ZEPLIN-III Two-Phase Xenon WIMP Detector

Results from the First Science Run

Henrique Araújo

Imperial College London & Rutherford Appleton Laboratory, UK

On behalf of the ZEPLIN-III Collaboration:

Edinburgh University (UK), Imperial College London (UK),

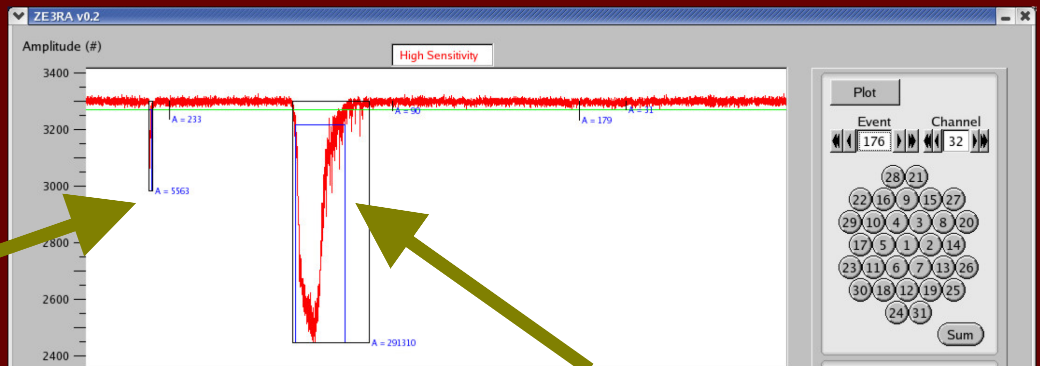
ITEP-Moscow (Russia), LIP-Coimbra (Portugal)

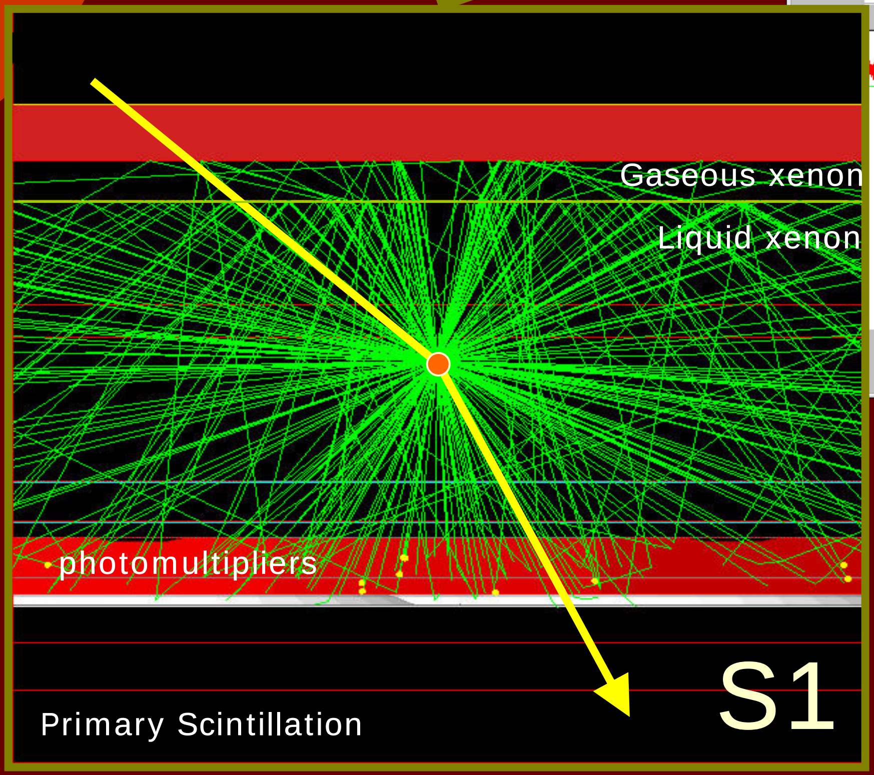
STFC Rutherford Appleton Laboratory (UK)

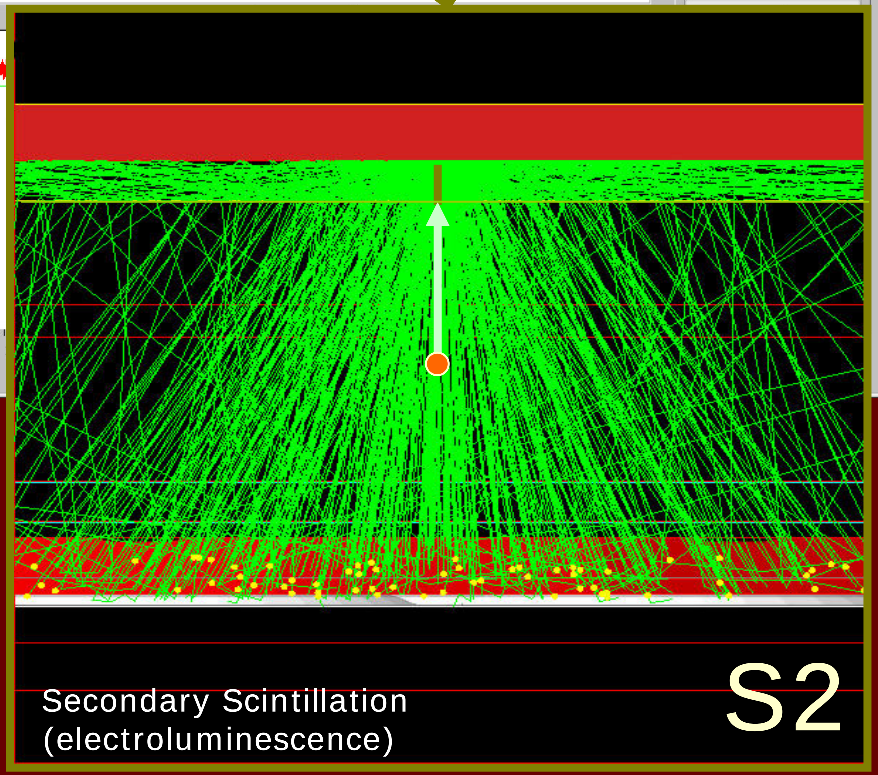
5th Patras Workshop, 13-17 July 2009, University of Durham, UK

ZEPLIN-III Operation Principle

Readout of <u>scintillation light</u> and <u>ionisation charge</u> with array of 31 photomultipliers

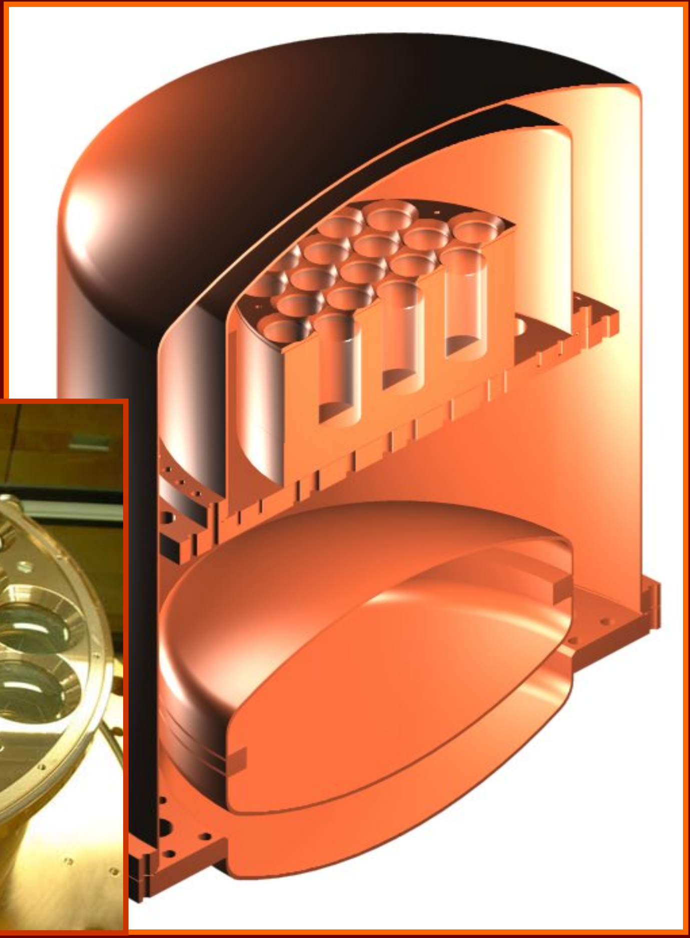


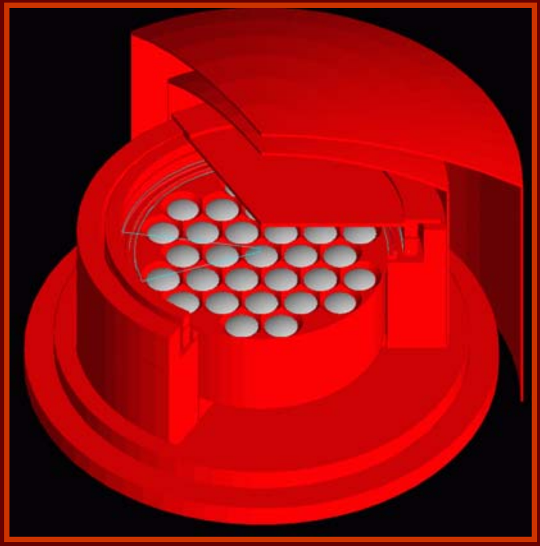




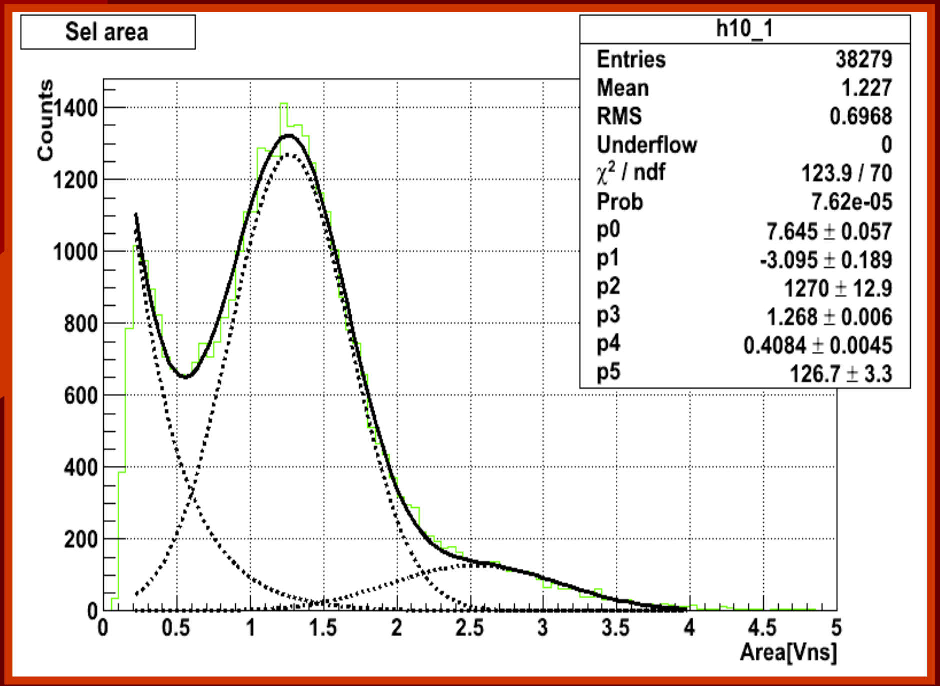
ZEPLIN III: High-Field, 2-Phase Xenon

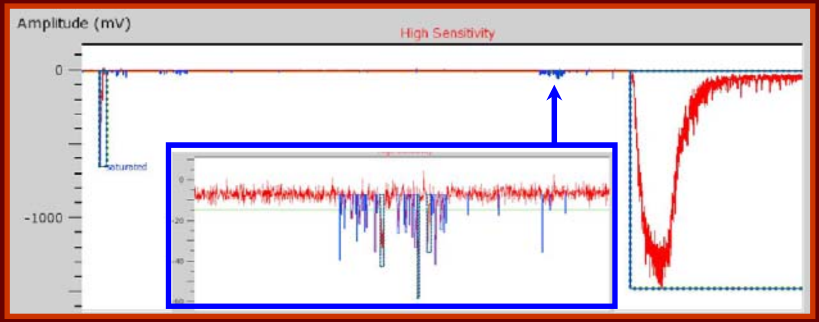
- ***Good light collection for scintillation***
  - ***Photomultipliers immersed in the liquid***
  - ***Slab geometry (35 mm drift height, D/h~10)***
- ***Better discrimination***
  - ***'Open plan' target, no extraction grids***
  - ***High field operation (4 kV/cm)***
  - ***Precision 3D position reconstruction***
- ***Low background construction***
  - ***Copper construction, low background Xe***

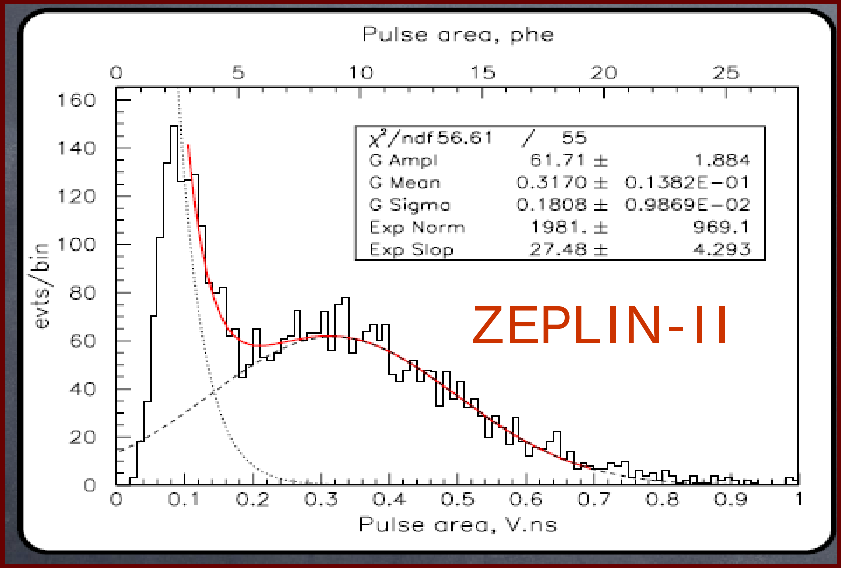




Single Electron Sensitivity in S2!







Sensitivity:

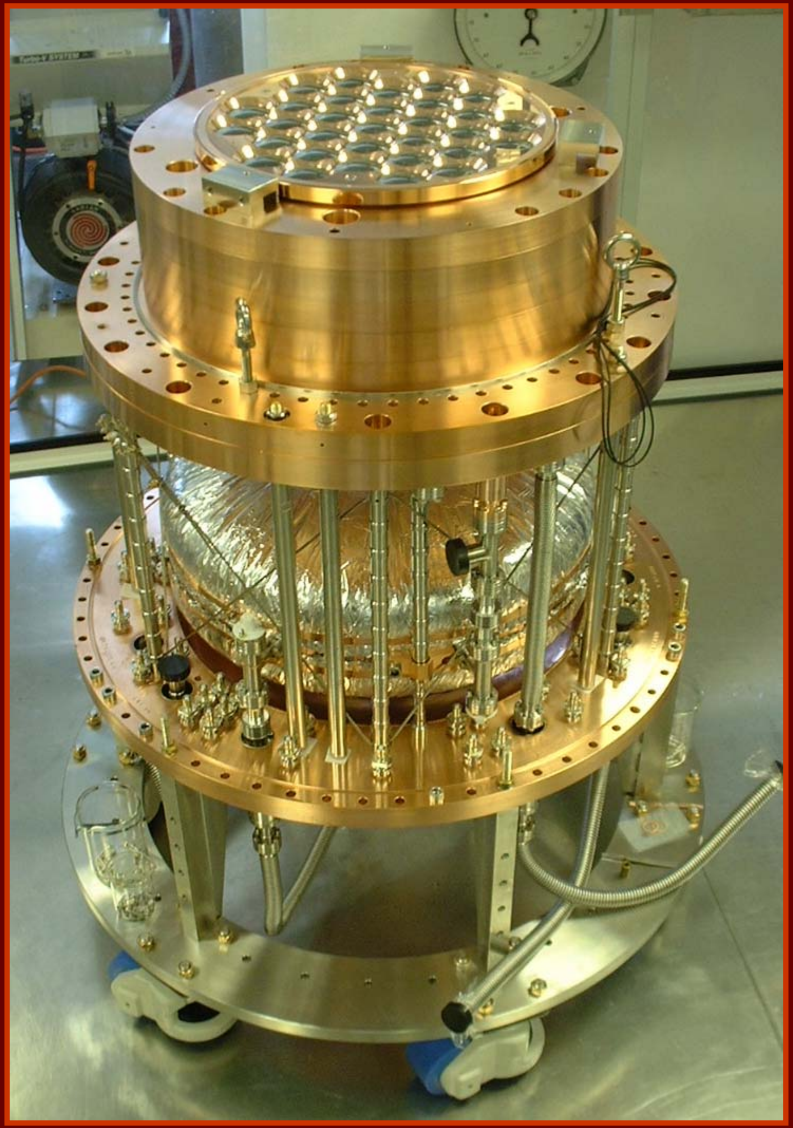
Quantum of ionisation measured in >kg LXe targets!

Calibration:

S2 electron yield calibrates absolute ionisation yields, electroluminescence, trigger thresholds

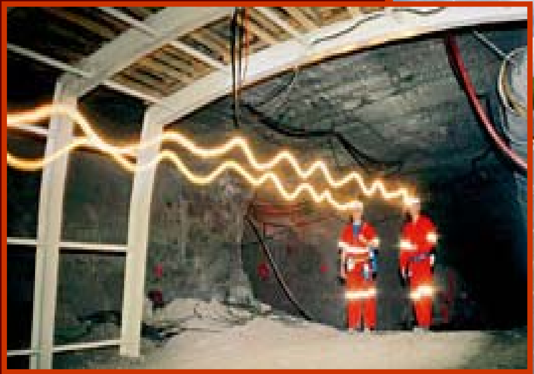
Edwards *et al.*, Astroparticle Phys. 30 (2008) 54

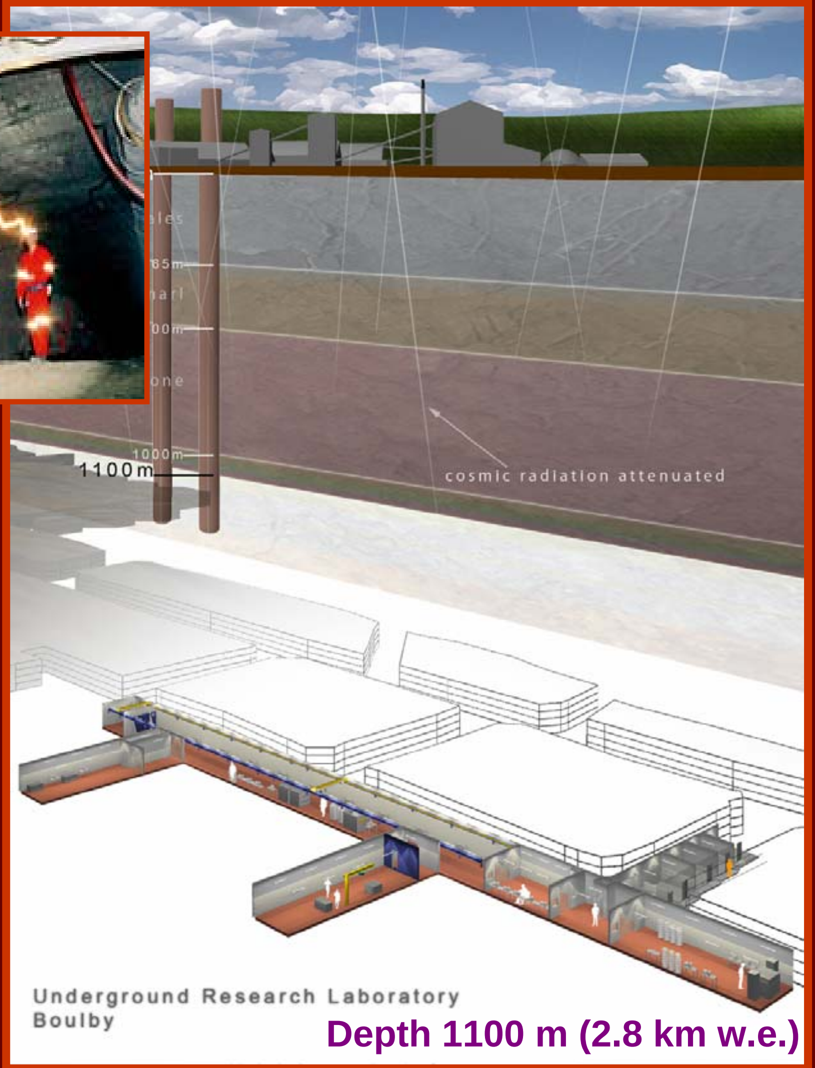
ZEPLIN III: Entrails



Boulby Underground Laboratory

We're all in the gutter, but some of us are looking underground...





Depth 1100 m (2.8 km w.e.)

Shielding: completed mid Feb 2008

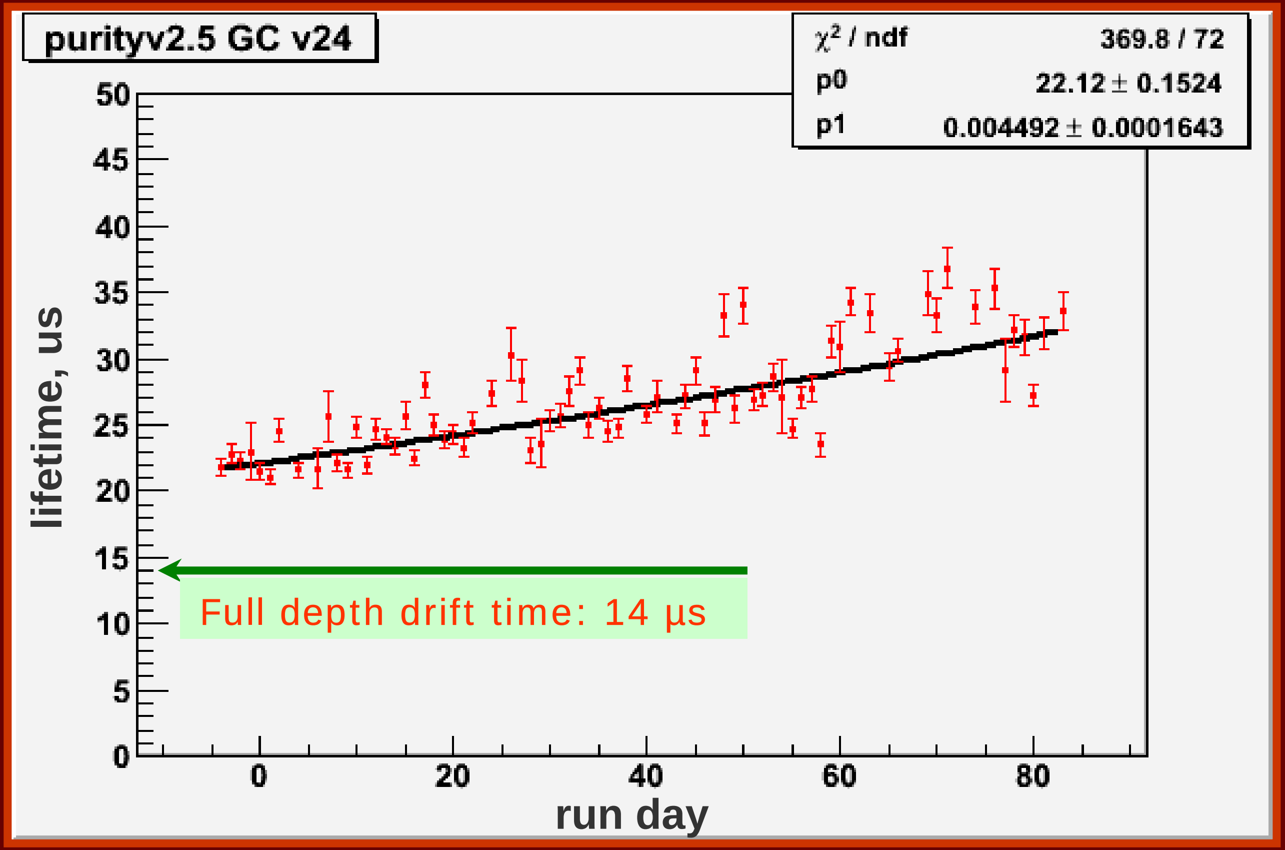
- Shielding against rock radioactivity
- 30 cm hydrocarbon, 20 cm boxed lead
- 10^5 attenuation for both neutrons and gamma-rays

First Science Run – parameters

- **Transport from lab at IC and recommissioning u/g during 2007**
- **Commissioning stage completed mid-Feb 2008**
  - All systems ready: gas handling, cooling, shielding, external levelling, DAQ, slow control, calibration delivery, data pipeline, …
- **Required electron lifetime achieved (>20 us)**
  - Purification in gas phase through external getters
  - No degradation once in target (construction with xenon-friendly materials)
- **Operational parameters defined**
  - 4 kV/cm in LXe, 8 kV/cm in GXe (17 kV between electrodes)
  - 4 mm gas gap, 1.6 bar operating pressure
  - S1 light yield 1.8 phe/keV @4 kV/cm (5.0 phe/keV @0 kV/cm)
  - S2 light yield ~20 phe/electron @4 kV/cm
- **Very stable operation for nearly 5 months!**
  - LN2 consumption: <20 litres/day as per thermal design
  - Stable pressure (temperature) throughout
  - Occasional (Poissonian) trips of PMT power supply
  - No anode/cathode trips during entire science run (many months)!

Free electron lifetime in liquid xenon

- First purification achieved ~20 us at high field (no degradation in target)
- (note that there is strong field dependence: low-field value >100 us!)
- This <u>increased</u> slowly during the run – with NO external recirculation!

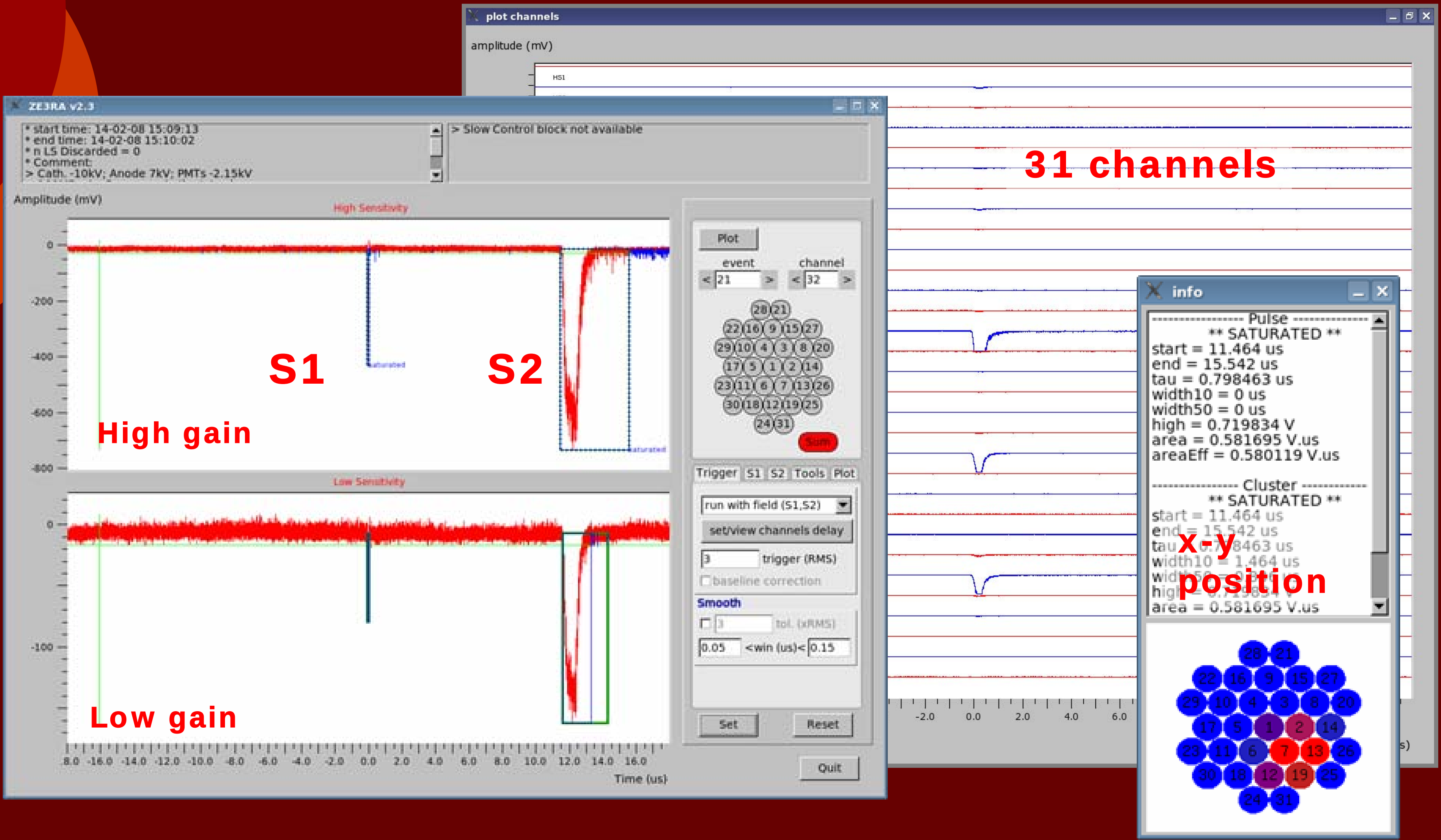


First Science Run – datasets

- **Early calibrations (Am-Be, Cs-137, Co-57, Co-60, …)**
  - Confirm performance, optimise operation parameters
- **First Science Run (shielded) begins 27 Feb 2008**
- **Daily calibration with Co-57 gamma-rays**
  - S1 & S2 stability, electron lifetime, levelling
- **Daily data dip-test (10%)**
  - Quality monitoring, electron-recoil background, analysis tuning
- **Science Run ends 20 May 2008**
  - 83 days at 84% duty cycle, 27 TB raw "dark" data
  - 850 kg*days raw exposure (12 kg LXe)
  - 450 kg*days fiducial exposure (6.6 kg LXe)
  - 128 kg*days efficiency-corrected exposure in WIMP-acceptance region
- **Final calibration runs**
  - Extended neutron (Am-Be) calibration (5 hours)
  - Extended gamma (Cs-137) calibration (122 hours, volume ~ dark data)
  - Engineering & Physics runs (a couple of weeks)

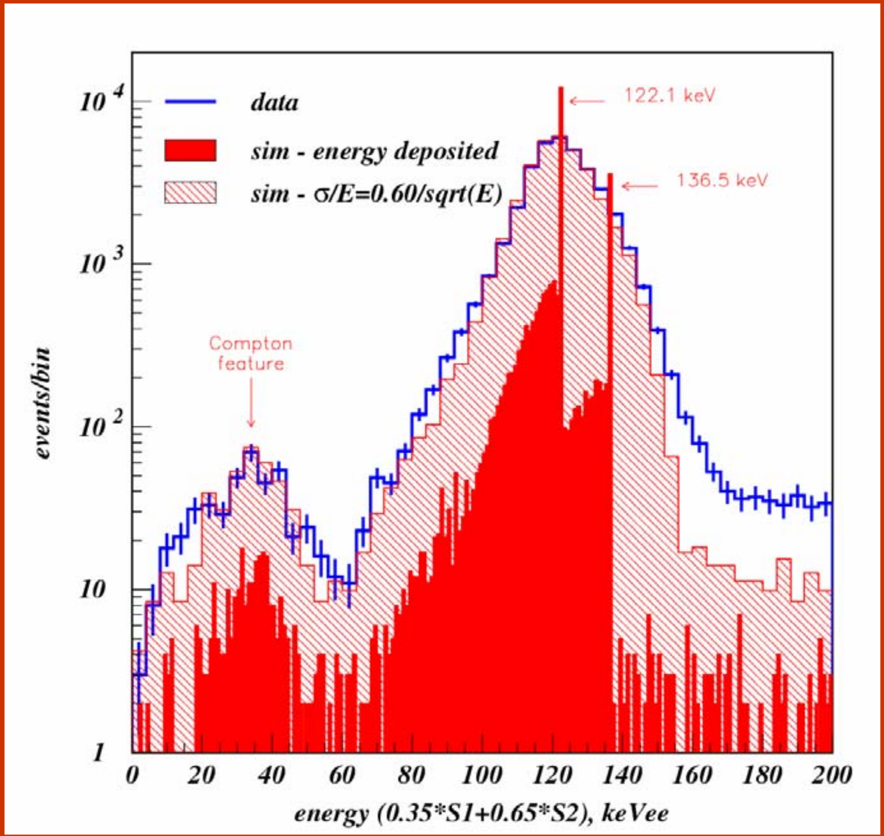
Data Processing

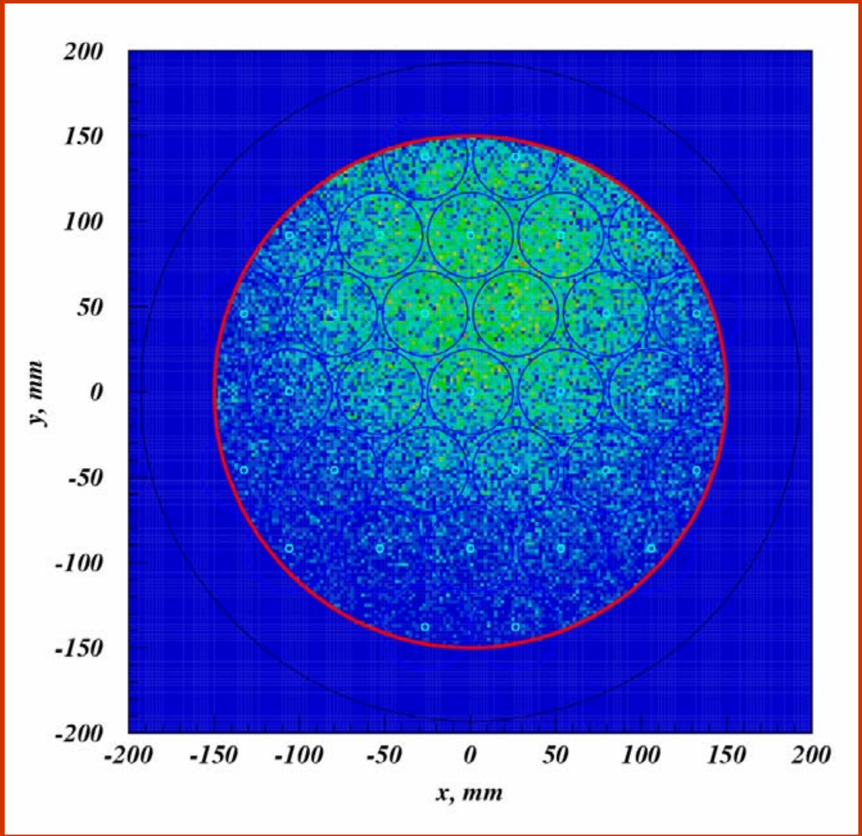
- Pulse finding and event display: ZE3RA (ZEplin 3 Reduction & Analysis)



Co-57 daily calibration

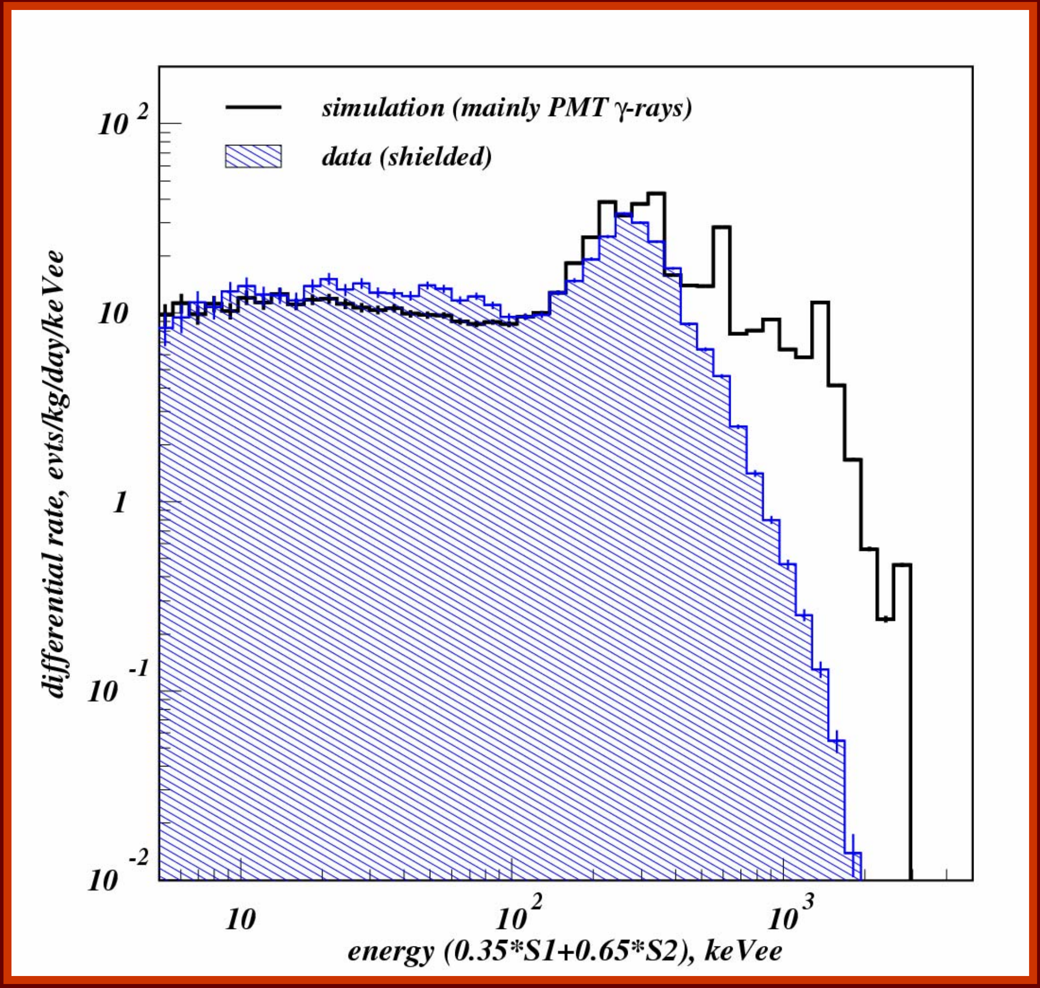
- Calibration is well understood – including low-rate, low-energy Compton feature
- Excellent energy resolution by exploiting S1-S2 anti-correlation (σ=5.4% @122keV)



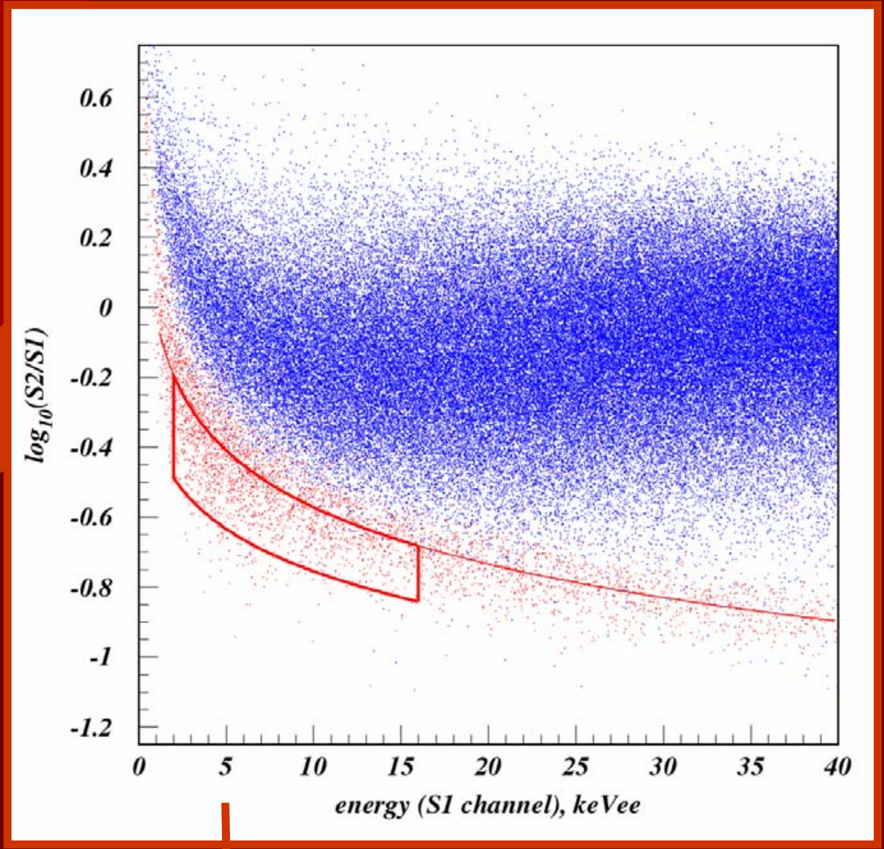


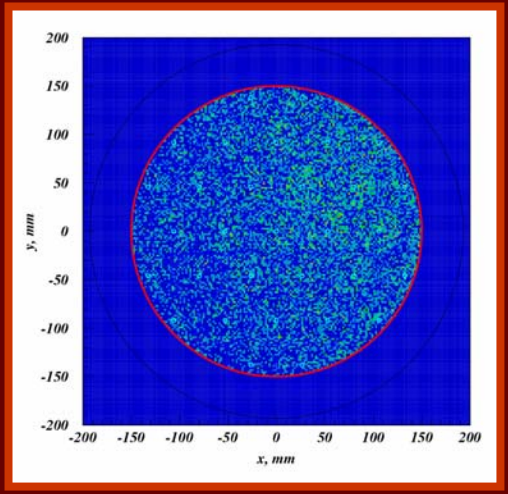
Low-energy gamma background

- 10 DRU – excellent agreement with MC prediction for PMT array



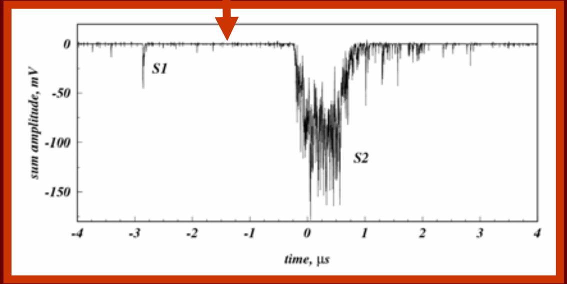
Nuclear recoil calibration (Am-Be neutrons)



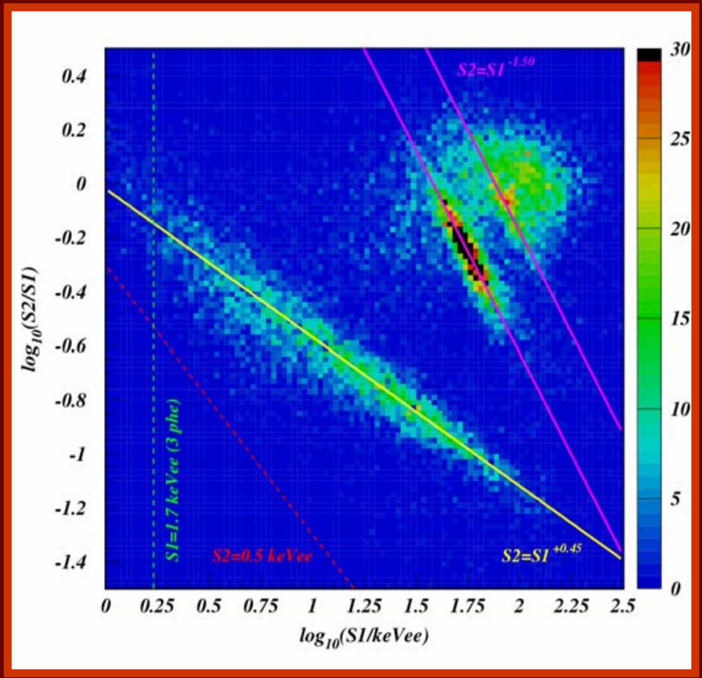


2-20 keVee NR
x-y distribution
biased towards
source location

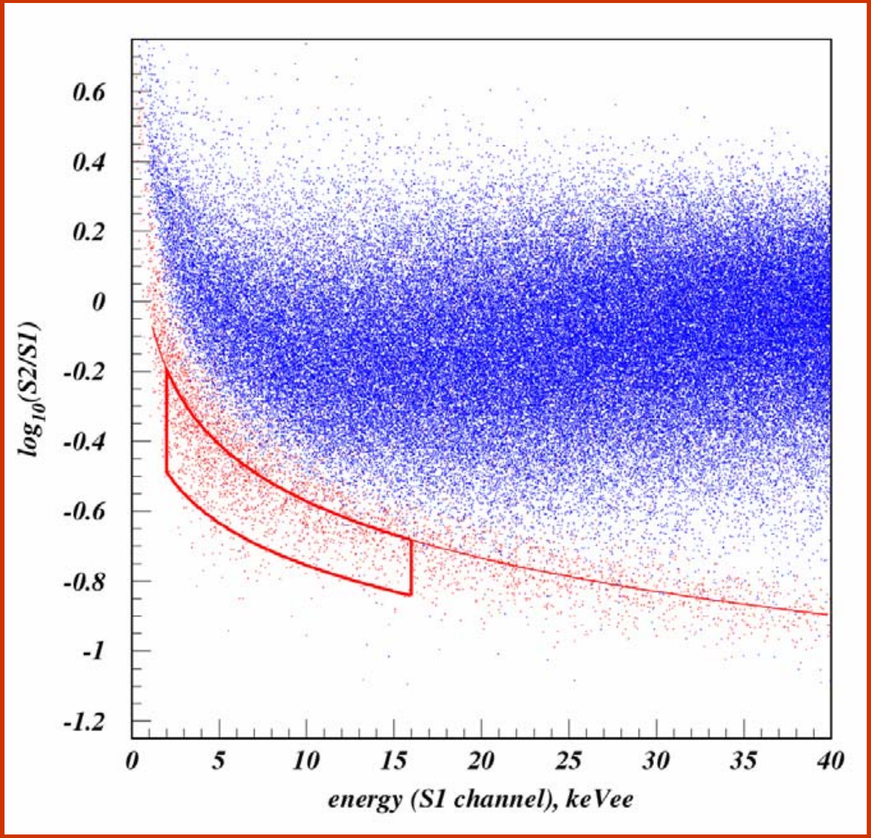
WIMP BOX:
2-16 keVee
$\mu-2\sigma$, μ

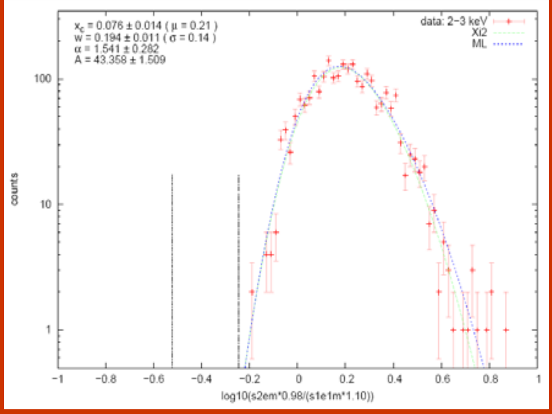


5 keVee NR
from neutron
elastic scatter



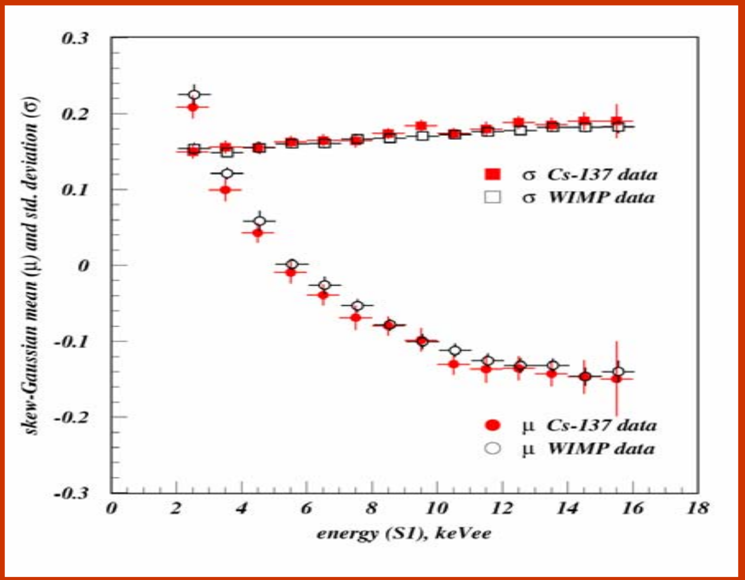
Electron recoil calibration (Cs-137 gammas)





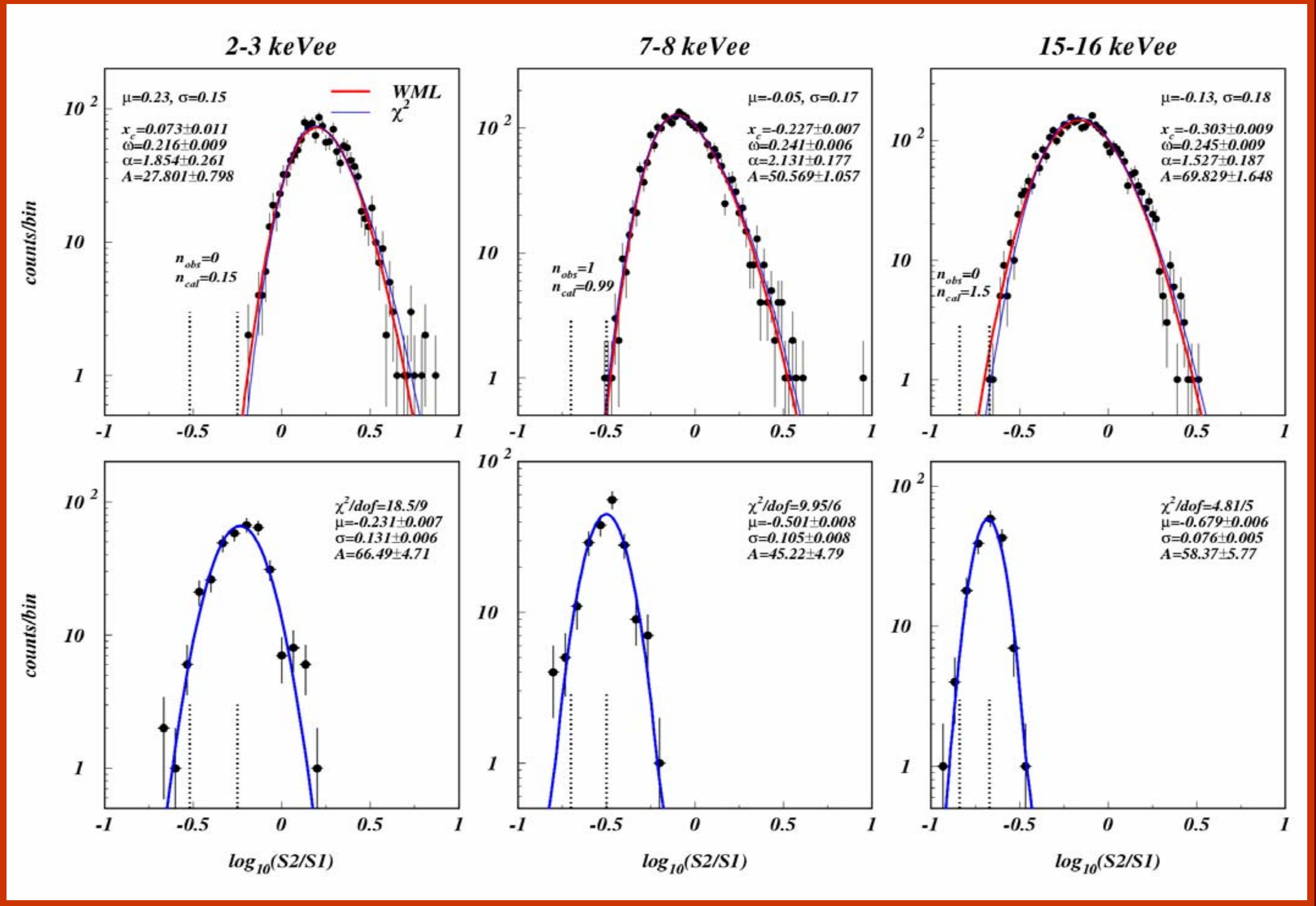
14 bins
in 2-16 keVee
fitted with
Skew-Gaussian
functions:

$$G(x|A, x_c, w, \alpha) = \frac{A\sqrt{2}}{w\pi} e^{-\frac{(x-x_c)^2}{2w}} \int_{-\infty}^{\alpha\frac{x-x_c}{w}} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt$$



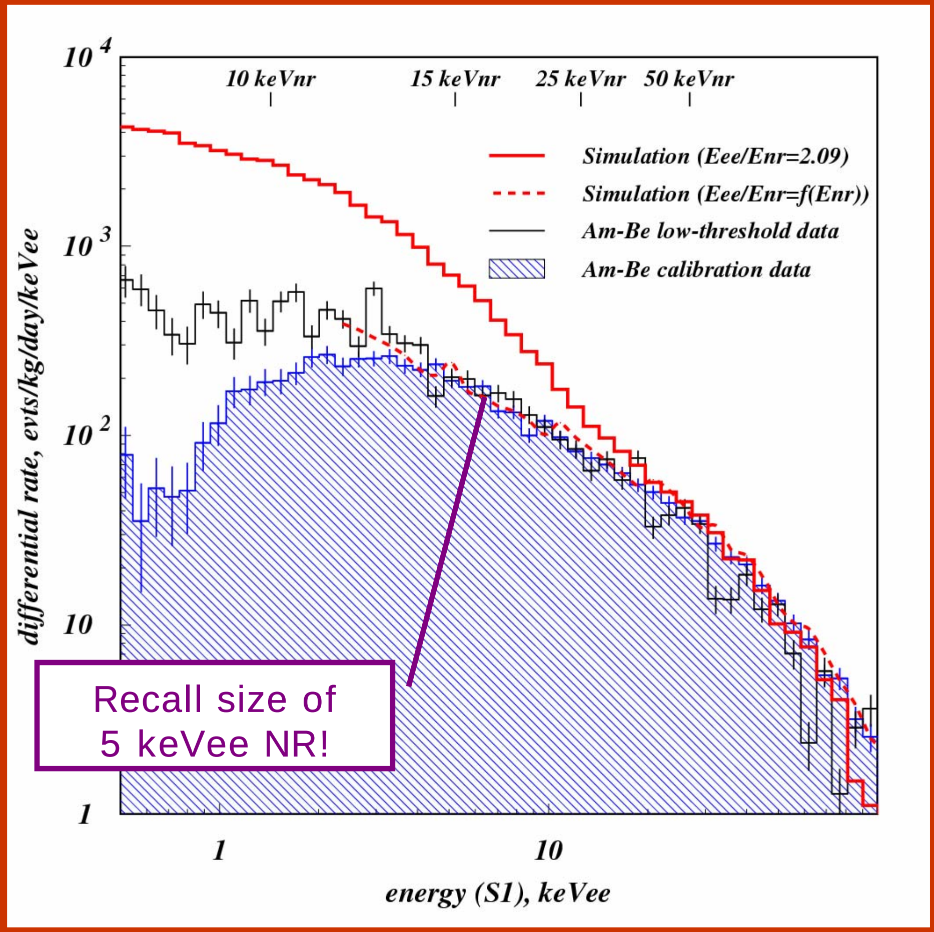
Electron-recoil populations in Cs-137 and WIMP-search datasets almost consistent, but small discrepancies exist due to higher rate and different source distribution

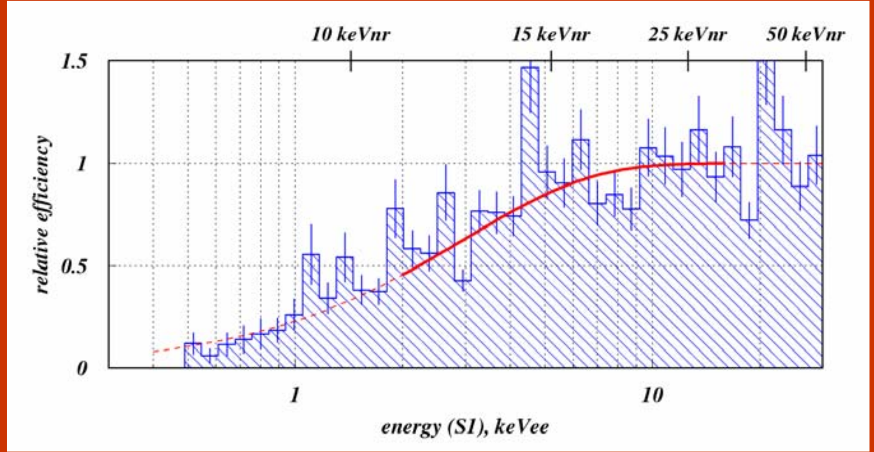
S2/S1 calibration (data and AmBe)

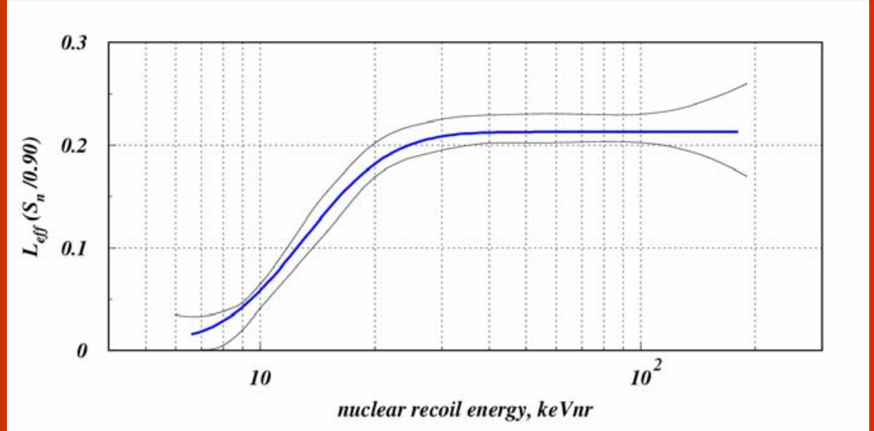


Prediction for ER leakage into WIMP acceptance box: 11.6±3.0 events

S1 response: E_{ee} to E_{nr} conversion





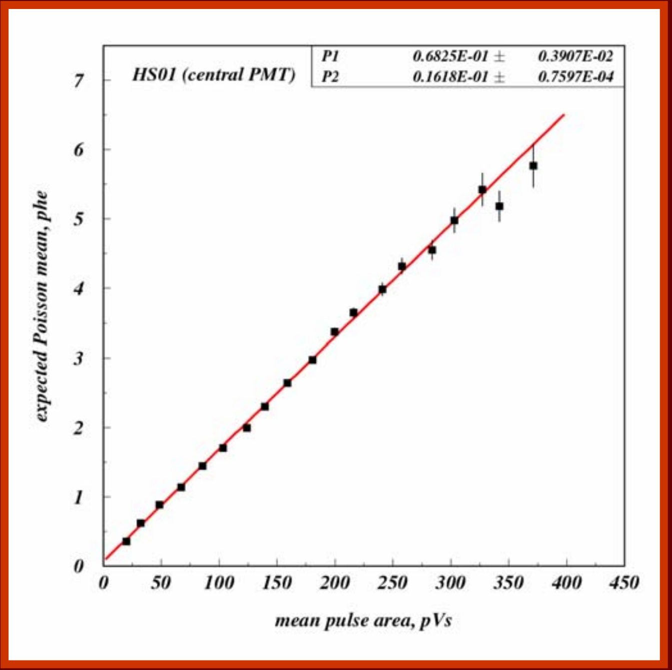


WIMP acceptance box: 2-16 keVee → ~10-30 keVnr

Looking for detection inefficiency

response sequence

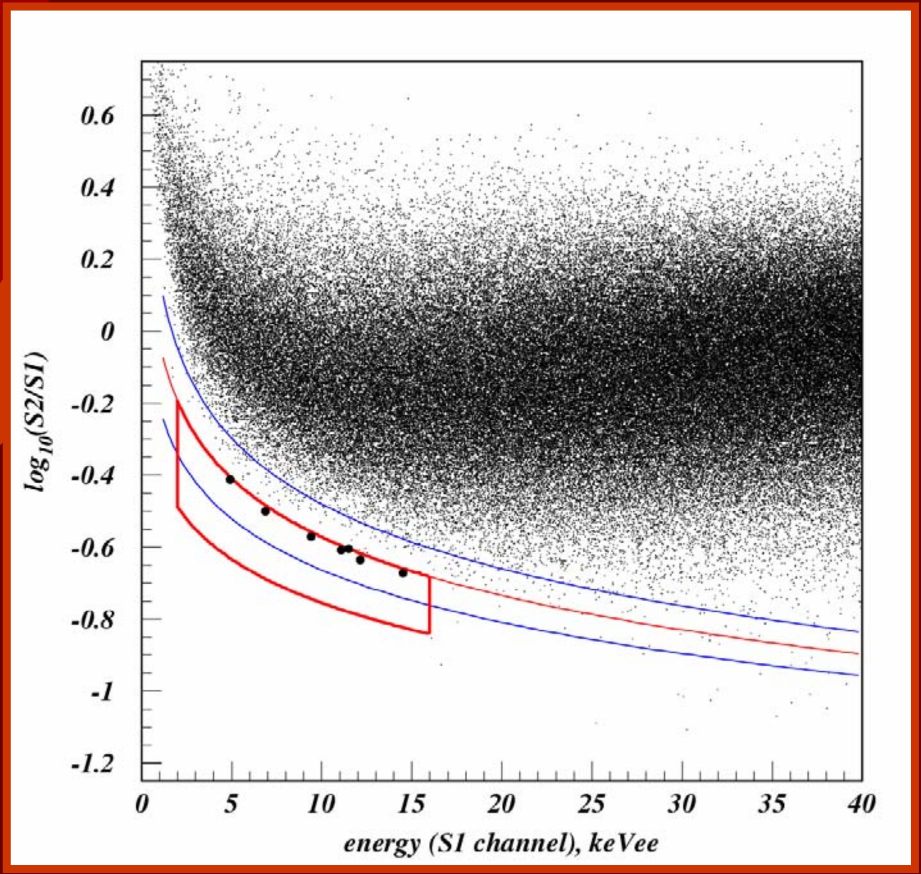
- ✗ Monte Carlo (GEANT4) systematics?
  - Correct implementation of ENDF-VI –VII
  - Resilient to most experimental parameters
  - Confirmed with independent MC FAUST
- ✗ Software cut efficiencies?
  - No significant effect at 10 keVee
  - Effect persists in uncut data
- ✗ Data reduction problem?
  - Visually scanned hundreds/thousands of events
  - Verified pulse parameterisations ‘by hand’
- ✗ Non-linear S1 response?
  - Very linear system over relevant response range
  - Confirmed by statistics-based calibration method
- ✗ Trigger inefficiency?
  - Software simulations confirm trigger function
  - Hardware tests (pulser) confirm trigger function
  - Lower-threshold AmBe dataset (effect <4 keVee)
- ✓ Varying scintillation yield?
  - Leff and/or Sn must vary with recoil energy!

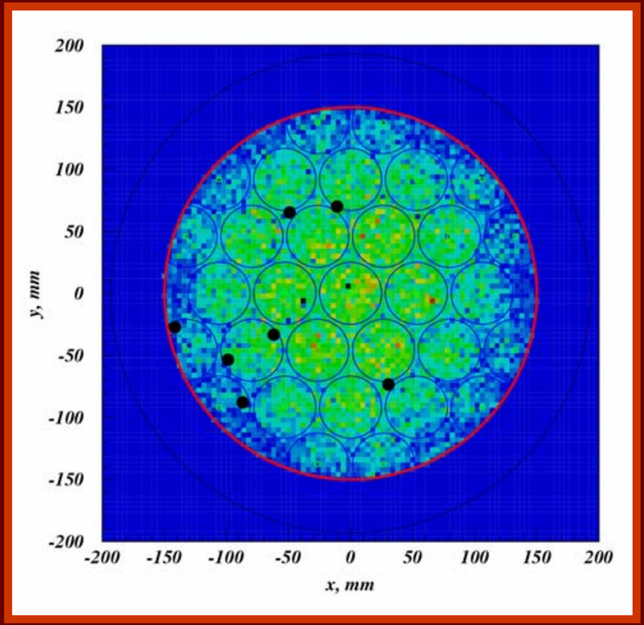


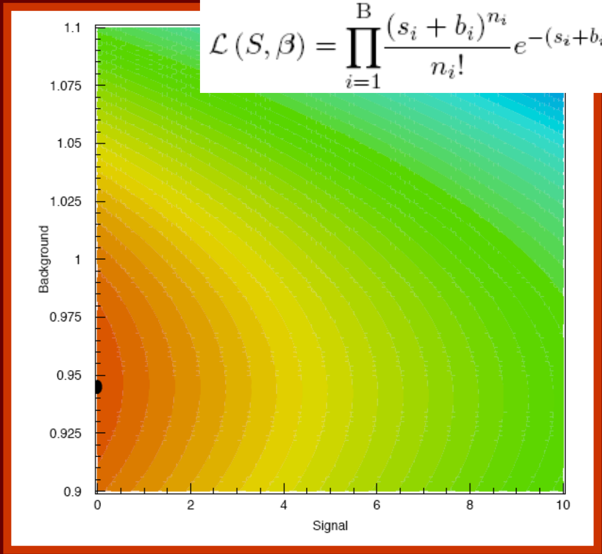
F. Neves et al, arXiv:0905.2523

$$E_{nr} = \frac{S1}{L_y} \frac{S_e}{L_{eff} S_n}$$

Science Data – 7 events in WIMP box





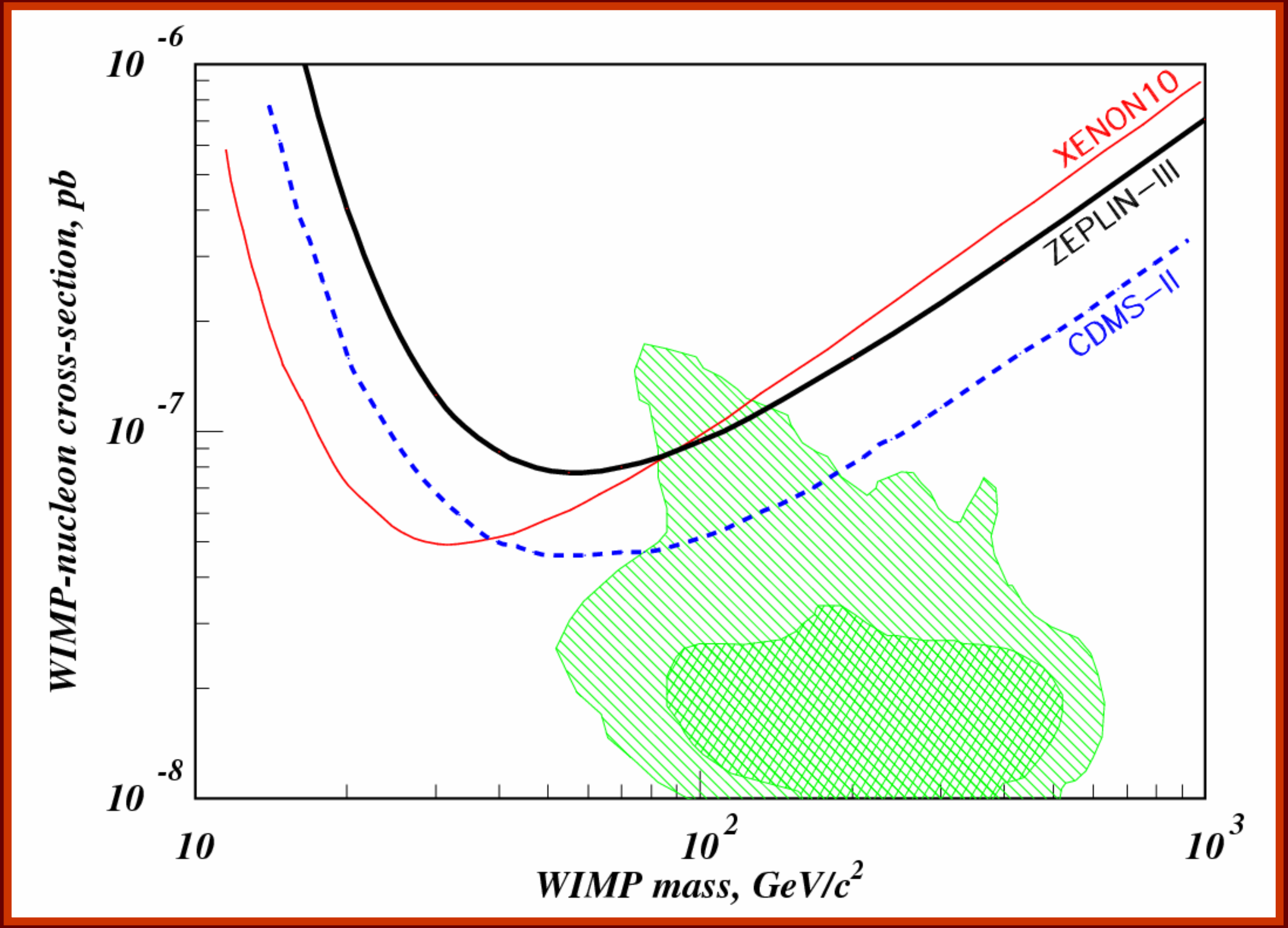


$$\mathcal{L}(S,\beta) = \prod_{i=1}^{B} \frac{(s_i + b_i)^{n_i}}{n_i!} e^{-(s_i+b_i)}$$

Maximum likelihood analysis with 1 nuisance parameter: varying width of ER Skew-Gaussian within errors

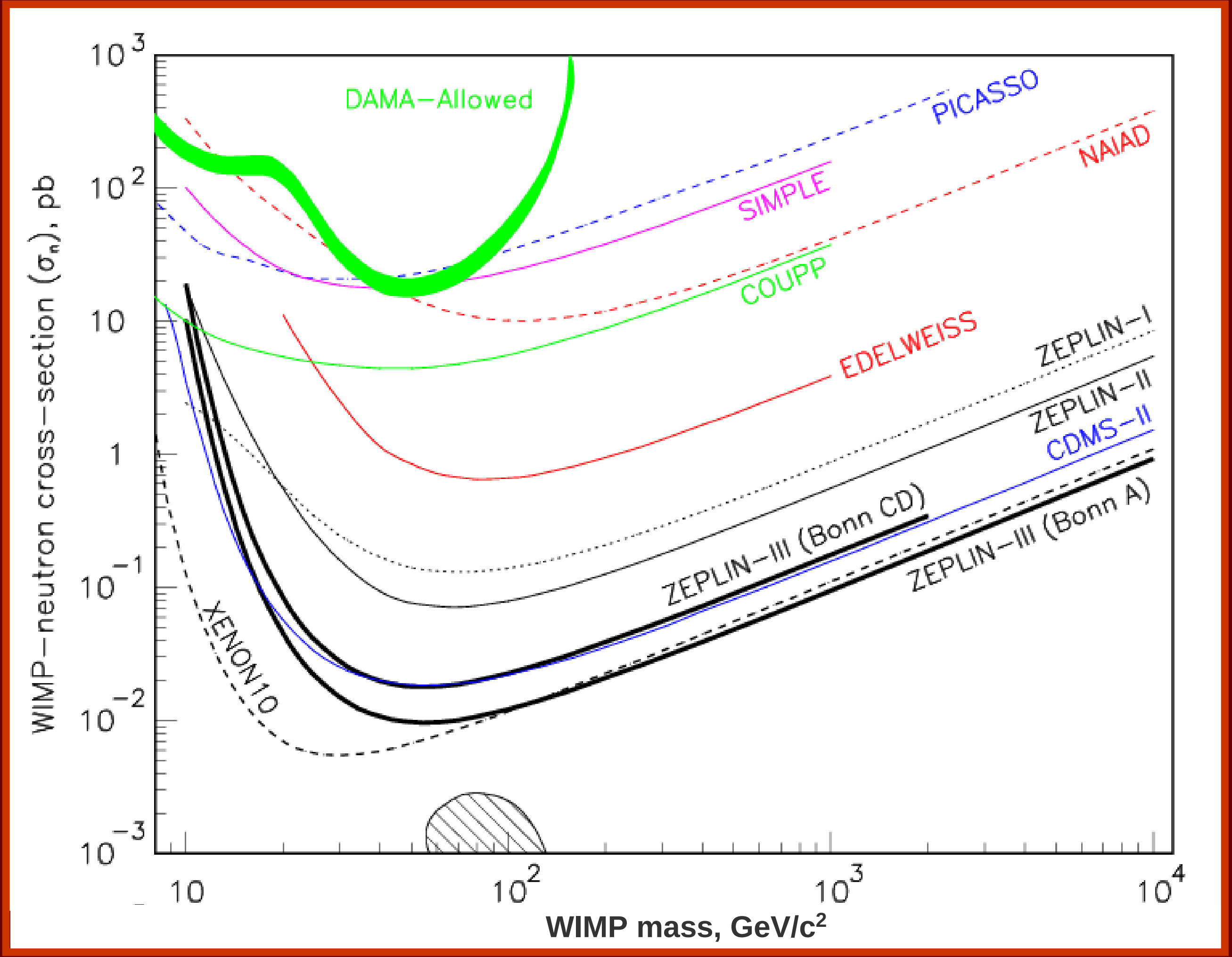
Global likelihood maximum: S=0, B=7 events
90% CL: 2.9 evts for 60 GeV WIMP (σ_{W-n} = 7.7x10^{-8} pb)

FSR Result – SI cross-section



Lebedenko et al, arXiv:0812.1150

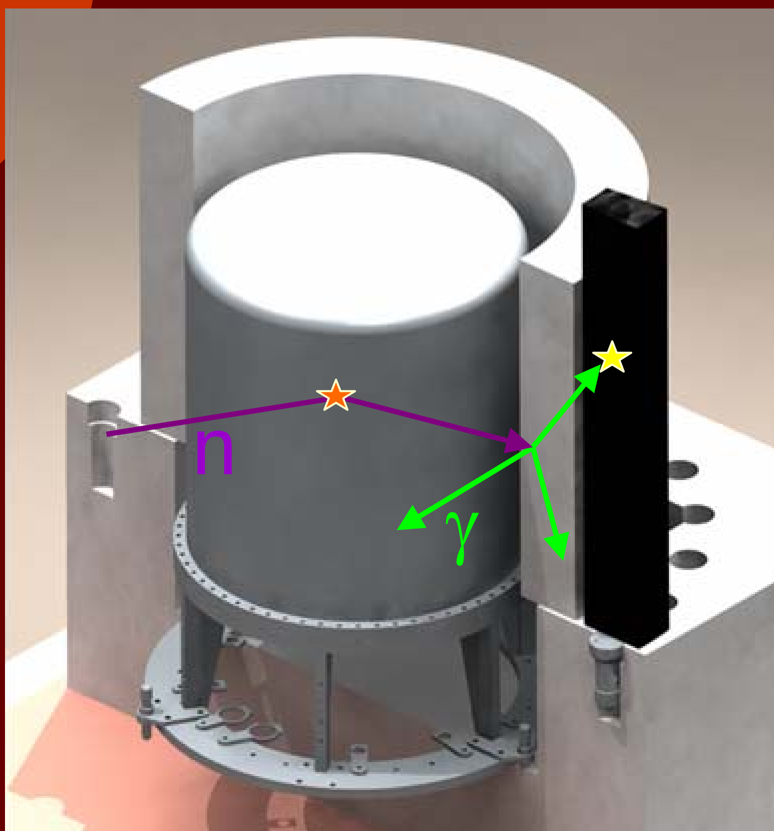
FSR Result – SD W-n cross-section



Lebedenko et al, arXiv:0901.4348

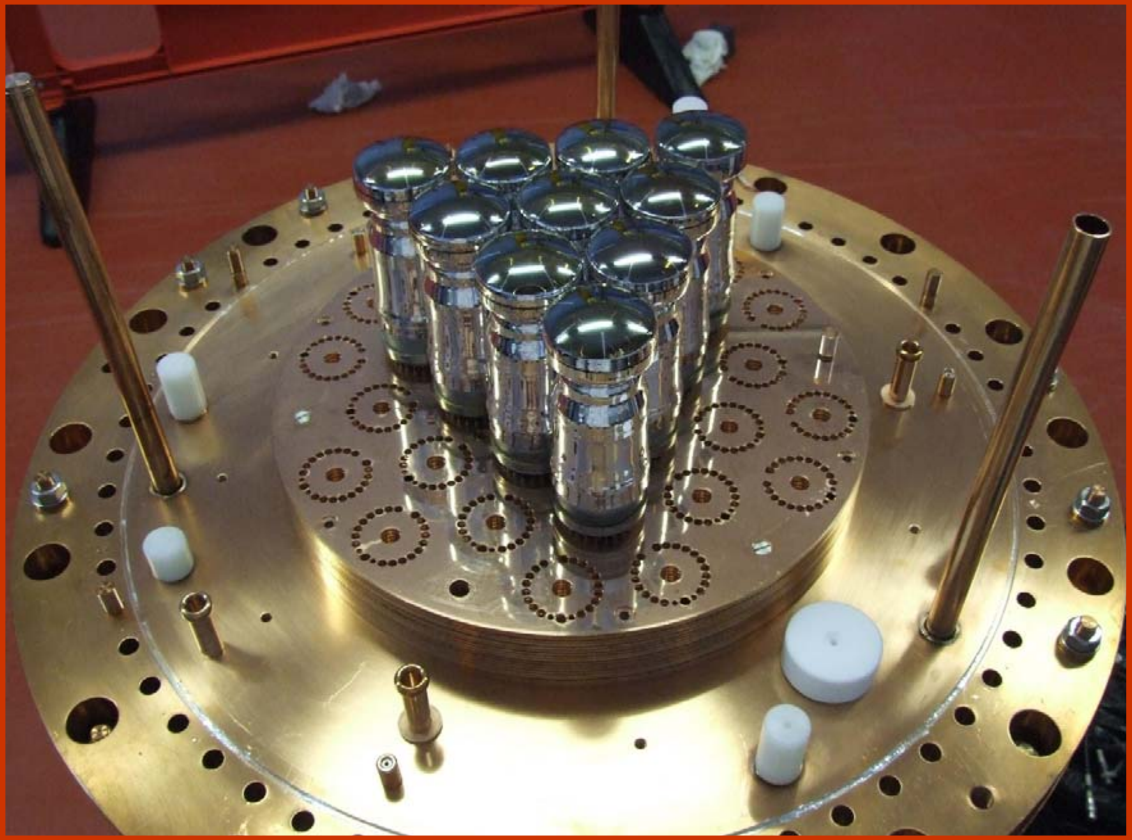
Phase II – Integration with Veto

- An important tool for both neutron rejection as well as diagnostics!
- Inner Gd-loaded hydrocarbon surrounded by plastic scintillator veto
- Delayed coincidence detection of capture gammas from Gd and H
- Final stages of commissioning – integration with ZEPLIN-III coming soon



Phase II – PMT Upgrade

- Existing PMTs limited sensitivity of first run (gammas-rays at least)
- Custom design for ultra low-background tubes, pin-by-pin compatible
- Factor ~30 improvement in gamma-ray activity expected



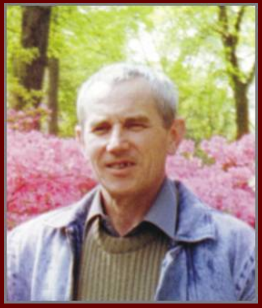
Summary

- Demonstrated long-term operation of two-phase xenon detector
- Achieved stable operation at high electric field (4 kV/cm)
- Stable (and improving!) electron lifetime with no recirculation
- Excellent electron/nuclear recoil discrimination (better than 1:5,000)
- Gamma background (PMT dominated) is well understood
- World-level SI and SD results (SI $\sigma_{W\text{-}n} = 7.7\text{x}10^{-8}$ pb)
- Second science run to begin soon with upgraded instrument
- Tenfold sensitivity improvement within reach (SI $\sigma_{W\text{-}n} < 1\text{x}10^{-8}$ pb)

In Memoriam

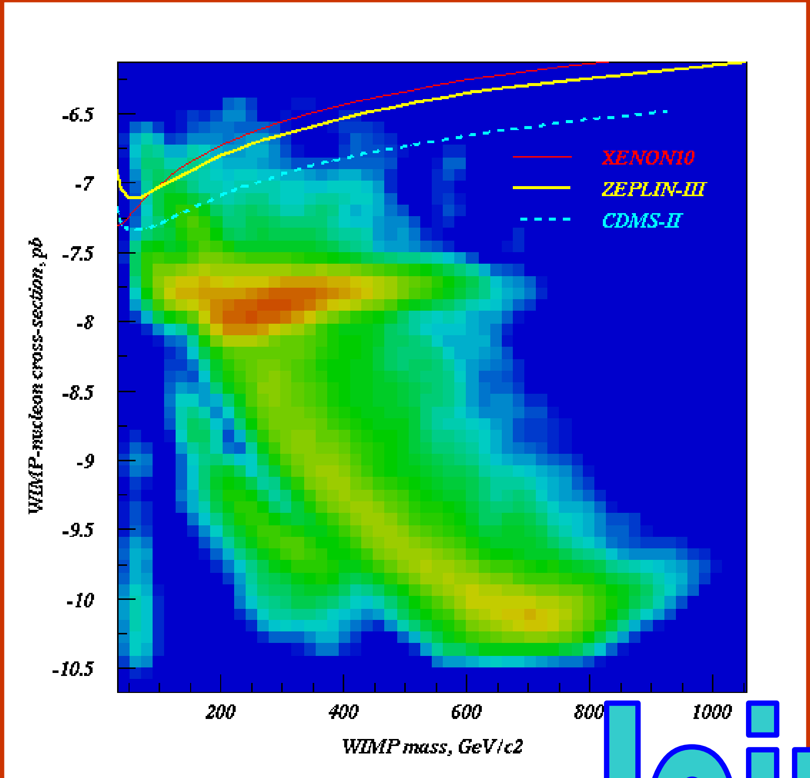
Vadim Nikolaevitch Lebedenko

1939 – 2008



LUX-ZEPLIN – tonne-scale targets

- Still a long way to go to exclude full SUSY parameter space!
- US LUX team and European ZEPLIN team have joined forces
- LZ3 3-tonne xenon at SUSEL + LZ20 20-tonne xenon at DUSEL



Join us!