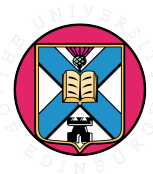


Final Results of the ZEPLIN-III Direct Dark Matter Search



Imperial College
London



DM in the news...

...easy come, easy go



16 September 2011

9 January 2012 Last updated at 19:07

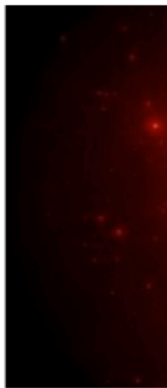
517 Share

Dark matter images reveal widest view of dark mystery

By Jason Palmer

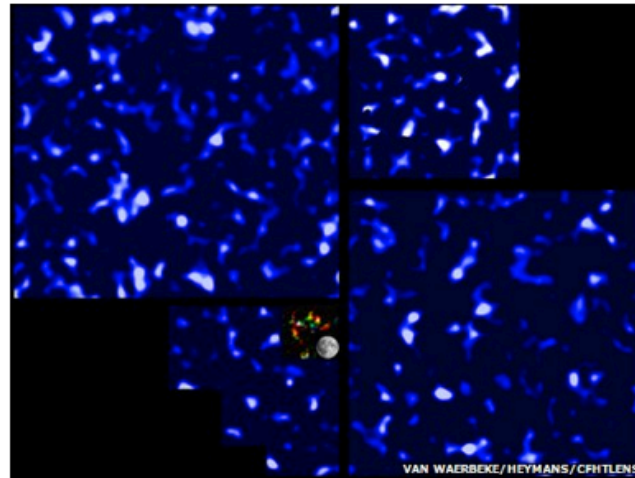
Science and technology reporter, BBC News, Austin, Texas

By Leila Battisti
Science reporter,



Dwarf galaxies are

Scientists' preferred
to make up more
revised.



The survey dwarfs the previous largest map, shown at centre alongside the moon for comparison of size in the sky

Researchers have released the biggest images yet detailing dark matter, the mysterious substance that makes up 85% of the Universe's mass.

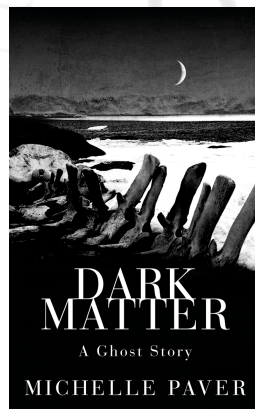
Related Stories

Dark matter themes

Case for DM
Certain Every,
strong
(Sorry Carlos!)
next week!

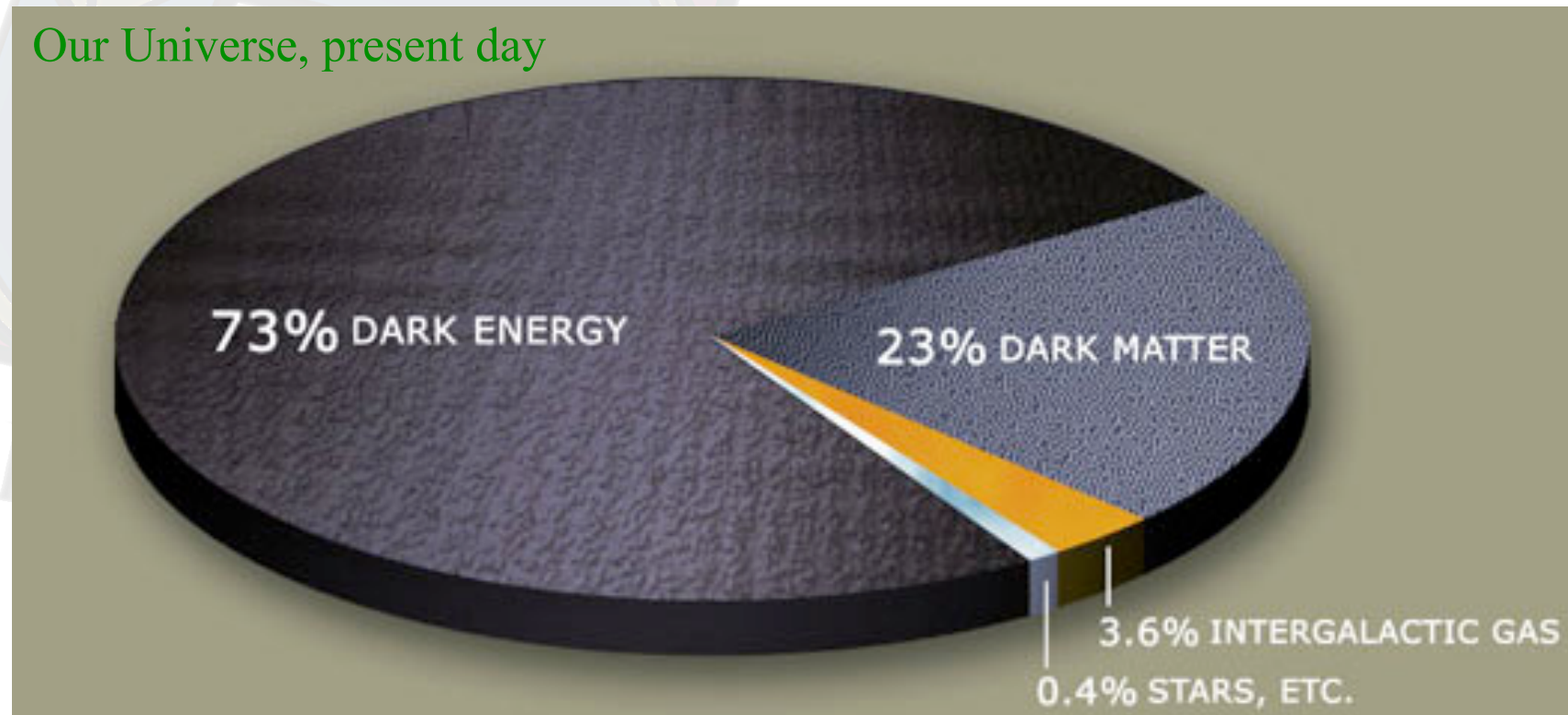


And don't forget DM in a wider public awareness!

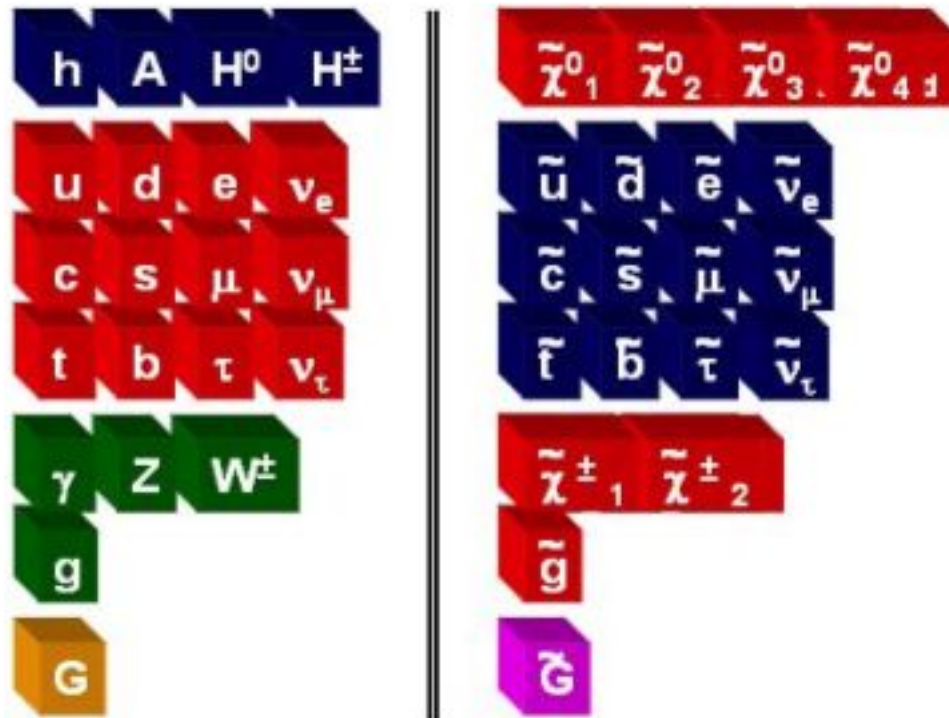


For this talk, basic premise...

Our Universe, present day



For this talk, basic premise...



WIMP is the lightest supersymmetric particle ('LSP'), χ , a linear combination of bino, wino and Higgsino fields.

$$\chi = \alpha \tilde{B} + \beta \tilde{W} + \gamma \tilde{H}_1 + \delta \tilde{H}_2$$

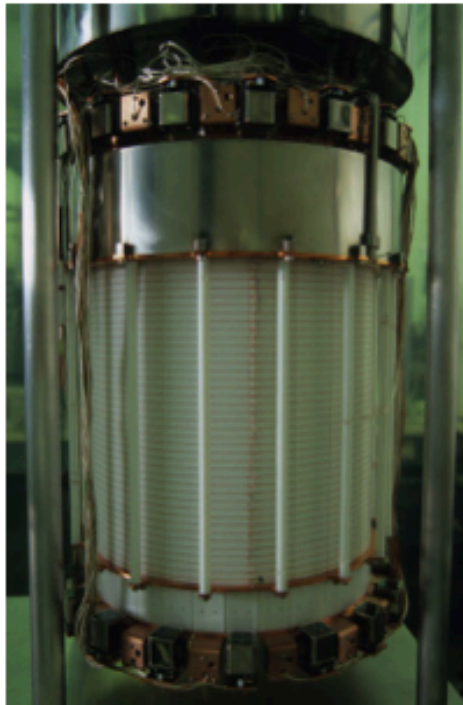
If SUSY is wrong, that doesn't stop galaxies rotating too fast. Direct DM searches are sensitive to many non-SUSY signals.

How to search for dark matter?

Indirectly



Directly

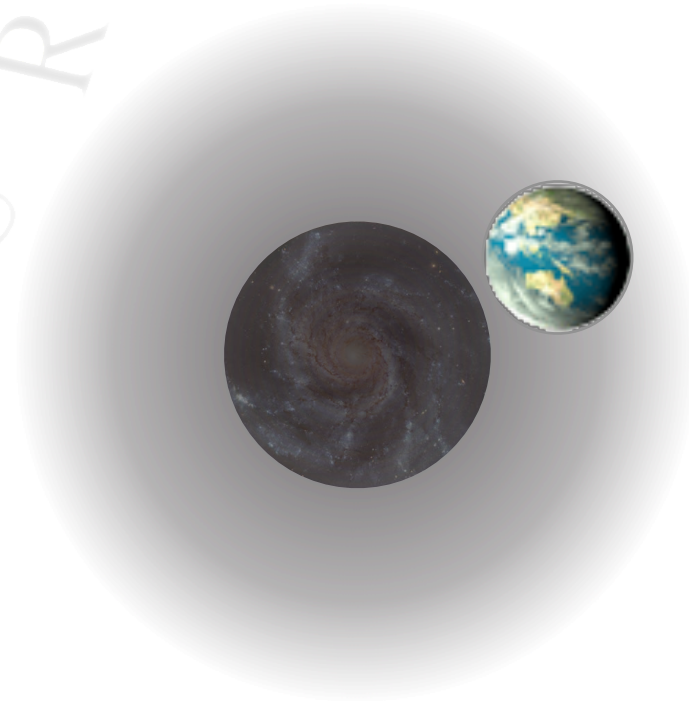


Collider



For this talk, basic premise...

- Earth should be passing through a halo of weakly interacting massive particles
- We search for the rare collisions of WIMPs with normal matter here on Earth.



How to directly detect dark matter?

In the most simple terms...

Make a device that should see nothing
from normal physics

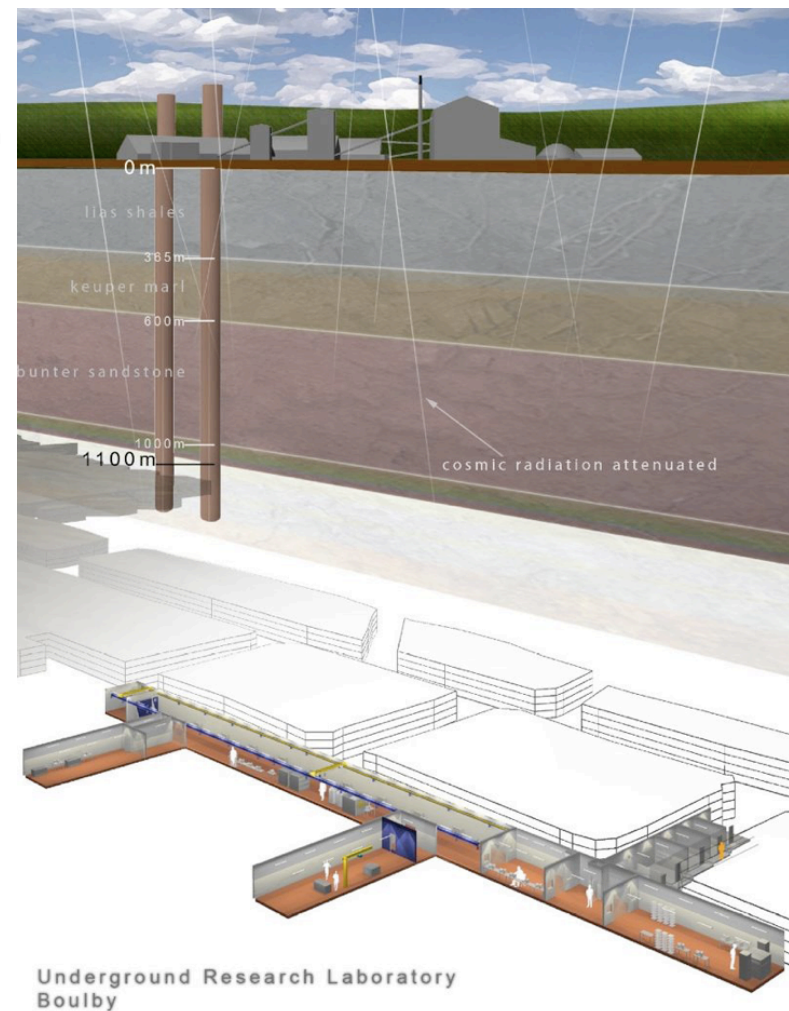
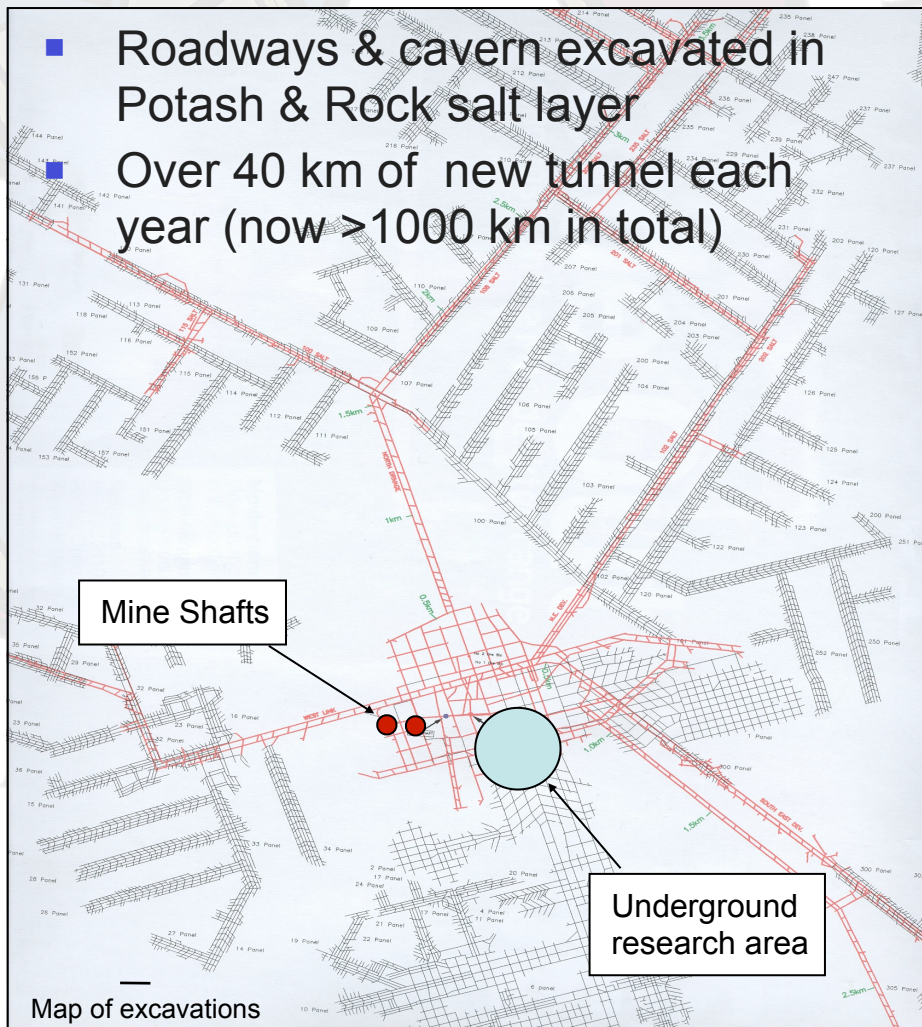
And see if there's anything still there...



WHERE SHALL WE SEARCH?

The Boulby Mine - A very dark place!





The natural radioactive backgrounds greatly reduced

Low background is not easy...

Cosmic Rays

Muons produced in showers
and muon-induced neutron
production



Radiological Backgrounds

From surrounding environment
(rock, etc.)



Construction Materials

Shielding
Detector interior
Photo Multiplier Tubes
(PMTs)

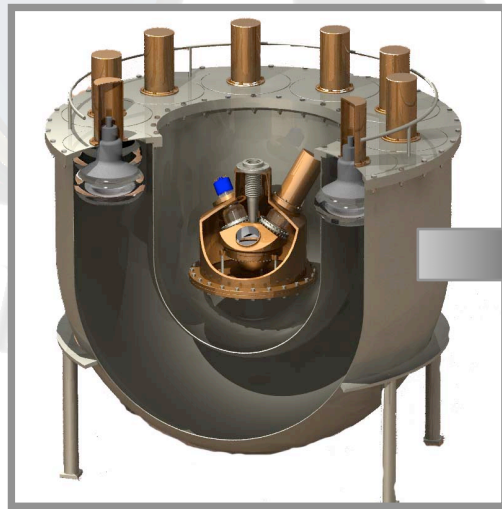
Discrimination between
event species, veto
detector,...

Low background is not easy...

- Every component is measured for radioactivity (U, Th, K)
- Fission, (α ,n), and γ -ray impact of that activity evaluated through full Monte Carlo
- Replacement or redesigns if necessary
- Gamma rays from PMTs limited the first science run
- Second Science Run planned from start

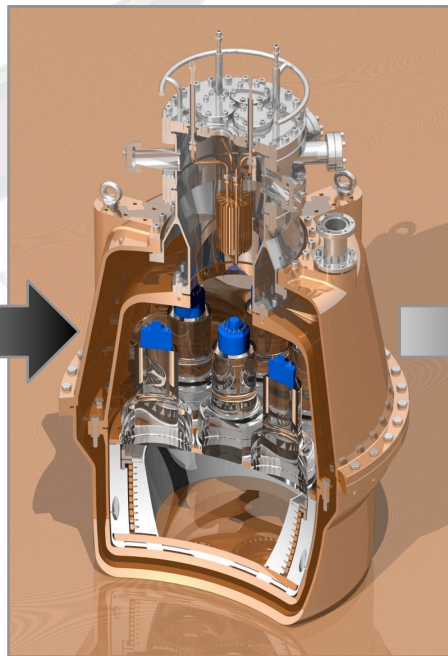
The ZEPLIN Programme

ZEPLIN-I



Single phase

ZEPLIN-II



**Two phase
Low field**

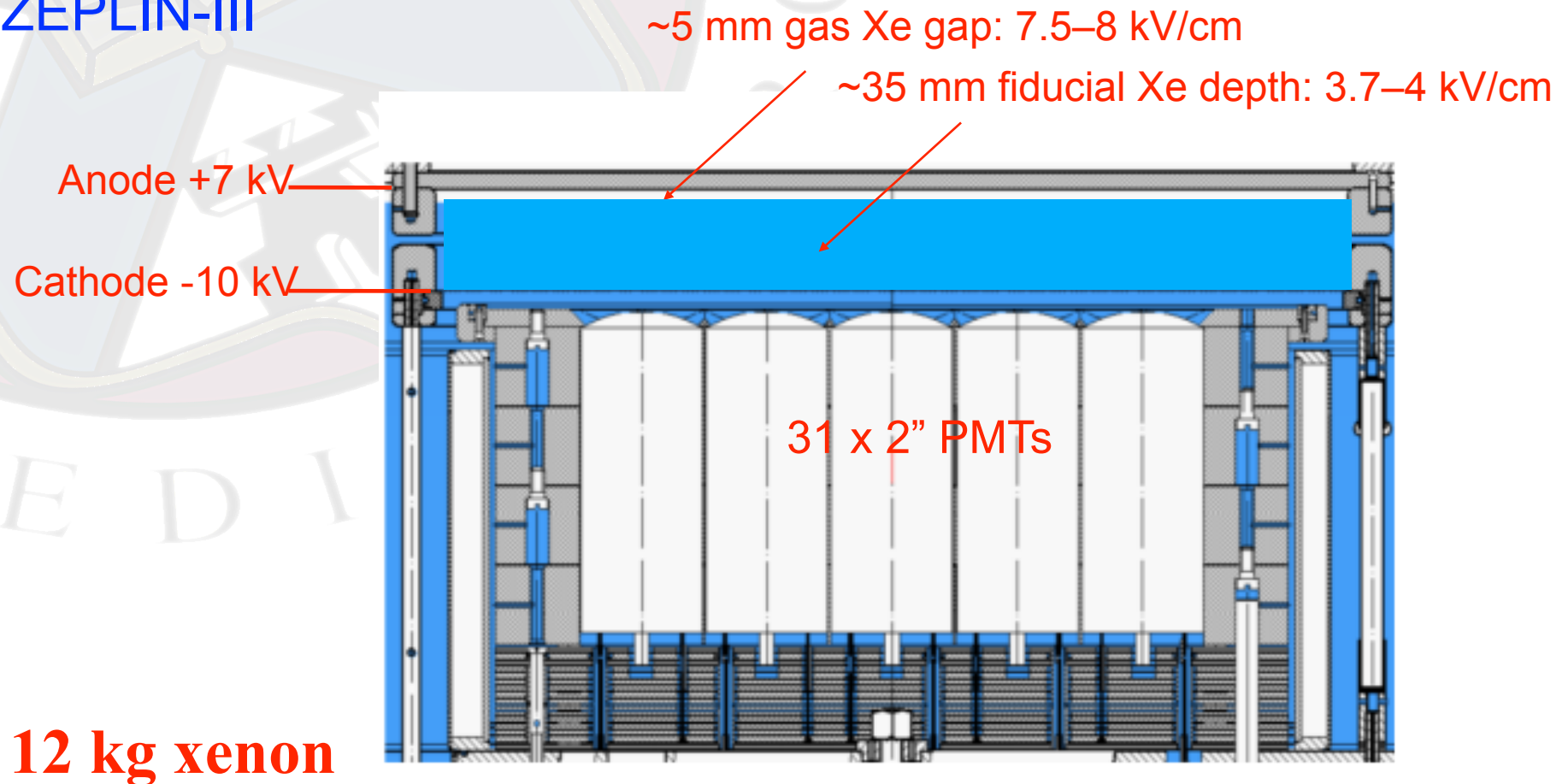
ZEPLIN-III



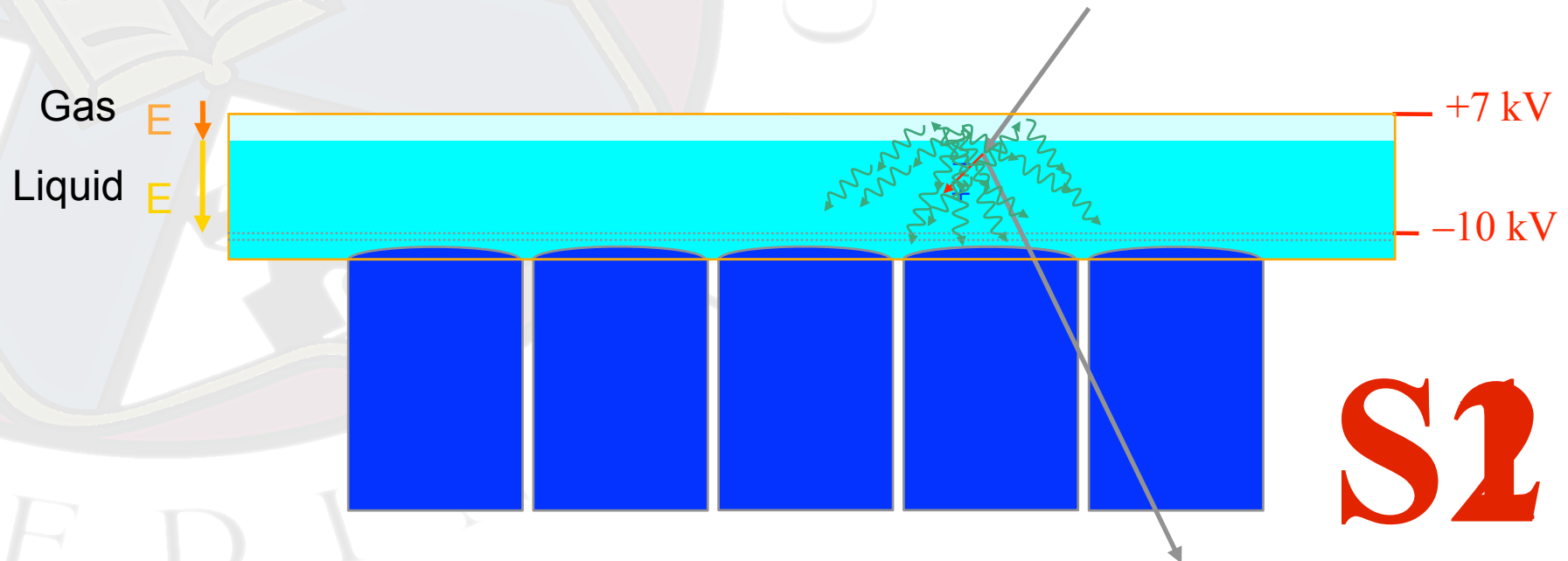
Two phase, high field, low bkgd

Two-phase Xenon

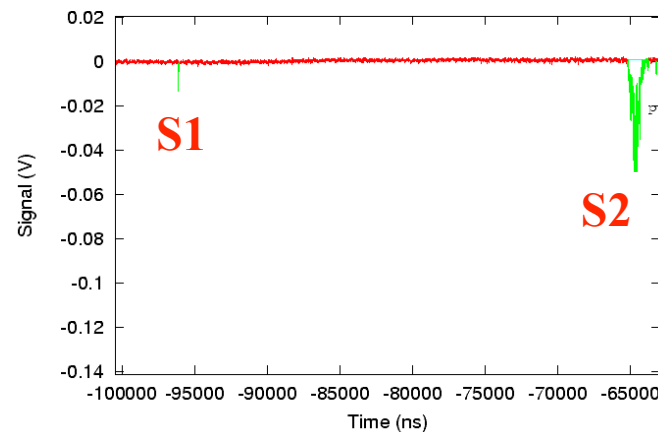
ZEPLIN-III



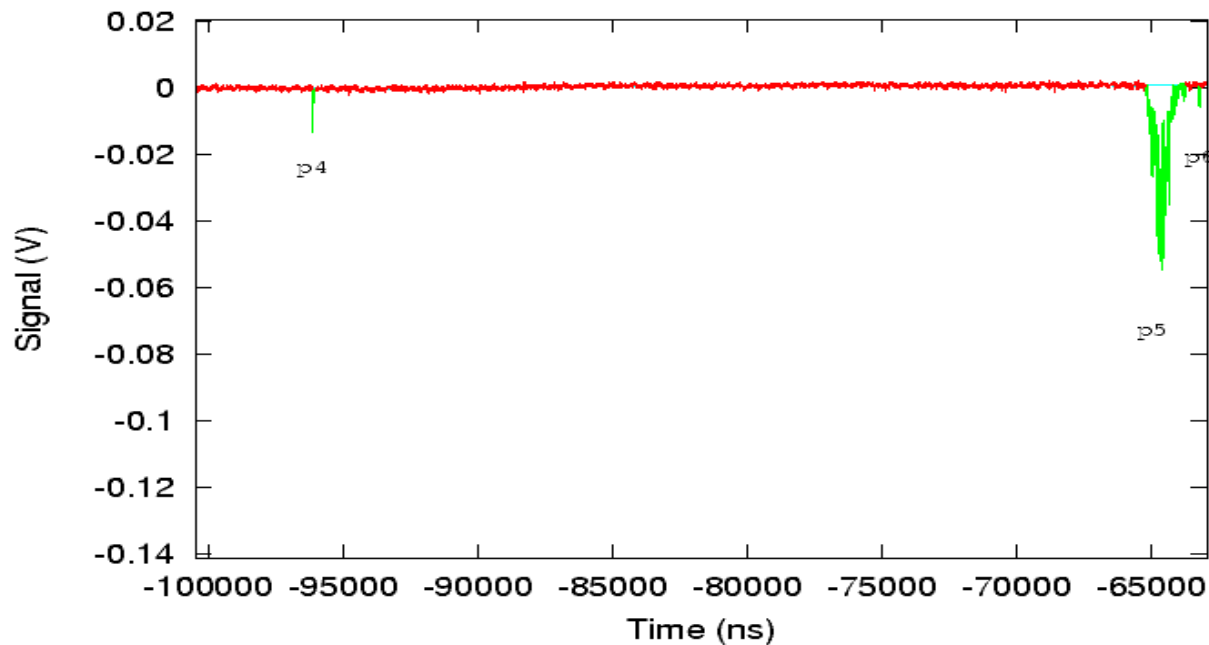
Two-phase technique



S1

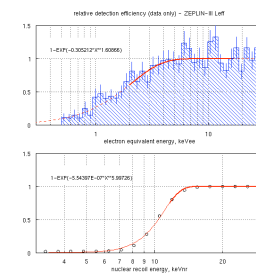
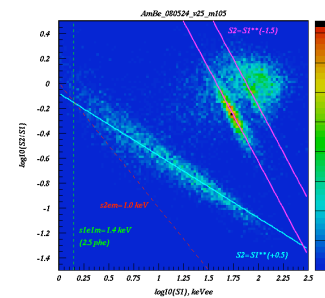
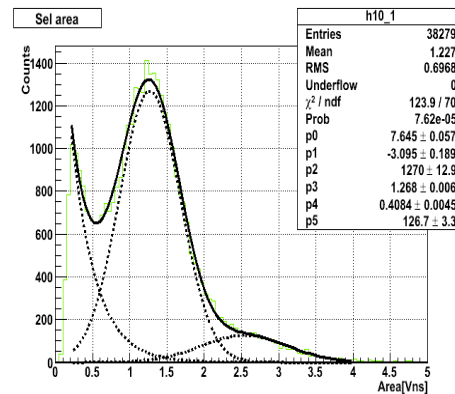
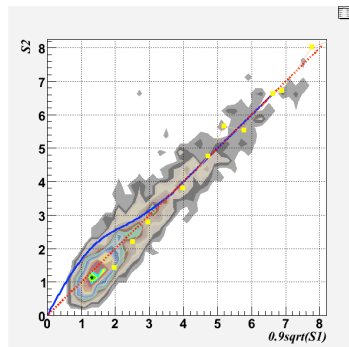
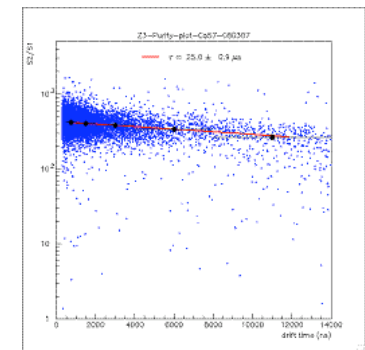
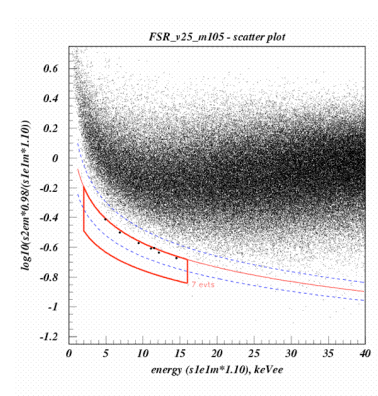
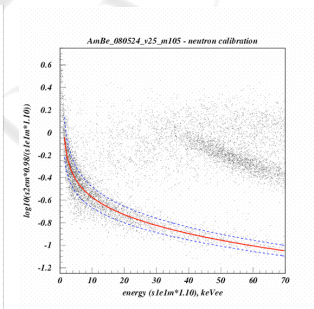
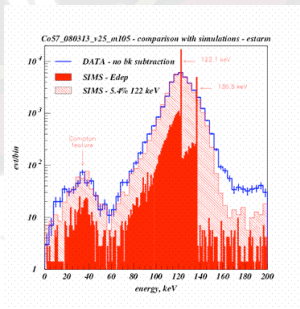
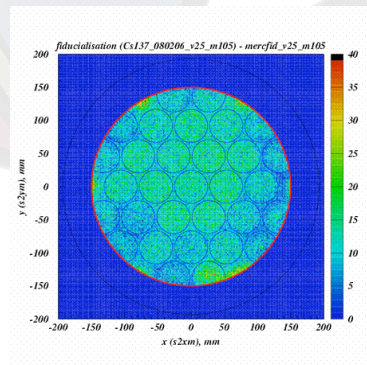
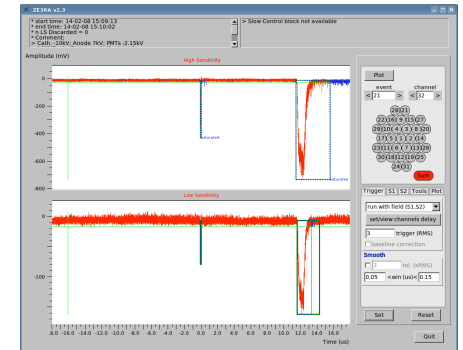
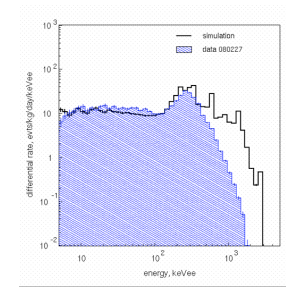
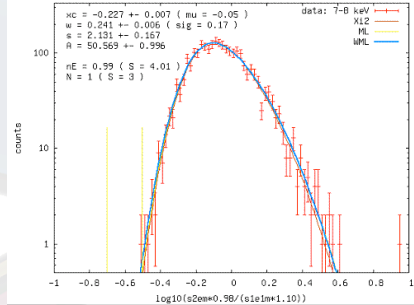
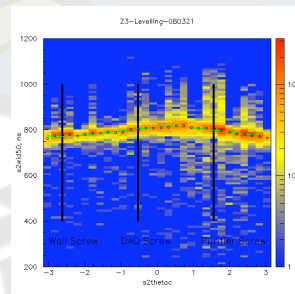
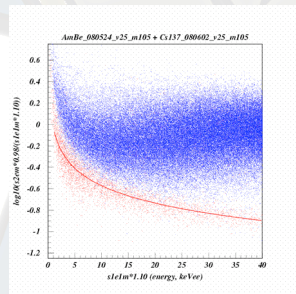


S1 and S2 timelines



- S1 short
- S2 long
- Time between S1 and S2 gives depth
- Discrimination:
 - $S2/S1 \sim 400$ e-/ γ
 - $S2/S1 \ll 400$ NR

First Science Run: analysis



First Science Run



Primary Science Publications

PRL 103, 151302 (2009) PHYSICAL REVIEW LETTERS 9 OCTOBER 2009

Limits on the Spin-Dependent WIMP-Nucleon Cross Sections from the First Science Run of the ZEPLIN-III Experiment

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(ZEPLIN-III)

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(Received 27 January 2009; revised manuscript received 5 September 2009; published 8 October 2009)

We present new experimental constraints on the WIMP-nucleon spin-dependent elastic cross sections using data from the first science run of ZEPLIN-III, a two-phase xenon experiment searching for galactic dark matter weakly interacting massive particles based at the Boulby mine. Analysis of ~ 450 kg days fiducial exposure allow us to place a 90% confidence upper limit on the pure WIMP-neutron cross section of $\sigma_{\text{SD}} \sim 1.5 \times 10^{-7}$ pb at 55 GeV/c² WIMP mass. Recent calculations of the nuclear spin structure based on the Bonn charge-dependent nuclear potential were used for the odd neutron isotopes ¹²⁹Xe and ¹³¹Xe. These indicate that the sensitivity of xenon targets to the spin-dependent WIMP-proton interaction could be much lower than implied by previous calculations, whereas the WIMP-neutron sensitivity is impaired only by a factor of ~ 2 .

DOI: 10.1103/PhysRevLett.103.151302

PACS numbers: 95.35.+d, 14.80.Lj

ZEPLIN-III completed its first run at the Boulby Underground Laboratory (UK) in search of weakly interacting massive particles (WIMPs), proposed to explain the nonbaryonic cold dark matter in the Universe. In several supersymmetry (SUSY) extensions to the standard model of particle physics, the lightest supersymmetric particle (LSP) is stable and its relic abundance could account for the dark matter observed today [1]. In some scenarios this particle is the neutralino, $\tilde{\chi}^0$ —a linear combination of the SUSY partners of the electroweak gauge bosons (photinos) and Higgs bosons (Higgsinos). Neutralinos are expected to scatter elastically from ordinary matter, producing low-energy nuclear recoils, predominantly through scalar (or spin-independent, SI) interactions. This is especially so for heavier elements ($A \geq 30$, with A the number of nucleons), for which the scattering involves the entire nucleus rather than individual nucleons. This coherence enhancement of the scalar term in the interaction cross section is proportional to A^2 . Our SI result excludes a WIMP-nucleon cross section above 8.1×10^{-7} pb for 60 GeV/c² mass with 90% confidence [2]. Nonetheless, axial-vector (or spin-dependent, SD) interactions could dominate in some SUSY scenarios in regions where the SI term is suppressed [3,4]. In addition, interaction of the DAMA annual modulation [5,6] in terms of

nuclear recoil caused by a dominant SD interaction [7] has remained viable for WIMP masses below ~ 15 GeV until recently. It is therefore important to continue pursuing the search in the SD channel. Xenon targets have good sensitivity to the WIMP-neutron interaction since approximately half of natural abundance consists of the odd-neutron isotopes ¹²⁹Xe and ¹³¹Xe (the proton interaction is highly suppressed for these isotopes, and neither is likely in the even-even nuclei). It is also possible that a SD inelastic interaction with these nuclei could be significant for relatively heavy WIMPs [8,9]. Deexcitation of low-lying nuclear states in ¹²⁹Xe and ¹³¹Xe (emitting 394 keV and 802 keV γ rays, respectively) provides a detection mechanism with low effective energy threshold, since the γ rays can be efficiently detected. Although neutrons also scatter inelastically producing the same signatures, differences in spatial distribution between signal and background might be exploited in very large detectors—assuming that the dominant γ -ray backgrounds could be suitably mitigated. Most direct search experiments are still focused on detecting nuclear recoils down to $\sim$ keV energies; this is so in the case described in this Letter.

WIMP search experiments propose to measure the total WIMP-nucleon elastic cross section, σ_{el} . Assuming domi-

PHYSICAL REVIEW D 80, 052010 (2009)

Results from the first science run of the ZEPLIN-III dark matter search experiment

V.N. Lebedenko,^{1,*} H.M. Araújo,^{1,2,†} E.J. Barnes,³ A. Bewick,³ R. Cashmore,³ V. Chapeau,³ A. Currie,³ D. Davidge,³ J. Dawson,³ T. Durkin,³ B. Edwards,³ C. Chag,³ M. Horn,³ A.S. Howard,³ A.J. Hughes,³ W.G. Jones,³ M. Joshi,³ G.E. Kalinowski,³ A.G. Kovalenko,³ A. Lindote,³ J. Liubarsky,³ M.I. Lopes,³ R. Lüscher,³ P. Majewski,³ A. Sd. Murphy,³ F. Neves,³ J. Pinto da Cunha,³ R. Preece,³ J.J. Quenby,³ P.R. Scovell,³ C. Silva,³ V.N. Solovov,³ N.J.T. Smith,³ P.F. Smith,³ V.N. Stukhanov,³ T.J. Sumner,³ C. Thorne,³ and R.J. Walker³

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(Received 8 December 2008; published 25 September 2009)

The ZEPLIN-III experiment in the Palmer Underground Laboratory at Boulby uses a 12 kg two-phase xenon time-projection chamber to search for the weakly interacting massive particles (WIMPs) that may account for the dark matter of our Galaxy. The detector measures both scintillation and ionization produced by radiation interacting in the liquid to differentiate between the nuclear recoils expected from WIMPs and the electron-recoil background signals down to ~ 10 keV nuclear-recoil energy. An analysis of 447 kg days of data acquired between February 27, 2008, and May 20, 2008, has excluded a WIMP-nucleon elastic scattering spin-independent cross section of $\sigma_{\text{SI}} \sim 10^{-7}$ pb at 60 GeV/c² with a 90% confidence limit. It has also demonstrated that the two-phase xenon technique is capable of better discrimination between electron and nuclear recoils at low-energy than previously achieved by other xenon-based experiments.

DOI: 10.1103/PhysRevD.80.052010

PACS numbers: 95.35.+d, 14.80.Lj, 29.80.Mv, 95.55.Vj

I. INTRODUCTION

A. Motivation

Searches for weakly interacting massive particles (WIMPs) are motivated by the coming together of unification schemes, such as supersymmetry, which predict new particle species, and extensive observational evidence which demonstrates the need for additional nonbaryonic gravitational mass within the Universe. That the WIMPs of supersymmetry naturally fulfill this need is remarkably persuasive. Indeed, WIMPs occur in other frameworks too. As a generic class of particle they are assumed to only interact nongravitationally with baryonic matter via the weak interaction. While this offers a mechanism for energy transfer and hence detection, it also implies rather low event rates and energy deposits: <0.1 events/kg/day and <50 keV, respectively. This dictates the use of sensitive underground experiments capable of specifically identifying energy deposits due to elastic scattering of incoming particles from target nuclei. ZEPLIN-III is the latest in a progressive series of instruments designed to

push steadily the sensitivity limits by exploring alternative approaches using xenon-based targets [1–3].

B. ZEPLIN-III

ZEPLIN-III is a two-phase (liquid/gas) xenon time-projection chamber specifically designed to search for dark matter WIMPs. Its design and performance details have already been presented elsewhere [4,5] and only a brief reminder is given here. The experiment is operating 1100 m underground. The active volume is a disc of 35 mm thickness and ~ 190 mm diameter which contains ~ 12 kg of liquid xenon above an array of 31 2-inch diameter photomultiplier (PMT). The PMTs, employed during this first science run were ETL DT700829Q [5], and they were used to record both the rapid scintillation signal, S1, and a delayed second signal, S2, produced by proportional electroluminescence in the gas phase above the liquid [6]. The PMT array was immersed in the liquid viewing upwards. The electric field in the target volume was defined by a cathode wire grid 36 mm below the liquid surface and an anode plate 4 mm above the surface in the gas phase. These two electrodes alone produce the drift field in the liquid (19 kV/cm), the field for extraction of the charge from the surface, and the electroluminescence field in the gas (78 kV/cm). A fiducial volume for WIMP searches was defined by using a time window for delays between S1 and S2, which selected a depth slice within the

*Deceased.

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Limits on inelastic dark matter from ZEPLIN-III

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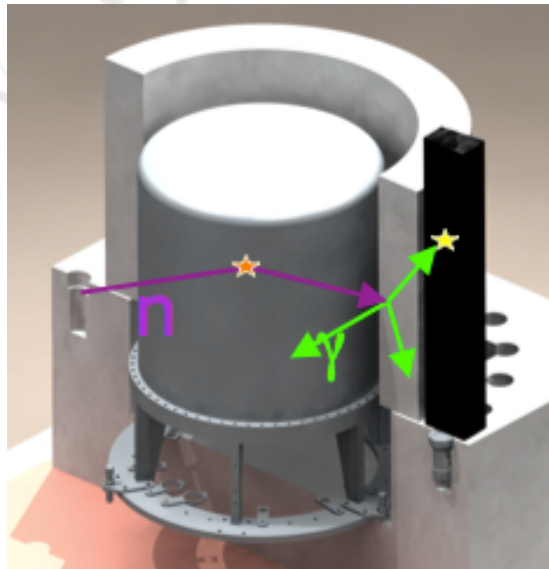
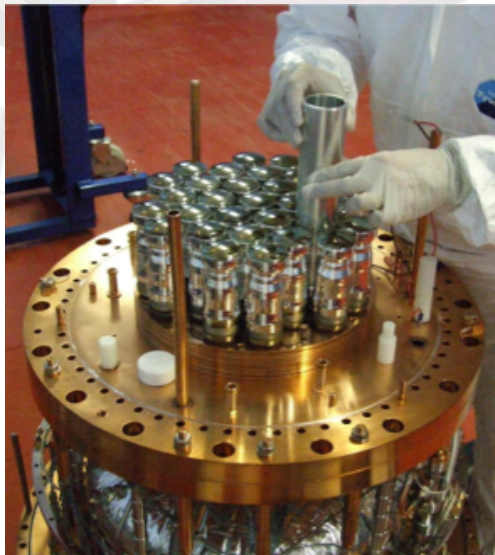
¹⁵²University of Oxford, UK

¹⁵³University of Oxford, UK

¹⁵⁴University of Oxford, UK

Phase-II Upgrades

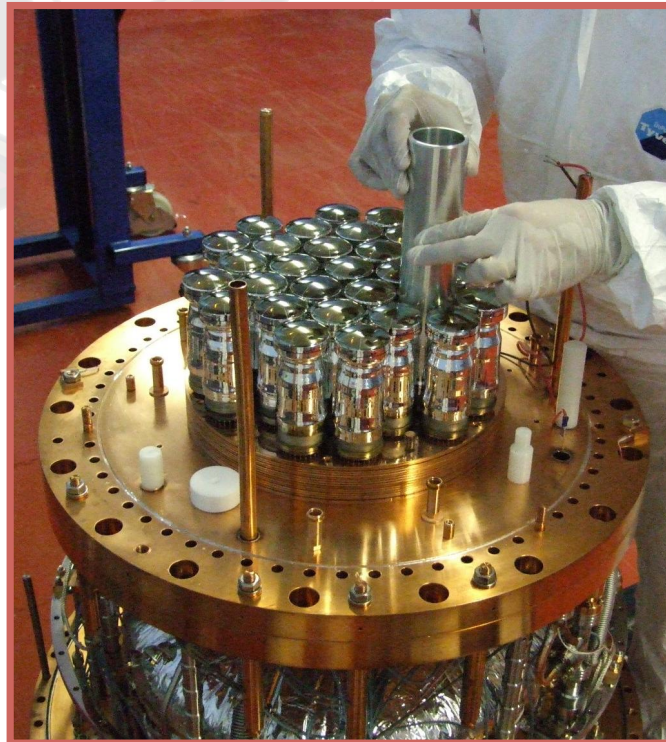
- Commissioned in 2009/10
- New photomultiplier array (greatly reduced background)
- New anti-coincidence veto (background reduction & diagnostic)
- New calibration hardware (reduction of systematics)
- System automation (underground effort, improved stability)



Complete
remote
operations
(duty cycle
96%)

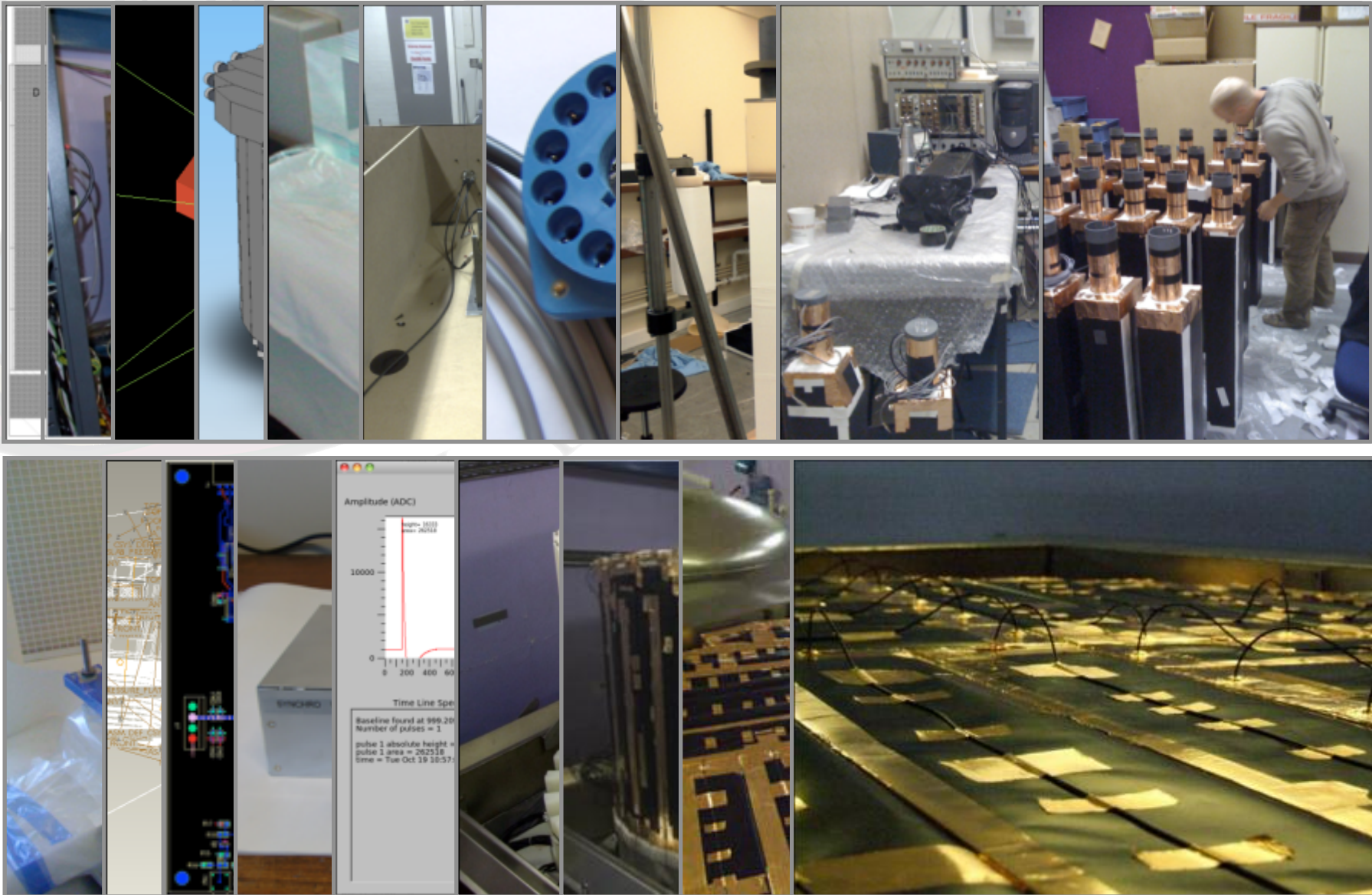
Photomultiplier Upgrade

- PMT gamma-rays limited sensitivity of first run by a large factor
- Custom design for ultra low-background tubes, pin-by-pin compatible
- Assembly onto ZEPLIN-III array in early 2010
- Aiming for 30x reduction in radioactivity to <50 mBq/PMT



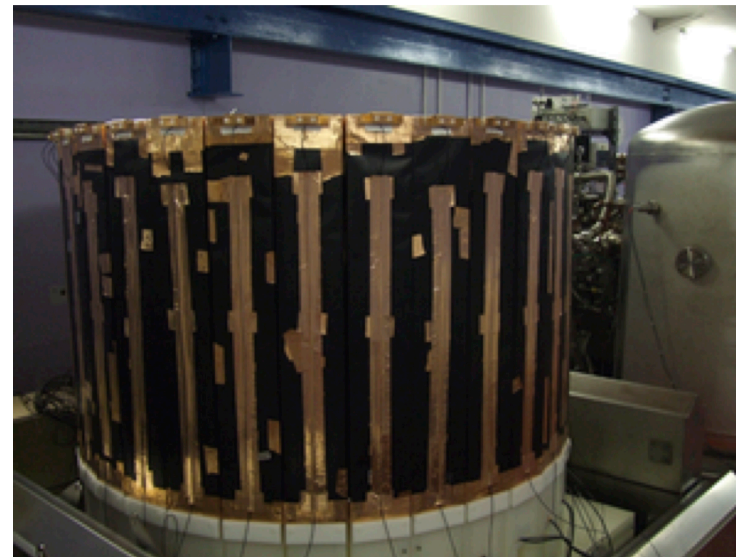
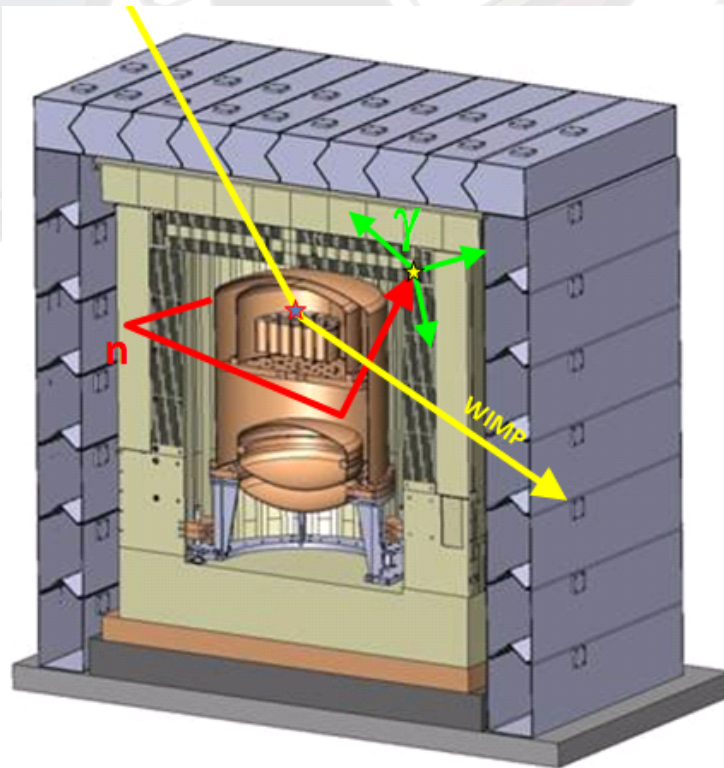
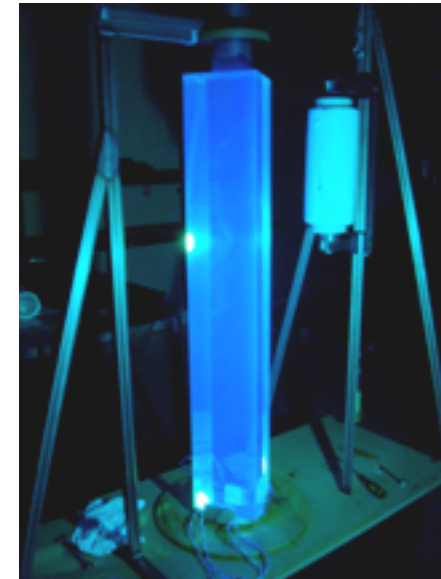
Retrofitting of Veto

“made in scotland, from girders”

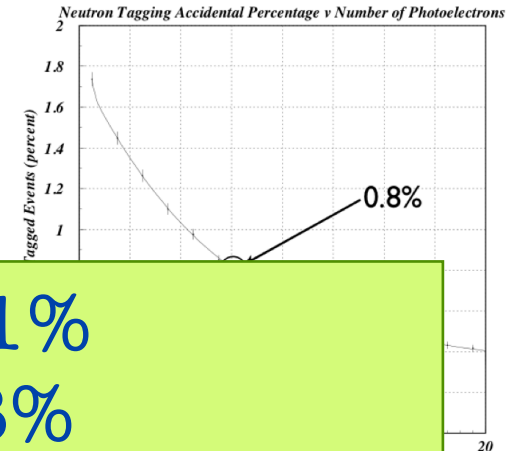
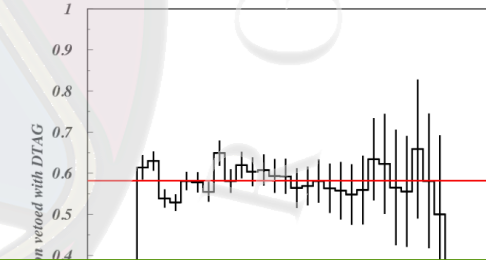
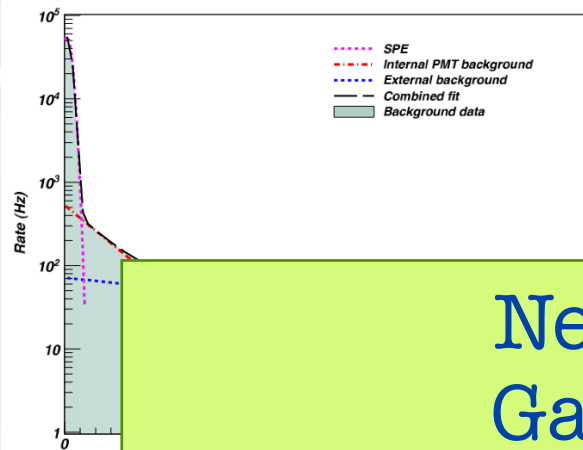


Veto Upgrade

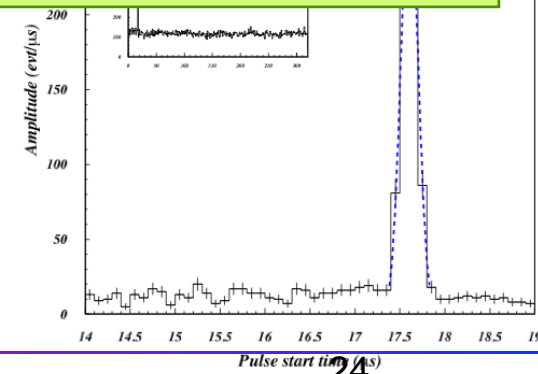
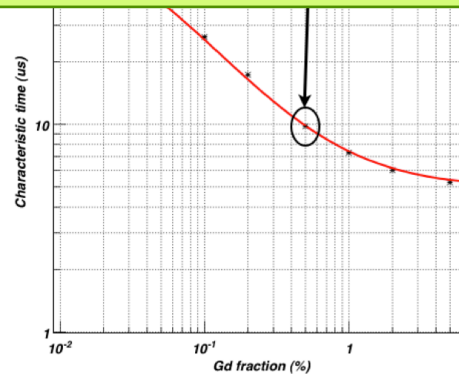
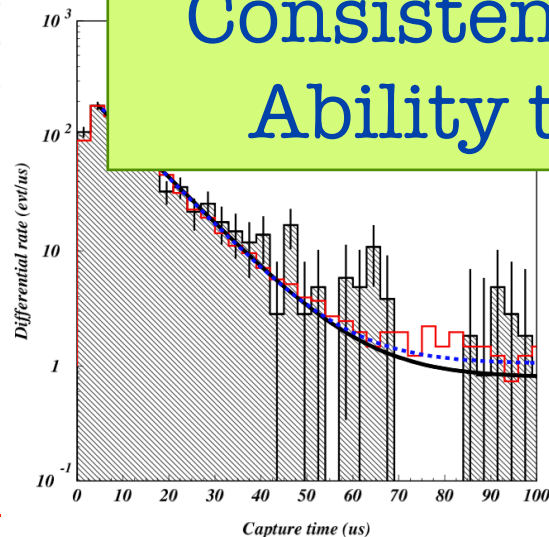
- 1 tonne plastic scintillator in 52 modules (UPS-923A)
- Scintillator 15cm thick, Gd loaded polypropylene 15cm thick
- Dedicated DAQ and monitoring system
- Radiation budget very low
- *Design: Astroparticle Physics 34 (2010) 151-163*
- *Performance: Astroparticle Physics 35 (2011) 76-86*
- *Quenching factor: Phys. Rev. C Submitted.*



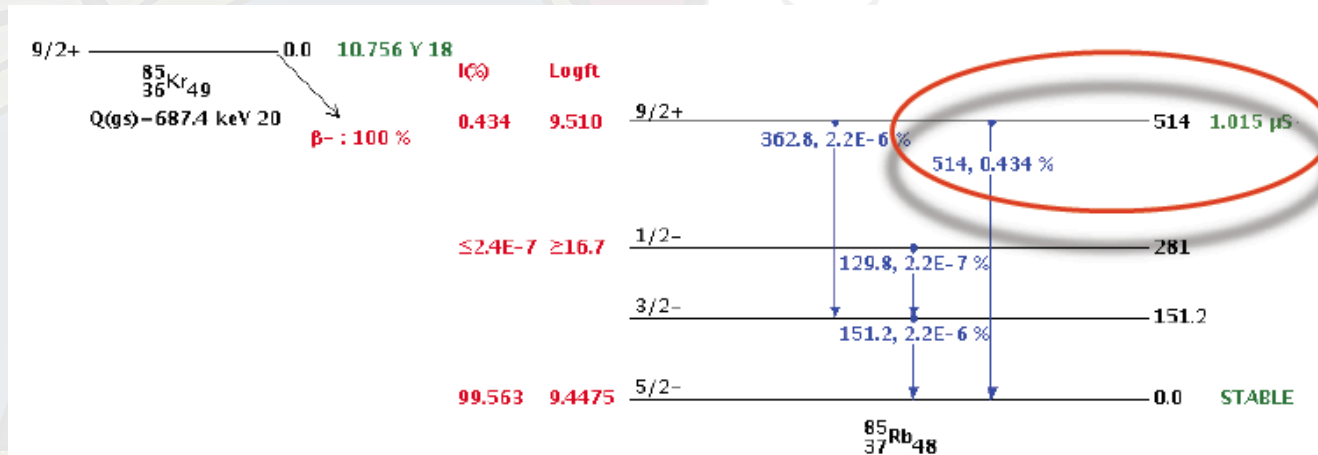
Veto Performance



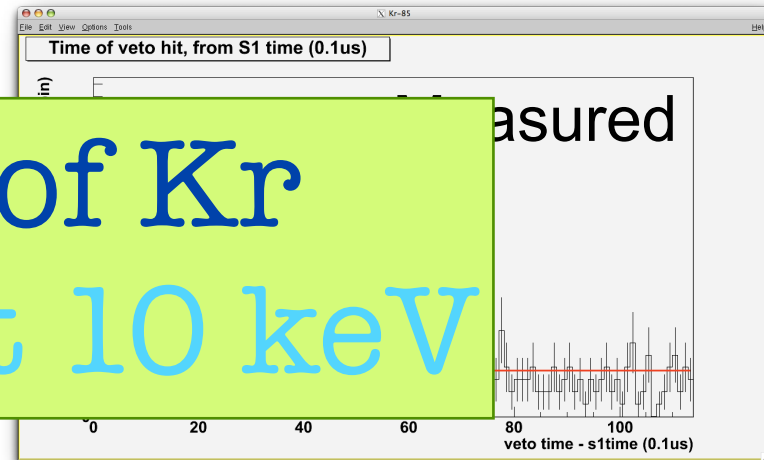
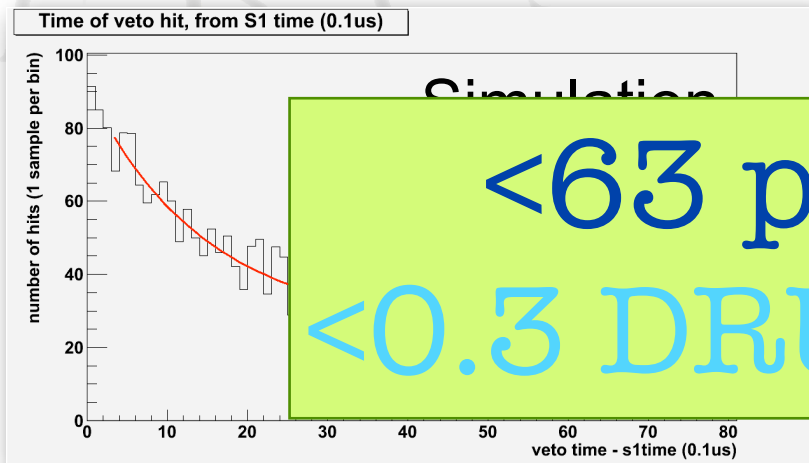
Neutron tagging 61%
Gamma tagging 28%
No increase in background
Consistent measure of backgrounds
Ability to view 28% of WIMP box



^{85}Kr contamination



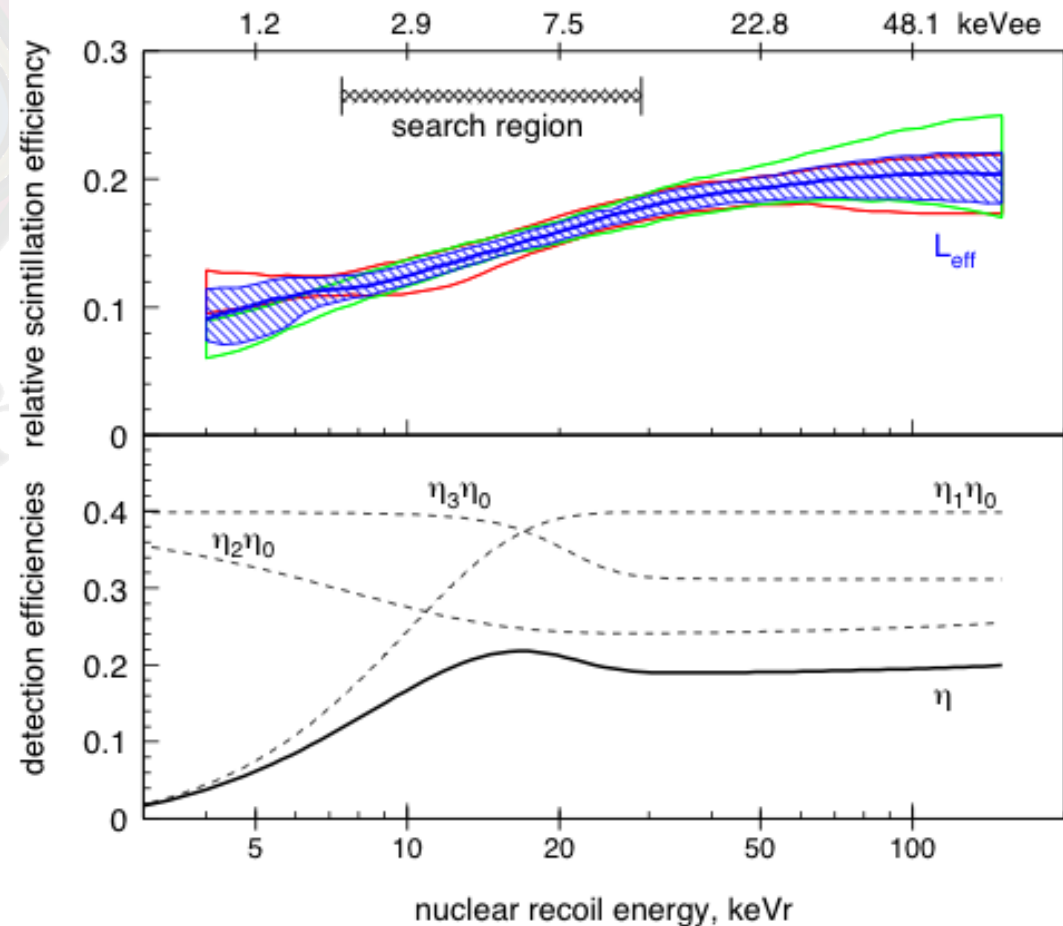
$$\Delta T = \text{time}(\beta \text{ in Z3}) - T(\gamma \text{ in Veto})$$



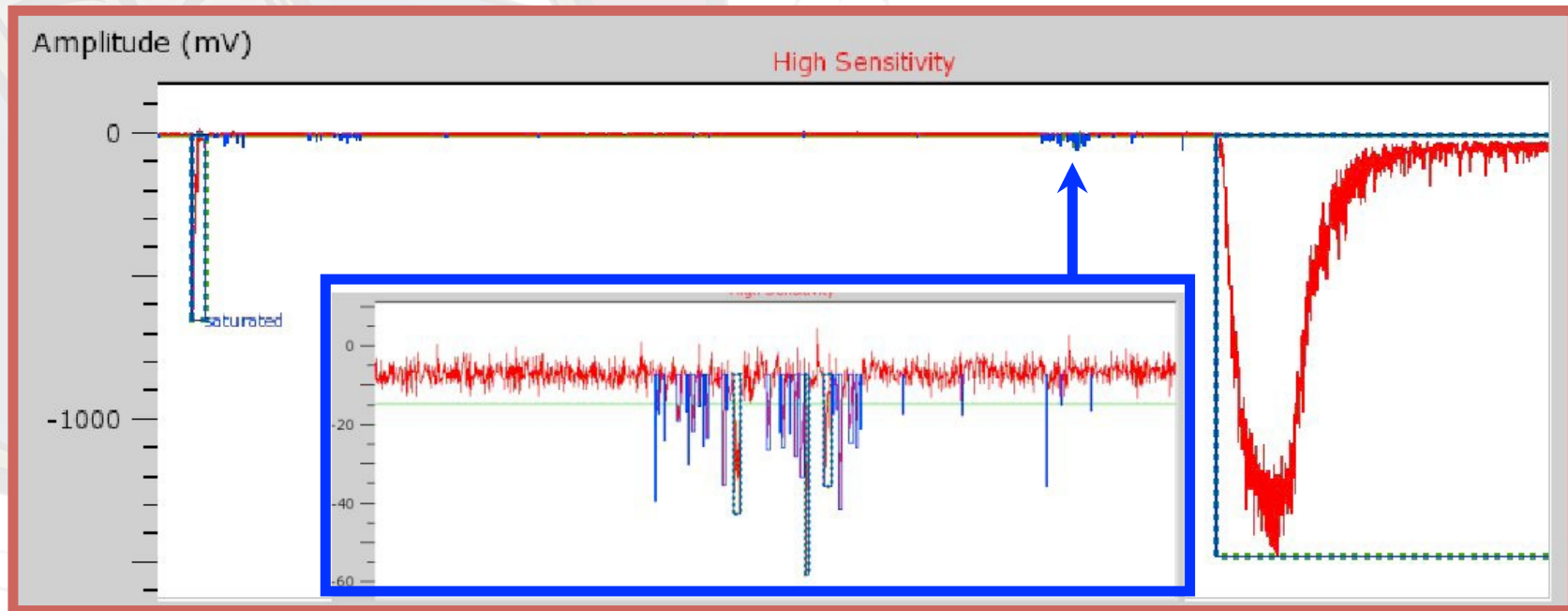
<63 ppb of Kr
<0.3 DRU at 10 keV

New “ L_{eff} ” Analysis

- Ratio of light emitted by a nuclear recoil to that of an electron recoil of the same energy
- Key input for analysis
- Response at very low energy important (we have a very low threshold instrument)
- Phys. Lett. B 705 (2011) 471-476



Single Electron Emission

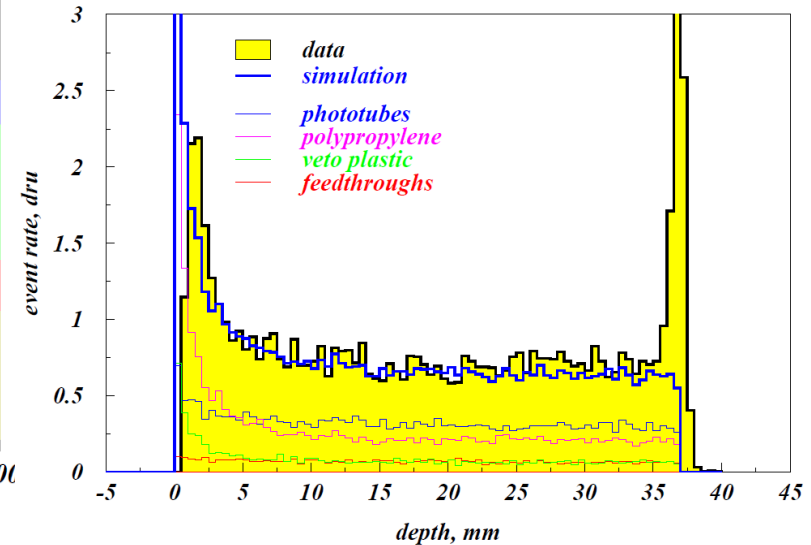
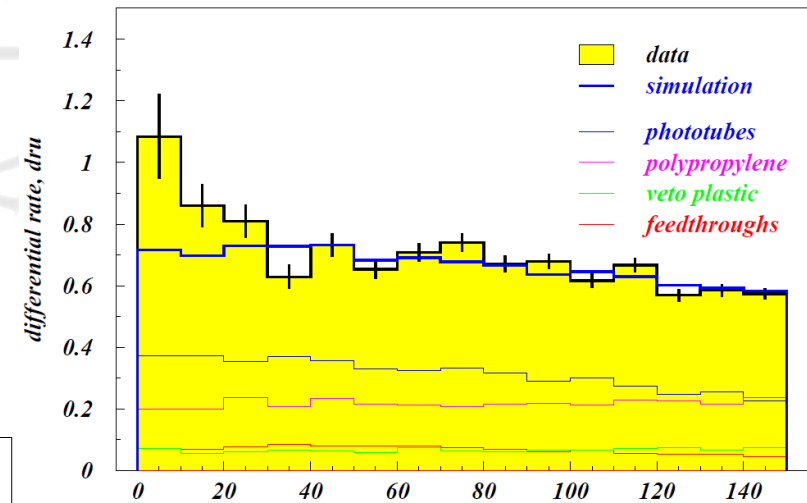
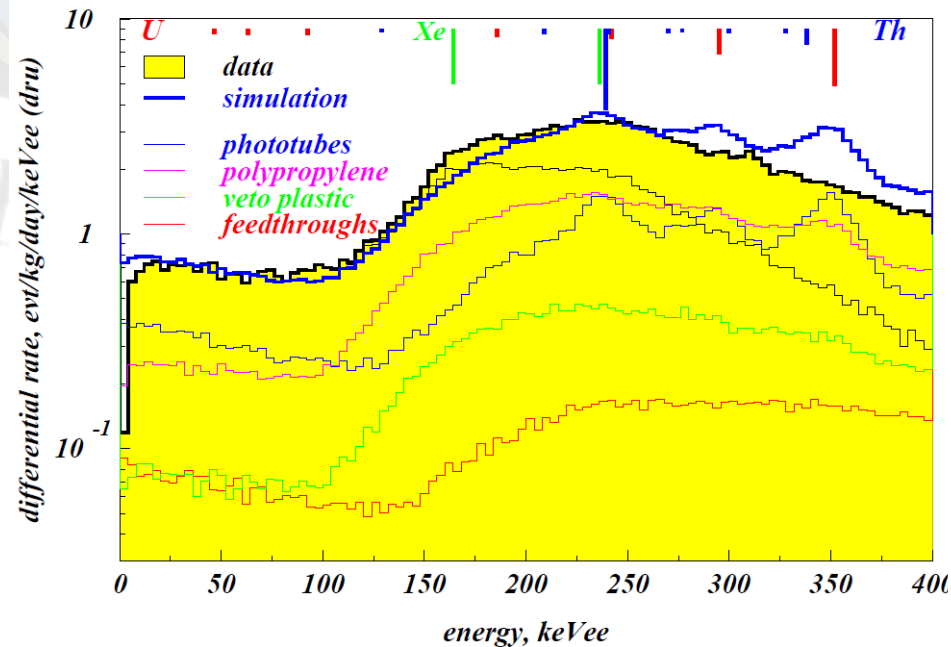


We can see individual electrons being pulled from the liquid surface!

Possible application to detection of coherent neutrino scattering. Submitted to *Journal of High Energy Physics*.

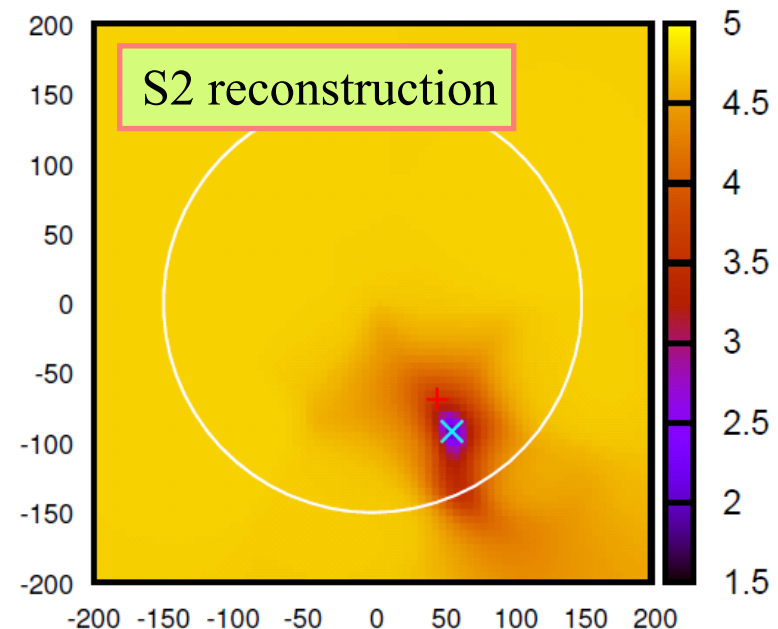
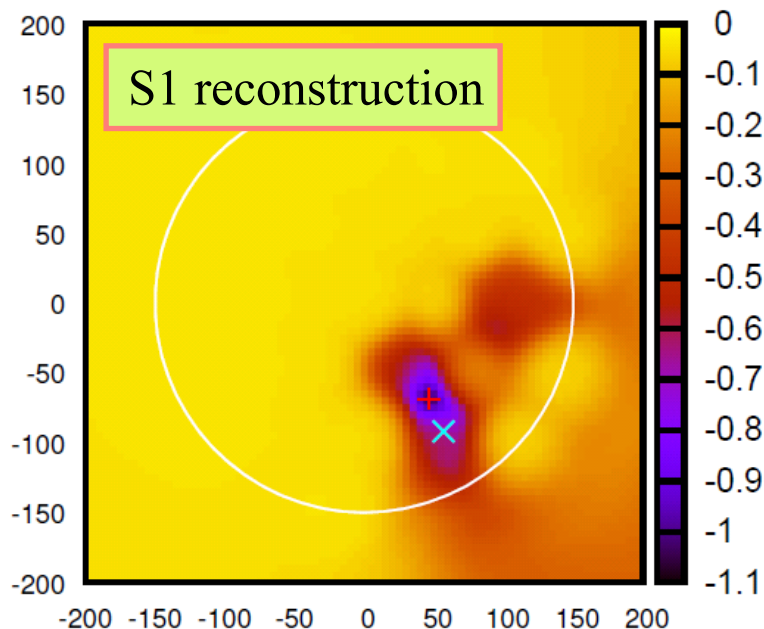
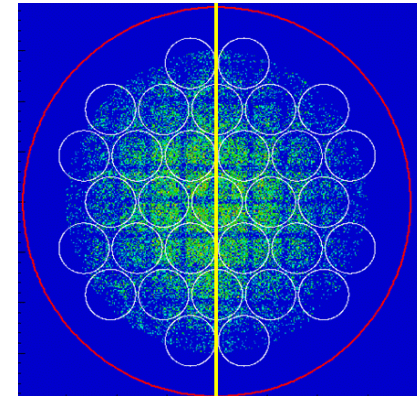
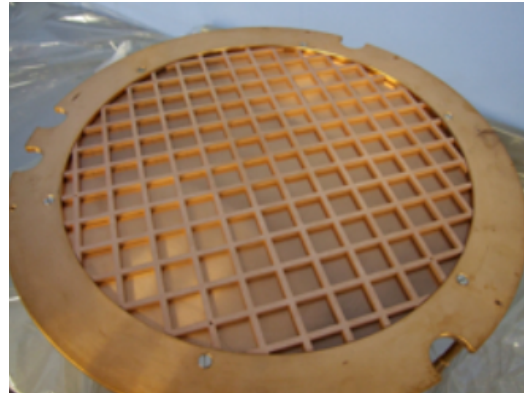
SSR Electron recoil backgrounds

- 0.75 evt/kg/day/keVee
(20x lower than in first run)
- Very good (absolute) agreement of energy and spatial distributions with component-level simulations
- PMT array 35x lower background
- Astroparticle Physics, Accepted



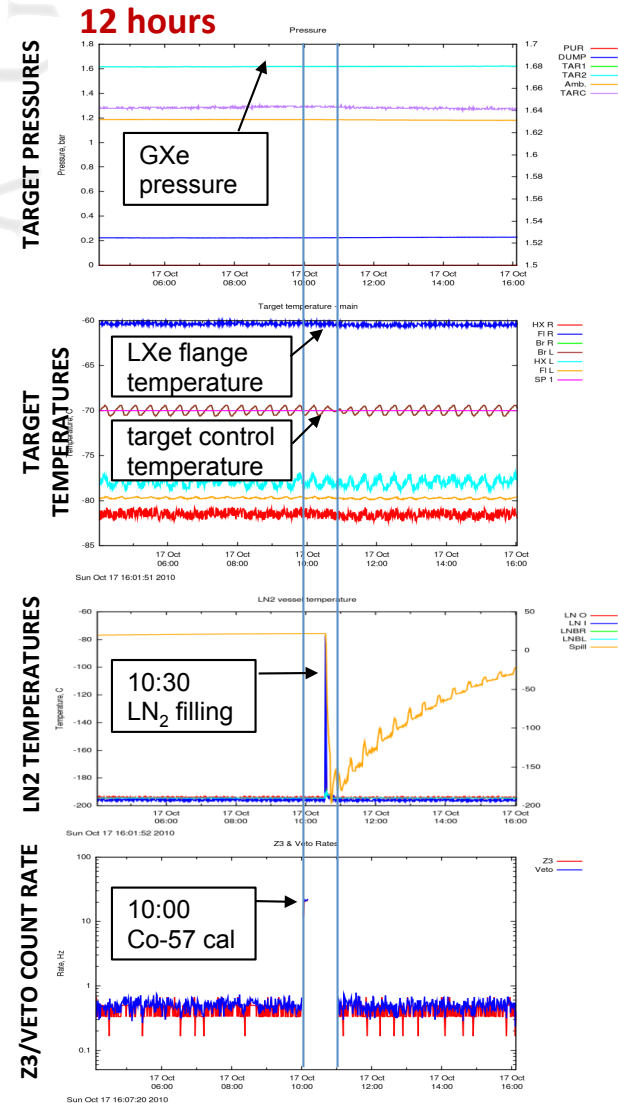
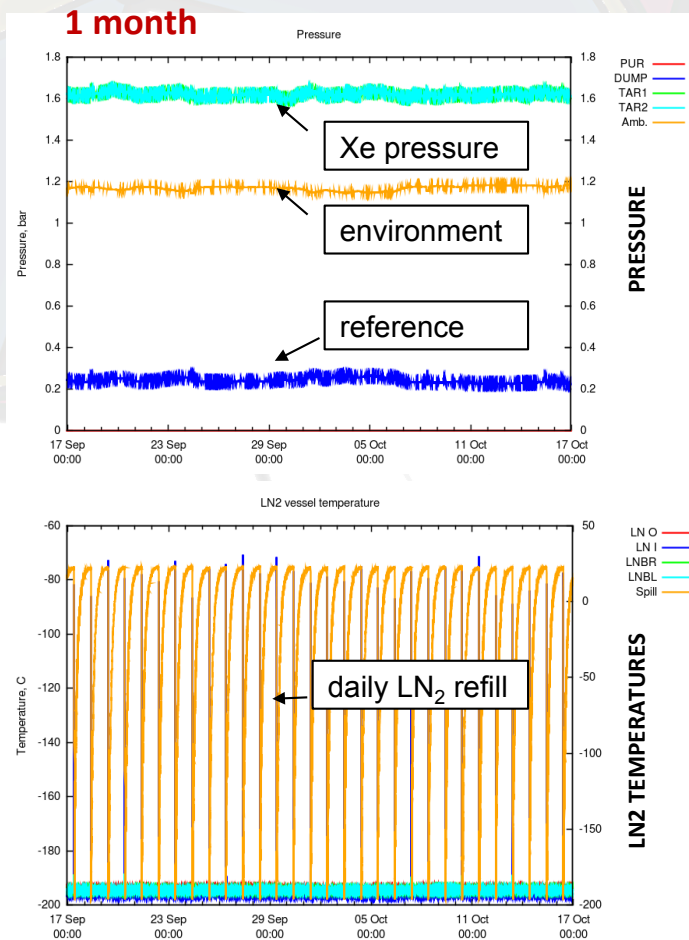
Vertex Reconstruction

- “Phantom Grid”
- dx, dy: 2mm, dz 20 μ m
- Development of spatial χ^2 maps
- Rejection of Multiple Scatter Single Ionisation (“living dead”) events
- JHEP Submitted

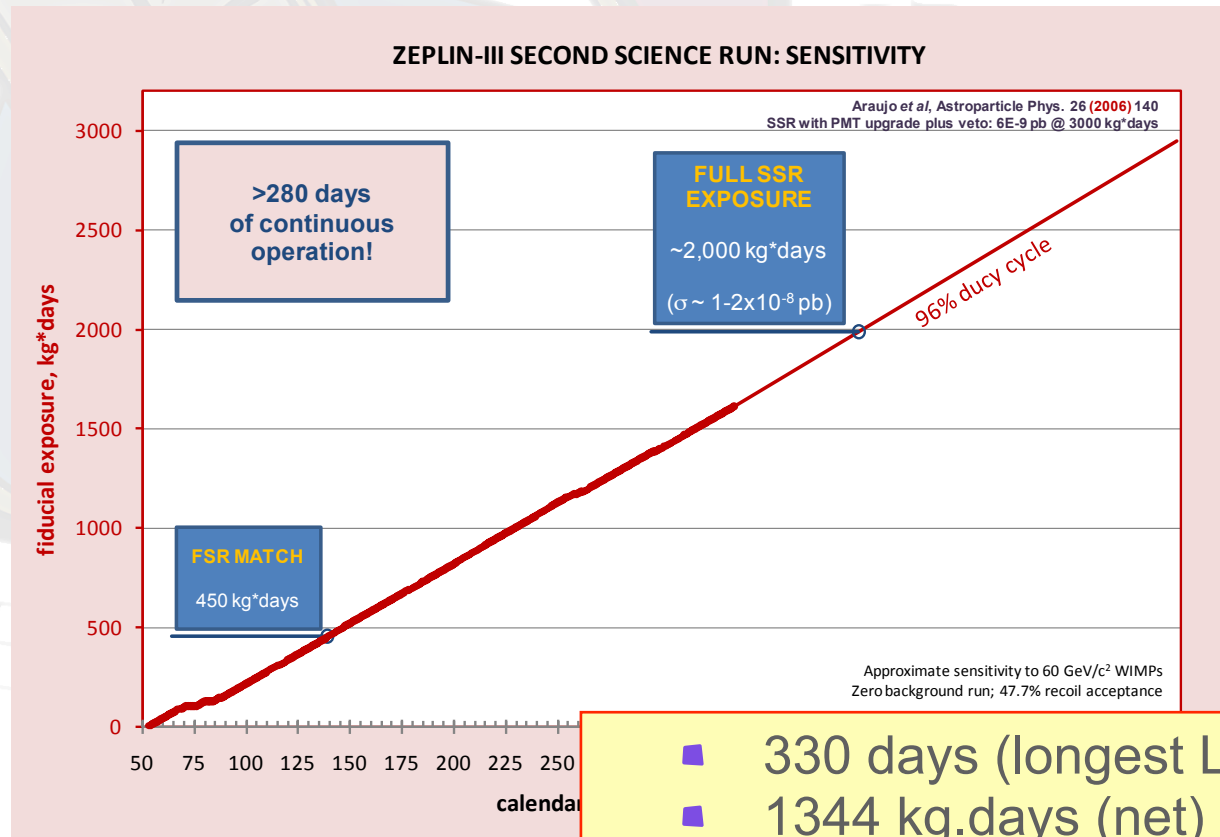


3 Nov 2008

SSR Operations



SSR Operations



- 330 days (longest LXe run ever)
- 1344 kg.days (net)
- Veto worked fabulously
- PMTs achieved background specifications
- PMTs suffered poor performance...

SSR Background Expectations

Material	mass, kg	e-recoil, dru [†]	ptag	n/year [‡]	dtag
Krypton-85	12.5	(<0.1)	~0	–	–
Ceramic feedthroughs	0.9	0.08	0.30	1.35	0.58
Photomultipliers	4.2	0.40	0.26	0.74	0.58
Rock (halite)	–	~0	~0	0.53	0.58
Polypropylene shield	1,266	0.25	0.04	0.10	0.58
Scintillator modules	1,057	0.09	~1	0.03	~1
Copperware	~400	(<0.1)	0.10	(<0.15)	0.58
Lead castle	~60,000	0.01	0.54	~0	0.58
Radon-222	(1 m ³ ?)	0.03	0.19	~0	–
Muon-induced	–	–	–	~0.3	~1
SSR total		0.86±0.05	0.28	3.05±0.5	0.58
SSR data		0.75±0.05	0.28	n/a	–
(FSR [6])		14.5±0.5	–	(36±18)*	–

Background expectation in 0.9-year dataset, in a/c with veto and realistic signal acceptance:

- 0.4±0.2 neutron scatters
- 9 ± 1 electron recoils

Main challenge is to achieve the same discrimination power as in FSR with new phototubes (poorer optical performance)

BACKGROUND EXPECTATION IN 1-YEAR DATASET

NEUTRONS			E-RECOILS		
total in 5-50 keVr		3.05	rate, evt/kg/day/keV		0.75
			total <20 keVee		35588
veto a/c	40%	1.22	veto a/c	72%	25623
duty cycle	90%	1.10	duty cycle	90%	23061
efficiencies	75%	0.82	efficiencies	75%	17296
acceptance	48%	0.39	discrimination	1:7,200	2.4

ZEPLIN-III

Second Science Run Result [Announcement](#)

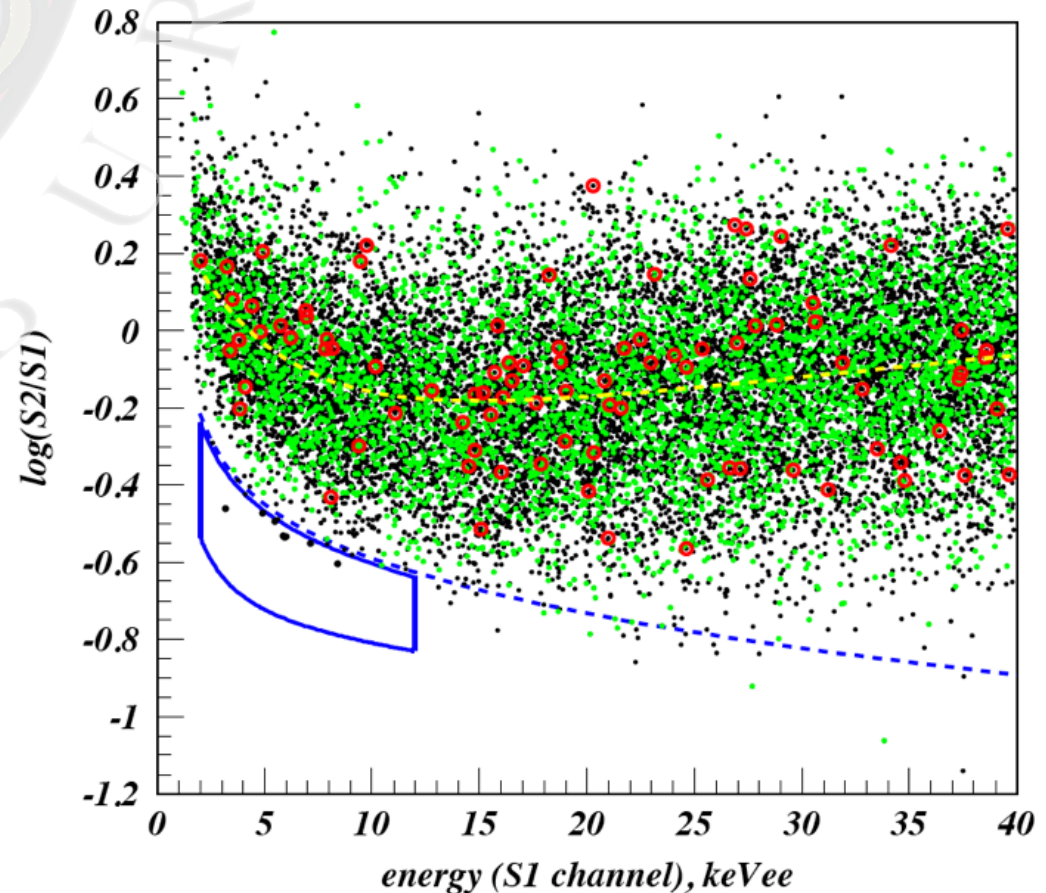
0 neutrons predicted

9 gamma rays predicted

...so what did
we see?

8 events in box

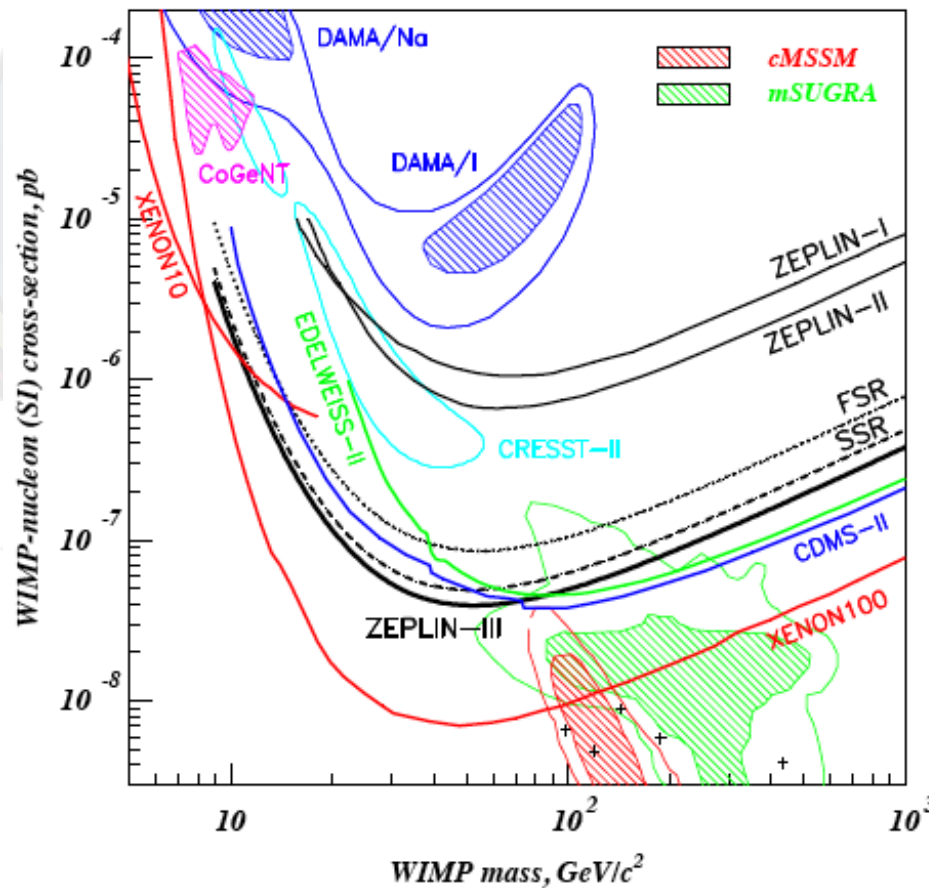
Consistent with γ background
Consistent with zero WIMPs



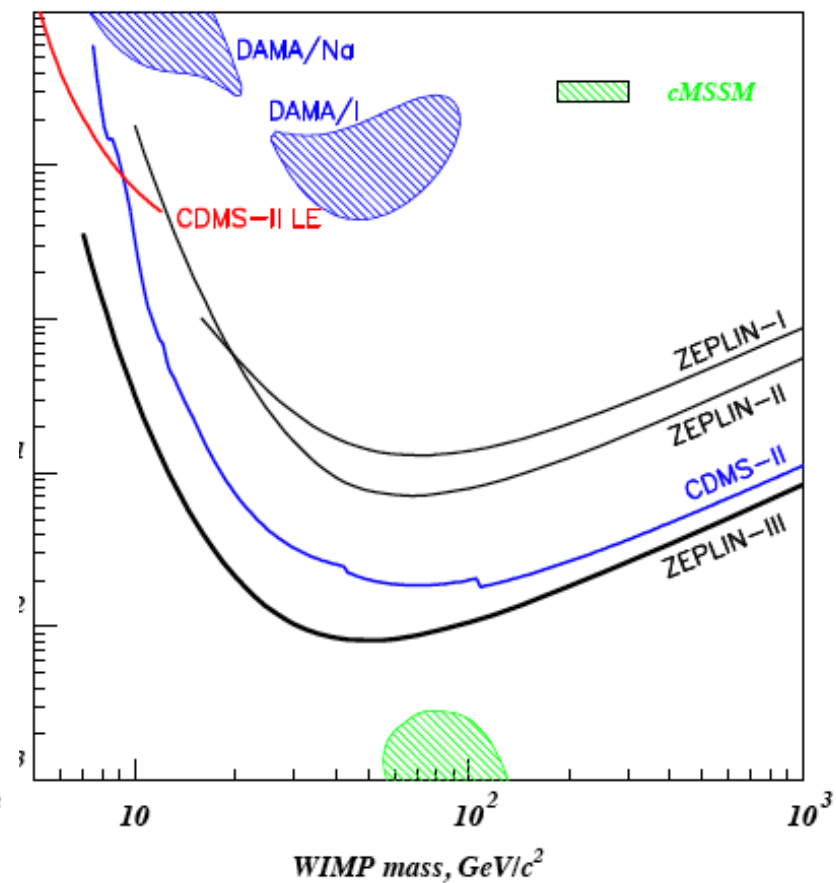
ZEPLIN-III

FINAL RESULTS (FSR + SSR Combined)

PLB Submitted



Second best SI limit



World leading SD limit

ZEPLIN-III 'in numbers'

Since underground deployment in late 2006

2,500 person·days underground effort at Boulby
870 daily entries in electronic log-book
204 internal reports (382 versions) in documents database
203 minuted progress meetings
862 catalogued datasets, 100 TB uncompressed data
12 xenon liquefactions (detector filling)
15,000 litres of liquid nitrogen used underground
Longest uninterrupted operation of a two-phase detector
0 emergency xenon dumps into safety chambers
0 accidents underground (occasional partridge killed on the A174)
6 international collaboration meetings
7 PhD theses (3 more to come)
Many, many cold evenings in Whitby

Extensive list of professional and public outreach activities listed in report

The background of the slide features a large, faint watermark of the University of Edinburgh crest. The crest includes a shield with a book, a quill, and a sun, with the words 'UNIVERSITY OF EDINBURGH' curved around it.

What next?

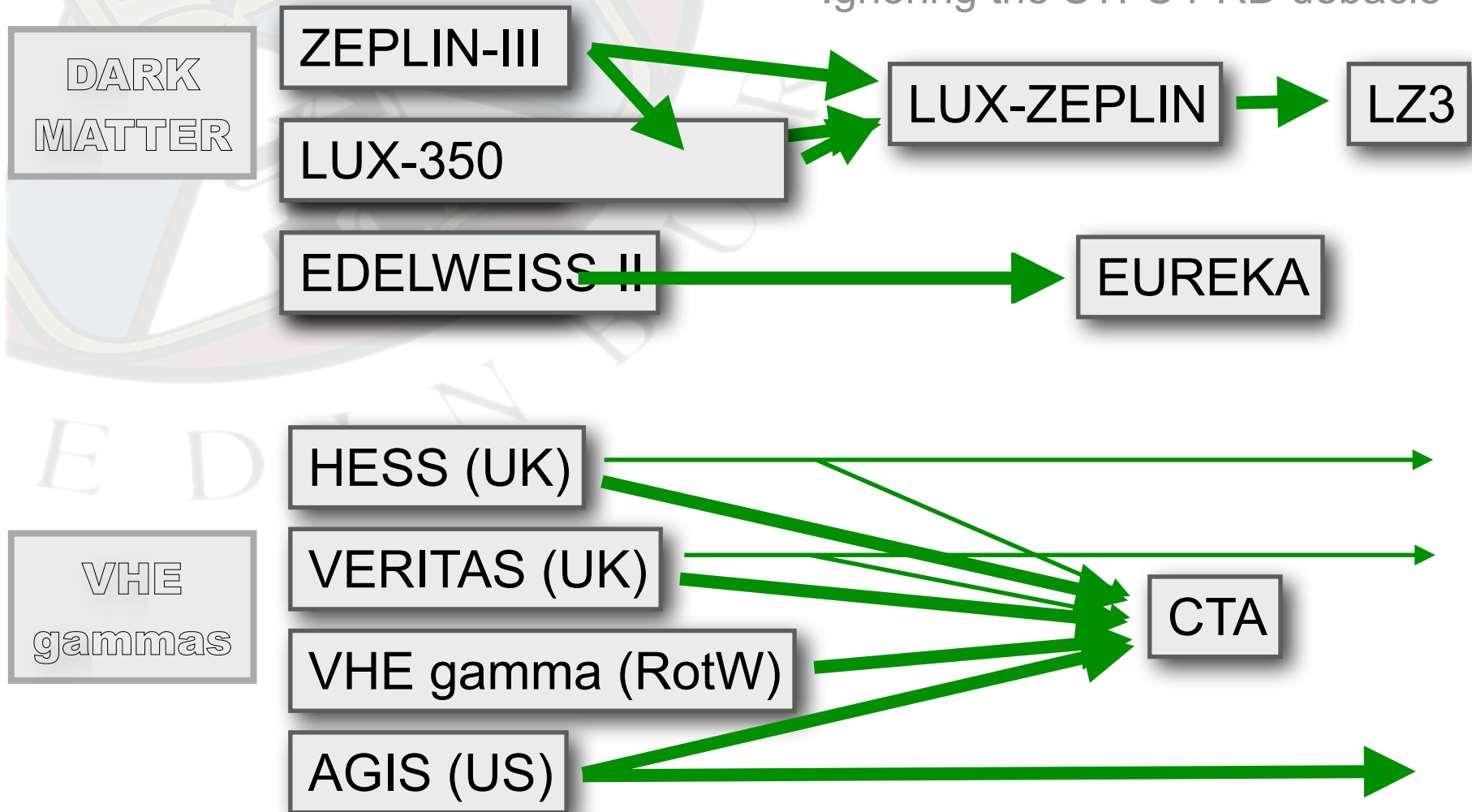
Since last Programmatic review

- STFC recognises PA overly reduced
- ZEPLIN-III extended (till July 2011)
- VHE Gamma Rays: ‘life support’
- Cosmic Rays: ‘hospice’
- Neutrino astrophysics: ‘parasitic’

“Particle Astrophysics Sustainability”
funding line introduced

Plans...

Ignoring the STFC PRD debacle



LUX Construction

at the Sanford Surface Facility



LUX Deployment

at the Sanford Surface Facility

April 2011



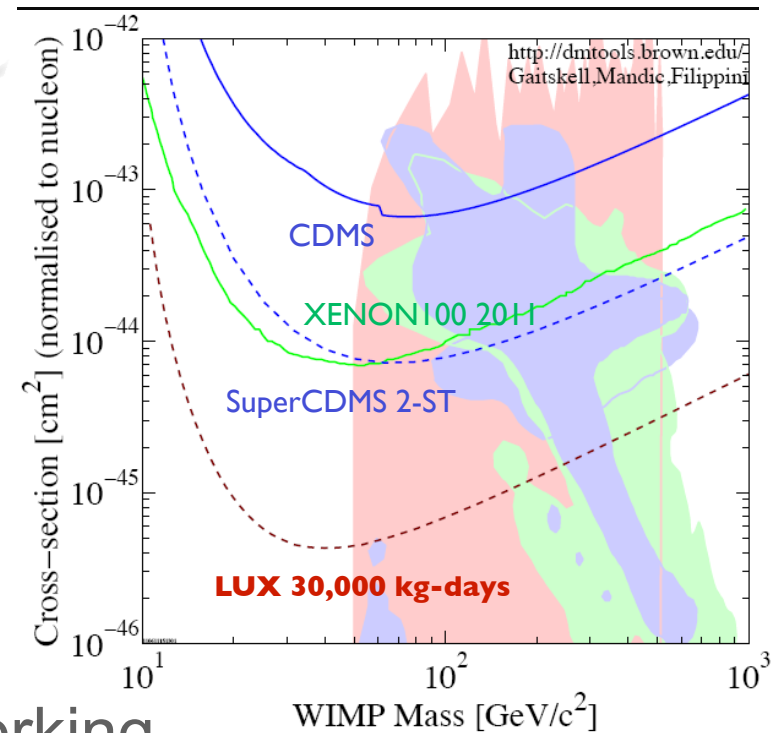
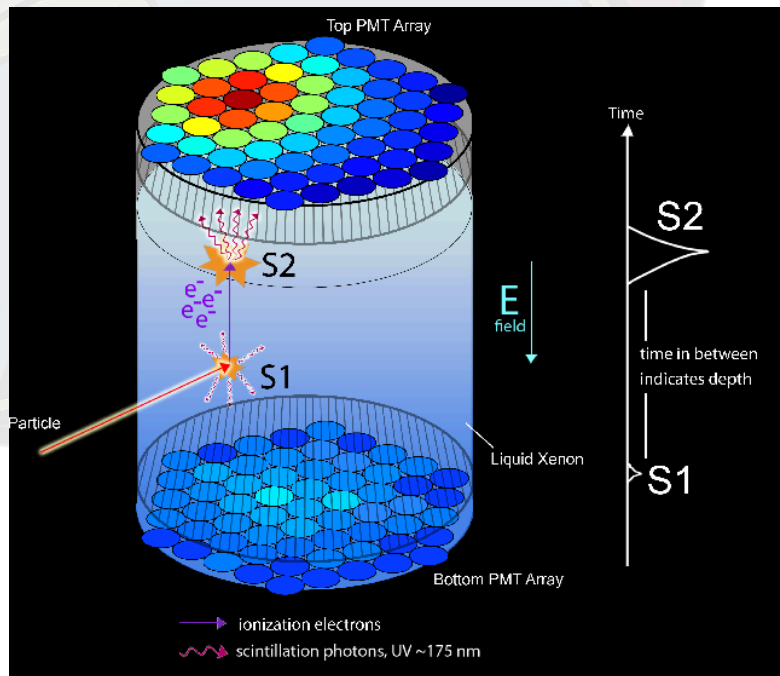
Photo by C. Faham

LUX Detector in Water Tank *Prior to May 2011 Cooldown* Sanford Surface Facility



LUX350

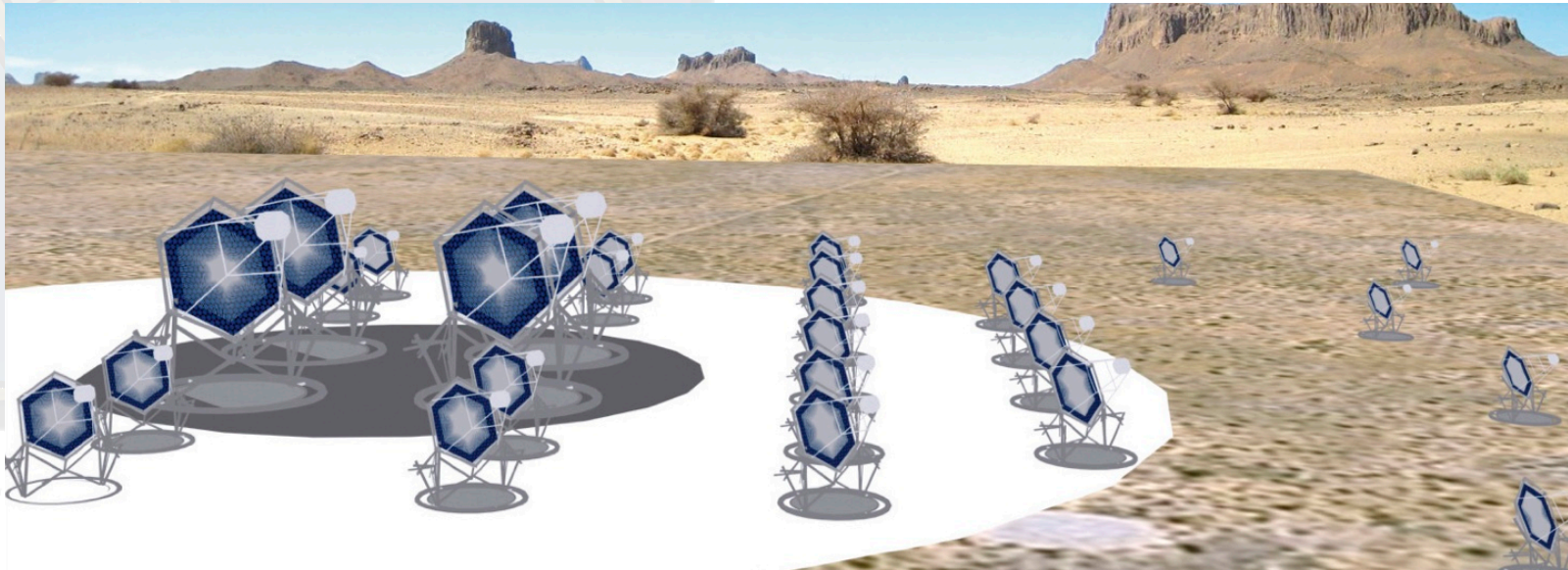
Large Underground Xenon



- Fully built, tested and working
- Awaiting deployment at SUSEL
- >15 institutes, >100 scientists

CTA

The Cherenkov Telescope Array



- 10 GeV - 100 TeV: The non-thermal Universe
- 10 x better 'in every way'
- UK leads Small Sized Telescope: highest energies
- Edinburgh roles: SAPO & minor role in PMT R&D
- Further contributions very welcome

CTA

The Cherenkov Telescope Array

Science Objectives:

Galactic Gamma-Ray Sources

- Supernova Remnants
- Pulsar Wind Nebulae
- Pulsar Physics
- Star-Formation Regions
- The Galactic Centre
- X-Ray Binaries & Microquasars

Extragalactic Gamma-Ray Sources

- Active Galactic Nuclei
- Extragalactic Background Light
- Gamma-Ray Bursts
- Galaxy Clusters

Fundamental Physics

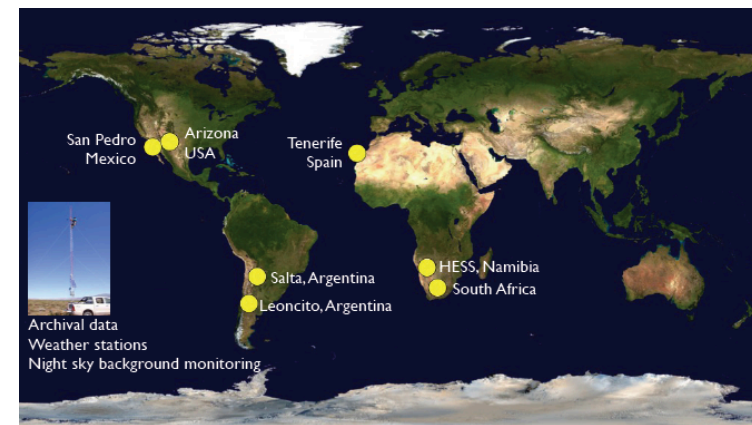
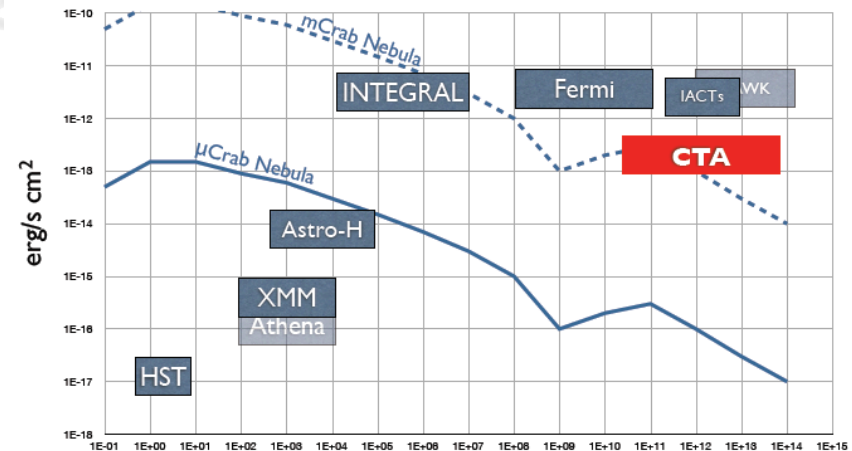
- Dark Matter
- Quantum Gravity
- Charged Cosmic Rays

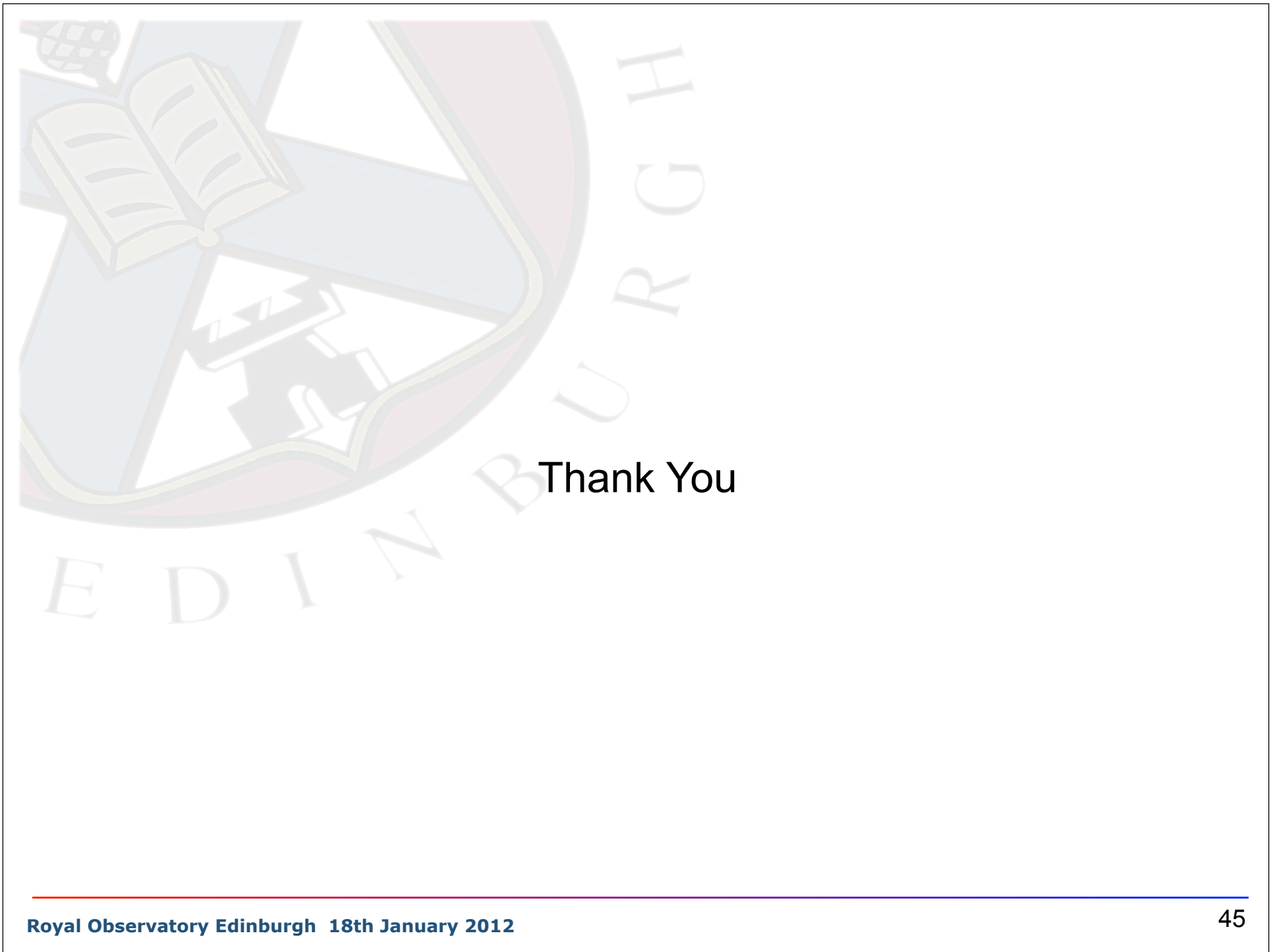
Optical Interferometry

- Optical Images of Stellar Surfaces

>500 scientists working in >25 countries
180ME project cost

Presently FP7 Preparatory Phase
Construction start ~2015
First light ~2017





Thank You