Cryogenic Dark Matter Search

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Outline

Motivation

Some WIMP direct detection physics

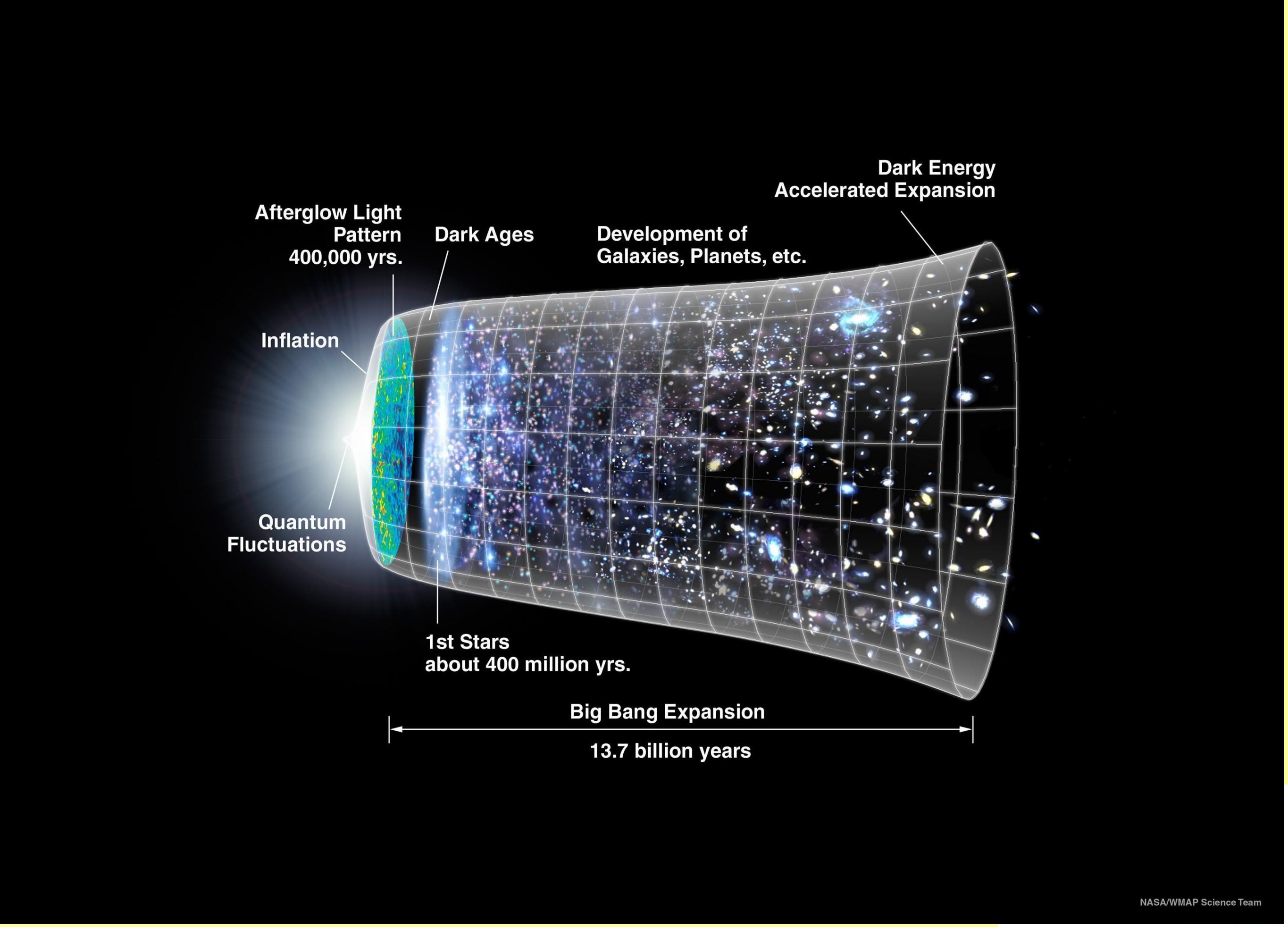
Introducing the experiment

Detection principle

Analysis chain

Physics potential of CDMS

Conclusions



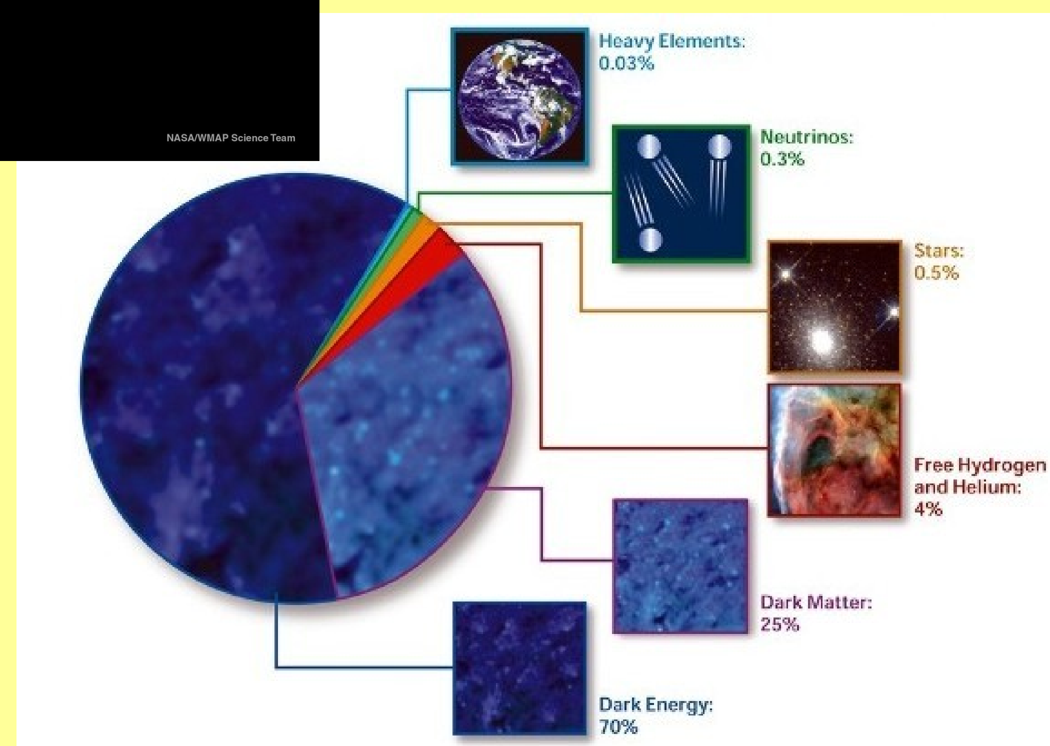
Structure forming needs initail, gravitational seeds.

Strong evidences for Dark Matter from astronomy.

The nature of the dominating part of matter in the universe is unknown.

Extensions of the SM give good candidates for WIMPs.

Maybe something completely different.



Recoil spectra of WIMP-nucleus scattering

$$\frac{dR_{(v_E, v_{esc})}}{dE_R} = \frac{R_0}{E_0 \cdot r} \cdot f(v_{0,} v_E, v_{esc}, E_{0,} r) \cdot F^2(q \cdot r_n)$$

$$R_0 = \frac{2}{\sqrt{\pi}} \cdot \frac{N_0}{A} \cdot \frac{\rho_{WIMP}}{m_{WIMP}} \cdot \sigma_0 \cdot v_0 \qquad E_0 = \frac{1}{2} \cdot m_{WIMP} \cdot v_0^2 \qquad r = \frac{4 \cdot M_T \cdot m_{WIMP}}{(m_{WIMP} + M_T)^2}$$

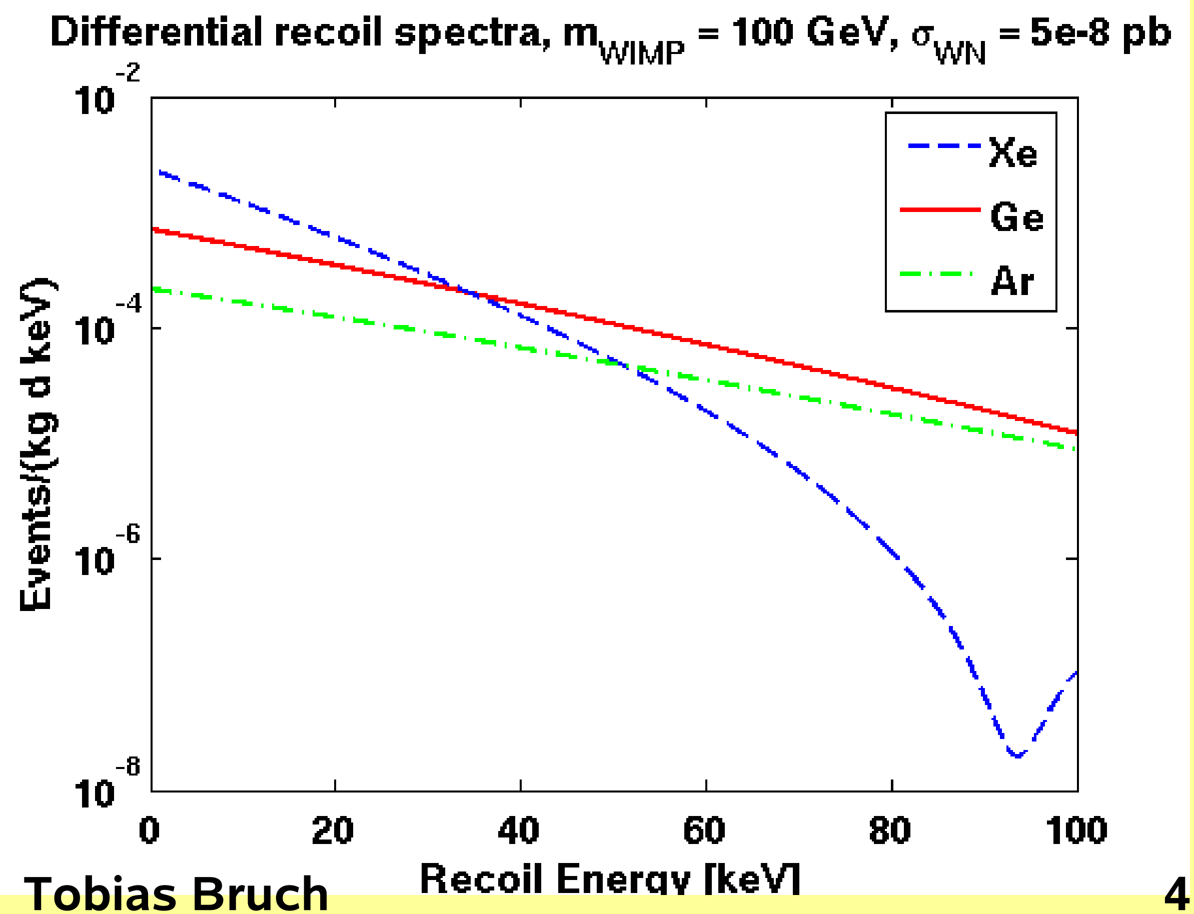
v_0 : mean velocity of WIMPs ~ 220 km/s

v_{esc} : escape velocity of WIMPs ~ 544 km/s

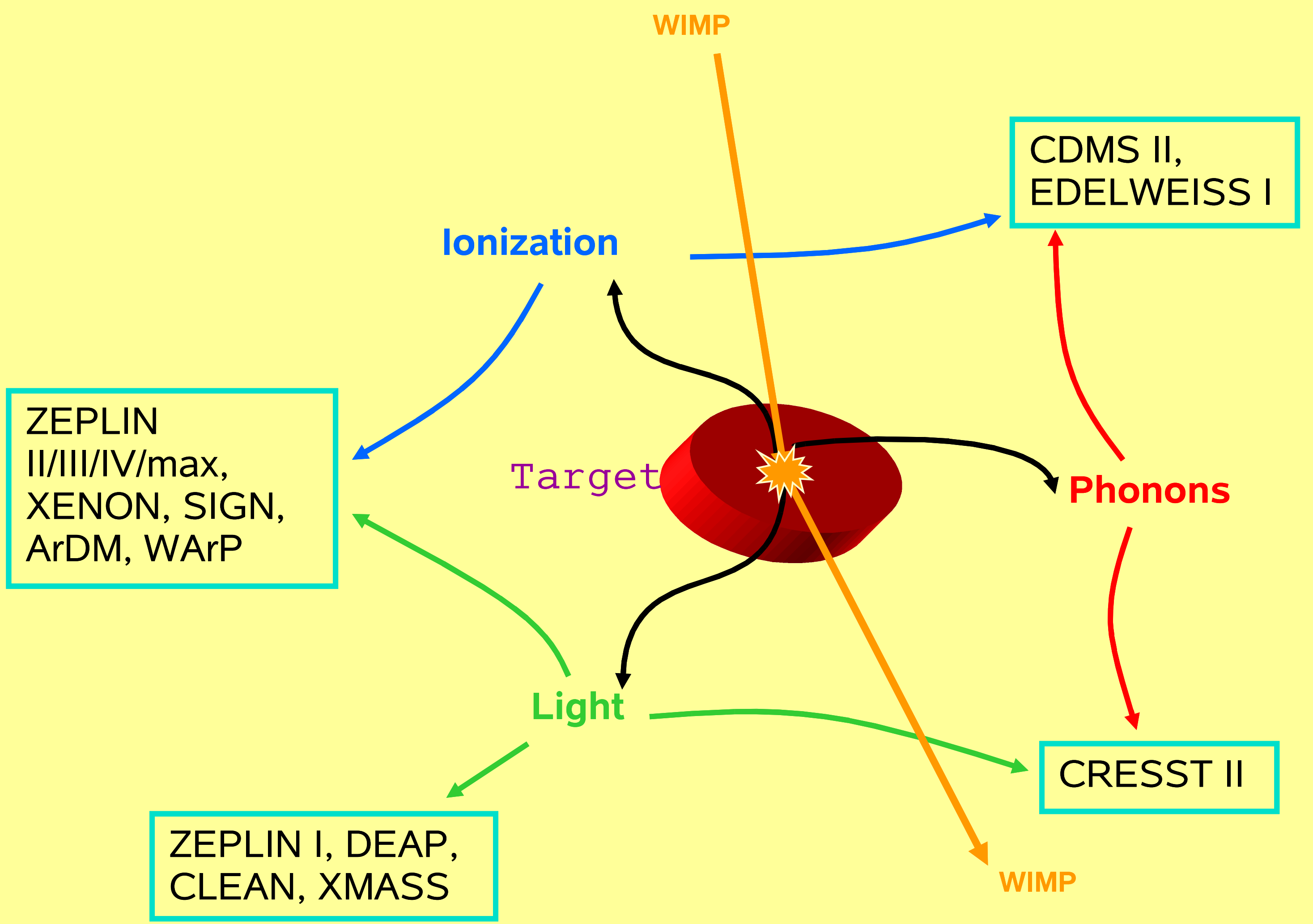
v_E : earth velocity ~ 232 km/s

ρ_{WIMP} : local WIMP density ~ 0.3 GeV/cm^3

σ_0 : WIMP-nucleus crossection, scales with A^2 (SI)



Detection and background rejection techniques



Several channels can be used to discriminate background from signal for low energetic recoils (~ < 100 keV).

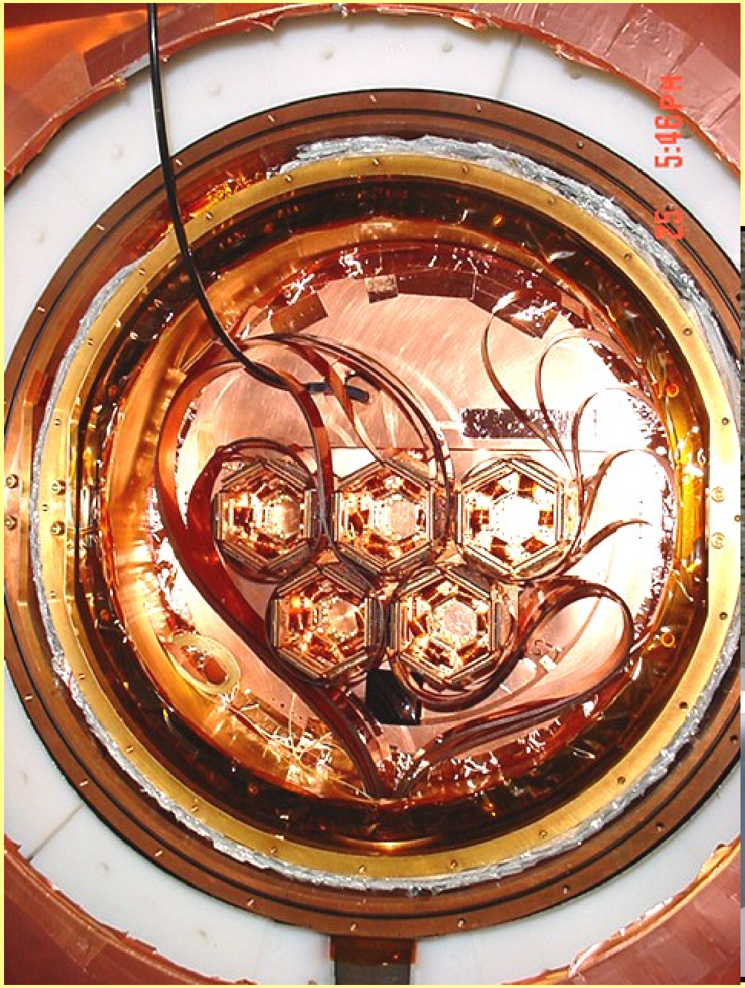
Apart from background discrimination , the minimization of all possible background sources (natural radioactivity, cosmic rays ...) is necessary.

Going underground

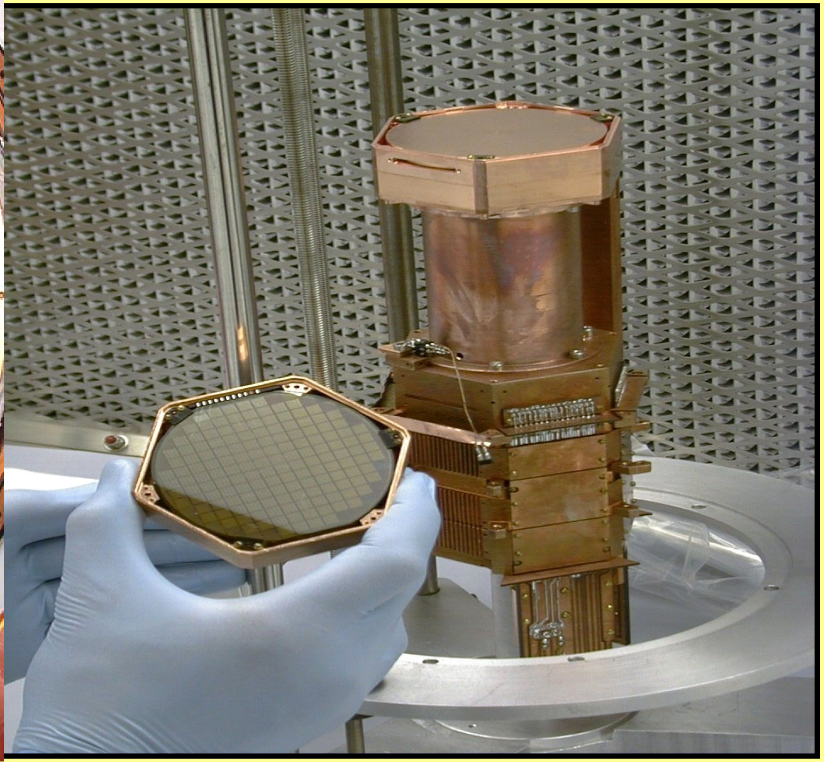
CDMS detectors

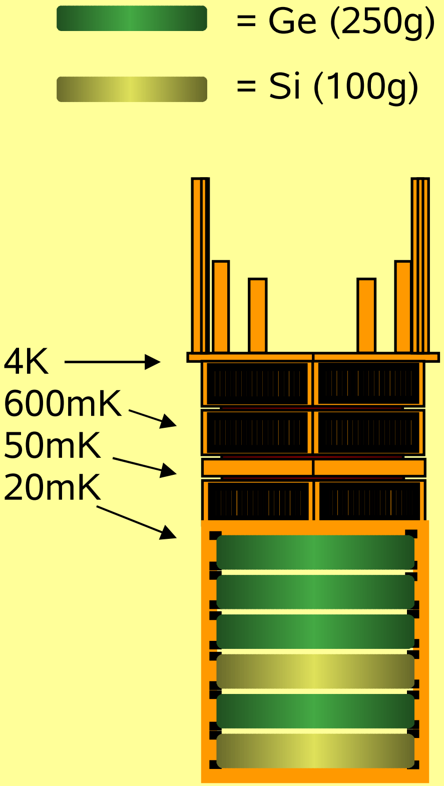
CDMS uses semiconductor (Ge; Si) detectors which measure the ionization and phonon signal of a recoil. These two signals provide an event by event discrimination between background (mainly gammas) and nuclear recoils (expected WIMP signal).

CDMS detectors are operated at cryogenic temperatures (~ 20 mK).

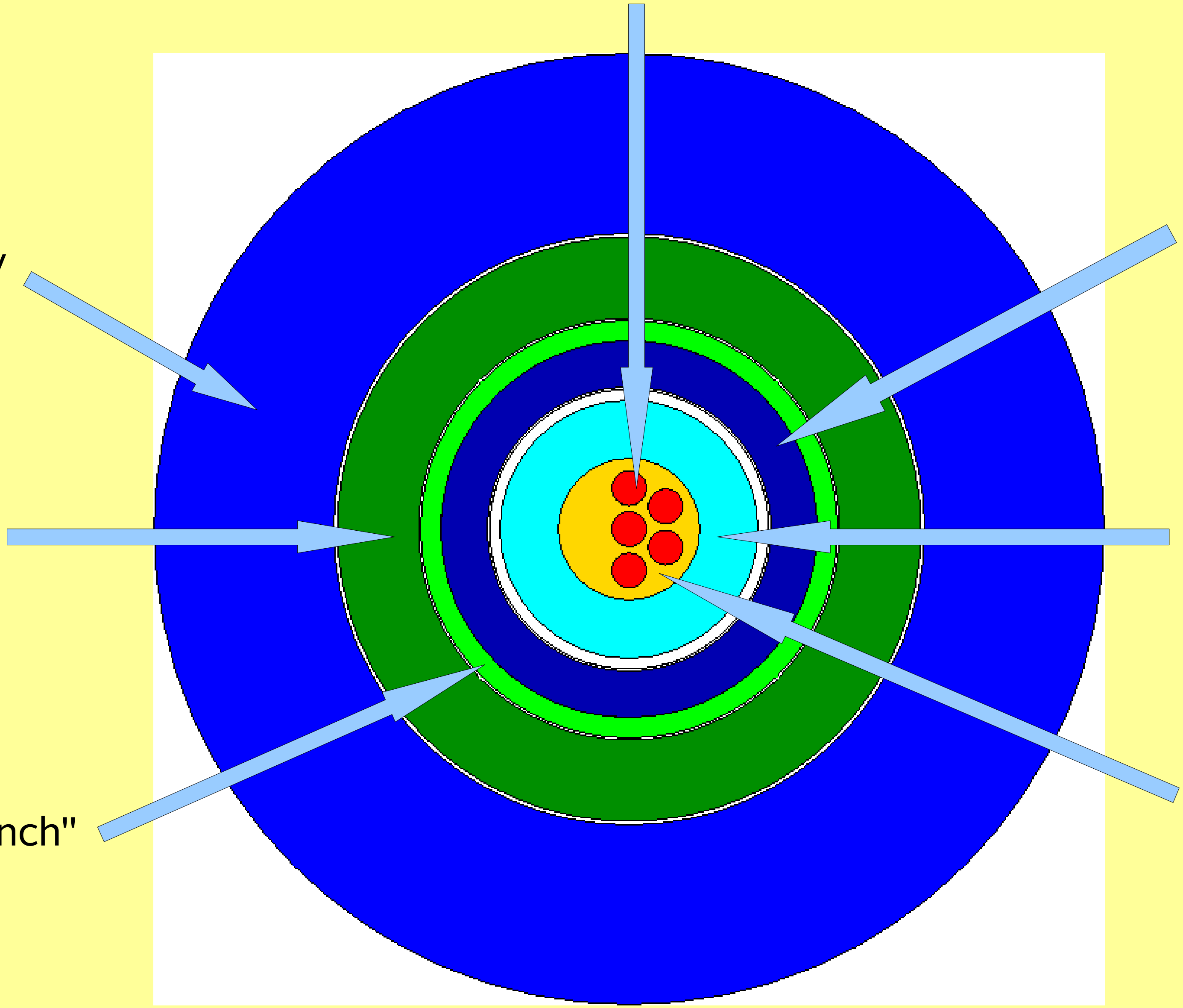


CDMS II now runs 5 towers (each containing 6 1 cm thick detectors).





Shielding of the detectors

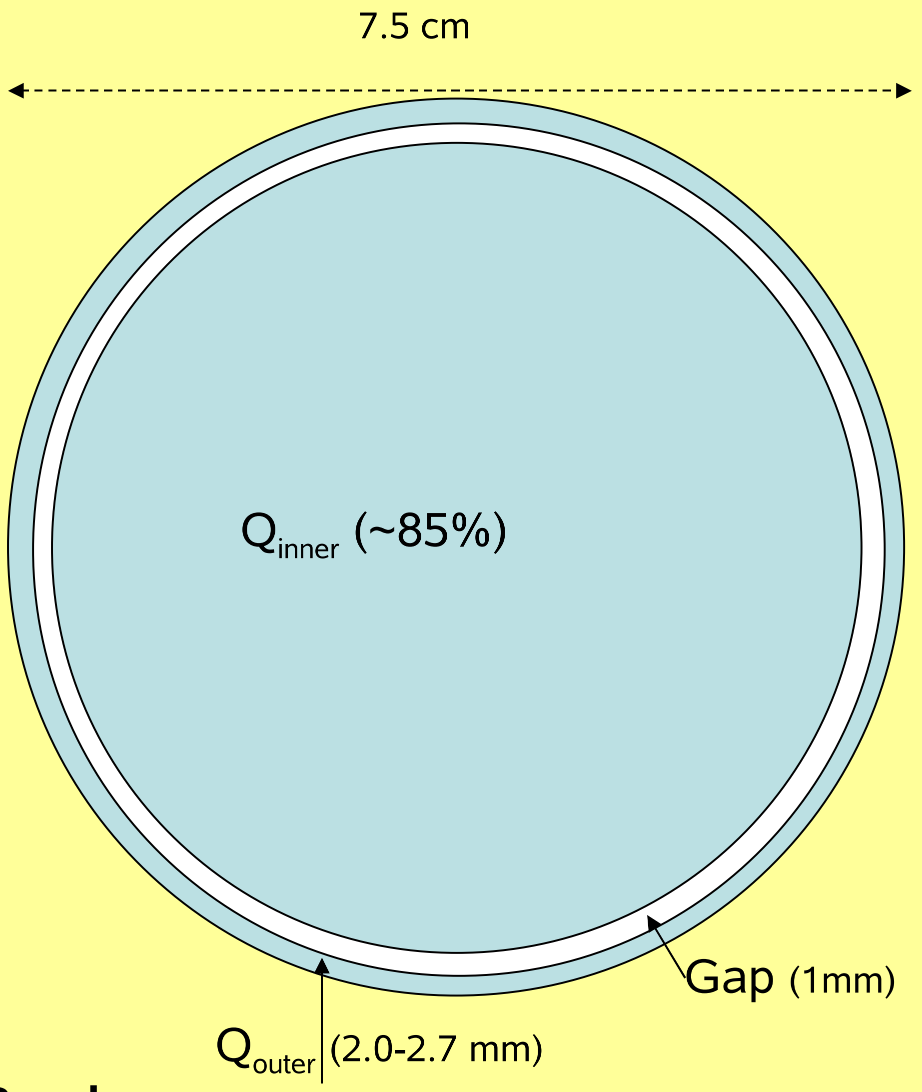


Excellent shielding necessary to suppress external neutron and gamma background.

Ionization Signal

A drift field of -3V/cm (-4V/cm) is applied to the Ge (Si) detectors.

Electron – Hole pairs created by an interaction drift towards the electrodes, inducing charge on the inner (Q_{inner}) and outer (Q_{outer}) electrode .



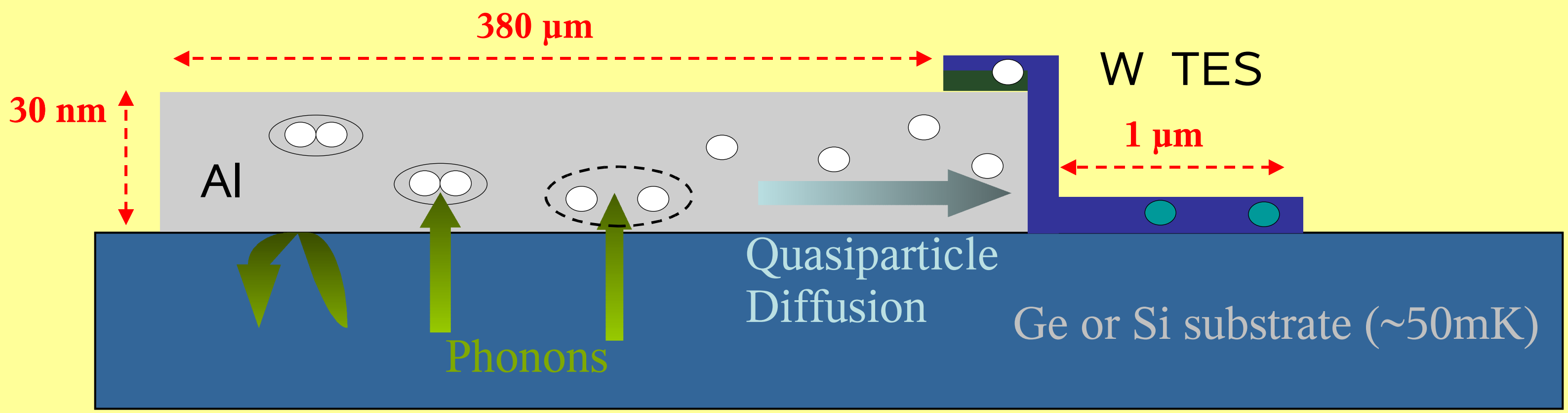
Since interactions at the crystal edges can have an incomplete charge collection, the outer electrode acts as a guard ring.

Events with a significant signal on Q_{outer} are rejected in the analysis.

Q_{outer} constrains our fiducial volume.

Capacitive readout of the signal.

Calorimetry using phonons



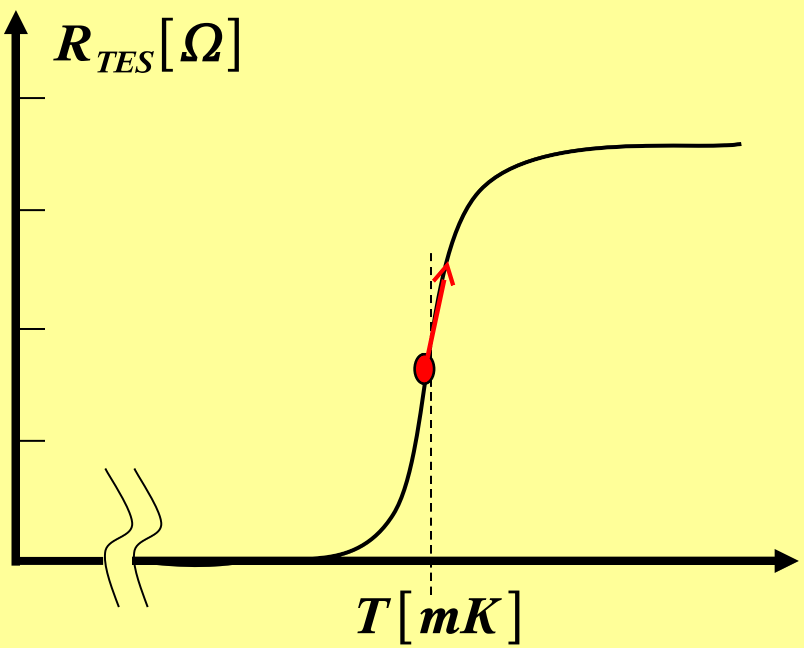
Phonons break Cooper-Pairs in super conducting Al film.

Quasiparticles (e^-) diffuse to the W TES, and deposit their energy →Temperature rises.

Rising temperature → higher resistance → lower current;

For stable operation apply constant Voltage.

$$I = \frac{U_{const}}{R} \qquad P = \frac{U^2_{const}}{R}$$



Signal is a dropdown in current, which is readout by a SQUID.

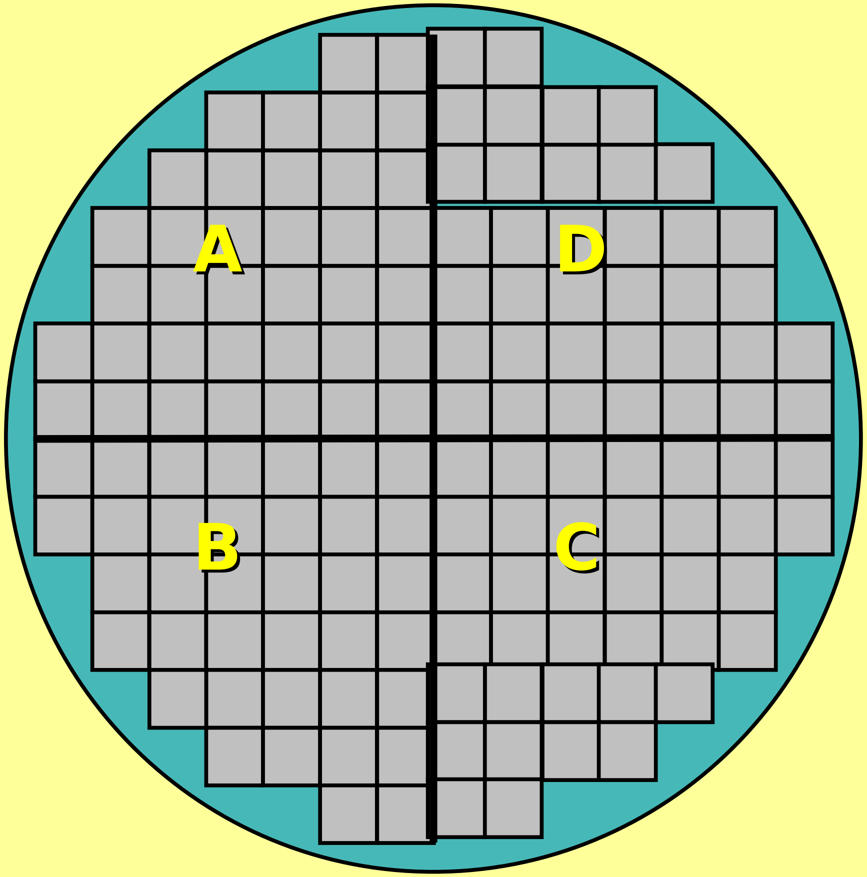
Getting more discrimination power for low yield events by segmented phonon readout

Each quadrant consists of 37 cells with 28 TESs per cell.

Segmented phonon readout useful for localization of an event in x-y plane.

Event location in the x-y plane can be reconstructed in two ways:

- Partition of energy among the four quadrants.
- Relative delay of phonon pulses in four quadrants.



Differences in the timing parameters in severeal quadrants can be used to disrciminate surface events.

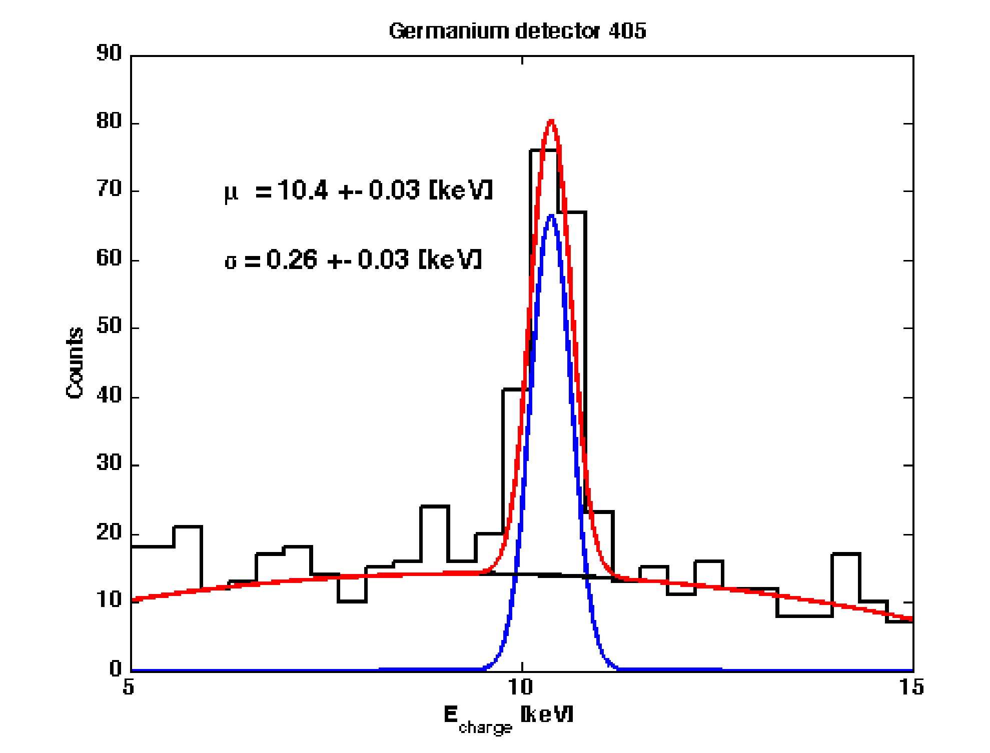
Energy calibration for low energetic events

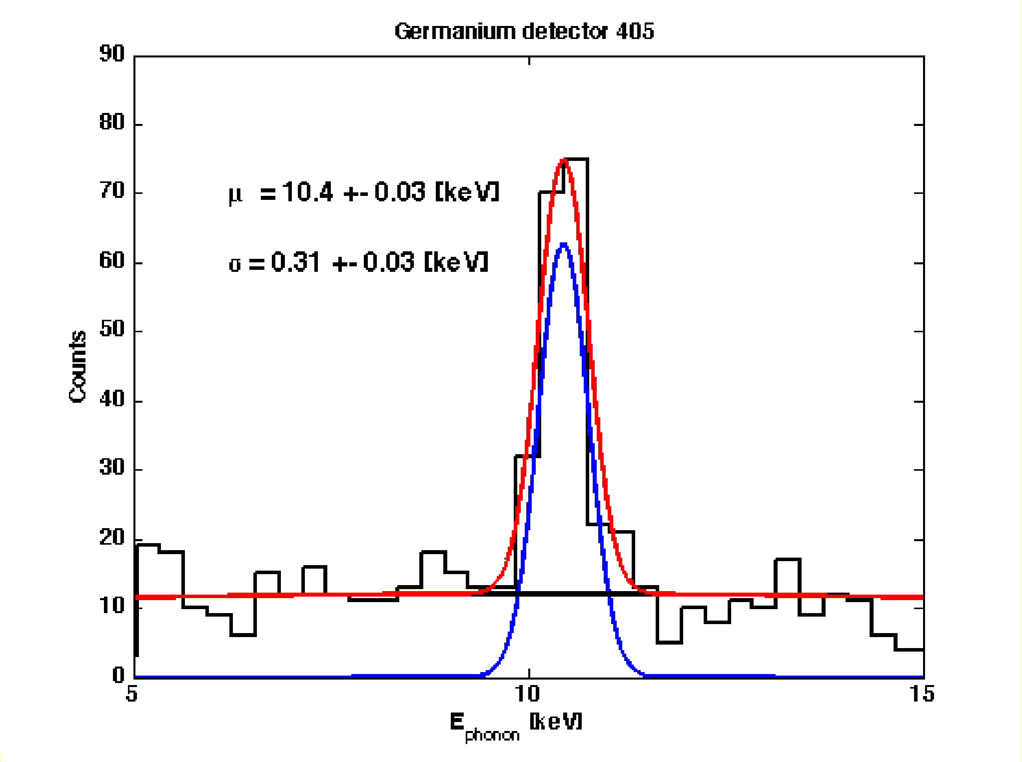
We are using the 10.4 keV line of the neutron activated Ge isotope:

$$^{70}\mathrm{Ge}+n\rightarrow{}^{71}\mathrm{Ge}\rightarrow{}^{71}\mathrm{Ga}+\gamma(10.36\,keV),\tau_{1/2}=11.4\,days$$

to determine the energy resolution of the charge and phonon channel for low energetic recoils.

In both channels we achieve an energy resoultion of: ~3 %





Signal and background interactions

Suppressed ionization signal for nuclear recoils.

True recoil energy of an event:

$$E_{phonon}$$

Yield defined as:

$$y = \frac{E_{charge}}{E_{phonon}}$$

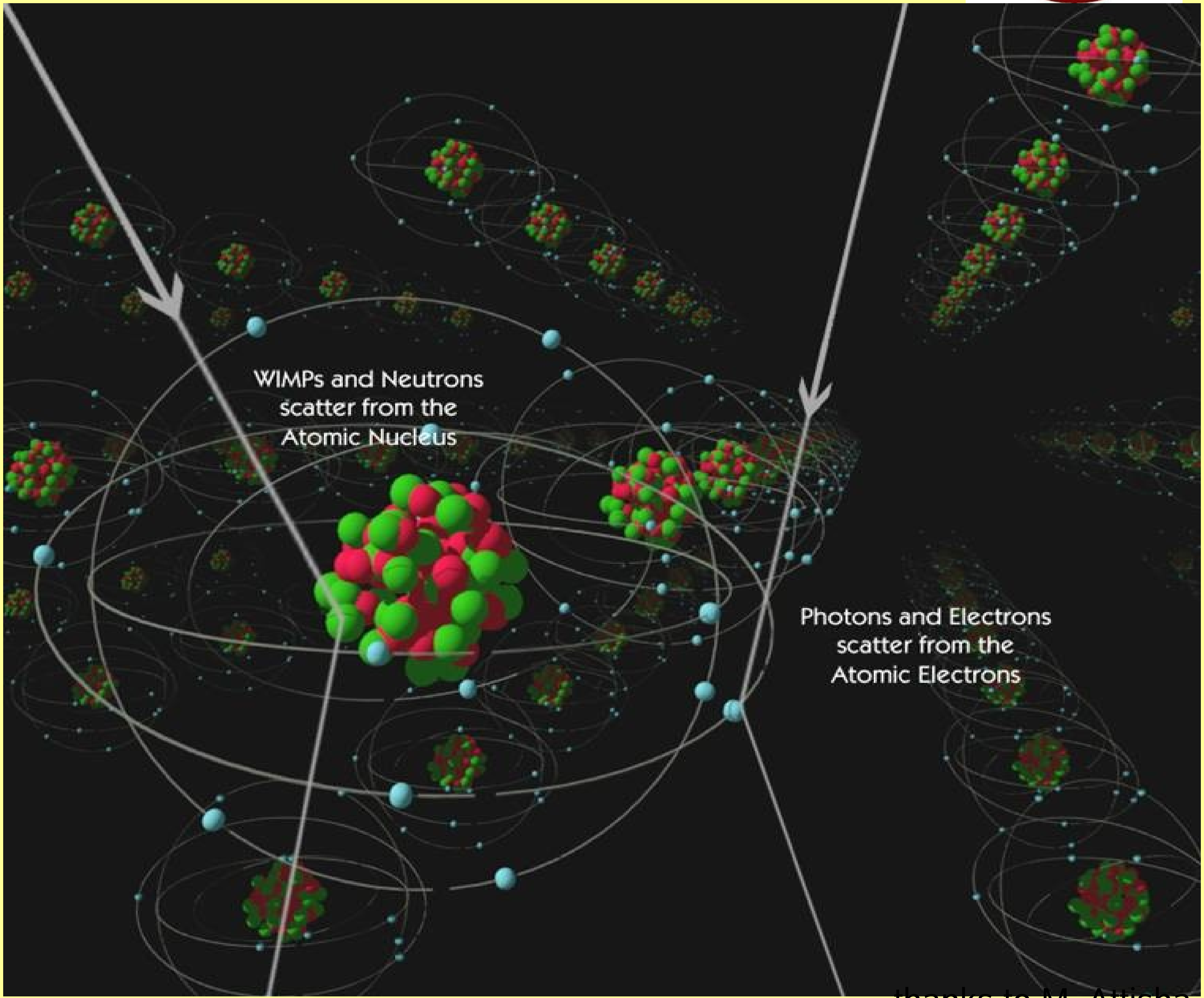
Electron recoil:

$$y = 1$$

Nuclear recoil:

$$y \approx 1/3$$

Yield is our main disrimination quantity.



thanks to M. Attisha

Analysis chain

Blind WIMP Search data

All interesting events are cut out from the data to ensure unbiased cut definitions

Select good WIMP Search runs

Define fiducial volume

Outer electrode signal is used to select events in the bulk region of the detectors

Define gamma and nuclear recoil band

Energy dependence of yield discriminator and signal region definition.

Use timing information from phonon pulses to get rid of background

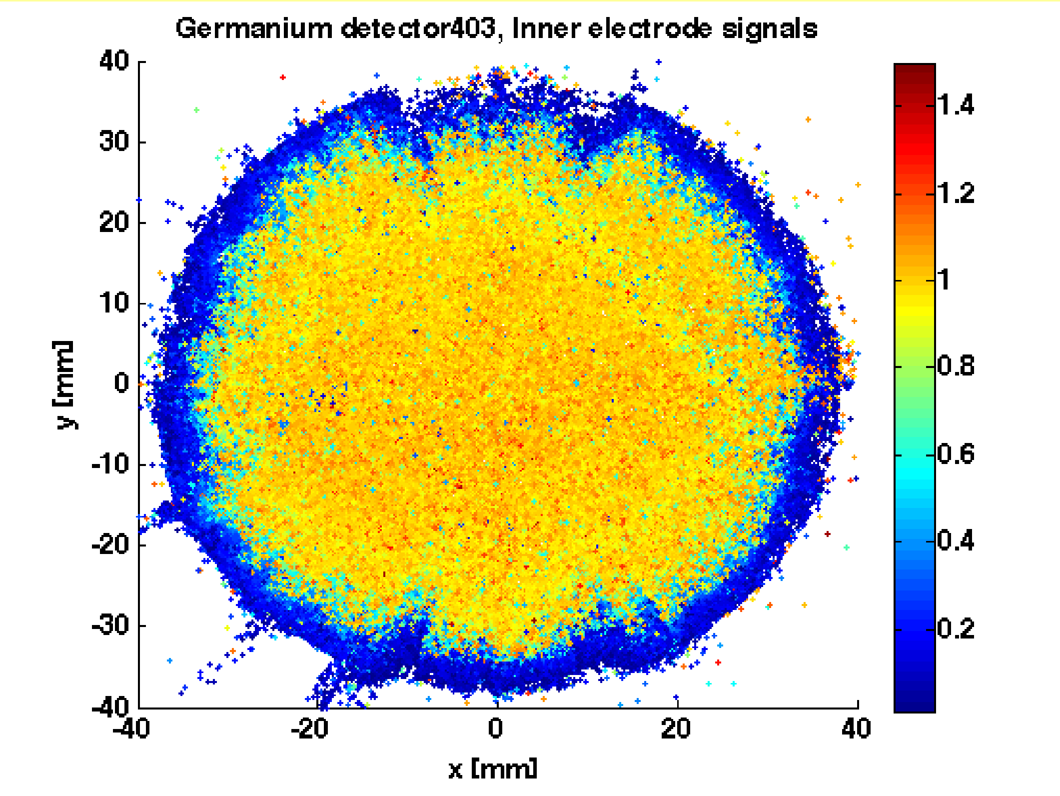
The timing properties of the phonon signal can be used to get rid of low yield events

Freeze cuts and calculate efficencies

Cuts are freezed and efficencies of the cuts are calculated before unblinding.

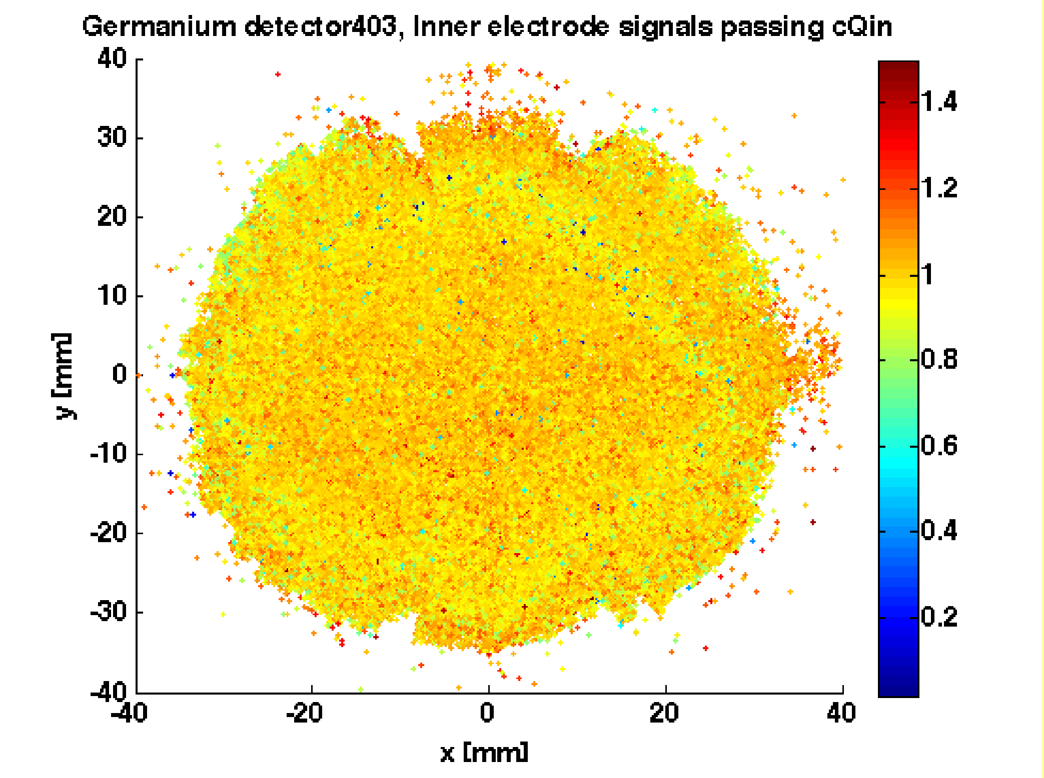
Unblind WIMP Search data and see what is left after applying selection cuts

Inner-electrode cut



The outer electrode signals can be used to select events which are in the bulk region of our detectors.

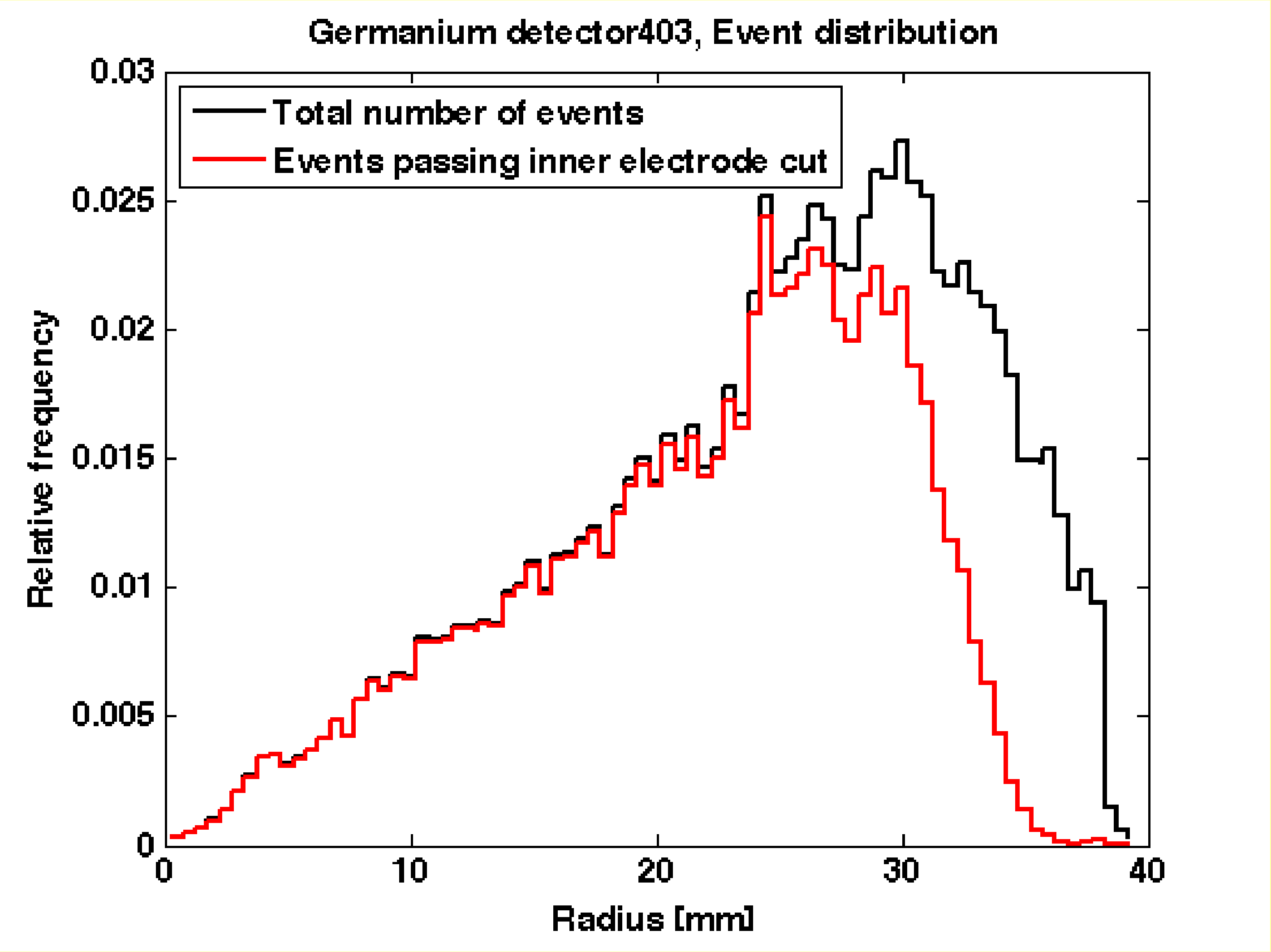
Incomplete charge collection for events at the crystal edges, could mimic nuclear recoils.



Complete charge collection for the majority of bulk events.

We will focus on bulk events with inclompete charge collection later.

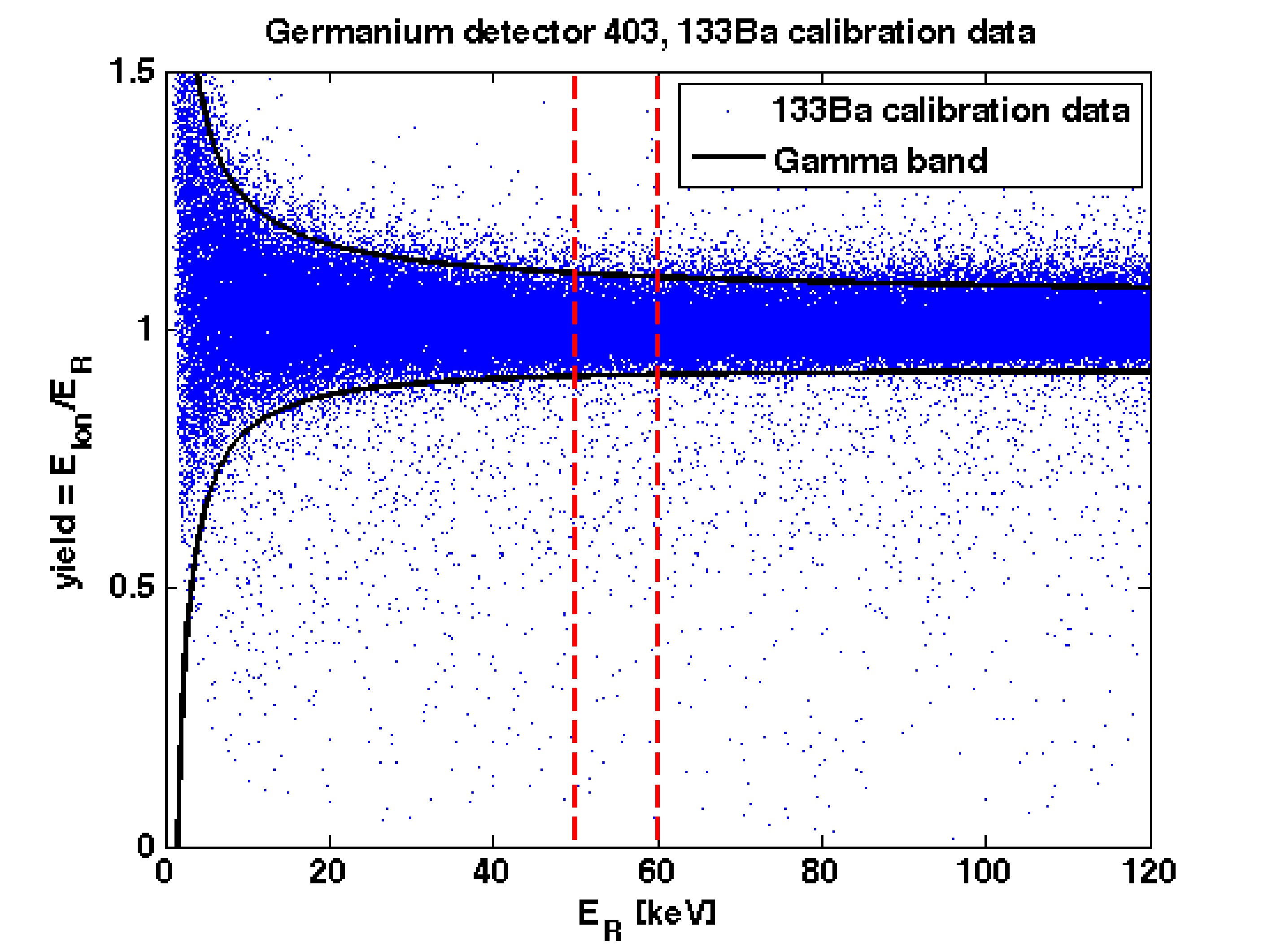
Radial distribution of 133Ba calibration events



No sharp cutoff through inner electrode cut.

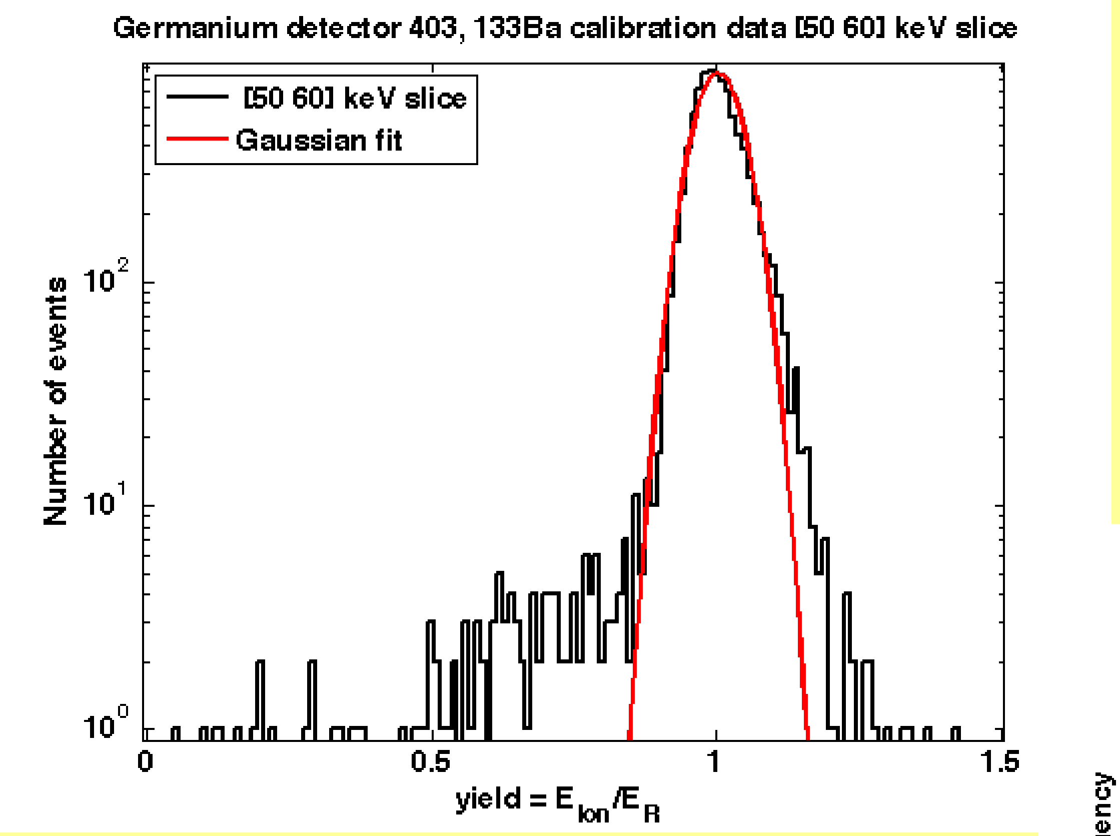
Fiducial volume is determined by the efficency of the inner electrode cut applied to 252 Cf calibrations.

Constructing the gamma-band



The gamma band defines the region of electron recoils and is constructed by 133Ba calibrations.

Gaussanity and low-yield events

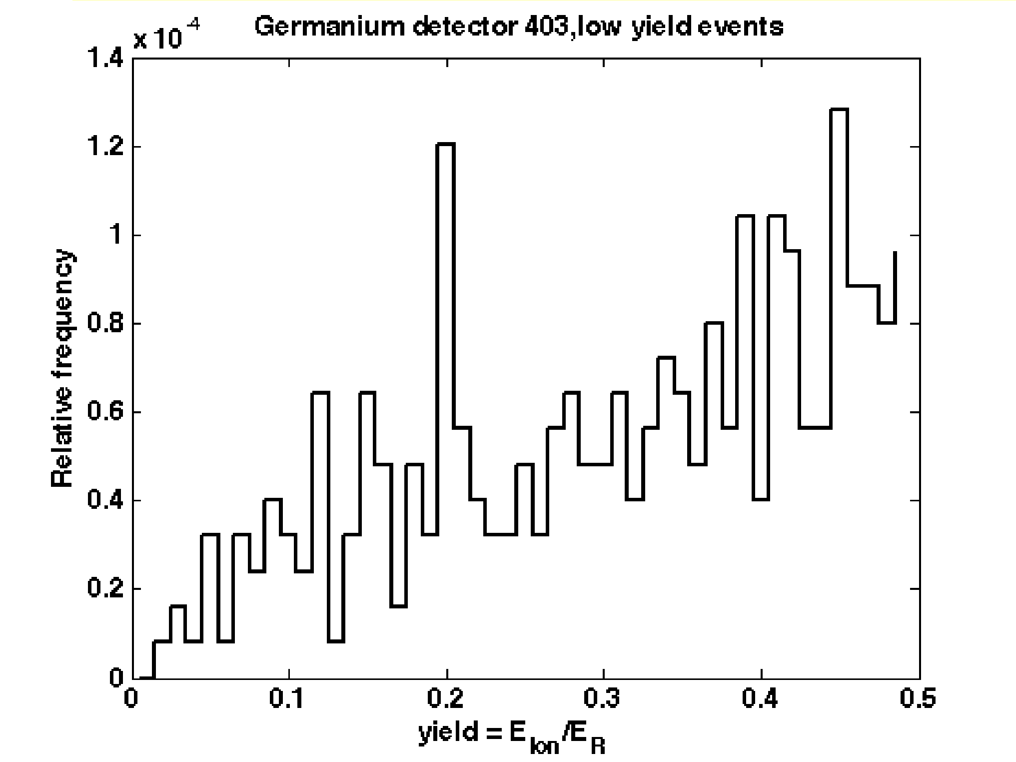


The mean and width of the gamma band is determined by fitting a gaussian to the data.

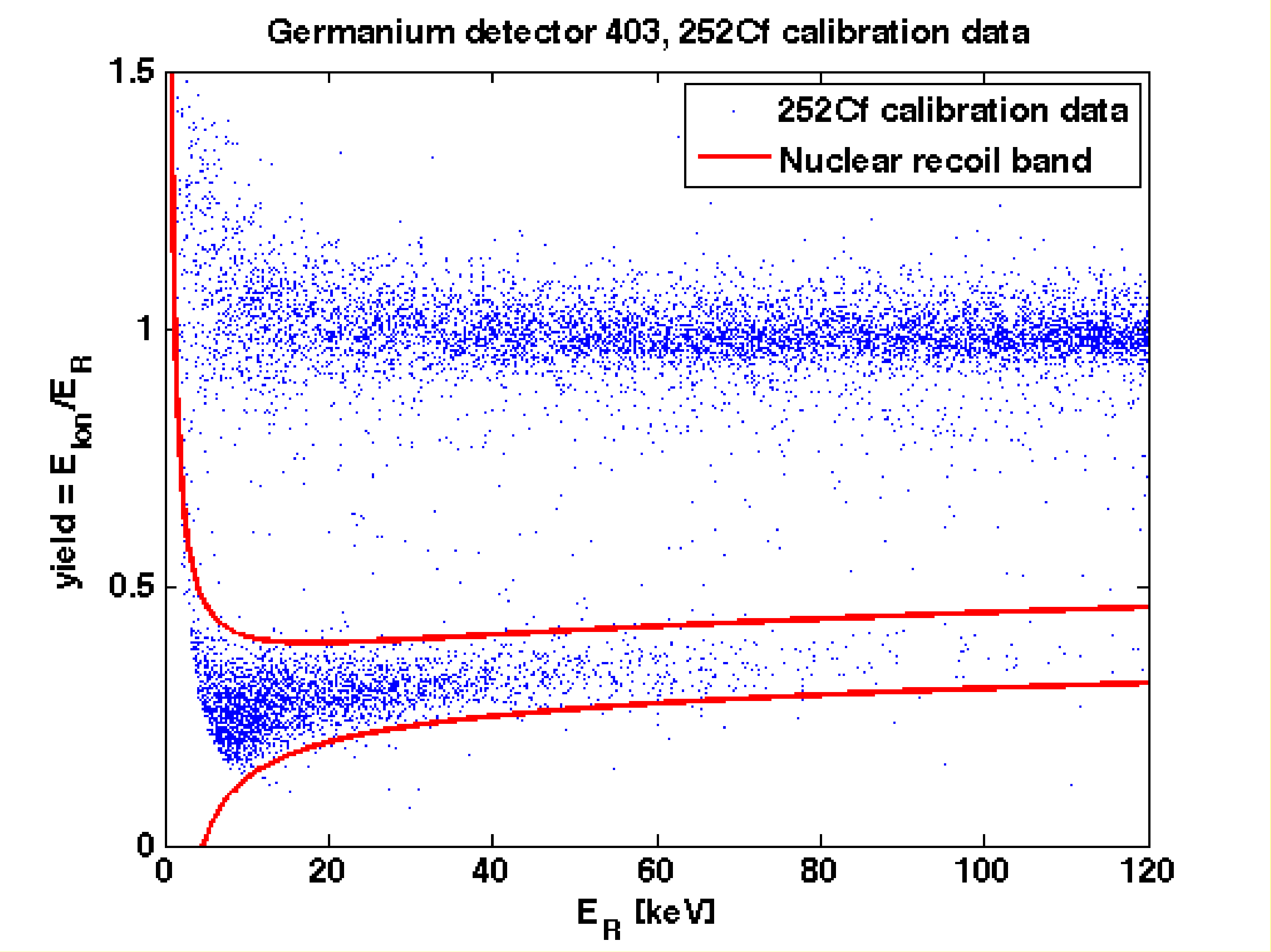
The non gaussian outliers are not considerd in the definition of the band.

Non-gaussian outliers are rare but they are our main background.

We will deal with these low yield events later in the analysis.



Defining the nuclear-recoil band

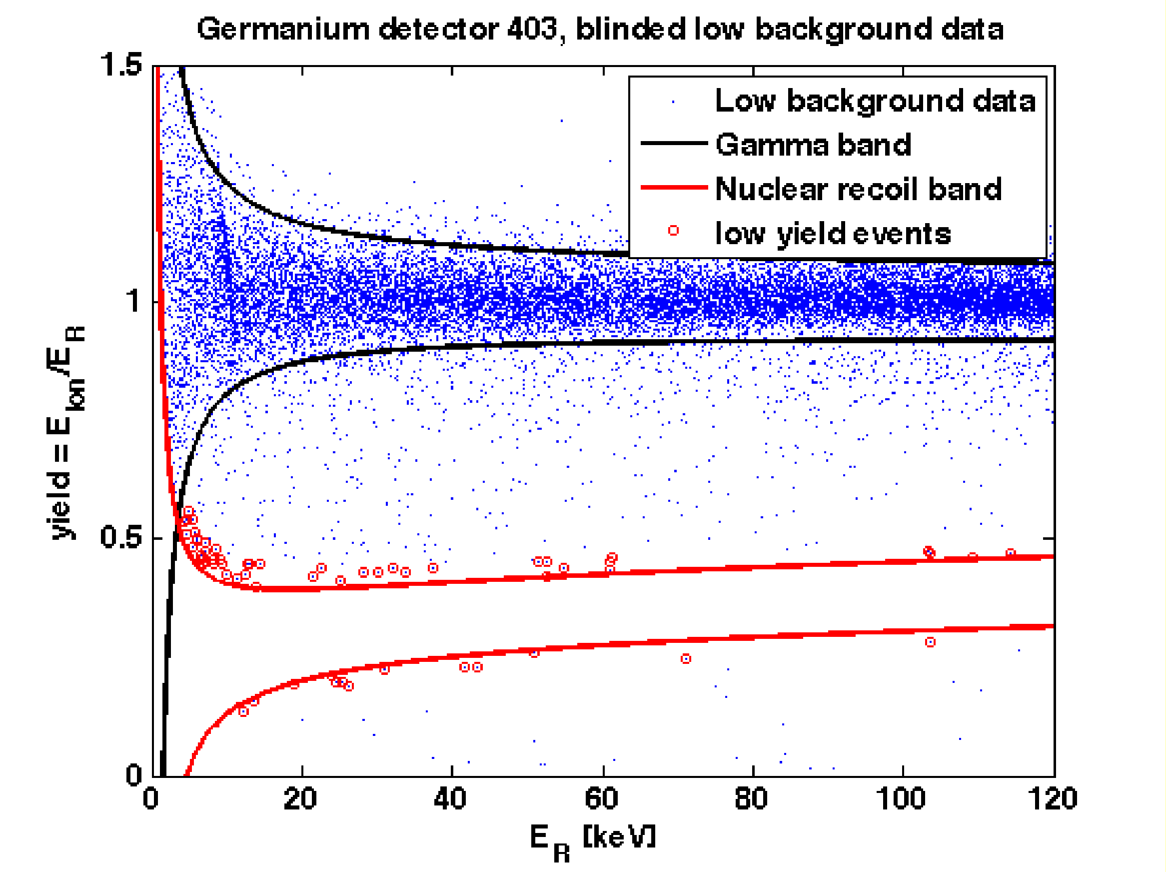


The nuclear recoil band is defined the same way as the gamma band, by using 252 Cf calibrations

Since WIMPs are expected to give nuclear recoils, the 2σ nuclear recoil band defines our signal region.

First look at blinded low background WIMP-Search data

The analysis of the WIMP search data is performed „blind“ (there are no events in the Signal region during the analysis). This ensures a non biased definition of selection cuts.



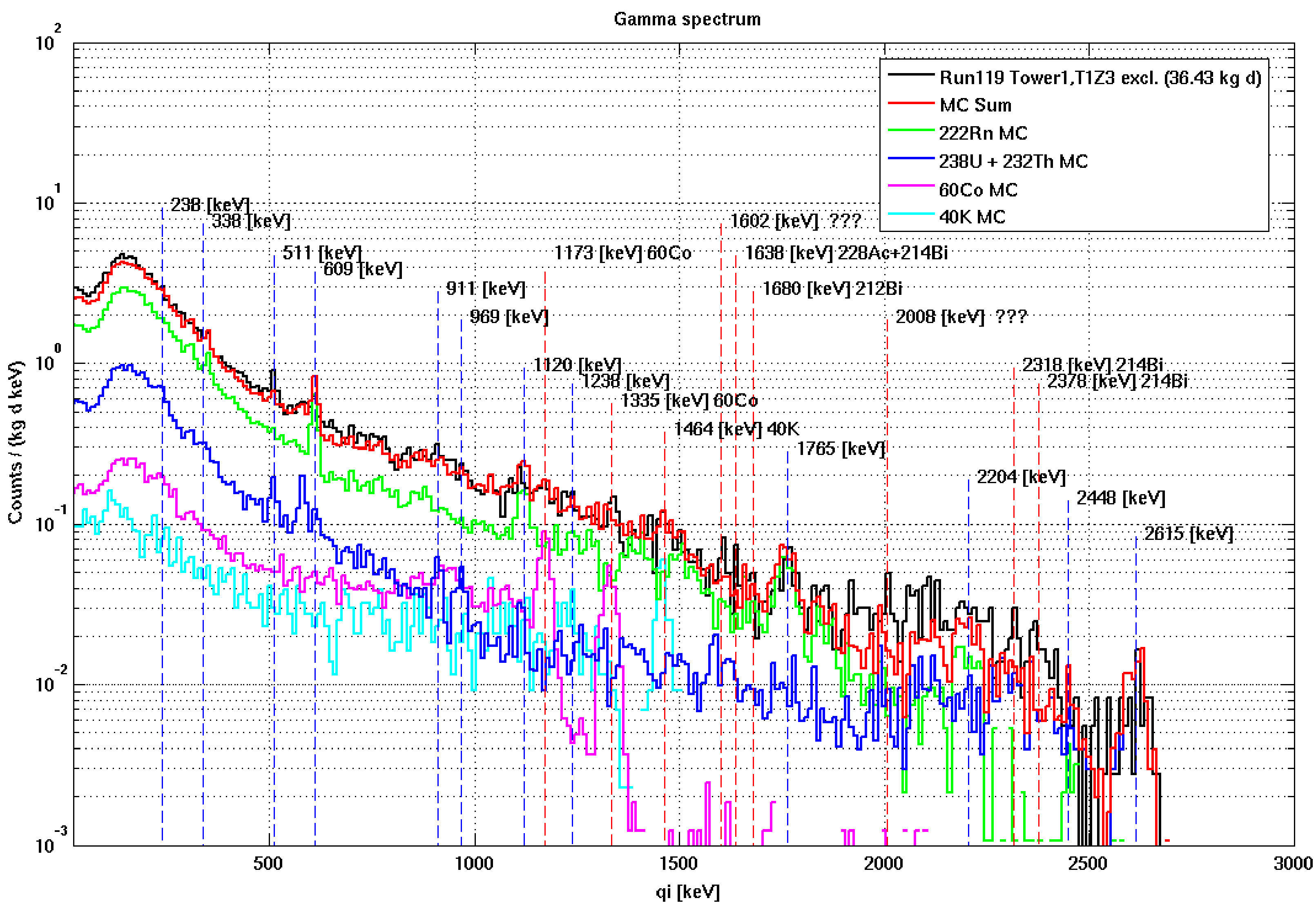
Since surface events suffer from back – diffusion of the charge carriers, they do have an incomplete charge collection.

Incomplete charge collection lowers the yield discriminator of these events. They leak into the signal region, and mimic nuclear recoils.

Low yield events are our main and most dangerous background.

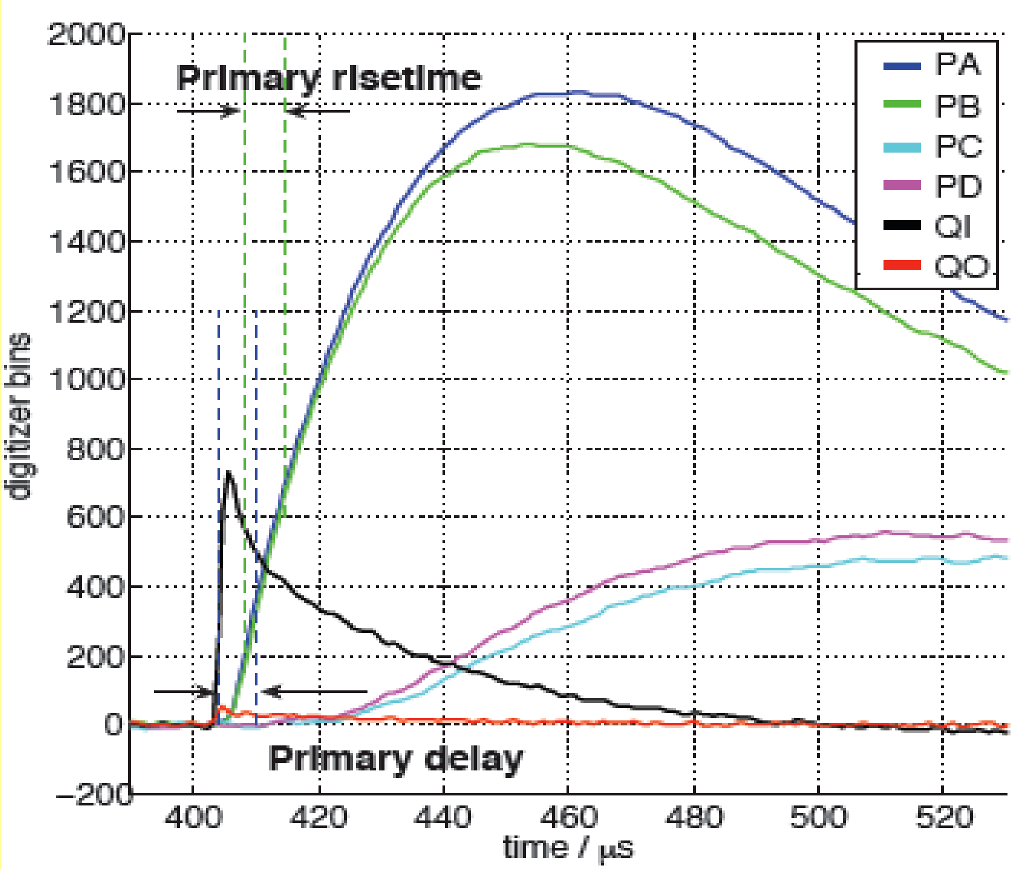
Discrimination of these events is achieved by using timing information of the phonon signals.

Understanding the origin of our background

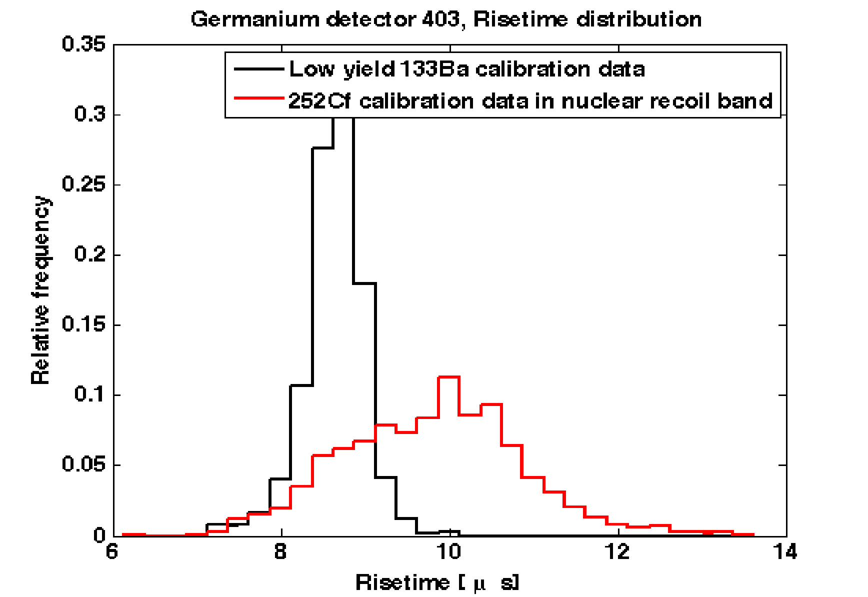


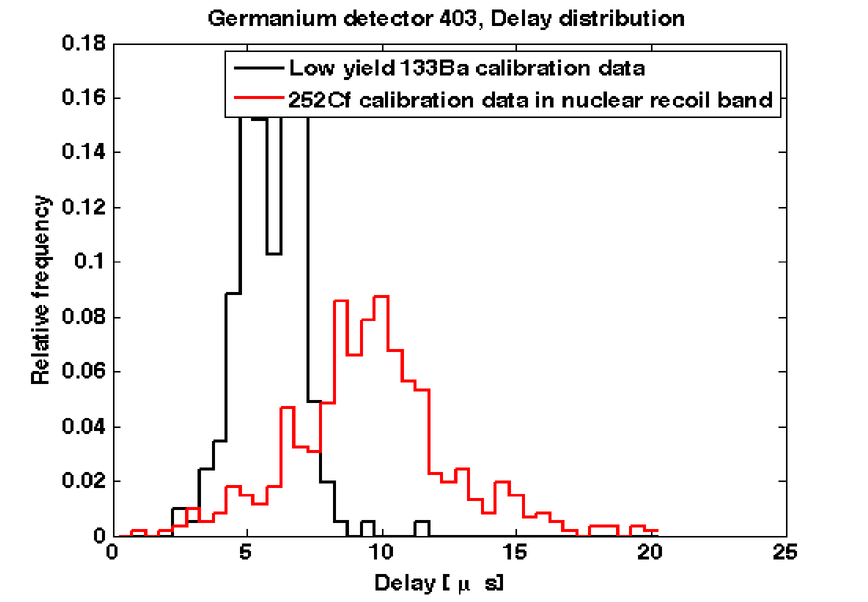
Natural radioactivity of our materials is causing our gamma background. MC simulations of known background sources matches the observed spectra very well.

A closer look at low yield events and differences between surface events and nuclear recoils



thanks to J. Filippini

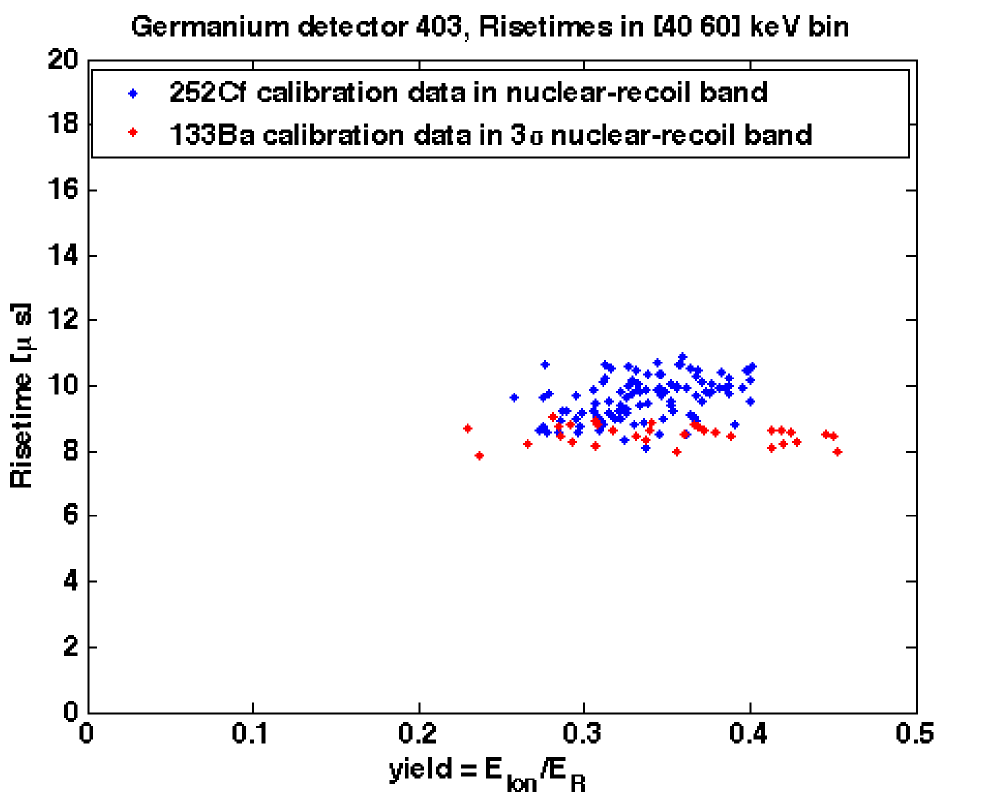




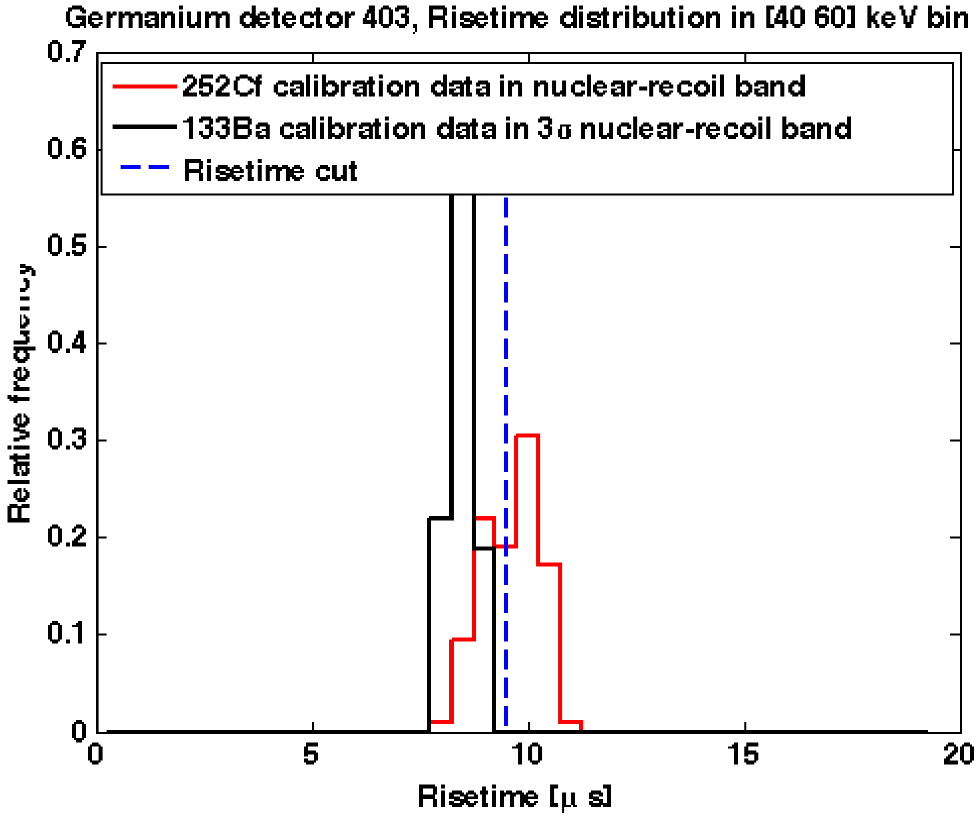
Surface events are faster in timing than bulk nuclear recoils.

Timing is a powerful discriminator, used to get rid of low yield events, providing a **background free** signal region.

Risetime of the phonon signal

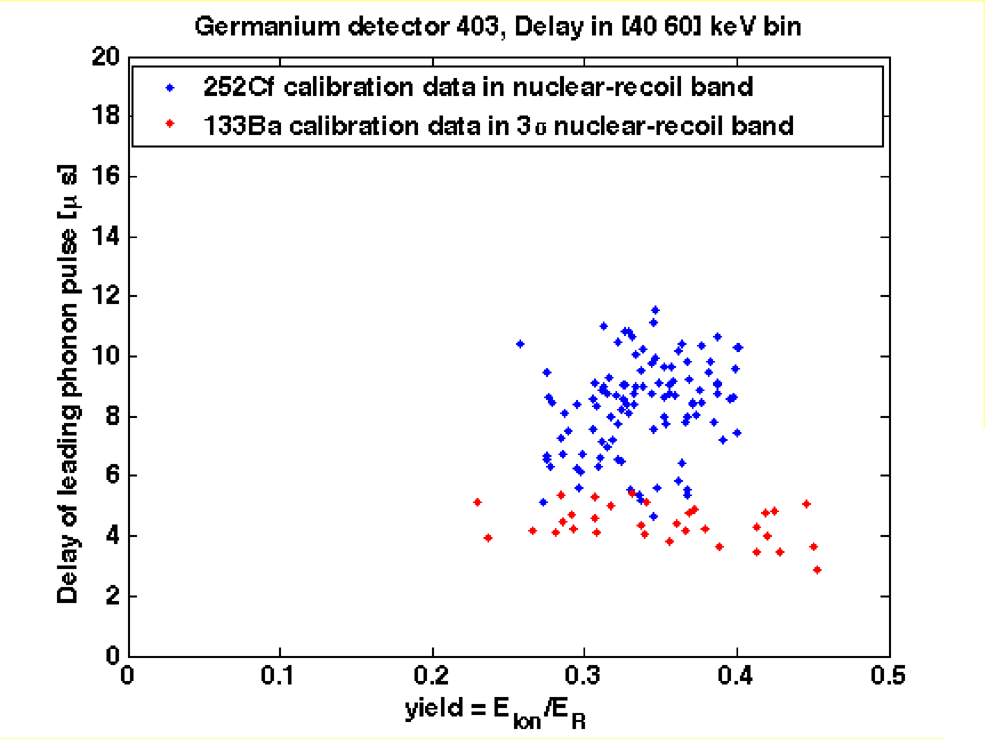


Even in the timing properties there are some gamma (beta) recoils which look like nuclear recoils.

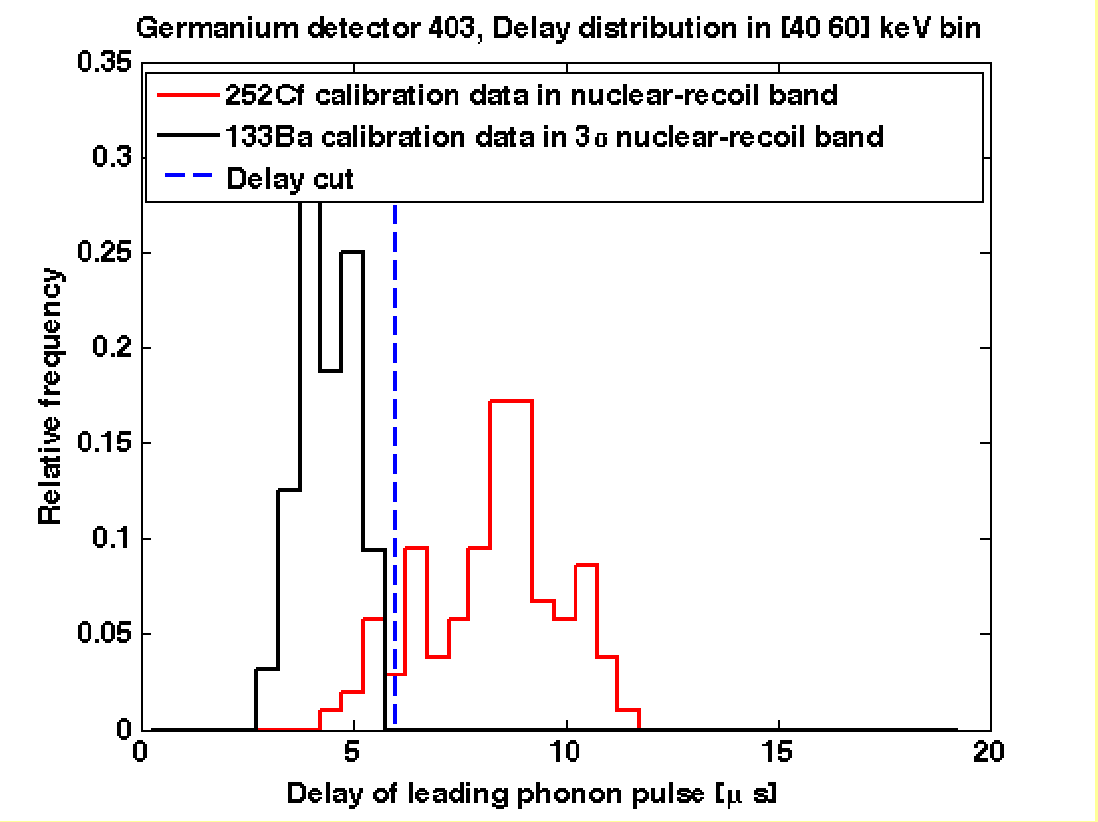


Cuts on the timing properties like risetime or delay can be set, which select nuclear recoils.

Delay of the phonon signal

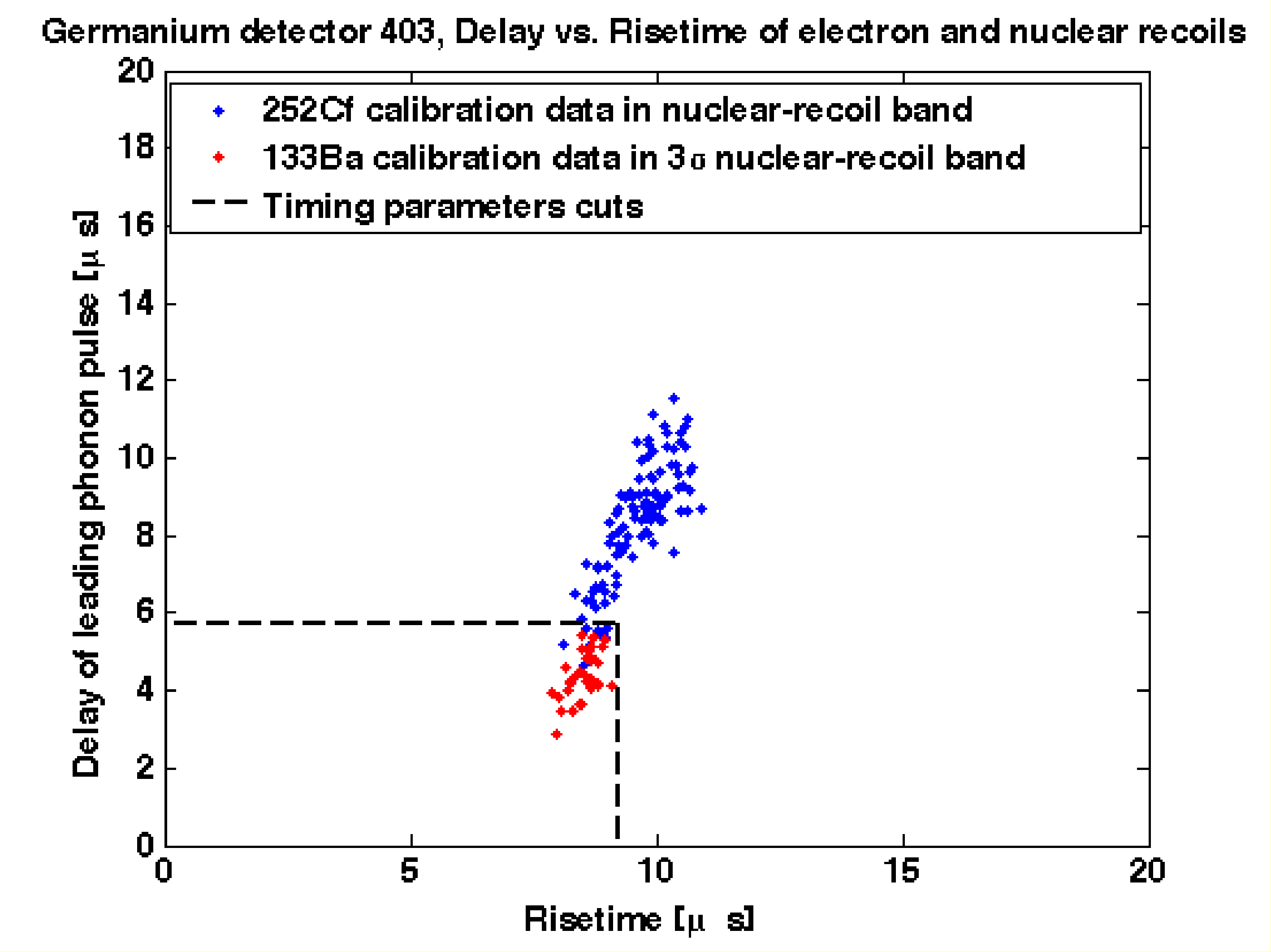


Because of high energetic phonon downconversion, the delay of the phononpulse has great discrimination power.



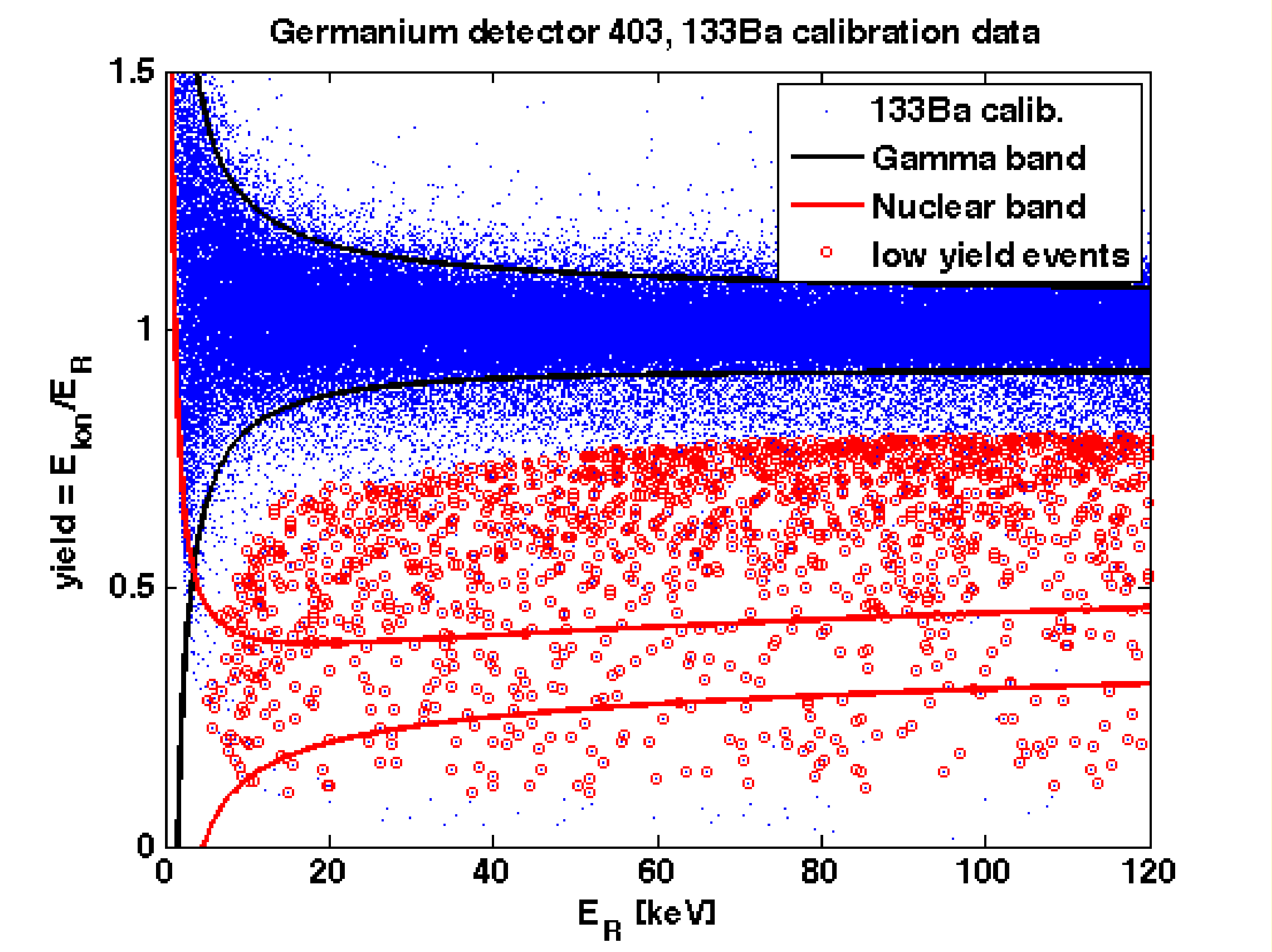
Cut can be set, such that all selected 133Ba events are excluded.

Cut on phonon- timing parameters



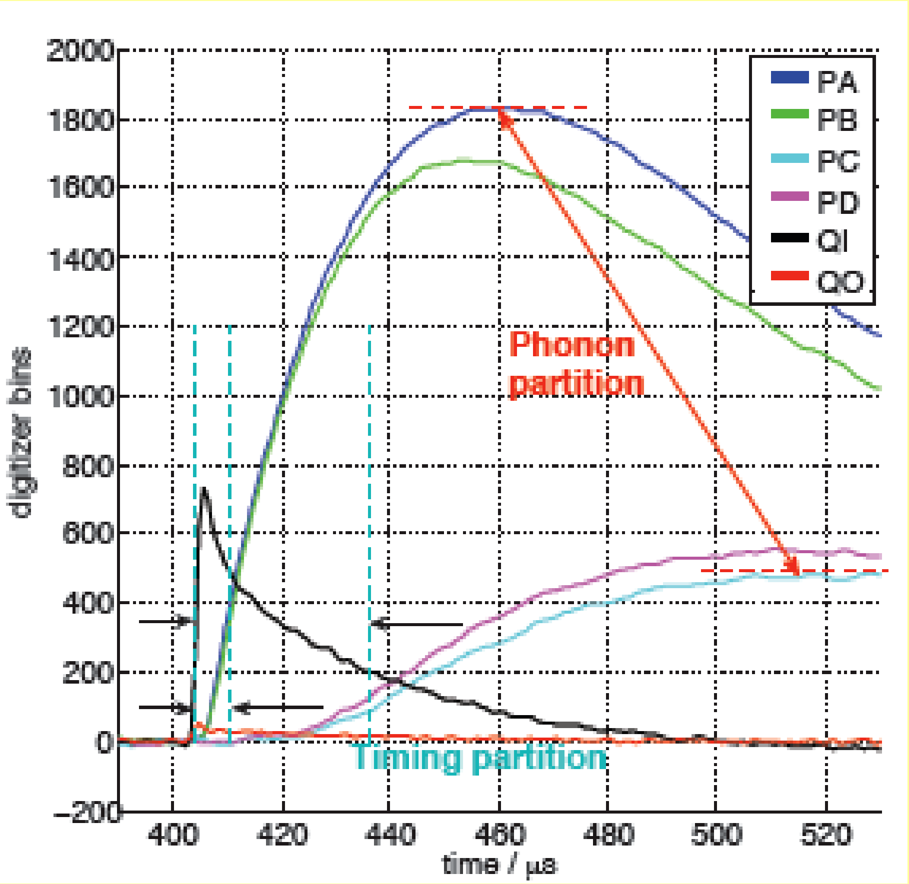
By selecting only 133Ba events which lie in the nuclear recoil band, the actual distribution of risetime and delay may be underestimated.

Being more conservative

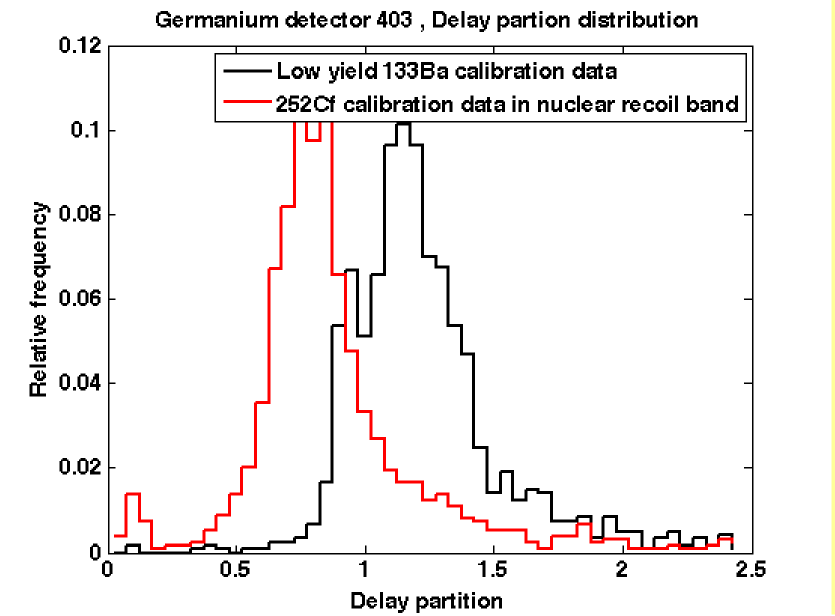


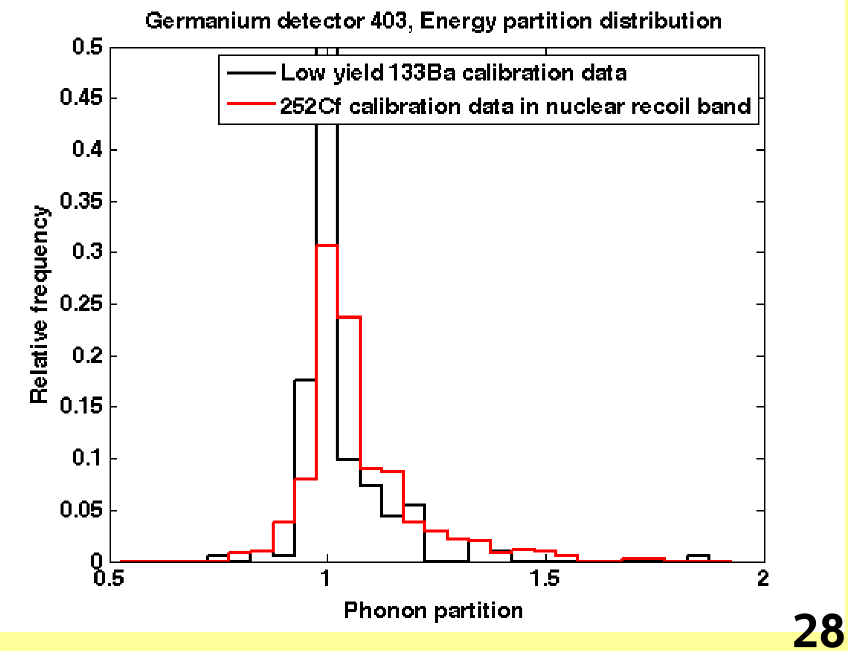
To gain more statistics and spread in the timing parameters distributions, we do not only select events which are close to the nuclear recoil band.

Using more information to select nuclear recoils



thanks to J. Filippini

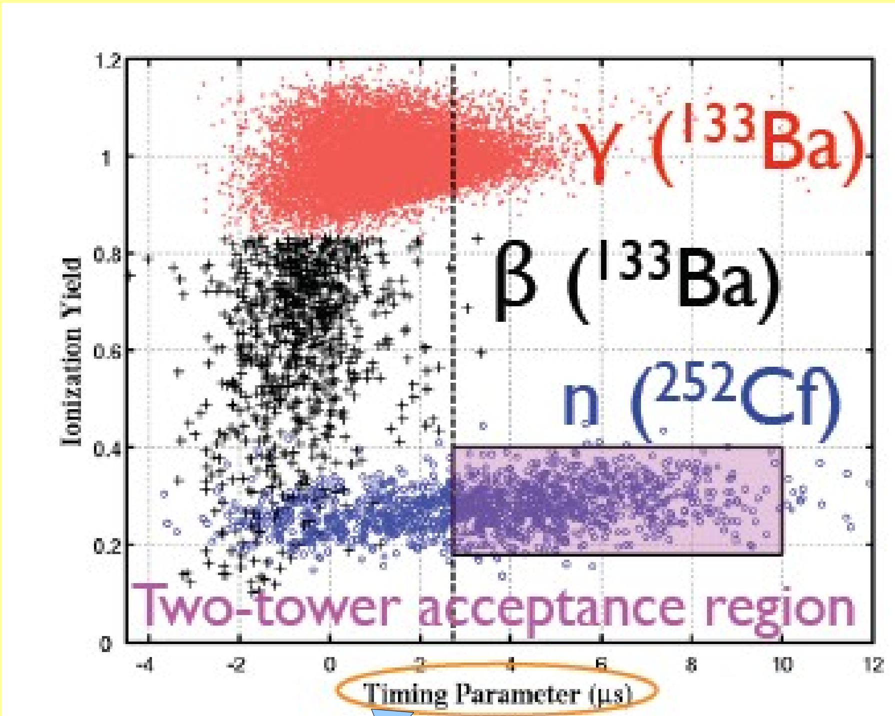




Parameters have not been used in past analysis (Run 118 + Run 119).

Parameters can be used in a extended timing analysis, to achieve better discrimination.

Using Phonon timing to discriminate surface events



Linear combination of risetime and delay: A.Reisetter, PRL 96, 011302 (2006).

Likelihood Analyses: V.Mandic et al. NIM A 553 (2005)

Cut-free estimate of signal and background populations.

χ^2 – Analyses:J.Filippini,R. Mahapatra, J. Sander

$$\chi^2_{\beta(n)} = (\vec{x} - \vec{\mu}_{\beta(n)})^T \cdot C^{-1}_{\beta(n)} \cdot (\vec{x} - \vec{\mu}_{\beta(n)})$$

3D (4D) space: risetime delay, delay partition (phonon partition).

Neural Networks: M.Attisha

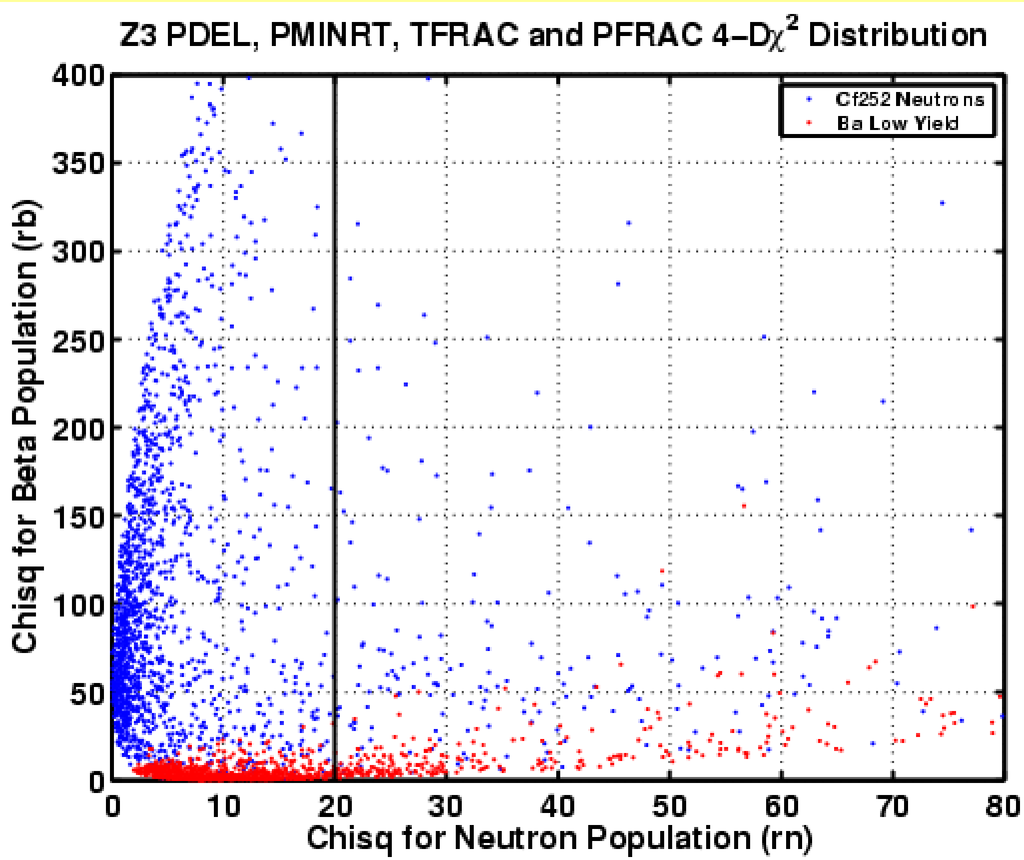
Risetime, delay, phonon partition, wavelet components.

Train to distinguish nuclear recoils from surface events.

Position Reconstruction: R.W. Ogburn, G.Wang

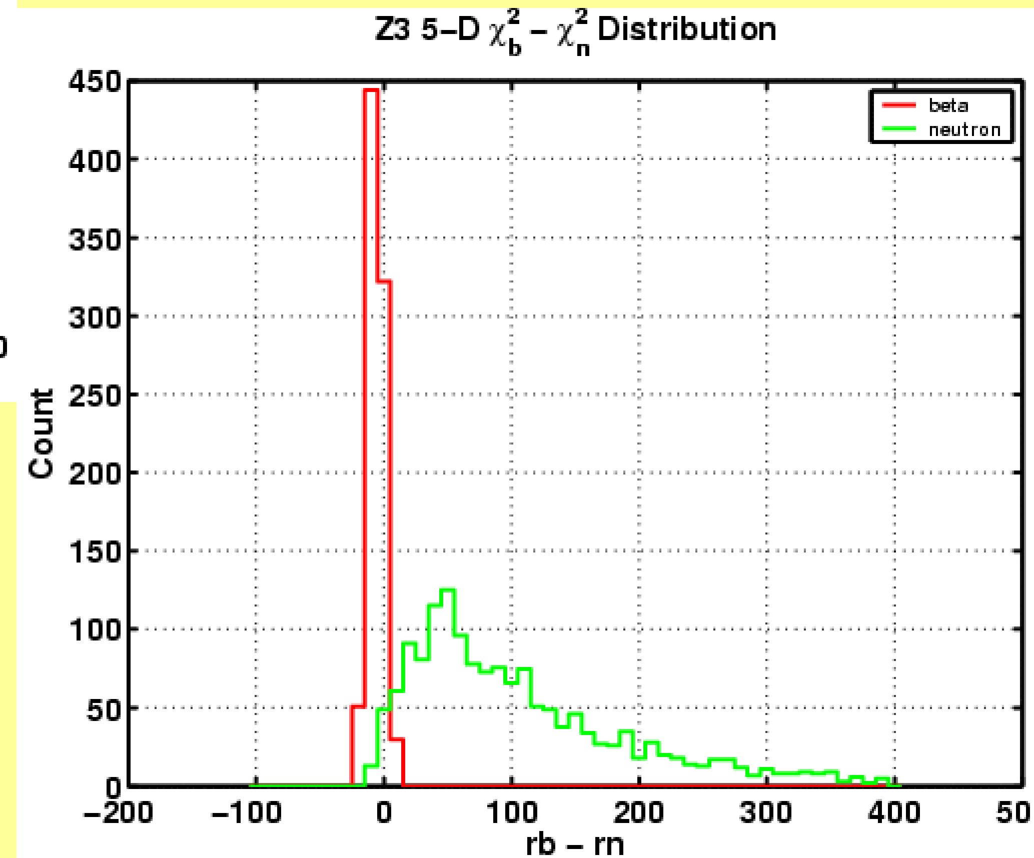
Vary cut with position, tag surface events by face.

χ^2 analysis of timing parameters



In a χ^2 analysis the distance of each event from the neutron distribution (rn) and beta distribution (rb) is determined.

thanks to R. Mahapatra



Again cut can be set to exlude all betas while maximizing the neutron acceptance.

Detection Efficency

Our detection efficency is determined by applying all cuts:

DataQuality & Threshold & Band & Fiducial volume & Timing parameters

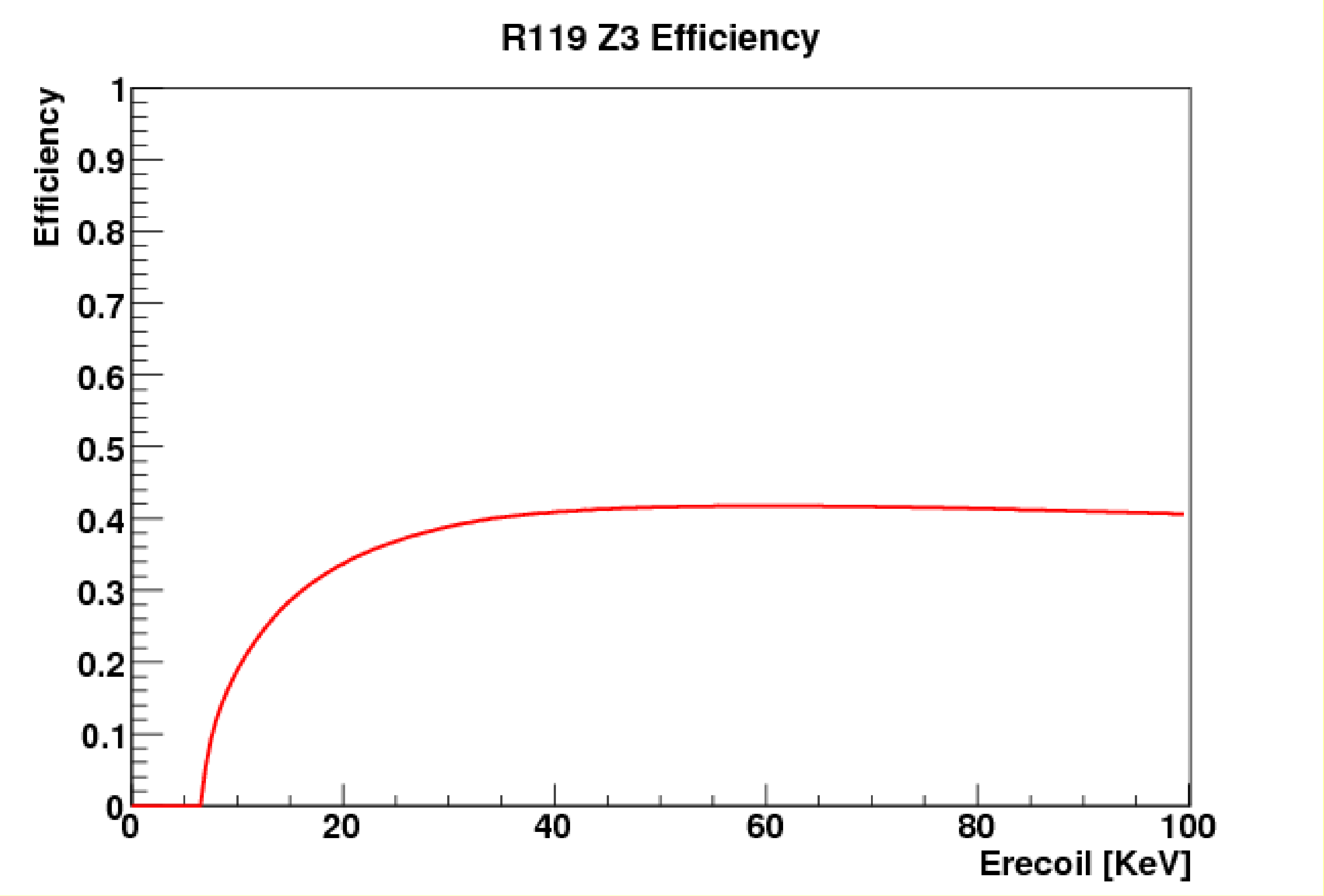
to 252Cf calibration data

thanks to J. Yoo

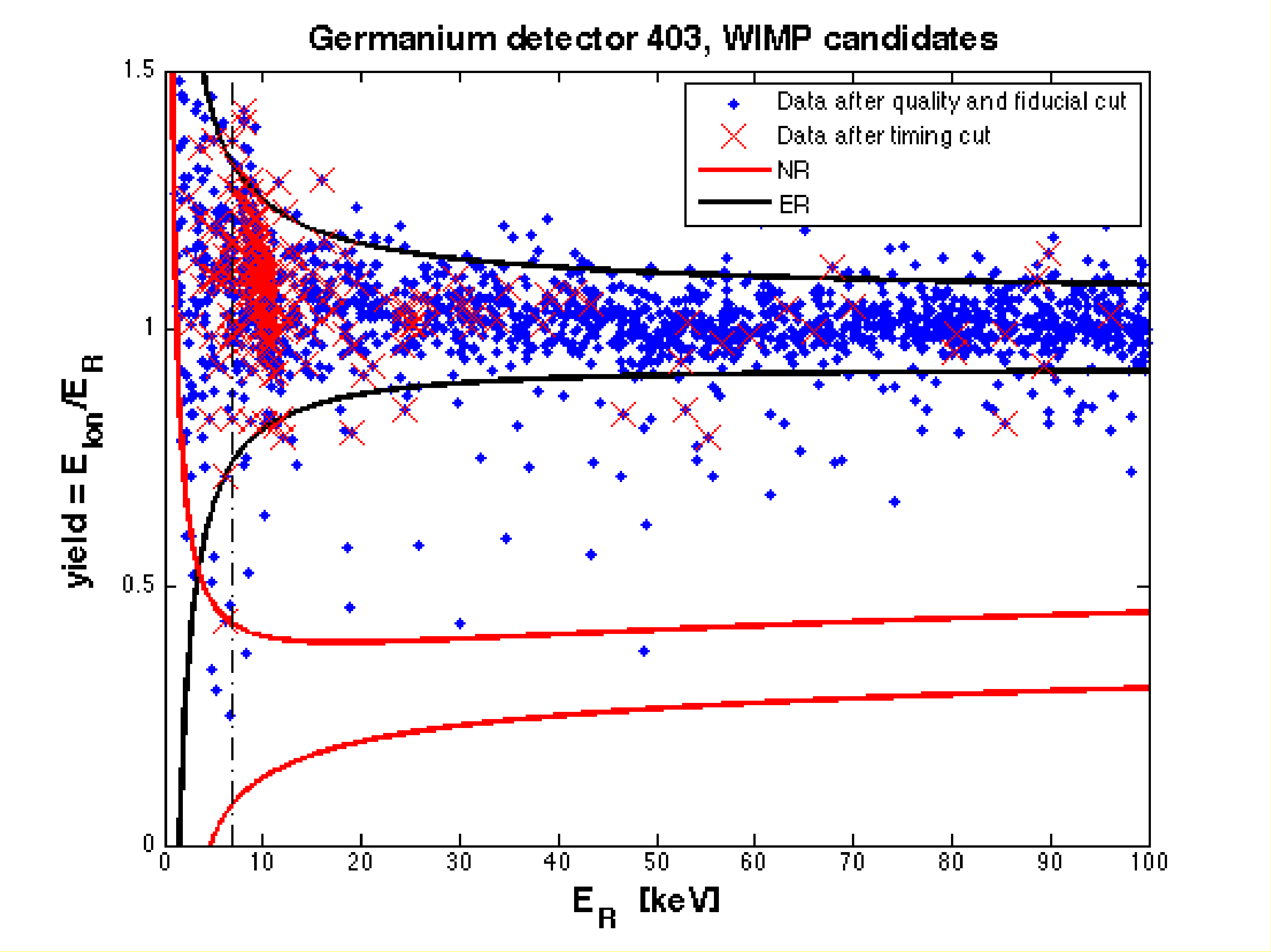
Since our cuts are energy dependent, the detection efficency is energy dependend.

Raw exposure and thereby sensitivity is reduced by this efficency.

After all cuts have been freezed and efficencys are calculated the WIMP search data is unblinded



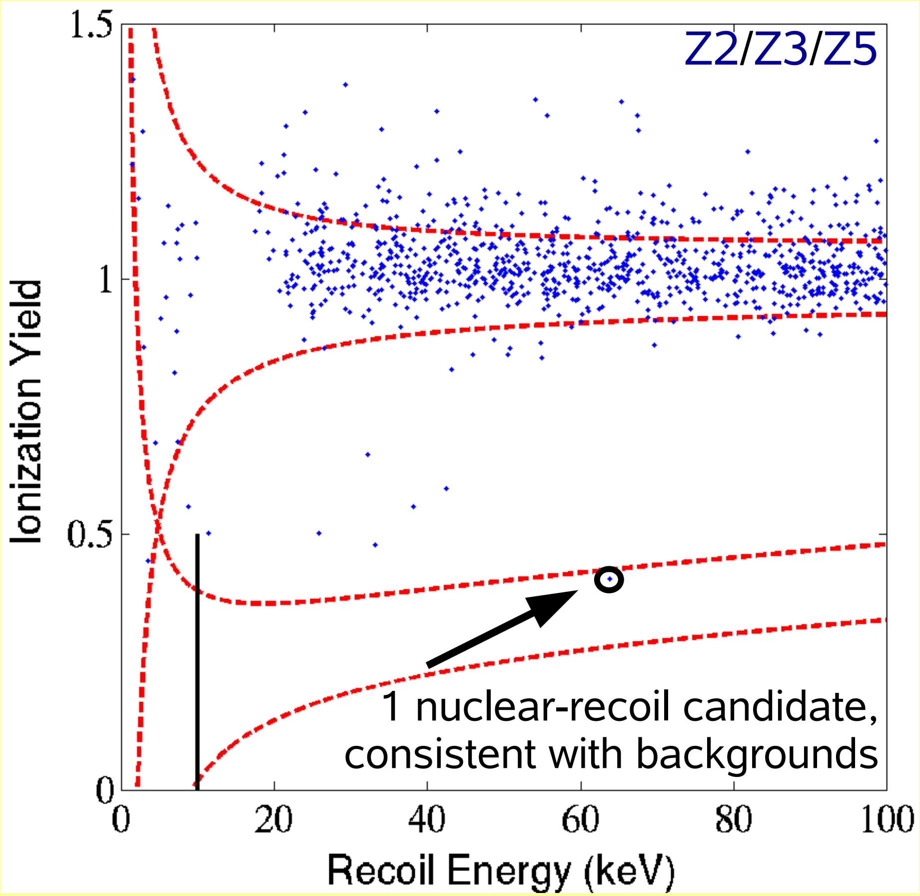
What is left after applying all cuts to the data?



The phonon timing parameters ensure a **background free** signal region.

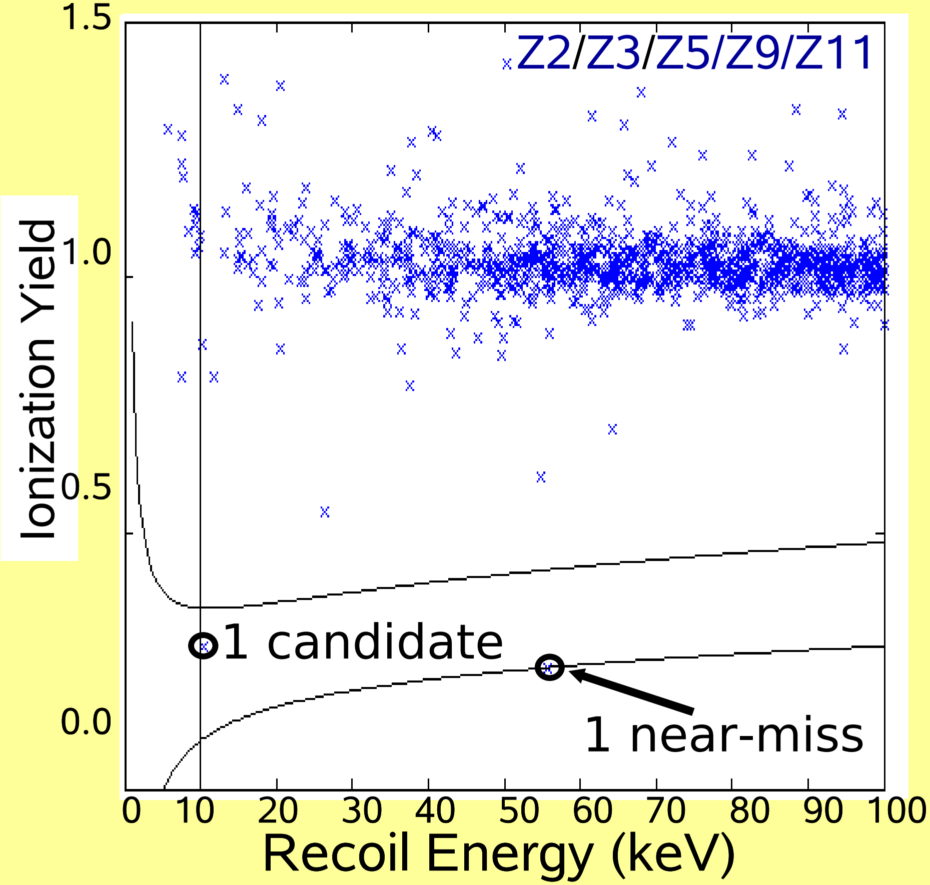
Results from Run 118 and Run 119

Run 118 WIMP-Search data after timing cuts, which reject most of electron recoils.



Phys. Rev. Lett. 93, 211301 (2004)

Run 119 WIMP-Search data after timing cuts, which reject most of electron recoils.



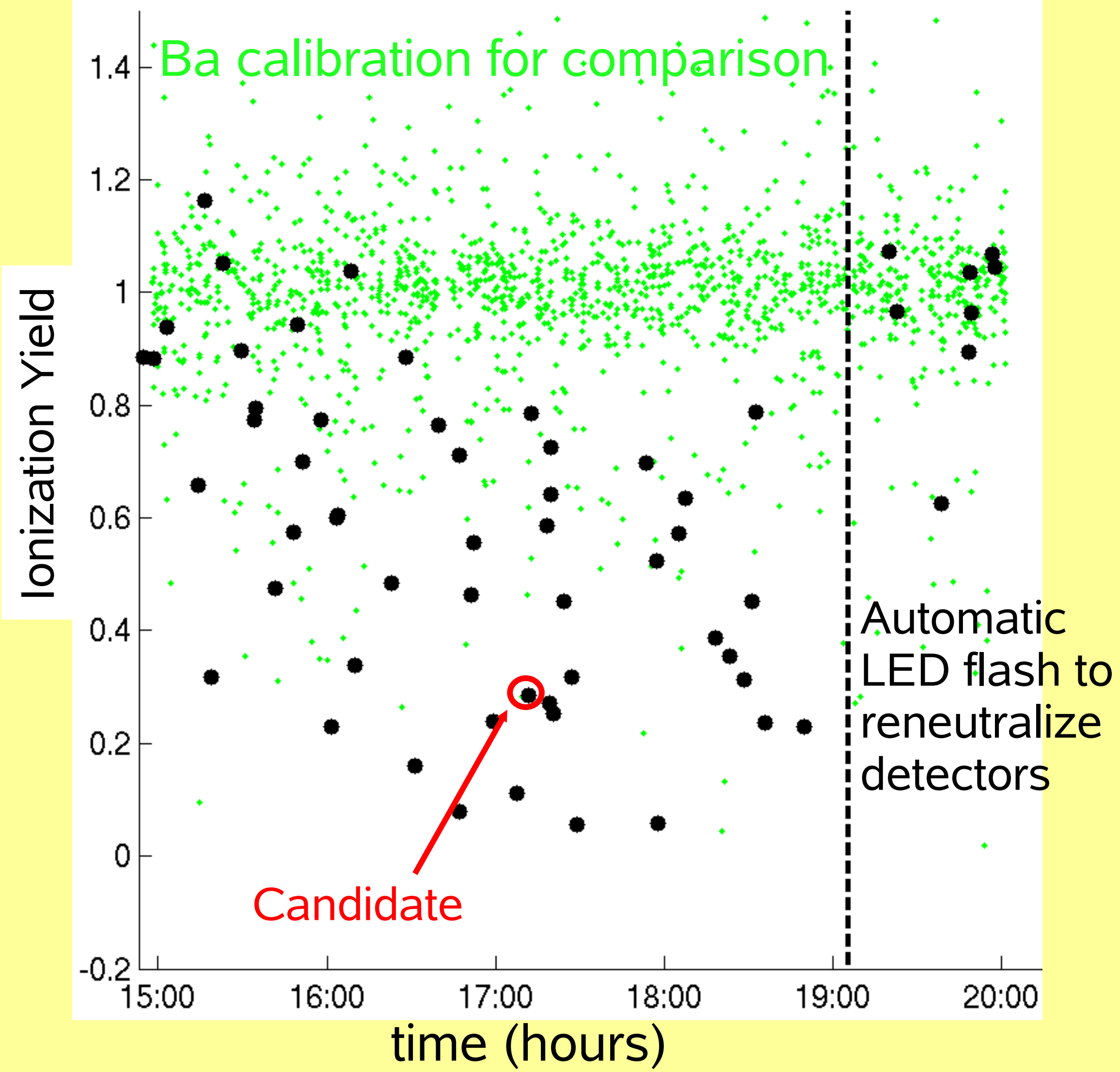
Phys. Rev. Lett. 96, 011302 (2005)

Candidate event in Run 119 WIMP-Search data

Data set containing the candidate event was taken immediately after extended exposure to strong 60Co source.

After many interactions, charge build up in crystal: **deneutralization**.

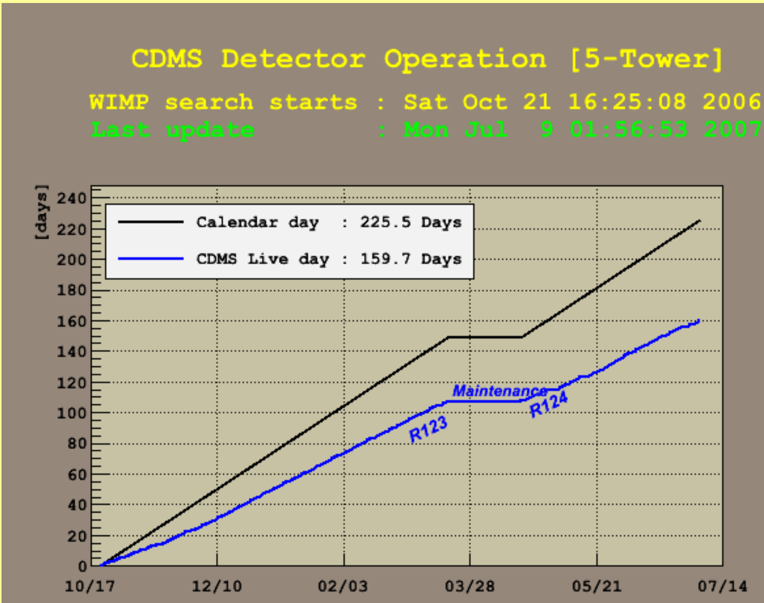
Ionization collection is suppressed until the crystal is **reneutralized** by LED flashing.

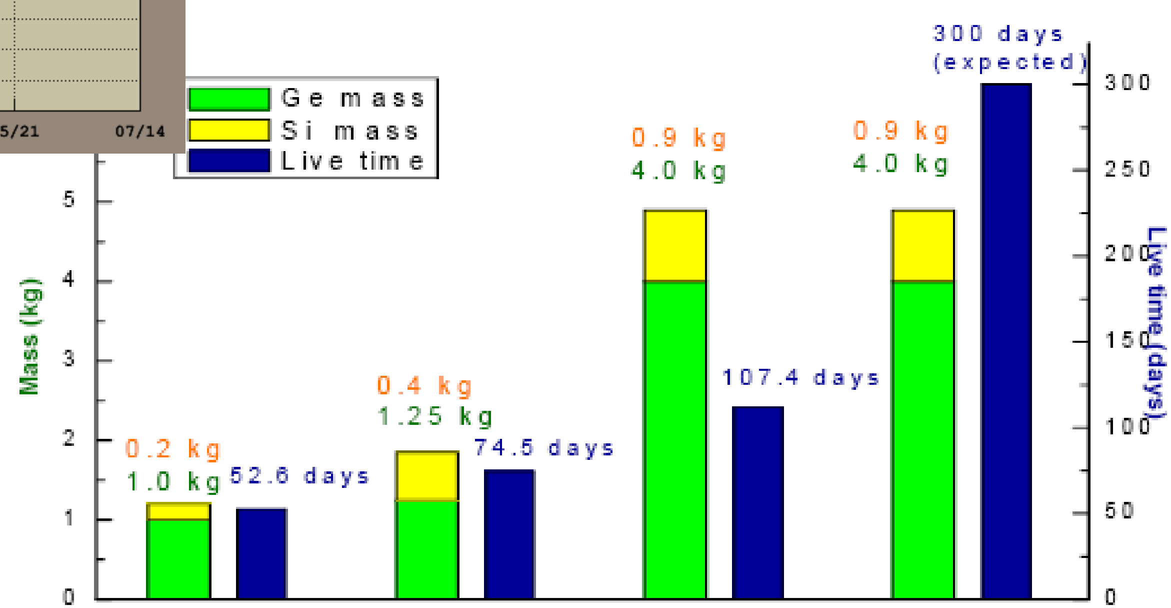


Status and plans for current setup at Soudan

Stable running for Run123 ended in March after 107.4 Live days.

After short maintenance period, cooldown for Run124. Stable running and data aqusition since May.





What can we study if no candidate events are observed?

If no valid candidate events are detected (Run118+Run119) upper limits can be set on the WIMP nucleon scattering cross-section.

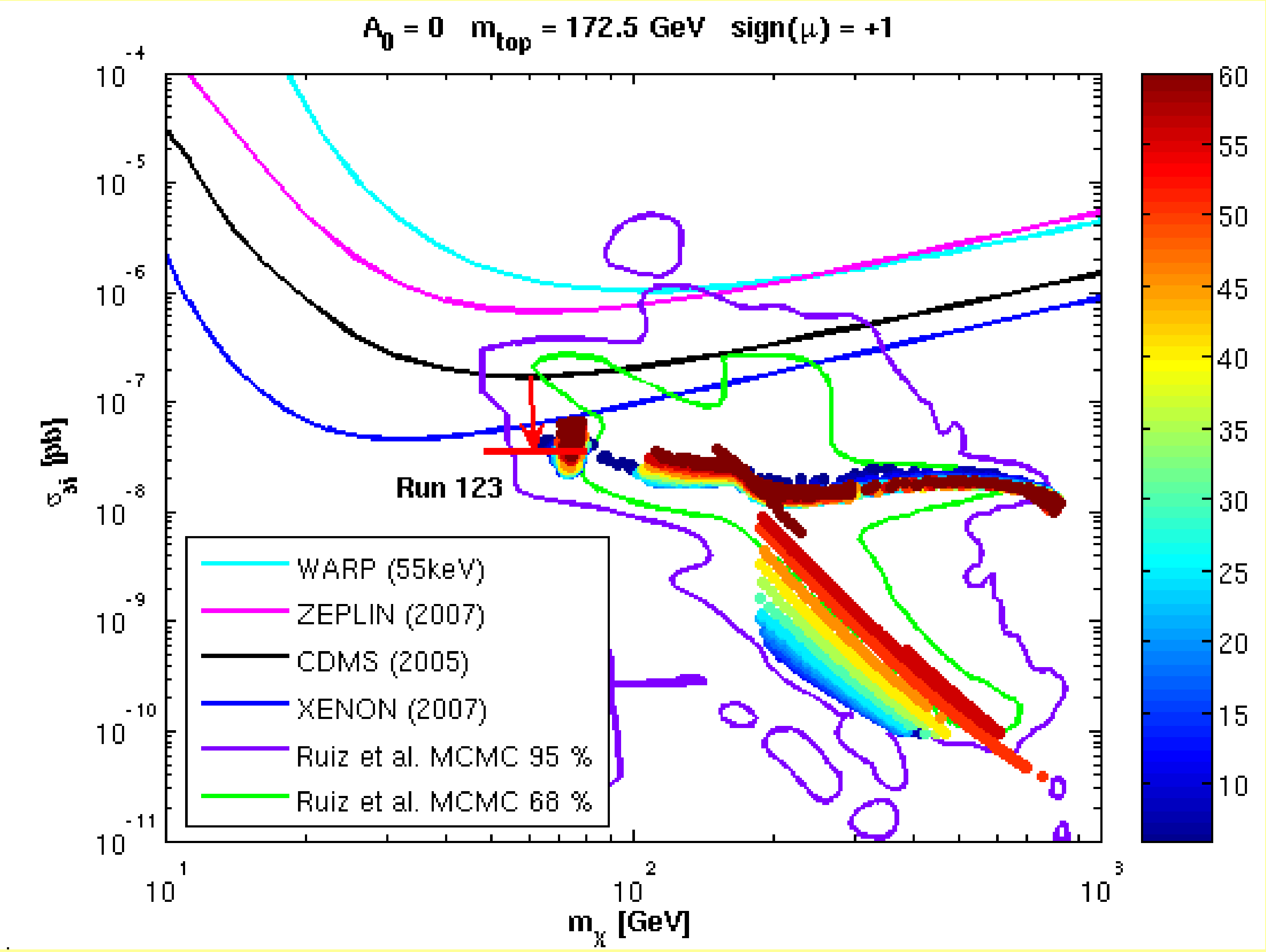
This mass dependent limits are independent of the nature of Dark Matter.

But they do depend on the assumed halo properties.

If $\rho > 0.3 \rightarrow$ better limit.

If $\rho < 0.3 \rightarrow$ worse limit.

Limit scales linear with local density.



What can we study if candidate events are observed?

If candidate events are detected we want to determine the mass and crosssection of Dark Matter particles.

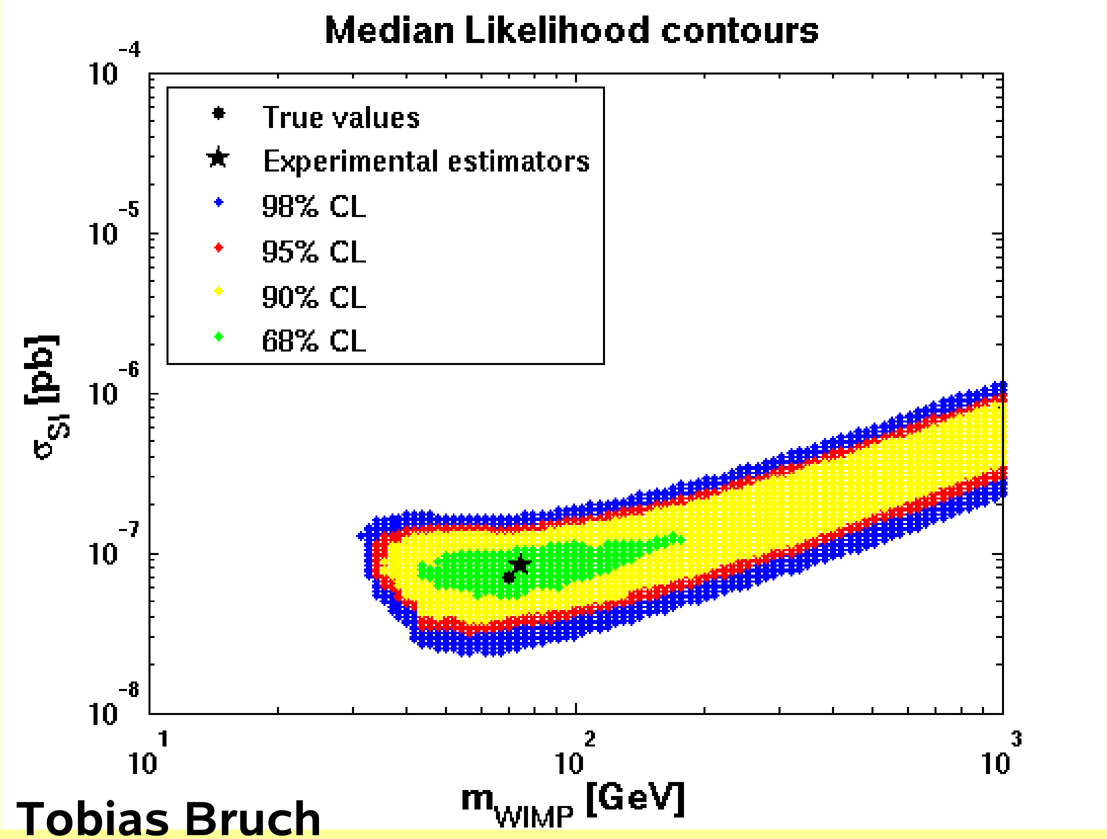
Simpelst approch would be a Likelihood estimation of confidencelevels.

Extendet Likelihood function is not χ^2 distributed for low statistics ($n \leq 10$).

Confidencelevel determination by $\ln L(\theta) = \ln L_{max} - Q/2$ ($Q=4.61$ for 90% CL and 2 dof) questionable.

Have to take „real“ data into account, possible improvement by Bayesian analysis.

Bayesian analysis needs prior, a certain parameter set for the true parameters has to be choosen which is a priori unknown.



Feldmann - Cousins Likelihoodratios

Use Likelihoodratio to determine propability of a parameter point.

$$\chi(\theta_{point}) = \frac{L(n|\theta_{point})}{L(n|\theta_{best})}$$

disfavoured $0 \leq \chi \leq 1$ favoured

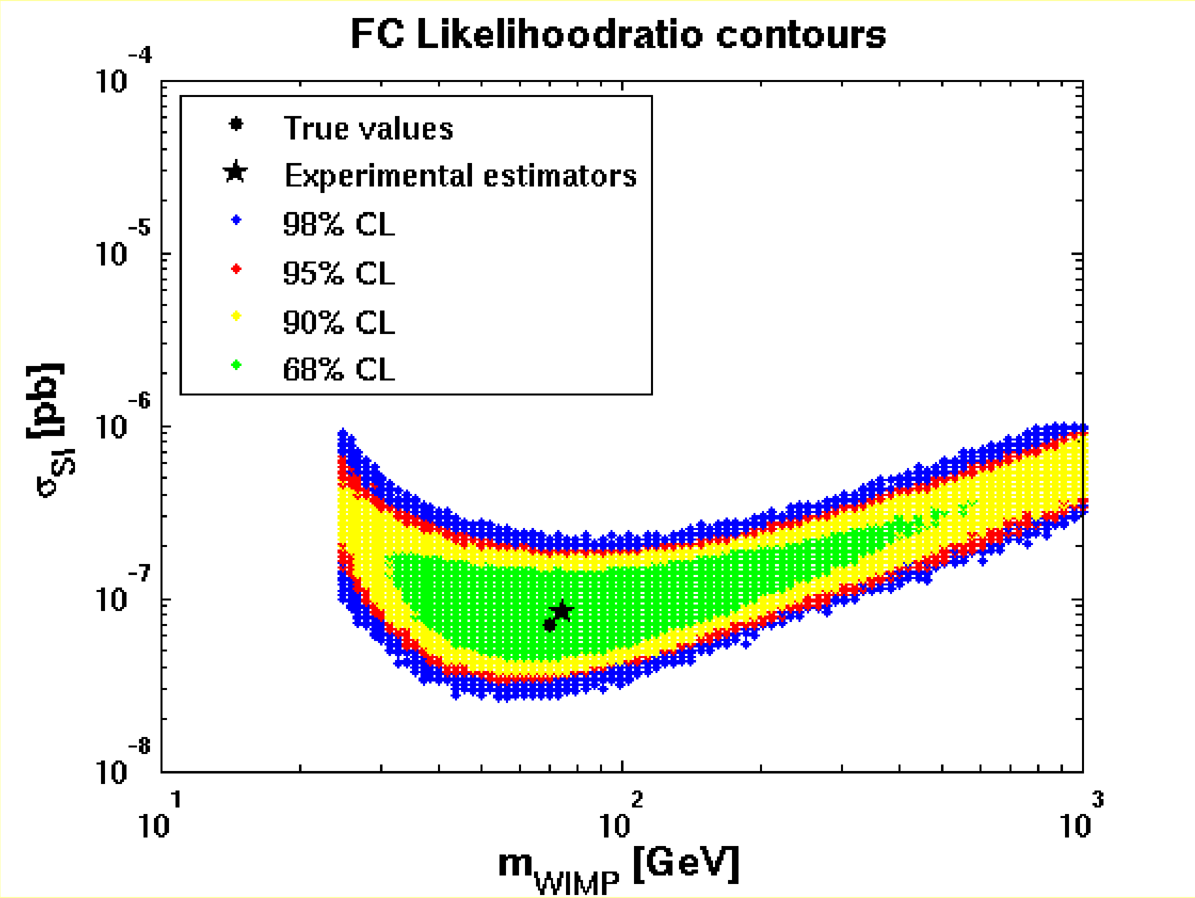
G.J. Feldman, R.D. Cousins, Phys Rev. D 57 (1998), 3873-3889

Likelihoodratio accurate for low statistics ($n \leq 10$).

For each parameter point run a lot of MC experiments and define χ_c such that α (CL)of these experiments have $\chi \geq \chi_c$.
For the „real“ data calculate χ_{test} for each parameterpoint. Find confidencelevels by Likelihoodratiotest. ($\chi_{test} \geq \chi_c$).

No need of prior, confidencelevels determined by Likelihood ratio test with „real“ data.

Needs a lot of computation time.



Conclusions

The direct search for the nature of Dark Matter is frontier physics with an excellent interlink between high energy physics and astroparticle physics.

The CDMS experiment uses high end technology in the search for Dark Matter.

The CDMS experiment has an event by event discrimination between background and expected signal.

Analysis of the Run 123 data is in progress.

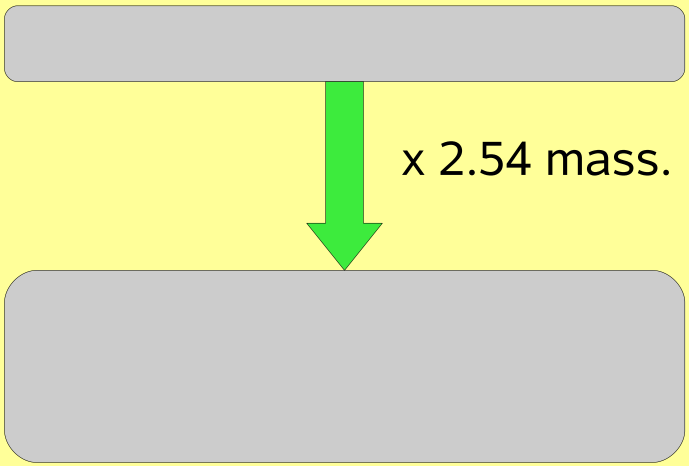
New analysis parameters and discriminants promise a **background-free** operation for current runs → **maximal discovery potential**.

Backup Slides

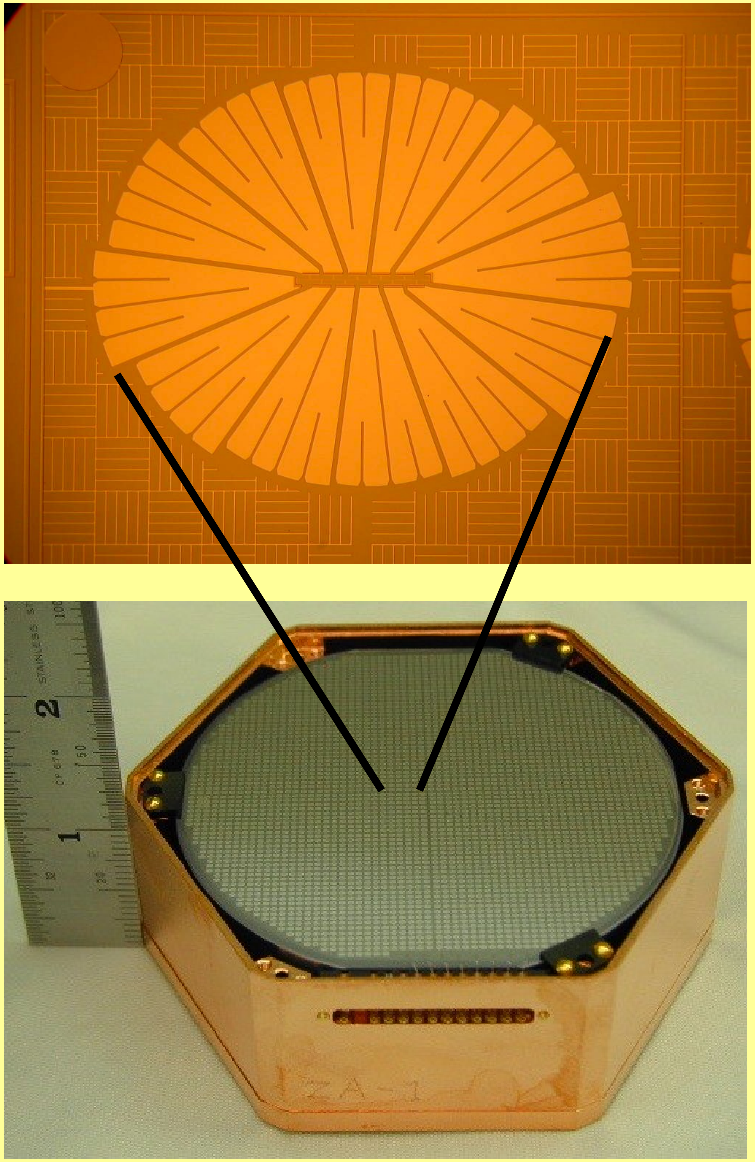
SuperCDMS at Soudan

New 1 inch thick ZIP detectors with an improved phonon readout.

ZIP used in the CDMS II setup.



ZIPs used in the first phase of SuperCDMS.



Improvement in phonon readout by new geometry of TESs, which maximizes the active Al coverage.

First results show an improved yield discriminator for 1 inch detectors.

Installation of the first two SuperTowers at Soudan at the end of 2008.

SuperCDMS at SNO-LAB

SuperCDMS will be split in four phases, with an increased mass at each phase reaching for a ton scale experiment.

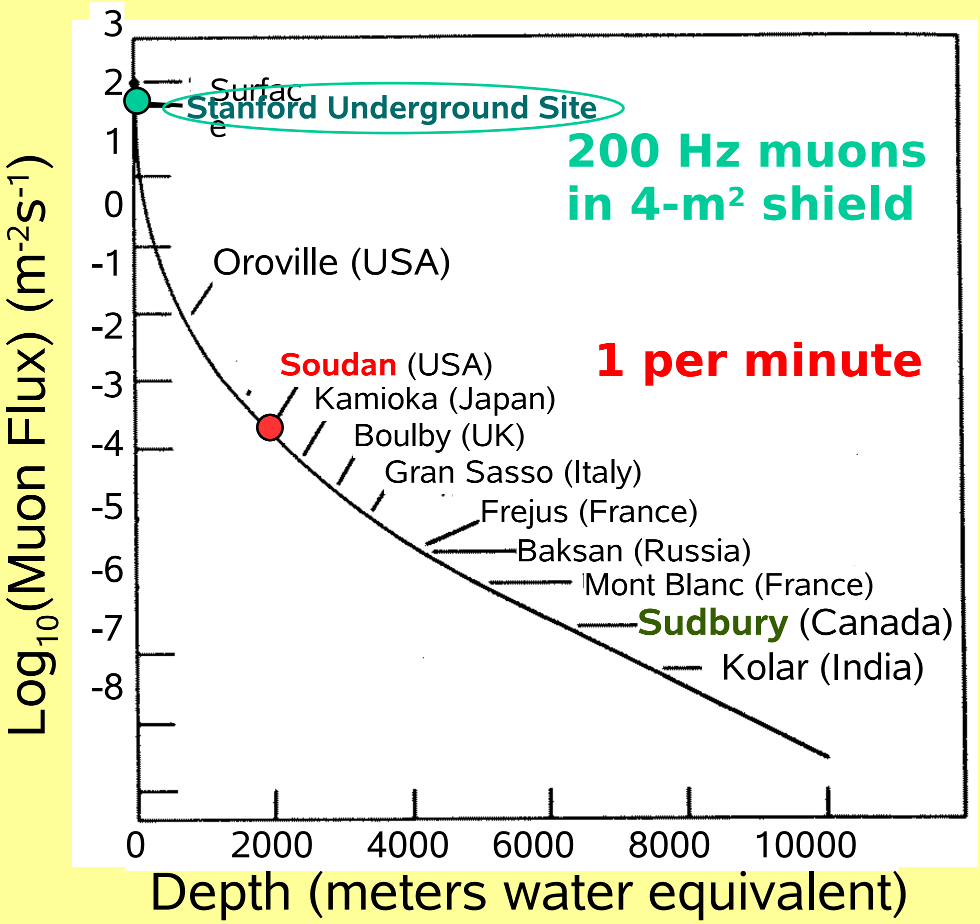
Phase A :

Operation of 7 SuperTowers with a total mass of 25kg at SNO-LAB.

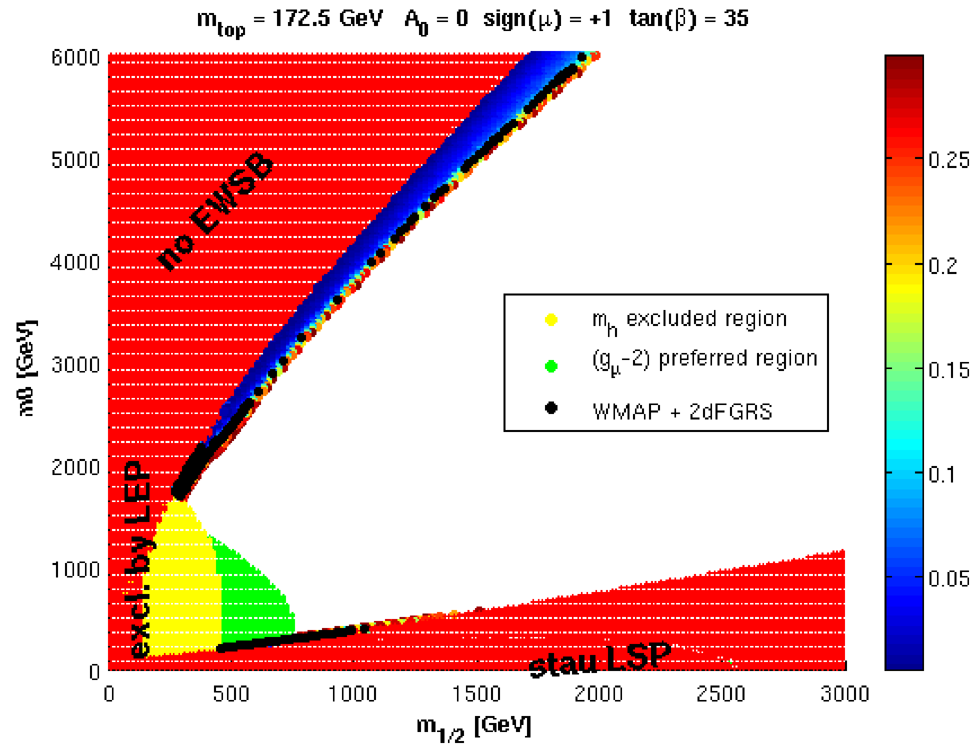
Retaining zero background for SuperCDMS:

Background rejection	×4
Analysis discrimination	×2
Background reduction	×5
Total Improvement	**= ×40**
Production rate per kg	×5

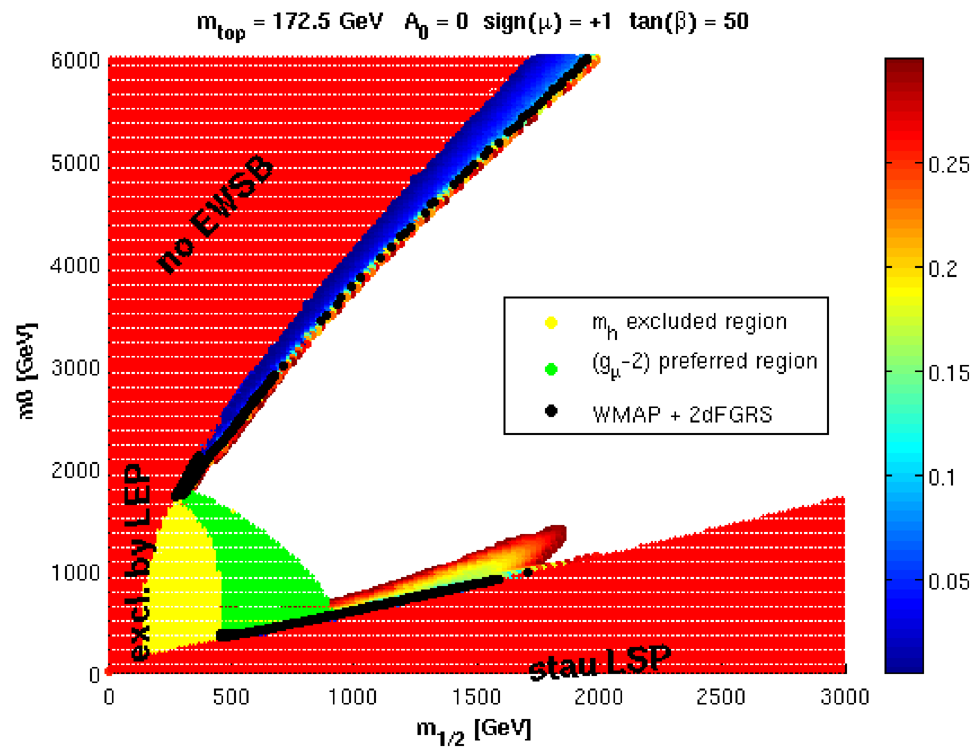
Table 2: Targeted improvement factors over CDMS II advanced analysis levels (see Section 3.2) to achieve SuperCDMS 25 kg sensitivities with zero background from internal sources. The cosmogenic fast-neutron background is eliminated by the SNO-LAB overburden of 6000 mwe.



Muon induced neutron flux negligible at SNO - LAB.



m_{top} = 172.5 GeV A_0 = 0 sign(μ) = +1 tan(β) = 35
m0 [GeV]
$m_{1/2}$ [GeV]
no EWSB
excl. by LEP
stau LSP
m_h excluded region
(g_μ-2) preferred region
WMAP + 2dFGRS
0.25
0.2
0.15
0.1
0.05



m_{top} = 172.5 GeV A_0 = 0 sign(μ) = +1 tan(β) = 50
m0 [GeV]
$m_{1/2}$ [GeV]
no EWSB
excl. by LEP
stau LSP
m_h excluded region
(g_μ-2) preferred region
WMAP + 2dFGRS
0.25
0.2
0.15
0.1
0.05