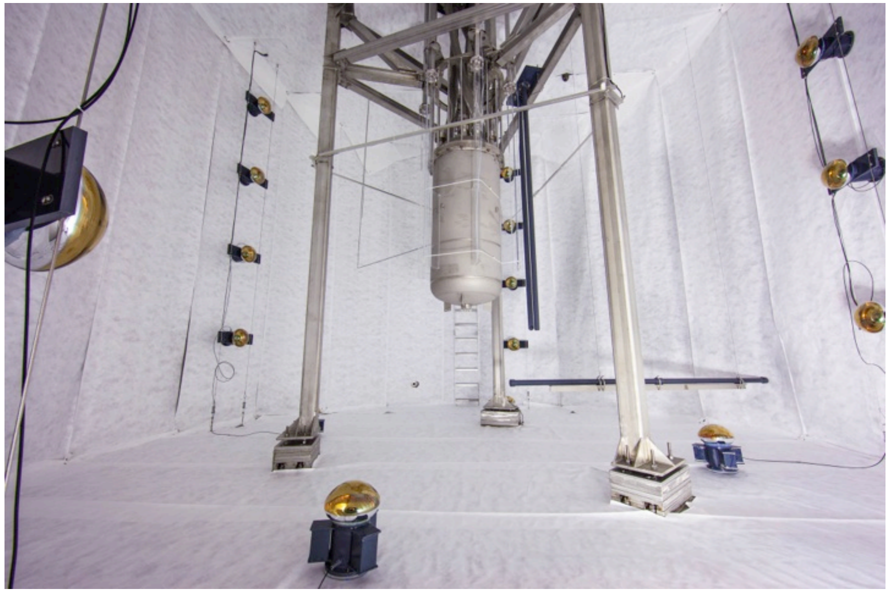
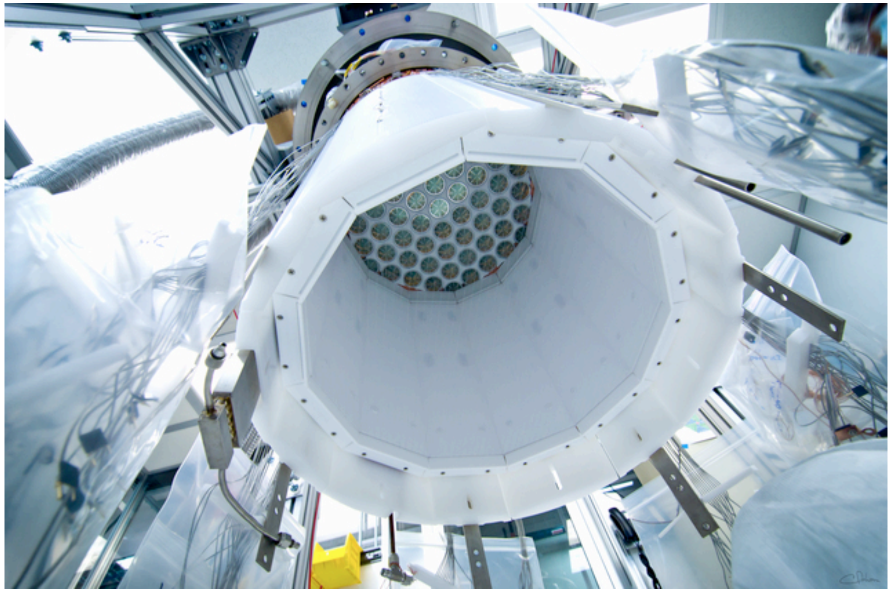
# Calibrating the LUX detector

Jim Dobson (j.dobson@ed.ac.uk), Oxford DMUK meeting, 8th Dec 14



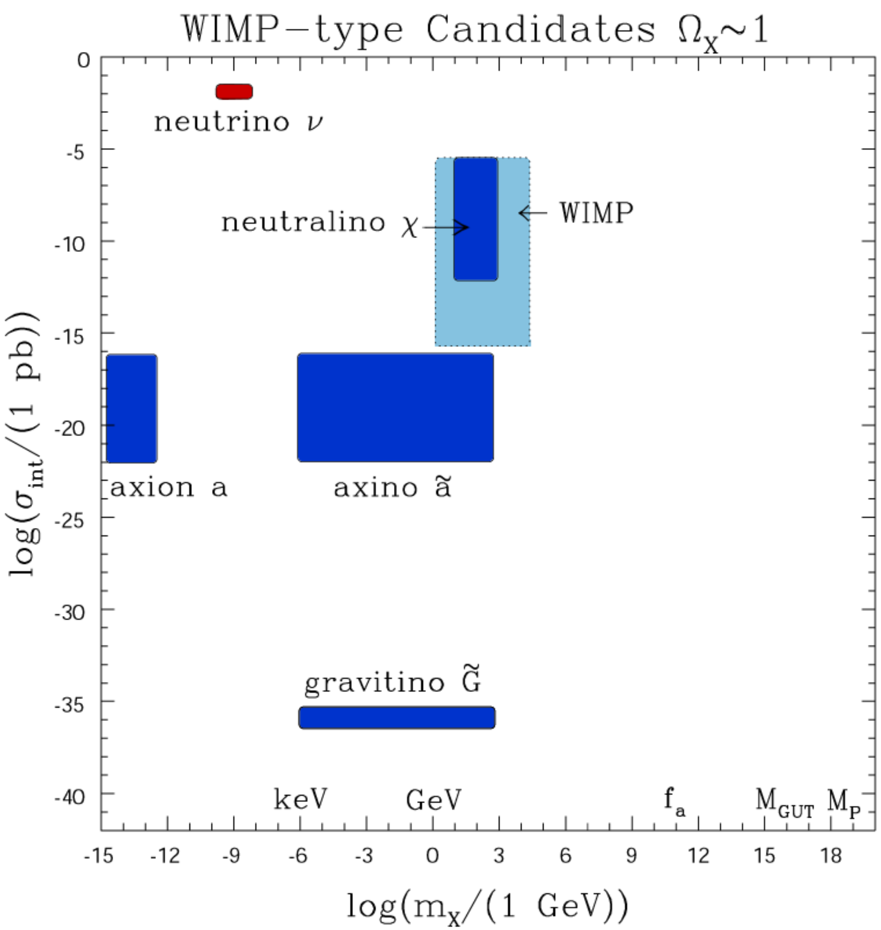


Overview of talk:

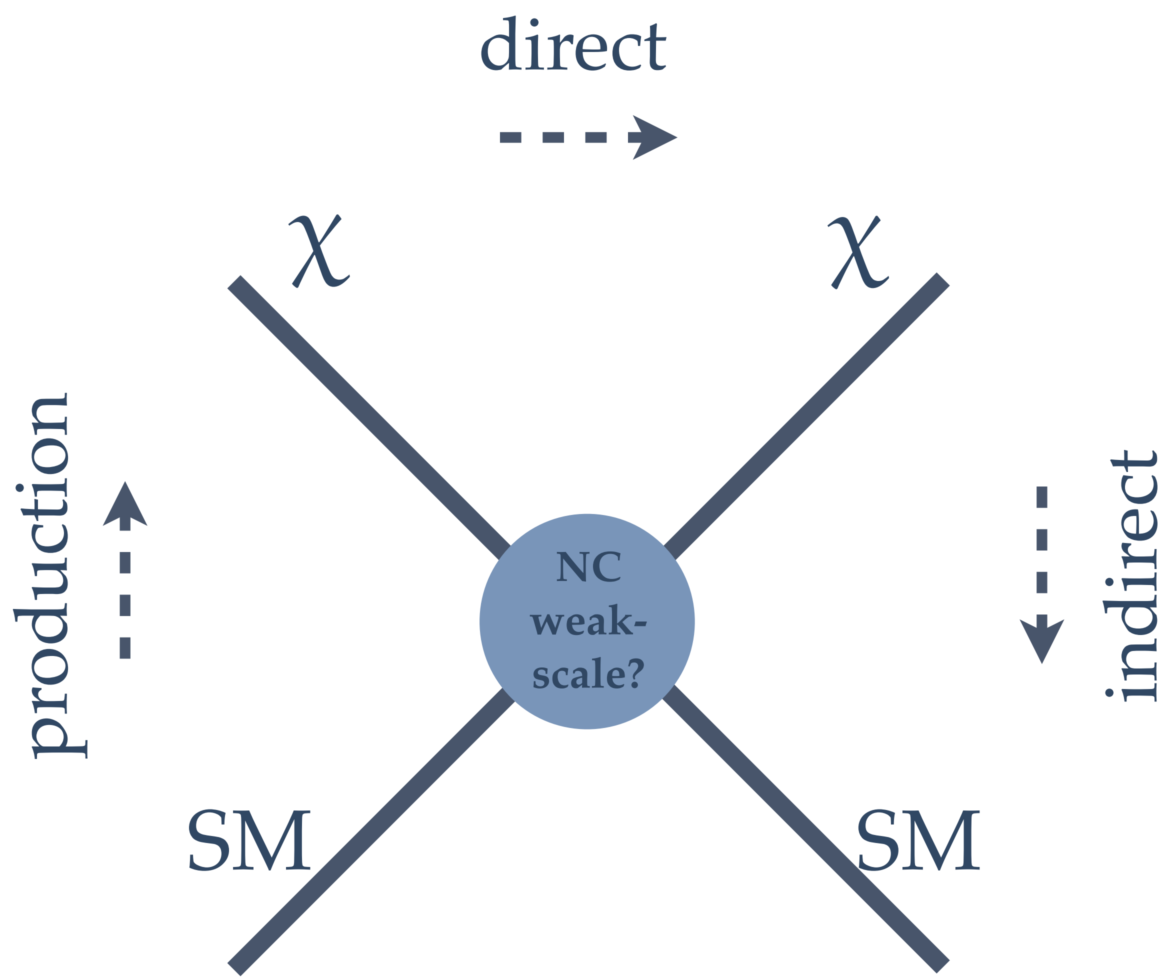
- ✦ Direct detection
- ✦ LUX and first results
- ✦ Calibrations in LUX

# Weakly Interacting Massive Particles (WIMPs)

- Favoured candidates for Cold Dark Matter (alternatives: Axions, sterile neutrinos, ...)
- Interacts only weakly with normal matter
- Expected to be neutral in most scenarios
- Non-relativistic freeze-out resulting in relic density today of ~1000/$m^3$
- Requires physics beyond the standard model:
  - Super-symmetry: LSP neutralino, $10^{-40}$ to $10^{-50}$ $cm^2$, mass range from $M_{proton} \rightarrow 1000 \times M_{proton}$
  - Universal Extra Dimensions: Stable KK, similar detection properties as neutralino

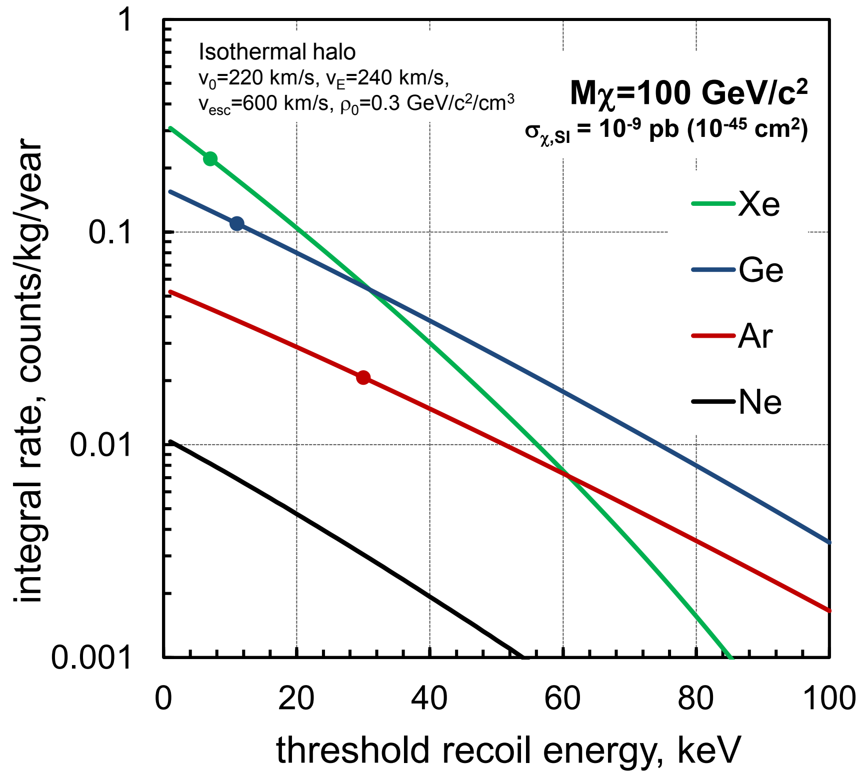


# Complementarity in detection techniques



# Direct detection of galactic dark matter

- Elastic scattering of galactic WIMPs off target material in terrestrial detector
- Isothermal with density profile ∝ 1/r2
- Local density $\rho_0$ = 0.3 GeV/cm$^3$
- WIMP speed ~ 220 km/s expect recoil O(10 keV)
- Expect ~ 1 event/kg/year




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

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

# Direct detection of galactic dark matter

- Elastic scattering of galactic WIMPs off target material in terrestrial detector
- Isothermal with density profile ∝ 1/r2
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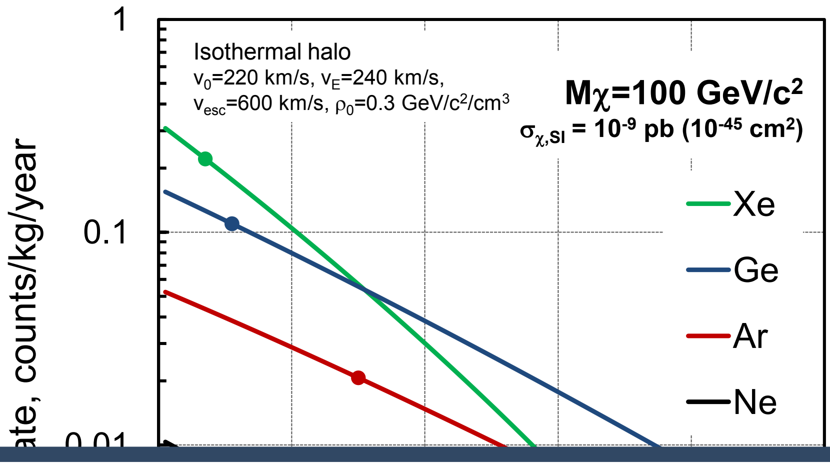



**Important factors for detector: large mass, low-radioactivity, low-energy threshold, high signal acceptance, ability to reject ER backgrounds (discrimination)**

threshold recoil energy, keV

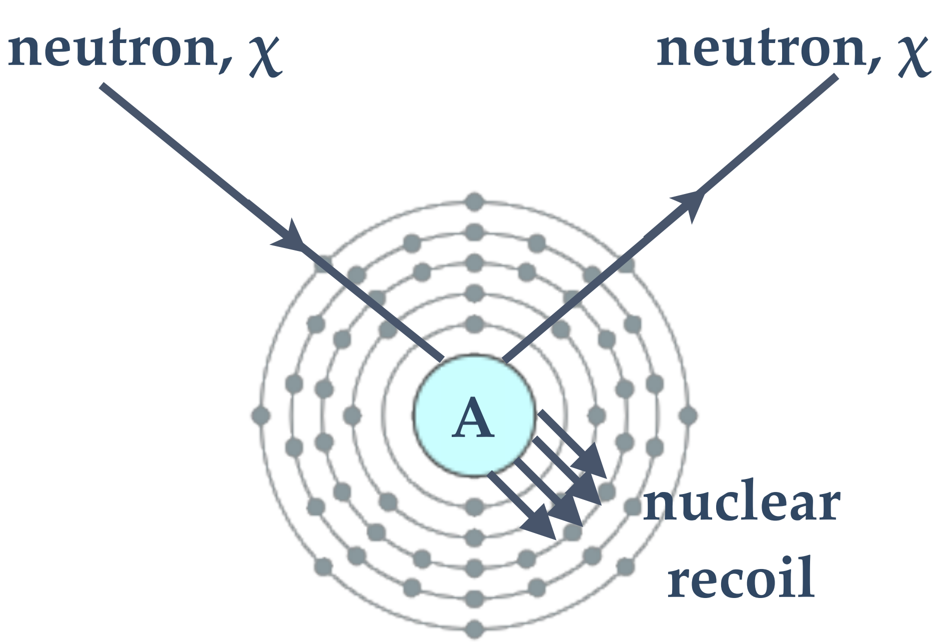
$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_0}{m_N m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}(v, E_R)\ \mathrm{d}v\,.$$

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

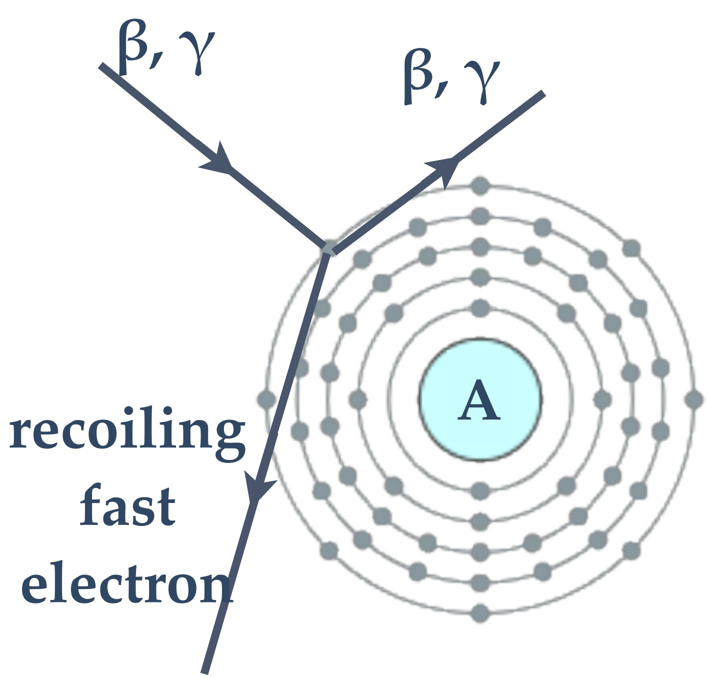
$$\sigma_0^{SI} = A^2 \left(\frac{\mu_N}{\mu_n}\right)^2 \sigma_n$$

# Direct detection: nuclear/electron recoils

- Nuclear recoil (NR): WIMPs and neutrons scatter predominantly off nucleus
- Electron recoil (ER): Interact predominantly with electrons
- Utilize differences to distinguish ER backgrounds - neutrons look identical to WIMPs so are irreducible background → shielding




NR in keVnr




ER in keVee

# Variety of detection technologies

**Ionisation Detectors**

Targets: Ge, Si, $CS_2$, CdTe

CoGeNT, CDEX, DAMIC, DRIFT, DM-TPC, GENIUS, IGEX, NEWAGE

**Light & Ionisation Detectors**

Targets: Xe, Ar

ArDM, LUX, WARP, DarkSide

Panda-X, XENON, ZEPLIN, LZ

cold ($LN_2$)

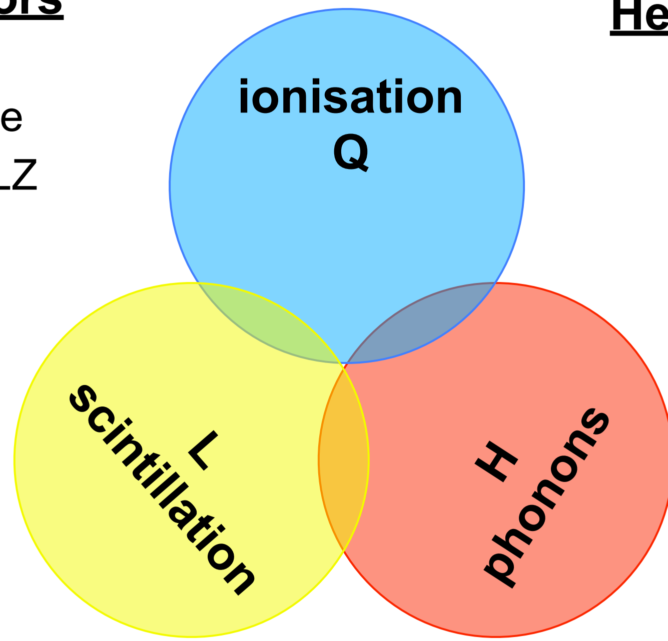
**Heat & Ionisation Bolometers**

Targets: Ge,Si

CDMS, EDELWEISS

SuperCDMS, EURECA

cryogenic (<50 mK)




**Scintillators**

Targets: NaI, Xe, Ar

ANAIS, CLEAN, DAMA, DEAP3600, KIMS, LIBRA, NAIAD, XMASS, ZEPLIN-I

**Bolometers**

Targets: Ge, Si, $Al_2O_3$, $TeO_2$

CRESST-I, CUORE, CUORICINO

**Light & Heat Bolometers**

Targets: $CaWO_4$, BGO, $Al_2O_3$

CRESST, ROSEBUD

cryogenic (<50 mK)

**Bubbles & Droplets**

$CF_3Br$, $CF_3I$, $C_3F_8$, $C_4F_{10}$

COUPP, PICASSO, PICO, SIMPLE

# The Large Underground Xenon (LUX) Experiment

The world's largest dual-phase xenon time-projection chamber

# LUX: 17 institutions, ~100 scientists

## 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 Group |
| 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 |
| Matthew Szydagis | 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 |


## University of Edinburgh

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

## 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

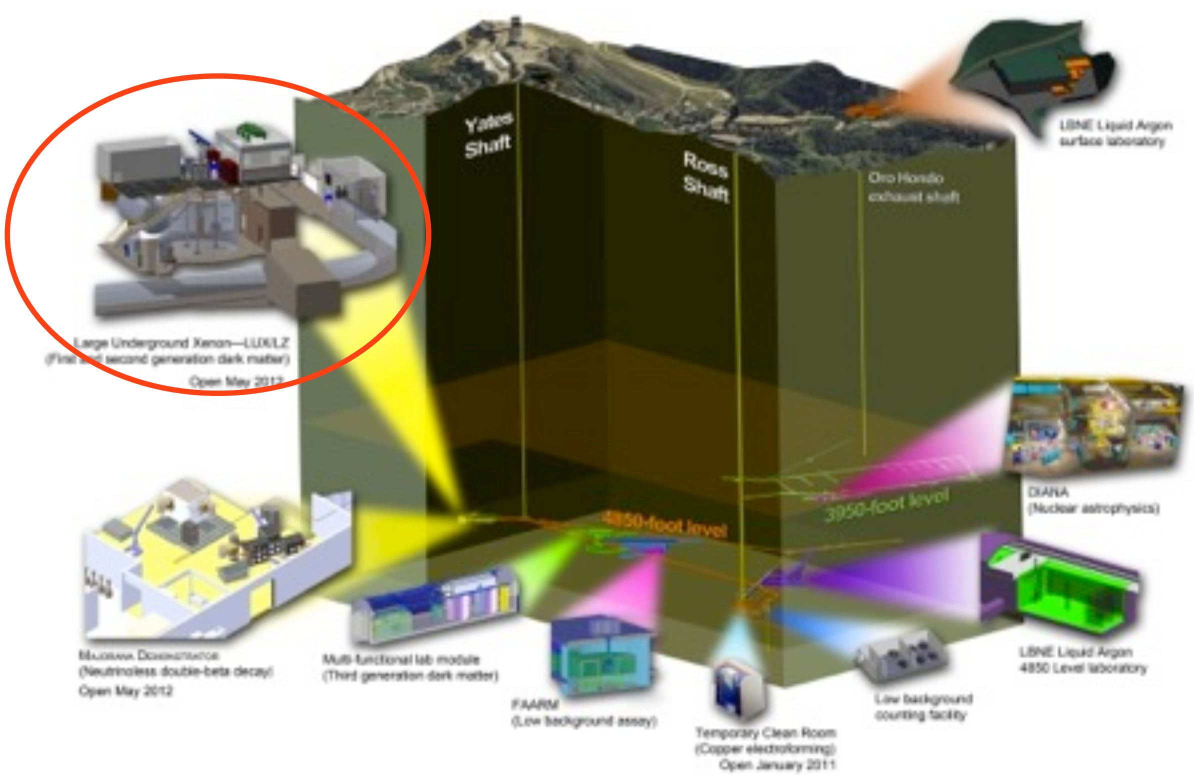
| | |
|---|---|
| Dongming Mei | PI, Professor |
| Chao Zhang | Postdoc |
| Angela Chiller | Graduate Student |
| Chris Chiller | Graduate Student |
| Dana Byram | *Now at SDSTA |

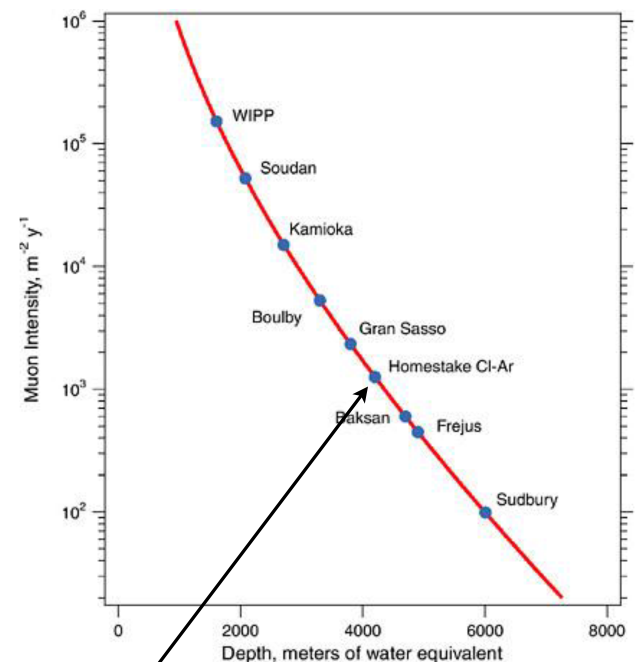
## Yale

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

# The Large Underground Xenon (LUX) experiment

- Two-phase liquid xenon time projection chamber (250 kg active)
- Located on the 4850’ level (4300 mwe) of the Sanford Underground Research Facility (SURF)

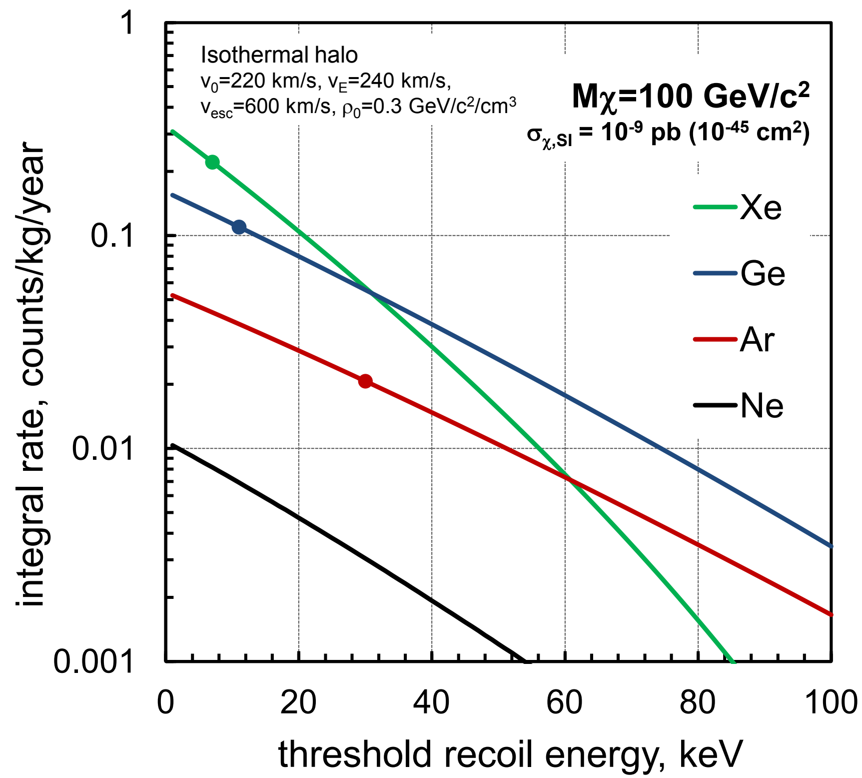


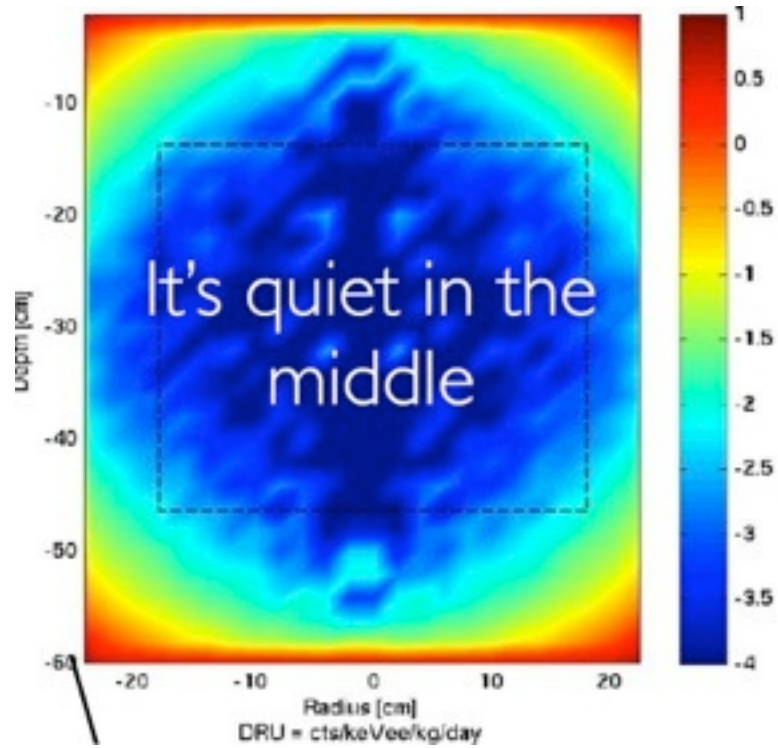




Muon flux reduced by $10^7$:
$55.2\ m^{-2}s^{-1}$ at surface $\rightarrow 1\times10^{-5}\ m^{-2}s^{-1}$

# Why use liquid xenon

- SI dR/dE goes as $A^2$, broad mass coverage above 5 GeV
- SD sensitivity from odd-neutron isotopes ($^{129}Xe$, $^{131}Xe$)
- Excellent self-shielding properties

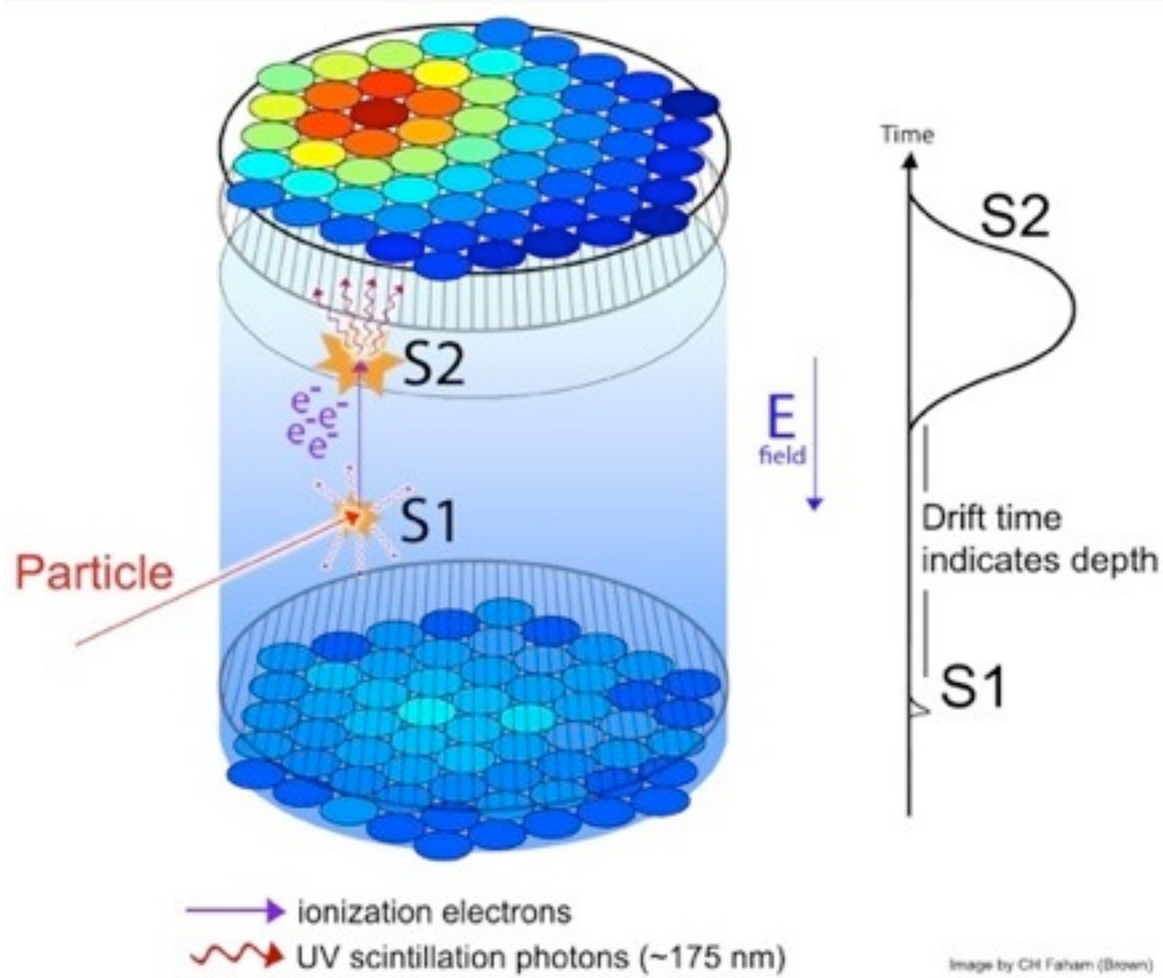


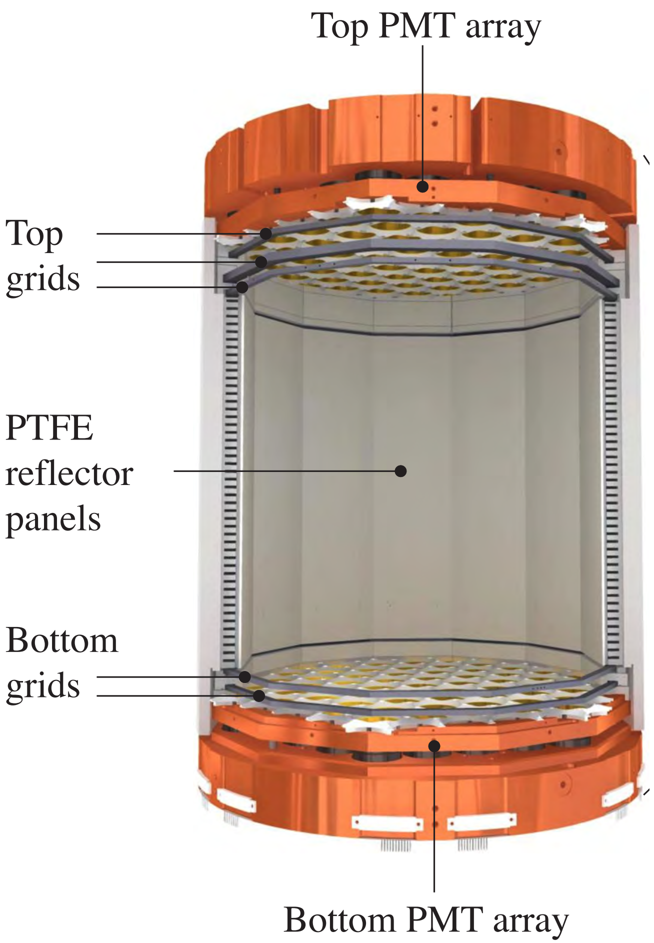
# Two-phase liquid xenon TPC

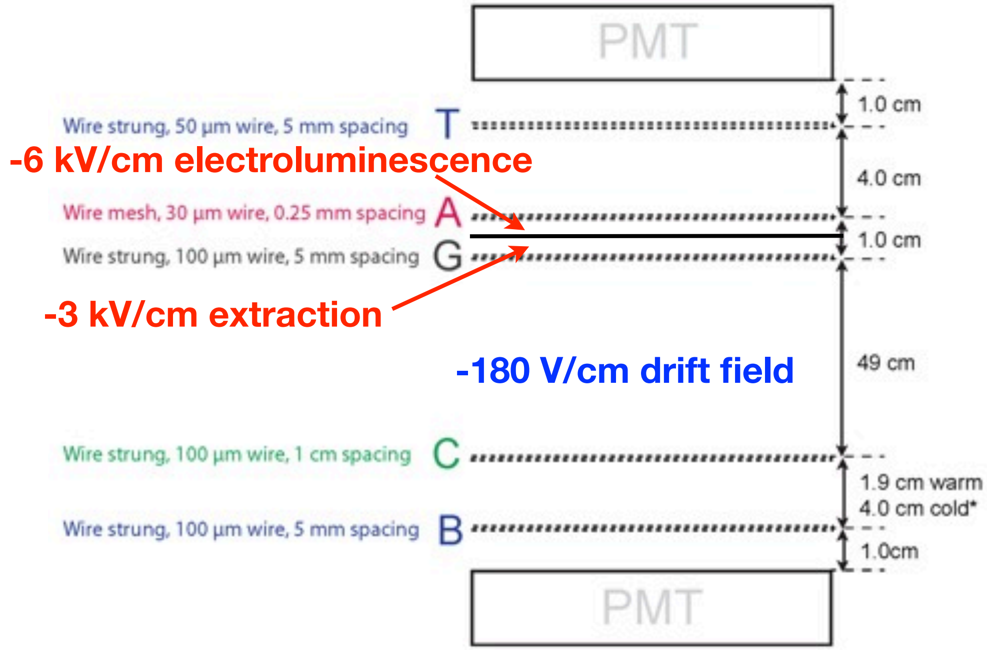
- S1: prompt scintillation signal
  - light yield ~60 ph/keV (ER, 0 field)
  - NR threshold ~5 keV
- S2: delayed ionisation signal
  - Electroluminescence in vapour phase
  - Nuclear recoil threshold < 1 keV
- S1+S2:
  - ER/NR discrimination (>99.5% rejection)
  - mm 3D vertex resolution

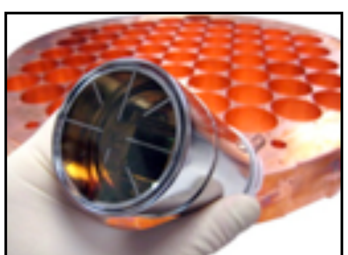
  → make use of self shielding



# The active region of LUX



Hamamatsu R8778 PMTs (61 top, 61 bottom)

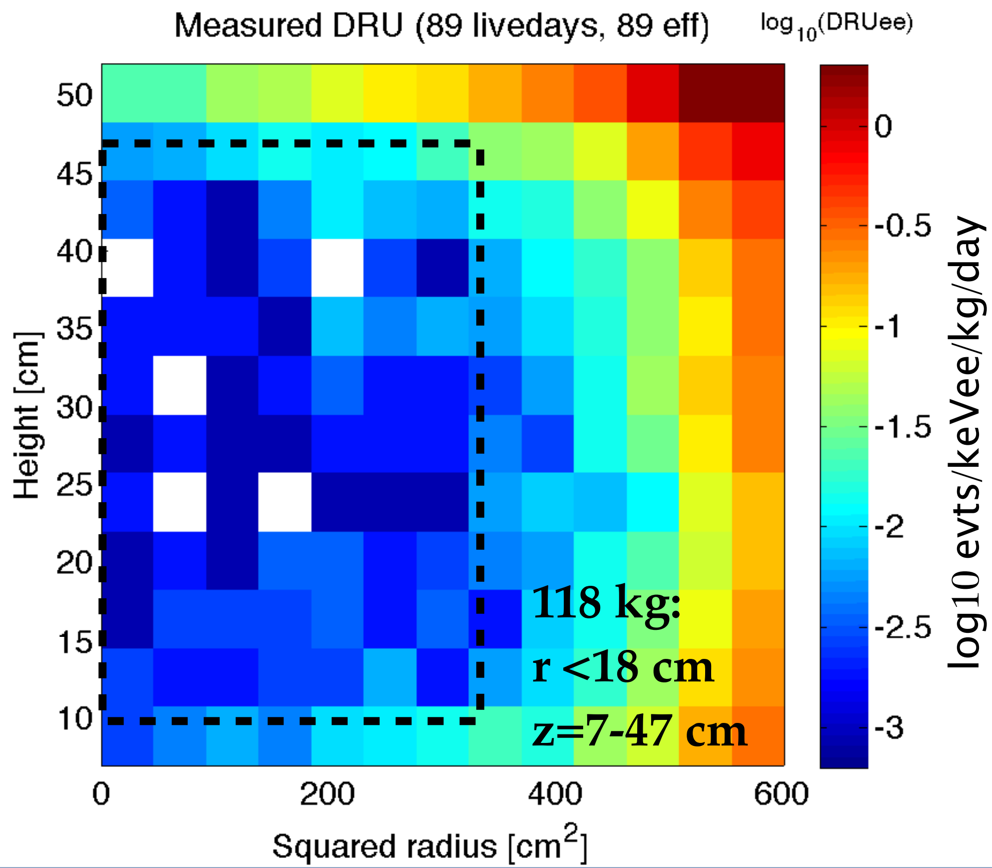
- Primary scintillation: PDE of 14%
- S2 single electron extraction efficiency: 65%
- Single extracted electron: 26 phe/e−

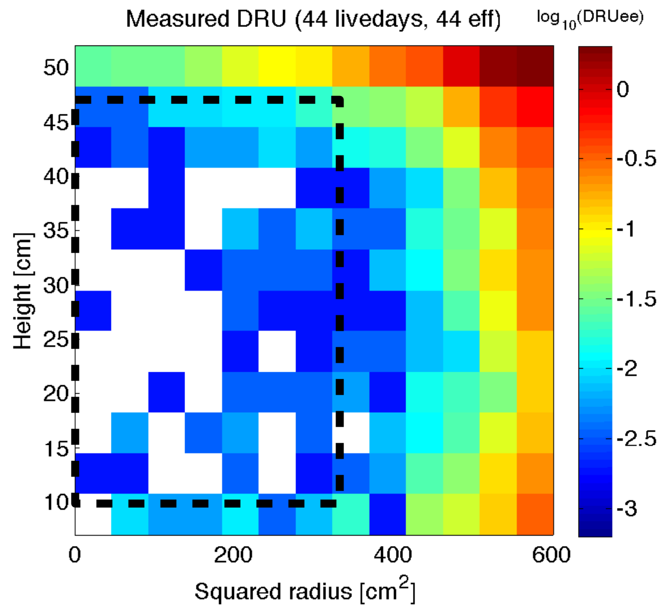
# Three pronged approach for ultra low background

- shielding from rock overburden + water tank
- high purity Xe + low background detector components
- LXe self-shielding + 3D position info

→ 3.1 ± 0.2 mDRU in 118 kg FV for Run 3

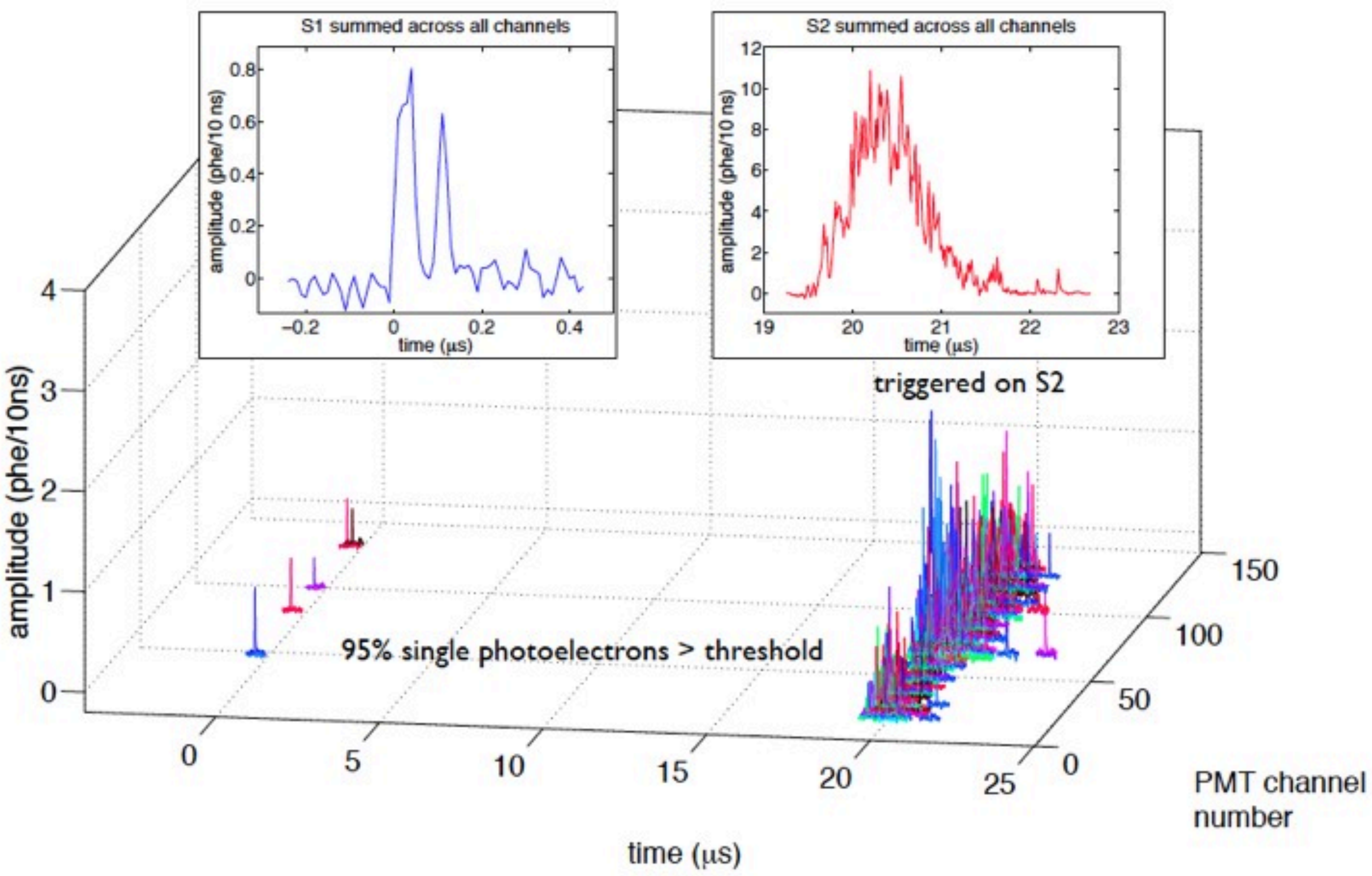
| Background Component | Source | $10^{-3}$ x evts/keVee/kg/day |
|---|---|---|
| Gamma-rays | Internal Components including PMTS (80%), Cryostat, Teflon | $1.8 \pm 0.2_{stat} \pm 0.3_{sys}$ |
| $^{127}$Xe (36.4 day half-life) | Cosmogenic 0.87 -> 0.28 during run | $0.5 \pm 0.02_{stat} \pm 0.1_{sys}$ |
| $^{214}$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 | $3.1 \pm 0.2_{stat}$ |



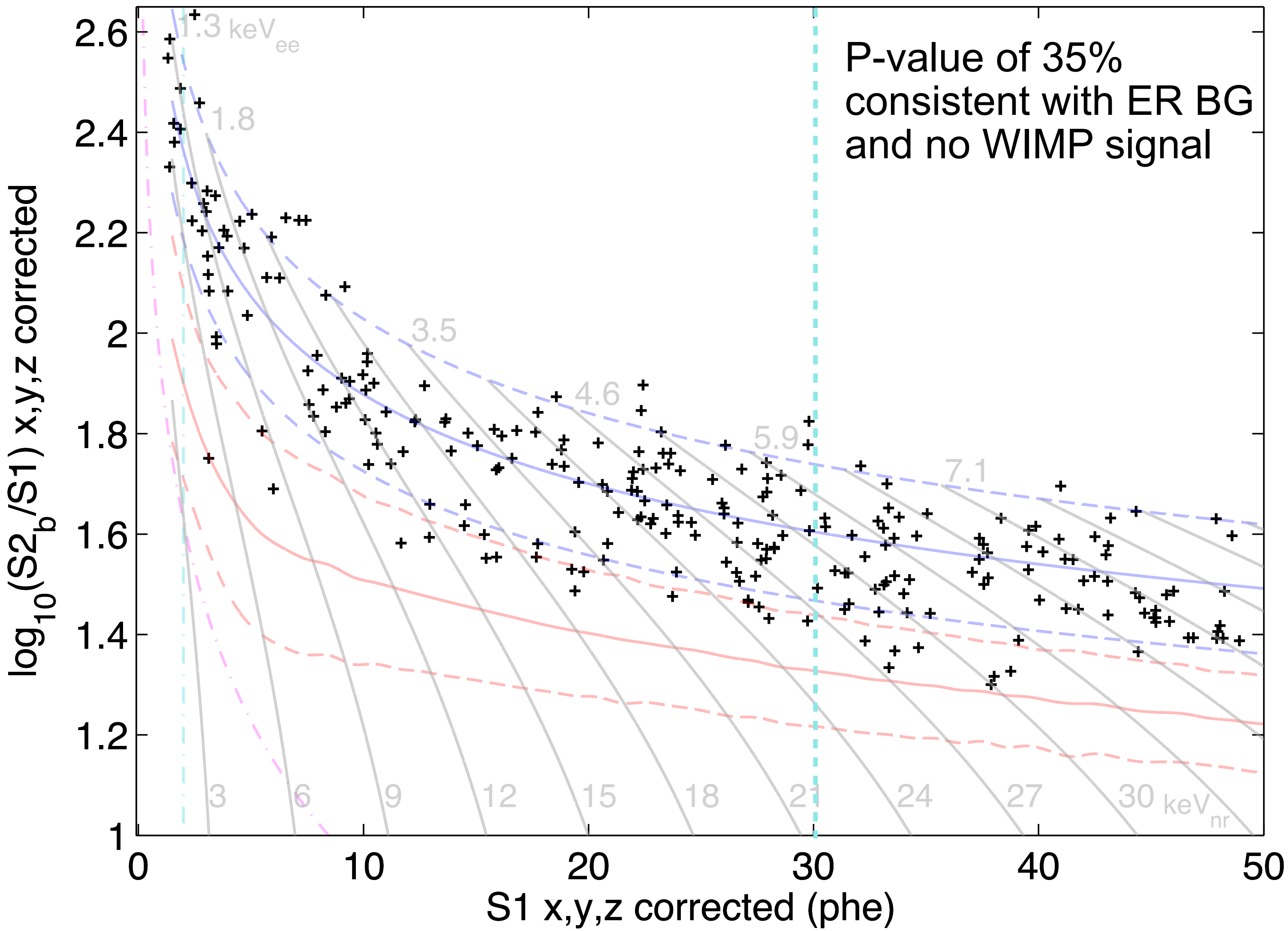

Astropart.Phys., 62:33–46, 2014.

# An example LUX event: 1.5 keV gamma



# Run 3: 85.3 live-days of data (Apr. → Aug. 13)

- 118 kg fiducial volume



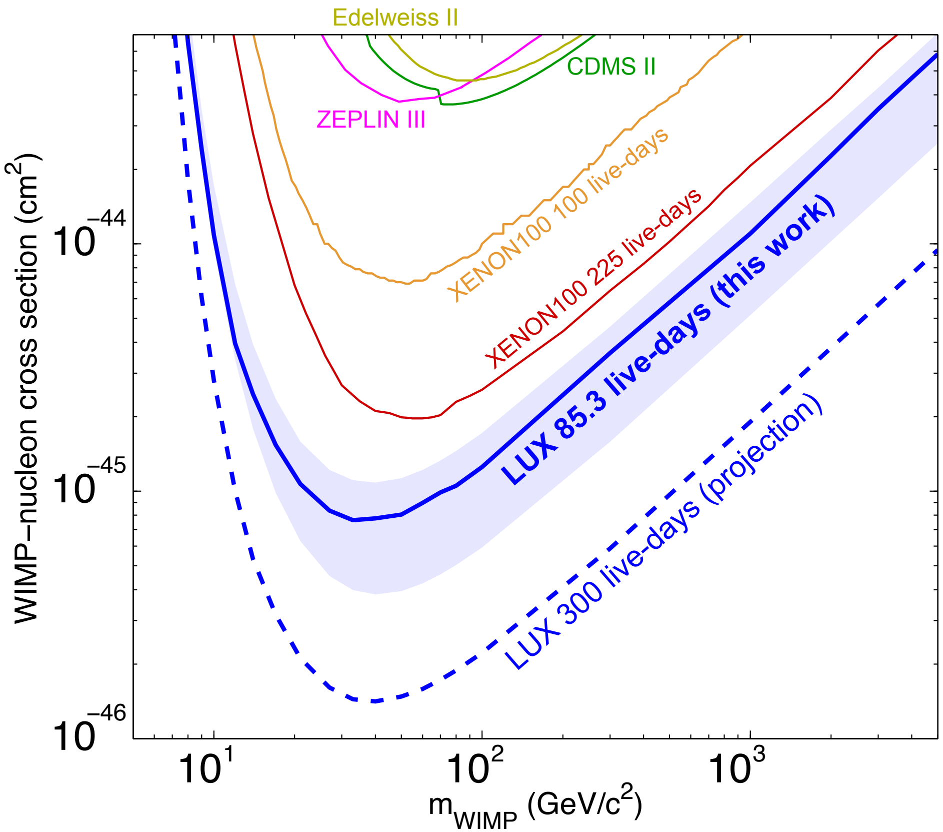
# Run 3: 85.3 live-days of data (Apr. → Aug. 13)

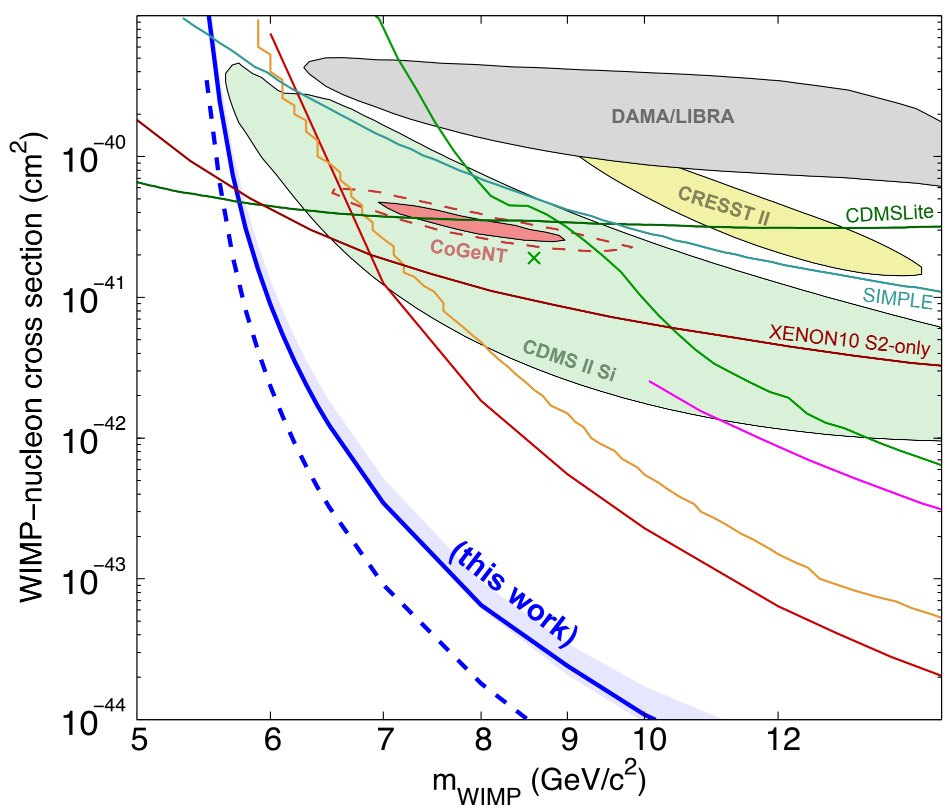
- World-leading limit for SI WIMP-nucleon elastic scattering:

  $7.6 \times 10^{-46}$ cm$^2$ @ 33 GeV/c$^2$

  → first sub-zeptobarn WIMP detector

  excluded existing low-mass WIMP signals

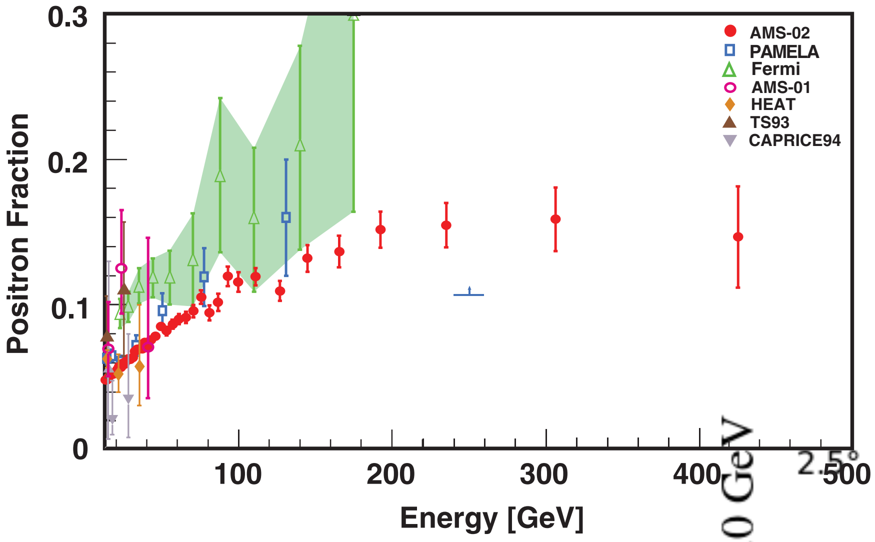


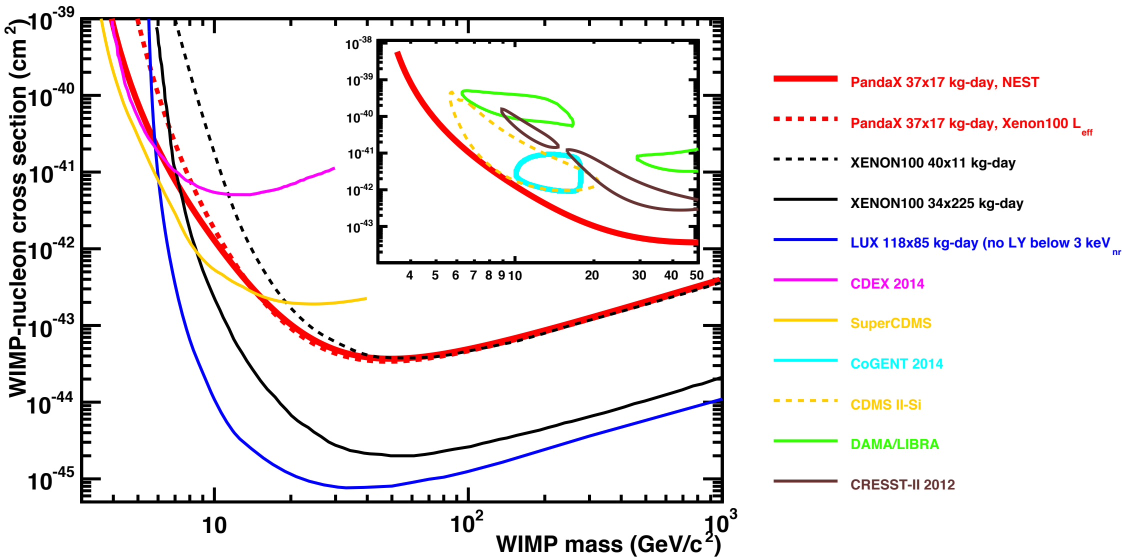



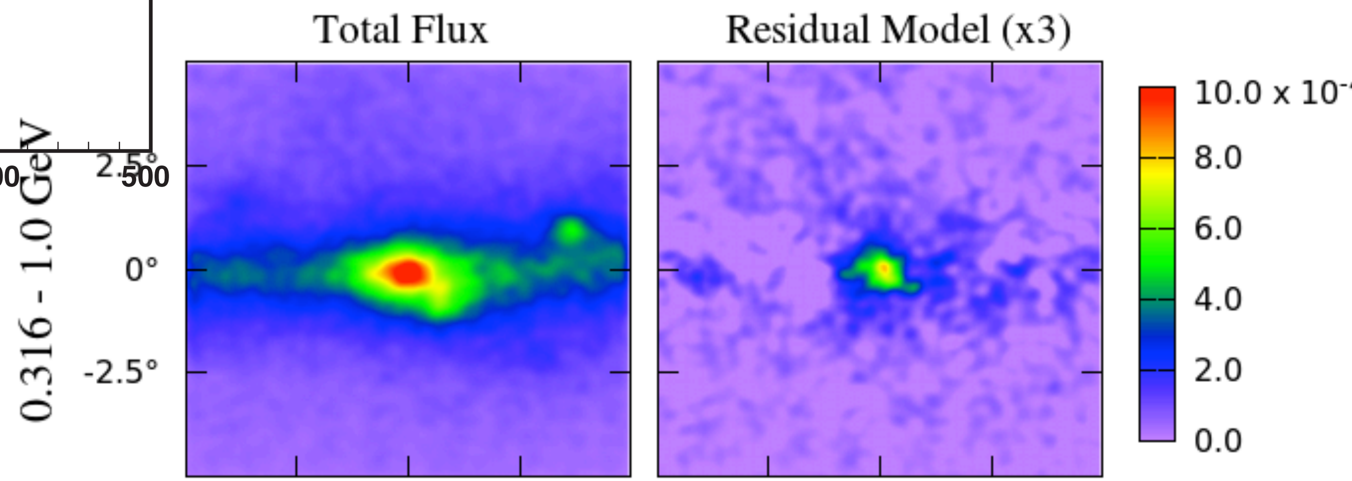

Phys.Rev.Lett., 112:091303, 2014

# Other recent DM exp. results

- Panda-X (two-phase Xe)
- DarkSide (single-phase Xe)
- AMS-02 positron fraction
- Fermi galactic center excess



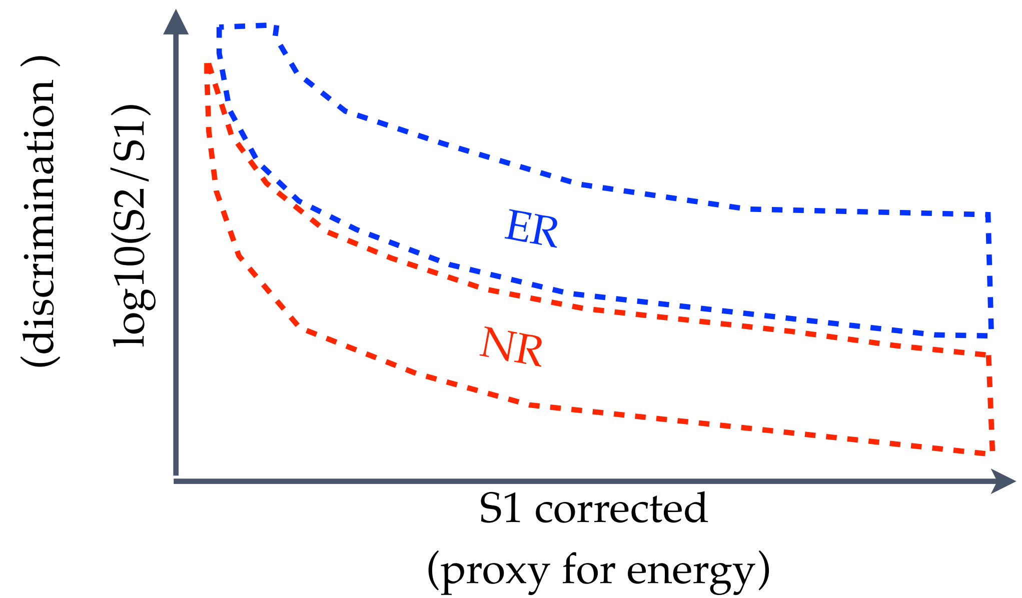



# Calibrating LUX

# Recap LUX Run 3: analysis strategy

- Profile Likelihood Ratio used as test statistic to compare data with predicted signal + background in 4 parameter space:

  S1, log10(S2/S1), r, z

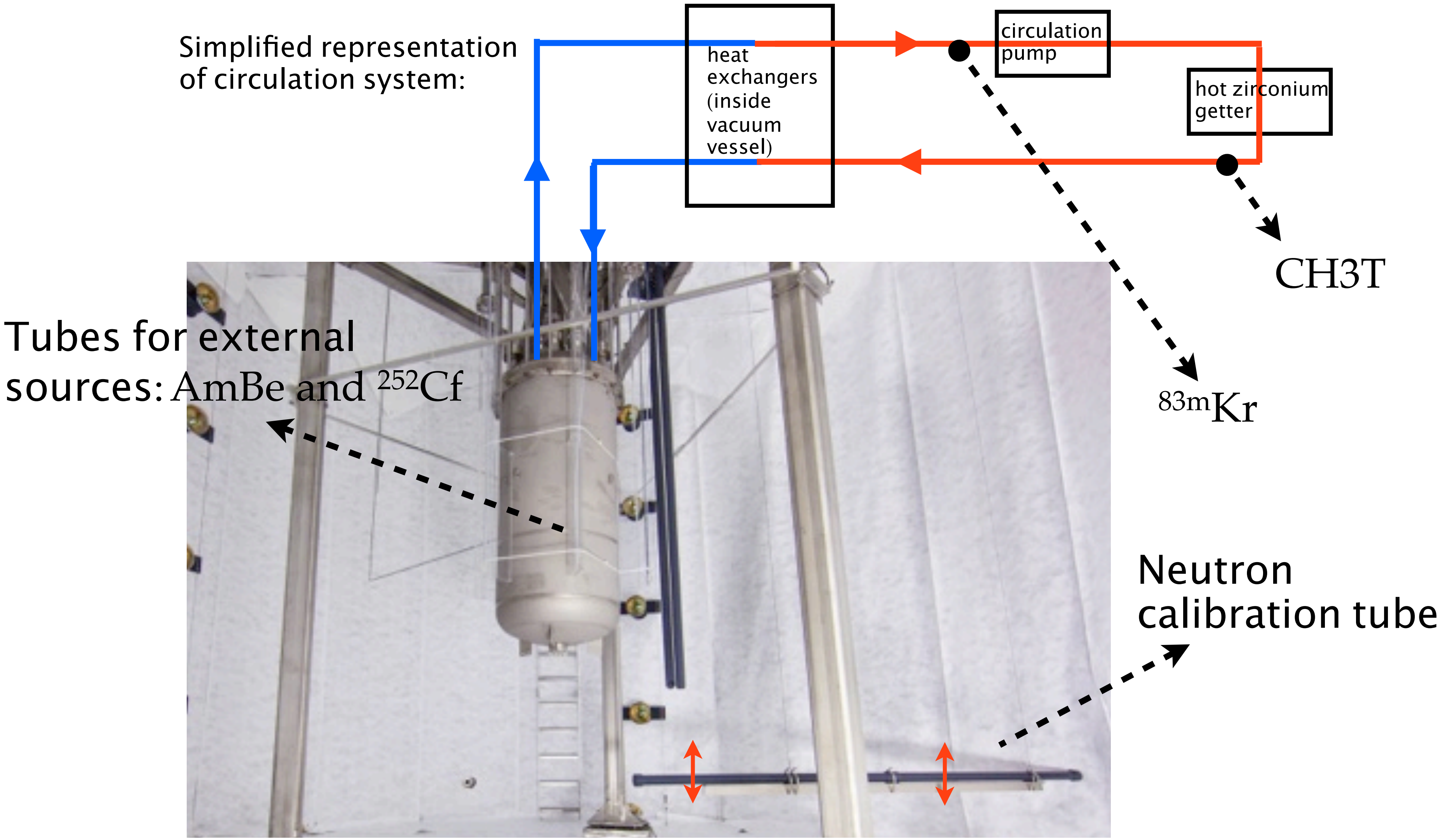



$$\mathcal{L}_{WS} = \frac{e^{-N_s - N_{Compt} - N_{Xe-127} - N_{Rn222}}}{\mathcal{N}!} \prod_{i=1}^{\mathcal{N}} N_s P_s(\boldsymbol{x}; \boldsymbol{\sigma}, \boldsymbol{\theta_s}) + N_{Compt} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Compt}}) + N_{Xe-127} P_{ER}(\boldsymbol{x}; \boldsymbol{\theta_{Xe-127}})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

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

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

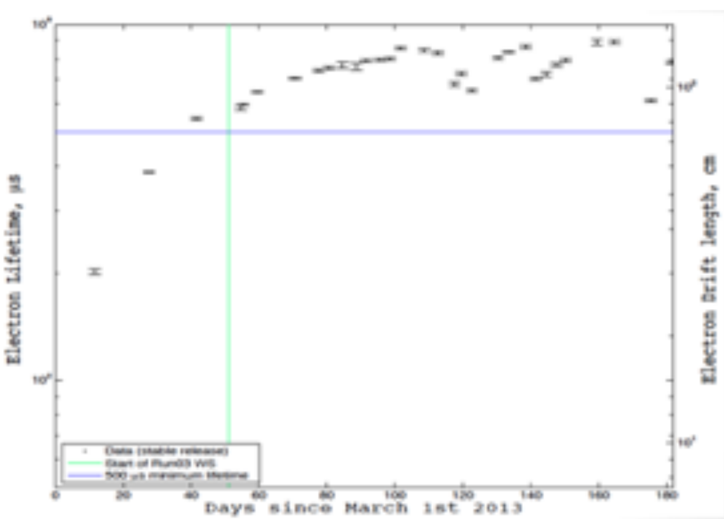
# An array of calibration techniques

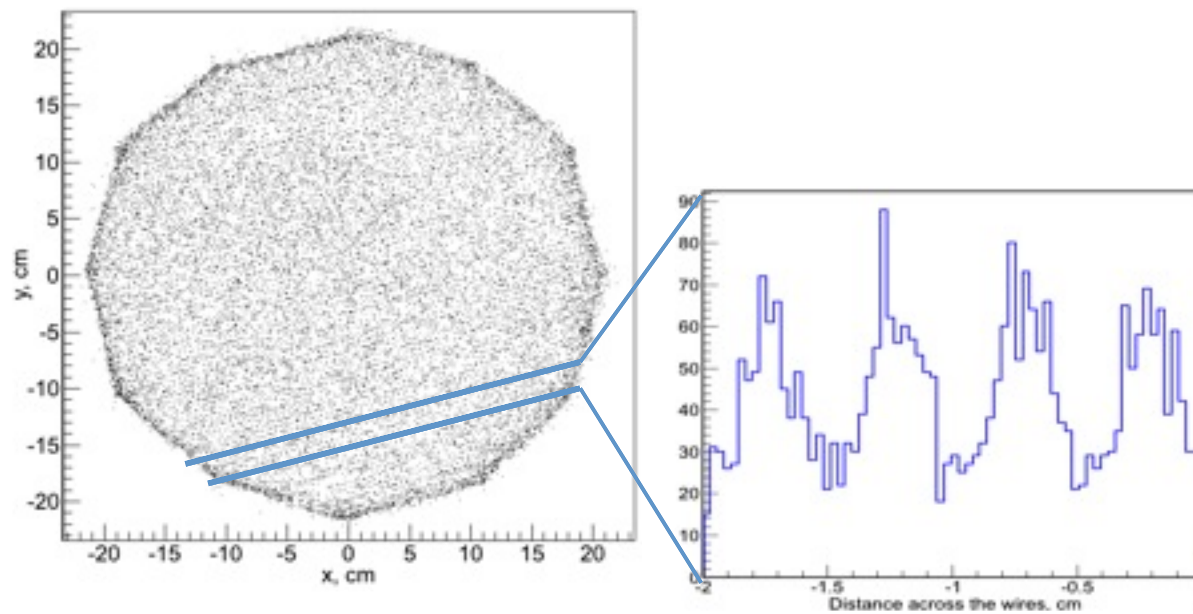


# ER: $^{83m}$Kr

- Internal high stats source ERs:
  - half-life ~1.8 hours, 32.1 + 9.4 keV betas
  - Used for:
    - Electron lifetime drift length measurements
    - Position reconstruction and S1 light corrections

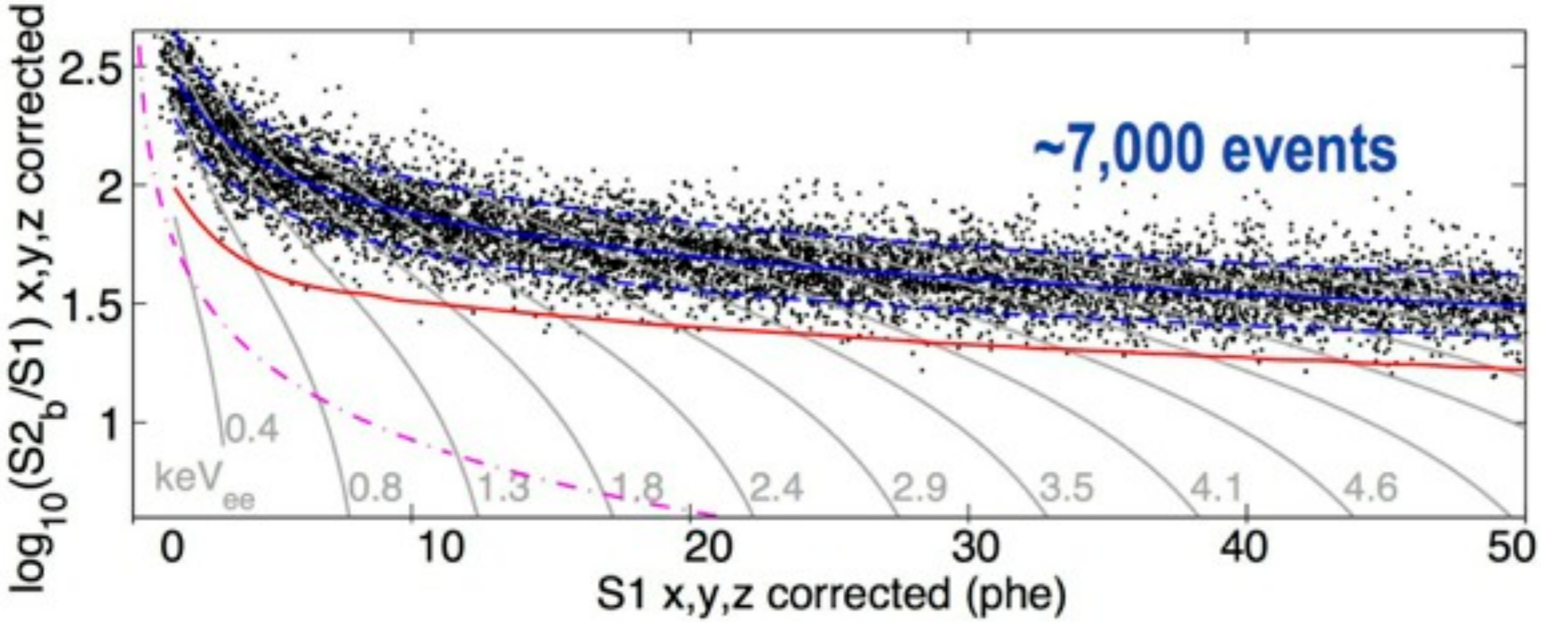
$^{83}$Rb coated charcoal plummed into gas system $\rightarrow$ $^{83m}$Kr



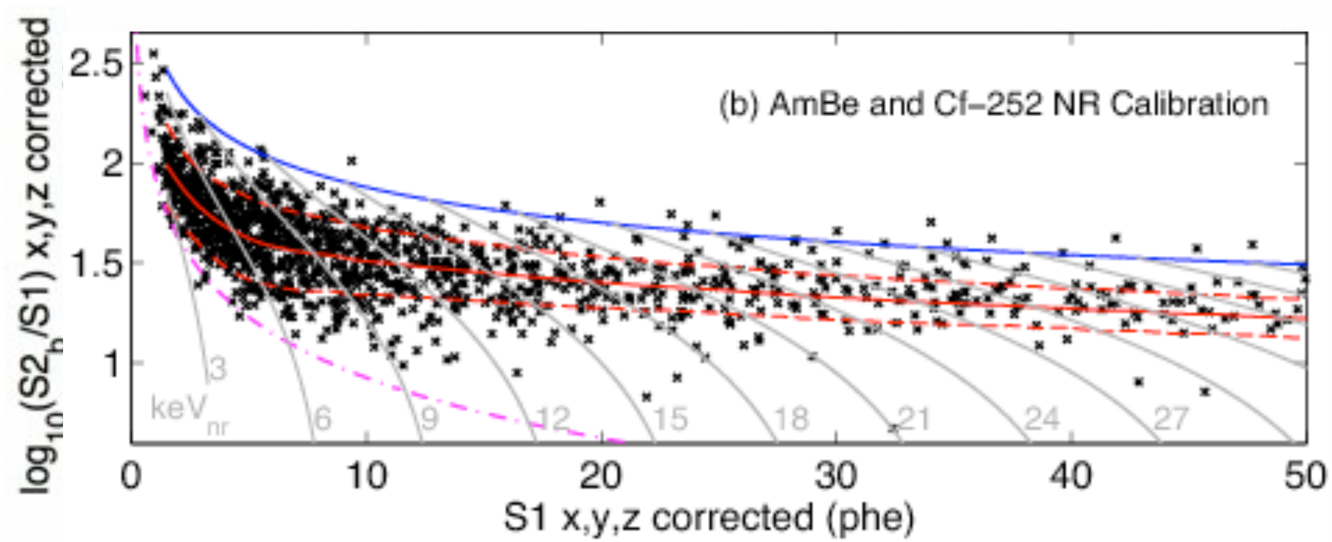
# ER: Tritiated methane

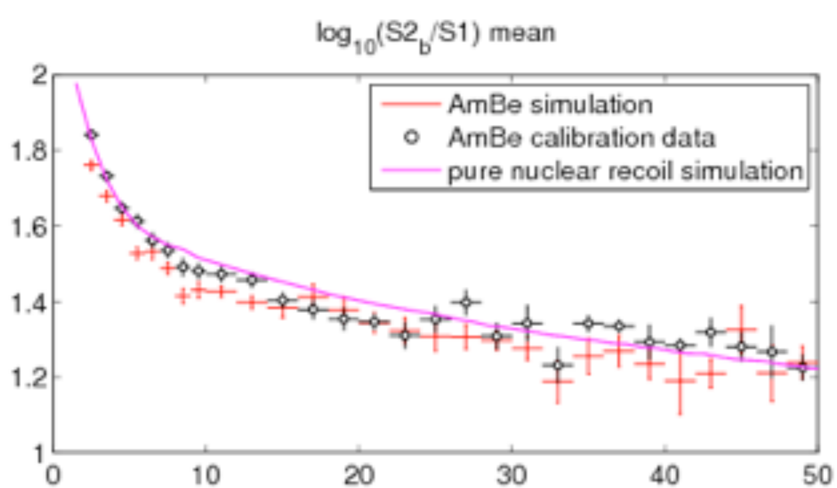
- CH3T injected into gas system
  - Beta decay with $T_{1/2}$ = 12.6 y
  - <E> = 5.9 keV, end point 18.6 keV
- High stats homogeneous source of low energy ER:
  - Used to define ER band and low energy threshold

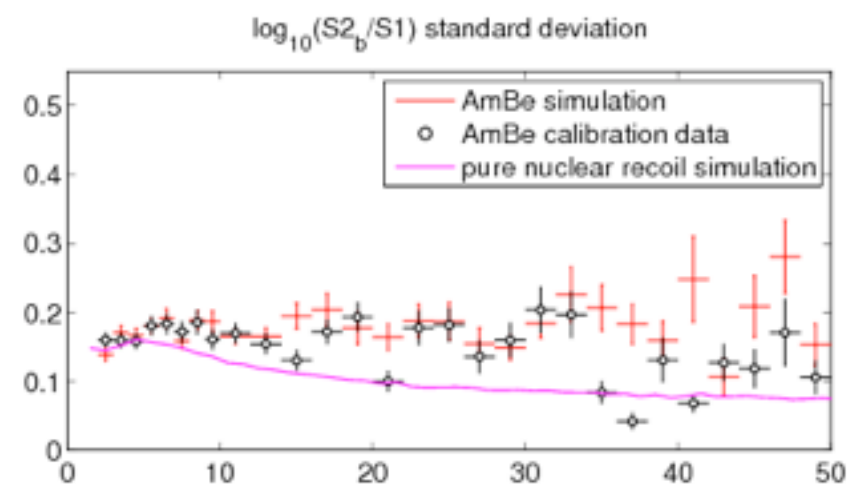



# NR: $^{241}$AmBe and $^{252}$Cf

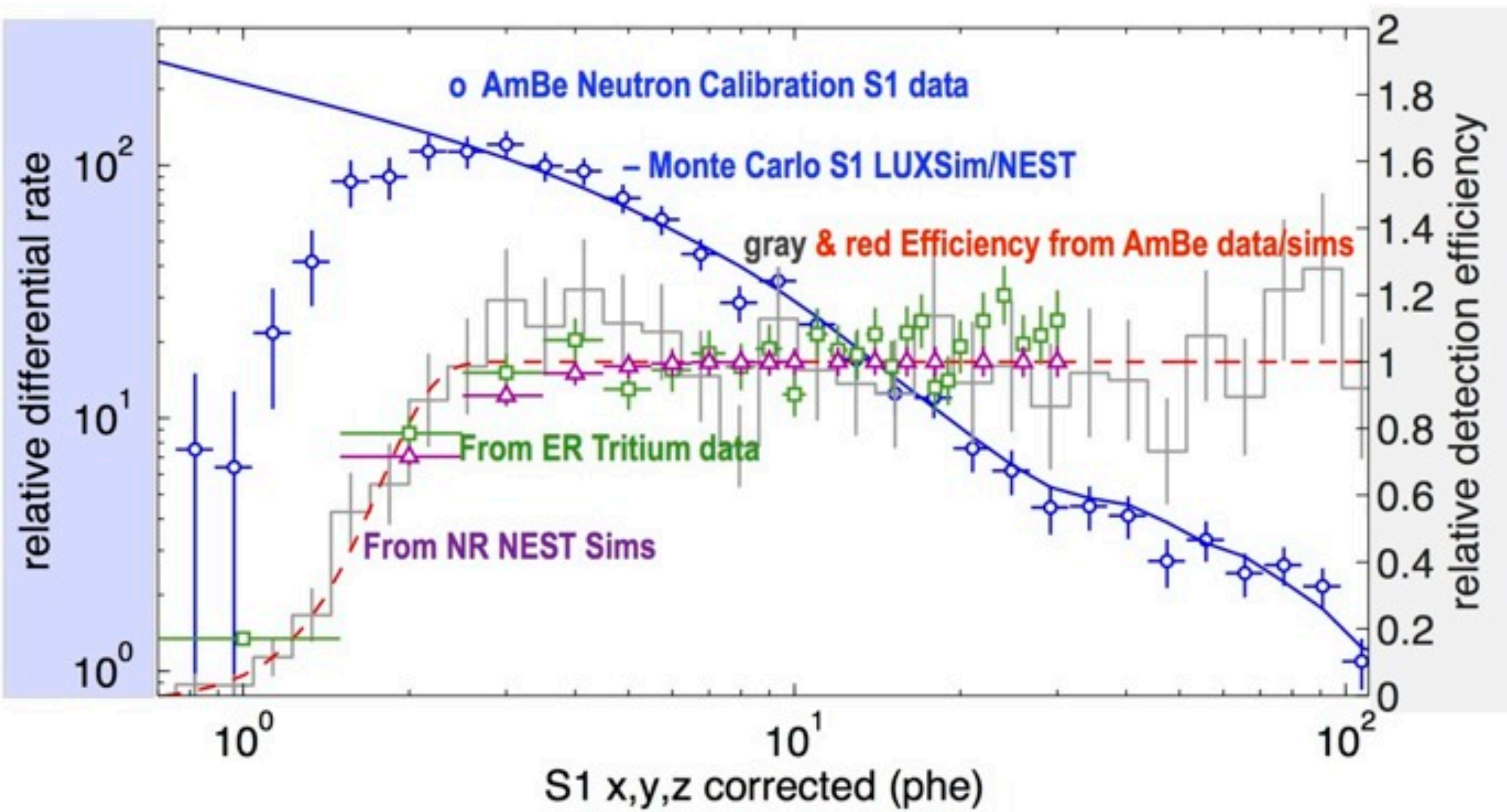
- Used for NR efficiency, to validate NR simulations (NEST + GEANT4 → data processing)



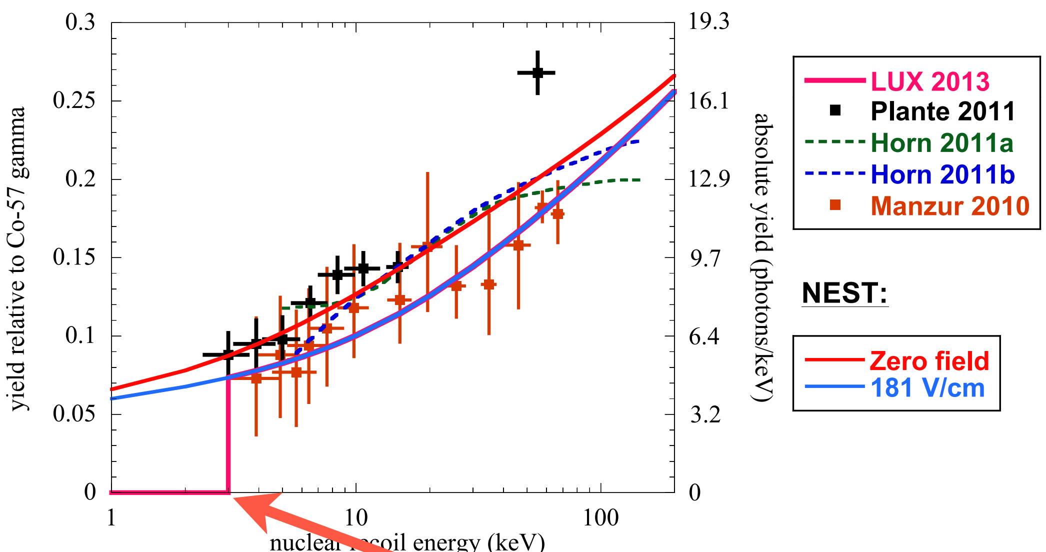
# Multiple studies of efficiency drop off at low-energy



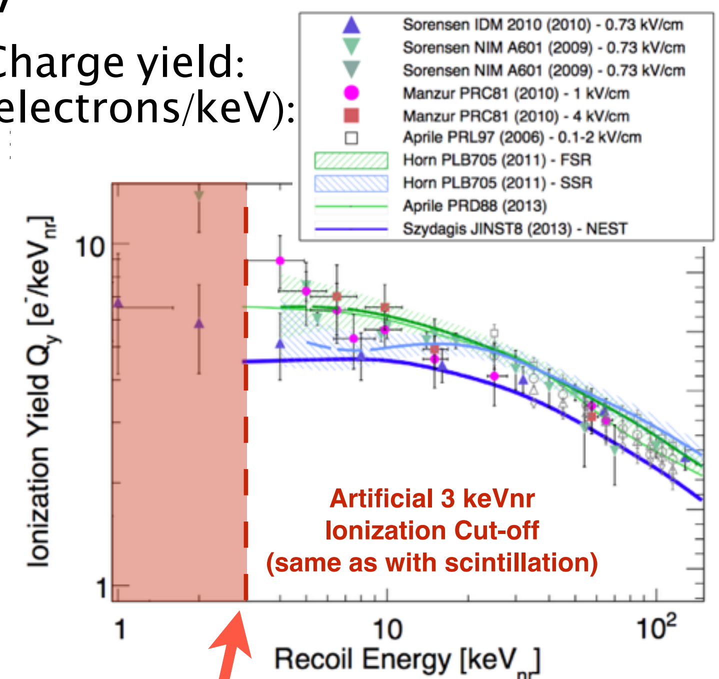
# Recap LUX Run 3: light and charge yields

- Yields at vertex based on Noble Element Simulation Technique (NEST), M. Szydagis, JINST 6, P10002 (2011)
- Anchored to experimental data
- Lack of data for NR response below 3 keV·

Light yield:

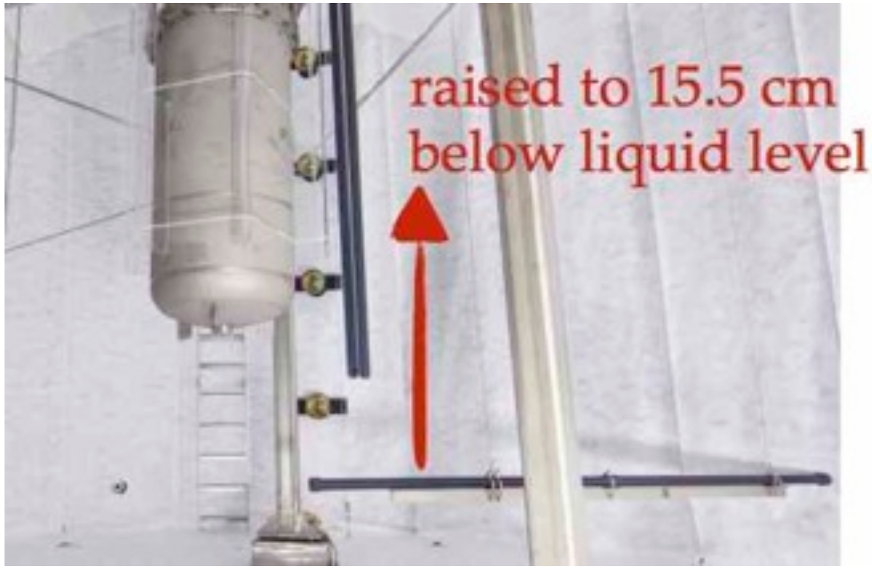


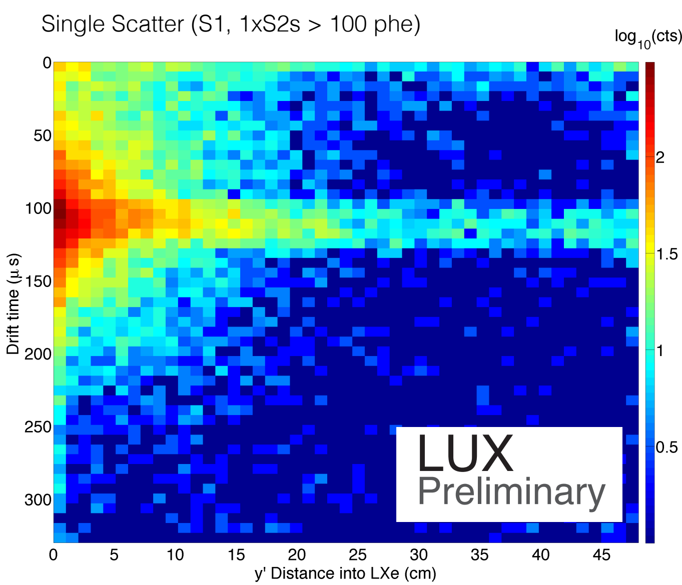

Charge yield: (electrons/keV):

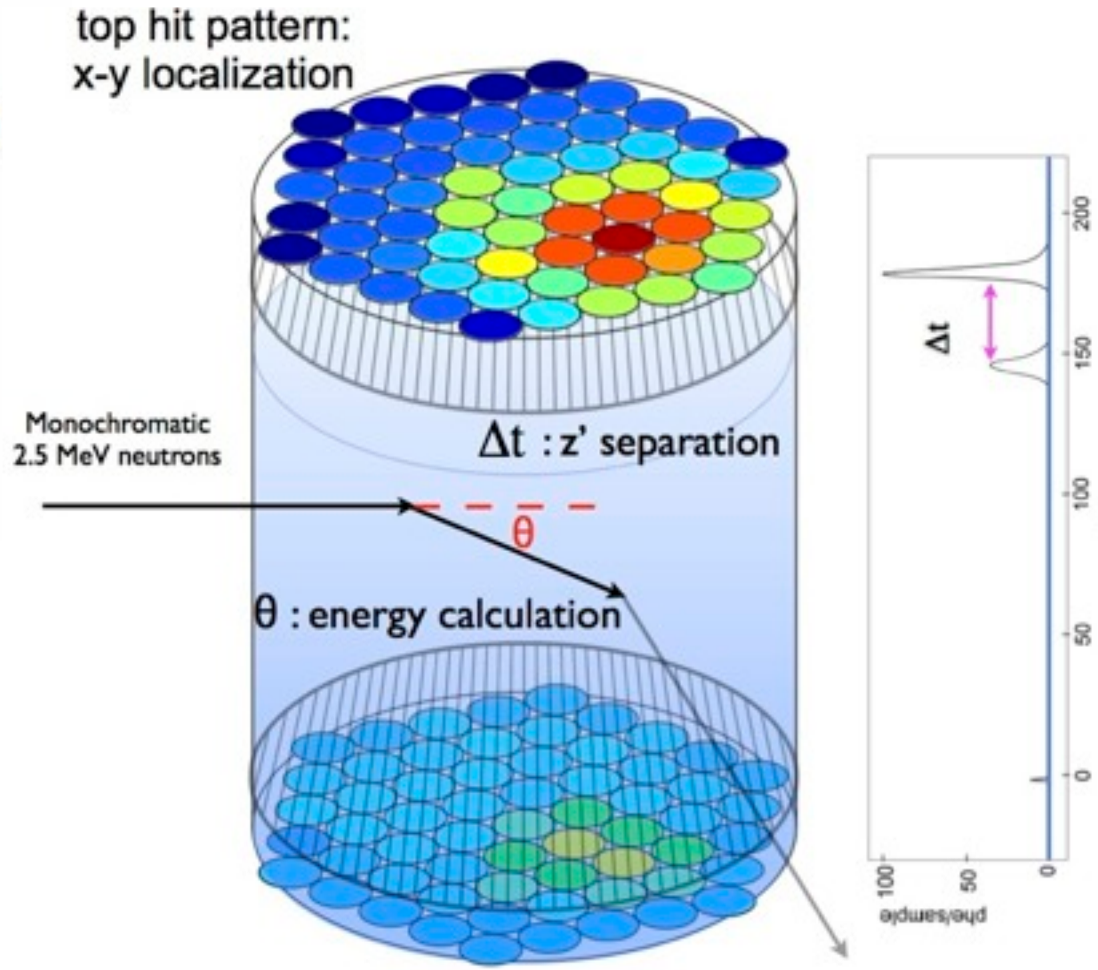



**For first WIMP search result LUX used conservative cut-off below 3 keVnr**

# NR: Deuterium-Deuterium neutron gun




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

# NR: absolute charge yield from multiple scatters

- Absolute charge yield measured to below 1 keV
- Sensitivity for recoils below Run 3 cut-off

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

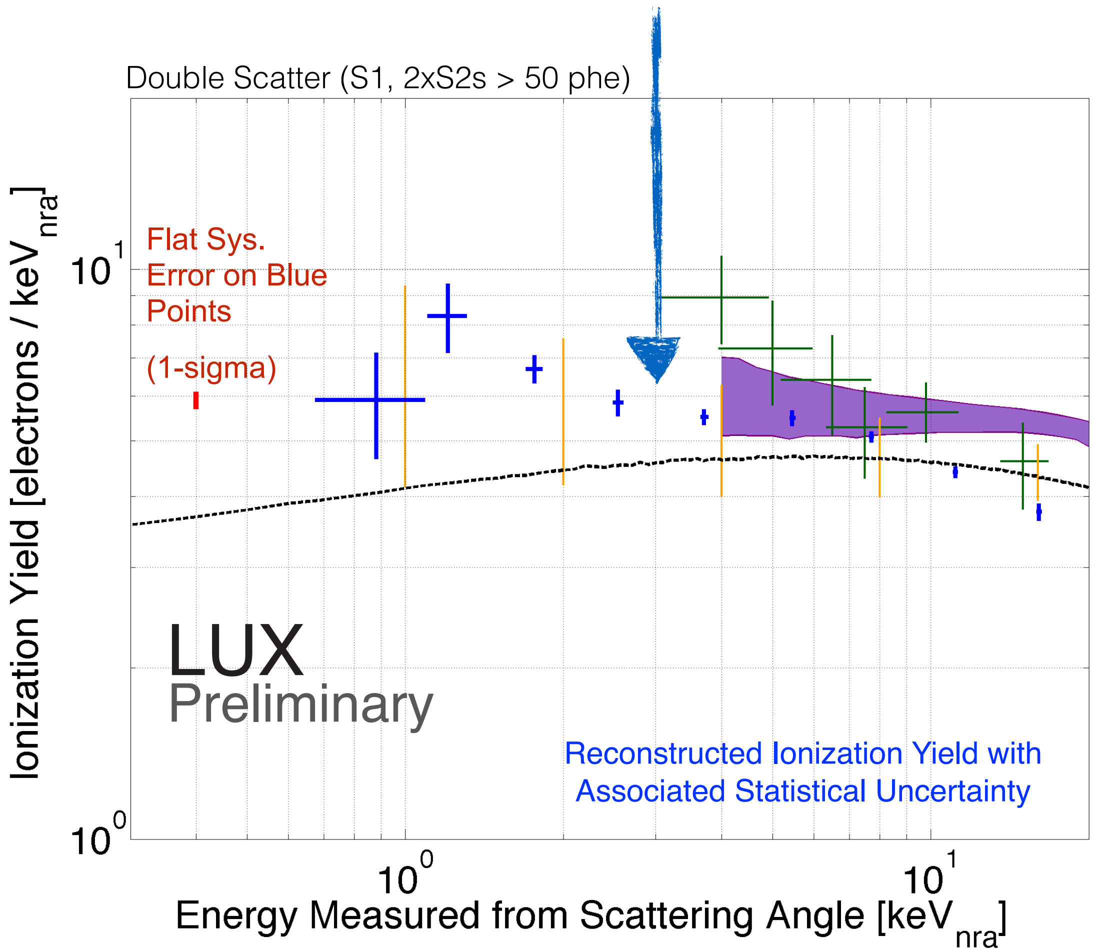
Green Crosses - Manzur 2010; 1 kV/cm <u>(absolute energy scale)</u>

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

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

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

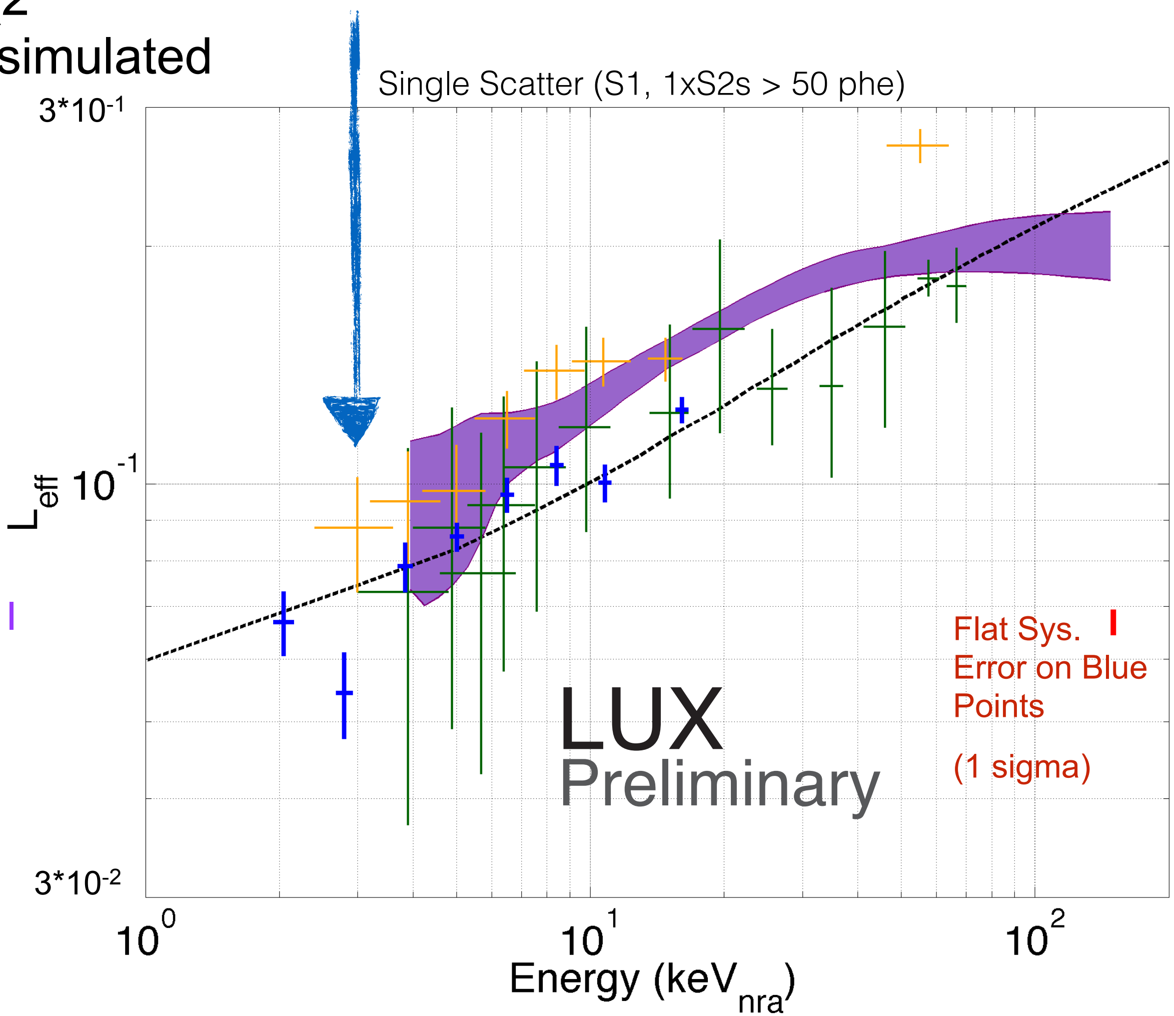
Run 3 WIMP result 3 keVnr conservative cut off



# NR: relative scintillation efficiency from single-scatters

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

Run 3 WIMP result 3 keVnr conservative cut off




**Blue Crosses - LUX Measured $L_{eff}$; reported at 181 V/cm (absolute energy scale)**

Green Crosses - Manzur 2010; 0 V/cm (absolute energy scale)

Purple Band - Horn Combined Zeplin III FSR/SSR; 3.6 kV/cm, rescaled to 0 V/cm (energy scale from best fit MC)

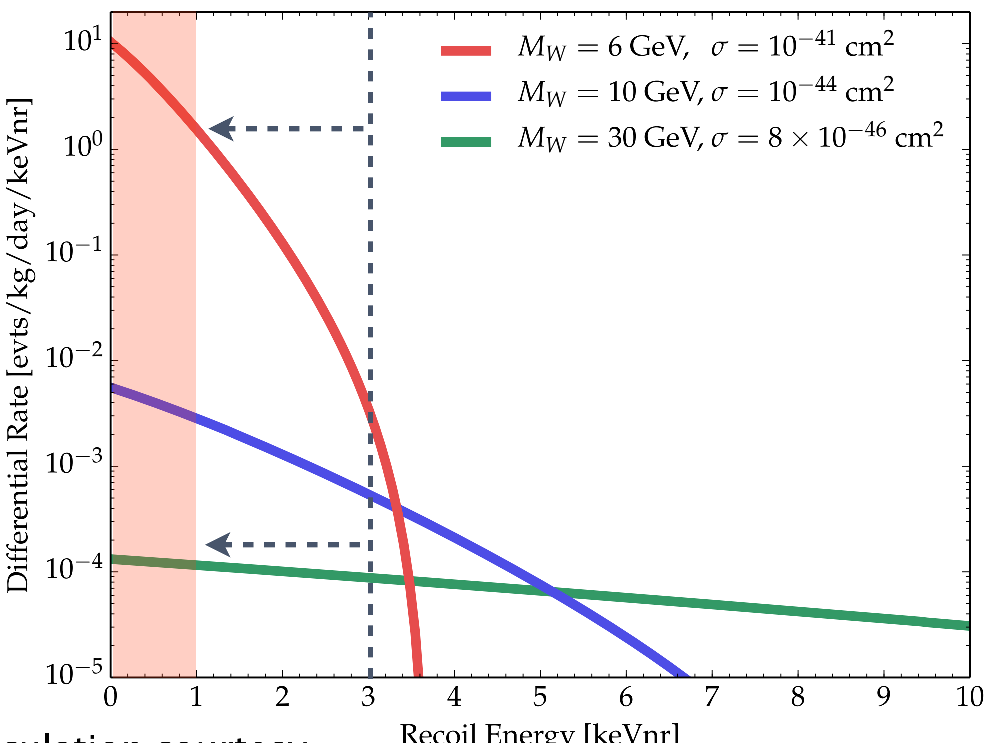
Orange Crosses - Plante 2011; 0 V/cm (absolute energy scale)

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

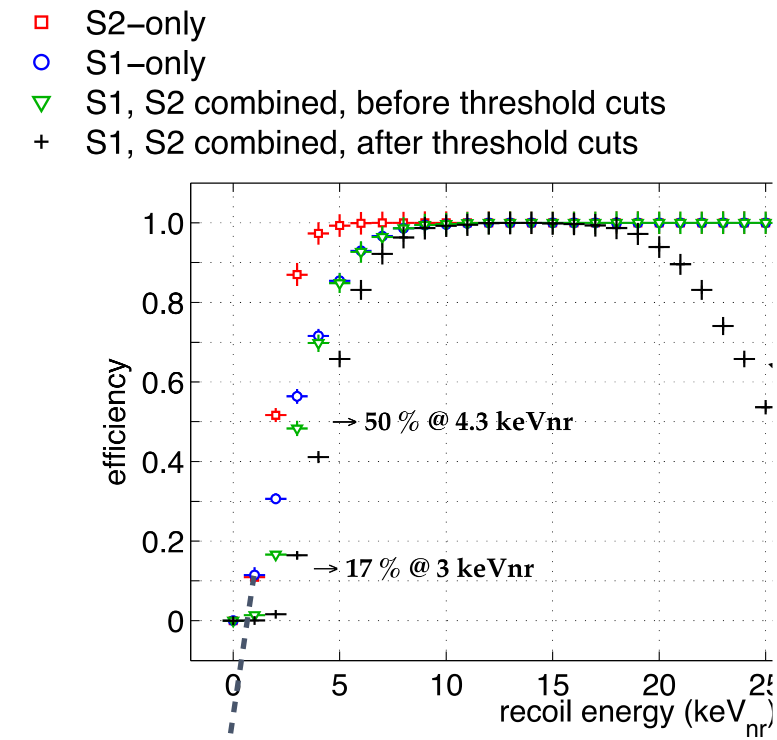
Full details:
http://www.pa.ucla.edu/sites/default/files/webform/20140228_jverbus_ucla2014.pdf
(forthcoming paper in preparation)

# What does this mean for low-mass WIMP sensitivity

Decreasing cutoff from 3 keV to 1 keV means we expect 1000 * more signal @ 6 GeV




Calculation courtesy of Aaron Manalaysay




Potential for sensitivity down to < 1 keV

# Summary and outlook

- With 3 months of data LUX's set world leading limit for SI WIMP-nucleon scattering
- Wide variety of calibrations used to validate detector response
- Low-energy neutron calibration post Run 3 provided direct measurement of NR energy scale in LUX
  - Expect re-analysis of first WIMP-search data with reduced threshold
- Many opportunities beyond SI:
  - SD, inelastic-DM, non-standard interactions, solar axions and ALPs
- Currently preparing for 300-day run, ~ ×5 improvement in sensitivity expected