IDPASC Dark Matter School

Evora. 14-18 December 2011

Direct search. Experimental

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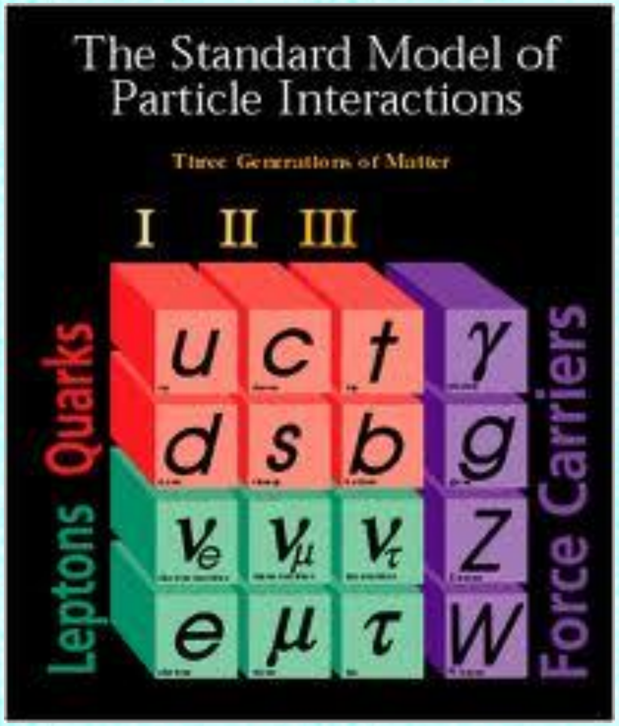
The standard models



Normal matter 4%

Neutrinos 0.15-1%

Dark matter 23%

Cosmological constant 73%

The Standard Model of Subnuclear Physics explains 5% of the universe with a vacuum energy some 120 orders of magnitudes too large

The Standard Model of Cosmology accounts the rest with:

- **A dark matter we don't see**
- **A cosmological constant we don't understand**

Direct Search of WIMPs

These lectures are limited to one possible type of cold dark matter (CDM)

Weak Interacting Massive Particles=WIMPs

Possibly the Neutralinos of SUSY theories

Only their direct experimental earches are considered

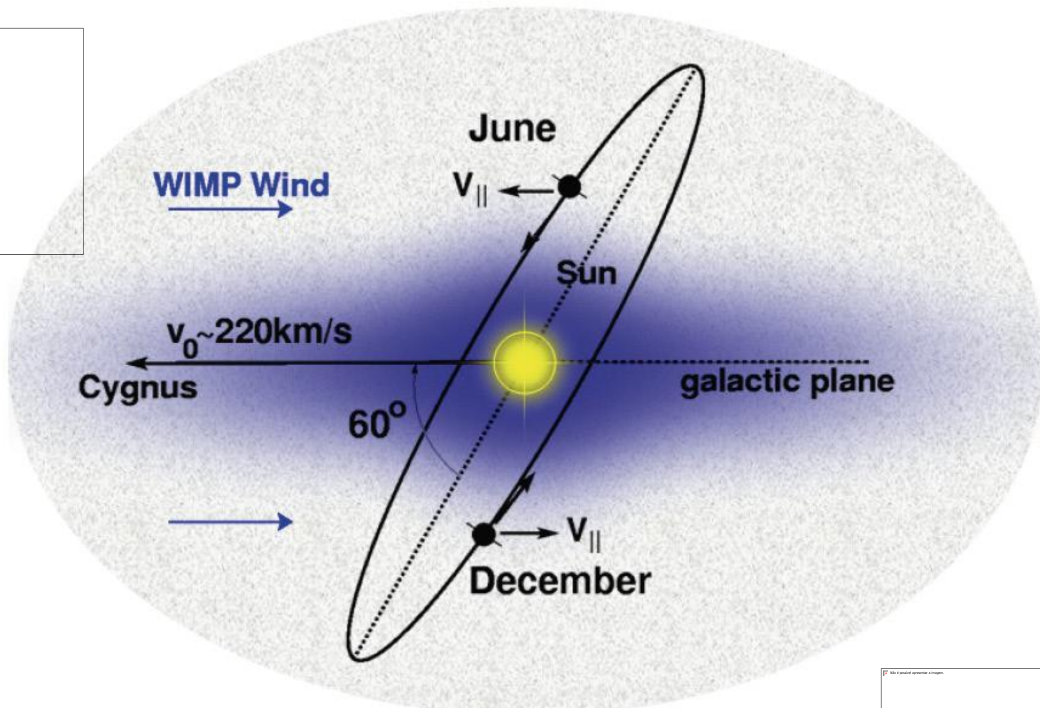
Velocity Distribution

$$f_\oplus(\vec{v},t) = f_{\rm gal}(\vec{v}+\vec{v}_\odot+\vec{v}_\oplus(t)) \qquad f_{\rm gal}(\vec{v}) \approx \begin{cases} N\exp\left(-v^2/\bar{v}^2\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

$\bar{v} \simeq 220\,\mathrm{km/s}$ $\qquad v_{\rm esc} \simeq 550\,\mathrm{km/s}$

sun velocity: $\vec{v}_\odot = (0, 220, 0) + (10, 13, 7)\,\mathrm{km/s}$

earth velocity: $\vec{v}_\oplus(t)$ with $v_\oplus \approx 30\,\mathrm{km/s}$



T. Schwetz, PPC11 CERN

The velocity distribution is assumed to be Maxwellian truncated at the escape velocity from the Galaxy v_{esc}=650 km/s

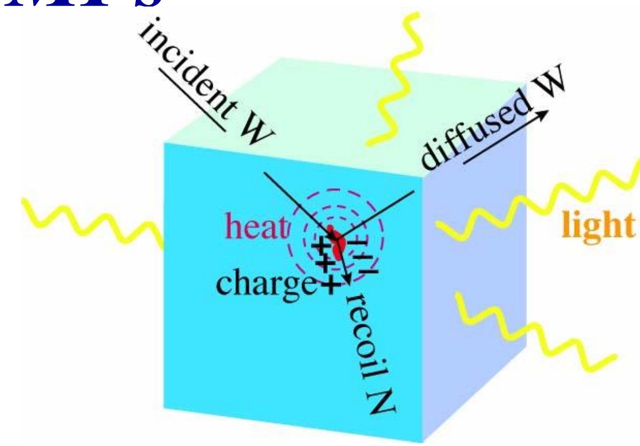
Direct Search of WIMPs

Look for WIMP-nucleus scattering, detect energy deposited by recoiling nucleus

Only a fraction (typically 20%) of the energy deposited by a slow nucleus detected as ionisation

Much larger fraction goes to heat

Thresholds 2-30 keV



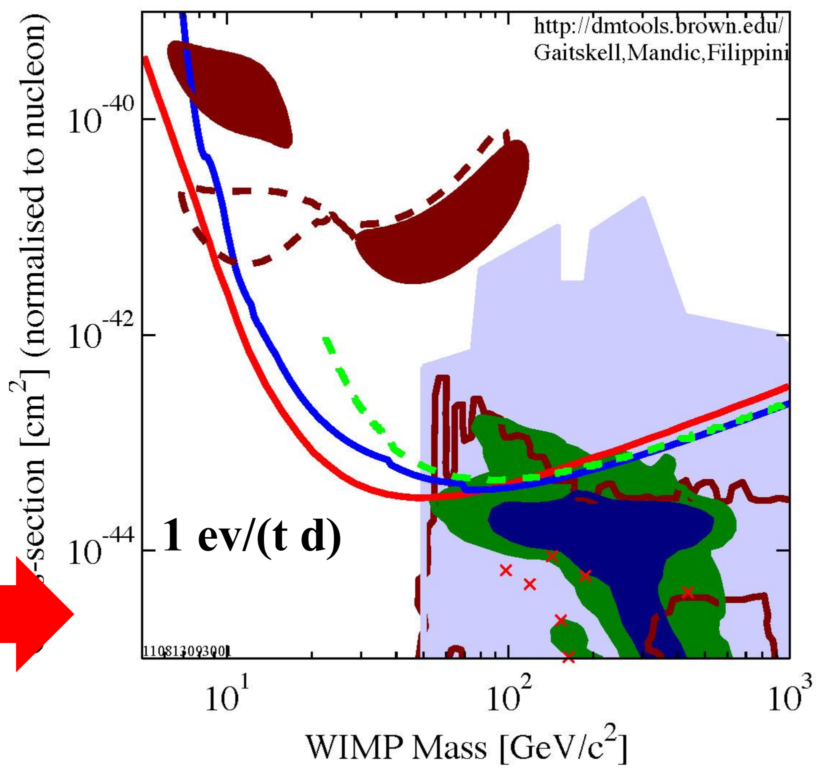
Two kinds of interactions of WIMPs with nuclei

•**SD** (spin dependent), coupling to nucleons spins; only unpaired nucleons couple to WIMPs

•⇒ odd number of p or of n ($J\neq 0$), $\propto J(J+1)$

• **SI** (spin independent), scalar interaction with the mass

•⇒ coherent process ⇒ cross-section $\propto A^2$



1 pb = 10^{-40} m^2=10^{-36} cm^2

Principles of WIMPs Detection

Target = Detector

Measure the energy deposited by the hit **nucleus**

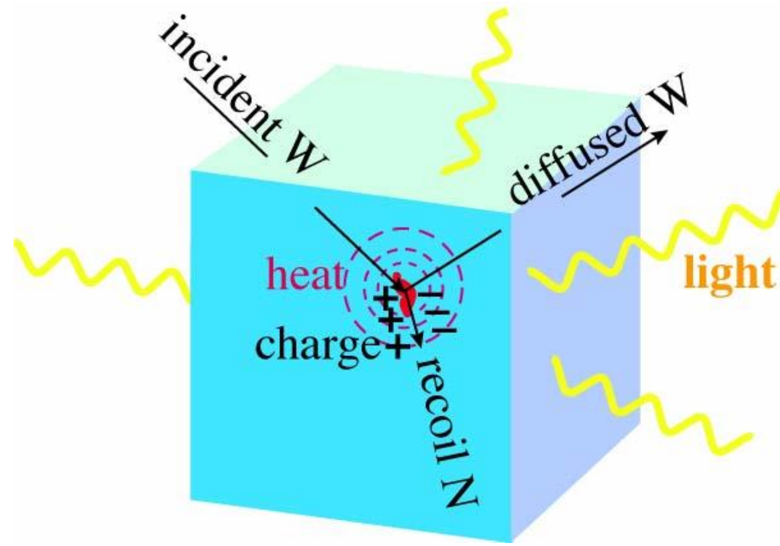
Part of this energy appears as **charge, light or heat**

Main challenges

- Signal rate is small
- Energy deposit is tiny (several keV)
- Signal spectrum decreases with increasing *E*

•3 basic backgrounds

- electromagnetic (β & γ); dominant $\Rightarrow$ electrons
- neutrons (and WIMPs) $\Rightarrow$ nuclear recoil
- surface contamination (partial energy release)



Against backgrounds

Underground laboratory

Search for characteristic signal: annual modulation (DAMA/LIBRA; ANAIS)

Shielding. Against external backgrounds only

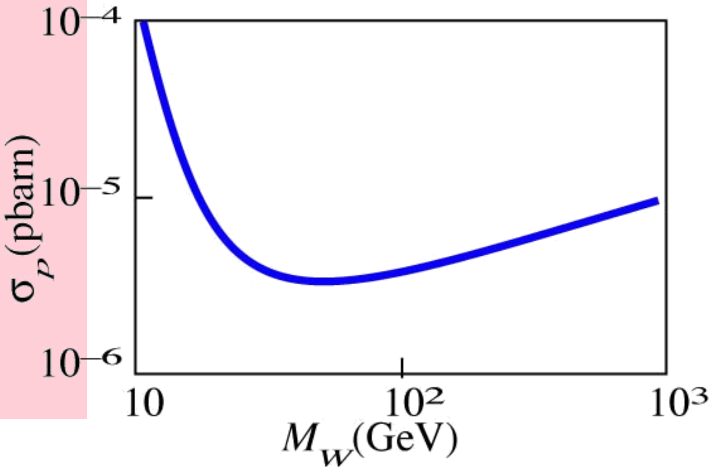
Active discrimination. Against external and internal background

- **Measure charge (free electrons) and heat (phonons)**
- **Measure charge (free electrons) and light (photons)**
- **Pulse shape discrimination (PSD)**
- **Reconstruct event position, define fiducial volume w/o surfaces**

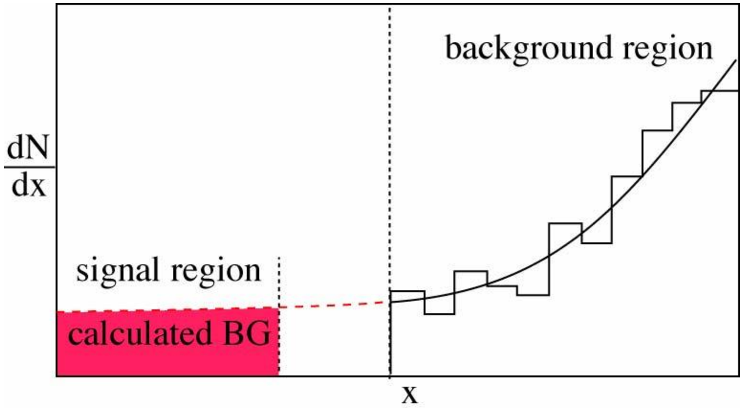
The Exclusion Plot

- **<u>Backgrounds cannot be accurately modelled and subtracted</u>**
  - develop blindly selection criteria to define a “background-free” region in the experimental parameters space = **signal region (SR)**
- Assume a halo model (local WIMP density, velocity,..)
- Calculate for each WIMP mass m_W the maximum possible signal rate allowed by the data

Result is model dependent



- Some experiments with **events in the SR** follow a dangerous (unreliable) procedure
  - Define, for each BG type, a “reference region”, in which that BG is dominating
  - Assume a BG model (e.g. dependence on energy)
  - Check it with calibrations and other data
  - Extrapolate in the SR. If more events are found, claim a signal

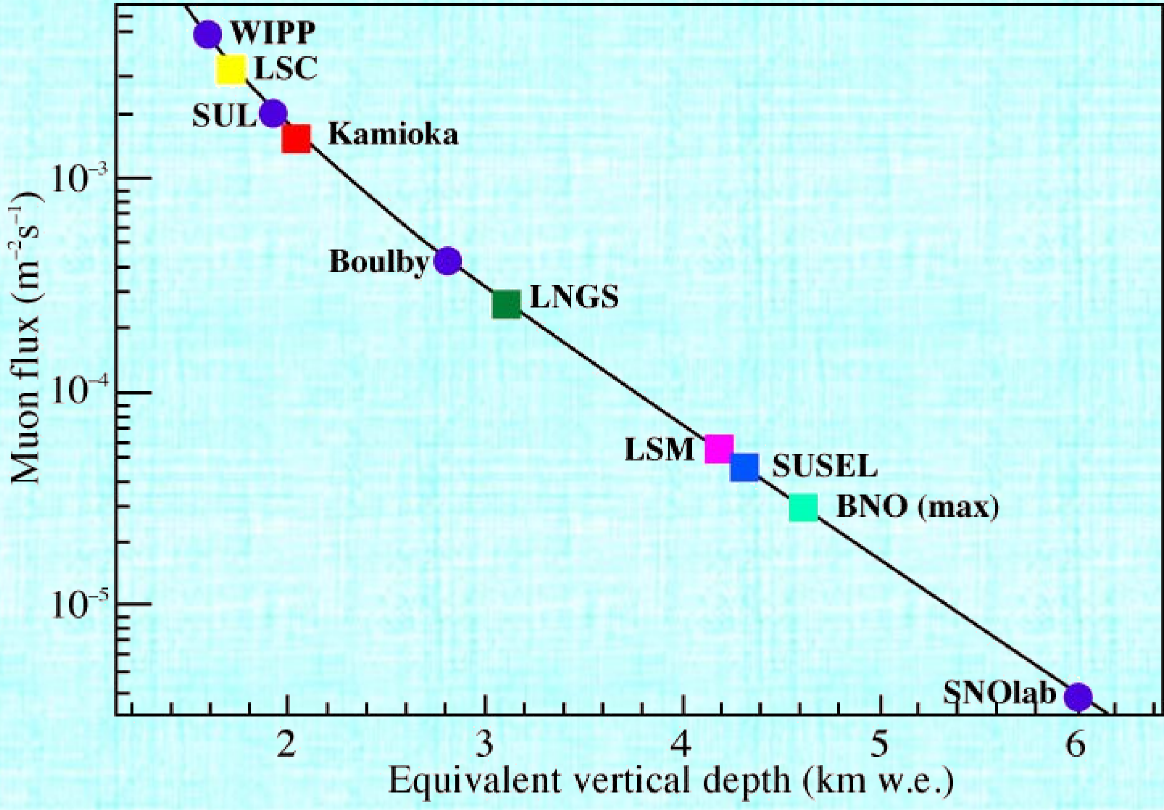


Tiny signals. Go underground

Underground Laboratories. Differences

- Depth (μ flux, spallation *n* flux)
    - Determines only a fraction of the background sources
    - Maximum cavity size decreases with increasing depth, costs increase, rock bursts risk increases
- Diameter & height of the halls
    - May limit the thickness of the shields (water tanks)
    - Depends on rock quality and depth
- Horizontal vs. vertical access (vertical more expensive and risky)
- Support infrastructures, personnel (quantity and quality)
- Underground area allocation policy, turnover of experiments
    - Scientific Committee: international vs. local (or national)
- Degree of internationality of the community

The field <u>is not</u> limited by lack of underground space



General procedures

Shielding; use only materials with low enough radioactive contaminants

Pb, Cu, Poli, water, noble liquids, scintillators

Grading with increasing radiopurity from external to internal layers

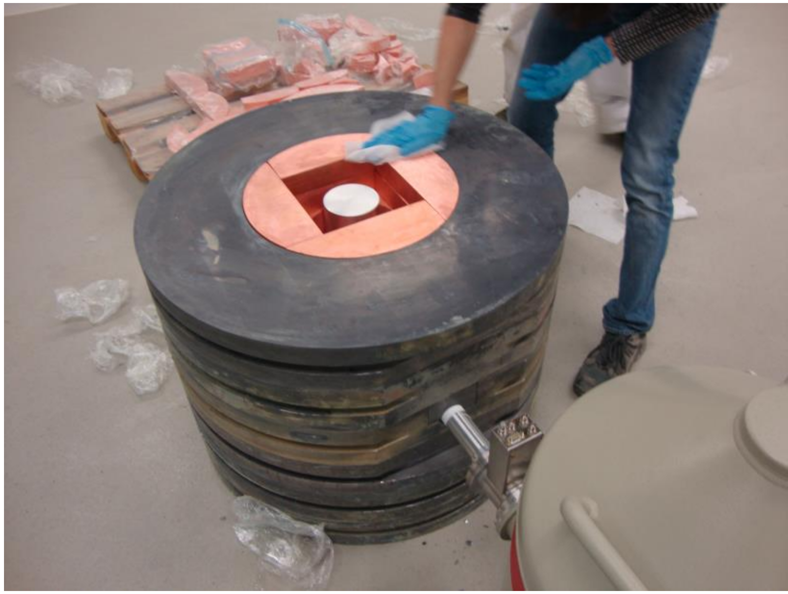
Proper simulation and analytical codes must be developed to evaluate the maximum tolerable contaminants in the detector and shields materials.

Background model and background budget calculations

Background model should be controlled on dedicated preliminary experiments

All materials should be screened to check within limits

HPGe Detectors, Mass spectroscopy, etc.



Selection procedures and background discrimination at analysis level should be defined blindly

Notice "traditional" shielding: Pb outside, Cu inside

Shielding ambient radioactivity with H2O

γ flux from U, Th, K = 0.5 $m^{-2}s^{-1}$ @ LNGS, almost depth independent

n flux from U, Th, K = 3.8×10^{-2} $m^{-2}s^{-1}$ @ LNGS, almost depth independent

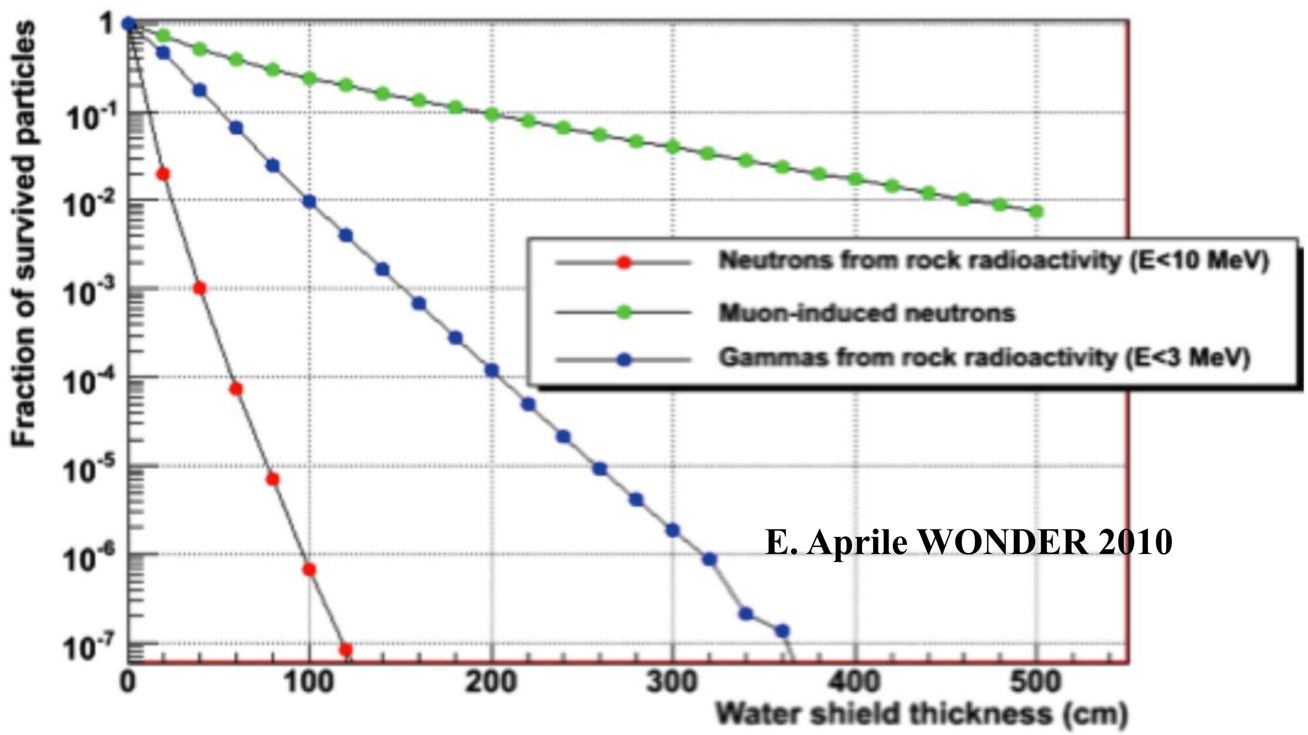
n flux μ-induced in rocks $\approx 8 \times 10^{-6}$ $m^{-2}s^{-1}$ @ LNGS, depth **dependent (**$\approx \times$ 10 @ LSC)

H. Wulandri et al. CRESST hep-ex0401032v1

Shielding materials must be sufficiently radio-pure. Water is an option

Consider radioactivity of the inner wall (if any)

Water shields thickness ⇒ 3-4 m



E. Aprile WONDER 2010

GERDA Water tank

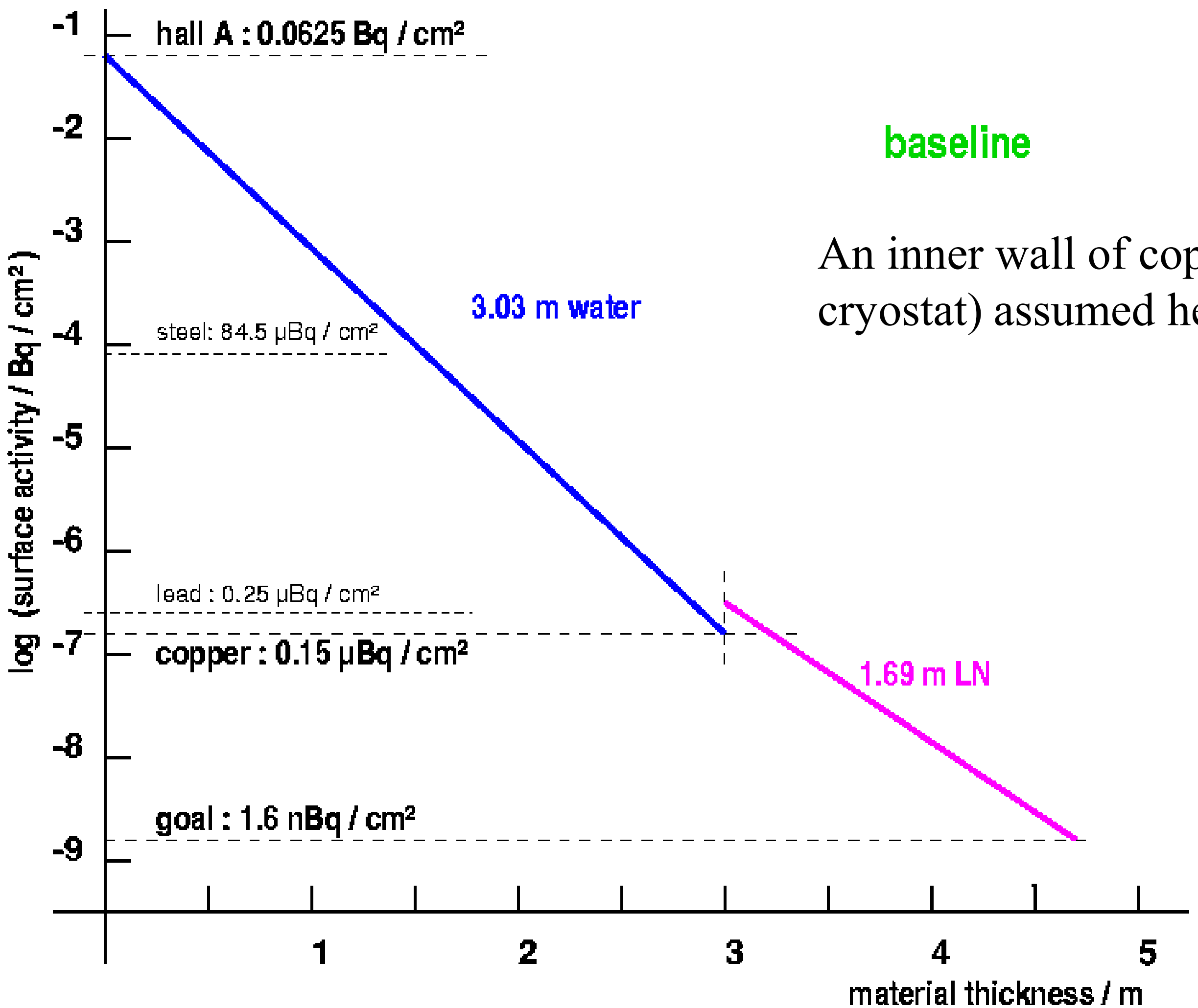
Designed for external γ,n,μ background $\sim 10^{-4}$ cts/(keV kg y) In the neutrinoless double beta decay region Q=2035 keV

∅ 10 m

H = 9.5 m

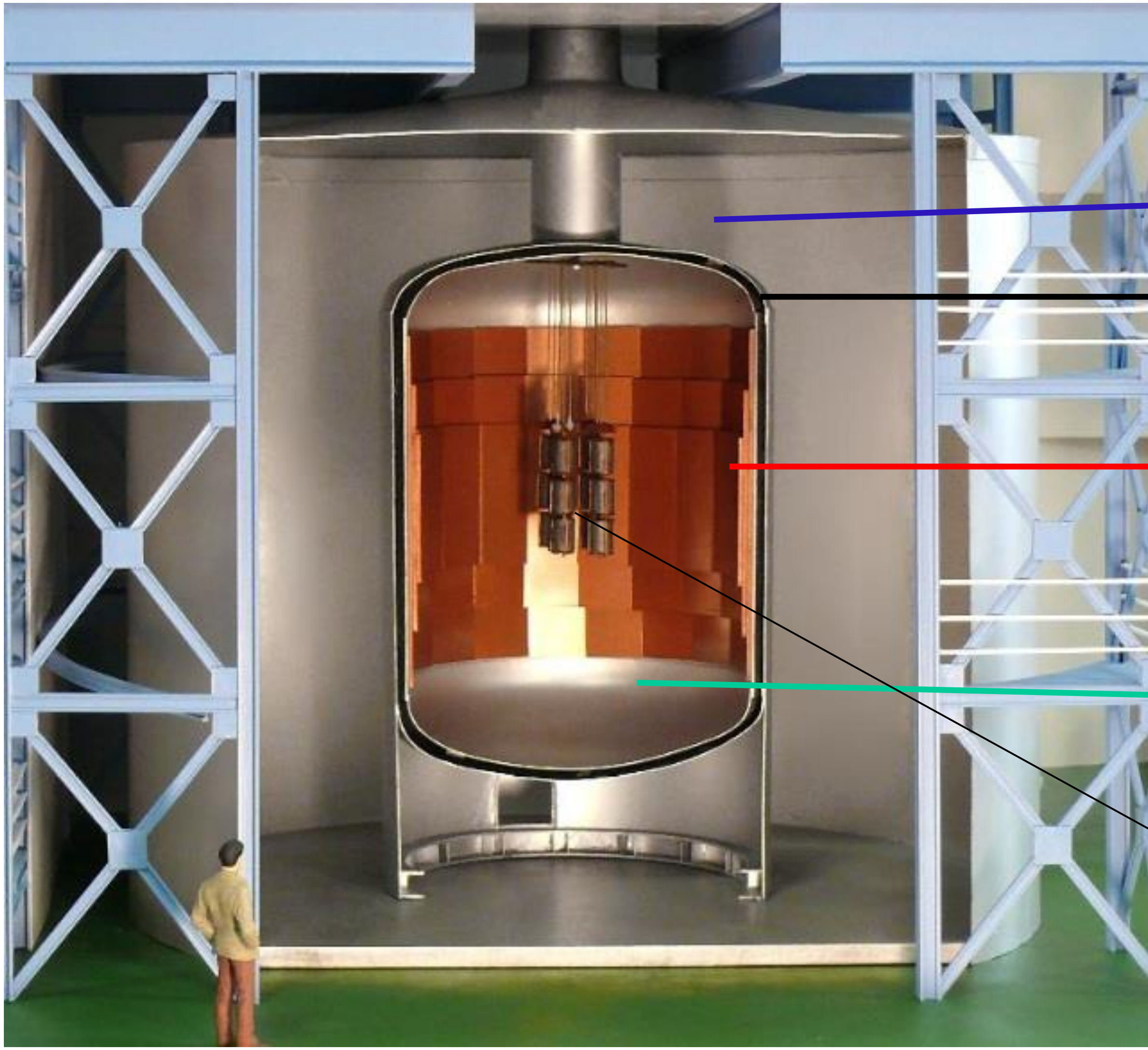
V = 650 m^3

How thick?



An inner wall of copper (the cryostat) assumed here

GERDA shields



Pure water in S/S tank
Active veto (Cherenkov light)

Cryostat: S/S screened for low radiaoctivity

Internal Cu lining (absorb gammas from S/S)

Pure L-Ar (5.0)

Ge array

Running/commissioning experiments

DAMA/LIBRA. Running at LNGS (Italy). 250 kg NaI Scintillators

KIMS. Running at Y2L (Korea). 100+ kg CsI Scintillators

ANAIS. Under development at LSC (Spain) 150-250 kg NaI Scintillators

CDMS II. Completed at SUL (USA). 4.75 kg Ge Bolometrs

EDELWEISS II. Running at LSM (France). 4 kg (40 kg foreseen) Ge Bolometers

CRESST2. Running at LNGS (Italy). 2.7 kg (10 kg foreseen) $CaWO_4$ Bolometers

XENON 100. Running at LNGS (Italy). 160 kg Xe Liquid/Gas TPC

DEAP 3600. Construction at SNOLab (Canada). 3600 kg Ar Liquid scintillation

CLEAN. Construction at SNOLab (Canada). 150 kg Ar/Ne Liquid scintillation

WARP. Under construction at LNGS (Italy). 140 kg Ar Liquid/Gas TPC

XMASS. Being installed at Kamioka (Japan). 850 (100 fid) kg Xe Liquid scintillation

ArDM. Under test at CERN, then @ LSC (Spain) 850 kg Ar Liquid/Gas TPC

COUPP. SNOLab (Canada). 60 kg. Bubble chamber. CF_3Br. Spin dependent

PICASSO. SNOLab (Canada). 80 kg. Superheated droplets. Spin dependent

More in different stages of R&D

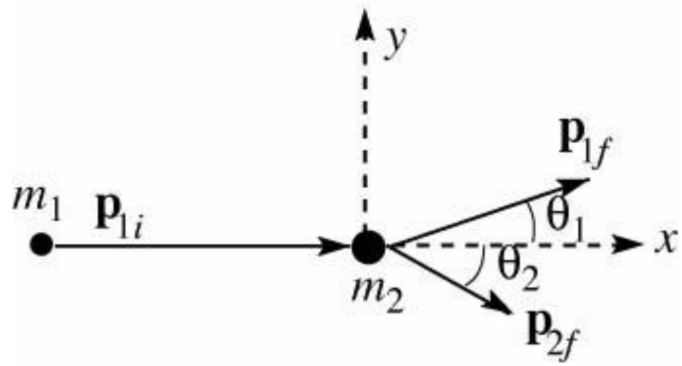
Characteristics of the techniques

Values reported in the table are indicative (no uncertainty reported here)

	Signal	*A*	eV/ pair	eV/ Pht	L_{eff}	$\sigma(E)/E$ (%) @ 662 keV	NR/ER discr	SD	↑	↓
NaI(Tl)	Pht	23 127	17	26	0.07 (I) 0.30(Na)	1.8	N	Y	2 A's EM	^{40}K
LXe	Pht	131	16	22	0.15	1.7?	Y	Y	selfsc	$\tau_3/\ \tau_1$
LAr	Pht	40	24	25	0.25	2?	Y	N		$\tau_3/\ \tau_1$
L/GXe	Pht&Q	131	*f*(E)	*f*(E)		1.8(ph&ch)	Y	Y	selfsc	$\tau_3/\ \tau_1$
L/GAr	Pht&Q	40	*f*(E)	*f*(E)		2	Y	N	selfsc $\tau_3/\ \tau_1$	^{39}Ar
Ge-bol	Phn&Q	73	3		0.3	0.2	Small	7%		Surface Vacuum
$WCaO_4$ bolom.	Phn&Pht	16,40 184				0.7	Y	N	3 A's	Surface Vacuum
Ge-diode	Q	73	3		0.3	0.2	Y	7%	EM	Surface Cosmog

Kinematics

Recoil kinetic energy as a function of θ_2
(more difficult for θ_1)



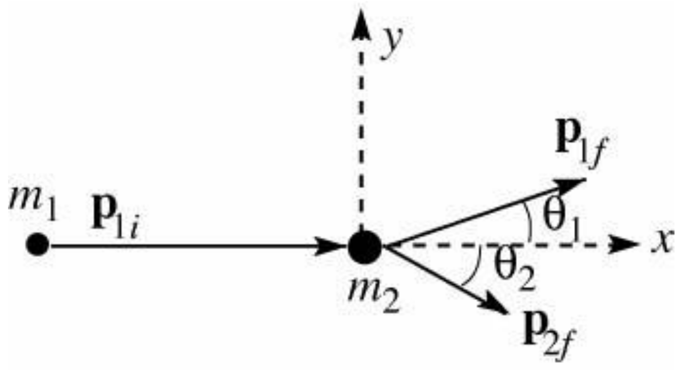
Square and express $\cos^2\theta_1$ and $\sin^2\theta_1$

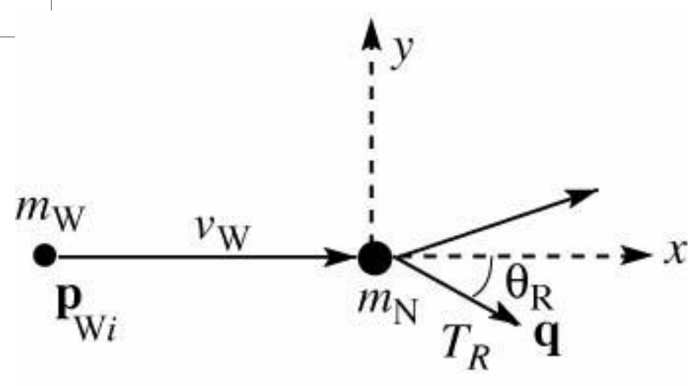
Sum

Divide by $2m_1$

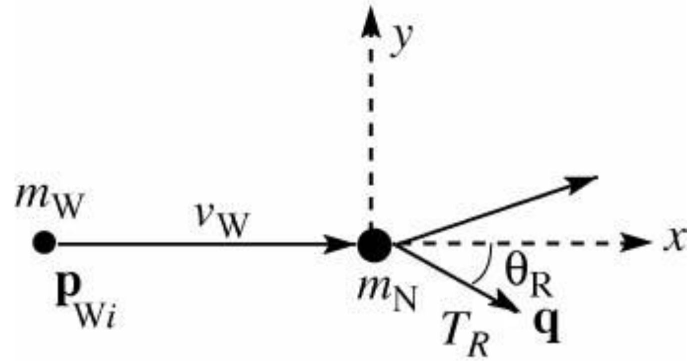
Energy conservation

Kinematics


y
x
m_1
$\mathbf{p}_{1i}$
m_2
$\mathbf{p}_{1f}$
θ_1
θ_2
$\mathbf{p}_{2f}$


y
x
m_W
v_W
$\mathbf{p}_{Wi}$
m_N
θ_R
T_R
$\mathbf{q}$

Kinematics

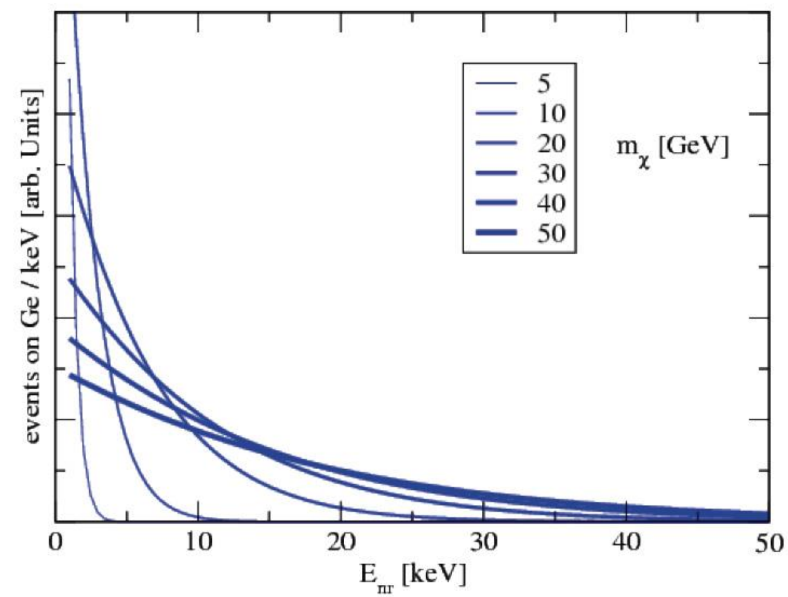


Minimum Wimp velocity
for recoil energy T_R

Recoil energy is largest for $m_N = m_W$

Sensitivity decreases at small (about 10 GeV) and large (several hundred GeV) WIMP masses

T_R specrum for smaller m_W decreases faster



WIMP vel. $\beta \approx 10^{-3} \Rightarrow T_W \approx 10^{-6} M_W$
$\Rightarrow T_W \approx 100$ keV for $M_W = 100$ GeV

Interaction rate

v_{Sun}=220 km/s

The WIMP interaction rate is proportional to

- the local WIMP density ρ [ρ=0.3 GeV/cm^3]
- the cross section on protons σ_p
- the mass of the nucleus squared (assuming coherent scattering) A^2
- the nuclear form factor $F(q)$, becoming very small at momentum transfer $q=(2ME_R)^{1/2}$ values high enough to resolve the nuclear structure. Depends on the nucleus
- the, time dependent, "average" WIMP velocity η
- Inversely to WIMP mass M_W and reduced mass squared

Example: $\sigma=10^{-8}$ pb, Ge detector, R(15-65 keV)=10^{-3} /(kg keV d)

Nuclear Form Factor

Form factor = Fourier transform of the spatial density (vs distance from centre) of the scattering centres

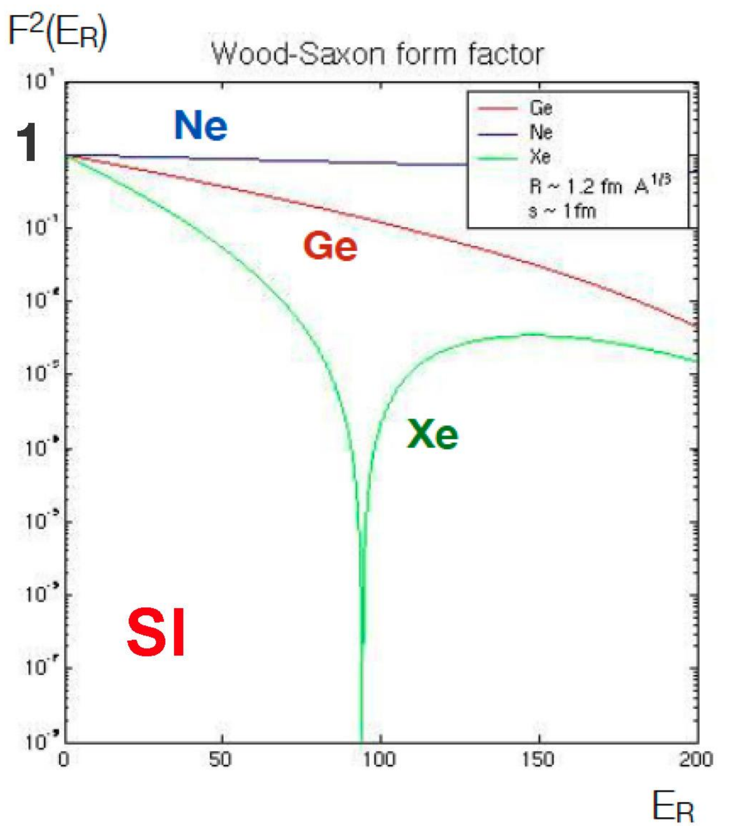
•Charge for charged particles scattering

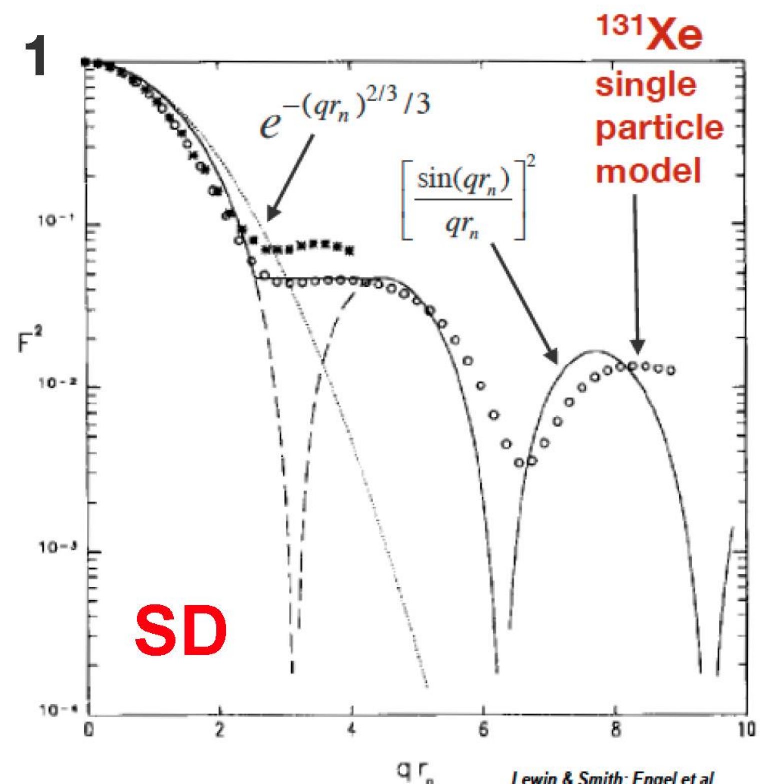
•Mass for WIMP SI coupling (and neutrons)

•Spin for WIMP SD coupling

Momentum transfer **q**

Coherent scattering only if $q < 1/R$





From C. Regenfus

Energy loss below 100 keV

The energy transfer in a **liquid** medium (Ne, Ar, Xe) is deposited as

•**ionisation** (electron-ion pairs)

•Example: 38% of the energy deposit in LXe (E=0)

•**excitation** (excited atoms or molecules) released as

•UV & visible (emitted in ns-μs)

•IR (ps) [see G. Carugno, NIM A **419** (1998) 617; G. Bressi et al. NIM A **440** (2000) 254]

•**Low energy free electrons** <lowest excited level

Depend on **linear energy transfer (LET), applied electric field (recombination)** and **on impurities (ppb level)**

Inorganic solid scintillators. NaI(Tl), CsI(Tl), BGO,..

•Scintillation (μs time scale)

•Example: 12% of the energy deposit in NaI(Tl)

•Phosphorescence (from milliseconds to days)

•IR radiation

•Heat

•Ionization (NaI(Tl) 17 eV per pair)

•Radiation damage: metastable color centres (days?)

Depend on **temperature**

Measuring W (in liquids)

Liquid Ar, Kr and Xe have a, spatially local, band structure

Correct measurement of the number of electron-ion pairs produced by radiation needs

•to minimize the loss of charge carriers by attachment to impurities ⇒ **ultra-purify the liquid**

•to minimize the recombination of electron-ion pairs ⇒ **apply a very high electric field**

•to estimate the deposited energy correctly ⇒ **electrodes should collect all electrons**

small gridded ionization chambers, irradiated with electrons and gamma-rays from internal radioactive sources.

Material	Ar	Kr	Xe
Gas			
Ionisation Potential (eV)	15.8	14.0	12.1
W (eV)	26.4	24.2	22.0
Liquid			
Gap energy (eV)	14.3	11.7	9.3
W (eV)	23.6	18.4	15.6

LXe has the smallest W-value, hence the the largest ionization yield, of all liquid rare gases.

Charge collection vs E

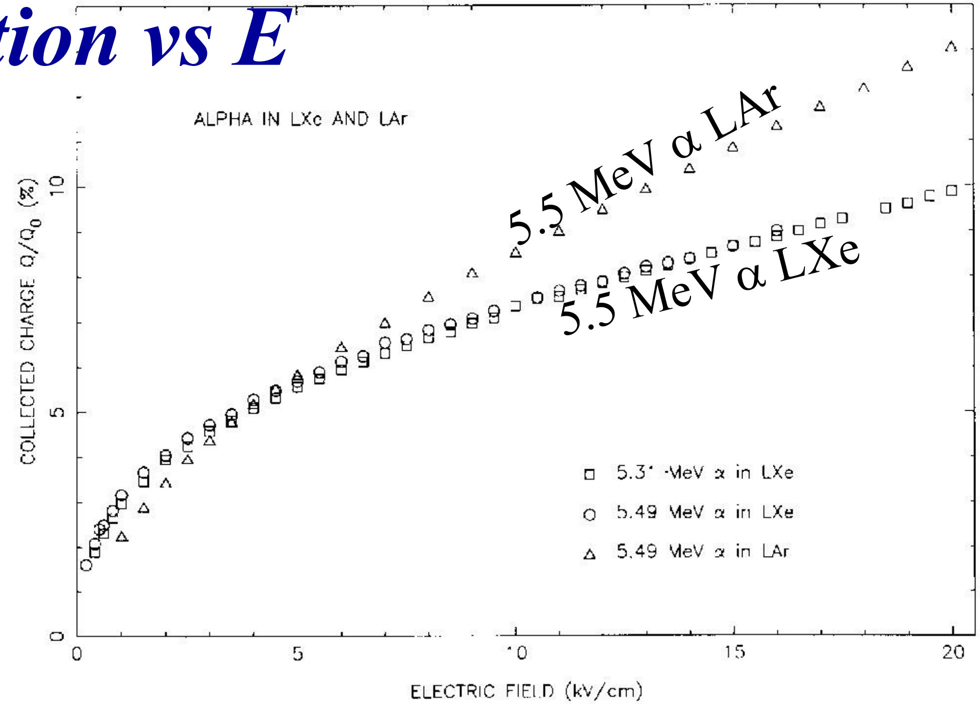
Recombination of electron - ion pairs depends on field **E**

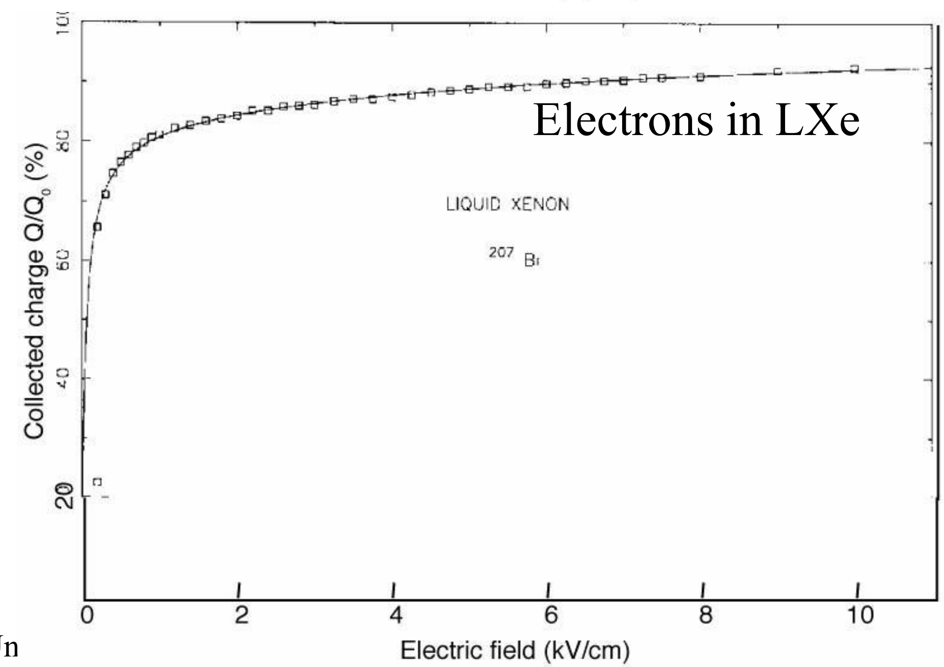
1. between the two original partners (**geminate recombination**. Onsager model)
2. between different partners (**columnar recombination**. Jaffe model)

Alphas ionise heavily (NR even more), producing a cylindrical track in which the largest fraction of energy is deposited (delta rays outside it) with a high recombination rate

Typically 10% of the charge is collected at fields E<20 kV/cm

For electrons (from 570 keV gammas) charge collection >90% already at E=5 kV/cm





L. Onsager; Phys. Rev. **54** (1938) 544

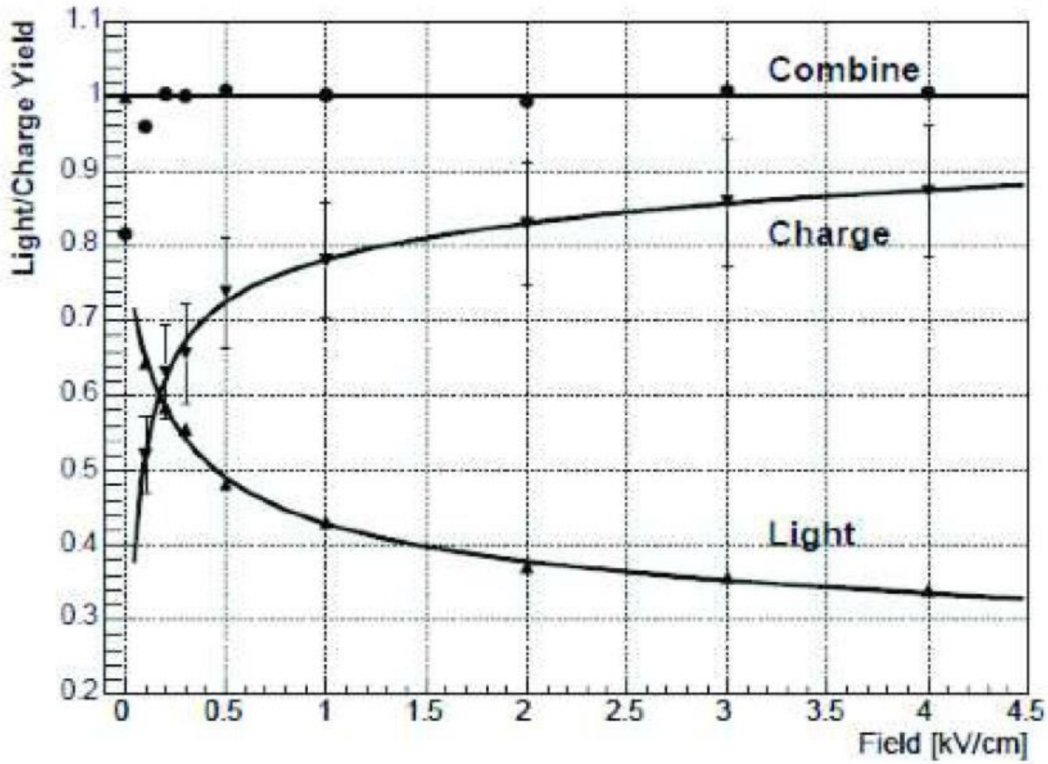
G. Jaffe, Ann. der Phys. **42** (1913) 303

Charge and light

Electric field reduces recombination

Light and charge as functions of the field. Electrons from 662 γ–rays

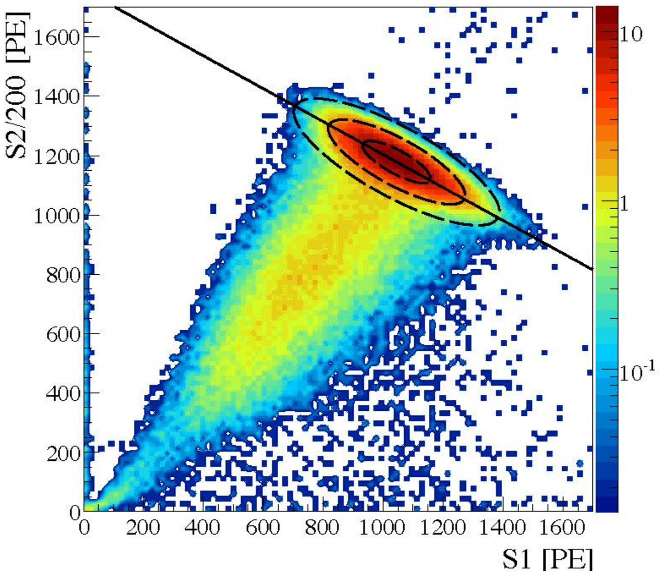
Liquid Xe



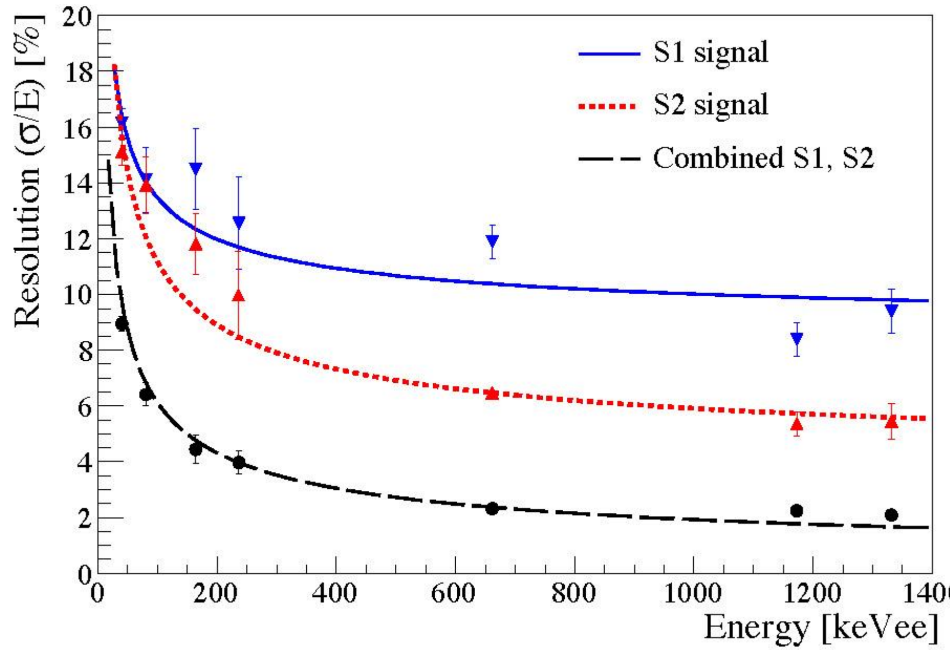
Aprile, E. *et al.*, 2007, *Nucl. Instr. Methods* **B** 173, 113.

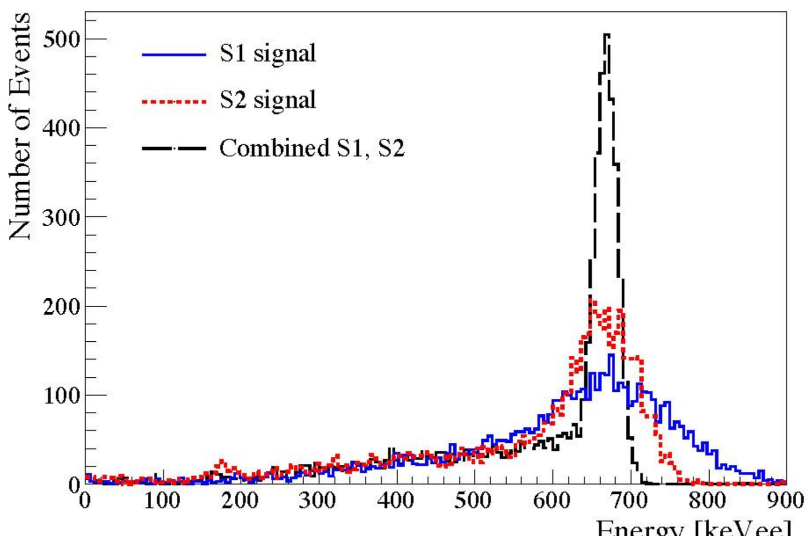
Charge and light

Anticorrelation of light and charge signal at ^{137}Cs line in XENON100 TPC



Calibration with several sources





S1 (light) σ/E**=12.5%**

S2 (charge) σ/E**=6.5%**

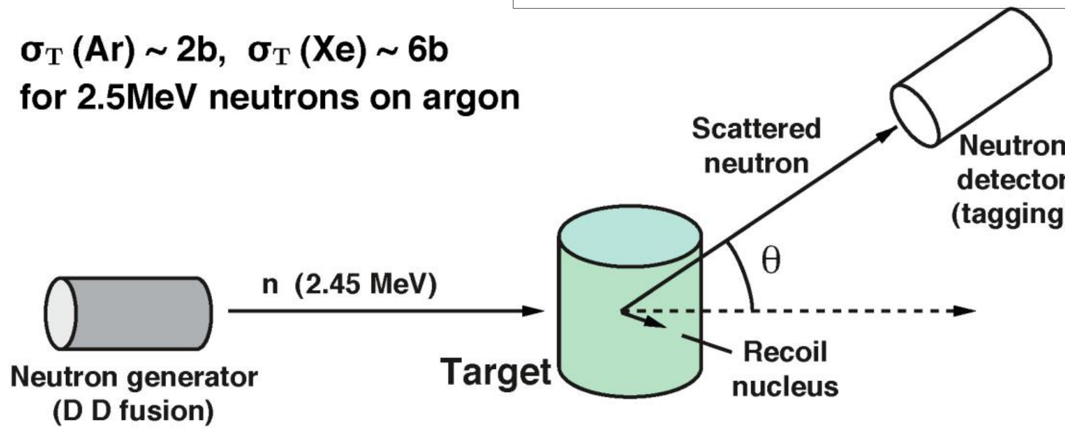
S1+S2 σ/E**=2.3%**

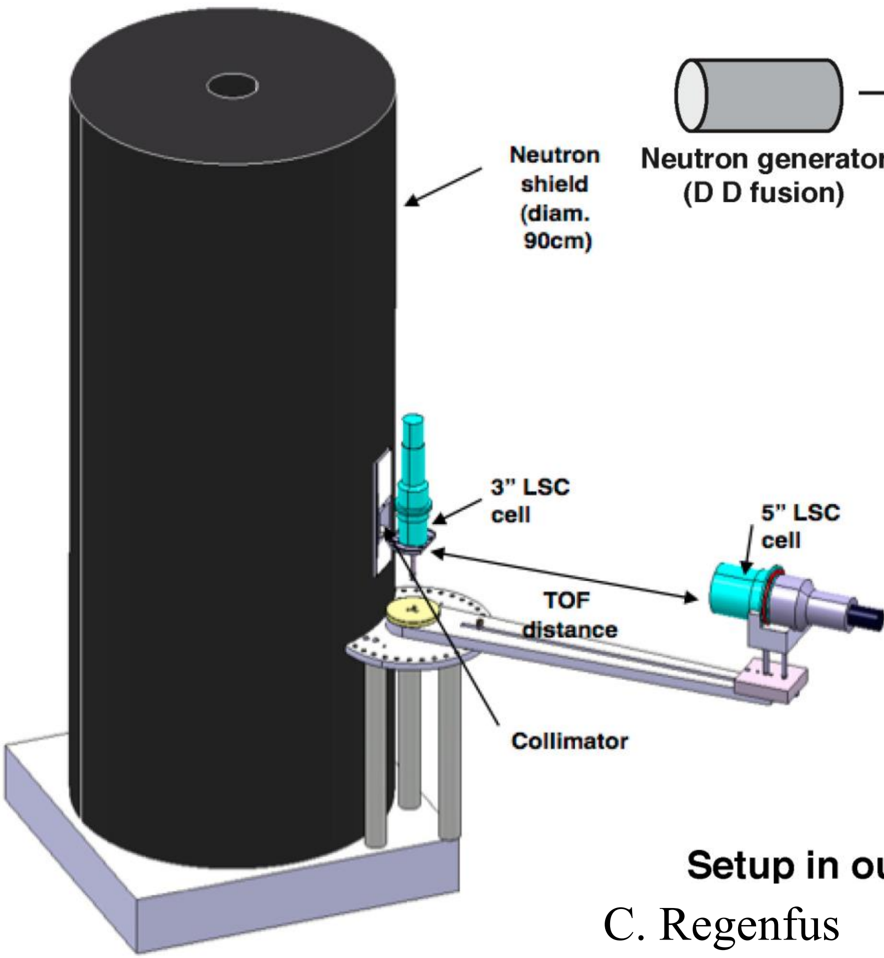
Aprile et al. arXiv 1107.2155

Measuring Leff

Sealed-tube neutron generators. Neutrons @ some 100 kV on a titanium deuteride target

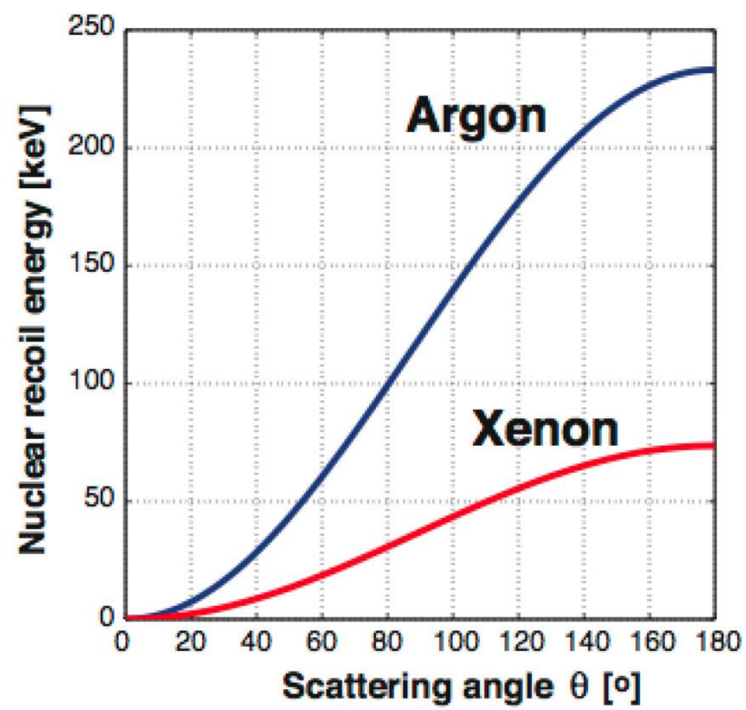
σ_T (Ar) ~ 2b, σ_T (Xe) ~ 6b
for 2.5MeV neutrons on argon





Setup in ou

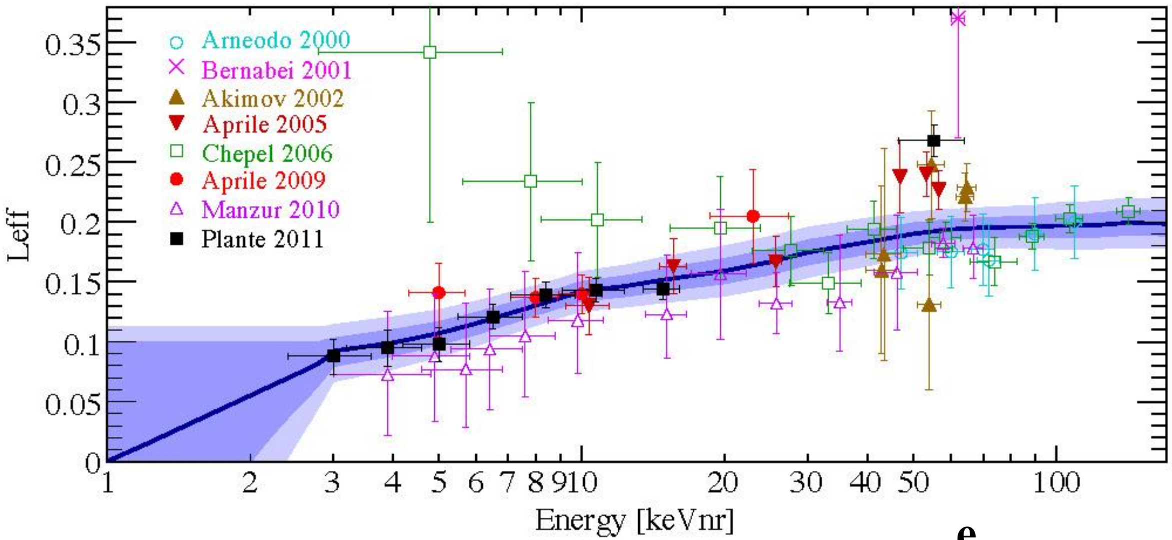
C. Regenfus



ArXiv 1104.2587

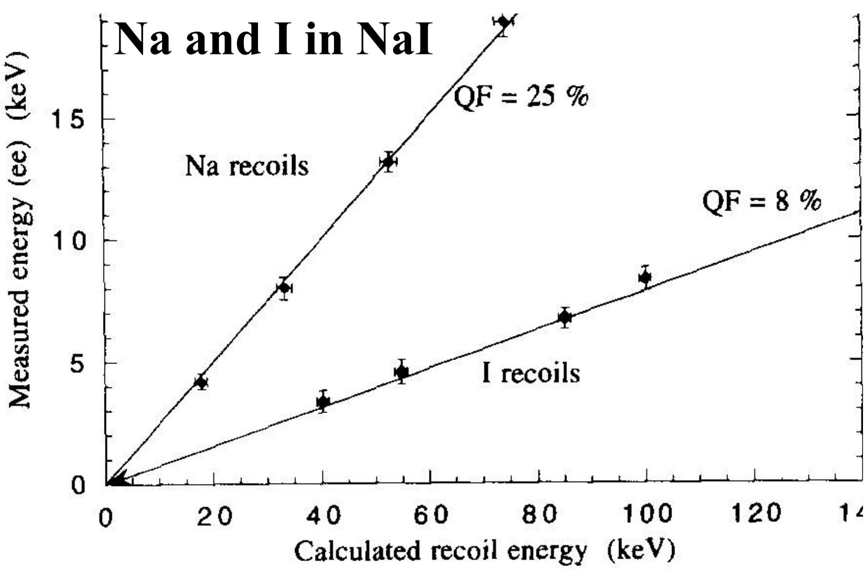
Xe, Na, I etc L_{eff} (or QF)

Liquid Xenon



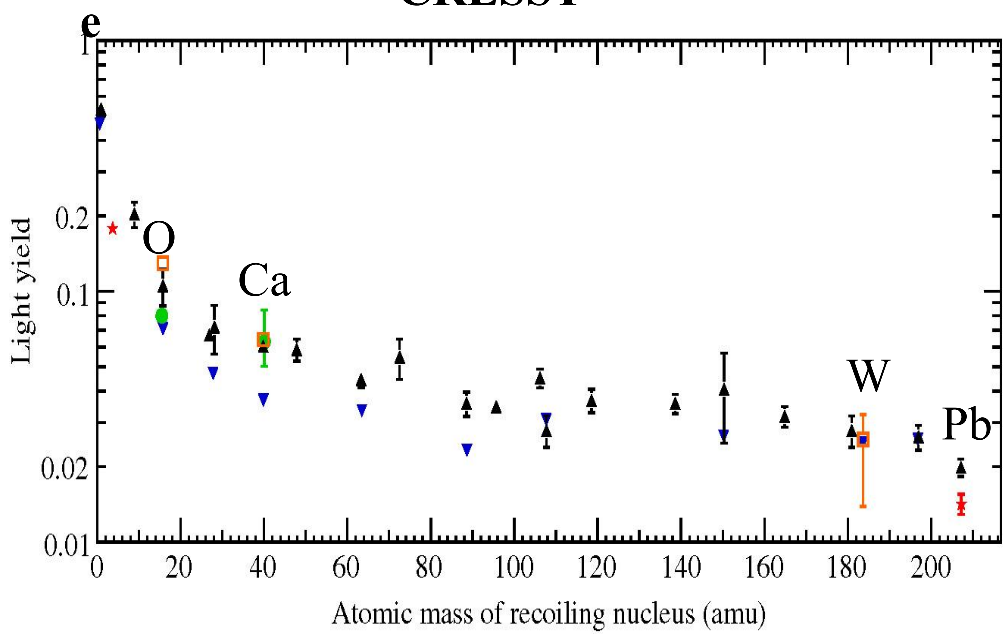
The effect is made explicit in the energy unit

- detected NR energy (keV_{nr})
- total recoil energy (as it were an ER) (keV_{ee})



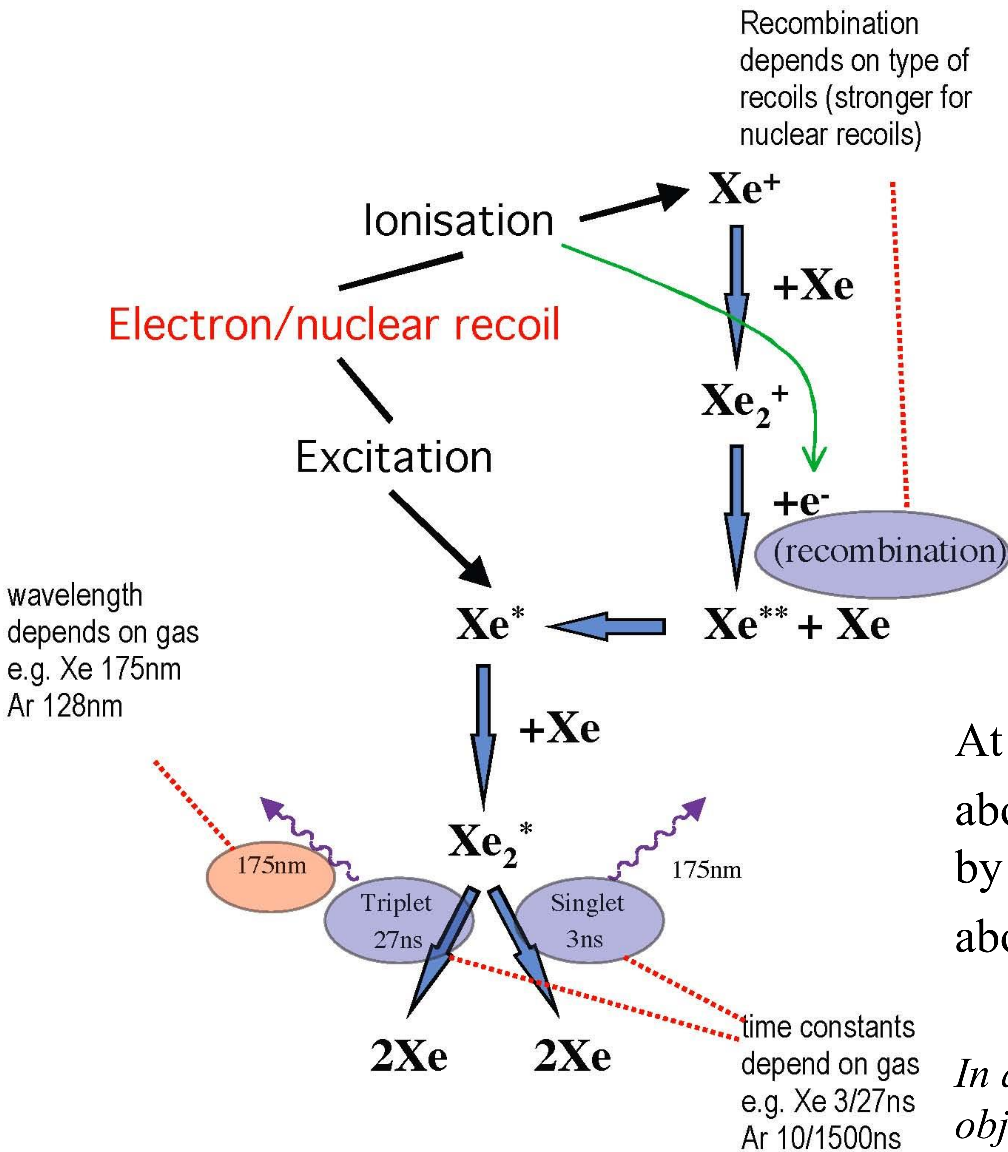
Gerbier et al. Astrop Phys **11** (1999) 287

CRESST



New Journal of Physics **11 (2009) 105017**

Charge and light in Liquid Xe/Ar



Excited dimers (excimers) and **molecular ions** formed by double collisions with metastable atoms

etc.

At **E**=0 scintillation light in LAr and LXe

about 70% due to excited molecules produced by **free electrons recombination**

about 30% due to **self trapped excitons**

In a liquid (excited) atoms are not independent objects. The excitation of one can propagate to others. Exicton is the quantum wave of excitation

Excimer de-excitation. Singlet and triplet

In liquid Ar the UV luminescence is due to the transitions to the ground level (two separate atoms) of the lowest molecular levels $^1\Sigma_u$ (Λ=0, total spin=0) and $^3\Sigma_u$ (Λ=0, total spin=1), within picoseconds

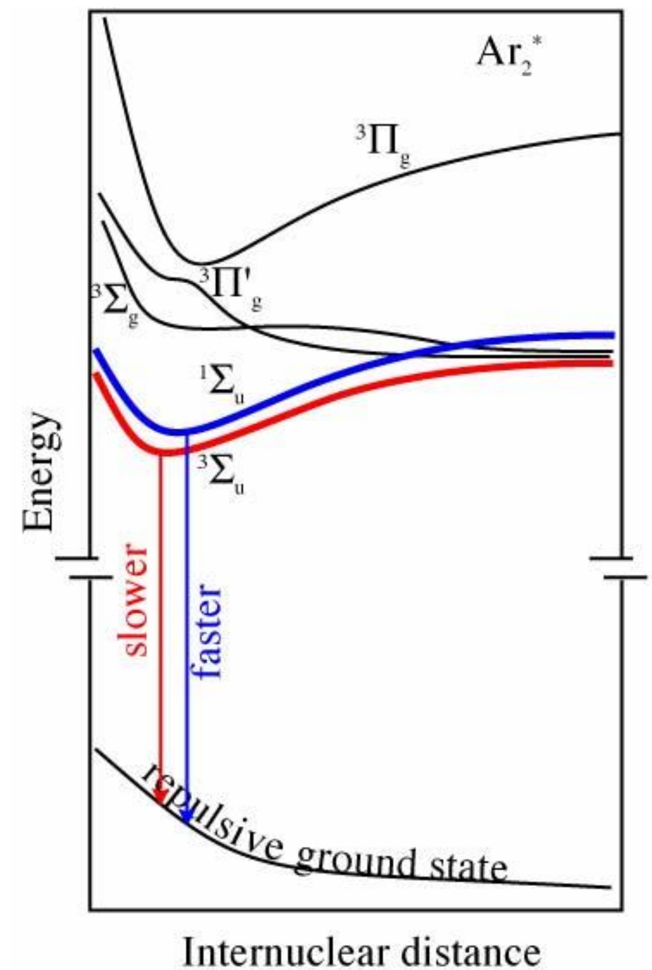
The singlet decay is strongly allowed (few ns lifetime)
The triplet decay need to flip one electron spin ($S=1 \rightarrow S=0$) and cannot go emitting a photon. Need to wait for collisions

In Xe similar situation even if total Λ, total S scheme not appropriate

NB. Emitted radiation is not re-adsorbed because too low energy to excite atomic levels

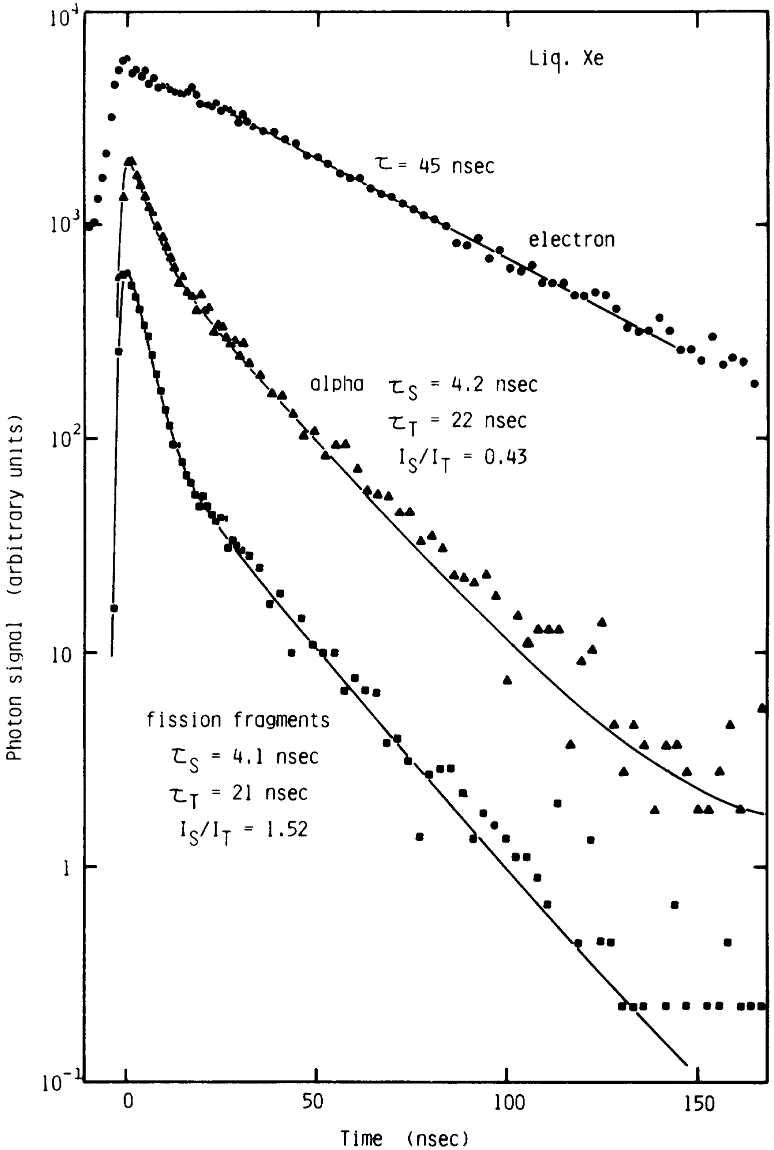
	T_1	T_3
Ne	5 ns	15.4 μs
Ar	7 ns	1.6 μs
Xe	4 ns	22 ns

Approximate and simplified



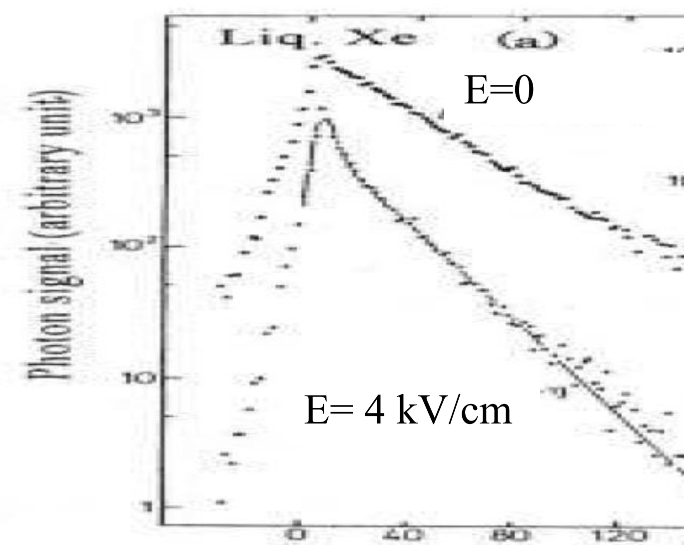
LXe no Electric filed

UV light λ=177.6 nm



Hitachi et al. Phys Rev **B** (1983) 5279

Electron curve has only one component with τ=45 ns.



It disappears if electric field is applied $\Rightarrow$ slow electron-ion recombin.

Lifetimes

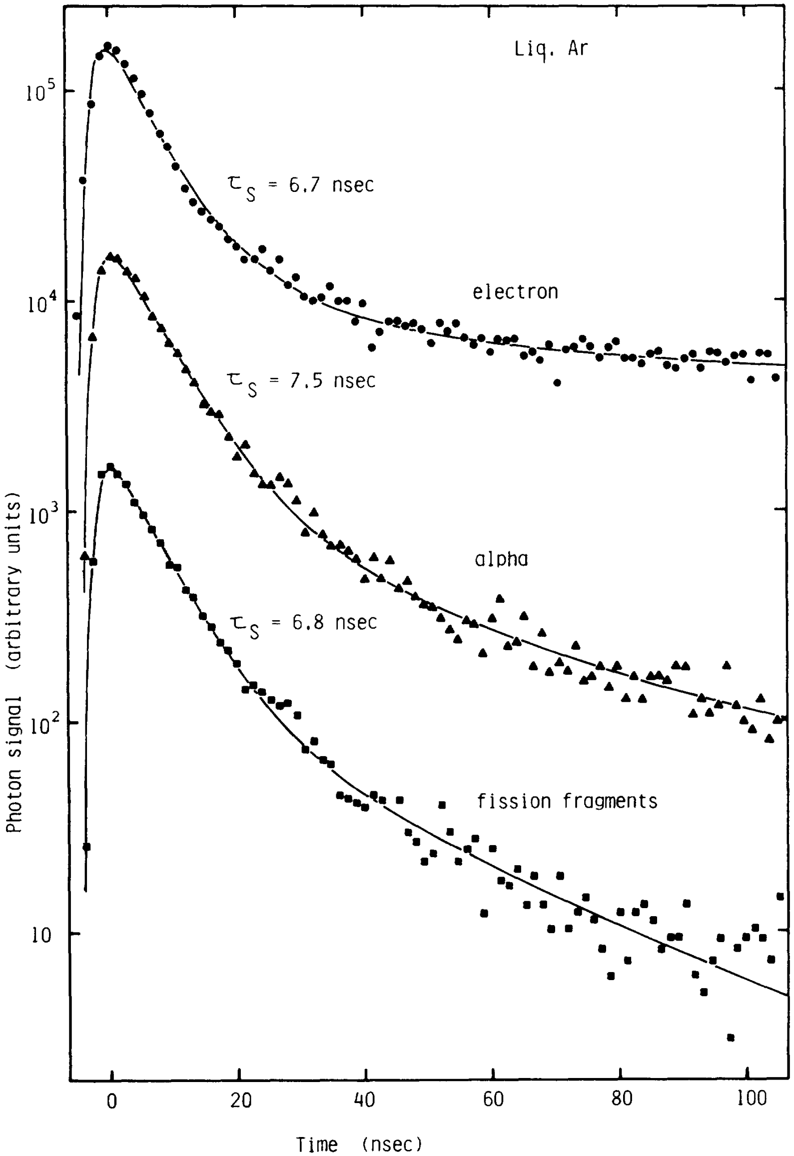
$^1\Sigma_u \Rightarrow 4$ ns

$^3\Sigma_u \Rightarrow 22$ ns

Alphas $I_S/I_T = 0.5$

Fission fragments $I_S/I_T = 1.6$

LAr no Electric filed



UV light λ=128 nm

Time evolution of the luminescence in L Ar without electric field

Lifetimes

$^1\Sigma_u \Rightarrow$ 7 ns

$^3\Sigma_u \Rightarrow$ 1600 ns (very sensitive to impurities)

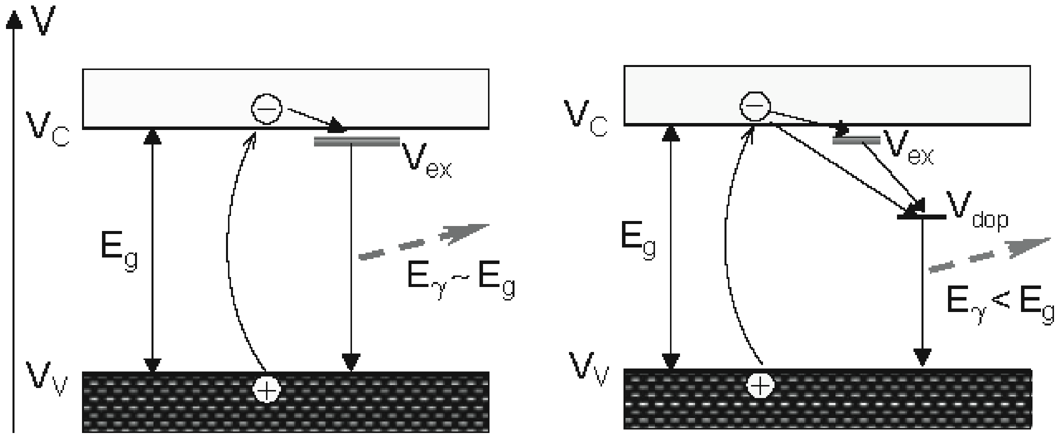
Electrons $I_S/I_T = 0.3$

Alphas $I_S/I_T = 1.3$

Fission fragments $I_S/I_T = 3$

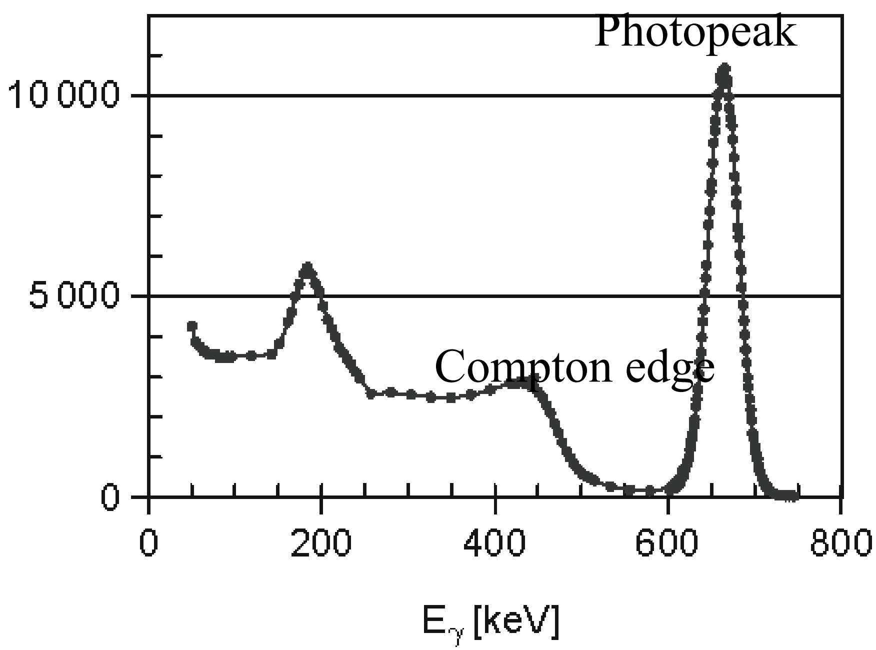
Hitachi et al. Phys Rev **B** (1983) 5279

Solid scintillators NaI(Tl), CsI (Tl)



In solid alkali halide crystals at room temperature the fraction of released energy emitted as light is small

Add dopant (Tl)



$2 \cdot 2 \cdot 2$ cm^3 is viewed by a 1 cm^2 Si photodiode. CsI(Tl) counter exposed to 662 keV γ rays from a ^{137}Cs source.
Energy resolution, Δ_{FWHM}/E_γ = 6%.

NB. Pure NaI scintillates at LN2 temperature

M. Moszynski et al. IEEE Trans Nucl Sci **49** (2002) 971; NIM A **505** (2003) 63; IEEE Trans Nucl Sci **50** (2003) 767

Channelling

•In a crystal the collision centres are arranged in periodic lattice

•The relevant *dE*/*dx* formula (Bethe–Bloch or others @ β $O(10^{-3})$) needs to be modified

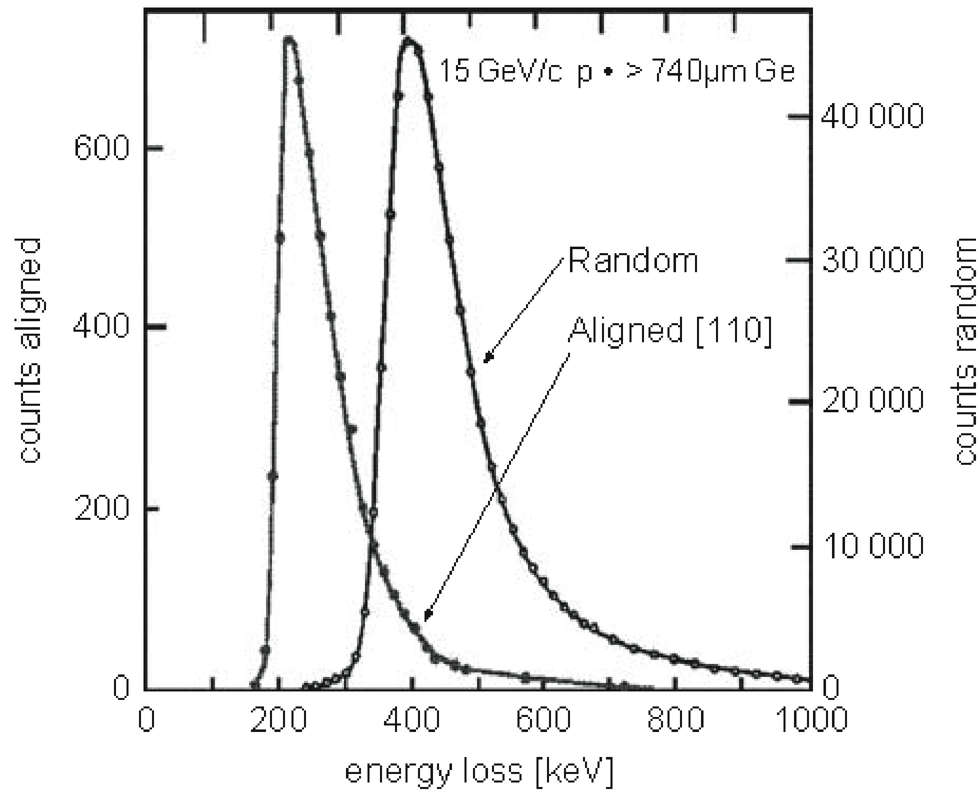
•Incoherent scattering at directions different from atoms lines

•Coherent scattering by strings or planes of atoms at directions close (within a fraction of degree) to crystal axis

•**Channelling directions**

  •**Anomalous (lower) energy loss**

•**Important for Si, Ge, NaI,…**



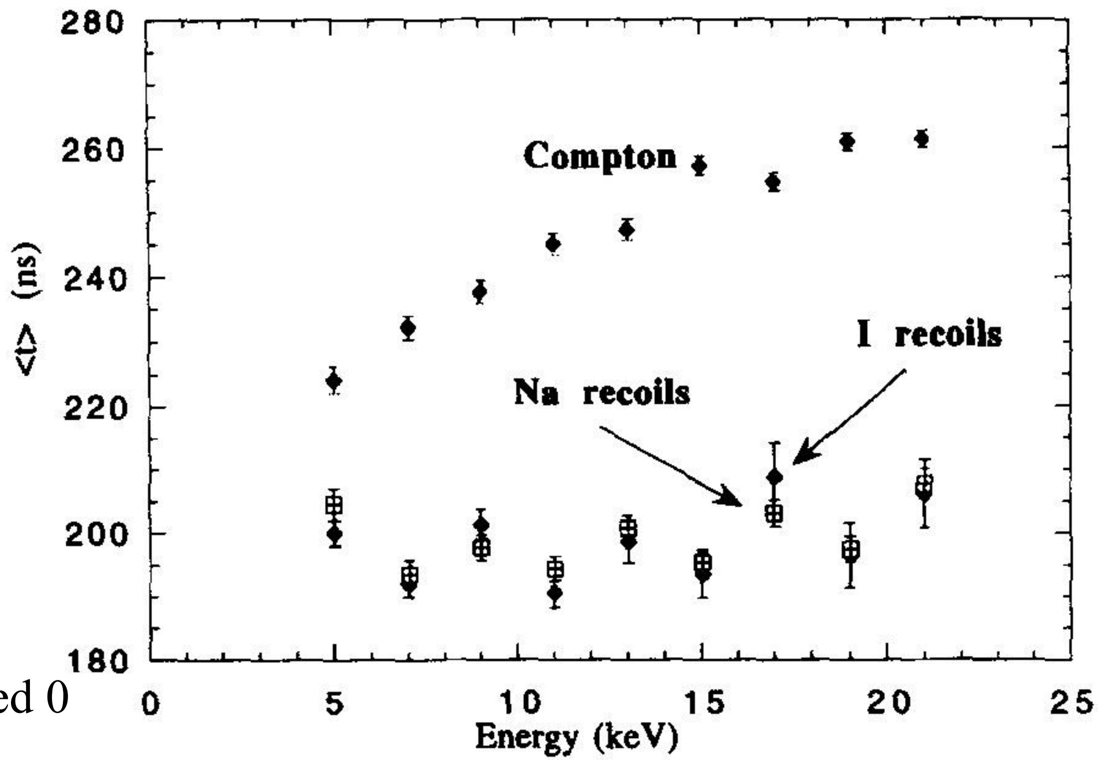
Fraction of channelled events

arXiv 0808.0704

NaI. Pulse shape

Bleu light λ=415 nm

First moment of the pulse time profile from calibration sources.
Electron recoil give a faster response than nuclear recoils
No difference between Na and I recoils
Difference becomes small at low energy
In practice PSD not useful also because surface events give short pulses too



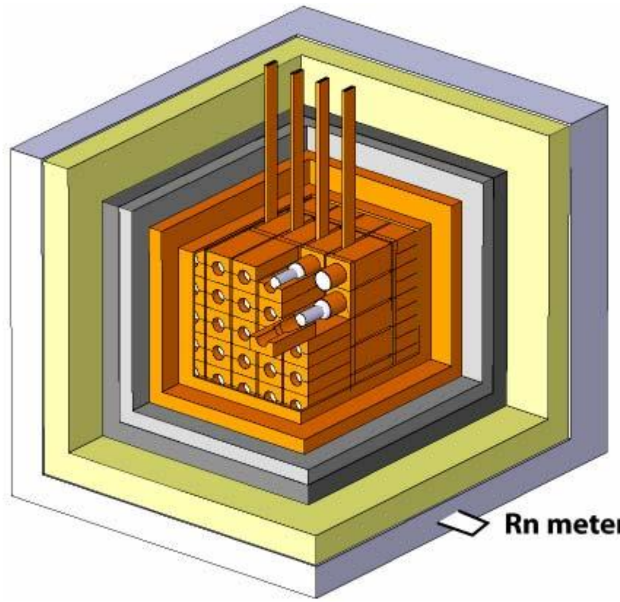
Note suppressed 0

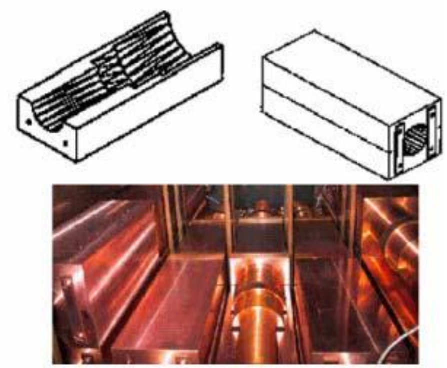
Gerbier et al. Astrop Phys **11** (1999) 287

DAMA & LIBRA

250 kg of NaI(Tl) supplied by St. Gobain, arranged in a 5 x 5 array of rectangular NaI bars, each 10.2 x 10.2 x 25.4 cm^3
Each bar is encapsulated in a radio-pure OFHC copper housing and viewed through special quartz lightguides at both end-faces by low-background PMTs
Sensitivity **5.5 – 7.5 pe/keV**

Hardware trigger
2-PMs coincidence, threshold=1 PE
Quantum efficiency = 30%
•single-hit events (visible energy in one bar only)
•pulse time structure characteristic of scintillation (100s ns) as opposed to short pulses (10s ns) for PMT-induced noise.





Graded shielding: radiopure Cu - Pb - Cd
Polyetilene&paraffin

NIM A **592** (2008) 297

External Backgrounds

Ambient neutrons penetrating the shields

Thermal neutron flux measured by looking at $^{23}Na(n,\gamma)^{24}Na$ and $^{23}Na(n,\gamma)^{m24}Na$.

$<1.2 \times 10^{-7} cm^{-2}d^{-1} \Rightarrow$ capture rate $<0.022\ kg^{-1}d^{-1}$ negligible

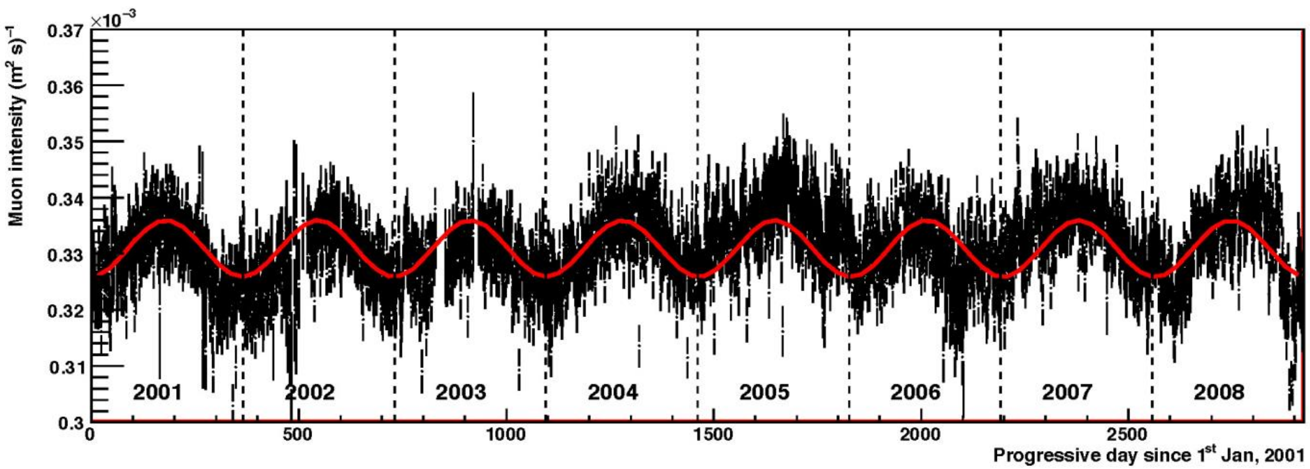
Fast neutron flux. MC from known LNGS ambient flux $\Rightarrow < 10^{-3} kg^{-1}keV^{-1}d^{-1}$

Muon flux Φ_μ= 20 m^{-2}d^{-1} . Order of magnitude calculation $\Rightarrow <3 \times 10^{-5} kg^{-1}keV^{-1}d^{-1}$

Muon flux modulation E_μ>1.3TeV,

LVD **0.0015±0.0006**. DAMA/LIBRA concludes: effect too small.

Max 5 July±15 d. DAMA-LIBRA max May 26±7 d (2 sigma)



LVD. 31st ICRC, Łódz, Poland, July 7-15 2009
MACRO Astropar. Phys **7** (1997) 109

Internal Backgrounds

DAMA developed sophisticated techniques over the years for radio pure NaI (Tl) powders and protocols for crystal growing (St Gobin is not allowed use that for others!)

Activity of the major radioactive nuclides traces measured in the crystals (including cosmogenic ^{125}I, ^{129}I, ^{210}Pb, ^{22}Na, ^{24}Na) and

^{228}Th	2 - 30 μBq/kg
^{238}U	several μBq/kg, may vary from crystal to crystal. Decay chain probably broken
^{nat}K	20 ppb (g/g)

^{40}K, abundance a_{40}=1.17×10^{-4}

89% beta decays to ^{40}Ca (maximum energy Q=1.31 MeV)

11% EC to ^{40}Ar (E=1.461 MeV), followed by **X or Auger de-excitation E_X =3.2 keV**

NIM A **592** (2008) 297

^{40}K

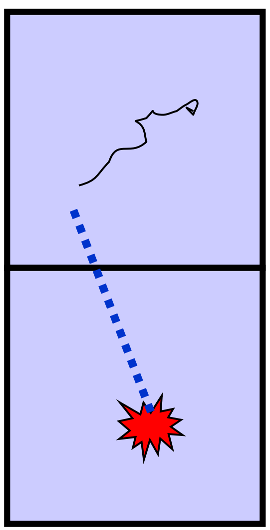
DAMA: protocols for extremely radio-clean NaI(Tl) crystals

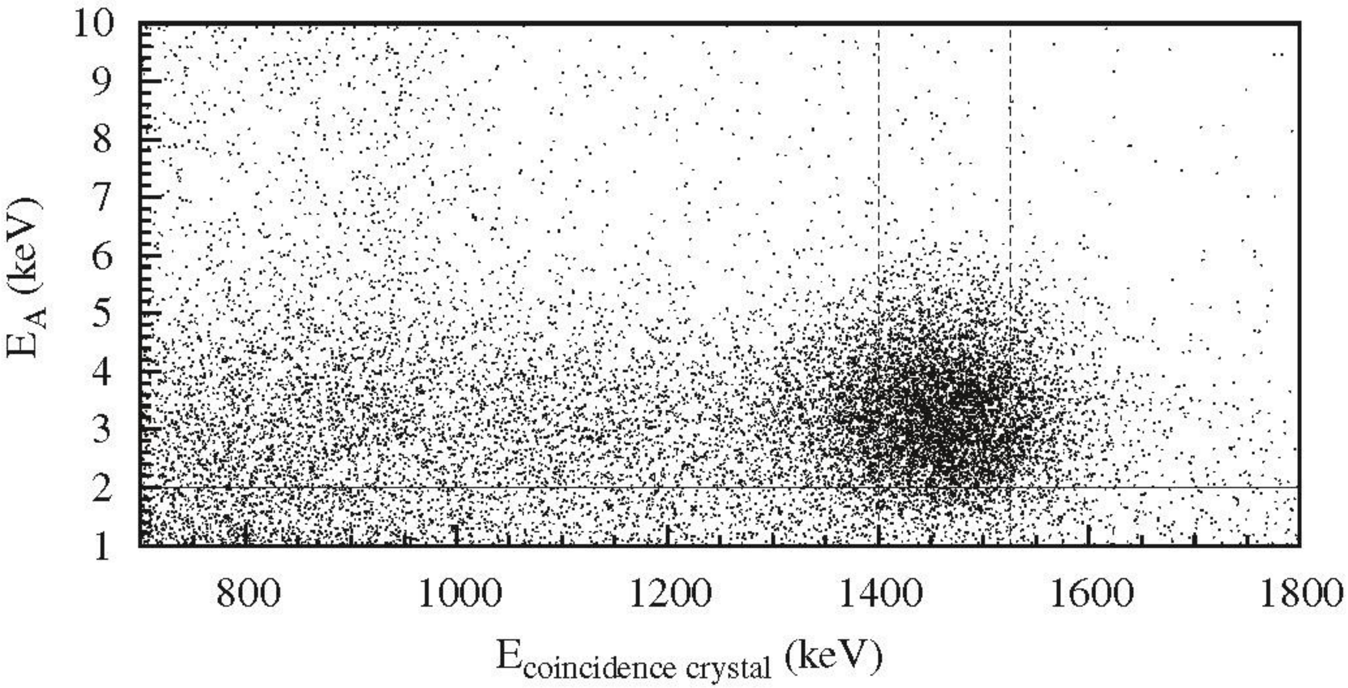
^{40}K in crystals = **20 ppb (g/g)** ^{40}K decays

•**89% beta** to ^{40}Ca (Q=1.31 MeV). No severe background

•**EC 11% EC** to ^{39}Ar (E_γ=1.461 MeV)

+ X ray/Auger electron E_X=3.2 keV. BKGRND when γ escapes





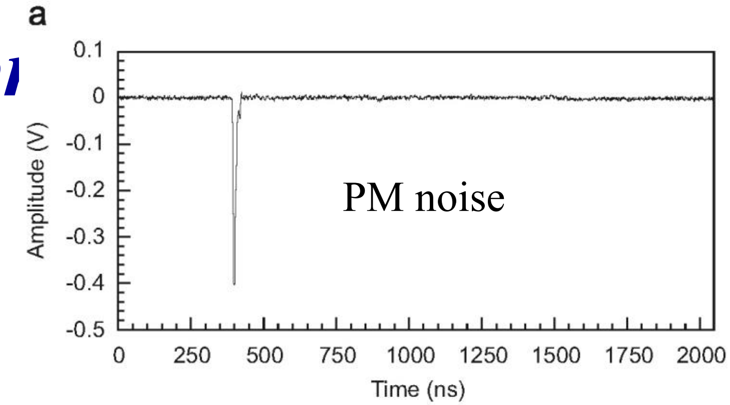
NIM A **592** (2008) 297

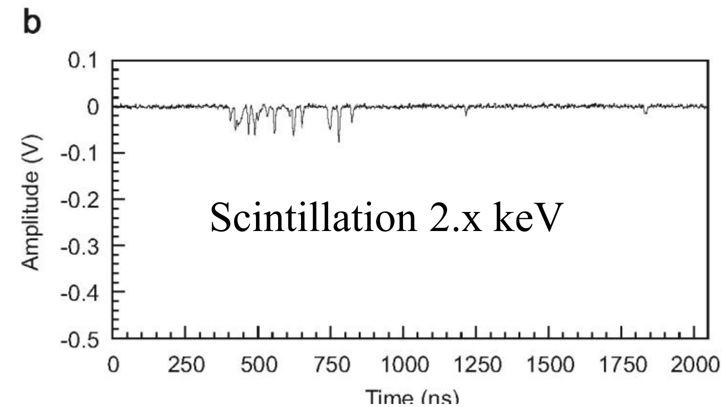
Noise suppression

Near threshold very small number of photelectrons

Noise reduction by

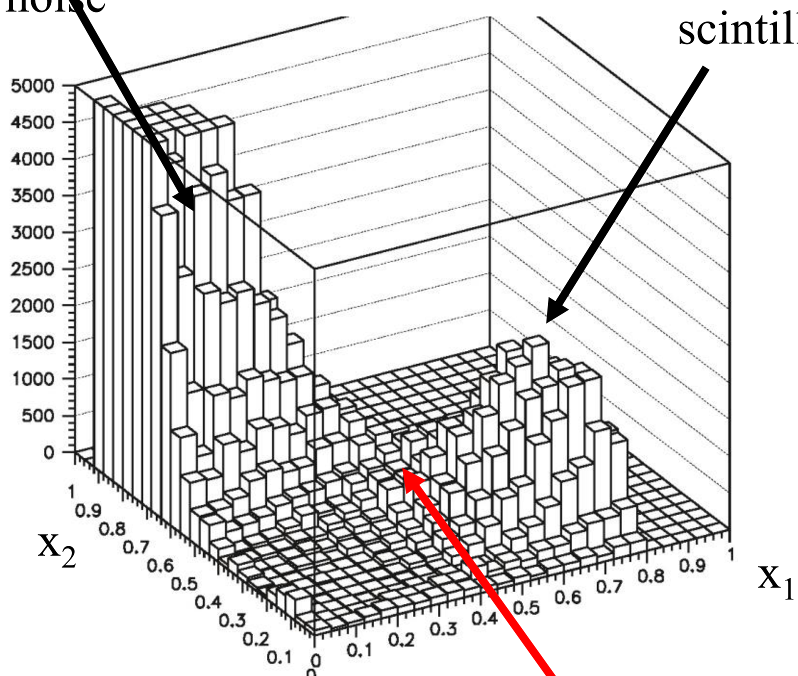
- coincidence between 2 PMs at the 2 ends
- fast vs slow pulses





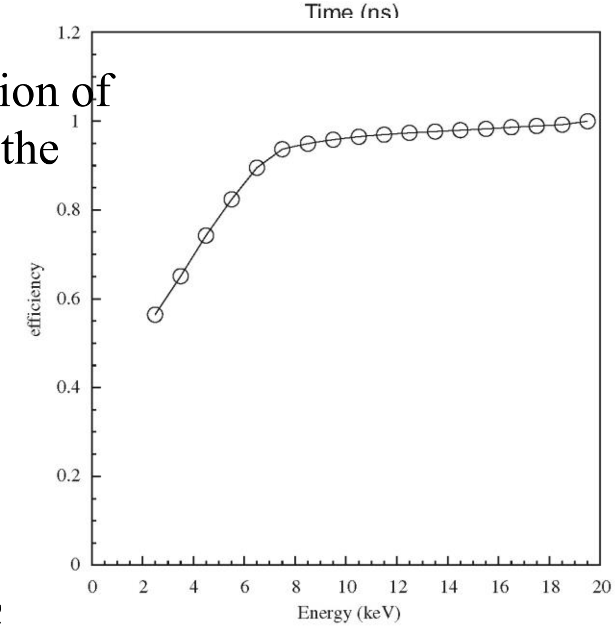
noise

scintillation

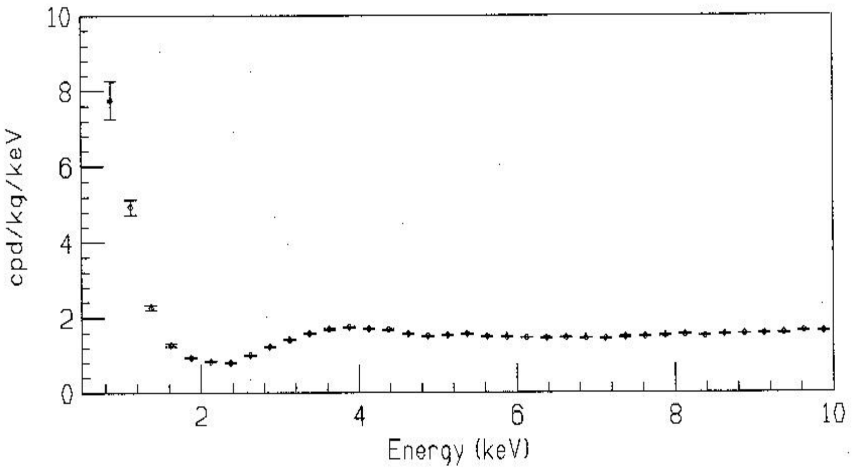


How cut?

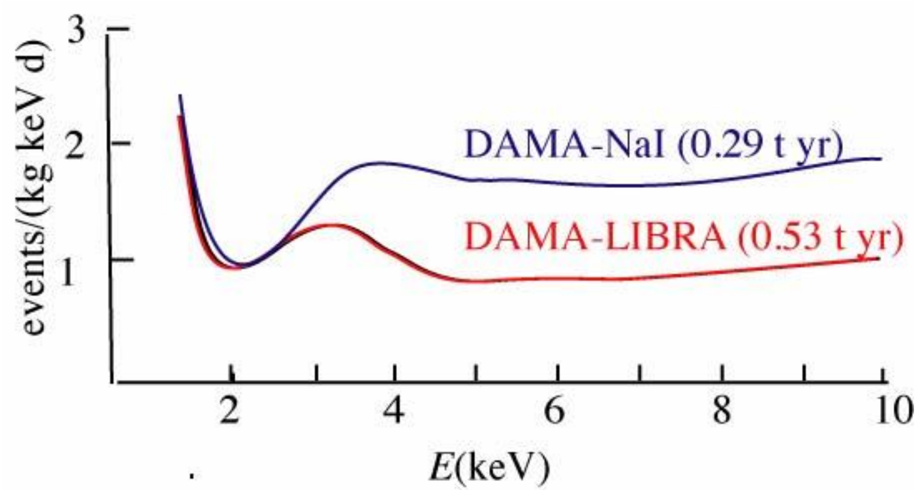
Strong variation of efficiency in the RoI

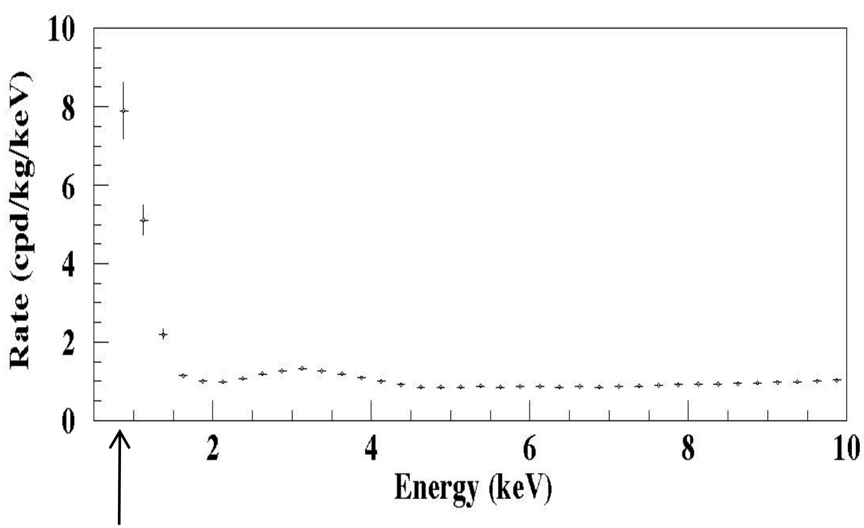


DAMA/LIBRA average energy spectrum



DAMA-LIBRA about 1/2 DAMA-NaI. Why?

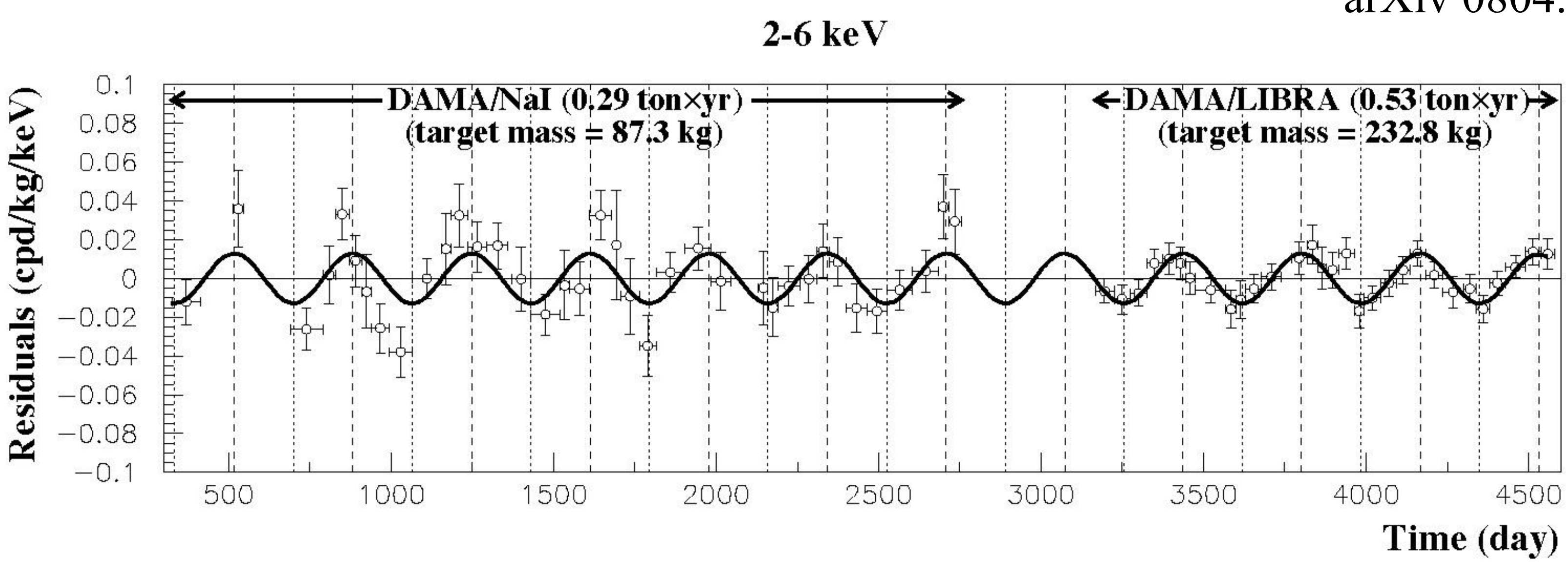




note 0 suppression

DAMA modulation signal

arXiv 0804.2741



Exposure = 0.82 t y

8.2 sigma evidence for modulation

Amplitude = 0.0131±0.0016

Period = 0.998±0.003 y

T maximum = 144±8 d (expected 152.5)

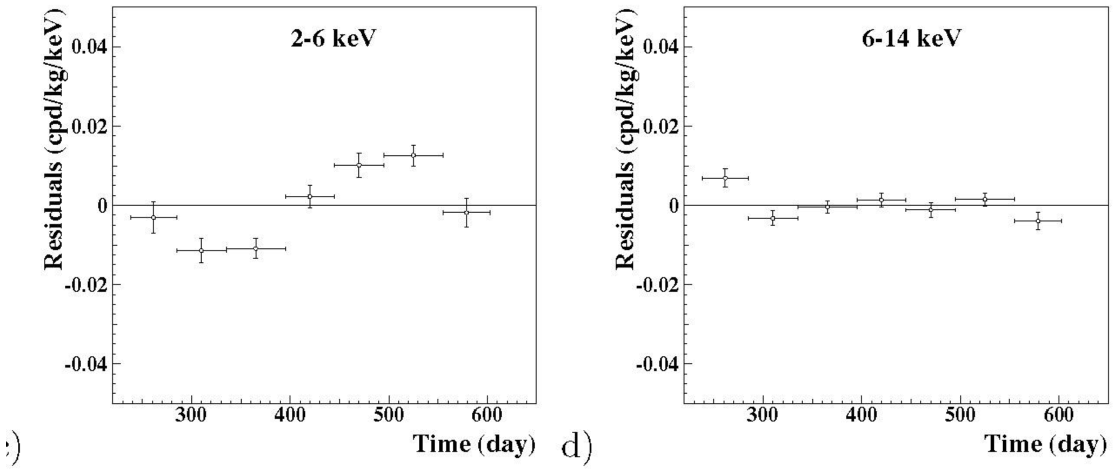
Effects mimic modulation? (1.2x10^{-2} dru)

Temperature <10^{-4} dru	**NO**
Rn < 2 x 10^{-6} dru	**NO**
Noise <10^{-4} mod ampl*	**NO**
Energy scale <2 x 10^{-4} dru	**NO**
Efficiency <10^{-4} dru	**NO**
Muon modulation < 3 x 10^{-5}	**NO**

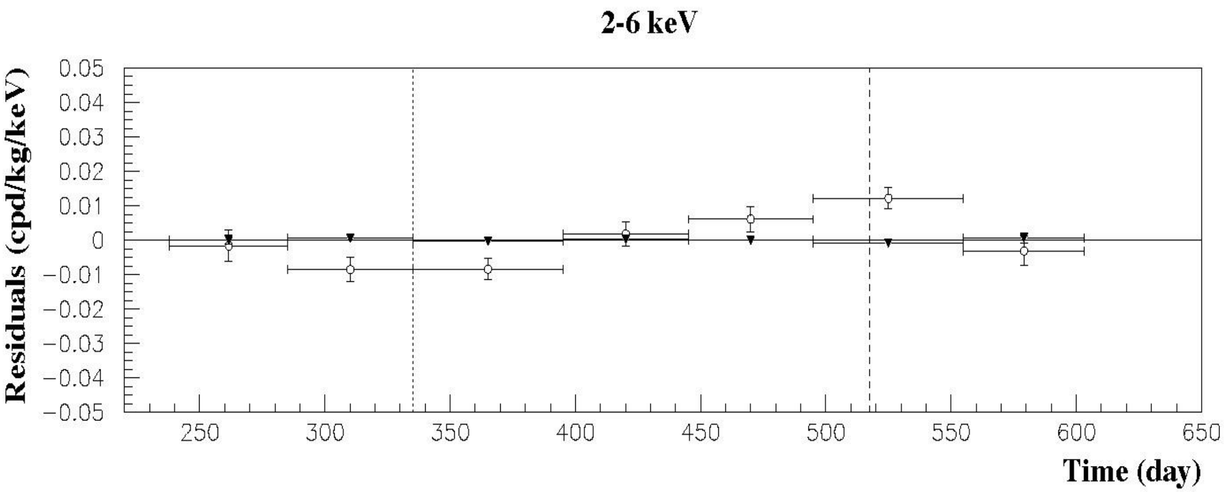
(*) hardware rate = 0.1 Hz/detector (2.5 Hz in total)
Fitted modulation amplitude (250 kg array) <1.8x10^{-3} Hz ➔<0.6/ (kg d)

DAMA modulation signal

arXiv 0804.2741



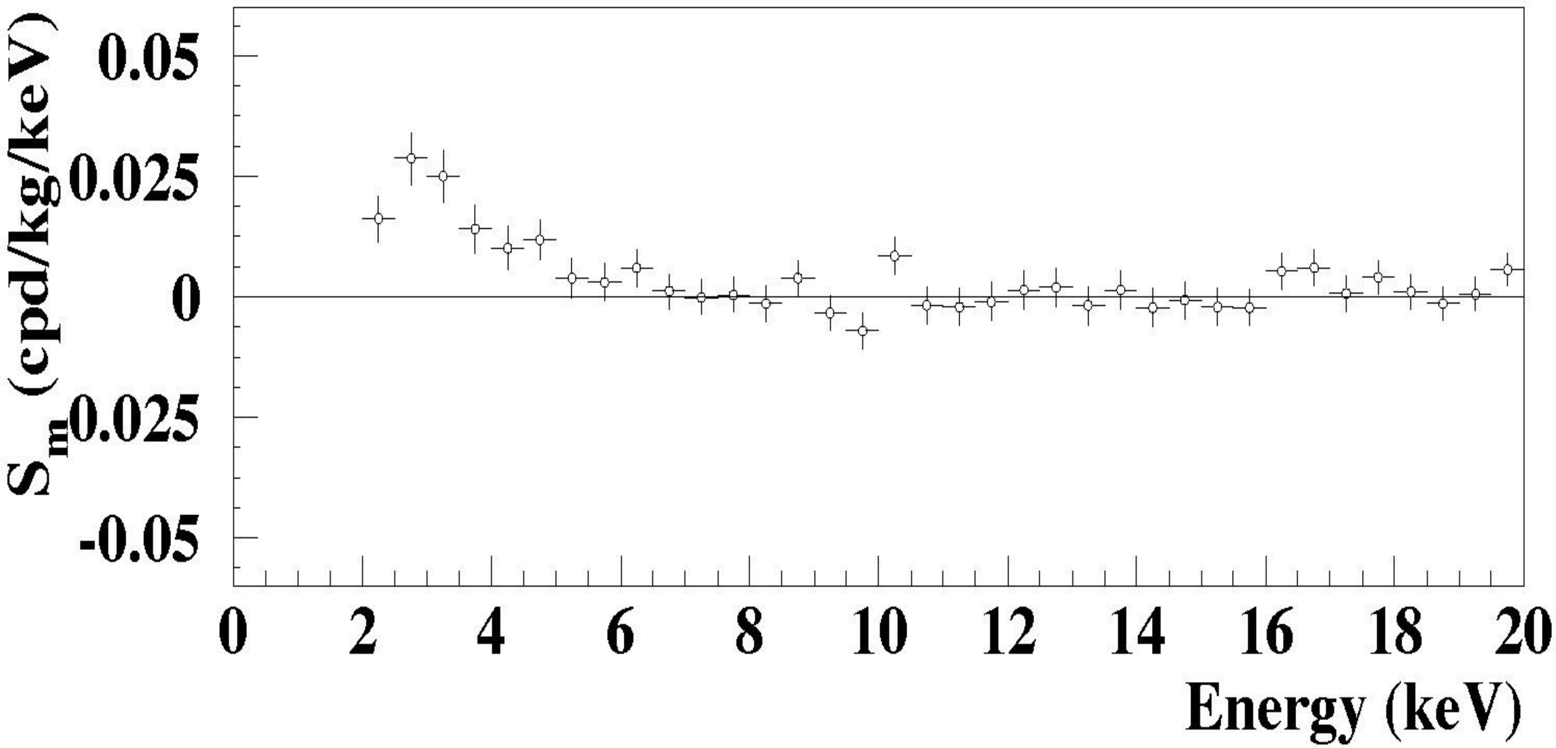
No modulation *E*>6 keV **OK**



No modulation in multiple hits **OK**

Modulation amplitude vs Energy

arXiv 0804.2741

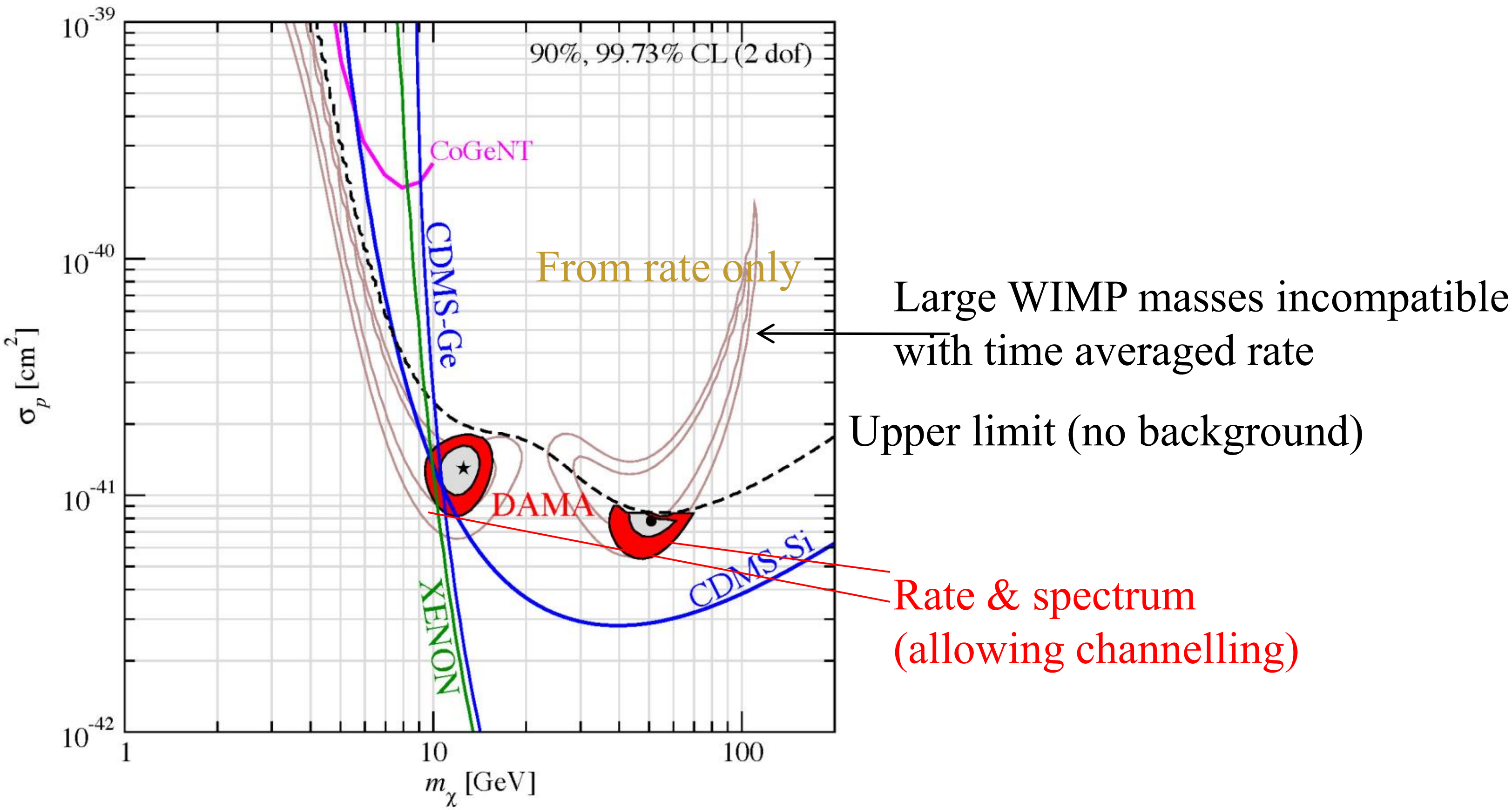


Modulation amplitude decreases (?) with increasing energy **OK (?)**

Fit W mass and SI cross section

Fairbairn & Schwetz
Arxiv 0808.0704

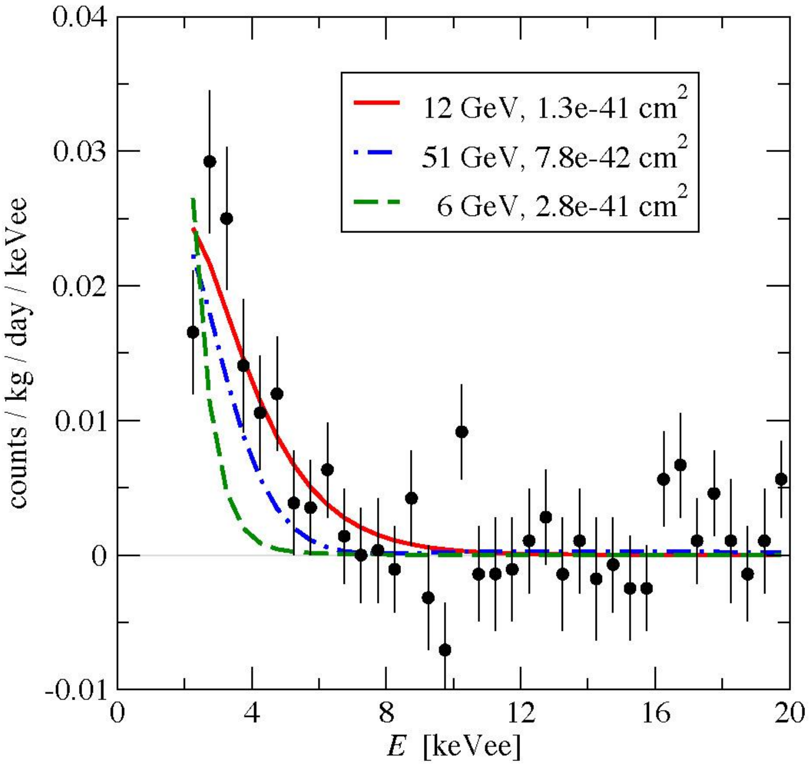
Model dependent. Spin independent coupling + “standard” halo model

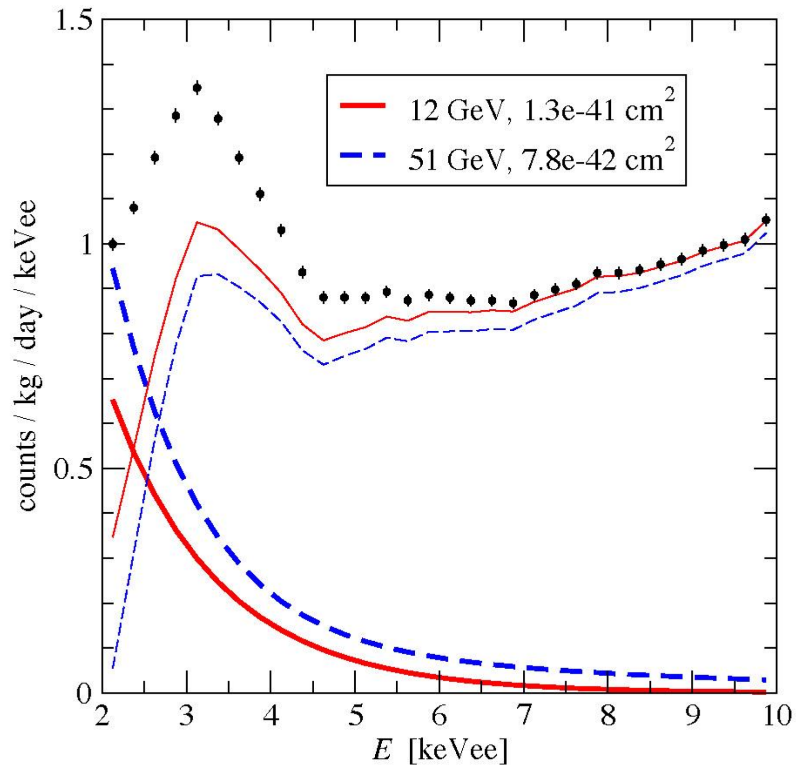


DAMA positive evidence can be made consistent with XENON10 and CDMS assuming lower and strongly asymmetric (larger in radial direction than in the tangential one) velocity dispersion

Fit W mass and cross section

ArXiv 0808.0704

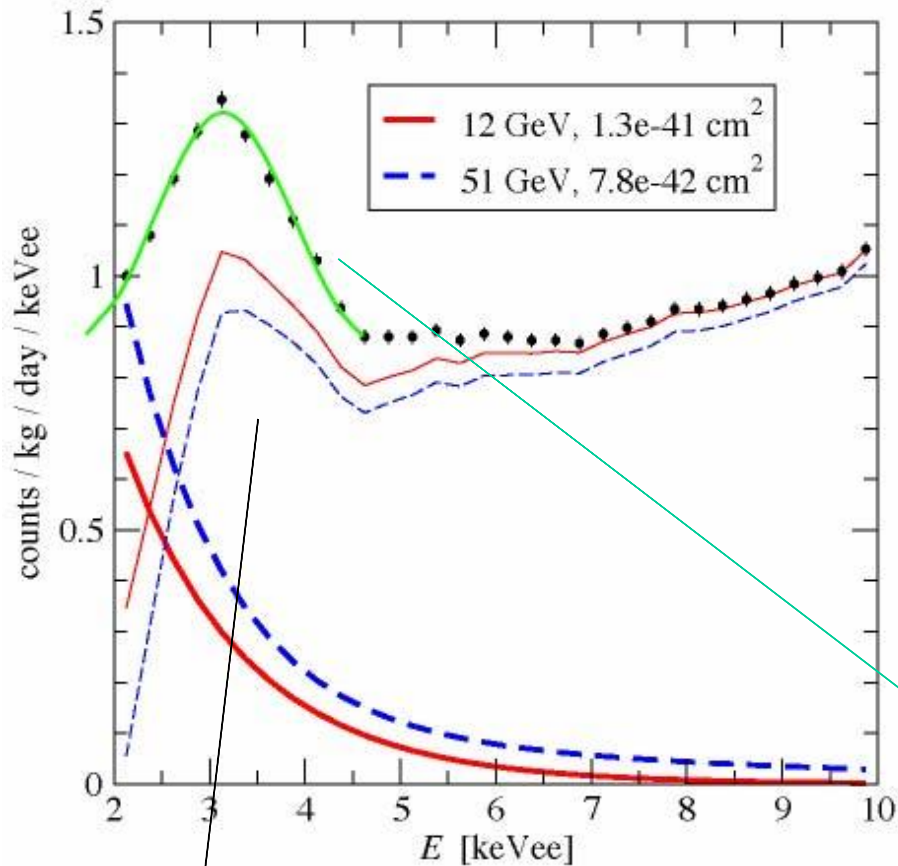




^{40}K *in the spectrum*

DAMA/LIBRA measured ^{40}K = 20 ppb

σ/E=25% at 3.2 keV or $\boldsymbol{\sigma}$**=0.8 keV**



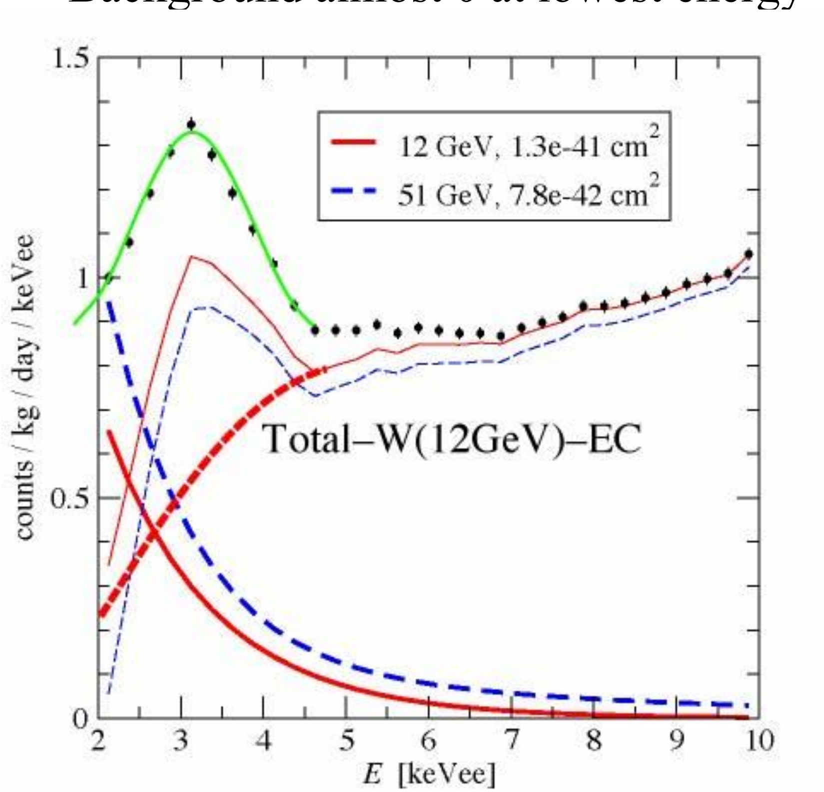
Could not find DAMA in papers value of the 1.46 keV γ escape probability
MC calculation by Cebrian gives 43% escape from a single similar crystal
Guess **20% escape probability**

Calculation gives the 3.2 keV ^{40}K peak (green curve)

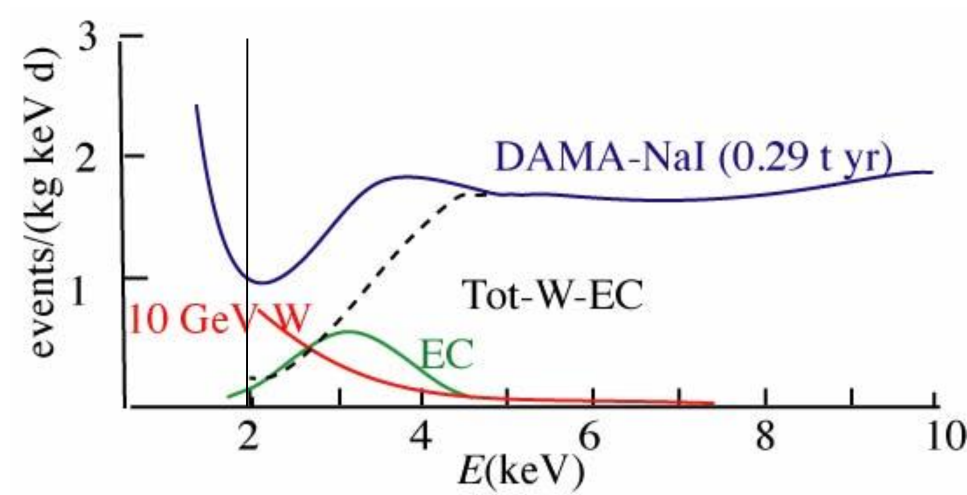
Still a rate of almost 1 kg^{-1}keV^{-1}d^{-1} available for signal & other backgrounds

Peculiar background spectrum

Background almost 0 at lowest energy

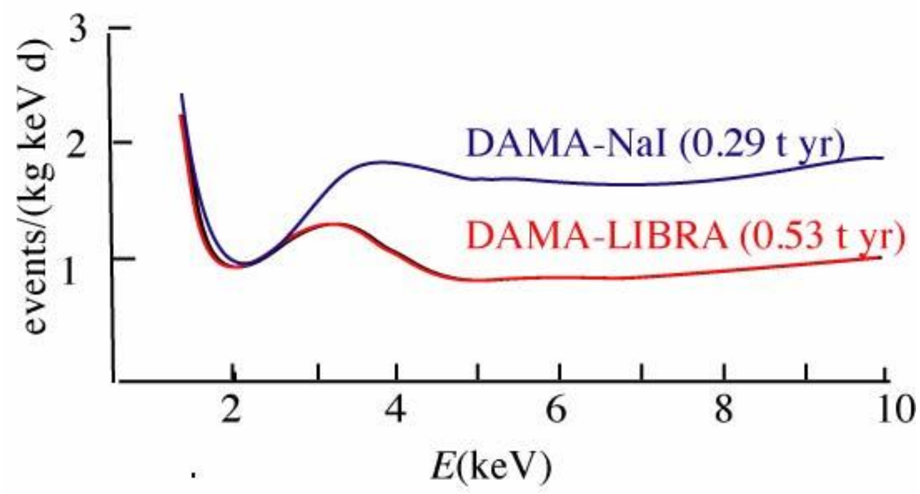


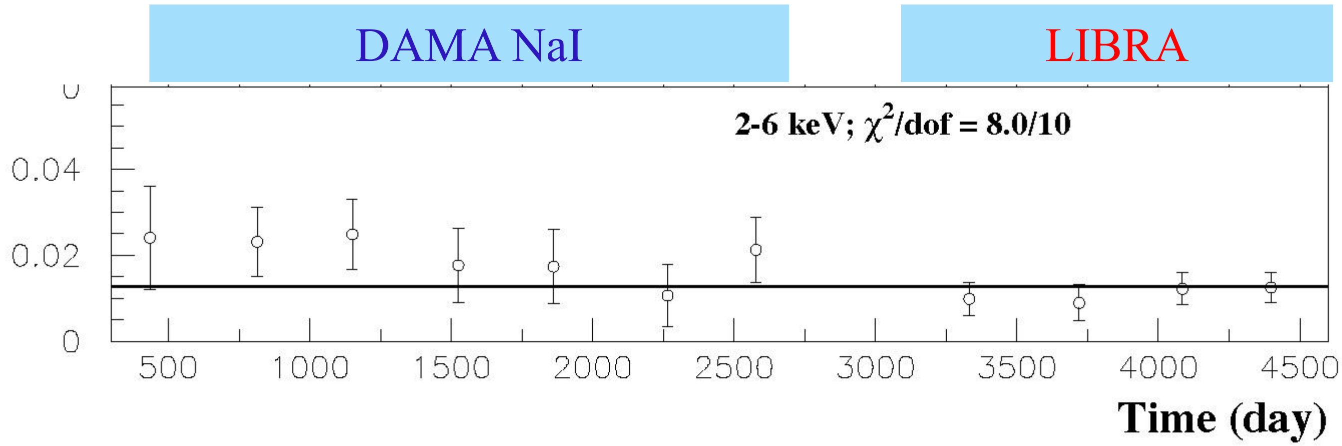
For DAMA NaI non EC background would grow from 0 at 2 keV to 2/(kg keV d) at 4 keV



DAMA should provide a background model to explain that

DAMA-NaI vs LIBRA





χ^2/d.f. ~ 2-2.5, but all DAMA above, all LIBRA below or on the average

ANAIS @ LSC

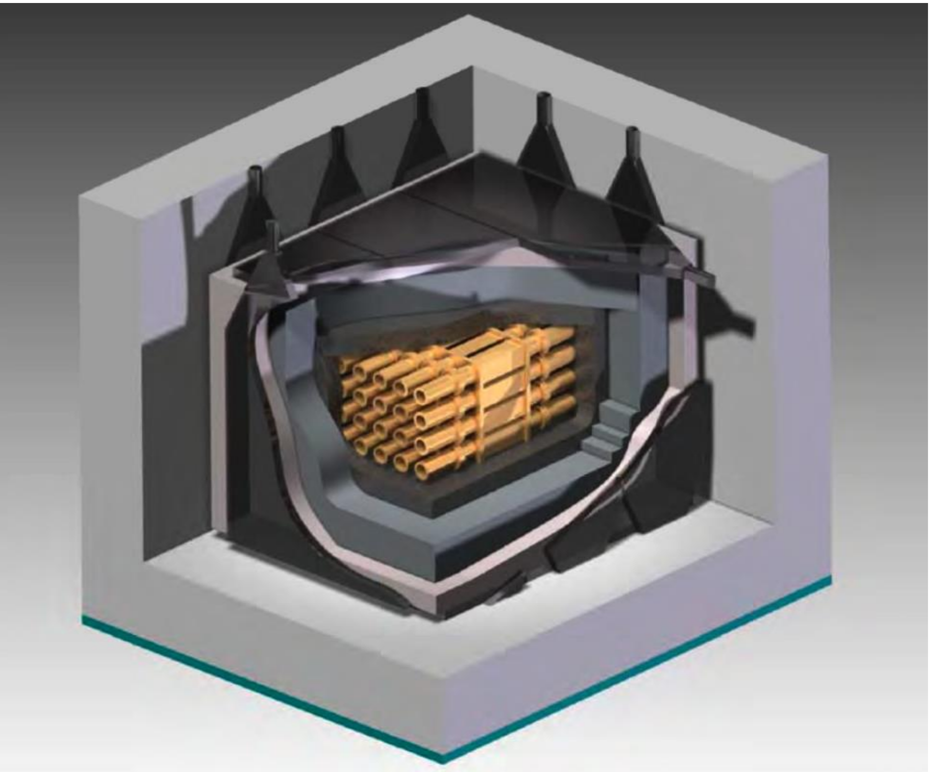
DAMA/LIBRA result is very important. It must be checked by an independent experiment

Comparison with experiments not looking for modulation is model dependent

Do not discriminate electromagnetic signal

Use NaI (same nuclei) crystals

Look for annual modulation



ANAIS

- Develop technique for **250 kg** NaI(Tl) crystals
- ^{40}K **< 100 ppb** in powder, **< 20 ppb** in crystal
  - 1 kg NaI from a first R&D process
    - ^{40}K traces measured with Ge
      - ^{40}K **>100 ppb**
  - 2nd differently produced sample under test (looks much better)
- Develop background model and test on prototypes (ANAIS-0)
- Aim: assemble in 2012

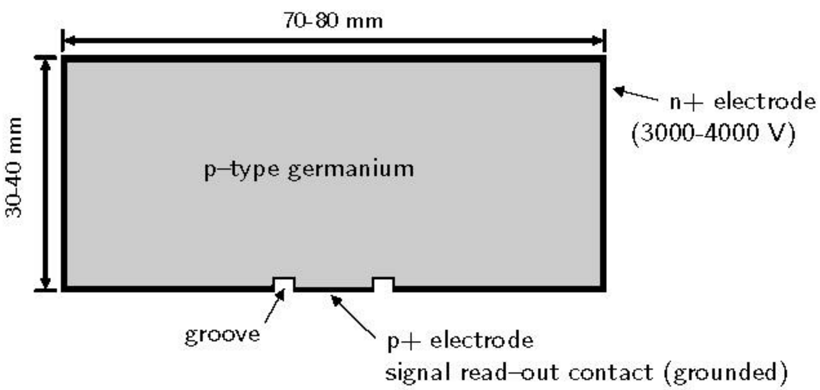
Canberra BEGe

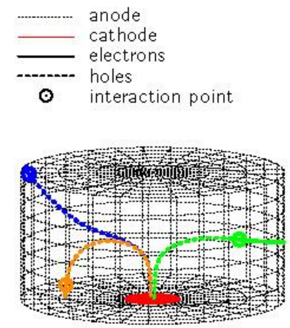
PPC (Point Contact) Ge detectors produced by Canberra as BEGe (Broad Energy Ge)

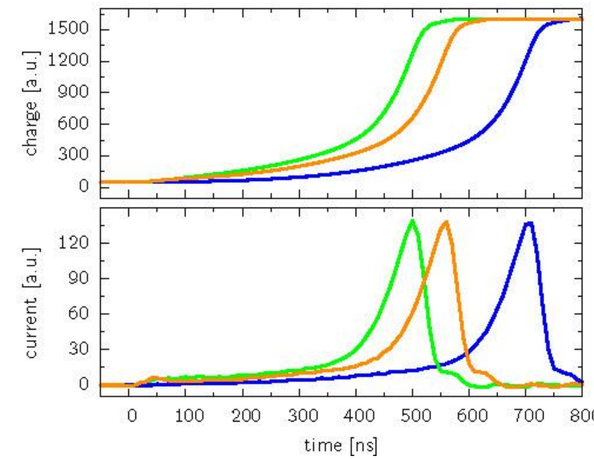
Very good energy resolution

Good control of the pulse shape: surface events suppression

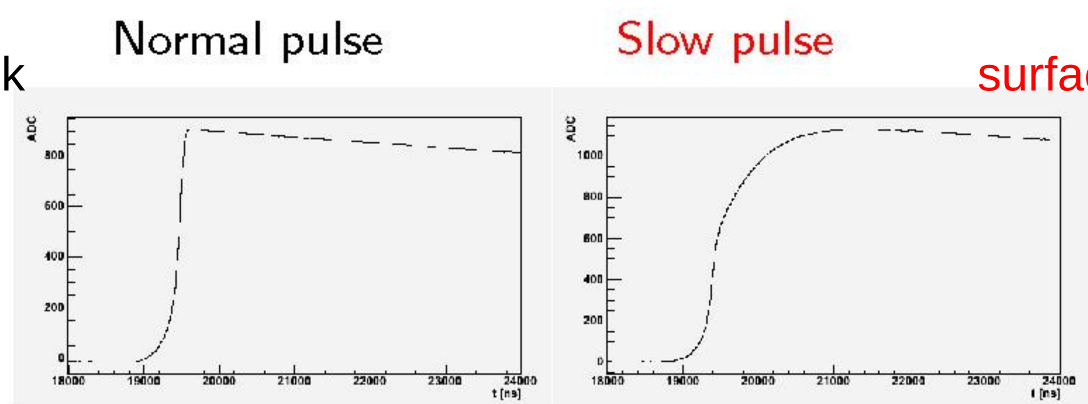
No electron recoil nuclear recoil discrimination. Data form GERDA experiment







bulk



surface

Surface vs bulk discrimination efficiencies smaller at low energy

Canberra Industries, Inc., http://www.canberra.com/products/485.asp.

CoGent-set up

ArXiv 1002.4703
ArXiv 1106.0650

Canberra 400 g BEGe detector in the Soudan Underground Laboratory (700 m depth)

Shields “similar to” PRL **101** (2008) 251301

from in to out:

•low-background NaI[Tl] anti-Compton veto

•5 cm of low-background Pb

•15 cm of standard Pb

•0.5 cm of borated neutron absorber

•>99:9% efficient muon veto,

•30 cm of polyethylene

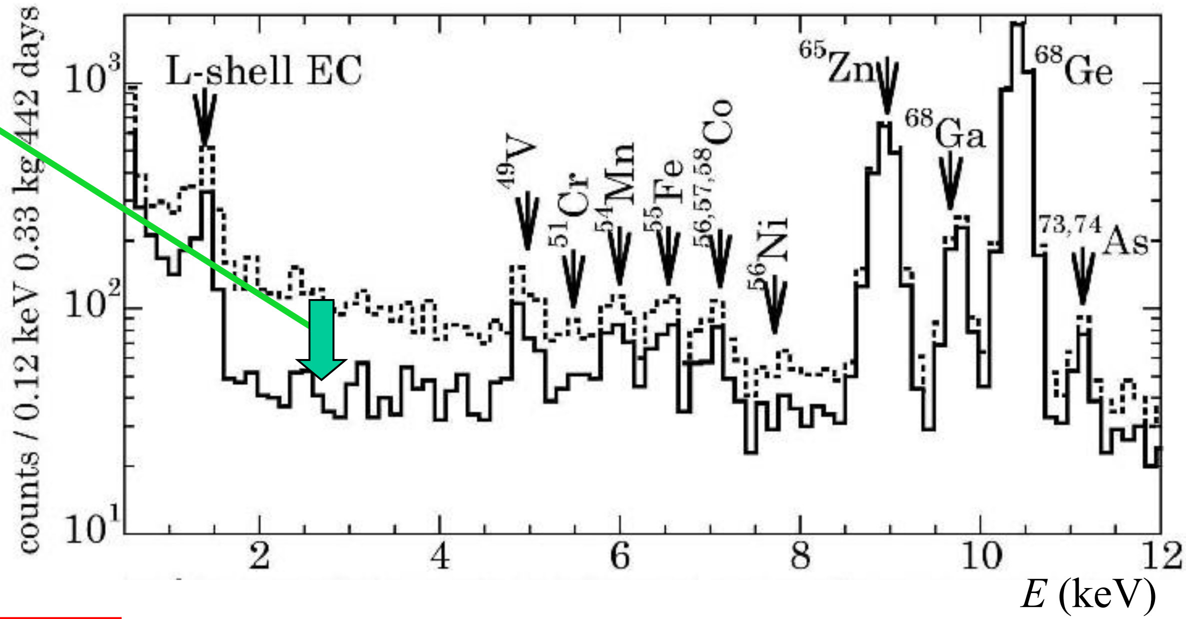
•low-efficiency large-area external muon veto.

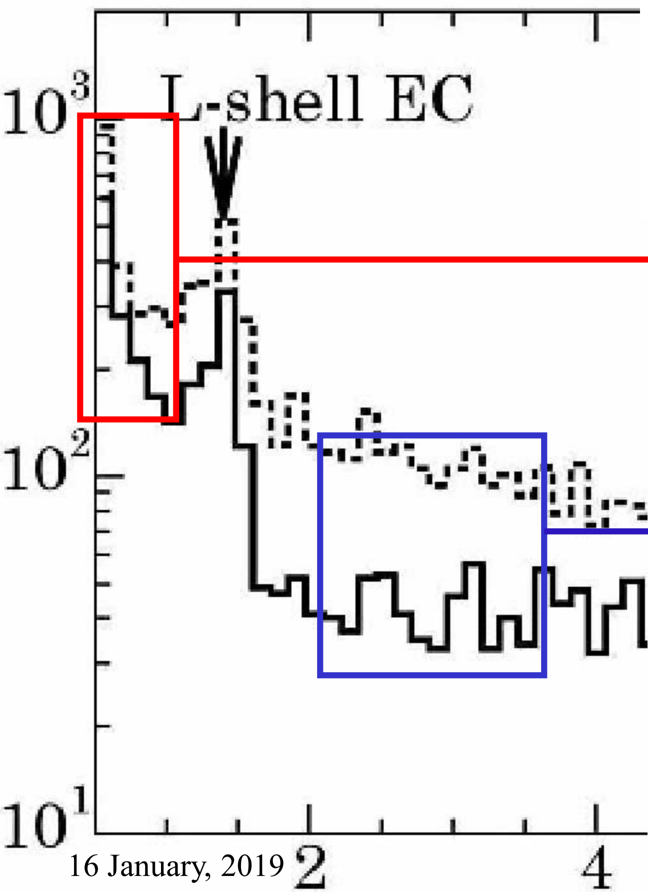
Very simple controls of the main parameters (temperature, Rn, etc.)

CoGent. DM “signal”

ArXiv 1002.4703
ArXiv 1106.0650

Suppress surface events

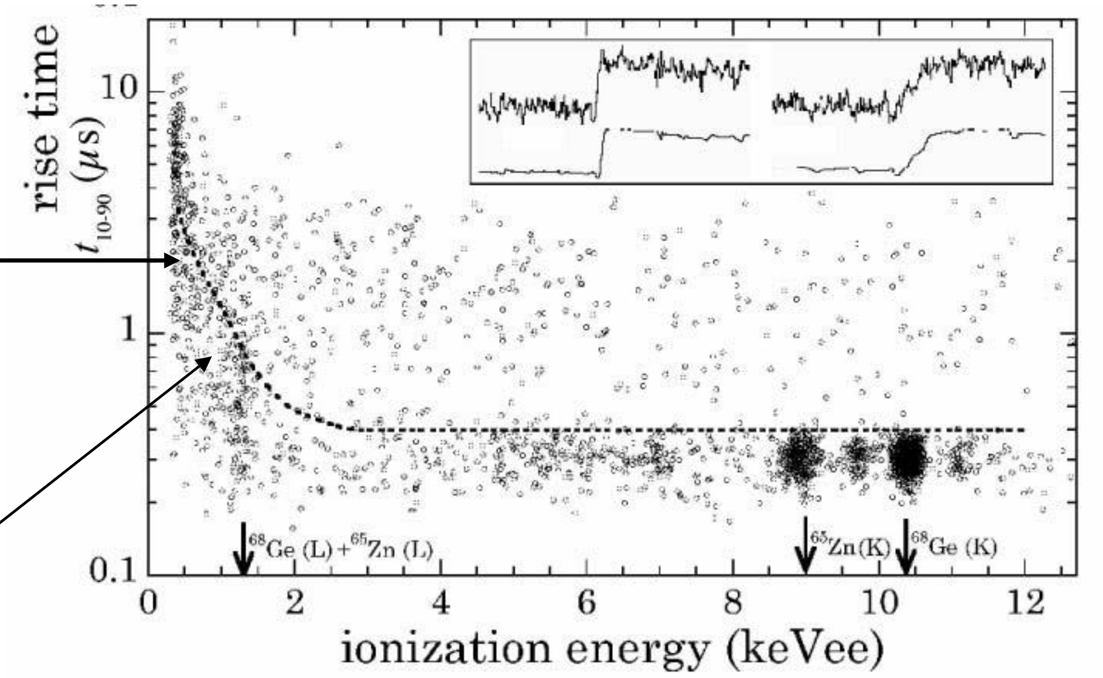




“signal” region: ≈65% of events survive

background region: ≈ 40% of events survive

CoGent. Surface vs bulk



90% signal acceptance for bulk events, determined with calibration sources

No quantitative evaluation of leakage from surface events ("it should be modest")

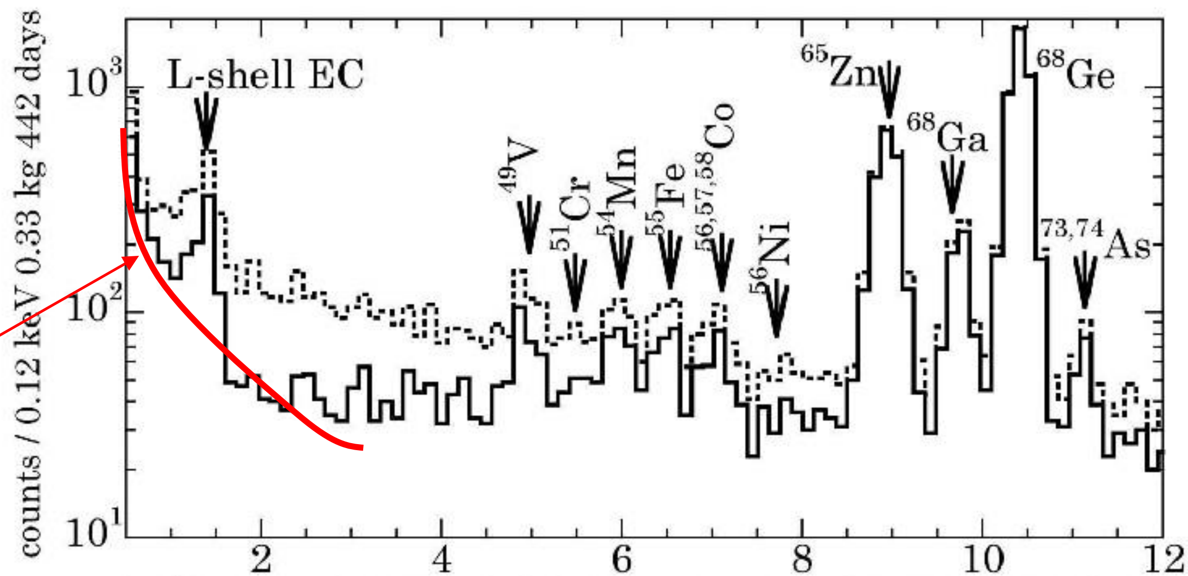
Proper evaluation needed

CoGent. The “signal”

ArXiv 1002.4703
ArXiv 1106.0650

Subtract L-shell EC (^{68}Ge, ^{65}Zn, ^{68}Ga), known from the K-shell observed lines

Assume rest = 100% DM signal



After surface event suppression, electron and nuclear recoils

Estimated backgrounds:

L-shell EC < ^{65}Zn: <10%

Neutrons: ≈ 0.1%

CoGent. Modulation

ArXiv 1106.0650

No modulation χ^2/dof =20.3/15

Modulation χ^2/dof =7.8/12

Marginal statistical significance

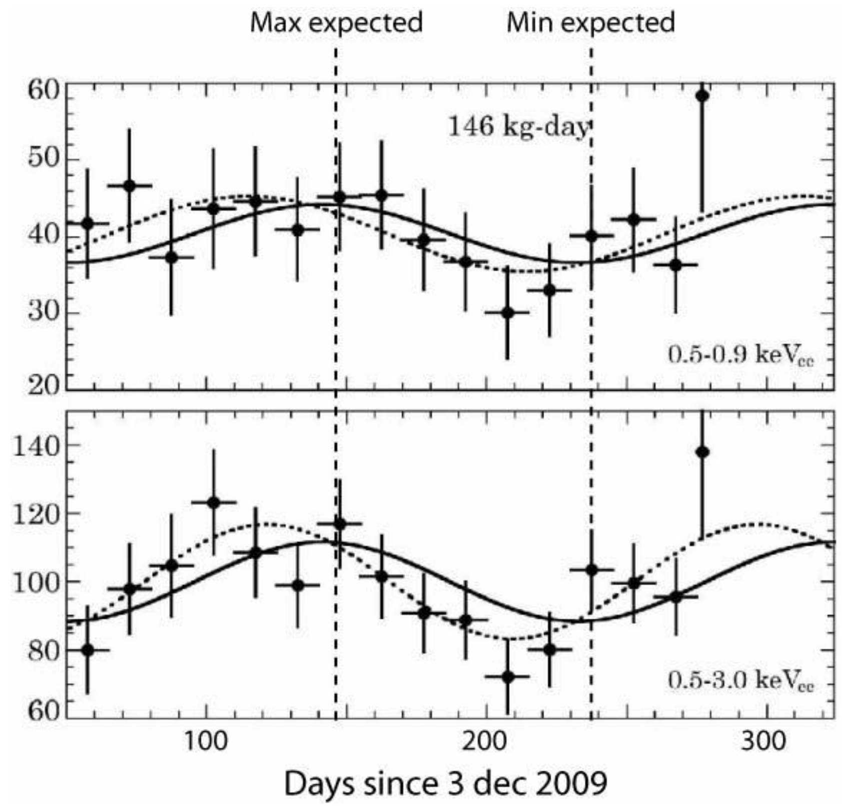
Modulation amplitude = 0.166±0.038

Much too large to be due to WIMPS

Period: 347±29 d **OK**

Minimum: 16±12 October

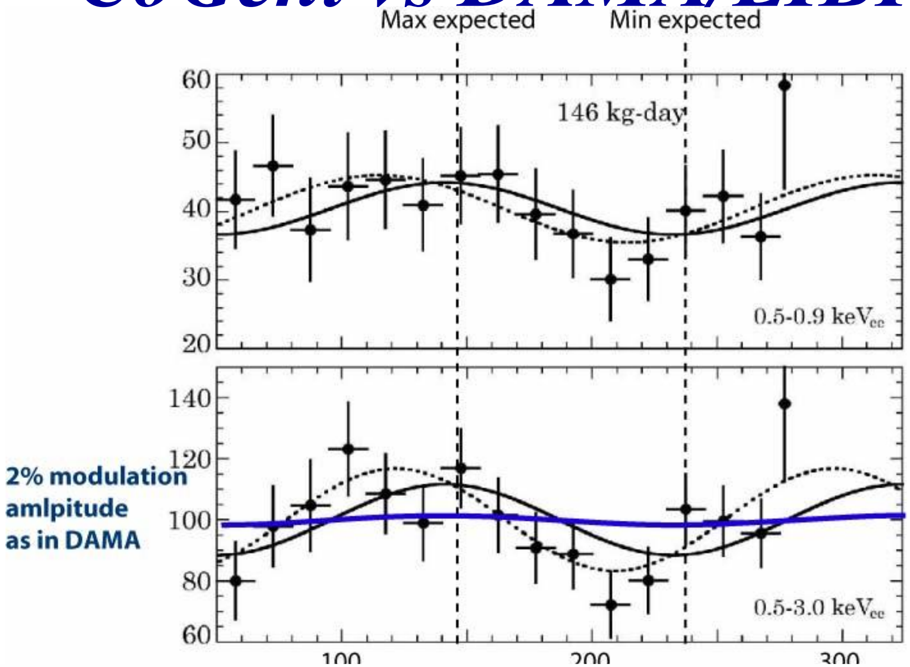
4.3 σ off expectation for WIMPs



Wait more data and better analysis. If it persists, it may show that background can be modulated, with 1 yr period (but phase, amplitude,..)

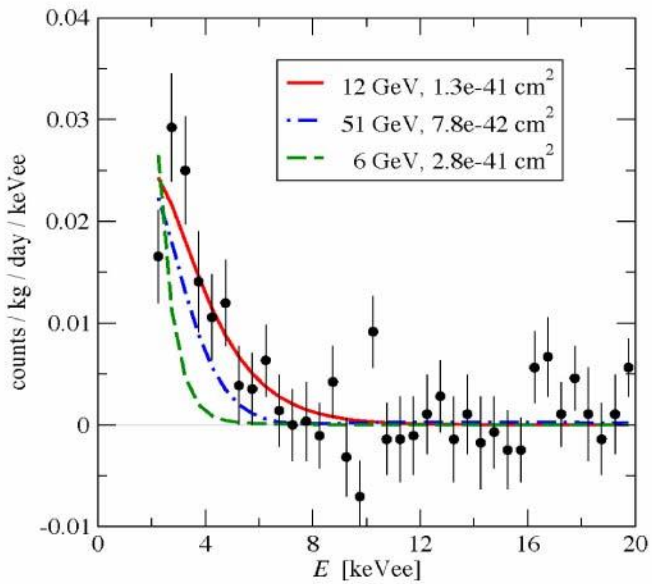
CoGent vs DAMA/LIBRA

Assuming CoGent and D/L see signal

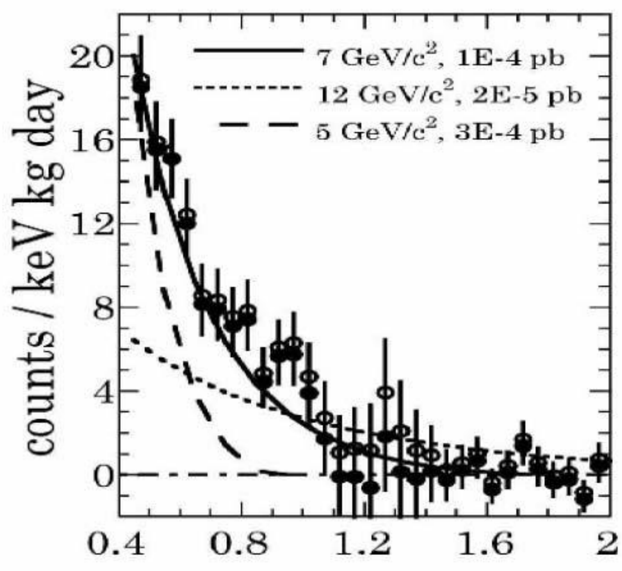


Modulation Contradiction

DAMA



CoGent

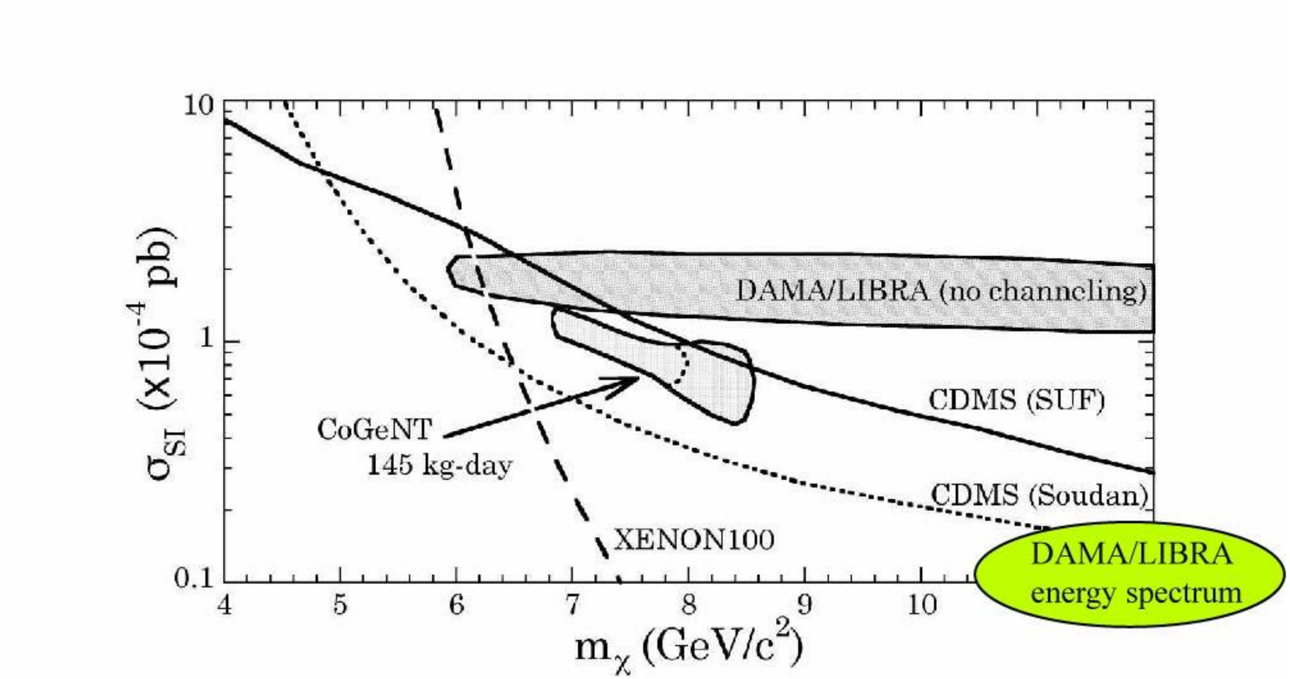


Mass spectrum Contradiction

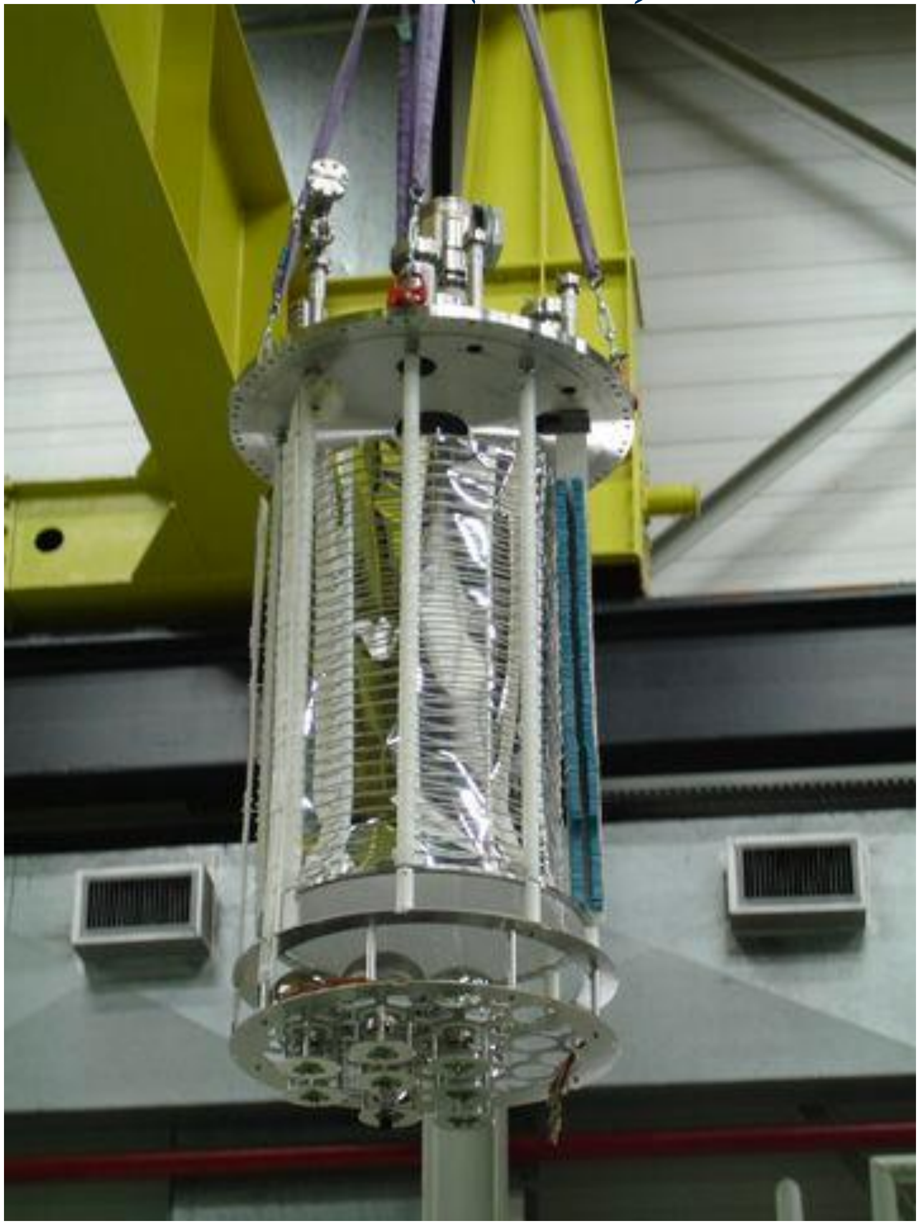
CoGent vs DAMA/LIBRA

WIMP mass and cross section

Contradiction



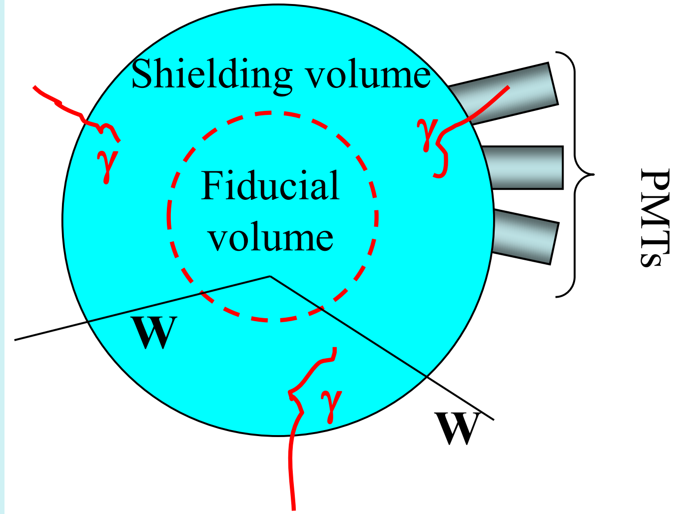
ArDM (LSC) & XENON100 (LNGS)



Noble Liauids self shielding

Noble liquids, Xe, Ar, and Ne look very promising for the WIMP detection, because

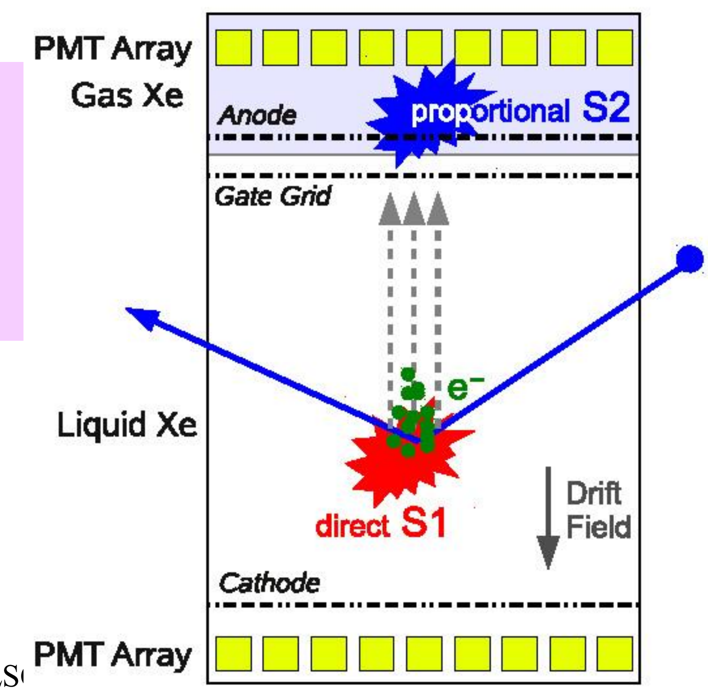
- can be easily assembled in large masses (scalability)
- can be cleaned from radioactive traces at very high levels
- self-shielding structures can be built, with the central part shielded by a large contiguous mass (in the same container) of the same liquid $\Rightarrow$ no free surface, no surface contamination
- Shield can be instrumented to act as a veto also in **one phase**



Two-phase (Liquid and Gas)

Localisation of the event with TPC

Discriminate between ER and NR by detecting primary scintillation and ionisation via proportional ionisation



Single phase: XMASS (Xe)

Double phase: XENON (Xe), WARP (Ar), ArDM (Ar)

XMASS @ Kamioka

Mass inside light sensors = 850 kg

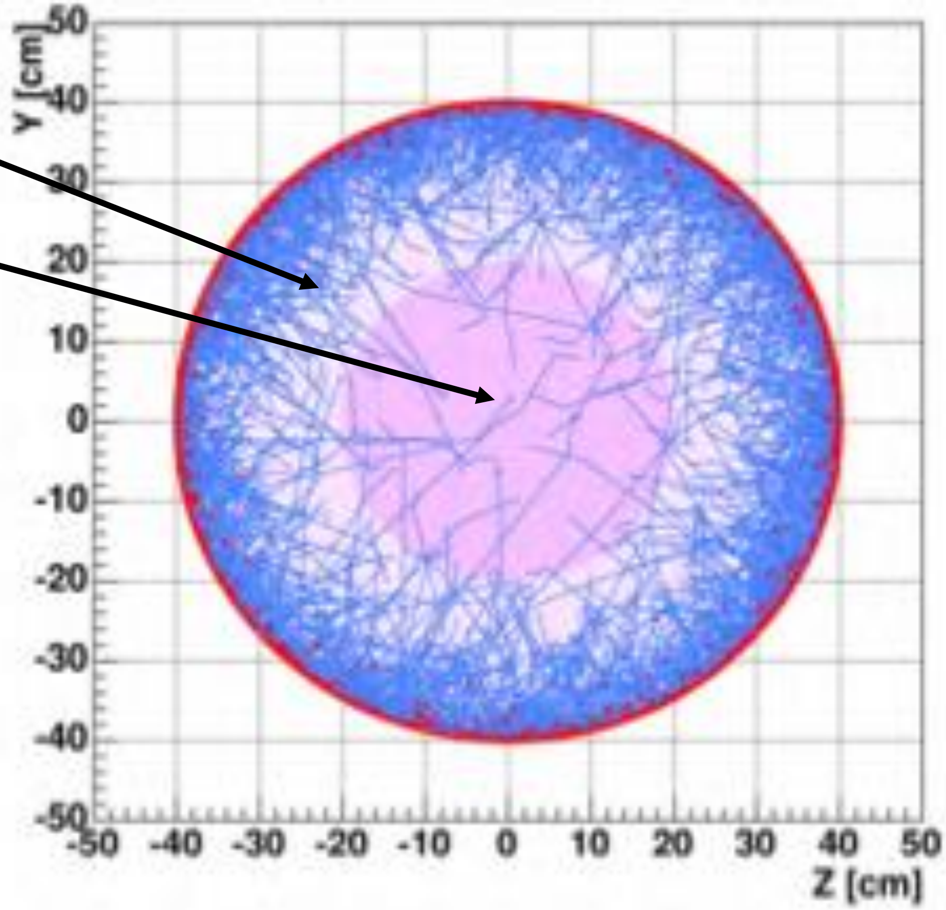
Fiducial mass = 100 kg

Simple self shielding results in

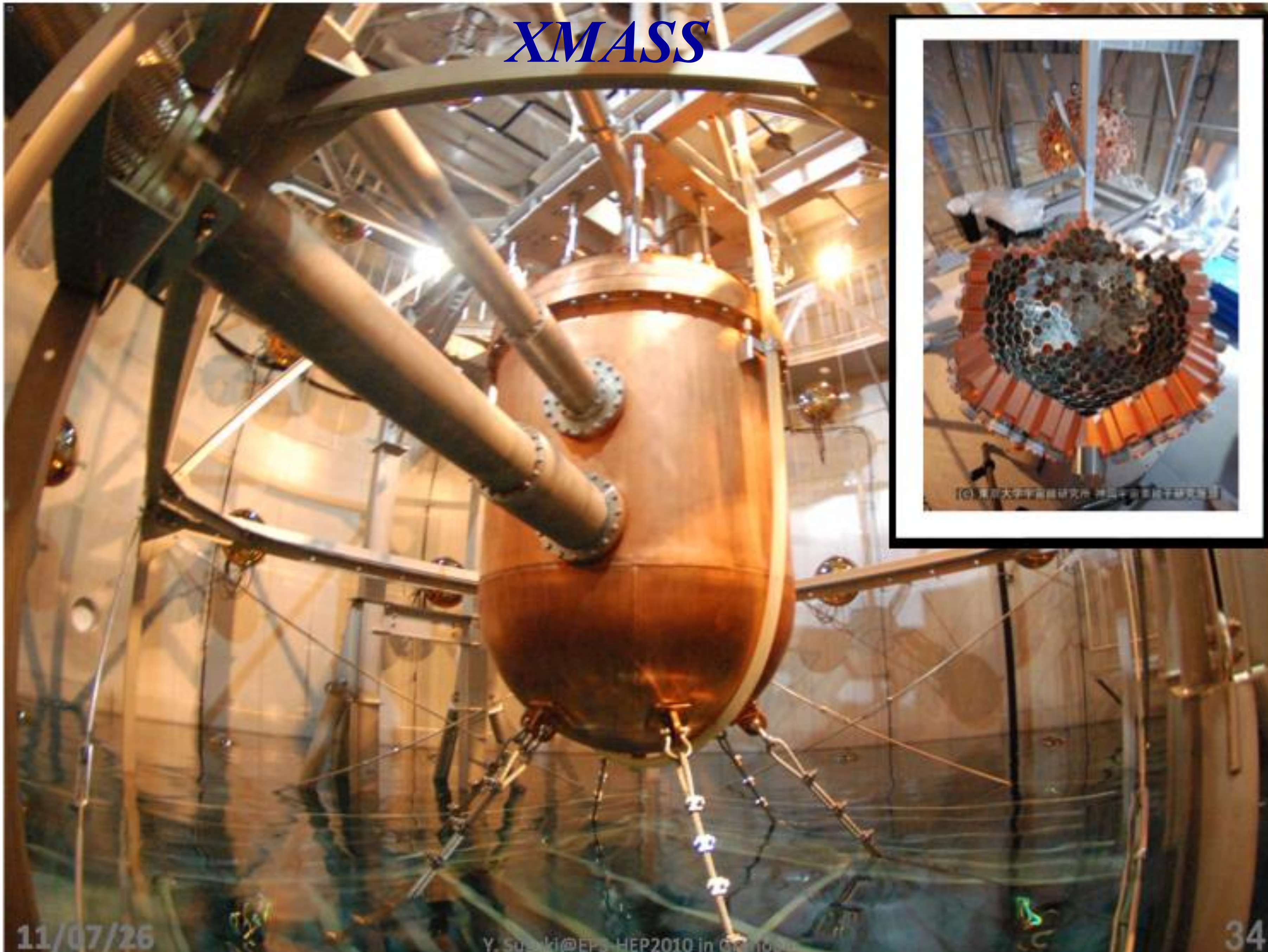
10^{-4}/(keV kg d) for NR and ER

further statistical identification & reduction of NR possible

Status: commissioning @ Kamioka



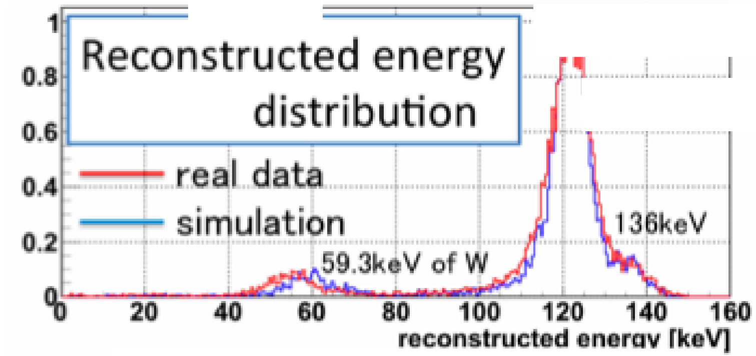
XMASS

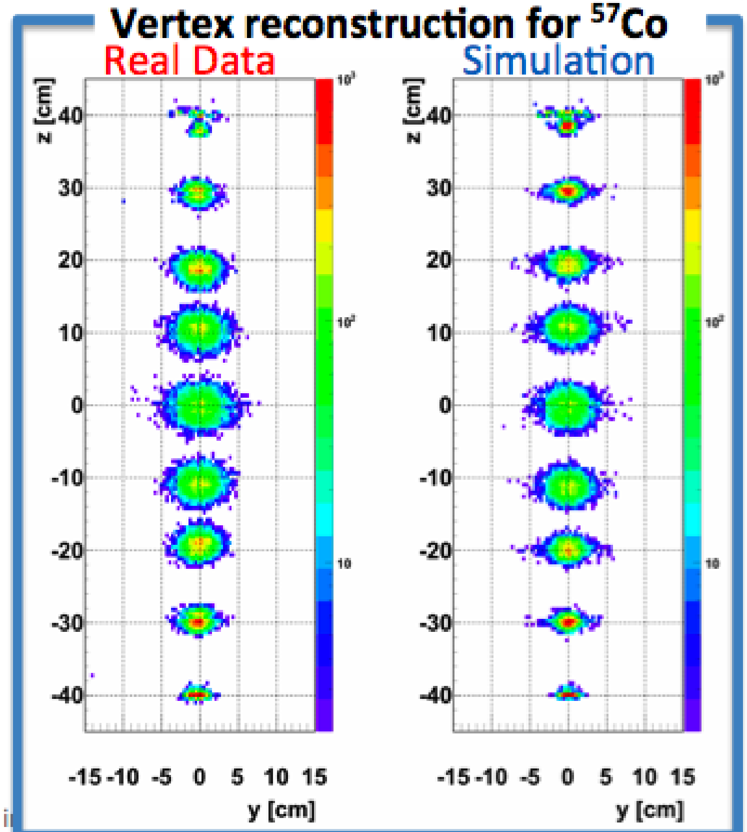


XMASS

XMASS: Measured property

- Reconstructed energy
  - ~4% rms @122 keV
- 15.1±1.2 ph-electrons/keV
- Position resolution (122keV)
  - 1.4cm RMS (@z=0cm)
  - 1cm RMS (±20cm)
- BG reduction
  - Low BG PMT
  - Material screening 250 pieces
  - Kr: distillation
  - 10mh x 10m ϕ ωater tank
- BG measured
  - ^{222}Rn: 8.2±0.5mBq
  - ^{220}Rn: < 0.28mBq





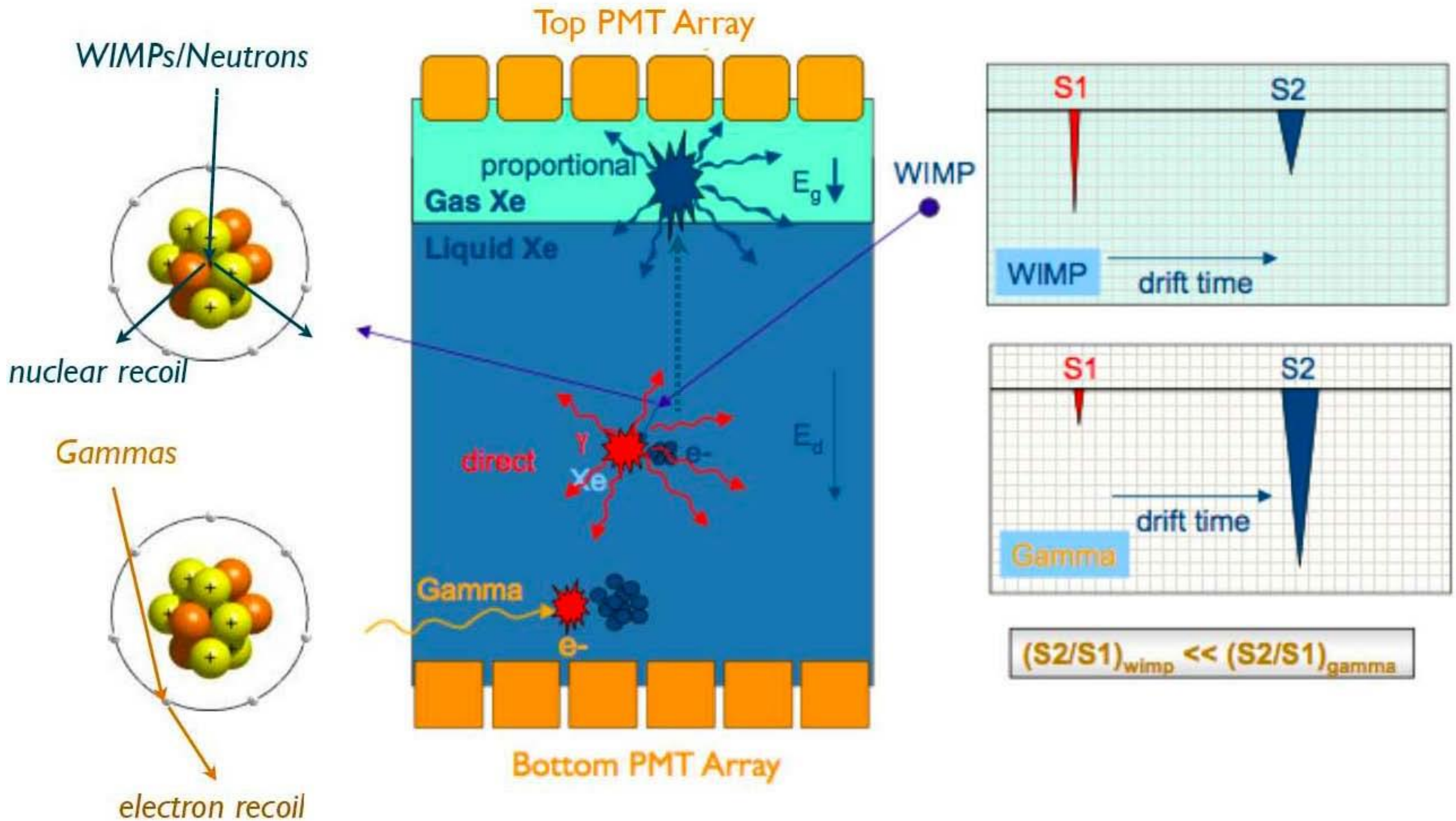
QE=28-39%
Coverage = 62%

6

Y. Suzuki HEP2011

Y. Suzuki@EPS-HEP2010

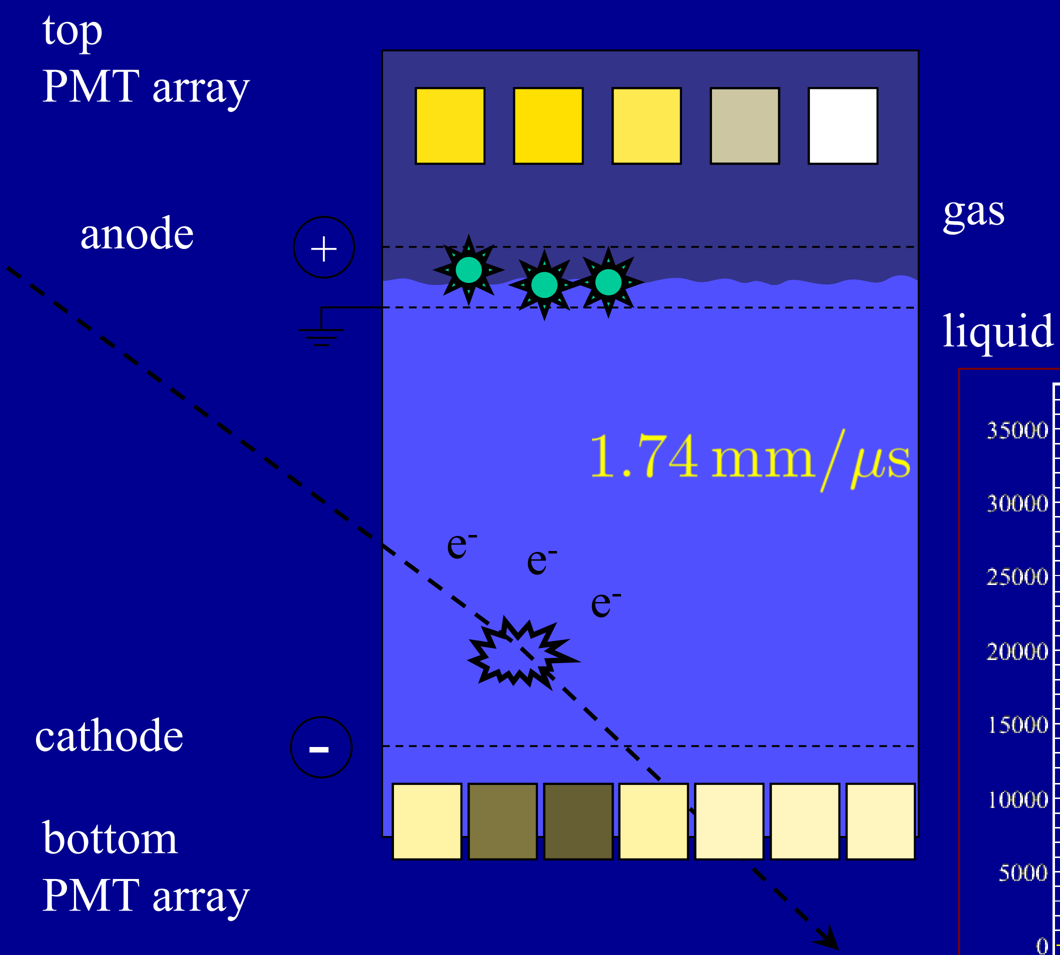
Dual phase Xe/Ar. Light vs charge S1/S2

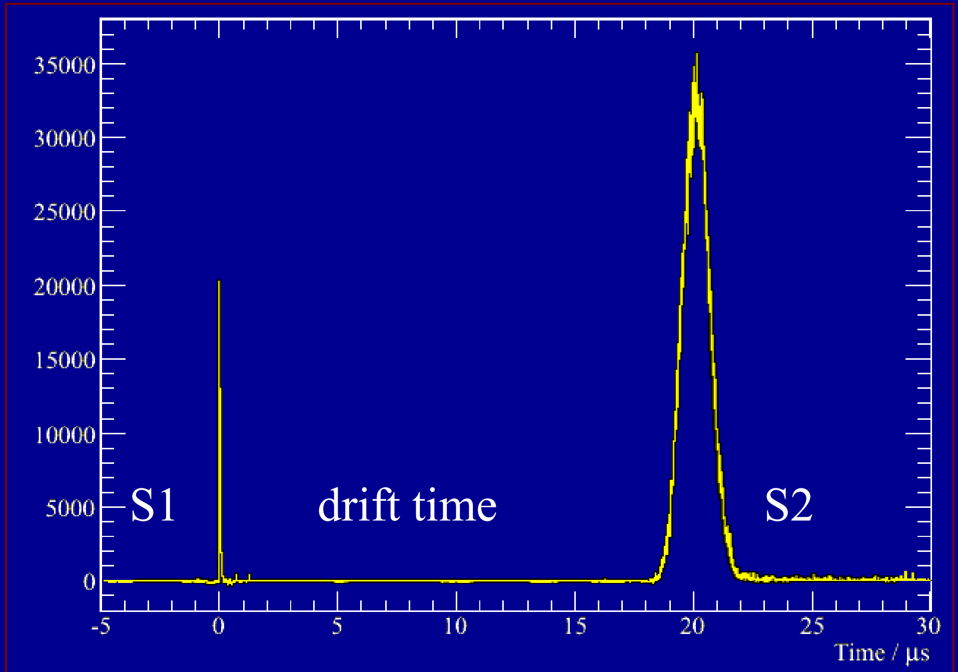


- **Two-phase (Liquid & Gas)**
  - **Localisation of the event via TPC ⇒ definition of fid. vol. without surfaces**
- **Discrimination** between nuclear and electromagnetic recoils by
  - **Detection of primary scintillation light <u>and</u> ionisation via proportional scintillation** (Benetti et al. in 1993)

Dual-PhaseTPC

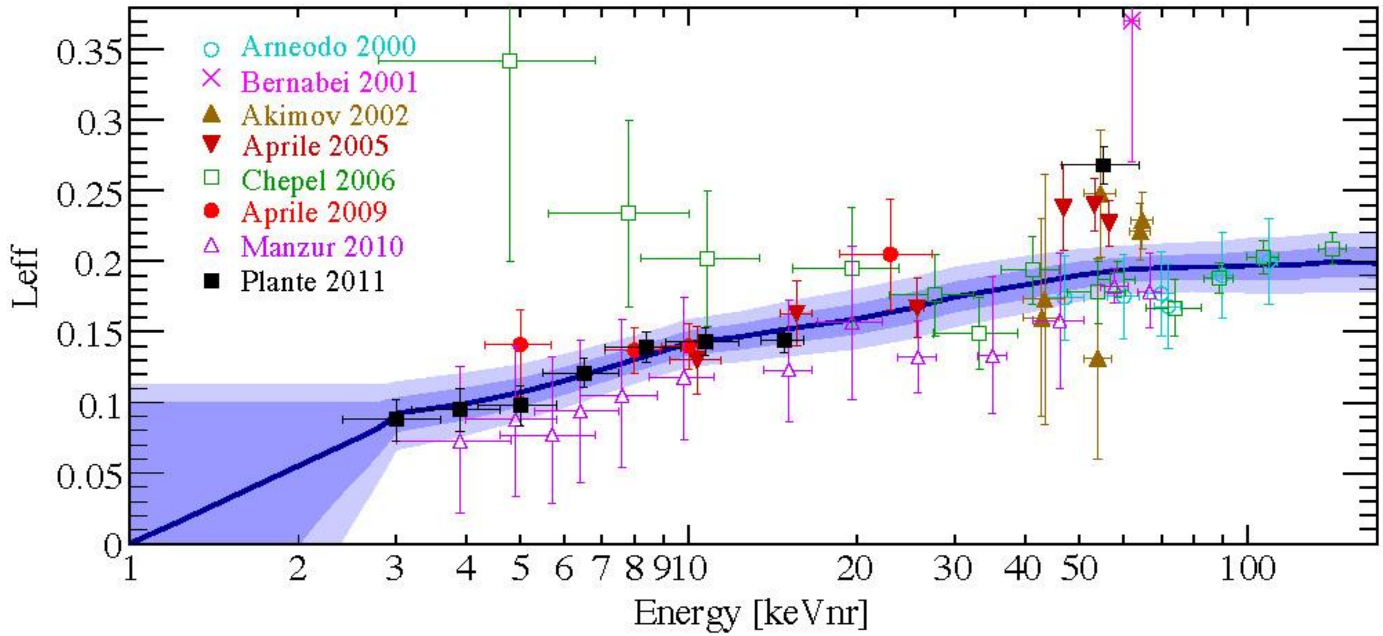
3D position information
with mm resolution
S2/S1-based discrimination better than 99%





XENON 100 L_{eff}

ArXiv 1104.2587



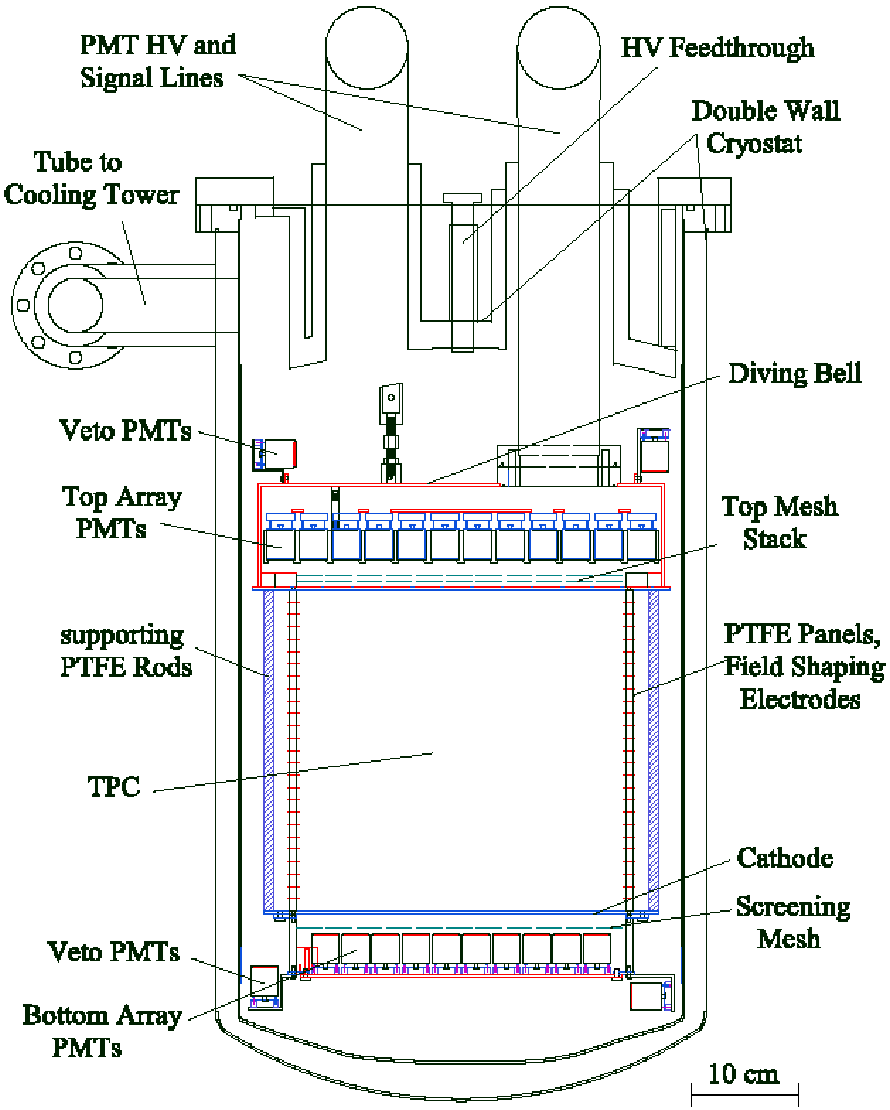
L_y: Light yield measured at 122 keV = (2.20±0.09) phel/keV

S_{ee}: Electric field quenching factor for ER = 0.58

S_{nr}: Electric field quenching factor for NR = 0.95

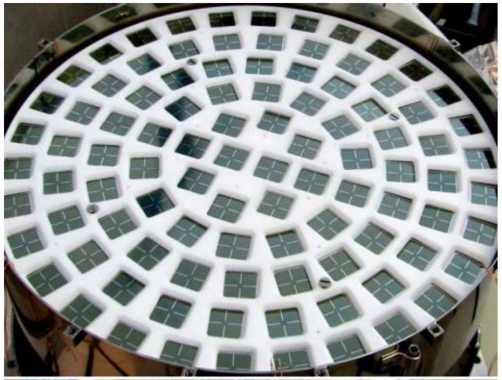
ArXiv 1107.2155

XENON 100 @ LNGS

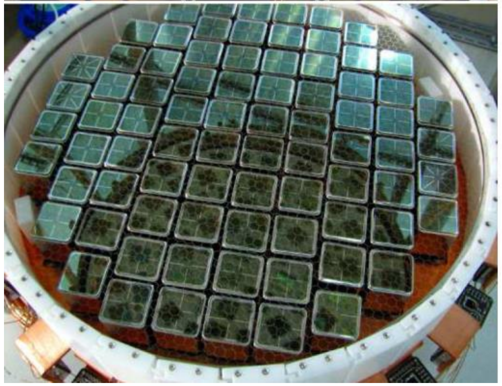


R/O of S1 and S2 with low background Hamamtzu PMs

- **Number of photoelectrons**
- **x,y reconstruction of the event (barycentre)**



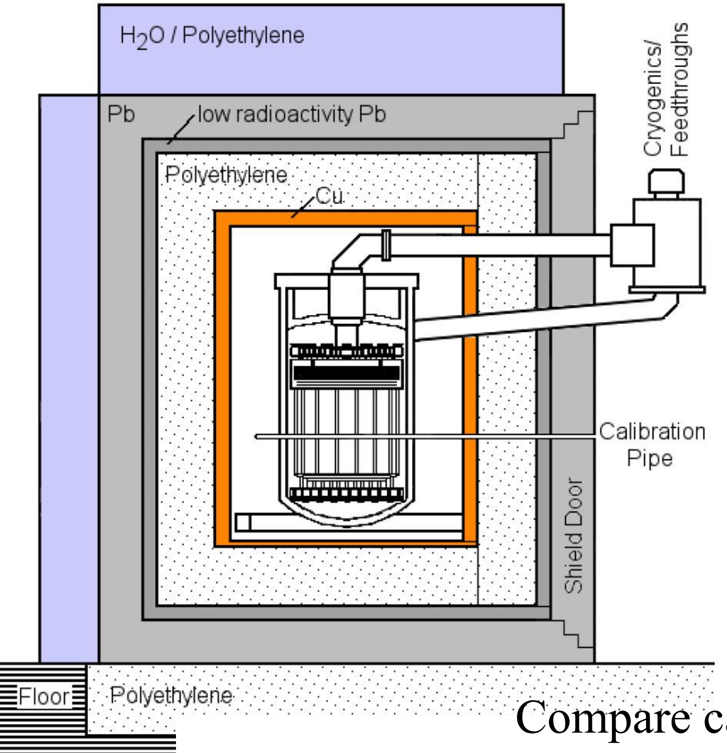
Top array, above the wires



Bottom array, in the liquid (refractive index = 1.7!)

XENON 100. EM Background

ArXiv 1101.3866



Screen all materials + Monte Carlo simulation

Design for <10^{-3}/(kg keV d) for each component

Main bknd components

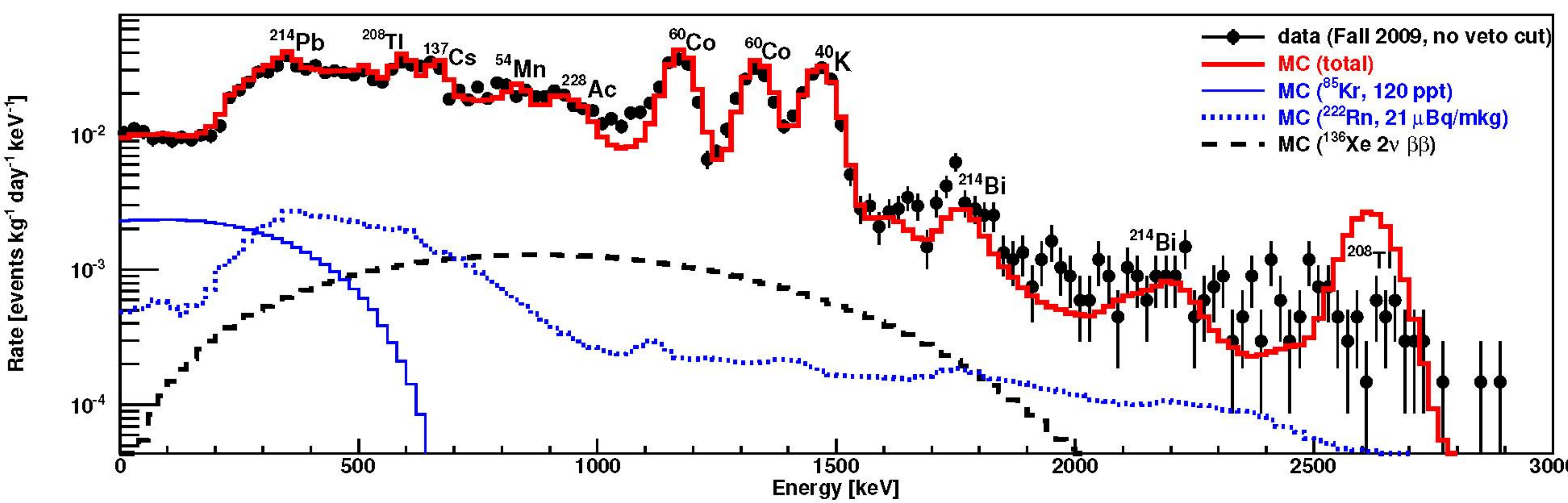
•Radioact. contamin. of detector and shields materials

•Intrinsic radioactivity of LXe

•^{82}Kr in Xe. 100 ppt required. Distillation and analysis procedures developed

•Decays of ^{222}Rn and progeny inside shields

Compare calculation with spectrum in preliminary technical run (2009)



XENON 100. Background

ArXiv 1101.3866

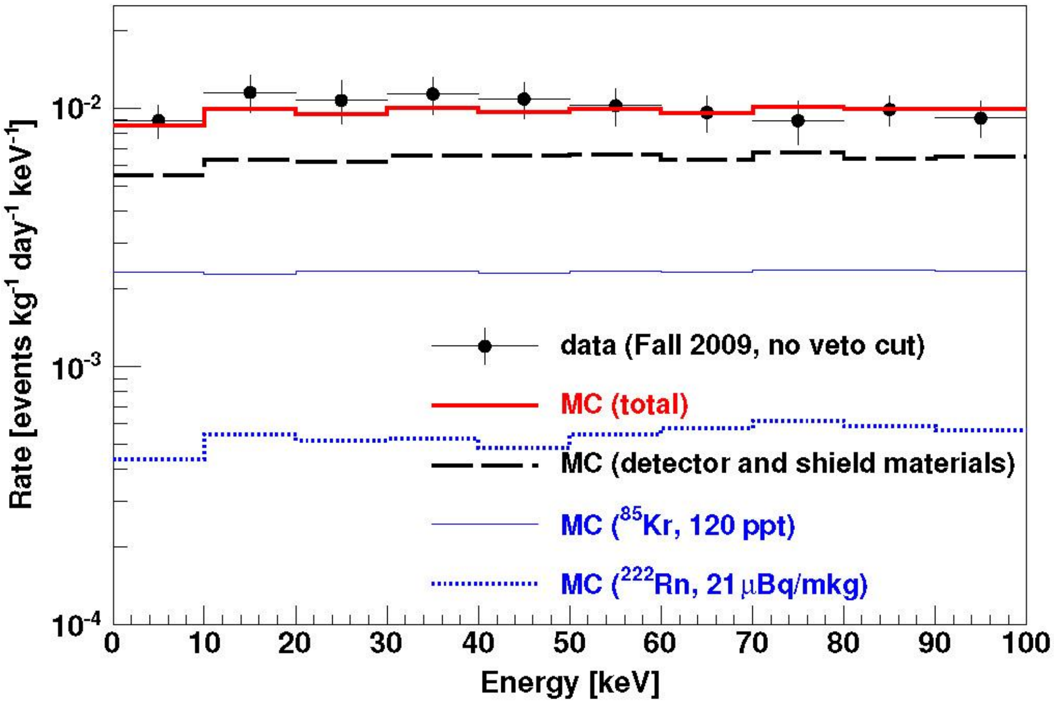
BG budget calculation (before S1/S2) for different fiducial masses and w &w/o active Xe veto cut

	Predicted rate [$\times 10^{-3}$ events$\cdot$kg$^{-1}\cdot$day$^{-1}\cdot$keV^{-1}]					
Volume	62 kg target		40 kg þducial		30 kg þducial	
Veto cut	none	active	none	active	none	active
Detector and shield materials	134.39	73.66	11.93	3.18	6.54	1.83
^{222}Rn in the shield (1 Bq/m^3)	5.95	1.72	0.92	0.16	0.16	0.02
^{85}Kr in LXe (120 ppt of ^{nat}Kr)	2.35	2.35	2.35	2.35	2.35	2.35
^{222}Rn in LXe (21 μBq/kg)	1.04	0.51	0.56	0.38	0.53	0.37
All sources	143.73	78.24	15.76	6.07	9.58	4.57

30 kg fiducial

No veto cut

Good agreement between model and data



XENON100. Fiducial volume

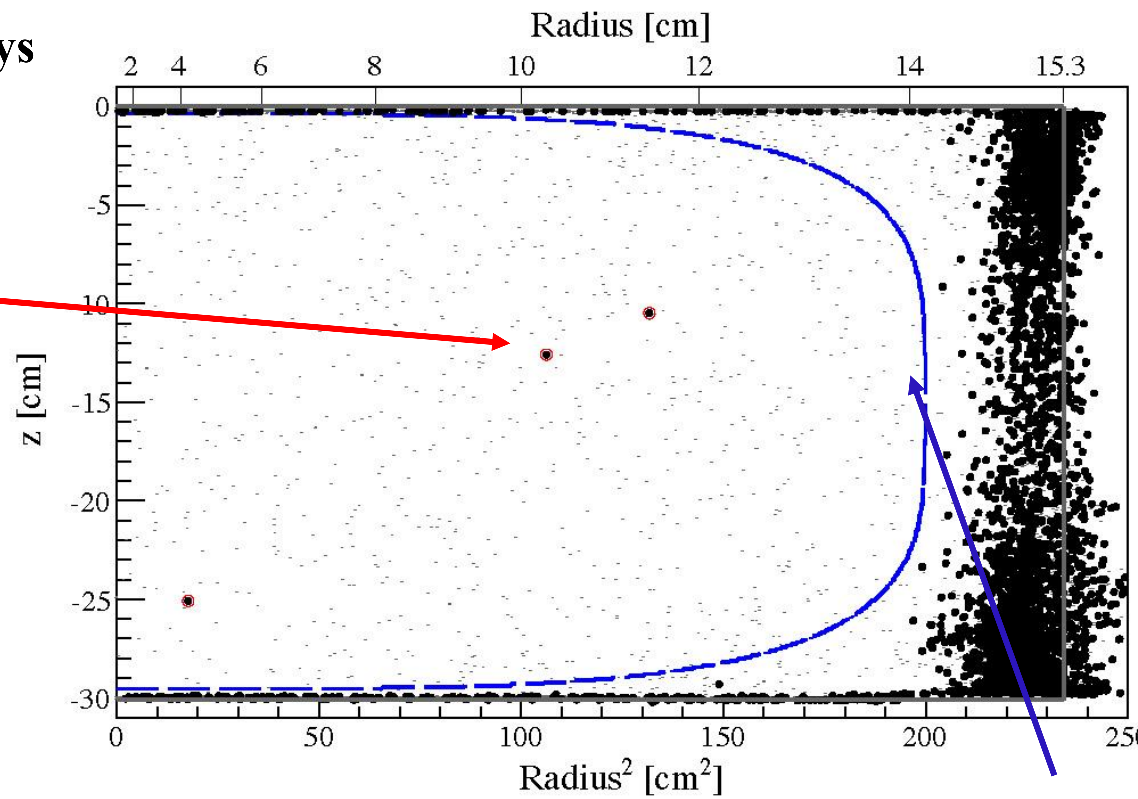
ArXiv 1104.2549

The power of self-shielding (and event position reconstruction)

Total mass = 161 kg: 99 kg active veto, completely surrounding the optically separated 62 kg target, of which 48 kg fiducial mass

48 kg fid. mass, 100.9 live days

Events in the signal region 8.4-44.6 keV$_{nr}$



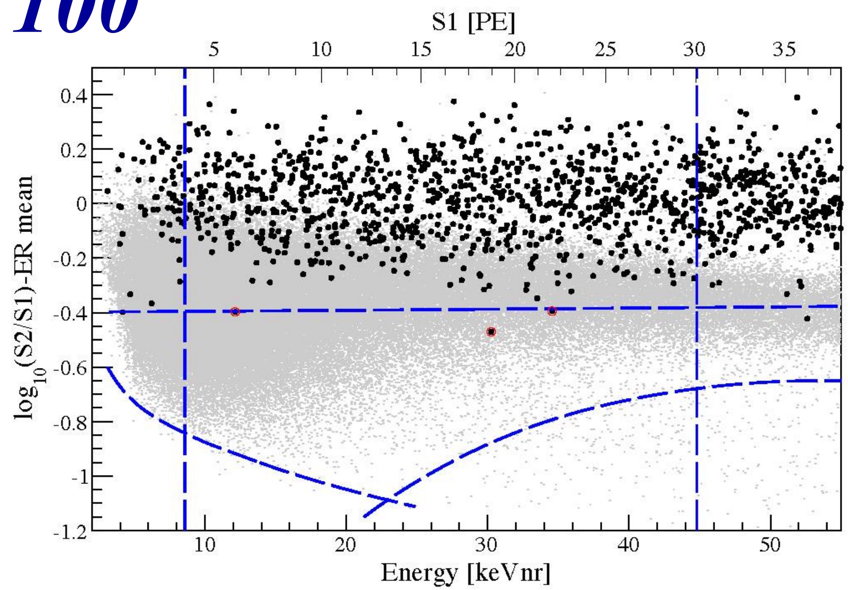
Fiducial volume

ER background in the signal region, before S2/S1 discrimination < 5 x 10^{-3}/(keV kg d)

Air leak during maintenance work ⇒^{82}Kr increase (w.r.t. to 0.7±0.1 ppb in 2010) arXiv:1104.2549v1; 13 Apr 2011

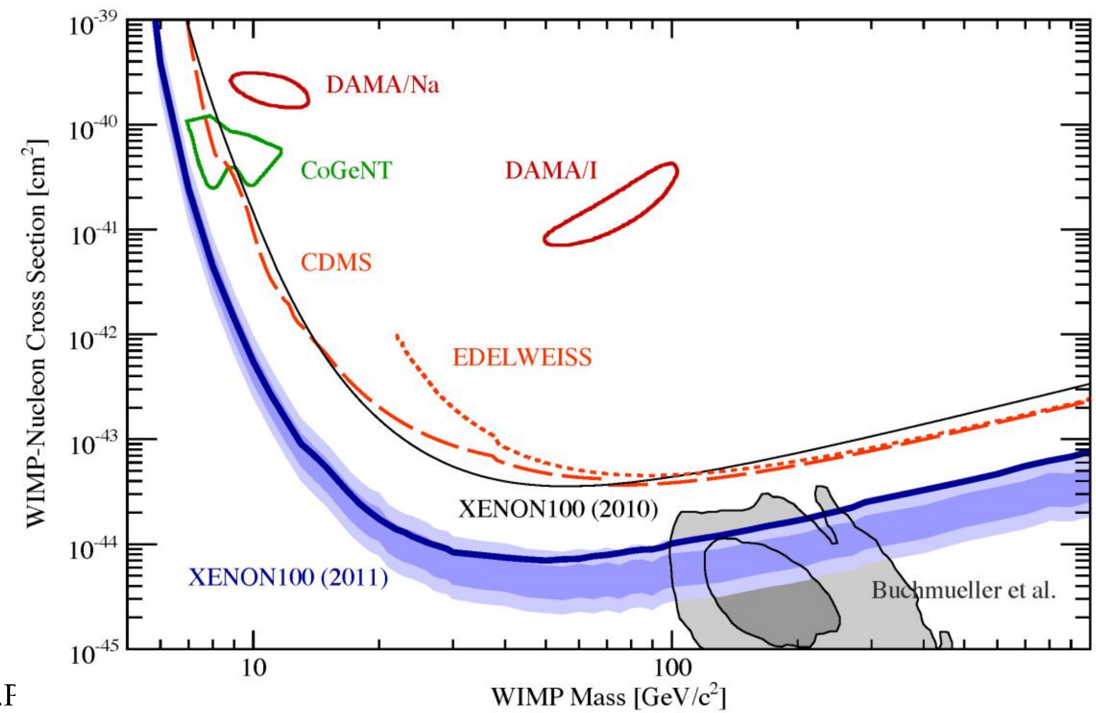
XENON 100

Cuts and search window (S2/S1 vs E_{nr}) defined without looking at physics data

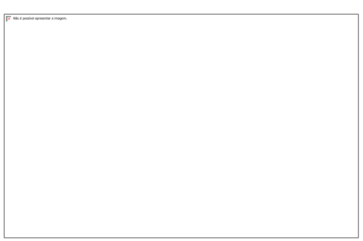


Calculated backgrounds

NR by n (μ induced etc.)	$0.11^{+0.08}_{-0.04}$
Gaussian leak from ER (^{82}Kr etc)	1.14 ± 0.48
Non-Gaussian from ER (^{82}Kr etc)	$0.56^{+0.21}_{-0.27}$
Total	**1.8 ± 0.6 ev.**

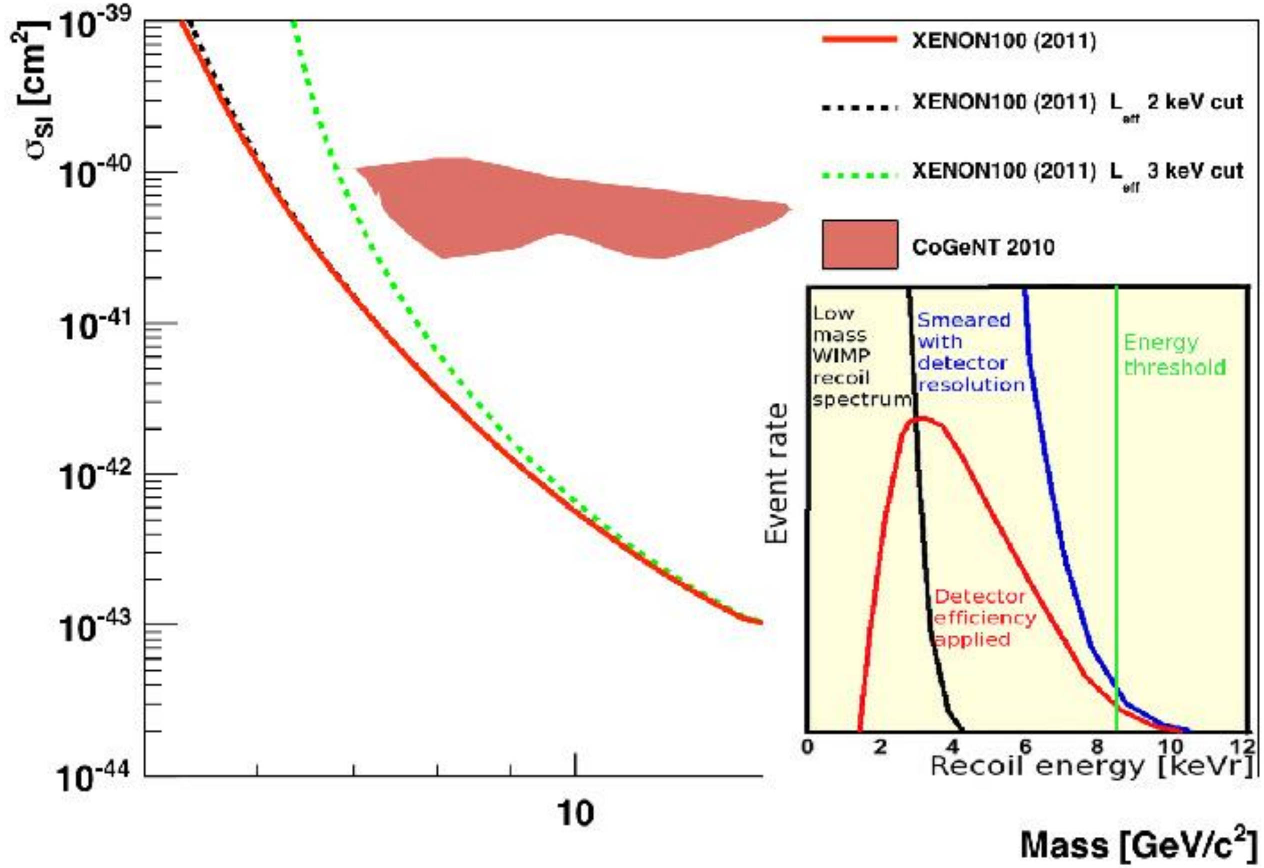


Limit calculated assuming isothermal & isotropic halo with



Buchmueller arXiv:1102.4585v1

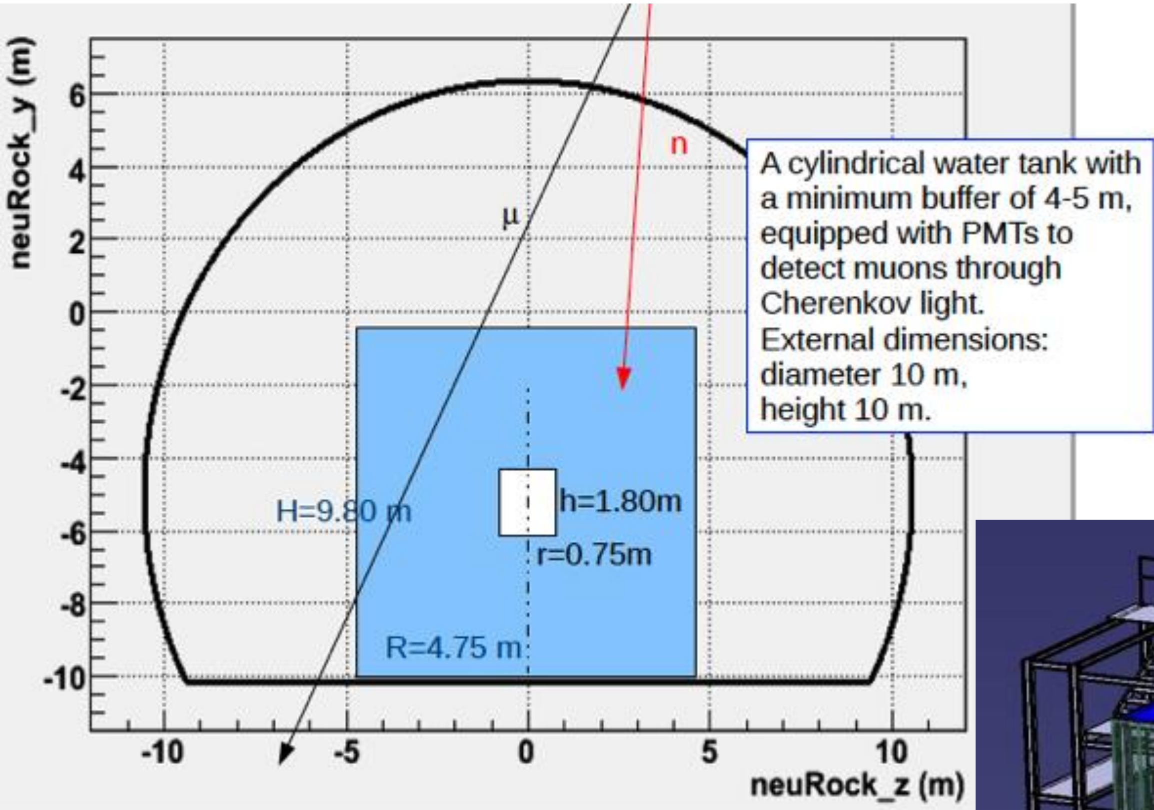
XENON 100 vs CoGent



Sensitivity at low masses only due to energy resolution

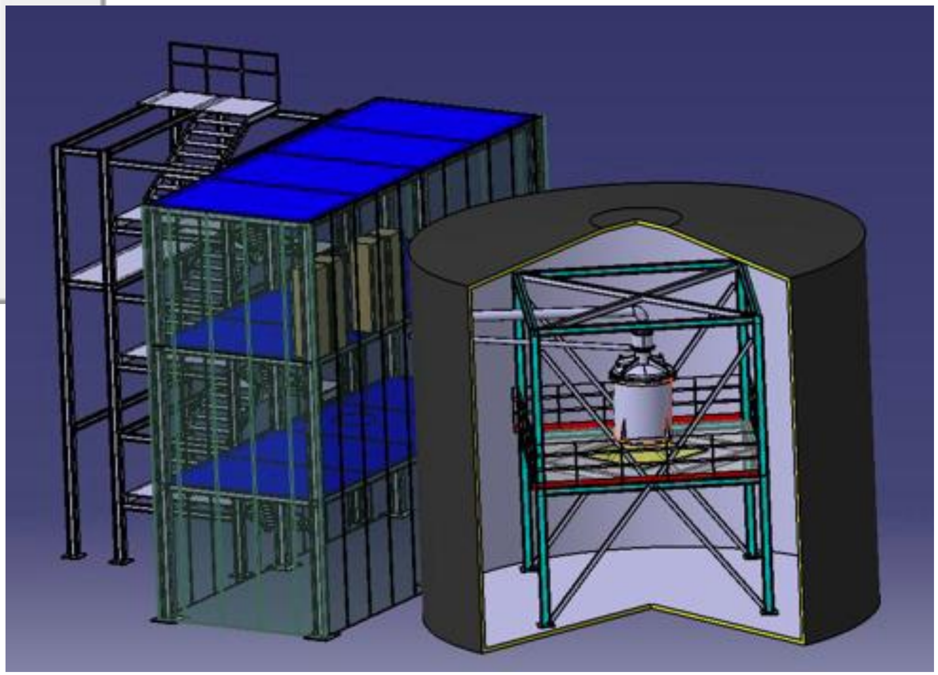
However cut at L_{eff} at 3 keV_{Rec} does not affect result of comparison with CoGent 2010

XENON1t

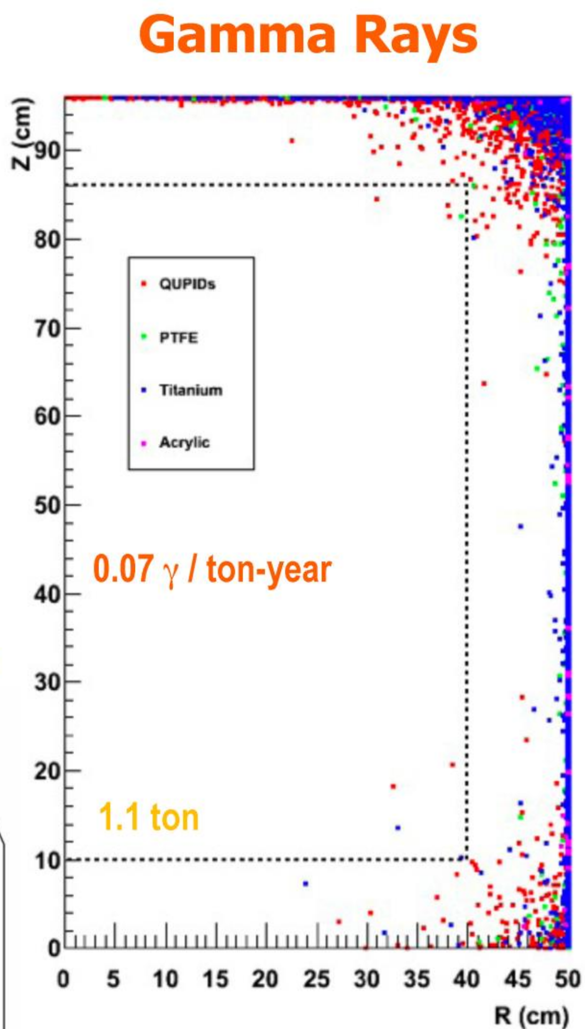


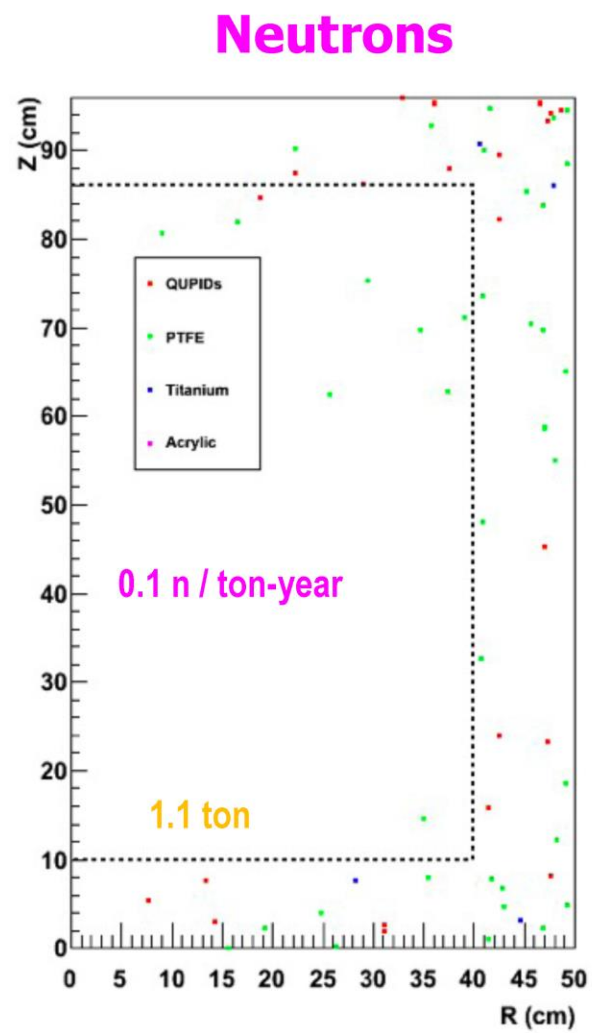
Larger sensitive mass requires reducing backgrounds in proportion

Water tank shield needed already @ LNGS depth, not @LSM depth

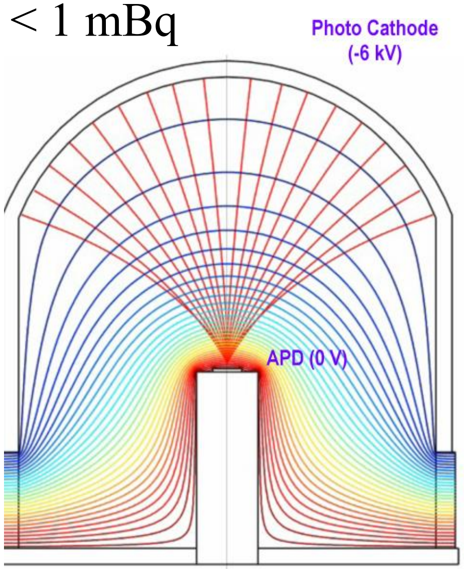


XENON 1t - Expected background from detector materials



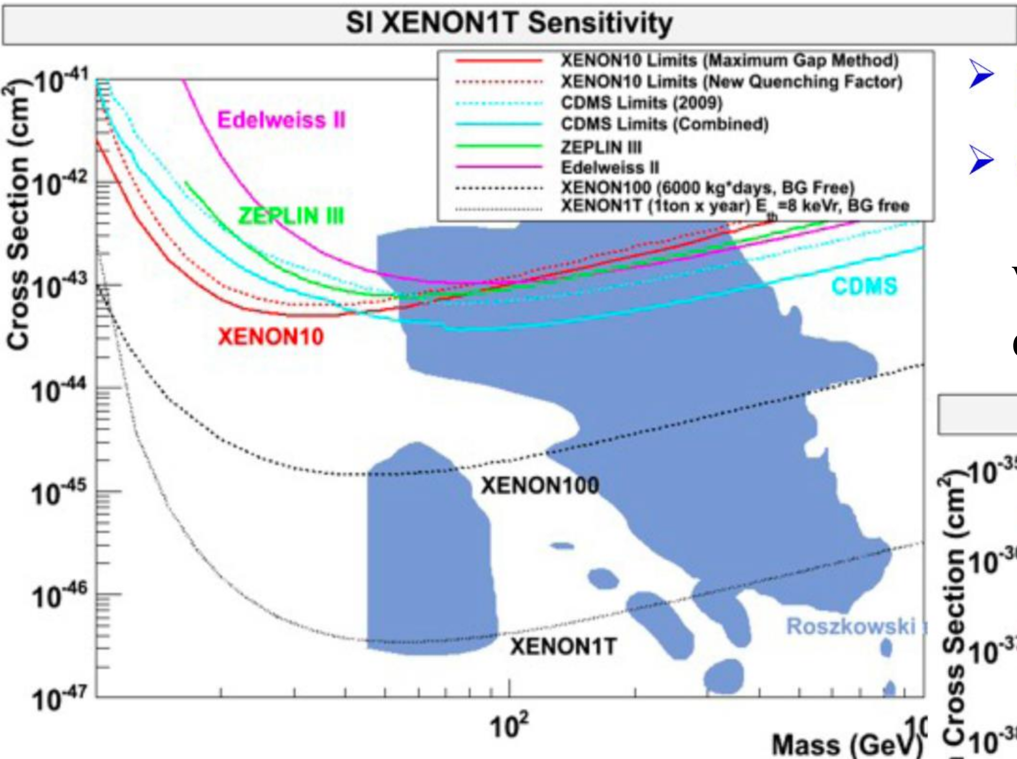


Hamamatzu QUPID
< 1 mBq



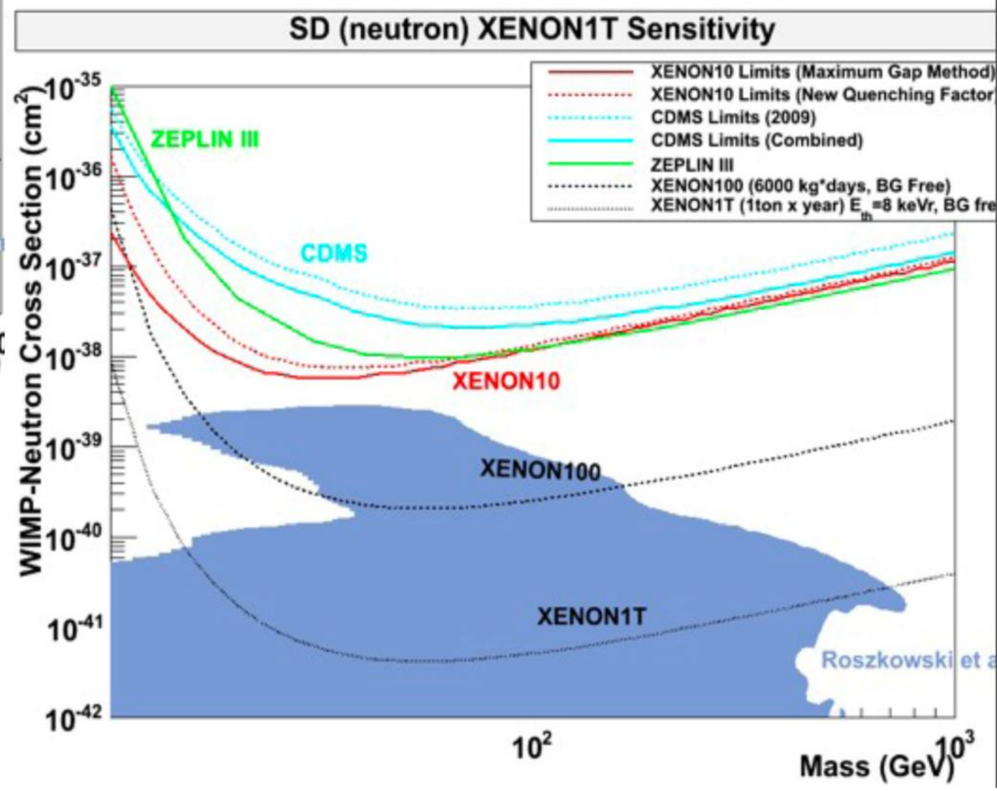
E. Aprile WONDER 2010

XENON 1t Reach SI & SD



- probe simultaneously SI and SD channels
- explore the entire MSSM parameter space

Water tank shield needed @ LNGS depth, not @ LSM depth

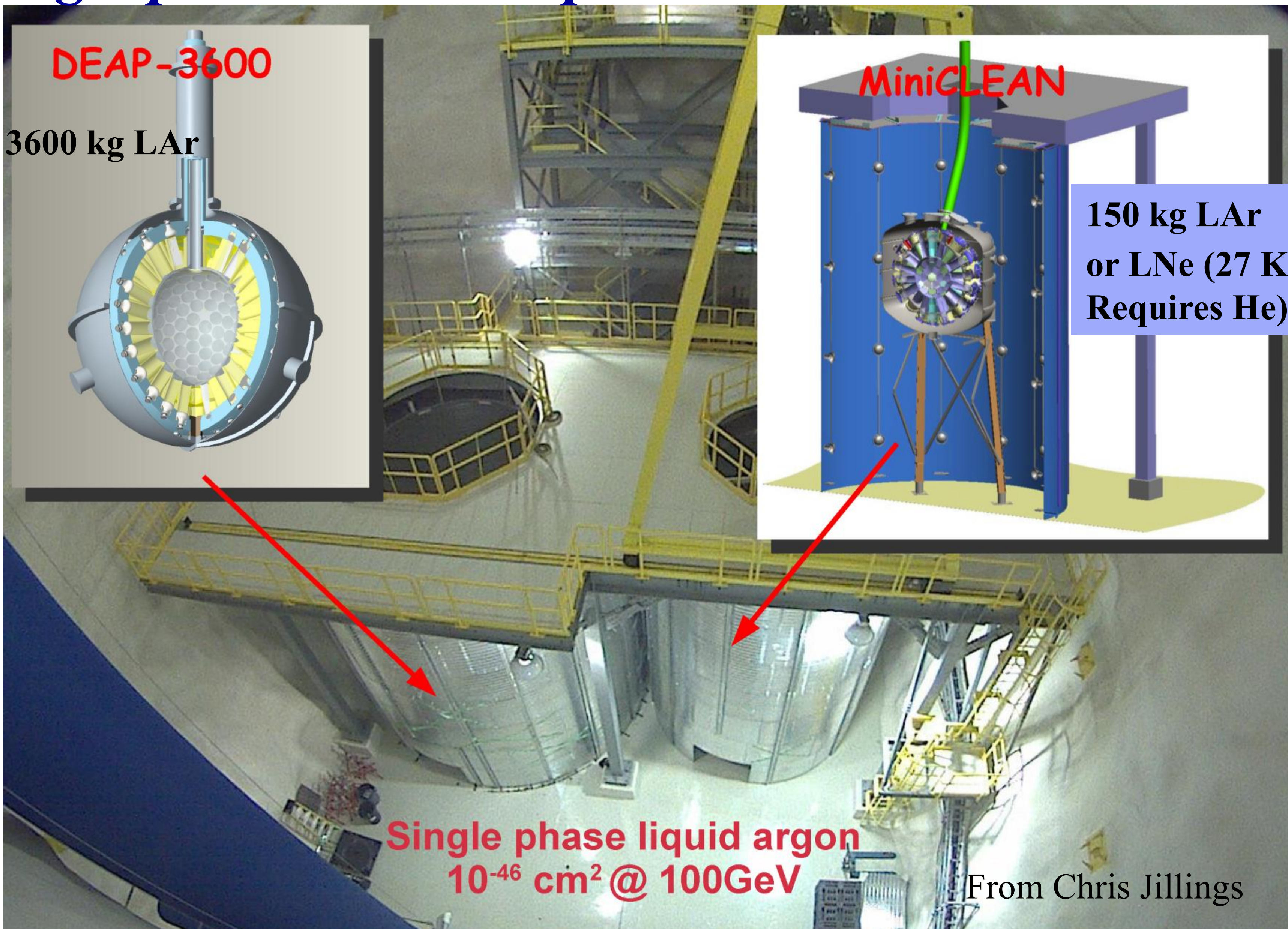


Xe isotopes: half spin half not

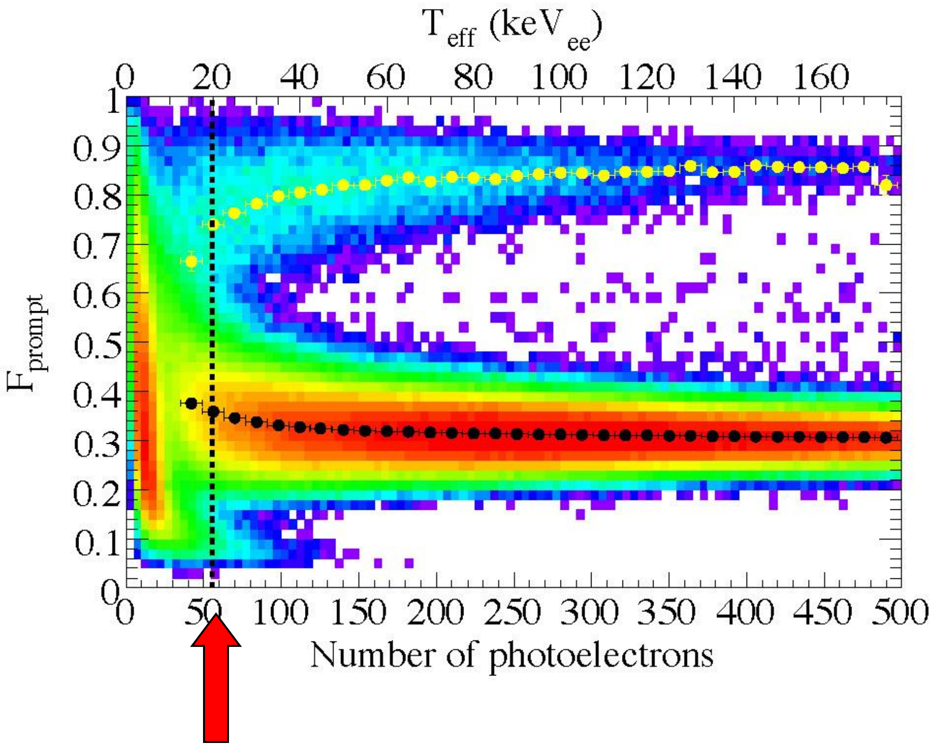
^{129}Xe ($1/2^+$)	26%
^{131}Xe ($3/2^+$)	21%
^{132}Xe (0^+)	27%
^{134}Xe (0^+)	10%
^{136}Xe (0^+)	9%

E. Aprile WONDER 2010

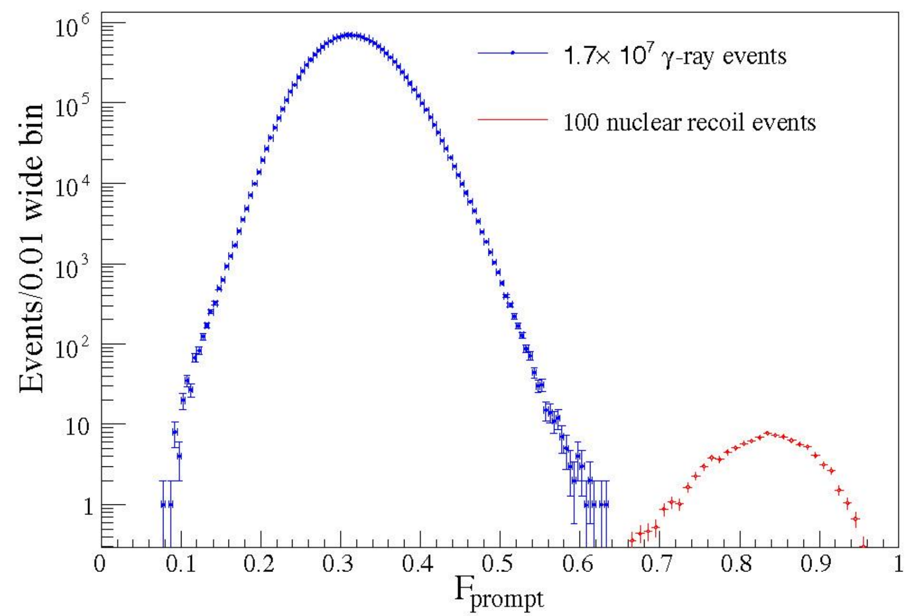
Single phase LAr. Deap and Clean at SNOLab



Deap/Clean. L_{eff} and discrimination



8×10^{-16} abundance of ^{39}Ar in atmospheric Ar
$\Rightarrow$ 1Bq/m^3 beta (Q=566 keV, τ=388 y)



Discrimination capability depends on the number of photoelectrons.

If an electric field is present the corresponding T_{eff} is higher.

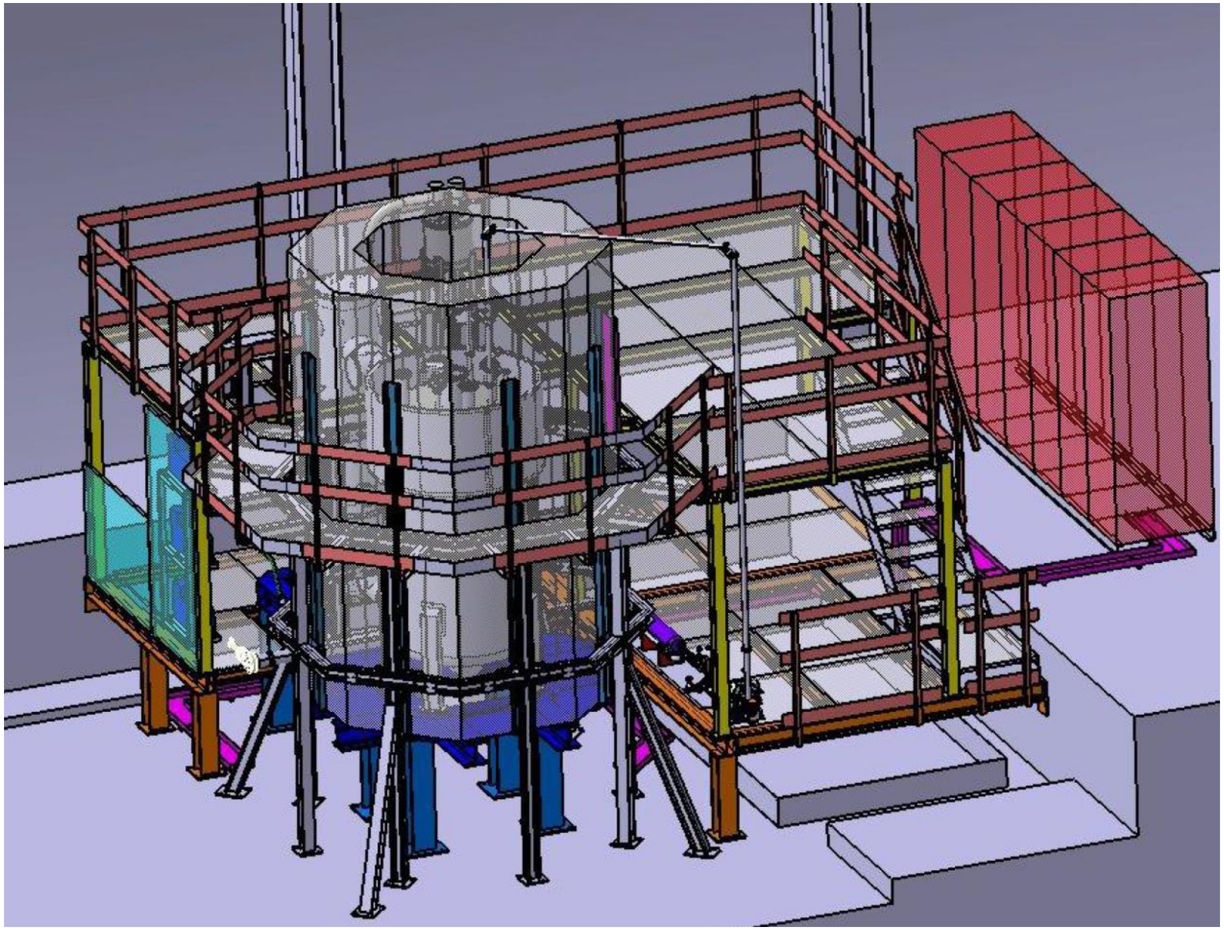
Prompt =<150 ns

PSD (Pulse Shape Discrimination) = 6×10^{-8} demostrated (**@ E=0**)

arXiv 0904.2930

Ongoing programme (DarkSide) in the USA for depleted Ar from underground sources (reduce ^{39}Ar by >20) [NIM A **587** (2008) 46]

ArDM 1 ton @ LSC



To be installed in Hall A LSC in 2012

ArDM

Phased approach:

1. Surface at CERN: build and commission 1-t L Ar TPC. (Done)
2. Underground at LSC. Develop underground infrastructures with LSC and science run with natural Ar (starts 2011)
3. Underground at LSC, phase 2. Science run using depleted Ar

ArDM sensitivity

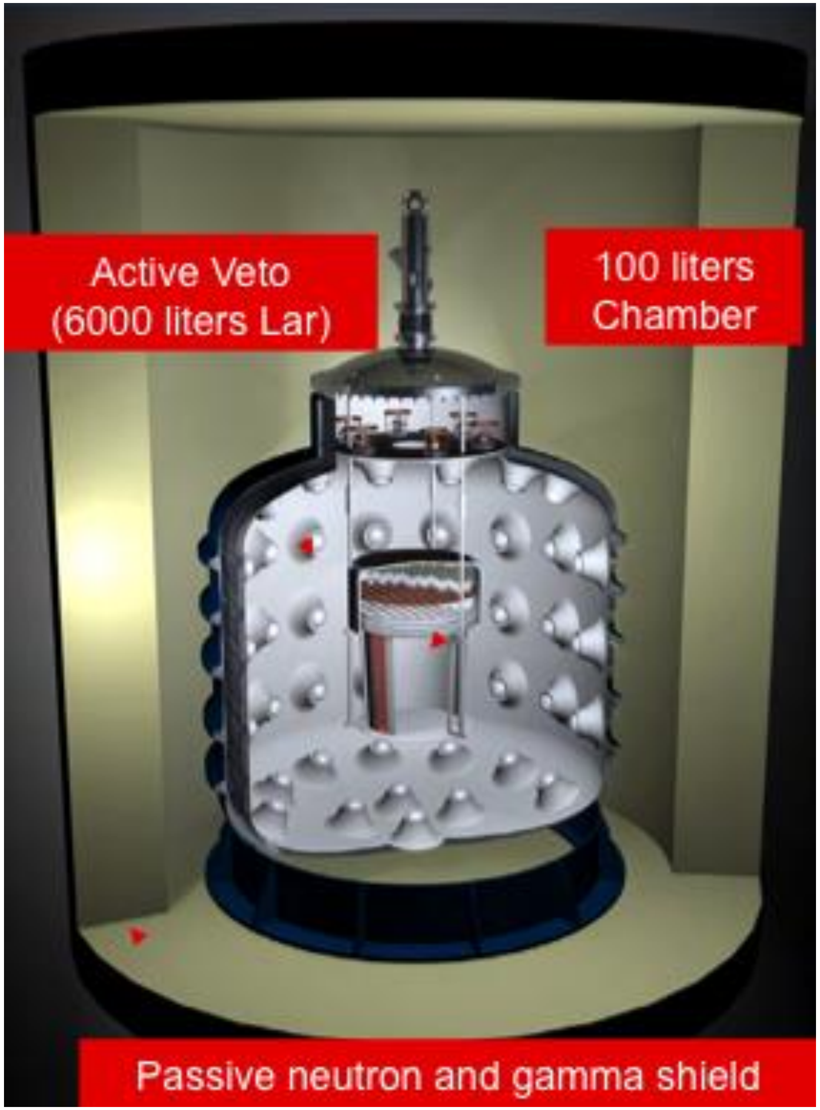
We assume:

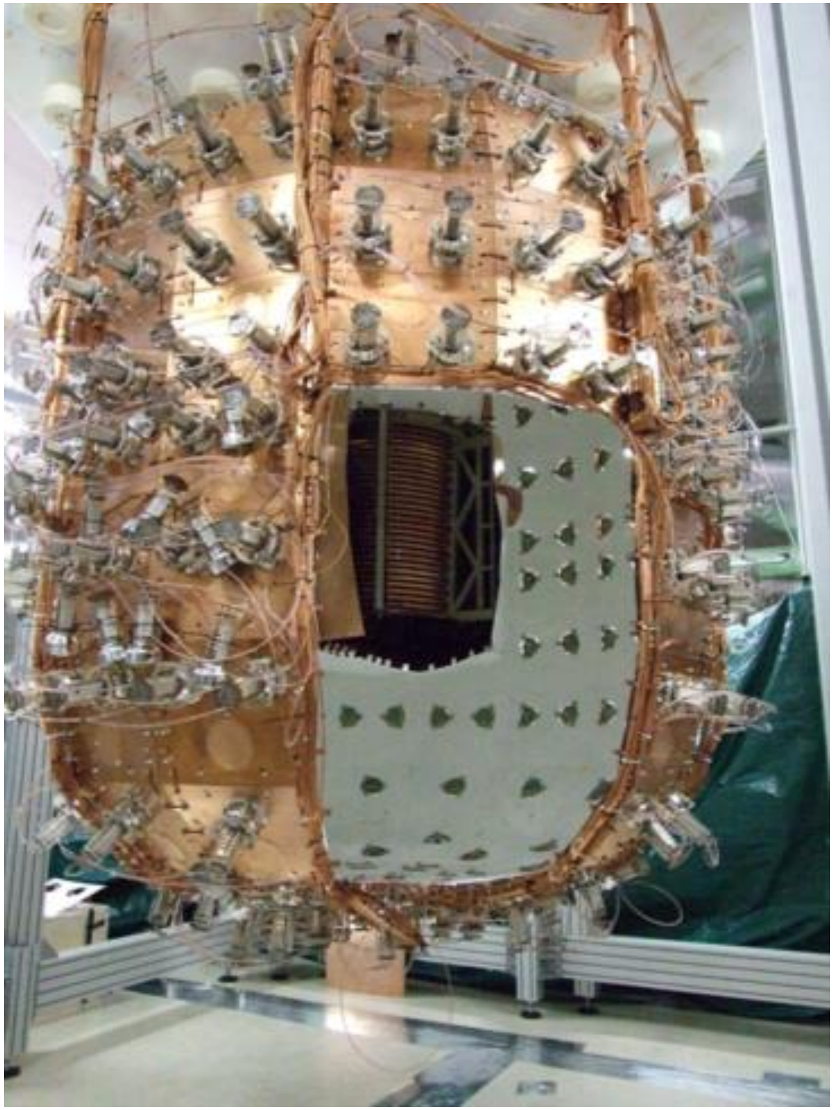
- 500 kg active mass after fiducialization.
- Background rejection: 10^7 (10^4 from PSD and 10^3 from S1/S2) for beta/gamma background
- Signal efficiency: 50%
- Neutrons from materials and neutron shield in place
- WIMP mass 100 GeV and xsec 10^{-44} cm^2
- Region of interest 30-100 keV

Ar39 [evt/day]	gamma [evt/day]	neutrons [evt/day]	background [evt/day]	WIMP rate [evt/day]
1.50E+06	47,500	0.07	0.22	0.25

A. Curioni

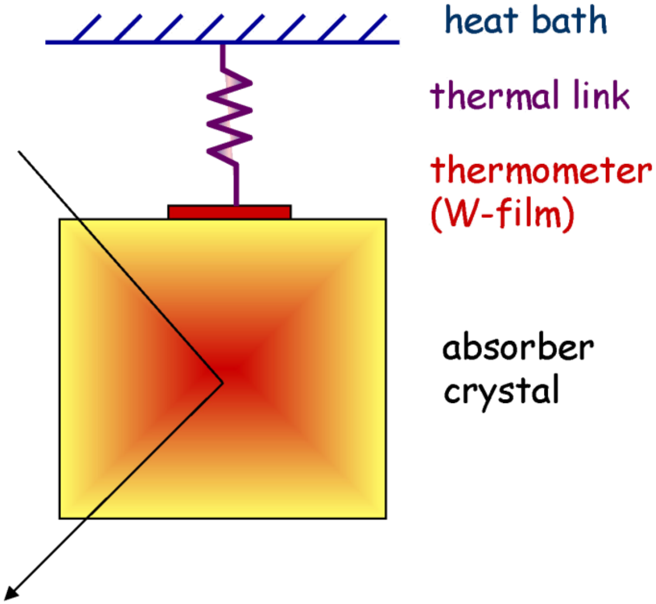
WARP at LNGS





Test run at LNGS

Bolometers



In a dielectric crystal

C= heat capacity
m= absorber mass
M= absorber molar mass
Θ_D = Debay temperature

Advantages
Low energy threshold (keV, sub-keV)
W(Ge)=3 eV/pair, W(Si)=3.8 eV/pair
Very good energy resolution
Measure all the energy deposit (L_{eff}=1)
Good ER/NR discrimination by measuring
light/phonons
charge/phonons
Surface/bulk discrimination by detecting
athermal phonons (pulse shape)

Disadvantages
Need milliKelvin technology
Shielding cryostat interference
Surfaces facing detectors in vacuum
Difficult to scale

CDMS II@SUL

One ZIP detector. M=250 g

Soudan Underground Lab (713 m dep)

19 Ge ZIPs (4.75 kg) + 11 Si ZIPs (2.75 kg)

3 Ge ZIPs not working properly

Charged particle track ⇒ e-h pairs & phonons

Ionisation charges drifted (**E**=3 V/cm) to 2 electrodes on one face

Phonons are collected before thermalisation on 4 thin film superconducting circuits on the other face

Ionisation yield = **Ionisation/Phonons** ⇒ NR-ER discrimination >10^4 (above 10 keV)

Ionisation yield for ER < 10 μm from **surface** is reduced ⇒ look like NR

Signal timing ⇒ NR-ER discrimination >10^6 (above 10 keV)

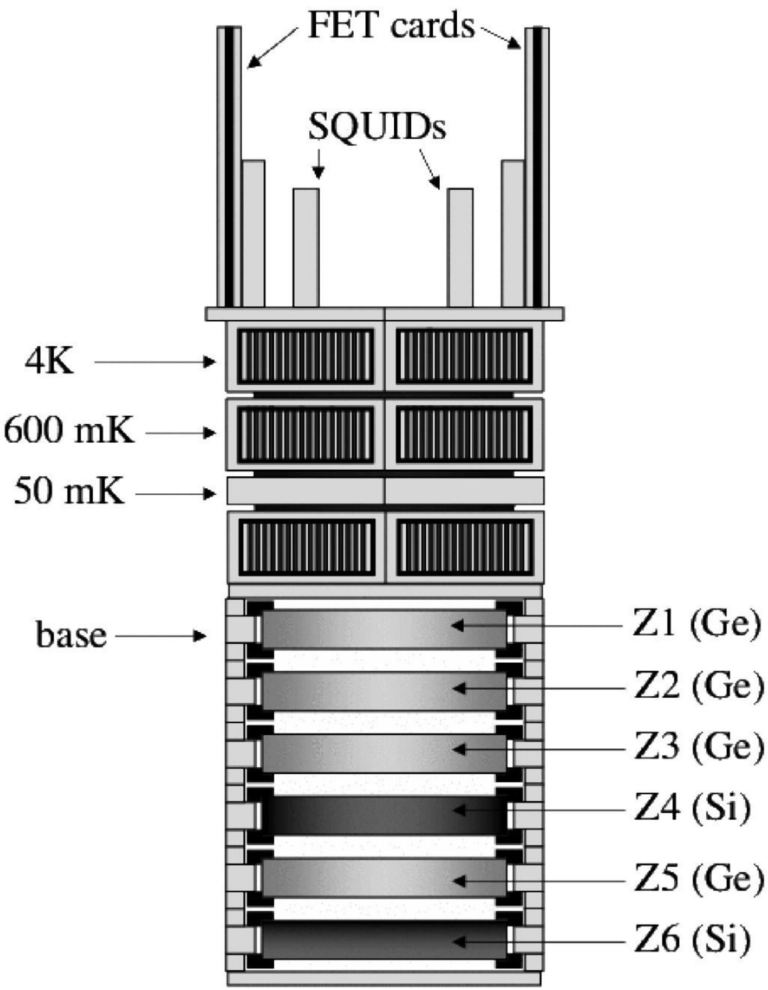
W(Ge)=3 eV/pair, W(Si)=3.8 eV/pair

Akerib et al. PR **D72** (2005) 052009

CDMS II. Towers & Cryostat

One of the 5 "towers"

In Si ZIP: similar rate for n, 5-7 smaller rate for WIMPs

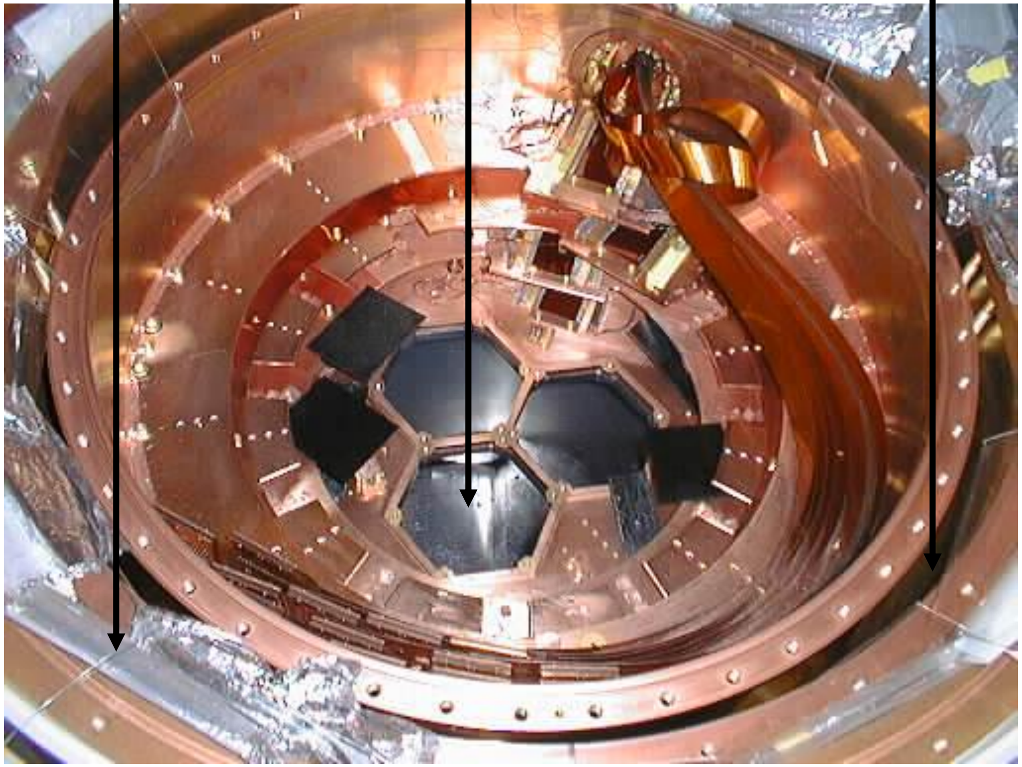


Plastic scintillators muon veto

Shield made of Pb from the ballast of a 18th-century French ship

Polyetilene shield later installed: 2.5 n flux attenuation

Mounting points for the detector assembly @ 10 mK



Akerib et al. PR **D72** (2005) 052009

Phonons. Basic concepts

Transfer of heat within non-metallic solids results in propagation of **elastic waves** associated with the **displacement of atoms** from their lattice sites

Traveling vibrational waves occur in spatially **localized, quantized units = phonons**

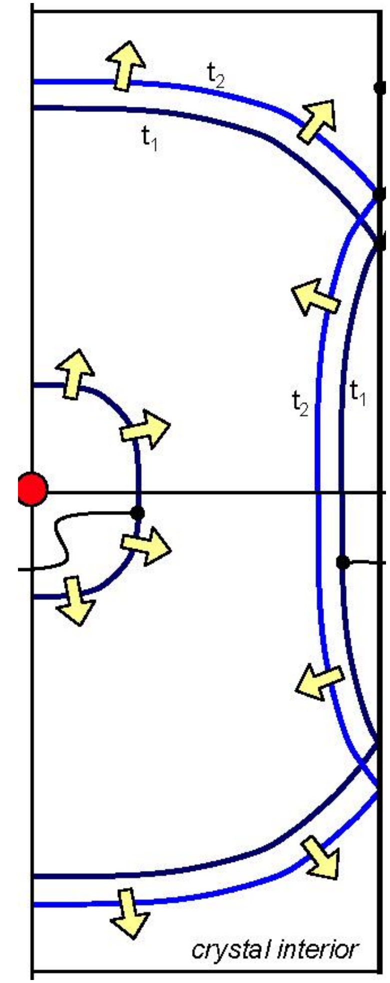
In single hyper-pure crystals at low temperatures, a phonon, of a given frequency *ν*, can disappear (mainly) by

- **scattering on impurities**
- **decay anharmonically (split in 2, each of lower frequency)** $\tau \propto \nu^{-5}$

Once converted to low frequencies: **ballistic** = straight-line trajectories over long distances without destruction or redirection

Simulation shows an energy wave propagating from a point sources, reflecting when it reaches the surface. Arrows are group velocities. Wave is not spherical because crystal is not isotropic

Several wave shapes, depending on the source vibration direction etc

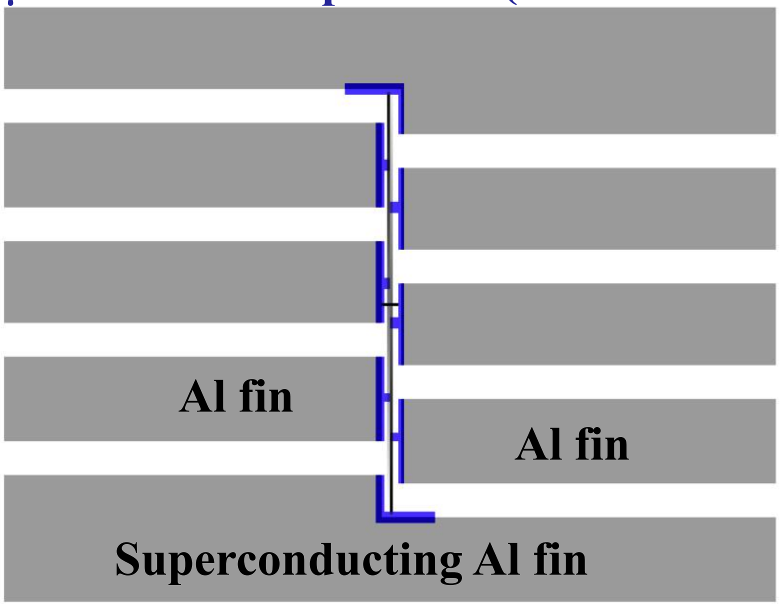


N. Zuckerman J. R. Lukes HT2007-32674

CDMS. QET, the phonon detector

QET = **Q**uasiparticle-assisted **E**lctrothermal-feedback **T**ransition-edge sensor (4144)

1 μm wide W strip = TES (Transition Edge Sensor)



- **TES** is stably maintained in the **SC-normal transition** by electro-thermal feedback
- Phonons reaching the surface scatter into Al fins creating **quasiparticle exicitations**
- Quasi-particle diffuse in the Al and enter TES
- Interactions between quasi-particles and W conduction electrons
- **⇒ Increase of electrons T ⇒ decrease of TES current Δ*I***

Ballistc phonons (< 1 THZ) travel @ υ_{sound}, do not scatter frequently

Higher initial population of ballistic phonons for ER (1) than NR (2) [due to the larger charge density produced by ER] ⇒ faster phonon leading edge for ER

Excess of ballistic phonons if energy deposited close to surface (3)

Phonon signal leading edge rise-time even faster than ER

Phys Rev **D72** (2005) 052009

CDMS II

Data: 4 periods Jul 2007-Sept 2008 @ SUL

•Exposure = **612 kg d**

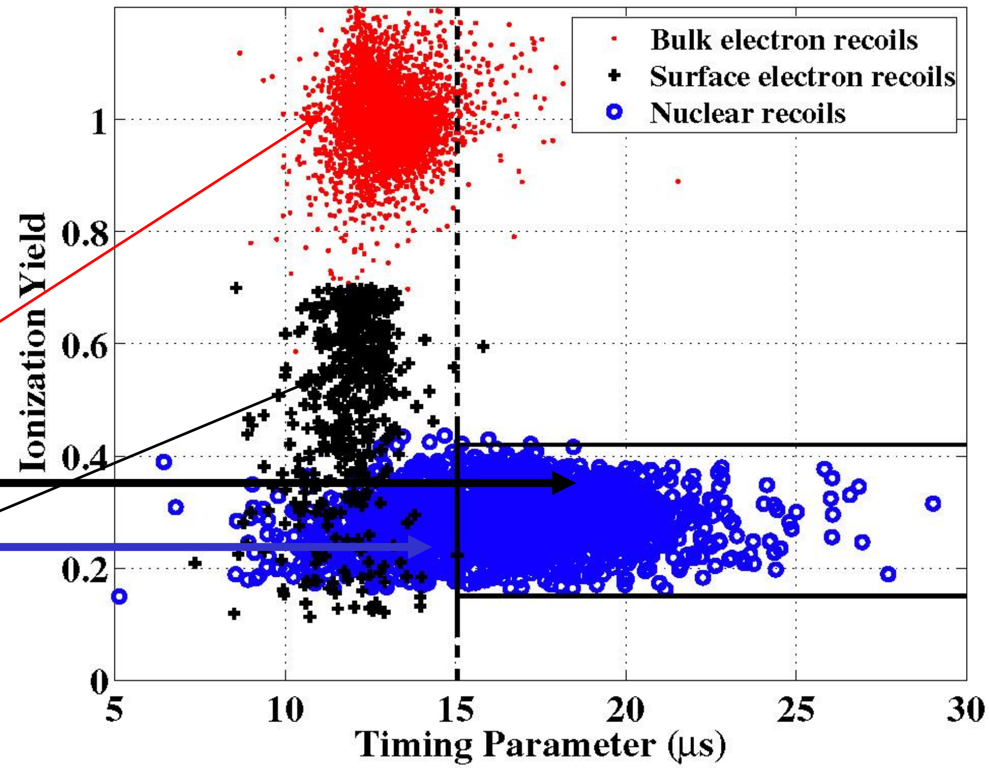
•10 keV < E_{NR}<100 keV off-line

•No energy in other detectors (unlike neutrons) or in scintillator shield

•Blind definition of **"Signal region"**

•Calibration: **NR with ^{252}Cf source**

•Calibration: ER **bulk** and **surface** with γs with ^{123}Ba source



•Measure phonon signal rise-time and delay w.r.t. ionosation signal ⇒ timing parameter

•Background model

•Surface γ rays from surfaces near the detectors. Major contribution: ^{210}Po.

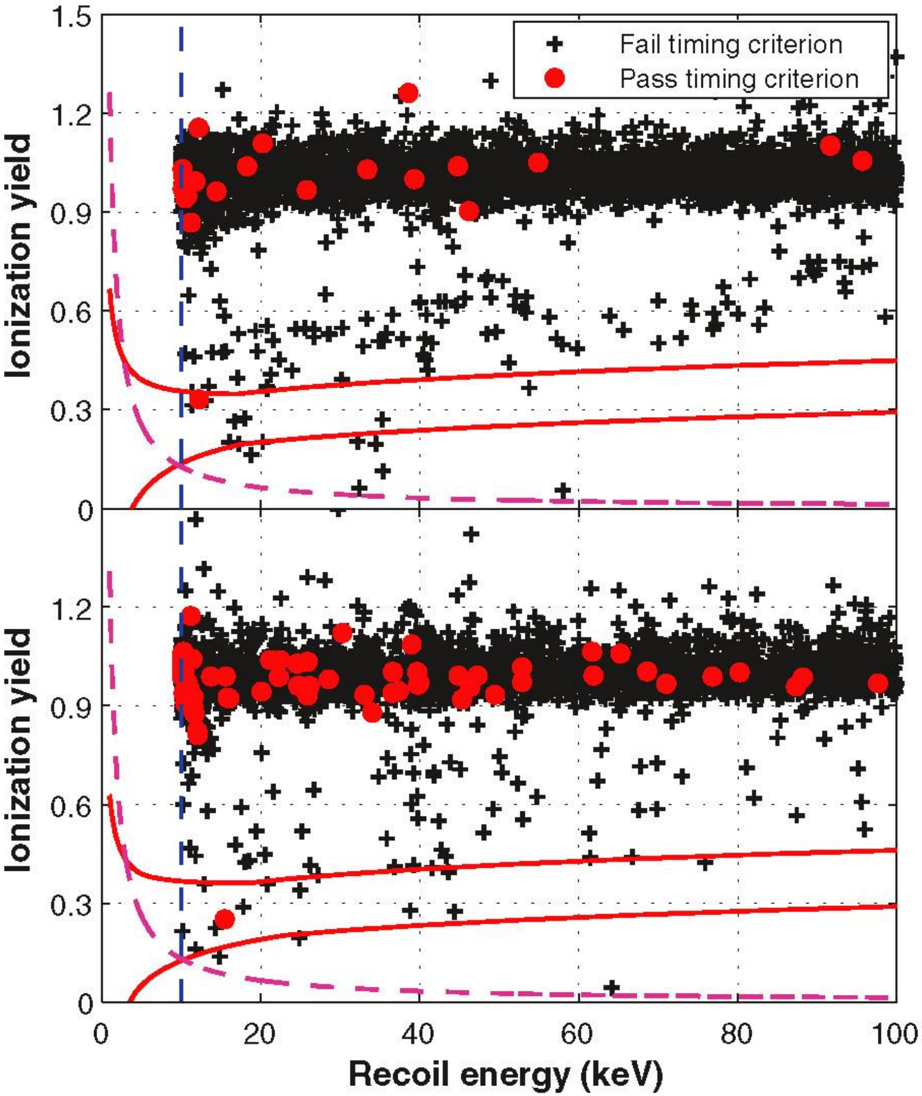
•Estimated leak to signal region = **0.8±0.1 (stat) ± 0.2 (syst)**

•Neutron induced recoils

•MonteCarlo and check on Si. Estimated background = **0.1**

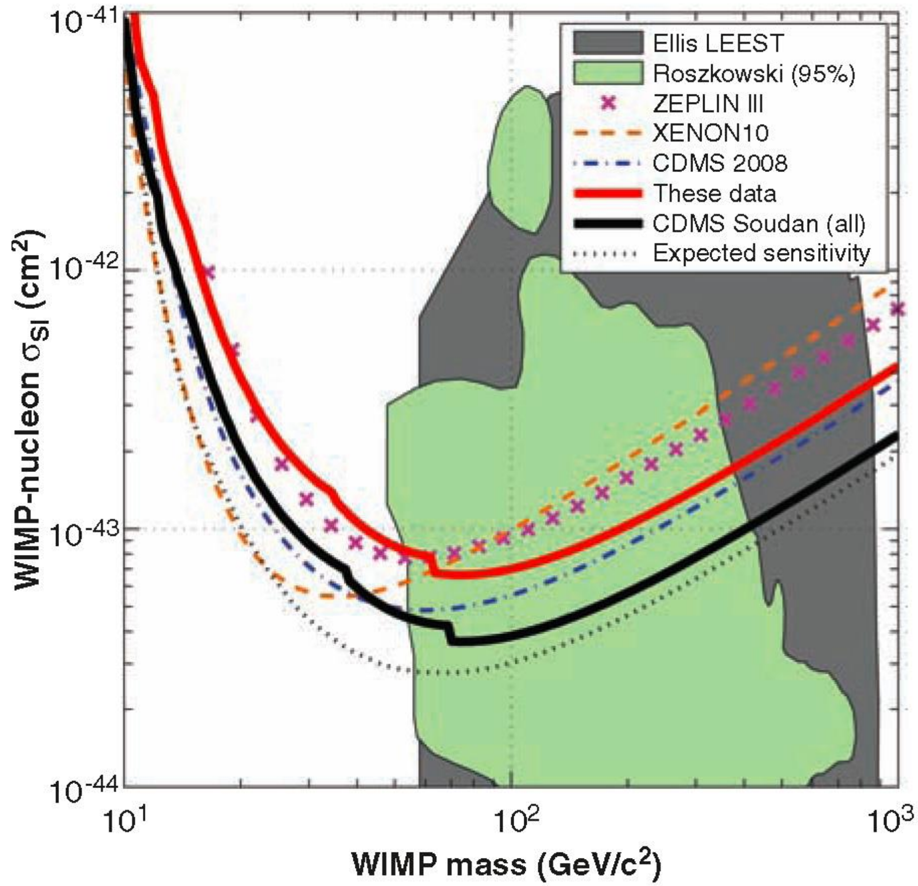
Ahmed et al. PRL **102** (2009) 011301

CDMS II Results



2 events in the signal region passing all selection criteria, E_R=12.3 keV, 15.5 keV

Probability to be background=23%

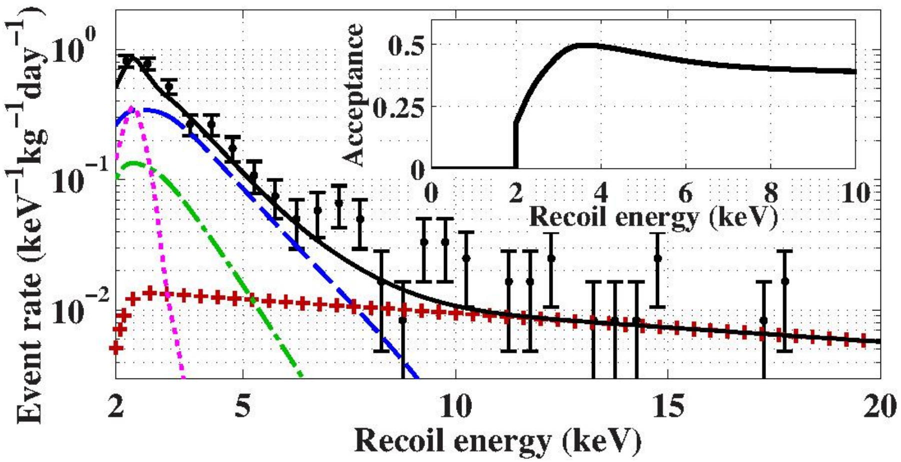


CDMS Science **327** (2010) 1619

CDMS Low Energy analysis

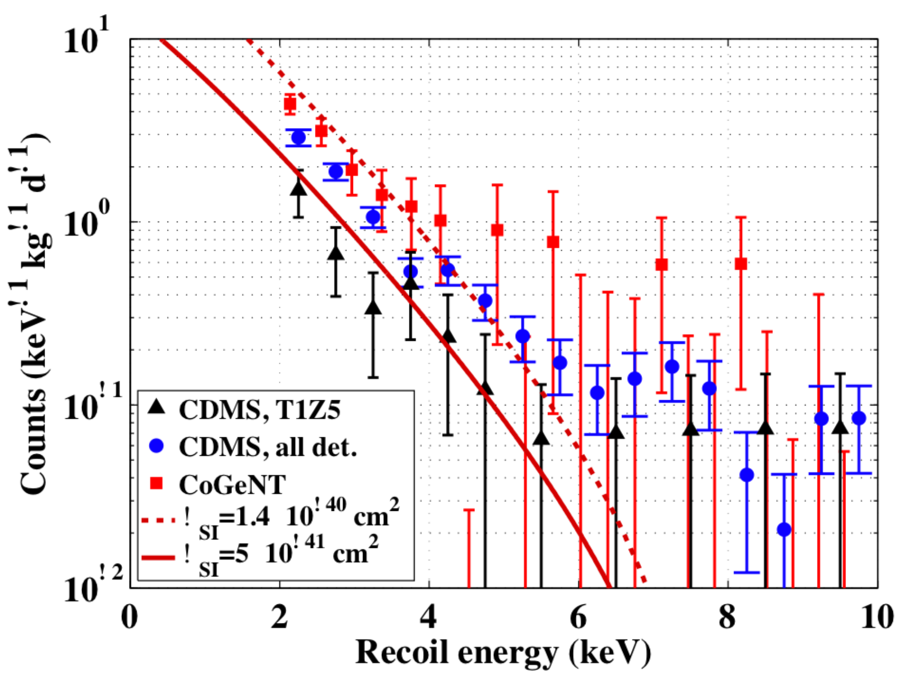
m_W<10 GeV produce E_R<10 keV ➔ low energy threshold @ 2 keV
Use only 8 best Ge ZIPs, rest as anticoincidence ➔ 241 kg d
Phonon based recoil energy scale

arXiv 1011.2482



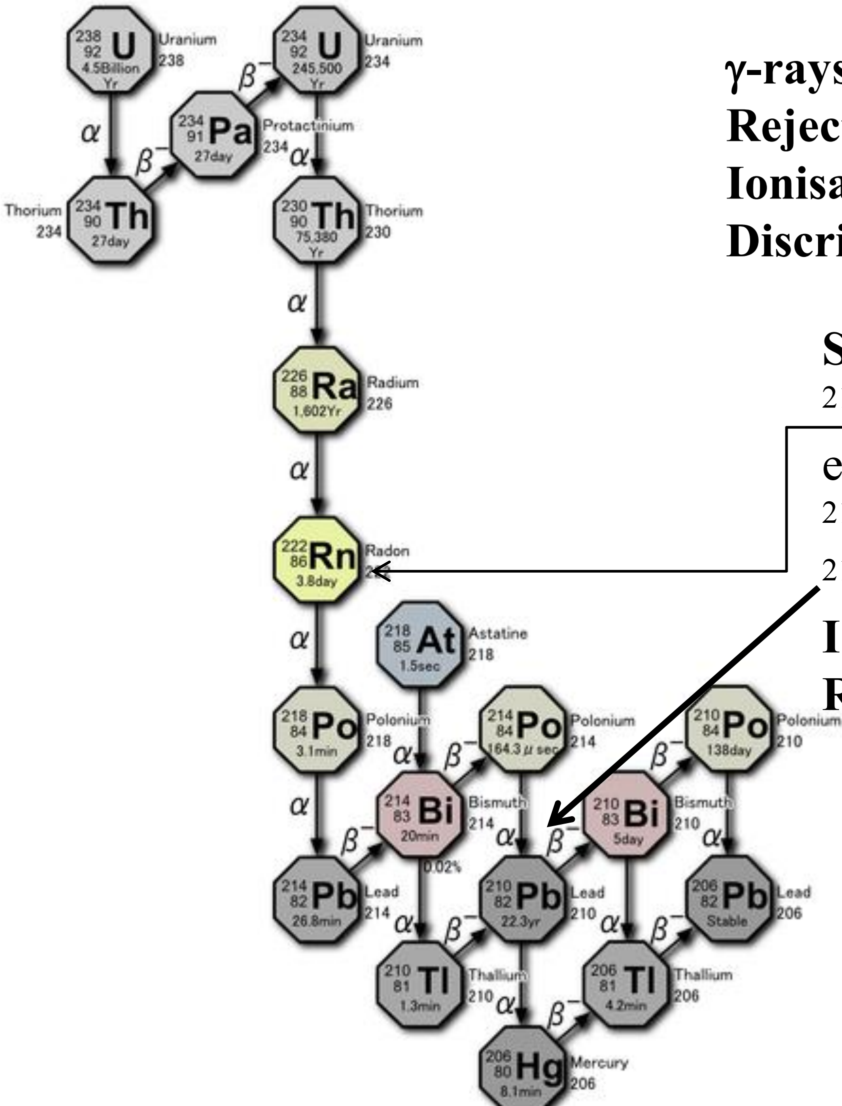
Recoil energy spectrum agrees with background expectations ("Zero-charge" ev.= ER near the edge of detector +Surface ev +bulk+1.3 X line)

Assume events to be signal
T1Z5 best discrimination against ER
Not compatible with CoGent "all-signal"
Continuous curve is for $\boldsymbol{m_W}$= 7 GeV
σ=5 x 10^{-41}cm^2 (best fit to CoGent) not excluded by CDMS, but requires that the largest fraction of the CoGent low energy excess to be background



EDELWEISS2@LSM. Backgrounds

Remember: $\sigma=10^{-8}$ pb, Ge detector, RoI=15<E_r<65 keV ➔ $R=10^{-3}$ /(kg keV d)



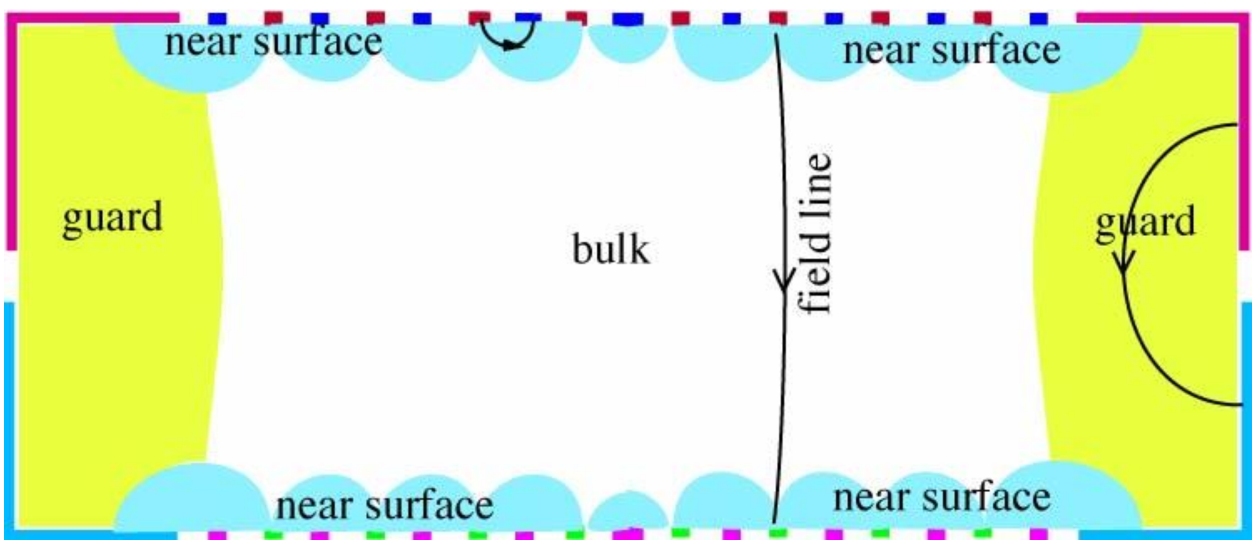
γ-rays interactions inside shields R_γ=10/(kg keV d)
Rejection needed=10 000
Ionisation yield for NR is about 1/3 smaller than ER
Discriminate by measuring heat and charge

Surfaces (detectors and supports)
^{210}Pb (doughter of Rn) emits Xrays & Conversion electrons in the energy of RoI
^{210}Pb β ➔ ^{210}Bi β ➔ ^{210}Po (α emitter)
^{210}Pb β ➔ ^{210}Bi* ➔X-rays 10-90 keV
In total: 2 ev/(kg keV d)
Rejection needed = 2000

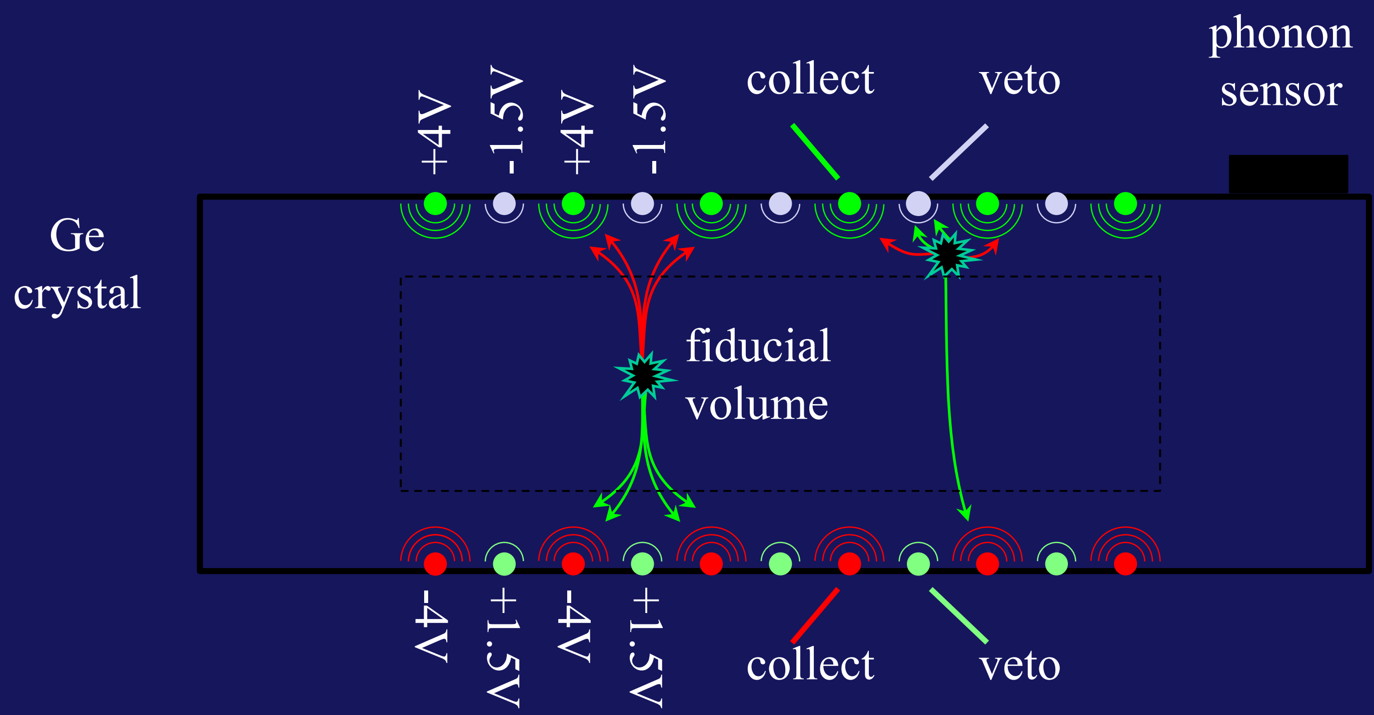
EDELWEISS 2. Detector concept

Phys. Lett. **B 681** (2009) 305

Measure heat Ge NTD thermistors
Measure charge and localise event:
coplanar grid technique
Grid of ring shaped electrodes on the top and bottom surfaces
Arrange potentials to define:
•Bulk zone
•Surface zones
•Guard zone
Claibtarion with ^{210}Po source
rejection = 60 000



EDELWEISS-II



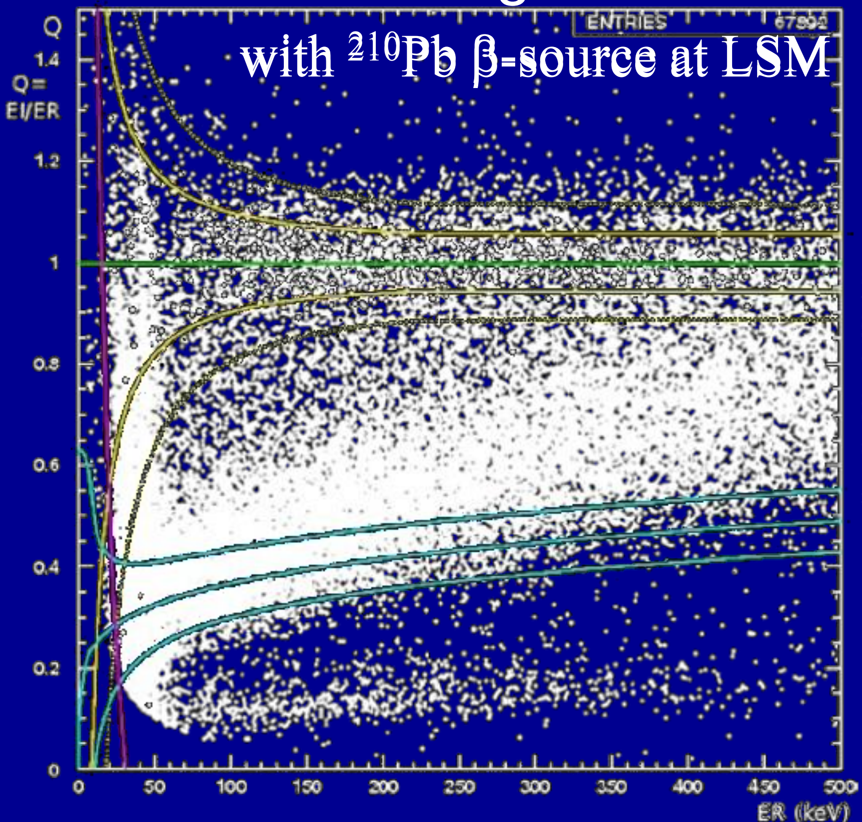
EDELWEISS-II Data

data from 1 year with ten 400g Ge crystals

meanwhile four 800g modules installed

with ^{210}Pb β-source at LSM

ionization/phonon yield



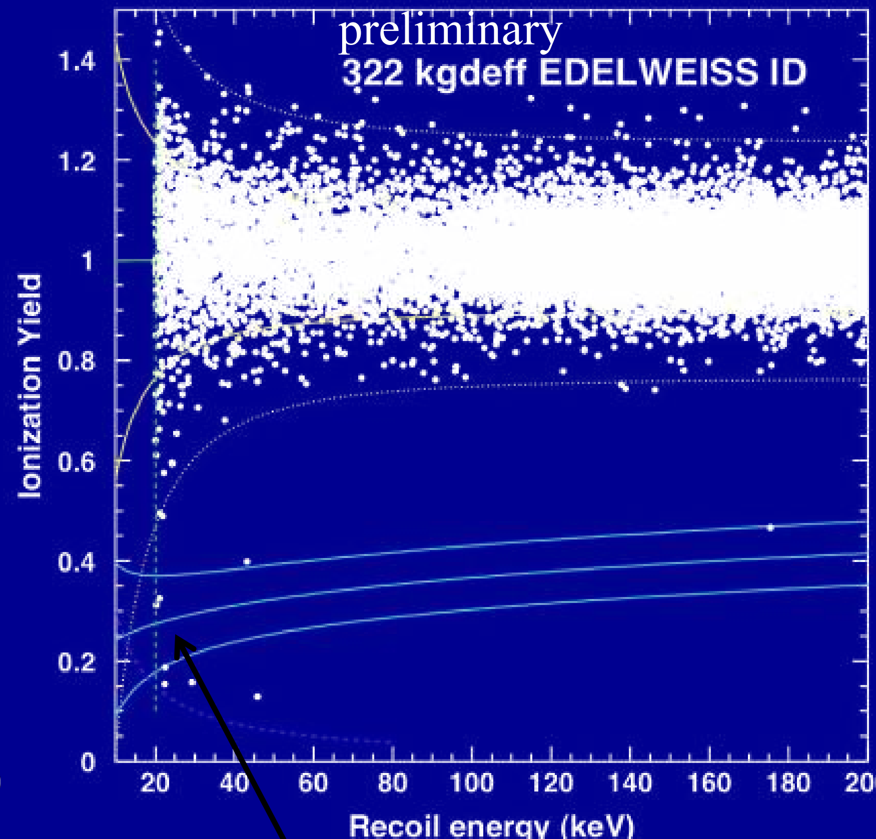
energy (phonon channel)

before fiducialization

after fiducialization

Kraus, IDM2010

preliminary

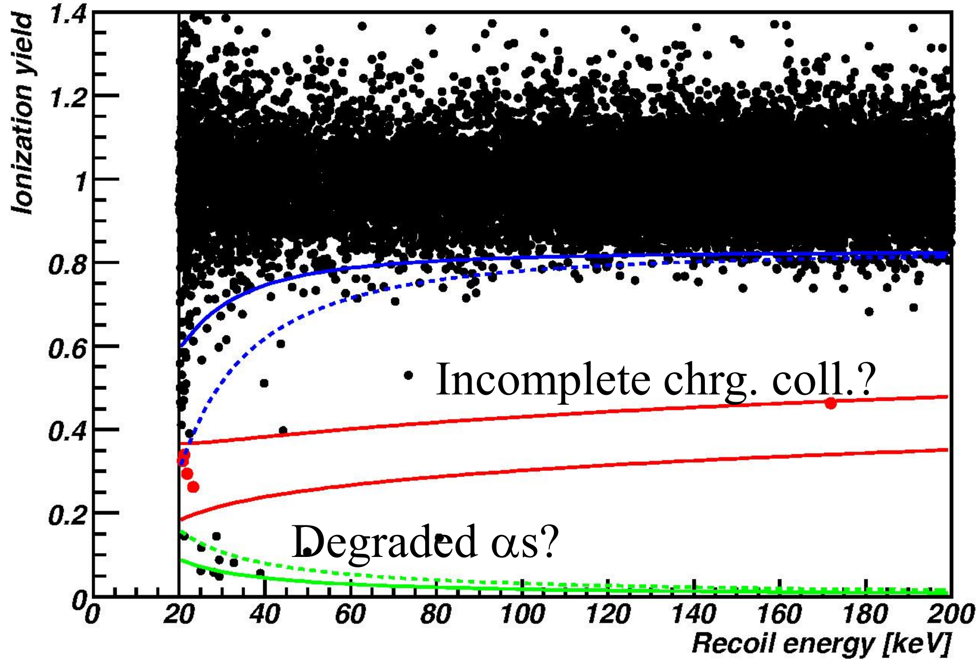


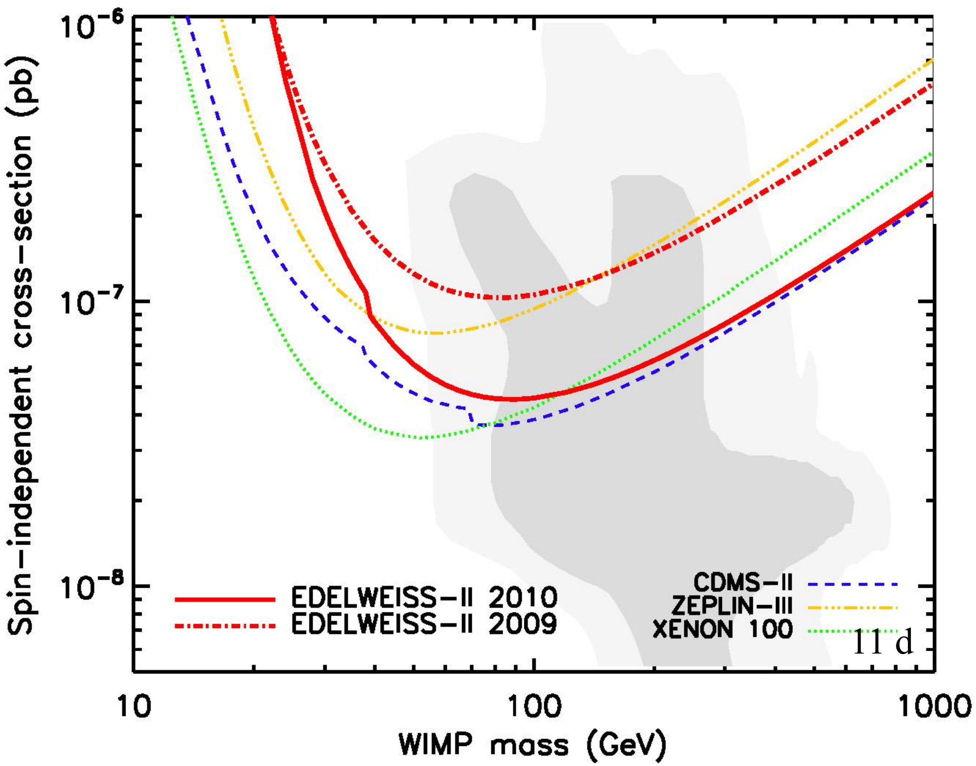
3 events near threshold

Armengaud, IDM2010

EDELWEISS 2. Results

10 Ge detectors (Ge-ID) 400 g each
Measure photopeaks from cosmogenic ^{65}Zn (9 keV) and ^{68}Ge (14 keV)➔**Fid. mass =160 g**
Exposure 384 kg d
Measure γ rej fact = (3±1) 10^{-5} (6 ev in the NR)





5 WIMP candidates in the signal region

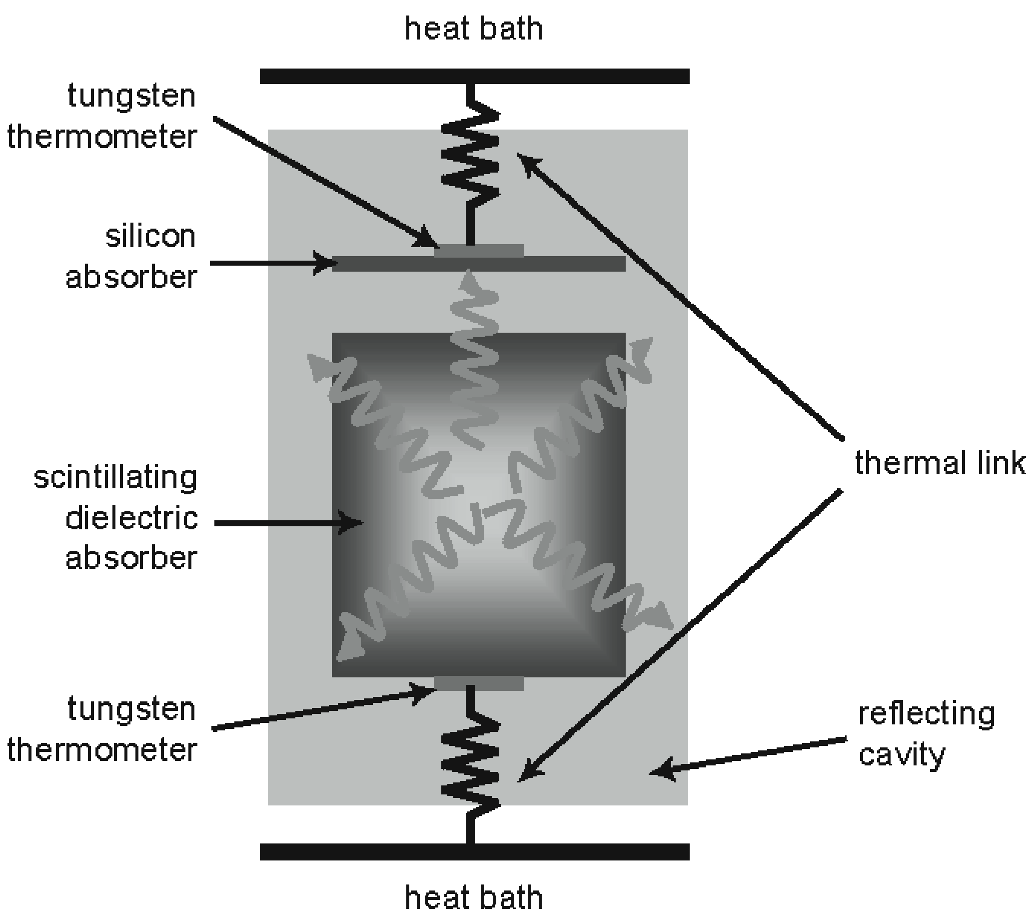
Background estimates

- γ induced non gaussian = 0.9
- leakege of surface events = 0.3
- μ-induced <0.4
- n from detector and shield = 1.3

Total bckgrnd < 3

arXiv 1103.4070

Scintillating bolometers



Scintillating bolometers (crystals) [$CaWO_4$, $CdWO_4$ or $ZnWO_4$] allow to measure at the same time

phonon production (largest fraction)

light yield (small fraction)

Nuclear recoils due to WIMP–nucleon (and neutron-nucleon) scattering produce **mainly phonons** and very little scintillation light

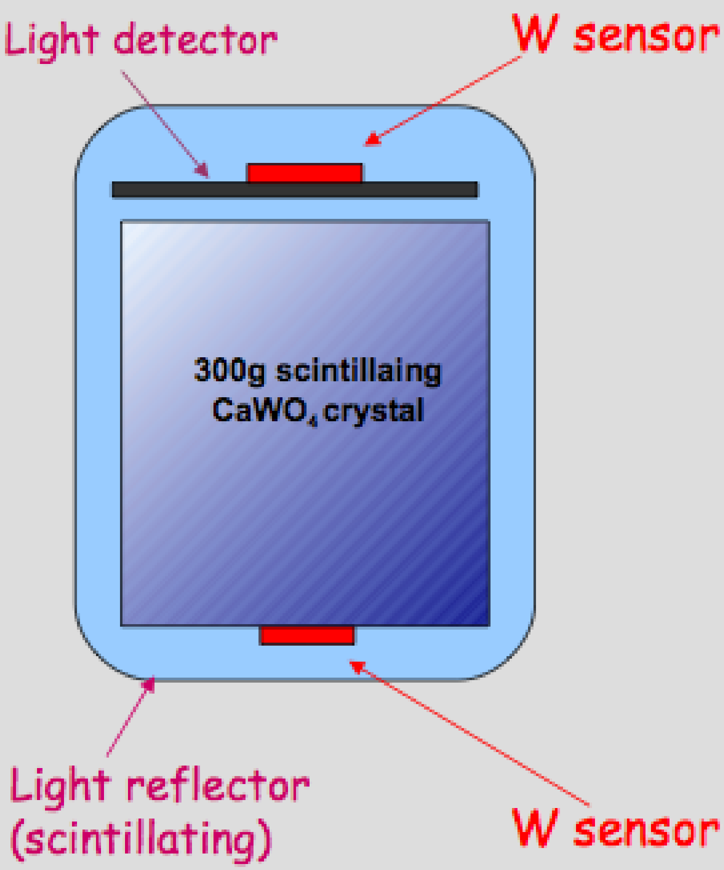
Electron recoils produce a substantial amount of **scintillation light**

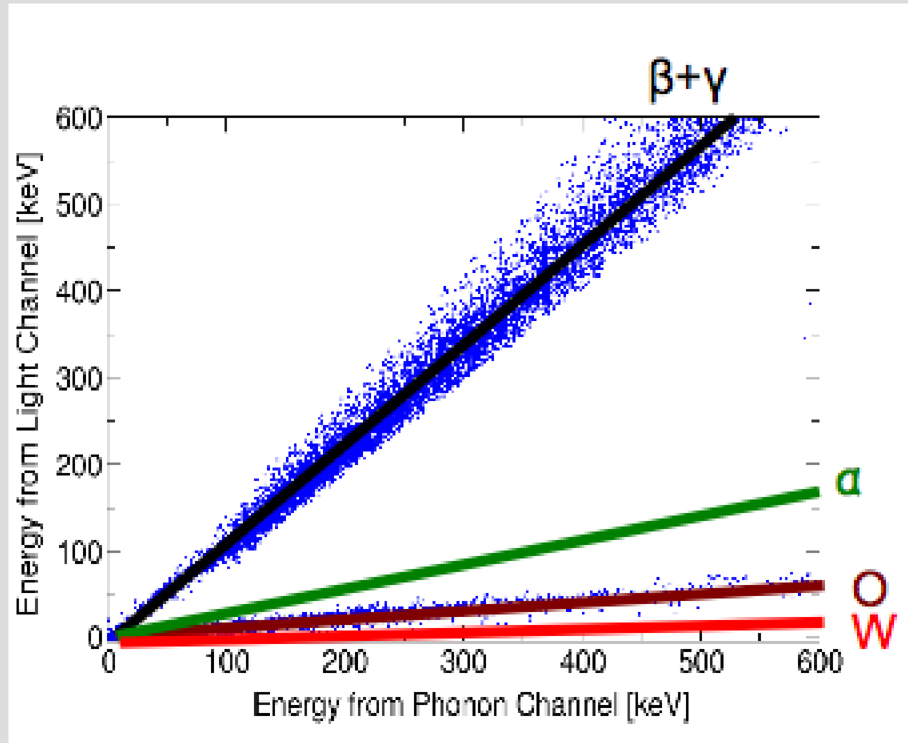
photon/phonon yield ratio depends on the recoiling nucleus

Largest fraction of energy eventually becomes heat. Heat channel measures true energy, both for electron and nuclear recoils

CRESST. Discriminating incident particle

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

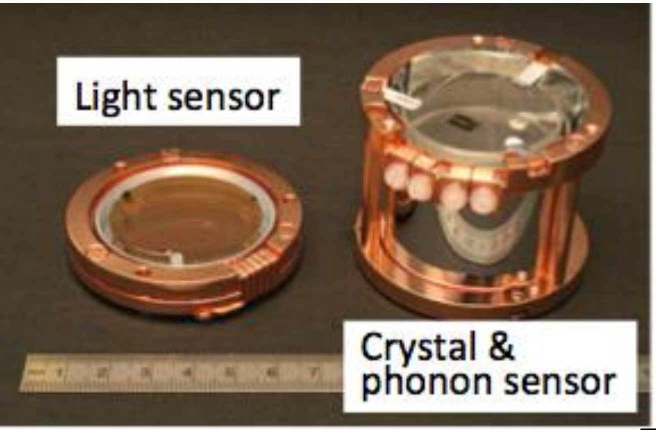


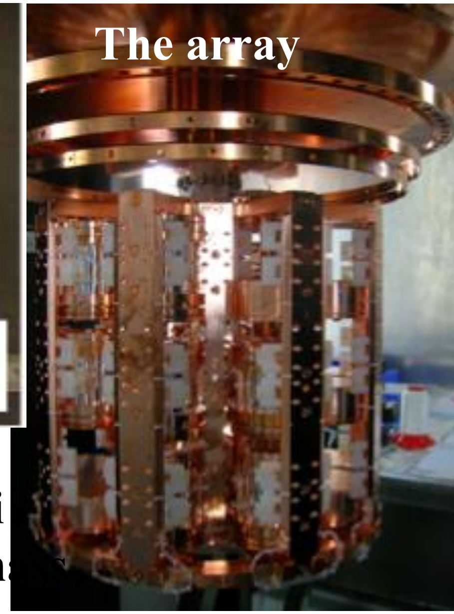


Discrimination between neutrons and WIMPs possible

W. Seidel Wonder 2010

CRESST-II





$CaWO_4$, **three different nuclei sensitive to different WIMP mass ranges**

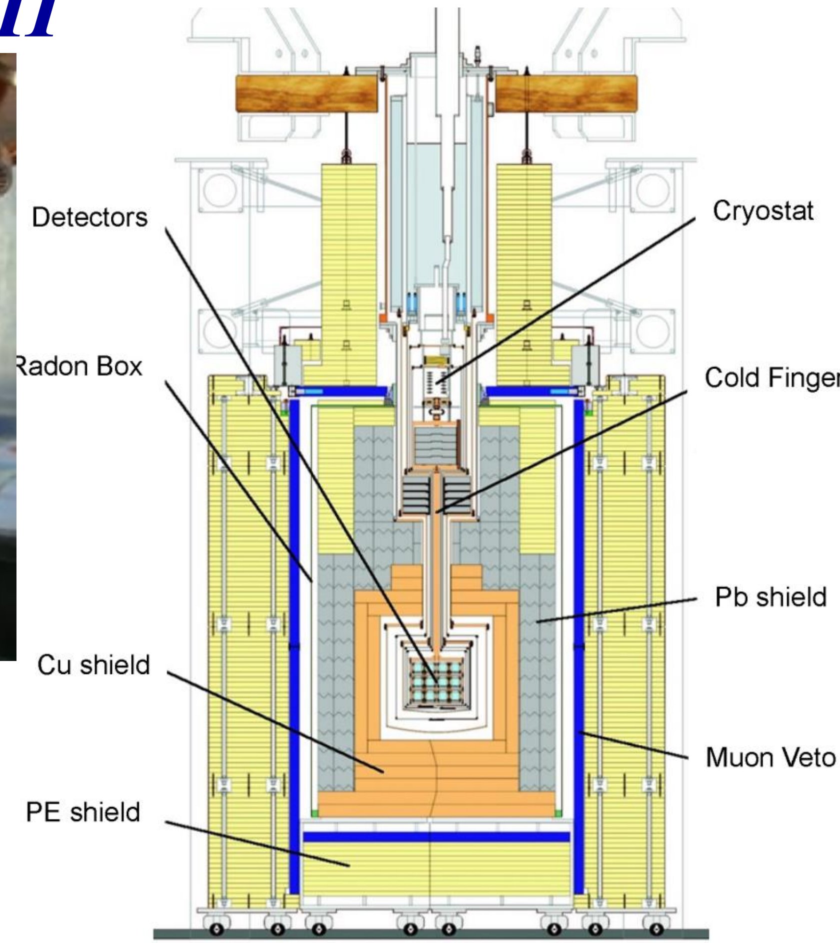
8 crystals (of 18), 0.3 kg each

Detect phonons (resolution different in different modules)

Detect scintillation light

e/γ light yield > α's & decreasing with nuclear recoil mass

Contamination on the supports surfaces can produce background being both in the same vacuum

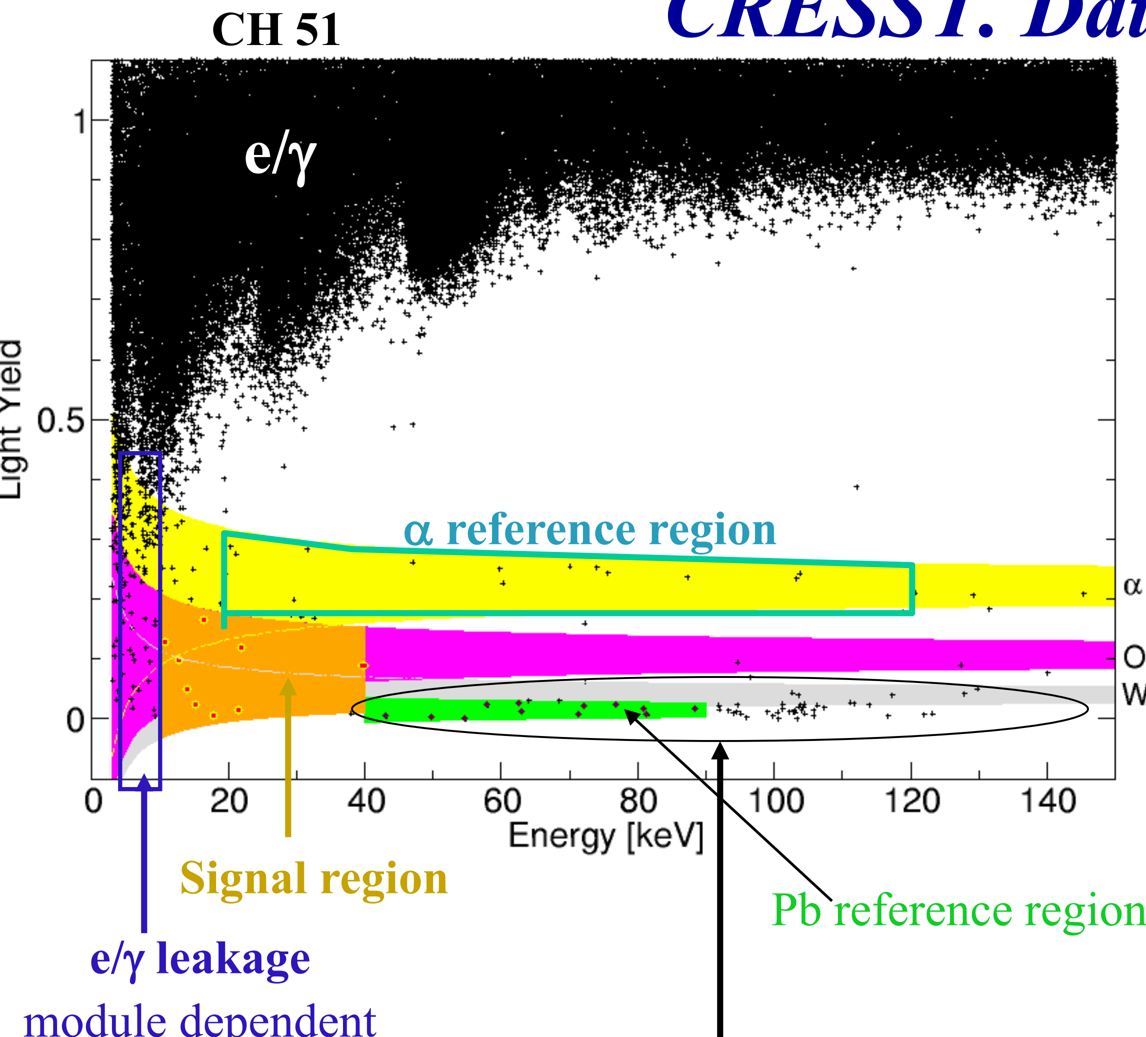


The cryostat and the shields

Exposure June 2009-April 2011: 730 kg day

CRESST. Data

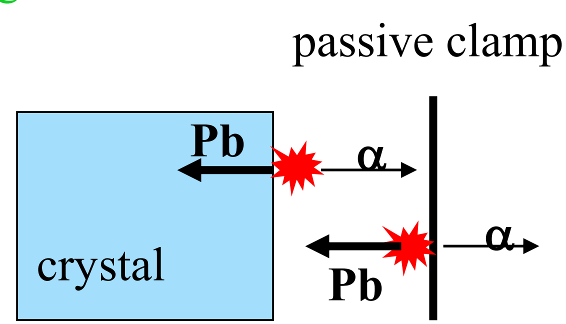
arXiv 1109.0702



- **BKG in W-recoil band too large**
- **Search for signal in O-recoil band**
- **Events in signal region=76**
- **Four BKG sources**
  - **e/γ leakage**
  - **Pb recoils**
  - **Degraded α** (contamin. in clamps)
  - **neutrons**
    - **n from rocks are shielded**
    - **contributes to BKG from**
      - n form (α,n) & fission inside
      - n by μ inside&outside

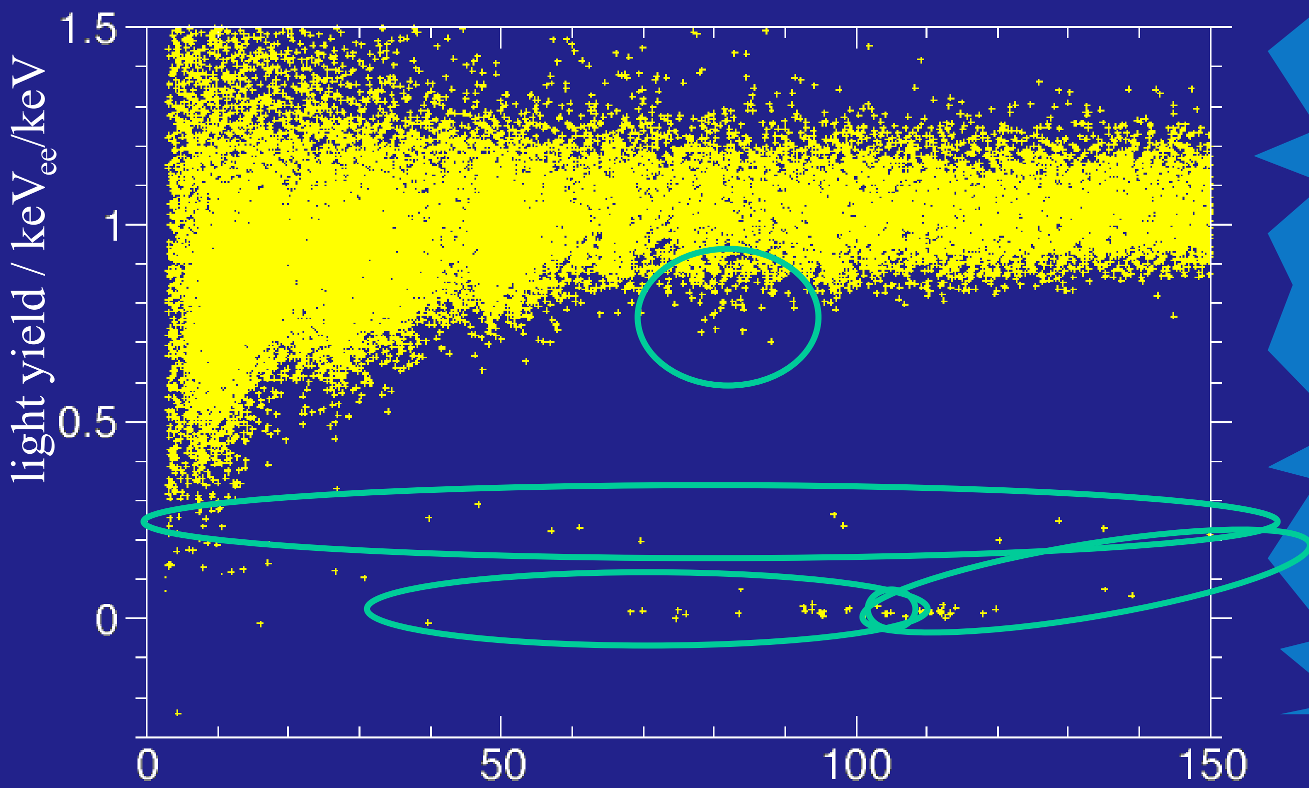
$^{210}Pb \Rightarrow {}^{206}Pb$ (103 keV) + α (5.3 MeV)

In other modules, tail to few 10 keV

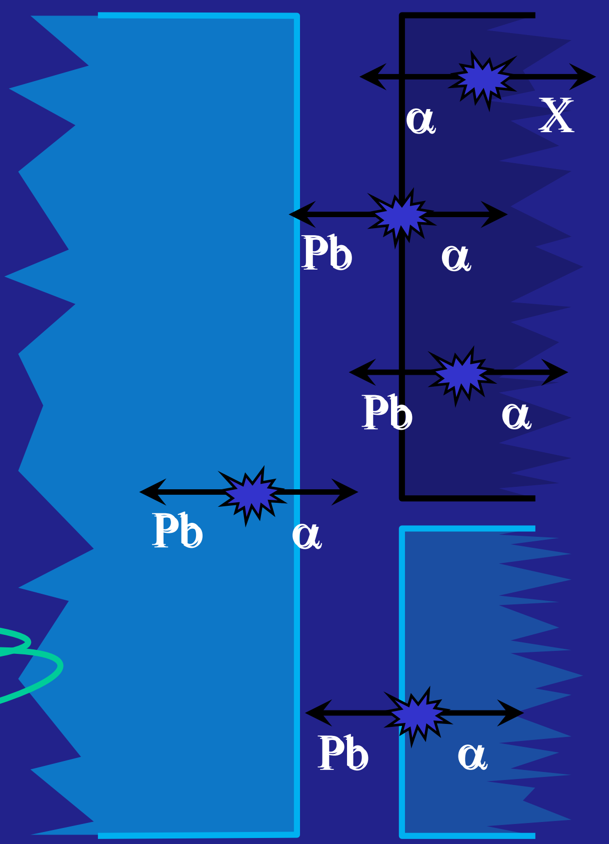


CRESST Background

$^{210}Po \rightarrow {}^{206}Pb$ (104keV) + α (5.4MeV)

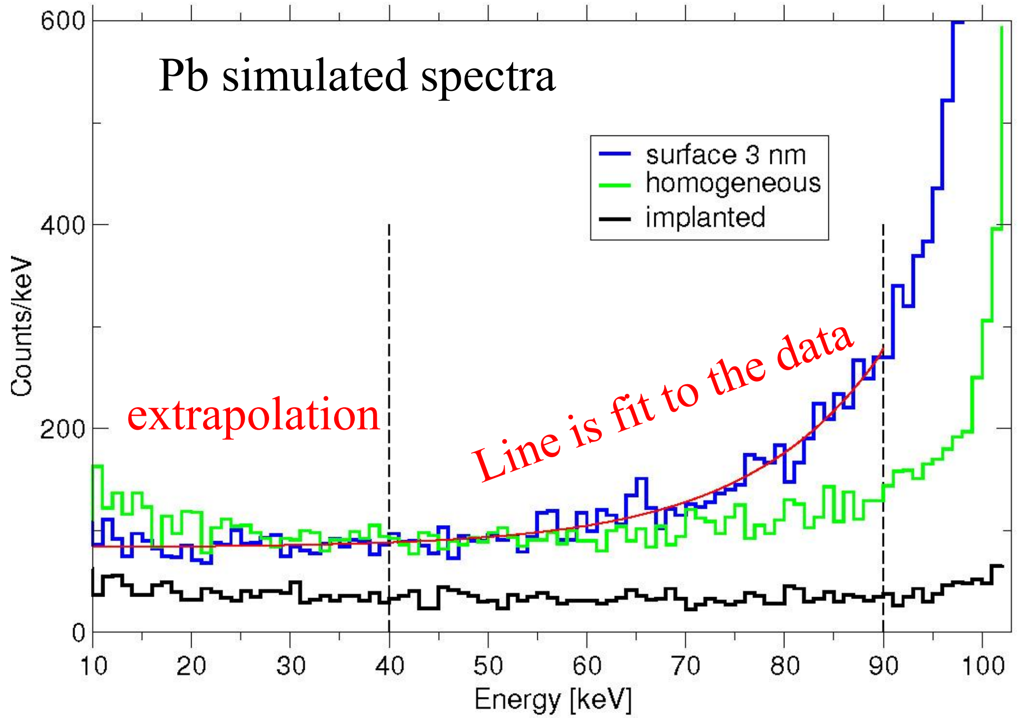


Seidel, IDM2010



CRESST. Background evaluation

arXiv 1109.0702



- For Pb and α
  - Define a "reference region"
  - Assume energy dependence dN/dE
  - Extrapolate tail into signal region
- For n
  - Use data (multiplicity) from source & coincidence with μ

Maximum likelihood to evaluate different contributions finds two maxima

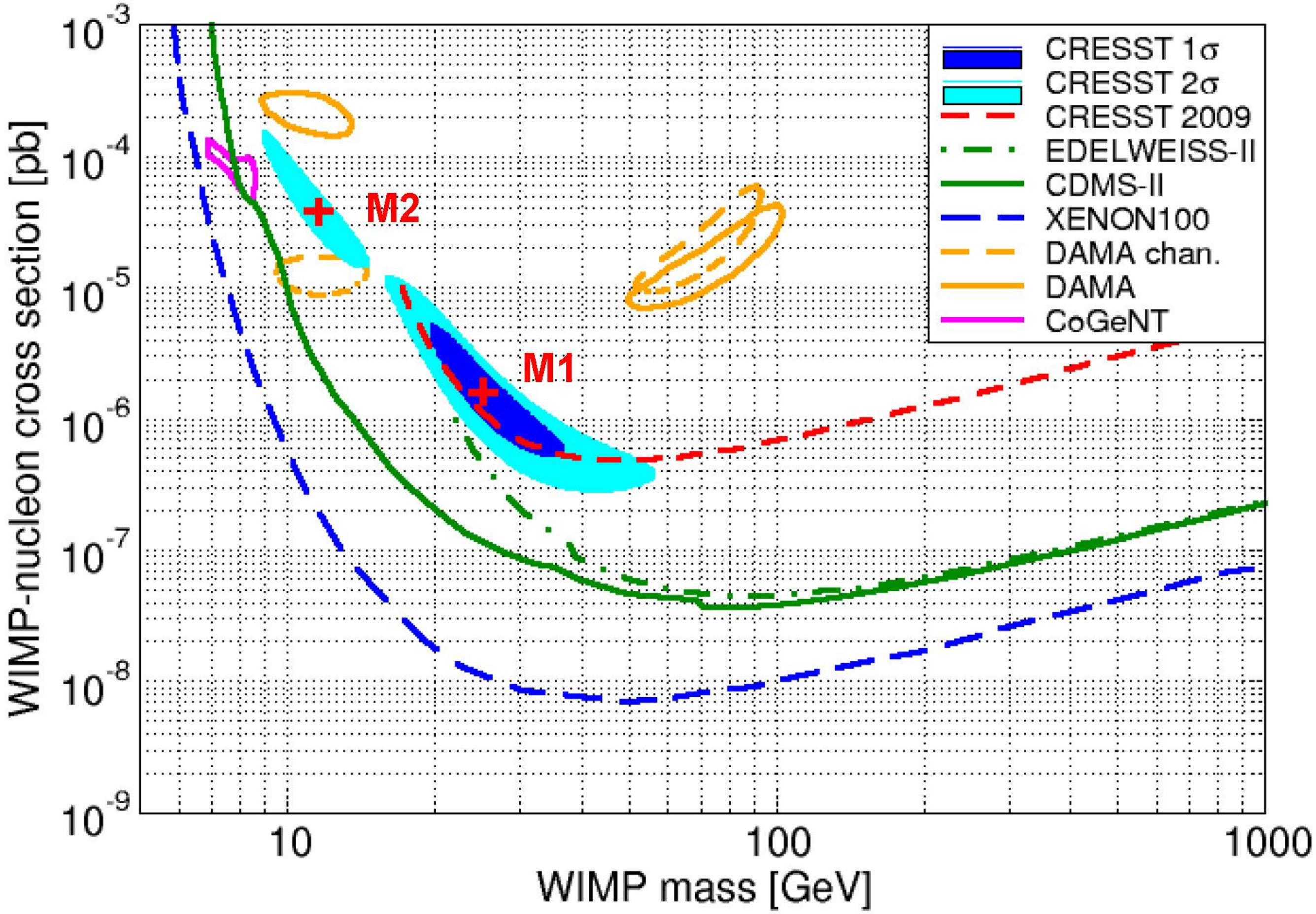
Total number of events should be **67**

	M1	M2
e/γ events	8.00 ± 0.05	8.00 ± 0.05
α events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$ **42**	$18.7^{+4.9}_{-4.7}$ **47.6**
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
	Tot = 71.4!	**Tot = 71.8!**

CRESST. "Signals" at low mass

arXiv 1109.0702

- If it were a signal
  - Incompatible with XENON100 and CDMS
  - Incompatible with "CoGent"
  - Incompatible with DAMA/LIBRA



Summary

- We have considered only one possible type of DM particles, but many other may exist
- Field is progressing quickly
- 1 ton detectors will explore a large fraction of the parameter space
- A discovery will need to be confirmed by a positive signal, annual modulation or directionality. Much larger masses needed
- LHC may give us input next year (positive or negative)
- Progress depends on the experimental ingenuity
- Still small laboratory stile physics
- Have fun
- Be curious
- Be critical