Direct Detection of Dark Matter

Alex Murphy

Dark Matter **http://www.ph.ed.ac.uk/nuclear/darkmatter/**
Nuclear astrophysics **http://www.ph.ed.ac.uk/nuclear/**

Where to begin…

General Interest Seminars
OPEN LECTURE

Lord Crawford's Astronomy Library

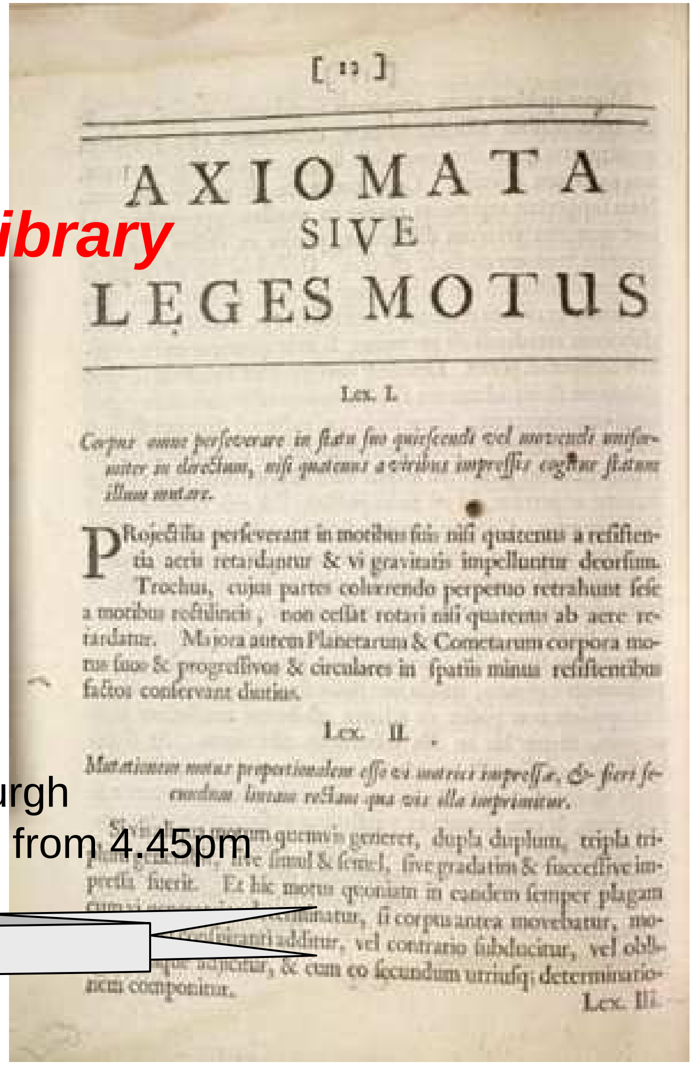
Professor Owen Gingerich

Harvard University

5pm Thursday 25th October 2007

Main Lecture Theatre
Michael Swann Building
The King's Buildings, University of Edinburgh
Coffee/Tea & Doughnuts will be served in the foyer from 4.45pm

www.ph.ed.ac.uk/seminars


[12]

AXIOMATA
SIVE
LEGES MOTUS

Lex. I.

Corpus omne perseverare in statu suo quiescendi vel movendi uniformiter in directum, nisi quatenus a viribus impressis cogitur statum illum mutare.

Projectilia perseverant in motibus suis nisi quatenus a resistentia aeris retardantur & vi gravitatis impelluntur deorsum. Trochus, cujus partes cohaerendo perpetuo retrahunt sese a motibus rectilineis, non cessat rotari nisi quatenus ab aere retardatur. Majora autem Planetarum & Cometarum corpora motus suos & progressivos & circulares in spatiis minus resistentibus factos conservant diutius.

Lex. II.

Mutationem motus proportionalem esse vi motrici impressae, & fieri secundum lineam rectam qua vis illa imprimitur.

... motum quemvis generet, dupla duplum, tripla triplum ... simul & semel, sive gradatim & successive impressa fuerit. Et hic motus quoniam in eandem semper plagam ... determinatur, si corpus antea movebatur, motui ... additur, vel contrario subducitur, vel obli... adjicitur, & cum eo secundum utriusq; determinationem componitur.

Lex. III.

More advertising

Royal Astronomical Society on Monday 26 November

Specialist Discussion Meeting on Dark Matter

Welcome: Alex Murphy

Chair: Wyn Evans

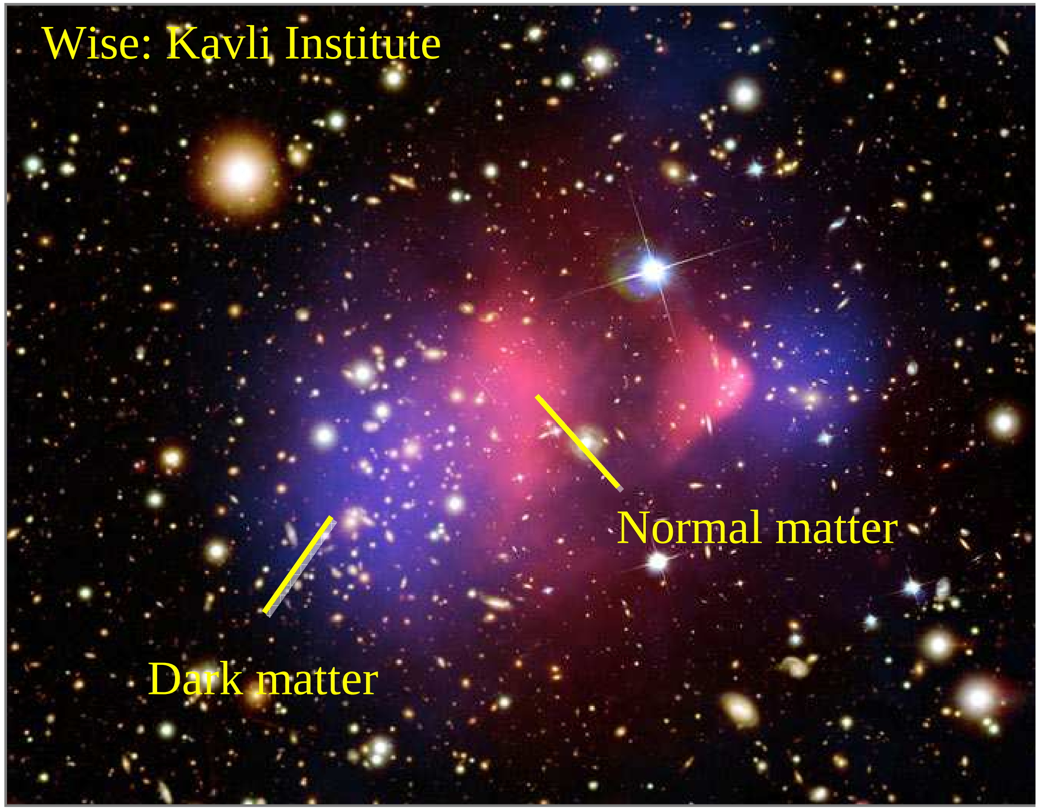
13:00 - 13:30	James Binney (Oxford):	Dark matter in the Galaxy
13:30 - 13:50	Anne Green (Nottingham):	Direct detection and the dark matter distribution
13:50 - 14:10	Mark Wilkinson (Leicester):	Observable properties of dark matter
14:10 - 14:40	Dan Hooper (Fermilab):	Indirect signatures of dark matter
14:40 - 15:00	Paula Chadwick (Durham):	HESS searches for dark matter annihilation in the Galaxy
15:00 - 15:30	Sergio Colafrancesco (Rome):	tbd

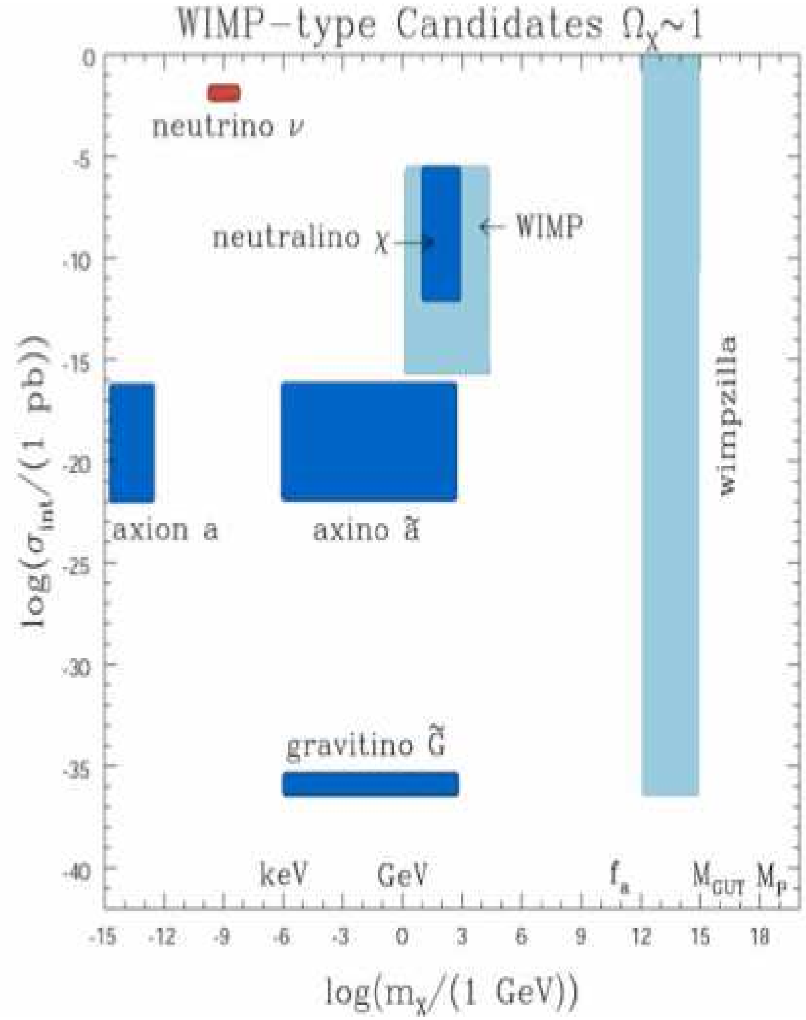
Tea/Coffee

Chair: Subir Sarkar

16:00 - 16:20	Hans Krauss (Oxford):	The future in cryogenic dark matter detection (EURECA))
16:20 - 16:40	Nigel Smith (Chilton):	tbd (ZEPLIN/ELIXIR)
16:40 - 17:00	Neil Spooner (Sheffield):	tbd (DRIFT/CYGNUS)
17:00 - 17:20	Ben Morgan (Warwick):	Optimizing WIMP directional detectors
17:20 - 17:30	Discussion	

The best evidence for physics beyond the SM!





Best motivated explanation: WIMPs

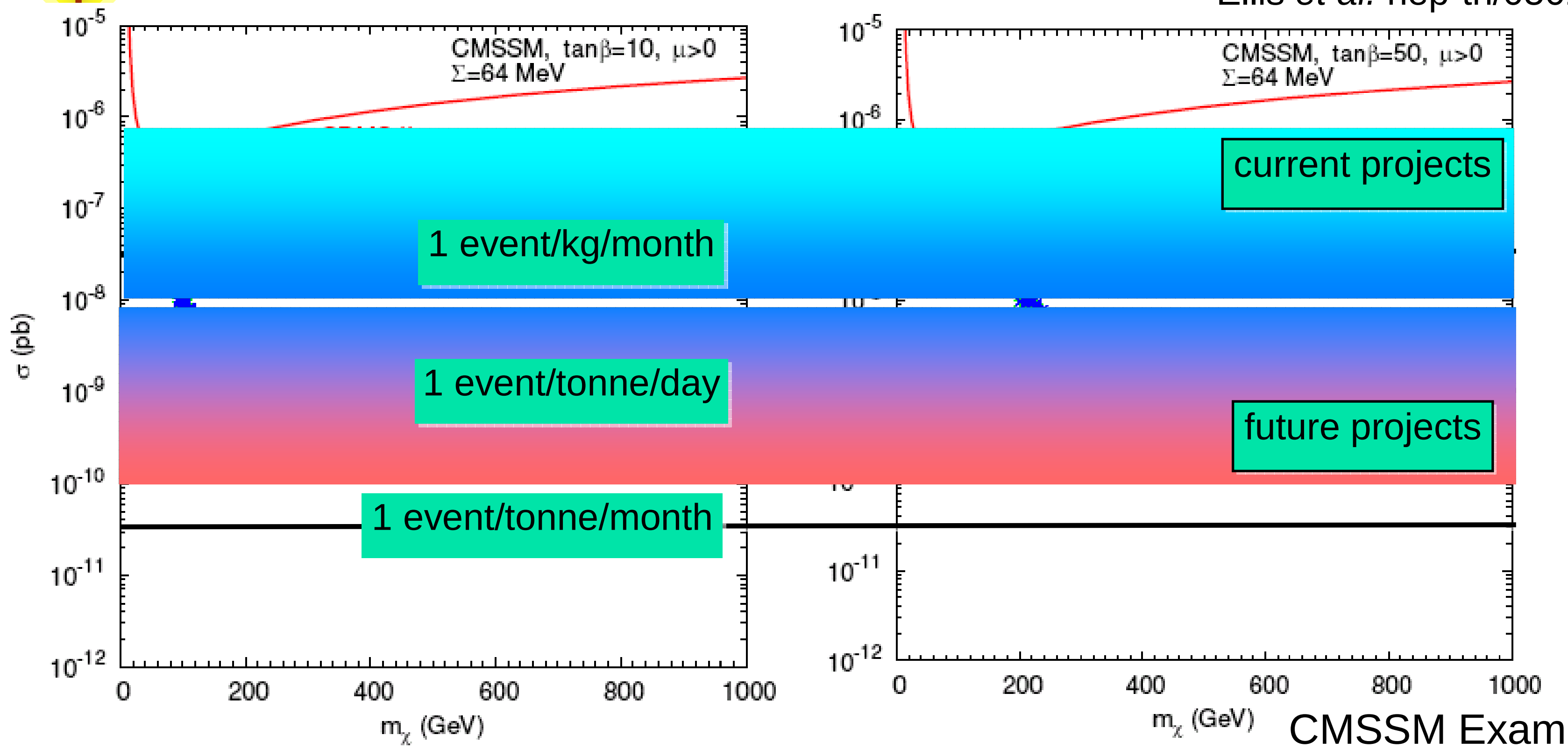
The Challenge

WIMP-like DM hypothesis…

- Earth should be passing through a halo of (probably) weakly interacting massive particles
- We would like direct evidence for the existence of these particles
- Search for their (rare) interactions with normal matter here on Earth.

How tough is this challenge?

Ellis *et al.* hep-th/0502001

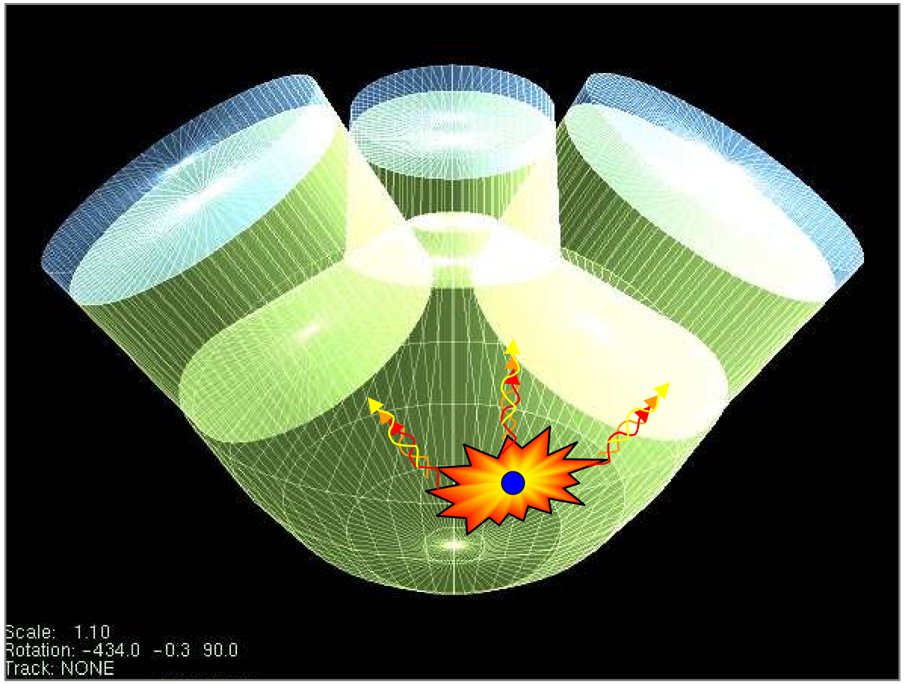


CMSSM Example

- Required sensitivity is ~10^{-7} - 10^{-10} pb
- May not need to go all the way for discovery...

General Methodology

- Active target
- Wimp scatters off a nucleus of the detector
- That nucleus recoils and deposits KE in detector, generating Scintillation, Ionisation and Phonons
- Time constants and ratios of signal types depend on incident particle type
  - Allows discrimination against e.g. γ-rays



Neutrons VERY HARD to discriminate against

What do we need to do…

- To cover lower reaches of parameter space…
  - The event rate is small AND the energy deposited is small
- Large scale detectors
  - target masses of tonne scale to provide count rate
  - Low background to allow signal to be seen
    - Remove intrinsic activity from detector
    - Remove external activity from surroundings
    - Reject γ, β
    - control/rejection of surface events
    - position sensitivity, segmentation, fiducialisation / self shielding
- Low (keV) energy threshold for nuclear recoil
  - The above, plus…
  - High gain
  - High efficiency

This is TOUGH!

Is this even feasible…?

- Is it possible to make a clean enough environment?
- Neutron production from
  - U/Th in detector material
  - U/Th in shielding material
  - U/Th in rock
  - μ spallation in detector material
  - μ spallation in shielding material
  - μ spallation in surrounding rock

→Deep underground

→ Radiologically pure components

→ Additional shielding from environment

Where to search for WIMPs?

EU underground sites

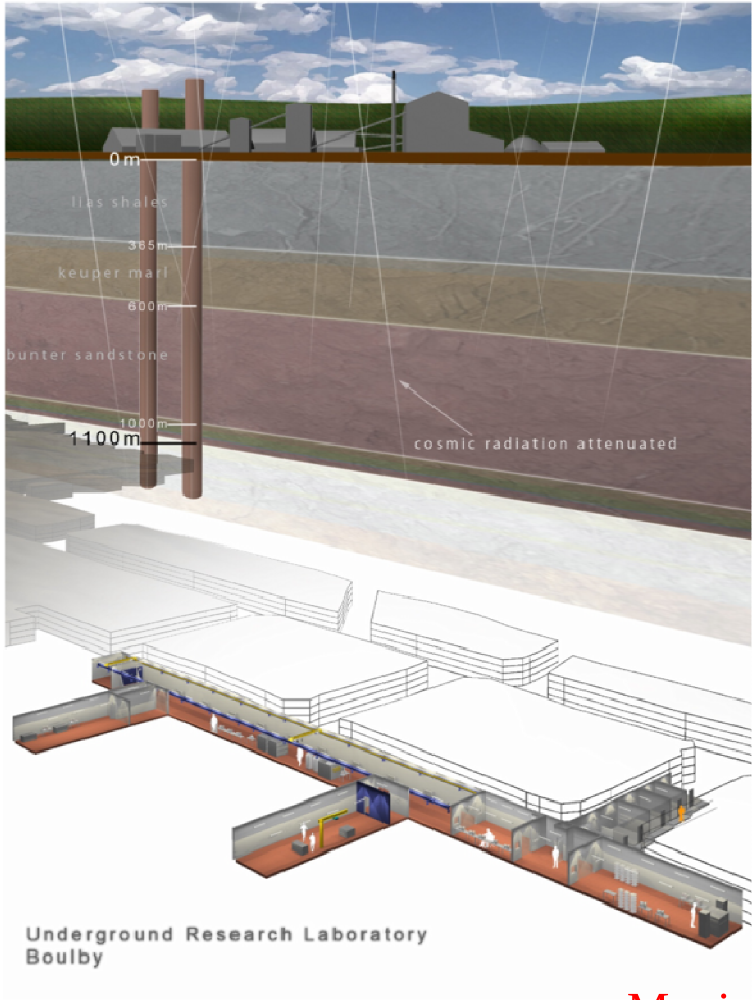
ApPEC Roadmap

Infrastructure	LNGS Gran Sasso	LSM Fréjus	LSC Canfranc	IUS Boulby	BNO Baksan	CUPP Pyhäsalmi
Year of completion	1987	1982	1986, 2005	1989	1977, 1987	1993 (2001)
Area (m^2)	13000	500	150+600	500+1000	550, 600	500-1000
Volume (m^3)	180000	3500	8000	3000	6400, 6500	100-10000
Access	Horizontal	Horizontal	Horizontal	Vertical	Horizontal	Slanted truck road
Depth (m.w.e.)	3700	4800	2450	2800	850, 4800	1050, 1444 up to 4060
Surface profile	Mountain	Mountain	Mountain	Flat	Mountain	Flat
Muon flux (m^{-2} day^{-1})	24	4	406	34	4320, 2.6	8.6 @ 4060m
Neutron flux (>1 MeV) (10^{-6} cm^{-2} s^{-1})	$O(1)$	$O(1)$	$O(1)$	$O(1)$	- , $O(1)$	?
Radon content (Bq/m^3)	$O(100)$	$O(10)$	$O(100)$	$O(10)$	$O(100)$	$O(100)$
Main past and present scientific activities	- DM - ββ - solar ν - SN ν - atmos. ν - monopole - nuclear astrophysics - CRs (μ) - LBL ν's	Eighties: - Proton decay - atmos.ν Now: - DM (Edelweiss) - ββ (NEMO, TGV)	- DM (IGEX-DM, ROSEBUD, ANAIS) - ββ (IGEX)	- DM (Zeplin I,II, III, DRIFT)	*BUST:* - solar ν - SN ν - atmos. ν - CRs (μ) - monopoles *SAGE:* - solar ν	- CRs (test set-up)
Number of visiting scientists	700	100	50	30	55	15

Plus SNOlab, SUSEL/DUSEL, …

The ‘local’ option

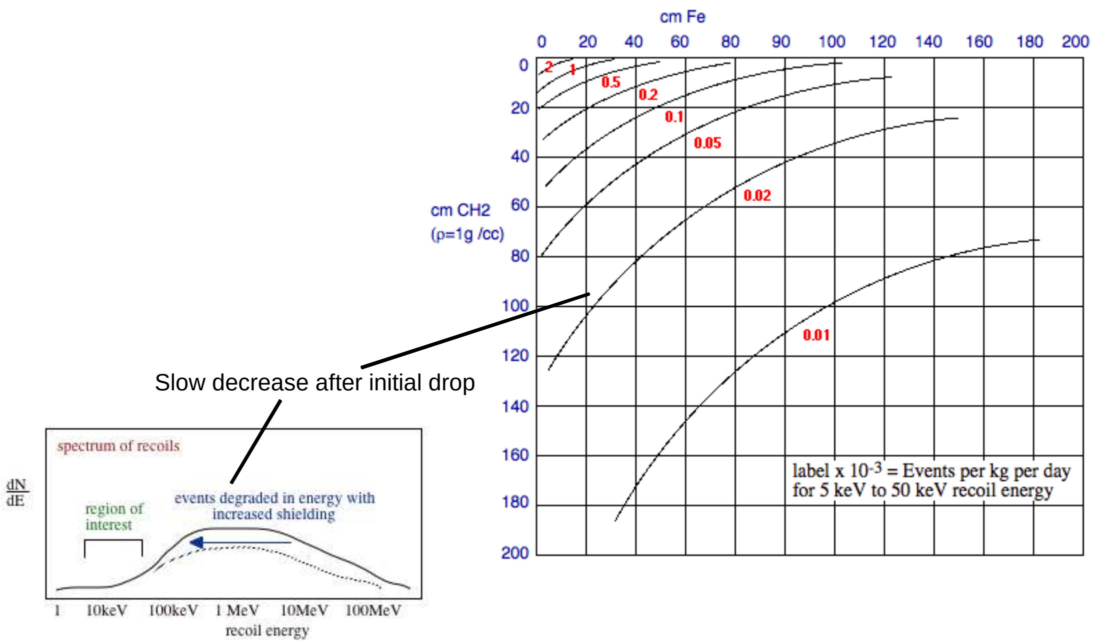
Boulby, U.K. site
1100m, 2.8km water equiv.
10^6 reduction in muon flux



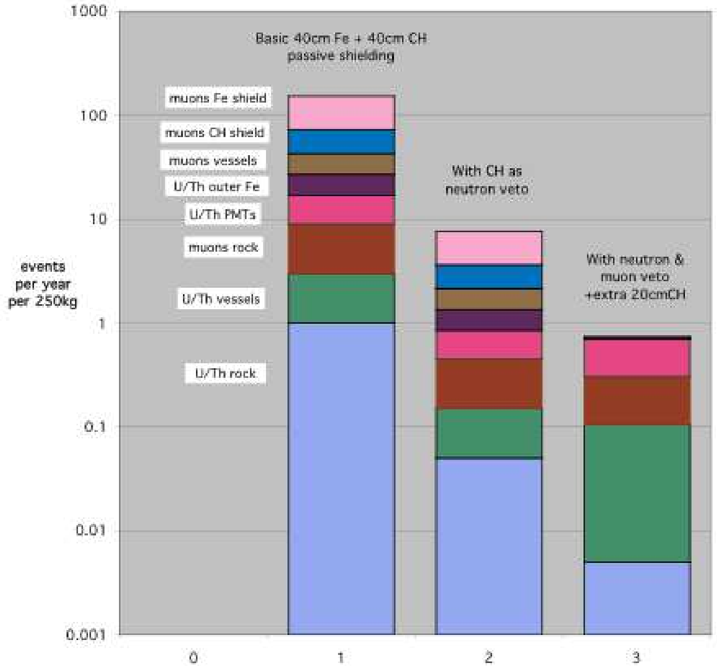
Movie

Neutron shielding requirements

- A combination of hydrocarbon, iron, and active veto…



C. Bungau *et al. Astropart. Phys.* ***23****, 1, 97 (2005)*

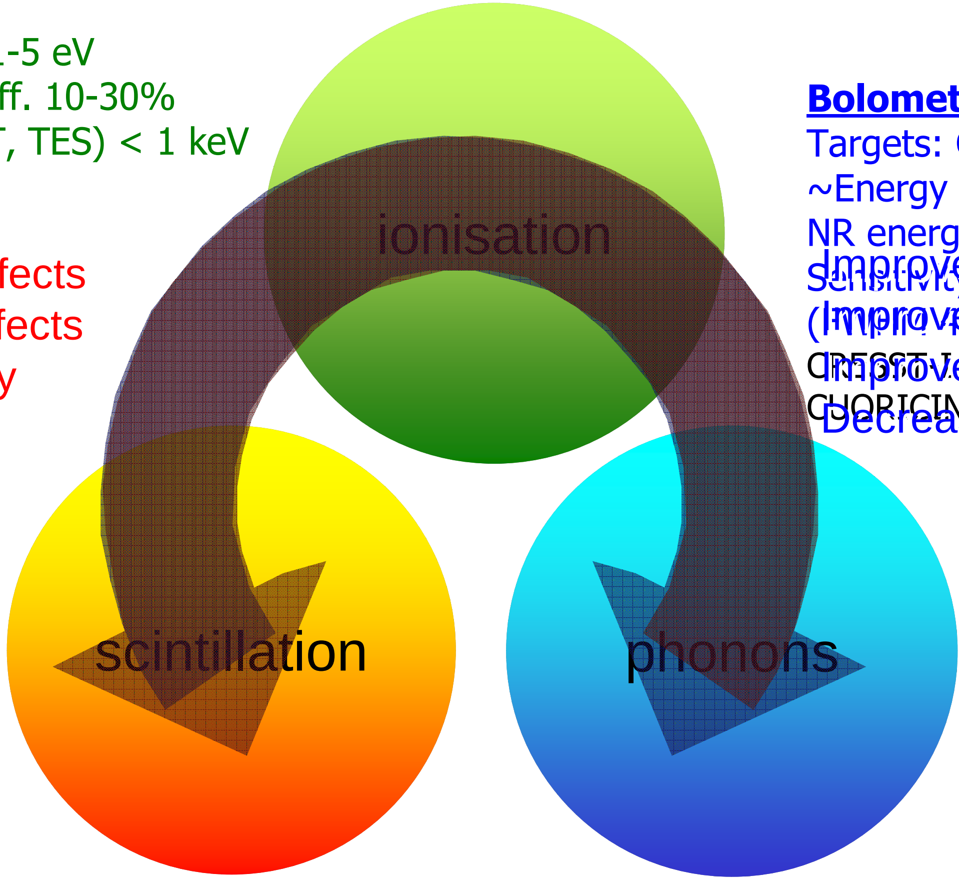


→Neutron background can be suppressed to required levels!

Detections techniques: Single channel

Ionisation Detectors
Targets: Ge, Si, CdTe
~Energy per e/h pair 1-5 eV
NR energy collection eff. 10-30%
Sensitivity (HEMT JFET, TES) < 1 keV
IGEX (4 keV), HDMS,
GENIUS (3.5 keV)

Improve surface effects
Improve volume effects
Improve scaleability



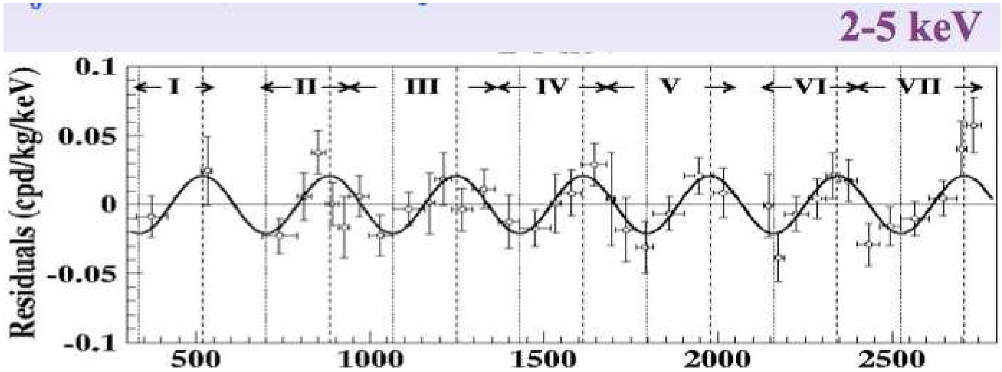
Bolometers
Targets: Ge, Si, Al_2O_3, TeO_2
~Energy per phonon ~meV
NR energy col. eff. (th.) ~100%
Sensitivity (TES) << 1 keV
(FWHM ~1.5 eV @ 6 keV x-rays)
CRESST I (0.6 keV),
CUORICINO, CUORE (5 keV)

Improve resolution
Improve threshold
Improve noise
Decrease temperature

Scintillators
Targets: NaI, Xe, Ar, Ne
~ Energy per photon ~15 eV
NR energy collection eff. 1-3%
Light gain 2-8 phe/keV
Sensitivity (PMTs) ~1 keV
ZEPLIN I (2 keV), NAIAD (4 keV)
DAMA (2 keV), DEAP,
CLEAN, XMASS (5 keV)

Single phase: Present status

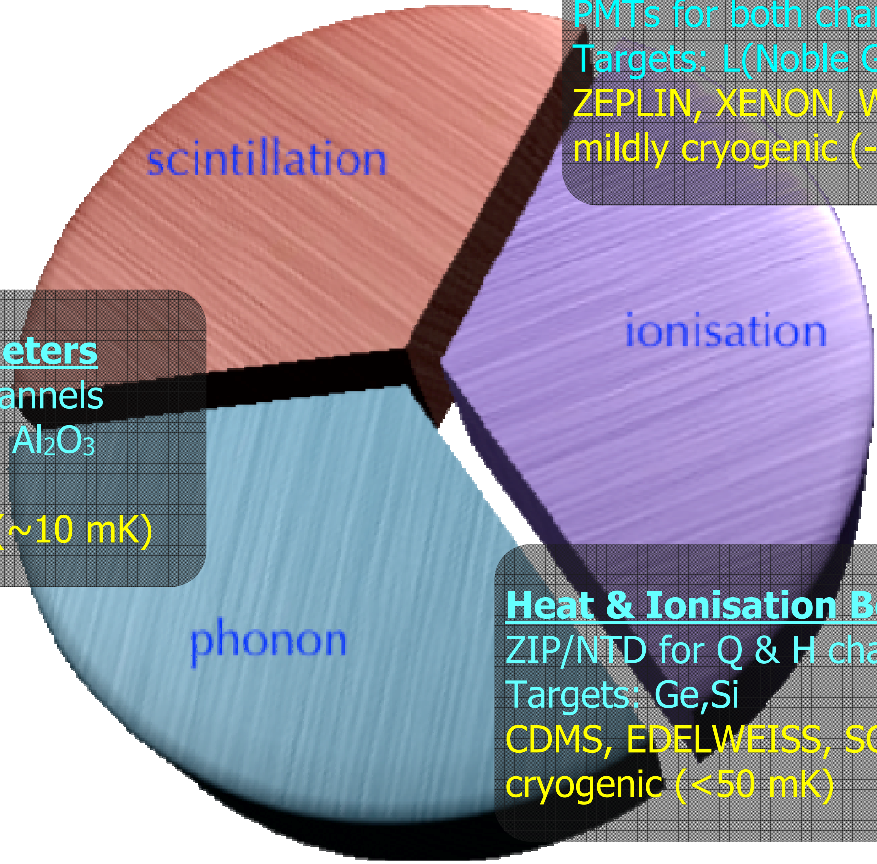
- DAMA signal
  - Annual modulation
  - 'controversial'
  - LIBRA: Results promised 2008



- Threshold techniques very promising
  - Picasso, COUPP

Hybrid detection techniques

Light & Ionisation Detectors
PMTs for both channel readout
Targets: L(Noble Gases)
ZEPLIN, XENON, WARP, ArDM, SIGN
mildly cryogenic (-100 C)



Light & Heat Bolometers
TES/NTD for L & H channels
Targets: $CaWO_4$, BGO, Al_2O_3
CRESST, ROSEBUD
even more cryogenic (~10 mK)

Heat & Ionisation Bolometers
ZIP/NTD for Q & H channels
Targets: Ge,Si
CDMS, EDELWEISS, SCDMS, EURECA
cryogenic (<50 mK)

All hybrid techniques have >99% nuclear recoil discrimination at 10keV NR

Present Status

The key question:

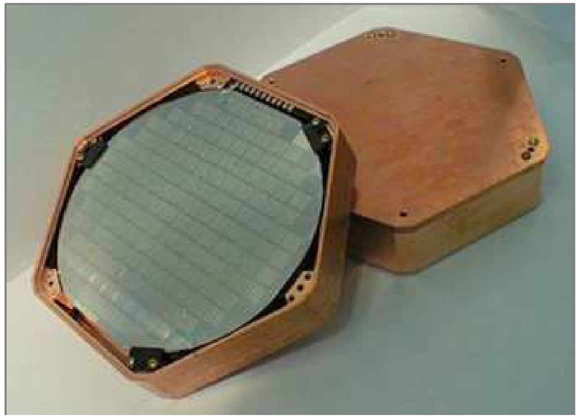
What's the best technology for scale up?

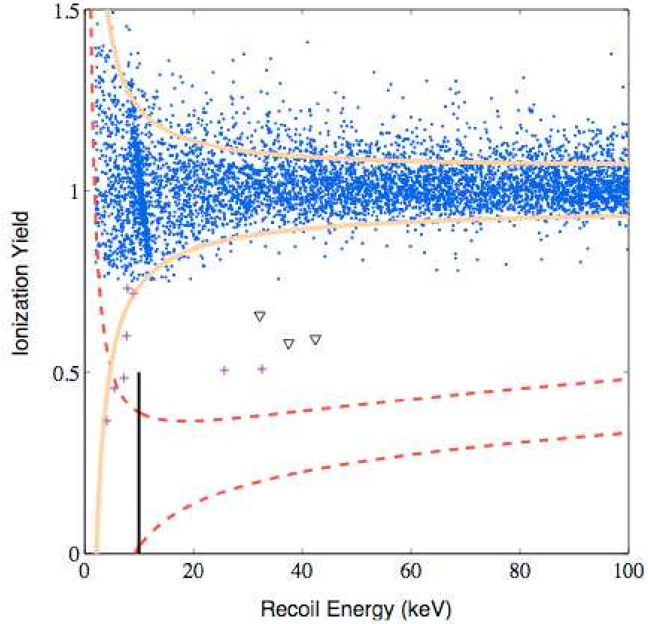
- Semiconductor or Noble Liquid
- EDELWEISS, CRESST, EURECA, CDMS, XENON, LUX, ZEPLIN, XMASS, ArDM, DEAP, WARP, CLEAN, SIGN…

Semiconductors

CDMS

- Phonons and Ionsation
- 97 kg.d exposure Soudan (6xGe, 4xSi)
- 430 kg.d analysis ongoing (19xGe, 11xSi)
- $2x10^{-8}$ pb expected final run (1300kg.d)
- Upgrade path: SuperCDMS
  - Bigger detectors, more detectors
  - Cleaner components
  - Better shielding
  - 'Phase B/C' → 150-1000kg scale system

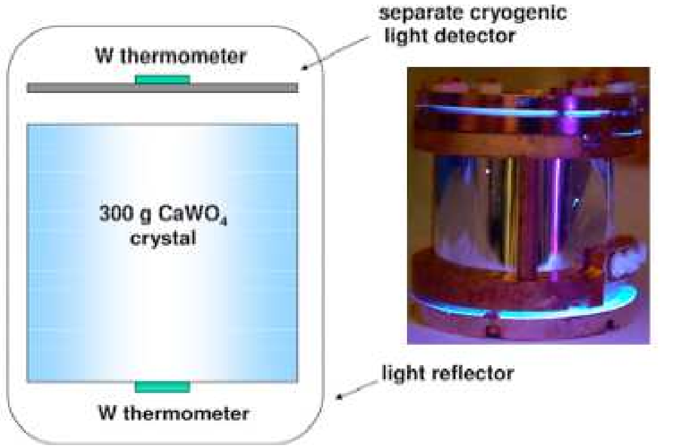


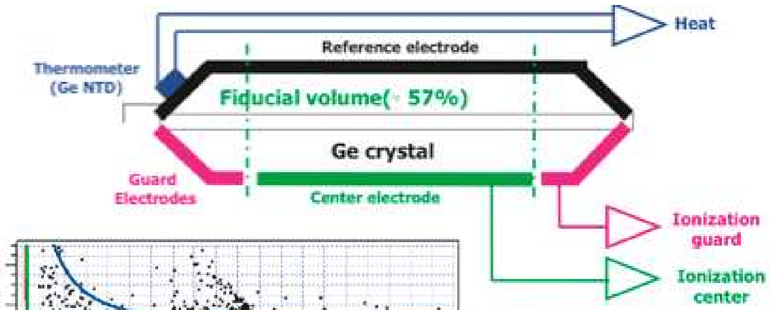


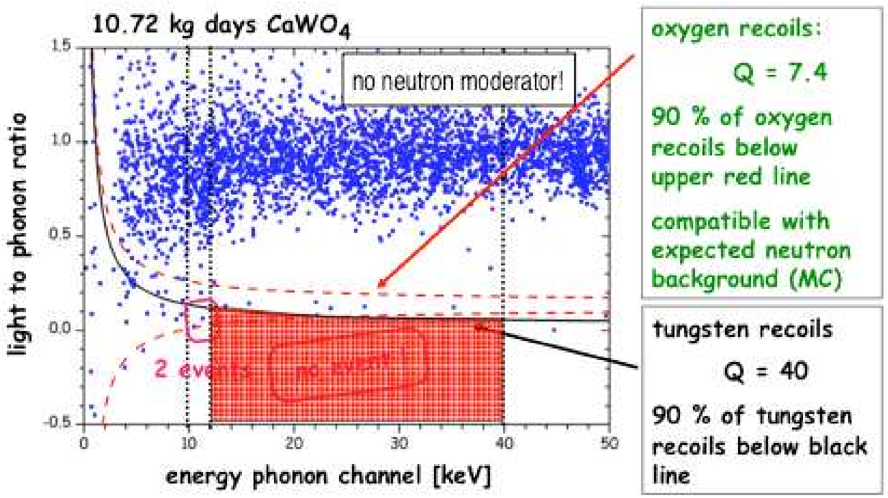
Semiconductors

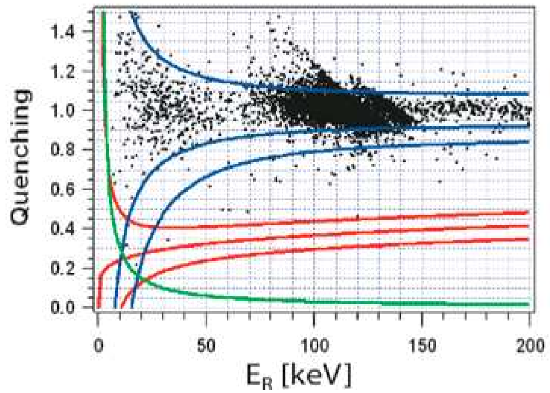
CRESST/EDELWEISS

- Scintillation/phonon, ionisation/phonon
- $CaWO_4$, Ge, Si
- 3kg.d, 6x 320g NTD, 2x 200g NbSi (2006)
- More data, 23x 320g NTD, 7x400g NbSi (2007)
- → EURECA, 100-1000 kg





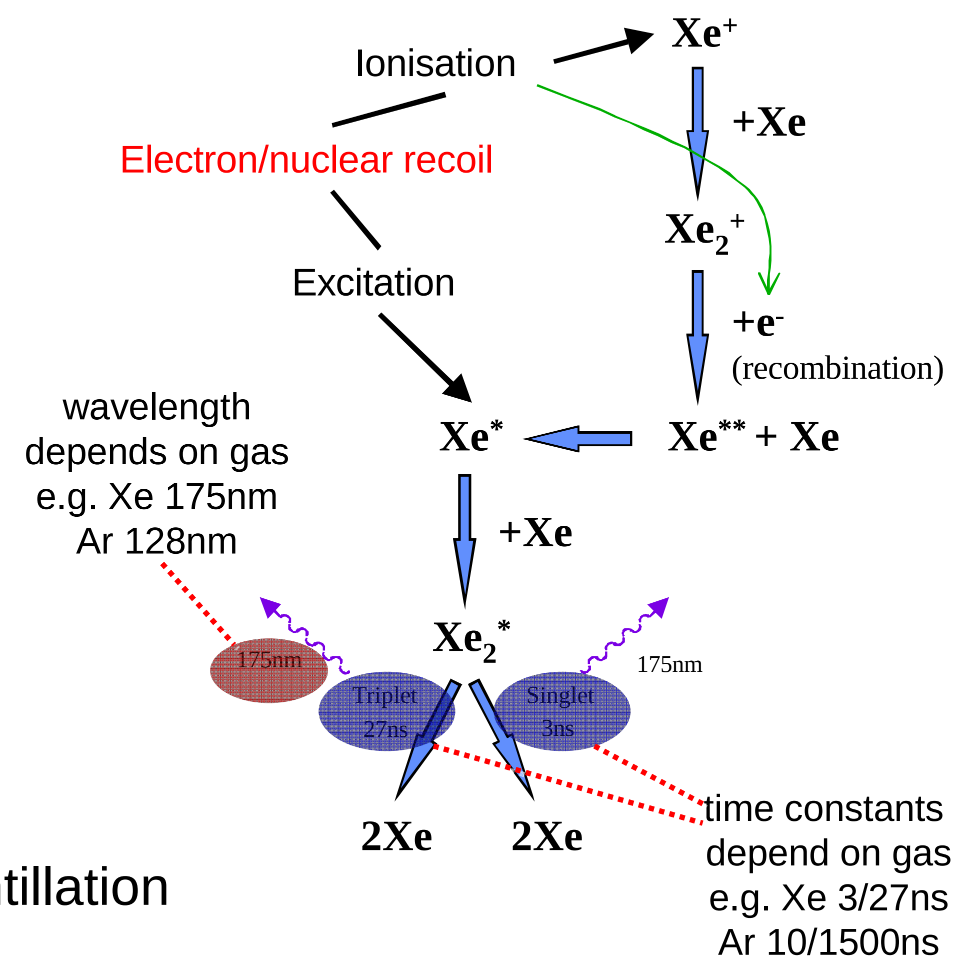




(Liquid) Noble Gas detectors

Gas	Single phase	Double phase
Xenon	ZEPLIN I, XMASS	ZEPLIN, XENON, XMASS
Argon	DEAP, CLEAN	WARP, ArDM
Neon	CLEAN	SIGN

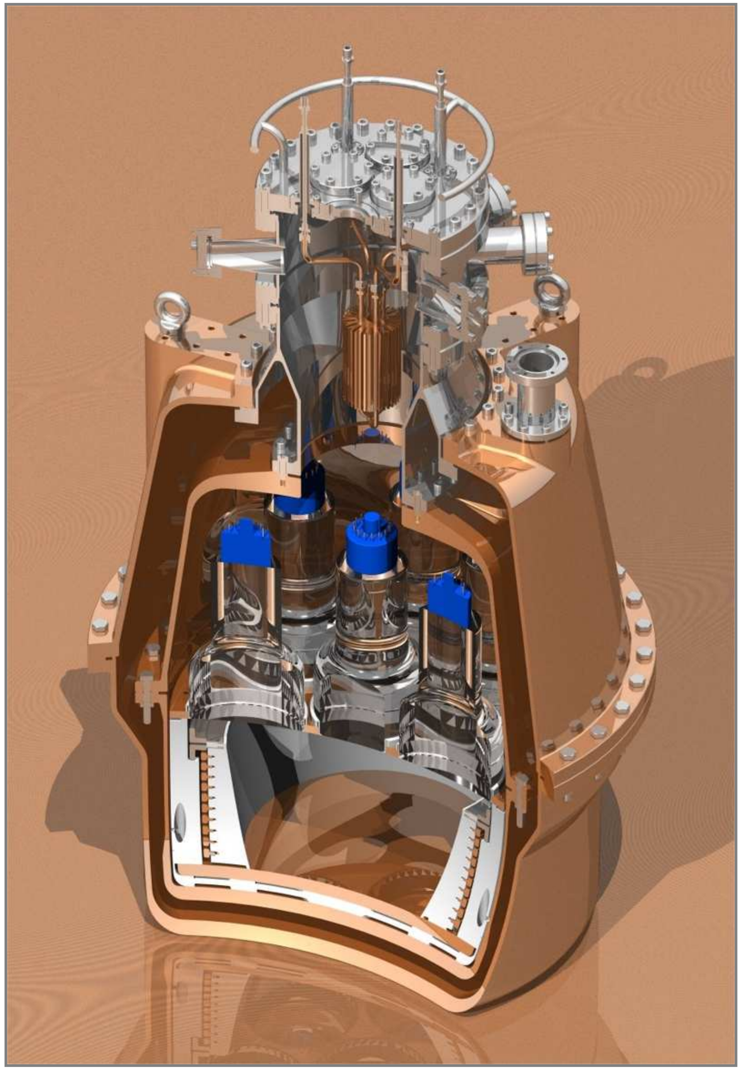
noble gas interaction process



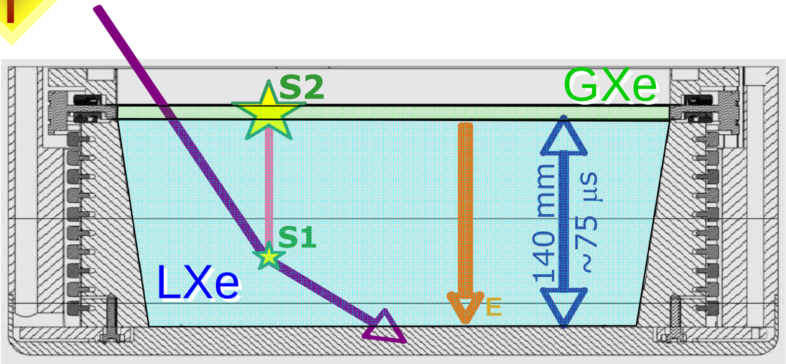
- Single phase – scintillation
  - recombination occurs
  - singlet/triplet ratio 10:1
    nuclear : electron
- Double phase - ionisation/scintillation

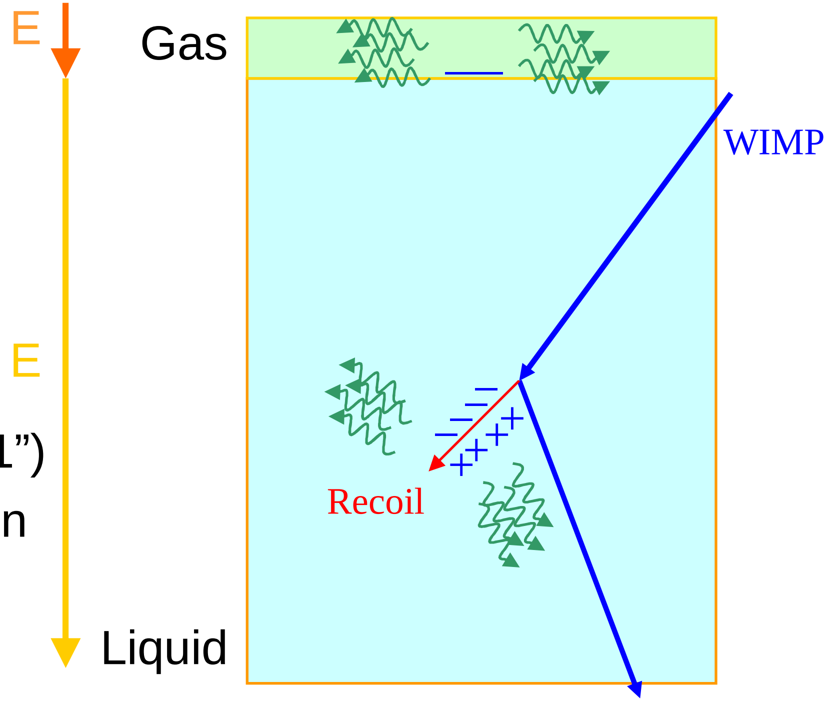
ZEPLIN II

- Scintillation / Ionisation
- 7.2 kg fiducial target mass
- 0.55 p.e./keV (with field)

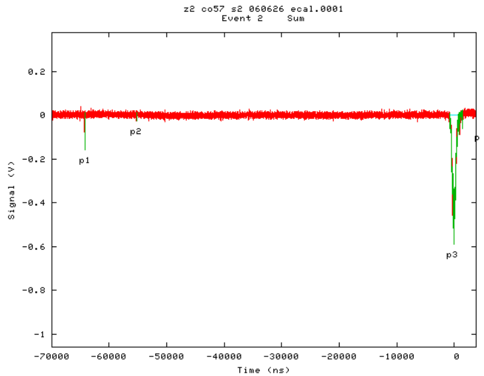


Two-phase Noble liquid method

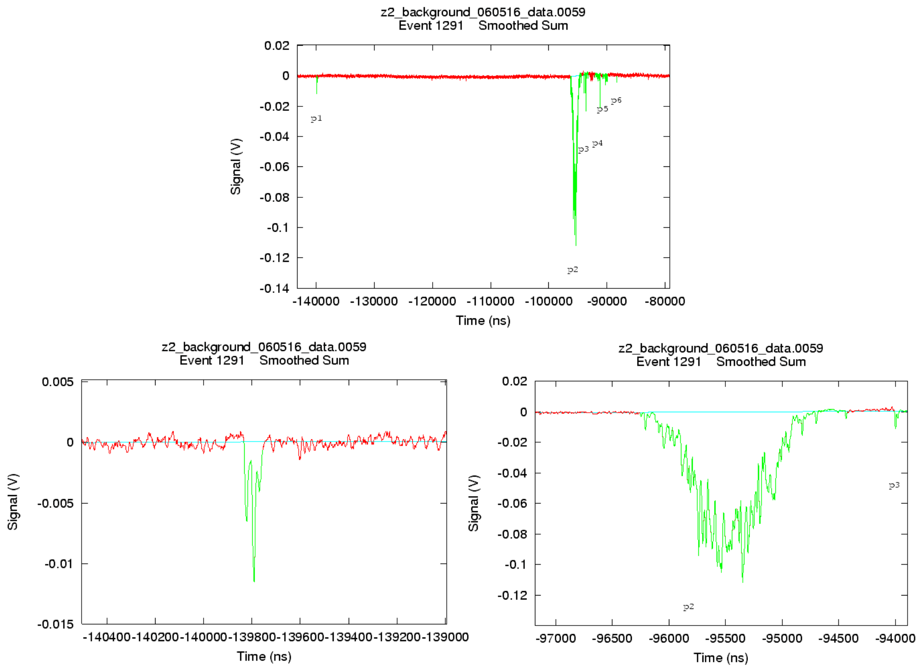




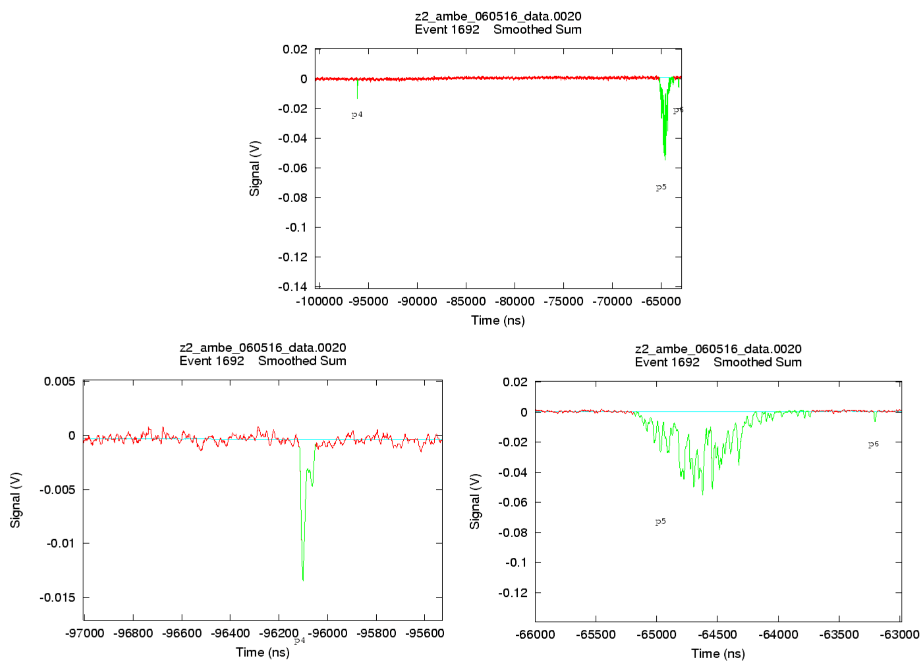
- Use PMTs to observe prompt scintillation (“S1”)
- Apply E-field: Extract a faction of the ionisation electrons
- Drift electrons through liquid
- Accelerate electrons through gas generating electroluminescence
- PMTs observe (depth) delayed electroluminescence (“S2”)
- S2/S1 is different for an electron compared to a nuclear recoil



Neutron/Gamma pulses: Zep II



Gamma ray interaction

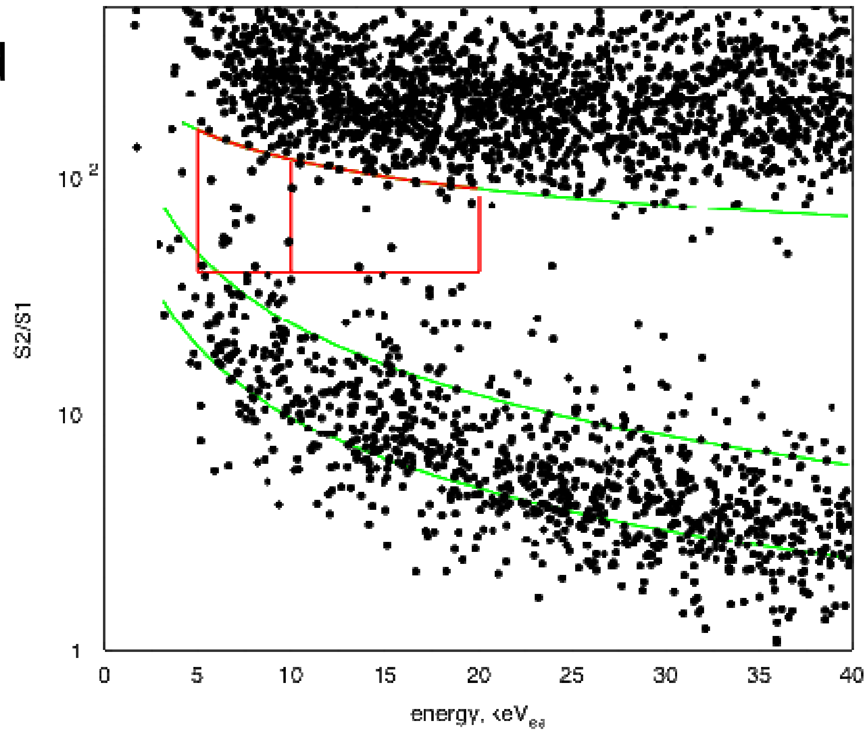


Neutron interaction

ZEPLIN II Science runs

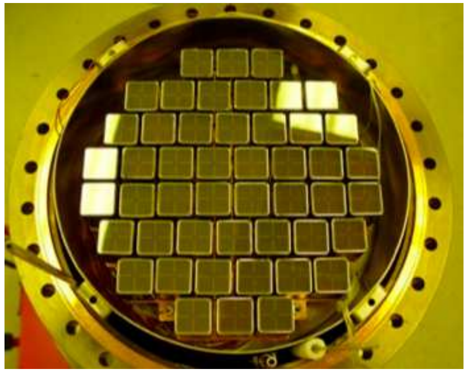
- Population due to radon-progeny events seen on walls
- 29 events seen, 28.6±4.3 expected
- 90% c.l. upper limit 10.4 n.r

  → <u>6.6x10^{-7}pb</u>



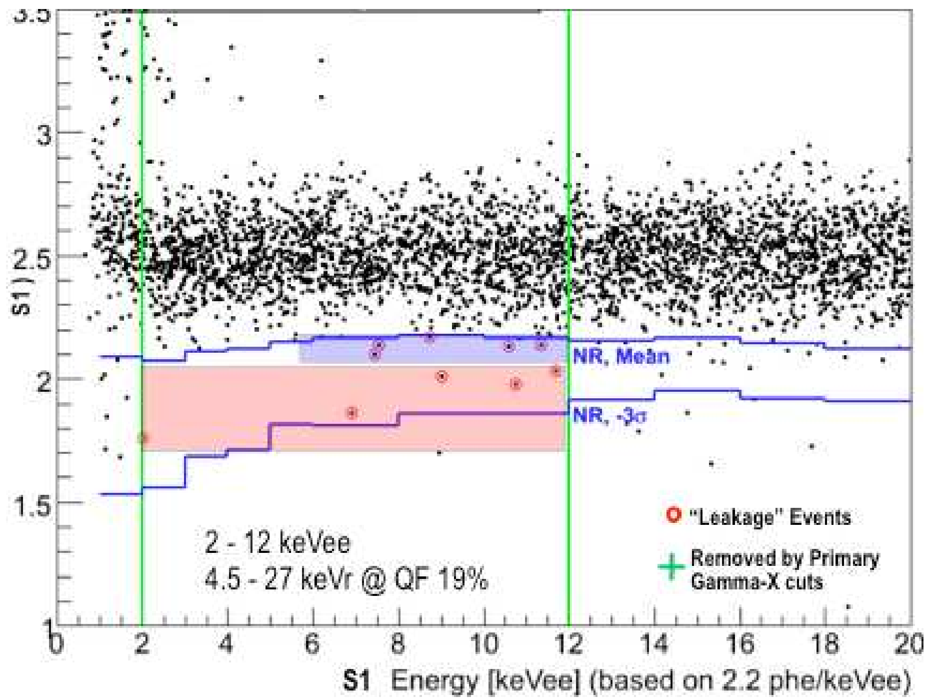
XENON

- XENON 10
  - 22kg target mass, 15kg active
  - 89 low b/g 1” PMTs in liquid and gas phase
    - 48 in gas, 41 in liquid
    - ~mm position reconstruction in x,y
  - Deployment at LNGS
  - Pulse tube cooling



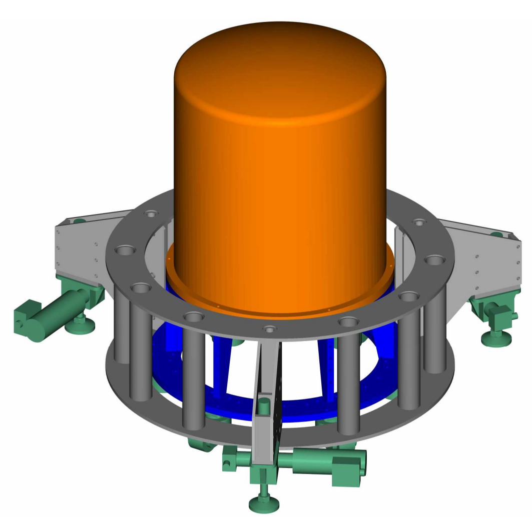
XENON Results

- Blind analysis on 58.6 days
  - Still not published, …controversial…
  - 50% n.r., 2-12 keV
  - 23 events in n.r. window
  - 10 events after all cuts
  - 6.8 expected from gamma leakage events
  - Yellin maximal gap analysis (single sided)
  - minimum at $4.5\text{x}10^{-8}$ pb
- Future XENON 100
  - 100kg target mass
  - background assessments completed
- And/Or… LUX
  - ~100 kg target mass
  - Homestake

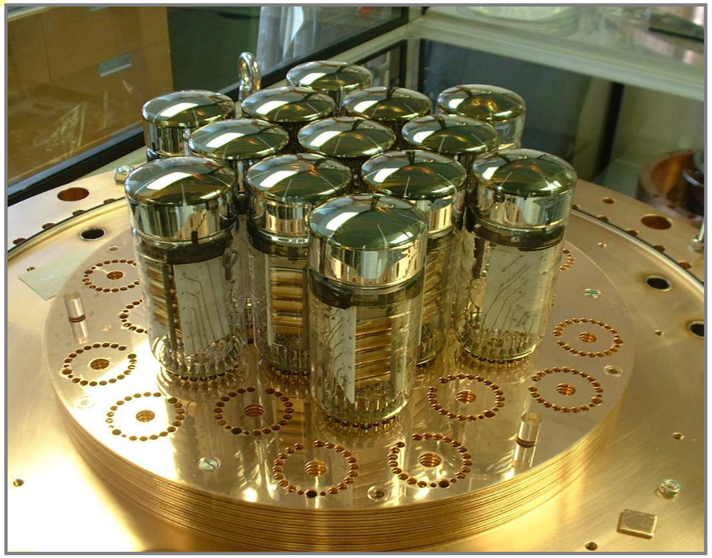


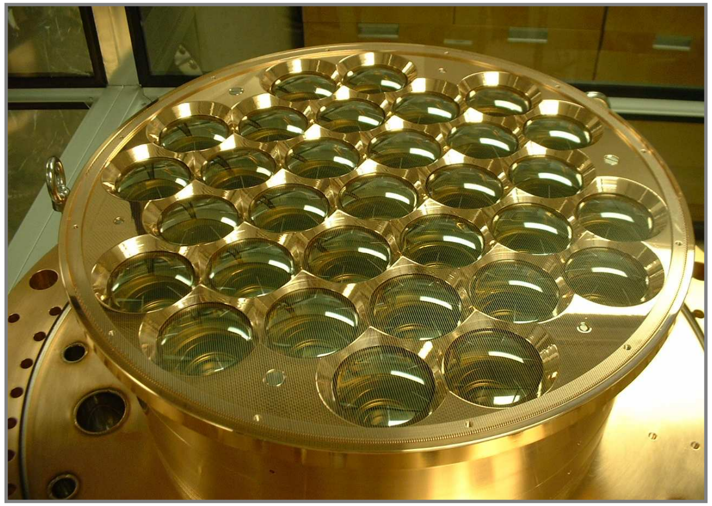
ZEPLIN III

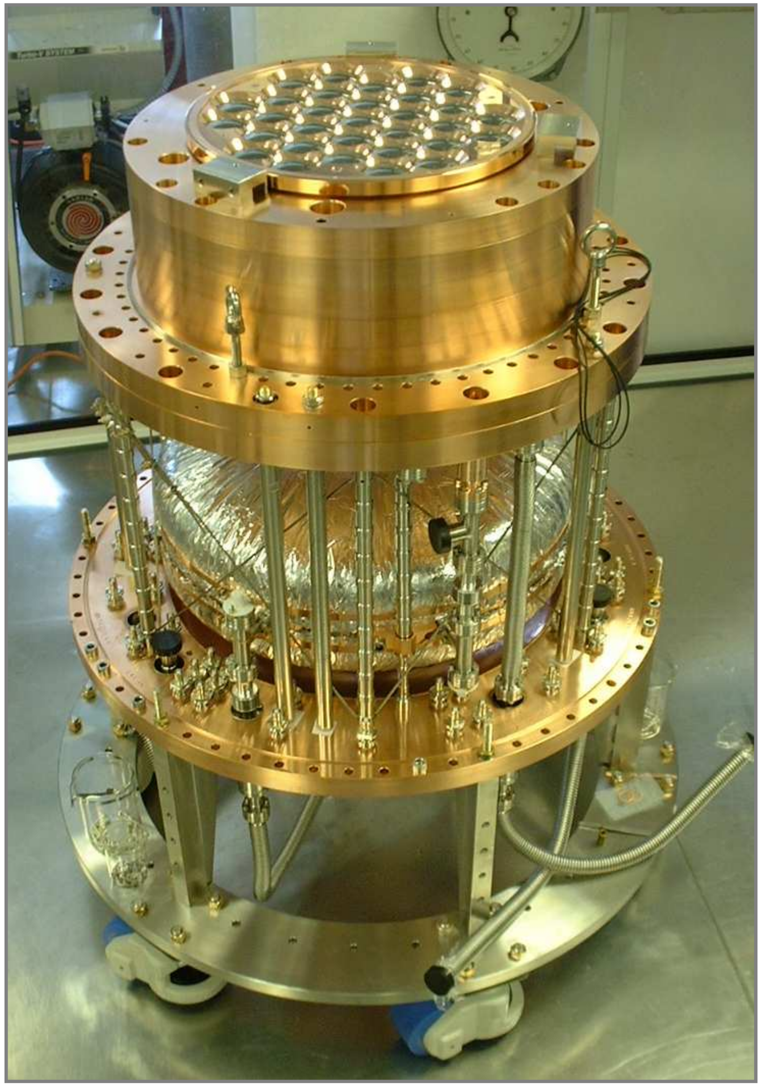
- High-Field, 2-Phase Xenon
  - Good light collection for scintillation
  - Slab geometry (35 mm drift height, D/h~10)
  - Photomultipliers immersed in liquid
- Better discrimination
  - ‘Open plan’ target, no extraction grids
  - High field operation (3-5 kV/cm)
  - Precision 3D position reconstruction
- Low background construction
  - Copper construction, low background Xe
  - 8kg fiducial mass
- 1st Science Run before Christmas?
- FP7 ELIXIR 1 tonne DS



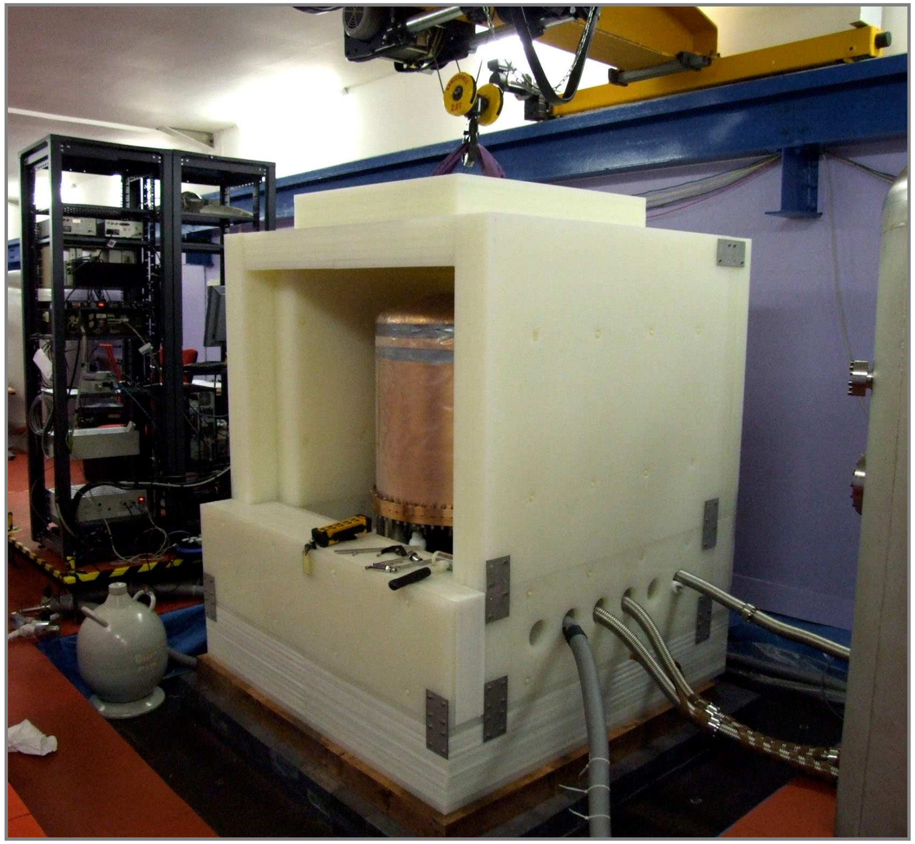
ZEPLIN III: Entrails

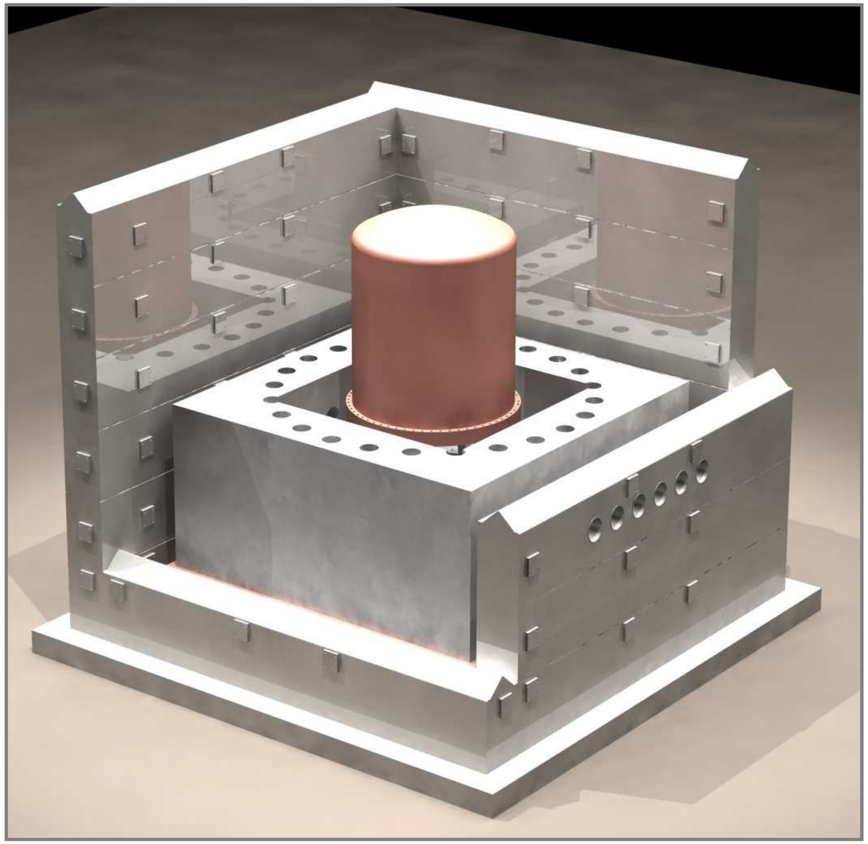






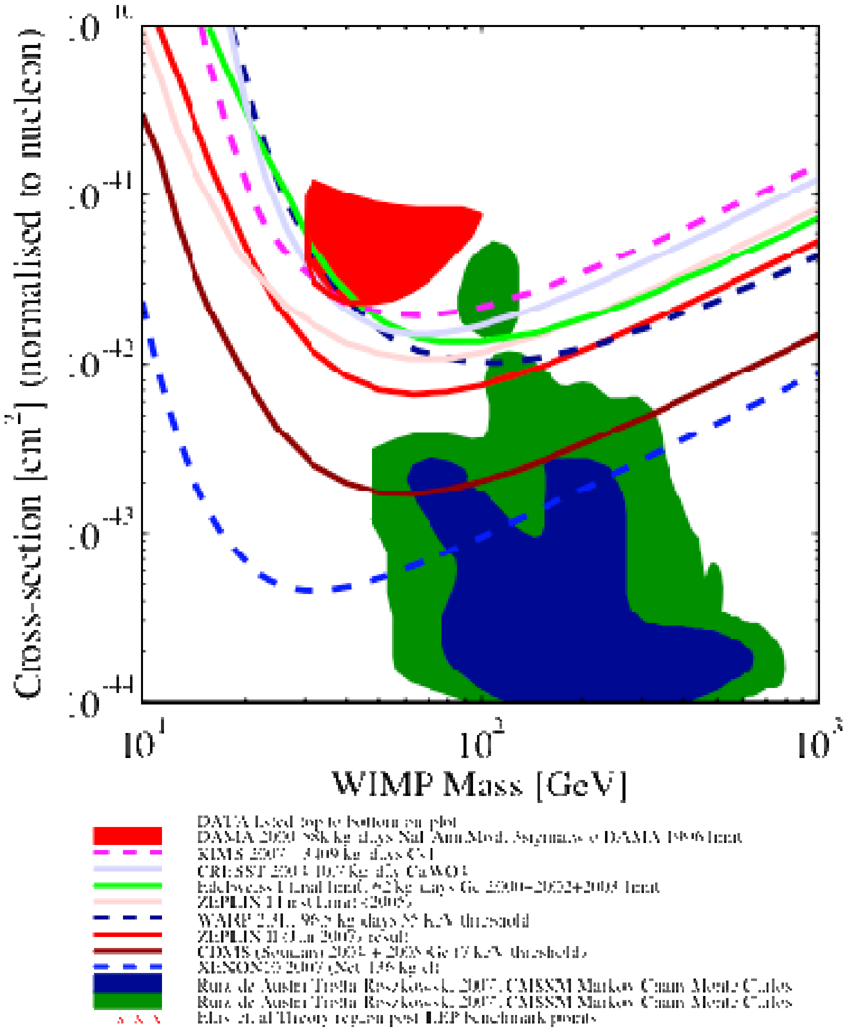
Shielding





Present status

- ‘Canonical’ halo model
- Spin independent interaction
- normalised to one nucleon



http://dmtools.berkeley.edu/limitplots/Gaitskell/Mandic

Future paths

Likely merger of groups for each technology as we 'approach' tonne-scale

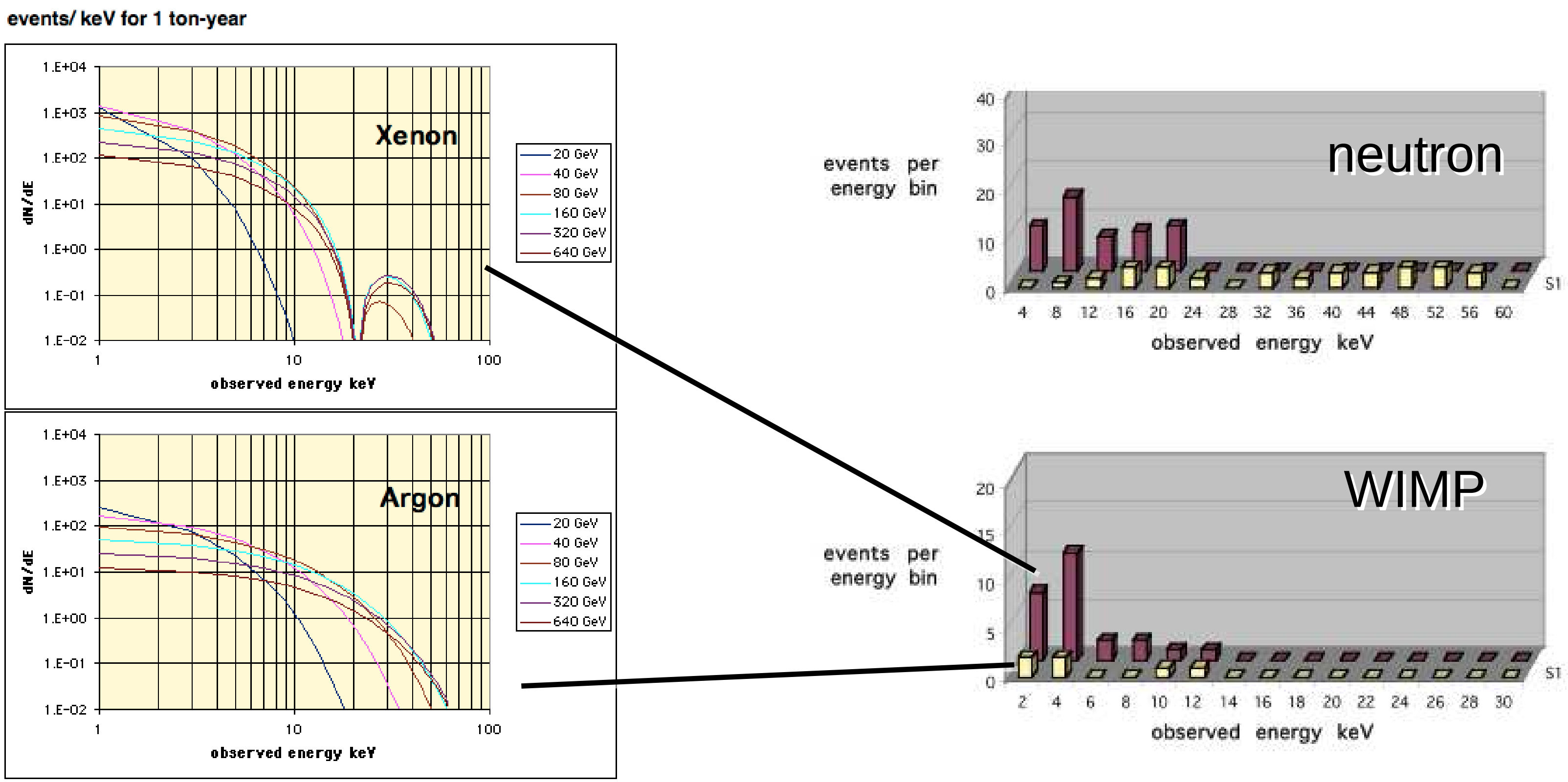
E.g.

- CRESST & EDELWEISS → EURECA
- Untenable to have XENON 100 and LUX2 and ELIXIR

But, genuine benefit in having multiple technologies

Complementarity of targets

- Comparison of rates in LXe and LAr detectors
- Shows effect of A^2 and form factor



Conclusions

- This is a hugely competitive field, many groups
- We need to reach tonne-scale
  - Searches the required parameter space.
  - Even if signal seen before then, we need sufficient events
  - This can be done!
  - This will be done (in ~5-7 yrs)
- Finances and limited effort *requires* a merger of groups
- But not necessarily choice between technologies
  - confirm/explore signal
- Once a signal is found, we need…
  - Confirmation, energy spectra, directional detectors, more events, bigger scales still!

Roll on Direct Dark Matter Detection Astronomy!

Thanks to my DM colleagues