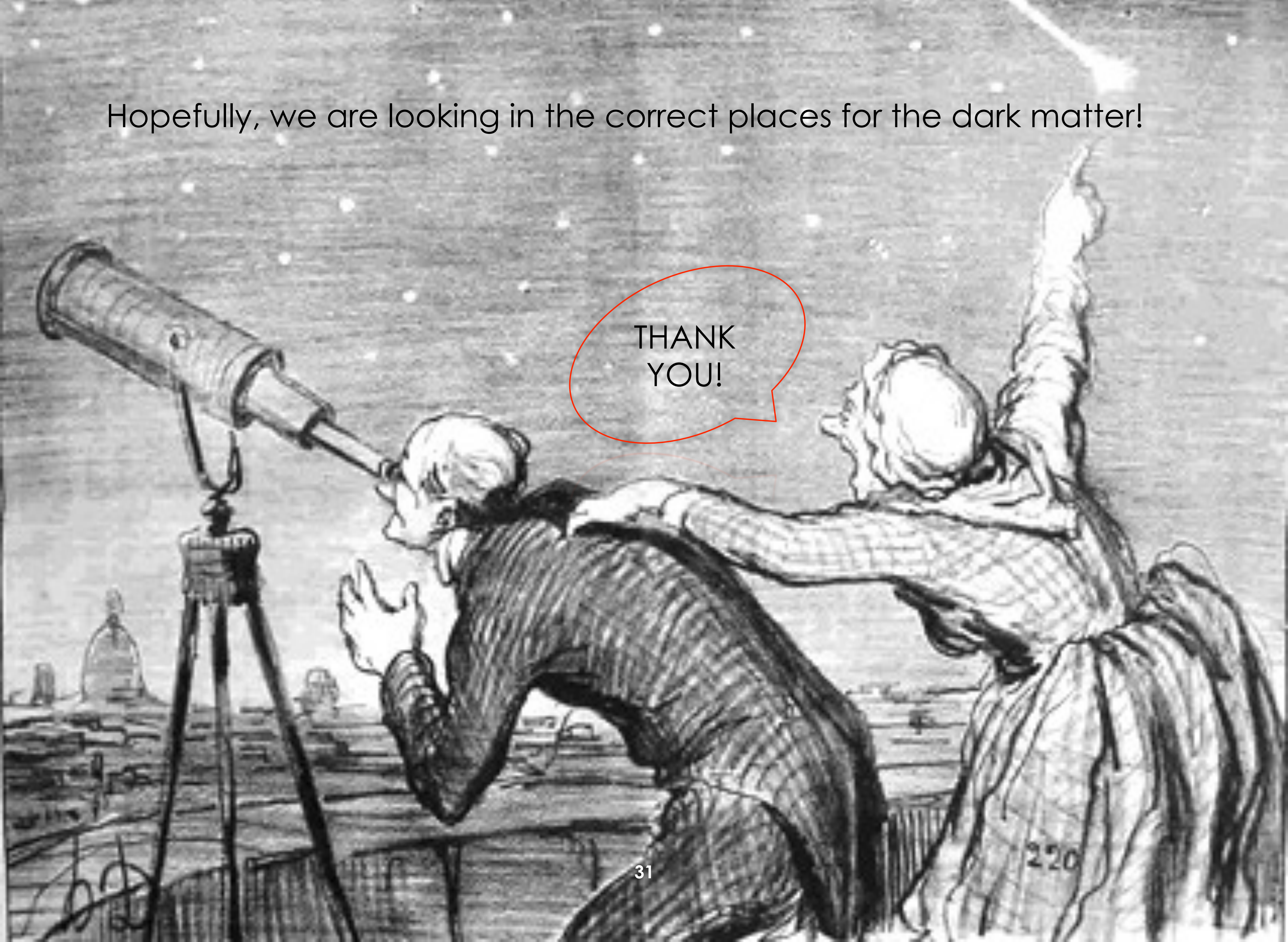
*plot and models from LZ's Conceptual Design Report, arXiv:**1509.02910**

Summary and Outlook

- New world-leading result, from LUX's 332 live-day search, cutting into unprobed parameter space
  - 33,500 kg-days exposure, most of any LXeTPC ever
- More publications forthcoming: SD, axions, inelastic DM, more detailed longer paper on the nitty-gritty, new calibrations that will be useful for future experiments like LZ, S1 pulse-shape discrimination, EFT operator limits…
  - Now: "Signal yields, energy resolution, and recombination fluctuations" -arXiv:1610.02076
- LUX-ZEPLIN (LZ) will come within ~one order of magnitude of the neutrino floor at high mass with multi-ton-scale detector and SURF infrastructure
  - One of only 3 down-selected DOE Gen-2 projects

Honoré Daumier, "Mr. Babinet, warned by his concierge of the arrival of the comet", illustration for Le Charivari, 22 September 1858.

Hopefully, we are looking in the correct places for the dark matter!



Additional Slides

for backup

See also especially:
https://idm2016.shef.ac.uk/indico/event/0/contribution/50/material/slides/0.pdf (the first announcement talk, by Dr. Aaron Manalaysay, this past July at the IDM conference in the UK)

Selected Publications:

Phys. Rev. Lett. 112, 091303 (2014)
Phys. Rev. Lett. 116, 161301 (2016)
Phys. Rev. Lett. 116, 161302 (2016)
Phys. Rev. D 93, 072009 (2016)

LUX timeline

Translation of confusing run names
Run01: systems test with GAr
Run02: technical surface run (Xe)

Astoparticle Phys., Vol. 45, May 2013, pp. 34–43

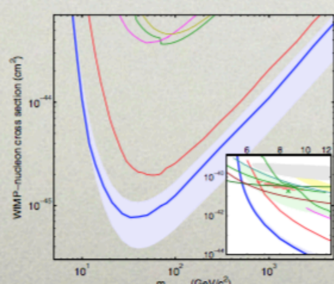
Run03: Three months / 95 days live underground
Run04: A 1-year / 332 live-day run

2008: LUX funded (DOE+NSF)

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

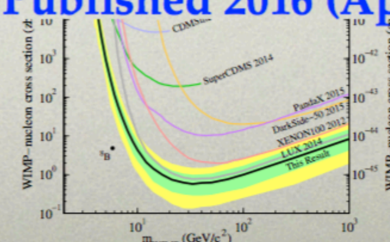
2013 (Apr): Commissioning complete

2014 (Mar): First results (3 months) reported



2014 (Sep): 332-day run started!

2015 (Dec.) 3-month run reanalysis posted. Published 2016 (Apr).



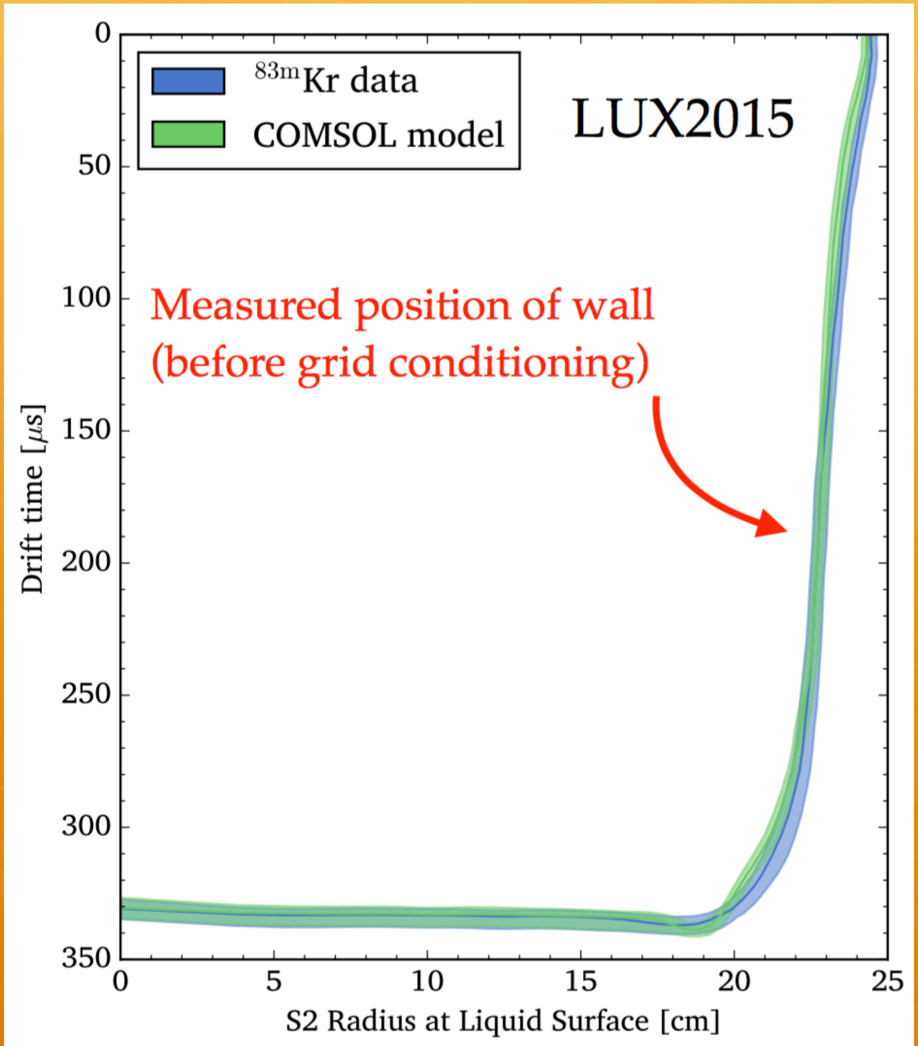
2016 (May): Run finished

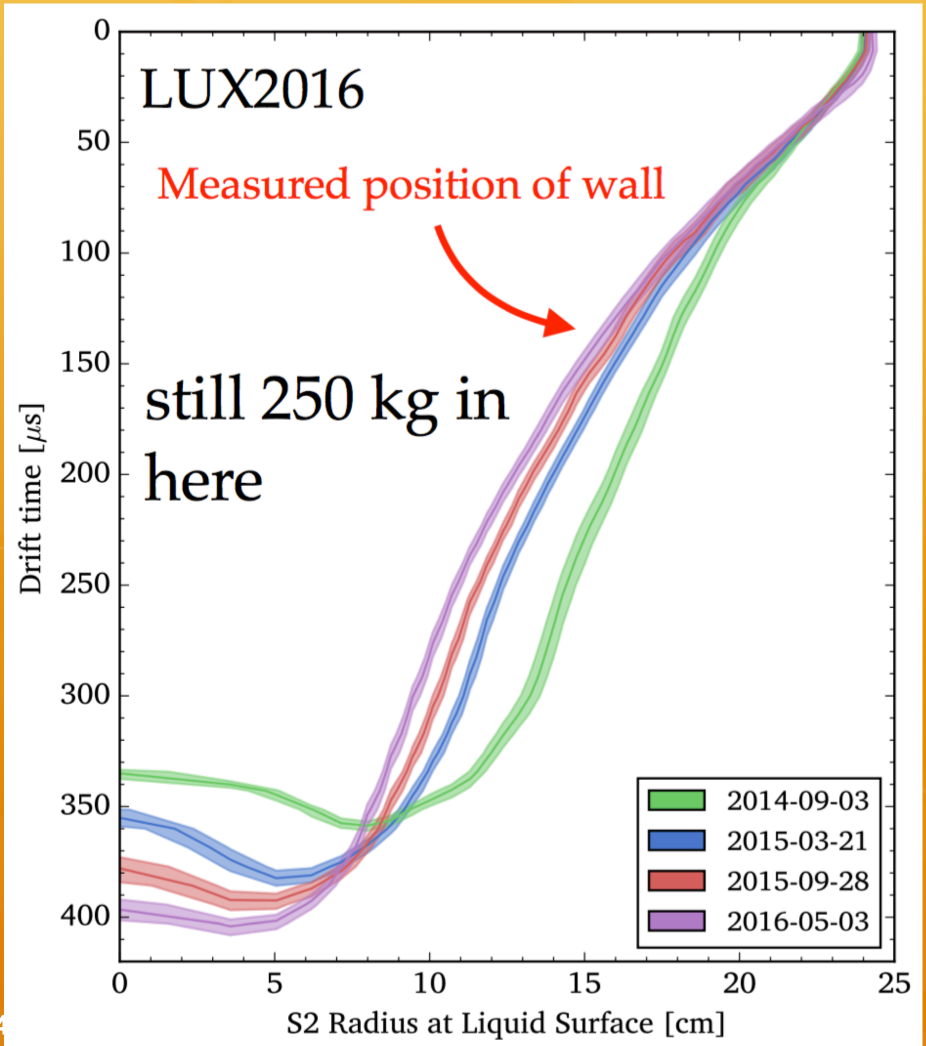
2016 (July): 332 days DM results presented

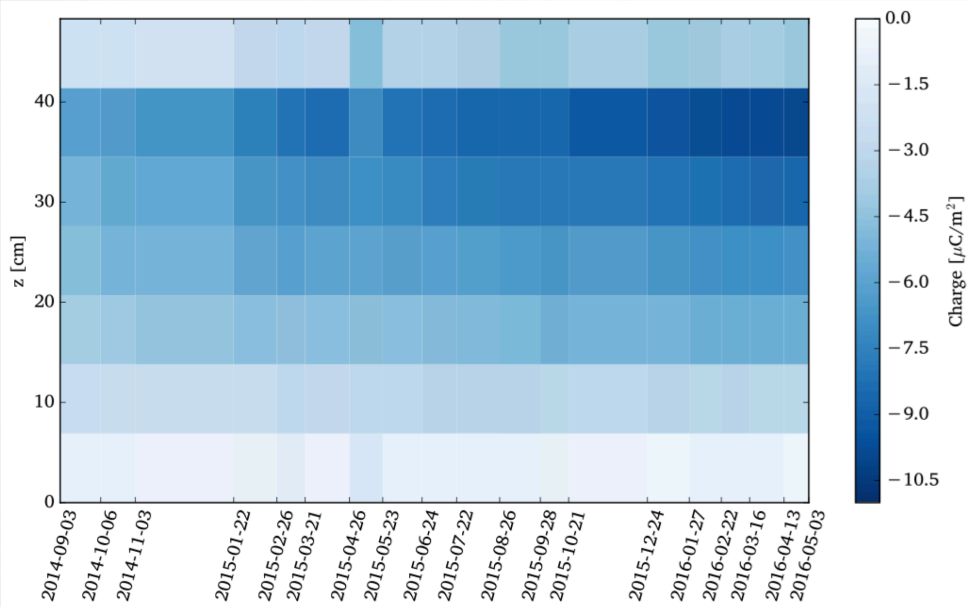
Not over: **analyses**!

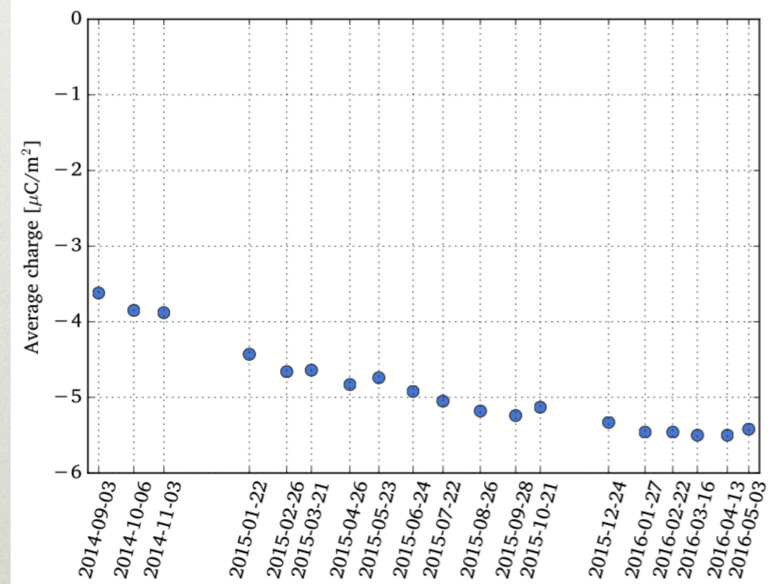
original sensitivity goals were exceeded

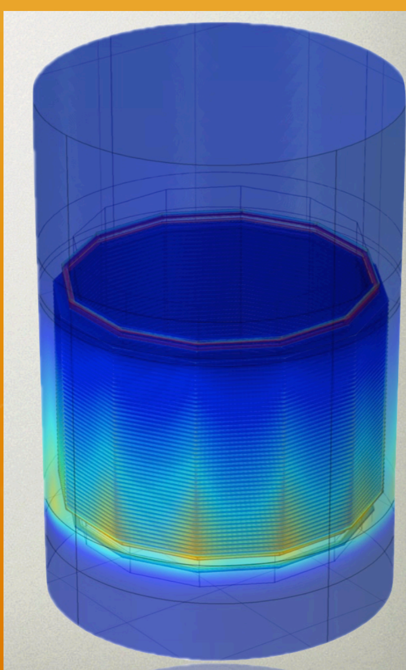
Electric Field Uniformity

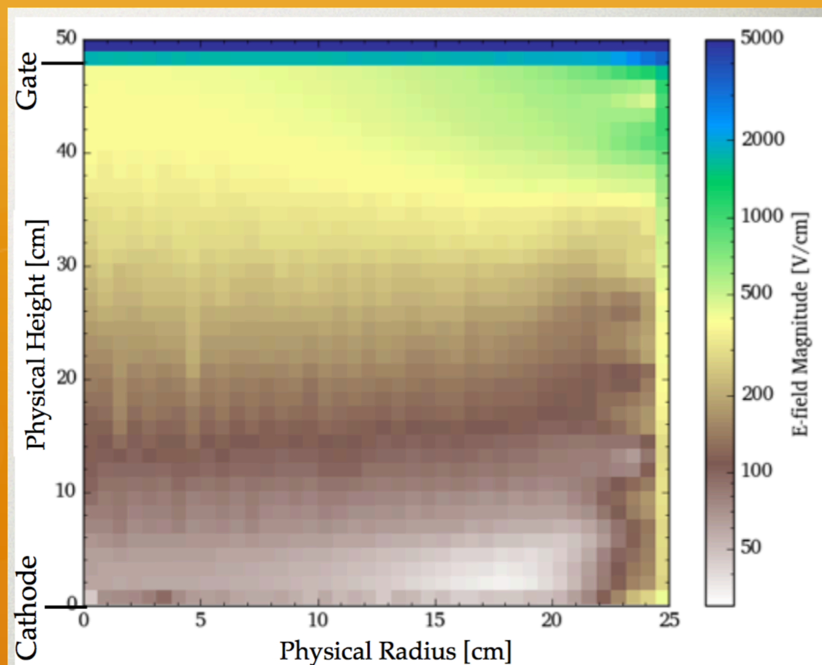




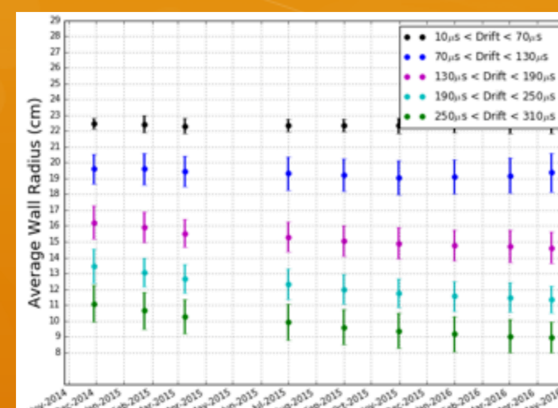


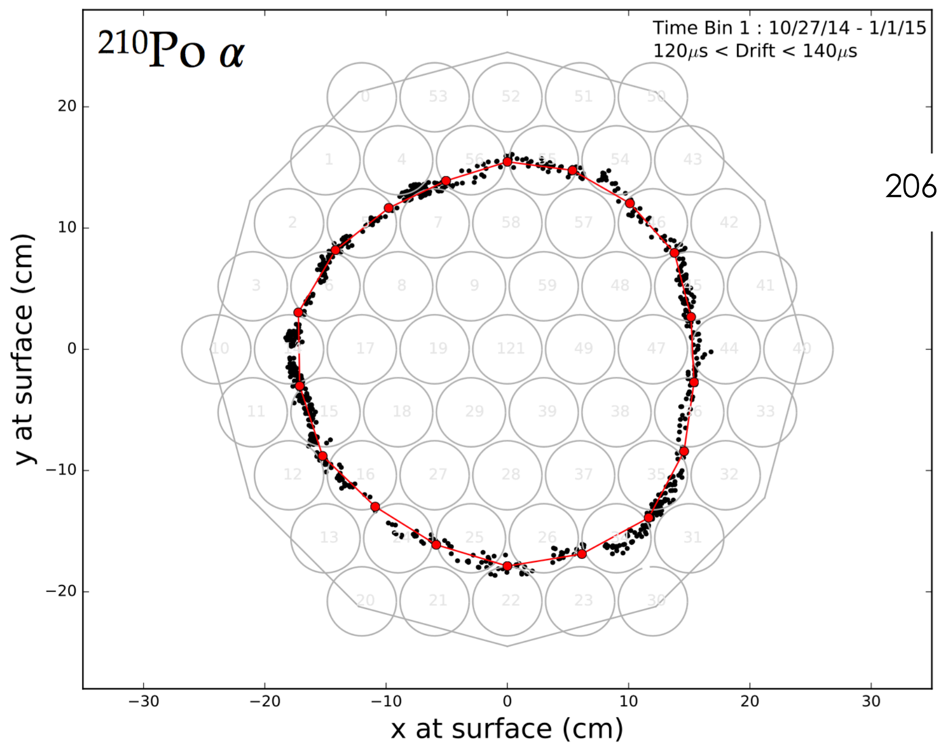


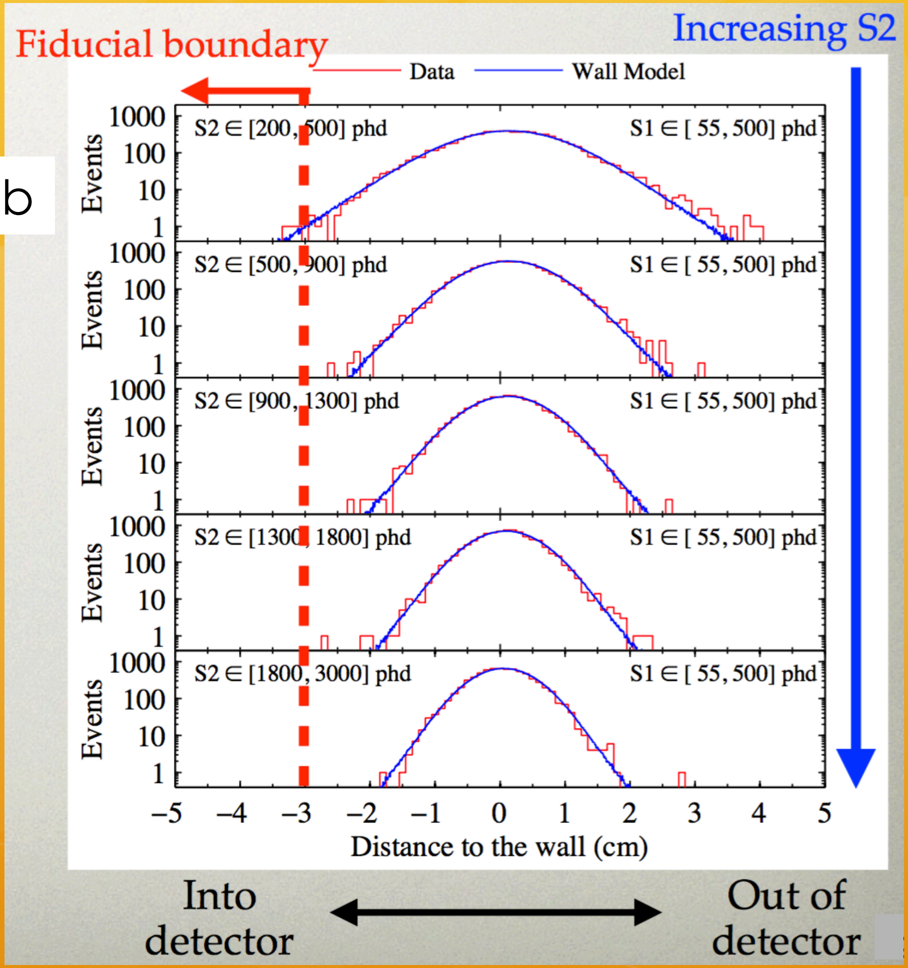


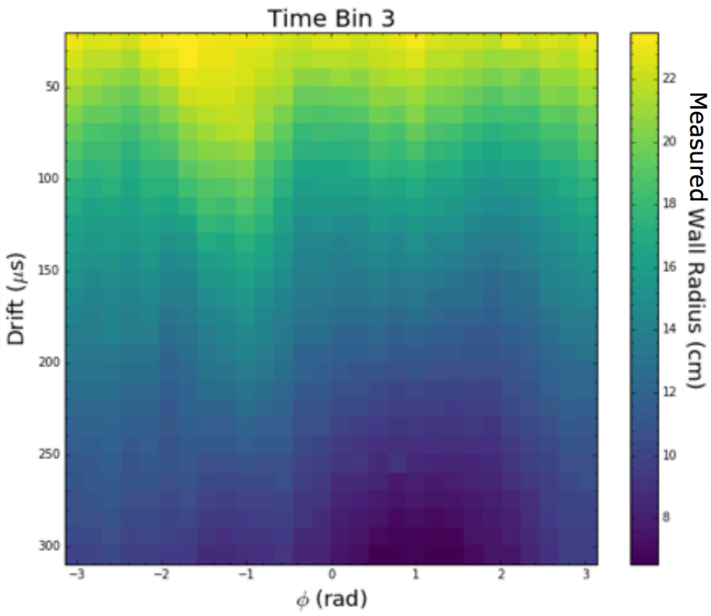


E-field modeling



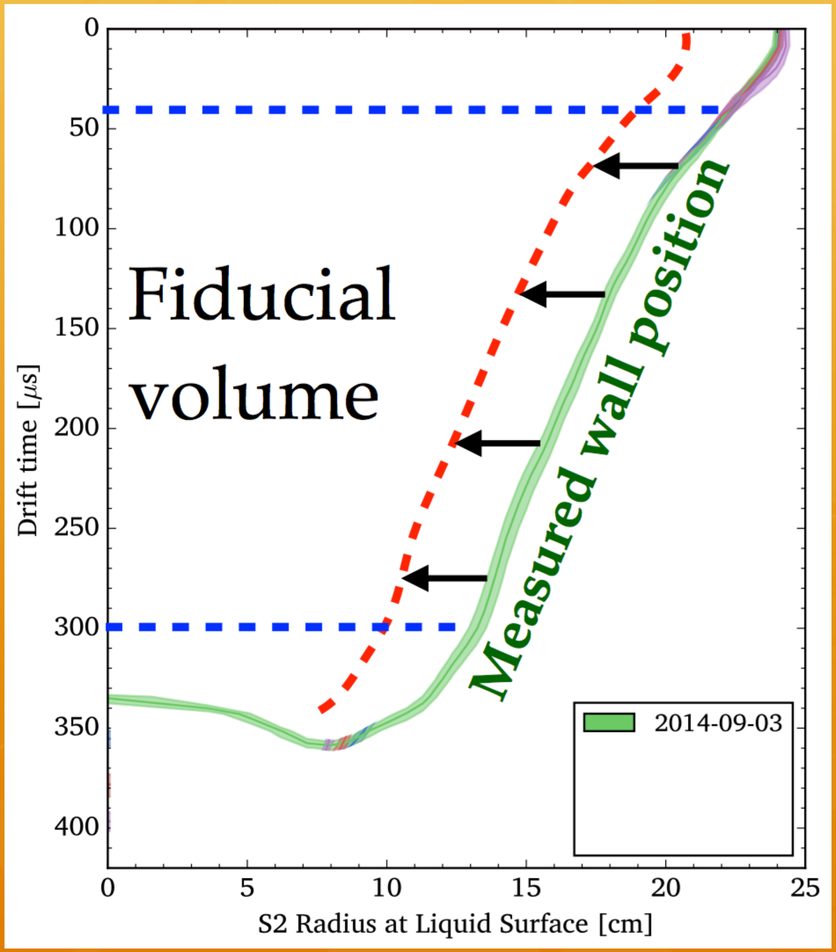


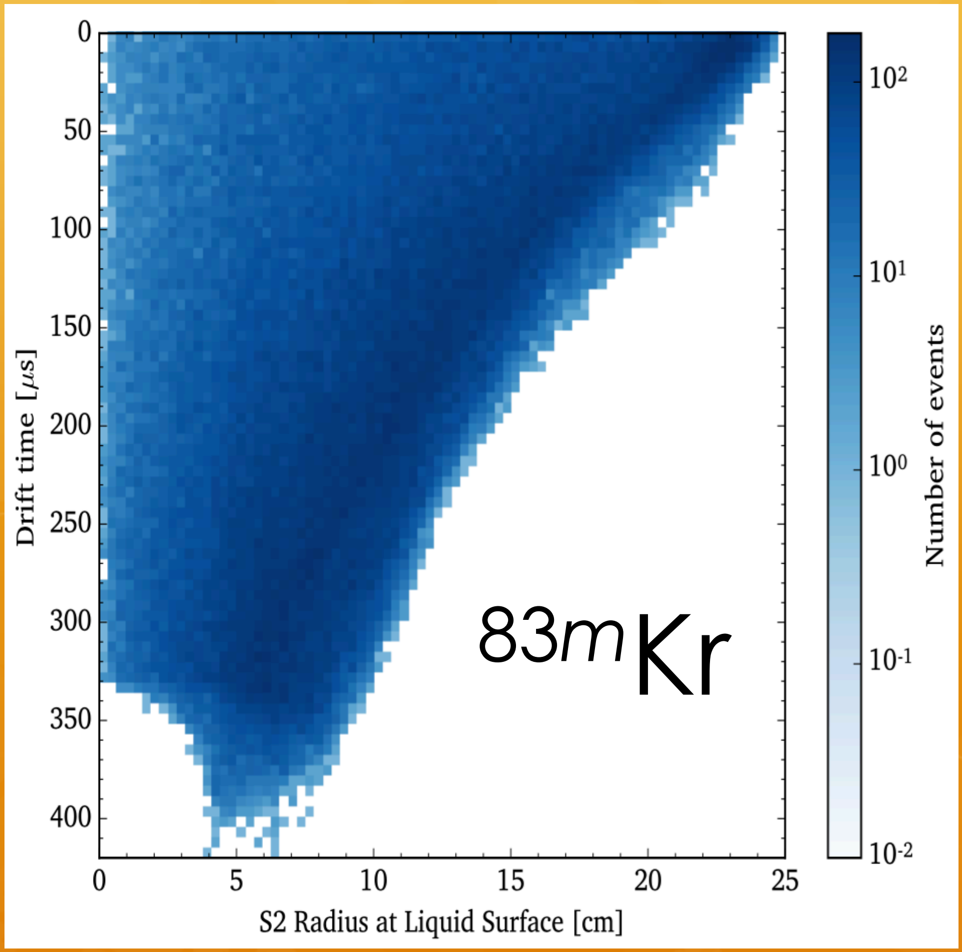




Wall Surface Background

Fiducial Calculation





Details of the WIMP search

the key dates

Original proposal objectives met; how often does that happen?!

- 11 September 2014 — 3 May 2016
- Live time (332.0 days)

Initial goal (2008): 300 live-days

  - Time-bin 1 (2014.09.09-2014.12.31): 46.8 live-d (31.8 d not salted)
  - Time-bin 2 (2015.01.01-2015.03.31): 46.7
  - Time-bin 3 (2015.04.01-2015.09.30): 91.6
  - Time-bin 4 (2015.10.01-2016.05.03): 146.9

Lots of tritium and DD calibrations in there as well

- Fiducial mass:

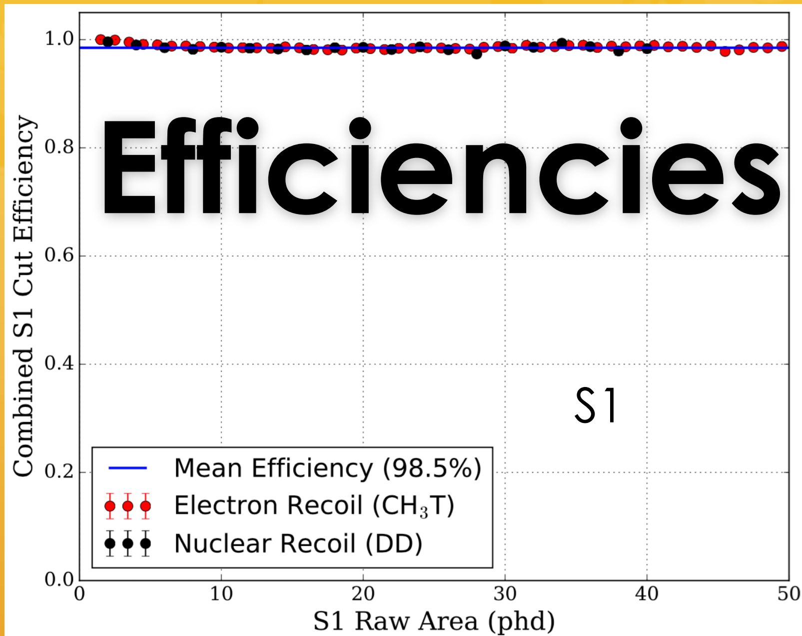
Initial goal (2008): 100 kg

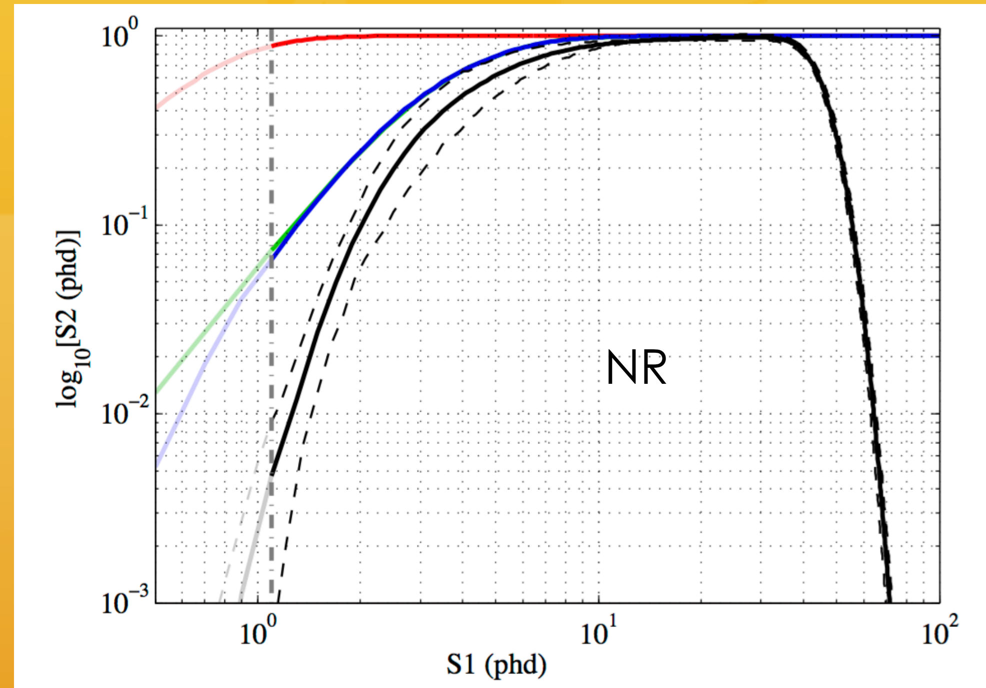
  - Time-bin 1: 105.4 ± 5.3 kg
  - Time-bin 2: 107.2 ± 5.4
  - Time-bin 3: 99.2 ± 5.0
  - Time-bin 4: 98.4 ± 4.9

Initial goal (2008): 30,000 kg-days

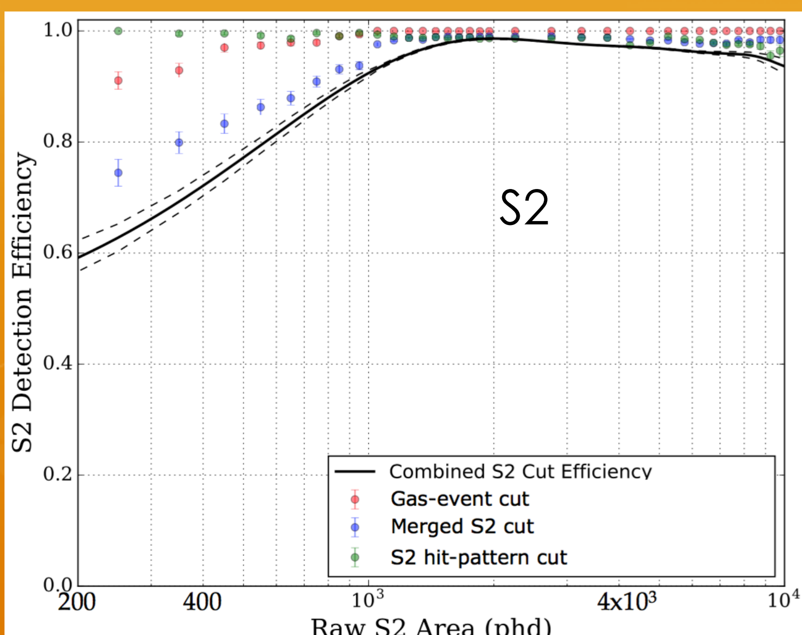
(33500 ± 1700) kg days

Efficiencies



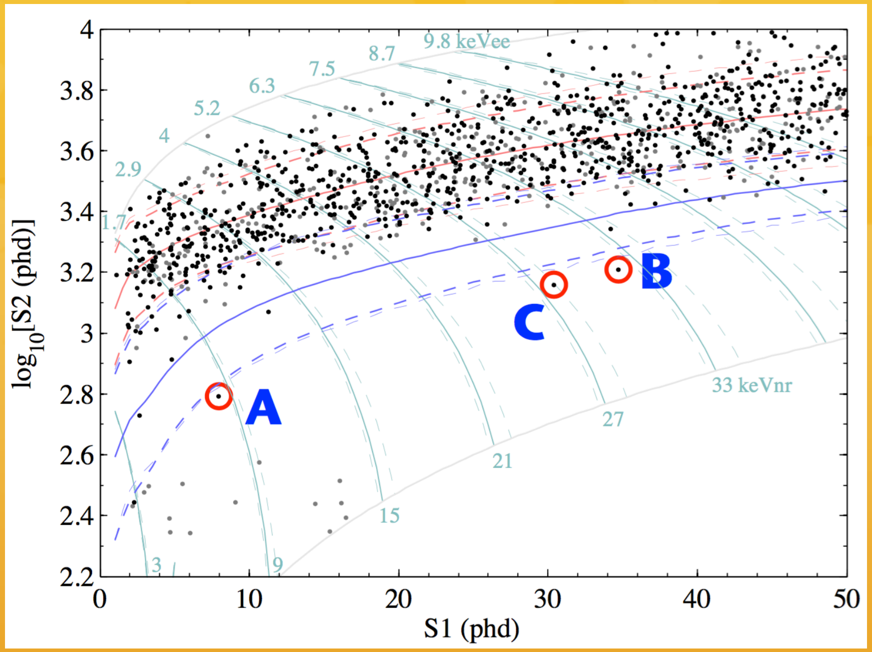


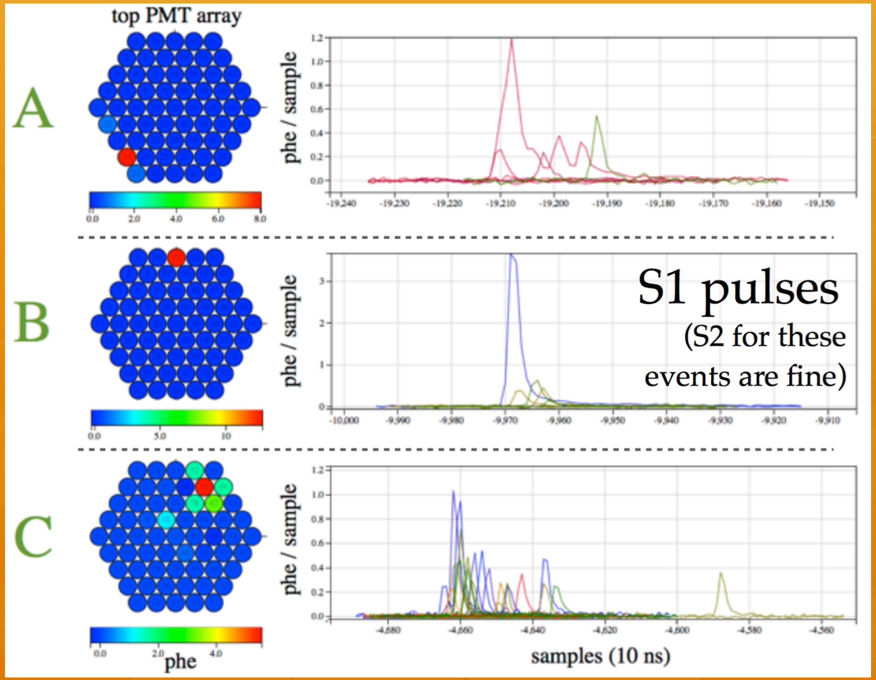
Caption: Efficiencies for NR event detection, estimated using simulation with parameters tuned to D-D calibration. In descending order of efficiency—red: detection of an S2 (≥2 electrons emitted); green: detection of an S1 (≥2 PMTs detecting photons); blue: detection of both an S1 and an S2; black: detection passing analysis selection criteria, including thresholds in *S1* and raw S2 size. Solid curves indicate exposure-weighted means, the variation in time and detector position are indicated for the final efficiency.

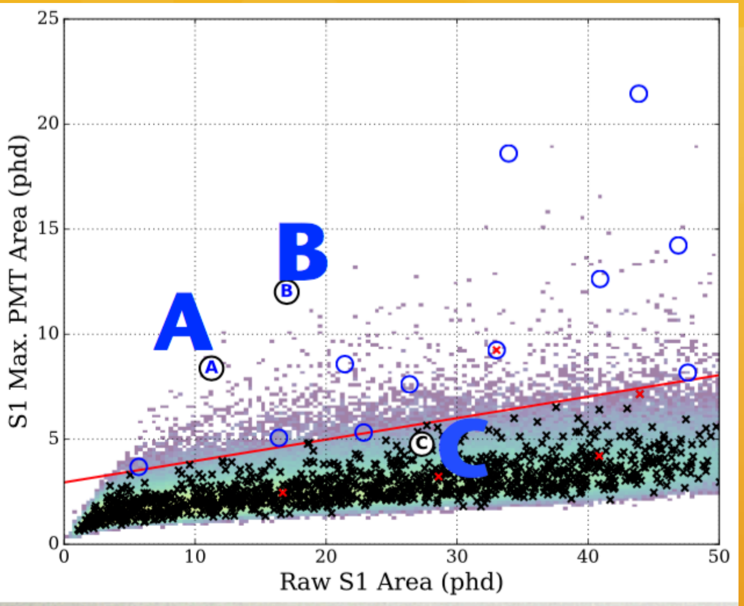


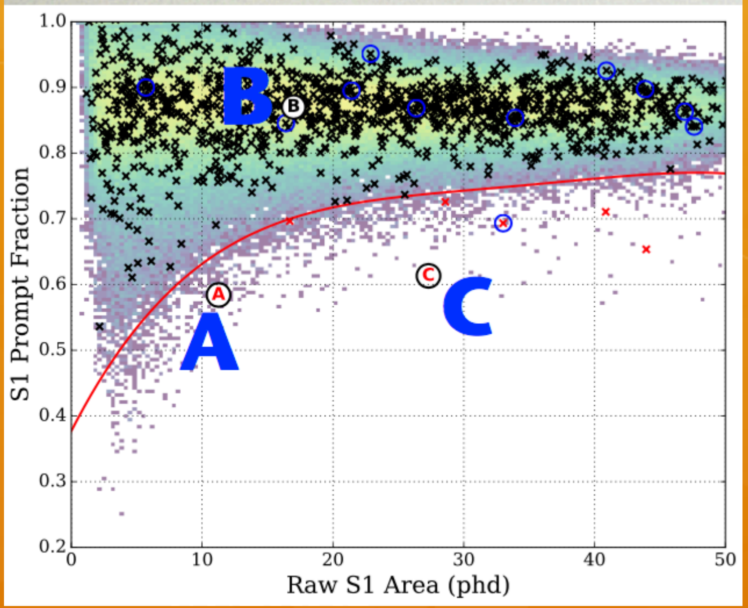
Lots of things push and pull to make
Run04 efficiency very comparable to 03

Pathologies



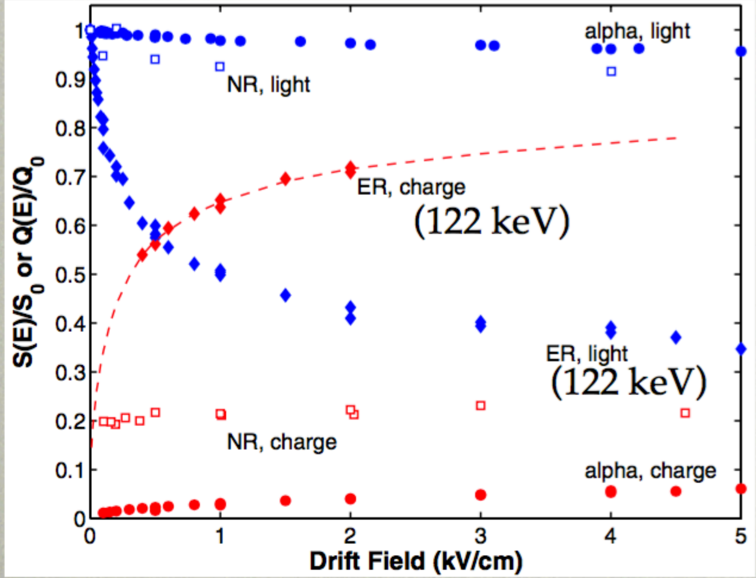




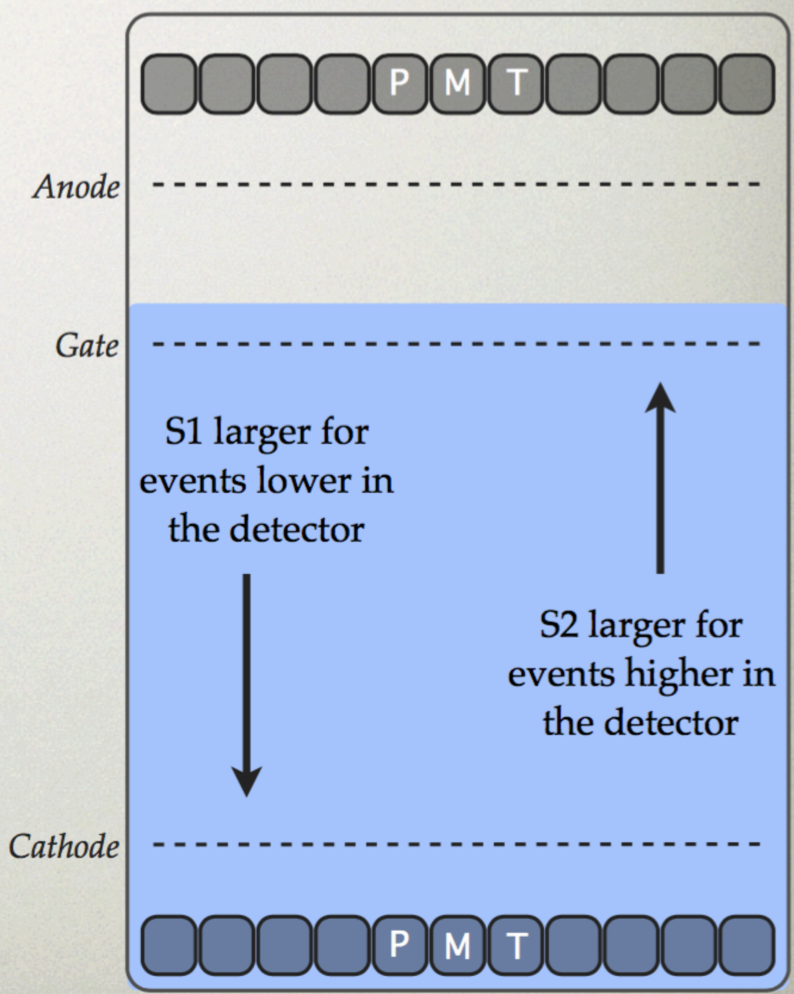


Position corrections

- 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.

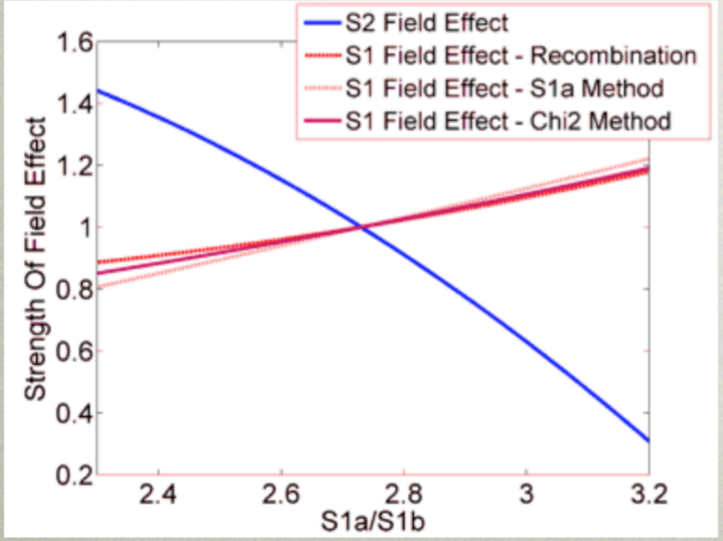


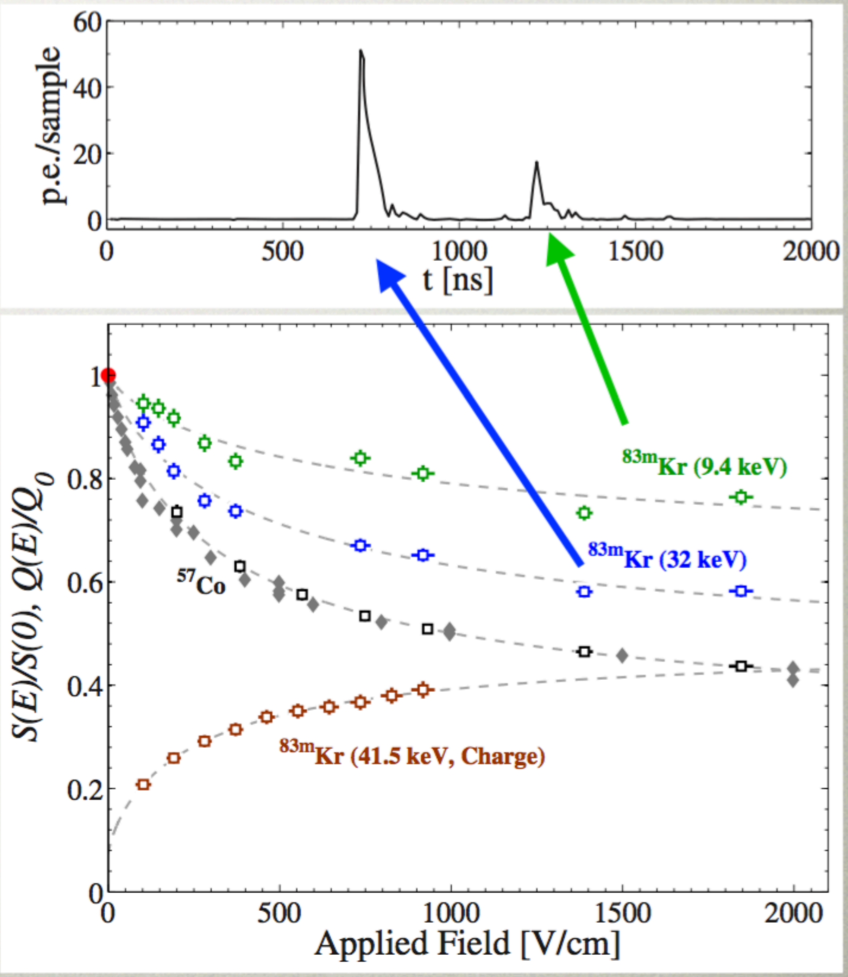
E. Aprile *et al.* PRL **97** (2006) 081302, astro-ph/0601552



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.

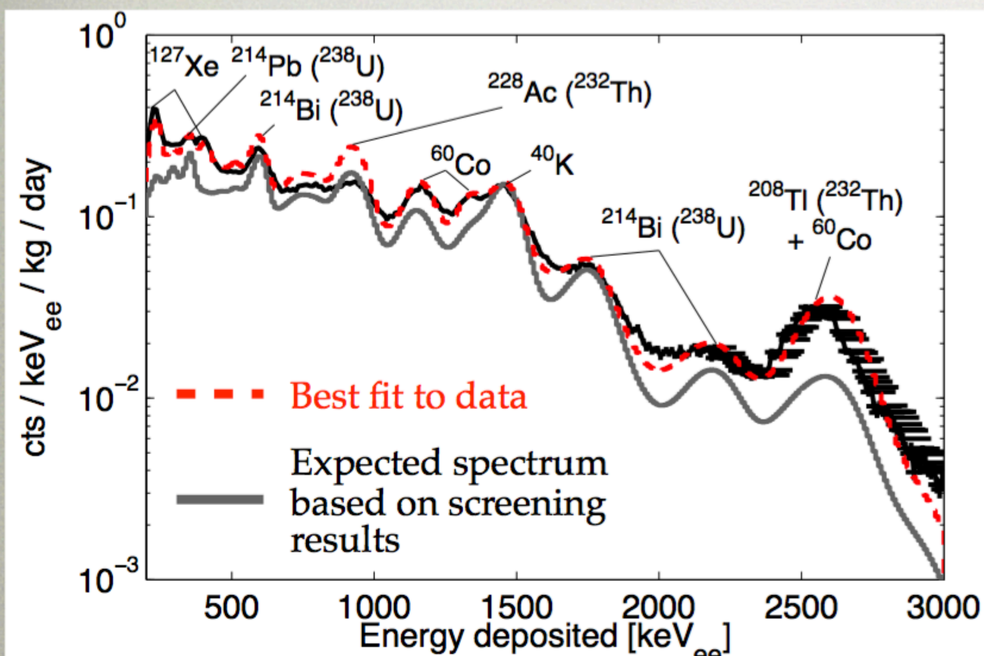




A.Manalaysay *et al.*, Rev.Sci.Instrum. **81** (2010) 073303, 0908.0616

Radiogenic backgrounds

- Backgrounds from radioisotopes in detector materials have not changed since the previous LUX results.



D.S. Akerib *et al.*, Astropart.Phys. **62** (2015) 33, 1403.1299

- In the first LUX results, there was a residual amount of ^{127}Xe among our stock of Xe, and was included as a background component.
- Here, the ^{127}Xe has decayed away and we neglect its contribution (>20 half lives at the beginning of this data set).