Imperial College
London

SHEDDING LIGHT ON DARK MATTER WITH LUX

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On behalf of the LUX Collaboration

University of Birmingham, 14 May 2014

OUTLINE

- Why dark matter(s)
- Catching WIMPs with the noble liquid xenon
- **Fiat LUX! First results**
- Beyond LUX and ZEPLIN

How do you solve a problem like DM?

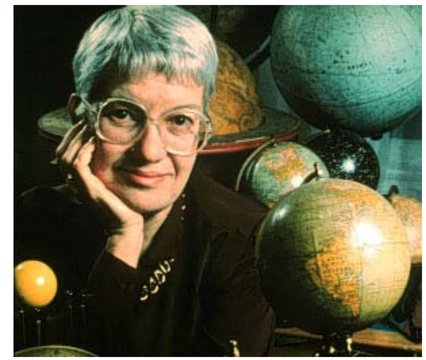
- Astrophysics

Astrophysical structures do not contain enough visible matter to keep them gravitationally bound

1970 ApJ 159, 379

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

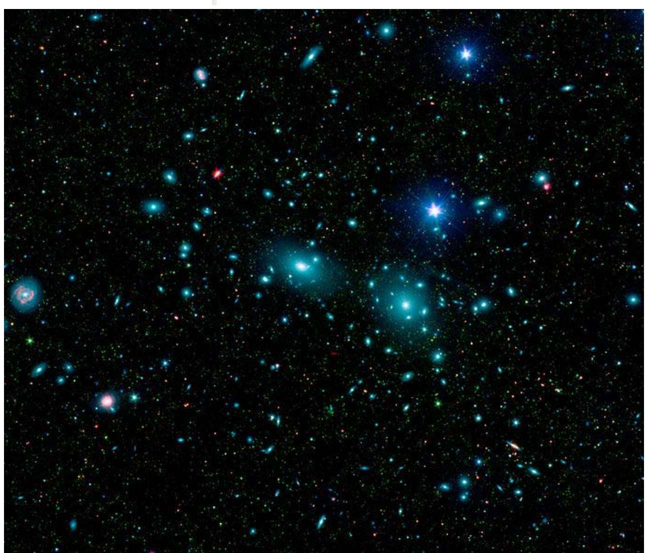
VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

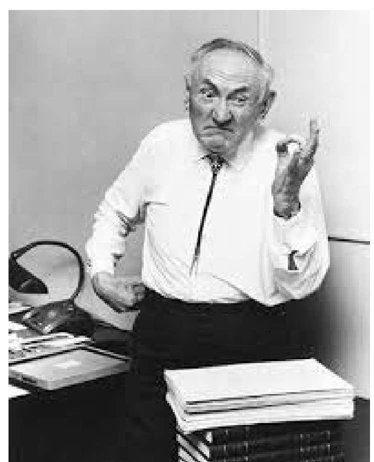


1937 ApJ 86, 217

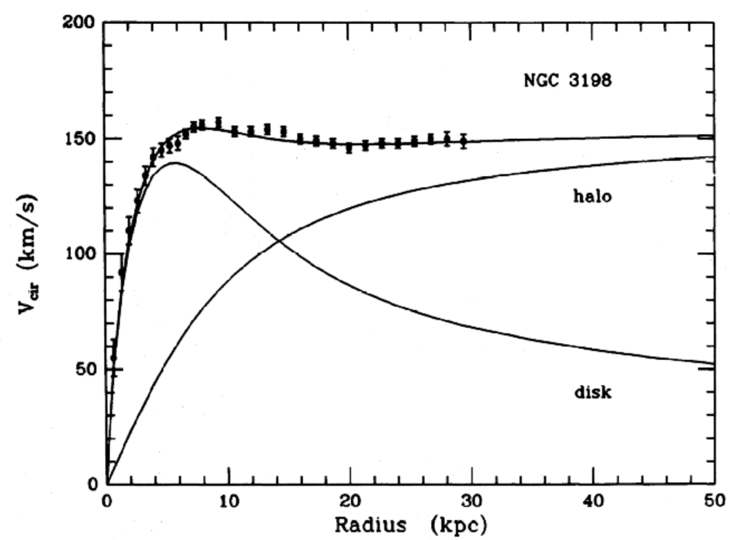
ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY





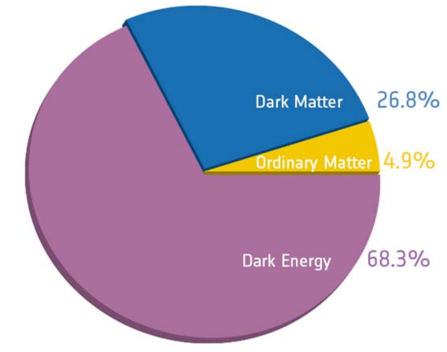
DISTRIBUTION OF DARK MATTER IN NGC 3198



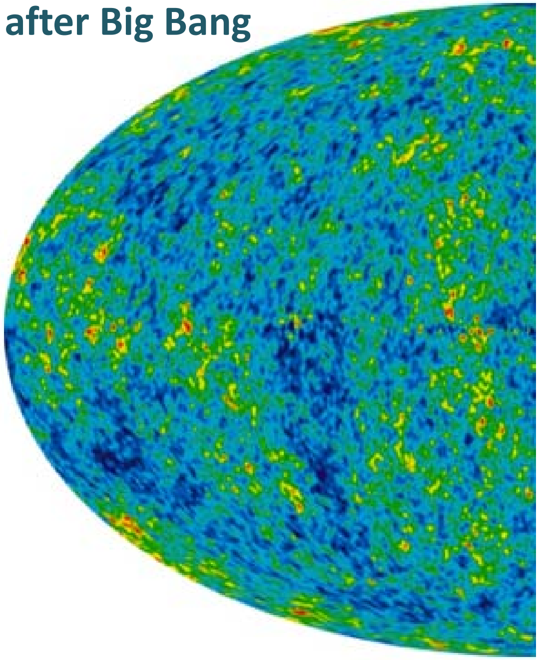
How do you solve a problem like DM?

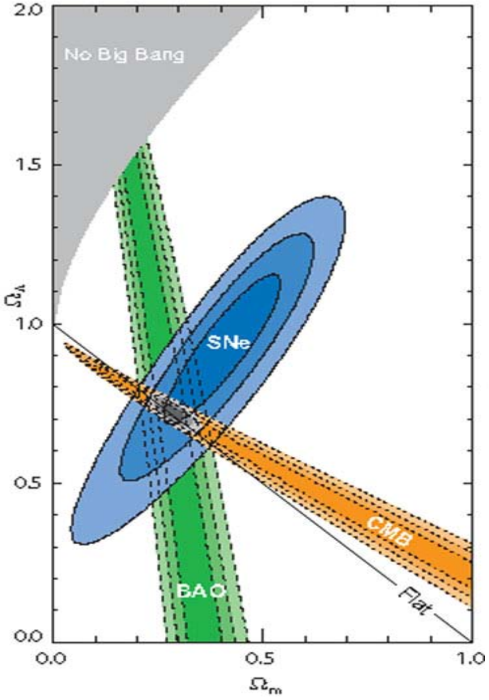
- Cosmology

  Λ-CDM is extremely successful: with two dark components (DE & DM), it predicts the distribution and evolution of the baryonic matter (the other 5%)

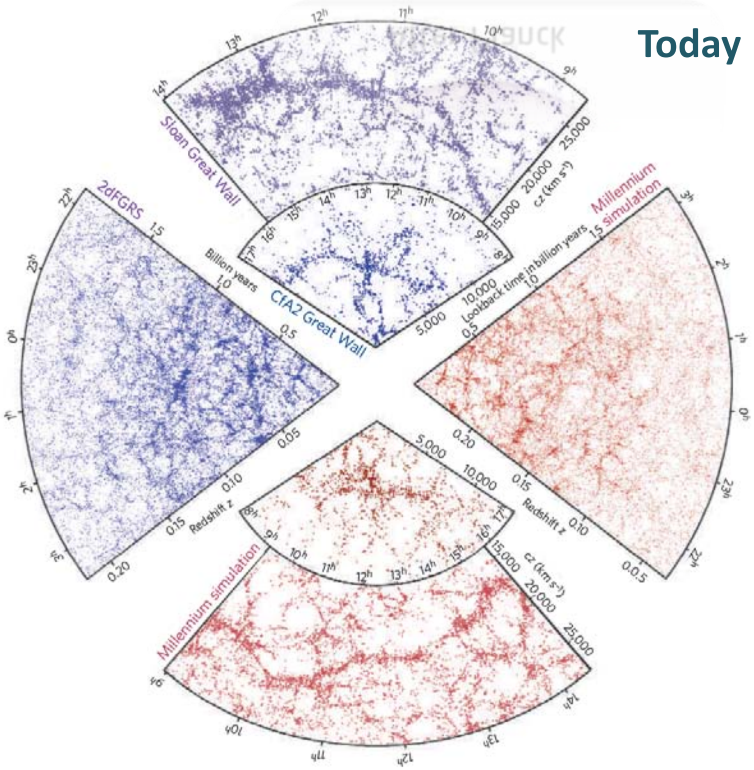


380,000 years after Big Bang





Today



How do you solve a problem like DM?

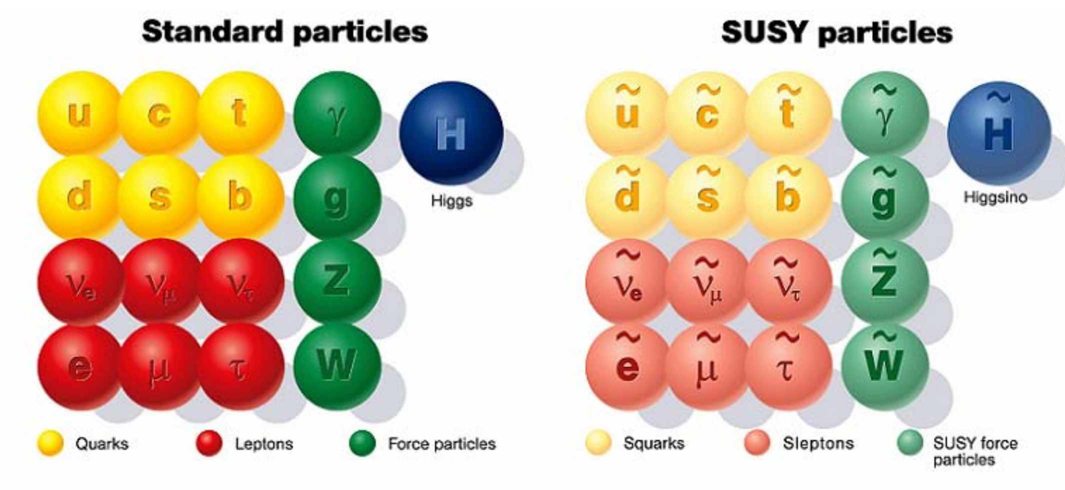
- Particle physics

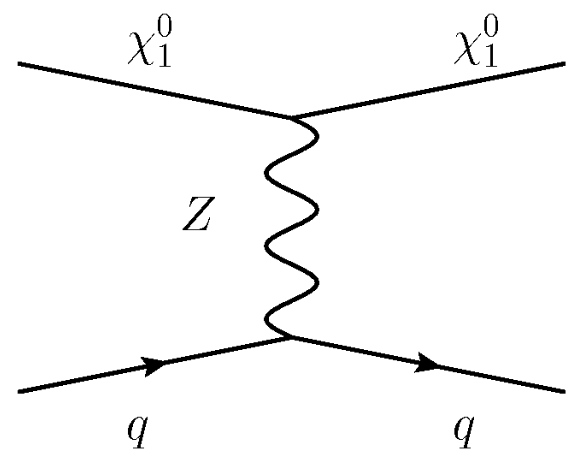
There is Physics Beyond the Standard Model (besides the obvious…)

E.g., why is the Higgs so light?

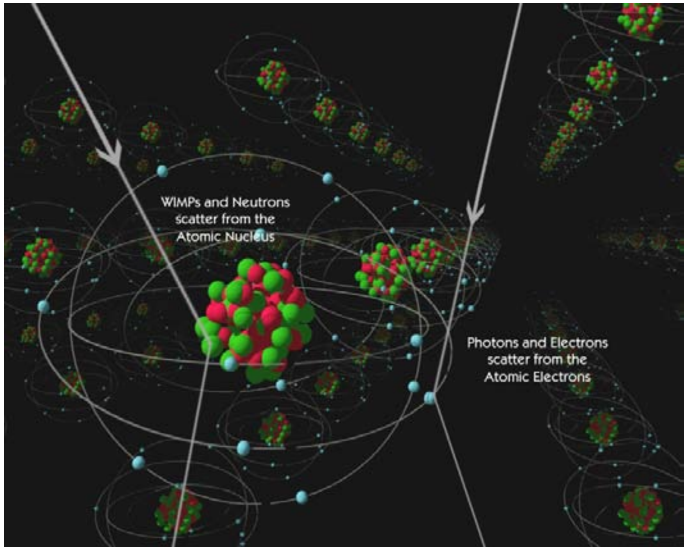
Supersymmetry can protect the Higgs mass from quantum corrections and keep it at the electroweak scale. SUSY would – quite independently – provide excellent dark matter candidates.

But no sign of SUSY at the LHC yet…



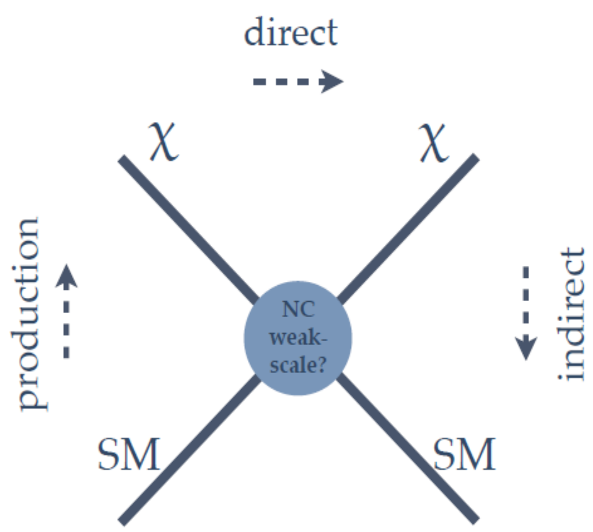


How to catch a WIMP



1. Direct detection (scattering XS)

- **Nuclear (atomic) recoils from elastic scattering**
- (annual modulation, directionality, A + J dependence)
- Galactic DM at the Sun's position – our DM!
- Mass measurement (if not too heavy)



2. Indirect detection (decay, annihil. XS)

- High-energy cosmic-rays, γ-rays, neutrinos, etc.
- Over-dense regions, annihilation signal $\propto n^2$
- Challenging backgrounds

3. Accelerator searches (production XS)

- Missing transverse energy, monojets, etc.
- Good place to look for particles…
- Mass measurement poor (at least initially)
- May not establish that new particle is the DM…

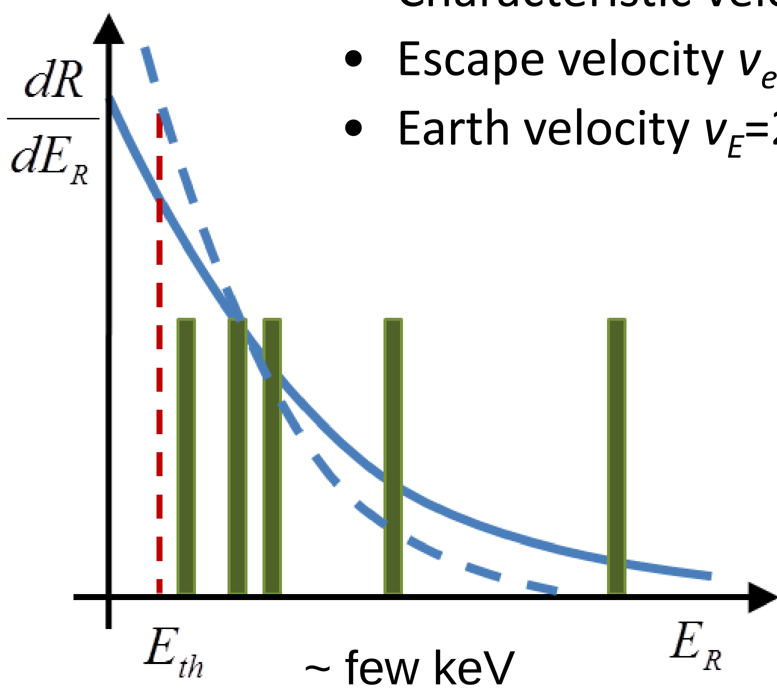
WIMP-nucleus elastic scattering rates

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

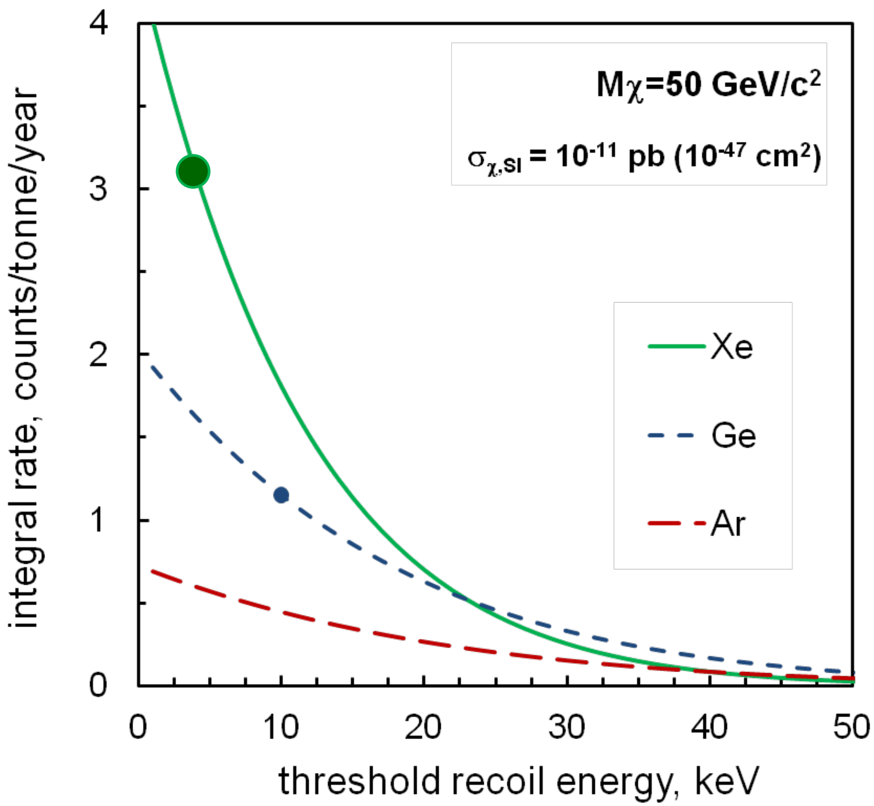


Nuclear recoil energy spectrum [events/kg/day/keV]

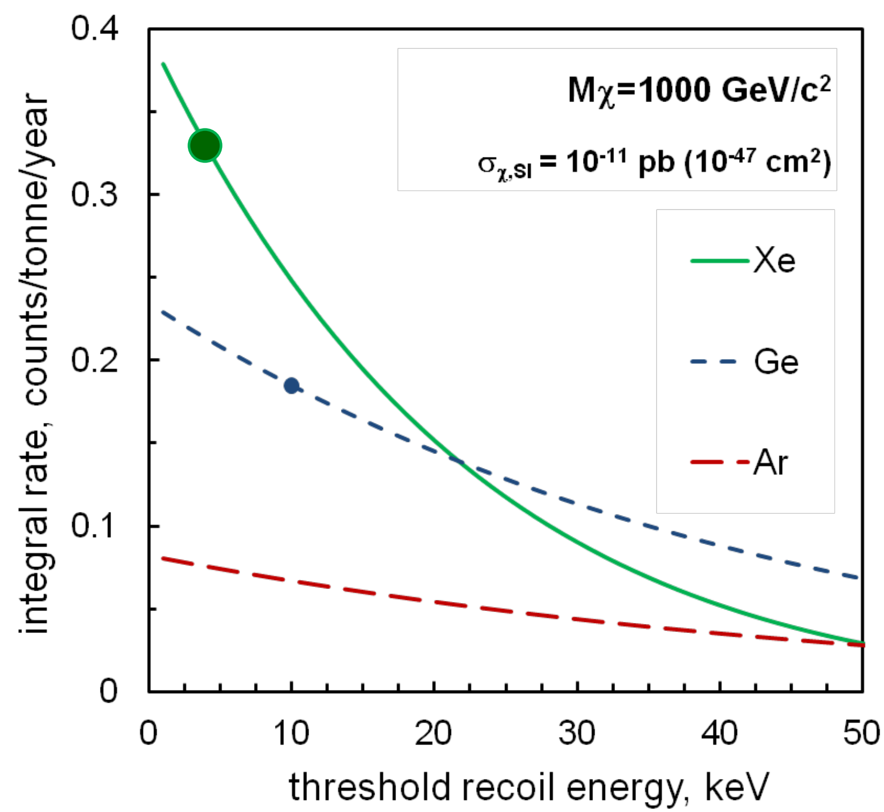
$$\frac{dR}{dE_R} = \frac{\rho_0 \sigma_A}{2 m_\chi \mu_A^2} F^2(q) \int_{v_{\min}}^{v_{\max}} \frac{f(\vec{v})}{v} d^3 v$$

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

THE NOBLE LIQUID XENON



Scattering rates for
← intermediate
and ↓ heavy WIMPs



Searches for

RARE *and* LOW ENERGY events:

a challenging combination

WIMP SEARCH TECHNOLOGY ZOO

Ionisation Detectors

Targets: Ge, Si, CS_2, CdTe

CoGeNT, DRIFT, DM-TPC

GENIUS, HDMS, IGEX, NEWAGE

Light & Ionisation Detectors

Targets: Xe, Ar

ArDM, **LUX**, WARP,

XENON, **ZEPLIN**

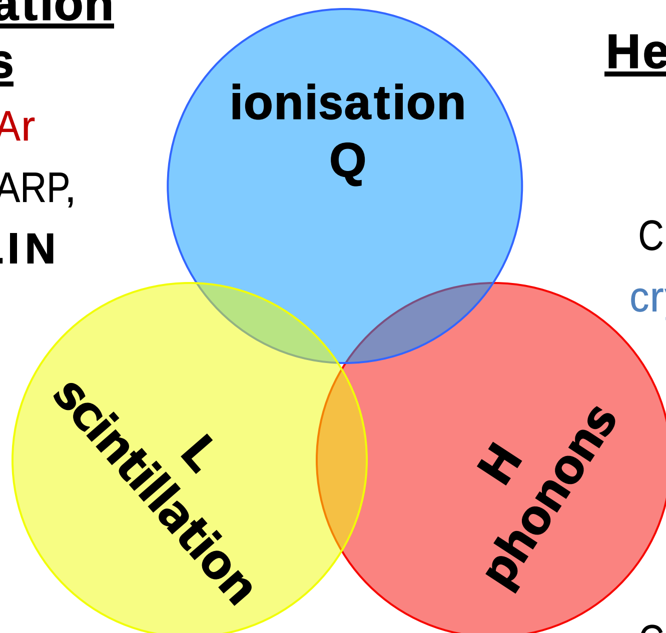
cold (LN_2)

Heat & Ionisation Bolometers

Targets: Ge,Si

CDMS, EDELWEISS

cryogenic (<50 mK)



Scintillators

Targets: NaI, Xe, Ar

ANAIS, CLEAN, DAMA,

DEAP, KIMS, LIBRA,

NAIAD, XMASS, ZEPLIN-I

Bolometers

Targets: Ge, Si, Al_2O_3, TeO_2

CRESST-I, CUORE, CUORICINO

Light & Heat Bolometers

Targets: $CaWO_4$, BGO, Al_2O_3

CRESST, ROSEBUD

cryogenic (<50 mK)

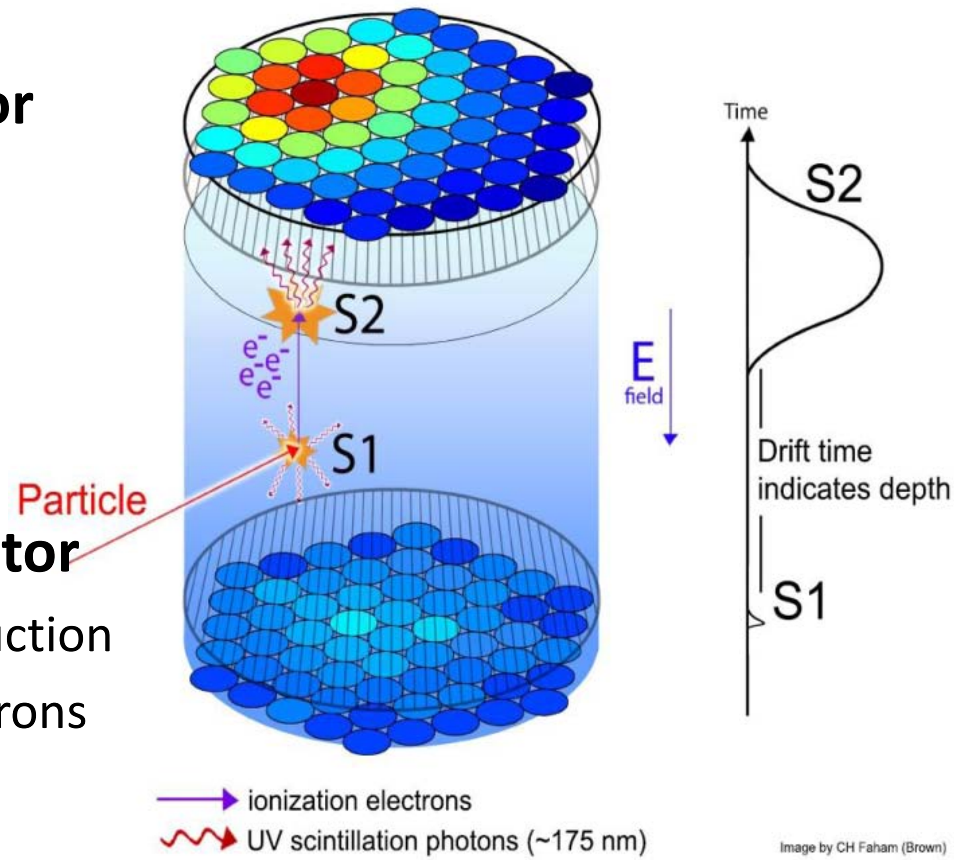
Bubbles & Droplets

CF_3Br, CF_3I, C_3F_8, C_4F_{10}

COUPP, PICASSO, SIMPLE

TWO-PHASE XENON DETECTOR / TPC

- **S1: LXe is an excellent scintillator**
  - Density: 3 g/cm^3
  - Light yield: >60 ph/keV (0 field)
  - Scintillation light: 178 nm (VUV)
  - **Nuclear recoil threshold ~5 keV**
- **S2: Even better ionisation detector**
  - S1+S2 allows mm vertex reconstruction
  - Sensitive to single ionisation electrons
  - **Nuclear recoil threshold <1 keV**



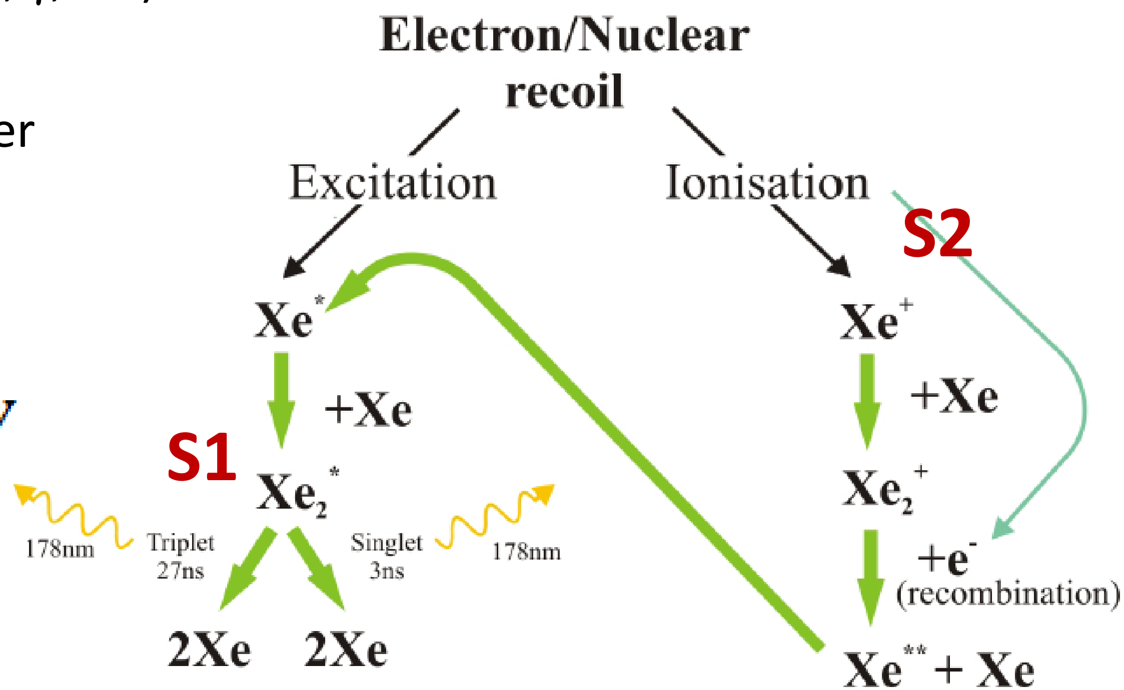
- **And a great WIMP target too**
  - Scalar WIMP-nucleon scattering rate dR/dE~A^2
  - Odd-neutron isotopes (^{129}Xe, ^{131}Xe) enable spin-dependent sensitivity
  - No damaging intrinsic backgrounds (^{127}Xe, $^{129m/131m}$Xe, ^{85}Kr, ^{136}Xe)

RESPONSE MECHANISM

- Understanding the detector response to nuclear recoils (NR) and electron recoils (ER) around detection threshold is crucial
- Electron-ion recombination is the key parameter
- NEST model able to predict S1 and S2 signals as a function of:
  - Particle species (α, β, γ, NR)
  - Applied electric field
  - Light yield of chamber
  - Recoil energy

$$E_{ee} = (n_\gamma + n_e)\, W$$

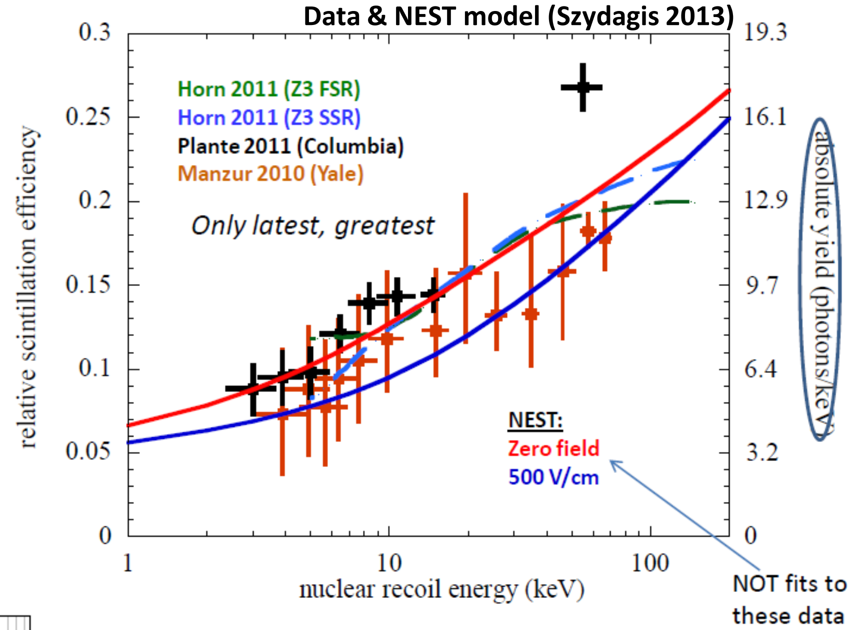
$$E_{nr} = \mathcal{L}^{-1}(n_\gamma + n_e)\, W$$

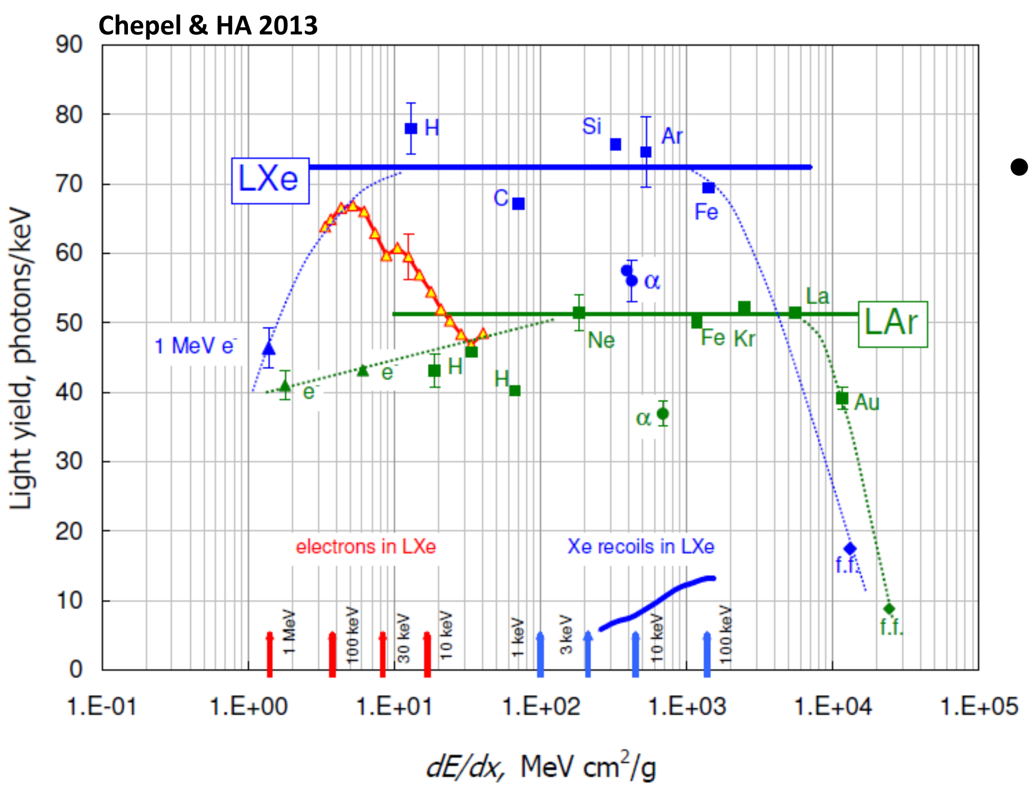


NEST (Noble Element Simulation Technique)
***Szydagis et al*, JINST 8 C10003 (2013)**
***Szydagis et al*, arXiv:1106.1613 (2011)**

SCINTILLATION (S1)

- **Detected with low-background photomultiplier tubes in high reflectance chamber**
  - 178 nm emission (no WLS)

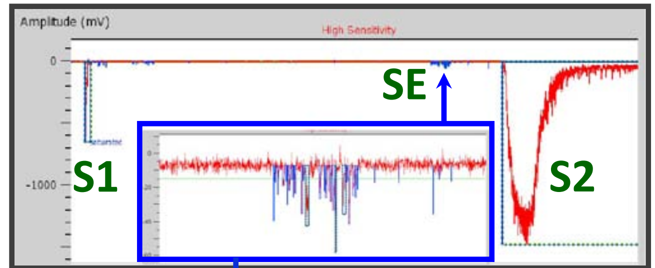




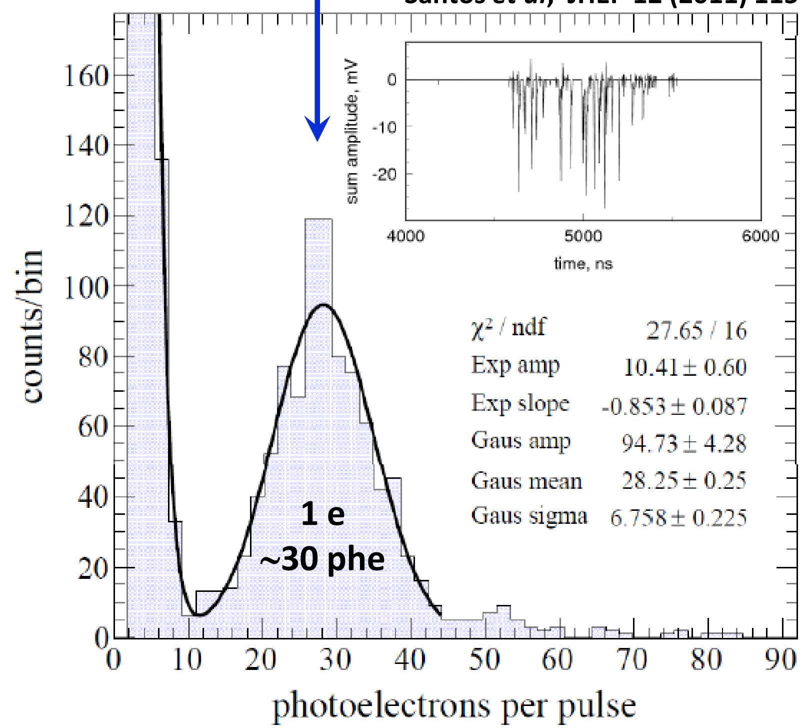
- **Nuclear recoil yield (L_{eff})**
  - Measured with neutrons
  - Quenched wrt electron recoils
  - dE/dx model no good at low E!
  - **Decreases gently to lower energy down to ~3 keV (measured)**

IONISATION (S2)

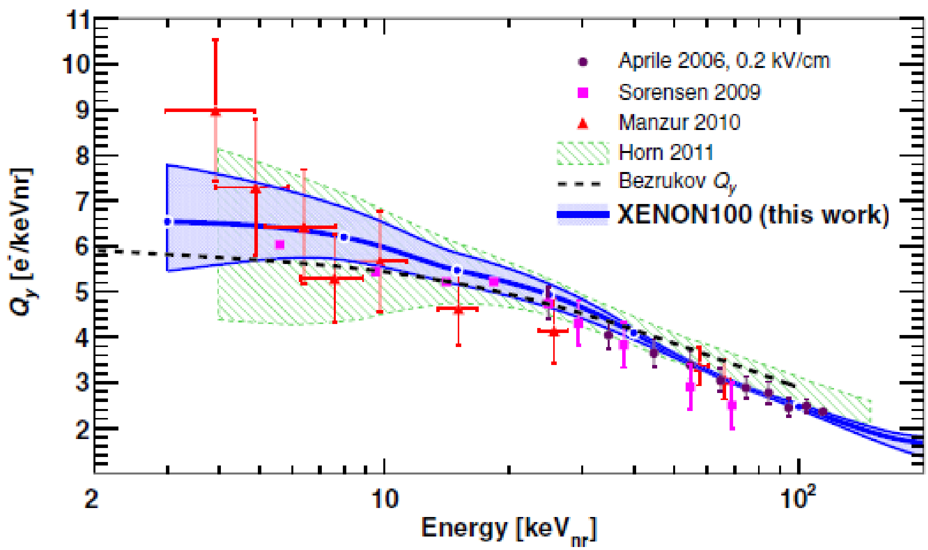
- **Measured via electroluminescence in xenon vapour**
  - Single electron sensitivity (easily)
  - High ionisation yield
  - Allows highly efficient trigger
  - Position and energy estimation
  - **Increases gently to lower energy down to ~3 keV (measured)**



Santos *et al*, JHEP 12 (2011) 115



E. APRILE *et al.*



BACKGROUND MITIGATION STRATEGY

Low background environment

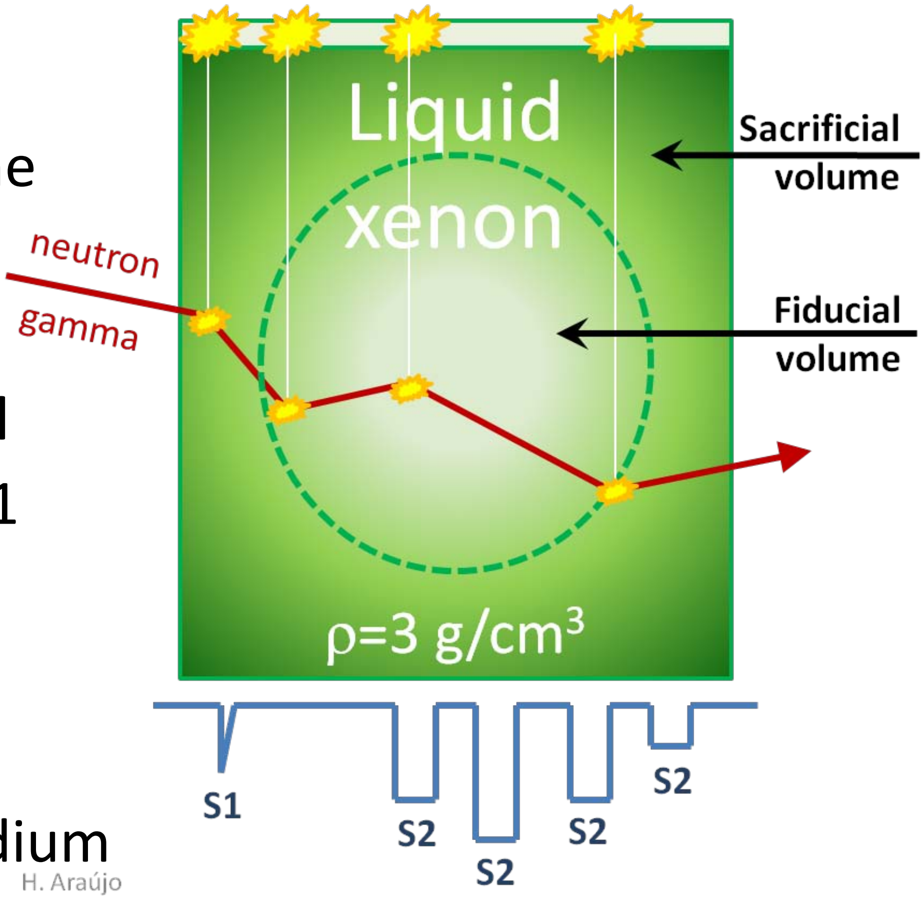
- Operation deep underground
- Material screening programme
- Local shielding (e.g. water)

Reject dominant ER background

- ER-NR discrimination by S2/S1 (electric field, light collection)

Exploit self-shielding

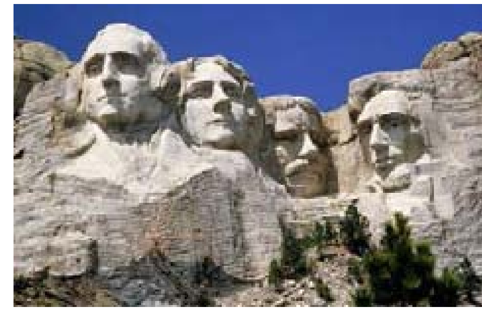
- Large, dense, continuous medium allied to good vertex resolution (few mm)

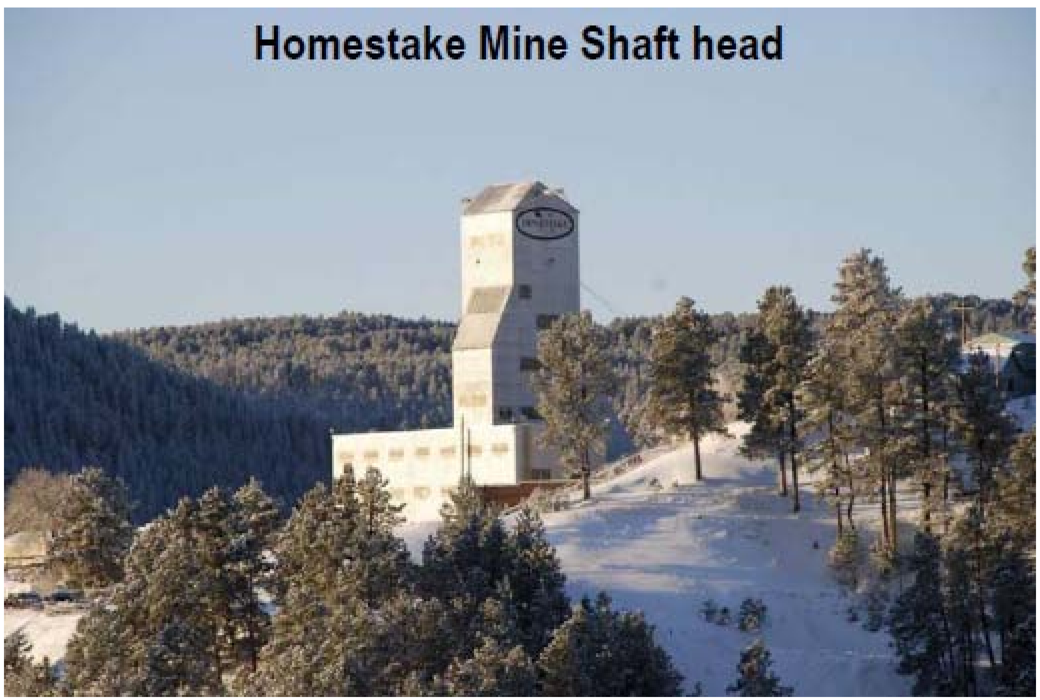


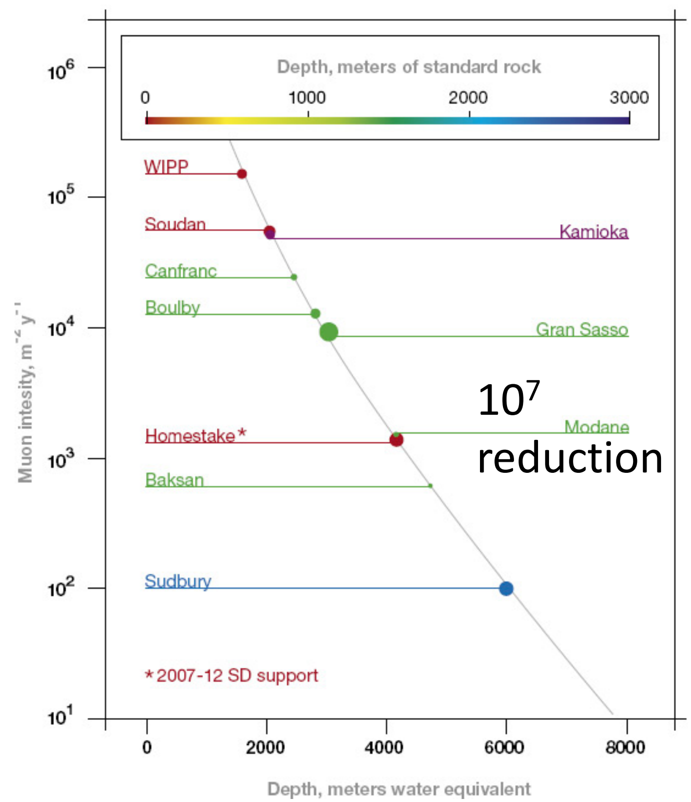
LARGE UNDERGROUND XENON EXPERIMENT

SANFORD UNDERGROUND RESEARCH FACILITY

Former Homestake Mine, Lead, South Dakota



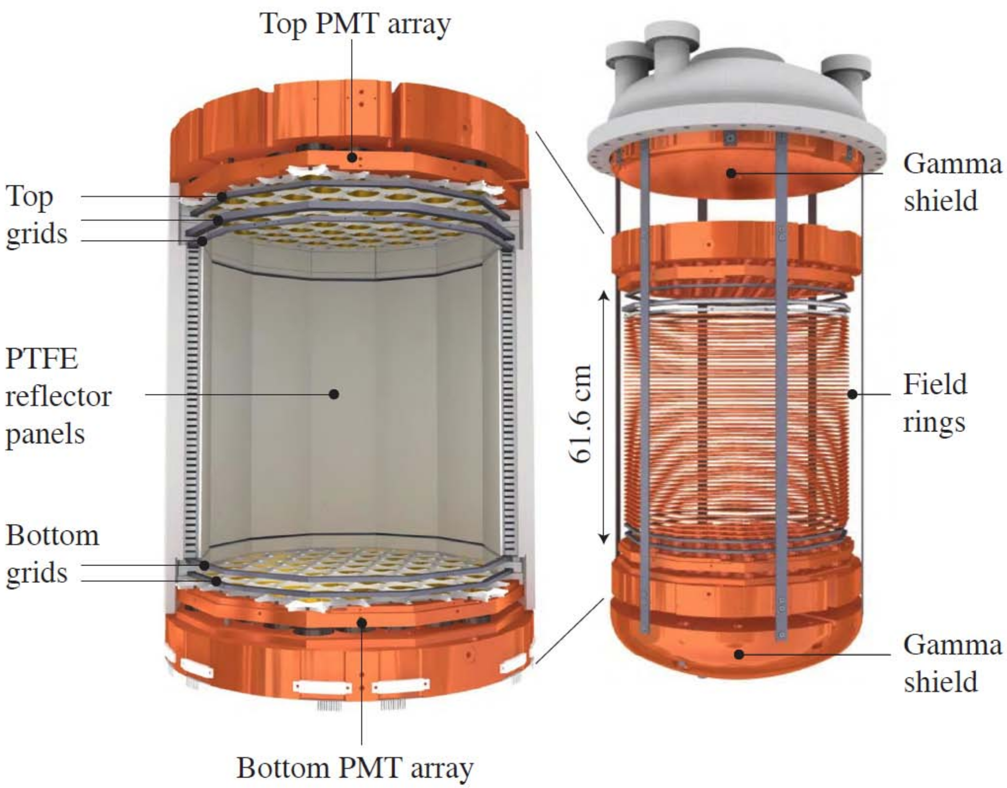


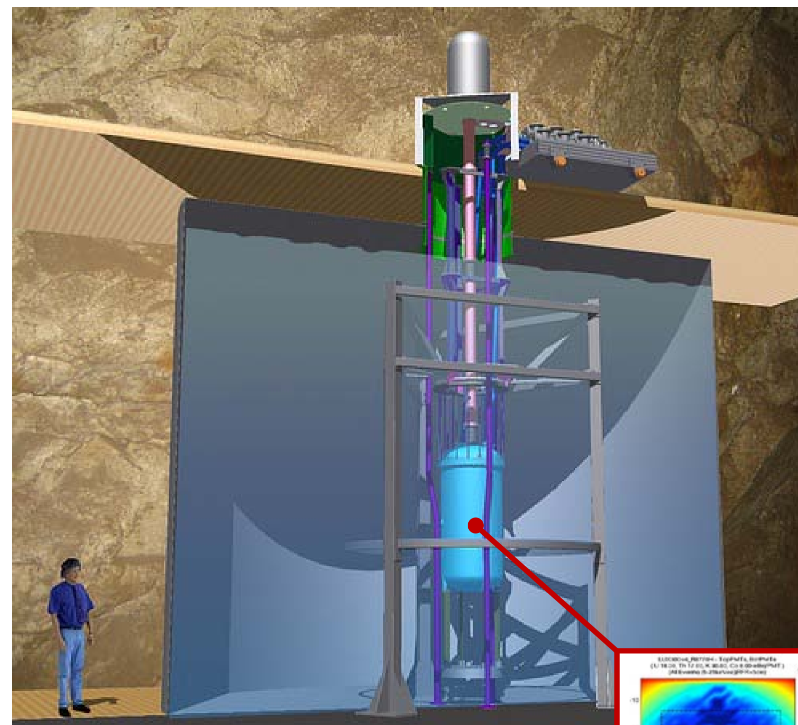


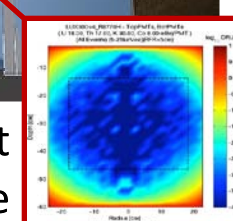
LARGE UNDERGROUND XENON EXPERIMENT

Two-phase xenon detector – LXe Time Projection Chamber

- 250 kg (active) mass of ultrapure liquid xenon (370 kg total)
- S1 and S2 light read out by two arrays of 62 ULB photomultiplier tubes
- External radioactivity shielded by ultrapure water (muon Cerenkov detector)







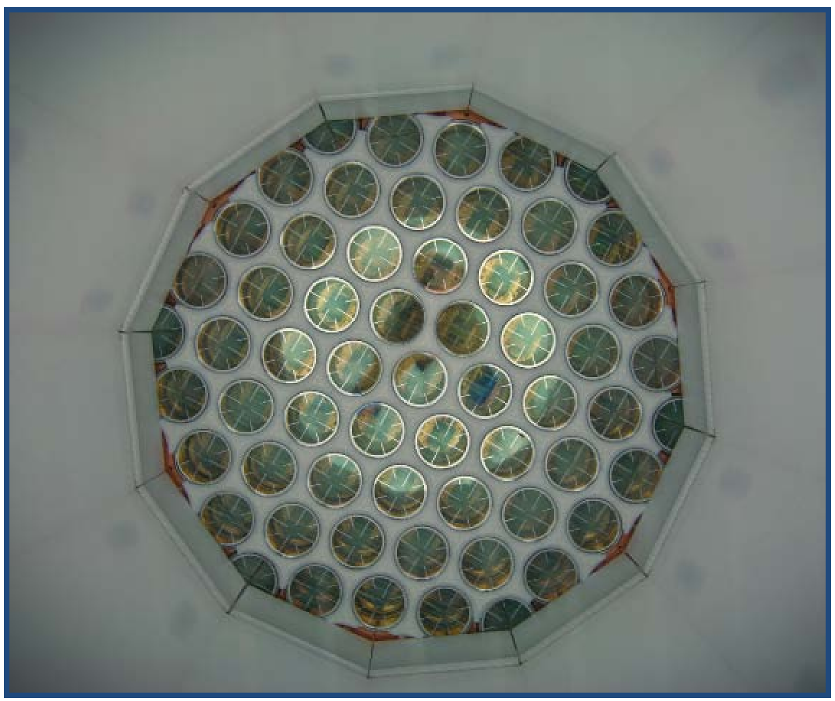
It's quiet in the middle

H Araújo

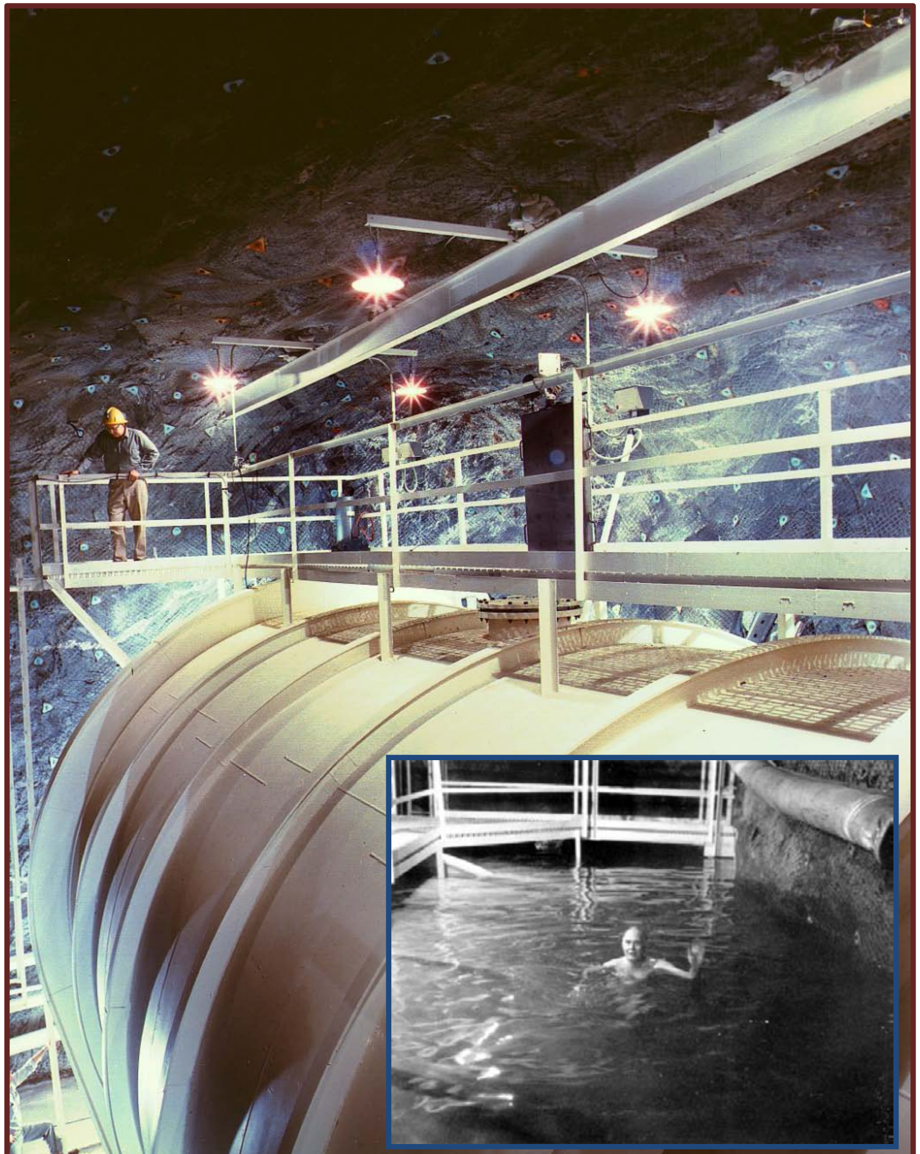
CONSTRUCTION & SURFACE TESTS

LUX Detector: arxiv:1211.3788

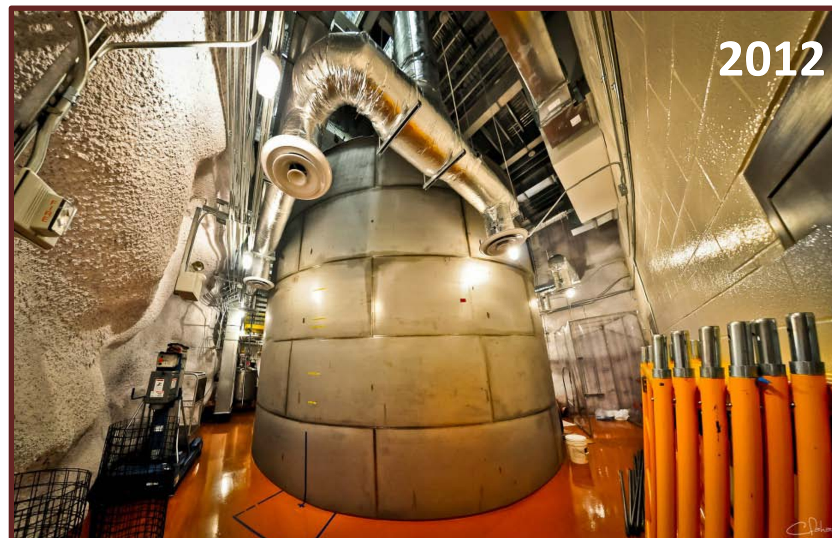
Surface tests: arxiv:1210.4569



SURF – DAVIS CAVERN, 4850-FT U/G LEVEL

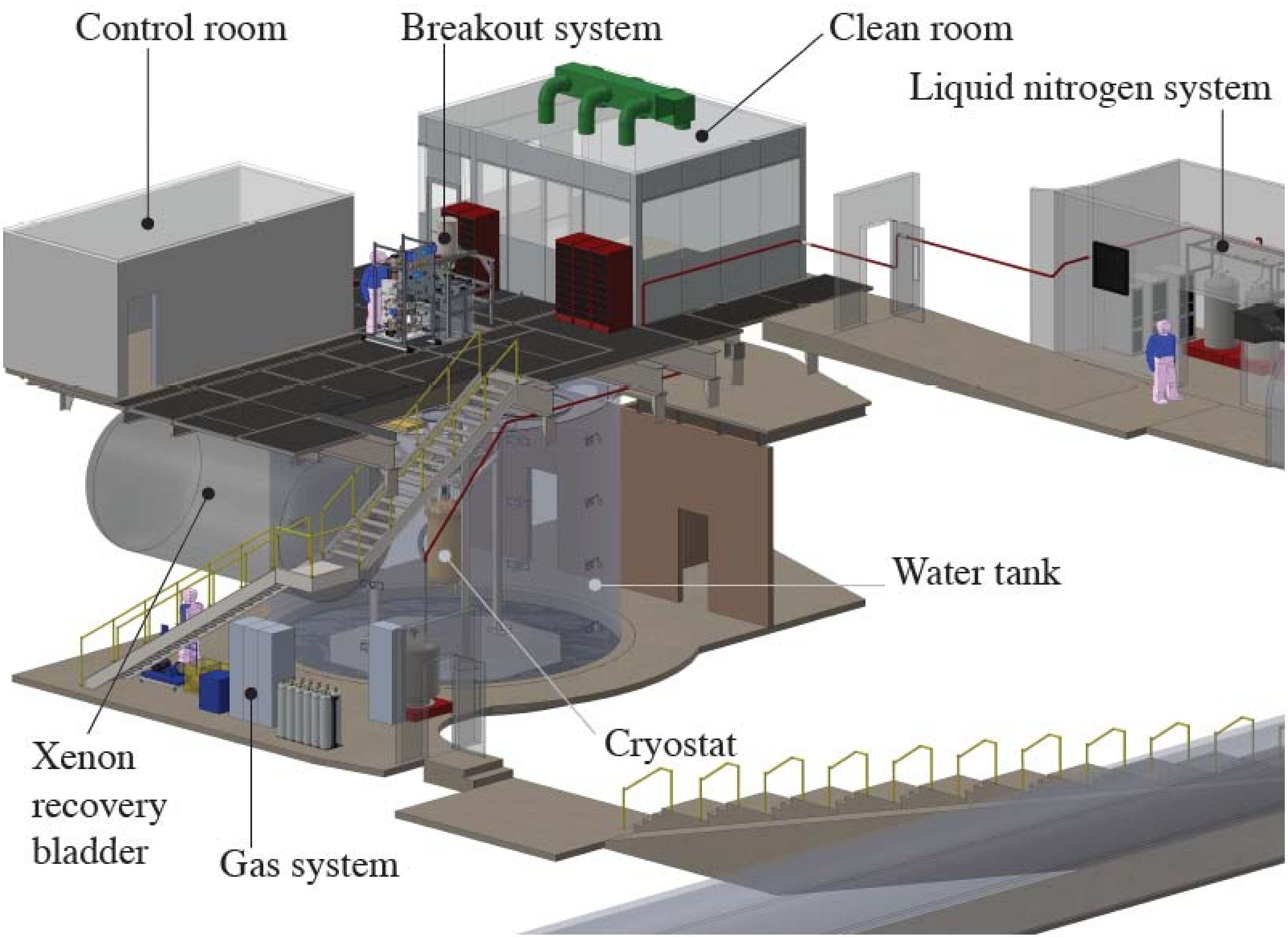


Ray Davis' Solar Neutrino Experiment

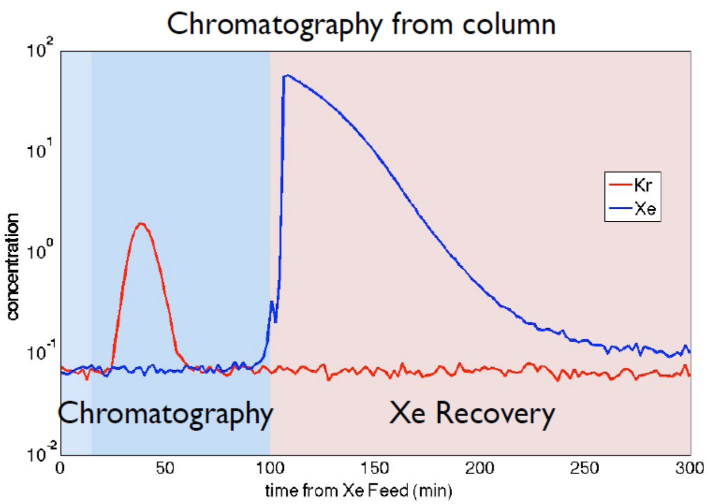


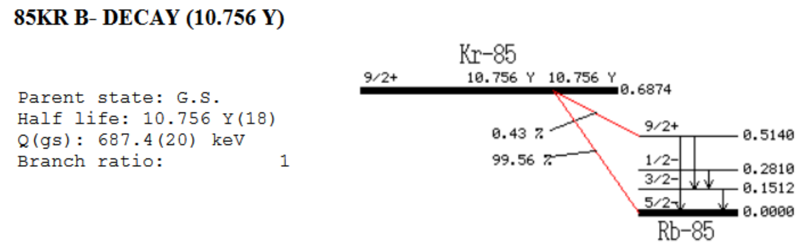
LUX Water Tank in Davis Campus

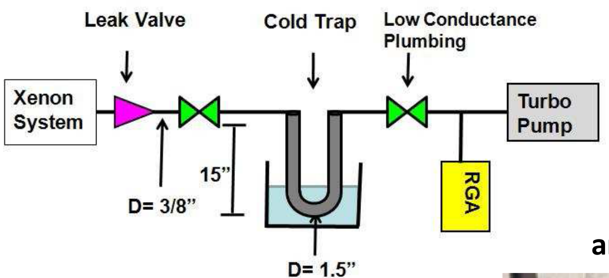
DAVIS CAMPUS LAYOUT

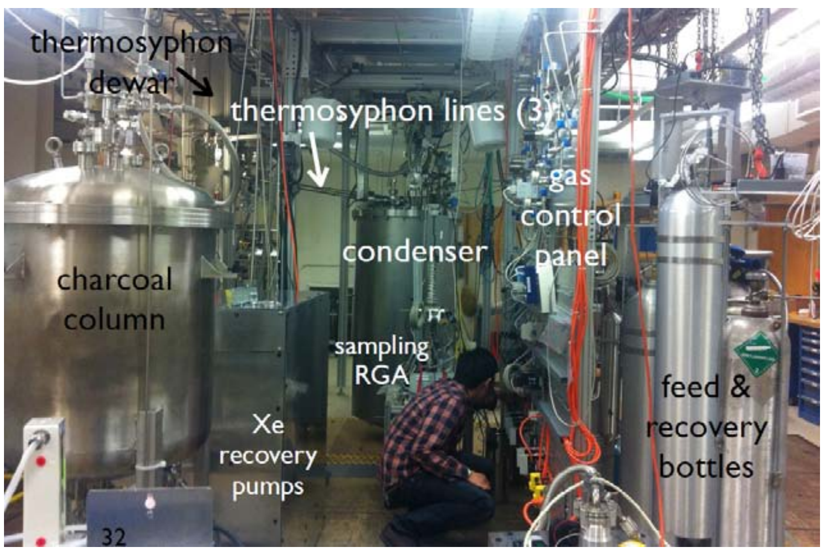


HARDWARE SYSTEMS – KRYPTON REMOVAL



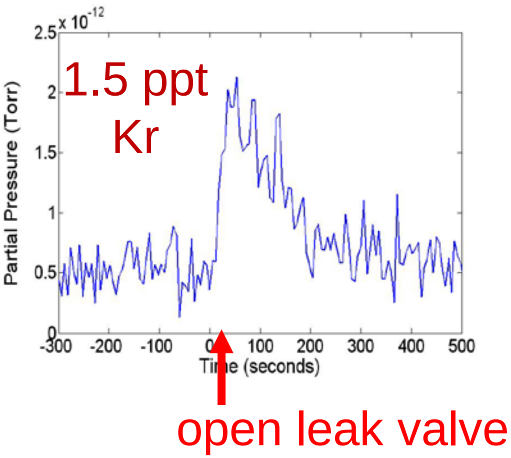






CWRU Kr removal system (130 ppb to 3.5 ppt)

arXiv:1103:2714



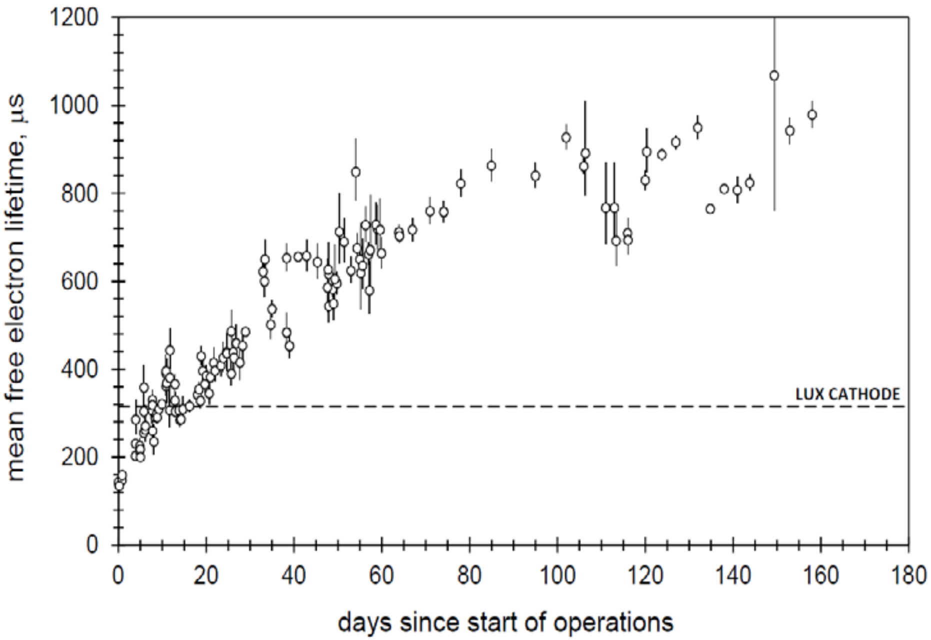
Xenon sampling (ppb-ppt)

HARDWARE SYSTEMS XENON PURIFICATION

- Removal of electronegative impurities to <ppb level
- Electrons from deepest interactions (near cathode) must be able to drift to liquid surface w/o being captured

Xenon circulation system (230 kg/day)

Free electron lifetime



Drift lengths ~1 m achieved in weeks

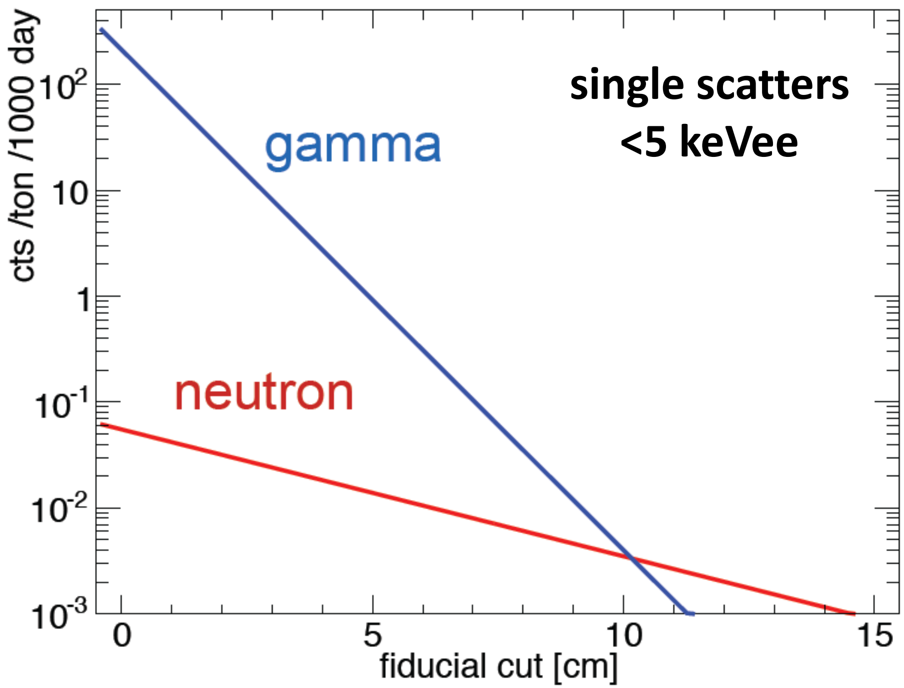
Combination of

- Materials selection
- Gas purification
- Ultra-sensitive sampling

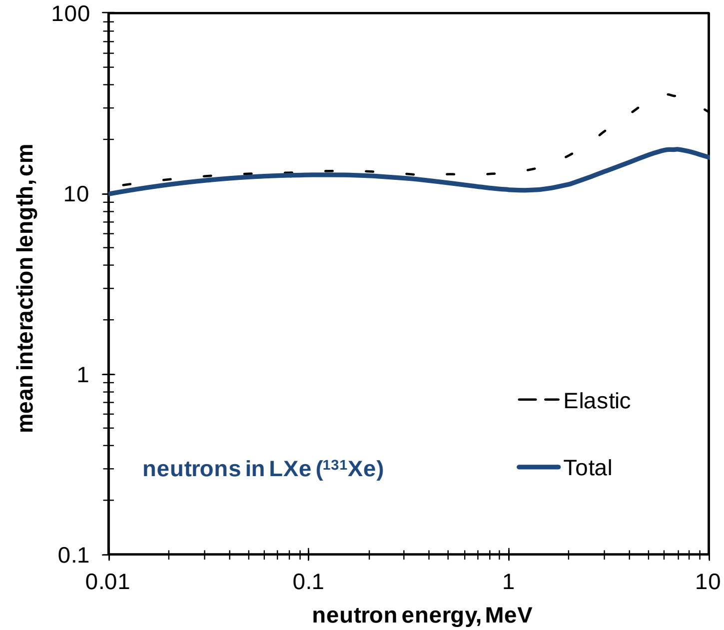
have all but eliminated this risk

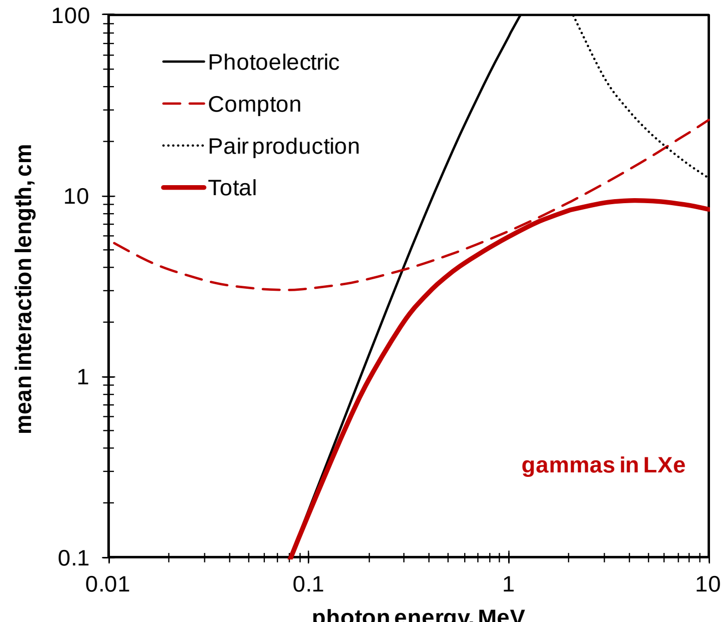
CALIBRATION

- Self-shielding becoming too successful! How can we calibrate these detectors?



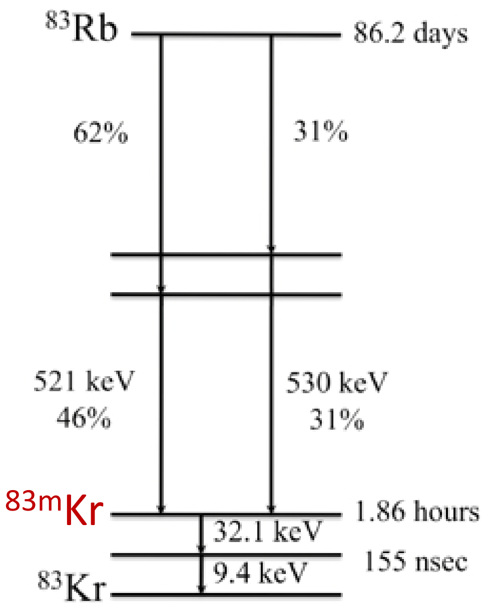
- Spike LXe target with clever sources…

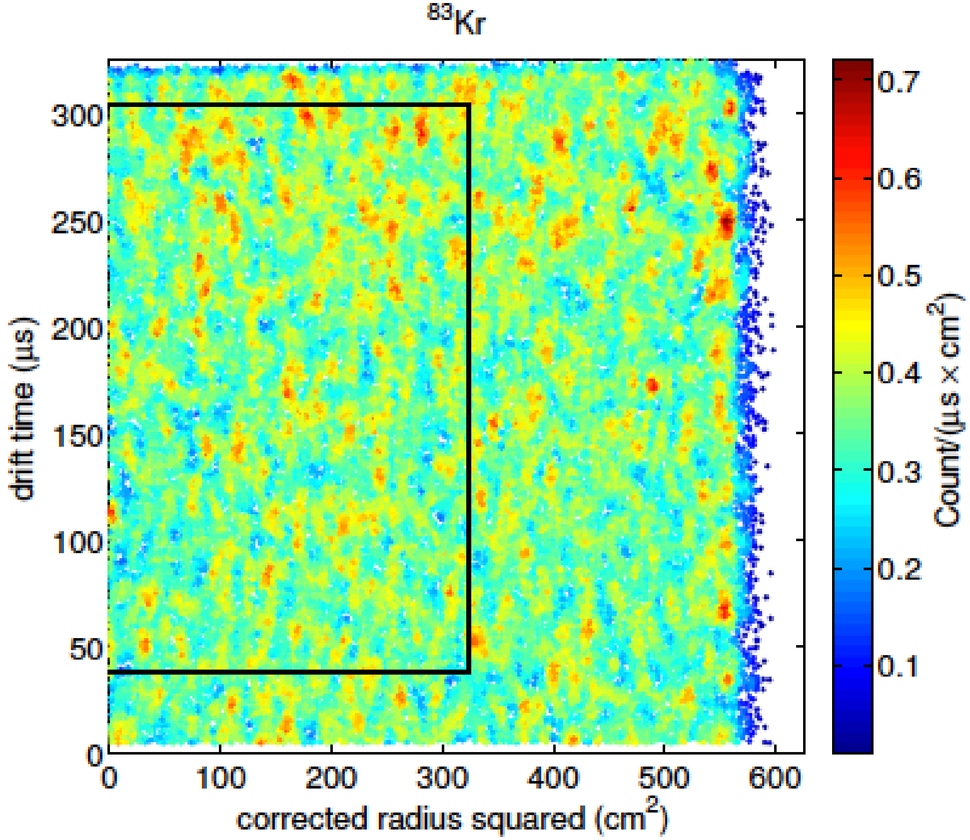




RESPONSE CALIBRATION

- S1 and S2 response calibration with dispersed ^{83m}Kr radioisotope
  - Routine injection, decays within detector, emitting 2 CEs ($T_{1/2}$=1.86 hrs)

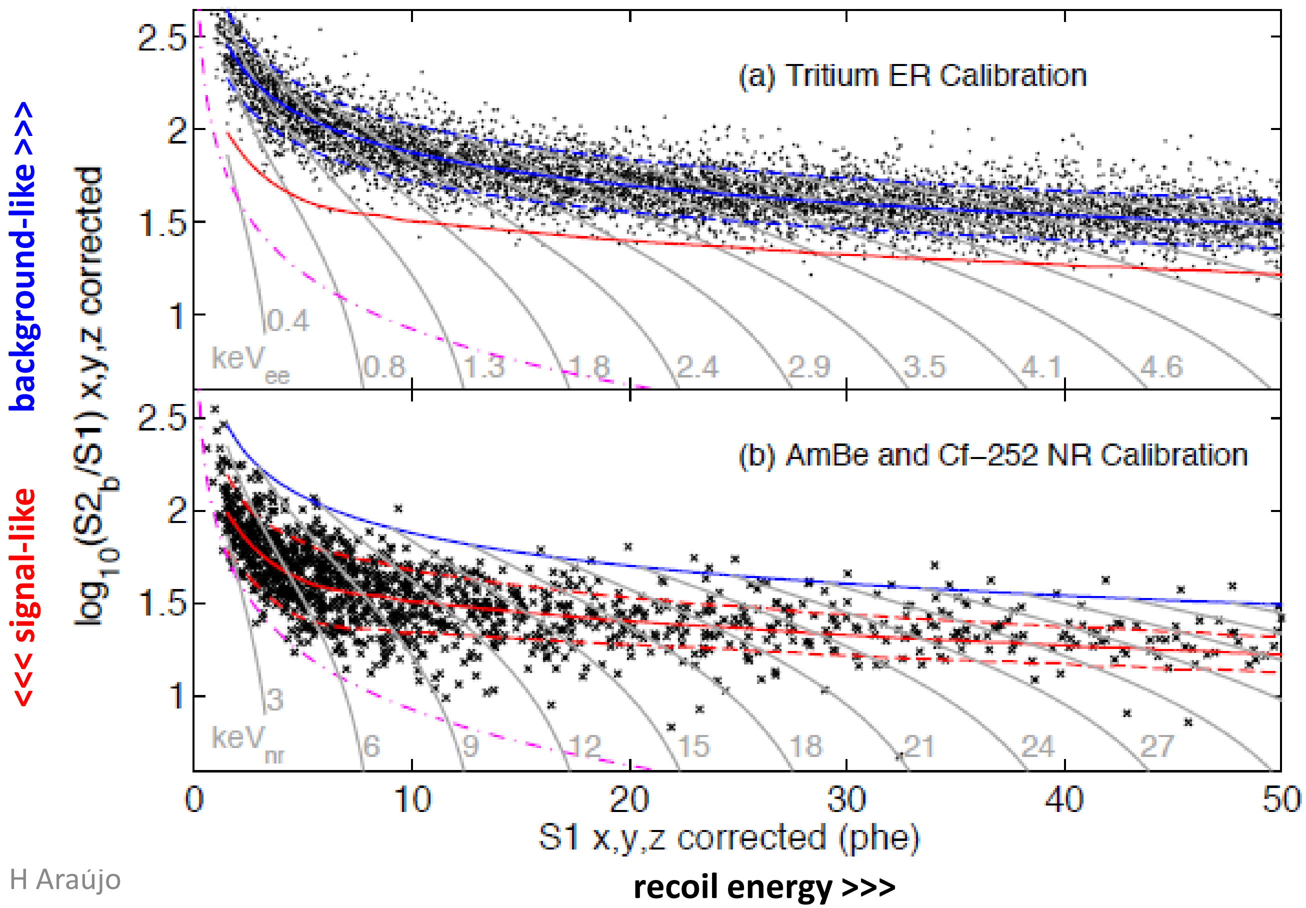


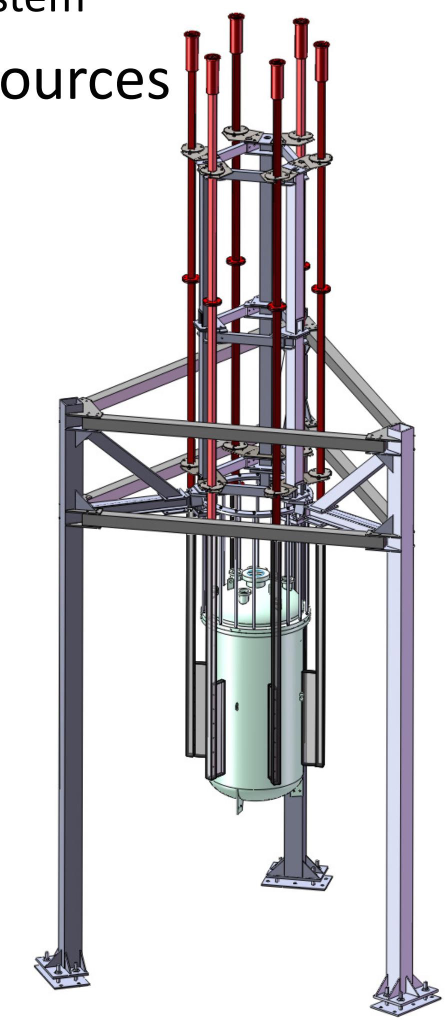


Kr-83m calibration source:
Rb-83 infused into zeolite, located within xenon gas plumbing

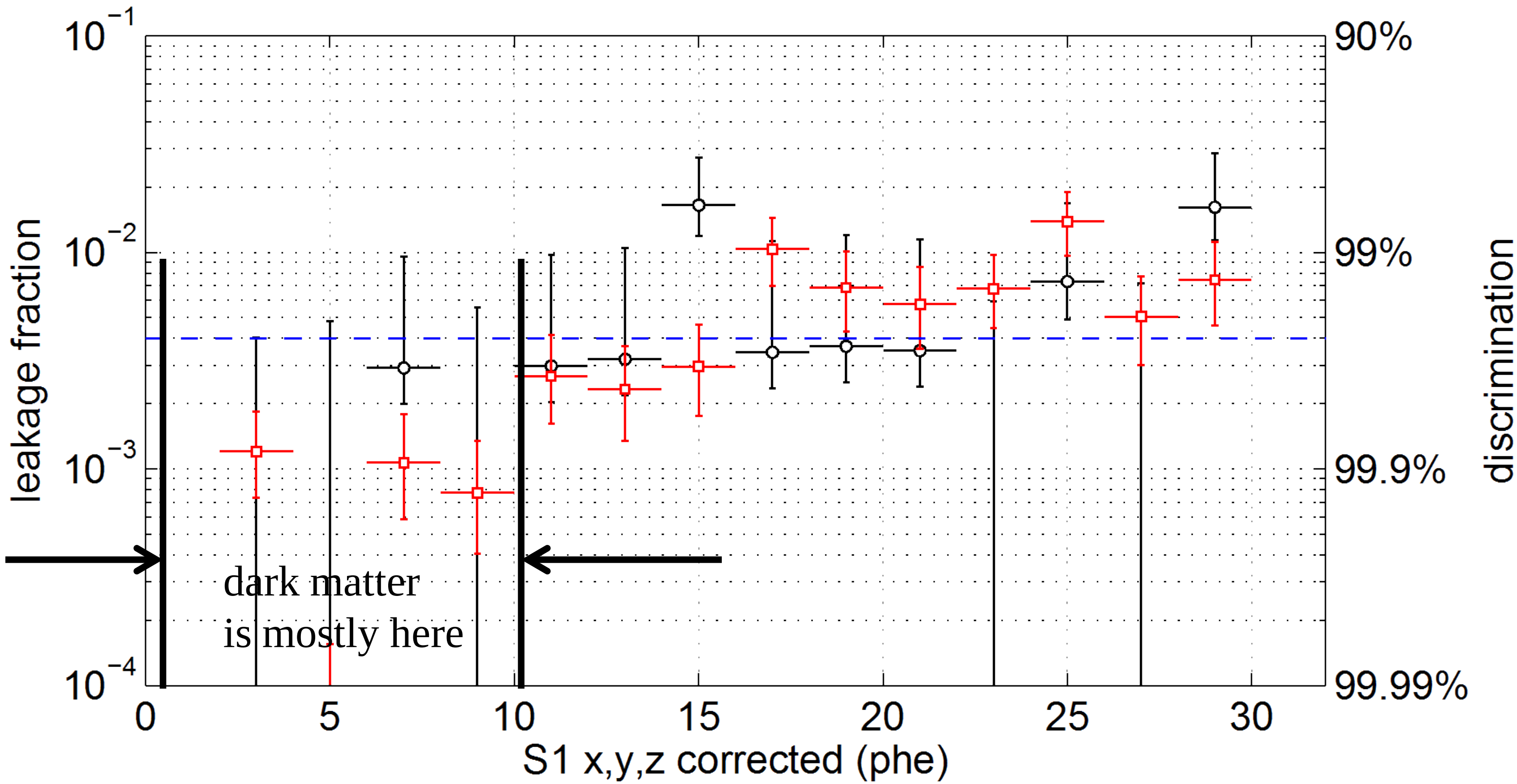
SIGNAL/BK CALIBRATION

- ER region (background) calibrated with dispersed tritium
  - CH_3T (β_{max}=18 keV): one off injection, removed by purification system
- NR region (signal) calibrated with external neutron sources





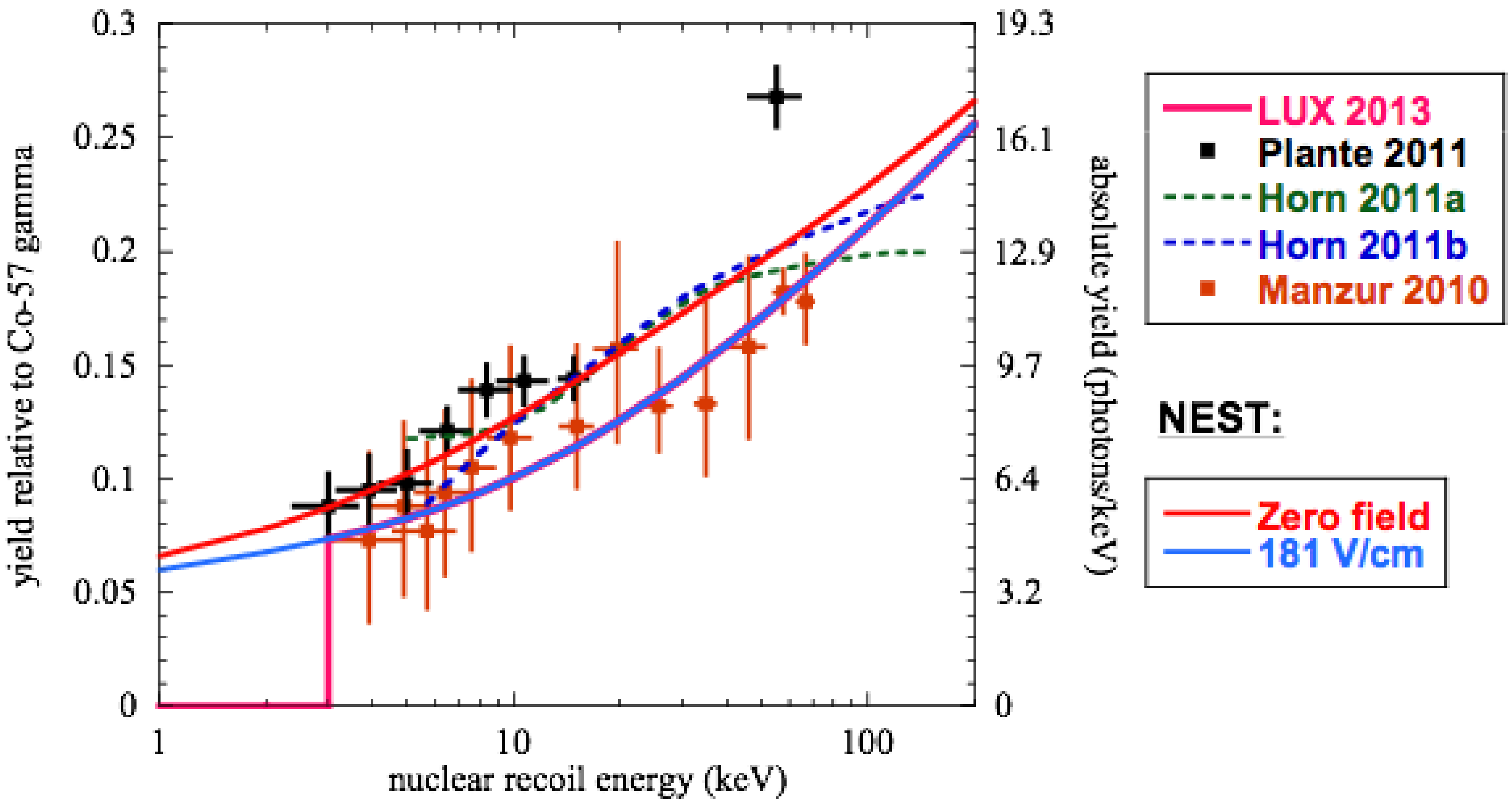
ER/NR DISCRIMINATION



99.6% average discrimination in 2-30 S1 photoelectrons (LUX goal was 99.4%), retaining 50% nuclear recoil acceptance – and gets better at low energy!

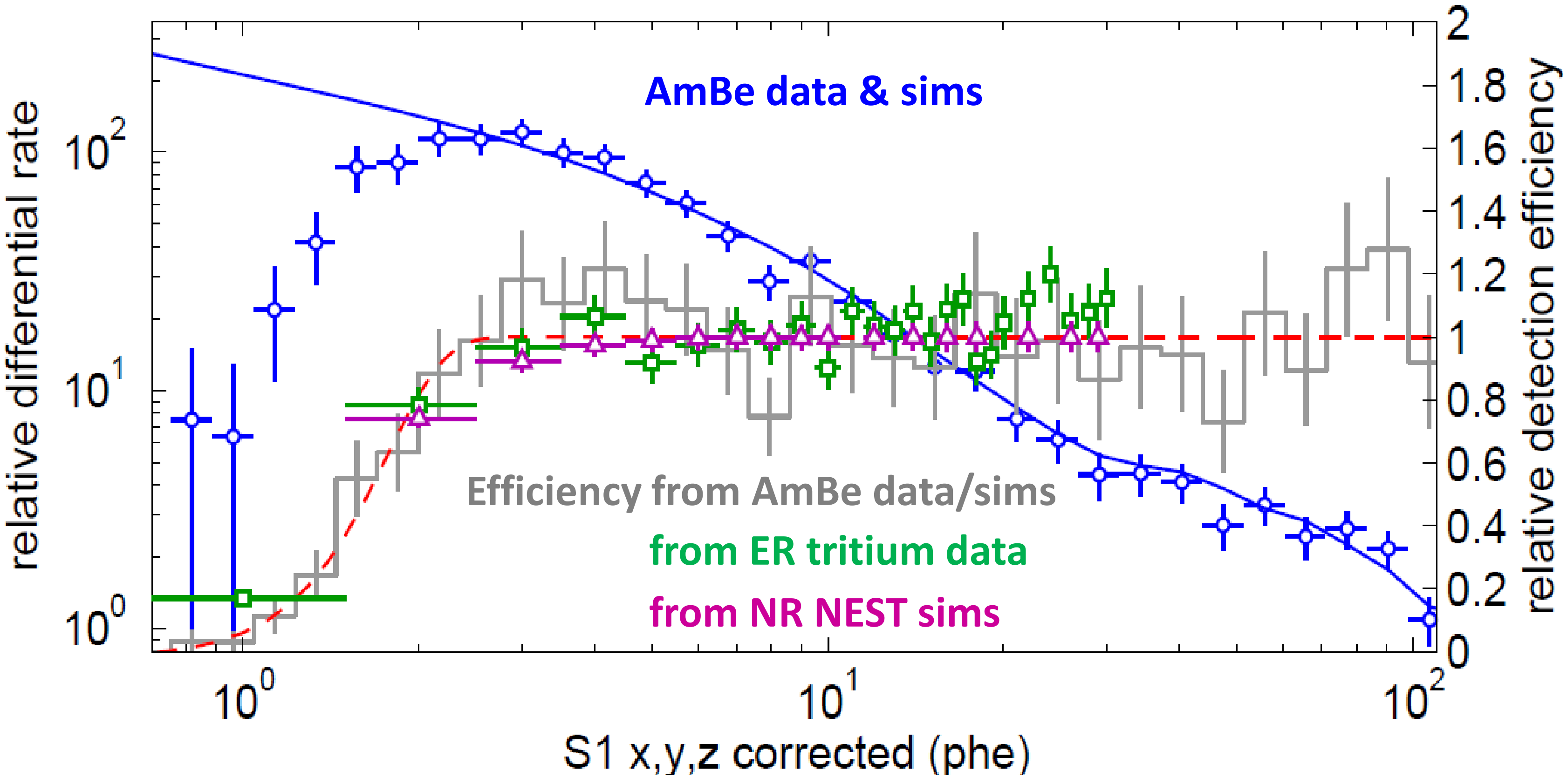
S1 ENERGY ESTIMATION

- As given by NEST down to 3 keV_{nr} , and 0 below that (conservative!)
- S1 photon detection efficiency >2.5x higher than XENON100

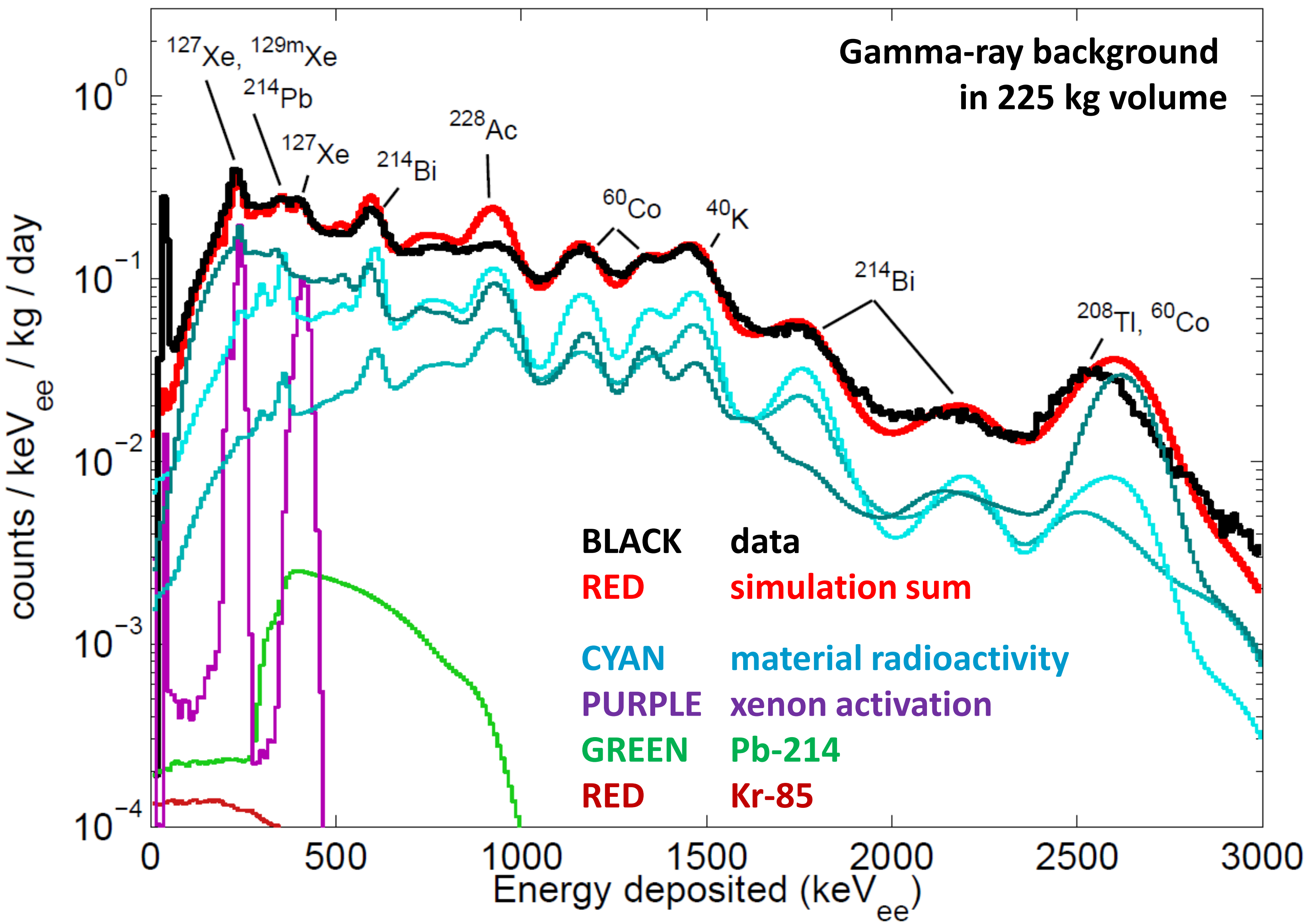


S1 ENERGY THRESHOLD

- Good agreement between data and simulation (both ER and NR)
- S1 threshold (50% efficiency) corresponds to ~4.3 keVnr



DOMINANT BACKGROUNDS



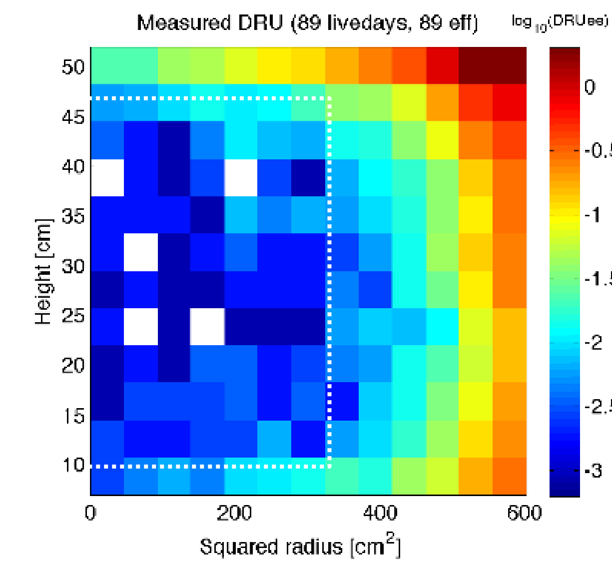
DOMINANT BACKGROUNDS

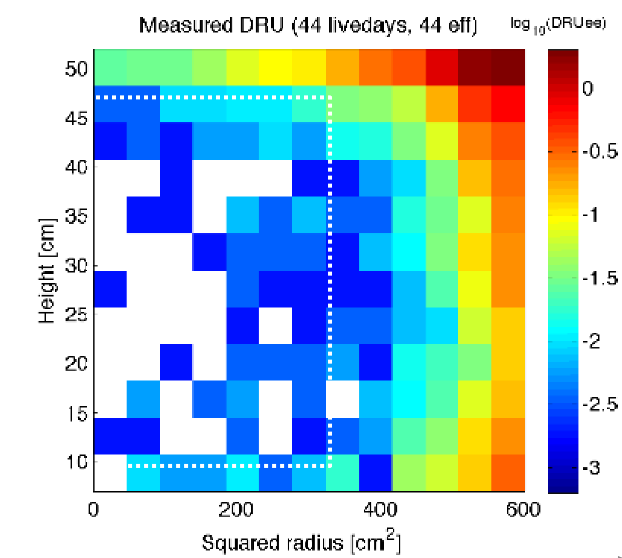
- Backgrounds in ROI: 118 kg, 0.9-5.3 keV_{ee}
- Negligible neutron background (0.06 evts)

Component	Source	mDRUee ($\times10^{-3}$ evt/kg/day/keVee)
γ-rays	Internal components, inc. PMTs (80%)	1.8 ±0.2$_{stat}$ ±0.3$_{sys}$
^{127}Xe *	Cosmogenic	0.5 ±0.02$_{stat}$ ±0.1$_{sys}$
^{214}Pb	^{222}Rn	0.11-0.22$_{(90\% CL)}$
^{85}Kr	3.5 ± 1 ppt	0.13 ±0.07$_{sys}$
Predicted	**Total**	**2.6 ±0.2$_{stat}$ ±0.4$_{sys}$**
Observed	**Total**	**3.6 ±0.3$_{stat}$**

* Xe-127: $T_{1/2}$ =36.4 days (0.87 → 0.28 mDRU during run)

ER < 5 keVee



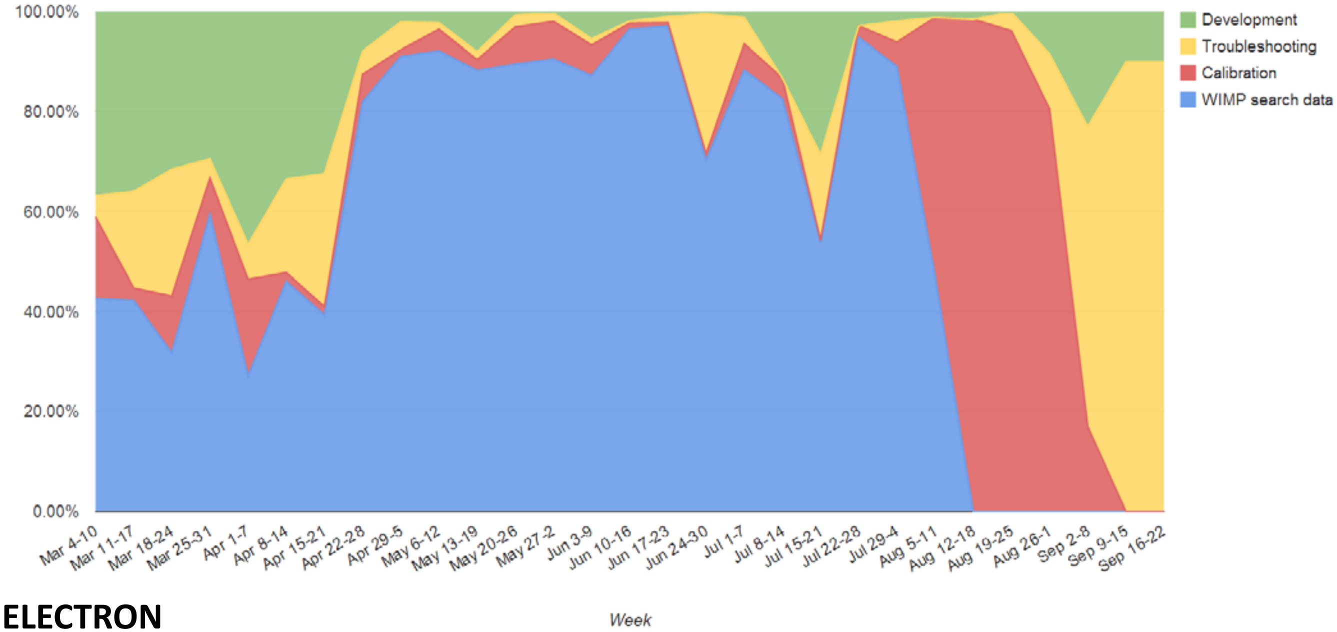


LUX RUN 3

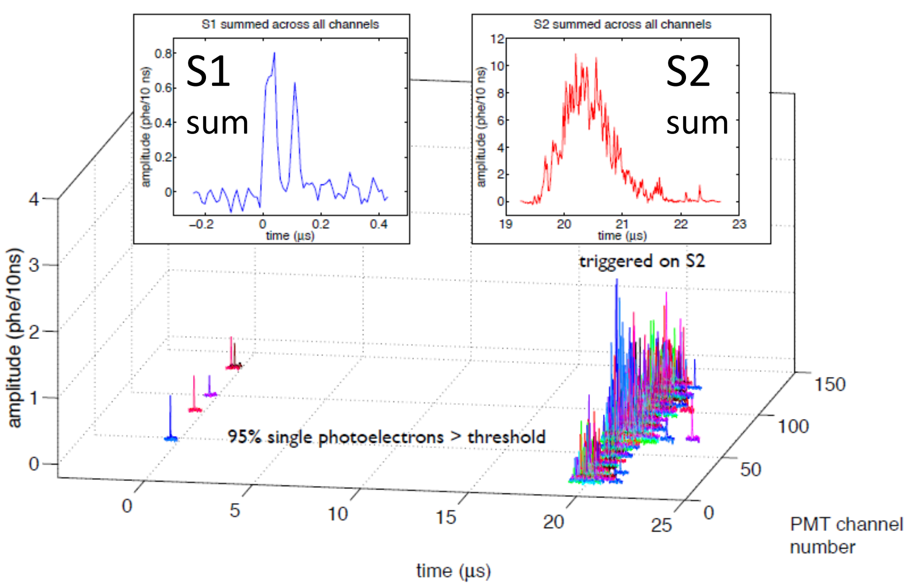
WIMP-search run

- 85.3 live days in 2013
- 118 kg fiducial mass
- Fiducial event rate at low energy:

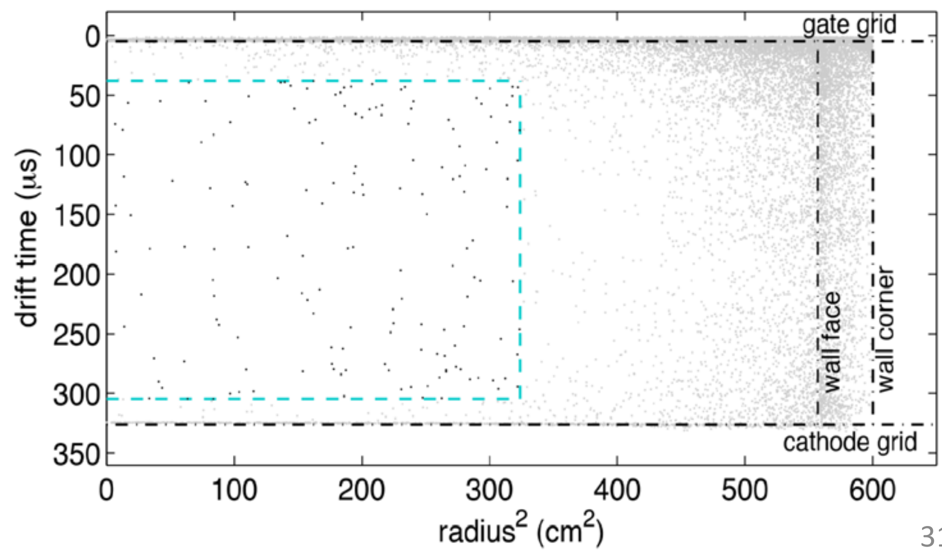
  ~2 events/day



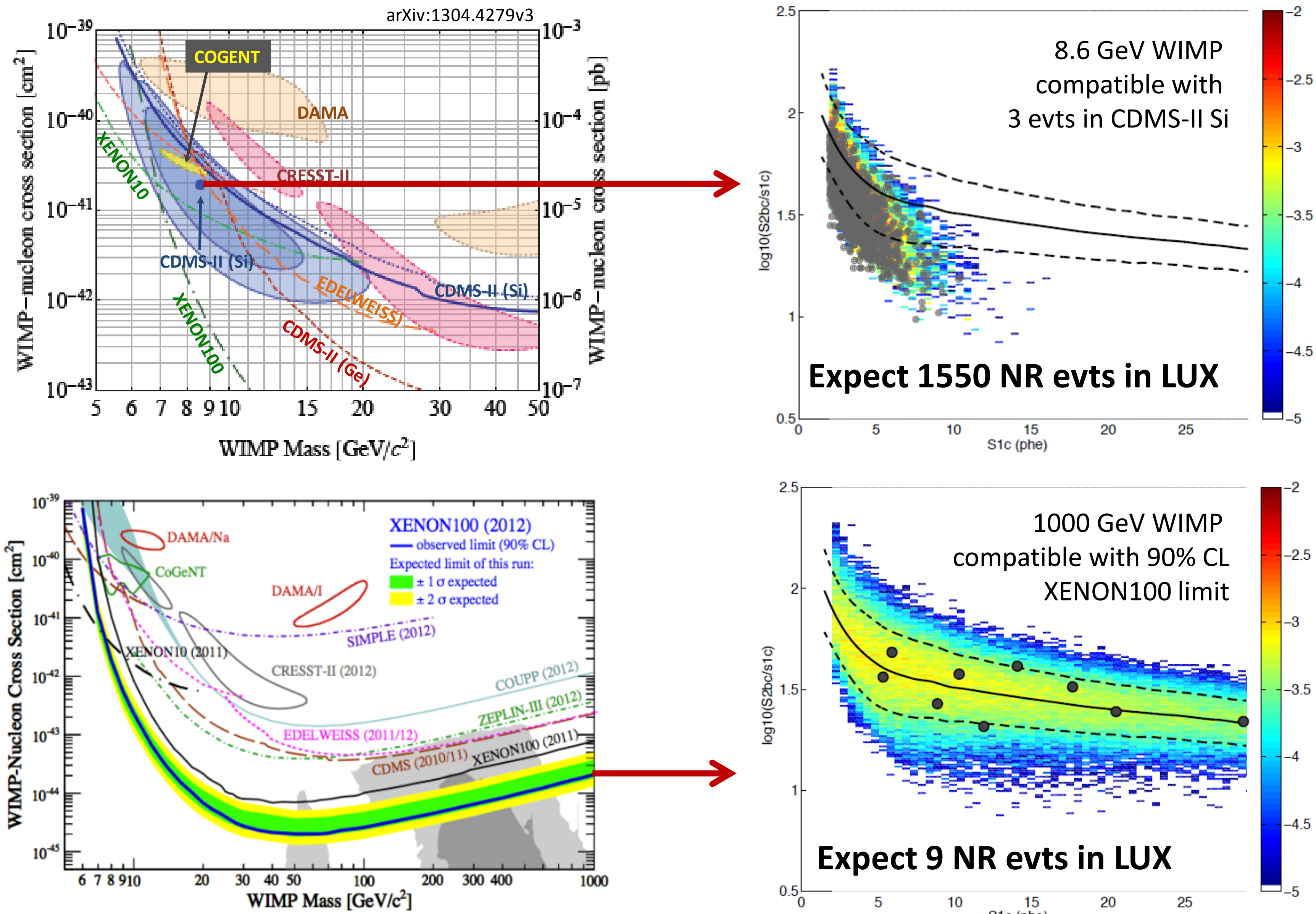
S1+S2 SIGNALS FROM 1.5 keV ELECTRON



BACKGROUND AT WIMP SEARCH ENERGIES



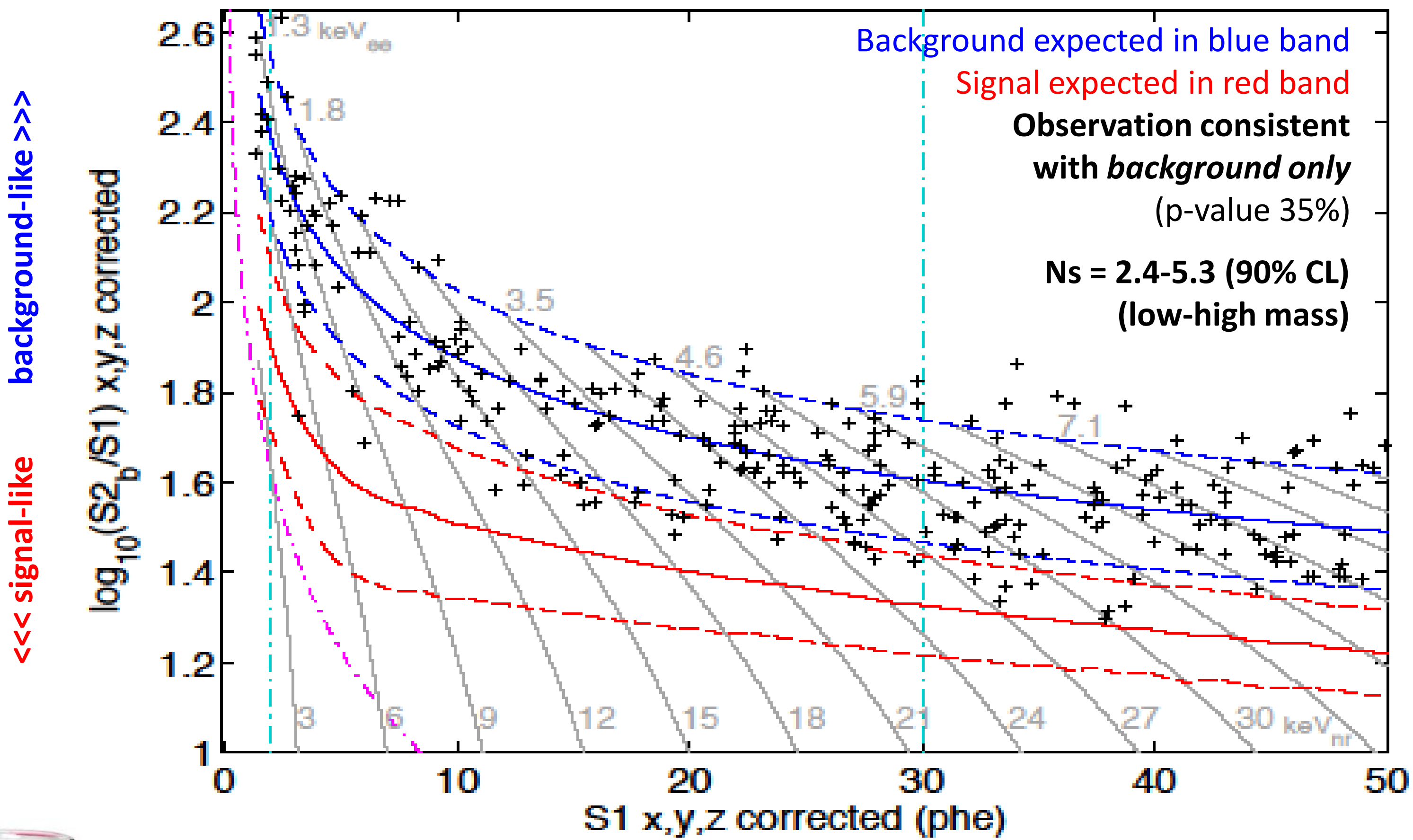
SOME OTHER WIMPS



LUX – FIRST RESULTS

Akerib *et al* (2013),
PRL 112, 091303

Events recorded in 85.3 live days of exposure



The Economist
"Absence of evidence, or evidence of absence?"

New York Times
"Dark Matter Experiment Has Detected Nothing, Researchers Say Proudly"

PLR SIGNAL ESTIMATION

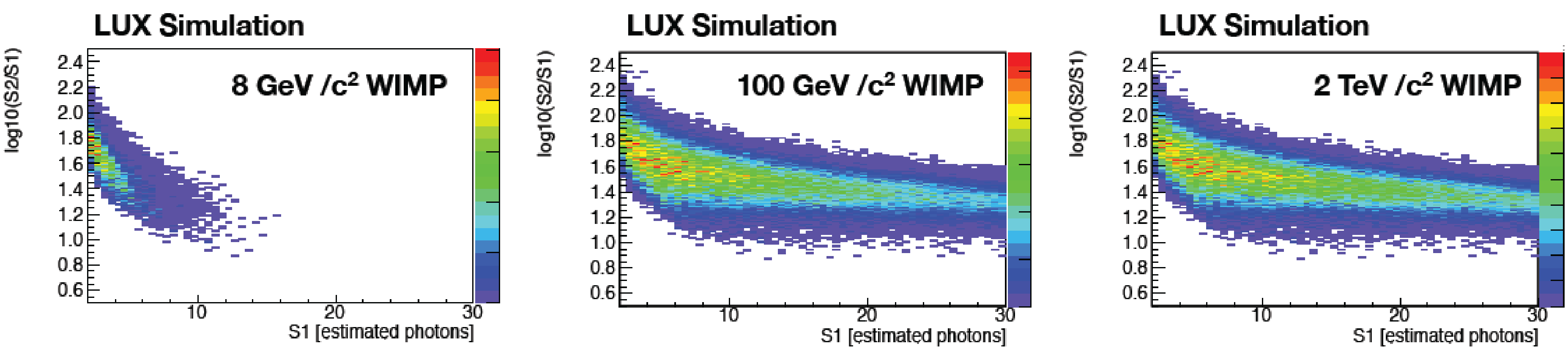
$$\mathcal{L}_{WS} = \frac{e^{-N_s - N_{Compt} - N_{Xe-127} - N_{Rn222}}}{\mathcal{N}!} \prod_{i=1}^{\mathcal{N}} N_s P_s(\boldsymbol{x};\boldsymbol{\sigma},\boldsymbol{\theta_s}) + N_{Compt} P_{ER}(\boldsymbol{x};\boldsymbol{\theta_{Compt}})$$
$$+ N_{Xe-127} P_{ER}(\boldsymbol{x};\boldsymbol{\theta_{Xe-127}})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

Observables: **x** = (S1, $\log_{10}$(S2/S1), r, z)

Parameter of interest: N_s

Nuisance parameters: N_{Compt}, N_{Xe-127}, $N_{Rn,Kr-85}$

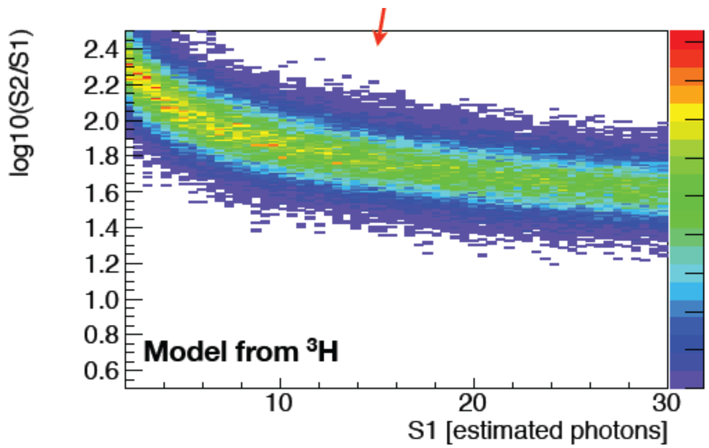
SIGNAL MODEL: simulated 2D PDFs including resolution/efficiencies; uniform in (r^2,z)

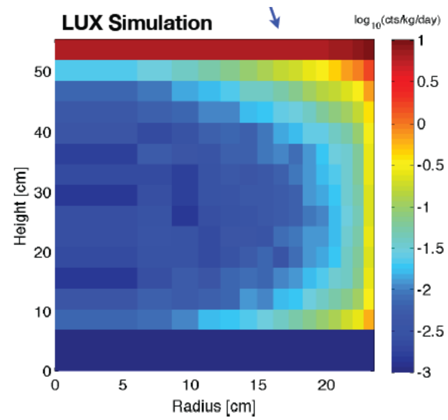


PLR SIGNAL ESTIMATION

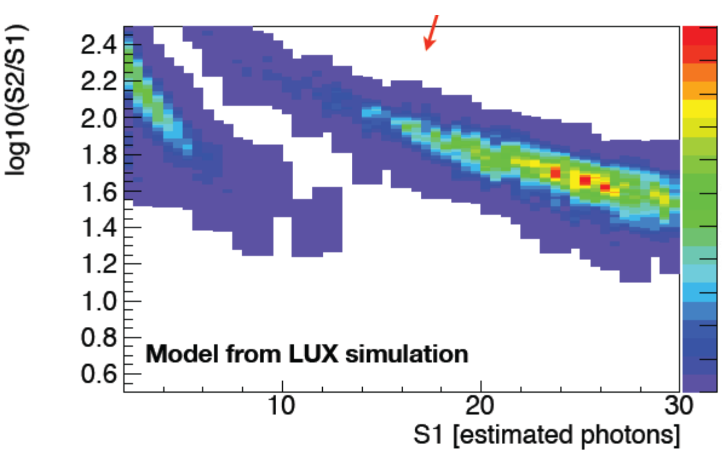
BACKGROUND MODELS: simulated 2D PDFs including resolution/efficiencies

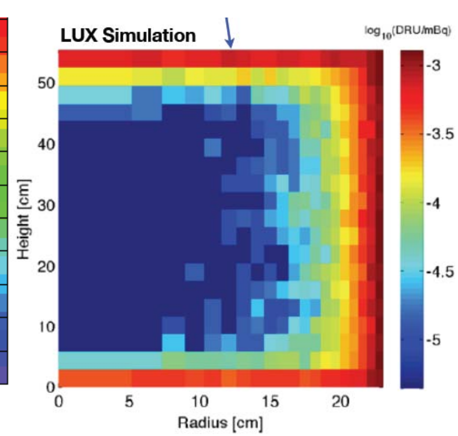
External radioactivity (Compton-scattered gammas)



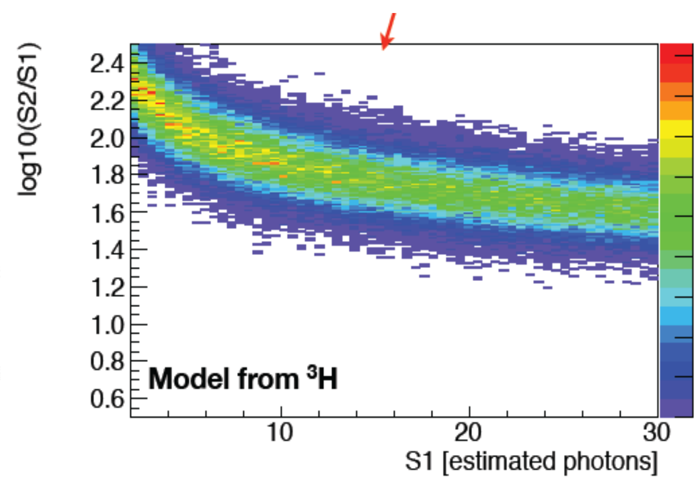


Xe-127 atomic cascade with HE gamma escape

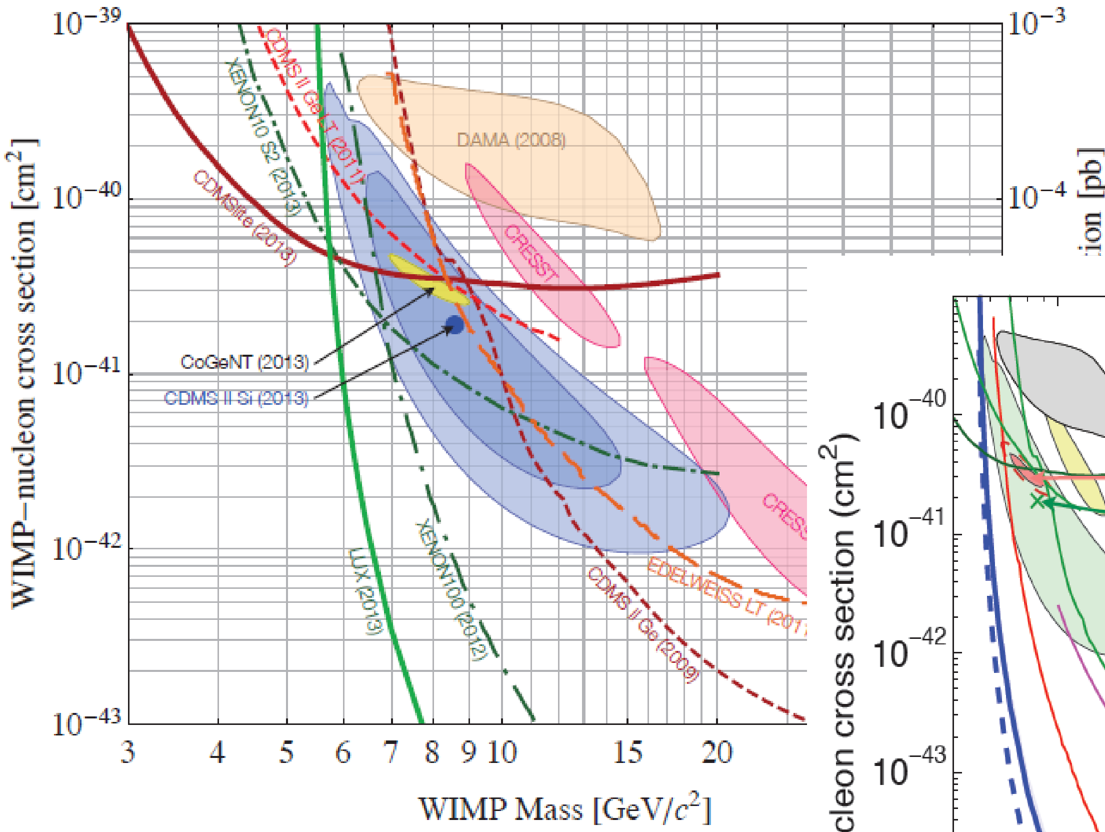




Pb-214/Kr-85
Uniform in Eee and space

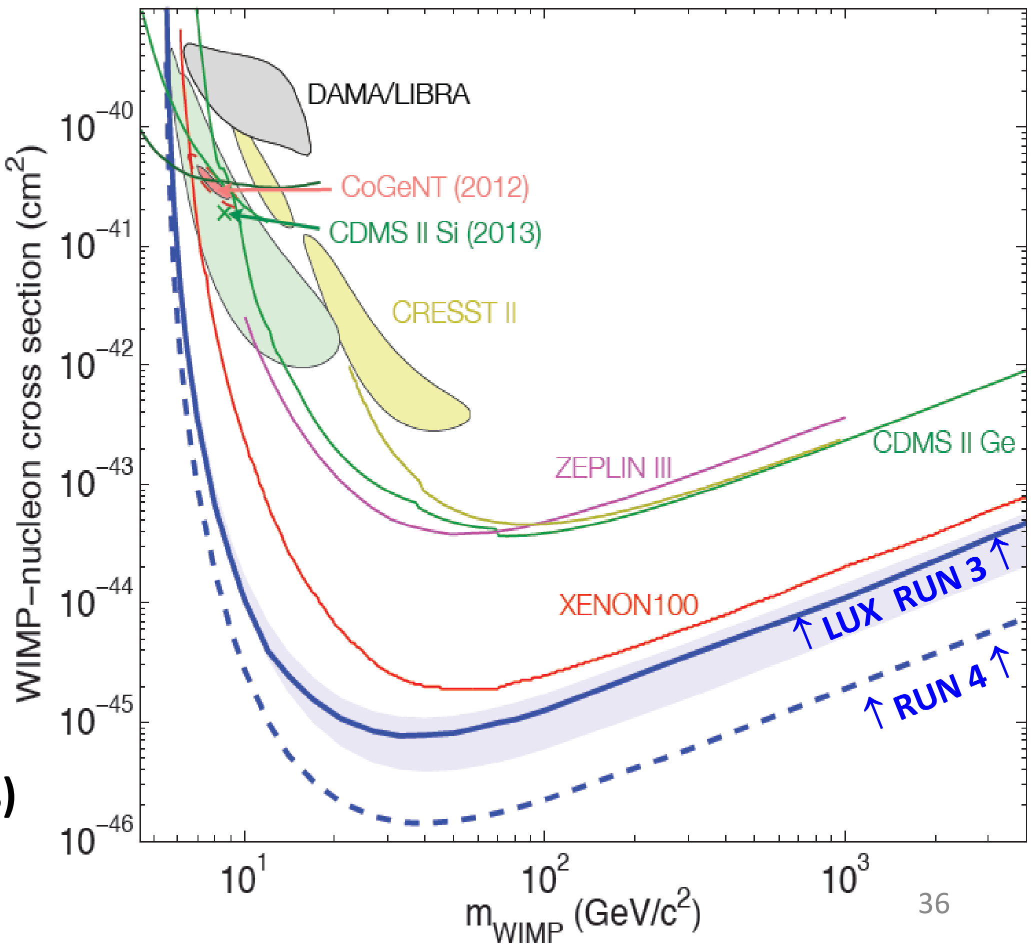


SPIN-INDEPENDENT WIMP-NUCLEON XS



90% CL EXCLUSION LIMITS ON SCATTERING XS v WIMP MASS

Akerib *et al* (2013), PRL 112, 091303



~20-fold improvement in sensitivity over XENON100 for low mass WIMPs (with conservative detection thresholds)

LUX COLLABORATION

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Richard Gaitskell	PI, Professor
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David Malling	Graduate Student
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Samuel Chung Chan	Graduate Student
Dongqing Huang	Graduate Student

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Wing H To	Postdoc
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Chang Lee	Graduate Student
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Peter Sorensen	Staff Physicist
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Alexander Lindote	Postdoc
Francisco Neves	Postdoc
Claudio Silva	Postdoc

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Doug Tiedt	Graduate Student

SDSTA

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Ray Gerhard	Electronics Engineer
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Matthew Szydagis	Postdoc
Richard Ott	Postdoc
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James Morad	Graduate Student
Nick Walsh	Graduate Student
Michael Woods	Graduate Student
Sergey Uvarov	Graduate Student
Brian Lenardo	Graduate Student

UC Santa Barbara

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Mike Witherell	Professor
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Susanne Kyre	Engineer
Carmen Carmona	Postdoc
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Scott Haselschwardt	Graduate Student

University College London

Chamkaur Ghag	PI, Lecturer
Lea Reichhart	Postdoc

Collaboration Meeting,
Sanford Lab, April 2013

University of Edinburgh

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Paolo Beltrame	Research Fellow
James Dobson	Postdoc

University of Maryland

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Richard Knoche	Graduate Student
Jon Balajthy	Graduate Student

University of Rochester

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Wojtek Skulski	Senior Scientist
Eryk Druszkiewicz	Graduate Student
Mongkol Moongweluwan	Graduate Student

University of South Dakota

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Angela Chiller	Graduate Student
Chris Chiller	Graduate Student
Dana Byram	*Now at SDSTA

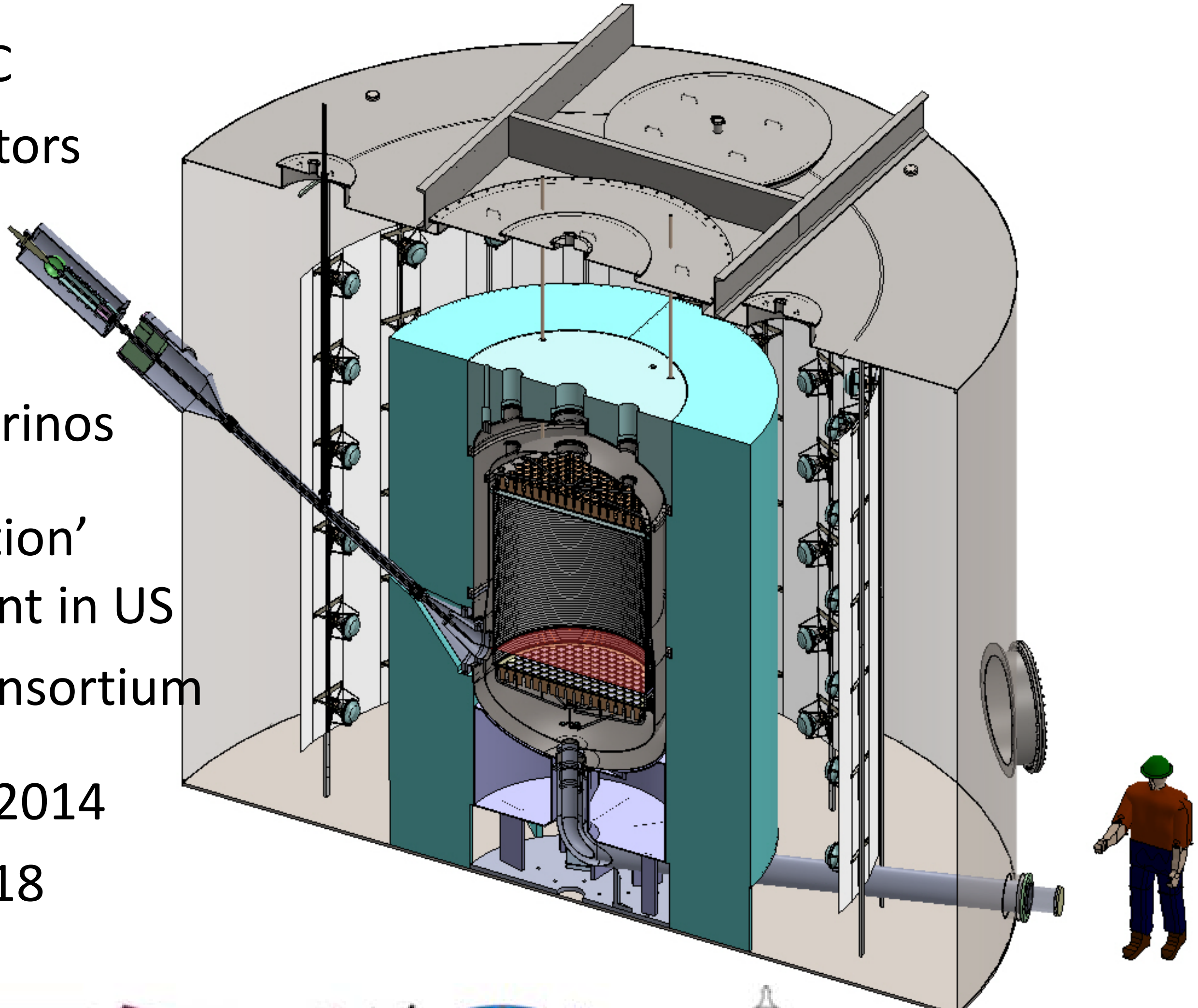
Yale

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

NEXT-GENERATION SEARCH

ZEPLIN → LUX → LUX-ZEPLIN (LZ)

- 7 tonne (active) LXe TPC
- Skin + Veto outer detectors
- Within LUX water tank
- Dominant backgrounds from astrophysical neutrinos
- 'DM Gen-2 down-selection' announcement imminent in US
- Supported by DMUK consortium
- Construction from end 2014
- Operations from 2017/18



Imperial College London

UNIVERSITY OF OXFORD

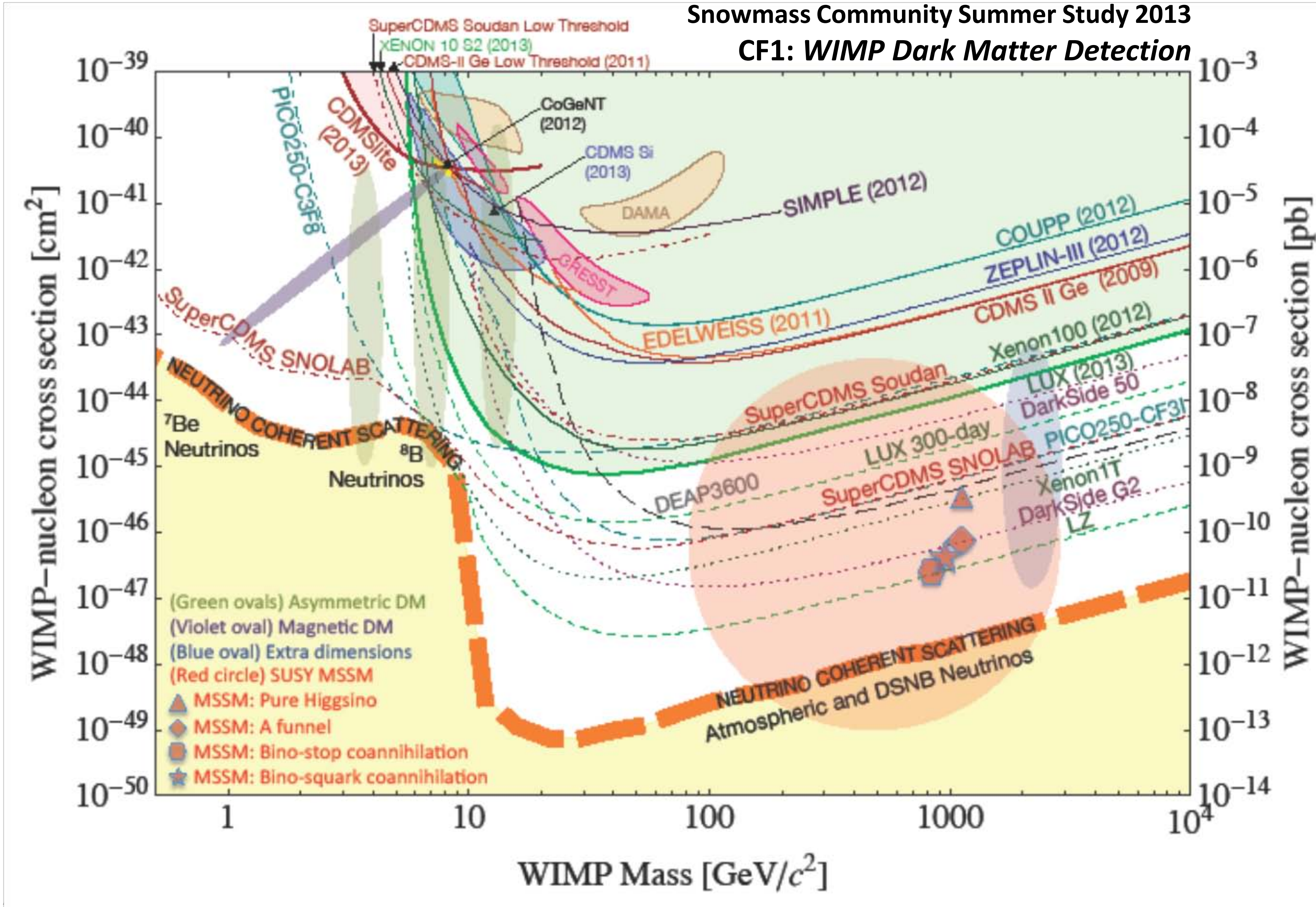
Particle Physics Rutherford Appleton Laboratory

The University Of Sheffield.

UCL

UNIVERSITY OF LIVERPOOL

TO BOLDLY GO – WHERE?



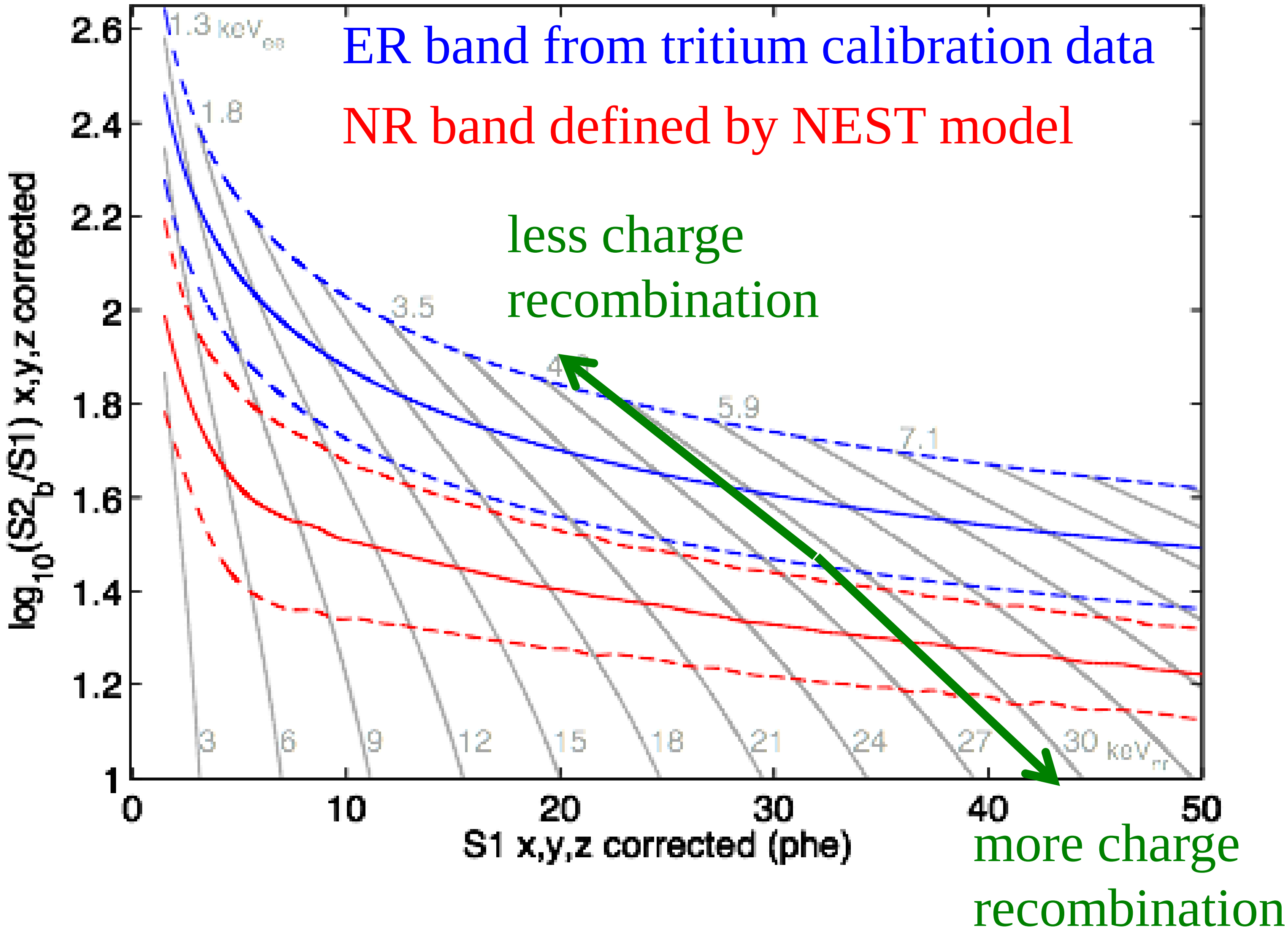
SUMMARY

- LUX Run3 set world-leading limits, and clarified low mass 'excitements'
- Less conservative Run3 analysis coming soon (lower S1 & S2 threshold)
- LUX Run4 about to start, with potentially ~5x better sensitivity reach
- Decision on next-generation LZ in the US and in the UK is imminent
- *One day DM will no longer be 'cool'. Until then, we must keep looking!*

Stephen Collins, The Guardian, Saturday 27 April 2013

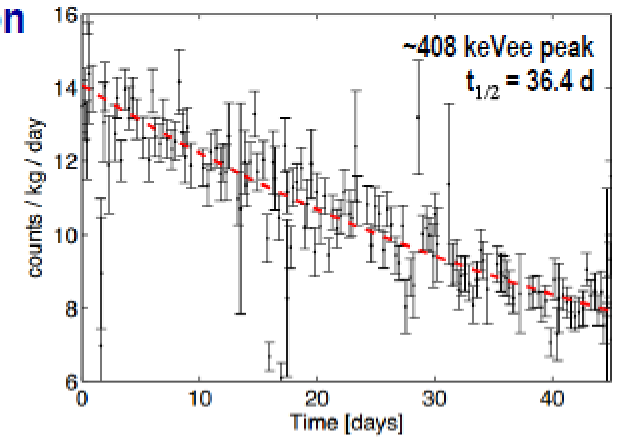
RESERVE SLIDES

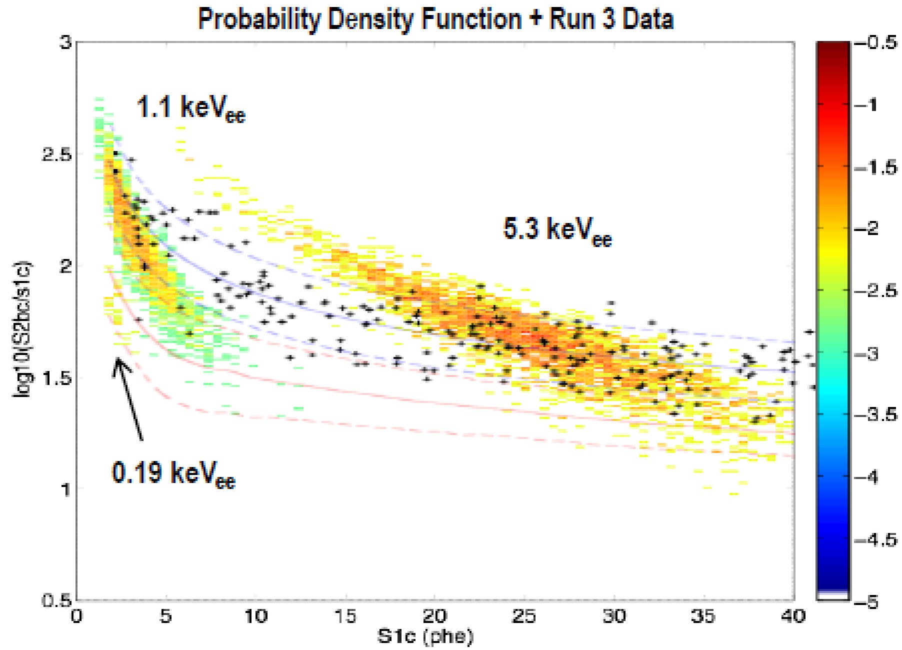
keVee and keVnr energy scales

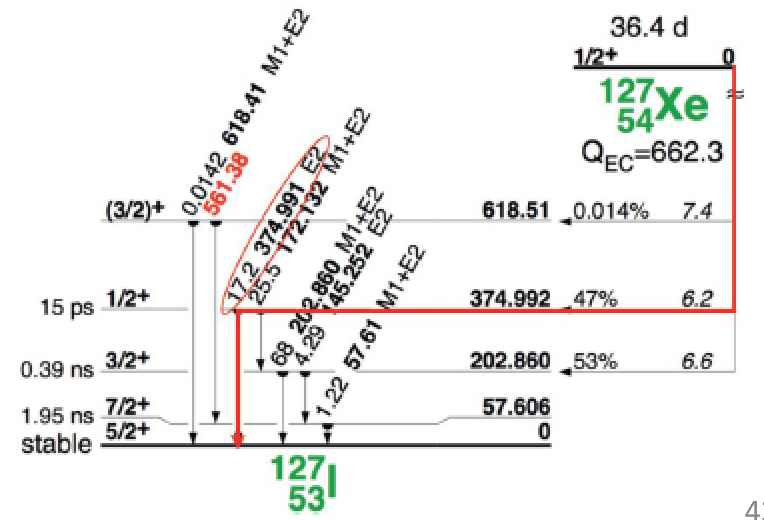


Xe-127 background

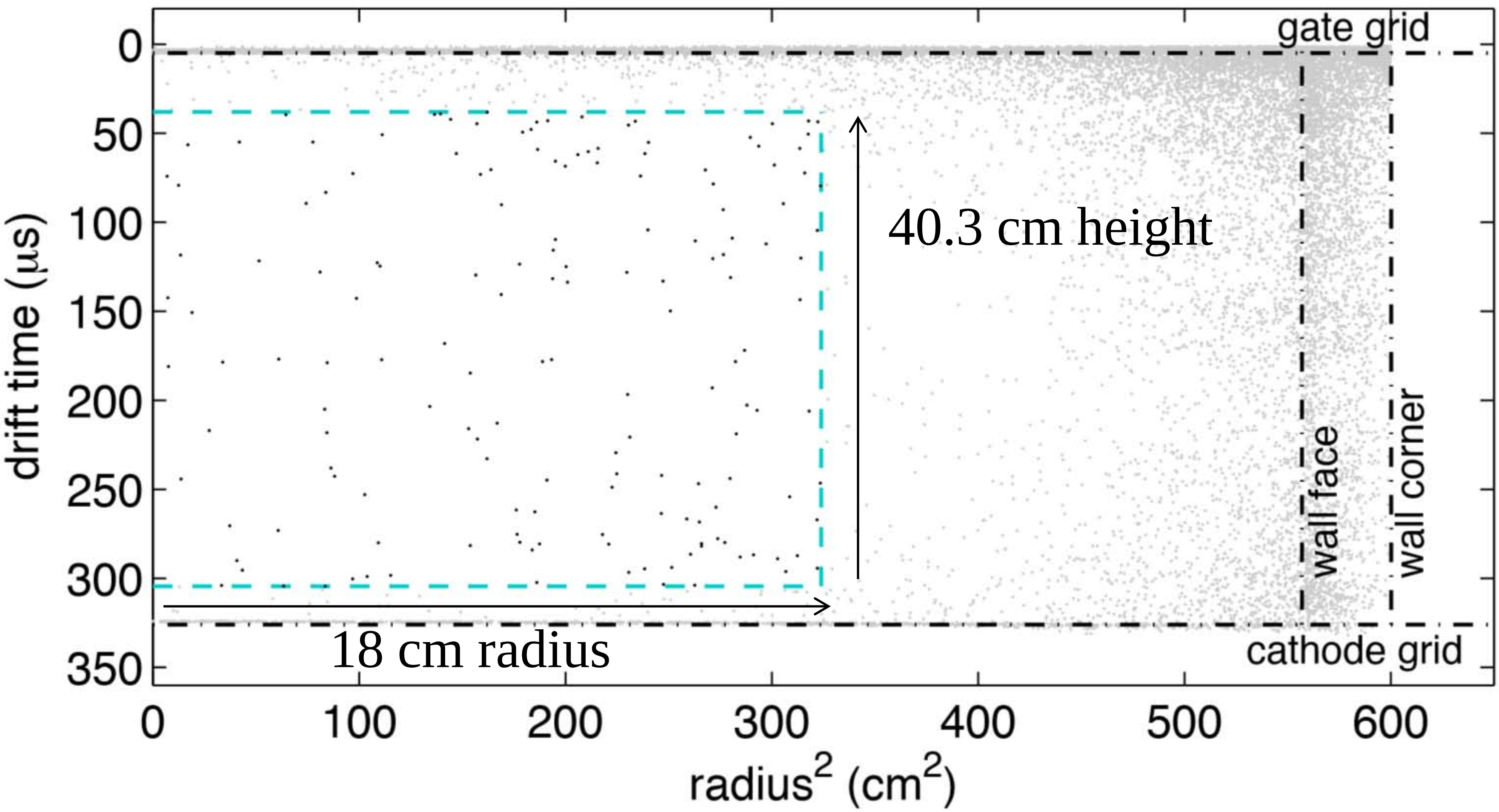
- Isotope of interest for WIMP search = ^{127}Xe
  - EC decay with gammas 203 or 375 keV, possibility to escape the active volume.
  - X-ray / Auger emission corresponding to ^{127}I levels: 33.2 keV_{ee} (K), 5.3 (L), 1.1 (M), 0.19 (N)
  - Depth-dependent background profile; data follows prediction
  - Contribution modeled as a nuisance in the PLR analysis
  - Accounts for 0.5 $mDRU_{ee}$ (avg) in WIMP ROI over Run 3
  - It will have disappeared for Run 4







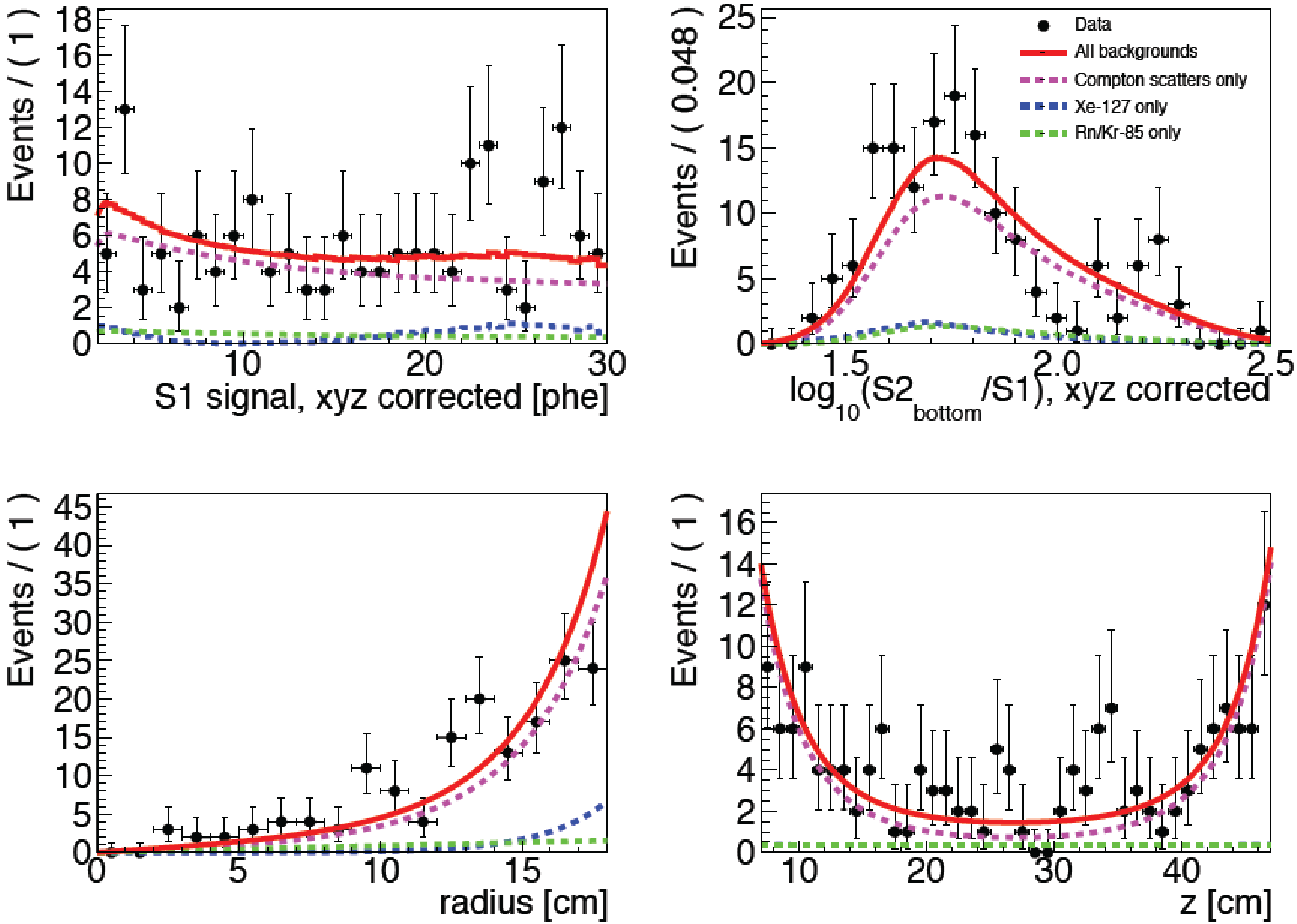
118 kg fiducial volume



Data selection

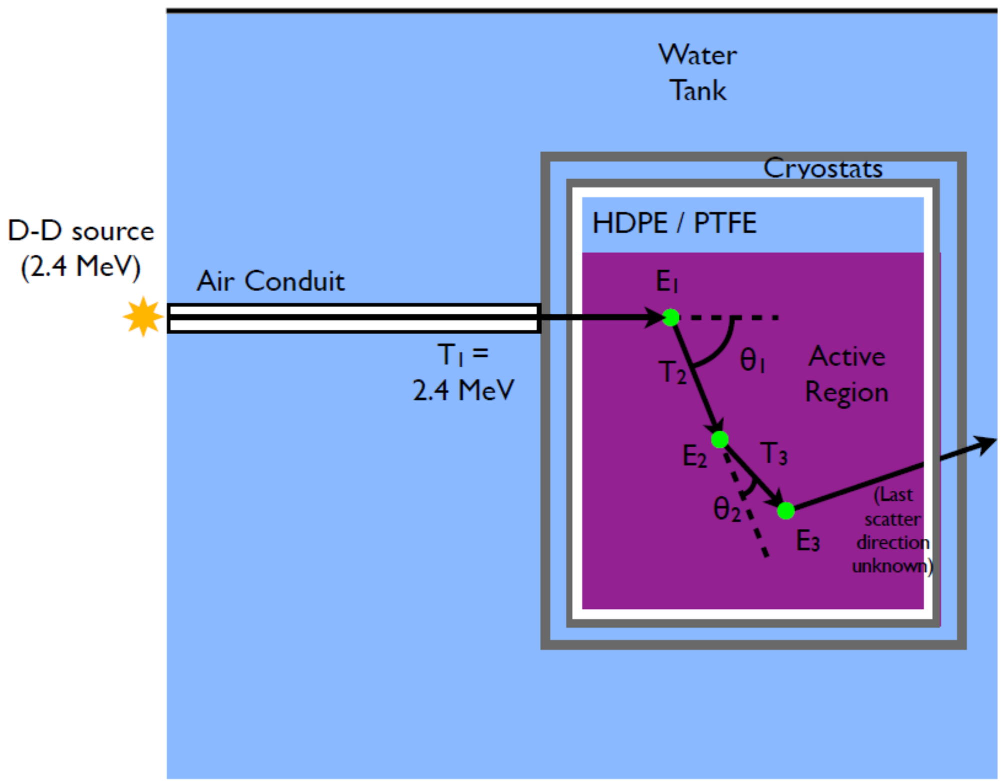
Cut	Description	Events Remaining
All triggers	S2 Trigger >99% for $S2_{raw}$>200 phe	83,673,413
Detector stability	Cut periods of excursion for GXe pressure, LXe level, applied voltages	82,918,901
Single scatter events	Identification of S1 and S2; single scatter cut	6,585,686
S1 energy	Accept 2-30 phe (energy ~0.9-5.3 keVee, ~3-18 keVnr)	26,824
S2 energy	Accept 200-3300 phe (>8 S2 electrons) Removes single-e/small S2 edge events	20,989
S2 single electron quiet cut	Cut if >100 phe outside S1+S2 identified in ±0.5 ms around trigger (0.8% deadtime)	19,796
Drift time cut from grids	Cut away from cathode and gate regions, 60 < drift time < 324 μs	8731
Fiducial volume (R,Z) cut	Radius < 18 cm, 38 < drift time < 305 μs, 118 kg fiducial	160

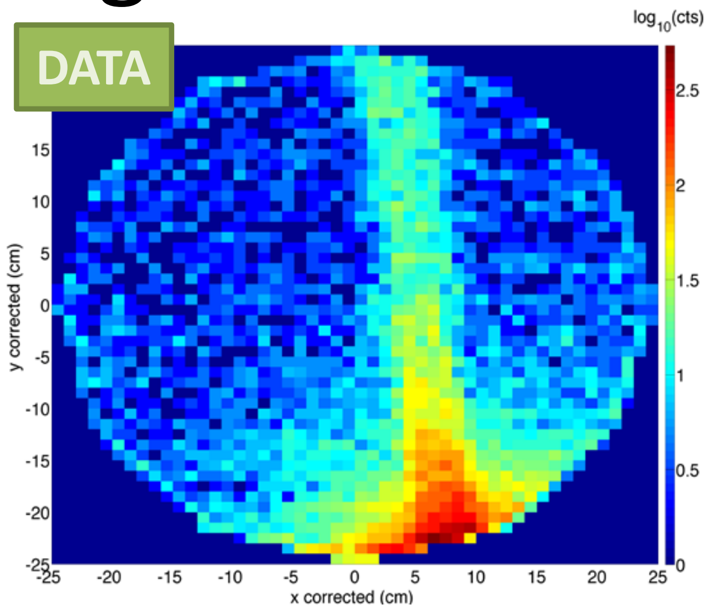
PLR fit projections

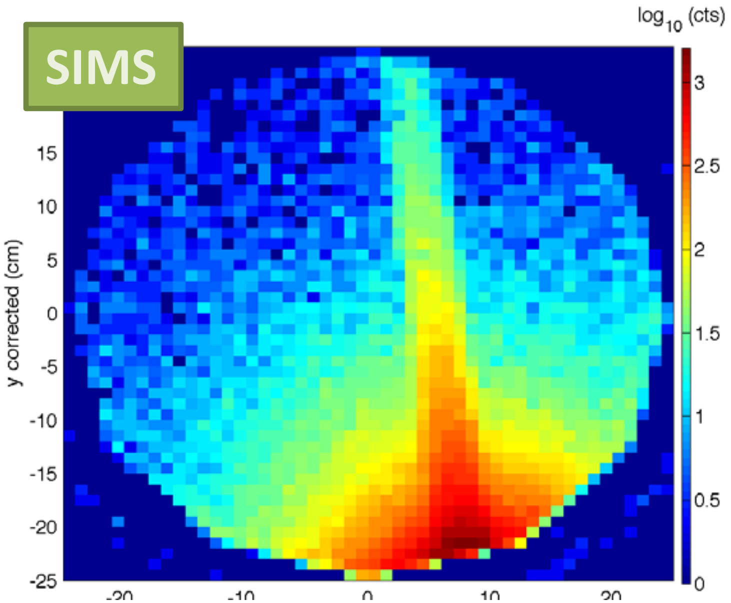


NR calibration with D-D generator

- Double scatters used to measure Q_i to ~1 keVr
- Single scatters used to measure L_{eff} to ~2 keVr

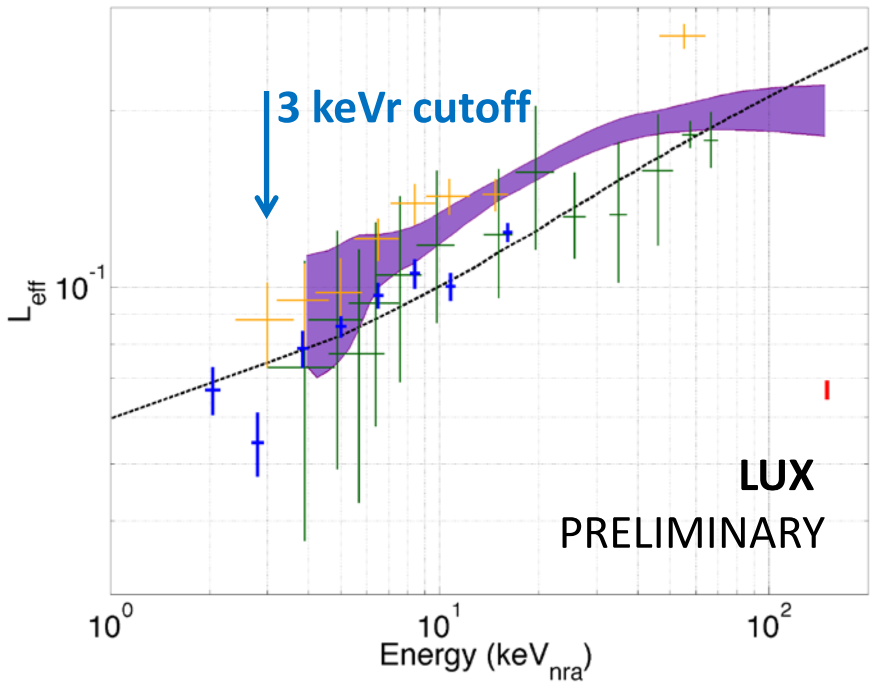






NR calibration with D-D generator

SCINTILLATION YIELD



IONISATION YIELD