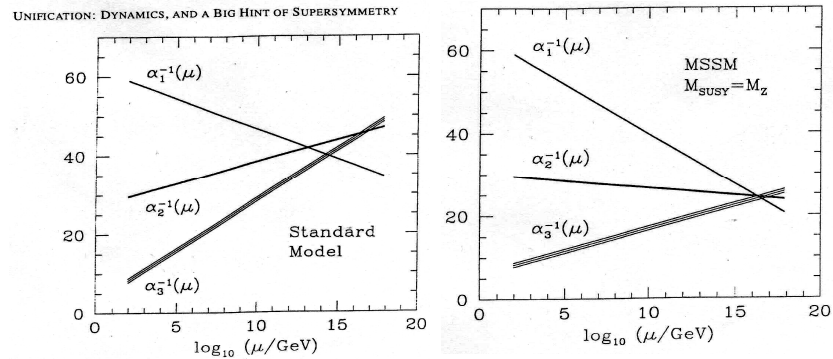
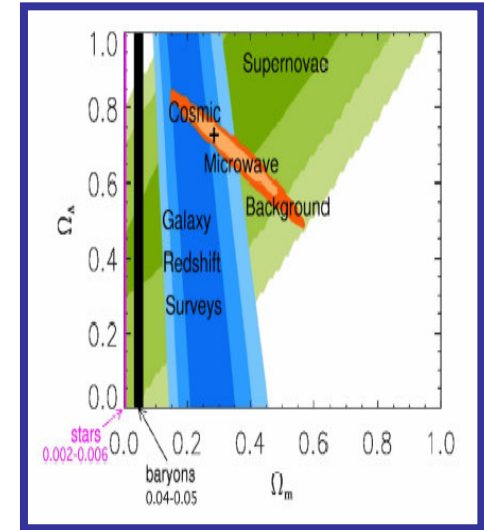


Dark Matter Experiments and Searches

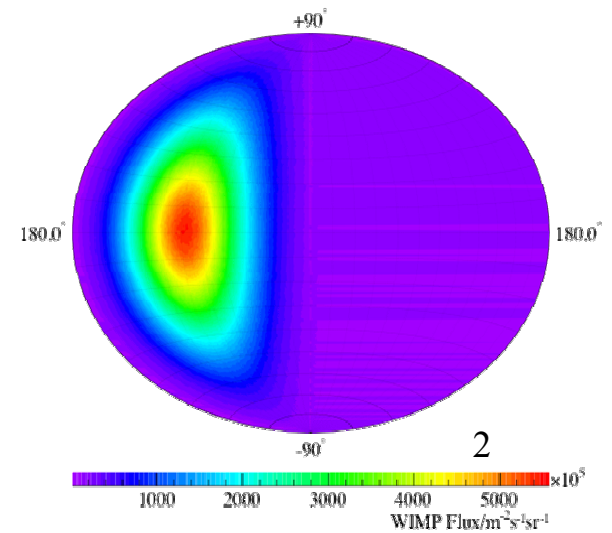
R.J.Cashmore
Principal Brasenose College, Oxford
and
Dept of Physics, Oxford

Scientific Motivation

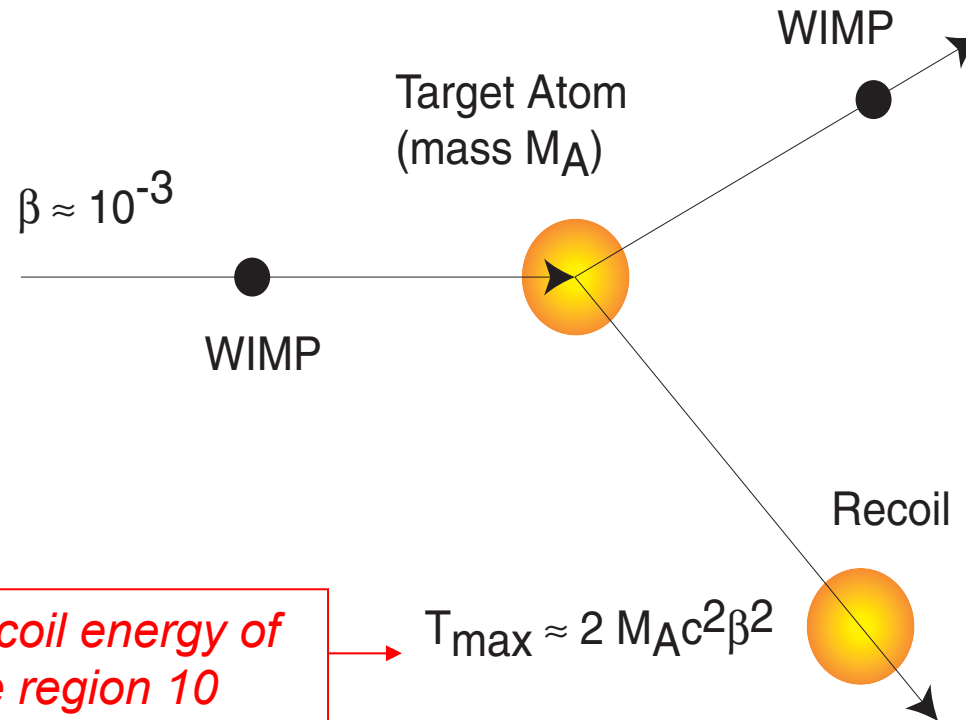
- **Cosmology** – is the dark matter that makes up 22% of the Universe in the form of massive particles?
- **Supersymmetry** – are these the particles predicted by supersymmetry?



- **Galaxy formation and dynamics** – how do these particles behave within galaxies?

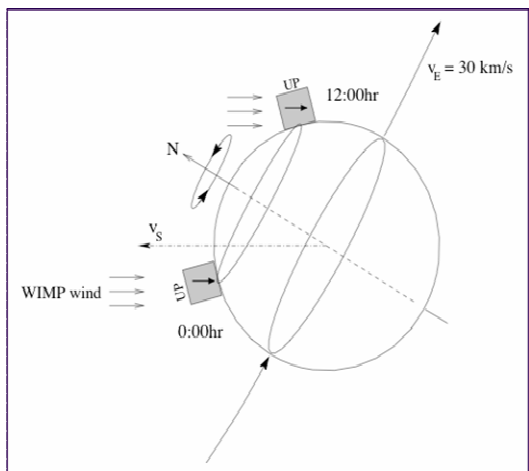
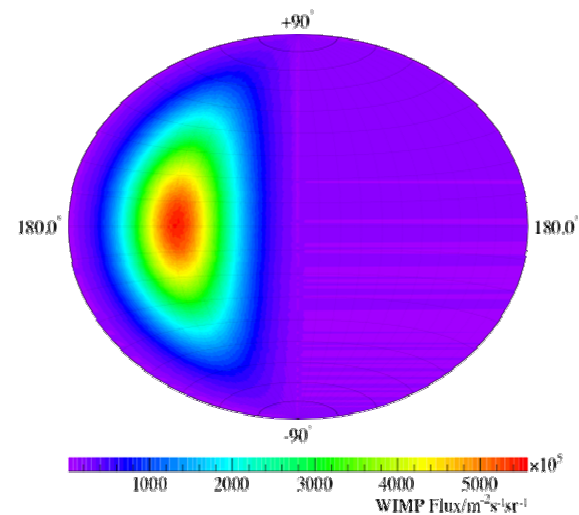
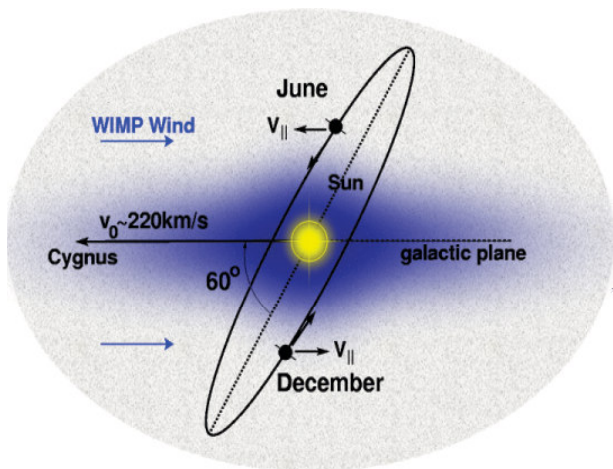


Direct Detection of WIMPS

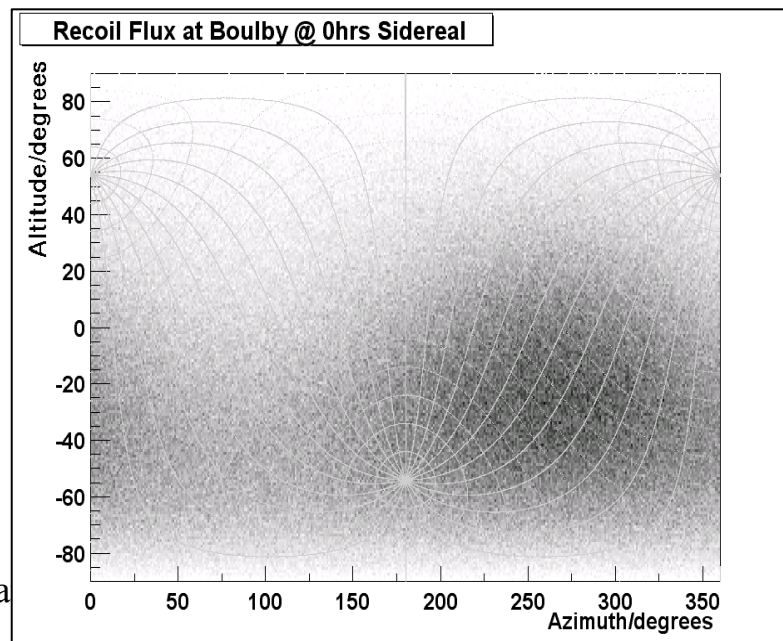


Typical detectable recoil energy of the target atom in the region 10
 $\square \div 100 \text{ keV}$

Directional Effects



R.Cashmore



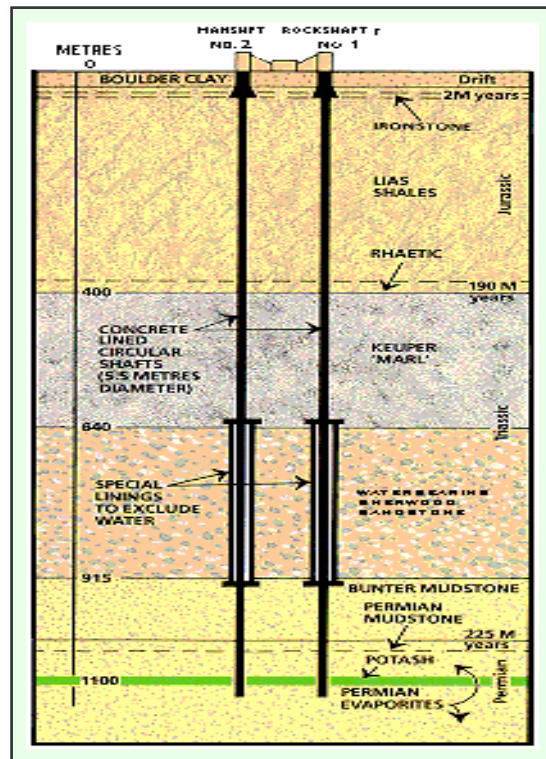
Da

Low Backgrounds Needed

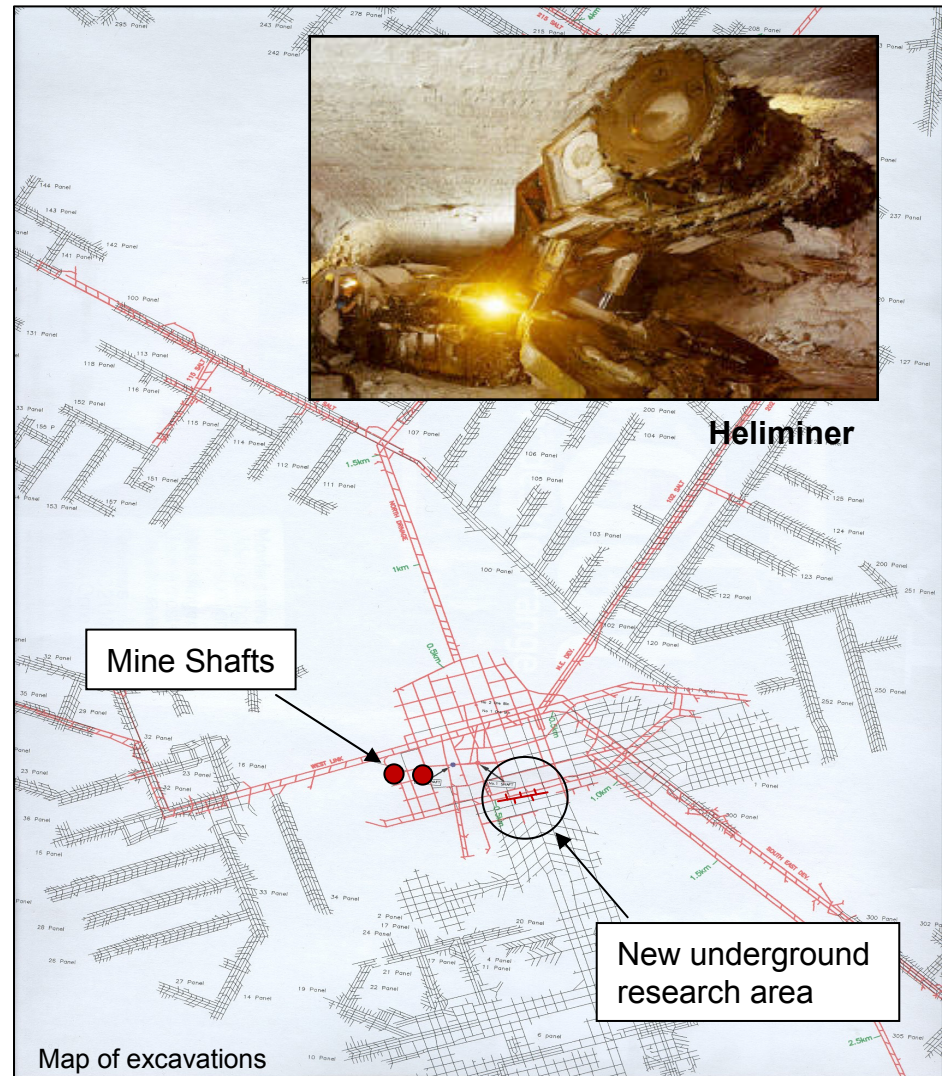
- Deep Underground mines,tunnels
 - Cut out cosmic rays
- Complete shieldingactive and passive
 - Cut out electrons,gammas,neutrons
 - radioactivity

The Mine

Geology



R.Cashmore



Dark Matter 2

6

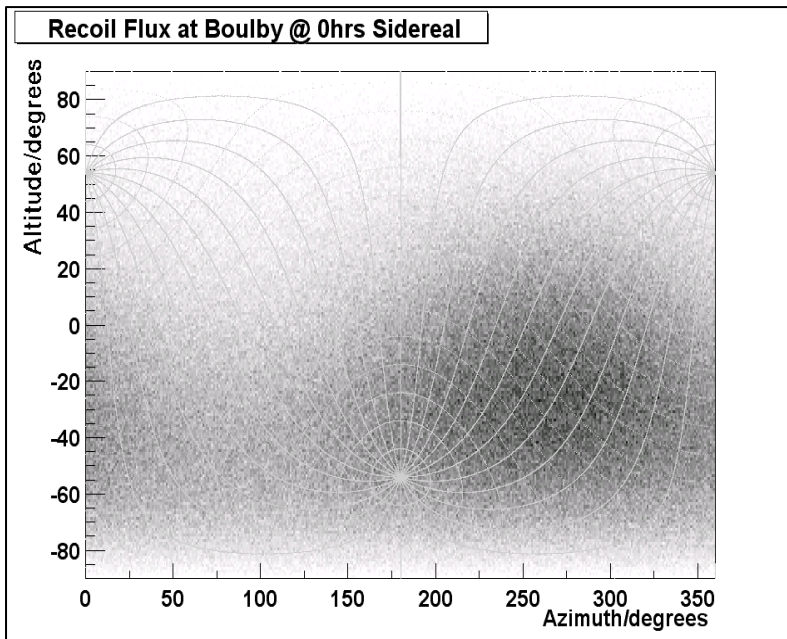
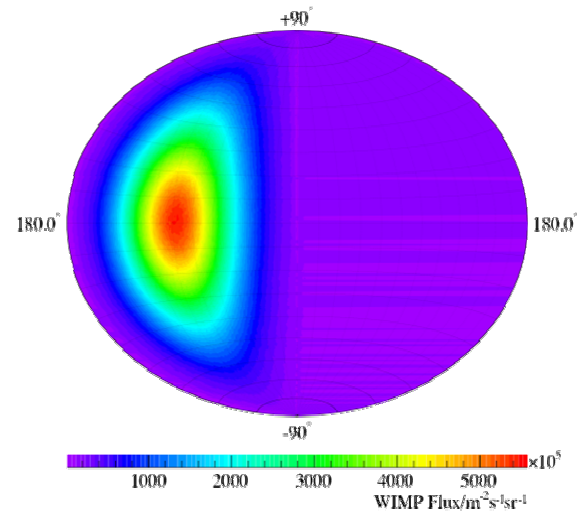
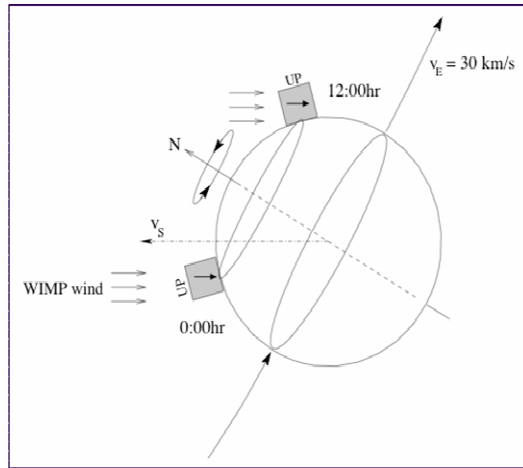
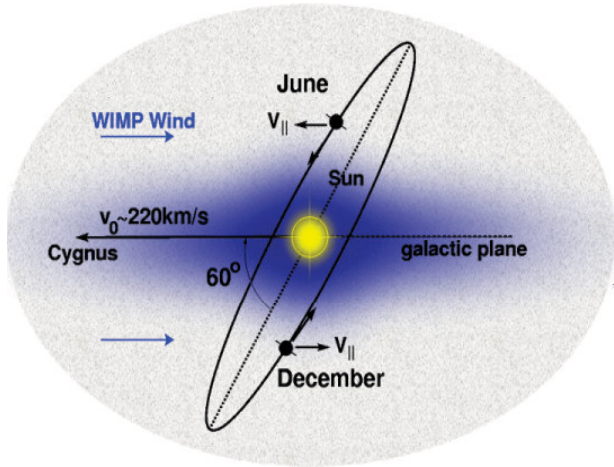
Gran Sasso Laboratory



Other Mines SOUDAN in Minnesota ...

Other tunnels FREJUS,Canfranc

DRIFT



Dark Matter 2

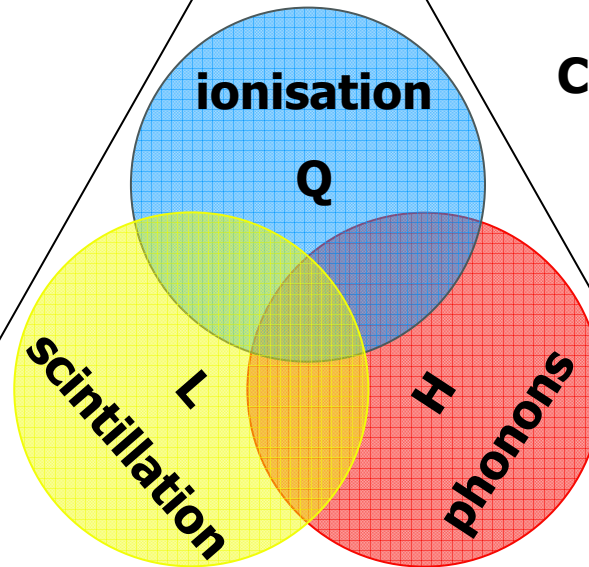
WIMP elastic nuclear recoils deposit $< 100\text{keV}$ of energy at a rate 10^{-5} to 1 event/day/kg

**IGEX,
DRIFTI, II**

\Rightarrow phonons, photons and charge whose relative proportions and /or characteristics depend on $dE/dx \Rightarrow$ particle type

**ZEPLIN II, III, MAX,
XENON**

CDMS, EDELWEISS



**NAIAD, ZEPLIN I,
DAMA**

CRESST I

**CRESST II,
ROSEBUD**

World **competition** is intense and uses a wide range of **complementary** techniques

Event-by-event particle identification requires compound information

Dark Matter 2

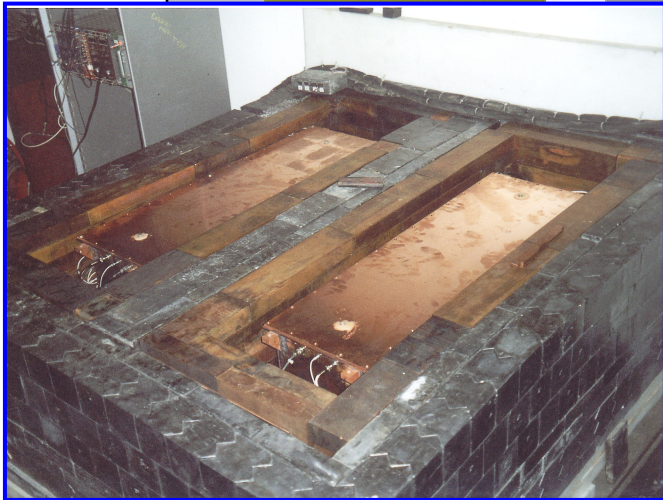
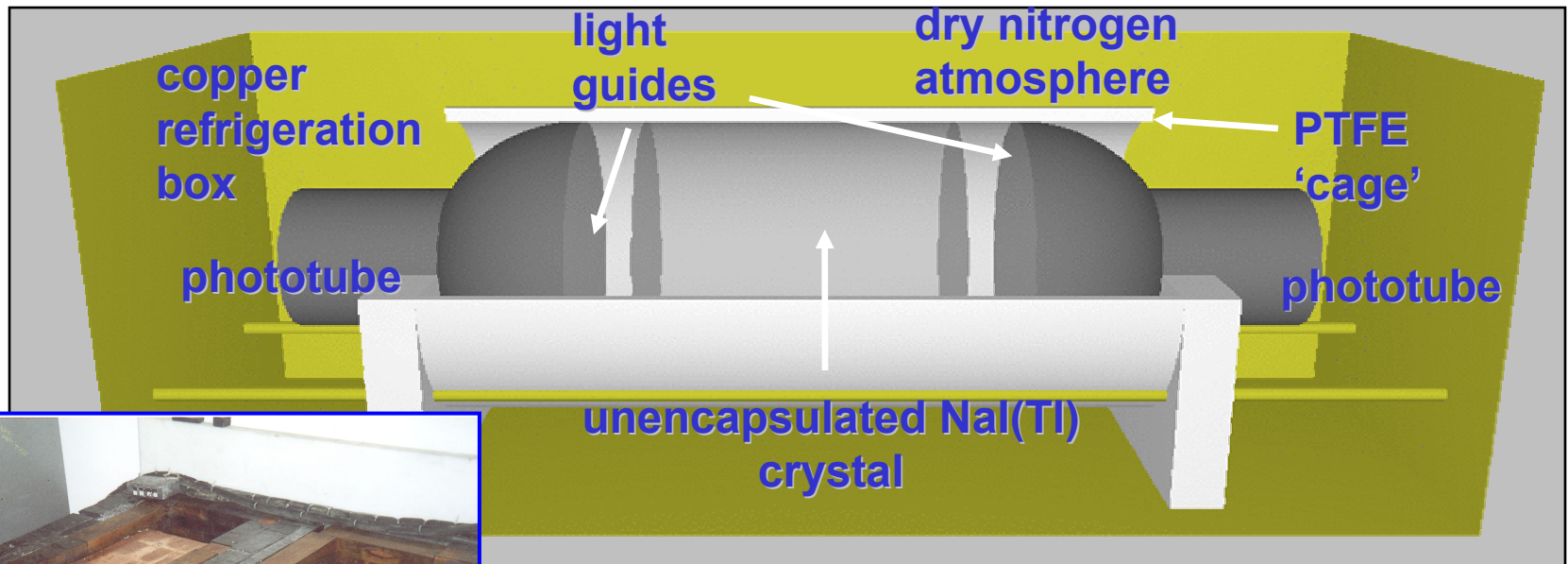
R. Cashmore

Some Completed Experiments

- DAMA
- NaIAD
- Xenon in ZEPLIN1

As Examples

NaIAD



Scintillation from unshielded NaI crystal, viewed by 2 PMTs

NaIAD array consists of 7 such detectors

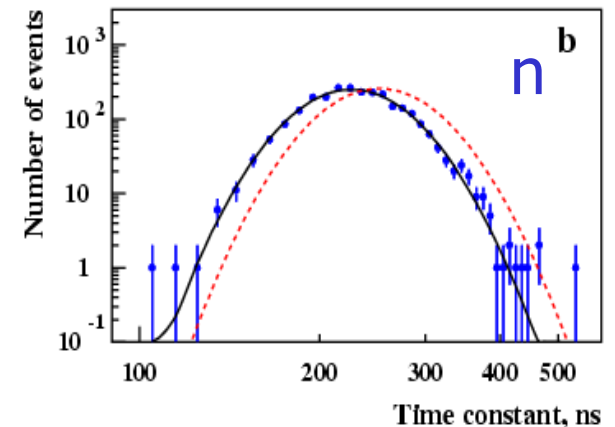
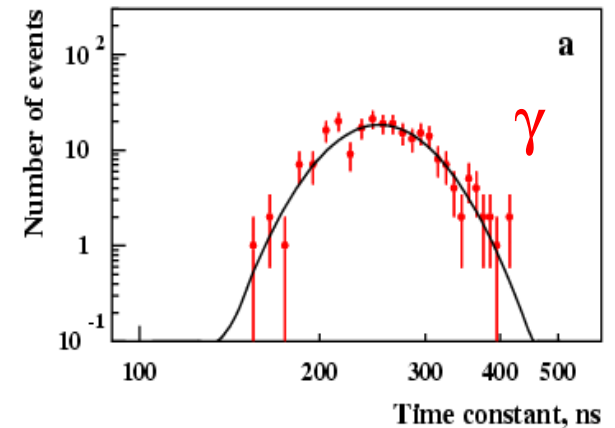
NaIAD: Discrimination



Distributions of fitted time constant against number of events (TCD) for the energy range 6-7 keV.

Top: TCD for electron recoils from gamma source.

Bottom: TCD for nuclear recoils from neutron source (dotted line shows fit from top graph).



Status of the art in the field

Short summary of the DAMA/NaI *Model Independent* result:

(data taking completed on July 2002; still producing physical results)

- Presence of modulation over 7 annual cycles at $\sim 6.3\sigma$ CL with the proper distinctive features for a CDM particle induced effect
- The deep investigation has shown absence of known sources of possible systematics and side processes able to account for the observed effect
- All the signature features satisfied by the data over 7 independent experiments of 1 year each one



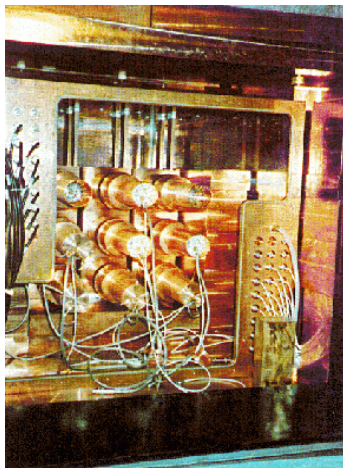
Performances: N.Cim.A112(1999)545-575, EPJC18(2000)283, Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127

Results on rare processes:

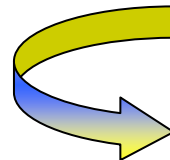
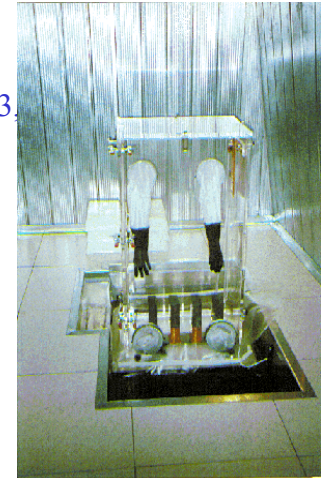
PLB408(1997)439, PRC60(1999)065501, PLB460(1999)235, PRL83(1999)4918, PLB515(2001)6, EPJdirect C14(2002)1, EPJA23(2005)7, EPJA24(2005)51

Results on Dark Matter particles:

PLB389(1996)757, N.Cim.A112(1999)1541, PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJ C18(2000)283, PLB509(2001)197, EPJ C23(2002)61, PRD66(2002)043503, Riv. N. Cim. 26 n.1 (2003)1-73, IJMPD13(2004)2127, ROM2F/2005/19



R.Cashmore



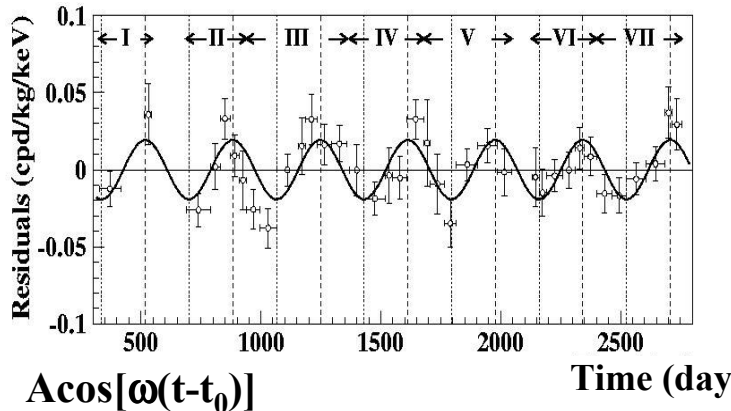
Dark Matter 2

corollary quest for a candidate

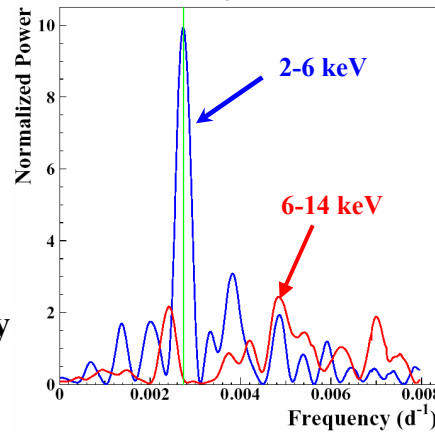
Final model independent result by DAMA/NaI

total exposure about $1.1 \times 10^5 \text{ kg}\times\text{d}$

Experimental residual rate of the single hit events in 2-6 keV over 7 annual cycles

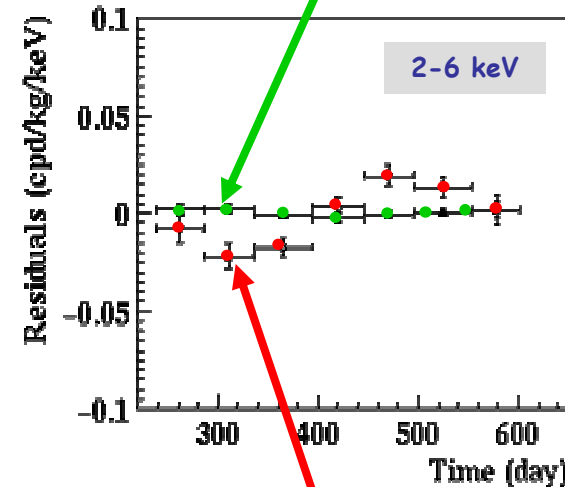


Power spectrum



Principal mode
 $\rightarrow 2.737 \cdot 10^{-3} \text{ d}^{-1} \approx 1 \text{ y}^{-1}$

experimental residual rate of the multiple hit events (DAMA/NaI-6 and 7) in the 2-6 keV energy interval: $A = -(3.9 \pm 7.9) \cdot 10^{-4} \text{ cpd/kg/keV}$



experimental residual rate of the single hit events (DAMA/NaI-1 to 7) in the 2-6 keV energy interval: $A = (0.0195 \pm 0.0031) \text{ cpd/kg/keV}$

$\text{Acos}[\omega(t-t_0)]$
 $P(A=0) = 7 \cdot 10^{-4}$
 Continuous line:
 $t_0 = 152.5 \text{ days}$, $T = 1.00 \text{ years}$
 from the fit:
 $A = (0.0192 \pm 0.0031) \text{ cpd/kg/keV}$

from the fit with all the parameters free:

$A = (0.0200 \pm 0.0032) \text{ cpd/kg/keV}$
 $t_0 = (140 \pm 22) \text{ d}$
 $T = (1.00 \pm 0.01) \text{ y}$

All the peculiarities of the signature satisfied

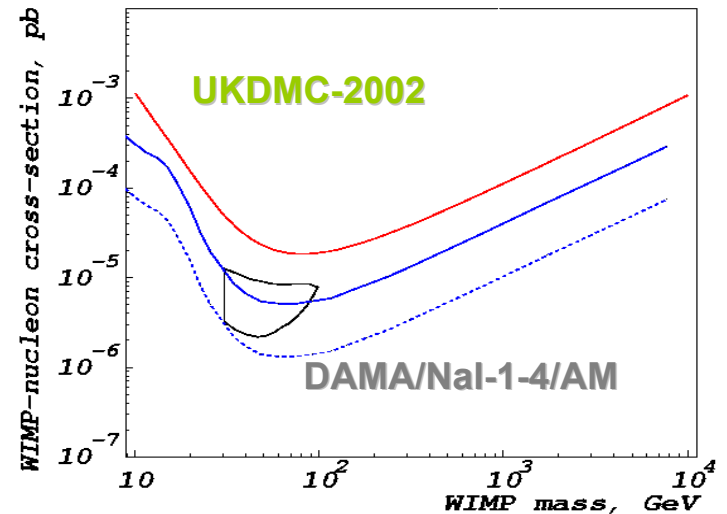
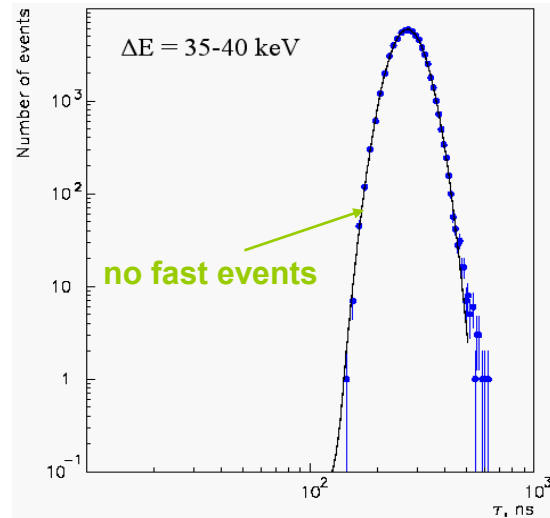
Multiple hits events = Dark Matter particle "switched off"

No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

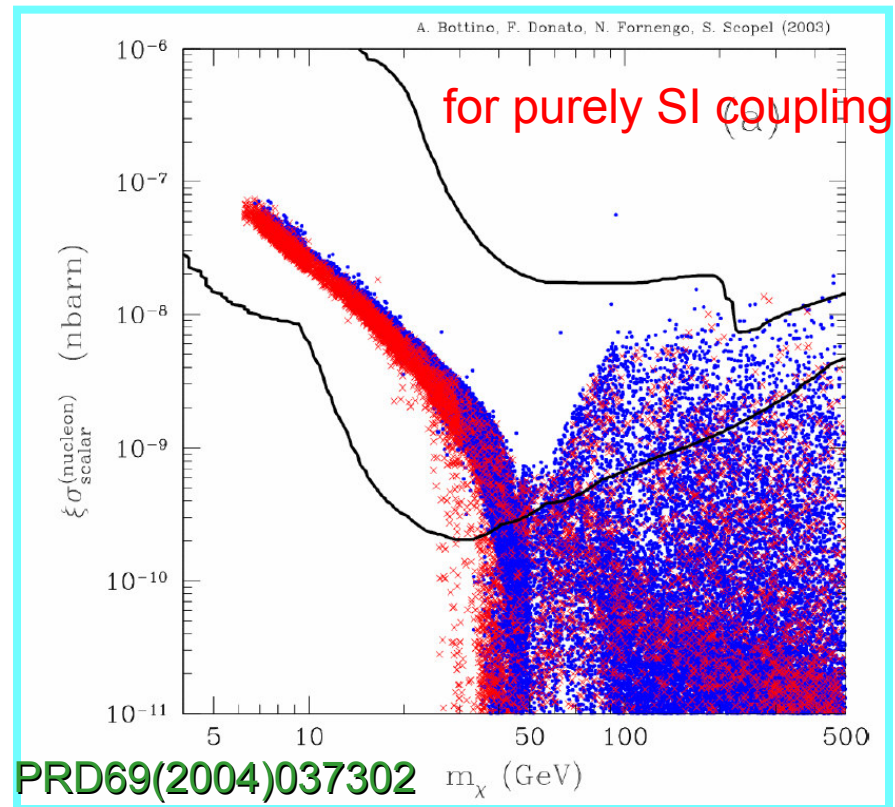
model independent evidence of a particle Dark Matter component in the galactic halo at 6.3σ C.L.

NaIAD Results

- Pulse shape discrimination:
 - Data consistent with known n-flux.
- Compare to DAMA collaboration
- DAMA report a *signal!*
 - Controversial!!!
 - Based on seeing an annual modulation of the signal in the expected region.
No pulse shape analysis
- Programme completed – focus on more promising technologies



Supersymmetric expectations in MSSM



When releasing the gaugino mass unification at GUT scale: $M_1/M_2 \neq 0.5$ (\checkmark);
(where M_1 and M_2 U(1) and SU(2) gaugino masses) low mass configurations are obtained

FAQ:

... DAMA/NaI "excluded" by CDMS-II (and others)?

OBVIOUSLY NO

They give a single model dependent result using ^{nat}Ge target

DAMA/NaI gives a model independent result using ^{23}Na and ^{127}I targets

No direct model independent comparison possible

Even taking their results on marginal exposure as they present... (e.g. systematic error in all the used procedures, etc.):

• In general? **OBVIOUSLY NO**

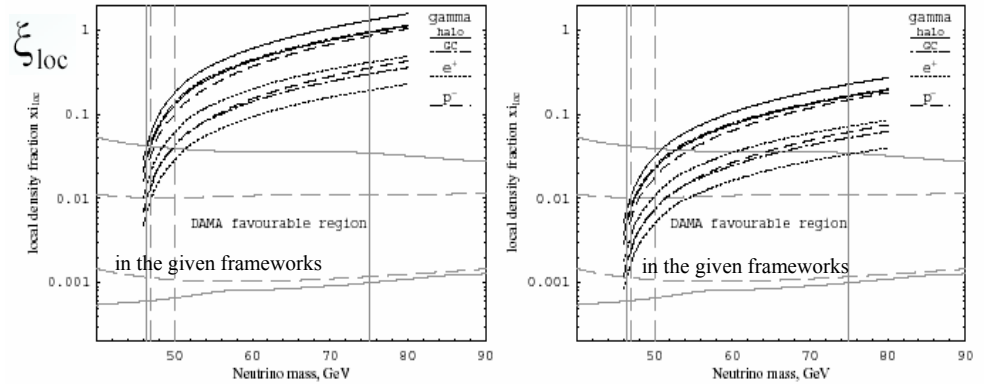
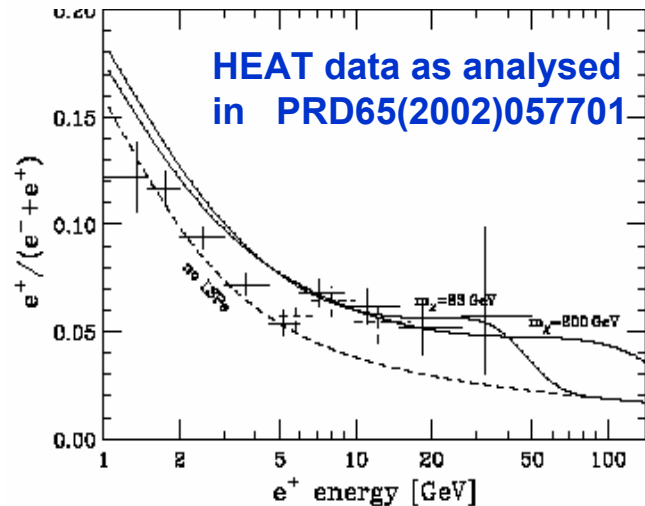
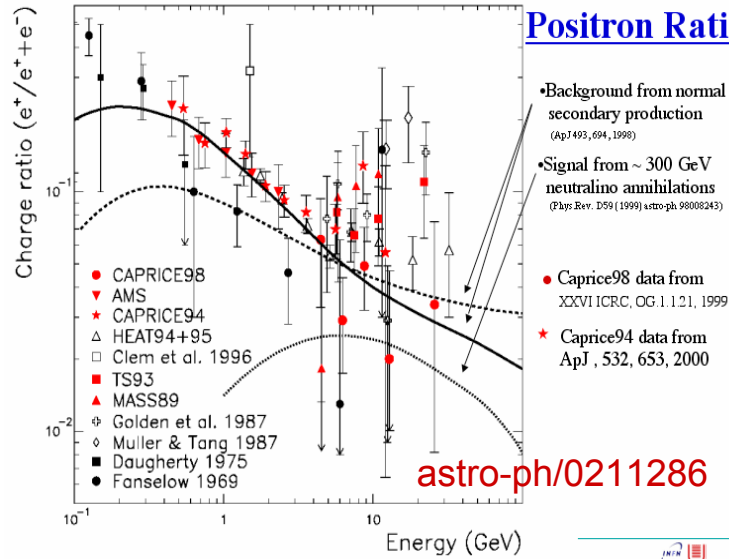
The different sensitivities to the various kinds of candidates, interactions and particle mass, the accounting for realistic and consistent halo models and accounting for existing parameters uncertainties, FFs and/or SF and existing uncertainties on related parameters, different scaling laws than assumed (possible even for the neutralino candidate), their proper accounting for experimental parameters and related uncertainties, the many possible scenarios, etc. fully "decouple" the results.

• At least in the purely SI coupling they only consider? **OBVIOUSLY NO**

they give a single result fixing all the astrophysical, nuclear and particle physics assumptions and all the expt. and theor. parameters values....; moreover, they usually quote in an uncorrect, partial and unupdated way the implications of the DAMA/NaI model independent result...; see above, etc.

Hints from indirect searches and not in conflict with DAMA/NaI for the WIMP class candidate

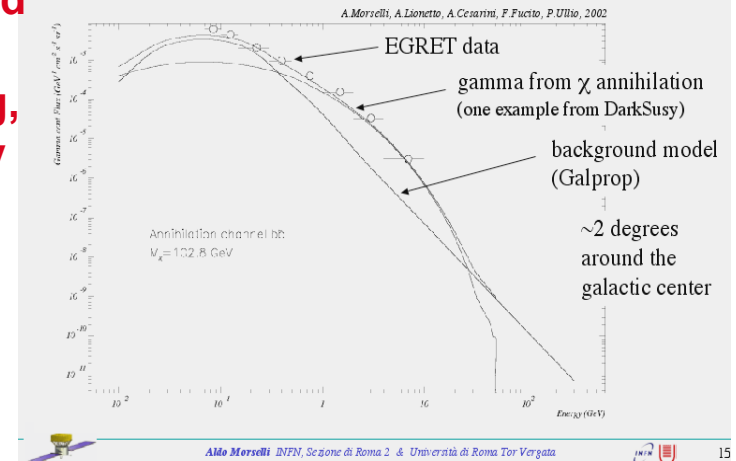
Some measurements performed by indirect search experiments have pointed out the presence of antiparticles and photons which could be ascribed to some classes of Cold Dark Matter particles annihilating in the halo



v's of 4th family

interpretation, evidence itself, derived M_{DM} and cross section depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.

EGRET data & Susy models



Dark Matter 2 In next years new data from DAMA/LIBRA and for indirect searches from Agile, Glast, Ams2, Pamela, ...

...many possible Dark Matter Particle candidates (+ multicomponent?):

WIMP class:

Detection by elastic scattering on nuclei:

Spin Independent coupling,
Spin Dependent coupling,
SI&SD mixed coupling,

(Riv. N. Cim. 26 n.1. (2003) 1-73
IJMPD 13 (2004) 2127)

Ex: Lightest Susy Particle as neutralino,
heavy 4-family neutrino, etc..

Detection by preferred inelastic scattering:

Ex: sneutrino Smith & Weiner

(hep-ph/0101138)

WIMP-like class (different particles with “similar” phenomenologies):

Subdominant heavy 4th neutrino and sterile dominant component

(see the analysis including the results of the indirect search in

hep-ph/0411093)

Lightest Kaluza Klein Particle,

hep-ph/0209262

Self Interacting Dark Matter Particle: (SIMP + SIDM model)

astro-ph/0409121

Mirror Dark Matter,

hep-ph/0308254

etc...

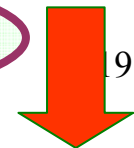
... every case within its features and uncertainties ...

& **BOSONIC** class (axion-like, Majoron, sgoldstino, familon, pseudo-Nambu-Goldstone bosons, Kaluza Klein axions, etc) : very different detection processes and phenomenologies

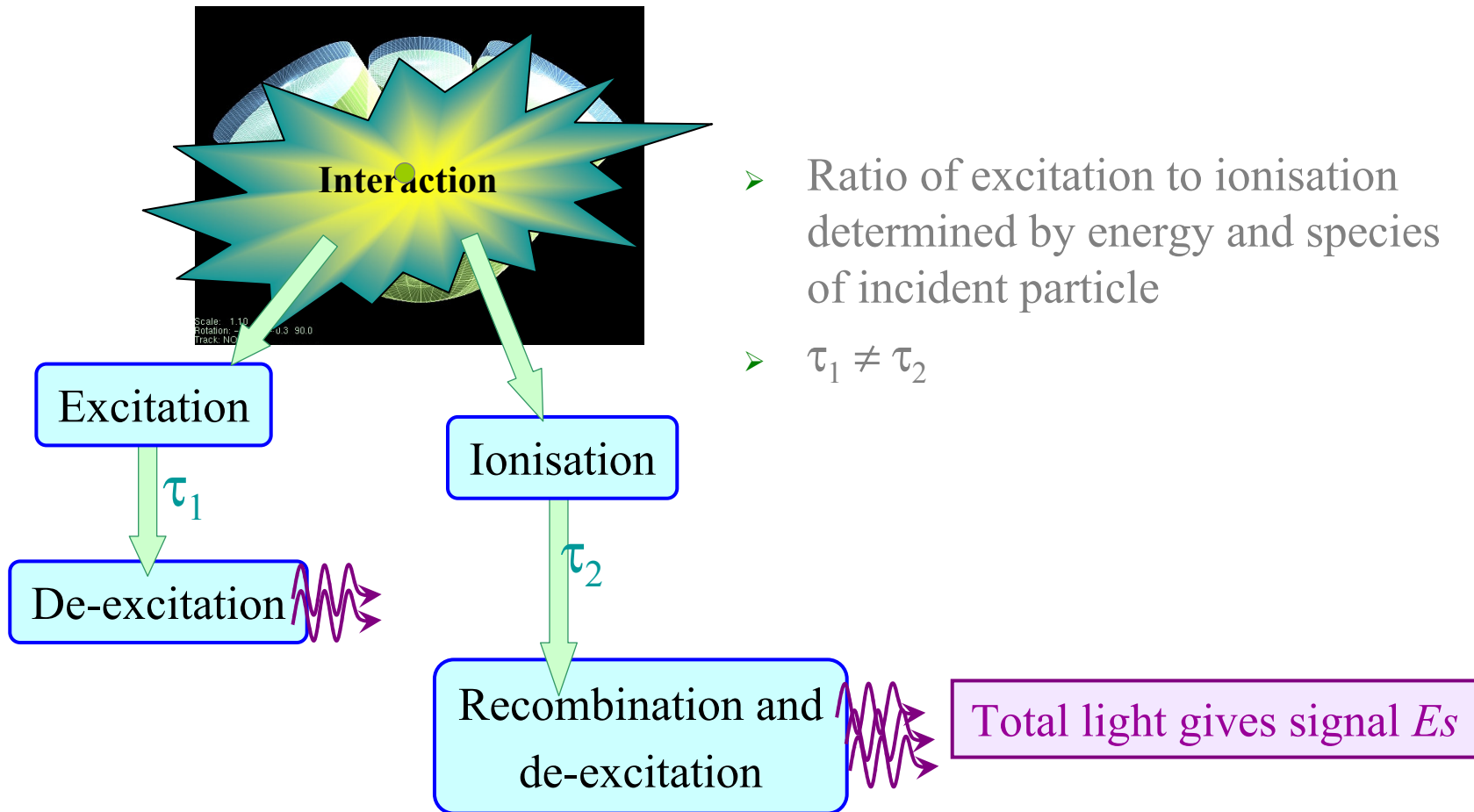
R. Casimiro

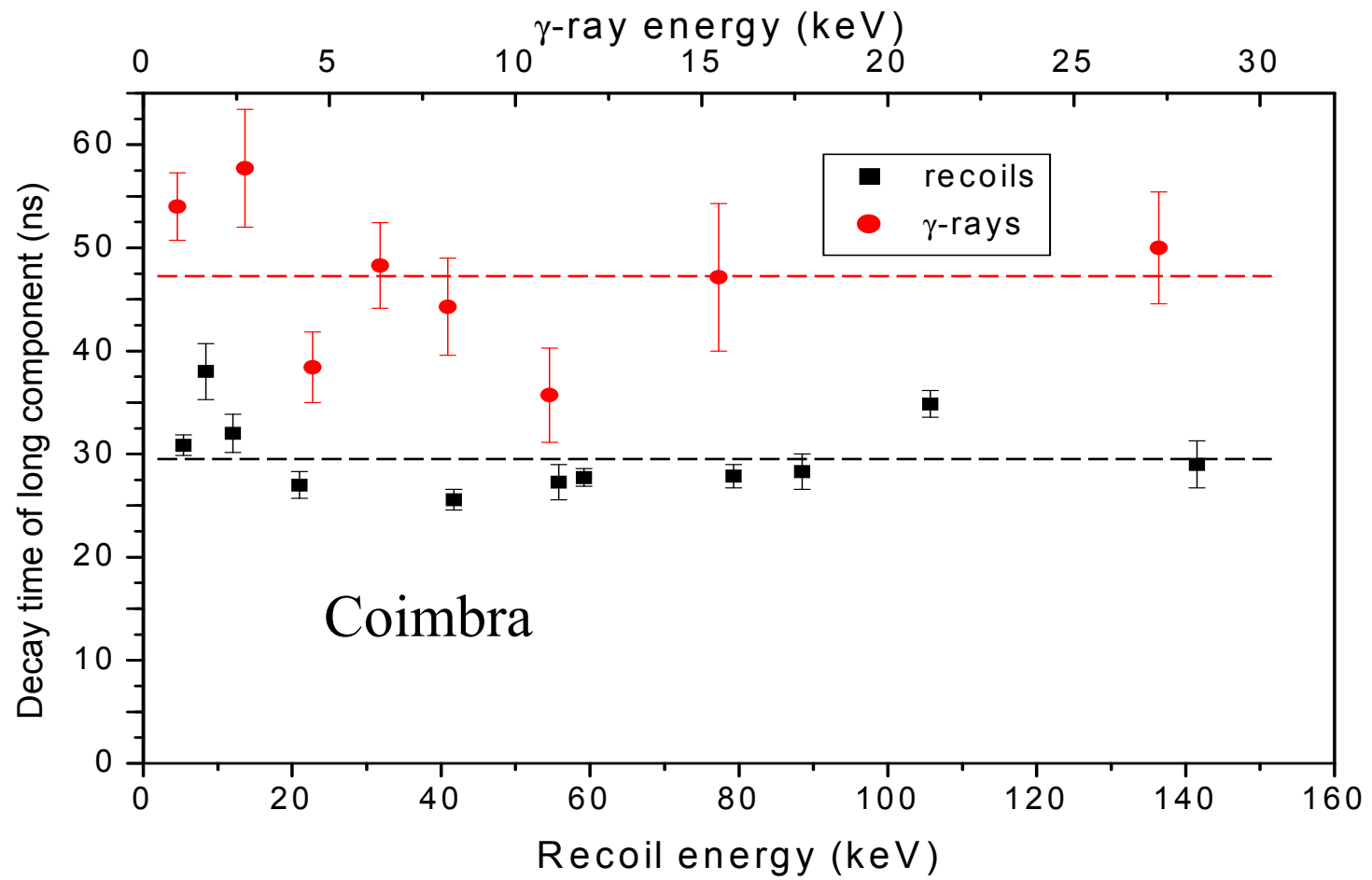
Dark Matter 2

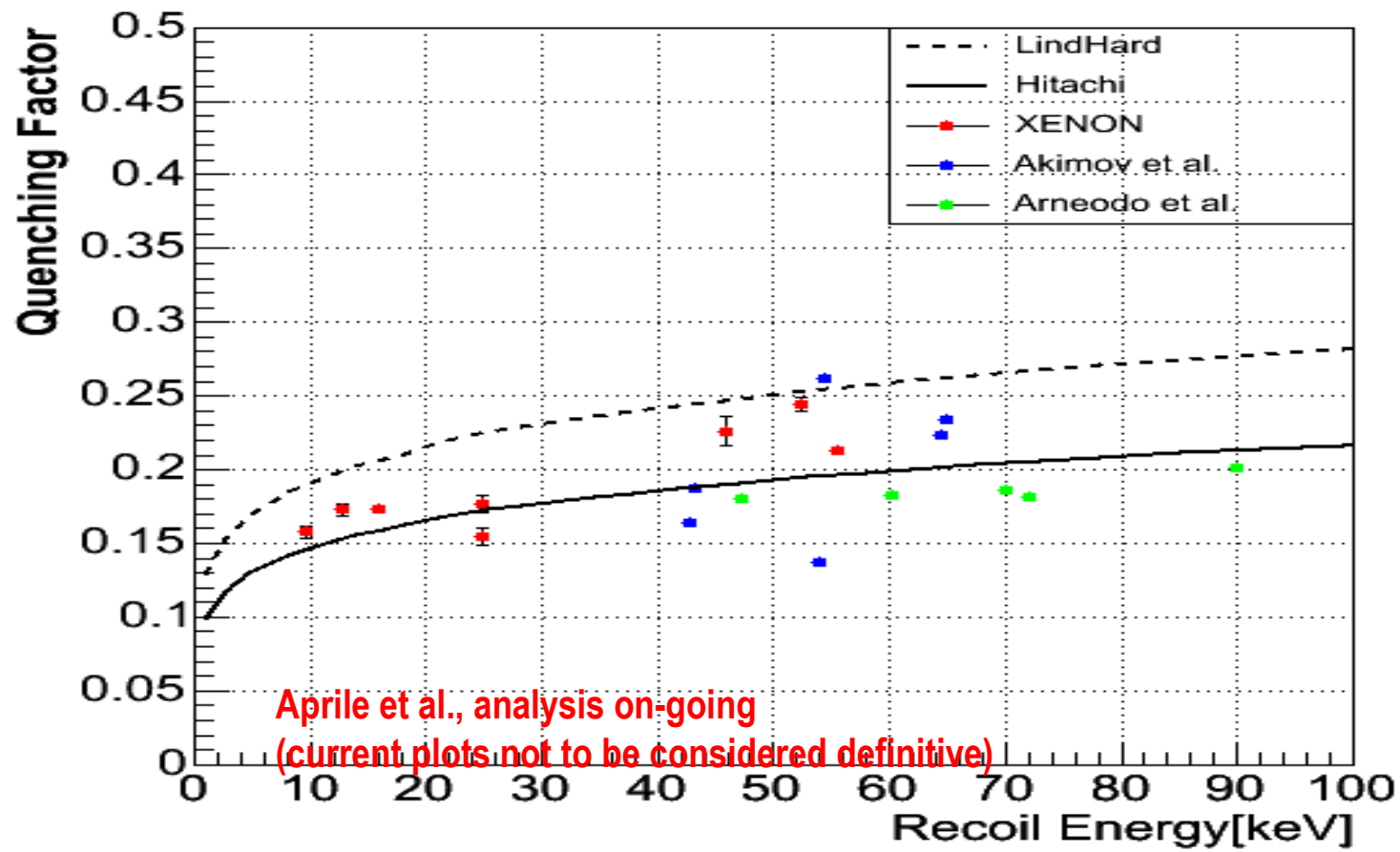
9



Liquid Xenon strategy



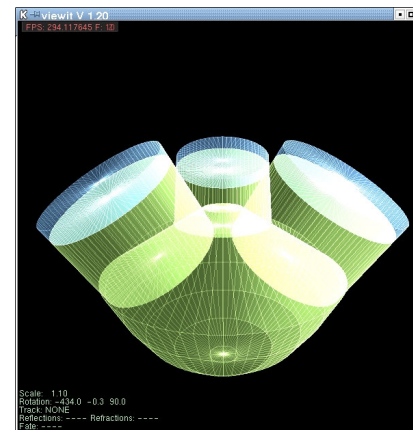
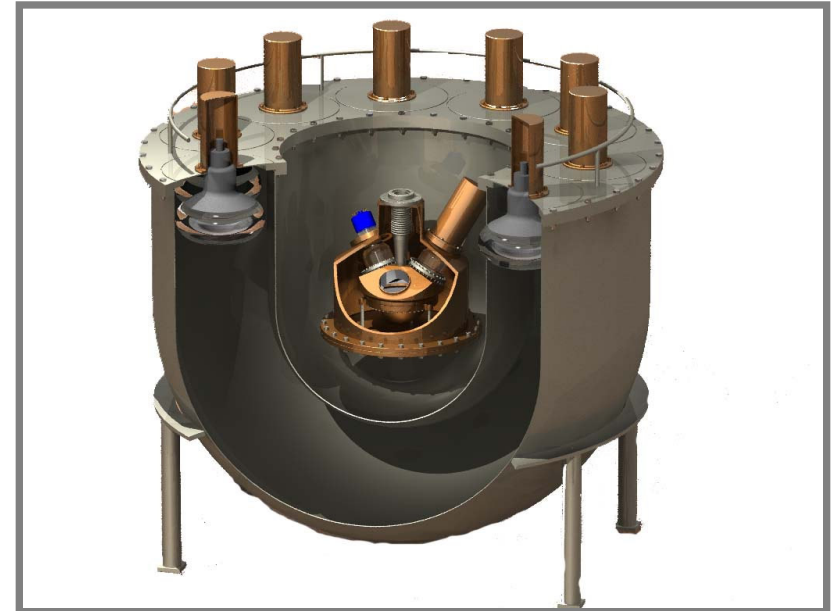




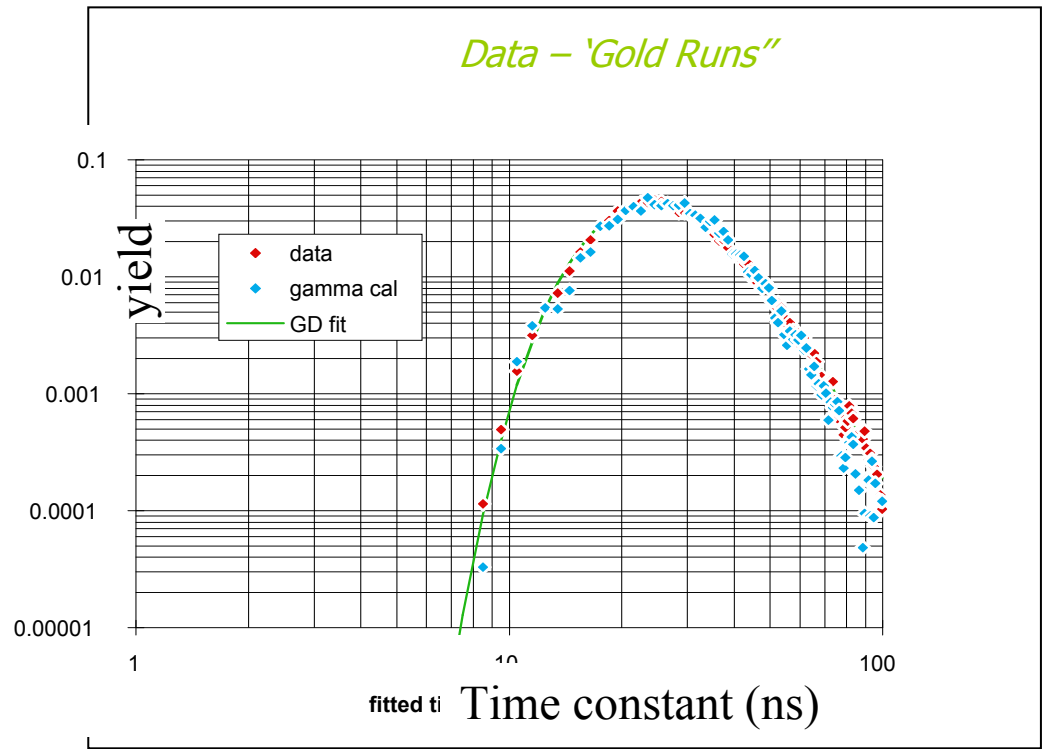
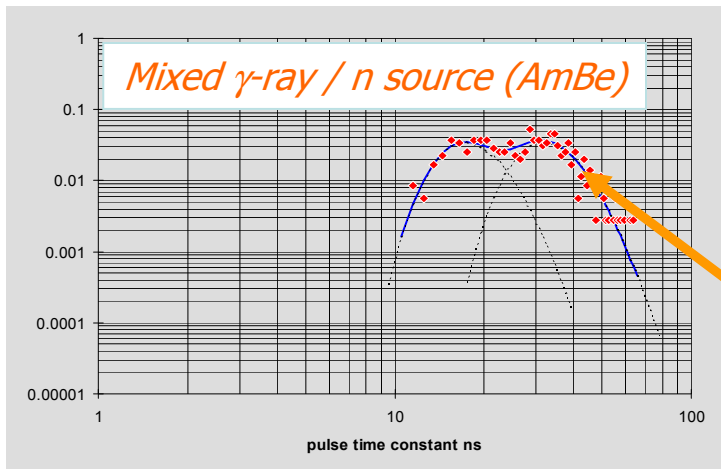
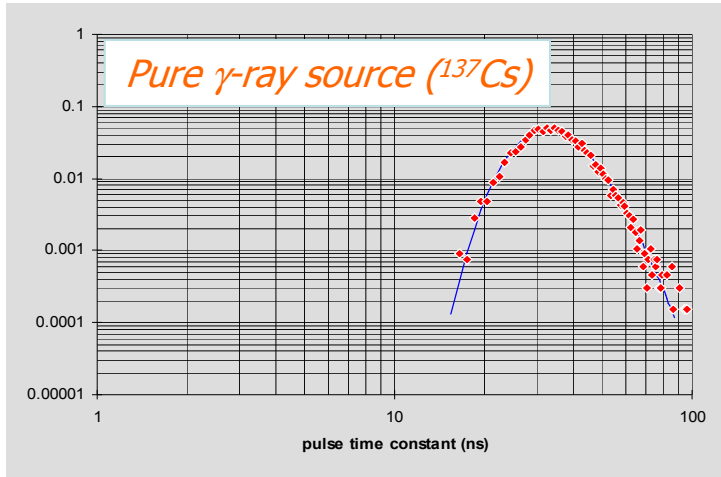
Zeplin I

Liquid Xenon

- Very pure
 - 3.1 kg fiducial volume
 - No long lived radionuclides
 - Available in large quantities
- Single phase (scintillation signal)
- ^{129}Xe : $\sigma_{\text{WIMP-Nucleon}} \propto A^2$
- Cryogenic: Low noise
- Good discrimination
- 30 cm wide U-shaped Compton veto



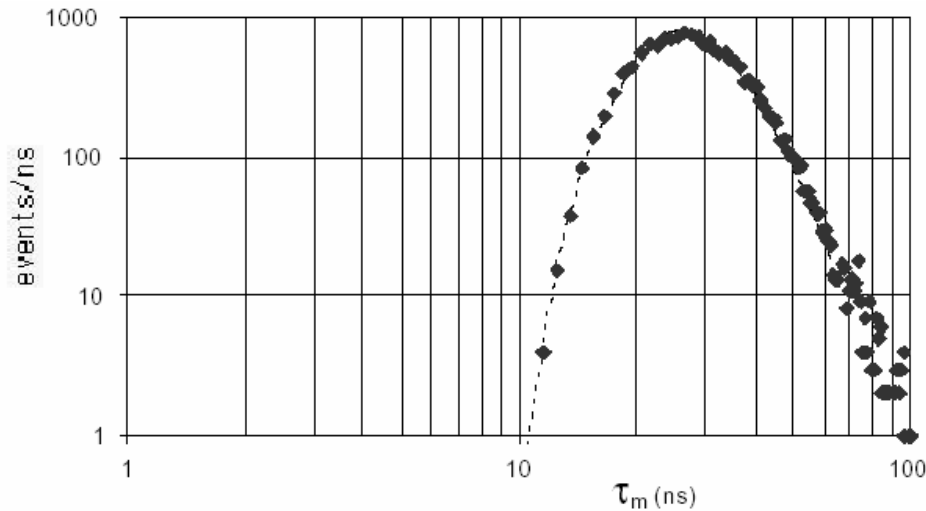
Zeplin I - Results



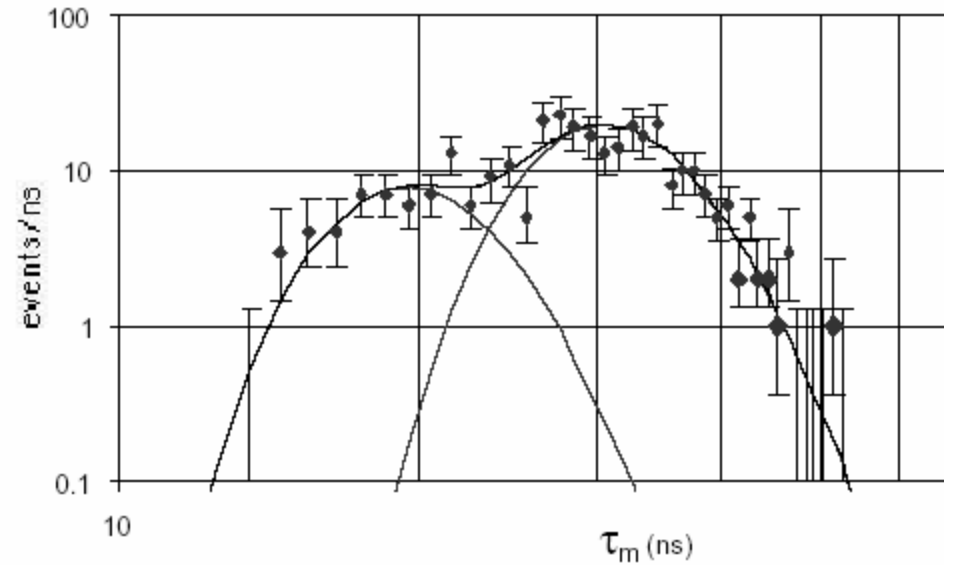
Better separation than NaI

Current ZEPLIN I Status

- Experiment is completed and final results paper is published
- Used pulse shape discrimination in scintillation channel to identify nuclear recoil candidate events
- No evidence of WIMP signals \Rightarrow upper limit



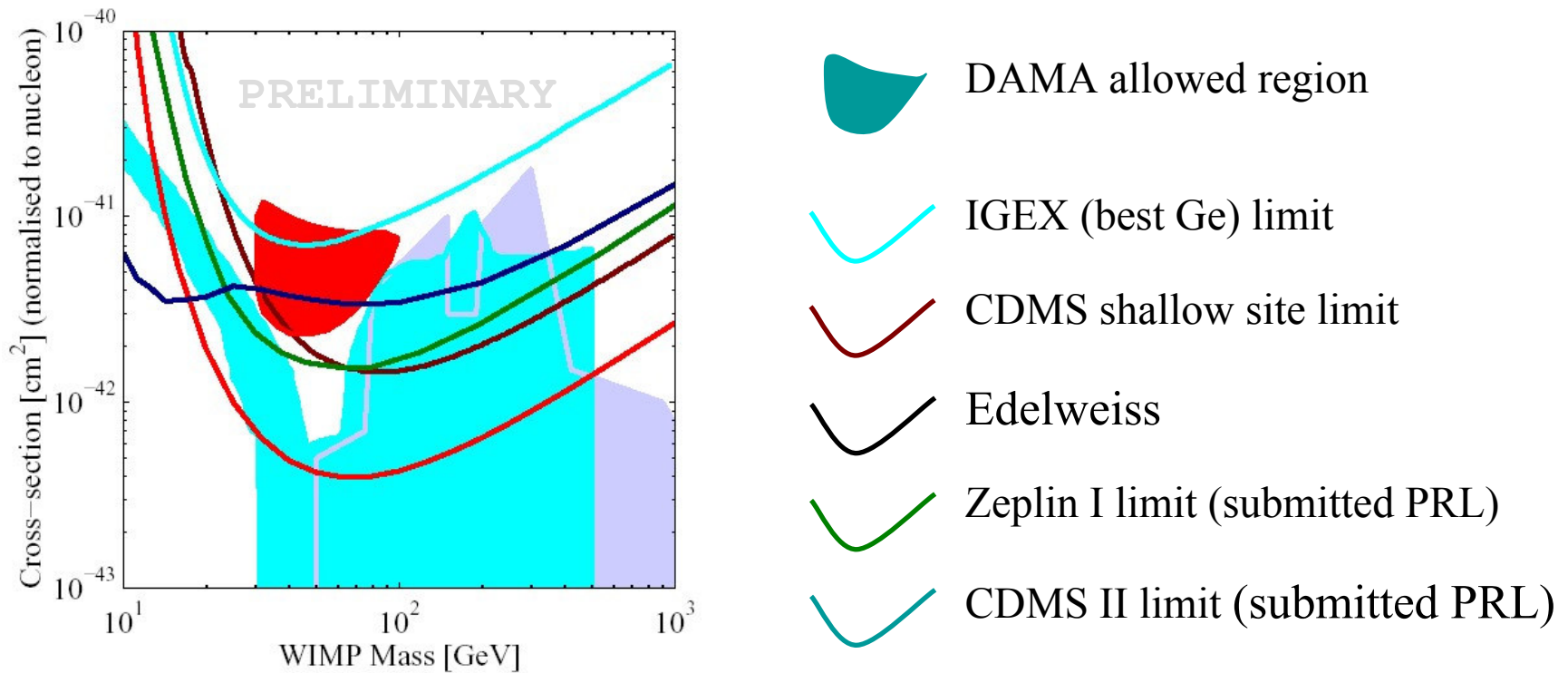
Underground data with gamma fit
R. Cash, *Dark Matter 2*
7-10 keV



Laboratory data from AmBe
20-30keV

Zeplin I Results

- Current world limits (*'Spin independent analysis'*)



World Status

- Comparison between experiments made using a 'standard' Galaxy model
- Separated into spin-independent (scalar) cross-sections and spin-dependent (axial) cross-sections and normalised to one nucleon

Spin independent

DAMA

IGEX

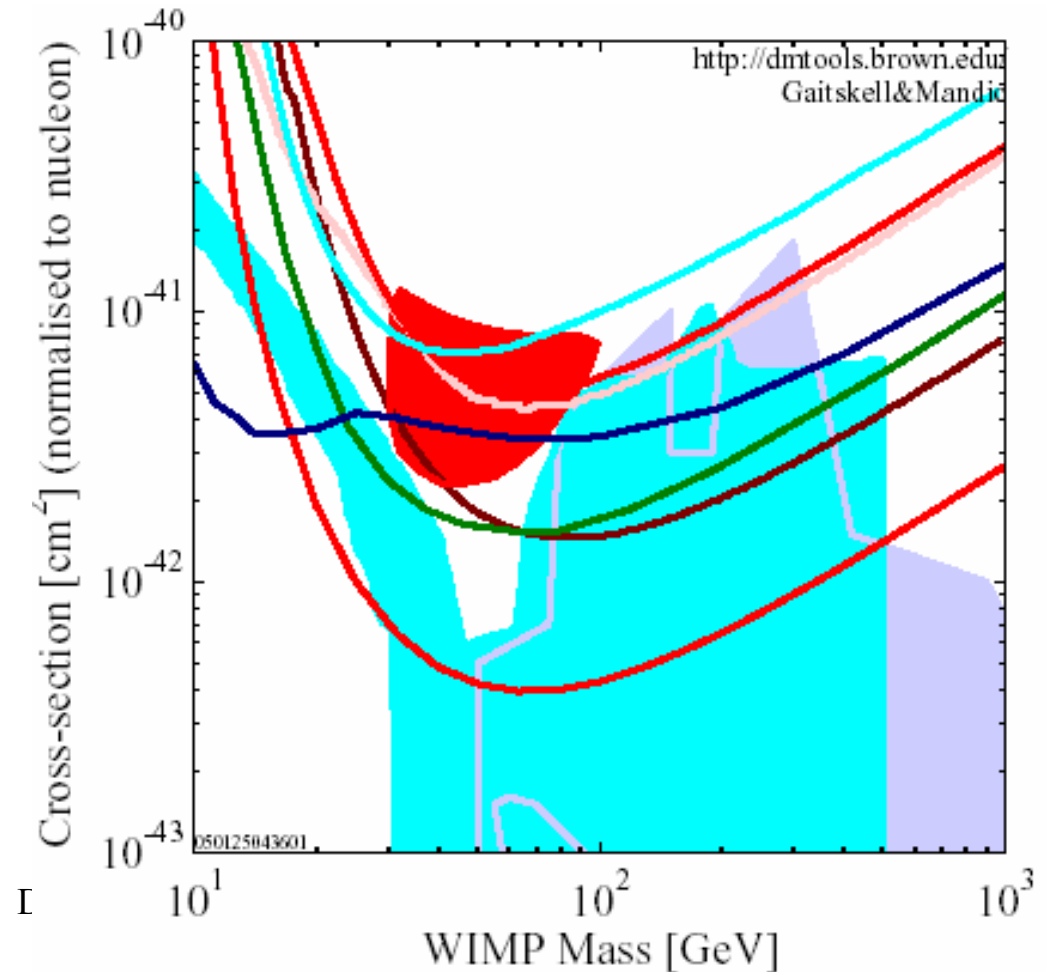
CRESST II

CDMS I

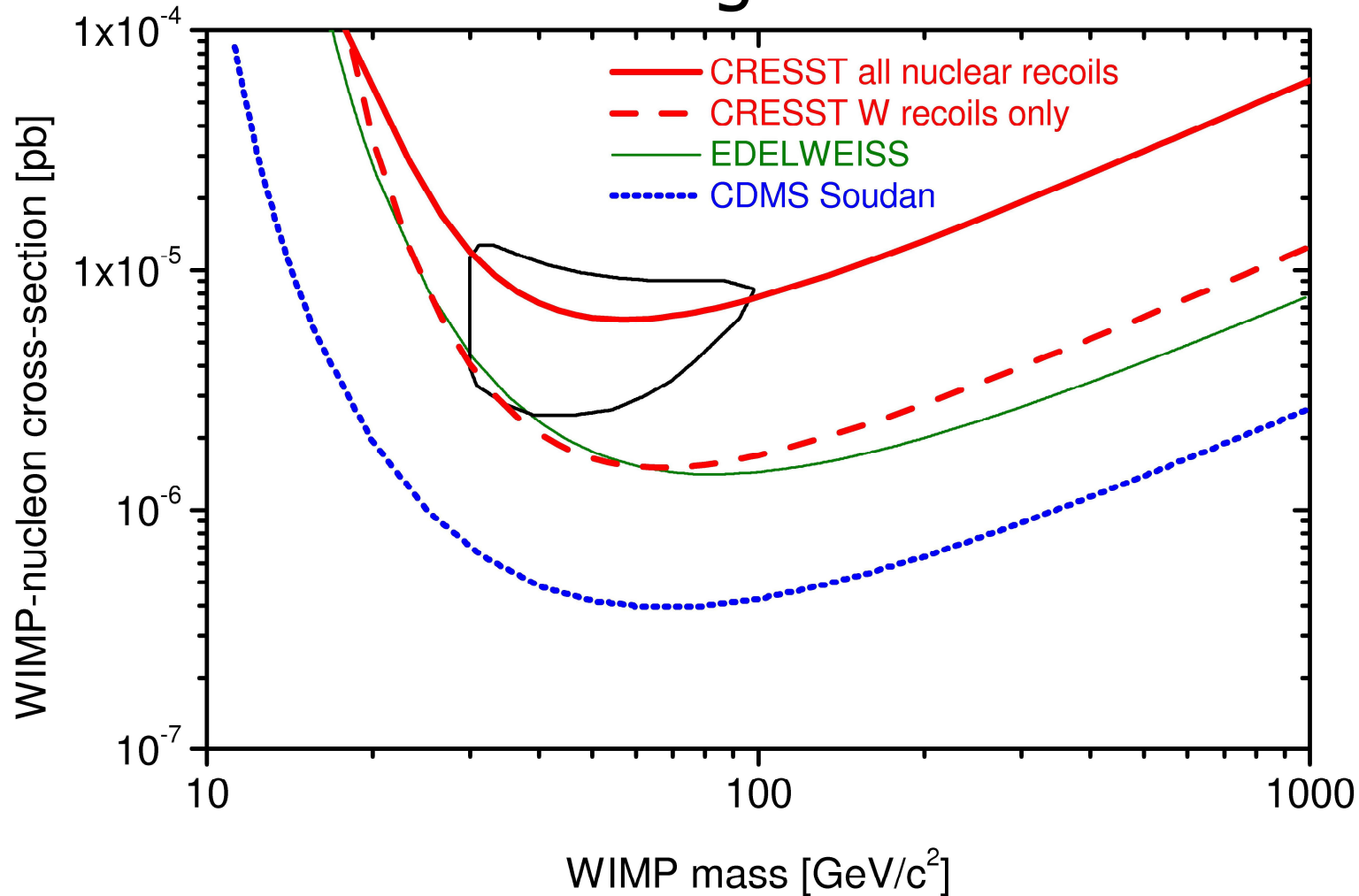
EDELWEISS

ZEPLIN I

CDMS II



Upper limit for spin independent WIMP nucleon scattering cross section

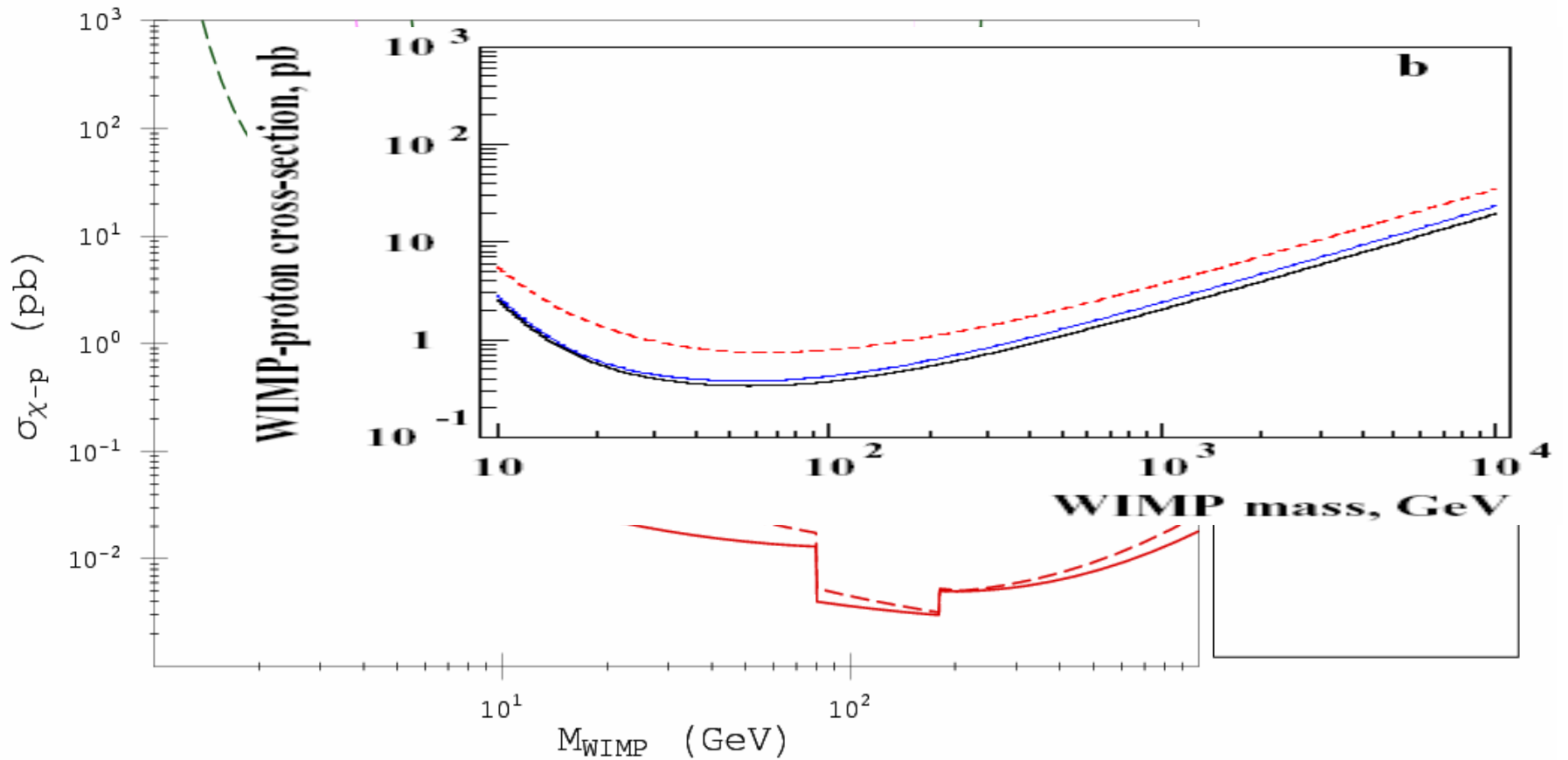


Astropart. Phys. 23 (2005) 325-339

World Status

Spin dependent

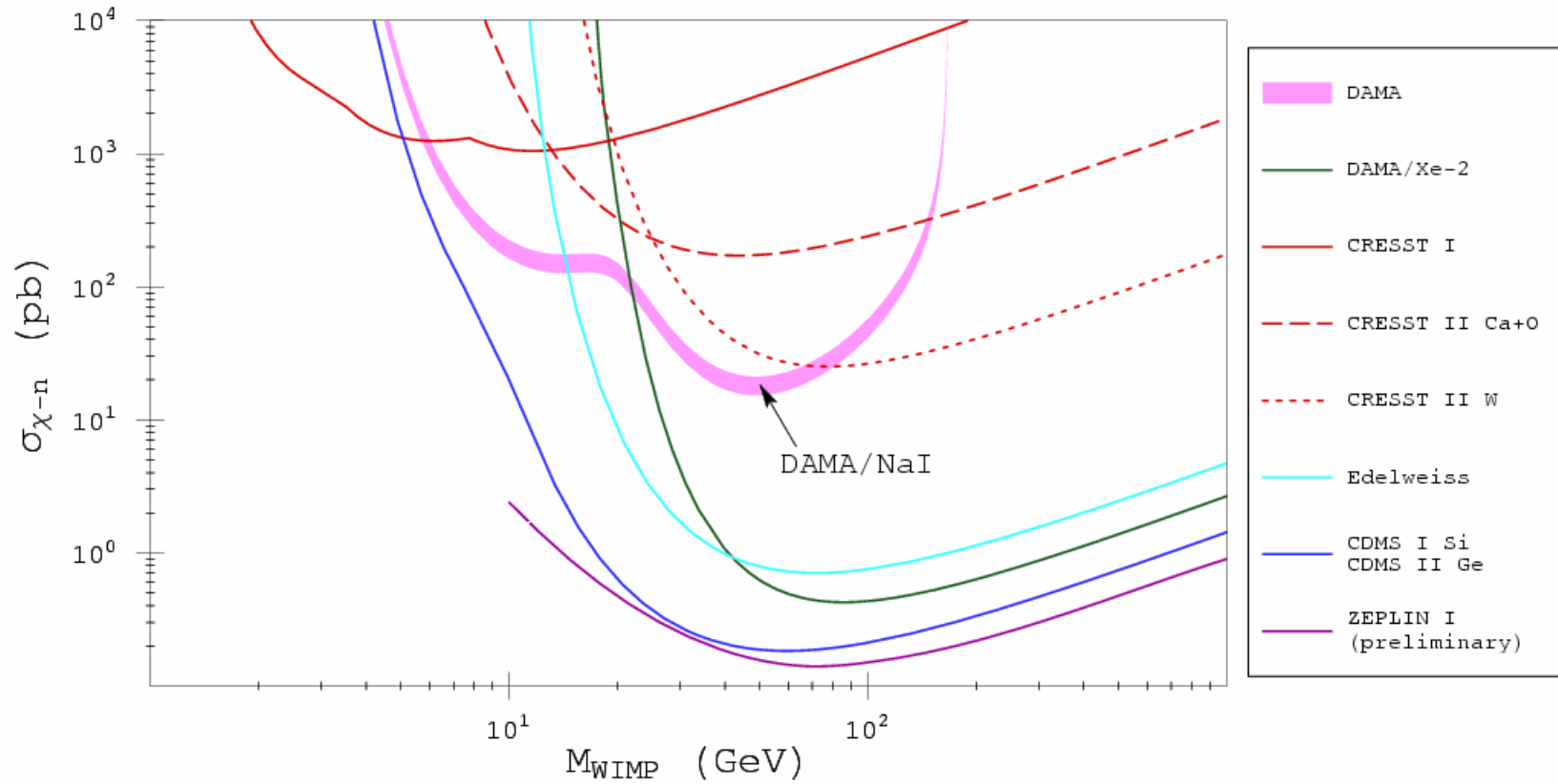
(a) Coupling to unpaired proton



World Status

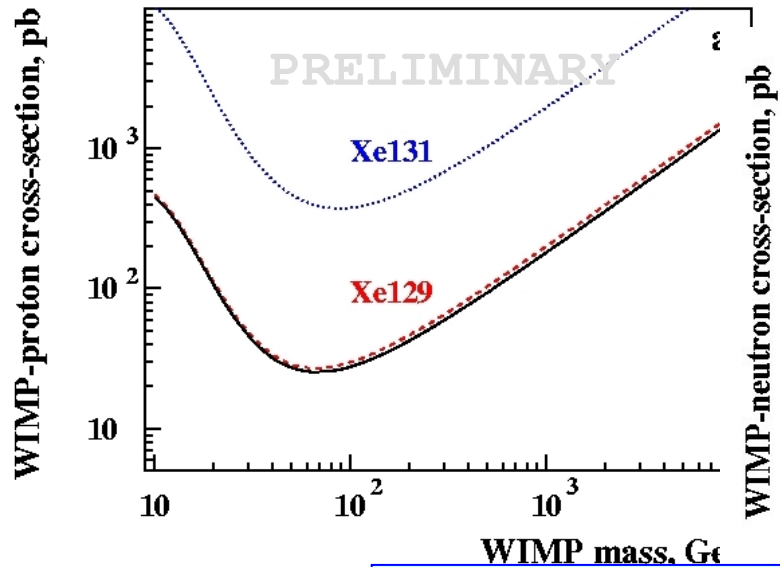
Spin dependent

(a) Coupling to unpaired neutron



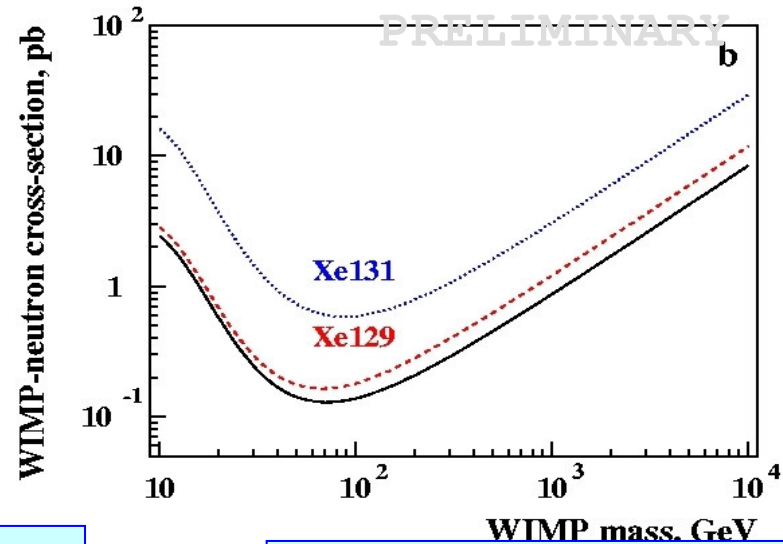
Zeplin I – Spin *dependent* limits

WIMP-proton interactions



NAIAD still better

WIMP-neutron interactions



The world best limits (by x100)

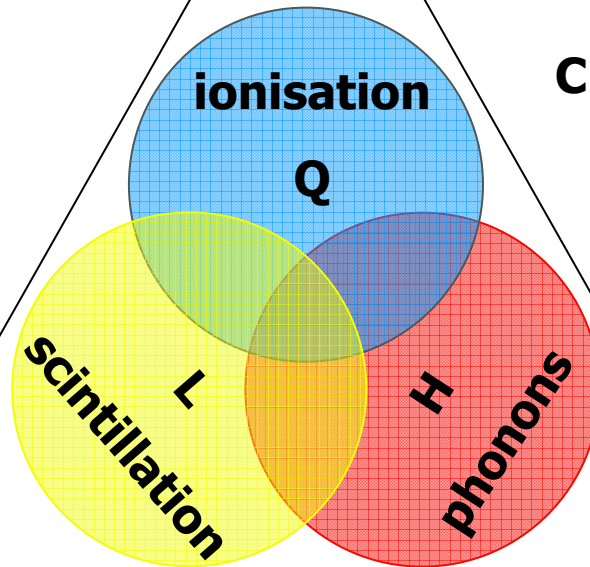
WIMP elastic nuclear recoils deposit $< 100\text{keV}$ of energy at a rate 10^{-5} to 1 event/day/kg

**IGEX,
DRIFTI, II**

\Rightarrow phonons, photons and charge whose relative proportions and /or characteristics depend on $dE/dx \Rightarrow$ particle type

**ZEPLIN II, III, MAX,
XENON, WARP**

CDMS, EDELWEISS



**NAIAD, ZEPLIN I,
DAMA**

CRESST I

**CRESST II,
ROSEBUD**

World **competition** is intense and uses a wide range of **complementary** techniques

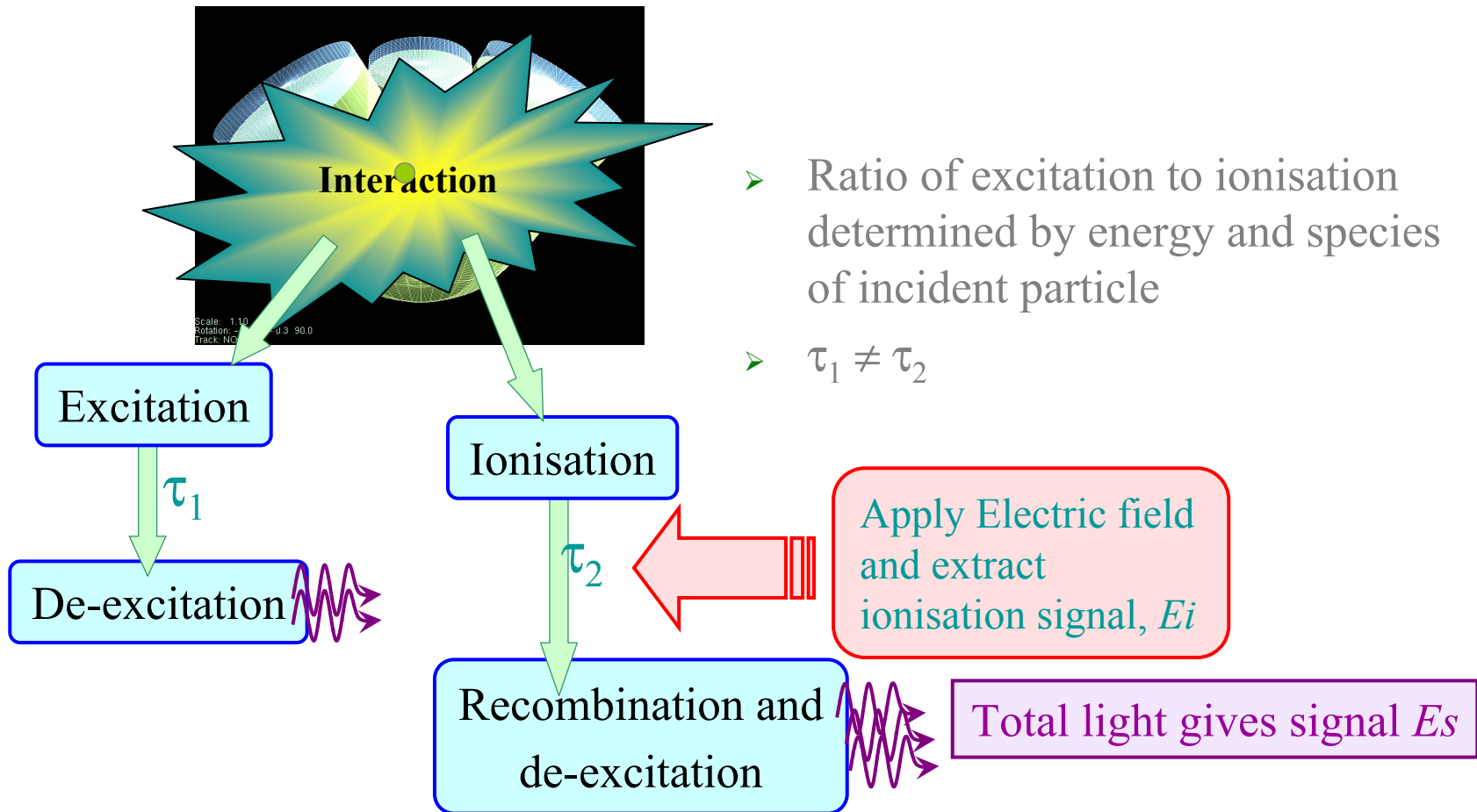
Event-by-event particle identification requires compound information

Dark Matter 2

R. Cashmore

32

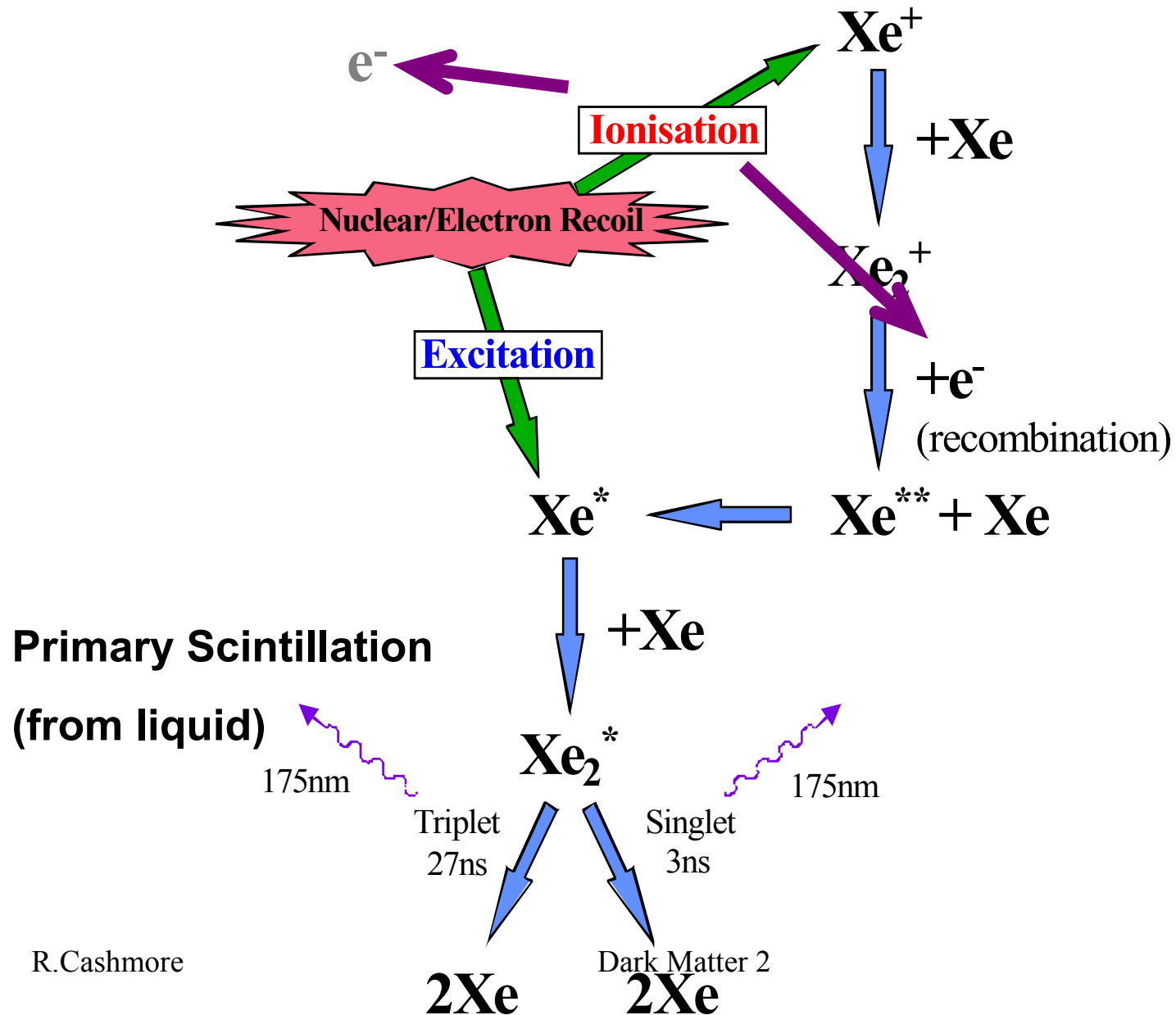
Liquid Xenon strategy



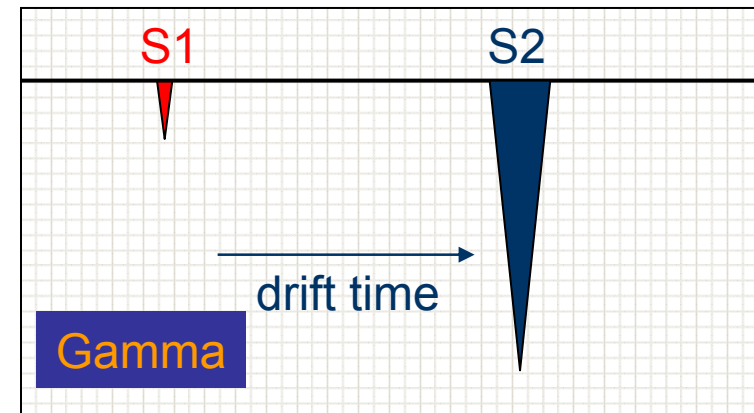
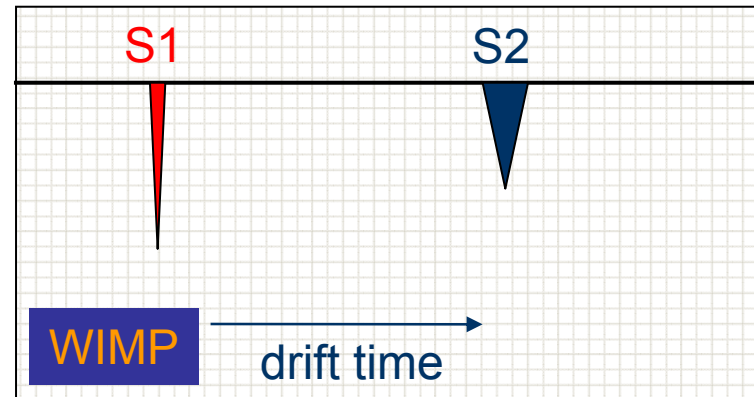
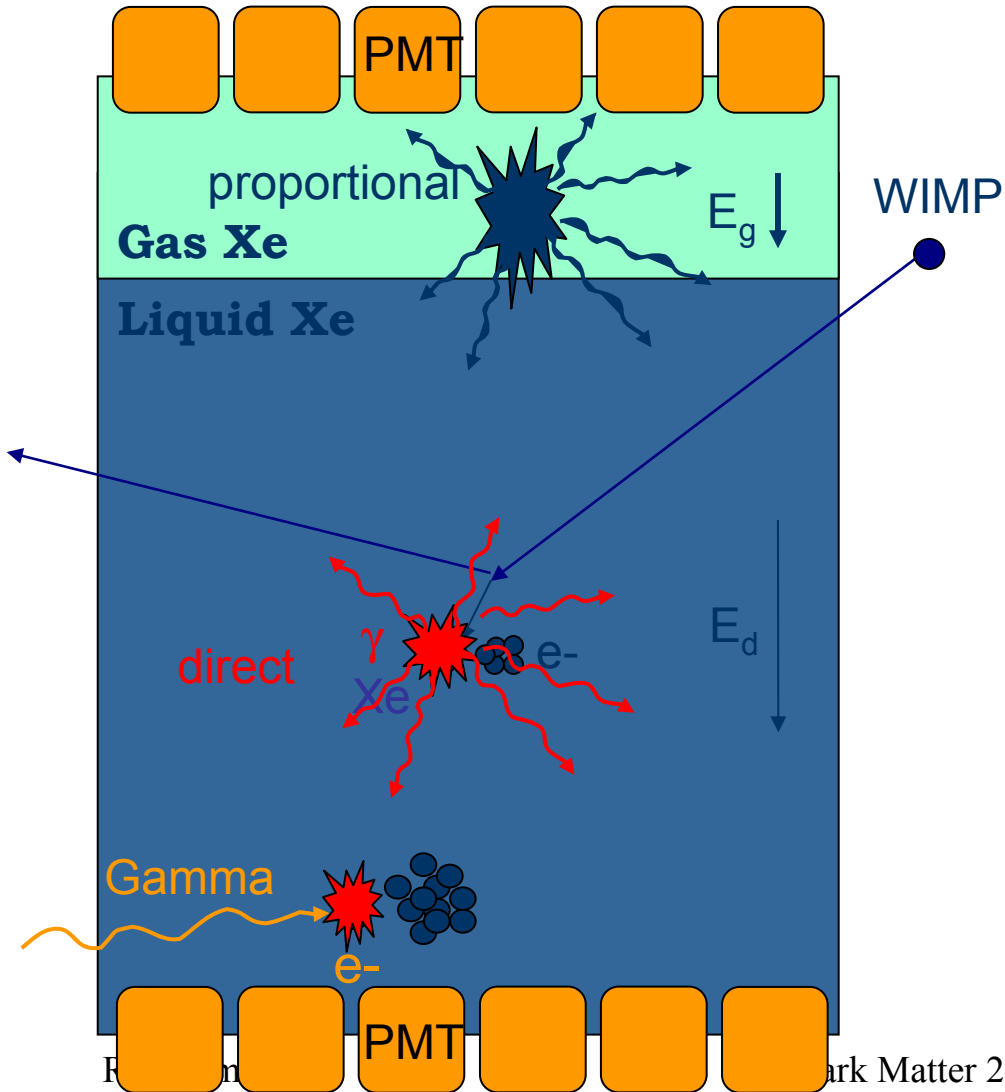
- Ratio of excitation to ionisation determined by energy and species of incident particle
- $\tau_1 \neq \tau_2$

Two phase discrimination: $(E_i/E_s)_{M.I.P} \gg (E_i/E_s)_{NuclearRecoil}$

ZEPLIN Programme



XENON Detector Concept & Event Discrimination



$$(S2/S1)_{wimp} \ll (S2/S1)_{gamma}$$

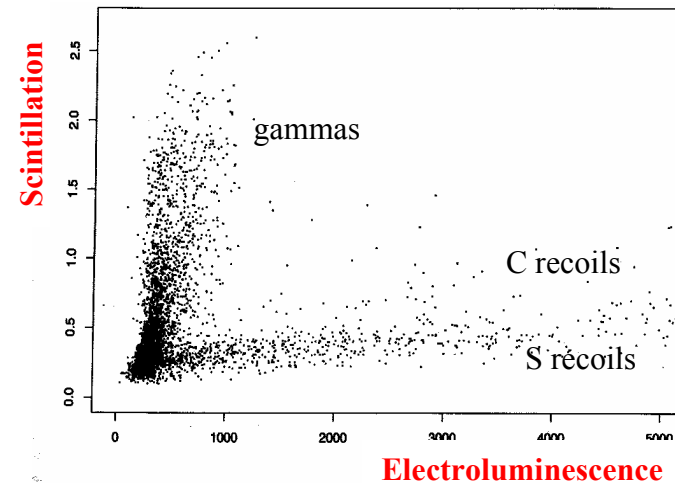
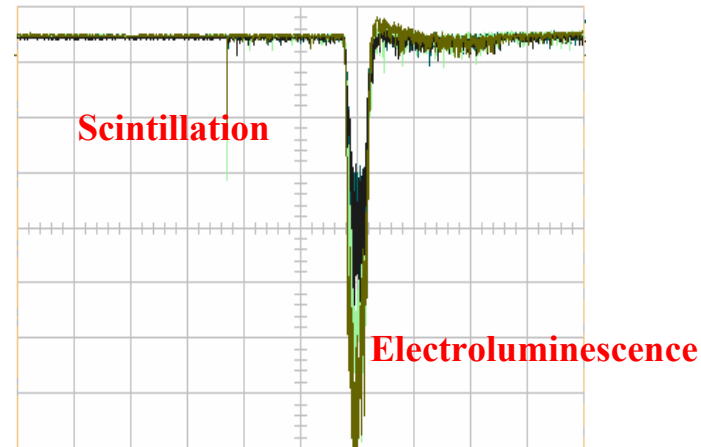
Two phase Xe discrimination

Apply electric field

→ extract an ionisation signal...

Proof of concept tests for a two-phase xenon detector: successful!

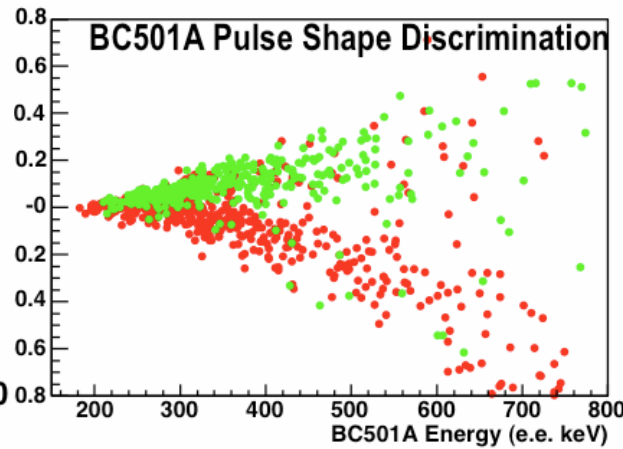
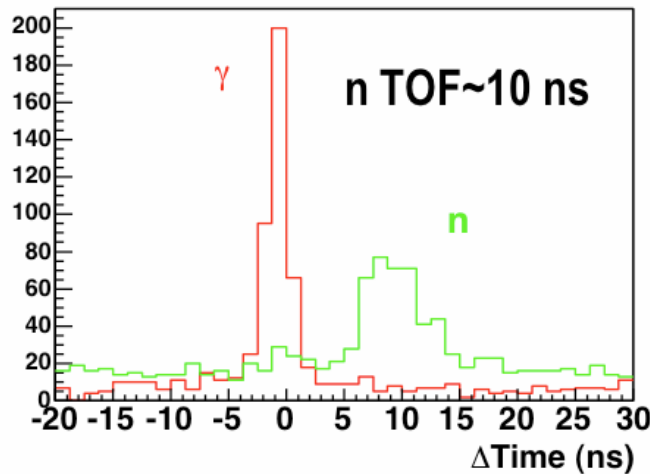
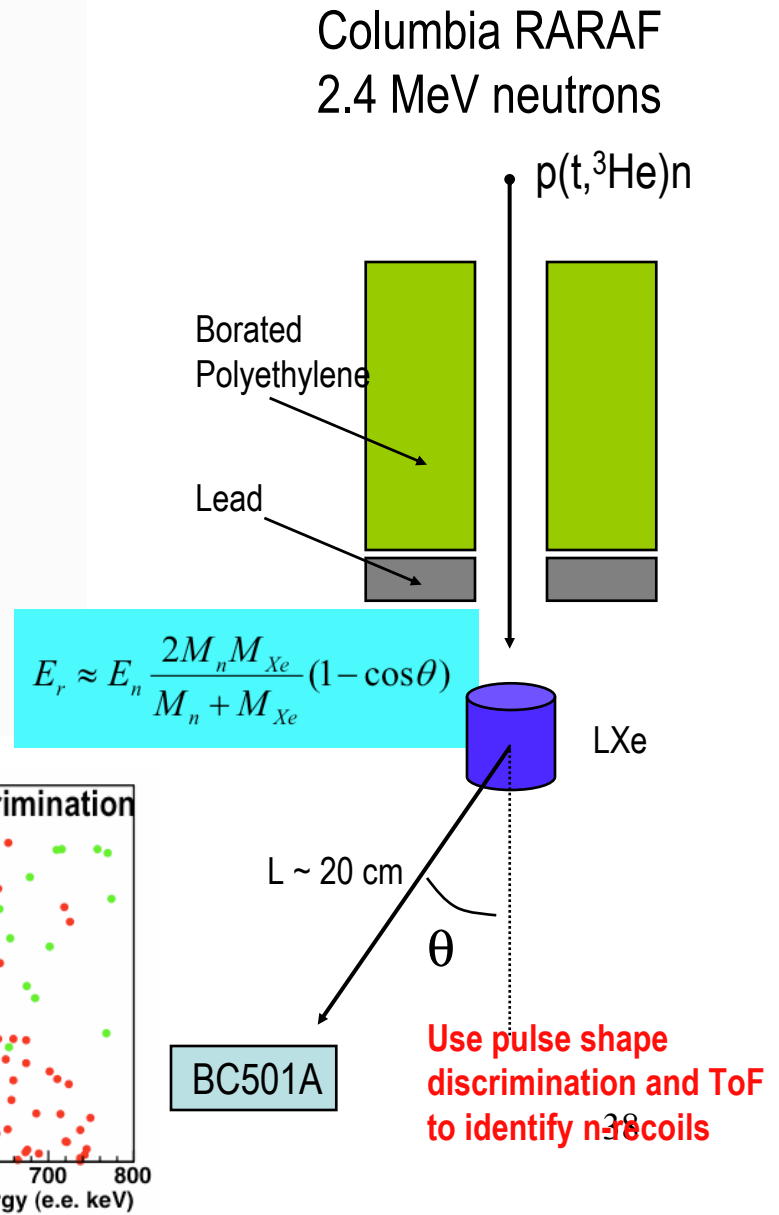
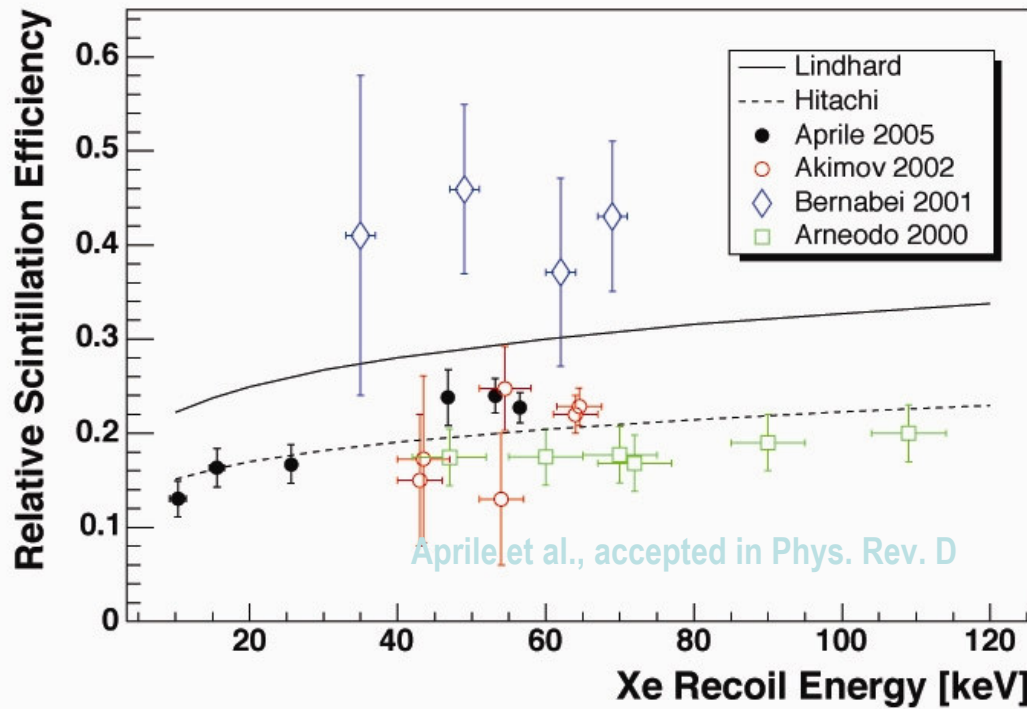
Construction of Zeplin 2/Zeplin 3 underway (Each ~30 kg Xe)...



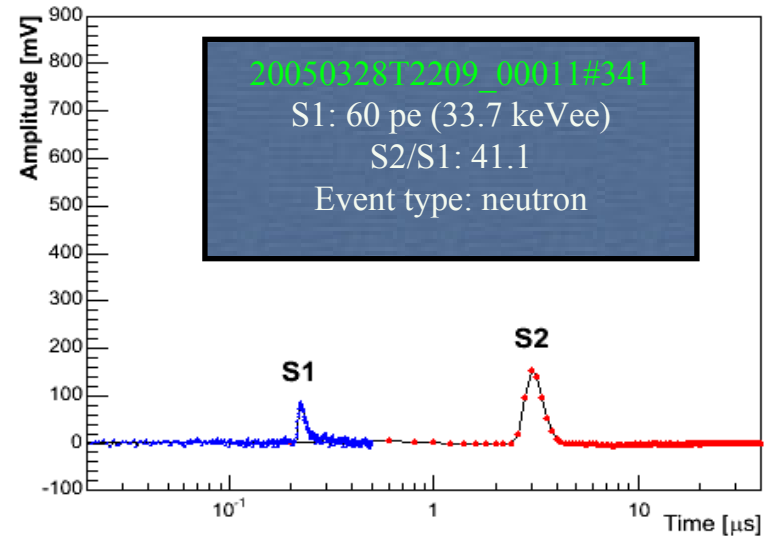
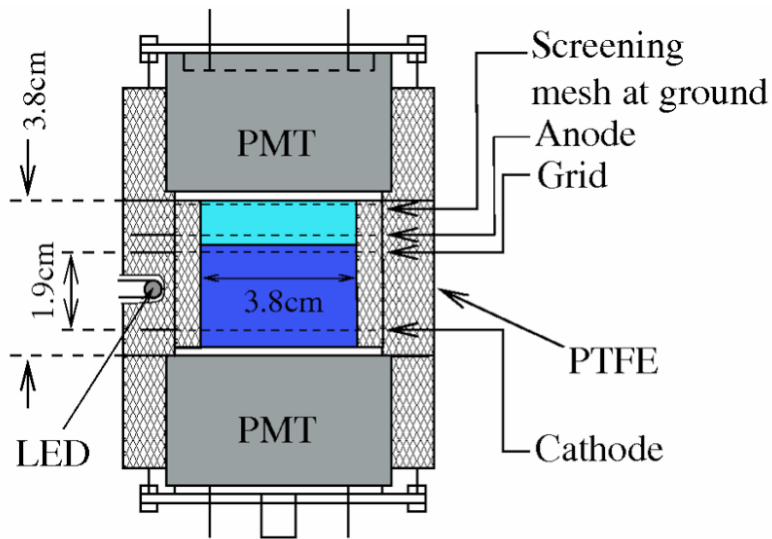
How much charge and how much light quenching for Xe recoils?

- ◆ **LXe Scintillation Efficiency for Nuclear Recoils**
 - The most important parameter for DM search
 - Since recoil ions are slow $\beta \sim 10^{-3}$, the Bethe-Bloch description of the ionization process is no longer applicable.
 - Both electronic and nuclear quenching take place
 - Available data inconsistent. No measurement below ~ 40 keVr
- ◆ **LXe Ionization Efficiency for Nuclear Recoils**
 - XENON (and other LXe concepts) rely on WIMP identification by simultaneous detection of recoil ionization and scintillation
 - No prior information on the ionization yield as a function of applied E-field
 - Need to know the ionization density along the track of a Xe recoil as a function of energy

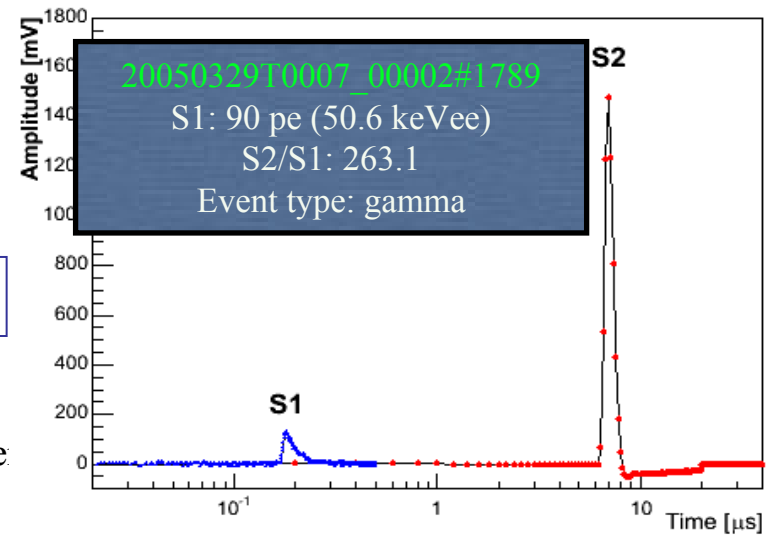
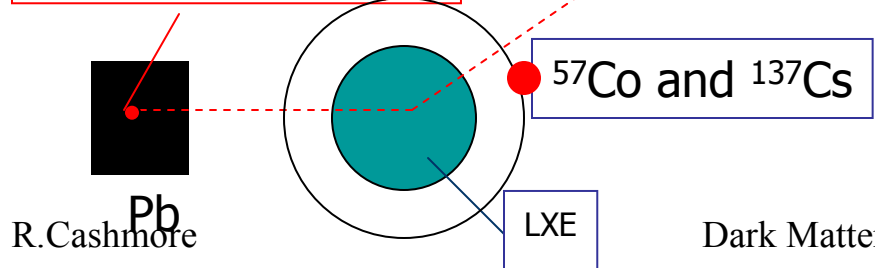
Neutron Beam: Xe-Recoils Scintillation Efficiency



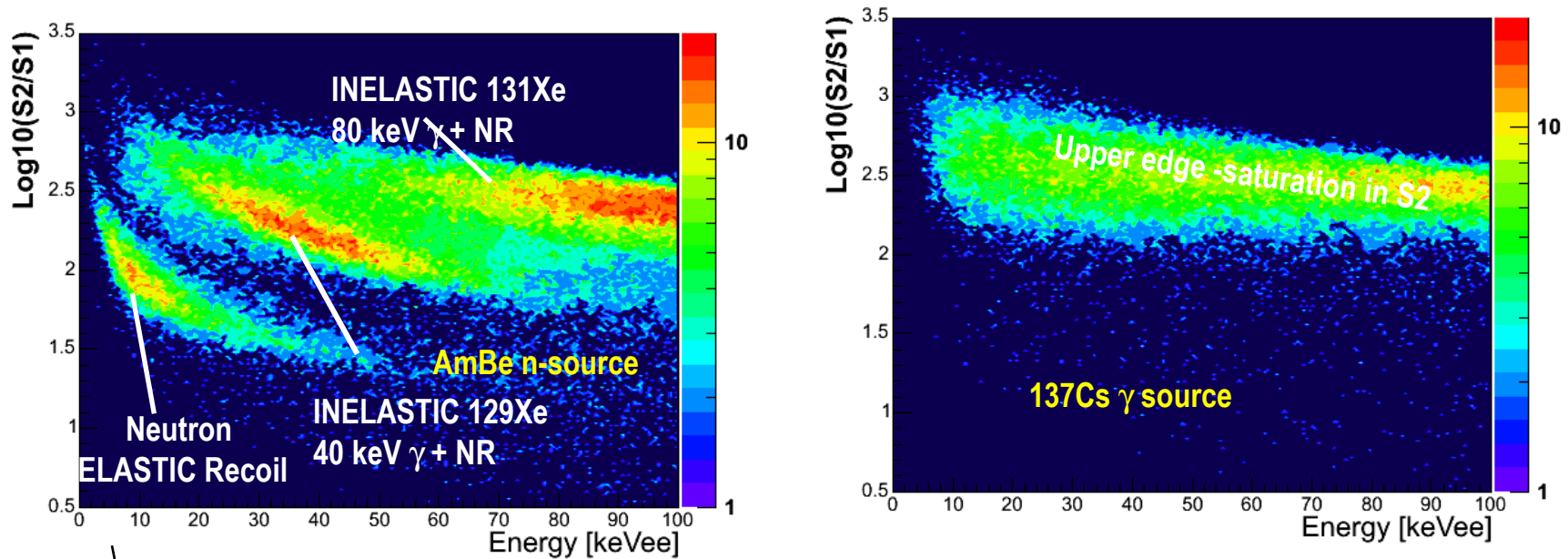
Gamma and Neutron Recoils Discrimination: Proof of Principle



AmBe - 10^7 neutron/sec

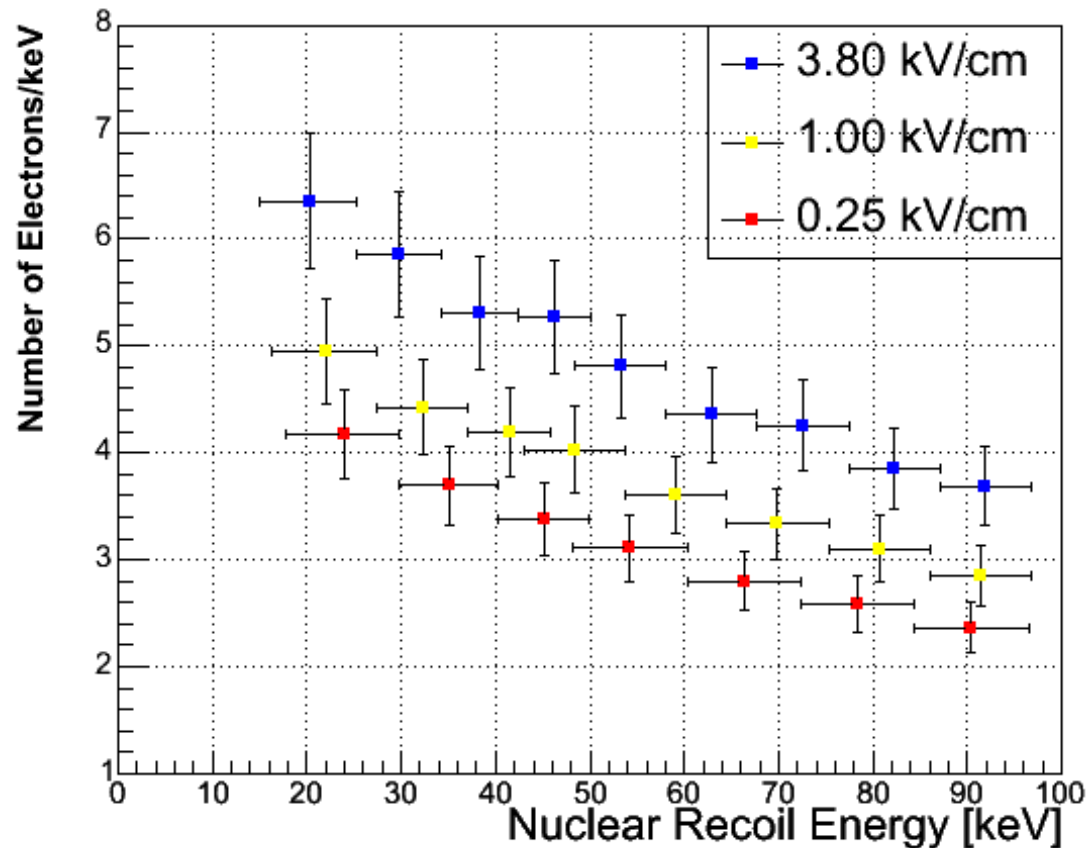


Gamma and Neutron Recoils Discrimination: Proof of Principle



Energy Threshold ER~5 keVee \rightarrow Recoil Threshold NR~10 keVr

Ionization Yield of Xe Nuclear Recoils

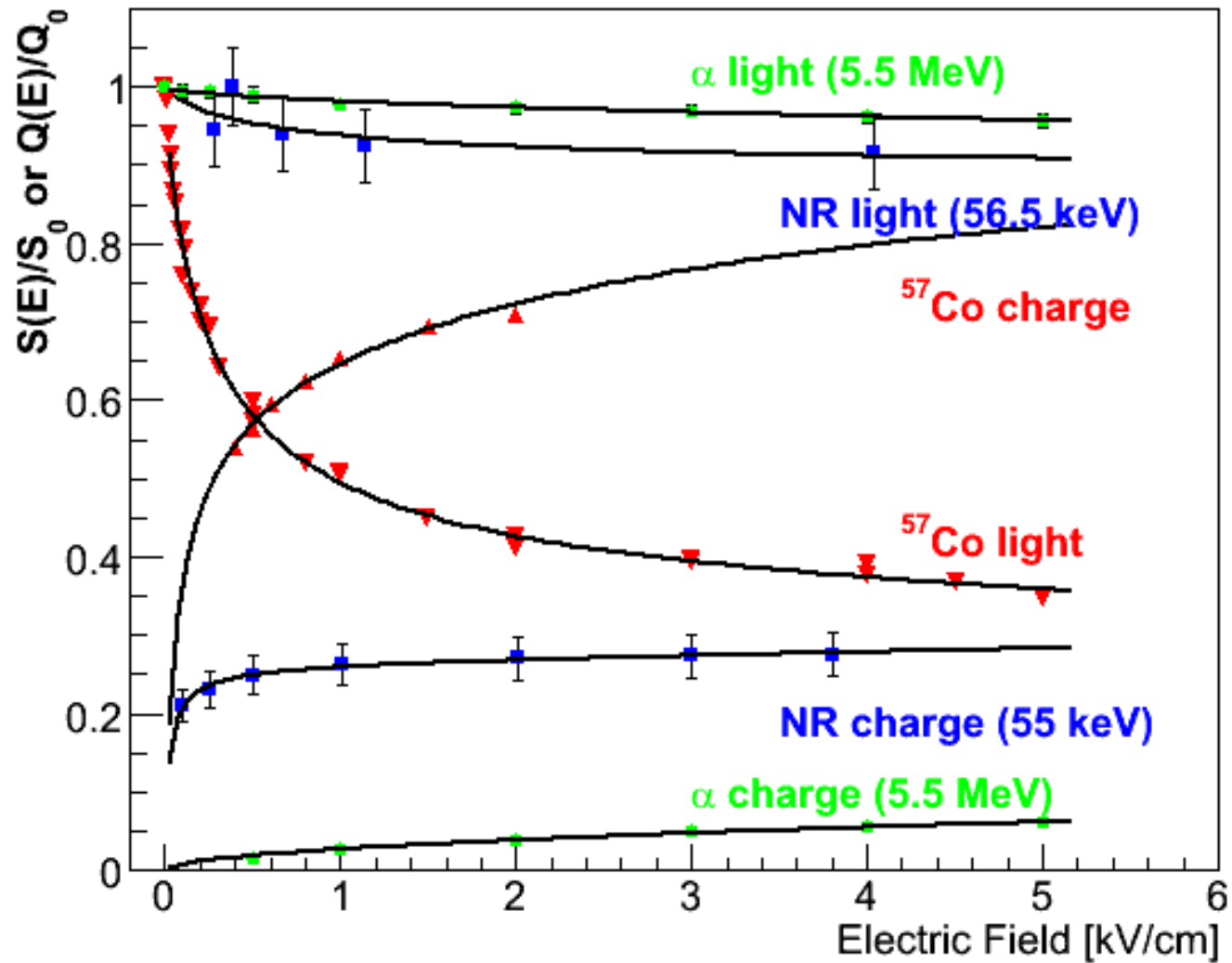


- Yield measured by two groups (Columbia/ Case) with different detectors agree within errors.
- Number of Electrons produced by nuclear recoils does not depend strongly on field.
- Calibration based on 122 keV gamma charge yield and on scintillation yield in n-beam.
- PRL in preparation

R. Cashmore

Dark Matter 2

Field Dependence of Q and S for α, γ and Nuclear Recoils



XENON10 TPC/Cryostat

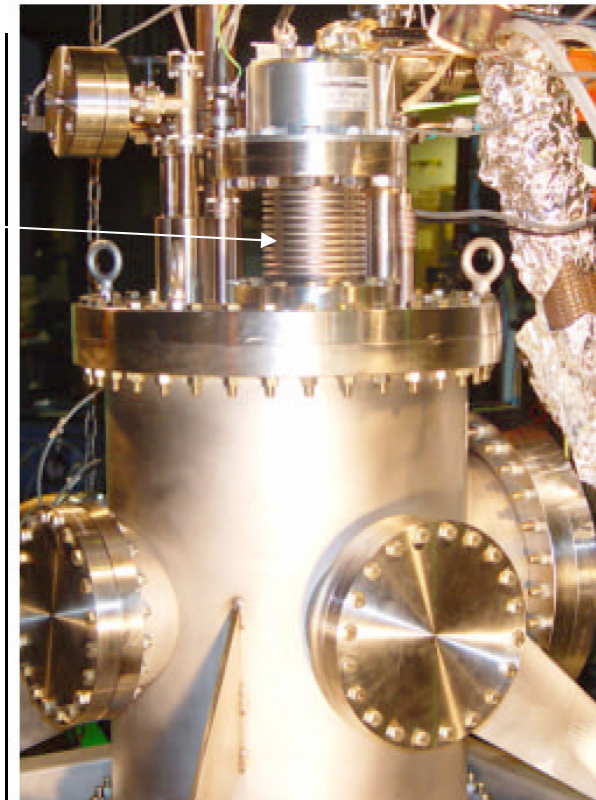
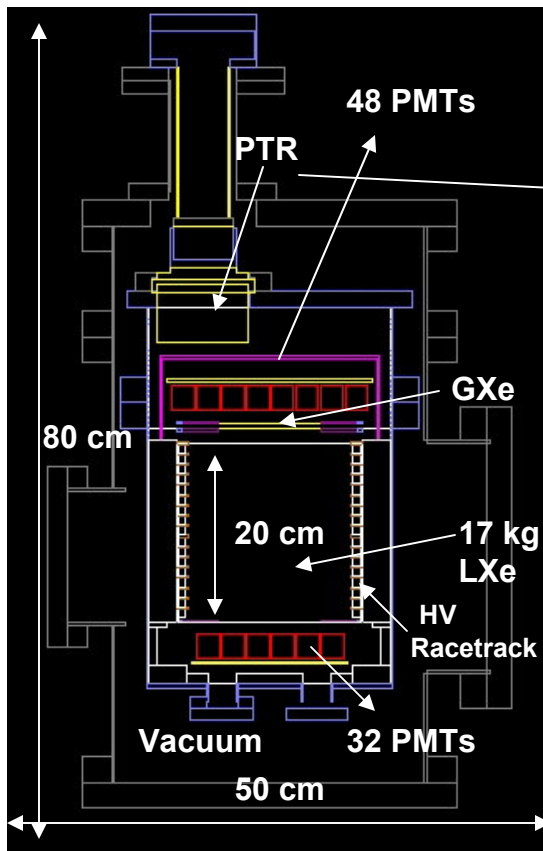
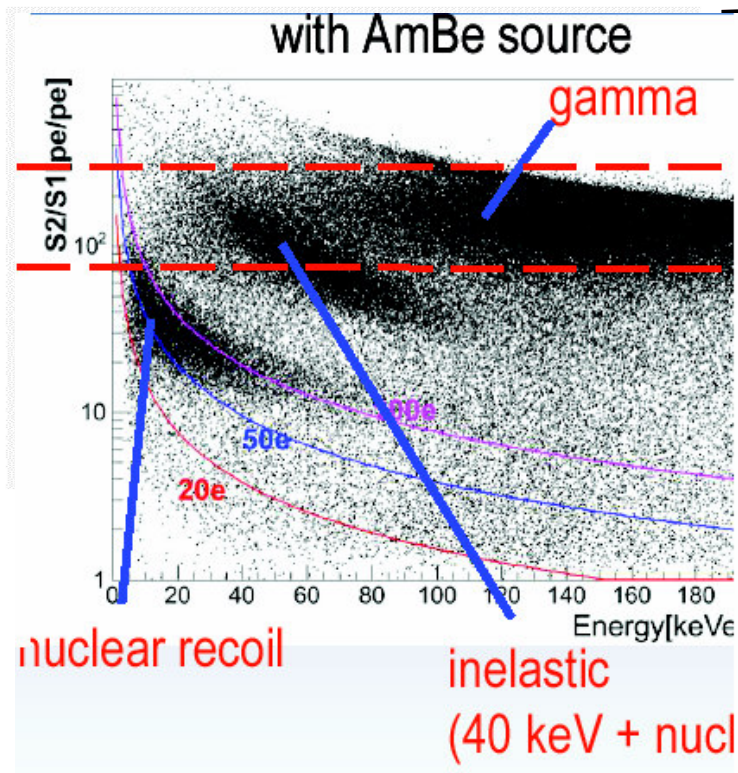


Figure 5. Photo of 10 kg Prototype

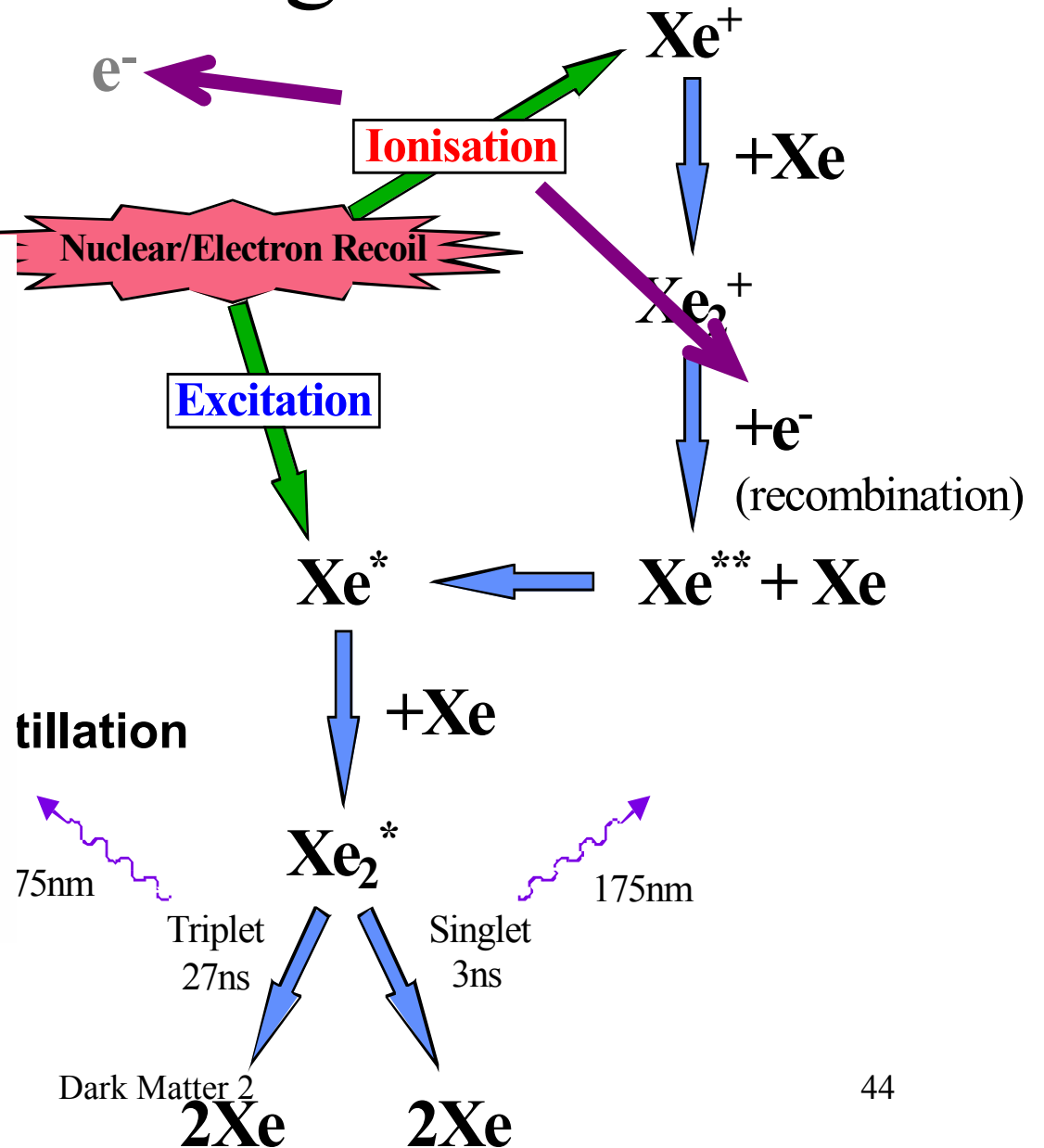
ZEPLIN Programme

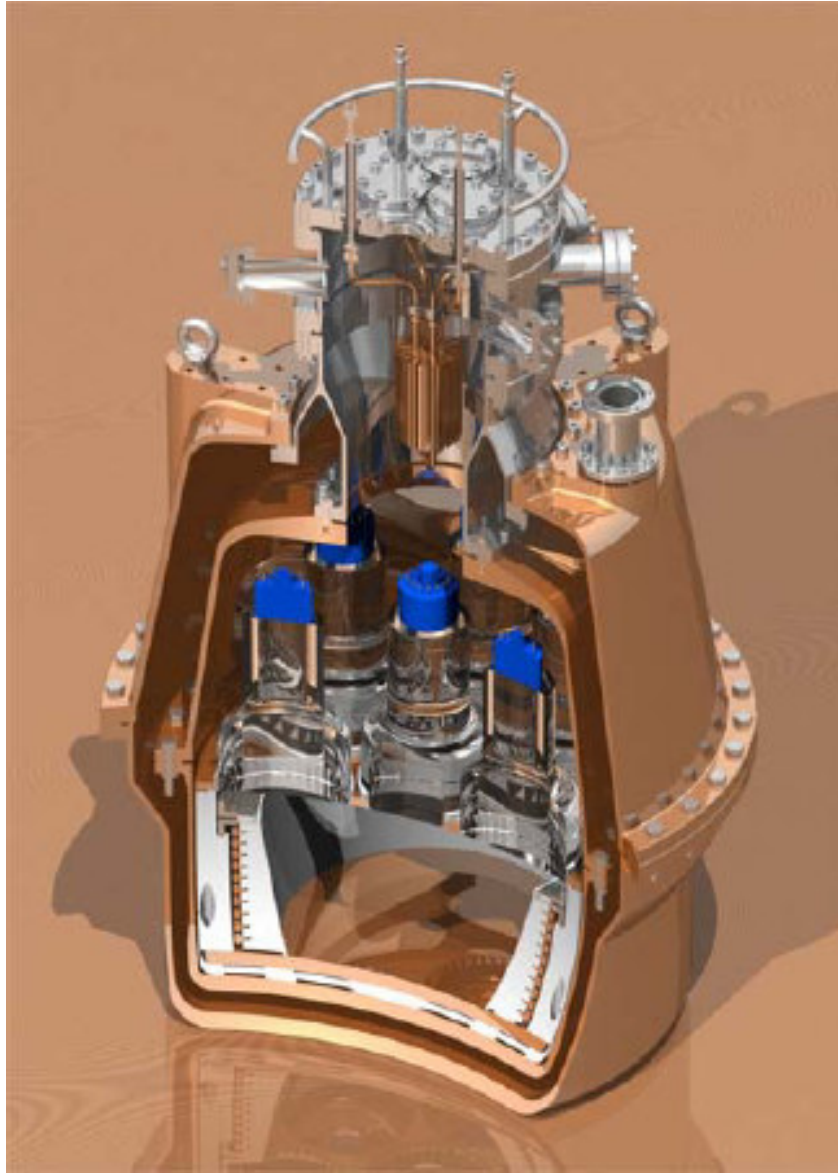
Ionisation
(Secondary scintillation
in gas)



Aprile et al. 2005

R.Cashmore

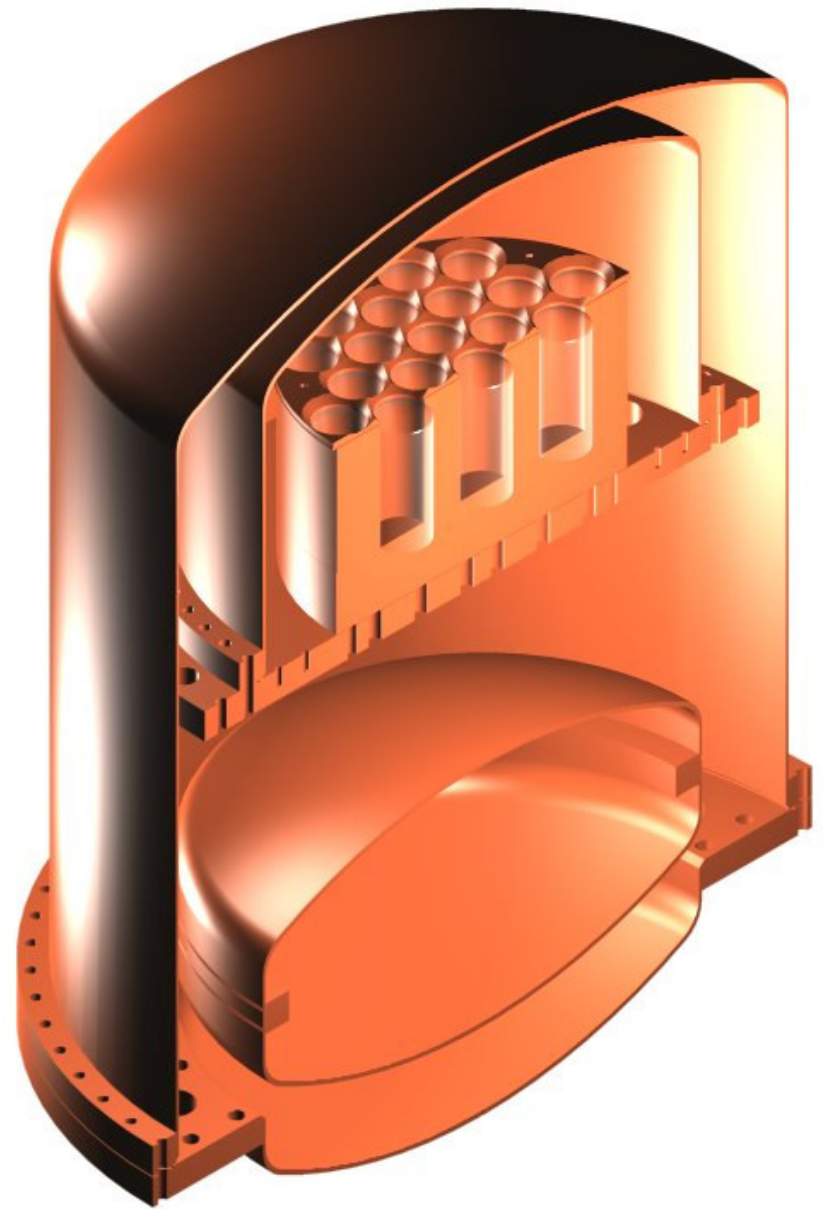




R.Cashmore

ZEPLIN II

Dark Matter 2



ZEPLIN III

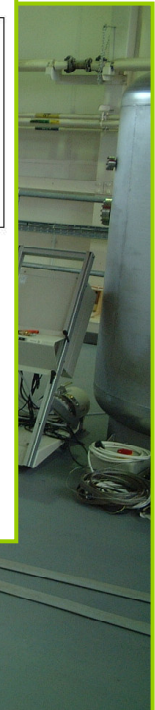
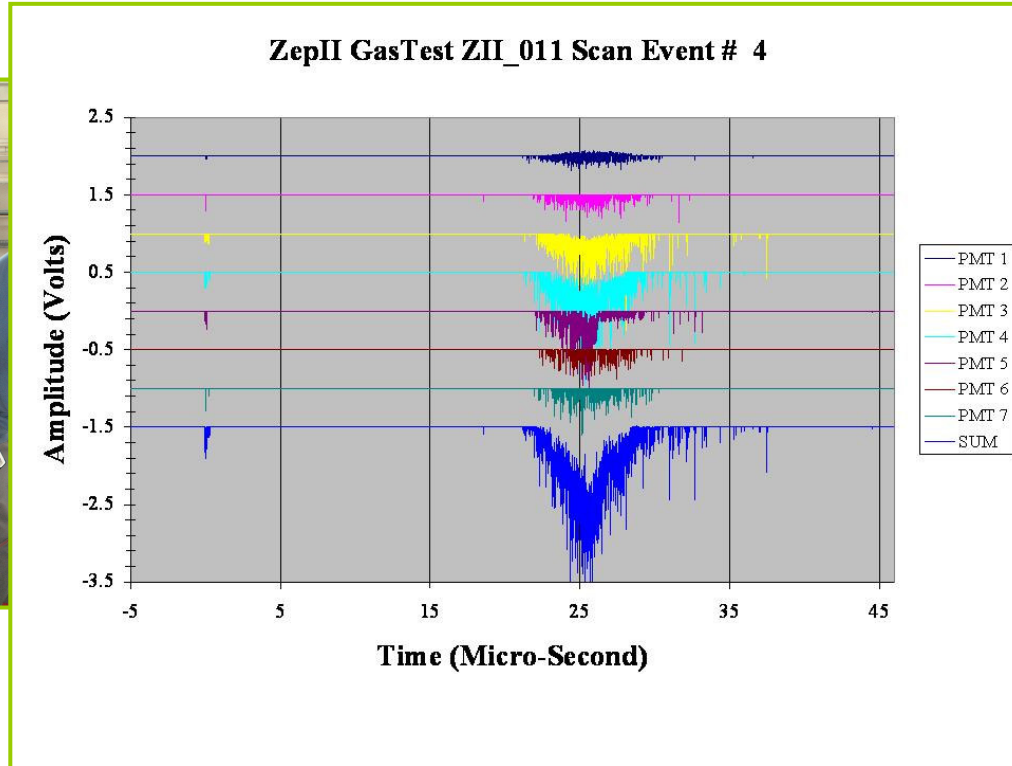
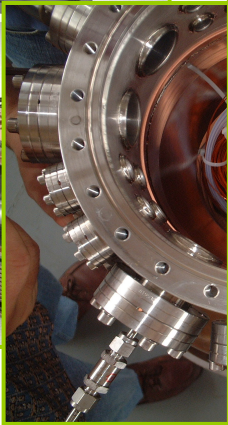
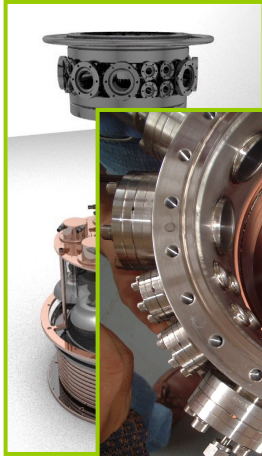
45

Current ZEPLIN II Status

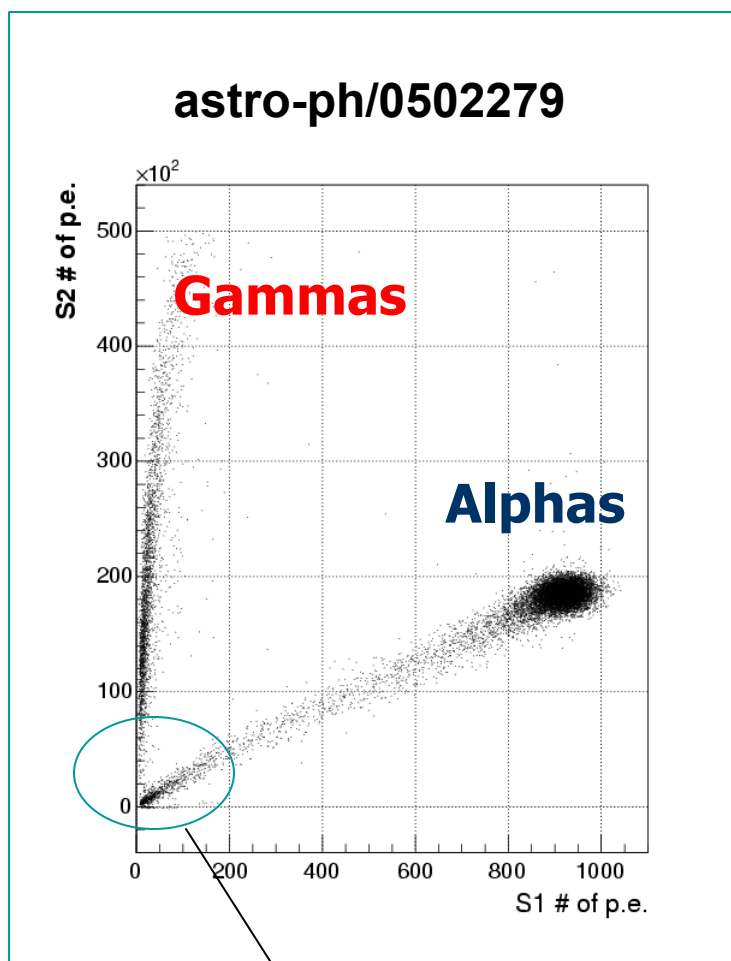
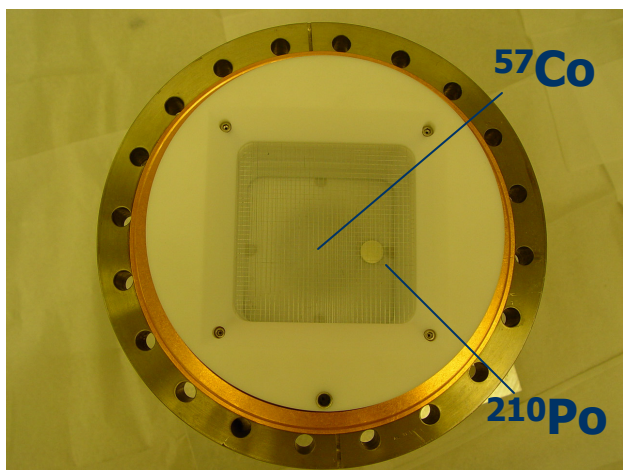
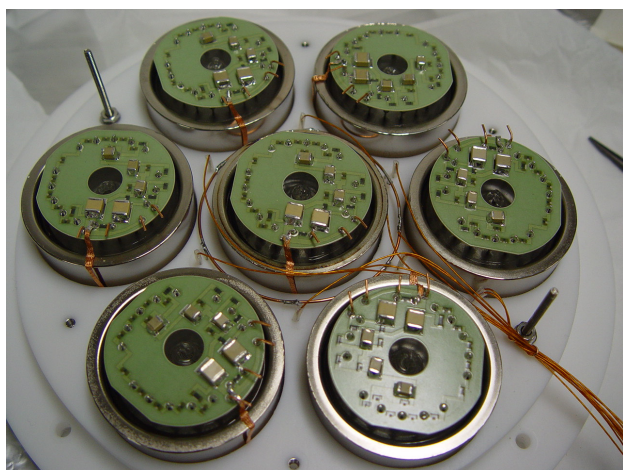
- **Fully assembled**
- **Gas tests**
- **Cooldown tests successful**
- **First test run with 40kg liquid completed**
- **Site preparations (veto/shield) complete**
- **Detector now operational underground**



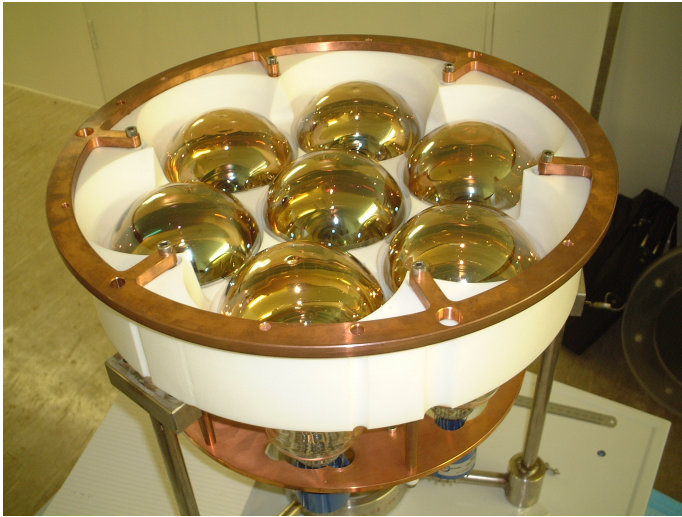
Zeplin II



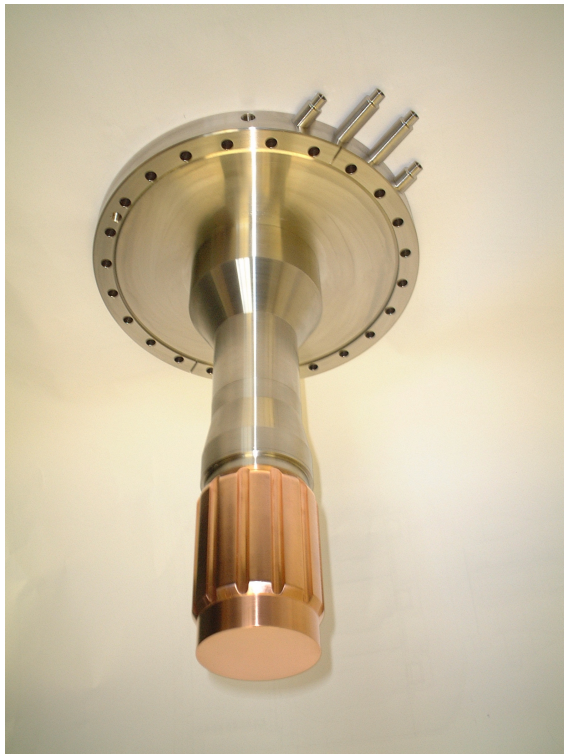
Gamma and Alpha Recoils Discrimination



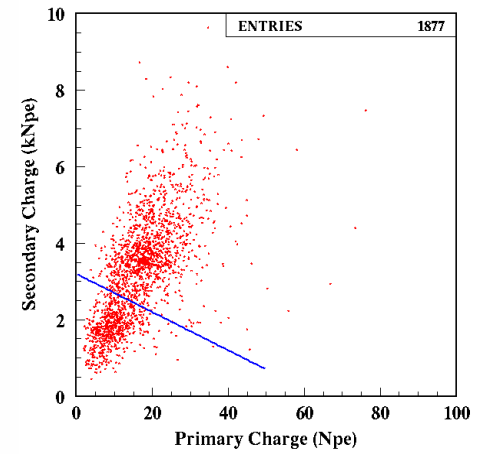
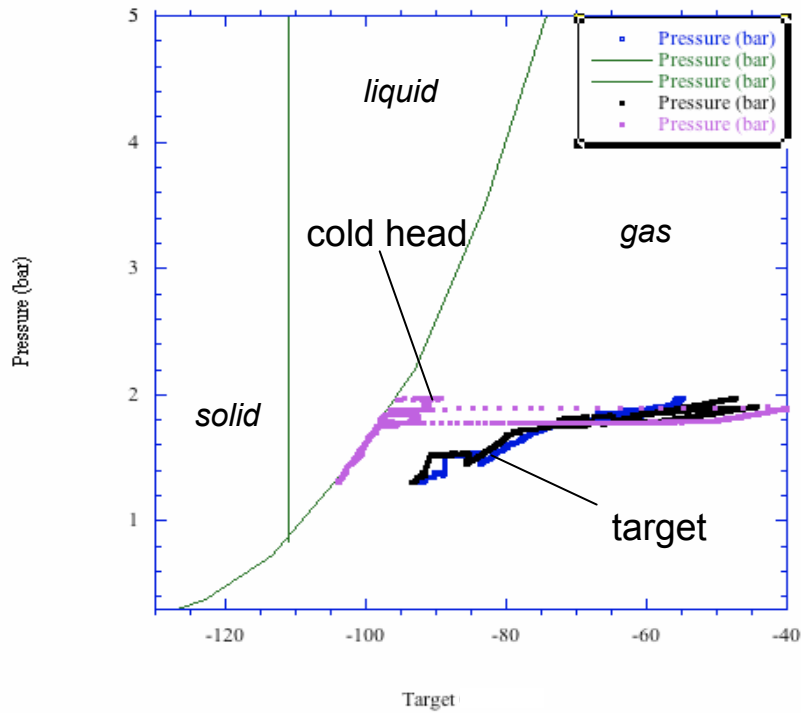
Low Energy Nuclear Recoils?



slowval.dat 4:19:32 pm 22/10/04



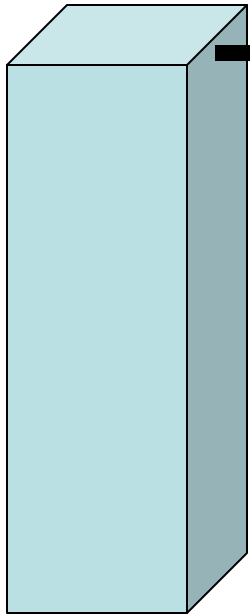
R. Casimiro



ZEPLIN II First Liquid Tests

Purifier and dump chambers

Polycold unit



ZEPLIN II with new internal target vessel, refurbished

PMTs, outgassed PTFE

Calibration source stand

Dark Matter 2

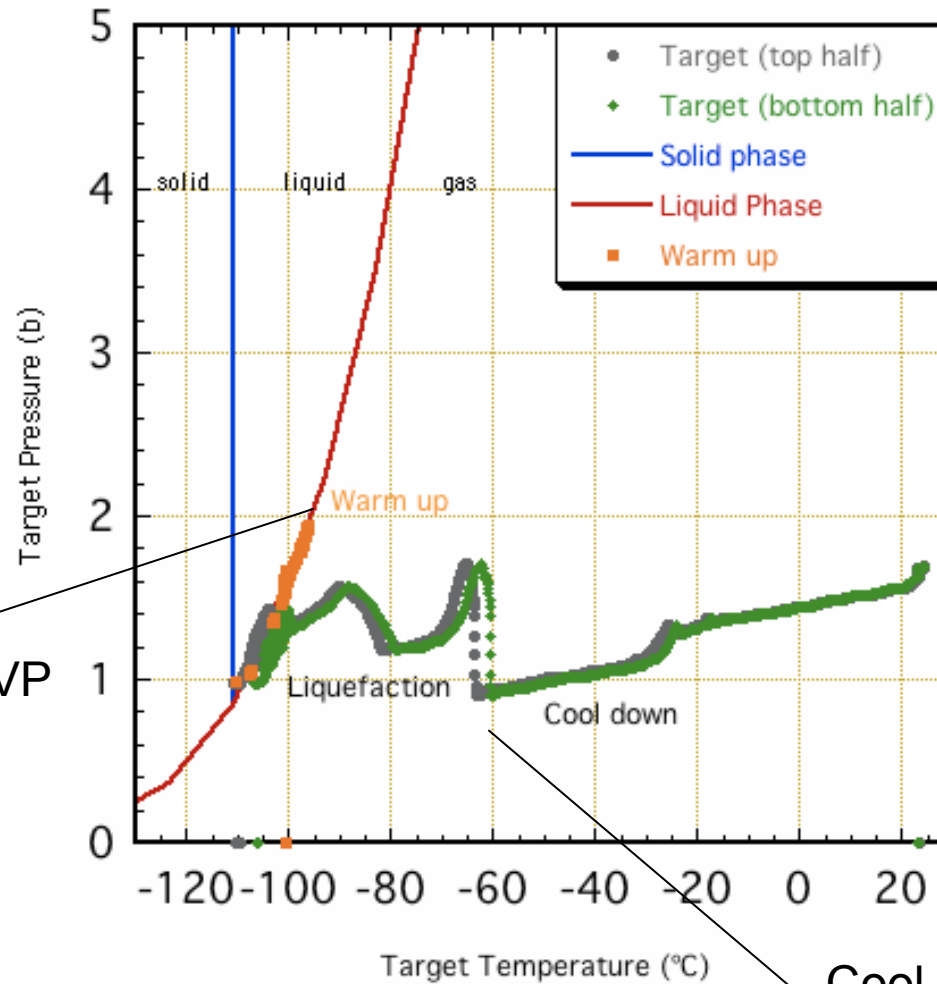
Xe input bottle (1 of 4)

40kg into target

50

First Liquefaction run

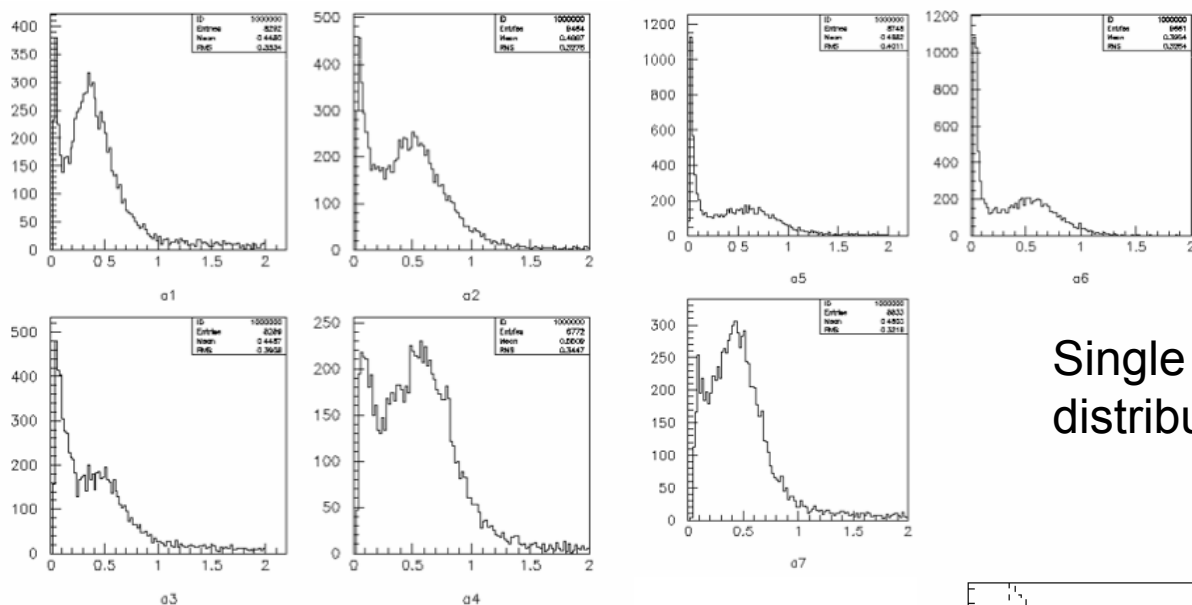
Xenon 40kg liquefaction - 150405



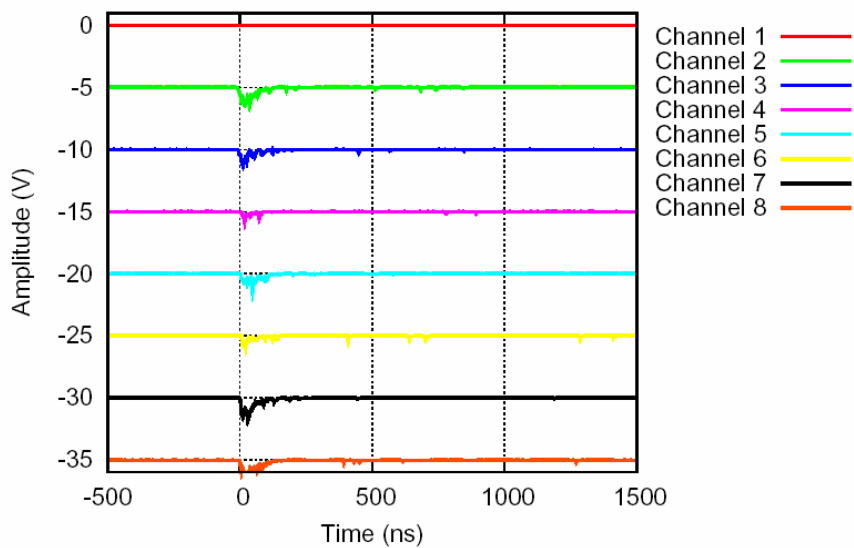
Warm up following SVP

Cool down with injection of xenon gas

Liquid Phase Data

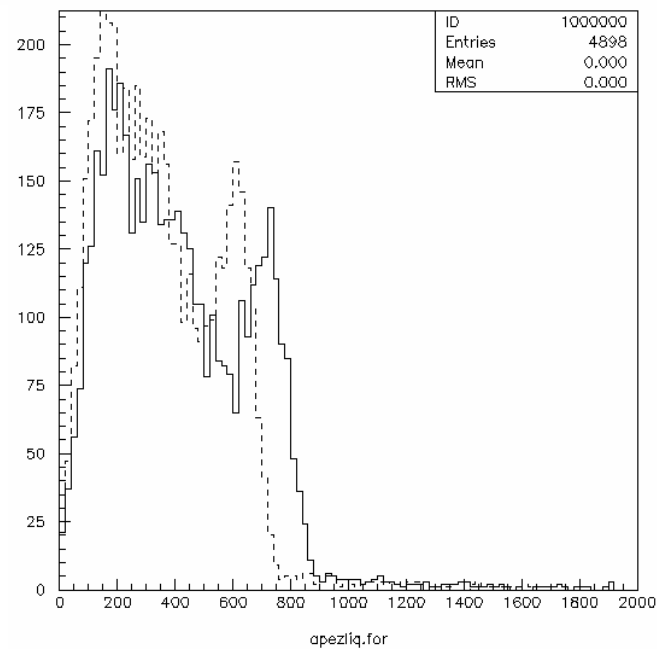


Single photoelectron distributions

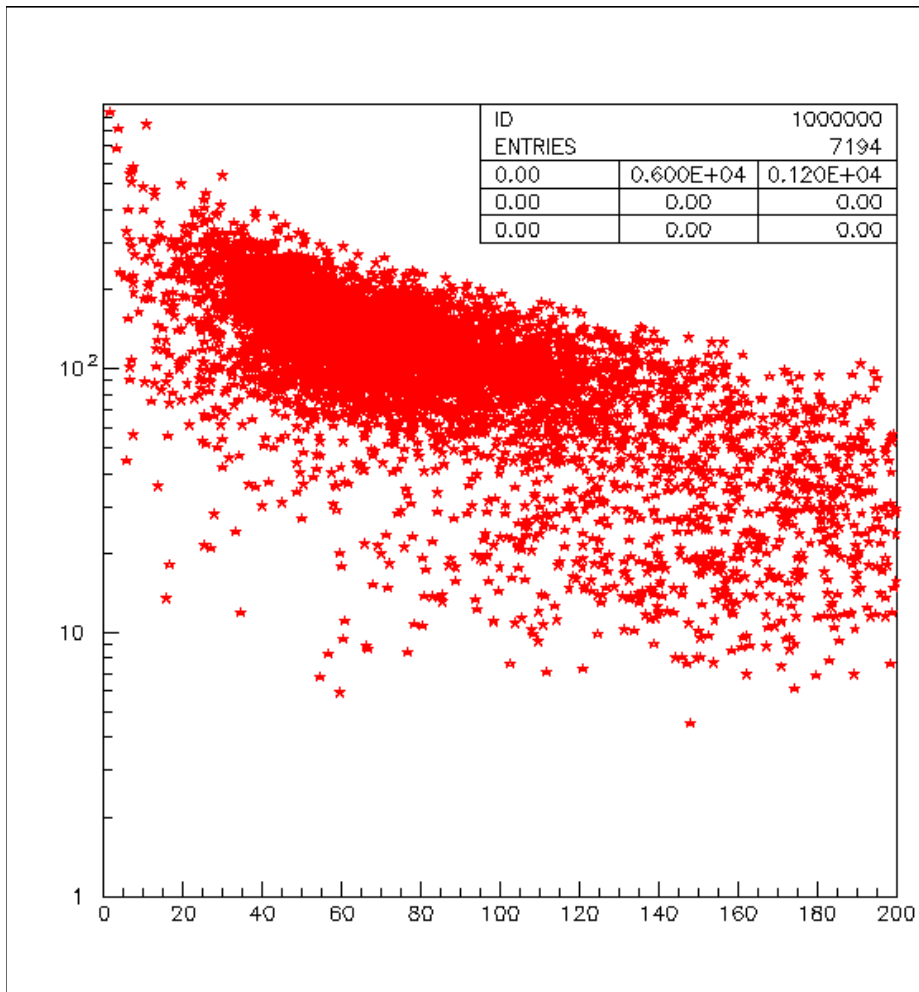


R.C

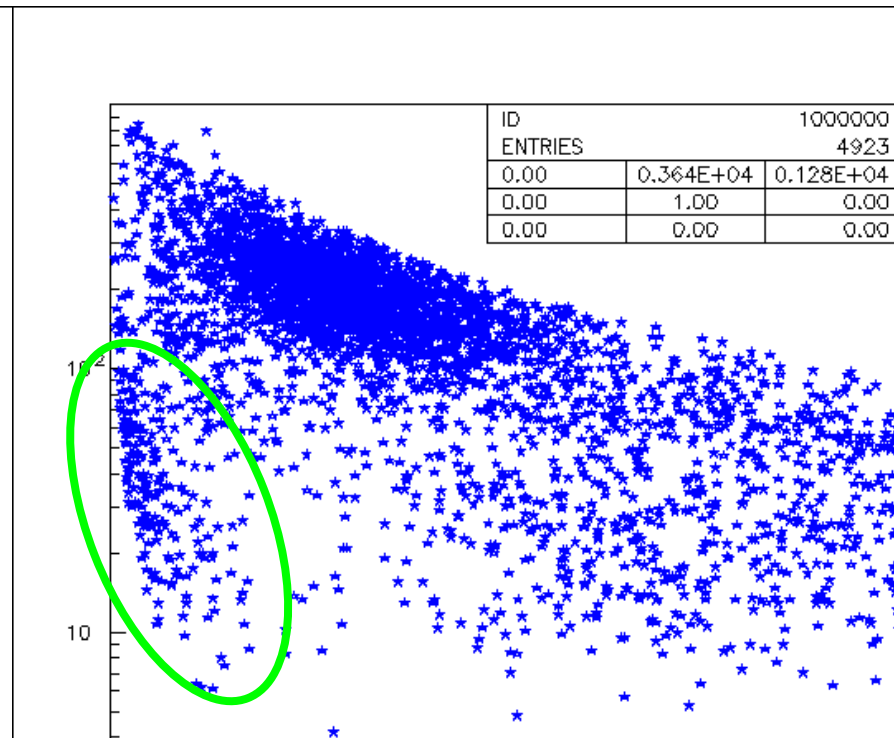
Raw gamma pulse



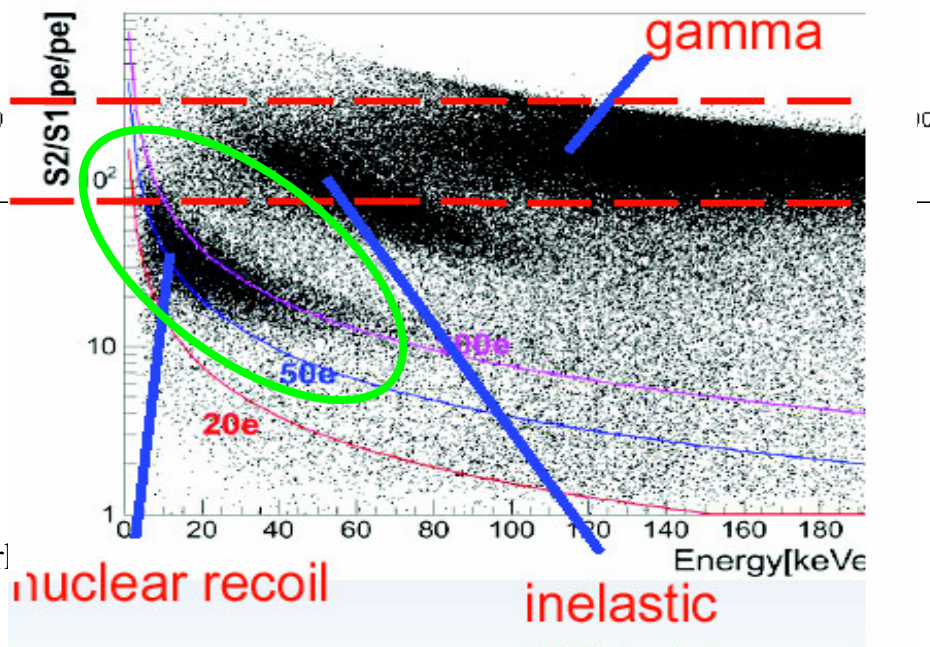
^{137}Cs spectrum



Gamma source events

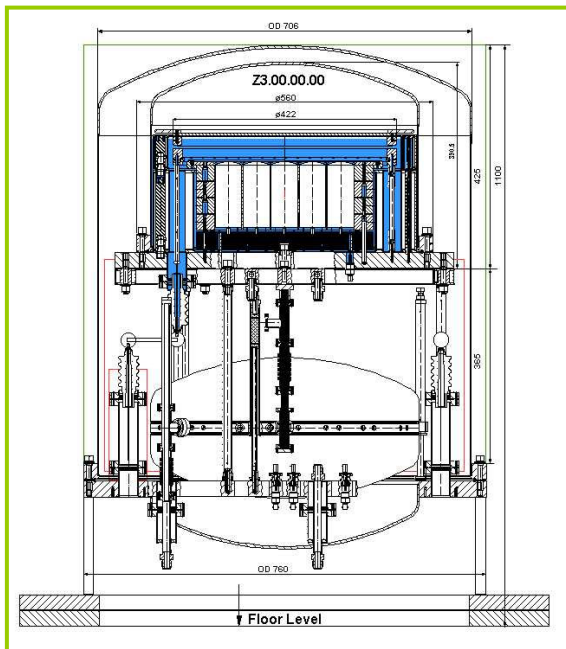


with AmBe source



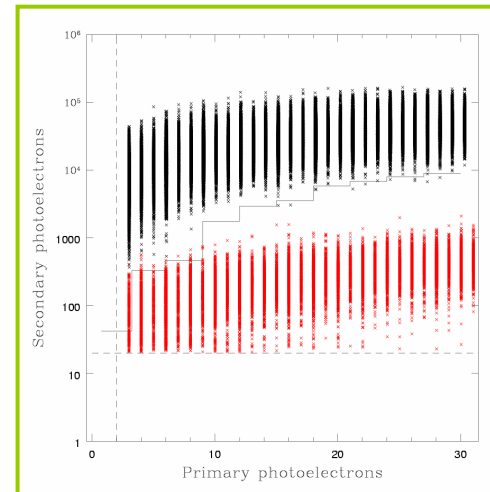
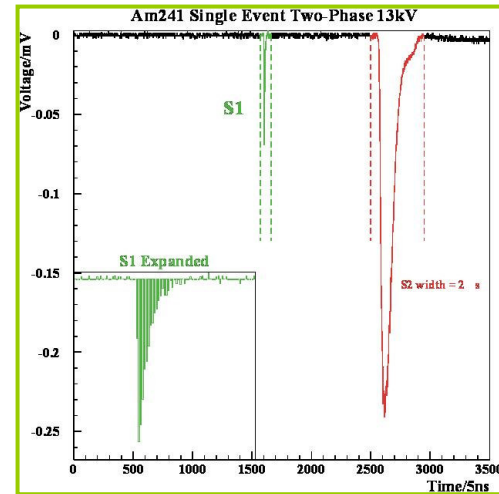
Zeplin III

- More ambitious advance in technology
- Much higher field



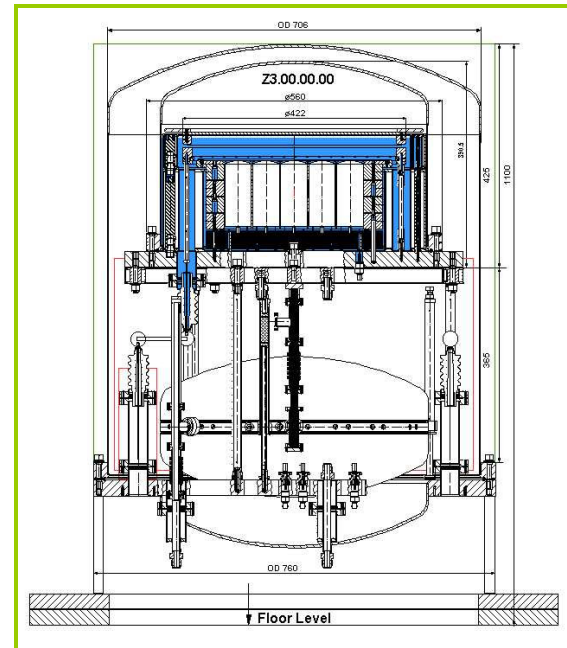
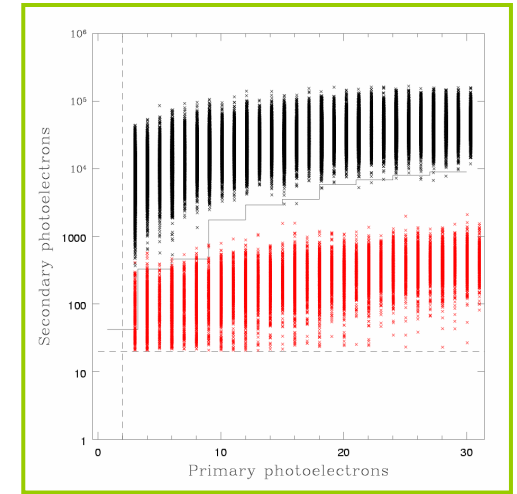
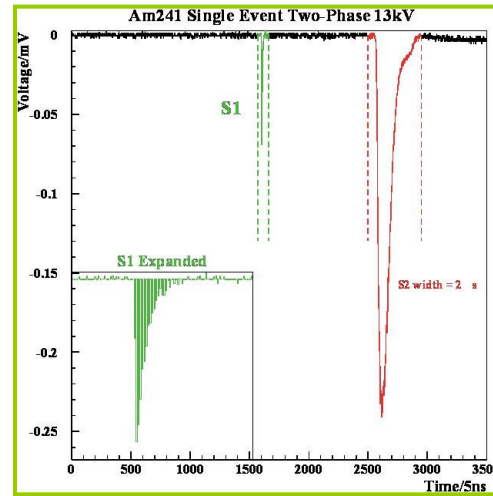
in liquid in

gher
(ZII)



Zeplin III

- More ambitious advance in technology
- Much higher field
- Extract charge from liquid in to gas phase
- Approx 5 times higher discrimination (c.f. ZII)

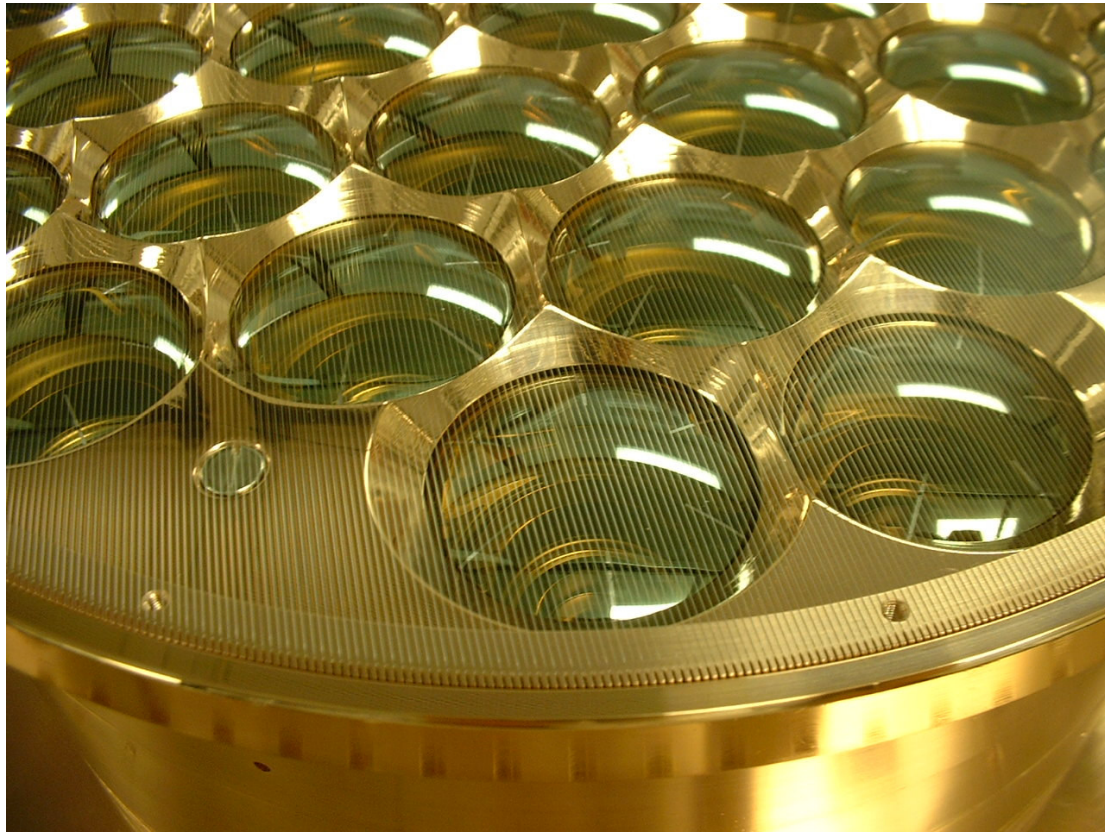
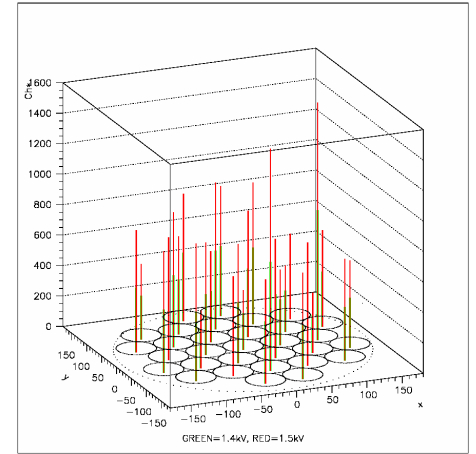
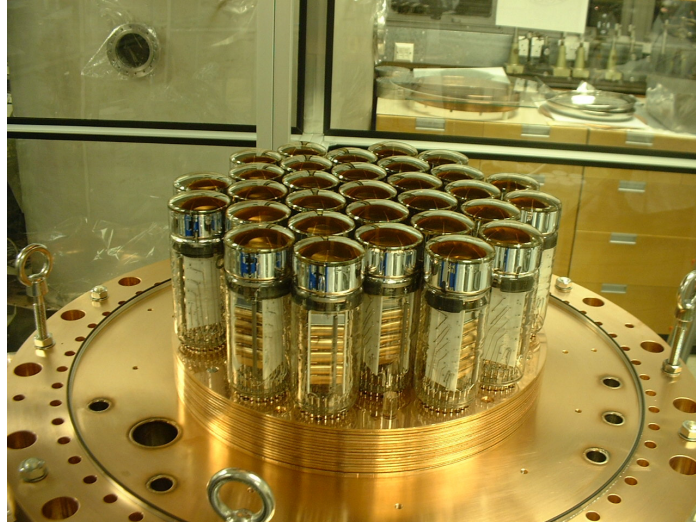


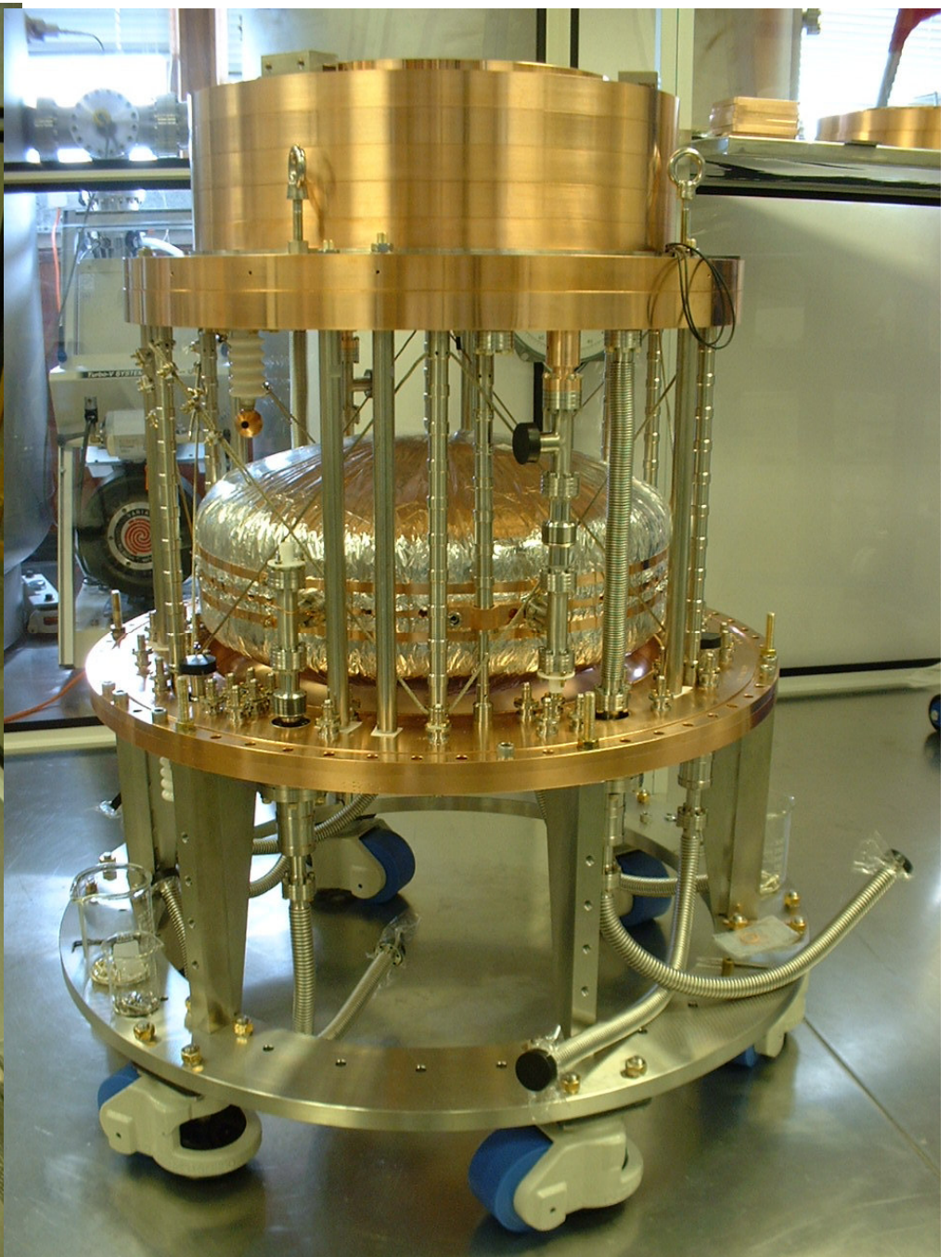
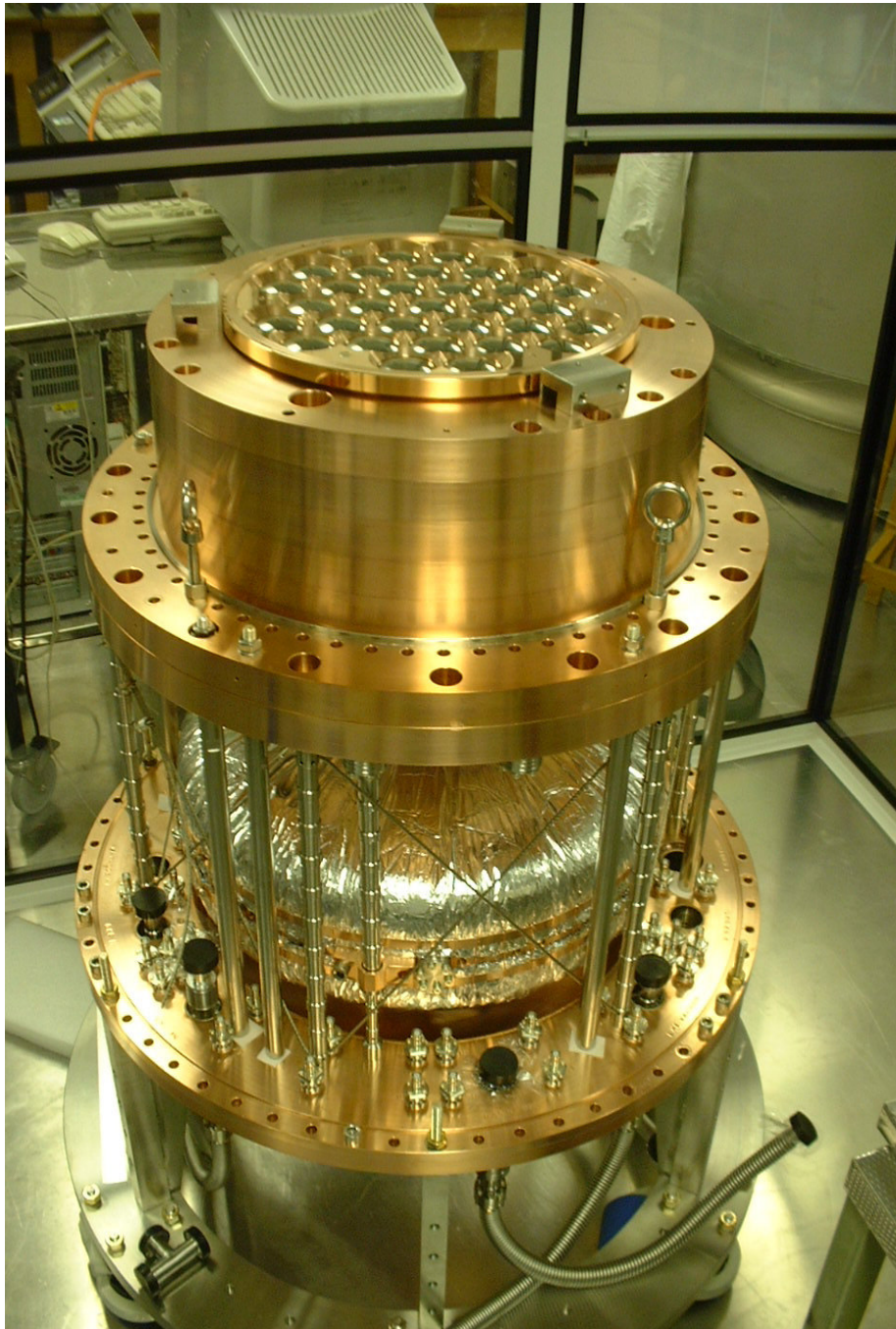


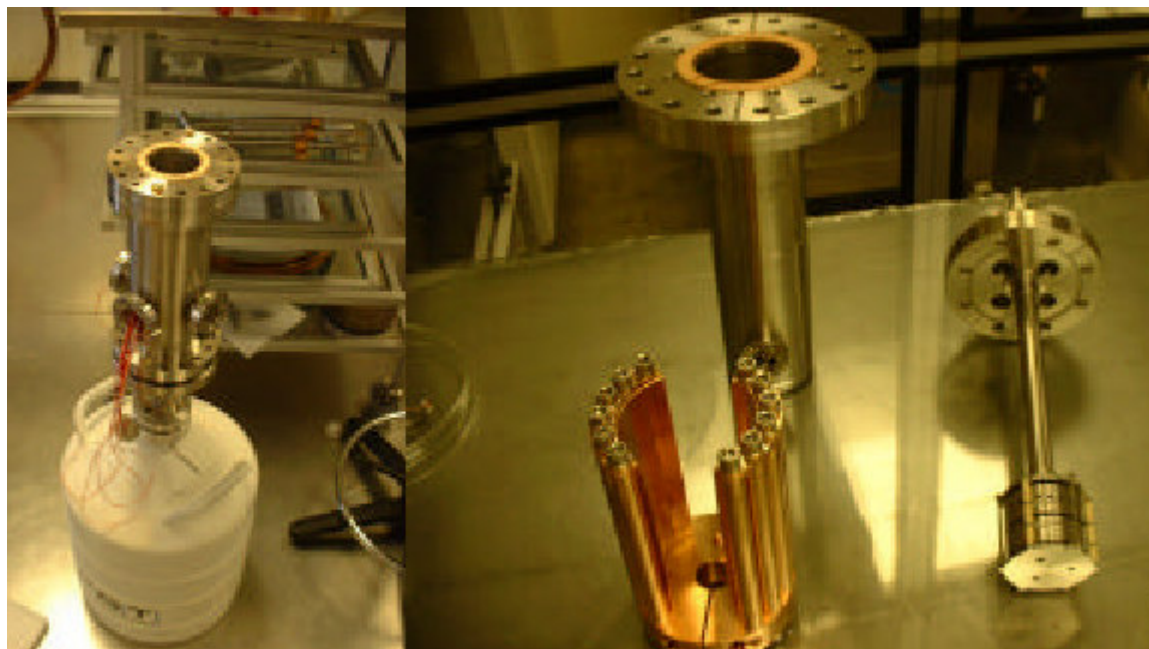
Zeplin III



**50 kg of pre-atomic
bomb test xenon (ultra
low Kr contamination)**







R.Cashmore

ZEPLIN III

Enhancements include

- **PMTs immersed in liquid \Rightarrow five times better light collection for primary**
- **Higher electric fields $\Rightarrow \sim 7\text{kV/cm} \Rightarrow$ better discrimination ($\sim 10^5$ at threshold!)**
- **Good 3-d position reconstruction from gas phase electroluminescence \Rightarrow well defined fiducial volume plus enhanced diagnostic capability**

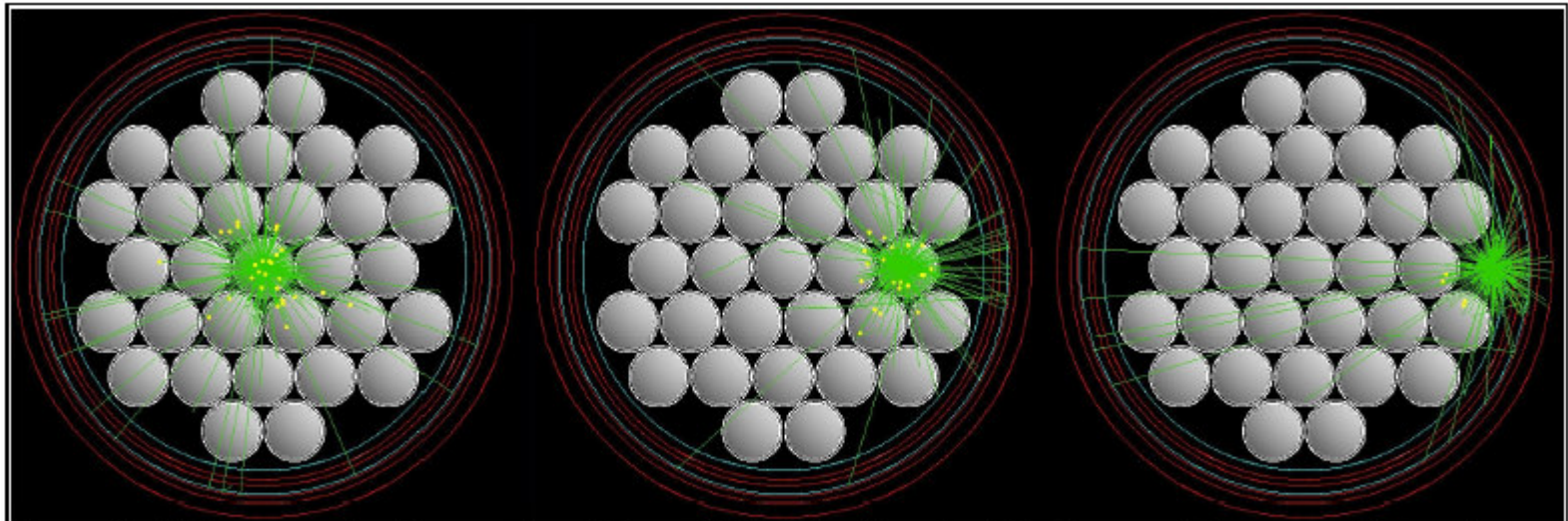


Figure 2: Light propagation (in green) and detected PMT hits (in yellow) for three typical events with one electron extracted from the liquid at different radii.

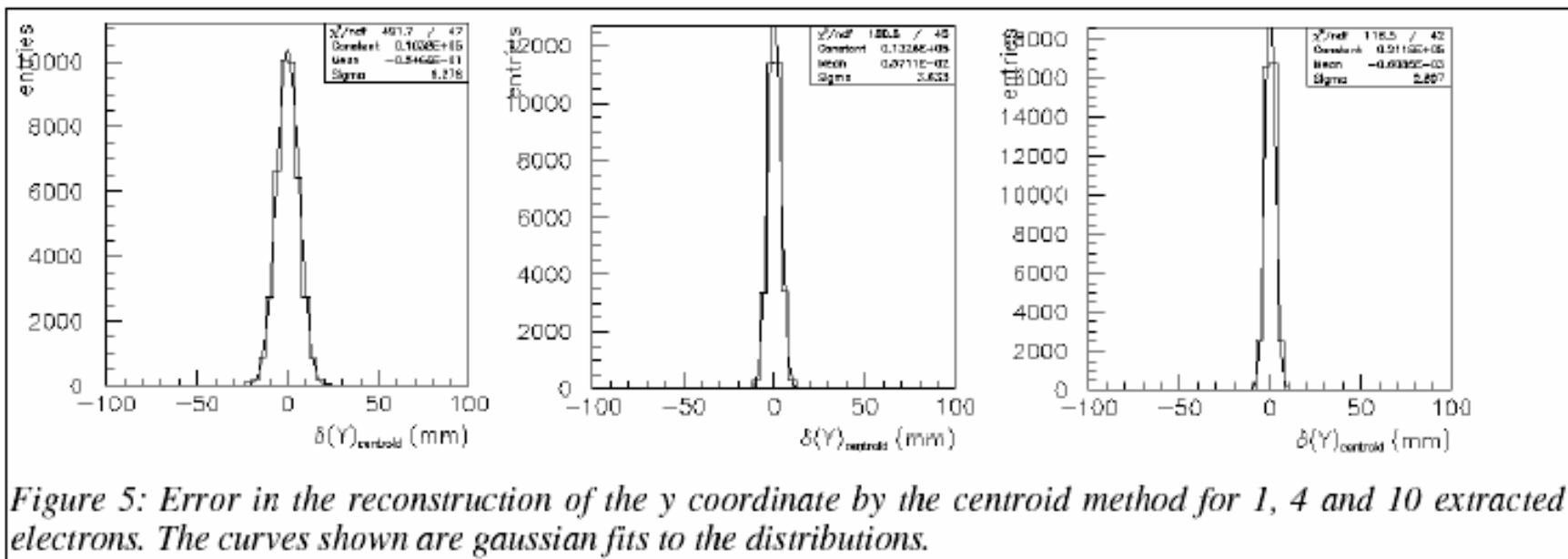


Figure 5: Error in the reconstruction of the y coordinate by the centroid method for 1, 4 and 10 extracted electrons. The curves shown are gaussian fits to the distributions.

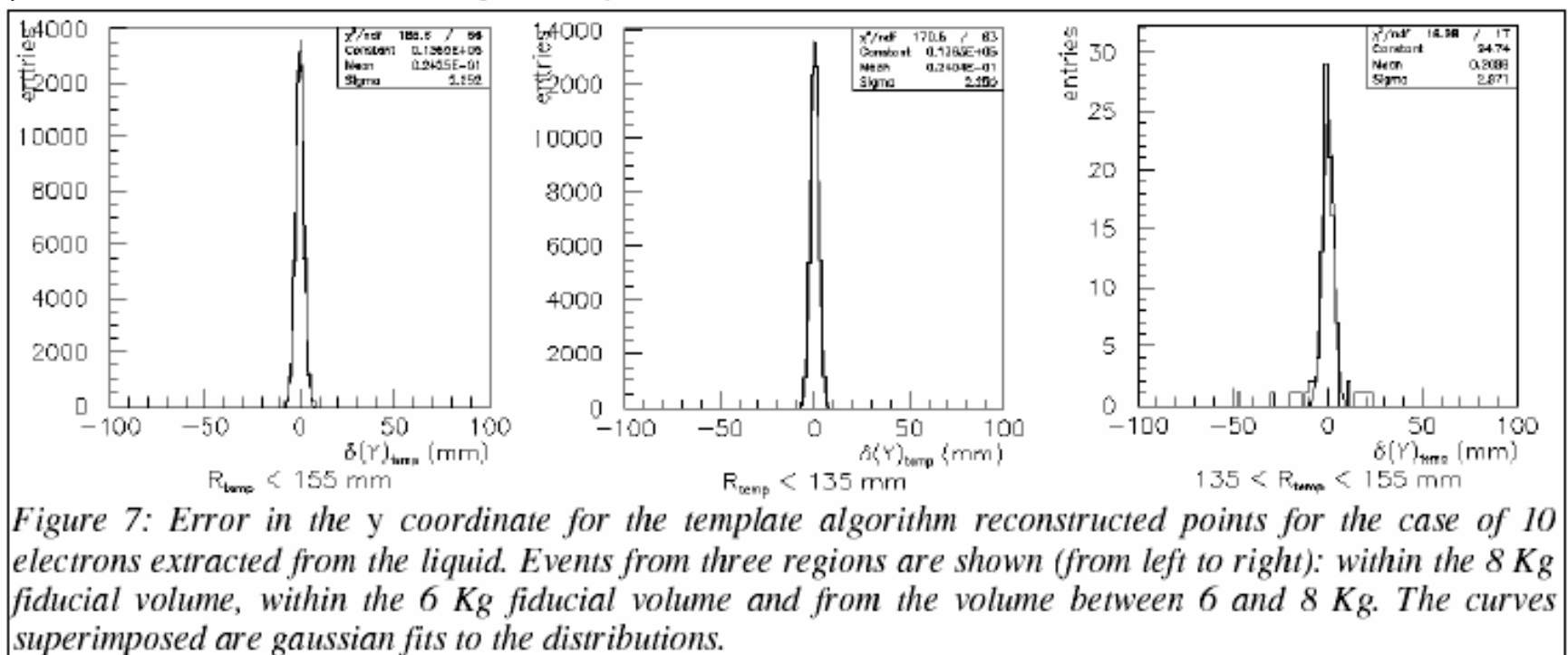
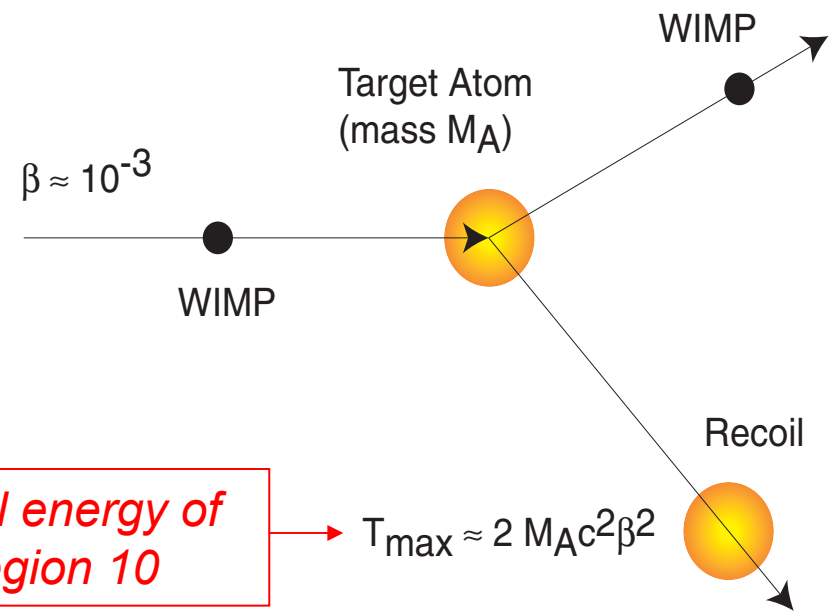


Figure 7: Error in the y coordinate for the template algorithm reconstructed points for the case of 10 electrons extracted from the liquid. Events from three regions are shown (from left to right): within the 8 Kg fiducial volume, within the 6 Kg fiducial volume and from the volume between 6 and 8 Kg. The curves superimposed are gaussian fits to the distributions.

Current ZEPLIN III Status

- **PMTs characterised at low temperature – published.**
- **Completed vacuum e-beam welding at The Welding Inst.**
- **Individual leak tests on all welds/seams to 10^{-10} mbar.l.s⁻¹**
- **Inner, outer and LN₂ vessels assembled and pressure tested at RAL – safety certification.**
- **Trial assembly of all parts**
- **First stage mechanical cleaning completed**
- **Cleanroom facility developed completed including customised cleaning procedures using ultrasonic bath and high pressure jets of water and alcohol.**
- **50kg low krypton xenon from ITEP**
- **Gas purification rig assembled**
- **Levelling system assembly ongoing**
- **Final assembly 85% complete**
- **On-line DAQ/analysis ready**
- **New lifetime monitor designed/built**

A large mass Liquid Argon detector under construction for the Gran Sasso Laboratory



Typical detectable recoil energy of the target atom in the region 10

$\square \div 100 \text{ keV}$

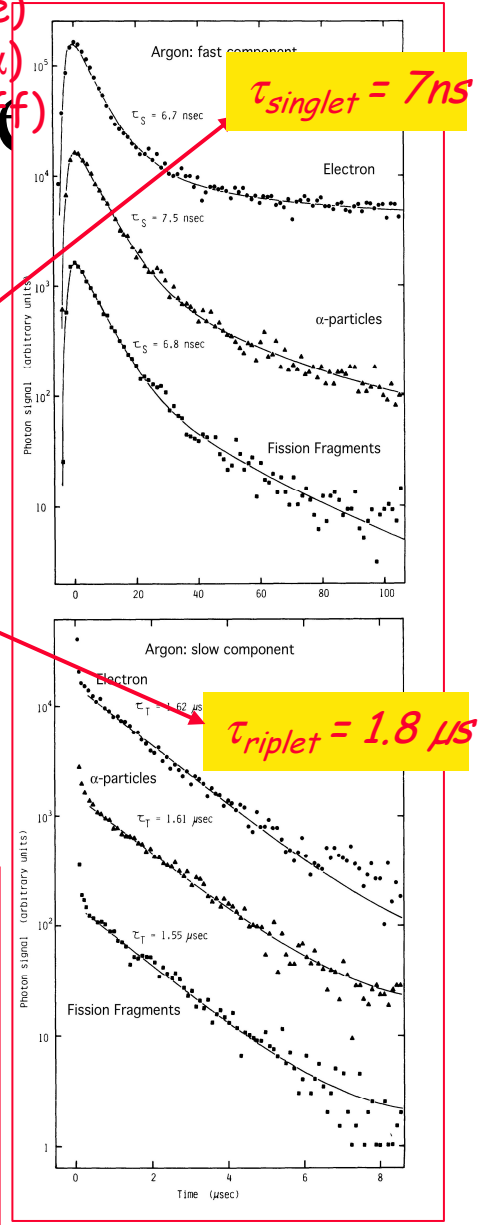
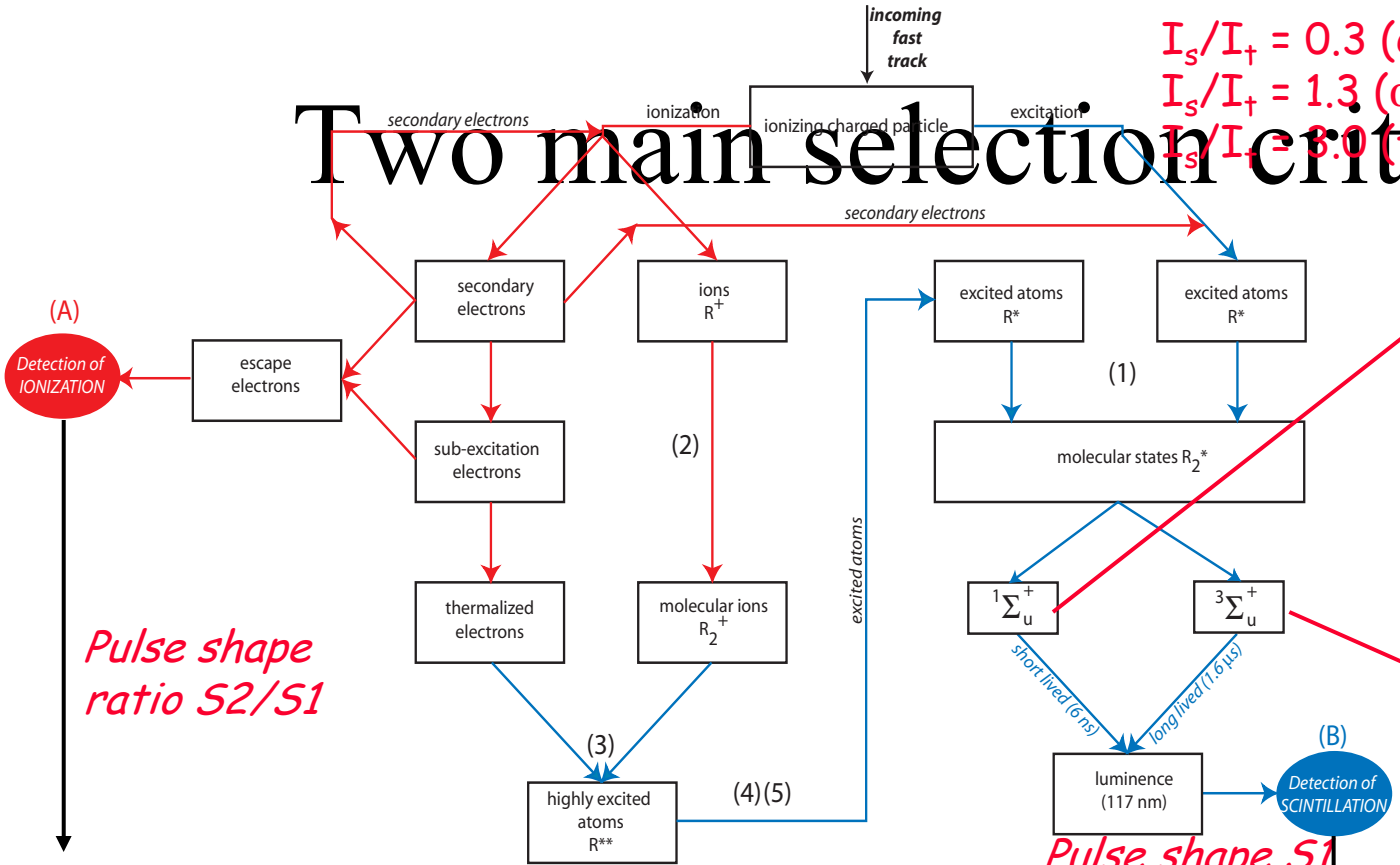
Another Argon advantage

- Time constants of singlet and triplet emission very different
 - Singlet ~ 7 nanosecs
 - Triplet ~ 1.8 microsecs

Populated differently by e's and NR's

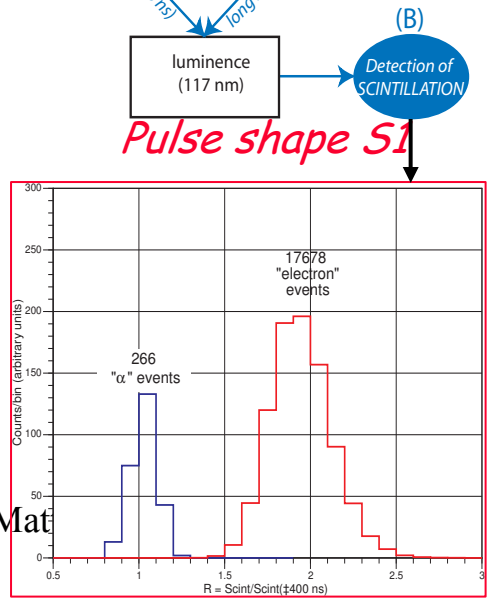
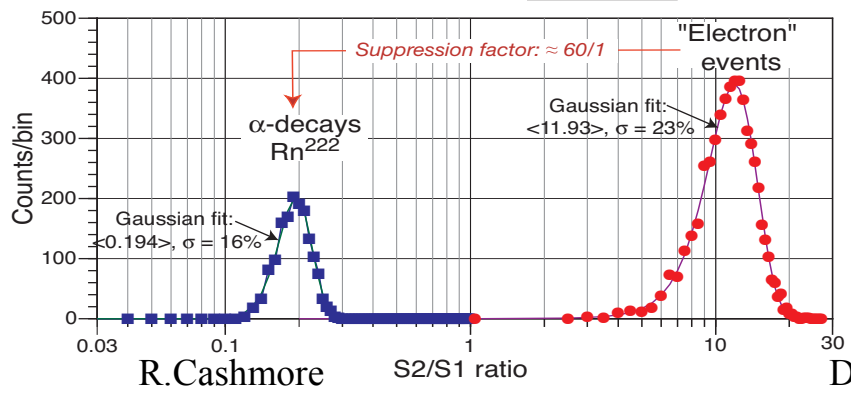
Two main selection criteria

$I_s/I_t = 0.3 (e)$
 $I_s/I_t = 1.3 (\alpha)$
 $I_s/I_t = 3.0 (ff)$



(A) Detection of IONIZATION

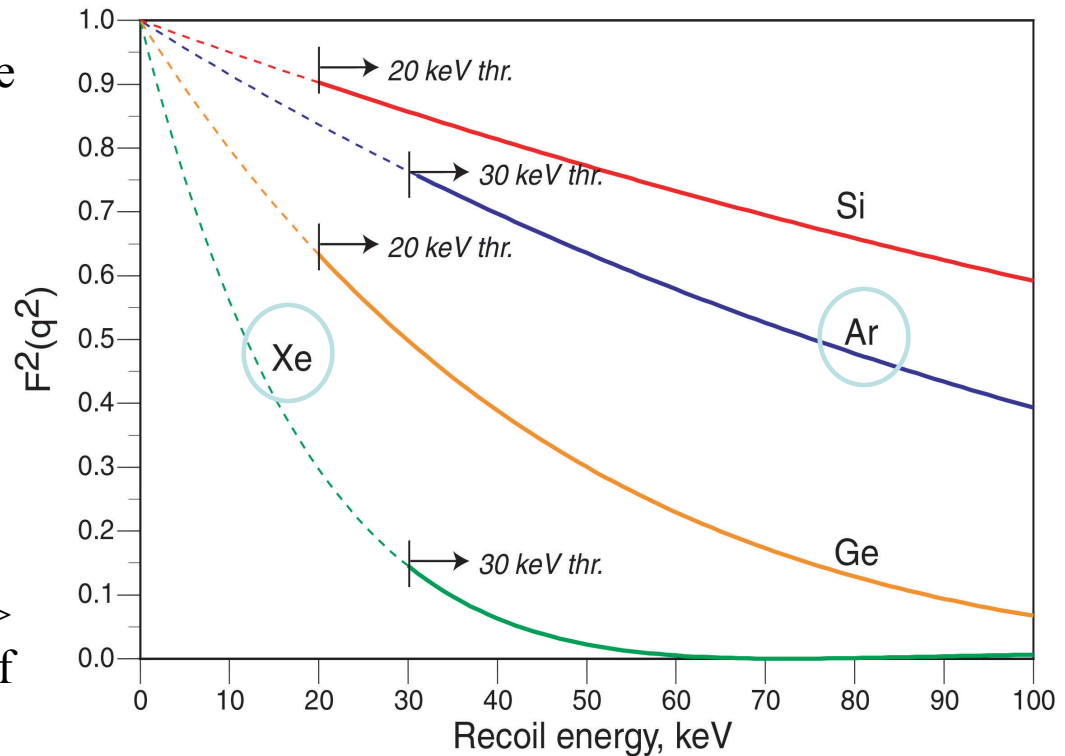
Pulse shape ratio $S2/S1$



Dark Mat

Advantages of Argon

- The suppression of the form factor is a function only of the recoil energy E_R and strongly dependent of the minimum recoil energy threshold.
- It is apparent that in the case of large A , as for Xe, the reduction factor is very large and it strongly depletes the "gold plated" events with largest energies.
- In practice no event with $E_R > 50$ keV survives in the case of Xenon.
- Argon is a pure isotope with $A = 40$ and zero nuclear spin.
- Ultra-pure liquid Argon technology is well supported industrially



- At a realistic energy threshold ($E_R = 30$ keV) both Argon and Xenon give very similar sensitivities since the a priori important coherence effect, very rapidly growing with A , is totally absorbed by the steeper form

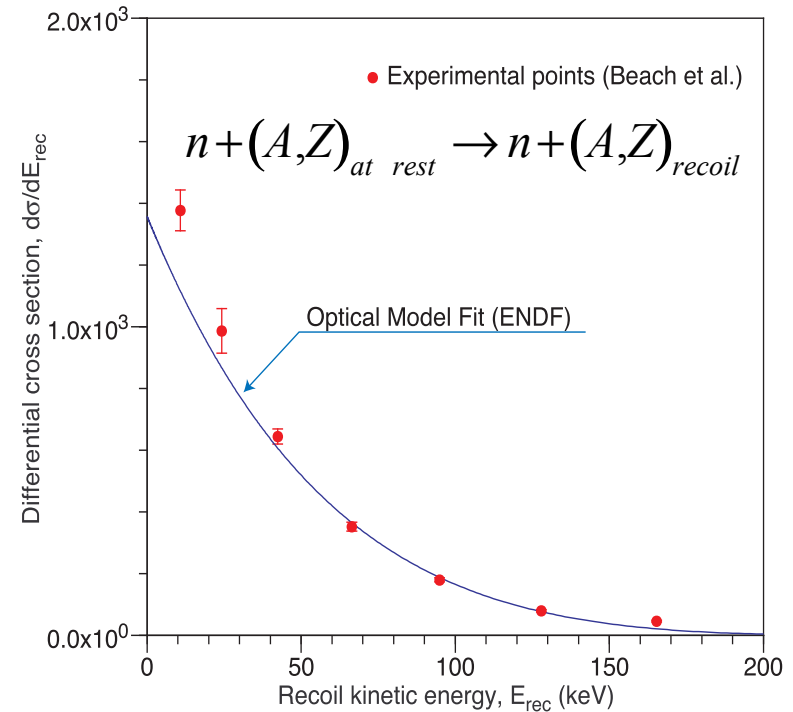
factor

Response to 14 MeV neutrons

- The 2.3 litre chamber has been exposed to the pulsed beam from a D-T 14 MeV neutron generator
- Fast neutrons interacting elastically with the Argon of the detector can be used to generate recoils in the energy range close to the one foreseen for a WIMP signal.
- As a main difference with respect to the α -events, now signals populate the energy interval which is appropriate to slow recoils from WIMP signals. They behave like “strongly interacting WIMP”.
- In order to convert the recorded number of photo-electrons due to the primary scintillation in LAr into an actual recoil energy, the experimentally measured dependence of the primary ionisation as a function of the Argon recoil energy has been introduced.

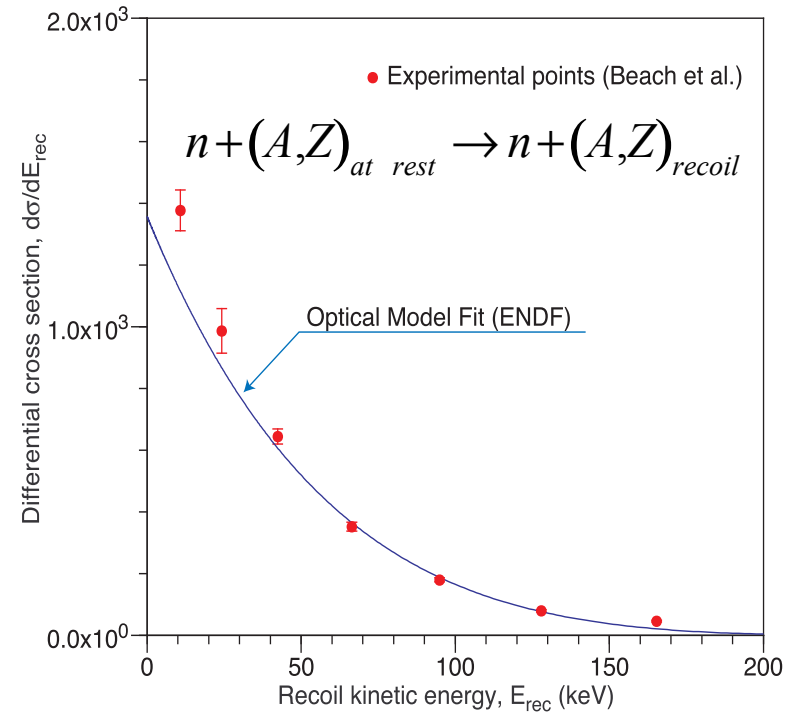
$$p(E_{rec}) = \Gamma f_N(E_{rec}) E_{rec}$$

Number of phe → $p(E_{rec})$
Light collection efficiency → Γ
Efficiency respect to min. ionising ($\beta = 1$) → $f_N(E_{rec})$
Recoil energy → E_{rec}



Neutron induced recoils have an about exponential energy spectrum, very close to the one expected from WIMP
 $\langle E_{rec} \rangle \approx 40 \text{ keV}$

Response to 14 MeV neutrons



Neutron induced recoils have an about exponential energy spectrum, very close to the one expected from WIMP

$\langle E_{rec} \rangle \approx 40 \text{ keV}$

Number of phe →

Light collection efficiency ↓

$$p(E_{rec}) = \Gamma f_N(E_{rec}) E_{rec}$$

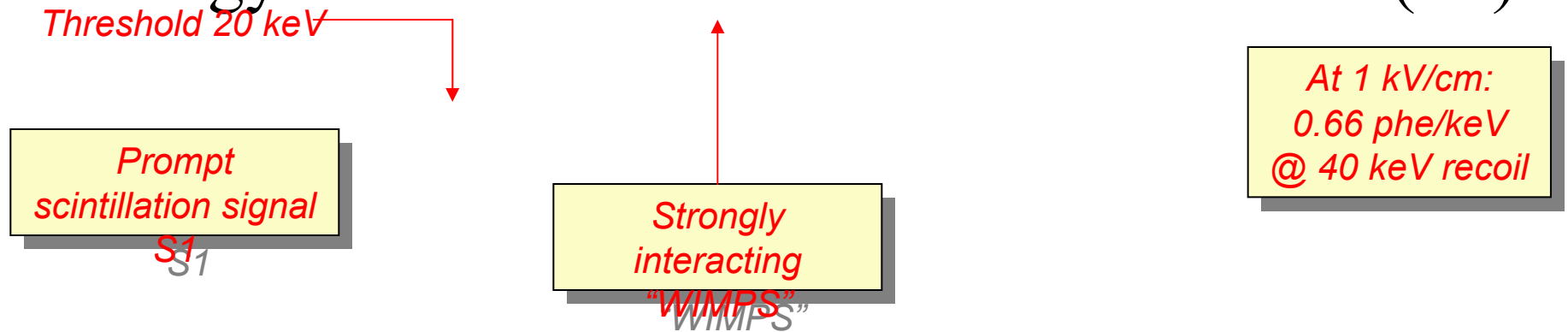
Efficiency respect to min. ionising ($\beta = 1$) ↑

Recoil energy ↓

R.Cashmore

D. A. M. 2

Energy distribution from scintillation in LAr (S1)

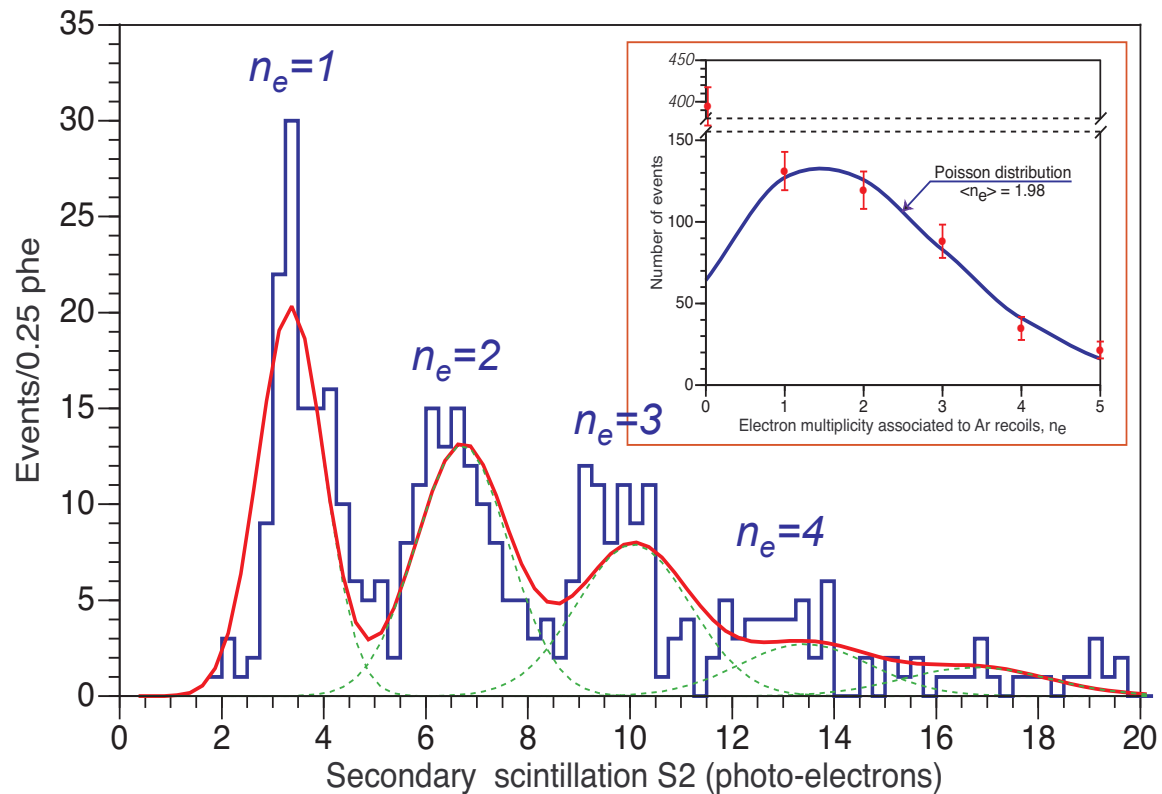


PARTICLE	S2/S1 (3.5kV/cm)
electrons (mip)	11.9
alphas (5-8 MeV)	0.19
nuclear recoil	- 0.1

- Experimental photo-electron distribution of events due to neutron recoils from 14.2 MeV neutrons. The continuous line is derived from the known recoil distribution of elastic scattering corrected by the

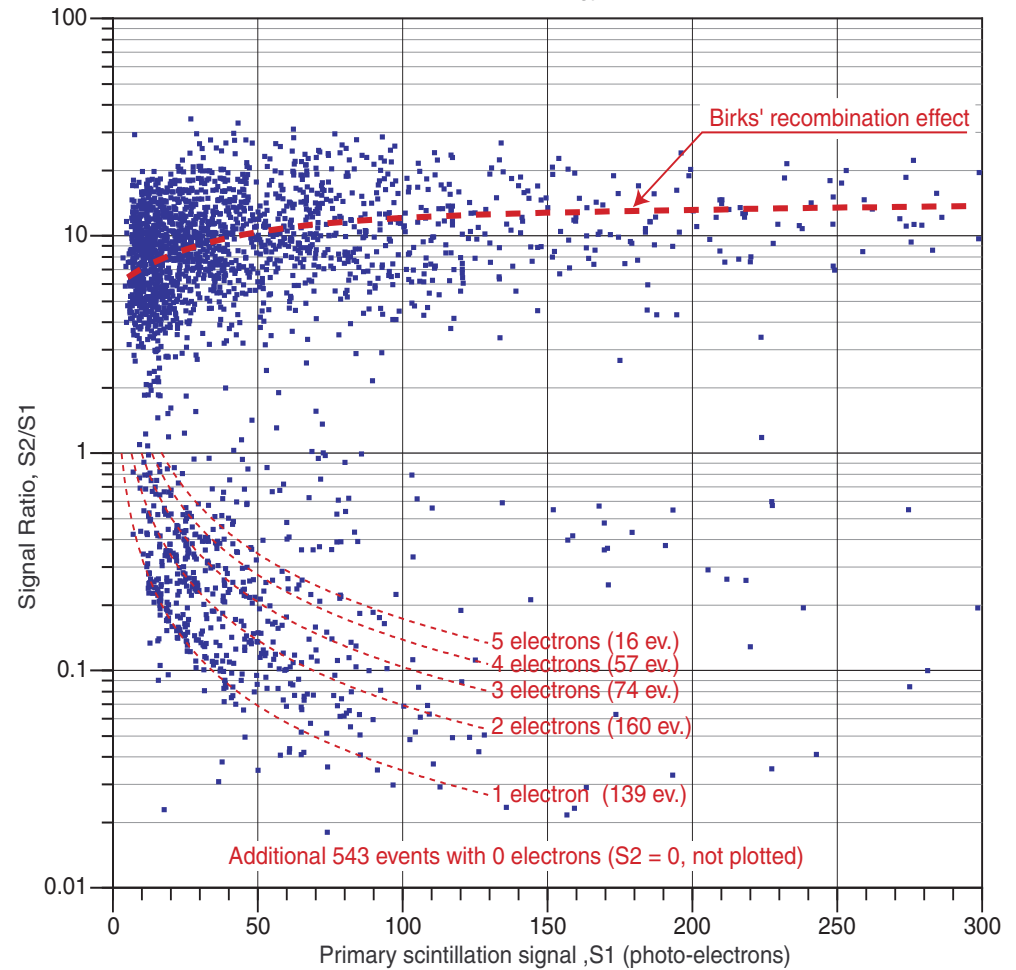
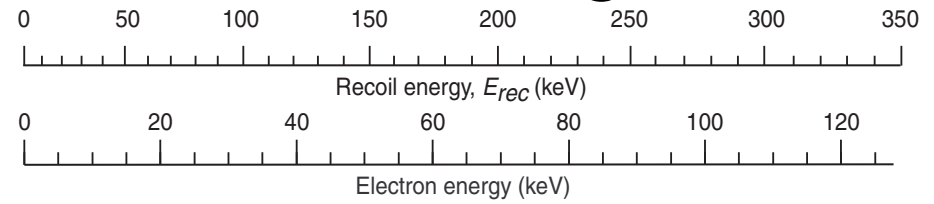
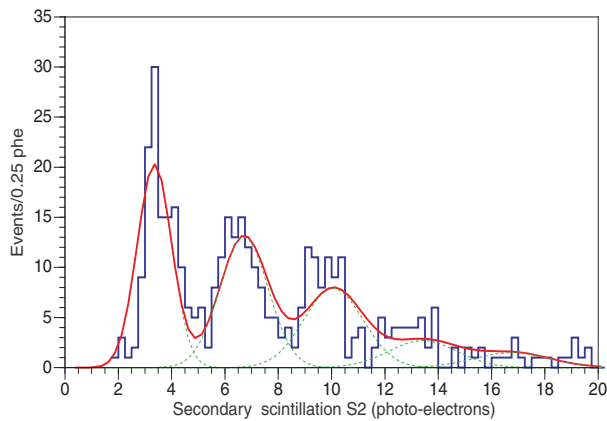
Number of electrons surviving recombination(S2)

- A cluster of electron events ($\approx 30\%$) due to recoils from neutron elastic scattering populate the region characterised by $S2/S1 < 1$
- They are well represented by a Poisson distribution and $\langle n_e \rangle = 1.88$
- A relatively large number of events with $n=0$, dominated by single phototube noise, have been removed.

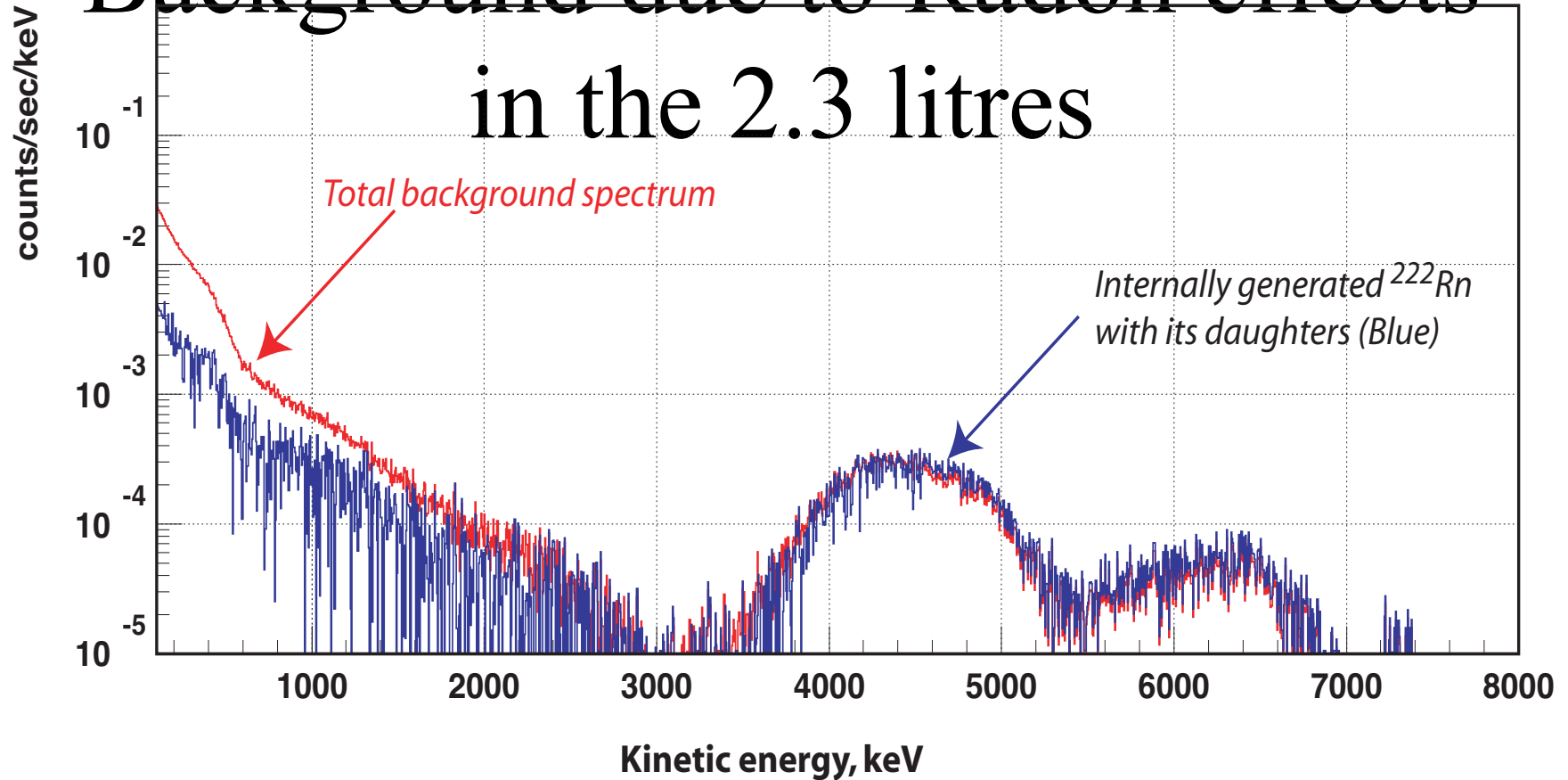


- The range of Argon ions recoiling from α -particle decay of ^{66}Ga has been found about $dE/dx \approx 4.2 \text{ keV}/(\mu\text{g}/\text{cm}^2)$, rather independent of E_{rec} , namely $\approx 2500 \times$ minimum ionising.
- Recombination (f.i. the so-called Box Model of Thomas and Imel) gives $\langle n_e \rangle = 2.0$
- The number of primary electrons should increase linearly with the applied electric field.
- $\langle n_e \rangle \neq 0$ permits a tri-dimensional localisation of the WIMP events in the detector.

S2/S1 vs. S1 distribution for 14.2 MeV generator.



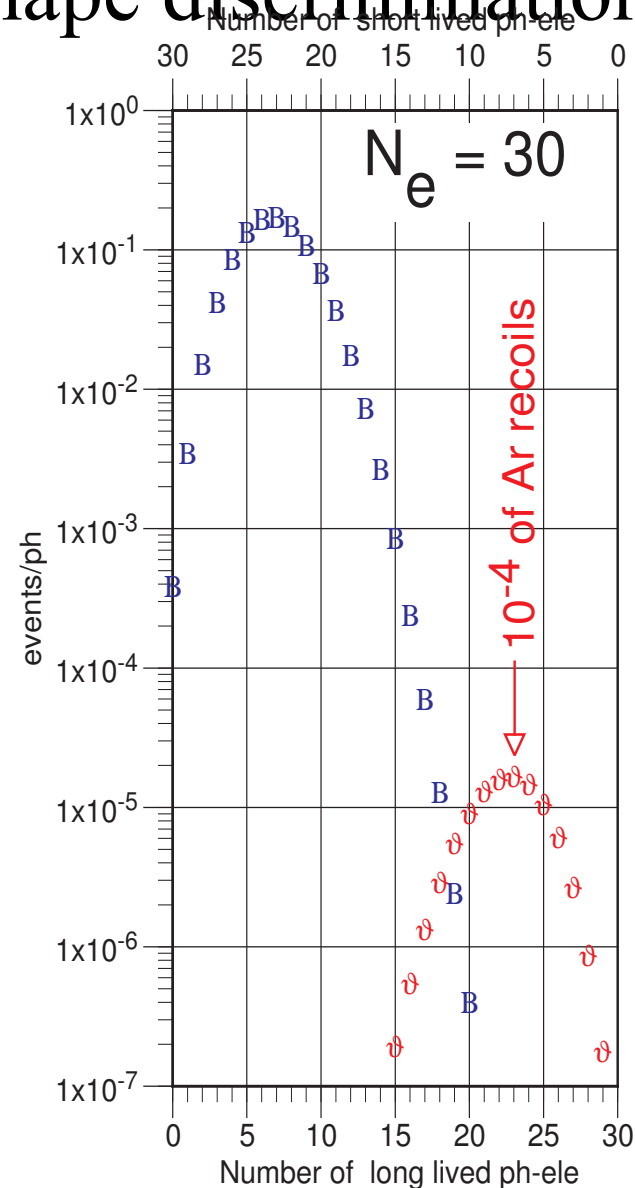
Background due to Radon effects in the 2.3 litres



Background identified by its natural decay rate

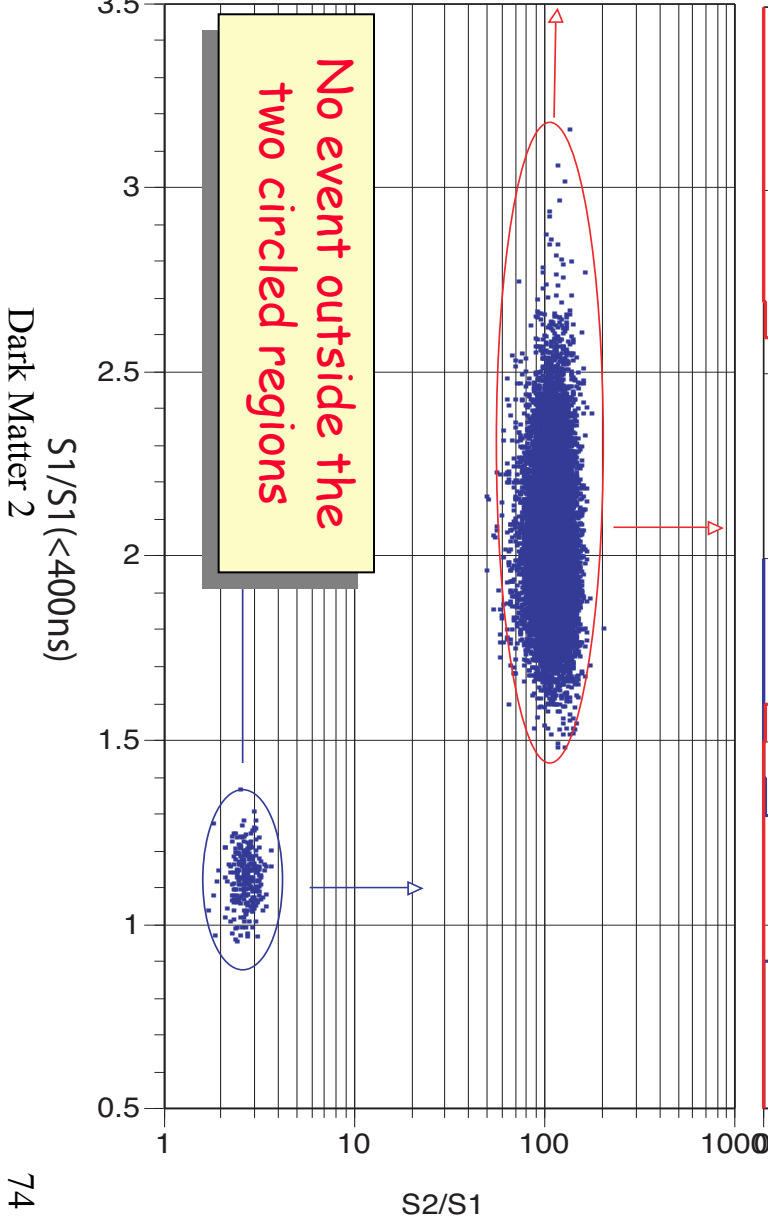
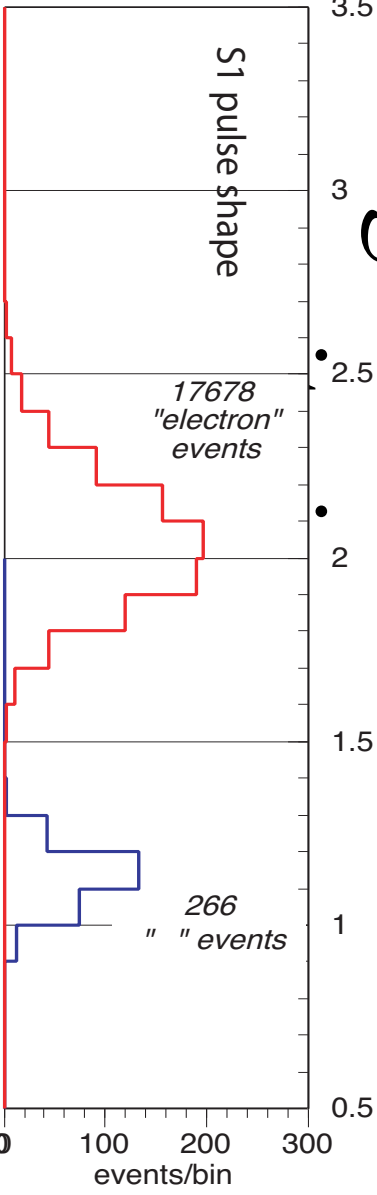
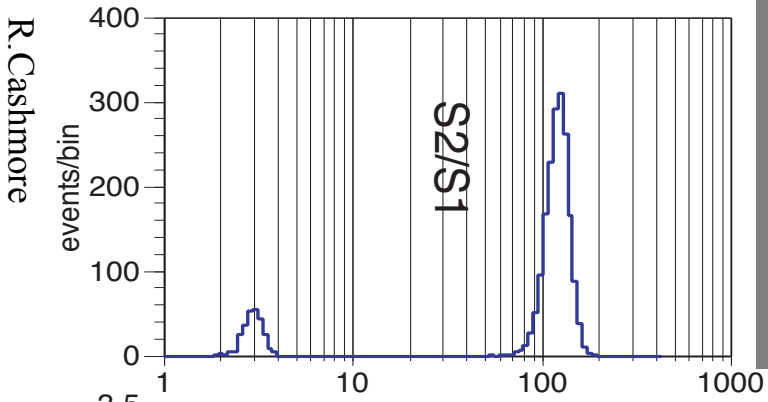
Statistical limitations of S1 pulse shape discrimination

- Calculations have been performed with a total number of photo-electrons $N_e = I_t + I_s = 30$. The average values of $I_s/(I_t+I_s)$ are respectively 0.23 and 0.75 for “electron like” and for Argon recoils.
- The actual subdivision in I_t and I_s according a binomial distribution, representing the statistical fluctuations in the number of photo-electrons is shown.
- In order to evidence the sensitivity of selection, the Argon recoil signal has been chosen to be 10^{-4} of the “electron like” signal. The separation of the two groups is quite acceptable.
- The separation may be very strongly improved with an increased number of photo-electrons, i.e. a more efficient light collection could considerably improve the quality of the method.



Combining the two selection

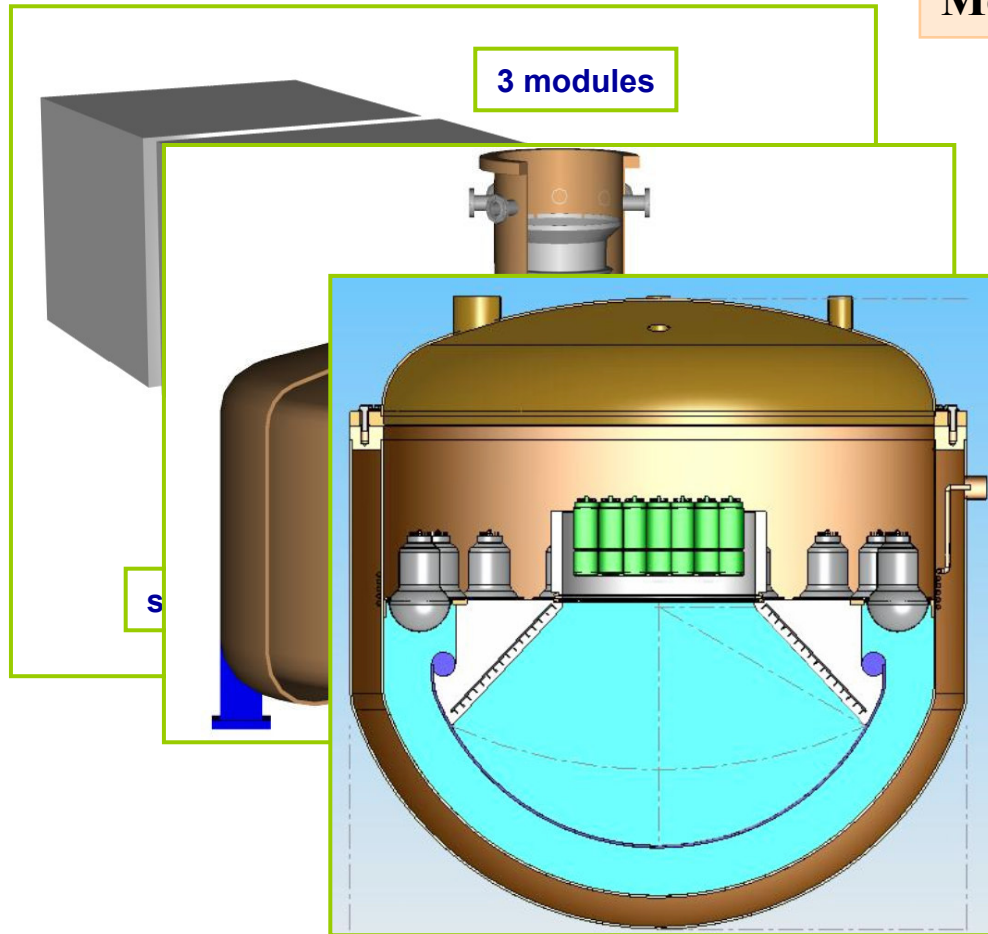
Complete agreement up to an observed level of $\approx 1/20000$



R. Cashmore

Dark Matter 2

ZEPLIN MAX - ONE TONNE FIDUCIAL!



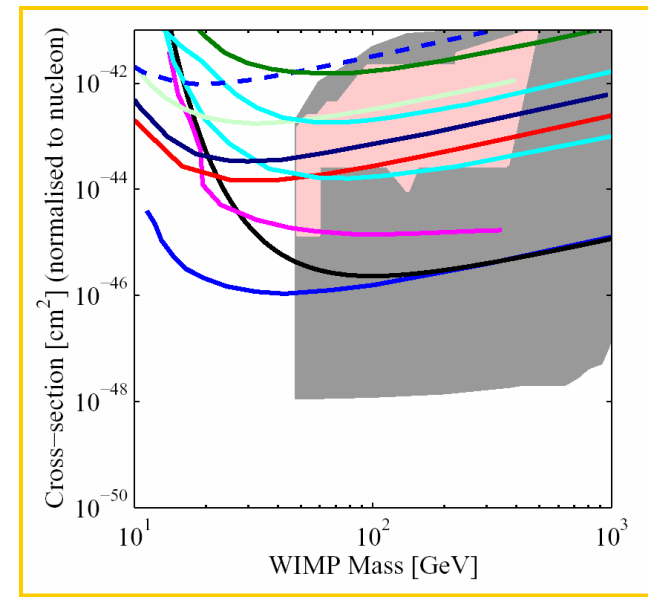
Motivation

Current world sensitivity limit: 4×10^{-7} pb
Supersymmetry predicts...

$$10^{-6} \text{pb} < \sigma_{\text{WIMP-nucleon}} < 10^{-11} \text{pb}$$

Zeplin II / III will reach at least 10^{-8} pb

Sensitivity reach of 1 T $\rightarrow 10^{-10}$ pb



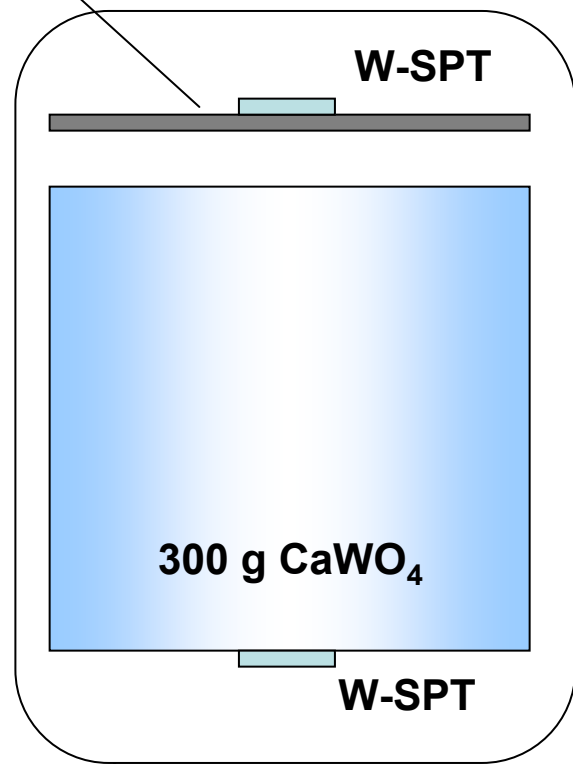
Solid State Detectors

- CRESST

CRESST-II Detector Concept

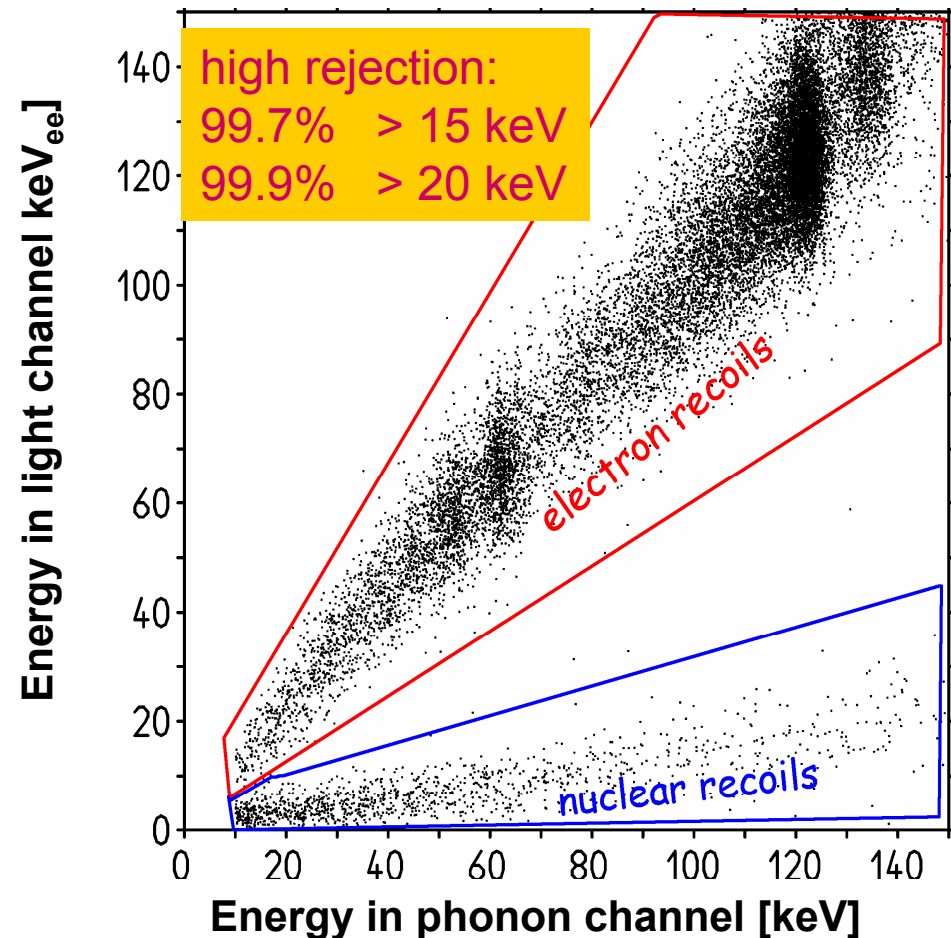
Discrimination of nuclear recoils from radioactive backgrounds (electron recoils) by simultaneous measurement of phonons and scintillation light

separate calorimeter as
light detector

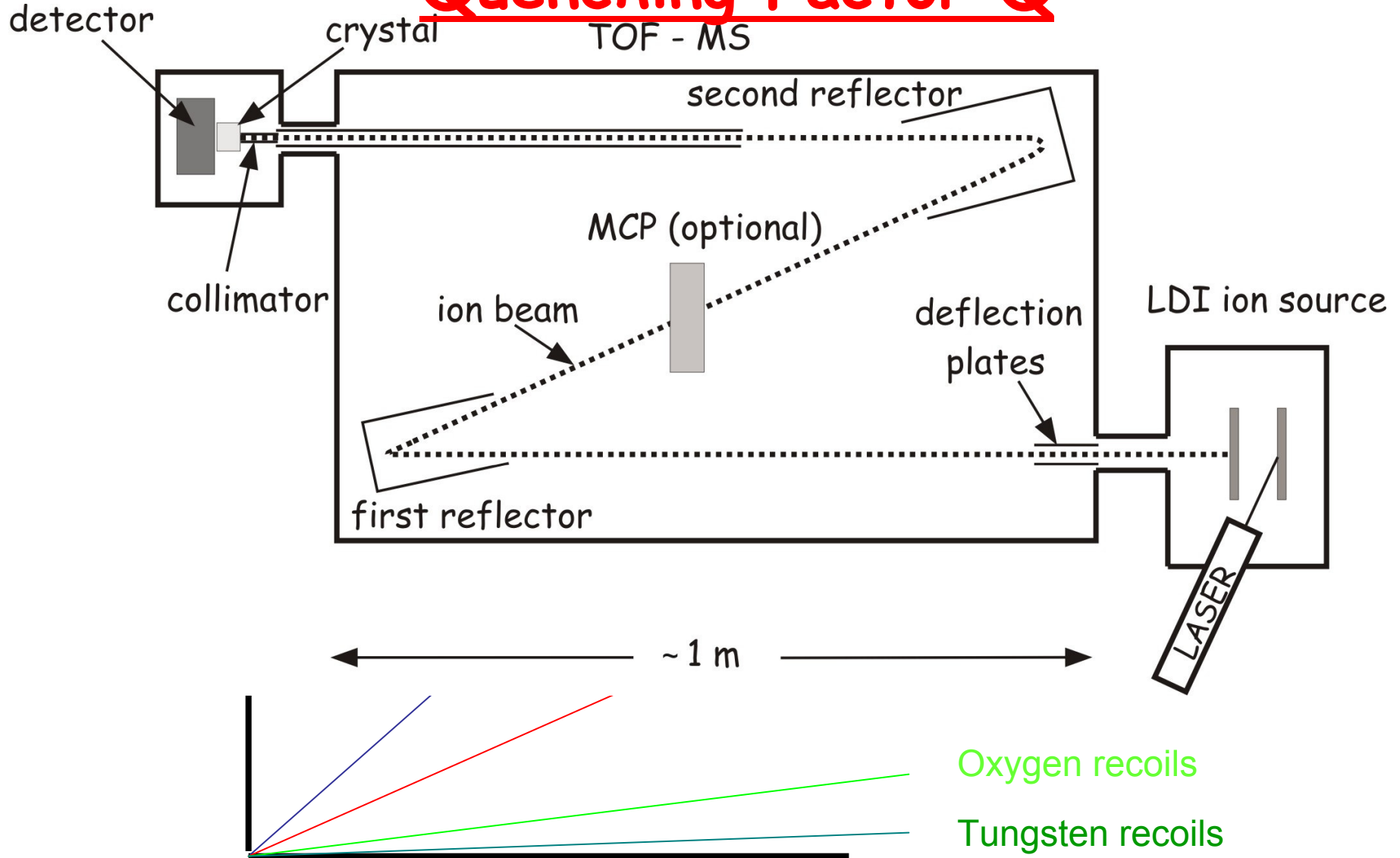


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light reflector

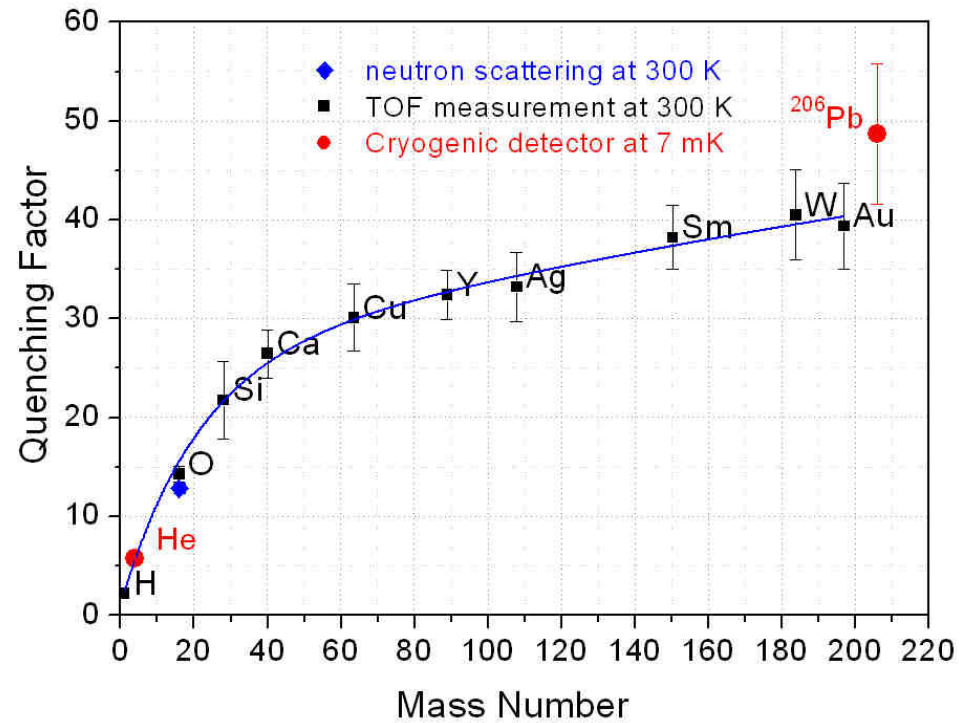
proof of principle



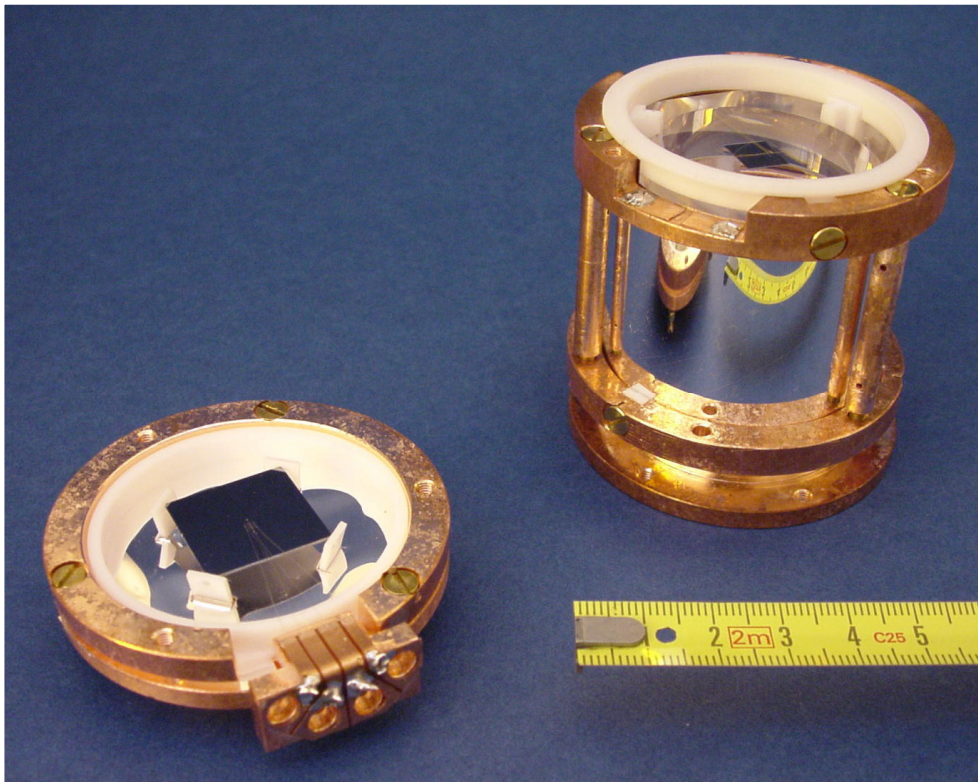
Quenching Factor Q



Quenching Factor Q



300 g detector module



Operating temperature ~ 10 mK

phonon channel:

300g CaWO_4

$\text{Ø} = 40\text{mm}$, $h = 40\text{mm}$

W-SPT $4 \times 6 \text{ mm}^2$

light channel:

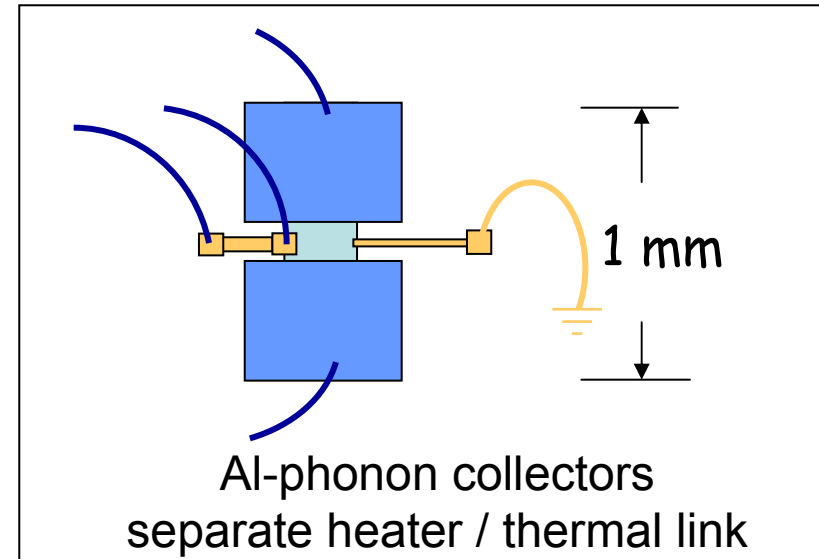
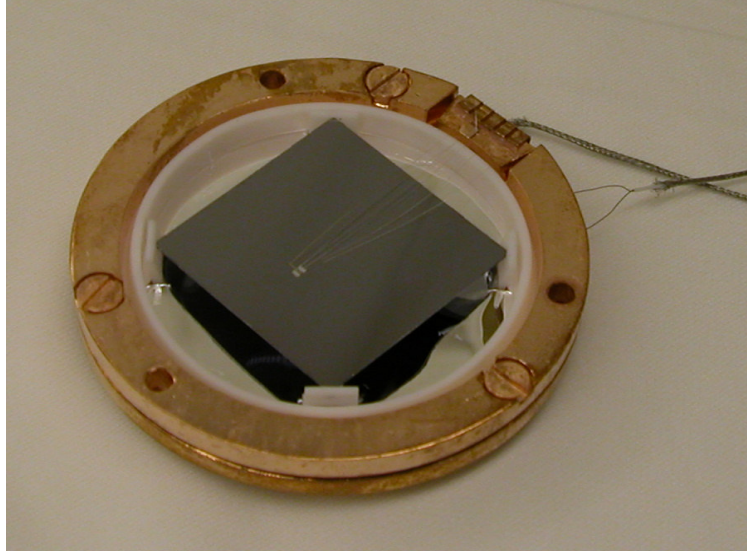
Si $30 \times 30 \times 0.4 \text{ mm}^3$

W-SPT with Al phonon
collector

reflector:

polymeric foil, teflon

Light Detector



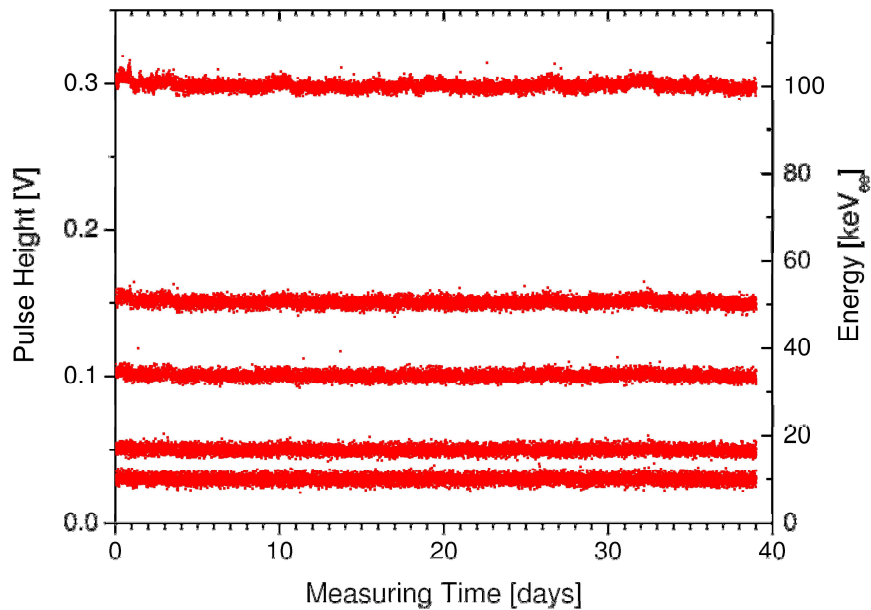
Si wafer ($30 \times 30 \text{ mm}^2$) read out by W-SPT

Effective threshold: $E_{\text{thresh,ee}} \sim 2 \text{ keV}$ (few photons)
10 to 20 eV absolute

Run 28 with two prototype detector modules taking data from 31st January to 23rd March 2004

Stability of detectors:

Very constant sensor response over a period of two months



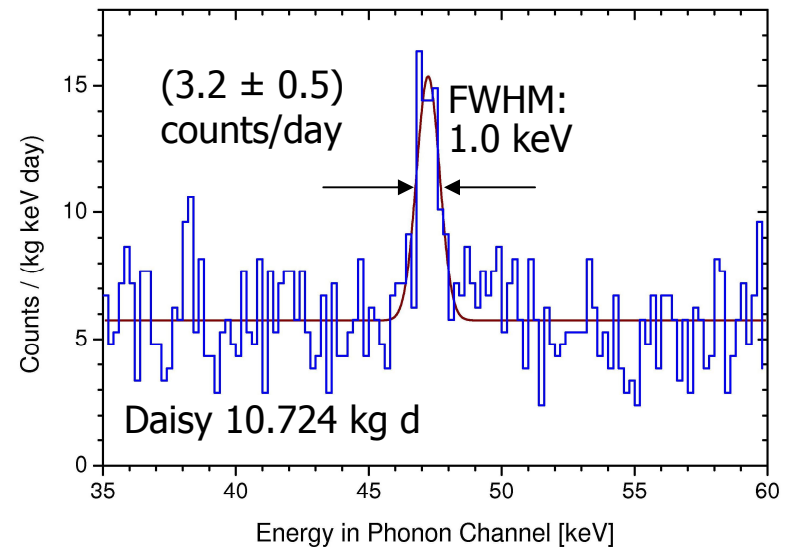
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Energy resolution of phonon detector:

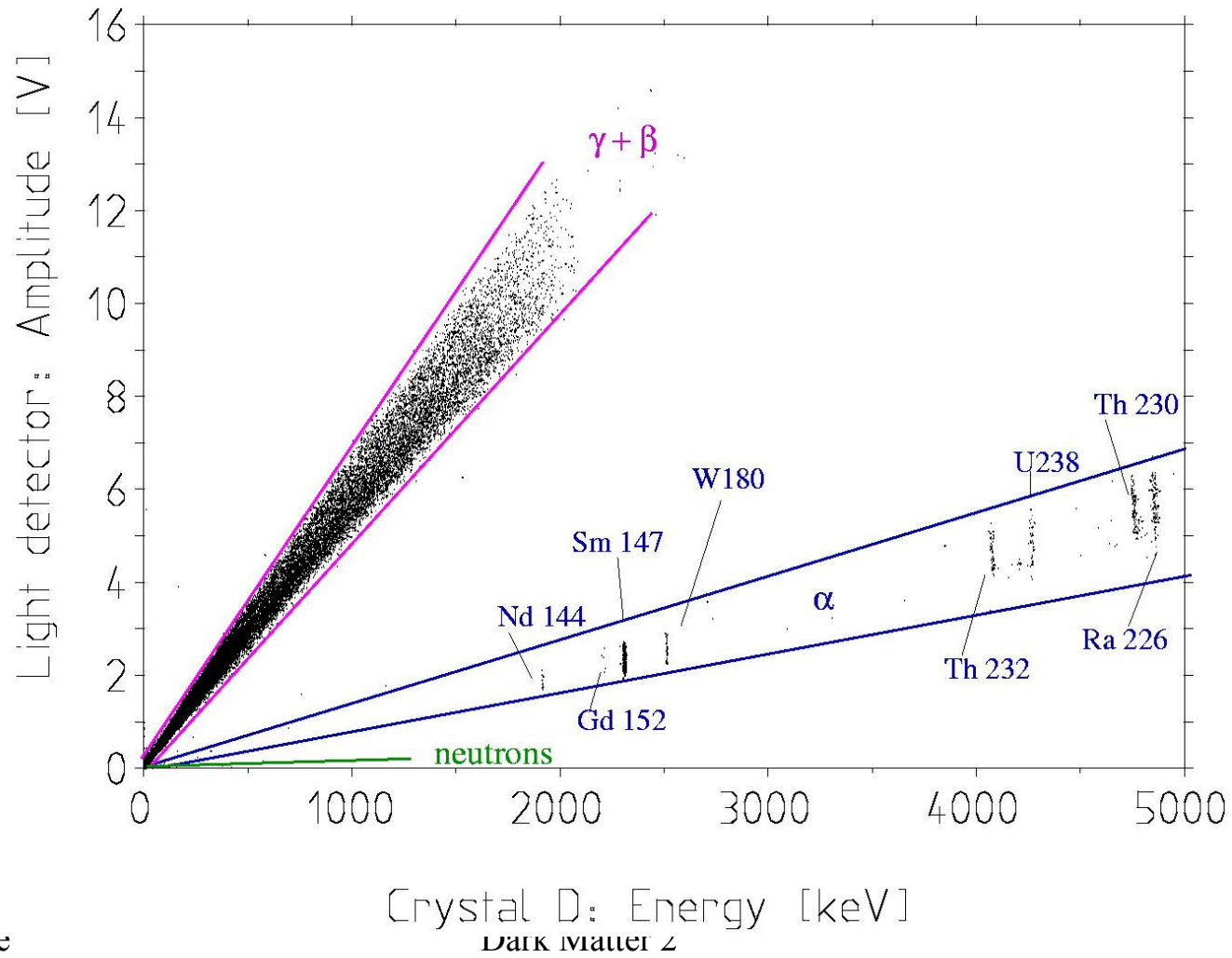
γ : 1 keV @ 46.5 keV:

α : 8 keV @ 2.3 MeV

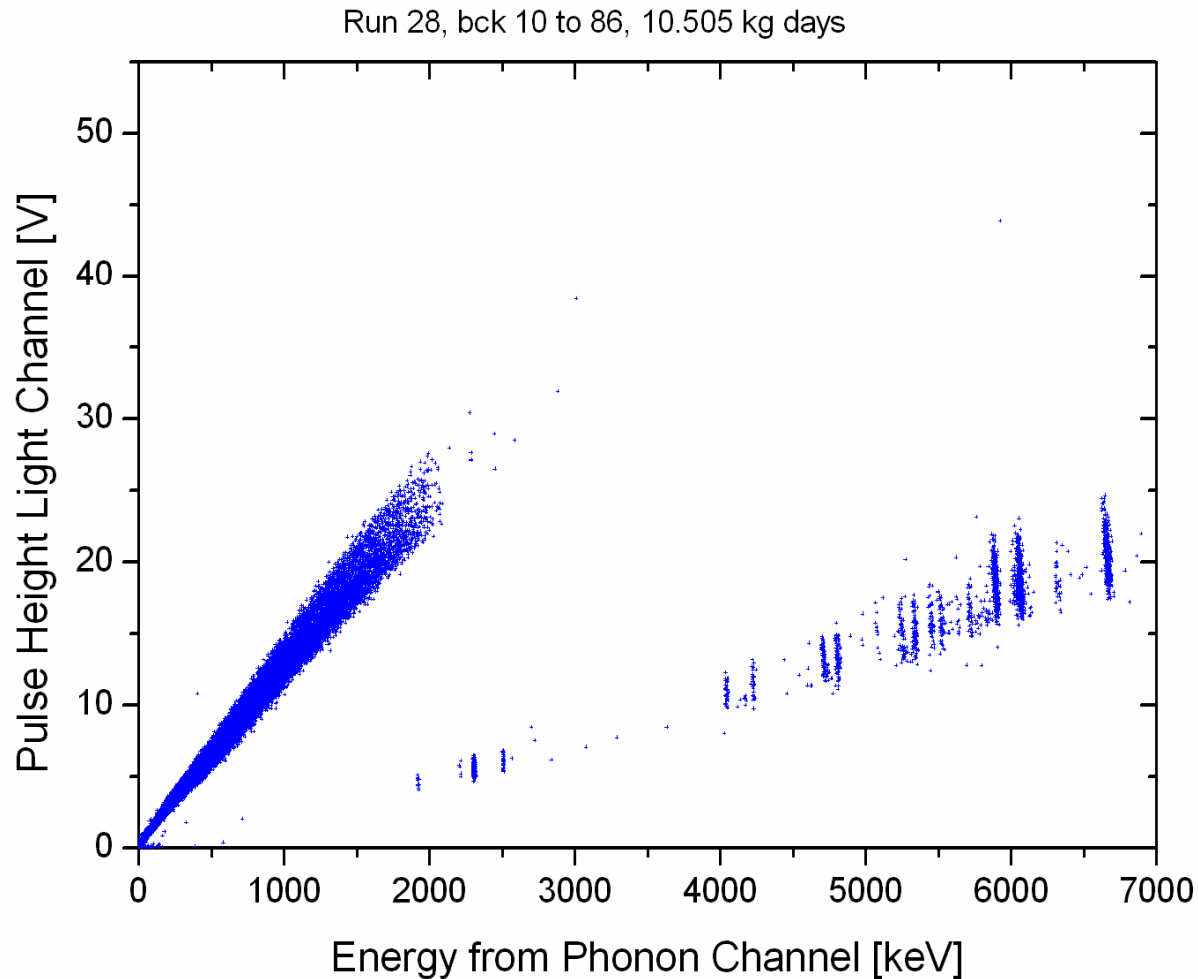


82

Energy in light vs. energy in phonon channel:

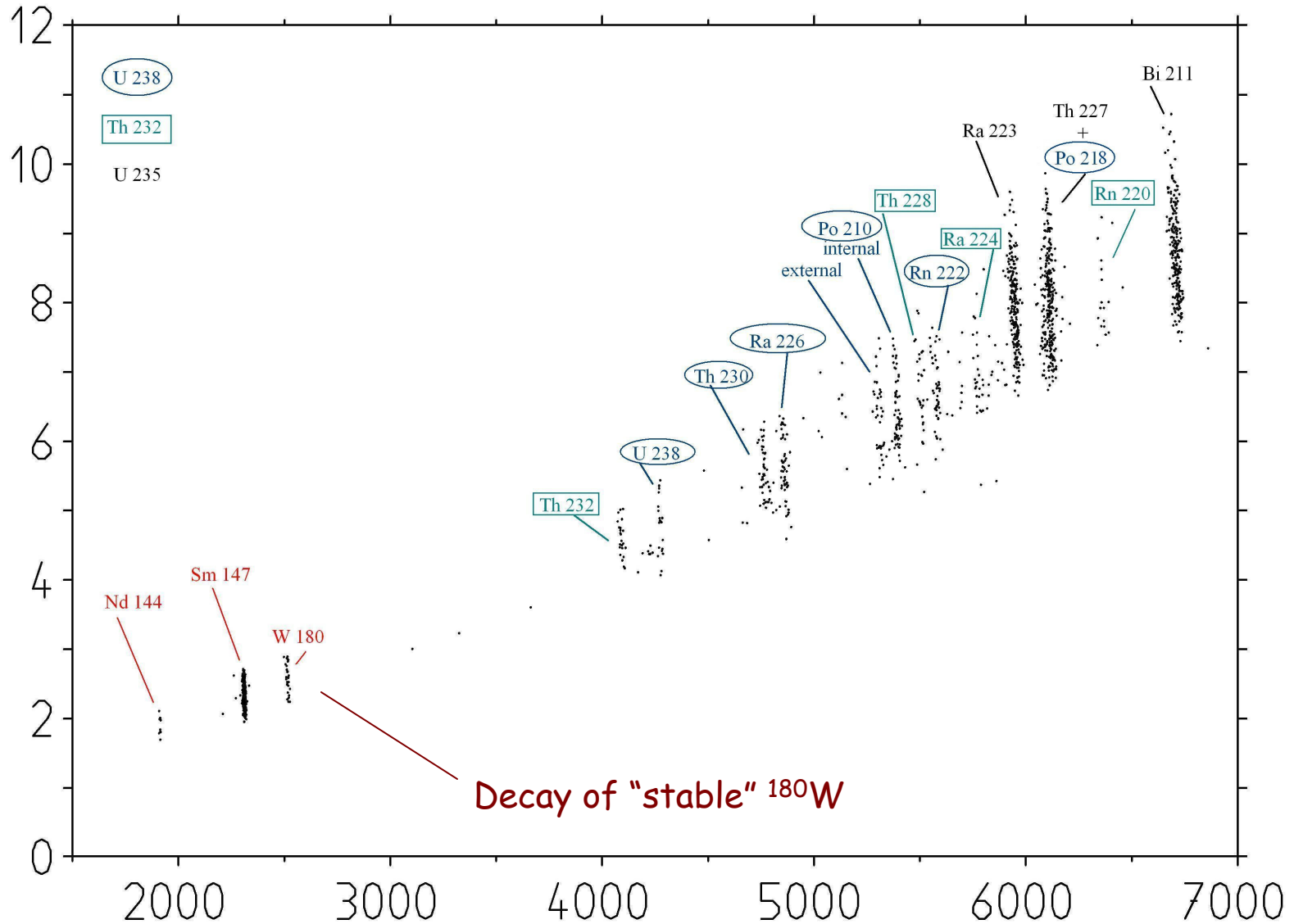


Detector Performance at high Energies

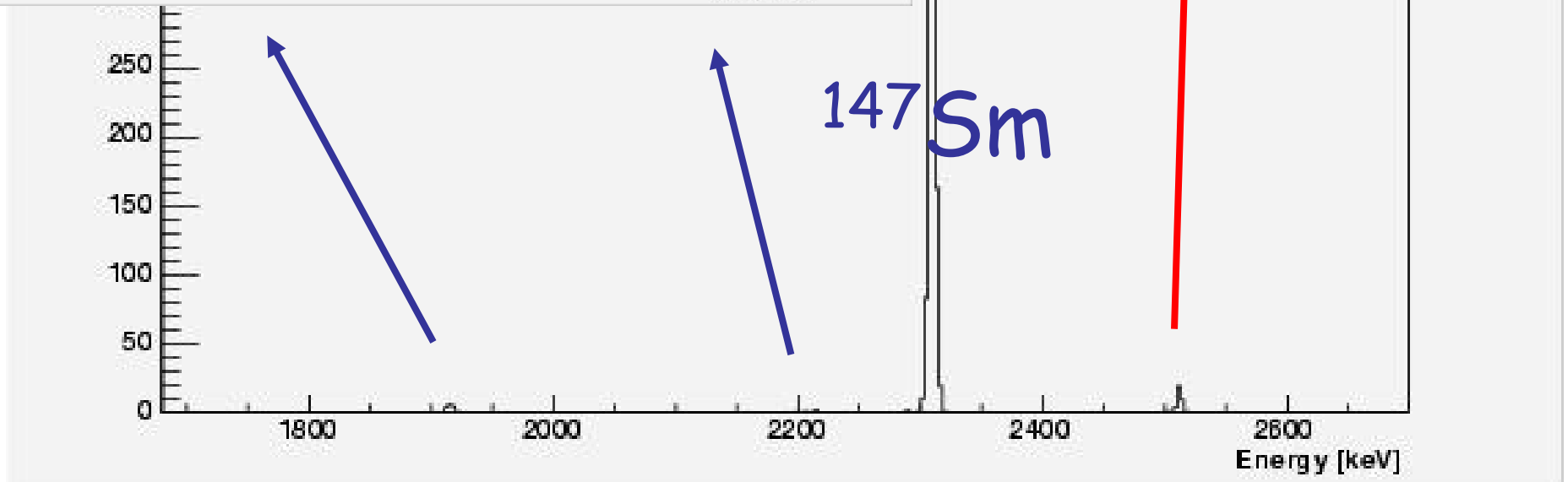
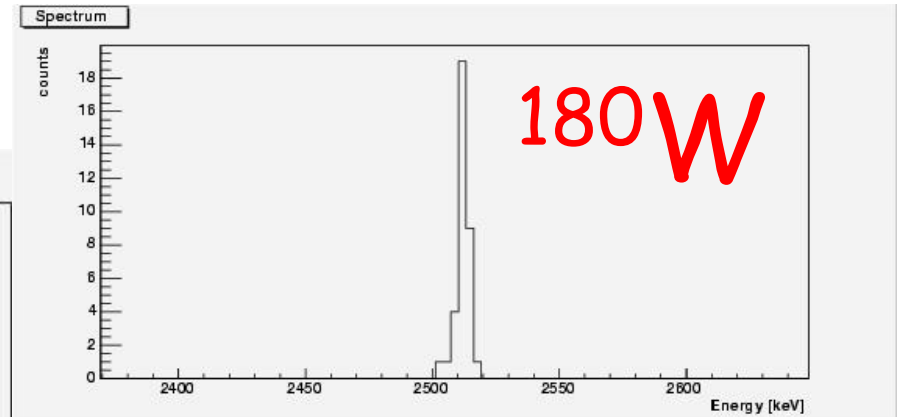
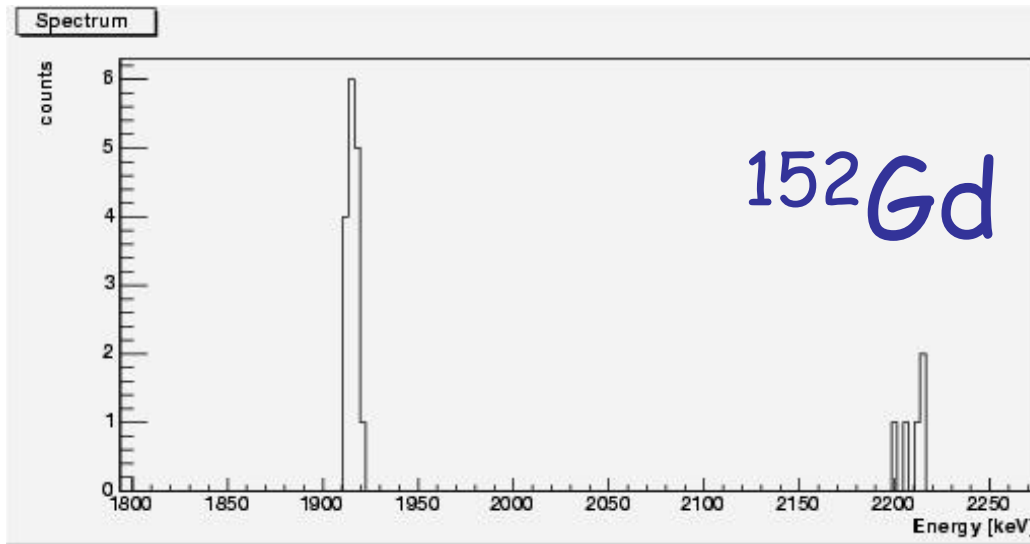


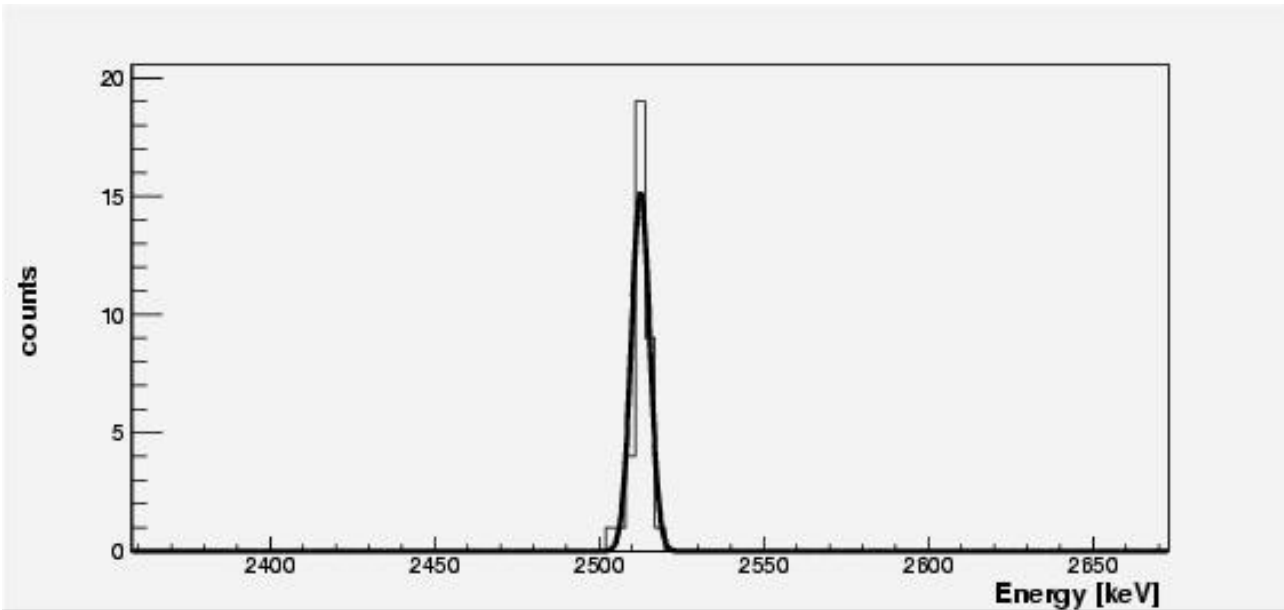
- Excellent linearity and energy resolution at high energies
- Perfect discrimination of β, γ from α 's
- Identification of alpha emitters (internal, external)

Identification of α -Emitters



^{144}Nd



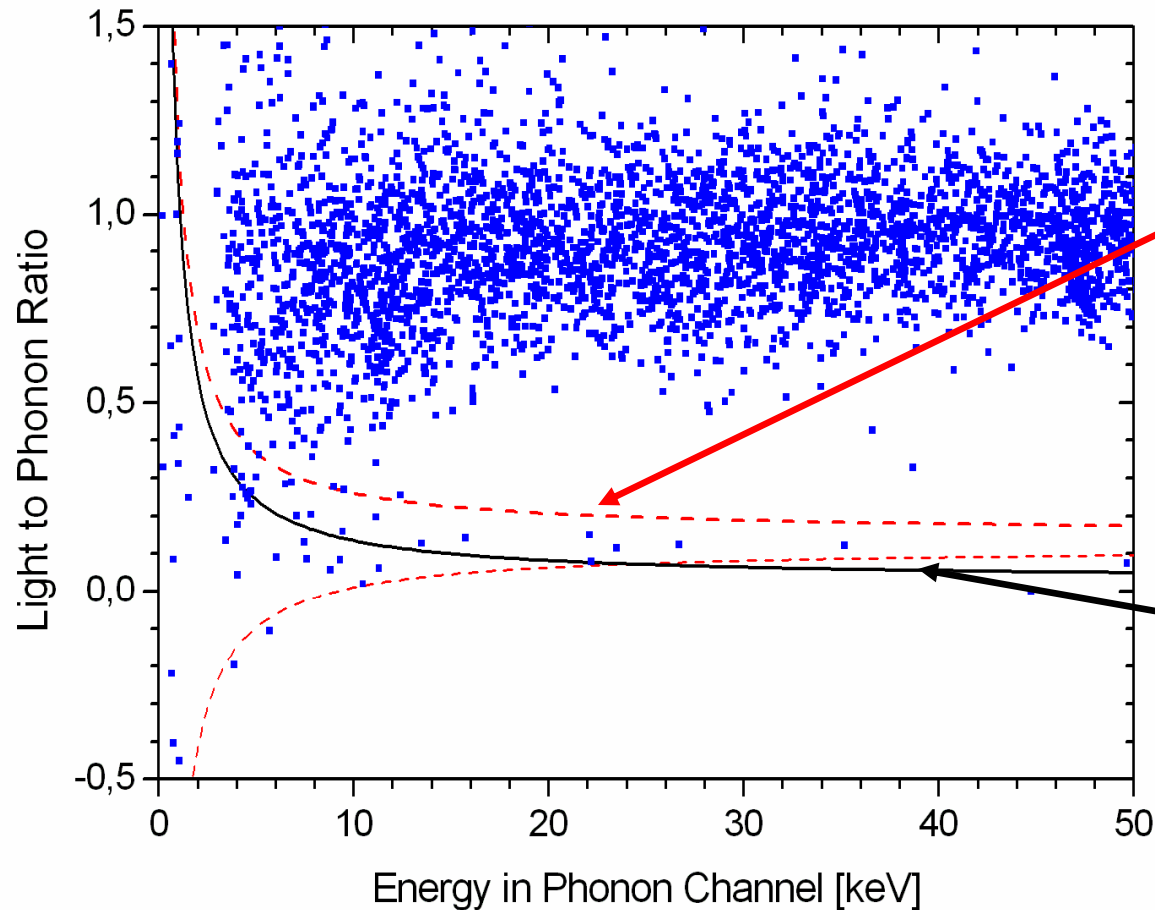


Half-life for the α -decay of ^{180}W
 obtained from the total exposure
 (28.62 kg days)

Half life	$T_{1/2} = (1.8 \pm 0.2) \times 10^{18}$ years
Energy	$Q = (2516.4 \pm 1.1 \text{ (stat.)} \pm 1.2 \text{ (sys.)})$ keV

Low Energy Event Distribution no neutron shield

10.72 kg days



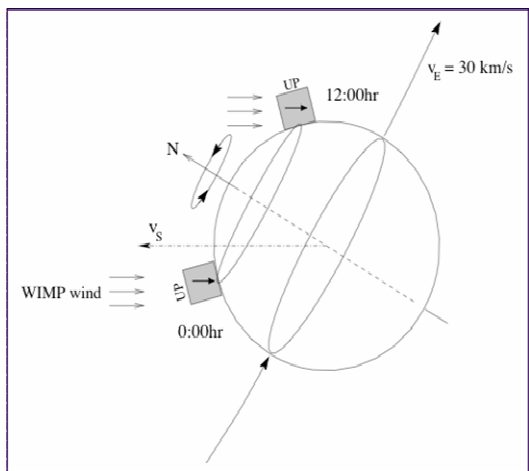
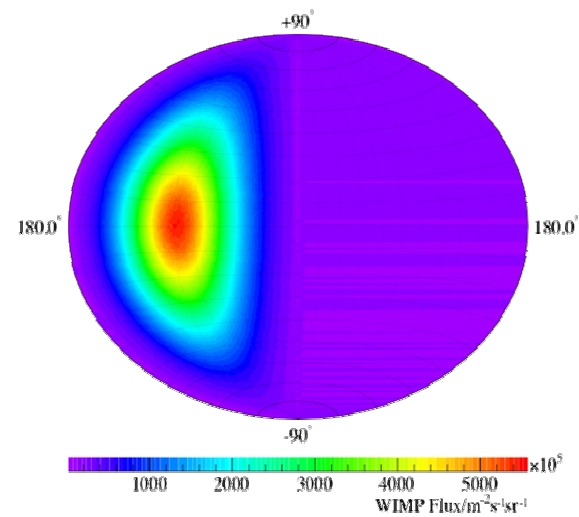
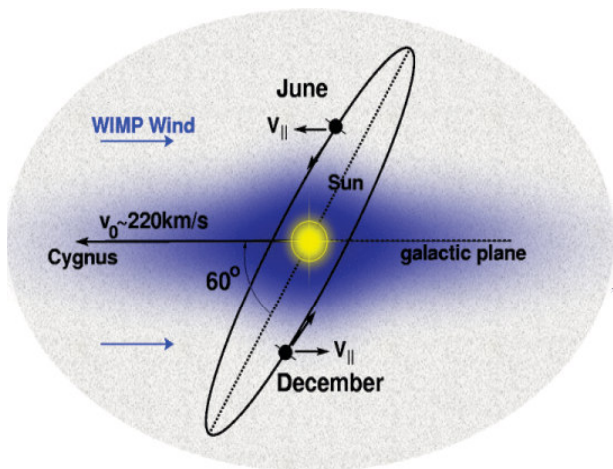
90% of nuclear recoils with quenching factor 7.4 below this line

90% of nuclear recoils with quenching factor 40 (tungsten) below this line

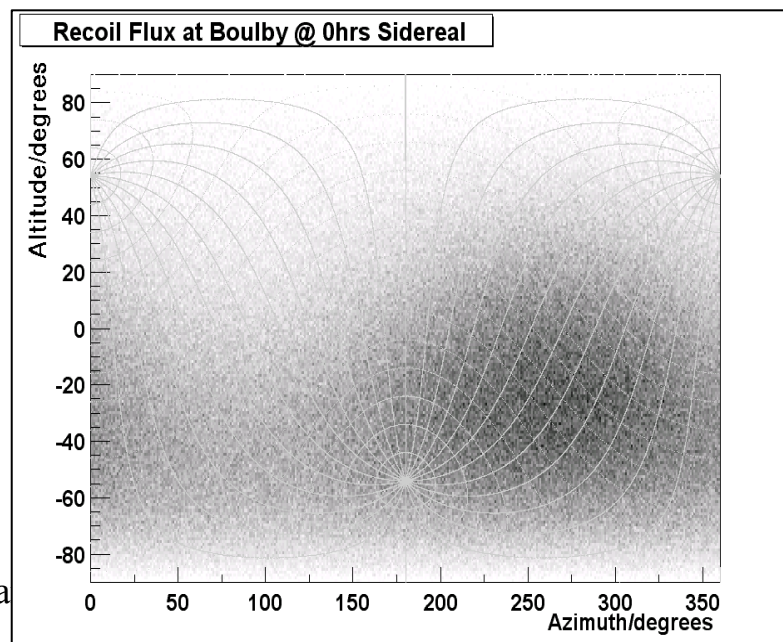
Directional Detectors

- DRIFT

Directional Effects

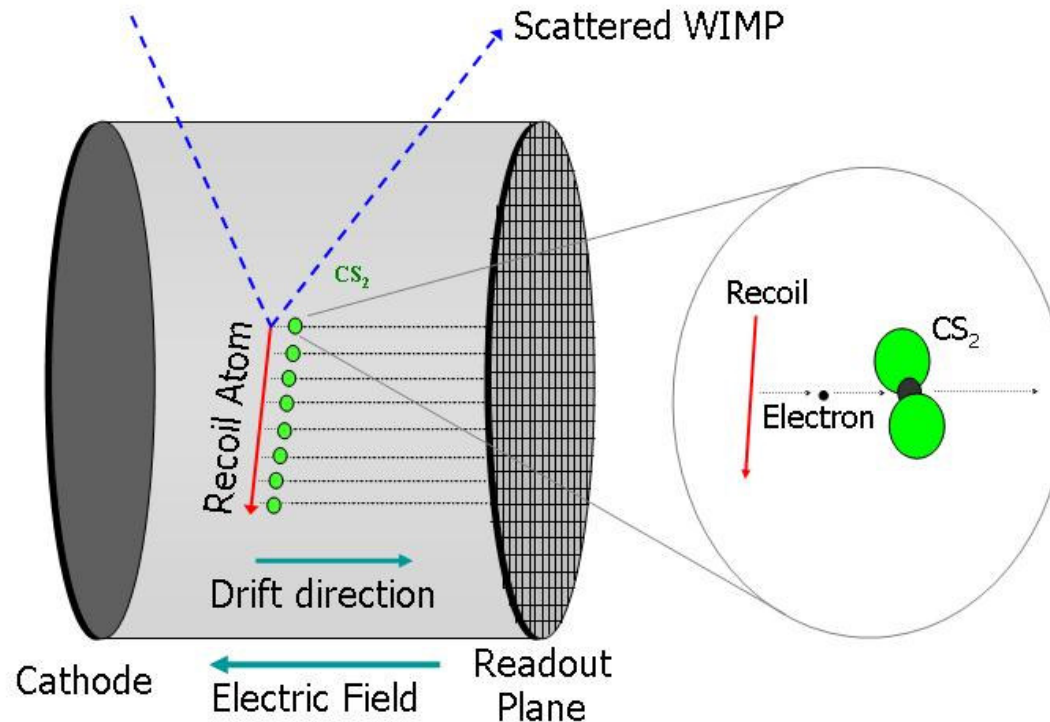


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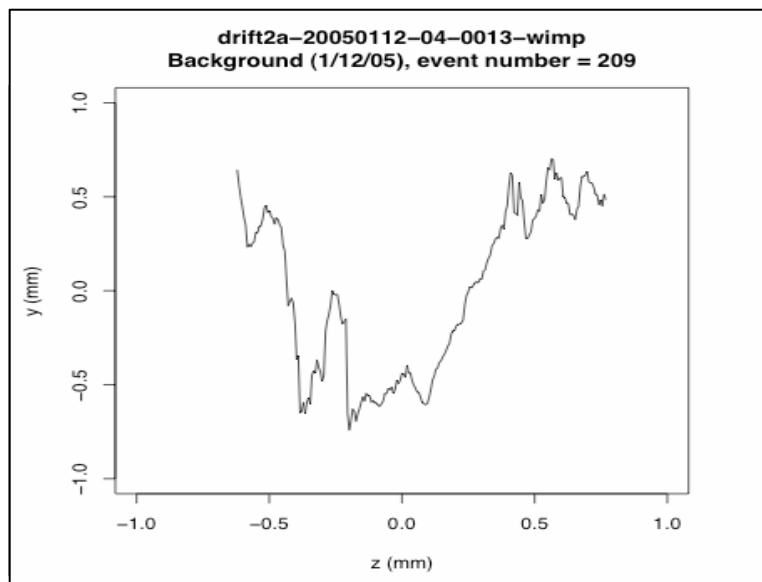
Da

90



Ionisation electrons rapidly attach to CS_2 molecules and these are drifted to read-out plane. High-field detaches electrons which are then detected in proportional gain mode using fine wire read-out

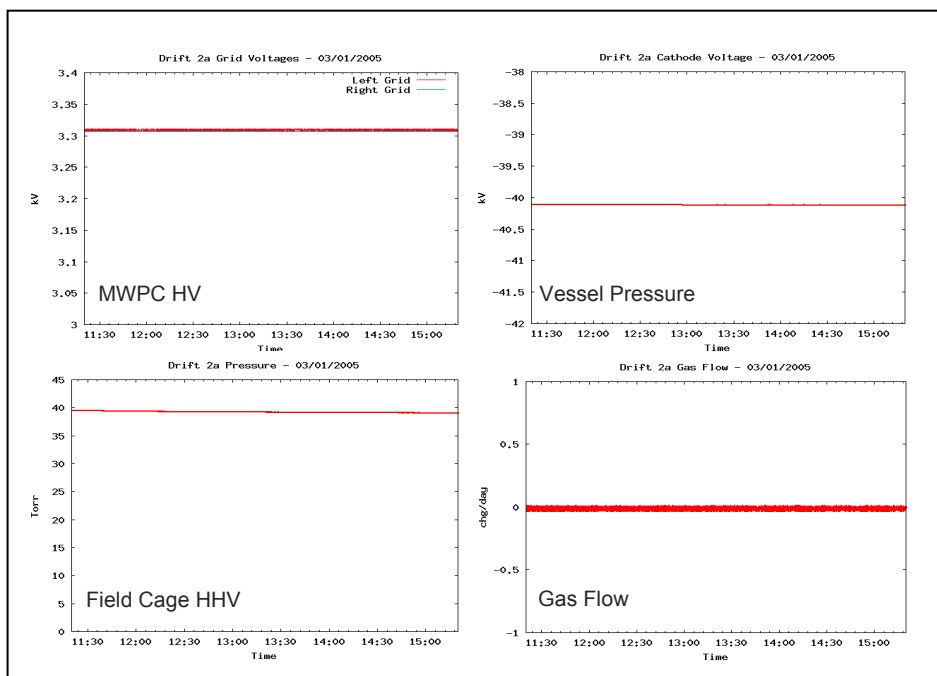
- **Discrimination from 'range' vs energy**
- **Directionality from TPC (axis) + dE/dx (sense)**
 - **x, y from crossed read-out wire grids (DRIFT I and II)**



Event reconstruction

Performance Summary:

- Both MWPCs in operation.
HV ≤ 3.3 kV - and stable.
- DRIFT Field ~ 800 V/cm (HHV = 40 kV)
> $\times 2$ increase in drift field cf DRIFT-I.
DRIFT velocity > 50 m/s
Diffusion reduced by factor 2
- Grid DAQ Trigger threshold < 5 keV
Raw data rate: 250 Hz.
Trig rate: 50 Hz (at 2 MHz sampling)
Noise = rms 5 mV,
Factor 3 lower than DRIFT-I
- Vessel leak rate < 10^{-8} torr.l.s $^{-1}$



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Dark Matter 2
Slow control monitoring

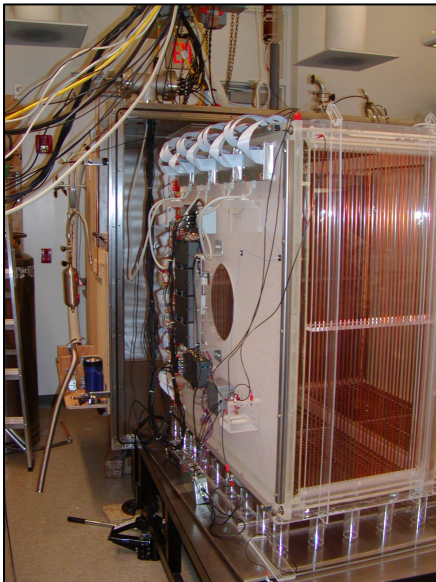
92

Current DRIFT Status

- **DRIFT 1**
 - completed its role as a technology demonstrator
 - paper published on technological achievements – Alner et al., *Nucl.Instrum. Meths. Res Phys.*, A535, 644-655
 - Discrimination against gamma and alpha backgrounds demonstrated.
 - Directionality capability confirmed (high energy).
 - Solutions have been found for all technical problems.
 - Achieved safe and stable operations underground.
 - Established ambient neutron background in Boulby
- **DRIFT II**
 - More robust modular design
 - streamlined coded DAQ
 - 3-D readout compared with 2-D
 - Higher drift field
 - Lower trigger threshold
 - First module is operational in Boulby

- **DRIFT II**

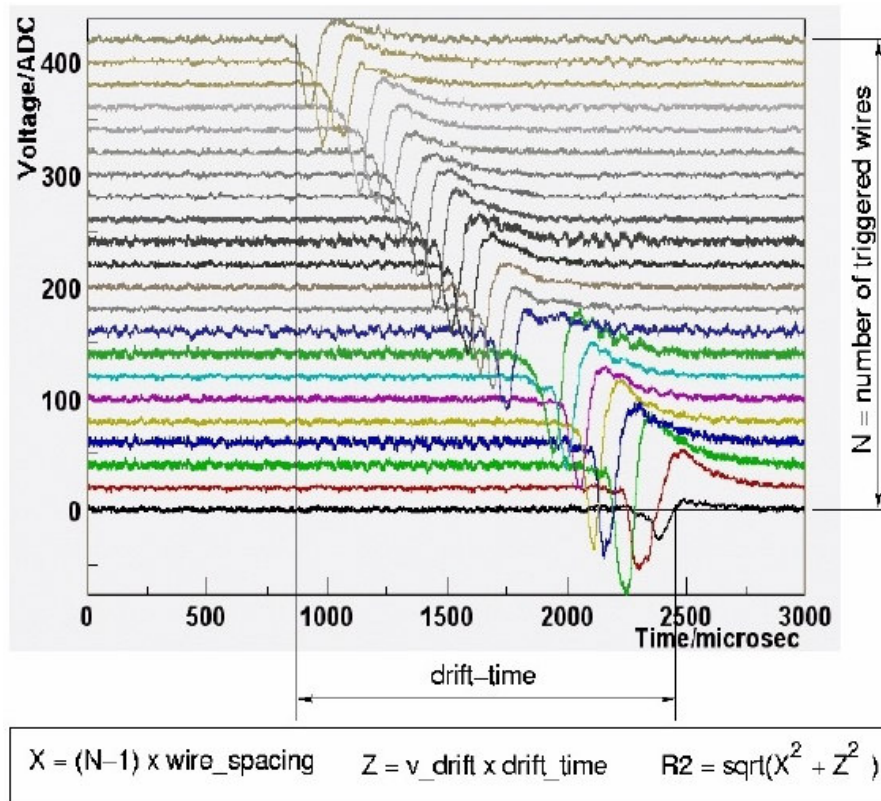
- **Redesign following review in 2003, using technological and operational experience learnt from DRIFT I, resulted in more robust modular design, removal of muon veto, streamlined coded DAQ, 3-D readout compared with 2-D.**
- **First **complete** detector module has successfully passed surface commissioning tests in the US and is installed and operational in Boulby**



R.Cashmore



Dark Matter 2



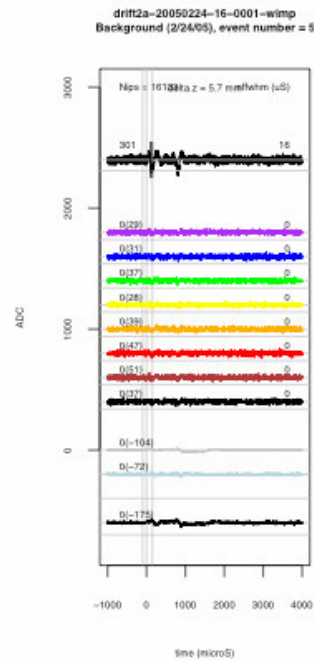
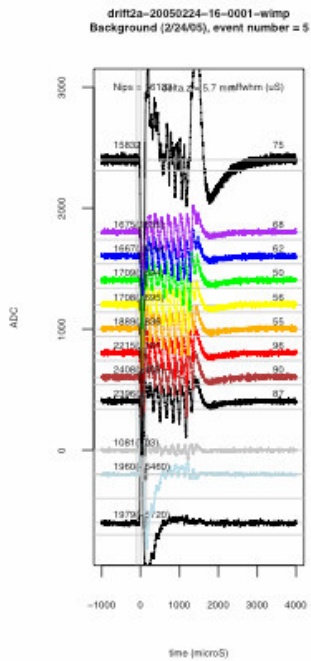
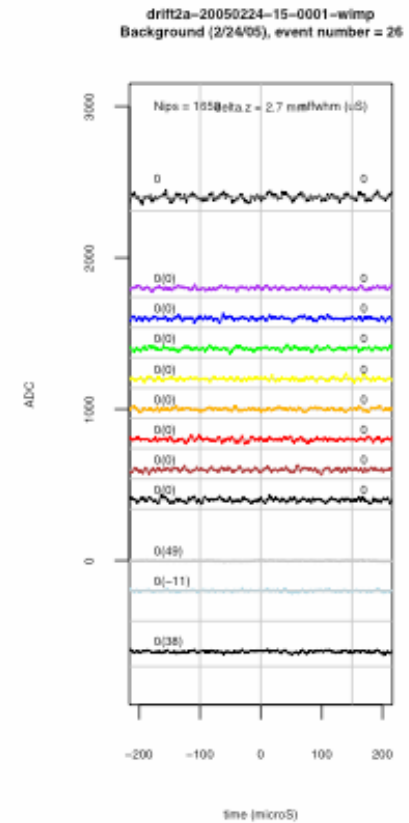
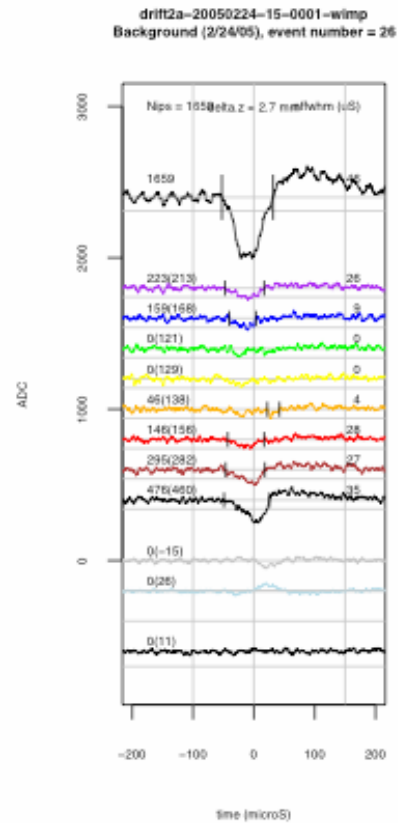
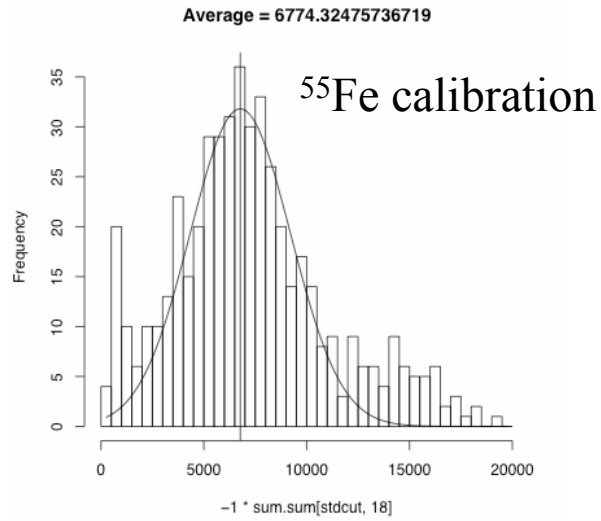
Challenges to *final* objective are:-

- Improve spatial resolution for better range determination and angular reconstruction down to lower thresholds
- Improve dE/dx measurement on each wire to improve threshold and allow start-stop determination for ‘sense’ determination
- Increase sensitive target mass
- Introduce new target nuclei

Solutions must be:-

- Viable for routine, reliable underground operations
- Viable cost solutions for tonne-scale deployments

Underground data from DRIFT IIa



neutron event from Cf source in LH detector
track length ~ 1 mm

alpha event in LH detector

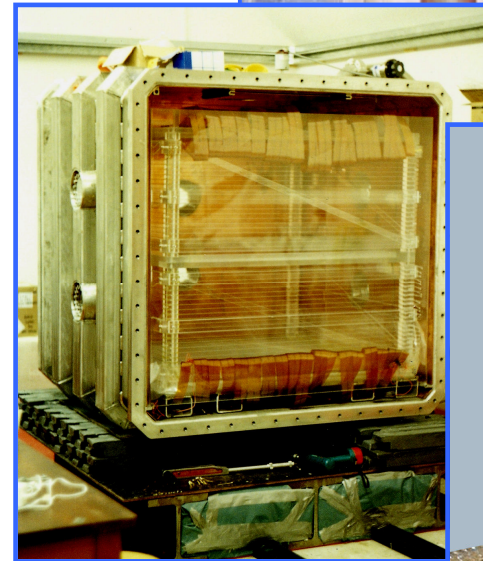
Dramatis personae

- NaI. (NAIAD)
 - High sensitivity
 - World's first significant limit



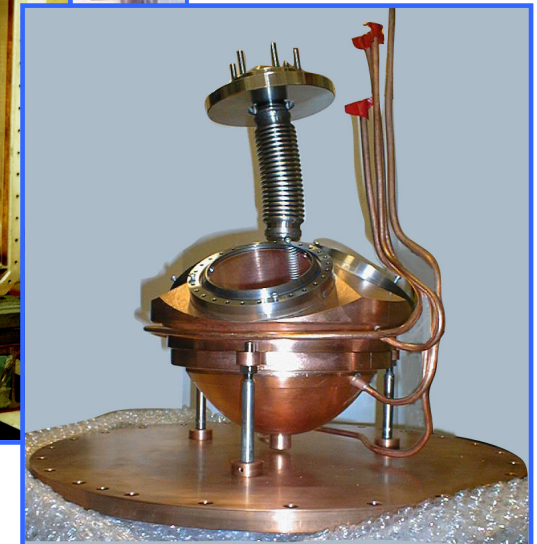
NAIAD
NaI(Tl) crystals

- Liquid Xe: (ZEPLIN)
 - Very pure
 - Cryogenic: Low noise
 - Good discrimination



DRIFT I

- Gas TPC (DRIFT)
 - Negative ion drift (CS_2)
 - Directional capability
 - Insensitive to gammas



Zeplin I

Reminder of World Status

- Comparison between experiments made using a 'standard' Galaxy model
- Separated into spin-independent (scalar) cross-sections and spin-dependent (axial) cross-sections and normalised to one nucleon

Spin independent

DAMA

IGEX

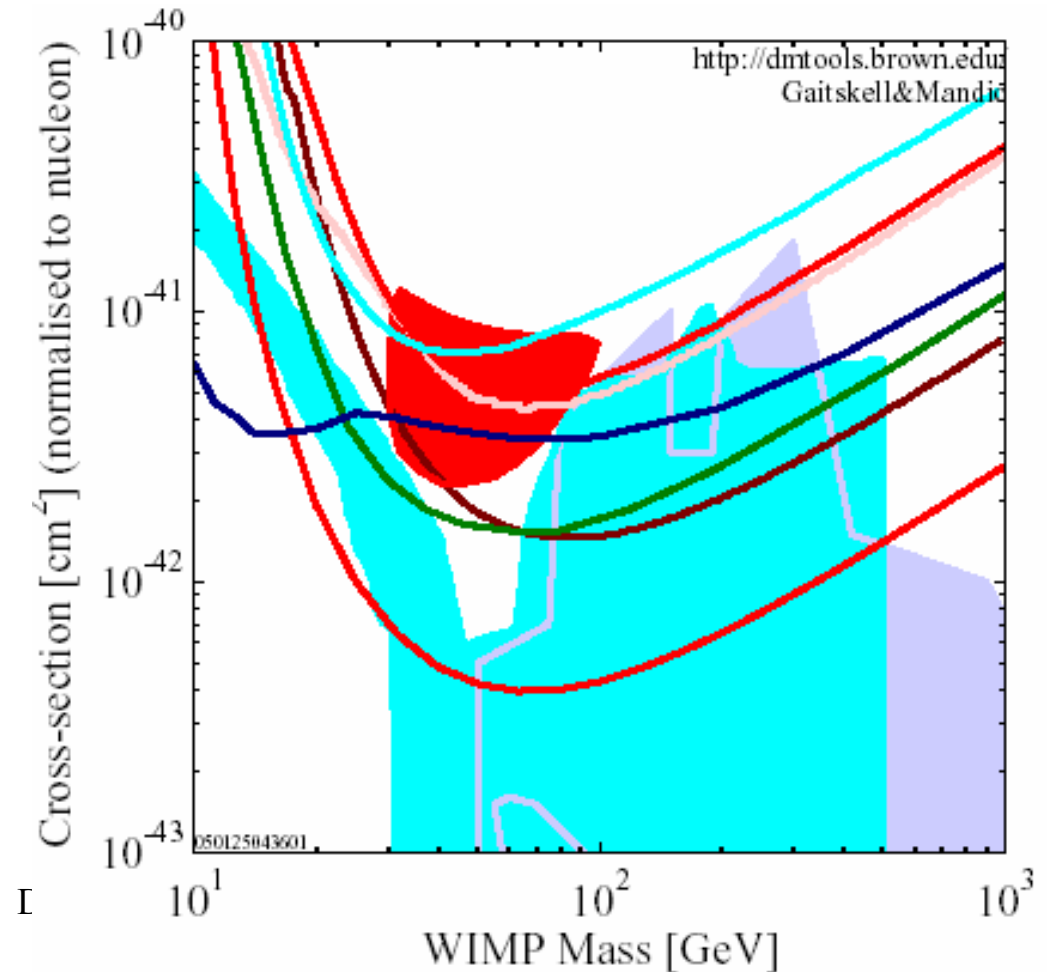
CRESST II

CDMS I

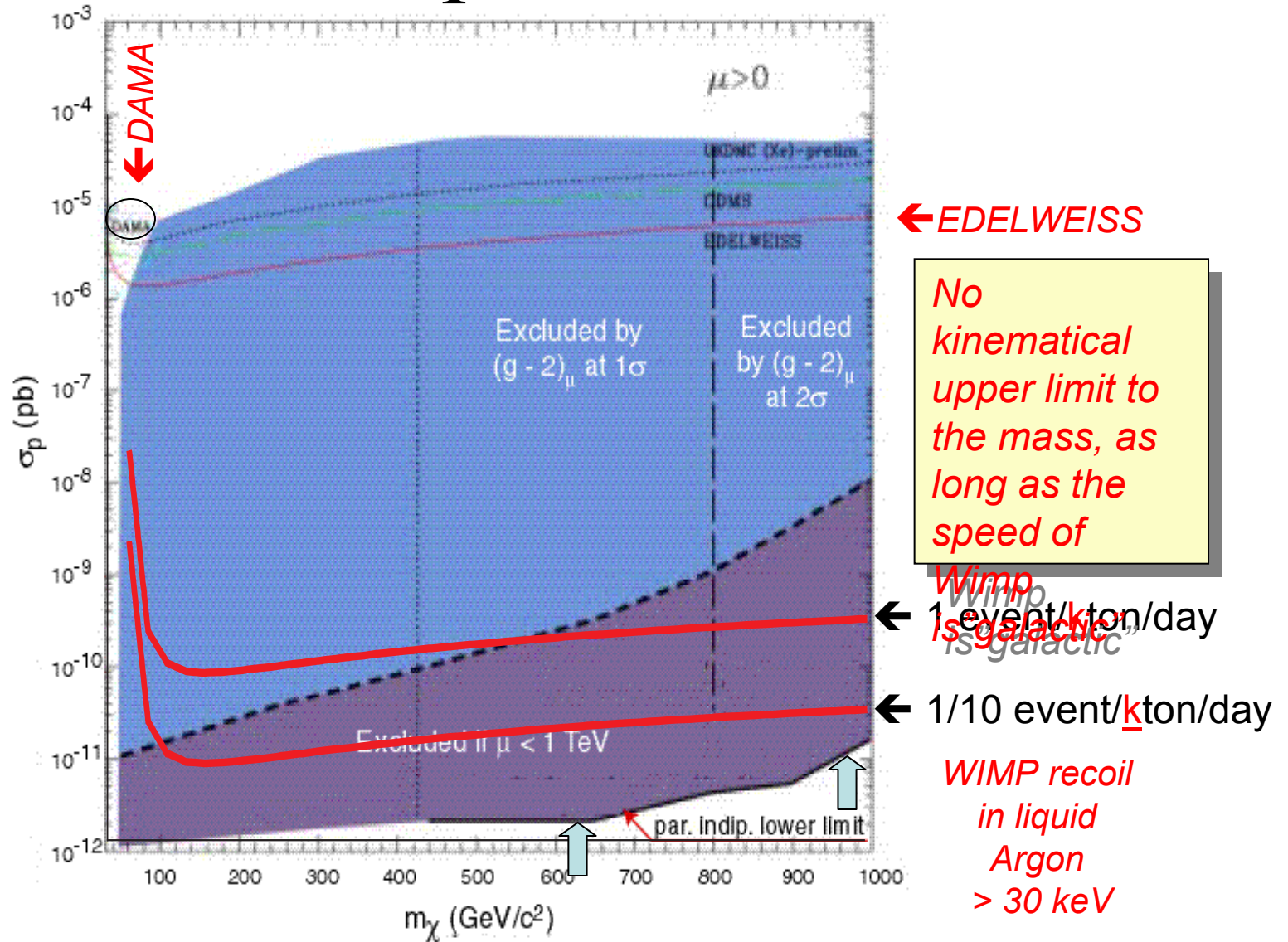
EDELWEISS

ZEPLIN I

CDMS II

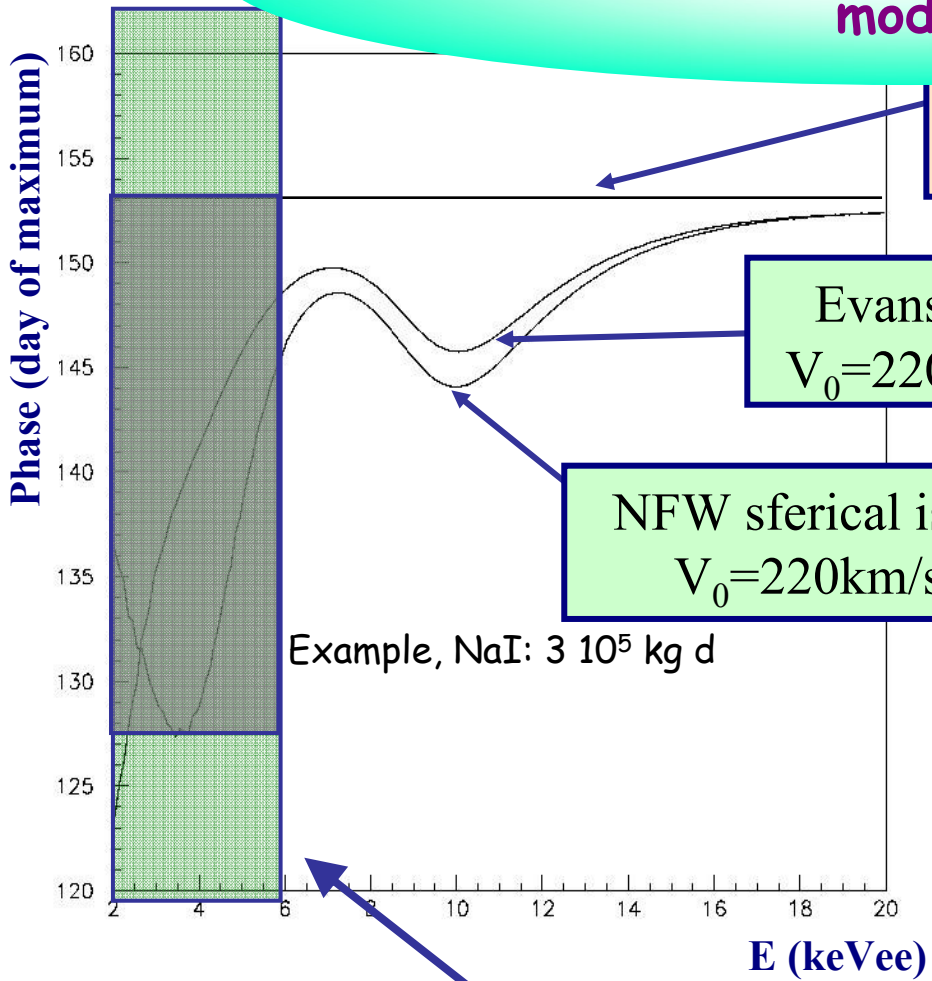


SUSY predictions



An example of possible signature for presence of WIMP streams in the Galactic halo

The streams effect on the phase depends also on the galactic halo model



Expected phase in the absence of streams $\phi = 152.5$ d (2nd June)

Evans' log axisymmetric non-rotating, $V_0=220$ km/s, $R_c=5$ kpc, ρ_0 max + 4% Sgr

NFW sferical isotropic non-rotating, $V_0=220$ km/s, ρ_0 max + 4% Sgr

Example, NaI: $3 \cdot 10^5$ kg d

The higher **sensitivity** of **DAMA/LIBRA** will allow an effective investigation of streams contribution in the galactic halo

DAMA/NaI results:
(2-6) keV $t_0 = (140 \pm 22)$ d

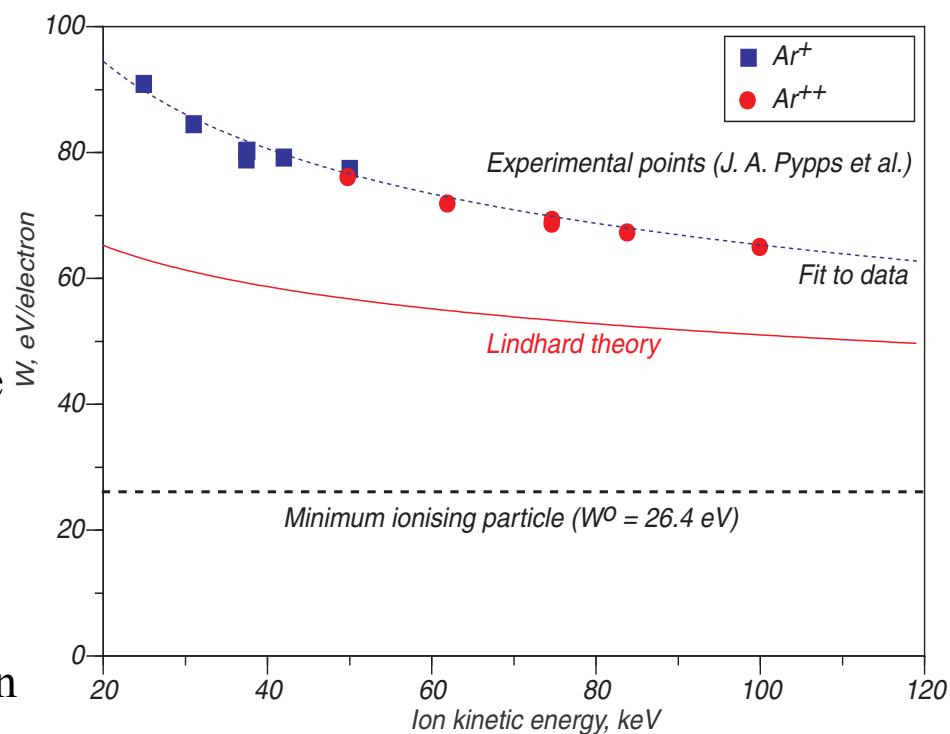
Summary

- Many alternative techniques
- Very Difficult Experiments
 - Need to check all approaches to know how to reach 1 tonne equivalent or more

Experimental Issue

Primary ionisation of slow recoils in Argon gas.

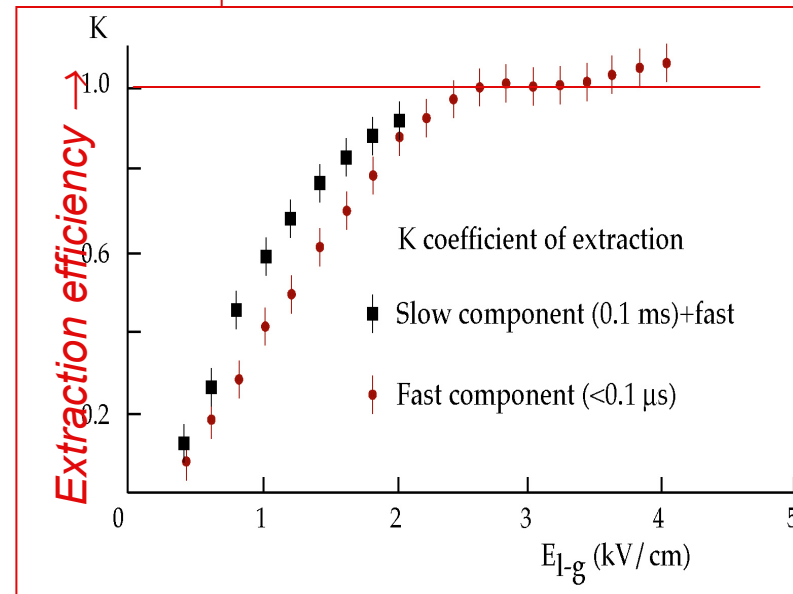
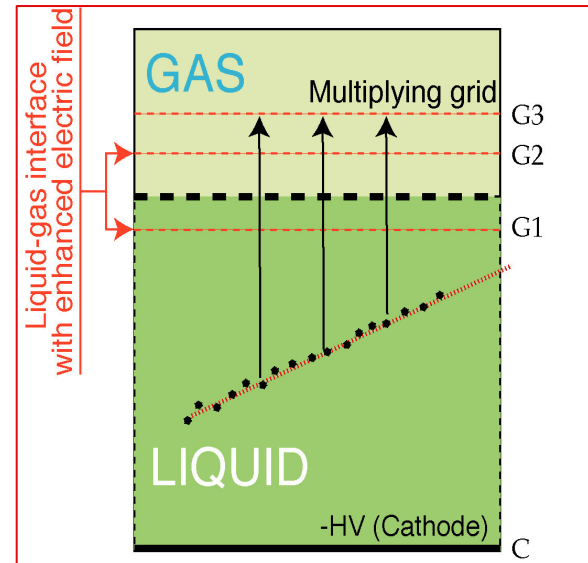
- For ion velocities smaller than the ones of atomic electrons the classic Bethe-Bloch description of the ionisation process is no longer applicable.
- At such speeds, single electron collisions are suppressed, and, unlike fast particles, energy losses arise almost exclusively from energy transfers to screened nuclei of the medium.
- The ionisation yield for Argon ions in Argon has been measured over the range 20 ÷ 100 keV and it shows a gradual decrease of the energy loss W required to produce a ion-electron pair, to be compared with the minimum ionisation value of $W_0 = 26.4$ eV/electron.



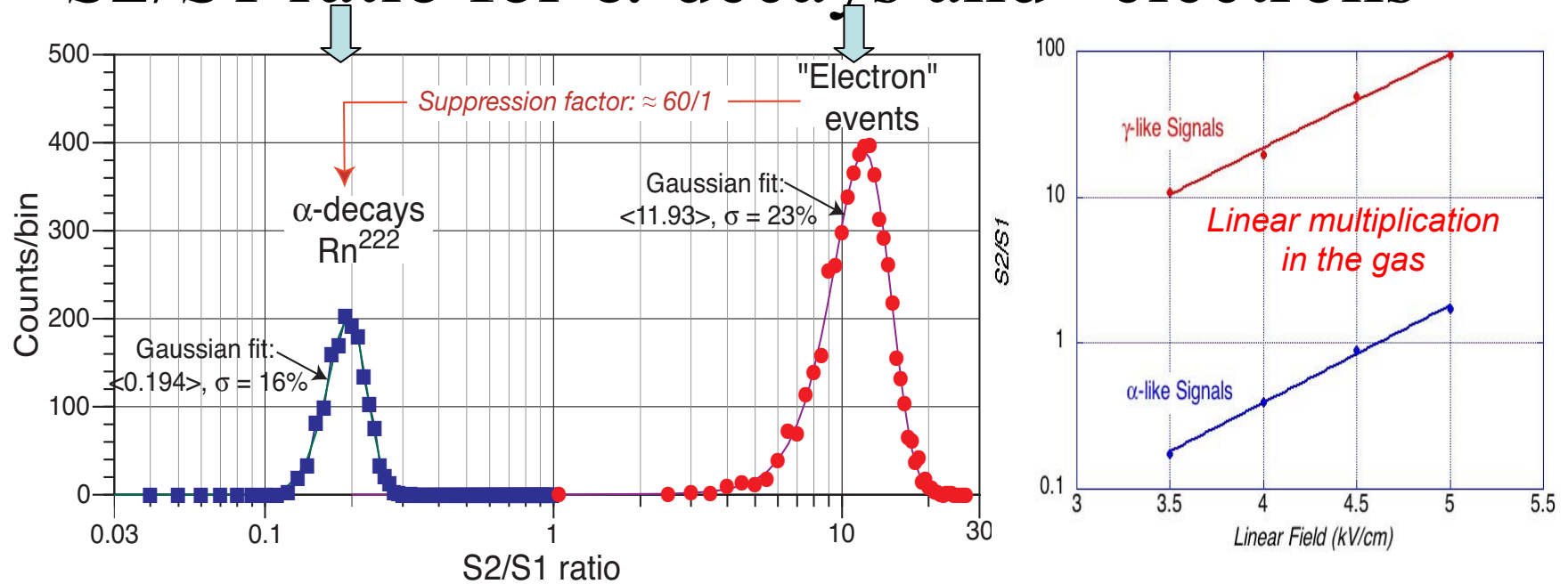
- According to these measurements, an Argon recoil with $E_{rec} = 40$ keV generates ≈ 530 primary electrons ($W_{rec} = 80$ eV/electron).
- In a liquid, the scintillation light is proportional to the number of primary electrons since, for practical drift fields, the liberated electron signal is strongly suppressed by columnar recombination

Detecting the small liberated electron signal (S2)

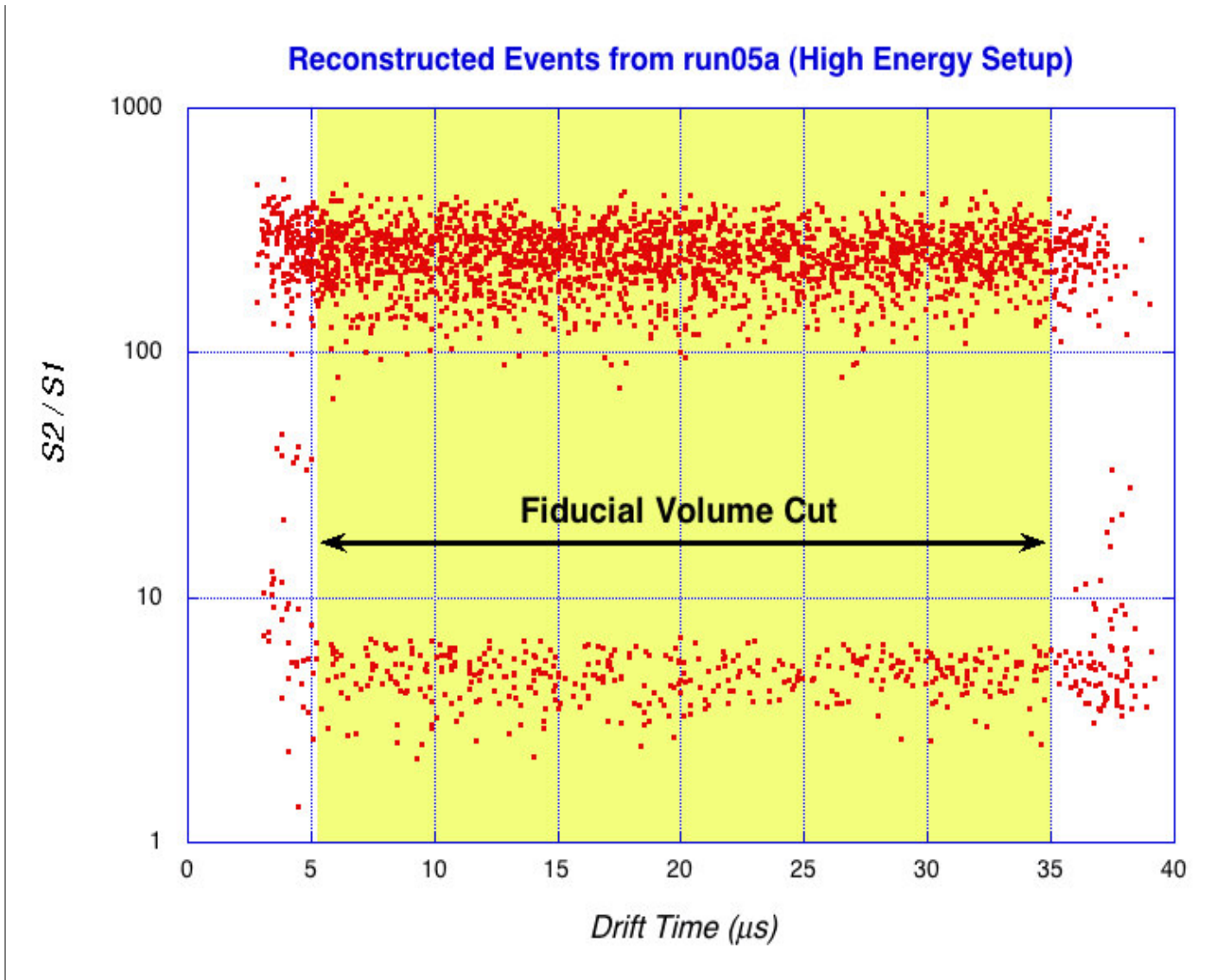
- While the scintillation signal can be detected by the U.V. light with the help of photo-tubes, the tiny electron signal cannot be directly recorded collecting the signal in the liquid.
- Of particular interest is the possibility of extracting ionisation electrons through the interface liquid-gas, since electrons can be easily multiplied in a gaseous medium.
- In order to do so, one has to overcome the potential barrier binding electrons to the liquid, introducing a **local, accelerating electric field**. It is found that:
 - at relatively low fields, electrons require a long time to be freed (slow component, typically a fraction of ms)
 - above a given threshold, the extraction is prompt
- At fields of the order of a few kV/cm the prompt extraction is practically complete, both for Xe and Ar.



S2/S1 ratio for α -decays and “electrons”

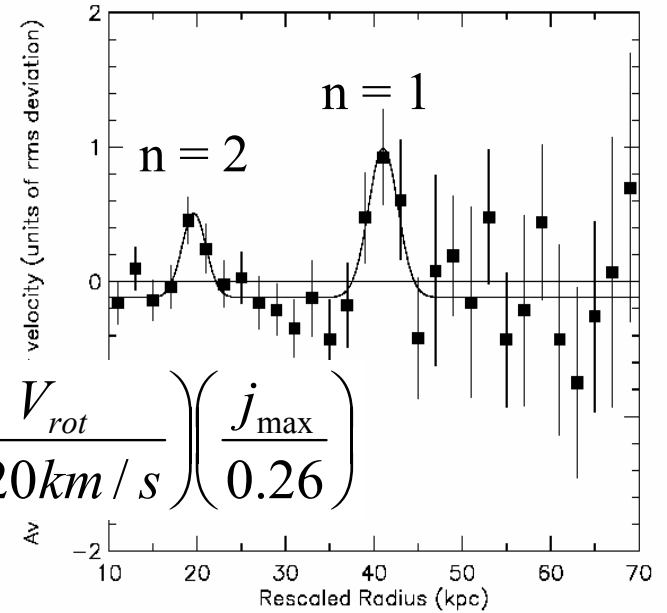
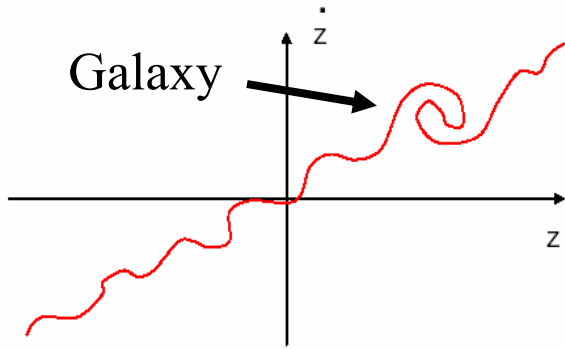


- Events are produced by spontaneous decays in the detector.
- A clear separation in two peaks is observed. the red peak is due to relativistic particles, the blue peak is a small contamination of α -decays of a time dependent contamination of Rn^{222}
- The latter signal, which is a sharp peak in S1 corresponding to an energy of 5.49 MeV, progressively disappears when the liquid is aging, with a characteristic half-life of 3.82 days
- Note the remarkable separation between the two effects
- R. Cashmore, Dark Matter 2014
Because of the very strong recombination for these events, the secondary signal S2 is strongly depressed with respect to S1 ($S2/S1 \approx 60/1$).



Why caustics?

Sikivie et al., Astro-ph/0405231

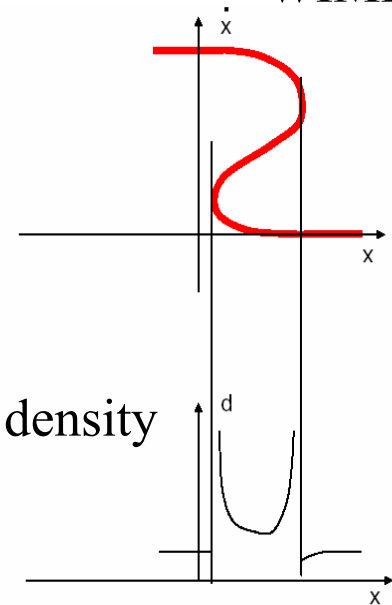


$$r_n = \frac{40 \text{ kpc}}{n} \left(\frac{V_{rot}}{220 \text{ km/s}} \right) \left(\frac{j_{max}}{0.26} \right)$$

$$\vec{V}(\vec{r}, t) = H(t)\vec{r} + \Delta\vec{V}(\vec{r}, t)$$

Hubble law

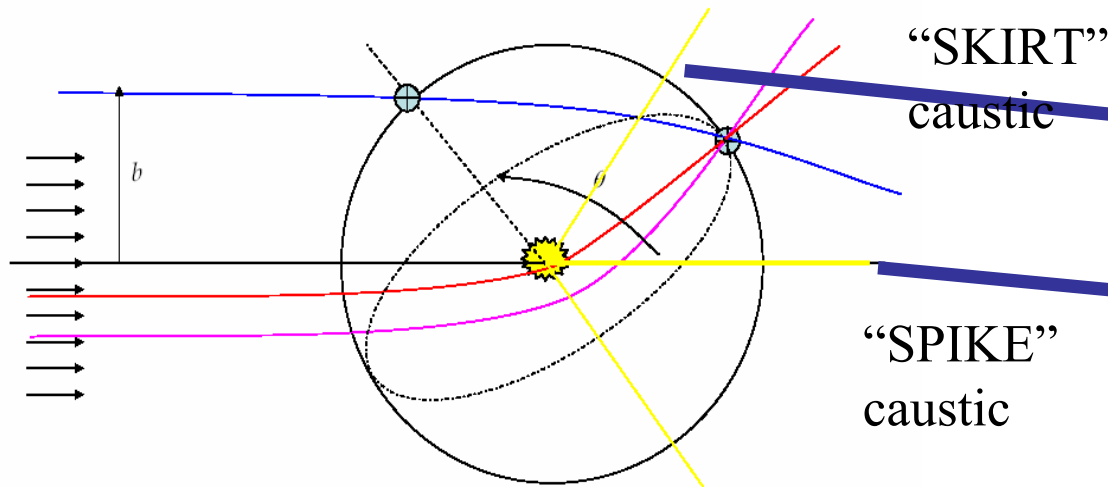
Peculiar velocity: a very tiny sheet, e.g for WIMPs: $V_p \sim 10^{-12}c$



Many cold streams, expected also in the solar neighborhood

n	$v_G^{n\pm}$ (km/s)	$v_{yG}^{n\pm}$ (km/s)	$v_{zG}^{n\pm}$ (km/s)	$v_{xG}^{n\pm}$ (km/s)	d_n^+ (10^{-26} gr/cm^3)	d_n^- (10^{-26} gr/cm^3)
1	620	130	± 605	/	0.3	0.3
2	560	230	± 510	/	0.8	0.8
3	530	320	± 420	/	1.4	1.4
4	500	405	± 300	/	3.4	3.4
5	480	470	0	± 100	170.	15.
6	465	400	0	± 240	6.5	3.4
7	450	330	0	± 305	4.1	1.3
8	430	295	0	± 320	2.0	1.1
9	420	240	0	± 340	1.5	0.7
10	410	200	0	± 355	1.0	1.0
11	395	180	0	± 350	0.9	0.9
12	385	160	0	± 350	0.8	0.8
13	375	150	0	± 345	0.7	0.7
14	365	135	0	± 340	0.7	0.7
15	355	120	0	± 335	0.6	0.6
16	350	110	0	± 330	0.6	0.6
17	340	105	0	± 320	0.5	0.5
18	330	95	0	± 315	0.5	0.5
19	320	90	0	± 310	0.5	0.5
20	310	80	0	± 300	0.4	0.4

a viable signature for DM streams in the solar neighborhood...



the periodical Earth orbit crossing of a caustic region can be investigate by underground direct detection experiment as DAMA/LIBRA

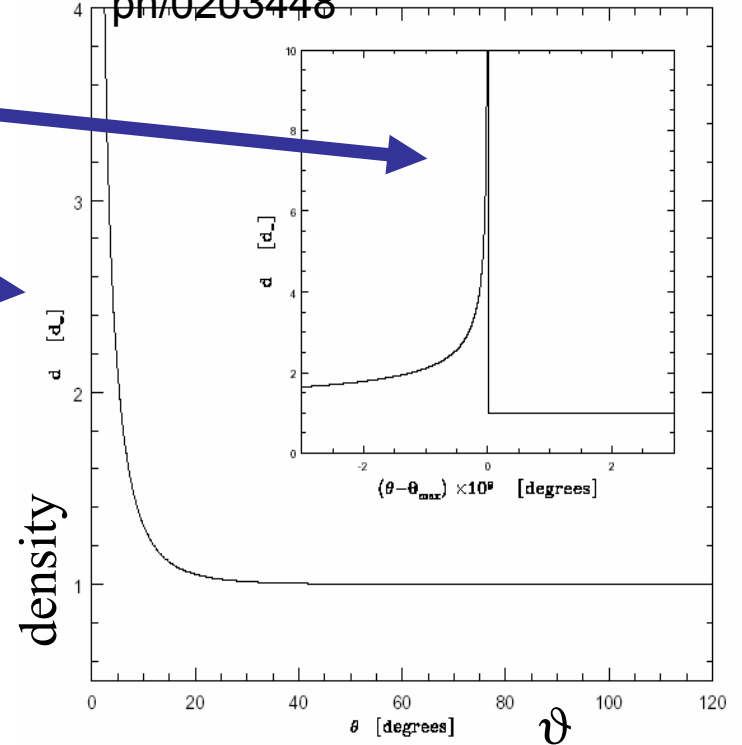
an example:

$$V_{\text{flux}} \sim 300 \text{ km/s} ; \sigma_V \sim 70 \text{ km/s}$$

Earth orbit within 10° from "spike"

R.Cashmore
sensitivity to $\rho_{\text{flux}} > \text{few } \% \rho_0$

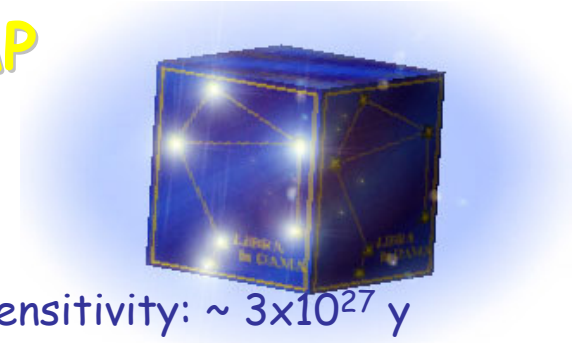
Sikivie et al. Astroph/0203448



Dark Matter 2

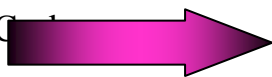


What can DAMA/LIBRA do beyond WIMP investigation by annual modulation signature in 5 years of running?



- **Possible PEP violating processes** maximal reachable sensitivity: $\sim 3 \times 10^{27}$ y
- **Possible CNC processes in ^{23}Na , ^{127}I**
in case of a rate ~ 0.1 cpd/kg/keV in the region of interest and of the same duty cycle as at present:
 - a) reachable sensitivity for CNC EC 10^{24} y 90%C.L. (or higher depending on r)
 - b) reachable sensitivity for e^- disappearance 10^{25} y at 90%C.L.(or higher depending on r)
- **Nucleon and di-nucleon decay** maximal reachable sensitivity: $\tau_n \rightarrow 10^{27}$ y
- **SIMP search** maximal explorable mass: above 10^{17} GeV
- **Neutral nuclearities** maximal explorable flux: $\sim 5 \times 10^{-12} \text{s}^{-1} \text{cm}^{-2} \text{ster}^{-1}$
- **WIMP search by inelastic scattering** reachable sensitivity for $r \sim 0.1$ cpd/kg/keV in the region of interest and the same duty cycle as at present 5 GeV/cm^3 ; lower rate can allow to explore physical regions
- **Solar axion search** maximal reachable sensitivity: $g_{a\gamma\gamma} \sim 10^{-10} \text{ GeV}^{-1}$
 ... and beyond (e.g. $\beta\beta$ decays with passive and active sources, tests for ν physics with artificial ν source, neutrino magnetic moment measurement, solar neutrino spectroscopy, etc.)

R.C.



higher sensitivity can be achieved with a 1 ton NaI(Tl) ultra-radiopure set-up