The Latest Results From the **LUX** Dark Matter Experiment in Lead, SD

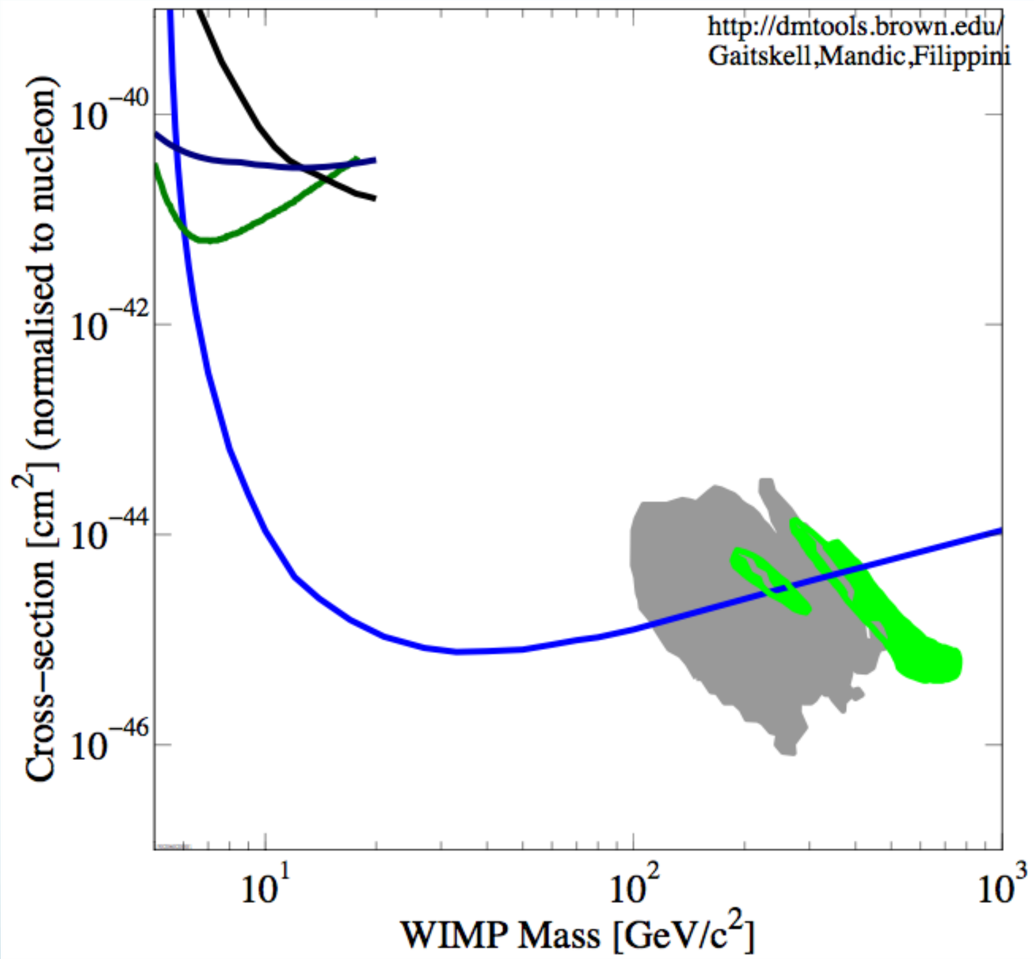
at the Sanford Underground Research Facility

www.luxdarkmatter.org

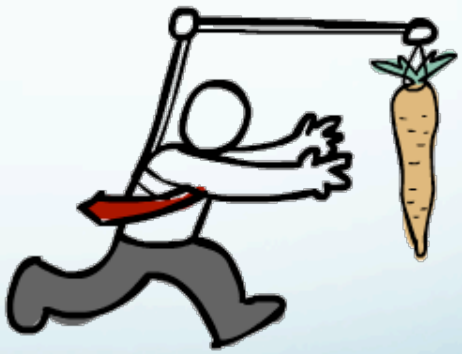
Matthew Szydagis, University at Albany, for the LUX collaboration

SUSY 2015 August 25th

Time Progression of Sensitivity



Years 2000-2013



Animation courtesy of Aaron Manalaysay, UC Davis

The LUX Collaboration

Brown

Richard Gaitskell	PI, Professor
Simon Fiorucci	Research Associate
Samuel Chung Chan	Graduate Student
Dongqing Huang	Graduate Student
Casey Rhyne	Graduate Student
Will Taylor	Graduate Student
James Verbus	Graduate Student

Imperial College London

Henrique Araujo	PI, Reader
Tim Sumner	Professor
Alastair Currie	Postdoc
Adam Bailey	Graduate Student
Khadeeja Yazdani	Graduate Student

Lawrence Berkeley + UC Berkeley

Bob Jacobsen	PI, Professor
Murdock Gilchriese	Senior Scientist
Kevin Lesko	Senior Scientist
Peter Sorensen	Scientist
Victor Gehman	Scientist
Attila Dobi	Postdoc
Daniel Hogan	Graduate Student
Mia Ihm	Graduate Student
Kate Kamdin	Graduate Student
Kelsey Oliver-Mallory	Graduate Student

Lawrence Livermore

Adam Bernstein	PI, Leader of Adv. Detectors Grp.
Kareem Kazkaz	Staff Physicist
R[illegible]enardo	Graduate Student

LIP Coimbra

Isabel Lopes	PI, Professor
Jose Pinto da Cunha	Assistant Professor
Vladimir Solovov	Senior Researcher
Francisco Neves	Auxiliary Researcher
Alexander Lindote	Postdoc
Claudio Silva	Postdoc

SLAC Nation Accelerator Laboratory

Dan Akerib	PI, Professor
Thomas Shutt	PI, Professor
Kim Palladino	Project Scientist
Tomasz Biesiadzinski	Research Associate
Christina Ignarra	Research Associate
Wing To	Research Associate
Rosie Bramante	Graduate Student
Wei Ji	Graduate Student
T.J. Whitis	Graduate Student

SD School of Mines

Xinhua Bai	PI, Professor
Doug Tiedt	Graduate Student

SDSTA

David Taylor	Project Engineer
Mark Hanhardt	Support Scientist

Texas A&M

James White †	PI, Professor
Robert Webb	PI, Professor
Rachel Mannino	Graduate Student
Paul Terman	Graduate Student

University at Albany, SUNY

Matthew Szydagis	PI, Professor
Jeremy Mock	Postdoc
Steven Young	Graduate Student

UC Davis

Mani Tripathi	PI, Professor
Britt Hollbrook	Senior Engineer
John Thmpson	Development Engineer
Dave Herner	Senior Machinist
Ray Gerhard	Electronics Engineer
Aaron Manalaysay	Postdoc
Scott Stephenson	Postdoc
Jacob Cutter	Graduate Student
James Morad	Graduate Student
Sergey Uvarov	Graduate Student

UC Santa Barbara

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

University College London

Chamkaur Ghag	PI, Lecturer
Sally Shaw	Graduate Student

University of Edinburgh

Alex Murphy	PI, Reader
Paolo Beltrame	Research Fellow
James Dobson	Postdoc
Tom Davison	Graduate Student
Maria Francesca Marzioni	Graduate Student

University of Maryland

Carter Hall	PI, Professor
Jon Balajthy	Graduate Student
Richard Knoche	Graduate Student

University of Rochester

Frank Wolfs	PI, Professor
Wojtek Skutski	Senior Scientist
Eryk Druszkiewicz	Graduate Student
Dev Ashish Khaitan	Graduate Student
Mongkol Moongweluwan	Graduate Student

University of South Dakota

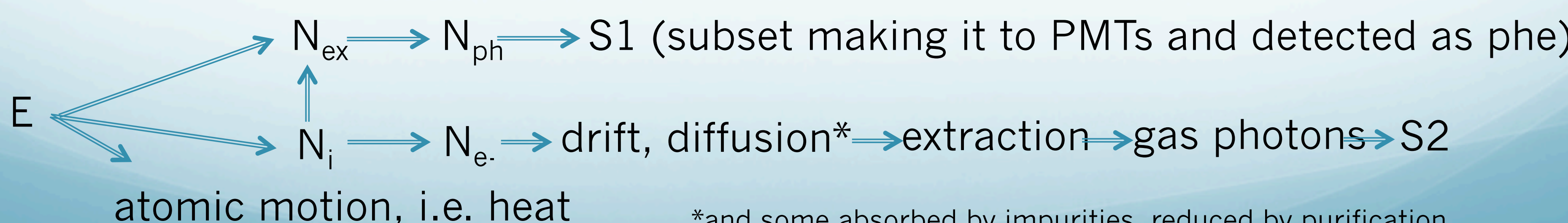
Dongming Mei	PI, Professor
Chao Zhang	Postdoc
Angela Chiller	Graduate Student
Chris Chiller	Graduate Student

Yale

Daniel McKinsey	PI, Professor
Ethan Bernard	Research Scientist
Markus Horn	Research Scientist
Blair Edwards	Postdoc
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Elizabeth Boulton	Graduate Student
Nicole Larsen	Graduate Student
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Lucie Tvrznikova	Graduate Student

Detector Response Mechanics

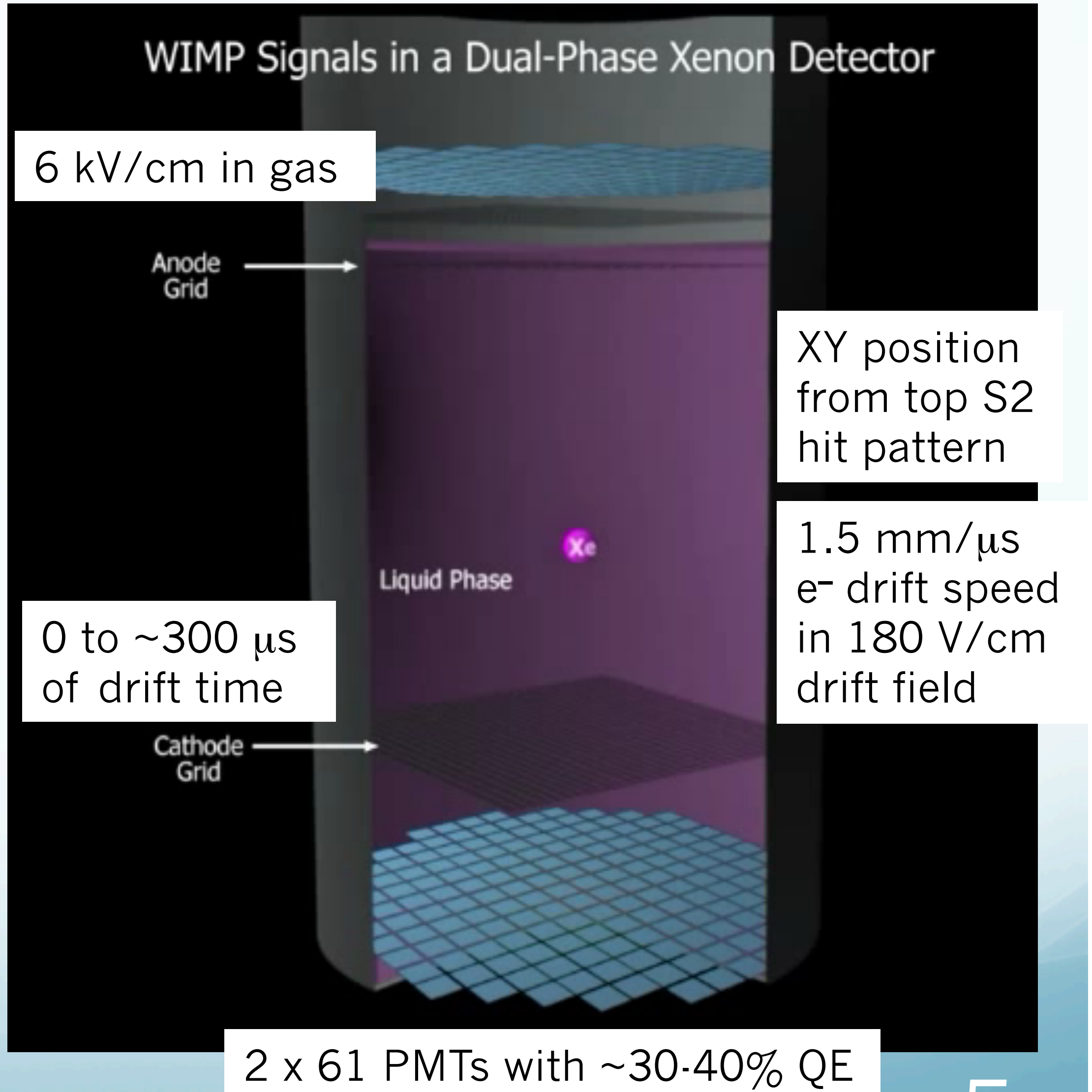
- Energy *E* is deposited into 3 channels: excitation, ionization, and heat
  - Heat is most prominent for nuclear recoil (NR), reducing the total number of measurable quanta with respect to electron recoil (ER)
- Excitation and recombination (electrons recaptured, into excited state) lead to the primary scintillation (S1)
- Escaping ionization electrons lead to the secondary scintillation (S2), adding to knowledge of energy



*and some absorbed by impurities, reduced by purification to point where electron mfp is much larger than drift length

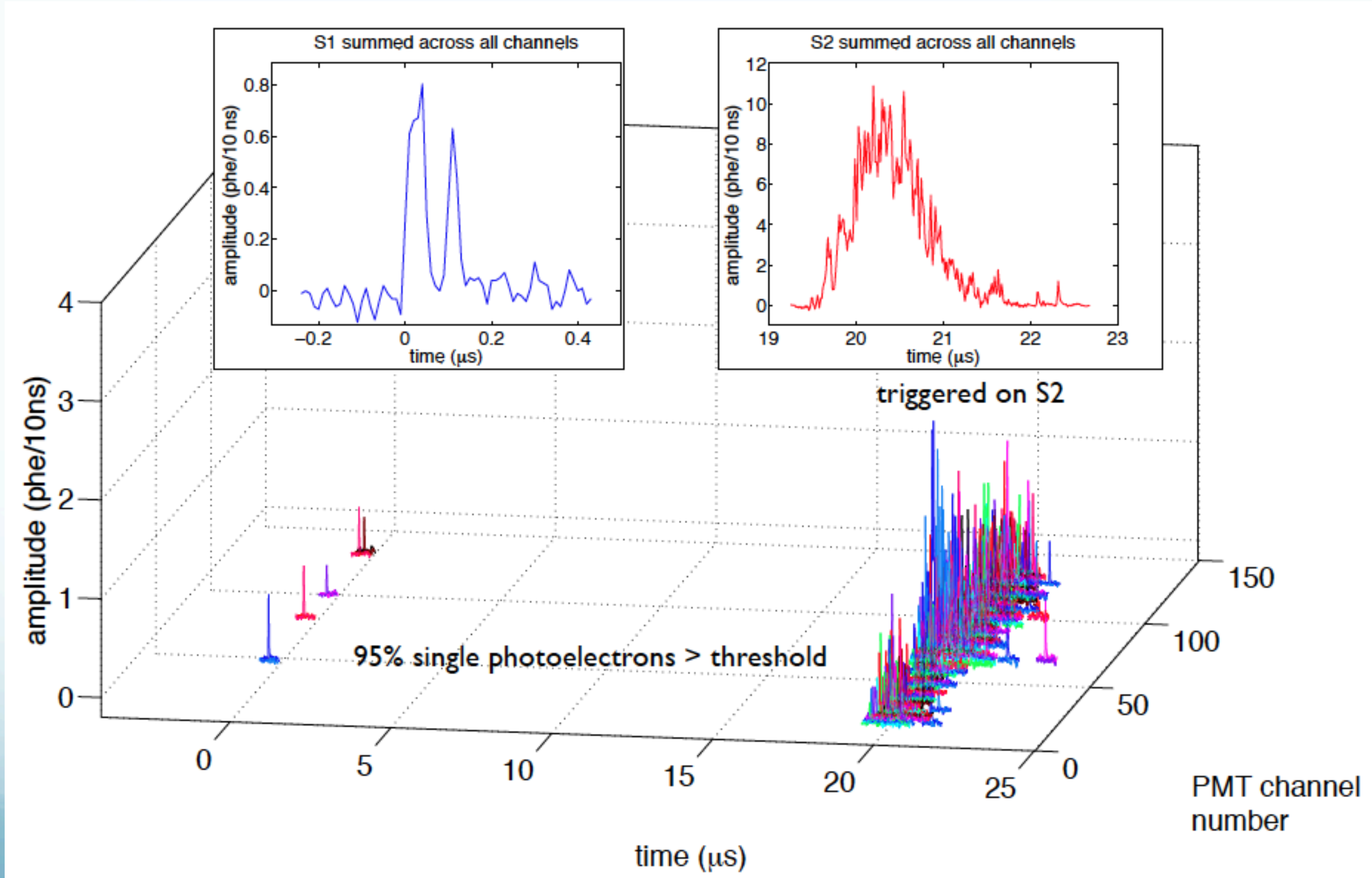
How LUX Works

- **L**arge **U**nderground **X**enon experiment
- Two-phase xenon TPC
- Discrimination of background: the ratio of S2 to S1 differs for NR compared to ER
- Fiducialization and multiple-scattering rejection powerful: LXe dense and high-Z, so good at self-shielding
- Looking for WIMPs to single-scatter NR...



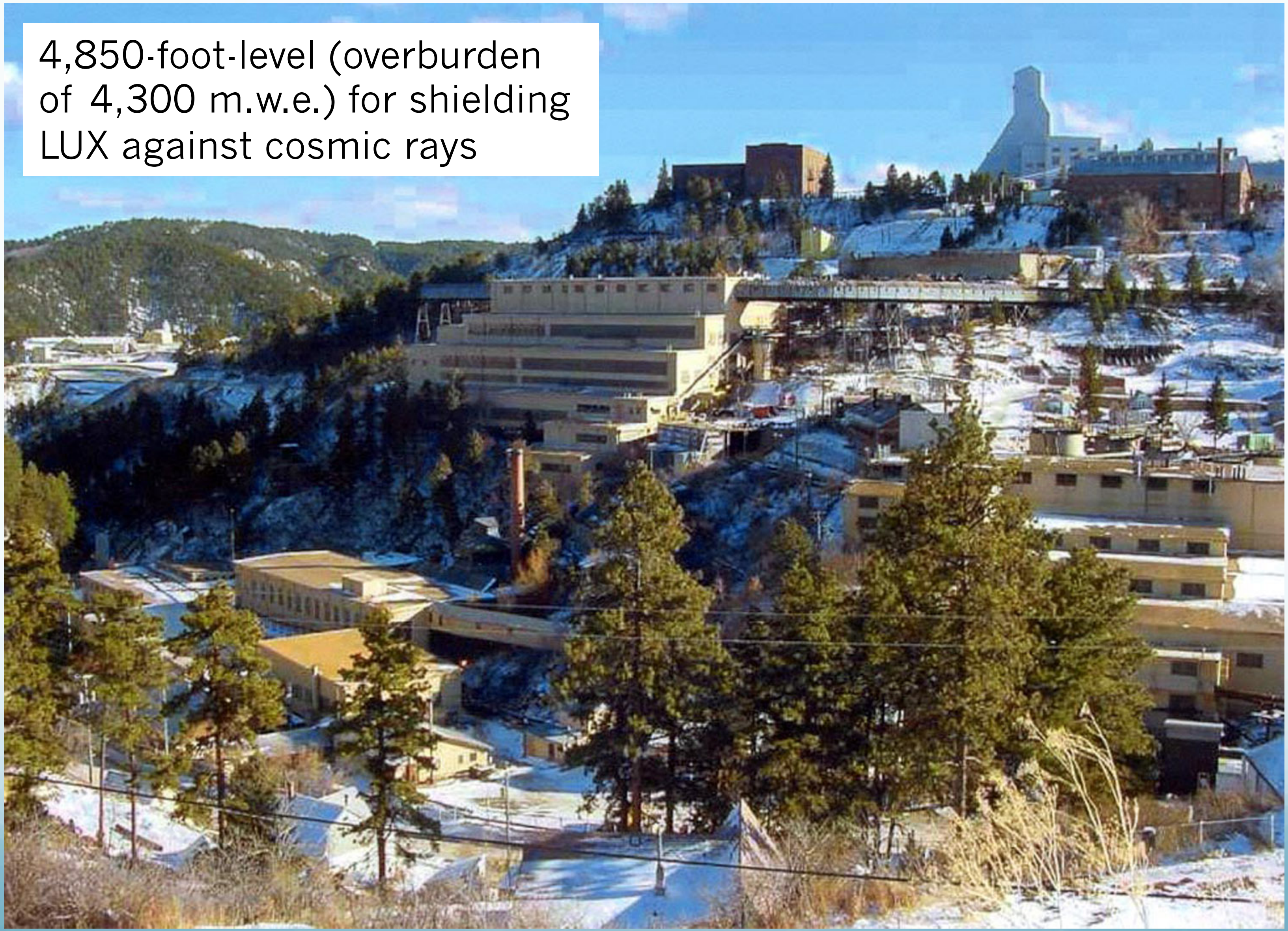
What a Typical Event is Like

1.5 keVee (combined energy reconstruction) ER event

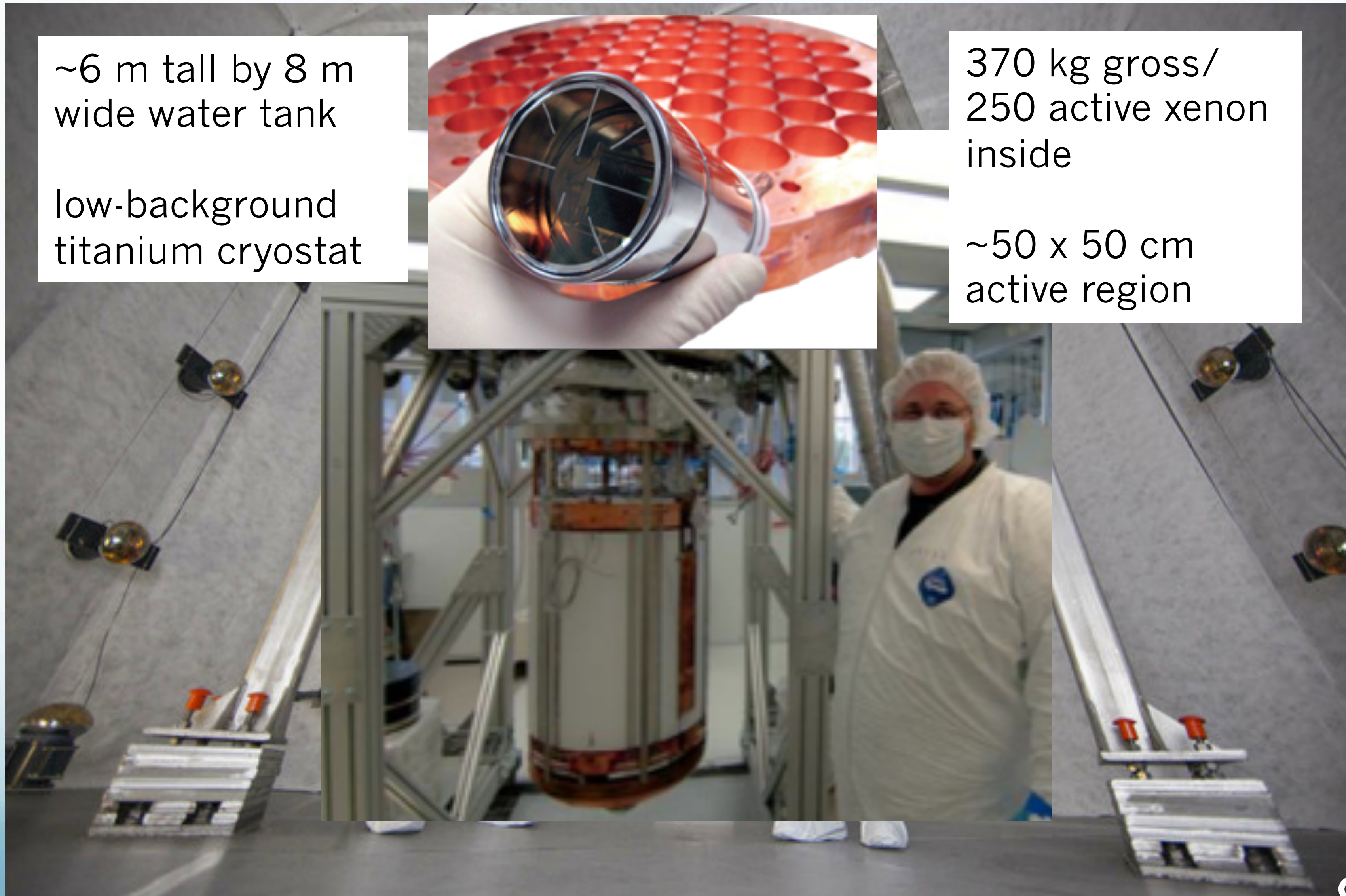


Deployed Not Too Far Away

4,850-foot-level (overburden of 4,300 m.w.e.) for shielding LUX against cosmic rays



Some Pics, Factoids



~6 m tall by 8 m wide water tank

low-background titanium cryostat

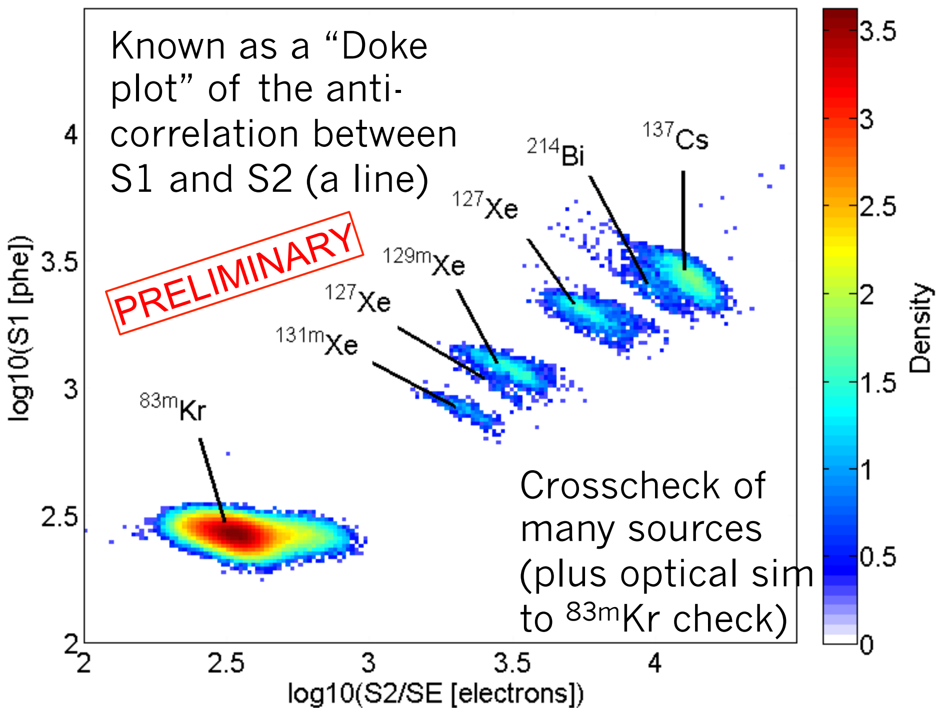
370 kg gross/ 250 active xenon inside

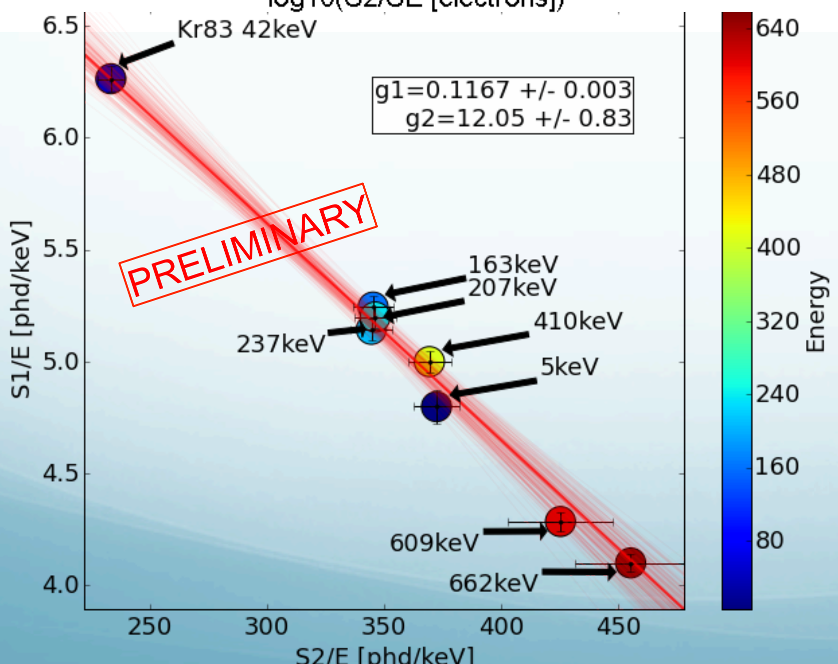
~50 x 50 cm active region

Event Energy Reconstruction

$$E = [N_{ph} + N_{e-}] * W = [(S1 / g_1) + (S2 / g_2)] * 13.7e\text{-}3 \text{ keV(ee)}$$

- g_1 is an efficiency that accounts for both geometric light collection and the QEs of the PMTs (product)
  - Defined for the center, with position variation, +/– ~20% between top and bot, mapped out with Kr83m
- g_2 accounts for electron extraction efficiency and number of photons detected per extracted electron
- Reconstructed energy not used directly in final dark matter analysis because after *absolute* calibrations of NR light and charge yields we can just simulate the S1 and S2 spectra for different WIMP masses
  - Though in this case we still need to know both g_1 & g_2
- NR has factor $L < 1$ accounting for fewer overall quanta (not just S1 photons) being generated due to NR being more effective making more NR (i.e. heat)





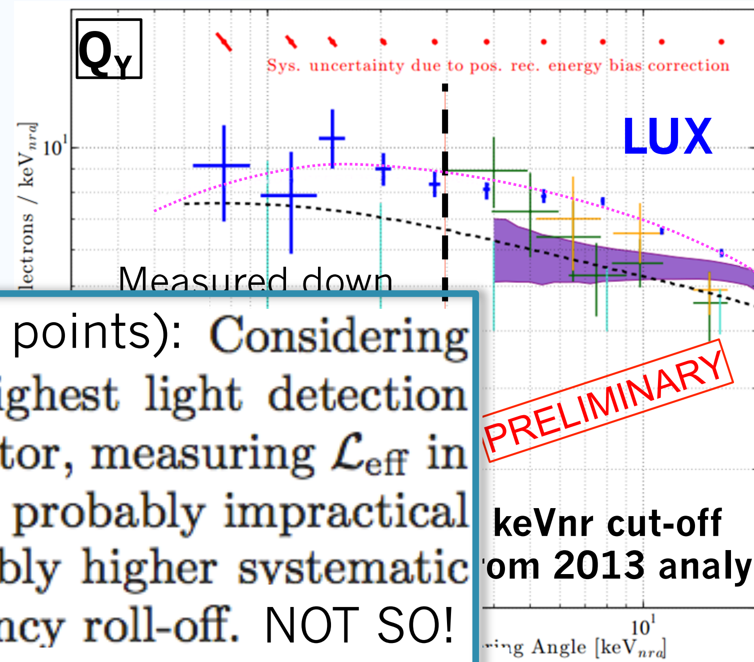
New Calculation of the g-Factors

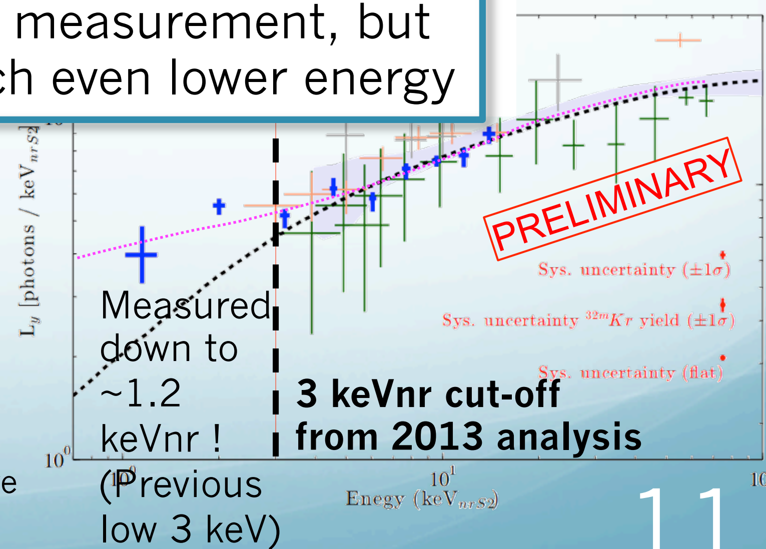
- 12% efficiency for the detection of a primary scintillation photon
  - Previously 14% quoted
- 49% extraction, coupled with 24.66 detected photons per single electron to make "g_2"
  - Triple checked: Doke plot, old data on alpha absolute charge yield and extraction efficiency
  - Previously said 65%, but product of absolute yield with it is what matters

NR Charge and Light Yields

- No longer relying on LUX AmBe, ^{252}Cf nor model from old data
  - No extrapolation from results of small, calibration chambers
    neede…
- Data fr…
  shown i…
  very pre…
  - Start… energ… For S1, S2 derived energy scale

Plante et al. 2011 (gold 0-field L_y points): Considering that this LXe detector has the highest light detection efficiencies achieved in a LXe detector, measuring $\mathcal{L}_{\text{eff}}$ in the near future at lower energies is probably impractical and will be subject to a considerably higher systematic uncertainty from the trigger efficiency roll-off. NOT SO! Plante made an excellent, crucial measurement, but we managed to find a way to reach even lower energy

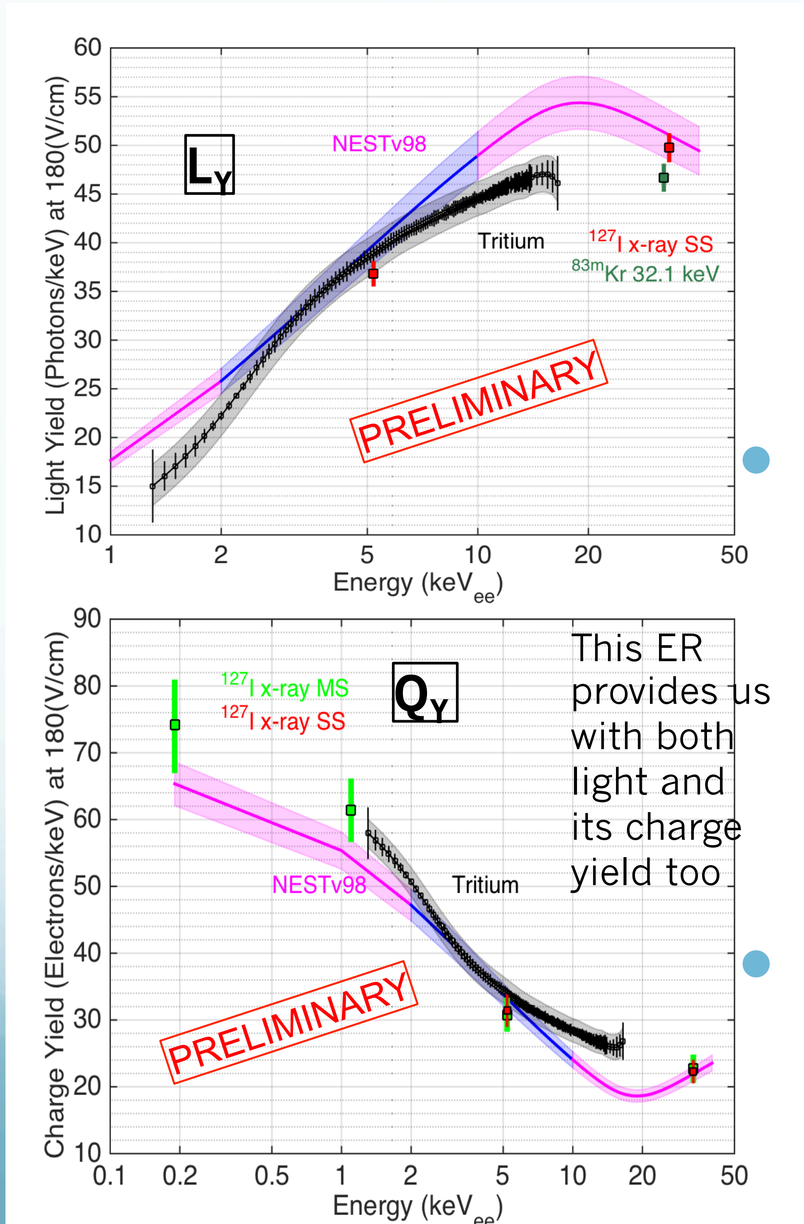




- Major effort to refine analysis
  - Optimization of event selection
  - Improved study of systematics
- New modeling

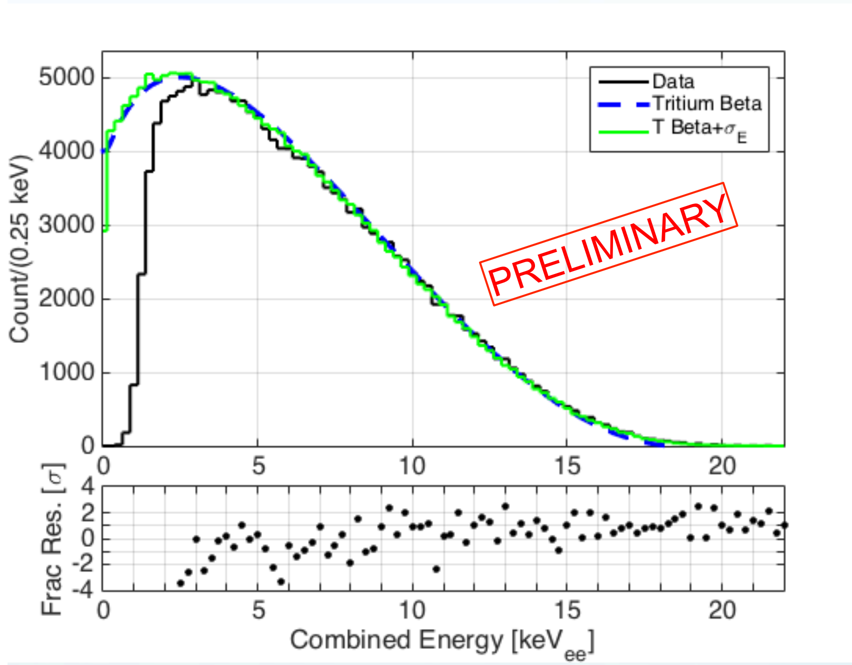
------ NEST 1.0 still too conservative
------ Modified NEST for re-analysis

Same Scrutiny for the ER Now



This ER provides us with both light and its charge yield too

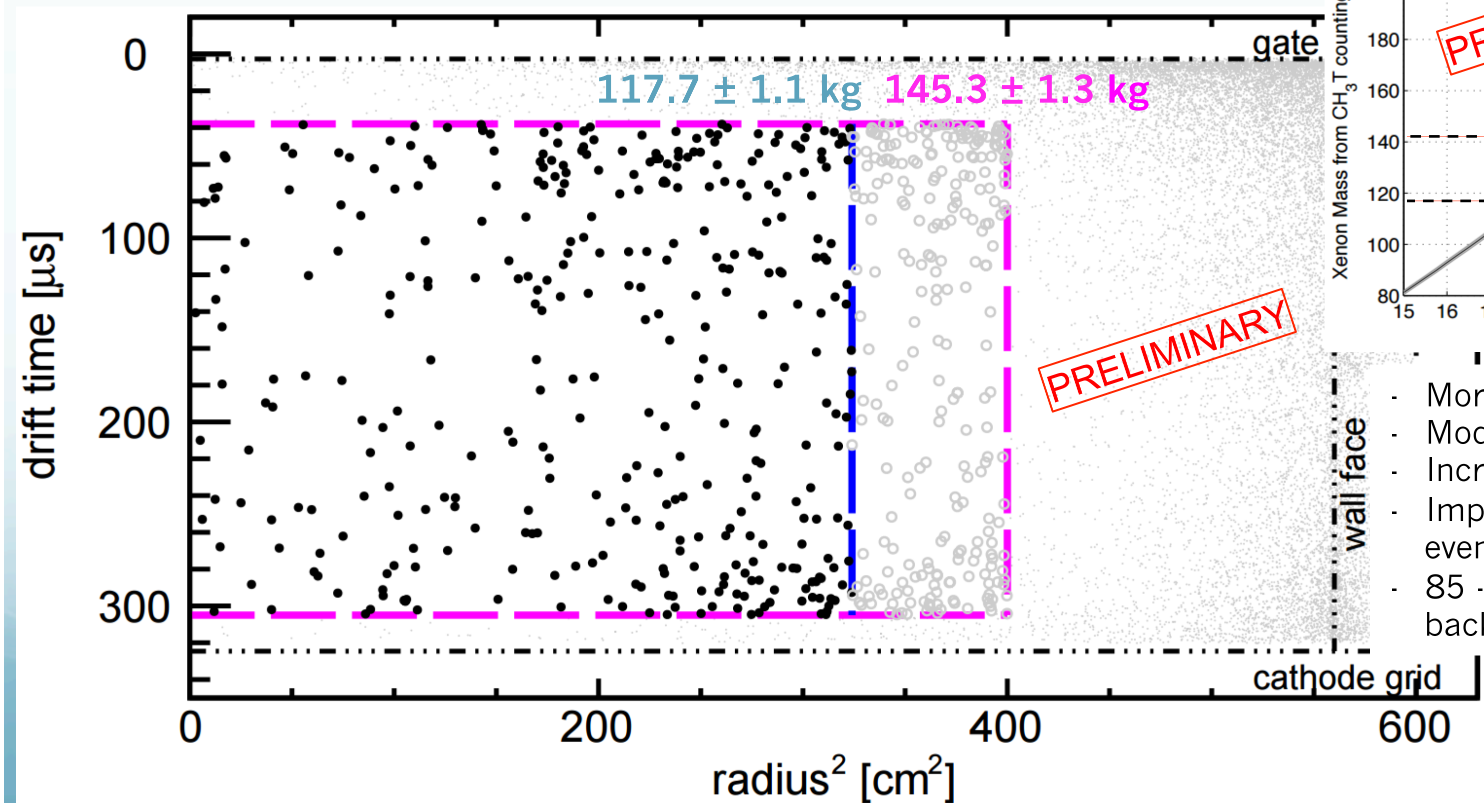
- Internally-deployed tritium source provides ER from 0 to 18 keVee
  - LUX measurably efficient at 1 keV!
  - Tells us what background looks … gly ER … out

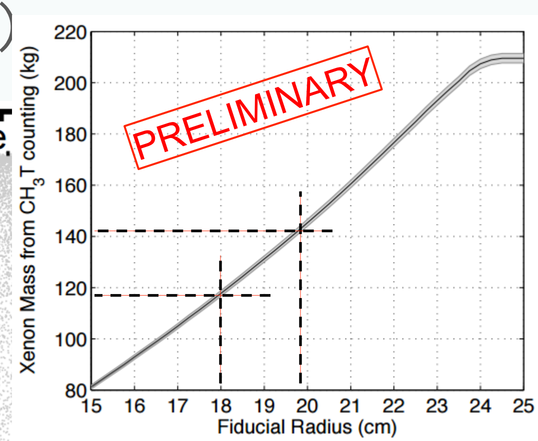


- … on in … ger … precise … for an NR … of S1
- Because uniformly distributed, used with ^{83m}Kr for good, accurate measure of the fiducial volume

Distribution of Backgrounds

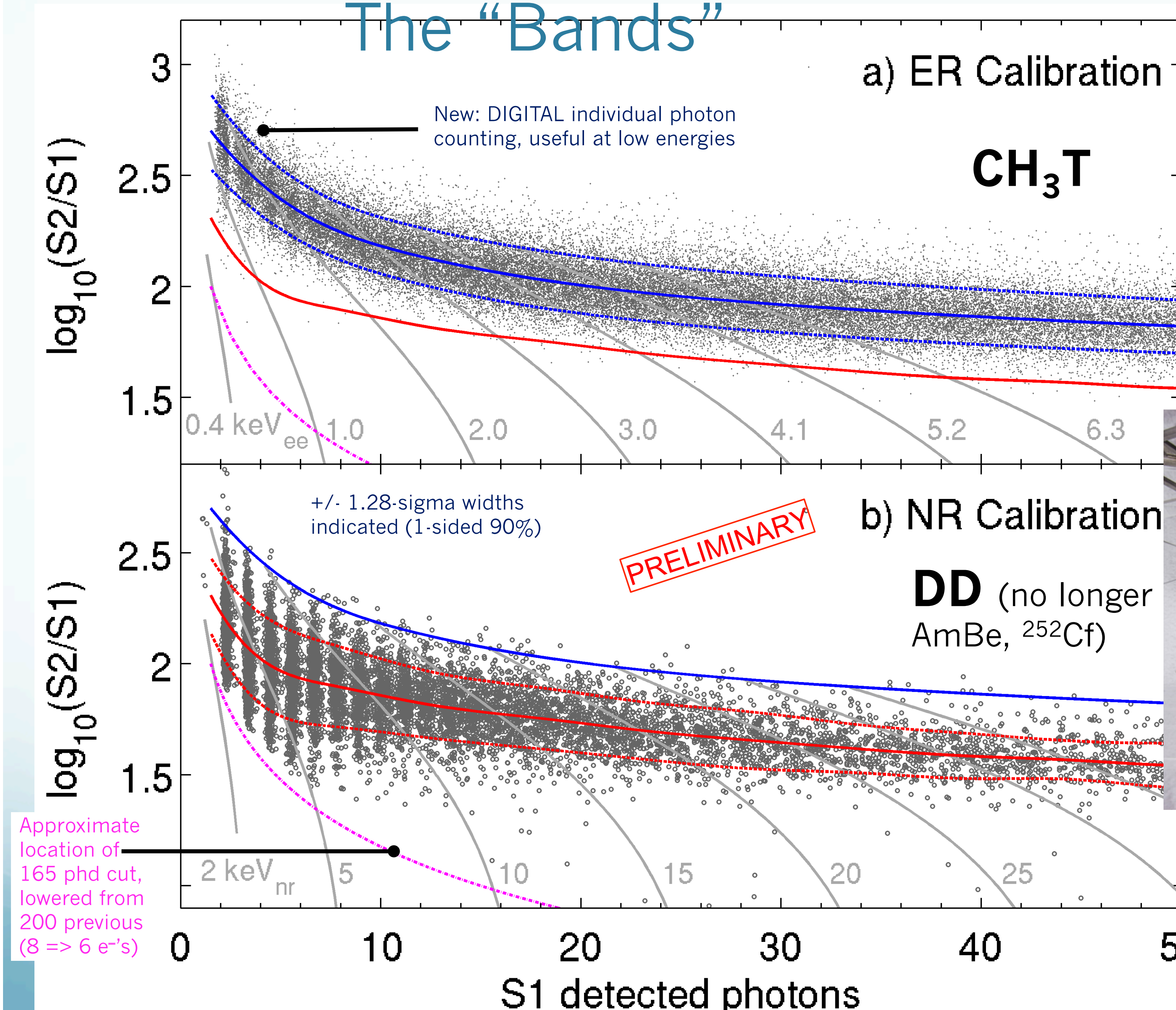
- 3.6 +/- 0.3 x 10^{-3} single scatters/(keV-kg-day) in low-energy regime
  - Measured 3.5 ppt Kr with RGA. PMT gamma-rays = biggest background
  - Cosmogenics from surface run have decayed away (Xe131m, Xe129m)
- No ER v. NR discrimination here: PLR deals with whole distribution. Potential fiducial mass increase (118 kg, 2013)

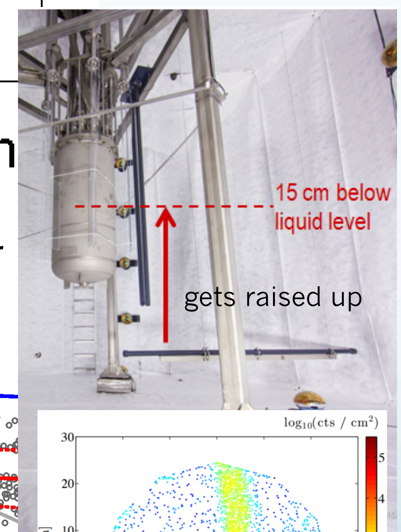


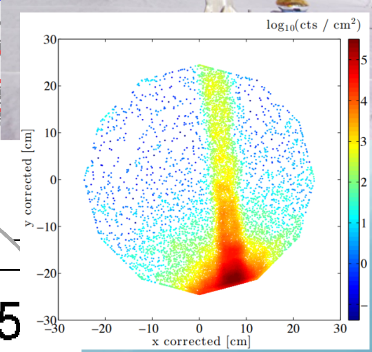


- More systematic sideband use
- Model of wall events: α's, ^{206}Pb
- Increased granularity in sources
- Improved rejection of noisy events ("bad area")
- 85 -> 95 live-days of background data included now

The “Bands”

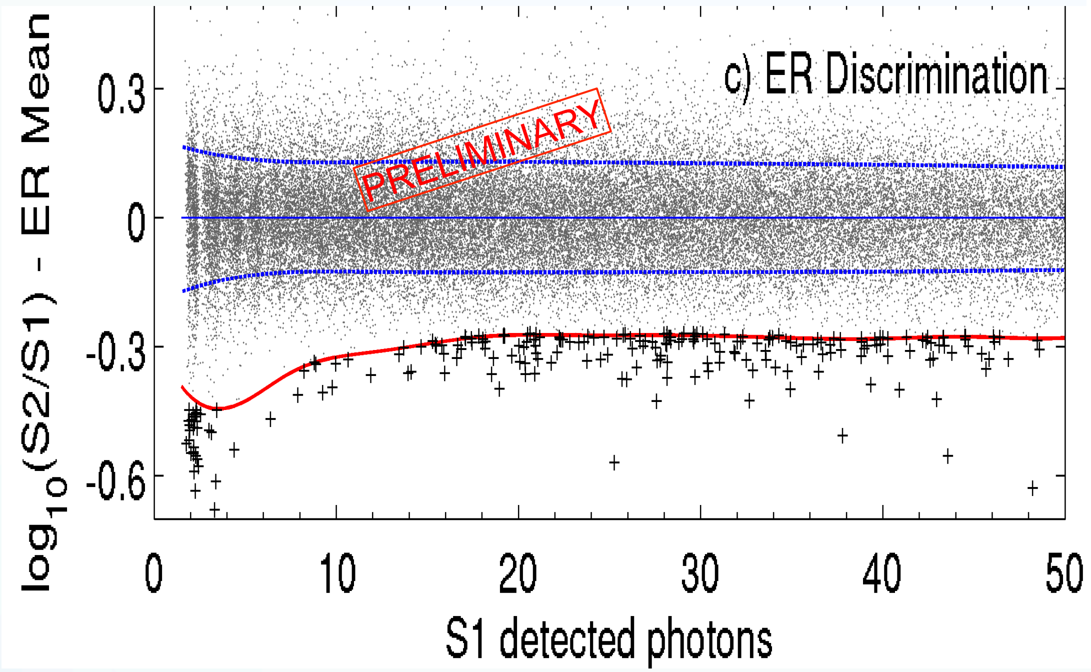


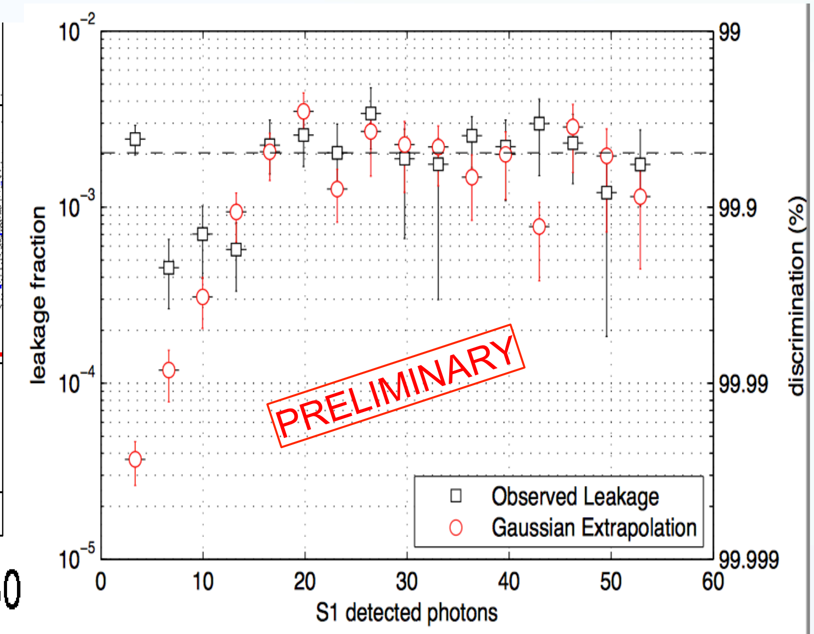




S1 and S2 are both position-corrected using Kr

ER Leakage into NR Band



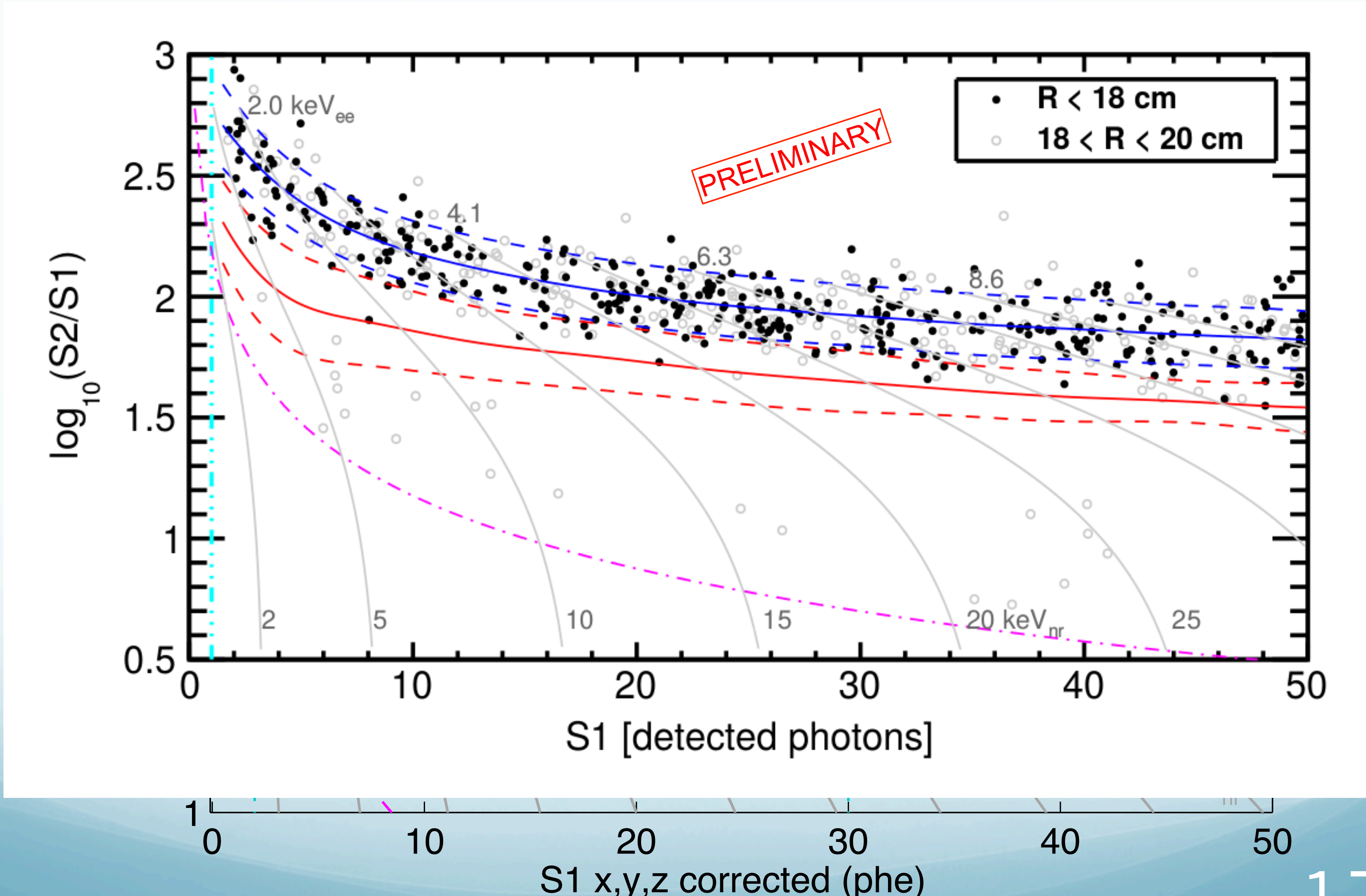


- 99.8 +/- 0.0003 (stat) +/- 0.01 (sys) % average discrimination (S1<50) accounting for all non-Gaussianities. Counting all ER events below continuous fit to NR band centroid (Gaussian) in discrete bins
- S1 photon detection efficiency as important as field for leakage
- Not used directly in our limit calculation, which is a PLR (Profile Likelihood Ratio) not cut-and-count, but illustrative and allows for comparison of the LUX separation to other / past experiments

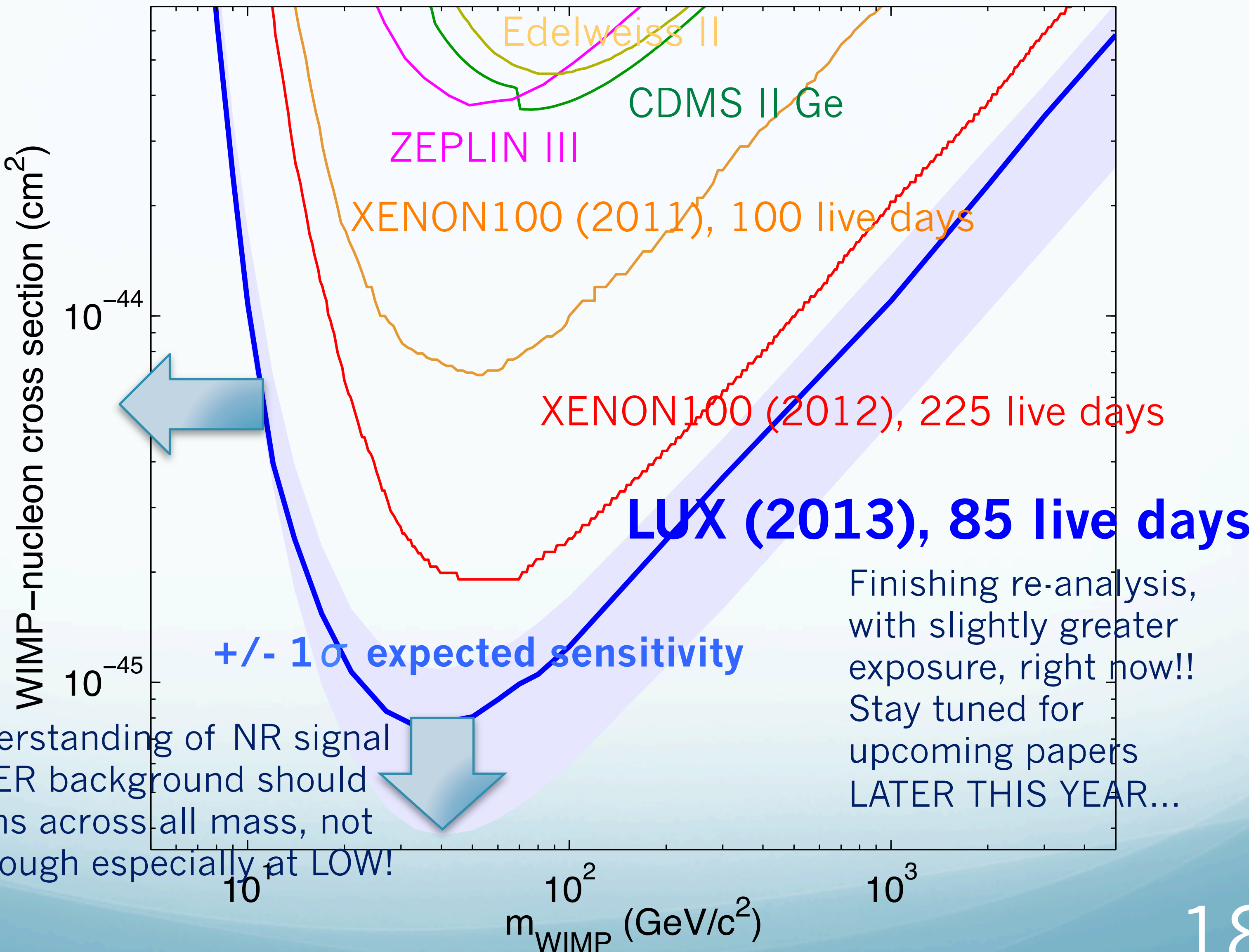
What Else Was Improved?

- Pulse finding algorithms, XY position reconstruction, baseline subtraction, definition of 1 detected photon
  - Including the aforementioned spike counting, which allows us to "beat" the ~35% resolution of single phe
  - "Thinner" ER band width; less chance to look like NR
- Taking non-uniformity of drift field into account (~10 V/cm difference between top and bot; higher at top)
  - When calculating e^- absorption length for S2 correction
  - When determining the e^- drift speed and event depth
- Additional nuisance parameters in PLR calculation
  - For instance g_2, which adjusts the effective charge yield, thus band means and energy threshold in S2 channel
- Lower threshold: now using 2 photons in different PMTs very simply instead of 2 phe minimum area
  - The previous cut would discount events that genuinely were 2 S1 photons, but fluctuated down in pulse area

Updated WIMP Search Result



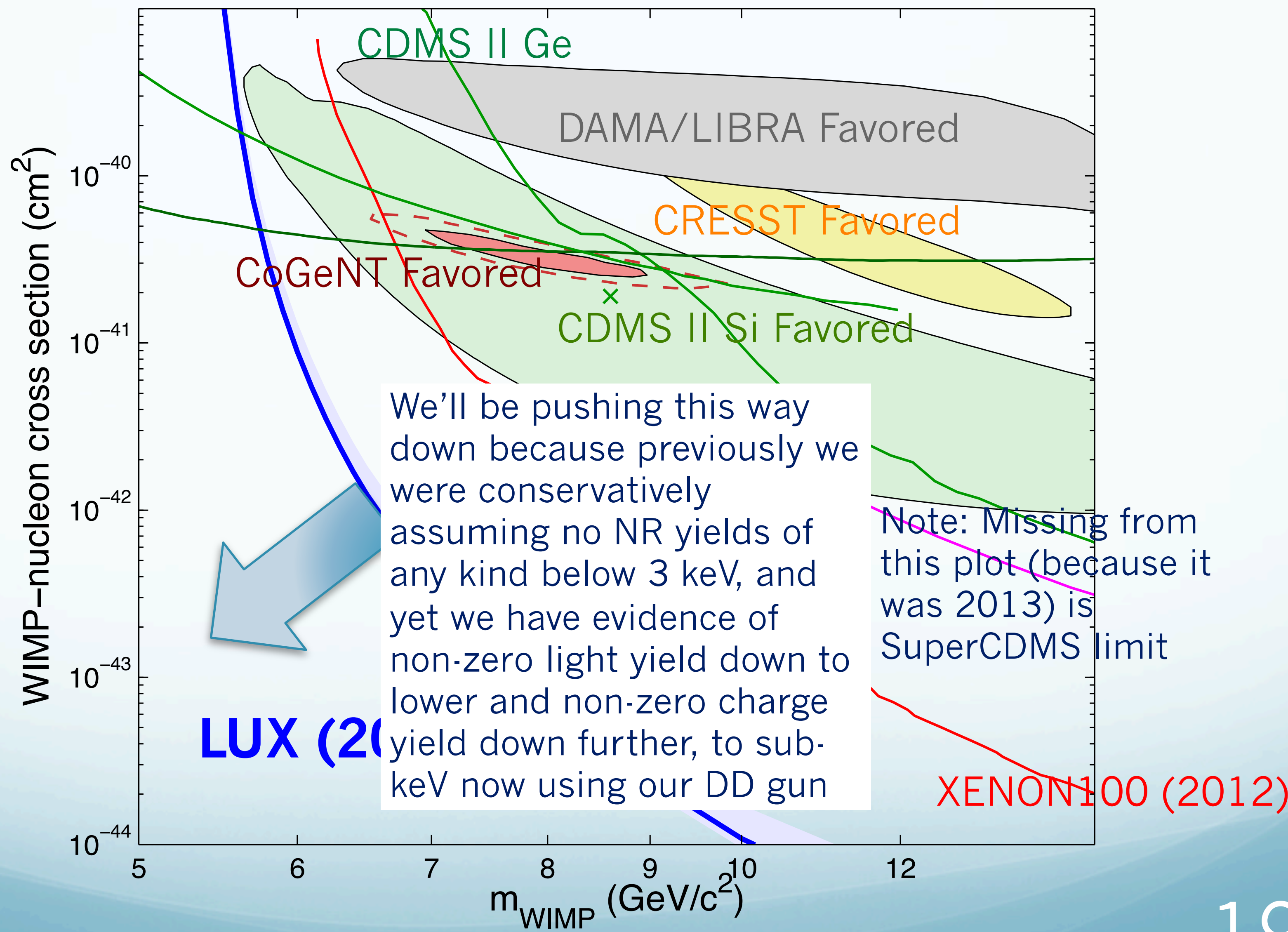
WIMP Dark Matter Limit



Finishing re-analysis, with slightly greater exposure, right now!! Stay tuned for upcoming papers LATER THIS YEAR…

Better understanding of NR signal as well as ER background should enable gains across all mass, not just low, though especially at LOW!

Our Low-Mass Sensitivity

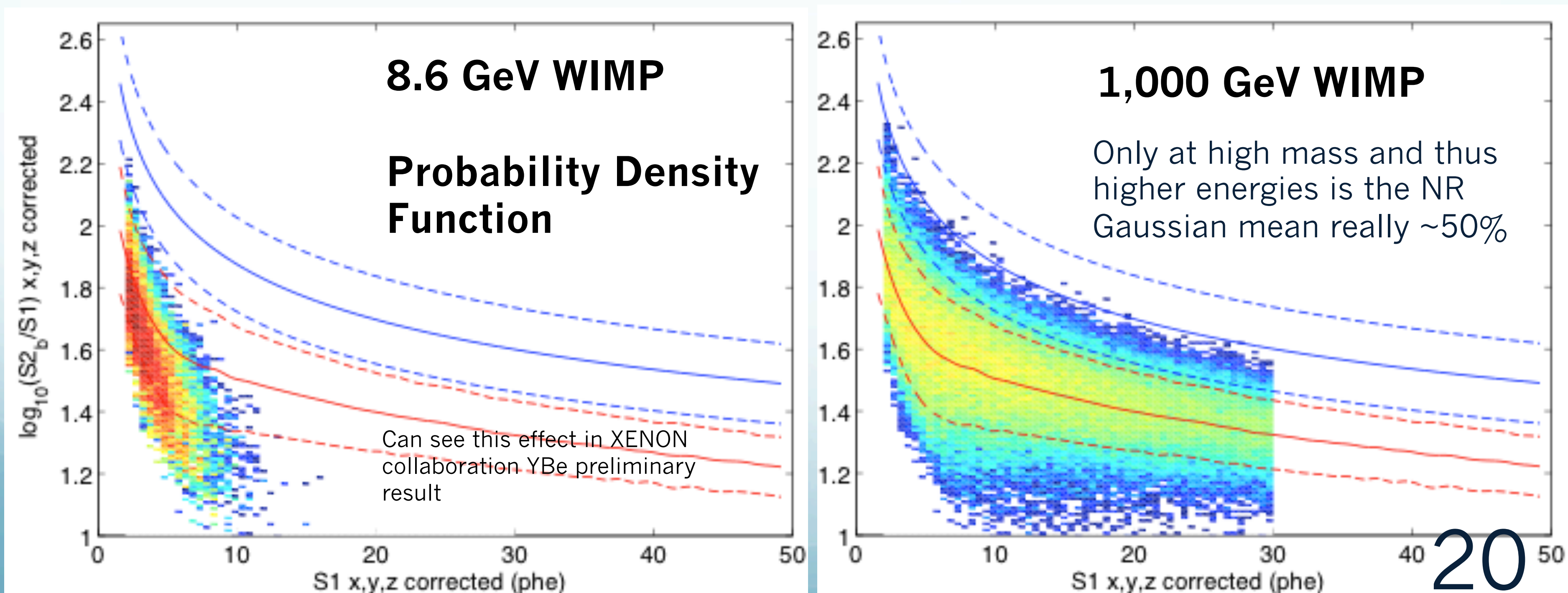


We'll be pushing this way down because previously we were conservatively assuming no NR yields of any kind below 3 keV, and yet we have evidence of non-zero light yield down to lower and non-zero charge yield down further, to sub-keV now using our DD gun

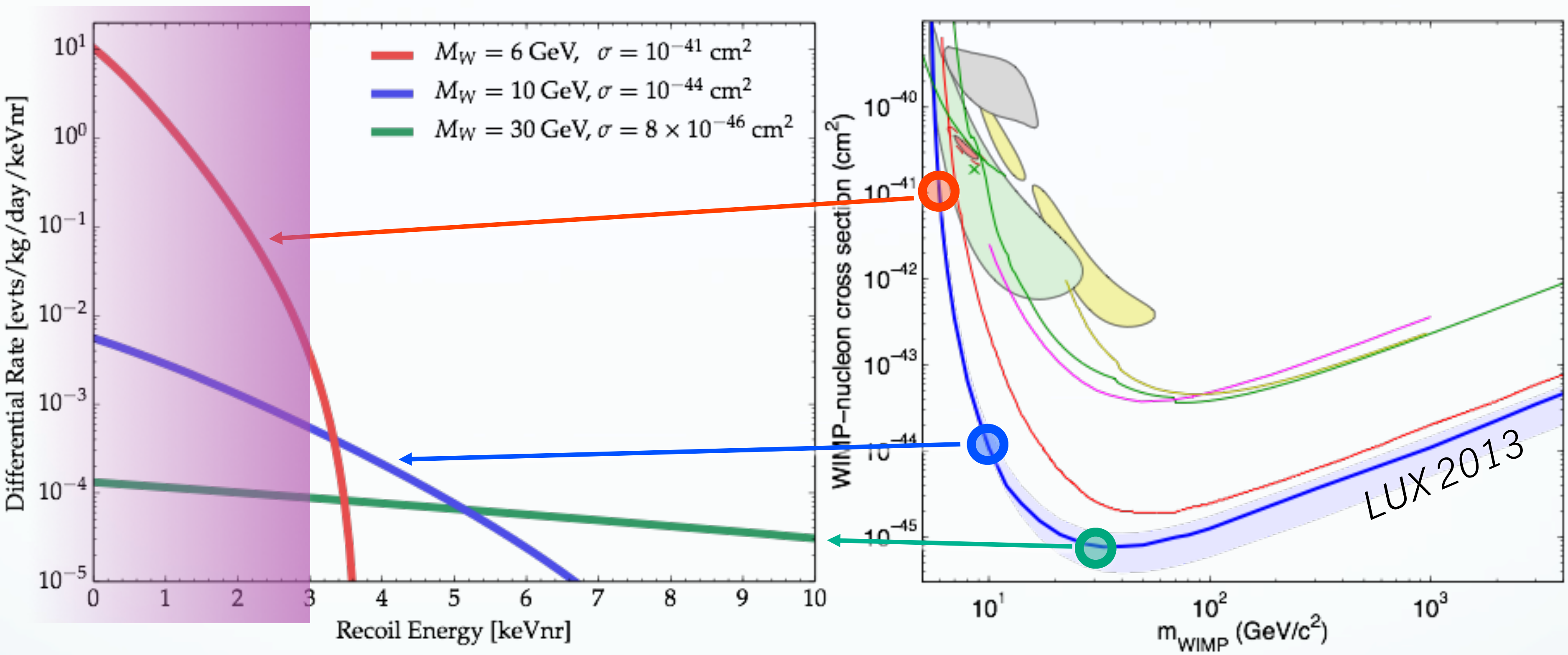
Note: Missing from this plot (because it was 2013) is SuperCDMS limit

Band at Different Masses

- Simulated signal model samples for different-mass WIMPs
- Lower-mass WIMPs not only produce less energetic recoils but appear lower in log(S2/S1) space: detections would be from upward fluctuations in S1, further away from ER
- Xe is more sensitive to light WIMPs than naïve assumption at least for the classic SI (spin-independent) interaction



Another Look at Light WIMPs



LUX 2013 upper limits assumed NO SENSITIVITY to recoils below 3 keVnr. This was not an *analysis* threshold, but an artificial one, a hard cut-off

Decreasing this response cutoff from 3 keV to 1 keV provides access to a factor of **1000* more signal** at M = 6 GeV/c^2, and higher masses affected

*Before folding in detection efficiencies for S1 and S2 pulse identification, pairing

A Bright Future for LUX

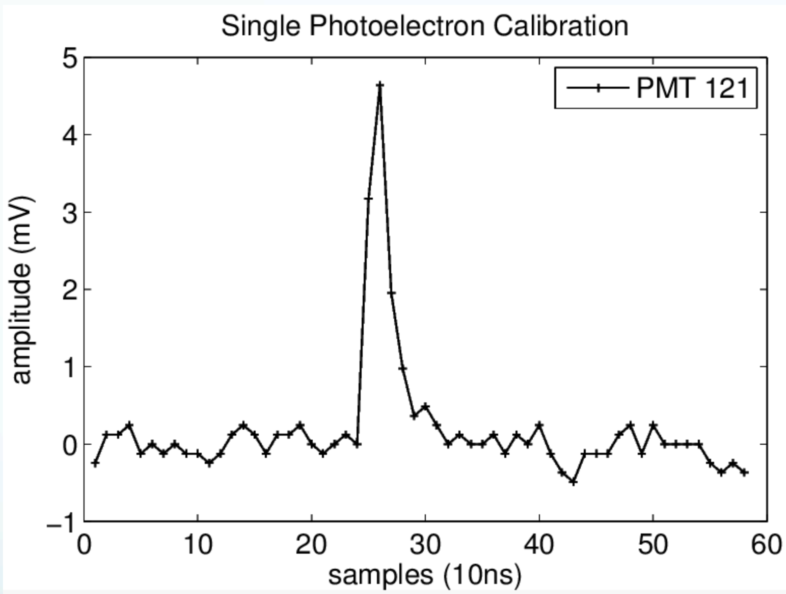
- Re-analysis of original exposure underway. Results soon
  - Dedicated DD and tritium papers also in preparation, et al.
- New analyses of the initial data set
  - Spin-dependent neutron and proton
  - Solar and galactic axion limits
  - S2-only limit for extreme-low-mass
  - Effective field theory, DEC, and more!!
- LUX has achieved the most kg-days of any xenon TPC, as well as the lowest energy threshold, the latter thanks to great light collection
- Anticipate continued use of great internal calibration sources (CH_3T, ^{83m}Kr) and DD neutron generator for same detector as WIMP search
- Working on next, 300-day run (blind, via salting), pushing sensitivity
- G2 WIMP experiment LUX-ZEPLIN coming (passed DOE CD-1 review)
  - Bigger (10 ton total) also better version of LUX and ZEPLIN LXeTPCs
  - Same location and infrastructure at SURF
- LUX still strictest limit on WIMP-nucleon spin-independent interaction cross-section across widest range of WIMP masses (A thought: NON-discovery is sometimes equally as valuable as discovery...)


SuperCDMS
LZ
The victors of the G2 hunger games...

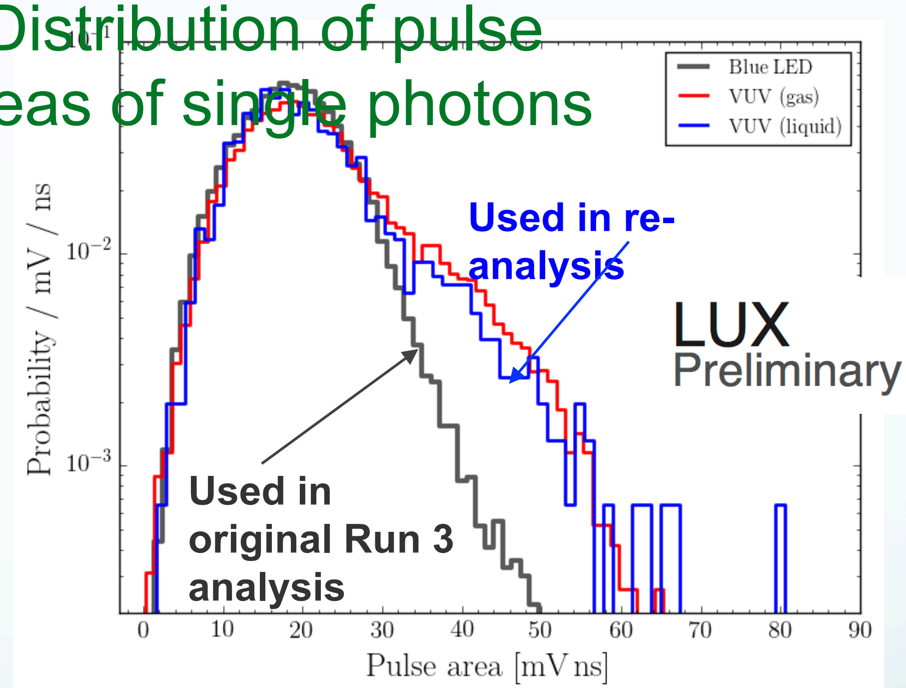
BACKUP MATERIAL

More on VUV Photons

Single Photo-electron



Distribution of pulse areas of single photons



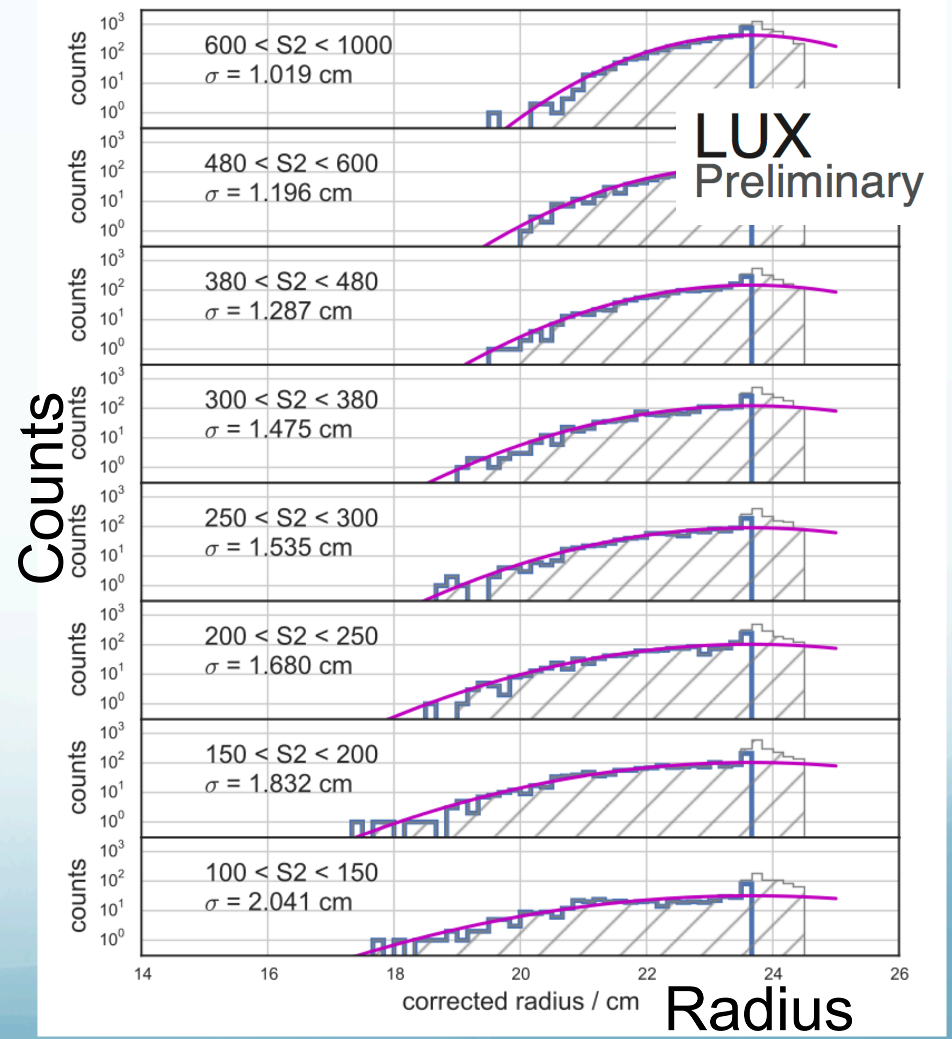
- Photon →PMT photocathode → single electron
- Except...
  - -Xe scintillation: 178 nm (6.97 eV in liquid). Calibration LEDs: 470 nm (2.6 eV)
- Two photo-electrons about 20% of the time in Xe
  - -phe (photoelectrons) → phd (detected photons)

Faham et al., http://arxiv.org/abs/1506.08748, has general (not just LUX) discussion of this quirky effect

Event Acceptance

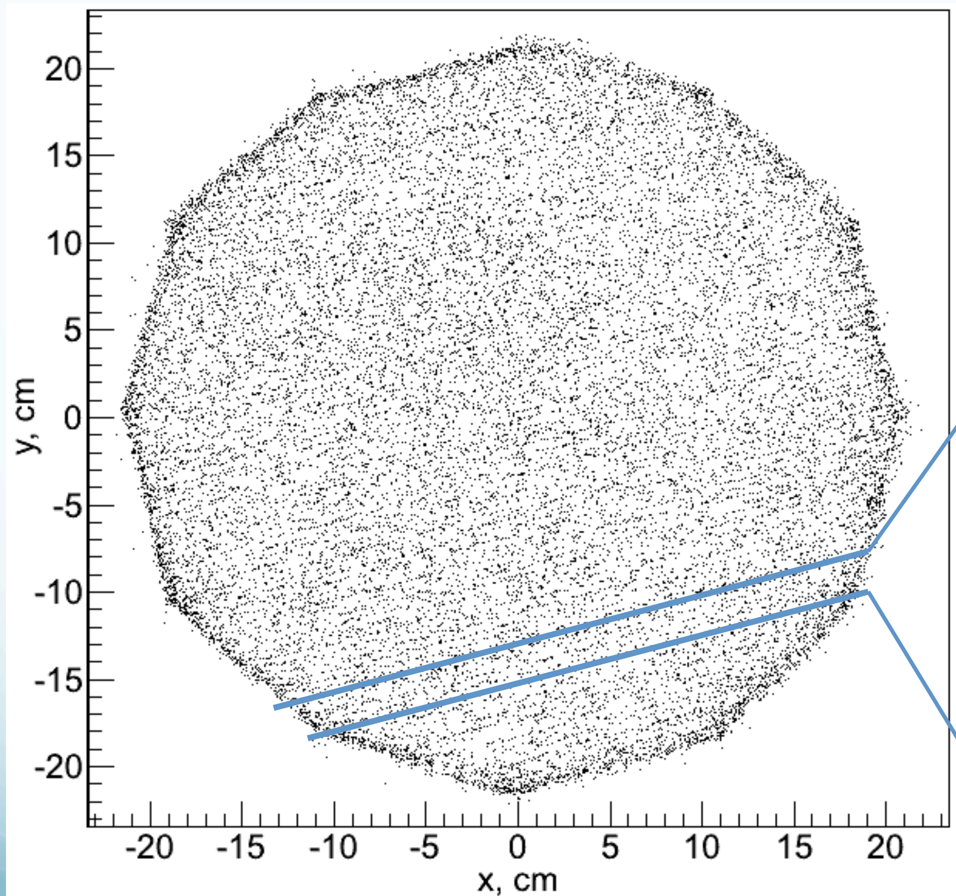
- 95 live days
- Larger fiducial mass (145 kg) thanks to the wall model
- S2 threshold of 165 phd
- Two-photon S1s accepted regardless of area
- 591 Events observed between S1 of 1 and 50 phd prior to the PLR

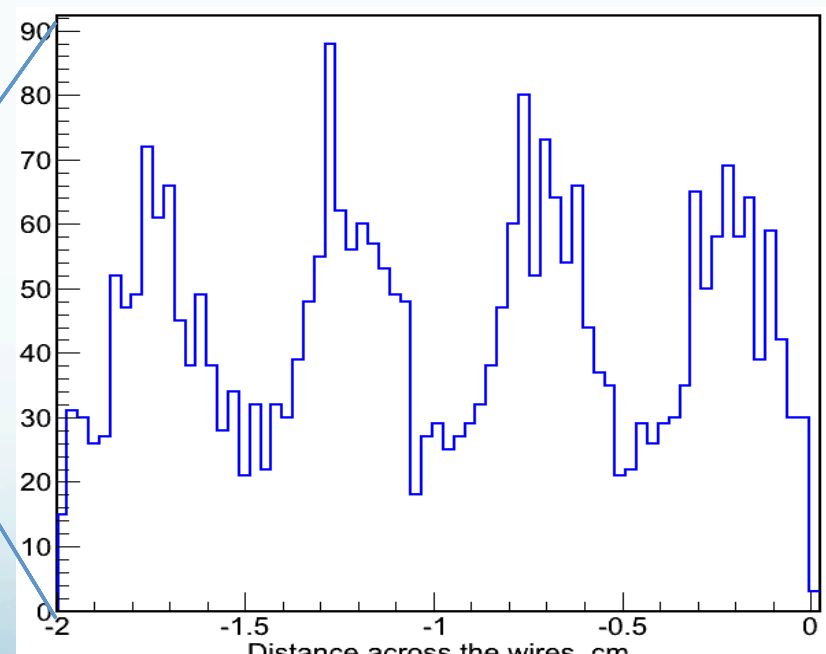
Penetration of Wall Events into Fiducial Volume

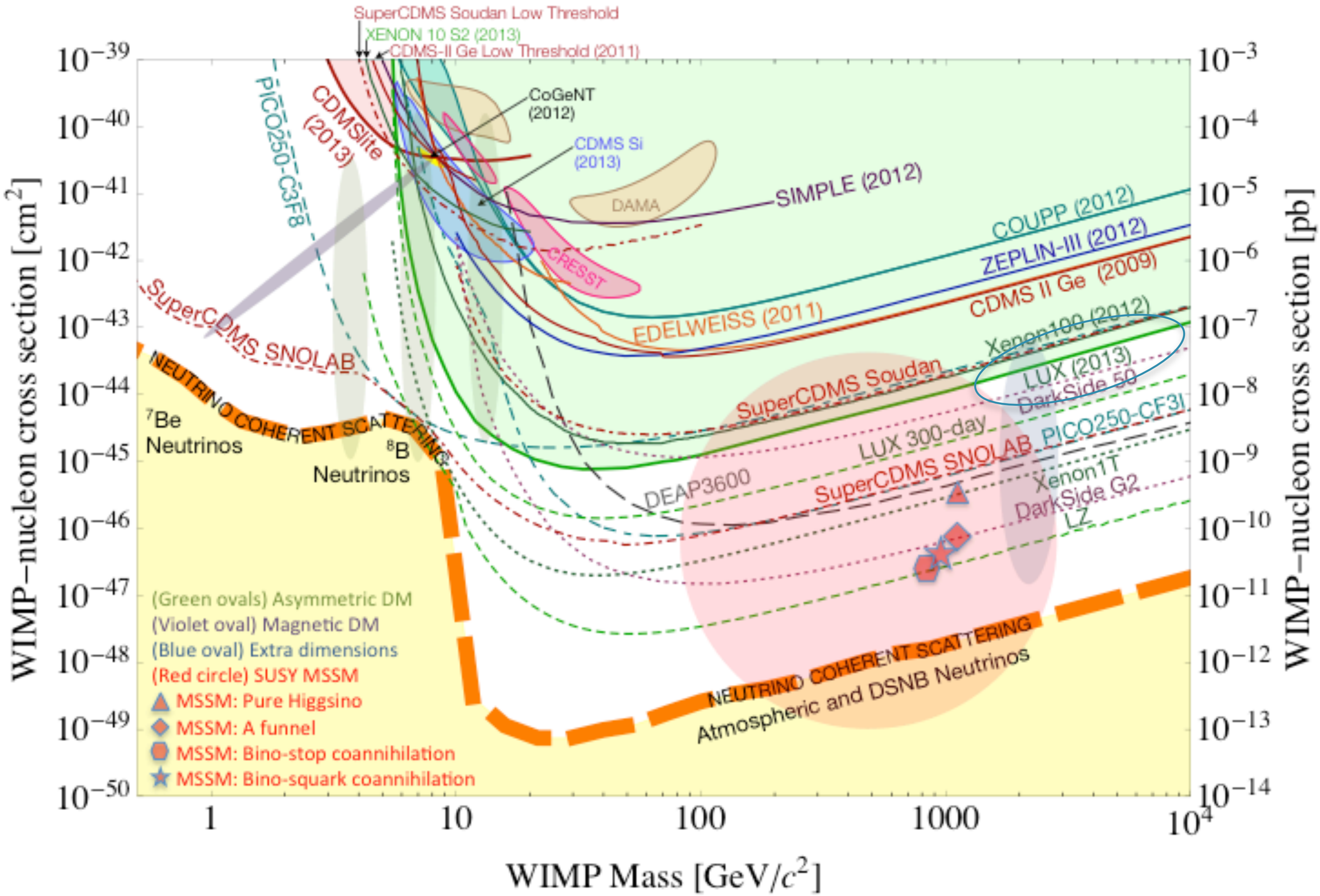


Position Reconstruction

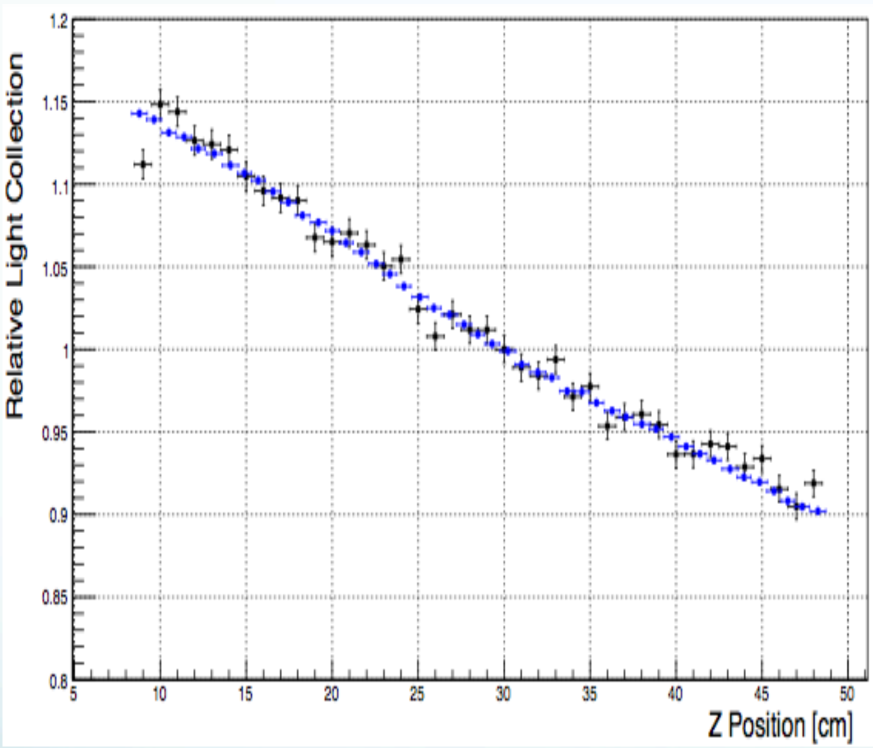
- Iterative approach used to optimize resolution (Mercury, developed by ZEPLIN)
- XY reconstruction of events near the anode grid resolves grid wires with 5 mm pitch

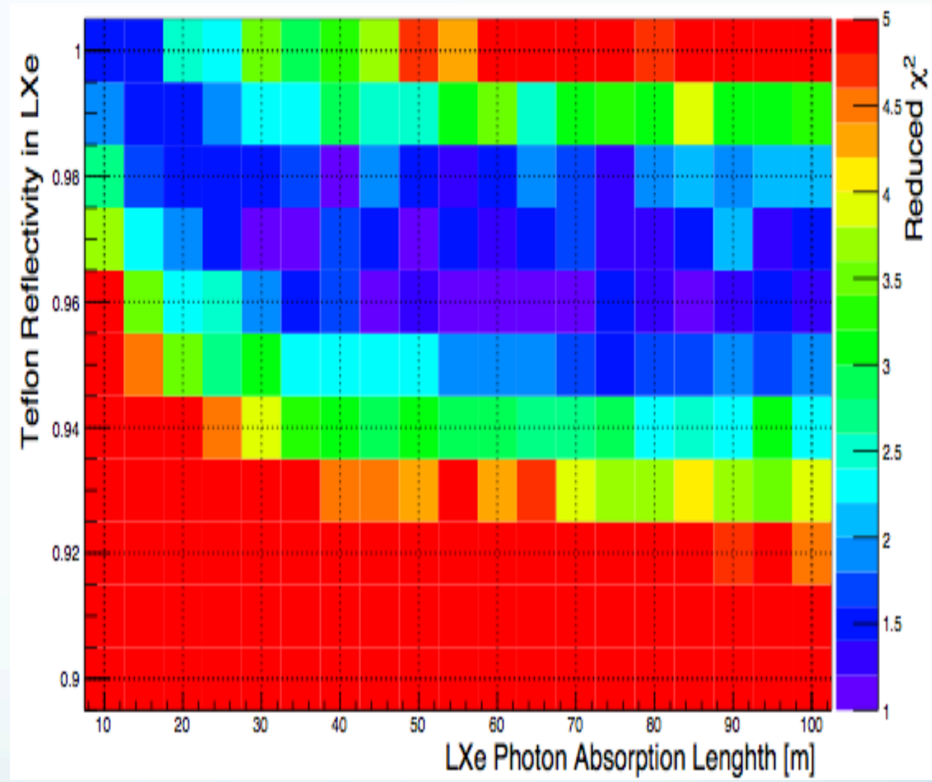





SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
CDMSlite (2013)
PICO250-C3F8
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
DarkSide 50
SuperCDMS SNOLAB
SuperCDMS Soudan
LUX 300-day
PICO250-CF3I
DEAP3600
Xenon1T
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c2]

Optical Model Verification





Resulting g_1 comes out as 0.119, only 2% off from Doke-plot measured value!

Example of CH_3T Removal