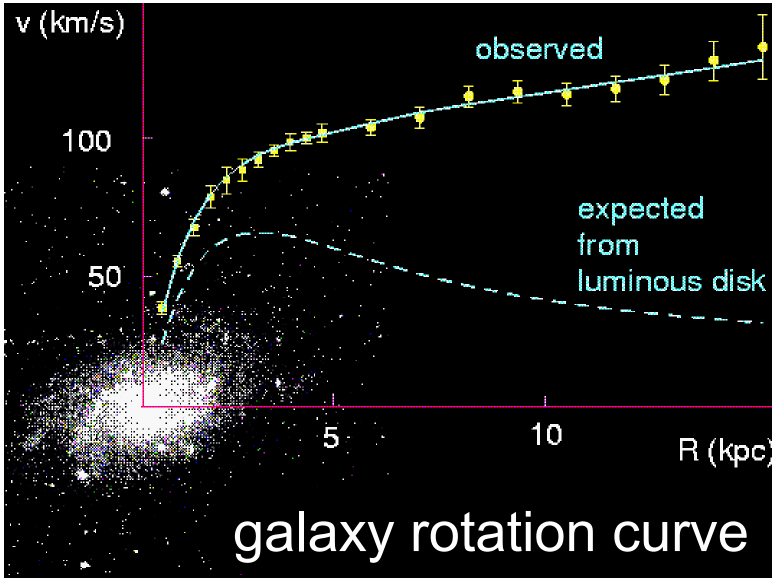
ISAPP
INTERNATIONAL SCHOOL ON ASTROPARTICLE PHYSICS

ISAPP Summer Institute 2009 at the Karlsruhe Institute of Technology

Direct Dark Matter search with cryogenic bolometers

- galactic DM halo models
- WIMP detection strategies
- direct DM search
  - detection schemes
  - DM search using cryogenic bolometers:
    - ionisation & heat
    - scintillation & heat
- where do we stand? what to come next?

galactic DM halo models



galaxy rotation curve

$$\boxed{\frac{\rho(r)}{\rho_{\mathrm{crit}}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}}$$

Navarro,Frenk&White, Astrophys.J.**490**, 493 (1997):
halo shape spherical, independent on halo mass

Milky Way: (r=8kpc)

$$\rho_0 = 0,3 - 0,5\ GeV\ \ cm^{-3}$$

$$v_{rms} \approx 270\ km\ s^{-1}$$

$$v_{esc} \approx 650\ km\ s^{-1}$$

→ DM halo also in Milky Way

Maxwell-Boltzmann distribution of WIMP´s in halo without net velocity:

$$\boxed{f(\vec{v}, \vec{v}_T) = e^{-(\vec{v}+\vec{v}_e)^2/v_0^2}}$$

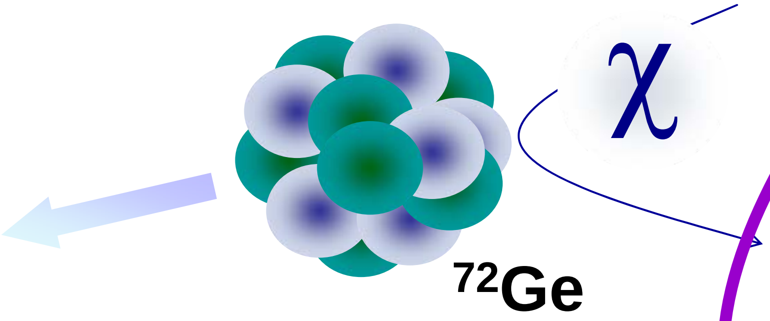
with $\bar{v} = \langle v^2 \rangle^{1/2} = v_0\sqrt{\frac{3}{2}}$ and v_0=220km/s, <v>=270 km/s

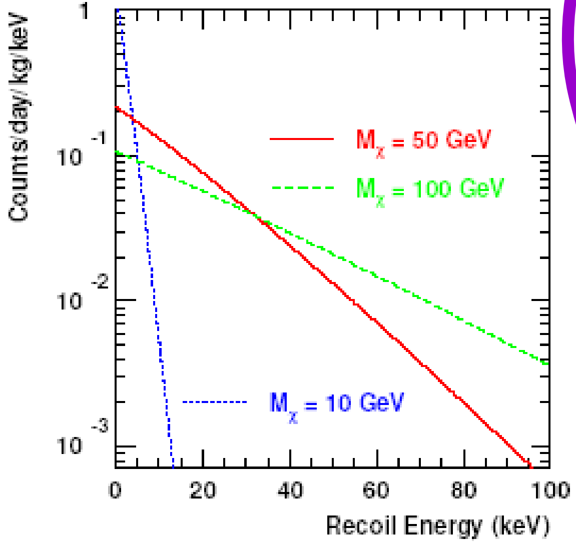
with v_{esc}=650 km/s ≡ escape velocity; v_e=235km/s ± 6% annual modulation

WIMP(χ) detection strategies

direct & indirect searches
scattering vs. annihilation

elastic scattering on a nucleus





- nuclear recoils:

- mass *50 GeV to ~ 1000 GeV*
- relative speed *270 km/s*

(~ our orbital velocity around galactic center)

$\Rightarrow$ only a few keV of recoil energy

- cross section $\sigma_\chi < 10^{-42} cm^2$
- local WIMP-density $\rho_\chi = 0.3\ GeV/cm^3$

(local density 0.3GeV/cm^3 → ~1 WIMP/200cm^3)

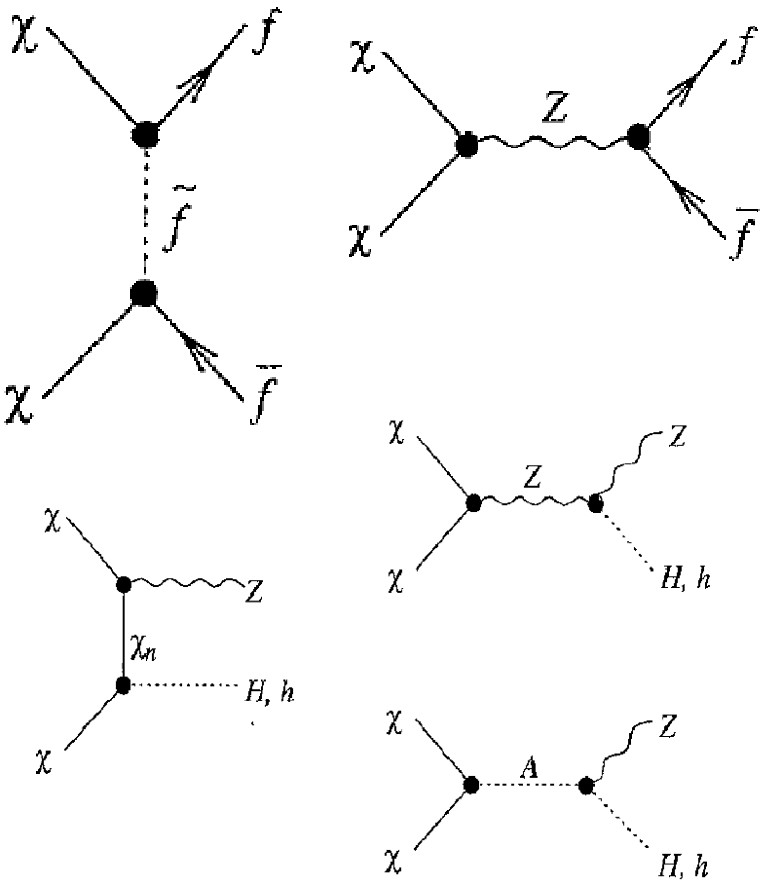
$\Rightarrow$ very very rare scattering events (< 1 / week / kg)

$\Rightarrow$ requirements

- annual modulation
- background suppression (active&passive)

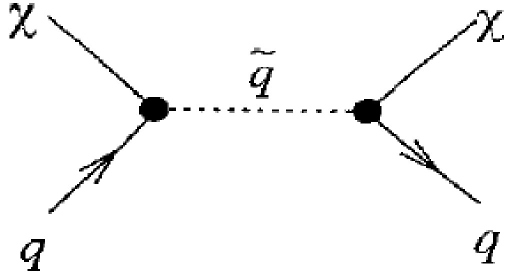
WIMP (χ) detection strategies

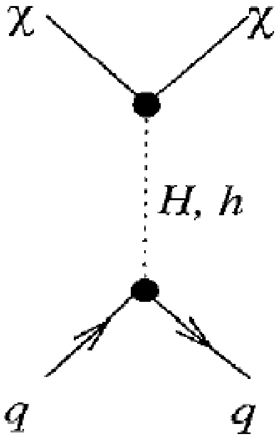
annihilation



scalar interaction

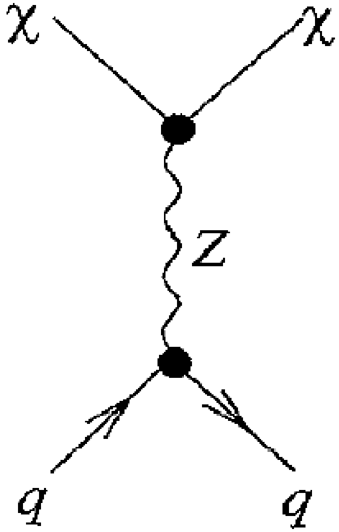
SI elastic scattering

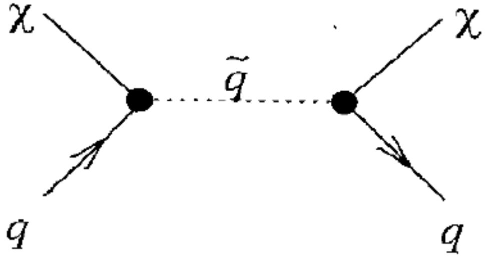




vector interaction

SD elastic scattering



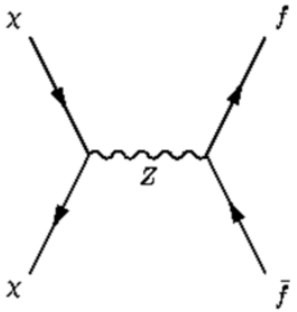


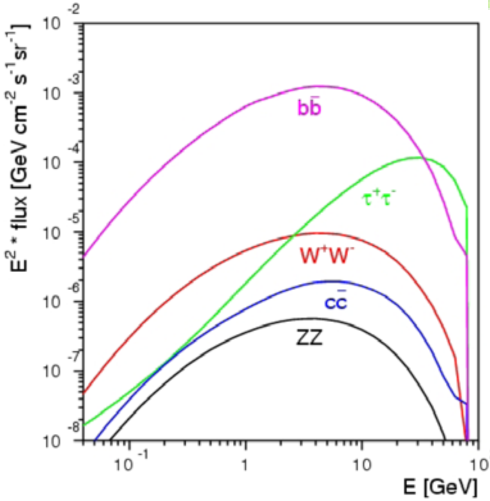
extract from
Jungman, Kamionkowski, Griest (1995)

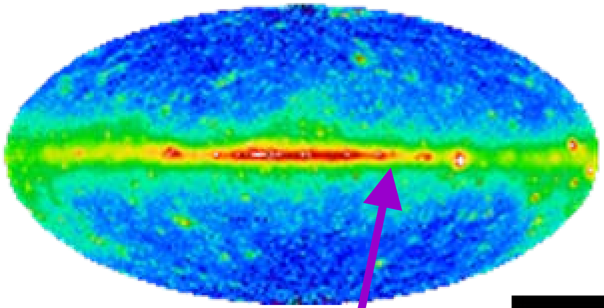
WIMP(χ) detection strategies

direct & indirect searches

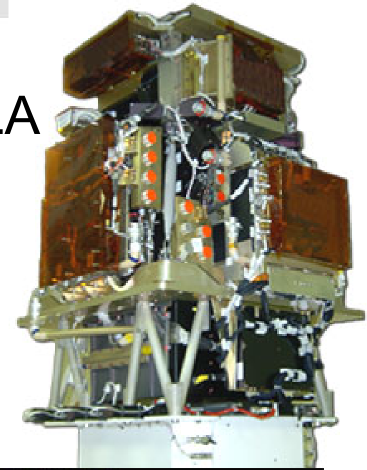
scattering vs. annihilation

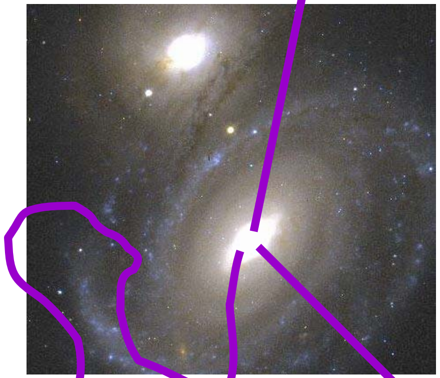


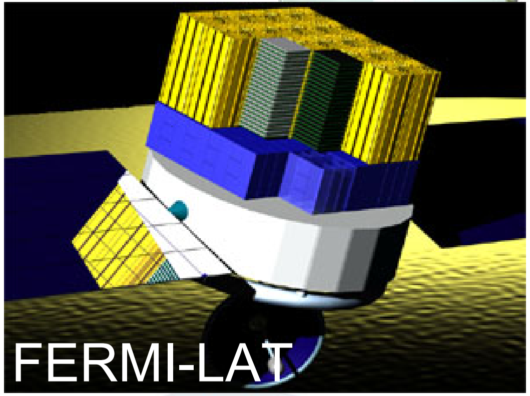




PAMELA



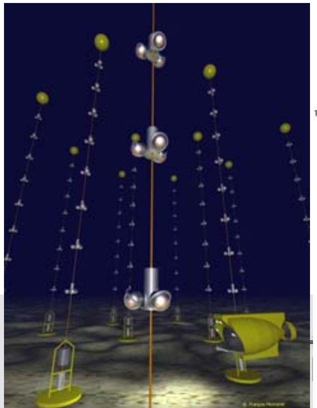


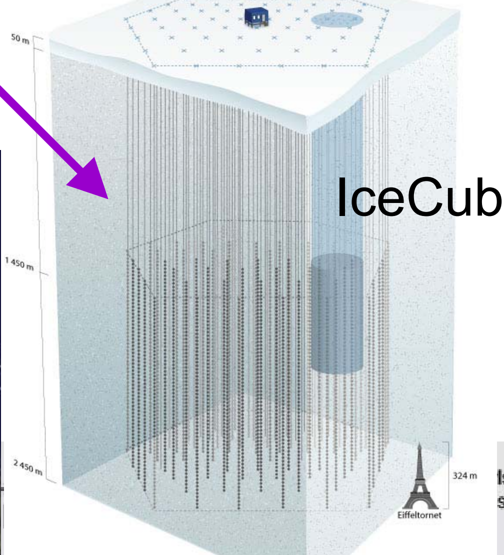


FERMI-LAT

AMS-2: $\bar{p}$, e^+, $\overline{He}$…

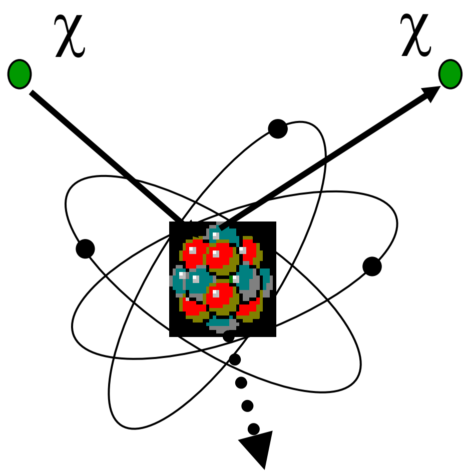
Antares





IceCube

WIMP(χ) direct detection strategies



spin-independent interaction (SI):

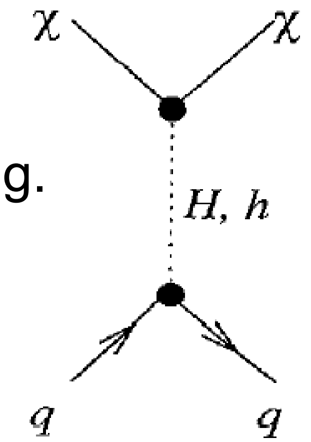
coherent scattering of χ off nucleus with A nucleon wave functions

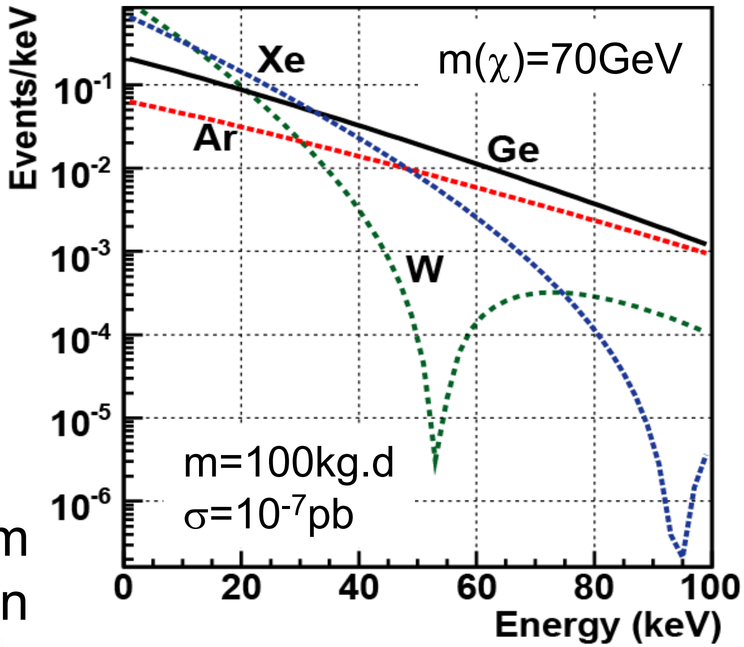
$$\sigma_{W-A} = \frac{\mu_A^2}{\mu_p^2}\left(Z+(A-Z)\frac{f_n}{f_p}\right)^2 \sigma_{W-p} = \sigma_{W-A} A^2 \frac{\mu_A^2}{\mu_p^2}\sigma_{W-p}$$

χ-A reduced mass

effective χ-p(n) coupling

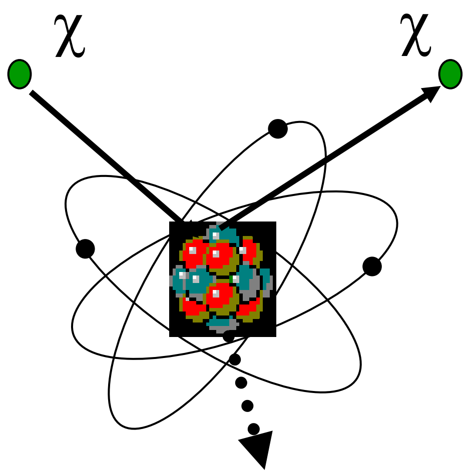
e.g.



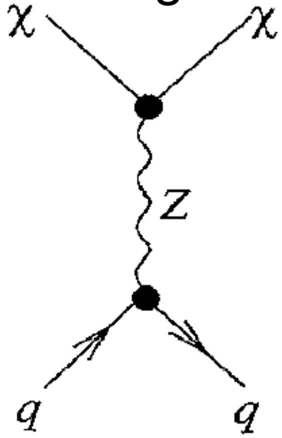


form factor from nuclear calculation

WIMP(χ) direct detection strategies



e.g.



χ-p reduced mass

spin structure function

effective χ-p(n) coupling

$$\sigma_{W-A} = \frac{\mu_A^2}{\mu_p^2}\,\frac{4}{3}\,\frac{J+1}{J}\left(\langle S_p\rangle + \langle S_n\rangle \frac{a_n}{a_p}\right)^2 \sigma_{W-p}$$

total nuclear spin

spin-dependent interaction (SD):

different amplitudes a(p), a(n) depending on nucleon carrying nuclear spin J

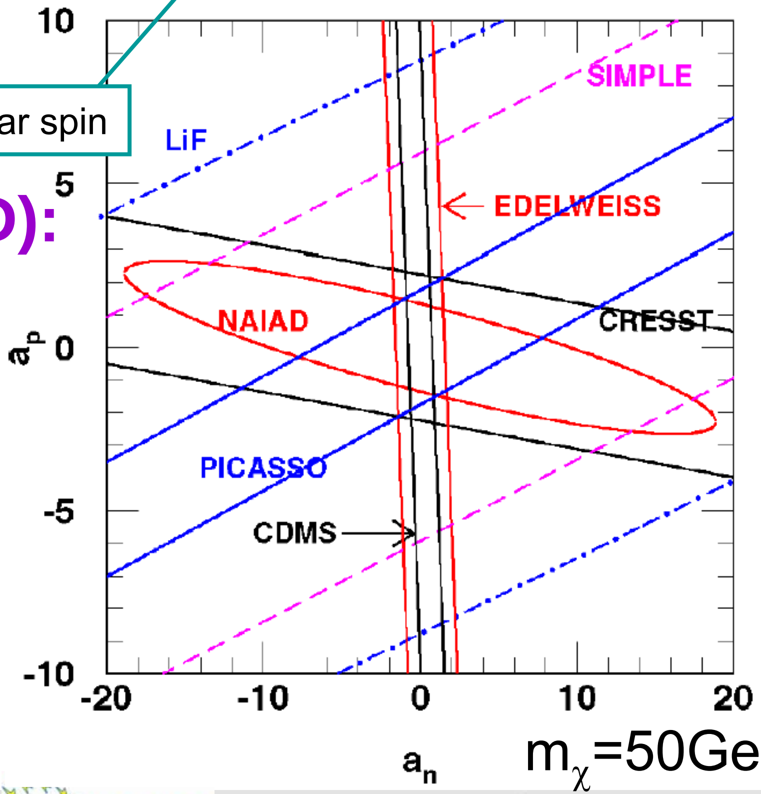
^{73}Ge: J=9/2 (Z=32,A-Z=41)→a(n)

^{27}Al: J=5/2 (Z=13,A-Z=14)→a(p)

^{7}Li: J=3/2

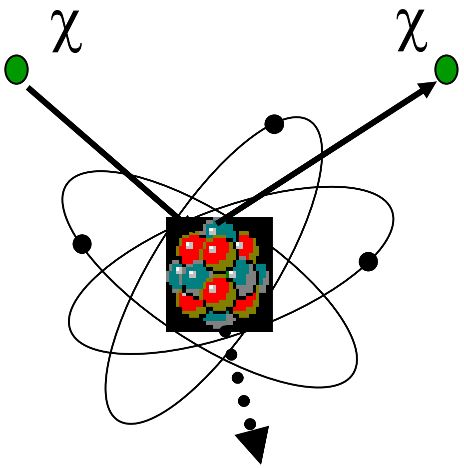
^{127}I: J=5/2

^{19}F: J=1/2



m_χ=50GeV/c^2

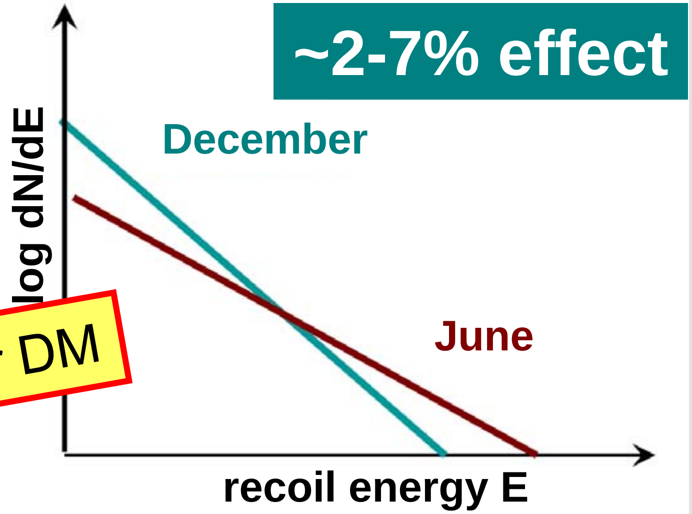
WIMP(χ) direct detection strategies



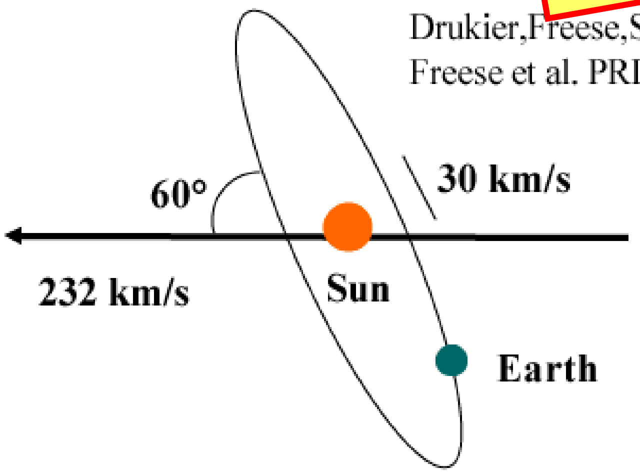
annual modulation:
different effective velocity of the earth against the (non-moving) WIMP halo

DAMA/LIBRA evidence for DM

~2-7% effect



Drukier,Freese,Spergel PRD86
Freese et al. PRD88



- $v_{sun} = 232$ km/s (Sun velocity in the halo)
- $v_{orb} = 30$ km/s (Earth velocity around the Sun)
- $g = \pi/3$
- $w = 2\pi/T$ T = 1 year
- $t_0 = 2^{nd}$ June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

Annual modulation of the rate

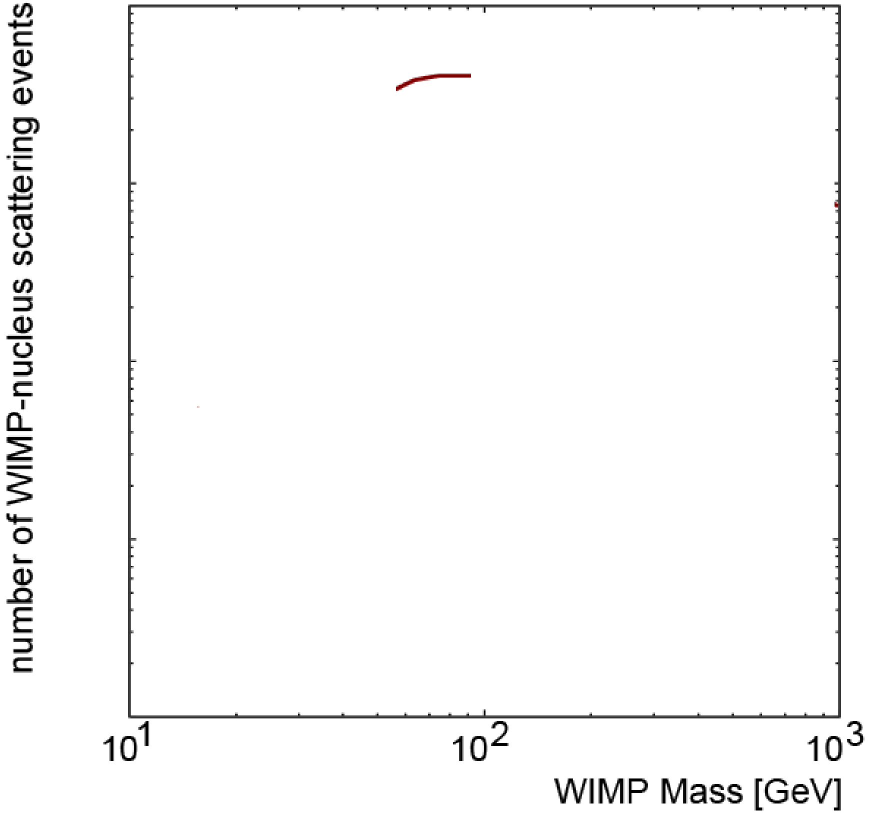
from exptl. spectra to WIMP parameters

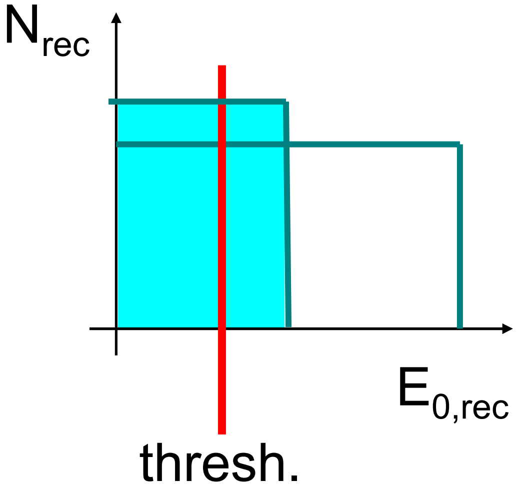
tutorial

$v_\chi = 10^{-3}\beta$, $\rho(DM) = 0.3\,\mathrm{GeV/cm^3}$
monoenergetic for simplicity

$E_{0,rec} = E_{\chi,kin} \times M_{red.}$
$= 1/2\, m_\chi c^2 \beta^2 \times 4 m_\chi m_{Ge}/(m_\chi + m_{Ge})^2$

$m_\chi \sim 72\,\mathrm{GeV} \rightarrow E_{0,rec} \sim 36\,\mathrm{keV}$





$m_\chi < m_{Ge}$

$\rightarrow E_{\chi,kin} \searrow$
$\rightarrow M_{red.} \searrow$
$\rightarrow E_{0,rec} \searrow\searrow$
$\rightarrow n_\chi \nearrow$

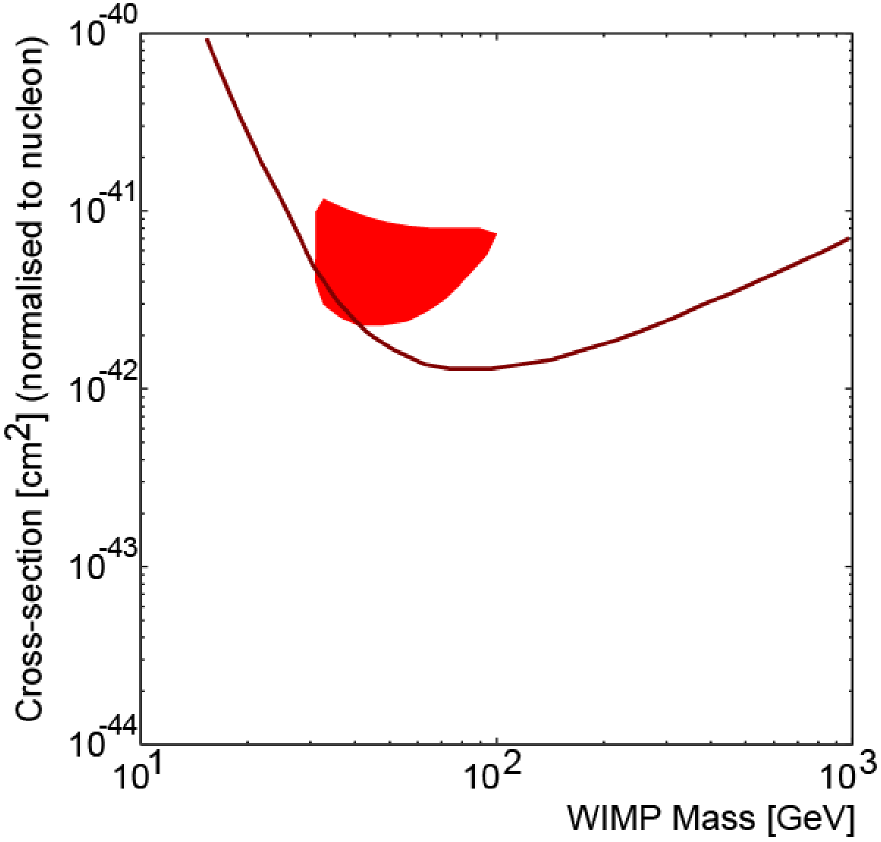
from exptl. spectra to WIMP parameters

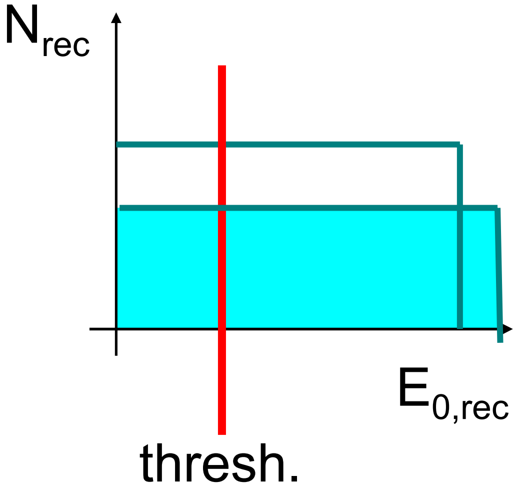
tutorial

$v_\chi = 10^{-3}\beta$, $\rho(DM) = 0.3\,\mathrm{GeV/cm^3}$
monoenergetic for simplicity

$$E_{0,rec} = E_{\chi,kin} \times M_{red.}$$
$$= 1/2\, m_\chi c^2 \beta^2 \times 4 m_\chi m_{Ge} / (m_\chi + m_{Ge})^2$$

$m_\chi \sim 144\,\mathrm{GeV} \rightarrow E_{0,rec} \sim 64\,\mathrm{keV}$





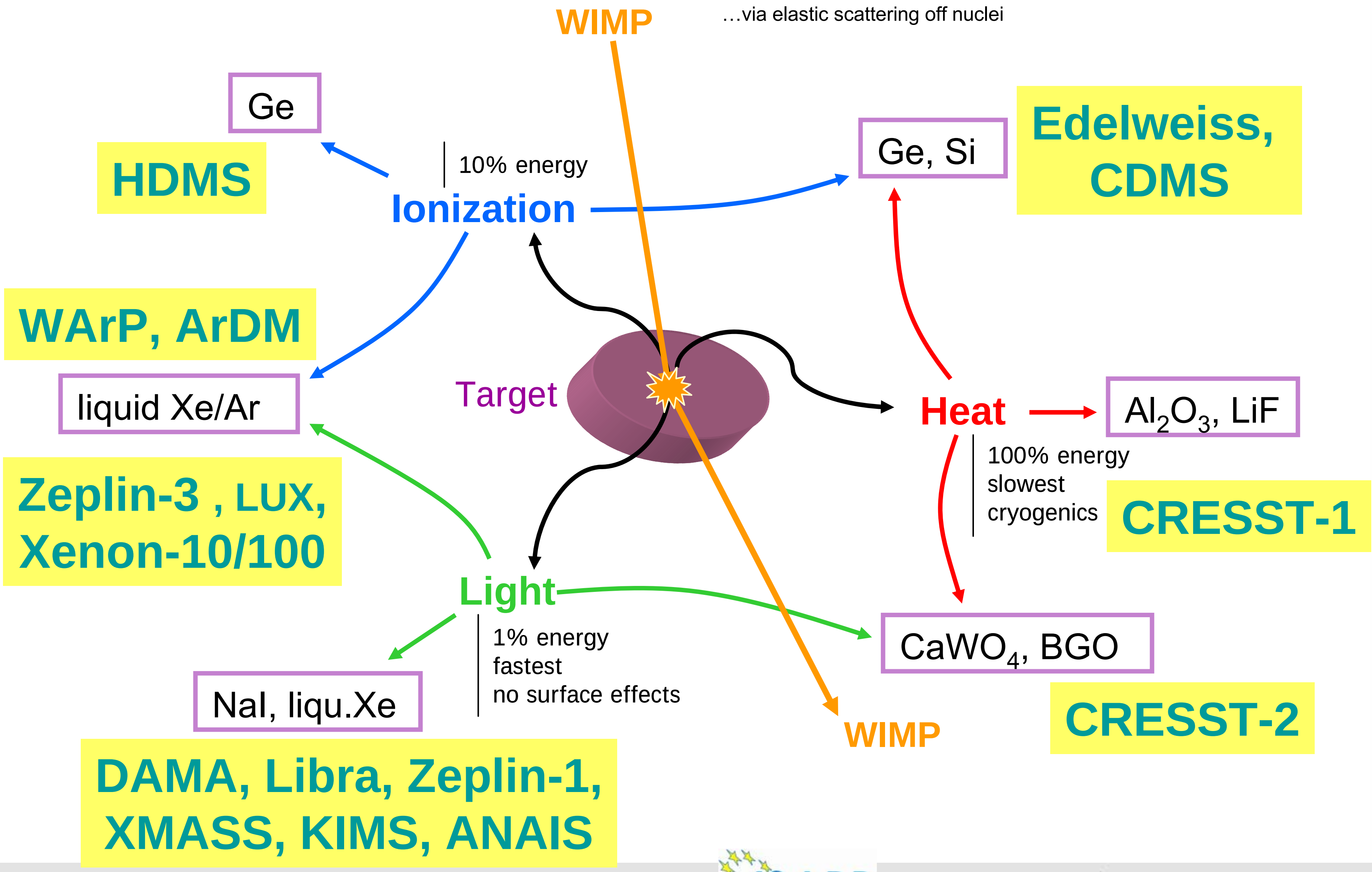
$m_\chi = 2 m_{Ge}$

$\rightarrow E_{\chi,kin}$ ↗
$\rightarrow M_{red.}$ ↘
$\rightarrow E_{0,rec}$ →
$\rightarrow n_\chi$ ↘

no events → exclusion curve

events → (m_χ, $\sigma_{\chi\text{-}n}$) with errors

WIMP(χ) direct detection schemes



WIMP

…via elastic scattering off nuclei

Ionization

10% energy

Ge

HDMS

Ge, Si

Edelweiss, CDMS

WArP, ArDM

liquid Xe/Ar

Zeplin-3 , LUX, Xenon-10/100

Target

Heat

Al_2O_3, LiF

100% energy
slowest
cryogenics

CRESST-1

Light

1% energy
fastest
no surface effects

NaI, liqu.Xe

DAMA, Libra, Zeplin-1, XMASS, KIMS, ANAIS

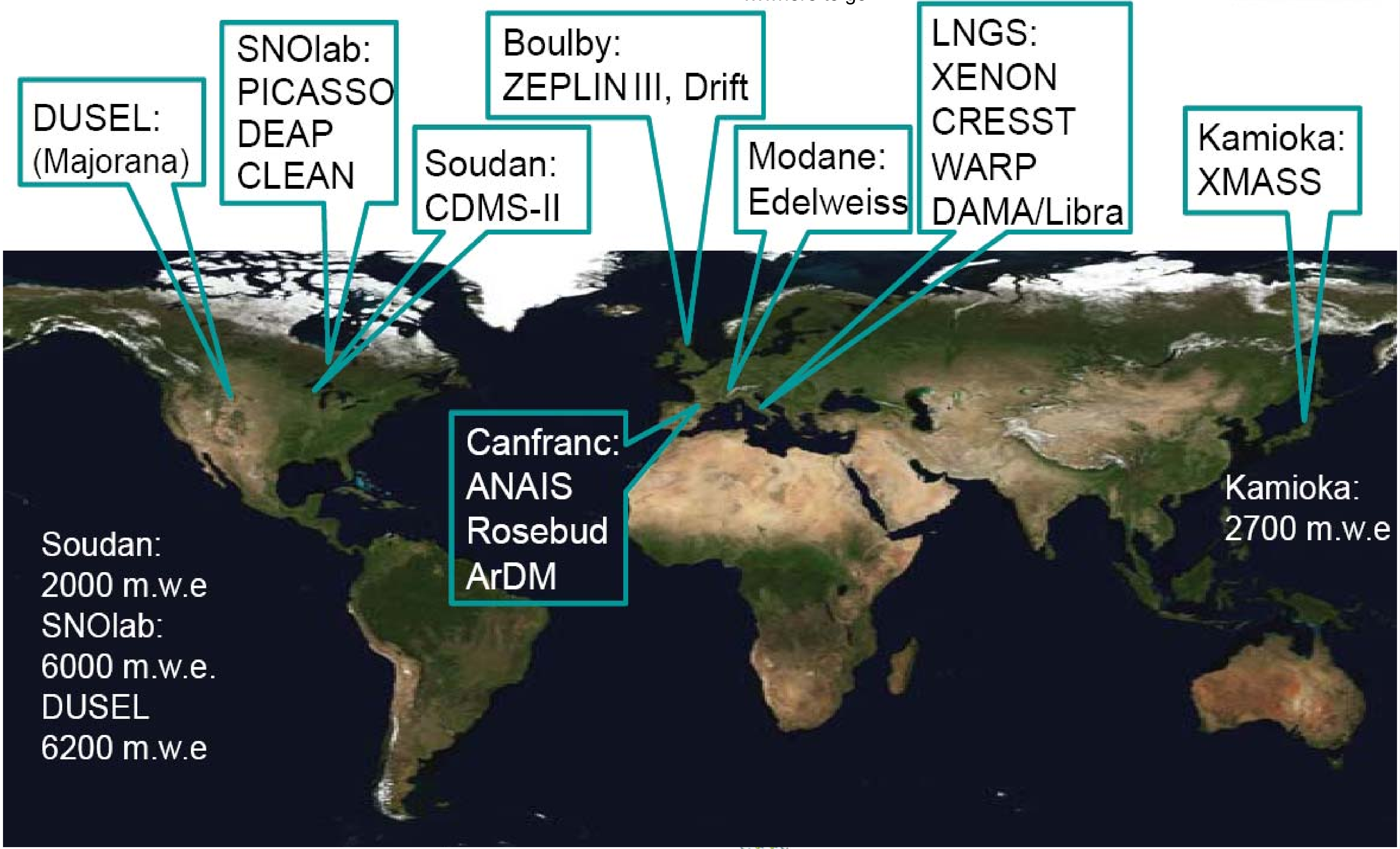
$CaWO_4$, BGO

CRESST-2

WIMP

WIMP(χ) direct detection schemes

…where to go



DUSEL:
(Majorana)

SNOlab:
PICASSO
DEAP
CLEAN

Soudan:
CDMS-II

Boulby:
ZEPLIN III, Drift

Modane:
Edelweiss

LNGS:
XENON
CRESST
WARP
DAMA/Libra

Kamioka:
XMASS

Canfranc:
ANAIS
Rosebud
ArDM

Soudan:
2000 m.w.e
SNOlab:
6000 m.w.e.
DUSEL
6200 m.w.e

Kamioka:
2700 m.w.e

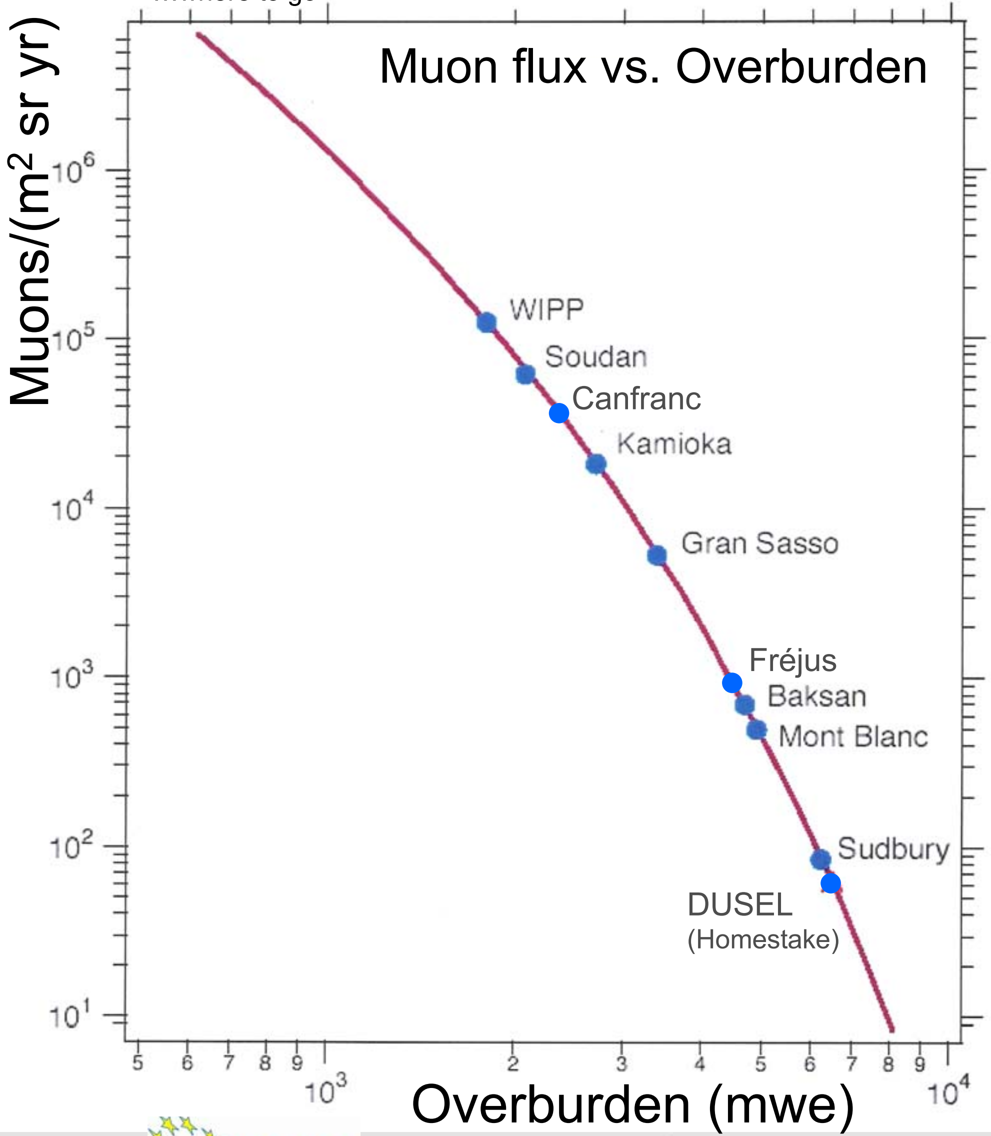
WIMP(χ) direct detection schemes

…what to do

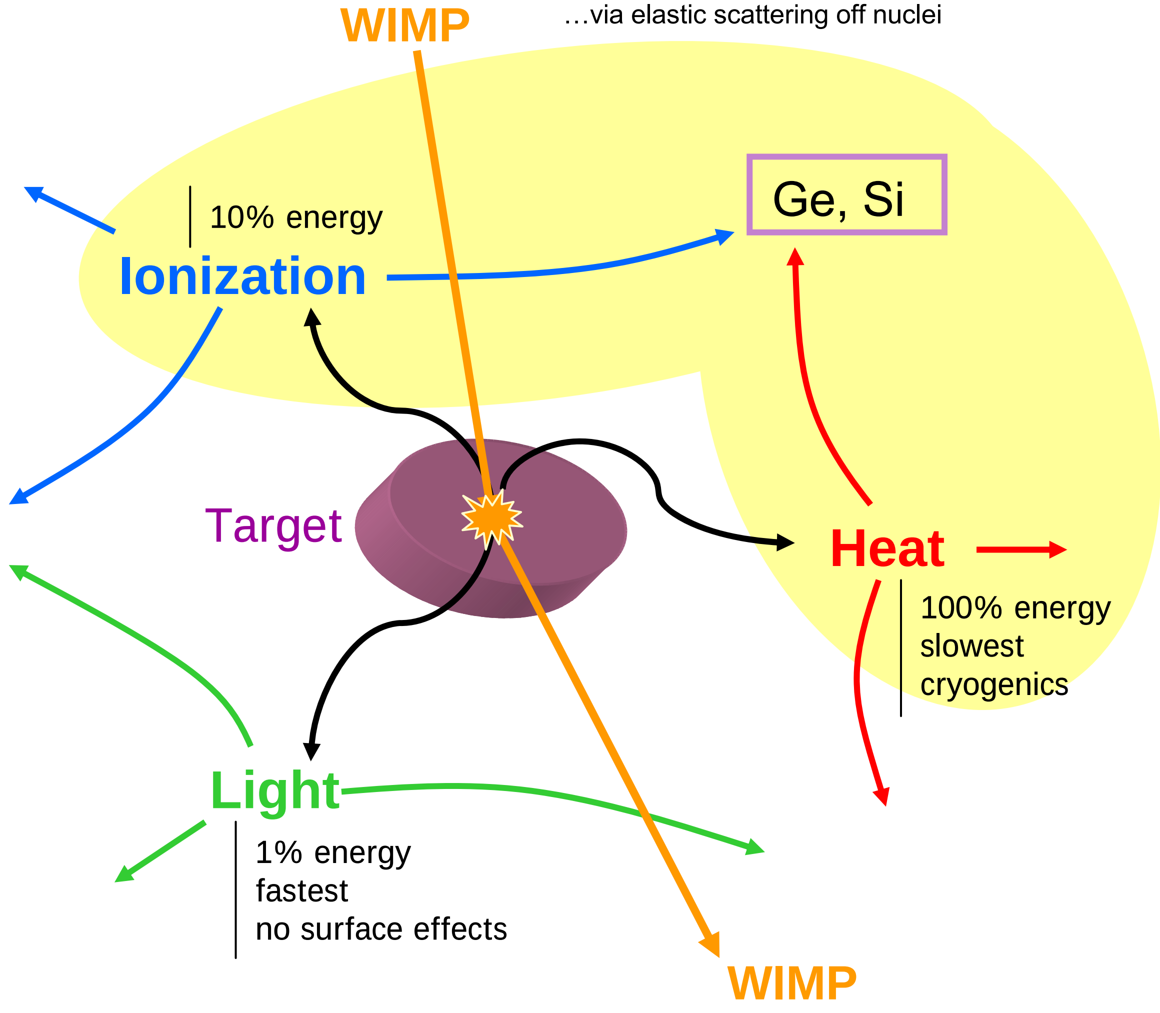
it´s all about shielding & background suppression:

- cosmic rays
- cosmic µ-induced n,p,π,α,…
- ambient activity:
  - (α,n) from rock
  - γ´s from concrete
  - ^{222}Rn in air (→^{210}Pb)
- material activity:
  - ancient Pb shield
  - HOFC copper
  - detector purification
  - PMT selection
- and active suppression!!

…where to go



Direct DM search using ionisation&heat



Ionisation&heat: principles

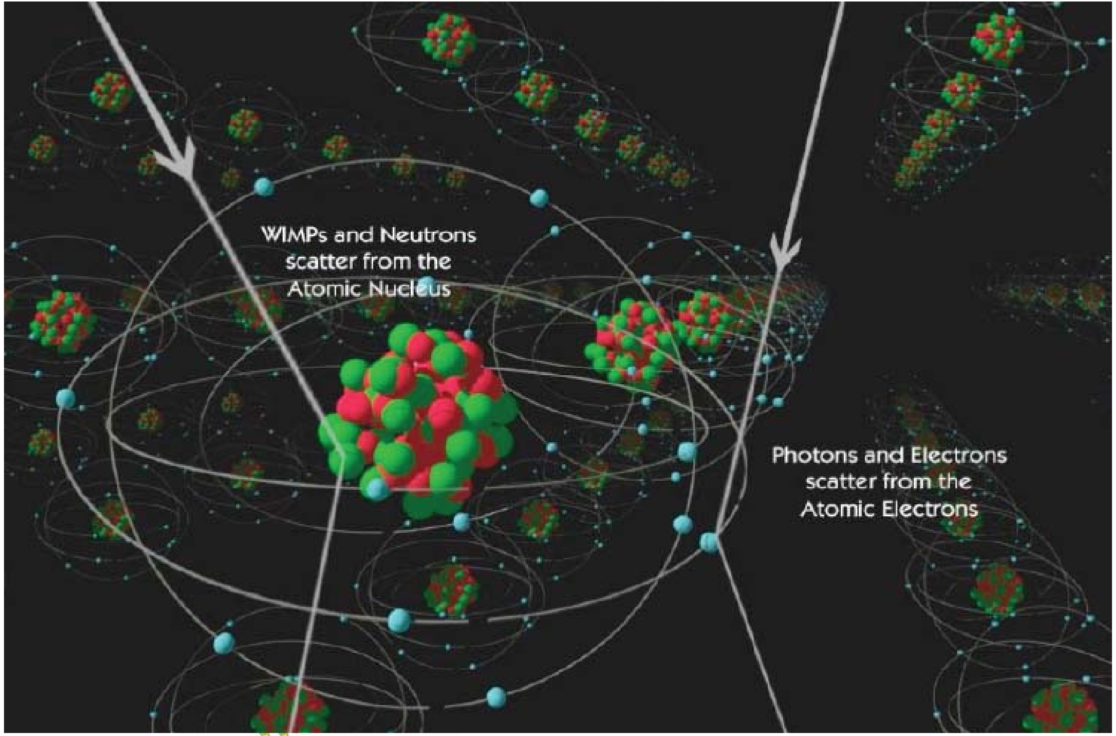
advantages:

- ➢ bolometric measurement of E_{dep}
- ➢ good energy resolution (e.g. 150eV@6keV)
- ➢ low threshold
- ➢ nuclear recoil → phonon signal → WIMP sensitivity
- ➢ PID capability via ionisation yield
- ➢ modular detectors
  → scalability

disadvantages:

- ➢ temperature few mK
  → technical challenge
- ➢ slow phonon signal
- ➢ surface events with lower ionisation yield
- ➢ limited target mass (so far)

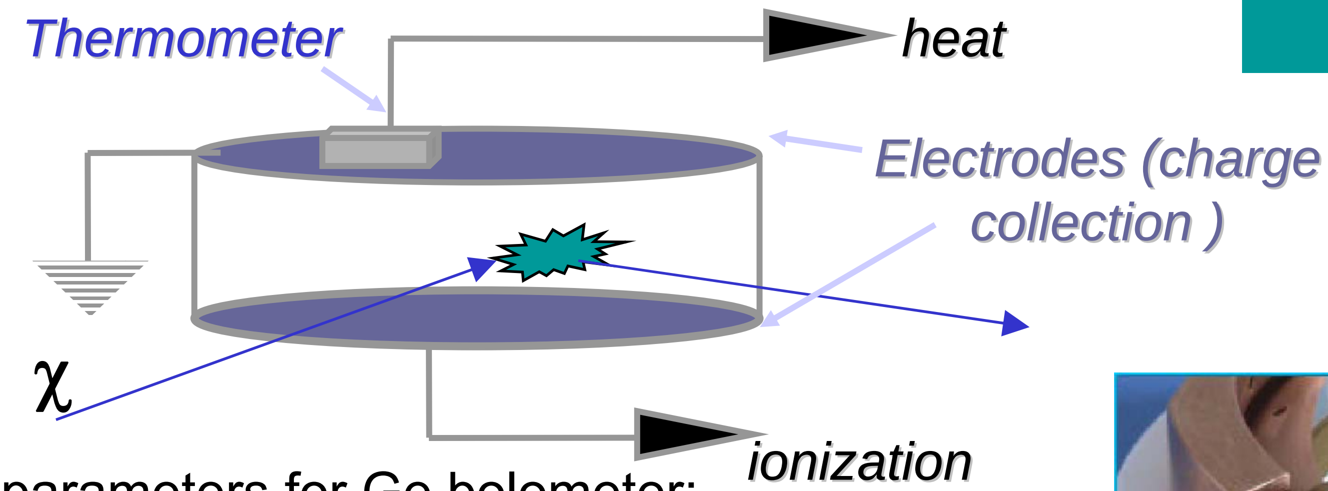
cryogenic mono-crystal



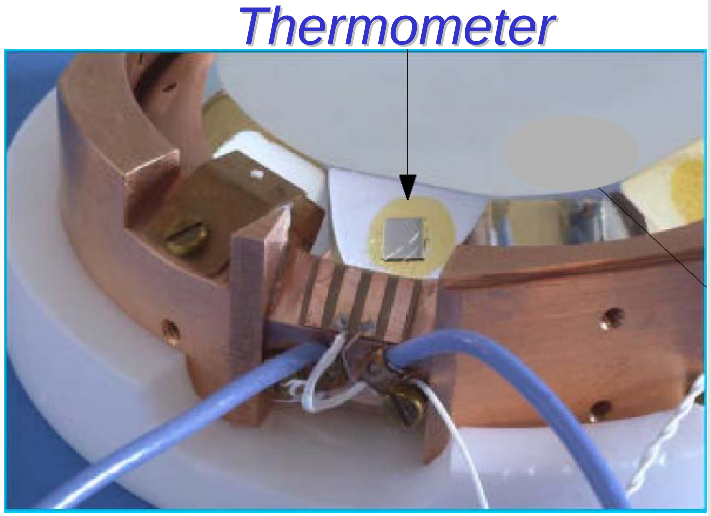
Ionisation&heat: principles

measuring principle:
χ scattering with energy deposit E_R leads to ΔT which can be read out via thermometer → detector with small $V \cdot C_V$ needed

$$\Delta T = \frac{E_R}{V \cdot C_V}$$



parameters for Ge bolometer:
$E = 3V/cm$
$T_{op} = 20mK$
$m = 300g$ (d=20mm; r=35mm)
$VC_V \sim 1nJ/K$ @ T_{op}
$G \sim 5nW/K$ thermal link to heat bath

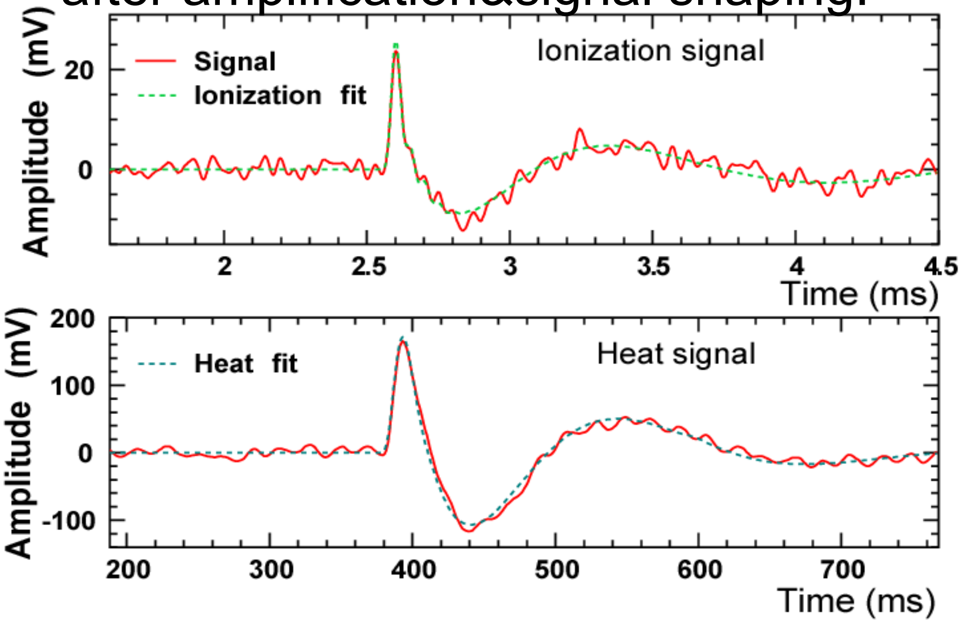


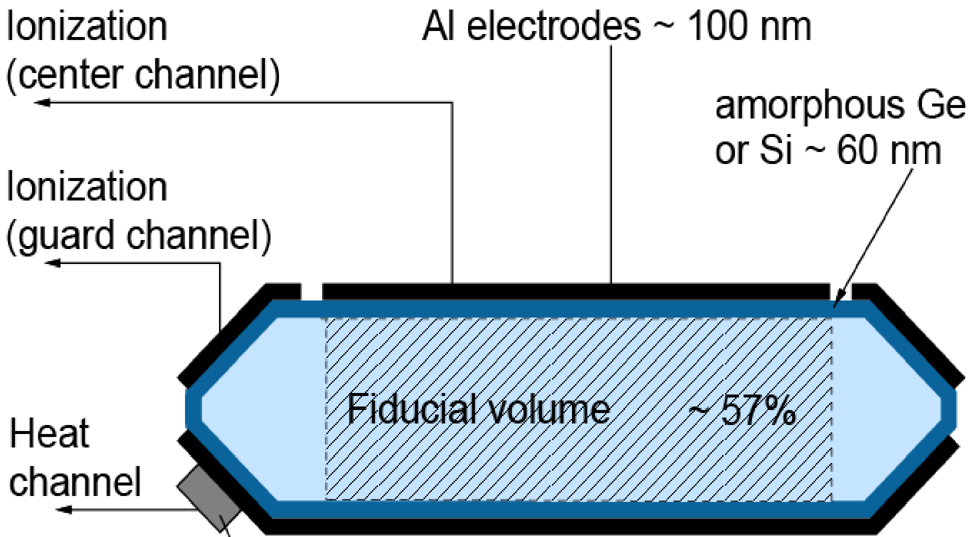
Ionisation&heat: pulses & signals

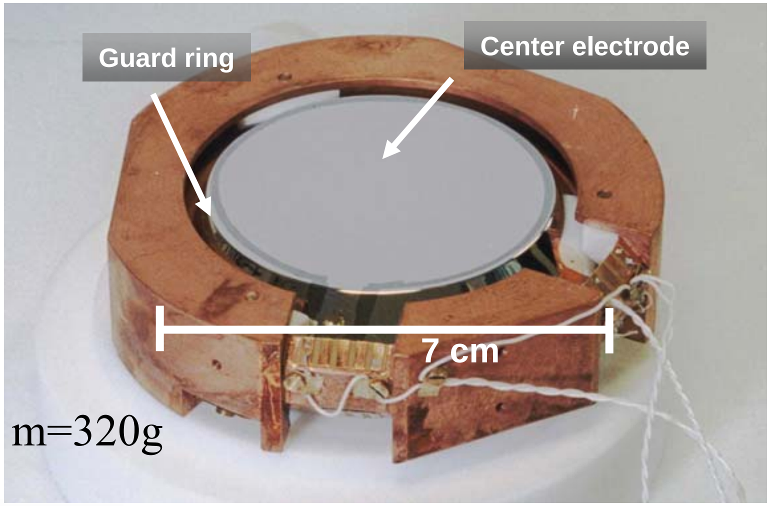
Ge-NTD detector in EDELWEISS:

$E \sim 10\ \mathrm{keV}_{ee}$
heat: $\Delta T = 1.3\mu K$; $\Delta U = 1\mu V$
$t_{rise} \sim 10\mu s - 10ms$; $t_{fall} \sim 100ms$
ionisation: $\Delta U = 0.5mV$
$t_{rise} \sim 100ns - 1\mu s$; $t_{fall} \sim 100\mu s$

after amplification&signal shaping:

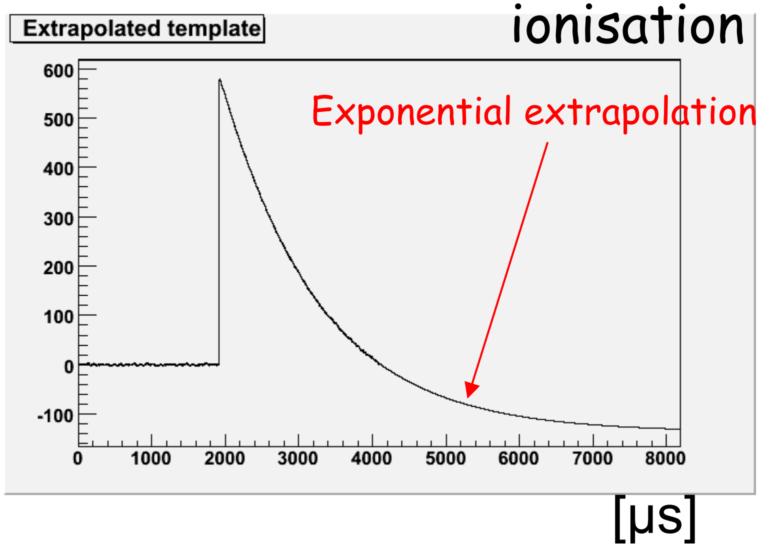


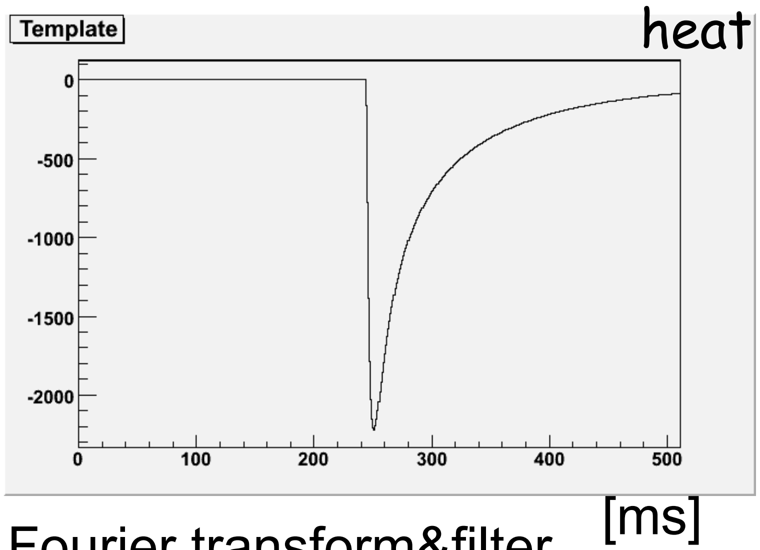




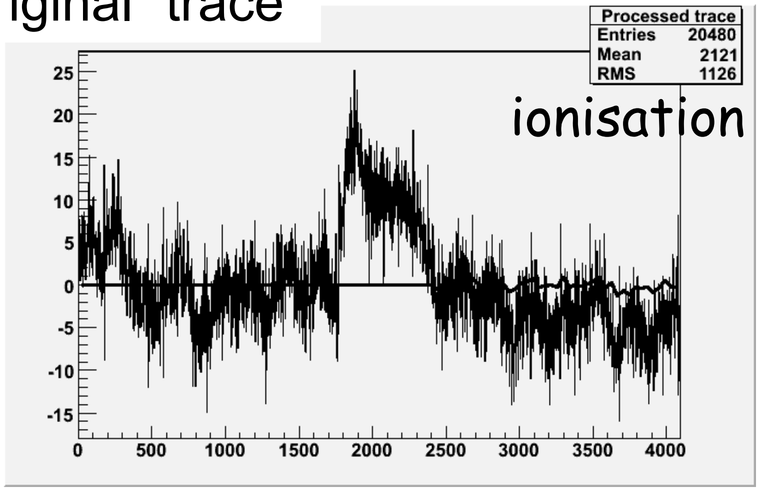
Ionisation&heat: pulses & signals

Templates built by event summation:

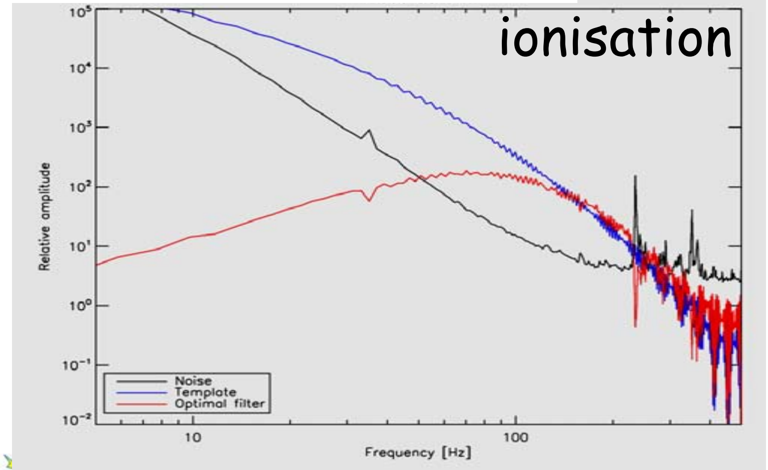




original “trace”



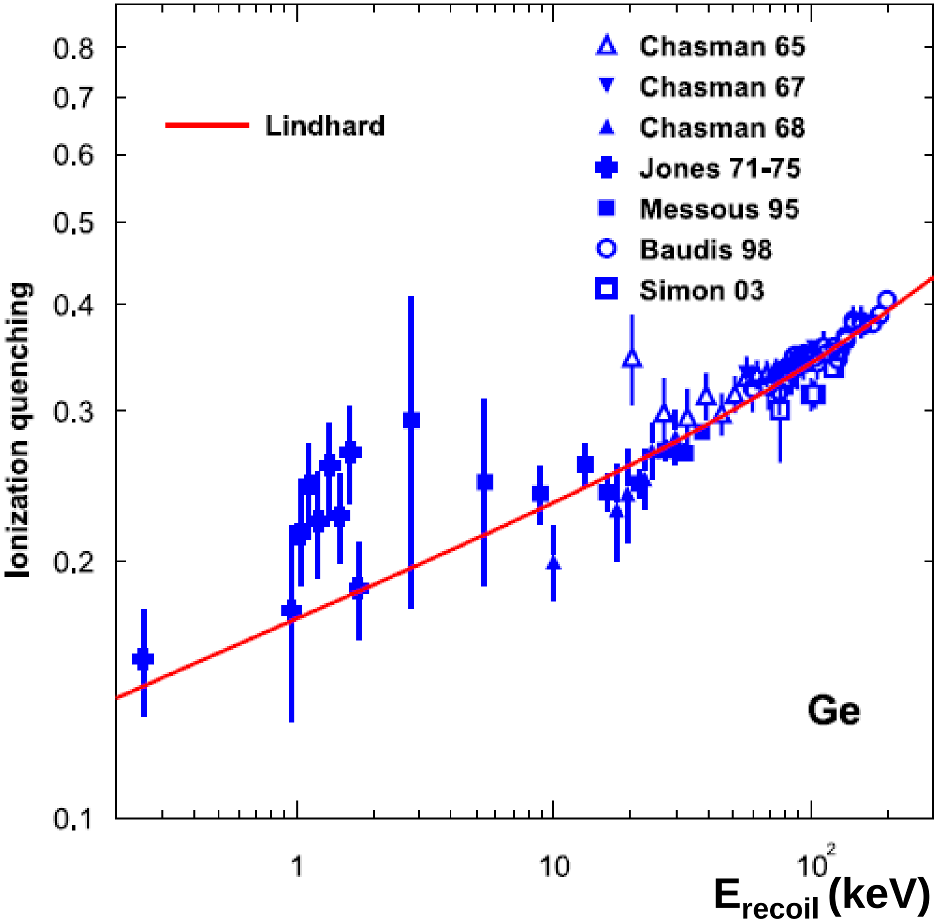
Fourier transform&filter

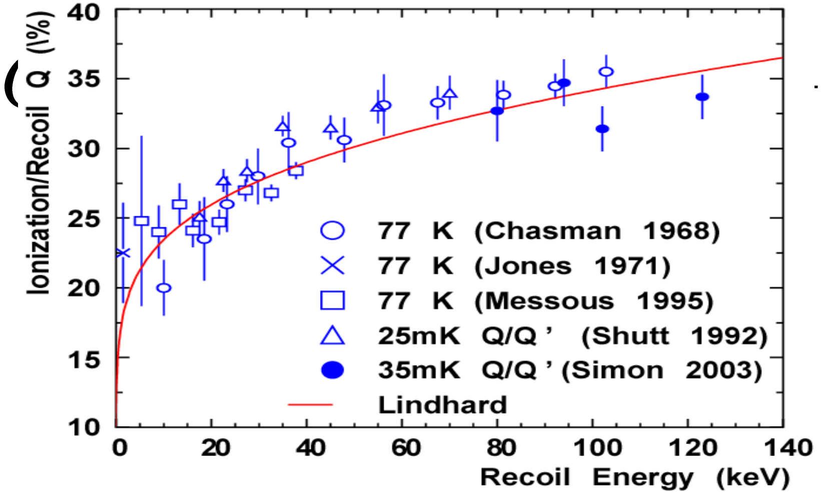


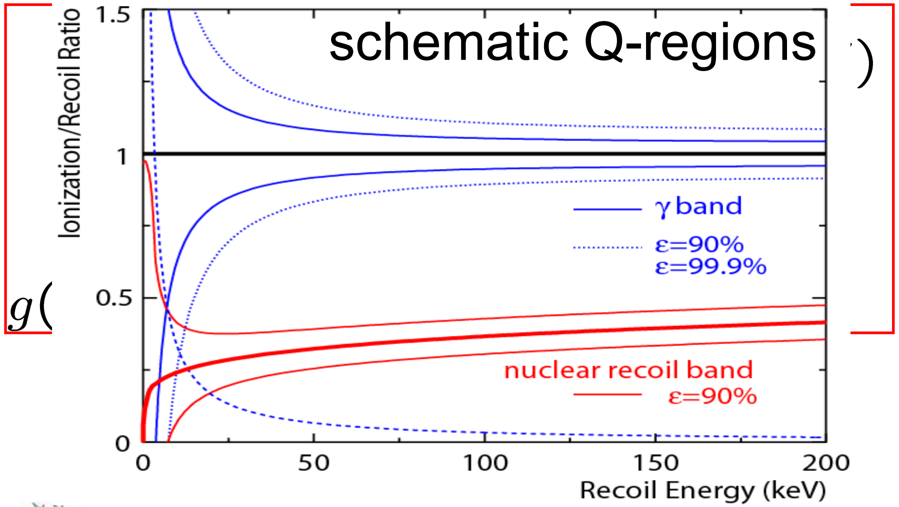
Ionisation&heat: quenching of ionisation

quenching of the ionisation signal
for nuclear recoils (in electron-equivalents)

➔ particle separation





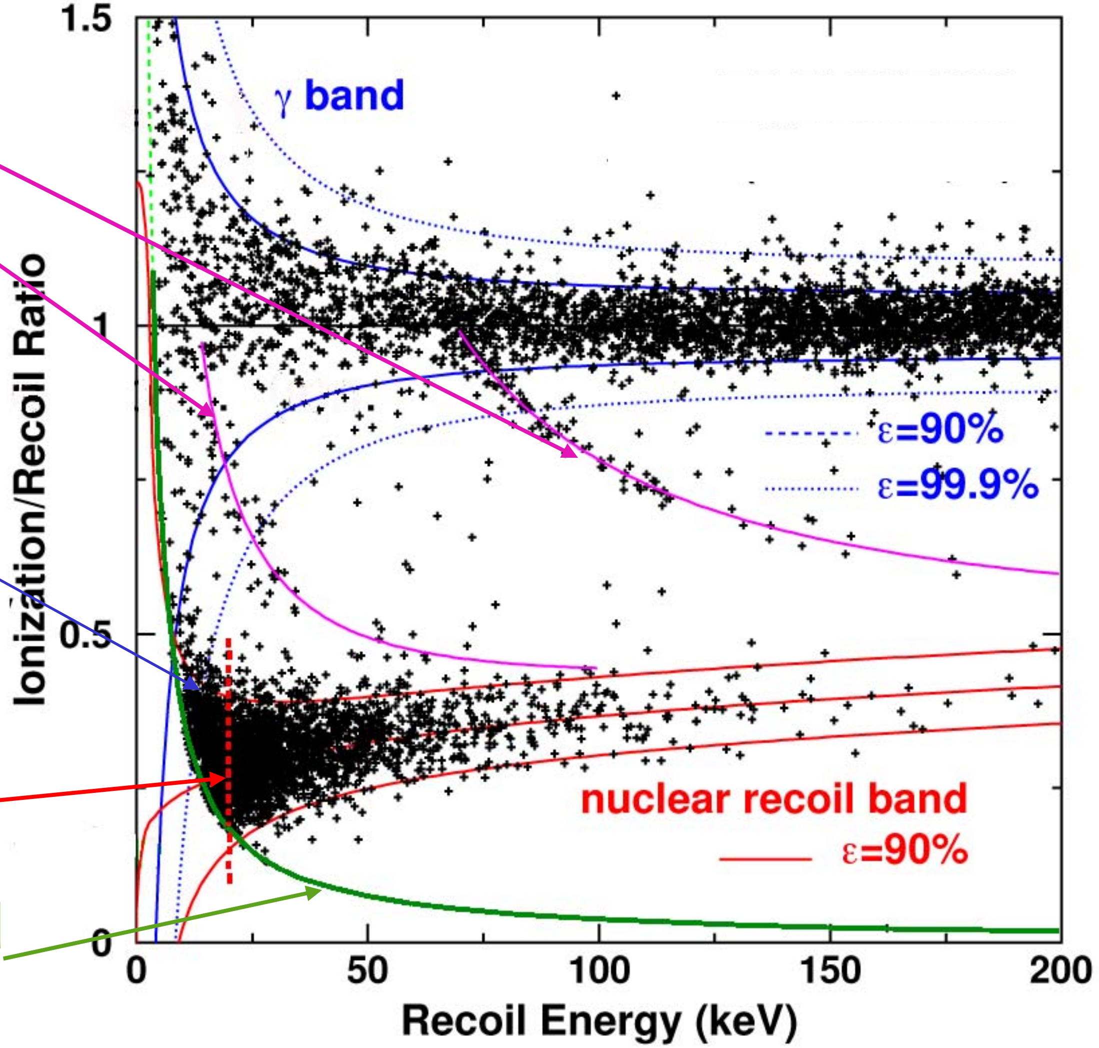


A. Benoit et al. NIM A577 (2007) 558

no quenching in (nuclear) phonon signal!

Ionisation&heat: calibration

calibration of a 320g Ge bolometer with ^{252}Cf (EDELWEISS)



^{73}Ge(n,n'γ) 68.8 keV
13.3 keV

n/γ discrimination
> 99.9%
for E_r >15 keV

Recoil threshold
20 keV

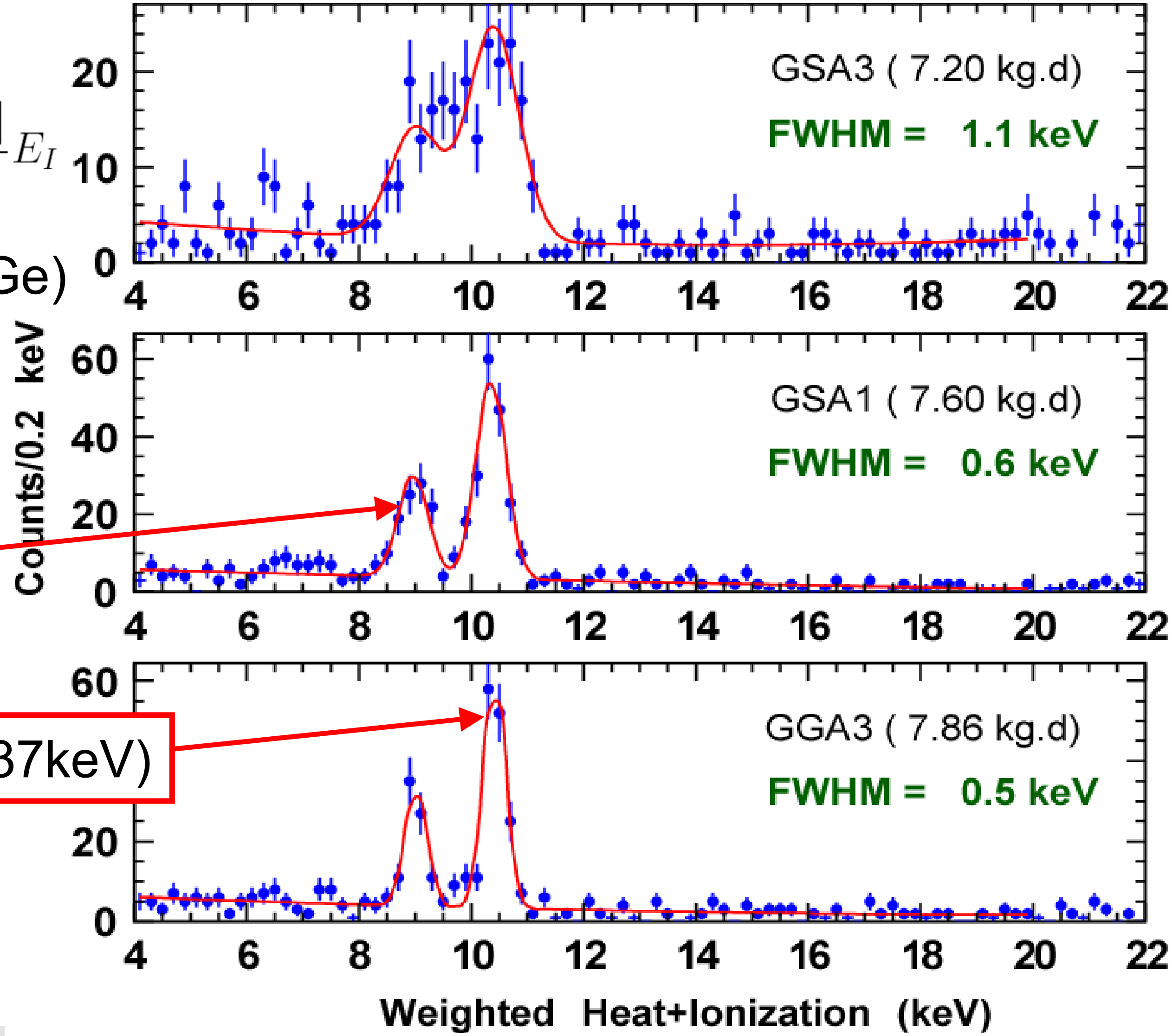
Ionization threshold
3.7 keV

Ionisation&heat: calibration

$$E_R = (1 + \frac{|V_{bias}|}{\epsilon_\gamma})E_H - \frac{|V_{bias}|}{\epsilon_\gamma}E_I$$

$Q = \frac{E_I}{E_R}$ and $\varepsilon_\gamma \approx 3.0V$ (Ge)

$V_{bias} = -4.0V$

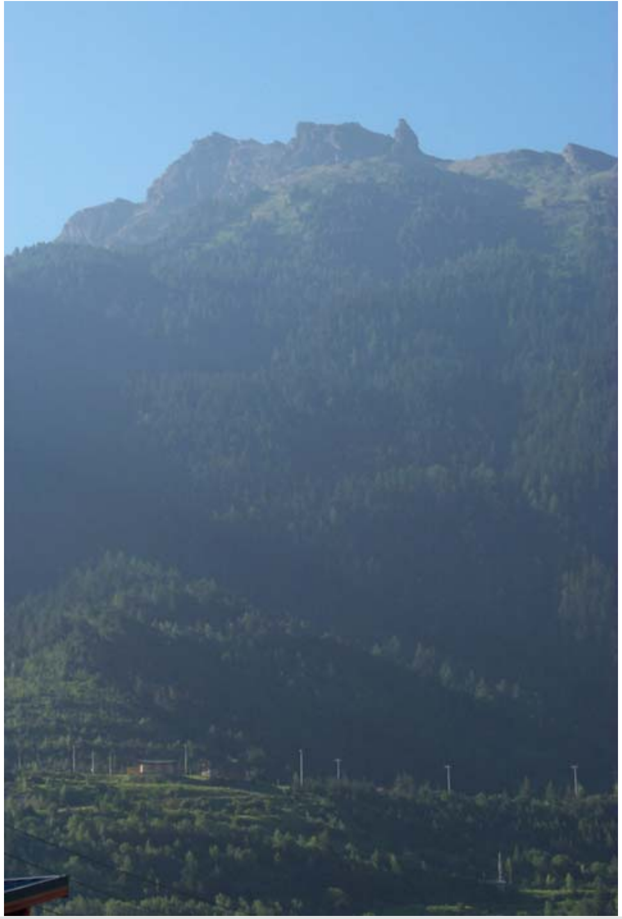


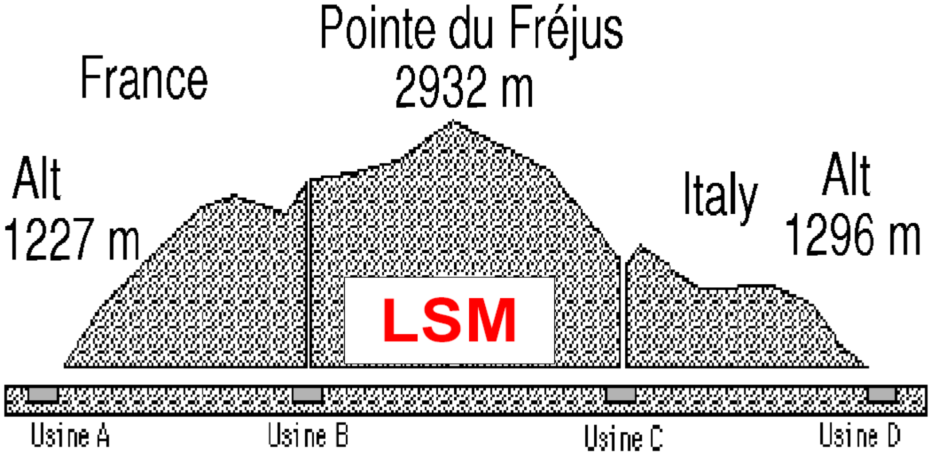
^{65}Zn EC (8.98keV)

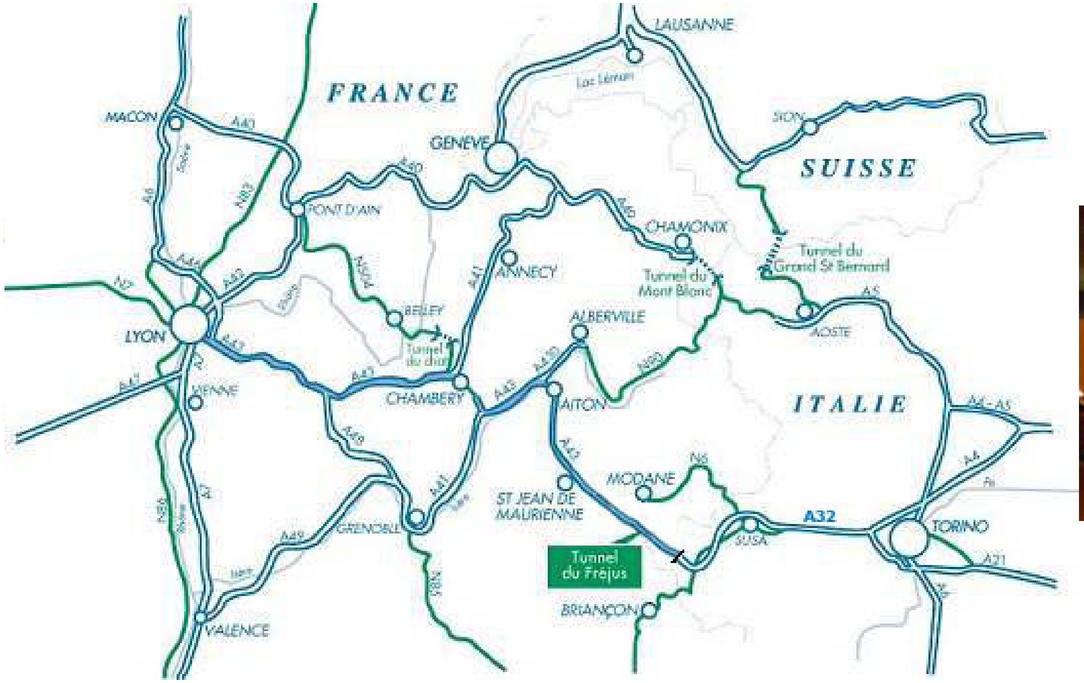
^{68}Ge+^{71}Ge EC (10.37keV)

EDELWEISS @ LSM

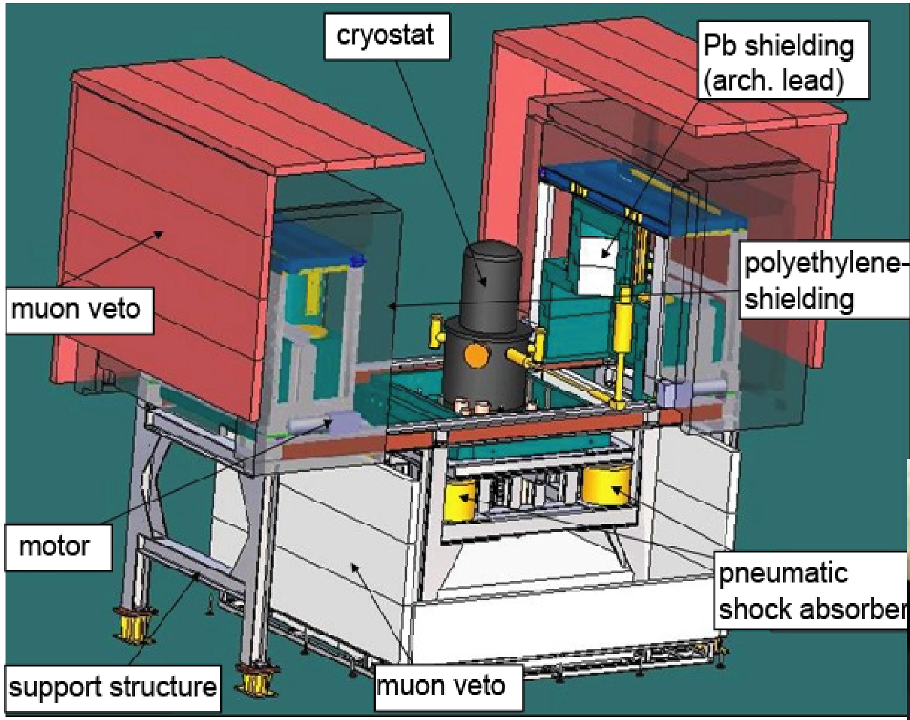
LSM
LABORATOIRE SOUTERRAIN DE MODANE

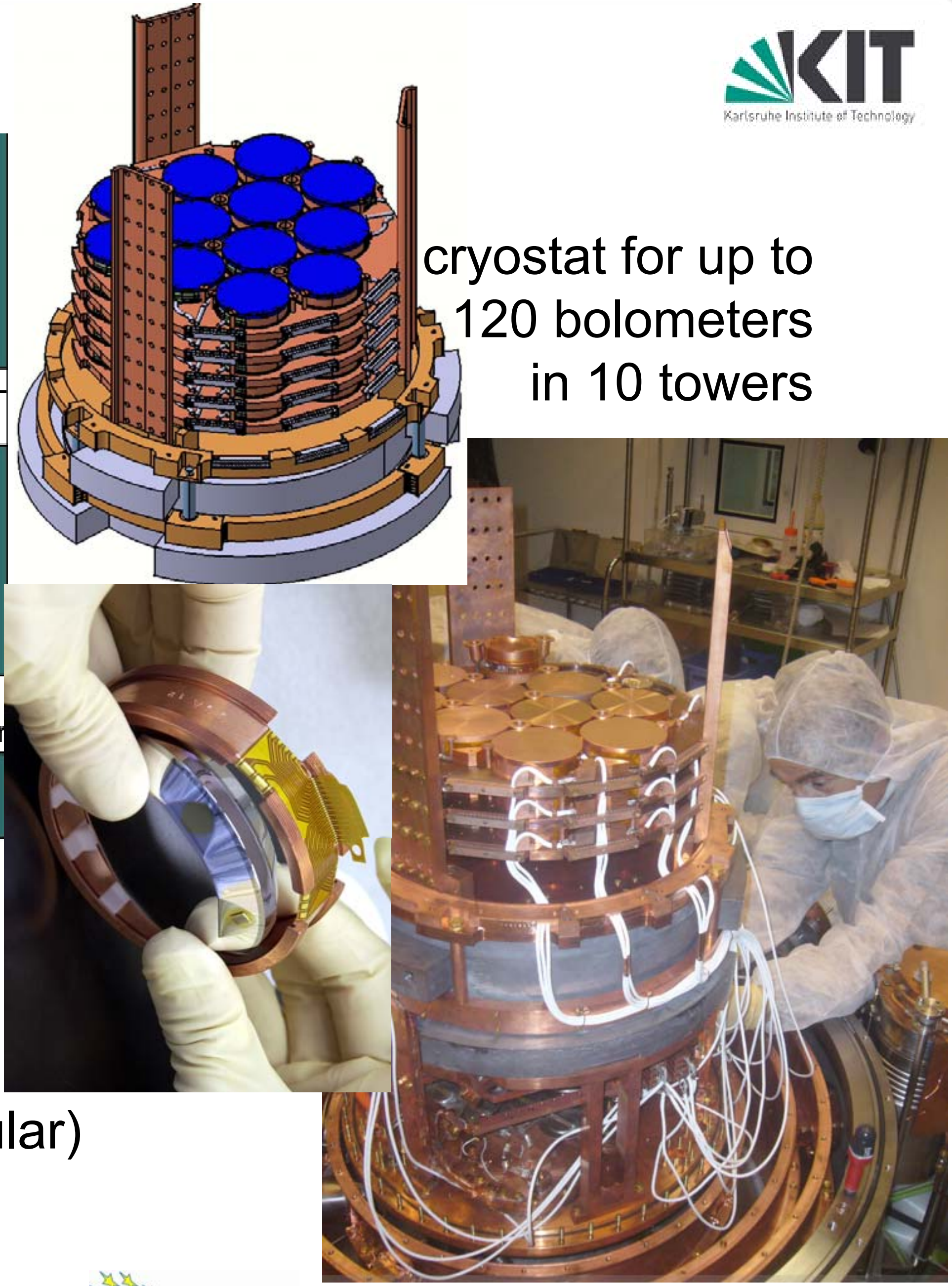






EDELWEISS @ LSM





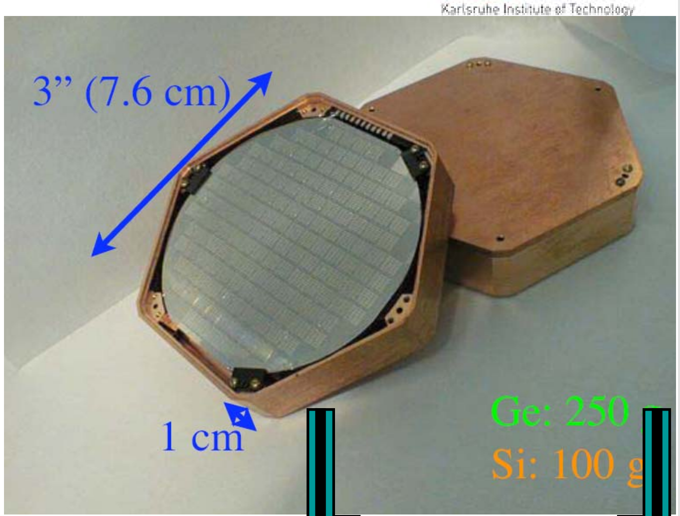
cryostat for up to
120 bolometers
in 10 towers

features:

- reversed cryostat (100l volume)
- shielded by 20cm Pb & 50cm PE
- atmosphere filtered against Rn
- hermetic active μ veto (100m^2 modular)
- 4 types of detectors in operation
- data taking since end of 2007

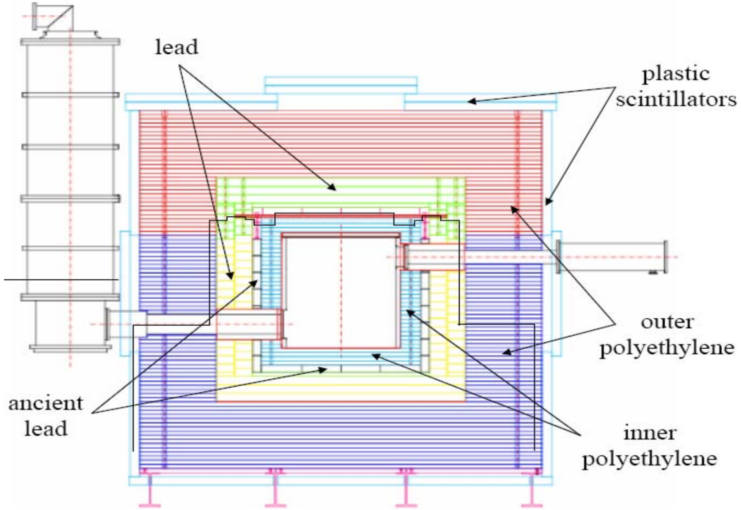
CDMS @ Soudan

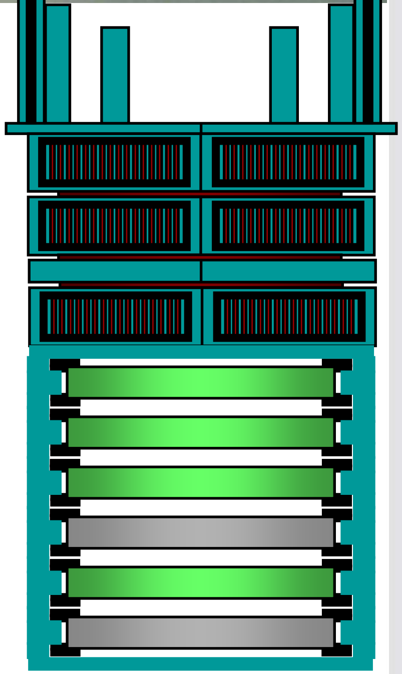
Soudan Mine, Minnesota



features:

- 30 detectors
  installed in 5 towers
- 4.75kg Ge & 1.1kg Si det´s
- data taking since 10/2006
  (>1000kg.d raw data)
- data published for 121.3kg.d effective exposure
  (arXiv:0802.3530v2; PRL 102, 011301 (2009))

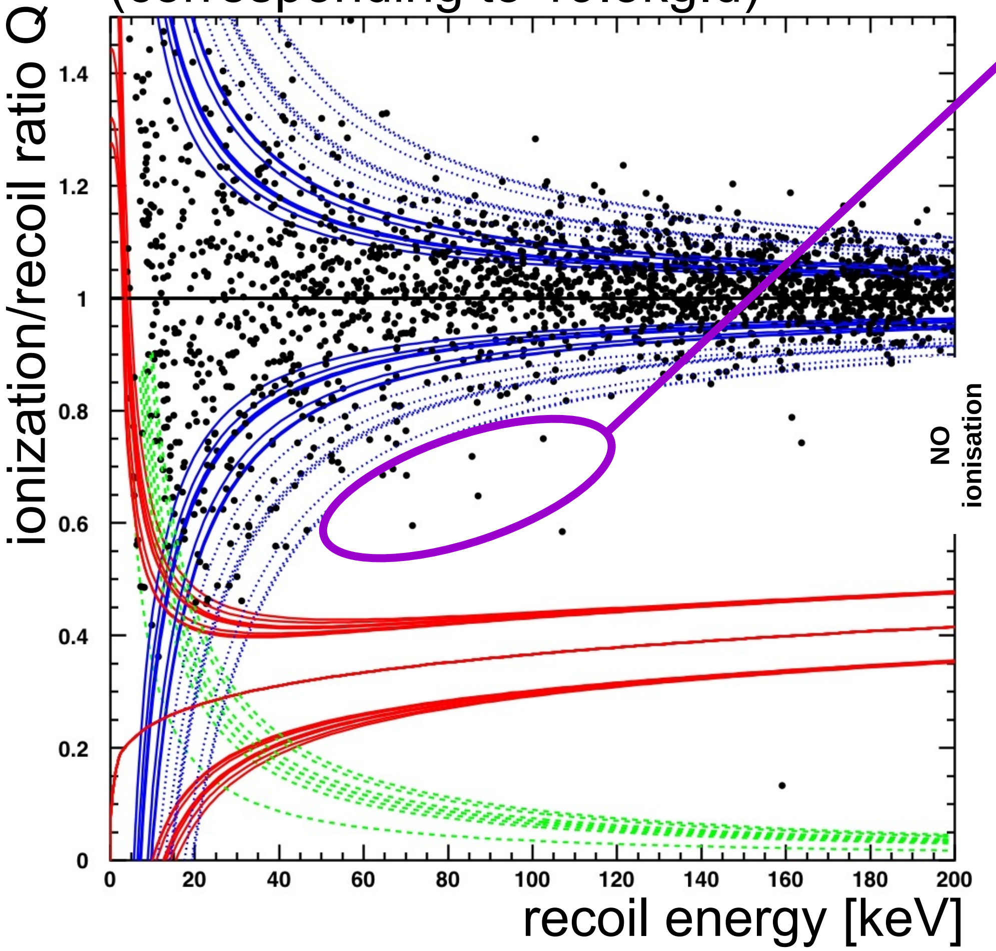


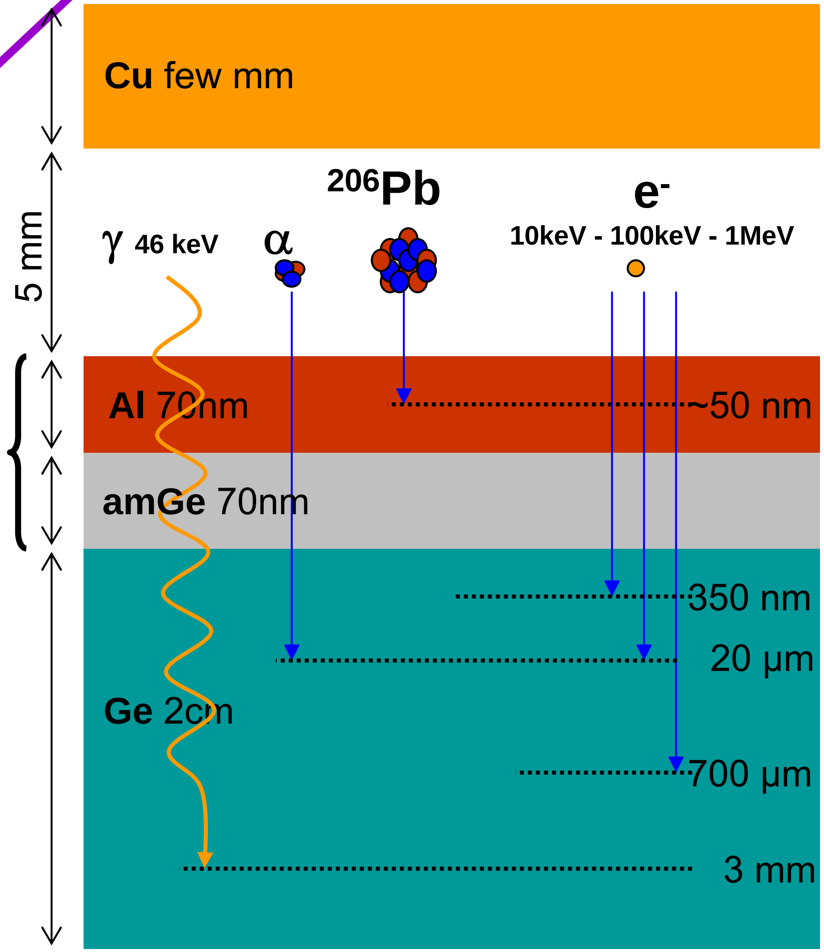


EDELWEISS @ LSM

data taken with 8 Ge-**NTD**-detectors (corresponding to 19.3kg.d)

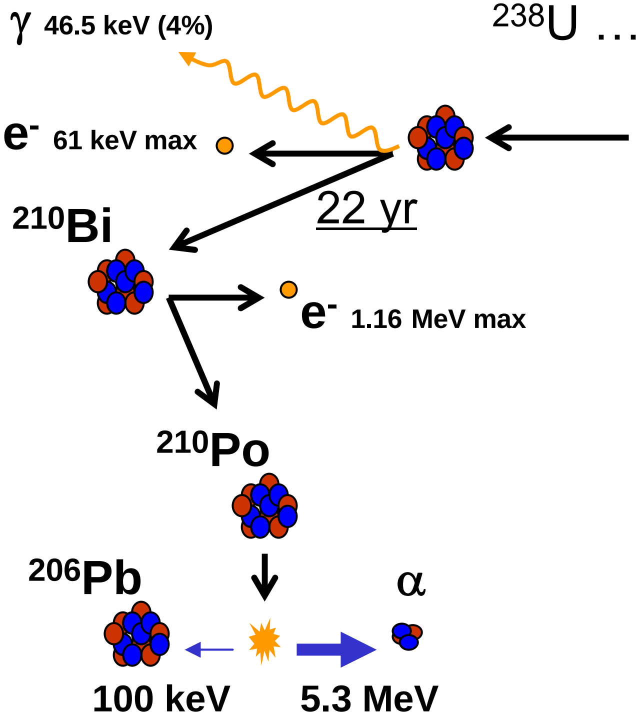
events with incomplete charge collection: “surface events”

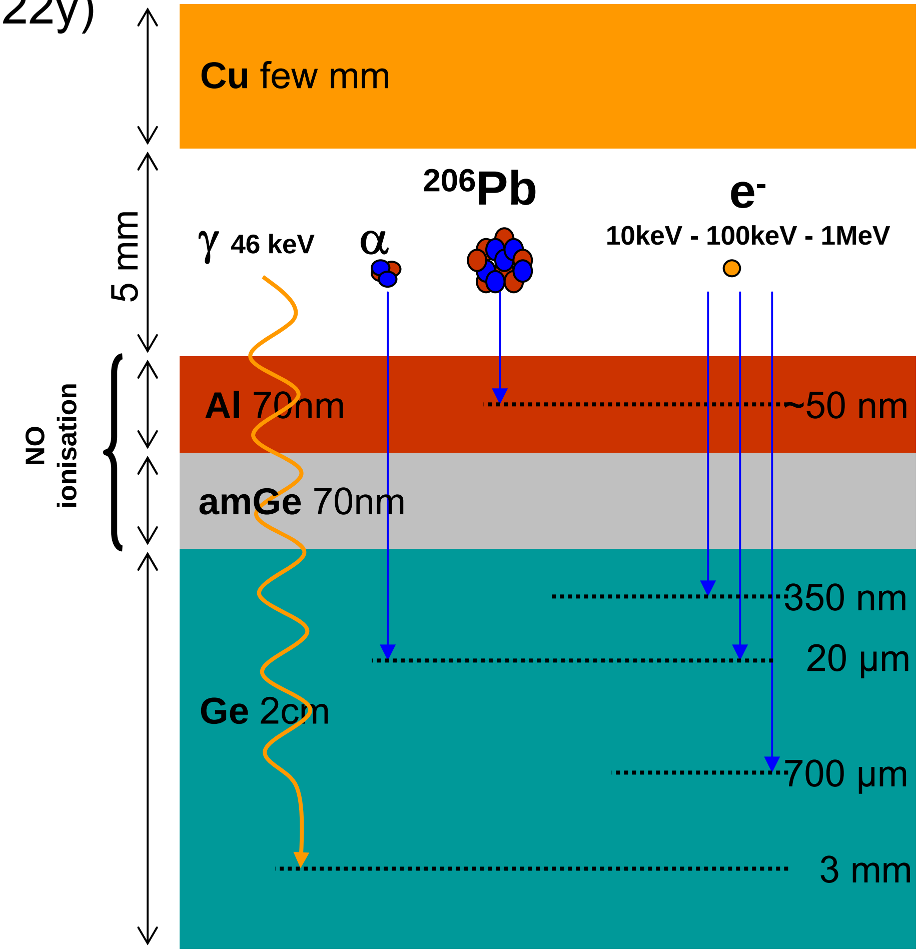




EDELWEISS @ LSM: bgd from Rn

^{238}U …→^{226}Ra(1600y)→^{222}Rn(3.8d)→^{218}Po(3.1min)→
^{214}Pb(26min) →^{214}Bi(19min)→^{214}Po(19min)→
^{210}Pb(22y)





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

Ionisation&heat: the challenge of rejecting surface events

strategy:

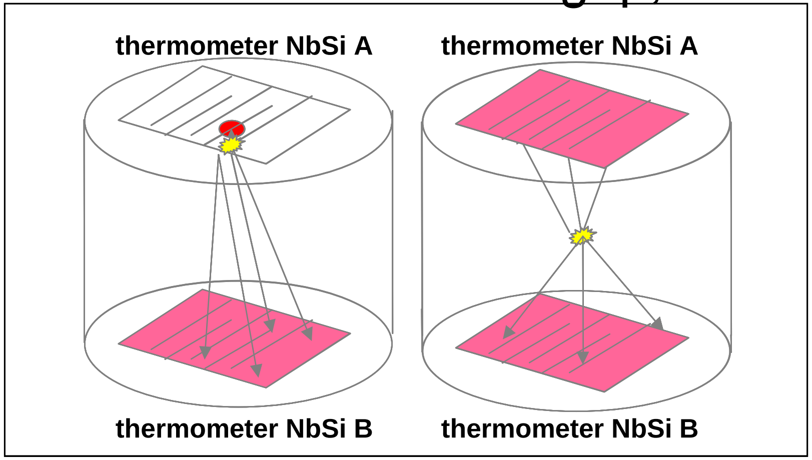
1. reduction of background sources
   (cleaning, material selection, air filtering, …)

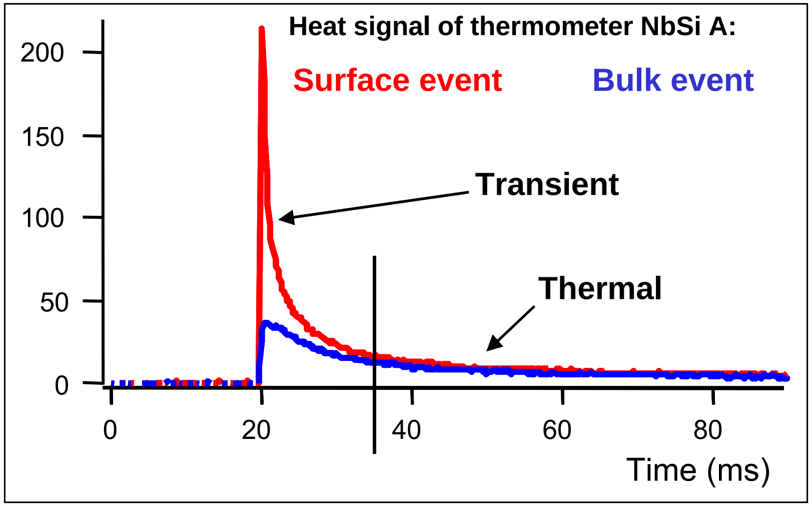
2. active suppression via phonon signal

3. active suppression via ionisation signal

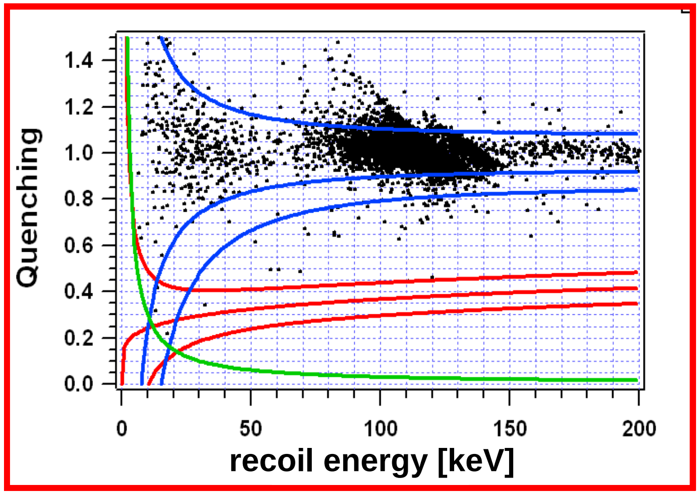
rejection of surface events

… via phonon signal (Edelweiss):
70nm thin film thermometer made of Nb_xSi_{1-x}
comb structure: 0.5mm gap, width 50µm, x=0.085





after rejection (1mm)

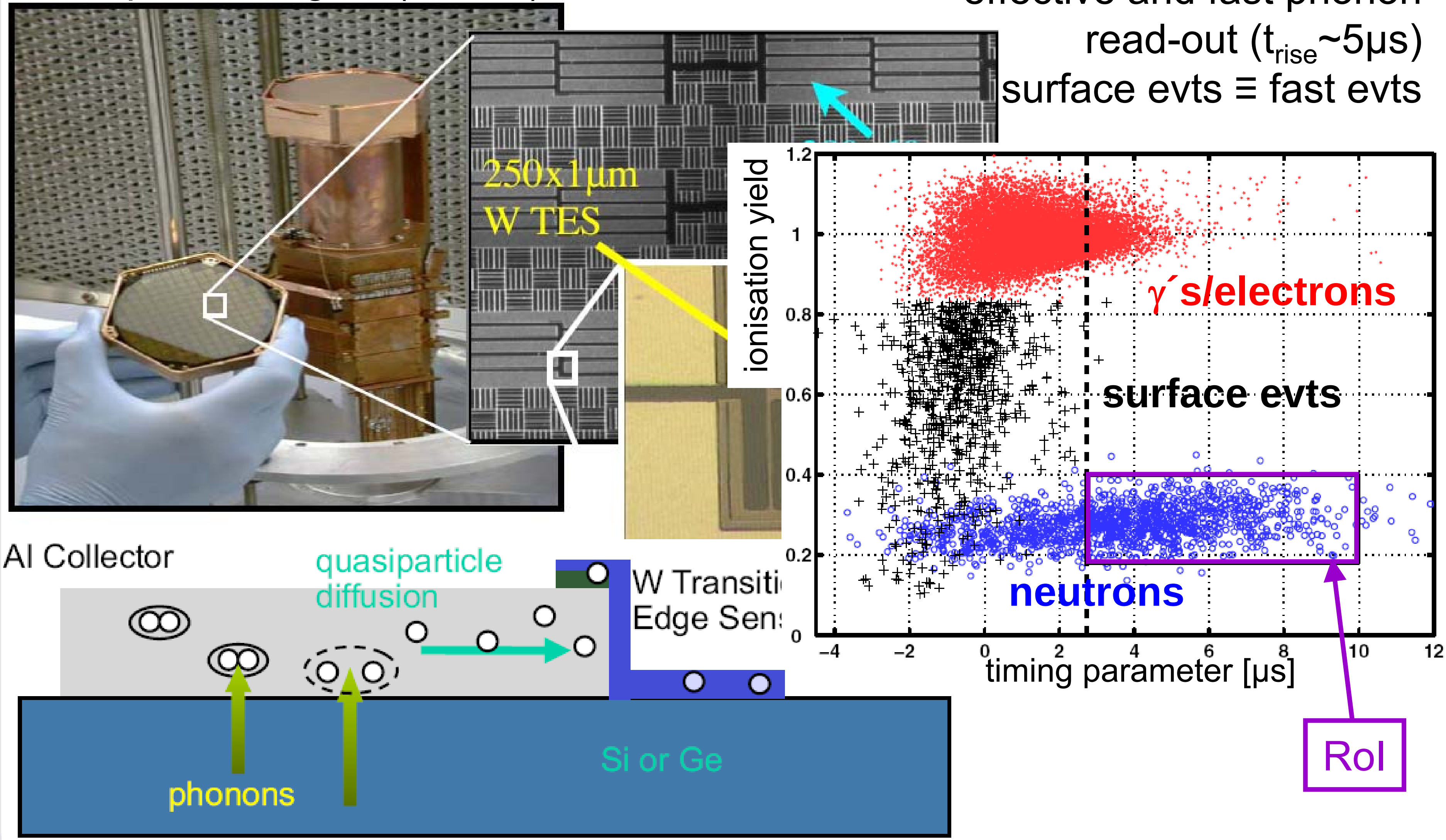


discrimination improvement of a factor of 20
fiducial volume reduction of ~10% only

rejection of surface events

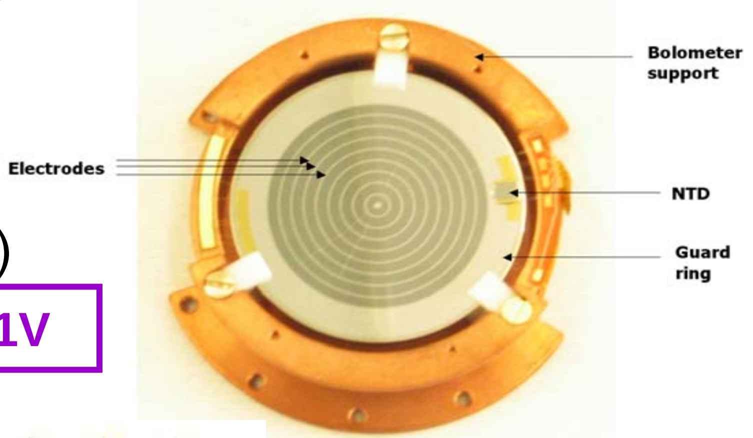
… via phonon signal (CDMS):

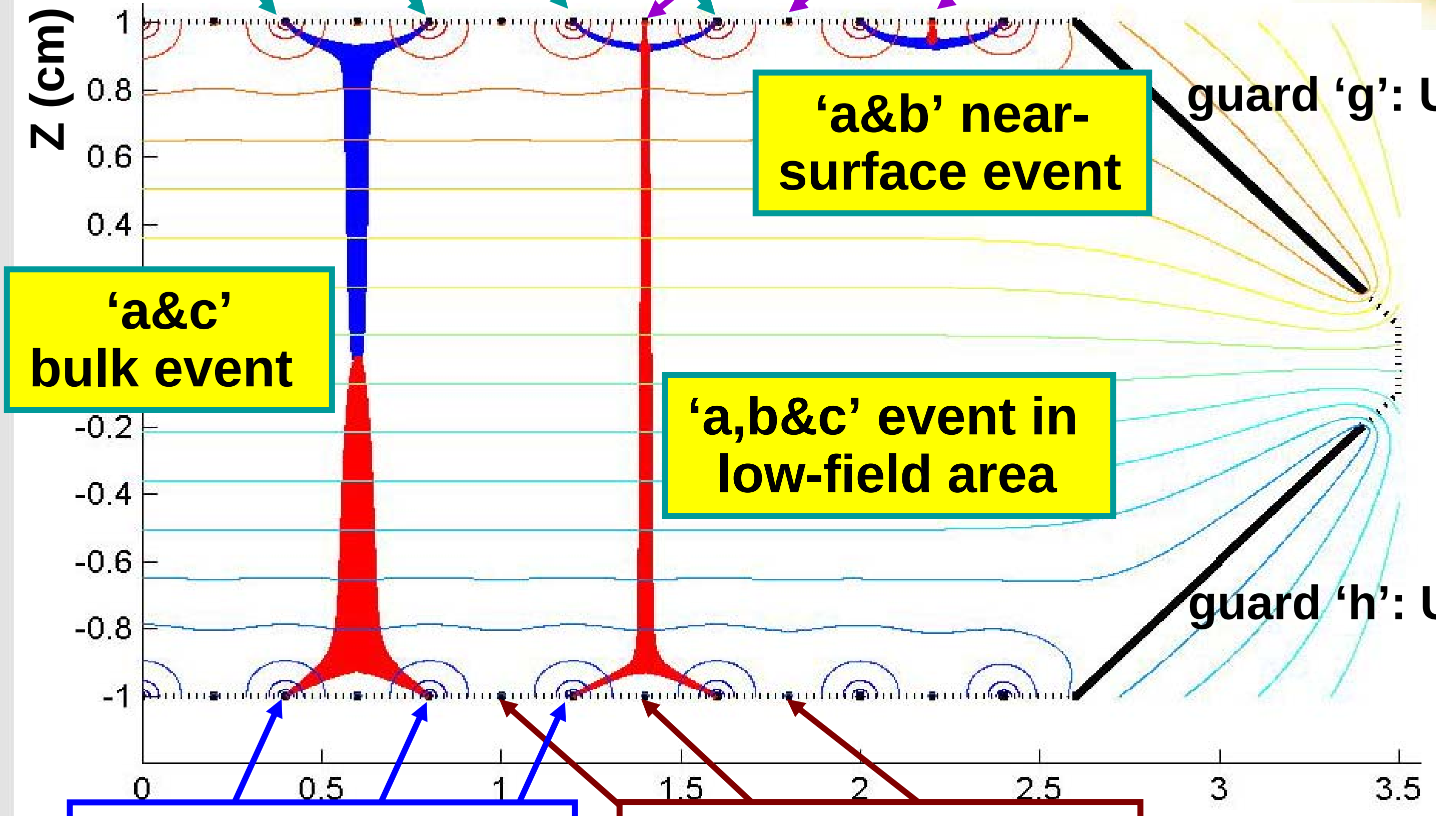
effective and fast phonon read-out (t_{rise}~5µs)
surface evts ≡ fast evts



rejection of surface events

… via ionisation signal (Edelweiss):
interleaved electrodes (width: 200µm; gap 2mm)





‘a’ electrodes: U=+2V

‘b’ electrodes: U=+1V

‘a&b’ near-surface event

guard ‘g’: U=+1V

‘a&c’ bulk event

‘a,b&c’ event in low-field area

guard ‘h’: U=-1V

‘c’ electrodes:U=-2V

‘d’ electrodes: U=-1V

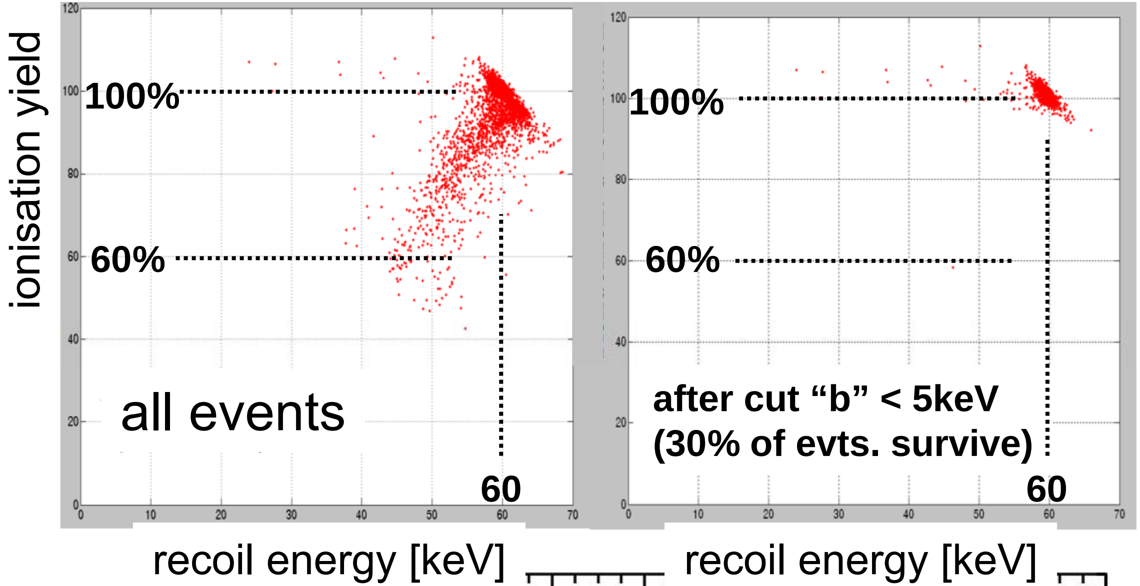
Radius (cm)

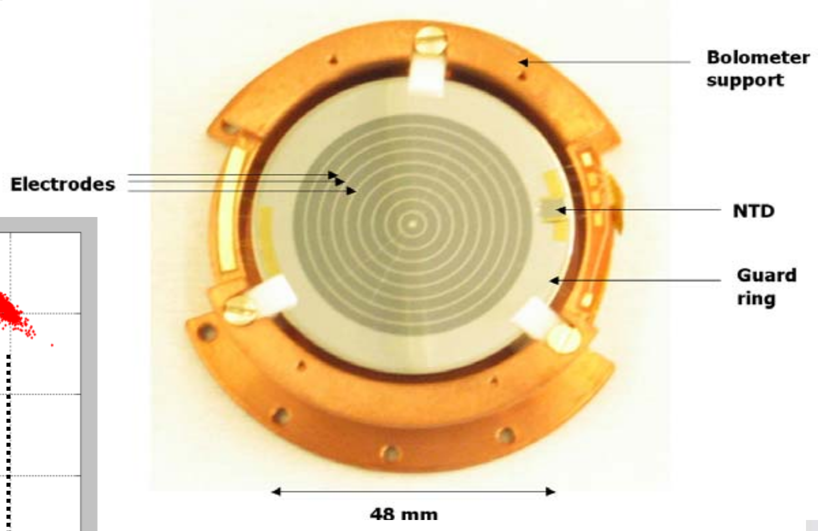
electron trajectories

hole trajectories

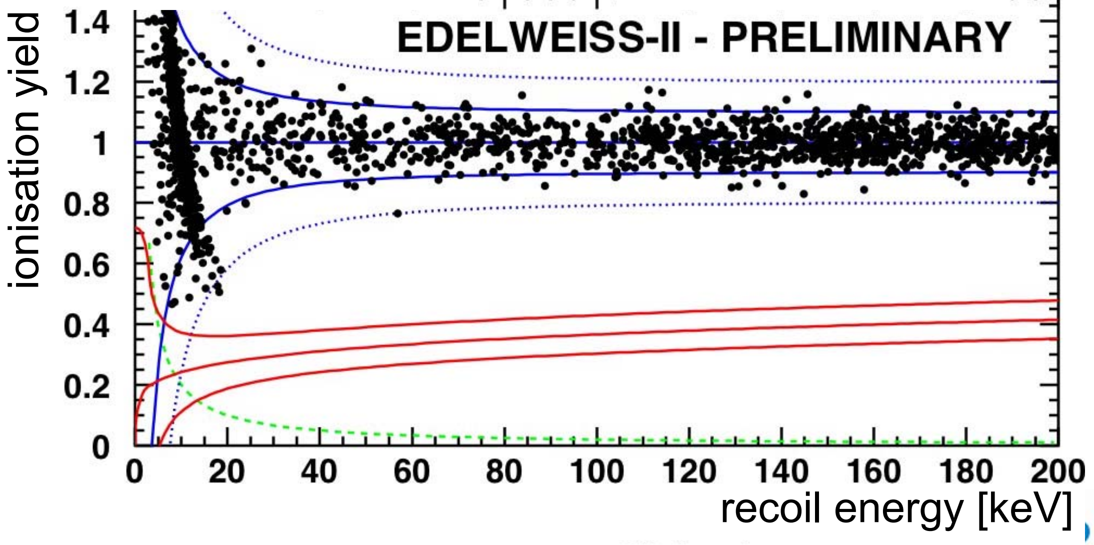
rejection of surface events

… via ionisation signal (Edelweiss):





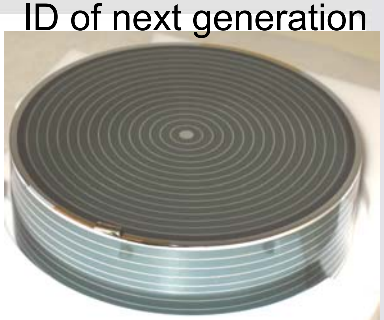
lab calibrations with
collimated ^{241}Am: **γ(60keV)**, α(3MeV)
^{109}Cd: β(18,62,84 keV), γ(22,25,88 keV)
rejection >99,7% for Y<50%



first data (18.6kg.d)
in Edelweiss cryostat
→ no “surface events”

ID-detector performance

ID of next generation

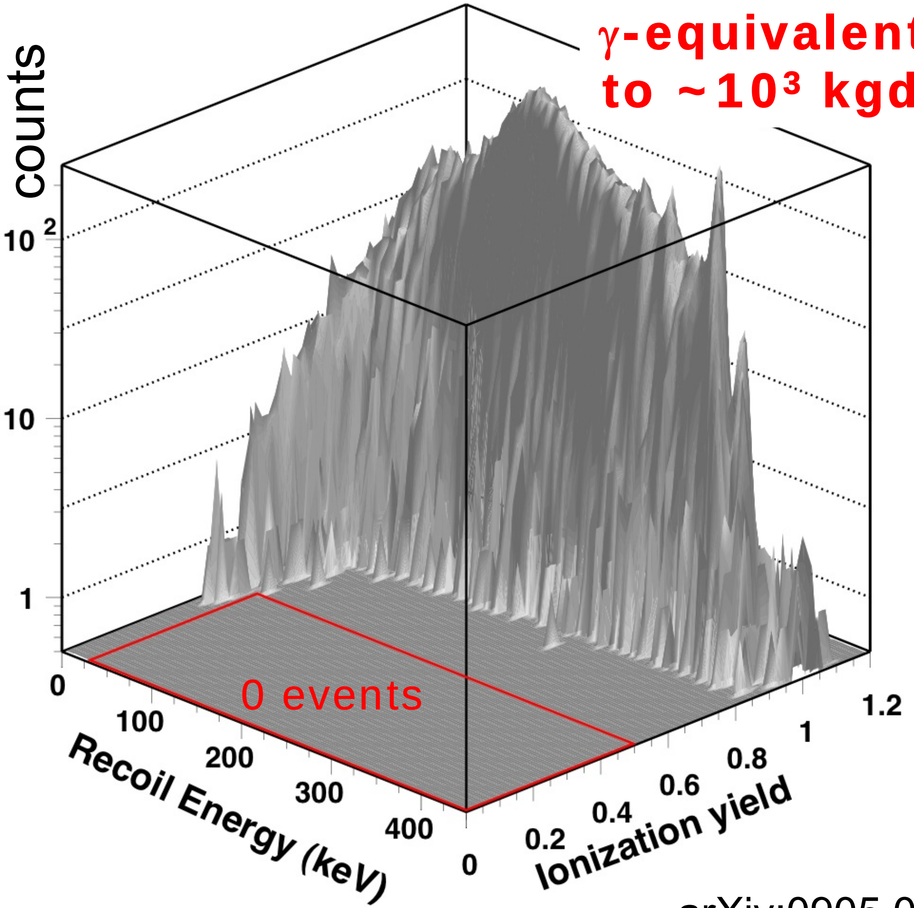


- Gamma rejection

  ~1 month ^{133}Ba calibration (~10^5 γ´s)

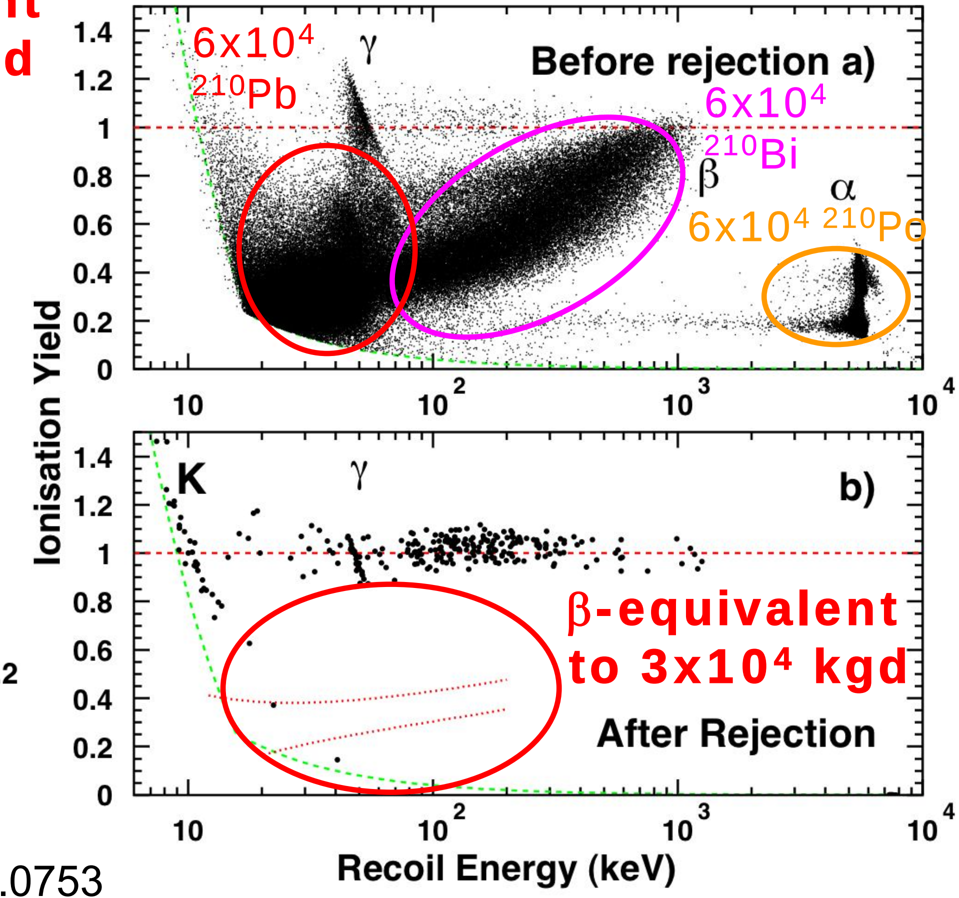
- Beta rejection

  ^{210}Pb source on 200g ID



γ-equivalent to ~10^3 kgd

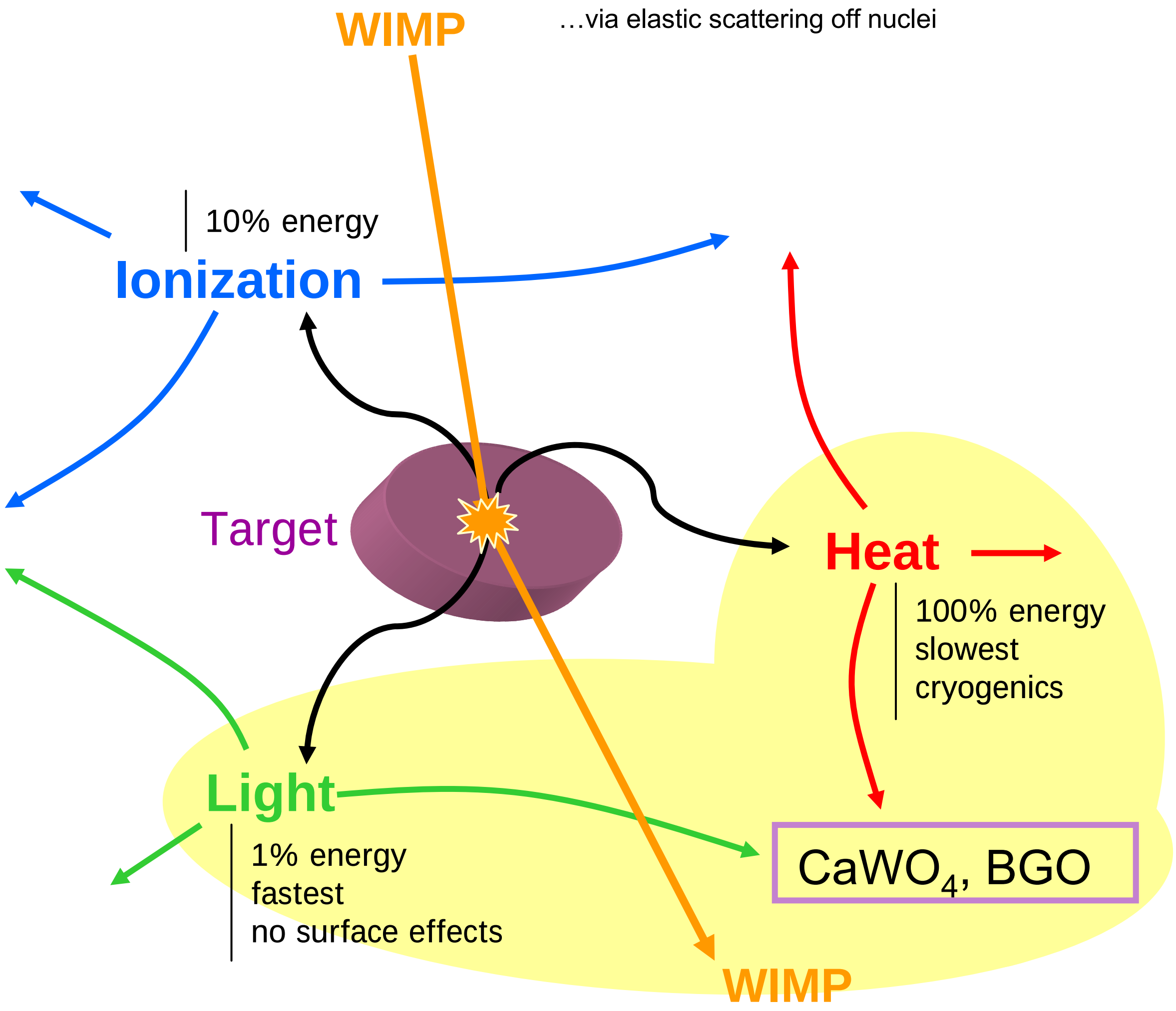
0 events



β-equivalent to 3×10^4 kgd

arXiv:0905.0753

Direct DM search using scint.&heat



Scintillation & heat

energy measurement with phonon channel,
PID via quenching of scintillation light:

CRESST-2:
@LNGS; 10x300g $CaWO_4$ (r=20mm, d=40mm);
light detection with Si bolometer; data taking

Rosebud:
@Canfranc; sapphire (Al_2O_3) crystals,
54g $CaWO_4$→ 10kg.d;
BGO ($Bi_4Ge_3O_{12}$) ^{209}Bi with J=9/2
→ SI&SD-search

Edelweiss-IAS:
@LSM; 50g Al_2O_3, R&D data taking

Scintillation & heat:
the CryogenicRareEventSearch withSuperconductingThermometers expt.

Max-Planck-Institut für Physik

University of Oxford

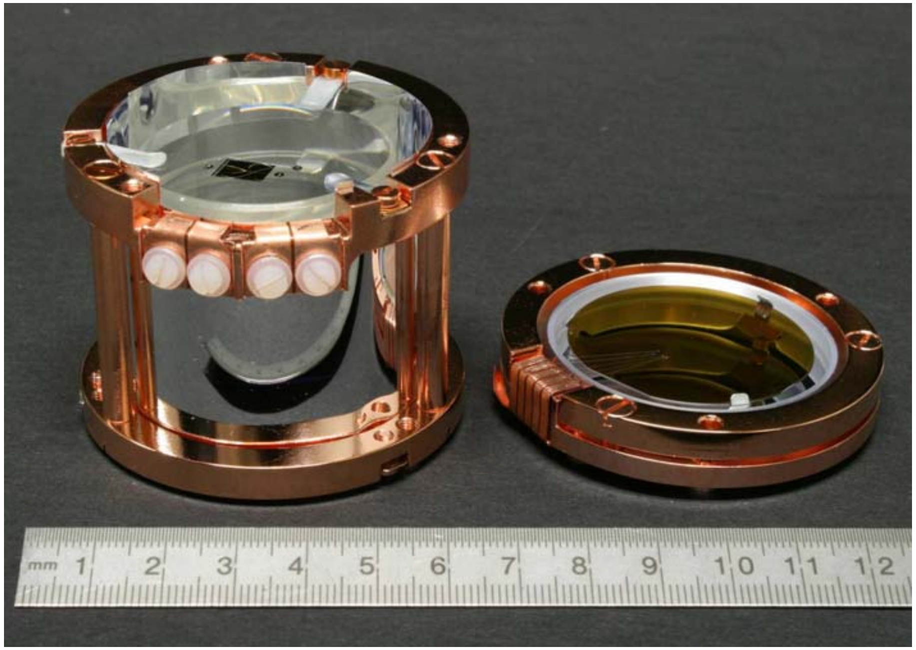
Technische Universität München

Laboratori Nazionali del Gran Sasso

Universität Tübingen

Features:
- mass : 10 kg $CaWO_4$
- threshold lower than 15 keV (recoils)
- excellent background discrimination
- **identification of recoil nucleus**

Scintillation & heat detector module



phonon channel:

300g $CaWO_4$ Ø = 40mm,

h = 40mm W-SPT 4 x 6 mm^2

light channel:

Si Ø = 30 mm; h = 0.4 mm

W-SPT with Al phonon collector

reflector:

polymeric foil, plastic

scintillator with Al reflector

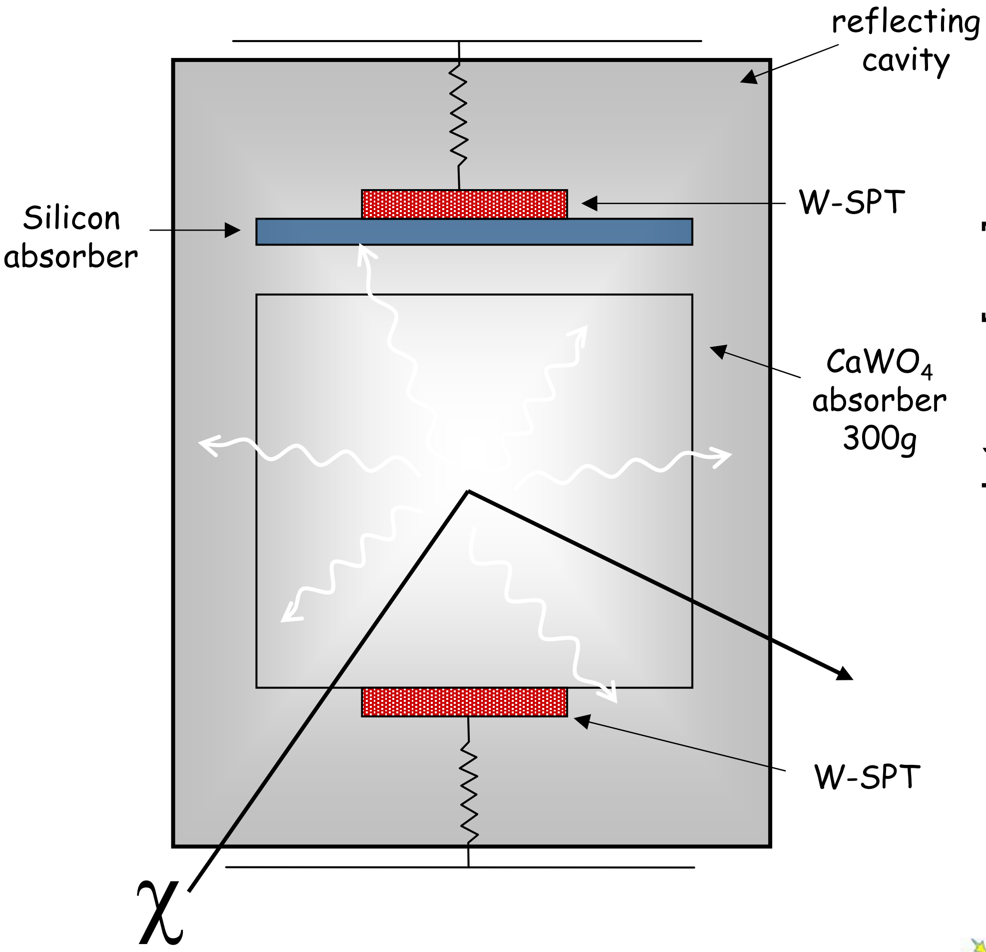
operating temperature:

10 mK

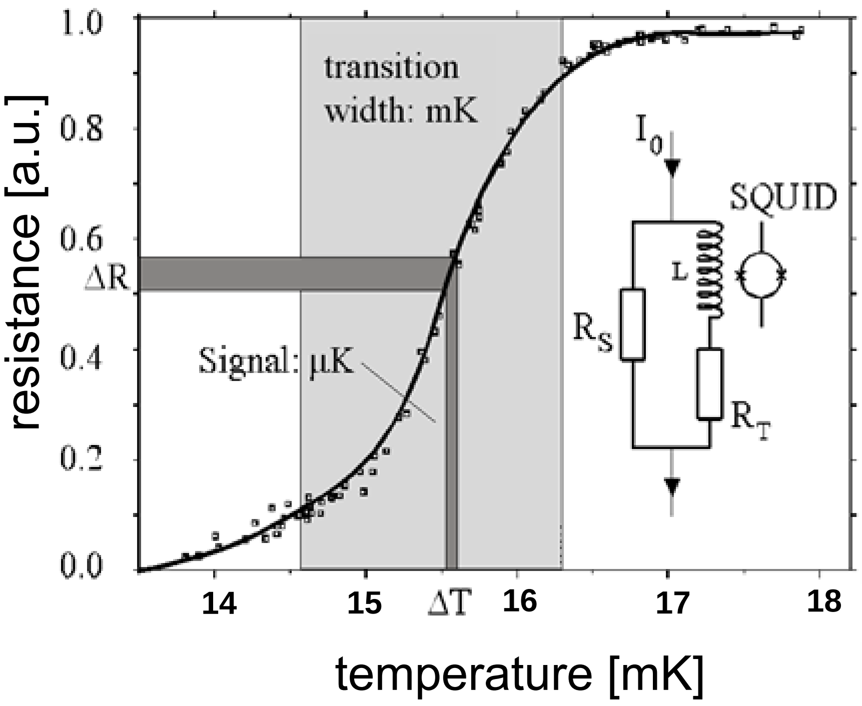
33 modules in CRESST II

Scintillation & heat

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

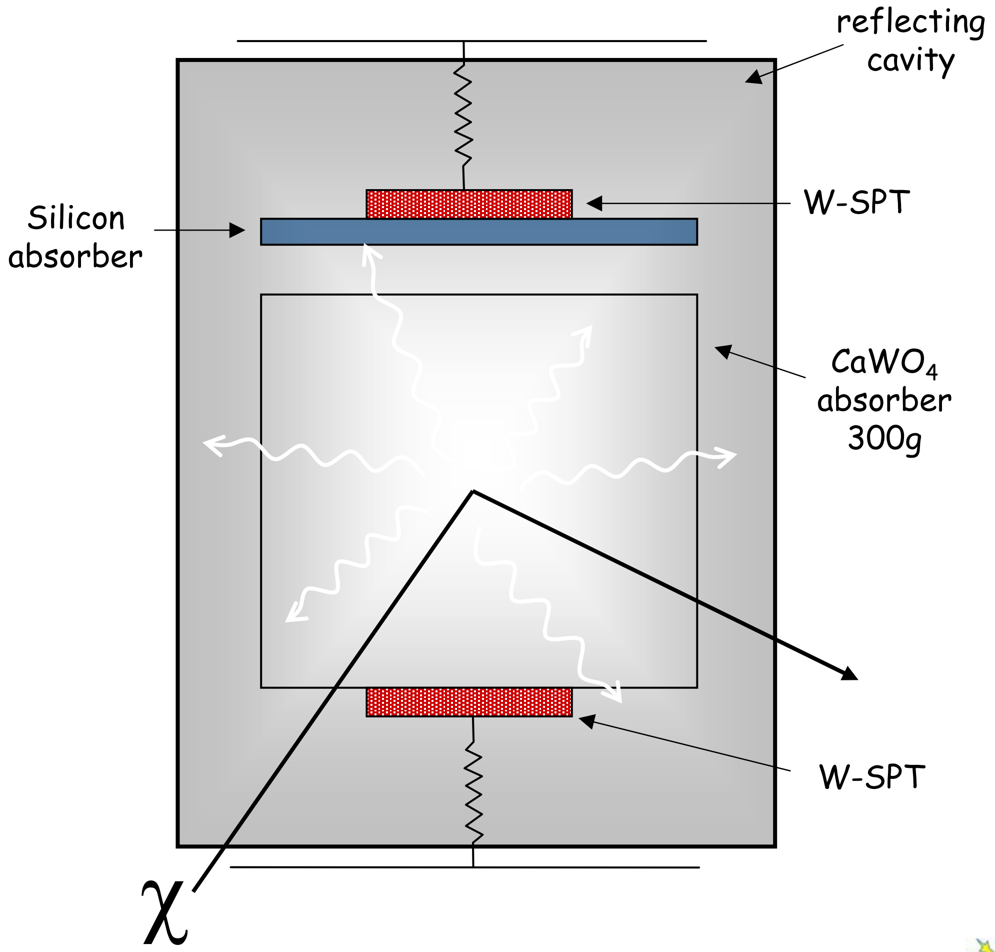


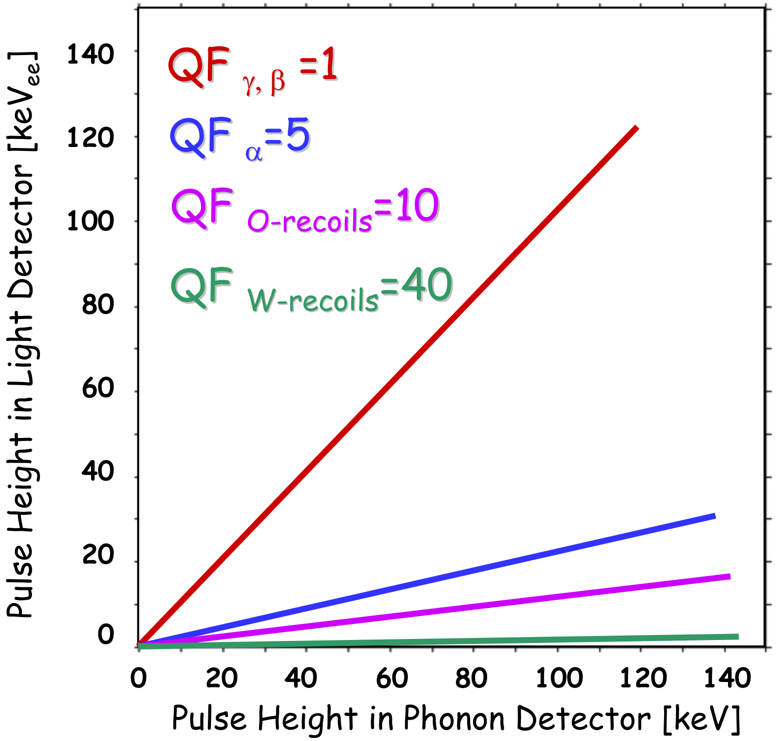
Transition **E**dge **S**ensor



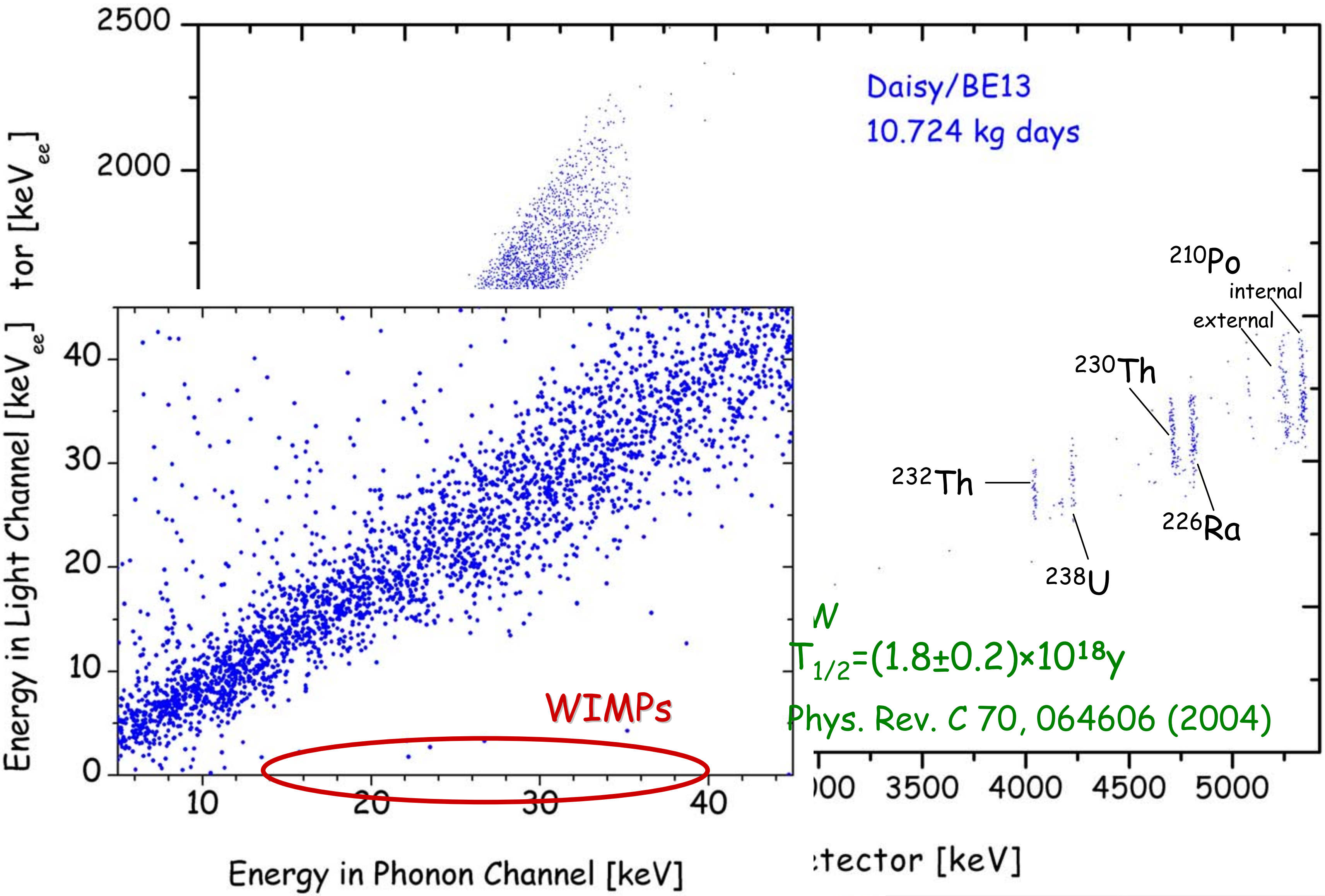
Scintillation & heat

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





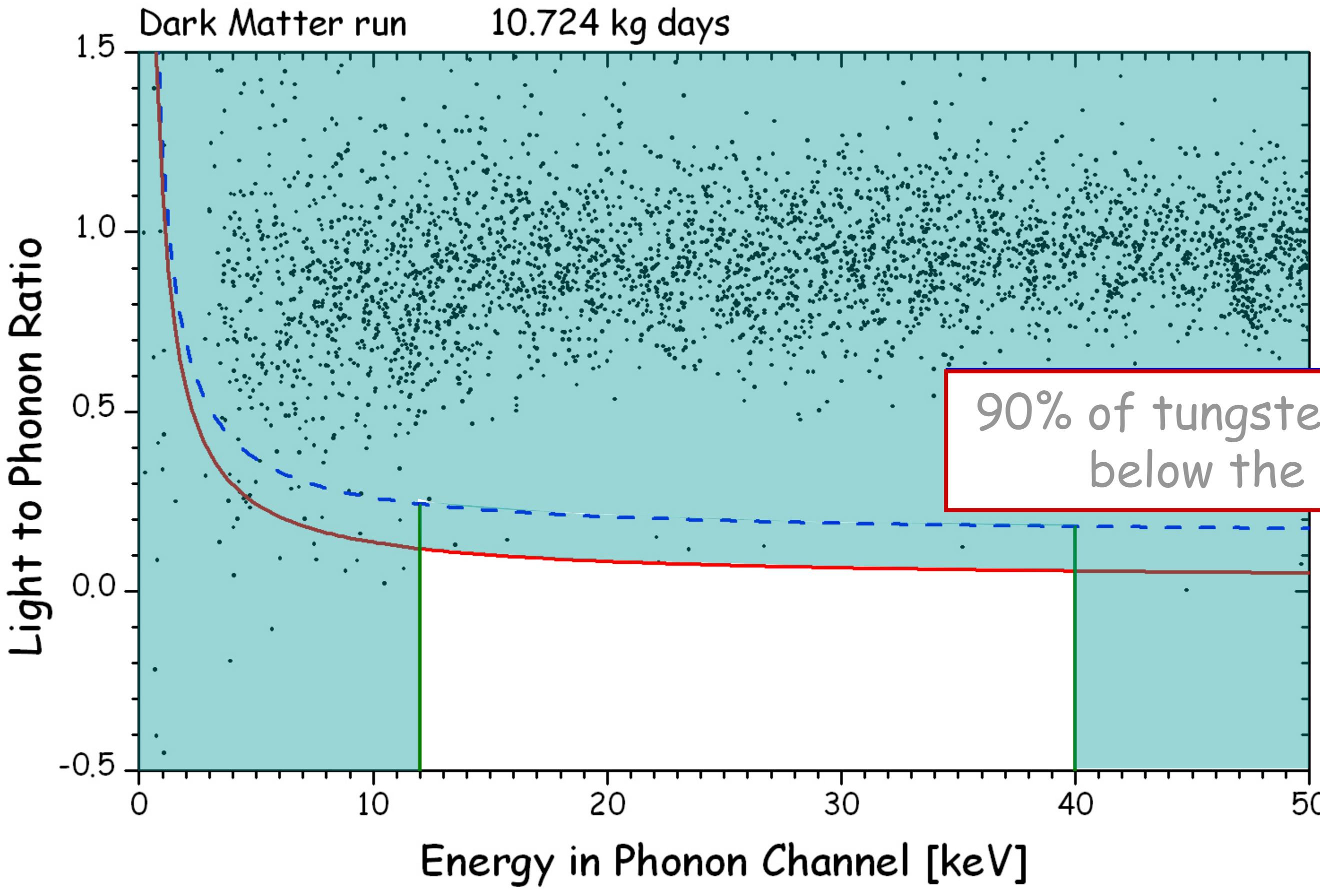
Scintillation & heat: CRESST II data



$T_{1/2}$=(1.8±0.2)×10^{18}y

Phys. Rev. C 70, 064606 (2004)

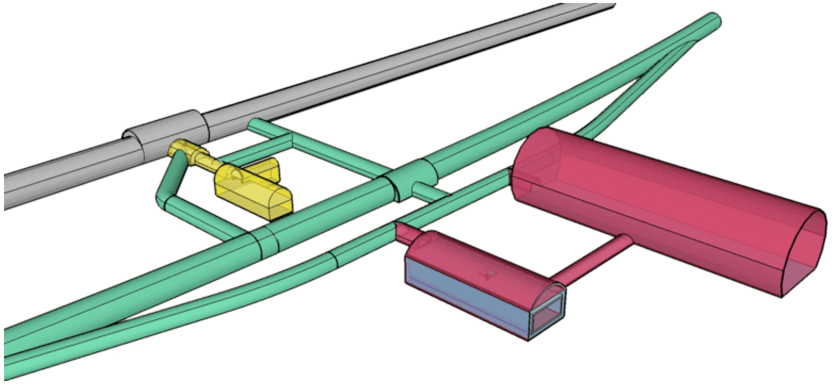
Scintillation & heat: CRESST II data

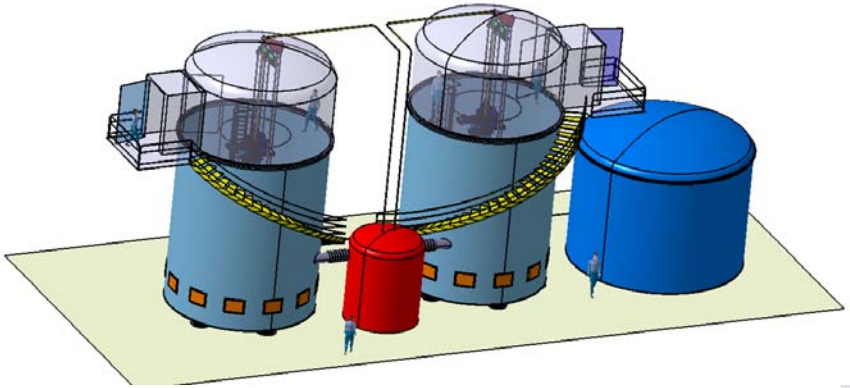


90% of tungsten recoils below the line

European cryogenic future:

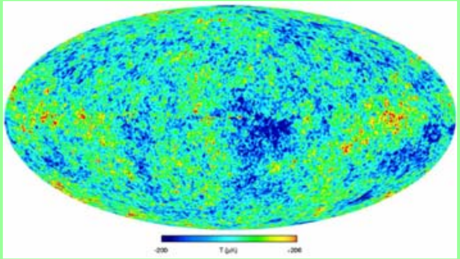
- EURECA: beyond 10^{-9} pb, major efforts in background control and detector development
- Joint effort from teams from EDELWEISS, CRESST, ROSEBUD, CERN, + others…
- >>100 kg cryogenic experiment, multi-target : Scintillators and Germanium
- Part of ASPERA European Roadmap
- Preferred site: ***60 000 m^3 extension of present LSM (4 $\mu/m^2/d$), to be excavated in 2011-2012***
- Design study start by the end of the year
- Start installation by 2013



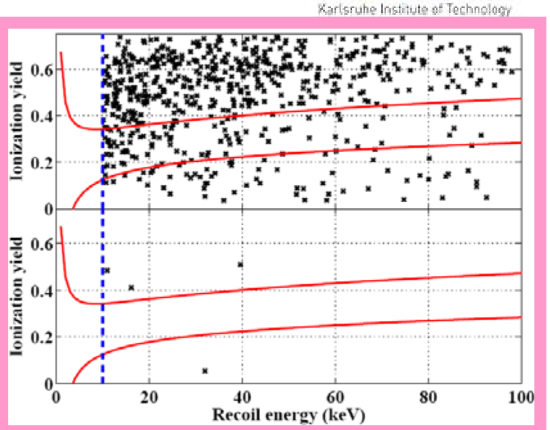


EURECA : 2 cryostats in water tanks

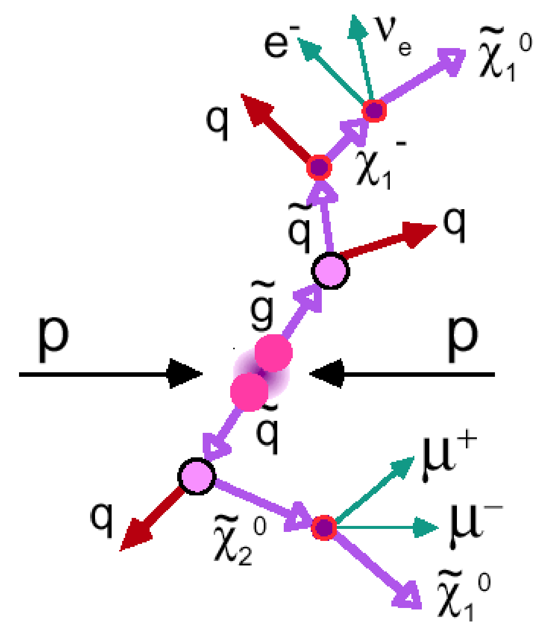
where do we stand? what to come next?



evidence of DM in astrophysics:
- galaxy motion/rotation
- galaxy crossing
- CMB+BBN→ΛCDM



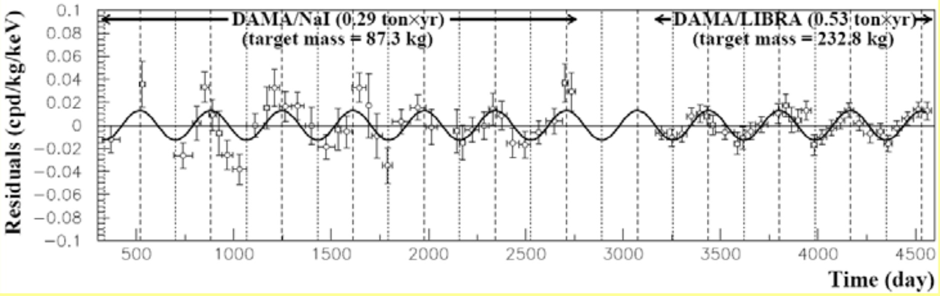
production of DM (χ) at the LHC?



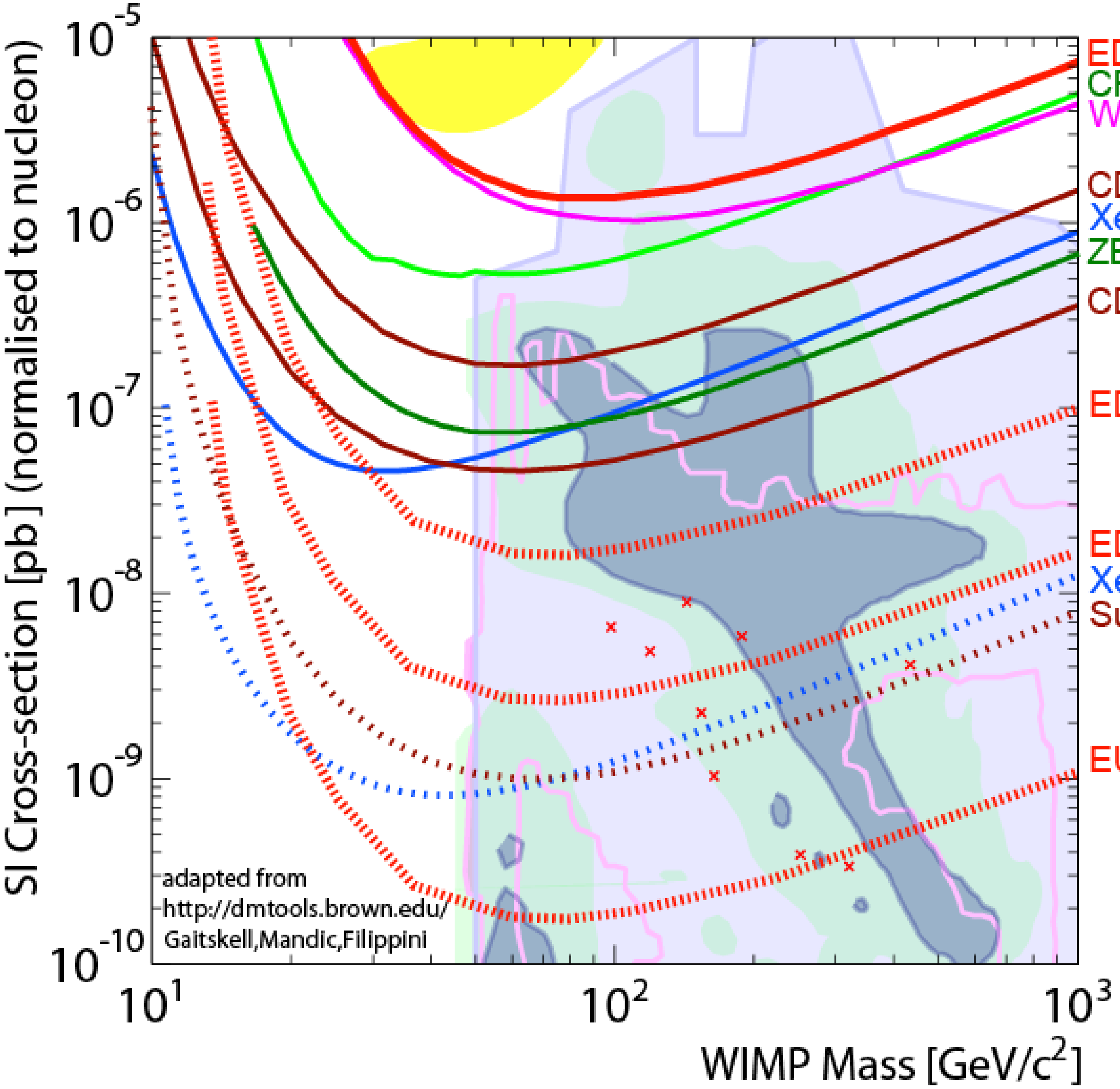
exptl. signature: missing E, p

no hints for DM from direct searches:
- no coherent scattering off nuclei (SI)
- no signal from nuclei with spin (SD)

hints for DM from astroparticle physics:
- annual modulation in DAMA/LIBRA
- GeV e^+ excess in PAMELA data



where do we stand? what to come next?



adapted from http://dmtools.brown.edu/ Gaitskell,Mandic,Filippini

EDELWEISS-1
CRESST-2
WARP

CDMS 04+05
Xenon10
ZEPLIN-3
CDMS 04+05+08

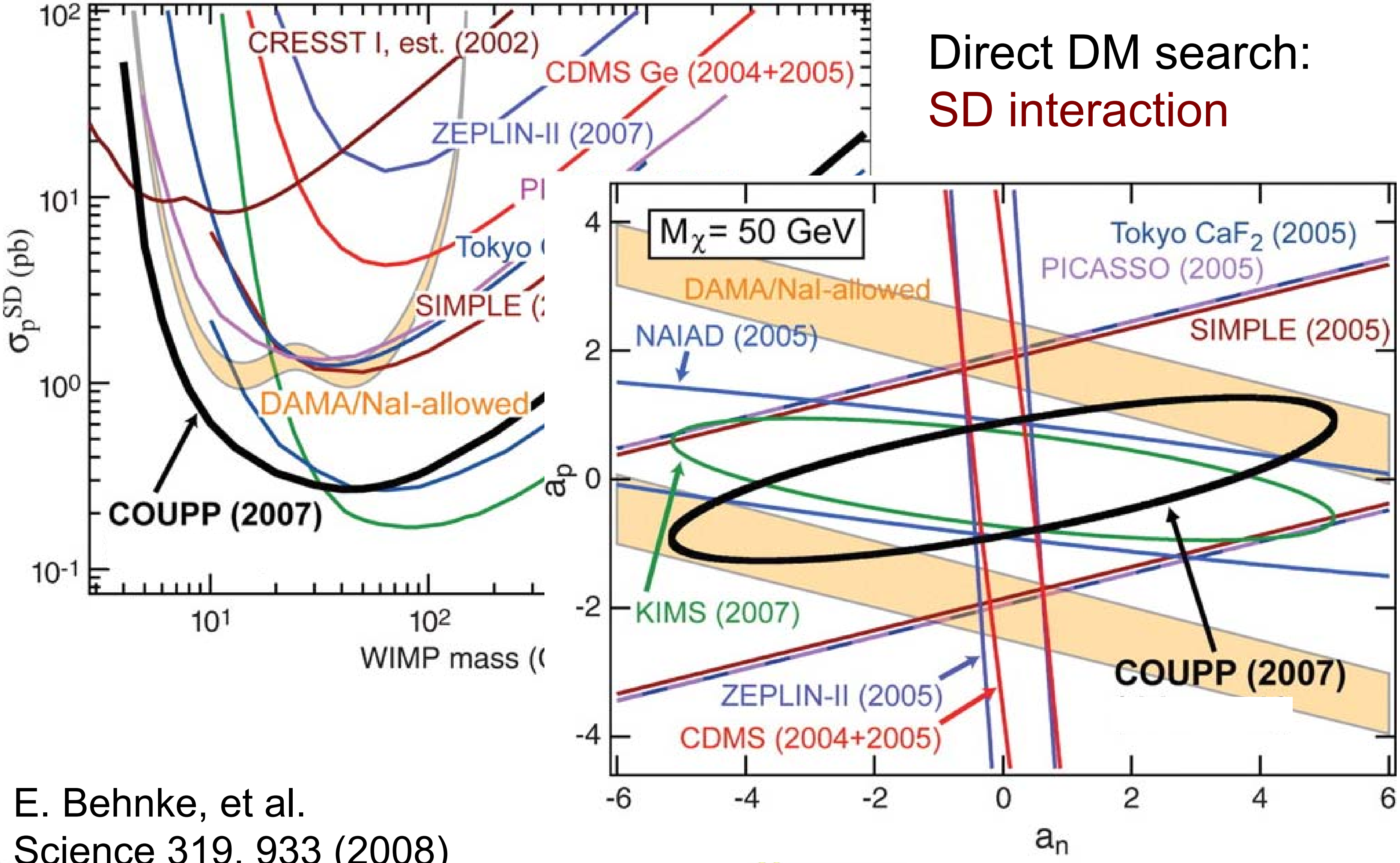
EDW2-800 kg.d ← **early 2011**

EDW2-3500 kg.d ← **2012**
Xenon100
SuperCDMS

EURECA → **from 2015 on**

Direct DM search:
SI interaction
status: $\sigma \sim 5\times10^{-43}$ cm^2
aim: $\sigma \sim 10^{-45}$-10^{-46} cm^2
theory: SUSY benchmark

where do we stand? what to come next?



Direct DM search:
SD interaction

E. Behnke, et al.
Science 319, 933 (2008)

where do we stand? what to come next?

new experiments starting/about to start/planned:

- direct DM search → 1ton cryogenic / 2-phase liquid
  → bubble chambers / scintillators
- indirect search → PAMELA, Fermi, ATIC, AMS-02
  → IceCube, CTA
- accelerators → LHC

- cosmology? Dark Energy?
- SuSy?

- remember:
ΛCDM concordance model
needs 96% unknowns!!!

memo: 13:00 at IK (Bldg.401)
excursion to KATRIN experiment