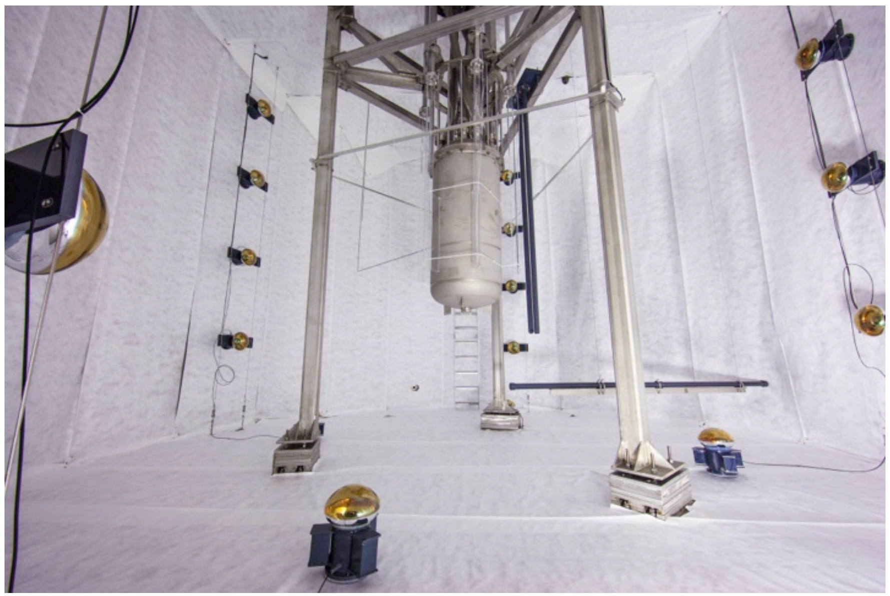
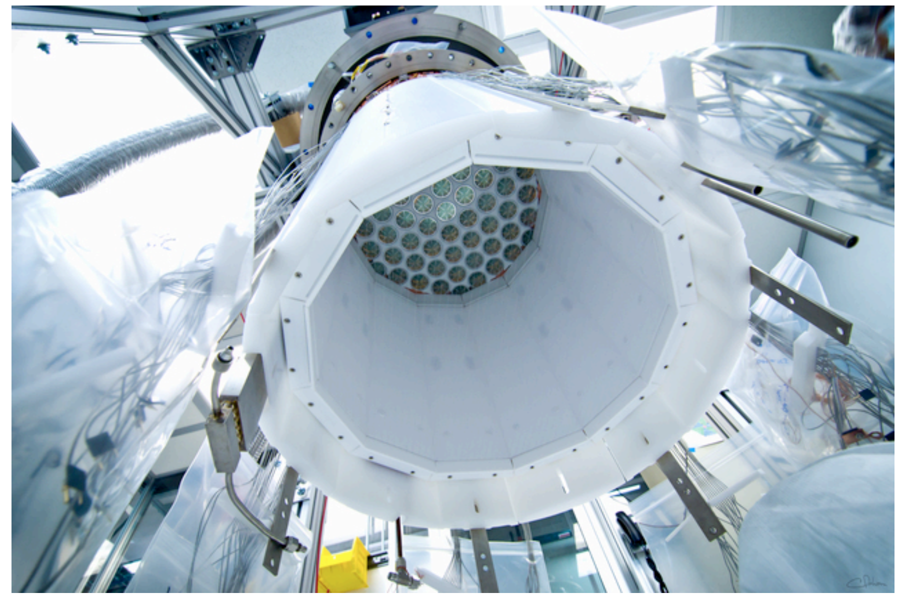
Searching for Dark Matter with the LUX experiment





PANIC2014 — 25th Aug. 2014

Jim Dobson for the LUX collaboration
(j.dobson@ed.ac.uk)

THE UNIVERSITY *of* EDINBURGH

Dark Matter first postulated in 1930s

- 1930s Fritz Zwicky
- and 1970s Vera Rubin

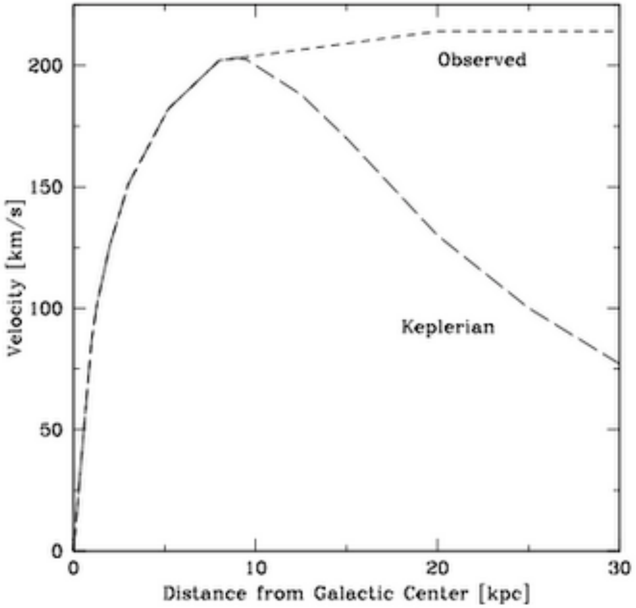
→ Galaxies are rotating too fast

→ 10 × more mass needed!

Coma cluster

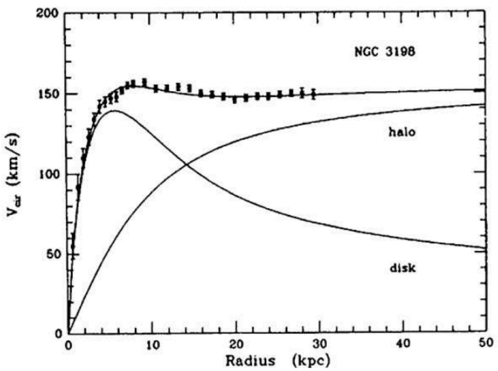
Vera Rubin

Rotation curves of galaxies

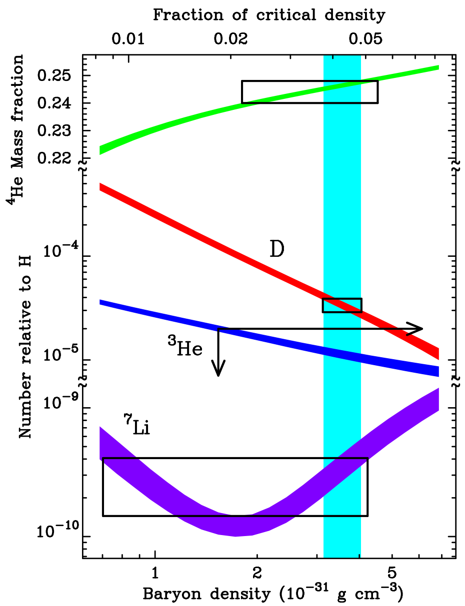


Much much more evidence since then

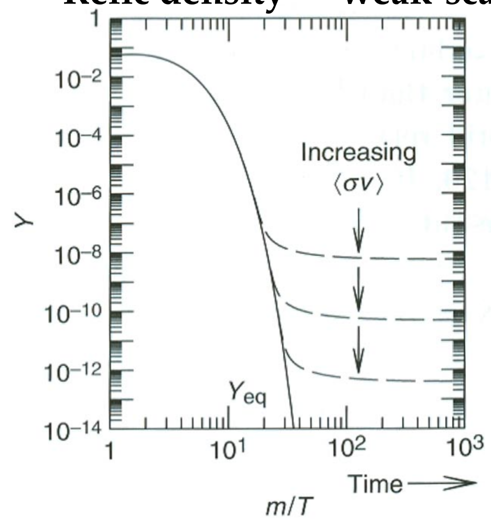
Rotation curve NGC-3198



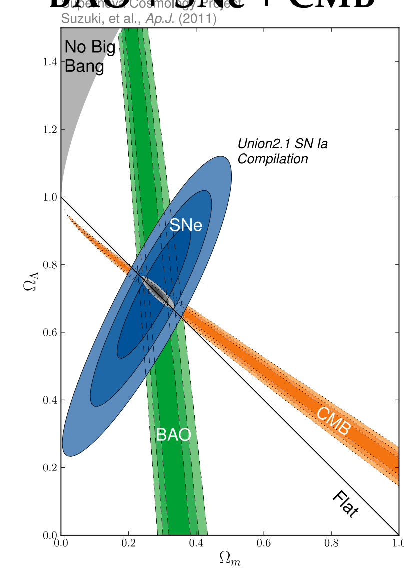
BBN



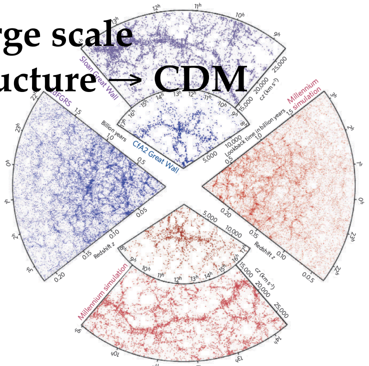
Relic density → weak-scale



BAO + SNe + CMB

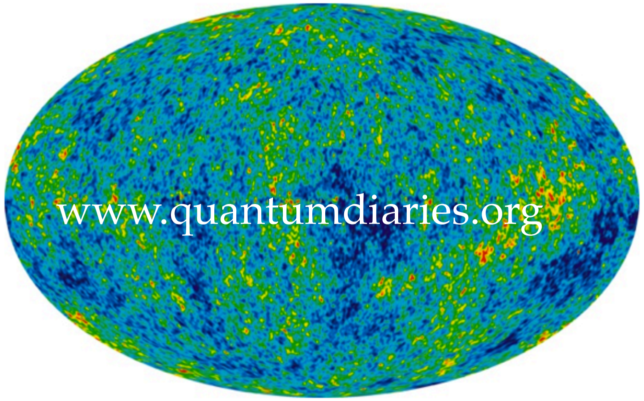


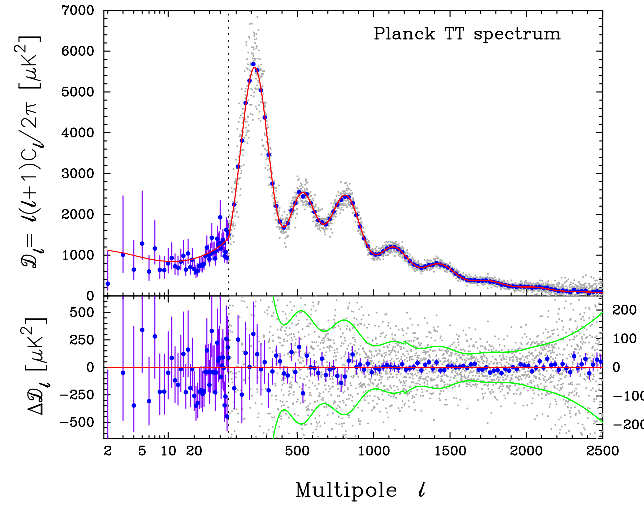
Large scale structure → CDM



Bullet-cluster: DM not MOND

CMB + BAO: precision tests of ΛCDM





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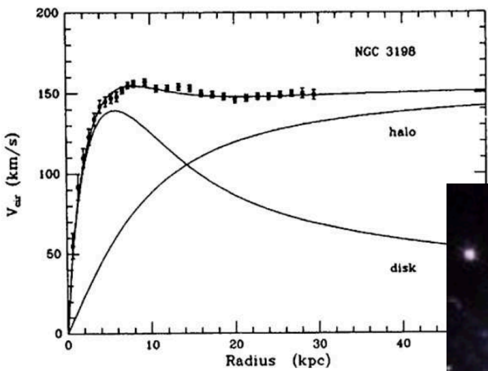

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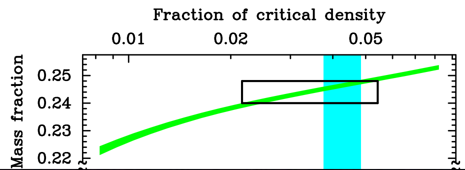

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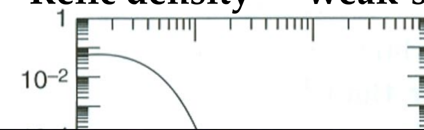
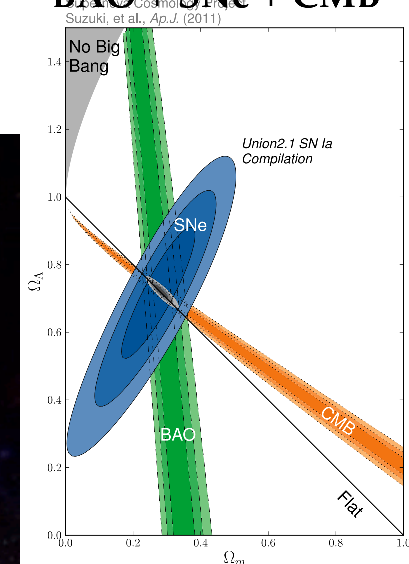


BAO + SNe + CMB



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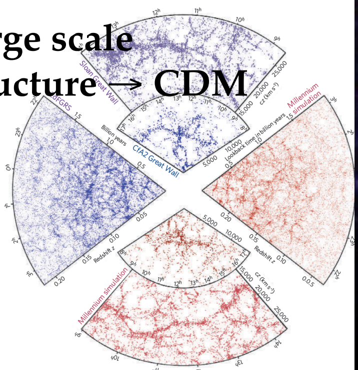
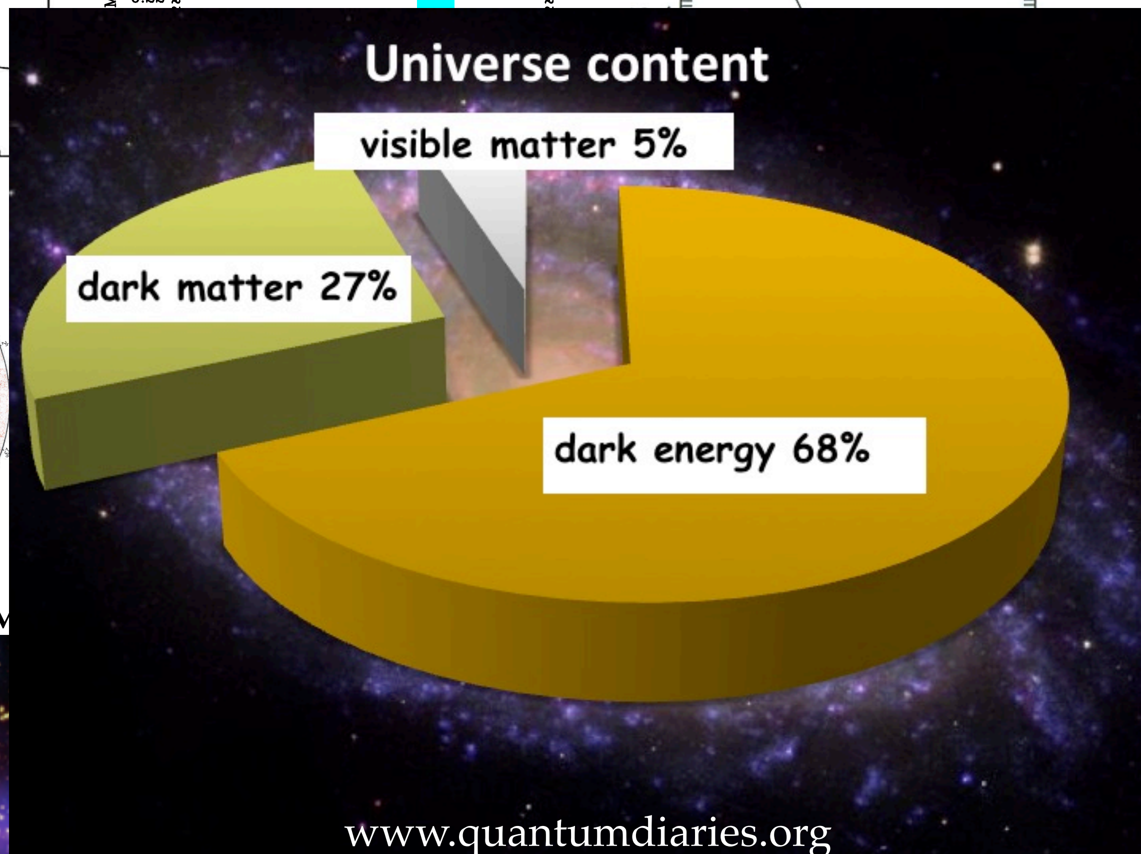
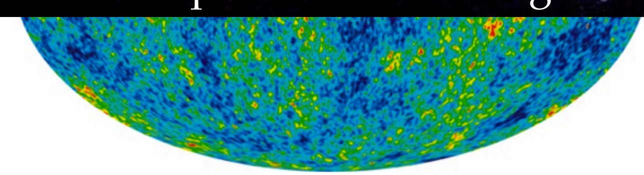
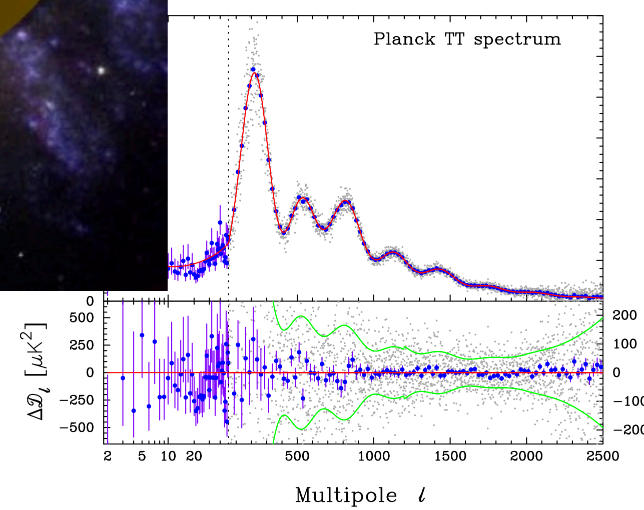


Bullet-cluster: DM not M







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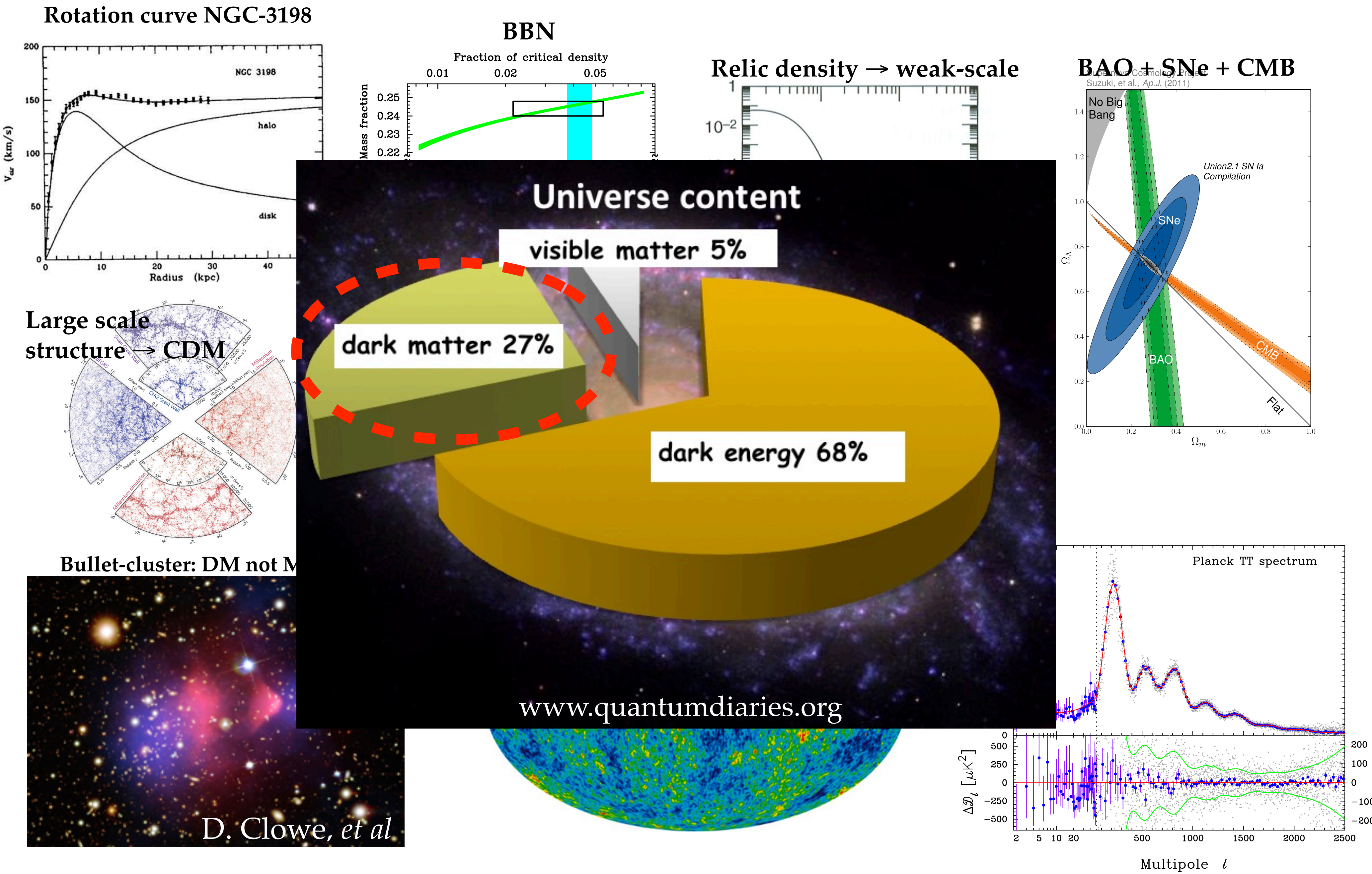
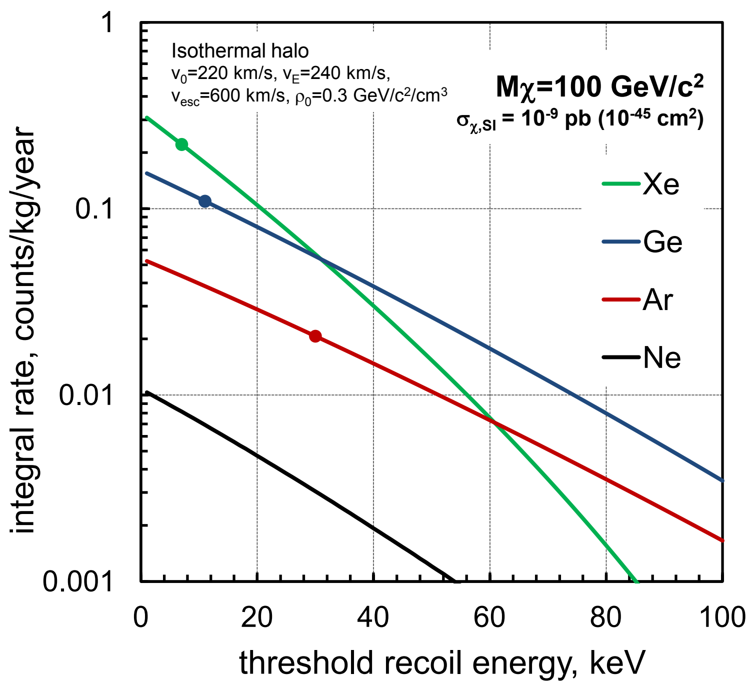


Detecting WIMPs

- Weakly Interacting Massive Particles:
  - Favoured candidates for Cold Dark Matter *(alternatives: Axions, sterile neutrinos, ...)*
  - Expected to be neutral in most scenarios
  - Interact only weakly with normal matter
  - Non-relativistic freeze-out resulting in relic density today of ~1000/m^3

- Look for nuclear recoil from elastic scattering of galactic WIMPs off material in terrestrial detector:
  - WIMP speed ~220 km/s → nuclear recoils O(10 keV)
  - Expect < 1 evt / kg / year



$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_0}{m_N m_\chi}\int_{v_{min}}^{\infty} v f(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}(v, E_R)\ \mathrm{d}v\,.$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_R} = \frac{m_N}{2\mu_N^2 v^2}\left(\sigma_0^{SI}F_{SI}^2(E_R) + \sigma_0^{SD}F_{SD}^2(E_R)\right)$$

$$\sigma_0^{SI} = A^2\left(\frac{\mu_N}{\mu_n}\right)^2\sigma_n$$

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  - Favoured candidates for Cold Dark Matter *(alternatives: Axions, sterile neutrinos, ...)*
  - Expected to be neutral in most scenarios
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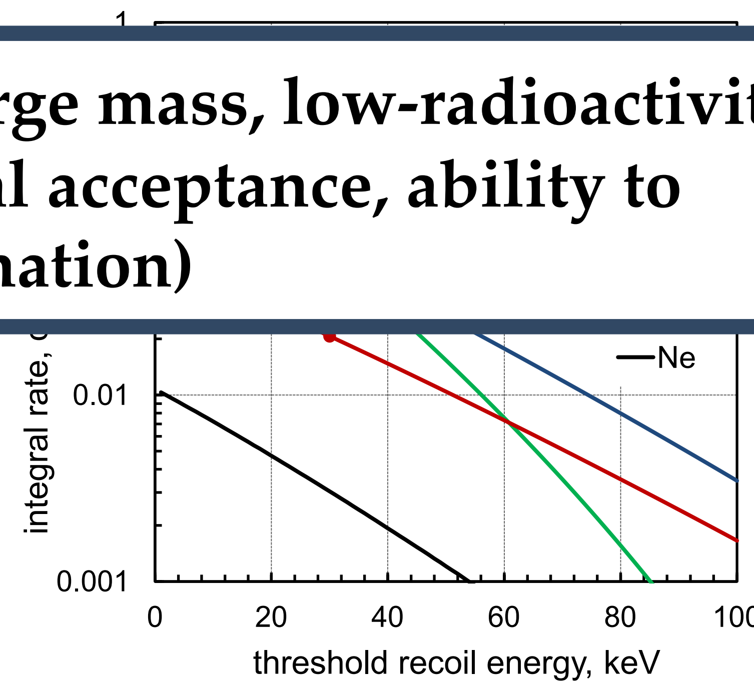
Important factors for detector: large mass, low-radioactivity, low-energy threshold, high signal acceptance, ability to reject ER backgrounds (discrimination)

recoils O(10 keV)

- Expect < 1 evt / kg / year



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The Large Underground Xenon (LUX) experiment

The worlds largest dual-phase xenon time-projection chamber

The LUX collaboration

Brown

Richard Gaitskell	PI, Professor
Simon Fiorucci	Research Associate
Monica Pangilinan	Postdoc
Jeremy Chapman	Graduate Student
David Malling	Graduate Student
James Verbus	Graduate Student
Samuel Chung Chan	Graduate Student
Dongqing Huang	Graduate Student

Case Western

Thomas Shutt	PI, Professor
Dan Akerib	PI, Professor
Karen Gibson	Postdoc
Tomasz Biesiadzinski	Postdoc
Wing H To	Postdoc
Adam Bradley	Graduate Student
Patrick Phelps	Graduate Student
Chang Lee	Graduate Student
Kati Pech	Graduate Student

Imperial College London

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

Lawrence Berkeley + UC Berkeley

Bob Jacobsen	PI, Professor
Murdock Gilchriese	Senior Scientist
Kevin Lesko	Senior Scientist
Carlos Hernandez Faham	Postdoc
Victor Gehman	Scientist
Mia Ihm	Graduate Student

Lawrence Livermore

Adam Bernstein	PI, Leader of Adv. Detectors
Dennis Carr	Mechanical Technician
Kareem Kazkaz	Staff Physicist
Peter Sorensen	Staff Physicist
John Bower	Engineer

LIP Coimbra

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

SD School of Mines

Xinhua Bai	PI, Professor
Tyler Liebsch	Graduate Student
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
Clement Sofka	Graduate Student

UC Davis

Mani Tripathi	PI, Professor
Bob Svoboda	Professor
Richard Lander	Professor
Britt Holbrook	Senior Engineer
John Thomson	Senior Machinist
Ray Gerhard	Electronics Engineer
Aaron Manalaysay	Postdoc
Richard Ott	Postdoc
Jeremy Mock	Graduate Student
James Morad	Graduate Student
Nick Walsh	Graduate Student
Michael Woods	Graduate Student
Sergey Uvarov	Graduate Student
Brian Lenardo	Graduate Student

UC Santa Barbara

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

University College London

Chamkaur Ghag	PI, Lecturer
Lea Reichhart	Postdoc
Sally Shaw	Graduate Student

SUNY Albany

Matthew Szydagis	PI, Professor

Collaboration Meeting, Sanford Lab, March 2014

University of Edinburgh

Alex Murphy	PI, Reader
Paolo Beltrame	Research Fellow
James Dobson	Postdoc

University of Maryland

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

University of Rochester

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

University of South Dakota

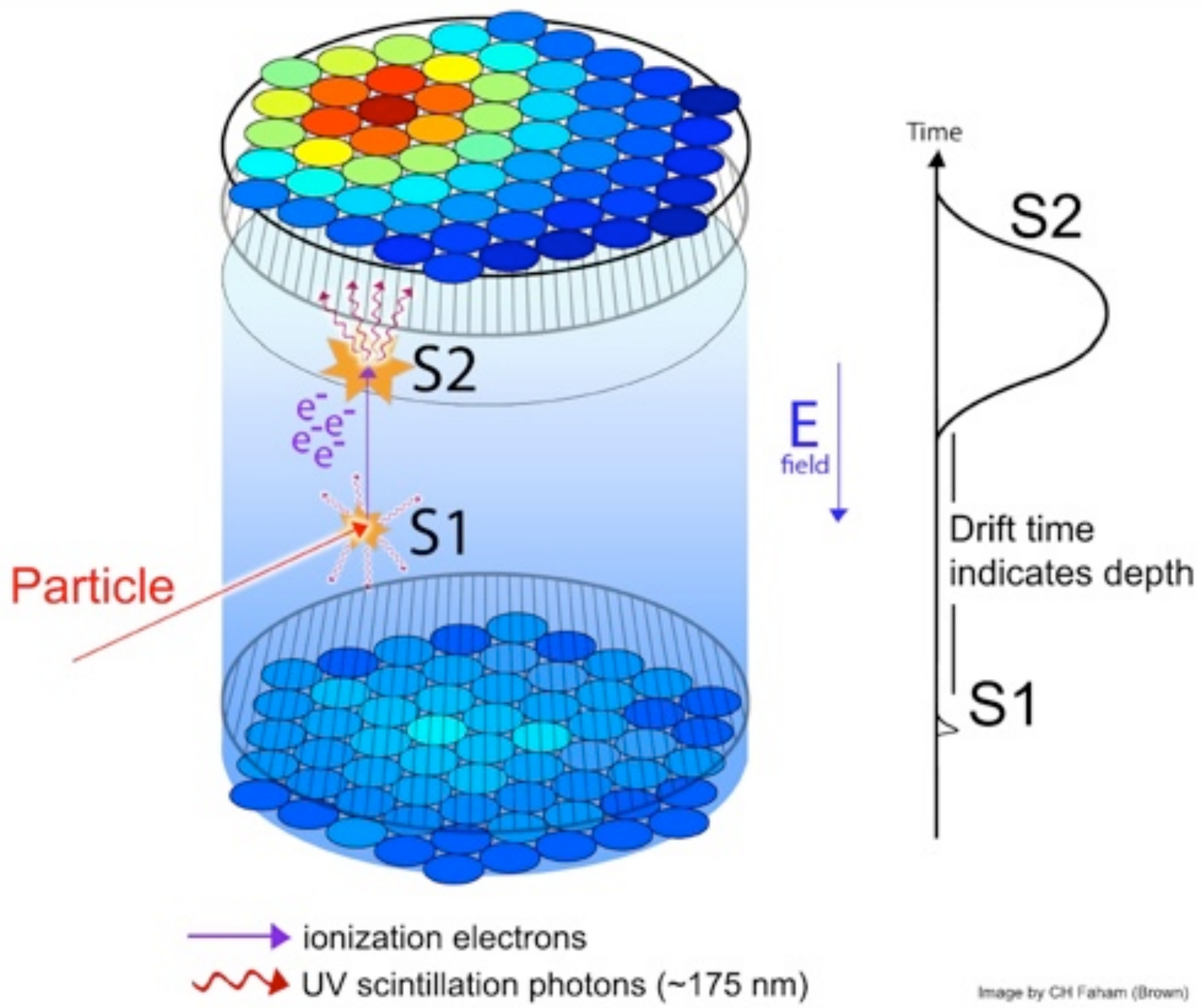
Dongming Mei	PI, Professor
Chao Zhang	Postdoc
Angela Chiller	Graduate Student
Chris Chiller	Graduate Student
Dana Byram	*Now at SDSTA

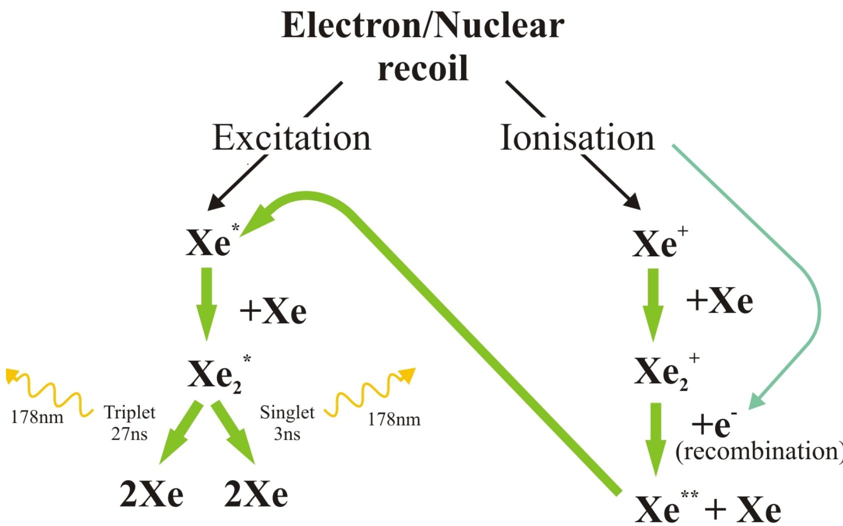
Yale

Daniel McKinsey	PI, Professor
Peter Parker	Professor
Sidney Cahn	Lecturer/Research Scientist
Ethan Bernard	Postdoc
Markus Horn	Postdoc
Blair Edwards	Postdoc
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Nicole Larsen	Graduate Student
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Ariana Hackenburg	Graduate Student
Elizabeth Boulton	Graduate Student

Principle of detection: dual phase xenon TPC

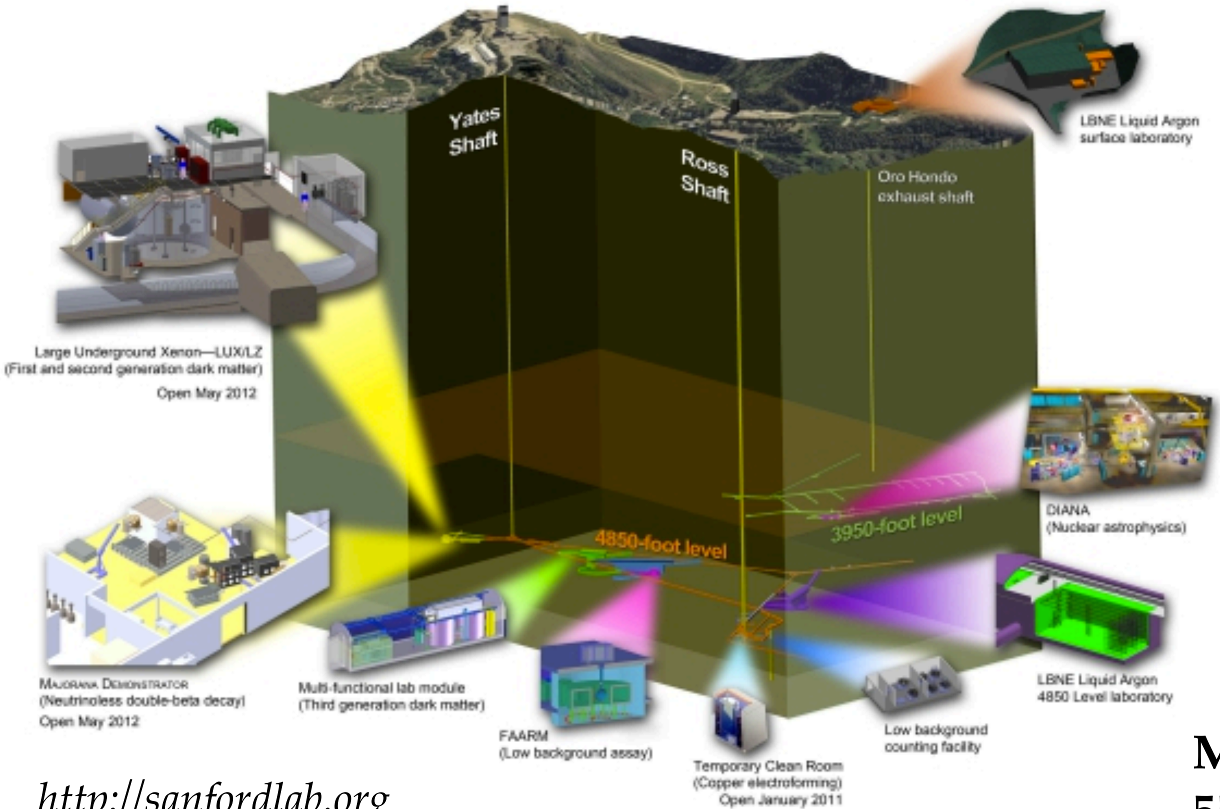
- Xe: scintillation+ionization, self-shielding, ~3 g/cm³ and self shielding, A² boost for σ_{SI}
- Energy reconstruction, 3D pos. rec., discrimination

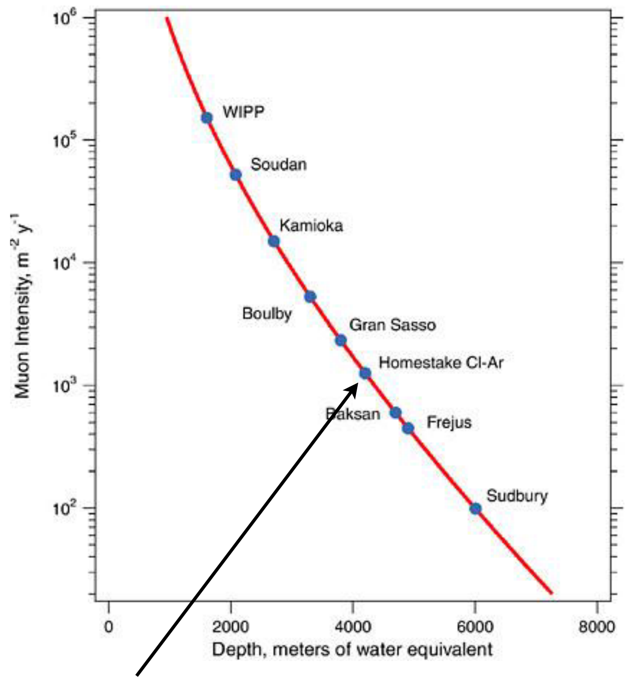




Sanford Underground Research Facility

- Deep underground science at former Homestake gold mine in Lead, South Dakota
- LUX based in Davis campus on the 4850′ level (1300 mwe)
- Excellent lab facilities and support

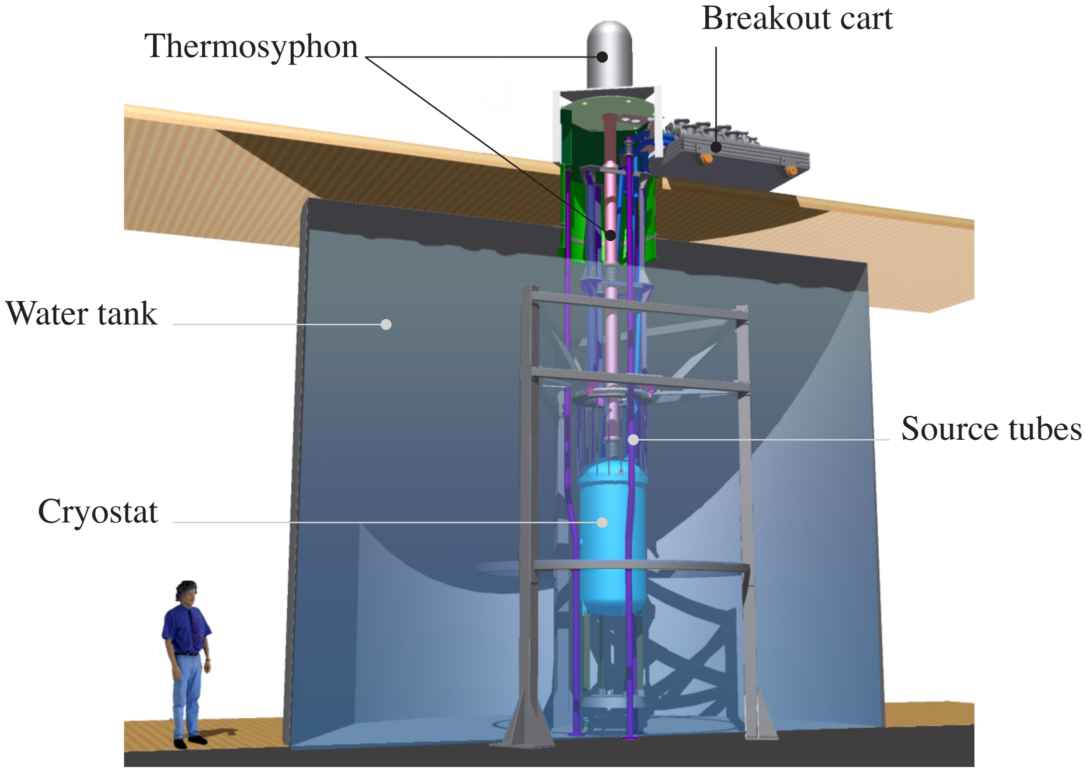


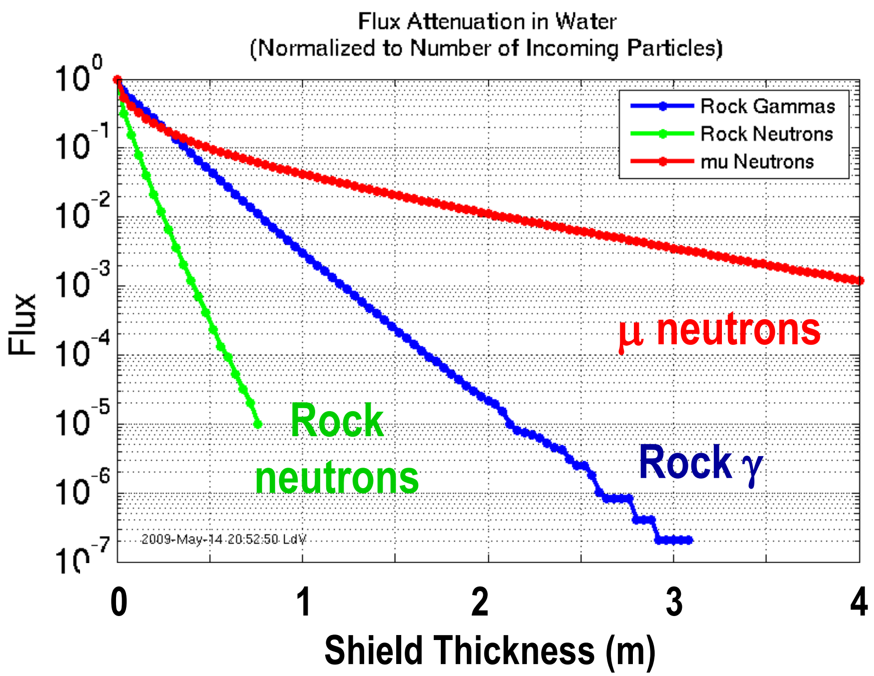


http://sanfordlab.org

Muon flux reduced by 10^7:
55.2 $m^{-2}s^{-1}$ at surface → 1×10^{-5} $m^{-2}s^{-1}$

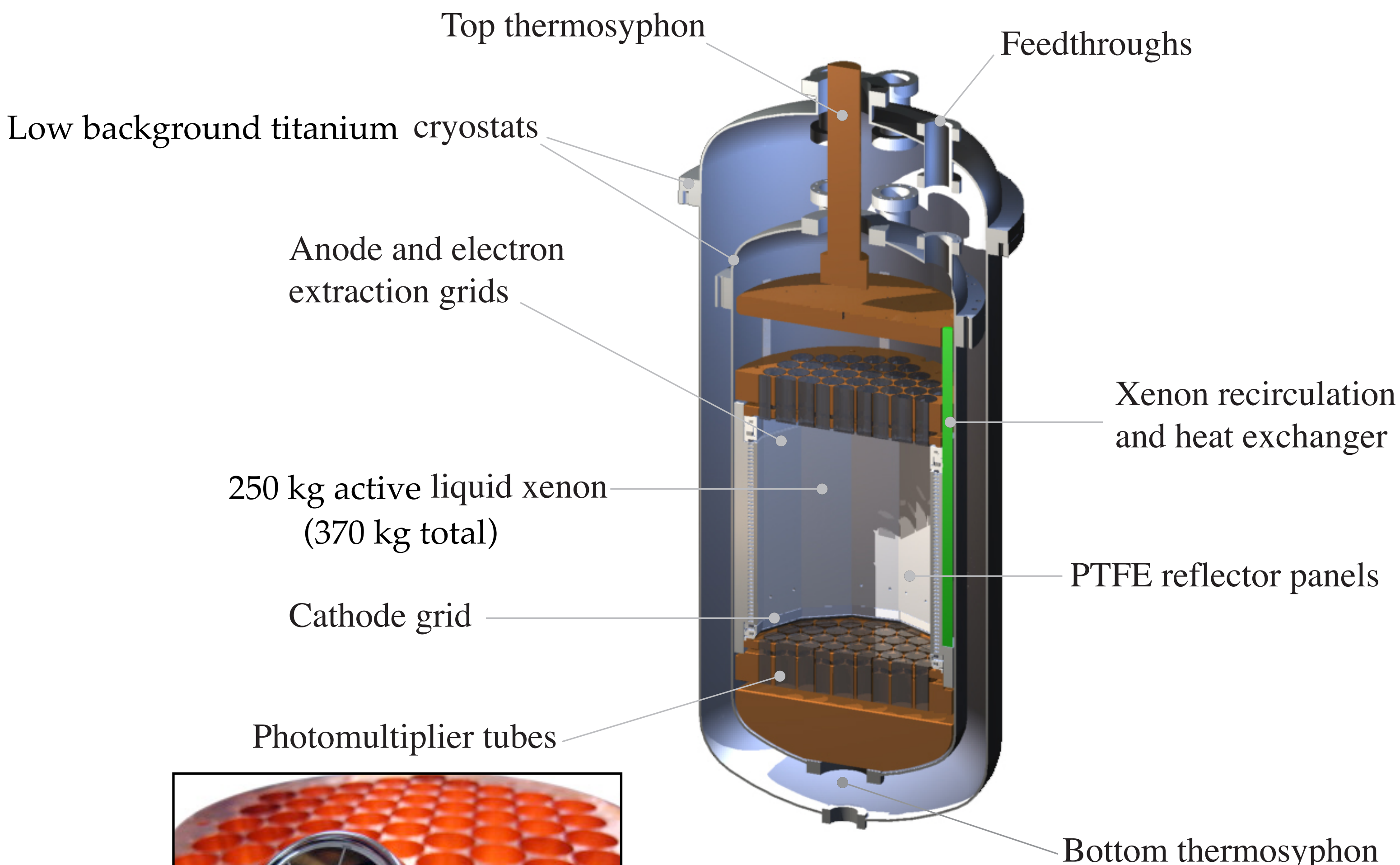
An ultra low background environment

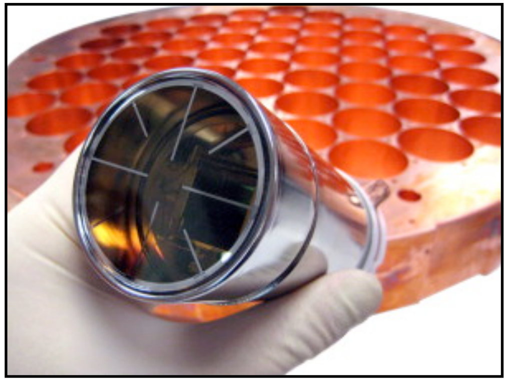




Full details of LUX backgrounds in recent paper: Astroparticle Physics (2015), pp. 33-46
http://arxiv.org/abs/1403.1299

The LUX cryostat

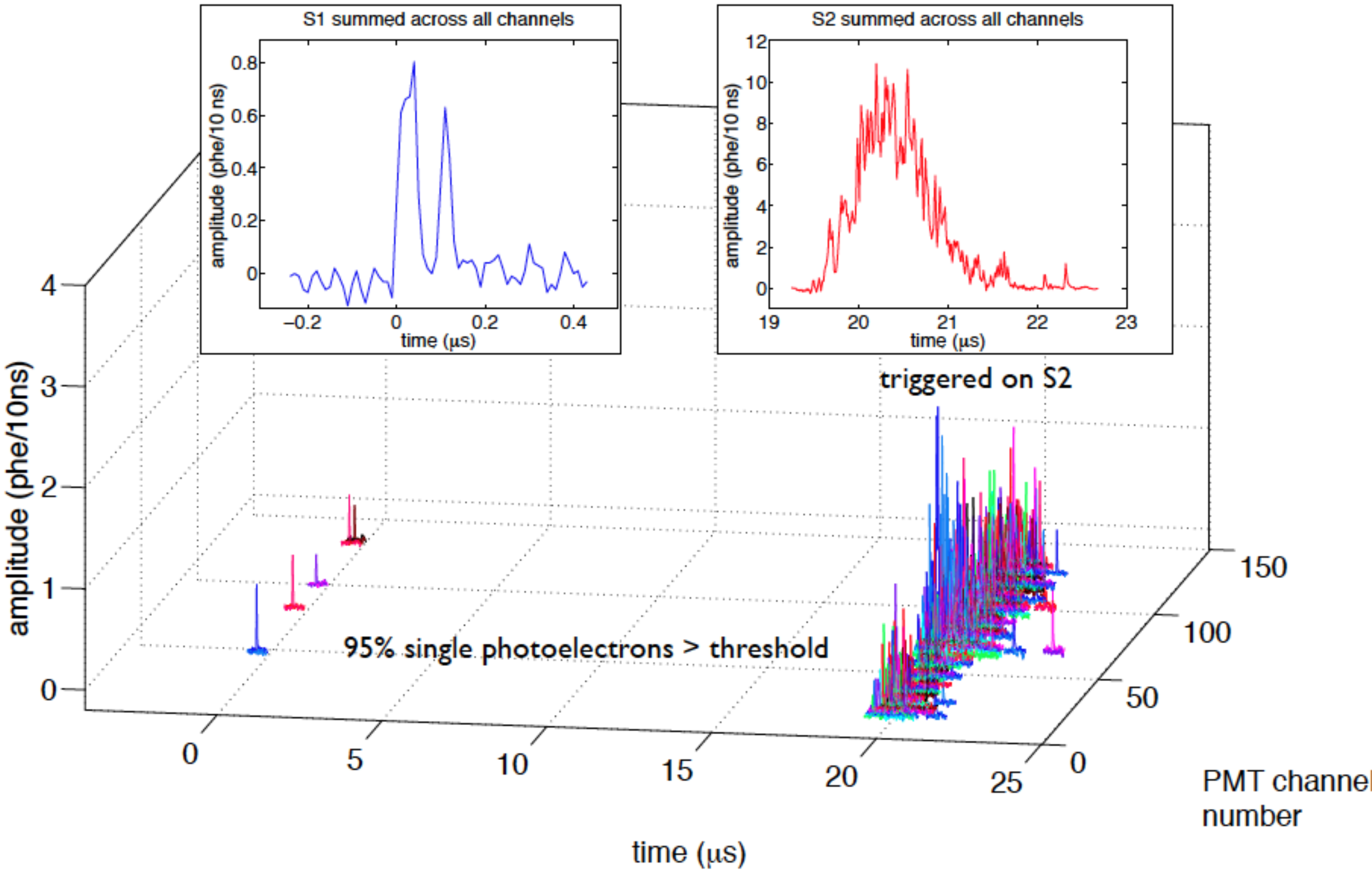




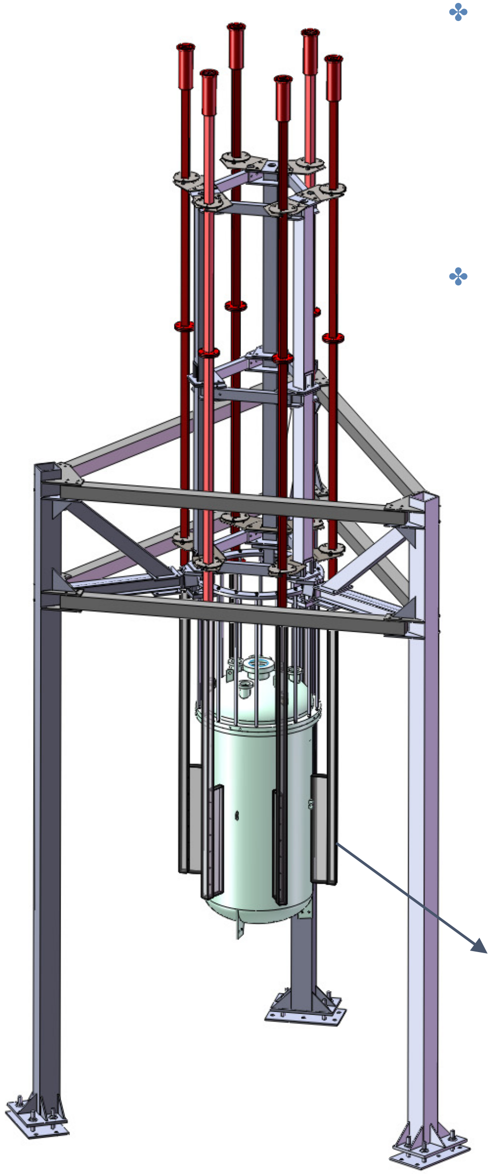
Hamamatsu R8778 PMTs (61 top, 61 bottom)

Full description of LUX:
NIM. A ***704****, 111-126(2013), arXiv:1211.3788*

A LUX event - 1.5 keV gamma ray scatter



Calibrating LUX

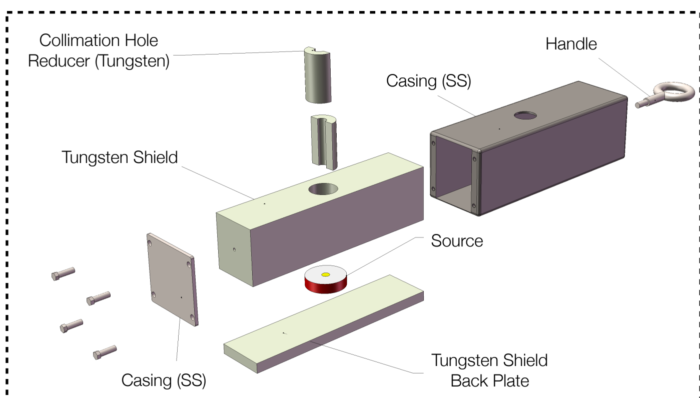


- External sources via source tubes:
  - Americium-beryllium (AmBe) and ^{252}Cf: low energy neutrons → validating NR models and detector sims, NR efficiencies

WIMP-like

- Xenon self-shielding → internal sources injected into circulation system preferable:
  - ^{83m}Kr: half-life ~1.8 hours, 32.1 + 9.4 keV betas → weekly purity, xyz corrections
  - Tritiated methane (CH3T): low energy betas (end point 18 keV). High stats, uniform and high purity → ER band, ER acceptance

external source holder



^{83}Rb coated charcoal plummed into gas system → ^{83m}Kr

Timeline of LUX so far

LUX funded in **2008** by DOE and NSF

Above-ground laboratory completed at SURF in **2011**
LUX assembled; above-ground commissioning runs completed

Underground laboratory completed at SURF in **2012**.
LUX moves underground in July to its new home in the Davis cavern.

Detector cooldown, xenon condensing and detector commissioning completed and gas phase testing completed April **2013**

Initial (3-month) WIMP search → October **2013**

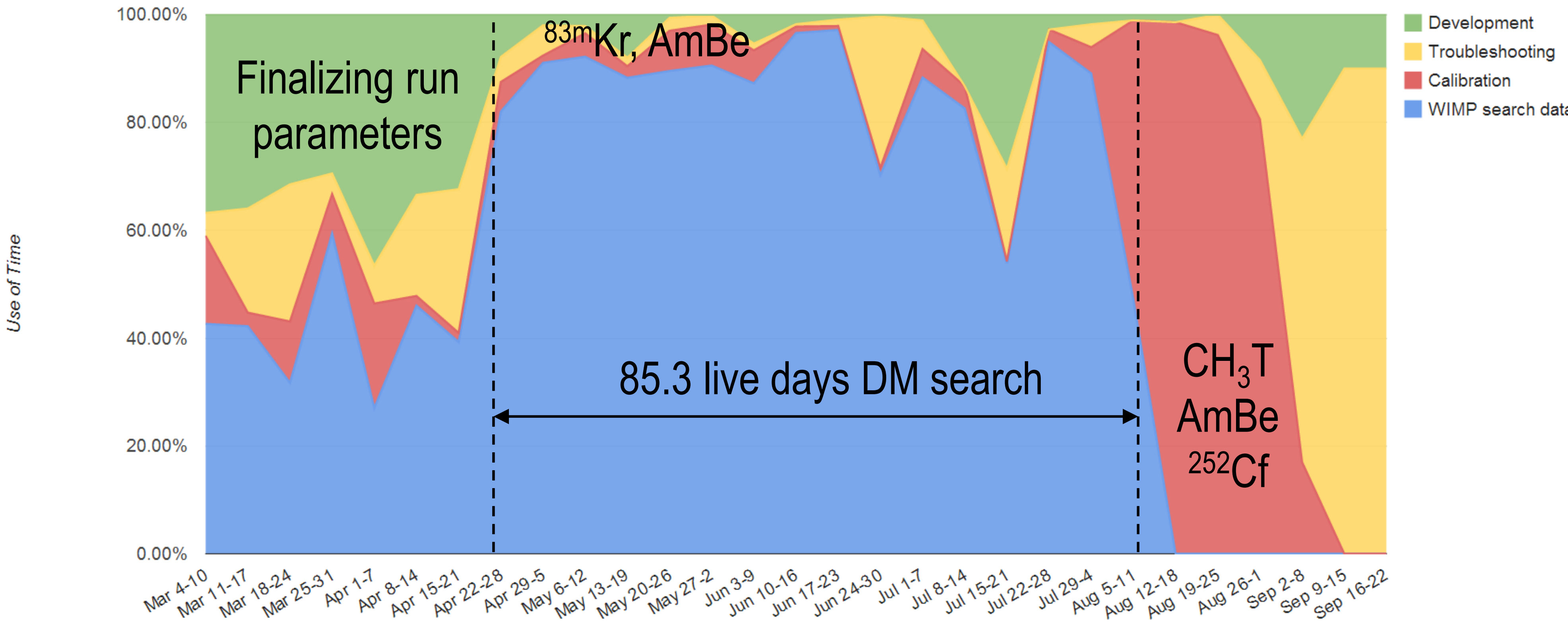
Neutron gun calibration Nov/Dec **2013**

Detector development and preparations for 300-day run: Jan **2014** → present

First dark matter results from LUX

118 kg and 85.3 days of live-time data

Run 3 data-taking

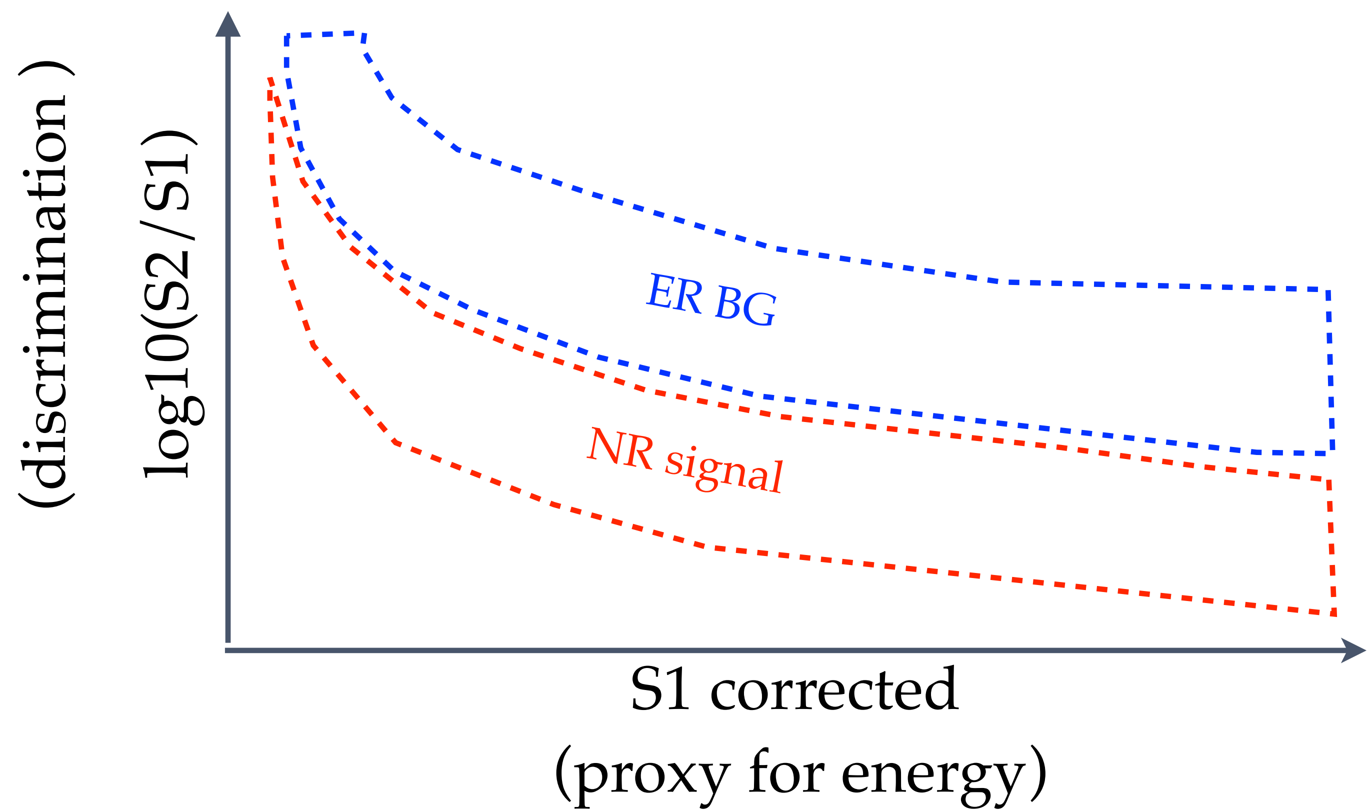


- $>95\%$ data taking efficiency over WIMP search region
- Kr and AmBe calibrations throughout, CH3T after WIMP search

Analysis strategy

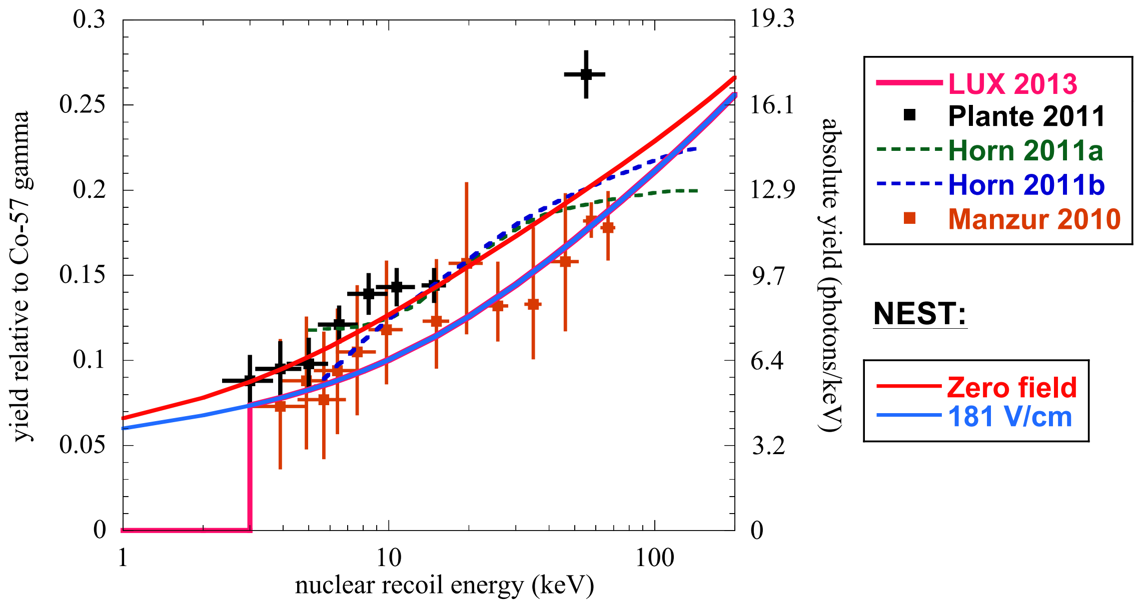
Unblinded analysis - aim for minimal cuts and high acceptance

Unbinned PLR to compare data with predicted signal + background in 4 parameter space: **x** = S1, log10(S2/S1), r and z

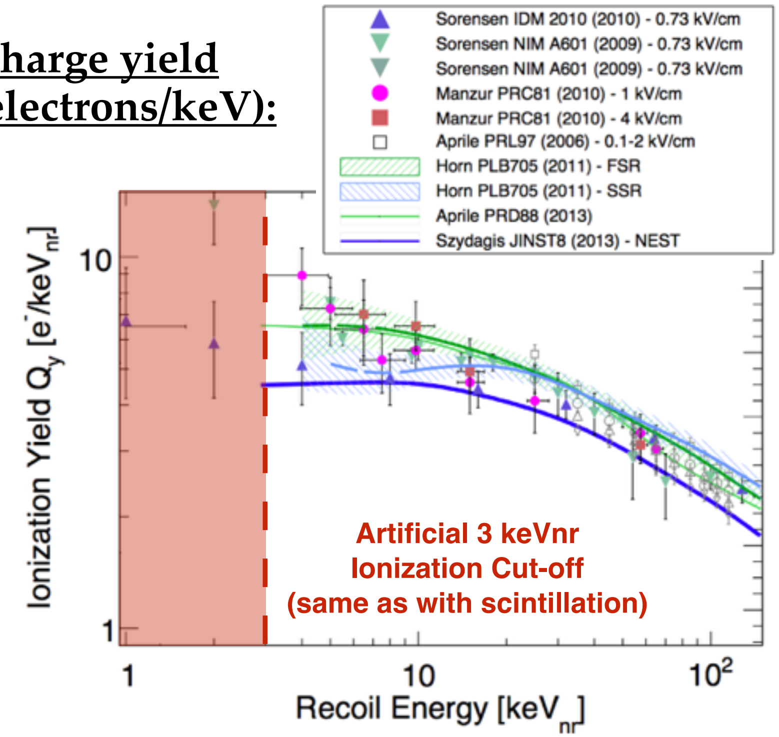


Light and charge yields from NEST

Light yield (photons/keV):



Charge yield (electrons/keV):



- Yields at vertex based on **N**oble **E**lement **S**imulation **T**echnique, *M. Szydagis, JINST 6, P10002 (2011)*
    - Uses full Lindhard model with Hitachi correction *Sorensen and Dahl, Phys. Rev. D 83 , 063501 (2011)*
- Anchored to experimental data
- Includes electric field quenching of light signal

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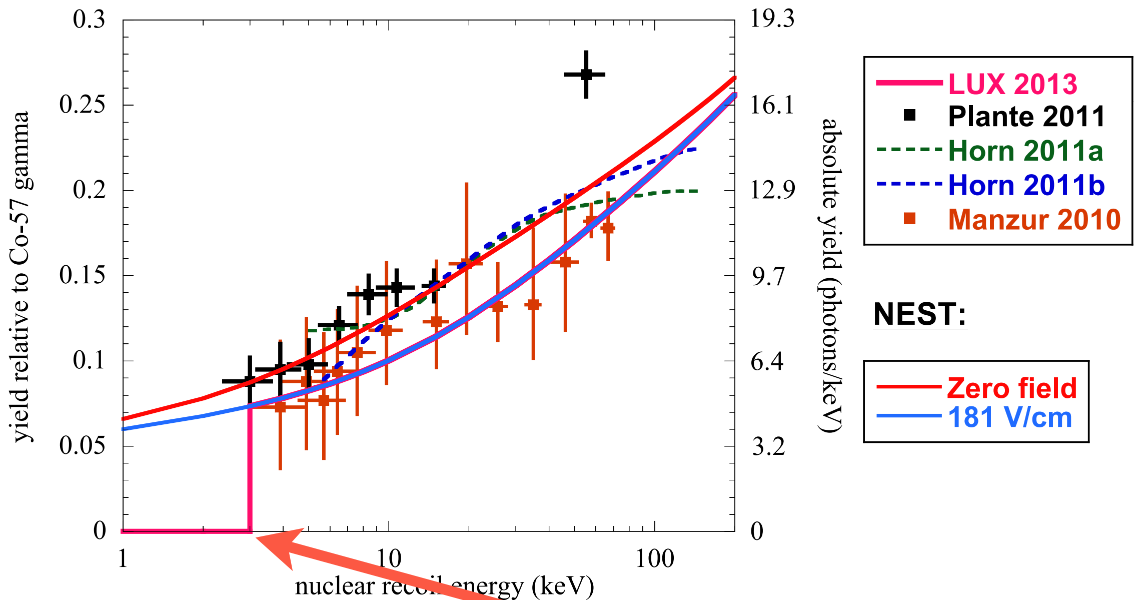

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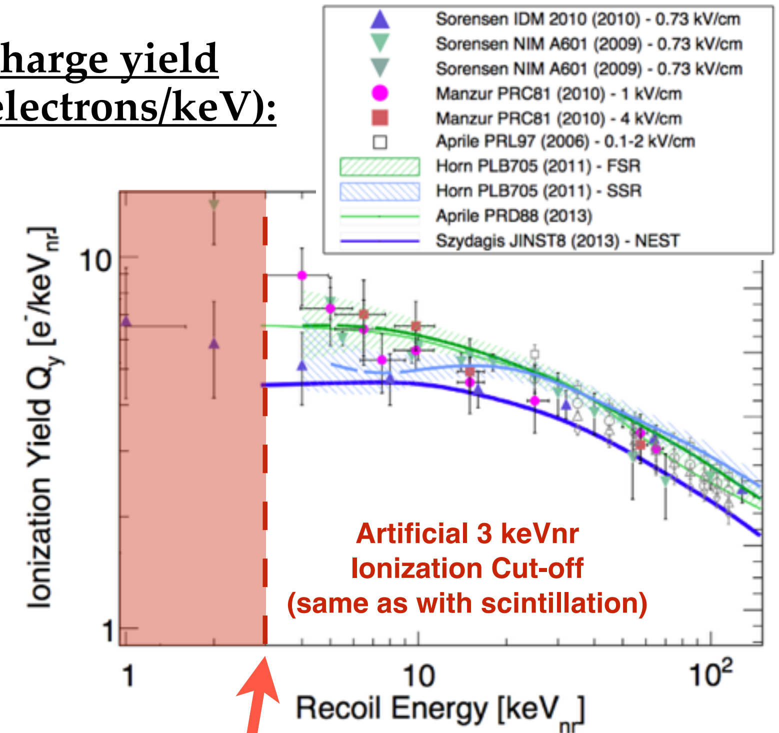

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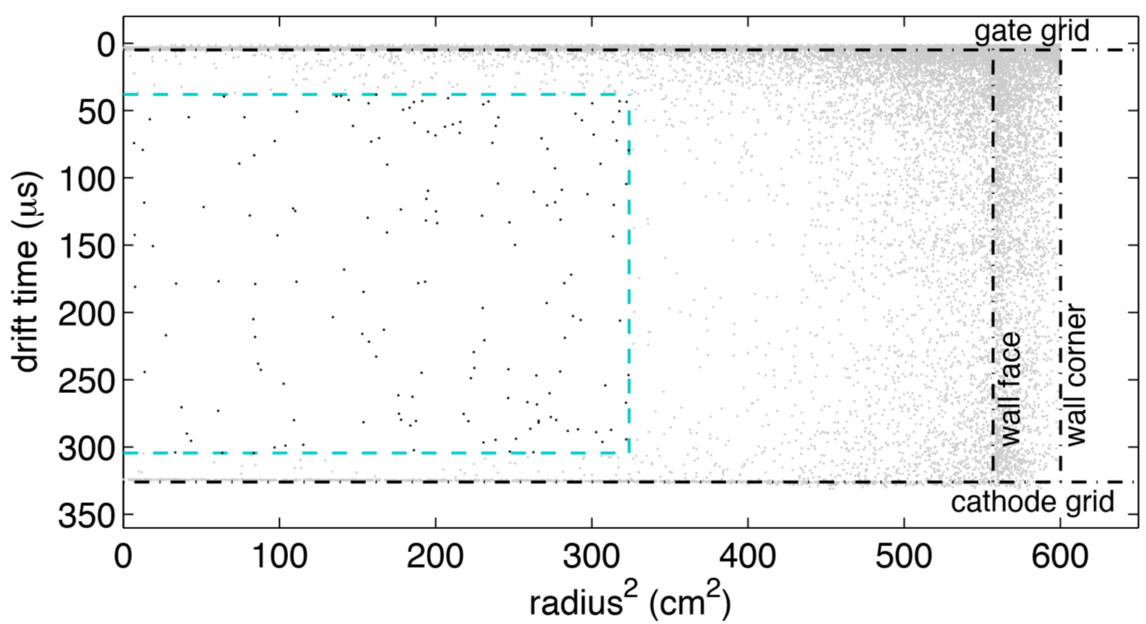
- Anchored to experimental data
- Includes electric field quenching of light signal

For first WIMP search result LUX used conservative cut-off below 3 keVnr

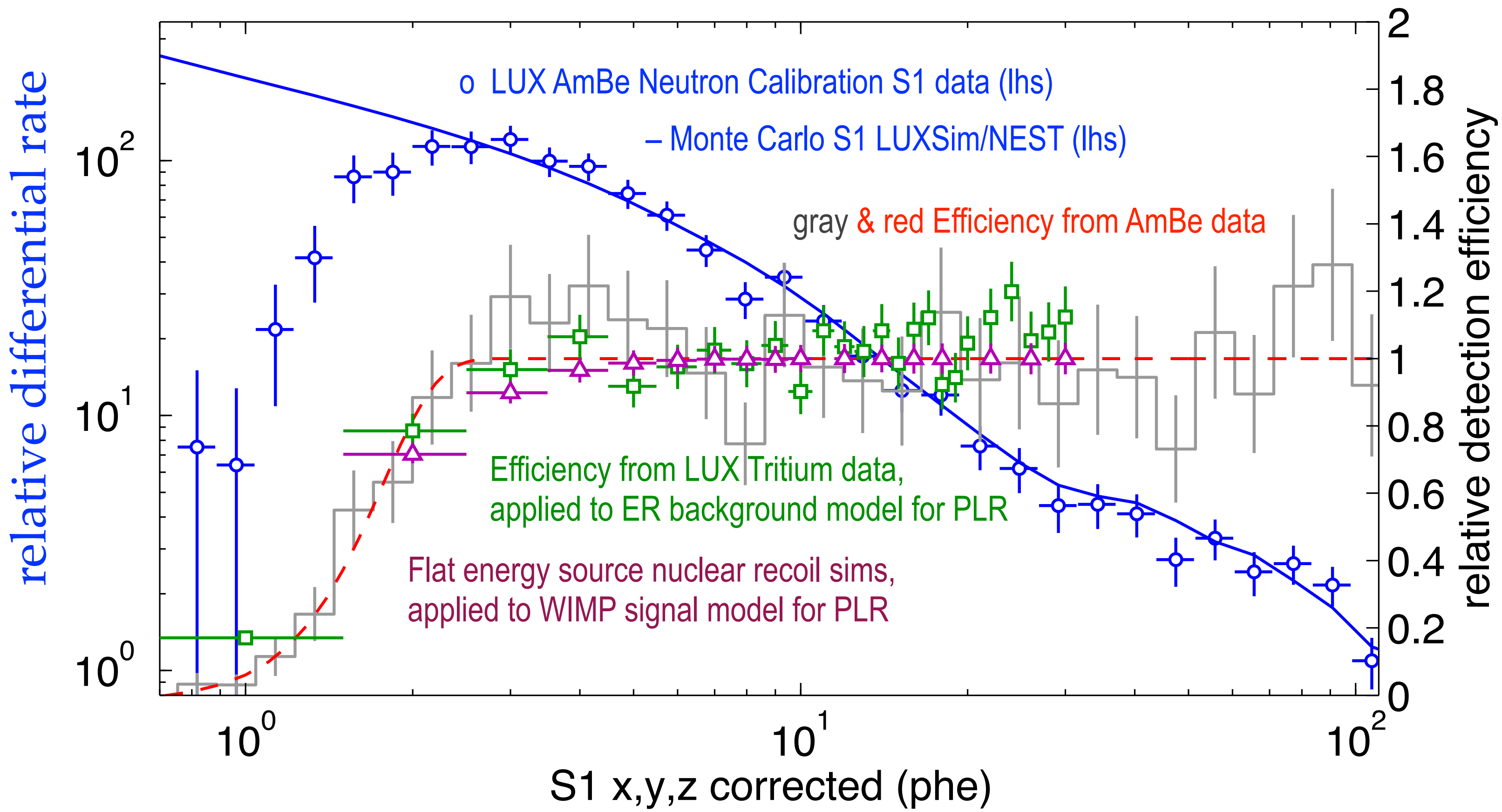
Run 3 event selection

Cut	Events Remaining
all triggers	83,673,413
detector stability	82,918,902
single scatter	6,585,686
S1 energy (2 – 30 phe)	26,824
S2 energy (200 – 3300 phe)	20,989
single electron background	19,796
fiducial volume	160

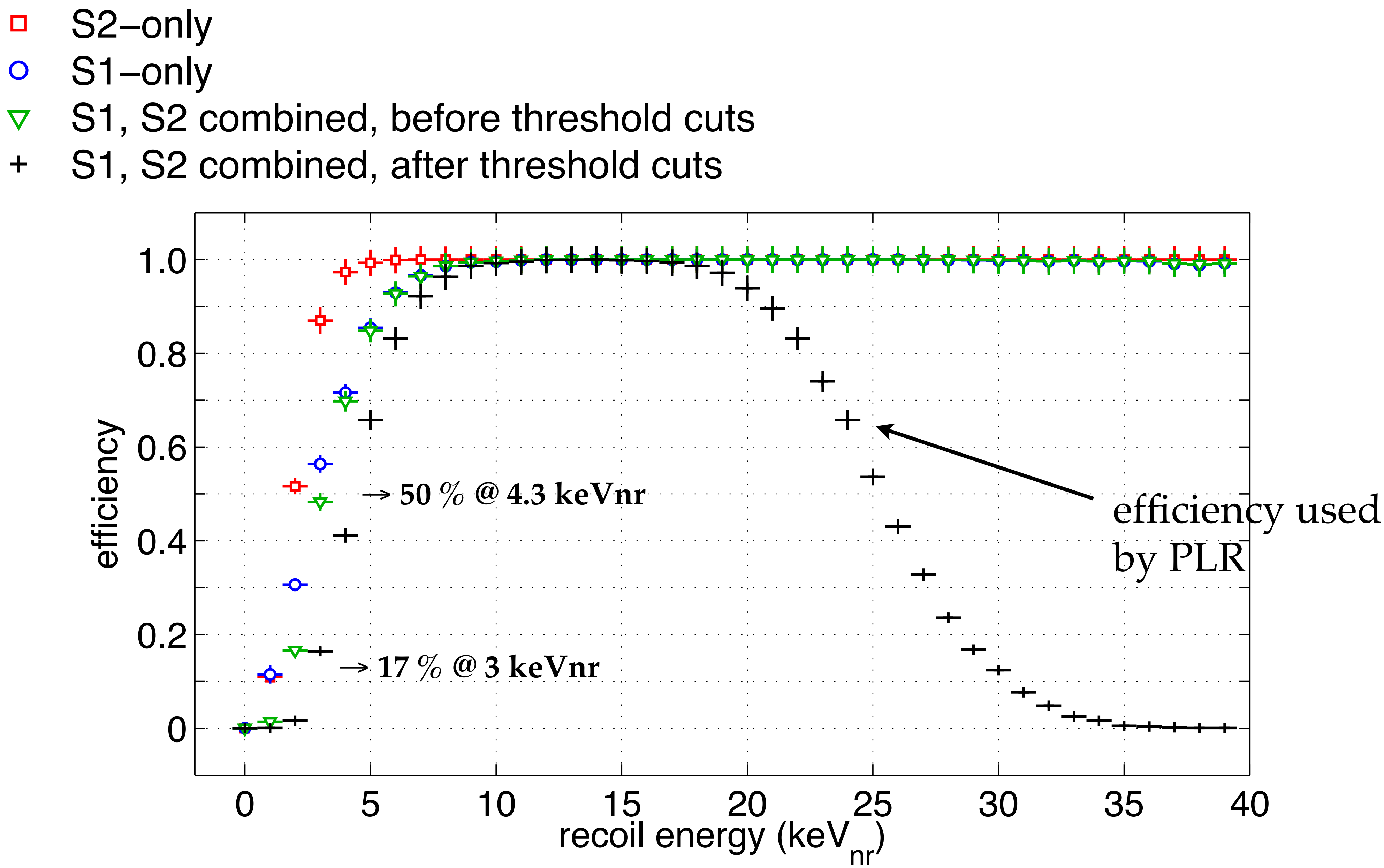


Extensive measurements and validation of efficiencies

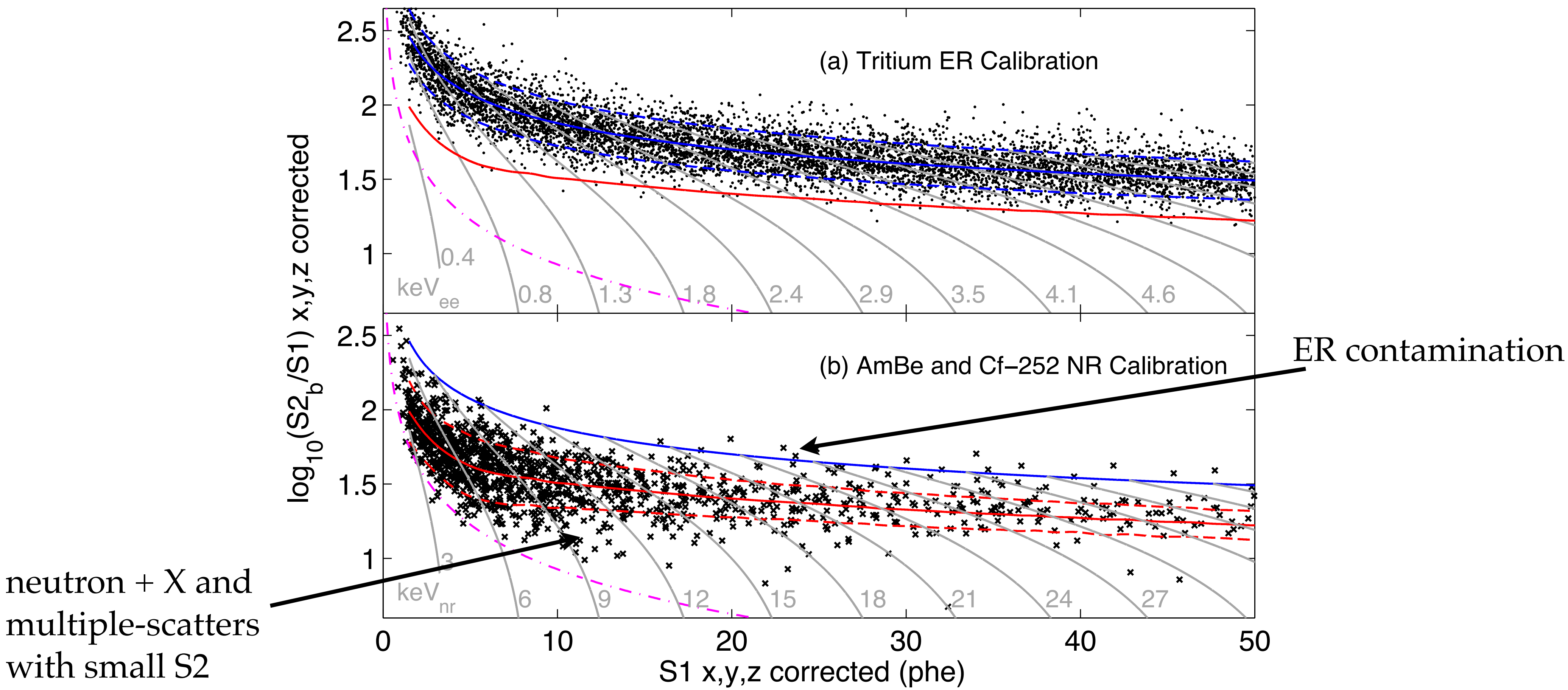
- AmBe neutron calibration, Tritium data, LED calibrations and full MC simulation of NR events (includes all analysis cuts):
  - Dominates overall efficiency



NR acceptance efficiency

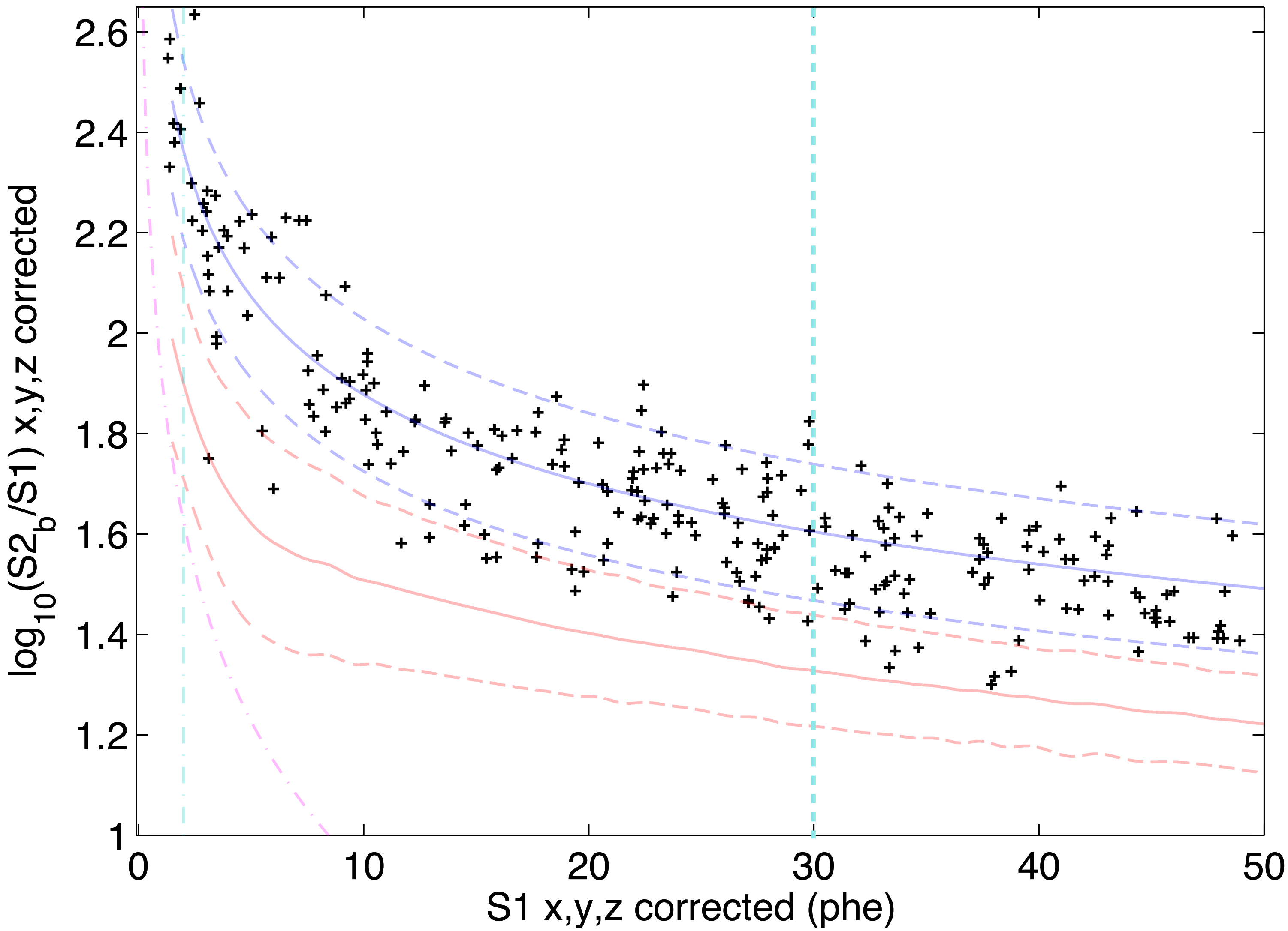


Background discrimination: ER and NR bands

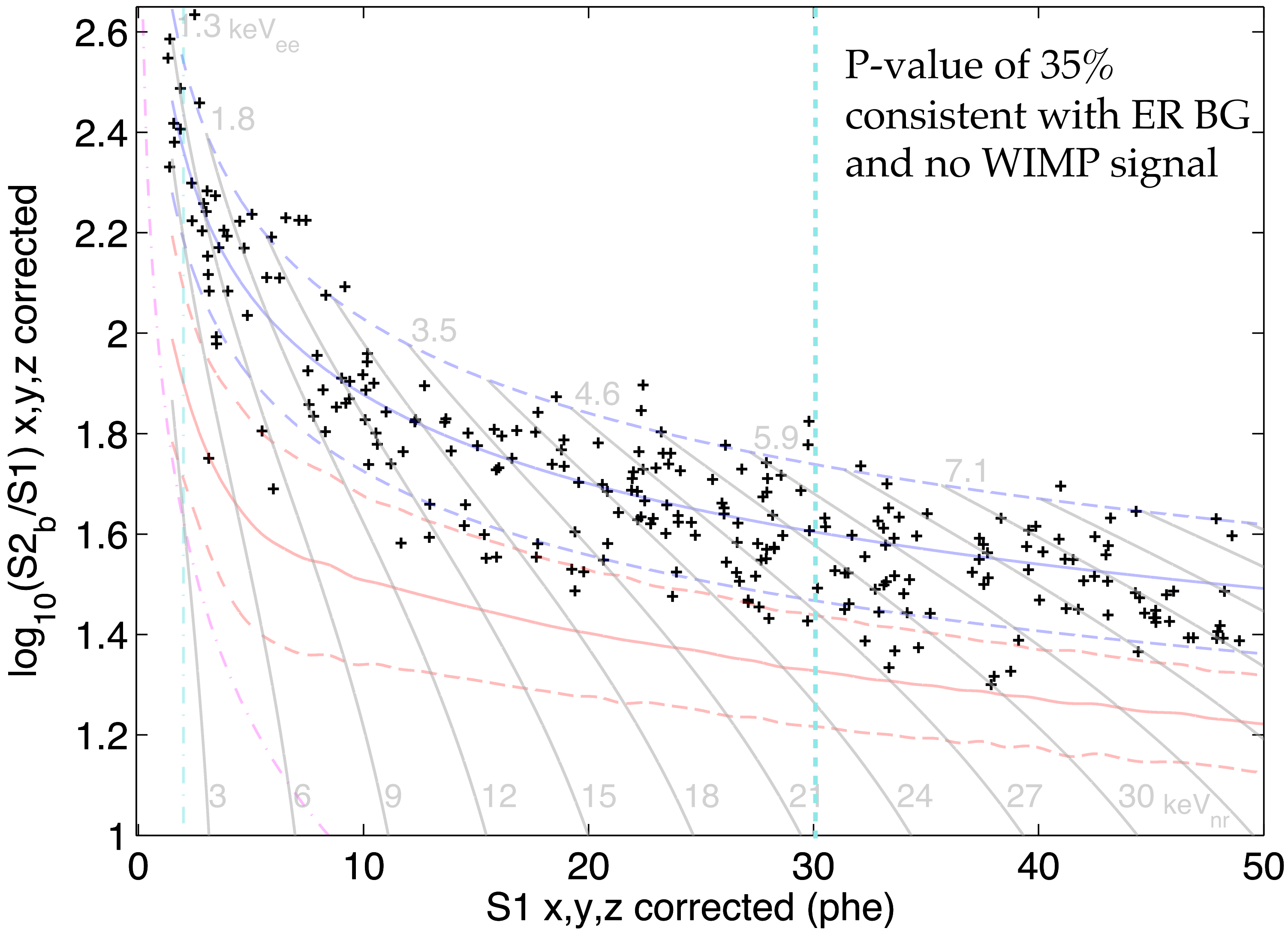


- ER band directly from high stats tritium calibration, NR band from sims validated against neutron calibration data
- For 50% NR acceptance average discrimination measured to be 99.6% in ROI [S1 2-30 phe]

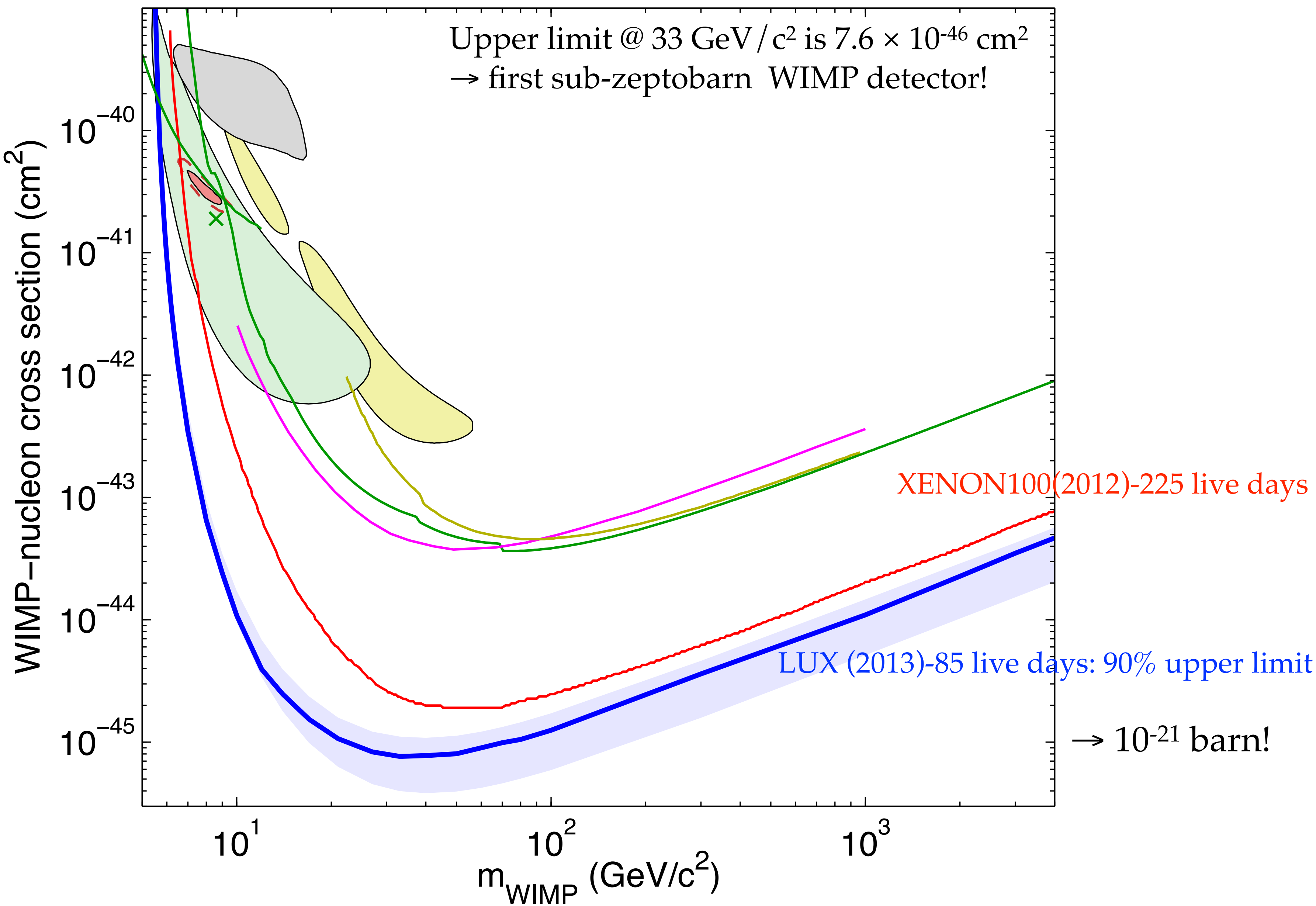
Run 3 LUX WIMP search: 85.3 live-days, 118 kg FV



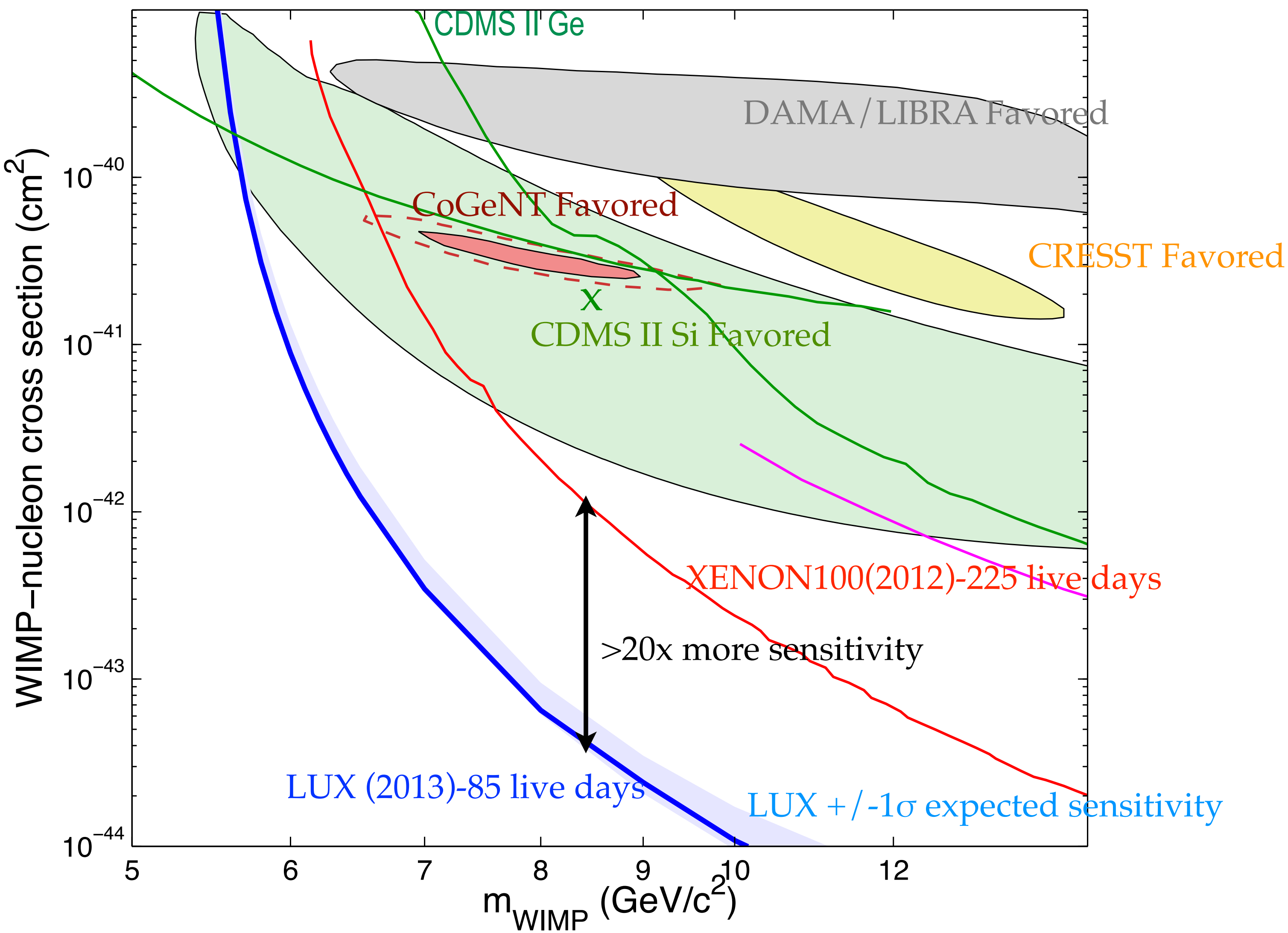
Run 3 LUX WIMP search: 85.3 live-days, 118 kg FV



Spin-independent sensitivity plots



Low-mass WIMPs excluded

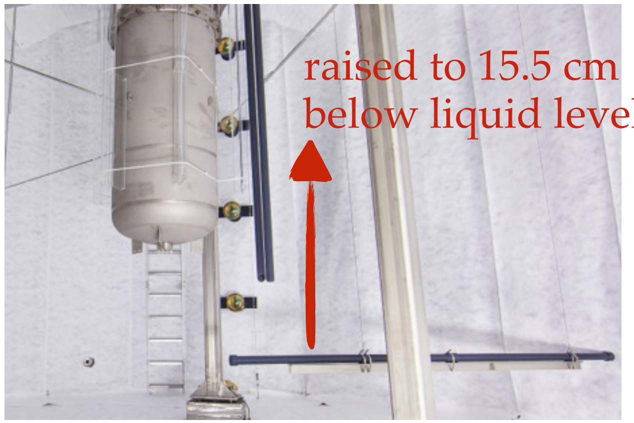


Neutron gun calibration

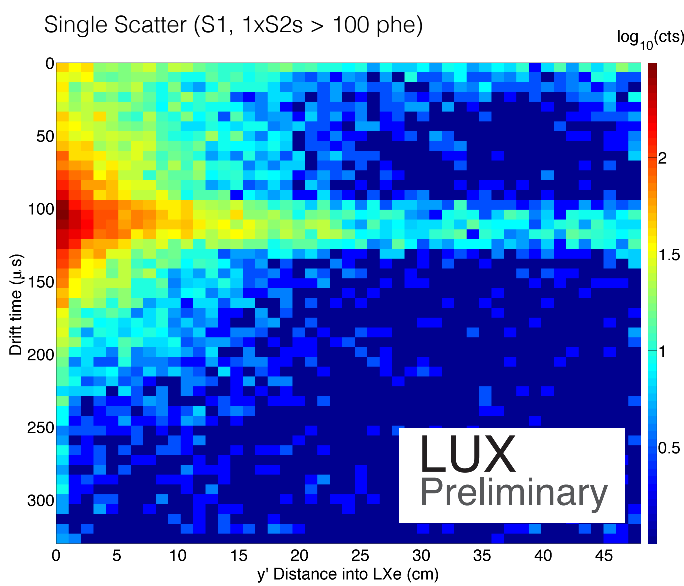
Following 2013 WIMP search run

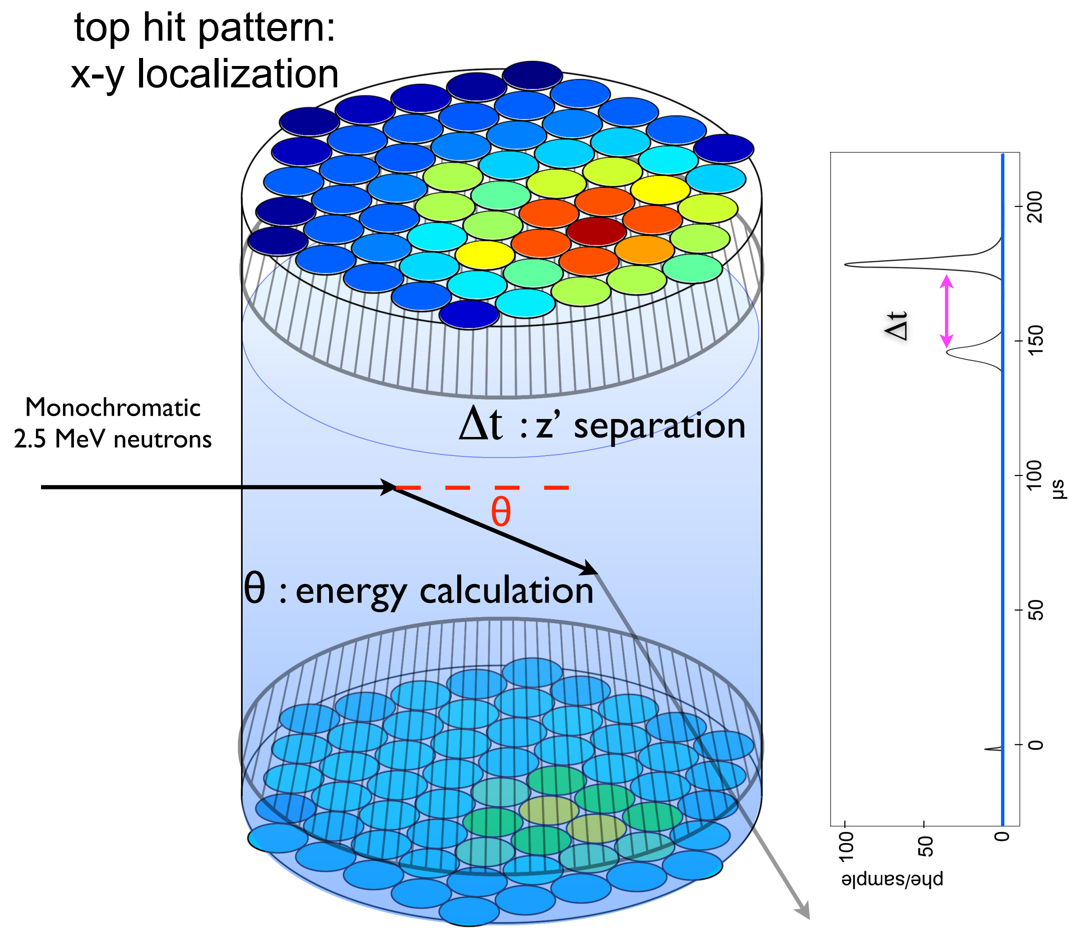
In situ neutron gun calibration in Autumn 2013

- 2.5 MeV monochromatic neutron generator outside water tank + adjustable neutron conduit to detector (leveled to ~1 degree)



- 105.5 live hours of neutron tube data





3D recon. S2 pos. for multi-scatter → scattering angle → recoil energy at first vertex:

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

Multiple-scatters → absolute charge yield

- Absolute charge measured to below 1 keV
- Demonstrates sensitivity for recoils below Run 3 cut-off

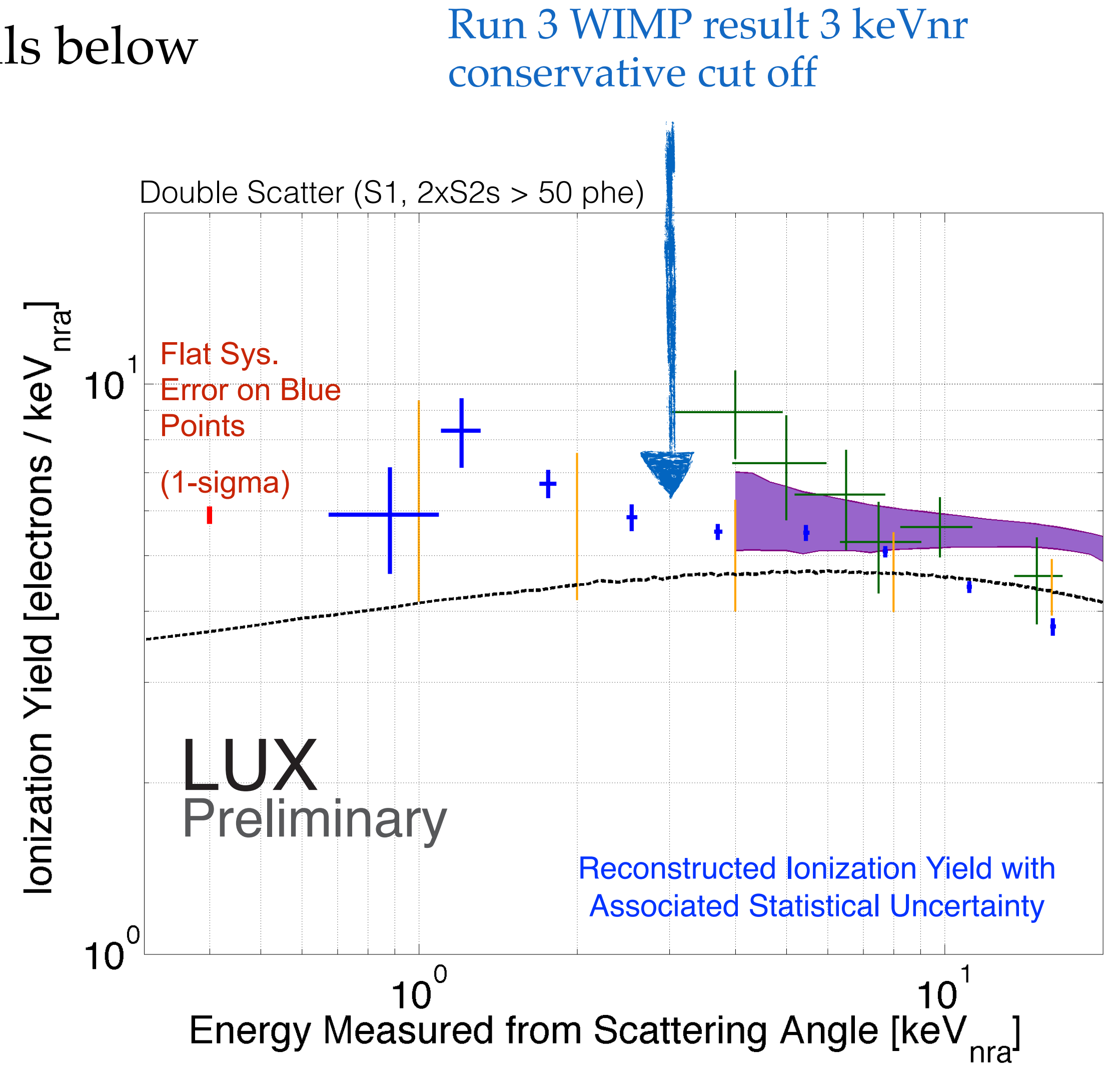
Blue Crosses - LUX Measured Qy; 181 V/cm (absolute energy scale)

Green Crosses - Manzur 2010; 1 kV/cm (absolute energy scale)

Purple Band - Z3 Horn Combined FSR/SSR; 3.6 kV/cm (energy scale from best fit MC)

Orange Lines - Sorensen IDM 2010; 0.73 kV/cm (energy scale from best fit MC)

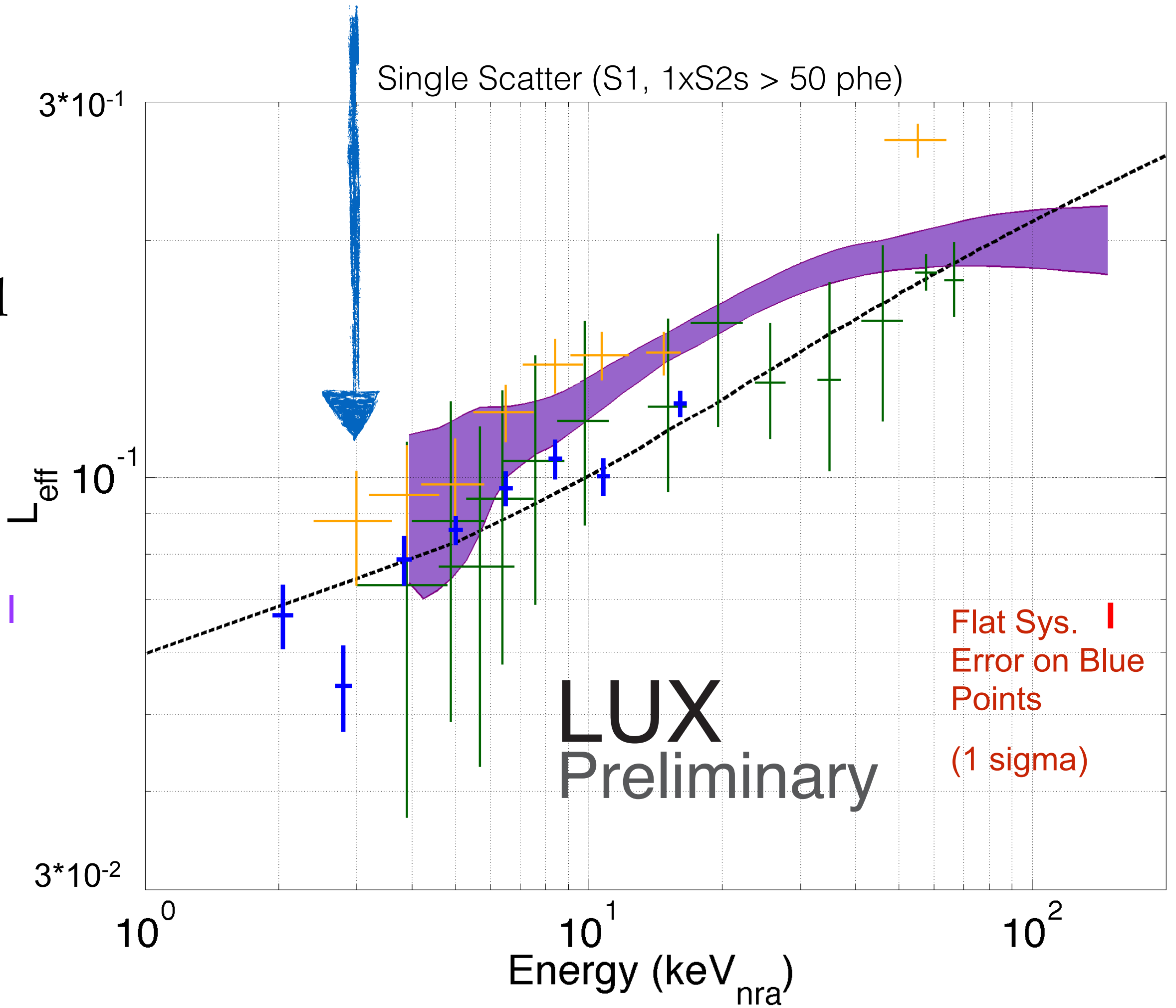
Black Dashed Line - Szydagis et al. (NEST) Predicted Ionization Yield at 181 V/cm



Single-scatters → light yield

- NEST + detector simulation to simulate single-scatter spectra
- Fit for L_{eff} in slices of S2 using χ^2 minimisation between data and simulated S1-spectra
- Energy scale from charge yield measurement

Run 3 WIMP result 3 keVnr conservative cut off



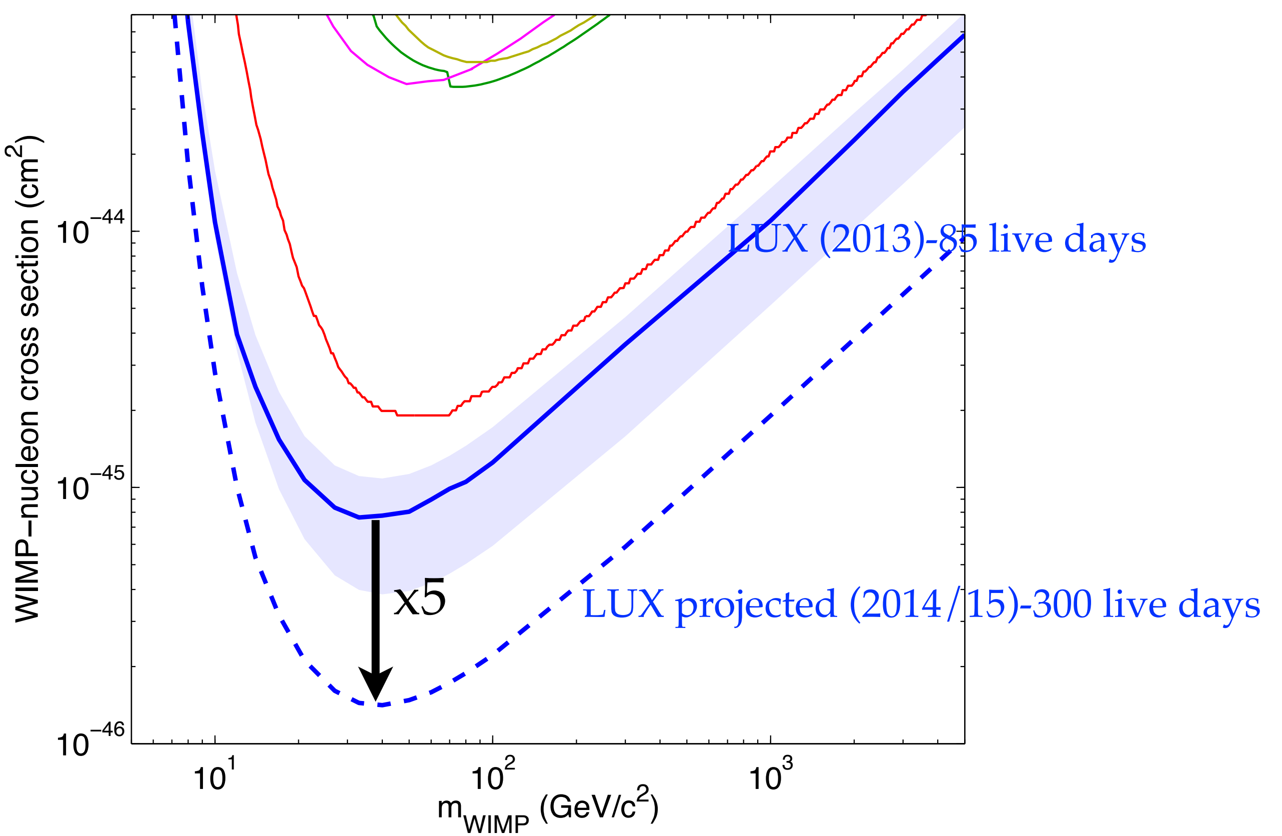
For more details:
http://www.pa.ucla.edu/sites/default/files/webform/20140228_jverbus_ucla2014.pdf
(forthcoming paper in preparation)

What's next?

New LUX analyses and 300 day run

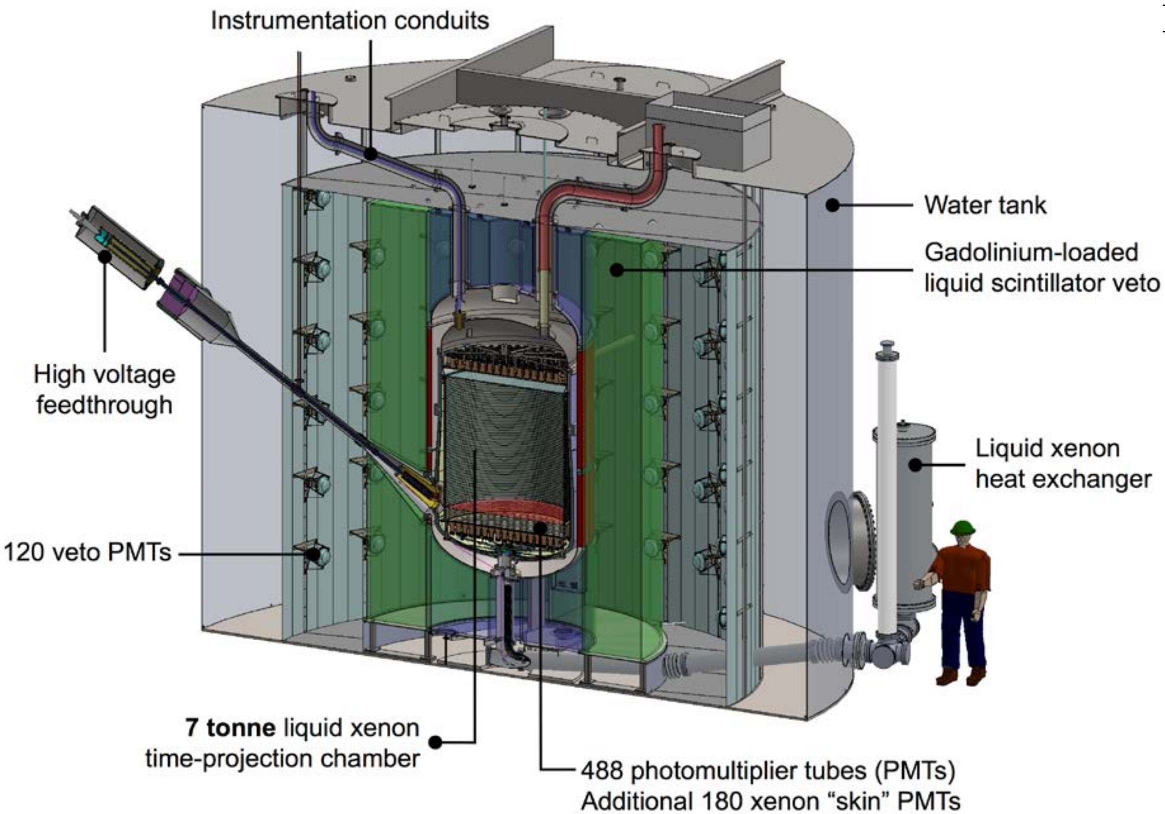
- **Lots of new papers in the pipeline:**
  - DD-data → revised Run 3 limit, S2-only, spin/momentum-independent limits, Axions, Halo/astrophysics-independent limits

- **300 day run expected to start soon:**
  - Not background limited
  - expect factor of ~5 improvement in sensitivity
  - → discovery possible

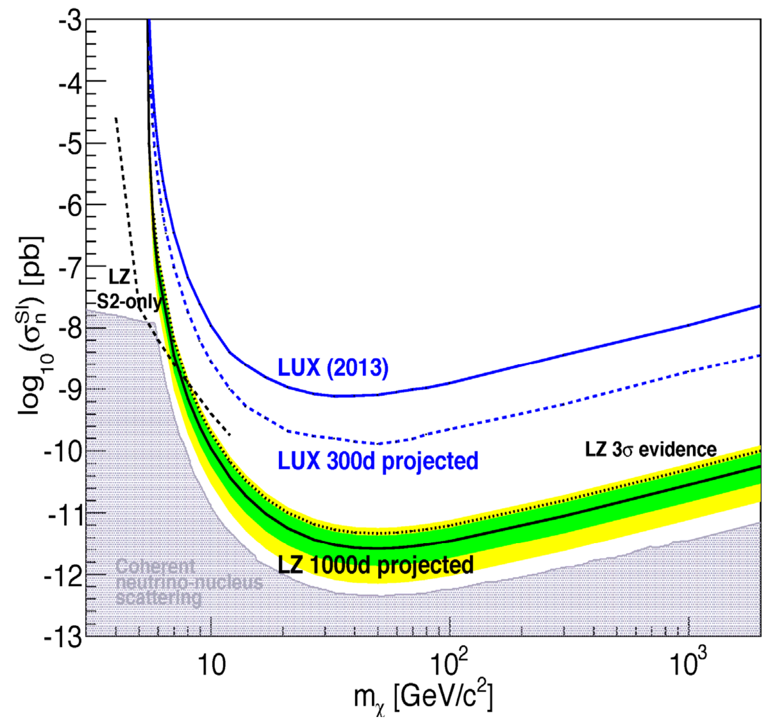


Longer term: LUX-ZEPLIN (LZ)

20 times LUX Xenon mass, active scintillator veto,
Xe purity at sub ppt level:



Projected sensitivity:



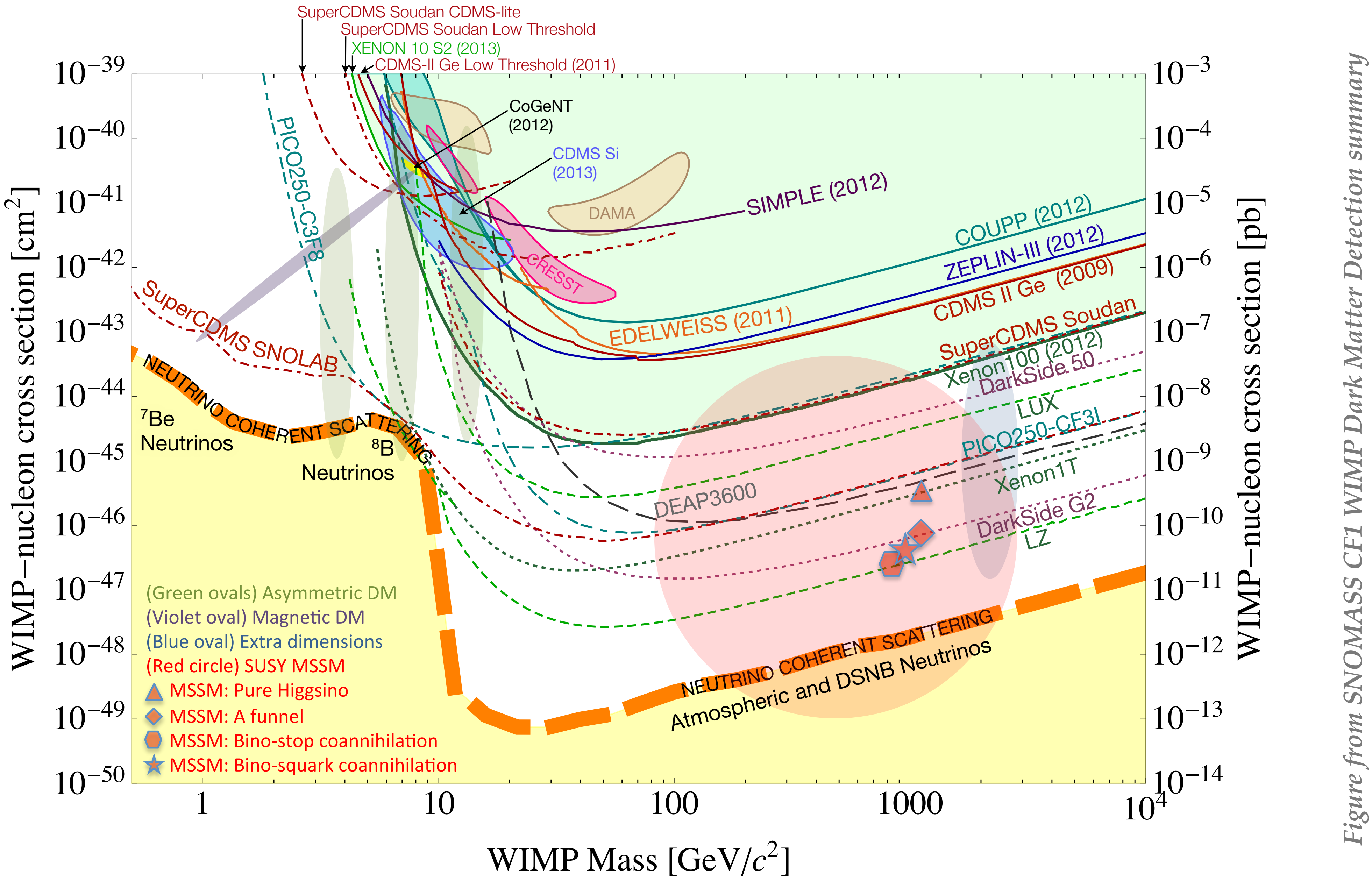
- Ultimate direct detection experiment - approaches coherent neutrino scattering backgrounds
- July 2014: selected as one of DOE/NSF second generation DM search experiments
- Scheduled to be deployed Davis lab 2016+

Summary

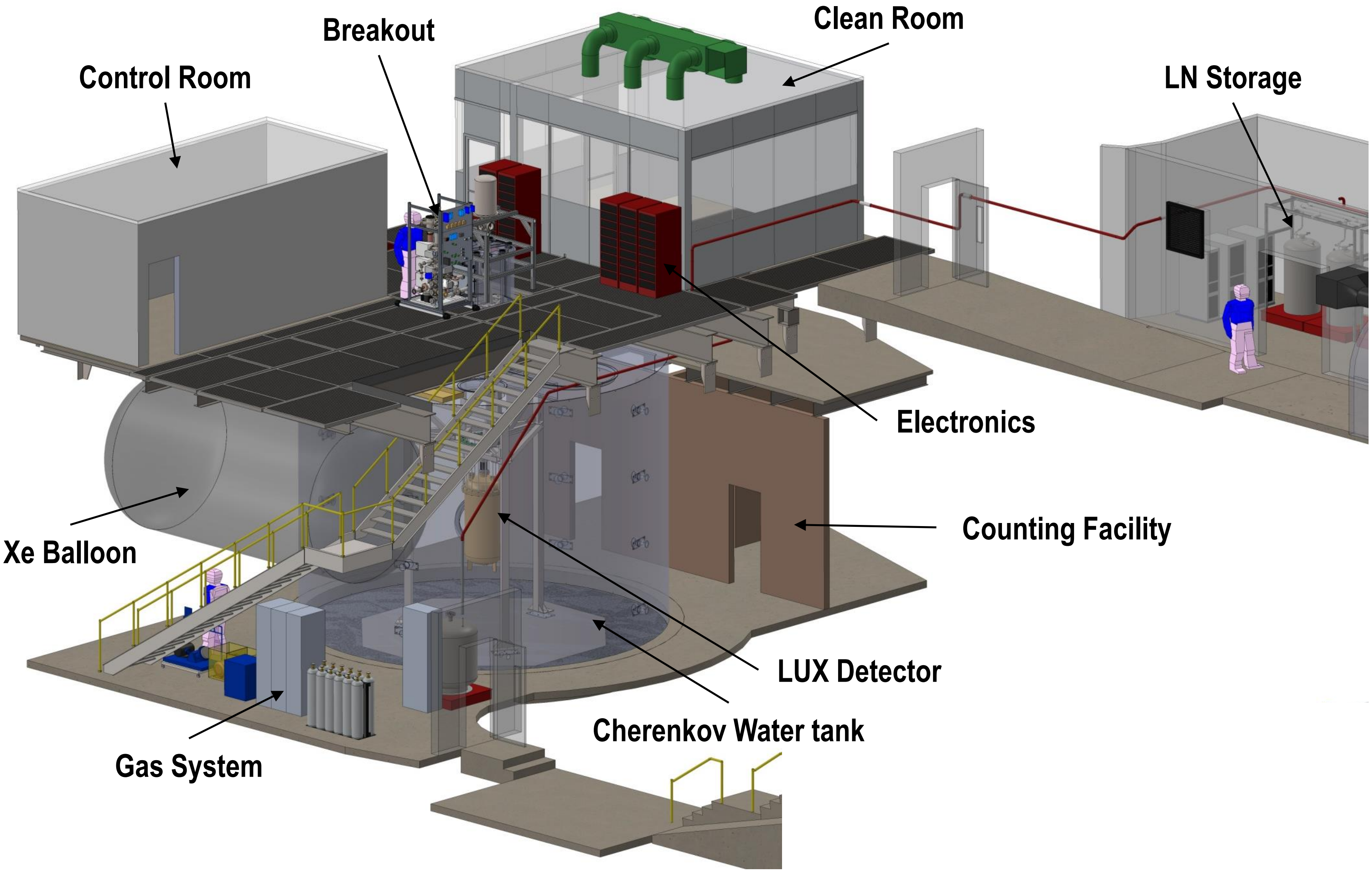
- With 85.3 live-days LUX set world's best limit on spin-independent scattering:
  - 90% UL 7.6×10^{-46} cm^2 @ 33 GeV/c^2 $\rightarrow$ first sub-zeptobarn WIMP detector
  - Low-mass WIMP signals excluded by LUX
- In situ measurement of energy scale for low-energy nuclear recoils
- LUX at the frontier of dark matter direct detection - exciting times ahead with the 300 day run, WIMP discovery possible!
- Longer term: LUX-ZEPLIN!

BACKUPS

WIMP search status < Oct. 2013



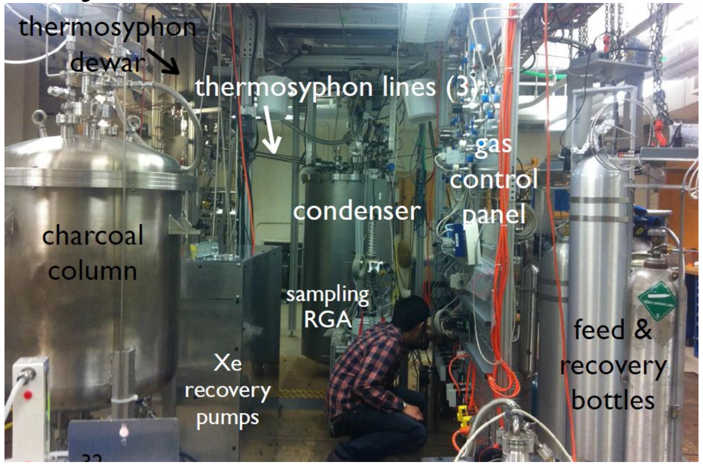
LUX in the Davis Cavern



LUX supporting systems

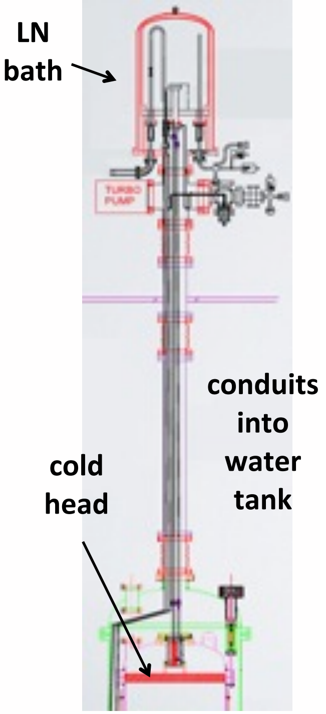
Circulation gas and sampling

Kr removal program at dedicated facility:



130 ppb to 3.5 ppt!

Thermosyphon

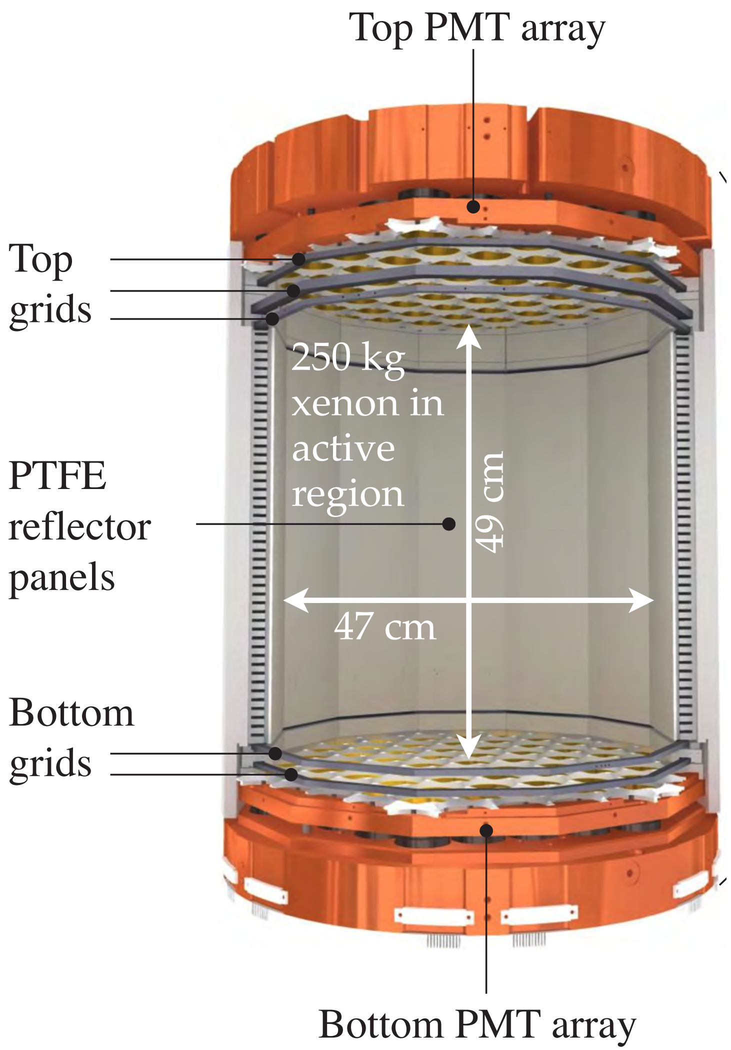


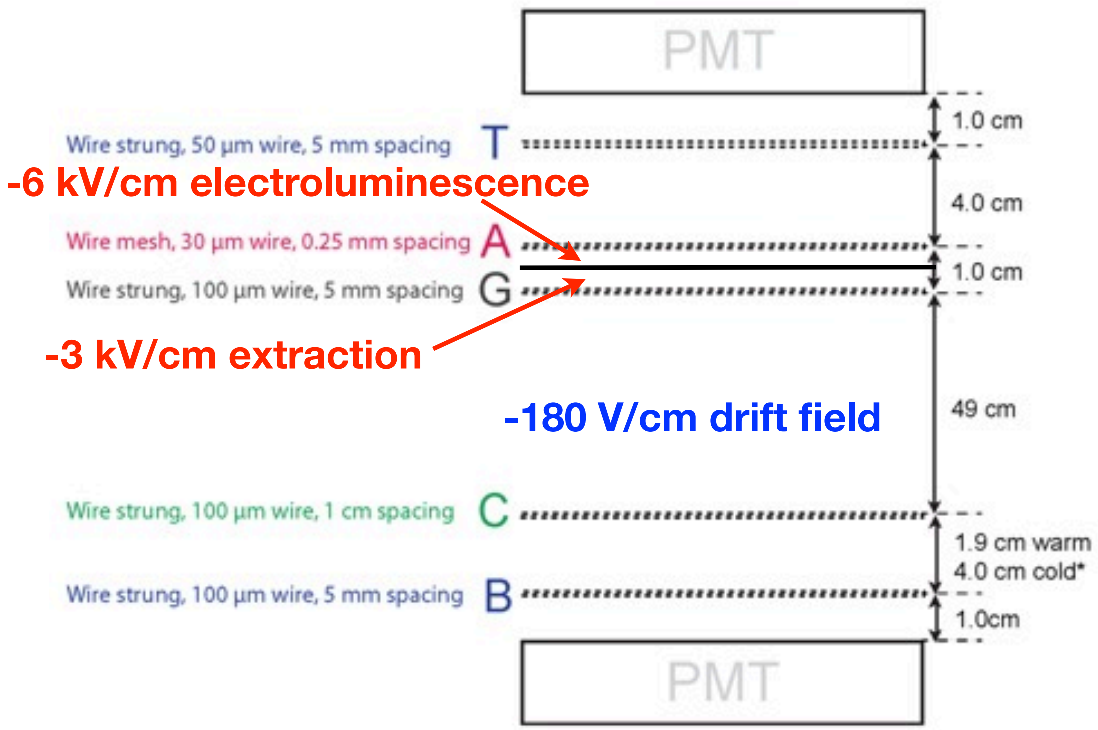
LUX Thermosyphon

Xe storage

Cathode HV feedthrough

The active region of LUX





- Primary scintillation: PDE of 14%
- S2 single electron extraction efficiency: 65%
- Single extracted electron: 26 phe/e-

Exceptional technical performance

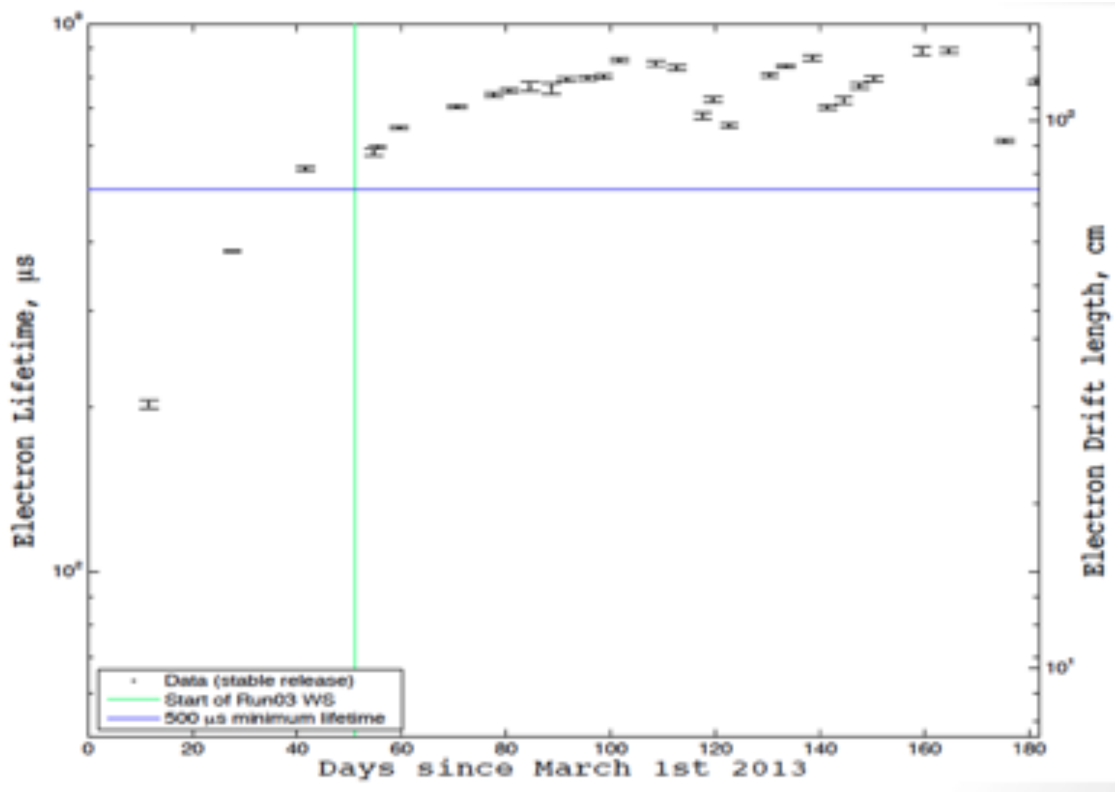
Low-energy electron recoil rate of 3e-3 events/keV/kg/day.

Kr/Xe ratio of 3.5 ppt.

Electron drift length longer than 130 cm.

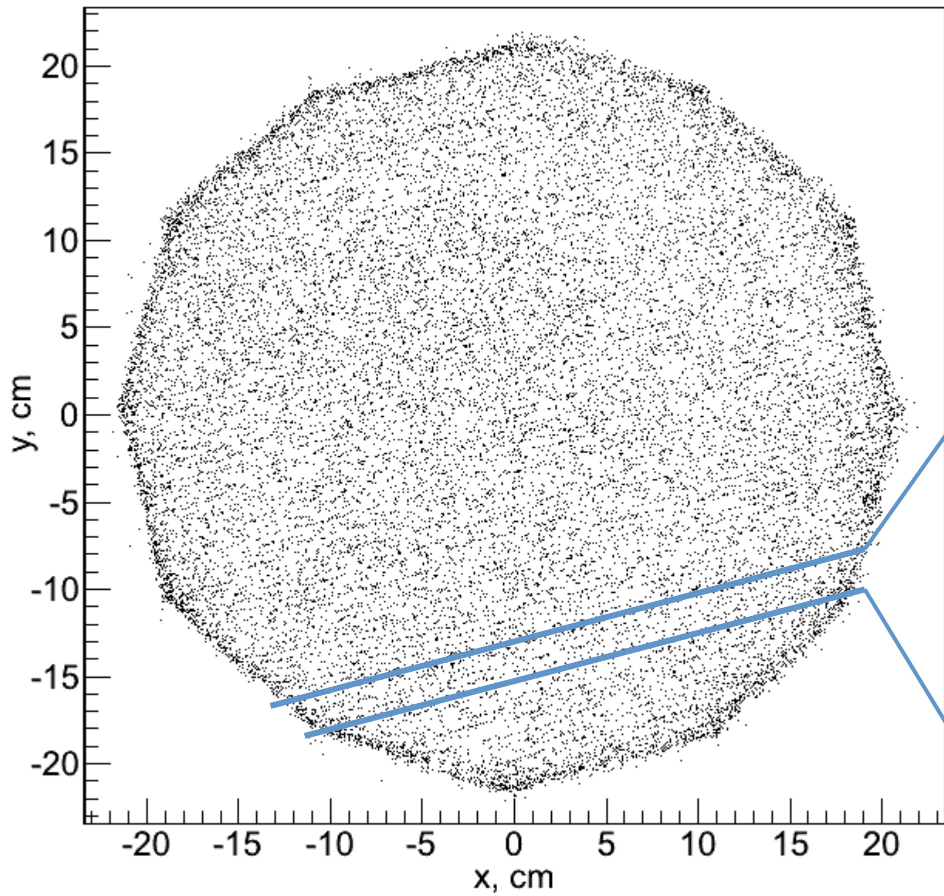
Light detection efficiency of 14%.

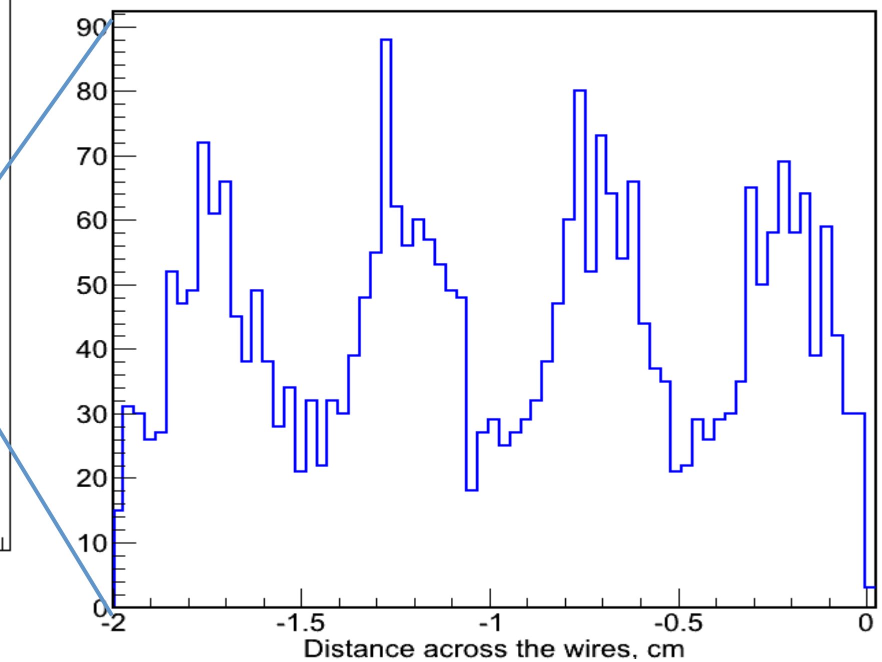
Electron recoil discrimination of 99.6%, with drift field of 181 V/cm.



Position reconstruction

- Drift time (1.5 mm/μs) for Z-position, XY position by fitting S2 hit pattern with Light Response Functions (LRFs) from high stats internal calibrations

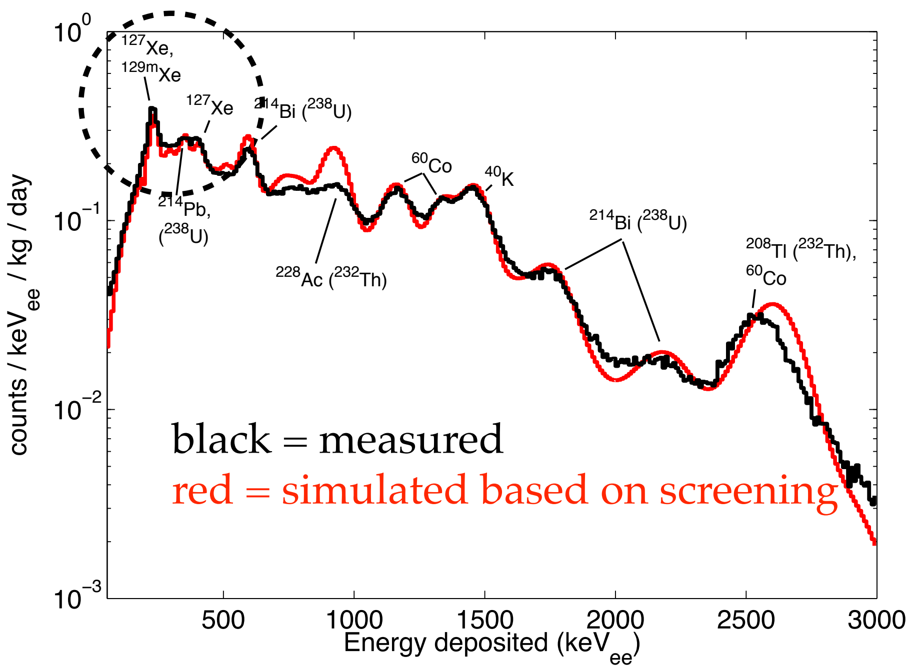




- XYZ info → fiducialisation and XYZ light collection corrections

Backgrounds in LUX

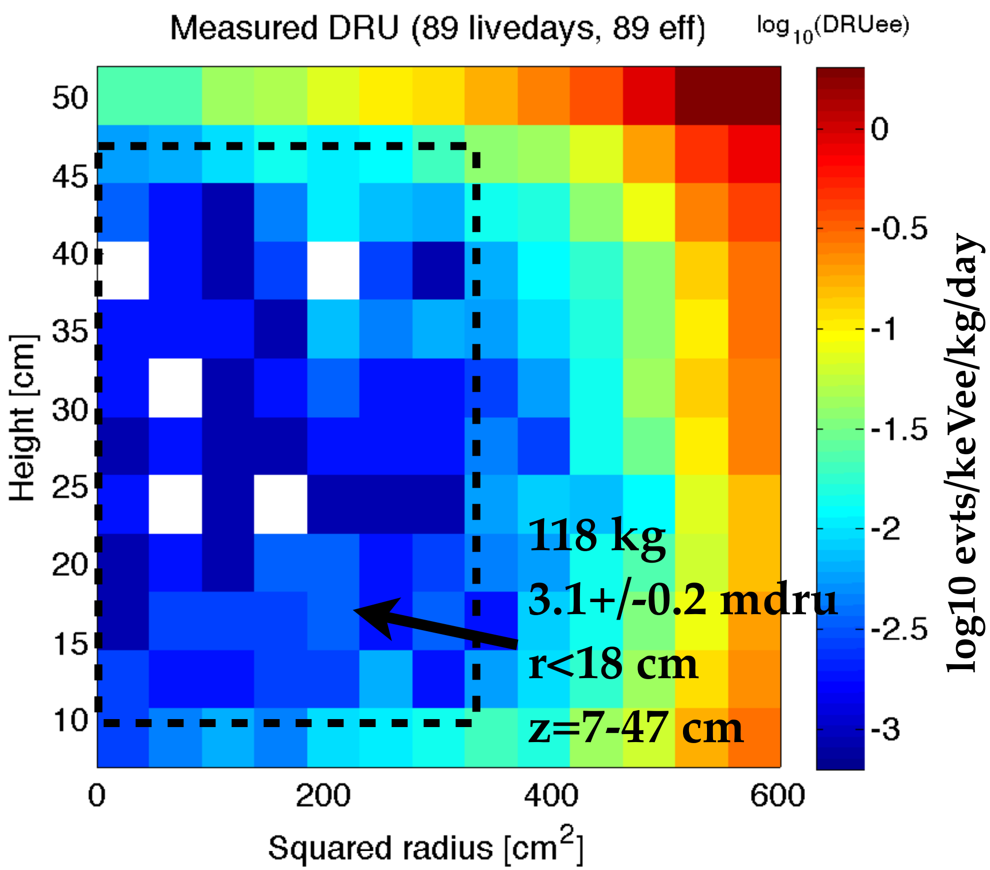
- Construction materials chosen for low radioactivity: Ti, Cu, PTFE
- Screened for radioactivity at SOLO counting facilities and at LBNL
- 118 kg fiducial reduces BG by 10^{-3}: gamma 1.8 mdru and neutron 500 ndru



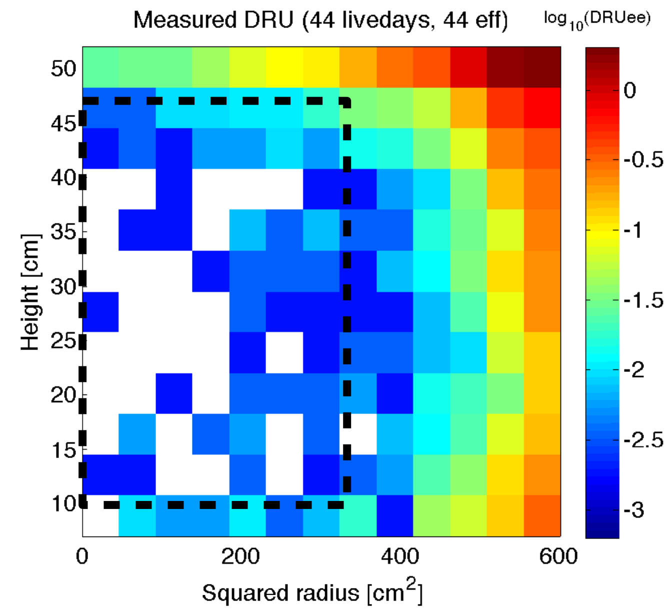
Background Component	Source	10^{-3} x evts/keVee/kg/day
Gamma-rays	Internal Components including PMTS (80%), Cryostat, Teflon	$1.8 \pm 0.2_{stat} \pm 0.3_{sys}$
^{127}Xe (36.4 day half-life)	Cosmogenic 0.87 -> 0.28 during run	$0.5 \pm 0.02_{stat} \pm 0.1_{sys}$
^{214}Pb	^{222}Rn	$0.11\text{-}0.22_{(90\%\ CL)}$
^{85}Kr	Reduced from 130 ppb to 3.5 ± 1 ppt	$0.13 \pm 0.07_{sys}$
Predicted	Total	$2.6 \pm 0.2_{stat} \pm 0.4_{sys}$
Observed	Total	$3.1 \pm 0.2_{stat}$

Backgrounds in LUX

- 118 kg average Apr. - Aug. is 3.1 mdru (0.5 mdru cosmogenic)
- 1 milli dru = 10^{-3} events/keVee/kg/day

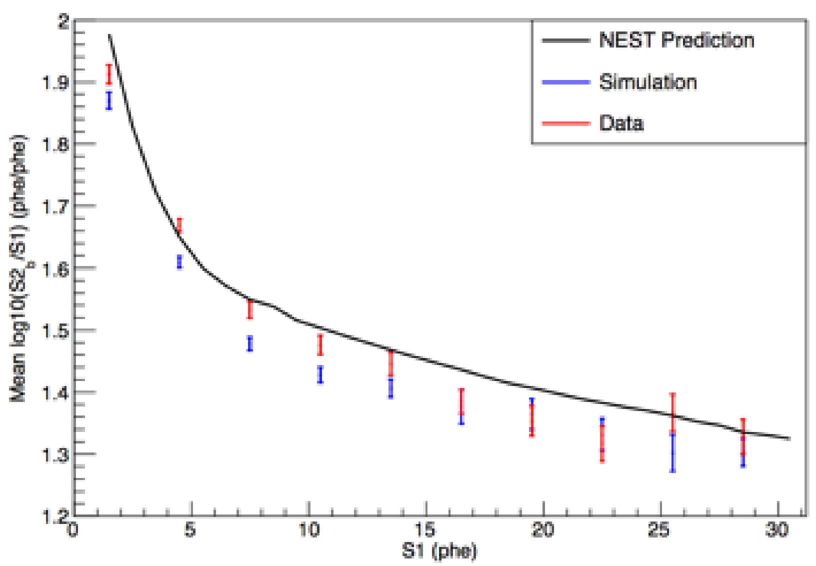


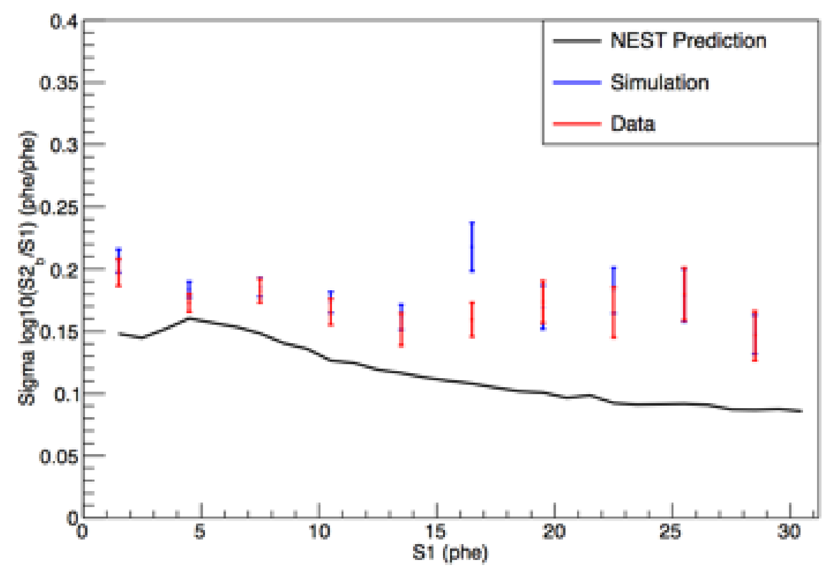
And going down with time!



Good agreement between NR sim and neutron calibs

- AmBe + Cf: low energy neutrons - peak at just above 2 phe S1 and out to 15 phe
- Comparison to NEST predictions for flat NR sim and NEST plus full detector simulation:





- Full sim matches data well as includes ER contamination and neutron+X
- WIMP data not expected to contain these so use flat NR sim for signal pdf

Profile likelihood ratio for limits

- Unbinned maximum likelihood compare data with prediction on event by event basis. Use:

4 observables: **x** = S1, log10(S2/S1), r and z

$$\mathcal{L}_{WS} = \frac{e^{-N_s - N_{Compt} - N_{Xe-127} - N_{Rn222}}}{\mathcal{N}!} \prod_{j=1}^{\mathcal{N}} N_s P_s(\boldsymbol{x}; \boldsymbol{\sigma}, \boldsymbol{\theta_s}) + \underline{N_{Compt} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Compt}})}$$
$$+ \underline{N_{Xe-127} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Xe-127}})} + \underline{N_{Rn} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Rn}})}$$

WIMP signal PDF:
- WIMP dE/dR for given mass (see earlier)
- efficiency from validated NR sims
- N_s is parameter of interest

Backgrounds as nuisance parameters:
- detector efficiencies included
- 30% uncertainty on overall rate

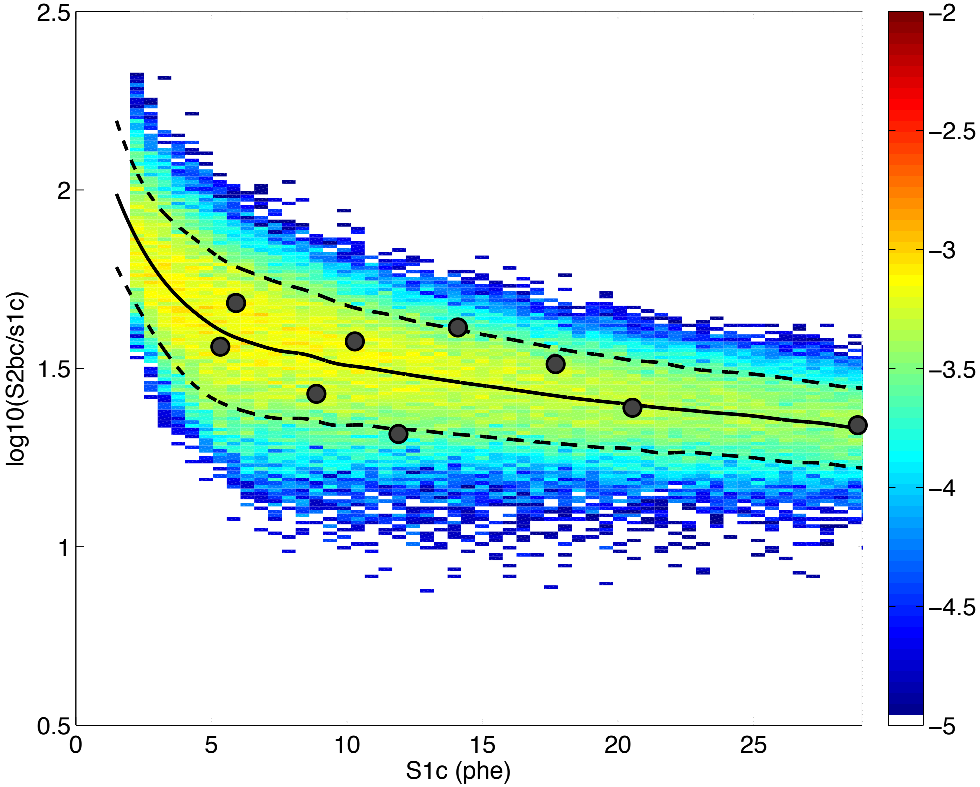
Ratio of this to null hypothesis used to create test statistic and extract 90% CI upper limit

Cross checked with simple cut and count method

Simulated response for hypothetical WIMP signals

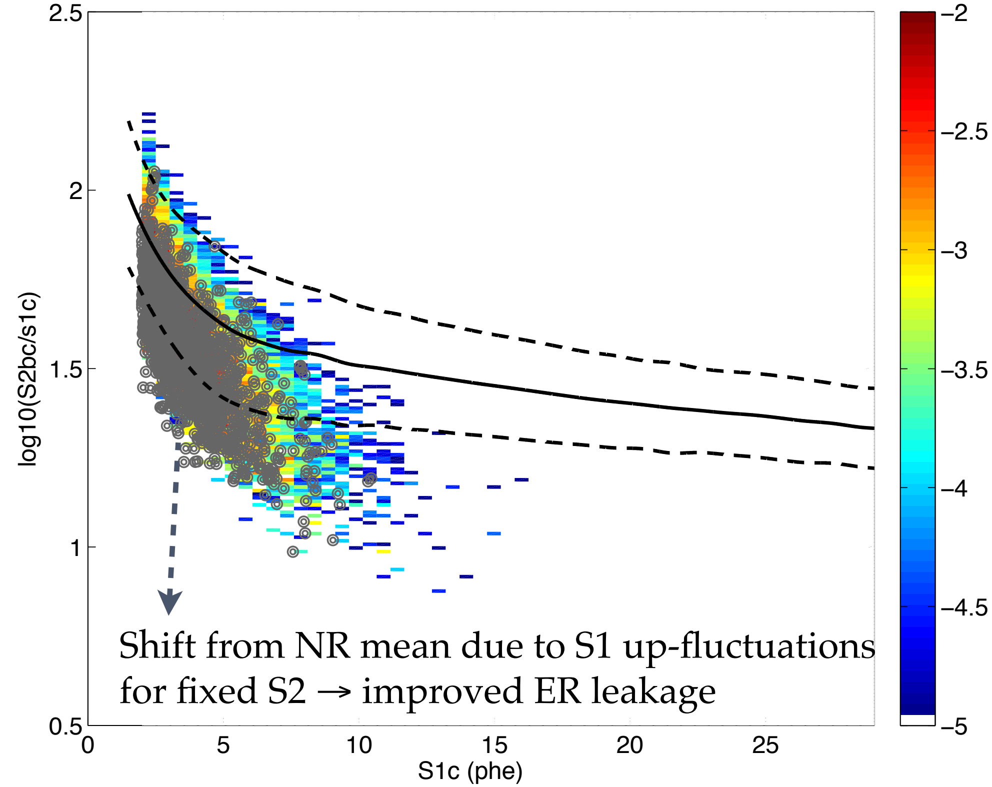
For 1000 GeV WIMP @ 1.9 ×10^{-44} cm^2, XENON100 90% CL:

→ expect 9 WIMPs in LUX search



For 8.6 GeV WIMP @ 2.0 ×10^{-41} cm^2, CDMS II Si (2012) 90% CL:

→ expect 1550 WIMPs in LUX search



Signal PDFs same as used in PLR and assume Standard Milky Way Halo parameters and conservative NR cut-off below 3 keVnr