# Recent results from LUX and status of LZ

Paolo Beltrame
University of Edinburgh
(on behalf of the LUX and LZ collaborations)

51st Rencontres de Moriond
Electro Weak and Unified Theories
La Thuile, 12-19 March, 2016.

# Outline

- The Large Underground Xenon (LUX) experiment

  New results on WIMP searches and calibration

- The LUX-ZEPLIN experiment

# Direct search

**Dark matter** (**DM**) Milky Way's halo
=> flux on Earth ~ $10^5$ $cm^{-2}s^{-1}$
$\rho_\chi$ ~ 0.3 GeV/$cm^3$ and 100 GeV/$c^2$

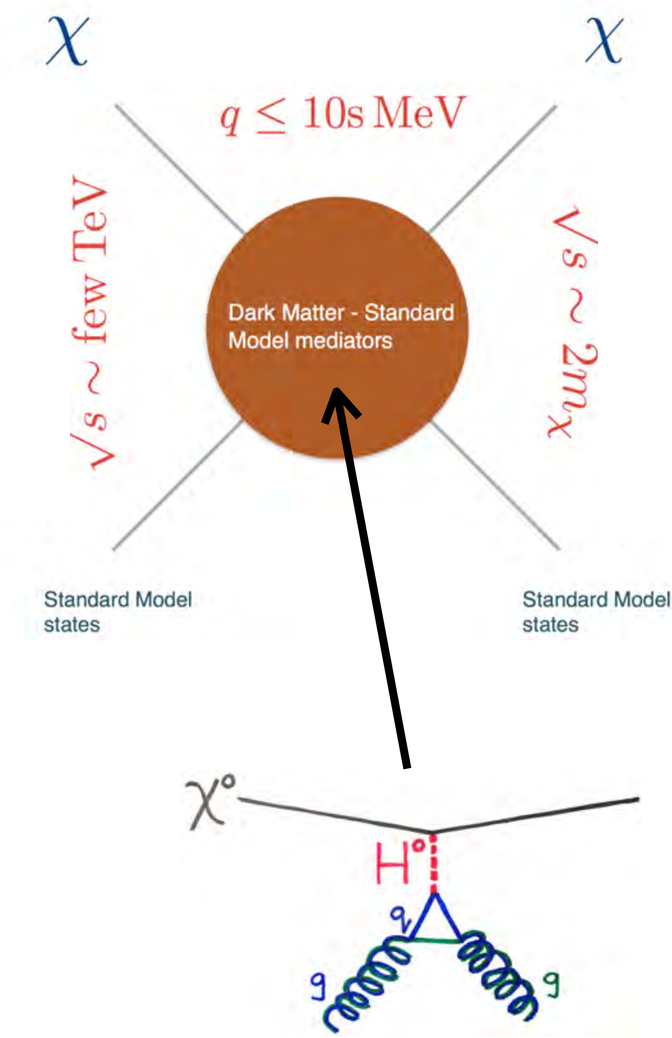
Basic goal: search for nuclear recoil from DM elastic scattering.

Simple dynamics: *cross section ∝ (form-factor)²*

Spin-independent: nucleon form-factor gives rise to $A^2$ enhancement due to coherence.

The dependence on $q^2$ is also contained in the form-factors.

Spin-dependent: form-factor depends on nuclear spin. No coherence enhancement.



# Large Underground Xenon

## 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 |
| Sean Fallon | Graduate Student |
| Steven Young | Graduate Student |

## UC Davis

| | |
|---|---|
| Mani Tripathi | PI, Professor |
| John Thmpson | Development Engineer |
| Dave Hemer | Senior Machinist |
| Ray Gerhard | Electronics Engineer |
| Aaron Manalaysay | Scientist |
| 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 |
| James 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 |

# LUX detector

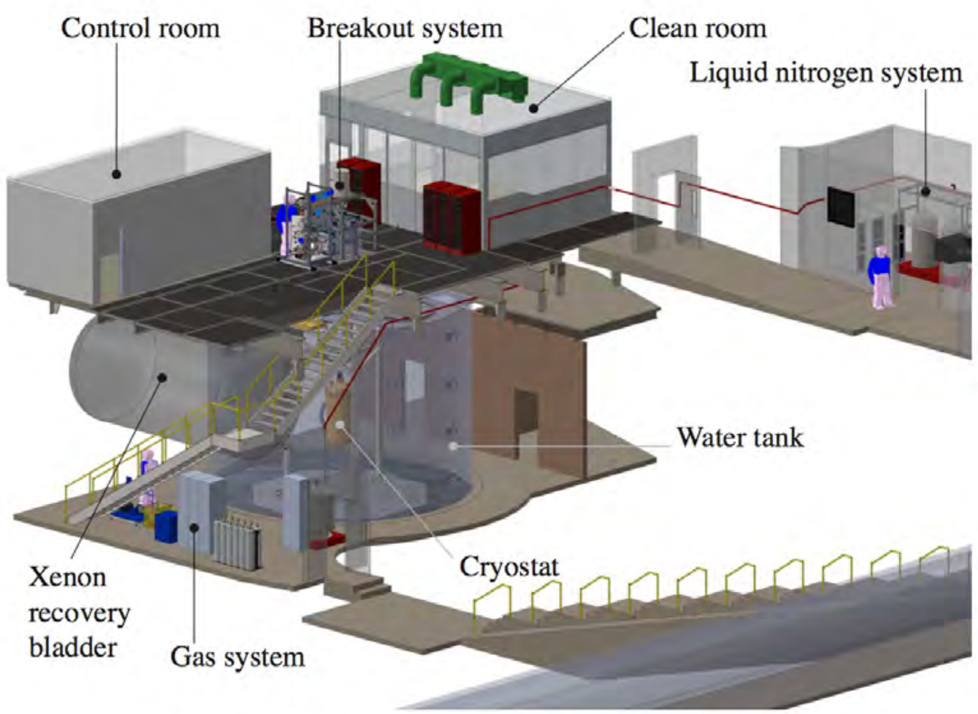
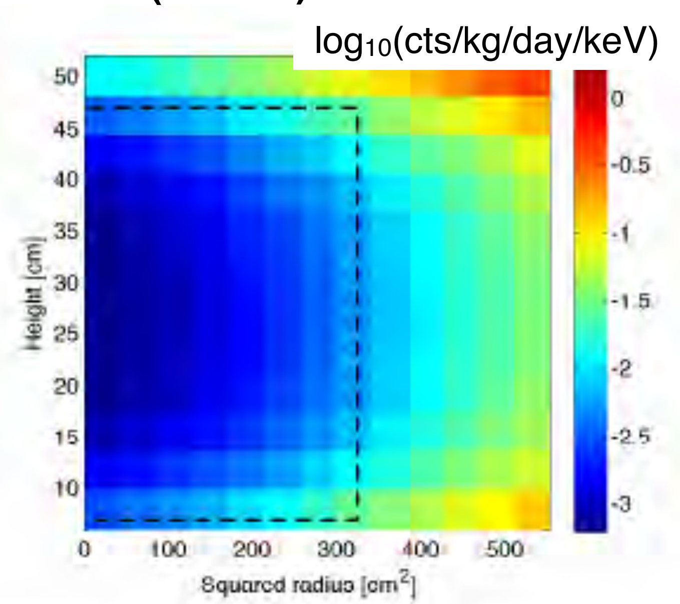


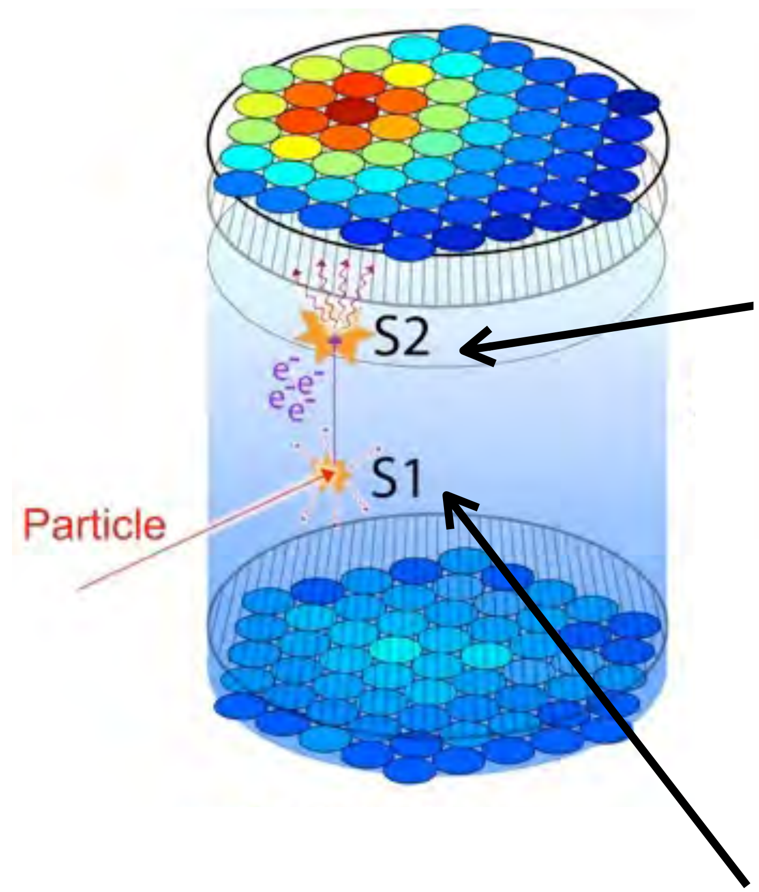

Figure 16: Rendering of the layout of the Davis Laboratory.

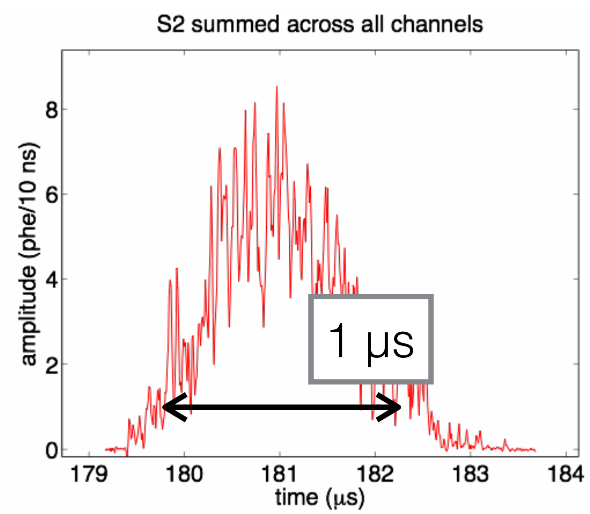
- Davis Cavern @ Sanford Lab (SURF), 4850 ft (1.5 km) underground
- 250 kg (47 x 49 cm$^2$) of active LXe dual phase time projection chamber (TPC)
- Two arrays each of 61 ultra-pure PMTs
- Reducing background:
  - cosmic μ flux reduced to 6.2 × 10$^{-9}$ cm$^{-2}$s$^{-1}$
  - low background materials
  - 3D event localisation (LXe target fiducialization)



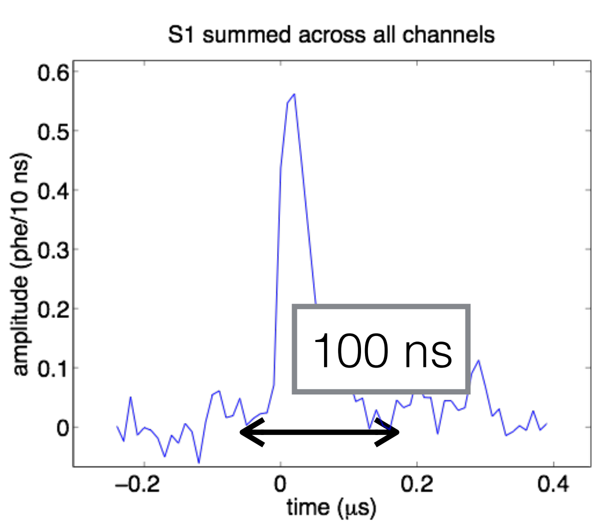
# S1, S2 and CES

## Liquid xenon / dual-phase time projection chamber (TPC)




**(Ionisation) S2**




**(Scintillation) S1**

**'Combined Energy scale'**

$$E = \frac{1}{L(E)} \cdot \left( \frac{S1}{g_1} + \frac{S2}{g_2} \right) \cdot W$$

- $W$ = 13.7 eV
- $g_1$ = Light Collection
- $g_2$ = Extraction + Light Eff.
- $L(E)$ = Lindhard Factor

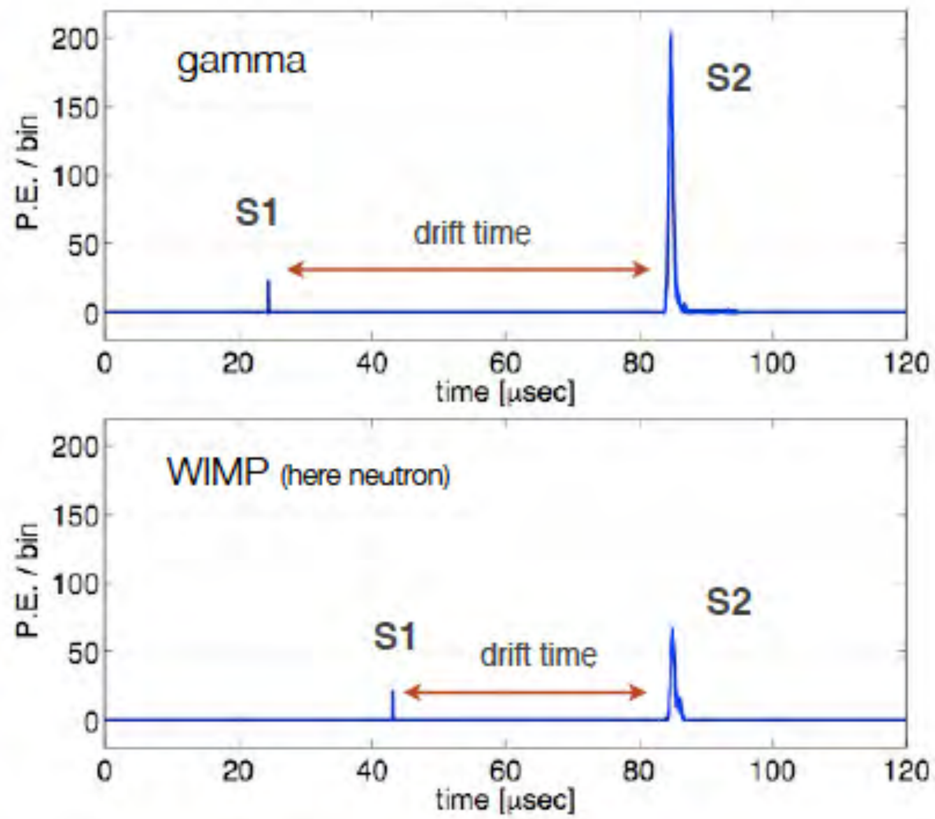
  Nuclear recoil enhancement of heat relative to electron recoils

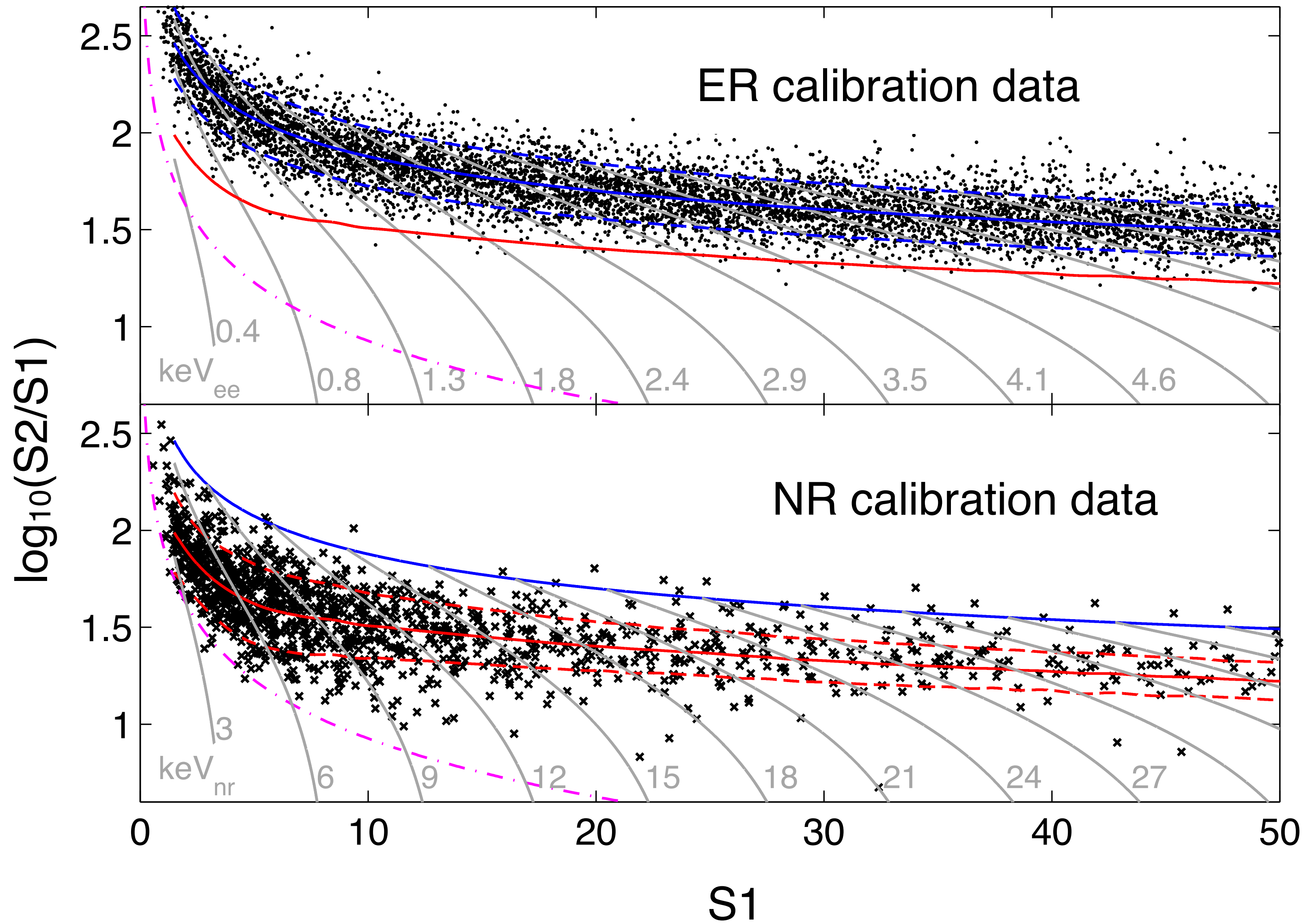
# Nuclear vs. Electron recoil

Combination of Scintillation (S1) and Ionisation (S2) event-by-event particle identification

**Electron Recoil (ER) events**

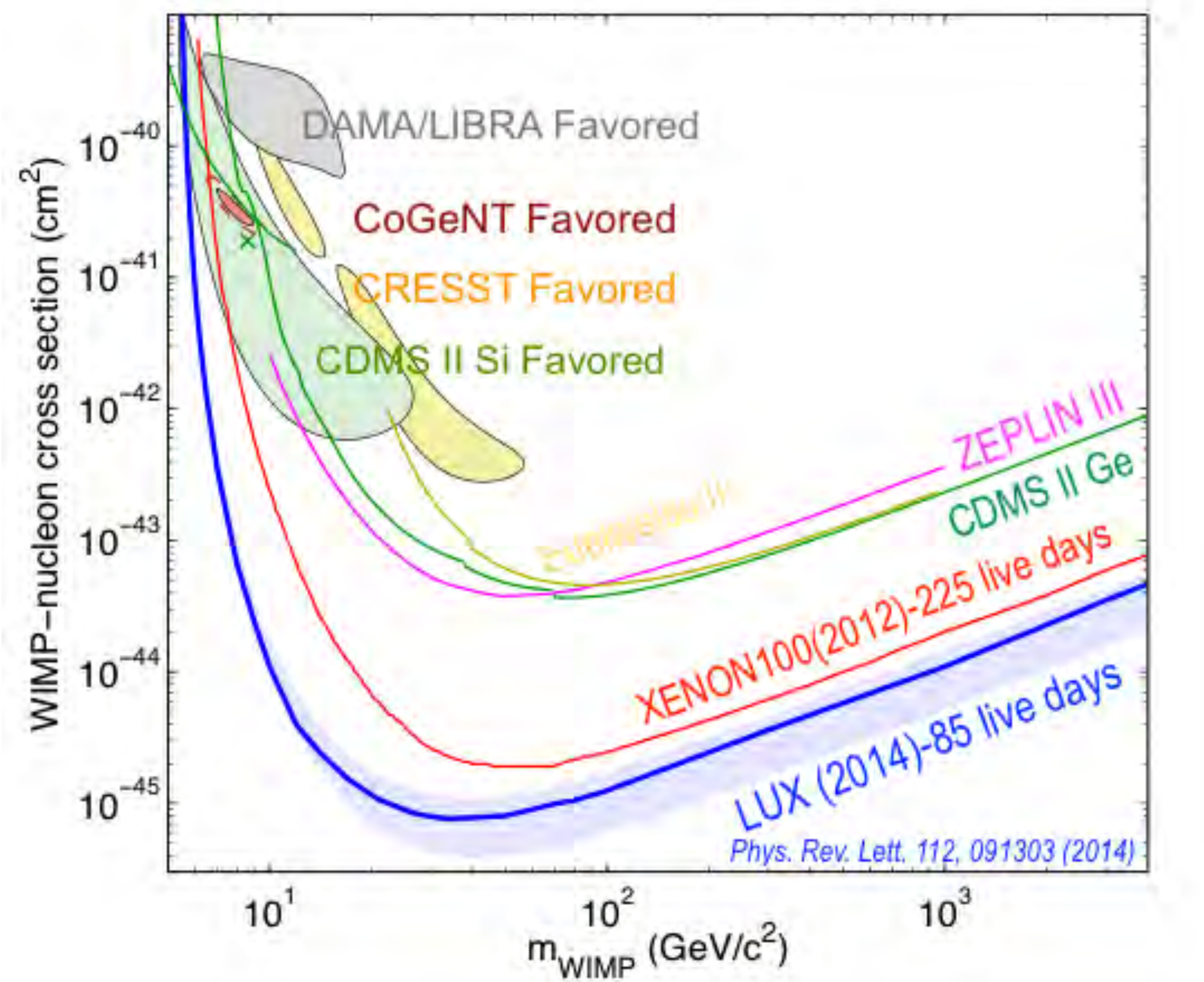
**Nuclear Recoil (NR) events**



# Reminder: 1st LUX results

Phys. Rev. Lett. 112, 091303 (2014)




Limit on Spin-Independent WIMP-nuclei at 7.6 x $10^{-46}$ cm$^2$ at 33 GeV/c$^2$

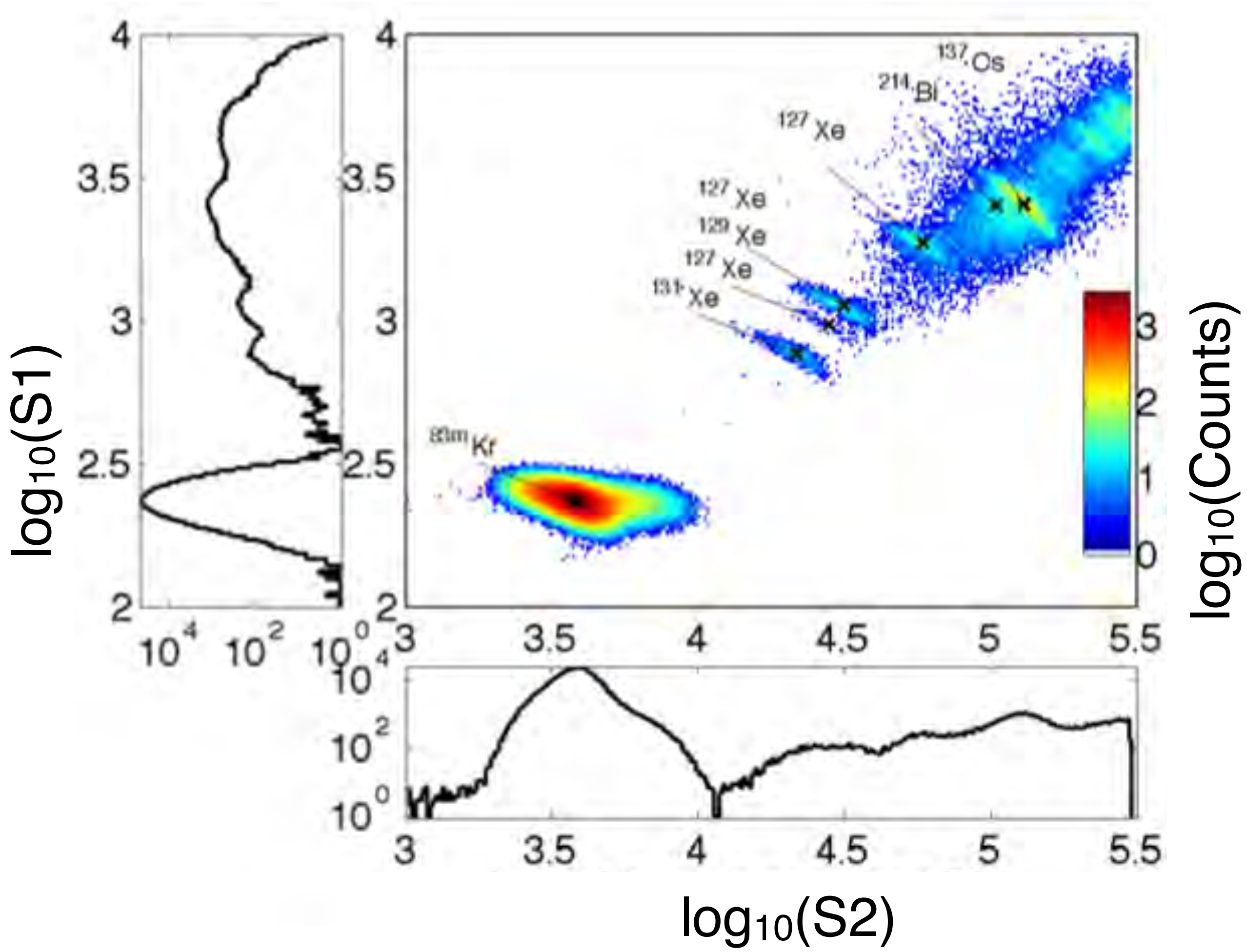
# LUX Run03 reanalysis

- Improved PMT response and light measurement:
  1. removed a bias in baselines;
  2. photon digital counting;
  3. photon response calibrated with VUV light.
- Improved calibration:
  1. electronic recoil (ER): mono energetic sources, and $CH_3T$ internal source;
  2. nuclear recoil (NR): mono energetic neutrons with *in-situ* D-D generator.
- New WIMP signal and background modelling.
- Improved profile likelihood ratio (PLR) analysis.

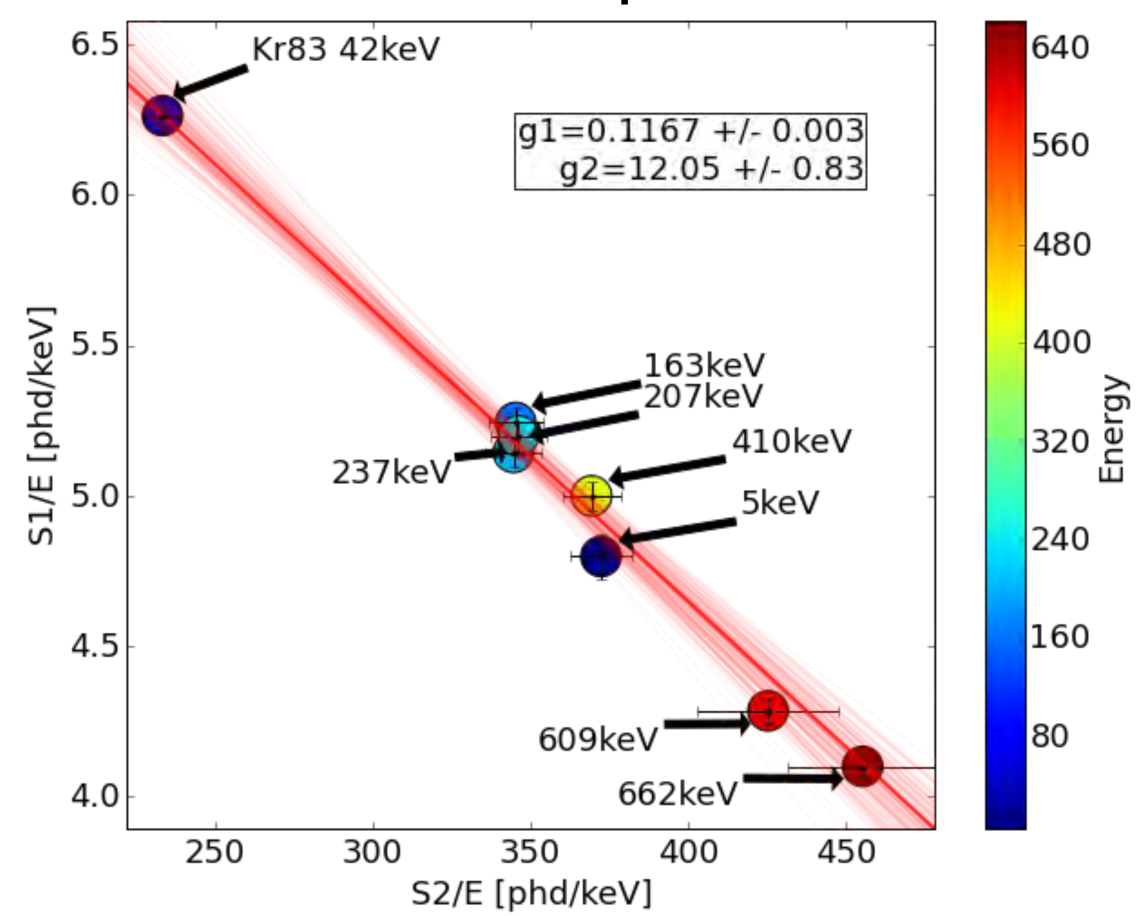
# ER Calibration

**5 - 662 keV Mono-energetic sources** in the mean-yields plane.

Line fit and W = 13.7 eV give absolute quanta.




‘Doke plot’




x-intercept => $n_\gamma$ —> 0; S2/E = $g_2$/W

y-intercept => $n_e$ —> 0; S1/E = $g_1$/W

$$E = \frac{1}{L(E)} \cdot \left( \frac{S1}{g_1} + \frac{S2}{g_2} \right) \cdot W$$

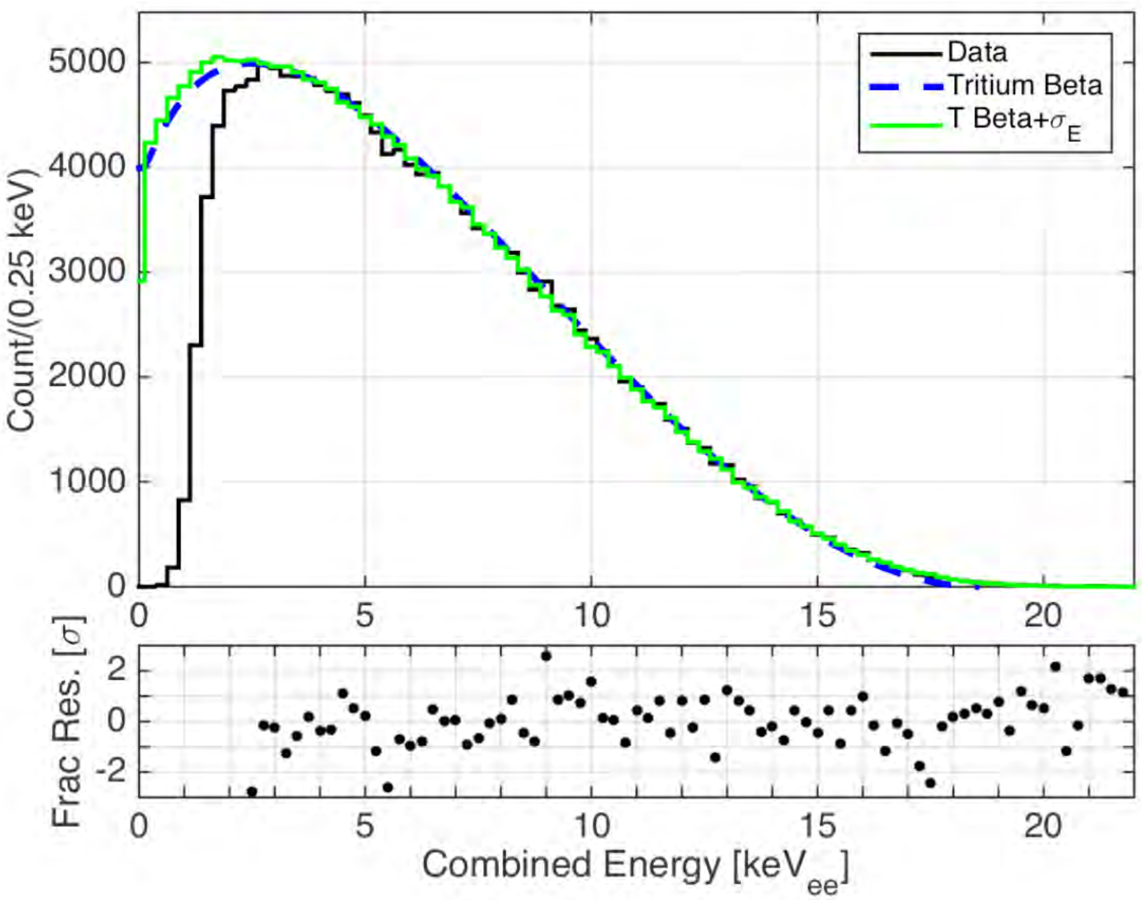
# ER Calibration

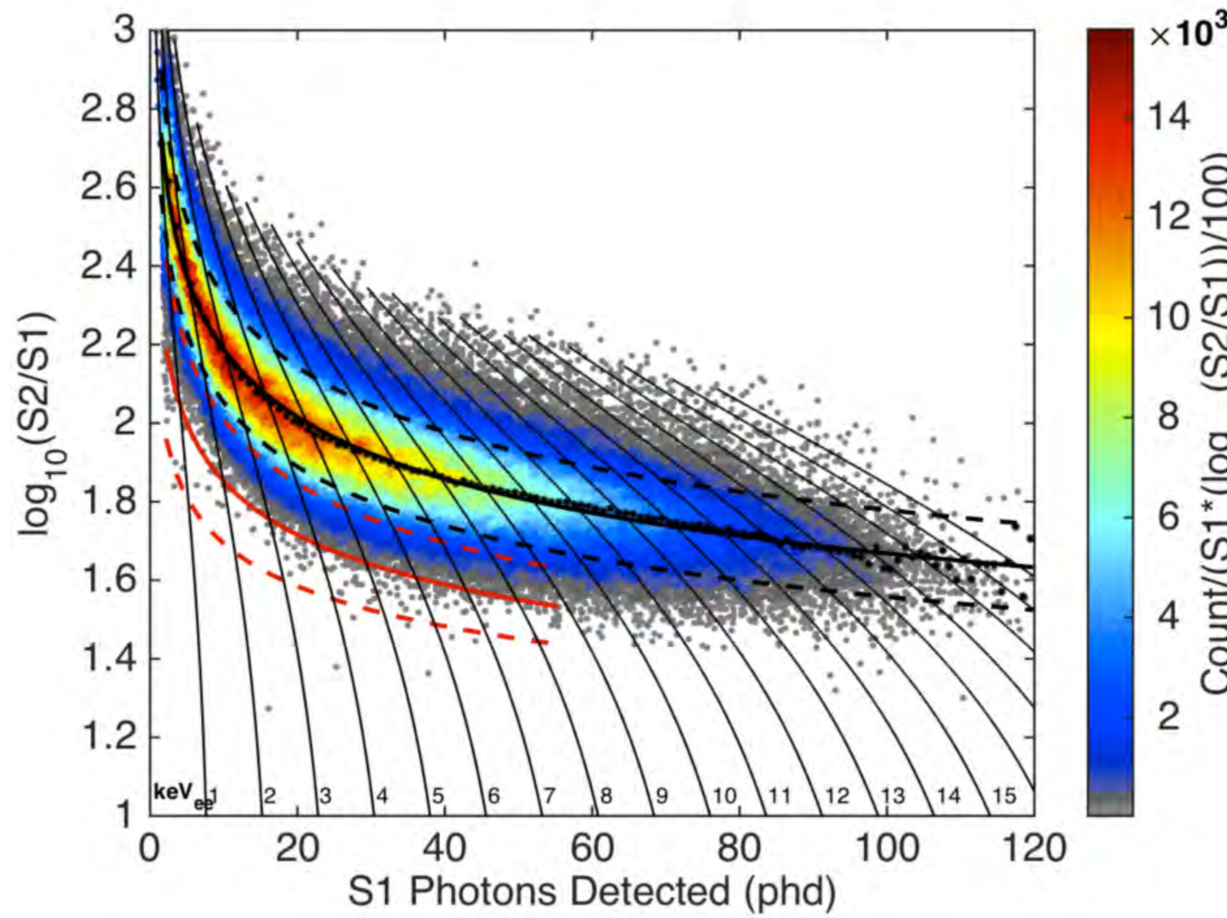
**0 - 18 keV $CH_3T$ (tritiated methane) internal source**

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

2nd campaign of $CH_3T$ calibration in LUX, Dec 2013 : 180 000 events

arXiv:1512.03133



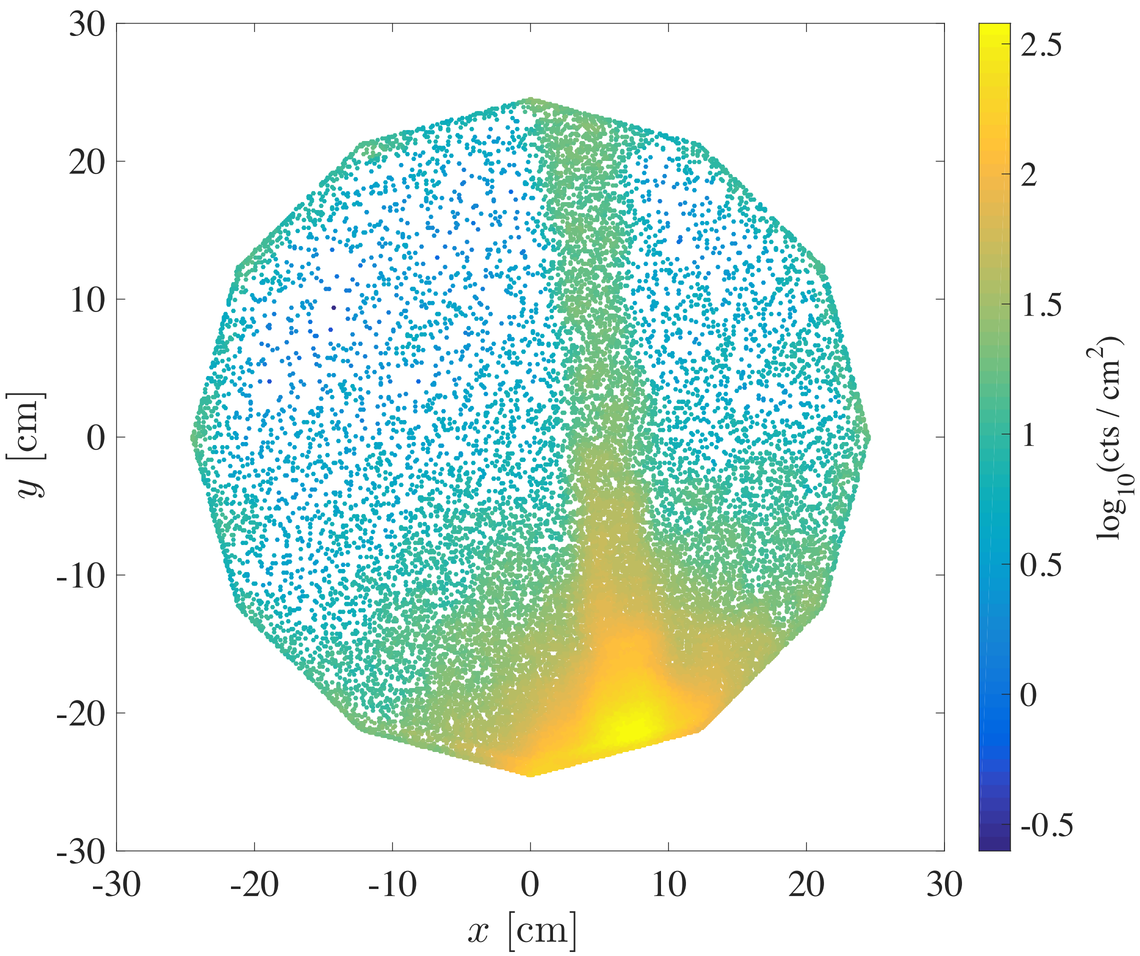



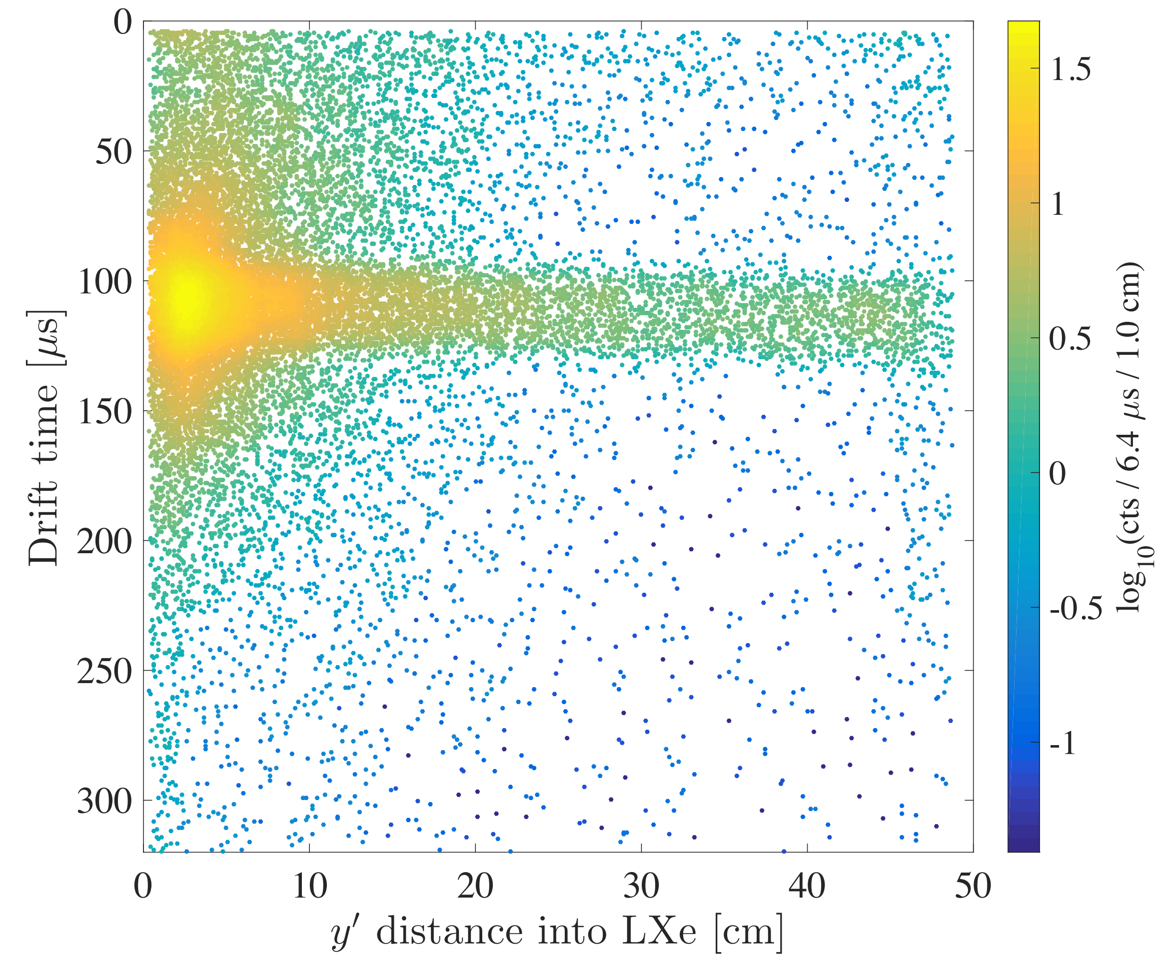
# NR Calibration

**Mono-energetic neutrons: D-D generator**

2.45 MeV neutron fired into LUX WIMP-like NR with:

- in situ measurement
- long lever-arm —> unique energy reach



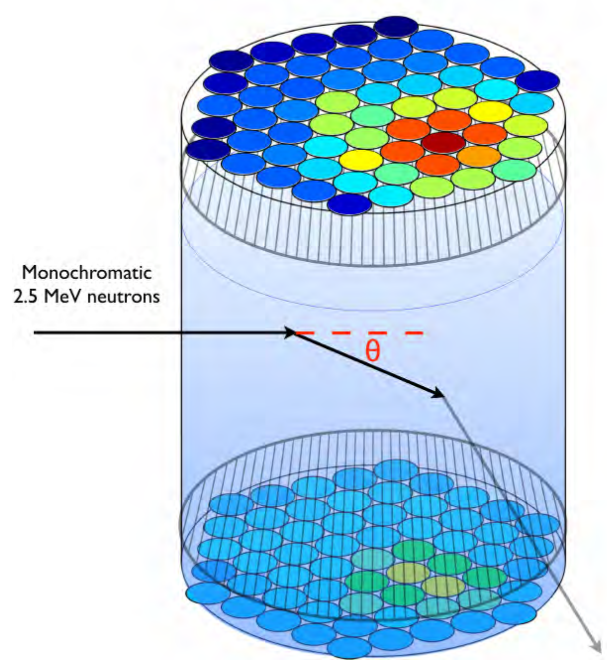



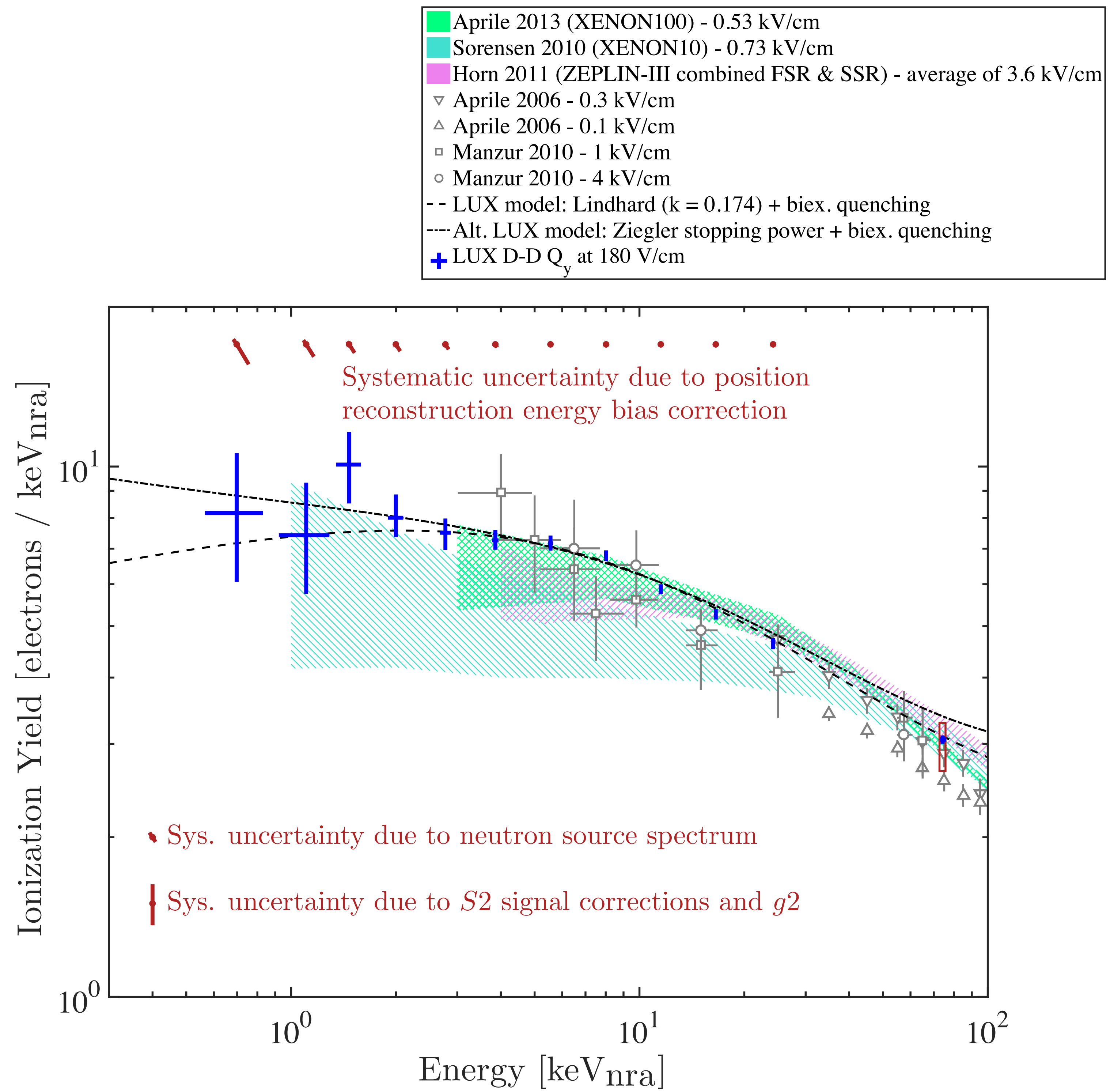
# NR Calibration

## Mono-energetic neutrons: D-D generator

**S2 vs energy via E(θ)**
**for multiple scatters**

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



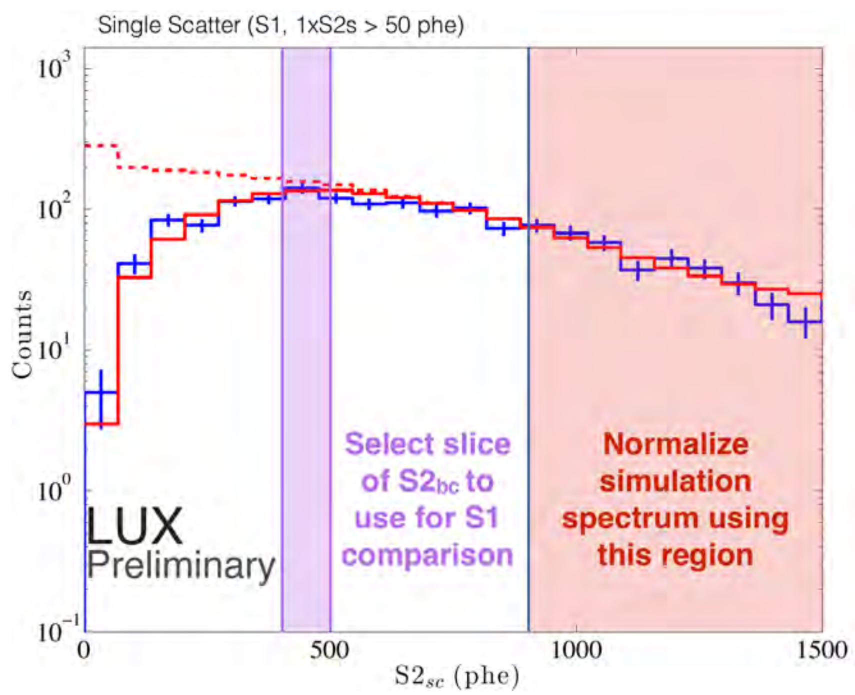



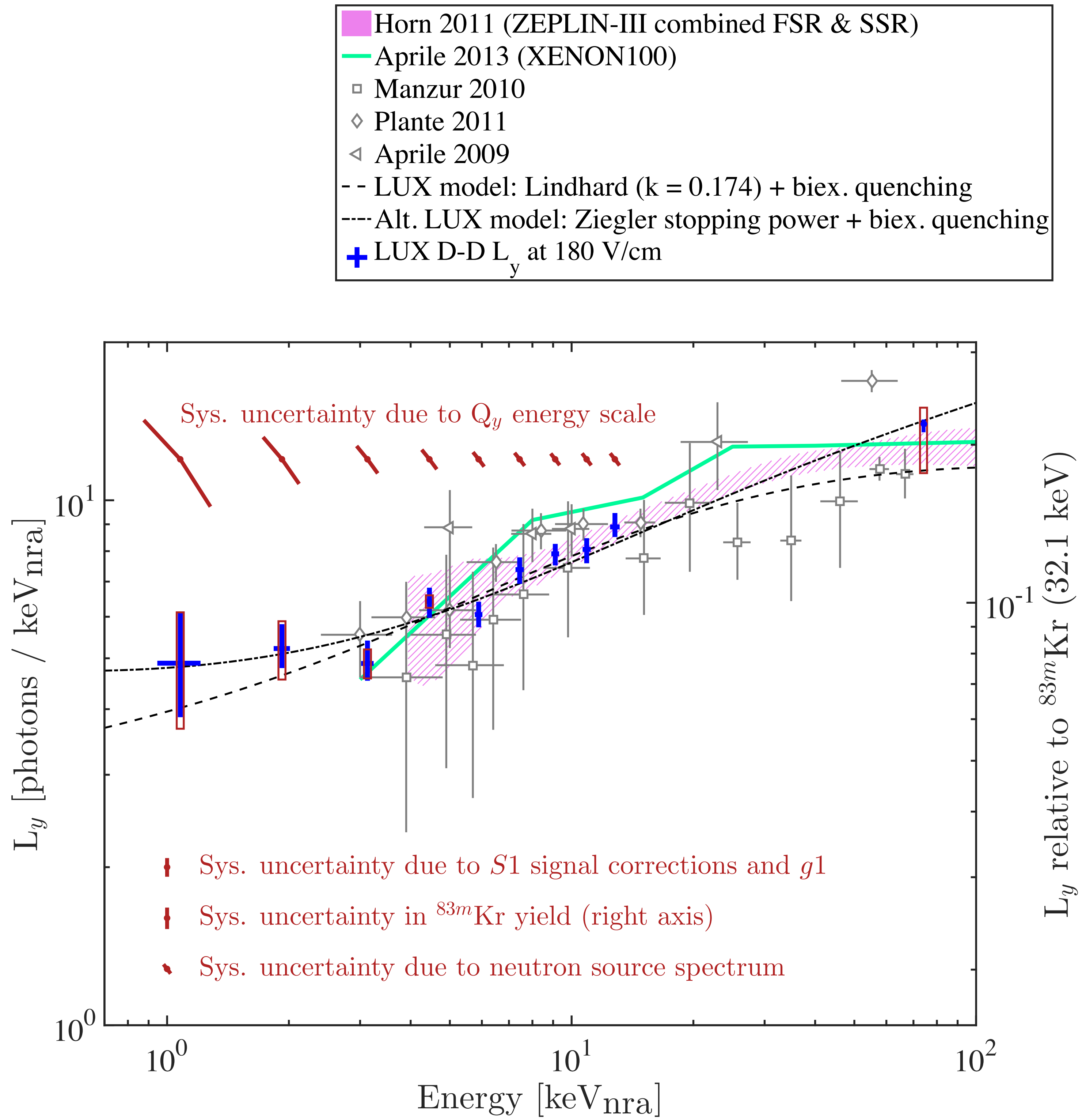

Paolo Beltrame

# NR Calibration

Mono-energetic neutrons: D-D generator

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



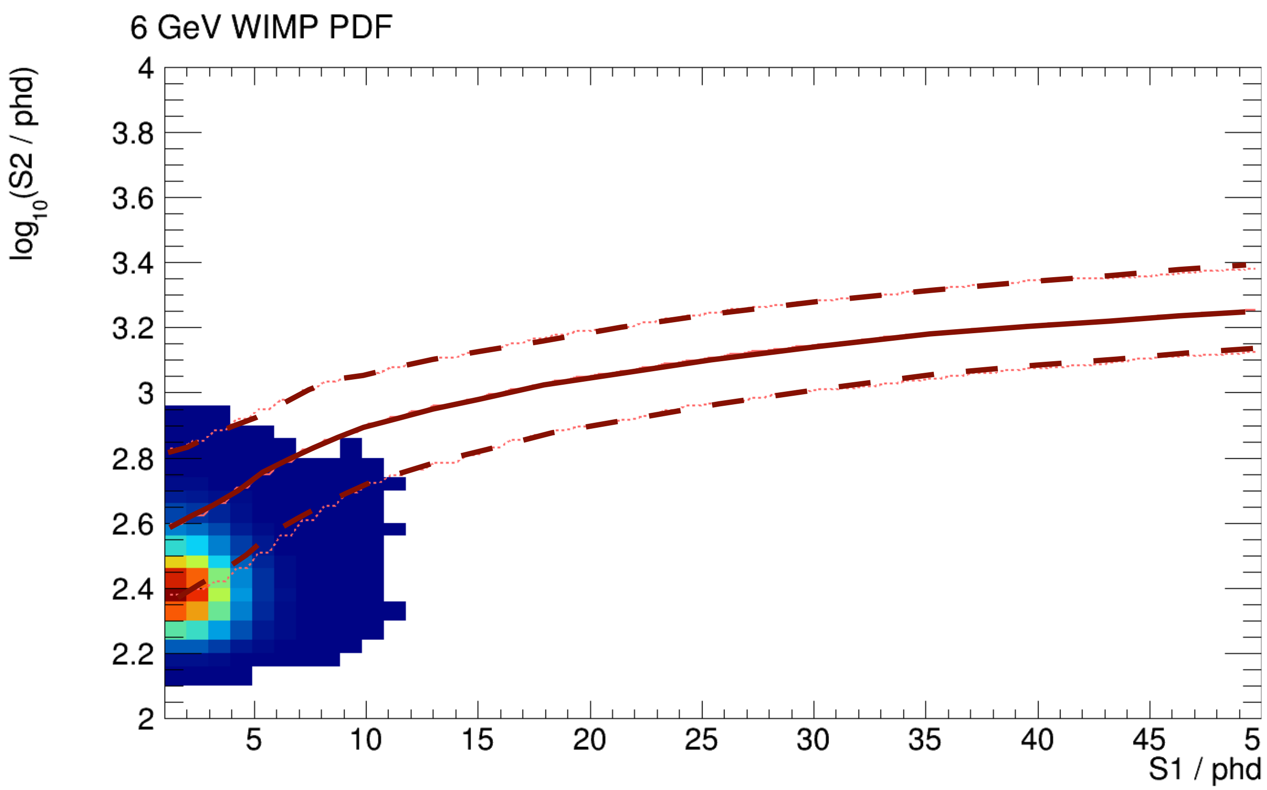



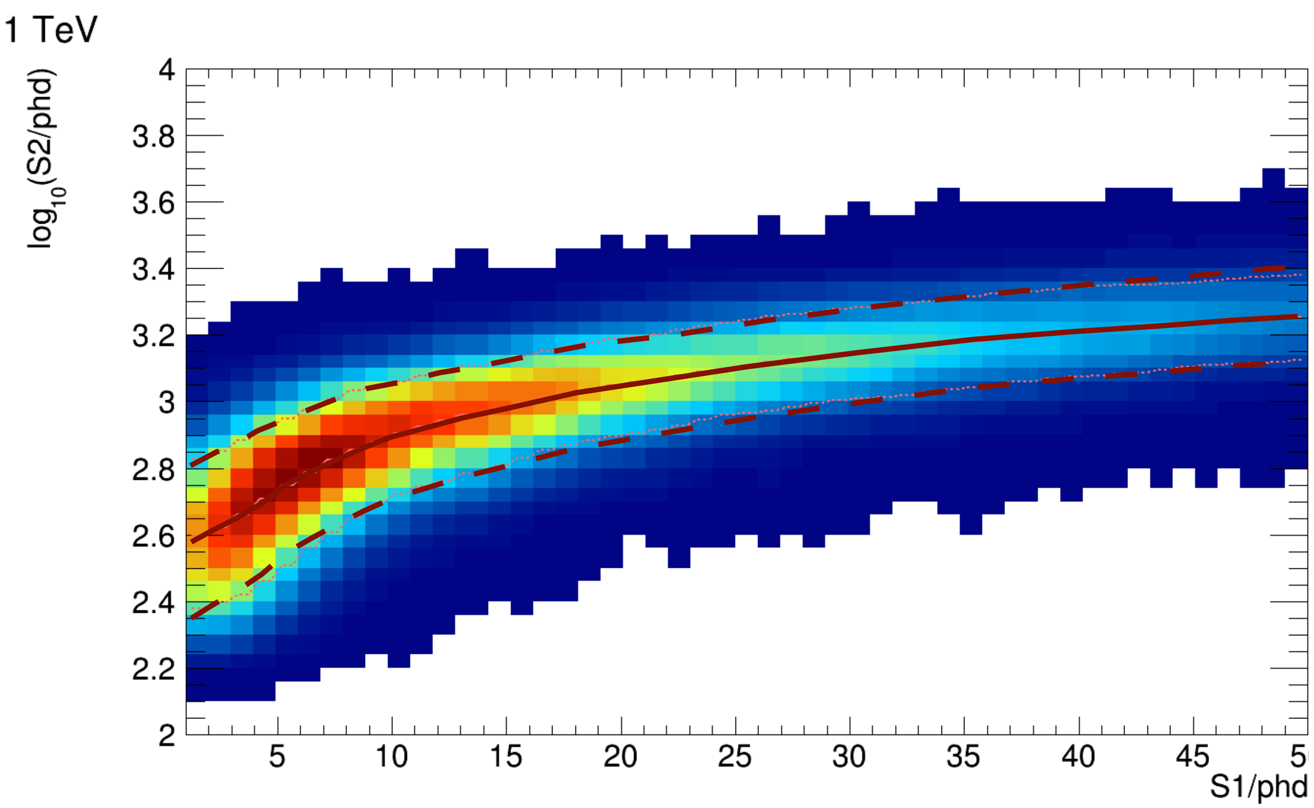
# Signal and background

| Source | Spectrum | 'S2/S1' | Spatial distribution |
|---|---|---|---|
| New **WIMPs** | ~ exponential | low (NR) | uniform |
| **Compton Scatters from material γ** | ~ flat | high (ER) | peripheral |
| **Internal β from Kr-85, Rn, impurities** | ~ flat | high (ER) | uniform |
| **X-rays from Xe-127 (λ = 36.4 d)** | 1 keV, 5 keV lines | high (ER) | peripheral |
| New **Decays on wall** | ~ flat | low, variable (NR and ER with charge loss) | high radius |

# Signal

| Source | Spectrum | ‘S2/S1’ | Spatial distribution |
|---|---|---|---|
| **WIMPs** | ~ exponential | low (NR) | uniform |




Simulation: Noble Element Simulation Technique (NEST), arXiv:1412.4417

Data: DD-tuned NEST-like model mass-dependence of the WIMP PDFs.

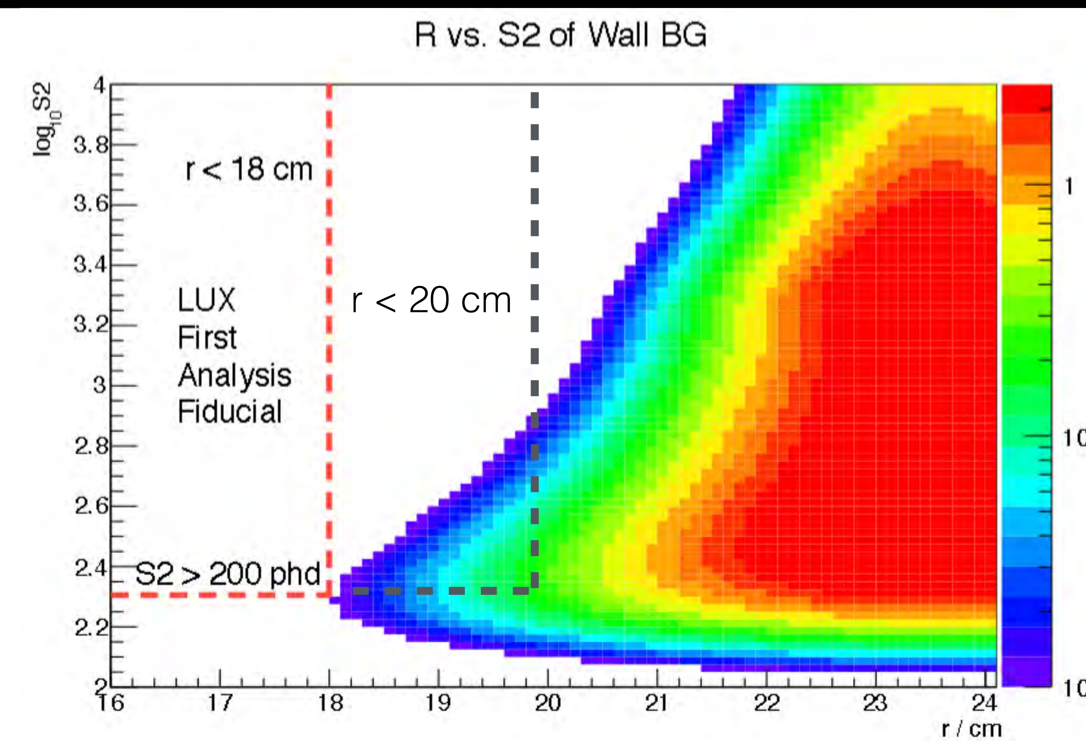
New test statistics profile likelihood: Nuisance params (Lindhard, $g_{2DD}$/ $g_{2WS}$).

# Background

- Detector Material: Gamma rays from Co-60, K-40, Tl-208, Bi-214
  Global fit to 3 MeV
  Asymmetric source from top and bottom
- Internal Background (in Xe): Ar-37, Kr-85m, Xe-127

| Source | Spectrum | 'S2/S1' | Spatial distribution |
|---|---|---|---|
| **Decays on wall** | ~ flat | low, variable (NR and ER with charge loss) | high radius |

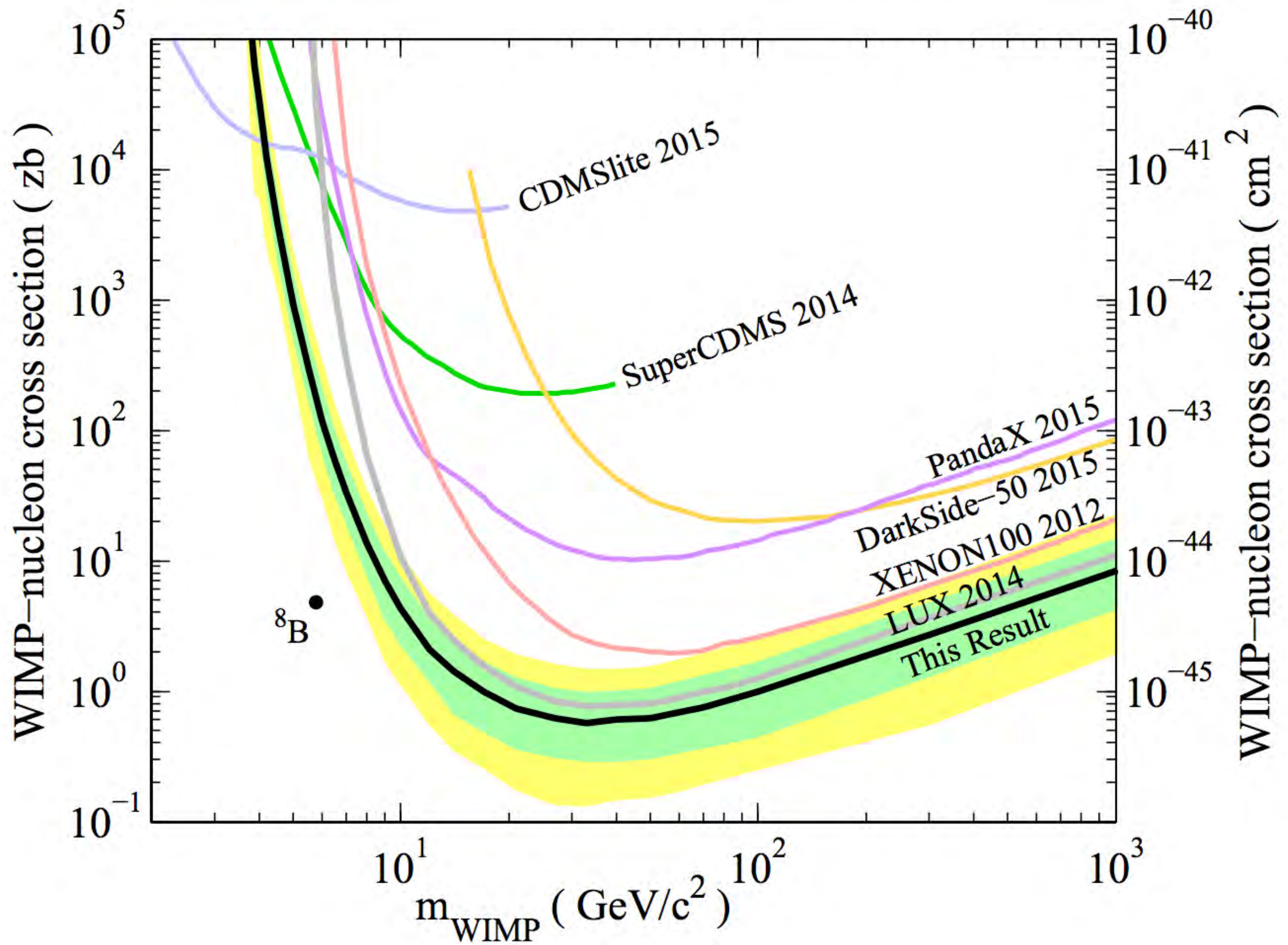
- Rn-222 - Pb-206
- Occurs on the wall at 24.2 - 5 cm
- Resolution leaks below 18 cm
- Charge loss
- Inclusion of 'wall background' increase fiducial radius to 20 cm



| | 2013 analysis | 2015 re-analysis |
|---|---|---|
| **Live days [days]** | 85 | 95 |
| **Fiducial Volume [kg]** | 118 | 145 |
| **S1 cut** | 2 - 30 phe | 1 - 50 phd |
| **S2 cut** | 200 phe (on S2 raw) | 165 phd (on S2 raw) |
| **Energy threshold** | 3 keV => 5.2 GeV/$c^2$ | 1.1 keV => 3.3 GeV/$c^2$ |

# Spin-independent

arXiv:1512.03506v2

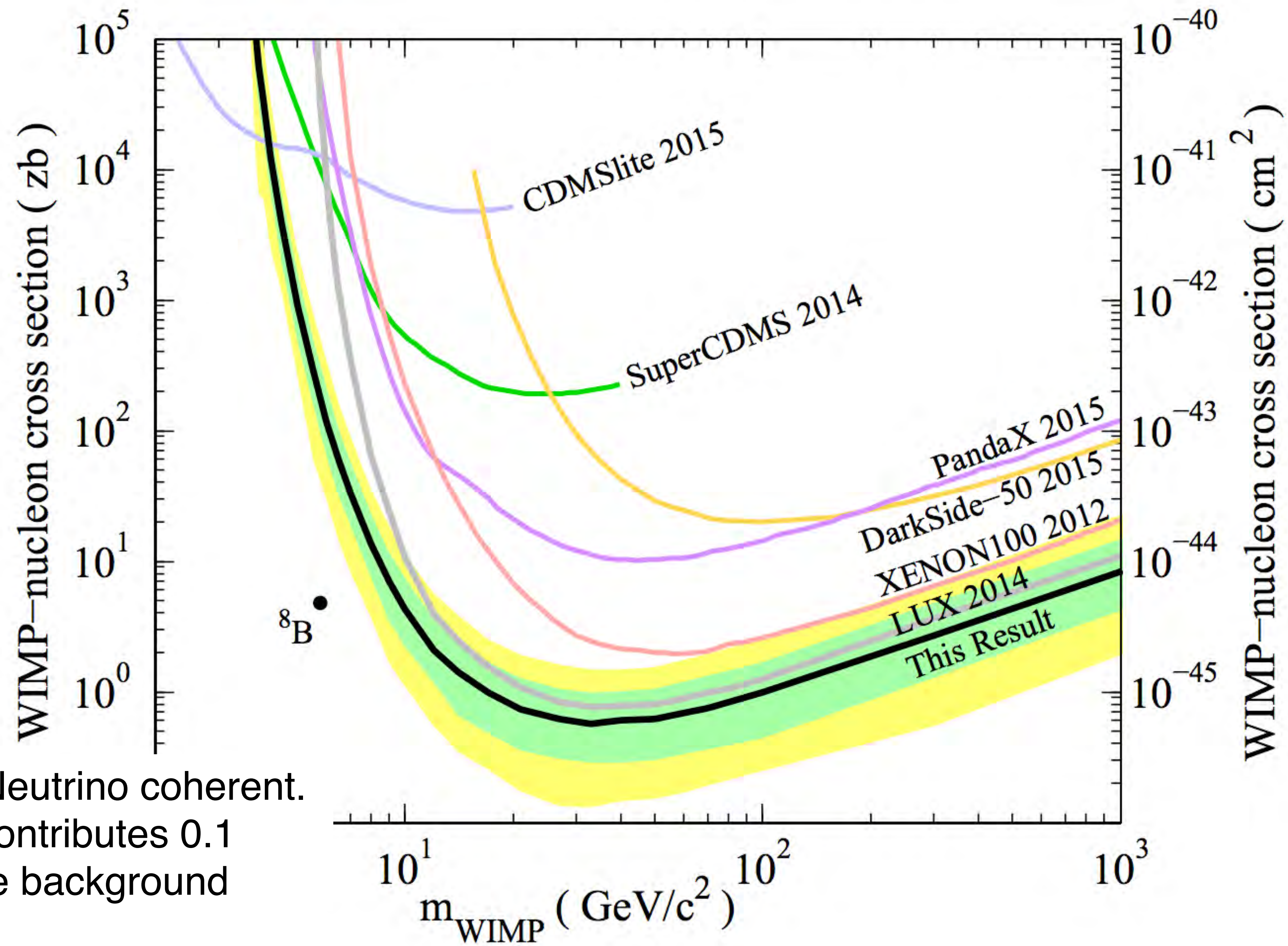



Limit on Spin-Independent WIMP-nuclei at $6 \times 10^{-46}$ cm$^2$ at 33 GeV/c$^2$

Paolo Beltrame

# Spin-independent

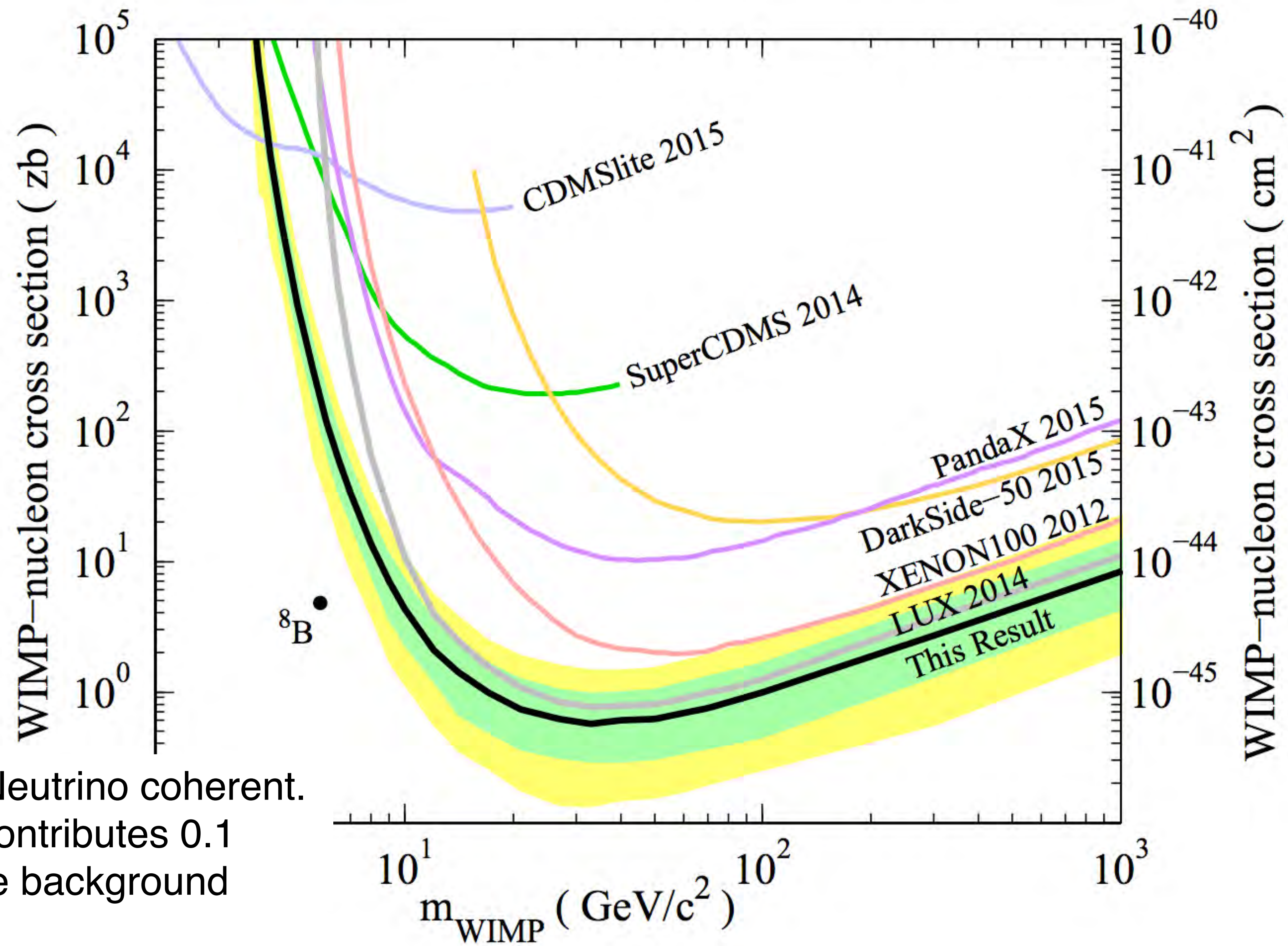
arXiv:1512.03506v2




B-8 Solar Neutrino coherent. Currently contributes 0.1 event to the background

Limit on Spin-Independent WIMP-nuclei at $6 \times 10^{-46}$ cm$^2$ at 33 GeV/c$^2$

# Spin-independent




$10^{-38}$ cm$^2$

Z exchange

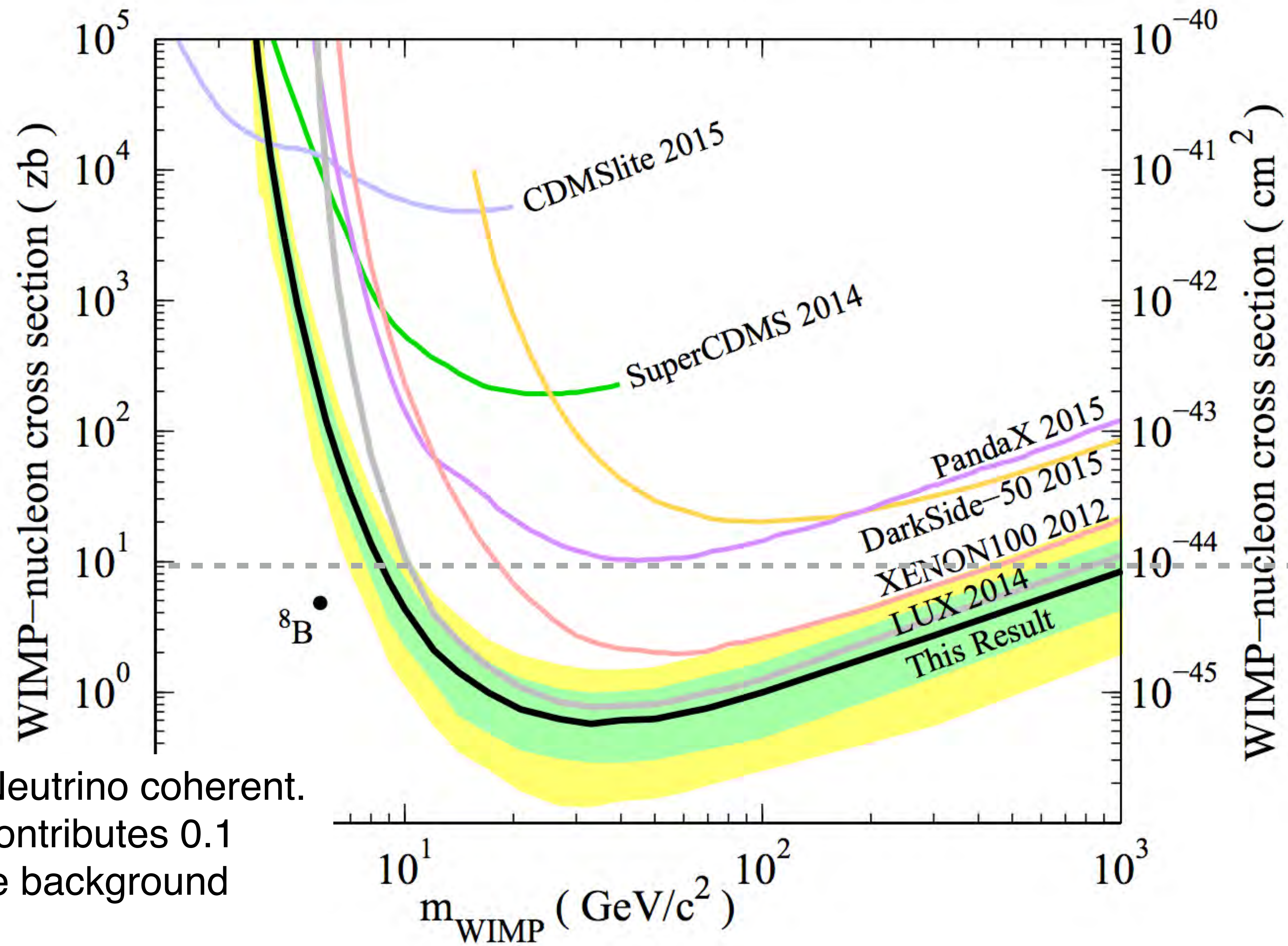
$\sigma \sim 10^{-2} \lambda_{Z\chi}^2$ pb

B-8 Solar Neutrino coherent. Currently contributes 0.1 event to the background

Limit on Spin-Independent WIMP-nuclei at $6 \times 10^{-46}$ cm$^2$ at 33 GeV/c$^2$

# Spin-independent

arXiv:1512.03506v2




$10^{-38}$ cm$^2$

Z exchange
$\sigma \sim 10^{-2}\lambda^2_{Z\chi}$ pb

Higgs exchange
$\sigma \sim 10^{-8}\lambda^2_{h\chi}$ pb

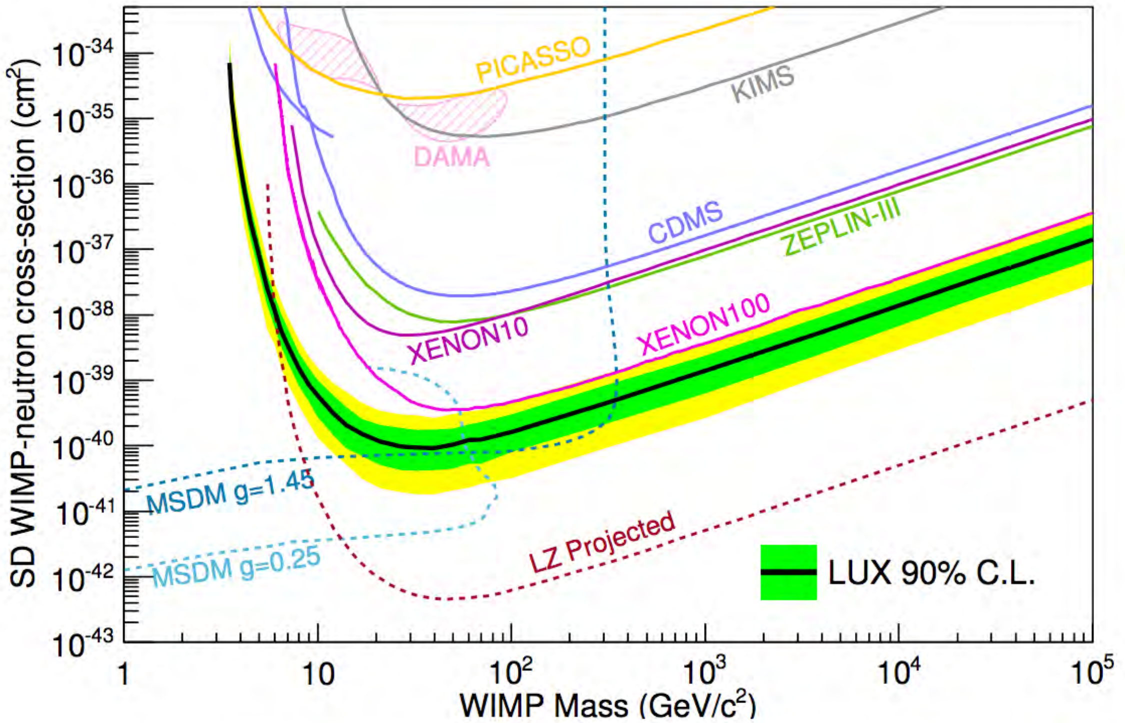
B-8 Solar Neutrino coherent. Currently contributes 0.1 event to the background

Limit on Spin-Independent WIMP-nuclei at $6 \times 10^{-46}$ cm$^2$ at 33 GeV/c$^2$

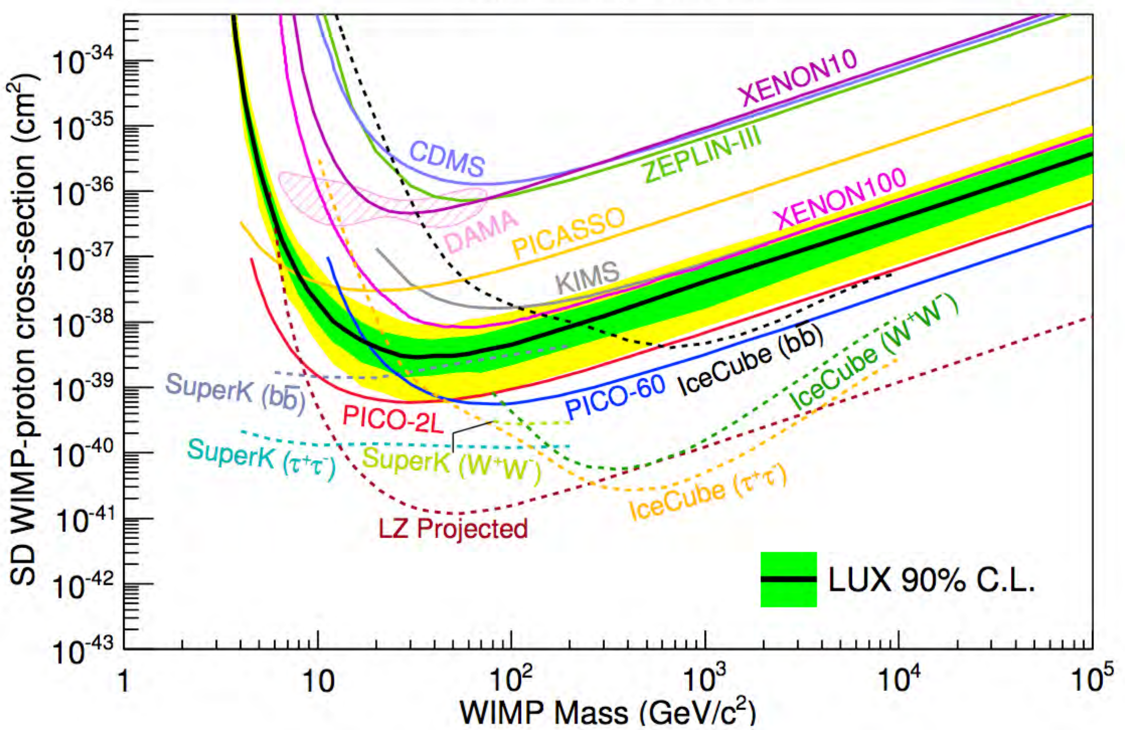
# Spin-dependent

arXiv:1602.03489

$$\sigma_{p,n} = \frac{3\mu_{p,n}^2(2J+1)}{4\pi\mu_N^2}\frac{\sigma_0}{S_A(0)}$$




- Same analysis framework used for Spin Independent



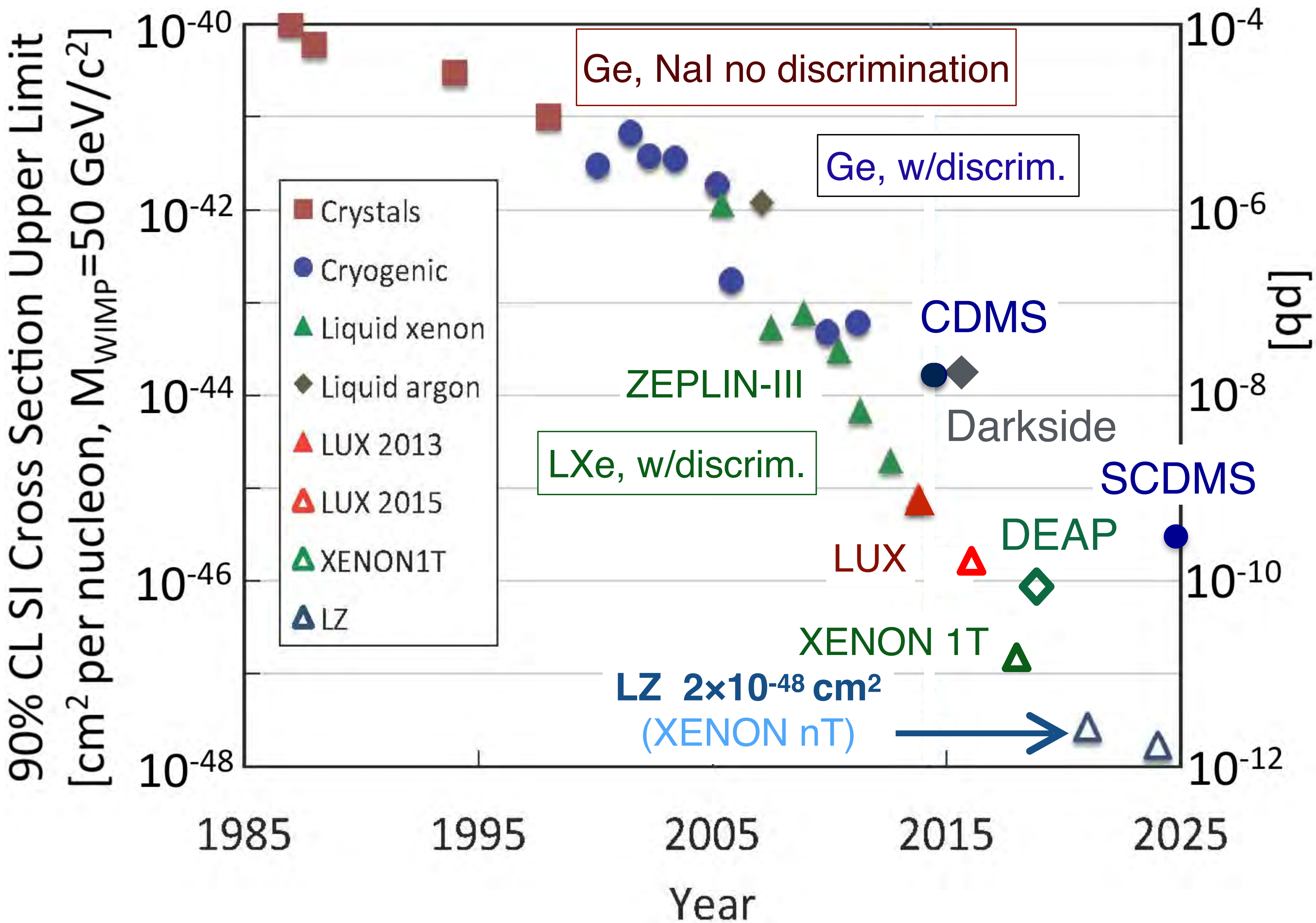

- Xenon Z = 54
- Xenon 131 ~ 24%
- Xenon 129 ~ 29%
- Enhances the Neutron-only scattering

# LUX plan

- Currently on data taking until mid of 2016
- Additional 300+ live-days of data (exposure increase by a factor of 4)
- E-field improved model
- Background models with full 3D information (ϕ)

- Further improvement in WIMP search
- Additional physics:
    - effective field theory limits
    - axion and axion-like particle
    - S2-only analysis

# Direct detection timeline




LED-ZEPPELIN
MOTHERSHIP
ROCK
ROLL


LUX-ZEPLIN
S.U.R.F.

# LZ = LUX + ZEPLIN

Counts: 31 Institutions
≈ 200 Headcount

Center for Underground Physics (Korea)
LIP Coimbra (Portugal)
MEPhI (Russia)
Edinburgh University (UK)
University of Liverpool (UK)
Imperial College London (UK)
University College London (UK)
University of Oxford (UK)
STFC Rutherford Appleton, and Daresbury, Laboratories (UK)
University of Sheffield (UK)

University of Alabama
University at Albany SUNY
Berkeley Lab (LBNL)
Brookhaven National Laboratory
University of California Berkeley
Brown University
University of California, Davis
Fermi National Accelerator Laboratory
Lawrence Livermore National Laboratory
University of Maryland
Northwestern University
University of Rochester
University of California, Santa Barbara
University of South Dakota
South Dakota School of Mines & Technology
South Dakota Science and Technology Authority
SLAC National Accelerator Laboratory
Texas A&M
Washington University
University of Wisconsin
Yale University

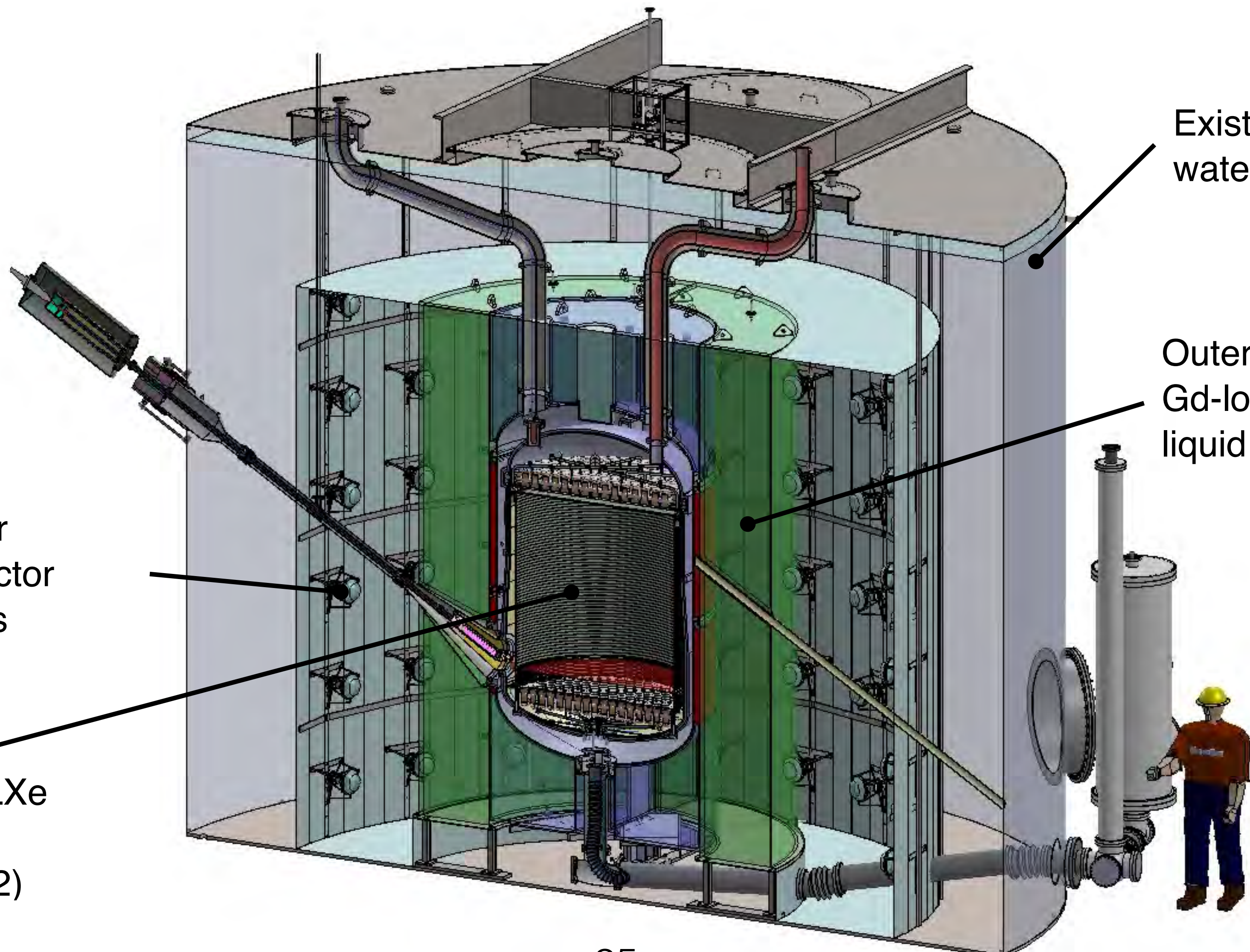
# The detector

(LUX):
world leading Generation-1 experiment, Sanford Underground Research Facility (SURF),
250 kg of active LXe target

→

LUX-ZEPLIN (LZ):
Generation-2 flagship experiment for Direct Detection in US and UK,
7 tonnes of active LXe target

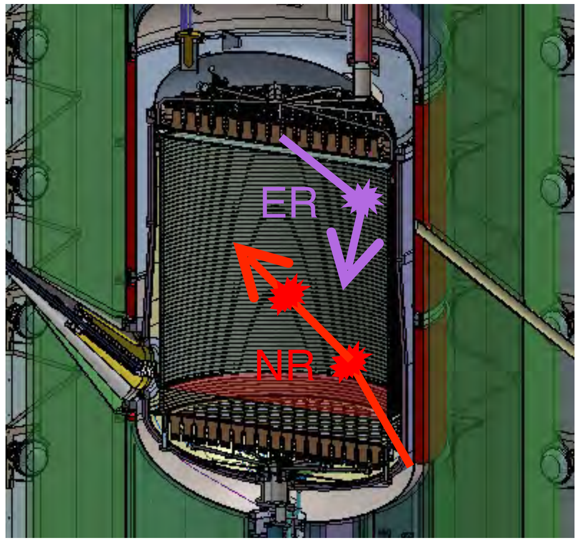
arXiv:1509.02910

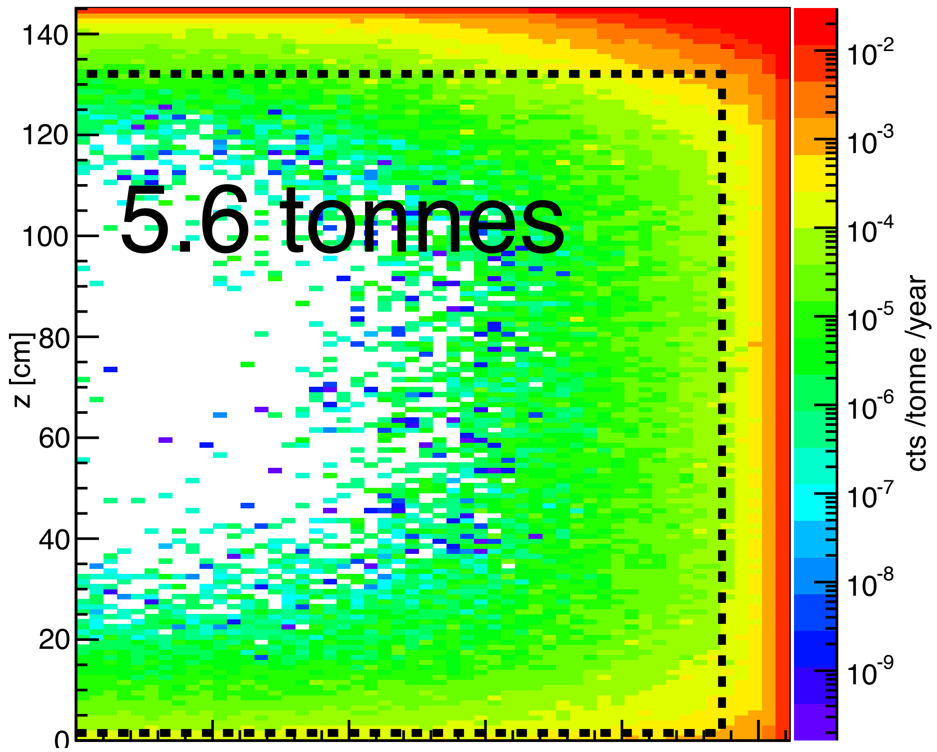


# Backgrounds rejection

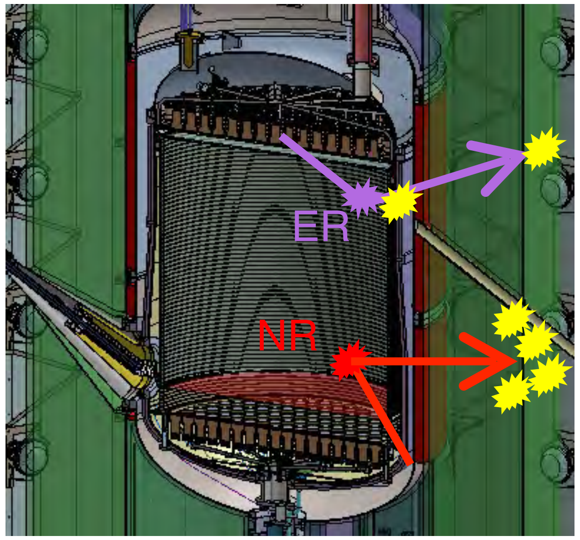
Detector material component backgrounds

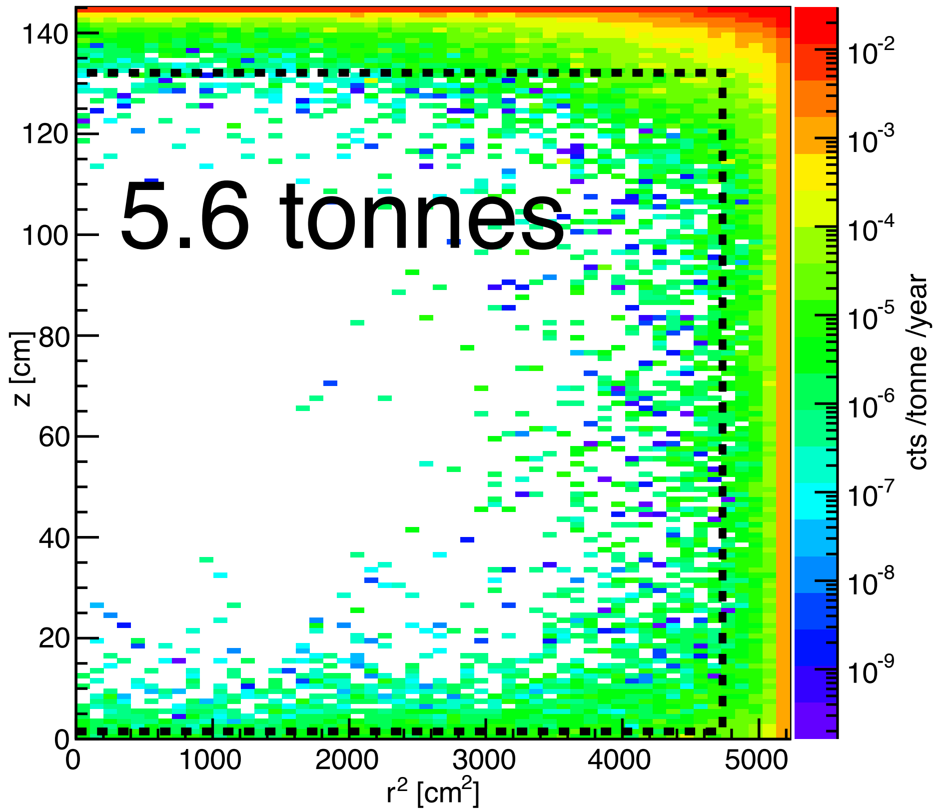
**LXe self shielding,**
**TPC multiple hit**




**LXe self shielding,**
**TPC multiple hit**
**+ LXe skin**
**+ Outer Detector**



# Backgrounds

Vast screening materials campaign for radio-pure components identification

Detailed simulation based on NEST and S1+S2 analysis

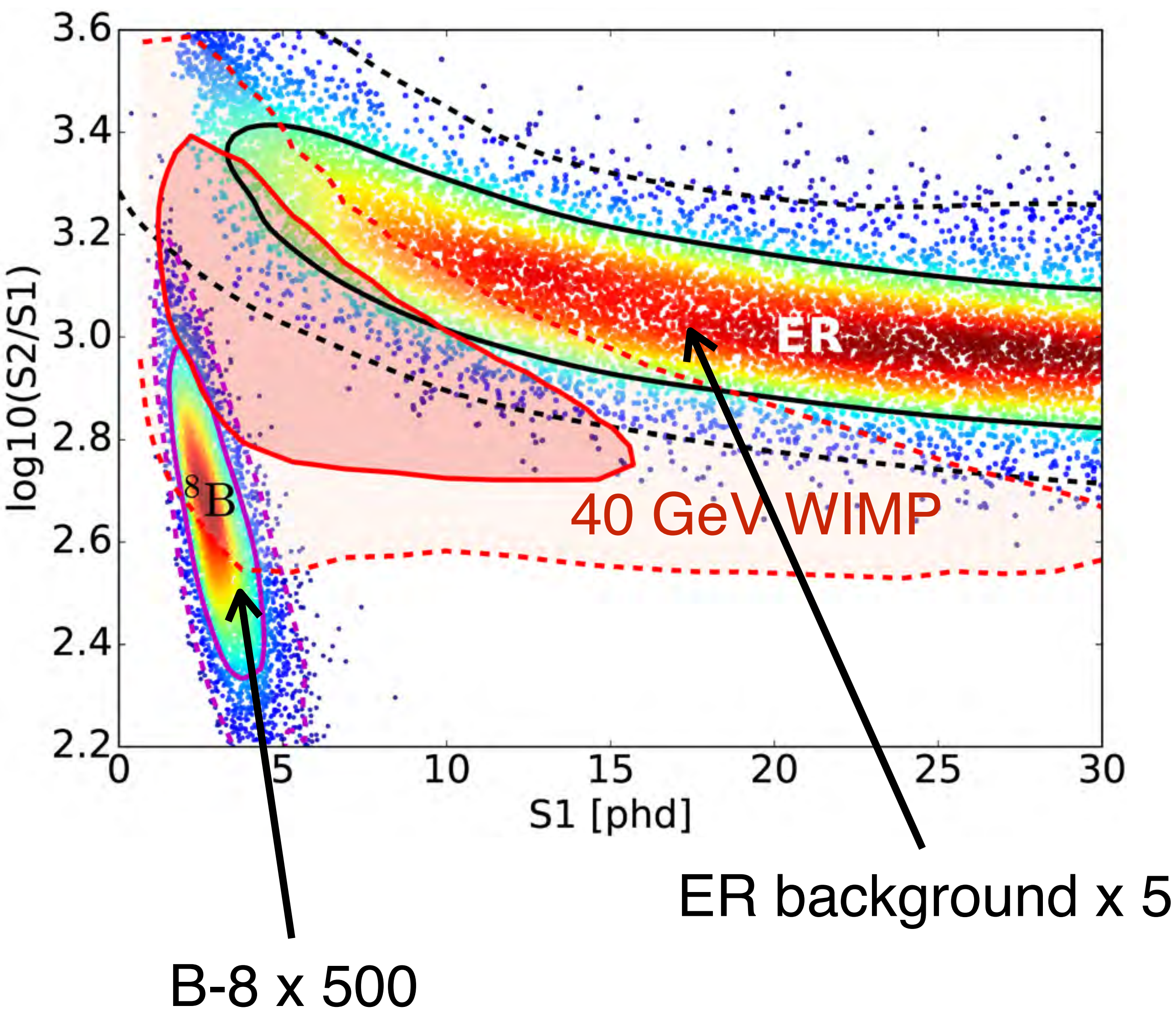
Projected sensitivity performed with PLR

| Background | Type | Counts in LZ nominal exposure (5,600 tonne-days) | Nuisance parameter uncertainty |
|---|---|---|---|
| $^{8}$B | NR | 7 | ±10 % |
| HEP | NR | 0.21 | ±30 % |
| DSN | NR | 0.05 | −50 % |
| ATM | NR | 0.46 | +33 % |
| pp solar $\nu$ | ER | 255 | 1 % |
| $^{136}$Xe ($2\nu\beta\beta$) | ER | 67 | 7 % |
| $^{85}$Kr | ER | 24.5 | ±5 % |
| $^{222}$Rn | ER | 782 | ±10 % |
| $^{220}$Rn | ER | 129 | ±10 % |
| Det. components | ER | 62 | ±10 % |
| Det. components | NR | 0.9 | ±10 % |

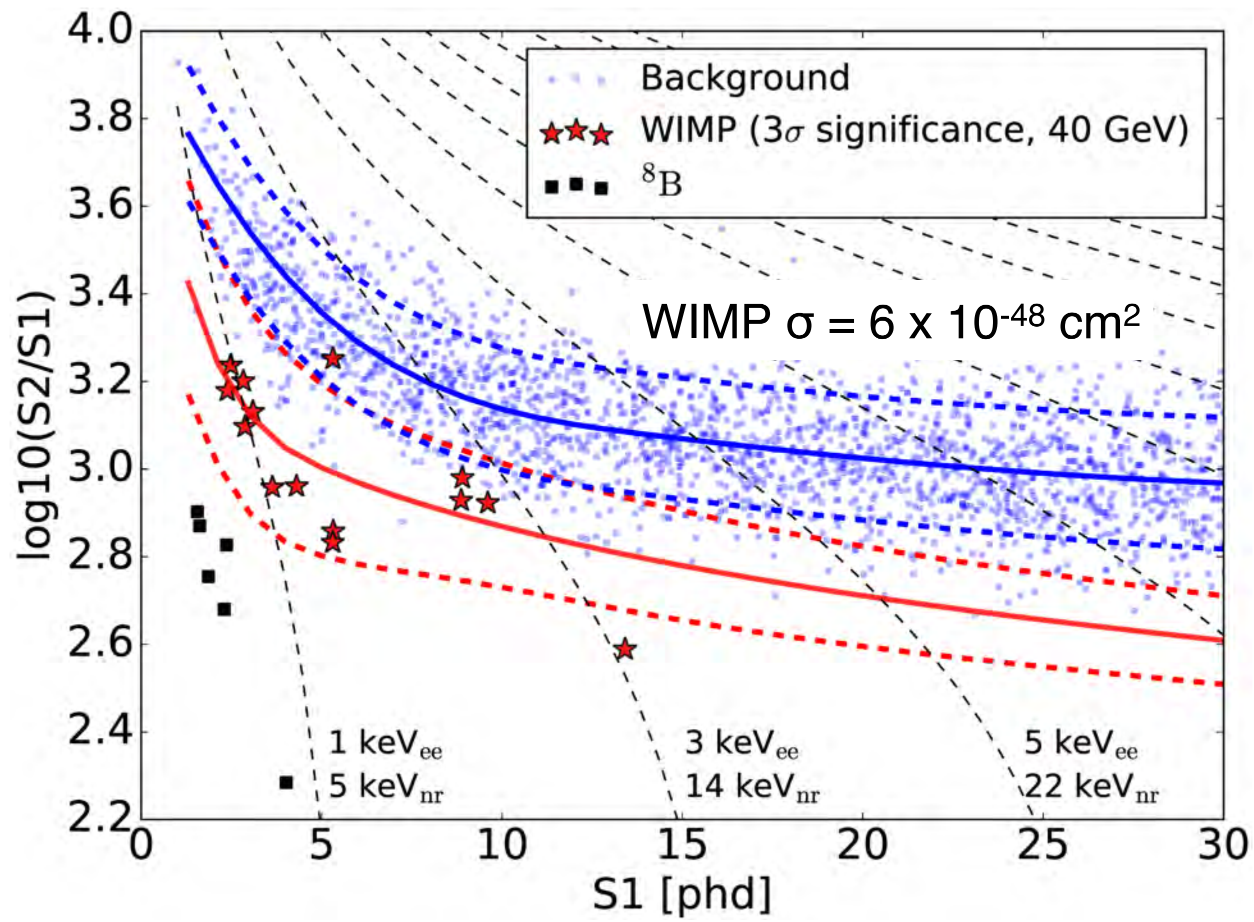
# Signal and background

Advanced analysis procedure PDFs for PLR

Signal and background models distributions




Simulated LZ experiment (1000 days, 5.6 tonnes fiducial)

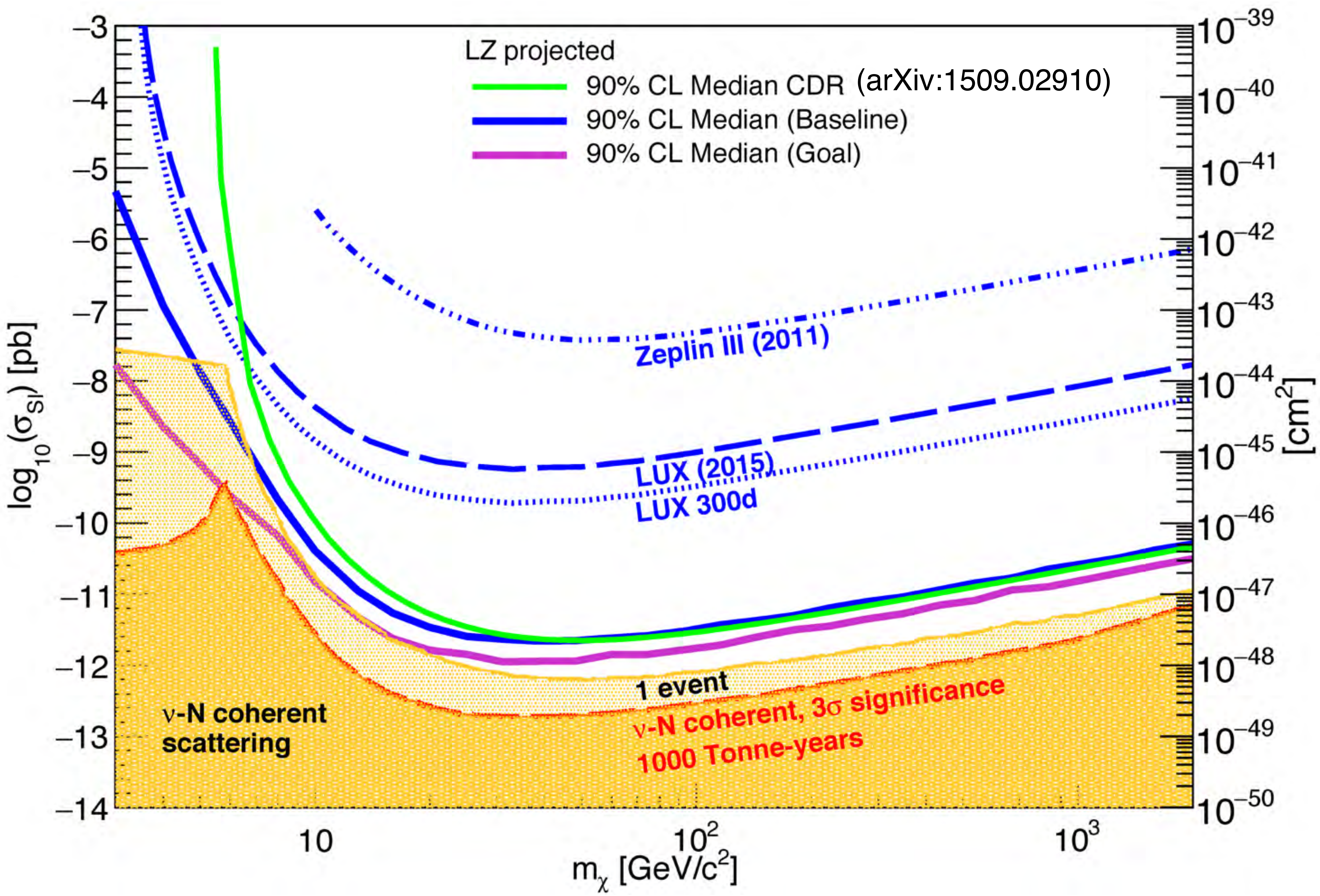


# Projected sensitivity

Simulated LZ experiment (1000 days, 5.6 tonnes fiducial)

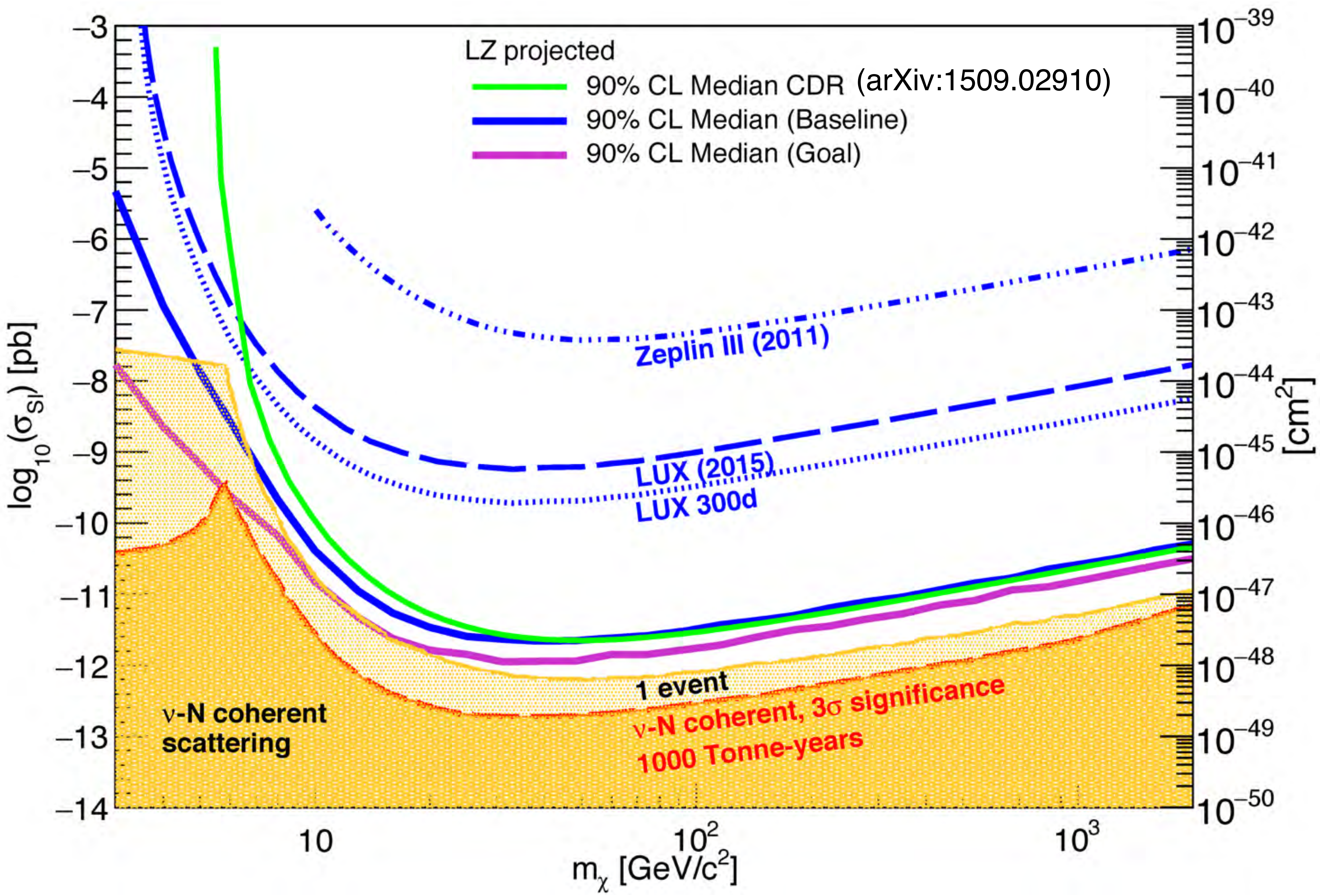
**Baseline**
**$\sigma_{SI}$ = 2.2 x $10^{-48}$ cm$^2$**
**B-8 = 7**
**ATM ν = 0.4**

**Goal**
**$\sigma_{SI}$ = 1.2 x $10^{-48}$ cm$^2$**
**B-8 = 220**
**ATM ν = 3**



# Projected sensitivity

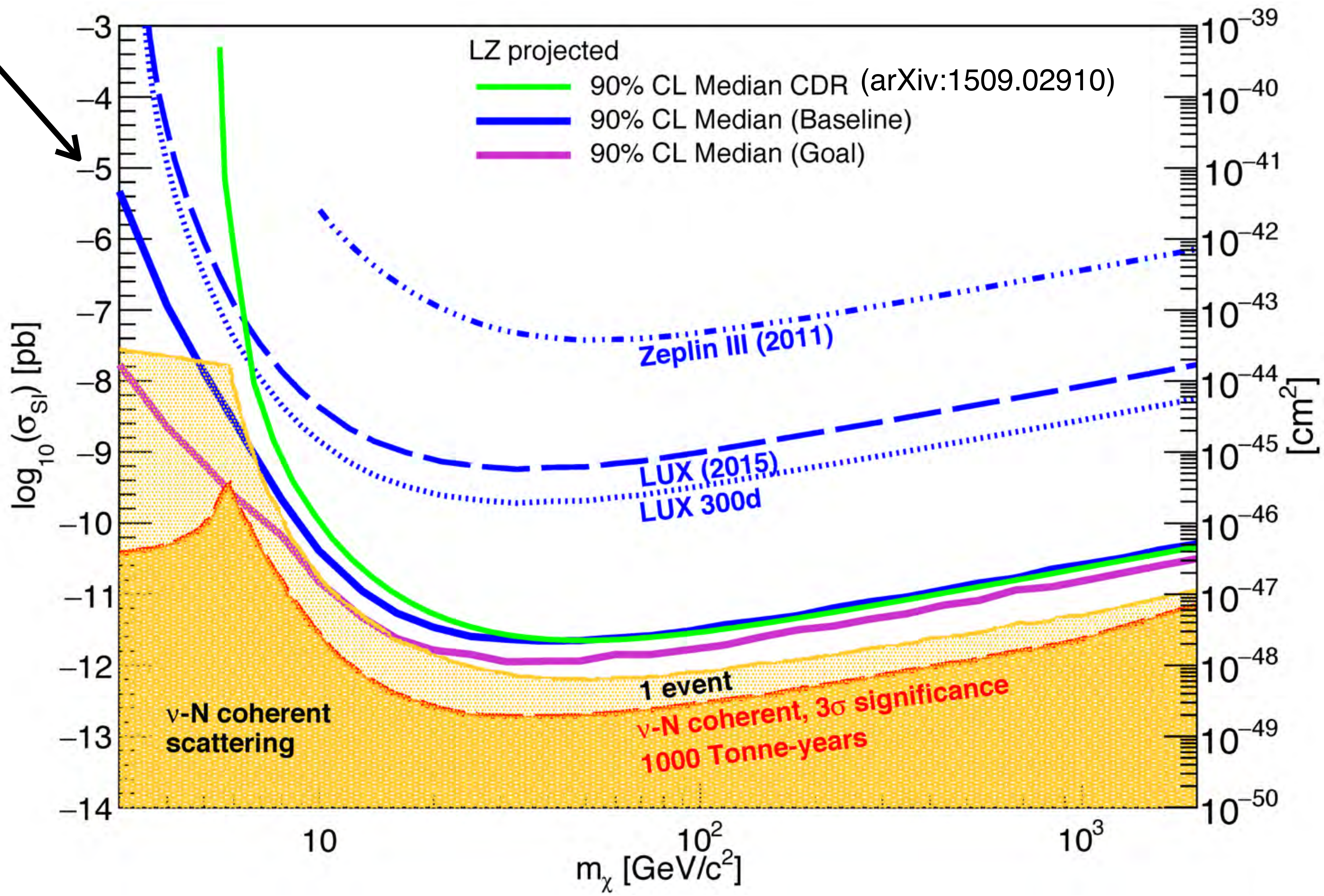
Simulated LZ experiment (1000 days, 5.6 tonnes fiducial)



# Projected sensitivity

Simulated LZ experiment (1000 days, 5.6 tonnes fiducial)

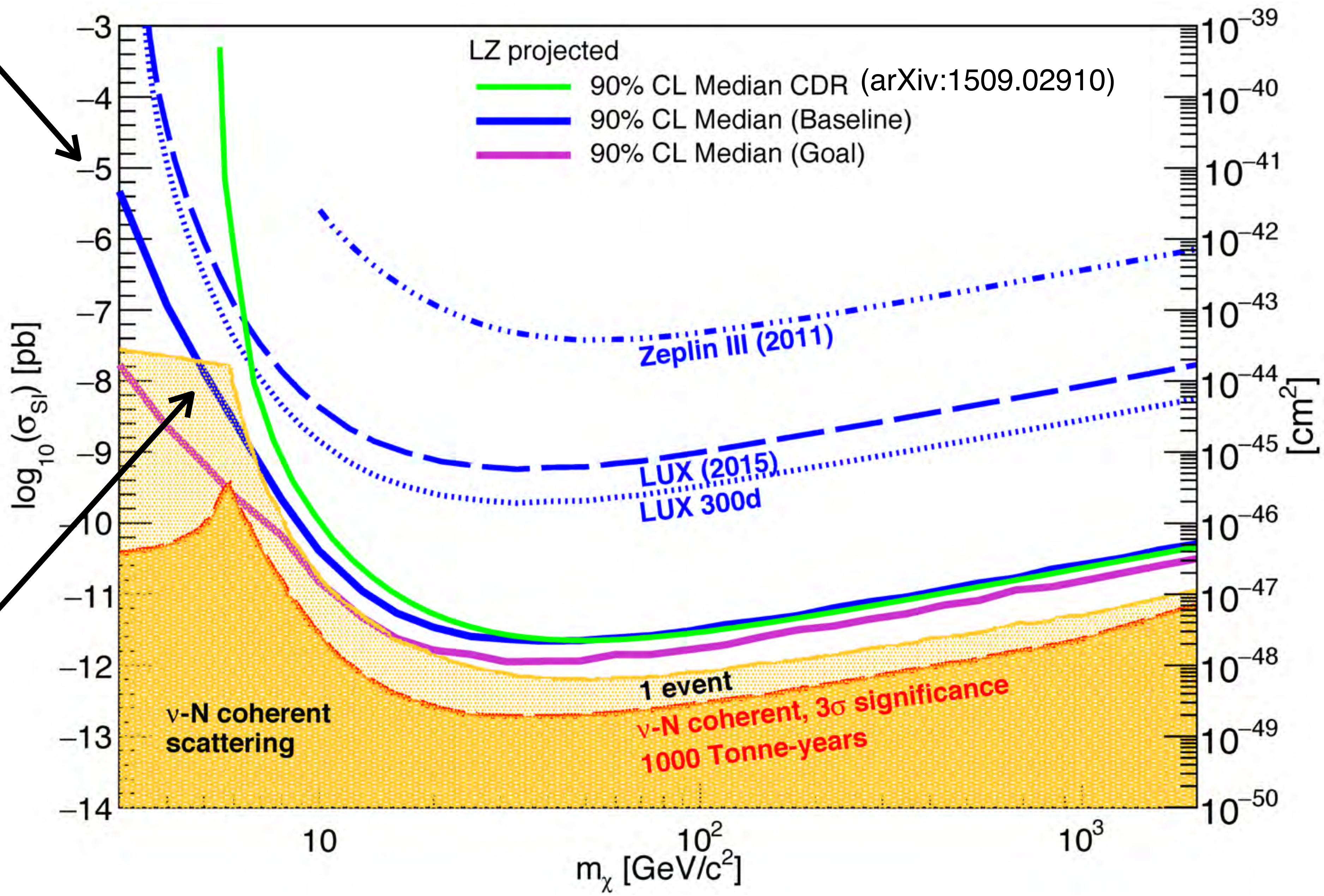
Lower threshold.
No 3 keVnr cutoff.
Updated Xe response from LUX



# Projected sensitivity

Simulated LZ experiment (1000 days, 5.6 tonnes fiducial)

Lower threshold.
No 3 keVnr cutoff.
Updated Xe response from LUX

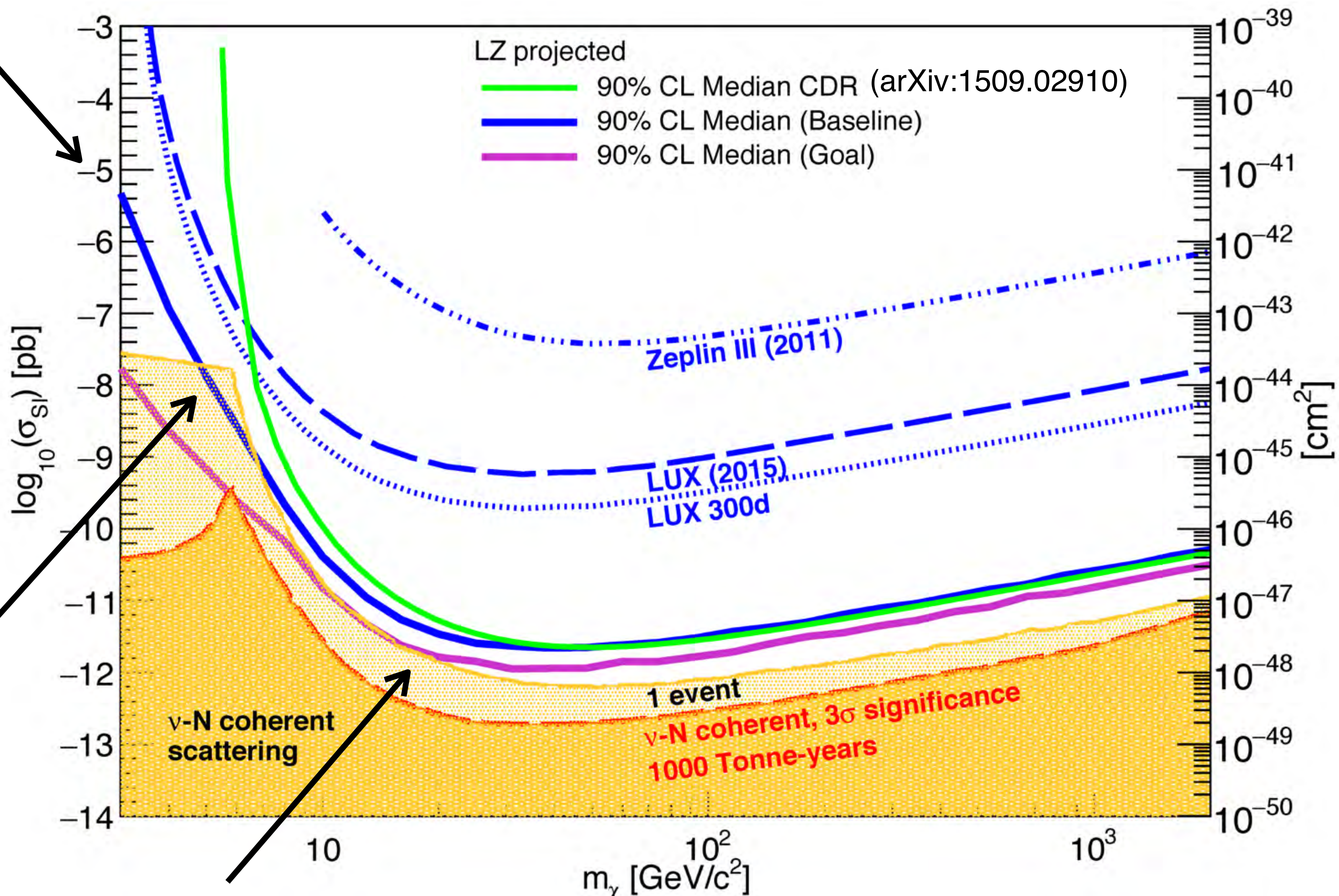



B-8 ~ 10 events

# Projected sensitivity

Simulated LZ experiment (1000 days, 5.6 tonnes fiducial)

Lower threshold.
No 3 keVnr cutoff.
Updated Xe response from LUX



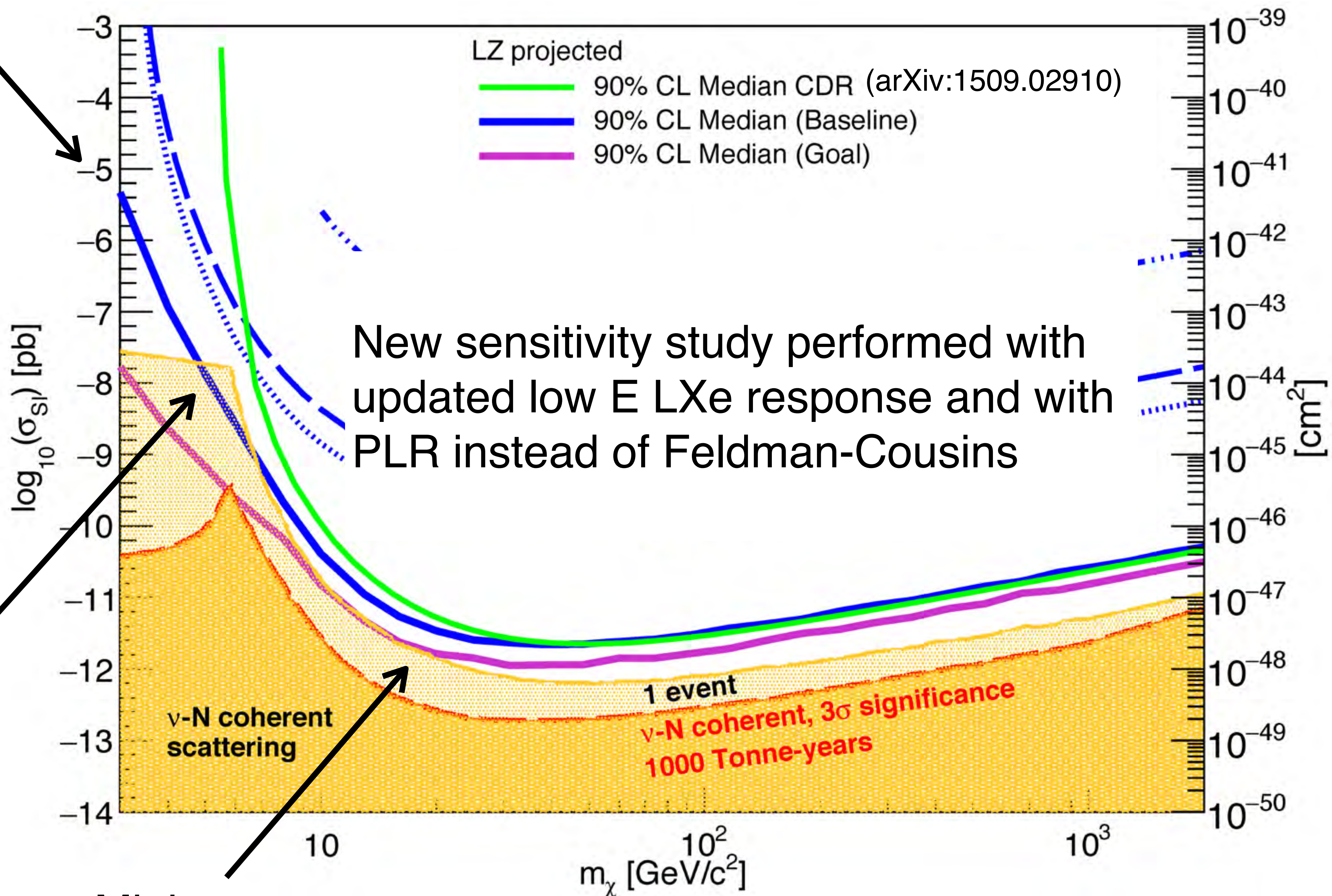

B-8 ~ 10 events

Minimum at 40 GeV/c$^2$

# Projected sensitivity

Simulated LZ experiment (1000 days, 5.6 tonnes fiducial)

Lower threshold.
No 3 keVnr cutoff.
Updated Xe response from LUX




B-8 ~ 10 events

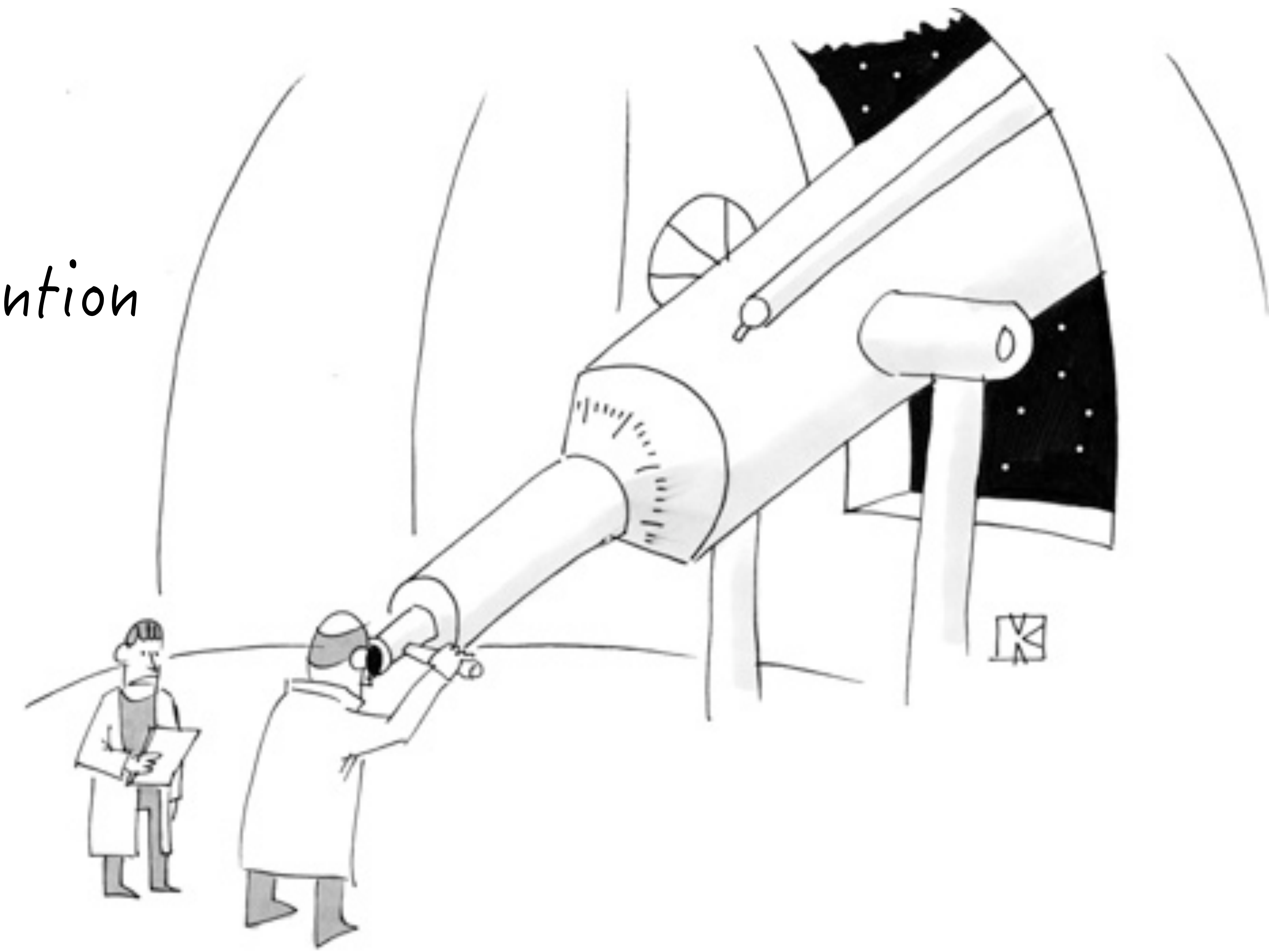
Minimum at 40 GeV/c²

# LZ timeline

| Year | Month | Activity |
|---|---|---|
| 2012 | March | LZ (LUX-ZEPLIN) collaboration formed |
| | September | DOE CD-0 for G2 dark matter experiments |
| 2013 | November | LZ R&D report submitted |
| 2014 | July | LZ Project selected in US and UK |
| 2015 | April | DOE CD-1/3a approval, similar in UK<br>Begin long-lead procurements (Xe, PMT, cryostat) |
| 2016 | April | DOE CD-2/3b review |
| 2017 | February | LUX removed from underground |
| 2017 | July | Begin surface assembly prep @ SURF |
| 2018 | May | Begin underground installation |
| 2019 | April | Begin commissioning |
| 2021 | Q3FY21 | CD-4 milestone (early finish July 2019) |
| 2025 | | Planning on ~5 year of operations |

Thank you for the attention

Thank you for the attention



"That isn't dark matter, sir—you just forgot to take off the lens cap."

# Backup Slides

# Liquid xenon

Noble element
=> Inert. Purified via gettering techniques

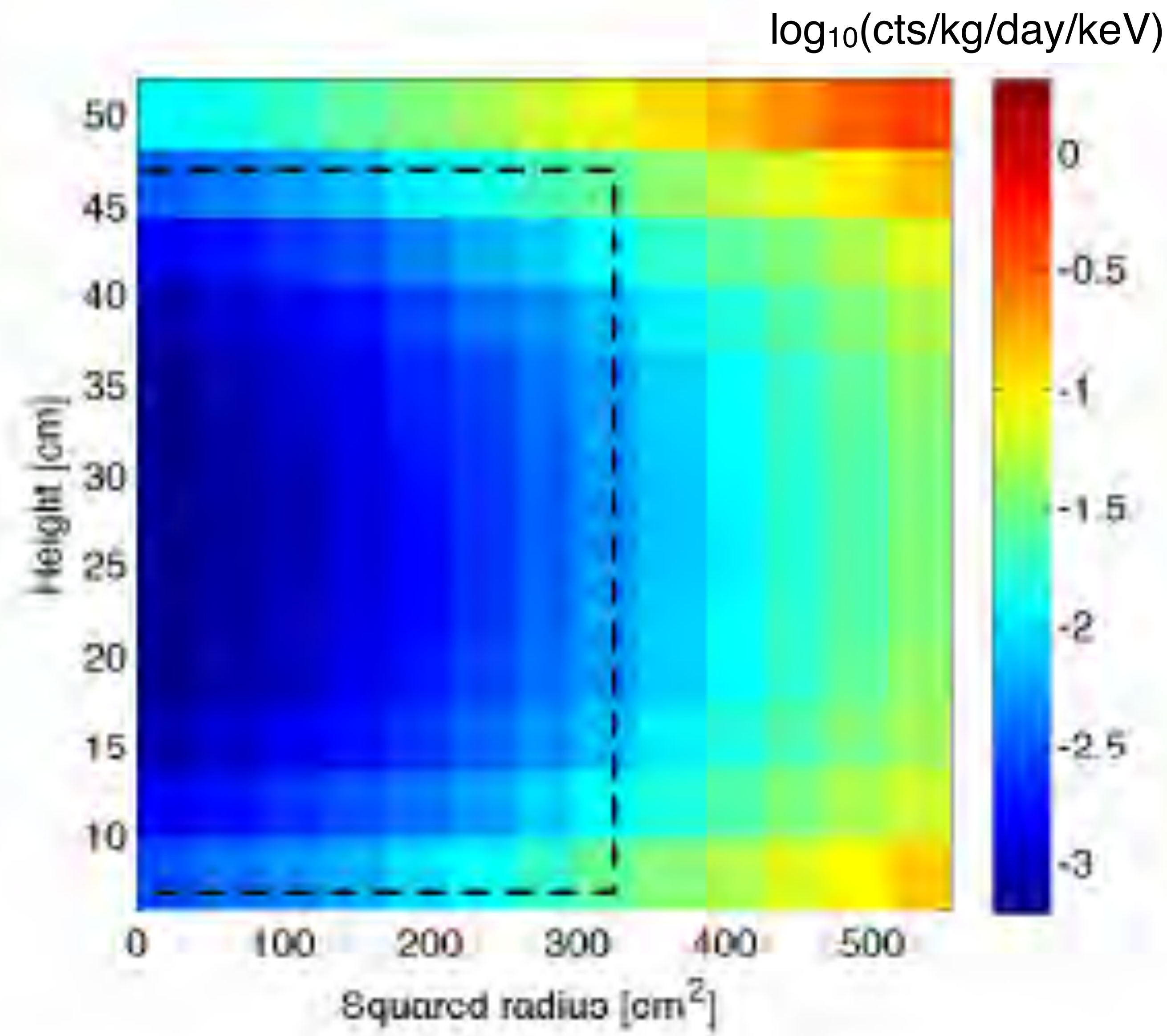
No long-lived radio-isotopes
=> useful in calibration

High density (~ 3 g/cm³)
=> self-shielding

Long electron drift lengths (few m)
=> scalable

Efficient scintillator

Higher sensitivity in the 2 - 25 keV energy deposit range



# Liquid xenon

Noble element
=> Inert. Purified via gettering techniques

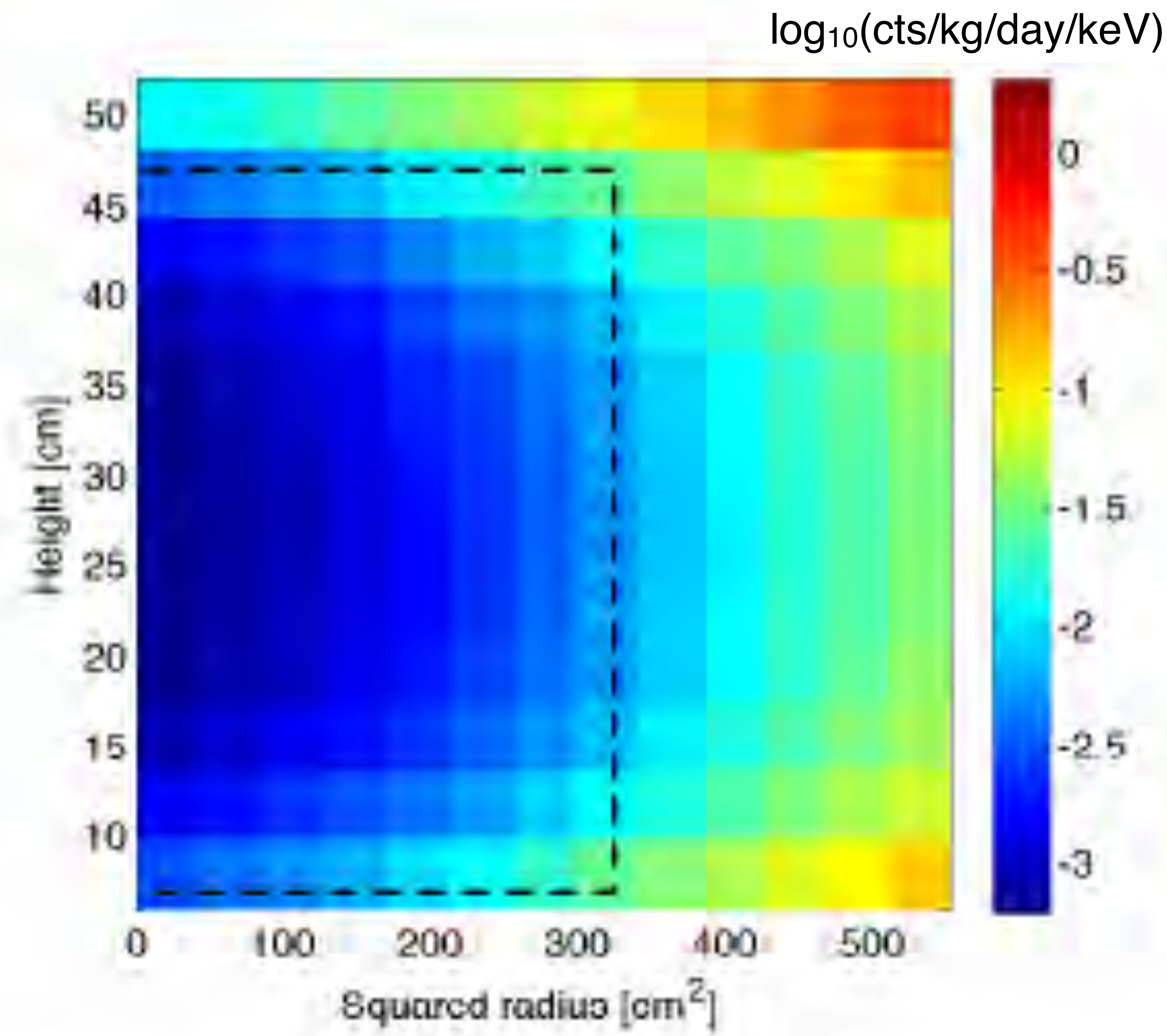
No long-lived radio-isotopes
=> useful in calibration

High density (~ 3 g/cm$^3$)
=> self-shielding

Long electron drift lengths (few m)
=> scalable

Efficient scintillator

Higher sensitivity in the 2 - 25 keV energy deposit range



# Liquid xenon

Noble element
=> Inert. Purified via gettering techniques

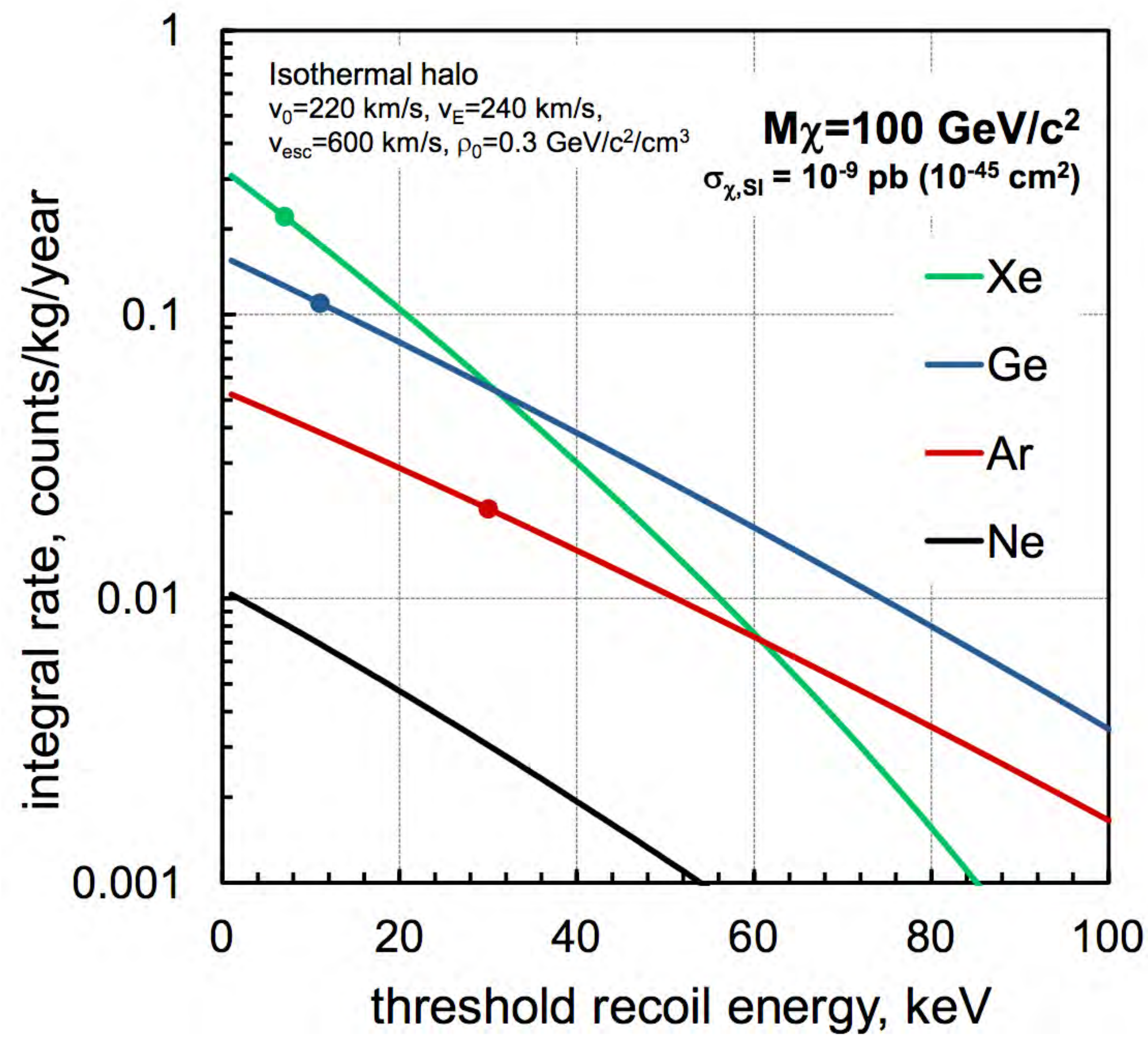
No long-lived radio-isotopes
=> useful in calibration

High density (~ 3 g/cm$^3$)
=> self-shielding

Long electron drift lengths (few m)
=> scalable

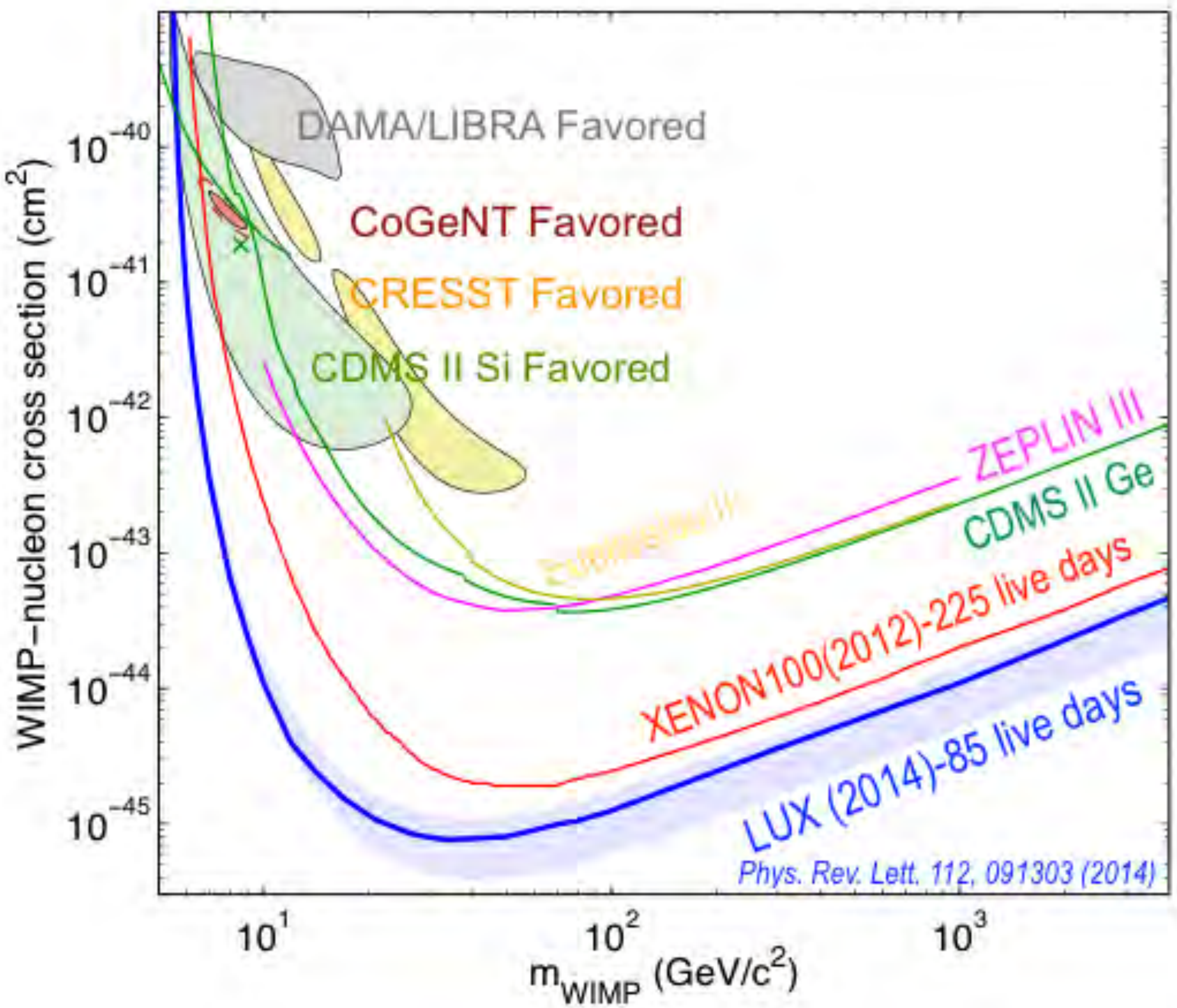
Efficient scintillator

Higher sensitivity in the 2 - 25 keV energy deposit range



# Reminder: 1st LUX results

Phys. Rev. Lett. 112, 091303 (2014)




- 118 kg fiducial x 85 live day
- Energy threshold at 3 keVnr
- $2 \leq S1 \leq 30$ phe
- $S2 > 200$ phe
- (99.6 ± 0.1)% ER rejection at 50% signal acceptance (180 V/cm)
- 160 events observed in data after selection cuts

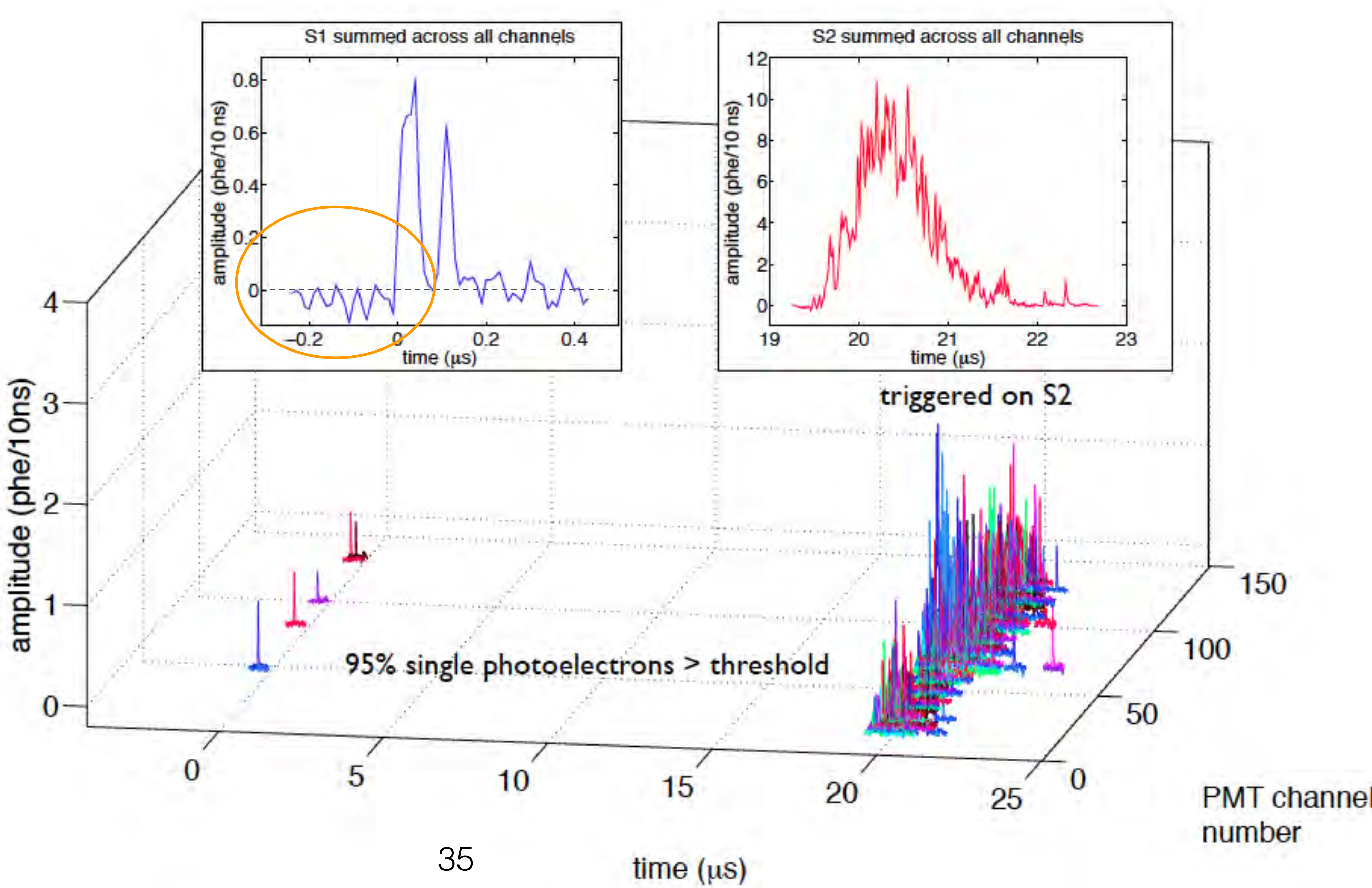
Analysis 4-parameter profile likelihood, p-value of 35% consistent with backgrounds

Limit on Spin-Independent WIMP-nuclei at 7.6 x $10^{-46}$ cm$^2$ at 33 GeV/c$^2$

# Measuring light

## Better estimators for detected photons

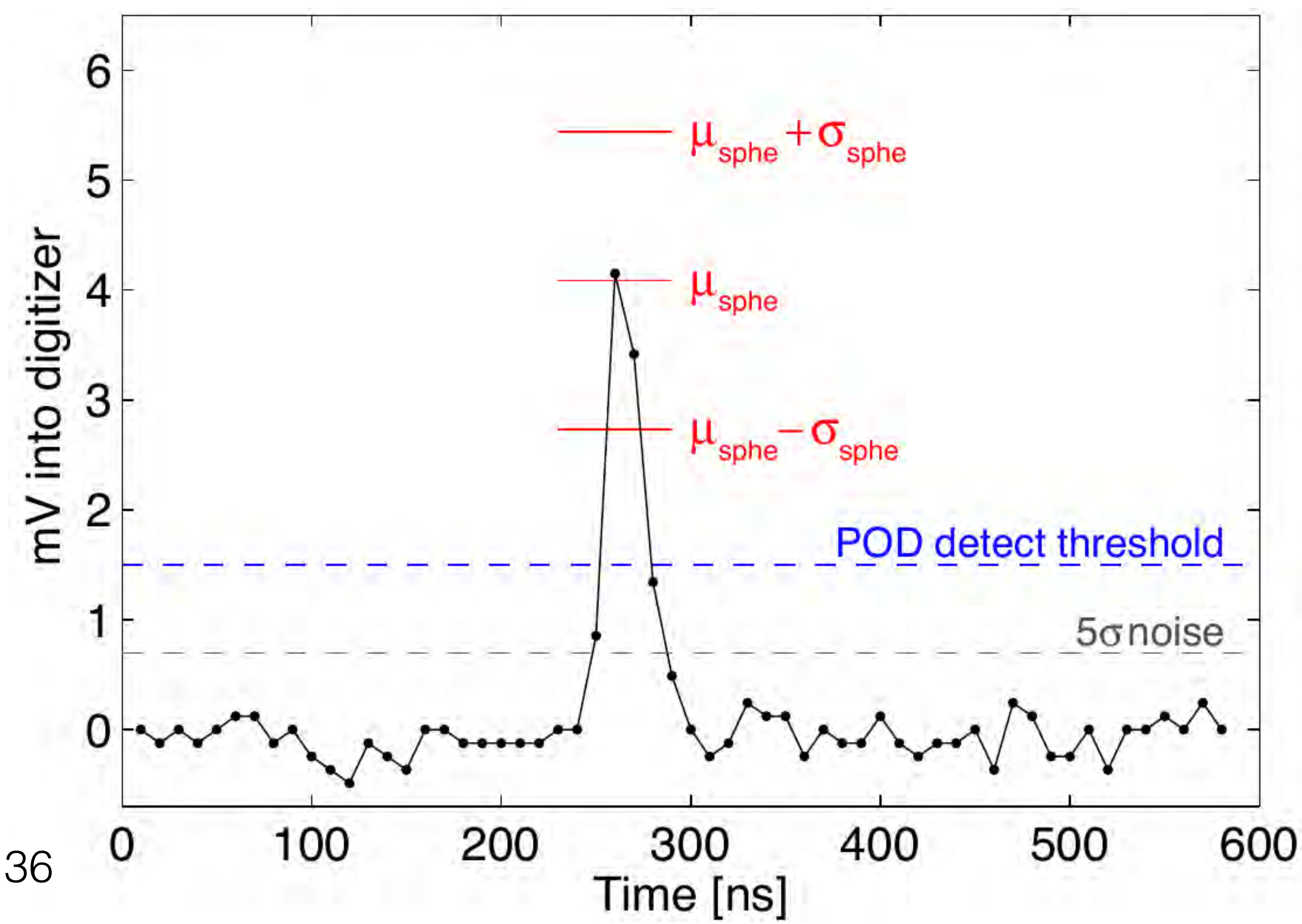
1. Removed a bias in baselines



# Measuring light

Better estimators for detected photons

1. Removed a bias in baselines
2. Digital counting of photons in PMT waveforms: less variance than area for sparse light

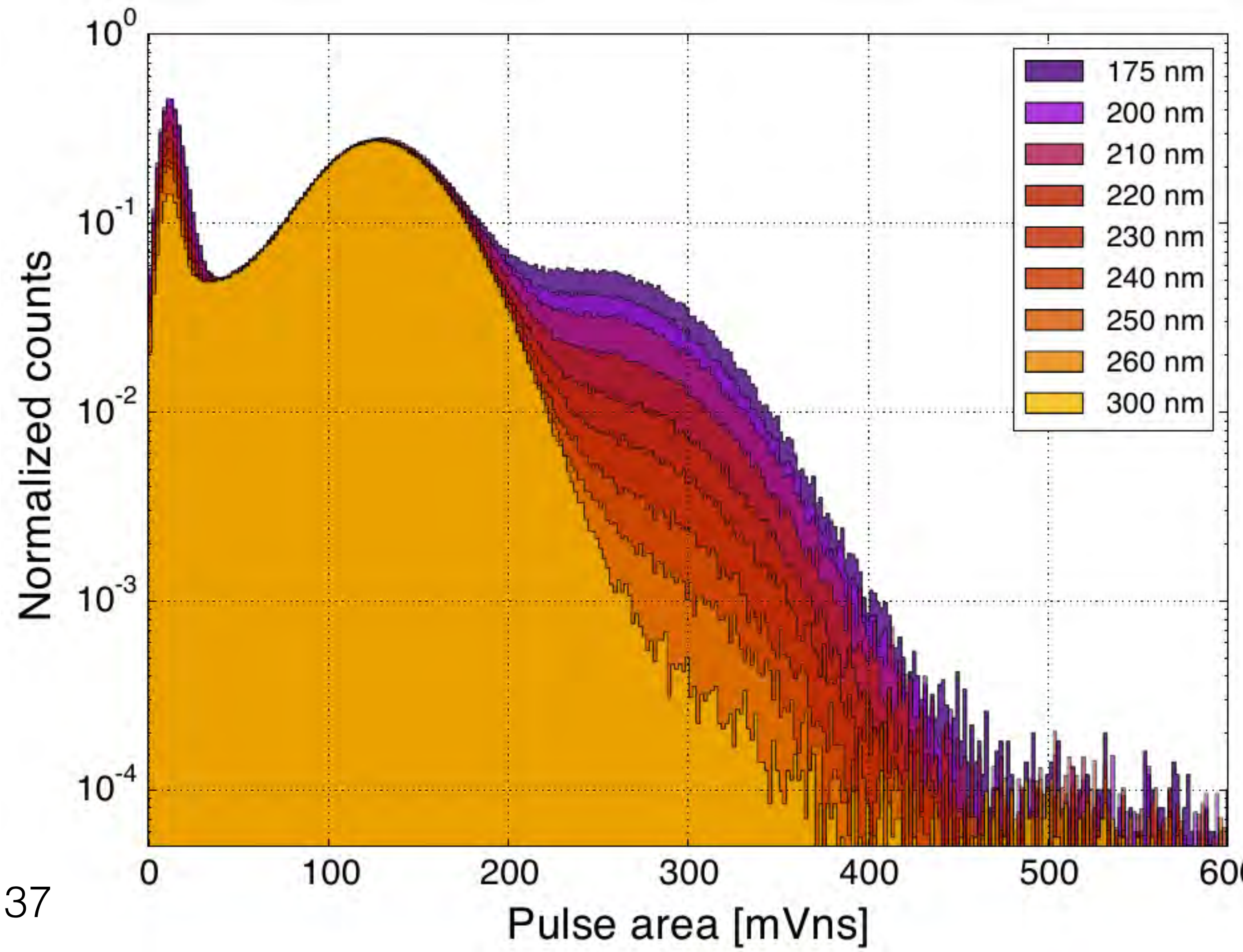


# Measuring light

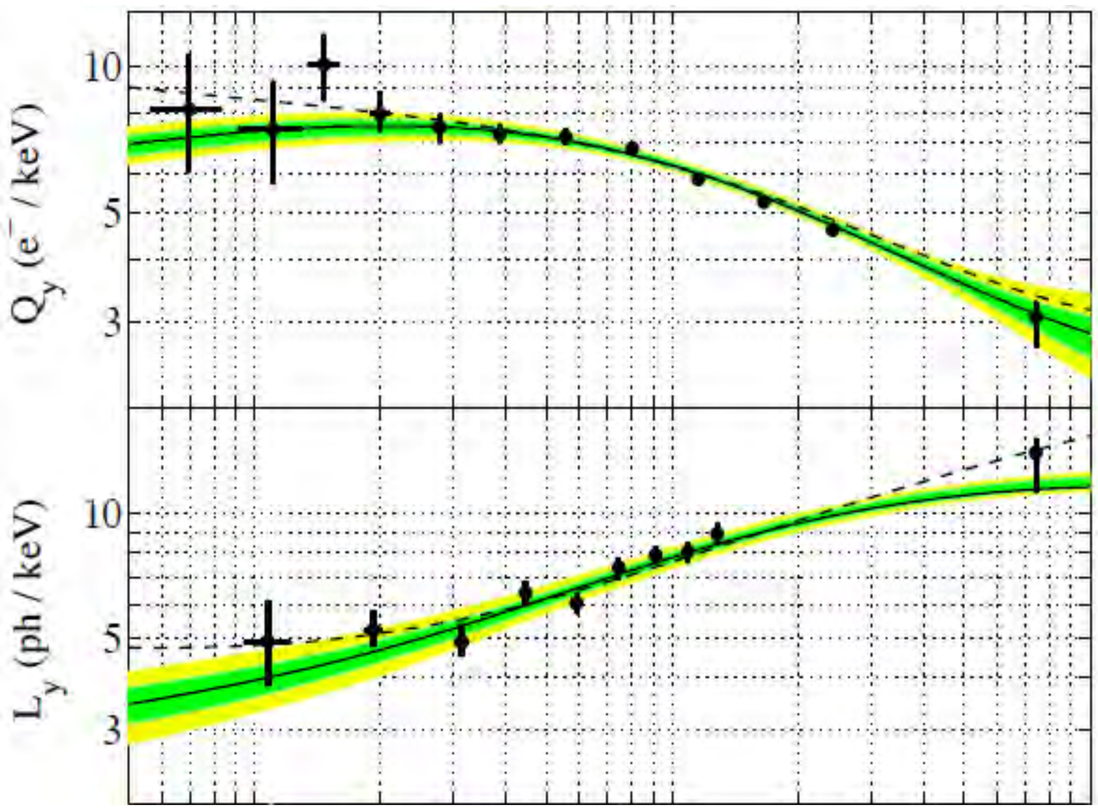
Better estimators for detected photons

1. Removed a bias in baselines
2. Digital counting of photons in PMT waveforms: less variance than area for sparse light
3. Photon response calibrated in the VUV (accounting for ~20% of 2phe from 1photon)

arXiv:1506.08748



# Calibration NR




$$E = \frac{1}{L(E)} \cdot \left( \frac{S1}{g_1} + \frac{S2}{g_2} \right) \cdot W$$

$$L = \frac{kg}{1 + kg}$$

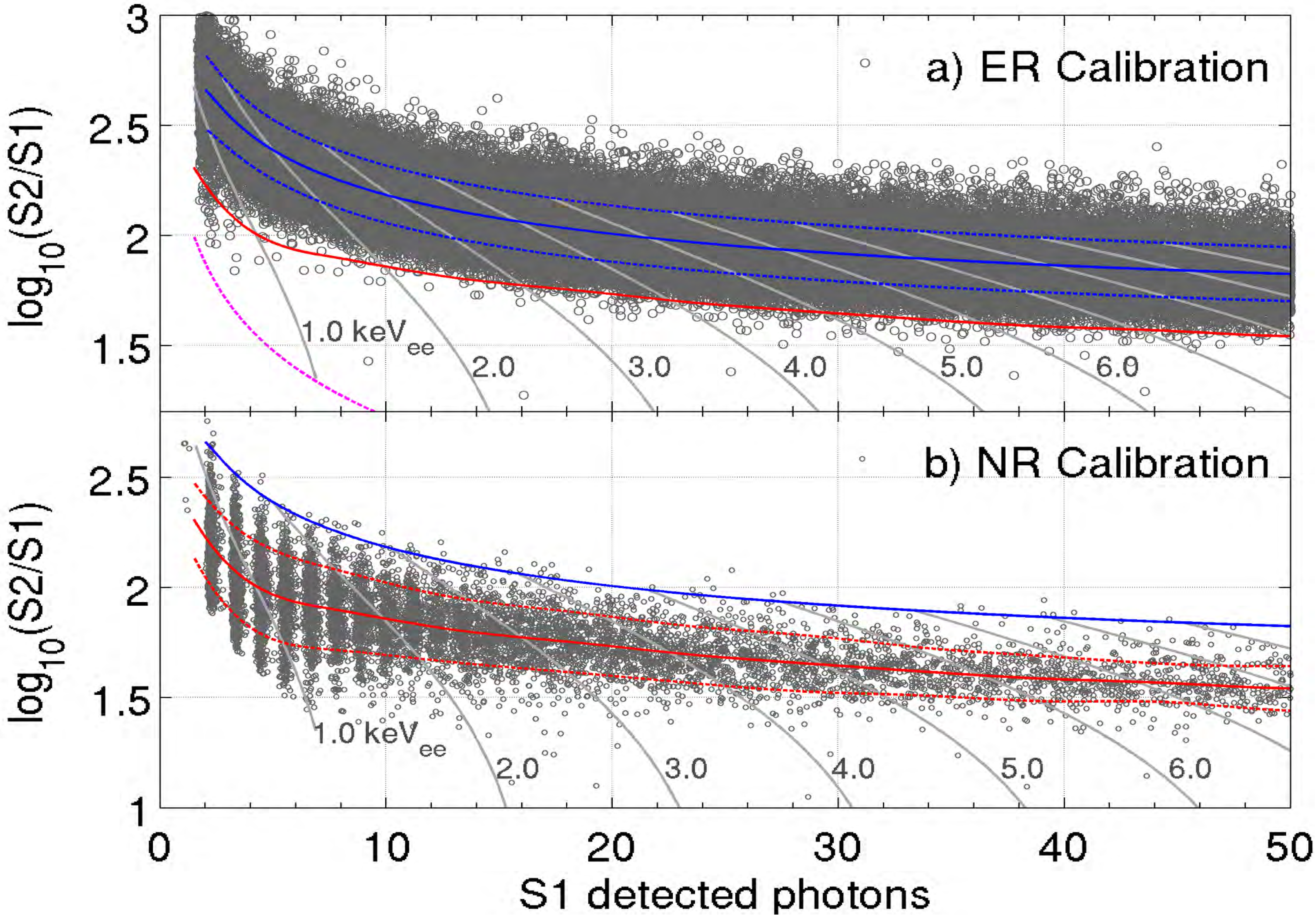
$$r = 1 - \frac{ln(1 + \mathrm{TIB}\ N_i)}{\mathrm{TIB}\ N_i}$$

$$q_f = 1 - \frac{1}{1 + \beta\epsilon^{1/2}}$$

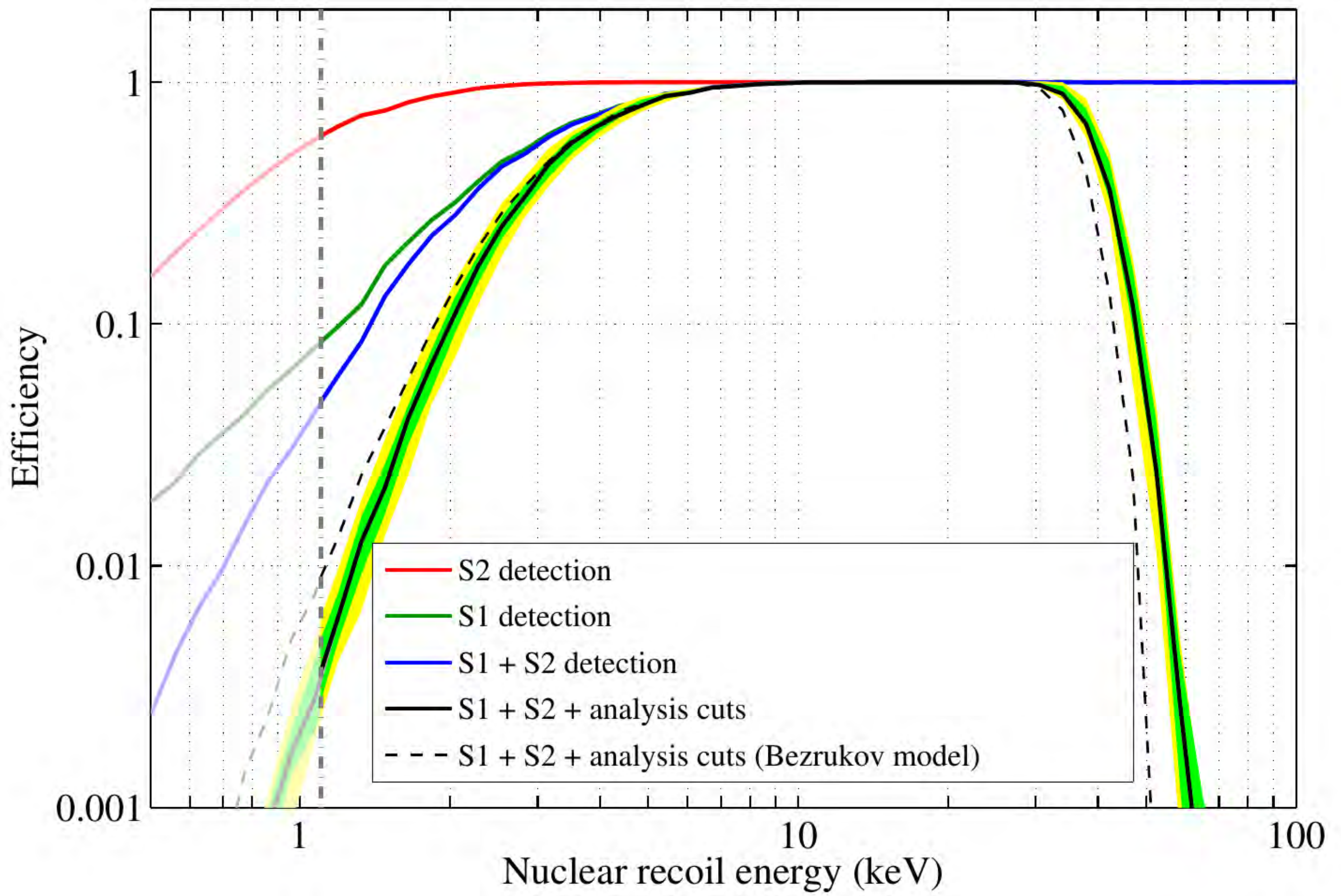
- NEST simulation package parameter best fit to DD-data in both charge and light yields
- Given $g_1$ and $g_2$, determine the *L(θ / E)*. θ are 5 Lindhard NR Parameters
- Implement full NEST simulation in the sensitivity calculation

Noble Element Simulation Technique (NEST), arXiv:1412.4417

# Calibrations



# Efficiency for NR




Signal calibration extended to < 1% efficiency threshold.

Modelling cutoff 3 keV —> 1.1 keV: WIMP 5.2 GeV/c$^2$ —> 3.3 GeV/c$^2$.

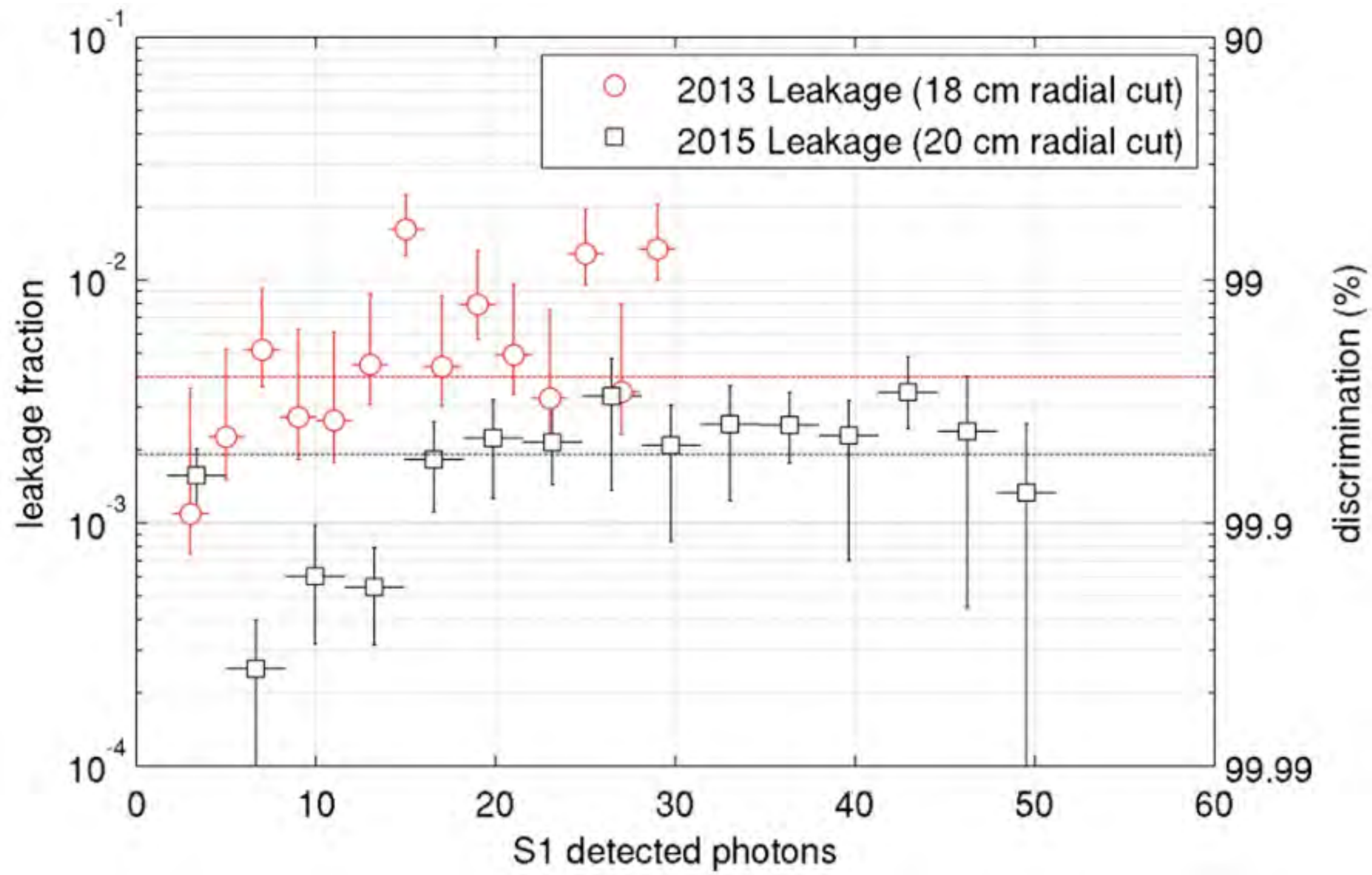
Bezrukov an alternative to the Lindhard model of NR energy loss to electrons.

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

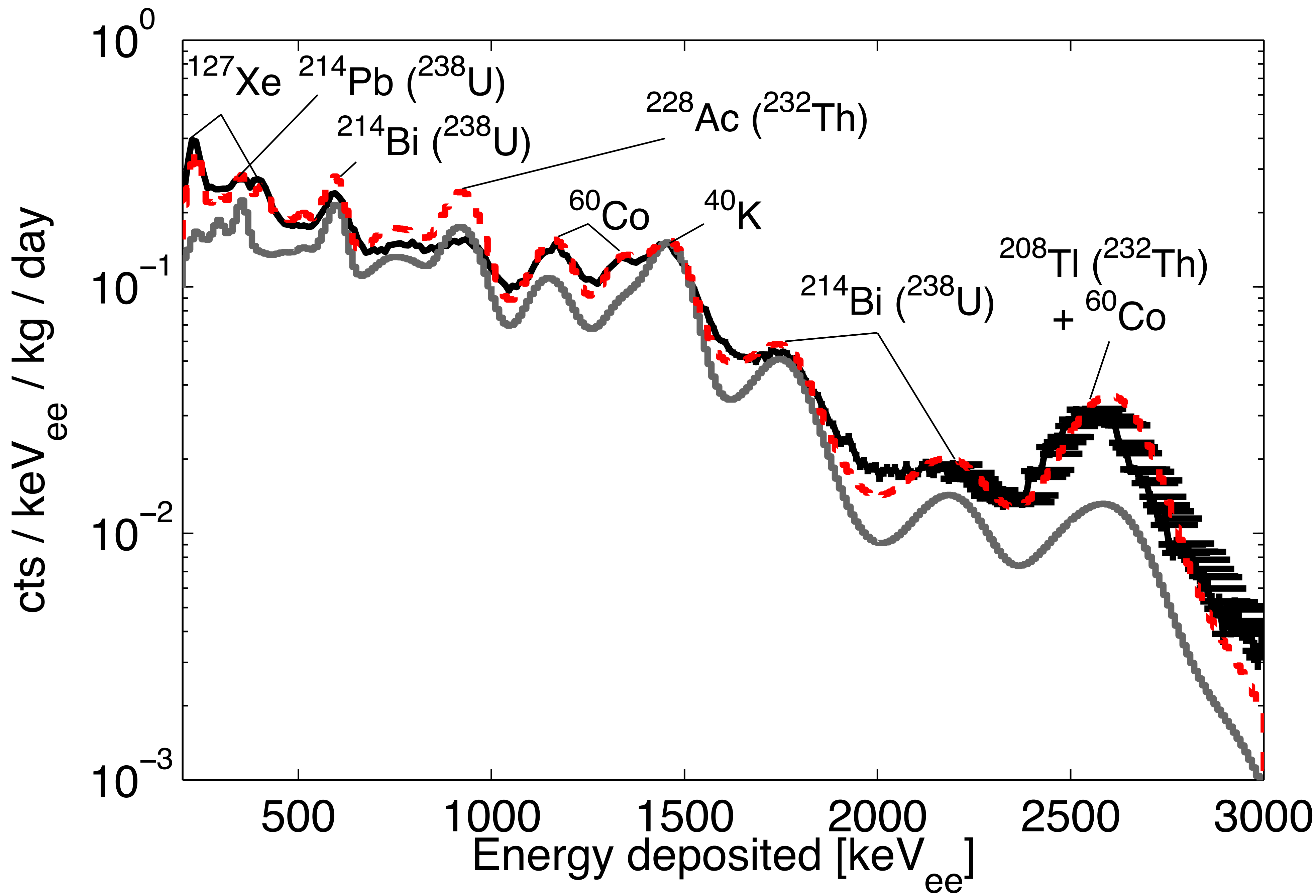
# Background Rejection

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

Analysis improvements and large tritium calibration sample boost performance and precision

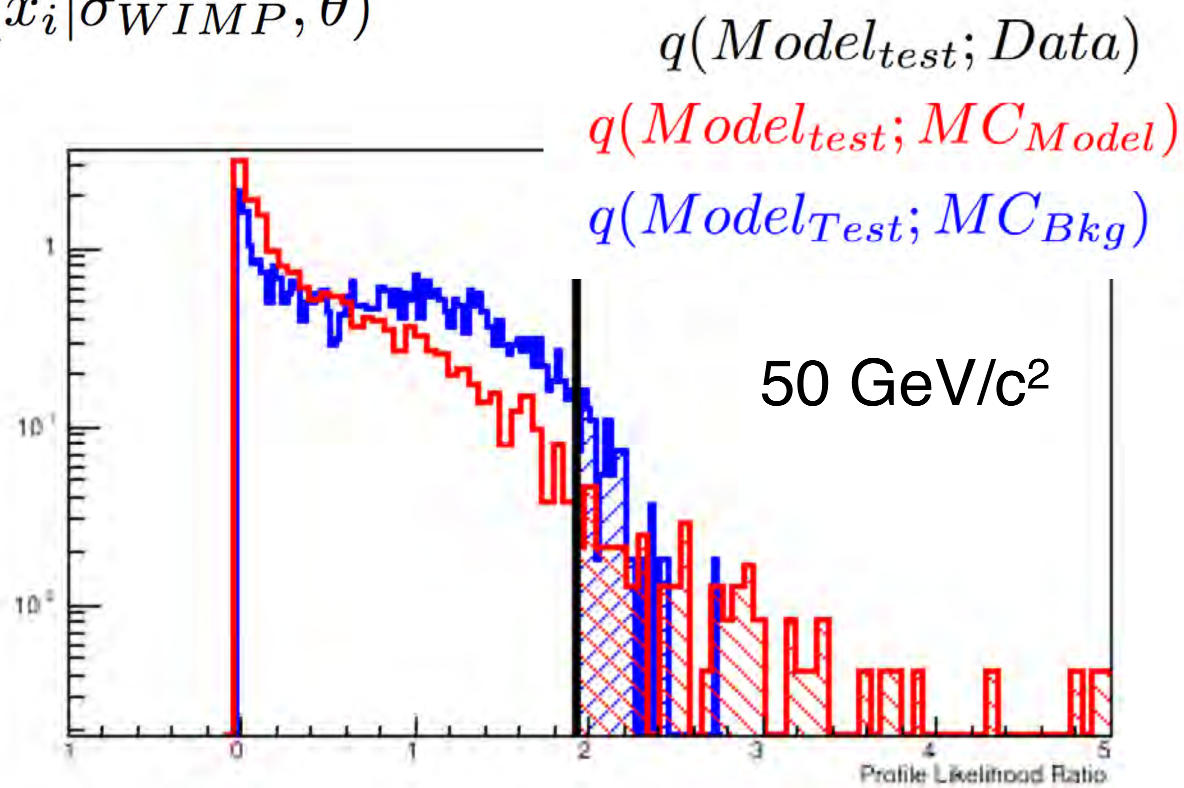


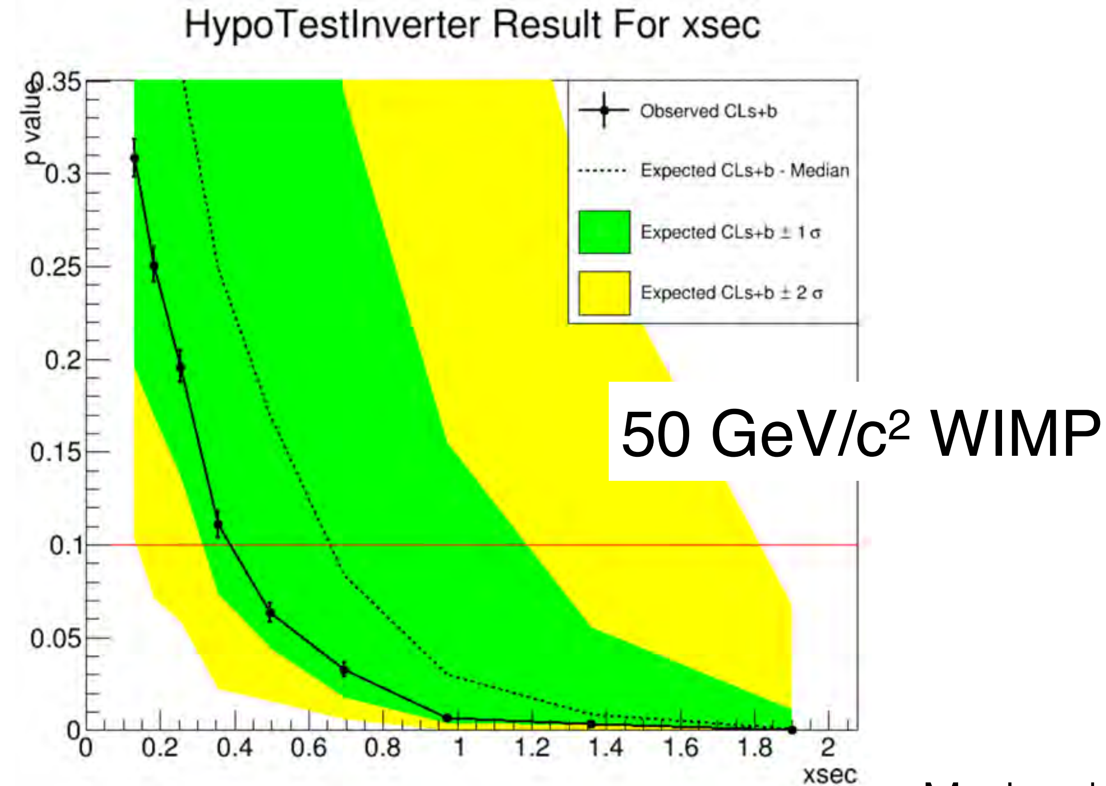
# Background Model



# Profile Likelihood

$$L(\sigma_{WIMP},\theta;x) = P(x;\sigma_{WIMP},\theta) = \prod_{i=1}^{n} P(x_i|\sigma_{WIMP},\theta)$$
$$x = \{S1, log(S2), r, z\}$$
$$\theta = \{N_{bkg}, \nu_{signal}\}$$
$$\lambda = \frac{L(\sigma^{Test}_{WIMP},\theta;x)}{L(\sigma_{WIMP},\theta';x)}$$
$$q = -2ln(\lambda)$$




- Fraction of Bkg.+Sig. MC above the Data in $q$ (obs. limit)
- Translate $L$ —> $p$-values
- Expected limits: counting from the mean of the Bkg.-only MC to Bkg.+Sig. Model
- ± 1σ , ± 2σ quantiles are shown in green and yellow

# Profile Likelihood

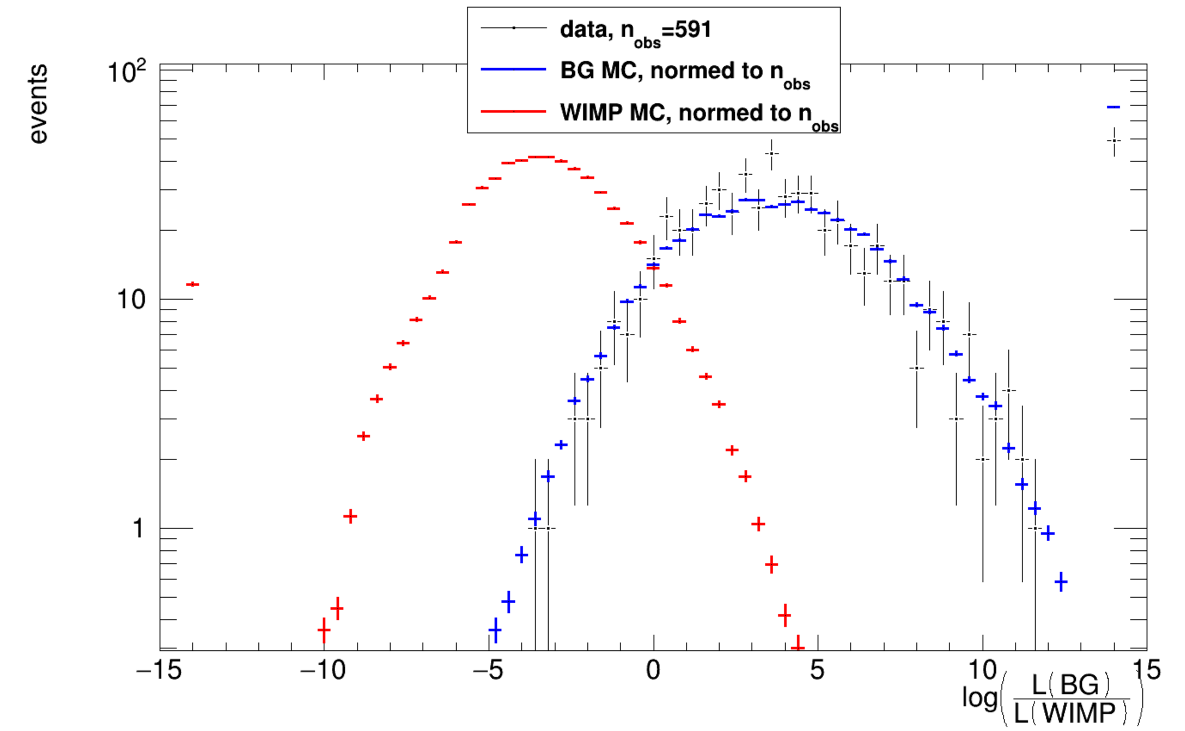
**Multivariate background rejection**, per-event discriminant.

Limit is un-binned PLR with 4 observables.

Nuisance parameters:

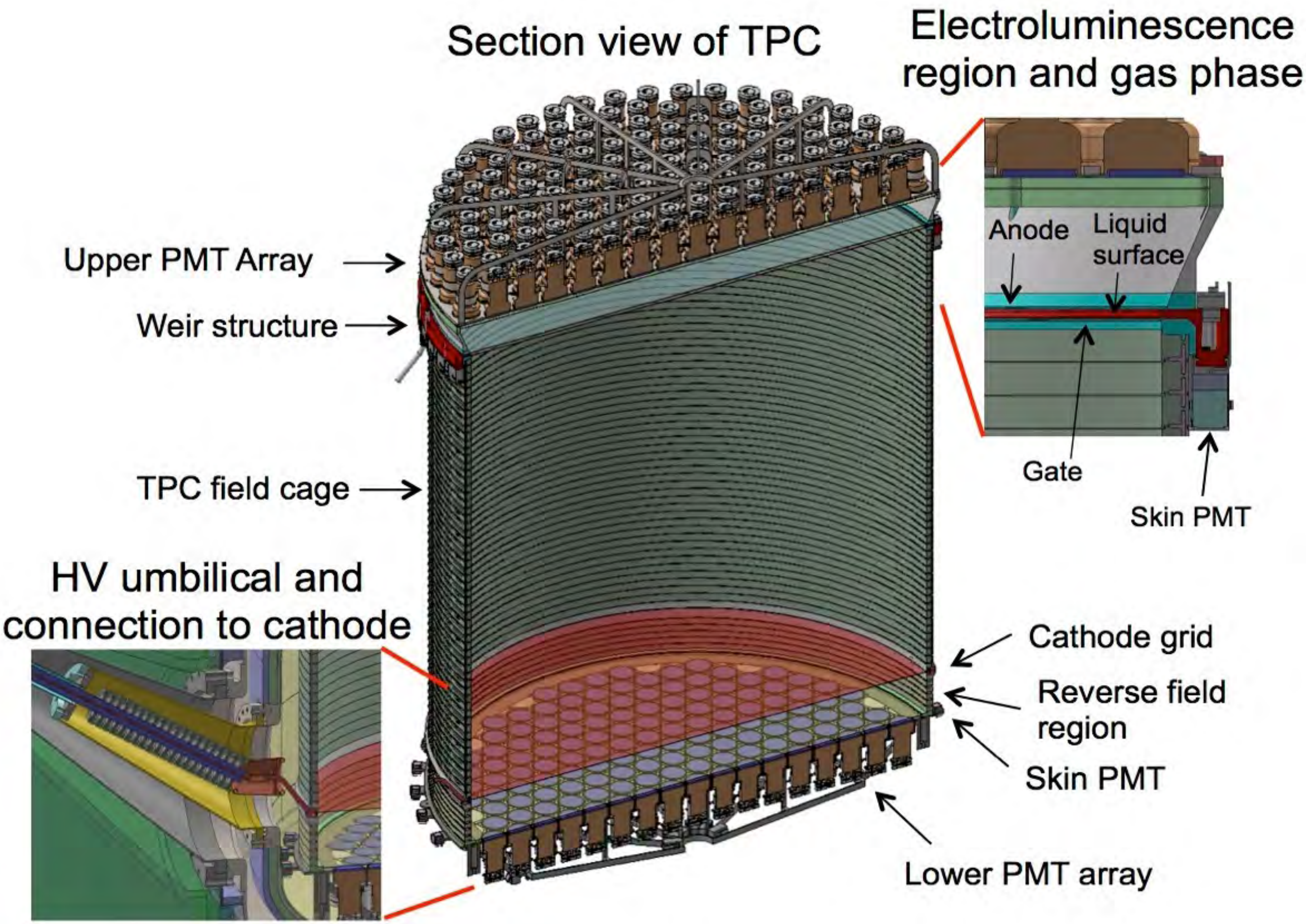
- background population normalisation
- WIMP PDF & efficiency.

**Power constraint** at median background-only limit.




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

# The detector



# Extensive calibration

- Building on experience from LUX
  - Kr-83m (routine, roughly weekly)
  - Tritiated methane (every few months)
  - External radioisotope neutron sources
  - External radioisotope gamma sources
  - DD neutron generator (upgraded early next year to shorten pulse)
- New in LZ
  - Activated Xe (Xe-129m and Xe-131m)
  - Rn-220
  - Am-Li
  - YBe

# Neutrinoless Double Beta Decay of Xe-126

- Use self-shielding to reduce gamma-ray backgrounds in a 1-2 tonne fiducial mass
- Projected sensitivity: 90% confidence level $T^{0\varpi}_{1/2}$ of $2 \times 10^{26}$ years
- Enriching the Xe target could increase this to ~ $2 \times 10^{27}$ years
- Current limit is $2.6 \times 10^{25}$ years (preliminary) from KamLND-Zen

# External Neutrino Physics

- Solar neutrinos
  - Expect about 850 pp neutrino events between 1.5 and 20 $keV_{ee}$
- Supernova neutrinos
  - Via flavor-blind coherent neutrino-nucleus scattering
  - For a 10 kpc SN, LZ would see about 50 events with energy > 6 keV and 100 events > 3 keV
- Sterile neutrinos
  - Could use a 5 MCi Cr-51 source near LZ
  - Excellent position reconstruction for better source normalization, higher sterile neutrino masses.
- Neutrino magnetic moment
  - Sensitivity near astrophysical limit of $2 \times 10^{-12}$ Bohr magnetons.