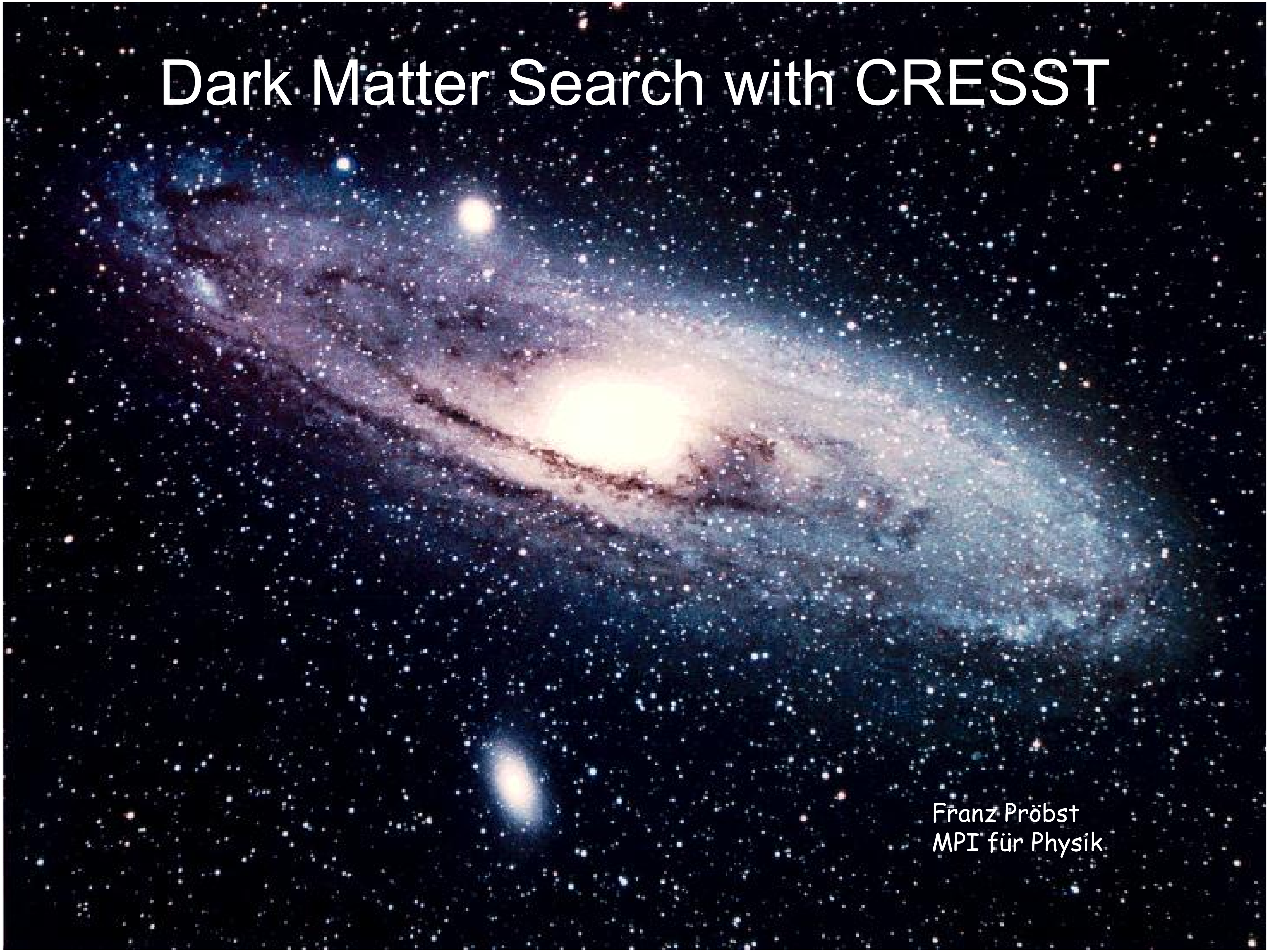
Dark Matter Search with CRESST



Franz Pröbst
MPI für Physik

Outline

- Direct detection
- Other direct searches (DAMA, 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 is similar to heavy majorana neutrino with weaker anihilation cross section. Ω=0.1 to 1 can be obtained almost „naturally" 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

WIMPs are cold, slow and gravitationally bound to galaxy.

Maxwellian velocity distribution in galactic rest frame

Velocity of sun adds to velocitiy distribution

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)

Elastic scattering rates and recoil spectra

$$\frac{dR}{dE} = N_n F(E)^2 \int \frac{\rho_\chi}{m_\chi} v \frac{d\sigma}{dE} f(\vec{v}) d^3 v;$$

$$\frac{d\sigma}{dE} = \frac{\sigma}{E_{\max}(v)} = \frac{\sigma M}{u^2 v^2}$$

S-wave scattering: flat from 0 to Emax

astrophysical parameters:

$$\rho_\chi = 0.3 \ \mathbf{GeV/cm^3}$$

$$f(v) \propto e^{\frac{-(\vec{v}+\vec{v}_E)^2}{v_0^2}}$$

$$v_0 = 230 \text{ km/s}$$

particle/nuclear physics parameters:

$F(E)$: nuclear form factor

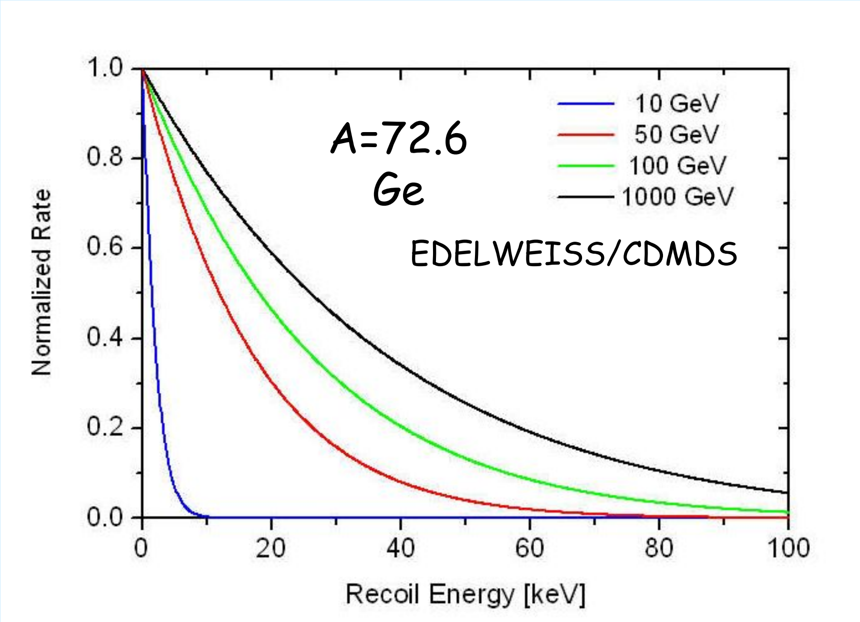
$\sigma_{sd} \propto \lambda^2 J(J+1)$ spin dependent

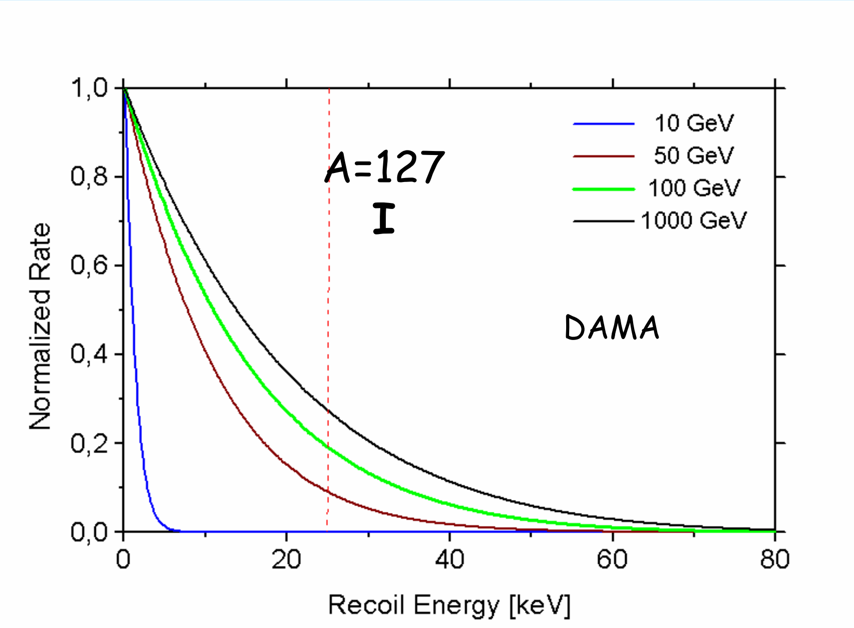
$\sigma_{si} \propto A^2$: spin independent

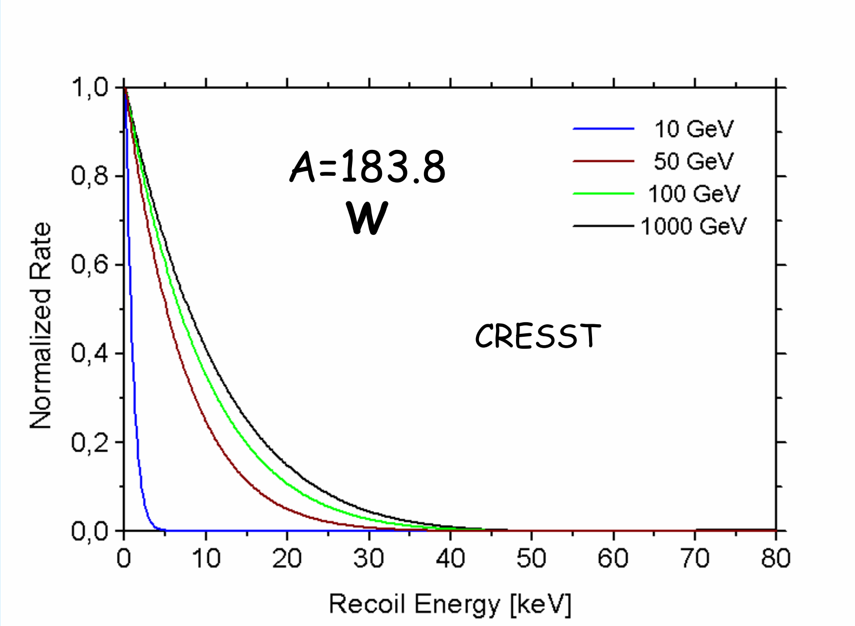
σ_{sd}: largely caused by unpaired proton or neutron, similar for all nuclei with spin

σ_{si}: the A^2 factor favors heavy nuclei, but form factor can be very small for heavy nuclei and large momentum transfers. Very low thresholds required to benifit from large A^2.

Recoil Spectra for various target nuclei

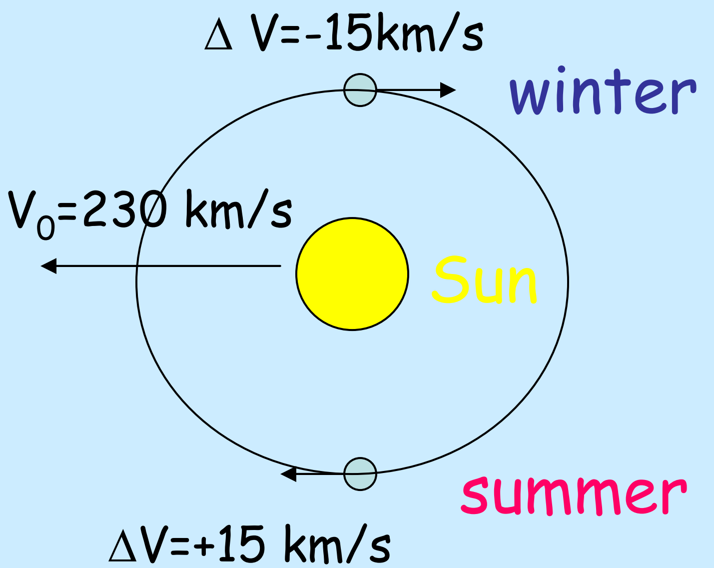


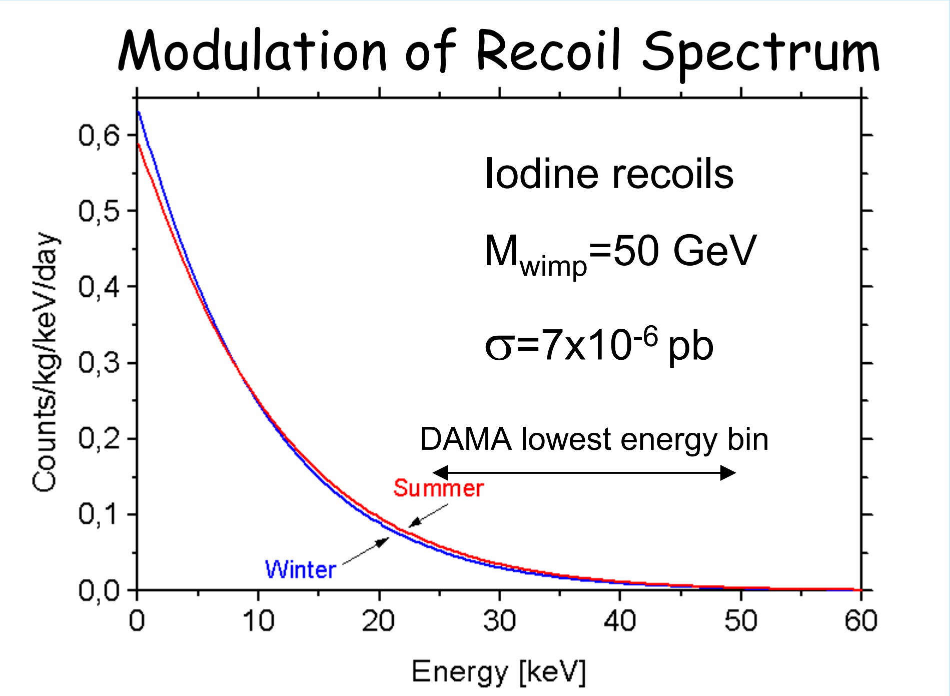


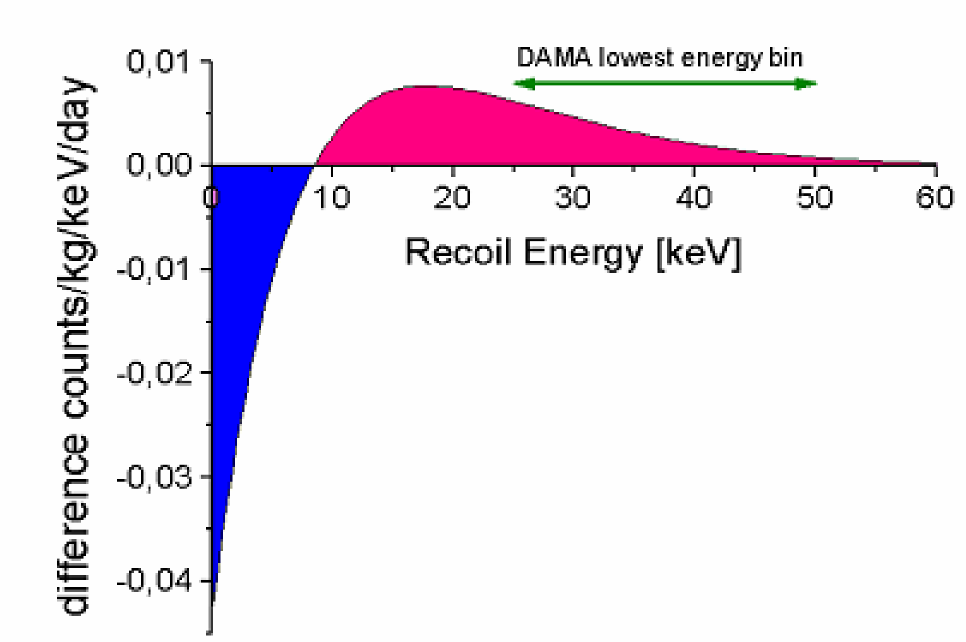


- Spectral shape depends on WIMP and target mass.
- Low thresholds required, especially for small WIMP masses and large A
- Strong formfactor suppression of large energy transfers for heavy nuclei ($\Delta E_{max} \sim 2Mv^2$ for m>>M).

Annual Modulation







- positive signature
- very small effect, strongly dependent on threshold

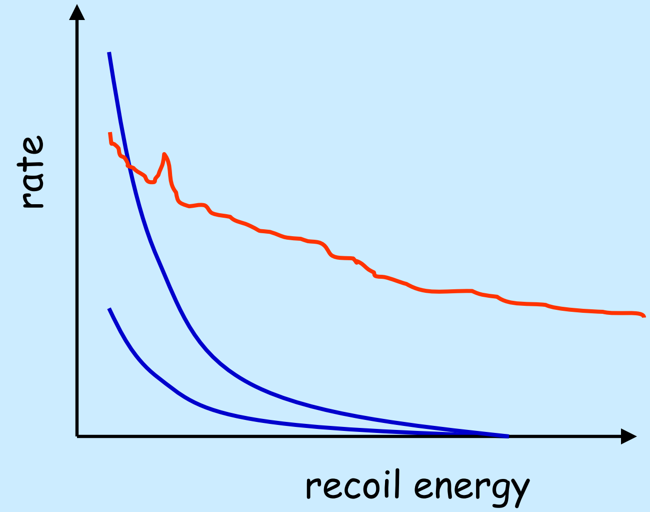
Sensitivity

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 furhter improvement once background rate B is measured statistically significant

$$\sigma \propto B$$



If there is no background

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

Linear improvement of sensitivity with exposure

Identification of WIMP signals

- **Nuclear Recoil**
- **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

Challenge of direct searches:

- **Very low event rate < 1/kg/day**
  (goal of upcoming experiments ~0.01/kg/day)
- **Nuclear recoil signals with keV energies and featureless spectrum.**

➔Very low threshold, extremely low background detectors

Most important signal region is just above threshold

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

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

The background we have to fight

•Cosmic rays and activation by cosmic rays:
➔ go deep underground to reduce muon flux by factor 10^{-6}. Strictly limit exposure of detectors and components.

•Natural radioactivity of surrounding rocks and materials:
➔ shield γ background with low background Pb and high purity Cu.

•Radon in air from U-Th chains:
➔gas tight radon box flushed with N_2

•Radioactive dust: ➔ clean room

•Natural radioactivity in materials:
➔ drastic material selection. But deep undergroundd and very well shielded residual $\beta+\gamma$ background typically ~100/kg/day.
➔detectors with excellent $\beta+\gamma$ discrimination from nuclear recoil signals needed

•Neutrons from rock (LNGS ~ 1 /kg/day):
➔ moderate with 50 cm of polyethylen

•Neutrons from muons in Pb/Cu shield (~0.02 /kg/day):
➔ need muon veto for $\sigma_{WIMP-nueleon}<10^{-8}$ pb

Detector Types

Classical detectors:

Ge and Si ionization detectors: charge signals
NaI, CaF scintillators: light signals

Recent Technologies:

Cryogenic detectors: heat or phonon signals measured at very low temperatures ~10 mK. Combined with charge (CDMS,EDELWEISS) or light signals (CRESST, ROSEBUD) they offer efficient $\beta\gamma$ discrimination.

Liquid Xenon: ionization+scintillation+PSD

How to discriminate residual $\beta+\gamma$ Background

Nuclear recoils characterized by:

•Reduced ionization efficiency in ionization detectors ~0.2 for Ge

•Reduced light yield in scintillators (~0.08 for I recoils in NaI)

•Phonons or heat measures ~100 % of deposeted Energy, independent of interaction type

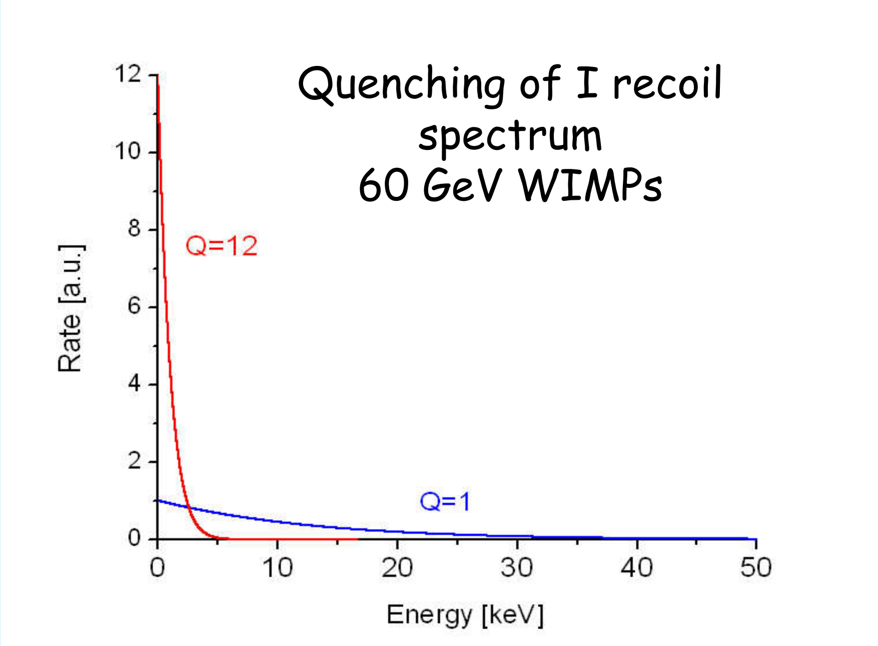
Combine two channels for efficient background discrimination

phonon+charge (EDELWEISS, CDMS)

phonon+light (CRESST, ROSEBUD)

Scintillation Detectors: NaI

- Well known and available technique
- Iodine as heavy target nucleus A=127
- Large crystals with very good radiopurity available
- Poor spectral resolution
- No β+γ 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

Experiments:

DAMA, UKDM-NaIAD, ELEGANT V

DAMA

Uni Roma/LNGS/Beijing collaboration

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

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

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

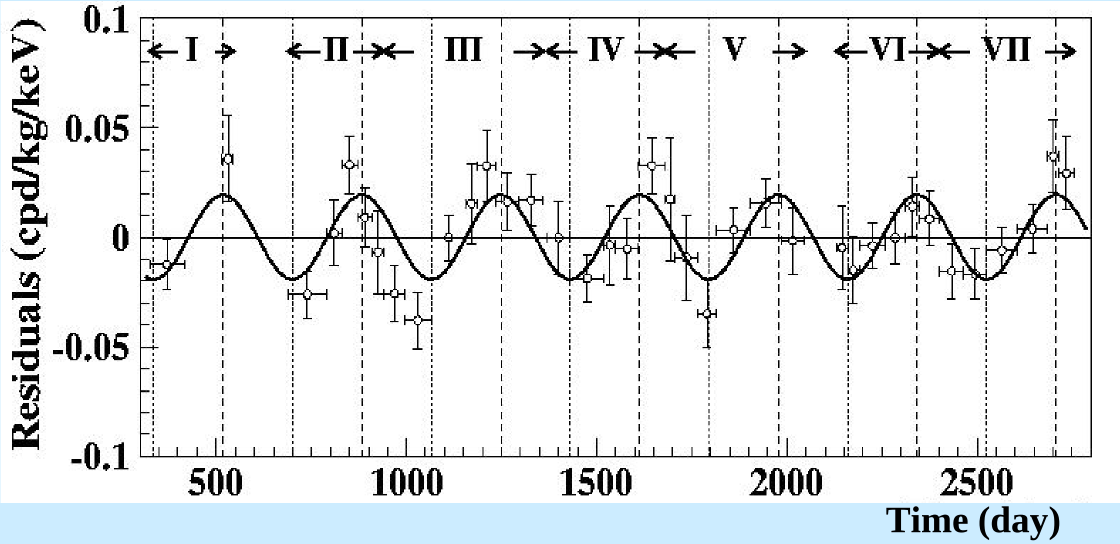
DAMA ended operation in July 2002

➔ LIBRA:Upgrade to ~250 kg detector. Running since March 2003

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, σ=(7±1)10^{-6} picobarn

EDELWEISS Collaboration

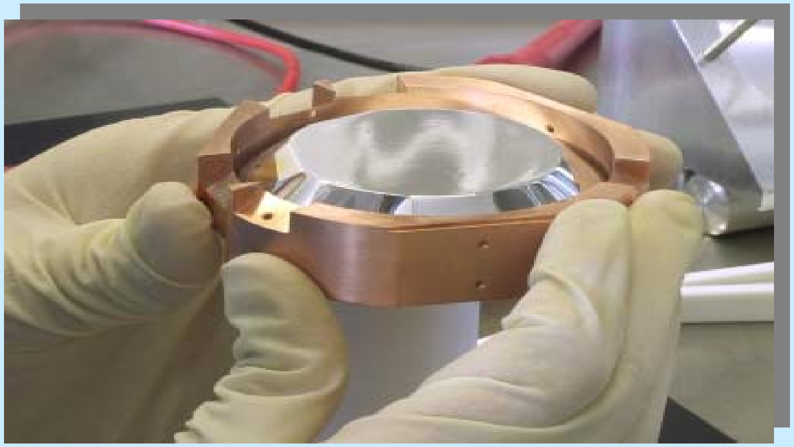
- **CEA-Saclay**
  - **DAPNIA data acquisition, detectors (NTD), background**
  - **DRECAM Cryogenics**

- **CNRS**
  - **CRTBT Grenoble Cryogenics**
  - **CSNSM Orsay Detectors NbSi, wiring**
  - **IAP Paris Low radioactivity**
  - **IPN Lyon Electronics, installation, background**

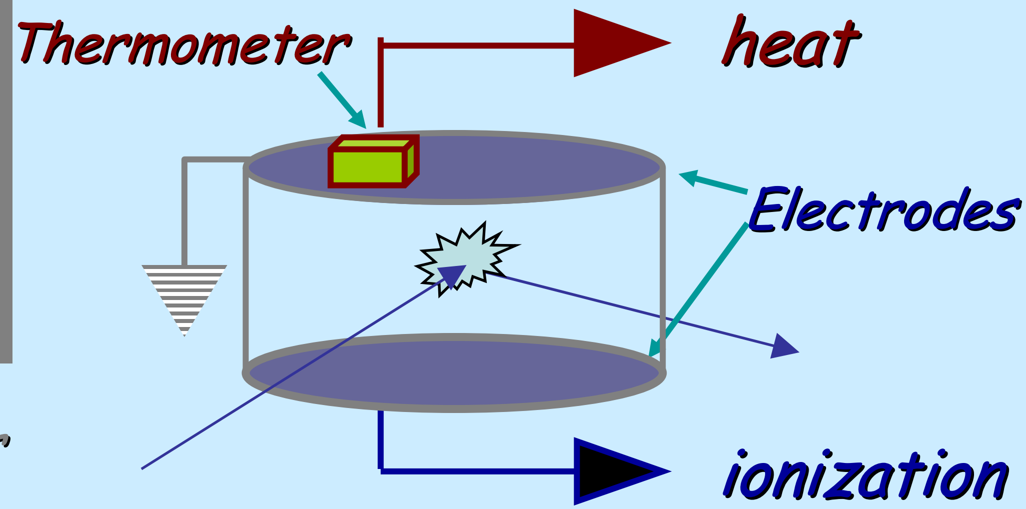
- **FZ-Karlsruhe and Univ. Karlsruhe Muon veto**
- **Dubna JINR DLNP Neutron detector, ^{73}Ge**

Modane Underground Laboratory (Fréjus, France):4800 mwe

EDELWEISS Ionization-heat cryogenic detectors



Edelweiss 320 g Ge detector

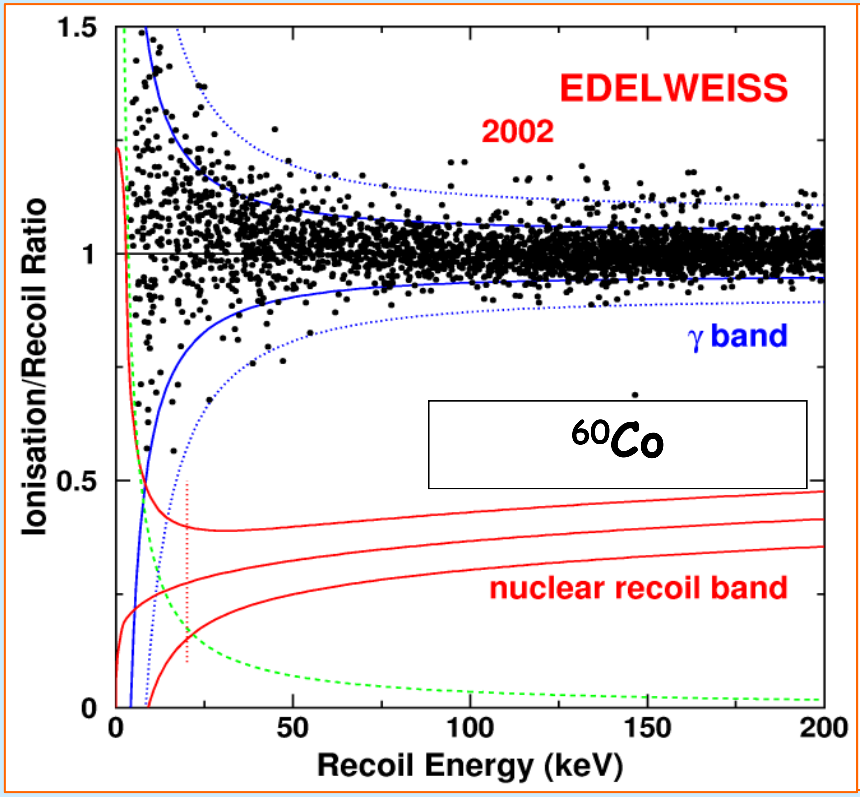


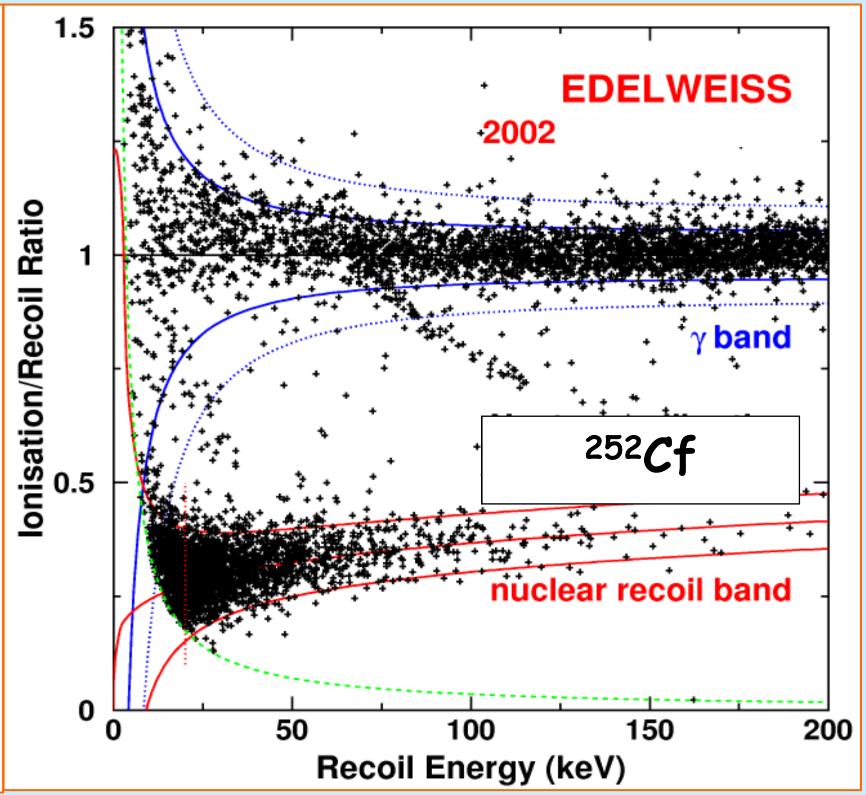
- Operated at 20 mK
- Ge NTD measures full deposited energy
- Different charge/heat ratio for nuclear recoils and electronic recoils ➔ event by event discrimination

EDELWEISS-I Discrimination Performance

^{60}Co calibration
no γ below ratio of 0.7

^{252}Cf calibration
Neutrons in nuclear recoil band

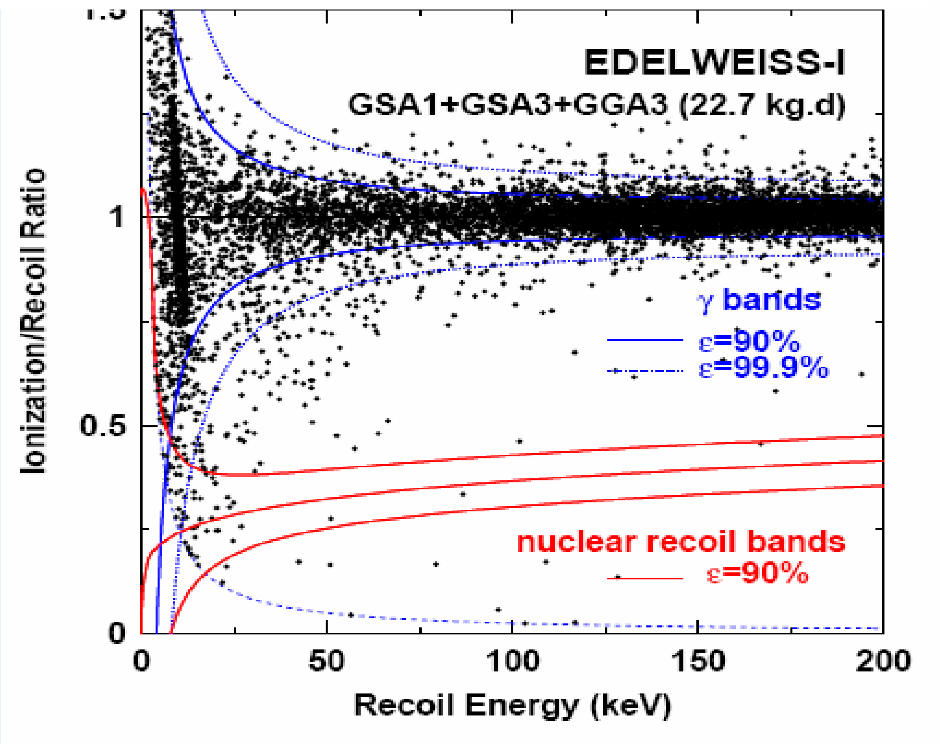


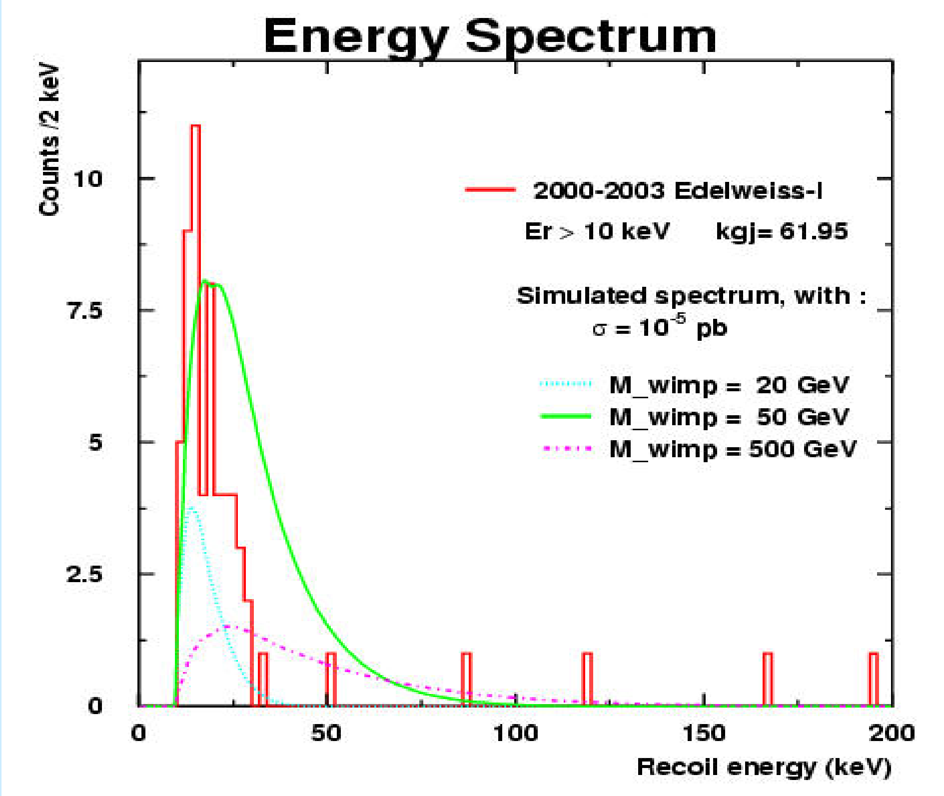


Excellent γ–n separation in calibration run
-> γ rejection > 99.9% for E_{recoil} > 15keV

EDELWEISS I combined Data

2003 data (phonon trigger)





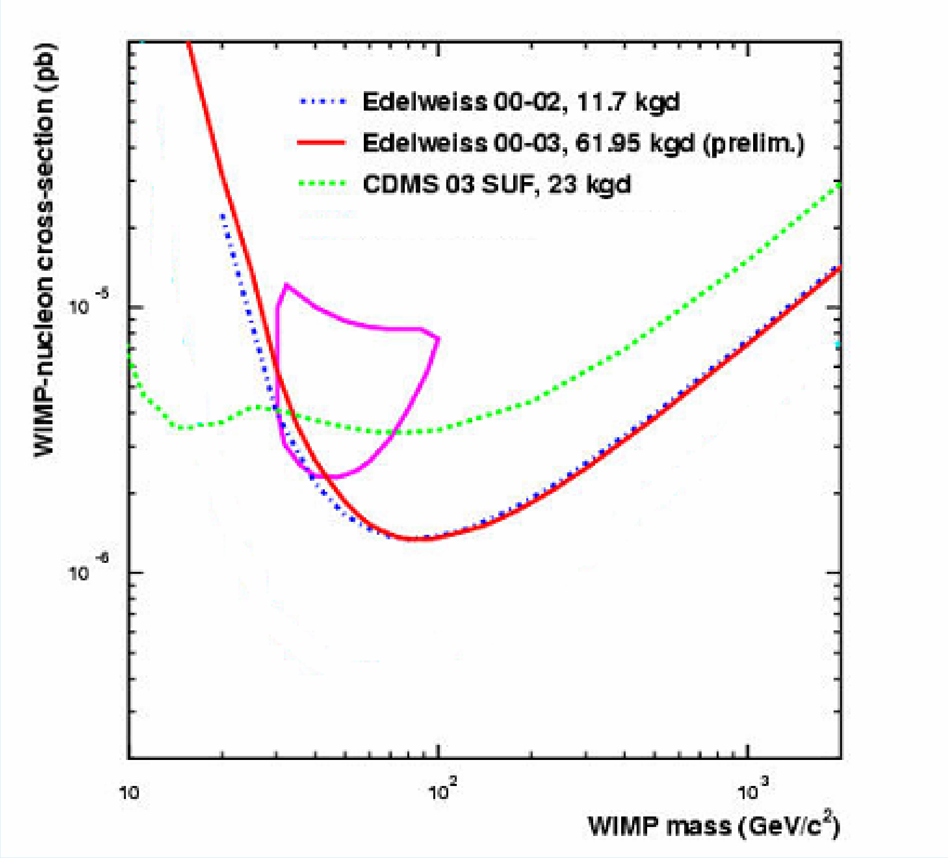
40 events between 15 and 200 keV in recoil band

No background subtraction for cross-sections limit extraction

EDELWEISS-I Sensitivity

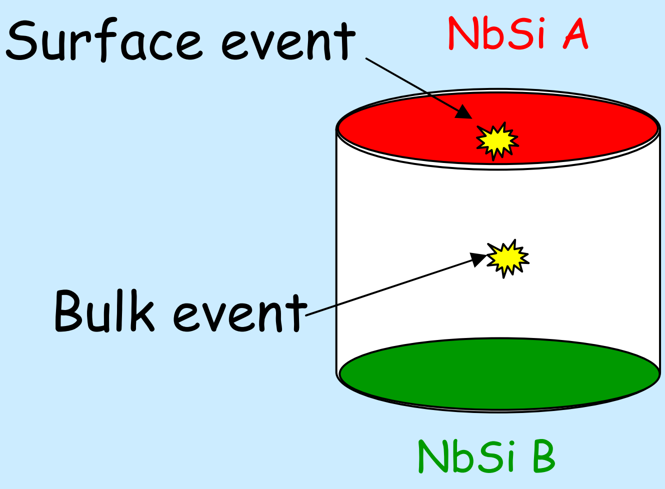
- EDELWEISS-I stopped March 2004
  ➔ upgrade for phase-II
- Complete data set ~ 62 kg days
  V.Sanglard et al, Phys.Rev.D 71(2005) 122002
- Confirms previous limit i.e. no further improvement
- DAMA positive evidence practically excluded in case of spin independent interaction

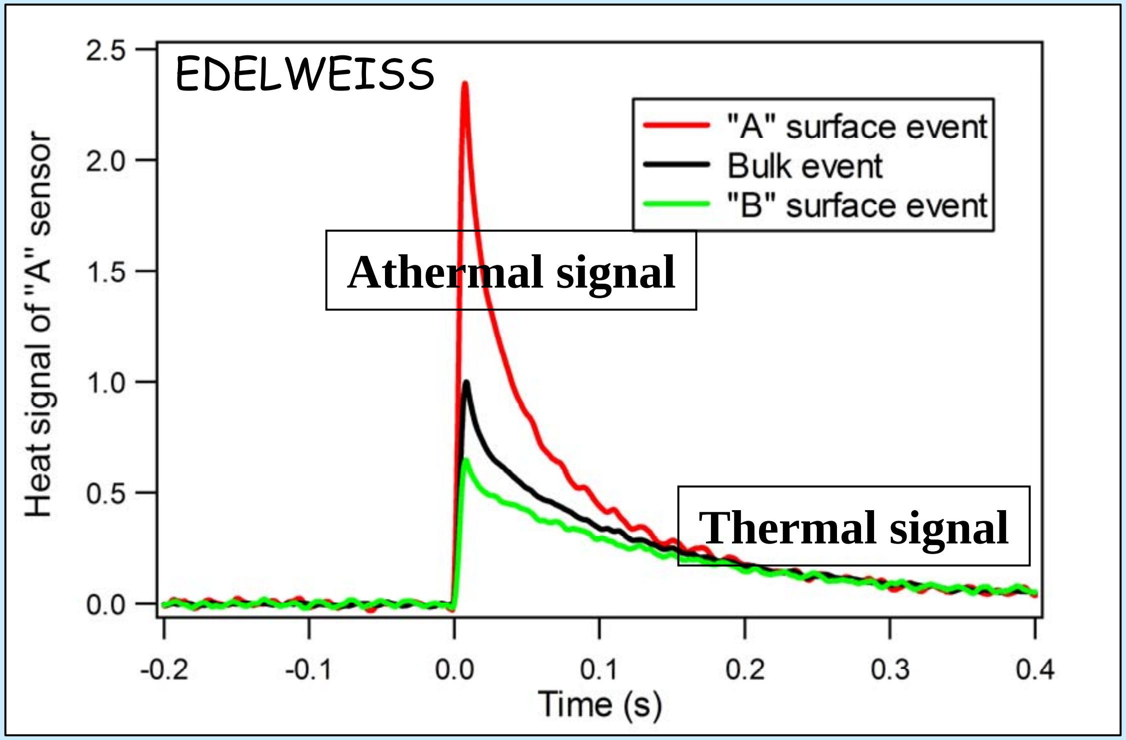
- Sensitivity limited by events in nuclear recoil band, which are most likely „surface events“, i.e. incomplete charge collection for events close to detector surface. Main limitation of technique.



Surface event identification
with NbSi films

-> Allows out-of-equilibrium phonons detection



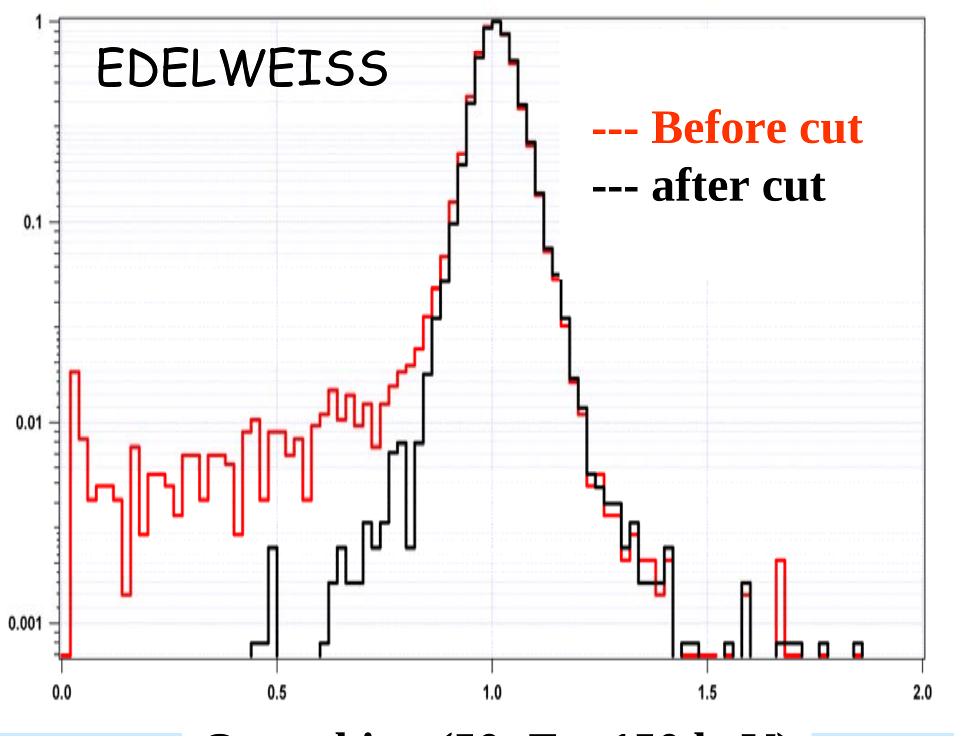


➔ Discrimination with athermal signal ratio

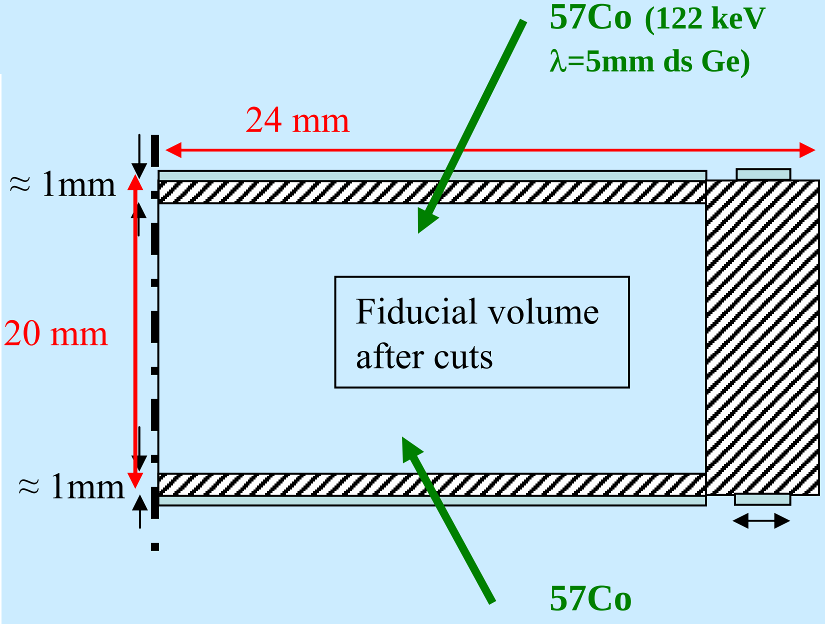
➔technique for EDELWEISS-II ?

NbSi discrimination performance

γ-ray ^{57}Co calibration



Quenching (50<Er<150 keV)



Removes 10% of the fiducial volume

-> rejection : 95% of the surface events

CDMS-II

Collaboration:

Brown University
Case Western Reserve University
University of Colorado at Denver
FNAL
LBL
Santa Clara University
Stanford University
University of California, Berkeley
University of California, Santa Barbara
University of Florida
University of Minnesota

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

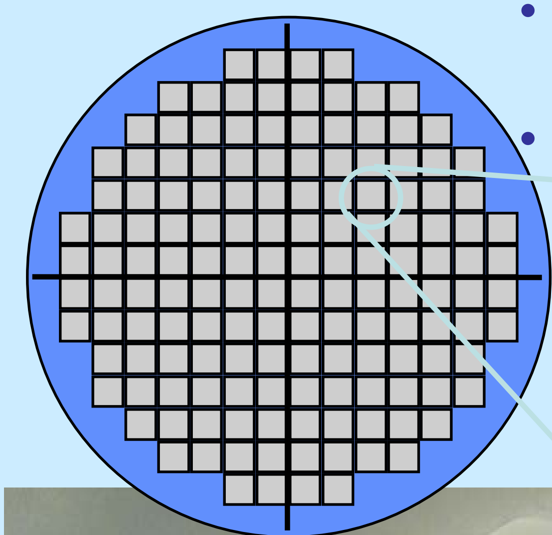
CDMS-II at SOUDAN mine:

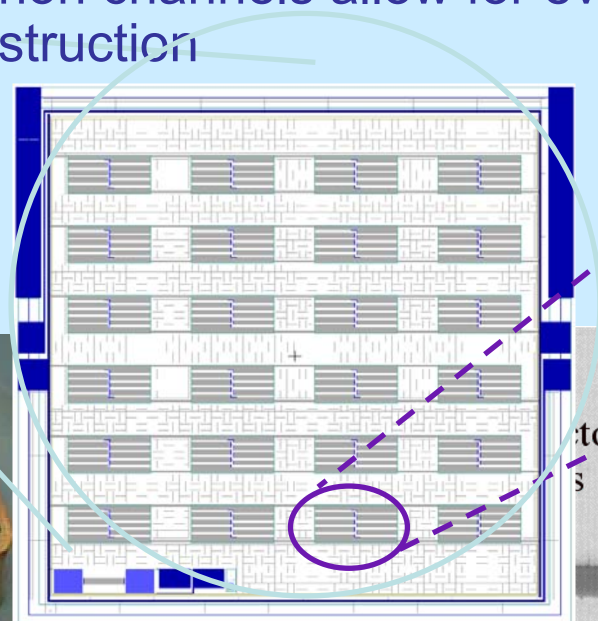
Setting up in mine at ~2000

- First data taking period Oct. 2003 to Jan. 2004
  (Phys. Rev. Lett. 93 (2004) 211201)
- Second data taking period March to August 2004 (astro-ph/0509259)

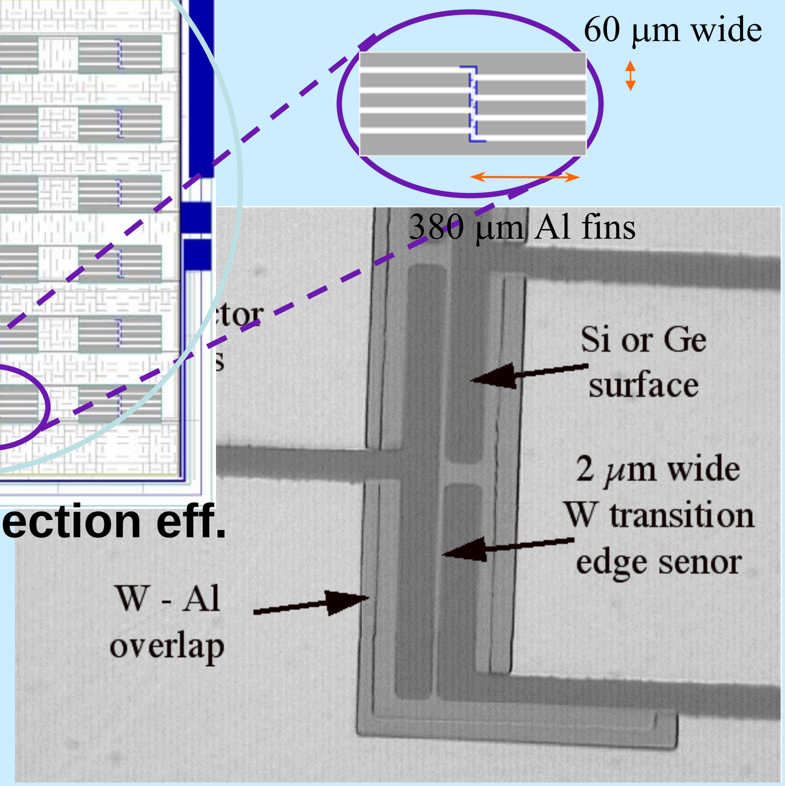
ZIP detector phonon sensor technology

- TES's patterned on the surface measure the full recoil energy of the interaction
- Phonon pulse shape allows for rejection of surface recoils (with suppressed charge)
- 4 phonon channels allow for event position reconstruction





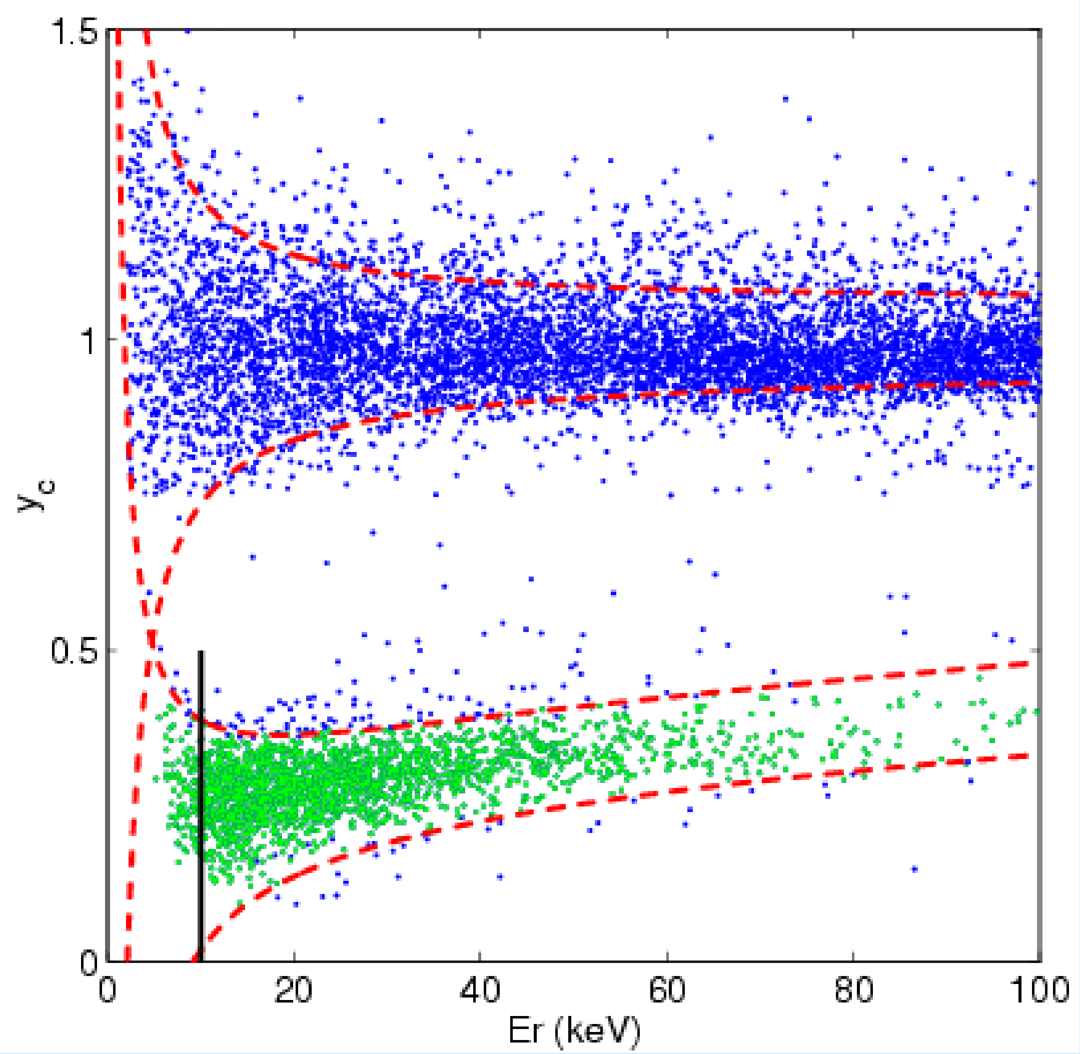
~25% QP collection eff.



^{252}Cf Neutron & Gamma calibration data

LARGE CALIBRATION SETS ESSENTIAL

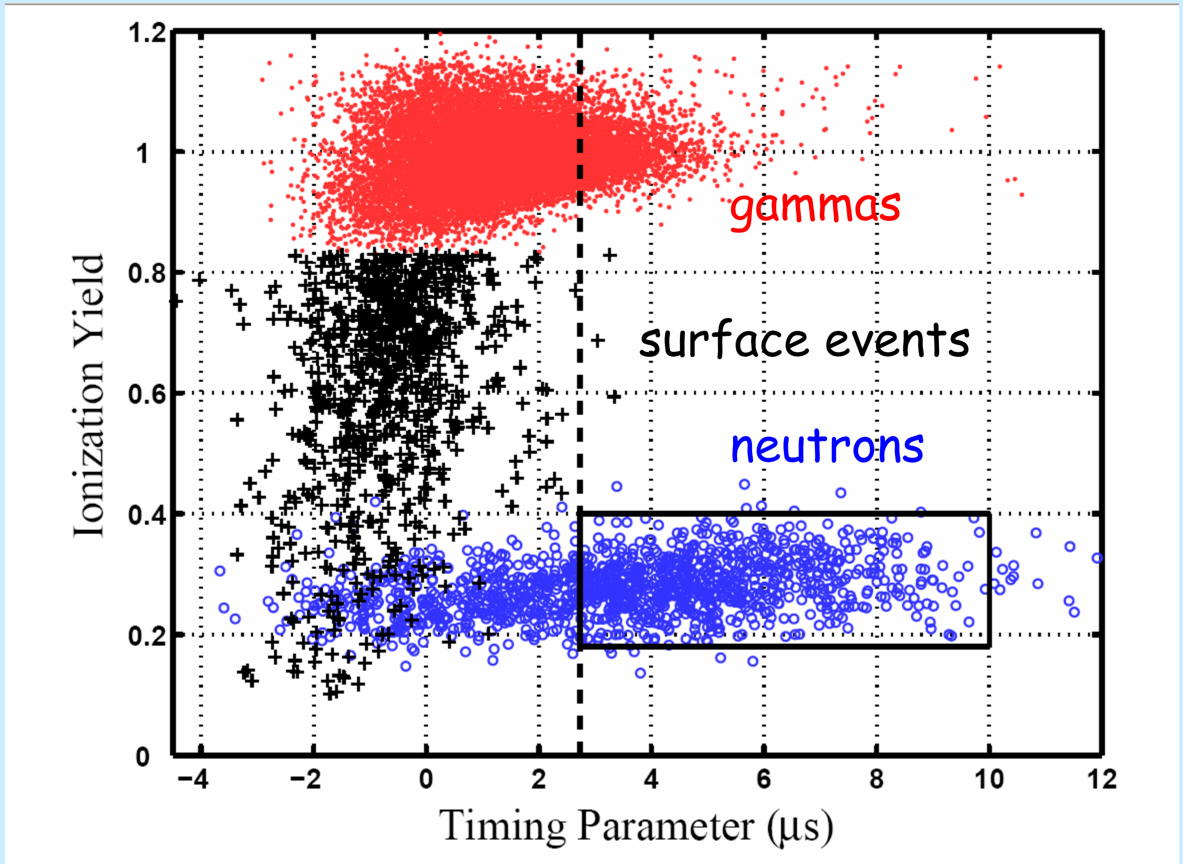
- Upper red dashed line are +/- 2 s gamma band
- Lower red dashed line are +/- 2 s nuclear recoil band with ^{252}Cf
- Separate high statistics calibrations with ^{133}Ba gamma source
- Cuts determined with calibration data as was the analysis threshold energy



^{133}Ba gamma & ^{252}Cf neutron calibrations

- Use phonon risetime and charge to phonon delay for discrimination of surface electrons "betas"
- Cuts and analysis thresholds determined from calibration data.

CDMS-II run March-August 2004, astro-ph/0509259



Nuclear recoil region of CDMS-II low background data bevor surface electron cut

CDMS-II run March to August 2004 astro-ph/0509259

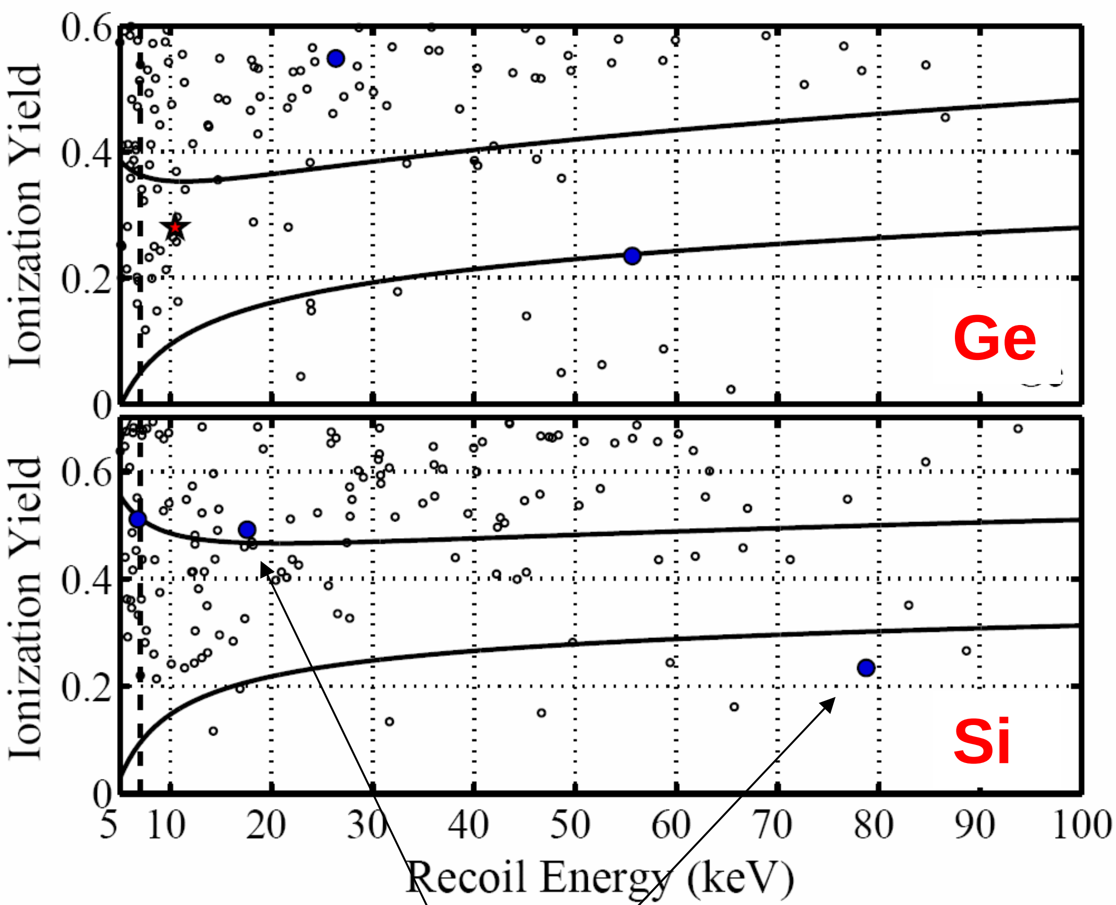
Ge data: 1 event survived surface cut

Si data: 0 events in signal region after surface electron cut

Cuts removes 70% of live time !

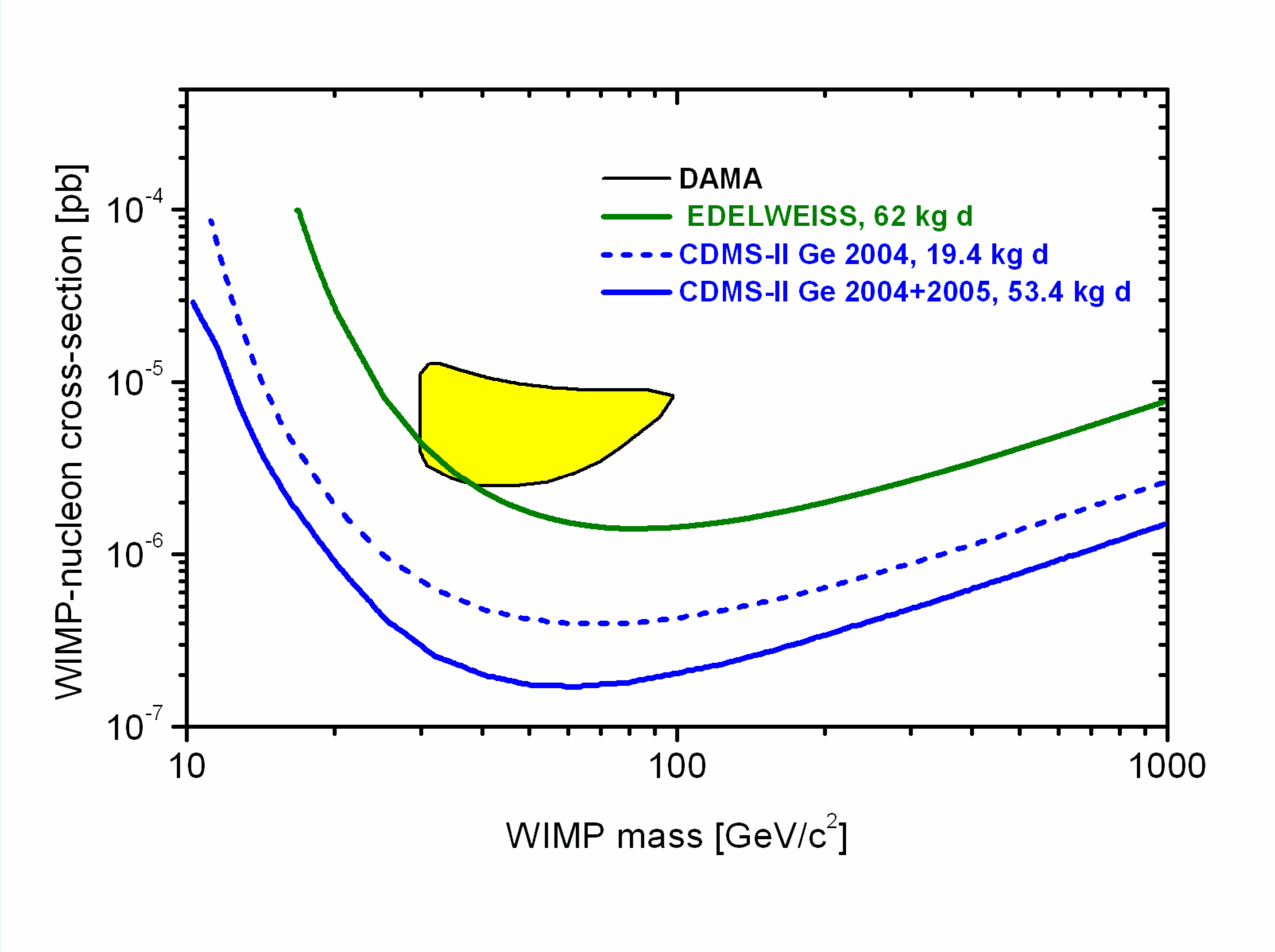
Total Ge data set:

53.kg d, 2 events in nuclear reocoil band



survivors outside signal region

New CDMS-II limits from Soudan Lab



CRESST

Collaboration:

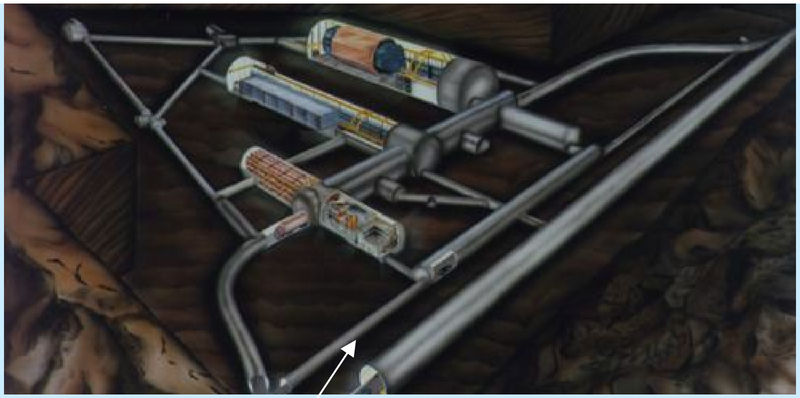
Max-Planck-Institut für Physik

University of Oxford

Technische Universität München

Laboratori Nazionali del Gran Sasso

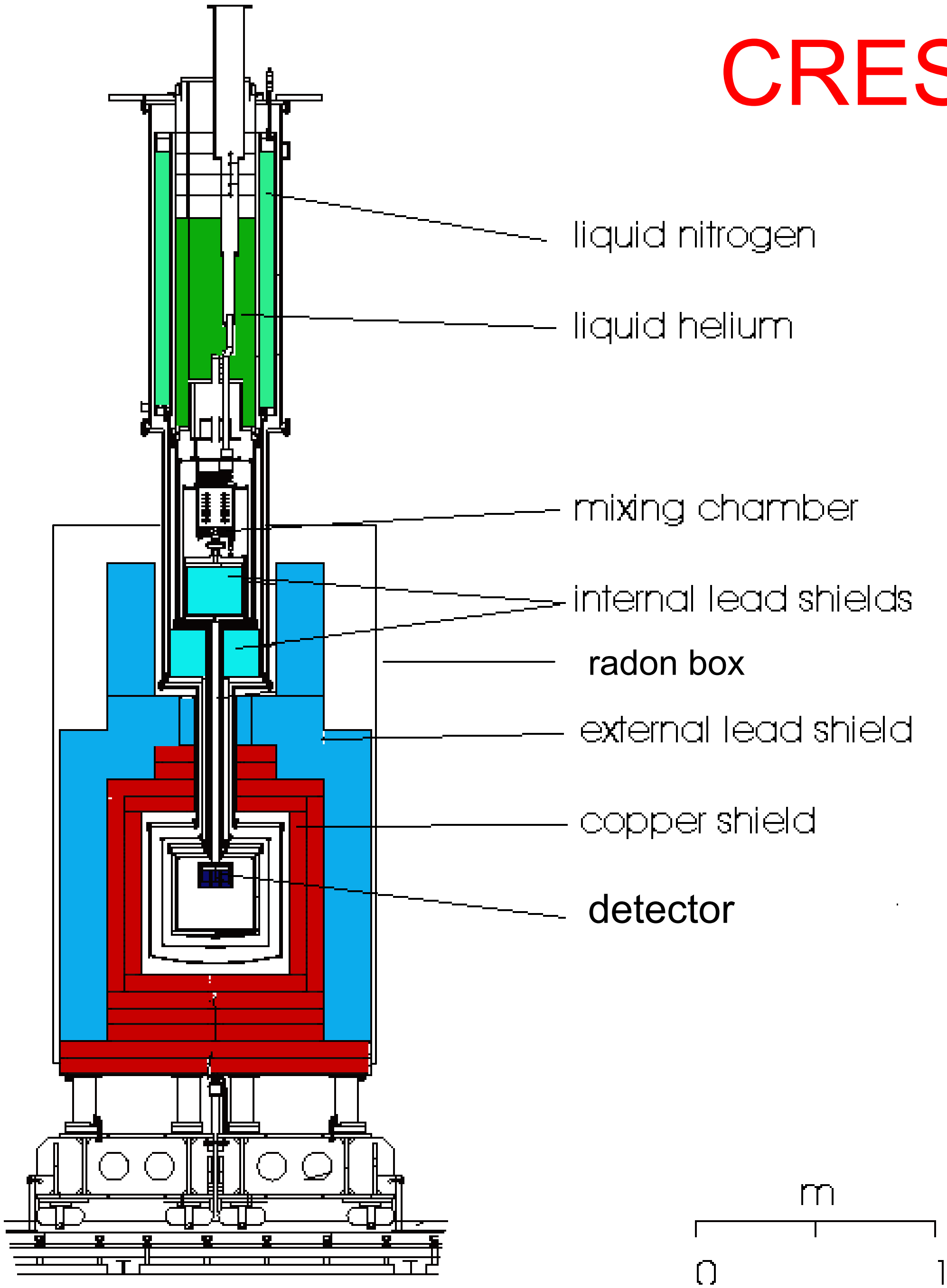
Universität Tübingen



Outline:

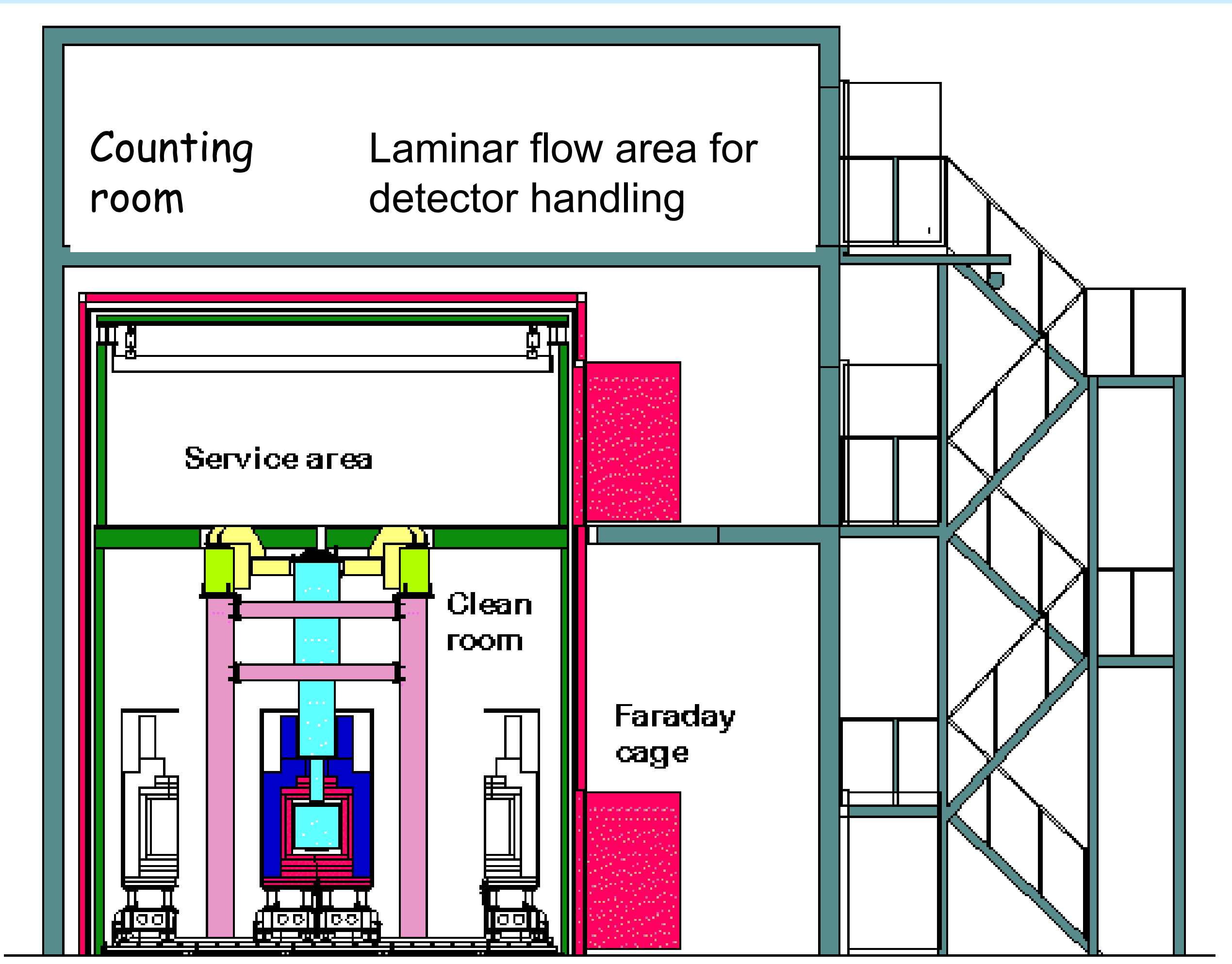
- CRESST setup in LNGS
- Detector concept
- Quenching factor measurements
- First results with two CRESST-II prototype detector modules (CRESST-I setup without neutron shield)
- Status of Upgrade for CRESST-II

CRESST Cryostat



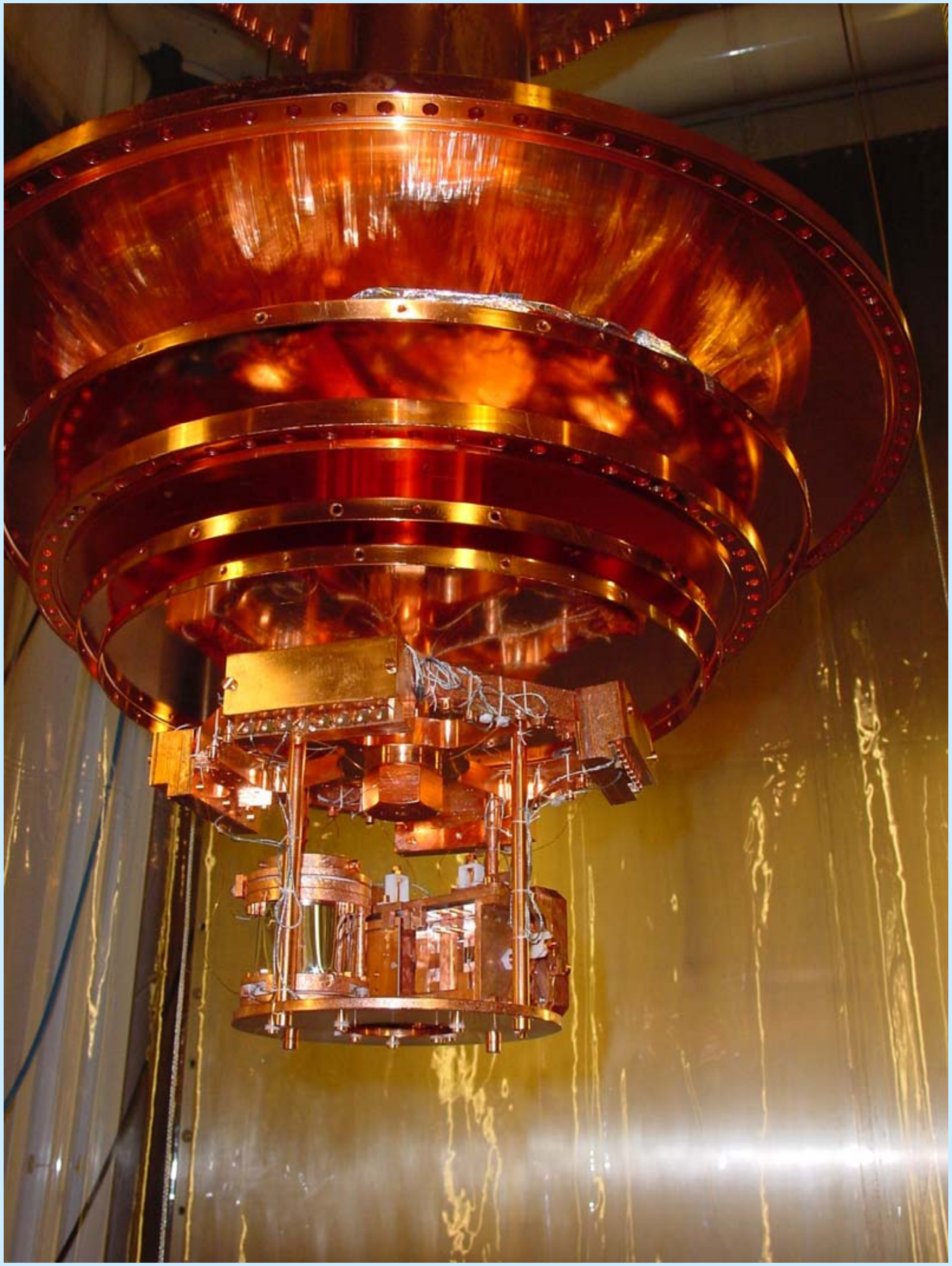
- *Only selected low background materials with minimized exposure to cosmic ray activation*
- *Cold Pb shields to block line of sight to detectors*
- *20 cm Pb +15 cm Cu shield*
- *No cryogenic liquids inside shielding*
- *Gas tight radon box around shield*
- *Cold box volume ~30 l, large enough for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

CRESST-Setup



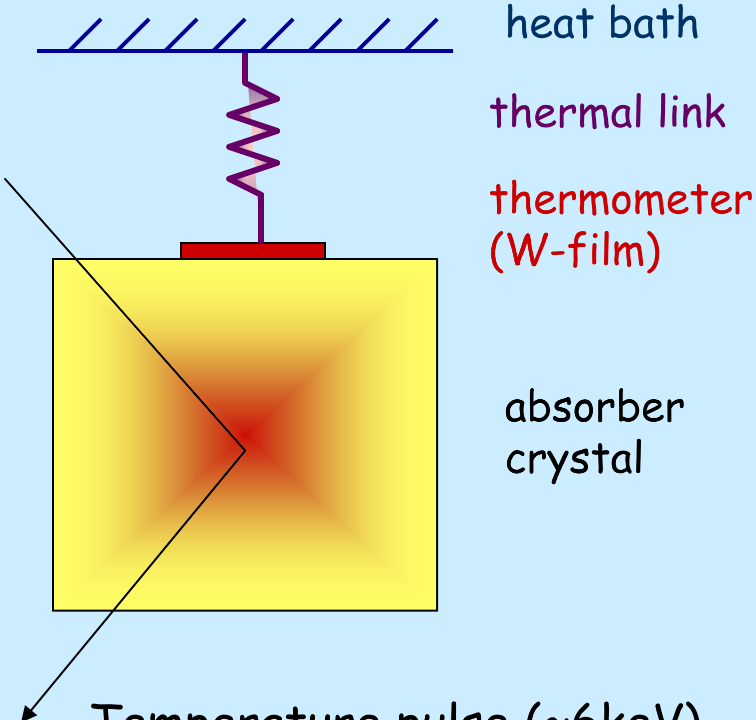
- Cryostat service area outside clean room
- Cryostat with efficient vibration insulation inside Faraday cage
- Lower level of Faraday cage is clean room
- Cold-box in clean room

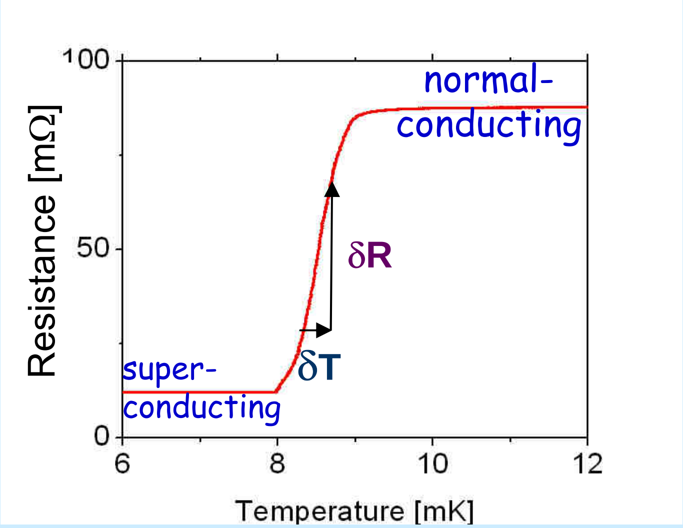
Cold Box and Schielding



Open Cold Box

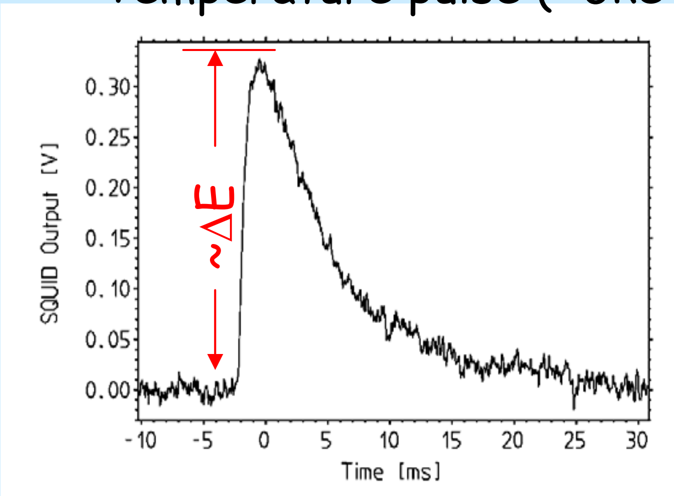
CRESST type Detectors





Width of transition: ~1mK
Signals: few μ K
Stablity: ~ μ K

Temperature pulse (~6keV)

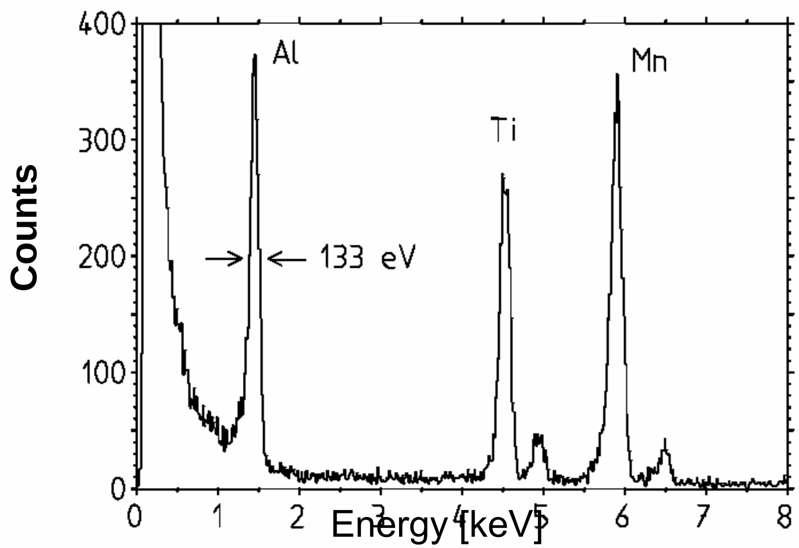


Advantages of technique:

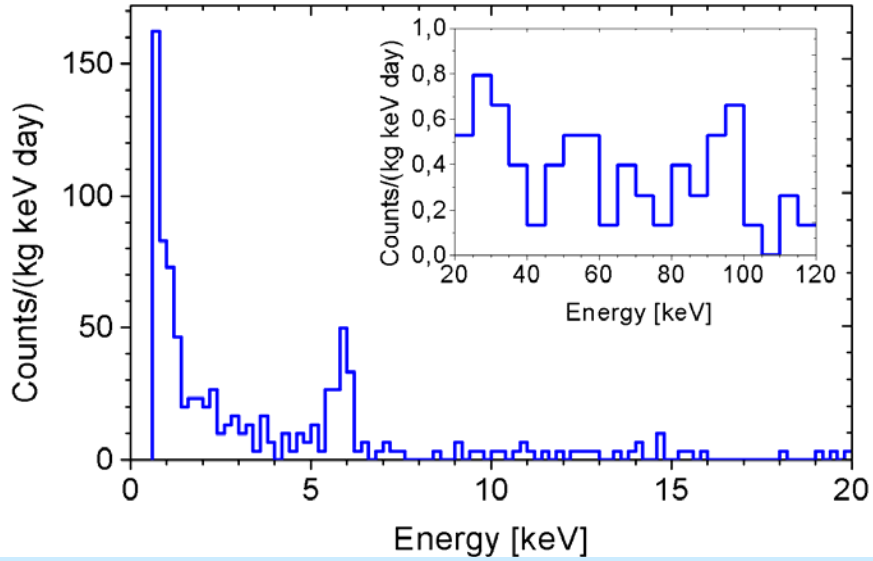
- -measures deposited energy independent of interaction type
- -Very low energy threshold
- -Excellent energy resolution
- -Many materials

CRESST-I: 262 g sapphire detectors

Test with x-ray source



Low background run



Excellent energy resolution:

133 eV @ 1.5 keV

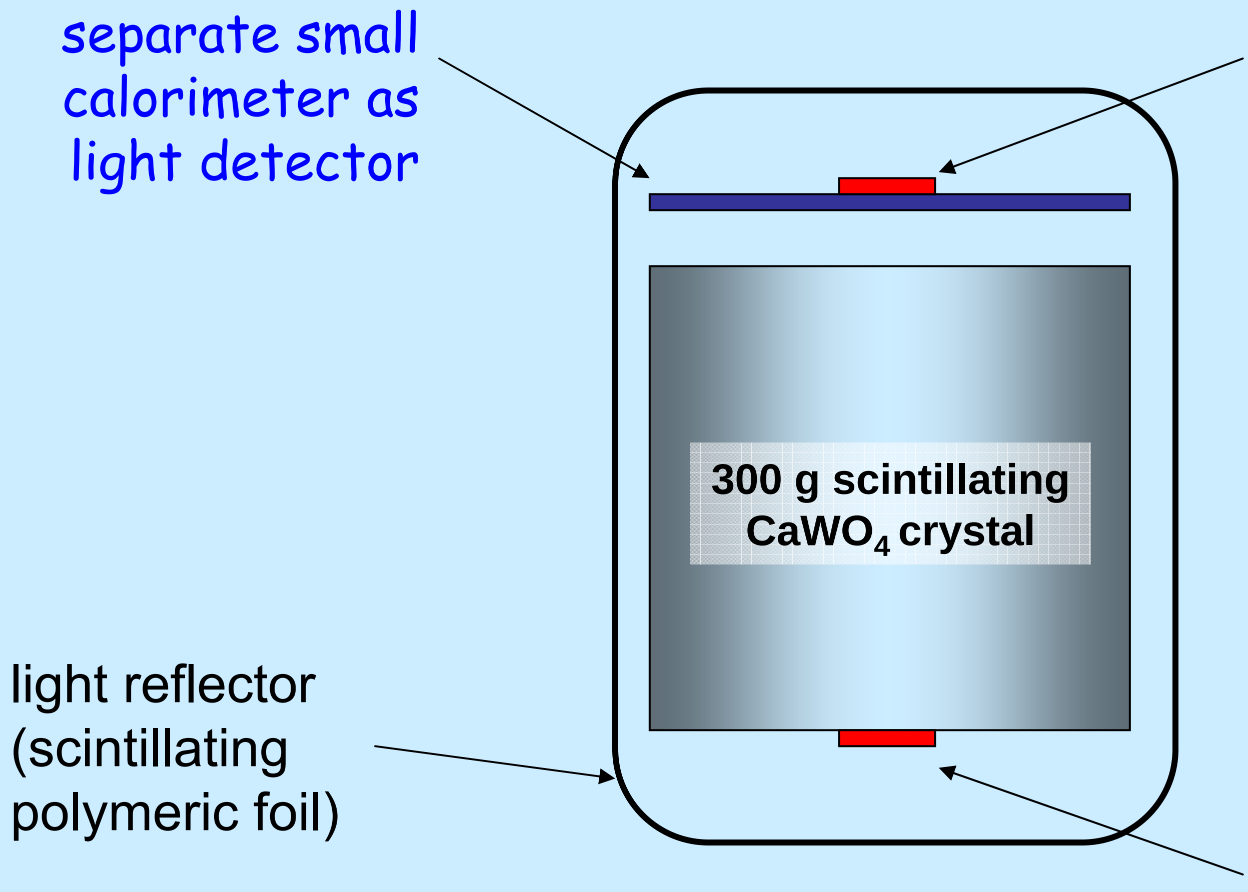
Threshold: 500 eV

Very 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

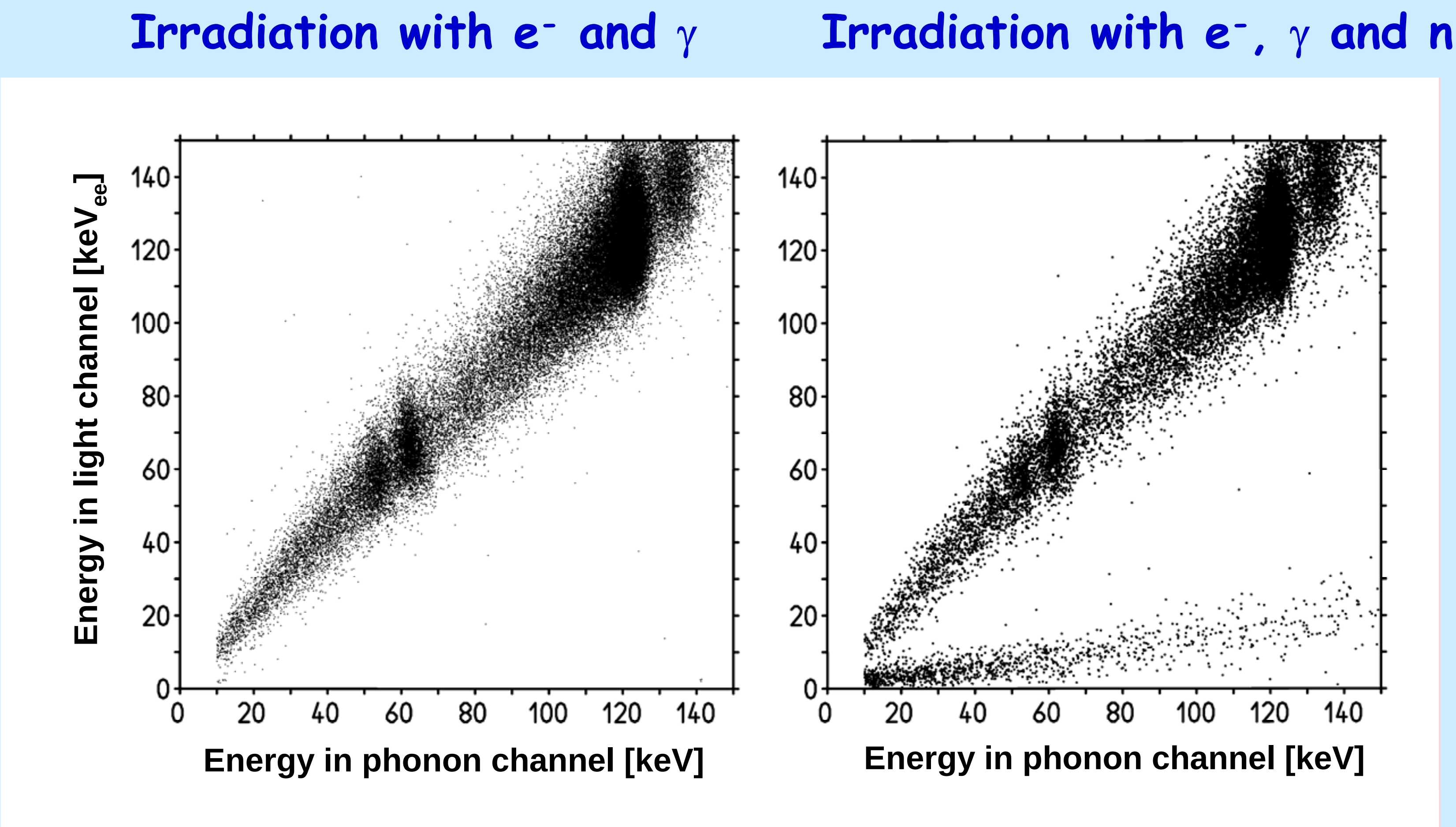
CRESST-II Detector Concept

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



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

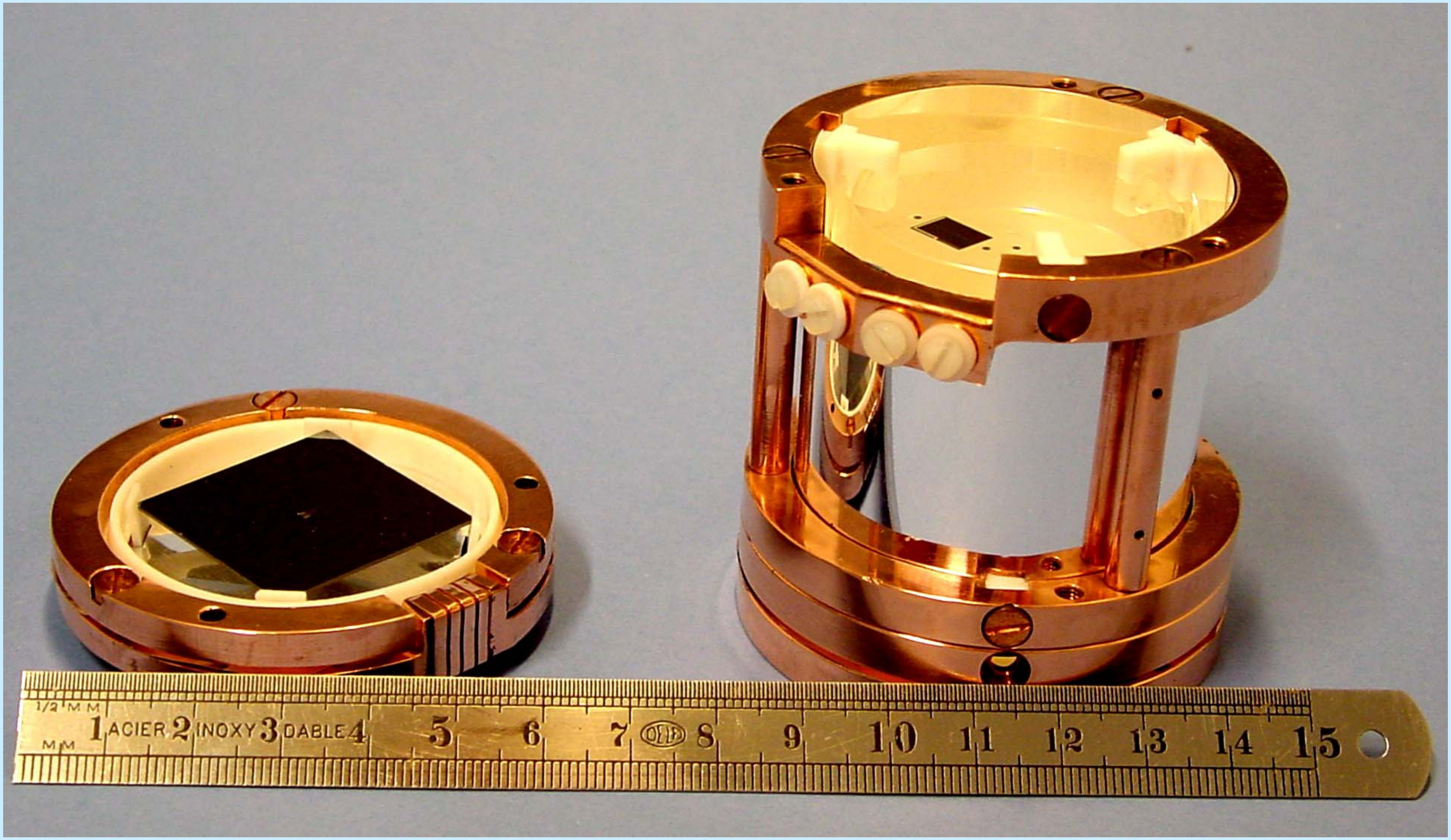
Proof of principle experiment



- No degratation of light yield for e^- surface events

- Efficient discrimination of e^- and γ background: 99.7% 15 to 25 keV

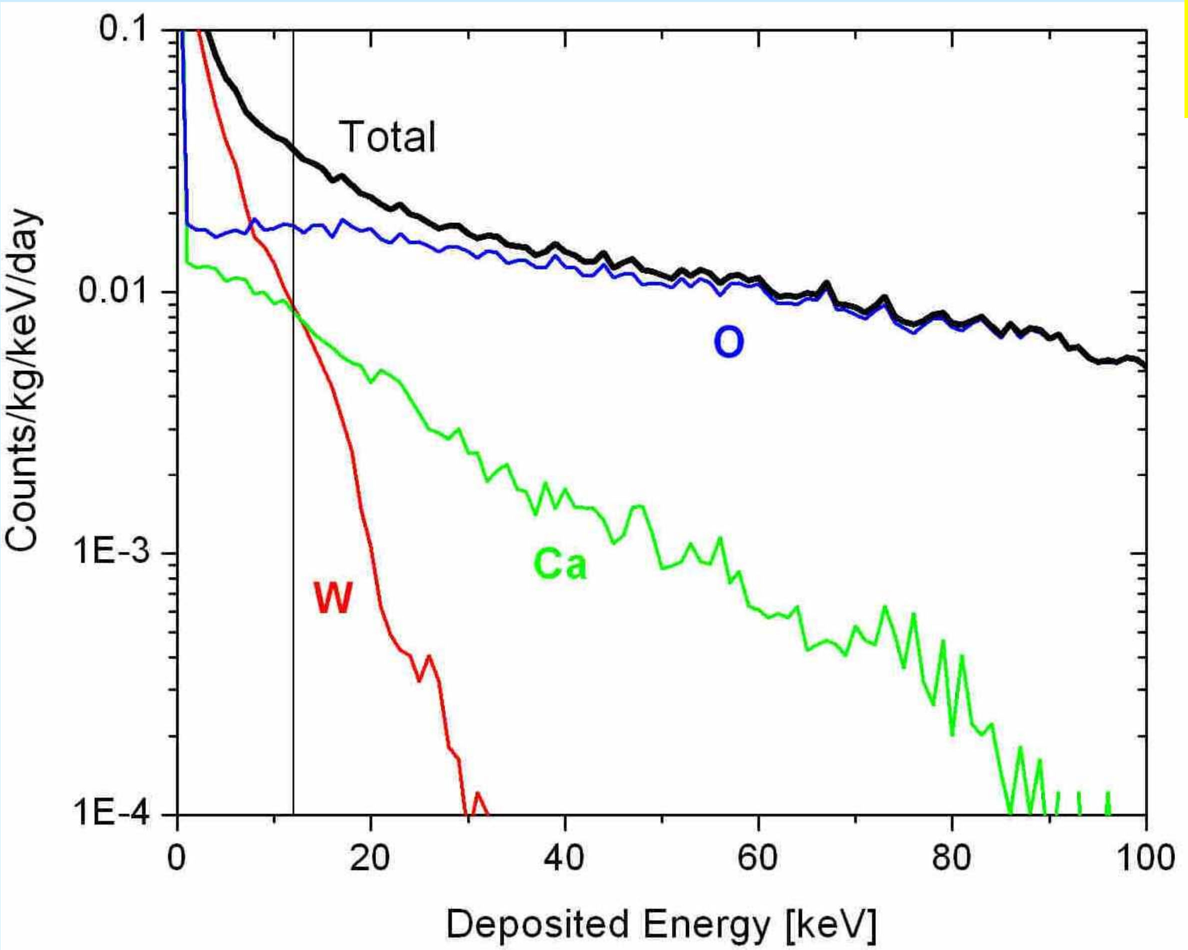
300 g CRESST-II Prototype Detector Module



CRESST-II: 33 detector modules ➔ 66 readout channels

Recoil energy spectrum in $CaWO_4$ expected from neutrons at Gran Sasso (no neutron shield)

Monte Carlo simulation dry concrete (H. Wulandari et al)



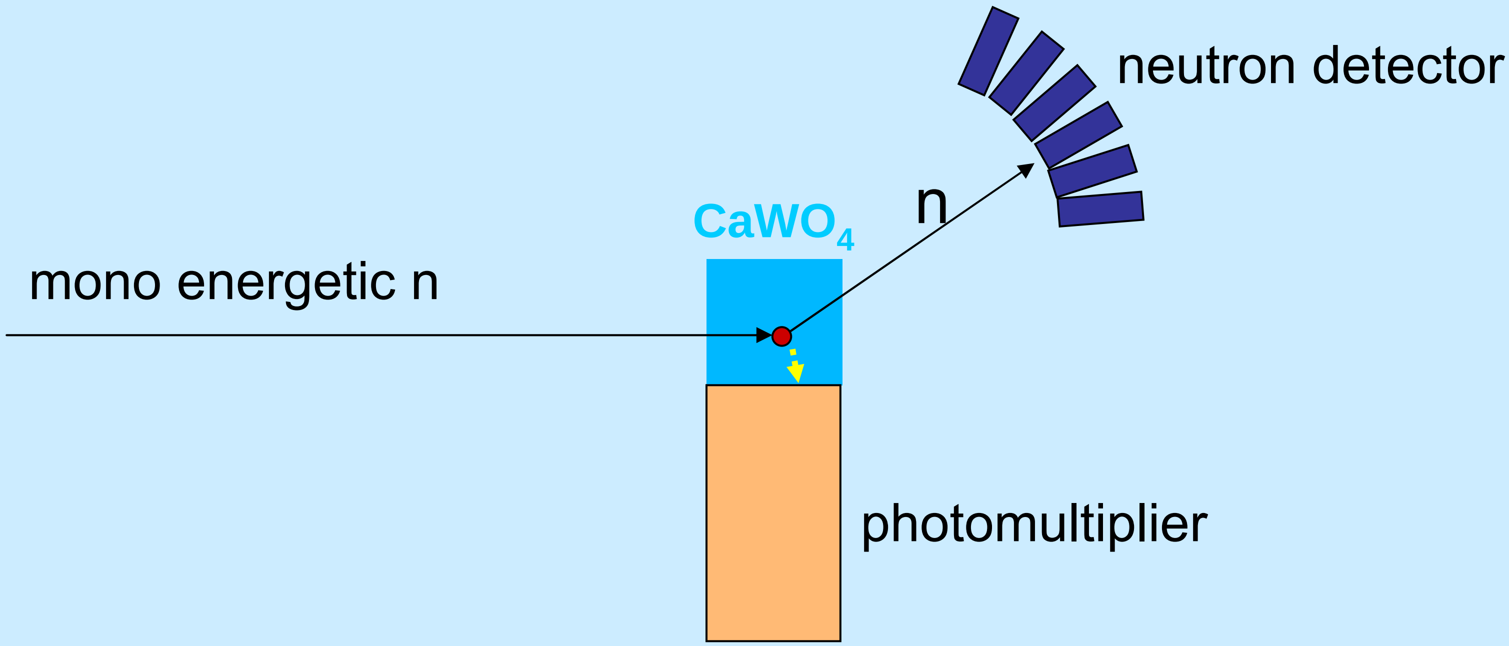
Contribution of W recoils very small above 12 keV

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

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

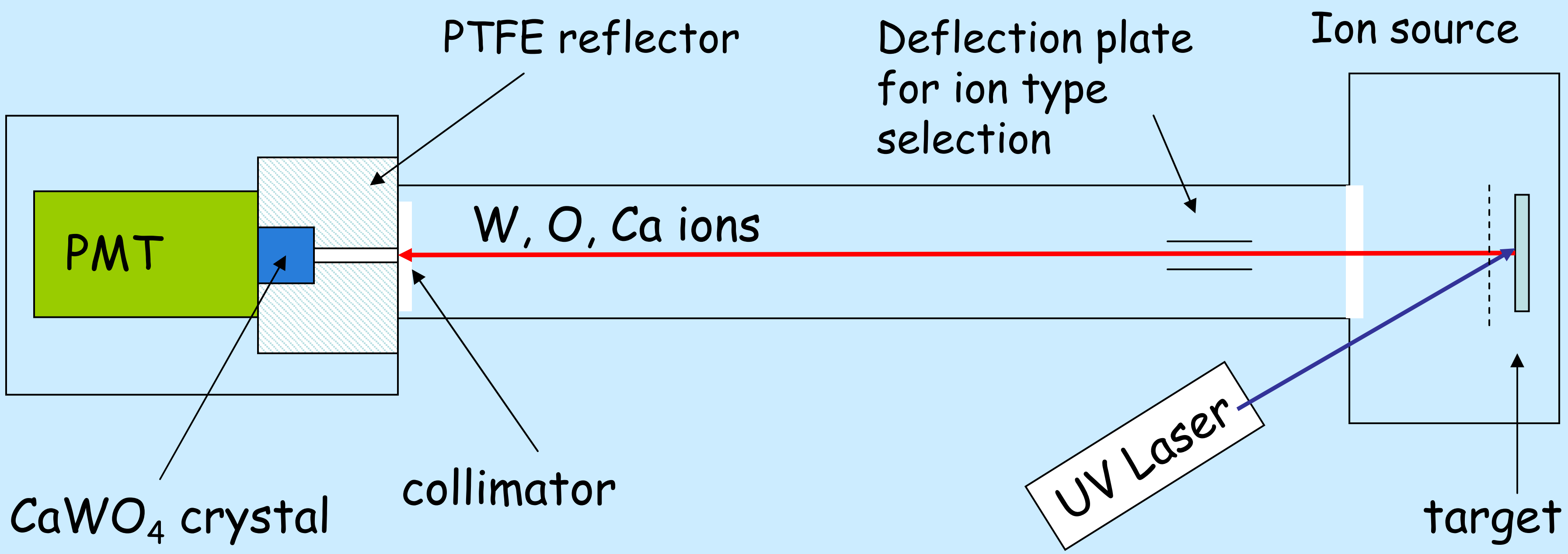
Quenching Factor measurement with neutron scattering

Thomas Jagemann, TUM



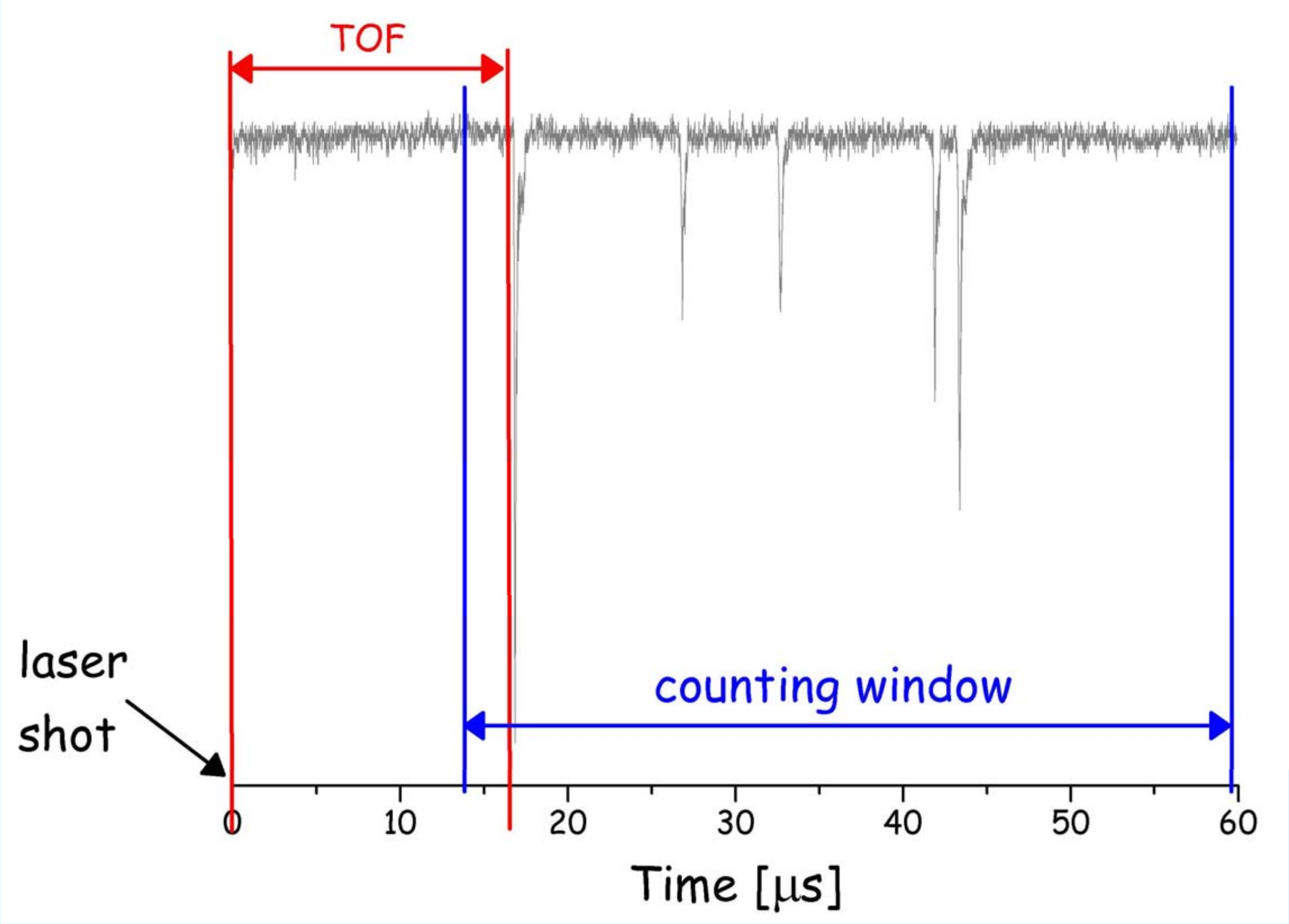
Measured value for oxygen: Q = 12.8±0.5
Only lower limit for W: Q > 33

Quenching factor measurement with TOF



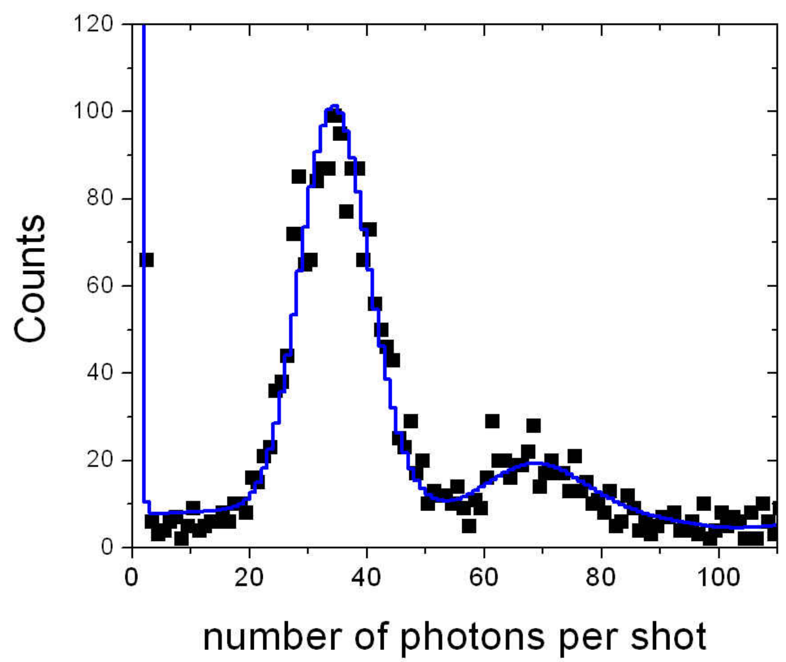
- UV Laser desorbs singly or doubly charged ions from almost any material. Acceleration to 18 keV (or 32 keV for double charged)
- Mount $CaWO_4$ crystal on PMT at end of flight tube and record single photon counts with fast digitizer
- Adjust laser intensity such that more than 1 ion arriving per laser shot is negligible.

Single photon counting after arrival of ion

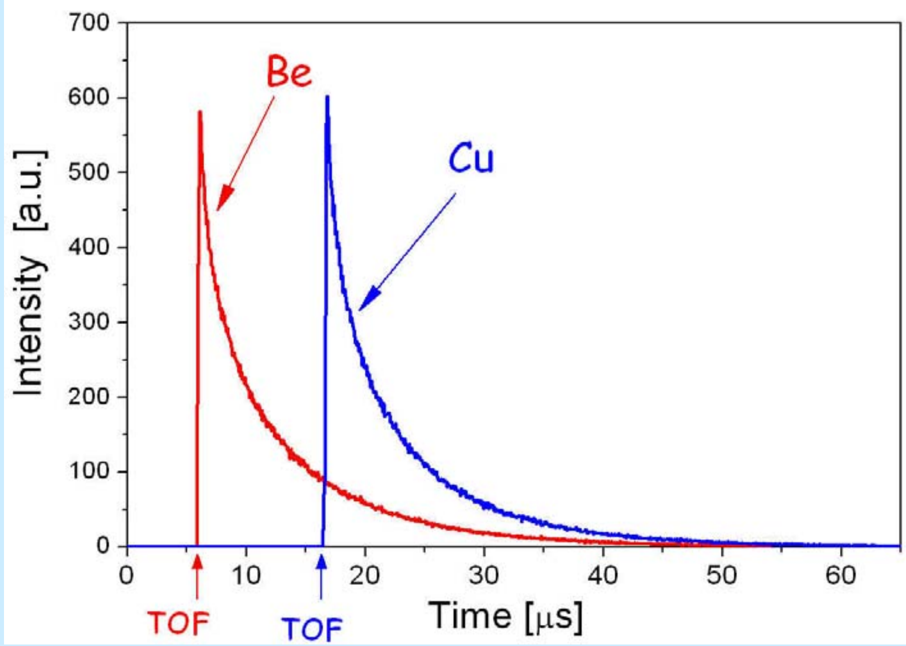


Quenching factor measurement with TOF

Photon counts per laser shot



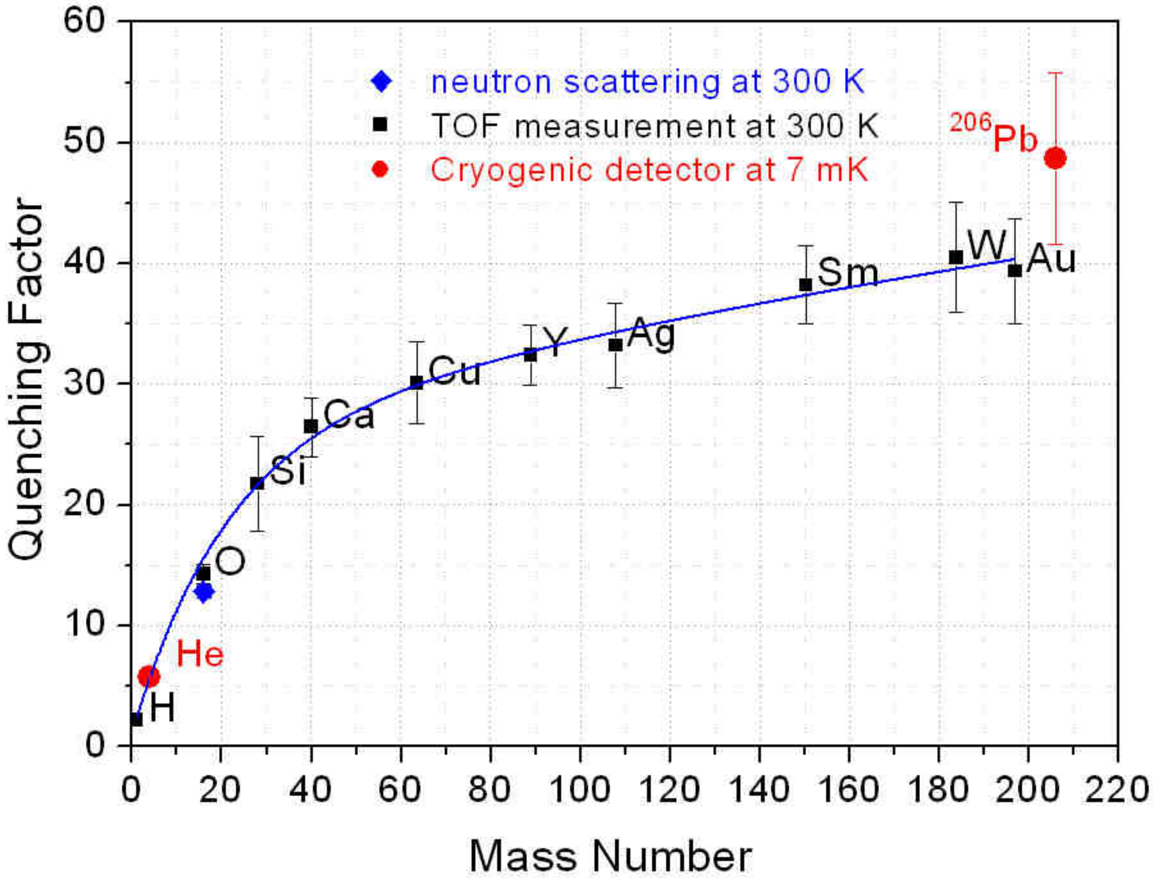
Light curve of $CaWO_4$



Comparision with photon counts per 6 keV x-ray yields quenching factor

Averaging digitizer traces for many laser shots yields light curve

Quenching Factors for various nuclei in $CaWO_4$

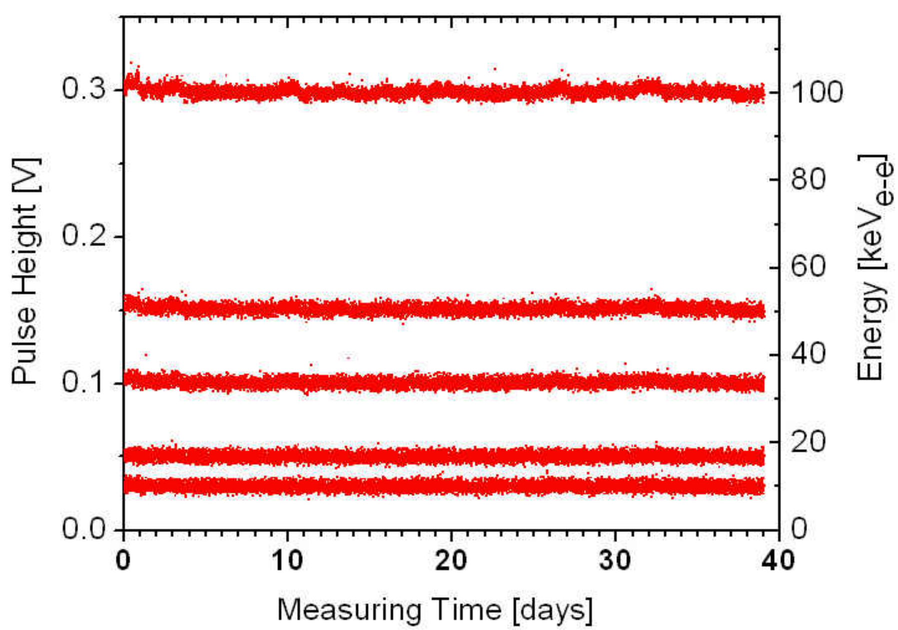


High value of Q=40 for tungsten ➔ very little light for recoils <40 keV

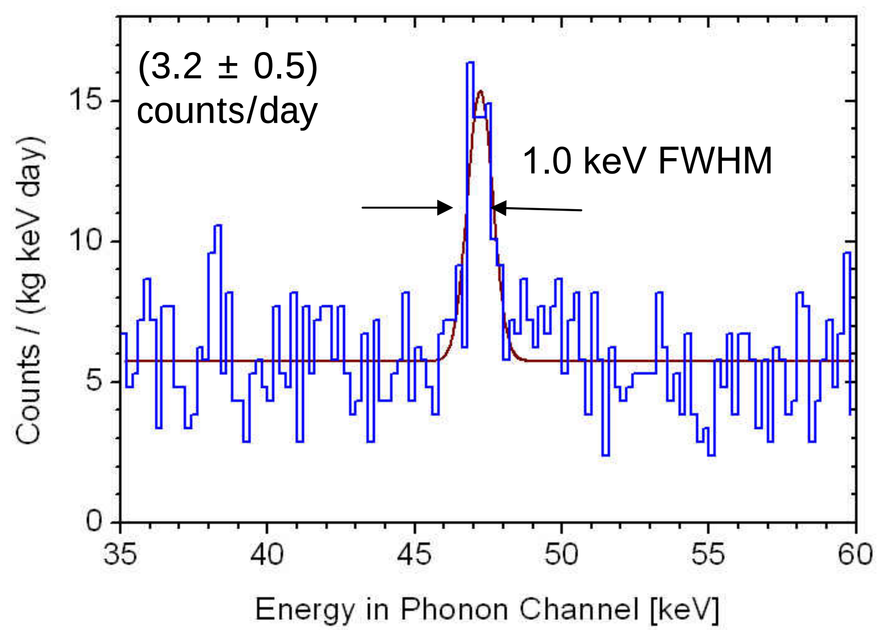
Discriminate W recoils (WIMPS) from O recoils of neutrons

Run 28 (1.5 month) with two 300 g prototype modules

Pulse height of heater pulses



Energy resolution of phonon channel



Very stable response over a period of 40 days

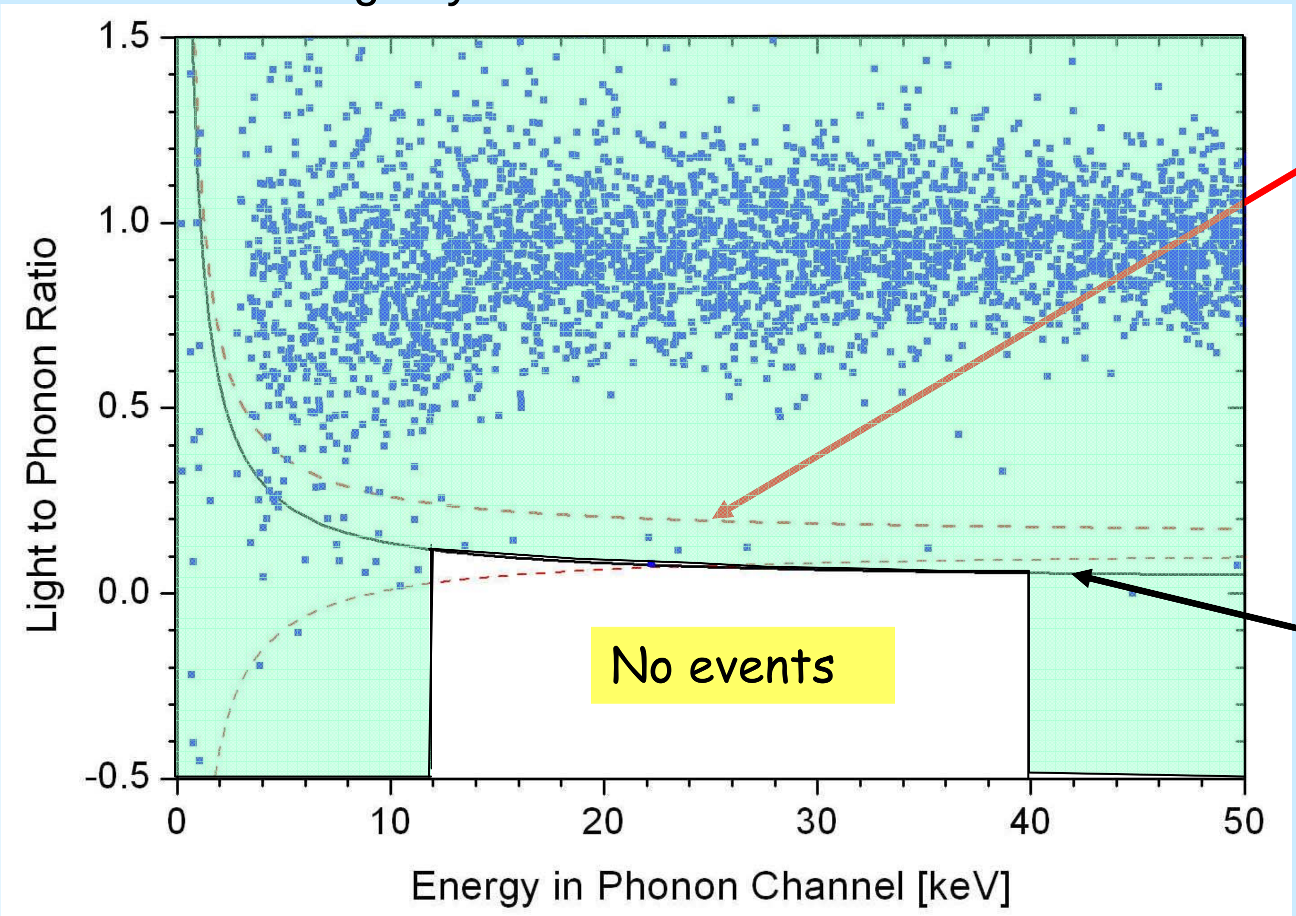
Very good energy resolution:

γ : 1.0 keV @ 46.5 keV

α : 6.7 keV @ 2.3 MeV

Run 28: Low Energy Event Distribution no neutron shield

10.72 kg days



90% of oxygen recoils below this line.

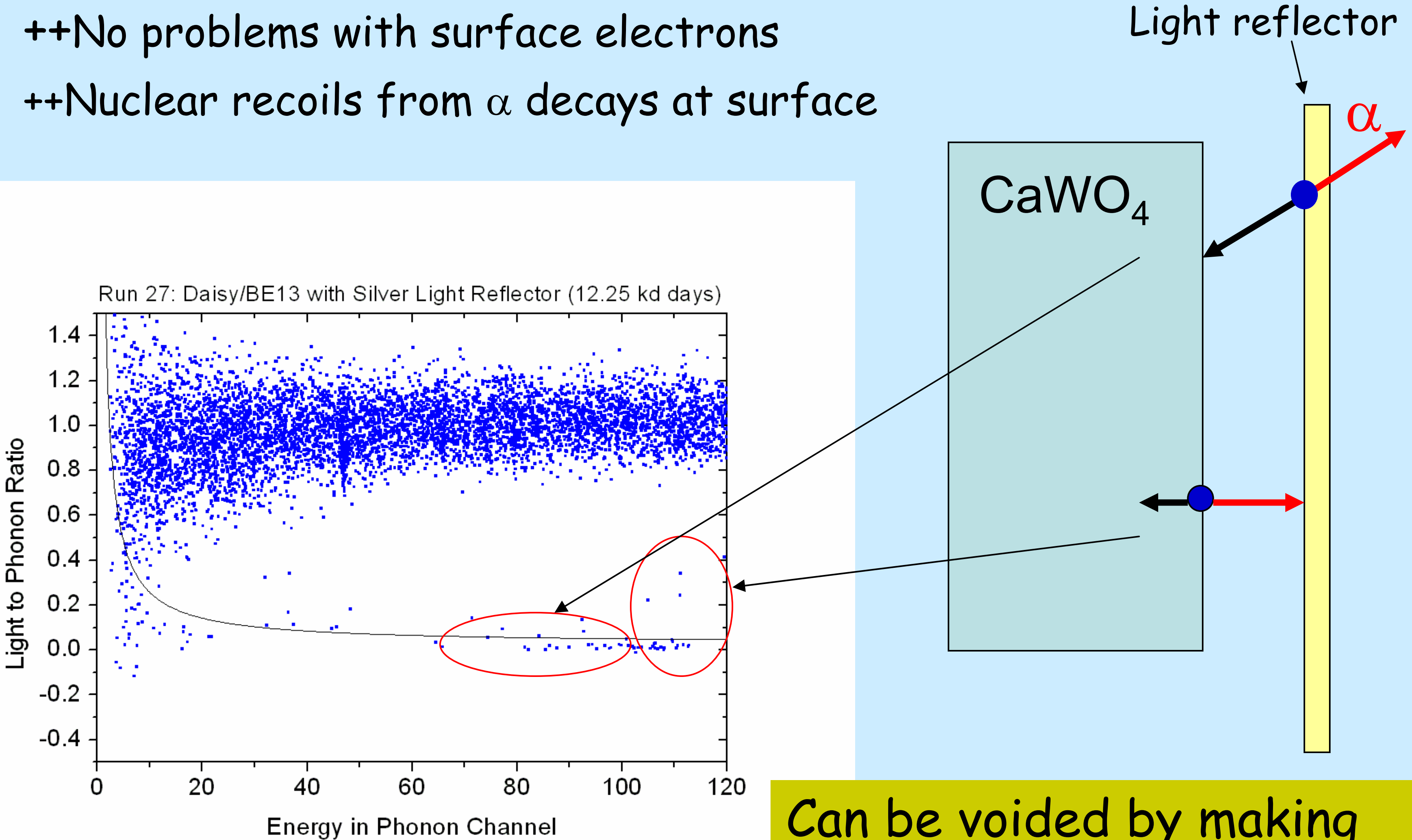
Rate=0.87±0.22 /kg/day compatible with expected neutron background (MC).

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

Avoiding the α nuclear recoil bckground

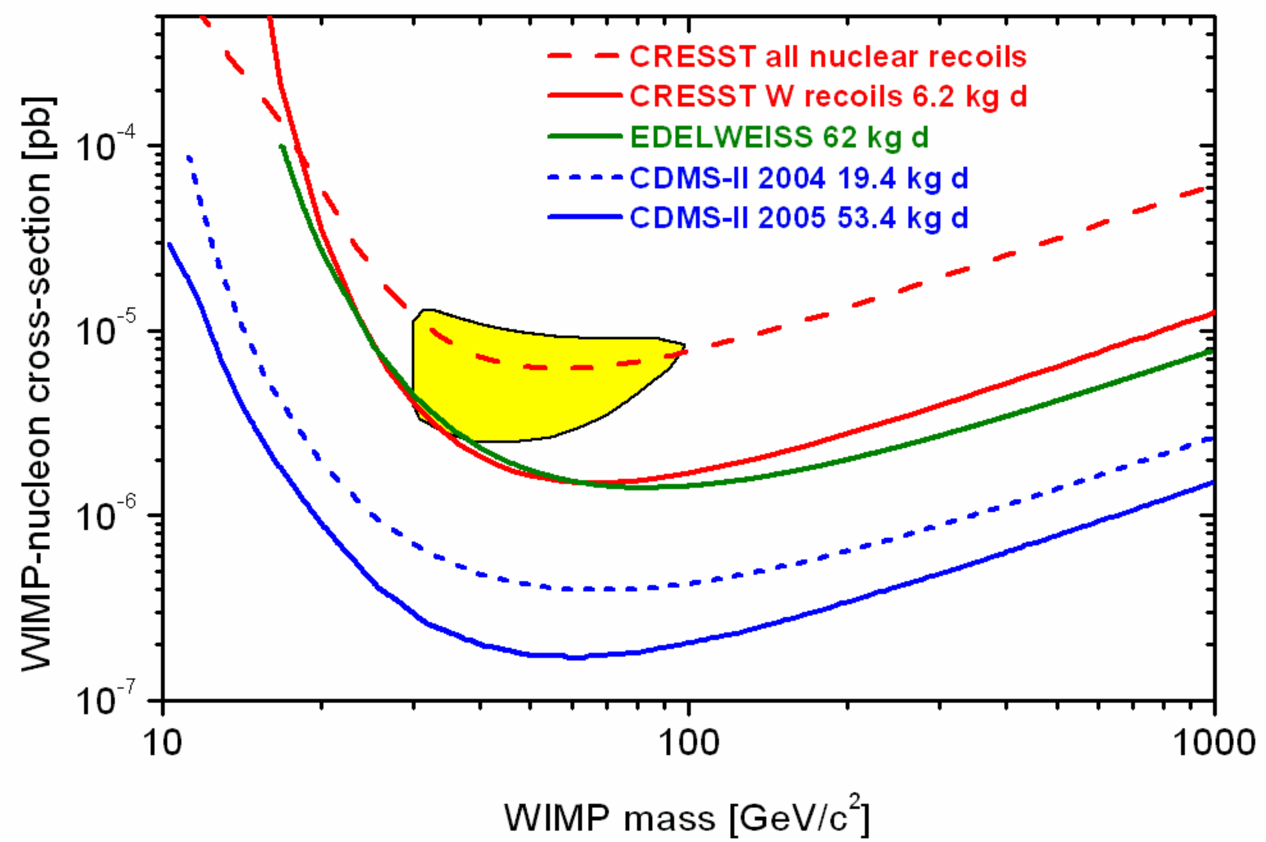
++No problems with surface electrons

++Nuclear recoils from α decays at surface



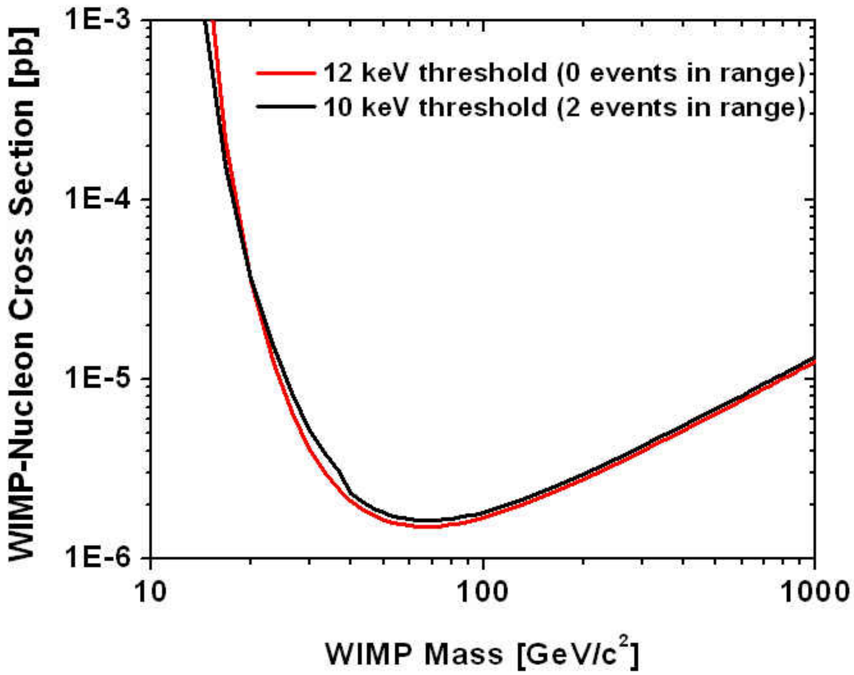
Can be voided by making light reflector scintillating

Upper limit for spin indepentend WIMP nucleon cross section

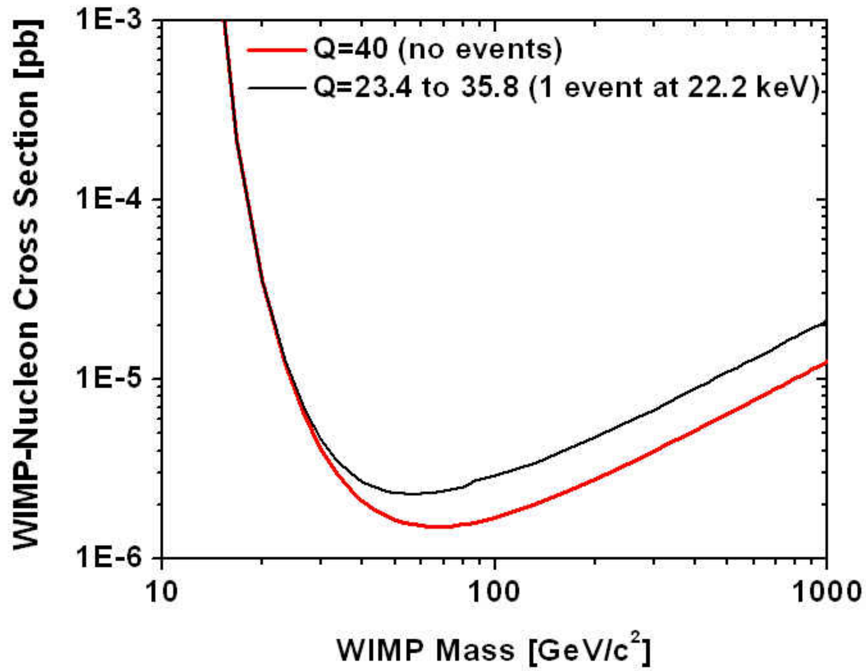


Stability of exlusion limit

Variation of threshold



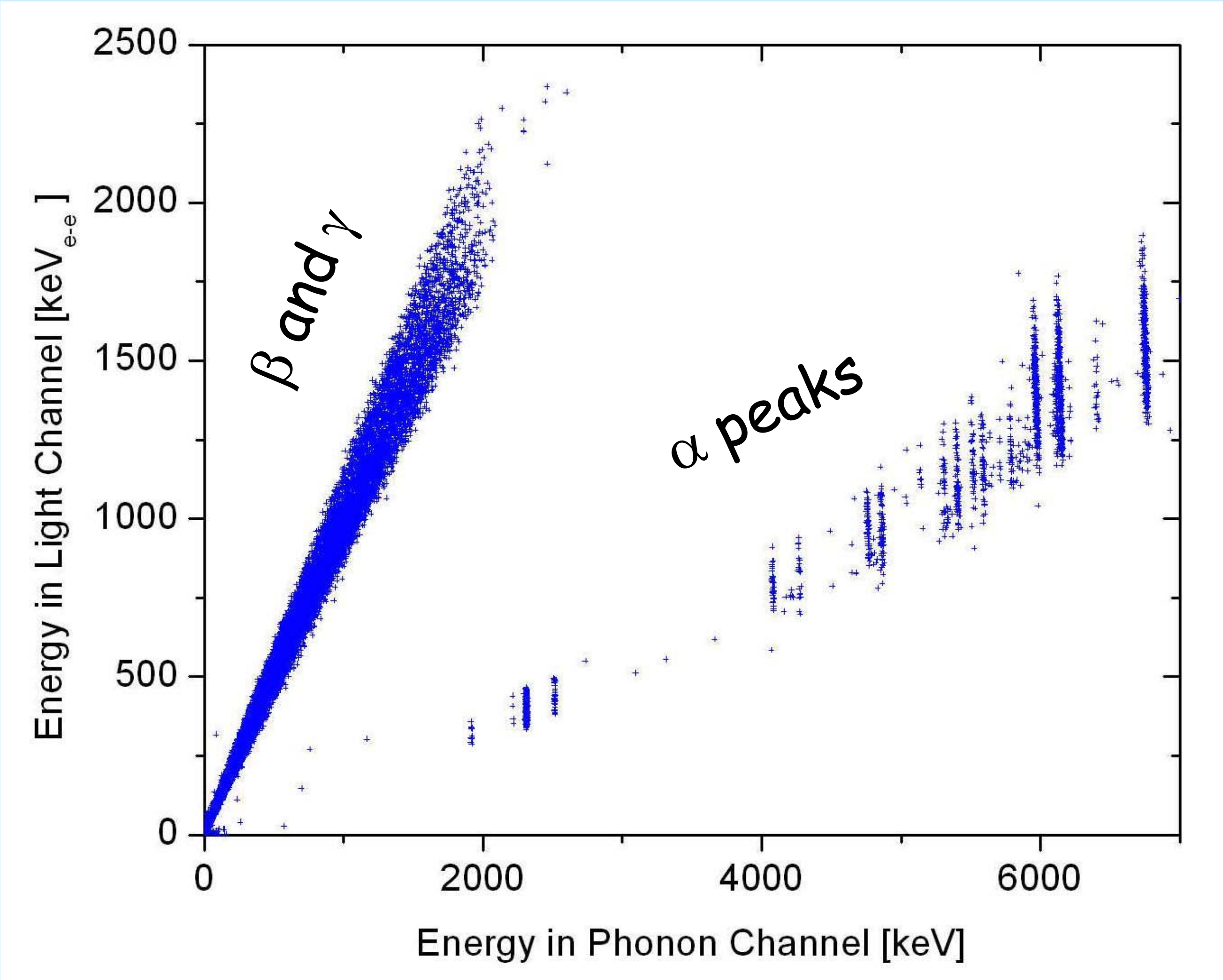
Variation of quenching factor



Including the 2 events at 10.5 and 11.2 keV has practically no effect on result.

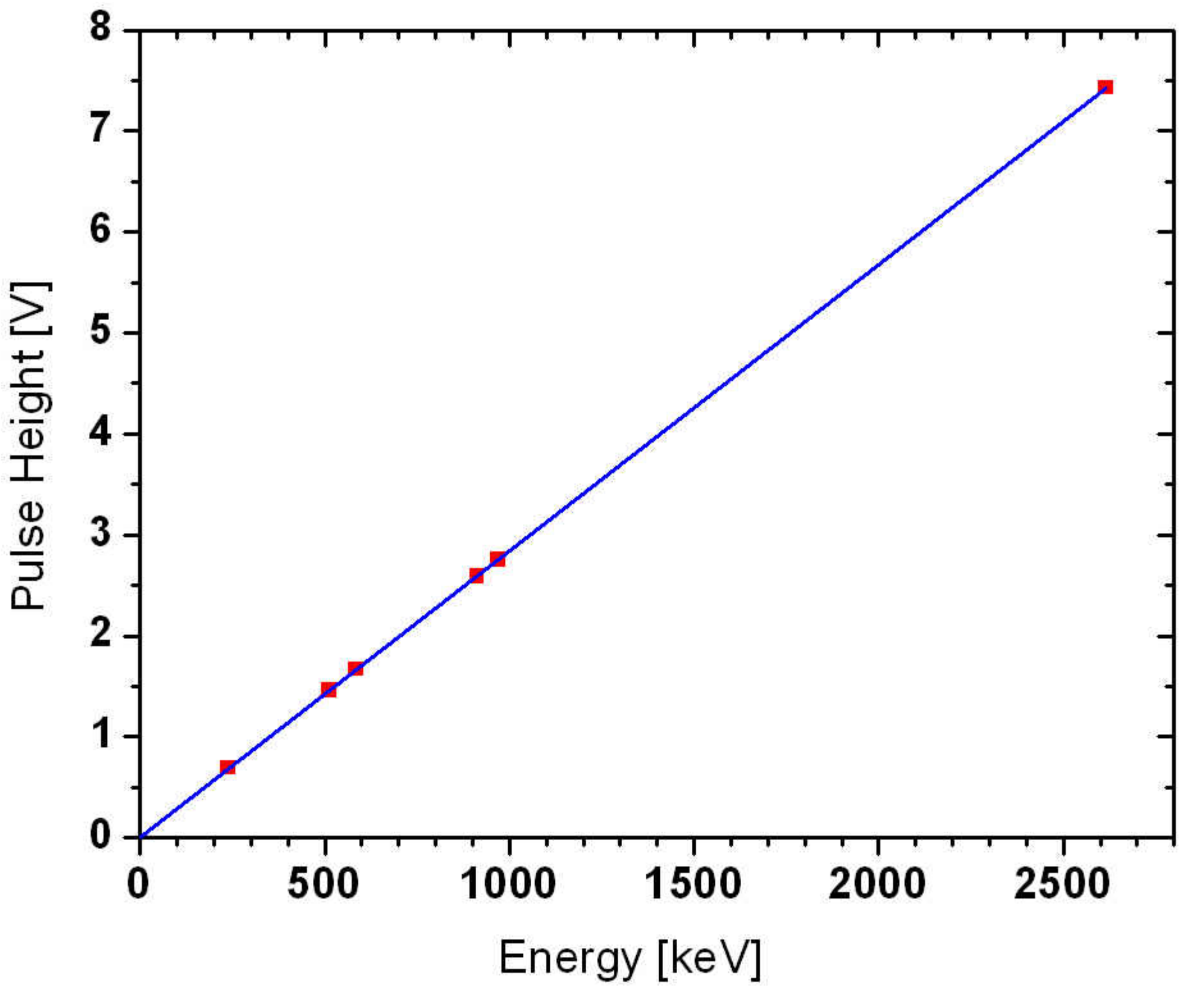
Variation of Q well beyond uncertainties has only small effect:
$\sigma = 1.6 \times 10^{-6} \rightarrow 2.3 \times 10^{-6}$ pb

Detector Performance at high Energies

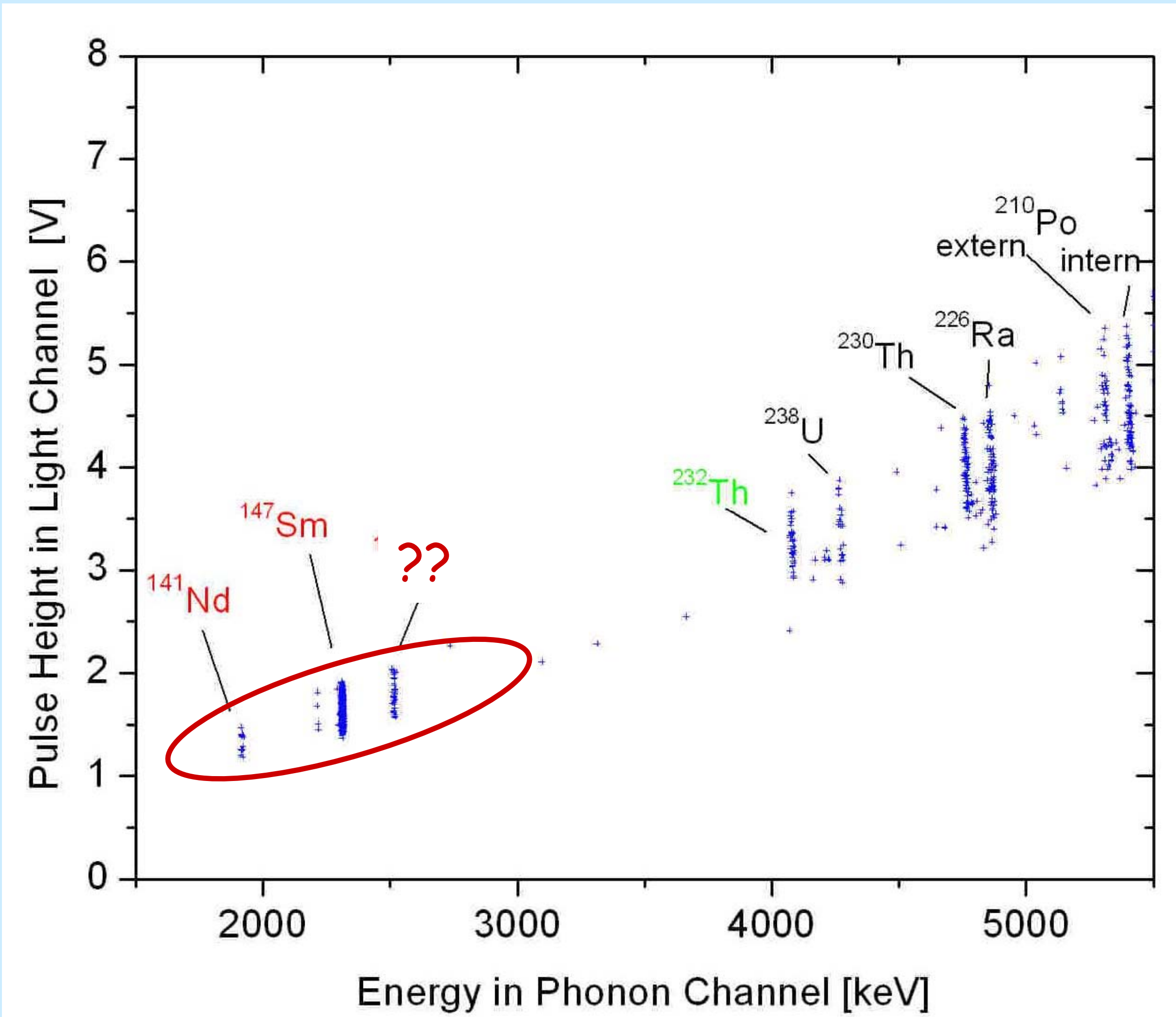


- Excellent linearity and energy resolution at high energies
- Perfect discrimination of β+γ from α's
- Identification of alpha emitters

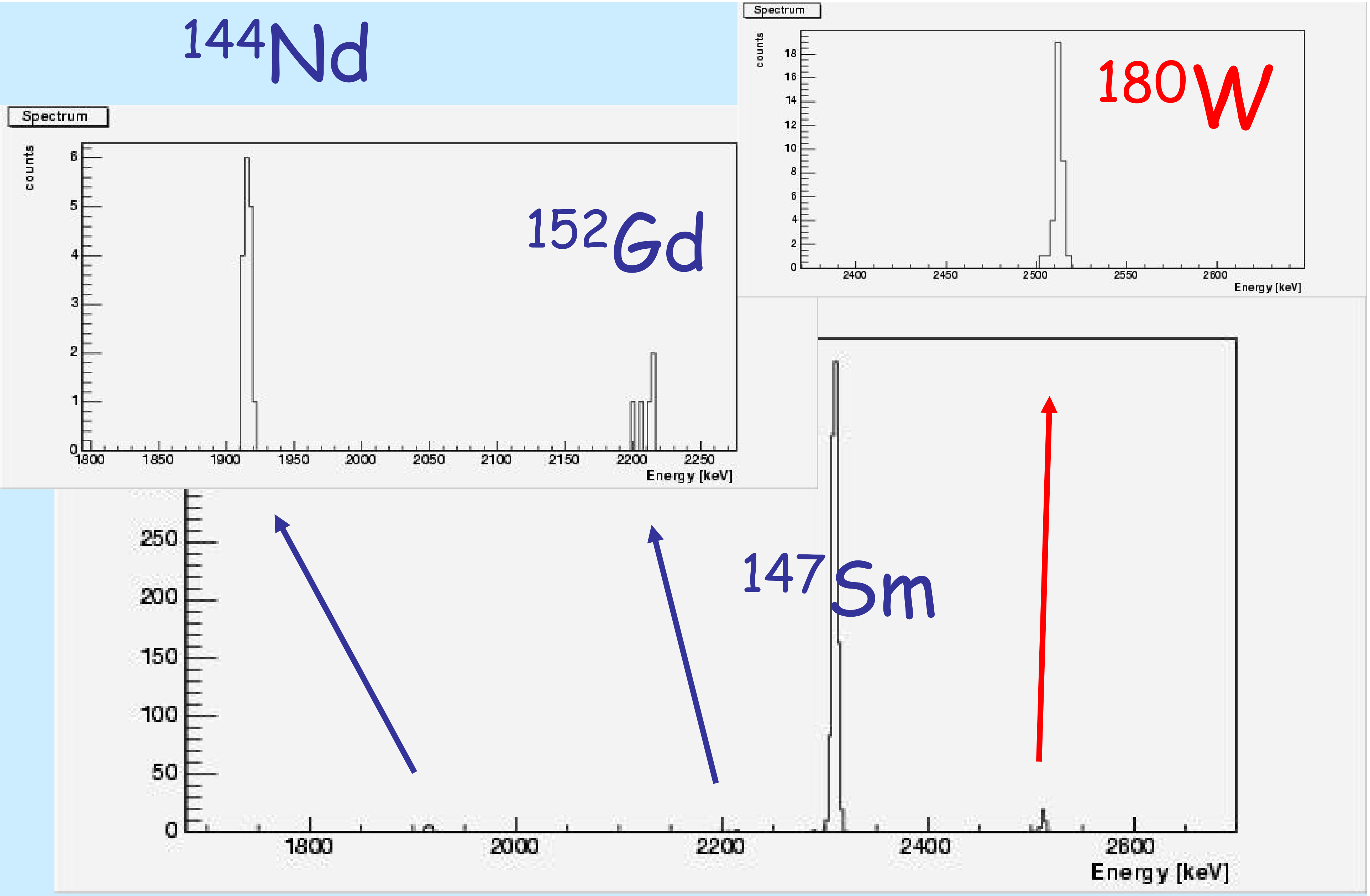
^{232}Th calibration: Linearity of detector response at high energies



Identification of α-Emitters

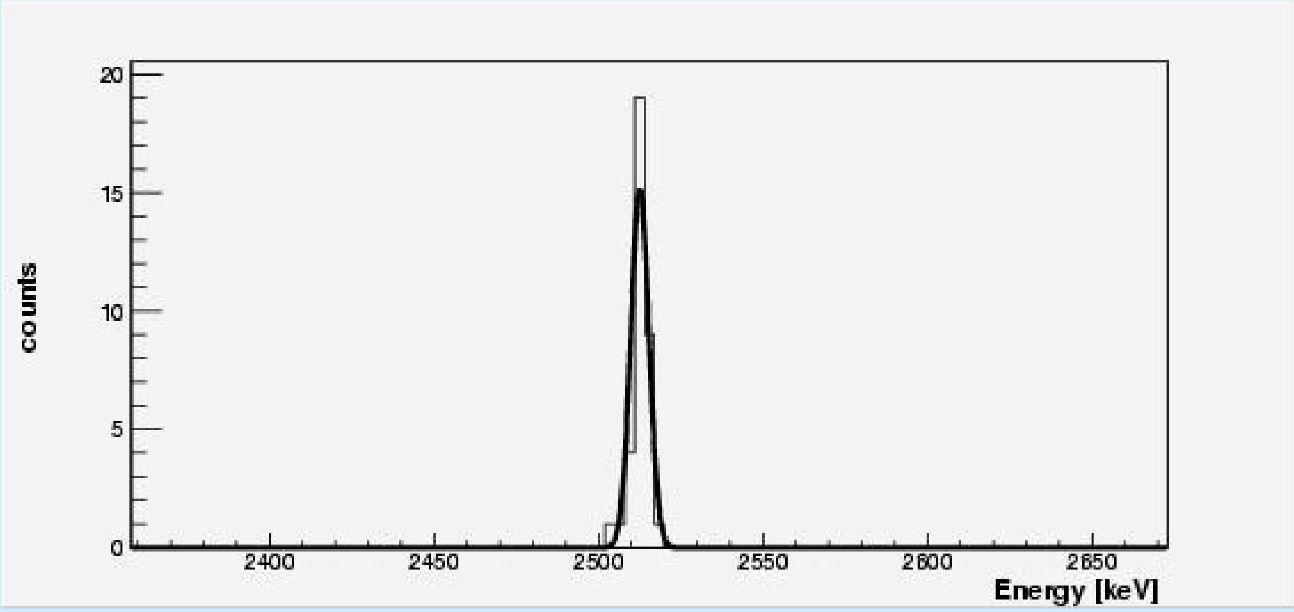


- Same light for extern and intern ^{210}Po ➔ no surface degradation
- Relatively low alpha rates: total ~ 2mBq/kg.
^{238}U ~2 10^{-12}g/g



α Decay of stable ^{180}W

Half-life for the α-decay of ^{180}W



exposure	28.62 kg days
Half life	$T_{1/2} = (1.8 \pm 0.2) \times 10^{18}$ years
Energy	$Q = (2516.4 \pm 1.1$ (stat.) ± 1.2(sys.)) keV

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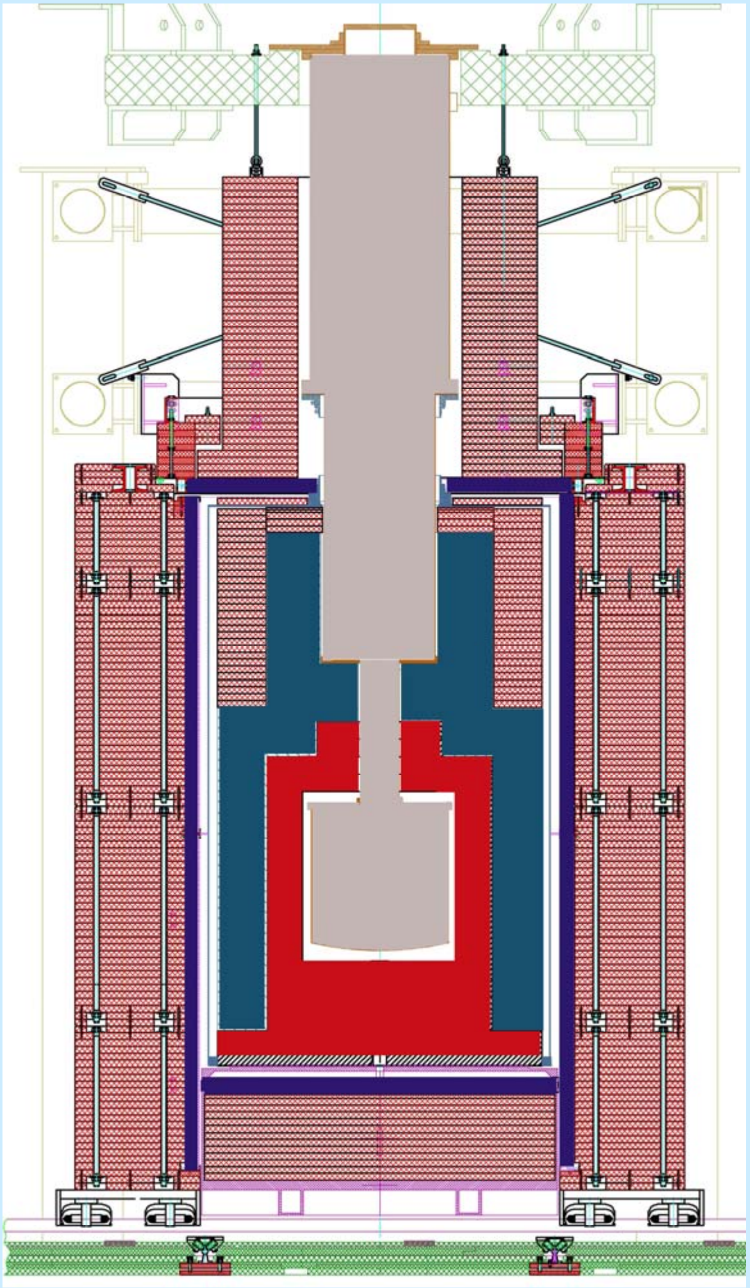
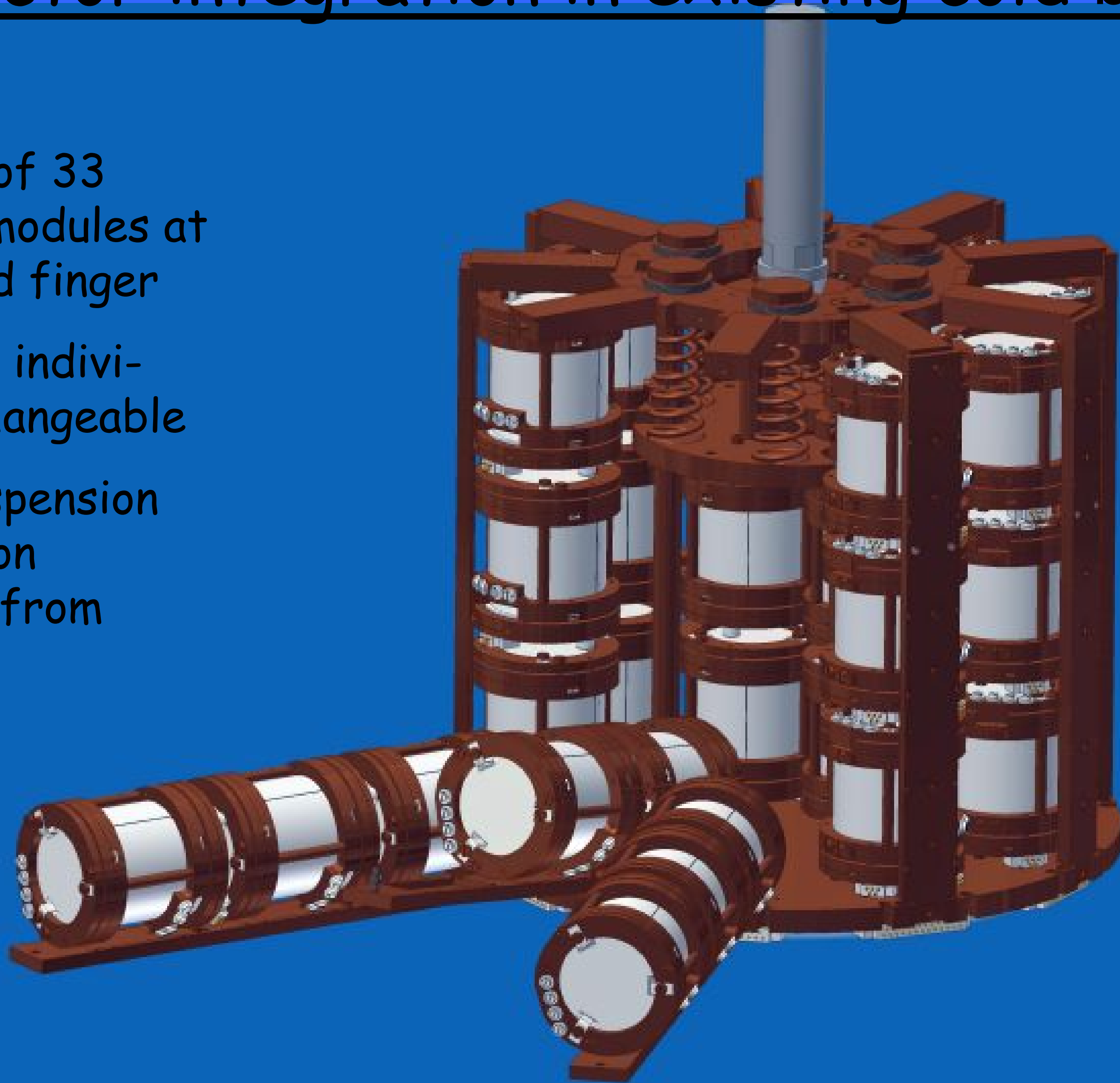


Status of Upgrade

- Read out electronics:
66 SQUIDs for 33 detector modules and DAQ ready
- Neutron shield:
50 cm polyethylen (installation complete)
- Muon veto:
20 plastic scintillator pannels outside Cu/Pb shield and radon box. Analog fiber transmission through Faraday cage (ready)
- Detector integration in cold box and wiring (entering fabrication stage)

Detector integration in existing cold box

- Mounting of 33 detector modules at end of cold finger
- Detectors individually exchangeable
- Spring suspension for vibration decoupling from cryostat.



CRESST Summary

- Two CRESST II prototype detectors have been operated for two months.
- Discrimination threshold (γ/β) well below 10 keV
- Type of recoiling nucleus identified above 12 keV
- Upgrade to 66 readout channels (10 kg target), installation of neutron shield and muon veto complete. Restart end of 2005
- CRESST-II is aiming for a sensitvity of $\sigma<10^{-8}$ pb

Experiments – MSSM Predictions

$\sigma = 10^{-6}$ pb:

~1 event/kg/day

~0.1 now reached

$\sigma = 10^{-8}$ pb:

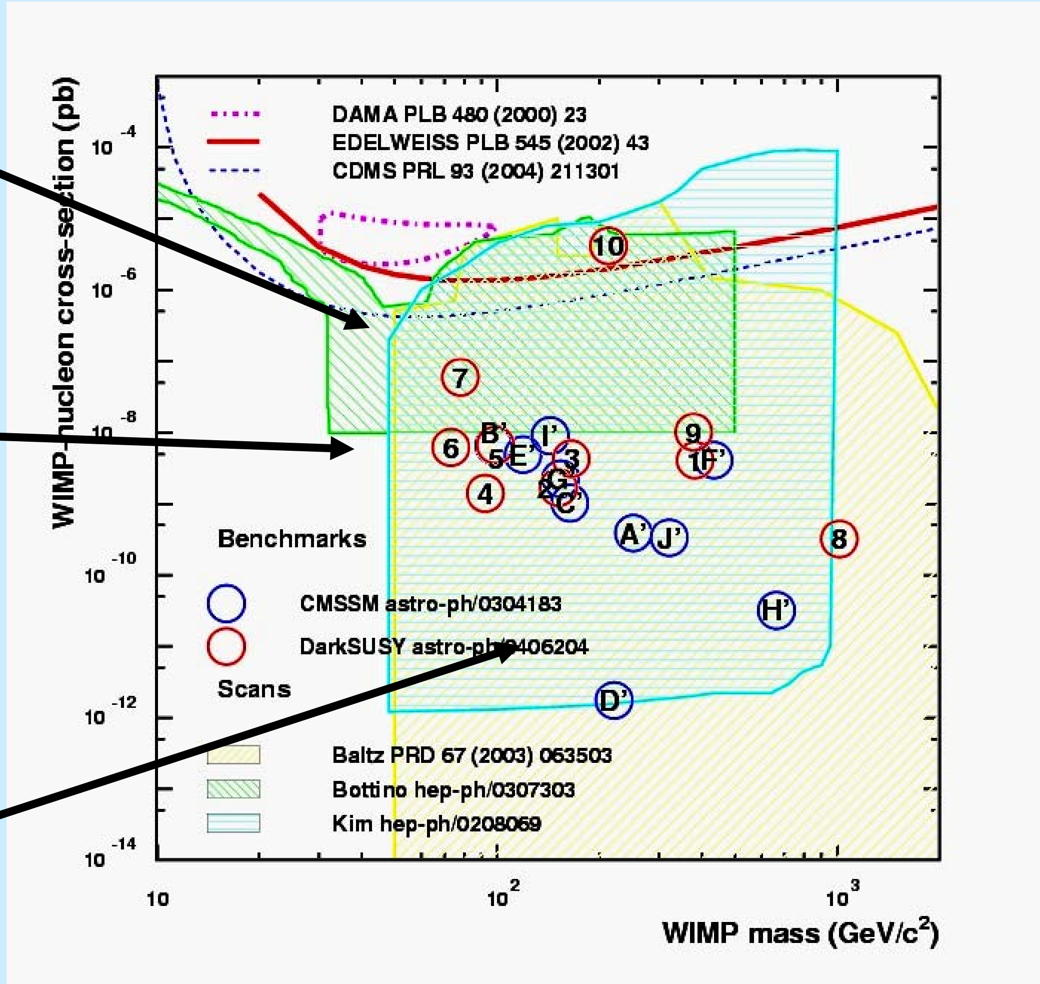
~1 event/kg/year

CDMS-II, CRESST-II and EDELWEISS-II aims

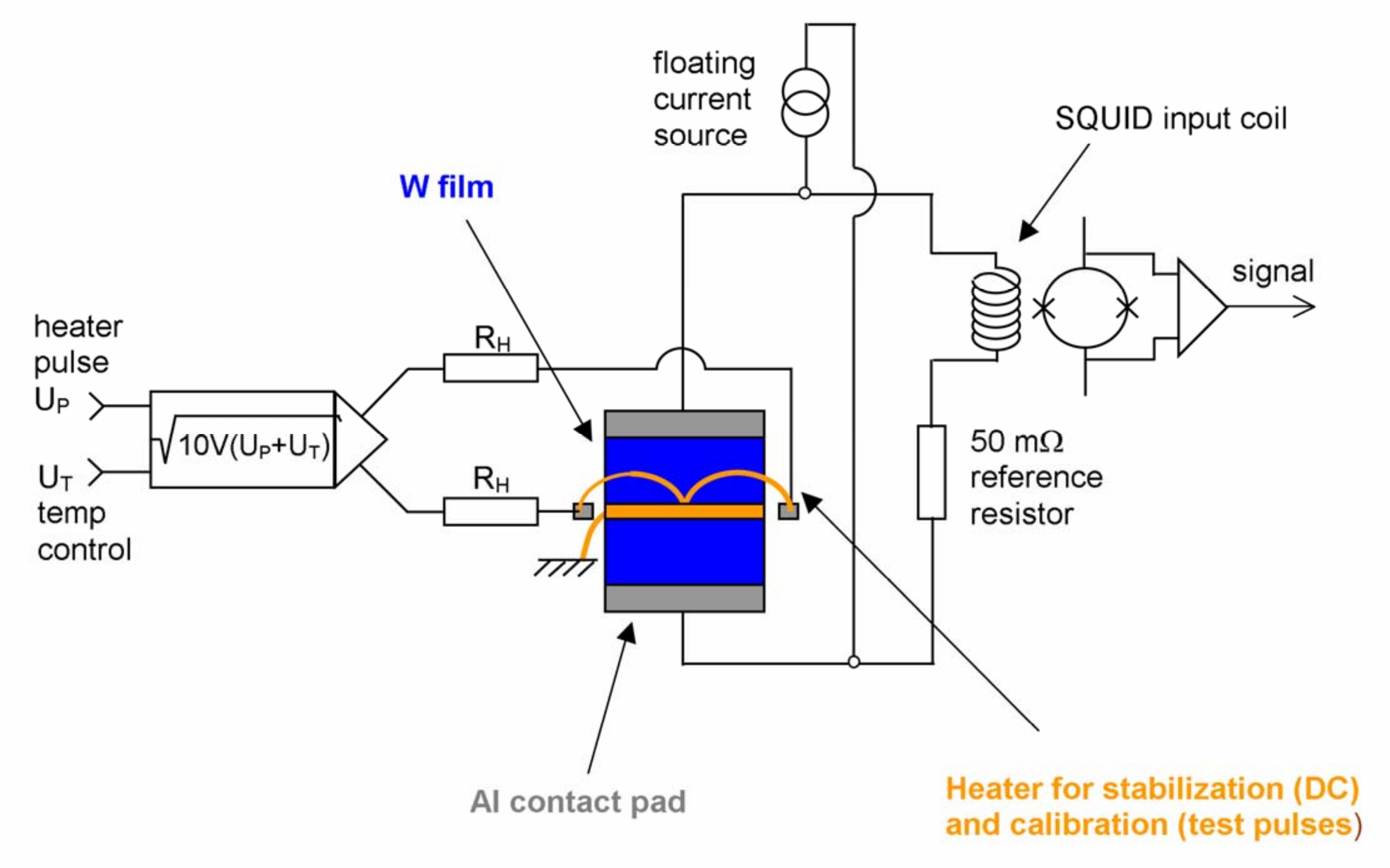
$\sigma = 10^{-11}$ pb:

~1 event/ton/year

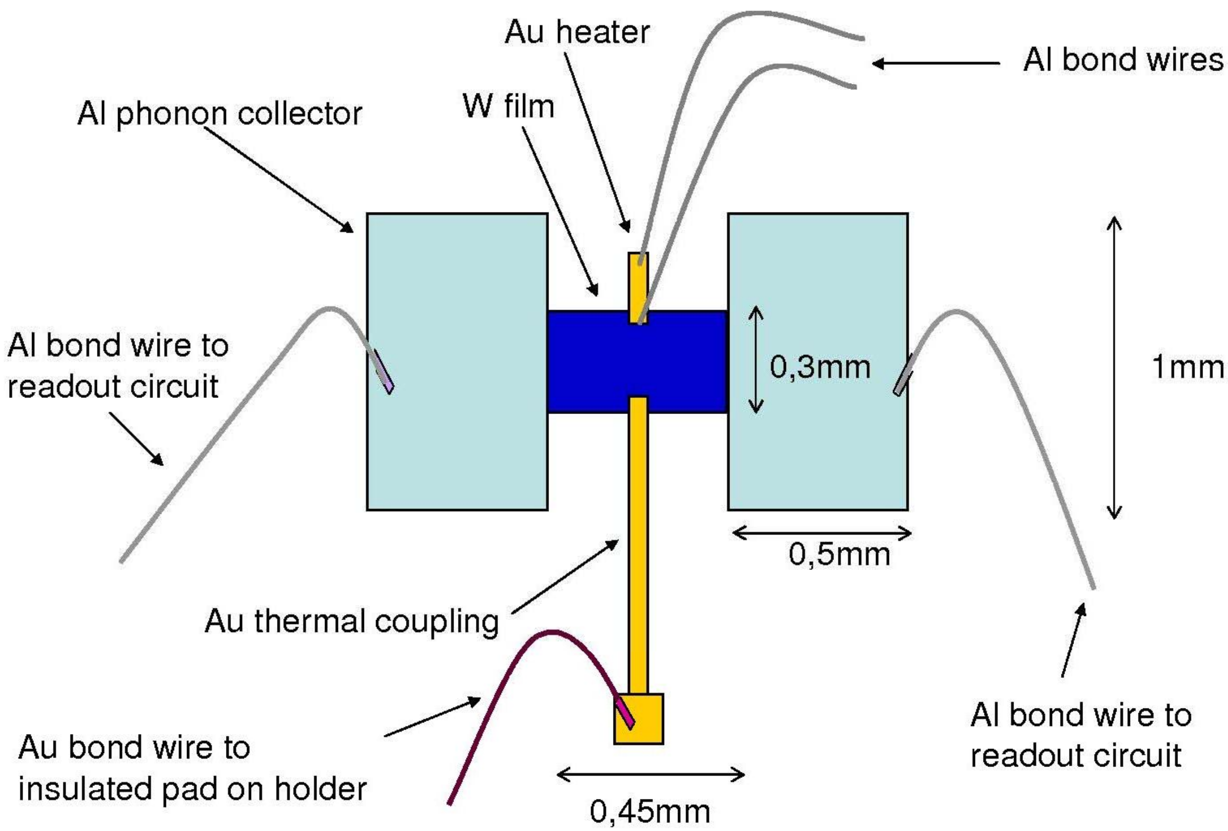
EU : EURECA, ZEPLIN max, ArDM
Non EU :SuperCDMS, XENON, XMASS



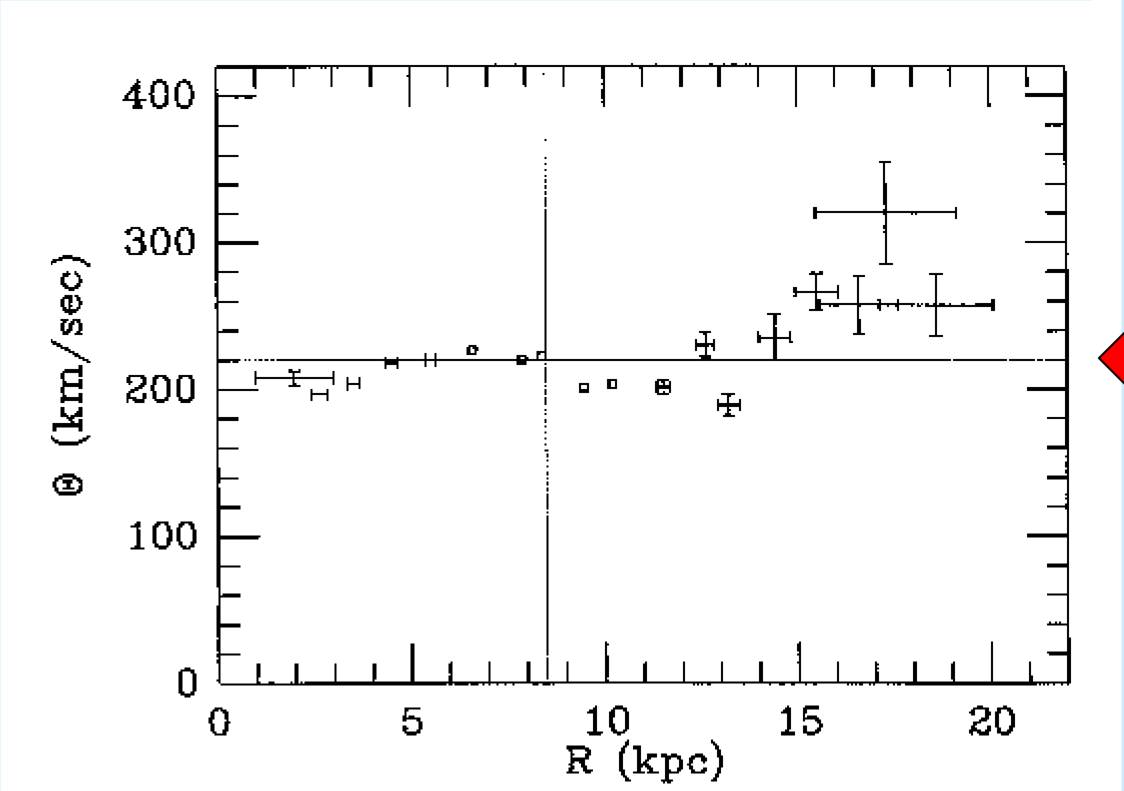
Readout and Heater Circuits



Phonon Sensor on Light Detector



Rotation Curve of our Galaxy



Fich and Tremaine (1991)

Rotation speed of sun

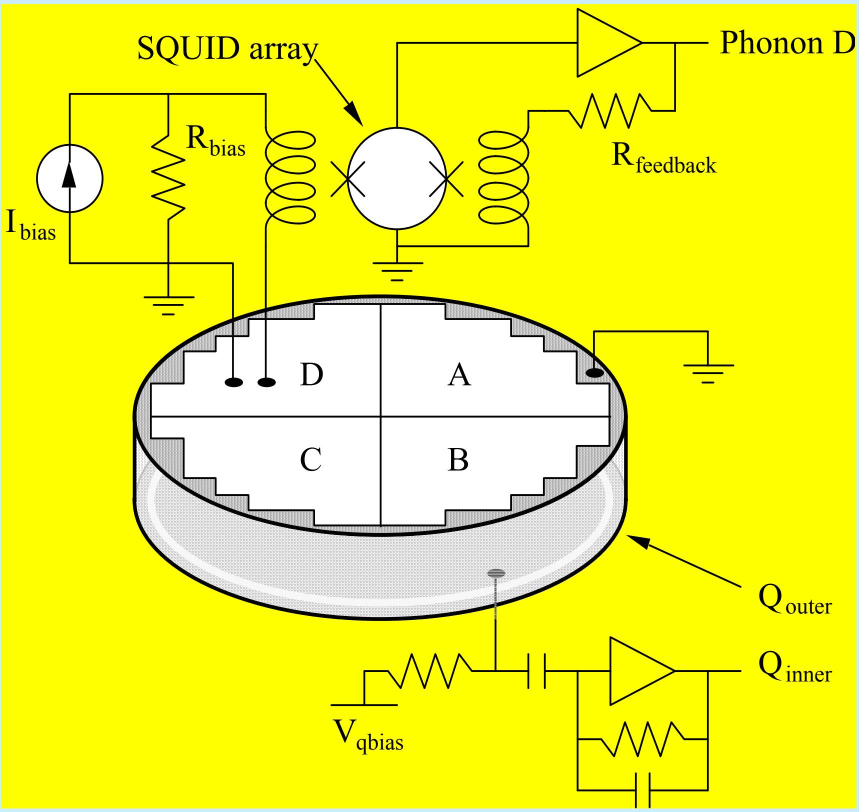
$v_{\odot} \approx$ 220 ... 230 km/h

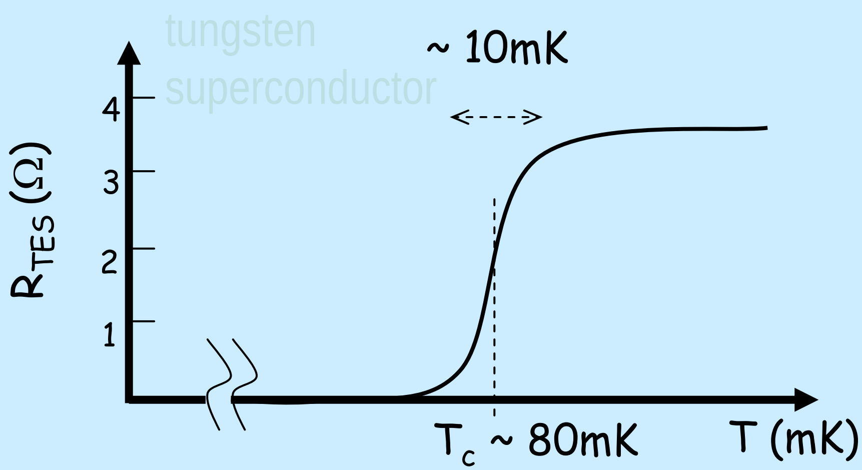
Dark matter density at our position: ρ=0.3 ... 0.5 GeV/cm^3

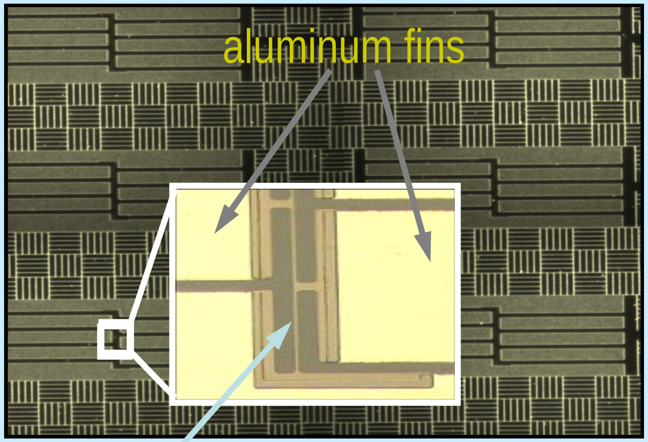
CDMS ZIP Ionization & Phonon Detectors

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







1 μ tungsten

250 g Ge ZIPs, 100g Si ZIPs