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}
ρ_χ ~ 0.3 GeV/cm^3 and 100 GeV/c^2

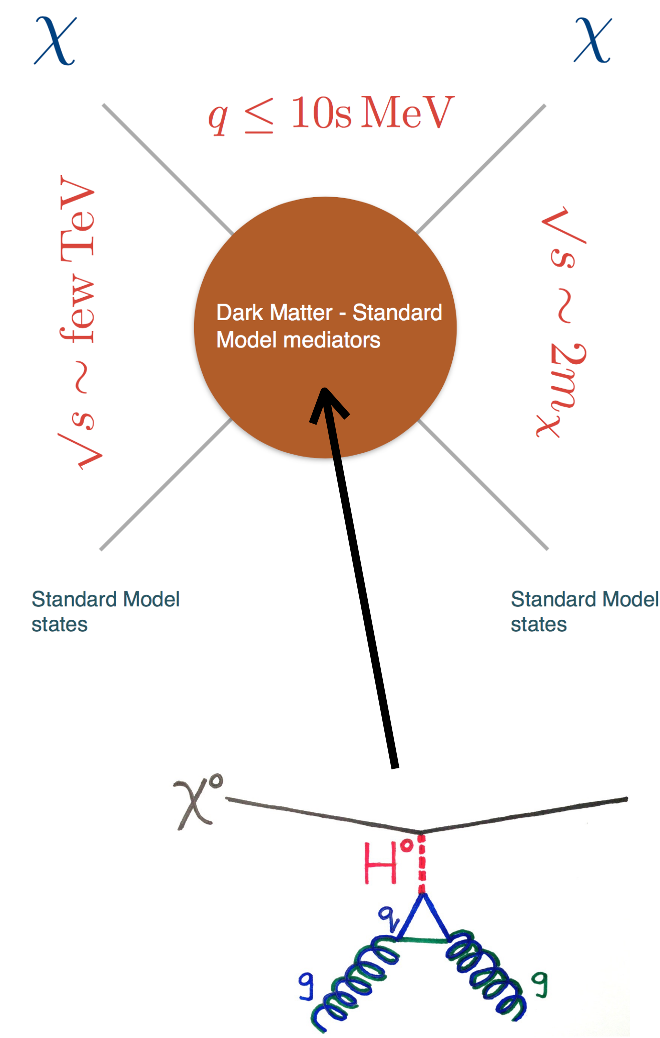
Basic goal: search for nuclear recoil from DM elastic scattering.

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

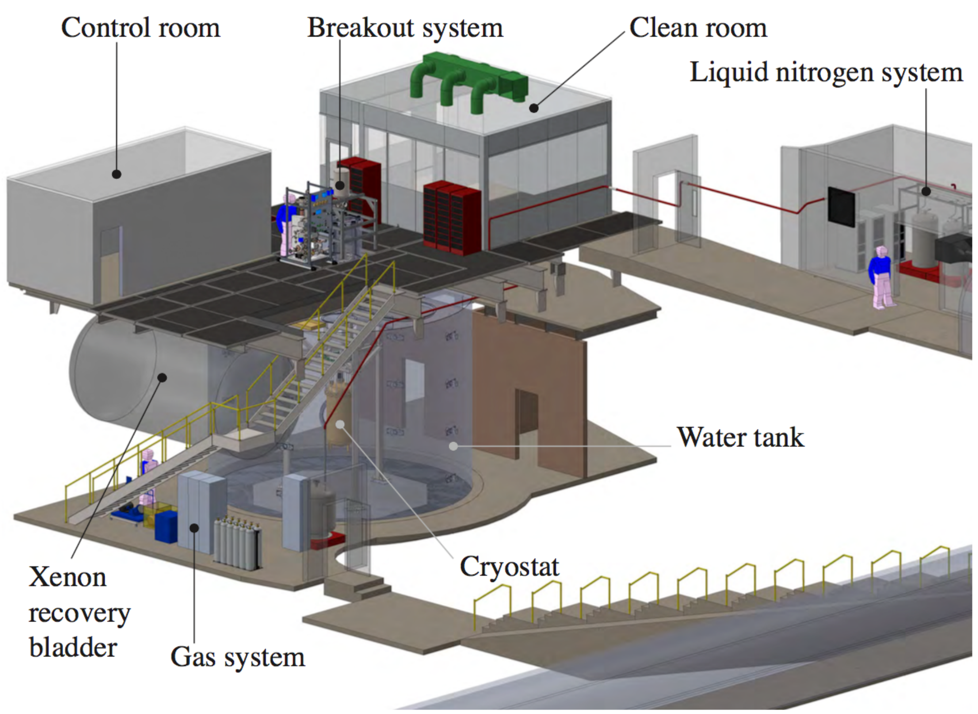
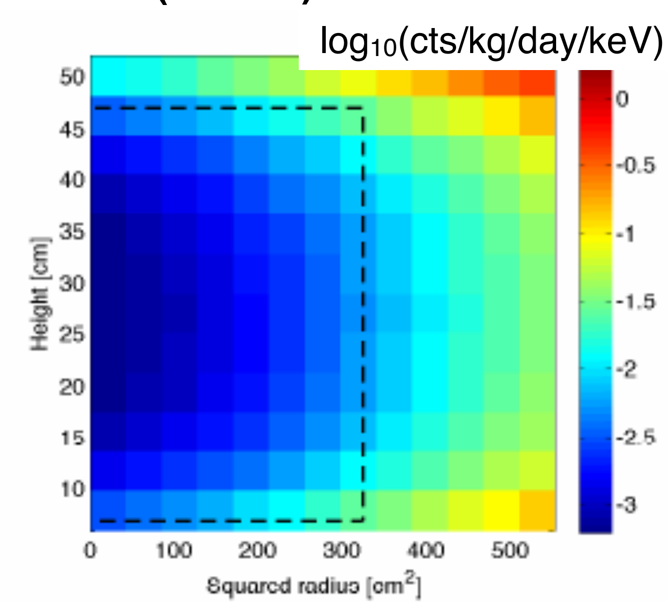


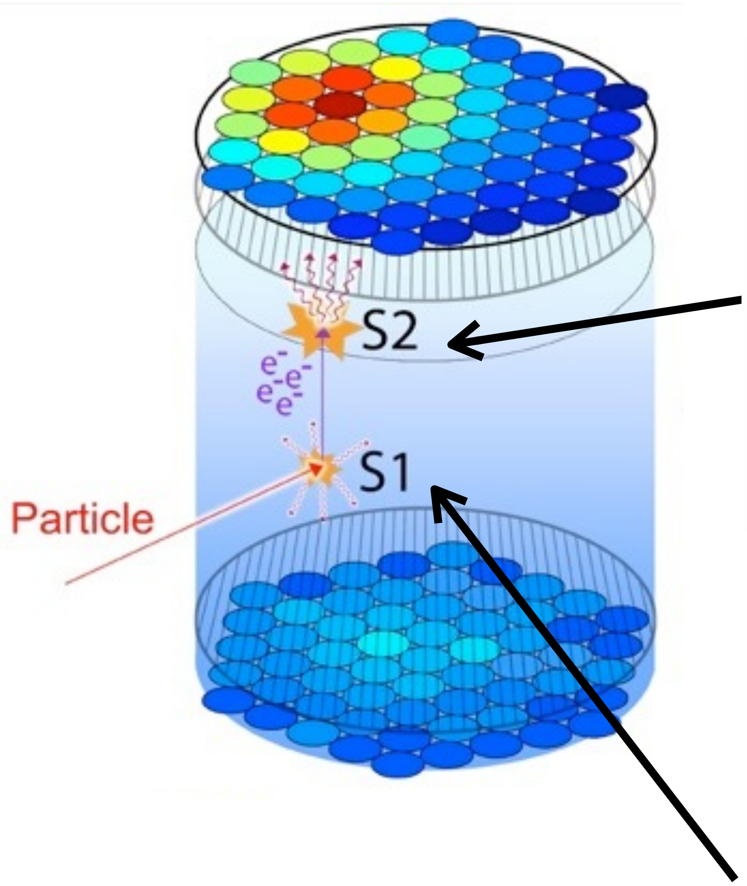
Figure 16: Rendering of the layout of the Davis Laboratory.

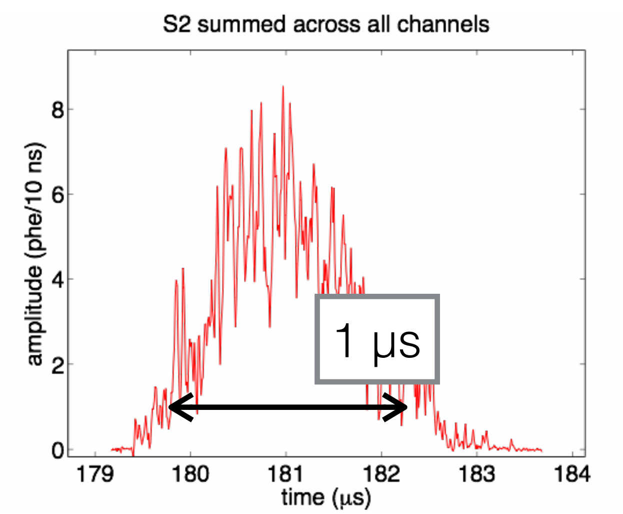
- Davis Cavern @ Sanford Lab (SURF), 4850 ft (1.5 km) underground
- 250 kg (47 x 49 cm^2) of active LXe dual phase time projection chamber (TPC)
- Two arrays each of 61 ultra-pure PMTs
- Reducing background:
  - cosmic μ flux reduced to 6.2×10^{-9} $cm^{-2}s^{-1}$
  - low background materials
  - 3D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



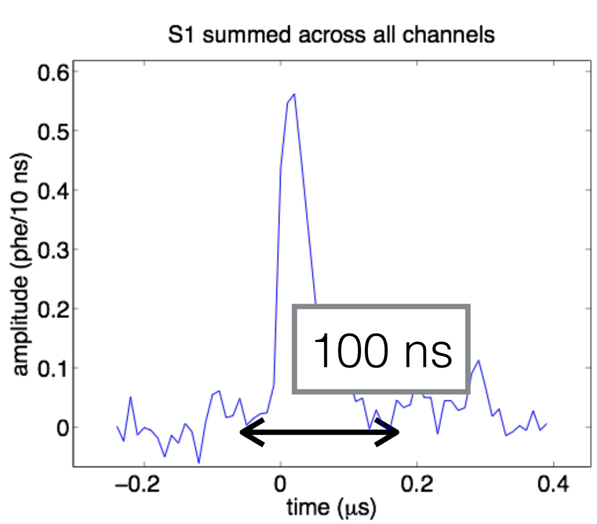
S1, S2 and CES

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

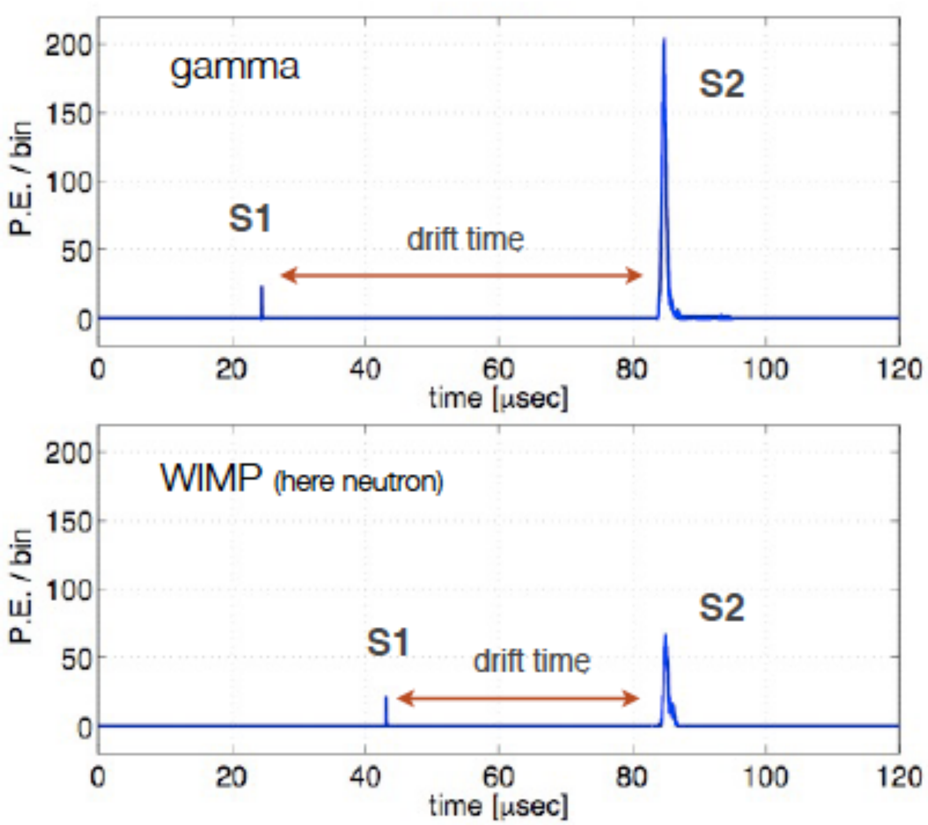
  Nuclear recoil enhancement of heat relative to electron recoils

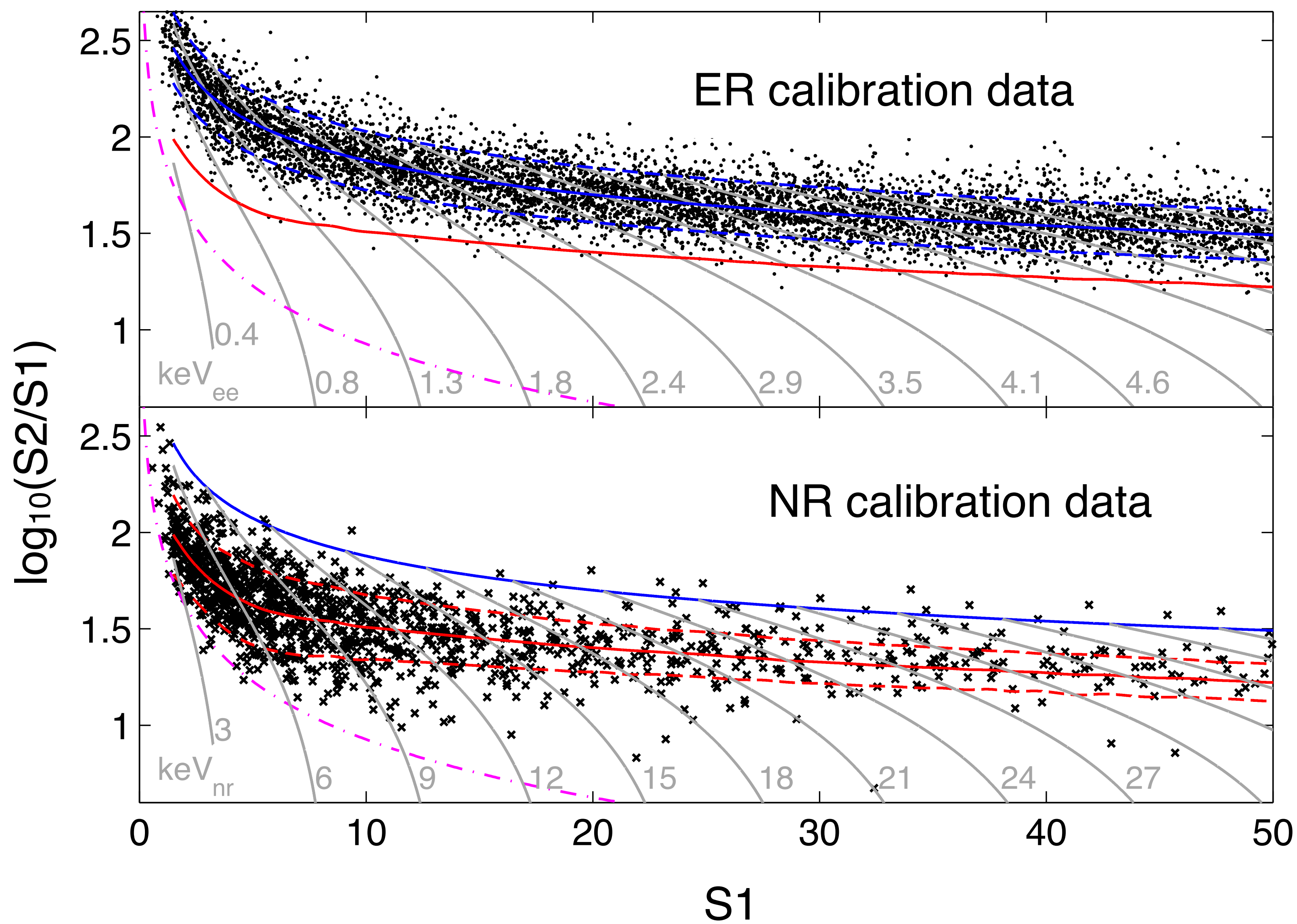
Nuclear vs. Electron recoil

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

Electron Recoil (ER) events

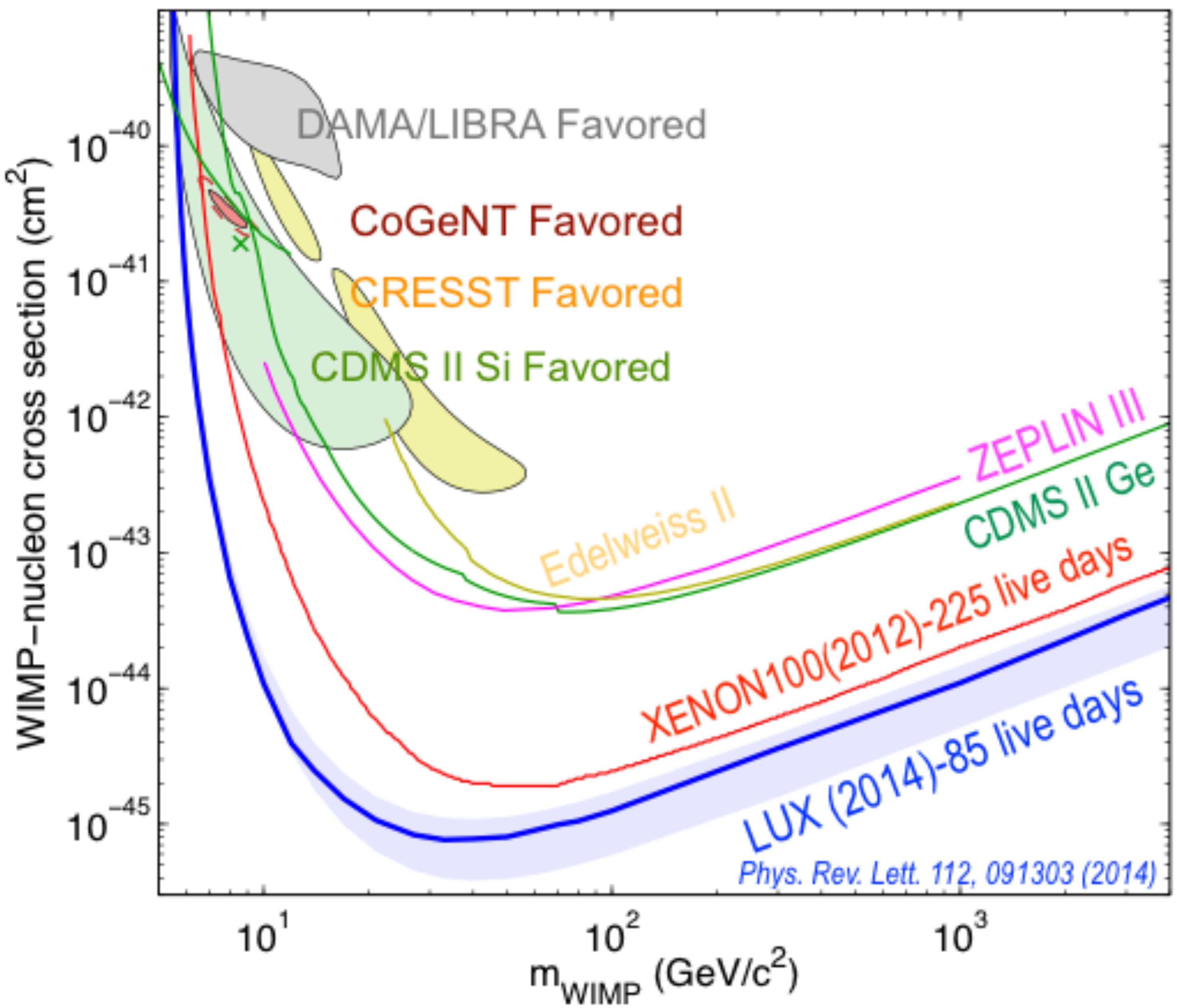
Nuclear Recoil (NR) events





Reminder: 1st LUX results

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



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

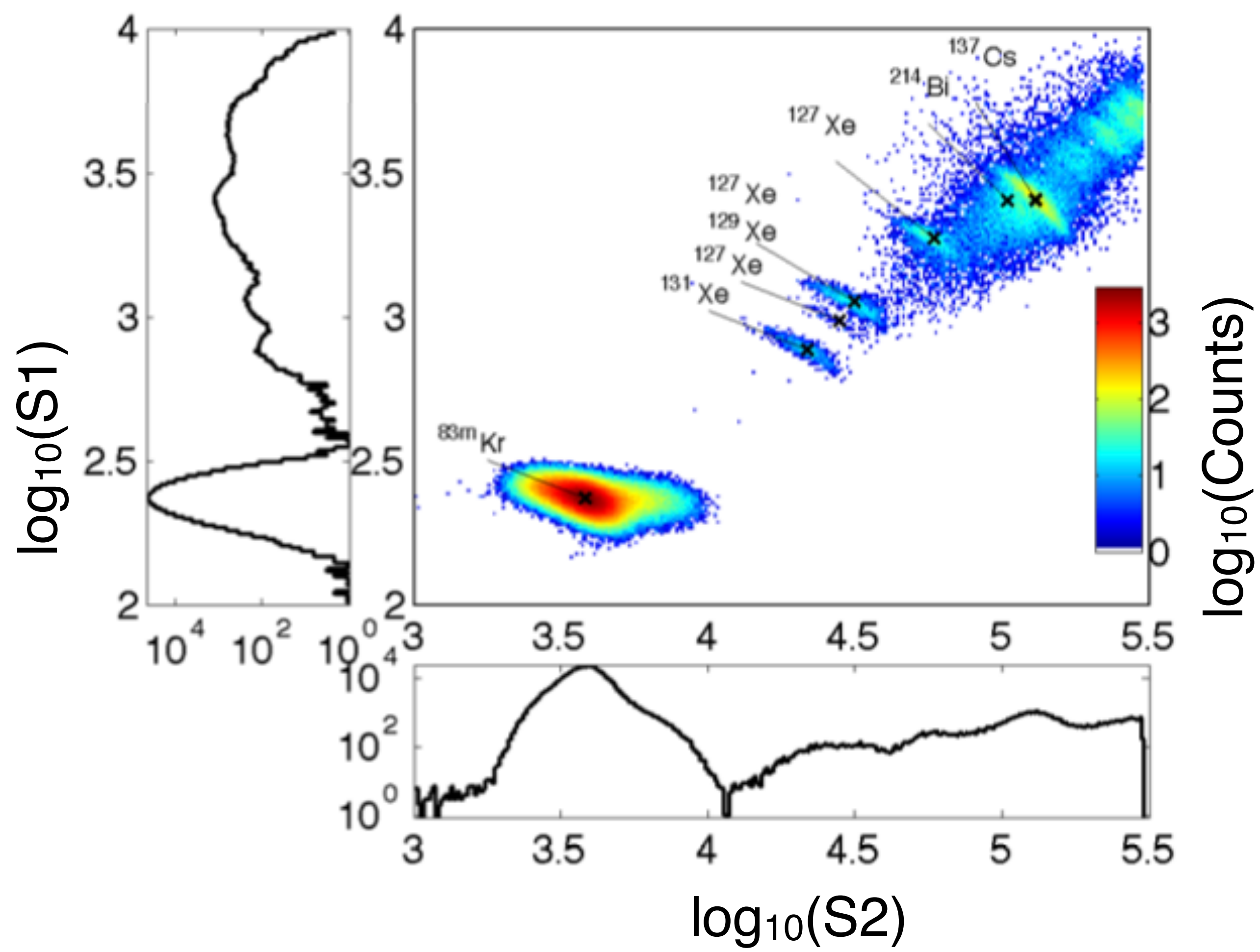
LUX Run03 reanalysis

- 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.

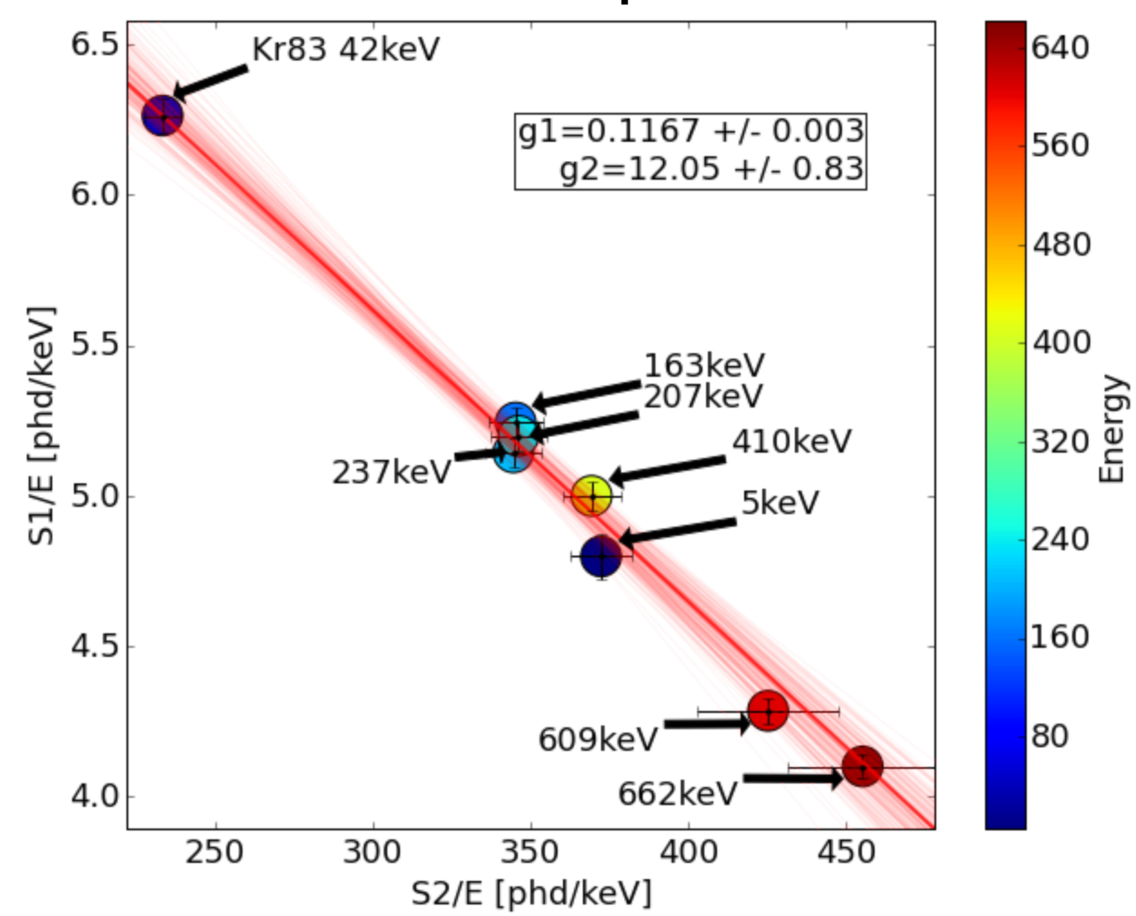
ER Calibration

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_γ —> 0; S2/E = g_2/W

y-intercept => n_e —> 0; S1/E = g_1/W

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

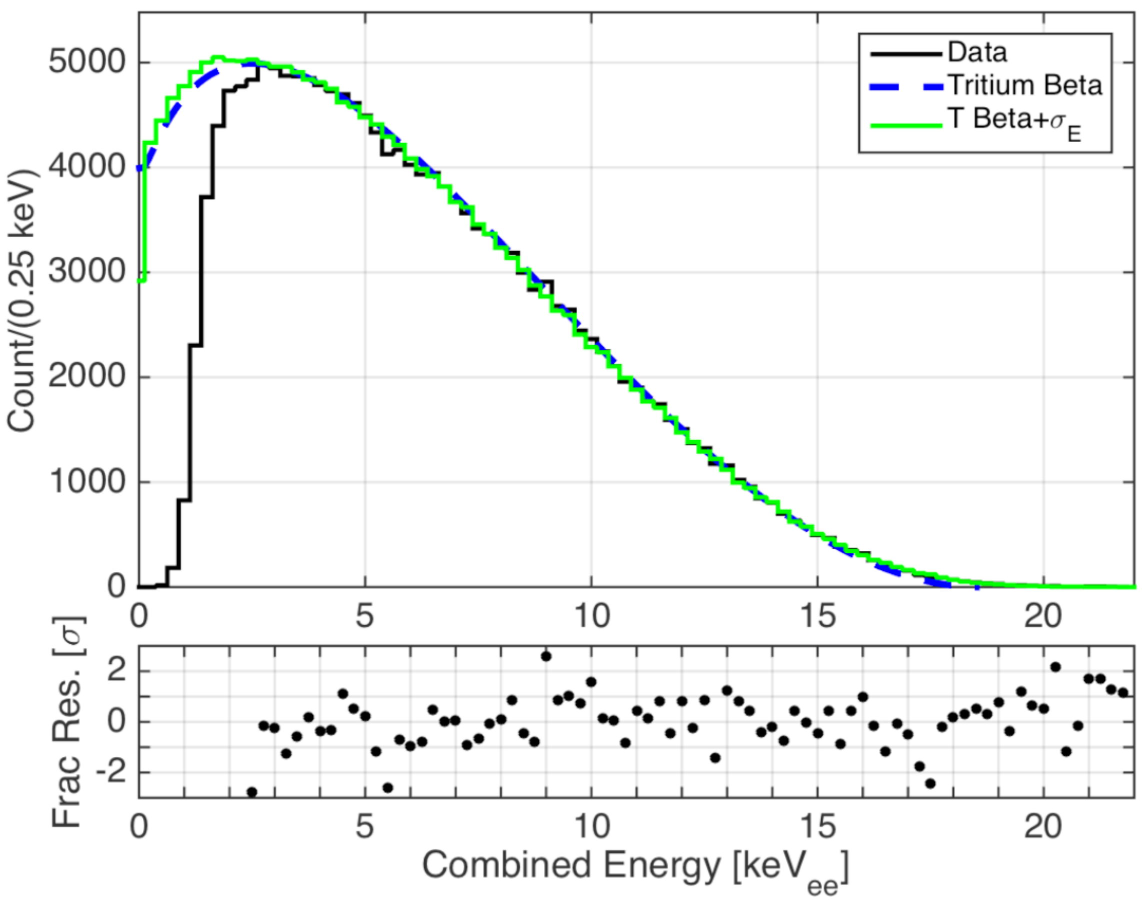
ER Calibration

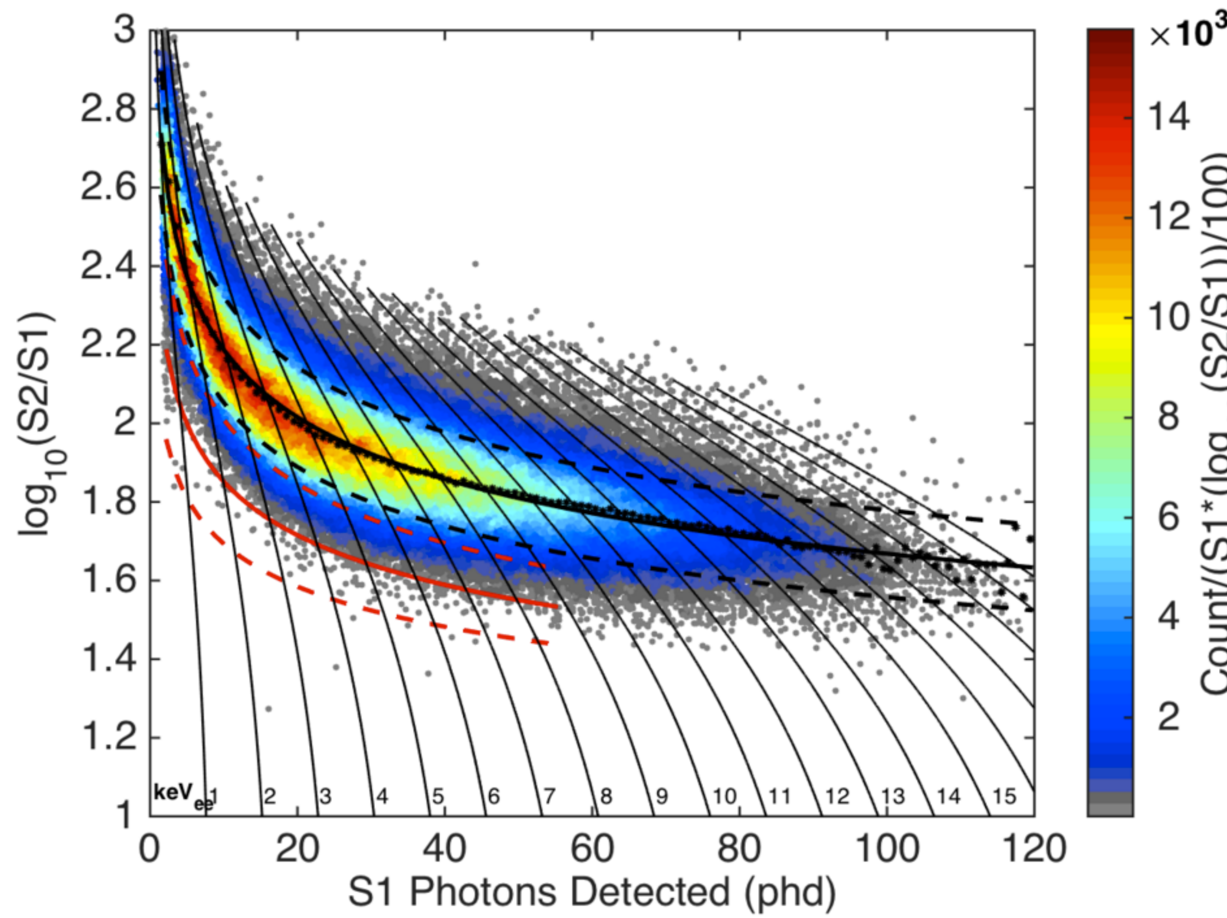
0 - 18 keV CH_3T (tritiated methane) internal source

- 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



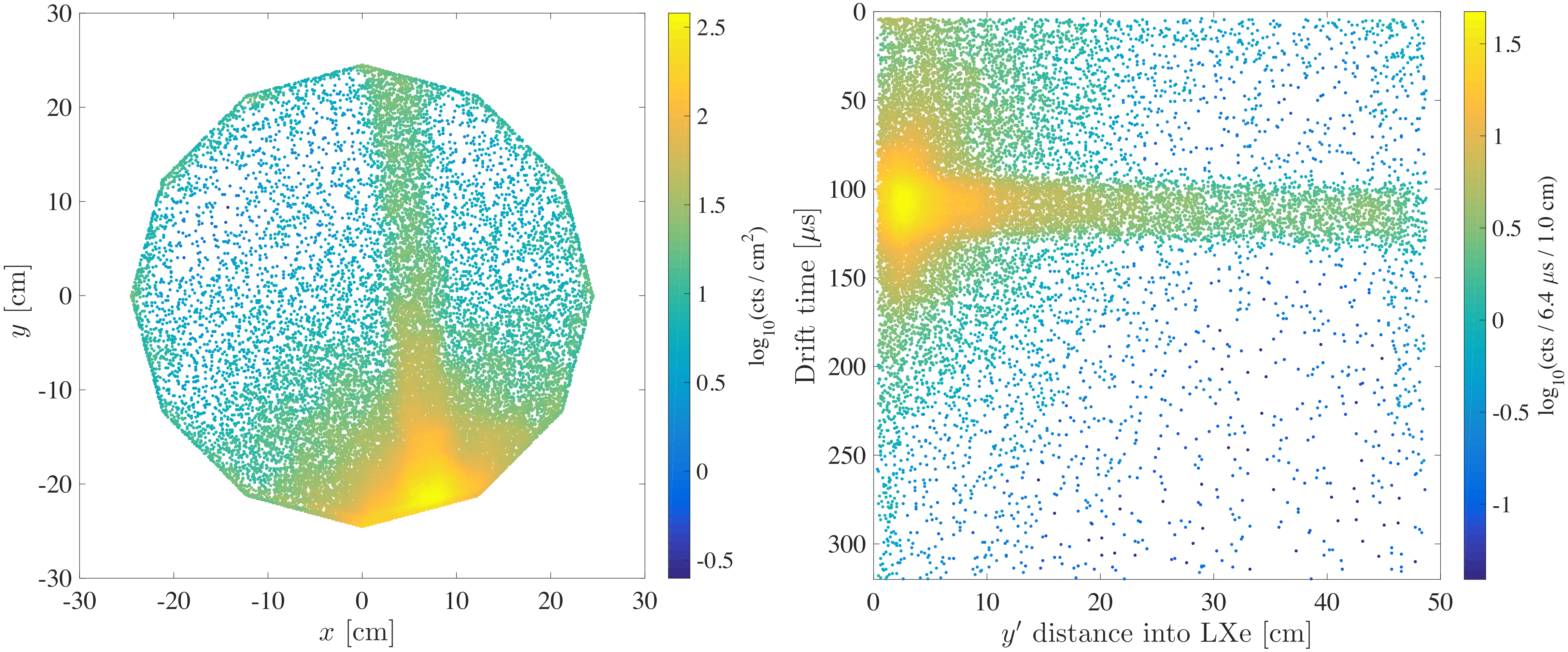


NR Calibration

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

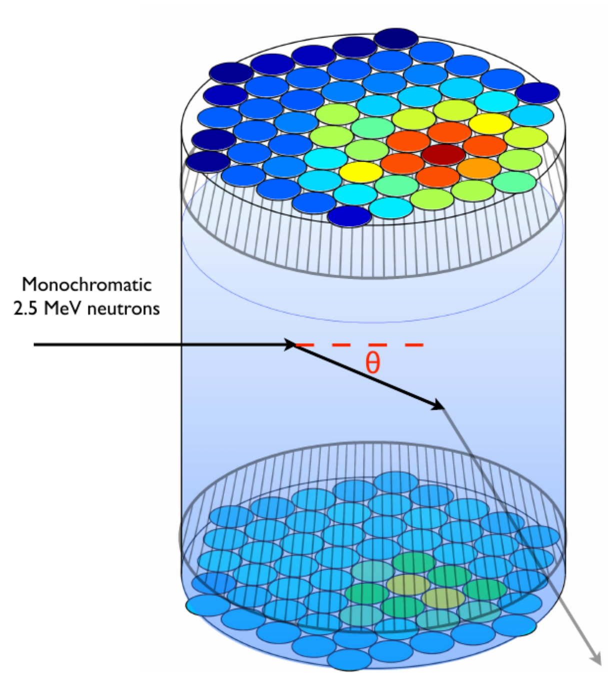


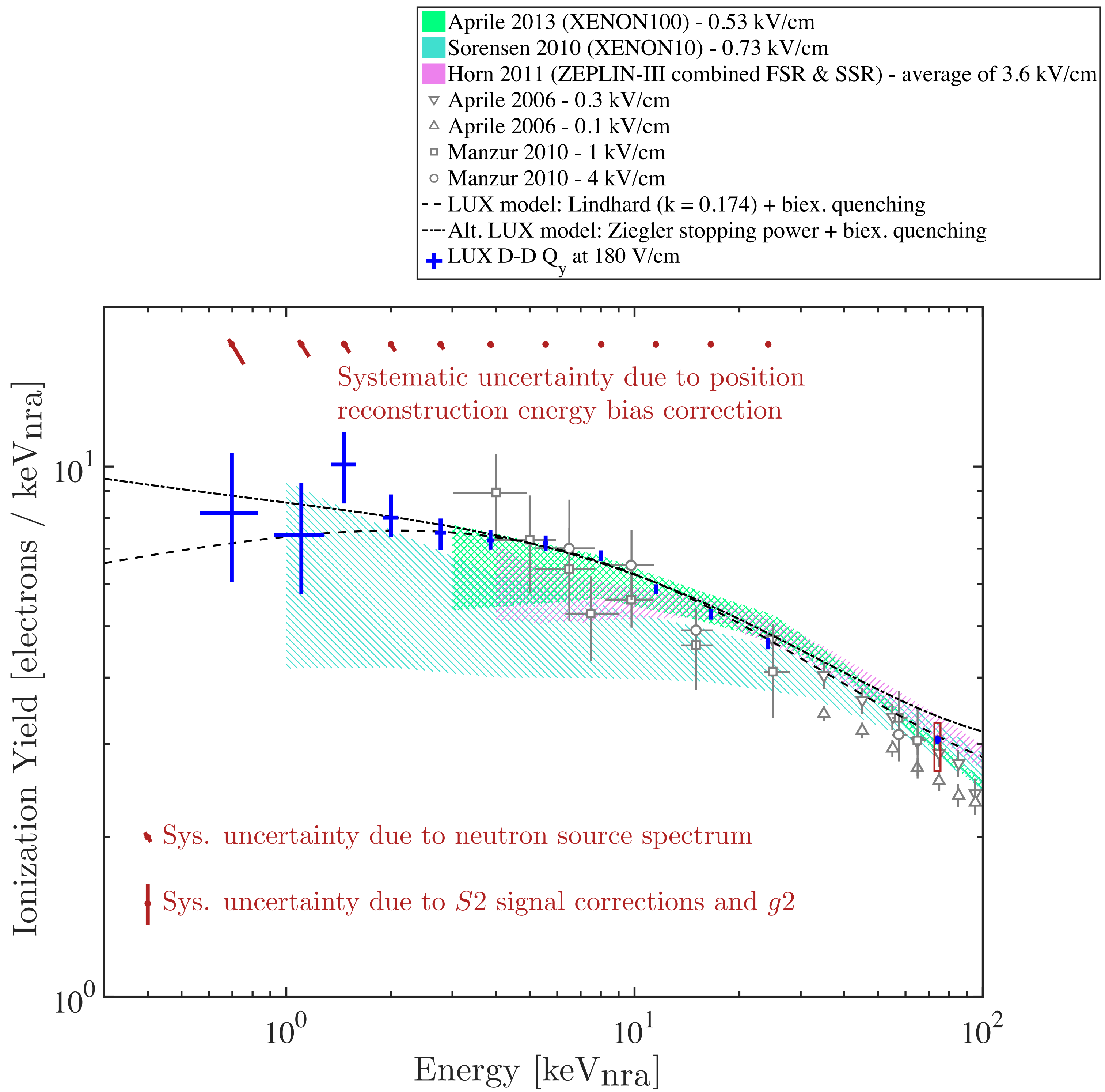
NR Calibration

Mono-energetic neutrons: D-D generator

S2 vs energy via E(θ) for multiple scatters

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



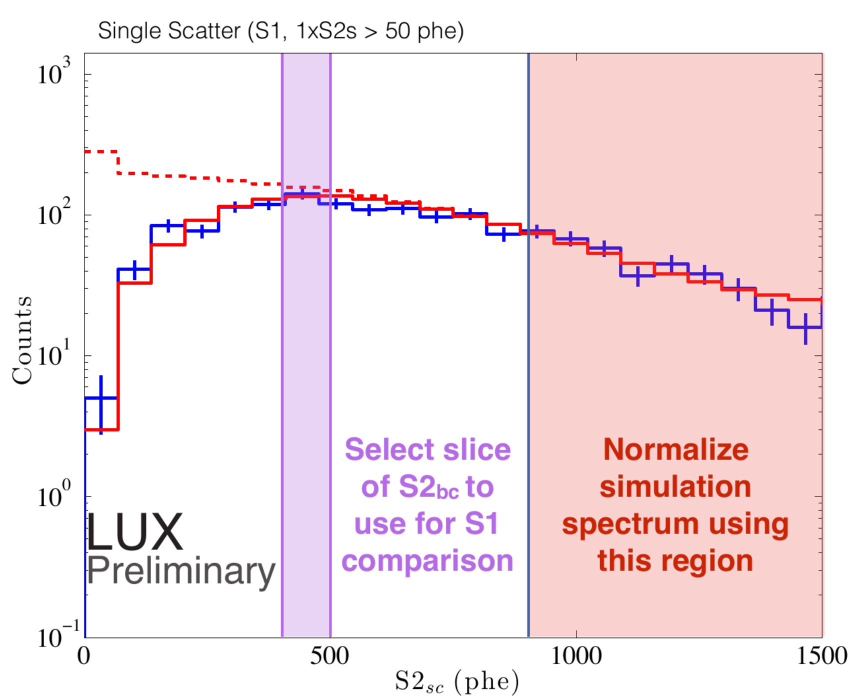


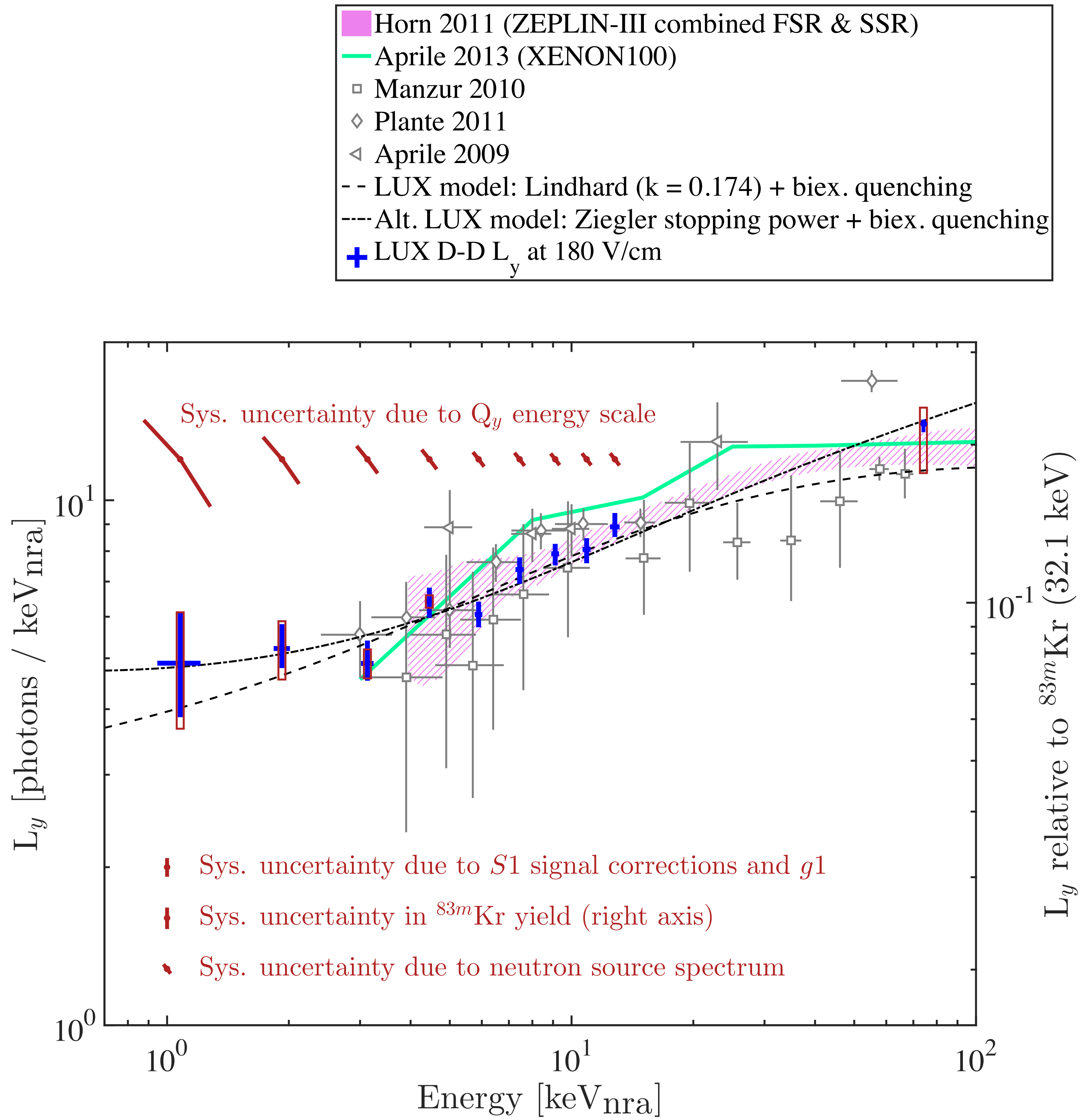
Paolo Beltrame

NR Calibration

Mono-energetic neutrons: D-D generator

S1 vs energy via E(S2) for single scatters



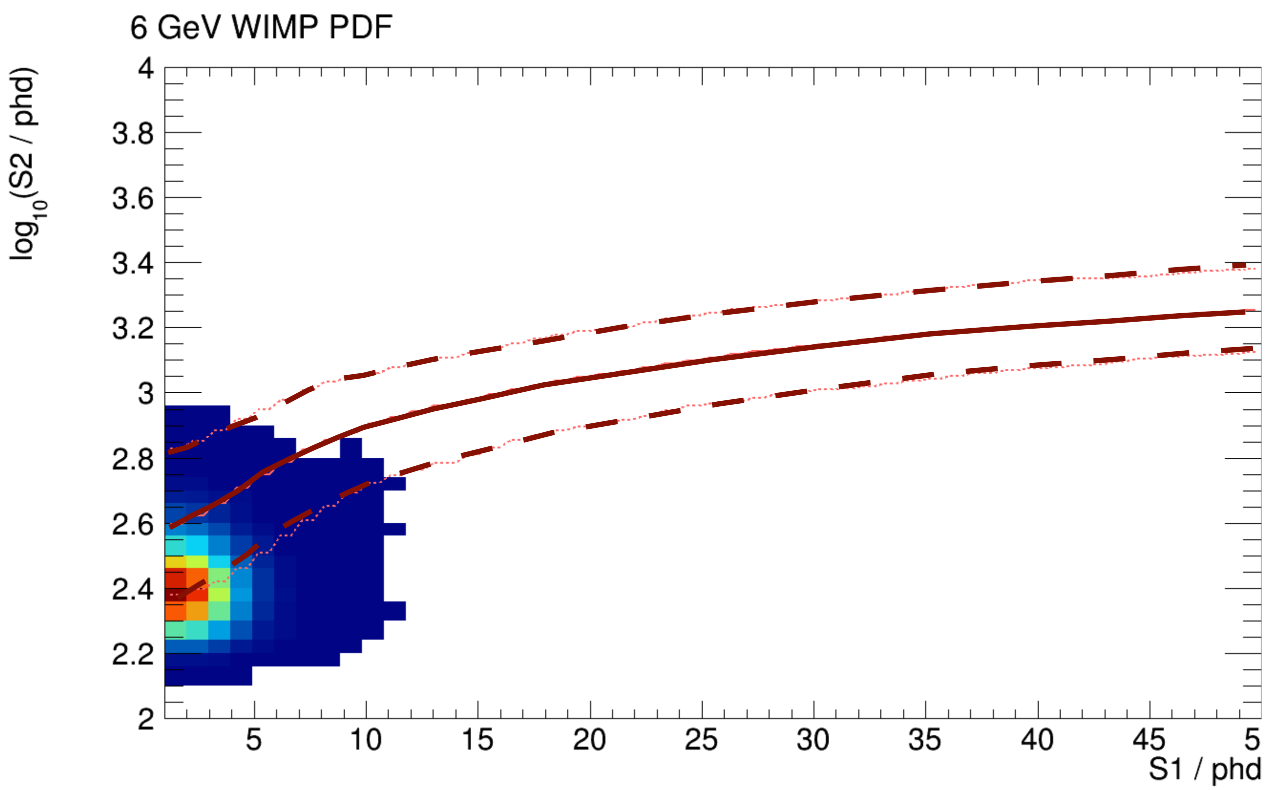


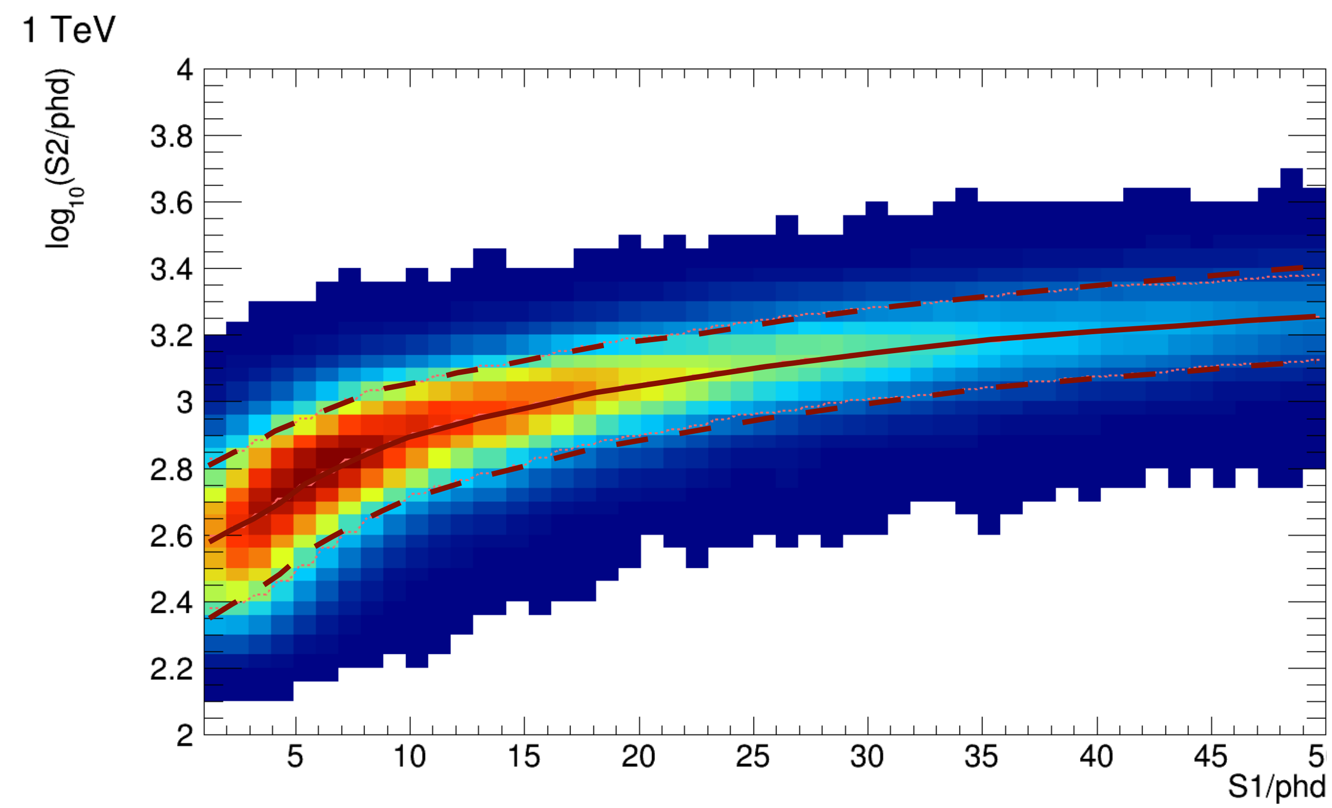
Signal and background

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.

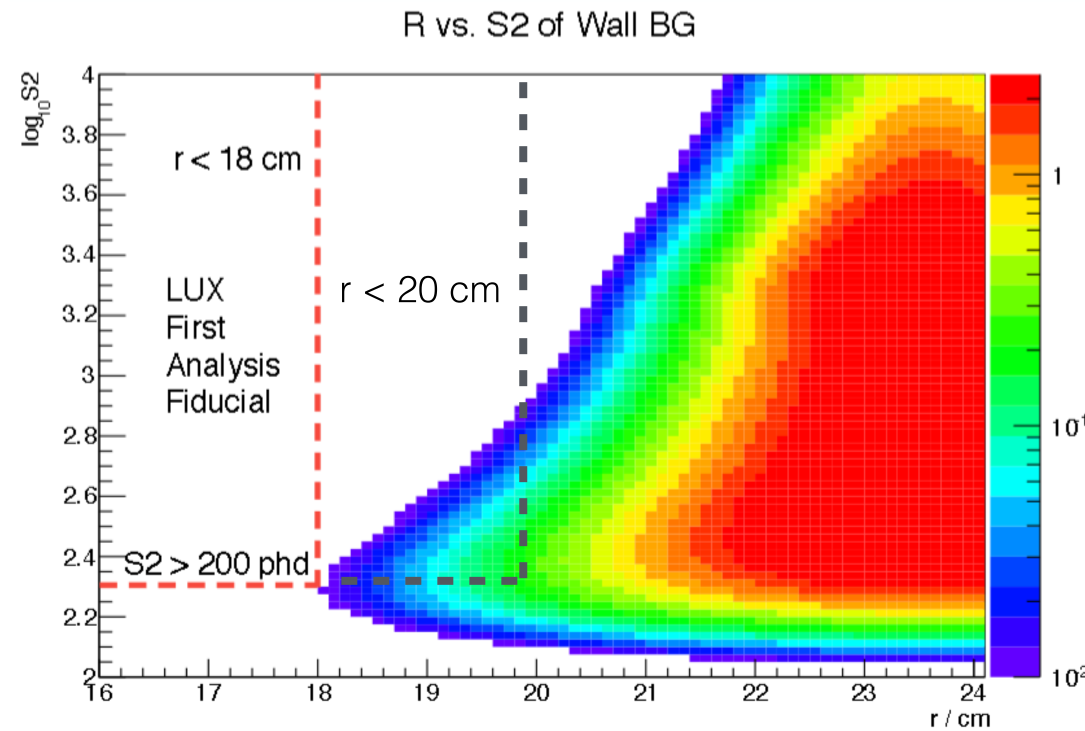
New test statistics profile likelihood: Nuisance params (Lindhard, g_{2DD} / g_{2WS}).

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

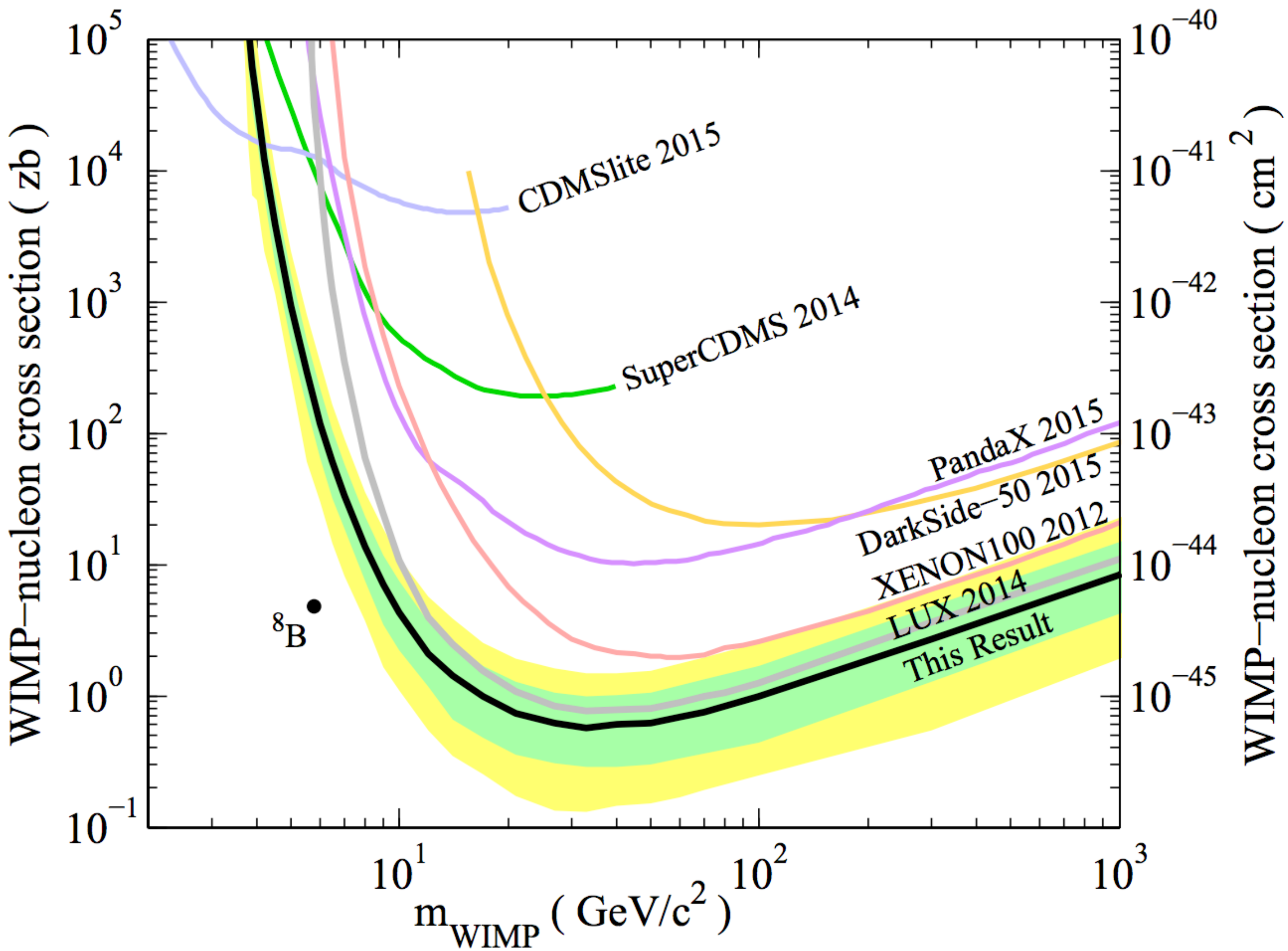
- Rn-222 - Pb-206
- Occurs on the wall at 24.2 - 5 cm
- Resolution leaks below 18 cm
- Charge loss
- Inclusion of 'wall background' increase fiducial radius to 20 cm



	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

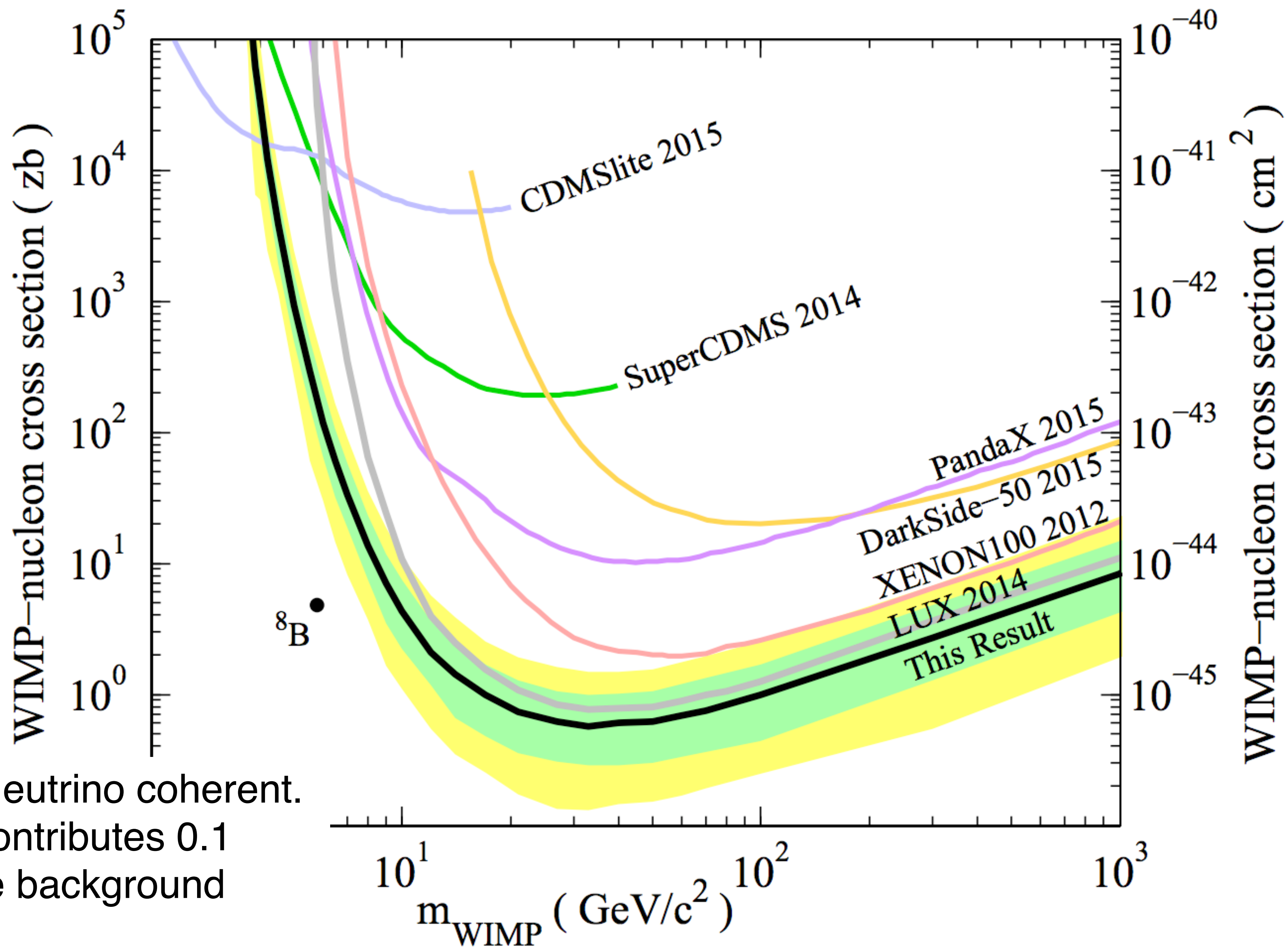
arXiv:1512.03506v2



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

Spin-independent

arXiv:1512.03506v2

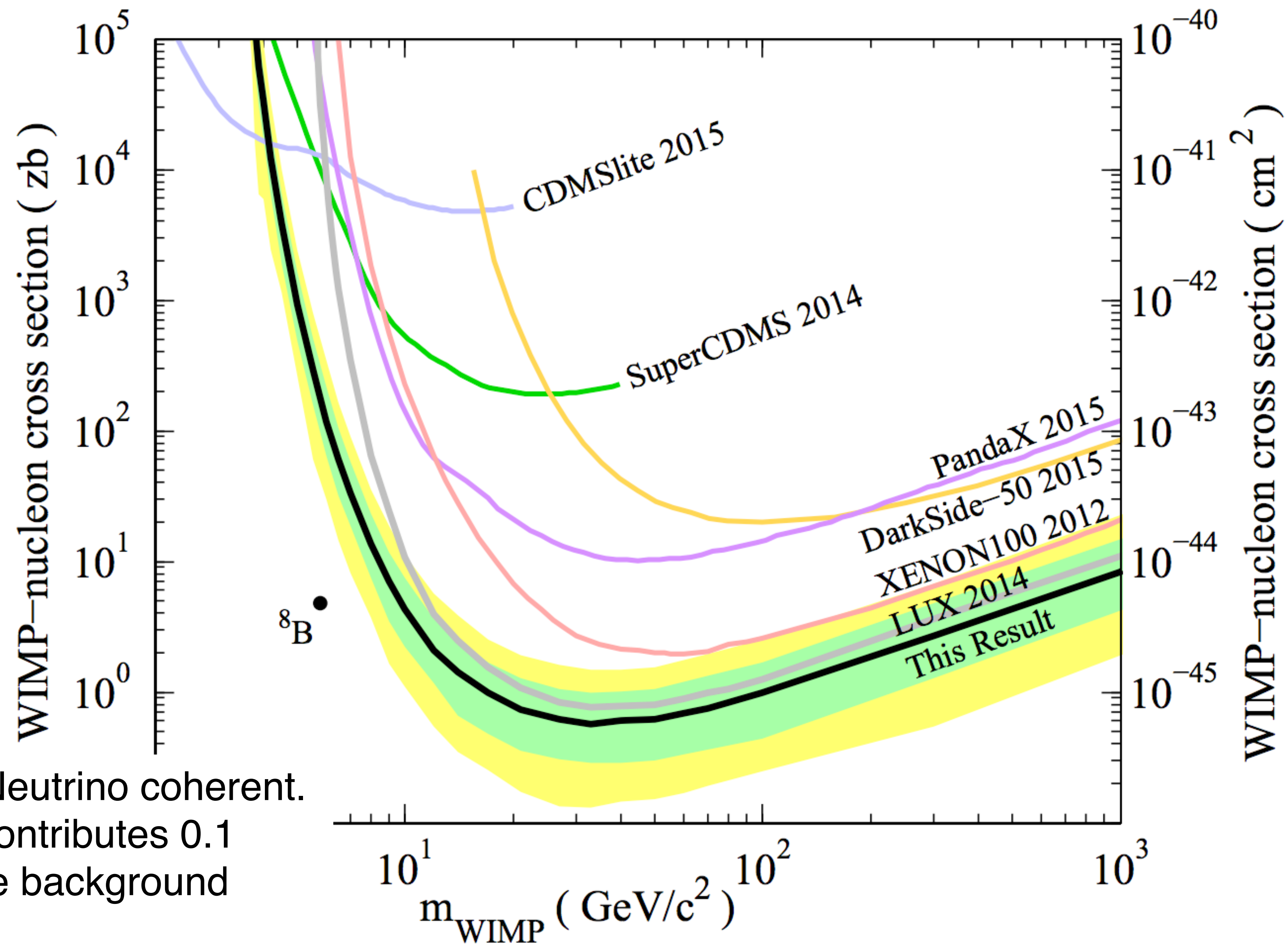


B-8 Solar Neutrino coherent. Currently contributes 0.1 event to the background

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

Spin-independent

arXiv:1512.03506v2



10^{-38} cm^2

Z exchange

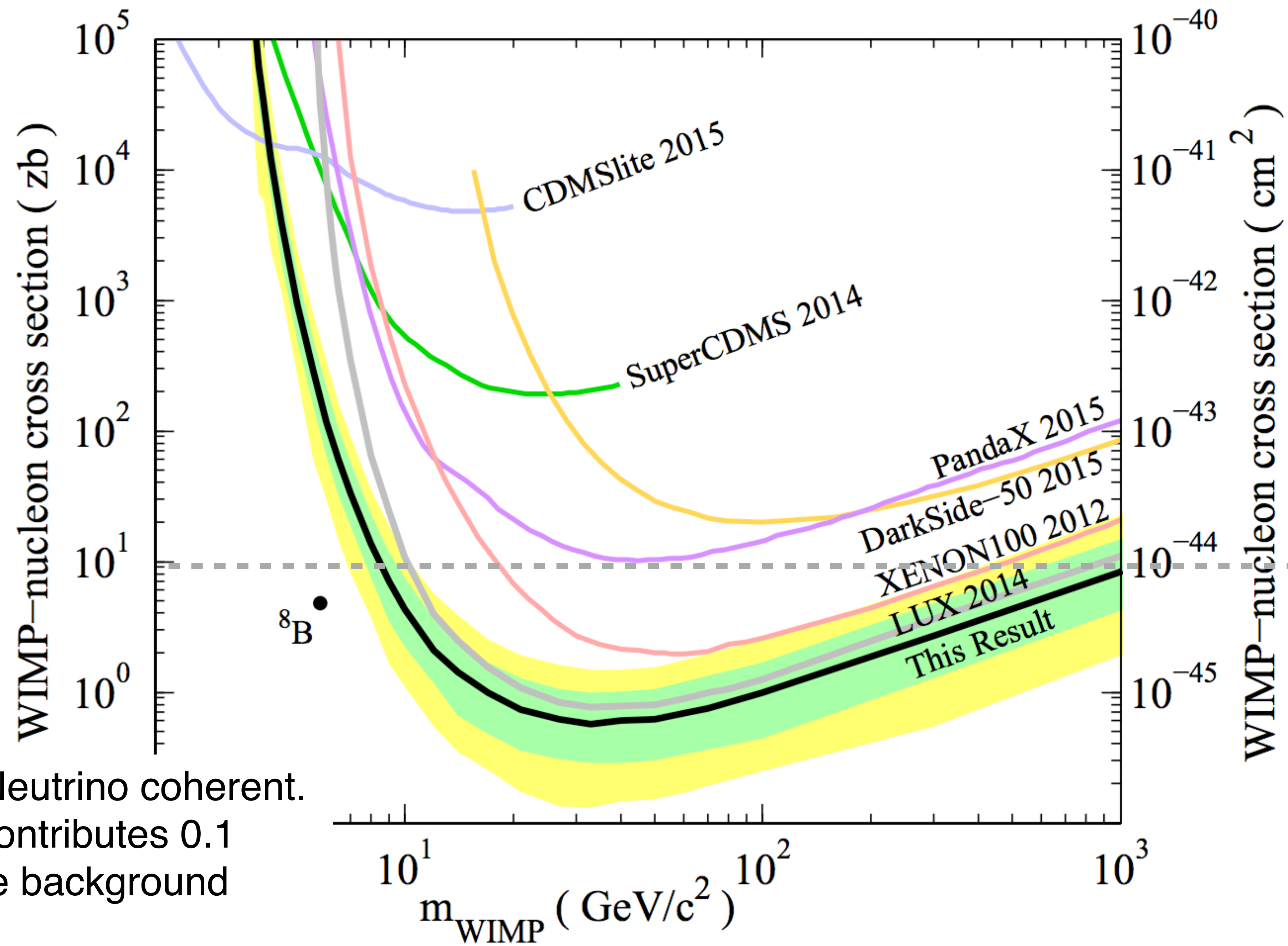
$\sigma \sim 10^{-2}\lambda_{Z\chi}^2$ pb

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

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

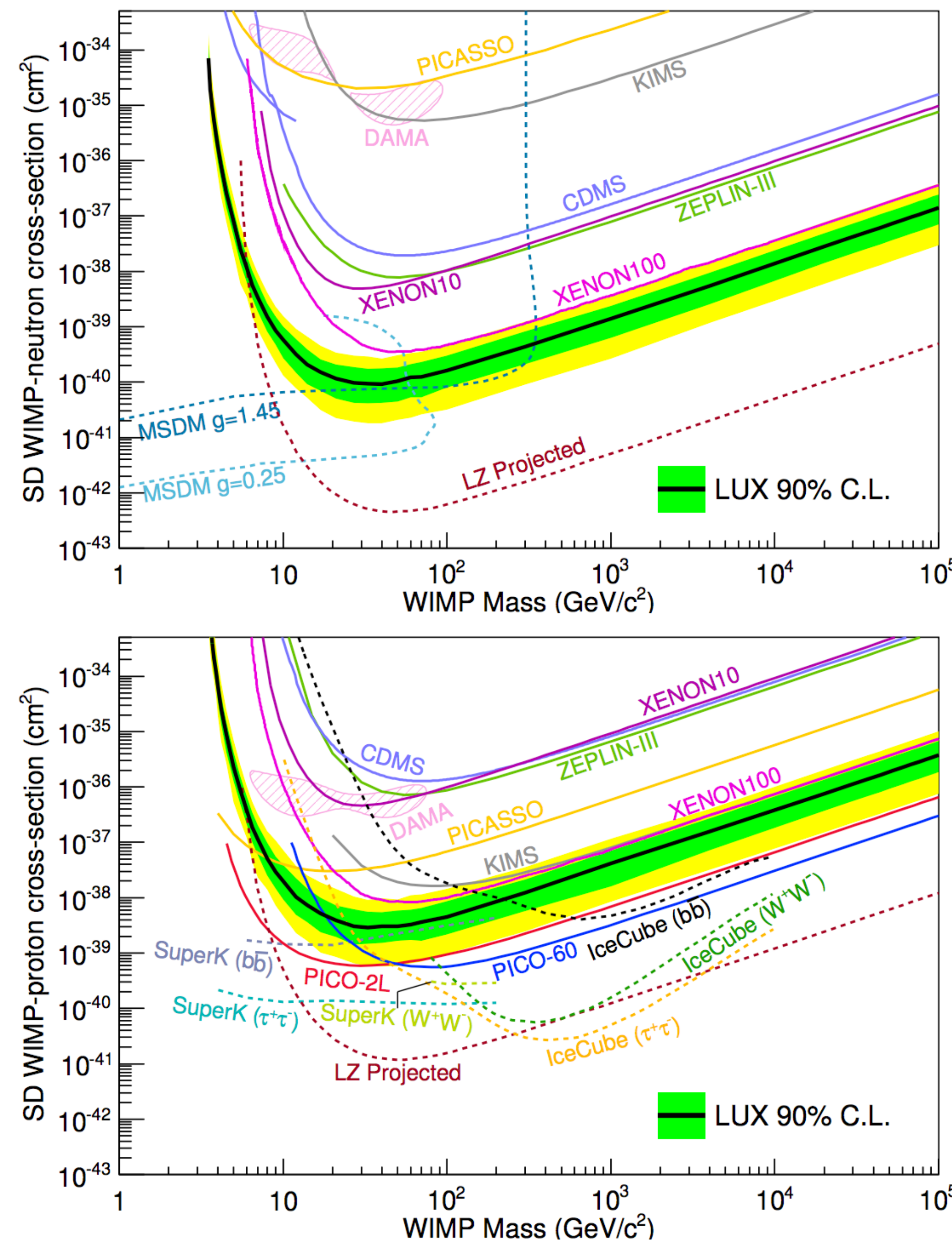
Spin-dependent

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

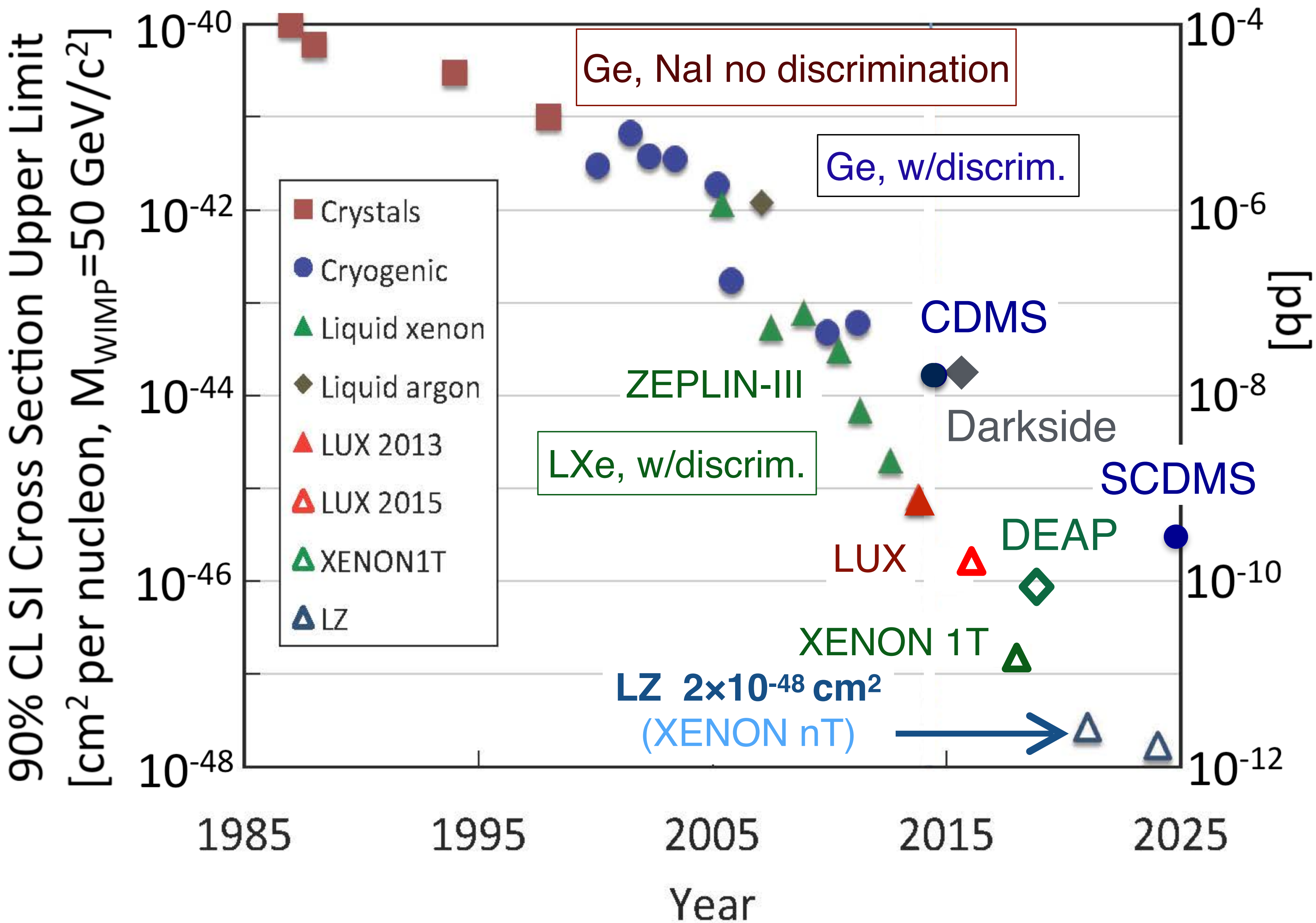


LUX plan

- 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)

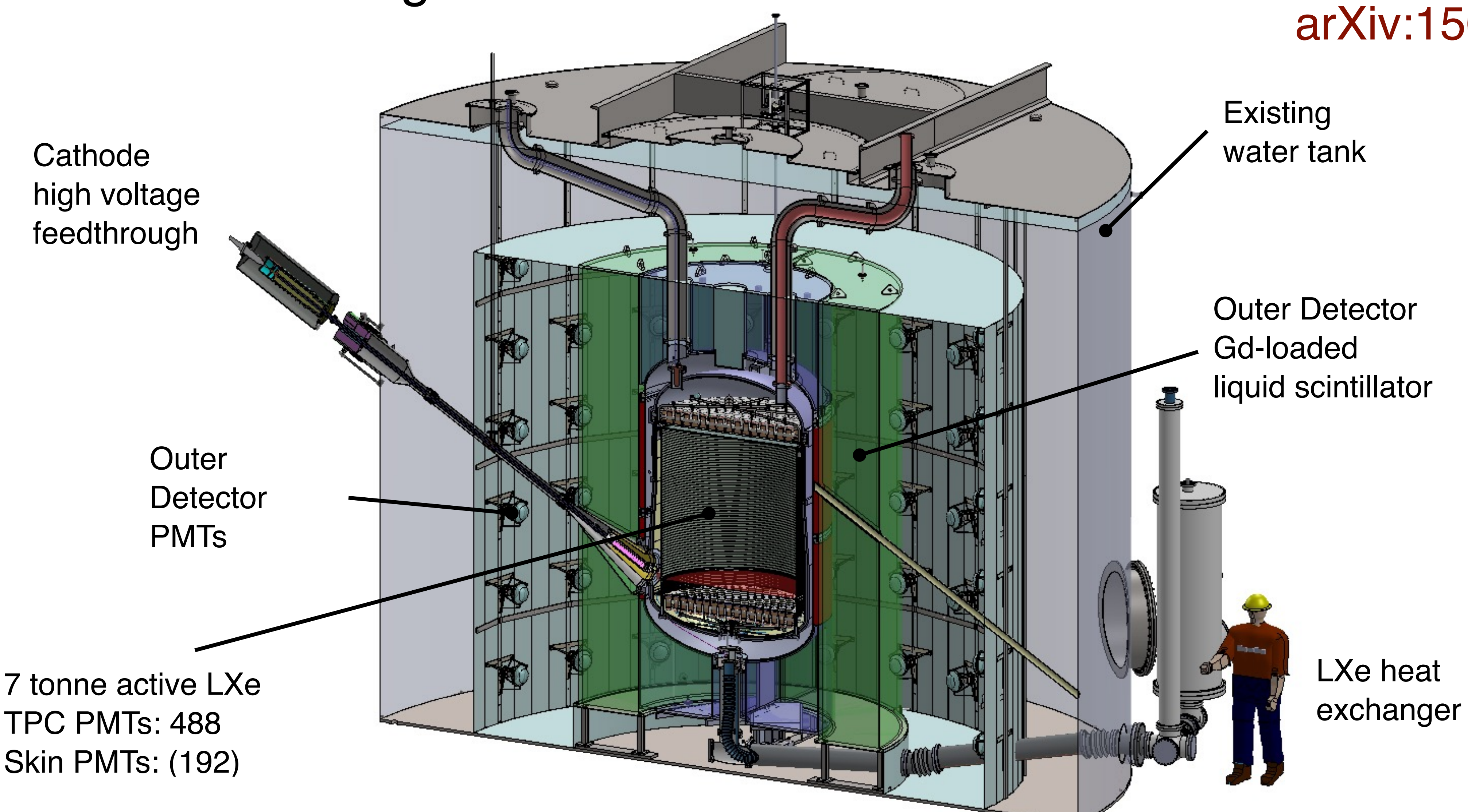
University of Alabama
University at Albany SUNY
Berkeley Lab (LBNL)
Brookhaven National Laboratory
University of California Berkeley
Brown University
University of California, Davis
Fermi National Accelerator Laboratory
Lawrence Livermore National Laboratory
University of Maryland
Northwestern University
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

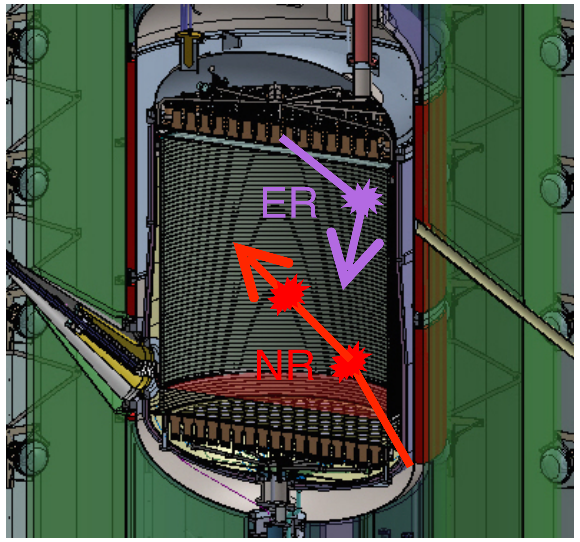
arXiv:1509.02910

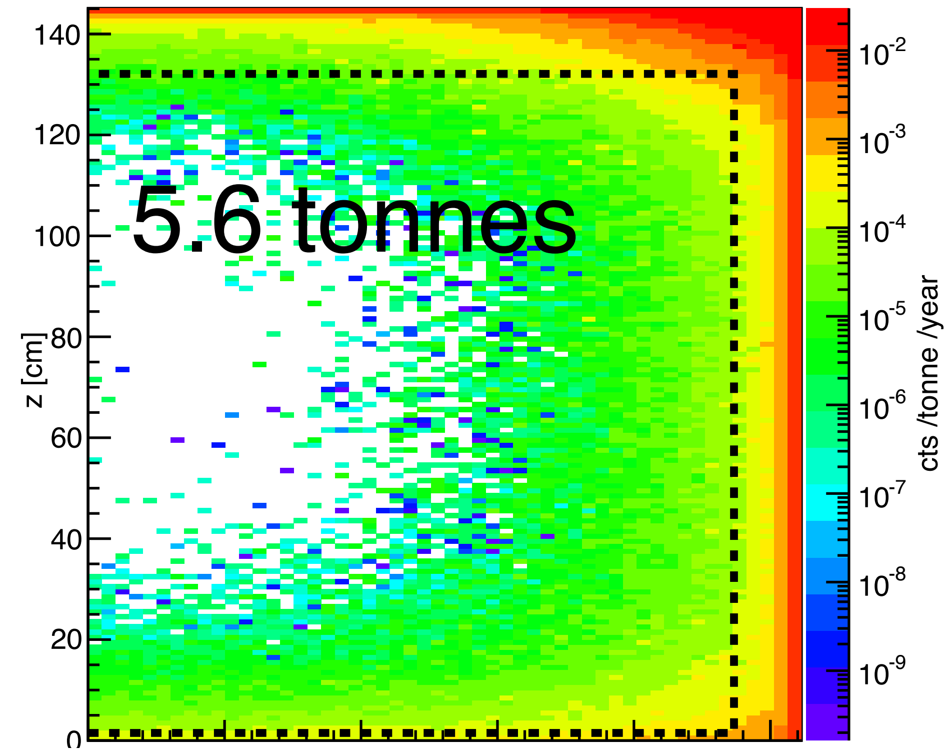


Backgrounds rejection

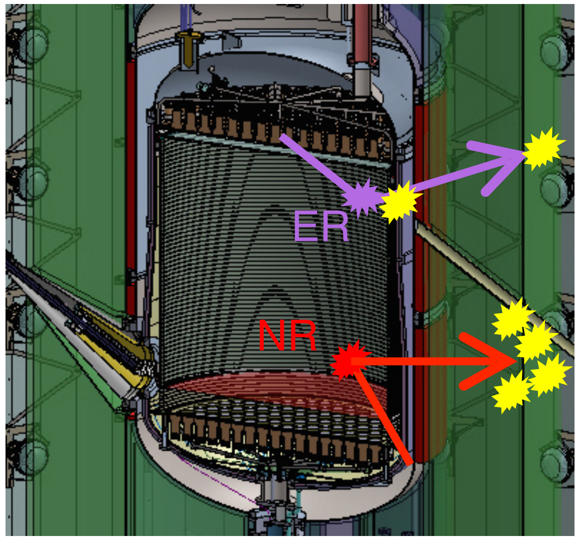
Detector material component backgrounds

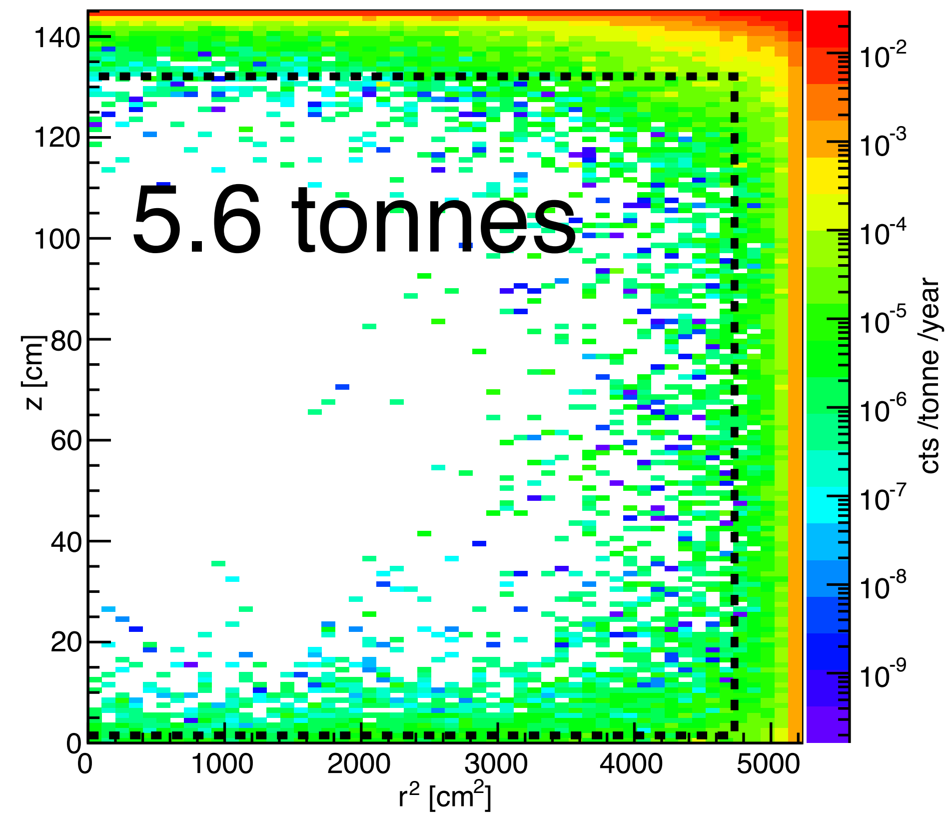
**LXe self shielding,
TPC multiple hit**





**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

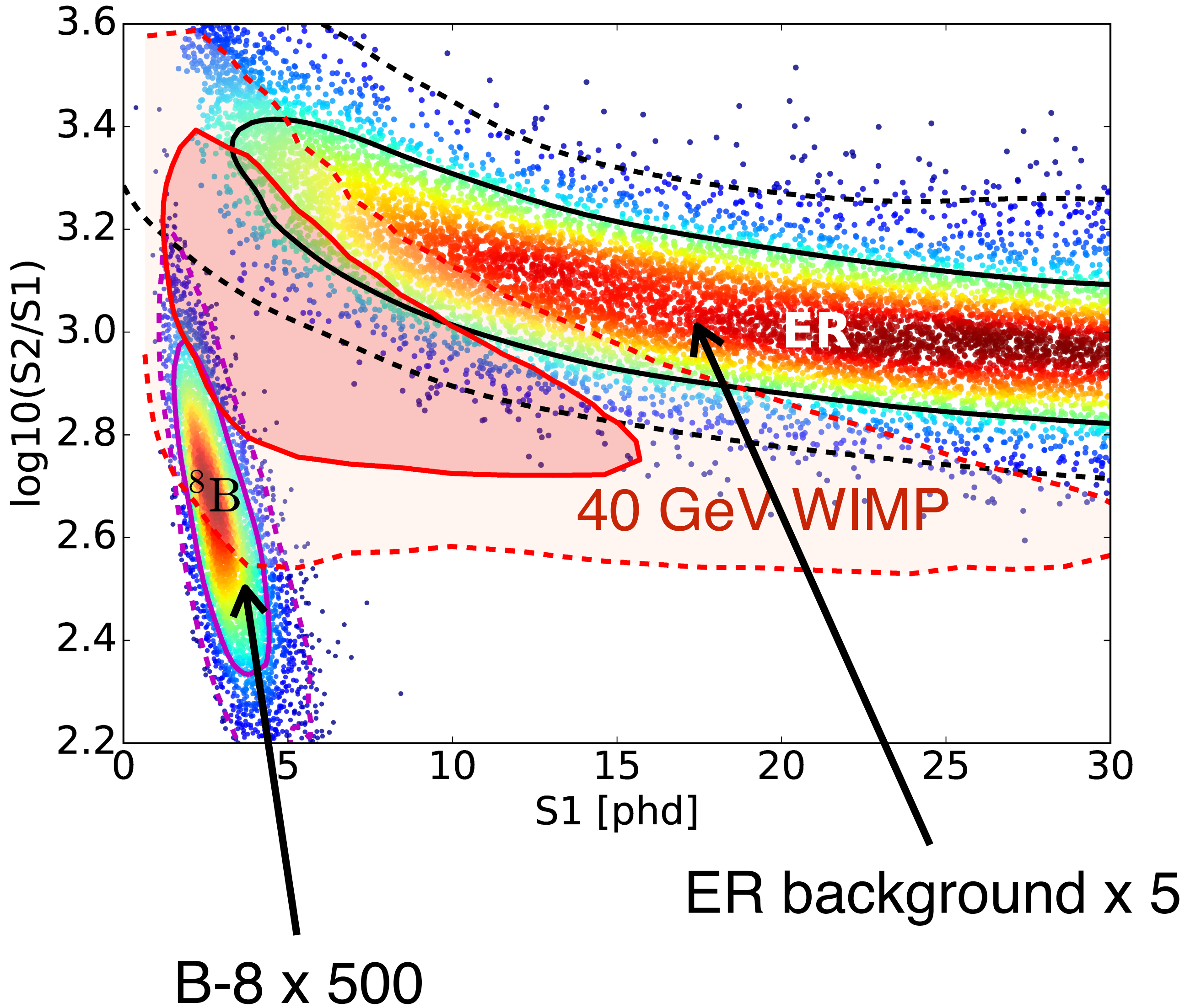
Projected sensitivity performed with PLR

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 ν	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 %

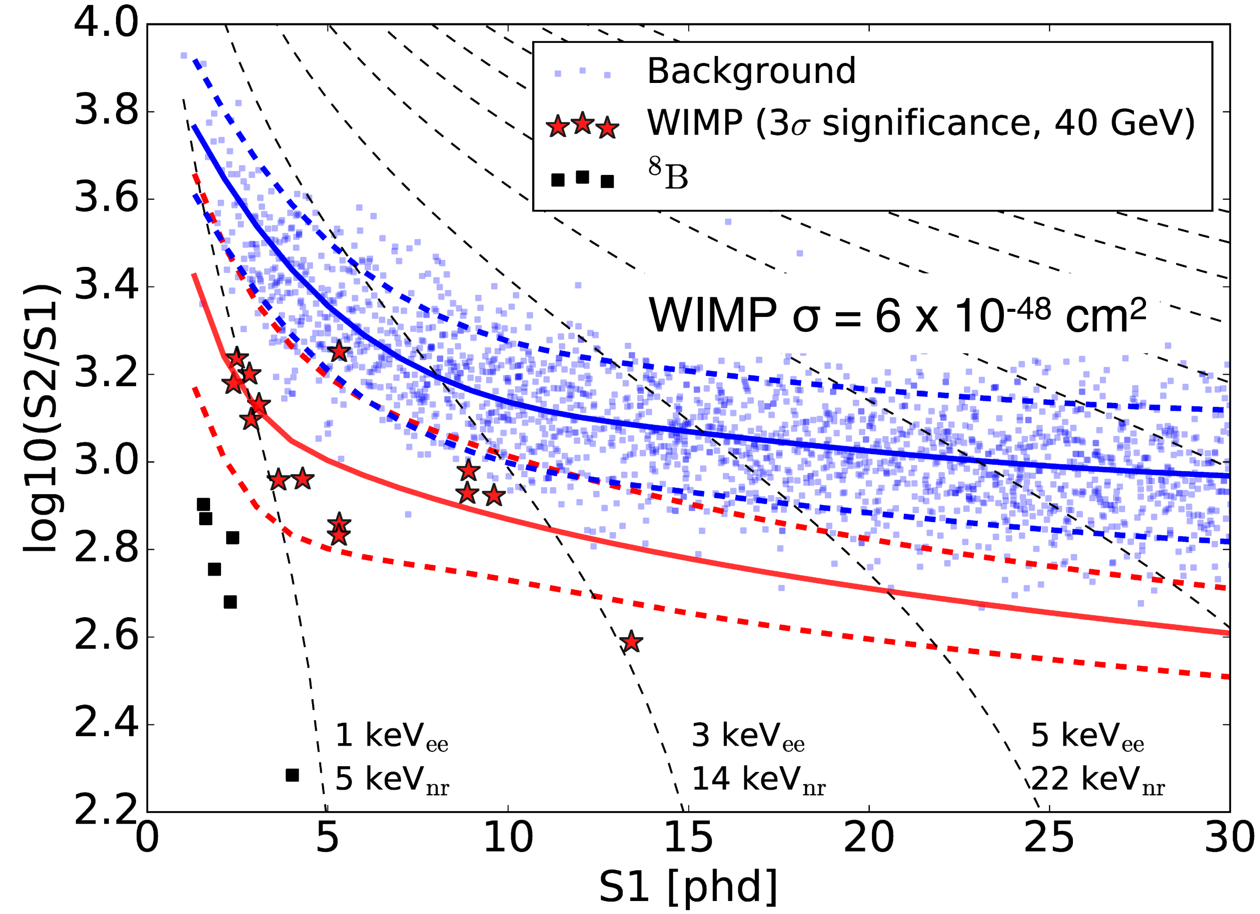
Signal and background

Advanced analysis procedure PDFs for PLR

Signal and background models distributions



Simulated LZ experiment (1000 days, 5.6 tonnes fiducial)

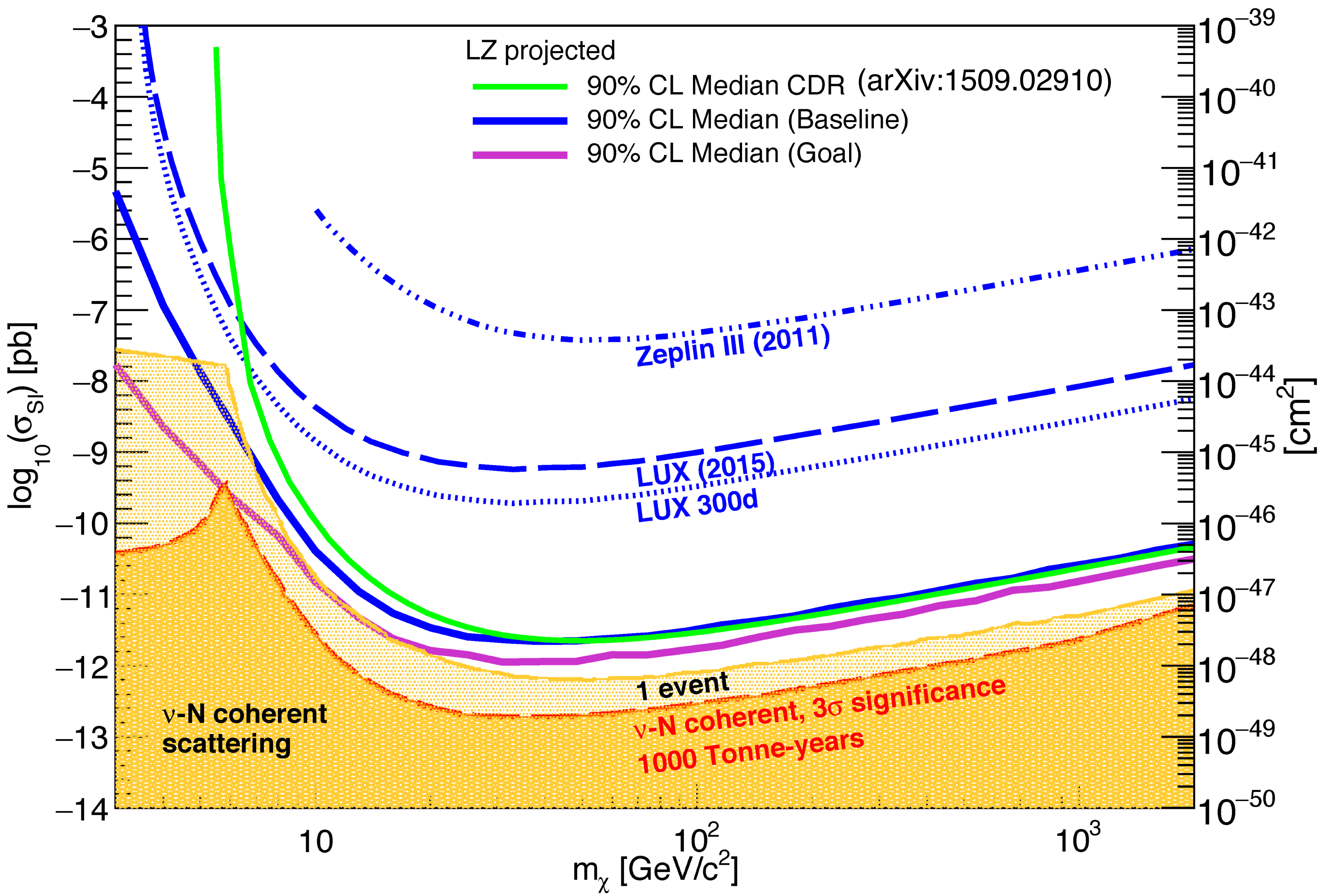


Projected sensitivity

Simulated LZ experiment (1000 days, 5.6 tonnes fiducial)

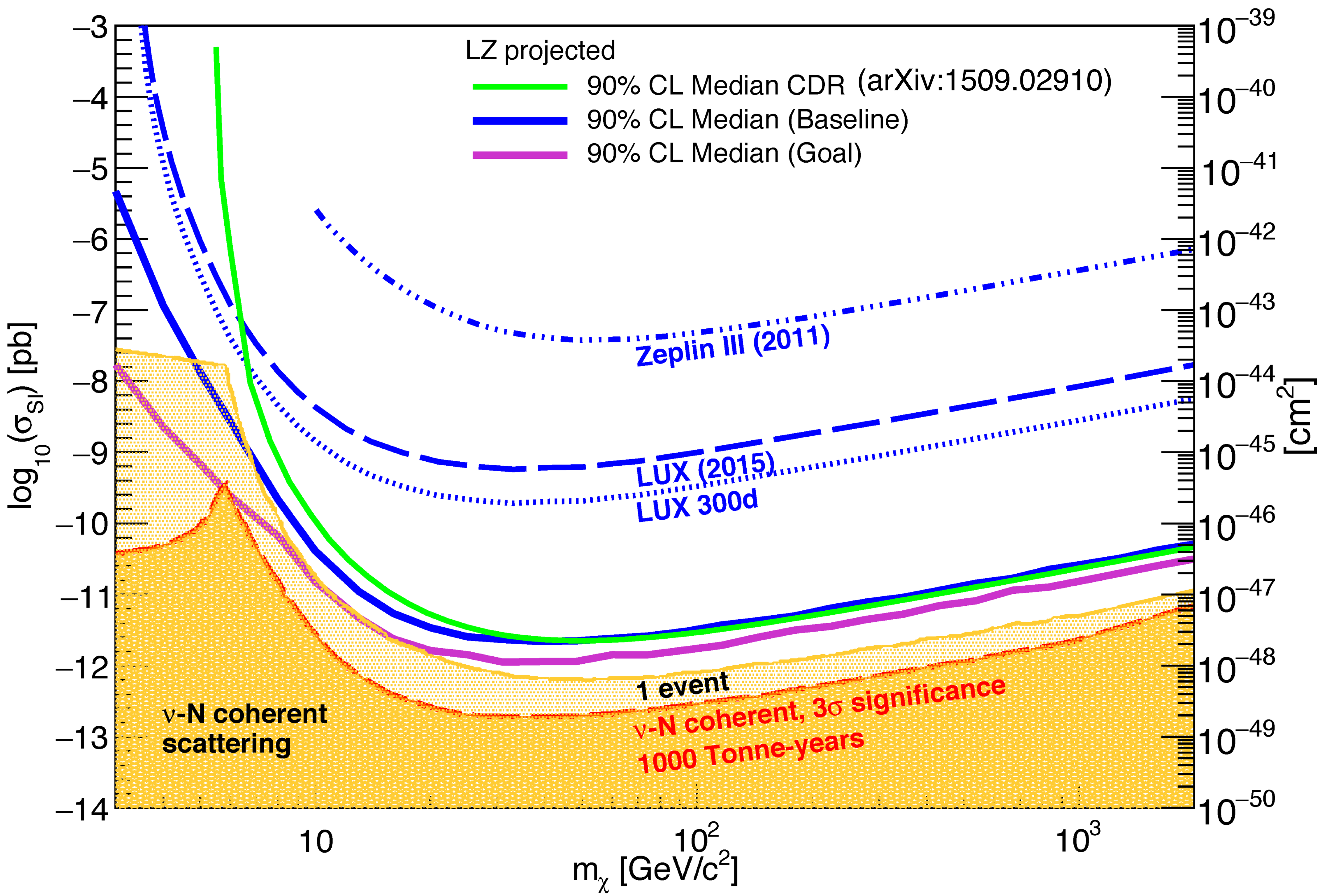
Baseline
σ_{SI} = 2.2 x 10^{-48} cm²
B-8 = 7
ATM ν = 0.4

Goal
σ_{SI} = 1.2 x 10^{-48} cm²
B-8 = 220
ATM ν = 3



Projected sensitivity

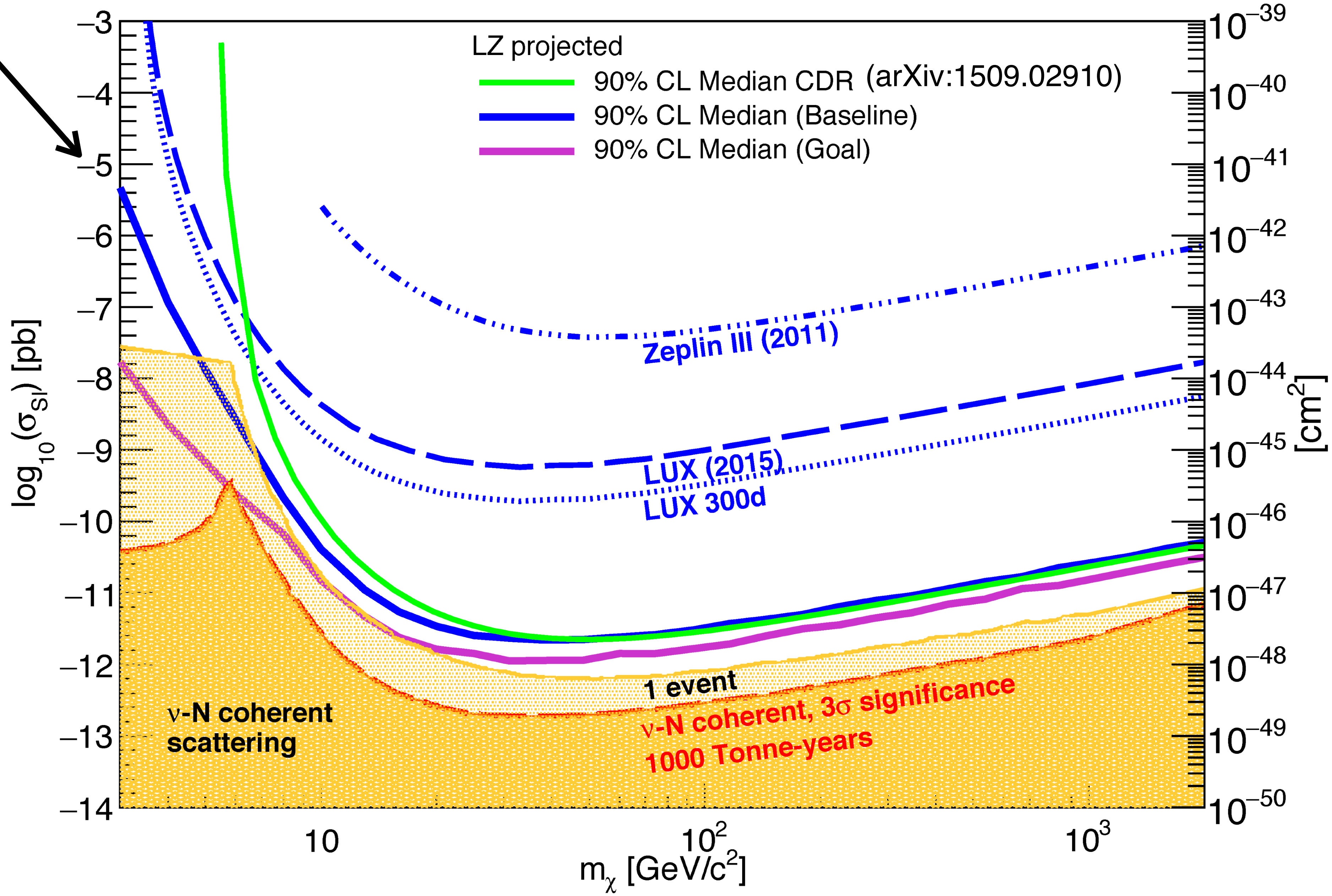
Simulated LZ experiment (1000 days, 5.6 tonnes fiducial)



Projected sensitivity

Simulated LZ experiment (1000 days, 5.6 tonnes fiducial)

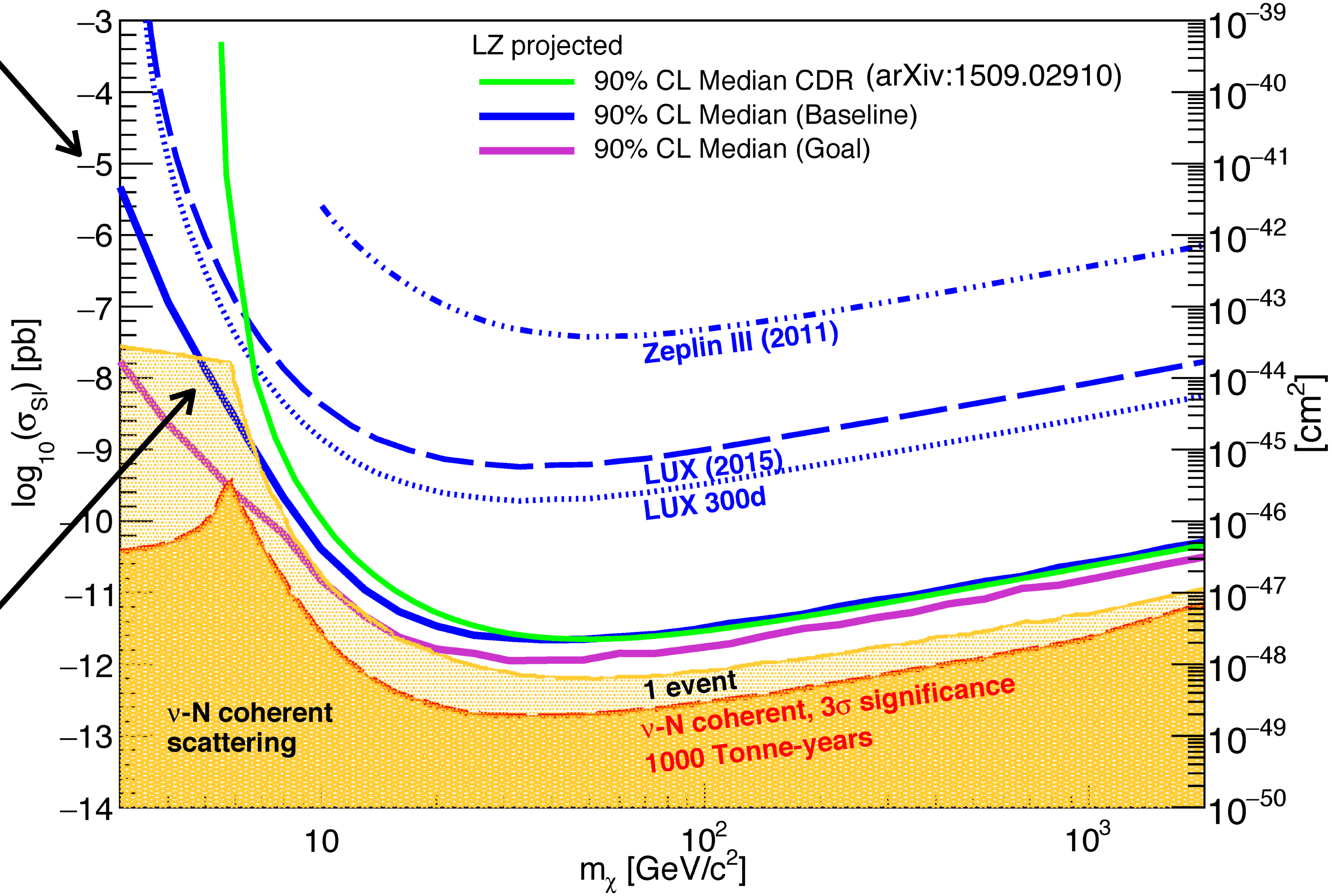
Lower threshold.
No 3 keVnr cutoff.
Updated Xe response from LUX



Projected sensitivity

Simulated LZ experiment (1000 days, 5.6 tonnes fiducial)

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

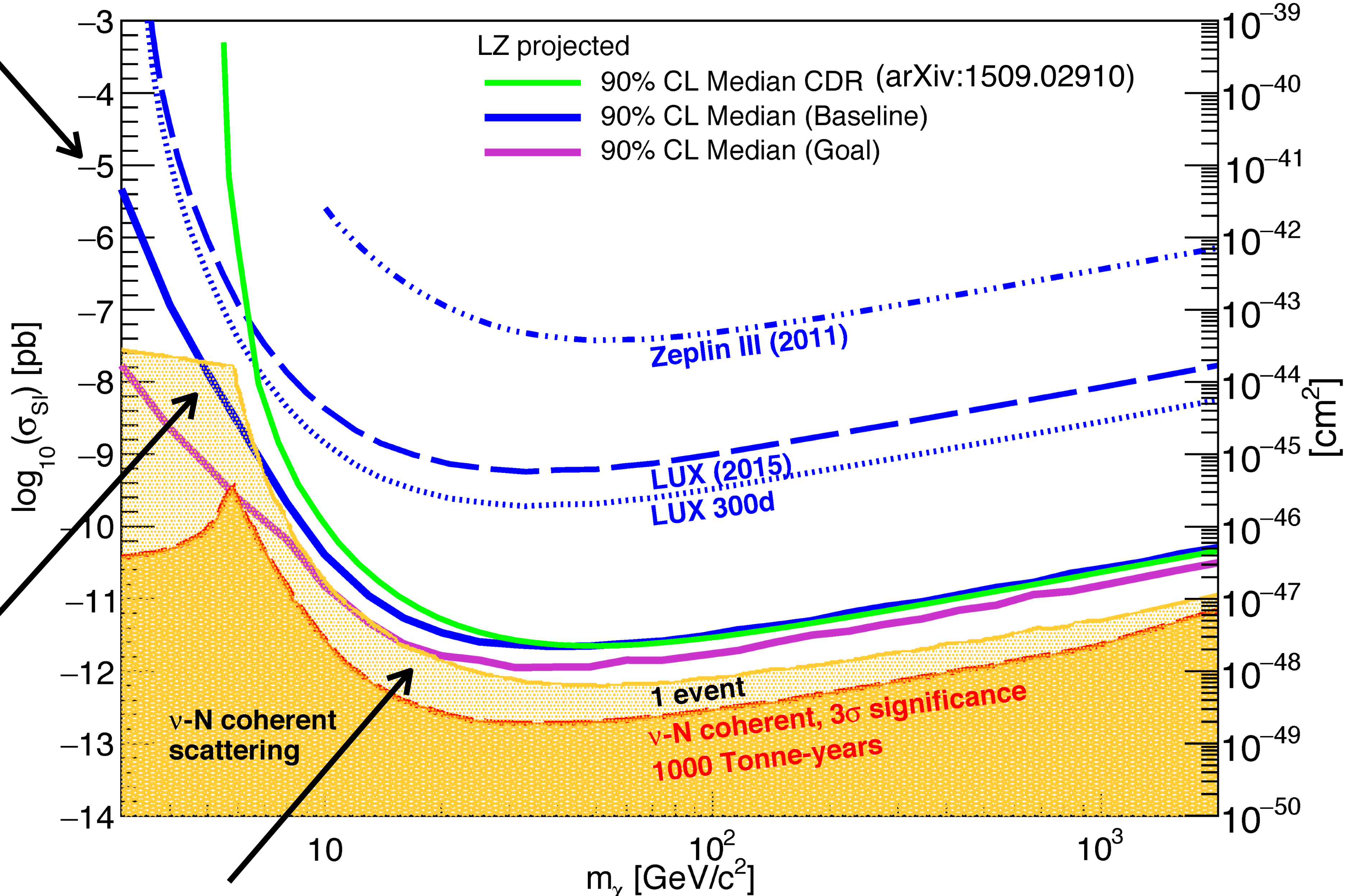


B-8 ~ 10 events

Projected sensitivity

Simulated LZ experiment (1000 days, 5.6 tonnes fiducial)

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



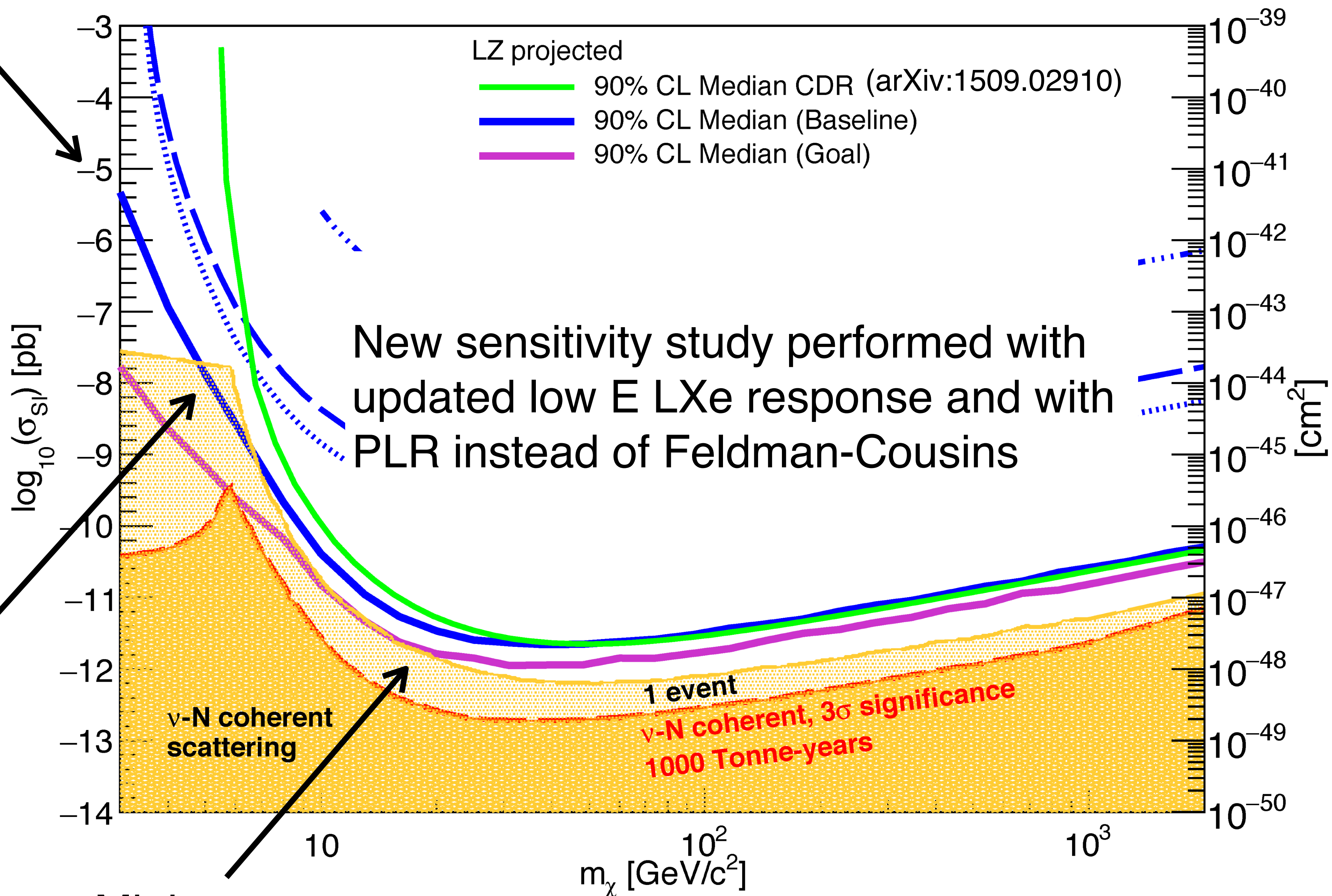
B-8 ~ 10 events

Minimum at 40 GeV/c²

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

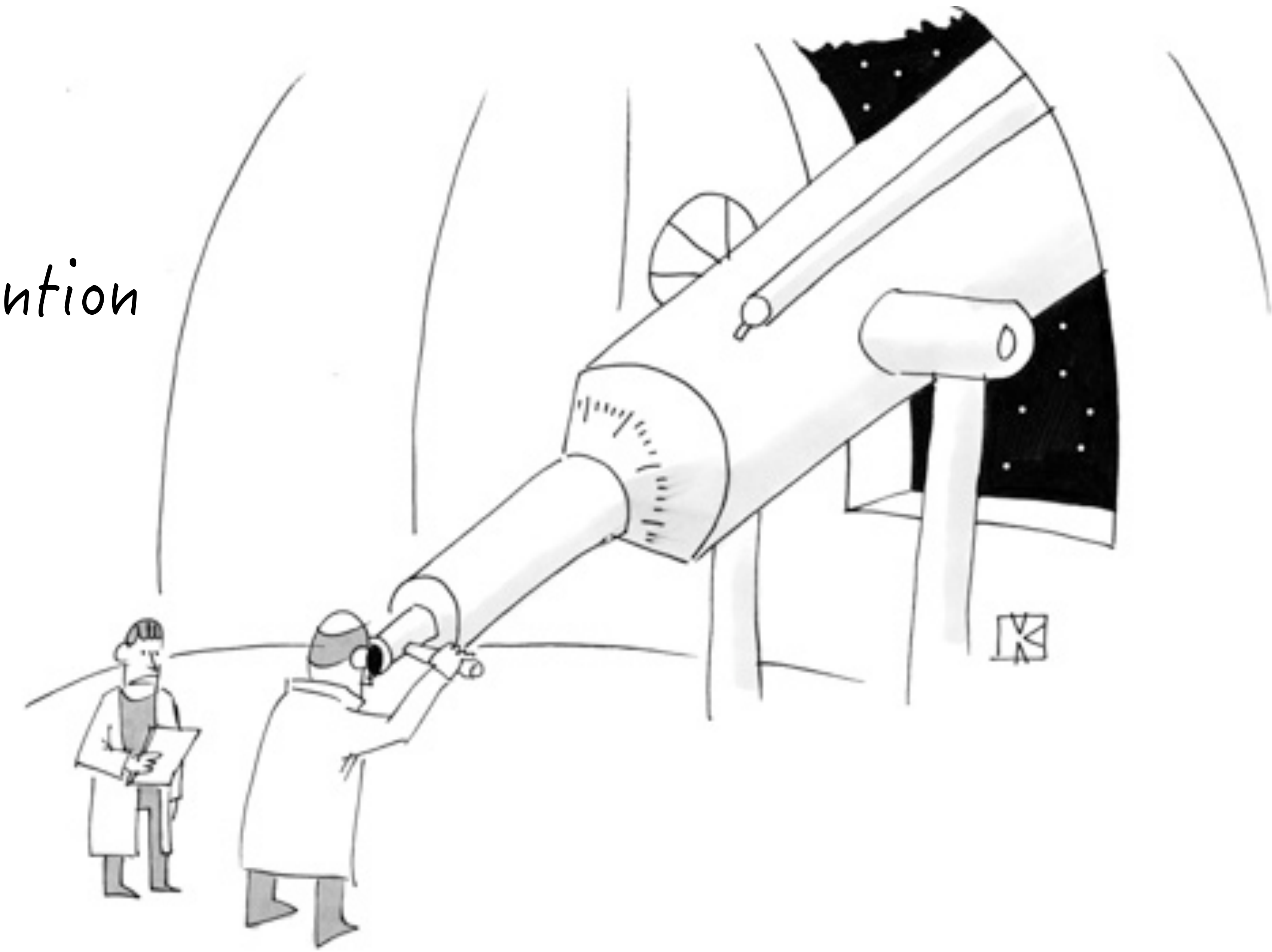
Minimum at 40 GeV/c²

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 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

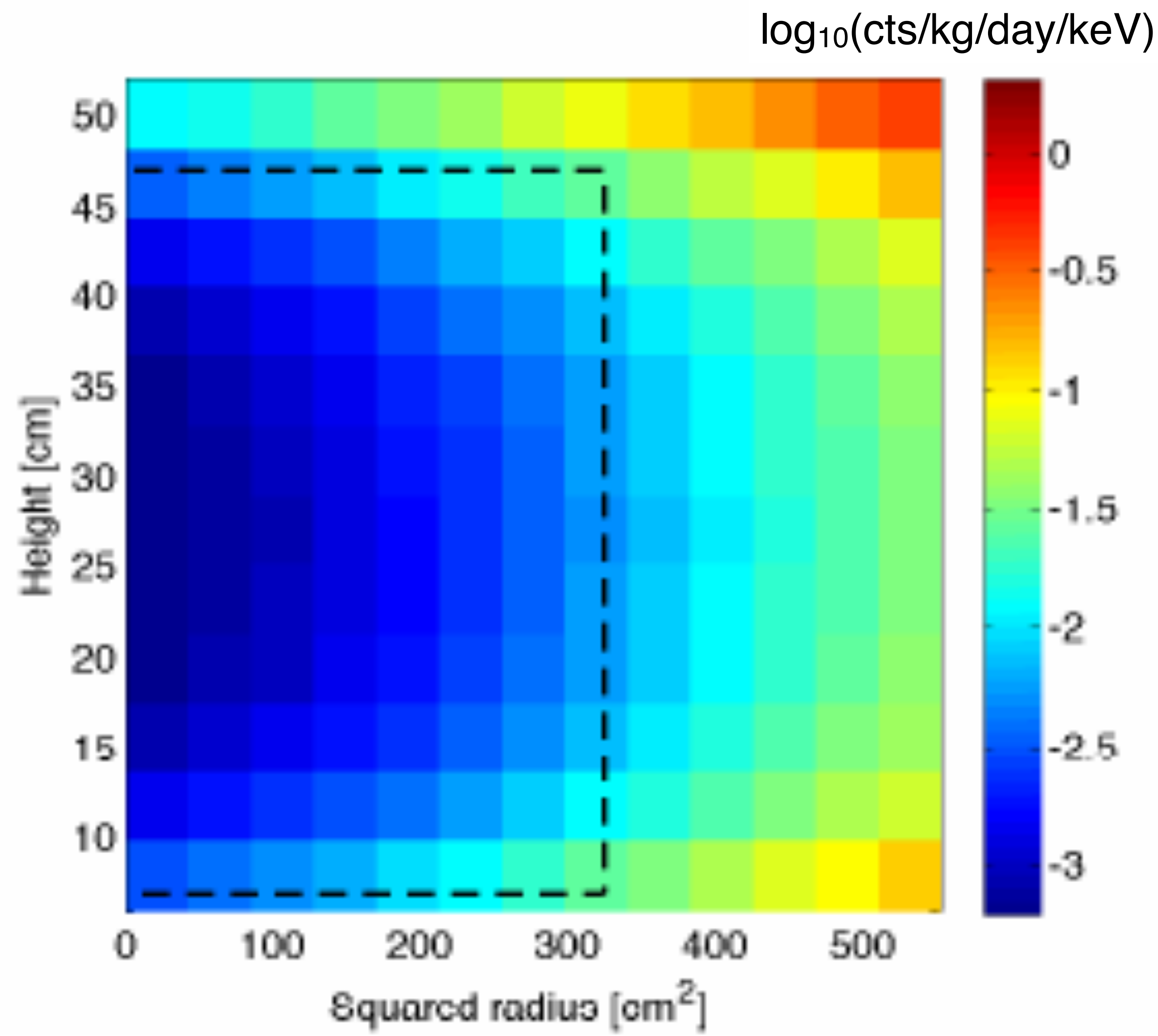
No long-lived radio-isotopes
=> useful in calibration

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

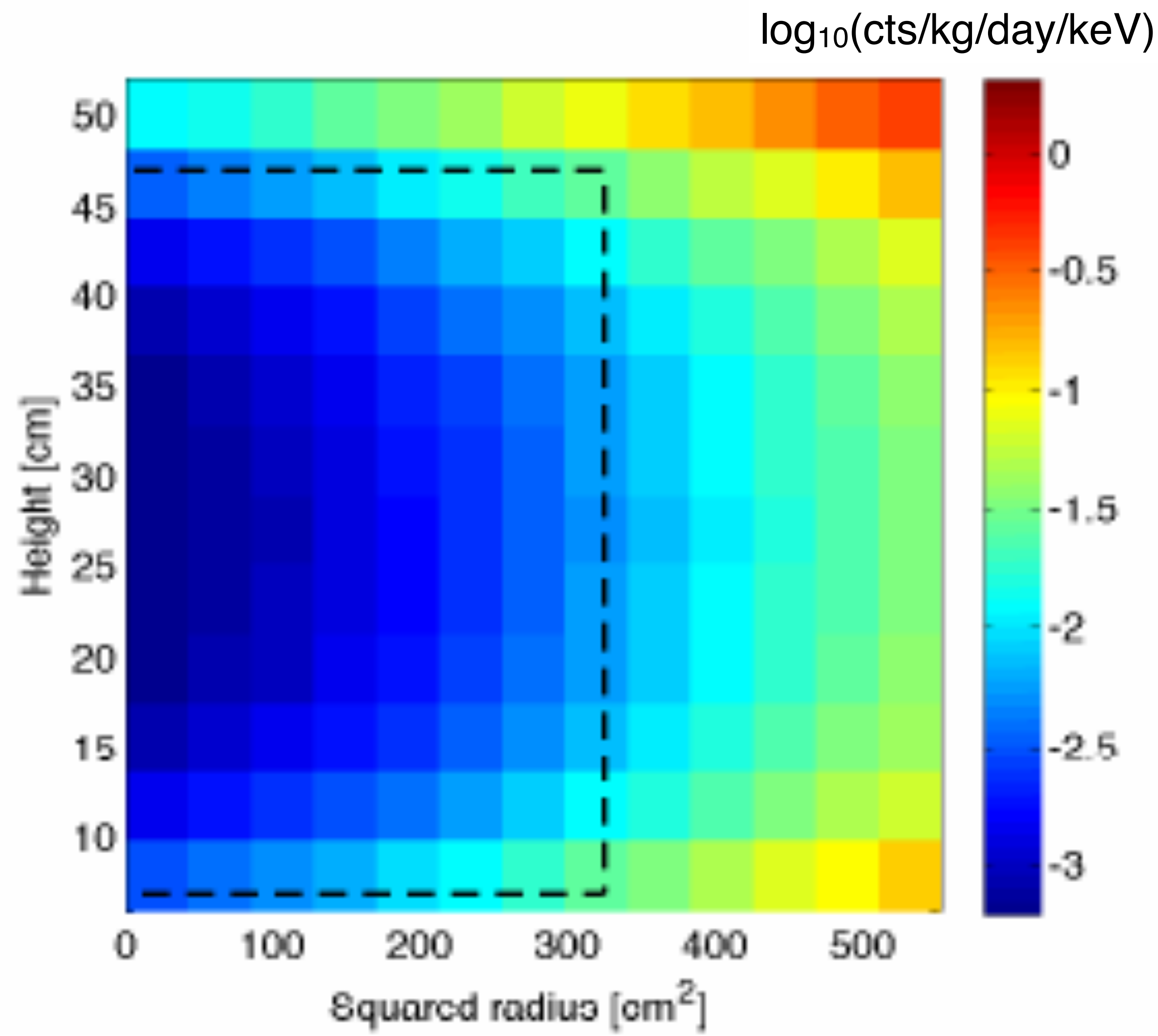
No long-lived radio-isotopes
=> useful in calibration

High density (~ 3 g/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

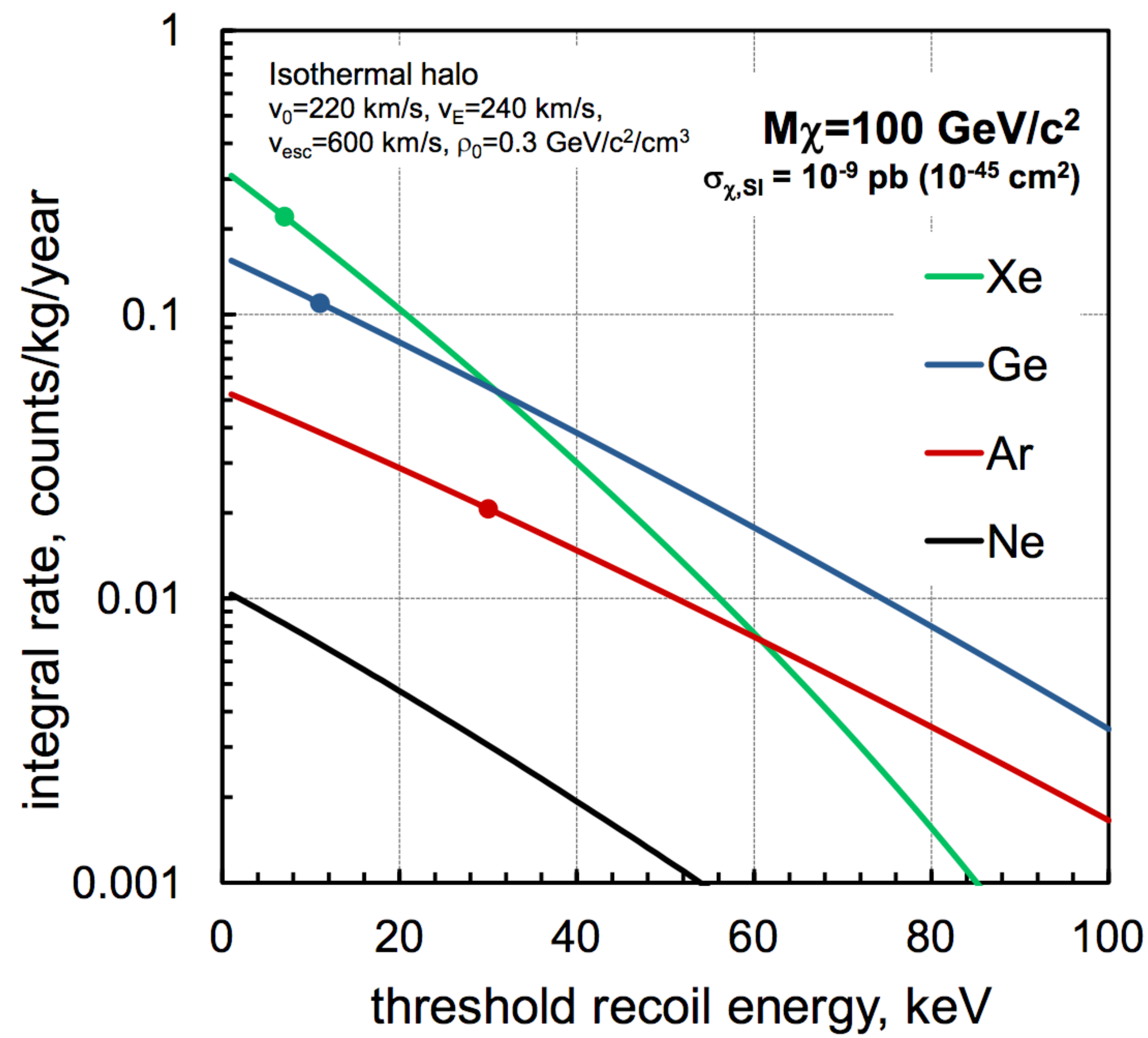
No long-lived radio-isotopes
=> useful in calibration

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

Long electron drift lengths (few m)
=> scalable

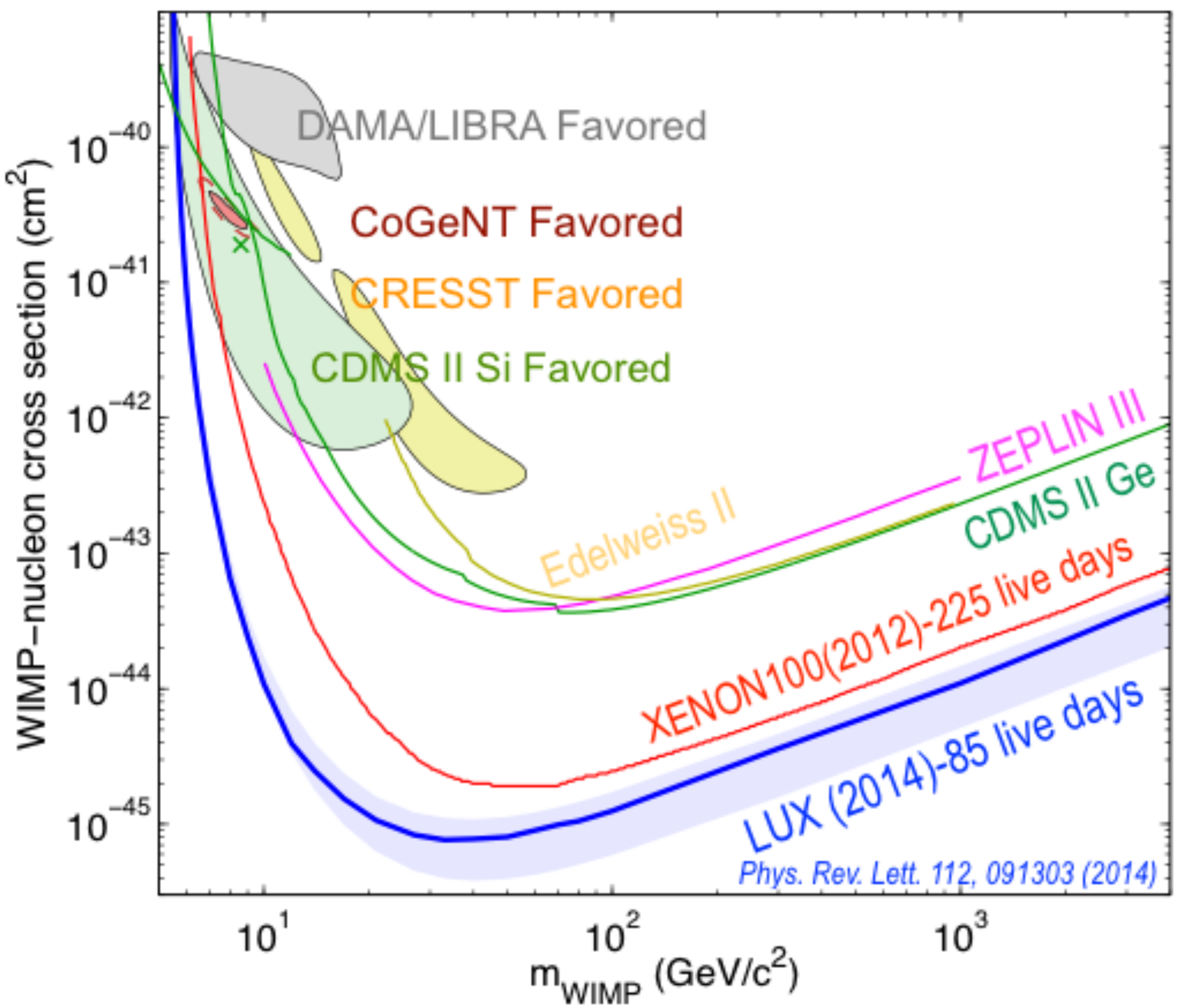
Efficient scintillator

Higher sensitivity in the 2 - 25 keV energy deposit range



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
- $(99.6 \pm 0.1)\%$ ER rejection at 50% signal acceptance (180 V/cm)
- 160 events observed in data after selection cuts

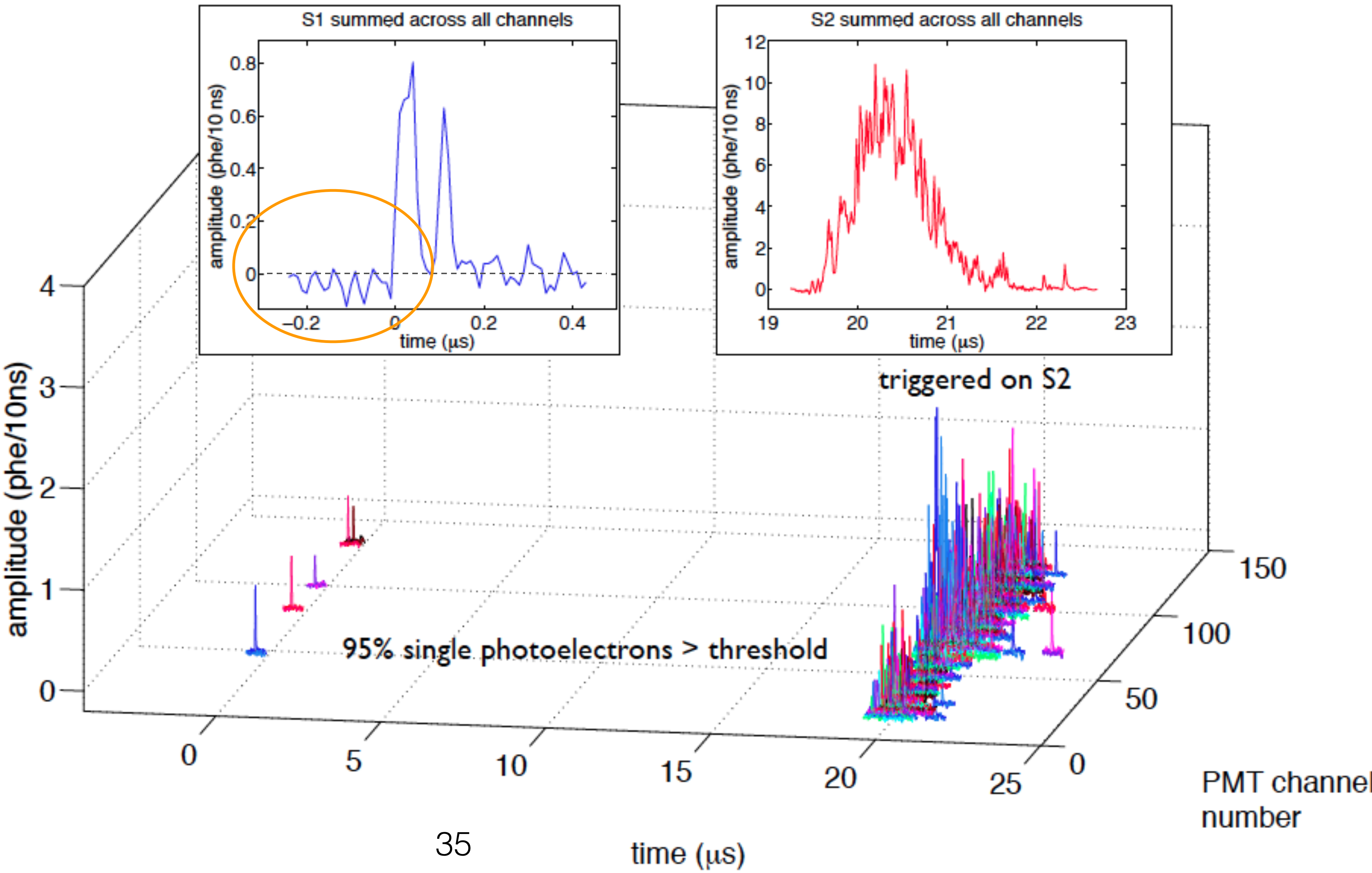
Analysis 4-parameter profile likelihood, p-value of 35% consistent with backgrounds

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

Measuring light

Better estimators for detected photons

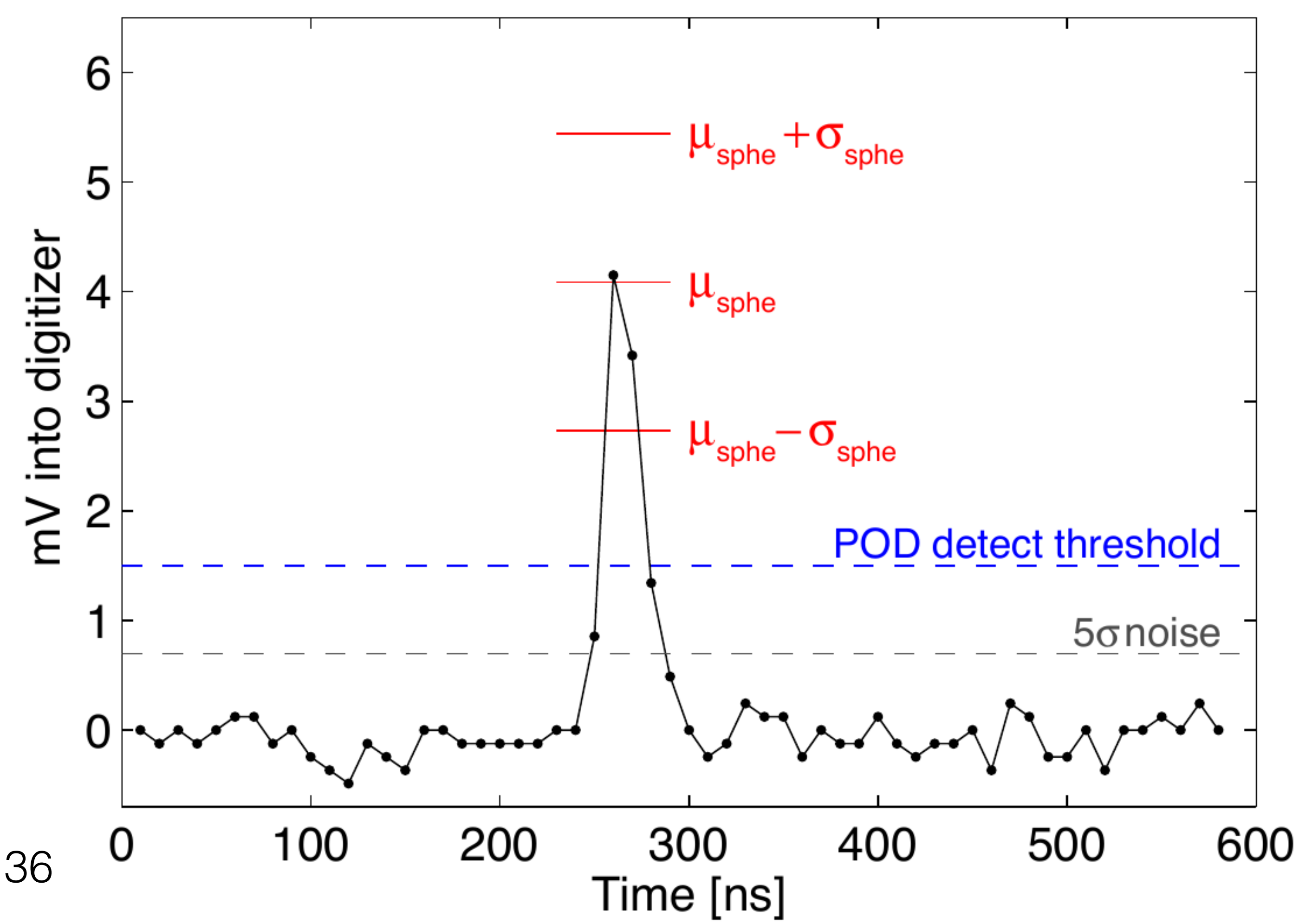
1. Removed a bias in baselines



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

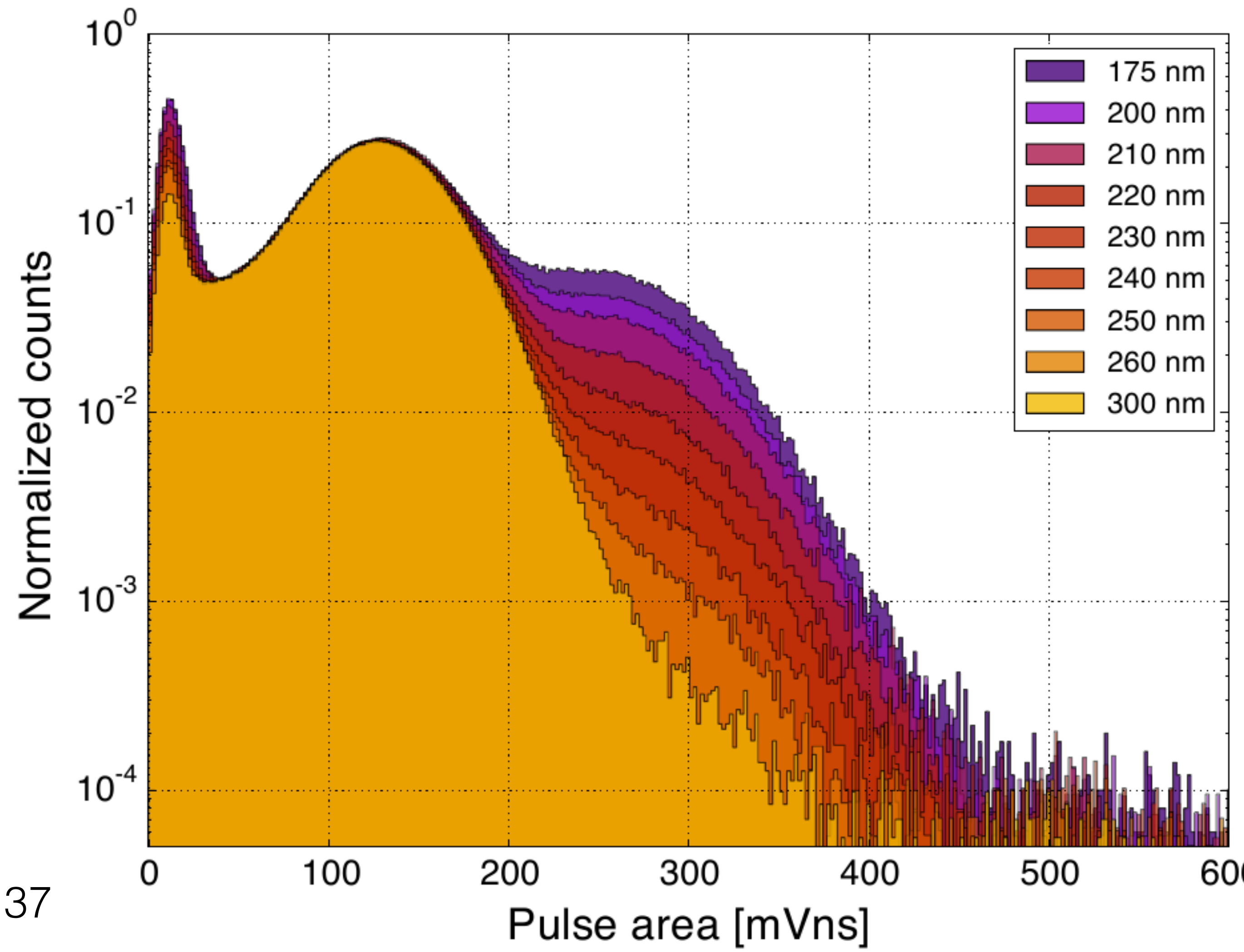


Measuring light

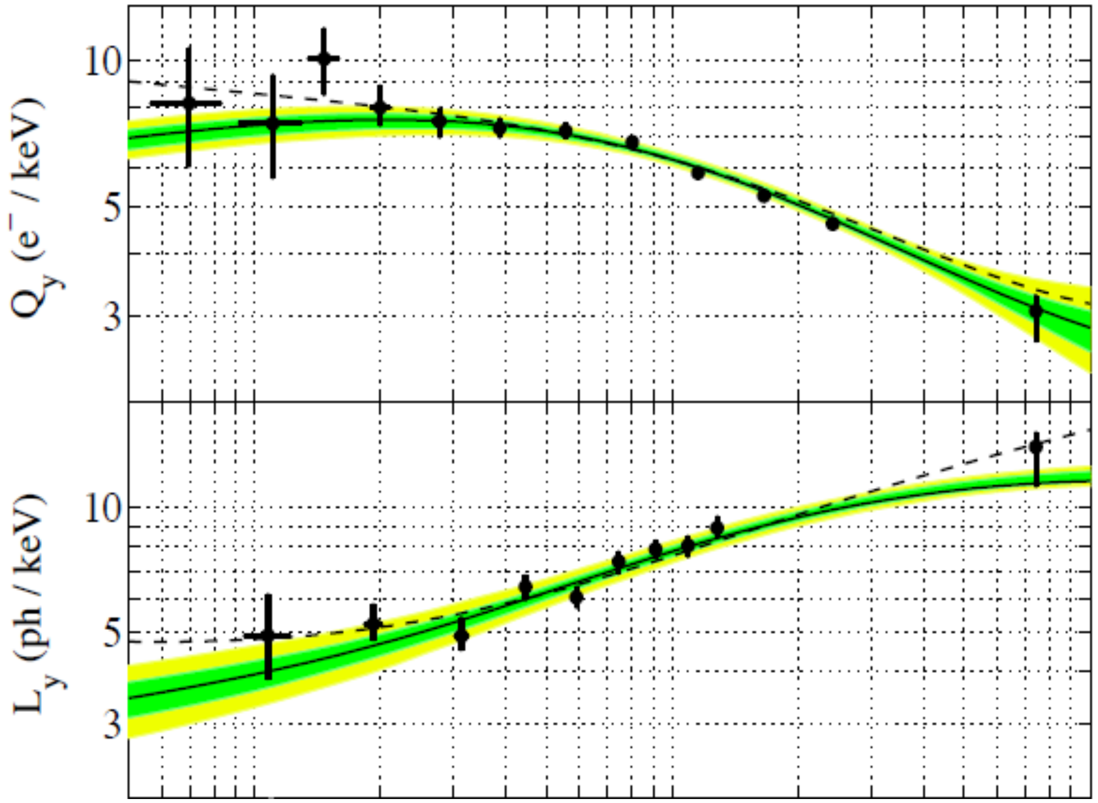
Better estimators for detected photons

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



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

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

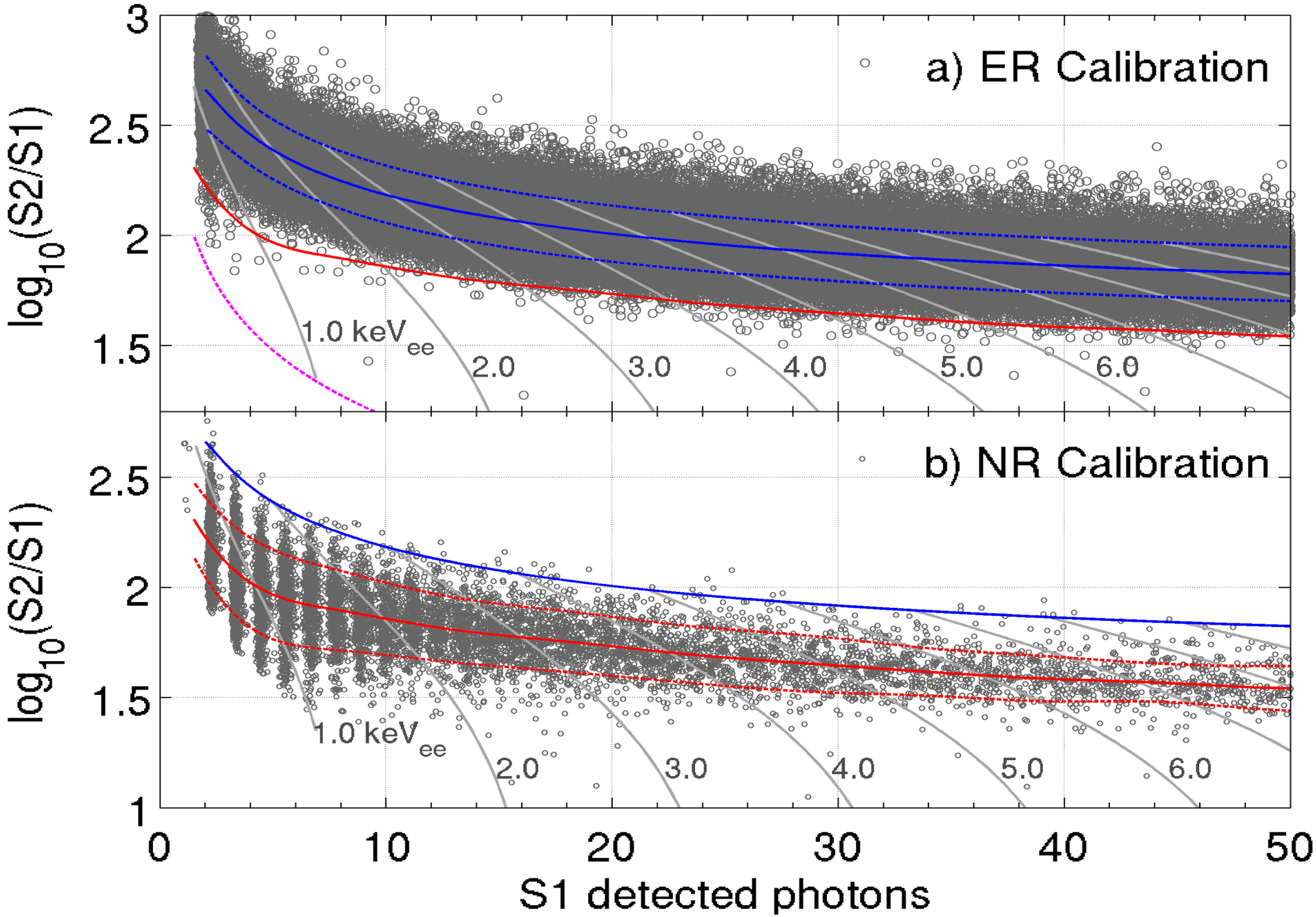
$$r = 1 - \frac{ln(1 + \text{TIB } N_i)}{\text{TIB } N_i}$$

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

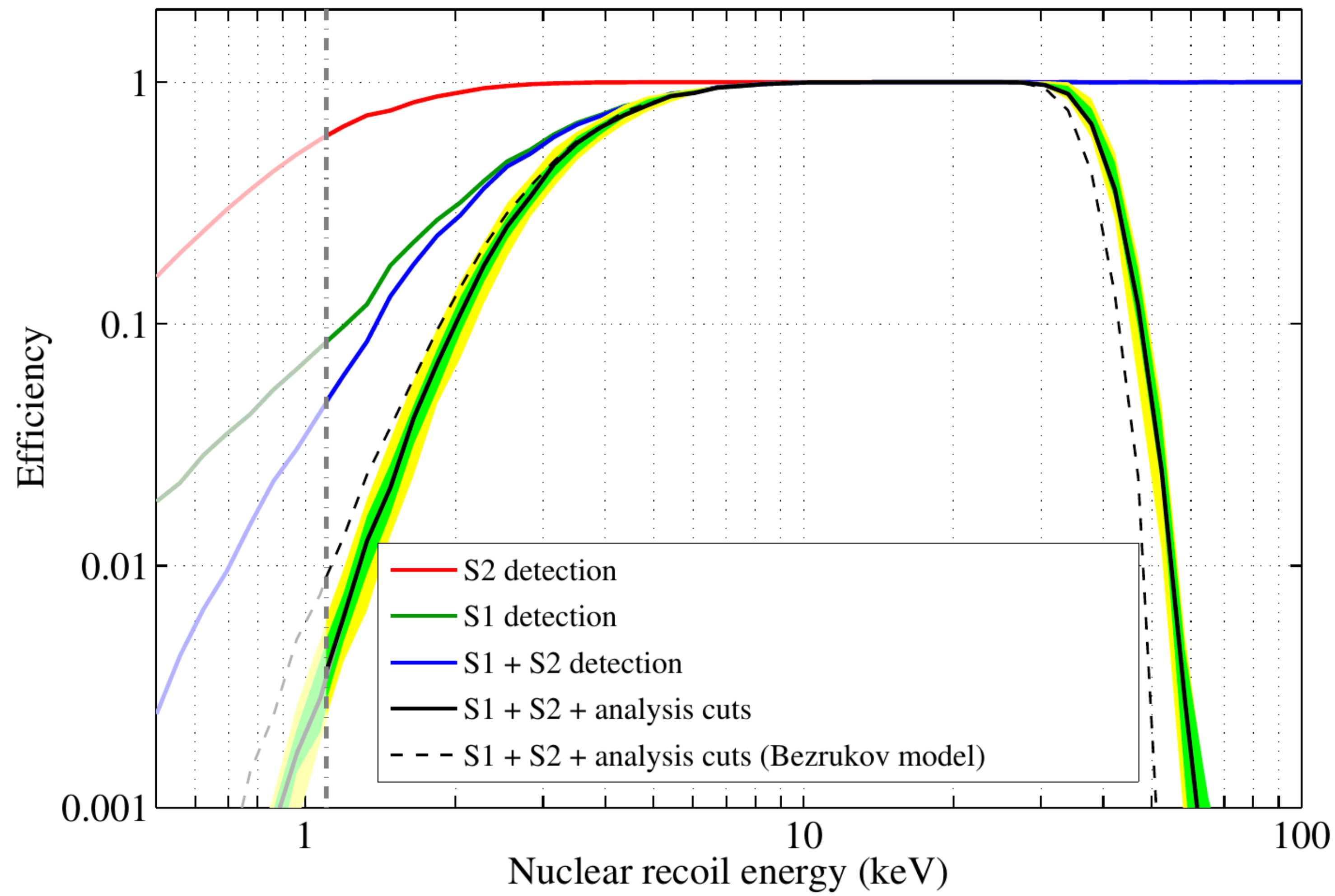
- NEST simulation package parameter best fit to DD-data in both charge and light yields
- Given g_1 and g_2, determine the *L(θ / E)*. θ are 5 Lindhard NR Parameters
- Implement full NEST simulation in the sensitivity calculation

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.

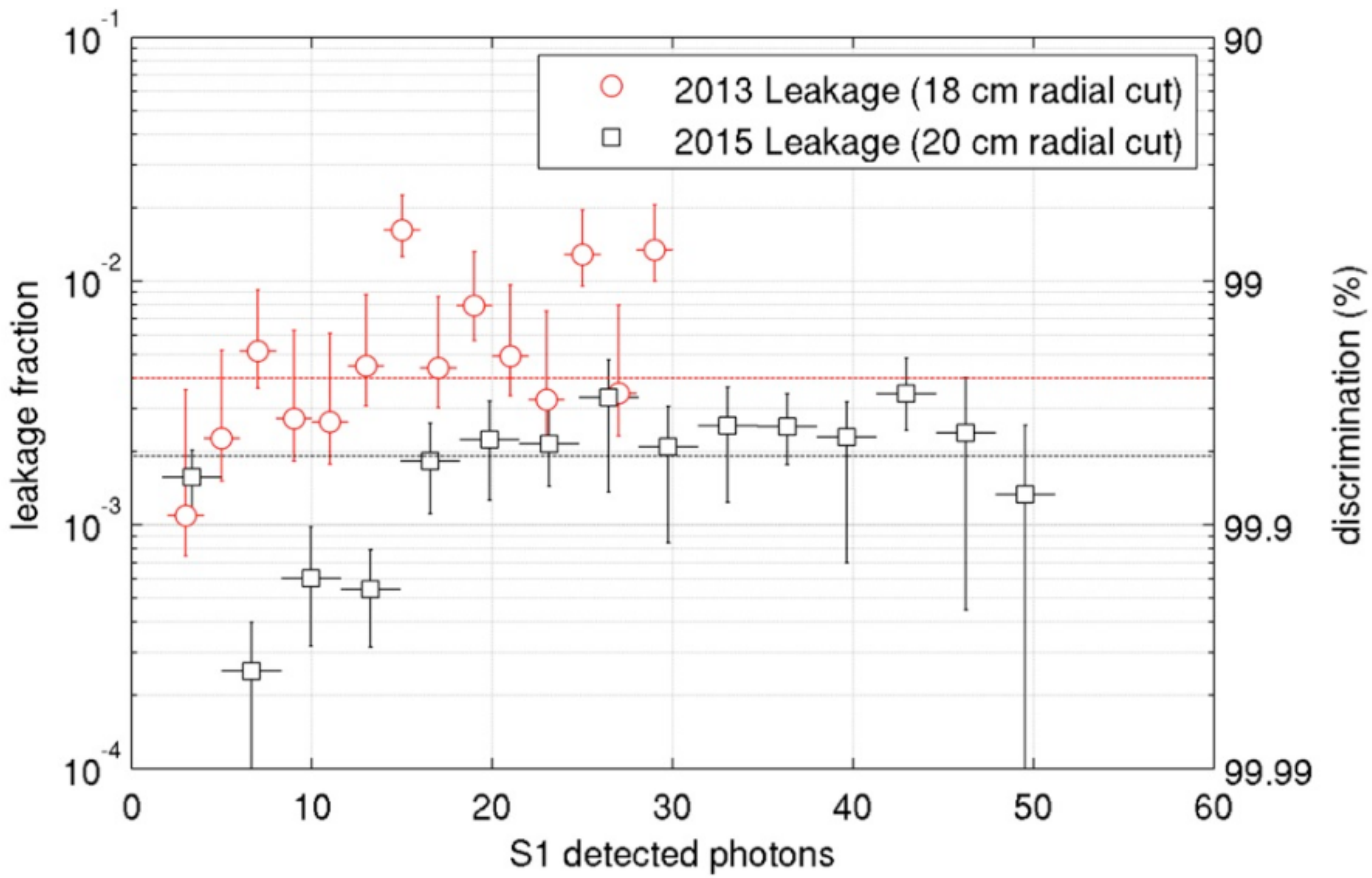
Bezrukov an alternative to the Lindhard model of NR energy loss to electrons.

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

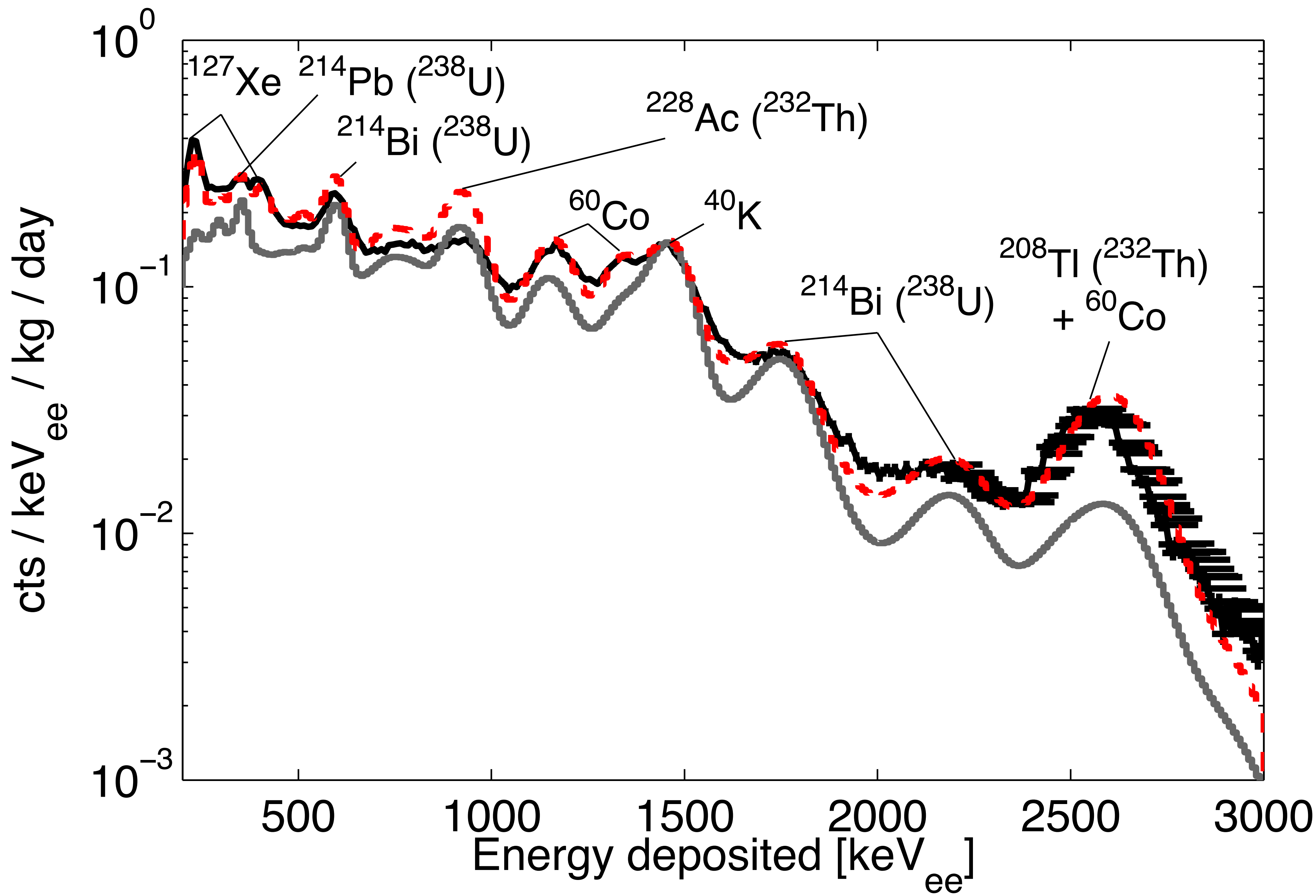
Background Rejection

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

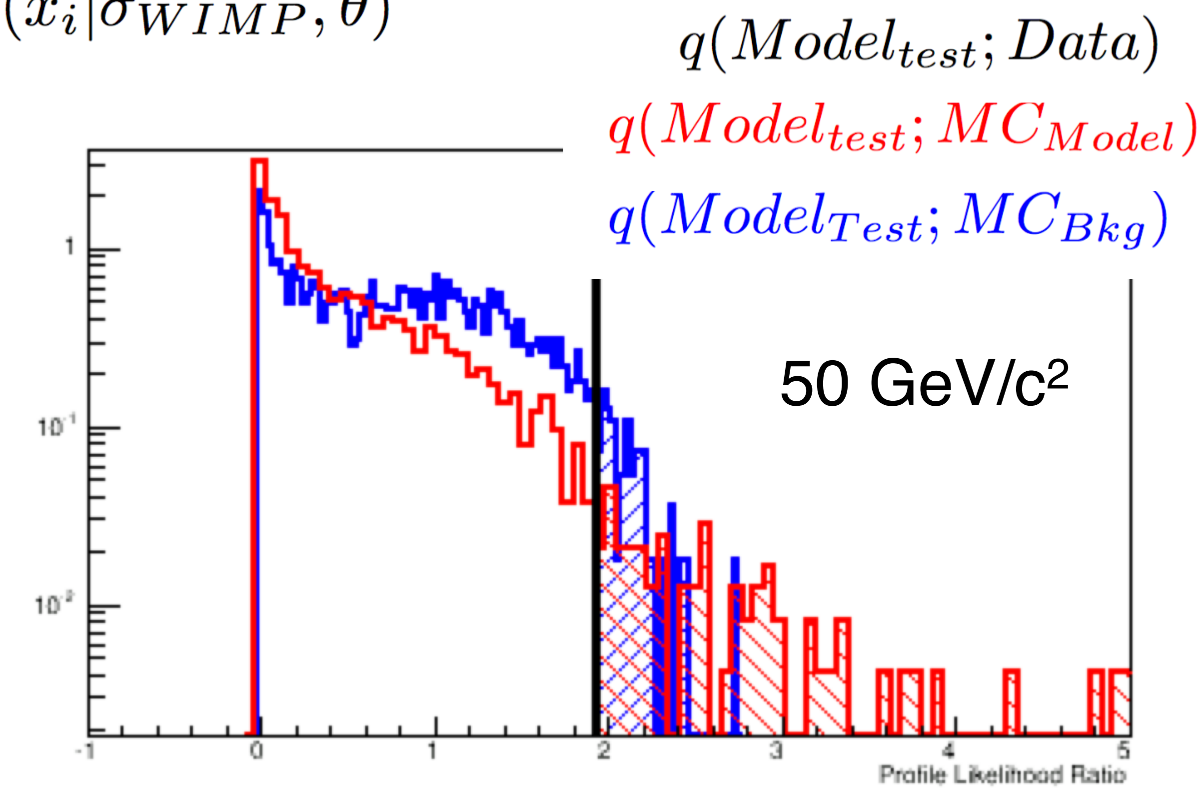
$$L(\sigma_{WIMP}, \theta; x) = P(x; \sigma_{WIMP}, \theta) = \prod_{i=1}^{n} P(x_i | \sigma_{WIMP}, \theta)$$

$$x = \{S1, log(S2), r, z\}$$

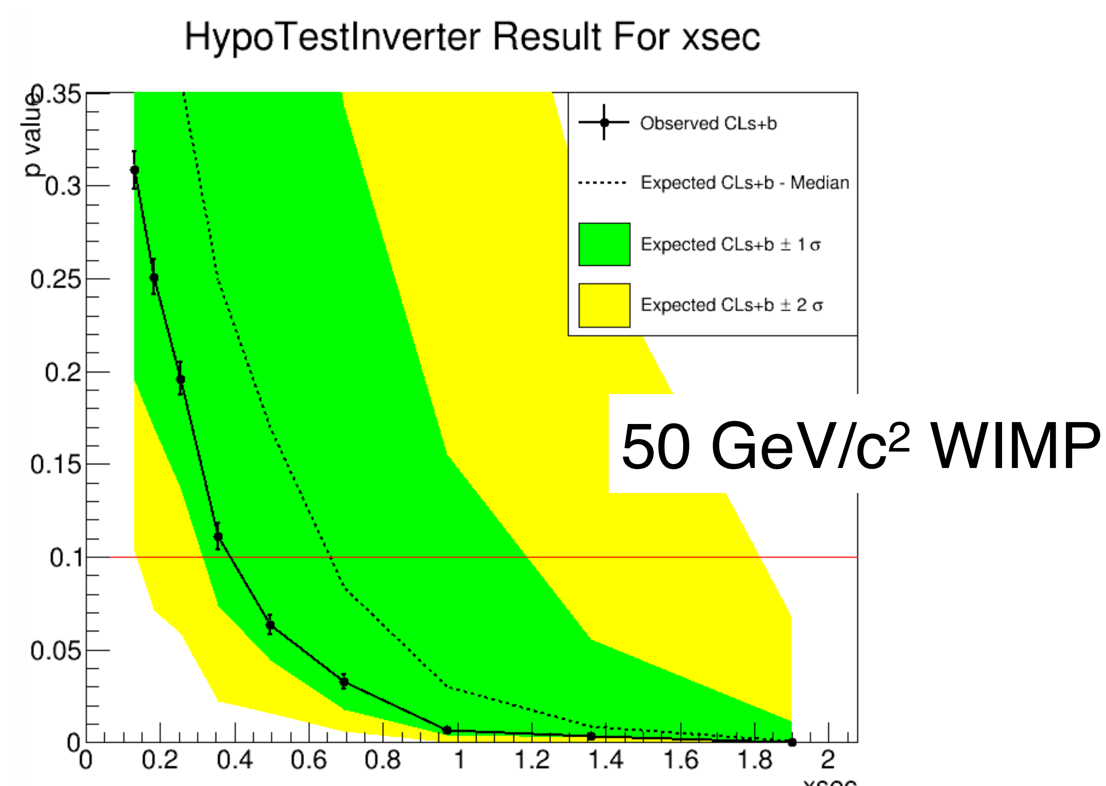
$$\theta = \{N_{bkg}, \nu_{signal}\}$$

$$\lambda = \frac{L(\sigma_{WIMP}^{Test}, \theta; x)}{L(\sigma_{WIMP}, \theta'; x)}$$

$$q = -2ln(\lambda)$$



- Fraction of Bkg.+Sig. MC above th 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

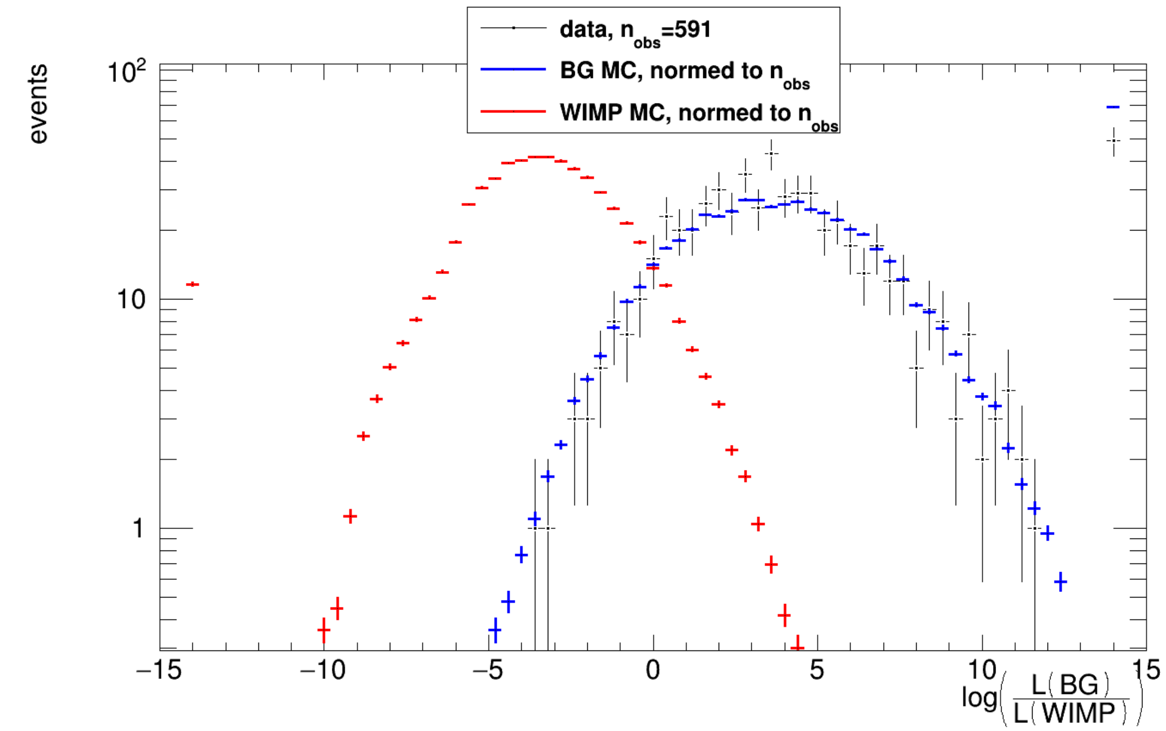
Multivariate background rejection, per-event discriminant.

Limit is un-binned PLR with 4 observables.

Nuisance parameters:

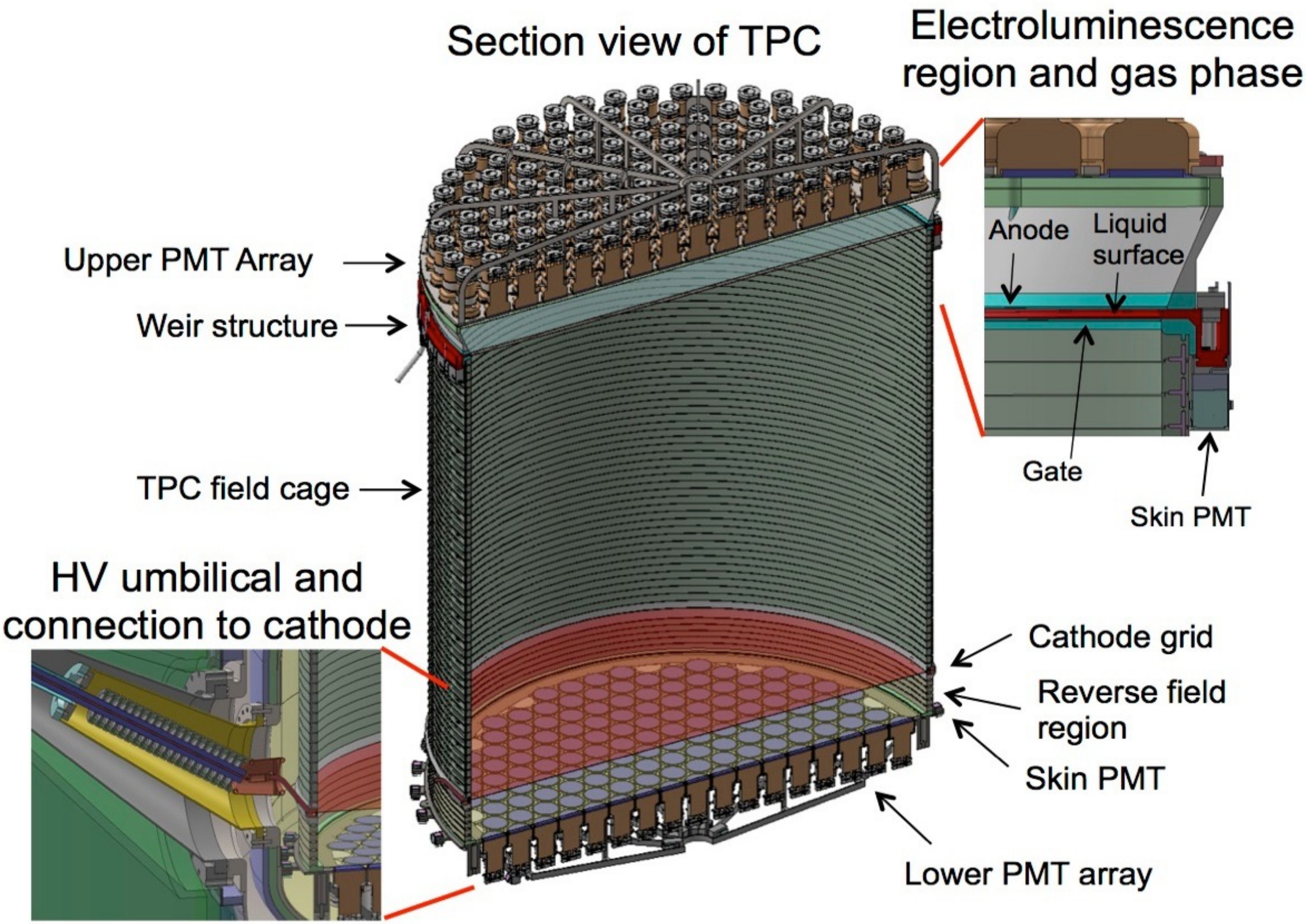
- background population normalisation
- WIMP PDF & efficiency.

Power constraint at median background-only limit.



Parameter	Constraint	Fit value
Lindhard k	0.174 ± 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

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 x 10^{26} years
- Enriching the Xe target could increase this to ~ 2 x 10^{27} years
- Current limit is 2.6 x 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 x 10^{-12} Bohr magnetons.