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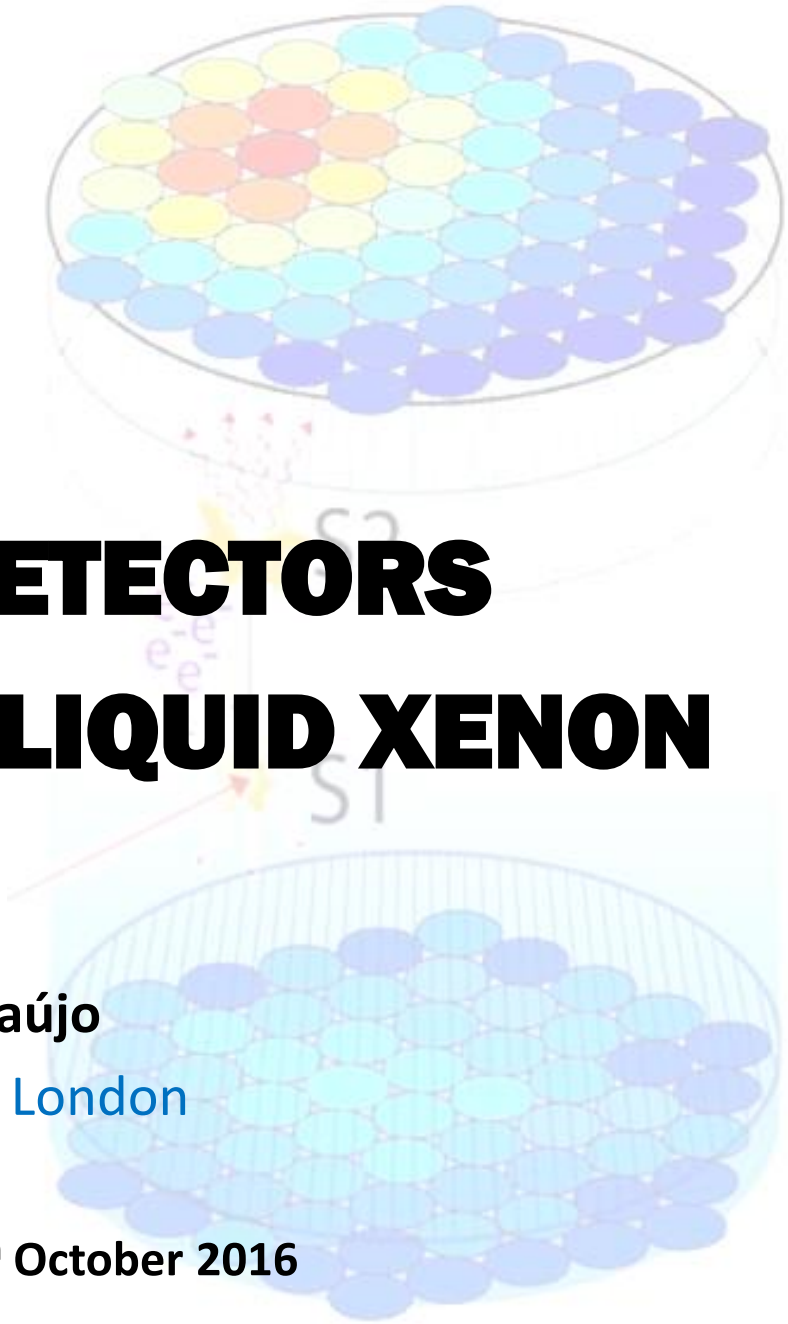


TWO-PHASE DETECTORS USING THE NOBLE LIQUID XENON

Henrique Araújo

Imperial College London

Oxford University – 18th October 2016

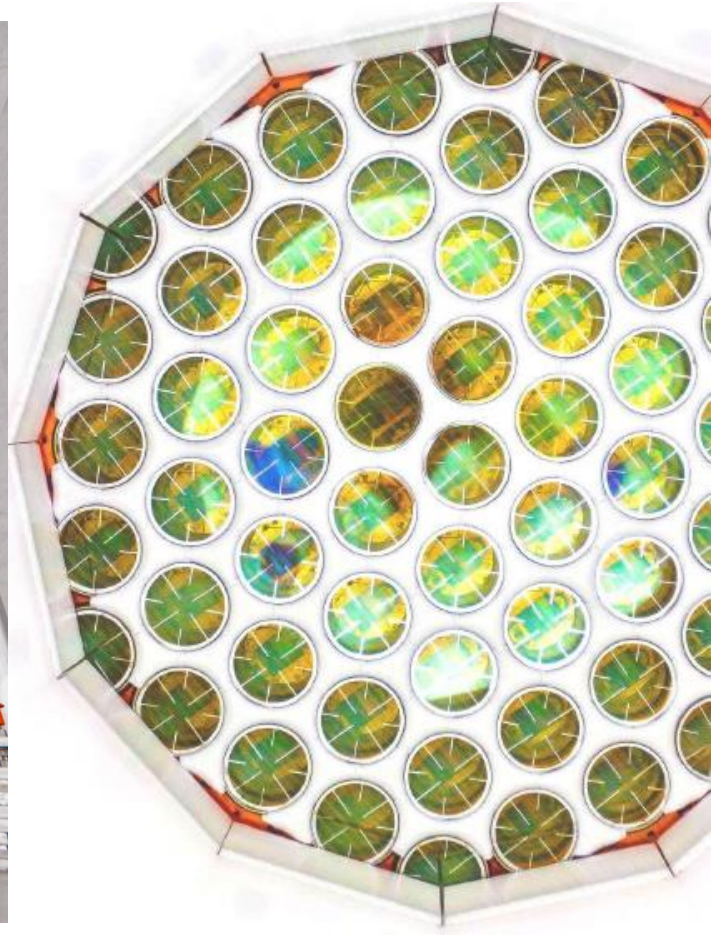
OUTLINE

- Two-phase xenon for (dark) radiation detection
  - Instrumenting a liquid xenon target
- Liquid xenon response(s) to radiation
  - Physics underlying the detector response

THE LUX EXPERIMENT

Relevant recent papers:
arXiv:1512.03133
arXiv:1608.05381
arXiv:1610.02076
arXiv:1608.07648

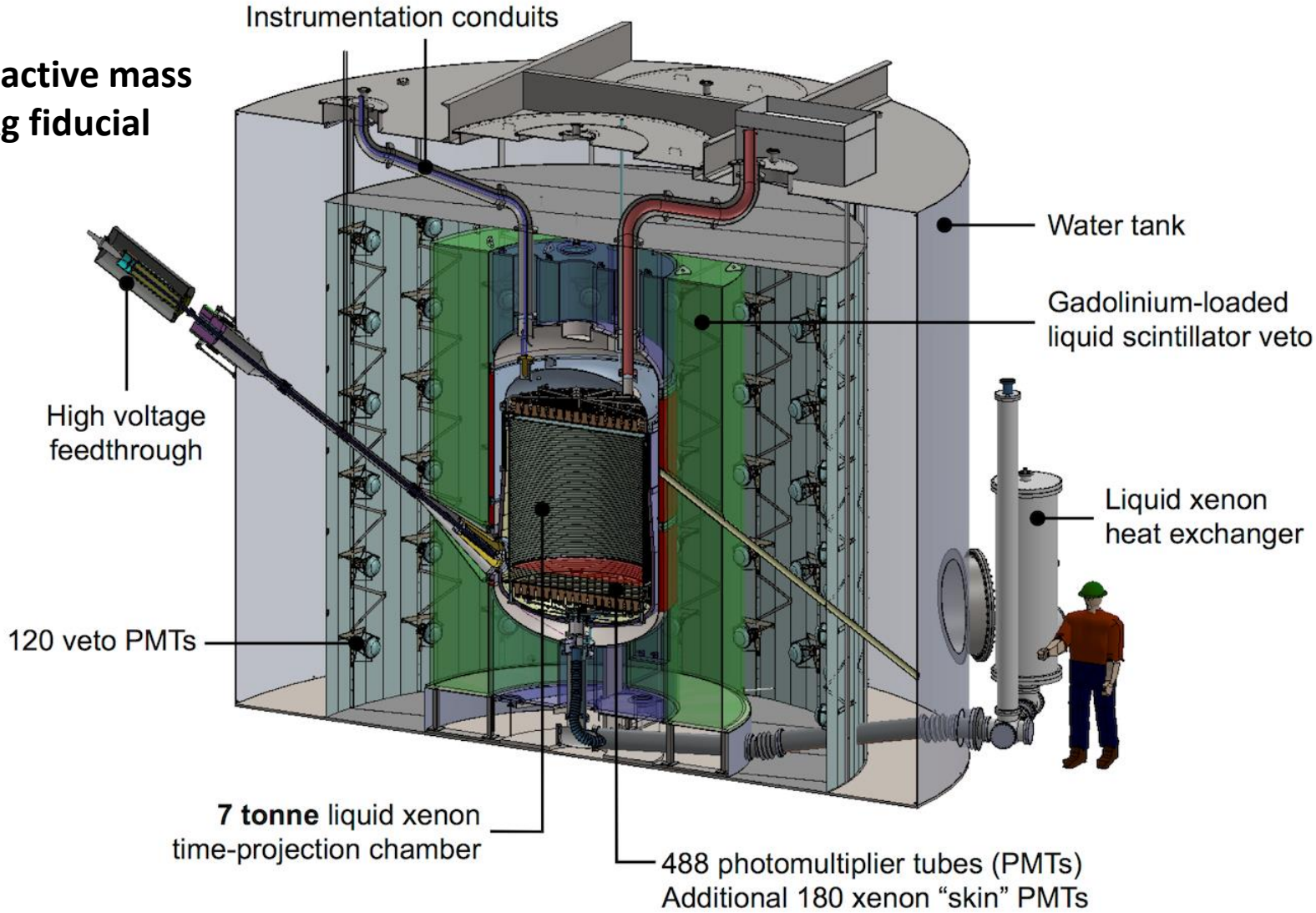
250 kg active mass
∼100 kg fiducial



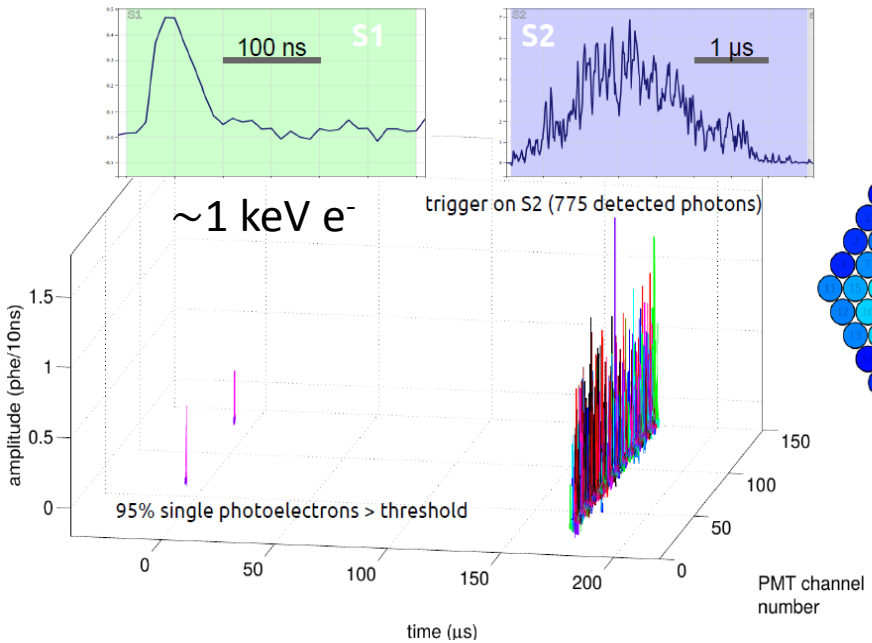
LUX-ZEPLIN (LZ)

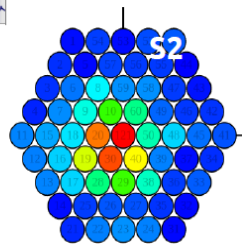
Conceptual Design Report
arXiv:1509.02910

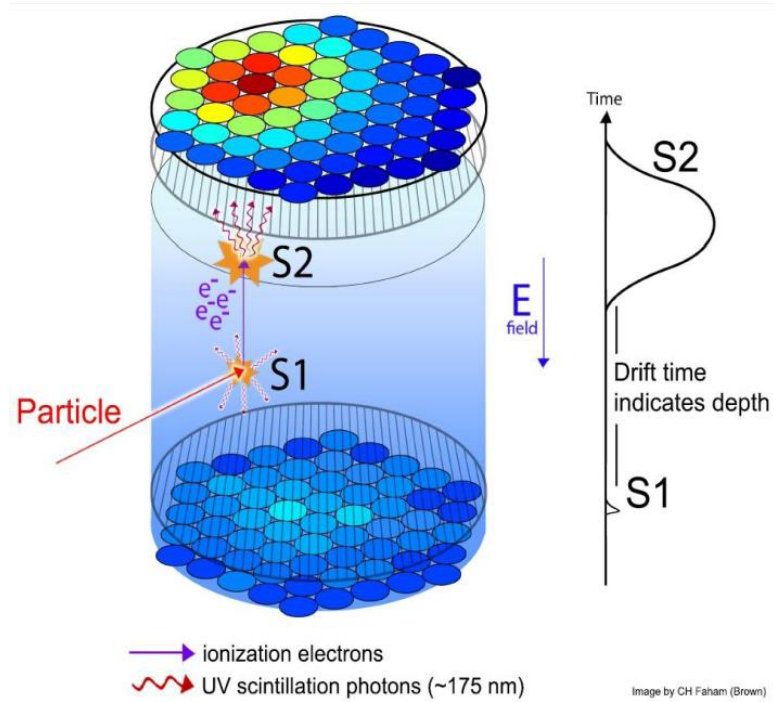
7,000 kg active mass
~5,600 kg fiducial

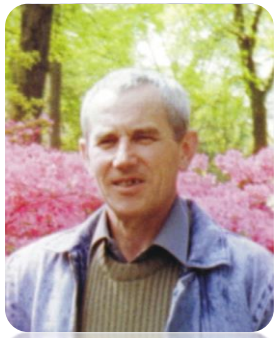


TWO-PHASE XE DETECTOR / LXe-TPC







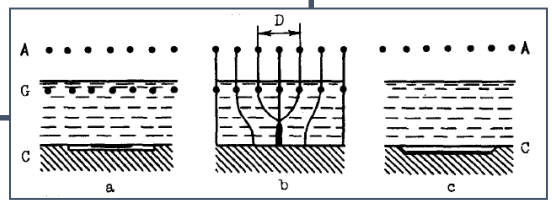


Vadim Lebedenko
1939 – 2008

JETP LETTERS VOLUME 11, NUMBER 11 5 JUNE 1970

NEW METHOD OF REGISTRATION OF IONIZING-PARTICLE TRACKS IN CONDENSED MATTER[1)]

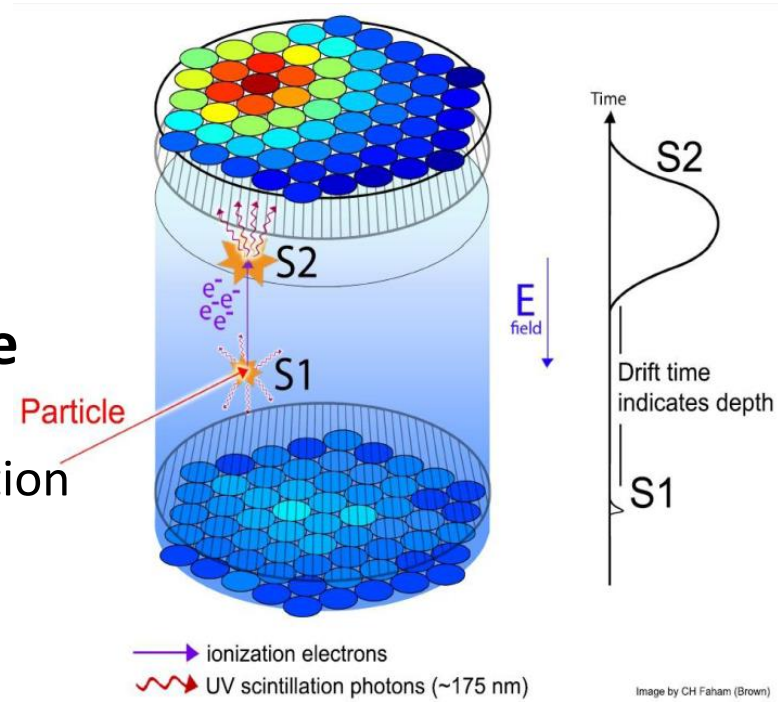
B.A. Dolgoshein, V.N. Lebedenko, and B.U. Rodionov
Moscow Engineering Physics Institute
Submitted 14 April 1970
ZhETF Pis. Red. 11, No. 11, 513 - 516 (5 June 1970)



TWO-PHASE XE DETECTOR / LXe-TPC

- **S1: Prompt scintillation**
  - Light yield: >60 ph/keV (0 field)
  - Scintillation light: 178 nm (VUV)
  - **Nuclear recoil threshold ~3-6 keV**

- **S2: Ionisation via electroluminescence**
  - Sensitive to single ionisation electrons
  - S1+S2 > vertex reconstruction, discrimination
  - **Nuclear recoil threshold <1 keV**



- **WIMP target**
  - Dense medium (3 g/cm^3), high Z (54), high A (131)
  - Spin independent WIMP-nucleon scattering rate dR/dE~A^2
  - Odd-neutron isotopes (^{129}Xe, ^{131}Xe) enable spin-dependent sensitivity
  - No intrinsic backgrounds (^{127}Xe, $^{129m/131m}$Xe, ^{136}Xe subdominant)
  - Others dispersible backgrounds can be controlled (^{85}Kr, $^{222/220}$Rn)

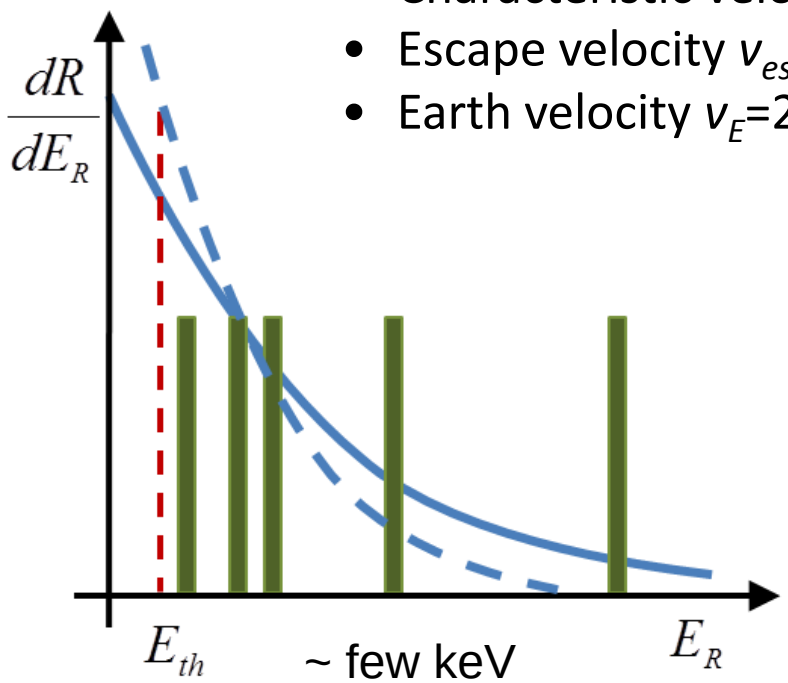
WIMP-NUCLEUS ELASTIC SCATTERING

The 'spherical cow' galactic model

- DM halo is 3-dimensional, stationary, with no lumps
- Isothermal sphere with density profile $\rho \propto r^{-2}$
- Local density $\rho_0 \sim 0.3$ GeV/cm^3 (~1/pint for 100 GeV WIMPs)

Maxwellian (truncated) velocity distribution, f(v)

- Characteristic velocity v_0=220 km/s
- Escape velocity v_{esc}=544 km/s
- Earth velocity v_E=230 km/s



Nuclear recoil energy spectrum [events/kg/day/keV]

$$\frac{dR}{dE_R} = \frac{\rho_0 \sigma_A}{2 m_\chi \mu_A^{\,2}} F^2(q) \int_{v_{\min}}^{v_{\max}} \frac{f(\vec{v})}{v} d^3 v$$

$$\frac{dR}{dE_R} \approx \frac{R_0}{E_0 r} e^{-E_R / E_0 r}, \quad r = \frac{4 m_W m_T}{(m_W + m_T)^2} \leq 1$$

XENON AS A WIMP TARGET

Xenon Isotopes

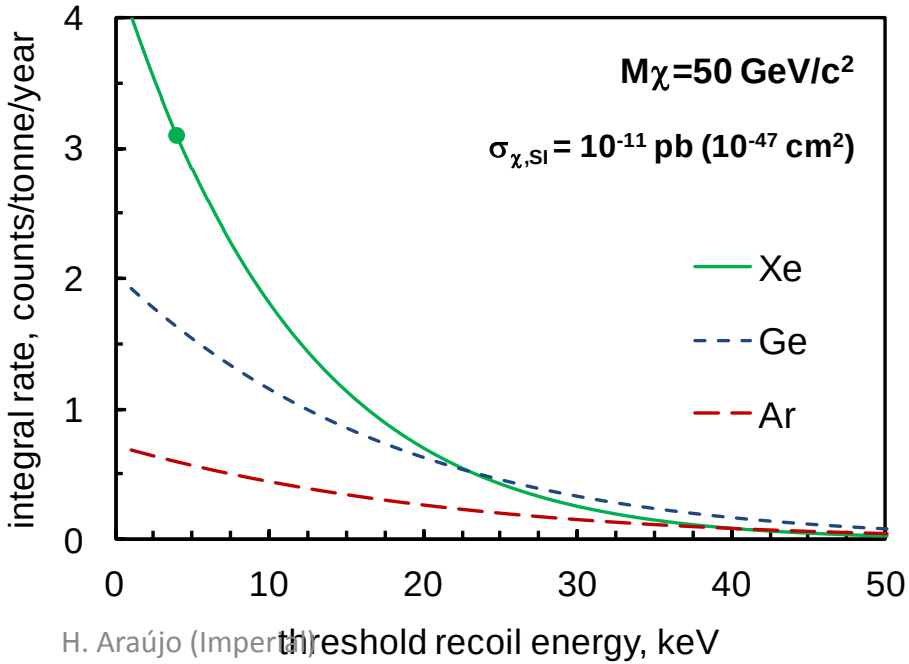
9 'stable'

$2\nu\beta\beta$ decays

Short-lived

High atomic mass (SI XS)

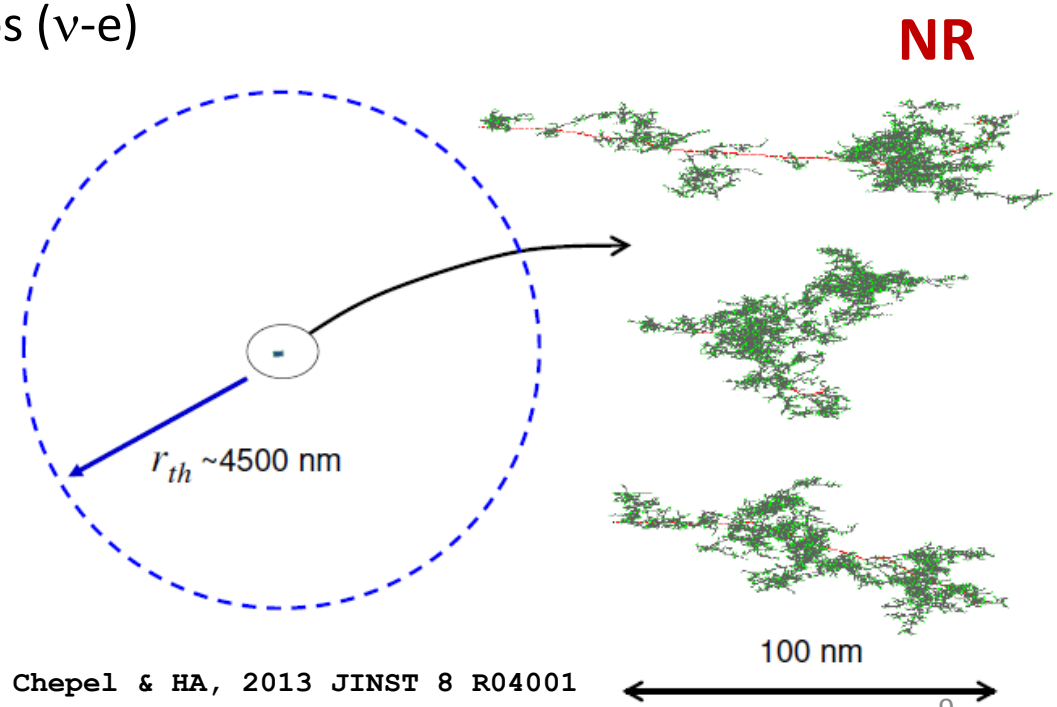
Odd-neutron isotopes (SD XS)



^{A}Z	$T_{1/2}$ or %	J^p
^{122}Xe	20 h	0^+
^{123}Xe	2.1 h	$(1/2)^+$
^{124}Xe	0.10%	0^+
^{125}Xe	17 h	$(1/2)^+$
^{126}Xe	0.09%	0^+
^{127}Xe	36 d	$(1/2)^+$
^{128}Xe	1.91%	0^+
^{129}Xe	**26.4%**	**$(1/2)^+$**
^{130}Xe	4.1%	0^+
^{131}Xe	**21.2%**	**$(3/2)^+$**
^{132}Xe	26.9%	0^+
^{133}Xe	5.2 d	$(3/2)^+$
^{134}Xe	10.4%	0^+
^{135}Xe	9.1 h	$(3/2)^+$
^{136}Xe	8.9 % (2.2×10^{21} y)	0^+

SIGNALS AND BACKGROUNDS

- WIMP signal: elastic scattering producing nuclear recoils (NR) in the **keV range**: primary recoil produces small atomic cascade
  - Also neutrons, neutrinos (ν-A)
- Background particles interact mostly with atomic electrons producing (keV) electron recoils (ER)
  - Gammas, betas, neutrinos (ν-e)
  - Also some signal models
- **Our goal:**
  To detect efficiently and discriminate between low-energy NR and ER, in as large a detector as possible



Chepel & HA, 2013 JINST 8 R04001

THE EXPERIMENTAL CHALLENGE

- Low-energy particle detection is easy ;)

  E.g. Microcalorimetry with Superconducting TES

  Detection of keV particles or photons with eV FWHM

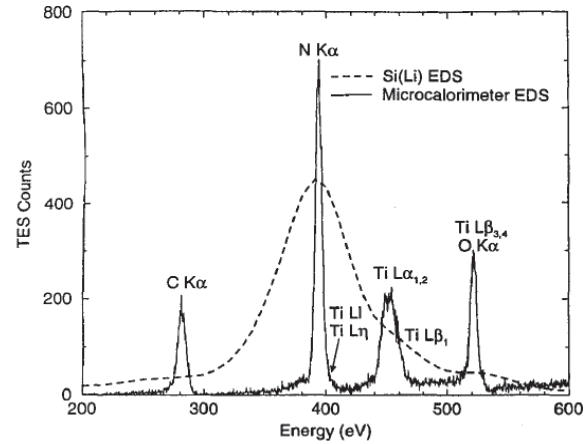
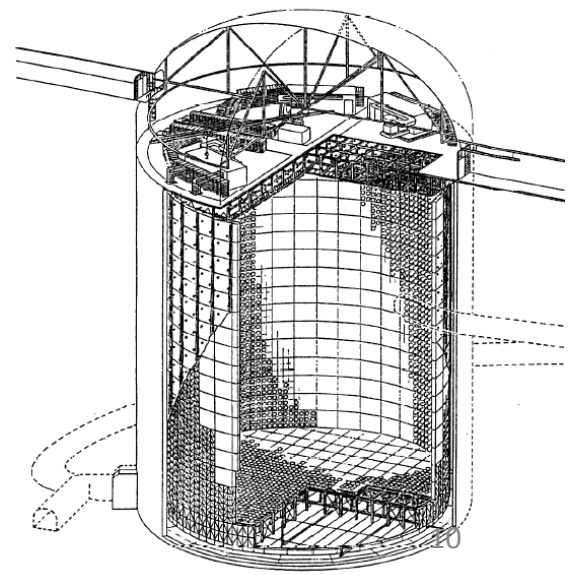


Fig. 3. Microcalorimeter EDS x-ray spectrum of TiN. The original spectrum was corrected for energy nonlinearity, resulting in a constant energy binwidth of 0.45 eV per channel over the energy range presented.

- Rare event searches are also easy ;)

  E.g. Super-Kamiokande contains 50 kT water

  Cut to ~20 kT fiducial mass: huge self-shielding effect



- But doing both is hard!

  Small is better for collecting signal

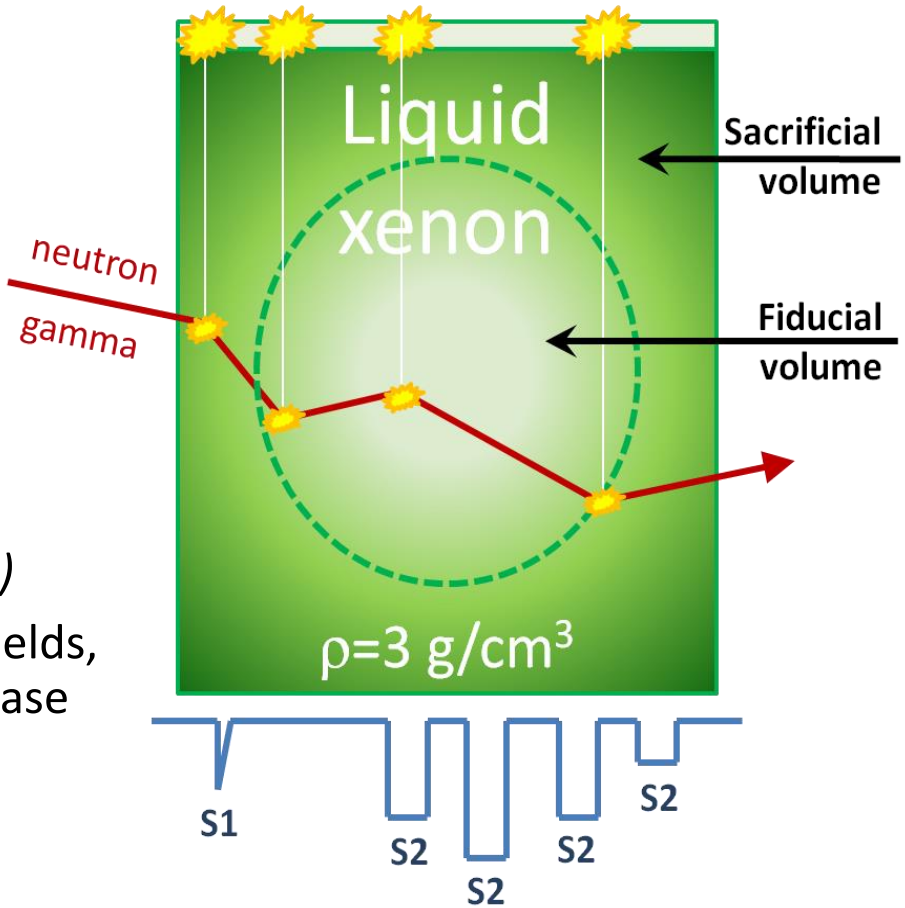
  Large is better to shield backgrounds

- And there is no trigger…

KEY DETECTOR REQUIREMENTS

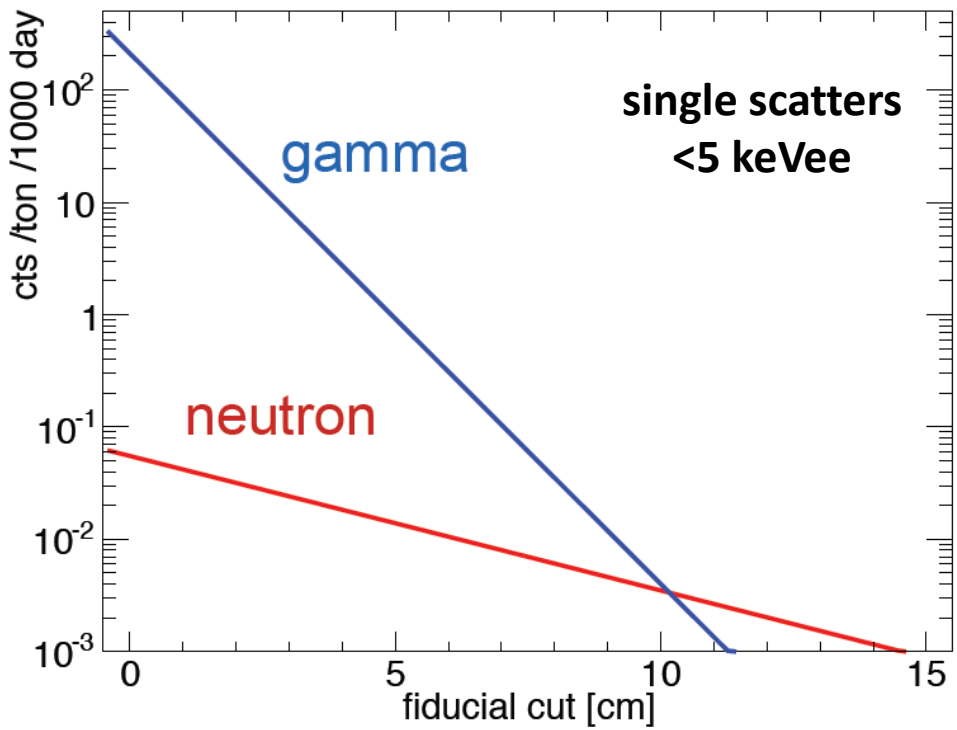
The success of the two-phase xenon technology relies on three aspects:

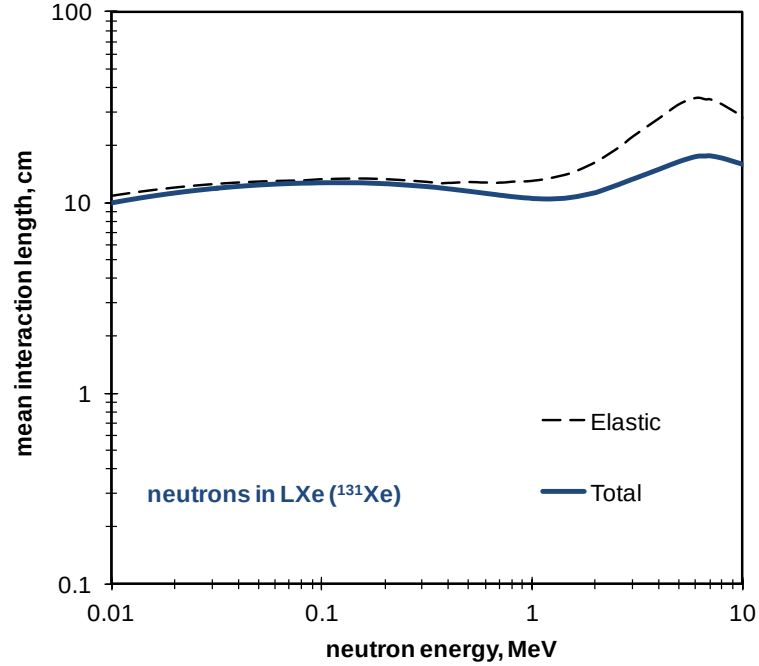
- **Low energy threshold (mostly S1)**
  - *Detectable WIMP scattering rate*
  - Scintillation yield, VUV reflectivities VUV QE, PMTs in the liquid phase
- **Accurate 3D imaging (mostly S2)**
  - *Background reduction (self-shielding)*
  - Electroluminescence yield, electric fields, electron lifetime, PMTs in the gas phase
- **ER/NR discrimination (S1 + S2)**
  - *Background reduction (NR selection)*
  - High yields, uniform detector, no 'funny' event topologies

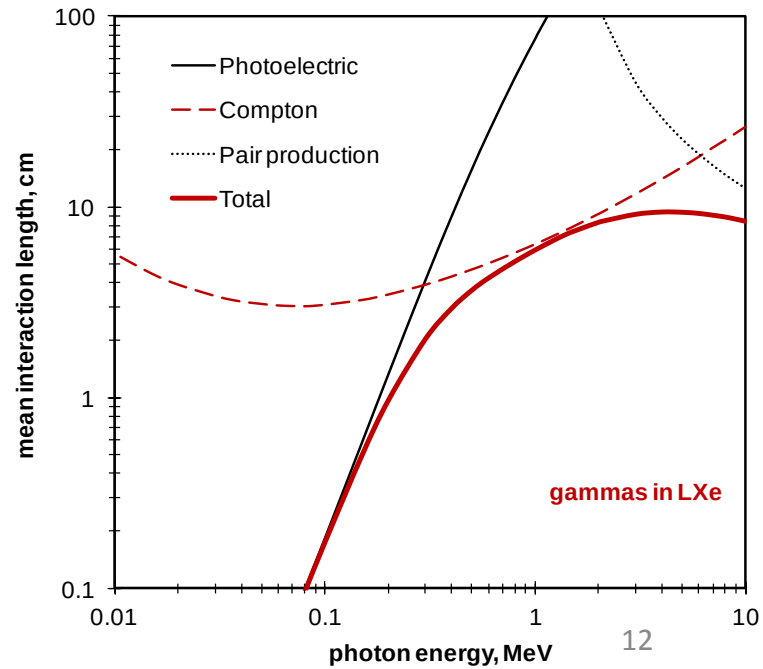


LXE SELF-SHIELDING

- Self-shielding of external backgrounds
- Interesting challenge for calibration…





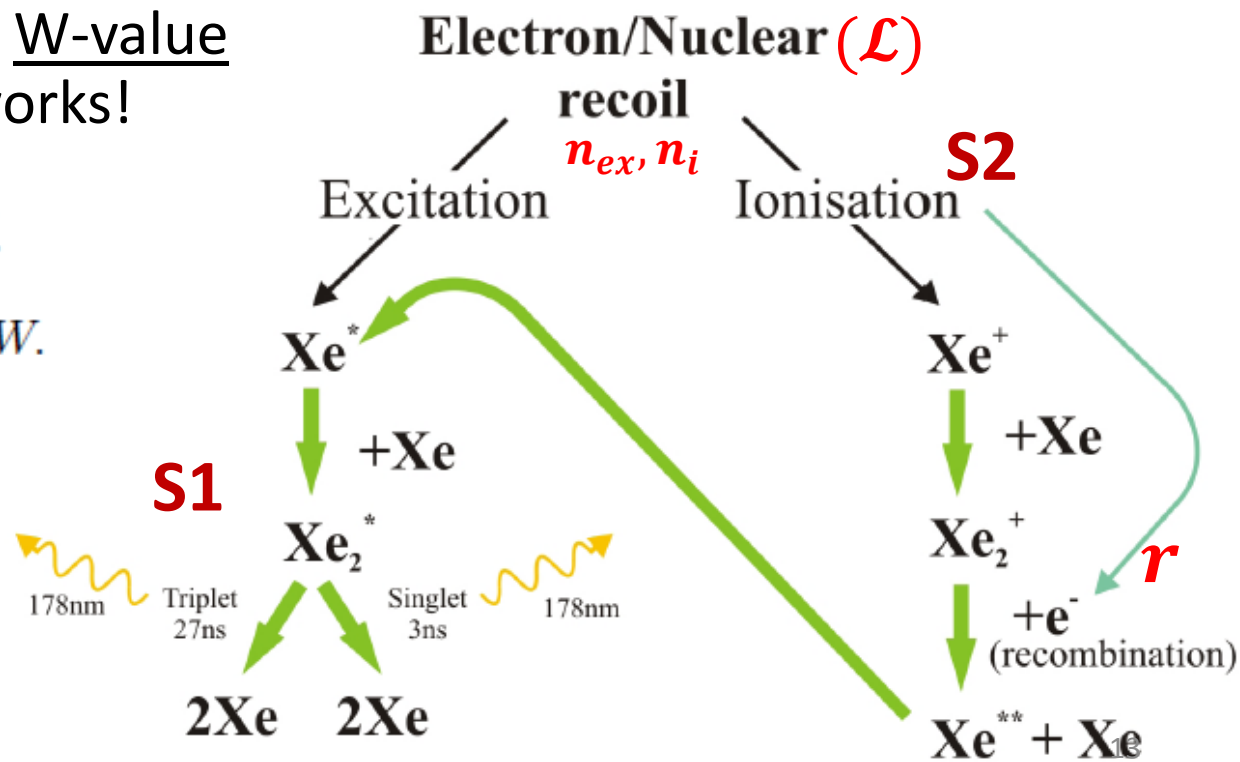


LXE RESPONSE TO RADIATION

- Understanding the detector response to nuclear recoils (NR) and electron recoils (ER) down to detection threshold is crucial
- S1 & S2 depend on: particle <u>species</u>, recoil <u>energy</u>, electric <u>field</u>
- Electron-ion <u>recombination</u> is a key parameter
- Model with single <u>W-value</u> for total quanta works!

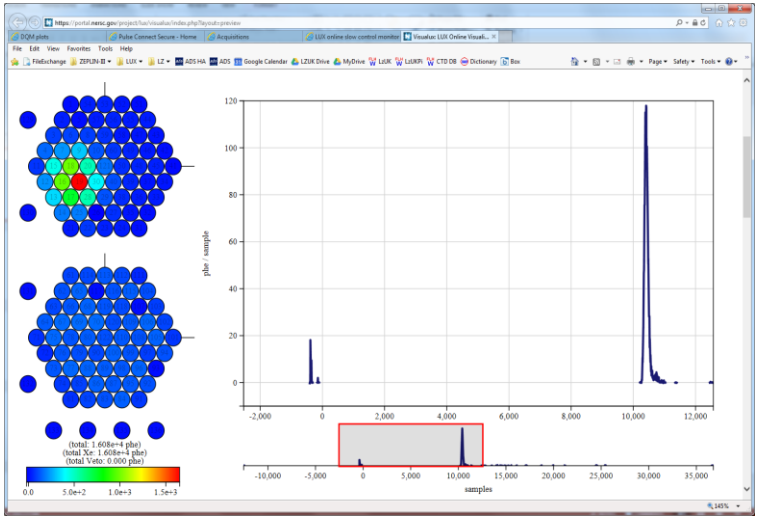
$$E = (n_e + n_\gamma) \cdot W.$$

$$E_{nr} = \mathcal{L}^{-1} \cdot (n_e + n_\gamma) \cdot W.$$

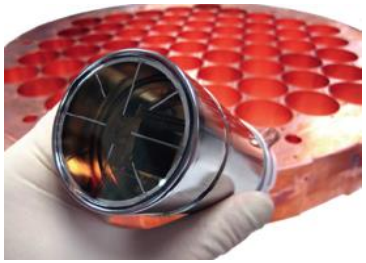


WHAT IS REQUIRED FOR A JOB WELL DONE

- **Understand the detector**
  - S1 (photon) detection, inc. measurement of S1 quantum
  - S2 (electron) detection, inc. measurement of S2 quantum
  - S1 & S2 photon detection efficiencies (inc. flat-fielding)
  - S1 & S2 absolute gains (g1, g2)
    - Relate detected quanta to energy deposit using known W-value
- **Understand LXe physics in ROI**
  - ER scintillation & ionisation yields
    - and fluctuations
  - NR scintillation & ionisation yields
    - and fluctuations



DETECTING PHOTONS (mostly S1)



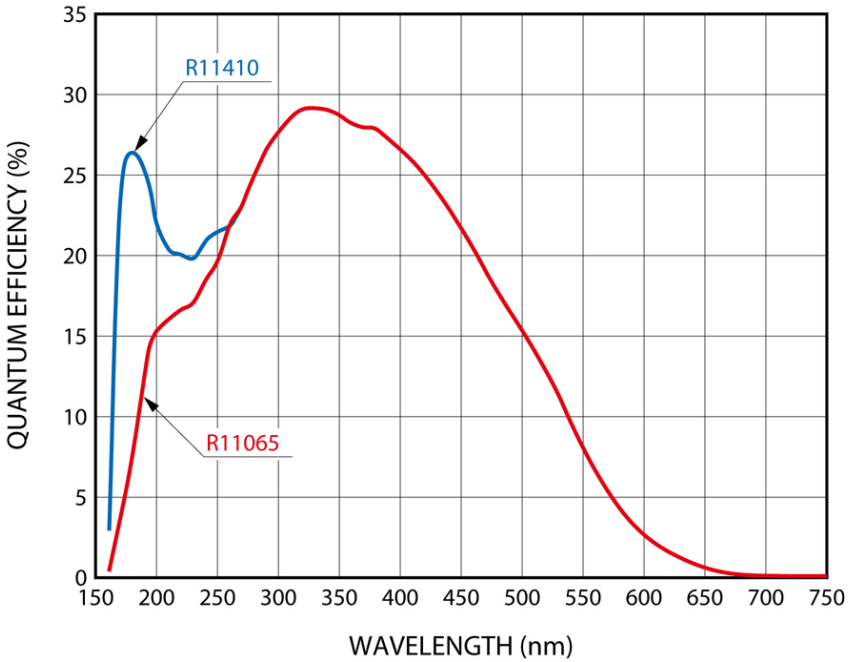
Quartz-windowed PMTs work very well at 178 nm

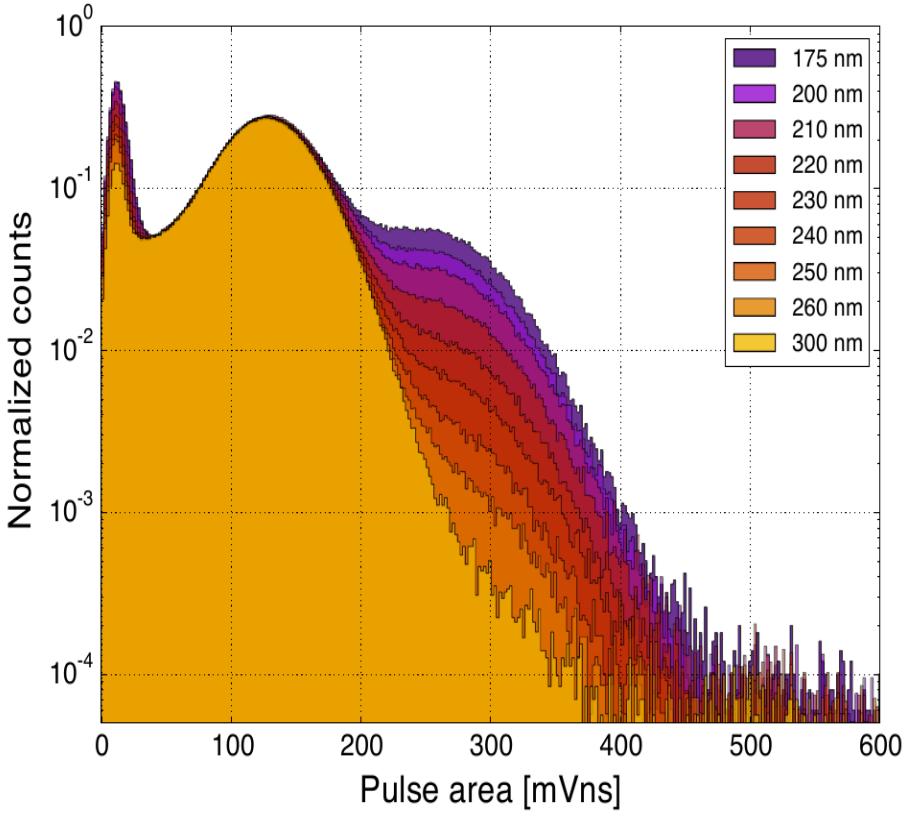
Resolved PMT backgrounds over last decade

Must calibrate QE in VUV: sometimes 2 phe/photon…

- Photon counting in PMT waveforms: #phe > #phd
- Improved resolution & linearity!

arXiv:1506.08748

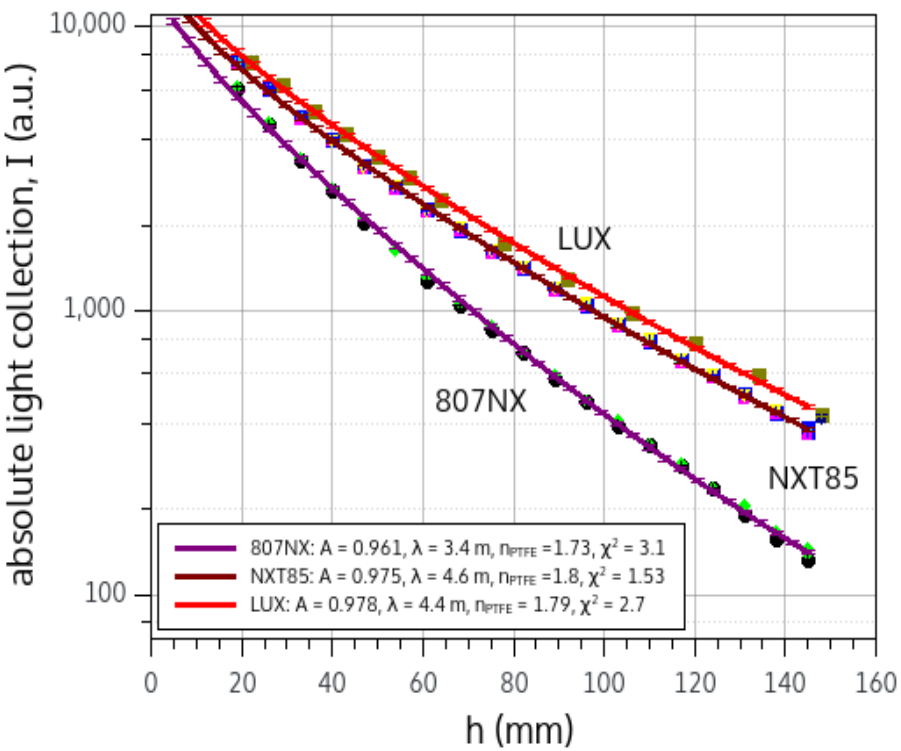


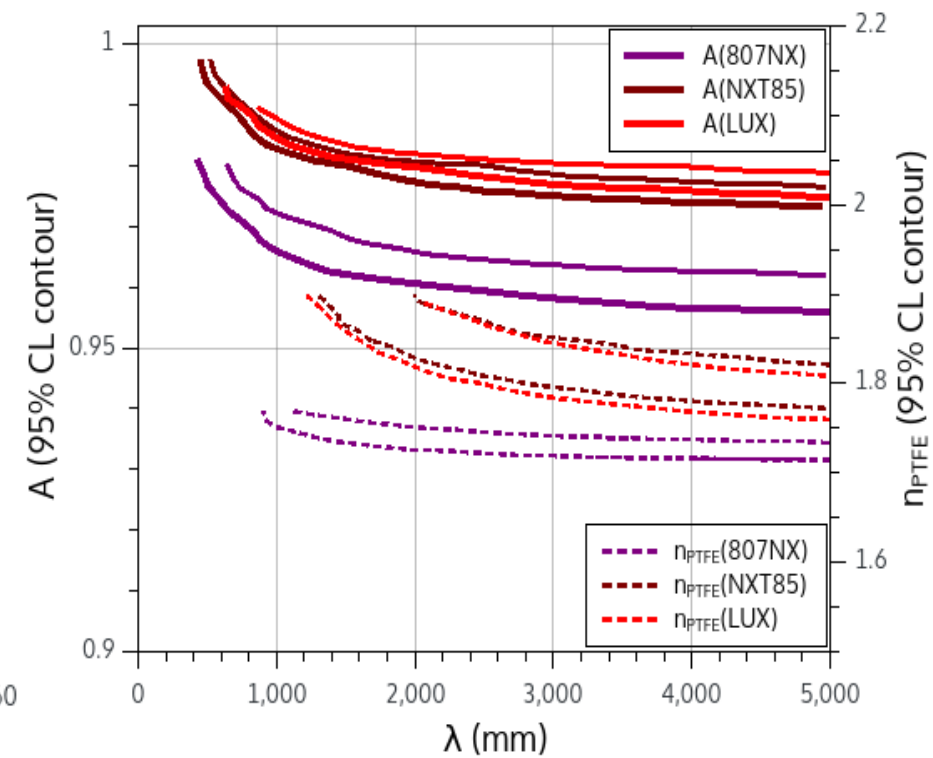


DETECTING PHOTONS (mostly S1)

PTFE is a magical material

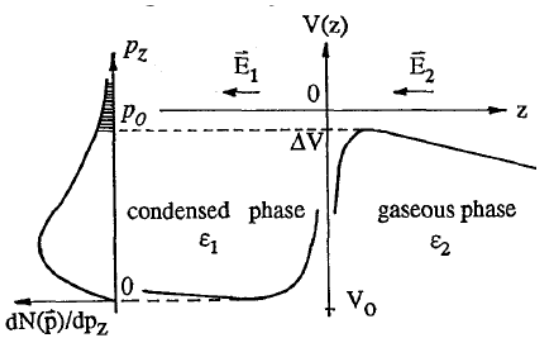
- Very high VUV reflectance when immersed in LXe; very low background; low outgas, compatible with LXe; great electrical properties,… We got lucky!
- External measurement of LUX PTFE
  - Best fit R=97.8% (>97.5% @95% CL) (F. Neves IDM2016)



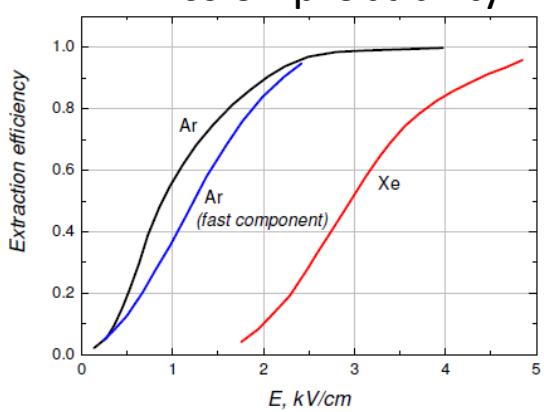


DETECTING ELECTRONS (S2)

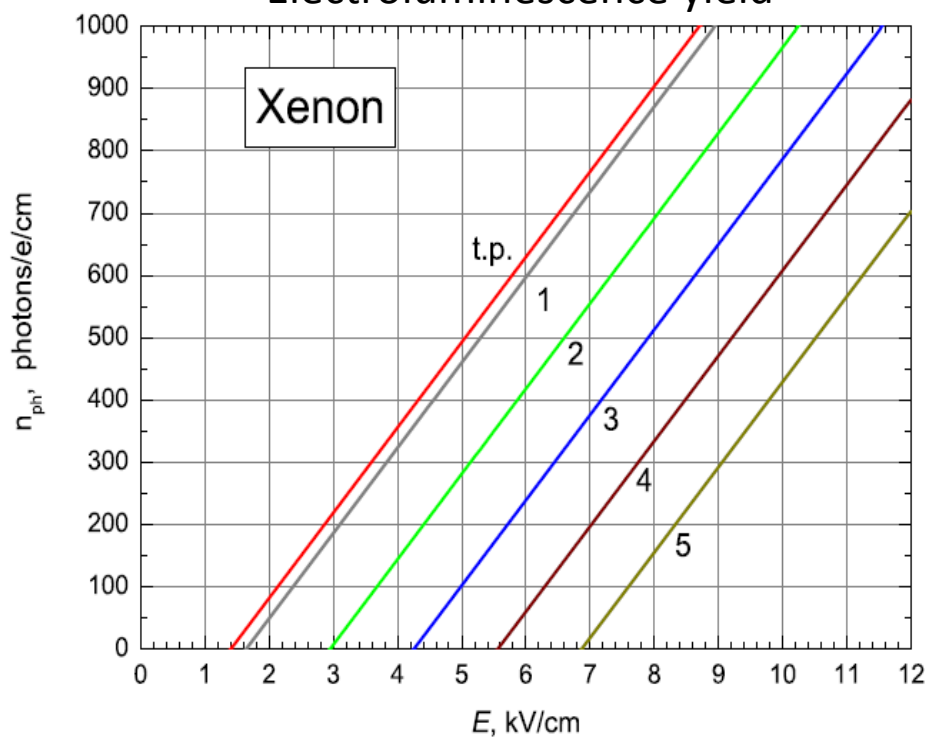
- **Drifting electrons from vertex to surface: need high e-lifetime**
- **Cross-phase electron emission requires at high fields (>5 kV/cm)**
- **Electroluminescence in the vapour phase** provides high gain for ionisation channel – and transduces signal to VUV photons



Emission probability

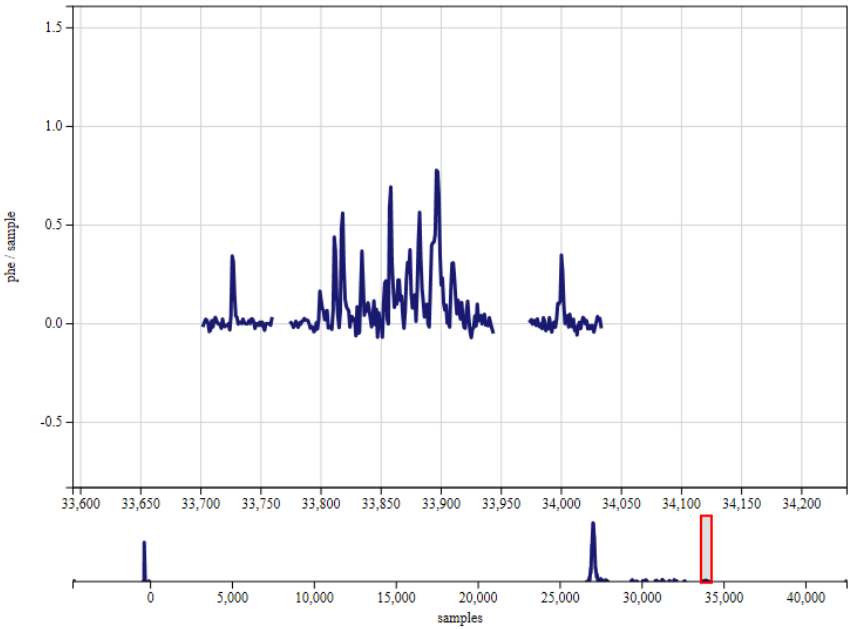


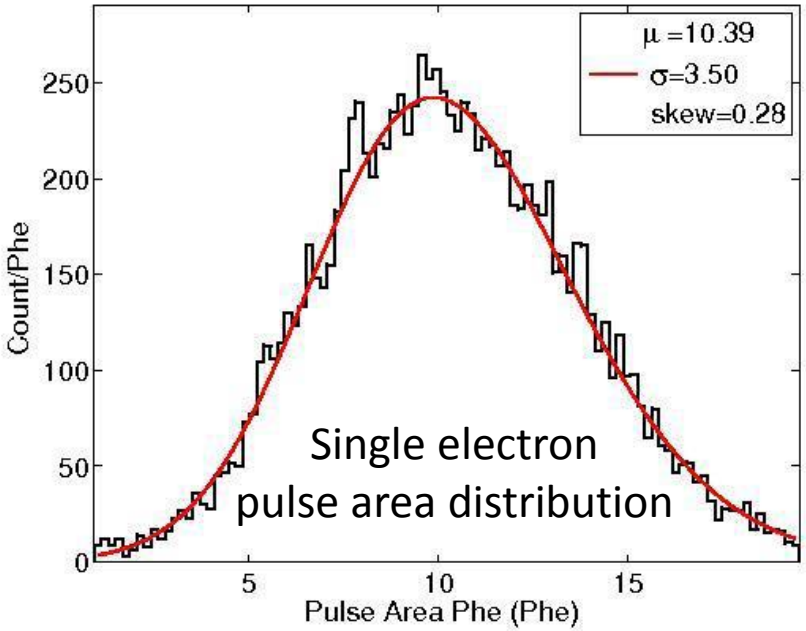
Electroluminescence yield



DETECTING ELECTRONS (S2)

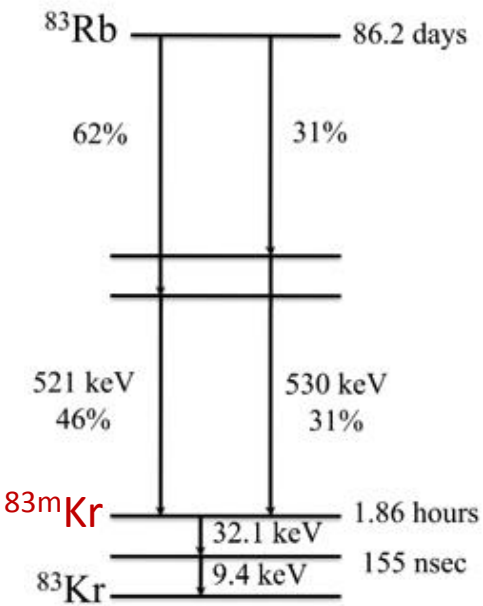
- **Single electron response: absolute calibration of S2 channel**
- **Electroluminescence gain depends on several parameters** which can vary during a long run (pressure, fields, liquid level,…)
- SE signal can be tracked to % level during run
- Pure sources of SE signals, e.g. VUV photoionisation of impurities

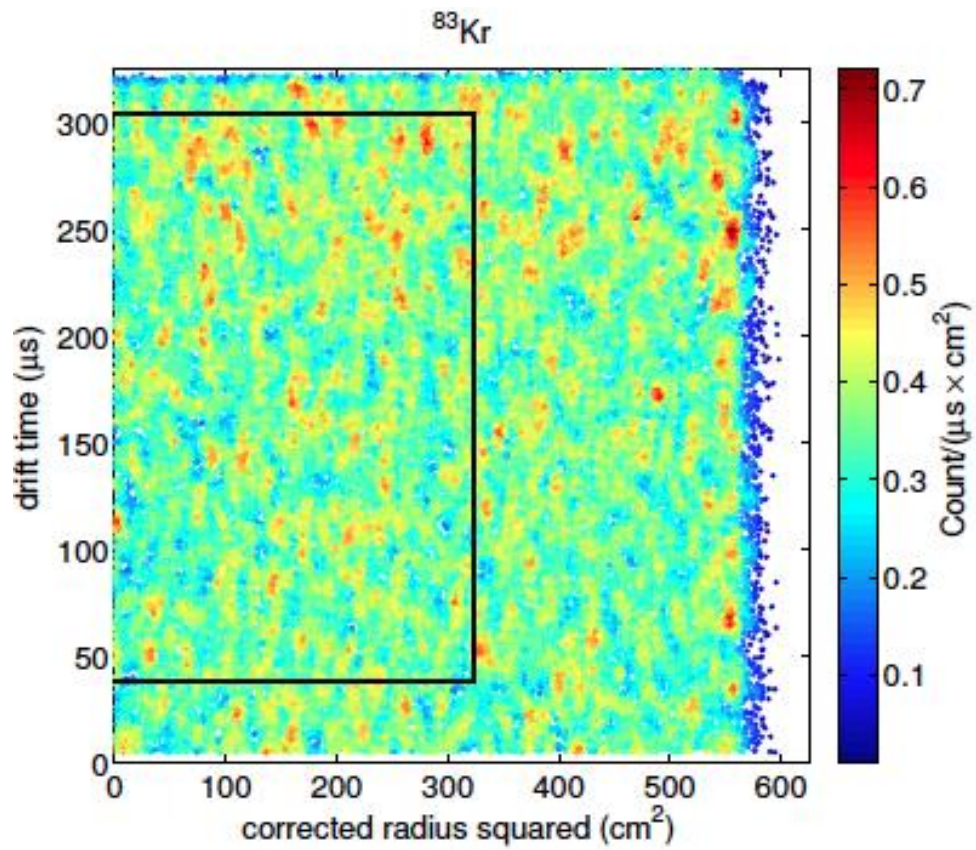




S1 & S2 PDEs – FLATFIELDING WITH ^{83m}Kr

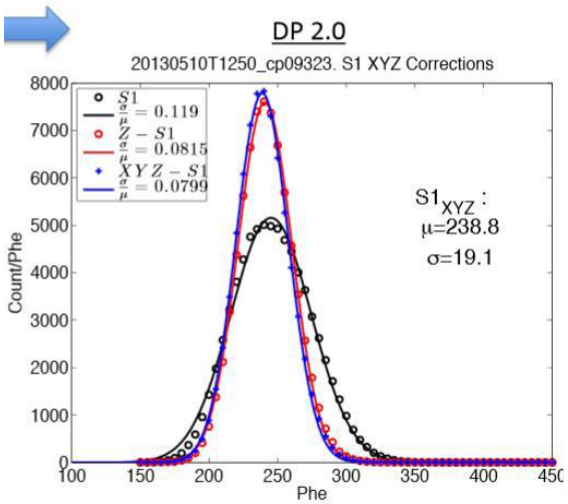
- X,Y,Z response calibration with dispersed ^{83m}Kr radioisotope
  - Routine injection, decays within detector, emitting 2 CEs ($T_{1/2}$=1.86 hrs)

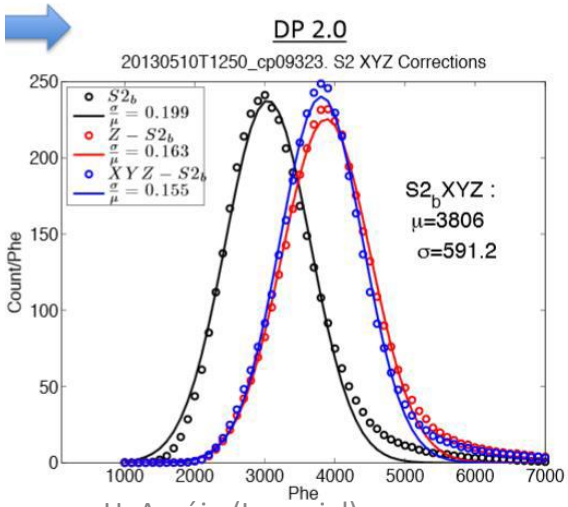




Kr-83m calibration source:
Rb-83 infused into zeolite, located within xenon gas plumbing

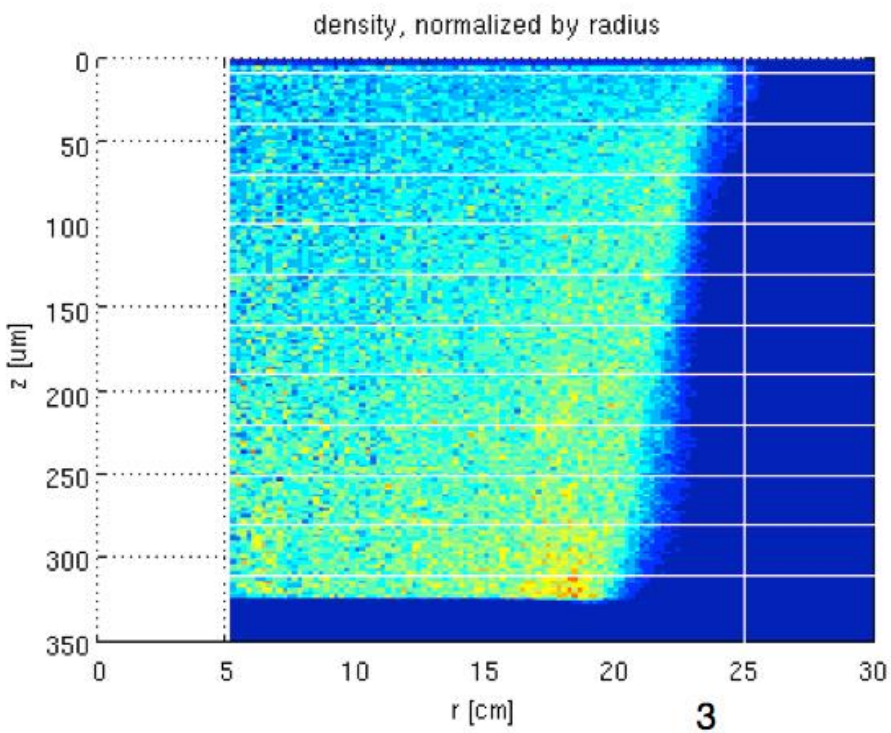
S1 & S2 PDEs – FLATFIELDING WITH ^{83m}Kr





Flat-fielding light collection – and field

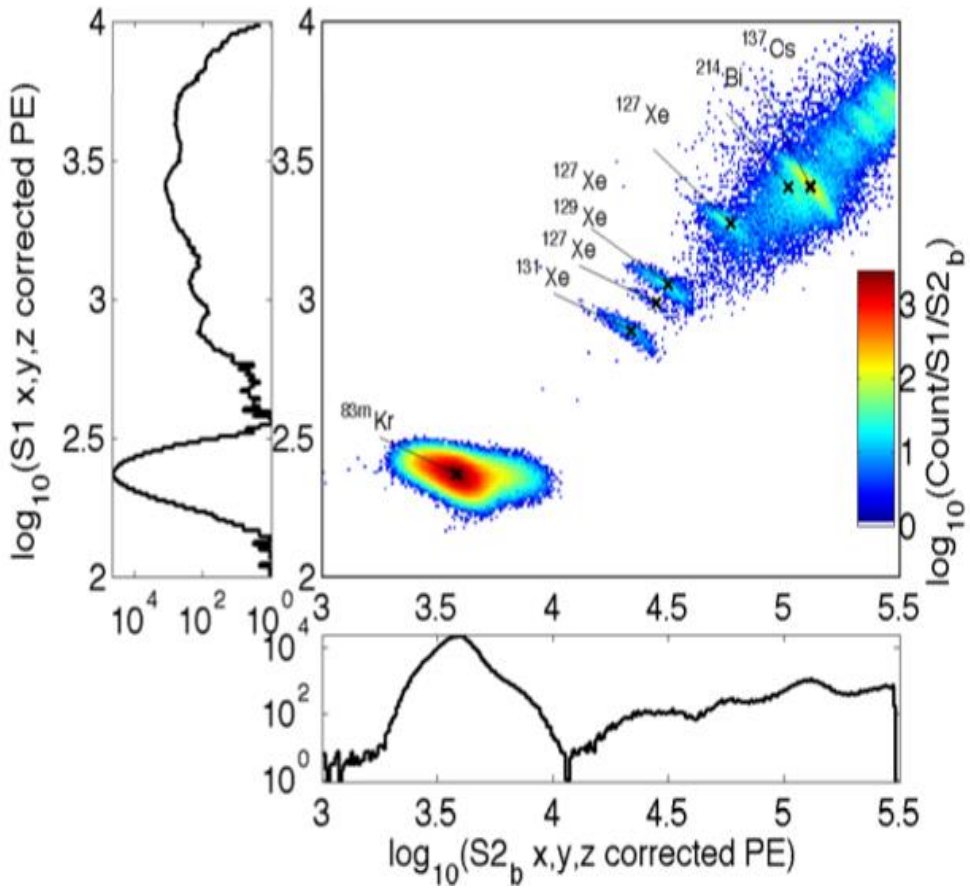
- g1 and g2 corrected to detector centre
- Field is non-uniform due to leakage through grids and other factors
- Varying field → light yield, drift speed,…

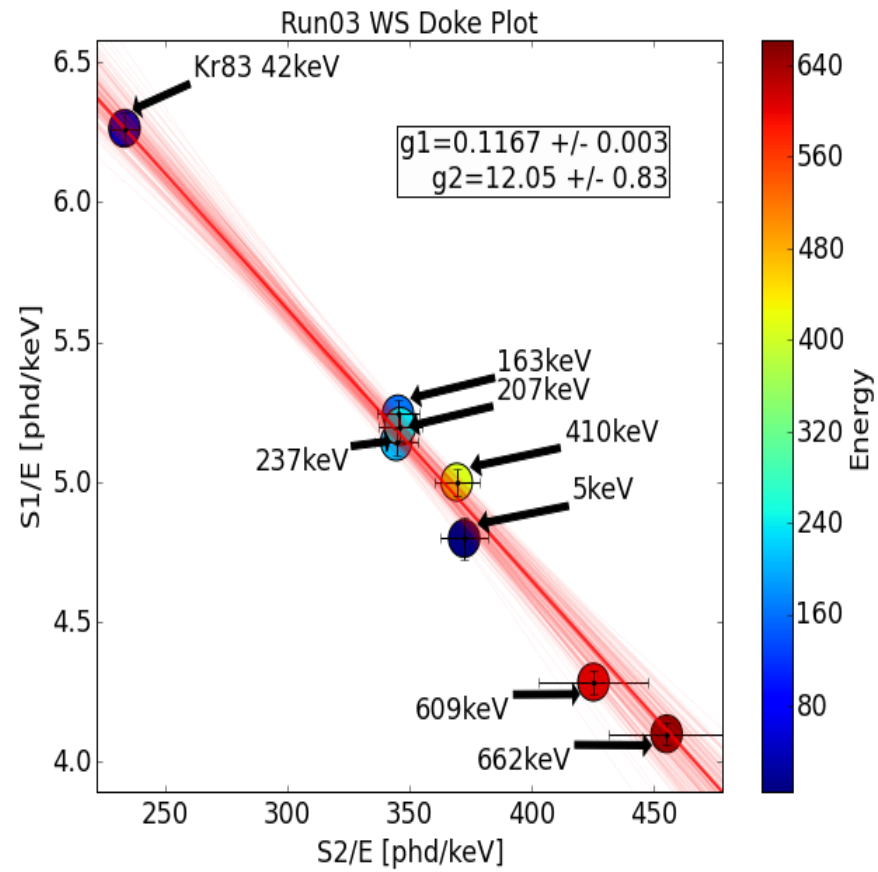


S1 & S2 ABSOLUTE GAINS: ER 'DOKE PLOT'

- Mono-energetic ER sources in the mean-yields plane (5-662 keV)
- Line fit and W-value = 13.7 eV give *absolute number of quanta*:

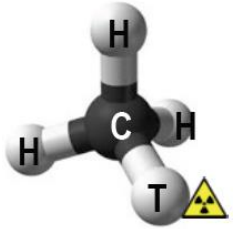
$\langle S1c[phd]\rangle = 0.117 \pm 0.003 \cdot n_{ph}$, $\langle S2c[phd]\rangle = 12.1 \pm 0.8 \cdot n_e$ $E_{total} = W \cdot (n_\gamma + n_e)$



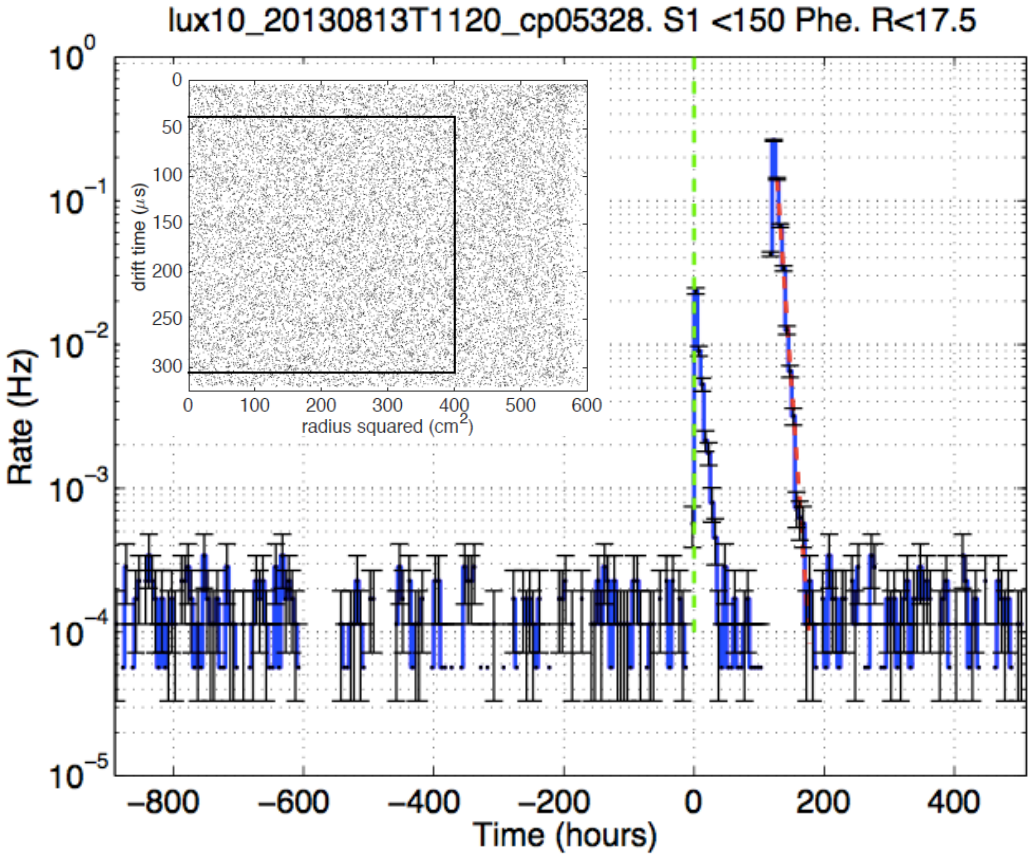


ER TRITIUM CALIBRATION (0–18 keV)

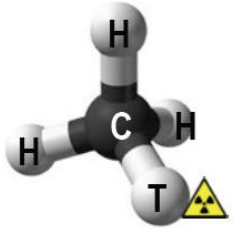
arXiv:1512.03133



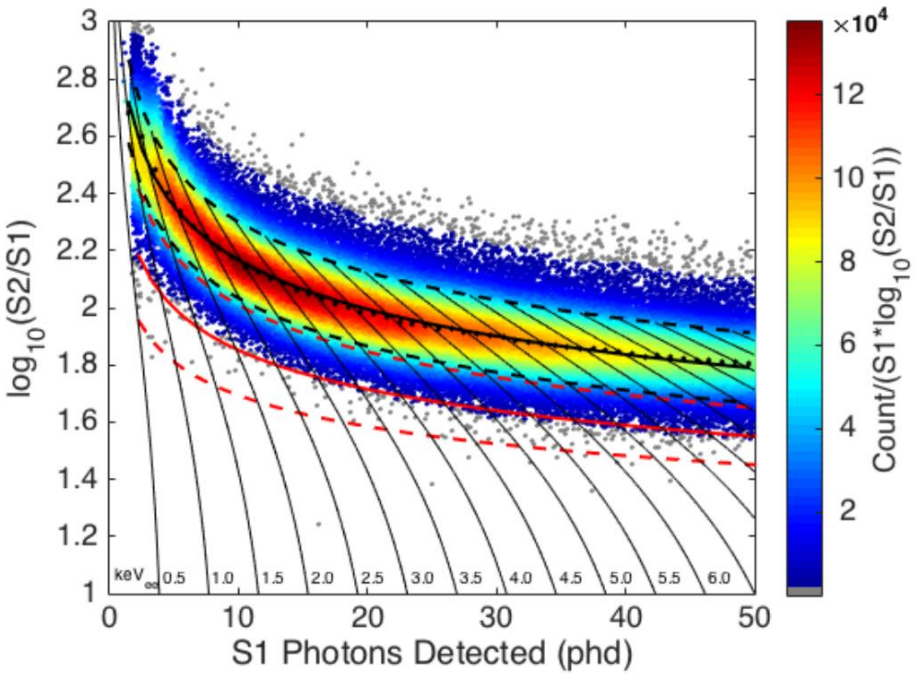
- Injection of CH_3T through gas system, removal through getter
- Extensive R&D at UMD followed by tests in LUX using CH4
- Progressive injections of CH_3T to confirm no residual background

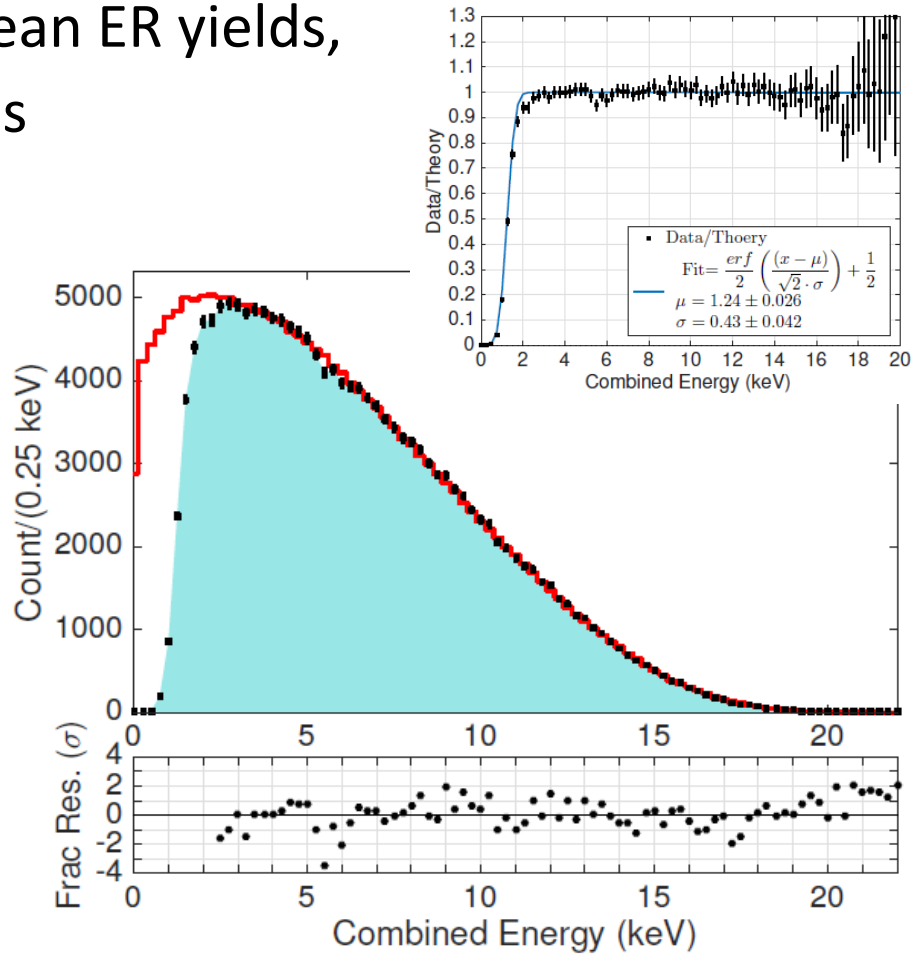


ER TRITIUM CALIBRATION (0–18 keV)

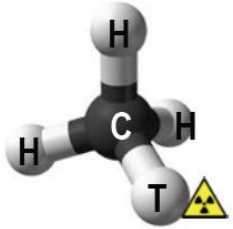


- Main CH_3T calibration campaign: 180,000 events
- Reconstruct spectrum using Doke Plot result
- Constrain detection threshold, mean ER yields, and ER recombination fluctuations



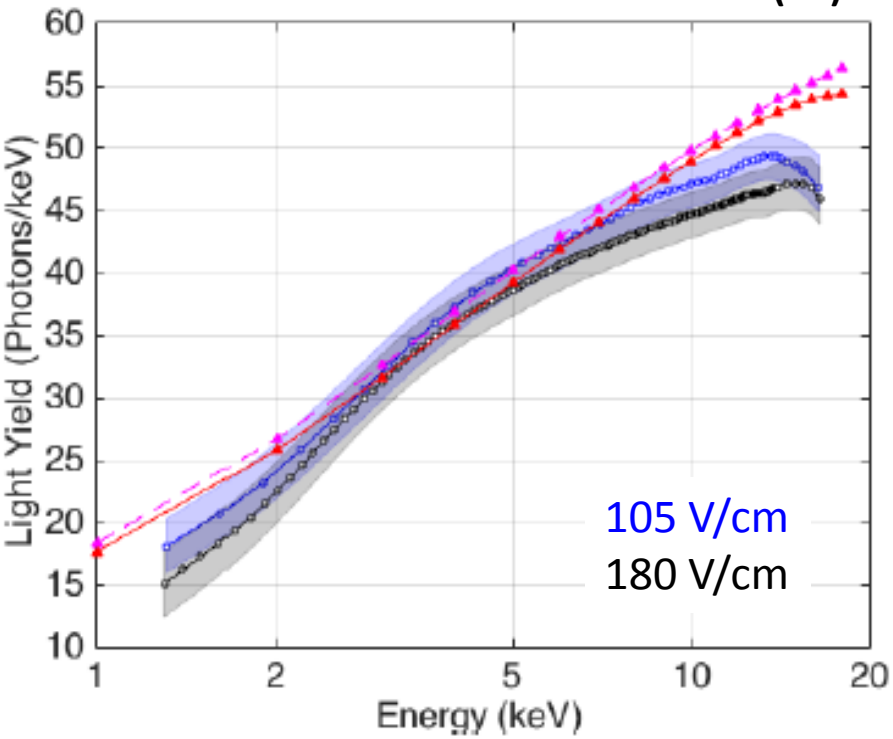


ER TRITIUM CALIBRATION (0–18 keV)

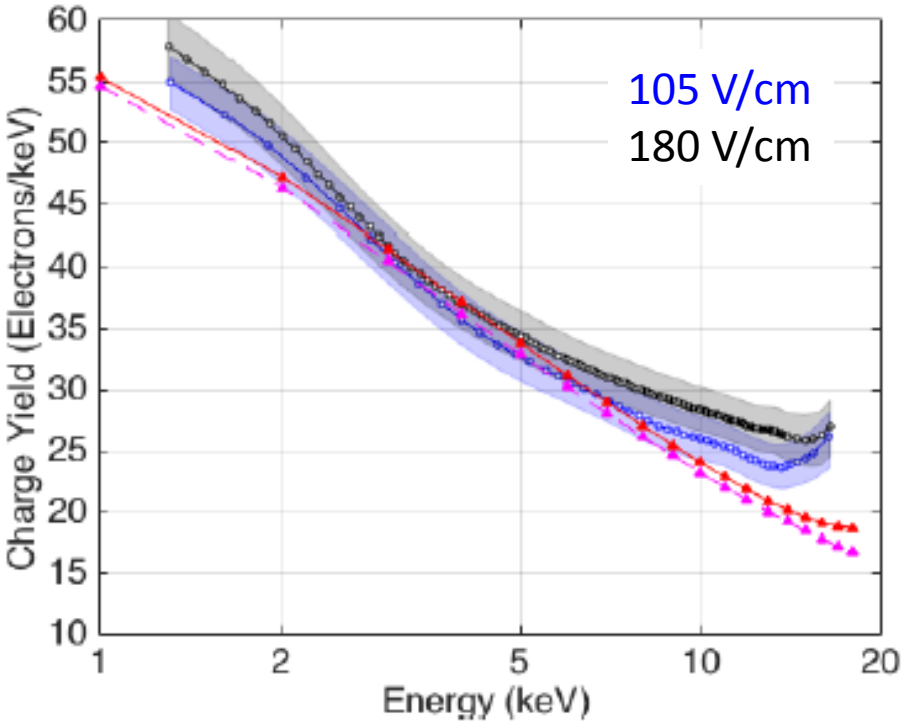


- Absolute ER light and charge yields for LXe (+ recombination)
- Essential to advance modelling – NEST tool (Szydagis et al)
- NEST is in turn needed to really understand WIMP sensitivity

LXe ABSOLUTE SCINTILLATION YIELD (ER)

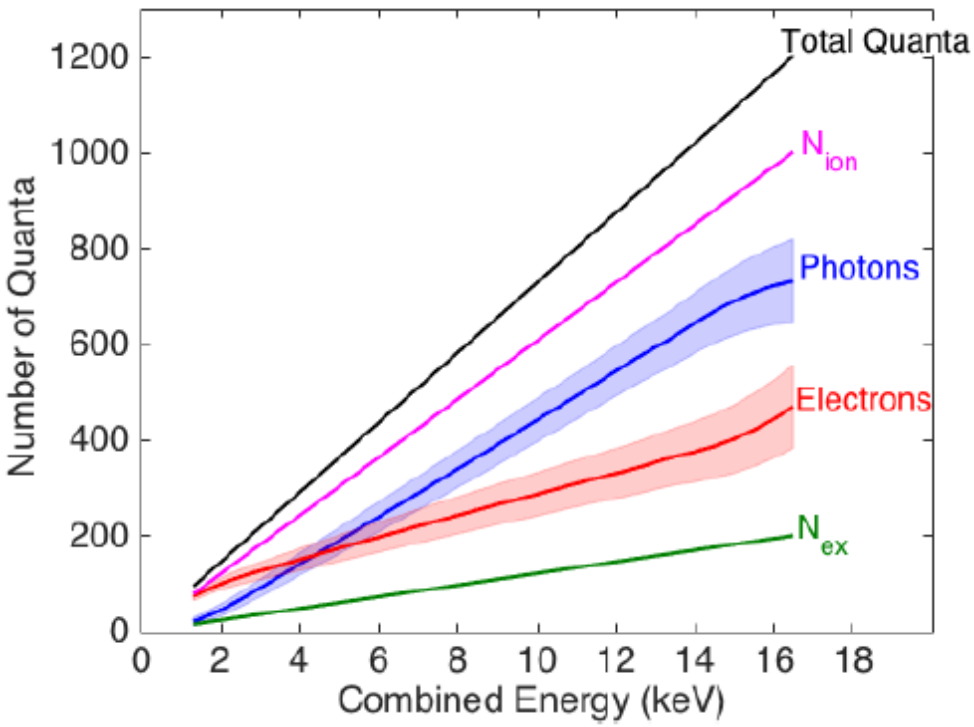


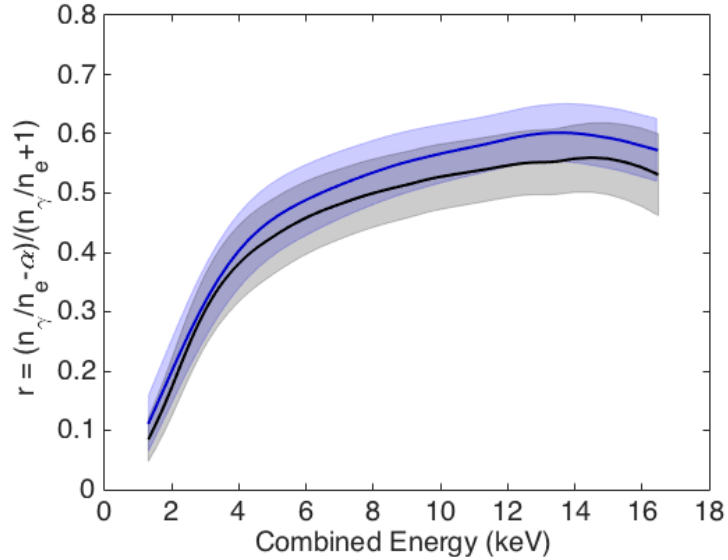
LXe ABSOLUTE IONISATION YIELD (ER)

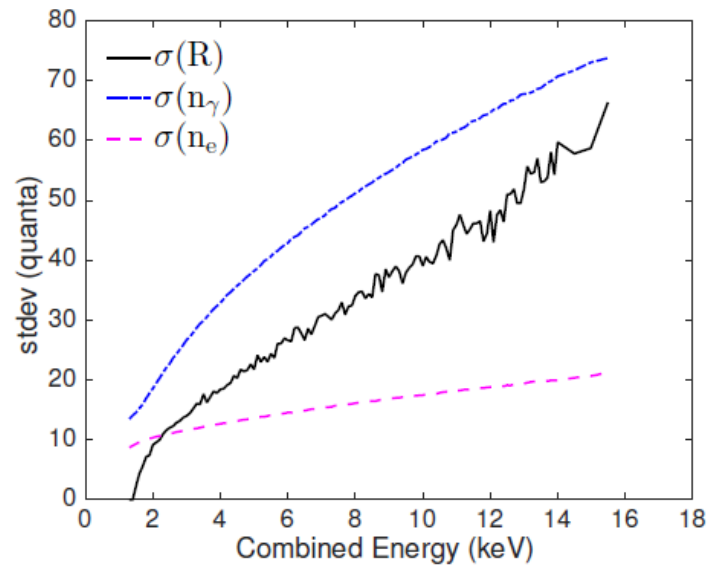


ER TRITIUM CALIBRATION (0–18 keV)

- **Recombination** fraction and its fluctuations for electron recoils (S1 and S2 event by event)

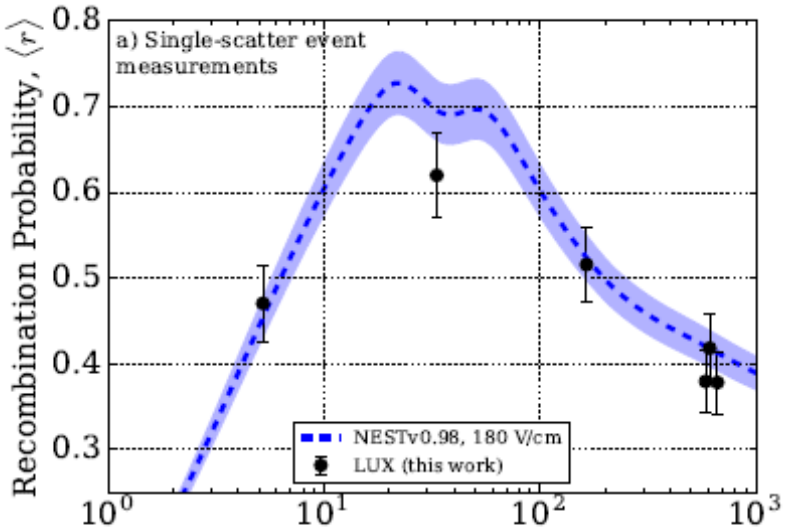


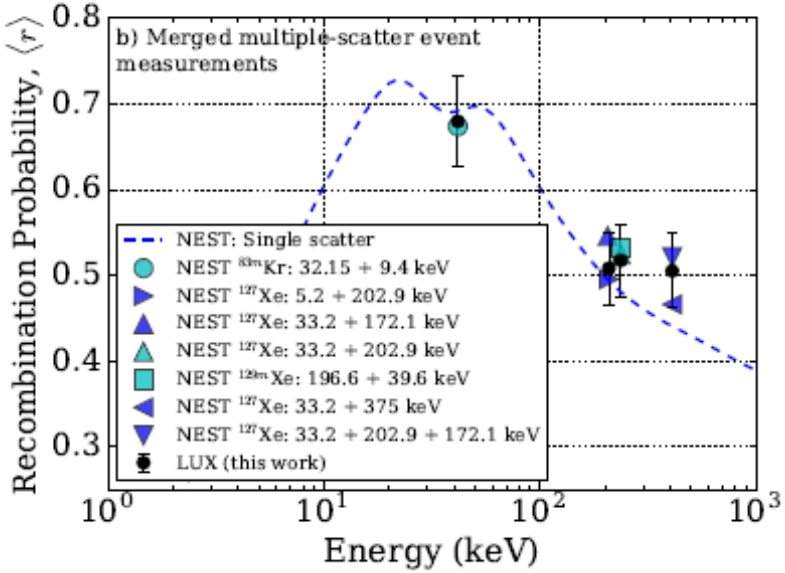


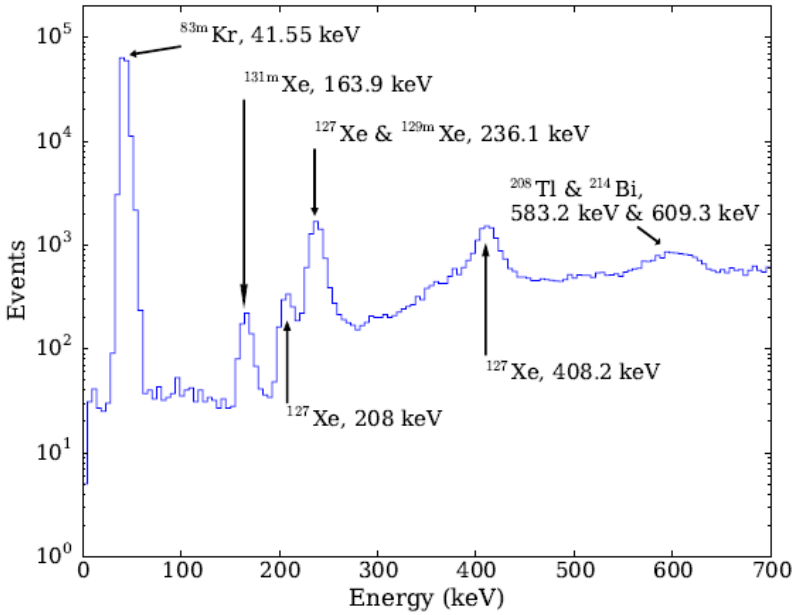


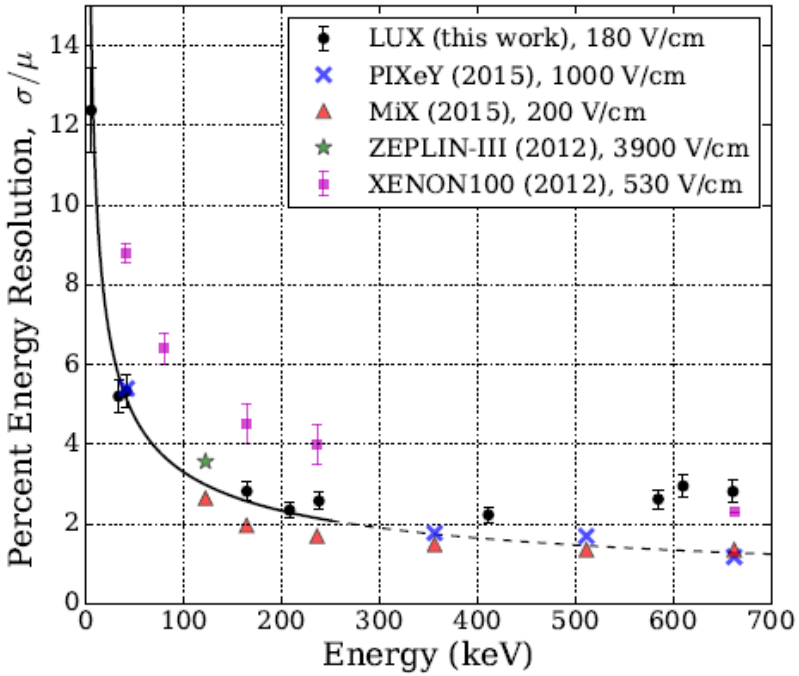
RECOMBINATION

1610.02076v1

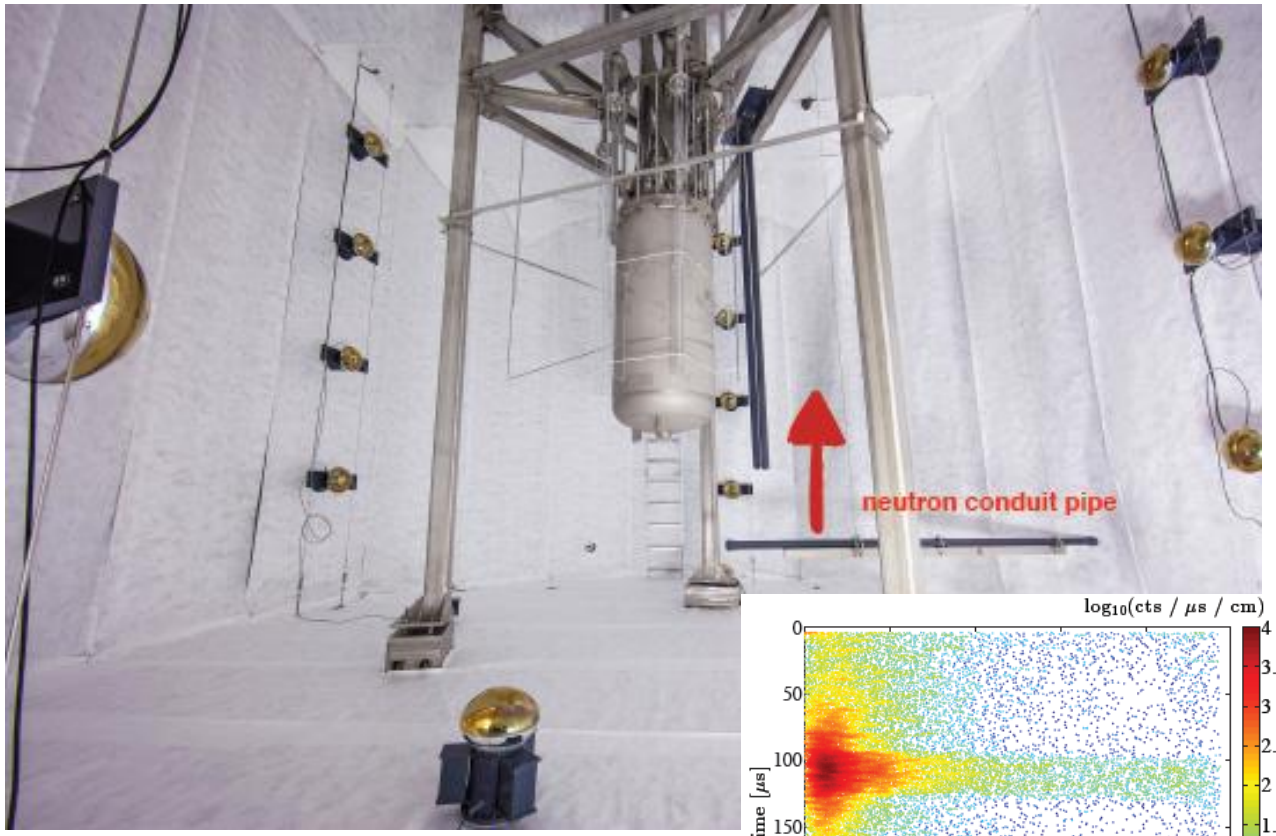






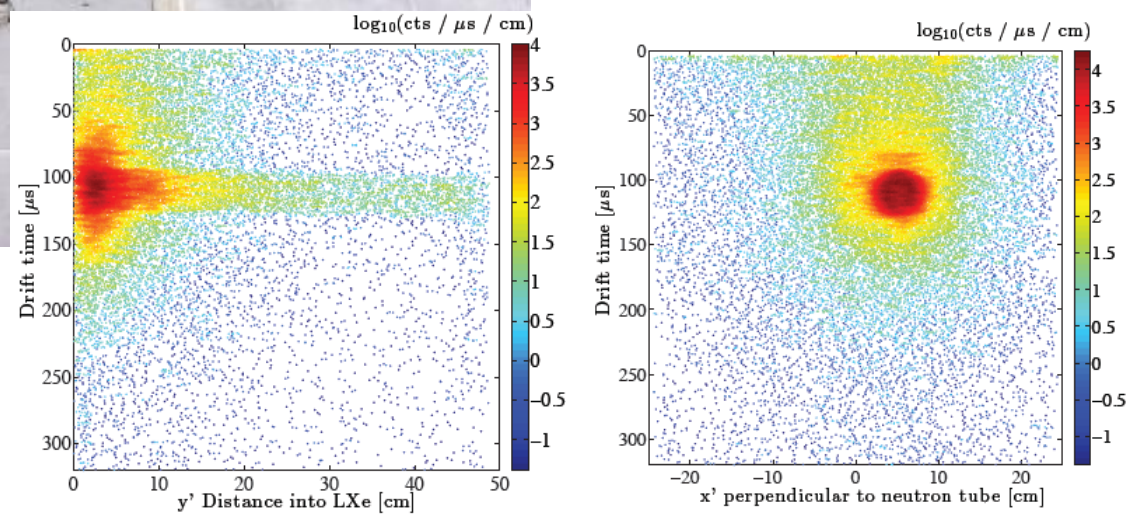


NR CALIBRATION WITH KINEMATICALLY-CONSTRAINED NEUTRON SCATTERS

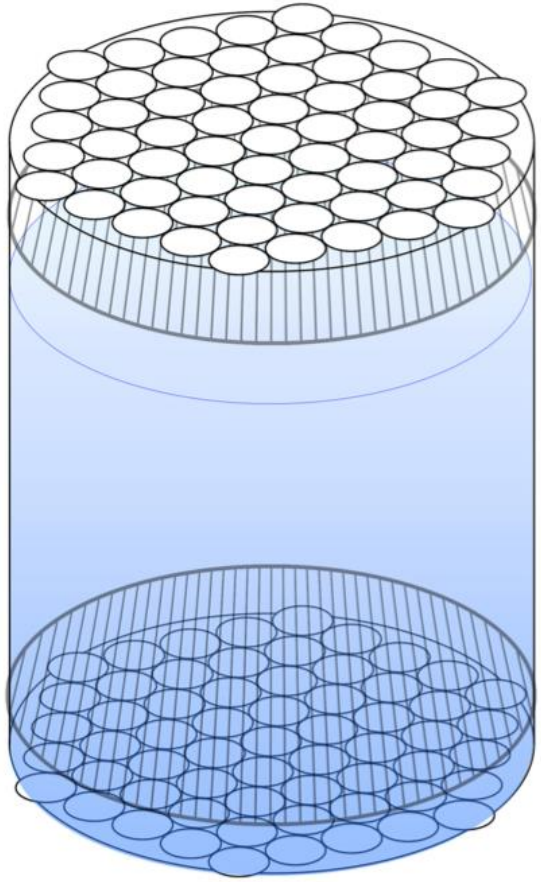


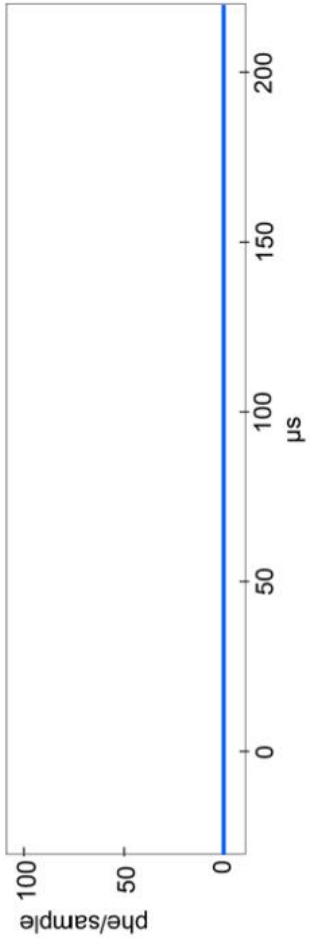
arXiv:1608.05381v1

D-D neutron generator outside of water tank
En=2.5 MeV



NR CALIBRATION WITH KINEMATICALLY-CONSTRAINED NEUTRON SCATTERS

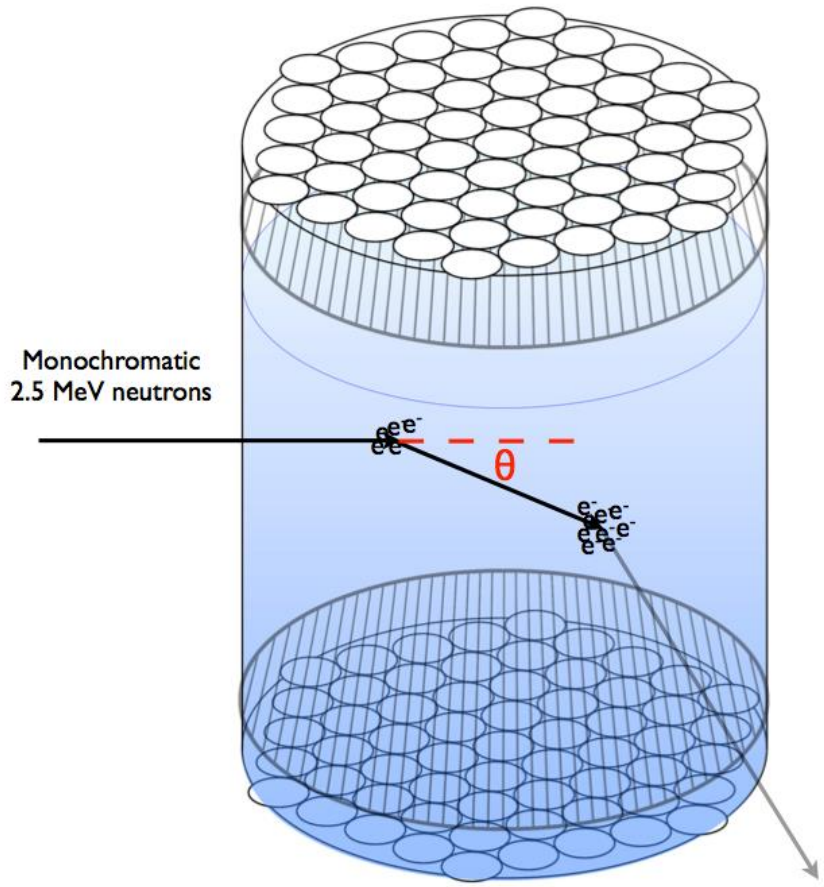


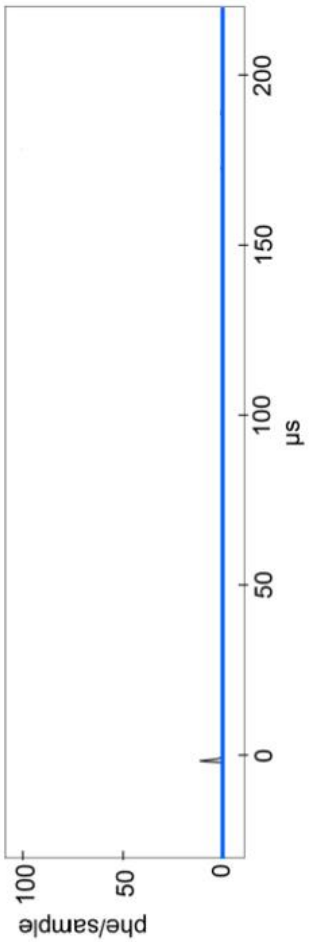


$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

Samuel Chan, Carlos Faham for the LUX Collaboration

NR CALIBRATION WITH KINEMATICALLY-CONSTRAINED NEUTRON SCATTERS





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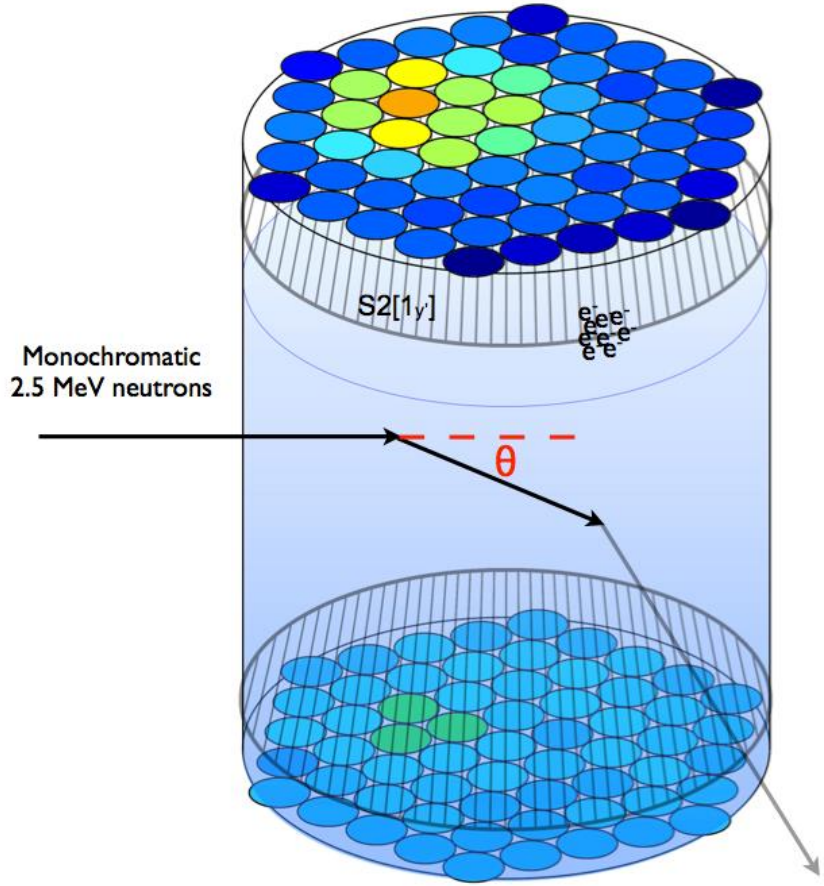

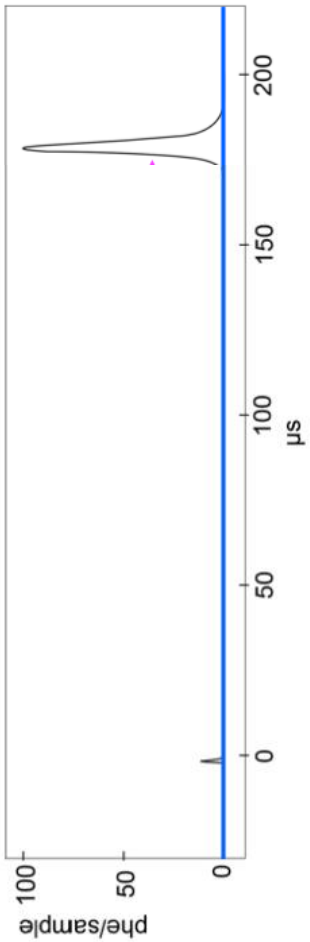

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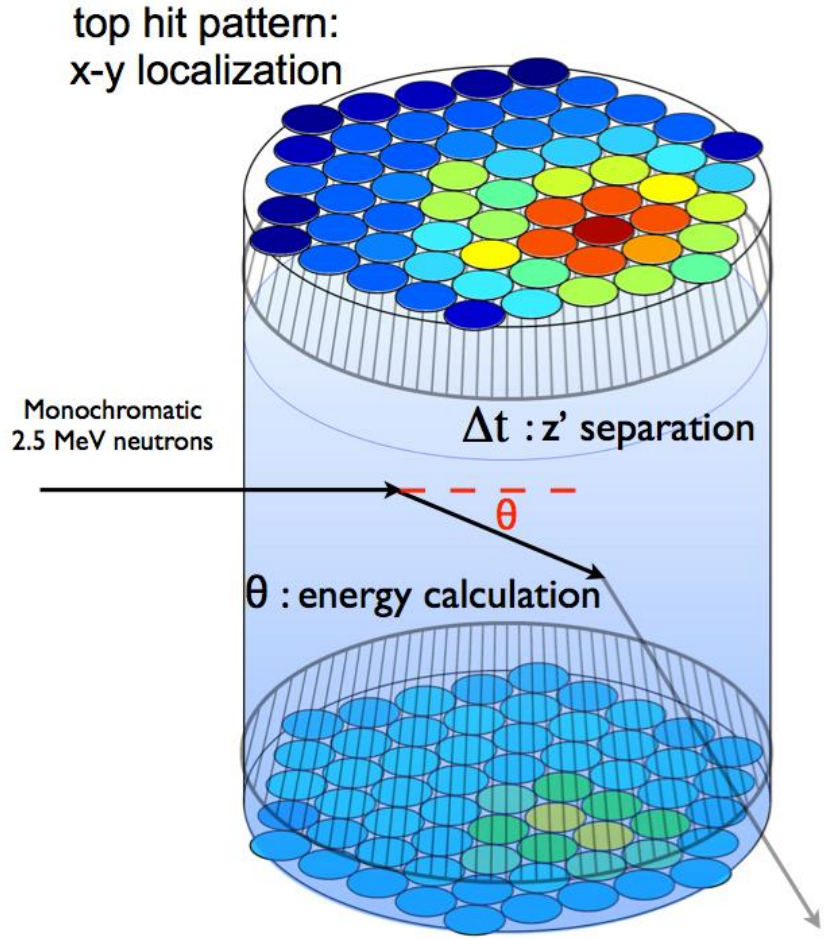
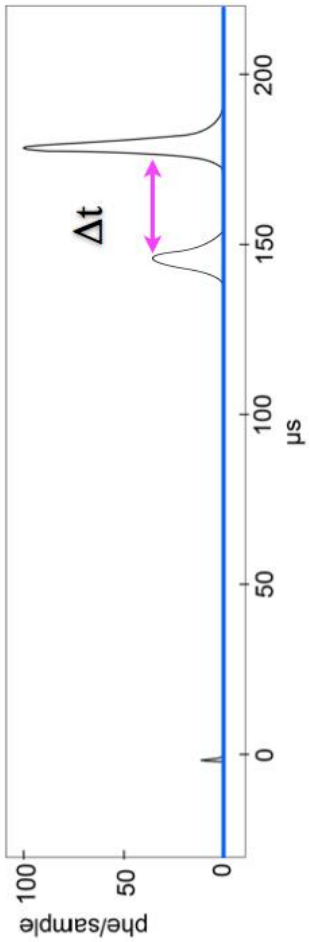
Samuel Chan, Carlos Faham for the LUX Collaboration

NR CALIBRATION WITH KINEMATICALLY-CONSTRAINED NEUTRON SCATTERS





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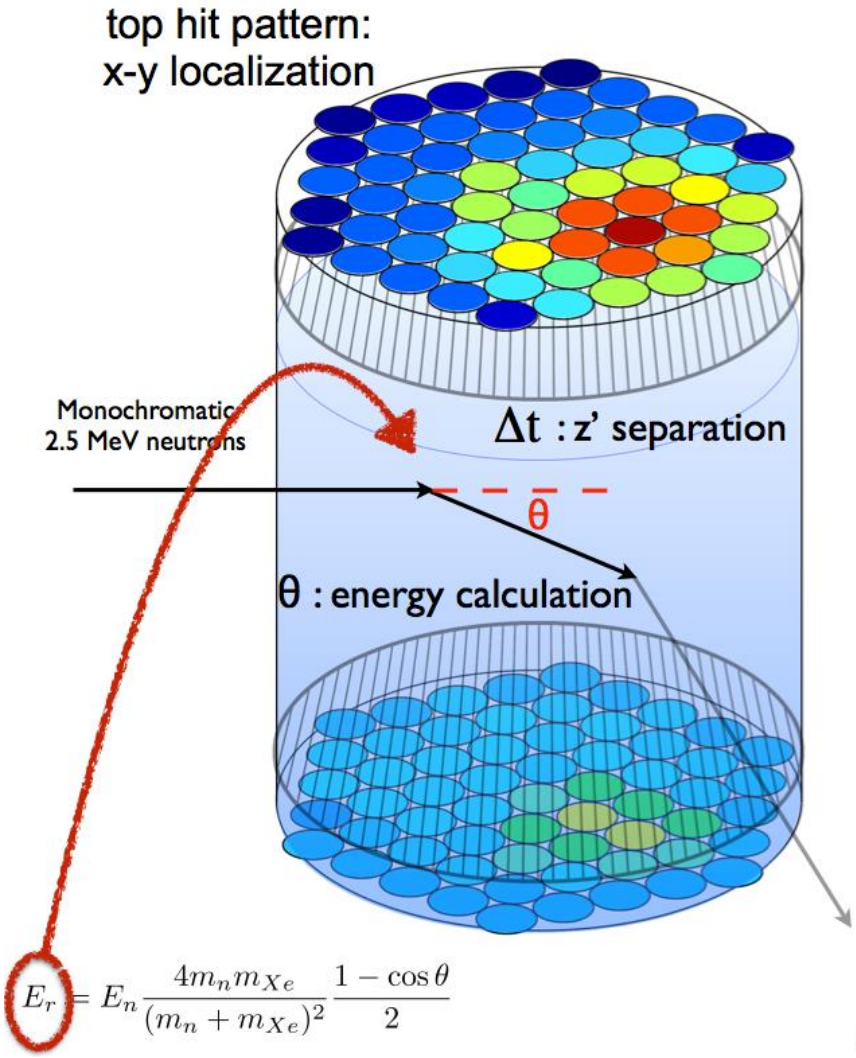
Samuel Chan, Carlos Faham for the LUX Collaboration

NR CALIBRATION WITH KINEMATICALLY-CONSTRAINED NEUTRON SCATTERS



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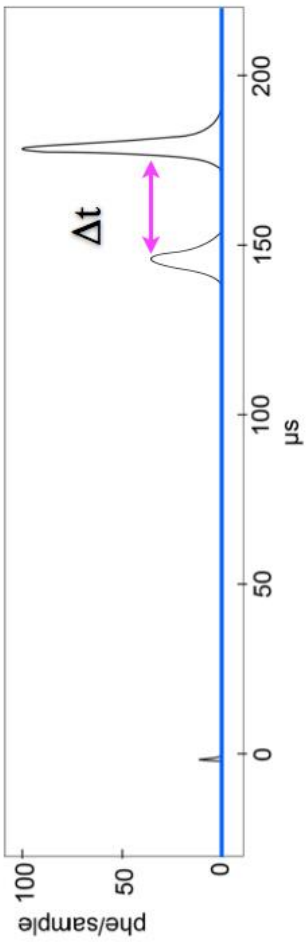

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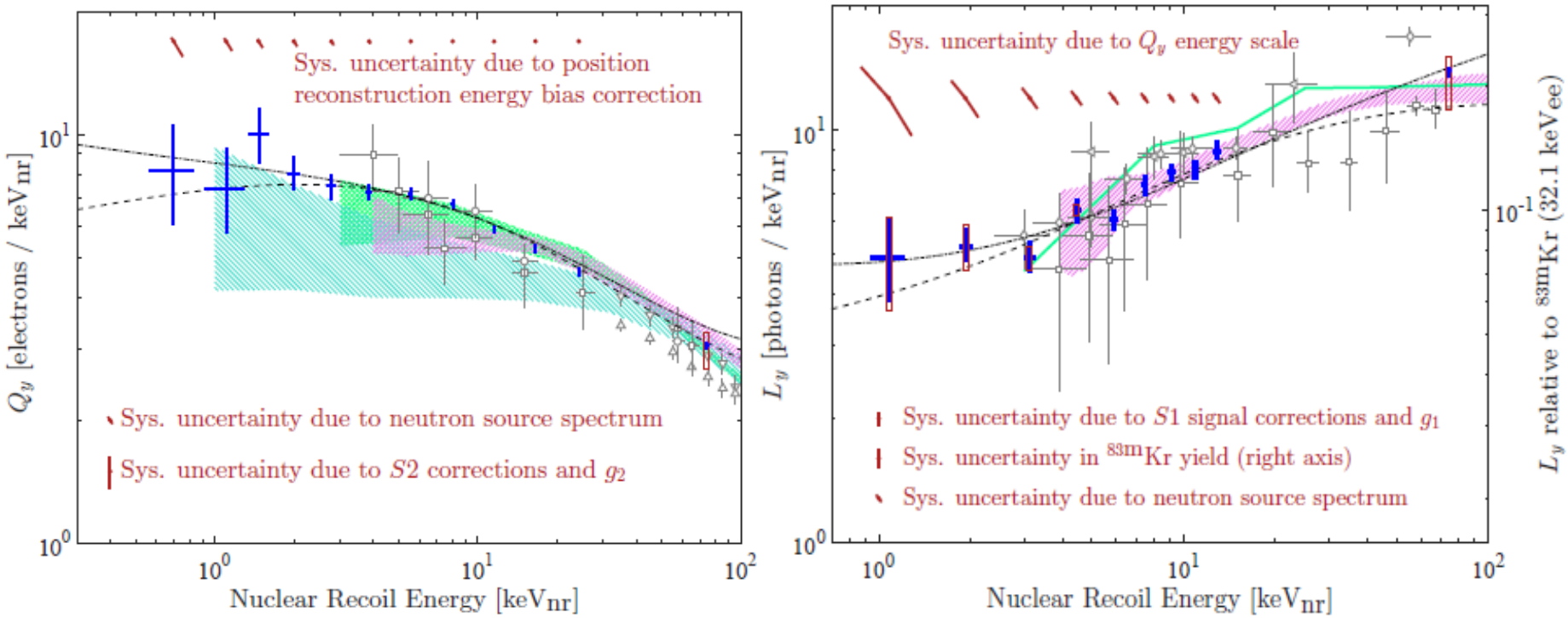
NR CALIBRATION WITH KINEMATICALLY-CONSTRAINED NEUTRON SCATTERS

- S2 yield versus absolute energy measured to 0.7 keV (was 3 keV)
- S1 yield measured to ~1 keV via single scatters (was 3 keV)



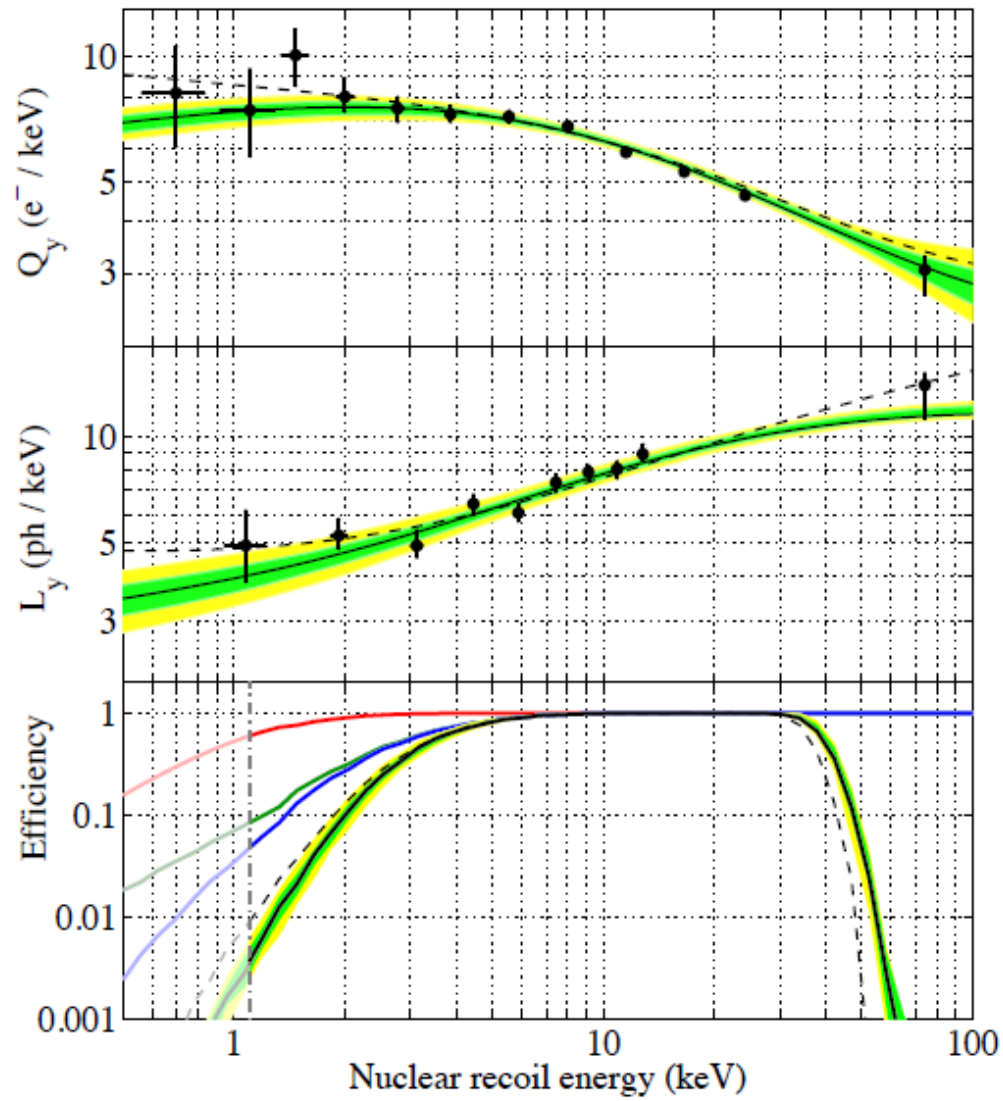
NR YIELDS & DETECTION EFFICIENCY

- **Lindhard** fit (solid line)
  Lindhard 1963
  Fit as in Lenardo 2015
- **Bezrukov** fit (dashed line)
  Bezrukov 2011
- **Add Ly + Qy to obtain $\mathcal{L}$**

$$E_{nr} = \mathcal{L}^{-1} \cdot (n_e + n_\gamma) \cdot W.$$

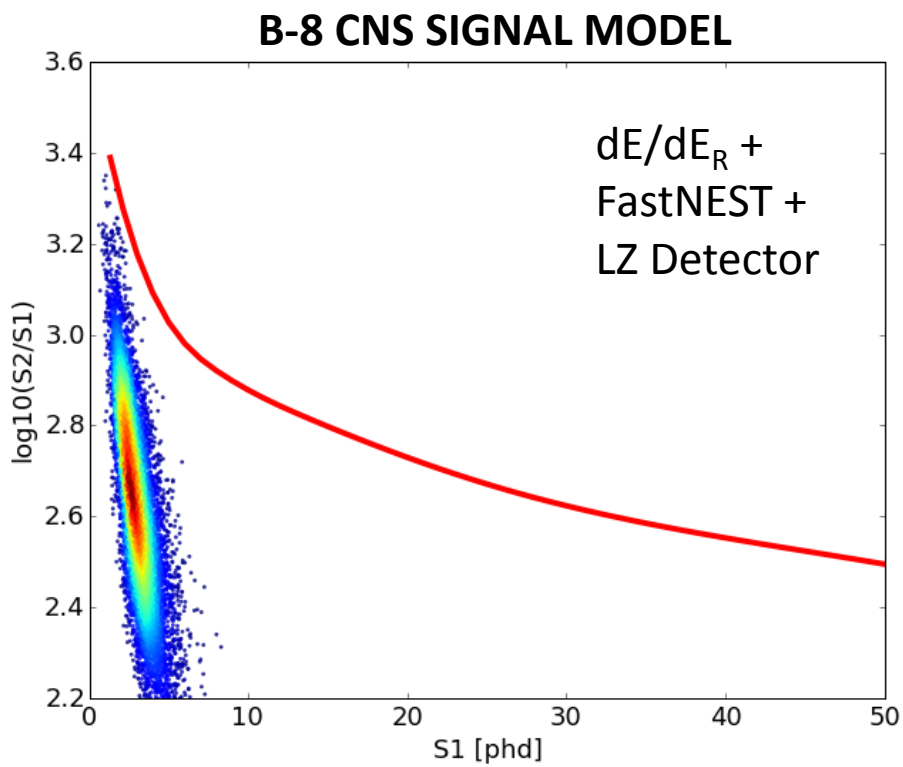
$$L = \frac{k\ g(\epsilon)}{1 + k\ g(\epsilon)}$$

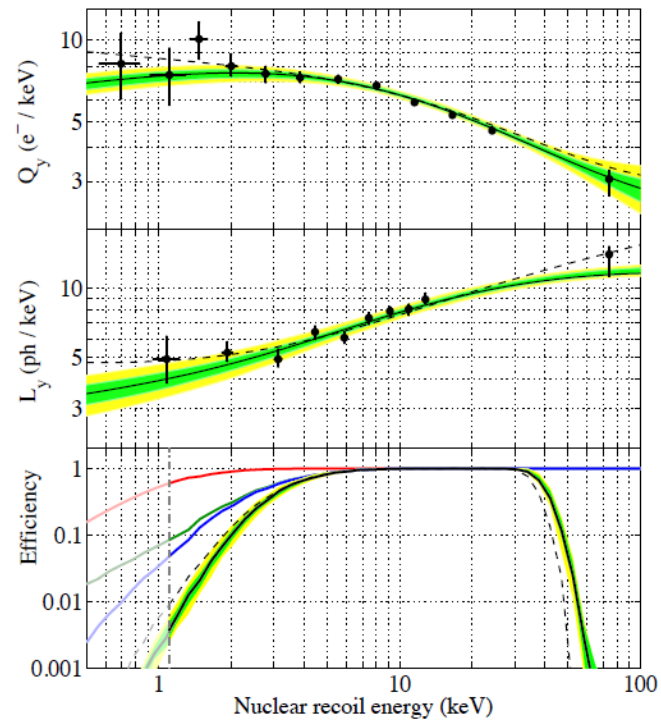
S2: 2 electrons emitted →
S1: 2 photons detected →
Events with S1+S2 →
+ raw S2 cut→



WHERE NEXT?

- Map out scintillation and ionisation yields down to ~0 keV
- Interesting physics is hiding below our threshold of a few keVr
- We run our of S1 but not S2 (still ~8 ionisations at 1 keVr)
- Remember challenge: must reach such energies in a large detector…

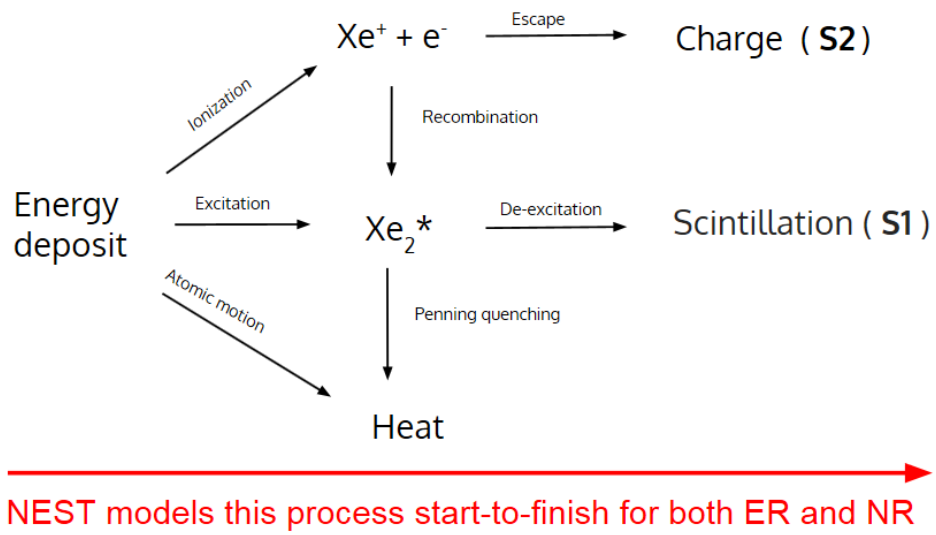




Thank you!

COMING BACK TO NEST

- Detector-independent simulation framework – Physics of interactions in LXe
- Compatible with Geant4, integration into full simulations
- Stand-alone code for fast calculations (FastNEST). Coming soon
- You should use NEST if you want to generate a convincing signal model in liquid xenon



Thomas-Imel recombination model

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

$$N_q = \frac{E_{\text{dep}}}{W}$$

ER

NR

$$N_q = N_q \, L$$

$$N_{\text{ion}} = \frac{N_q}{1 + (N_{ex}/N_{ion})}$$

$$N_{\text{ex}} = N_q - N_{\text{ion}}$$

$$n_e = (1 - r) N_{\text{ion}}$$

$$n_\gamma = (N_q - n_e) \frac{1}{1 + \alpha \, \epsilon^\beta}$$

Lindhard suppression of NR signal

$$L = \frac{k \, g}{1 + k \, g}$$

NEST is free and publicly available: http://www.albany.edu/physics/NEST.shtml – see recent slides

NR model (LUX/NEST)

Charge production:

$$n_e = L(E_0) \times \frac{E_0}{W}\left(\frac{1}{1+N_{ex}/N_i}\right)(1-r) + C\,\frac{n_{ph}}{f_l}(1-f_l)$$

Light production:

$$n_{ph} = L(E_0) \times \frac{E_0}{W}\left(1 - \frac{1}{1+N_{ex}/N_i}(1-r)\right) \times f_l$$

Five free parameters:

- N_{ex} / N_i
- TIB (4 ς)
- A
- k or α
- C

NR signal loss:

$$L = \frac{k\ g(\epsilon)}{1+k\ g(\epsilon)} \quad \text{or} \quad \alpha\frac{s_e}{s_e+s_n}$$

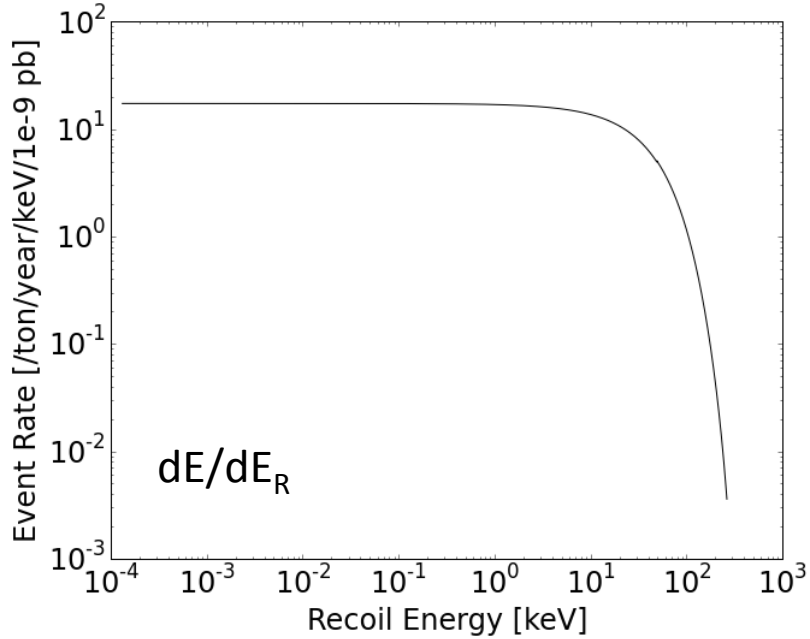
Bi-excitonic quenching / ionization:

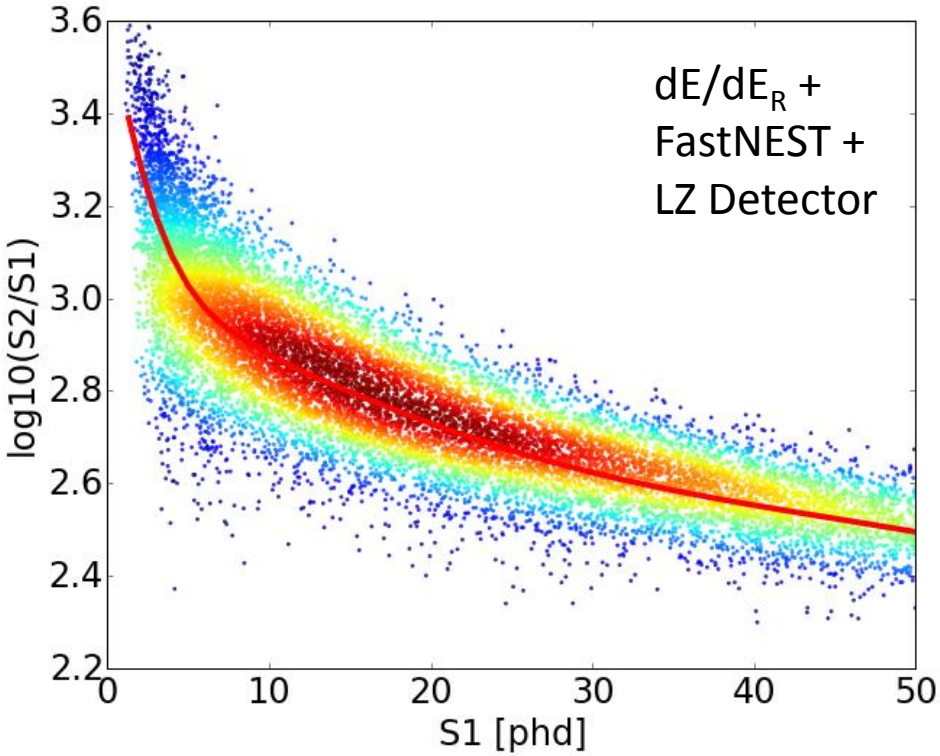
$$f_l = \frac{1}{1+A\ s_e}$$

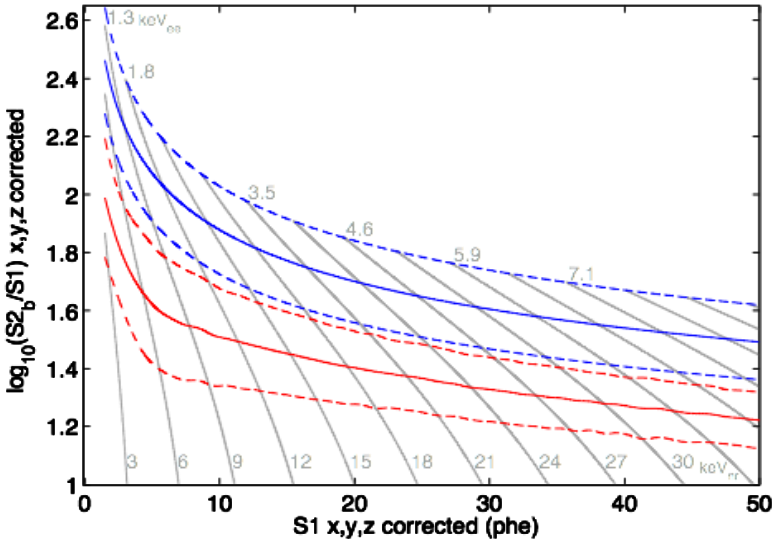
Thomas-Imel recombination:

$$r = 1 - \frac{\ln(1+N_i\,\varsigma)}{N_i\,\varsigma}$$

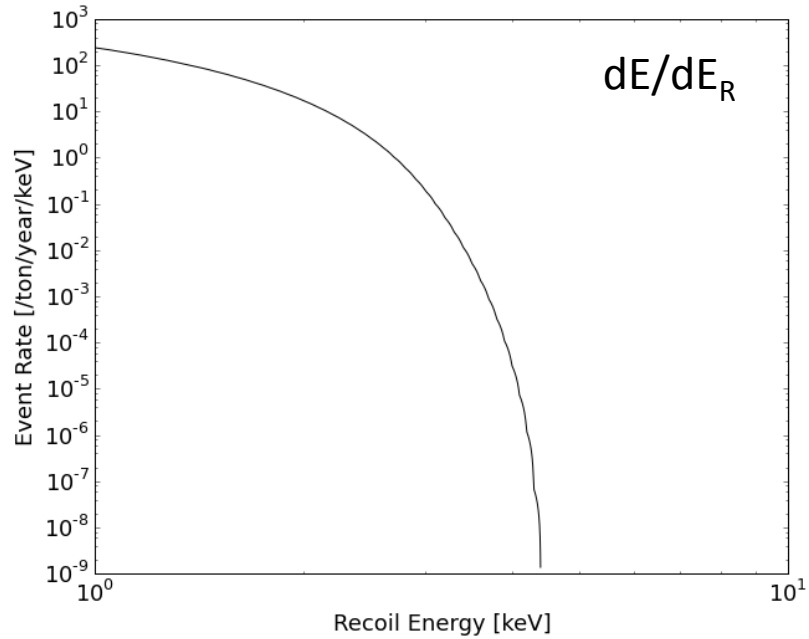
SIGNAL MODEL: HEAVY WIMPS

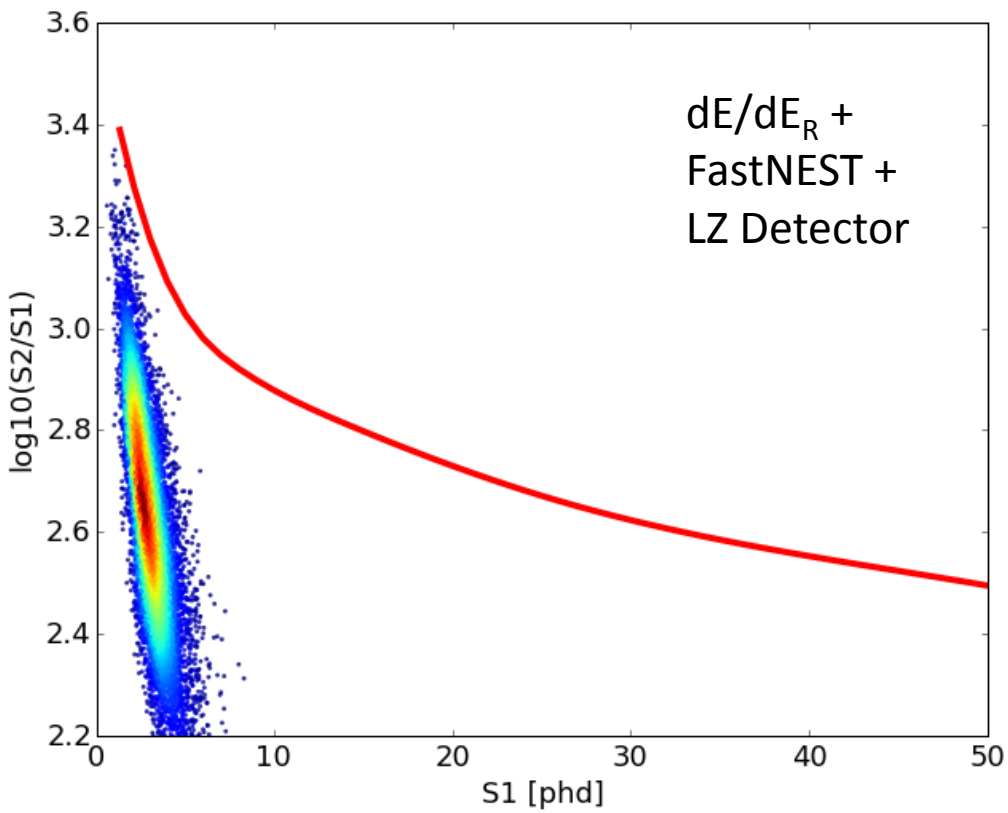


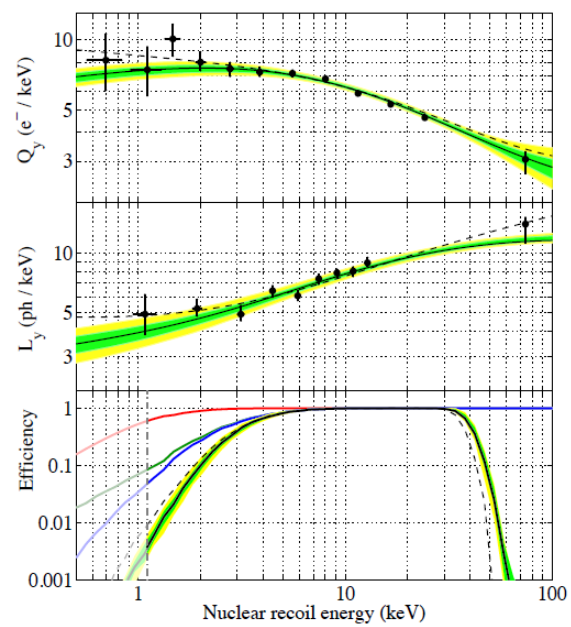




SIGNAL MODEL: B-8 NEUTRINOS (OR LIGHT WIMP)

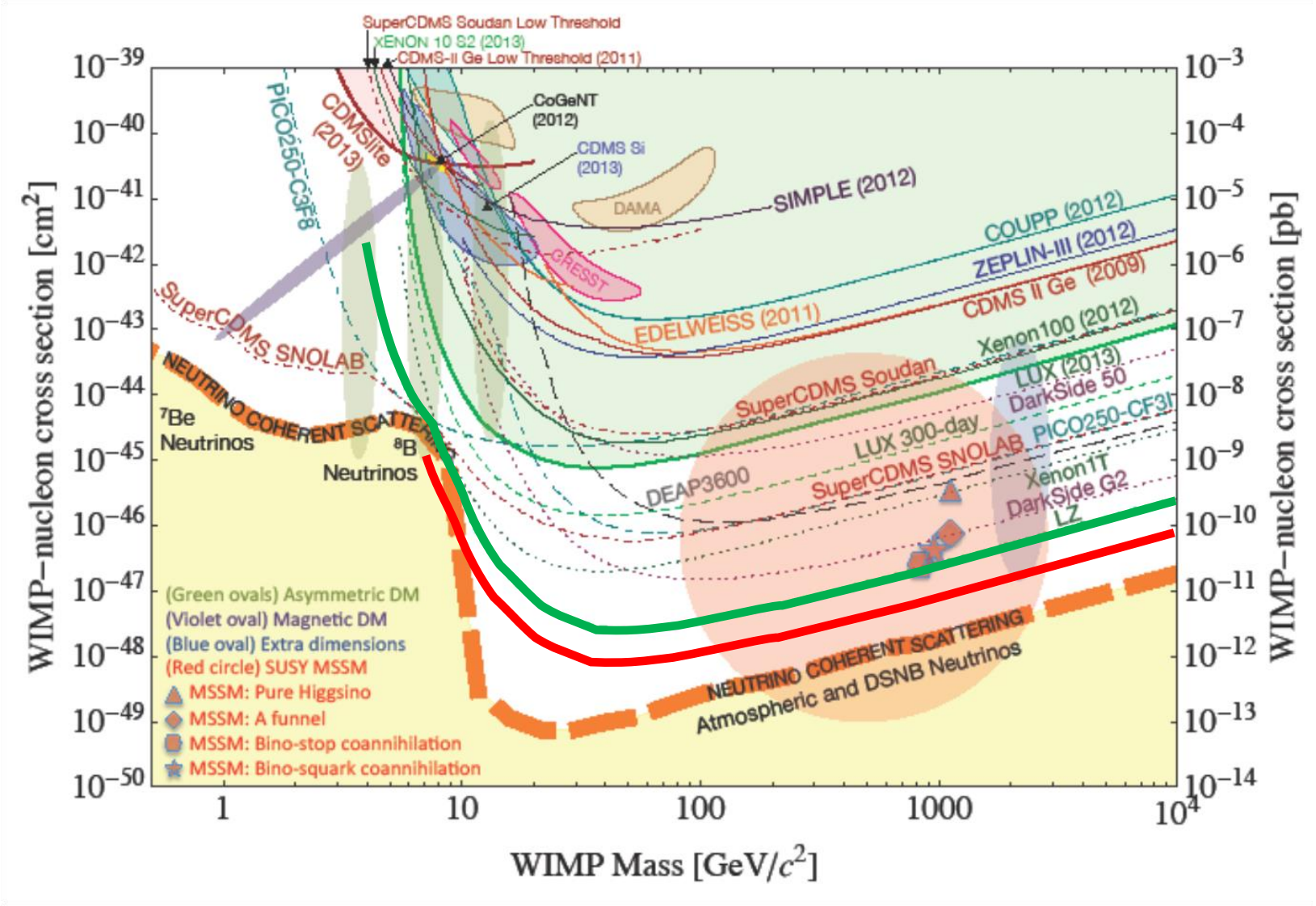






Requirement: 3×10^{-48} cm^2 at 50 GeV

LZ SENSITIVITY



NR model (LUX/NEST)