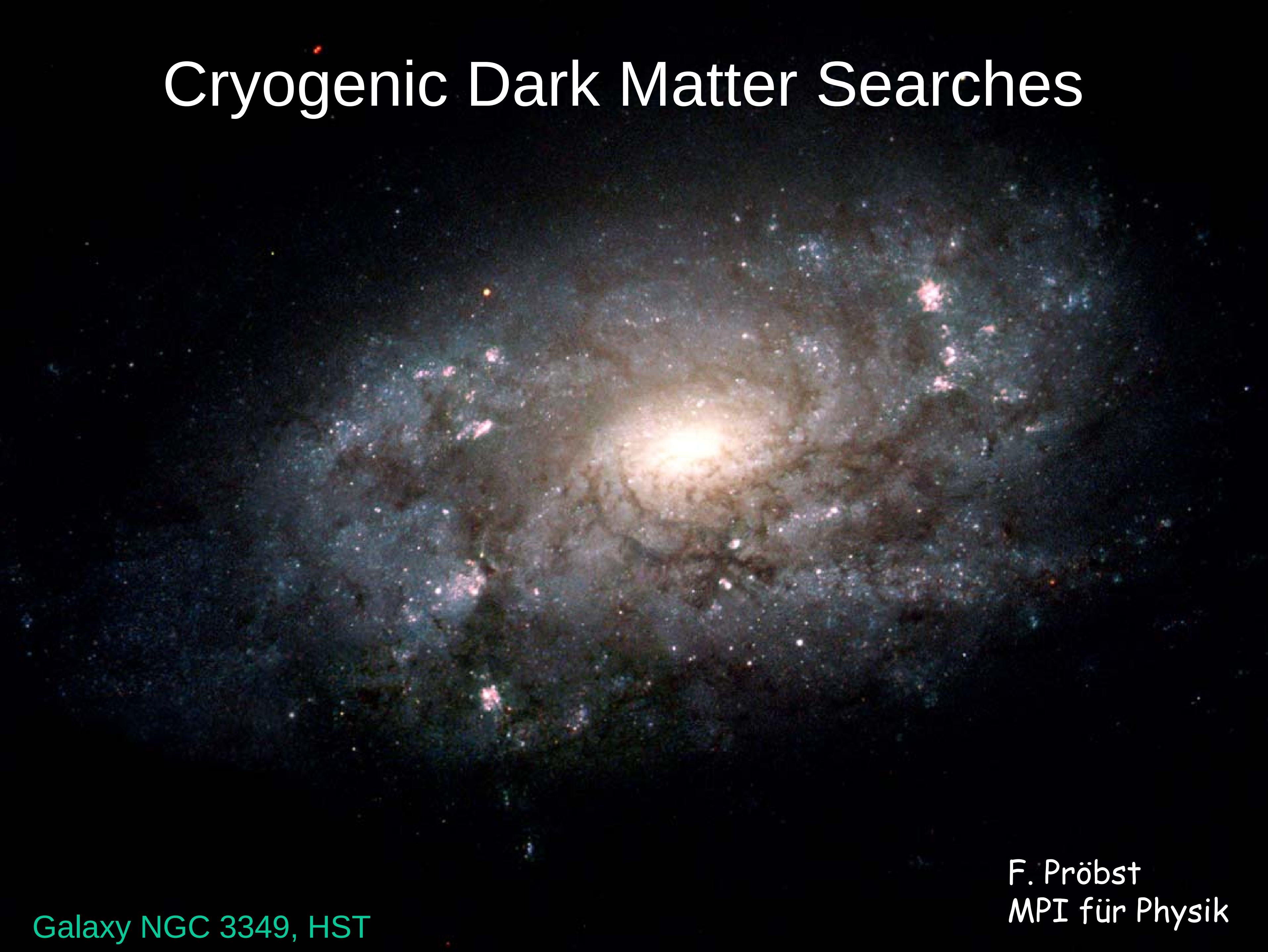
Cryogenic Dark Matter Searches



F. Pröbst
MPI für Physik

Galaxy NGC 3349, HST

Outline

- Direct detection
- Major direct searches with cryogenic detectors: results and performance critical factors

    EDELWEISS,

- CMDS
- CRESST

Weakly interacting massive particles

WIMPS: massive particles (> GeV) with weak interaction and **stable,** thermally produced in the early universe and still there.

Favored candidate: neutralino, the lightest supersymmetric particle.

$$\chi = a\tilde{B} + b\tilde{W}^{3} + c\tilde{H}_{1} + d\tilde{H}_{2}$$

χ phenomenologically similar to heavy majorana with weaker annihilation cross section which gives $\Omega \approx 0.1$ for a wide range of parameters and neutralino masses.

$\sigma_{el} \Leftrightarrow \sigma_{\chi\chi}$ depends on composition

Search Mass-σ_{el} plane as wide as possible

In general χ have spin and spin independent (coherent) interaction. Spin independent usually dominates due to A^2 factor

WIMPs are cold, slow and gravitationally bound to galaxy.

Maxwellian velocity distribution in galactic rest frame $v_{rms} \approx 270$ km/s

Velocity of sun in galaxy shifts velocitiy distribution seen on earch

How to detect WIMPs

Indirect detection

Looking for annihilation products :

→ in space : GLAST, AMS, …

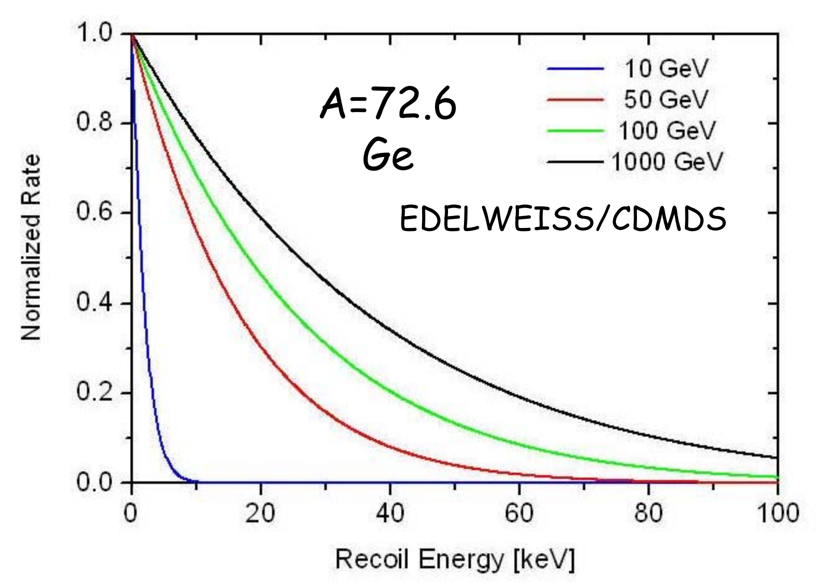
→on Earth : Amanda, Antares, Nestor,
HESS, HEAT,
SuperK, MAGIC…

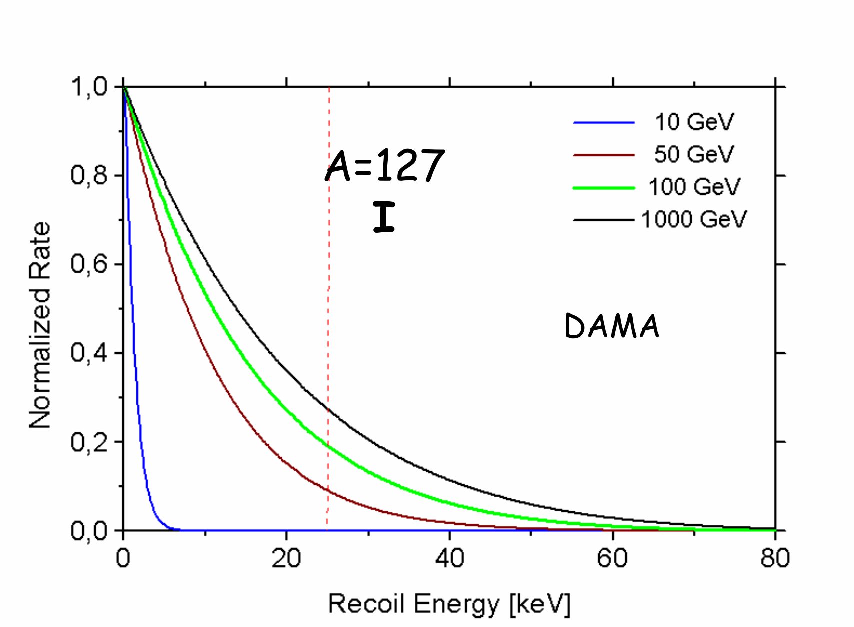
Direct detection

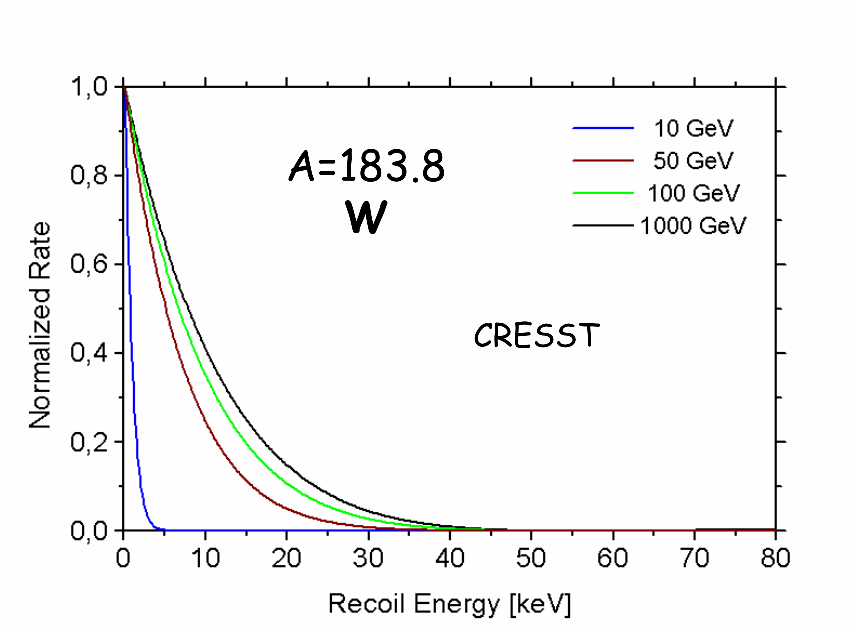
Elastic scattering of WIMPs on nuclei

Signal: low energy nuclear recoil
(some 10 keV)

Recoil Spectra for various target nuclei

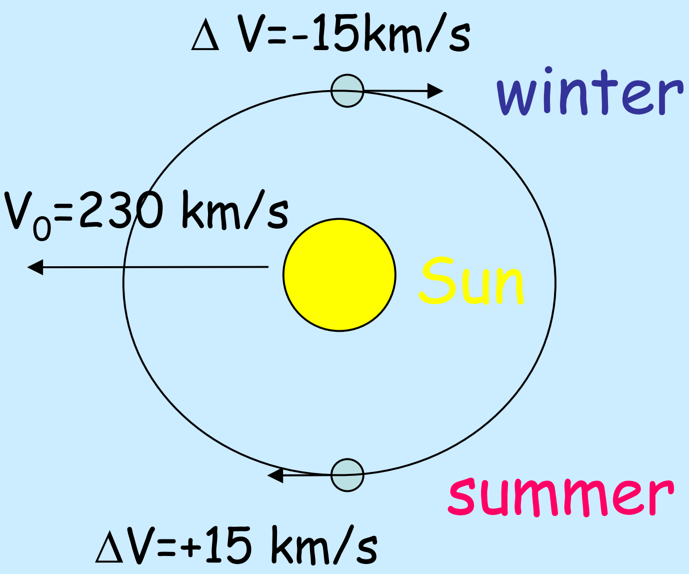


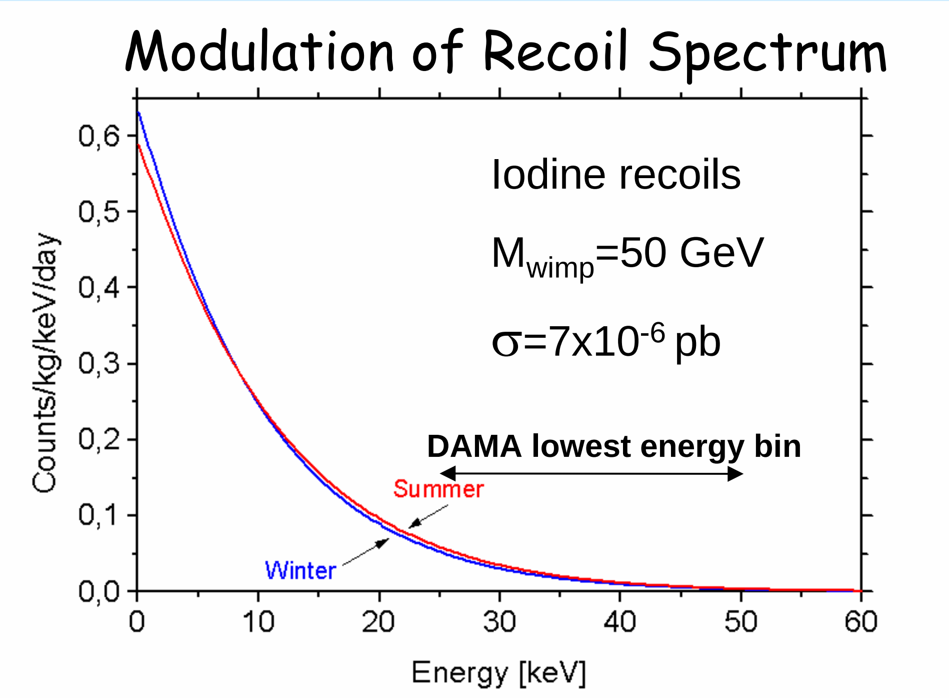


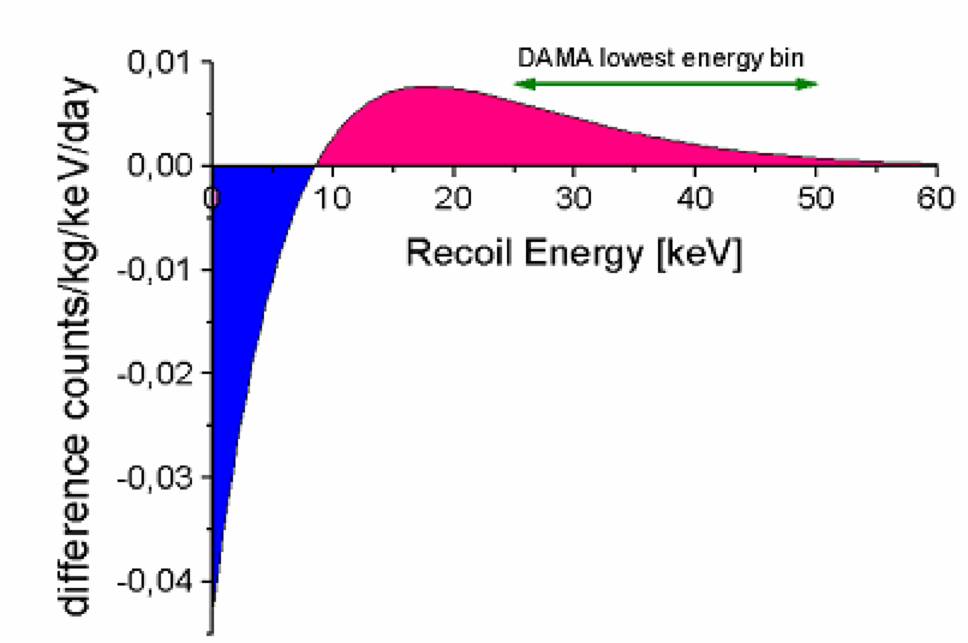


- Spectral shape depends on WIMP and target mass.
- Low thresholds required, especially for small WIMP masses and large A
- Formfactor suppression of large energy transfers for heavy nuclei.

Annual Modulation







- positive signature
- very small ~ few % effect, strongly dependent on threshold

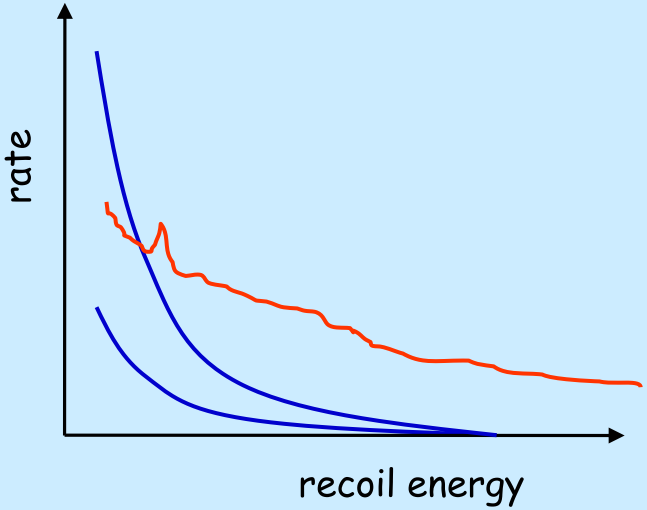
Sensitivity - which σ can be excluded ?

If there is background:

Sensitivity is given by the smallest cross section producing a WIMP contribution which can not be hidden under the measured spectrum.

No further improvement once background rate B is measured statistically significant

$$\sigma \propto B$$



Without background:

Linear improvement with exposure

$$\sigma \propto \frac{1}{Mt}$$

Identification of WIMP signals

- **Nuclear Recoil discrimination**
- **Shape of recoil spectrum**
- **Correct scaling of rate and spectrum for different target nuclei**
- Annual modulation
- Diurnal variation in directionality

Detector Requirements for Direct Detection

Challenges for direct searches:

- Very low event rate: < 1 count/week in a 1 kg detector (goal of phase-II (EDELWEISS,CDMS, CRESST) experiments <1 count/year in a 1 kg detector)

- Nuclear recoil signals with keV energies and featureless spectrum.

➔Very low threshold, extremely low background detectors, efficient nuclear recoil discrimination

Most important signal region is just above threshold

➔Need very good shielding from environmental electromagnetic, vibrational and acoustic noise sources.

➔Need continuous control of stability of detector response and threshold to confirm that detector is really able to measure such low energies

The backgrounds we have to fight

Underground site to protect from cosmic muons

Natural radioactivity of surrounding rocks and materials:

- ➔ shield γ background with low background Pb and high purity Cu.
- ➔ surround shielding with gas tight radon box flushed with N_2
- ➔ clean room to protect from radioactive dust
- ➔ careful material selection.

Deep undergroundd and very well shielded residual $\beta+\gamma$ background typically ~100/kg/day.

➔**detectors with excellent nuclear recoil discrimination needed**

Nuclear recoil backgrounds:

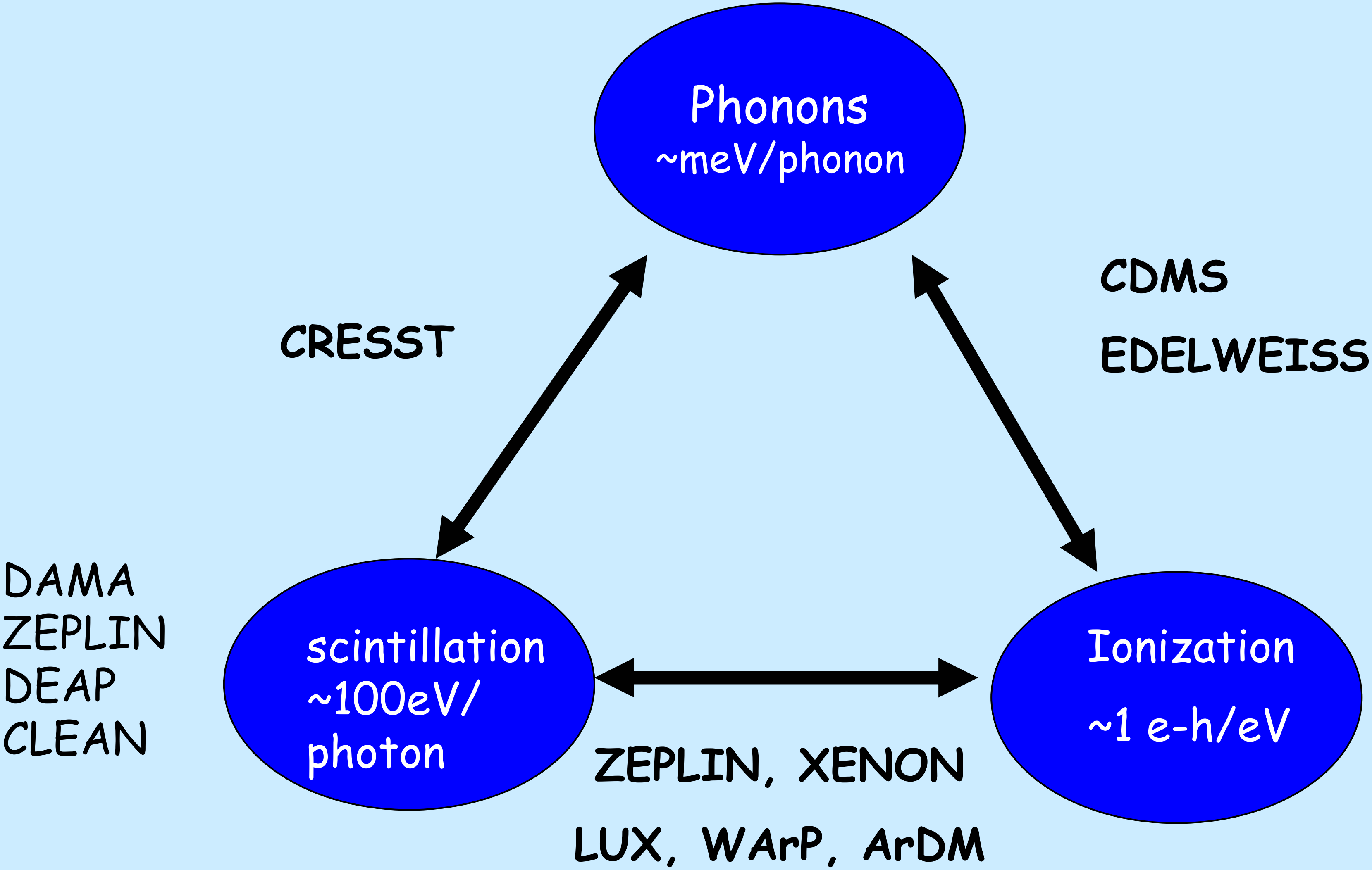
•**Neutrons from spontaneous fission and α/n reactions in rock** (LNGS ~ 1 /kg/day): ➔ moderate with 50 cm of PE

•**Neutrons from muons in Pb/Cu shield (~0.02 /kg/day):**

➔ need muon veto for reaching $\sigma_{\text{WIMP-nueleon}}$~$10^{-8}$ pb

•**Recoil nuclei from ^{210}Pb contaminations on external surfaces:** ➔ discrimination of surface events (CDMS) or other tricks (CRESST)

Nuclear recoil discrimination strategies



Phonons
~meV/phonon

CRESST

CDMS

EDELWEISS

DAMA
ZEPLIN
DEAP
CLEAN

scintillation
~100eV/
photon

Ionization

~1 e-h/eV

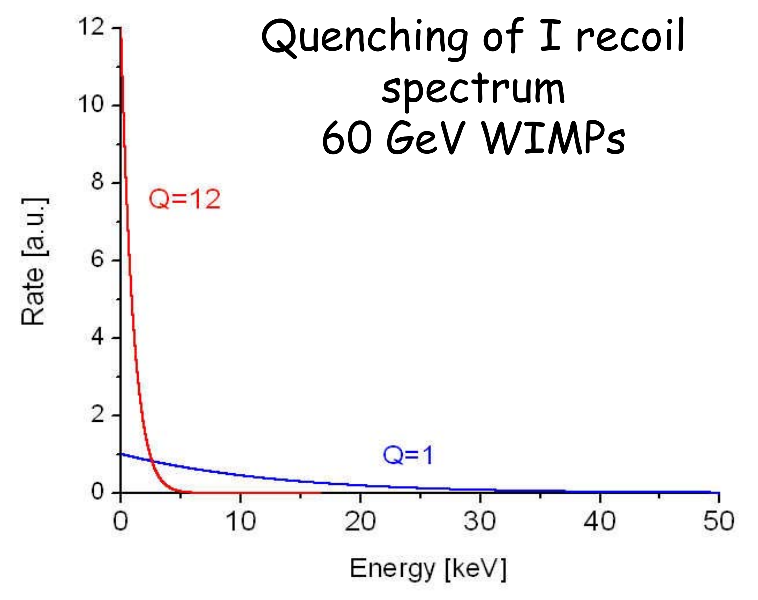
ZEPLIN, XENON

LUX, WArP, ArDM

Scintillation Detectors

Experiments:
NaI: DAMA/LIBRA, UKDM-NaIAD ..
CsI: KIMS

- Well known and available technique
- Iodine as heavy target nucleus A=127
- Large crystals with very good radiopurity available
- Poor spectral resolution
- No $\beta+\gamma$ discrimination on event by event basis



Iodine recoils have quenching factor Q=12, 24 keV recoils e.g. appear at 2 keV

Recoil spectrum sqeezed by factor Q
➔ very low threshold needed

Signal/background improved by factor Q

DAMA/LIBRA

Roma/LNGS/Beijing collaboration

DAMA: ~ 100 kg NaI in Gran Sasso, 7 years of data

9.7 kg NaI crystals, 10 cm light guide, 2 photomultipliers in coincidence, extremely low energy threshold 2 keV

In low background Cu/Pb/polyethylen Box inside radon-box

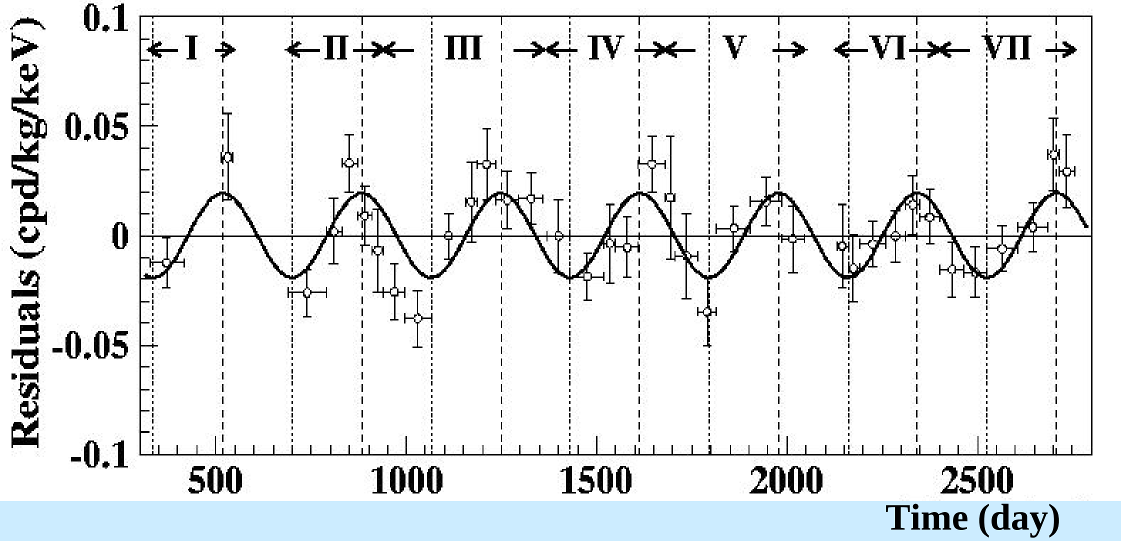
DAMA ended operation in July 2002

LIBRA:
Upgrade to ~250 kg detector. Running since March 2003. First data released spring 2008.

DAMA-Evidence

Phase and amplitude consistent with WIMP signature during more than 6 years wit 6.2 σ statistical significance.

About 107 800 kg d of data



Systematics:
Detector stability
„Background stability“

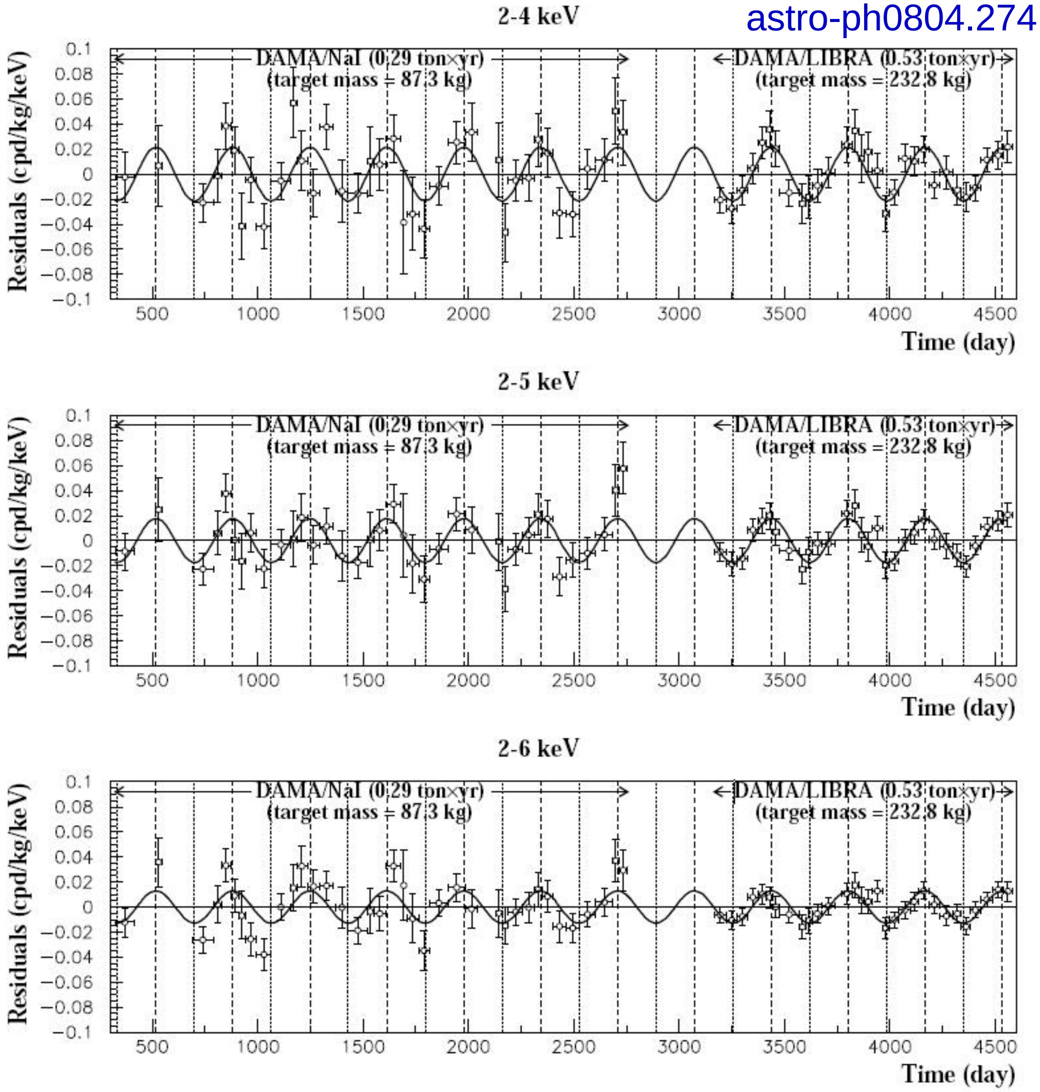
Riv. N. Cim. 26 n. 1 (2003) 1-73

WIMP mass (52±10) GeV, $\sigma=(7\pm1)10^{-6}$ pb

Rather controversial, as a number of other experiments failed to see WIMPS at that level of cross sections

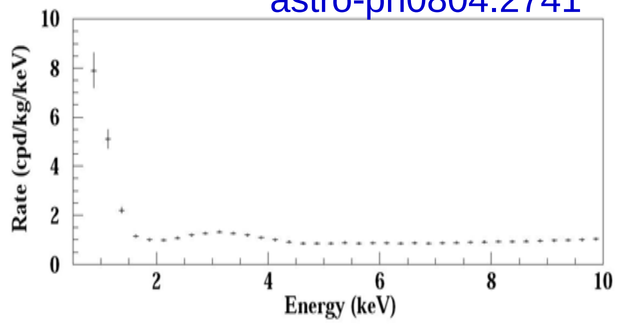
DAMA/LIBRA 2008 Data

Modulation signal in 3 energy ranges



astro-ph0804.2741

Energy Spectrum



astro-ph0804.2741

- Presence of oscillation now at 8.2 σ C.L.
- Careful study of systemactic effects and possible side reactions fails explain signal modulation
- Renewal of claim that DM has been detected

EDELWEISS

Collaboration: **CEA-Saclay, CSNSM Orsay, CRTBT Grenoble, IAP Paris, IPN Lyon , FZ/Uni Karlsruhe, JINR Dubna (total ≈ 50 people)**

Modane Underground Laboratory (Fréjus,France): 4800 mwe

EDELWEISS-I
1 kg stage

Low background dilution cryostat

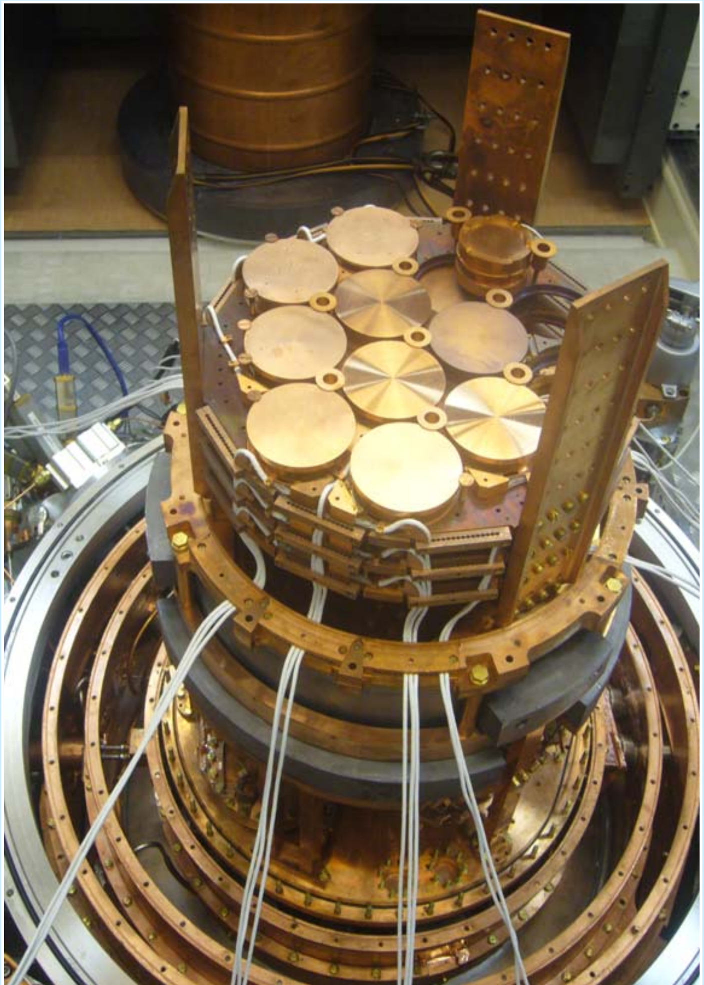
Roman lead shields

3x320 g detectors

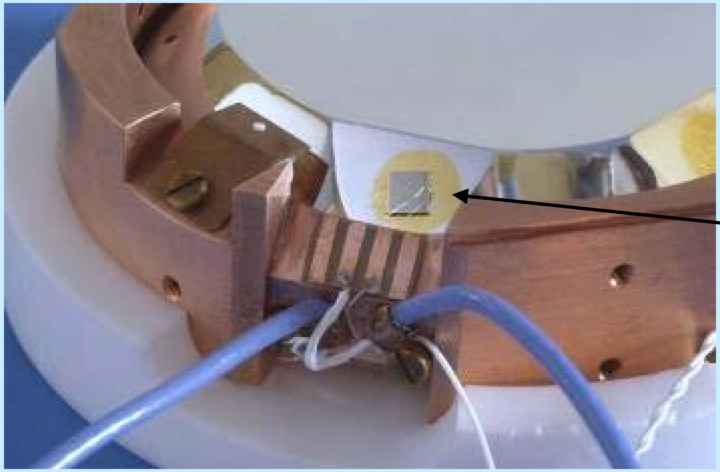
~1996 to March 2004

EDELWEISS-II
30 kg stage

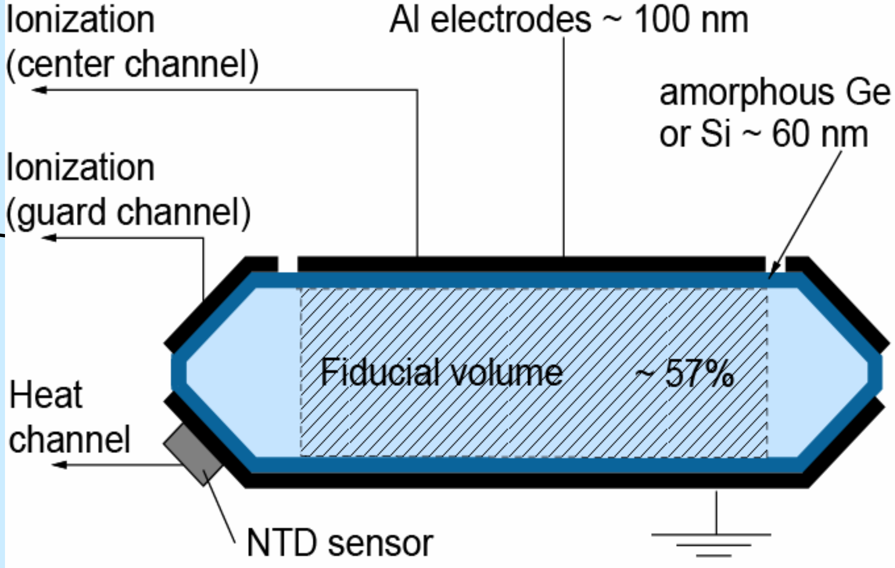
- Large volume ~50 l, reverse cryostat
- up to 110 detectors
- Installation 2005-2006
- Commissioning runs in 2006-2007.
- Results not yet available



EDELWEISS Ge Ionization-Heat detectors



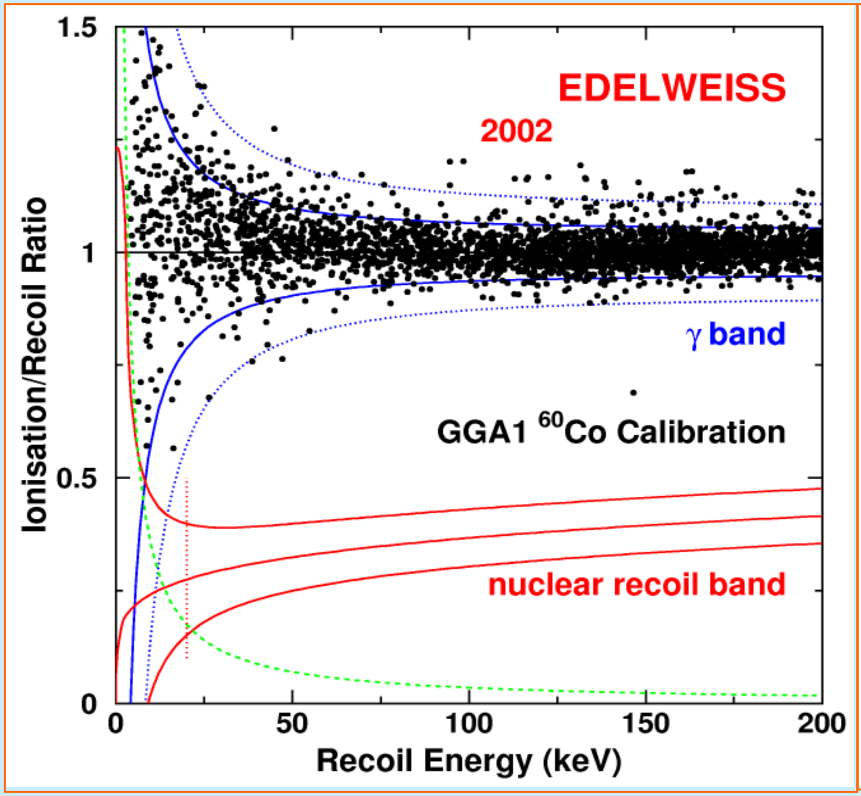
Edelweiss 320 g Ge detector

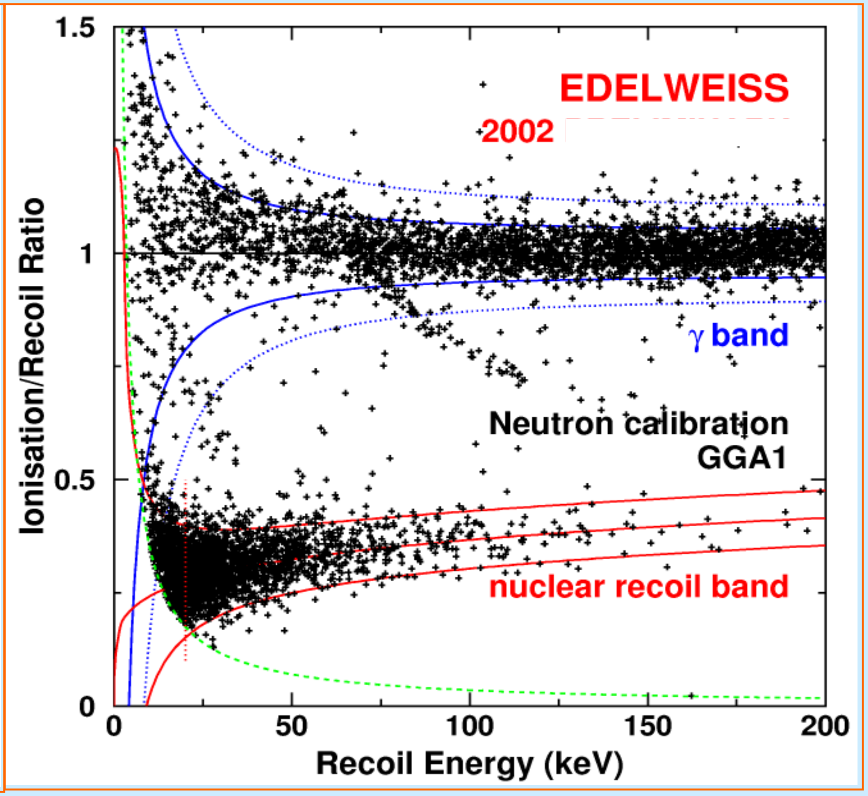


- **Heat signal:** NTD-Ge thermistor @ 17 mK
- **Ionisation signal:** @ few V/cm
- **Signal ratio** gives event by event recoil discrimination.
- Central/guard charge signal allows fiducial volume cut

EDELWEISS-I Discrimination Performance

^{60}Co calibration **^{252}Cf calibration**

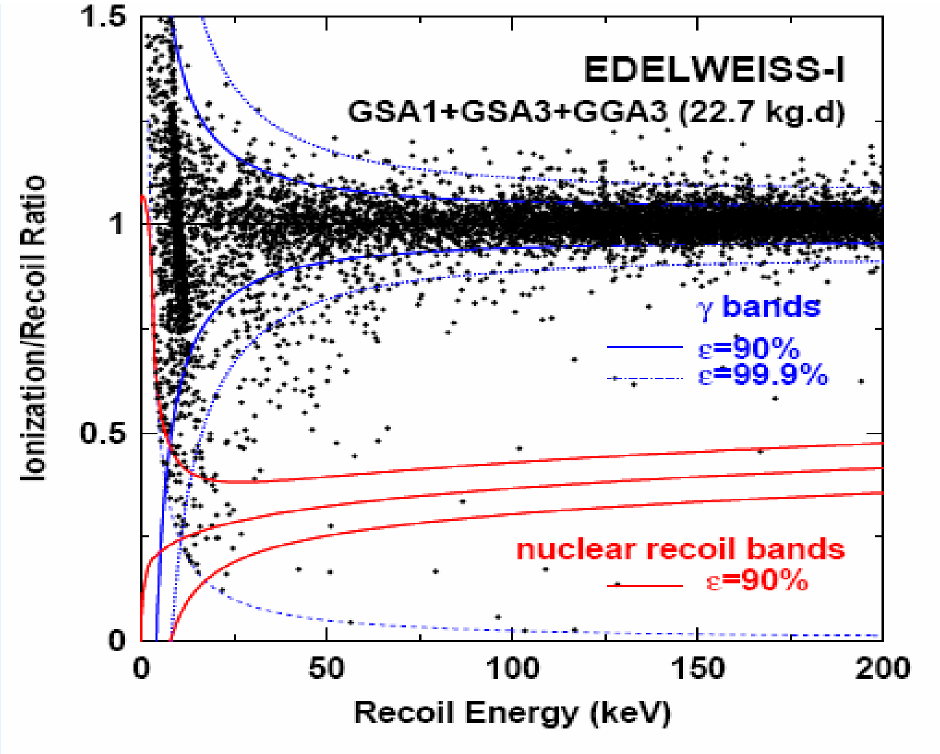




- Excellent gamma-n separation in calibration run.
- Rejection > 99.9% for recoil energies$_{l}$ > 15keV

EDELWEISS-I Data

2003 data



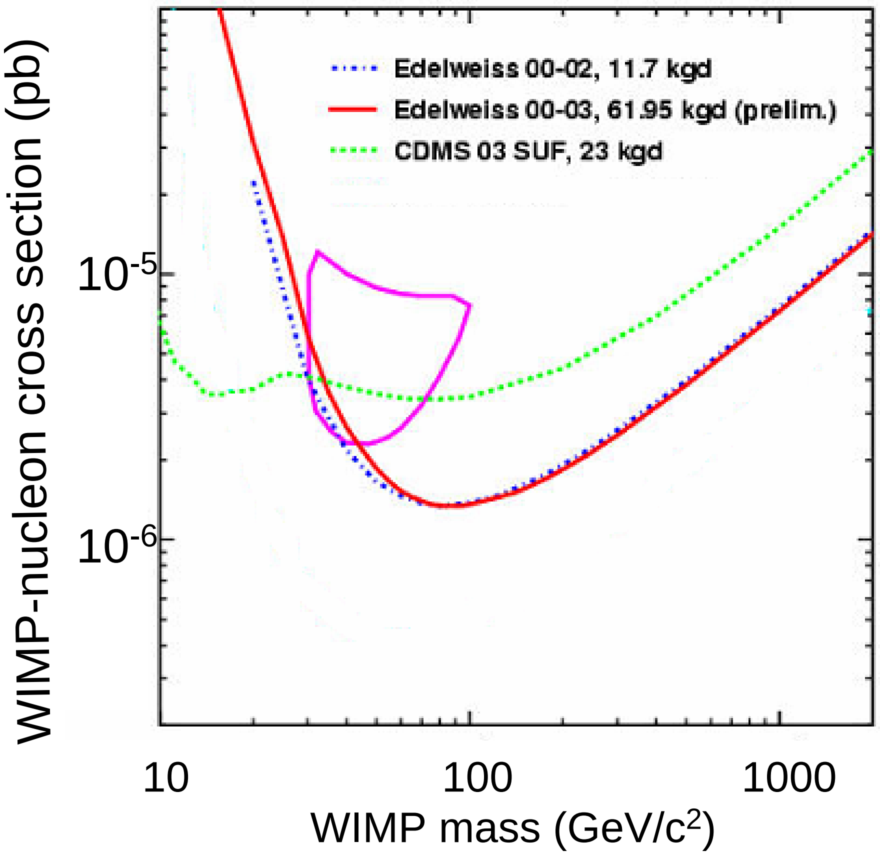
V.Sanglard et al,
Phys.Rev.D 71(2005) 122002

- 40 events in recoil band above 15 keV in 62 kg-days of combined data
- Very likely due to incomplete charge collection for electrons interacting at crystal surface.

EDELWEISS-I Final Result

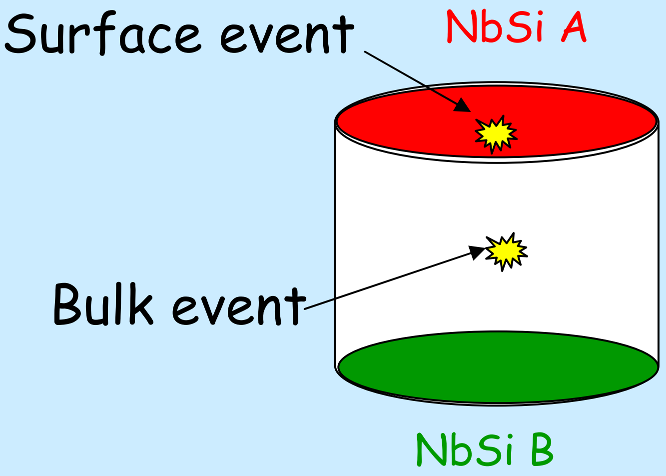
- EDELWEISS-I ended March 2004 for upgrade to phase-II
- Complete data set ~ 62 kg days
- No further improvement to previous limit (11.7 kg days) due to background.
- Sensitivity limited by leakage of surface events into nuclear recoil band. Main limitation of technique.
- DAMA positive evidence excluded in case of spin independent interaction

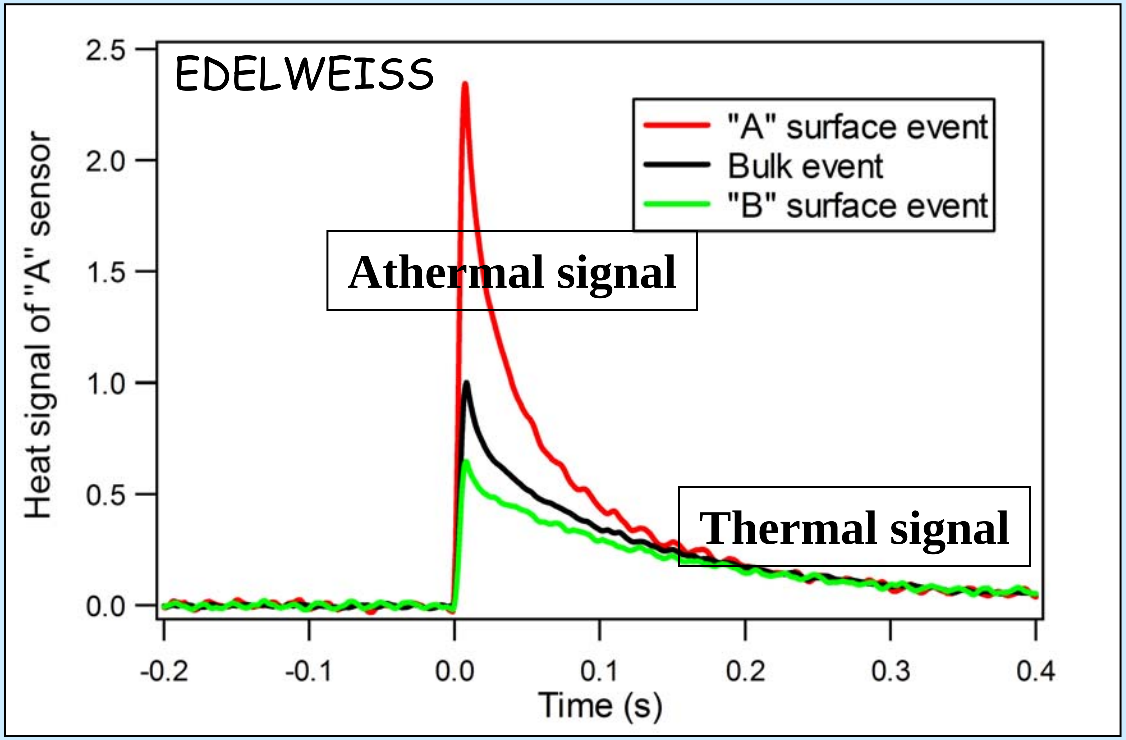
Sanglard et al, Phys.Rev.D 71(2005) 122002



EDELWEISS: Surface event identification with NbSi films

Allows detection of nonthermal high frequency phonons detection

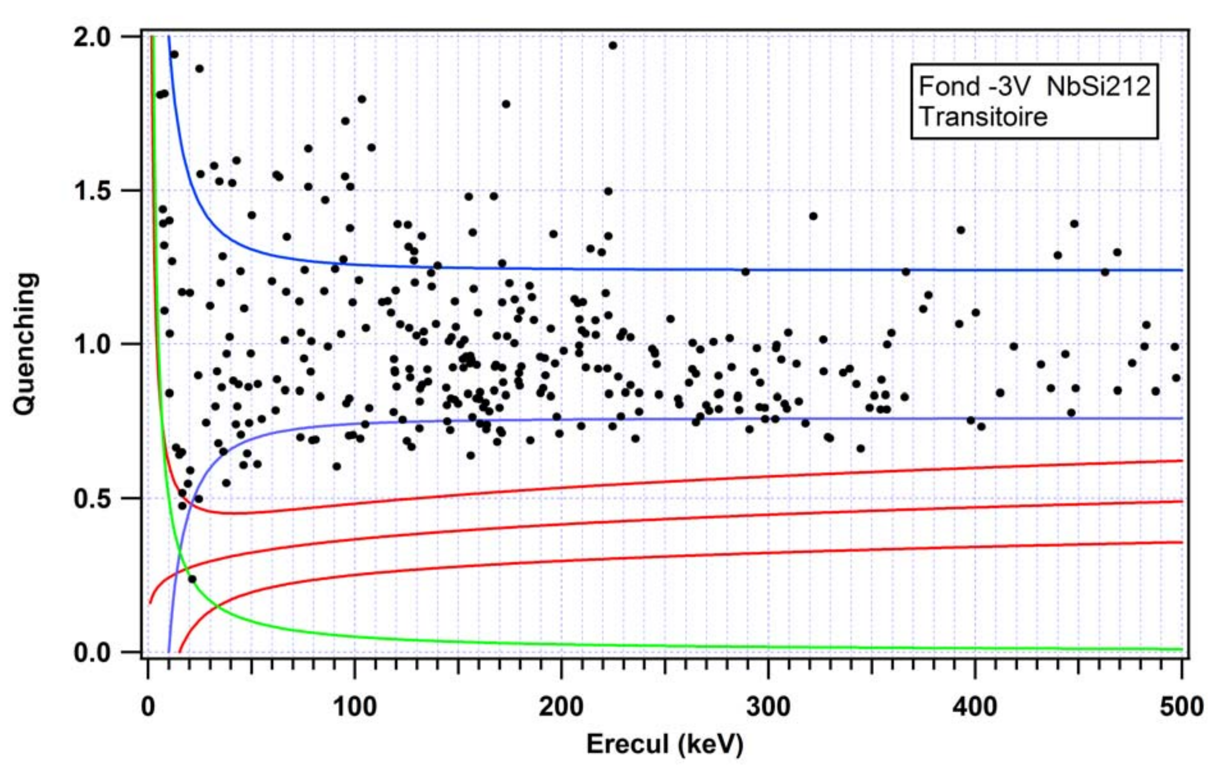




- ➔ Discrimination with athermal signal ratio
- ➔ Technique for EDELWEISS-II ?

400 g Ge-NbSi detectors: First data

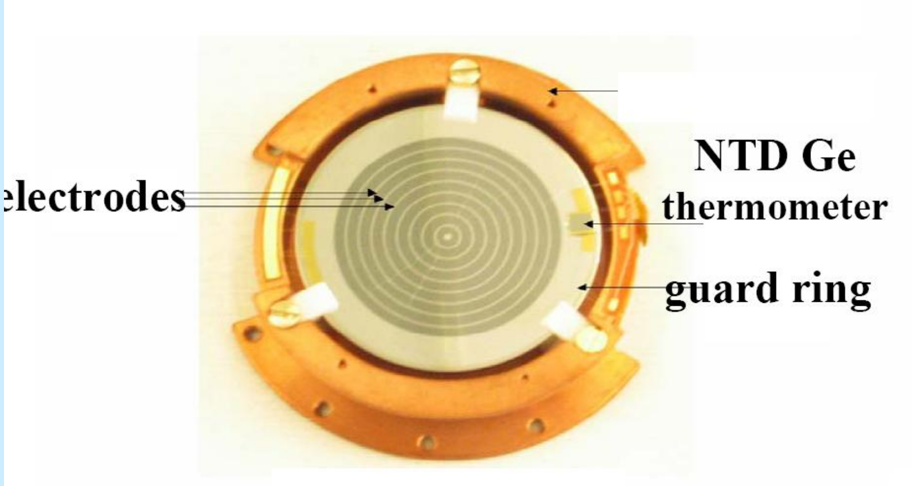
data taken with 1 **NbSi** detector in EDELWEISS-II set-up
May&June 2007: 1.5 kg d (fiducial)



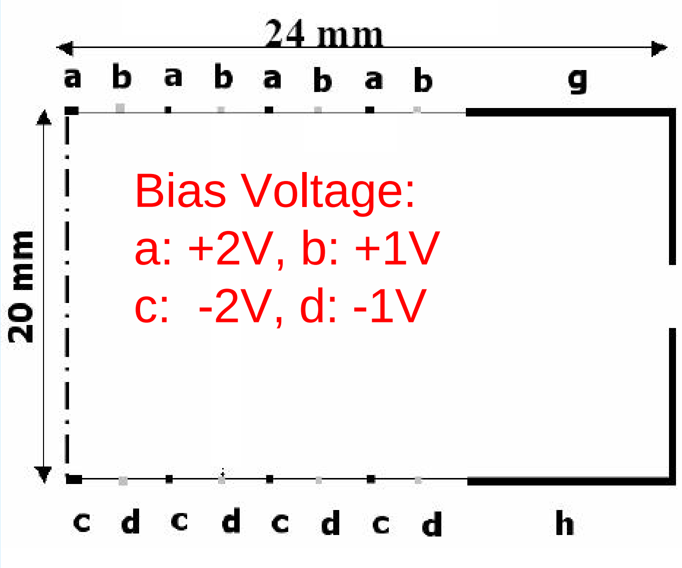
- Surface event rejection works, resolutions still needs tuning

Ge Detectors with Interdigitized Electrodes

New development for EDELWEISS-II



Top view



Bias Voltage:
a: +2V, b: +1V
c: -2V, d: -1V

Cross-section

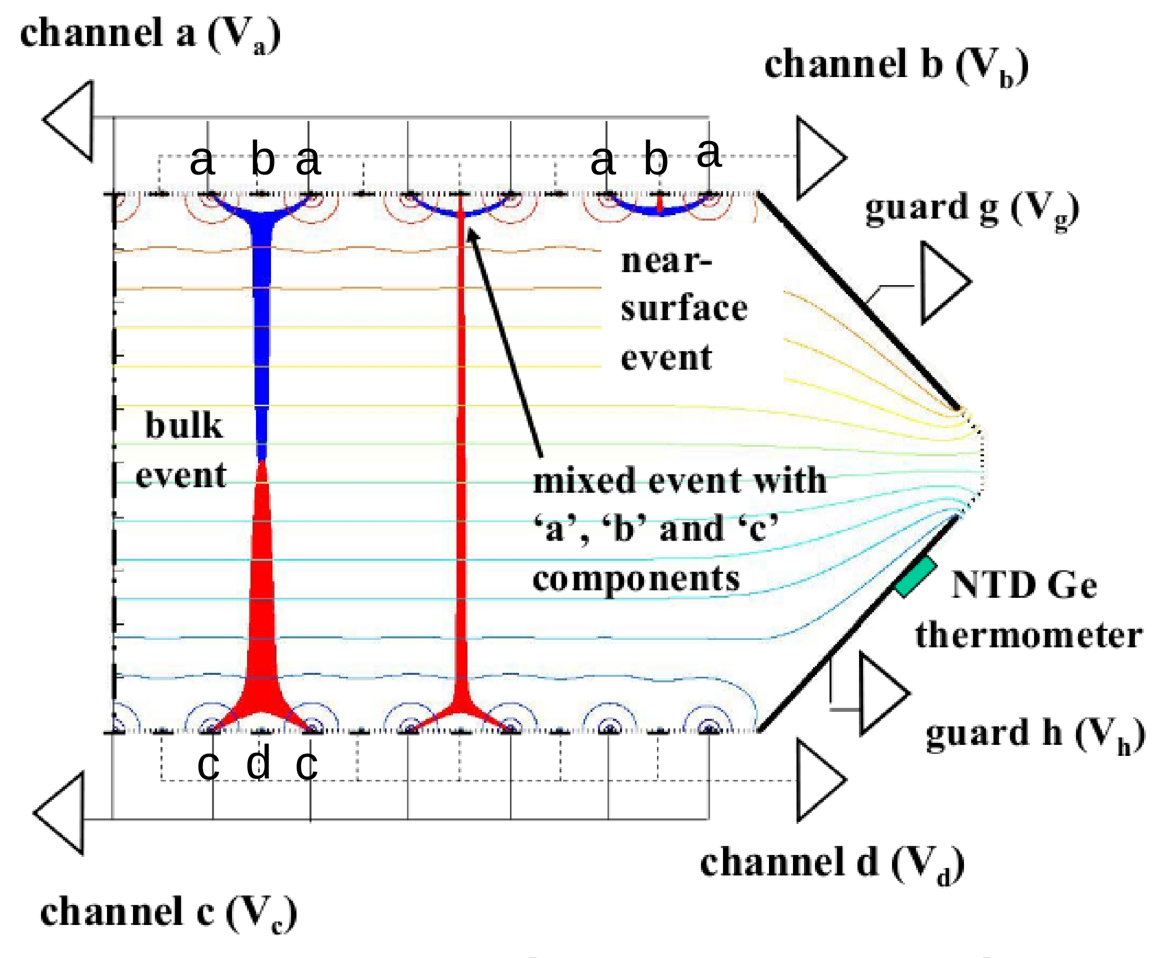
- 200 g Ge disk with annular Al electrodes with hydrogenated amorphous Ge layer for improved charge collection
- 7 measurement channels, 6 charge (a,b,c,d + 2 guard) + heat channel

ID Electrodes: Operating principle

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

Surface events
top surface:
$Q_a \neq 0$ & $Q_b \neq 0$
$Q_c = Q_d = 0$

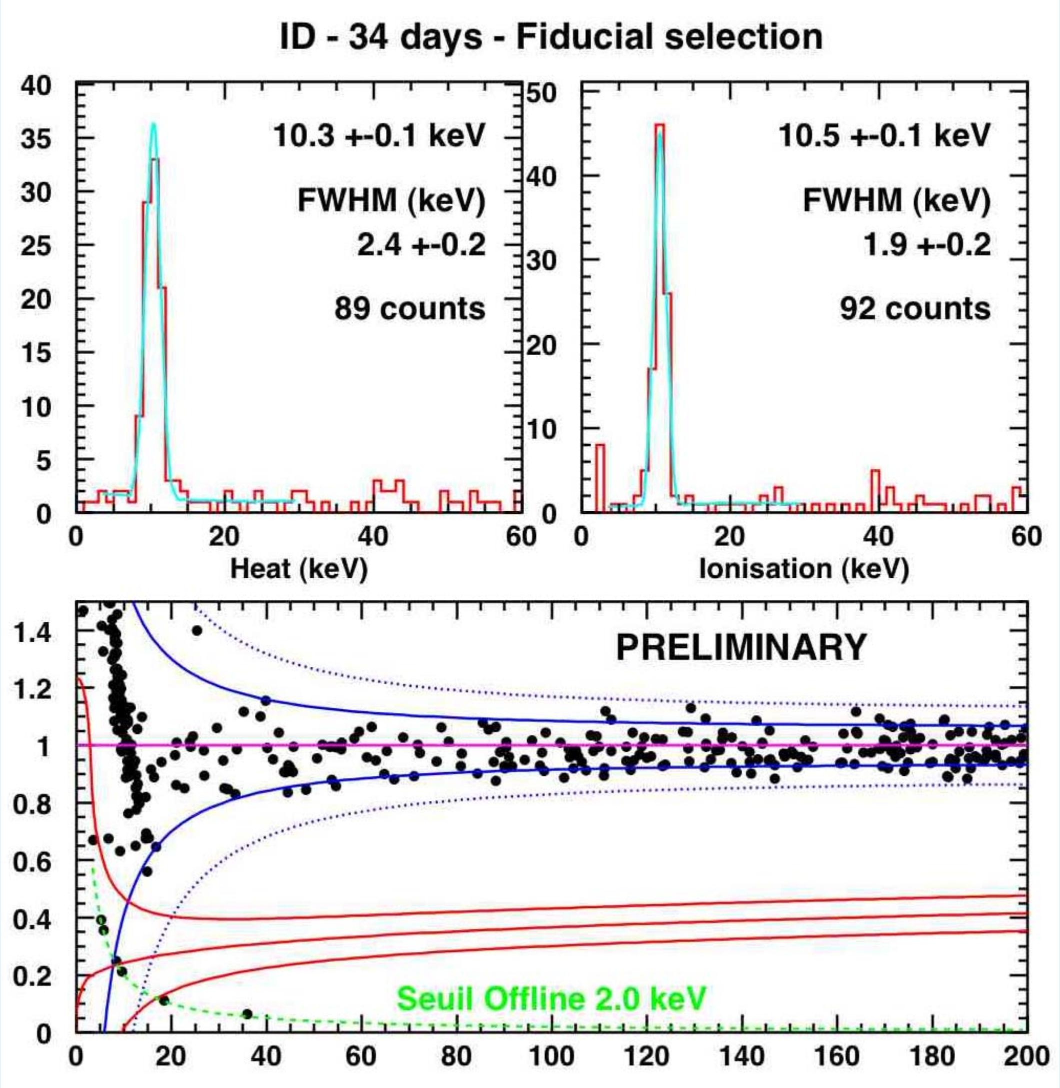
bottom surface:
$Q_a = Q_b = 0$
$Q_c \neq 0$ & $Q_d \neq 0$



Typical bias voltages:
V_a = 2V, V_b = 1V
V_c = -2V, V_d = -1V

EDELWEISS-II: Status of ID Detectors

First detector (200g) with interleaved electrodes in LSM



- Good energy resolution
- Encouraging discrimination performance
- Need more statistics to really judge

New 400 g ID's installed this spring in EDW-II set-up

CDMS

Brown University
Case Western Reserve University
University of Colorado at Denver
FNAL, LBL
Santa Clara University

Stanford University
Universty of California, Berkeley
University of California, Santa Barbara
University of Florida
University of Minnesota

CDMS at SUF shallow site (17 mwe): ended in 2002.

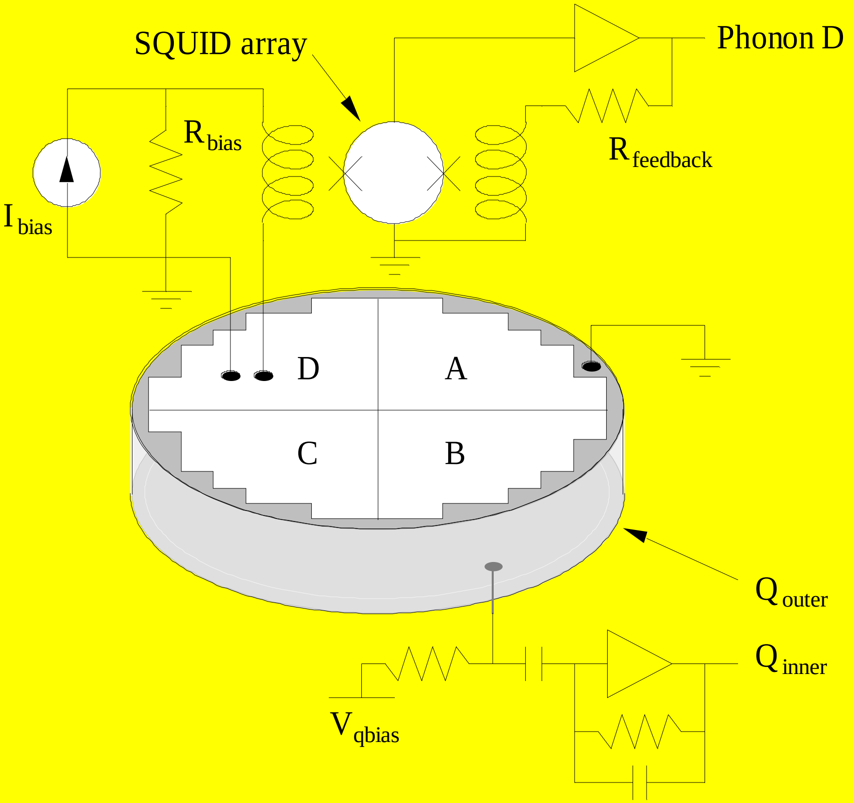
CDMS-II at SOUDAN mine:

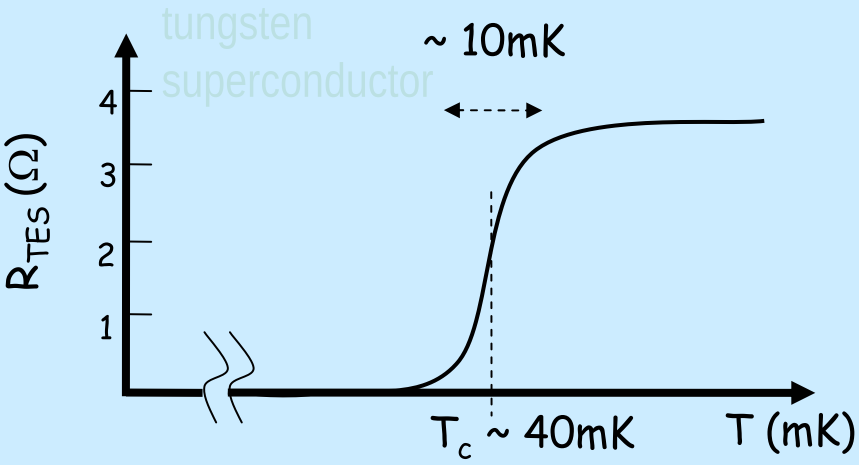
- **Setting up in mine at ~2000**
- **First data taking period Oct. 03 to Jan. 04, 1 tower run, ~1 kg**
  (Phys. Rev. Lett. 93 (2004) 211201
- **Second data taking period March to August 2004, 2 tower run, ~2 kg**
  (Phys. Rev. Lett. 96 (2006), 011302)
- **Since Oct. 2006, 5 tower run, ~ 5kg**
- Oct. 2006 to July 2007 data released in 2008 (astro-ph/08023530)

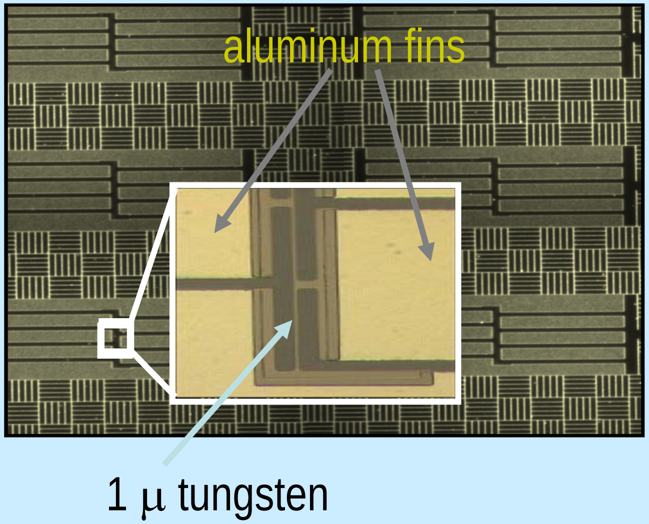
CDMS ZIP Ionization & Phonon Detectors

Fast athermal phonon detection

- Superconducting thin films of W with Al-quasiparticle traps, in four quadrants for position resolution
- Phonon pulse shape allows for rejection of surface recoils (with suppressed charge)
- Central charge electrode+guard ring on back side



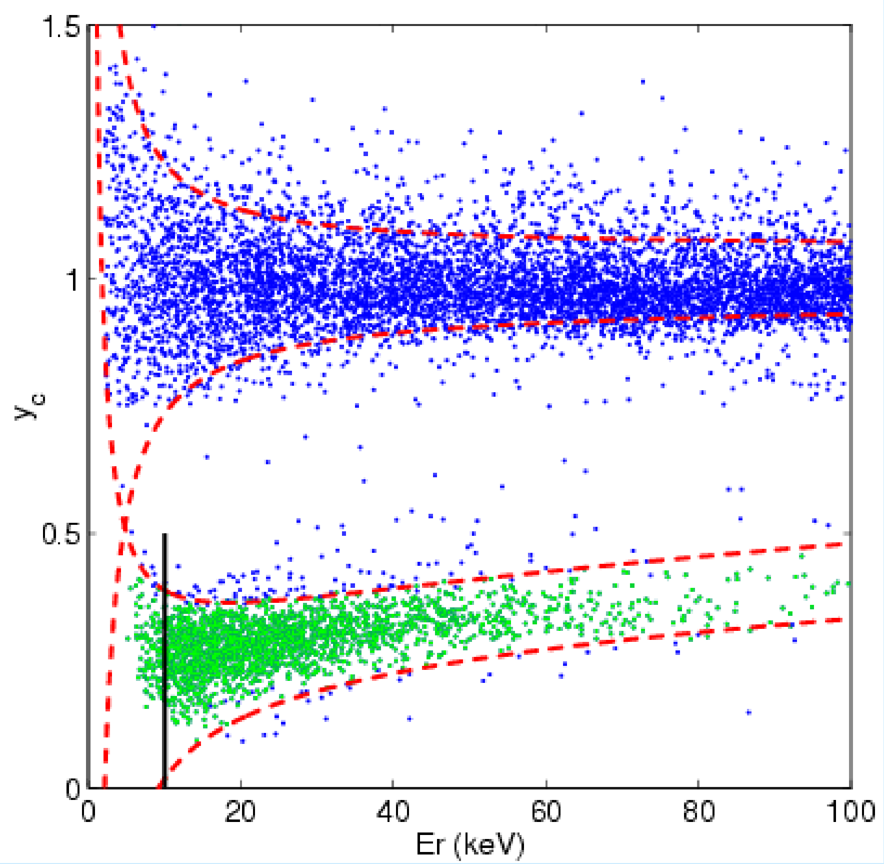




250 g Ge ZIPs, 100g Si ZIPs

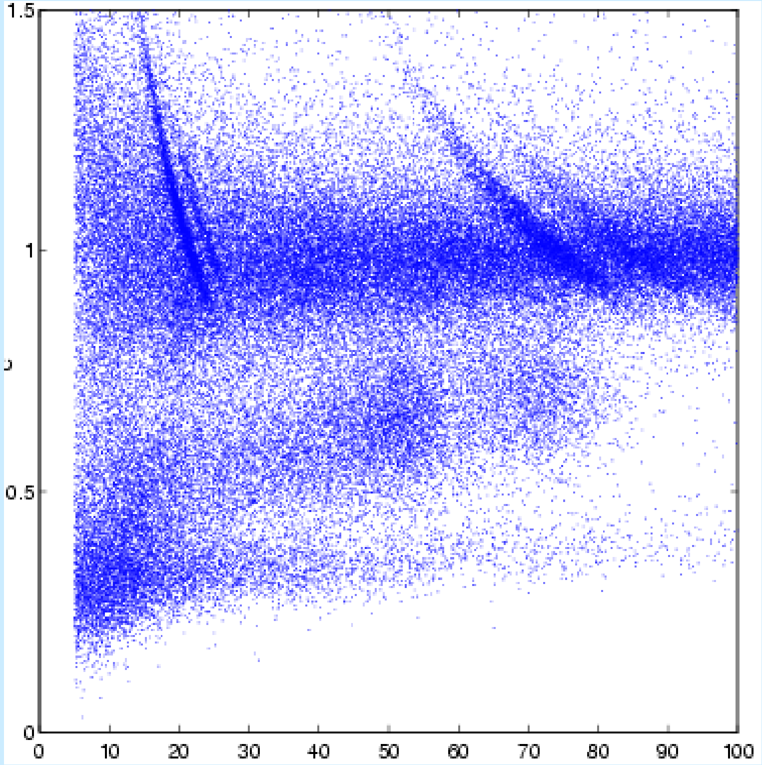
CDMS ZIP detectors

^{133}Ba γ + ^{252}Cf neutron calibration



- Excellent n/γ separation in calibration data

Internal e$^-$ (^{109}Cd)+ neutron source



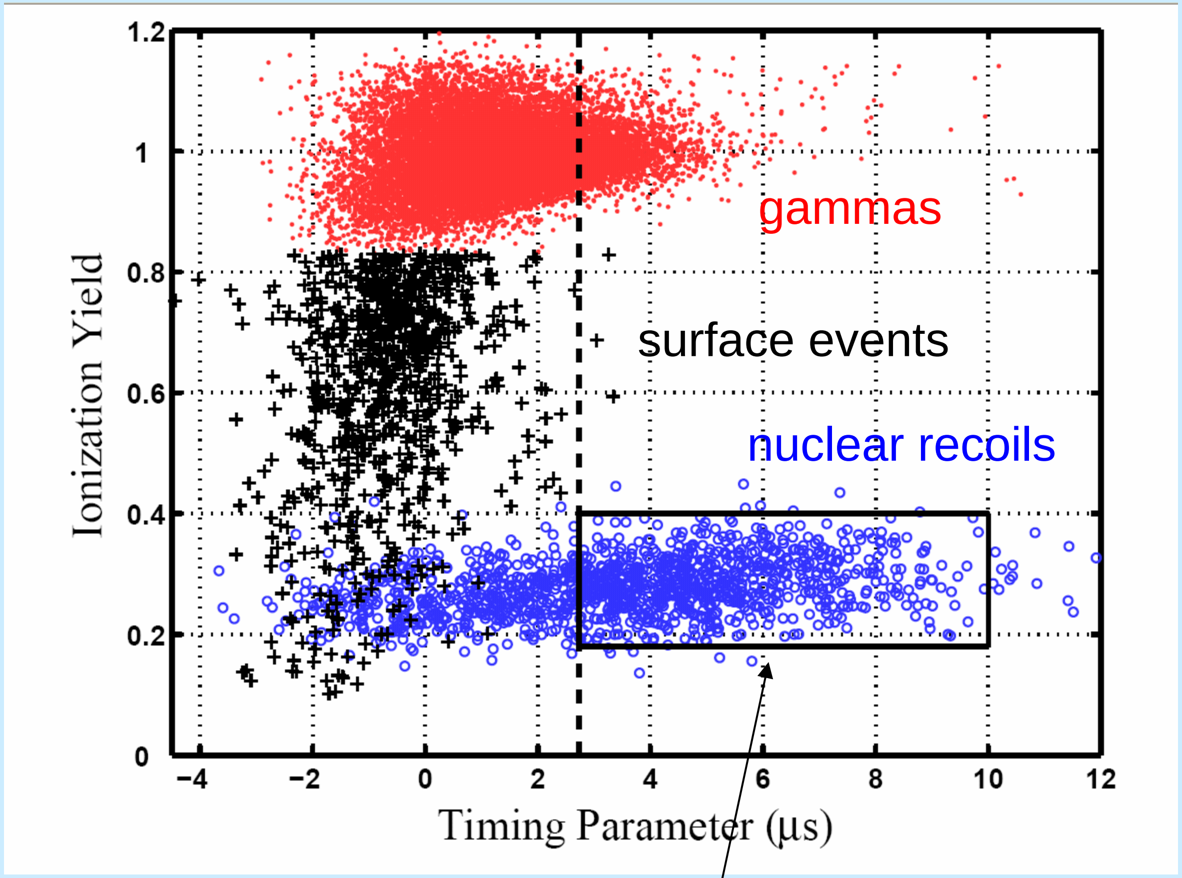
Incomplete charge collection for surface electrons mimics nuclear recoils

ZIP detectors timing cut

- Phonon rise time and charge to phonon delay allows rejection of surface events

- Definition of cuts with high statistic ^{133}Ba gamma and ^{252}Cf neutron calibrations

CDMS-II run March-August 2004, PRL 96 (2006) 11302



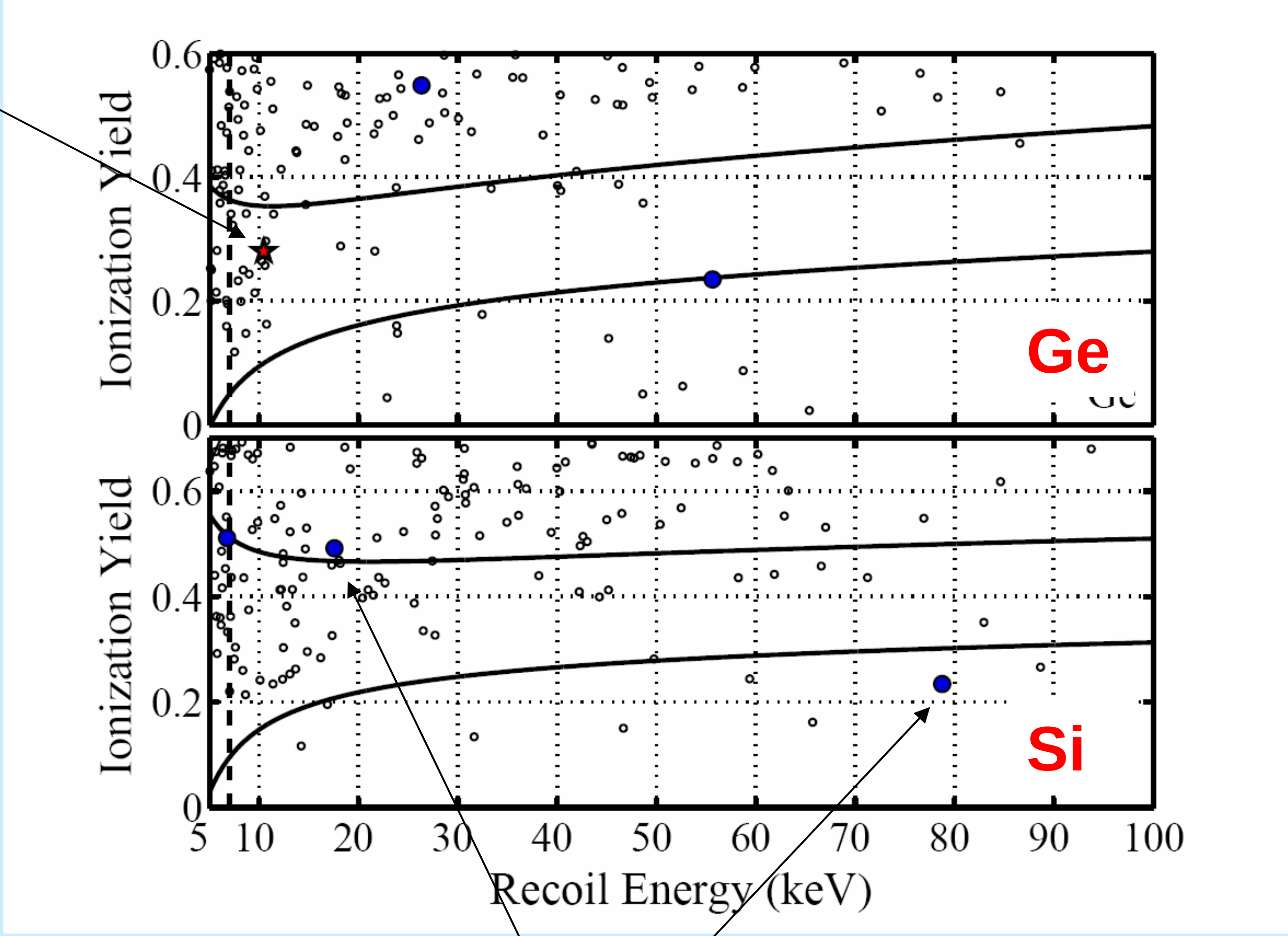
Accepted recoil signal region

CDMS ZIP detectors: physics run 2004

CDMS-II run March to August 2004, PRL 96 (2006) 11302

- Ge data: 1 event survived surface cut
- Si data: 0 events in signal region after surface electron cut
- Cuts removes ~65% of live time

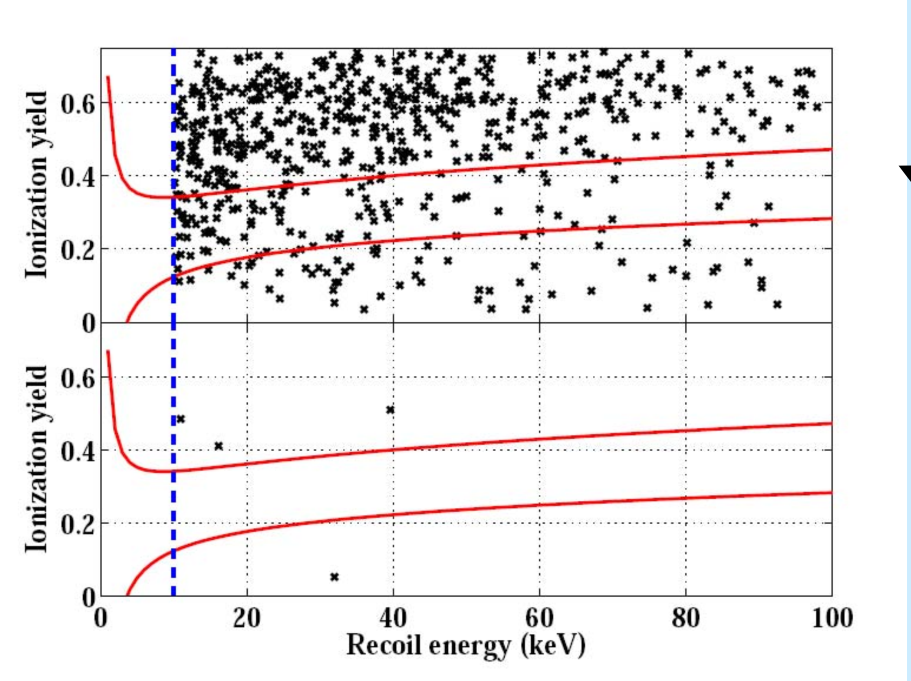
2003+2004 Ge data sets: 2 events in nuclear reocoil band in 53 kg d,



survivors outside nuclear recoil signal region

CDMS: Two 5 tower runs in 2006/2007

Nuclear recoil signal region

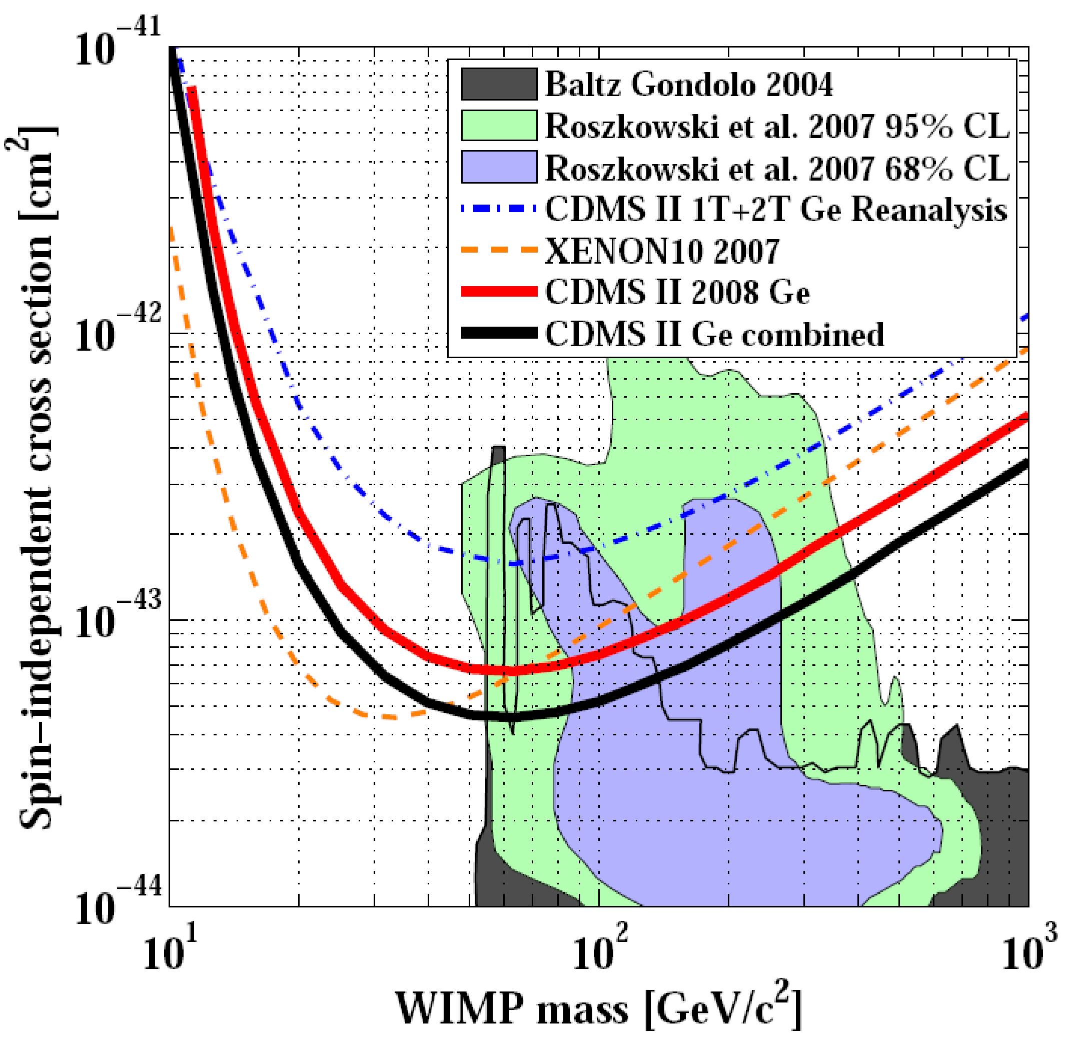


after all cuts but timing cut

also with timing cut

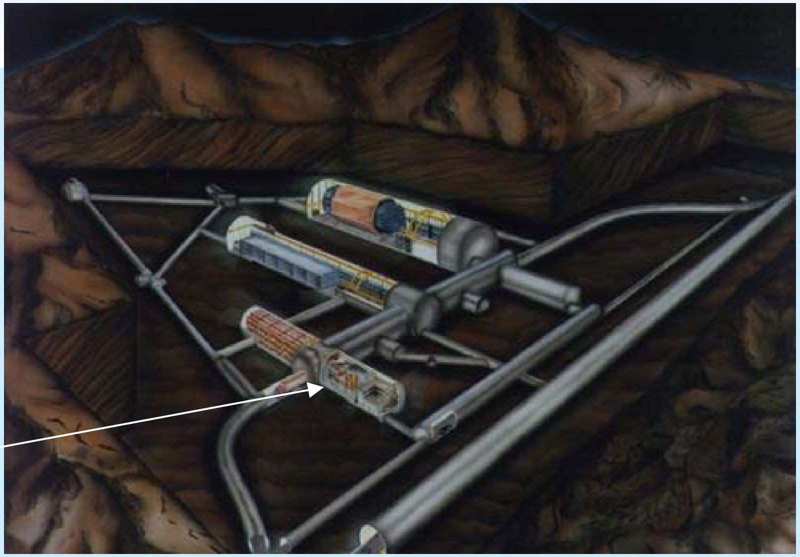
- Data sample: 397.8 kg-days (cuts remove ~70%)
- 121.3 kg-days after cuts. No event in nuclear recoil region above 10 keV. Cuts were tuned for 0.5 expected.

CDMS 2008 limit



- Best present limit
- Cuts in central SUSY parameter space

CRESST



Collaboration:

MPI für Physik

University of Oxford

TU München

Universität Tübingen

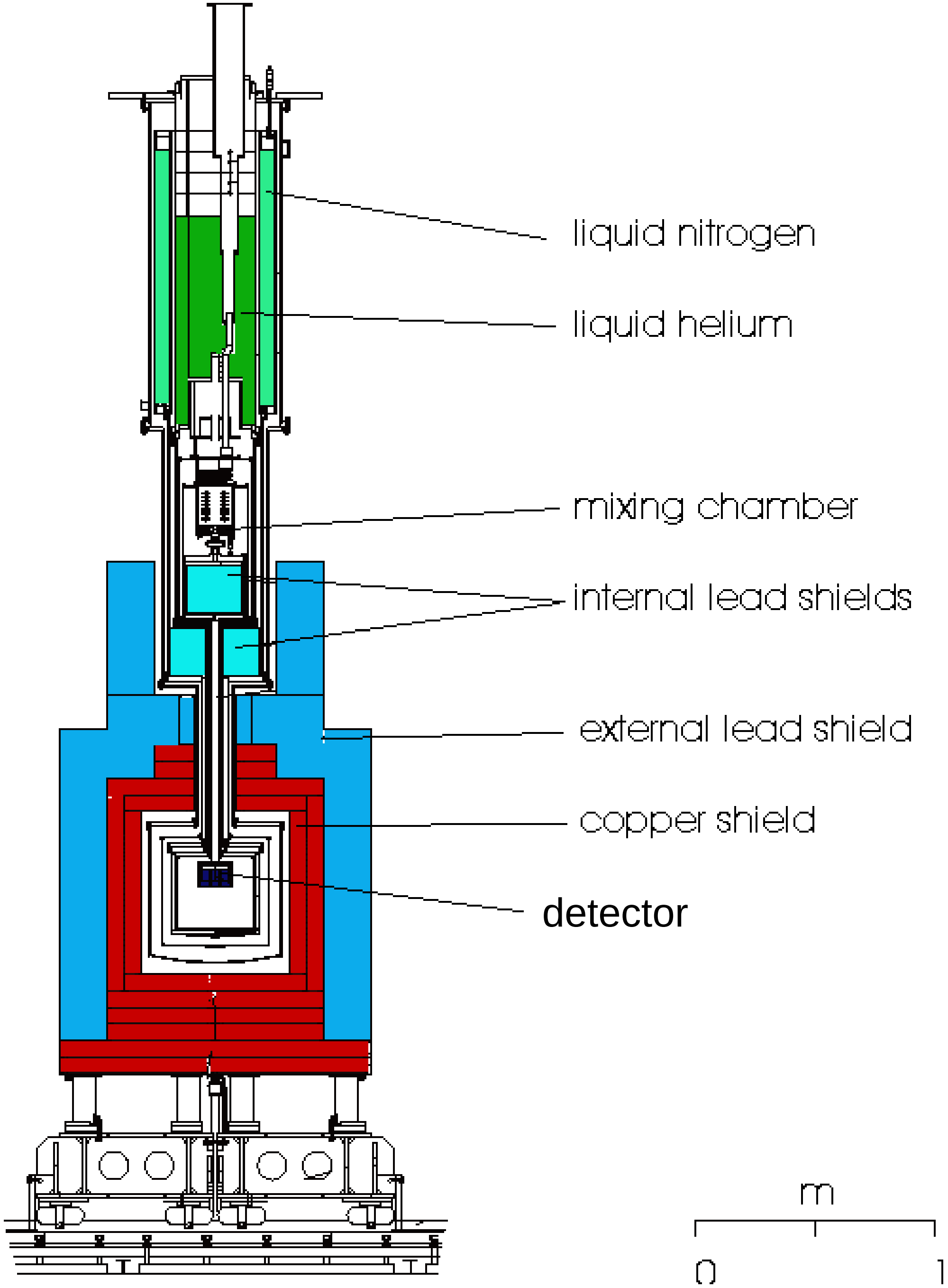
Laboratori Nazionali del Gran Sasso

CRESST

Run Summary:

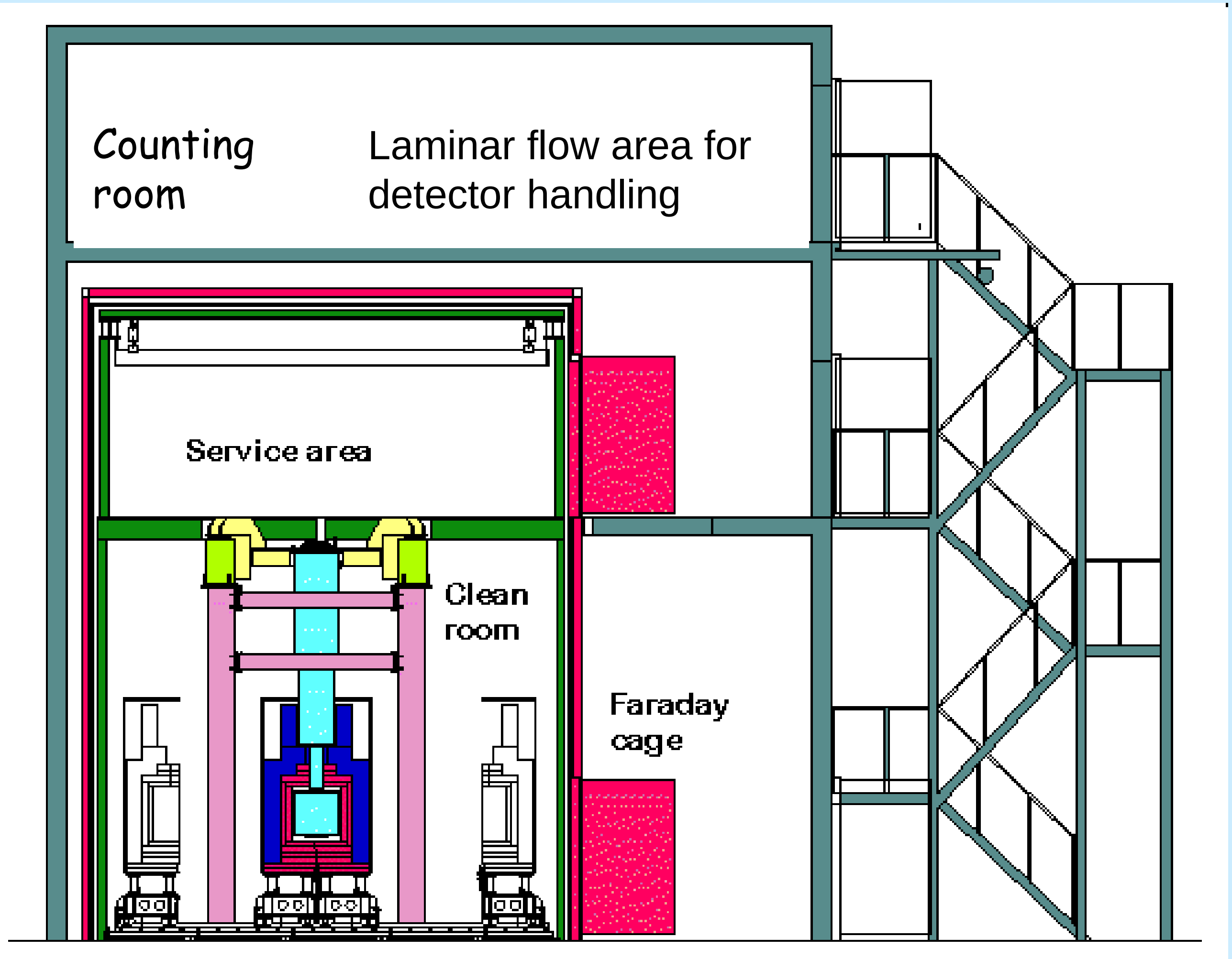
- CRESST-I ended in March 2001
  ==> move to hall A
- Series of tests of new phonon/light detectors in 2003
- Short physics run with two 300g phonon/light detectors
  ==>2004 results
- Upgrade of setup for CRESST-II 2004 to 2006
- Commissioning run in 2007 with 3 detector modules
  ==> 2007 results
- Run with 17 detector modules has started recently

CRESST Cryostat



- Only selected low background materials with minimized exposure to cosmic rays activation
- 20 cm Pb +15 cm Cu shield
- Cold Pb shields to block line of sight to detectors
- No cryogenic liquids inside shielding
- Gas tight radon box around shield
- Cold box volume ~30 l, large enough for CRESST-II detectors

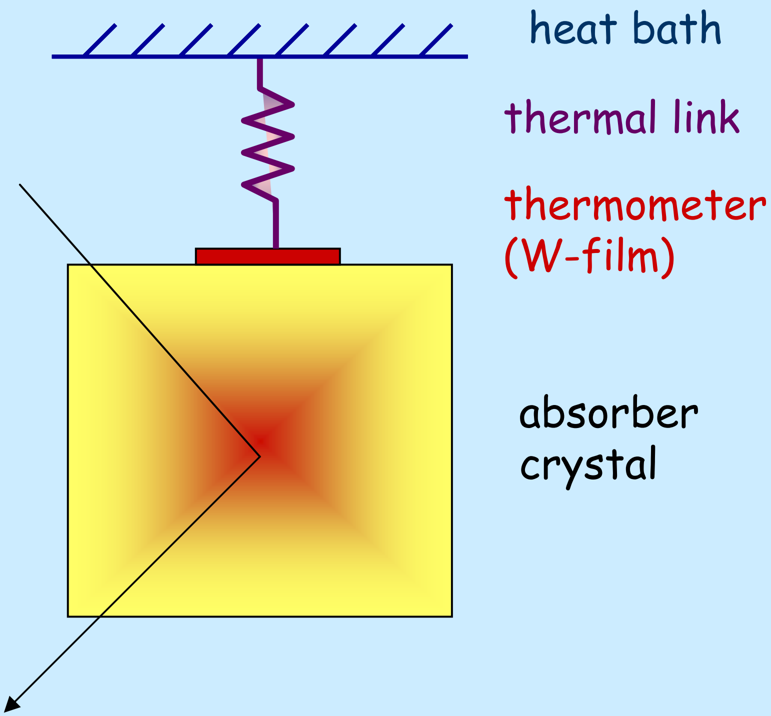
CRESST-I Setup



- Free standing Faraday cage, lower level is clean room
- Cryostat with efficient vibration insulation in Faraday cage
- Cryostat service from first floor, outside clean room

Cold Box and Pb/CuSchielding

CRESST type Detectors

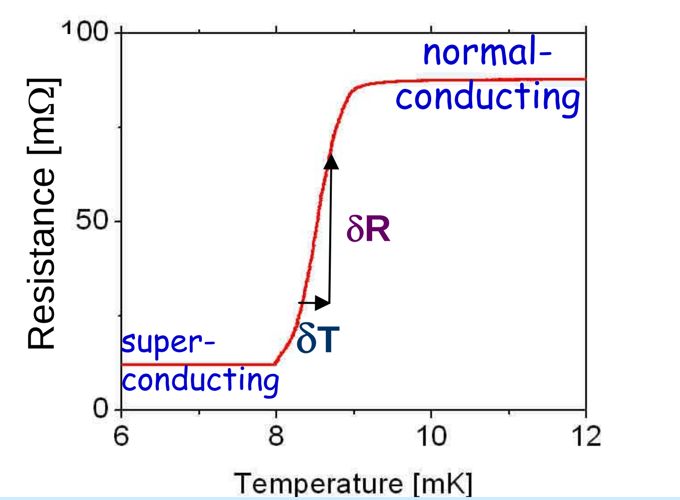


heat bath

thermal link

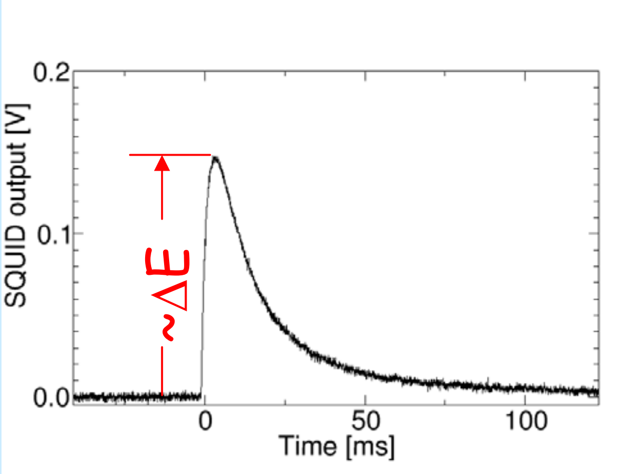
thermometer (W-film)

absorber crystal



SQUID based read out circuit
Width of transition: ~1mK, keV signals: few μ K
Longterm stablity: ~ μ K

Temperature pulse

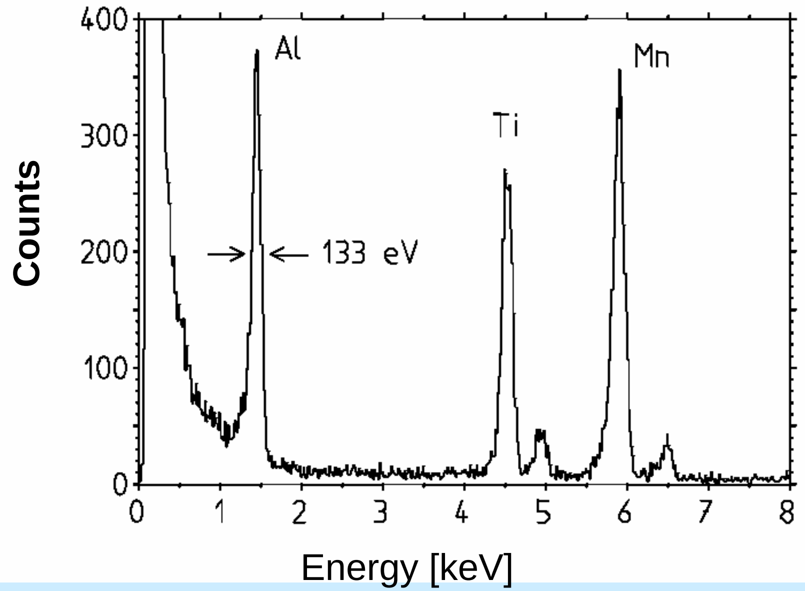


Advantages of technique:

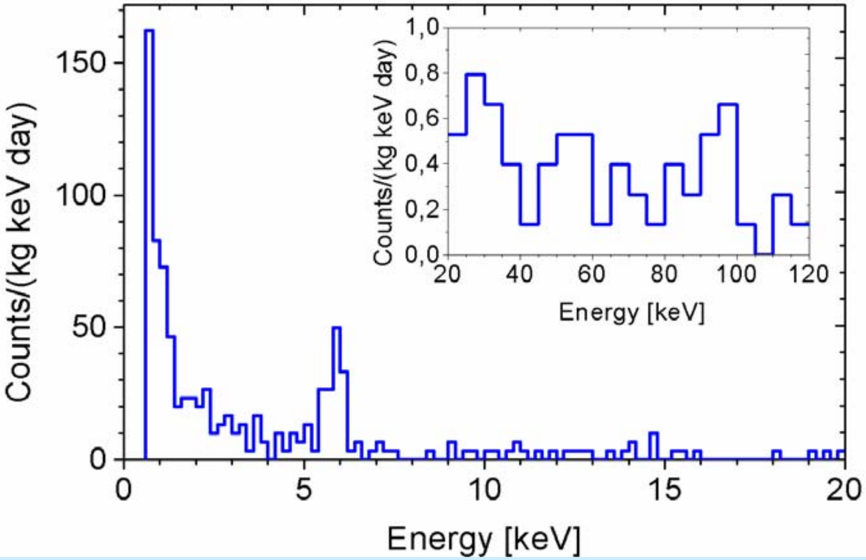
- measures deposited energy independent of interaction type
- Very low energy threshold
- Excellent energy resolution
- Many materials

CRESST-I: 262 g sapphire detectors

X-ray calibration



Low background run



Excellent energy resolution:

133 eV @ 1.5 keV

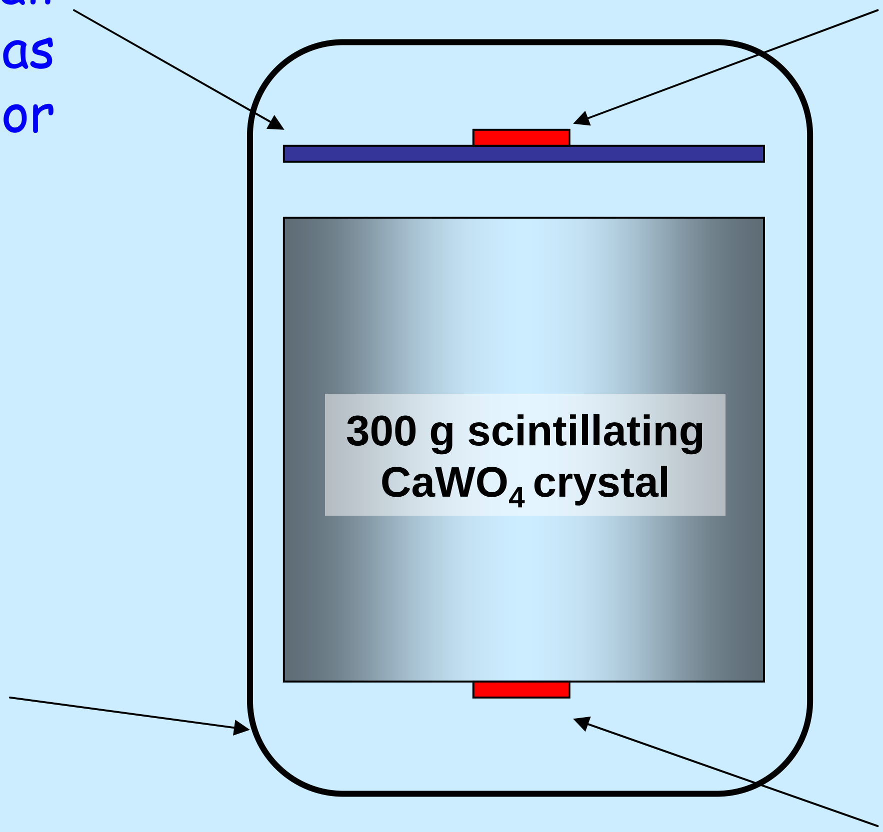
Threshold: 500 eV

Low background: (0.73±0.22) counts /(kg keV day) in 15 keV to 25 keV range

< 0.3 counts/(kg keV day) @ 100 keV

CRESST-II Detector Concept

Discrimination of nuclear recoils from radioactive $\beta+\gamma$ backgrounds by simultaneous measurement of phonons and scintillation light



separate small calorimeter as light detector

W-thermometer

300 g scintillating $CaWO_4$ crystal

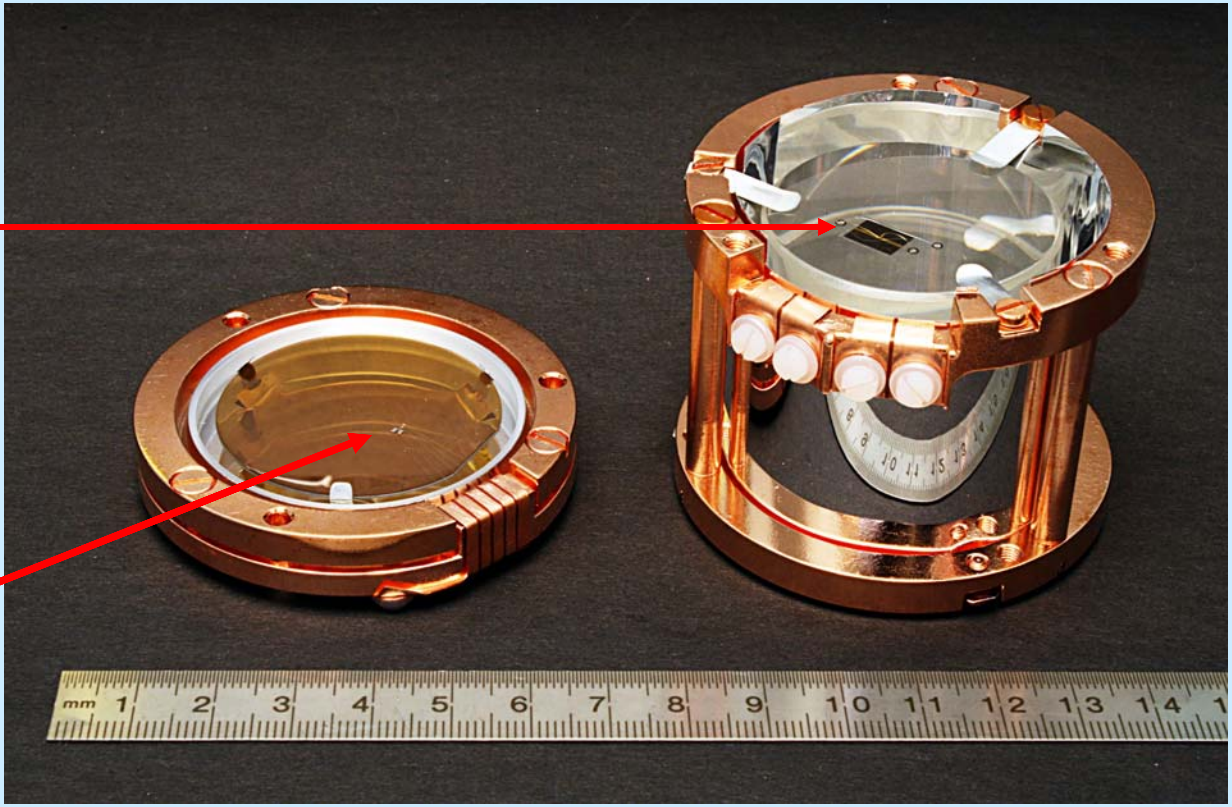
light reflector (scintillating polymeric foil)

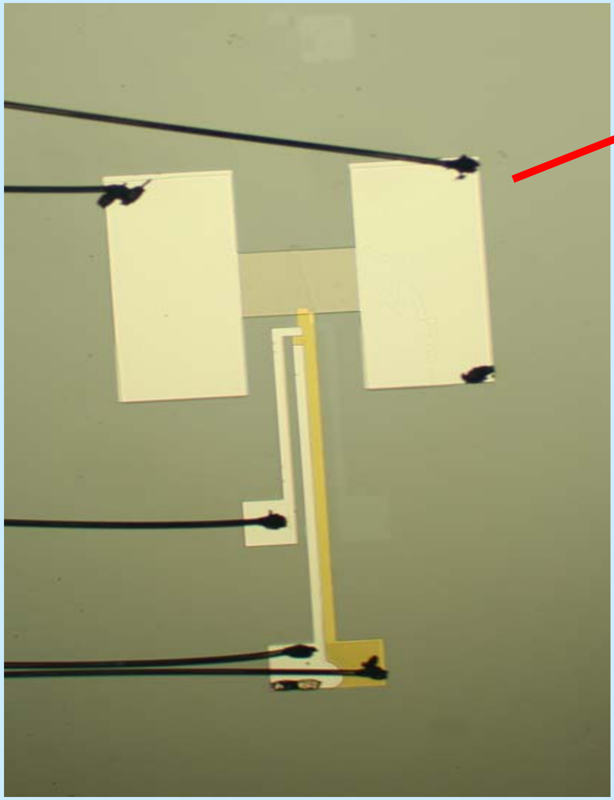
W-thermometer

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

300 g CRESST-II Detector Module

The phonon detector:
300 g cylindrical $CaWO_4$ crystal. Evaporated tungsten thermometer with attached heater.



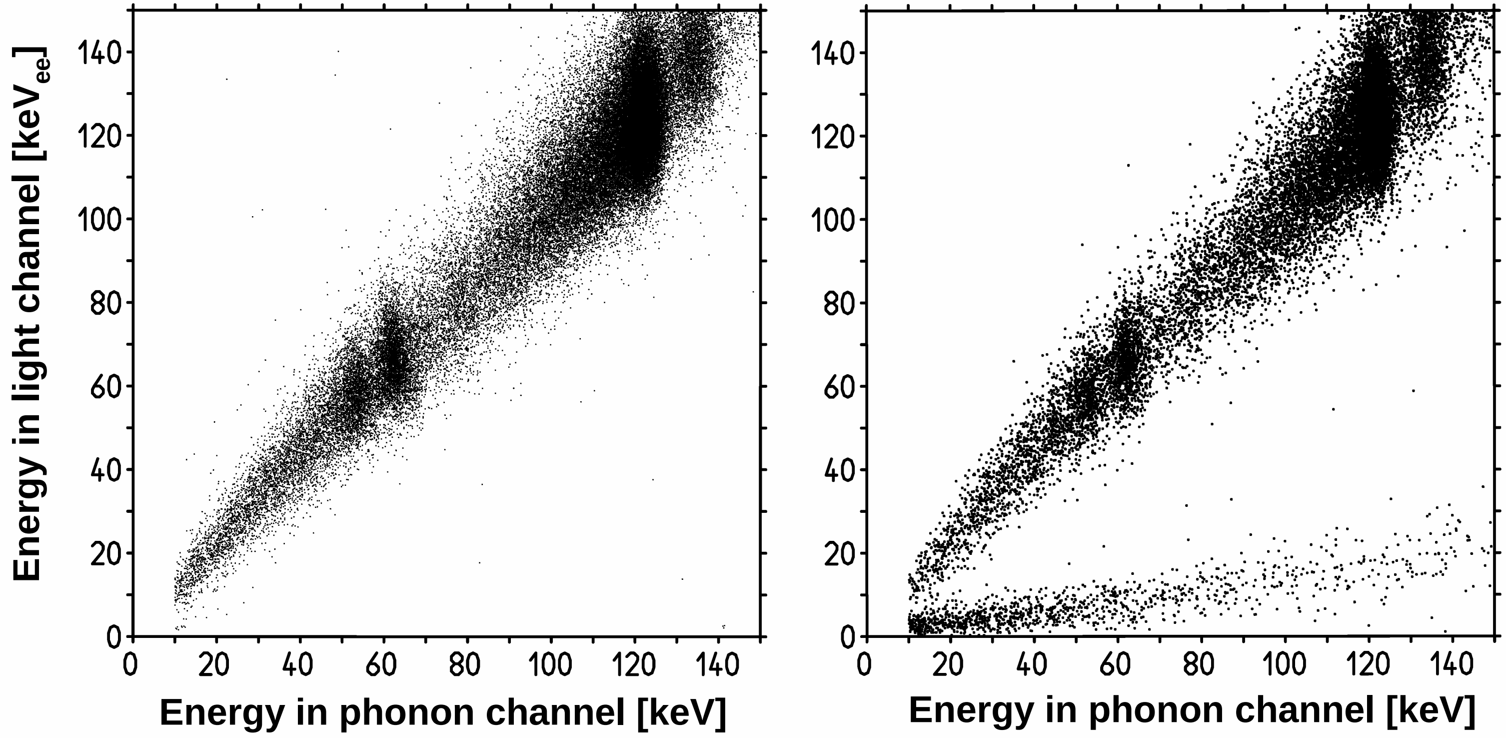


The light detector:
Ø=40 mm silicon on sapphire wafer.
Tungsten thermometer with attached aluminum phonon collectors and thermal link.
Part of thermal link used as heater

CRESST-II: up to 33 detector modules

Proof of principle

Irradiation with γ and e^- **Irradiation with e^-, γ and n**

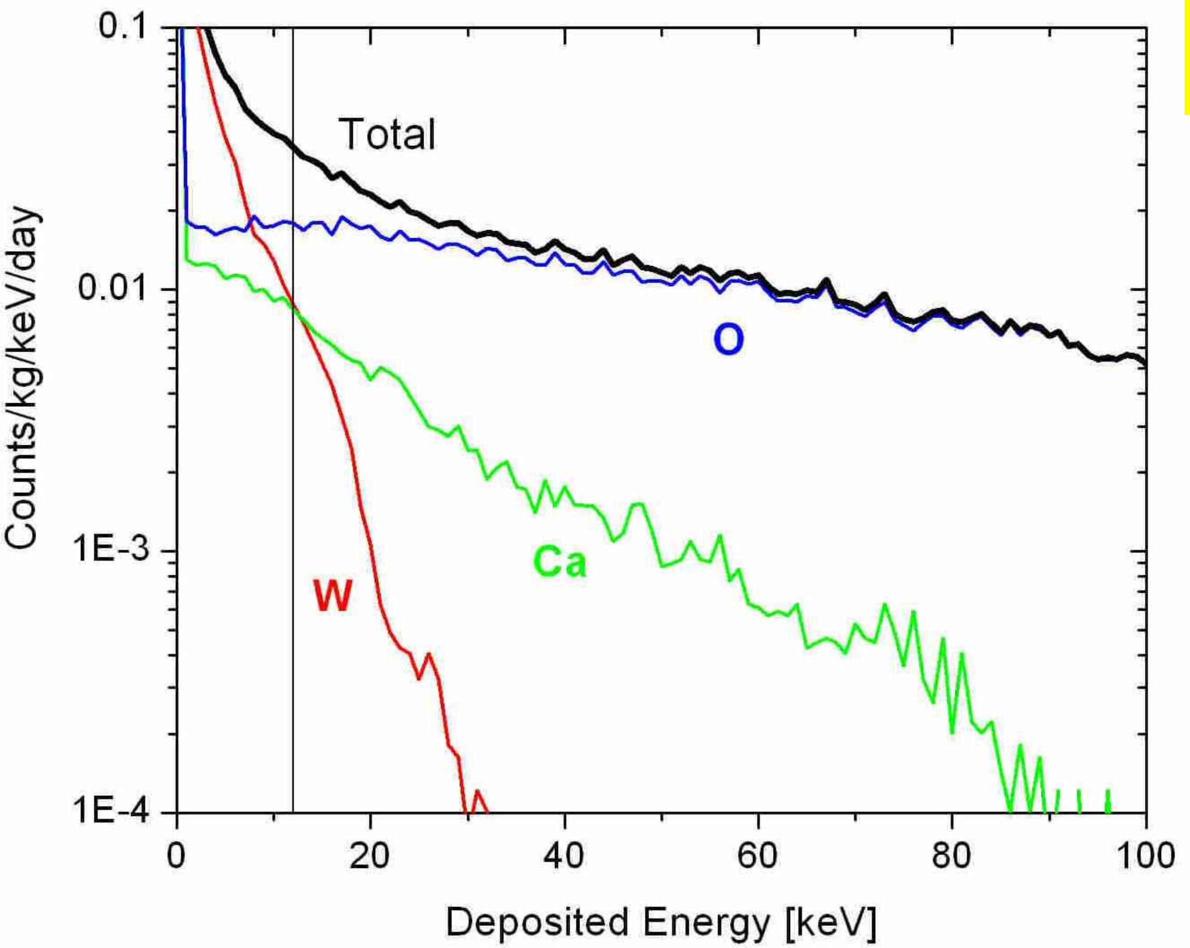


- No degratation of light yield for e^- surface events. Main advantage of technique

- Efficient discrimination of e^- and γ background above 15 keV

Recoil spectrum in $CaWO_4$ expected from unshielded neutrons at Gran Sasso

Monte Carlo simulation dry concrete (H. Wulandariet al.)



Contribution of W recoils very small above 12 keV

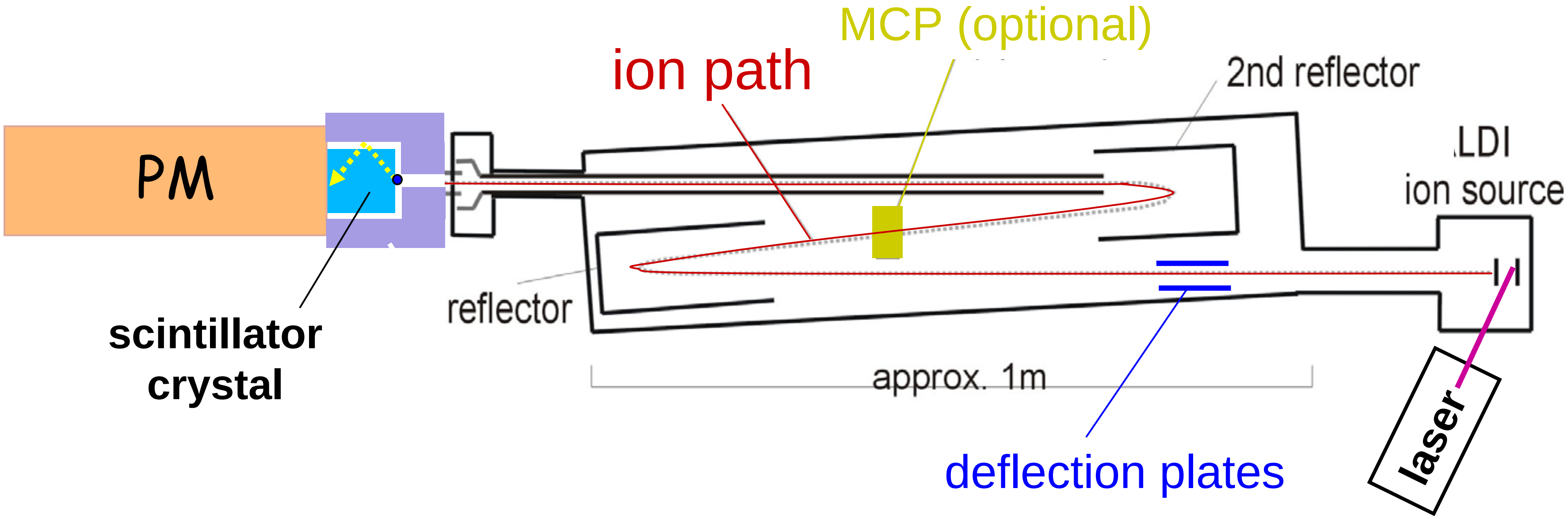
$\sigma \propto A^2$ for WIMPs with spin independent interaction

- **WIMPs scatter on W (A=184) nuclei**
- **Neutrons mainly on Oxygen**

Discriminate neutron background from WIMP singnal ??

Quenching Factor Measurements

Time of flight mass sepctrometer

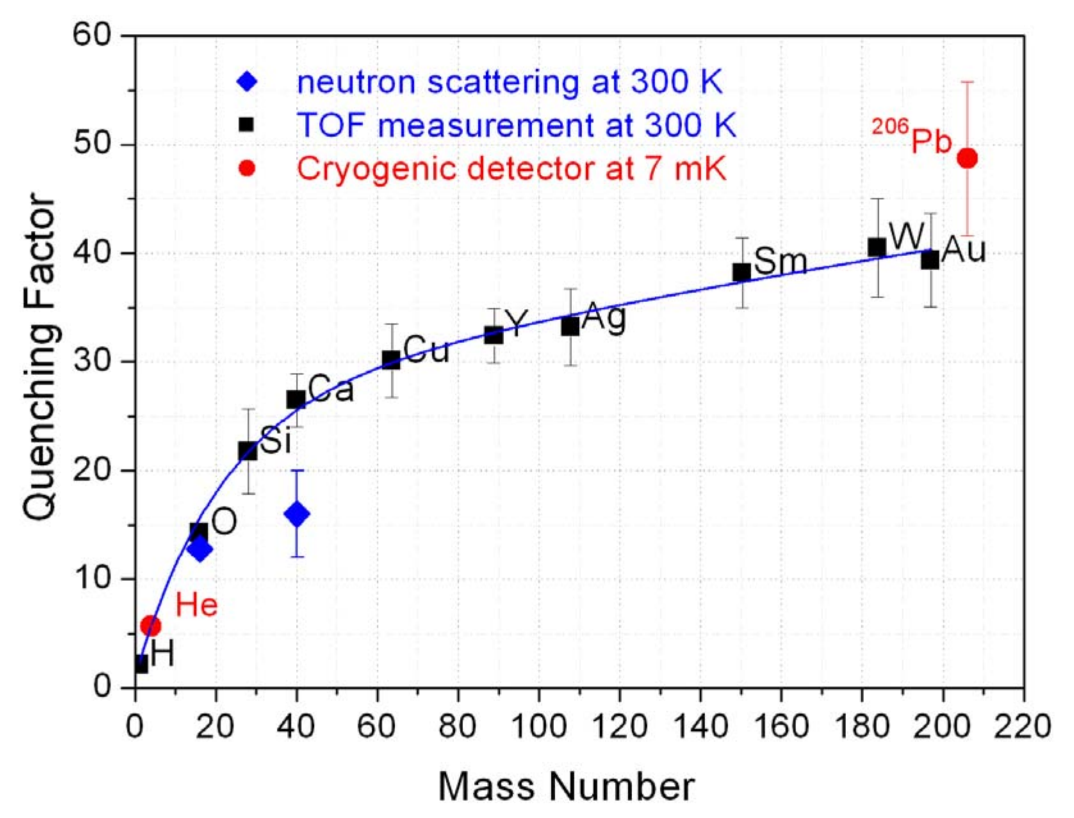


- CaWO$_4$ scintillator crystal irradiated with singly ionized single atoms
- Photon counting in narrow time window from arrivel time
- Almost background free method

- Nucleus (energy) dependent measurements.

Quenching factor vs. atomic mass

$$QF_{NR} = \frac{\text{Light yield of } \gamma\text{-interaction with energy E}}{\text{Light yield of n-recoil interaction with energy E}}$$



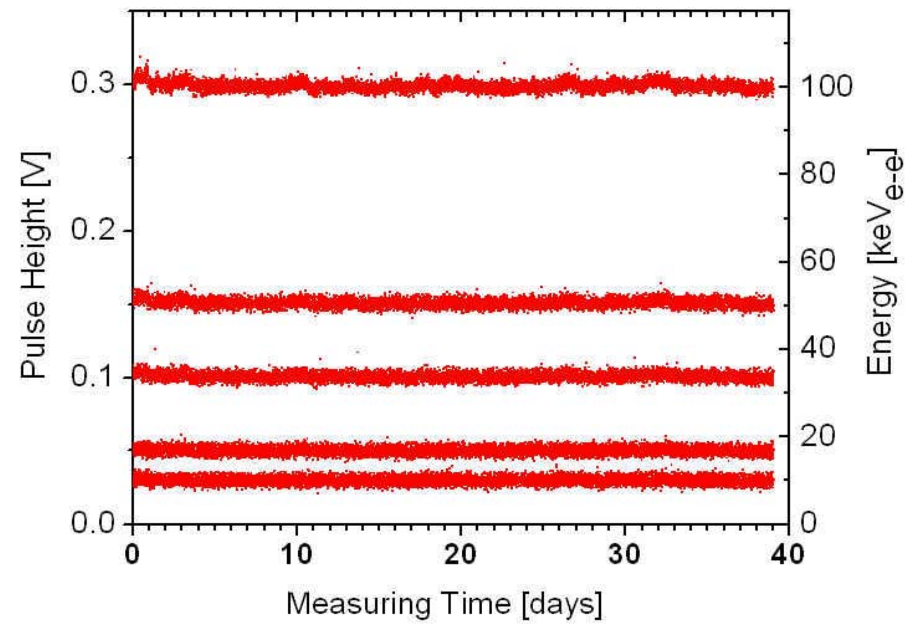
W recoils have significantly lower light yield

⬇

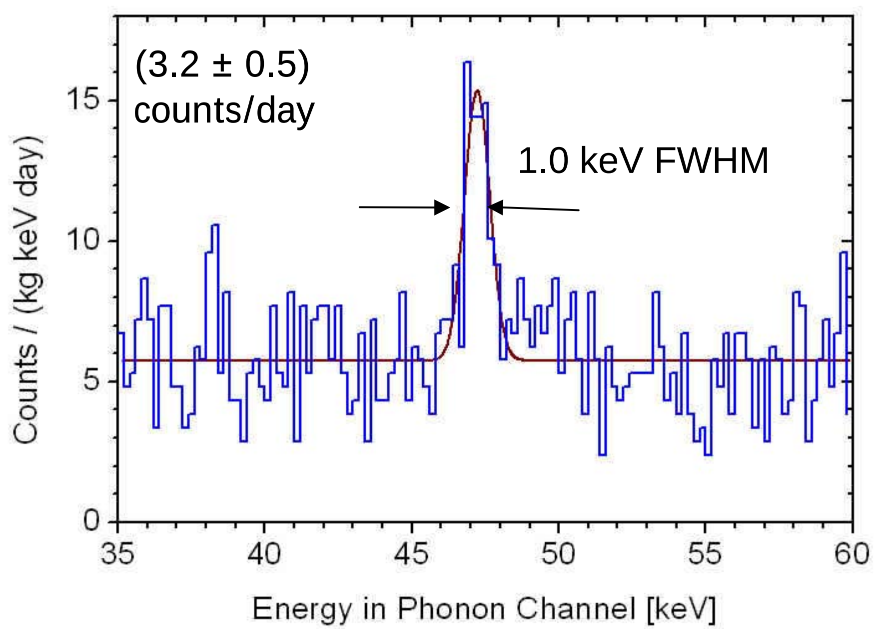
Possible to distinguish WIMP-W recoils from neutron-O recoils

First physics run (run28) in CRESST-I setup

Pulse height of heater pulses



Energy resolution of phonon channel



Stable response over the whole measuring period of 40 days

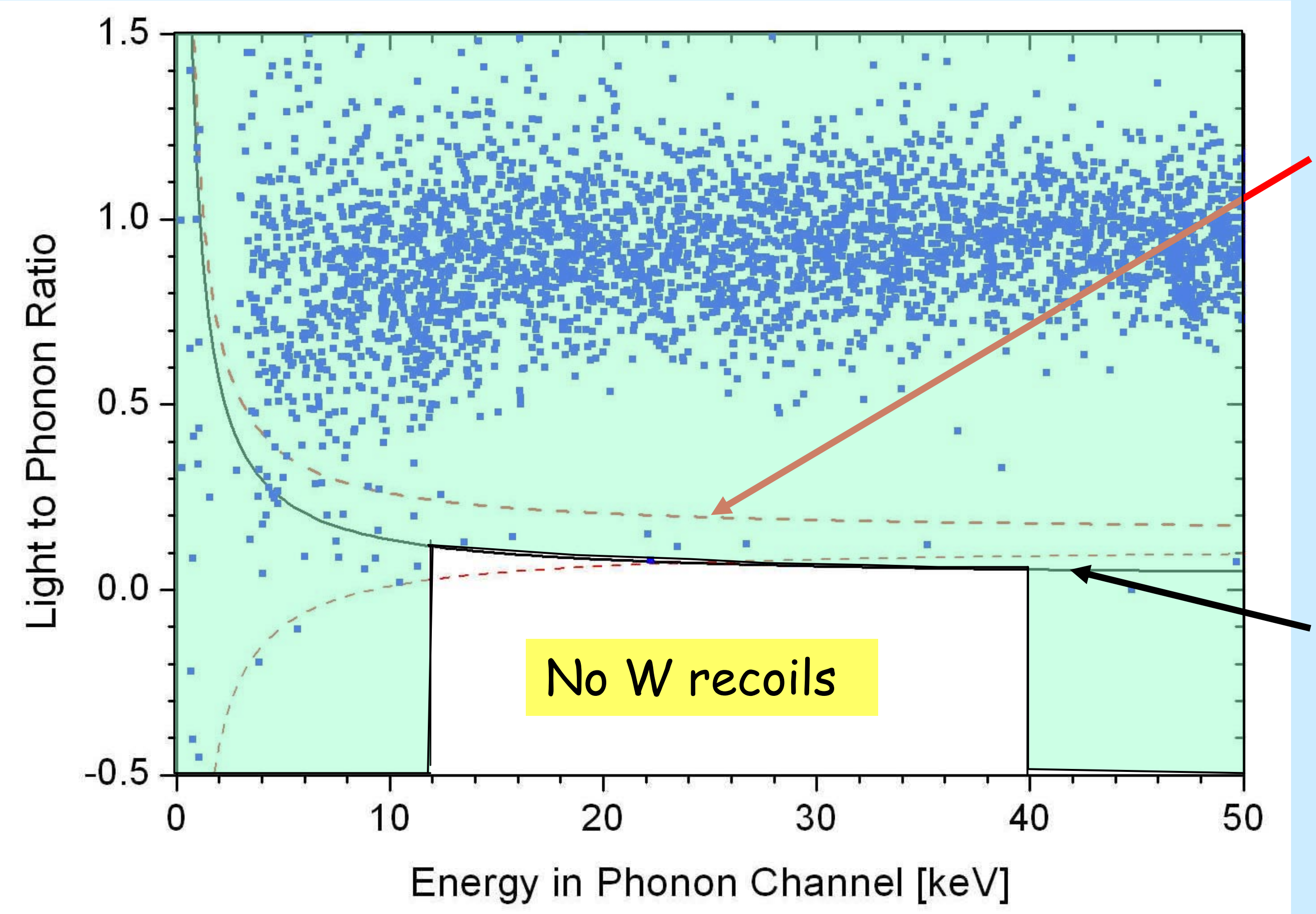
Very good energy resolution:

γ : 1.0 keV @ 46.5 keV

α : 6.7 keV @ 2.3 MeV

Run28: Low Energy Event Distribution

10.72 kg-days, without neutron shield

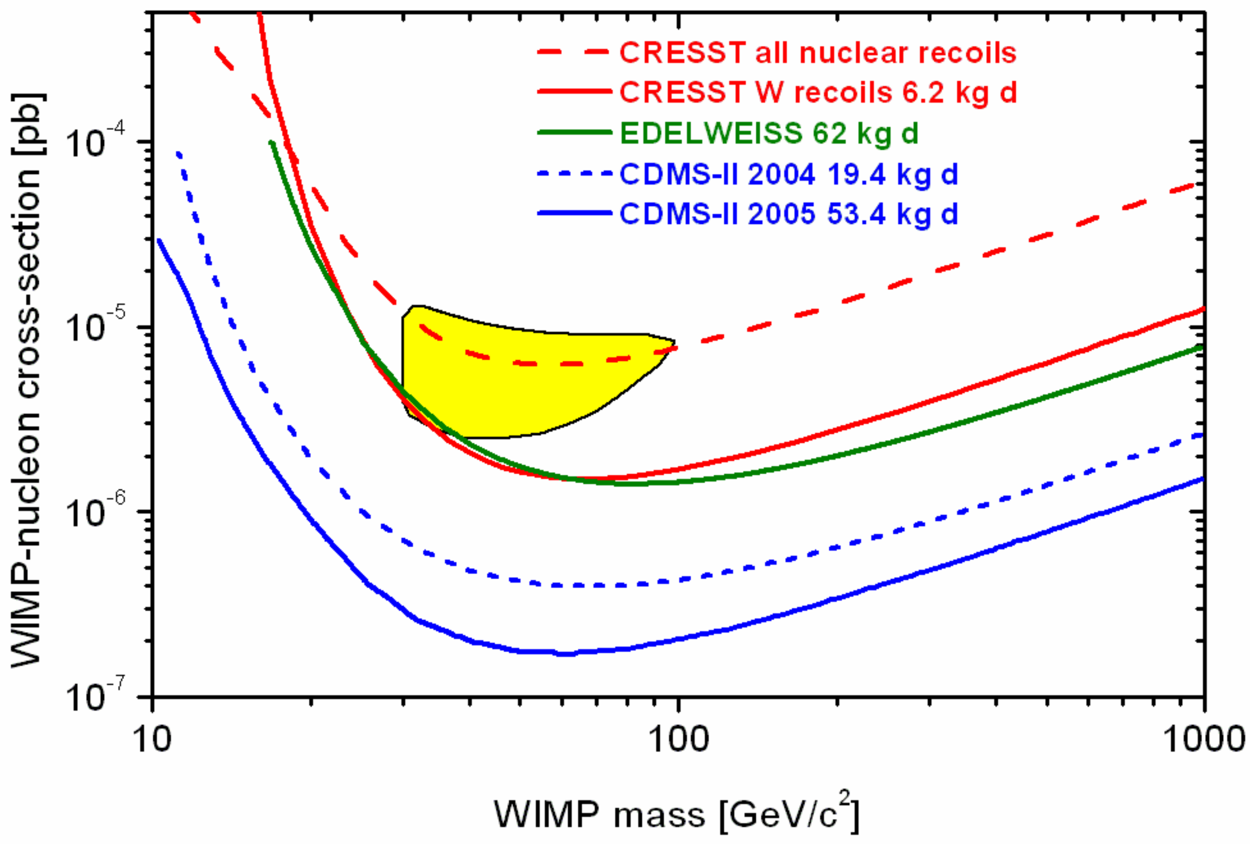


90% of oxygen recoils below this line.

Rate=0.87±0.22 /kg/day compatible with expected neutron background (MC).

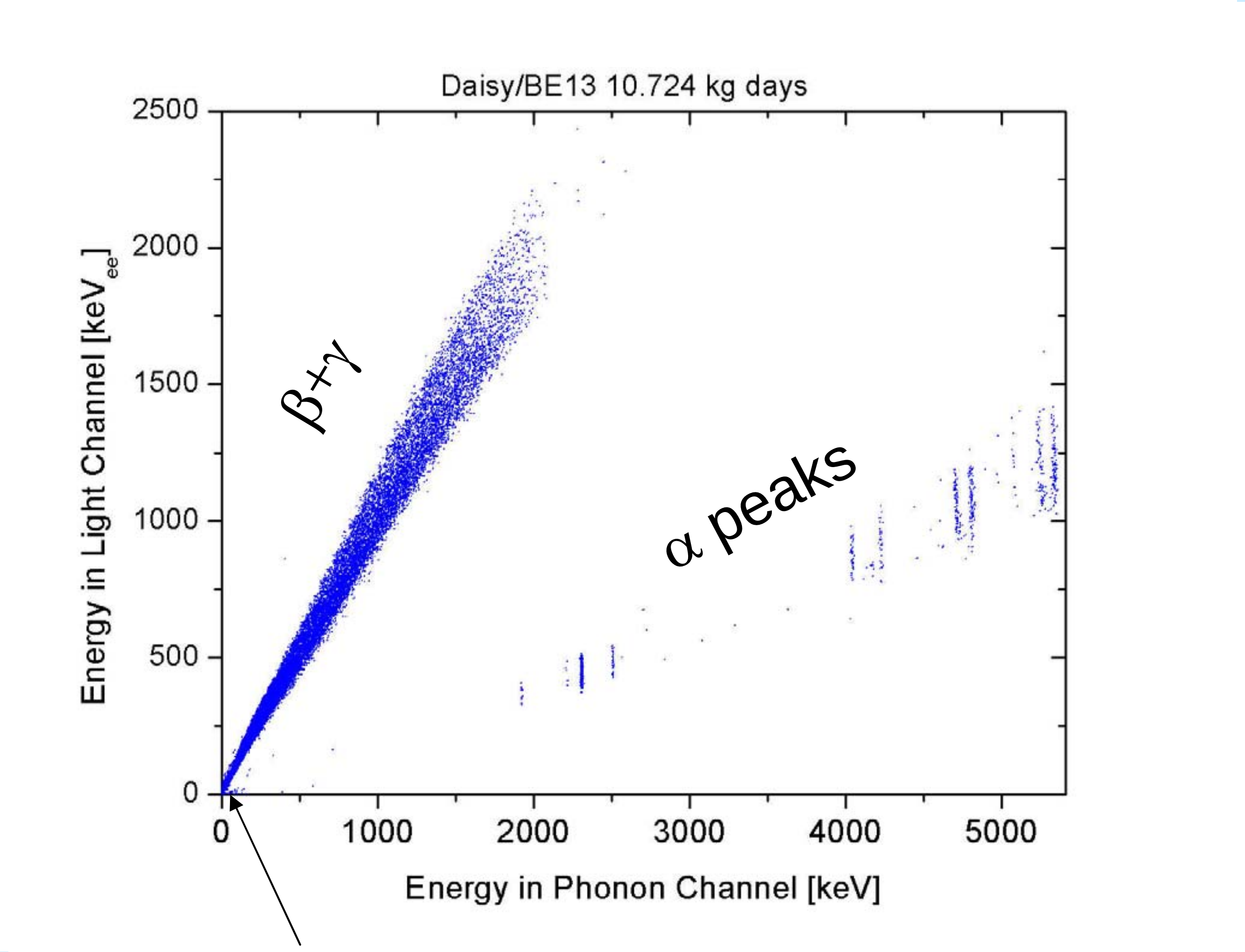
90% of tungsten recoils Q=40 below this line.

Upper limit for spin independent WIMP nucleon cross section



Result from 2 month run with 2 CRESST-II prototype detectors still without neutron shield

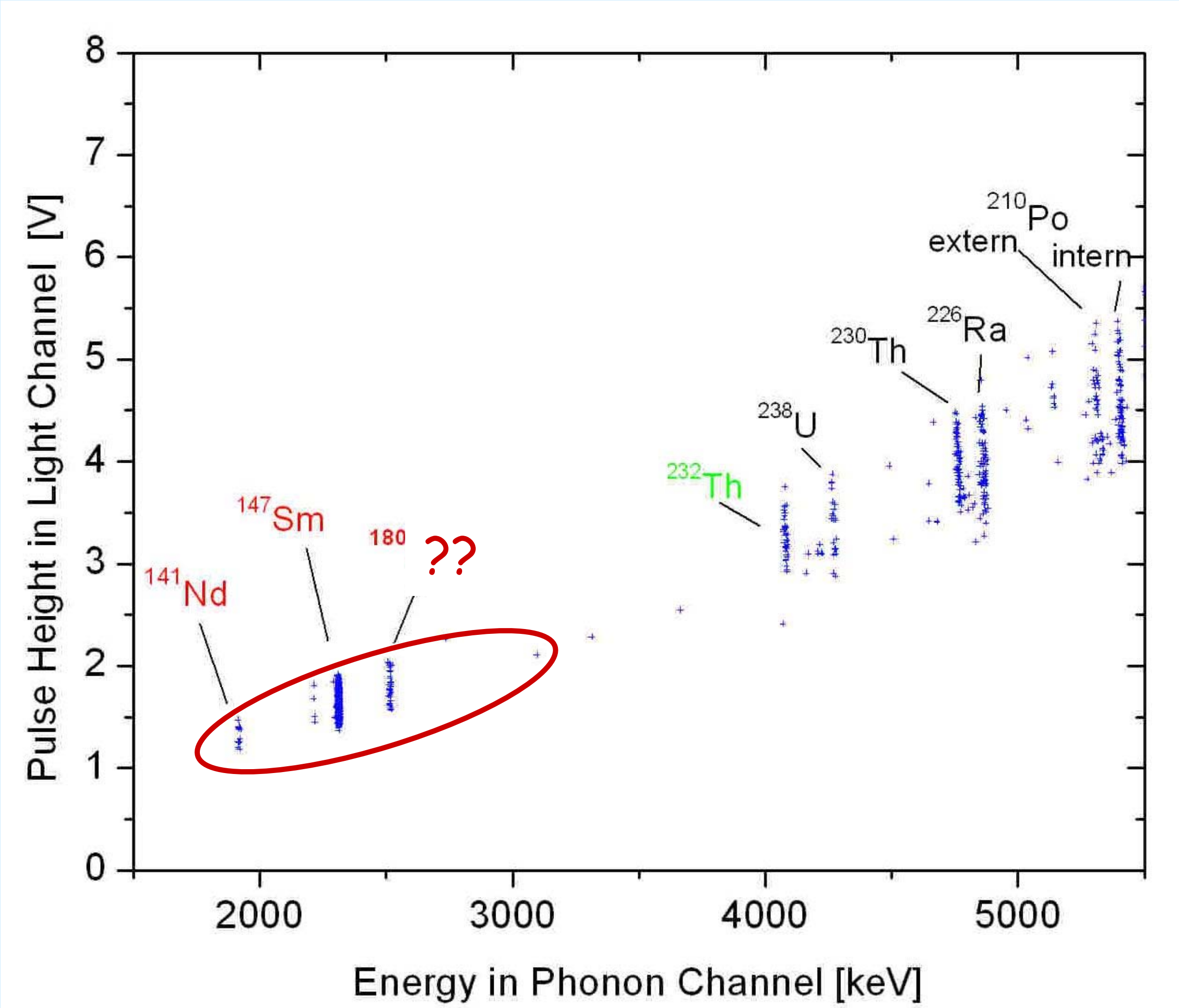
Detector Performance in wide energy range



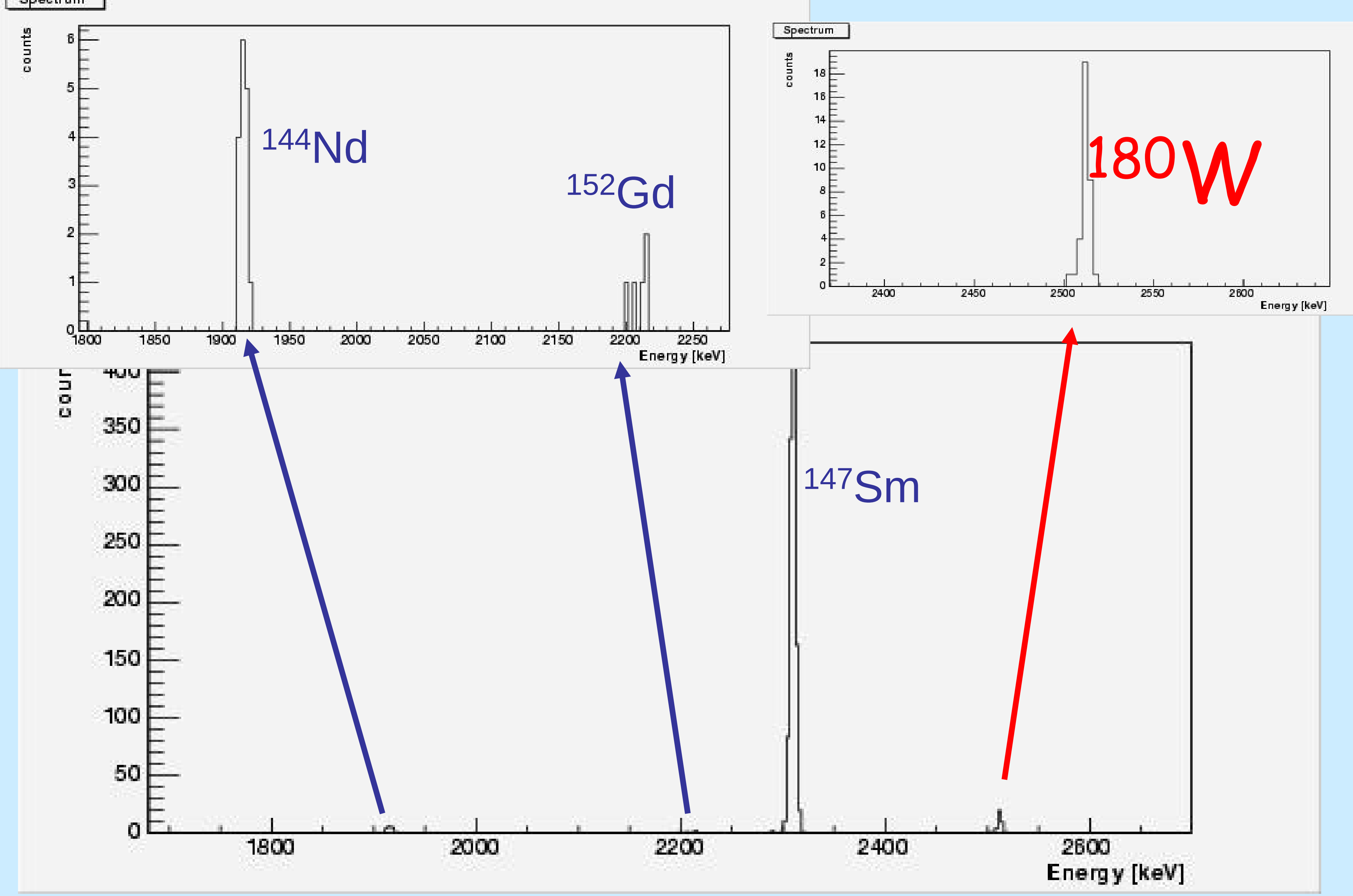
neutrons
and WIMPs

- Enormous dynamic range
- Excellent linearity and energy resolution in whole energy range
- Perfect discrimination of β+γ from α's
- Identification of alpha emitters

Identification of α-Emitters

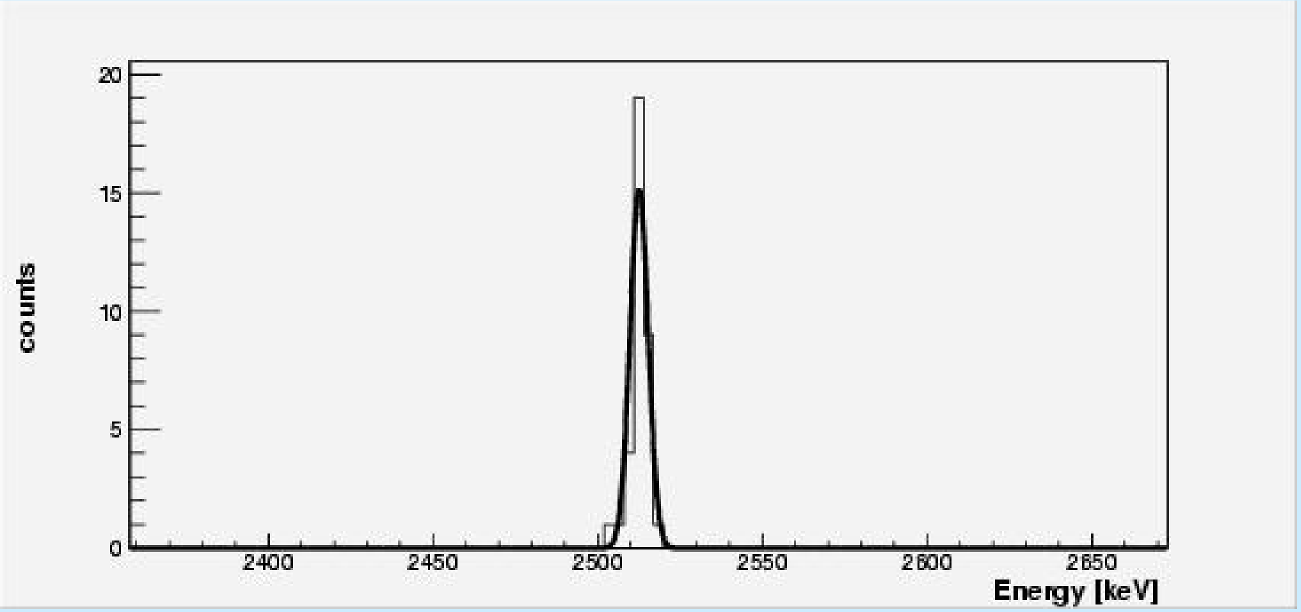


- ➢Reasonably low alpha rates: ~ 2mBq/kg total
- ➢All peaks of U/Th chains identified
- ➢Rare earth rate consistent with ICPMS
- ➢Same light for extern and intern ^{210}Po ➔ no surface degradation



α-decay of „stable“ ^{180}W

Half-life for the α-decay of ^{180}W



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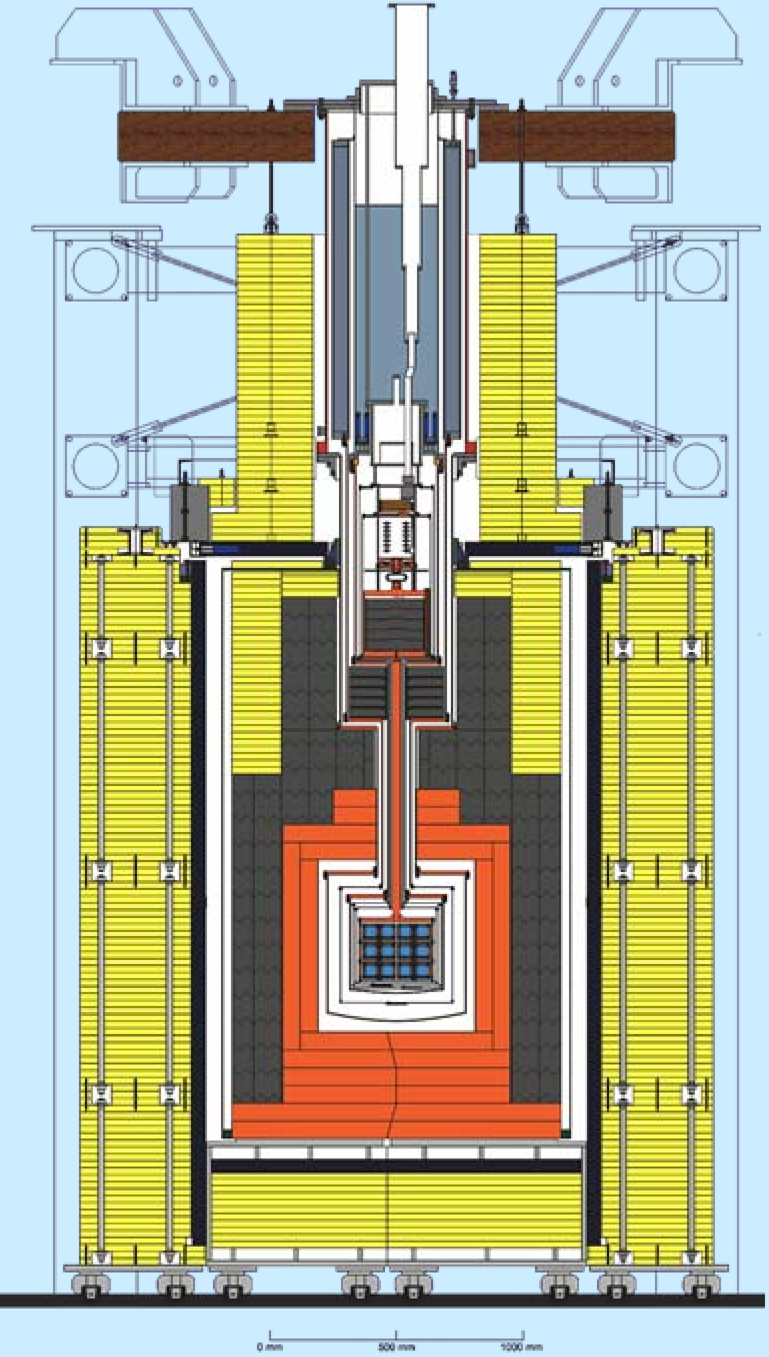
Half life: $T_{1/2} = (1.8 \pm 0.2) \times 10^{18}$ years
Energy: $Q = (2516.4 \pm 1.1\ (\text{stat.}) \pm 1.2(\text{sys.}))$ keV

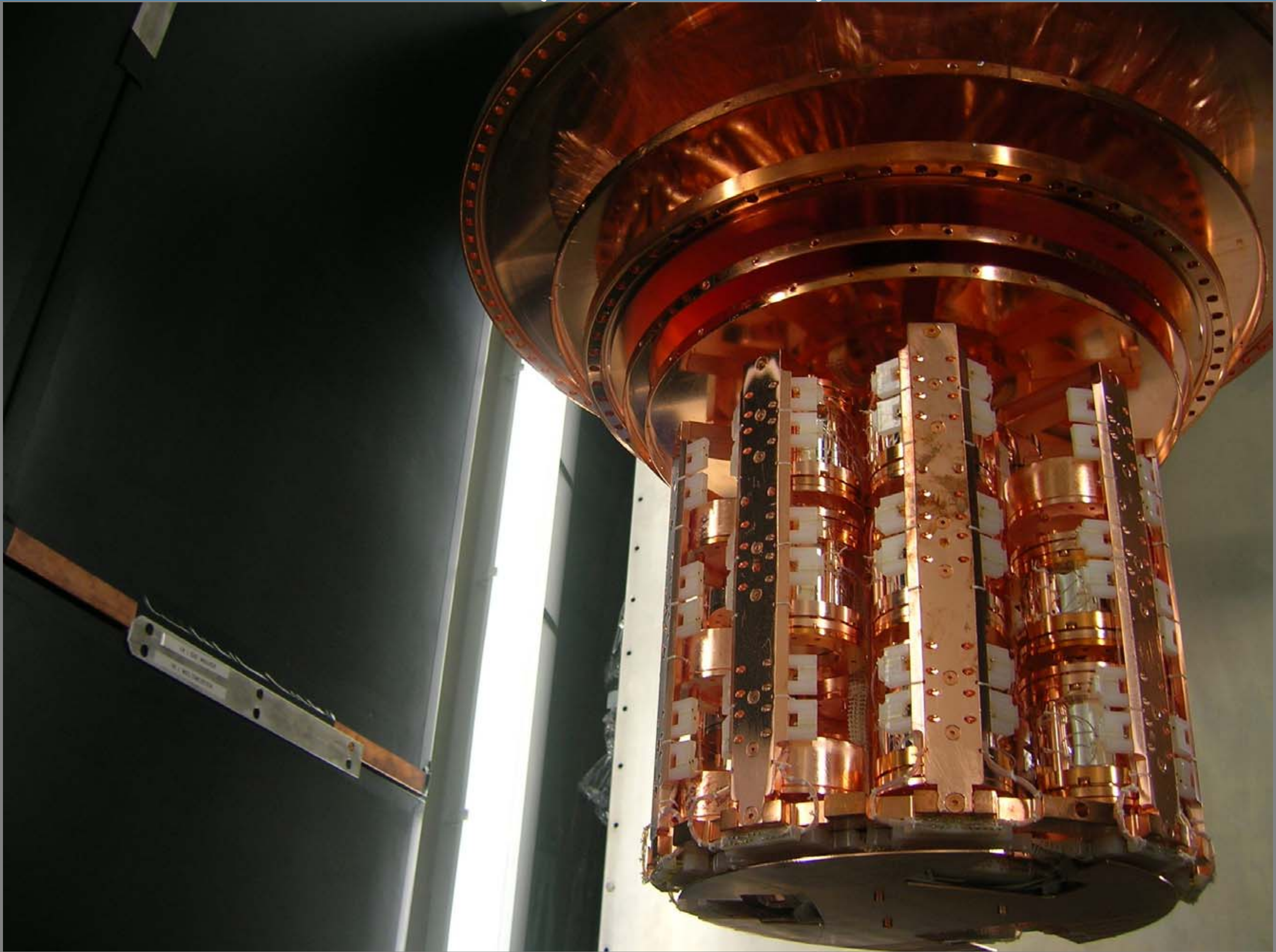
First unambiguous detection

Upgrade for CRESST-II

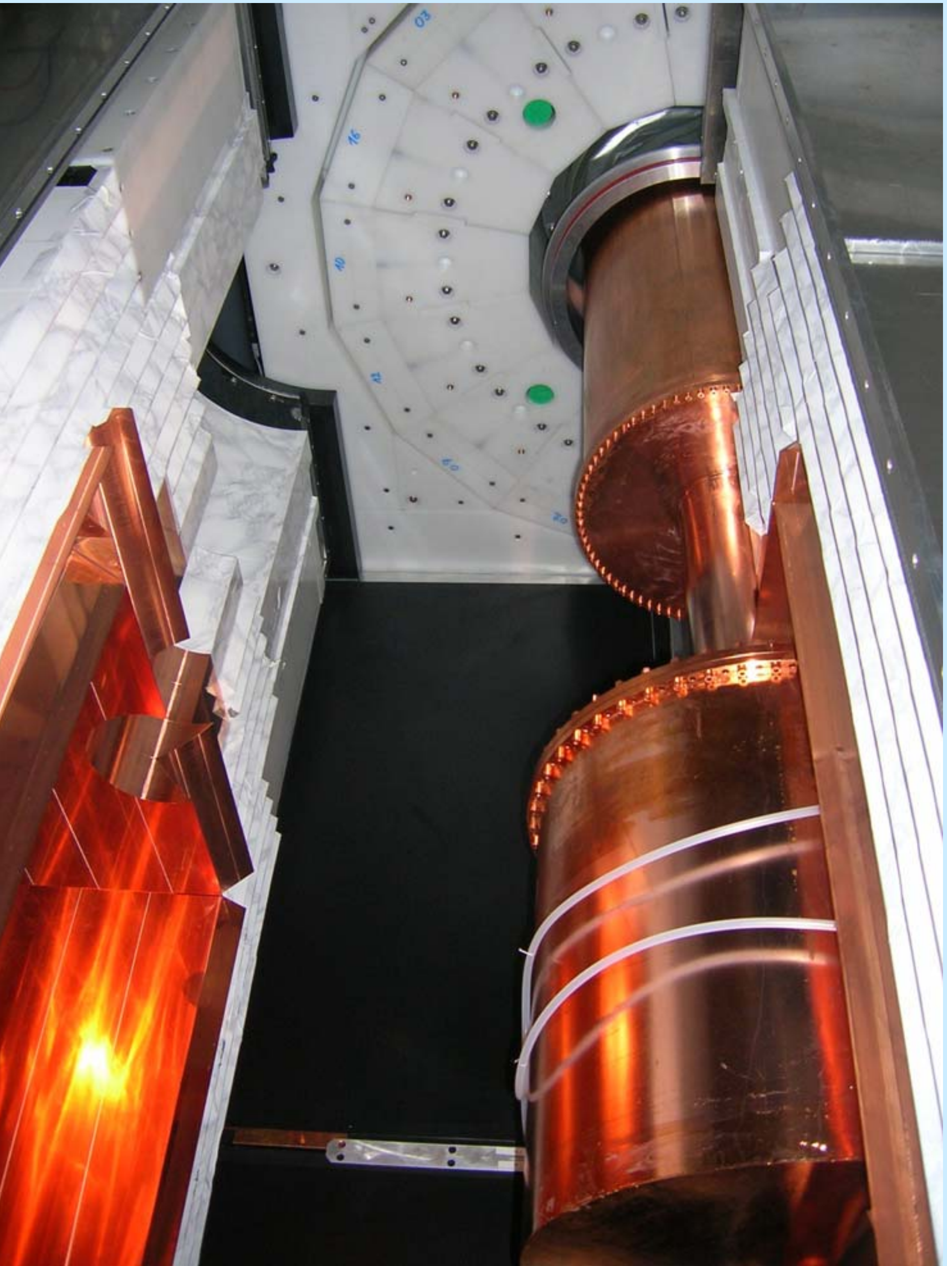


- **New read out and biasing electronics**:
  66 SQUIDs for 33 detector modules
- **Wiring for 66 channels**
- **Detector integration in cold box**
- **New DAQ**
- **Neutron shield:** 50 cm polyethylen
- **Muon veto:** 20 plastic scintillator pannels
  outside Cu/Pb shield and radon box.
  Analog fiber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

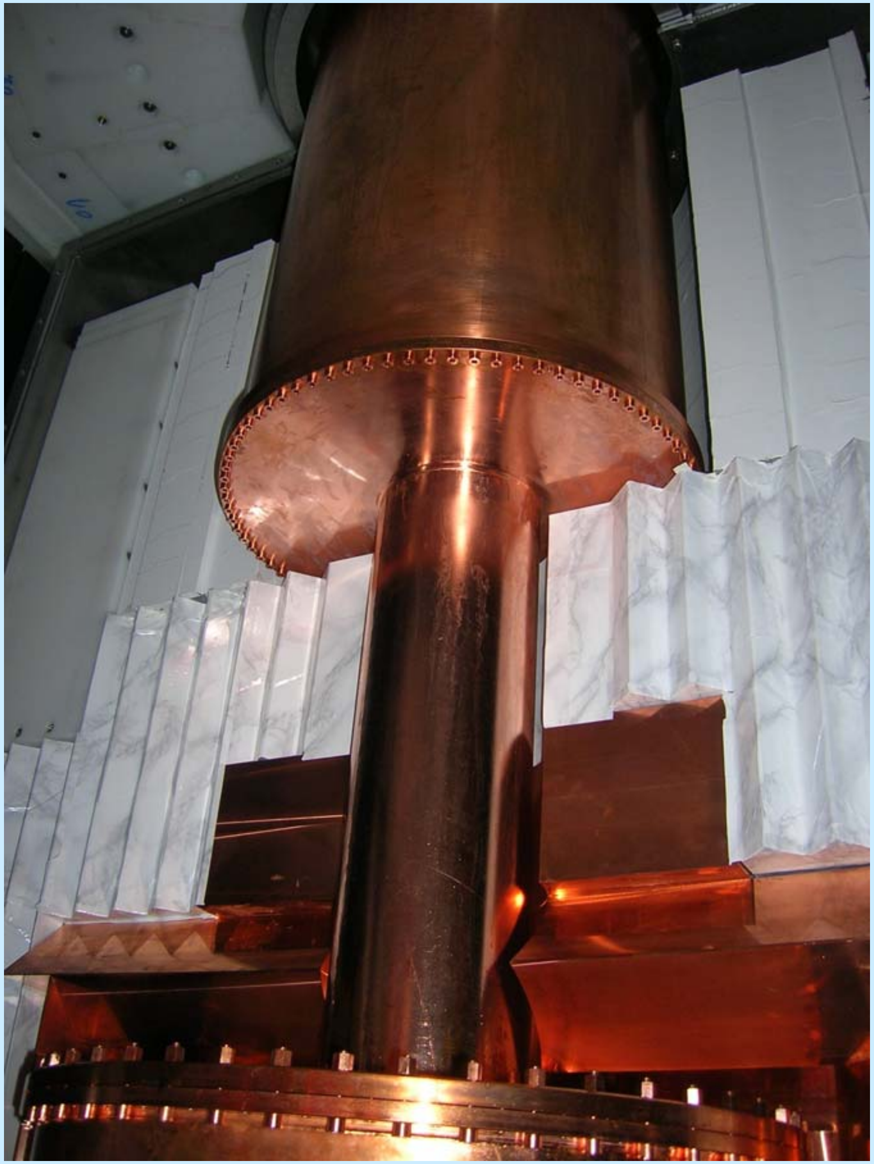
9 Detector Modules mounted for commissioning run (Oct. 2006)



Coldbox closed



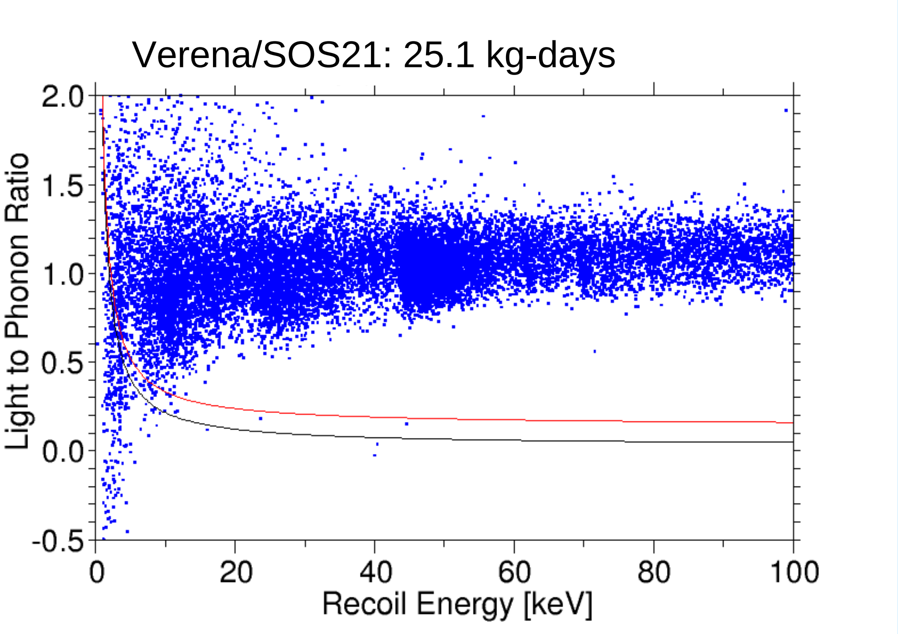
Half Cu/Pb schield closed

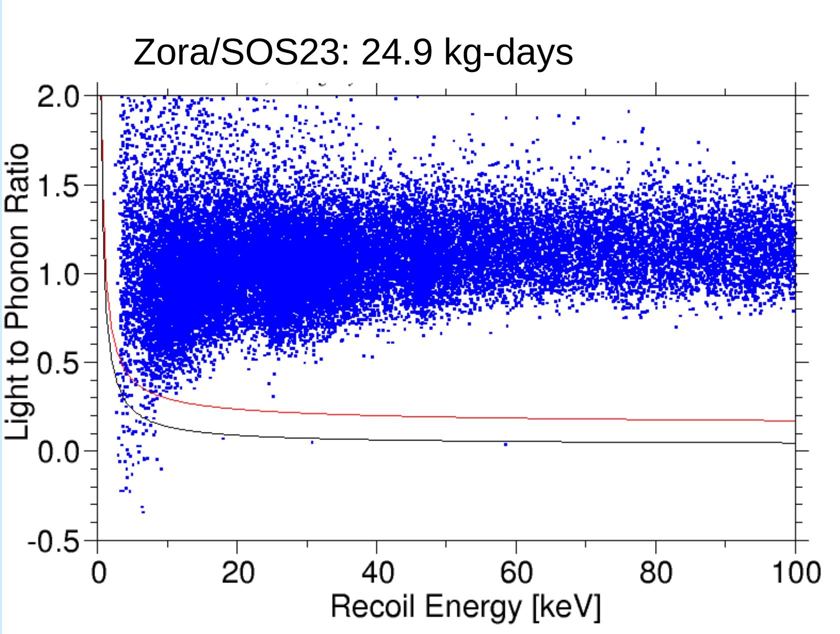


Summary of commissioning run

- Oct. 2006 to Nov. 2007
- Cooling problems of inner tower
- 7 Phonon channels O.K delivering sub keV energy resolution. Due to cooling and SQUID problems only 2 complete modules were working. The light detector of a third one suffered from em interferences.
- Despite some residual problems with em interferences in light channels 50 kg-days of dark matter data were taken towards the end of the run.

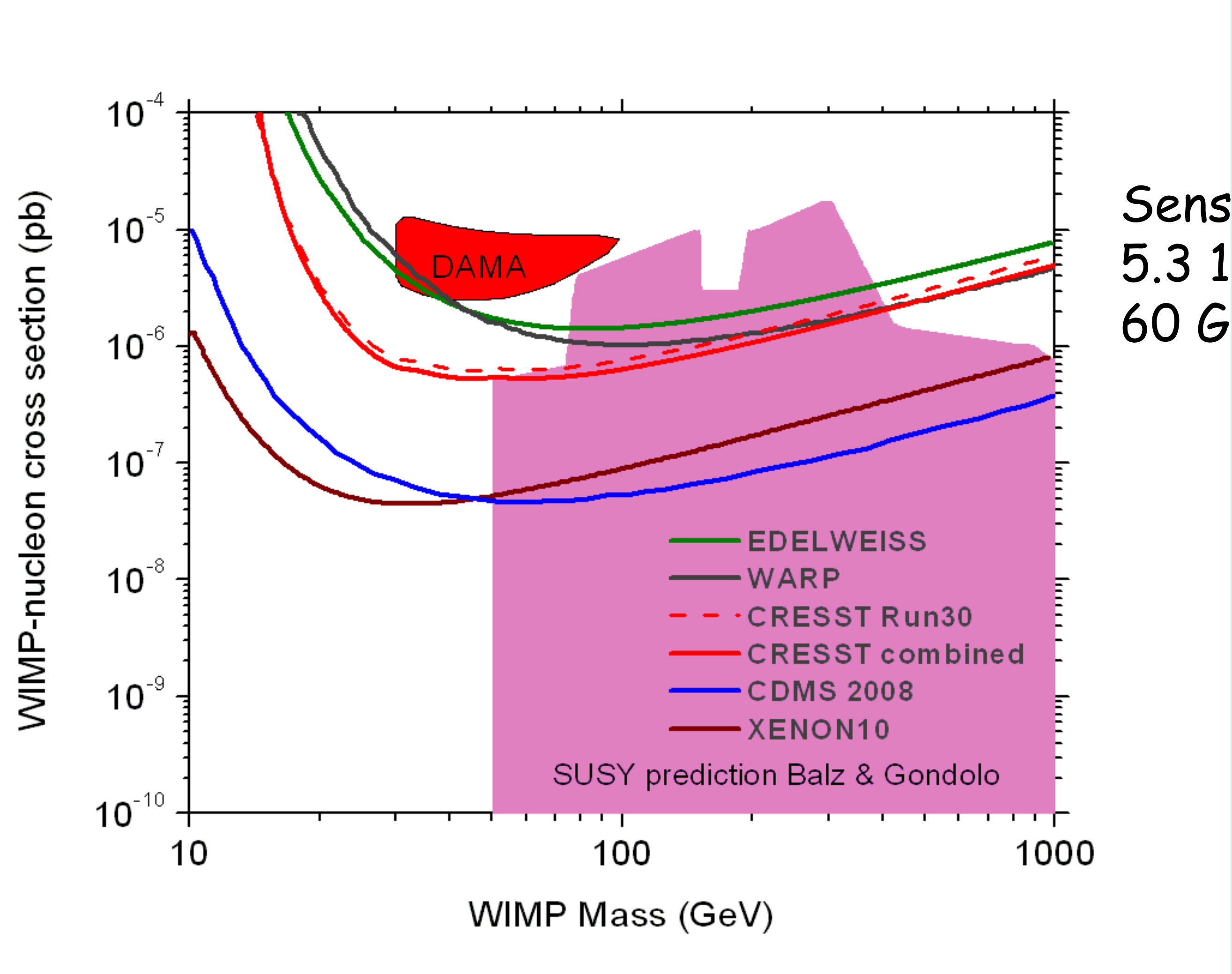
Data from commissioning run





- 3 Tungsten recoils in 10 to 40 keV range in 50 kg-days
- Neutron background strongly reduced. Some weak parts of neutron shielding identified and patched towards the end of the run. Not enough statistics afterwards to see whether it helped.
- Still wider β/γ band compared to previous run due to residual electronic interference in light detectors.

Spin independent exclusion limits



Sensity (combined):
5.3 10^{-7} pb for
60 GeV WIMPs

CRESST: New Run31 just started

- 17 detector modules mounted (total ~5 kg) in May 2008, some with design modifications to explore origin of residual background. Presently setting up the detectors.

  Design modification of detectors include:
  - --Improved perfection of covrage of all internal surfaces with scintillating material to further optimize rejection of ^{206}Pb recoils.
  - --New method of sensor fabrication to improve light yield by ~50 %
  - --New material: $ZnWO_4$, lower radiactive background, more light

- Commercial digital part of SQUID electronics replaced by quiet custom design to minimize potential sources of em interference disturbing the light detectors

Conclusions

•Present experiments (1 kg scale) reach now a sensitivity ~4.6×10^{-8} pb for spin independent independent interaction; now CDMS-II and XENON10, soon CRESST-II and EDELWEISS-II.

•In 2008 to 2010 several existing experiments will reach 10^{-8} pb testing a significant range of SUSY parameter space

•For covering most of supersymmetric parameter space a sensitivity of 10^{-10} pb is needed, requireing 100 kg to 1 tonne detector mass scale:

Super CDMS, EURECA, XENON100, WArP, ArDM, ...

Multiple technologies are necessary for a convincing discovery

The End