Dark Matter Direct Detection using Cryodetectors

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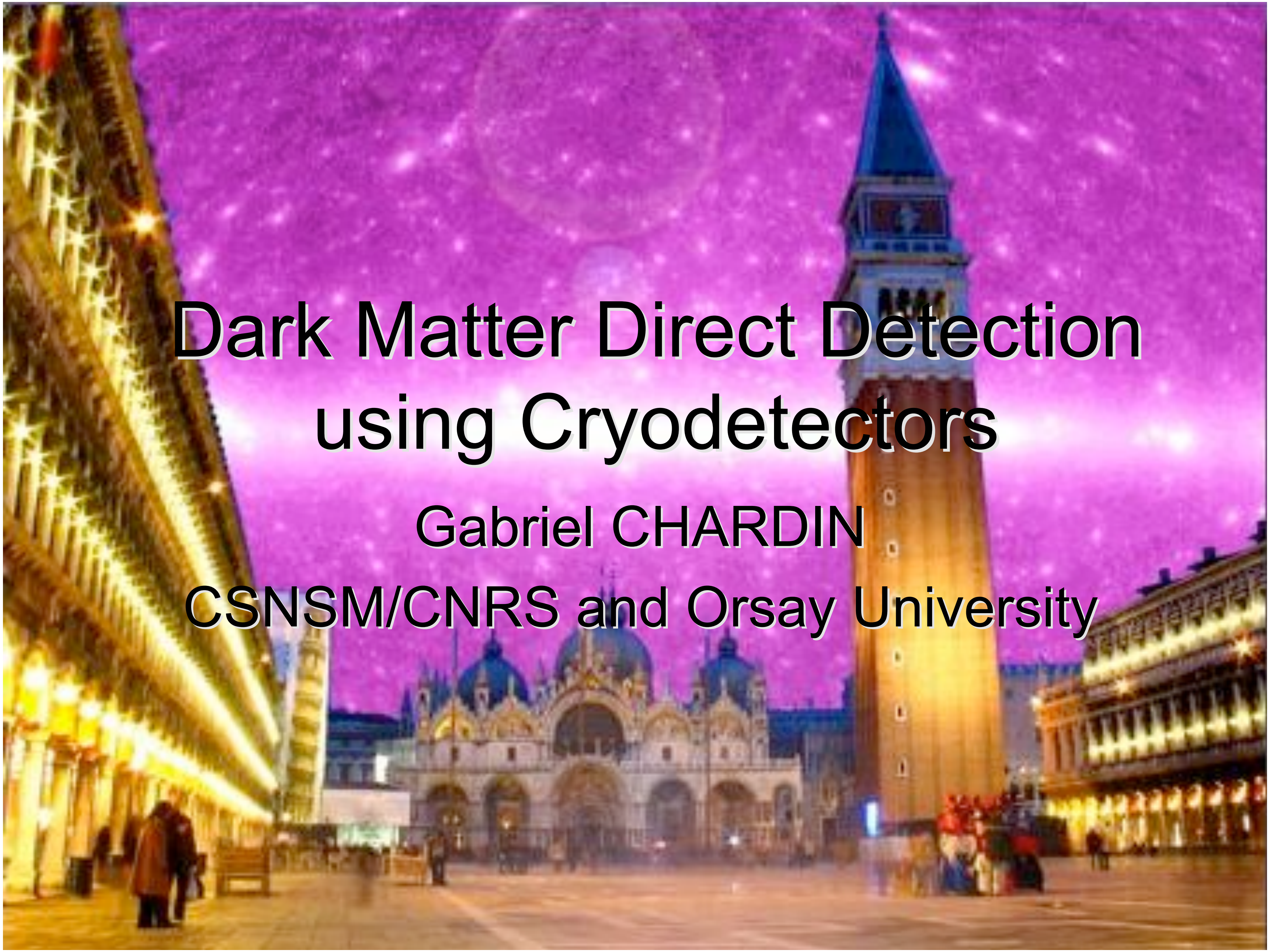
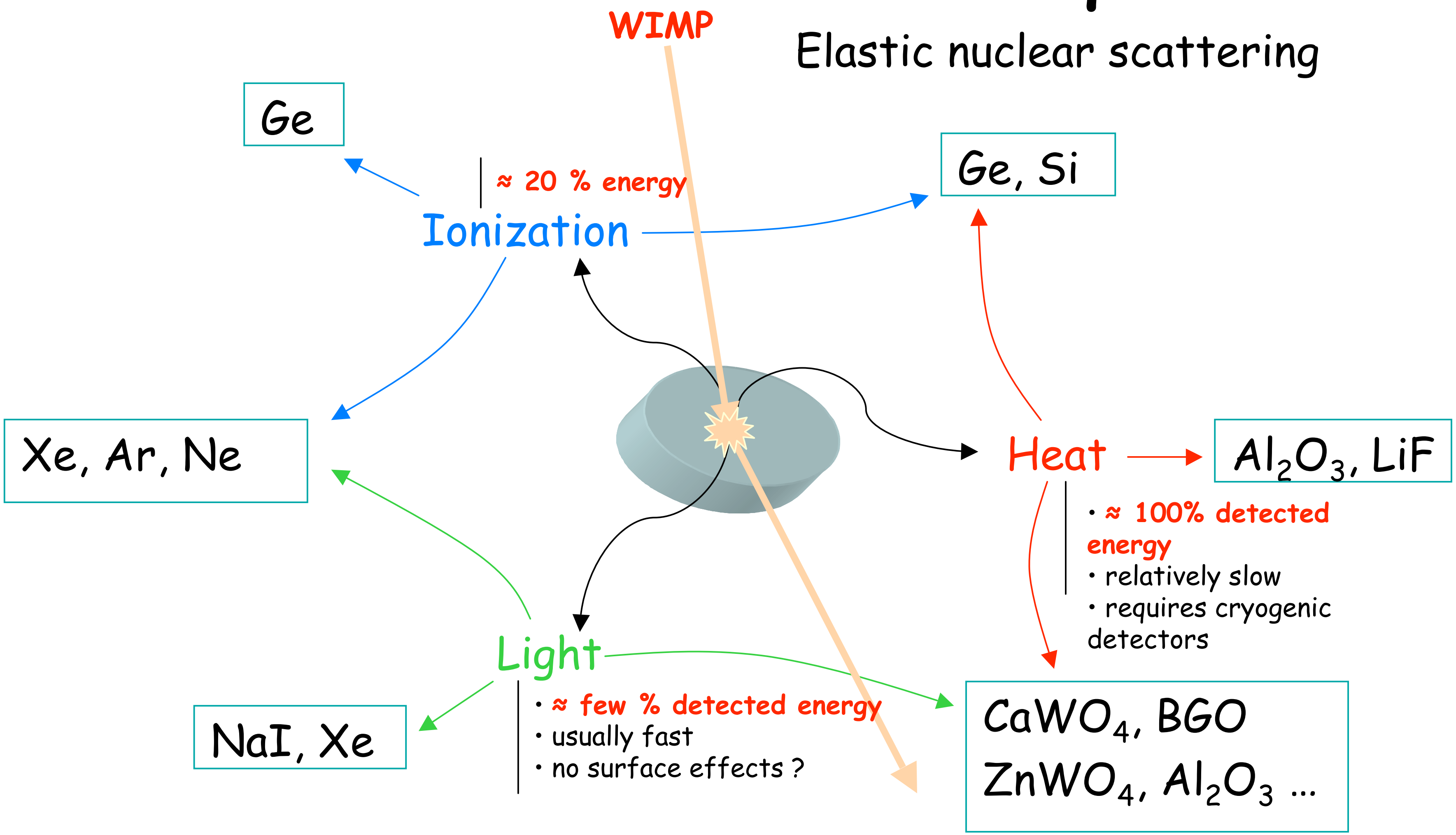


Outline

- What are we looking for ?
- Background discrimination is essential
- Main discrimination schemes
  - Ionization-phonon detectors:
    CDMS, EDELWEISS
  - Light-phonon detectors:
    CRESST, ROSEBUD
- Comparison with noble liquid/gas targets
- Conclusions

after Drukier and Stodolsky, PRD 30 (1984) 2295
(and Goodman and Witten (1985))

Direct detection techniques

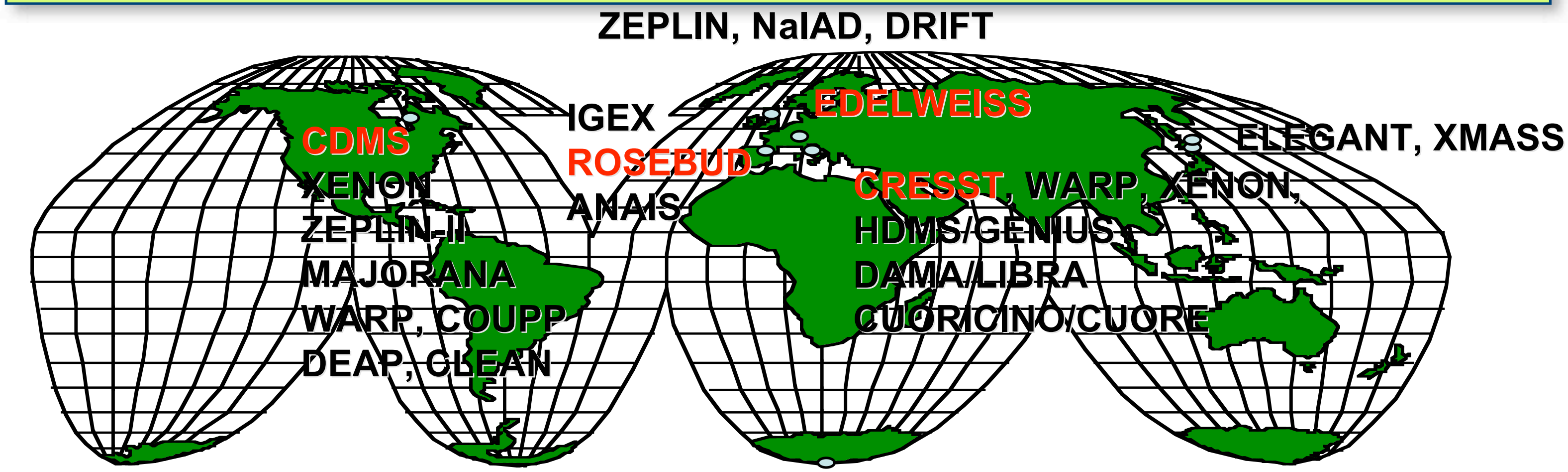


Some current direct detection experiments

Discrim.	Name	Location	Technique	Target	Status
None	CUORICINO	Gran Sasso	Heat	41 kg TeO2	running
	GENIUS-TF	Gran Sasso	Ionization	42 kg Ge in liq. N_2	running
	HDMS	Gran Sasso	Ionization	0.2 kg Ge diode	stopped
	IGEX	Canfranc	Ionization	2 kg Ge Diodes	stopped
Statistical	DAMA	Gran Sasso	Light	100 kg NaI	stopped
	LIBRA	Gran Sasso	Light	250 kg NaI	running
	NaIAD	Boulby mine	Light	65 kg NaI	stopped
	DRIFT	Boulby mine	Low pressure TPC	CS_2	running
	ZEPLIN-I	Boulby mine	Light	4 kg Liquid Xe	stopped
	XMASS	Kamioka	Light	100 kg Xe	running
Event-by-event	**CDMS-I**	Stanford	Heat + Ionization	1 kg Ge + 0.2 kg Si	stopped
	CDMS-II	Soudan mine	Heat + Ionization	5 kg Ge + 1 kg Si	running
	CRESST-II	Gran Sasso	Heat + Light	10 kg CaWO4	starting
	EDELWEISS-I	Modane	Heat + Ionization	1 kg Ge	stopped
	EDELWEISS-II	Modane	Heat + Ionization	10 kg Ge	starting
	XENON-10	Gran Sasso	Ionization + Light	10 kg Xe	starting
	WARP	Gran Sasso	Ionization + Light	3 kg Ar	running
	ZEPLIN-II	Boulby mine	Ionization + Light	10 kg Xe	starting
	PICASSO	SNO	Metastable gel		
	SIMPLE	Rustrel	Metastable gel		
	COUPP	Fermilab	Bubble chamber	Freon-type liquids	prototype

(Some) Wimp direct detection experiments

- CDMS-II (Ge and Si @ Soudan Mine, USA)
- EDELWEISS-II (Ge @ Fréjus, France)
- CRESST-II ($CaWO_4$, $ZnW0_4$) @ Gran Sasso, Italy
- ROSEBUD (CaWO4, Al2O3) @ Canfranc, Spain
- XENON-10 @ Gran Sasso, ZEPLIN-II @ Boulby, DRIFT, NaIAD
- WARP @ Gran Sasso, 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)
- XMASS, ELEGANT, LiF @Japan
- + Future experiments: SuperCDMS, EURECA , XENON-100, GERDA



Experimental challenges

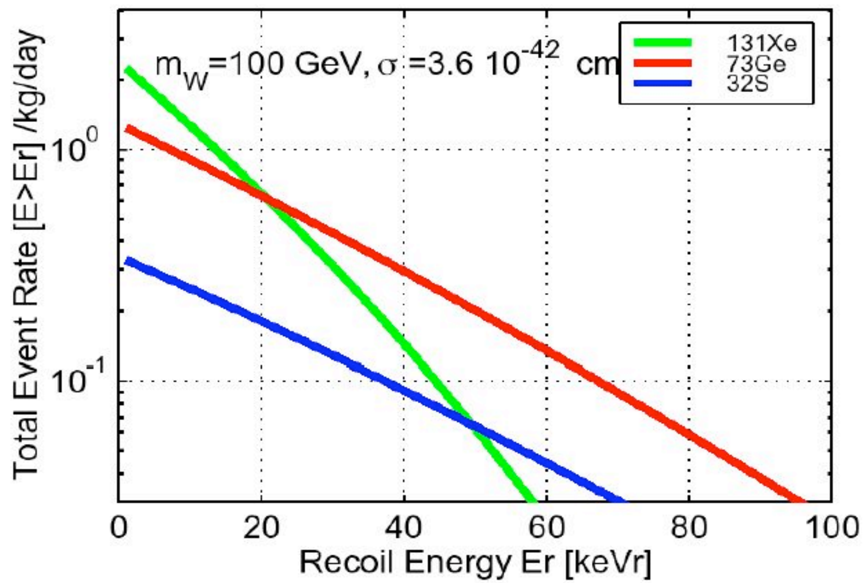
- Background suppression
  - Deep underground sites
  - Radio-purity of components
  - Active/passive shielding

- Large target mass required

- ~ few keV energy threshold

- Stability and reproducibility

- **Discriminate recoil populations**
  - **Photons scatter off electrons**
  - **WIMPs/neutrons off nuclei (few keV to few tens of keV)**
  - radon heavy nuclear recoils, alpha tails…



Expected Energy Spectra for a 100 GeV WIMP, illustrating the importance of the choice of detector material

CDMS II Collaboration

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Z. Ahmed, S. Golwala

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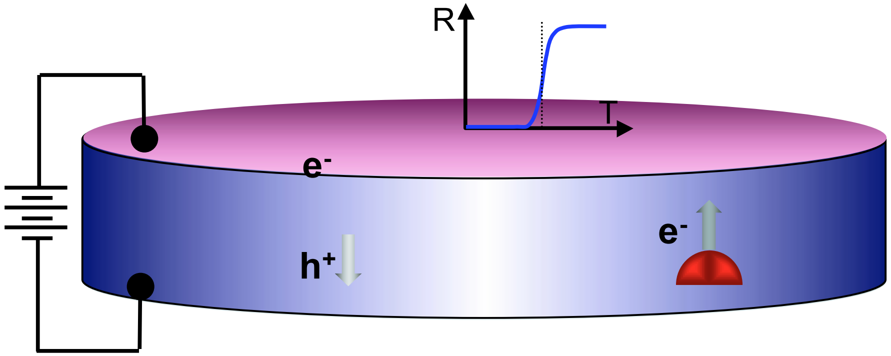
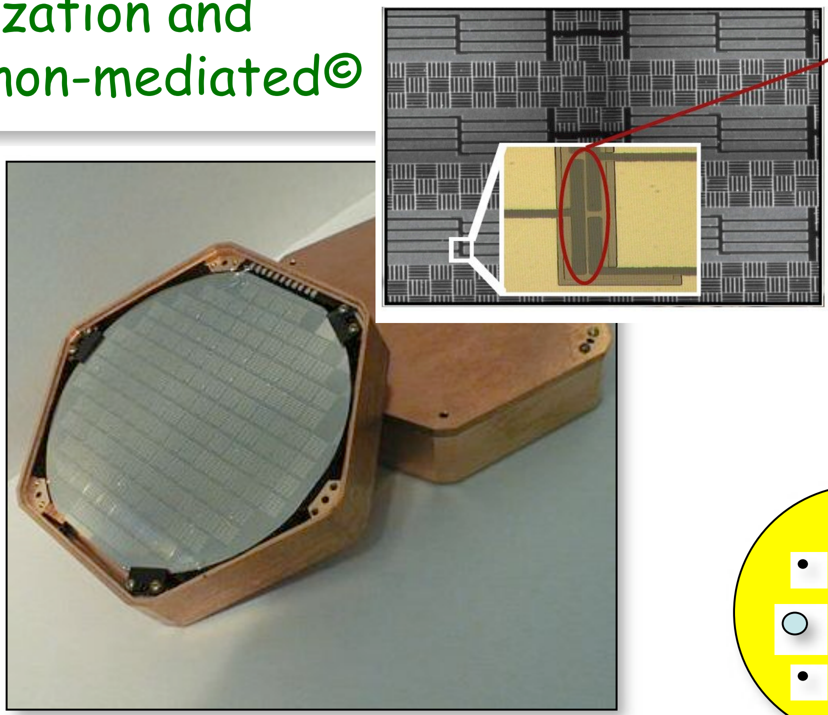
CDMS @ Soudan

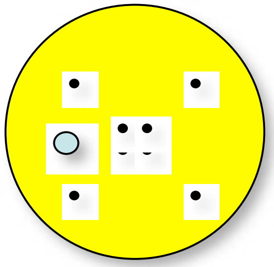


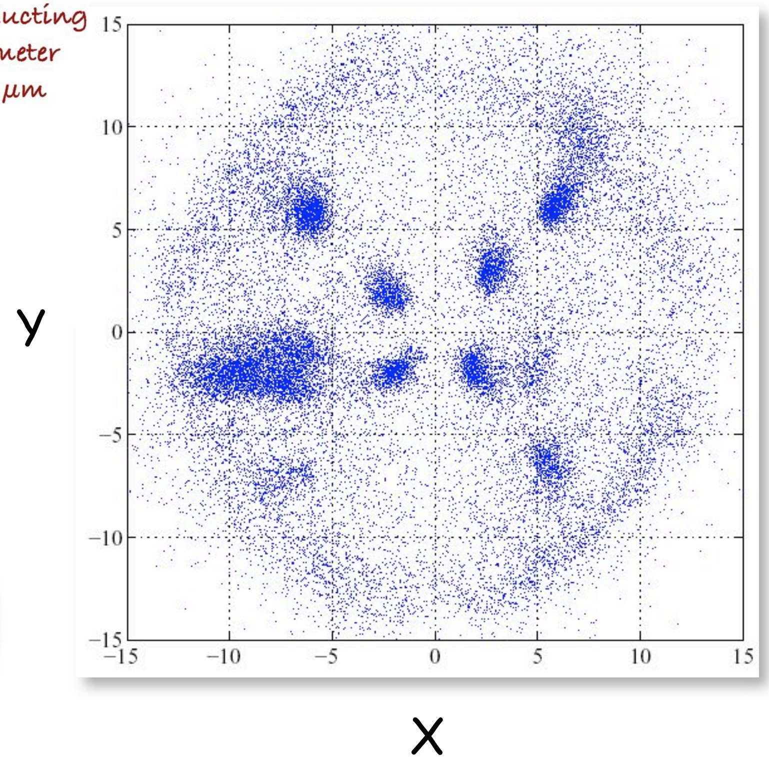
250 g Ge or 100 g Si crystal
1 cm thick x 7.5 cm diameter

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

Z-sensitive
Ionization and
Phonon-mediated©

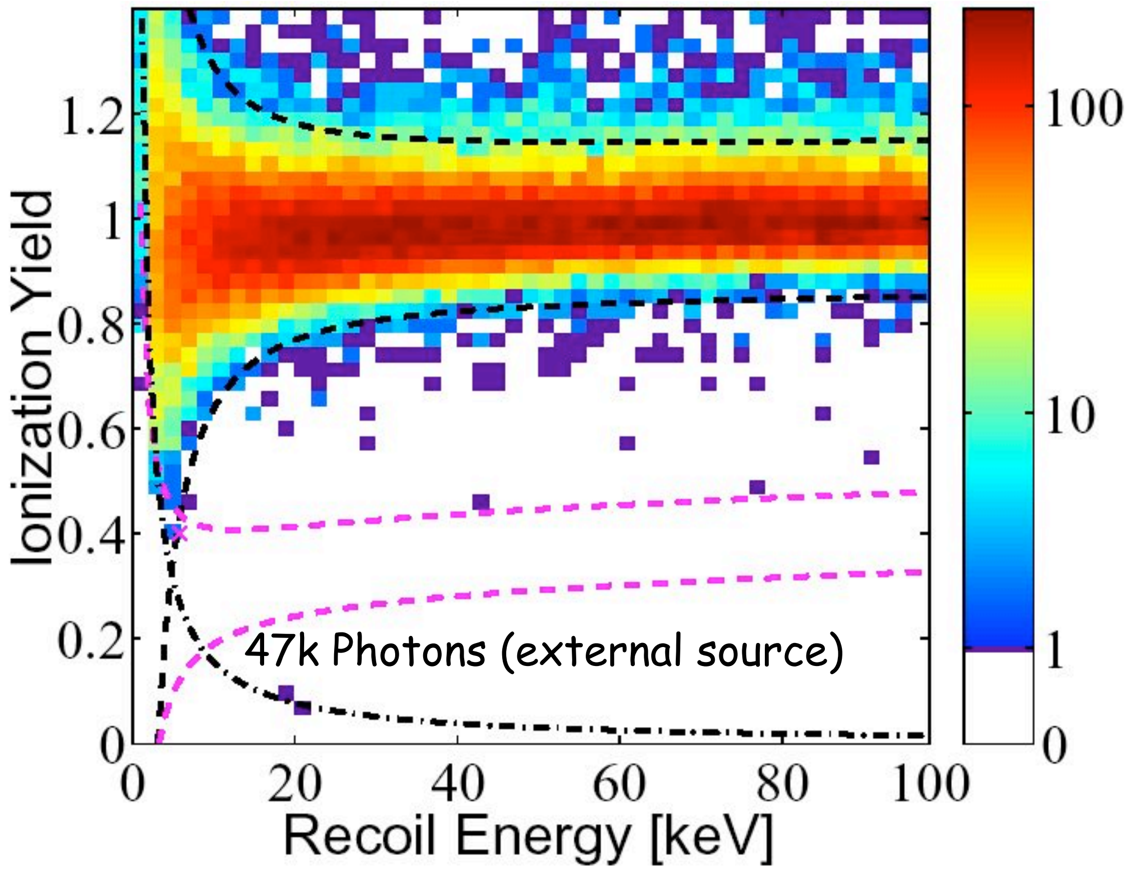






CDMS II Background Discrimination

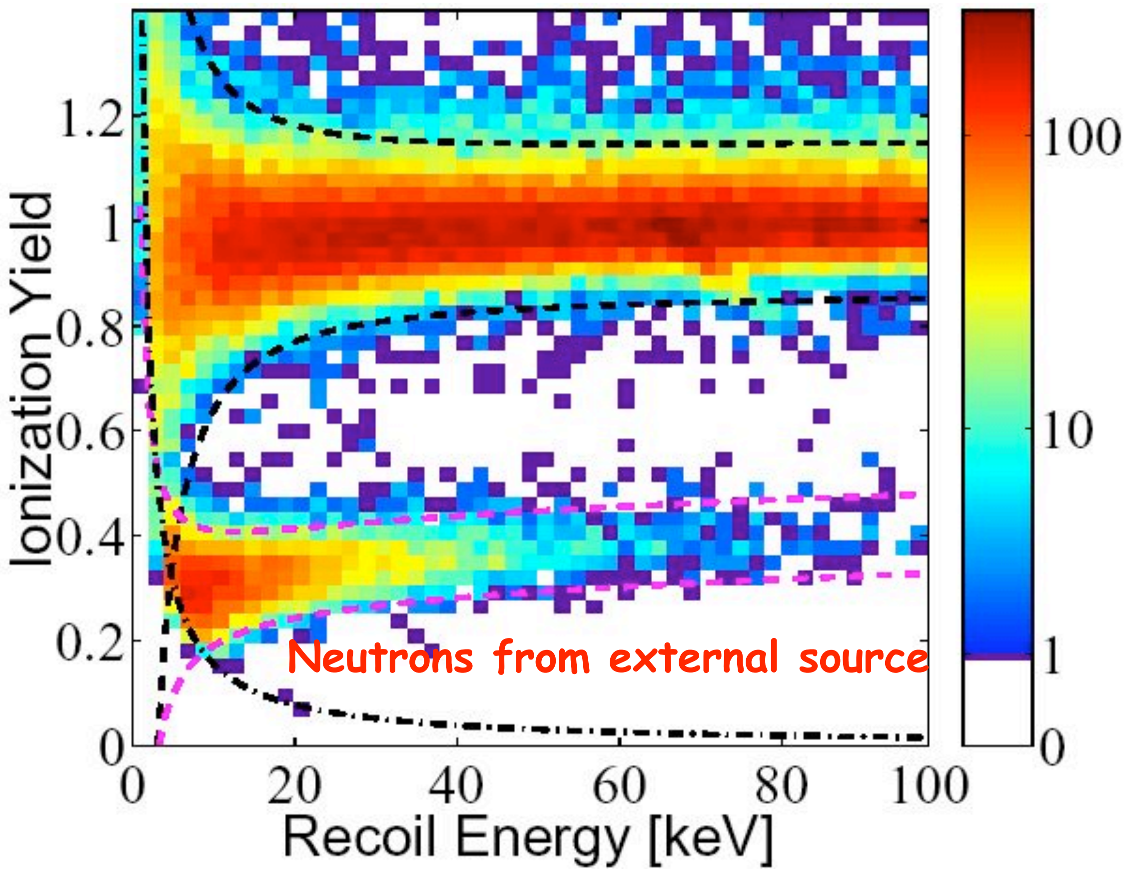
- Ionization Yield (ionization energy per unit recoil energy) depends strongly on type of recoil
- Most background sources (photons, electrons, alphas) produce electron recoils



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'

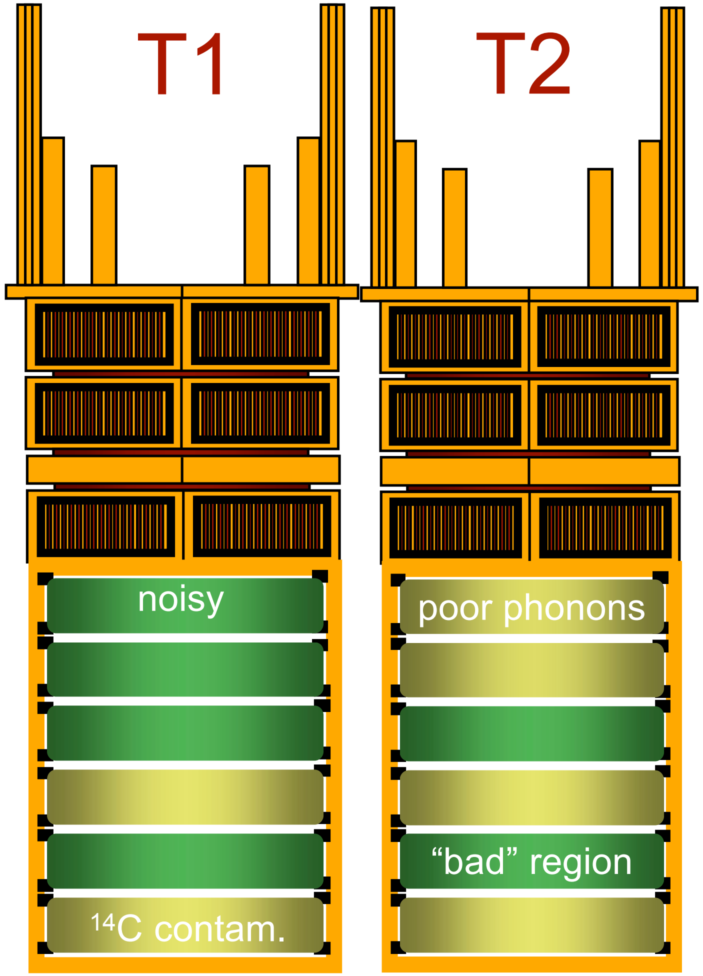


Ionization + Timing:

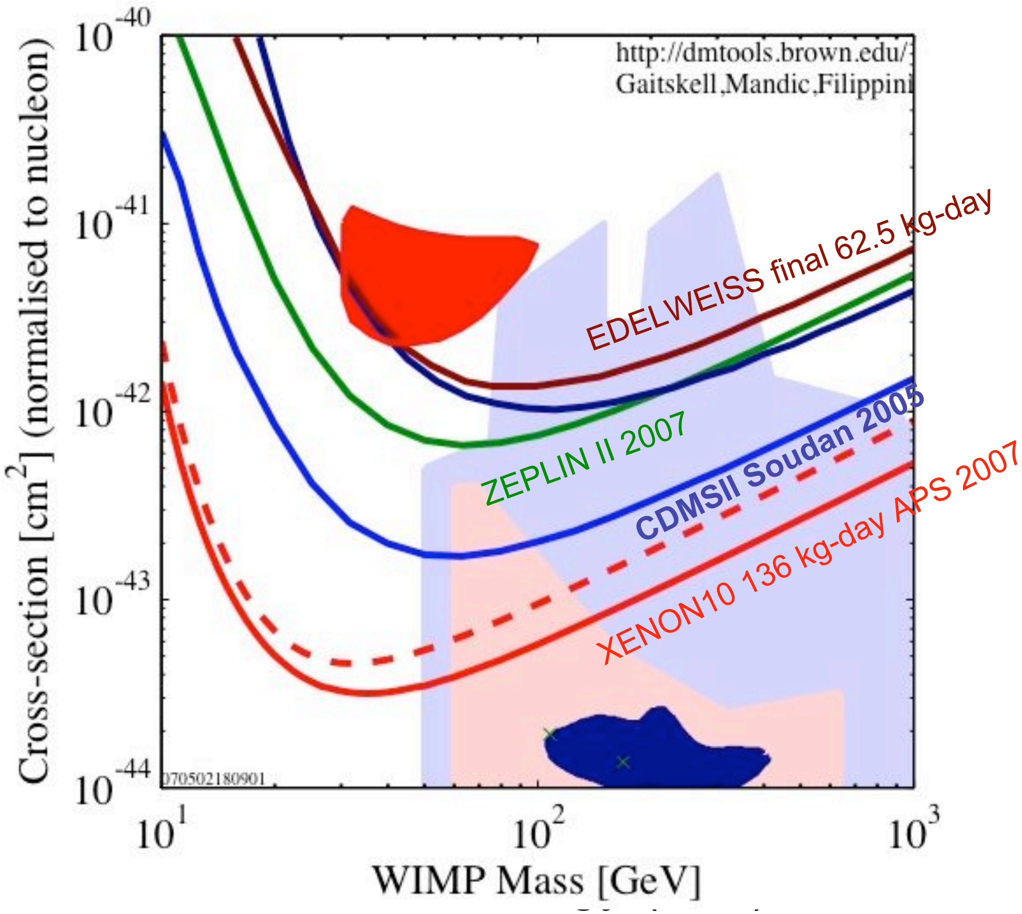
Reject **99.9998%** of **Gammas**, **99.8%** of **surface** events

(Ge 1 and 1.5 kg)

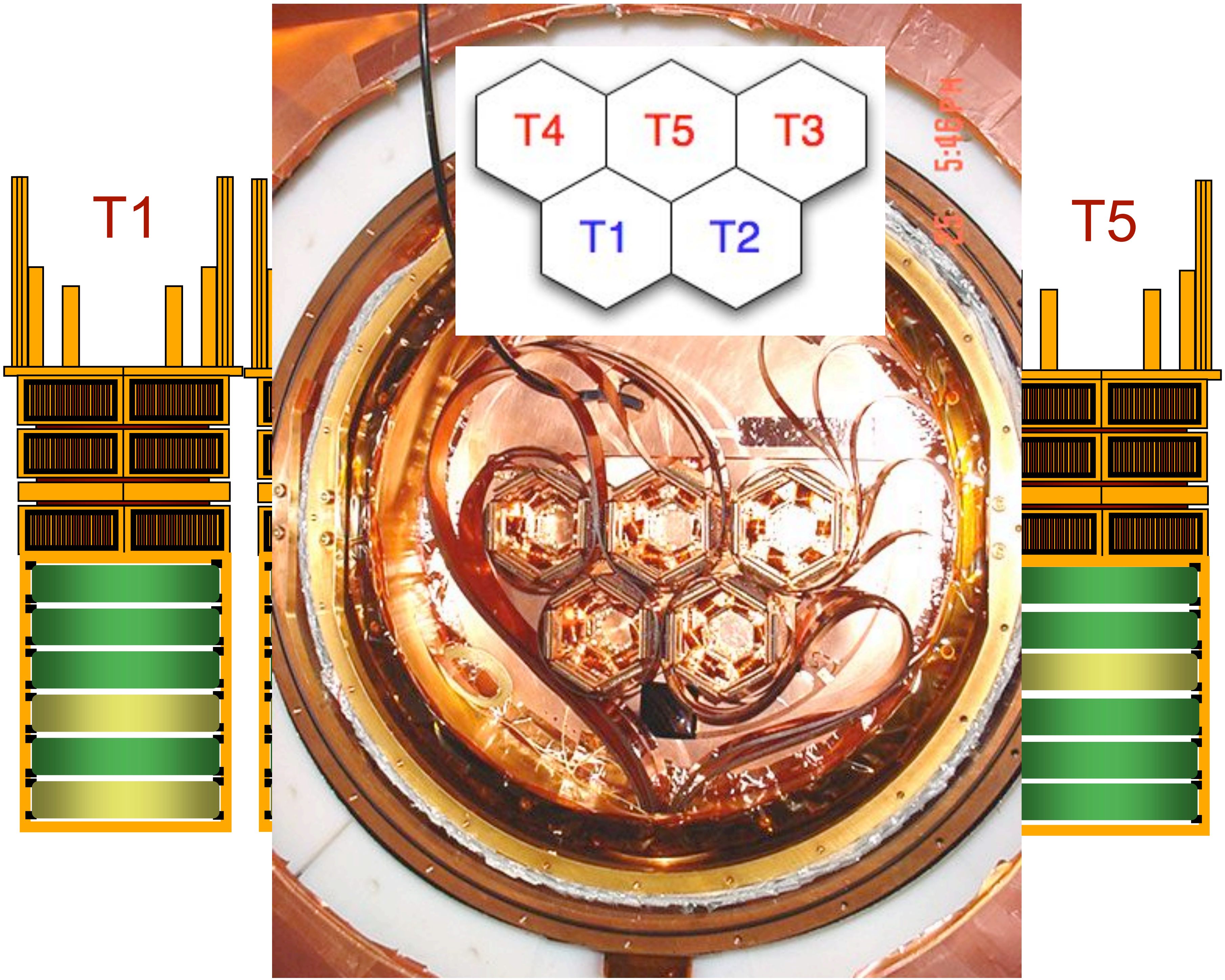
October 2003 January 2003: 52.6 kg.day
March 2004 August 2004: 96.8 kg.day



96.8 (31.0) kg-days



Phys. Rev. Lett. 96, 011302 (2006)


T1
T4
T5
T3
T1
T2
T5

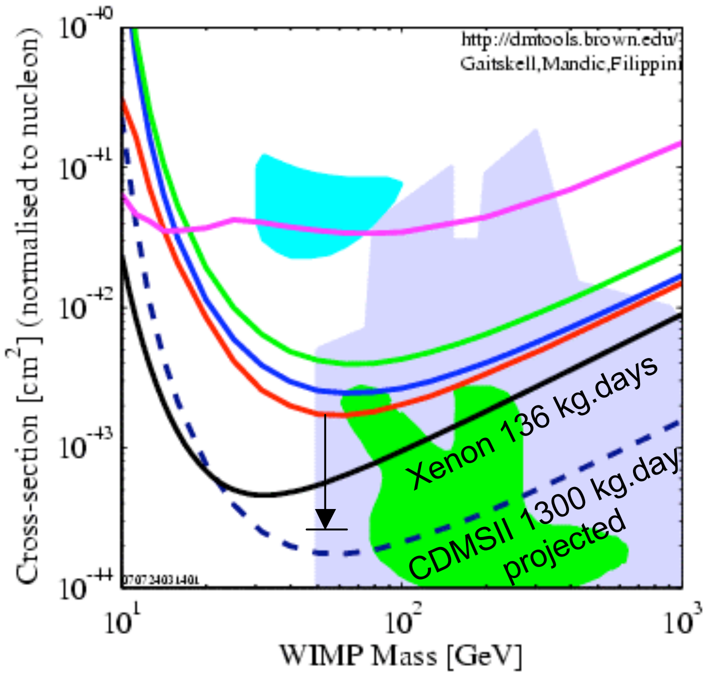
CDMS expected sensitivity increase

52.6 kg.days
10/2003 to 01/2004

93.1 kg.days
03/2003 to 08/2004

653 kg.days
10/2006 to 03/2007
1300 kg.days
04/2007 to …

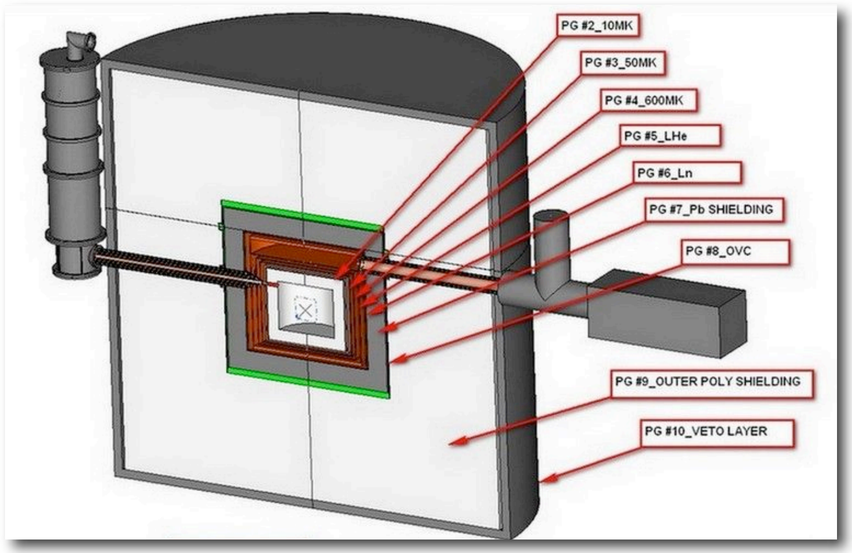
The analyses planned to be finalized by this fall



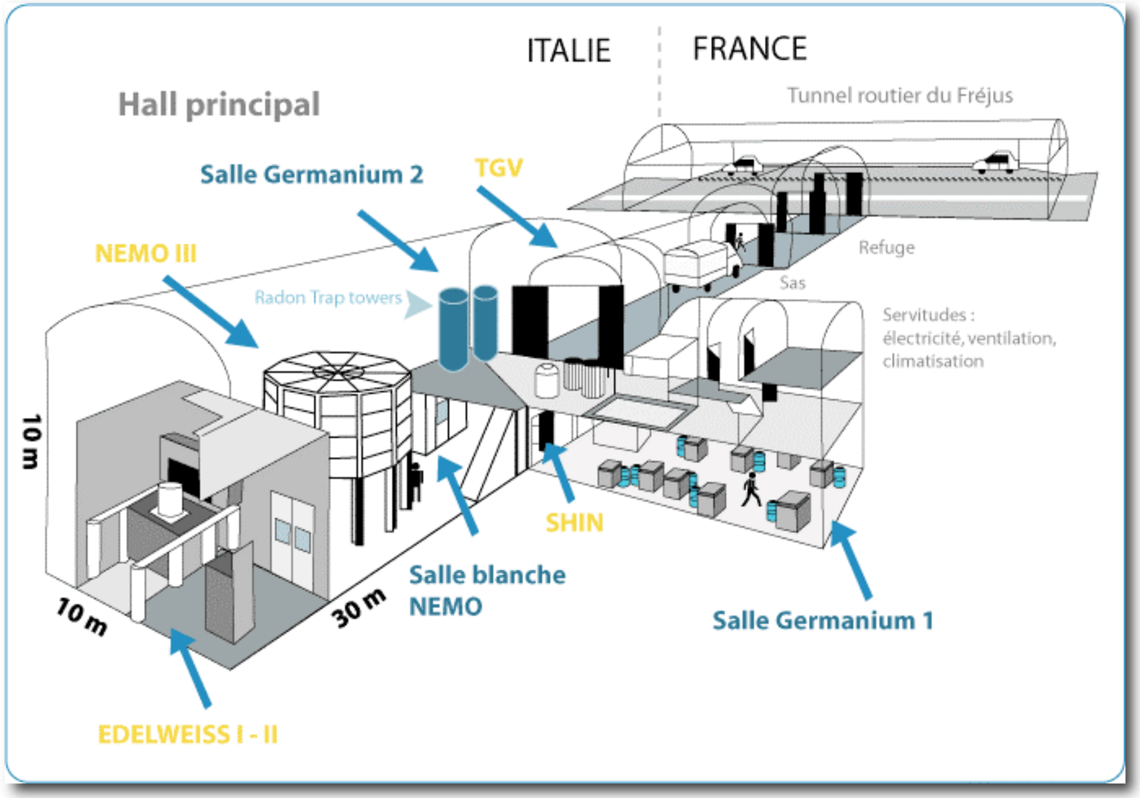
Strategy: zero background
Hence no background subtraction…

From CDMS-II in Soudan to SuperCDMS in SNOLab

- Talk by J. Fillipini, PS7



EDELWEISS, Modane Underground Lab

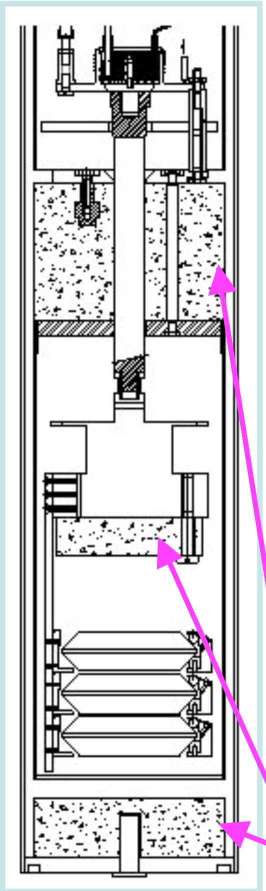


- 1700 m depth in the Fréjus Tunnel (4800 we)
- 4 μ/m^2/day ($\approx 2 \times 10^6$ less than at the surface)
- 1500 neutrons (>1 MeV)/m^2/day (rock radioactivity)

EDELWEISS I: 1kg (stopped)

3 x 320g detectors, 1 liter experimental volume, cryostat made with low radioactivity materials in the Frejus Underground Laboratory

External shield: 30cm paraffin, 20cm lead and 10cm copper



1st data taking: 4.5 kg.d
Fall 2000 GeAl5,GeAl6,Ge8

2nd data taking : 8.6 kg.d
Spring 2002 GGA1,GeAl9,GeAl10

3rd data taking : 19 kg.d
Oct.-Mar 2002 GGA3, GSA1, GSA3

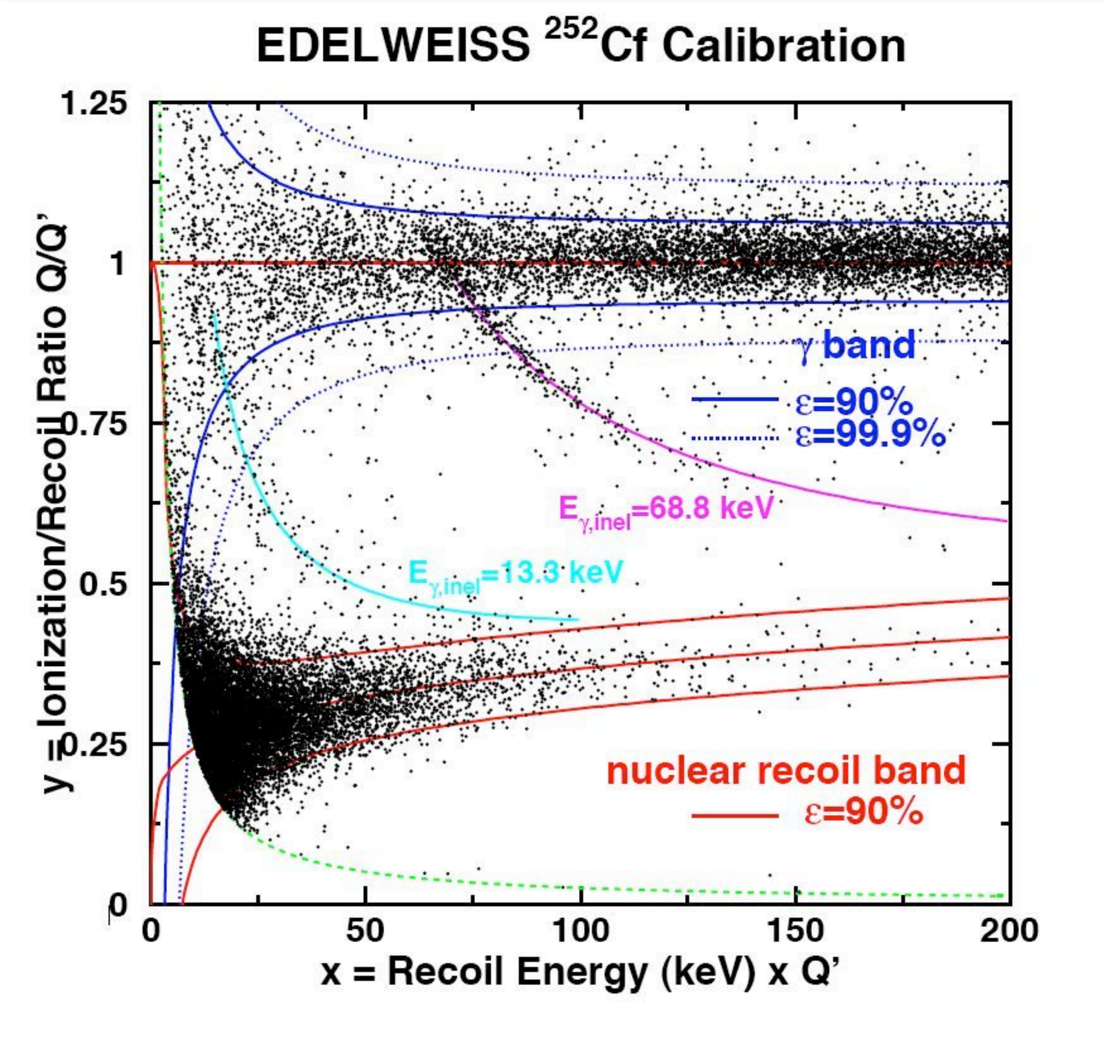
4th data taking : 30 kg.d
April-Nov 2003 GGA3, GSA1, GSA3

Total exposure : 62 kg.d fiducial

Archeological lead

Edelweiss: event-by-event discrimination

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



Neutron + gamma calibration

Nuclear recoil discrimination down to 20 keV threshold :

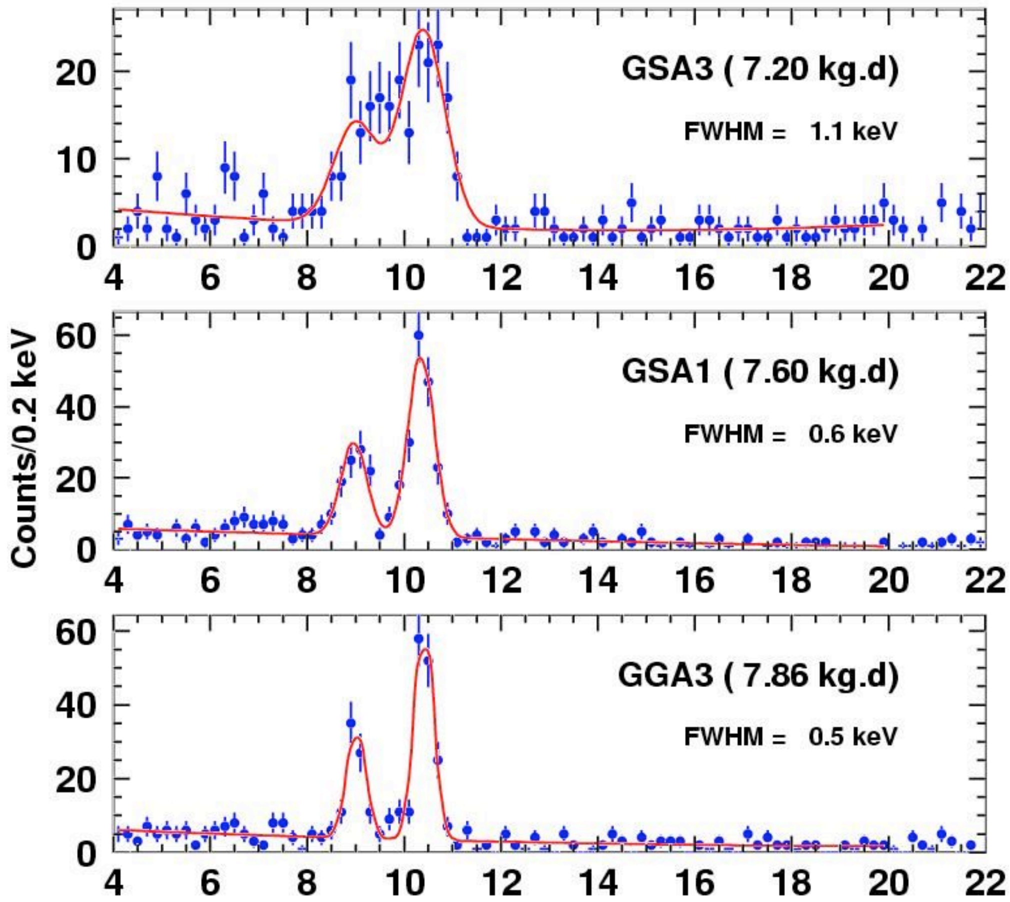
γ-ray rejection > 99.99 %

EDELWEISS thermal detectors: excellent energy resolution

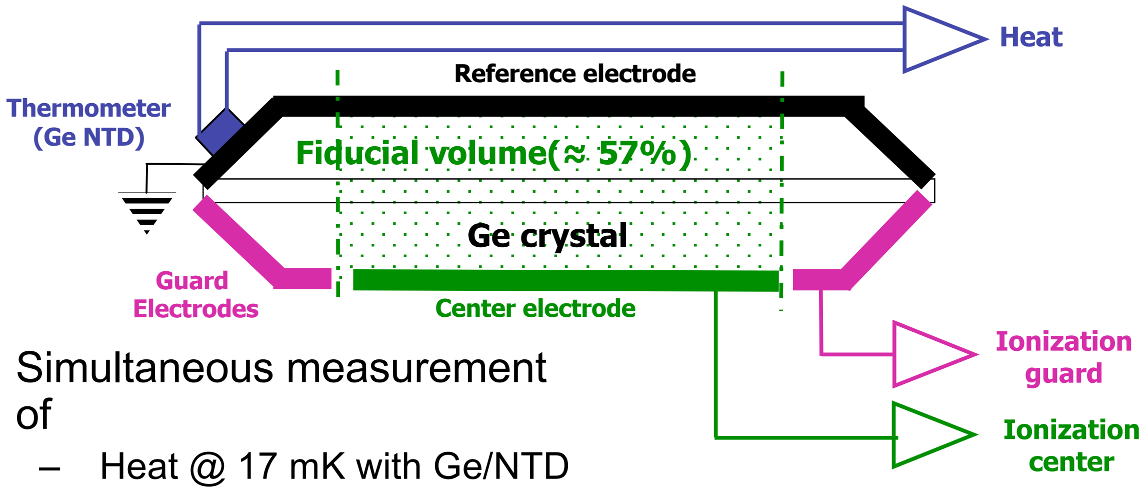
- Sub-keV energy resolution on phonon channels (300eV FWHM on two detectors)
- ≈1 keV FWHM on charge channels

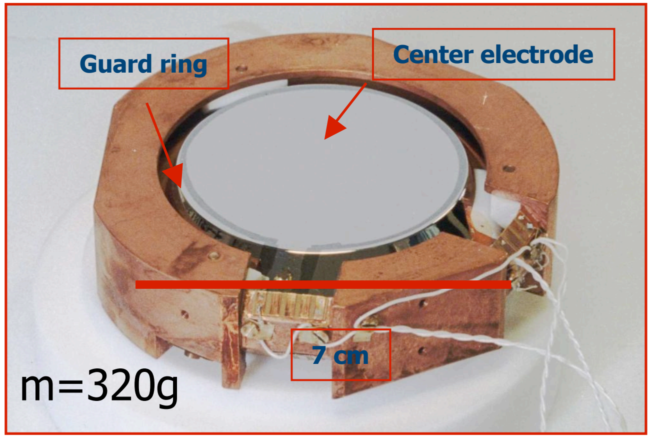
- Background comprehension down to a few keV e.e.

stable over periods of months

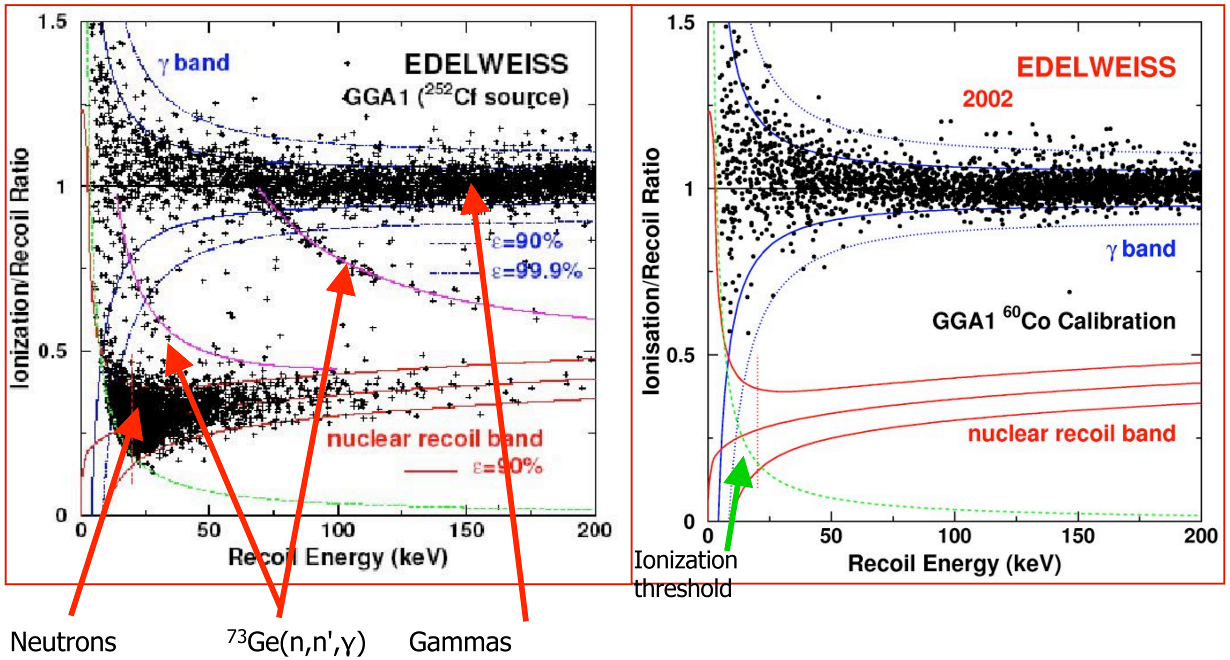


Heat and Ionization Ge detectors





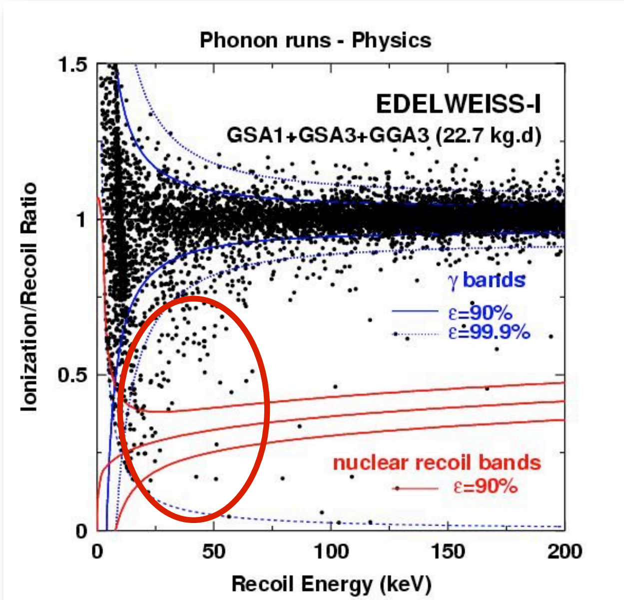
- Simultaneous measurement of
  - Heat @ 17 mK with Ge/NTD sensor
  - Ionization @ few V/cm with Al electrodes
- Different charge/heat ratio for nuclear and electron recoils (WIMP and neutron have lower charge than γs, βs)
- Discrimination event-by-event of electron recoils (main background)
  - E_I/E_R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

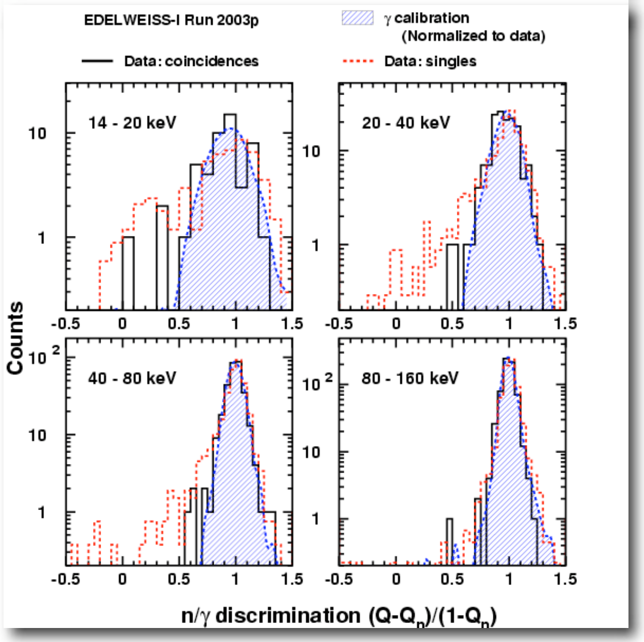


EDELWEISS-I limitations

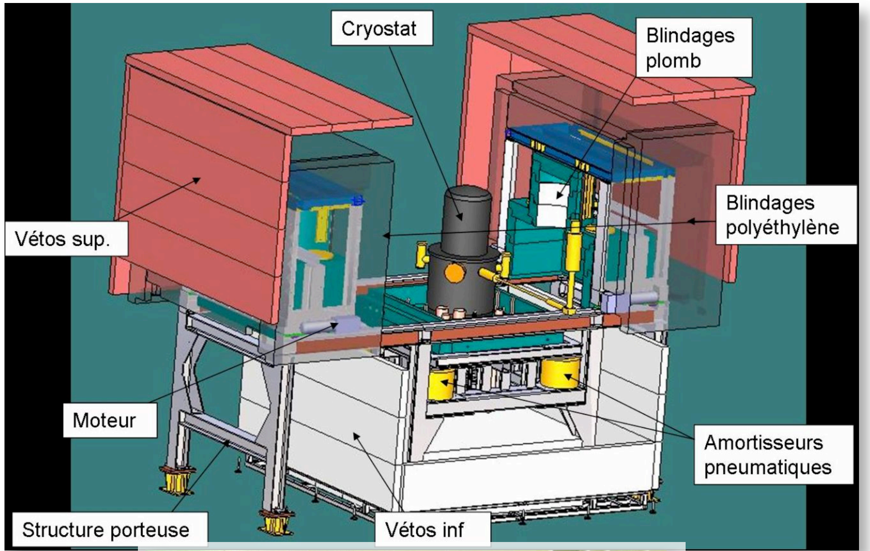
- Several runs between 2000 and 2003
- Last run = data taking with trigger on heat signal
- Improved efficiency at low energy (50 % at 11 keV)
- Stable behavior over 4 months of the detectors
- Fiducial exposure: 22 kg.d
- 18 nuclear recoil candidates > 15 keV

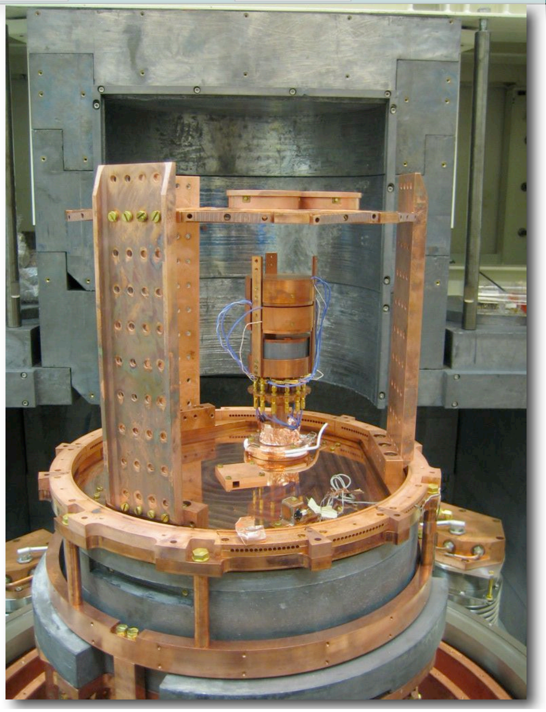
- Possible backgrounds
  - Residual neutron flux
    - 1 n-n coincidence observed
    - 2 single expected by MC
  - Surface electron recoils
    - Miscollected charge events at low energy
    - Leak of events down to the nuclear recoil band not visible in coincidence events
- Further, studies concerning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





Edelweiss-II improvements





- **Radiopurity**
  - Dedicated HPGe detectors for systematic checks of all materials
  - **Clean Room** (class 100 around the cryostat, class 10 000 for the full shielding
  - **Deradonized air** -from NEMO3 radon trap- from 10 Bq/m3 to 0.1 Bq/m3
  - Thicker shield : 20 cm Pb shieding
- **Neutron Shielding**
  - EDW-I : 30 cm paraffin
  - EDW-II : **50 cm PE** and better coverage
- **μ veto** (>98% coverage)
  - Neutron detectors in coincidence with veto under development (Karlsruhe/Dubna)

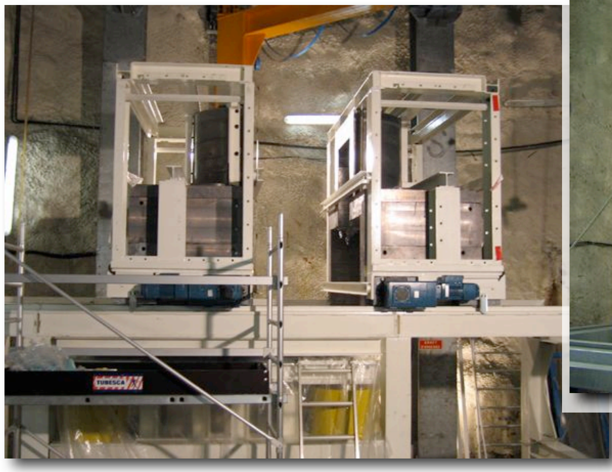
- =>**Aimed sensitivity (EDW-I * 100)**

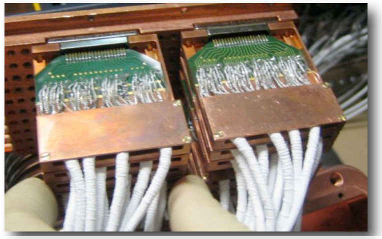
  $\sigma_{w\text{-}n} \approx 10^{-8}$ pb with 15 to 30 kg

  0.002 evt/kg/day (Er>10keV)

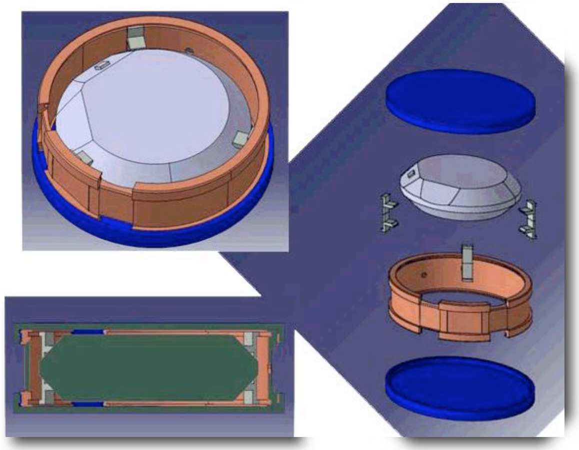
  = neutron coming from not tagged μ interacting in the rock

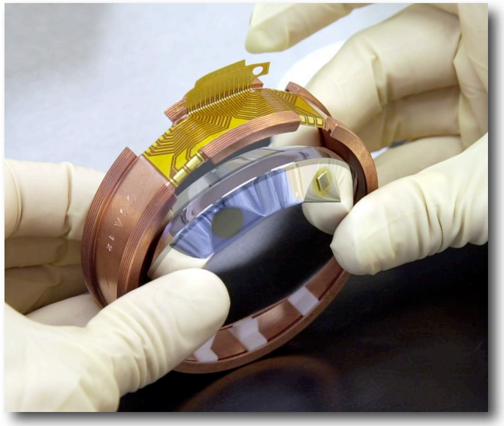
Installation 2005-mid 2006





First phase of EDELWEISS-II





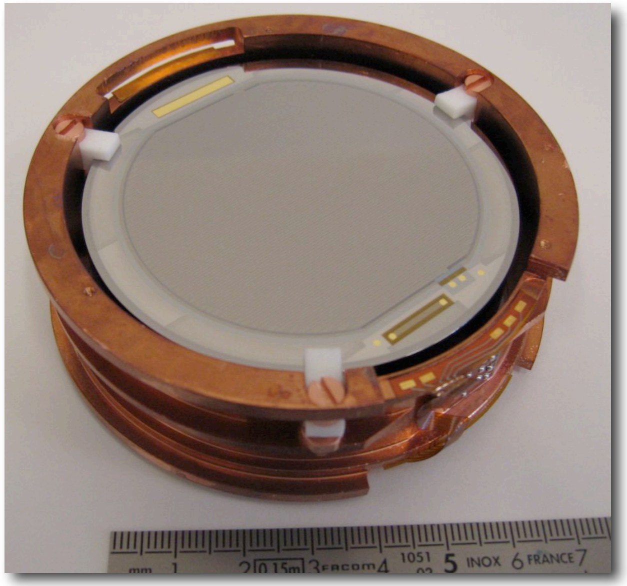
23*320g Ge/NTD

♦ Developed by CEA Saclay and Camberra-Eurisys

♦ Amorphous Ge and Si sublayer (**better charge collection for surface events**)

♦ Optimized NTD size and homogeneous working T (16-18 mK) : **keV resolution**

♦ New holder and connectors (Teflon and copper only)

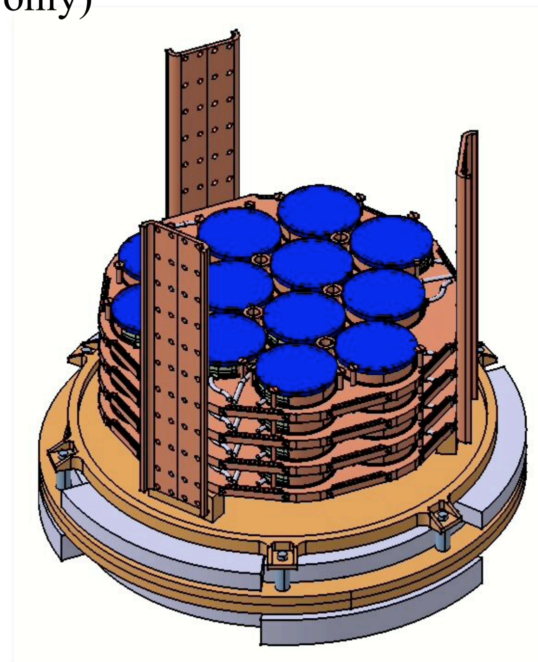


7*400g Ge/NbSi detectors

♦ Developped by CSNSM Orsay

♦2 NbSi thin films thermometer for **active surface events rejection**

♦Still under R&D with 200g detectors in labs



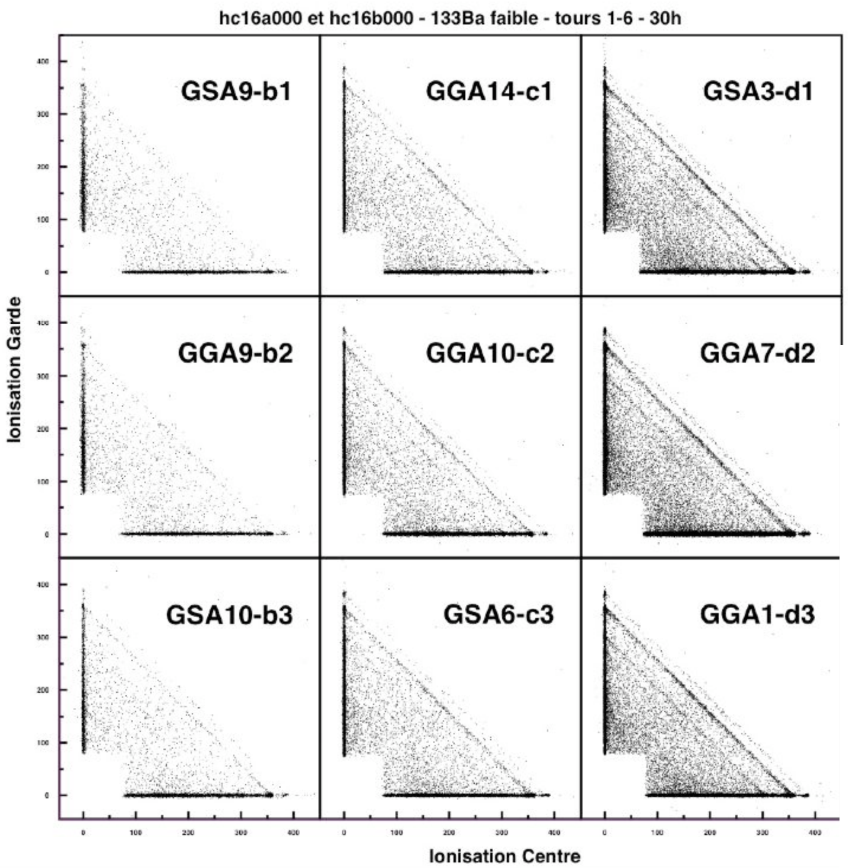
May 20th, 2007 : 28 detectors installed

22 * 320 g NTD
1 * 70 g Ge73 NTD
1 scintillator/phonon det
2 200 g NbSi (600 Angs)
1 400 g NbSi (125 Angs)

Some results from commissioning runs

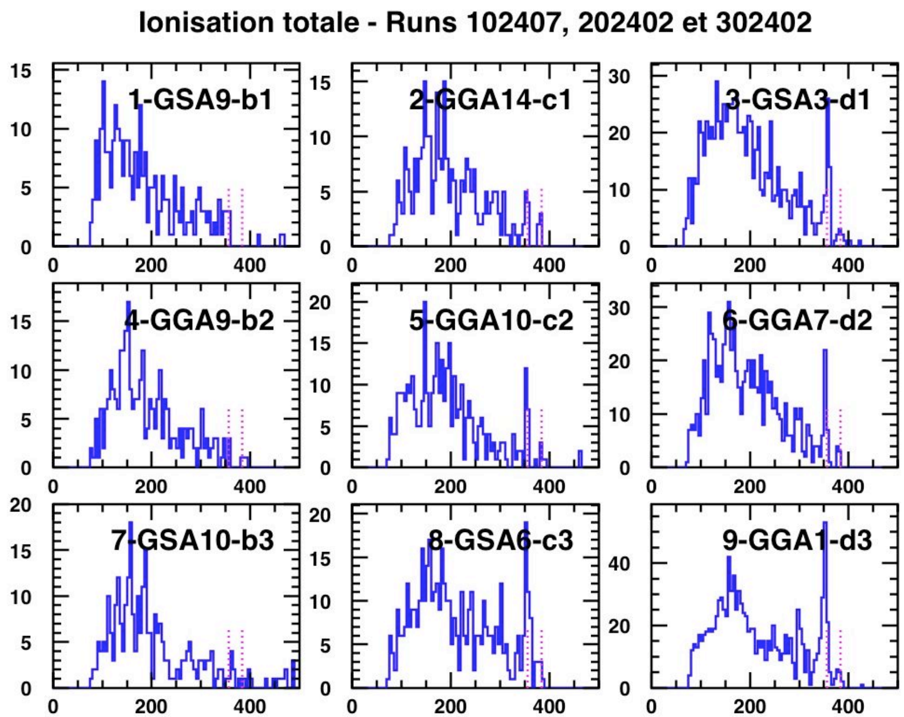
- Resolution
  - Charge : at around 2 keV, some of order 1 keV, = Edw1)
  - Heat : still limited by noise induced by « cold making » machines (pulse tubes, reliquefier) few keV (<1 keV in Edw1)
- Stability with time
  - Cryo : ok when working, but still pbs with pulse tubes
  - Noise : can be reduced
- Reproducibility between detectors (NTD)
  - Out of 21 NTD : 2/3 are ok = all three detector channels with good resolutions

Calibrations with 133 Ba



example of ionisation monitoring plots

3 « towers »

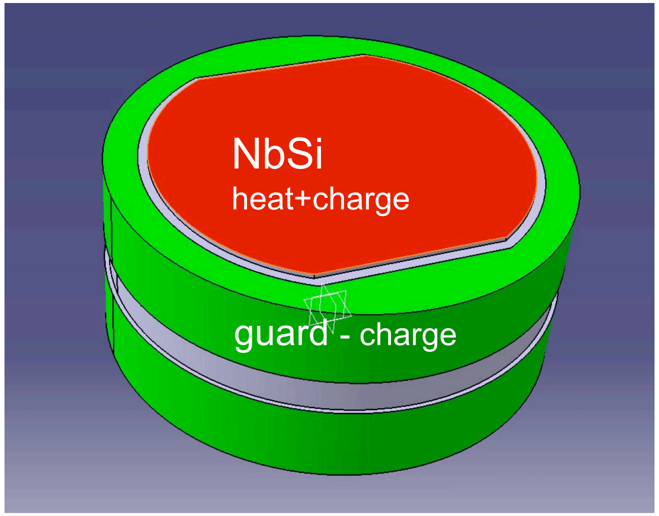


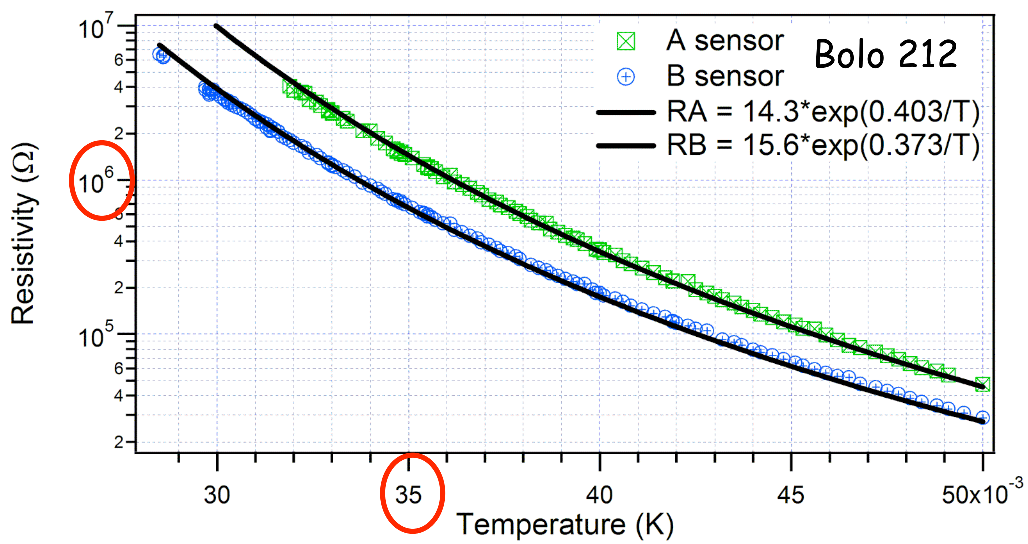
Bolometer design.

- 200 g or 400 g Ge absorber
- a-Si sub-layer
- Nb or Al electrodes (guard) – Nb 500 μm interdigitized electrodes (centre)
- Two a-Nb_xSi_{1-x} thin film sensors (60 nm thick, x~0.085)
- Pd heating, Au pad thermal link

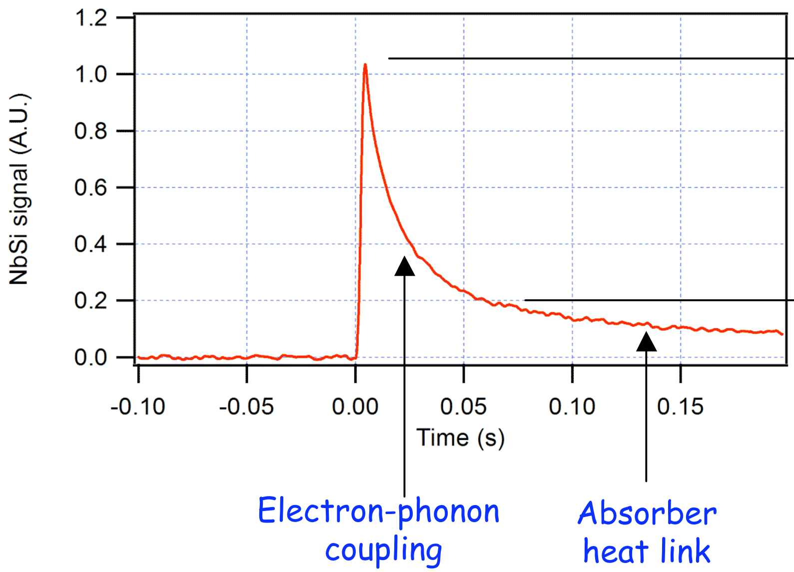
NbSi used to collect centre charges and measure heat signal
Comb design: increased sensitivity to local heating (surface events)

Same design for the two sides





Sensitivity to high-energy phonons



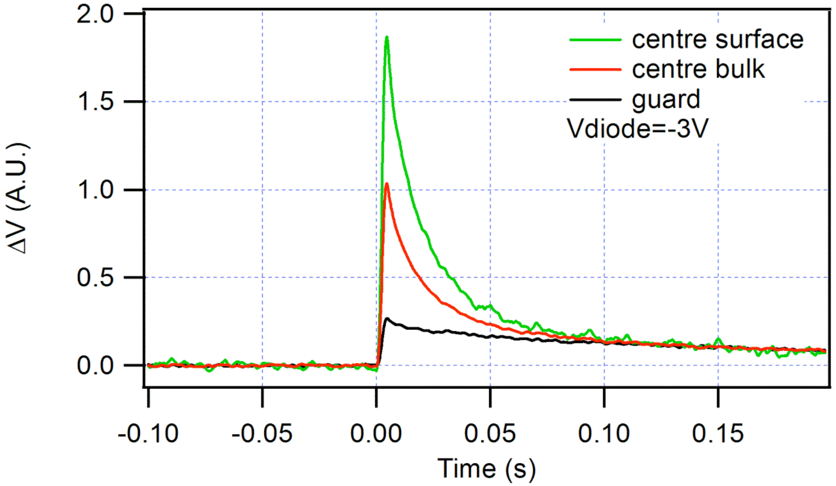
$\Delta T_{transient} = \varepsilon E/C_e$

Double exponential decay time
Direct absorption of high energy phonons by the NbSi

$\Delta T_{thermal} = E/C$

Ge ionization-heat detectors:

$$\Delta T_{transient} = \frac{\varepsilon_{ph} E_{phonons} + \varepsilon_L E_{Luke} + \varepsilon_R E_{Recomb}}{C_e}$$



modeling of the pulses at various V_{diode} (Bolo212):

$2\% < \varepsilon_{ph} < 30\%$, z dependence (r dependence?)

$2\% < \varepsilon_L < 4\%$ r dependence

$0 < \varepsilon_R < 20\%$ r dependence

r dependence (very off z-axis events have lower amplitude)
z dependence : probe near-NbSi surface events

z - surface identification

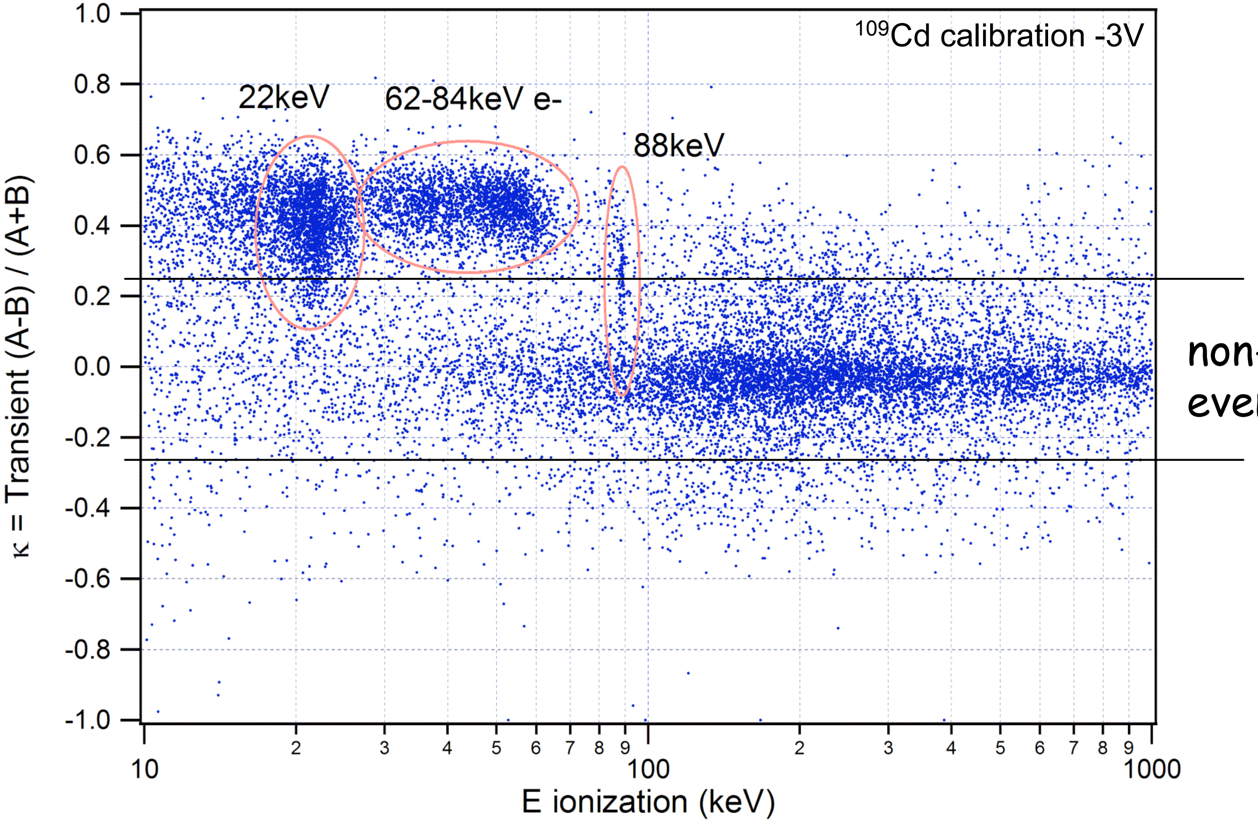
^{109}Cd source facing the top (A) NbSi sensor

Localization factor: $\kappa = \dfrac{Tr_A - Tr_B}{Tr_A + Tr_B}$

$|\kappa| > 0.3$ rejects 97% of near surface events
rejects events less than 2 mm underneath the NbSi
no energy dependence below 100 keV

^{109}Cd energies and absorption lengths

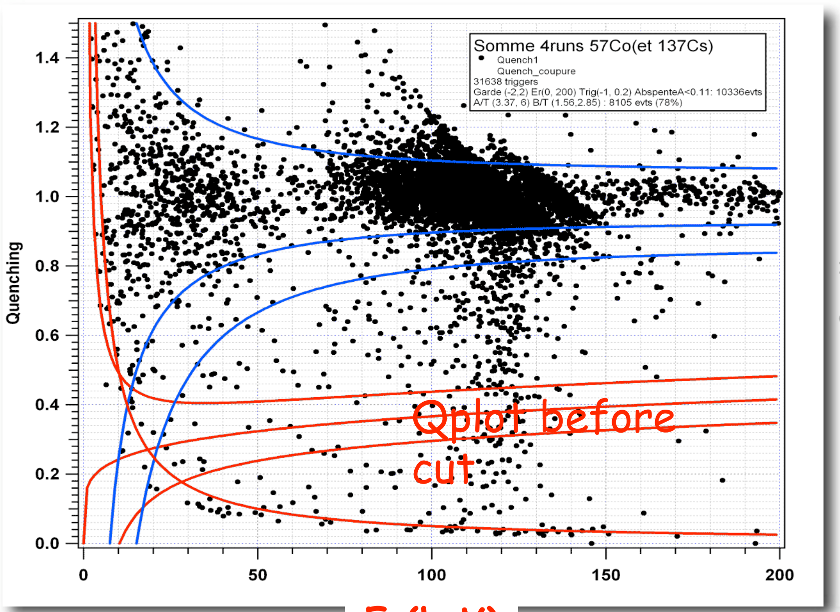
18 keV electrons	4 μm	charge deficit
22 keV X-rays	58 μm	small deficit
25 keV X-rays	82 μm	small deficit
62.5 keV electrons	34 μm	charge deficit
84 keV electrons	55 μm	charge deficit
88 keV gammas	2.5 mm	no deficit



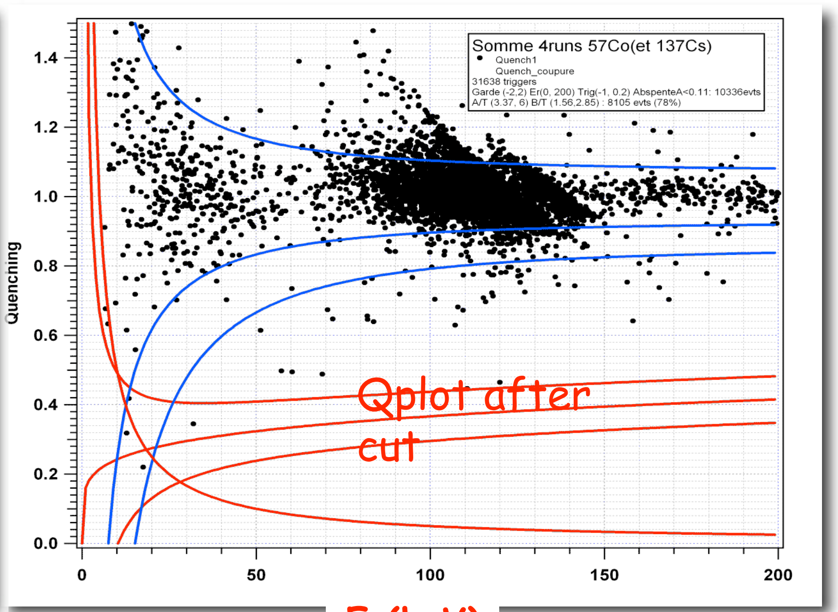
non-rejected events

Identification of surface events with Ge/NbSi detector (3)

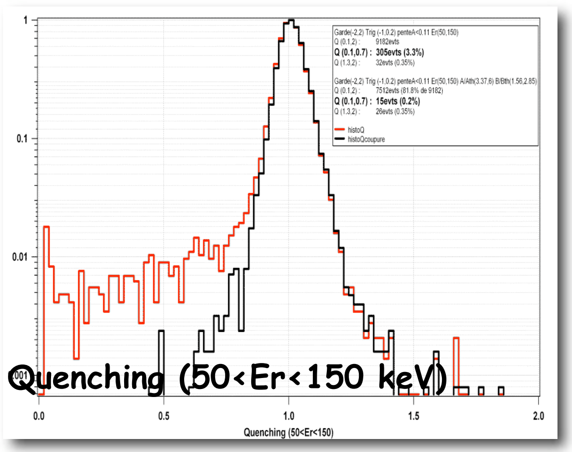
Quenching



Er(keV)



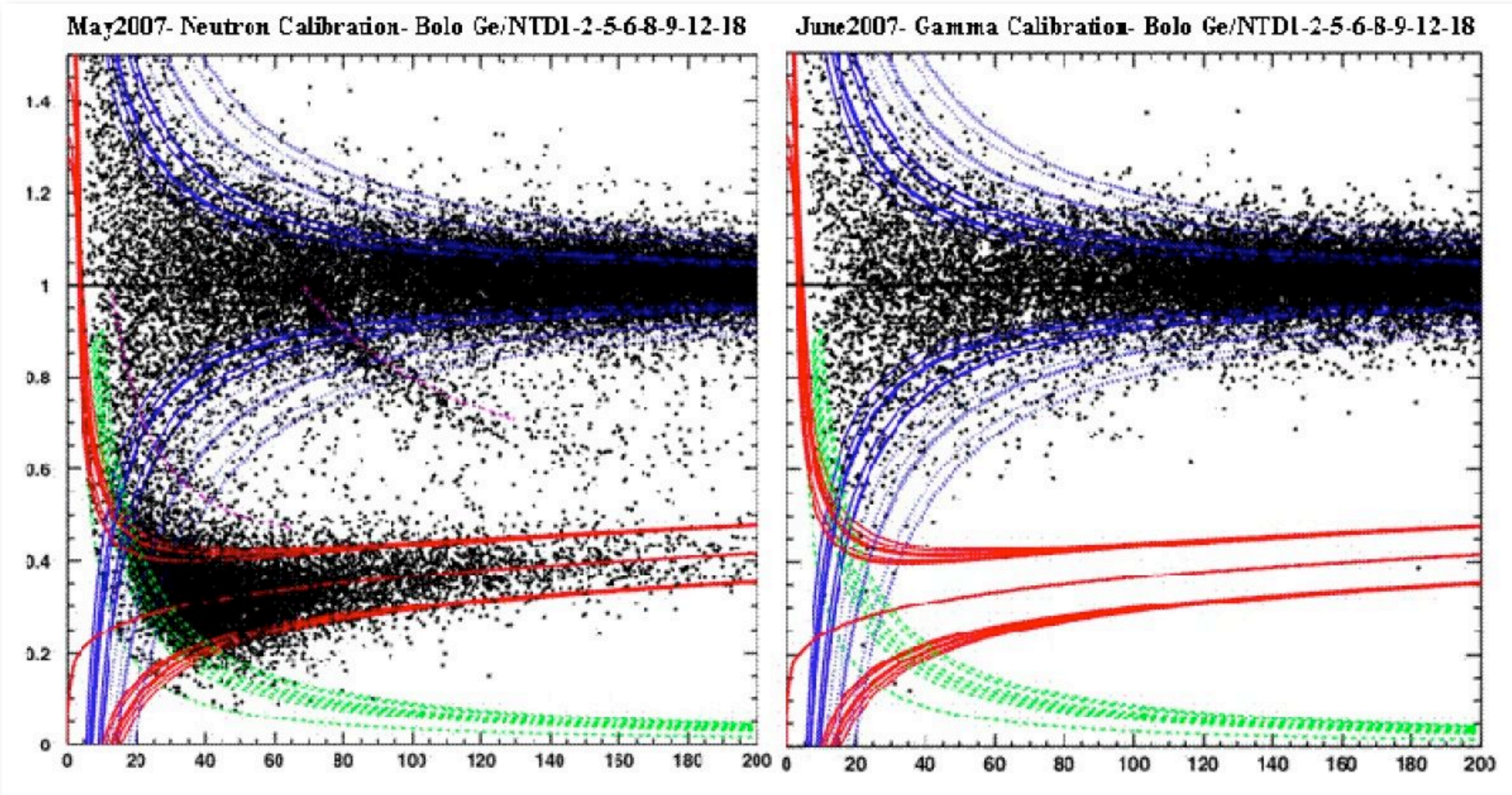
Er(keV)



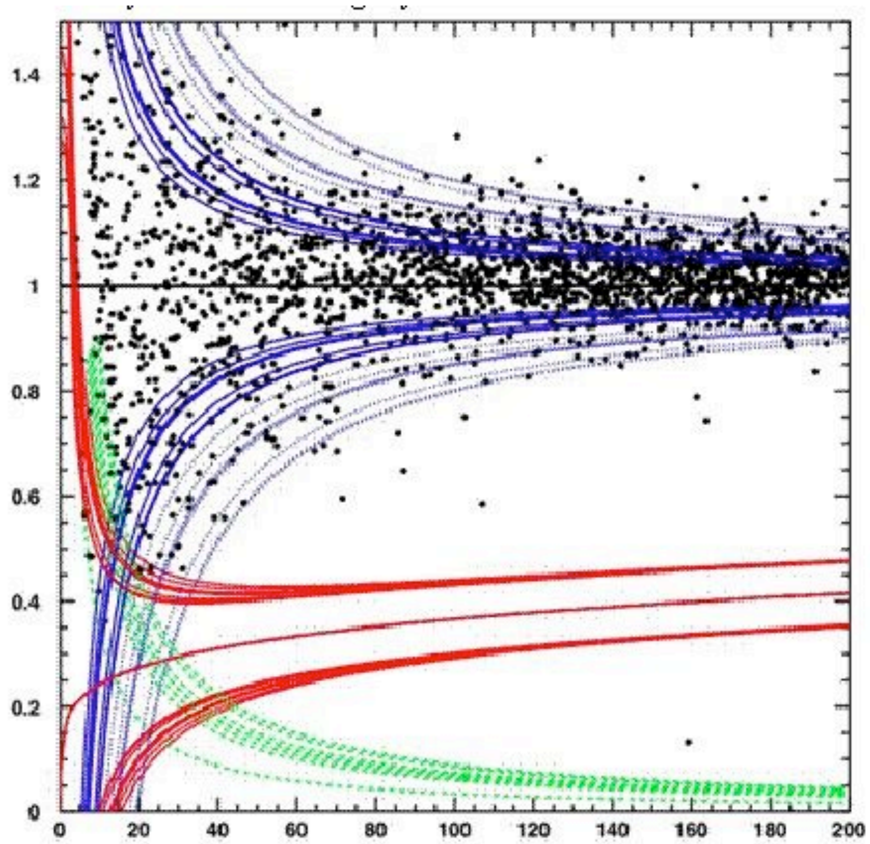
- **95% of the uncomplete collection events are rejected**
(20% of the total events) for a fiducial volume of 90%
- **Similar results on physics data taking**

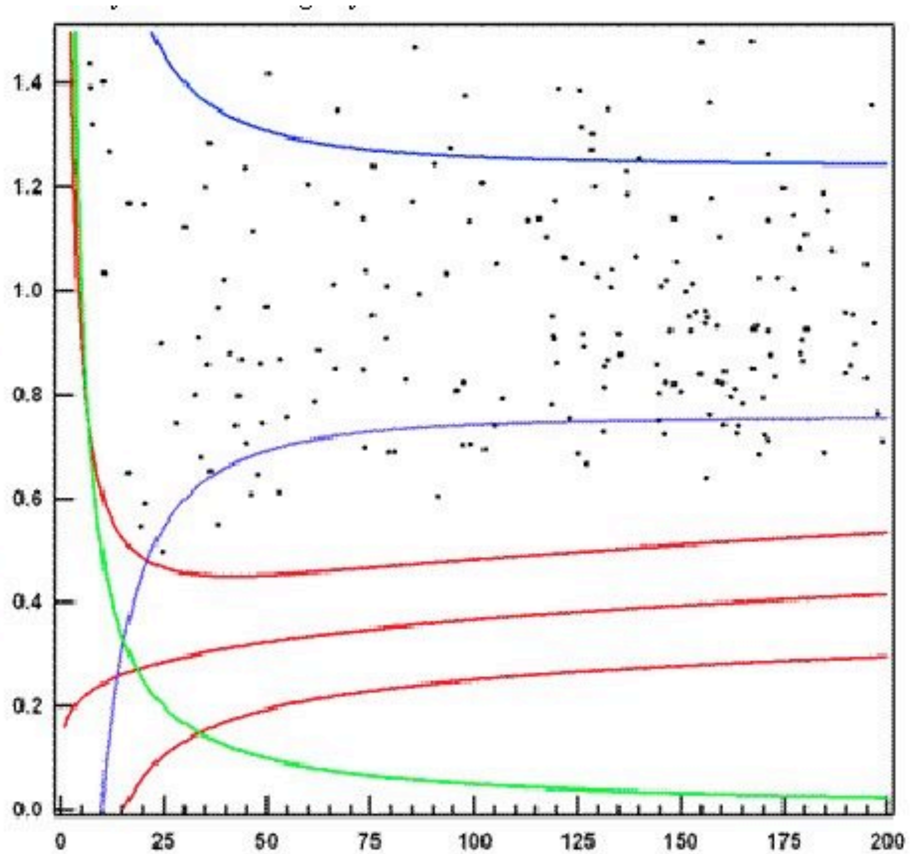
- **7 optimized (size and resolution) 400 g Ge/NbSi detectors in EDELWEISS-II**

Neutron and gamma calibrations in EDELWEISS-II
May-June 2007

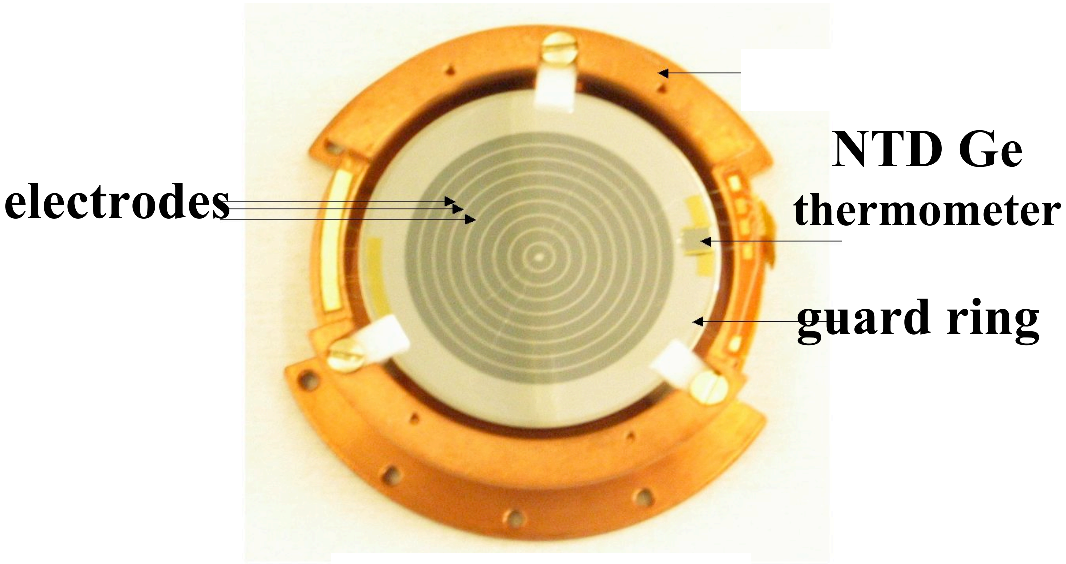


Very first physics data taking in EDELWEISS-II
May-June 2007, First ≈20 kg x days (fiducial)

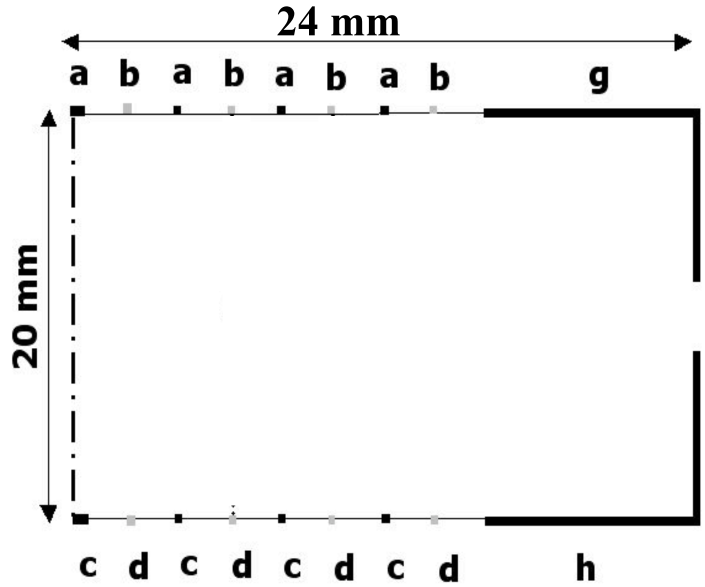




Interdigitized charge-phonon detector



Top view

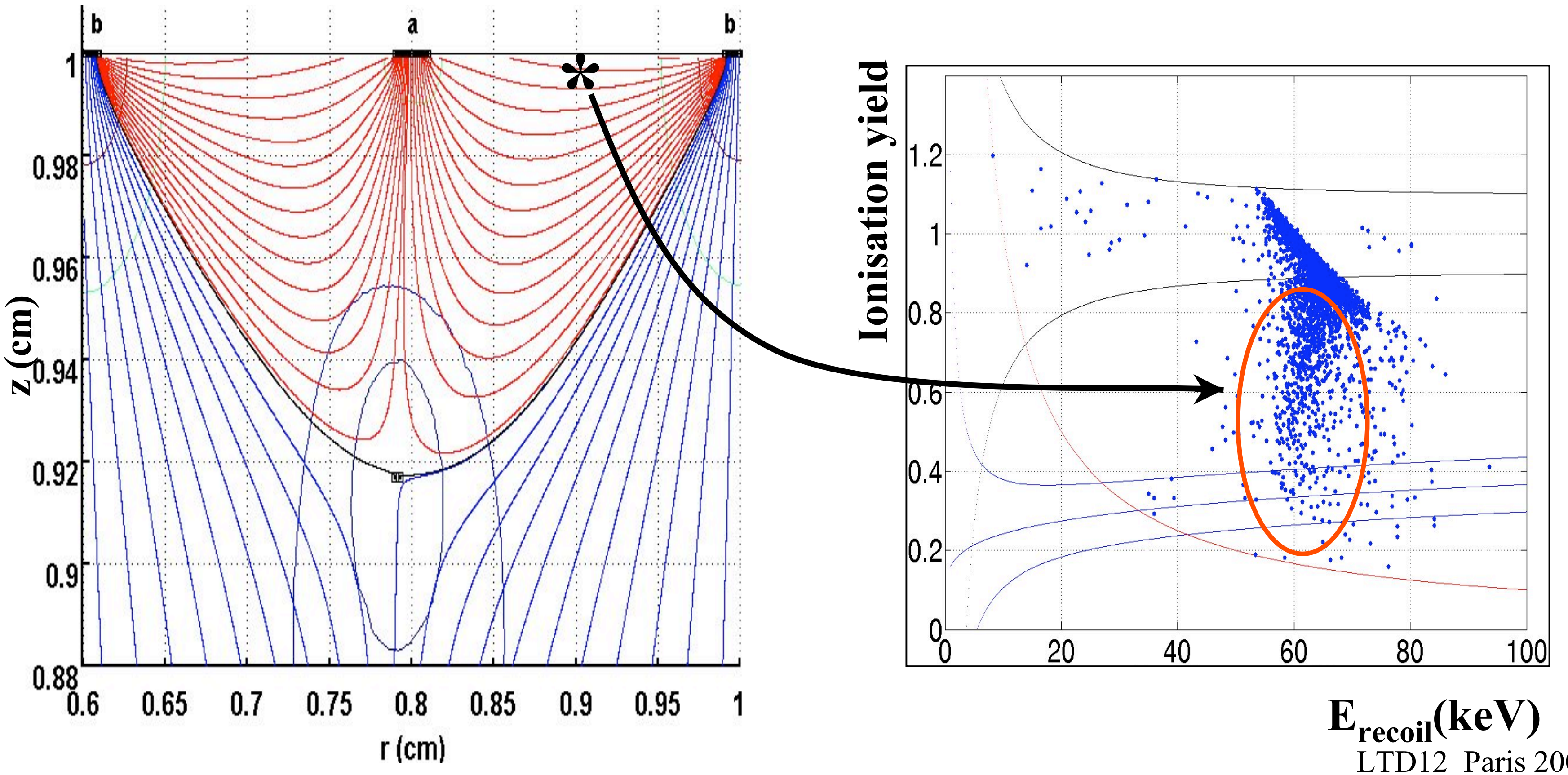


Cross-section

- 200 g Ge crystal
- Hydrogenated a-Ge underlayer for improved charge collection
- Annular aluminum electrodes, interconnected by ultrasonic bonding (strip width: 200 µm; pitch: 2 mm)
- 7 measurement channels: 6 charge (7 MHz bandwidth) + heat (Ge NTD)
- Edelweiss I, low radioactivity refrigerator reconditioned for these experiments

Events of incomplete charge collection: carrier trapping at the free surfaces

- ***Frisch grid (1944)***
- ***Coplanar grid detector (P.N. Luke 1995)***
- ***Cryogenic Ge detector (P. Brink 2005)***
- ***Interdigit EDW detector (A. Broniatowski 2006)***



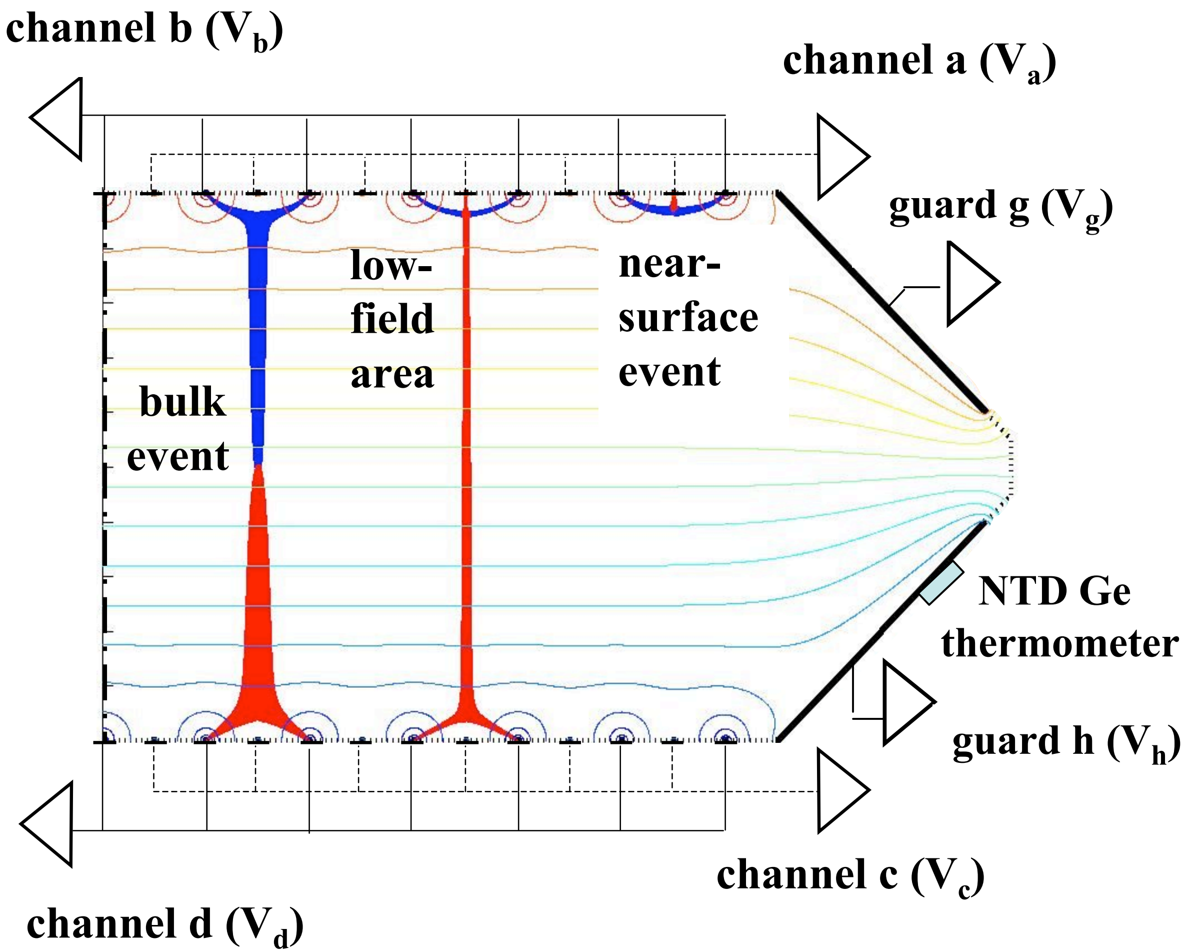
LTD12 Paris 2007

Mode of operation

Bulk events:
$Q_a = Q_c = 0$
$Q_b = - Q_d$

Surface & near-surface events (top surface):
$Q_c = Q_d = 0$
$Q_a \neq 0$ & $Q_b \neq 0$

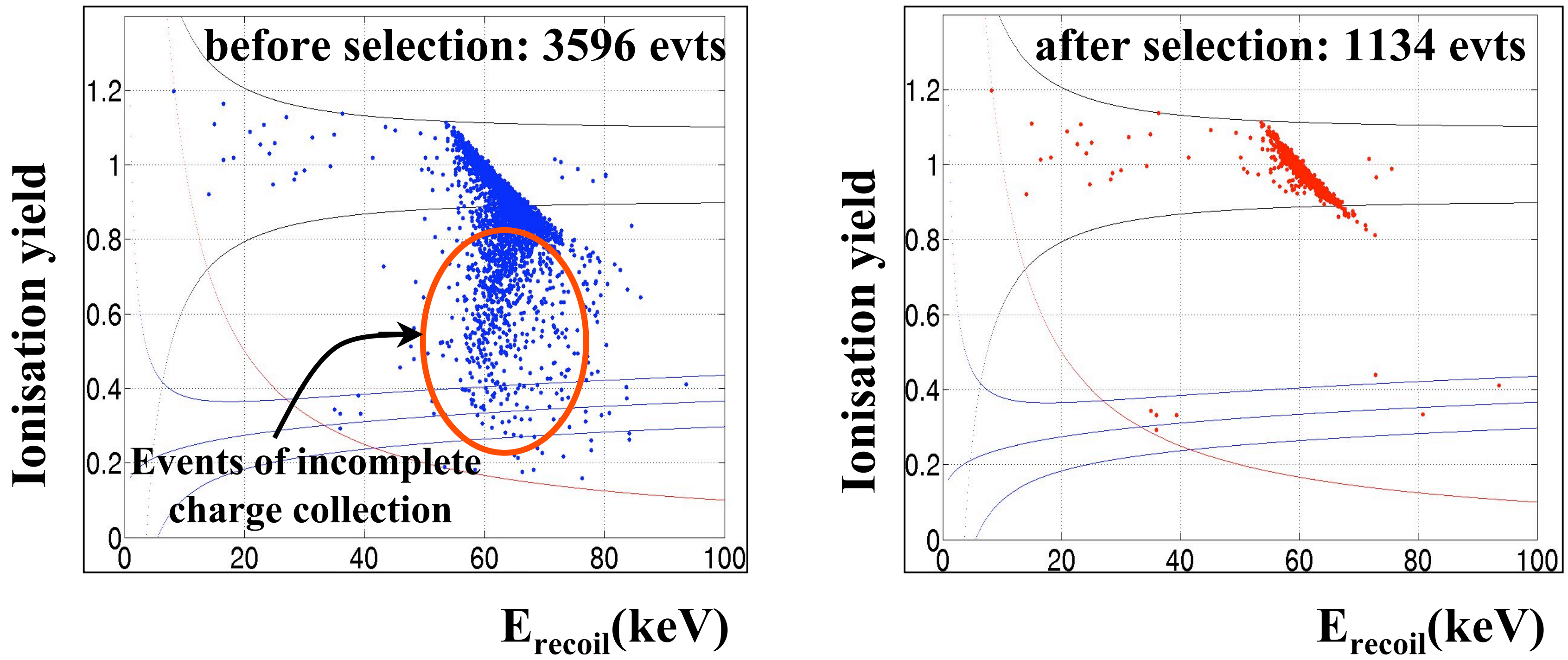
(bottom surface):
$Q_a = Q_b = 0$
$Q_c \neq 0$ & $Q_d \neq 0$



* **Voltage biases: $V_a = 1V$, $V_b = 2V$, $V_c = -1V$, $V_d = -2V$, $V_g = 0.5V$, $V_h = -0.5V$**

Test experiment with a ^{241}Am γ source (60 keV photons)

Cuts: $|Q_a| > 2$ keV & $|Q_b + Q_d|\,| > 2$ keV (e.e.) → event rejected



Voltage biases: V_a= -0.25V, V_b= 2V, V_c= 0.25V, V_d= -2V, V_g= 0.5V, V_h= -0.5V

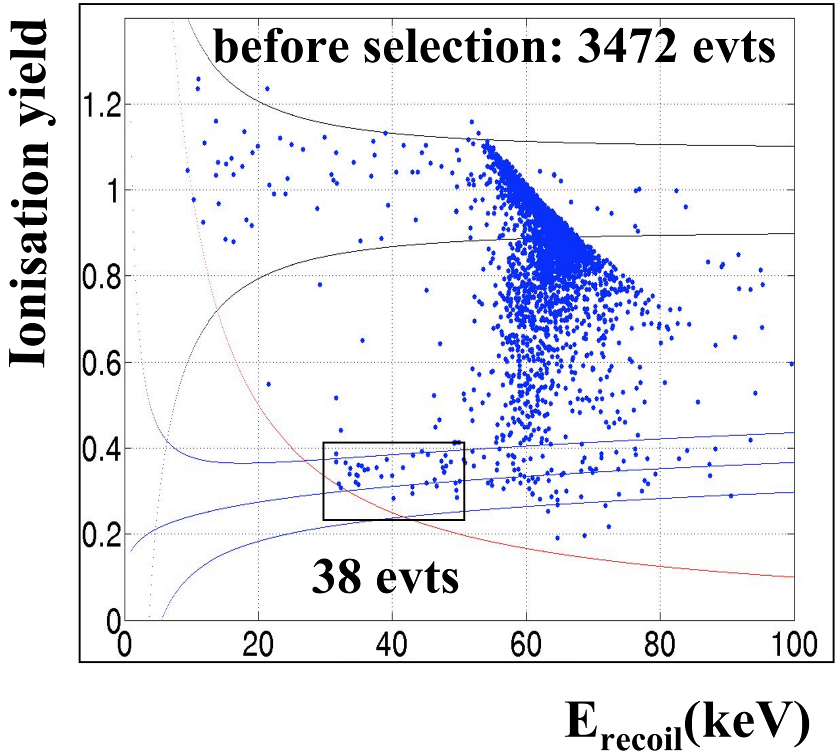
Trigger threshold in ionization: 12 keV (e.e.)

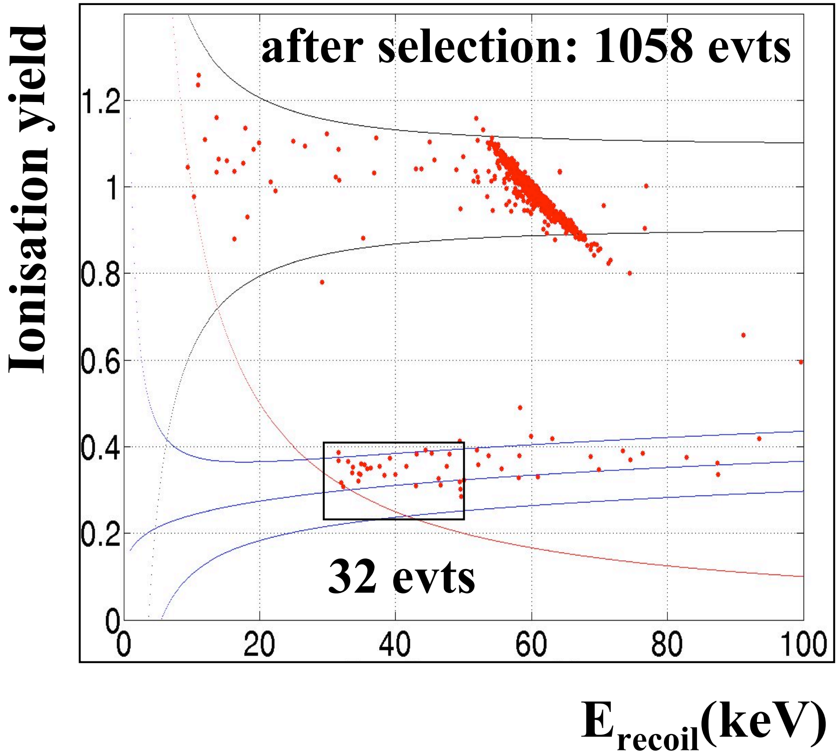
Baseline energy resolution of the ionization channels: 1 keV (e.e.)

Heat channel resolution: 4 keV (FWHM)   T = 17 mK

^{241}Am γ source + ^{252}Cf neutron source

- Same cuts & same bias conditions as the last slide

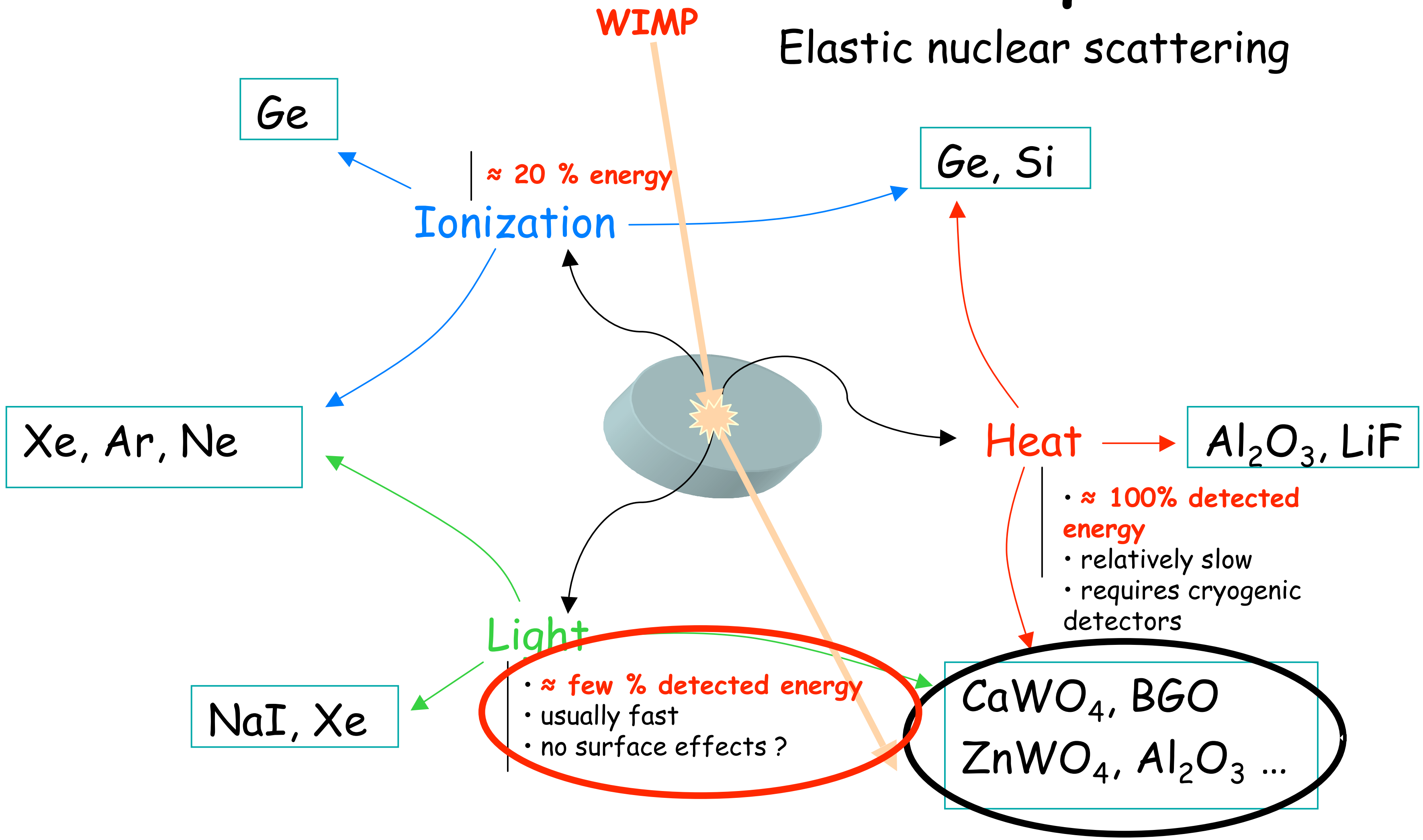




- Loss in fiducial volume: (38-32) / 38 ~ 15 %

after Drukier and Stodolsky, PRD 30 (1984) 2295
(and Goodman and Witten (1985))

Direct detection techniques

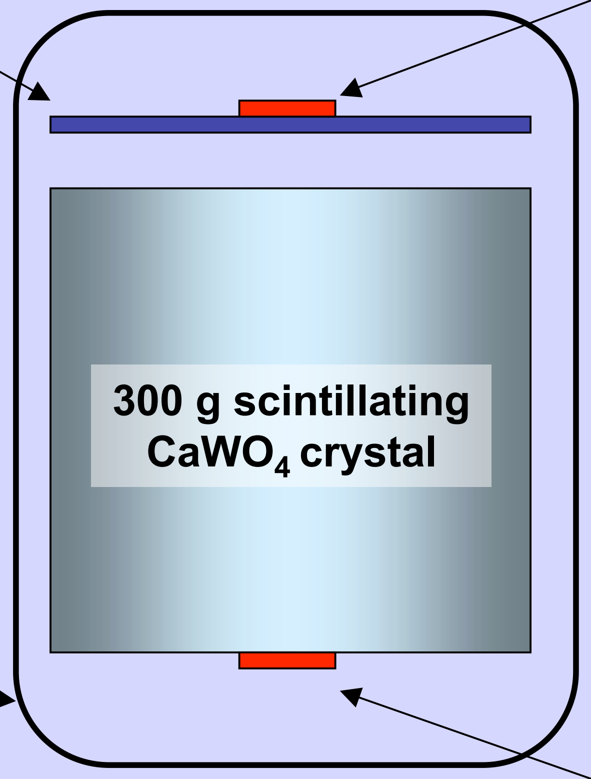


CRESST-II Detector Concept

Simultaneous measurement of **phonons** and **scintillation light** for discrimination of nuclear recoils from radioactive α,β,γ backgrounds.

separate small calorimeter as light detector

W-thermometer
Tc≈10 mK
SQUID readout



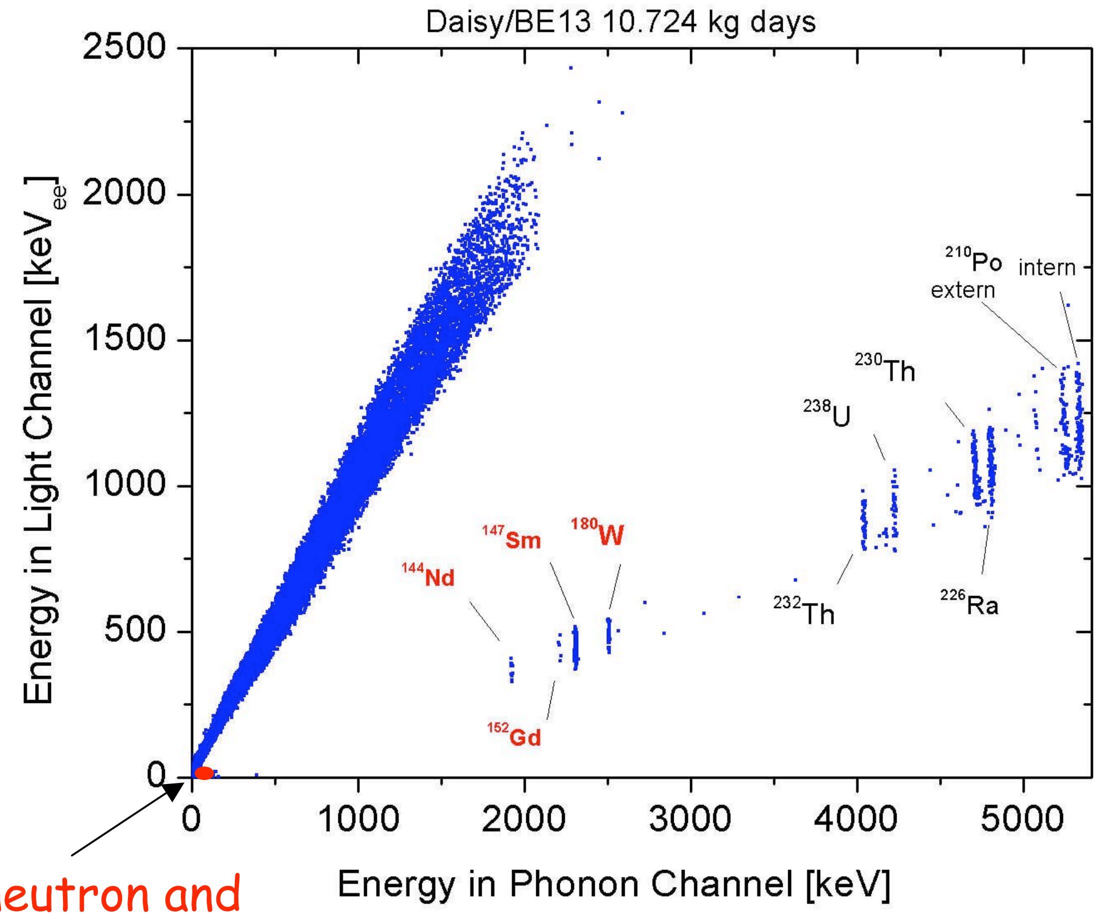
- Works also with $CaMoO_4$, BGO, Al_2O_3, ….

light reflector (scintillating polymeric foil)

W-thermometer with

SQUID readout

2004 data with 300g detector in CRESST-I setup

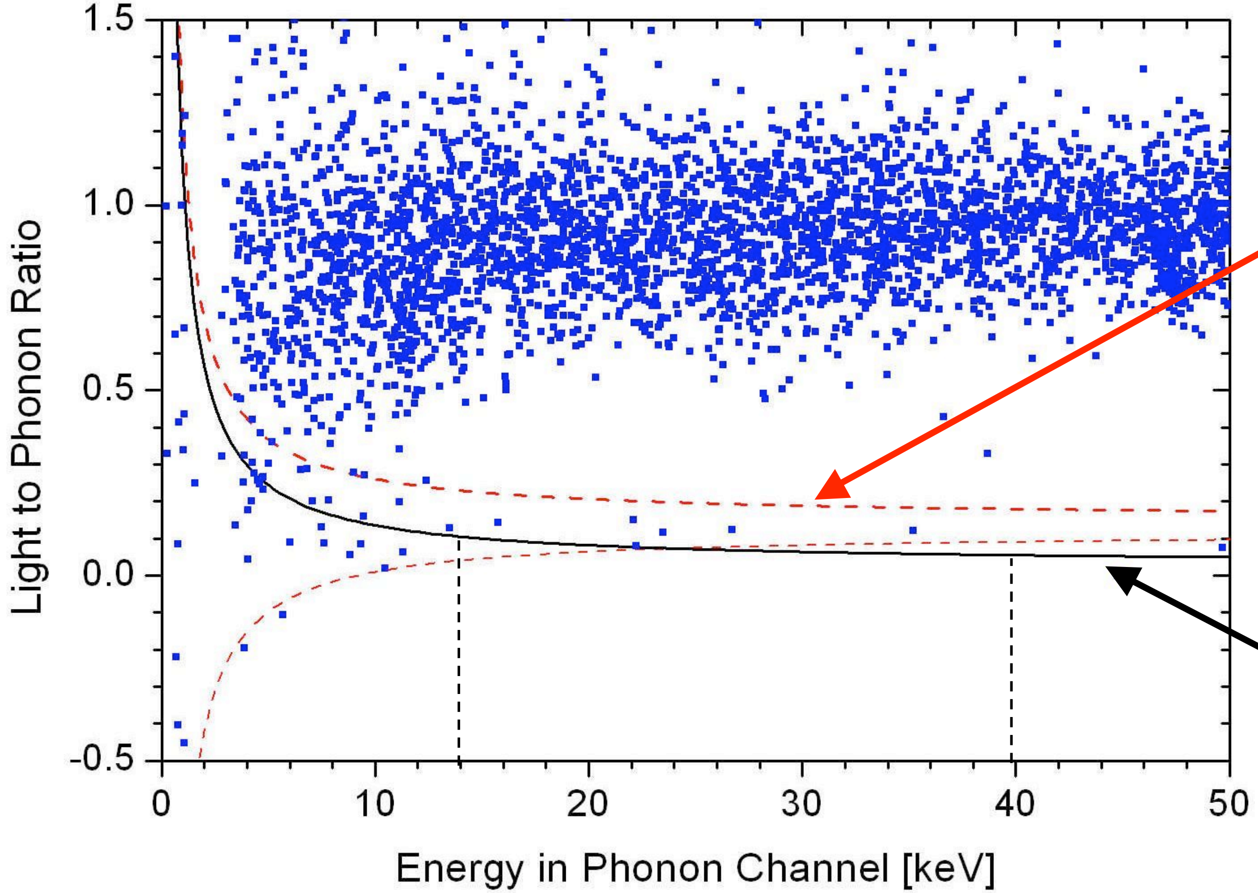


neutron and WIMPS

- 1.5 month run in 2004 before upgrade of CRESST setup
- Excellent linearity and energy resolution in whole energy range
- Perfect discrimination of $\beta+\gamma$ from α's
- Good energy resolution (ΔE=6 keV @ 2.3 MeV) allows identification of alpha emitters
- alphas on surface und in volume give same light

Low Energy Event Distributionin CRESST-I setup without neutron shield

2004 data 10.72 kg days



90% of oxygen recoils below this line. Rate=0.87±0.22 /kg/day compatible with expected neutron background.

90% of W recoils below this line. No W recoils in 12 to 40 keV range

O recoils mostly from neutrons, W recoils mostly from WIMPs

==> good sensitivity despite neutron background

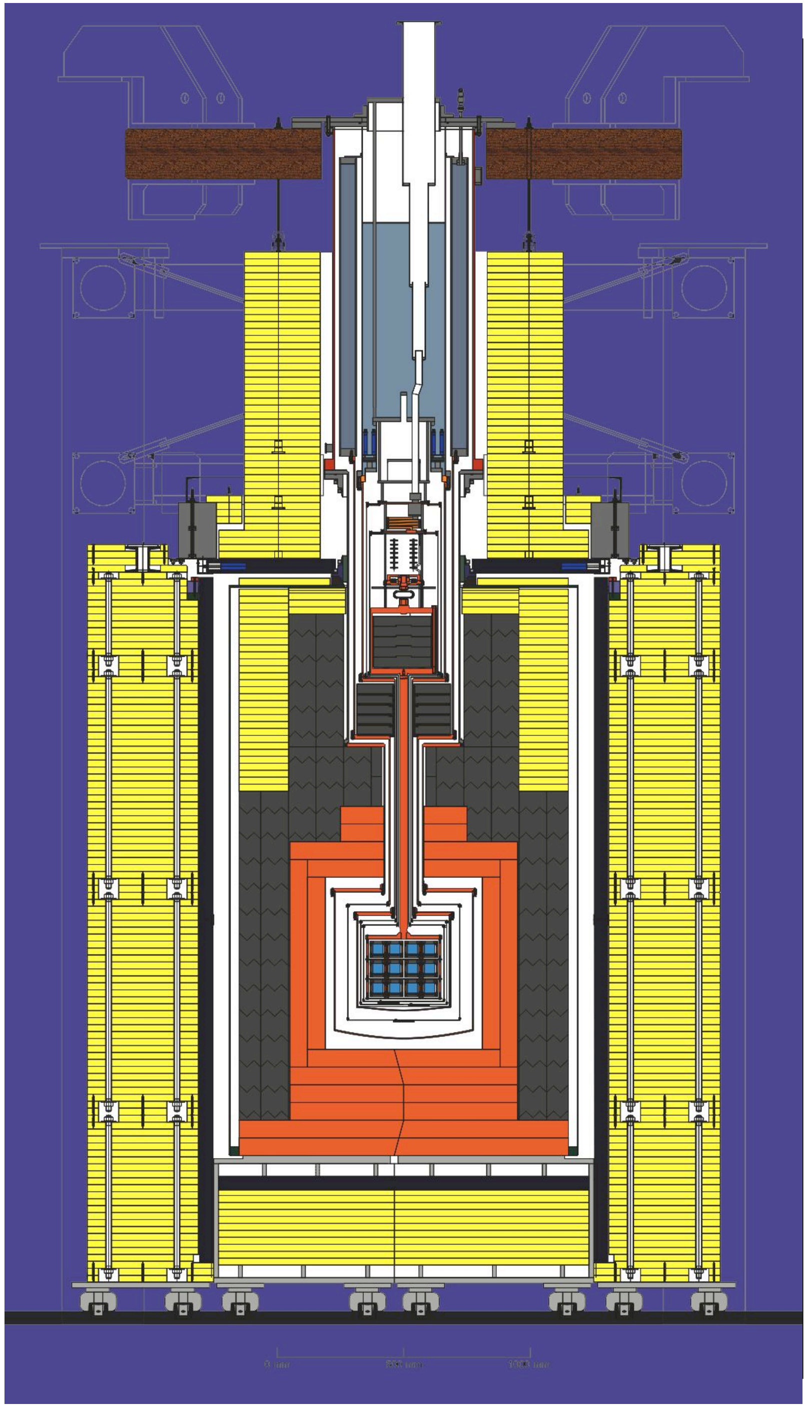
CRESST restart after upgrade

•Cryostat cold since Oct. 2006

•Commissioning run until end of March 2007 to fix issues with SQUID electronics causing disturbances in light channels .

•First physics run with 3 detectors since April 2007. About 60 kg days expected until September (σ~10^{-7} pb assuming no background appears)

Oct. 2006: Mounting detectors

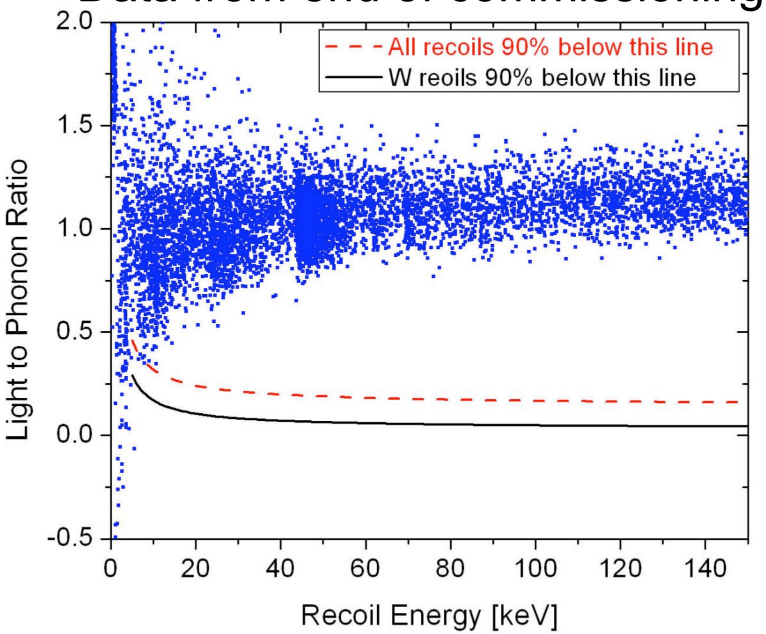


Upgrade for CRESST-II

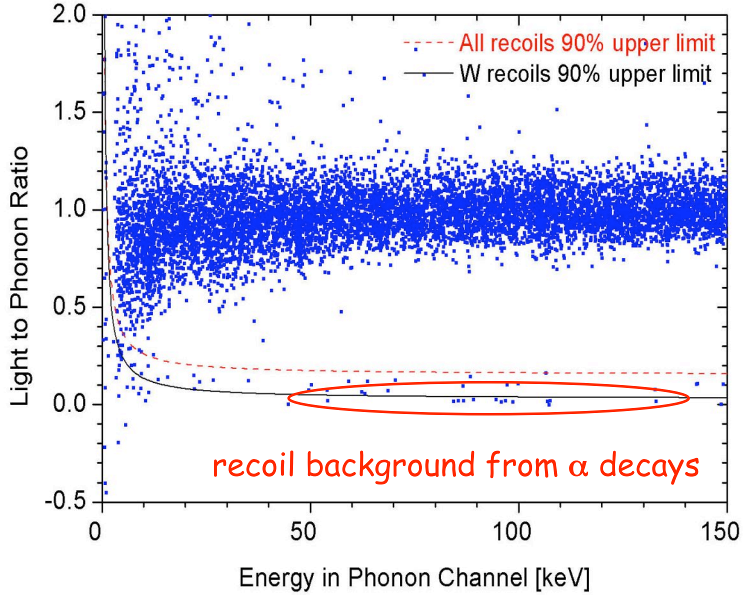
- **New read out and biasing electronics**:
  66 SQUIDs for 33 detector modules
- **Wiring for 66 channels**
- **Detector integration in cold box**
- **New DAQ and slow control**
- **Neutron shield:** 50 cm PE (12 tons)
- **Muon veto:** 20 plastic scintillator panels outside Cu/Pb shield and radon box.
  Analog fiber transmission through Faraday cage

Preliminary Results from CRESST-II Commissionning Run

Data from end of commissioning Run



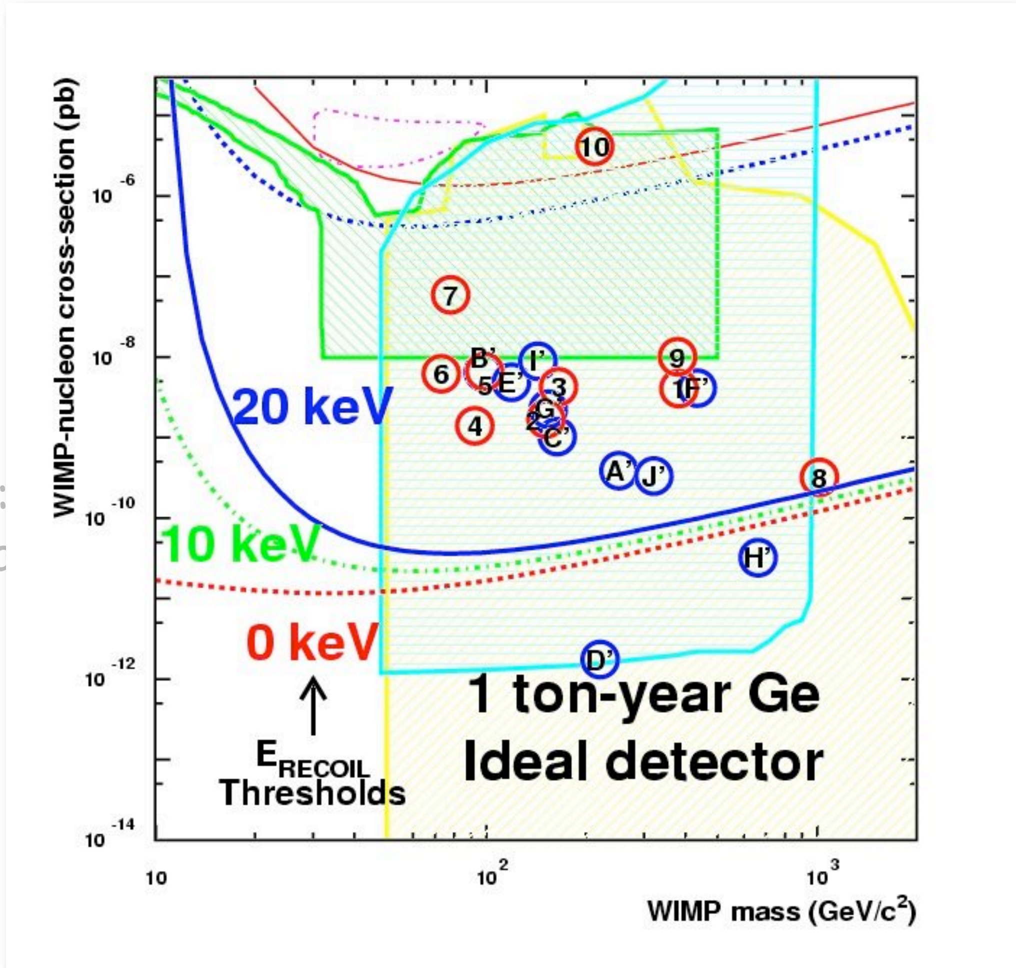
Run28: 10.5 kg days



- Neutron background disappeared. Installed neutron shield is efficient
- Recoil background from alpha decays completely disappeared (now 100% scintillating inner surface of detector module)
- Width of β/γ band still suffers a bit from electronic interference in light detectors.
- **New result presented at TAUP-2007**

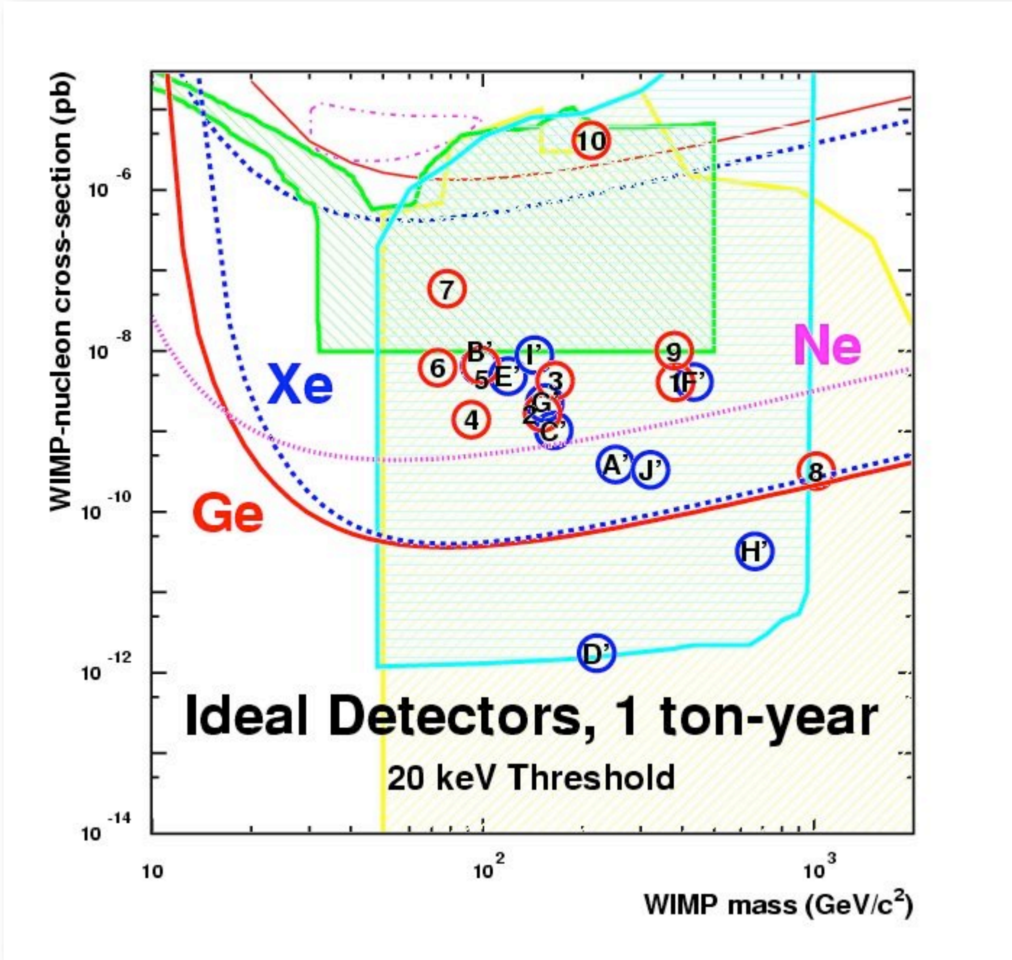
Towards 10^{-10} pbarn sensitivity

- Sensitivity depends on experimental threshold, especially at low M_{WIMP}
- Threshold in *recoil* energy: advantage of thermal signal (wrt reduced yields of ionization, scintillation).



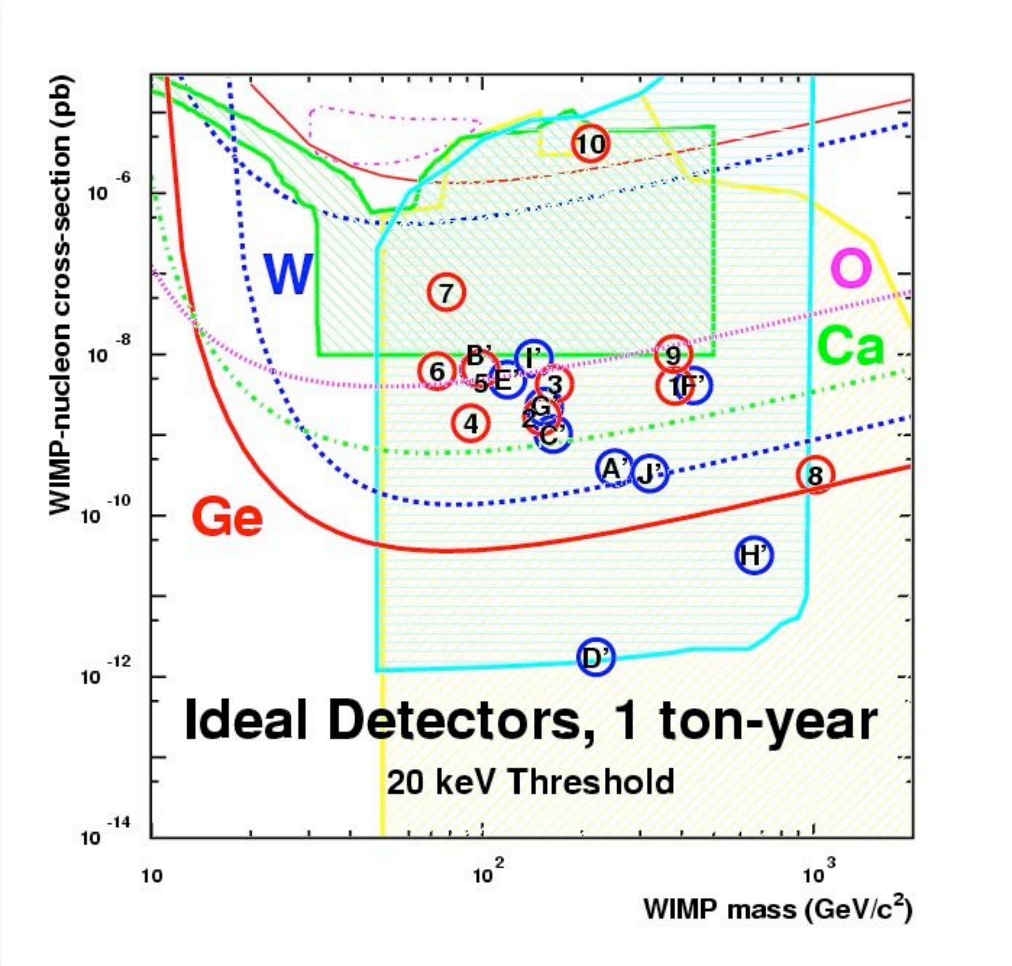
$CaWO_4$ or Ge, Ar, Xe … ?

- Large A favored by $A^2\mu^2$ dependence
- Nuclear form factors reduce this effect for A>~100
- Combination of small and large A can test $A^2\mu^2$ dependence
  - Neutron rate ~ $A^{2/3}$



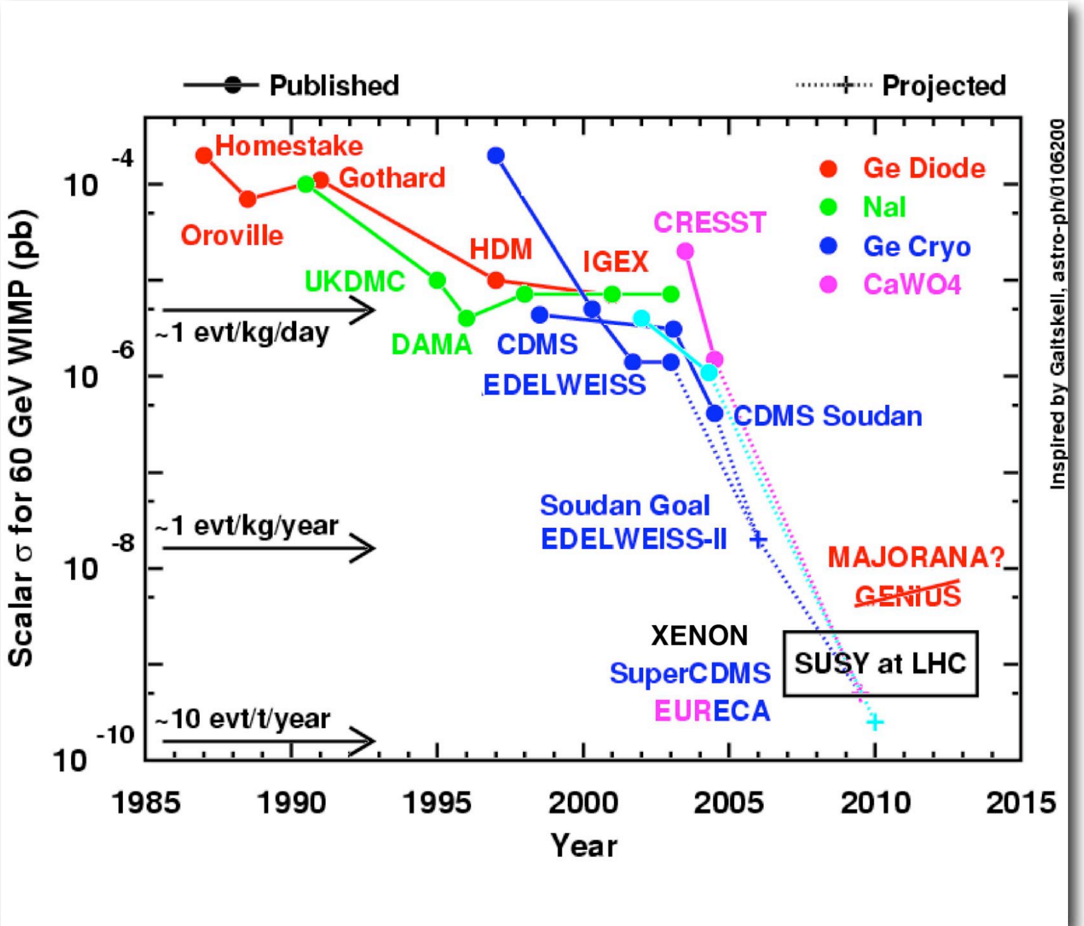
$CaWO_4$ or Ge, Ar, Xe … ?

- 1 ton Ge slightly more sensitive than 1 ton $CaWO_4$
- … but possible comparison of W and Ca+O rates highly interesting
- Best: *compare Ge and $CaWO_4$*
- Other scintillators with diff. A (ex: Al_2O_3)?



Moore's sensitivity law ?

- Rapid evolution of sensitivity of discriminating experiments (CDMS, EDELWEISS, CRESST, XENON, WARP, …)
- But goals are still ≈3 orders of magnitude beyond present best performances



(After Gaitskell)

The EURECA Collaboration

CRESST, EDELWEISS, ROSEBUD + CERN

United Kingdom

Oxford (H Kraus, coordinator)

Germany

MPI für Physik, Munich

Technische Universität München

Universität Tübingen

Universität Karlsruhe

Forschungszentrum Karlsruhe

Russia

DNLP Dubna

France

CEA/DAPNIA Saclay

CEA/DRECAM Saclay

CNRS/CRTBT Grenoble

CNRS/CSNSM Orsay

CNRS/IPNL Lyon

CNRS/IAS Orsay

Spain

Zaragoza

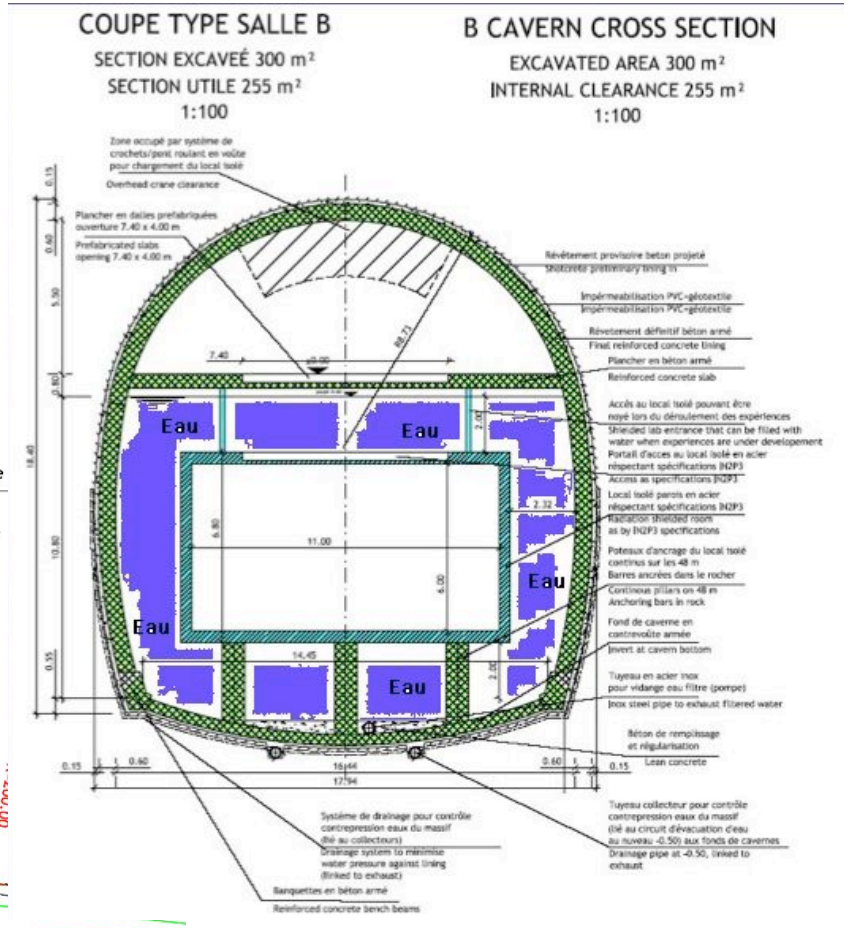
CERN

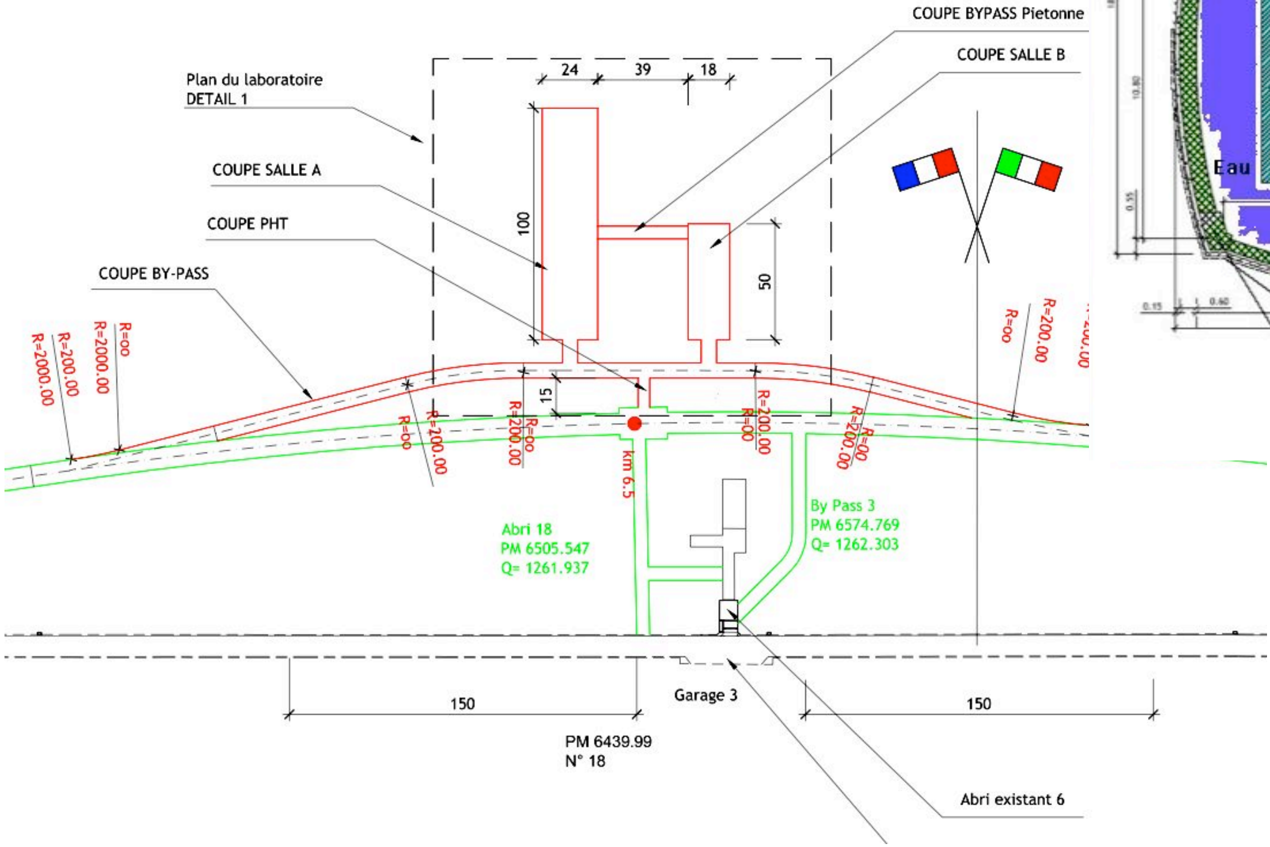
EURECA in LSM

Submarine / Swimming Pool

Clean Infrastructure

Access Policy

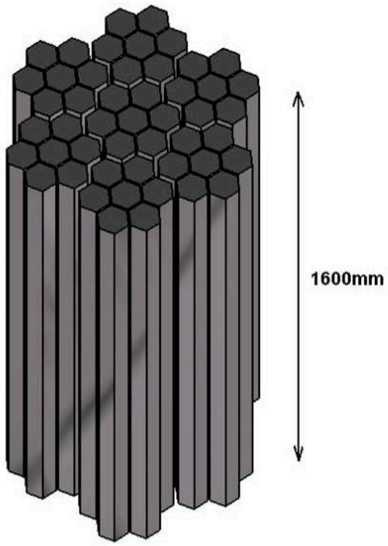




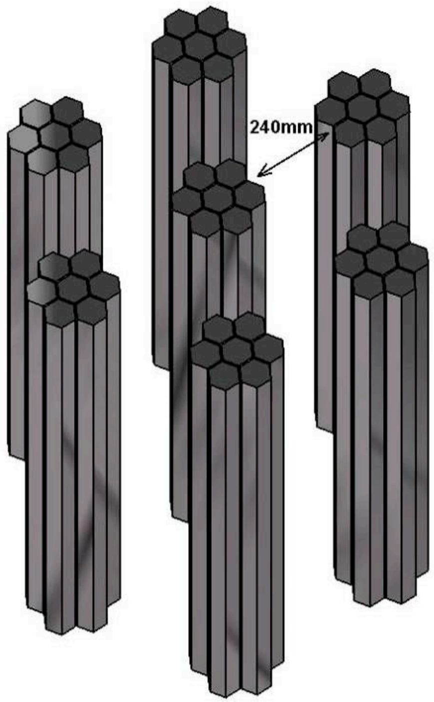
EURECA: Cryostat Layout and Design

- Separation of dilution refrigerator and detector unit
- Easy access to cryostat as well as detector unit
- Number and size of pipes / feedthrough
- Closest package of detectors
- Load lock system or individual cryostats
- Detector exchange without long interruption
- Different detectors types / expansion

1 Cryostat
with 7 Towers

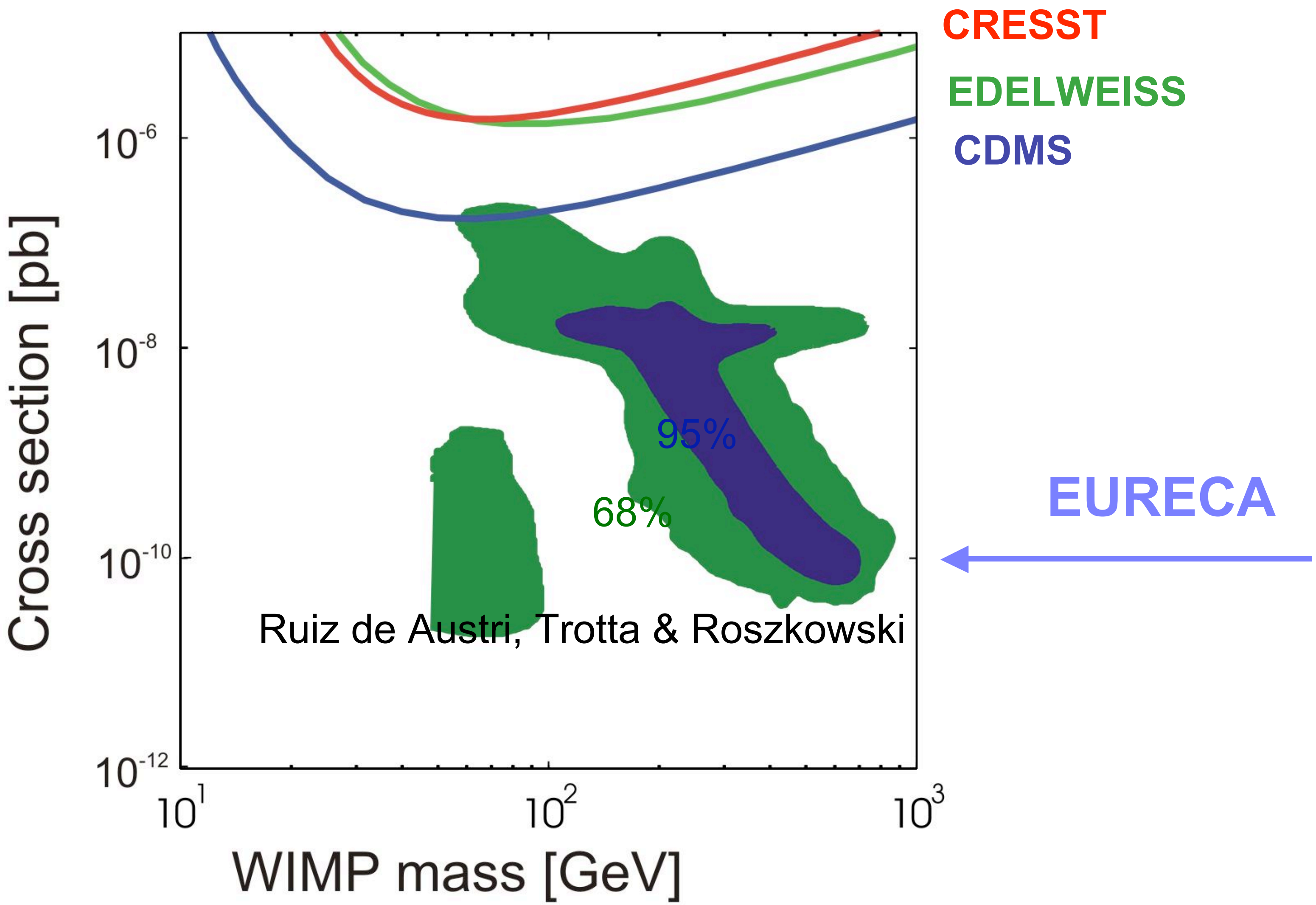


7 independent Cryostats
with 7 Towers



1 Cryostat
with 19 Towers

EURECA, SuperCDMS aim



(Partial) conclusions

- **Event-by-event discrimination is essential**
- Two main techniques to detect WIMPs: **cryogenic** and **noble gas/liquids**
- Cryogenic detectors (CDMS, Edelweiss, CRESST, ROSEBUD) : **excellent discrimination** properties and **energy resolution**
- But : **challenging scalability…**
- Rare gas targets:
  - XENON and WARP progressing rapidly (ArDM already at tonne scale)
  - Readily scalable, zero background/background subtraction strategy ?
- Control of the neutron background; identification of heavy surface nuclear recoils essential (see WARP e.g.)
- 2007-2010 : Both **SuperCDMS** and **EURECA** are in their Design Study stage, and studying scalability towards tonne scale
- ≈ 2010 : decision on experiments with 10^{-10} pbarn sensitivity