Karlsruhe Institute of Technology

Ge detectors at ultra-low temperature for DM search

SuperCDMS, CRESST, EDELWEISS

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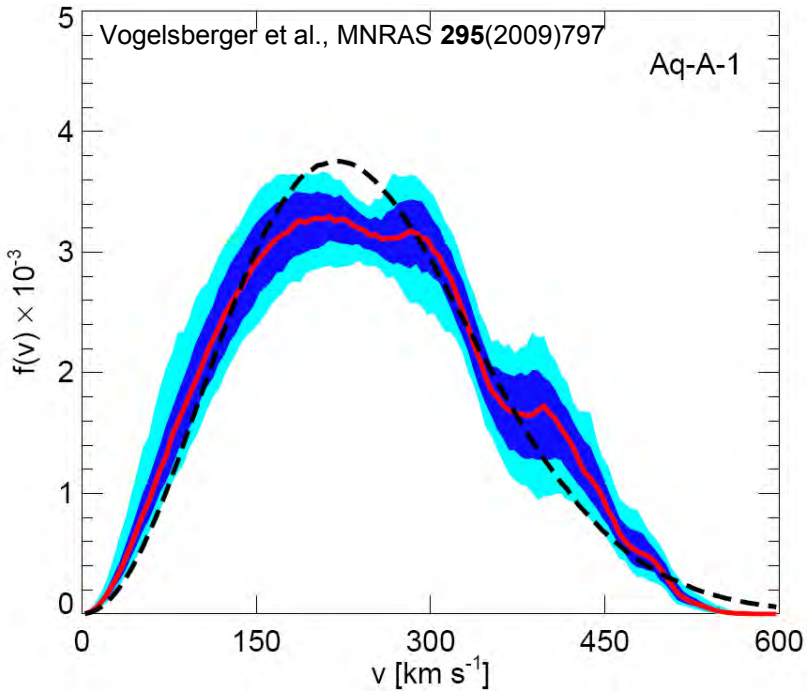
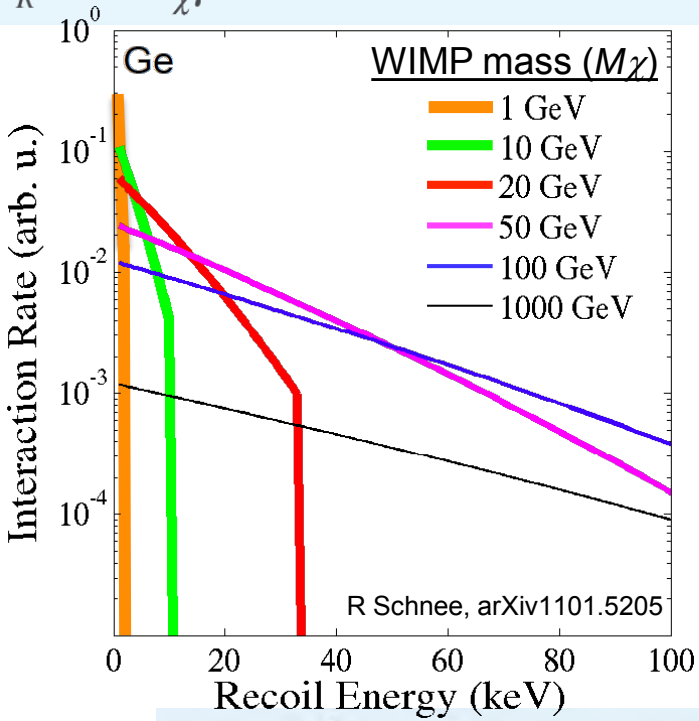
DM search principles in a nutshell

decent approximation for most “standard searches”:
spherical diffuse DM halo (with small substructures) with Maxw.-Boltzm.-like velocity distribution

δ_c(MW, r=8 kpc)~10^5 (~0.3 GeV/cm^3)
<v> ~ 270 km/s and v_{esc}~544 km/s

$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{2 m_\chi \mu^2} F^2(E_R) \int_{v > \sqrt{m_N E_R / 2\mu^2}}^{v_{max}} \frac{f(\vec{v},t)}{v} d^3 v$$

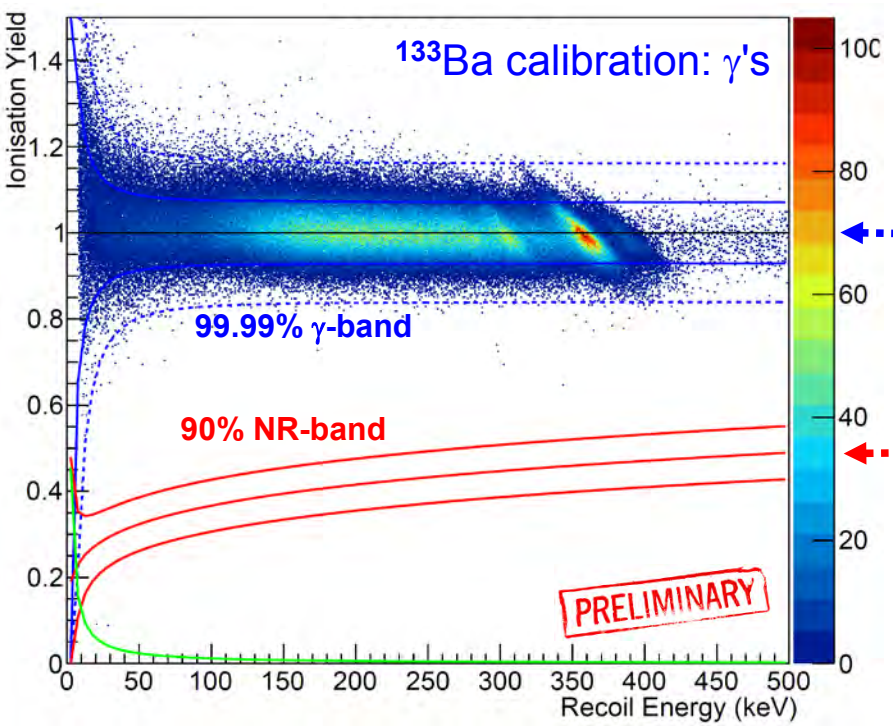




$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta)$$

Ge crystals at T=20mK:

phonons → E_{recoil}; ionisation → PID

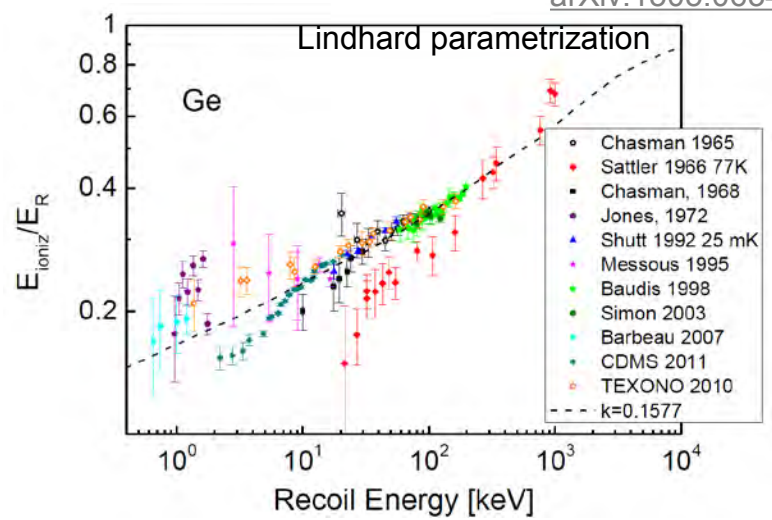


Ionization yield $Q = E_{ion} / E_{recoil}$

Electron Recoils:
Q = 1
(by normalization)

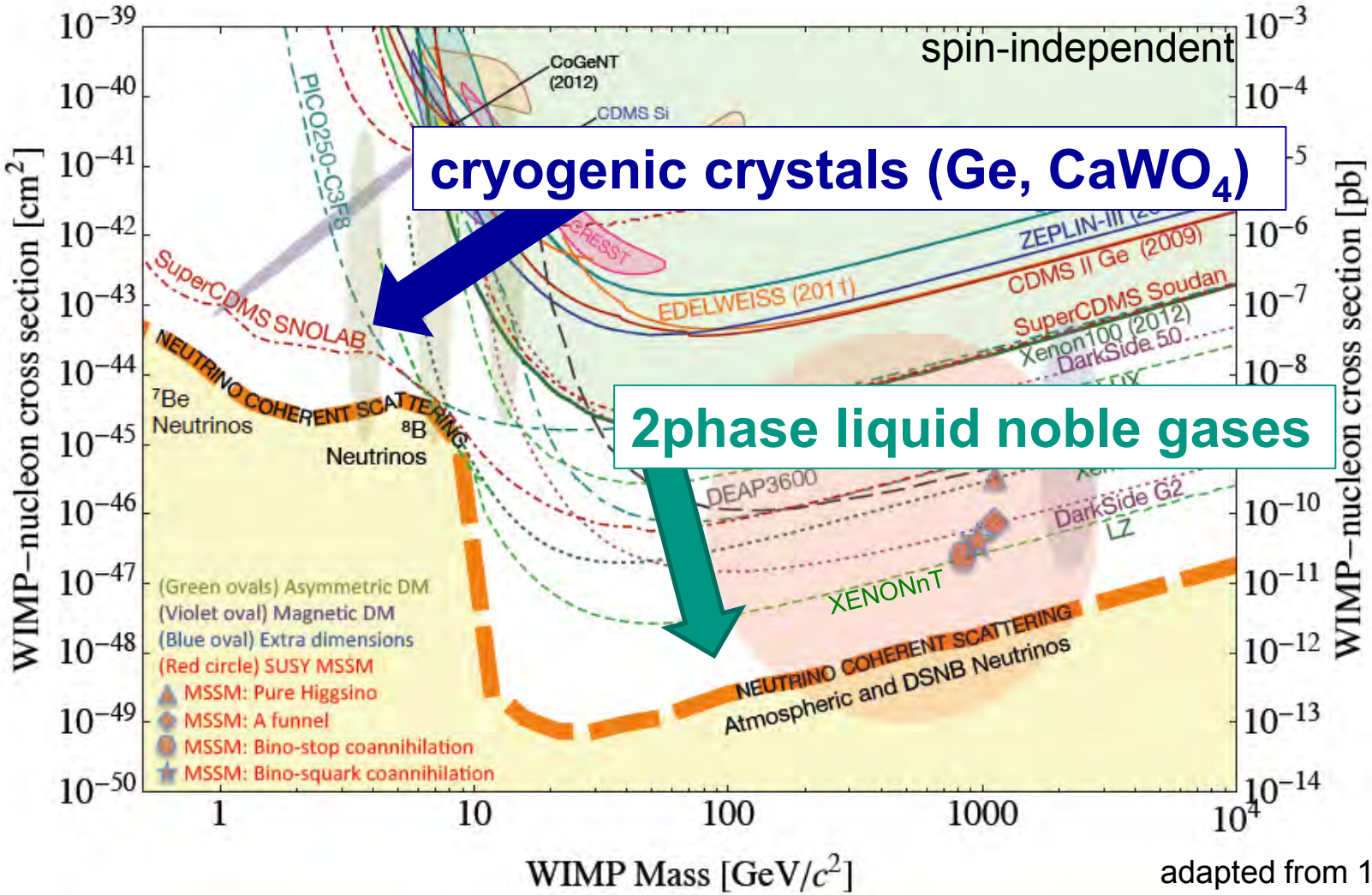
Nuclear Recoils:
Q ≈ 1/3 (*"quenching"*)

arXiv:1505.06340



~1% E_{dep} → scintillation
~10% E_{dep} → ionisation
~100% E_{dep} → phonons (heat)

“revised” perspective → low mass WIMPs



adapted from 1401.6085

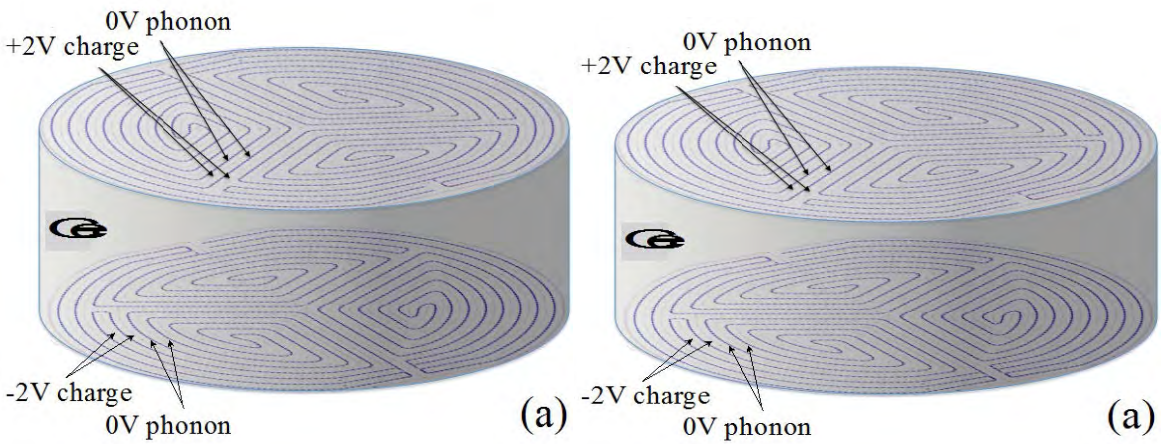
SuperCDMS

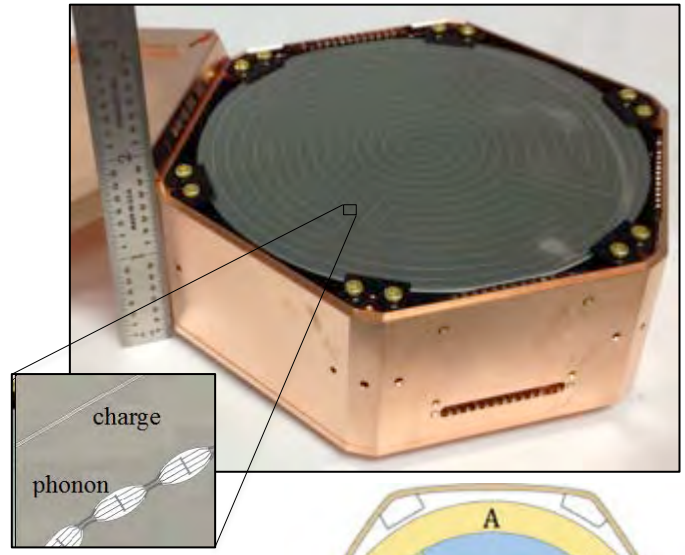
SuperCDMS Ge detctors

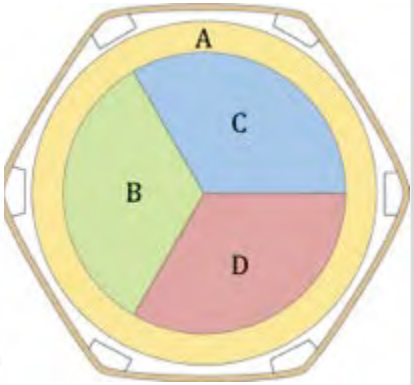
SuperCDMS iZIP – 600g Ge

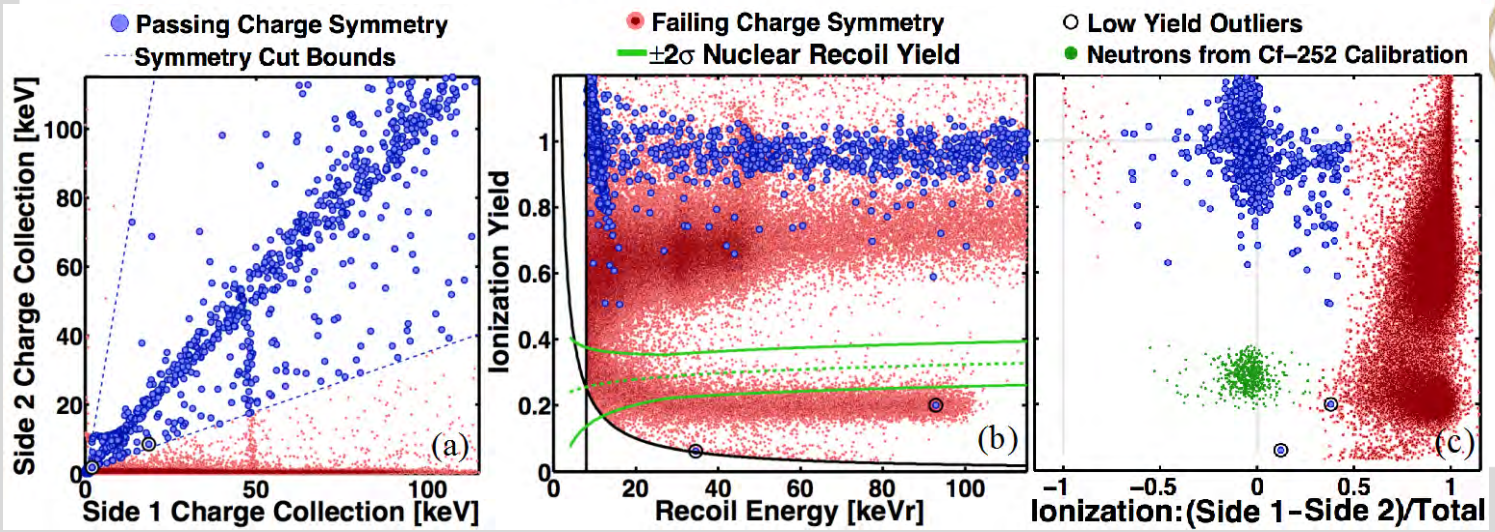
interleaved **Z**-dependent **I**onization and **P**honon det.

- 3D reconstruction in the fiducial volume
- Improved surface event rejection





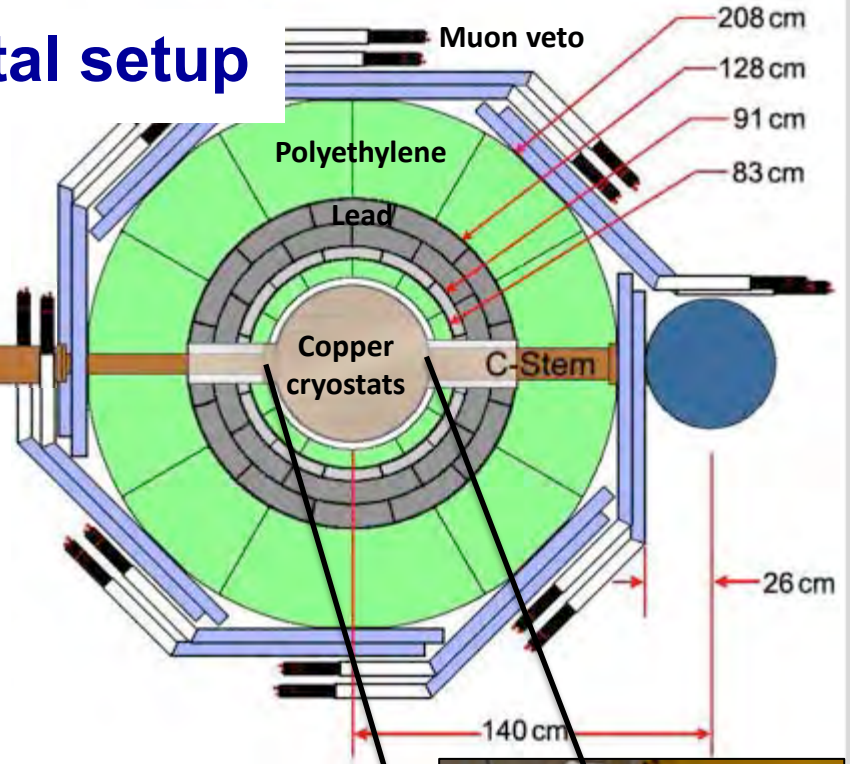




CDMS/SuperCDMS – experimental setup

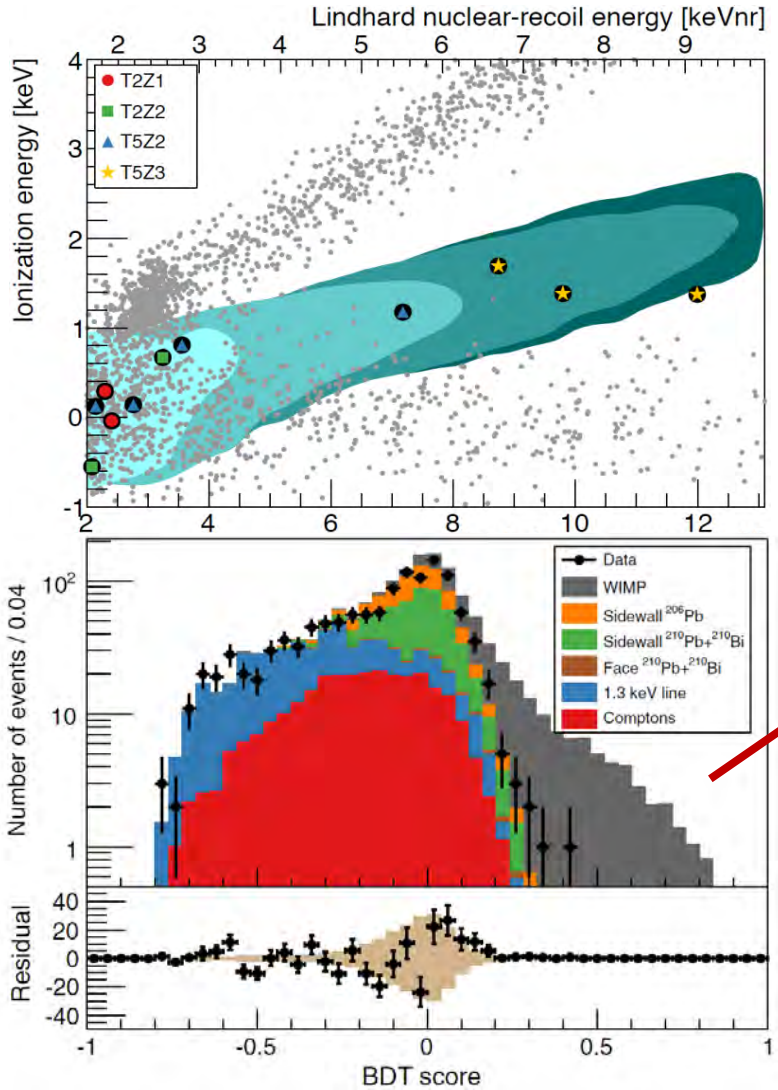
- Operates at 50 mK
  - Employs ^{3}He-^{4}He dilution refrigerator
- Target configuration
  - Detectors: 19×240g Ge 11×110g Si

	T1	T2	T3	T4	T5
Z1	G6	S14	S17	S12	G7
Z2	G11 ★	S28	G25 ★	G37 ★	G36
Z3	G8	G13 ★	S30	S10	S29
Z4	S3	S25	G33 ★	G35 ★	G26 ★
Z5	G9 ★	G31 ★	G32 ★	G34 ★	G39 ★
Z6	S1	S26	G29 ★	G38 ★	G24



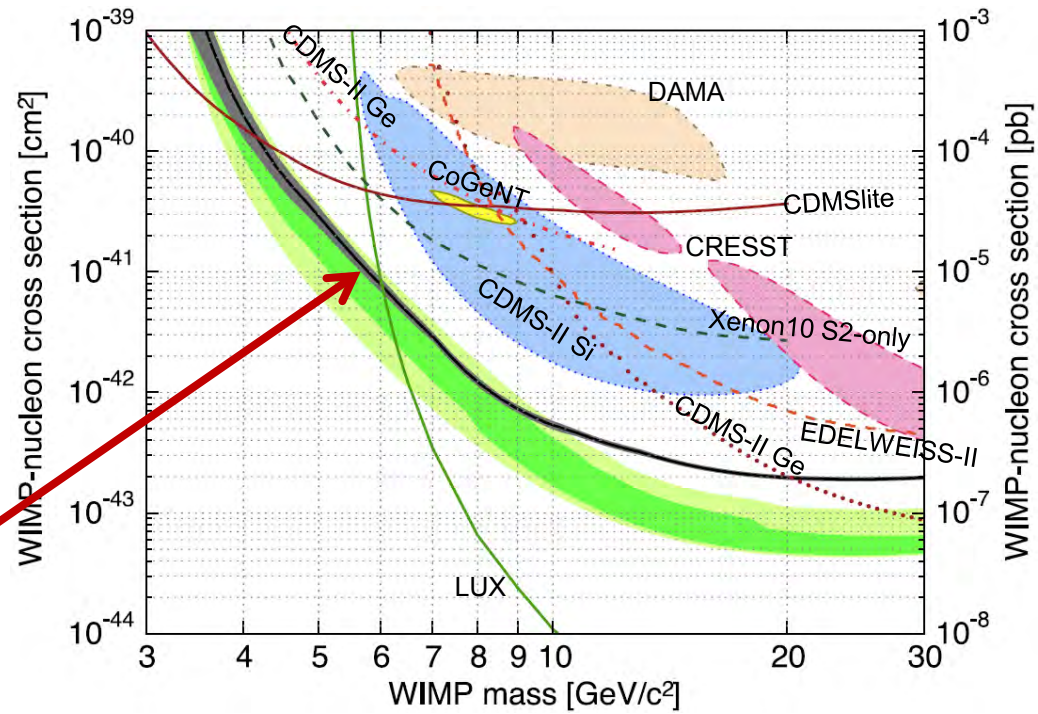
- Shield at Soudan
  - Plastic scintillator panels muon veto
  - Polyethylene neutron moderator
  - Lead for γ-ray shielding
  - Copper cryostats and inner components

SuperCDMS highlight I



low mass WIMP search with discrimination

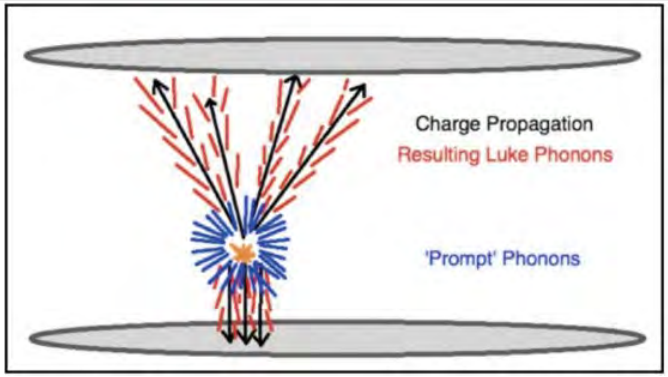
577 kg.d (10/12—06/13)

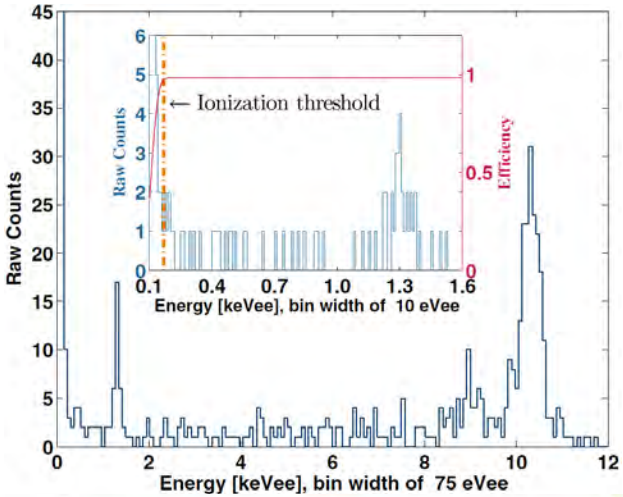


arXiv:1402.7137;
PRL **112**, 241302 (2014)

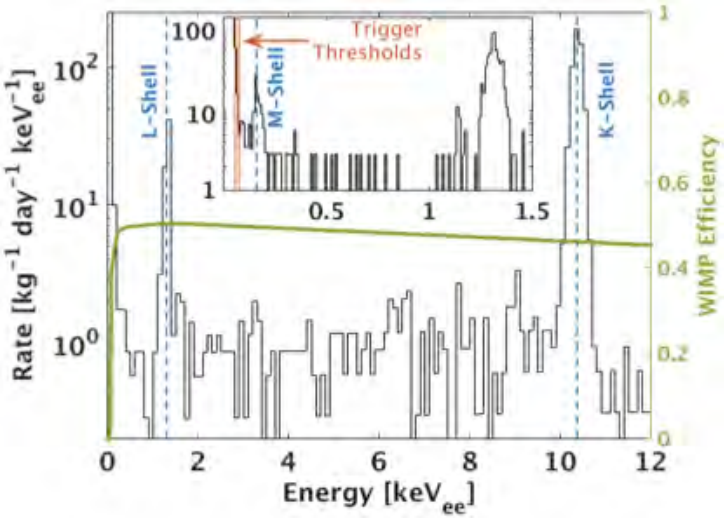
SuperCDMS highlight II

NL-amplified heat → lower threshold
→ no e/n separation

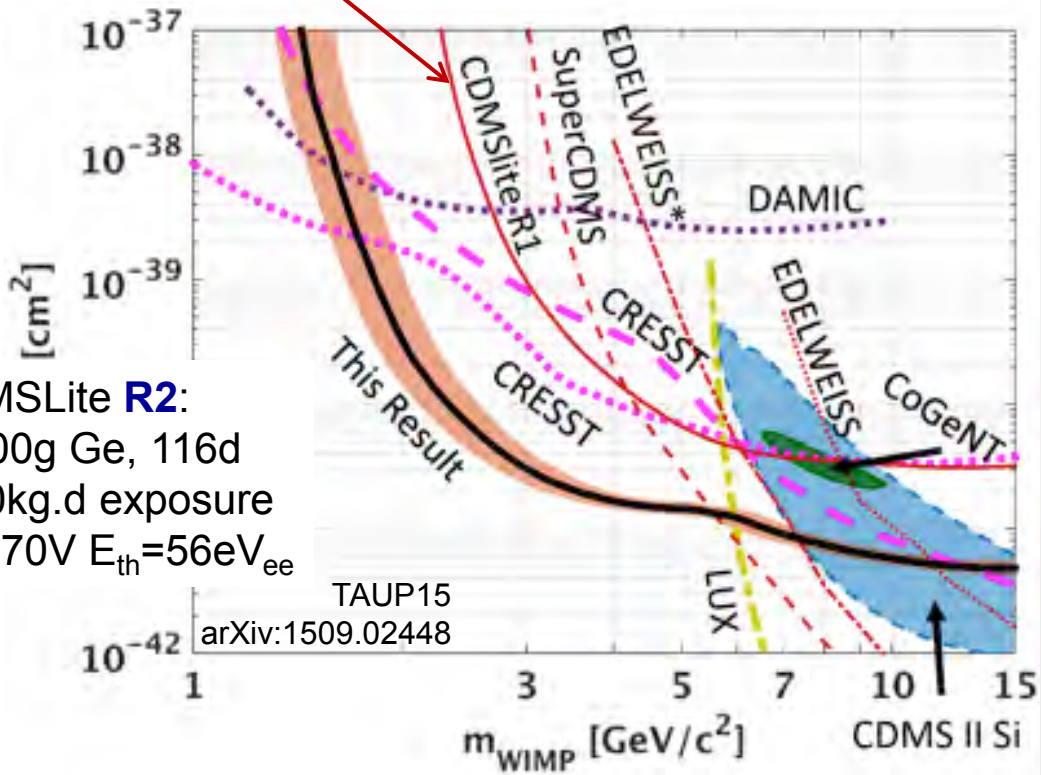




CDMSLite **R1**:
1x600g Ge, 10 days; V_b=69V → E_T=24×E_r
E_{thresh}=170eV_{ee}, PRL **112**, 041302, 2014



CDMSLite **R2**:
1x600g Ge, 116d
→70kg.d exposure
V_b=-70V E_{th}=56eV_{ee}

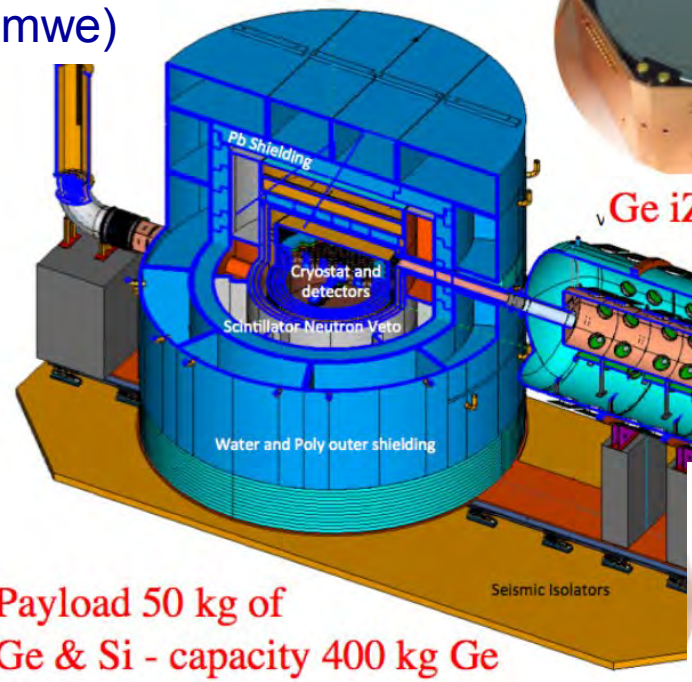


TAUP15
arXiv:1509.02448

SuperCDMS next steps:

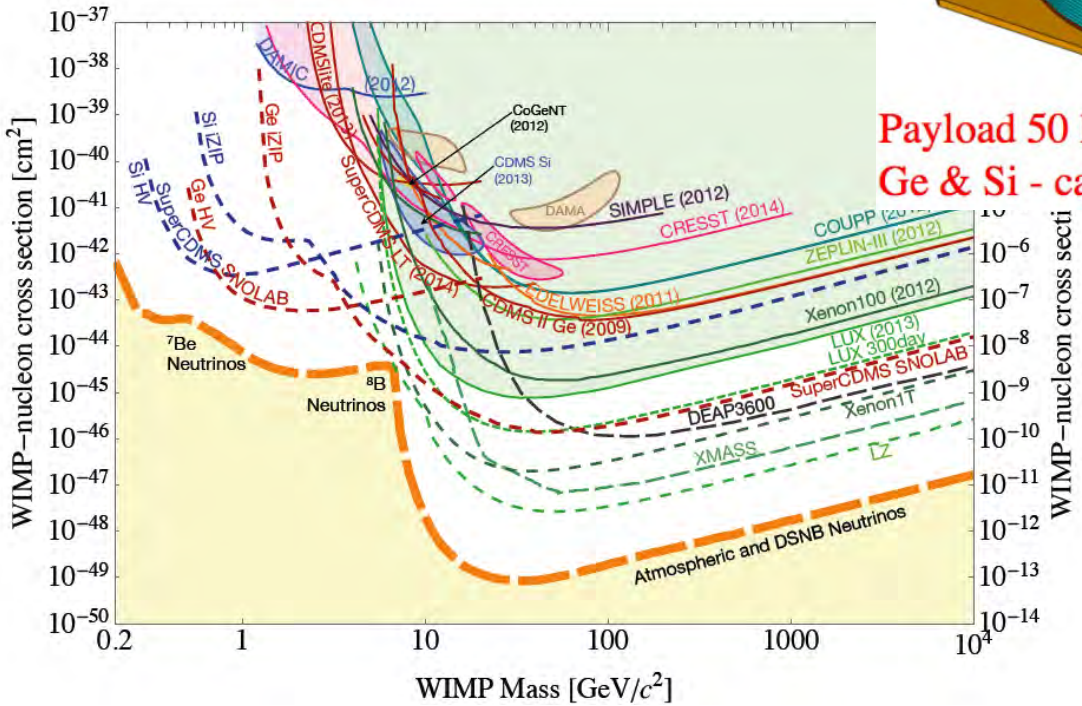
Soudan (2090mwe) → SNOLAB (6010mwe)

G2 experiment (2018+):
5 towers with Ge
→ $m\chi \geq 5$ GeV
1 tower 3Ge+3Si
→ $m\chi \geq 0.3$ GeV (NL)



Ge iZIP 1.4 kg

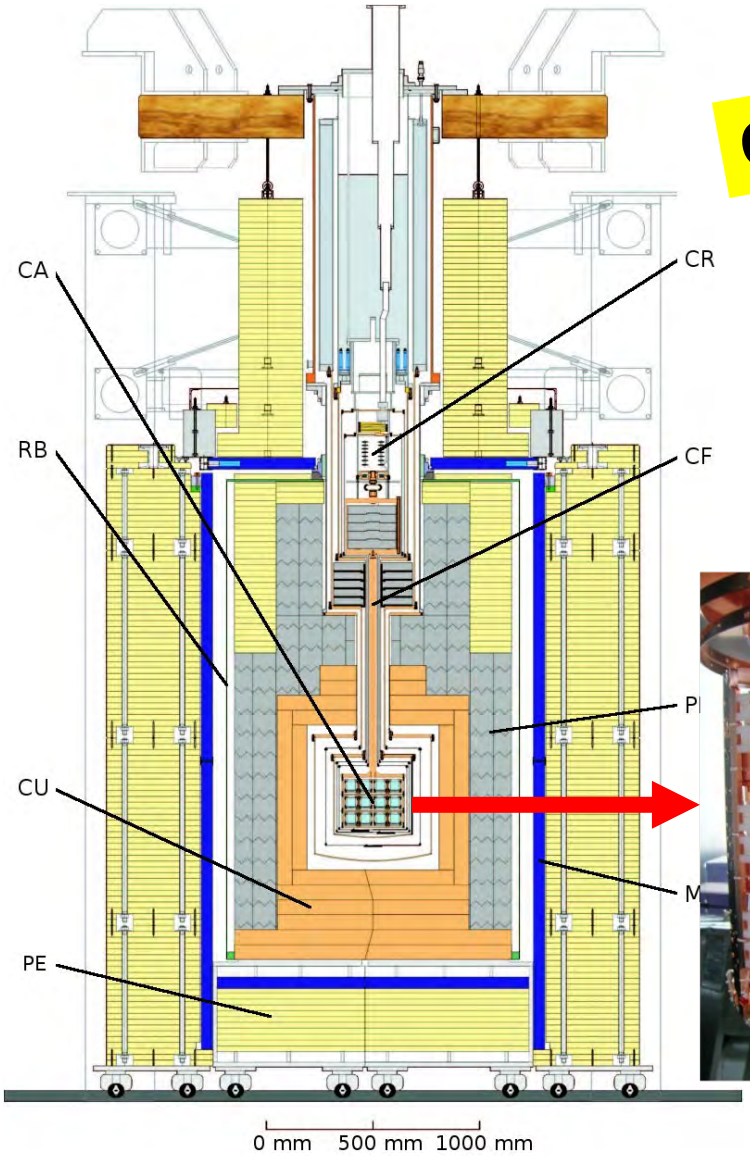
Payload 50 kg of
Ge & Si - capacity 400 kg Ge



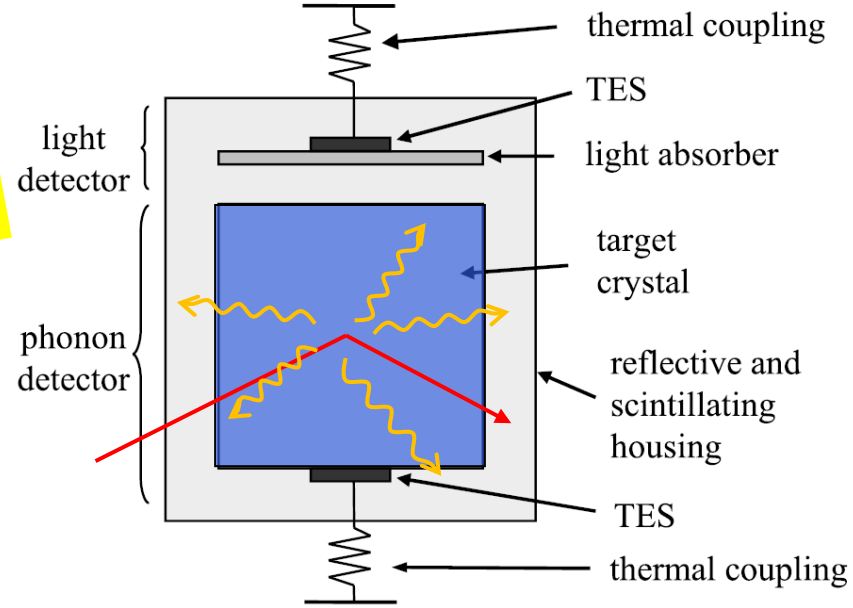
Ge Tower 8.4 kg

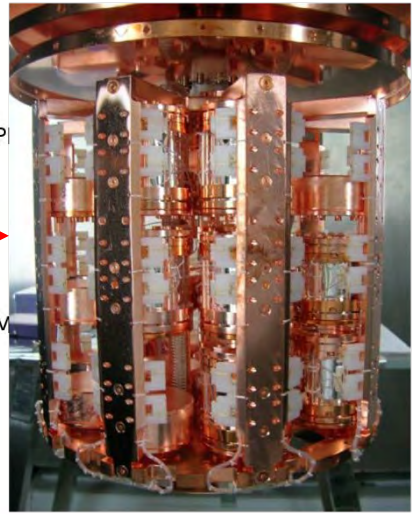
CRESST

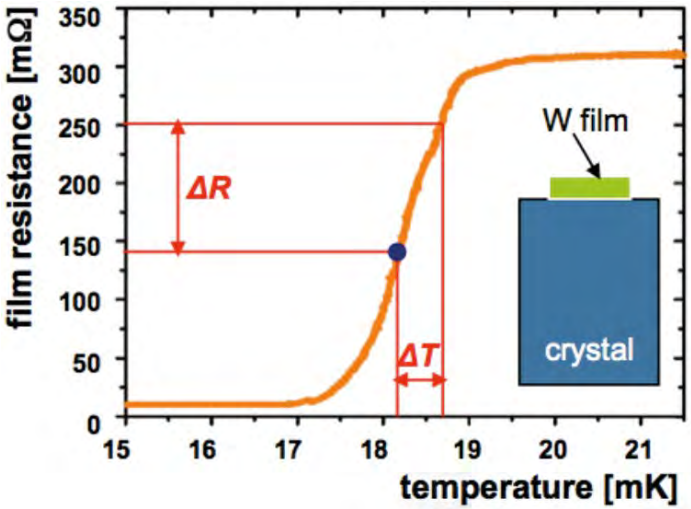
CRESST @ LNGS (Italy)



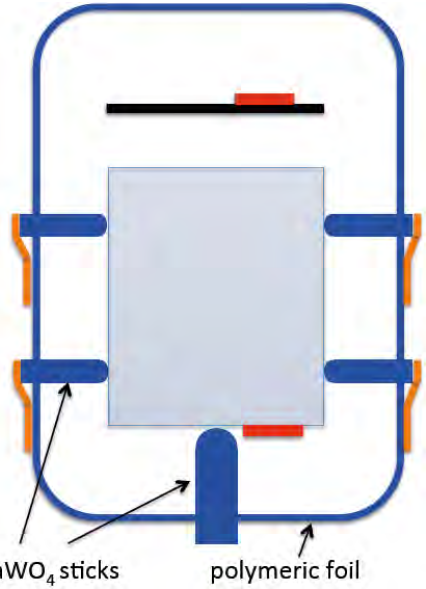
$CaWO_4$





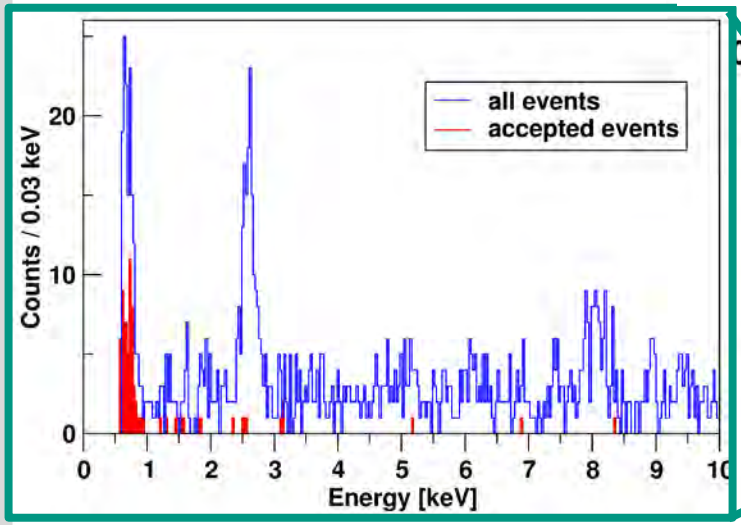


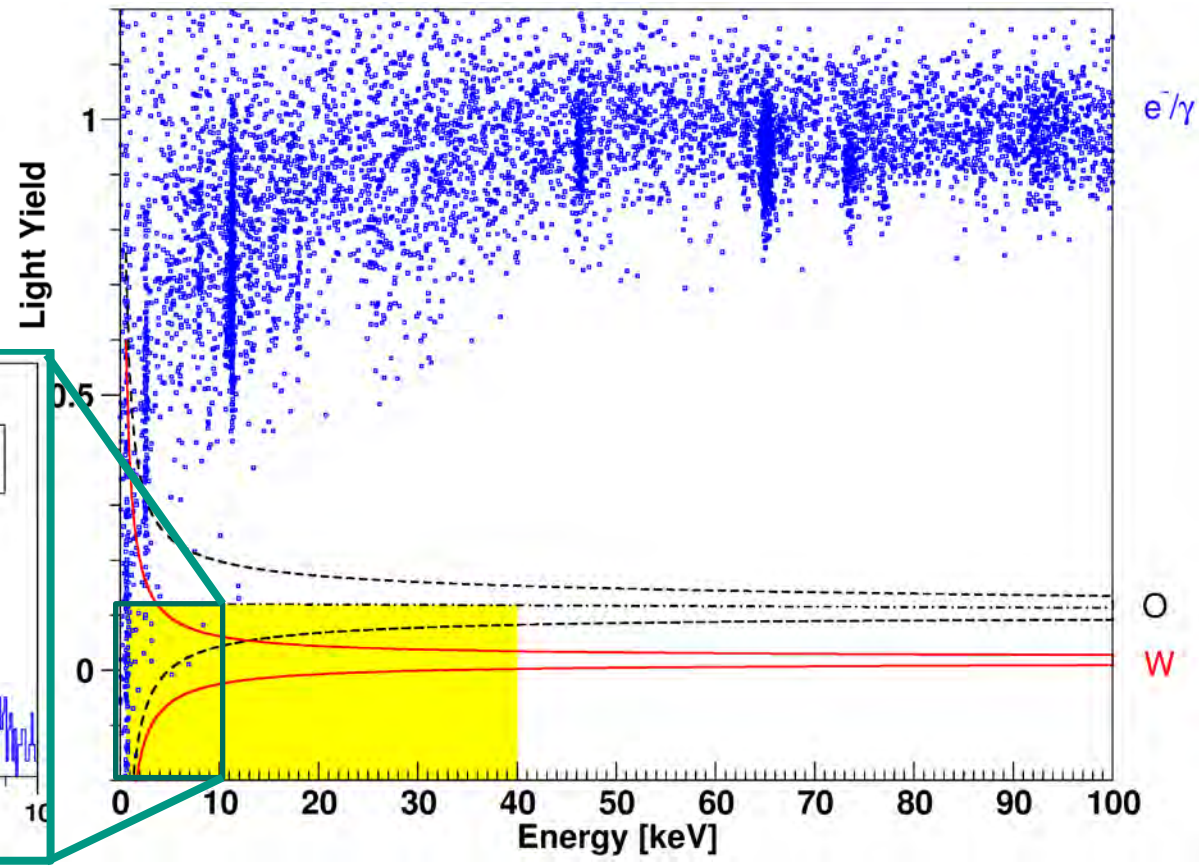
CRESST-II phase 2



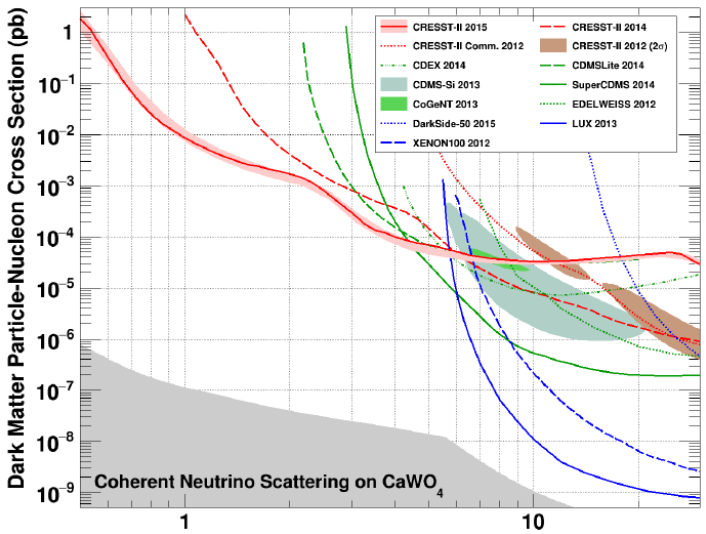
exposure (1 crystal with m=249g):
29.35 kg live days
E_{th}=603eV

arXiv:1407.3146; Eur. Phys. J. C (2014) 74:3184





CRESST-II phase 2 to CRESST-III phase 1

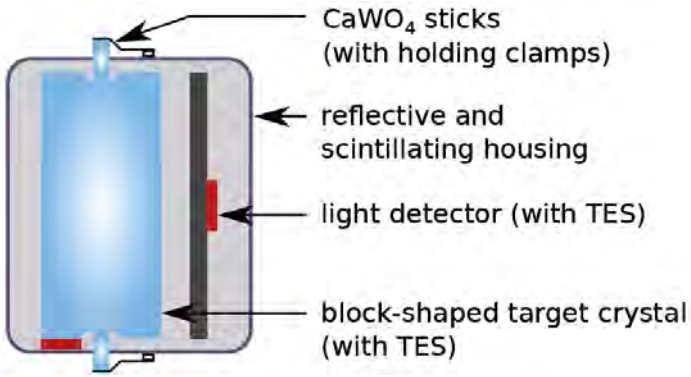


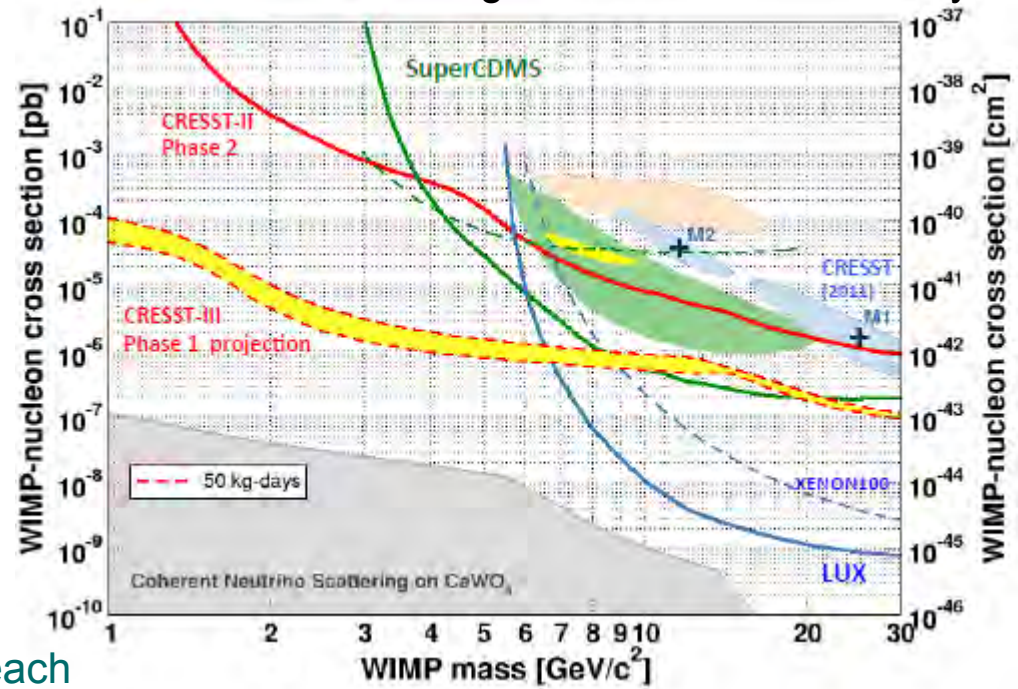
arXiv:150901515

2014: exposure (1det):
29.35 kg live days
3.5 cts/keV/kg/day
2015: exposure (1det):
52 kg live days
E_{th}=307eV
8.5 cts/keV/kg/day

assumed improvements:

- 100 eV threshold
- detected light increased by 3
- light det. noise reduced by 2

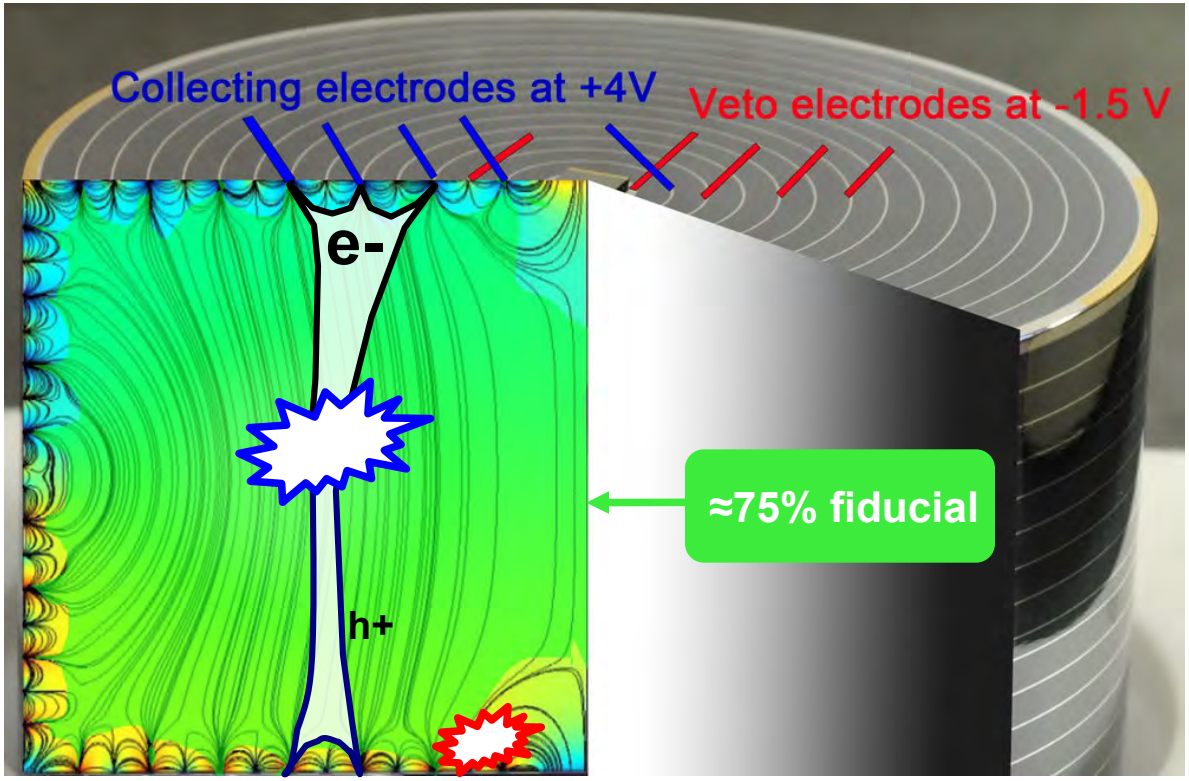




50 kg-days small
≈ 1 year of running with
~10 small mod's of 24g each

EDELWEISS

Surface event rejection with the *Fully Inter-Digitized* (FID) electrode readout design

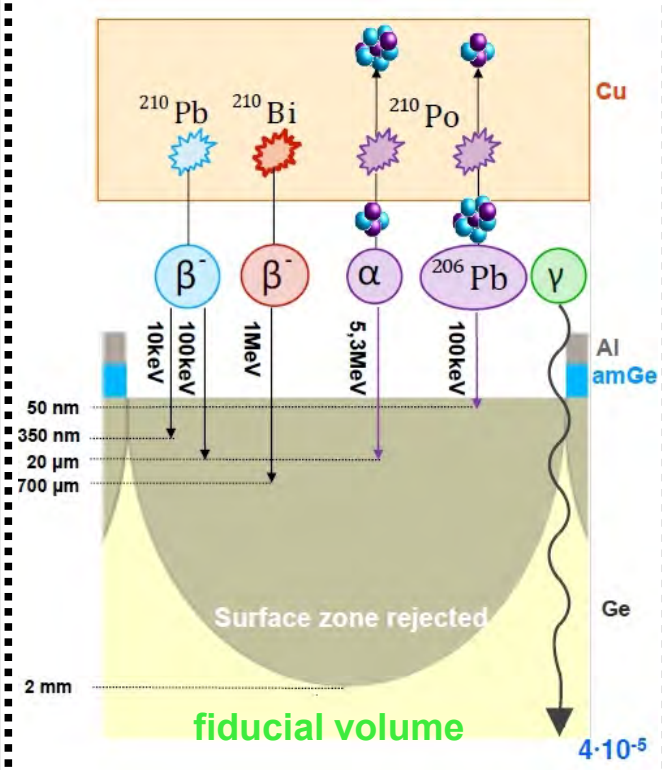


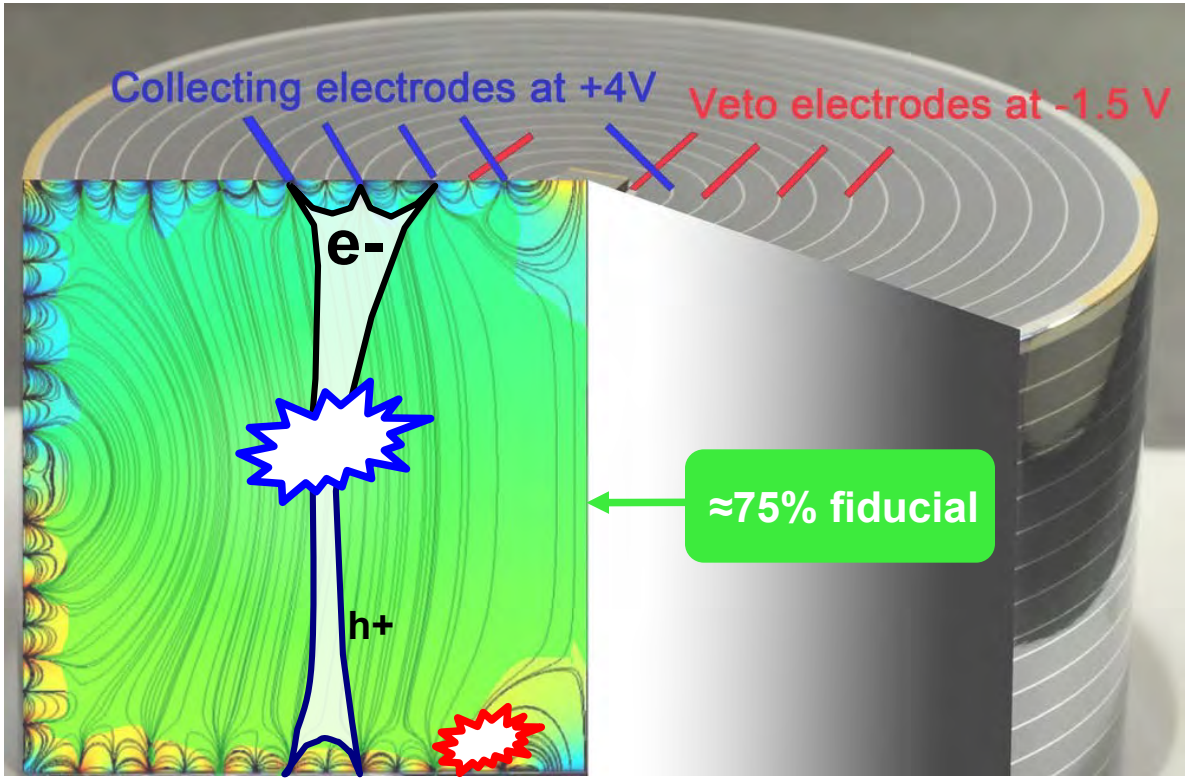
bulk event:
charge collection on
collecting electrodes

surface event:
charge collection on
veto electrodes

Surface event rejection with the *Fully Inter-Digitized* (FID) electrode readout design

From calibration measurement with implanted ^{210}Pb source:



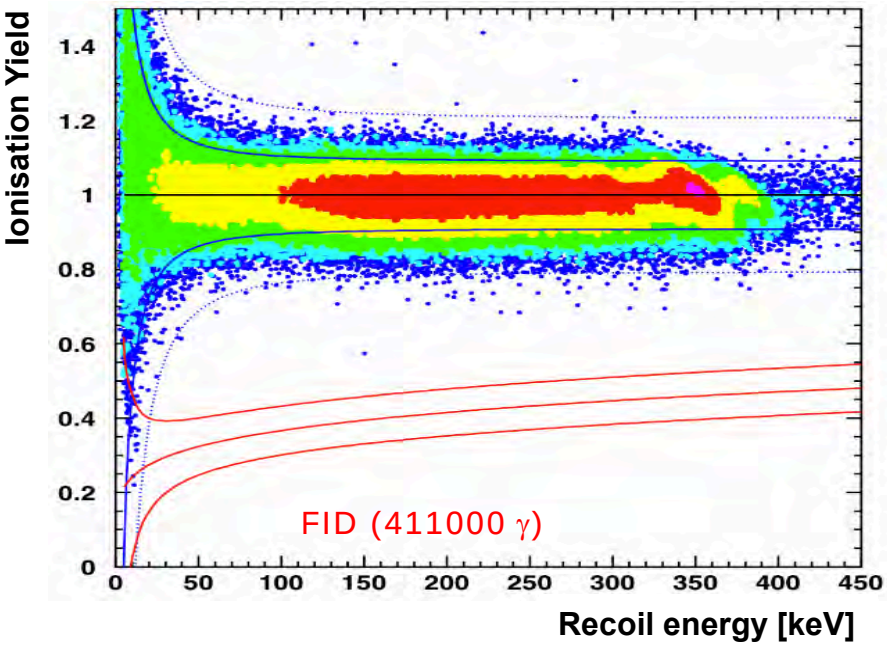


bulk event:
charge collection on collecting electrodes

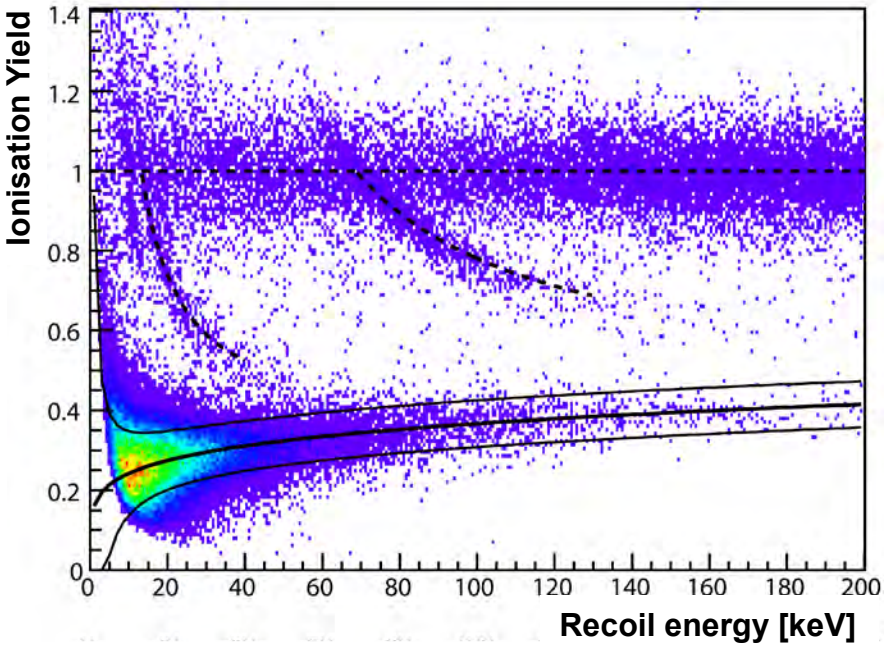
surface event:
charge collection on veto electrodes

calibration with γ/n-sources

γ calibrations with ^{133}Ba



n calibrations with AmBe



more than 400.000 γ´s
γ suppression factor <6x10^{-6}
<1 ”NR” for every 100k 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

The EDELWEISS shielding concept

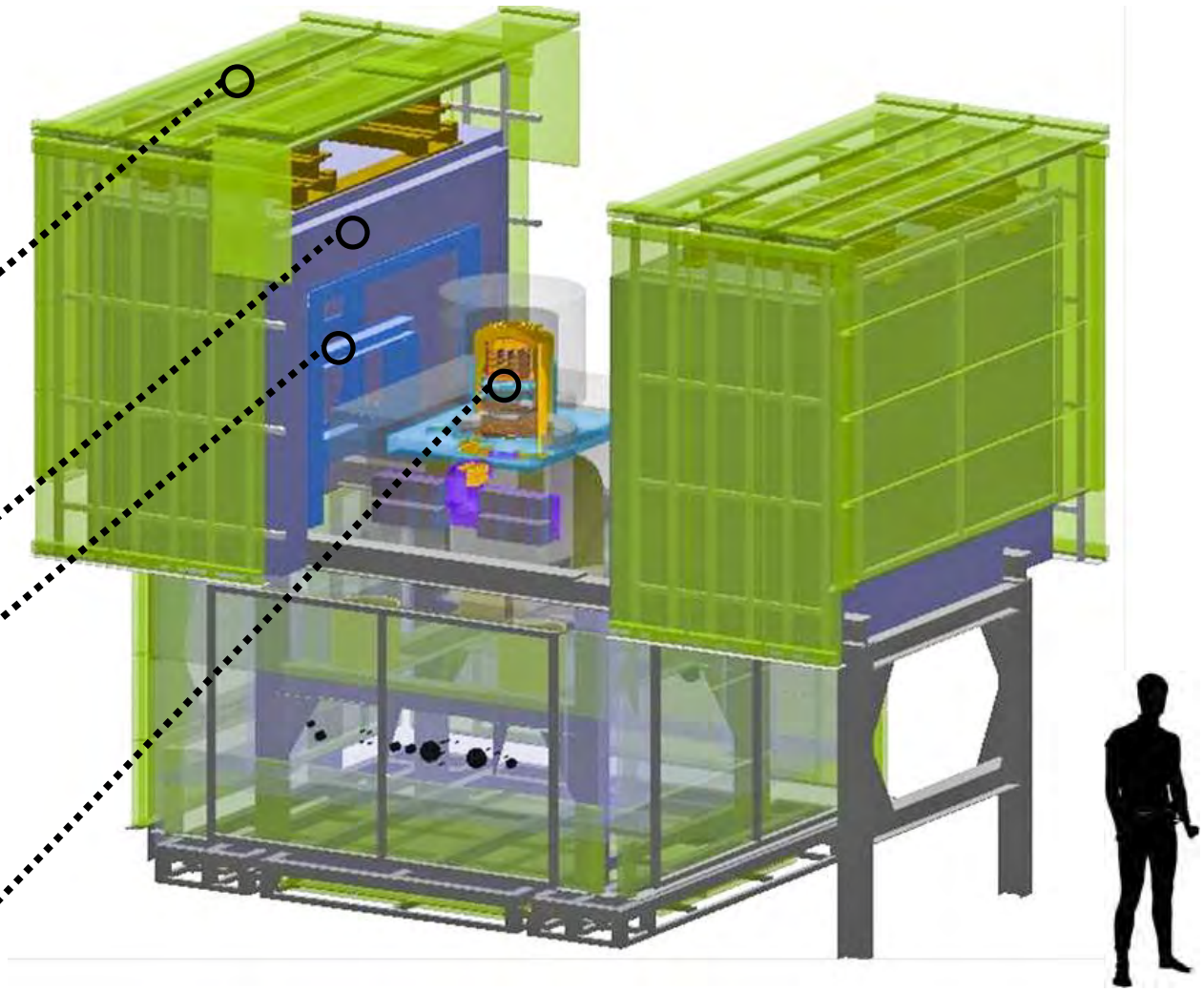
clean room (Rn)
with derodanized air supply
(from 10 Bq/m³ → ≈ 30 mBq/m³)

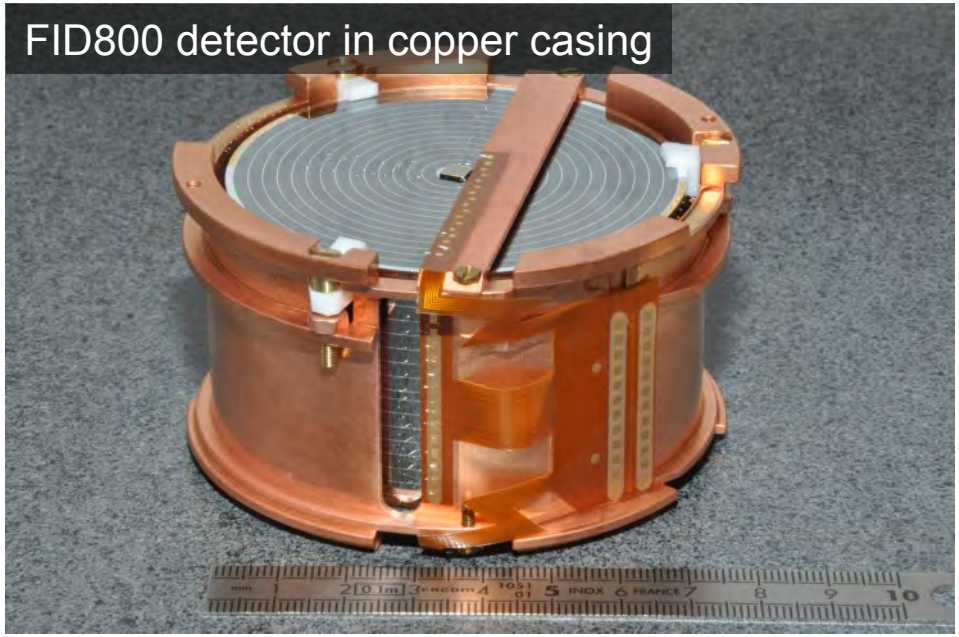
active muon veto (μ)
98% geometric coverage

polyethylene shield (n)
50cm, for moderation

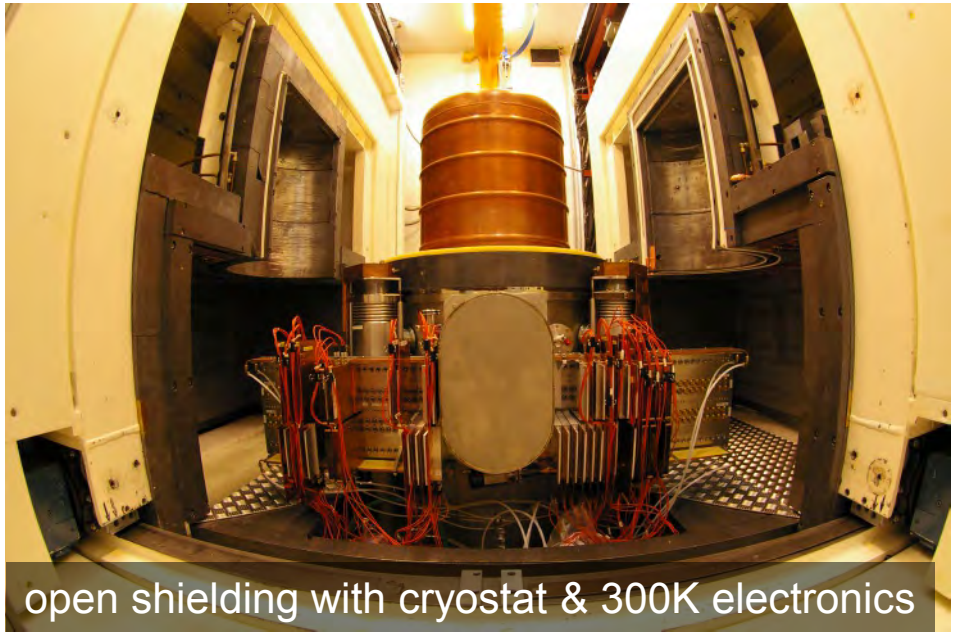
lead shield (β, γ)
18cm + 2cm roman lead

copper cryostat (β, γ)
with additional internal PE and Pb




FID800 detector in copper casing


open cryostat and bolometer plates


open shielding with cryostat & 300K electronics

2014/2015 data for WIMP search

8 months of physics data 2014/2015
with 24 x FID800 detectors

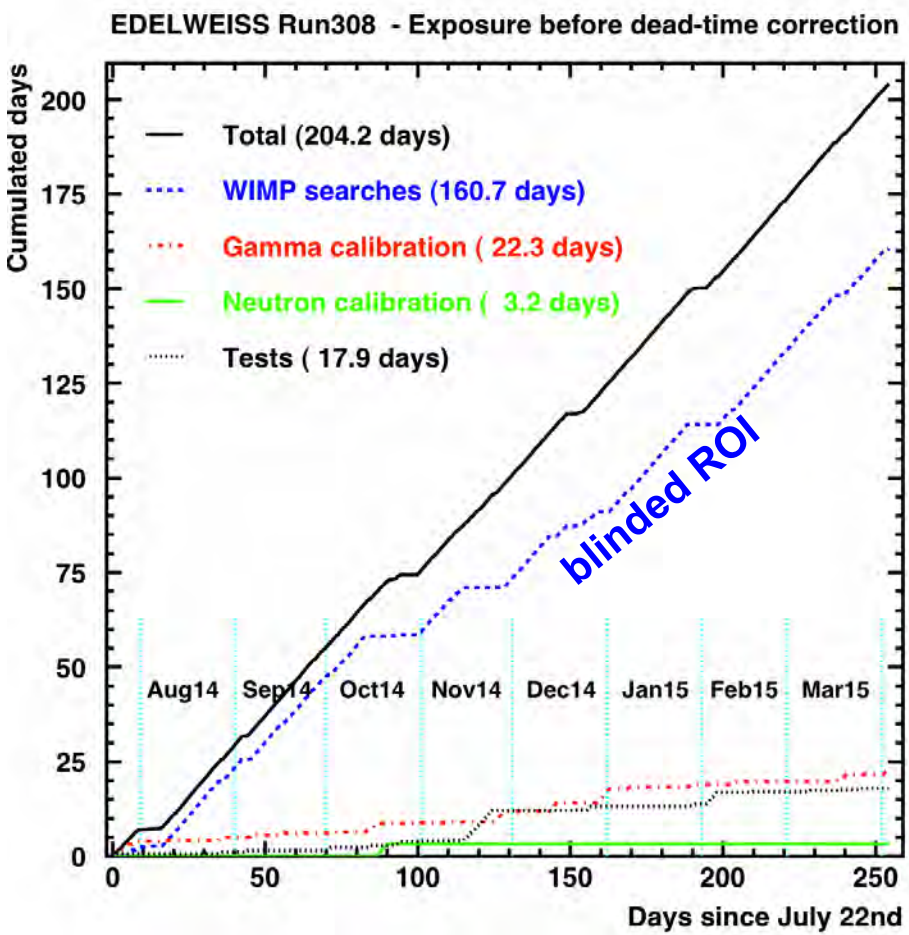
Low mass WIMP search:

- blinded ROI
- **8 detectors** with good baselines and low trigger thresholds
- homogeneous data set
- analysis threshold in heat:

  4x FID800 @ 1.0 keVee

  4x FID800 @ 1.5 keVee*

*1 keVee ≈ 2.4 keVnr



582 kg.days (fiducial)
(EDELWEISS-II: 113 kg.days)
sensitivity for WIMPs in [4,30] GeV

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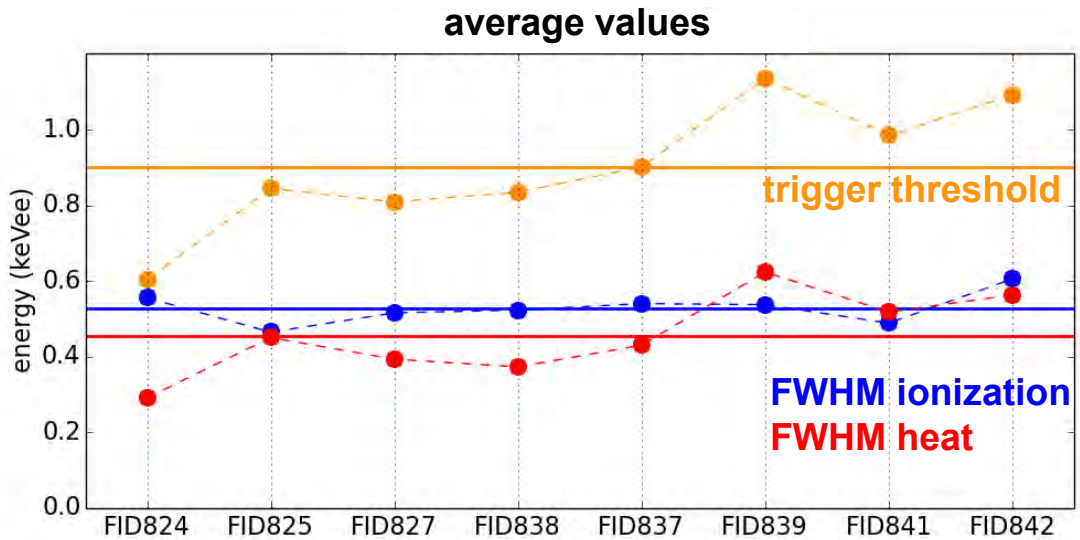
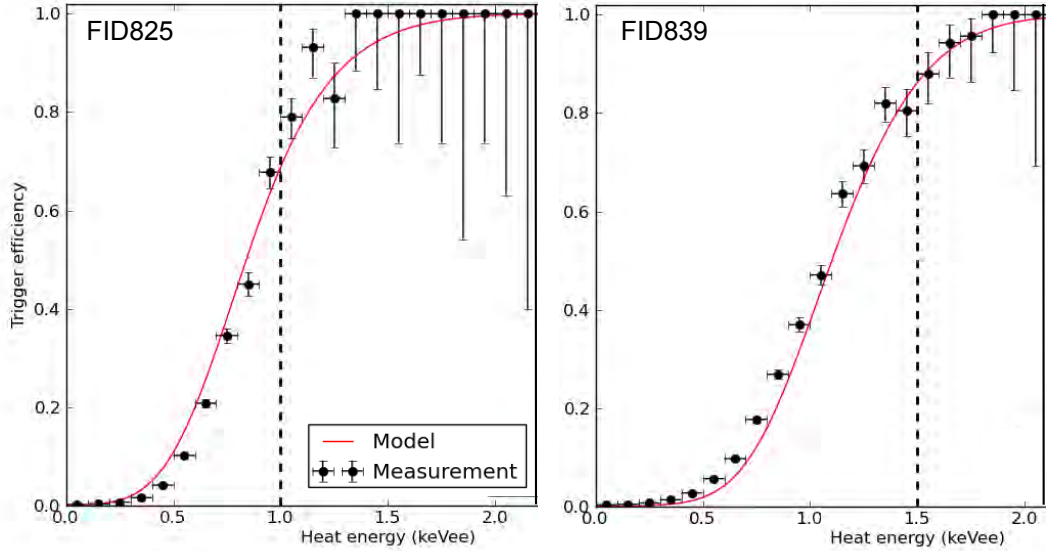
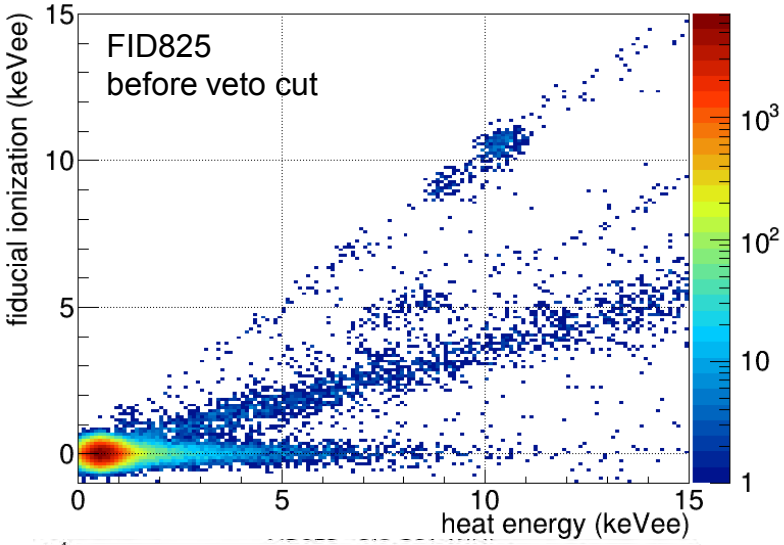
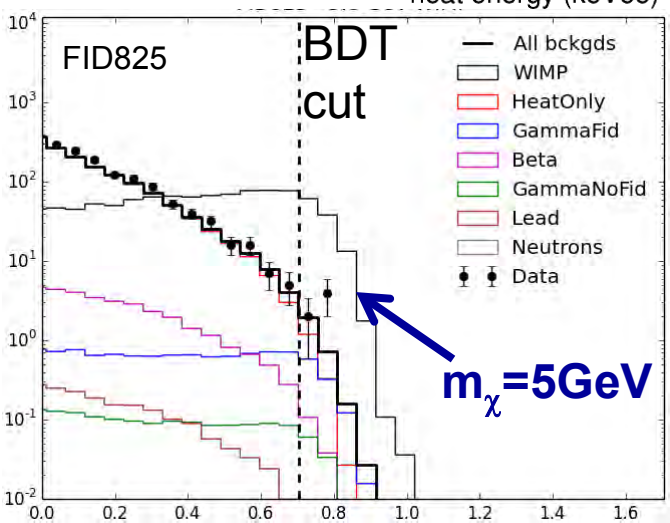




EDELWEISS status: improved low-mass WIMP sensitivity





- data taking 07/2014 — 04/2015
- blind analysis
- 8 detectors with $1keV_{ee}/1.5keV_{ee}$ threshold
- 582 kg·day (fiducial) exposure
- boosted decision tree (BDT) & profile LHD

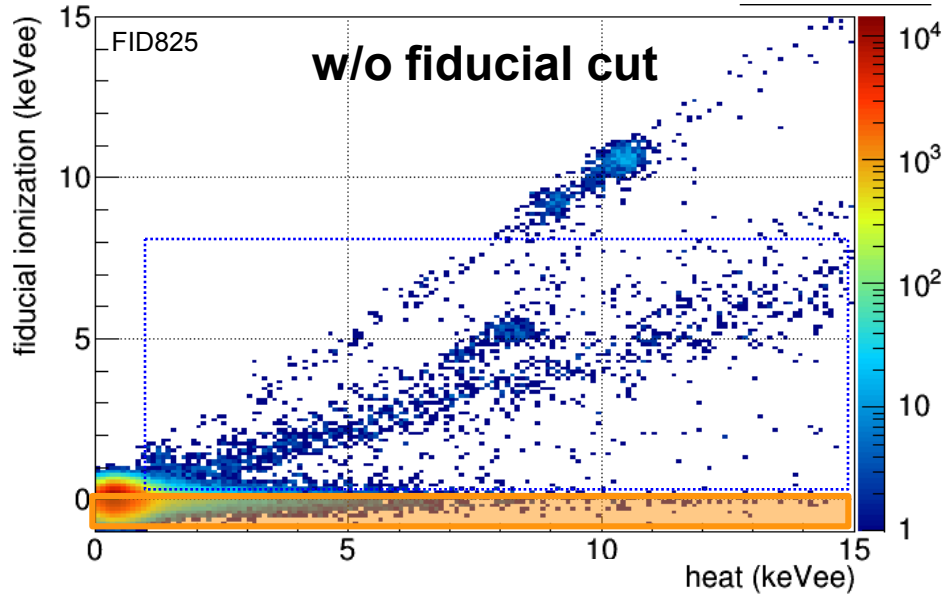
For each detector:

- one BDT distribution for each WIMP mass [4, 5, 6, 7, 10, 15, 20, 30] GeV
- backgrounds normalized to expected # of evts
- **BDT cut** optimized before unblinding

For all 8 detectors in BDT selected cut window:

m_χ	N_bkgd expected	N_bkgd observed	p-value (stat only)
5 GeV	6.14	9	0.17
20 GeV	1.35	4	0.10

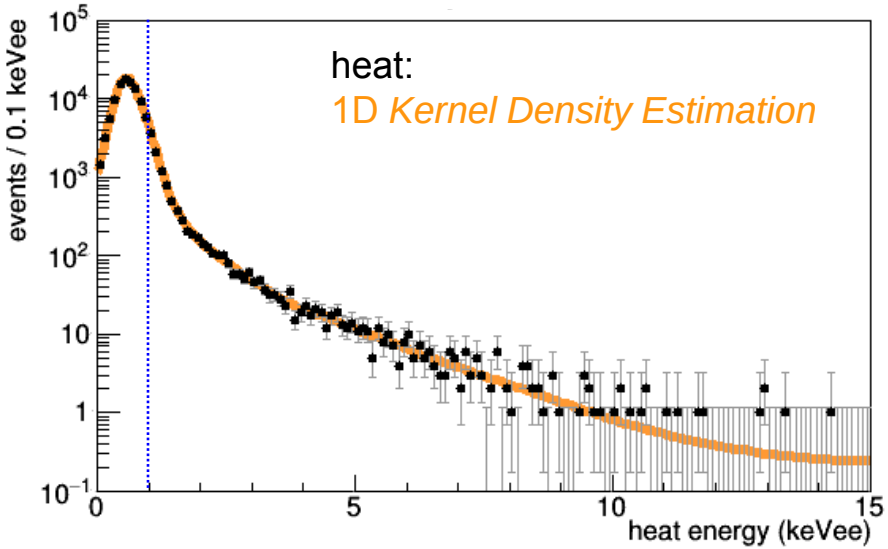
heat-only events

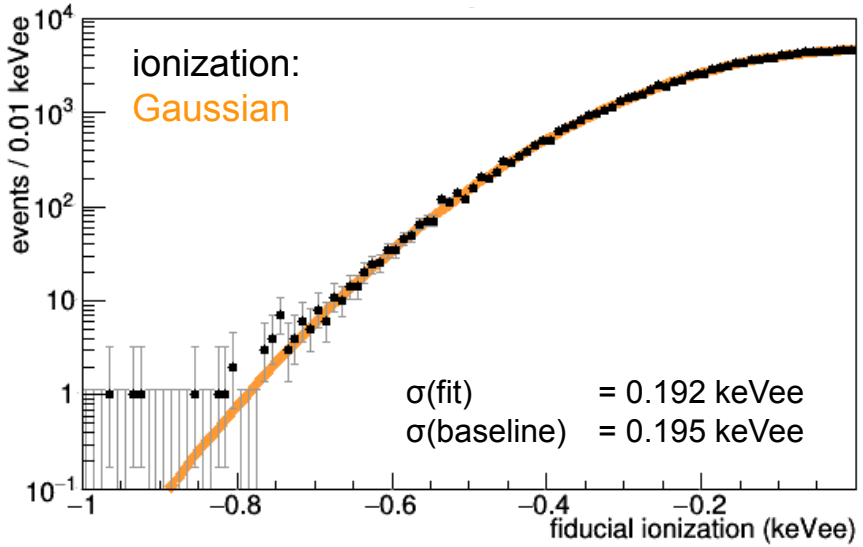


our dominant detector background:

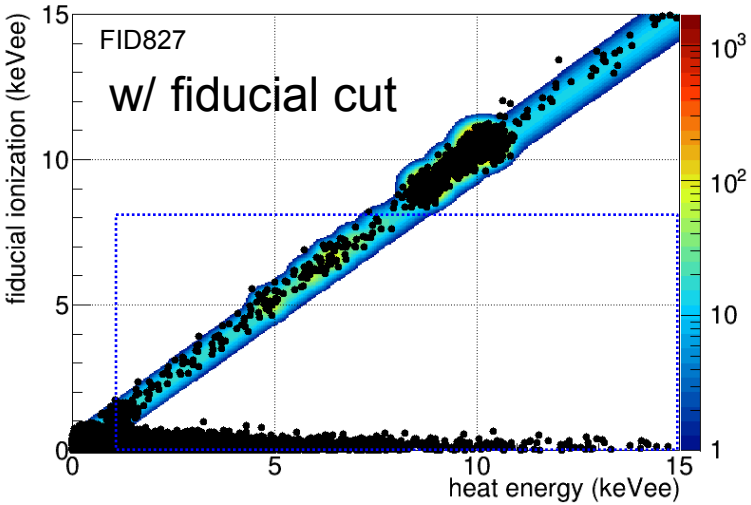
- origin still under investigation (probably mechanical)
- Gaussian ionization spectrum as expected from noise

→ **ionization < 0 keV sideband** is used to model these events





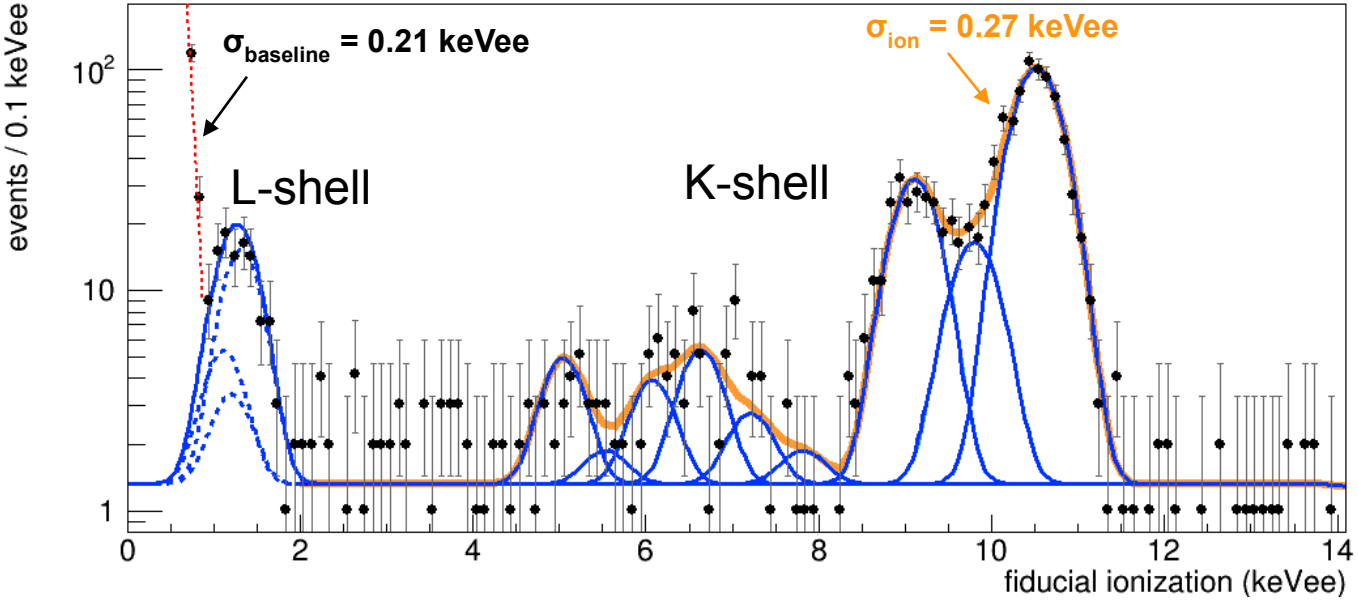
bulk gammas



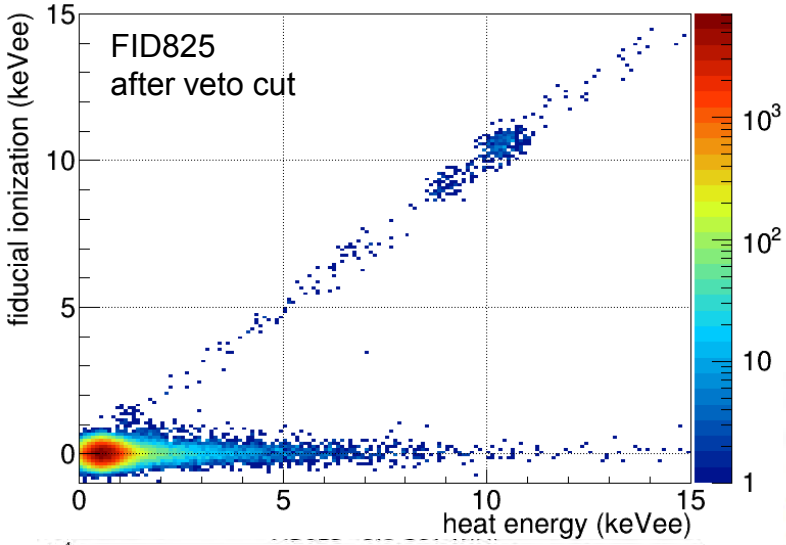
fit of fiducial gammas in [3, 15] keVee heat energy:

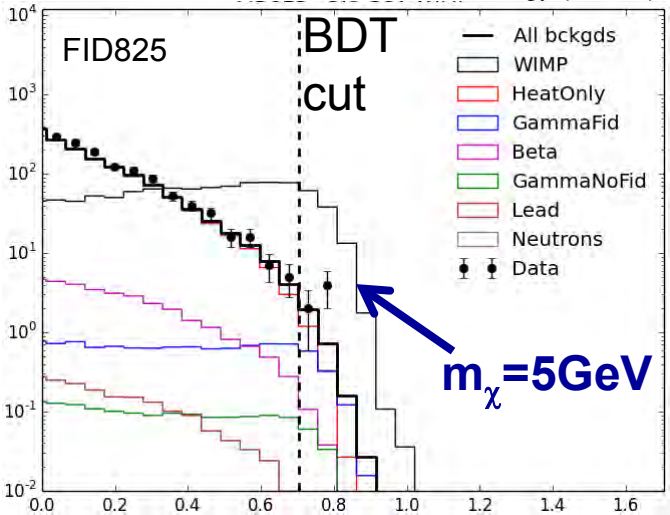
- K-shell peaks and flat compton spectrum
- flat component extrapolated down to 0 keV
- L-shell peak intensity derived from K-shell peaks and L/K-ratio ~ 0.11*

*J. Bahcall, Phys. Rev. 132, 362 (1963)

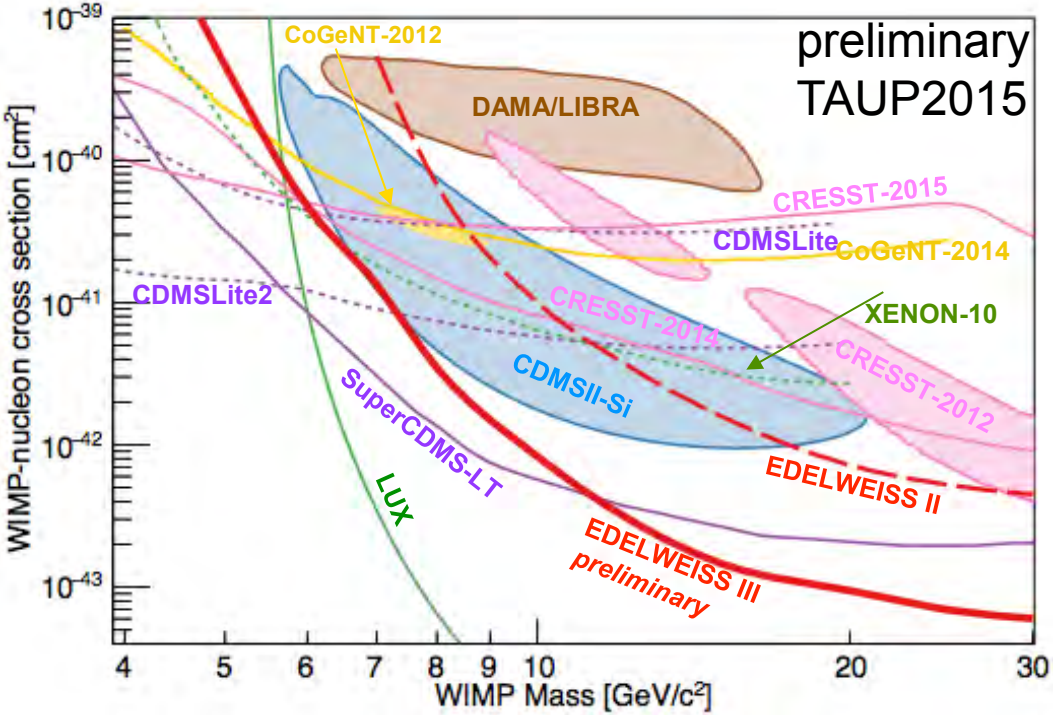


EDELWEISS status: improved low-mass WIMP sensitivity





- data taking 07/2014 — 04/2015
- blind analysis
- 8 detectors with $1keV_{ee}/1.5keV_{ee}$ threshold
- 582 kg·day (fiducial) exposure
- boosted decision tree (BDT) & profile LHD

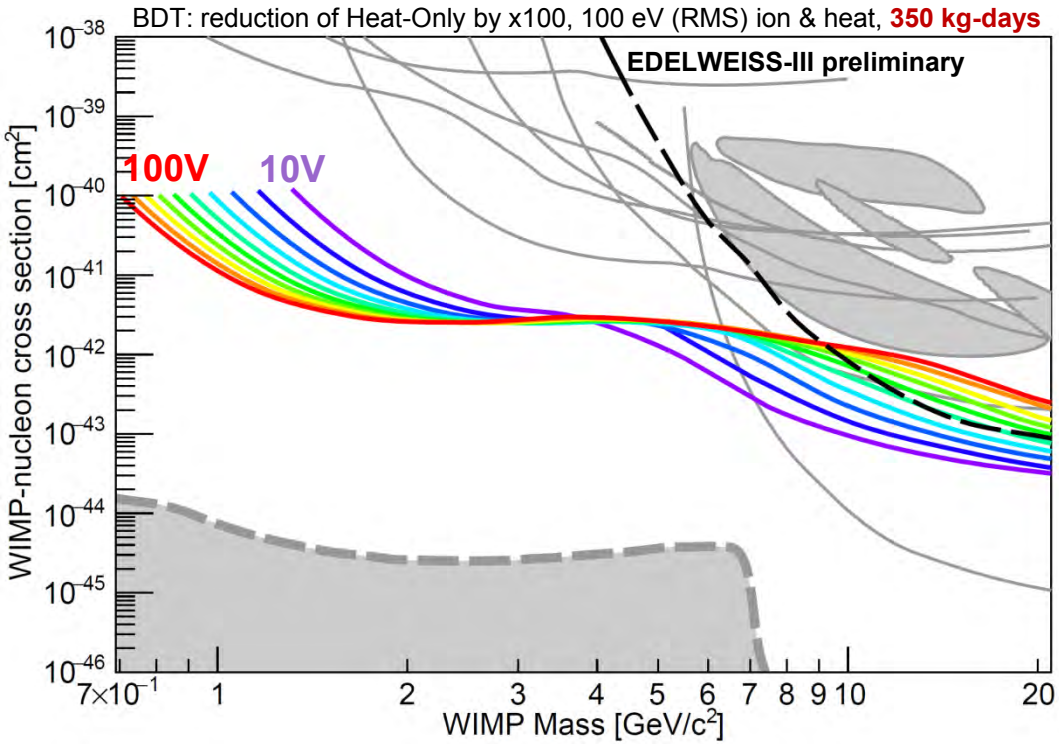


EDELWEISS-III perspective

- Poisson limits **w/o** background subtraction
- *preliminary* 90% C.L. exclusion limit for spin-independent WIMP-nucleon scattering:
  4.6 x 10^{-40} cm² @ 5 GeV
  6.2 x 10^{-44} cm² @ 30 GeV

→ **factor 40 improvement @ 7 GeV & new data down to 4 GeV**

- cross checks with 2d profile likelihood analysis ongoing and in good agreement
- post-unblinding checks ongoing
- *"high energy analysis"* coming soon

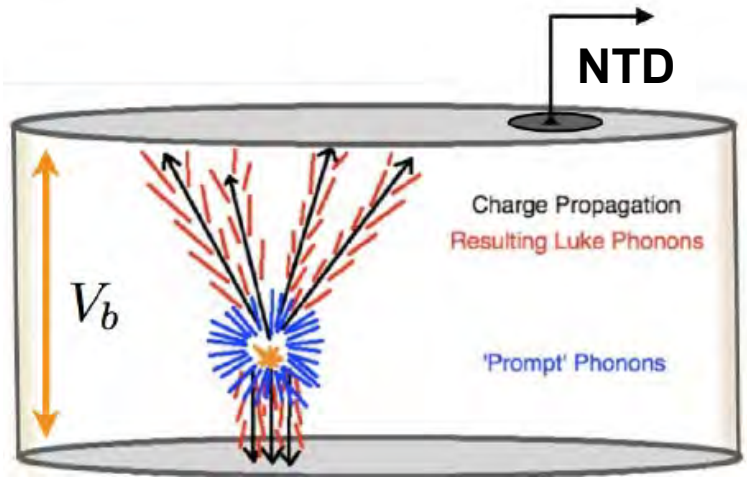


Current run:

- DAQ resumed in June 2015
- 23 FID800 installed (12 new)
- 1 FID200 for "High-Voltage" R&D (Neganov-Luke amplification)

R&D on HEMT
to lower ionization threshold down to σ_{ion} = 100 eV
R&D on heat sensors and HV (Luke-Neganov)
goal σ_{heat}= 100 eV and reduce recoil threshold
R&D to reduce heat-only events

voltage-assisted heat amplification aka Neganov-Luke mode

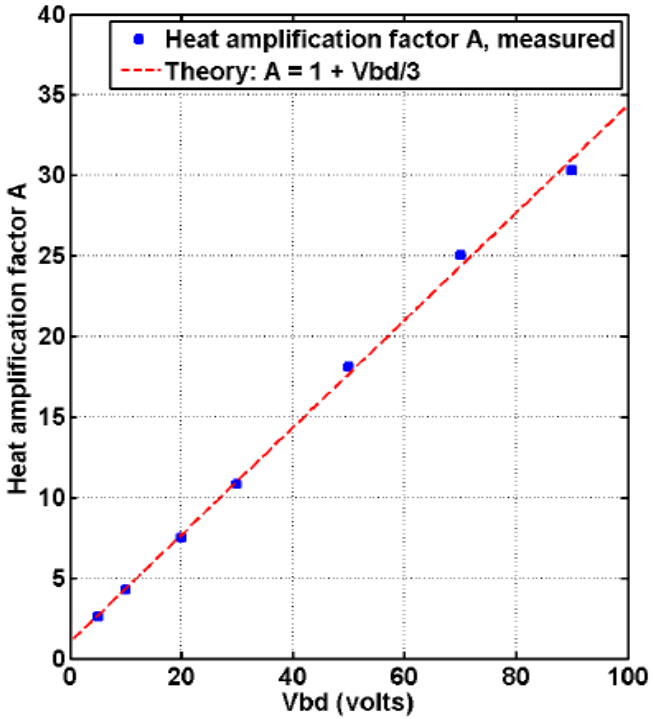


Heat signal amplitude: H = GE,
E = deposited energy from an impinging particle
G = (1+qU/ε) is the heat gain.
example :
U = 180V → heat gain G for γ interactions
(ε=3 eV/e.h. pair) : G = 61

Ionization only, uses phonon instrumentation to measure ionization!
→ **No event-by-event discrimination of NR**

→ **lower threshold ~100eV$_{NR}$**

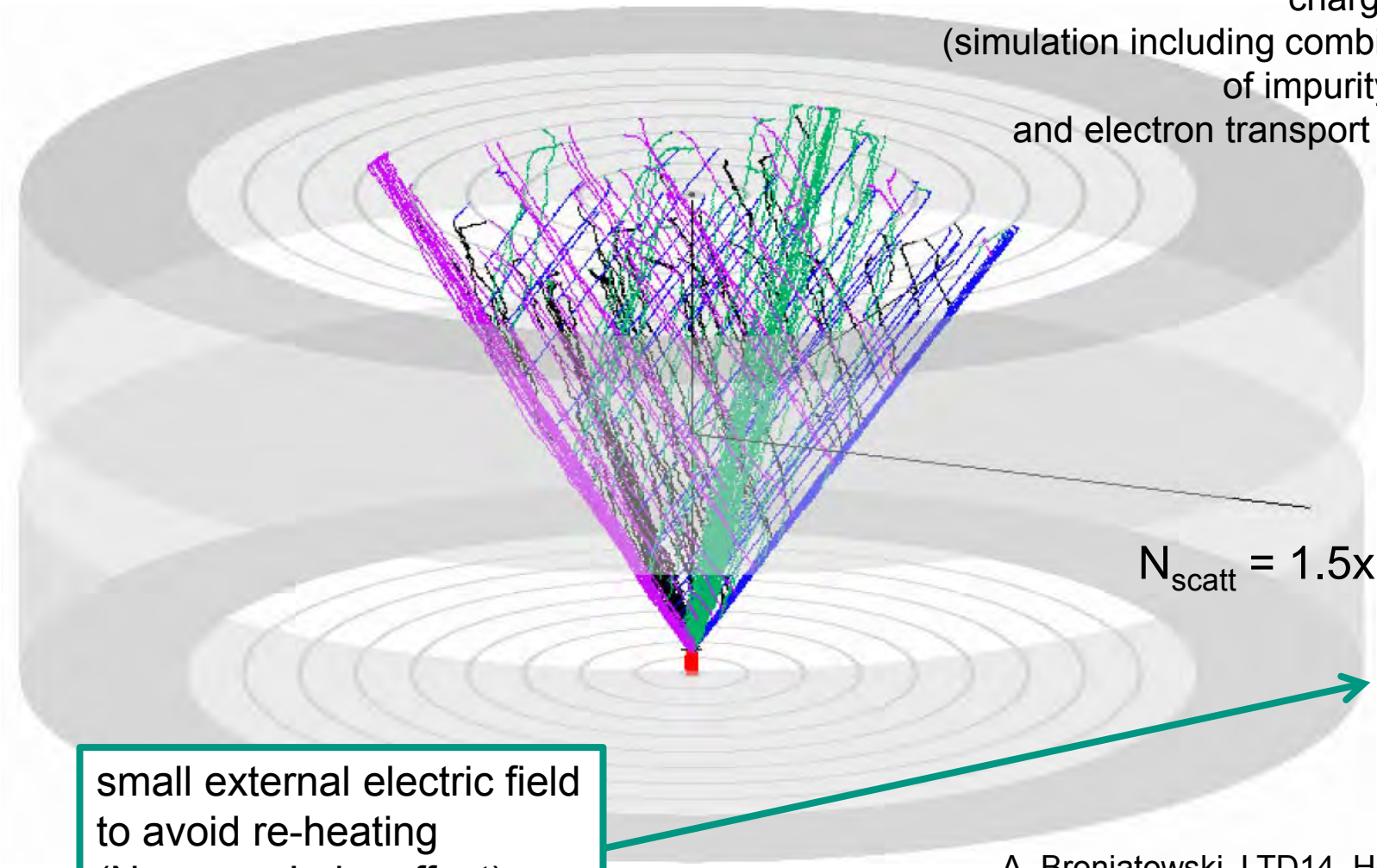
60keV bulk event
T=23mK



A. Broniatowski
CSNSM Orsay
LTD16 Grenoble

charge transport in Ge at T<1K

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



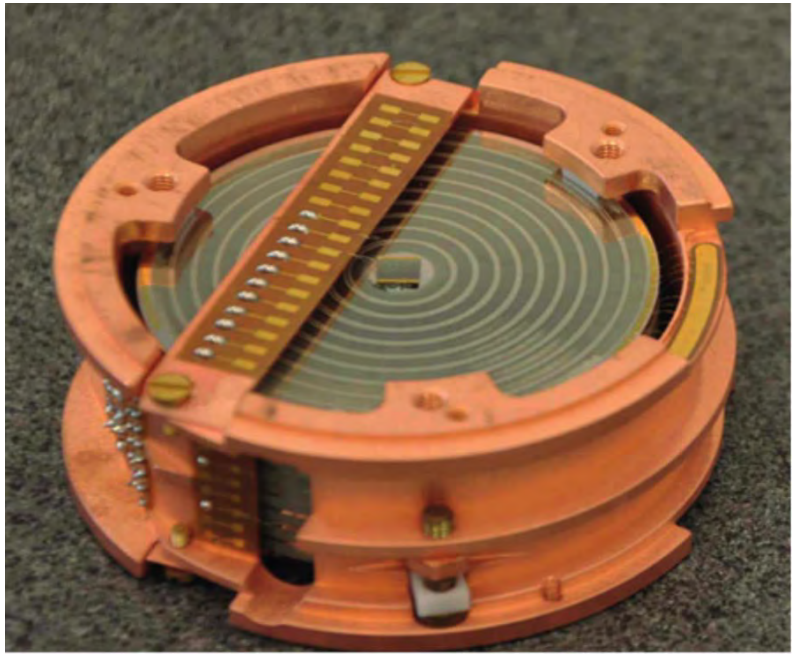
$N_{scatt} = 1.5 \times 10^{10} cm^{-3}$

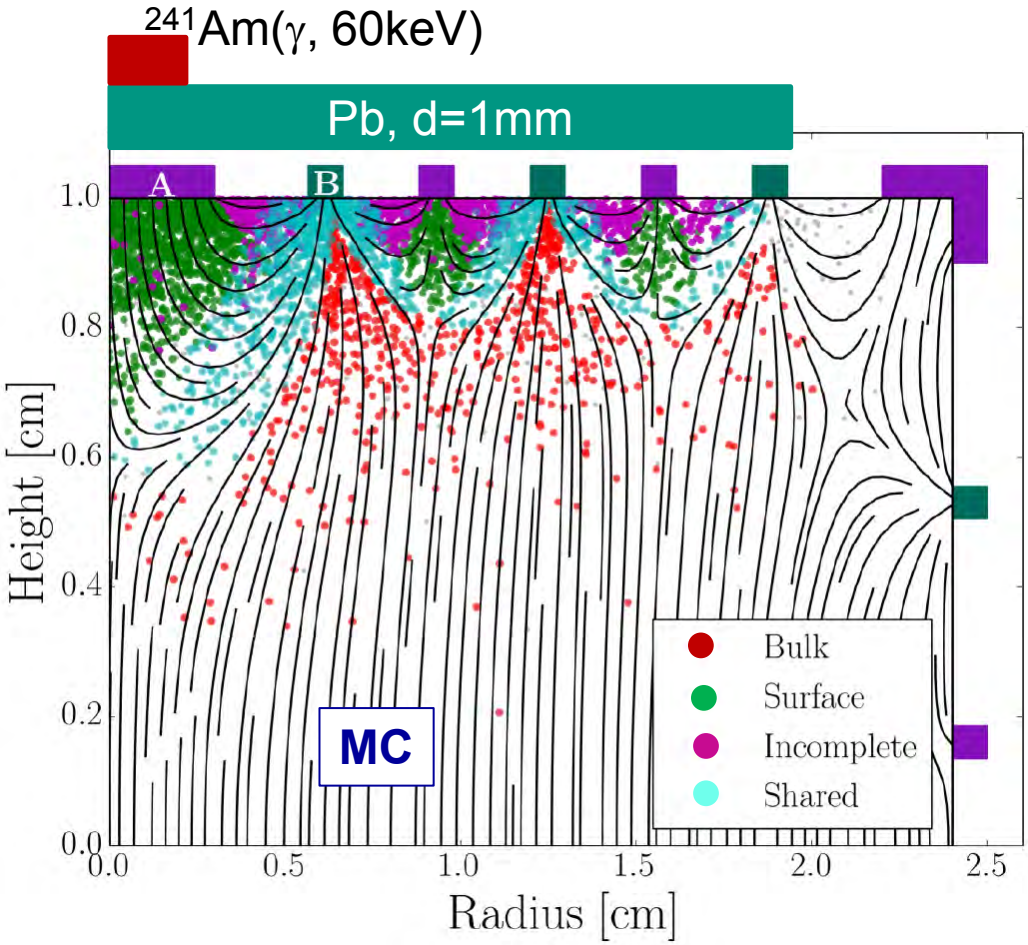
$V_a = 1V$

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

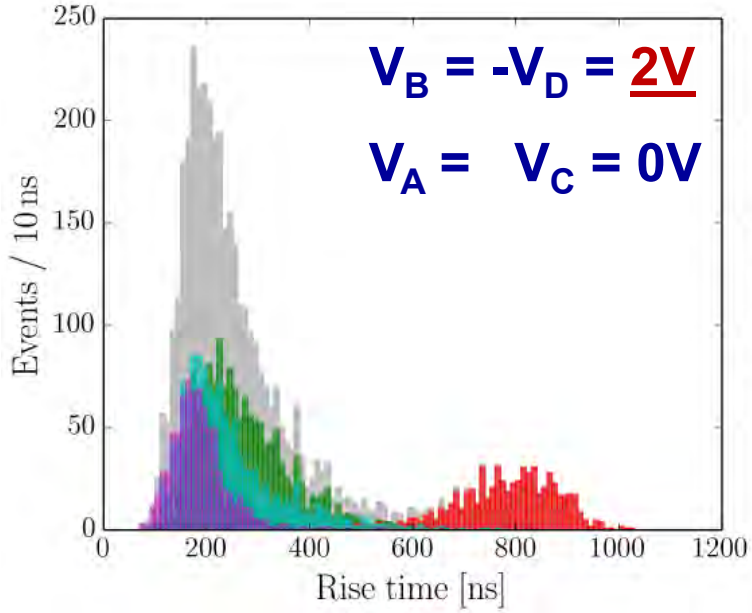
A. Broniatowski, LTD14, Heidelberg, 2011
E. Olivieri et al., J of Low Temp Phys (2012)

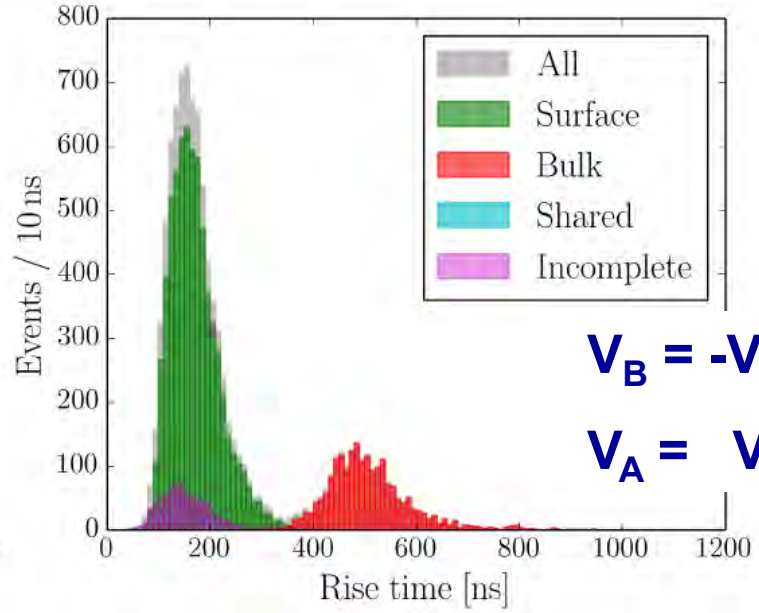
understanding charge collection: amplitude & shape (risetime)

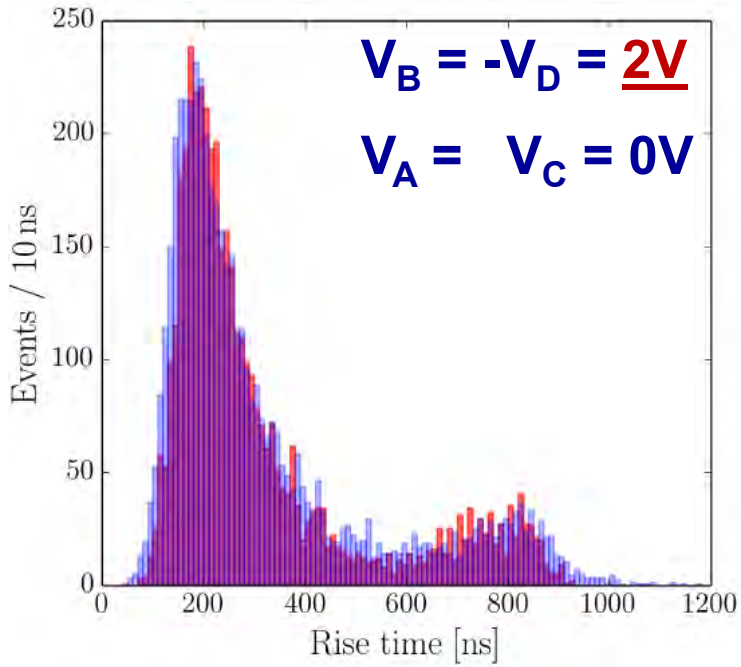


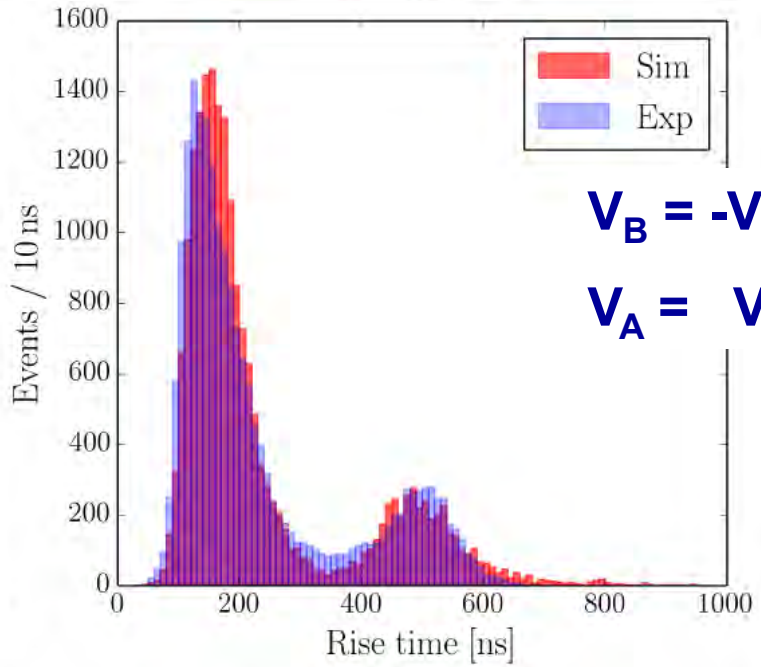


special measurements at CSNSM Orsay (together with KIT)
using a 200g n-type HP Ge crystal in planar mode, but separate readout (A,B,C,D)









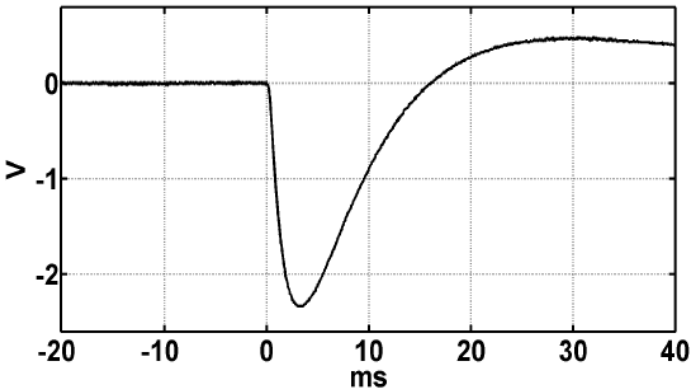
Nadine Foerster, LTD16, Grenoble

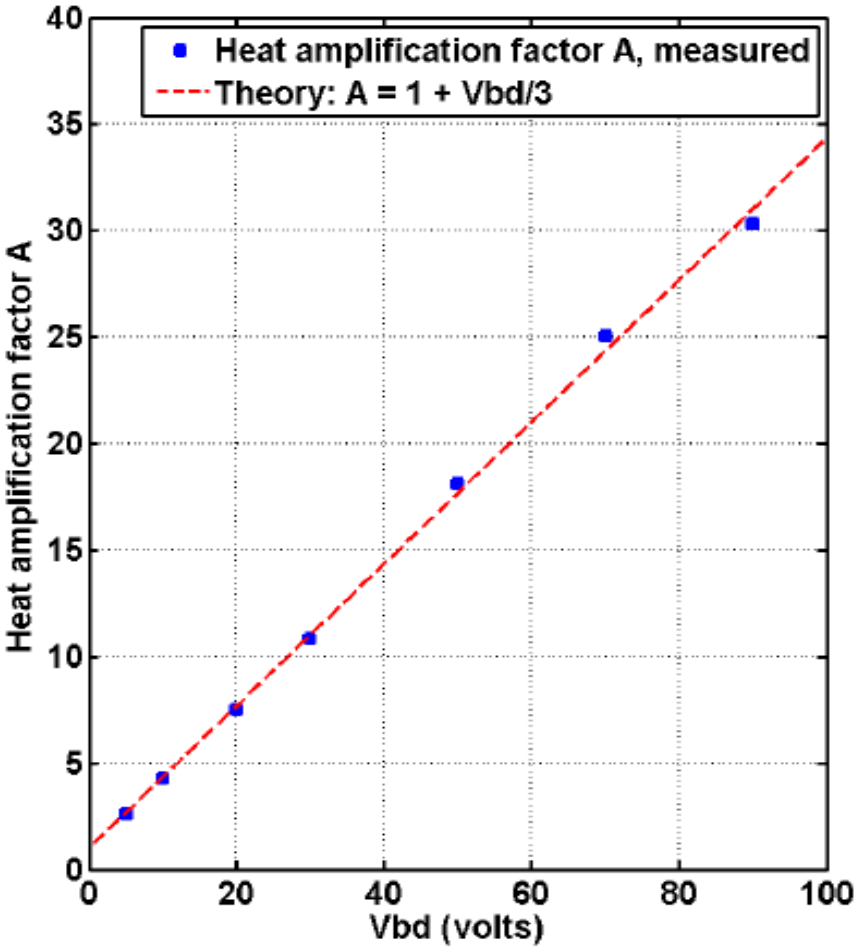
signal investigation for Ge in NL-mode

$V_B = -V_D =$ **90V**

$V_A = V_C = 0V$, T=23mK

$^{241}Am(\gamma, 60keV)$





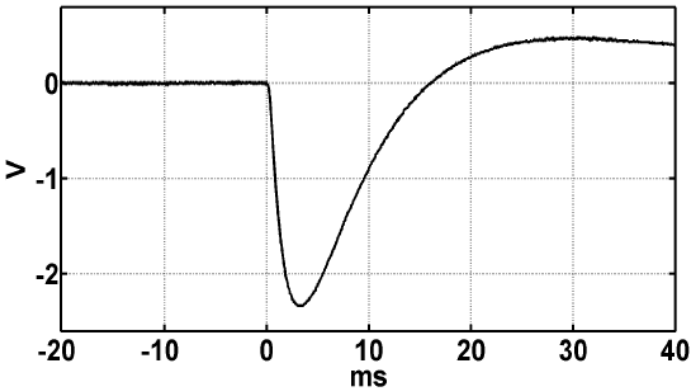
A. Broniatowski, LTD16, Grenoble

signal investigation for Ge in NL-mode

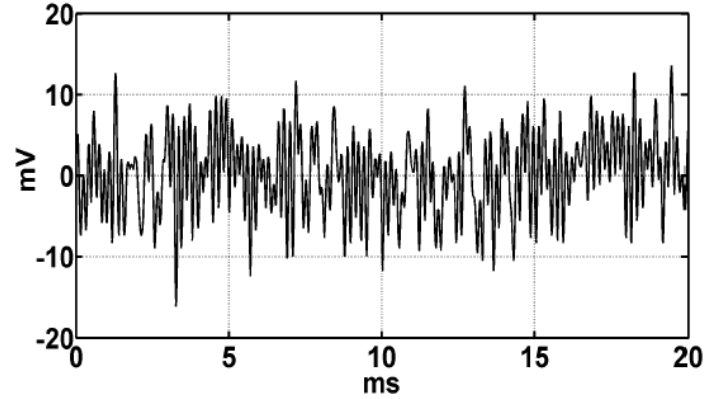
$V_B = -V_D =$ **90V**

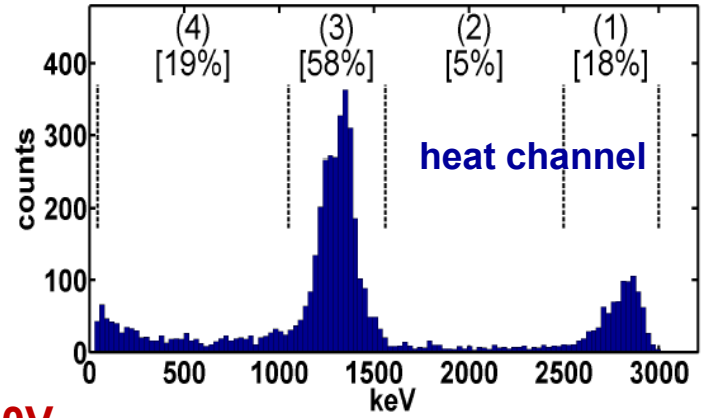
$V_A = V_C = 0V$, T=23mK

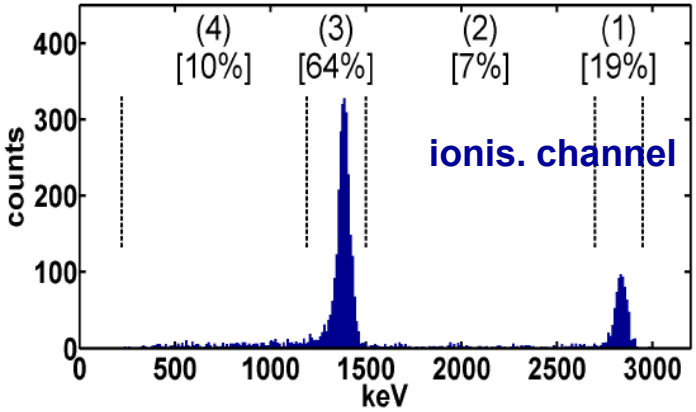
^{241}Am(γ, 60keV)



noise level







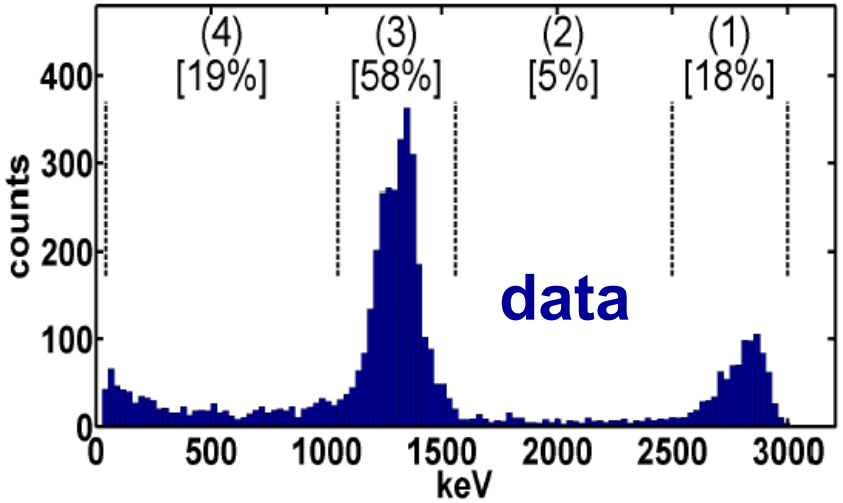
$V_B = -V_D =$ **70V**

$V_A = V_C = 0V$, T=30mK

1: bulk; 3: surface
2: shared, 4: surface w/ charge trapping

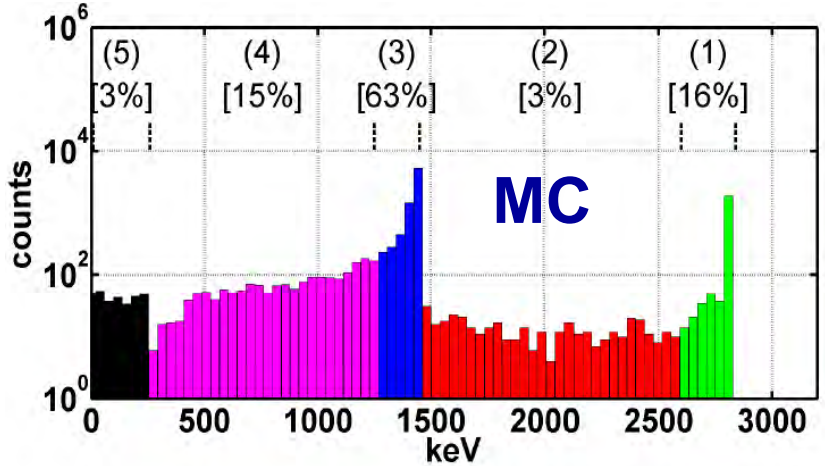
A. Broniatowski, LTD16, Grenoble

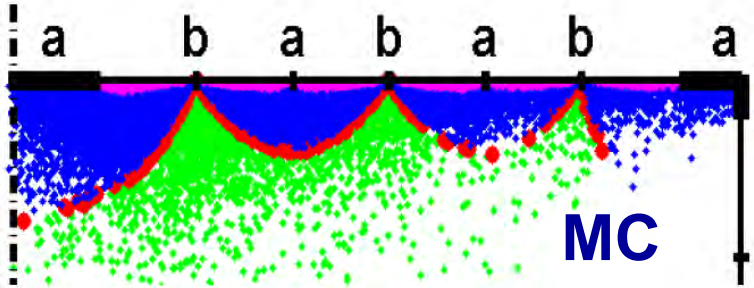
signal investigation for Ge in NL-mode



Issues for further investigations:

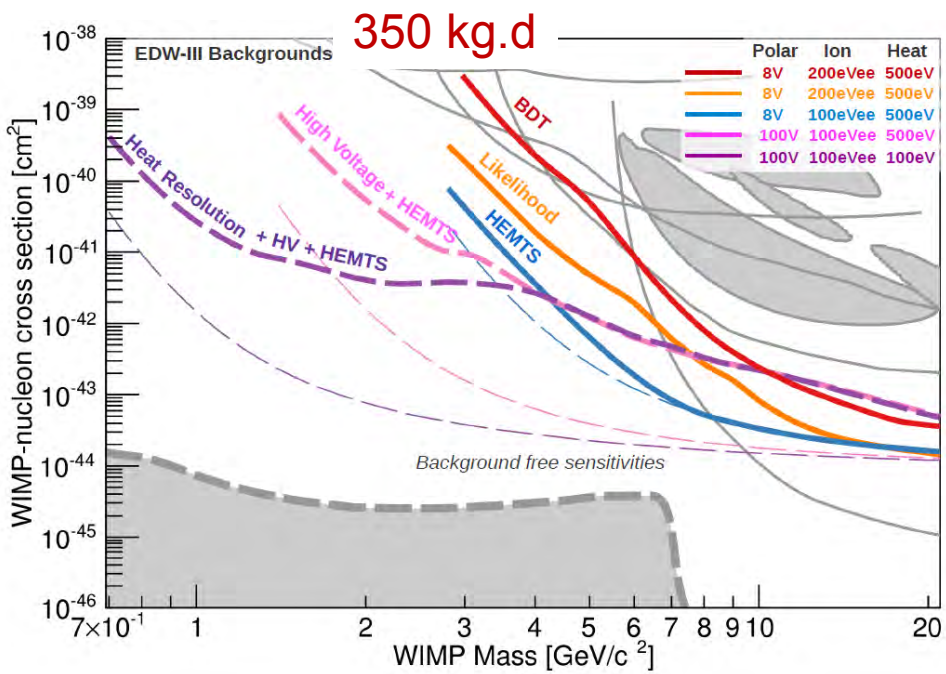
- Choice of biasing conditions for optimal heat measurements: planar vs. veto configurations.
- Detector response to low-E evts.
- Energy resolution (especially: dependence on site of energy deposition).

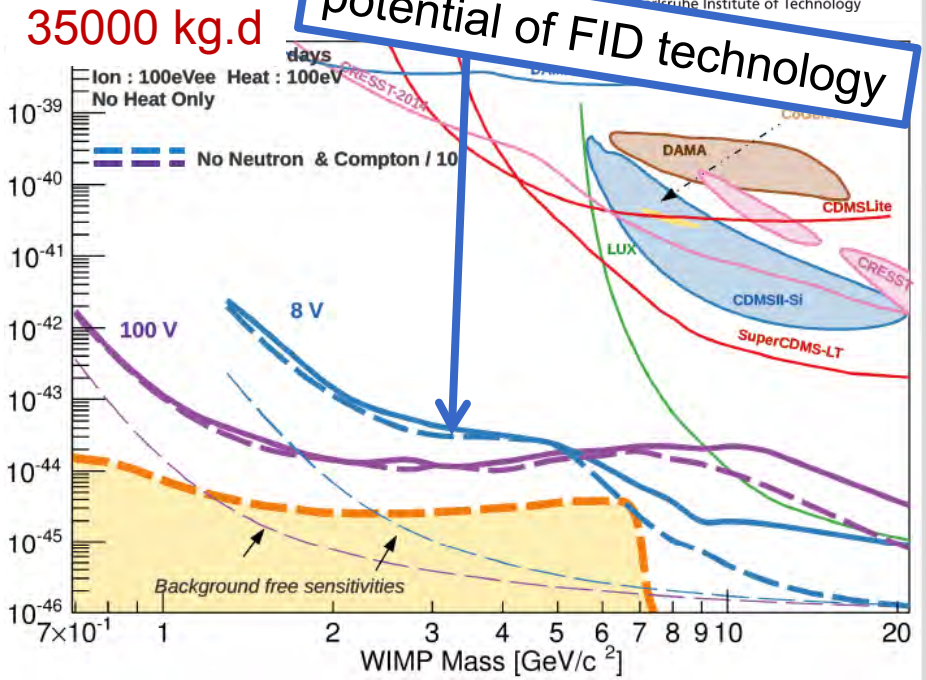




A. Broniatowski, LTD16, Grenoble

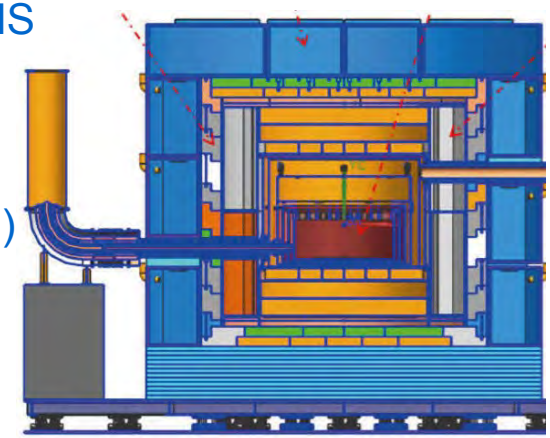
EDELWEISS-III & beyond



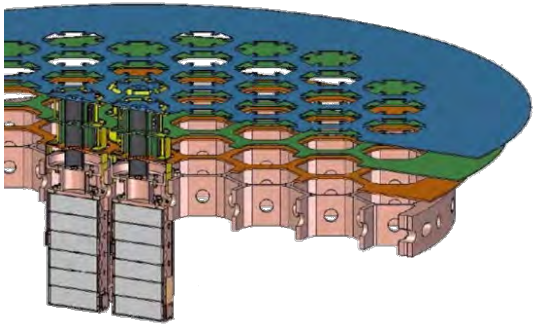


potential of FID technology

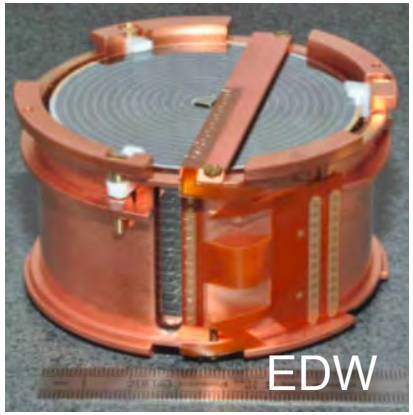
- EURECA cooperation with SuperCDMS
  → joint facility at SNOLAB (2019++)
  with common tower design
  for different detector technology
  (SuperCDMS, CRESST, EDELWEISS)

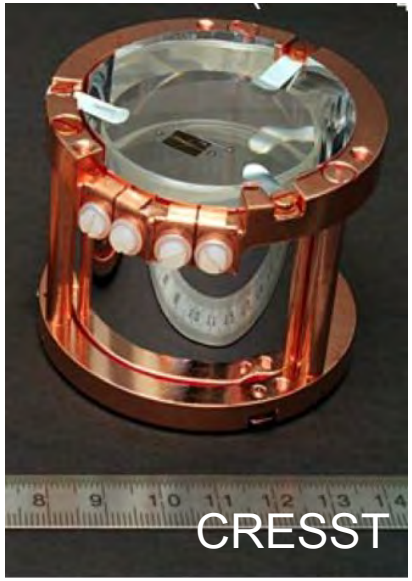


SuperCDMS@SNOLAB

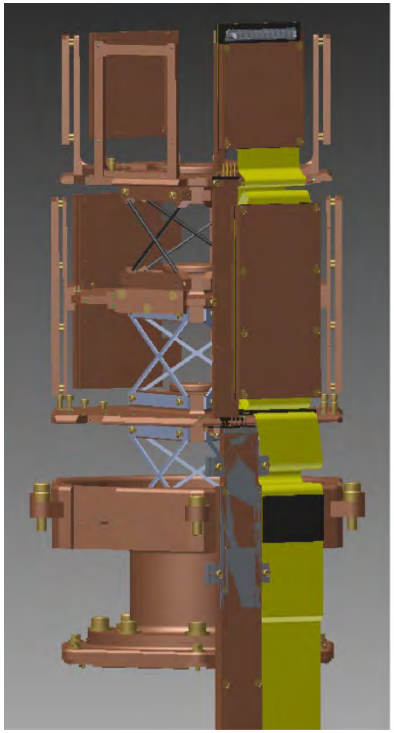


SuperCDMS/EURECA

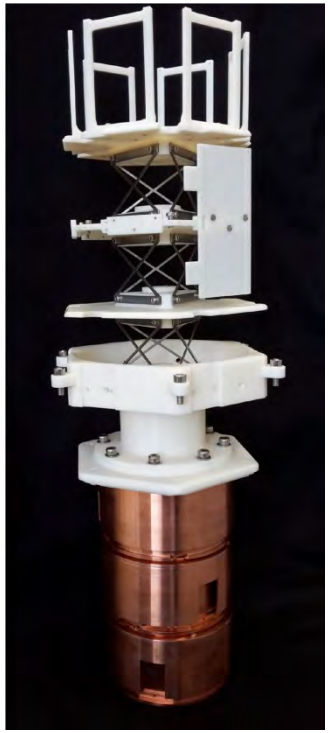




- common cryogenic infrastructure
- space for ~400kg of modular detectors
- compatible interface with tower design
- common cabling & readout electronics
- 1st phase: 50kg SCDMS + 50kg EURECA



SCDMS design



KIT mockup of tower

conclusion and outlook

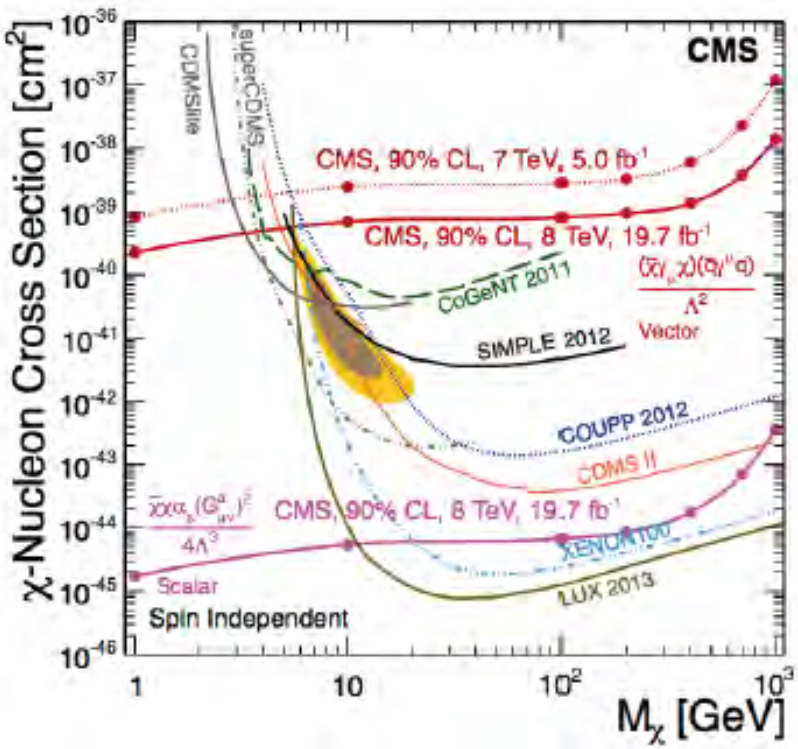
Ge detectors at ultra-low T for DM search:

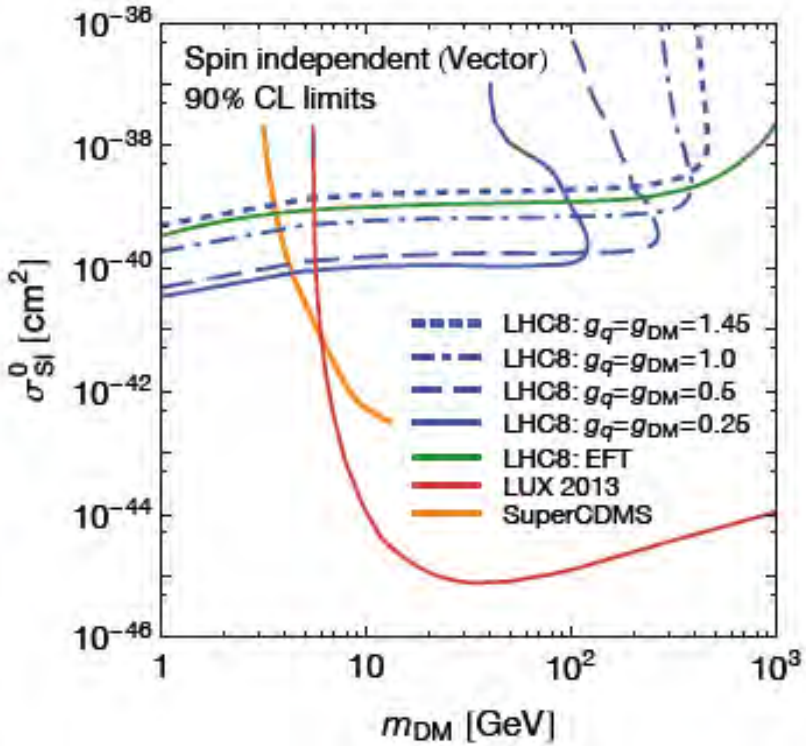
- low bias mode: E_{thr} ~ 500eV with full e/n discr.
- high bias (NL) mode: $E_{thr} \leq 50eV_{ee}$
- parameter region 1GeV < m_{χ} < 10GeV testable
- surface bgd rejection under investigation
- next generation: SNOLAB joint infrastructure

Comparison with direct detection

Malik, CM et al
arXiv:1409.4075

- EFT limit overestimates at high mass/underestimates at low mass



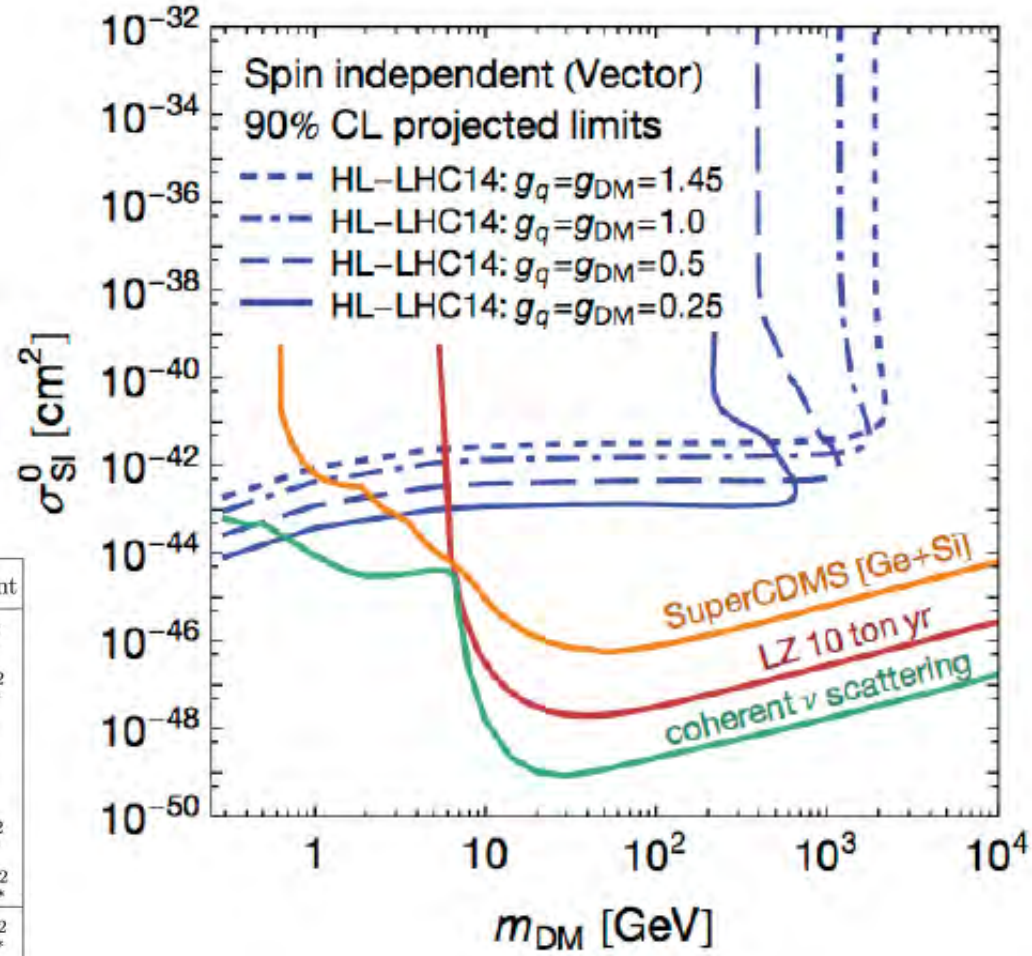


EFT operators

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Goodman et al
arXiv:1008.1783



DD: scattering off u and d
Monojet: coupling to all quarks