Karlsruhe Institute of Technology

Ge detectors in fundamental research

direct DM search

search for $0\nu\beta\beta$ decay

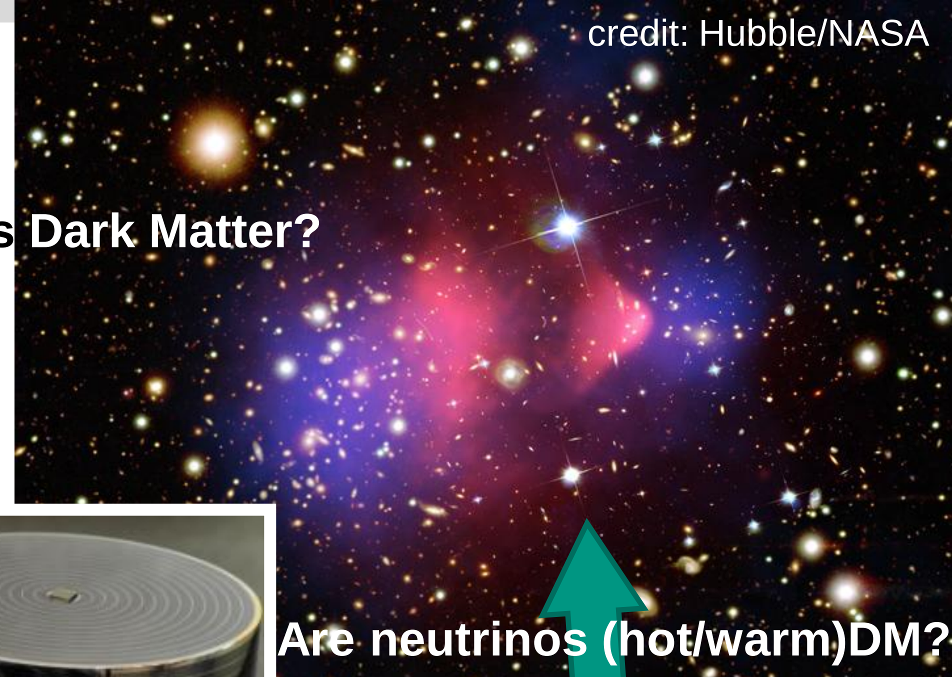
spectroscopy

Klaus Eitel
KIT Center Elementary Particle and Astroparticle Physics (KCETA)

Symposium of the Sino-German GDT Cooperation
Tübingen, 8 April 2013

Fundamental research

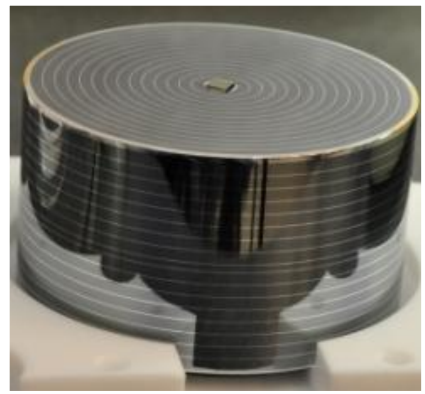
& Ge detectors



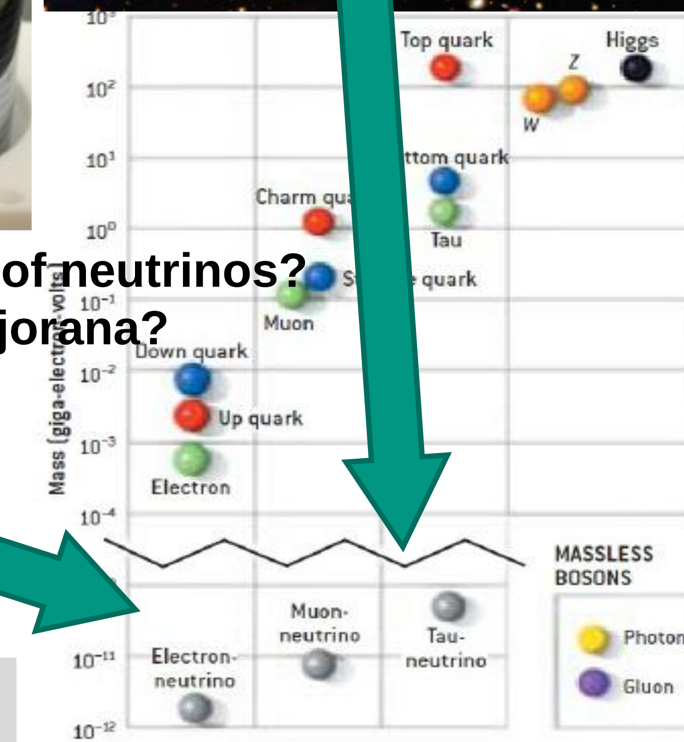
What is Dark Matter?

How did structures form?

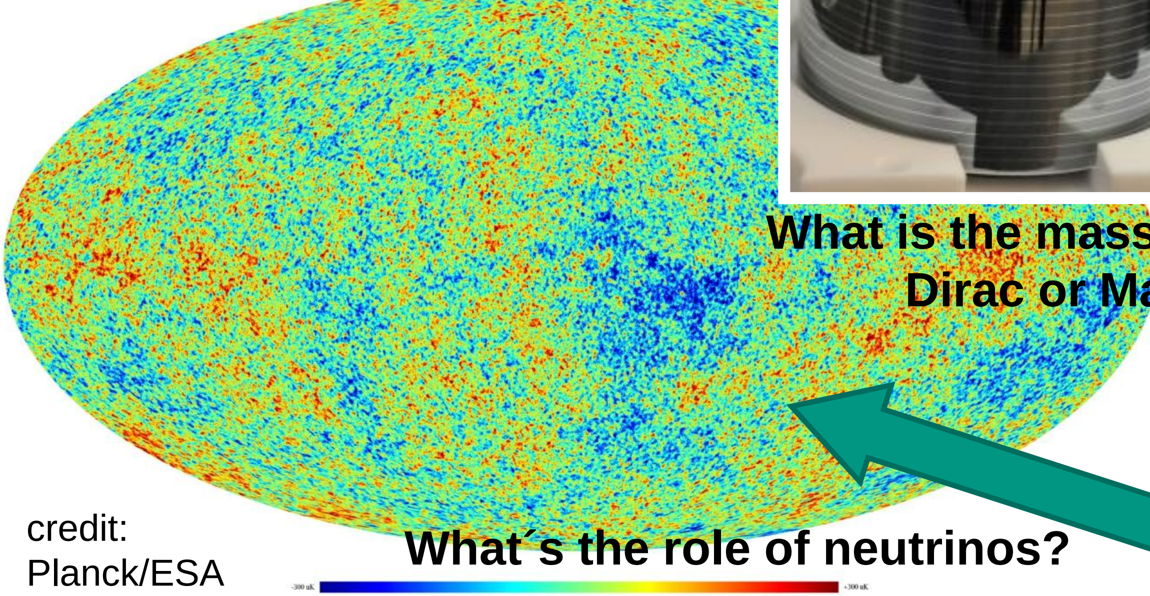
How did the Universe evolve?



Are neutrinos (hot/warm)DM?



What is the mass of neutrinos? Dirac or Majorana?

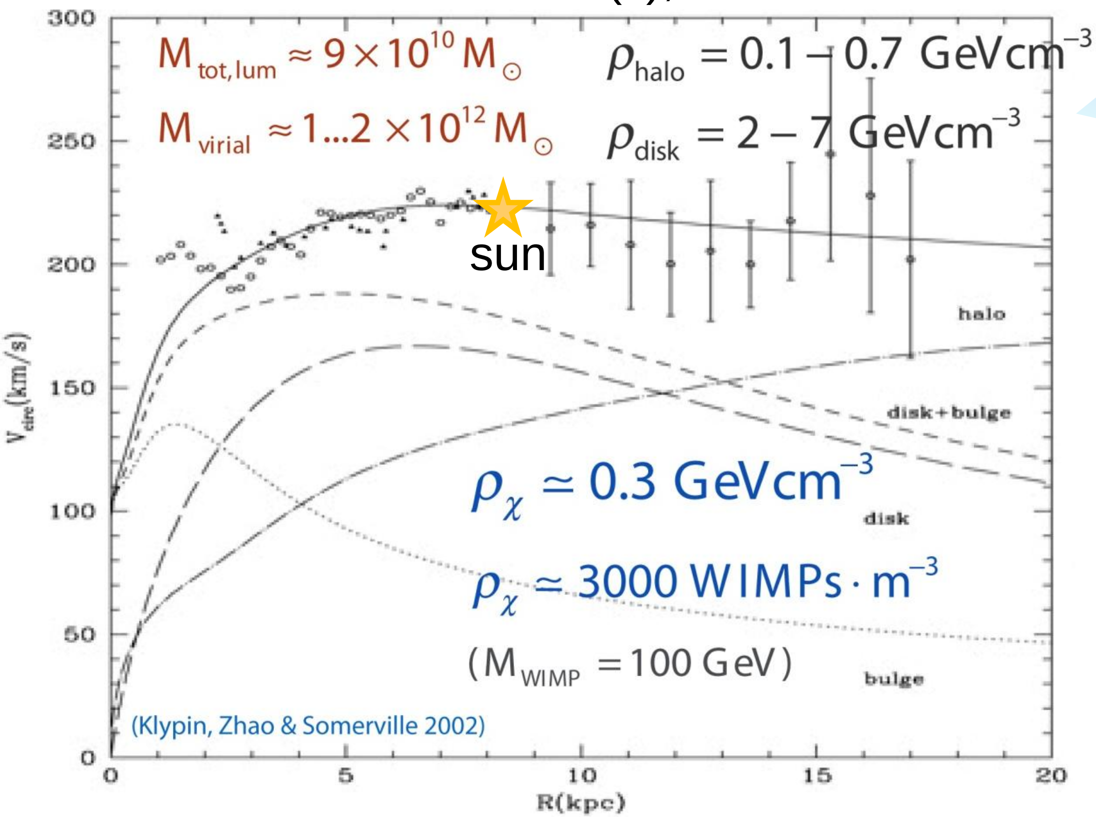


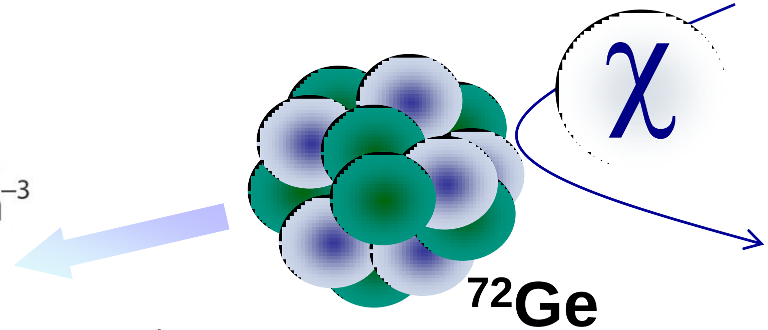
credit: Planck/ESA

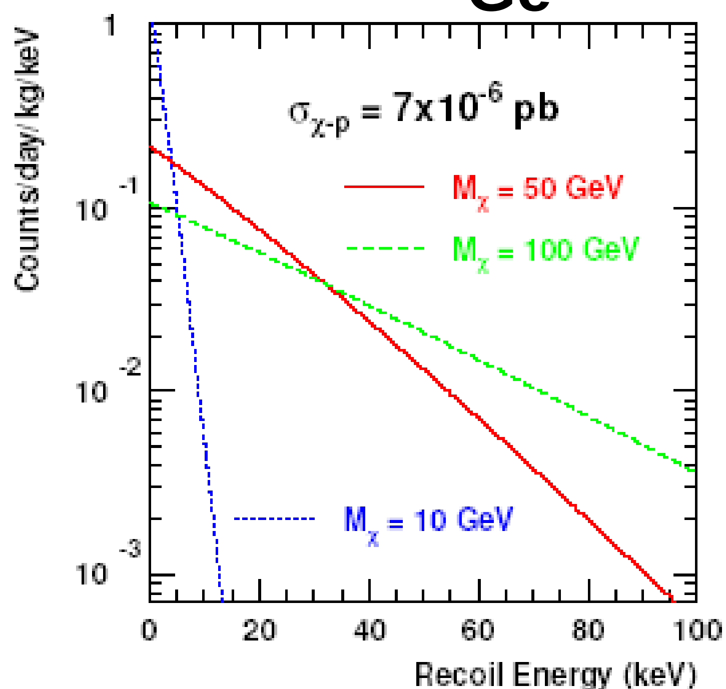
What´s the role of neutrinos?

direct DM search refresher

diffuse DM halo within our Milky Way
with ~ Maxwell-Boltzmann f(v), $<v^2>^{1/2}$ ~270km/s

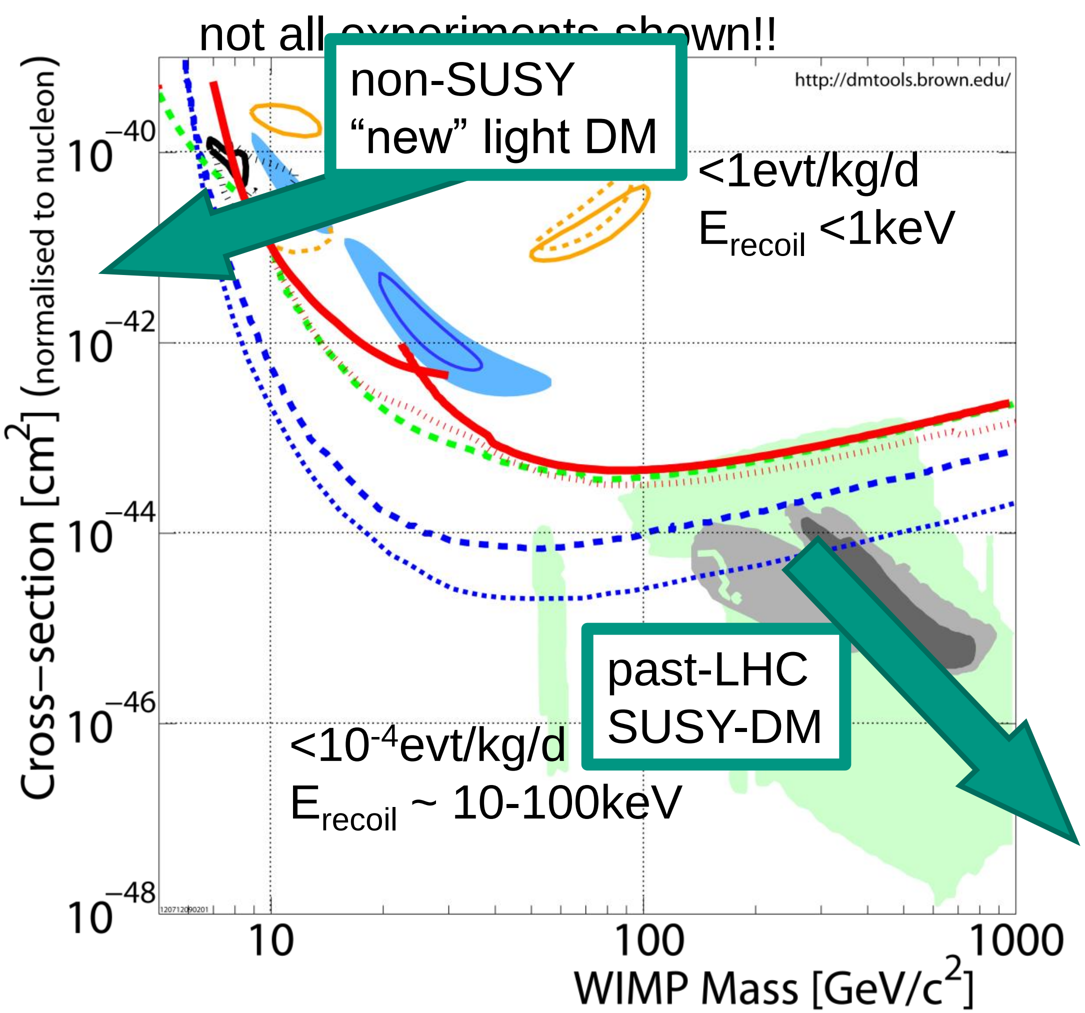






→ nuclear recoils at rates of <1evt/kg/year
with E(recoil) ~ 1—100 keV

direct DM search refresher



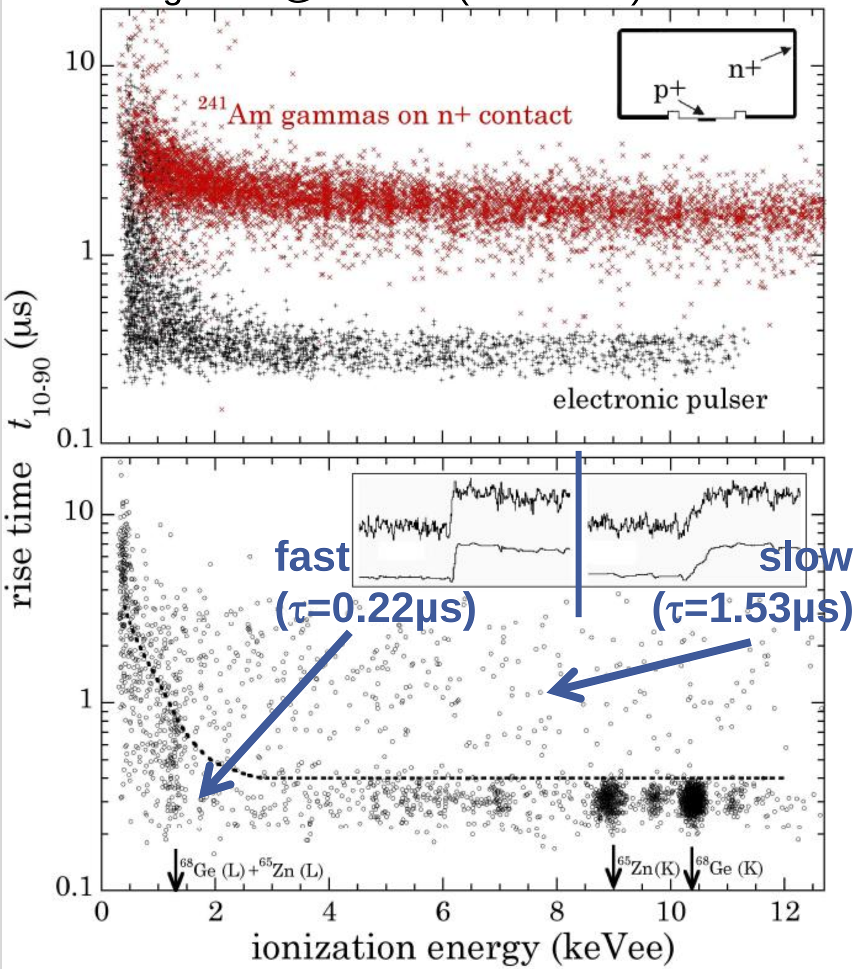
EDW-II PLB **702**,5 (2011) 329
+ PRD**86**, 051701(R) (2012)
EDW-II & CDMS PRD**84** (2011)
DAMA/LIBRA EPJ **C56** (2008)
CoGeNT PRL **106** (2011)
CRESST II 2σ EPJ C**72**(2012)1971
CRESST II 1σ EPJ C**72**(2012)1971
CDMS Science **327**, 1619 (2010)
+ Low E, PRL **106** (2011)
XENON100 PRL **107** (2011)
XENON100 PRL **109**, 181301 (2012)
Buchmüller et al, 2011
Bertone et al, 2011

requirements:
- low thresh
- low bgd
- discrimination power
- reliability
- mass production

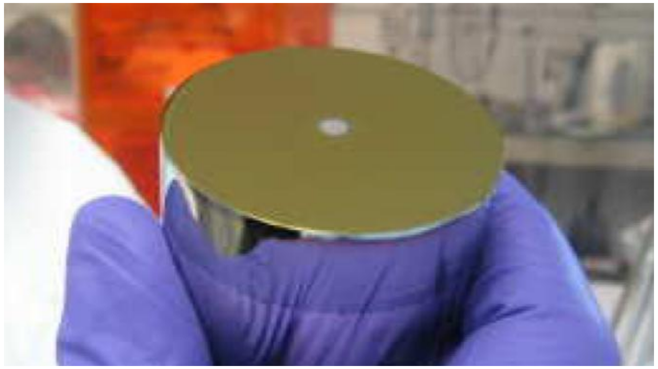
DM search with PPC HPGe detectors

→ CoGeNT

440g PPC @Soudan (2100mwe) with rise time discrimination



C. Aalseth etal., arXiv:1002.4703v1

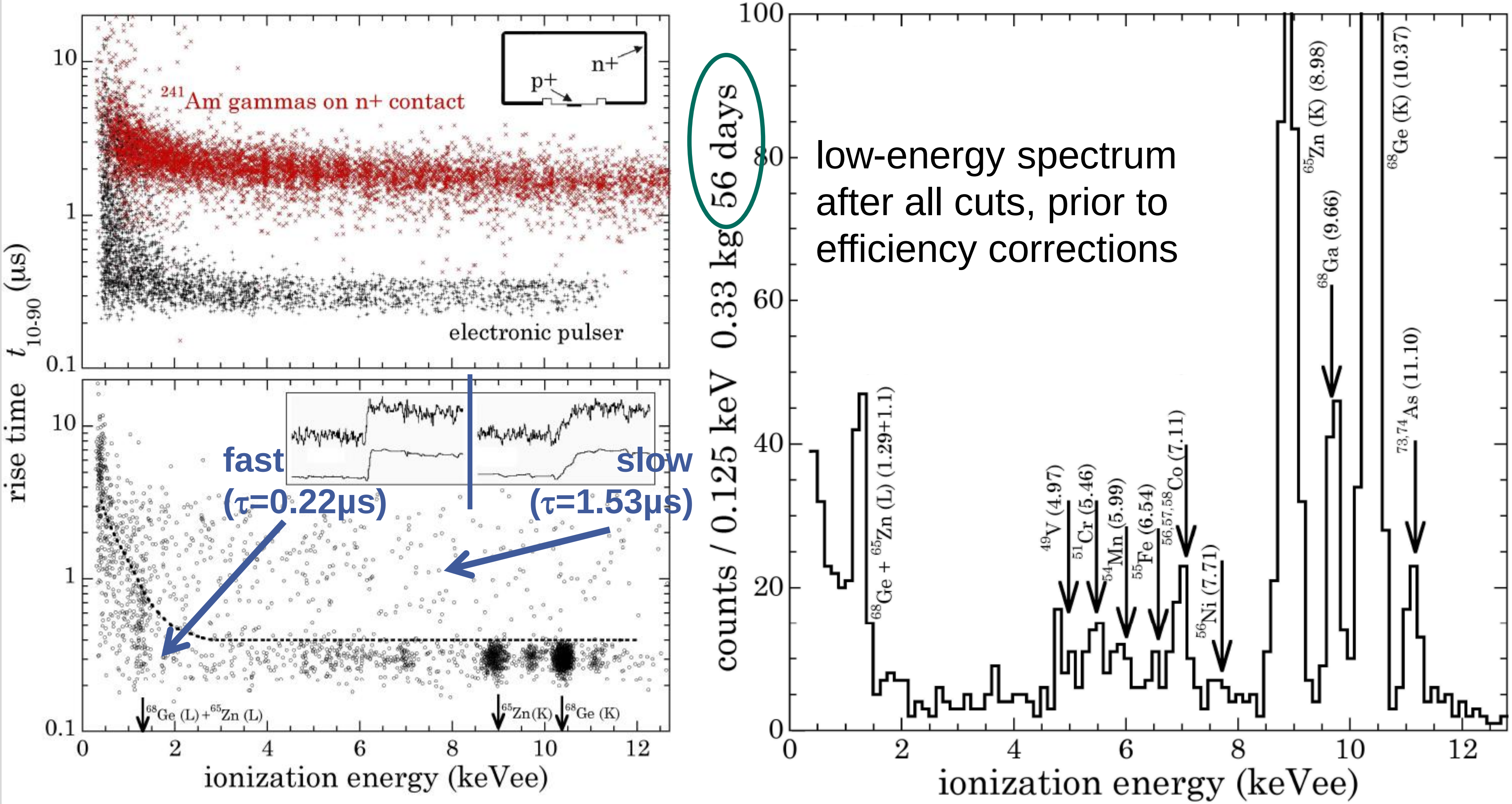


Property	Value
Manufacturer	Canberra (modified BEGe)
Total Mass	443 gram
Estimated Fiducial Mass	∼330 gram
Outer Diameter	60.5 mm
Length	31 mm
Capacitance	1.8 pF (at 3000 V bias)

C. Aalseth etal., arXiv:1208.5737

DM search with PPC HPGe detectors

→ CoGeNT

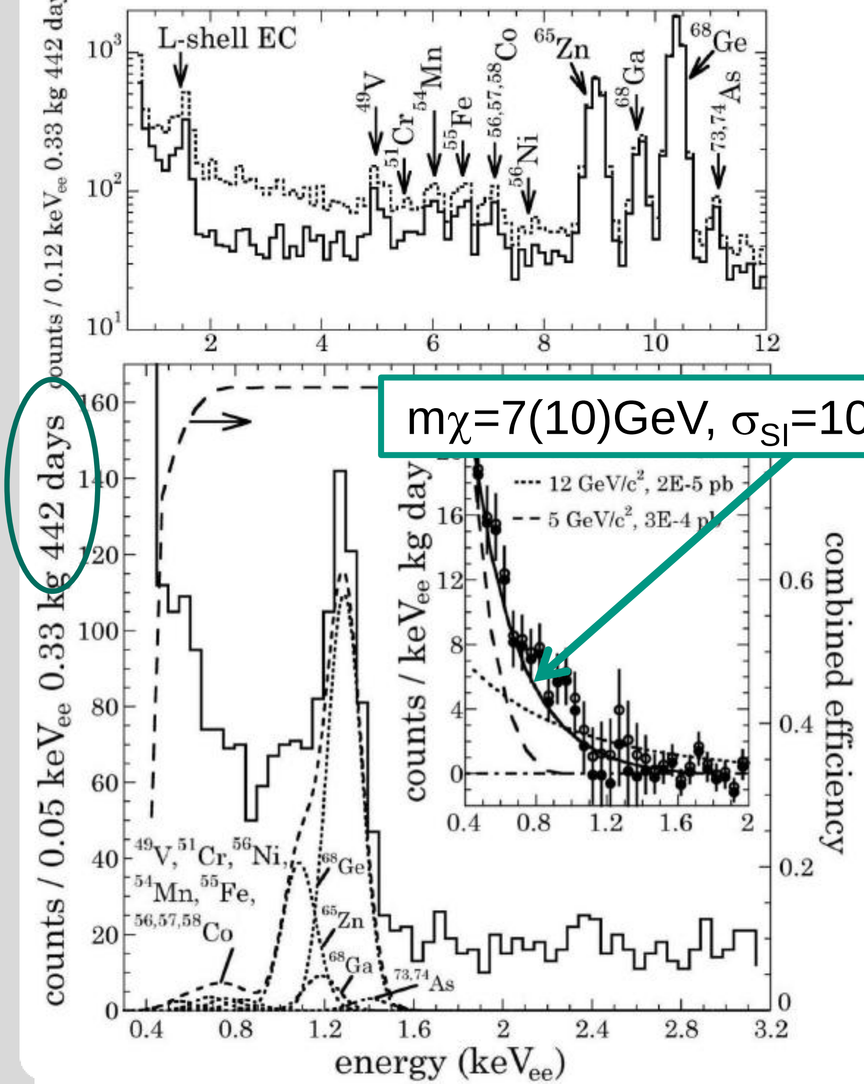


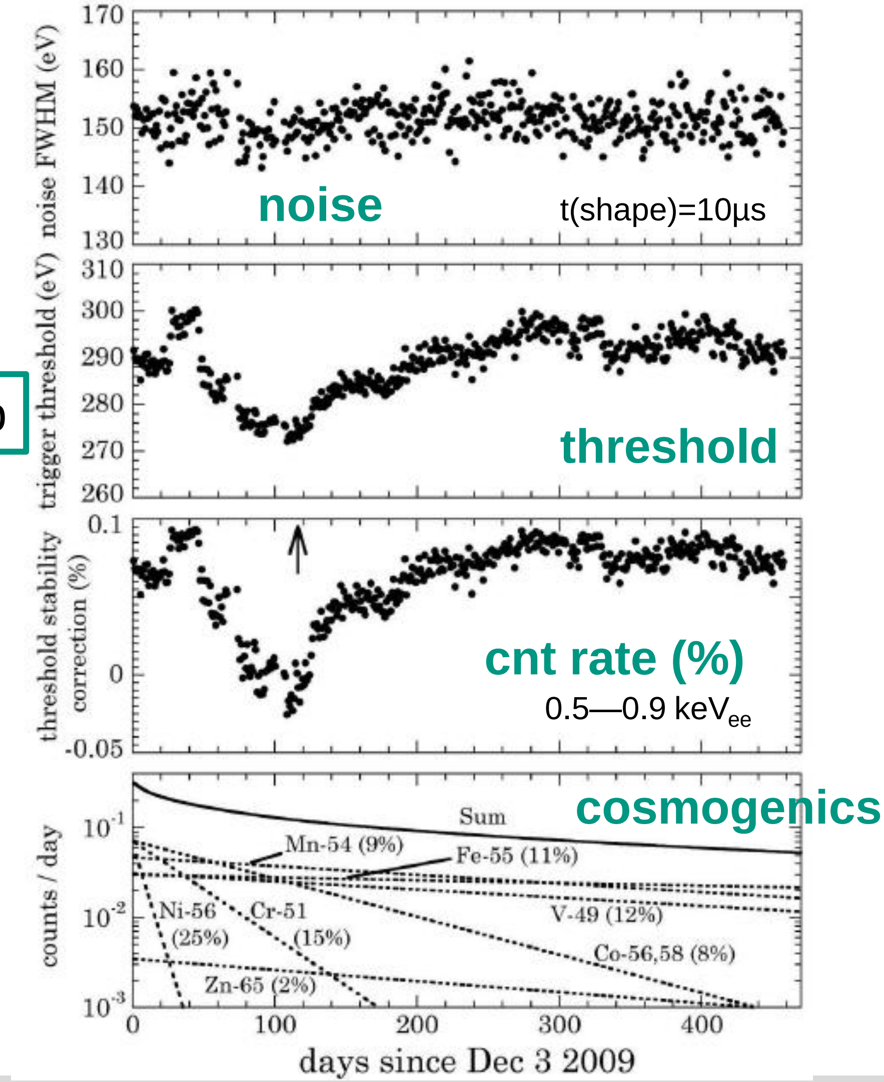
C. Aalseth et al., arXiv:1002.4703v1 (PRL106:131301,2011)

DM search with PPC HPGe detectors

→ CoGeNT

PRL107 (2011) 141301

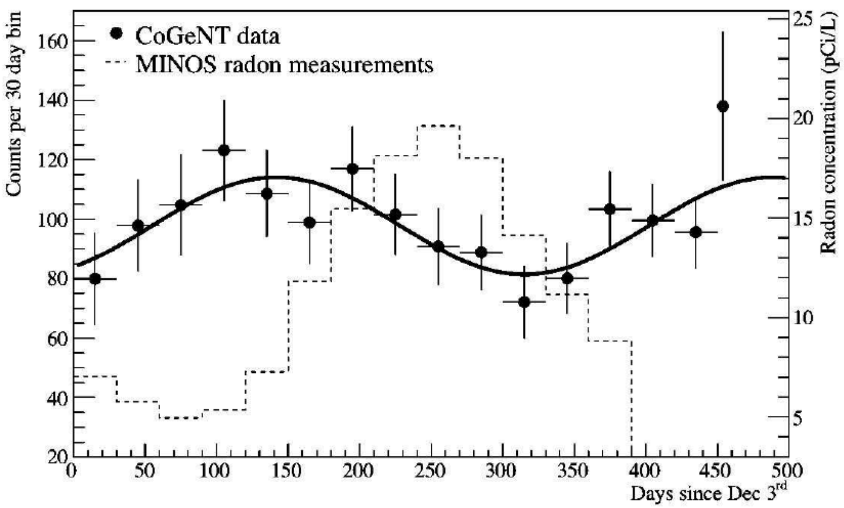


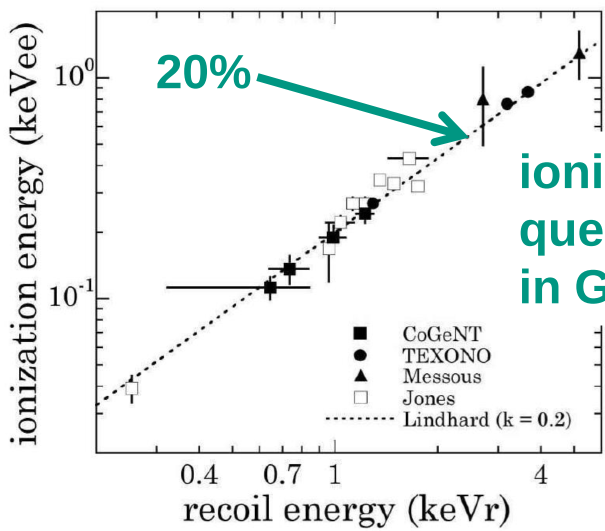


DM search with PPC HPGe detectors

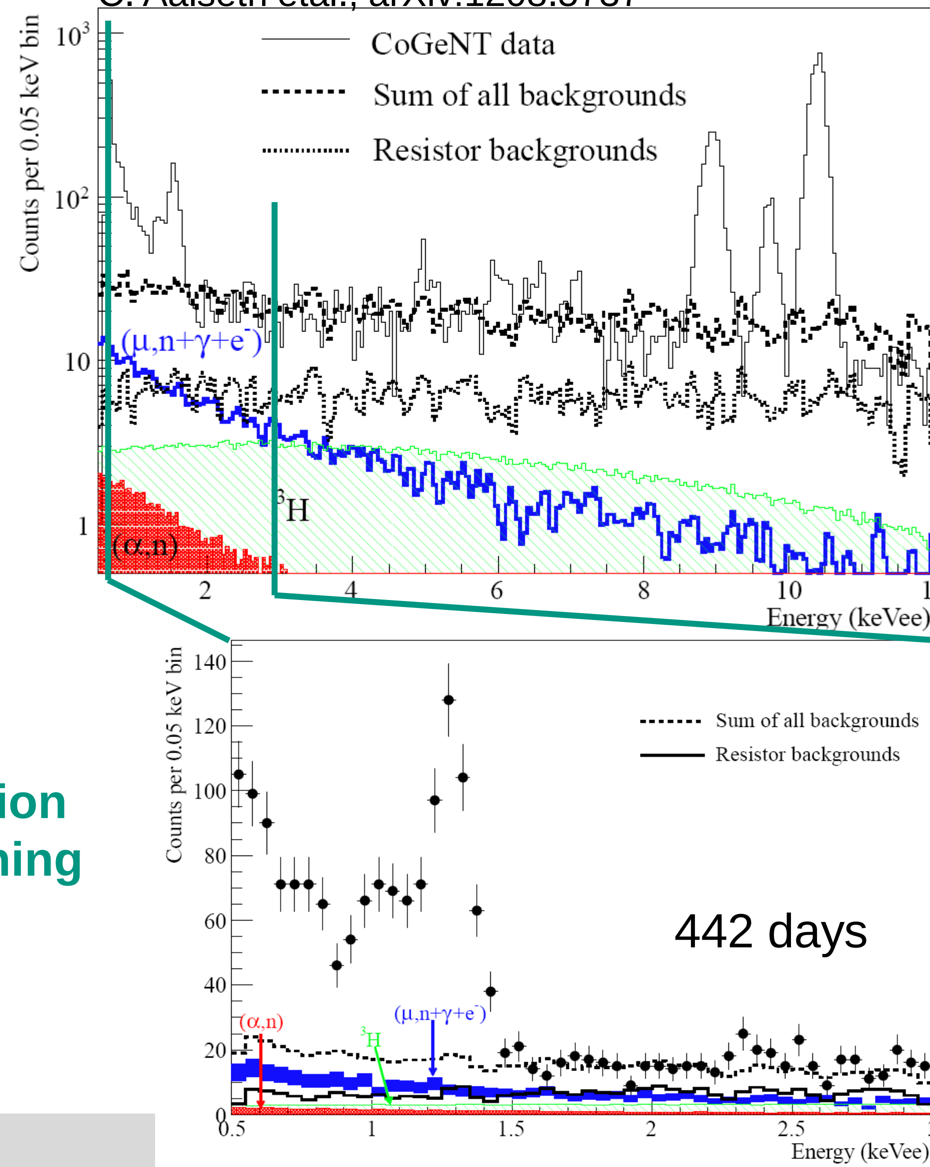
→ CoGeNT

C. Aalseth etal., arXiv:1208.5737



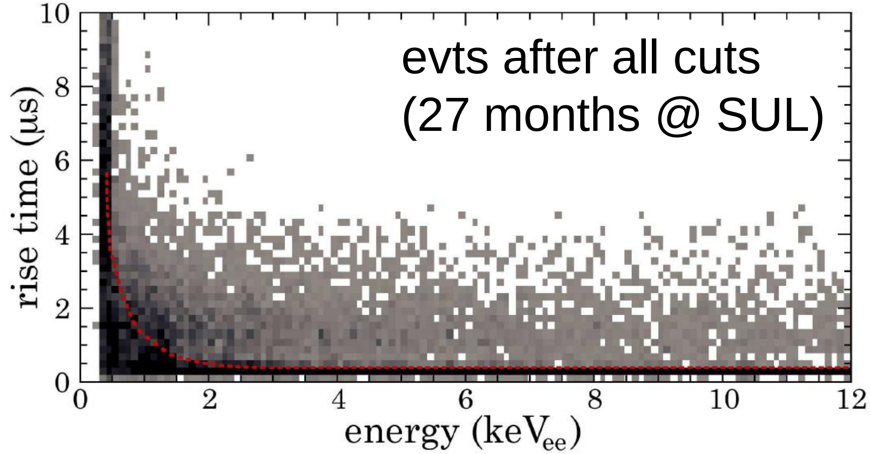


ionisation quenching in Ge

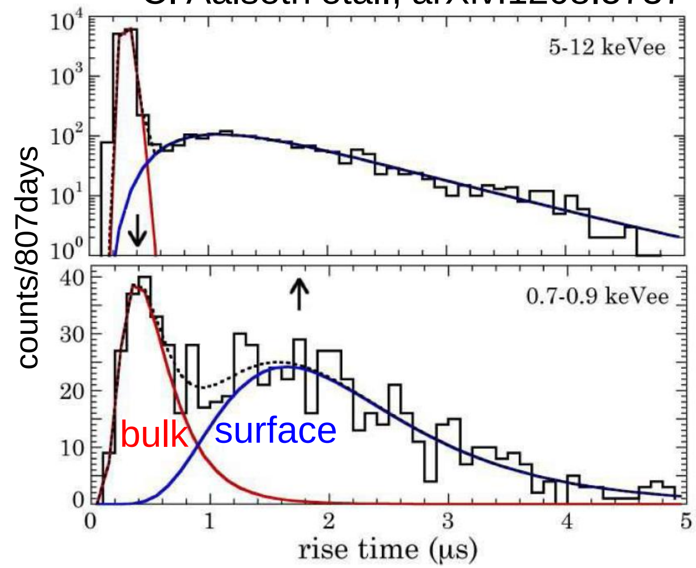


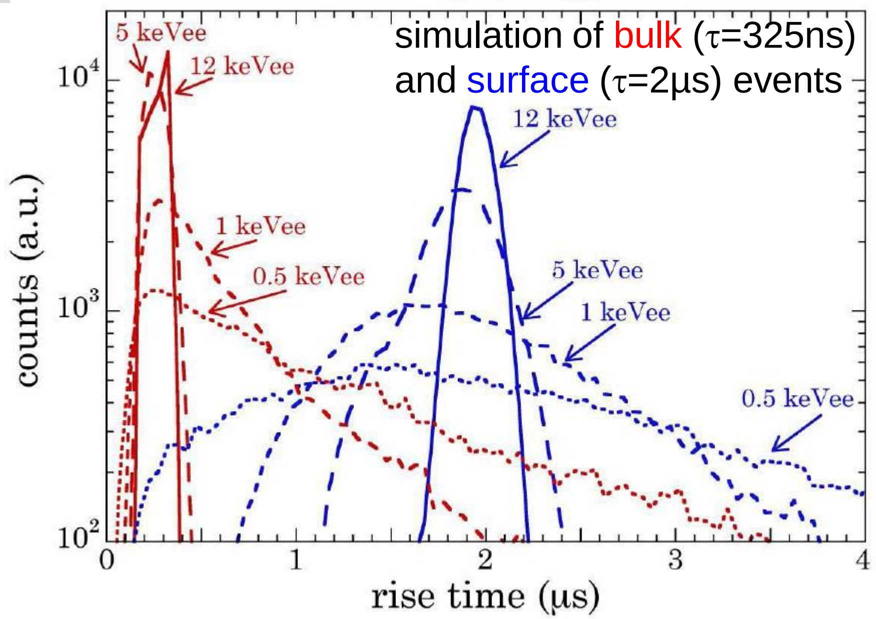
DM search with PPC HPGe detectors

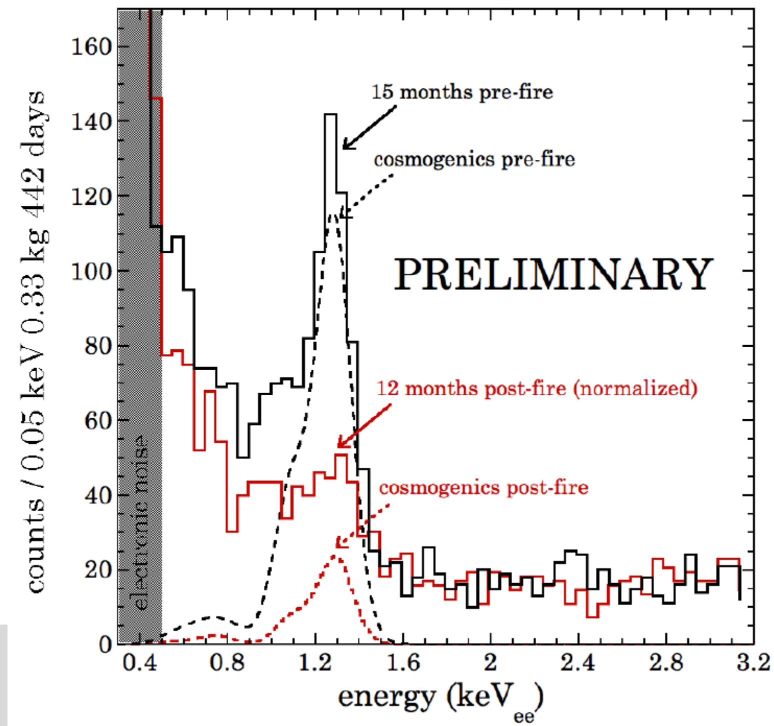
→ CoGeNT



C. Aalseth etal., arXiv:1208.5737





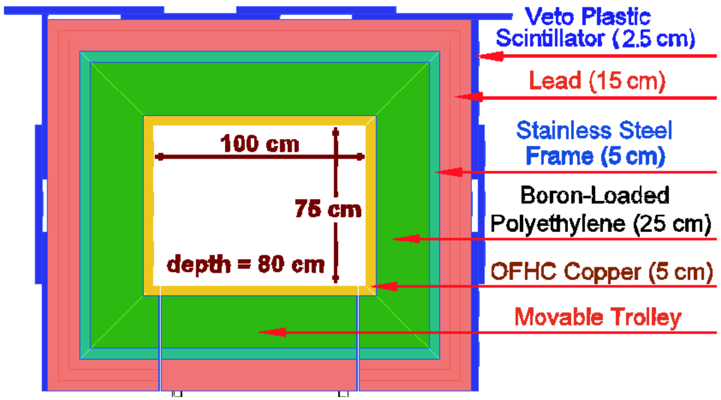


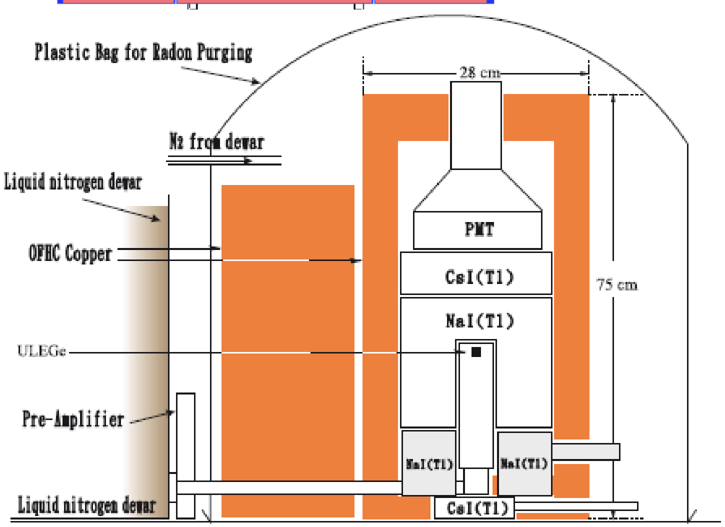
J. Collar, IDM2012, Chicago

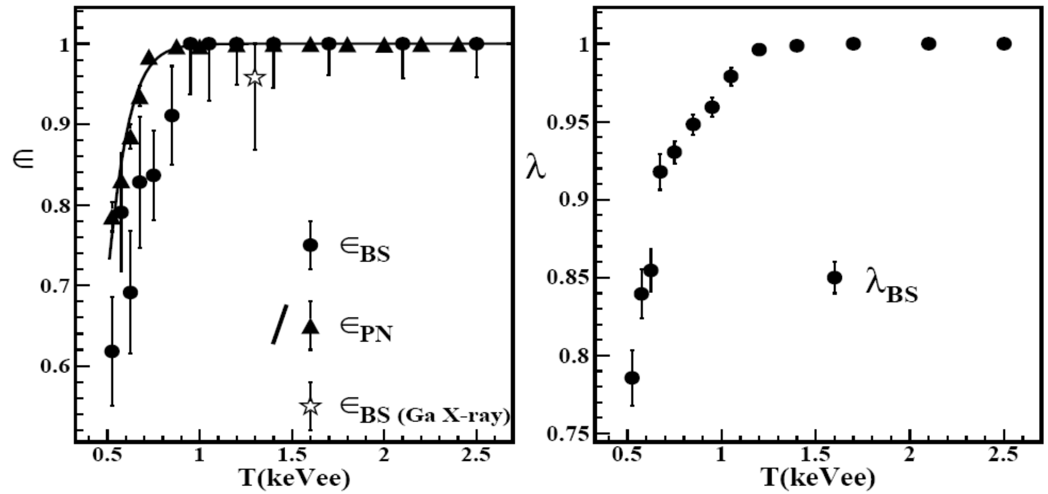
DM search with PPC HPGe detectors

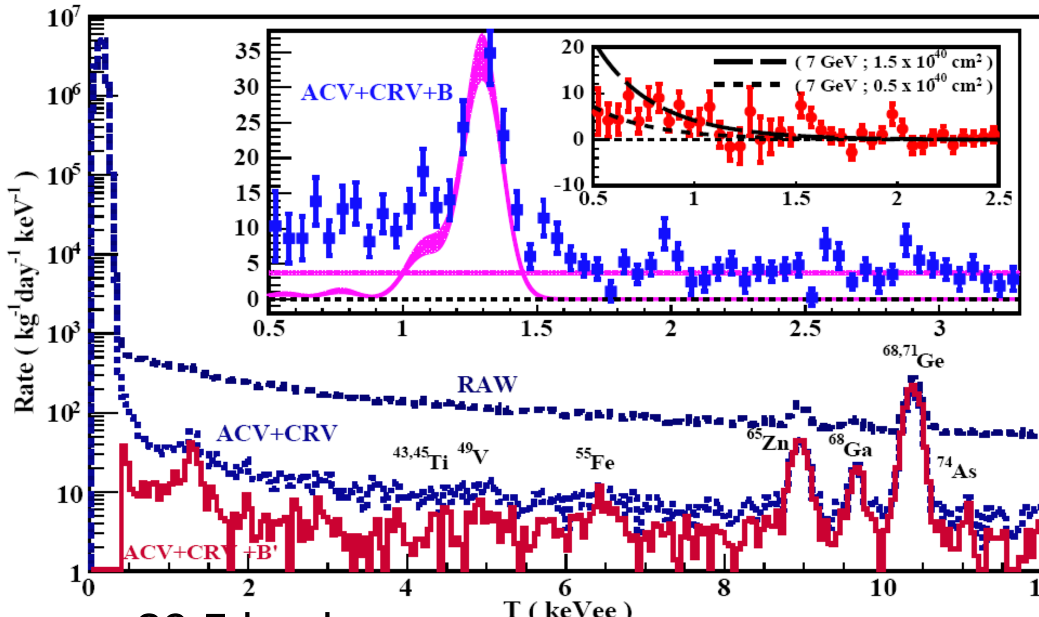
→ TEXONO

926g(840g$_{fid}$) PPCGe@Kuo-Sheng Reactor Neutrino Laboratory









39.5 kg.d

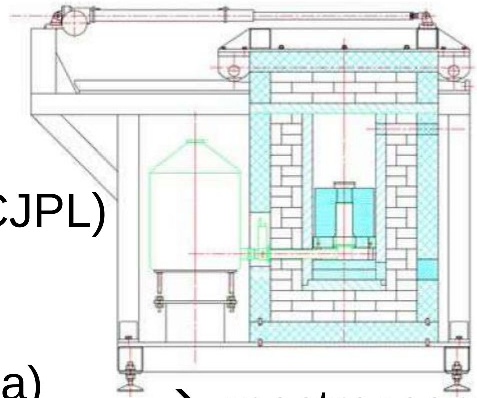
S. Lin et al, arXiv:0712.1645
S. Lin et al, PRD79:061101,2009
H. Li et al., arXiv:1303.0925

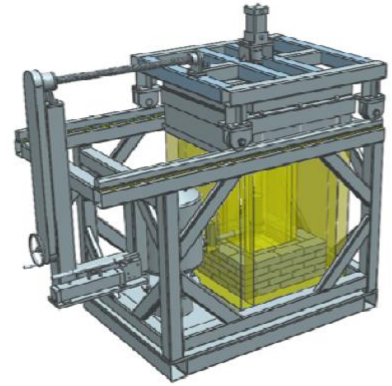
DM search with PPC HPGe detectors

→ CDEX

China Jin-Ping Underground Laboratory (CJPL)

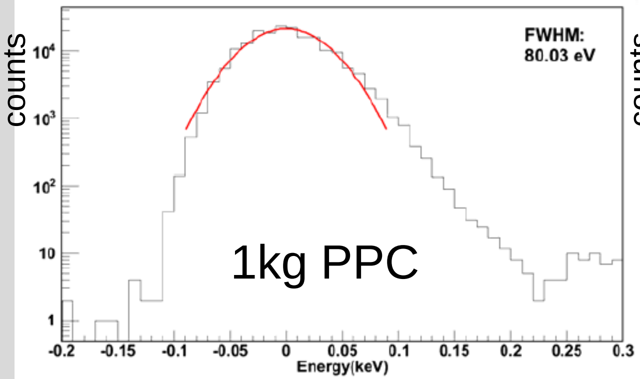
CDEX-1 (running since 11/2010):
20g (4x5g) ULEGe &1kg-PPCGe (Canberra)

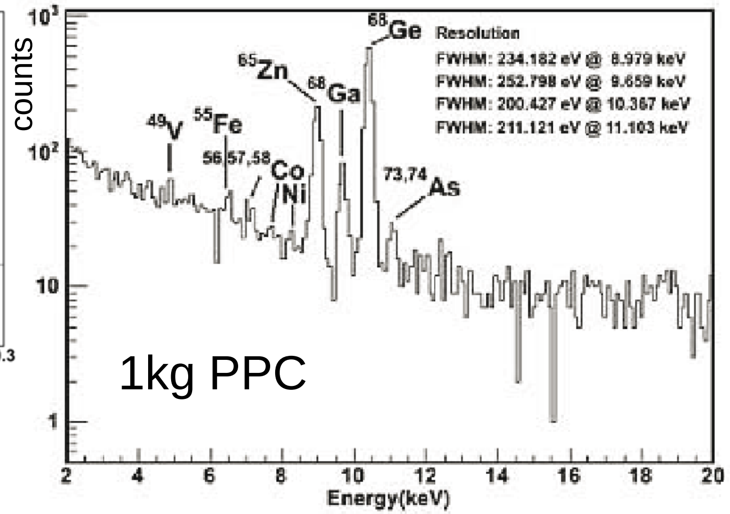


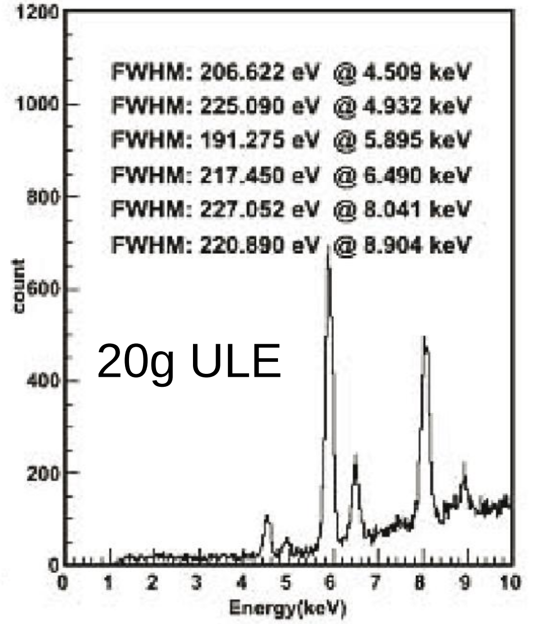


→ spectroscopy with 709g HPGe

CDEX-10 (MC & design study):
10kg PPCGe surrounded by LAr active shielding

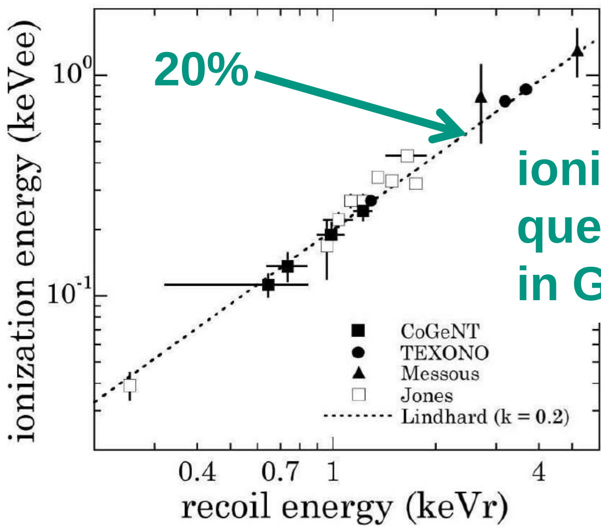


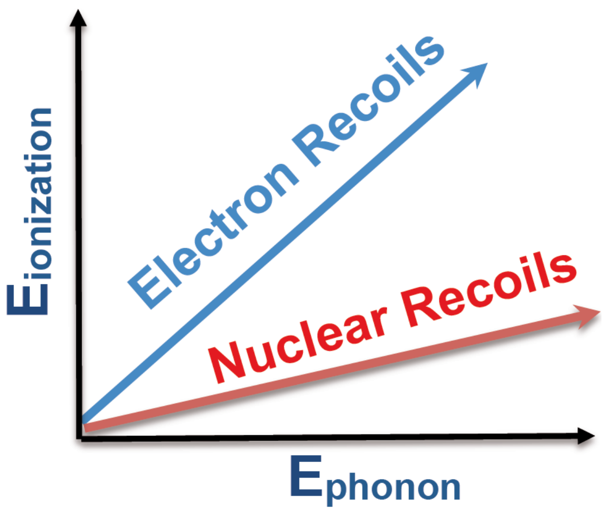


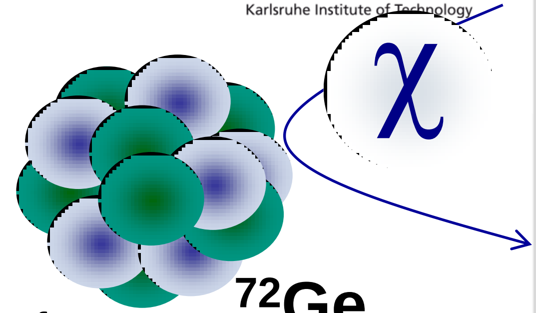


K. Kang et al., arXiv:1303.0601

DM search with cryogenic HPGe detectors







combination of

ionisation (charges)
→ **bgd discrimination**

and

heat (phonons)
→ **energy measurement**

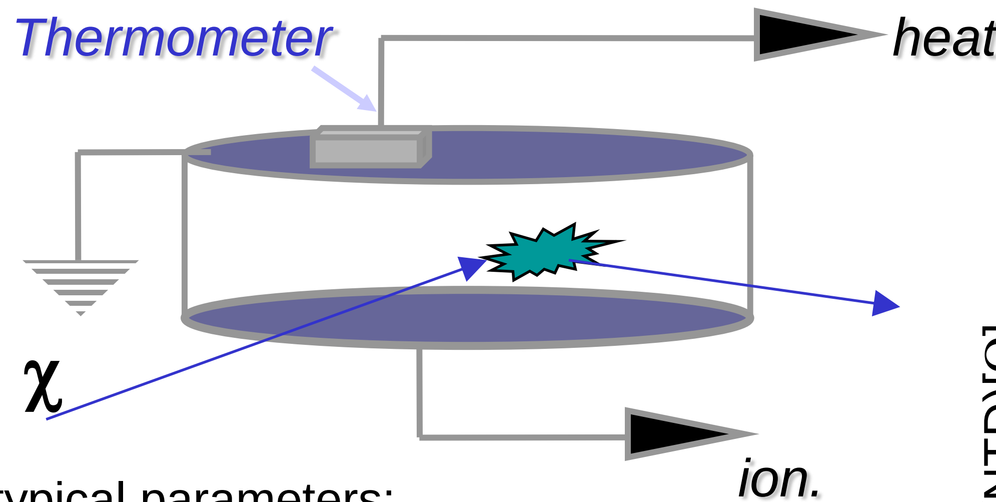
requires T~10-50mK !

DM search with cryogenic HPGe detectors

→ EDELWEISS

χ scattering with energy deposit E_R leads to ΔT read out via thermometer → detector with small $V \cdot C_V$ needed

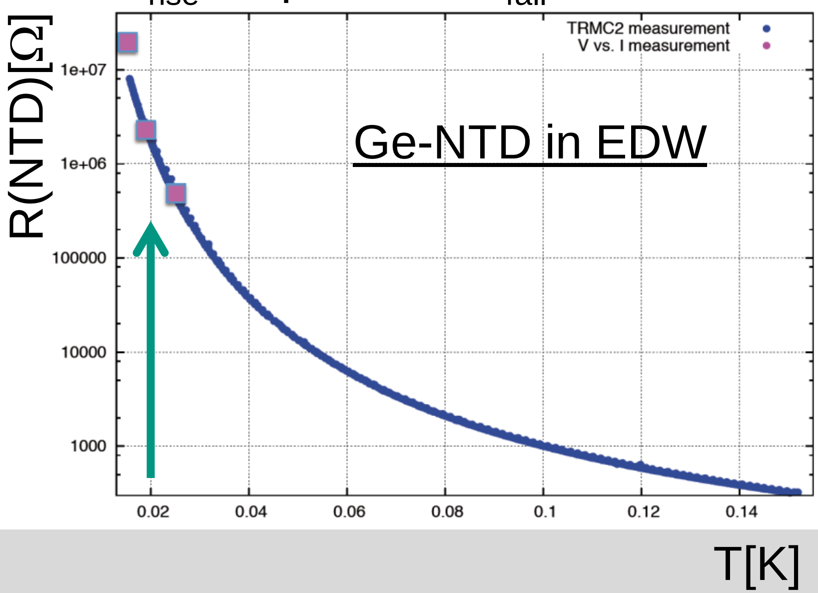
$$\Delta T = \frac{E_R}{V \cdot C_V}$$



E ~ 10 keV_{ee}

heat: ΔT=1.3µK; ΔU=1µV

t_{rise}~10µs-10ms; t_{fall}~100ms



typical parameters:

E = 3V/cm

T_{op} = 20mK

m = 400g (d=20mm; r=35mm)

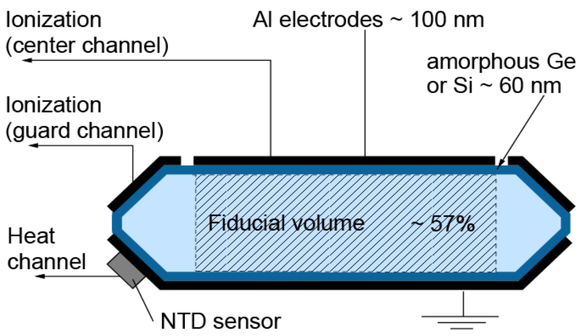
C=VC_V ~ 1nJ/K @ T_{op}

G ~ 5nW/K thermal link to heat bath

DM search with cryogenic HPGe detectors

→ EDELWEISS

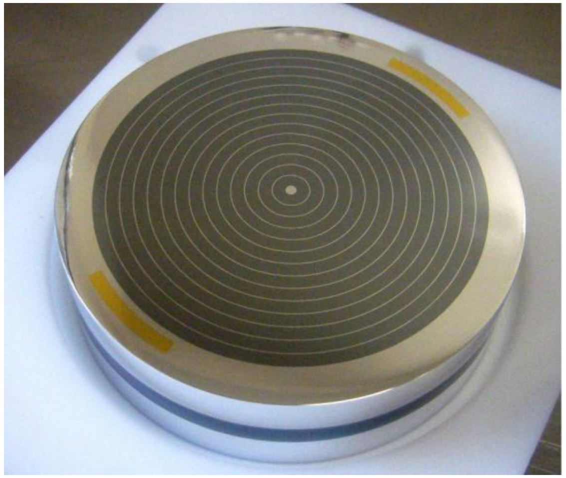
- **Heat measurement (NTD sensor)**
  → $E_{recoil} \approx E_h$ (after NL correct.)
- **Ionization measurement @ few V/cm**



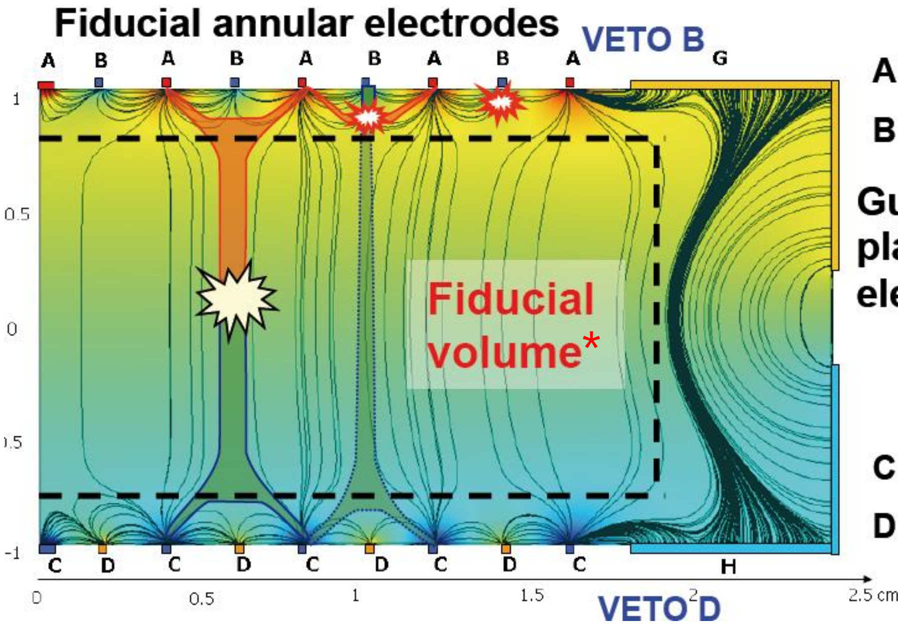
1st generation GeNTD 320g all planar electrodes

- n-type HPGe
- $|N_a\text{-}N_d| < 10^{10}$ cm^{-3}
- dislocations (EPD) ~2000/cm^2

2nd generation ID400



ID400g



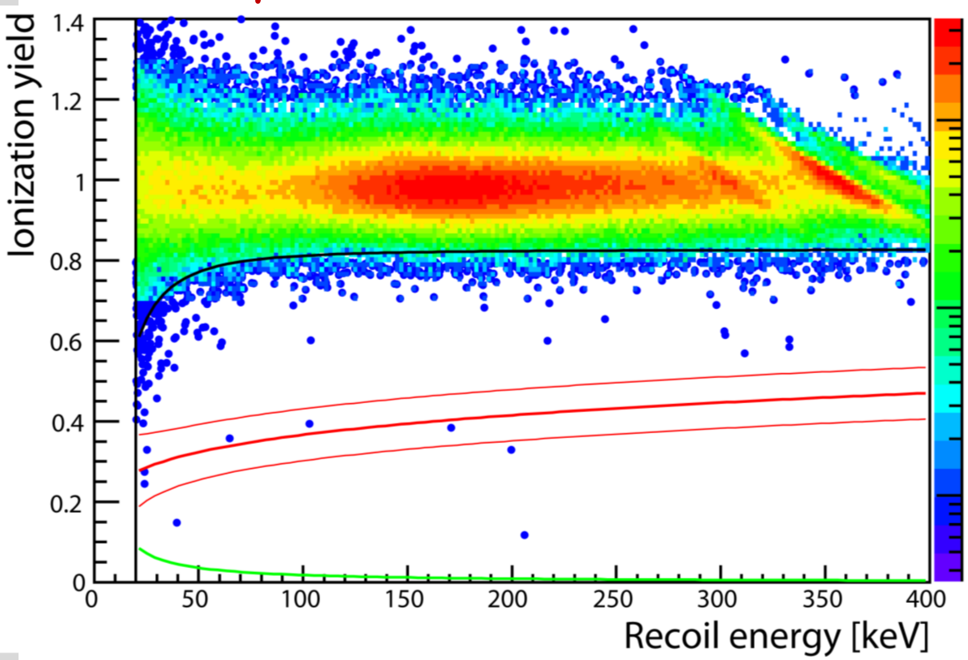
A: +4 V
B: -1.5V
Guard planar electrode
C: -4 V
D: +1.5V

*measured via cosmogenic γ lines

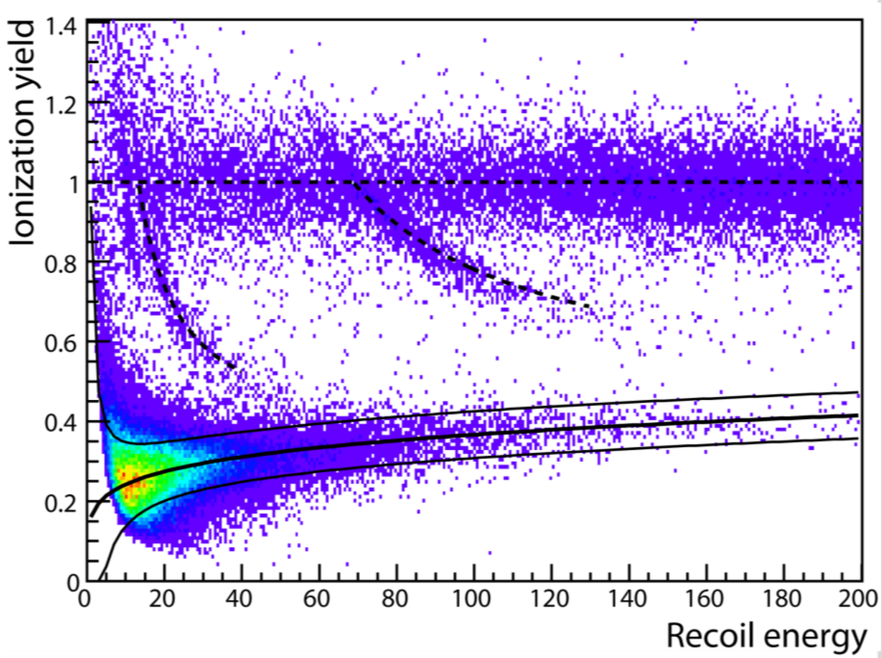
DM search with cryogenic HPGe detectors

→ EDELWEISS

γ calibrations with ^{133}Ba



n calibrations with AmBe



more than 350.000 γ´s
γ suppression factor 3x10^{-5}
1 "NR" for every 30k γ´s (20-200keV)

90% CL signal region
Q = 0.16 $E_r^{0.18}$ from <10 to 200keV
(detection efficiency below 20keV)

P. Di Stefano et al., ApP14 (2001) 329; O. Martineau et al., NIMA 530 (2004) 426 ; A. Broniatowski et al., PLB 681 (2009) 305

DM search with cryogenic HPGe detectors

→ EDELWEISS

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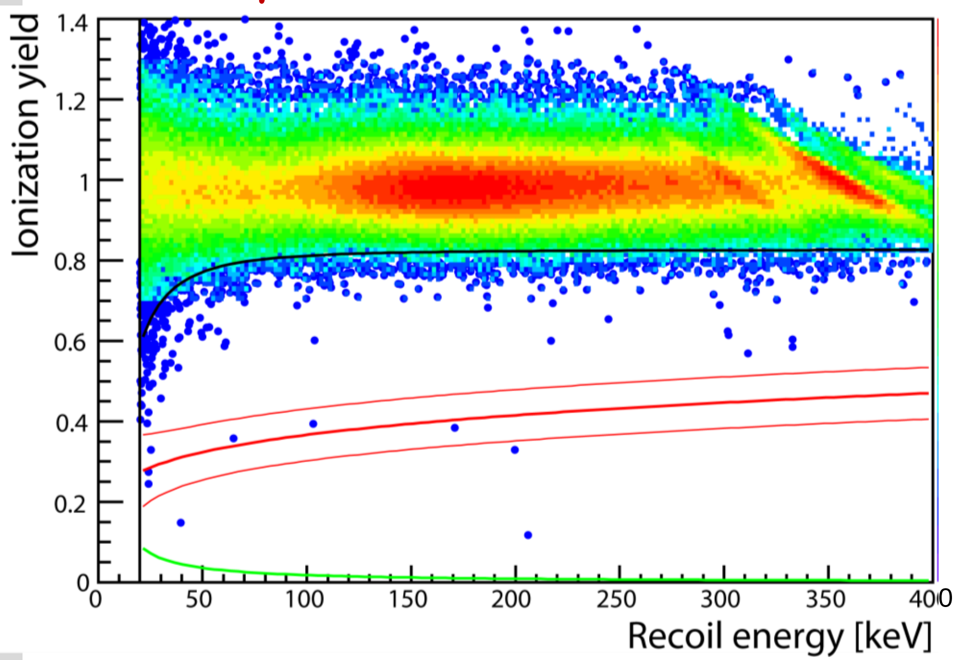
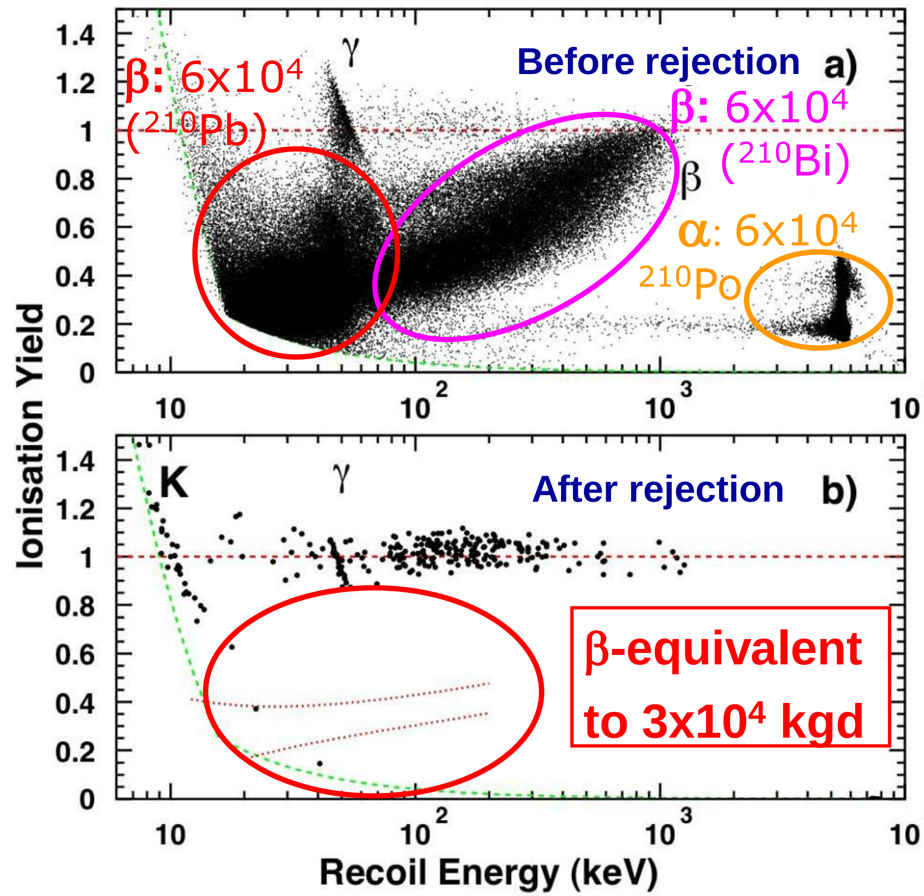


rejection of surface events



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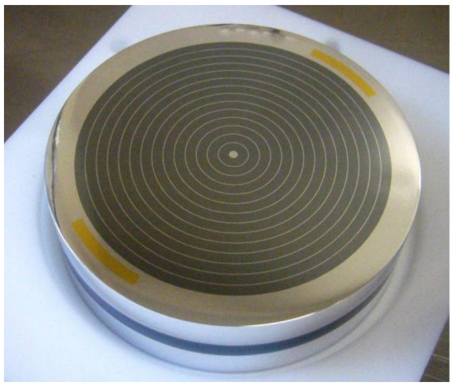
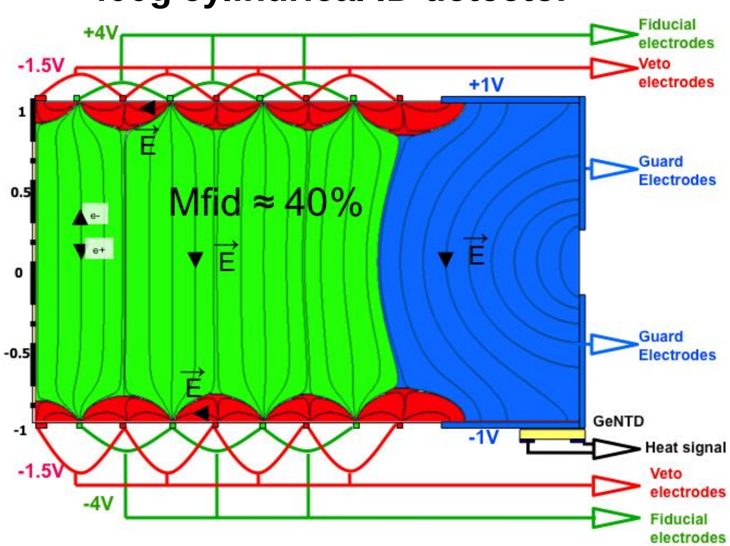
DM search with cryogenic HPGe detectors

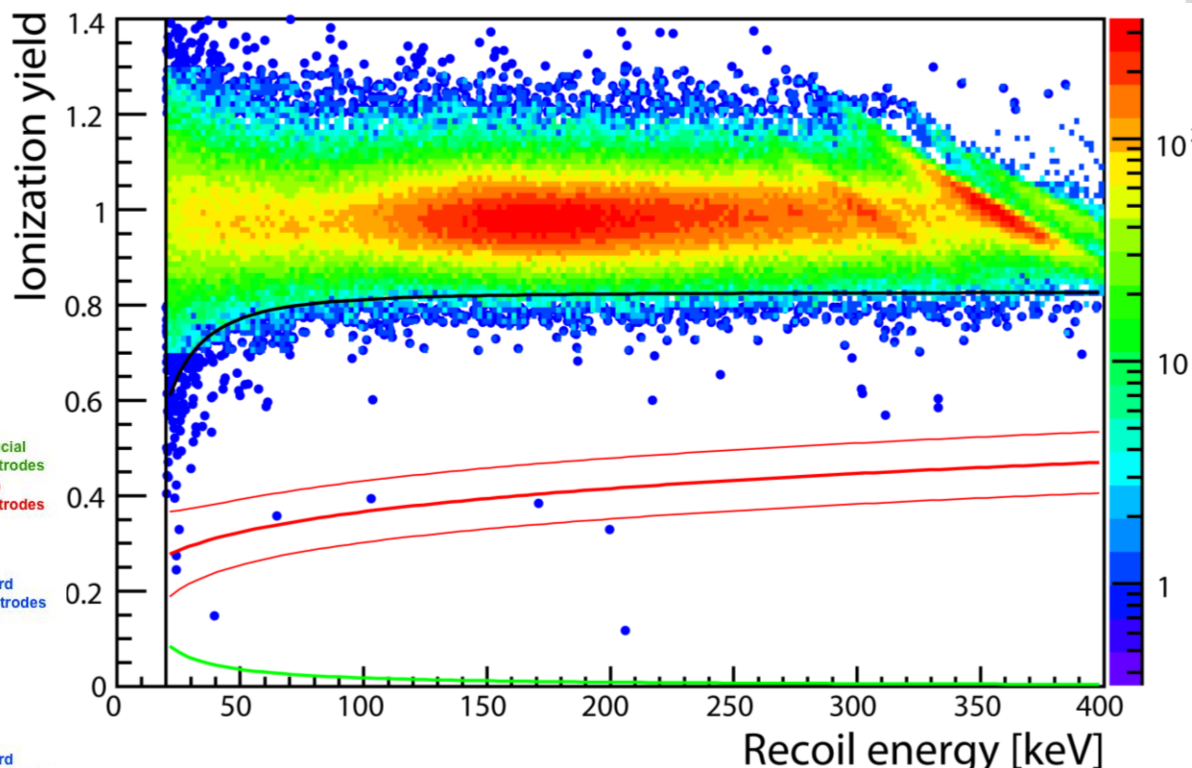
→ EDELWEISS

2. generation ID detectors with lateral planar electrodes



400g cylindrical ID detector



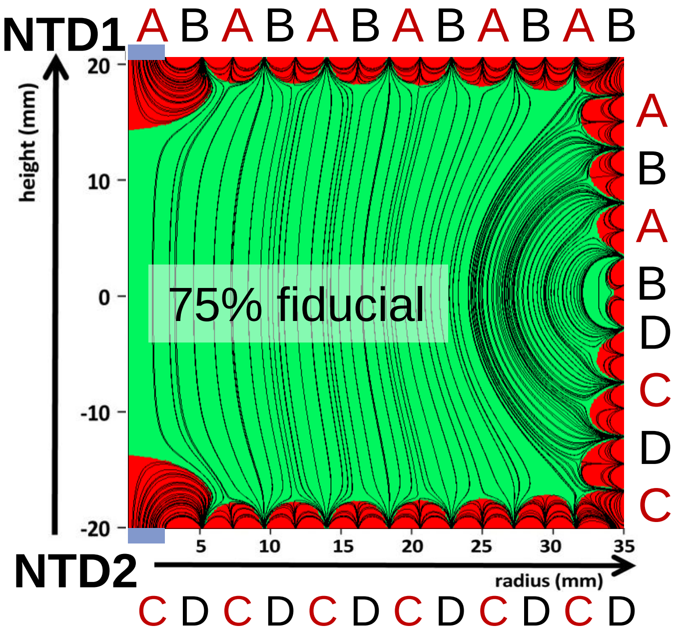


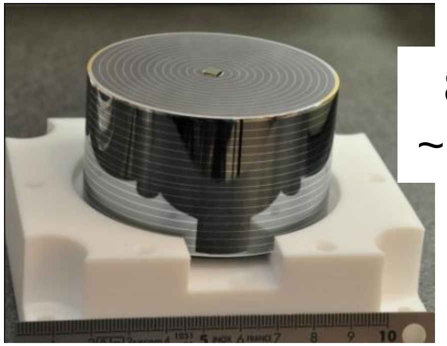
6 “NR evts” in 350.000 gamma calib evts

DM search with cryogenic HPGe detectors

→ EDELWEISS

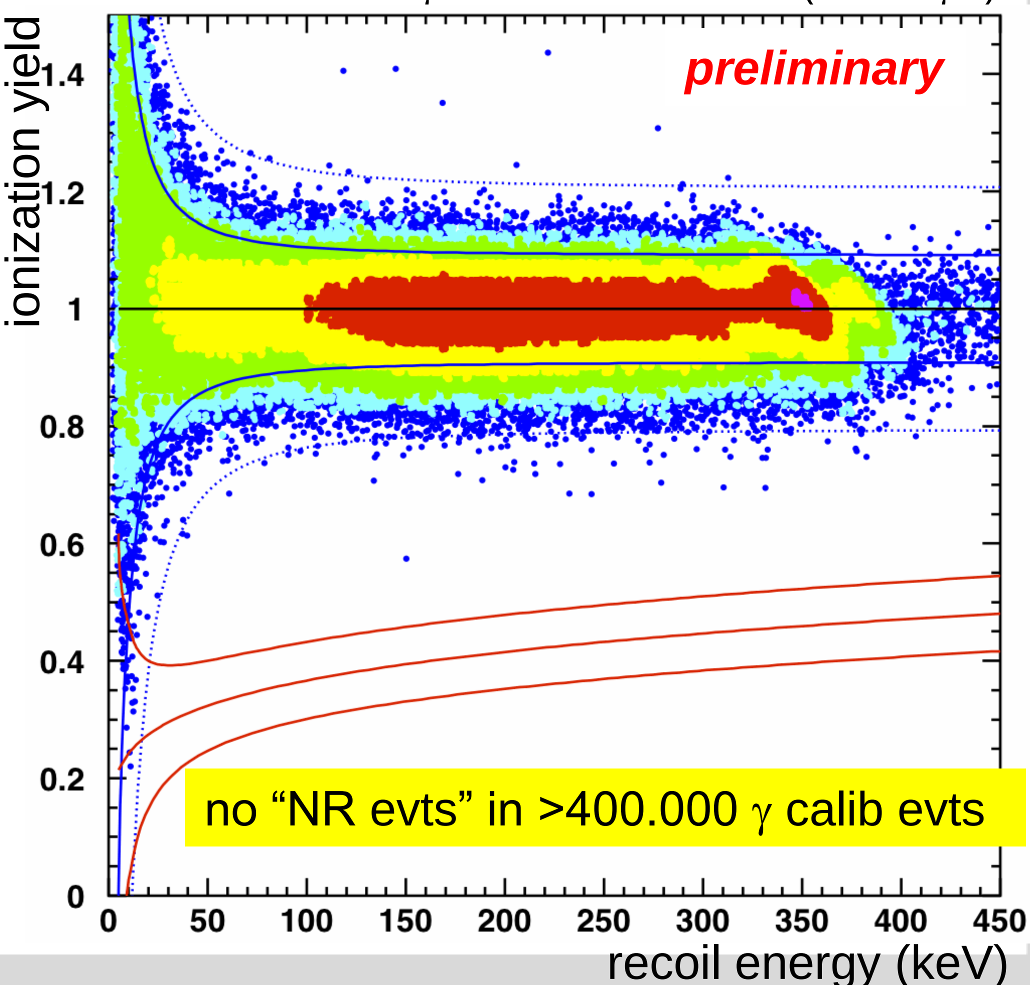
3. generation: FID detectors with rings on all surfaces





800g total mass
~600g fiduc. mass

γ-calibration with ^{133}Ba (411663γ´s)

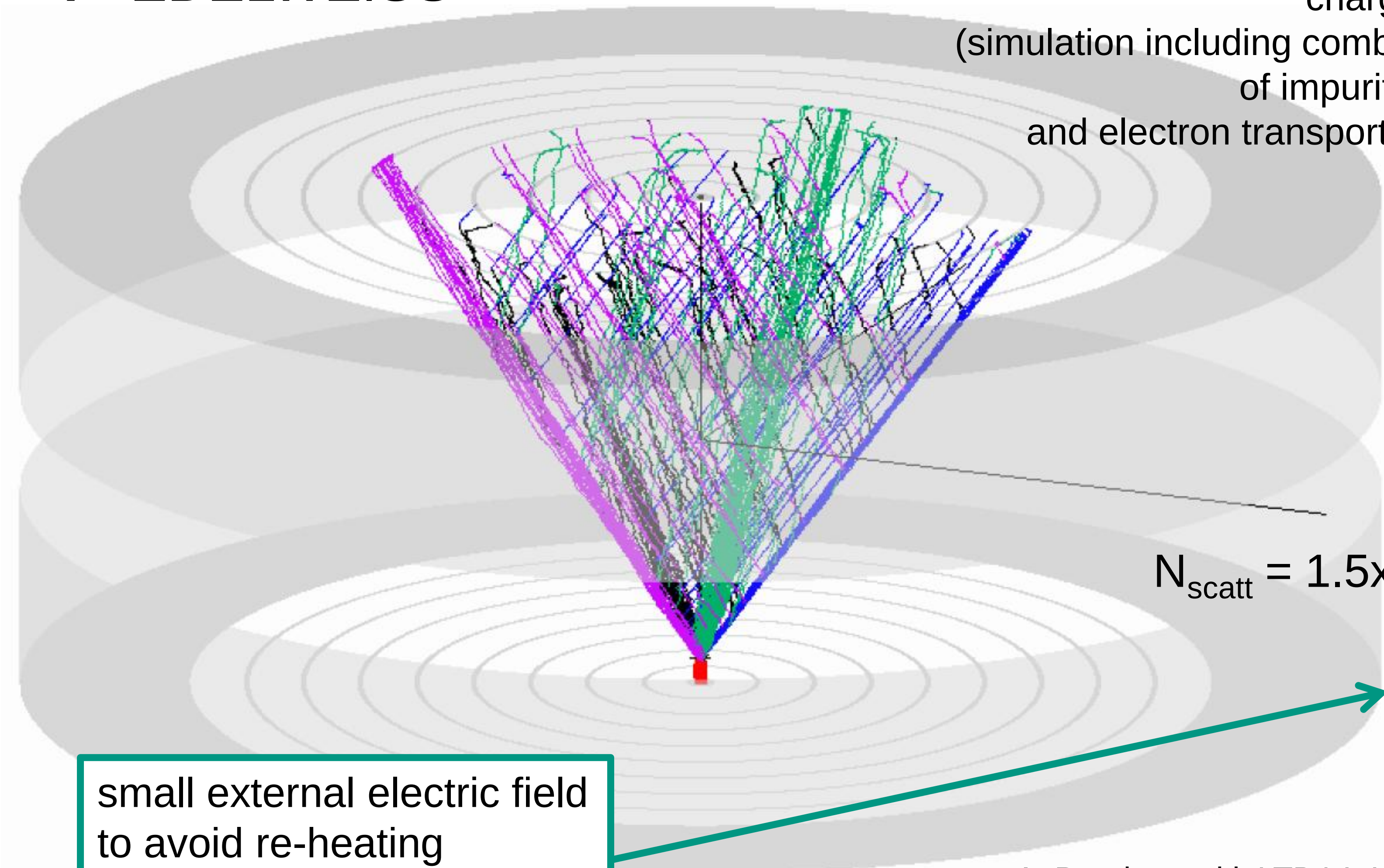


no "NR evts" in >400.000 γ calib evts

DM search with cryogenic HPGe detectors

→ EDELWEISS

charge migration
(simulation including combined effects
of impurity scattering
and electron transport anisotropy)



$N_{scatt} = 1.5x10^{10}cm^{-3}$

$V_a = 1V$

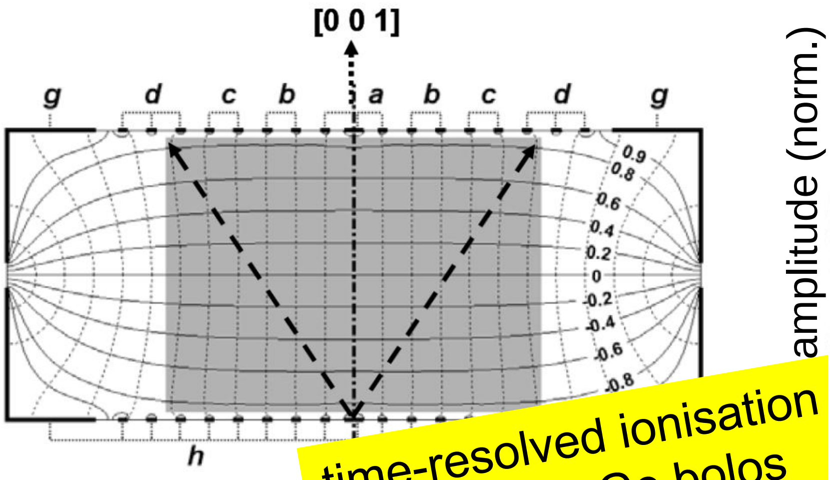
small external electric field
to avoid re-heating
(Neganov-Luke effect)

A. Broniatowski, LTD14, Heidelberg, 2011
E. Olivieri et al., J of Low Temp Phys (2012)

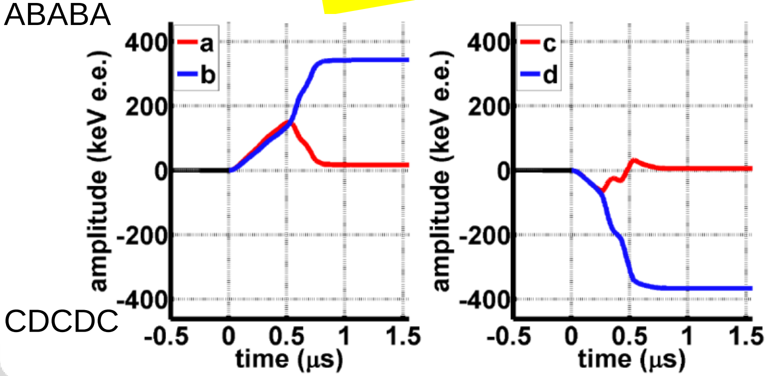
DM search with cryogenic HPGe detectors

→ EDELWEISS

$+V_a = +V_b = +V_c = +V_d = +V_g = -V_h$



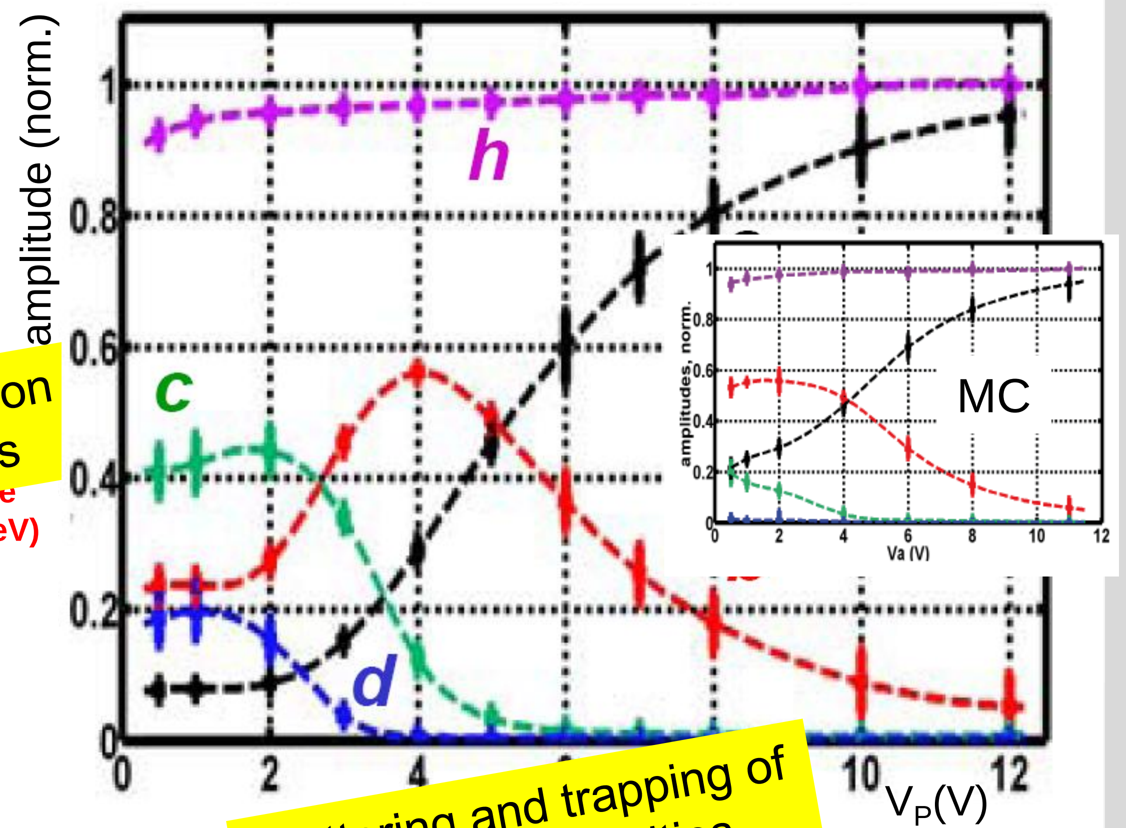
time-resolved ionisation in cryogenic Ge bolos



60keV electron collection pattern

n-type, $|N_d - N_a| < 10^{10}/cm^3$

$|N_d - N_a| = 10^{11}/cm^3$



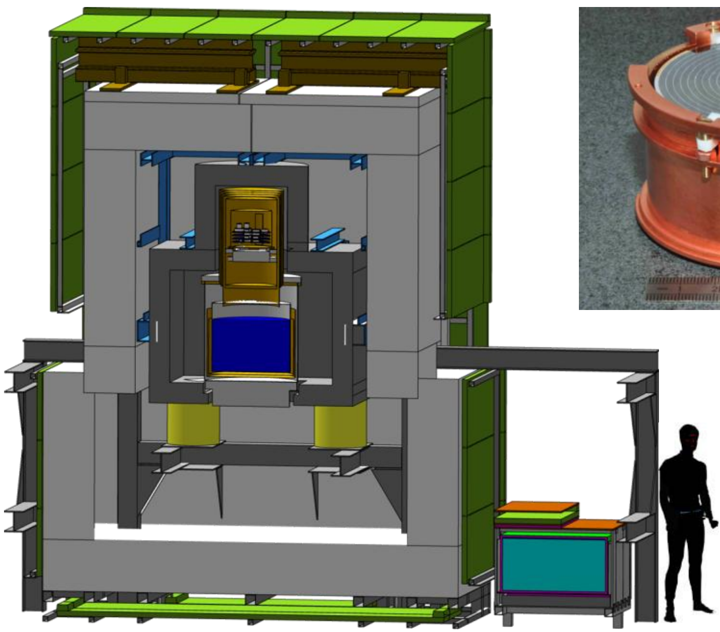
scattering and trapping of electrons on impurities

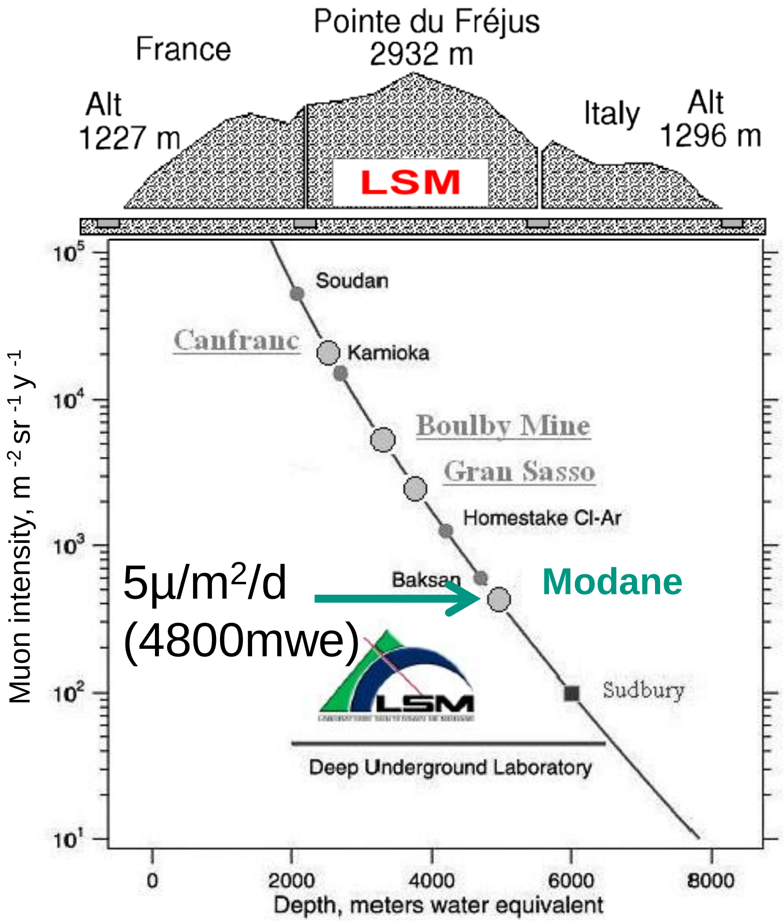
…D14, Heidelberg, 2011

…en et al., J of Low Temp Phys (2012)

DM search with cryogenic HPGe detectors

→ EDELWEISS-3





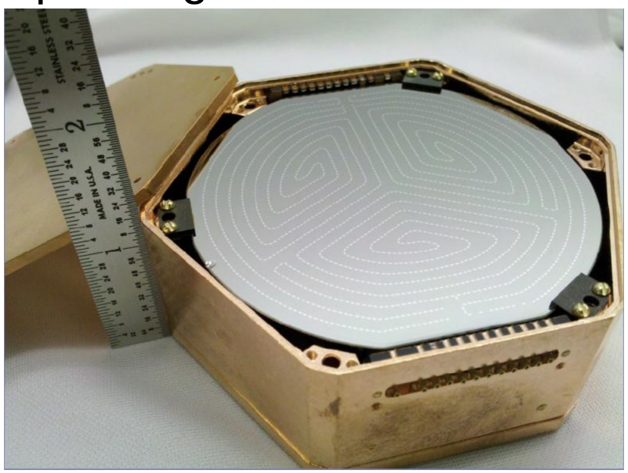
Background (20 – 200 keV)	EDW-2 (evt / kg.d)	EDW-3 (evt / kg.d)
gamma rate (before Q-rej.)	82	14 – 44
ambient neutrons	$(2.6 - 8.1)\cdot10^{-3}$ mainly due to cables and connectors	$(0.8 – 1.9)\cdot10^{-4}$

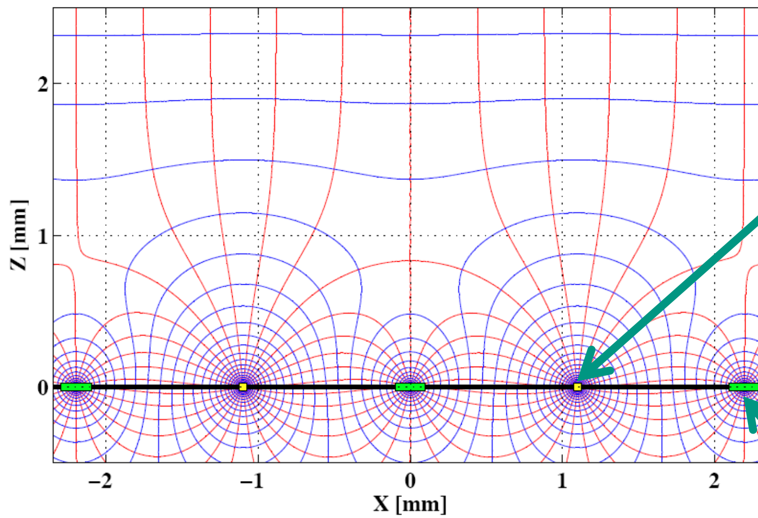
04/2013: 15 FID800 installed; commissioning & calibration ongoing
→40 FID800 (~25kg fid.) by 10/2013
→ ~10.000 kg.d ≡ σ_{si}=2 10^{-45} cm^2

DM search with cryogenic HPGe detectors

→ Super-CDMS

15 ultra-pure Ge crystals: 76 mm x 25 mm (3” x 1”), 0.6 kg
4x2 high sensitivity **phonon channels :** ***each quadrant***
2x2 **charge channels :** ***outer ring, inner disc***
operating at T ~ 50 mK





charge electrode

phonon TES rail

iZIP: interleaved Z-sensitive Ionization and Phonon detectors

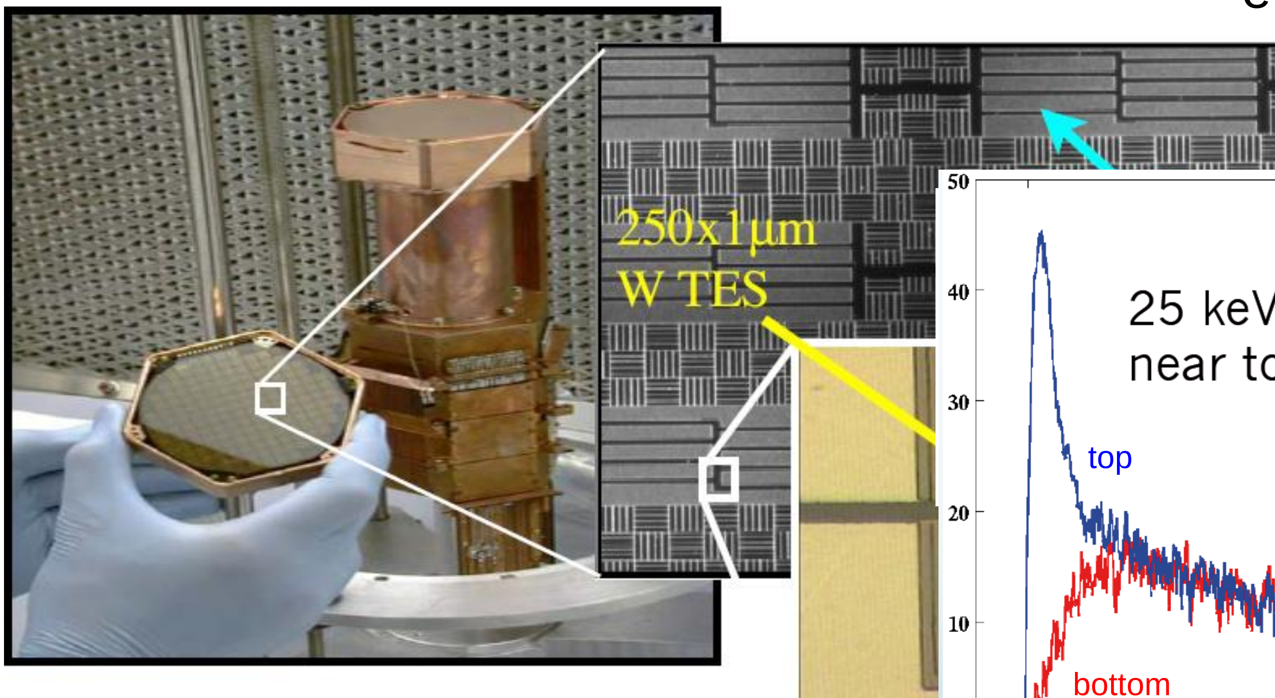
surface events

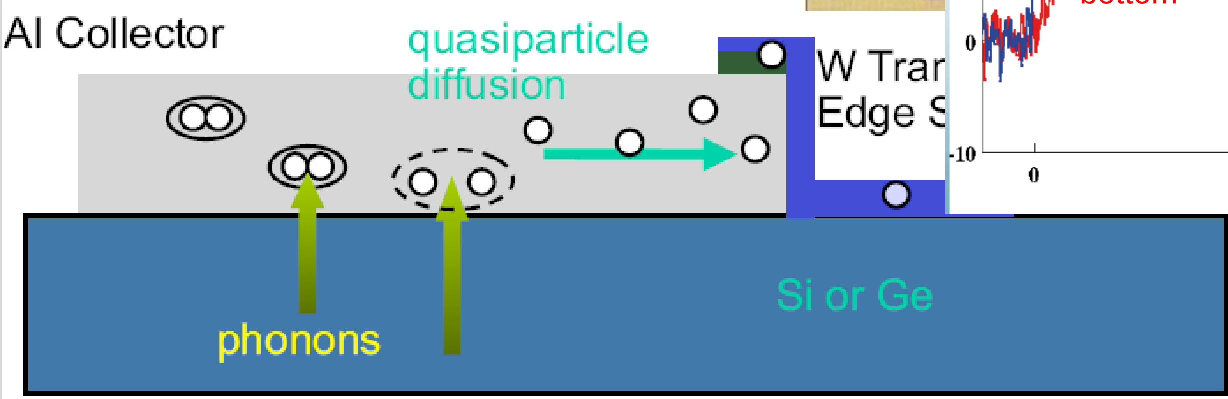
- show up on one detector side only
- have fast phonon signal

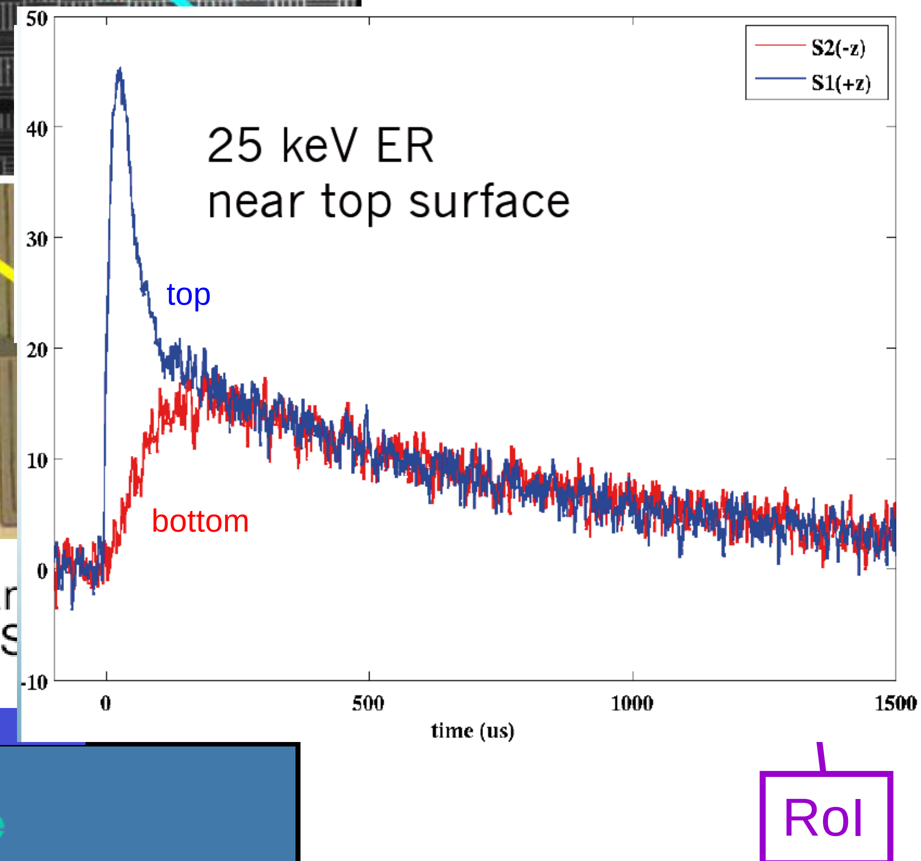
DM search with cryogenic HPGe detectors

→ Super-CDMS

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







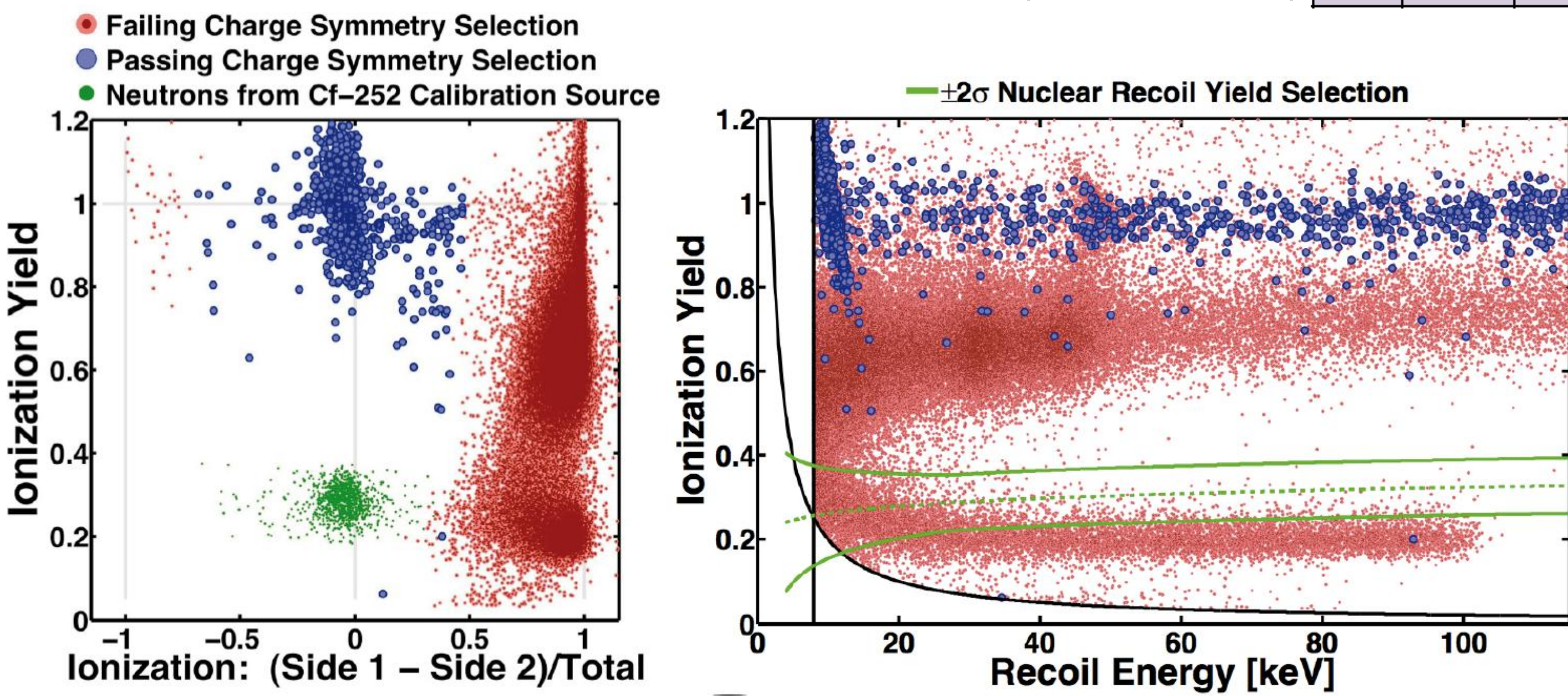
DM search with cryogenic HPGe detectors

→ Super-CDMS

surface rejection tests using implanted 210Pb on Si wavers

^{210}Pb→(63.5keV ß-)
^{210}Bi→ (1.17MeV ß-)
^{210}Po→(5.3MeV α)
^{206}Pb (105 keV recoils)

Type	E [keV]	P [%]
β-	17	84
β-	63.5	16
Aug E	8.2	37
CE	30.2	60
CE	42.5	14
X-ray	~10.8	24
X-ray	46.5	4



surface rejection requirements: surface event leakage to **<2x10^{-5} at 90% CL** ✓

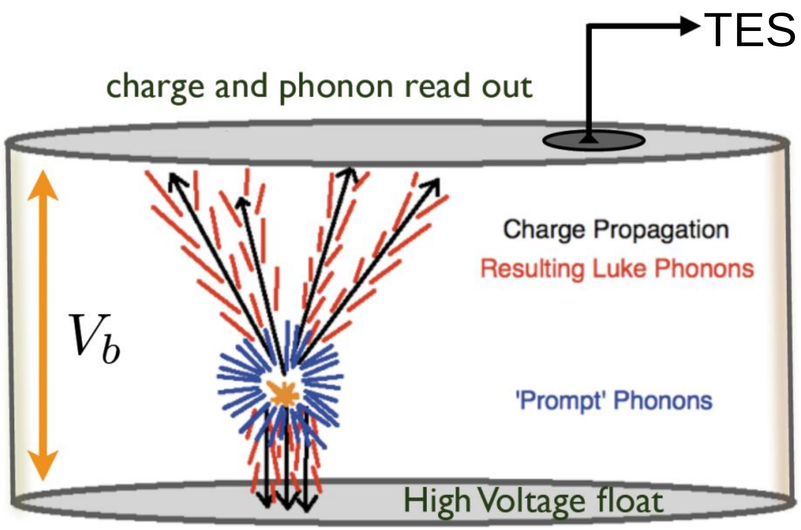
DM search with cryogenic HPGe detectors

→ CDMS-lite (low ionis. thresh. expt)

low mass WIMP search

e.g. m(χ)=10GeV; E_{rec}=1keV

→ 0.85keV(phonon) + 0.15keV(ion.)



amplification ~24 reached

E_{thresh}=0.085 keV_{ee} reachable

no more evt-based ER/NR discrimination

Bias voltage accelerates e/h

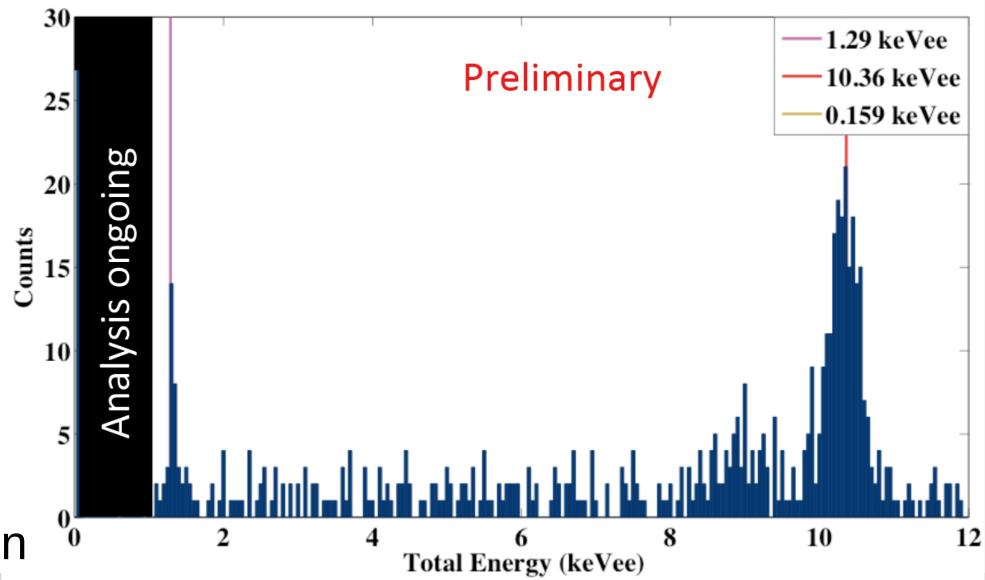
"terminal velocity" → max KE of ~ 30 meV

Under high bias, work done on e/h:

> 10 eV >> 30 meV

"excess energy" is shed as Luke phonons:

$E_{Luke} = N_{e/h} \times eV_{bias}$ $V_{bias} \leq 70V$

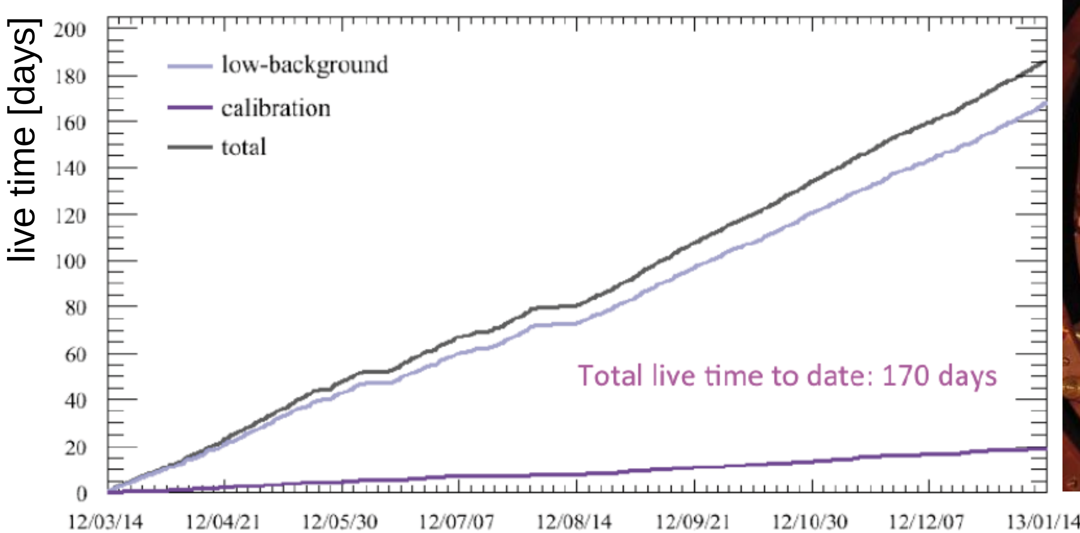


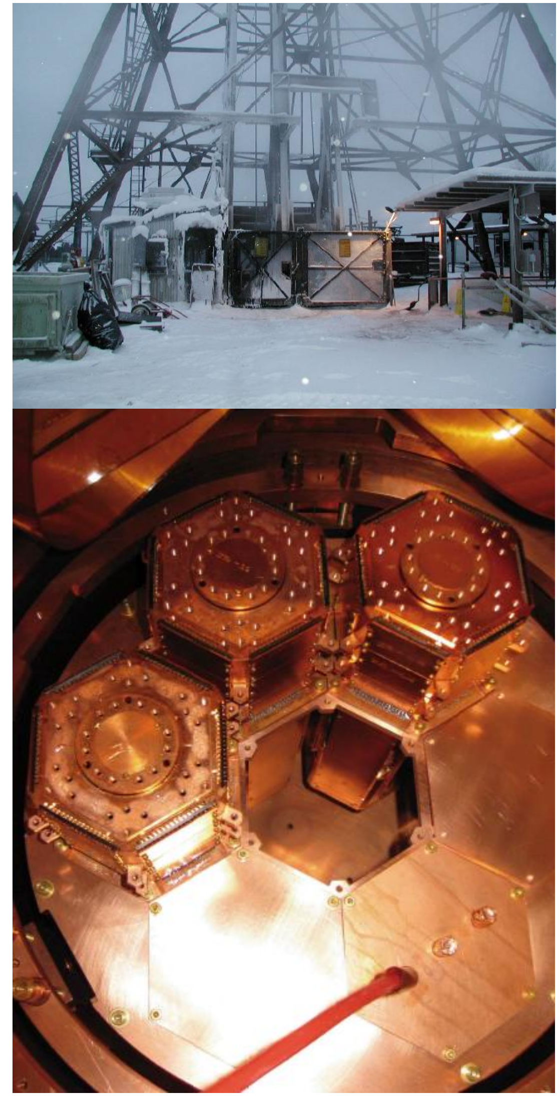
DM search with cryogenic HPGe detectors

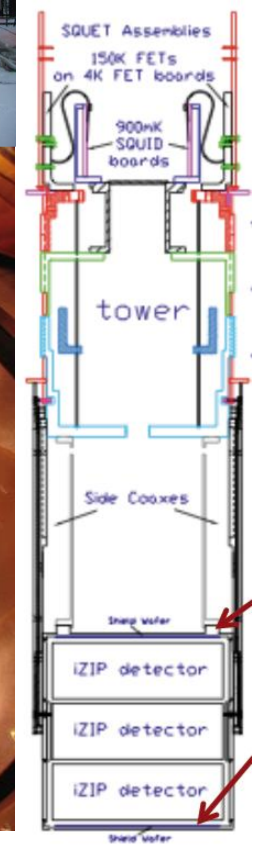
→ Super-CDMS

SuperCDMS: 2 experiments with substantial detector improvements

- SuperCDMS-**Soudan**, **operating 10 kg** Ge array (5x 3det´s à 600g; 1kg-det´s)
- SuperCDMS-**SNOLAB**, **proposed 200 kg** Ge array

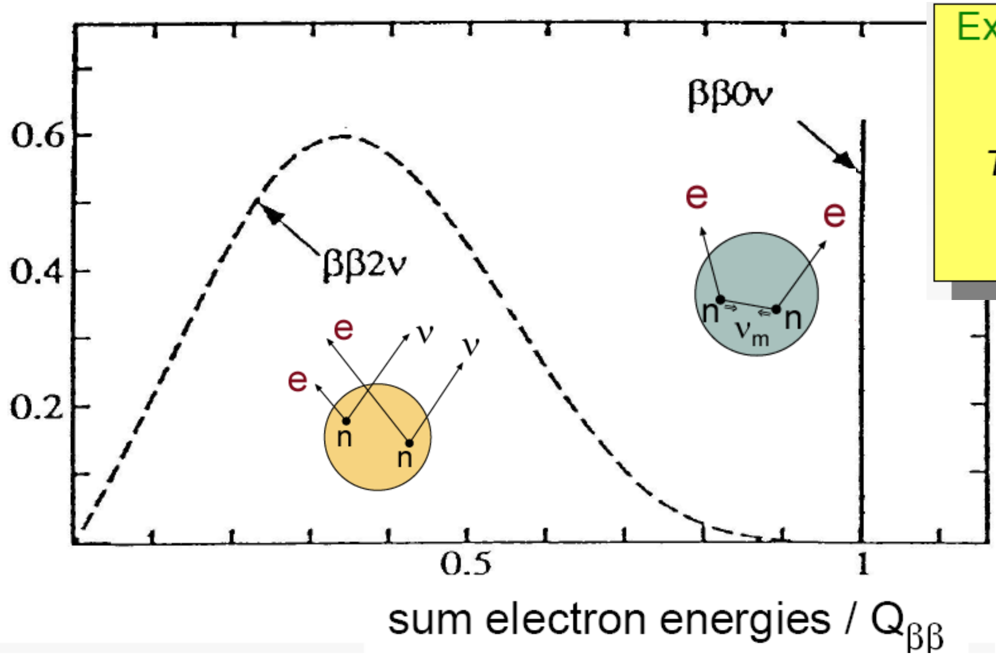






Search for 0νββ with HPGe detectors

→ generalities



Experimental sensitivity

$$T_{1/2}(90\%CL) > \begin{cases} \frac{\ln 2}{2.3}\frac{N_A}{A} a \cdot \epsilon \cdot Mt & \text{for } N^{bkg}=0 \\ \frac{\ln 2}{1.64}\frac{N_A}{A} a \cdot \epsilon \sqrt{\frac{Mt}{B \cdot \Delta E}} & \text{for large } N^{bkg} \end{cases}$$

ßß0ν:
- electronic
- pointlike
- 2-3 MeV

WIMP DM:
nuclear recoil
pointlike, bulk
~few keV

^{100}Mo → ^{100}Ru + 2e- + 2ν, Q=3035.0keV

^{136}Xe → ^{136}Ba + 2e- + 2ν, Q=2461.9keV

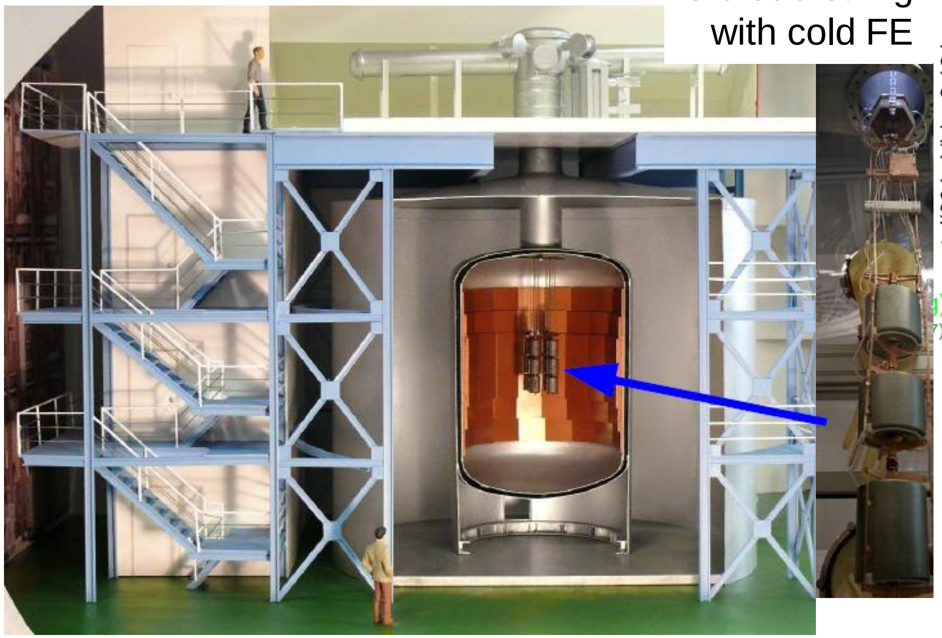
^{76}Ge → ^{76}Se + 2e- + 2ν, Q=2039.1keV

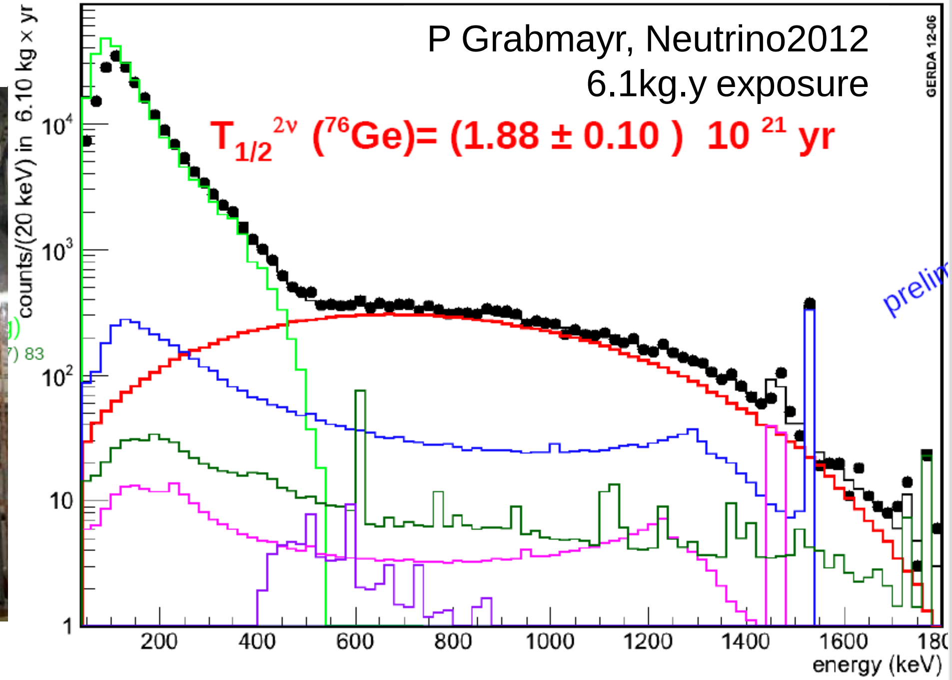
requirements:
- low background (→ ~cts/ROI/t/y)
- single-site electronic
- good energy resolution (~4keV@2039keV)

Search for 0νββ with HPGe detectors

→ GERDA

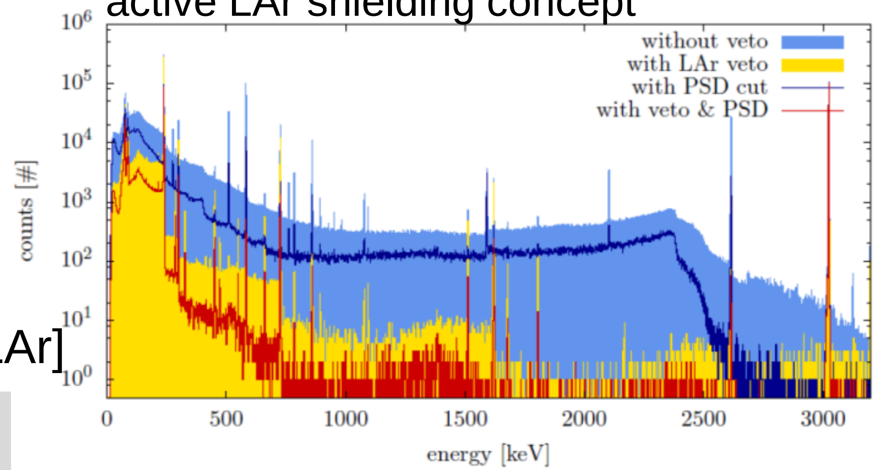
3-diode-string
with cold FE





6 ^{76}Ge$_{enr}$ + 3 Ge$_{nat}$ (14.6kg+6.6kg BEGe)
running since Oct 2011 (phase 1)
$Q_{ßß}$ ± 20keV blinded (4.5keV@2039keV)
BI($Q_{ßß}$±100keV)
= 0.020 + 0.006 – 0.004 cnts/(keV kg y)
phase 1→2 transition (addtl.3.5kg ^{76}Ge$_{enr}$)
→ BI = 0.001 cnts/(keV kg y) [**new BEGe**+LAr]

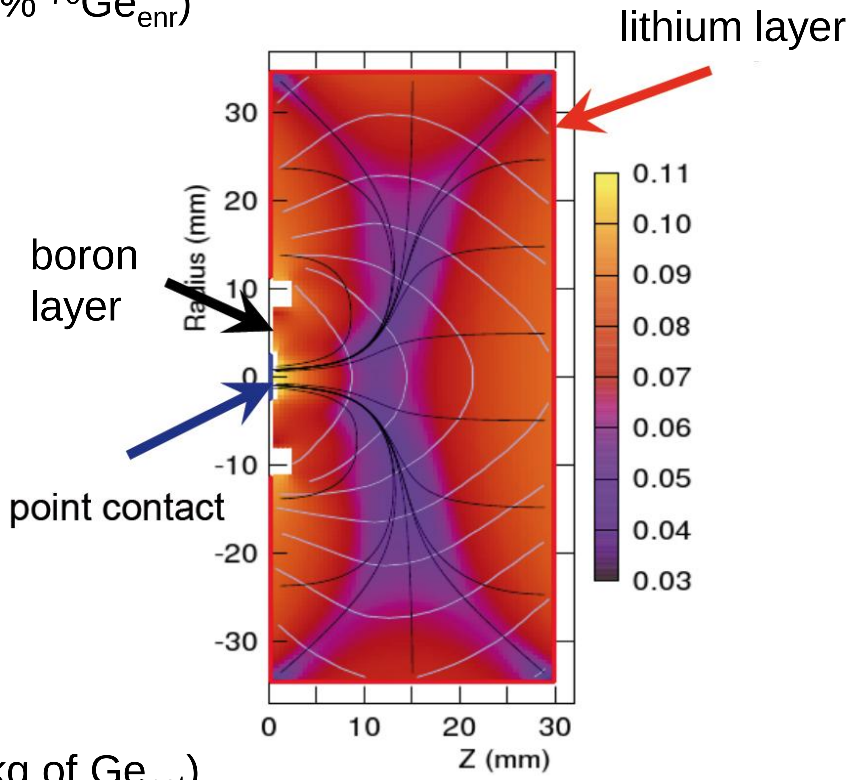
active LAr shielding concept



Search for 0νββ with HPGe detectors

→ MAJORANA

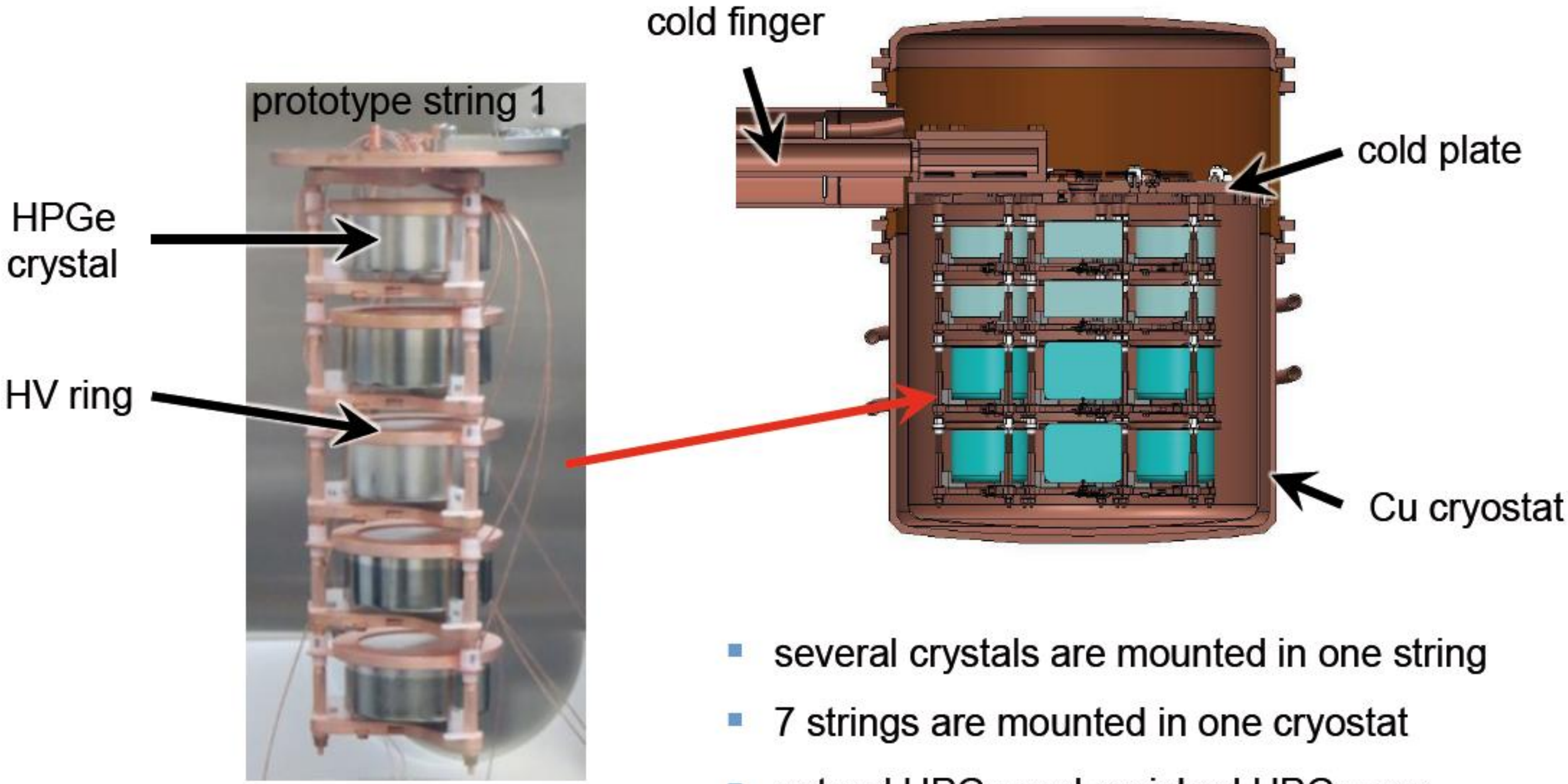
MAJORANA DEMONSTRATOR located at Sanford Underground Research Facility (SURF)
~1.5 km (4200 m.w.e); PPC HPGe (86% $^{76}Ge_{enr}$)



40 kg of Ge detectors
(30 kg of 86% $^{76}Ge_{enr}$ crystals and 10 kg of Ge_{nat})
2 independent ultra-clean cryostats made of electroformed Cu
low-background passive Cu and Pb shield with active muon veto

Search for 0νββ with HPGe detectors

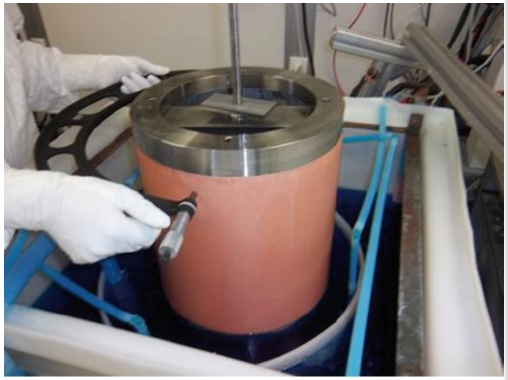
→ MAJORANA

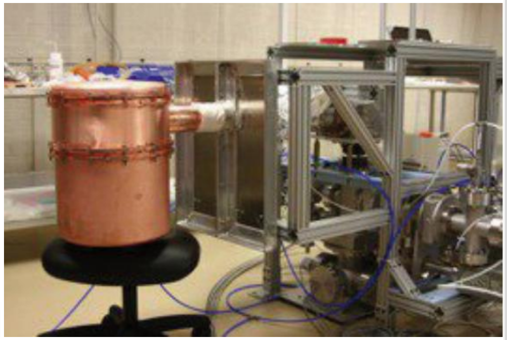


- several crystals are mounted in one string
- 7 strings are mounted in one cryostat
- natural HPGe and enriched HPGe ppc detectors are used

Search for 0νββ with HPGe detectors

→ MAJORANA

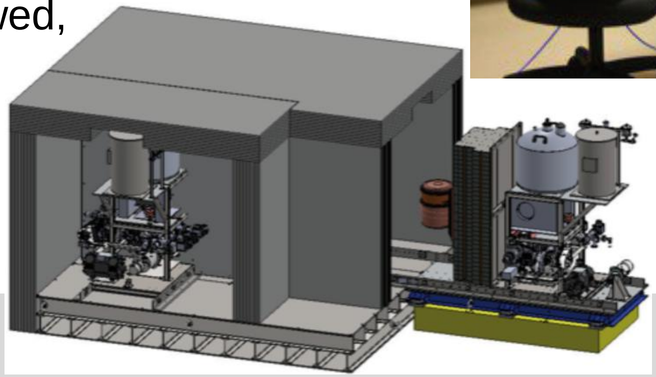




MAJORANA DEMONSTRATOR status as of 03/2013:

- installing experimental hardware at underground lab at SURF
- operating 16 Cu electroforming baths
  (10 @ SURF, 6 at shallow underground site @ PNNL)
- multiple det´s working in string with full set of low bgd components
- reduction and refinement processing facility built and operational
- processing of 42 kg of $^{76}Ge_{enr}$ complete
- production of enriched detectors at ORTEC ongoing
- first batch of 5 $^{76}Ge_{enr}$ detectors shipped underground
- characterization of enriched detectors underground
- >50% of the electroformed Cu produced,
  including all of the major parts for cryostat 1
- prototype cryostat fabricated and assembled
- prototype vacuum system designed, reviewed,
  assembled, and being operated

2013 planning:
Cryostat 1 with 3 strings $^{76}Ge_{enr}$,
4 strings Ge_{nat}



F. Fränkle,
DPG Dresden,
2013

Gamma-ray spectrometry with HPGe detectors

→ generalities

Best limits U, Th ≅ 10 μBq/kg for reasonable time of measurement (~ 1 month)

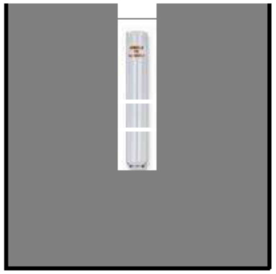
$$\text{Detection Limit} \approx \frac{\sqrt{\text{Backg. R}}}{\varepsilon\ .\ \text{I}.\ \text{M}.\sqrt{\text{t}}}$$

R = resolution
ε = efficiency
I = intensity of the line
M = sample mass
t = time of measurement

COAXIAL

high mass

WELL



high efficiency

SEMIPLANAR

high resolution
at low energies

The choice depends on what we want to measure

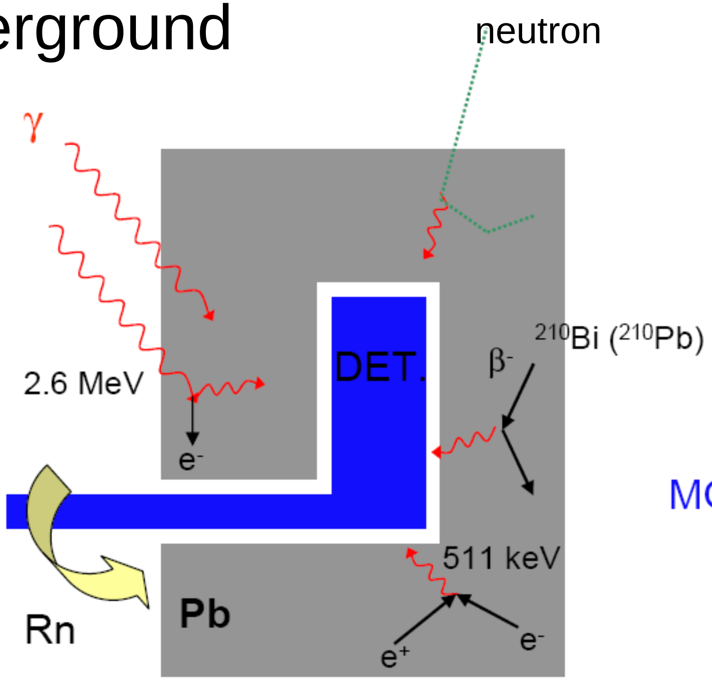
For all types: To improve sensitivity → BACKGROUND REDUCTION

Pia Loaiza, ILIAS meeting, Jaca, Feb 2008

Gamma-ray spectrometry with HPGe detectors

→ generalities

Background components in Ge spectrometry deep underground



- External gamma radiation (up to 2.6 MeV ^{208}Tl)
- neutrons from fission and (α,n) reactions
- Rn and its progenies
- Radioimpurities in cryostat

MOST IMPORTANT : MATERIAL SELECTION

Done in iterative steps

ILIAS* database on radiopurity of materials built using MySQL system combined with php scripts which allow to communicate from web page to the database **http://radiopurity.in2p3.fr/**

http://radiopurity.org (AARM and others)

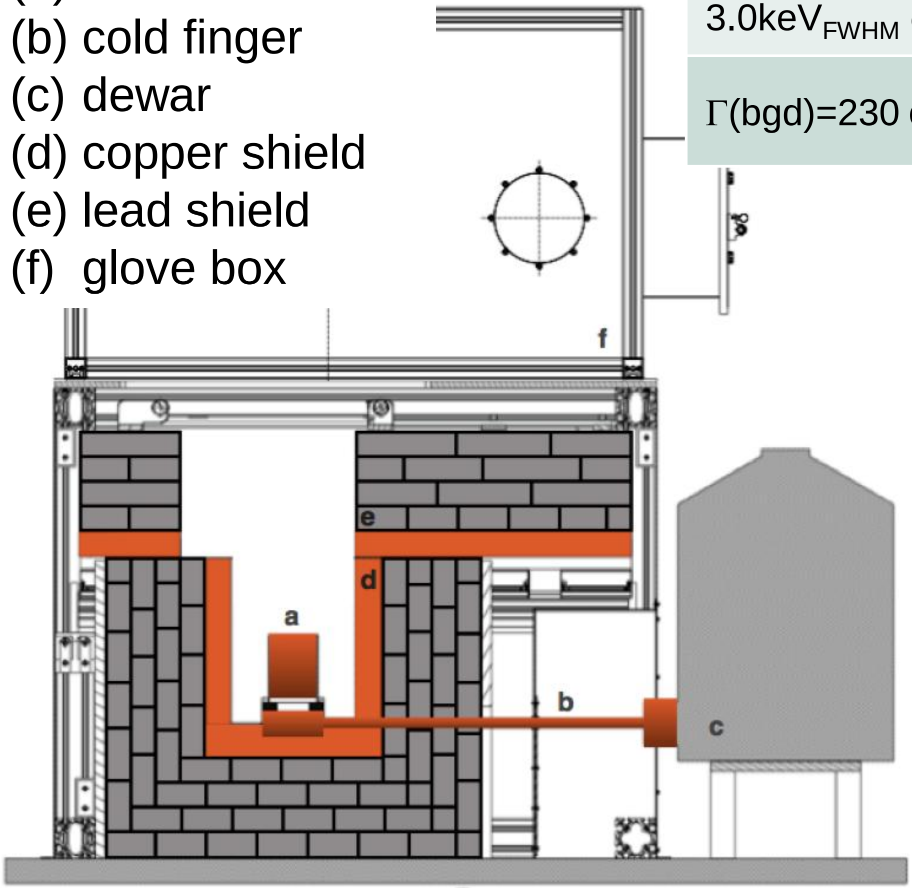
*FP6 European project for the development of the underground science

Gamma-ray spectrometry with HPGe detectors

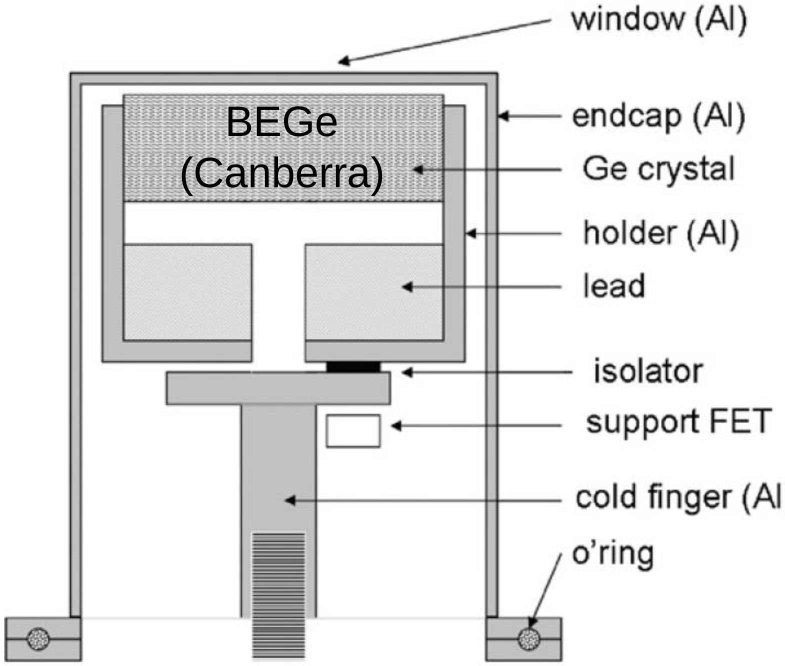
→ GATOR/Ge@LSM

p-type coaxial HPGe	planar BEGe
m=2.2kg	d=80mm, h=30mm (m=800g)
3.0keV$_{FWHM}$ @1332 keV	700eV$_{FWHM}$@ 122keV
Γ(bgd)=230 cts/d [100-2700]keV	Γ(bgd)=140 cts/d [20-1500]keV

(a) HPGe detector
(b) cold finger
(c) dewar
(d) copper shield
(e) lead shield
(f) glove box



L. Baudis et al., JINST 6 P08010, 2011 (GATOR@LNGS)

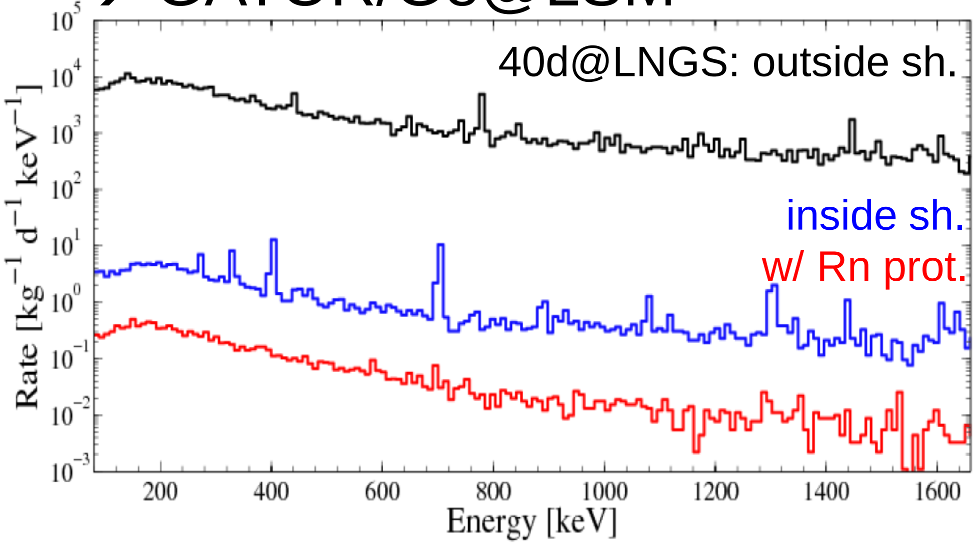


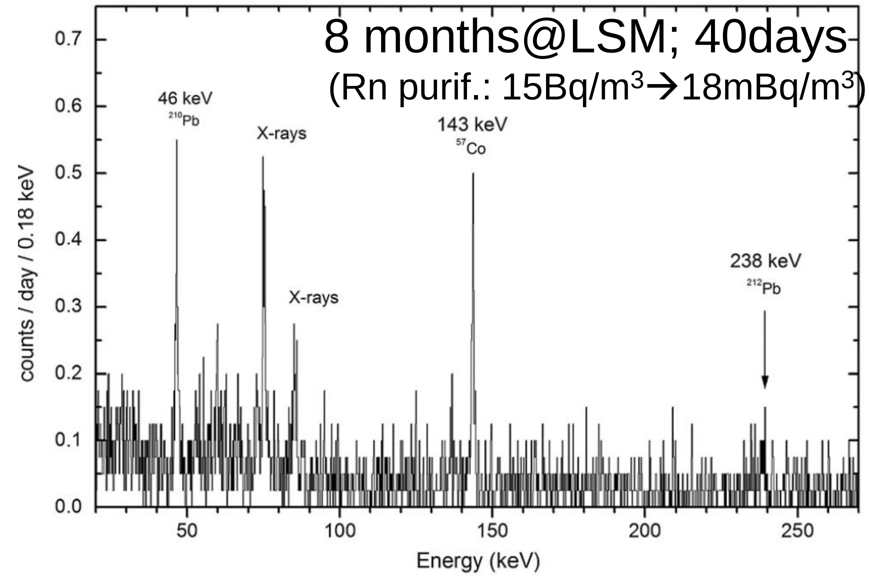
P. Loaiza et al., NIM A634 (2011) 64 (Ge@LSM)

Gamma-ray spectrometry with HPGe detectors

Karlsruhe Institute of Technology

→ GATOR/Ge@LSM





nuclide (line keV)	GATOR	Ge@LSM	GeMPI
$^{238}U/^{214}Bi$ (609)	0.6±0.2	<0.30	0.50±0.45
^{210}Pb (46)	NA	1.76±0.25	NA
^{137}Cs (662)	0.3±0.1	<0.26	NA
^{40}Ka (1461)	0.5±0.1	<0.36	0.6±0.4
$^{232}Th/^{212}Pb$ (238)	<0.5	0.28±0.18	NA

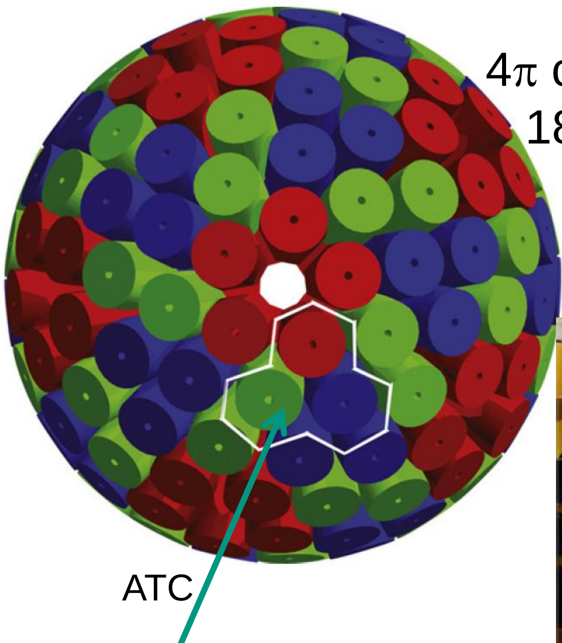
intrinsic bgd in cts/day

Gamma-ray spectrometry with HPGe detectors

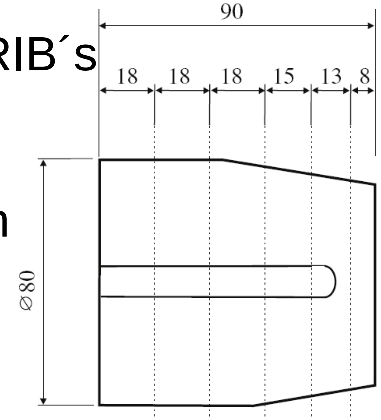
→ AGATA (Advanced GAmma Tracking Array)

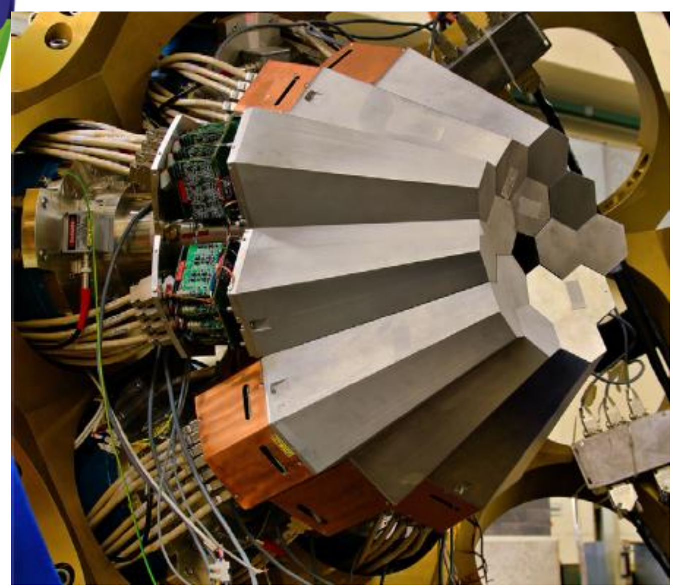
γ spectroscopy (100keV-20MeV-range) at RIB´s (FAIR, HIE-Isolde, SPIRAL2, SPES)

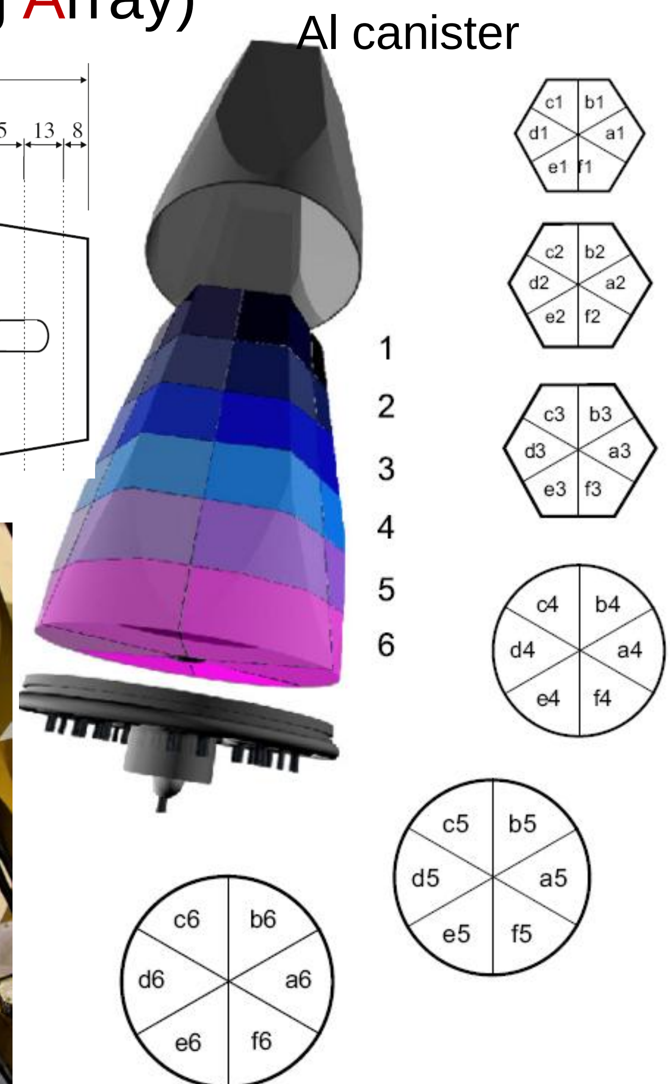
4π coverage through 180 detectors



60 x 3 x (6x6+1core) = 6660 channels





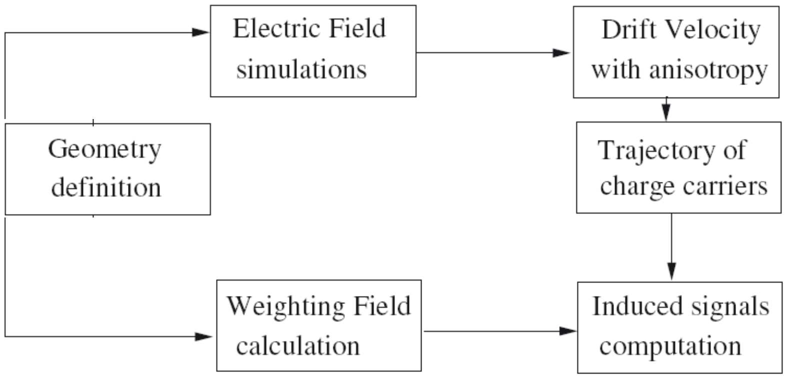


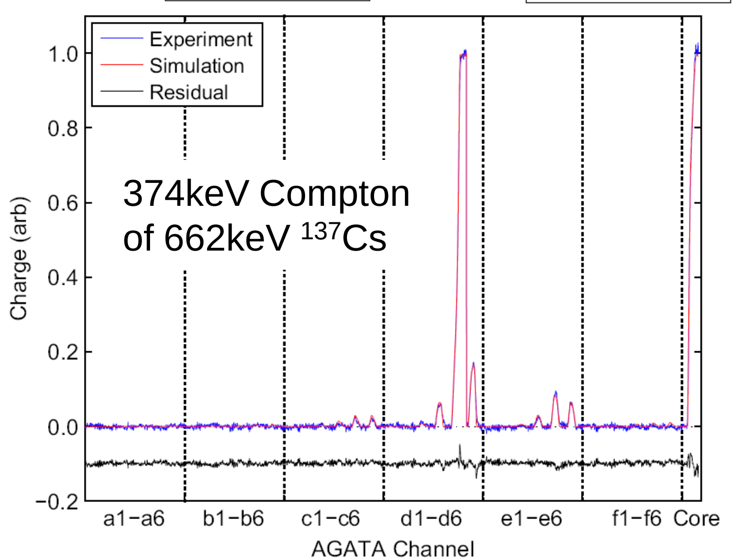
Gamma-ray spectrometry with HPGe detectors

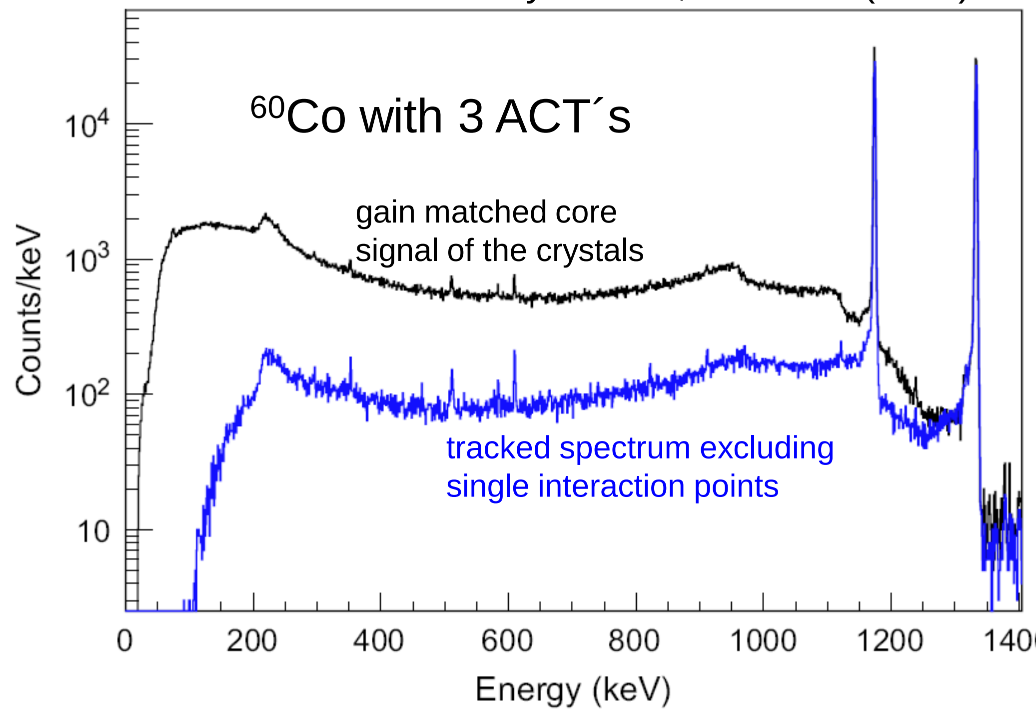
→ AGATA

Multi **G**eometry **S**imulation of e/h drift in n-type HPGe (no space charge; +1V sens.electr.)

S. Akkoyun et al., NIMA668 (2012) 26





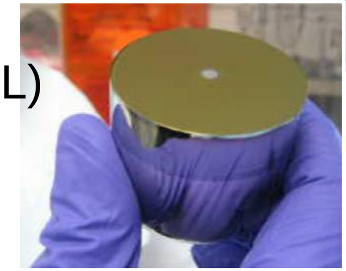


P/T(raw) = 16.8% (no low cutoff)
P/T(tracked)= 53.9% (no low cutoff)
= 54.6% (>200keV)
ε(tracked/raw)=84.5%

HPGe detectors in fundamental research

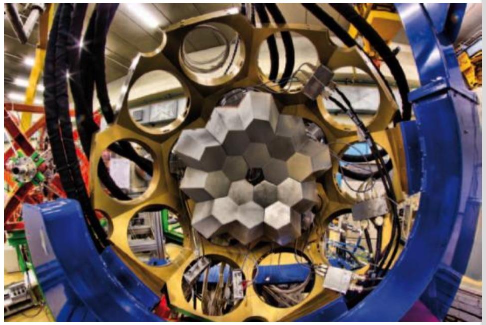
→ outlook

- **ionisation&heat HPGe bolometers in direct DM search**
  15kg Super-CDMS@SUL & 30kg EDW running
  → SuperCDMS@SNOLAB/EURECA → 150kg...1000kg



- **ppc Ge detectors in direct DM search**
  CoGeNT running → C-4 (10x CoGeNT@SUL)
  TEXONO running → CDEX 10kg...1000kg

- **BEGe/ppc Ge in $0\nu\beta\beta$ search**
  GERDA ph1 (15kg $^{76}Ge_{enr}$) running
  → ph2 (>20kg $^{76}Ge_{enr}$) with BI = 0.001 cnts/(keV kg y)
  MAJORANA demonstrator ~5kg $^{76}Ge_{enr}$ in 2013 → 40kg



- **coaxial/segmented/planar Ge in spectroscopy**
  GeMPI/GATOR/Ge@LSM:
  ultra-low-bg spectroscopy for material selection
  AGATA: 4π spectrometer with excellent eff. (82%)
  (tracking/shaping/simulation)

special thanks to

→ Florian Fränkle (UNC; Majorana)

→ Alex Broniatowski (CSNSM; Edelweiss)

→ Jorge Puimedon (Zaragoza; Rosebud)

→ Pia Loaiza (LSM)

→ Hassan Chagani (UMN; Super-CDMS)

→ Ritoban Thakur (Fermilab; CDMS-lite)

apologies to experiments/activities not covered