Updated dark matter results from the 2013 LUX data

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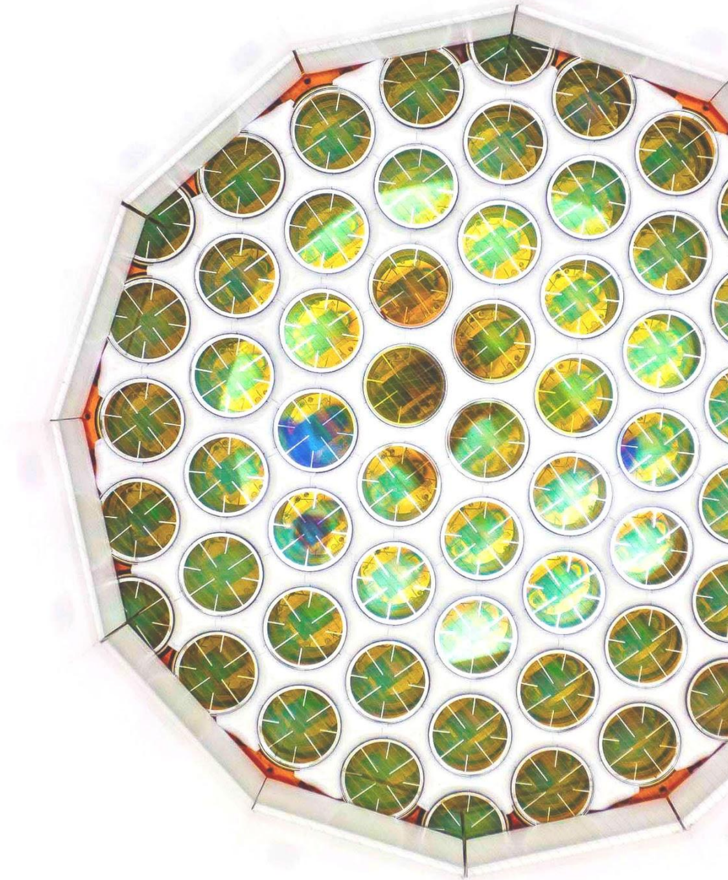
Alastair Currie (Imperial College)

2016-05-03



Imperial College London

LUX

LZ

Contents

- Principles of LUX-type dark-matter detectors
- Updates from the first result:
    - event measurement
    - background calibration
    - signal calibration
- Search data, results and implications

Direct dark matter search with LUX

Xe direct detection, in round numbers

- What's kinematically accessible with Xe?

  $m_{min}[\text{GeV}] \approx 3\cdot(E_{min}[\text{keV}])^{1/2}$

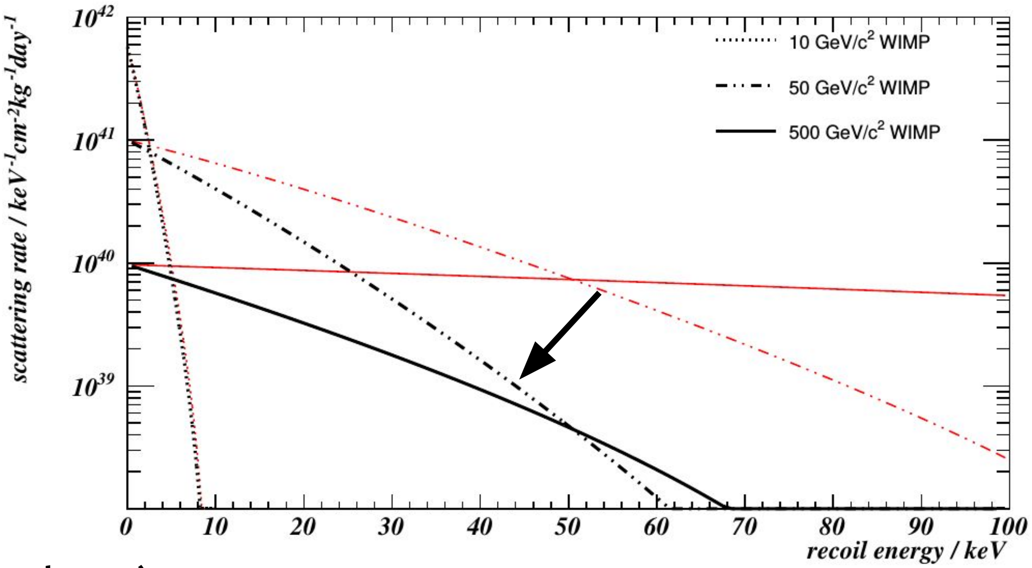
- Recoil spectrum ~ $\exp(-E/rE_0)$

  DM mass m_D ; $v_0^{\,2} \approx 5\text{e-}7\,c^2$

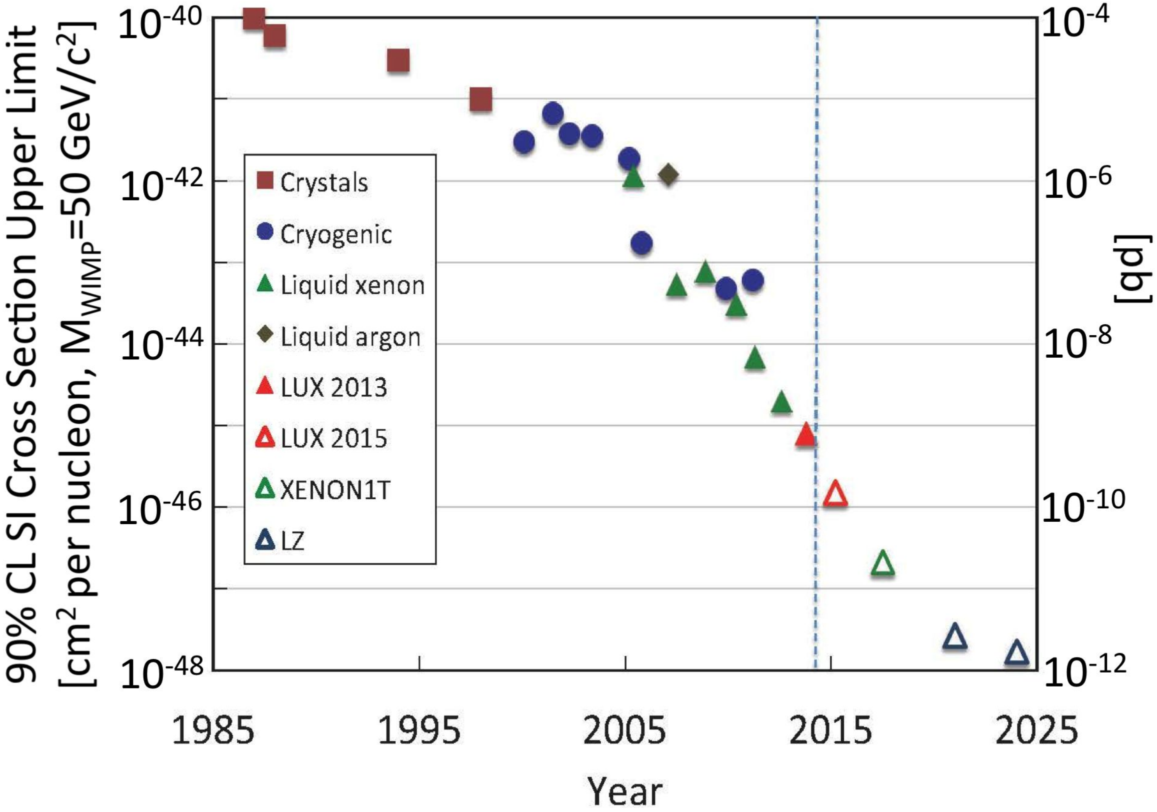
  $r = 4\cdot\mu_{XeD}/(m_{Xe}+m_D)$; $E_0 = ½m_D\cdot v_0^{\,2}$

- Order-of-magnitude rate:

  10^{41} per keV.kg.day.cm^2 (SI WIMP-nucleon)



Progress vs time, 50 GeV WIMP mass

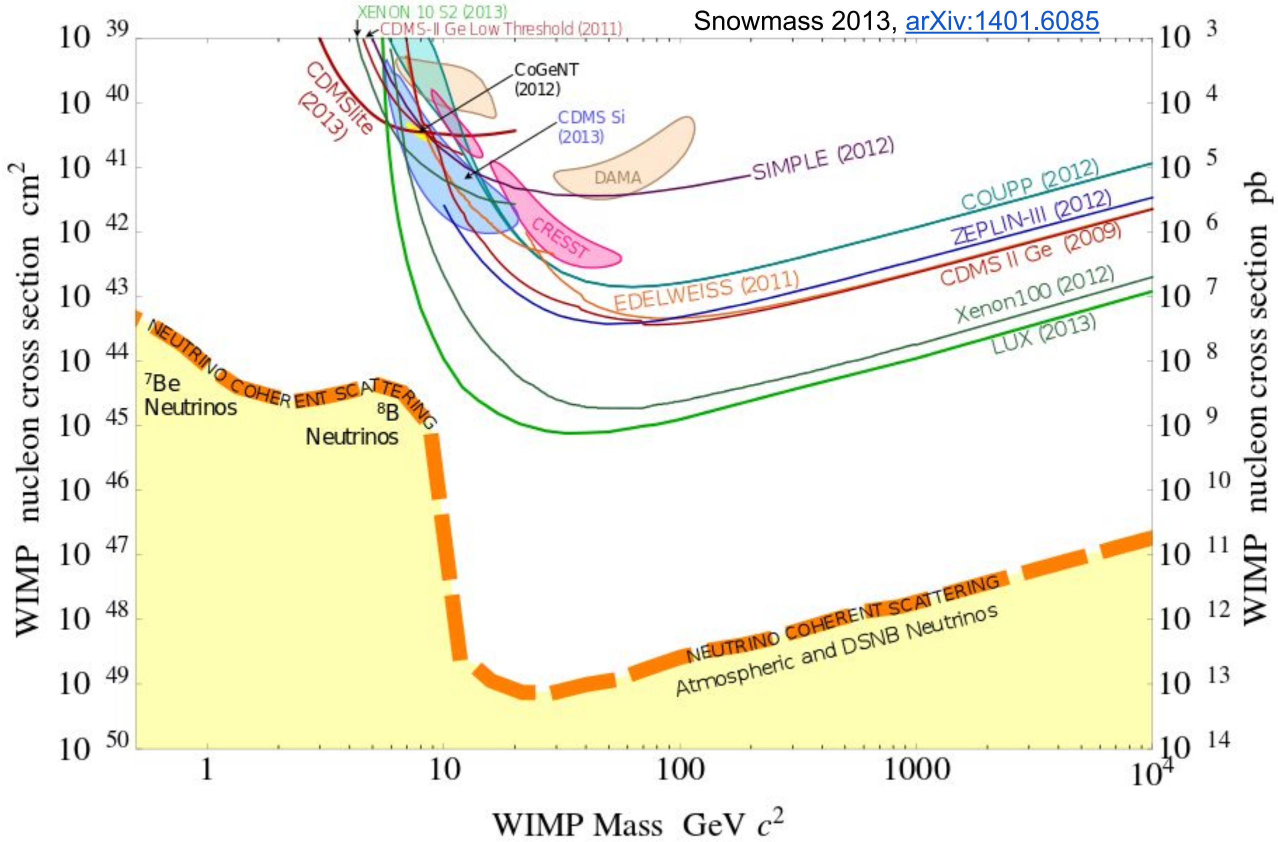


The LUX experiment

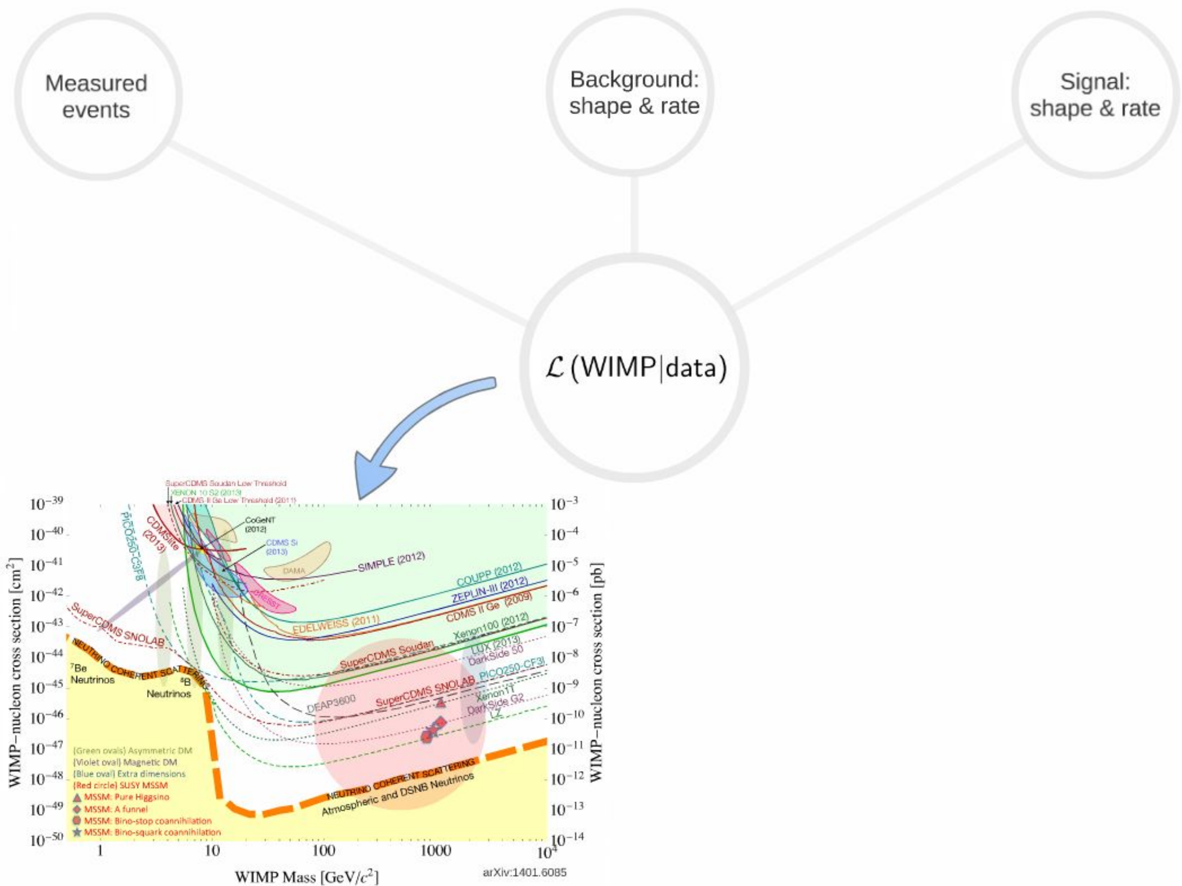
- Large Underground Xenon
- 250 kg active mass
- Few keV threshold with good BG rejection
- Few 10^{-3} counts per keV.kg.day in FV
- Deployed 1.5 km UG (4300 mwe) in 2012

Direct WIMP search big picture (2013)

Snowmass 2013, [arXiv:1401.6085](https://arxiv.org/abs/1401.6085)



High-level likelihood



LUX, a two-phase Xe TPC

- Energy loss to atomic electrons (also thermal motion, not measured)
- S1 (scintillation) and S2 (ionisation)
- Single detected quanta are obvious
- Event variables are light, charge and 3D position

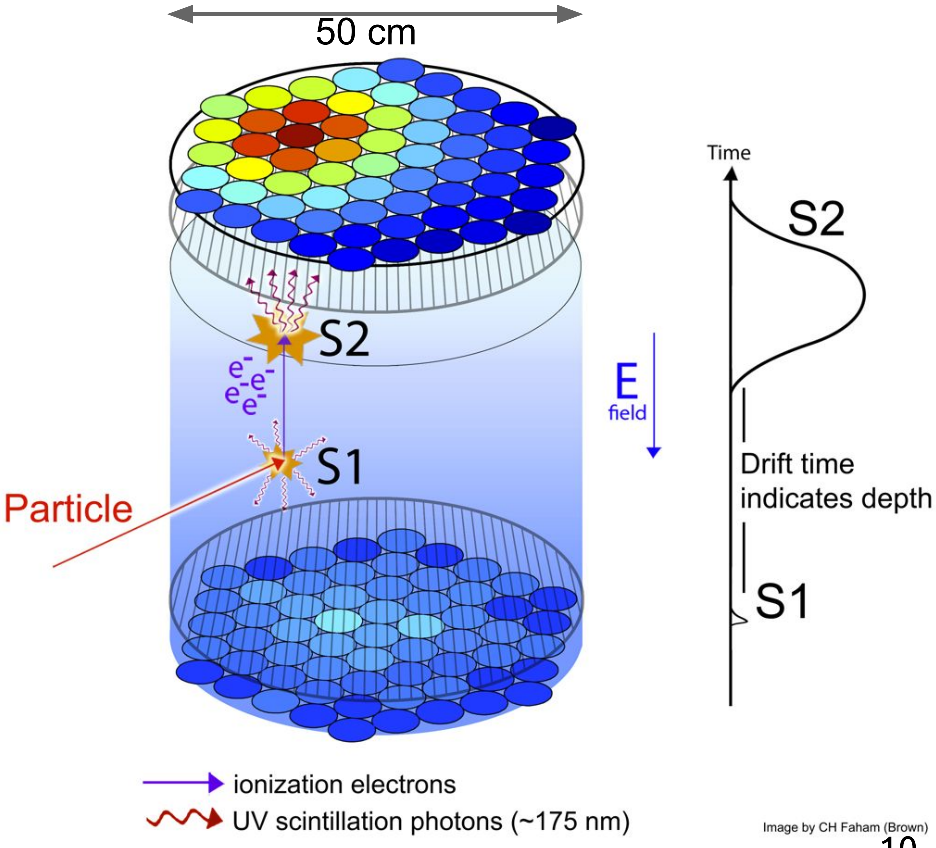
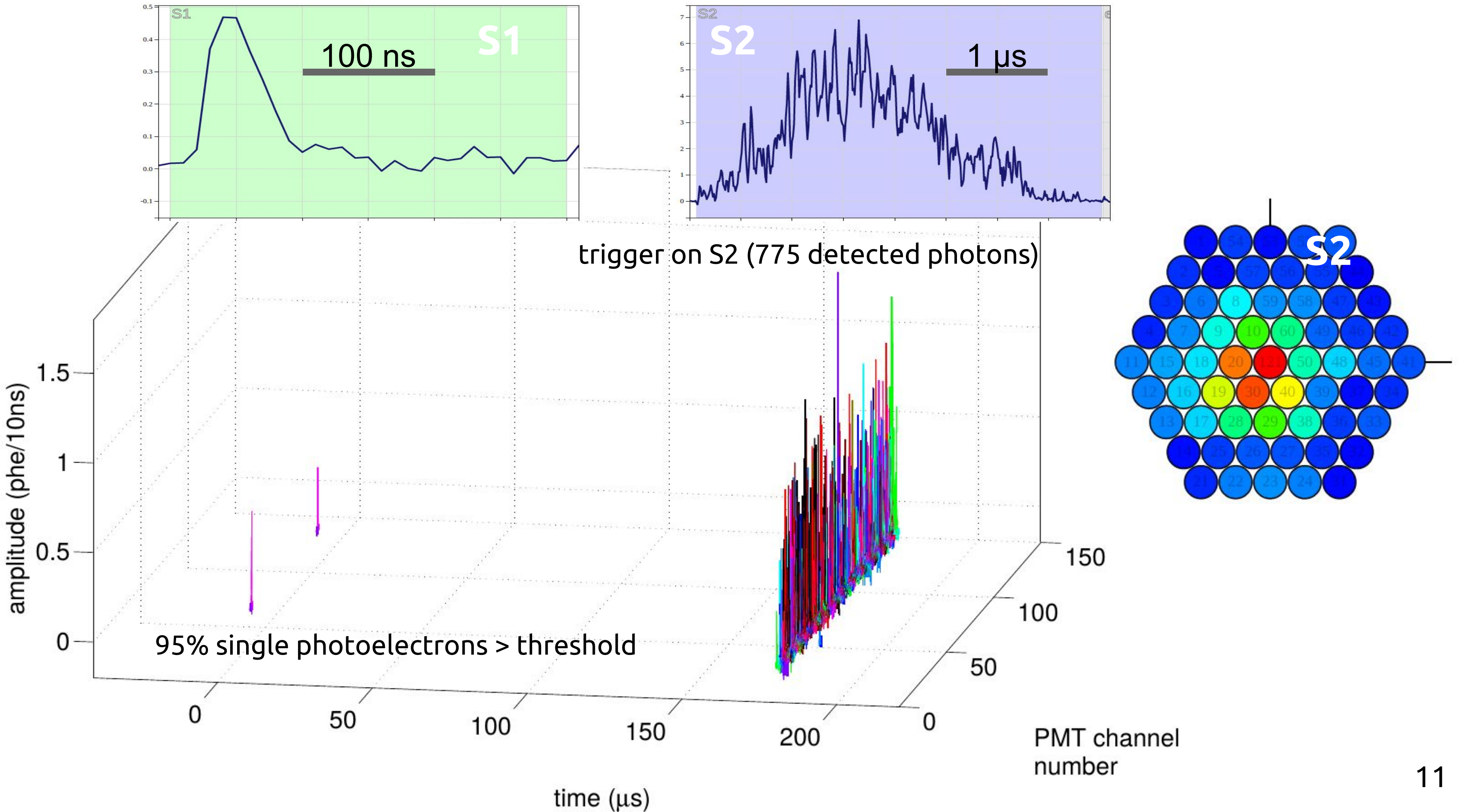
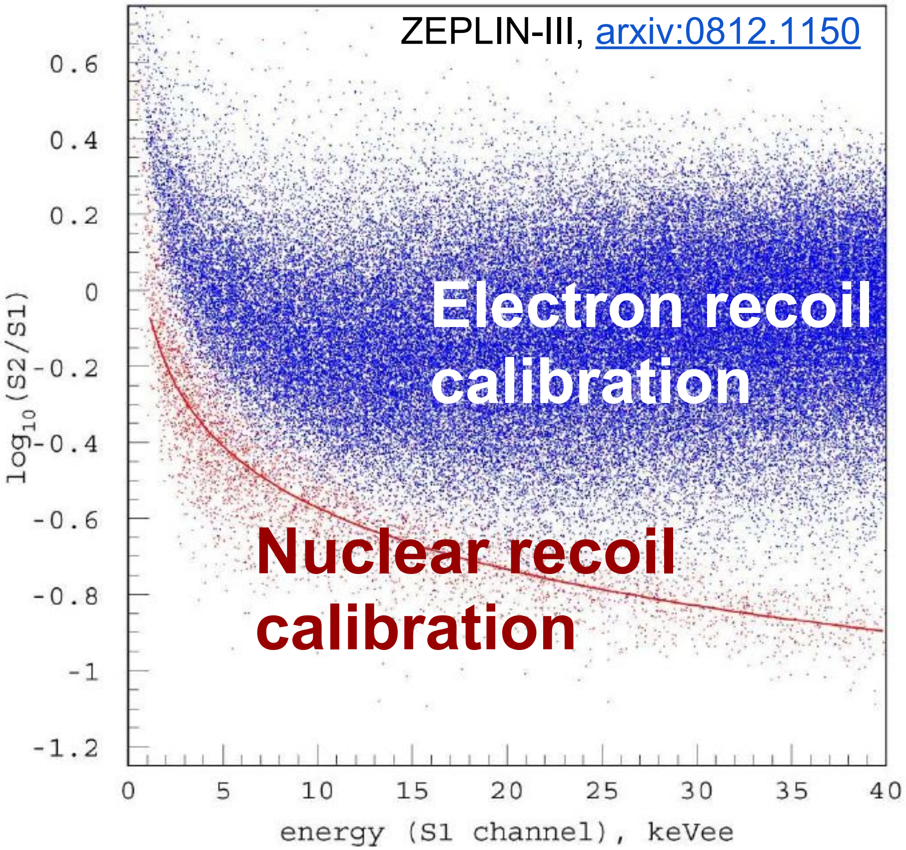


Image by CH Faham (Brown)

Near threshold: 1.5 keV electron recoil



Charge vs light to tell ER from NR



- Track density: lowered ratio of charge to light
- Nuclear stopping power: fewer signal quanta at given energy

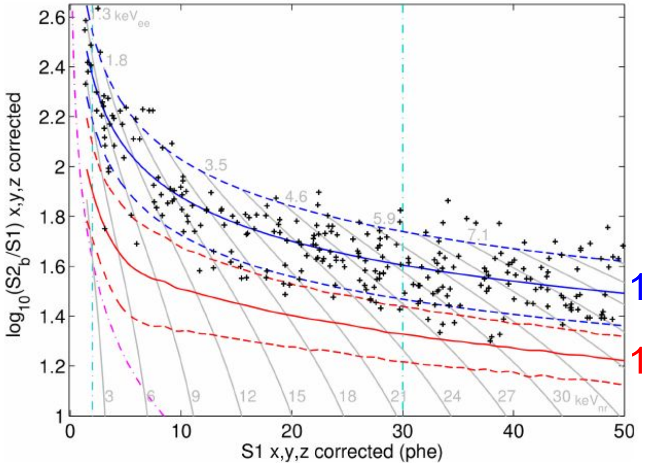
Signal, background, telling the difference

Source	Spectrum	Charge-to-light ratio	Location
WIMPs	c. exponential	low (NR)	uniform
Compton scatters from materials γs	**c. flat**	**high (ER)**	**peripheral**
internal βs from Kr-85, Rn impurities	**c. flat**	**high (ER)**	uniform
X-rays from Xe-127 (**λ=36.4 d**)	**1, 5 keV lines**	**high (ER)**	**peripheral**
decays on walls	**c. flat**	low, variable (NR and ER with charge loss)	**high-radius**

Recall: first result

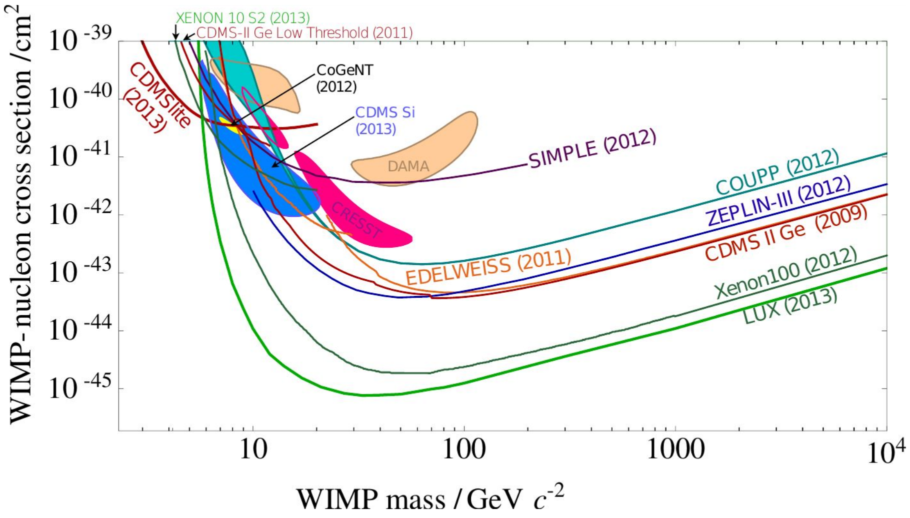
- 85.3 net days
- 118 kg fiducial (r<18 cm)
- 2–30 phe $S1_c$
- $S2_{raw}$>200 phe
- conservative 3 keV signal cutoff $\rightarrow$5.2 GeV m_{min}
- 4-observable likelihood, 90% UL
  - 2.4–5.3 WIMP counts
  - min. cross section $8\times10^{-46}cm^2$

PRL **112**, 091303 (2014)



10,50,90% flat-in-*E* ER

10,50,90% flat-in-*E* NR

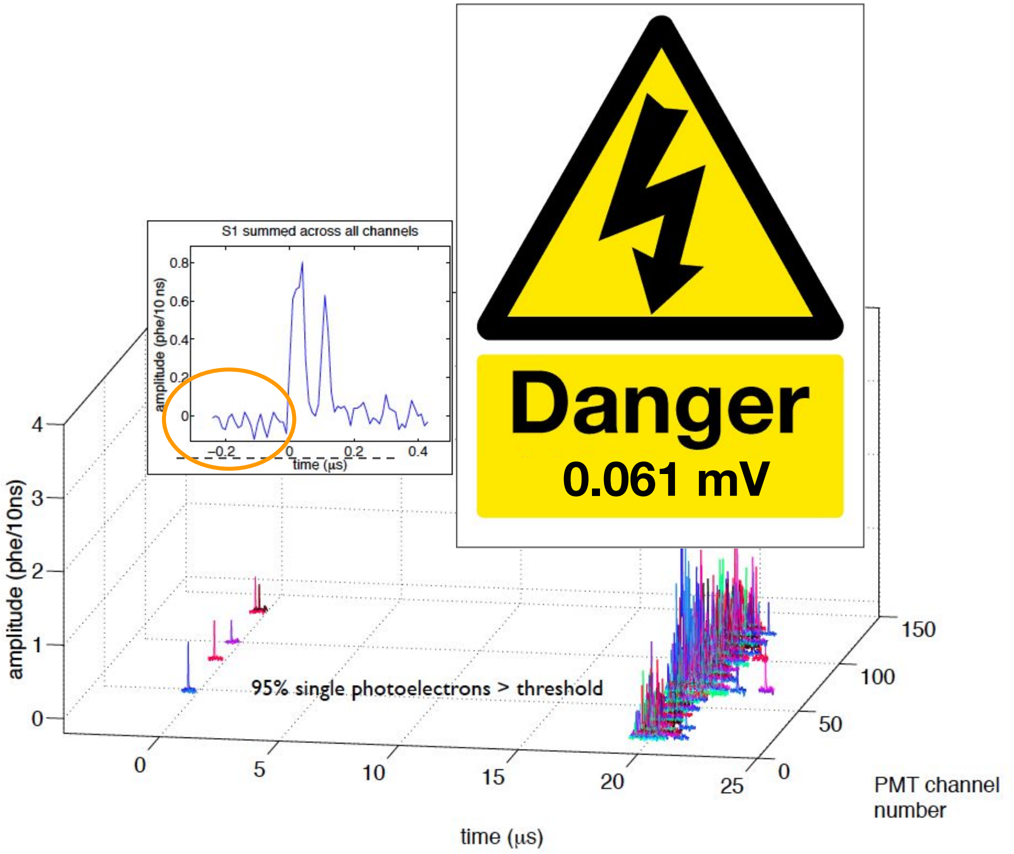


Reanalysis: measuring light

Measuring light

Better estimators for detected photons:

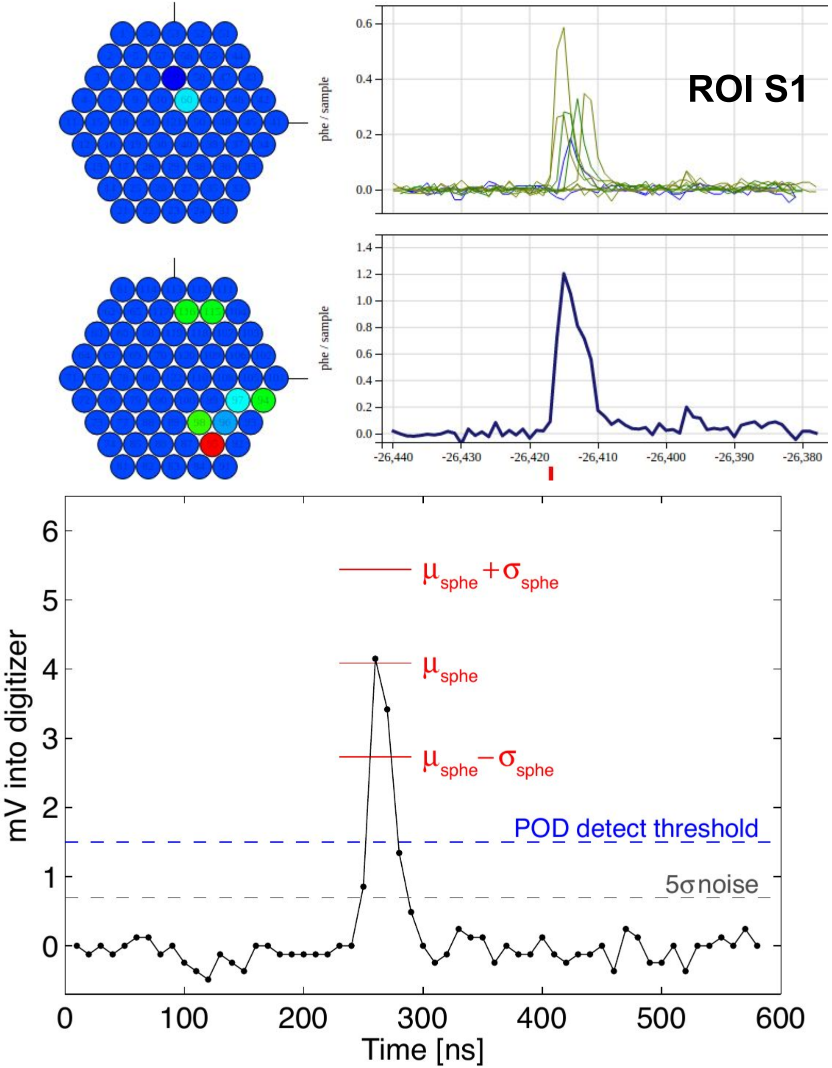
- **Removed a bias in baselines**
- Digital counting of photons in PMT waveforms
- Photon response calibrated in the VUV



Measuring light

Better estimators for detected photons:

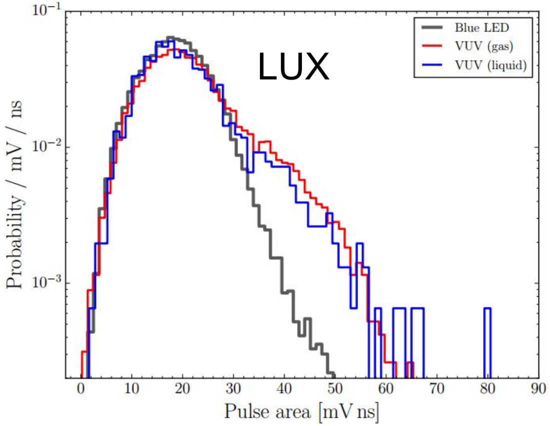
- Removed a bias in baselines
- **Digital counting of photons in PMT waveforms: less variance than area for sparse light**
- Photon response calibrated in the VUV

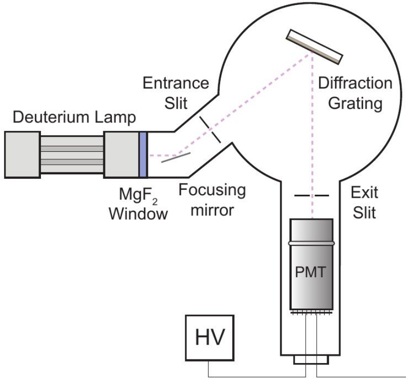


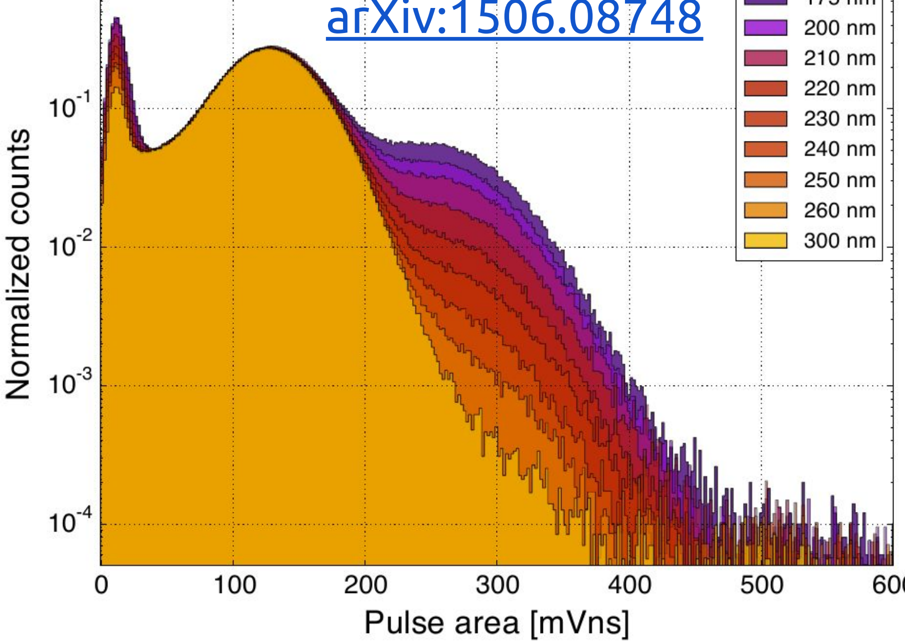
Measuring light

Better estimators for detected photons:

- Removed a bias in baselines
- Digital counting of photons in PMT waveforms
- **Photon response calibrated in the VUV (2 phe from 1 photon)**







arXiv:1506.08748

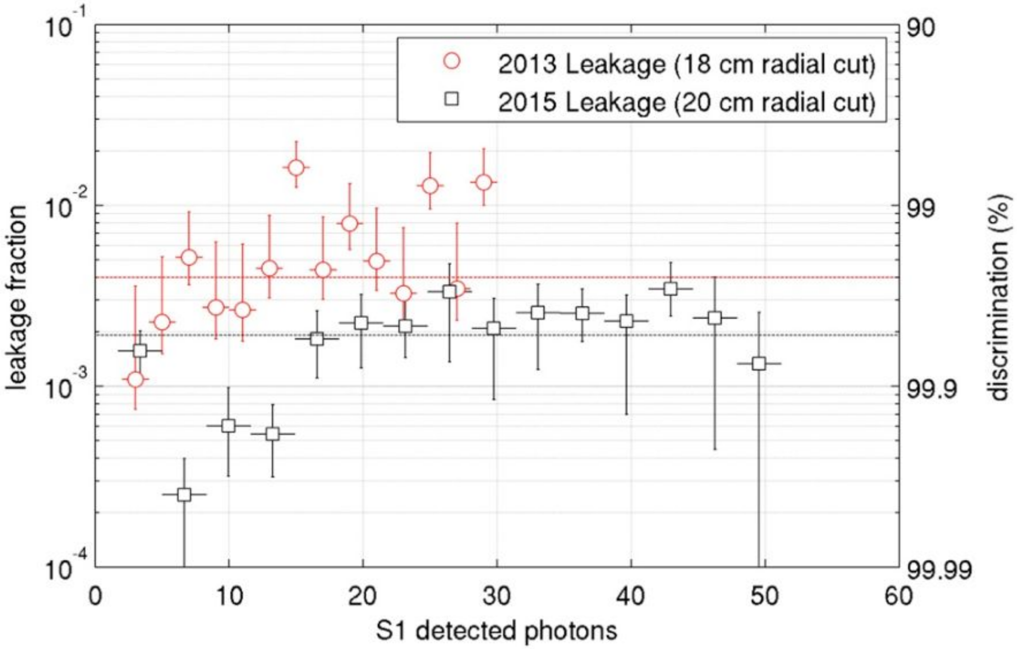
Net result: BG rejection

Figure of merit: ER rejection at 50% acceptance of NR calibration, based on charge|light

Better leakage performance & precision. S1 averages:

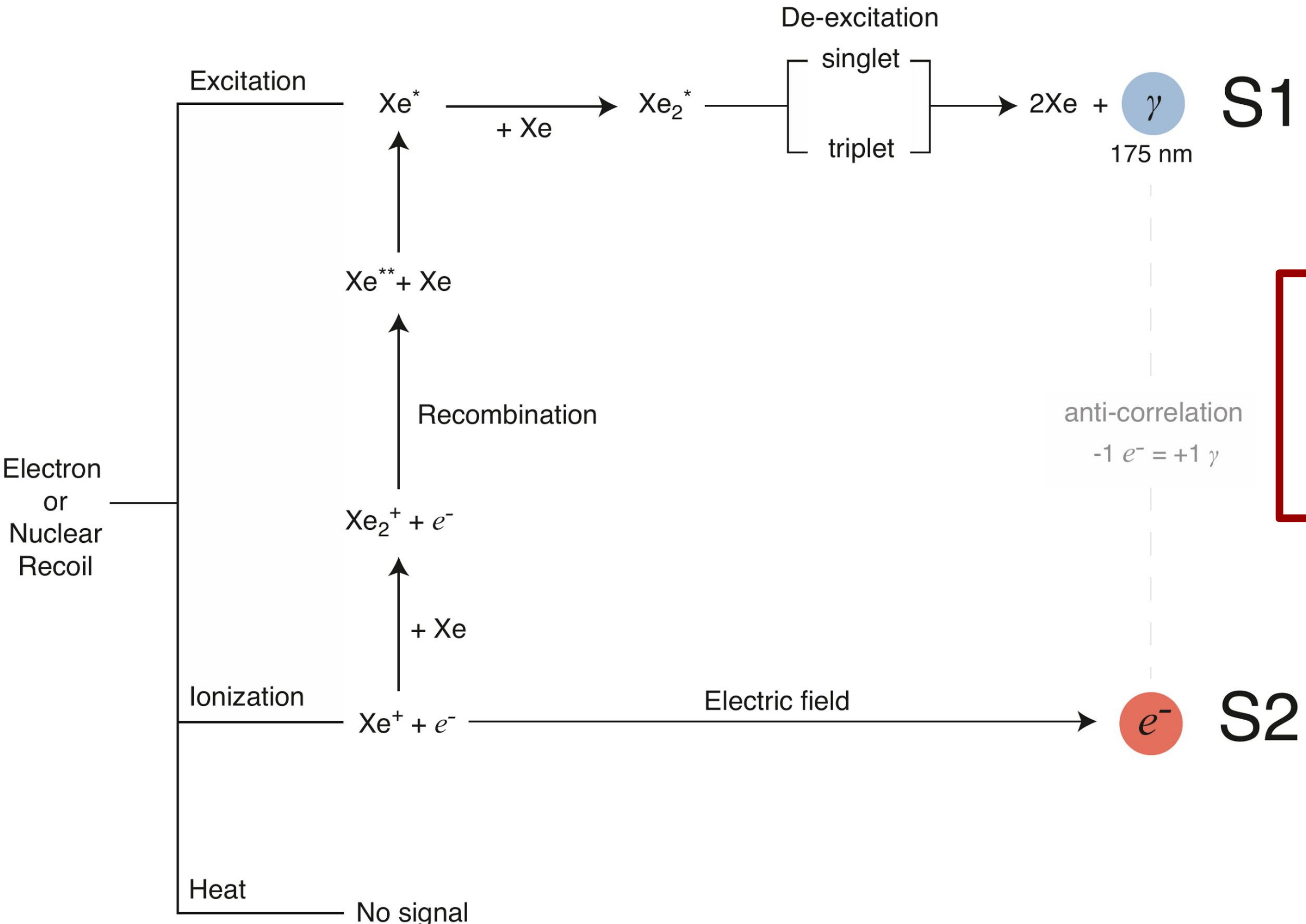
0.4±0.1%

→**0.19**±0.02(stat.)±0.1(syst.)%



Reanalysis: absolute signal quanta, and electron-recoil calibration

Signal quanta from tracks in LXe



$$\langle S1[\mathrm{phd}] \rangle = g_1 \cdot n_{phot}$$

$$\langle S2[\mathrm{phd}] \rangle = g_2 \cdot n_{elec}$$

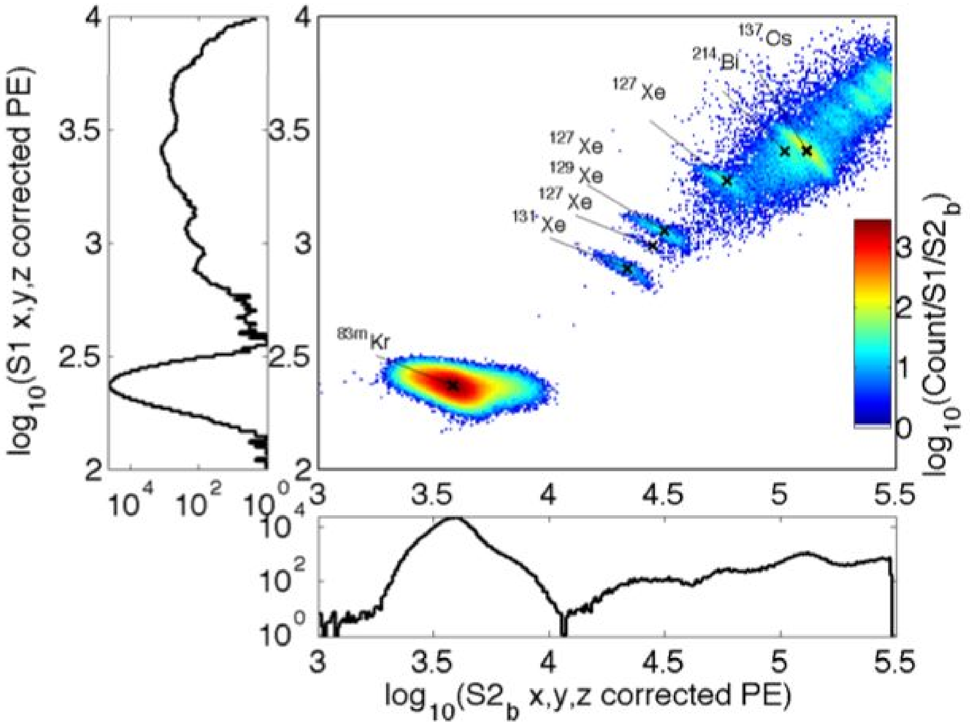
C.Faham thesis

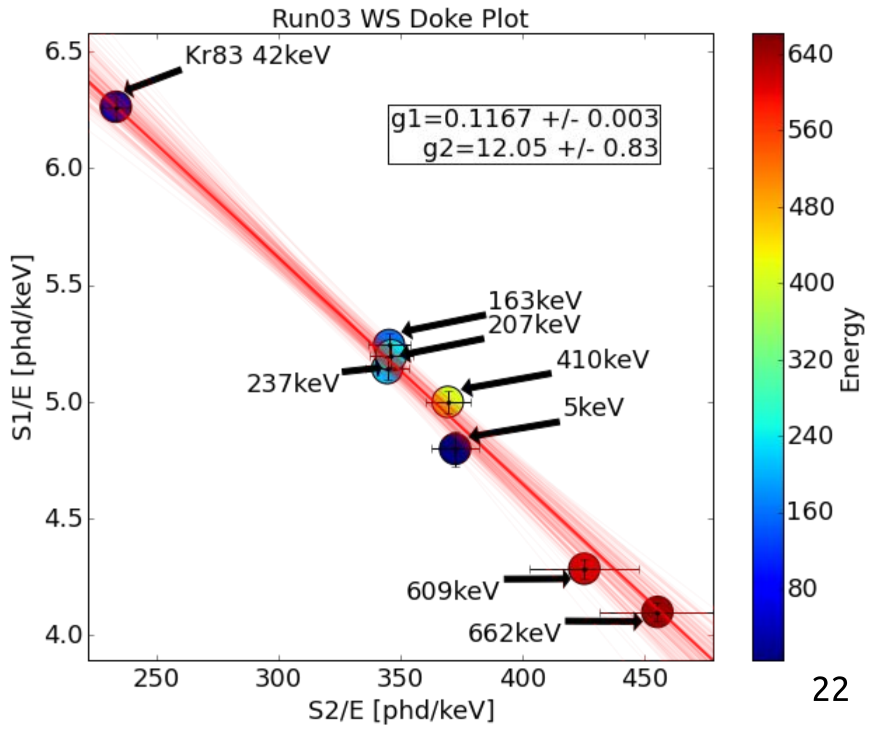
ER ‘Doke plot’ (5–662 keV)

Monoenergetic sources in the mean-yields plane.

Line fit and $W = 13.7$ eV give **absolute quanta**:

$$\langle S1[\mathrm{phd}]\rangle = 0.12\cdot n_{phot}\ ,\ \langle S2[\mathrm{phd}]\rangle = 12\cdot n_{elec}$$



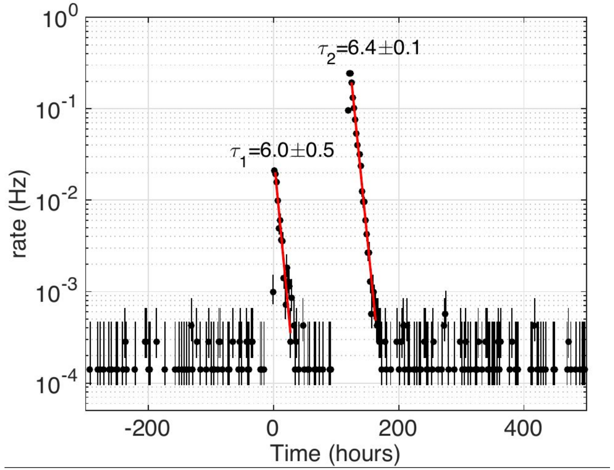


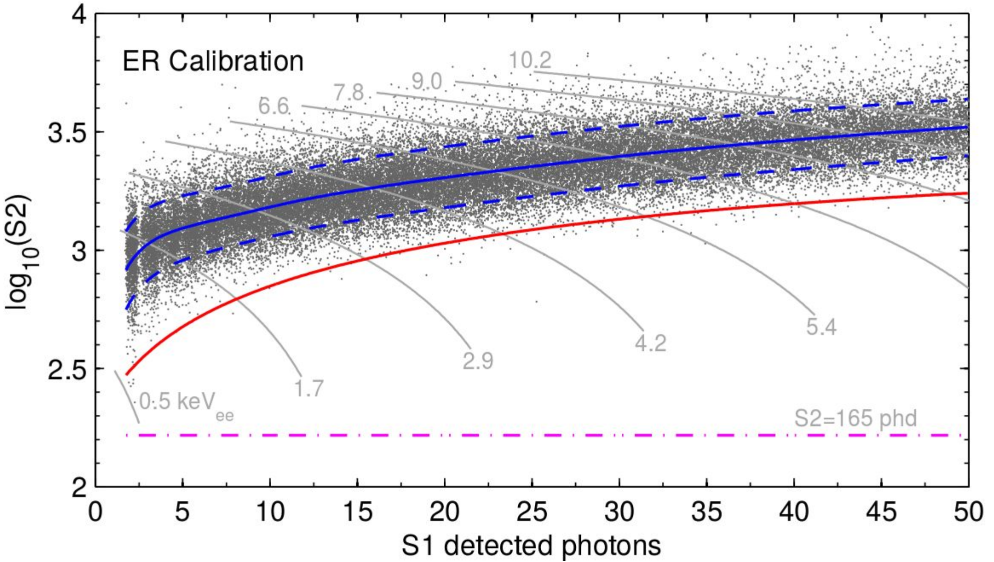
Calibration with tritium (0–18 keV)

Tritiated methane internal source

- Beta-decay to calibrate ER background (peaks at 2.5 keV)
- 12 year tritium half-life
- CH_3T: 6 hr effective half-life via getter

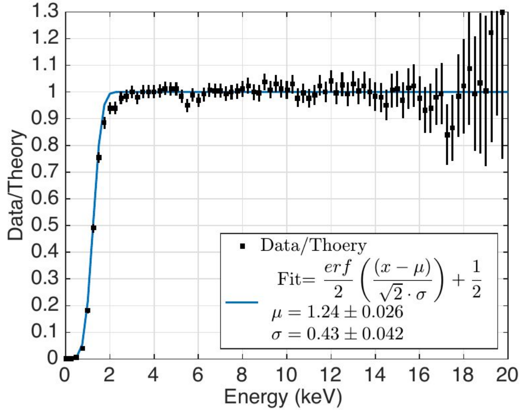
2nd campaign of CH_3T calibration in Dec 2013 : **170 000 FV events**

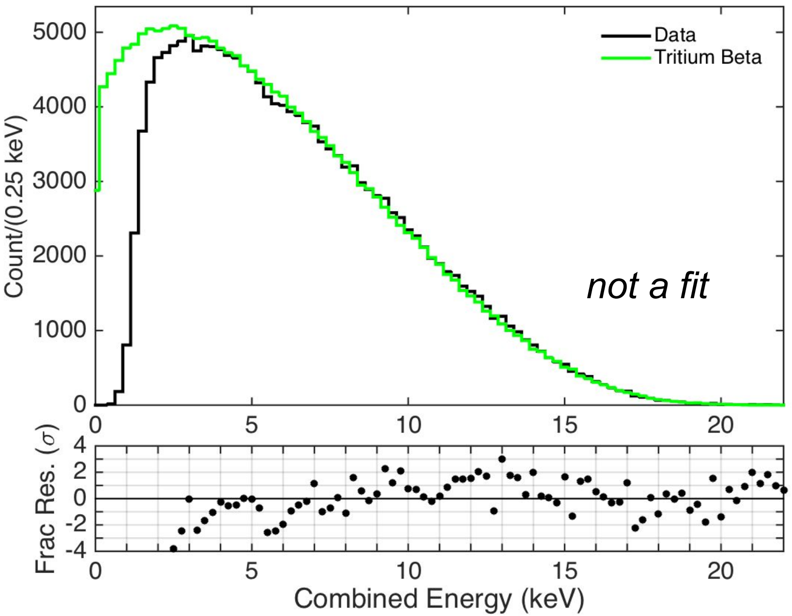




Tritium results (1512.03133)

- Spectrum validates Doke result
- Yields (with covariance) go into Compton, beta and X-ray BG models





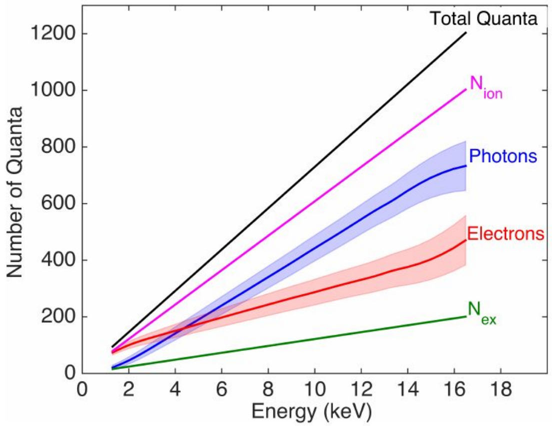
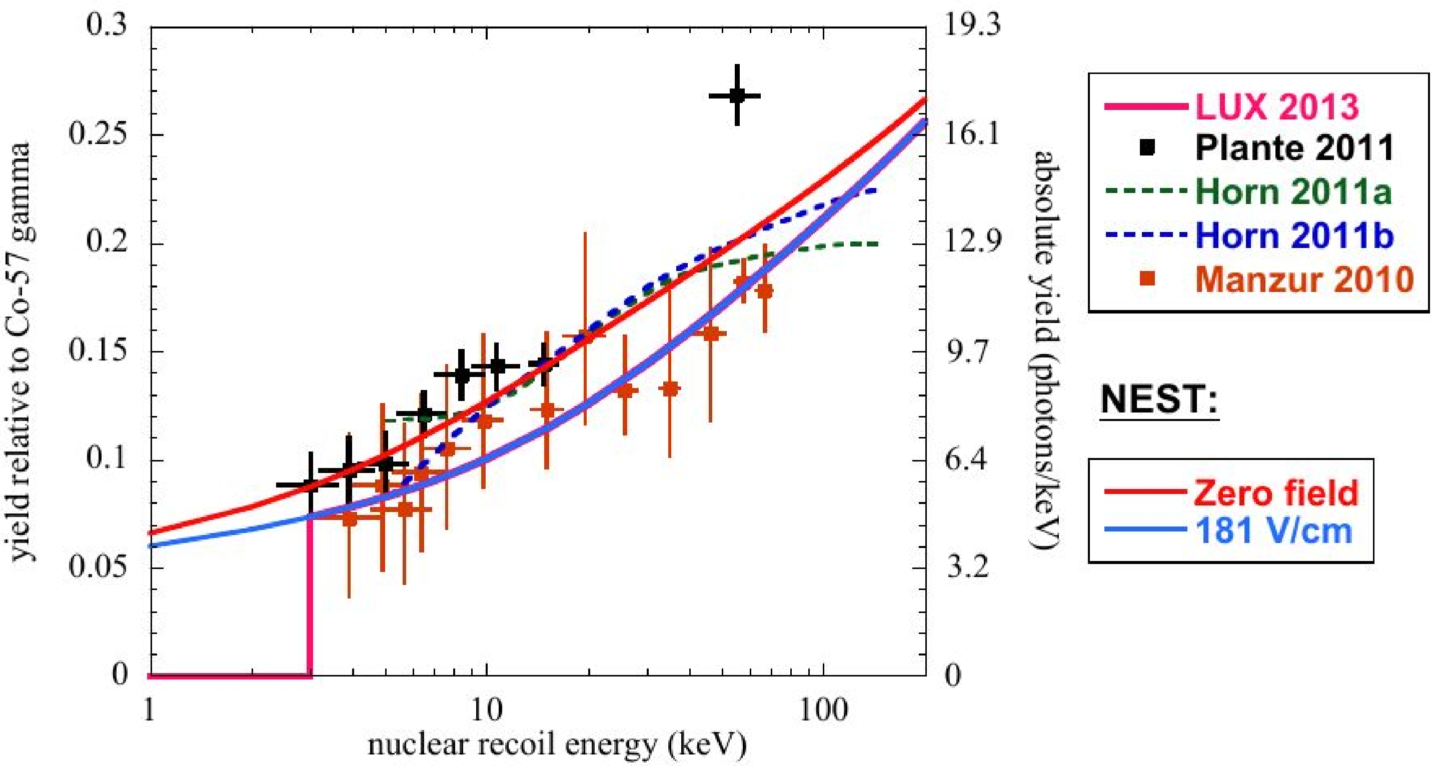


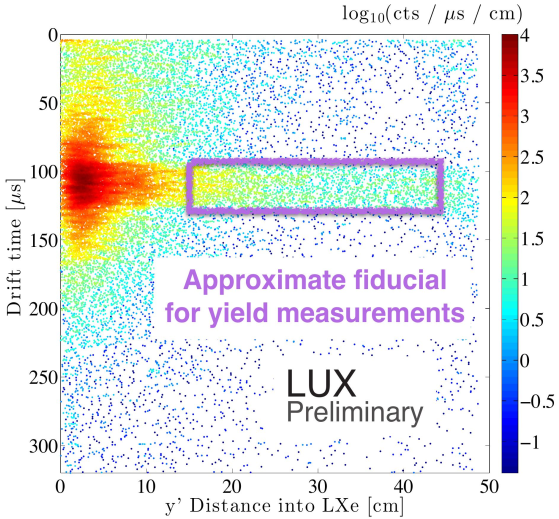
FIG. 9: Top: The mean number of electrons (red) and scintillation photons (blue) produced in LUX at 180 V/cm as a function of energy. The bands indicate the correlated systematic errors on g_1 and g_2. Also shown are the total number of quanta, primary ions, and primary excitons, assuming an exciton-to-ion ratio of $\alpha = 0.2$.

Reanalysis: calibration of the WIMP NR signal

Yield for LXe scintillation by NR, 2013



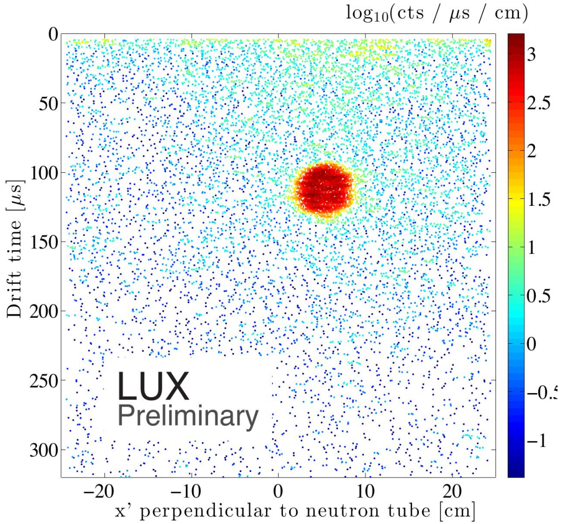
Monoenergetic neutrons: the D-D beam



D-D fusion neutrons collimated by 3.8 m conduit.

>15 cm into the xenon, 95% of neutrons within 4% of nominal 2.45 MeV.

(Also a good test of position reconstruction.)

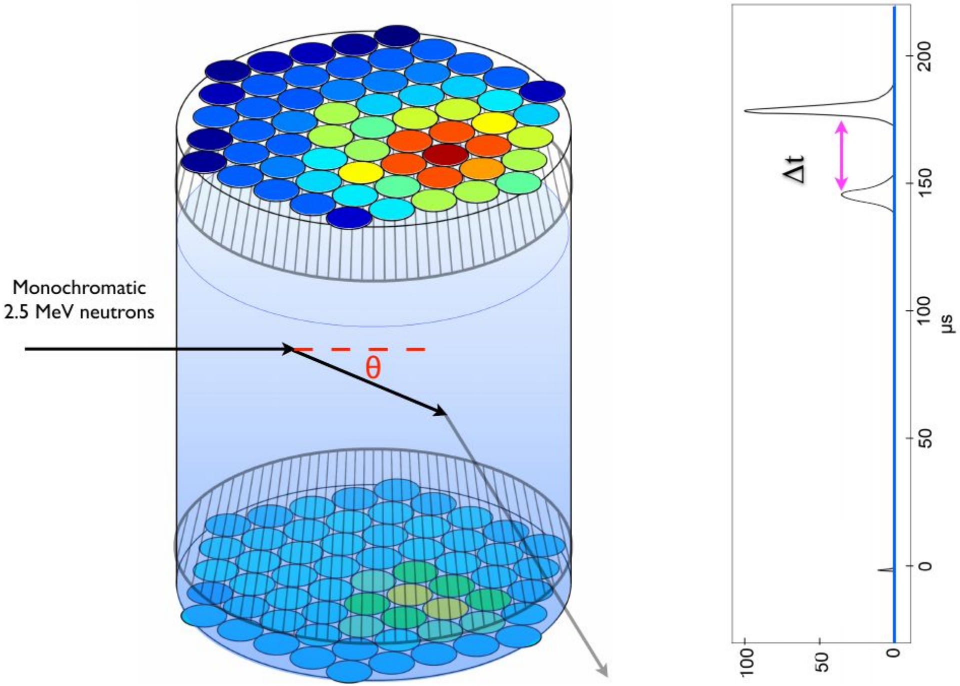


NR *in situ* with kinematically determined energy: the D-D analysis

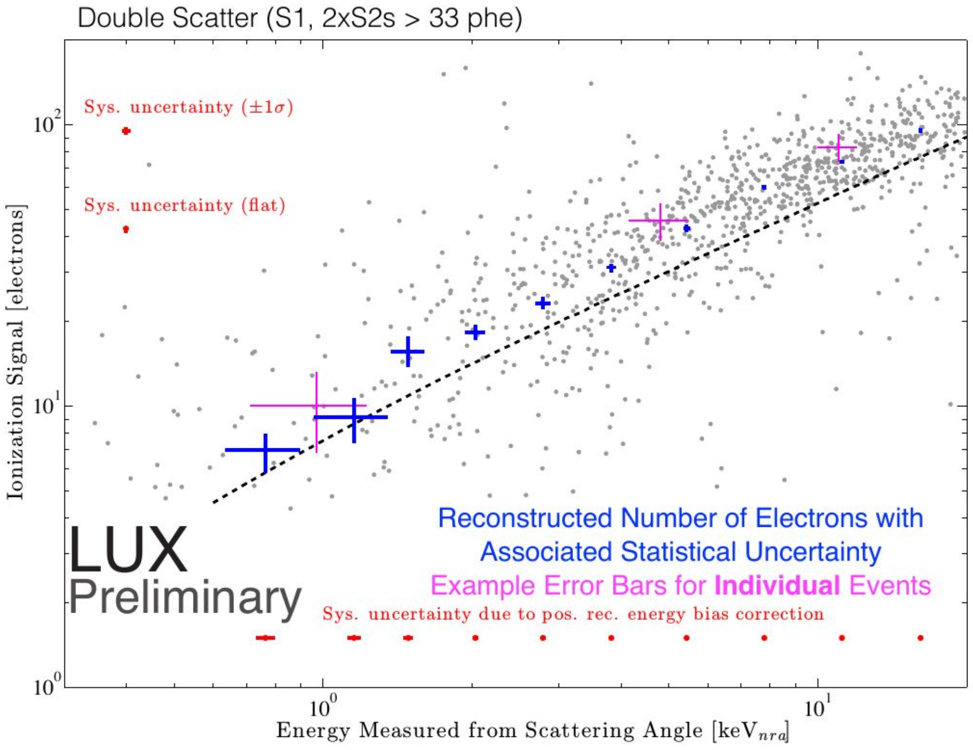
$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

E_r=(37 keV)·(1-cosθ). WIMP-like NR with:

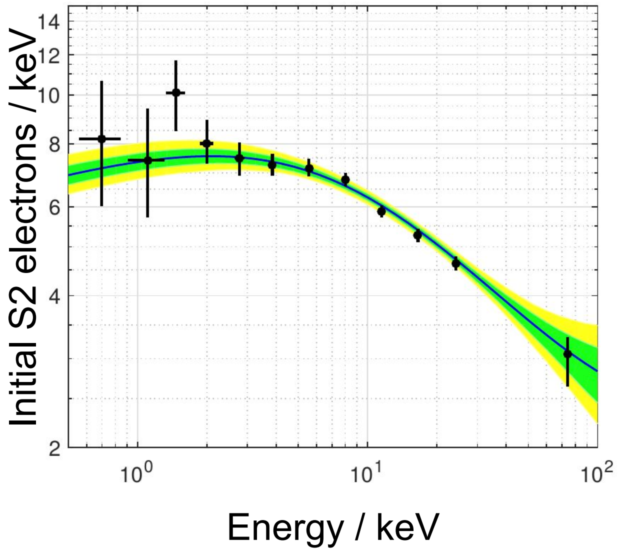
- minimal background and passive material
- in situ measurement, cancelling gain systematics in signal model
- long lever-arm → lowest energy reach with this technique



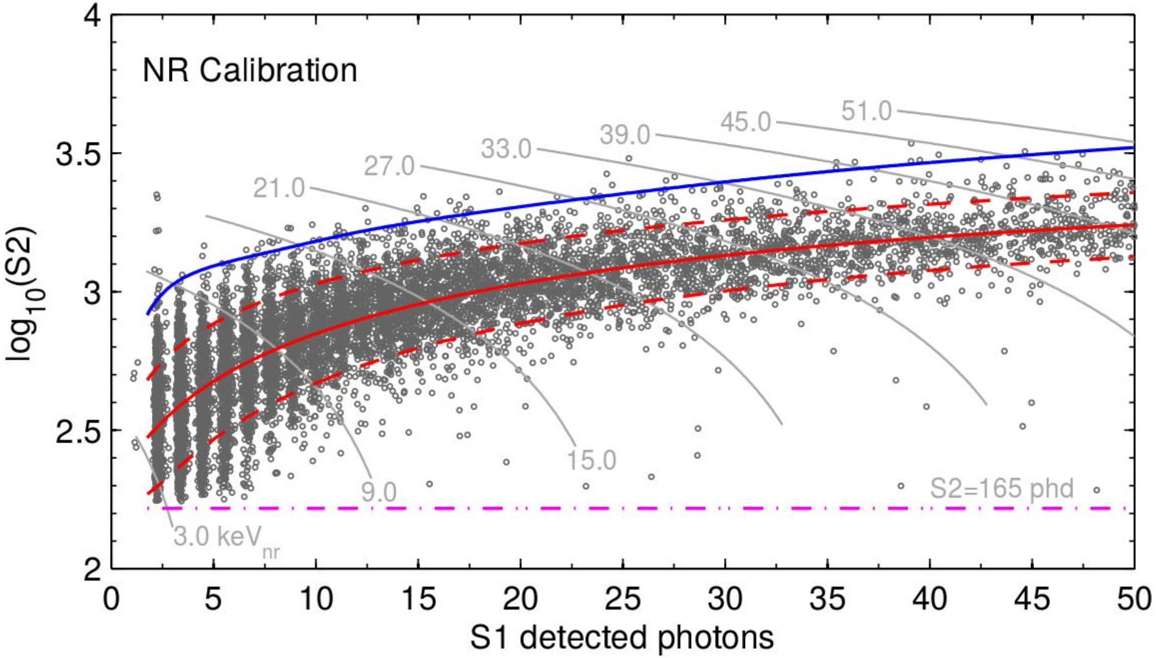
$S2$ vs energy via $E(\theta)$ in multiple scatters



- Lowest bin: 0.7 keV, 6 initial electrons (1eS2 =25 phd)
- Parametrisation to make WIMP PDFs:



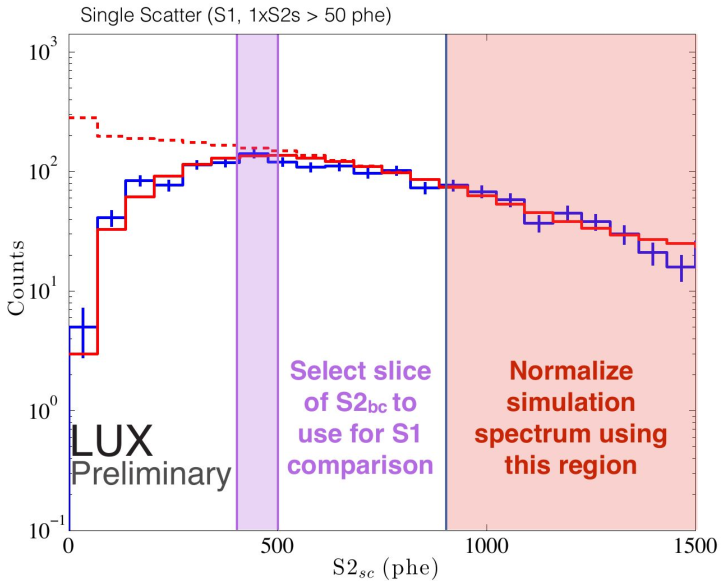
Single-scatter D-D population

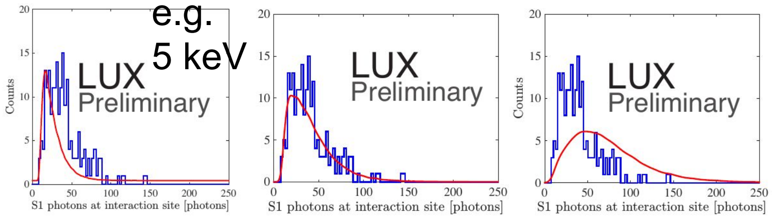


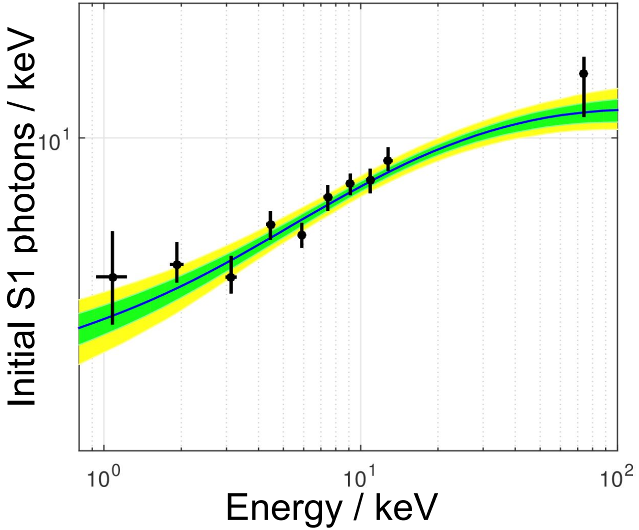
S1 vs energy via *E*(*S2*) for single scatters

S1 spectrum in S2 bins modeled via:

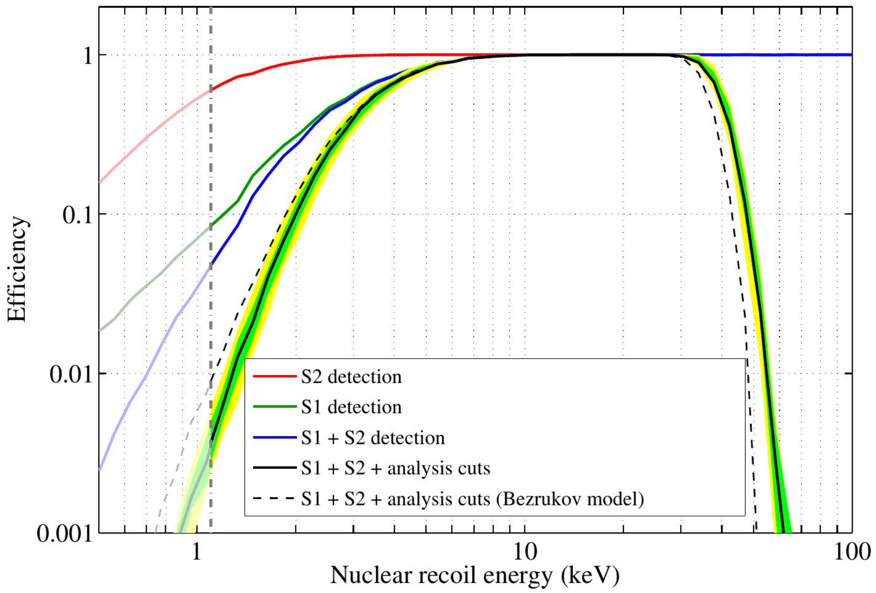
- JENDL-4.0 for *E* spectrum,
- S2(*E*) result
- Scintillation yield parametrisation (NEST) with a scaling parameter; fit this per bin for black points.







Net result: WIMP efficiency



Signal calibration extended to <1% efficiency threshold (WS cuts).

Modelling cutoff 3→1.1 keV: accessible mass 5.2→3.3 GeV/c^2.

Bezrukov ([Astopart.Phys 35, 119]) an alternative to the Lindhard model of NR energy loss to electrons.

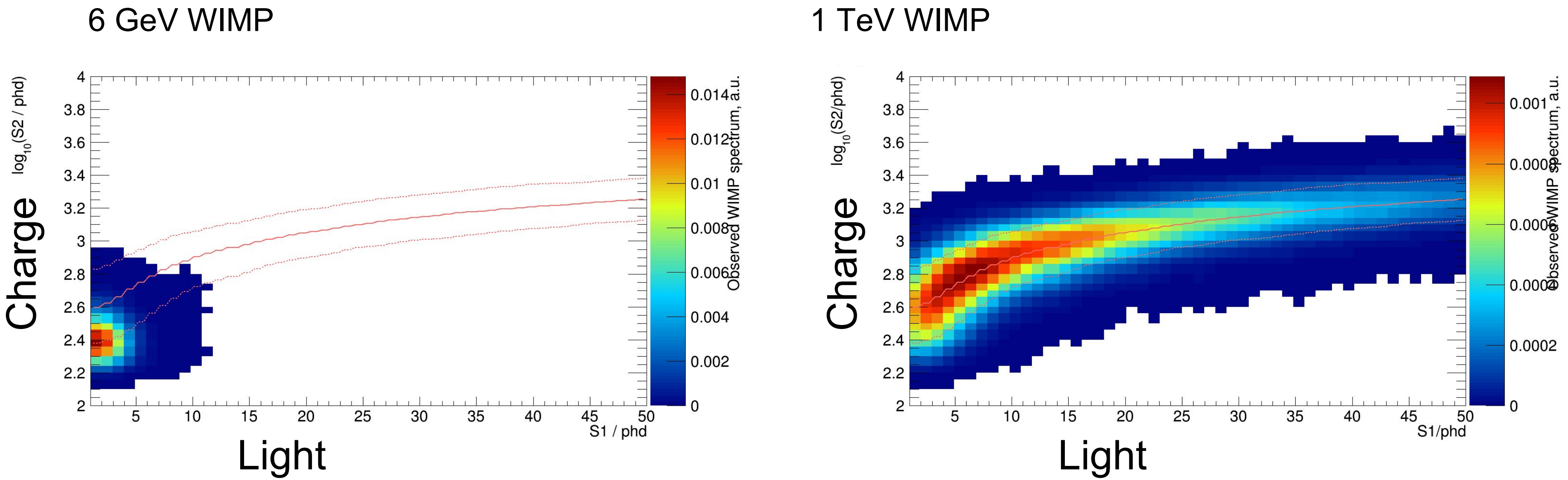
- Both consistent w/data; set limit with lower-yield Linhard.

Reanalysis: model components and the limit

Signal, background reminder

Source	Spectrum	Charge-to-light ratio	Location
WIMPs	c. exponential	low (NR)	uniform
Compton scatters from materials γs	**c. flat**	**high (ER)**	**peripheral**
internal βs from Kr-85, Rn impurities	**c. flat**	**high (ER)**	uniform
X-rays from Xe-127 (**λ=36.4 d**)	**1, 5 keV lines**	**high (ER)**	**peripheral**
decays on walls	**c. flat**	low, variable (NR and ER with charge loss)	**high-radius**

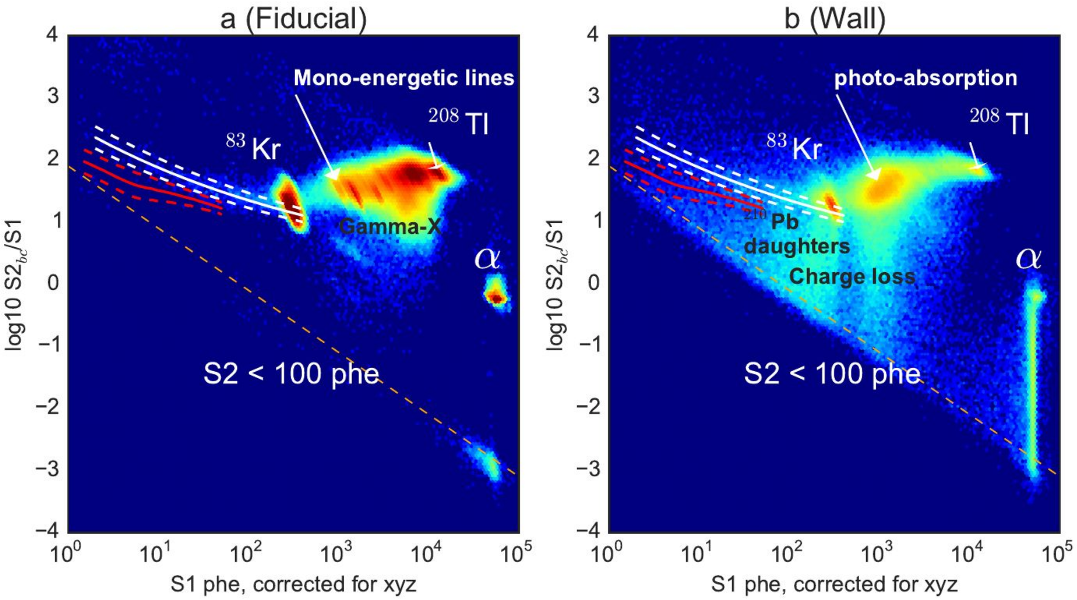
WIMP signal, in observable quantities



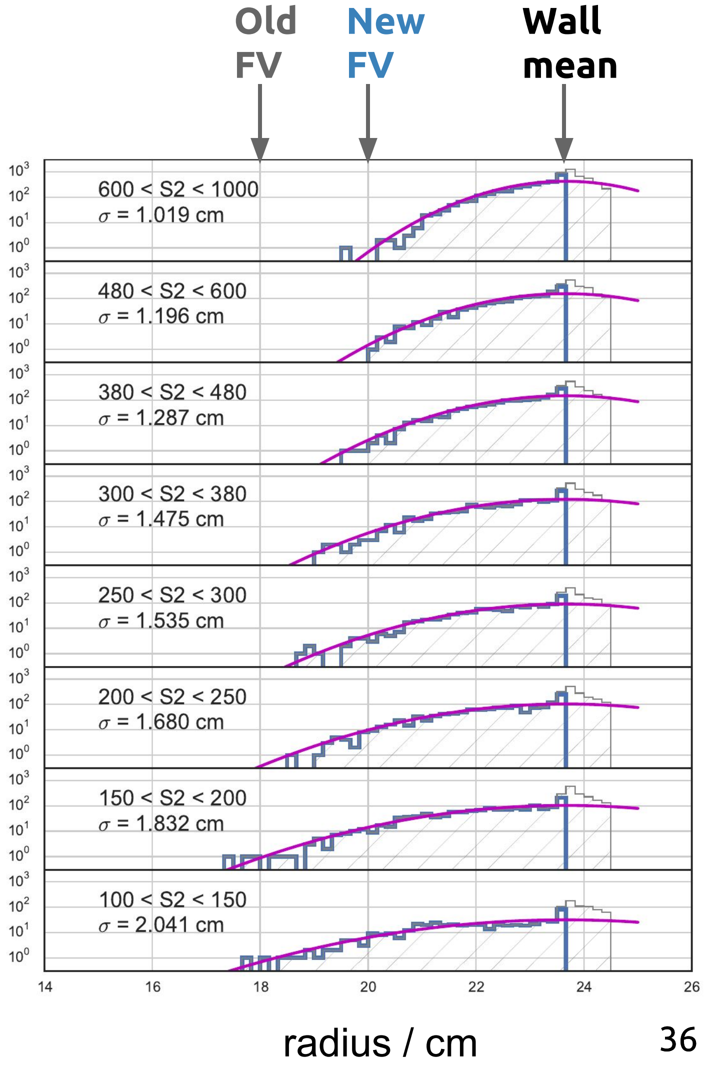
Non-negligible nuisance params (Lindhard *k*, $g2_{DD}/g2_{WS}$); evaluate by MC in the fit.

Use DD-tuned NEST-like model to capture **mass-dependence** of the WIMP PDF.

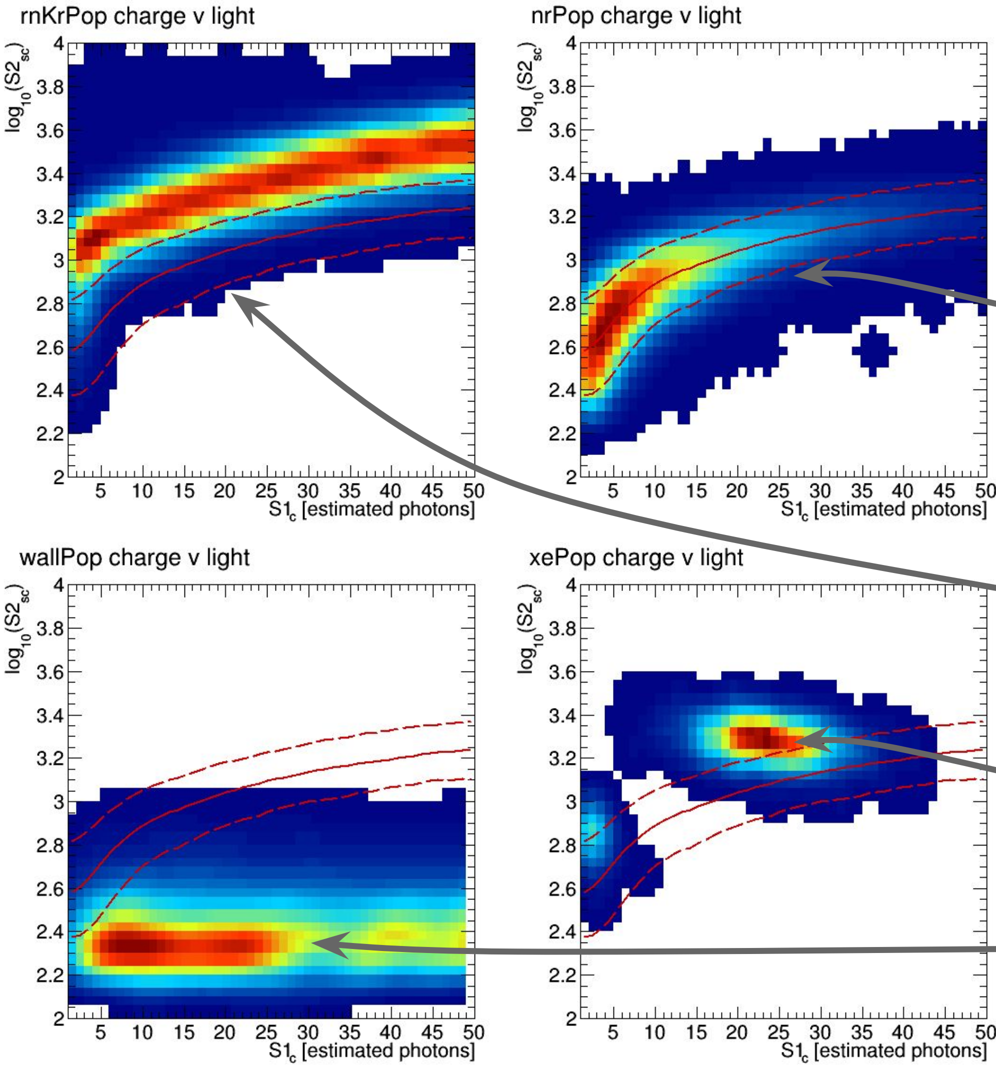
Calibration of decays on the wall



C. Lee Ph.D. thesis, CWRU, 2015



Low-energy LUX PDFs at a glance

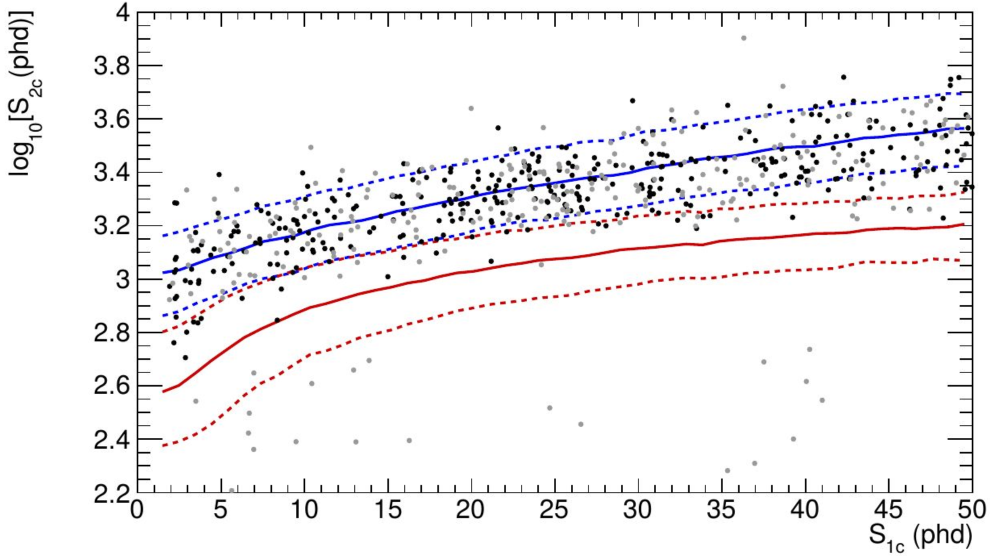


Source
WIMP (e.g. 50 GeV)
Compton scatters from materials γs
internal βs from Kr-85, Rn impurities
X-rays from Xe-127
decays on walls

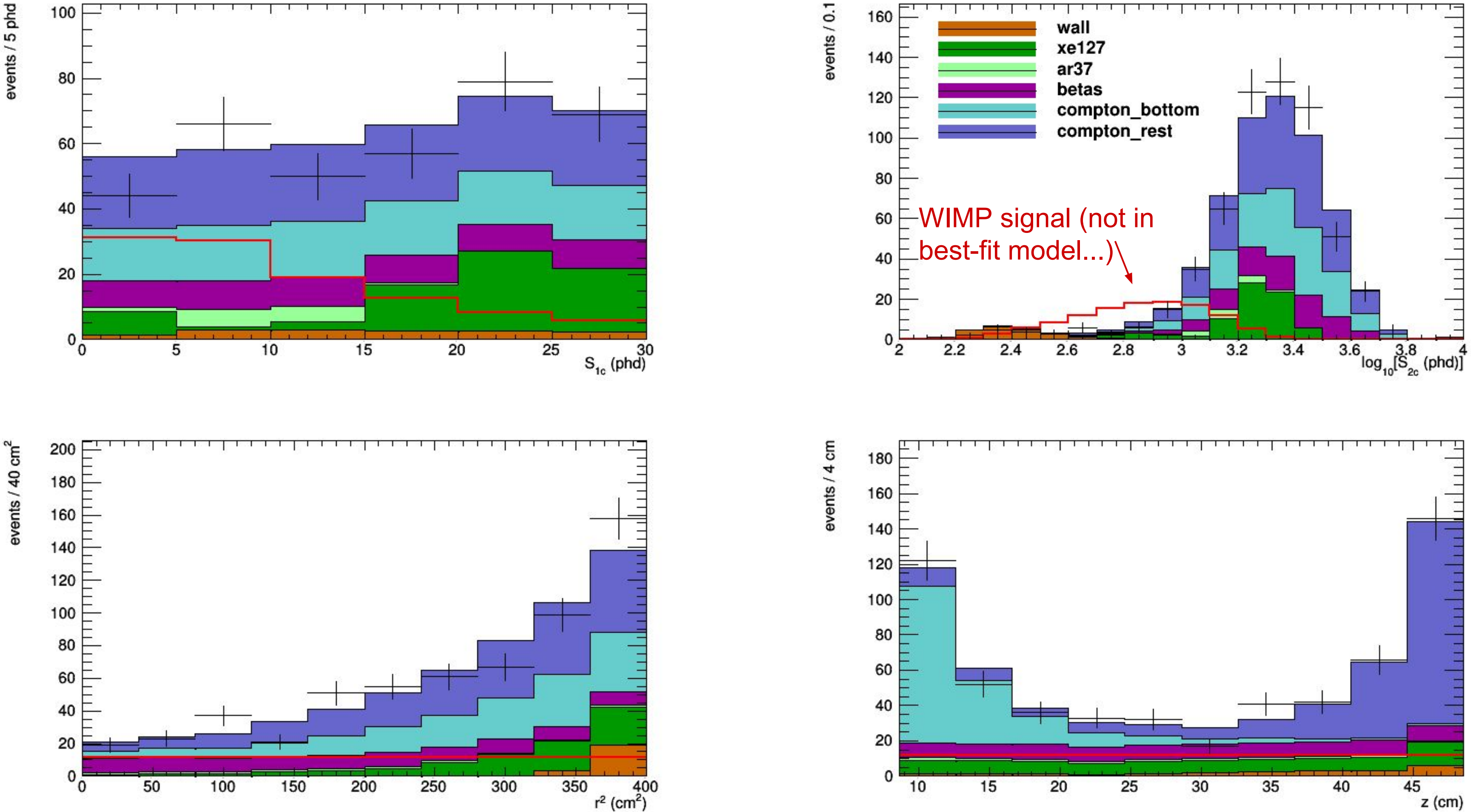
Search data, reanalysed

Onwards and downwards:

- **95 days** net (previously 85 d)
- **145 kg** fiducial (118 kg)
- **1–50 phd** $S1_c$,>2 raw photons (2–30 phe)
- $S2_{raw}$>**165 phd** (200 phe)
- conservative **1.1 keV** signal cutoff →**3.3 GeV** m_{min} (3.0 keV, 5.2 GeV)



Projections of best-fit model, data



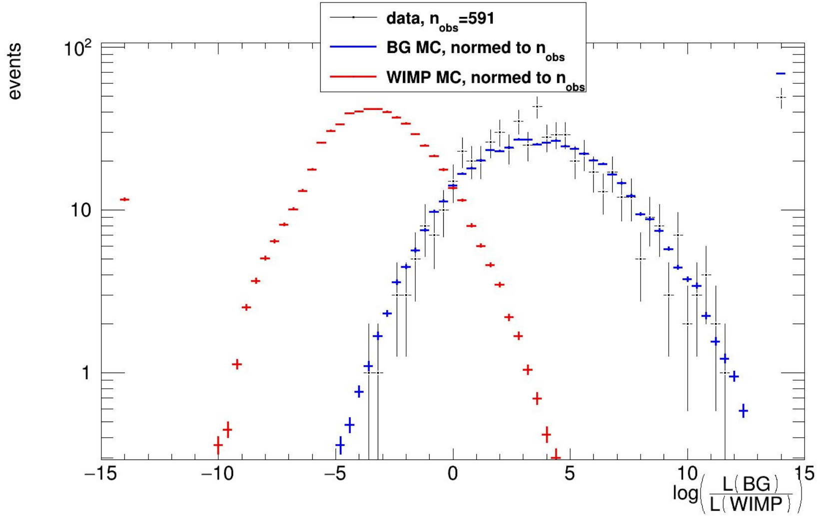
Setting confidence intervals

Per-event discriminant (top) illustrates **multivariate BG rejection**.

Real limit is unbinned PLR with 4 observables, implemented in RooStats. **Best fit xs=0**.

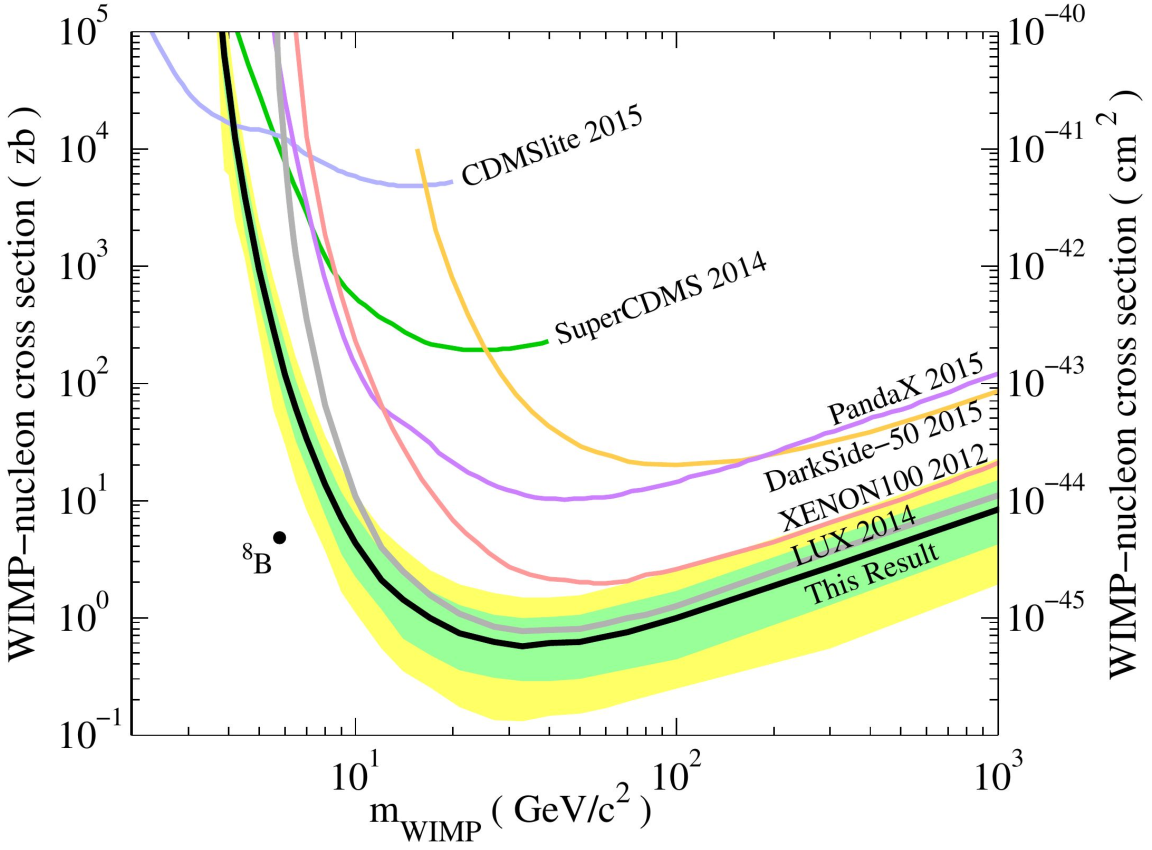
Nuisance parameters for BG population normalisation and WIMP PDF & efficiency.

Observed limit 1–2σ low (i.e. lucky fluctuation) so apply **power constraint** at median BG-only limit.



Parameter	Constraint	Fit value
Lindhard k	0.174 ± 0.006	-
S2 gain ratio: $g_{2,\mathrm{DD}}/g_{2,\mathrm{WS}}$	0.94 ± 0.04	-
Low-z-origin γ counts: $\mu_{\gamma,\mathrm{bottom}}$	172 ± 74	165 ± 16
Other γ counts: $\mu_{\gamma,\mathrm{rest}}$	247 ± 106	228 ± 19
β counts: μ_β	55 ± 22	84 ± 15
^{127}Xe counts: $\mu_{\mathrm{Xe\text{-}127}}$	91 ± 27	78 ± 12
^{37}Ar counts: $\mu_{\mathrm{Ar\text{-}37}}$	-	12 ± 8
Wall counts: μ_{wall}	24 ± 7	22 ± 4

90% UL on SI cross section

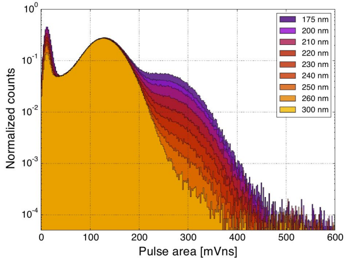


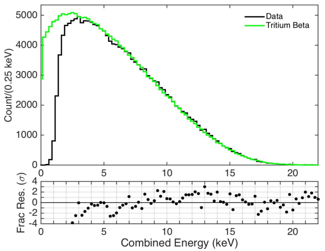
Conclusions

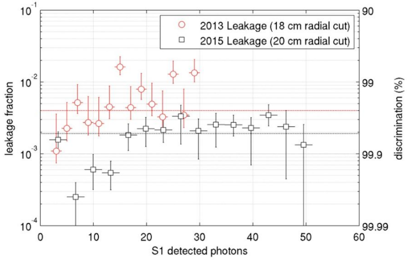
Since the 2013 LUX analysis:

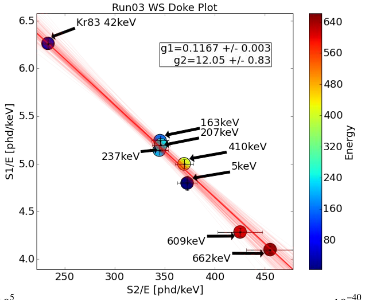
- New understanding of PMT response to VUV.
- Lower analysis thresholds
- ER calibration
    - Doke plot
    - 180k tritium events 0–18 keV
- Empirical wall model: more FV
- S1 yield to 1.1 keV nuclear recoils with DD generator

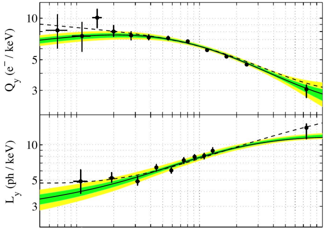
Calibration and techniques that will extend the reach of XENON*T, LZ, etc.

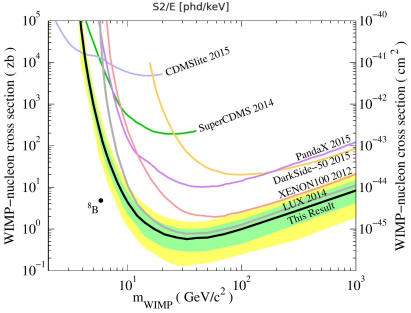












Also: LUX Run 4 ongoing with higher fields, acquired livetime >200 days.

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
Brian Lenardo	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
Jim Dobson	Postdoc
Sally Shaw	Graduate Student

University of Edinburgh

Alex Murphy	PI, Reader
Paolo Beltrame	Research Fellow
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