Dark Matter Direct Detection: Mostly cryogenic detectors

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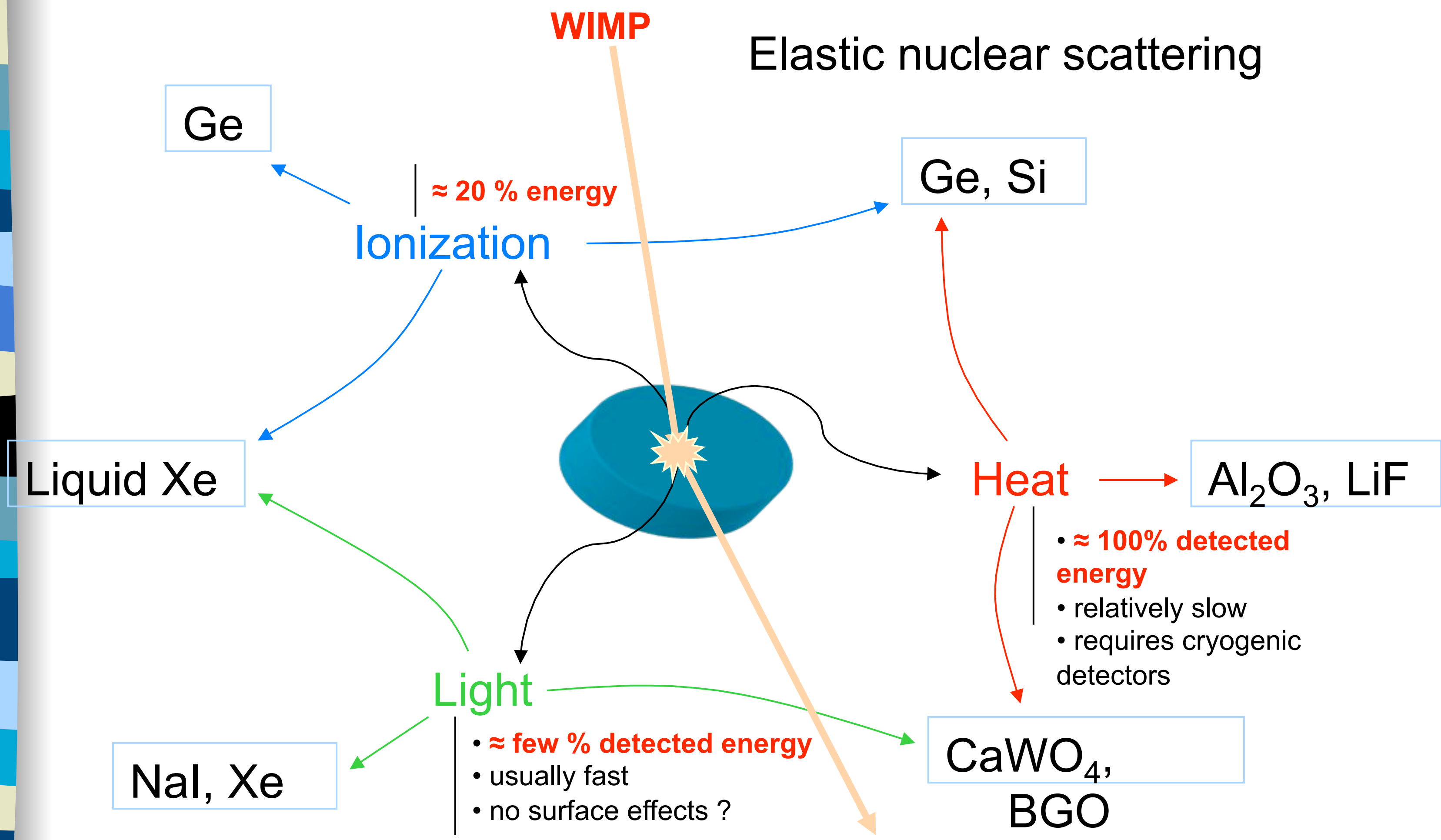
Outline

- Why cryogenic detectors ?
- Sensors and a few examples of detectors
- Charge-phonon detectors
- Light-phonon detectors
- Some other detectors
- Conclusions and prospects

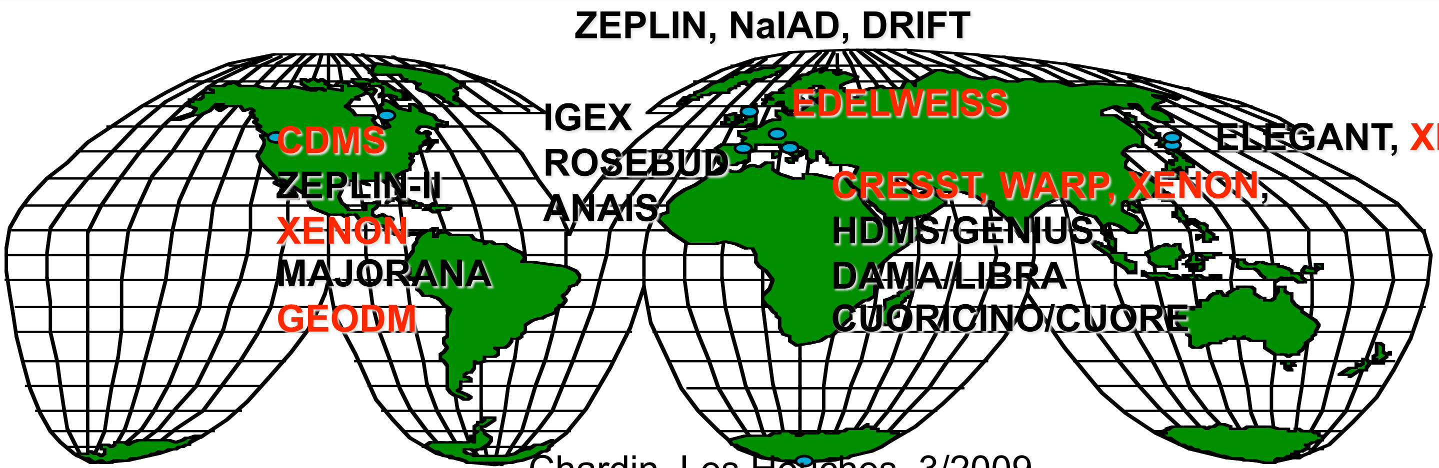
after Drukier and Stodolsky, PRD 30 (1984) 2295

Direct detection techniques



Wimps direct detection experiments

- CDMS-II @ Soudan Mine
- EDELWEISS-II (cryo Ge @ Fréjus)
- CRESST-II (cryo $CaWO_4$, $ZnW0_4$) @ Gran Sasso
- ROSEBUD (cryo Al203, CaWO4) @ Canfranc
- XENON-10, XENON-100, ZEPLIN, DRIFT, NaIAD
- WARP, ArDM (liquid argon)
- DAMA/LIBRA (NaI, Xe @ Gran Sasso)
- IGEX @ Canfranc, HDMS/GENIUS-TF (Ge) @ Gran Sasso
- CUORICINO/ CUORE ($Te0_2$) @ Gran Sasso
- SIMPLE, MACHe3, ORPHEUS (Bern)
- ELEGANT, LiF @Japan
- + Future experiments: SuperCDMS/GEODM, EURECA , XENON-1ton, XMASS, …



Initial motivations

- Heat capacity varies as T^3 (dielectric materials), or as T (metal)

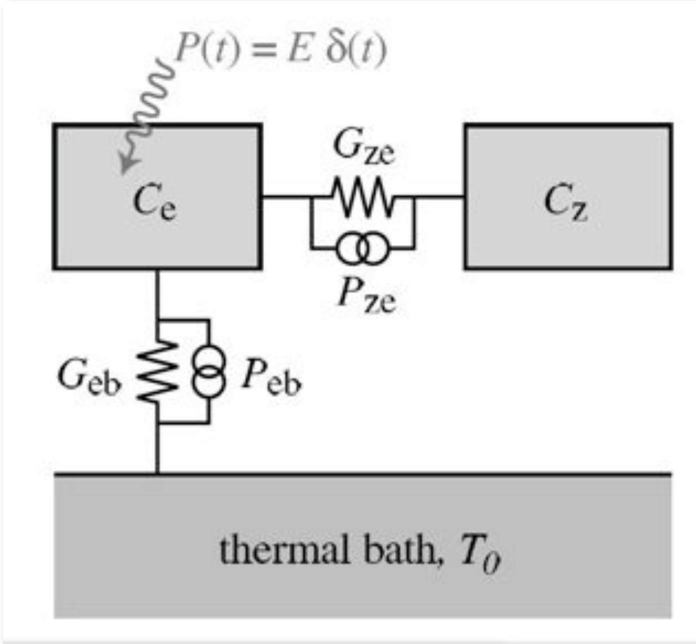
- Sensitivity to a given ΔE better at low T
- Phonons meV or less : intrinsic resolution in principle excellent

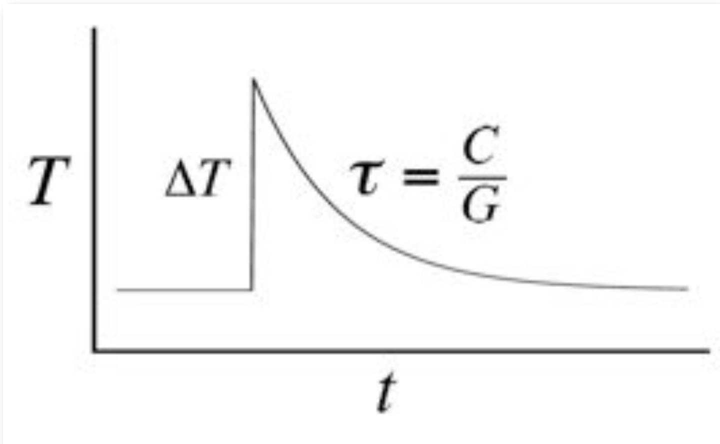
$$\delta E_0 = 2.35\sqrt{\epsilon F E_0}$$

- Also, possibility to combine heat (phonon) measurement to light or charge for scintillating and semiconductor materials

Detector principle

- 1- Energy input in detector absorber
- 2- Coupling between absorber and sensor (NTD, TES, MMC, …)
- 3- Slow recovery by weak coupling to thermal bath





Pioneering microcalorimeters

- From: S.H. Moseley, J.C. Mather, D. McCammon, J. Appl. Phys. 56 (1984) 1257 to the XQC array
- N. Coron, et al., Nature 314 (1985) 75

0.5 mg diamond composite bolometer

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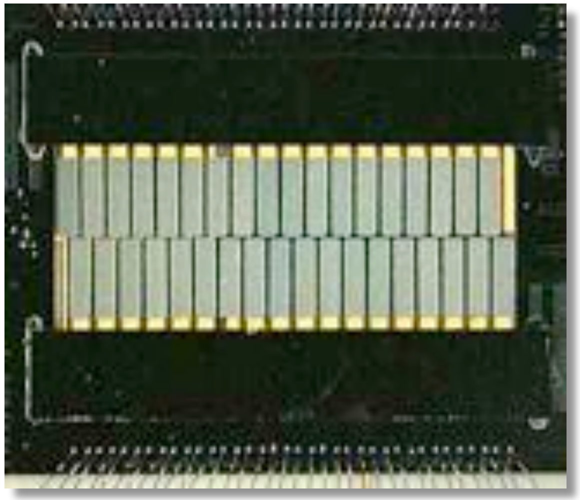
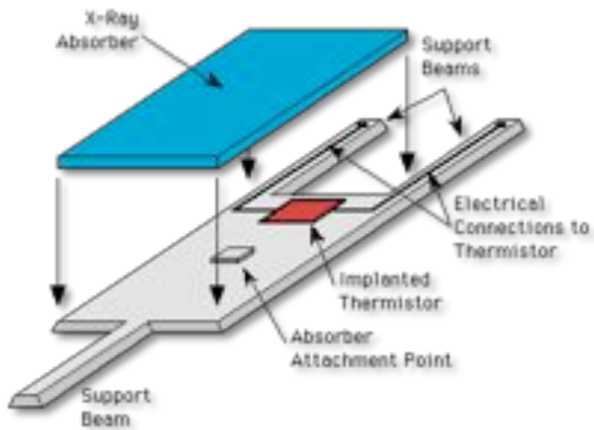




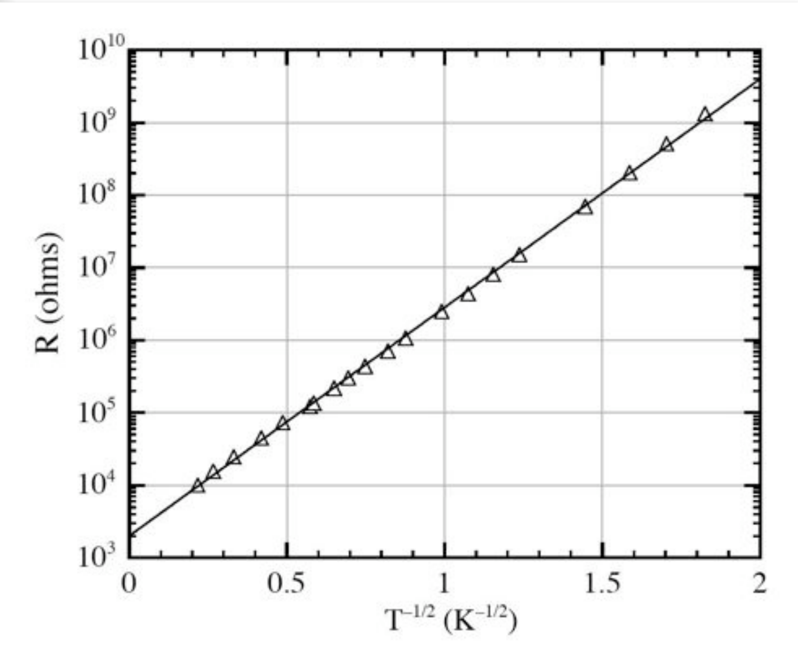
XQC array (end 90’s)

Sensors: MIT

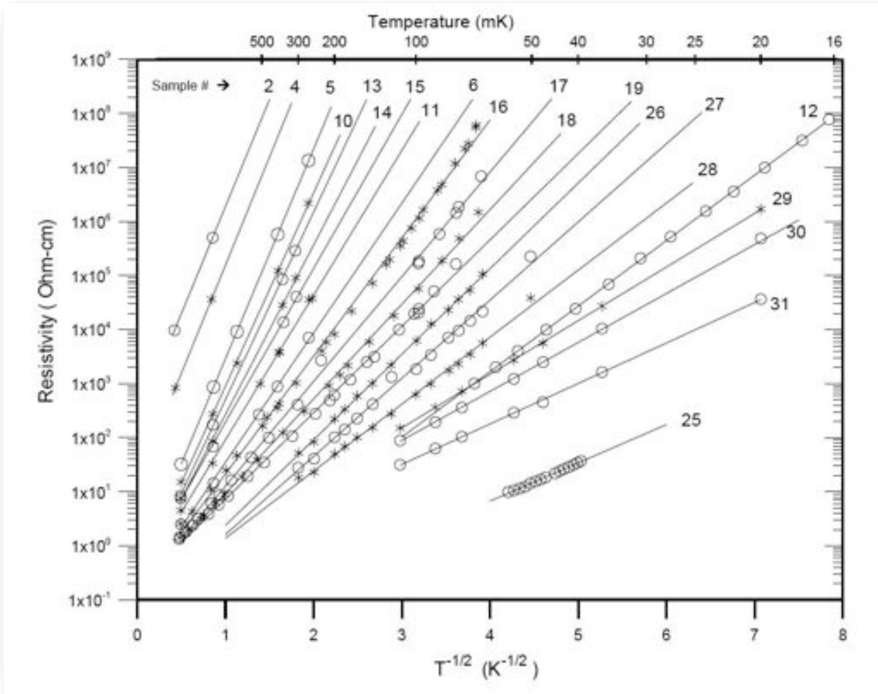
- Metal-Insulator Transition (MIT)
  - Implanted Si (ion implant)
  - Neutron Transmuted Doped (NTD) Ge
  - Amorphous thin film sensors (e.g. $Nb_xSi_{(1-x)}$, or $Y_xSi_{(1-x)}$)
- Excellent thermistors, usually used in MΩ to GΩ range
- Predictibility of impedance initially difficult (produce several batches) for ion implant (also for NTD)
- Homogeneity critical
- High temperature diffusion: much better homogeneity for implanted Si (limitation: few µm thick)

Sensors: MIT (Metal-Insulator Transition)

- Adjustable MΩ to GΩ impedance
- Usually several batches produced
- Variable range hopping (Mott, Efros, Shklovskii)



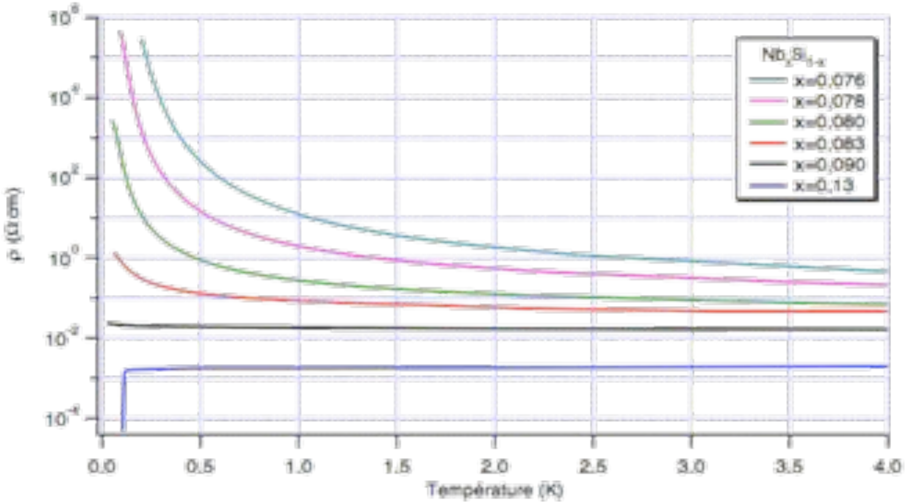
Ion implanted Si impedance scaling (McCammon et al.)

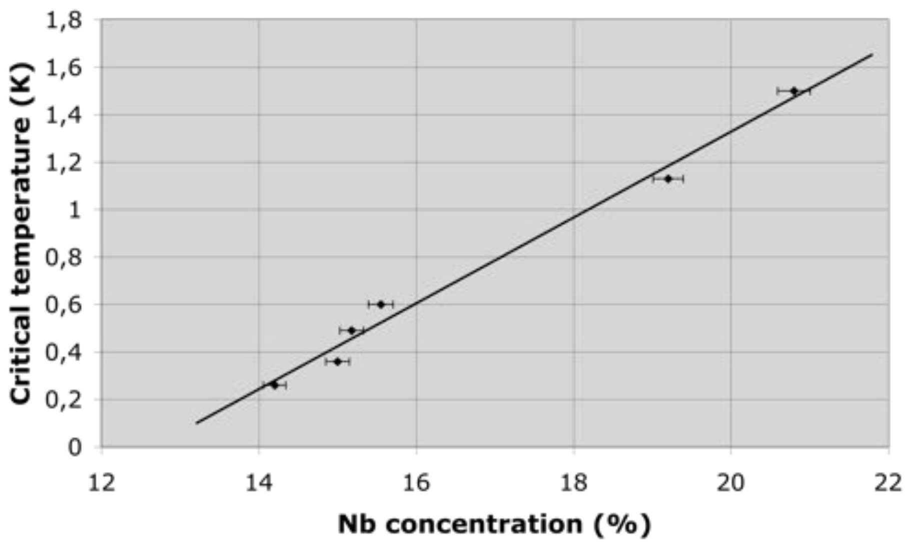


Various batches of NTDs (Beeman and Haller)

Nb-Si alloy

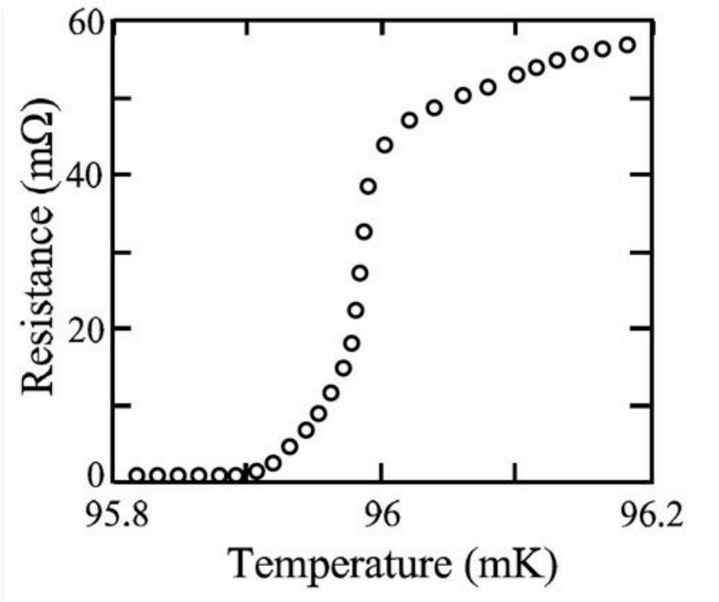
- Co-evaporation made at CSNSM (Orsay)
- Nb < 9%: semiconducting
  - Anderson insulator
  - High electron-phonon thermal coupling
  - 1/f noise
- Nb > 9%: superconducting
  - Tc depends on Nb concentration

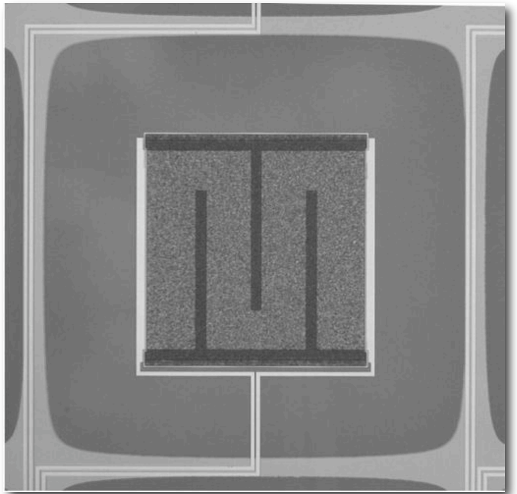


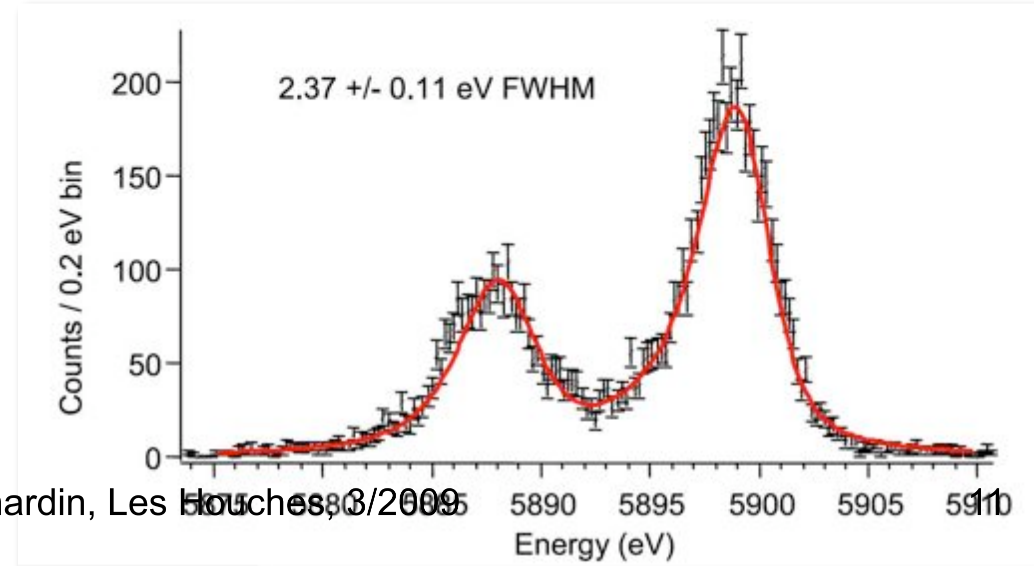


Transition edge sensors

- Principle
- α = R/T dR/dT can be >> 1000 !
- Single pixel example
- Oustanding energy resolution

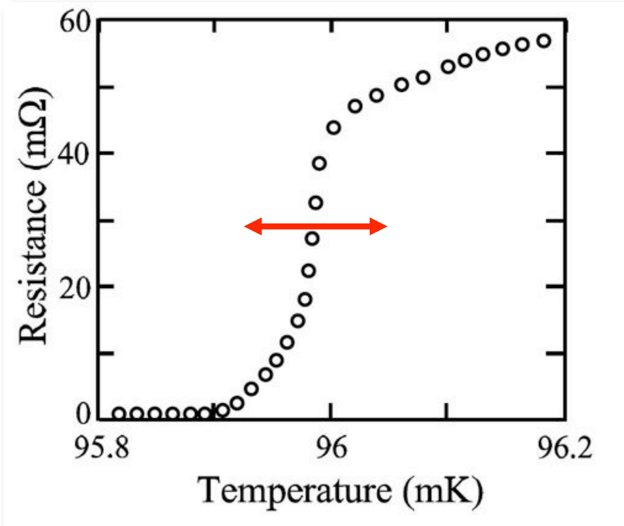




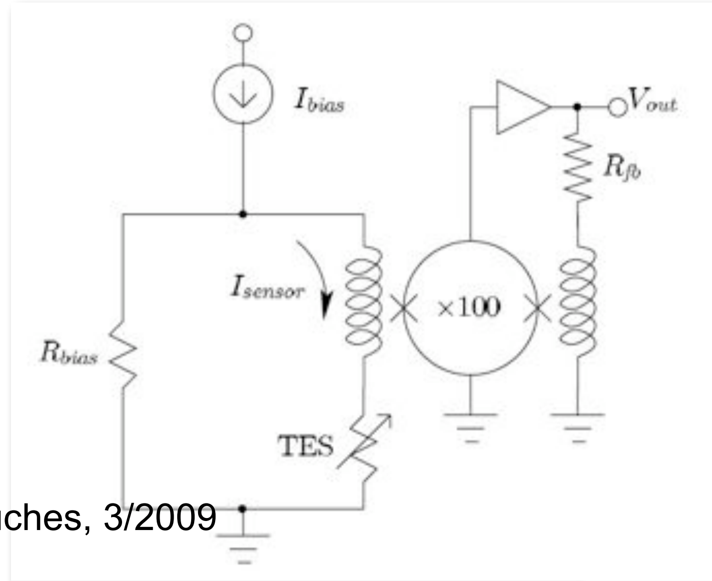


Sensors: Transition edge (TES)

- Initial problems:
  - Reproducibility of T_c
  - Adjustment by magnetic impurity implantation (Fe), but tedious
  - Instability when current biased
- Solution to most of these points: negative electro-thermal feedback (ETF)
- Let the sensor self-bias with low T thermal bath
- Adjust regulation power to keep sensor at same impedance
- Signal = - Regulation power

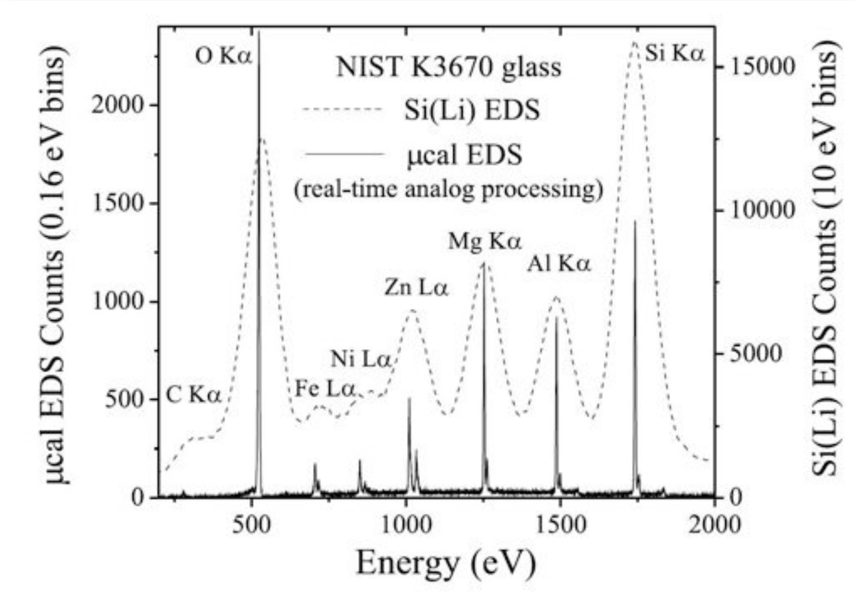


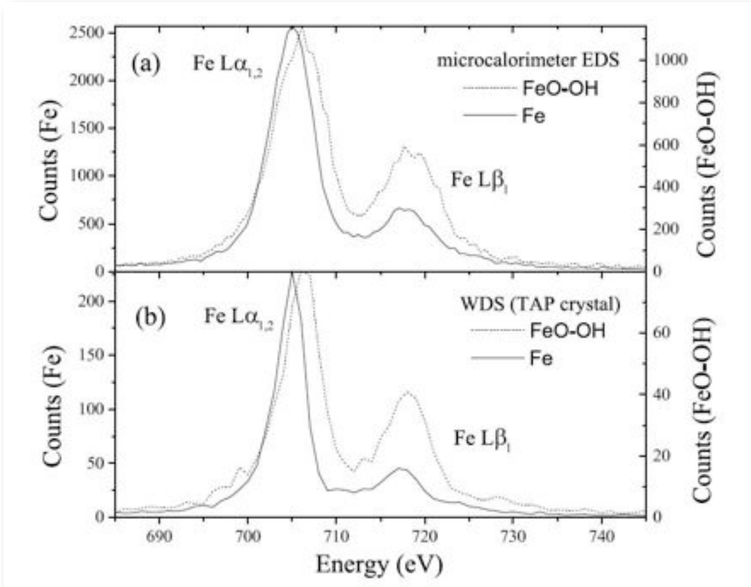
After Irwin et al. (2005)



Sensors: Transition edge (TES)

- Oustanding energy resolution
- Comparison with best silicon detectors
- Performances similar to WDS (wavelength dispersive)
- Ability to detect environmental effects



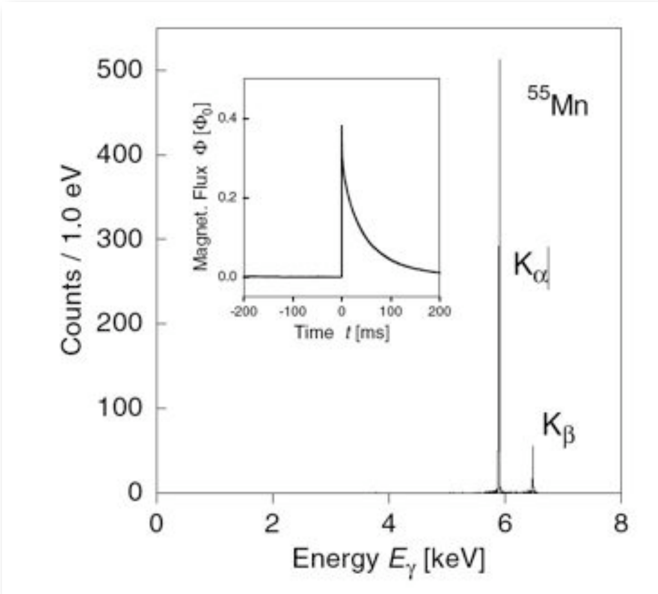


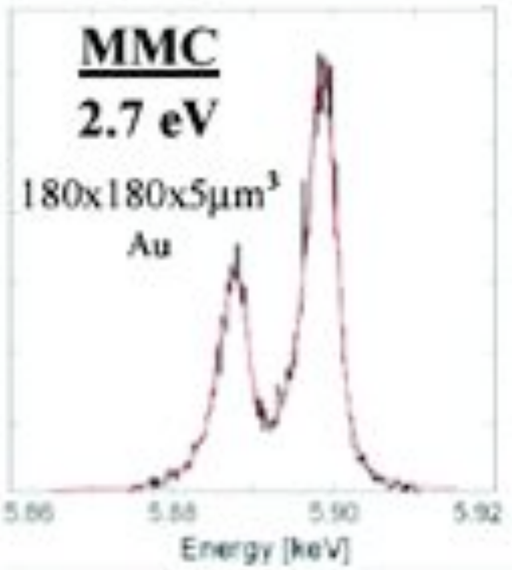
Metallic Magnetic Calorimeters

- Paramagnetic sample in relatively low B (≈ few mT)
- Initial attempts (Bühler and Umlauf) used 4f ions embedded in dielectrics: nice energy resolution, but rather slow detectors
- In 1993, Bandler et al. proposed to embed paramagnetic ions in metals: much faster response (≈ 10^{-7} s)
- Excellent energy resolution (≈ 3 eV @ 6 keV)
- At present, most studied system Au:Er
- Perspectives of further improvements in energy resolution

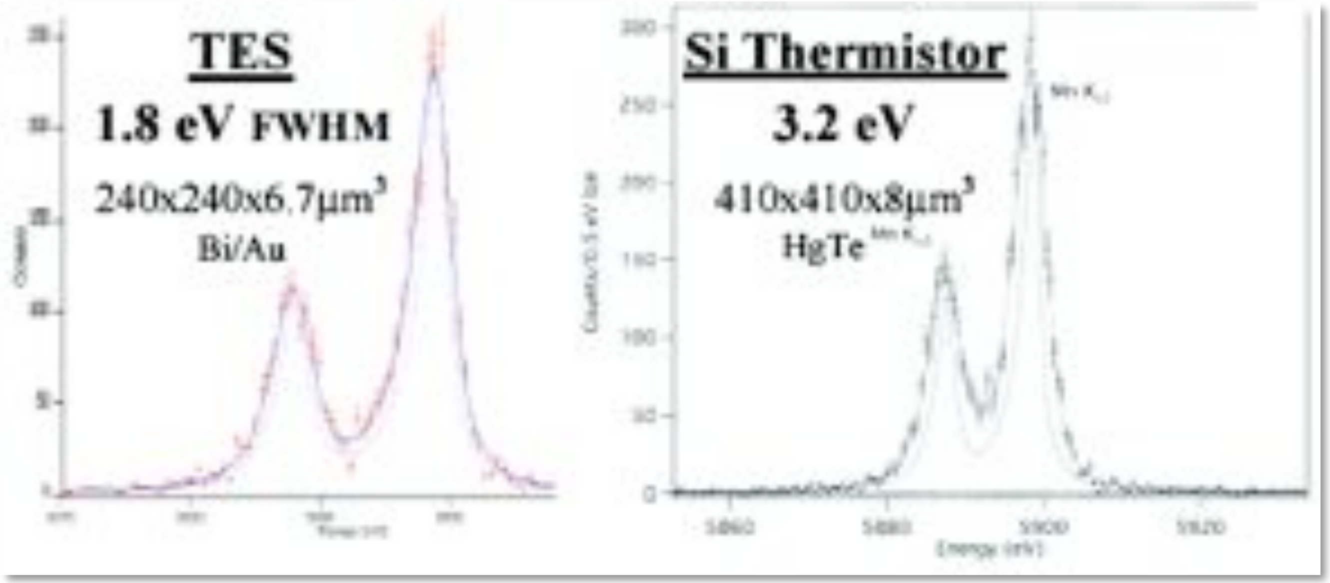
Metallic Magnetic Calorimeters

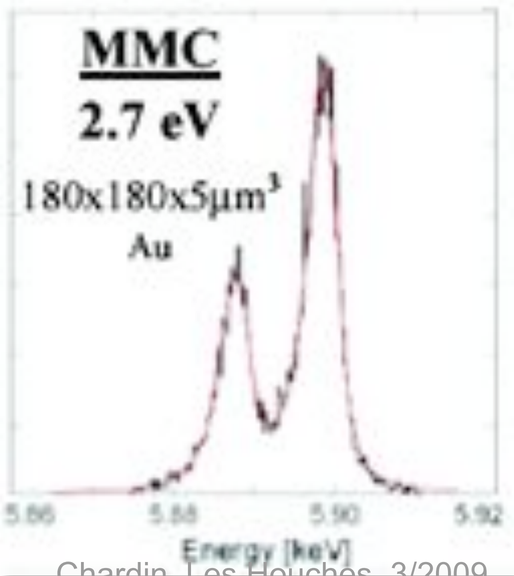
- Excellent energy resolution (≈ 3 eV @ 6 keV)
- Comparable to TES resolution
- Already some applications





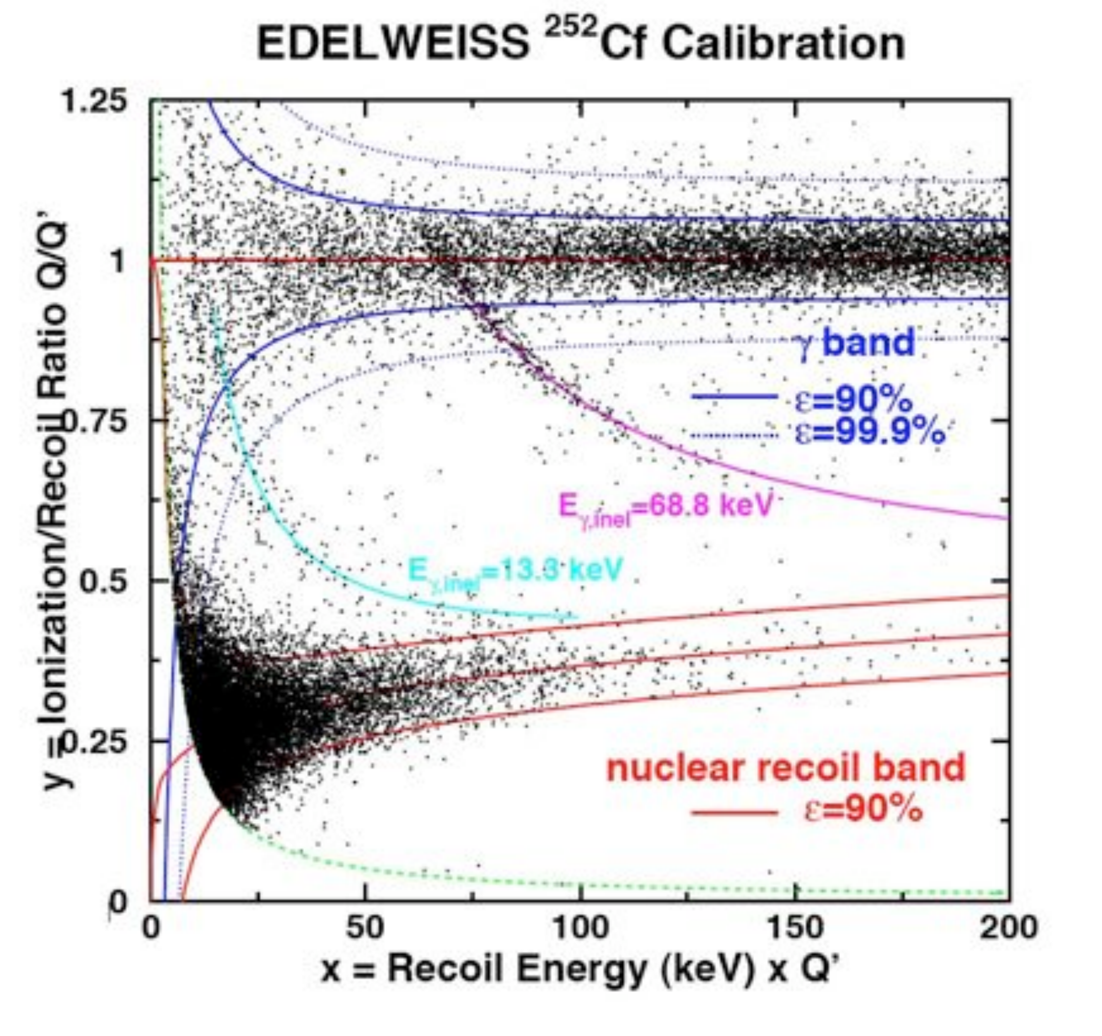
Best present performances of Single Pixel Microcalorimeters





Edelweiss experiment

O. Martineau et al., astro-ph/0310657/

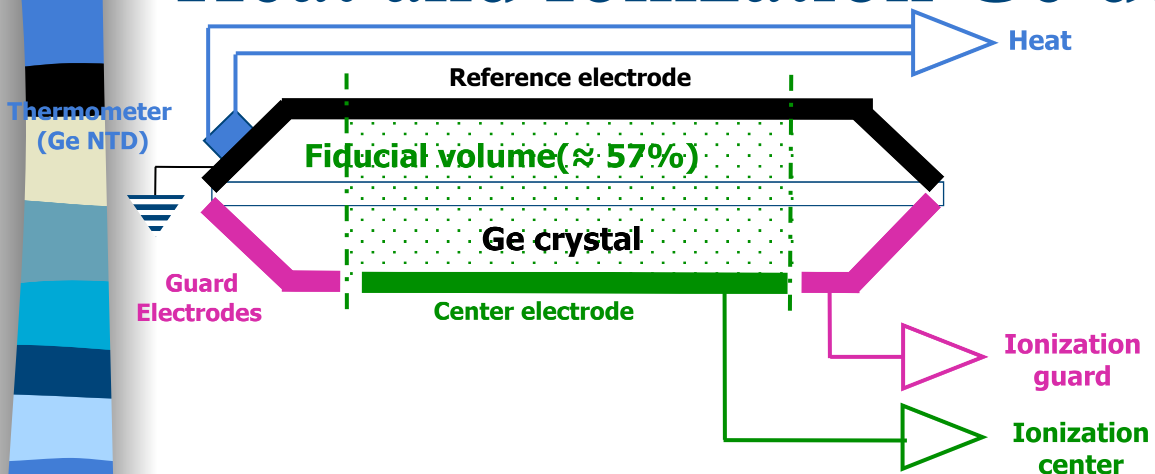


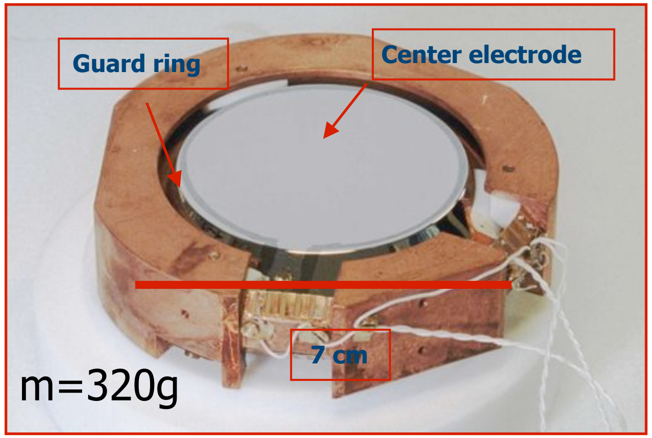
Neutron + gamma calibration

Nuclear recoil discrimination down to 20 keV threshold :

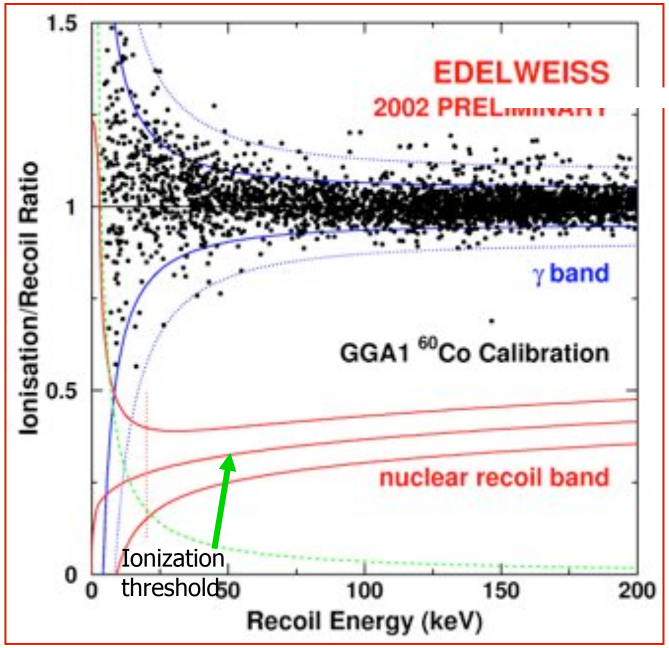
γ-ray rejection > 99.99 %

Heat and Ionization Ge detectors



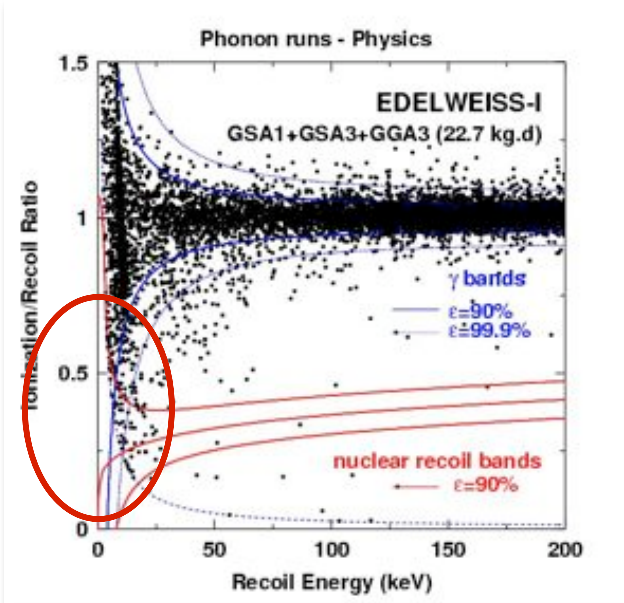


- Simultaneous measurement of
  - Heat @ 17 mK with Ge/NTD sensor
  - Ionization @ few V/cm with Al electrodes
- Different charge/heat ratio for nuclear and electron recoils (WIMP and neutron have lower charge than γs, βs)
- Discrimination event-by-event of electron recoils (main background)
  - E_I/E_R = 0.3 for nuclear recoils
  - E_I/E_R = 1 for electronic recoils

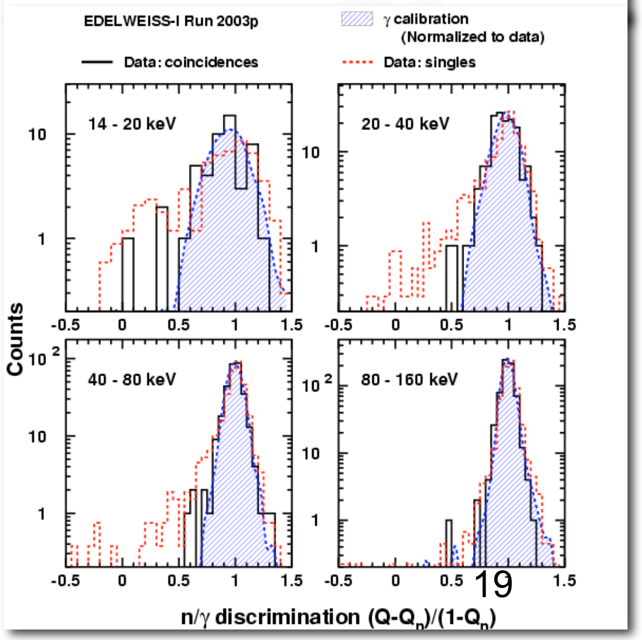


EDELWEISS-I limitations

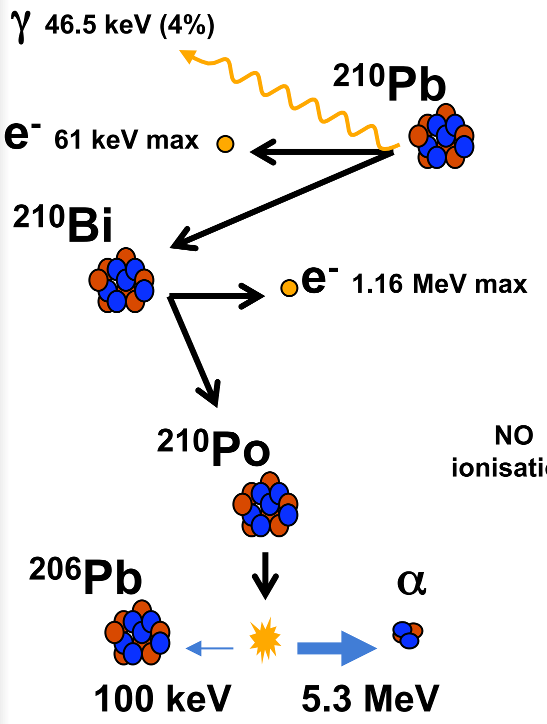
- Several runs between 2000 and 2003
- Last run = data taking with trigger on heat signal
- Improved efficiency at low energy (50 % at 11 keV)
- Stable behavior over 4 months of the detectors
- Fiducial exposure: 22 kg.d
- 18 nuclear recoil candidates > 15 keV

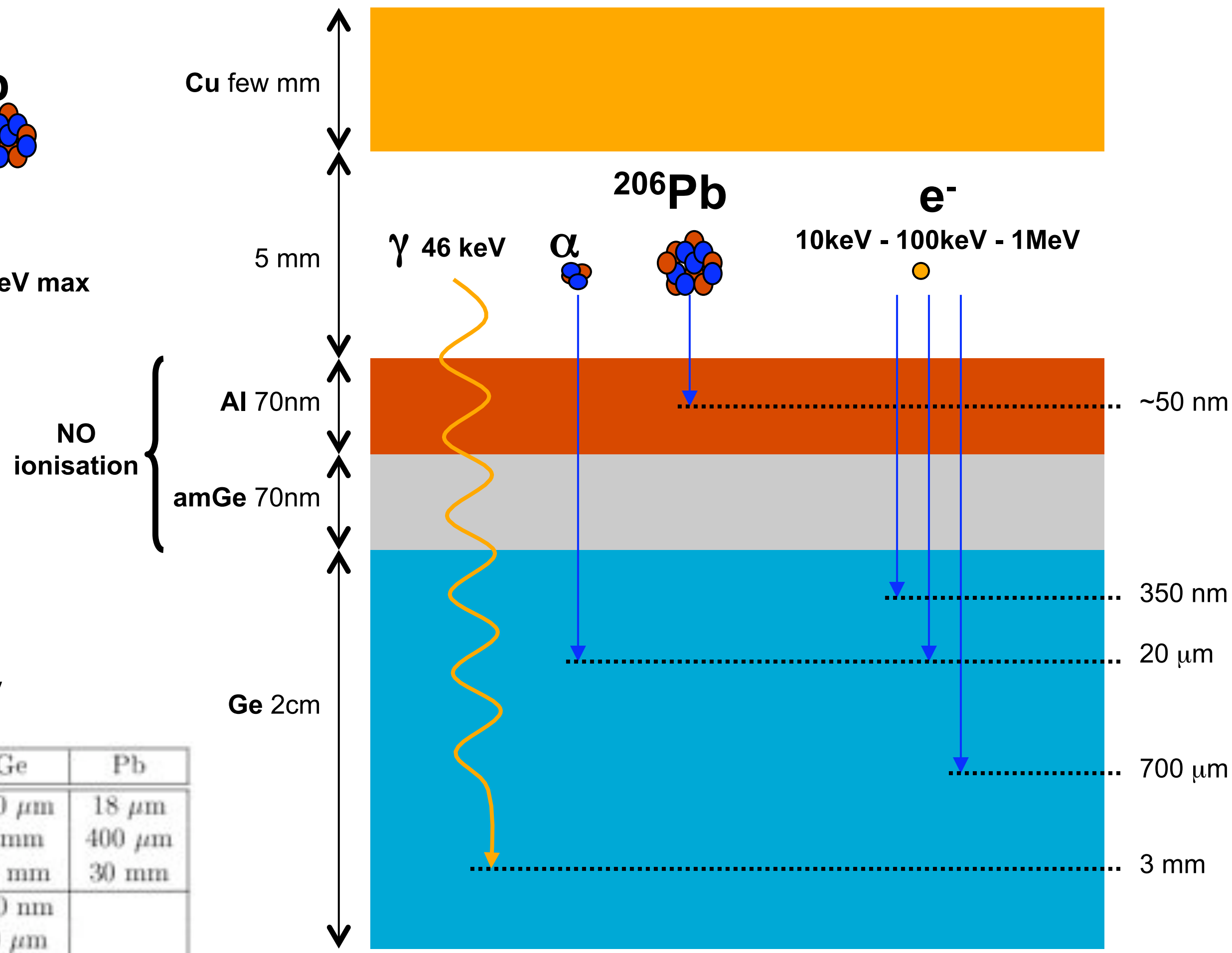


- Possible backgrounds
  - Residual neutron flux
    - 1 n-n coincidence observed
    - 2 single expected by MC
  - Surface electron recoils
    - Miscollected charge events at low energy
    - Leak of events down to the nuclear recoil band not visible in coincidence events
- Further, studies concerning the possible origins for these backgrounds



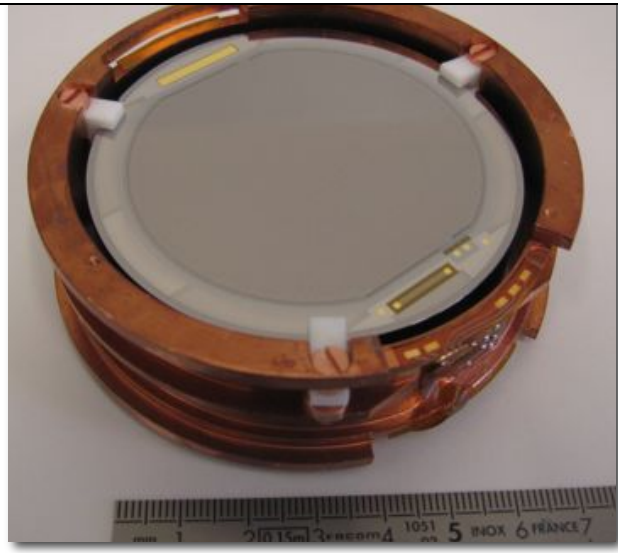
^{210}Pb and Penetration Lengths

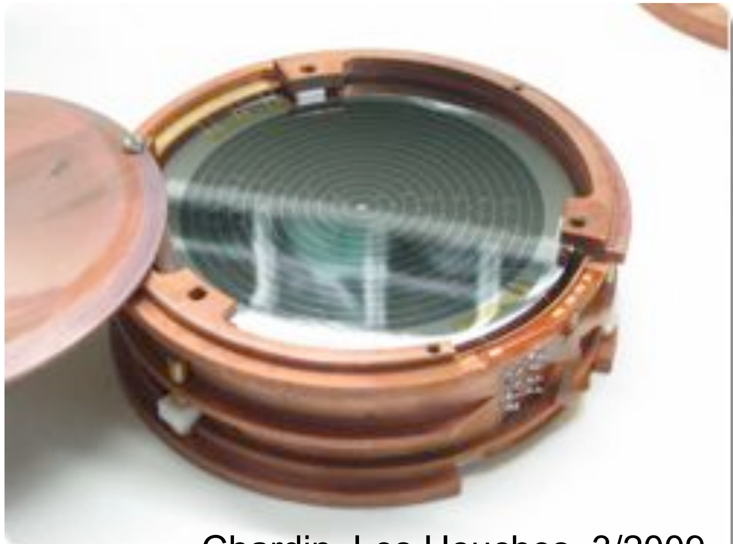




Particule	Energie	Cu	Ge	Pb
Gamma	10 keV	9 μm	170 μm	18 μm
	100 keV	6 mm	8 mm	400 μm
	1 MeV	40 mm	80 mm	30 mm
Electron	10 keV	200 nm	350 nm	
	100 keV	11 μm	20 μm	
	1 MeV	340 μm	700 μm	
Alpha	5.3 MeV	11 μm	19 μm	15 μm
Polonium	100 keV	40 nm	68 nm	

EDELWEISS-II setup in LSM

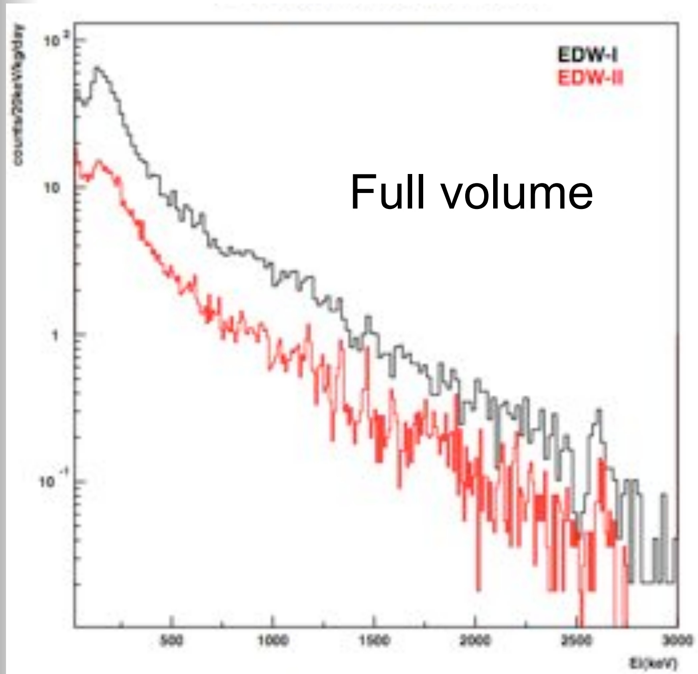




-Bolometric detectors with NbSi with identification and rejection of surface events
-Interdigit detectors with identification and rejection of surface events
- Large number of channels/wires
- Operation in underground site: remote operation of dilution cryostat and helium reliquefier

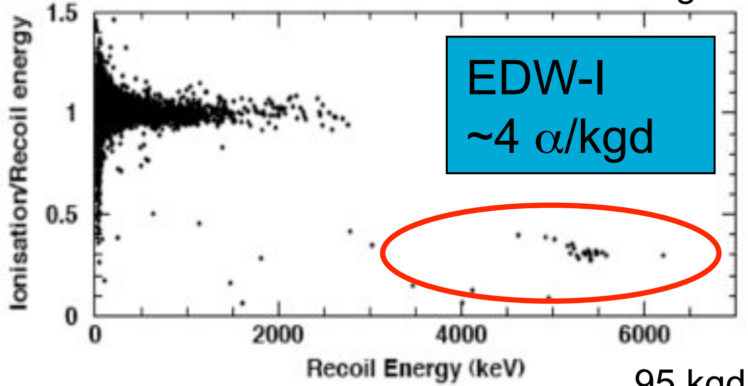
GeNTD data: improved bakgrounds

- Gamma background reduction of x3 relative to EDELWEISS-I
- ^{210}Pb-chain background: reduction of x2 relative to EDELWEISS-I

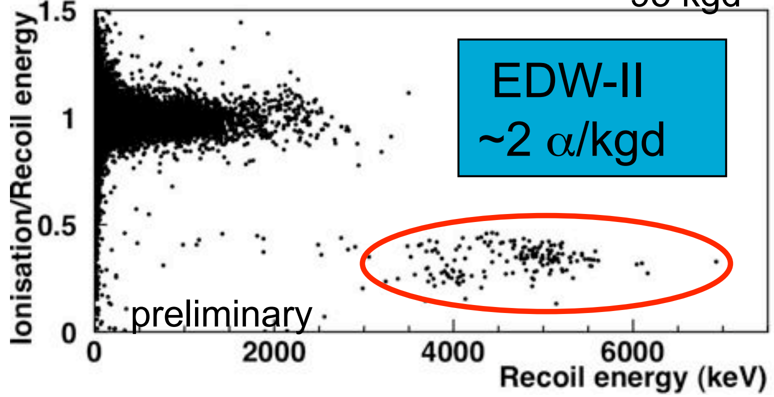


Further bkg reductions after fiducial + coincidence cuts, and in ID

5 kgd

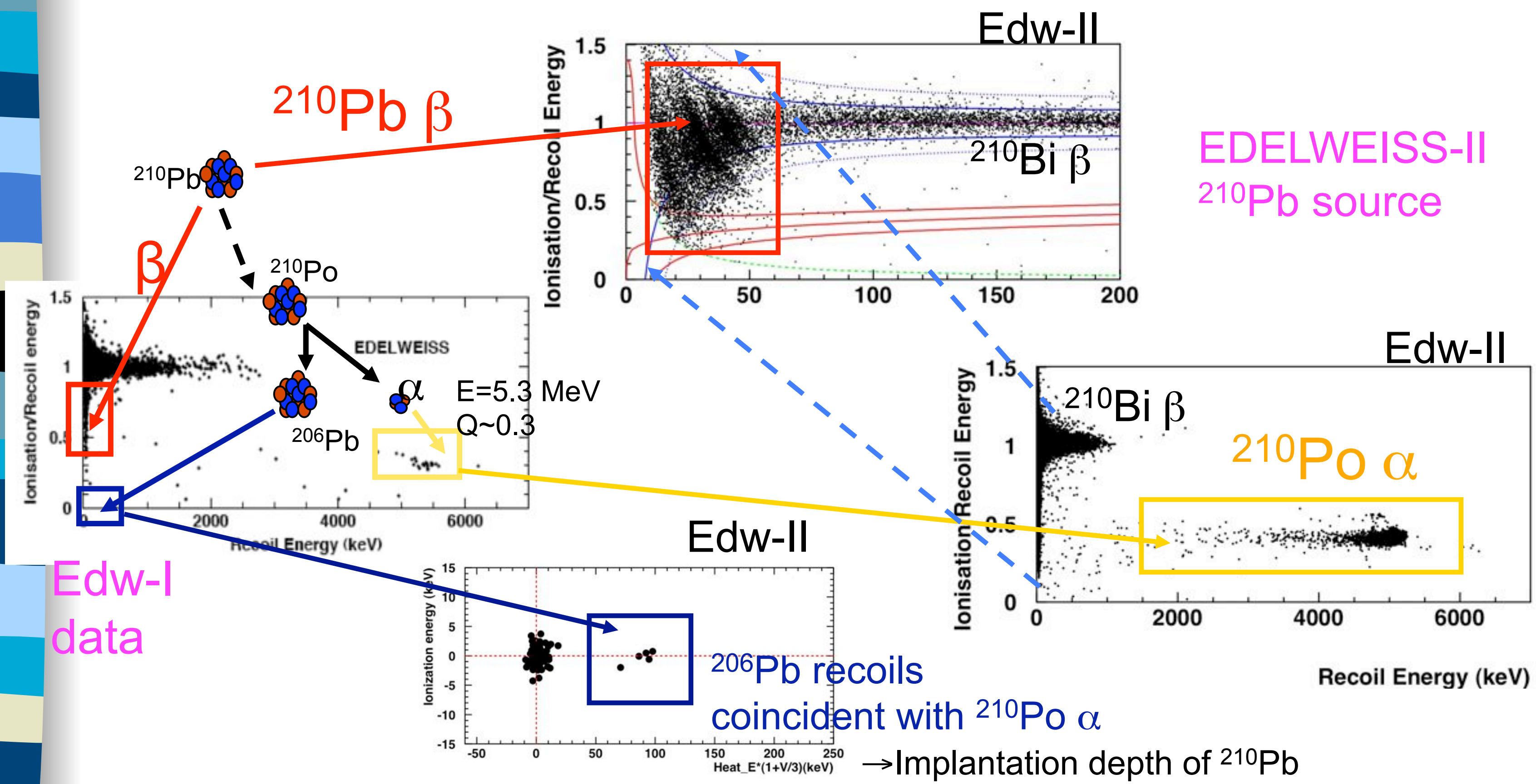


95 kgd



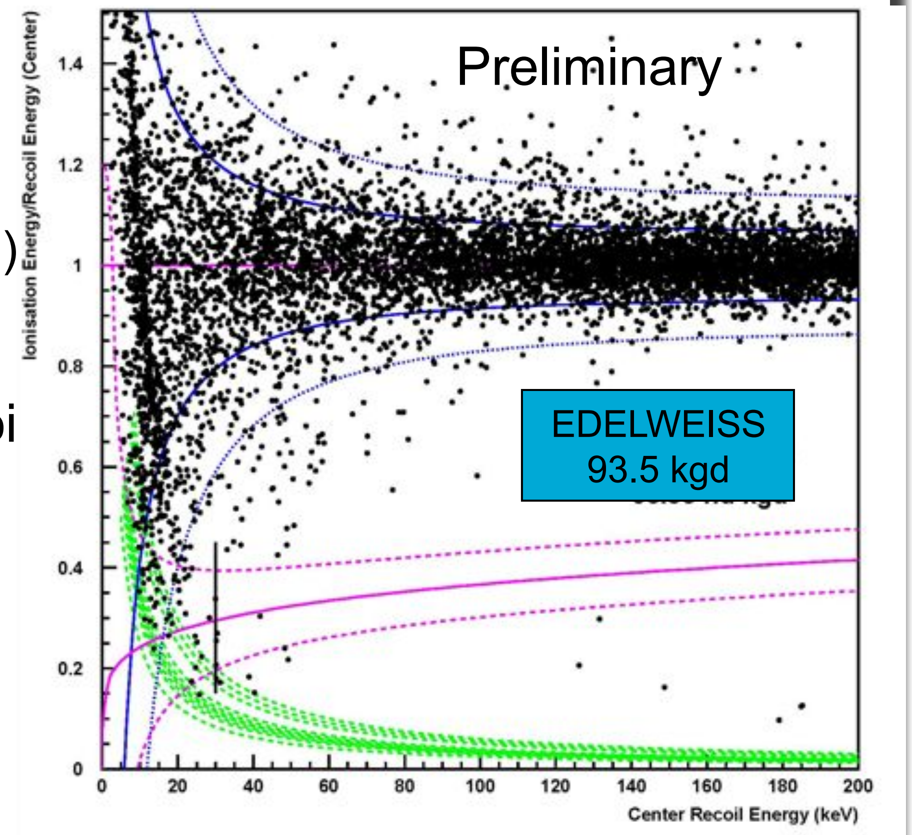
EDELWEISS-II ^{210}Pb source calibration

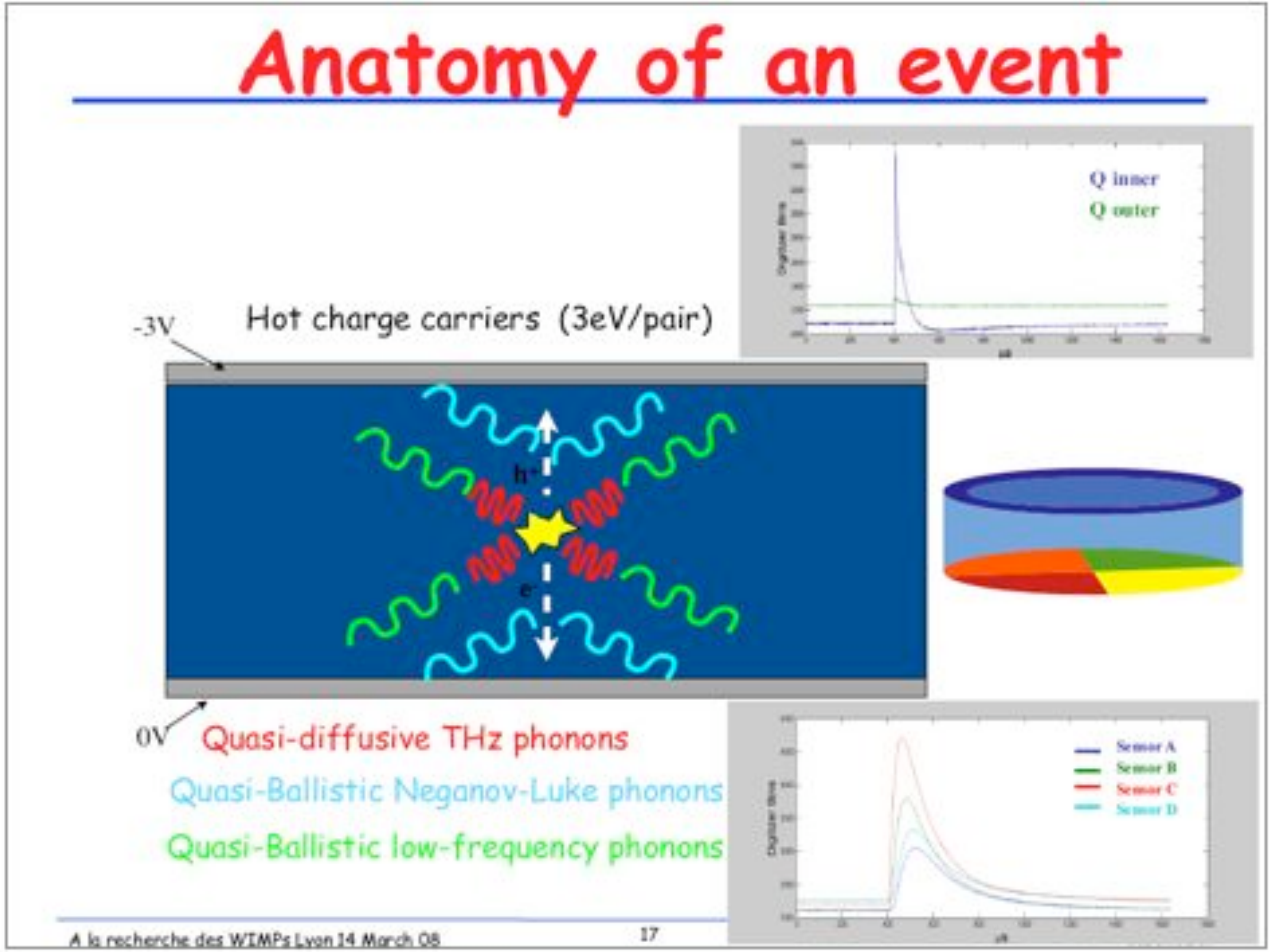
- Confirms interpretation of EDW-I bkg as ^{210}Pb surface β.
- Response of detectors to this important background



Physics run with GeNTD

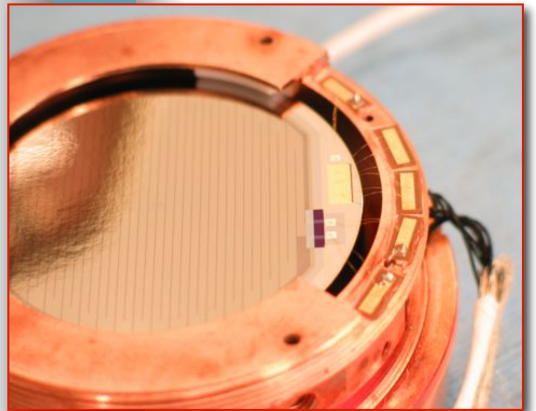
- 11 detectors with <30 keV threshold
  - Threshold chosen before start of run
    (EDW-I results → expected β bkg)
- 93.5 kg.day
- 3 events observed in nuclear recoi band
  - 31, 31 and 42 keV
- Evidence for events with deficient charge collection




Anatomy of an event
Hot charge carriers (3eV/pair)
-3V
0V
Quasi-diffusive THz phonons
Quasi-Ballistic Neganov-Luke phonons
Quasi-Ballistic low-frequency phonons
Q inner
Q outer
Sensor A
Sensor B
Sensor C
Sensor D
A la recherche des WIMPs Lyon 14 March 08
17

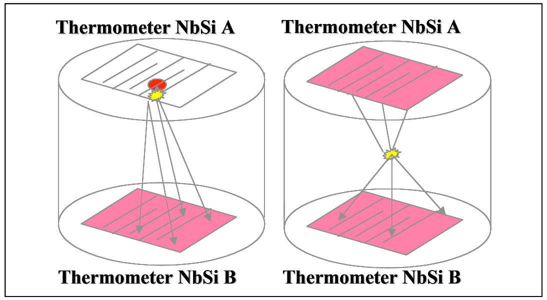
Identification of surface events with Ge/NbSi detector

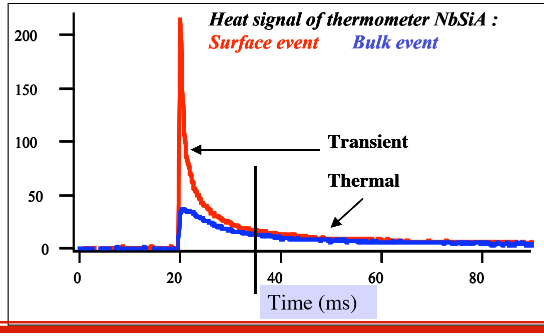
Athermal phonon measurement with NbSi thin film thermometers

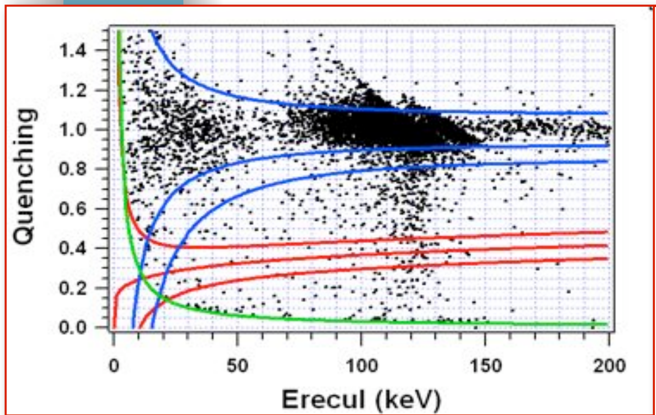


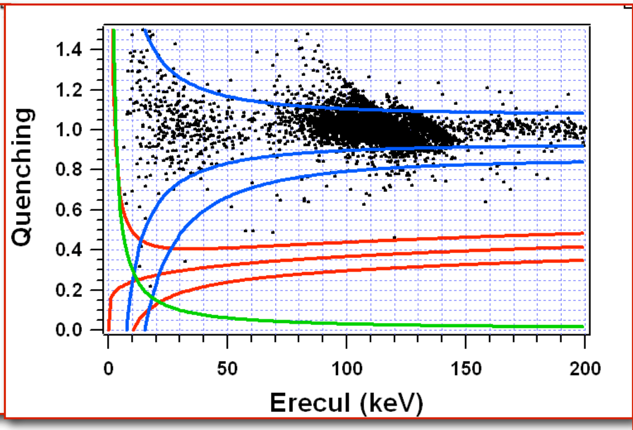
Heat and ionization Ge detectors

- Each signal = thermal + athermal component
- For surface events, athermal higher in NbSia
- Thermal signals proportionnal to the deposited energy







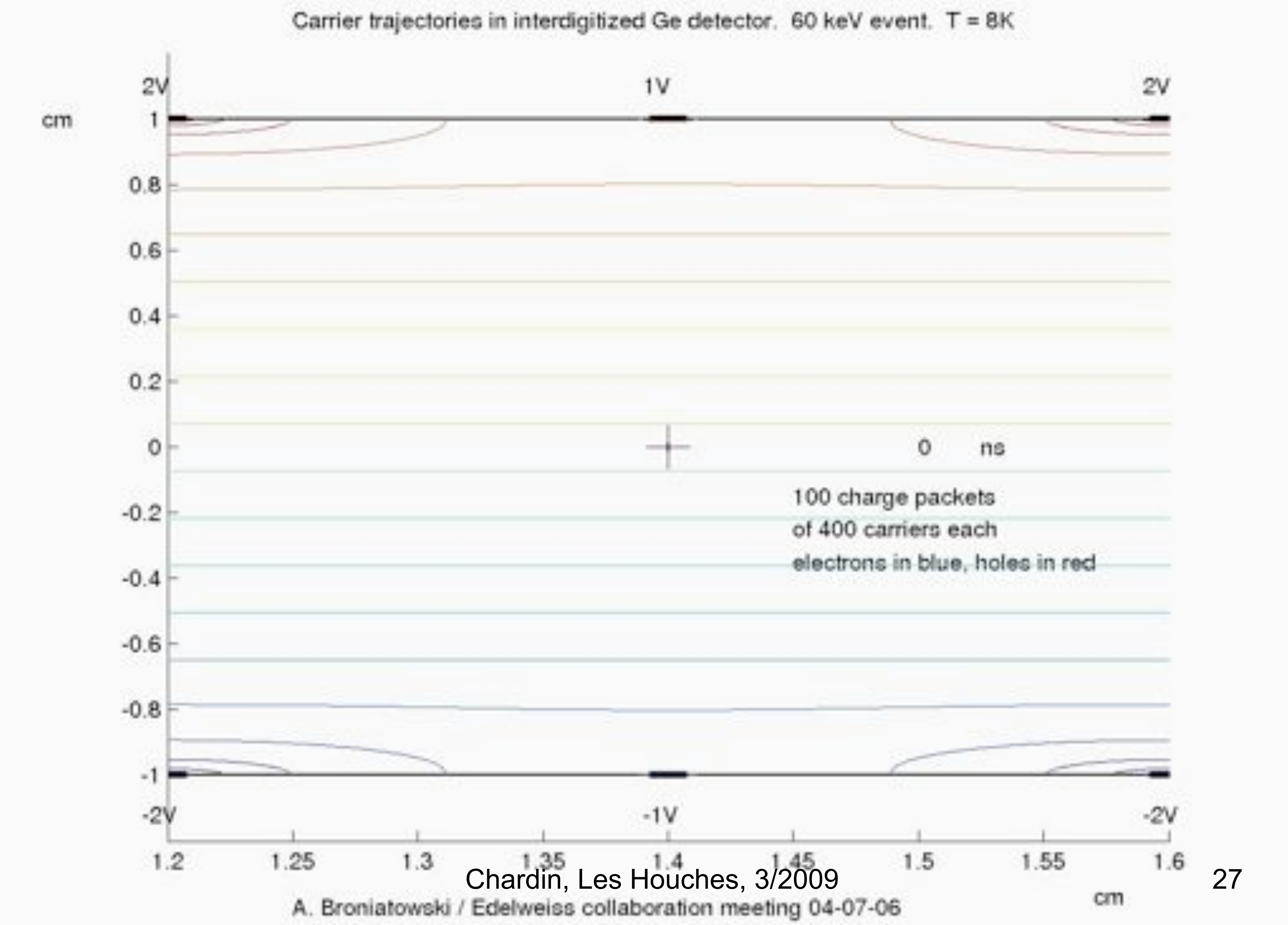


Before rejection

After rejection (1mm cut)

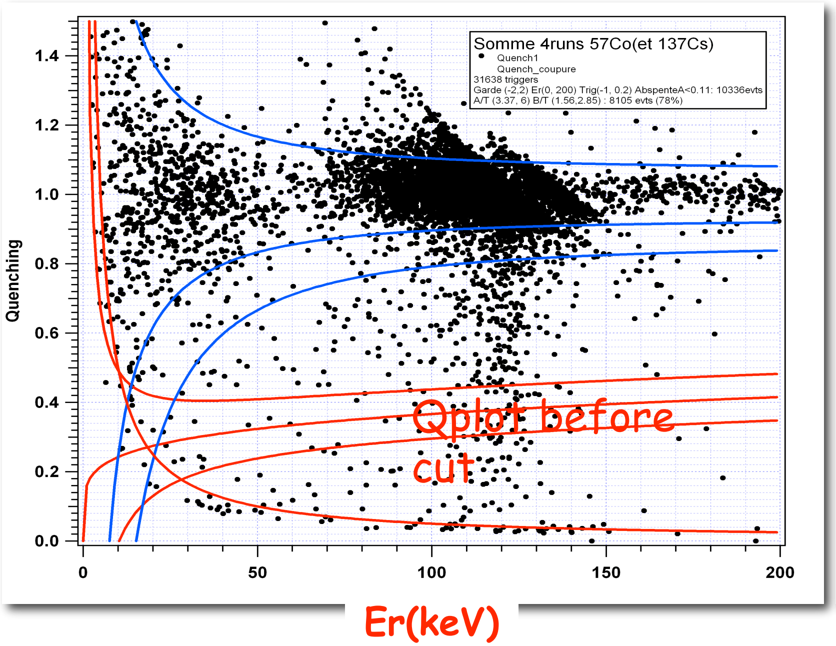
- Tests with 200g prototype in EDELWEISS-I
- Improvement of a factor 20 of the rejection
- Fiducial volume reduction of 10 %

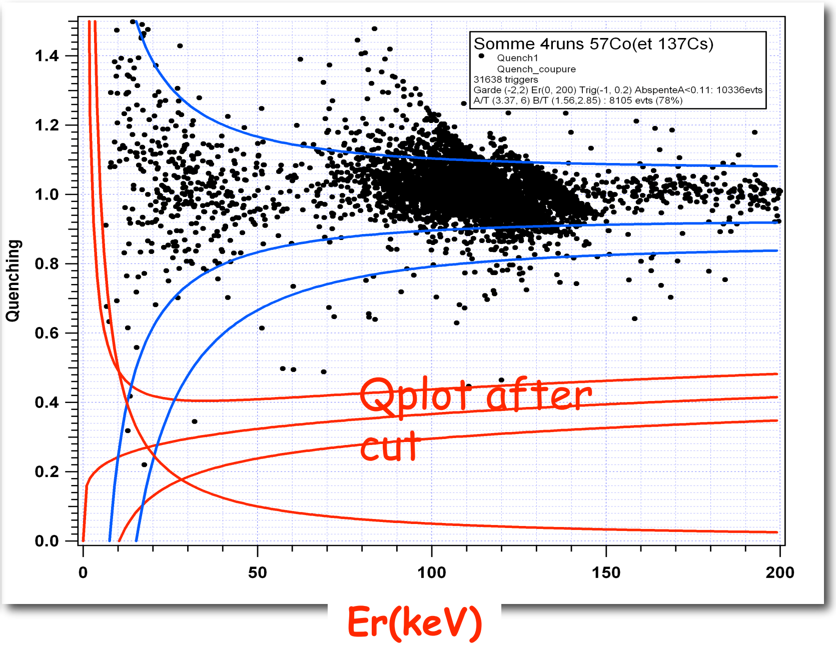
Simulation of InterDigit Detector

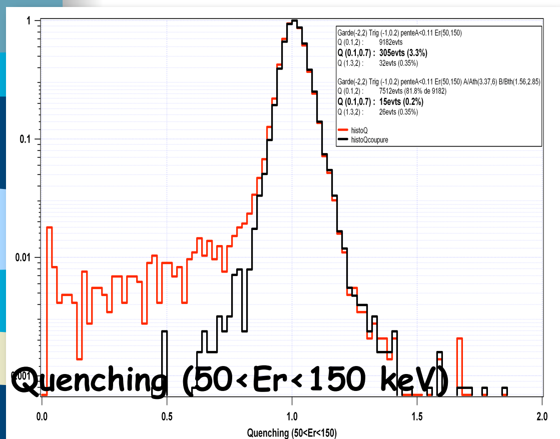


Identification of surface events with Ge/NbSi detector

Quenching





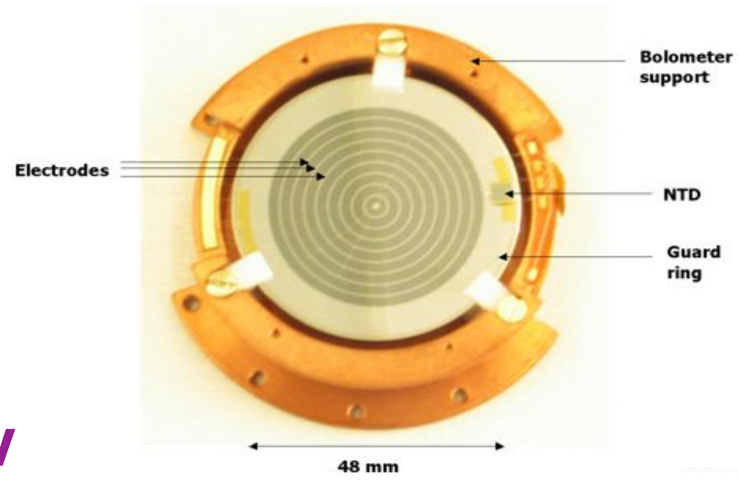


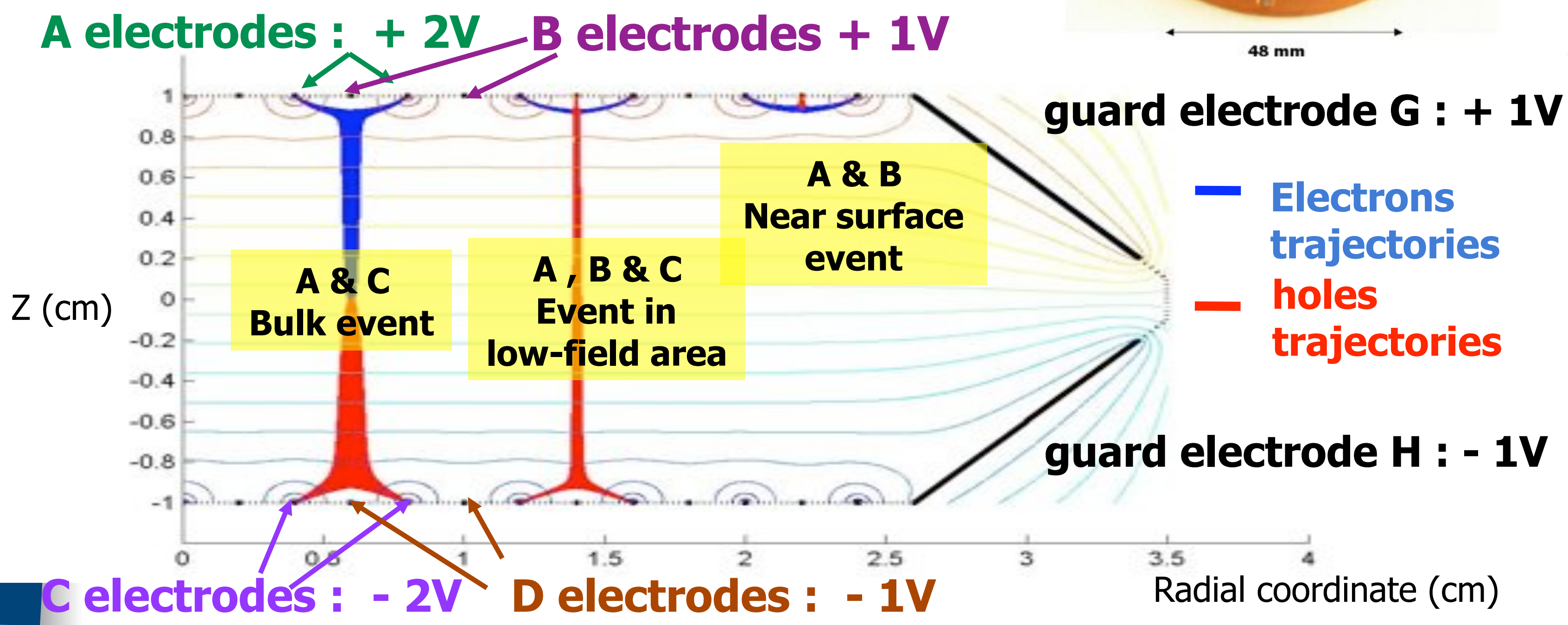
- **95% of the uncomplete collection events are rejected**
(20% of the total events) for a fiducial volume of 90%
- **Similar results on physics data taking**

- **7 optimized (size and resolution) 400 g Ge/NbSi detectors in EDELWEISS-II**

EDELWEISS: InterDigit Detectors

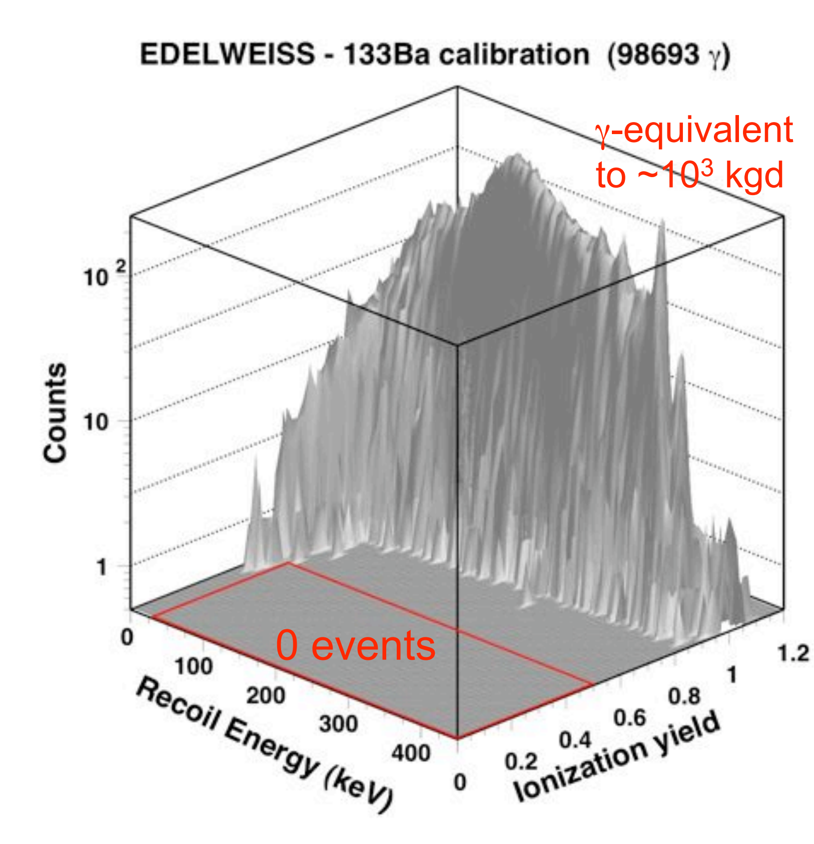
- GeNTD heat sensor
- E-field modified near surface with interleaved electrodes
- B + D signals = vetos against surface events
- 1x200g and 3x400g tested in 2008
- 10x400 g in operation in 2009



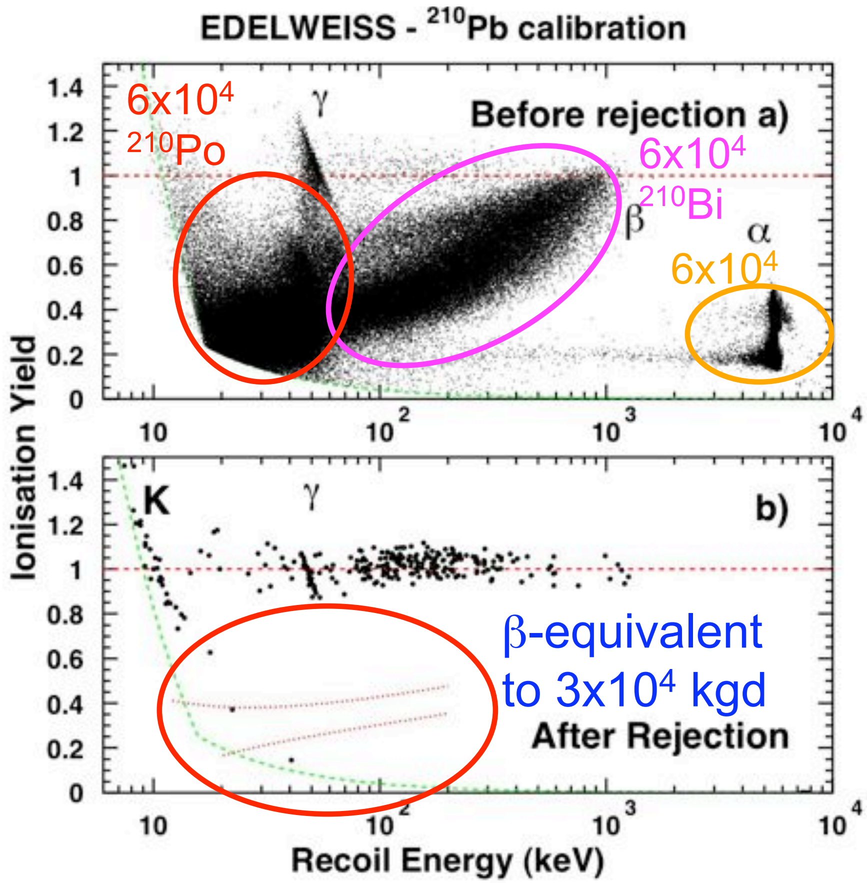


ID detector rejection

- Gamma rejection of 400g
  - ~1 month calibrations



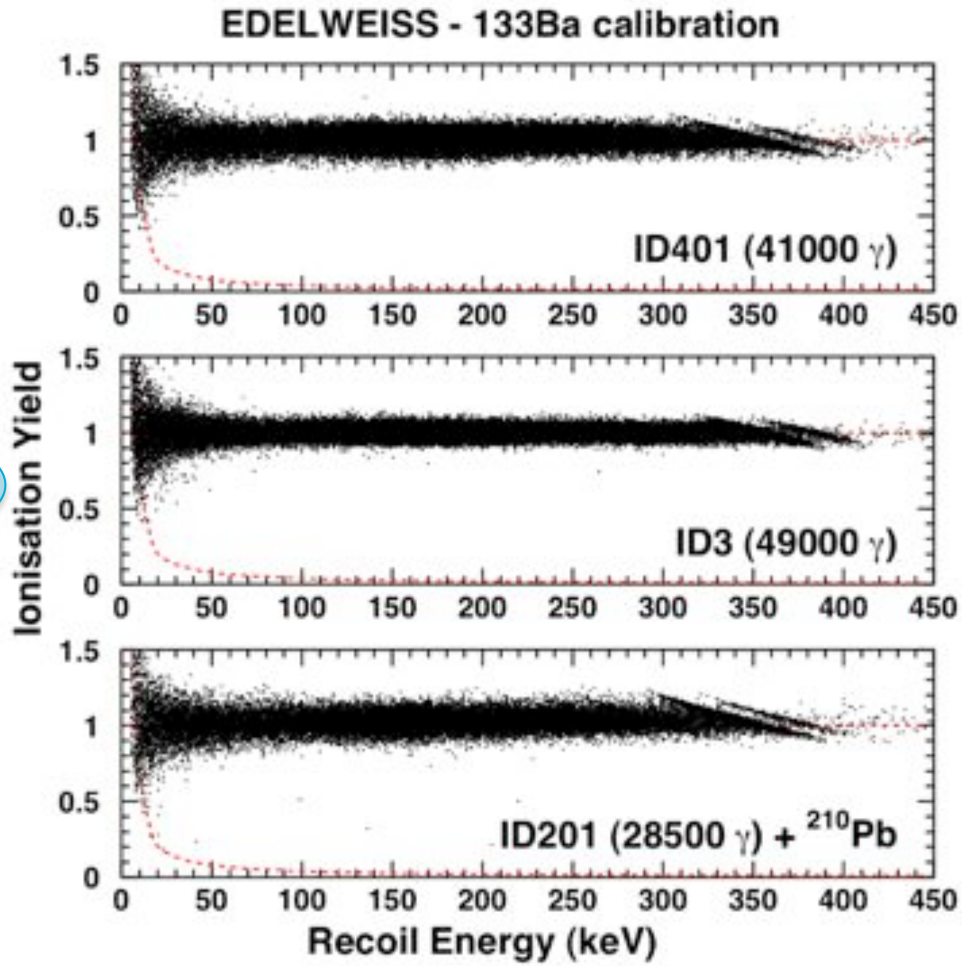
- ^{210}Pb β rejection of 200g



Check of course that γ-ray rejection still excellent

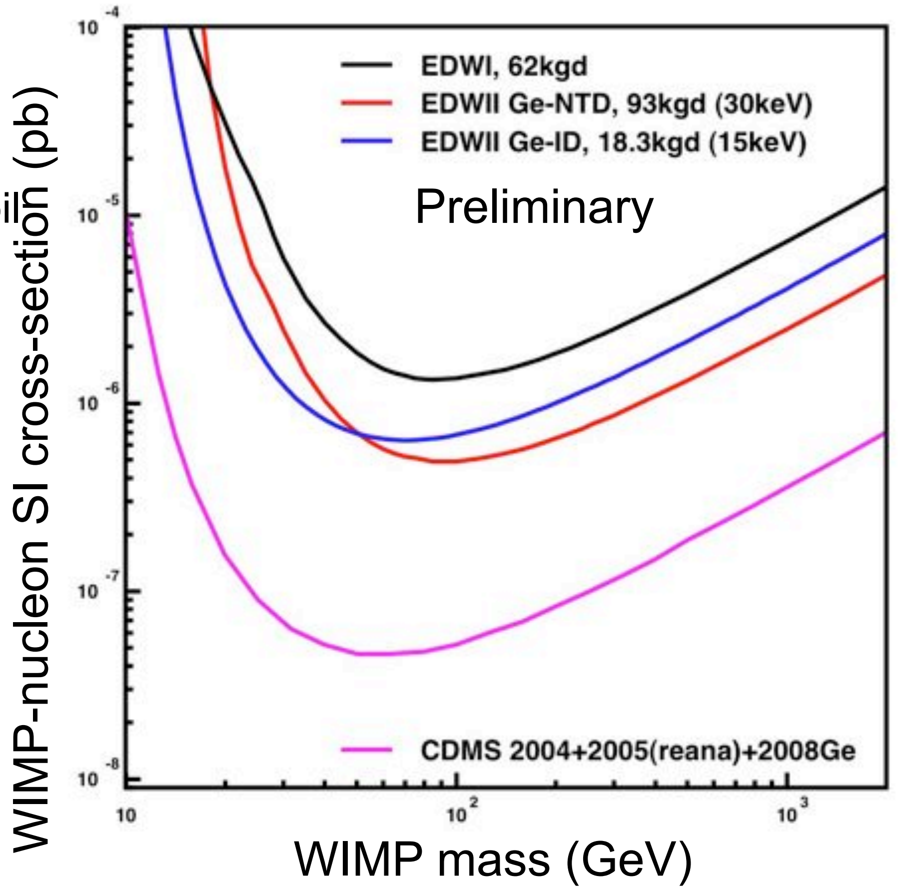
Rejection 20-500 Q<0.5:

- ID401 +ID3 : 0 / 89 000
- Rejection < ~2.6 x10^{-5}
- Equivalent to background exposure ~ 2 000 kg.d



Limits with GeNTD and ID detectors

- 93.5 kgd GeNTD
  - 11 detectors x 4 months
  - 30 keV threshold
  - 3 events observed in nuclear recoil band
- 18.6 kgd ID
  - 2 detectors x 4 months
  - 15 keV threshold
  - No nuclear recoils
  - No evts outside γ band
- Jan. 2009: 10 ID detectors
  - x 20 improvement in 8 months: 4×10^{-8} pb
  - More detectors build in 2009



CDMS II Collaboration

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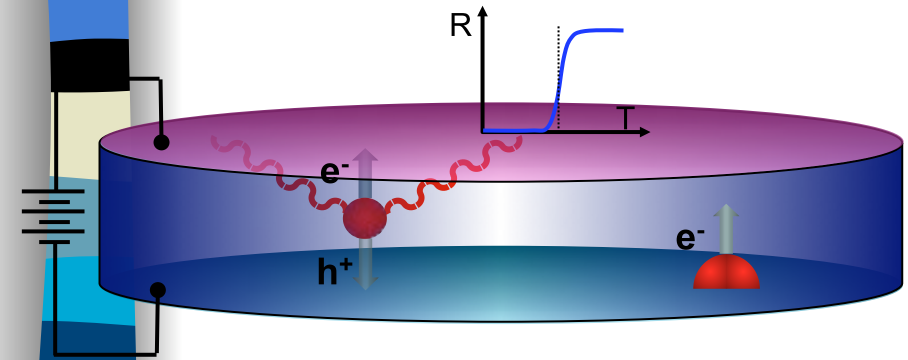
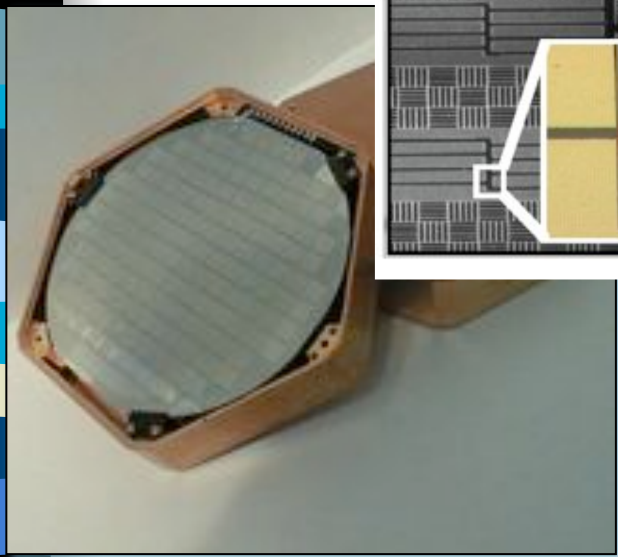
CDMS @ Soudan

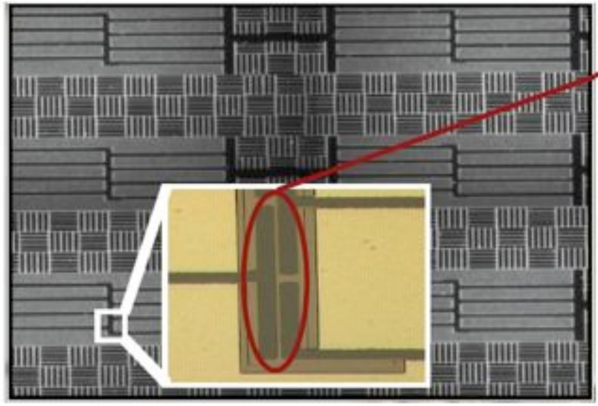


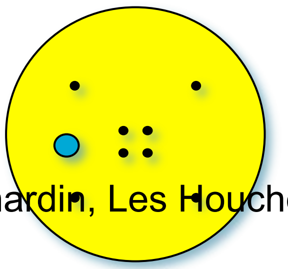
250 g Ge or 100 g Si crystal
1 cm thick x 7.5 cm diameter

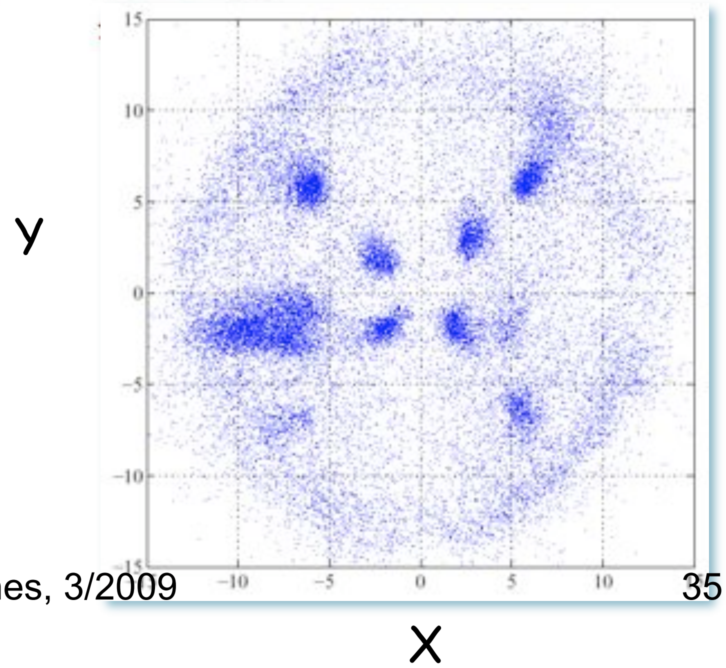
Collect athermal phonons:
- XY position imaging
- Surface (Z) event veto based on pulse shape risetime

Z-sensitive ***I***onization and ***P***honon-mediated©



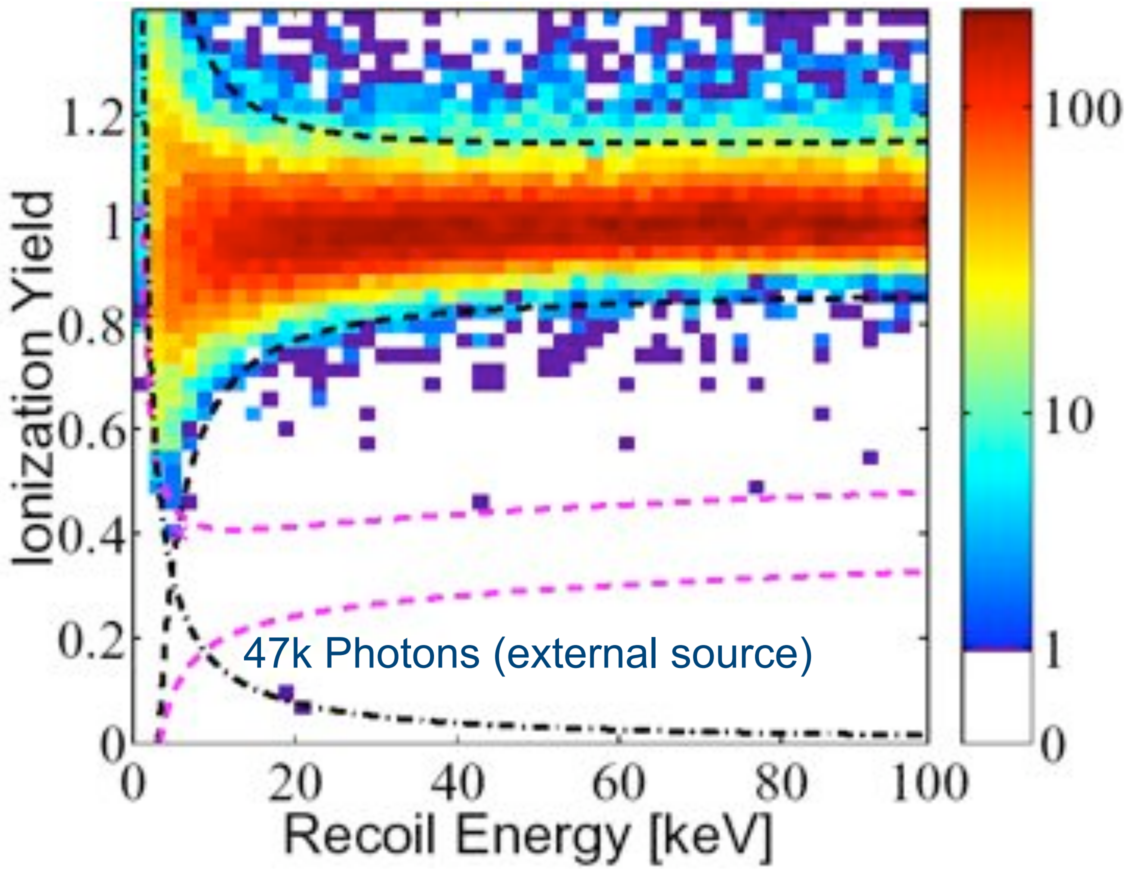






CDMS II Background Discrimination

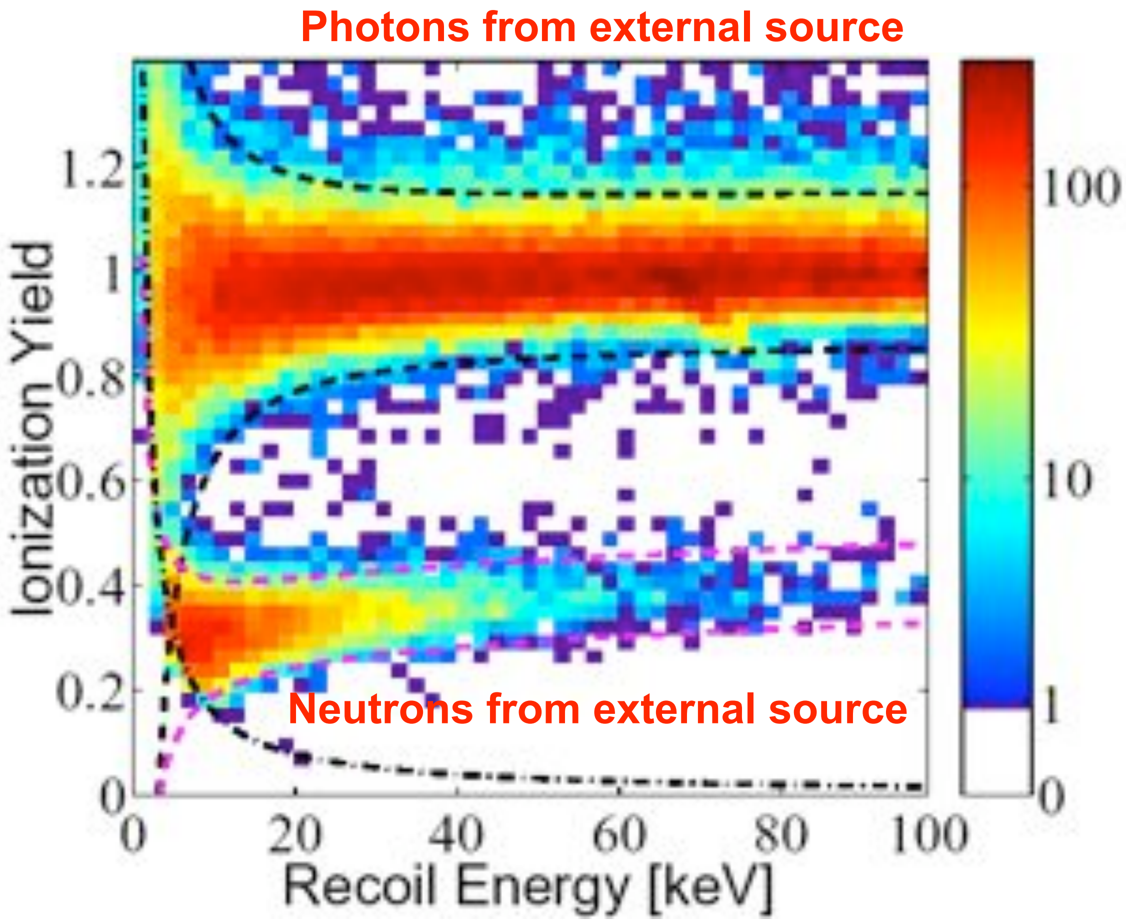
- Ionization Yield (ionization energy per unit recoil energy) depends strongly on type of recoil
- Most background sources (photons, electrons, alphas) produce electron recoils



CDMS II Background Discrimination

- Ionization Yield (ionization energy per unit recoil energy) depends strongly on type of recoil

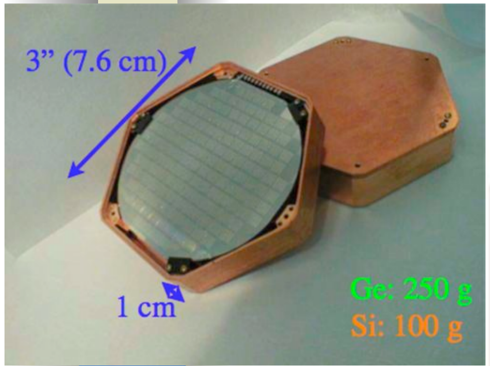
- Ionization yield alone rejects >99.9% of gammas, >75% of ‘betas’



Ionization + Timing:

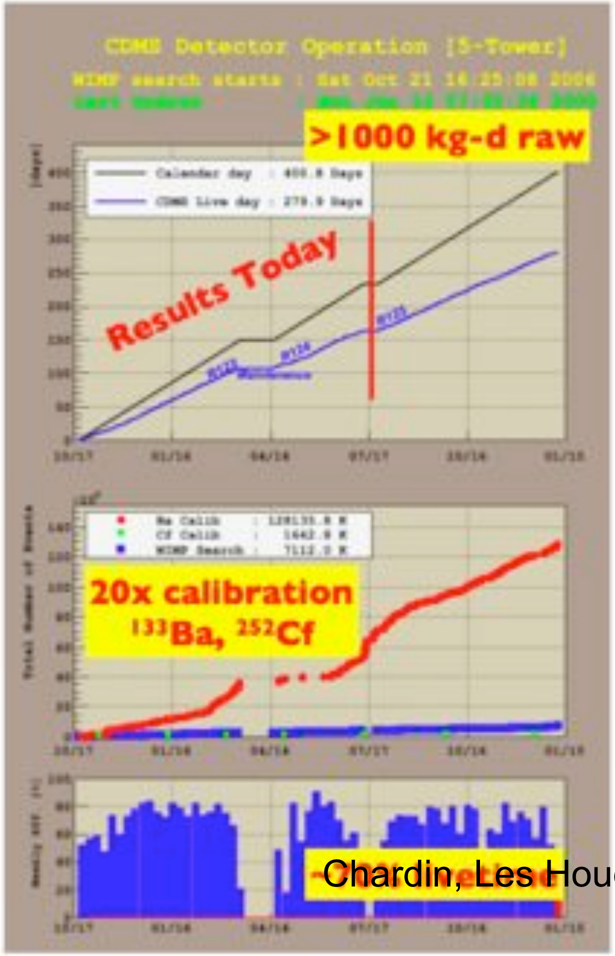
Reject **99.9998%** of **Gammas**, **99.8%** of **surface** events

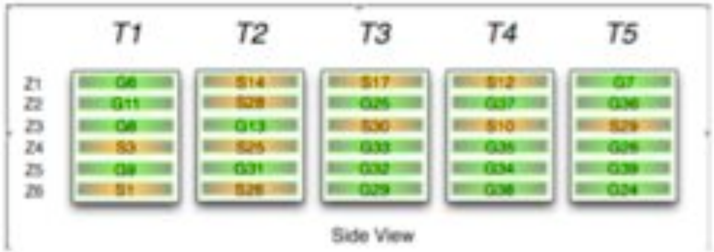
CDMS 2008



First CDMS 5-Tower Results

Rupak Mahapatra





Three successful 5-T data runs so far:

- Run 123 (10/21-3/21): **430 kg-d** Ge (raw)
- Run 124 (4/20-7/16): **224 kg-d** Ge (raw)
- Run 125 (7/21-1/09): **465 kg-d** Ge (raw)
- Run 126 (1/17-date): **ongoing**

>10x the 2-Tower exposure so far!

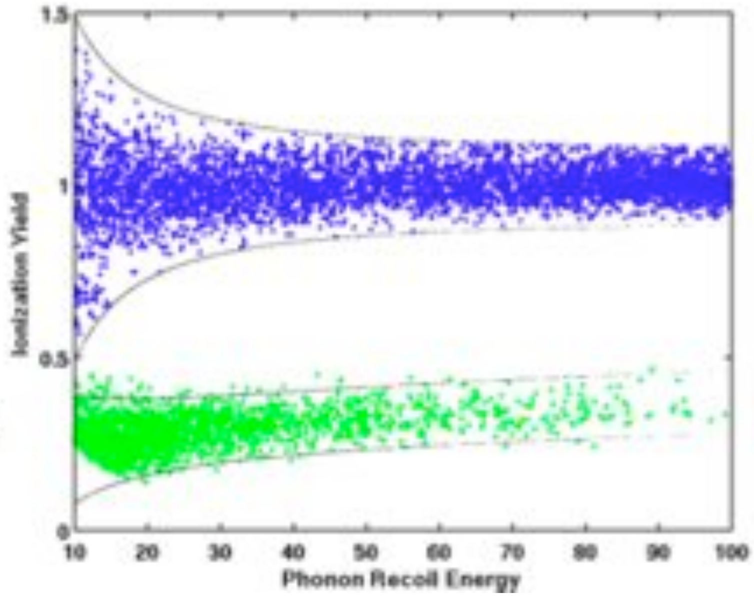
We have analyzed Run 123+124 Data

~Double exposure waiting to be analyzed

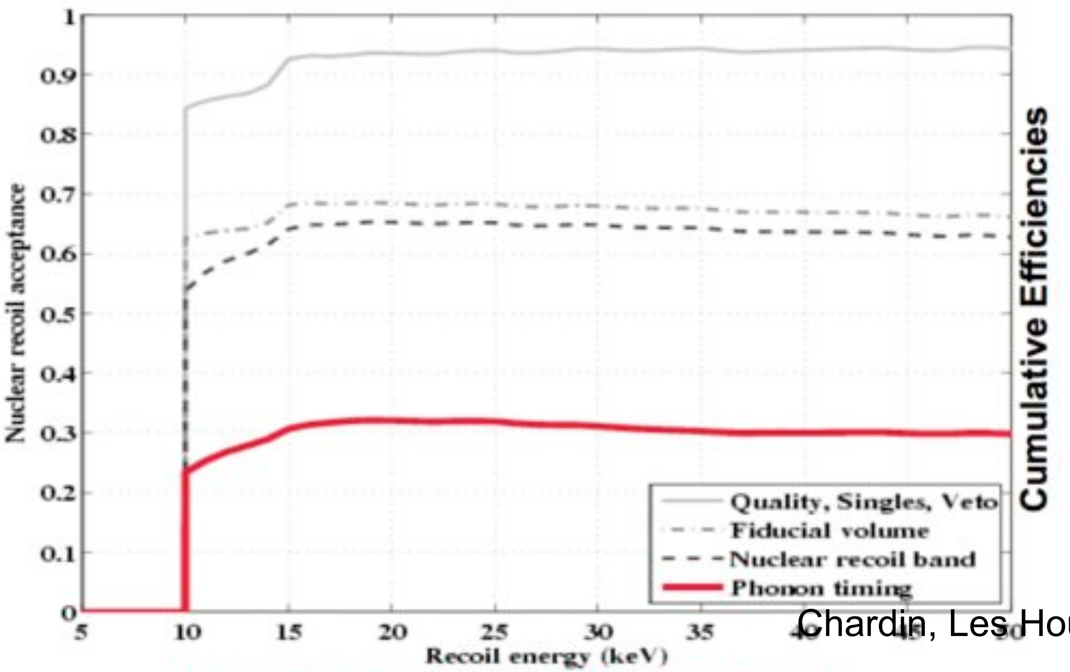
WIMP Candidate: Blind Analysis

All cuts set blind, without looking at signal

- In good Fiducial Volume
- In the Nuclear Recoil Band
- Not surface event: phonon timing cut
- Not a Multiple Scatter



Efficiencies

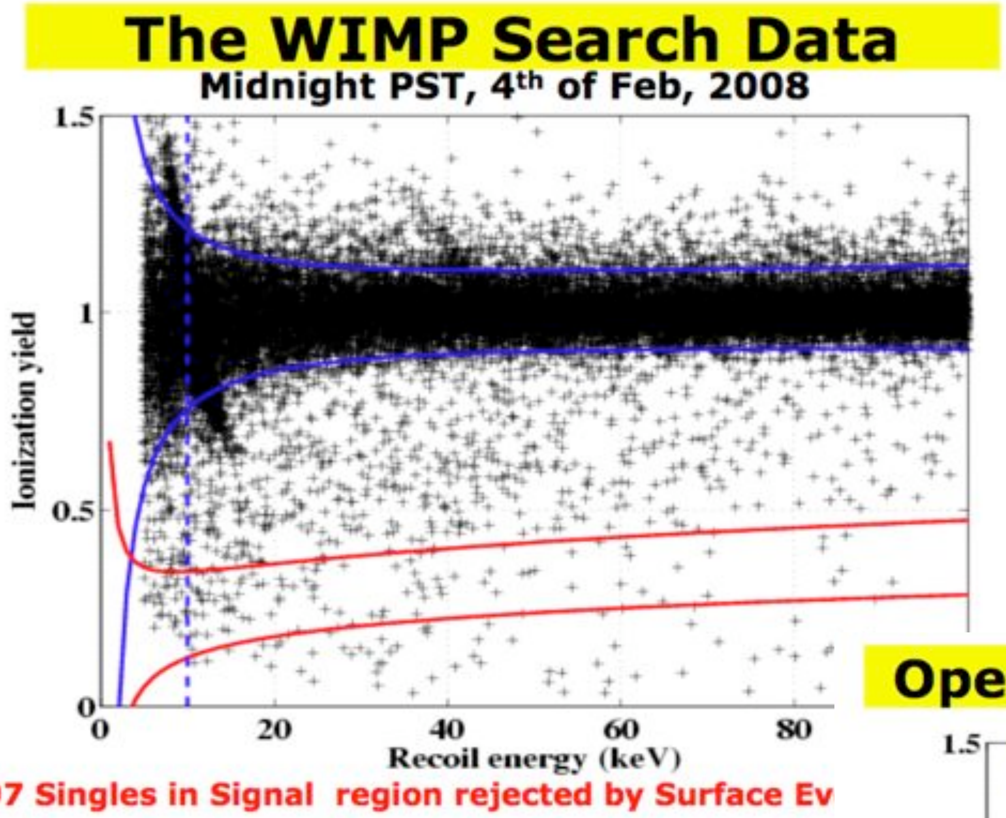


Efficiency plot includes effect of Fiducial Volume Cut

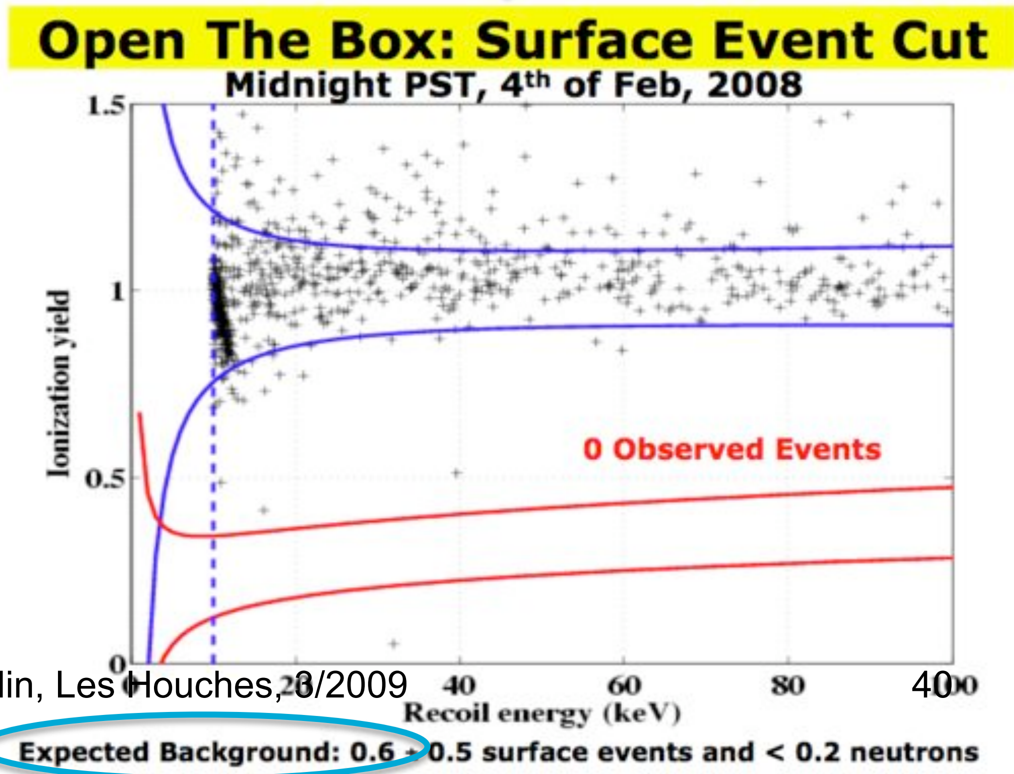
⇒Would expect roughly 650 kg.d * 30% effective/fiducial exposure= 200 kg.d

Actually used exposure is **125 kg.d**
7/19 detectors used because of "variations of performances" on run 124

WIMP search. Of the 19 Ge detectors, three suffering reduced performance from readout failures and one from relatively poor resolution, have been left out of the present report. The remaining 15 Ge detectors were used for the run 123 analysis. Eight of these detectors were excluded from WIMP search during the shorter run 124 due to systematic variations in performance between the two runs. Along with the Si detectors, the analysis of data from these detectors is ongoing and remains blind.

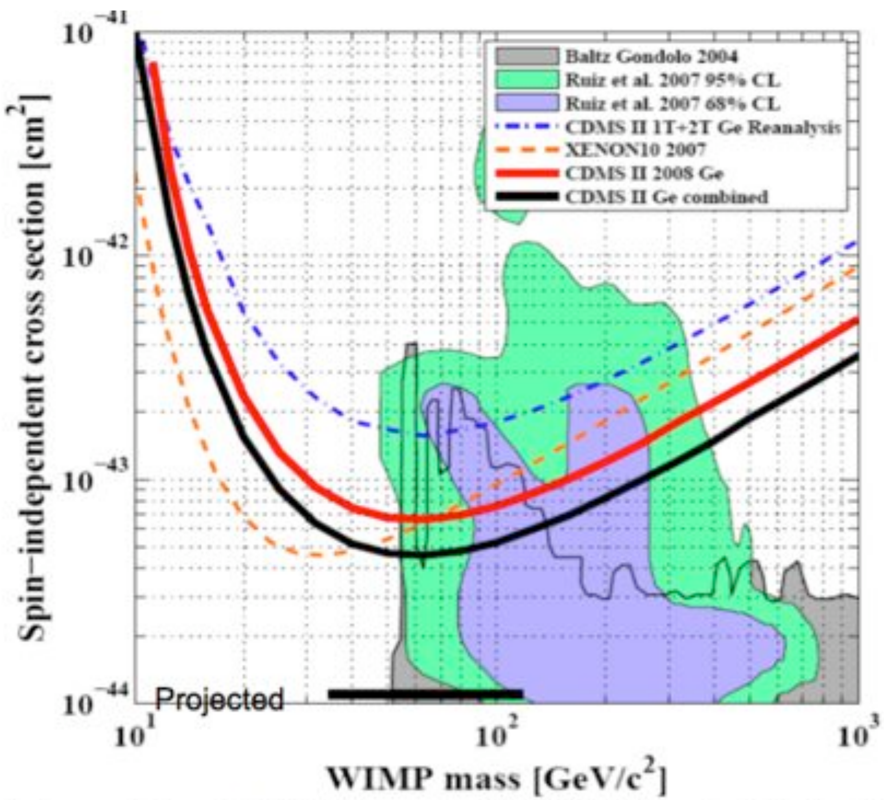


After applying cut on surface events, 0.6 evt expected, none seen



Before cut on surface events 77 evts predicted in ROI

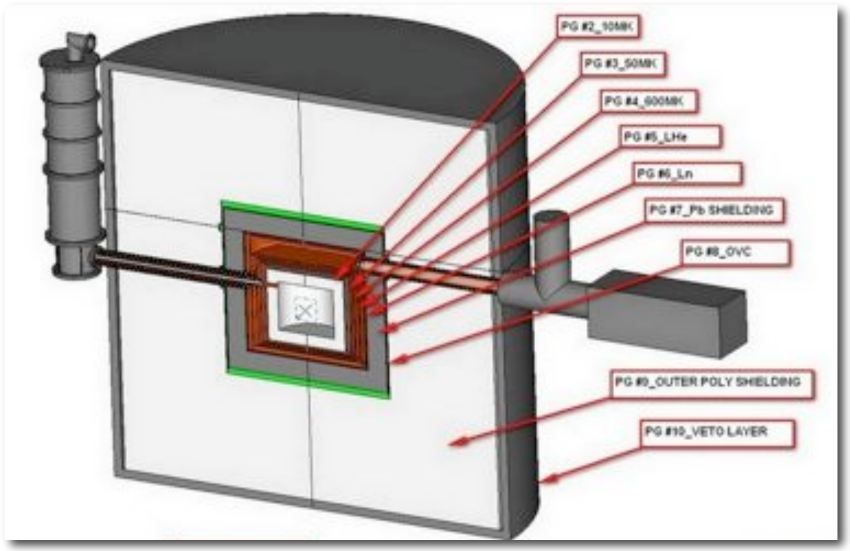
XENON vs CDMS sensitivities



Reanalysis result from 1T+2T Data available in W. Ogburn's (Stanford) Thesis

- Xenon-10 and CDMS have similar sensitivies
- CDMS : additional 1000 kg.d raw data, open box fall 2008

From CDMS-II in Soudan to SuperCDMS in SNOLab



CRESST-II experiment (Gran Sasso)

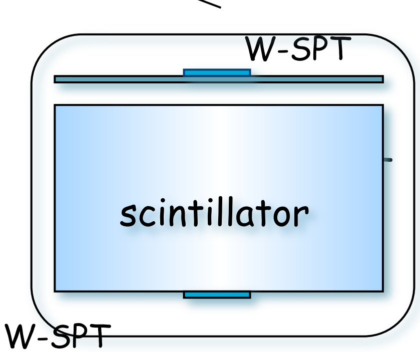
Background discrimination by simultaneous detection of phonons and light

Works with many absorber materials

$CaWO_4$, $PbWO_4$, BaF, BGO

(other tungstates and molybdates)

separate calorimeter as light detector

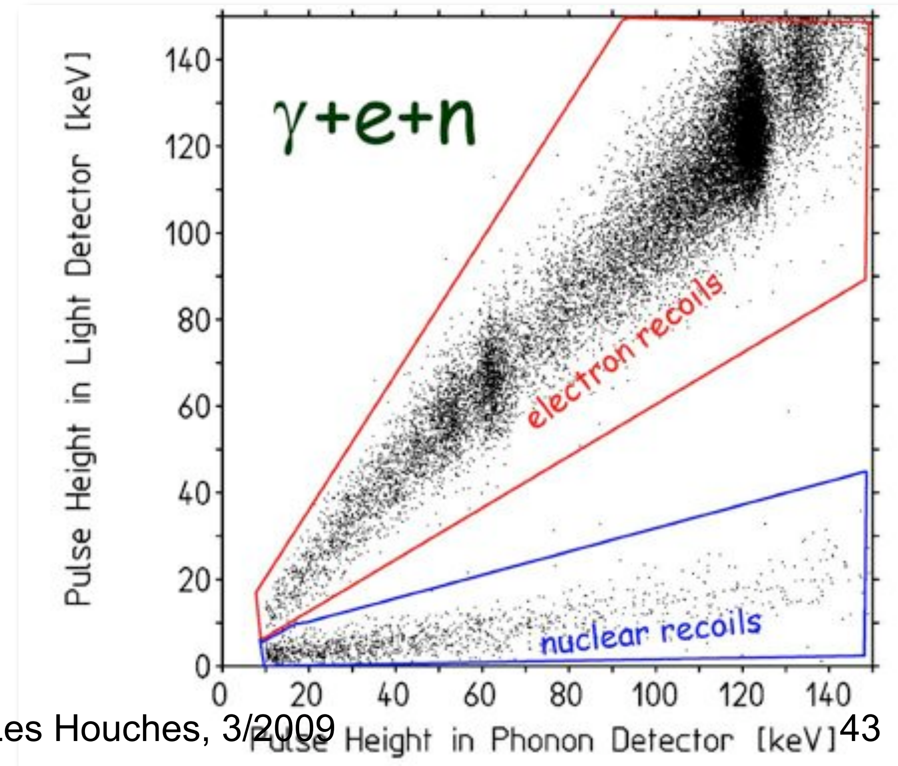


light reflector

High rejection:

99.7% E > 15 keV

99.9% E > 20 keV



Appl. Phys.Lett. **75**(9),1335(1999)

CRESST II

Features:

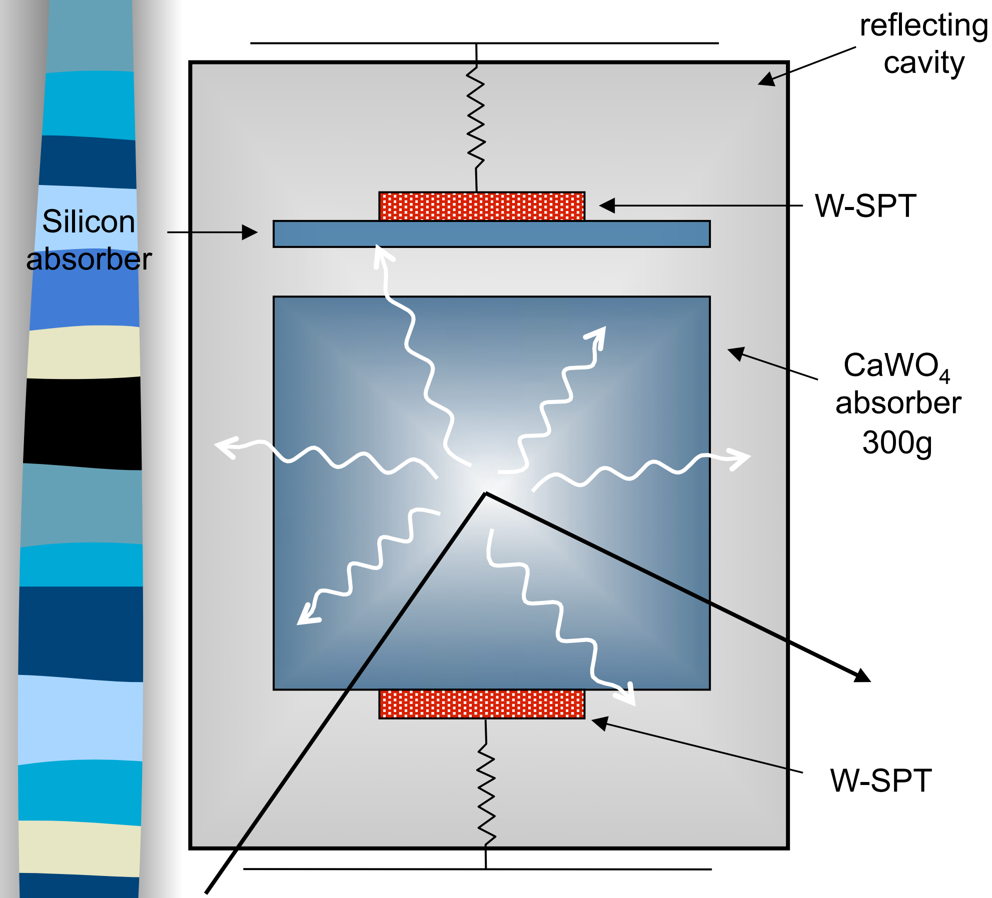
- mass : 10 kg $CaWO_4$
- threshold lower than 15 keV (recoils)
- excellent background discrimination
- **identification of recoil nucleus**
  (unique an important for
  positive identification of a WIMP signal)

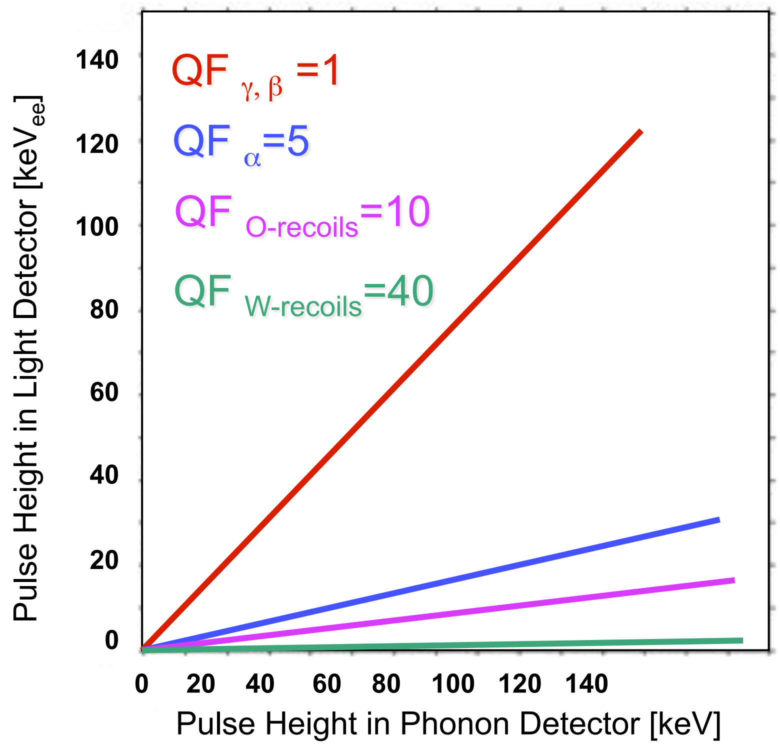
Goal:

Sensitivity better than 10^{-8}pb

CRESST detector module – background discimination

multaneous measurement of phonons and scintillation light to discriminate nuclear recoil signals from radioactive background

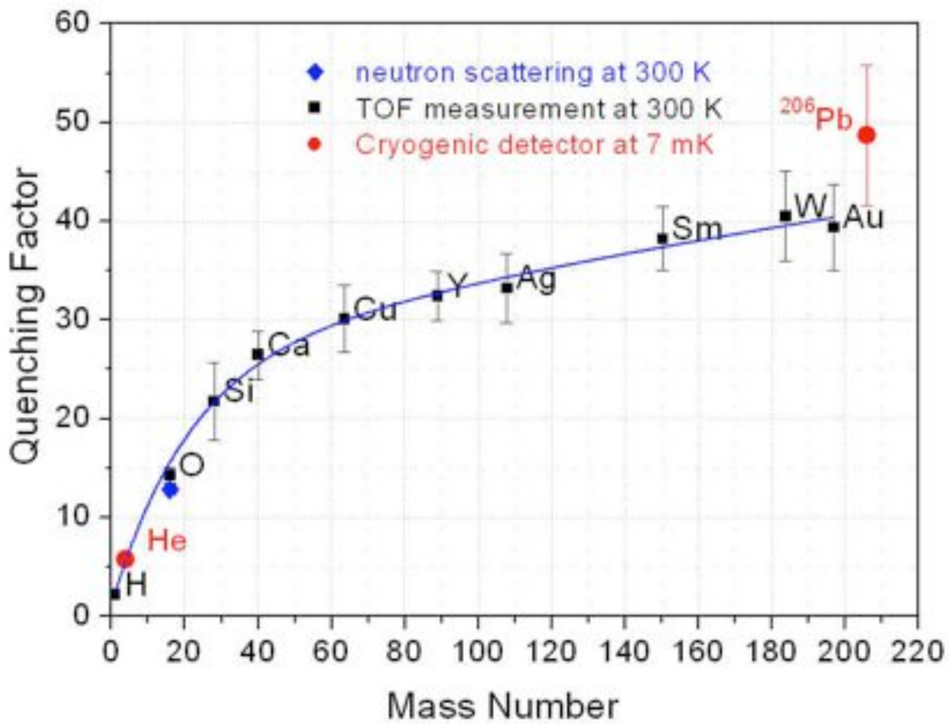




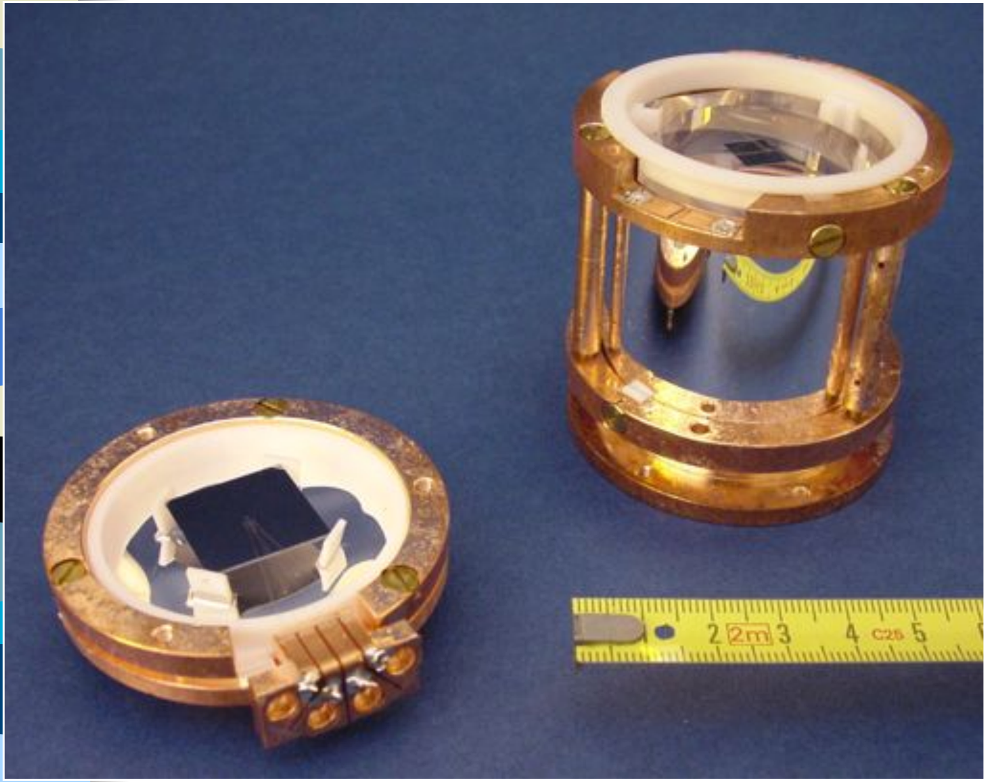
Quenching Factor Q

Every particle has a different quenching factor Q
Q= photon light signal / particle light signal   (both of same energy)

Note: two measurements at millikelvin temperatures: ^{4}He and ^{210}Pb



300 g detector module



phonon channel:

$300g\ CaWO_4$

Ø = 40mm, h = 40mm

W-SPT 4 x 6 mm^2

light channel:

Si 30 x 30 x 0.4 mm^3

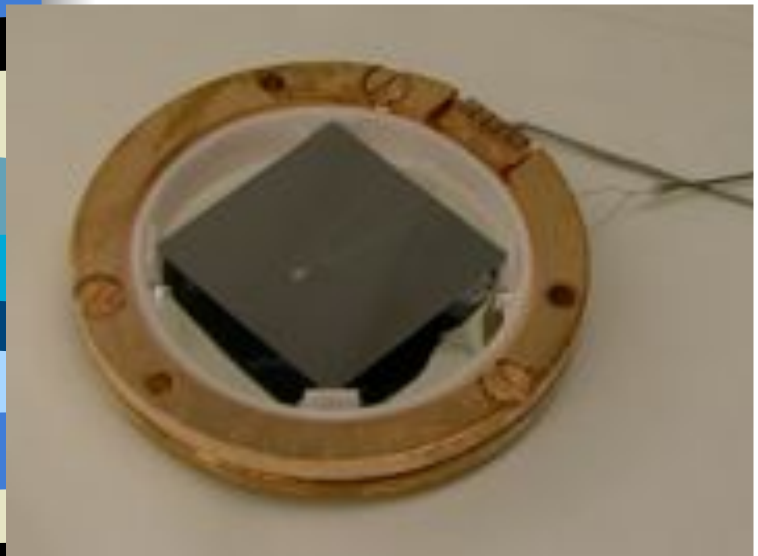
W-SPT with Al phonon collector

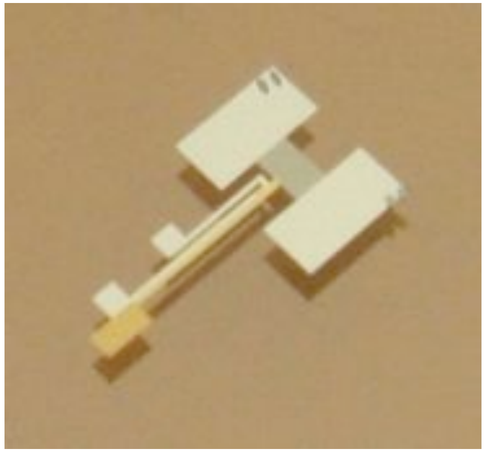
reflector:

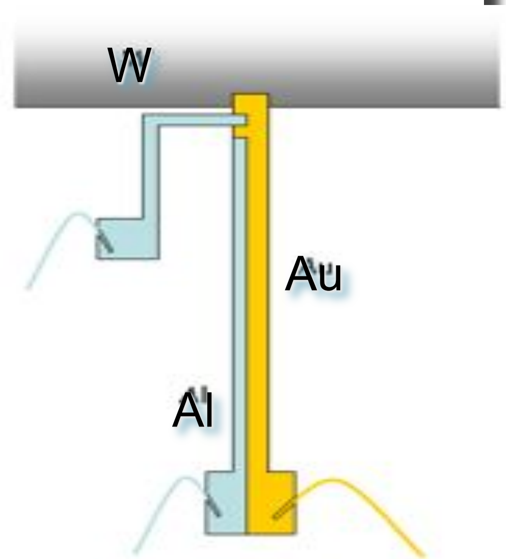
polymeric foil, teflon

Operating temperature ~10 mK

Light Detector







Al-phonon collectors
separate heater / thermal link

Si wafer (30 x 30 mm^2) read out by W-

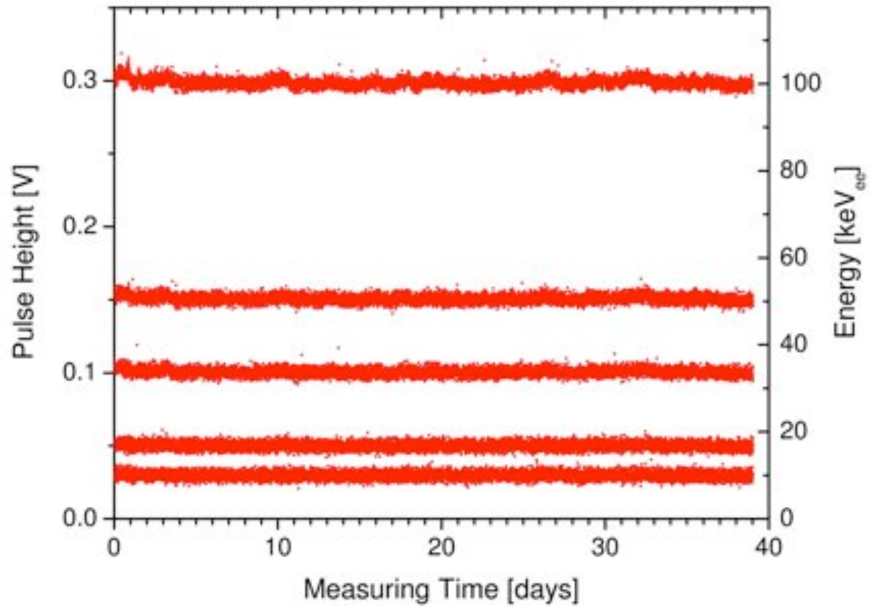
Effective threshold: $E_{thresh,ee}$ ~ 2 keV (few photons)

10 to 20 eV absolute

Run with two prototype detector modules

Stability of detectors:

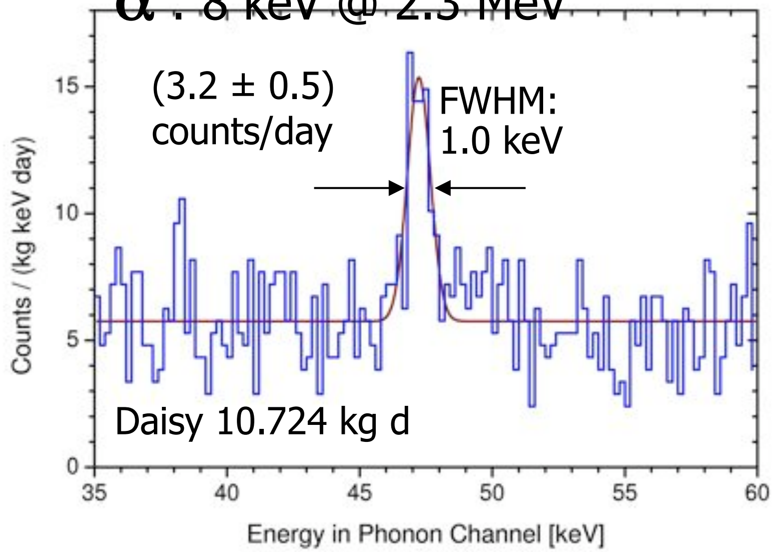
Very constant sensor response over a period of two months



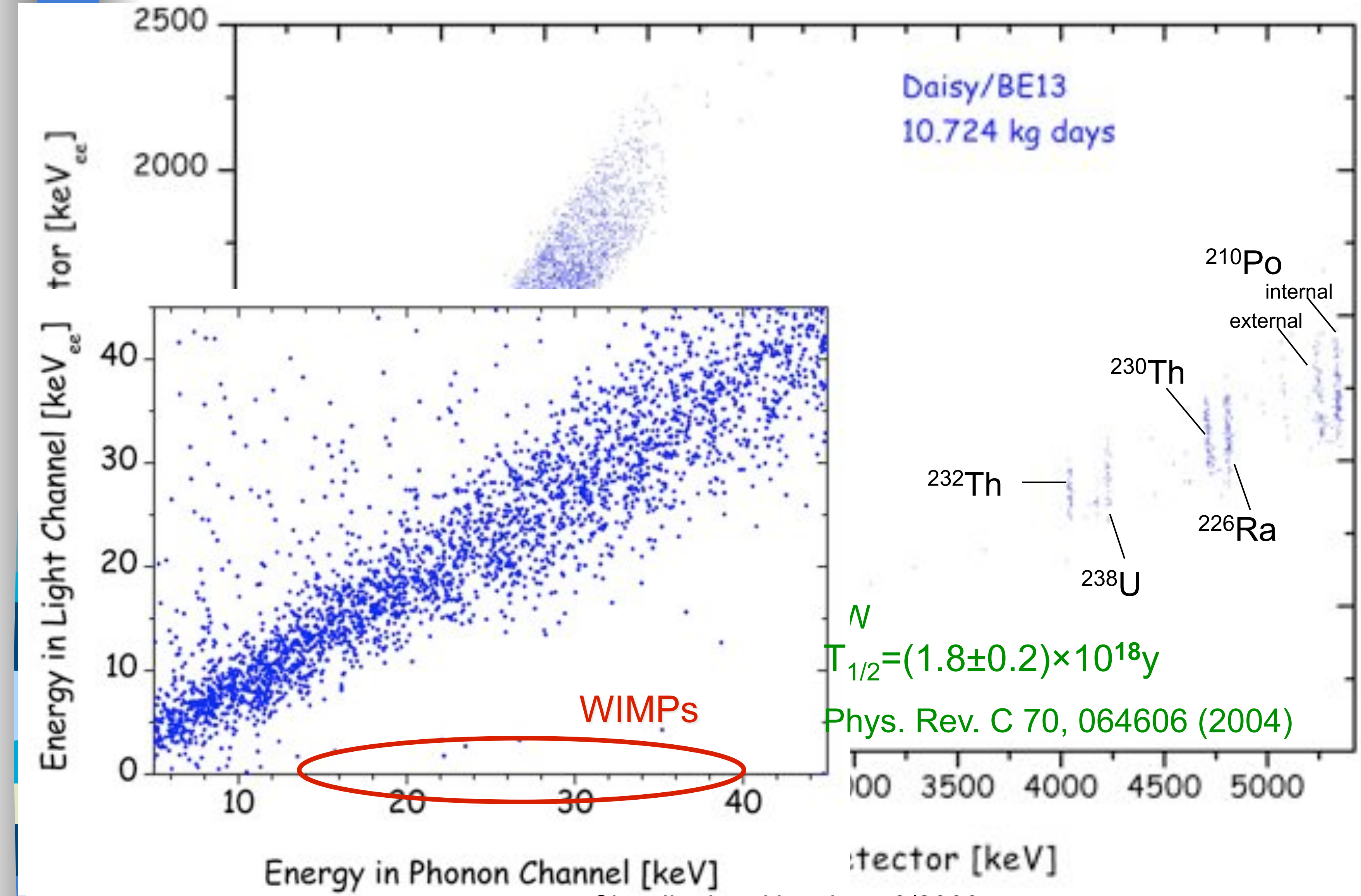
Energy resolution of phonon detector:

γ : 1 keV @ 46.5 keV:

α : 8 keV @ 2.3 MeV

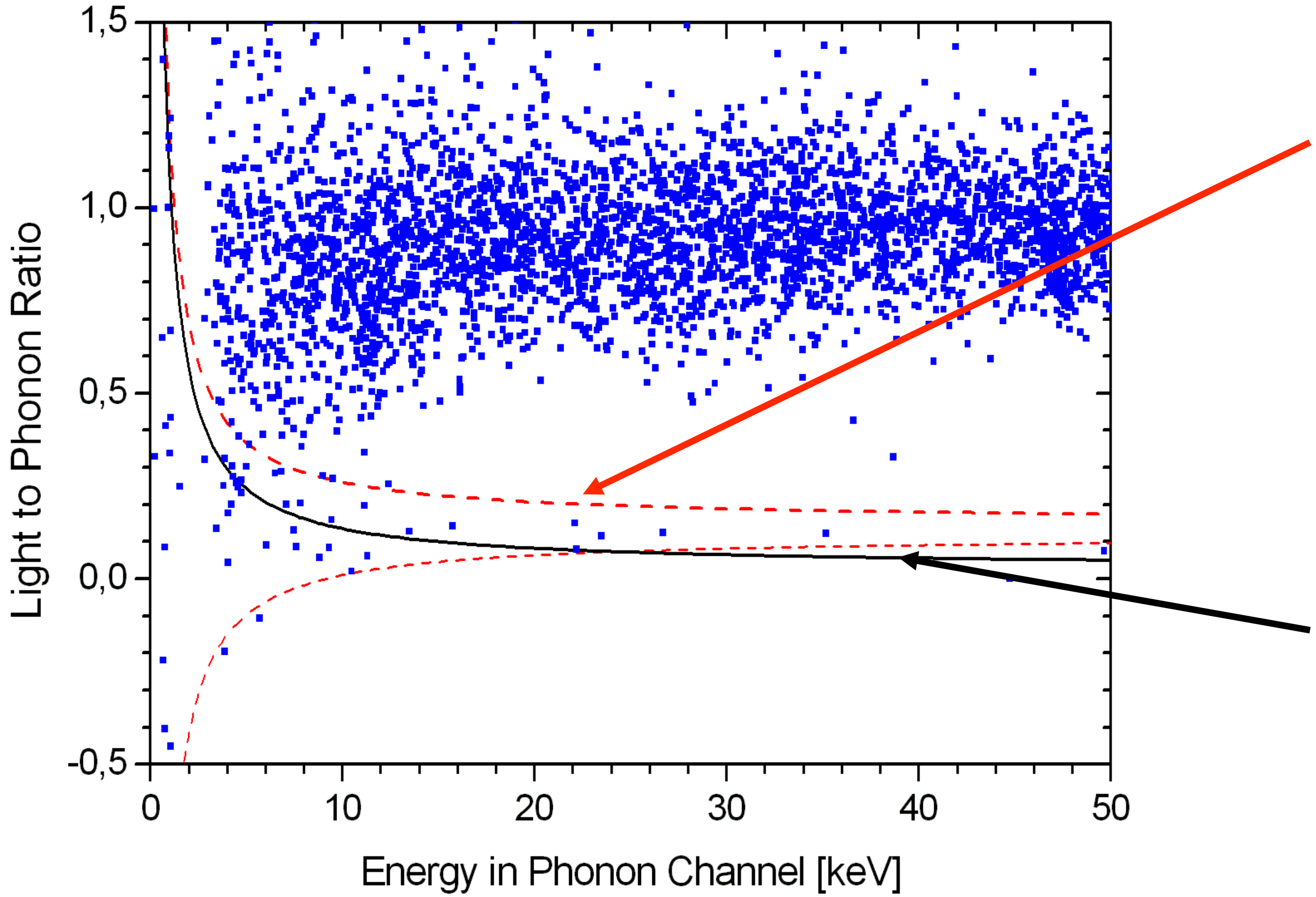


CRESST detector module – background discrimination



Low Energy Event Distribution no neutron shield

10.72 kg days



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

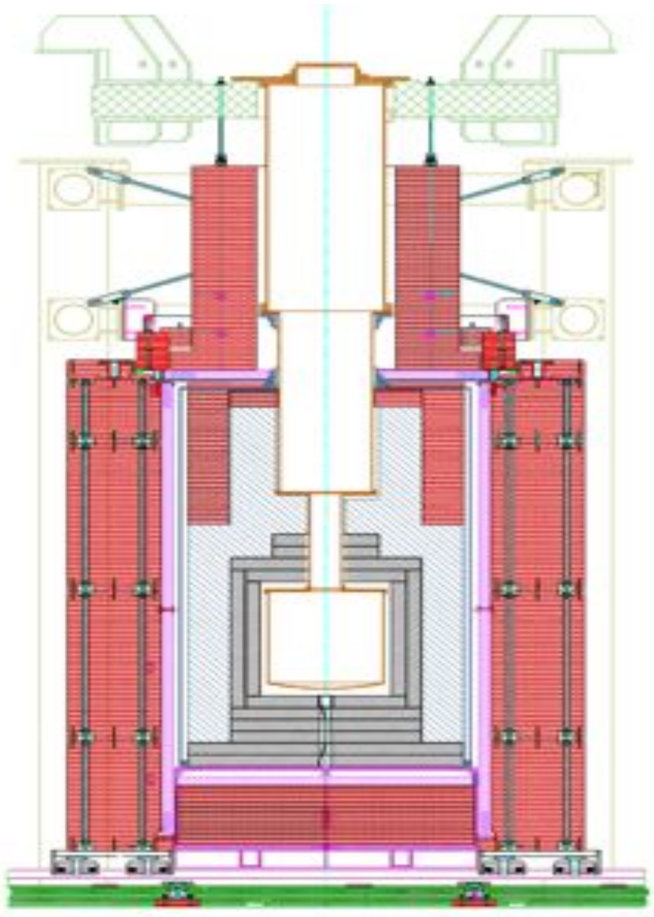
90% of nuclear recoils with quenching factor 40 (tungsten) below this line

Upgrade

- installation of 66 SQUID ….channels to readout 33 ….detector modules (10 kg); ….wiring, electronics, data ….acquisition…

- installation of PE neutron ….moderator and plastic ….scintillator μ-veto

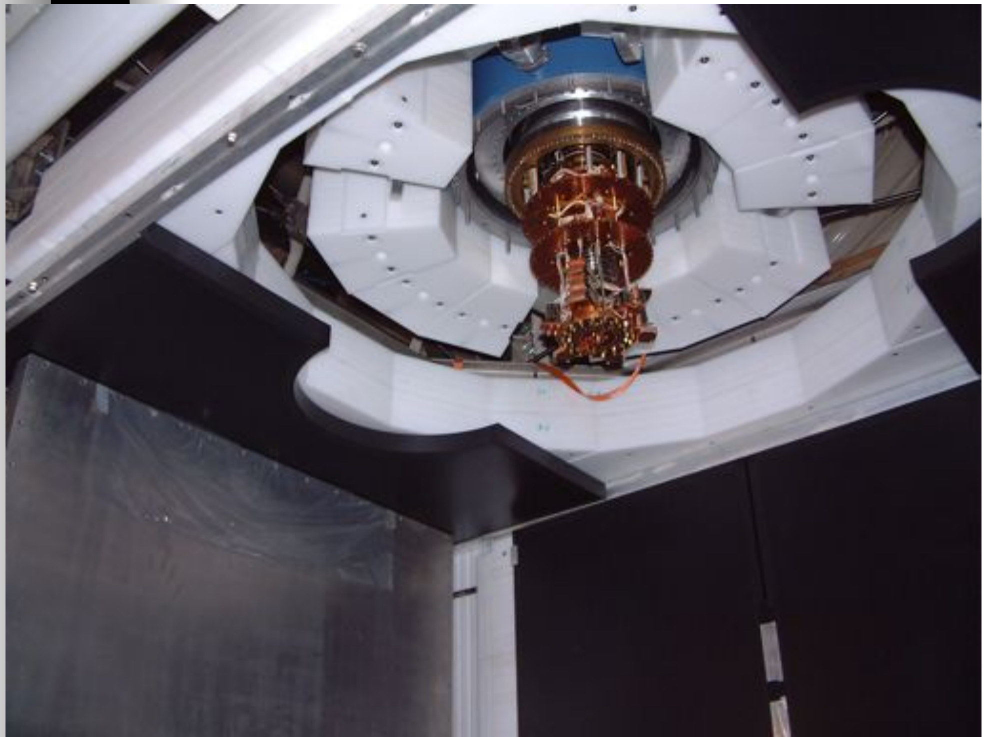
shielded cryostat



PE neutron moderator

plastic scintill. μ-veto

PE- shielding and muon veto



50 cm PE – shielding (12 tons)
Plastic scintillator muon veto

66 channel SQUID system

new wiring for 66 channels

- 576 wires into Helium bath
- 432 wires to mixing chamber (7mK)
-288 wires from mixing chamber to detectors

Low background connectors and solder

Detector support structure

special low background, low heat leak copper
low background CuSn2 springs

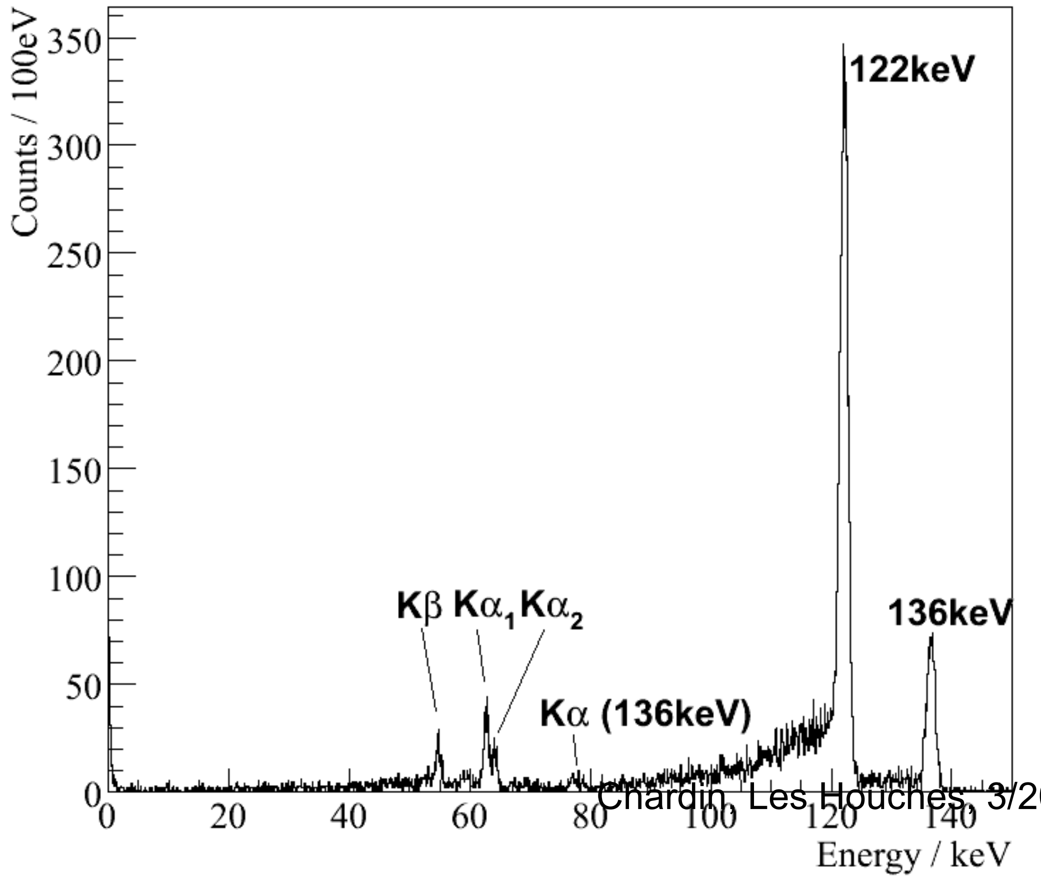
Commissioning run

- 10 detector modules build in (3kg)
- cryostat running
- first measurements started .

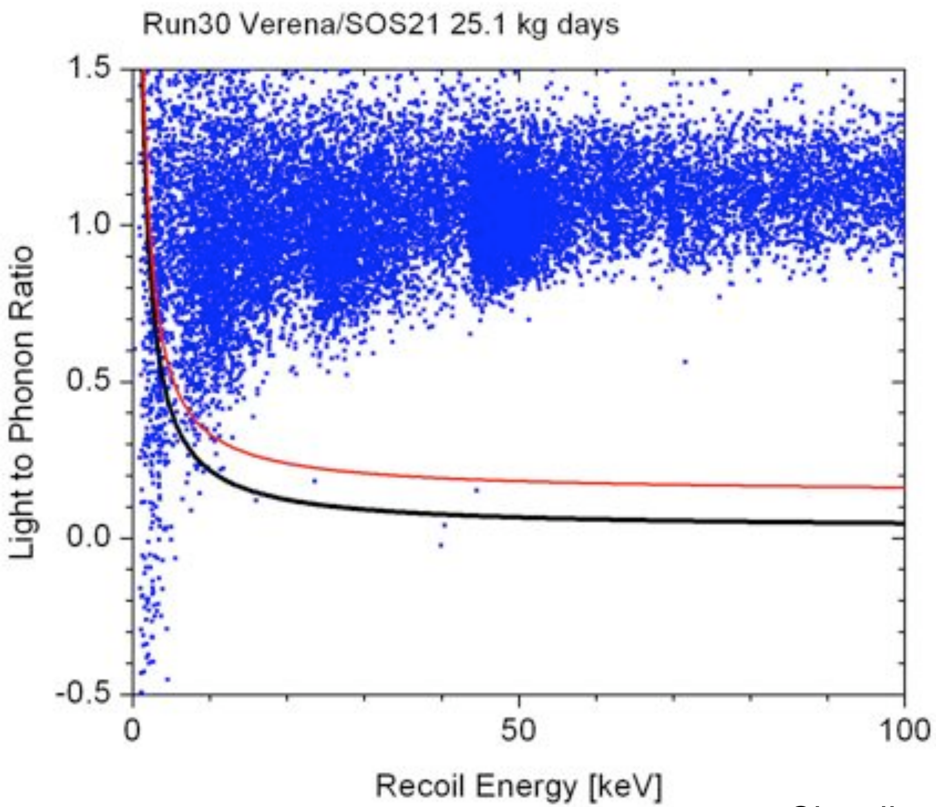
Phonon detectors

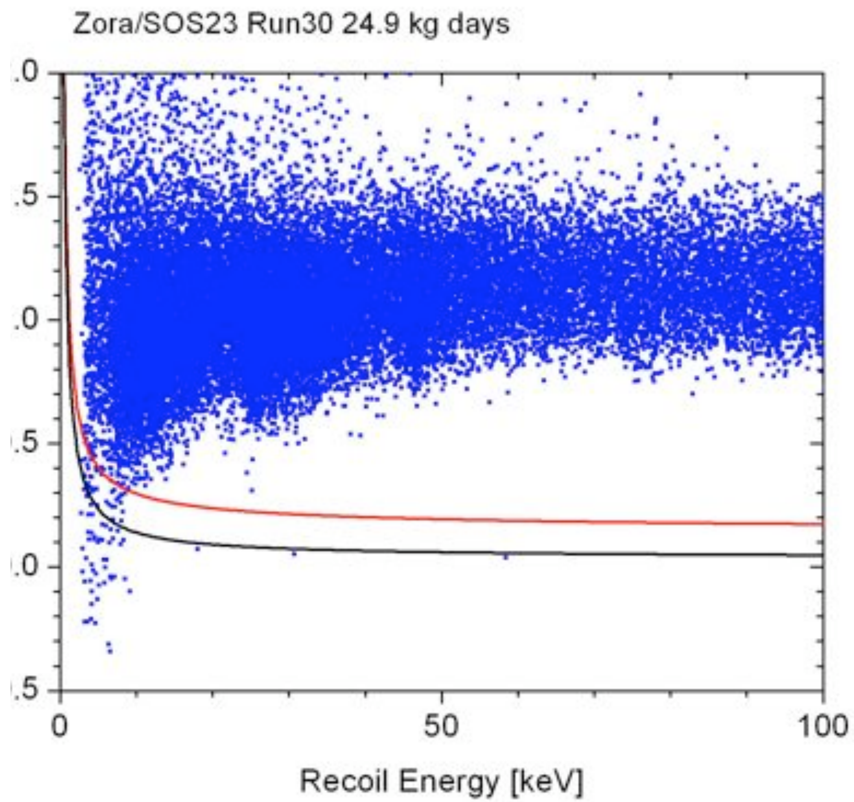
Good performance

Co-57 Calibration, Detector Verena



Discrimination and background





Origin of the background

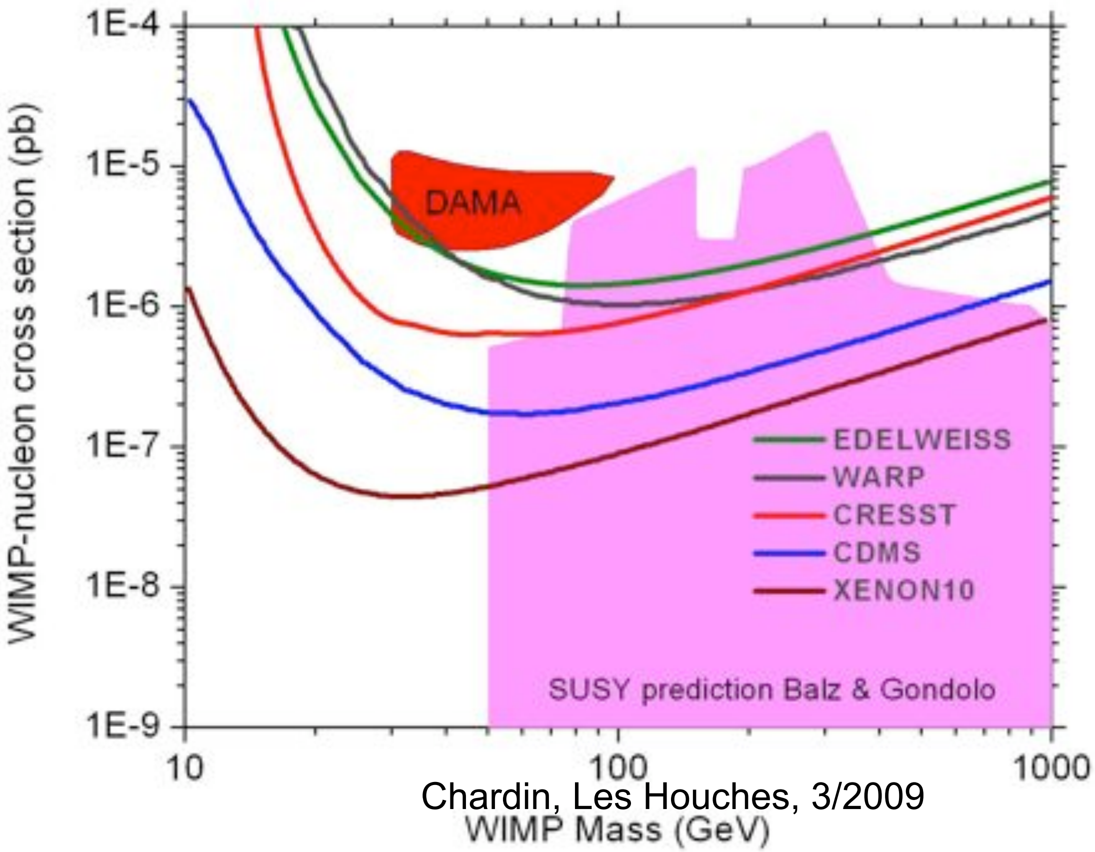
- Neutrons (hole in shielding fixed)
- Electronic noise
- a-emitters

next

-Neutron calibration
-Install new light detectors and start physics run

Preliminary limits

no neutron calibration yet

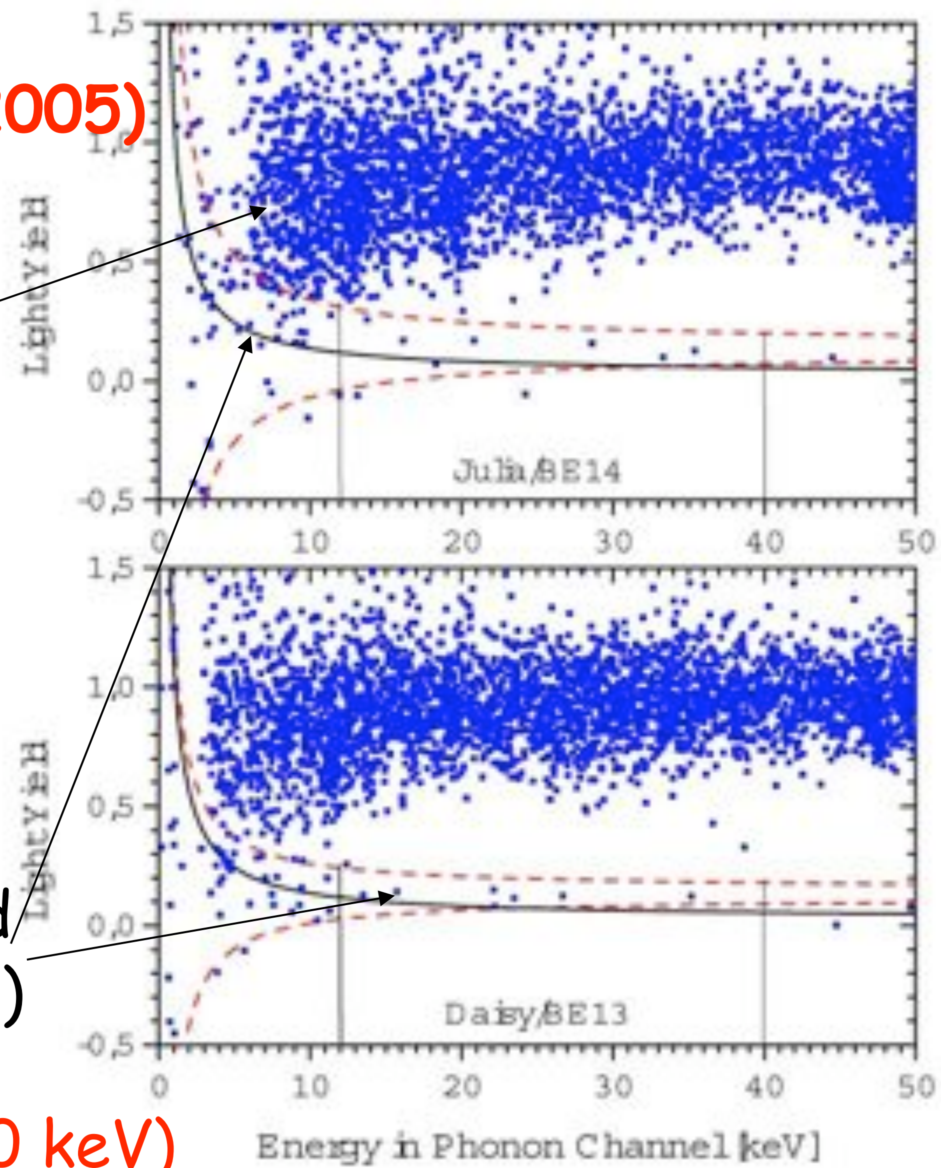


First CRESST-II result
astro-ph/0408006
Astropart. Phys. (2005)

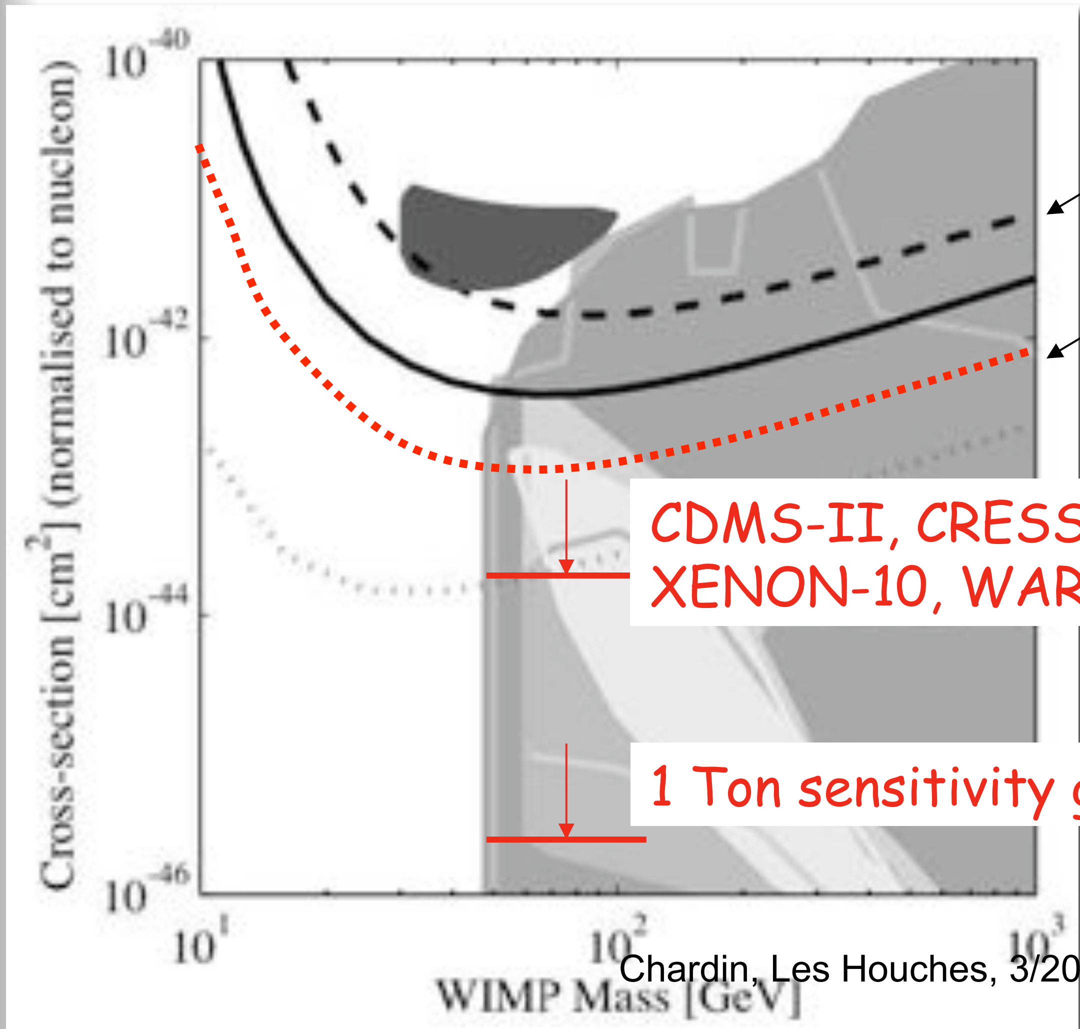
γ-ray background

neutron background
(oxygen recoil band)

No tungsten recoil
in Daisy data (12-40 keV)



Experimental status and theoretical predictions



EDELWEISS, CRESST
CDMS present
sensitivities

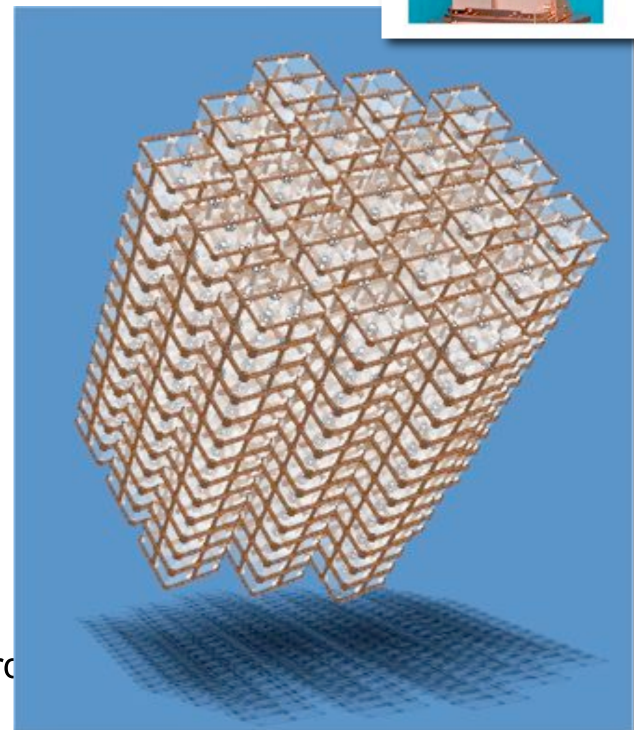
CDMS-II, CRESST-II, EDELWEISS-II,
XENON-10, WARP-10 … sensitivity goals

1 Ton sensitivity goal (optimistic)

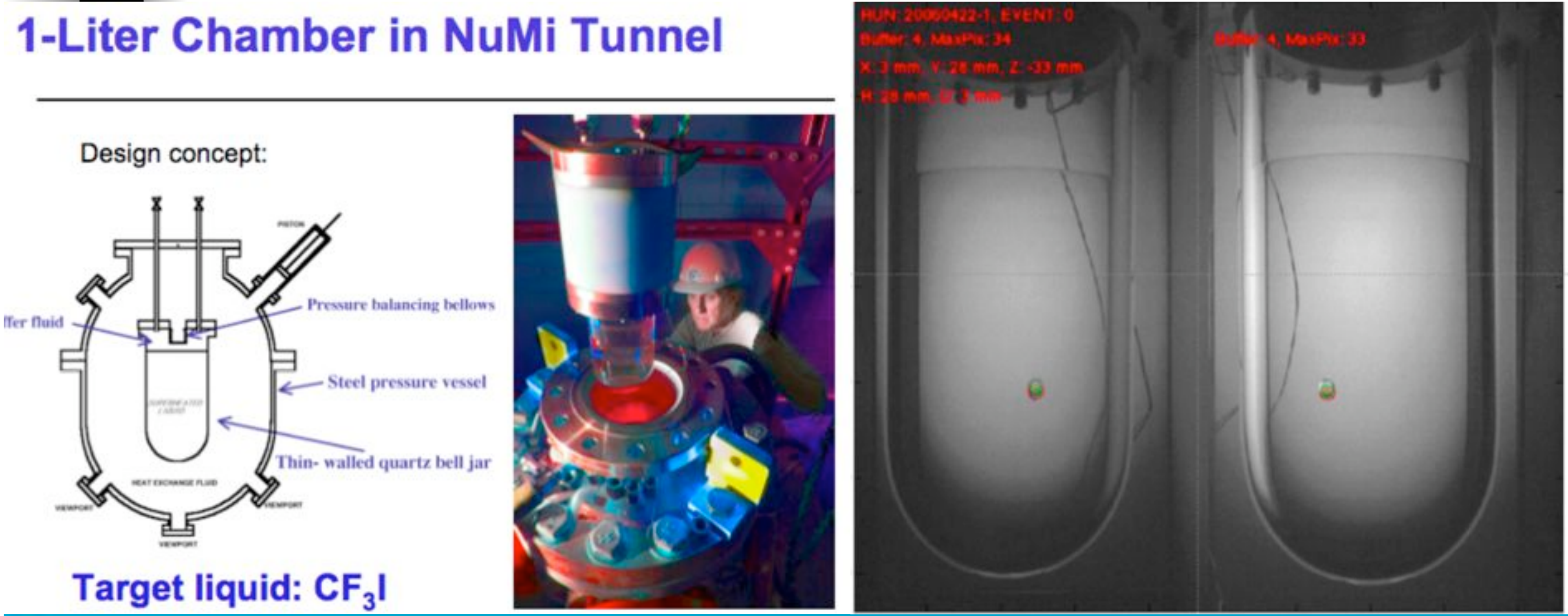
after dmtools
R. Gaistkell and V. Mandic

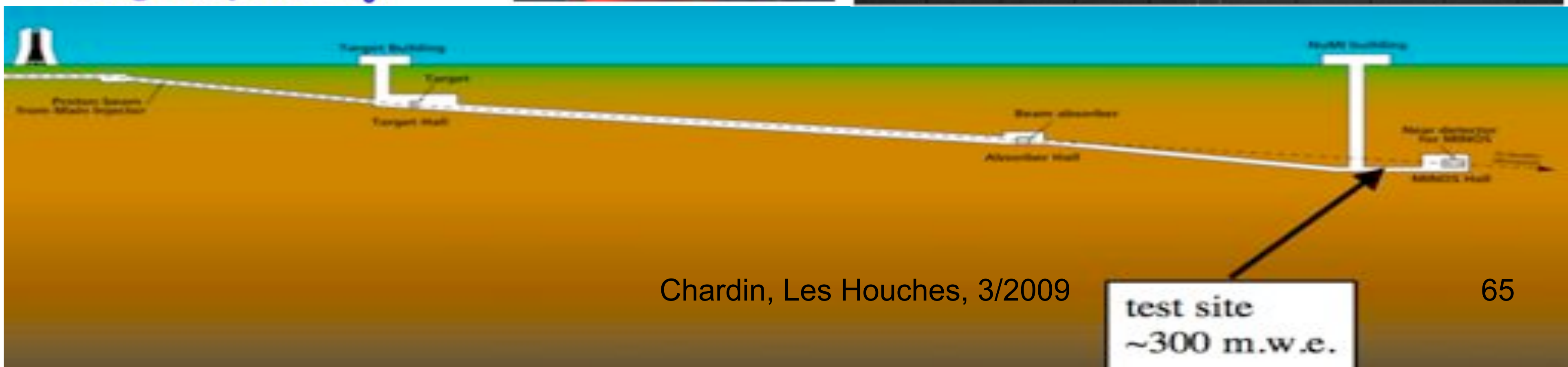
High compacity array

- CUORICINO: largest mass cryogenic experiments (42 kg at T ≈ 10mK)
- Crystal mass >≈ copper structure mass
- For CUORE-type array, possibility to identify neutrons by multiple interactions



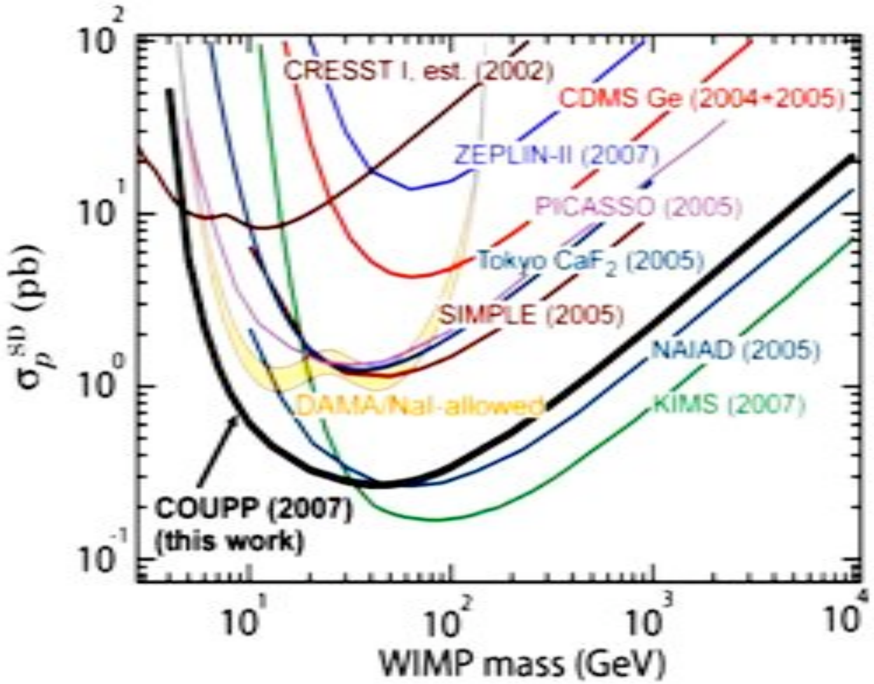
COUPP : the old bubble chamber



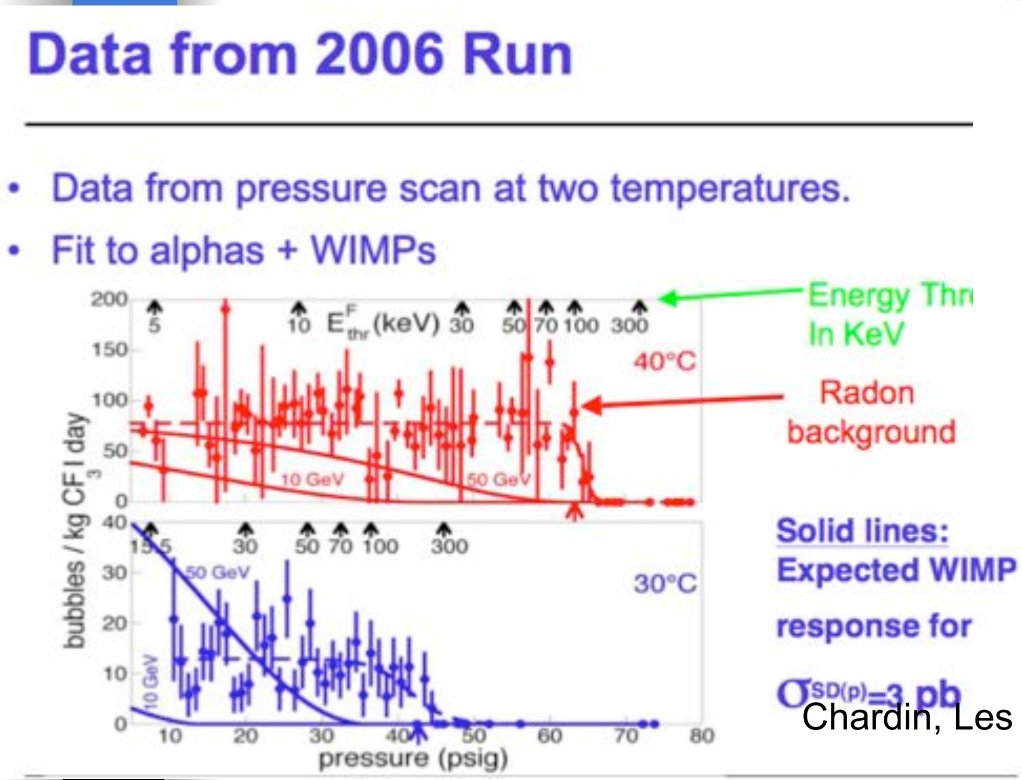


COUPP results

- Insensitive to em backg
- "Digital" response but
- Tuning of T and P allows energy scan



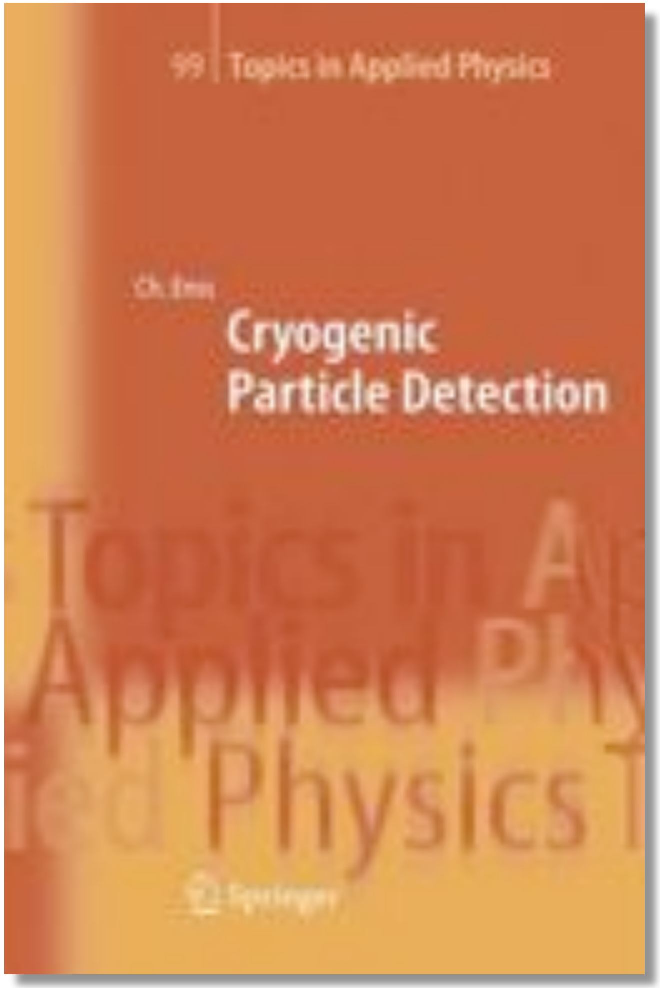
- Good sensitivity with 19F nucleus to SD pure p couplings (even in presence of high radon background)
- Building 20 and 60 kg vessels



Cryoelectronics developments

- Challenges in cryoelectronics :
  - Large number of wires
  - heat load constraints (exercises)
  - development of custom cables and amplification components (FETs)
- High impedance channels (CUORE, EDELWEISS, EURECA) : develop ultra-low noise low dissipation AsGa FETs (LPN Marcoussis)
- Low impedance channels : SQUID electronics (IPHT Jena, MPI Muenchen, Oxford, APC Paris…)
- For both types of channels : multiplexing is mandatory for most matrices applications
- **Cryogenic detectors : relatively slow signals →**
  - **digitize very early (close to cryostat) the analog signals**
  - **digital filter (after anti-aliasing low-cost filter…)**
  - **digital trigger**

References



If you want to know more about "Cryogenic Detectors",

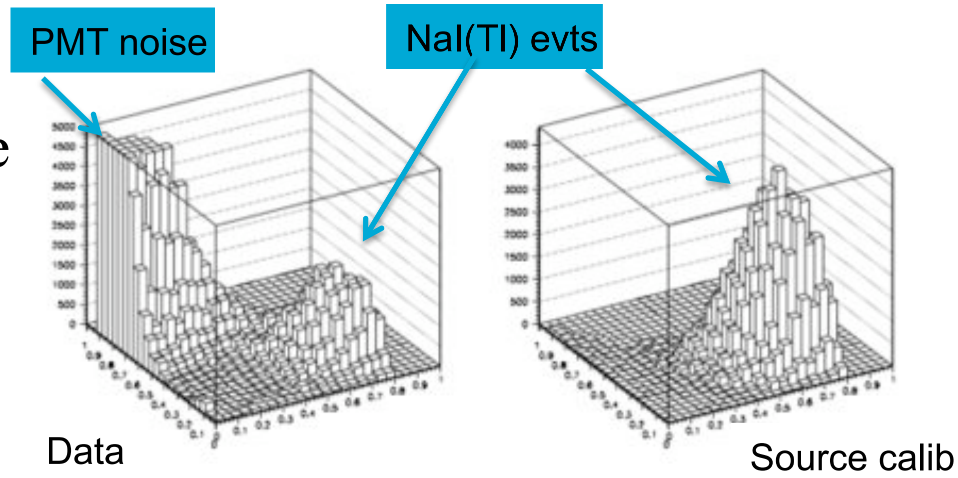
Cryogenic Particle Detection
ed. Christian ENSS
(Springer, Heidelberg, 2005)

Together with the Proceedings of the LTD-12 and LTD-11 conferences:

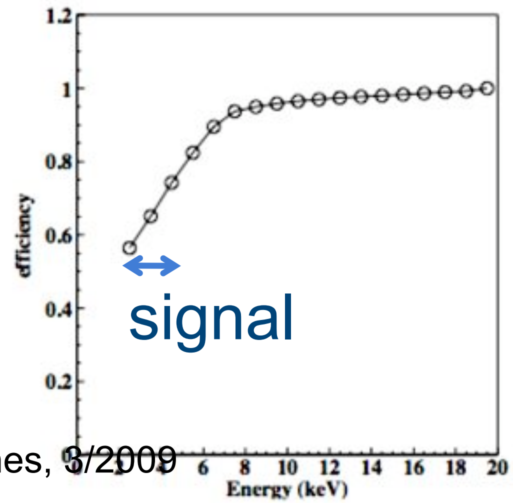
Proceedings LTD-12, J. Low Temp. Phys. 151 (2008)
Proceedings LTD-11, Nucl. Instr. Meth. A 559 (2006)

DAMA evidence for dark matter ?

- Exp questions to investigate
- 1)Tricky analysis at threshold
  - Signal in energy window dominated by PMT noise
  - Signal at threshold in varying efficiency energy region
  - =>influence of cuts on noise rejection, signal power ?
  - => difference of efficiencies for signal and background ?

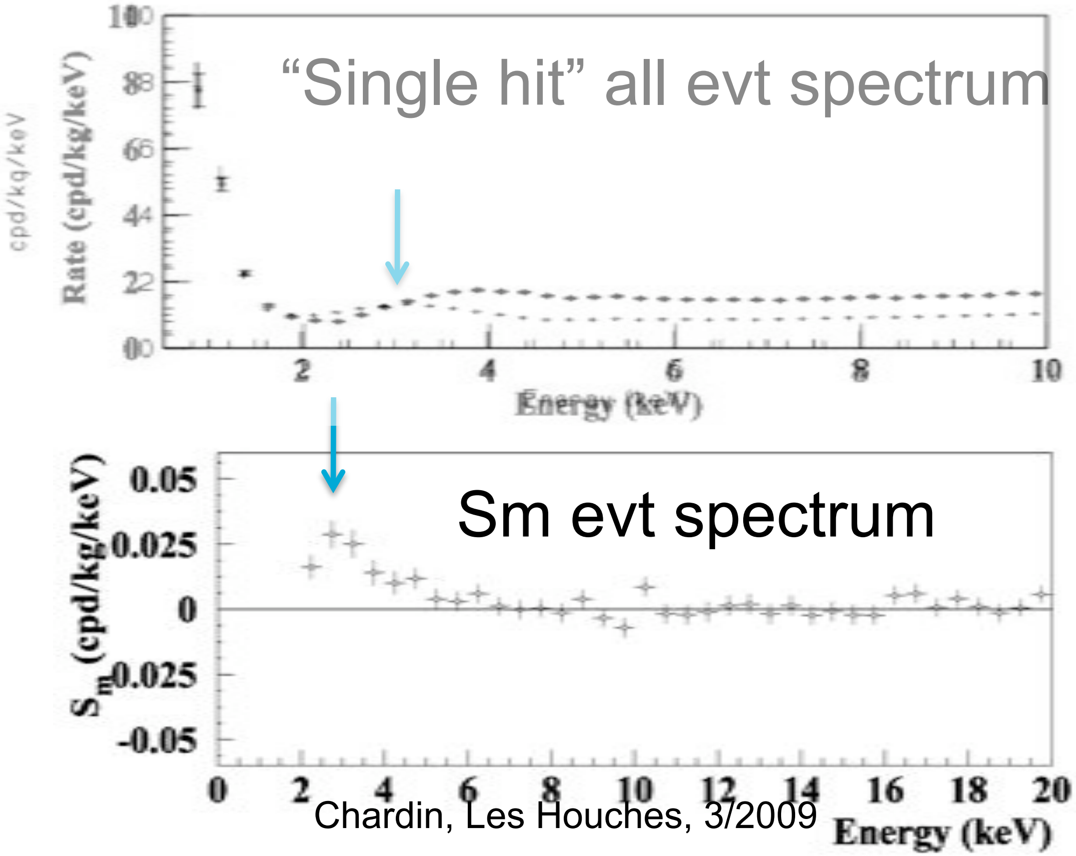


2-4 keV region : pulse shape analysis for PMT



DAMA evidence for dark matter ?

- 3) Coincidence of Sm signal with 3 keV peak of ^{40}K in all spectrum ?
  - Looks like the modulation of a peak ?
  - What is the expected contribution from ^{40}K ?



2003 spectrum

DAMA LIBRA : how to go ahead ?

- Open data policy recommended by ILIAS and ASPERA
- Blind analysis
- “Duplicate” experiment : KIMS (CsI), ANAIS (NaI)
- Explore low energy/mass regions
- In any case, alternate observation by other experiment is needed
- Bahcall’s proposal at TAUP2003

KIMS

Korea Invisible Mass Search

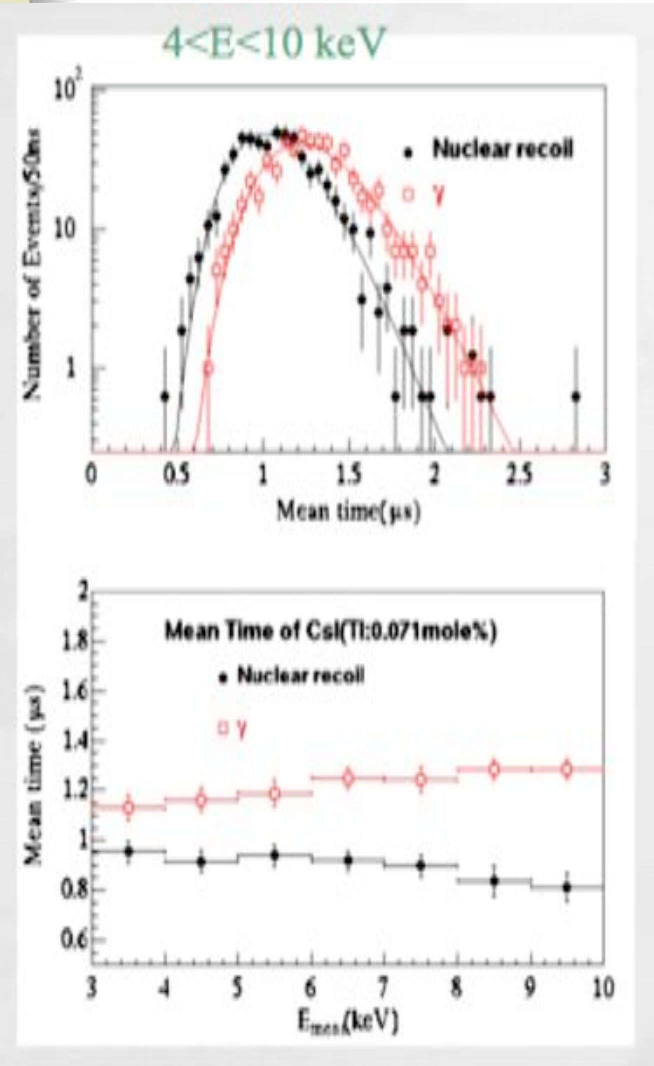
CsI(Tl)

	<Sp>	<Sn>
Cs-133	-0.370	0.003
I-127	0.309	0.075
Na-23	0.248	0.019

	CsI(Tl)	NaI(Tl)
Photons/MeV	~60,000	~40,000
Density(g/cm3)	4.53	3.67
Decay Time(ns)	~1050	~230
Peak emission(nm)	550	415
Hygroscopicity	slight	strong

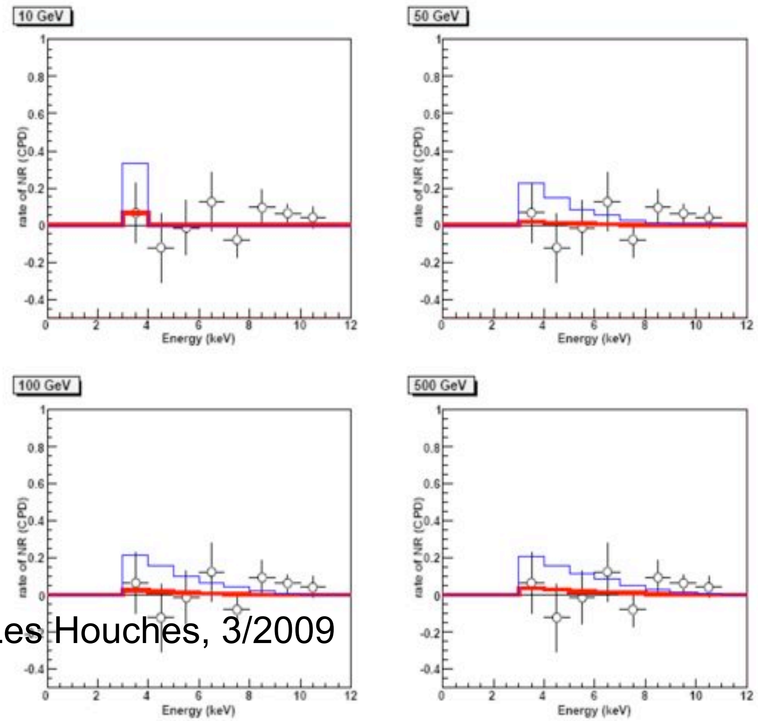
CsI(Tl) : 4 * 8.7 kg crystals

- Pulse shape discrimination on 3409 kg.d



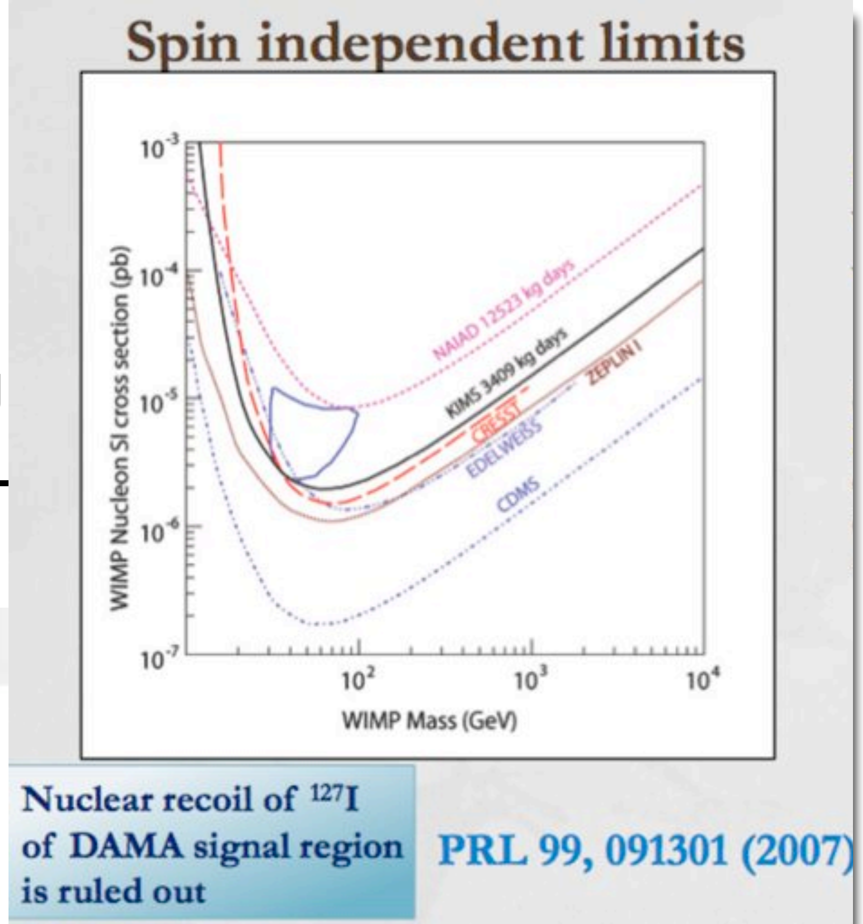
Data used for this analysis

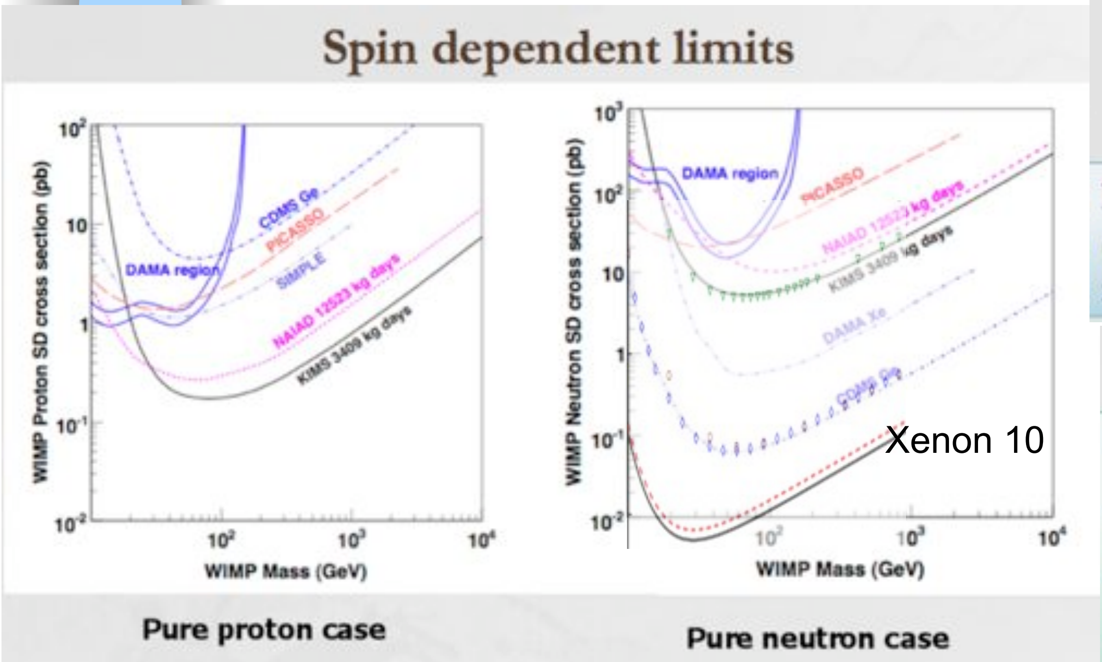
Crystal	p.e./keV	Mass(kg)	Data(kg·days)
S0501A	4.6	8.7	1147
S0501B	4.5	8.7	1030
B0510A	5.9	8.7	616
B0510B	5.9	8.7	616
Total		34.8	3409



KIMS : results

- Direct comparison with DAMA (same nucleus) for SI coupling
- Best limits on proton SD cross-section



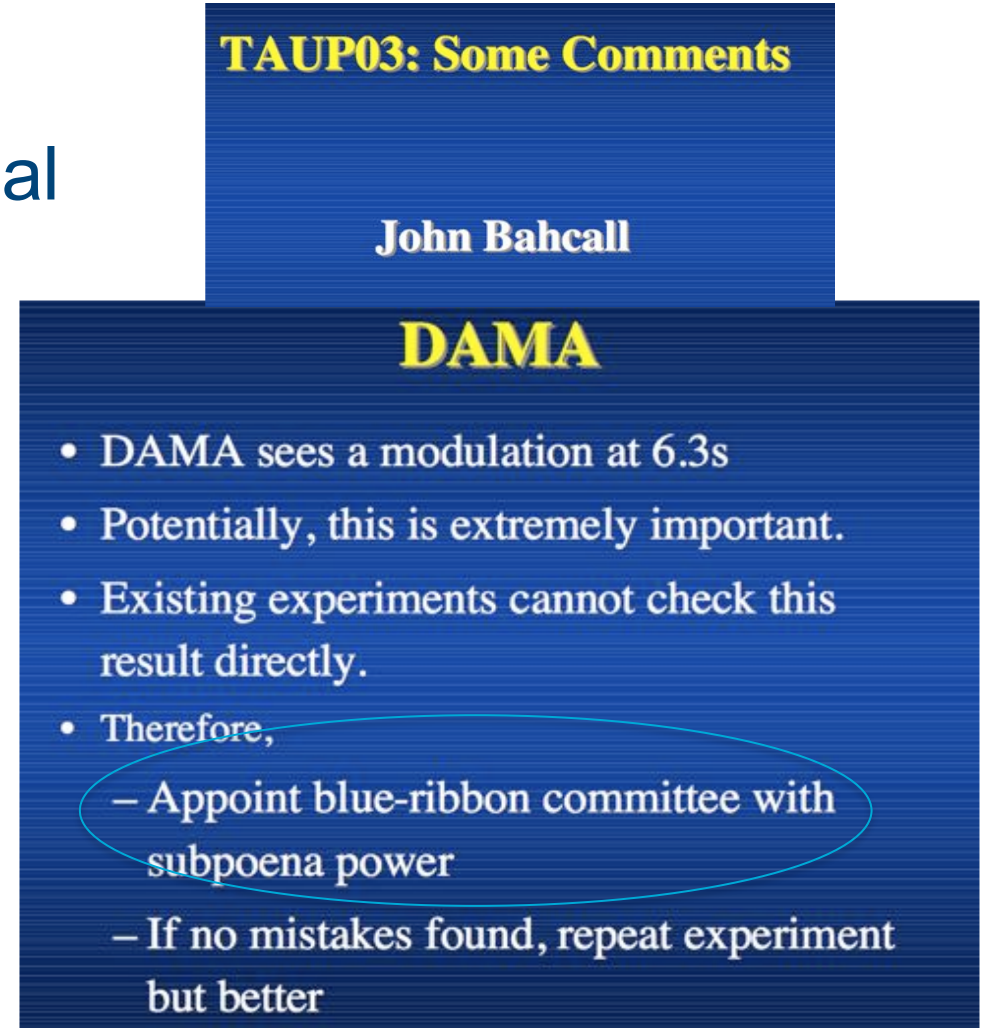


Latest News (sept 07)

- 12 crystals(104.4kg) installed in the shield
- 1st Calibration run was over
- Started data taking for annual modulation
- Expect a stable data taking for more than a year

DAMA LIBRA : how to go ahead ?

- Bahcall's proposal at TAUP2003



Conclusions

- Cryogenic detectors provide an excellent, although technically challenging, solution to the detection of WIMPs
- Two main techniques : charge-phonon (mainly Ge) and light-phonon (several potential targets) are complementary
- Surface events have been a big challenge for Ge detectors, but ZIP and Interdigit detectors provide nice strategy against this initial limitation (need for convergence ? Only one Ge expt)
- Light-phonon detectors offer potentially a multiplicity of targets, and do not suffer at the present level of sensitivity from surface effects
- Main problem for light-phonon detectors: phonon only events
- ≈ 2010 : decision on discriminating tonne-scale DM experiment in Europe (and similar process in the US)
- Cost for tonne-scale experiments (50-100 M€ range) requires convergence
- Xenon TPC and Ge appear at present as best candidates