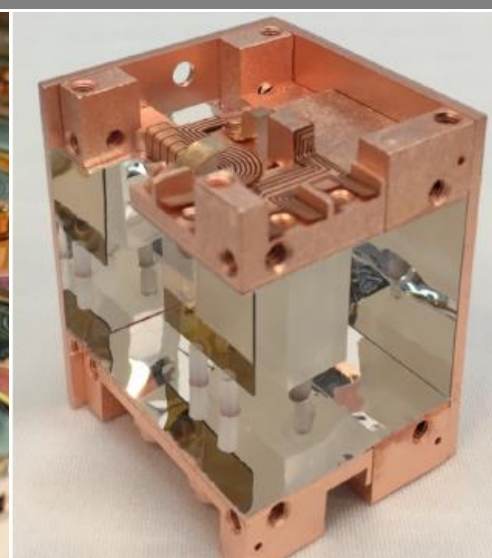
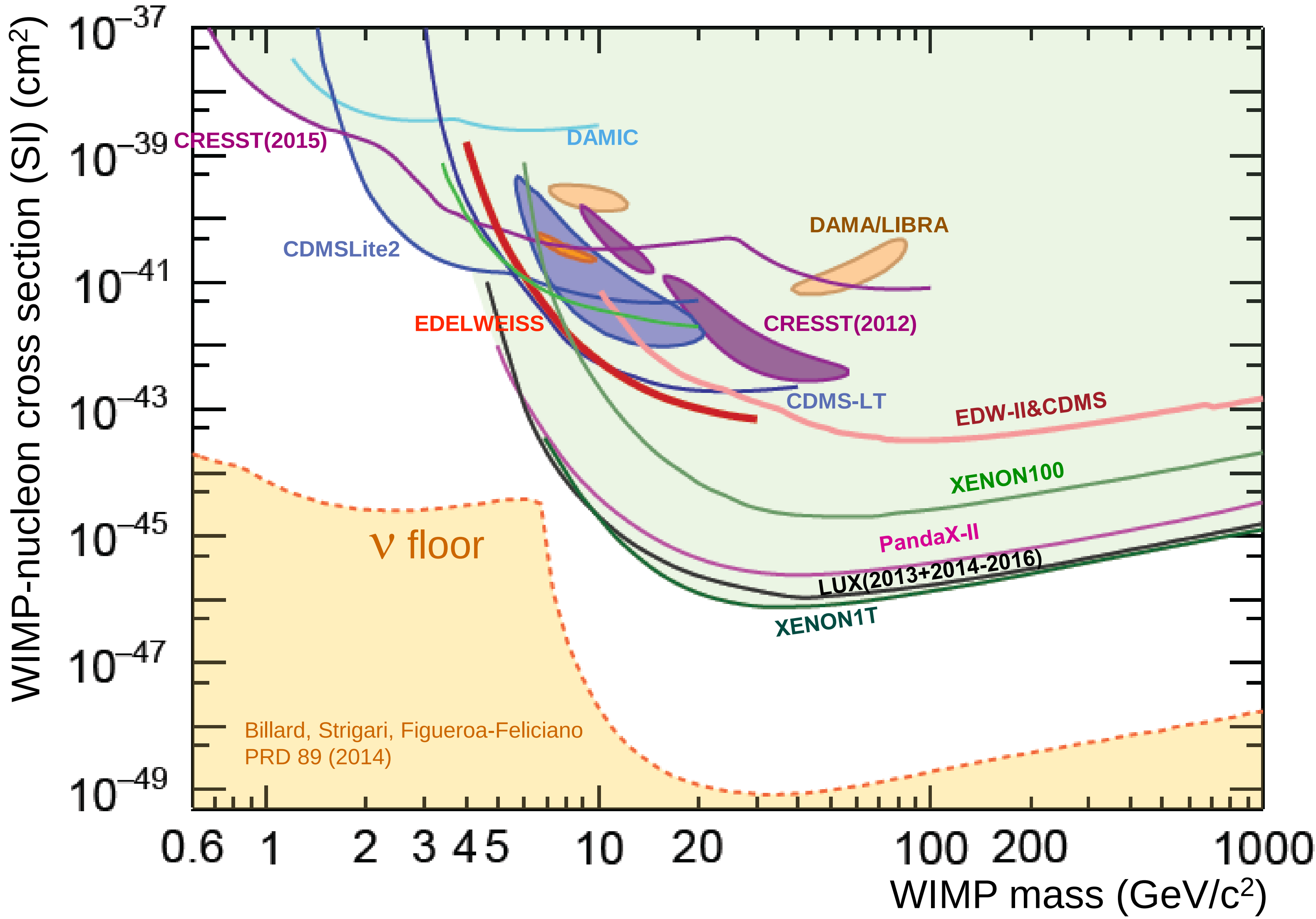
Low threshold crystal detectors for Dark Matter search

Klaus Eitel


WIMP search: status and strategy



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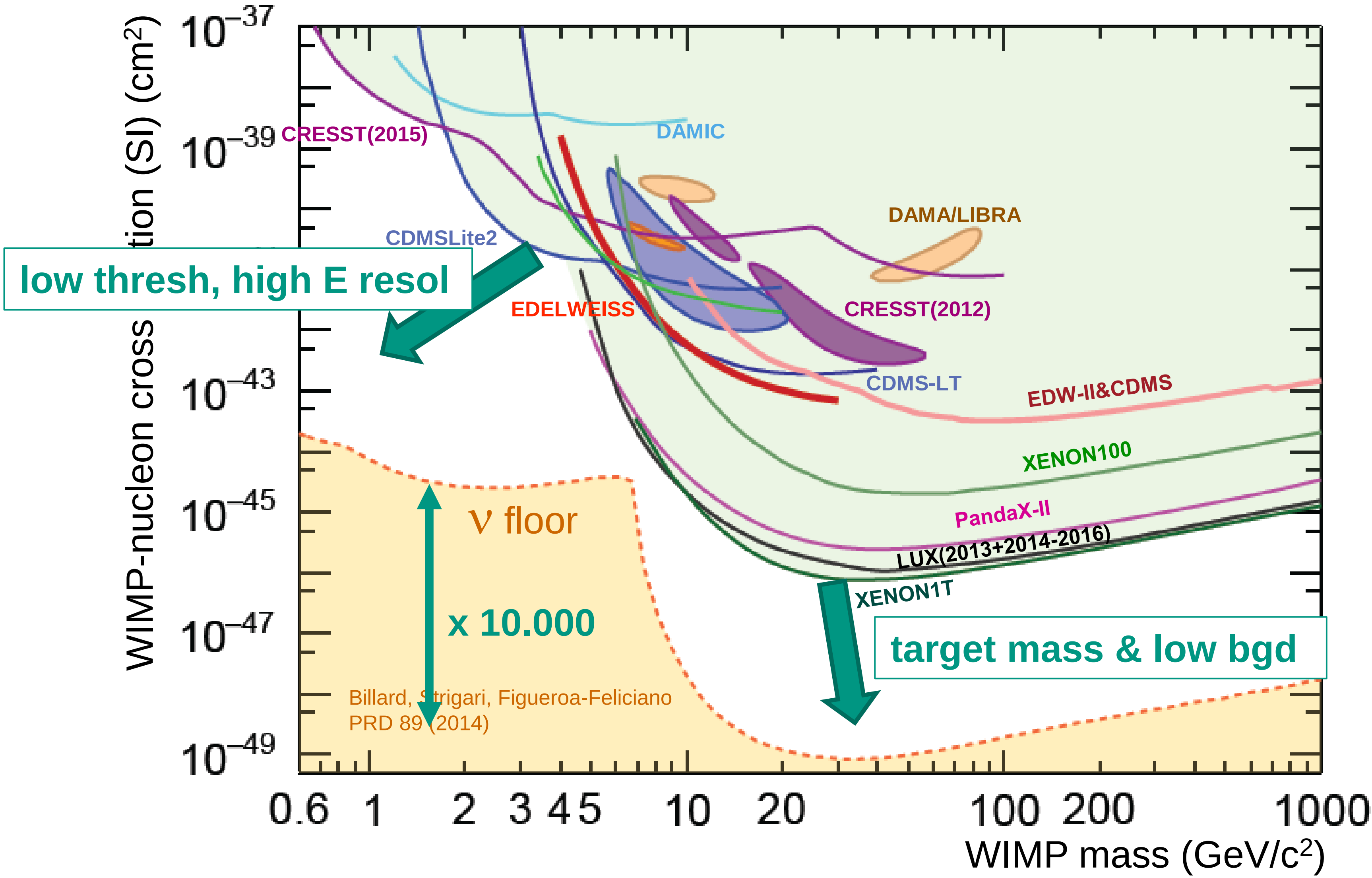

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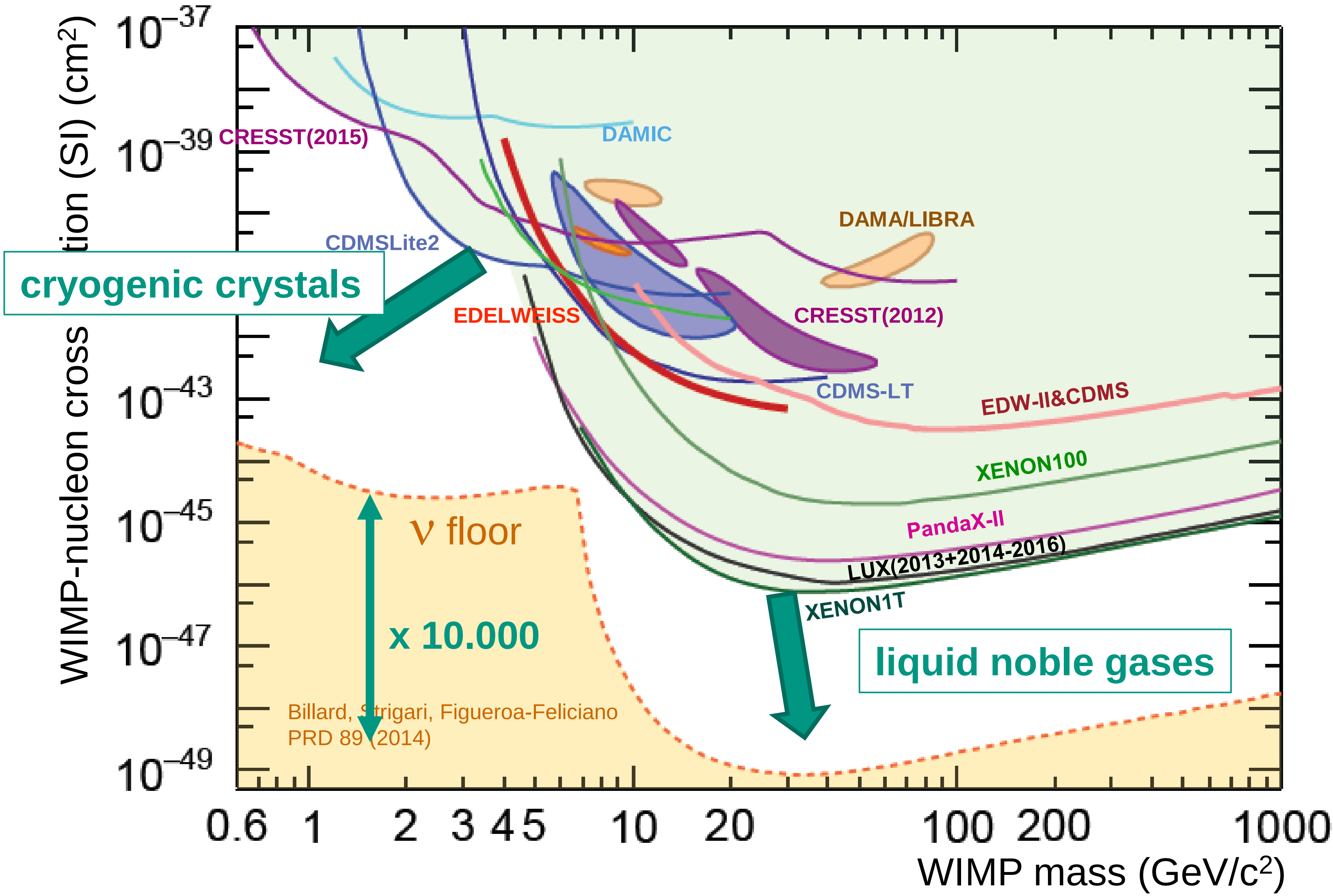
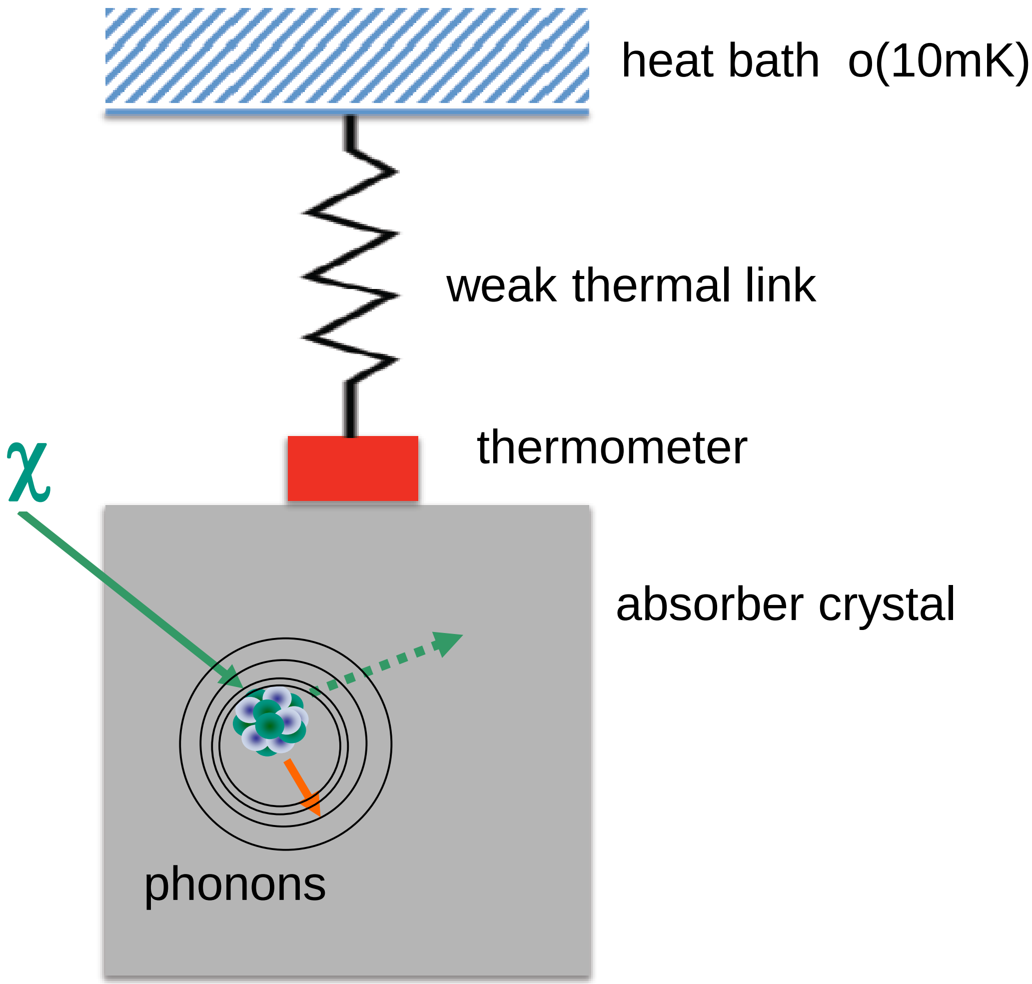


Cryogenic detectors (crystals)



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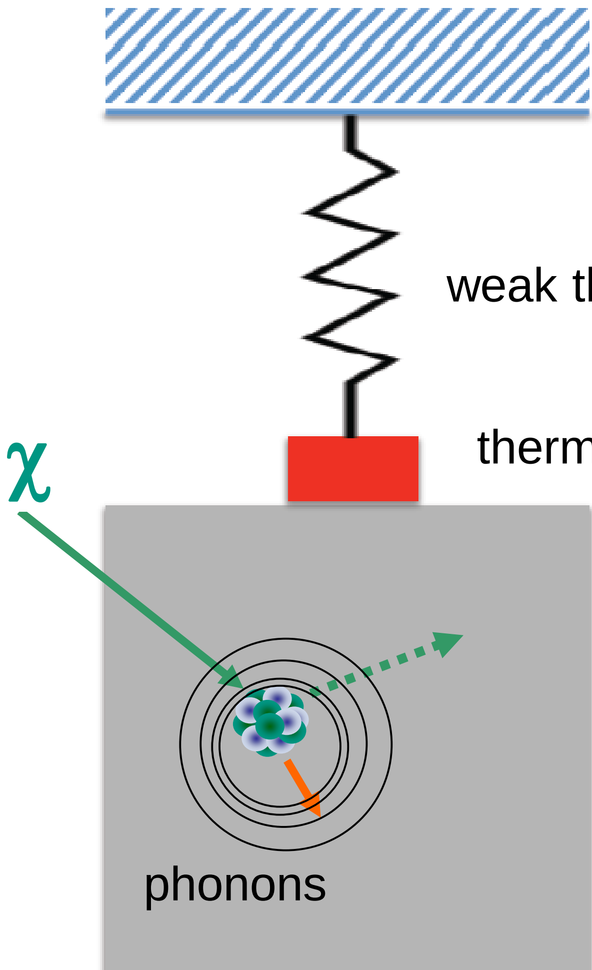
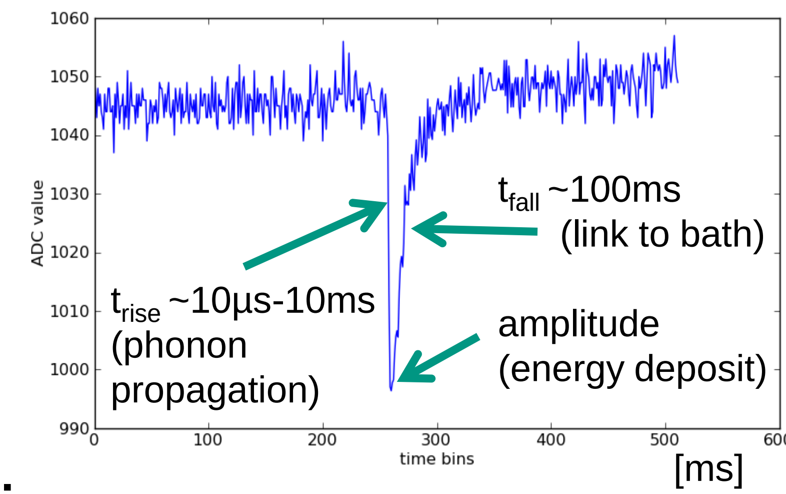
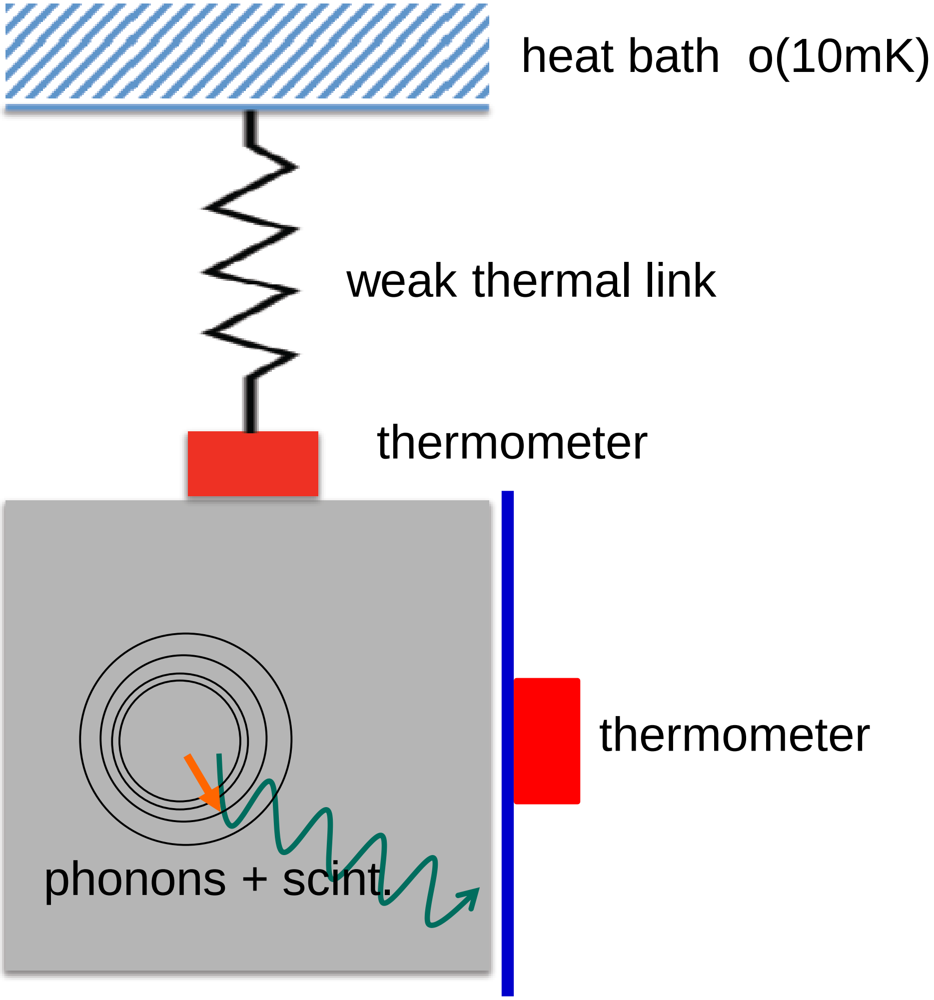




operation at mK:
temperature increase from
particle interactions can be measured!
(1-10keV → µK)
calorimeter:
direct measurement of total energy deposit!

Cryogenic detectors (crystals)



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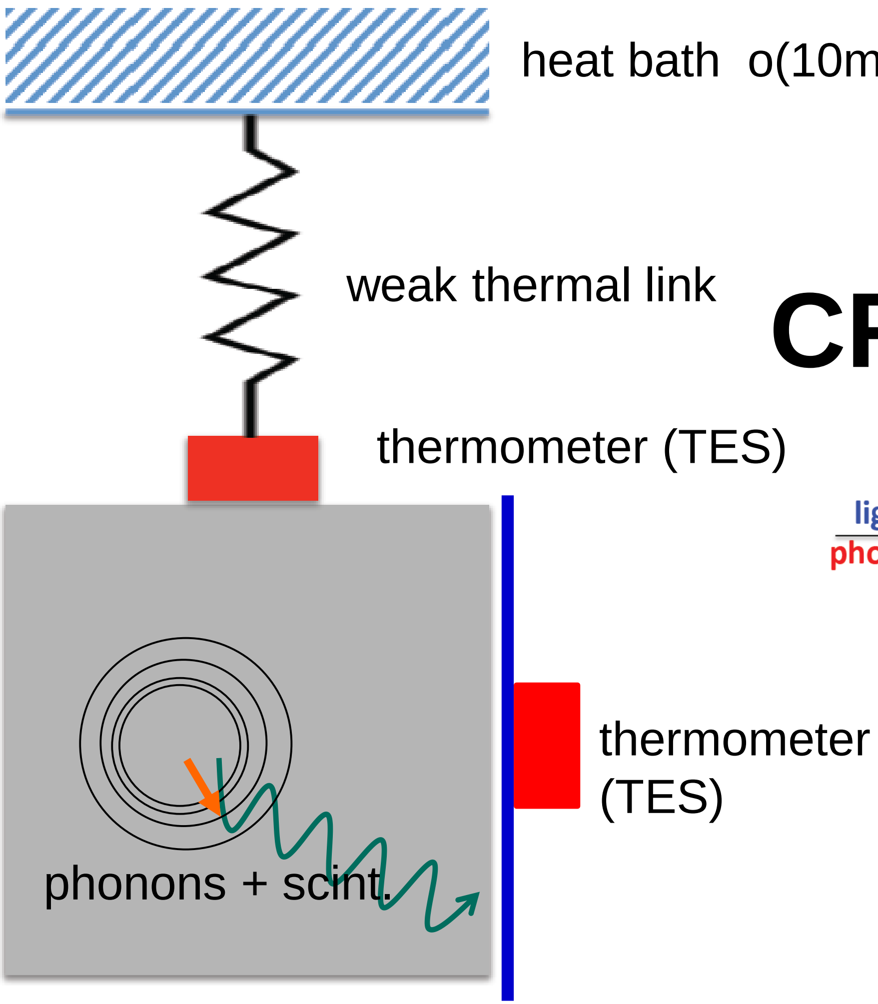
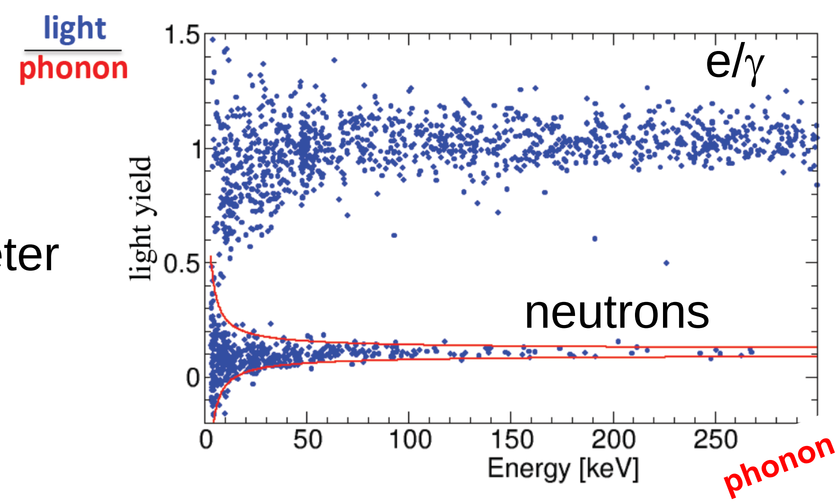


CRESST ($CaWO_4$)



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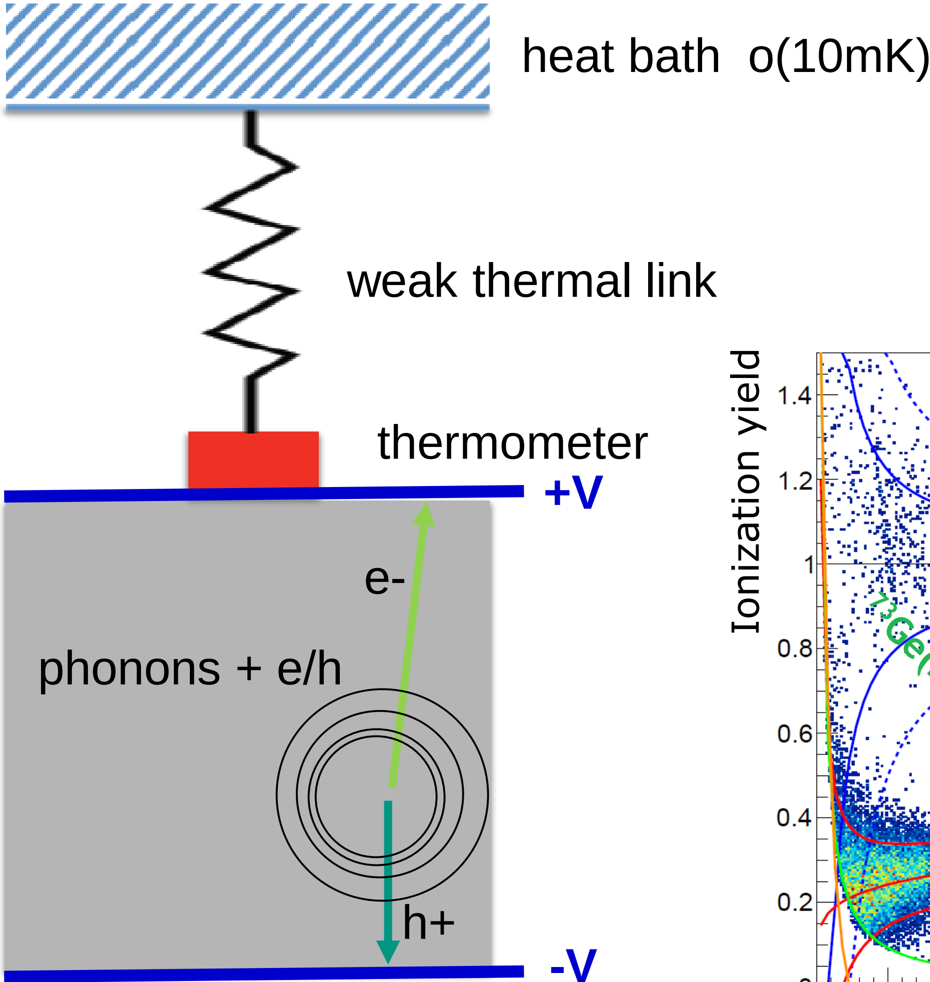
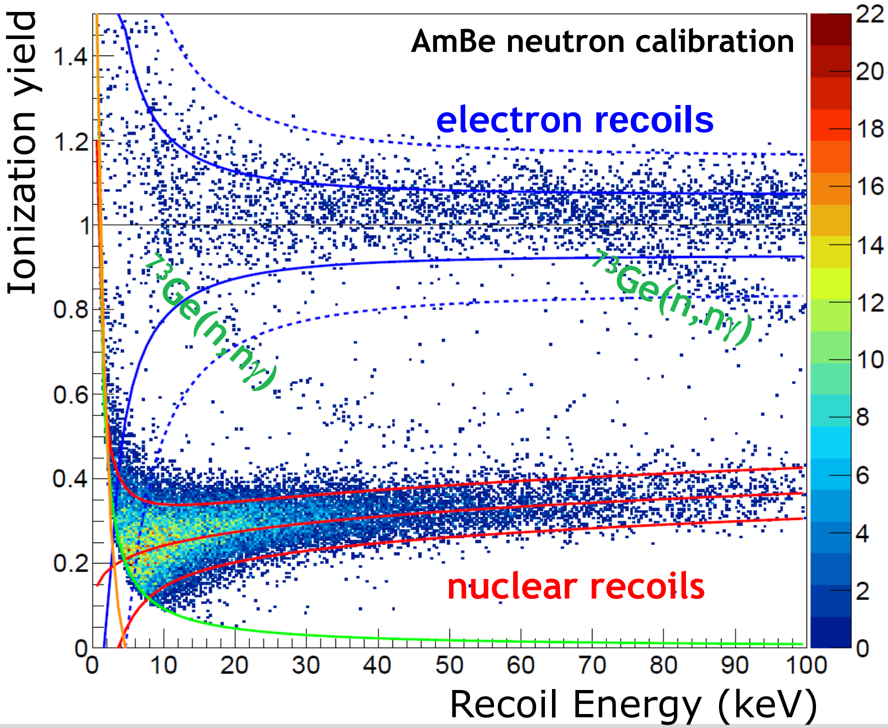
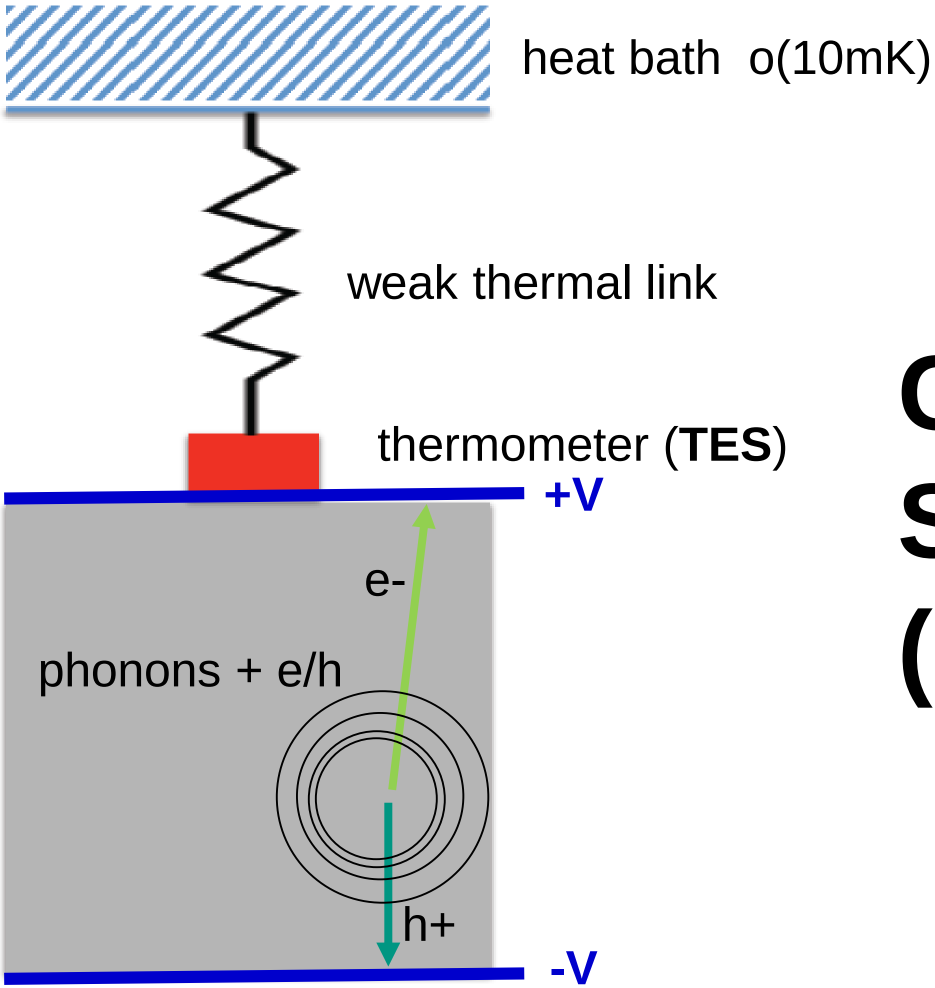


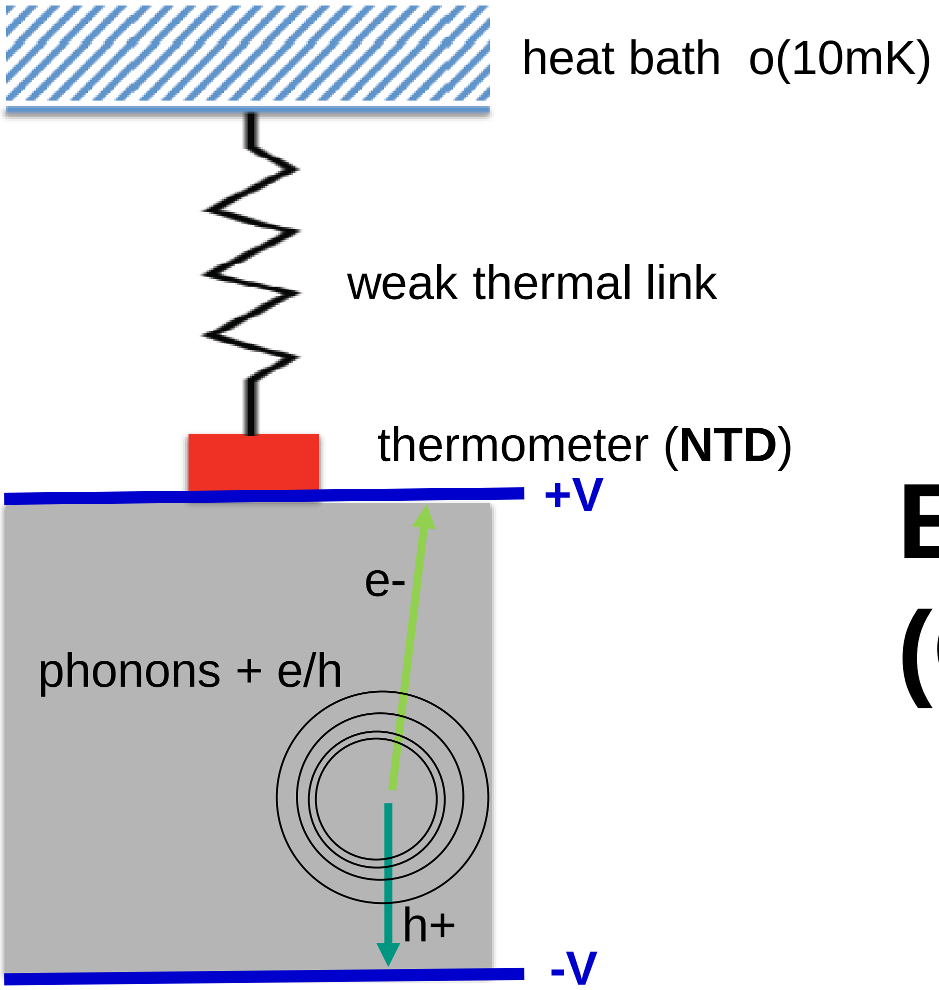


Cryogenic detectors (crystals)



CDMS
SuperCDMS
(Ge & Si)

Cryogenic detectors (crystals)

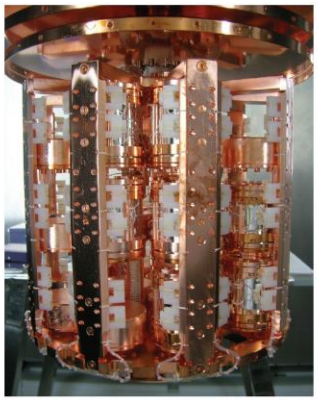


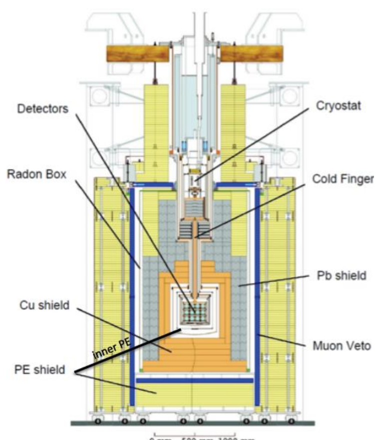
EDELWEISS (Ge)

CRESST

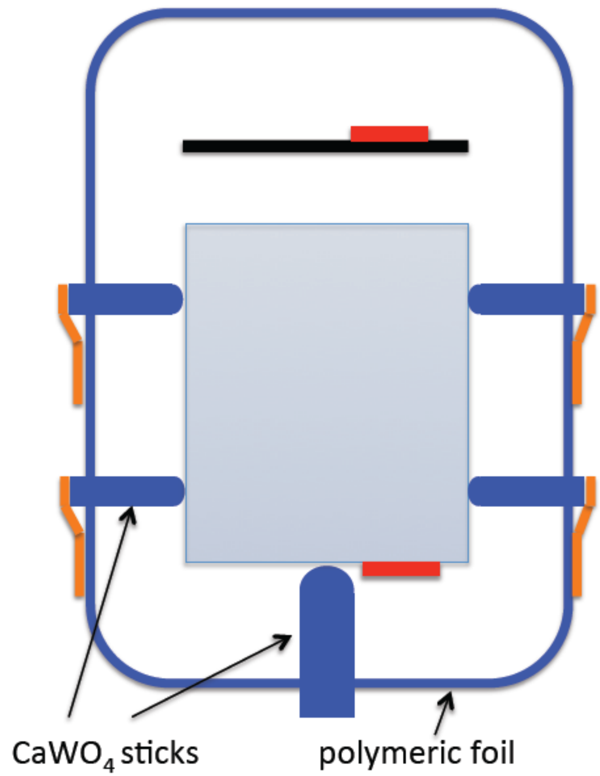
Cryogenic Rare Event Search with Superconducting Thermometers (at LNGS)

CRESST-II phase 2
data taking 7/2013 – 8/2015



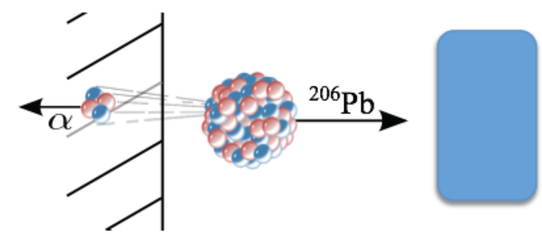


CRESST-II detector module



Polymeric foil + $CaWO_4$ sticks

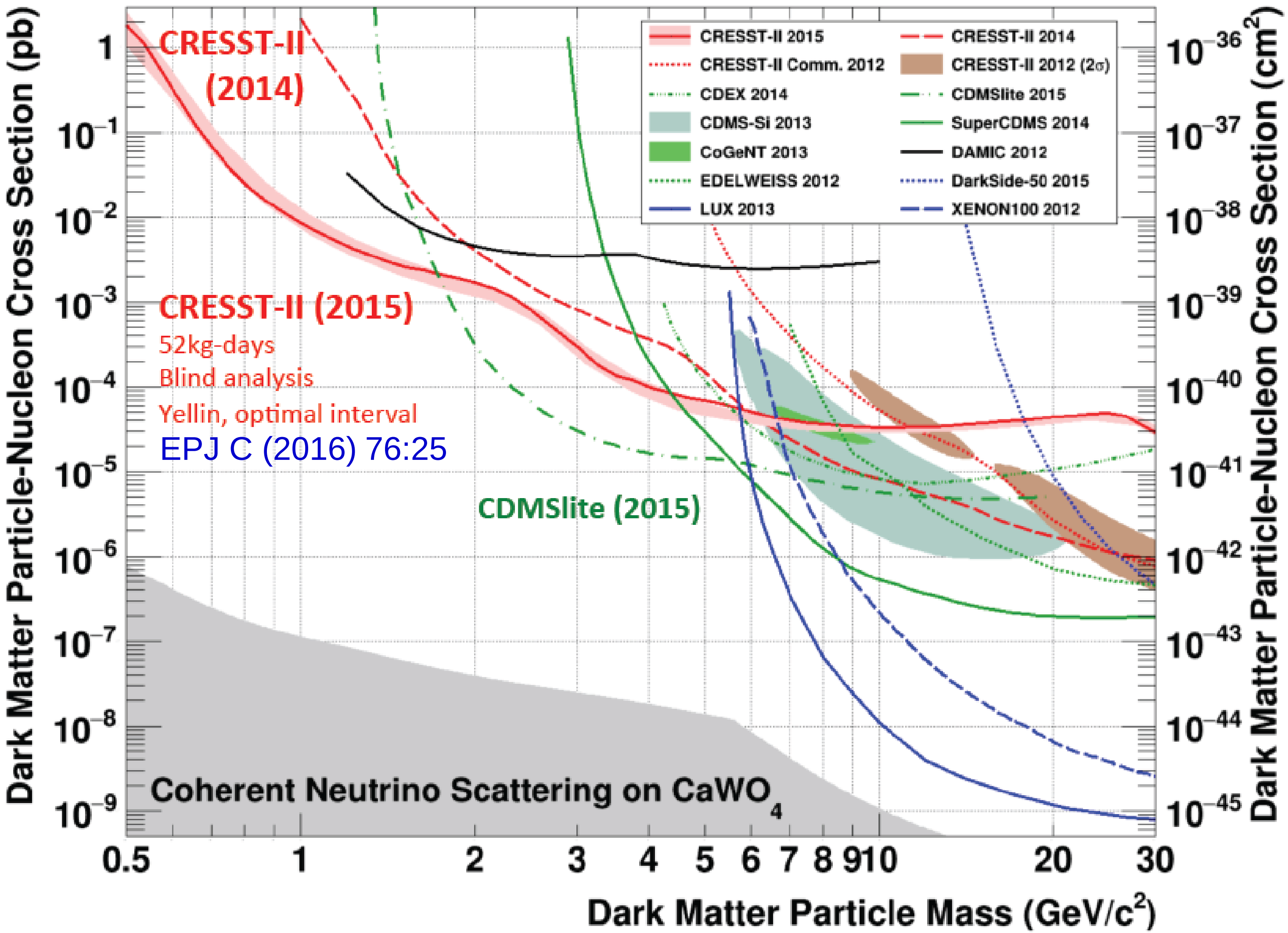
- Fully-scintillating detector housing
- Efficient rejection of surface backgrounds



R. Strauss et al. arxiv:1410.1753 EPJ-C (2015)
R. Strauss et al. arxiv:1410.4188 JCAP 06(2015)030

R. Strauss, Direct Dark Matter Detection: Experiment meets Theory, March 6-8, 2017, Munich

CRESST-II results



CRESST-III

Karlsruhe Institute of Technology

Status quo

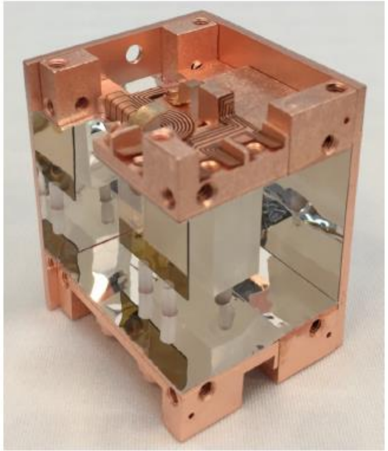
m = 250g
V = 32x32x40 mm^3

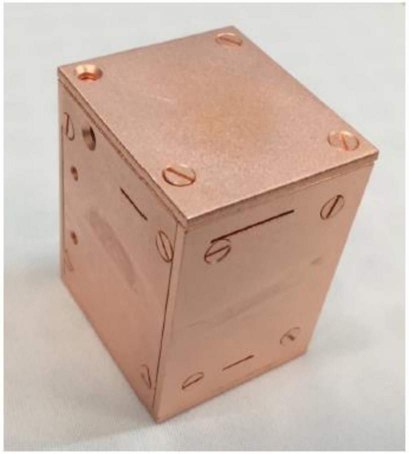
Scale down size by factor 10

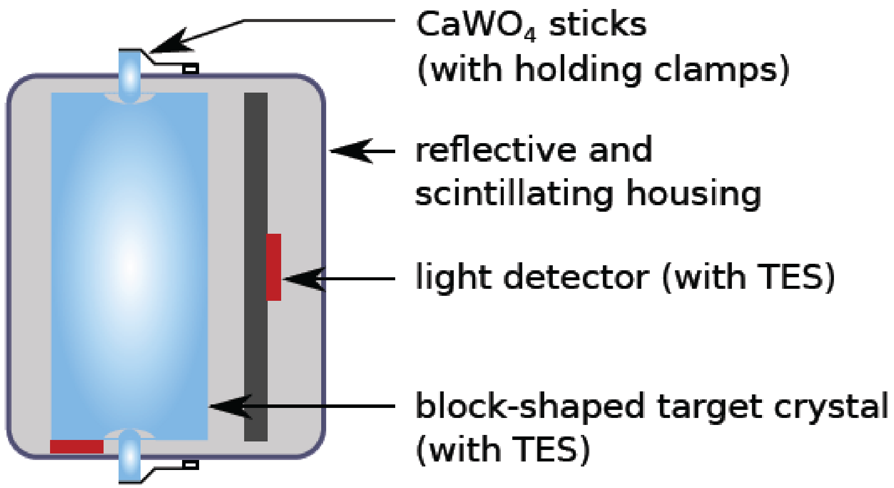
m=24g

Phonon threshold: $E_{th} \lesssim 500$eV **improvement by a factor of 5-10**

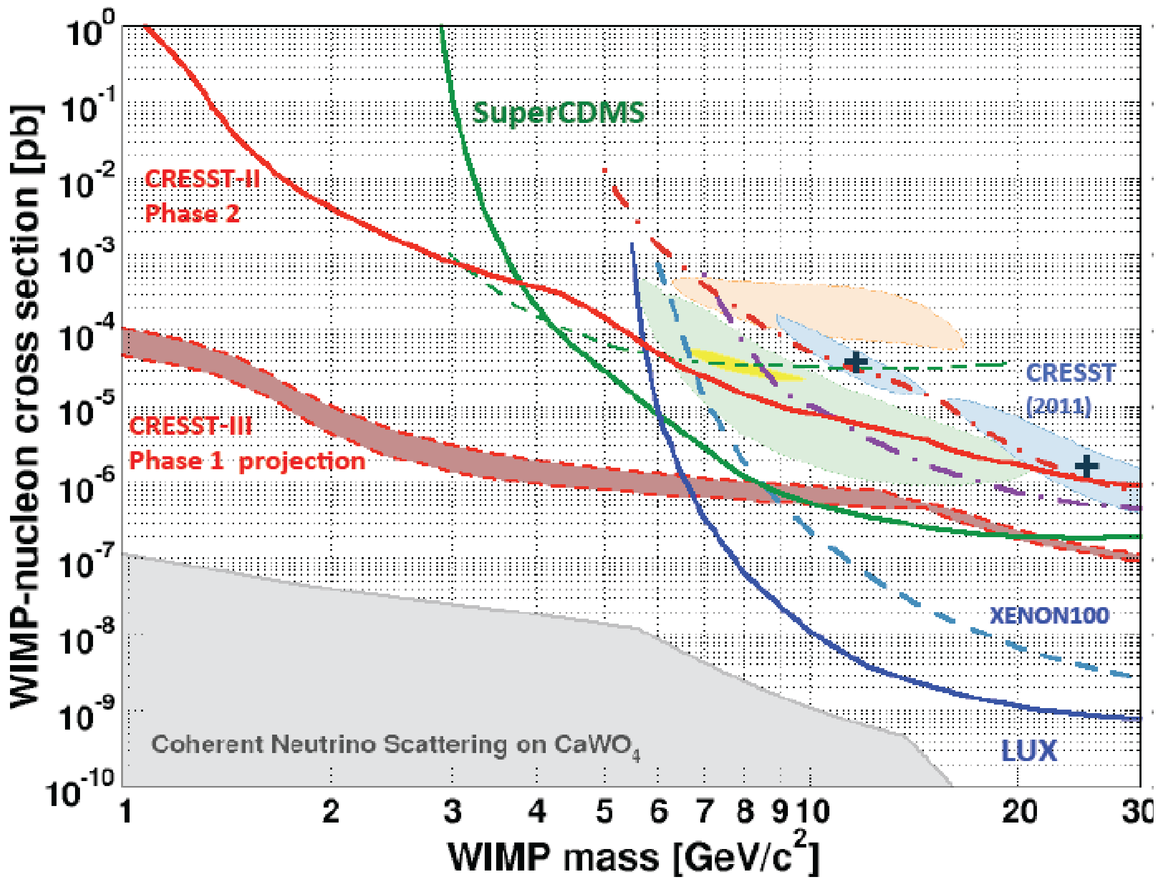
Light-detector res.: $\sigma \approx 5$ eV **improvement by a factor of 2**

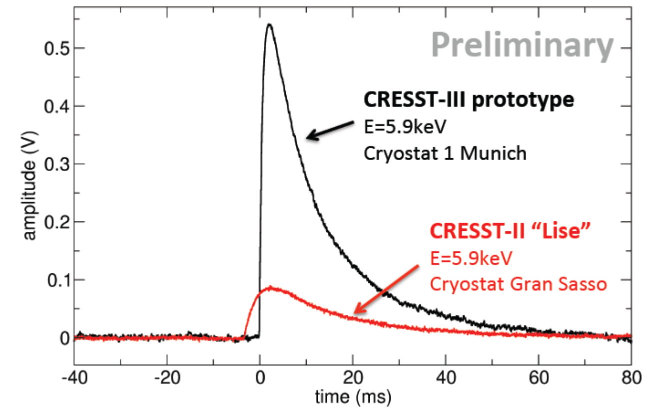






CRESST-III phase 1





data taking started Sept 2016

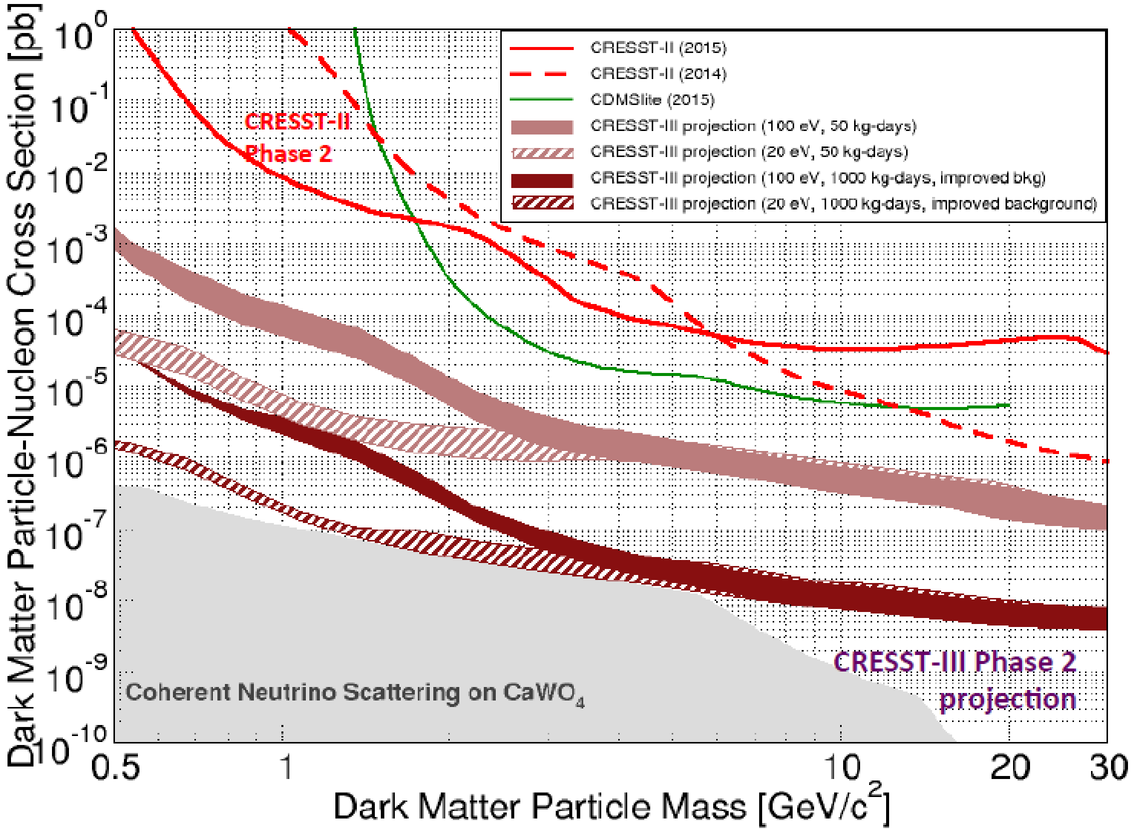
better than design E_{th}=100eV

expect first data release
by July/Aug
(LTD17, TAUP)

10 x 24g detectors operated for one year
≈ **50 kg-days** (net)

R. Strauss, Direct Dark Matter Detection: Experiment meets Theory, March 6-8, 2017, Munich

CRESST-III phase 2



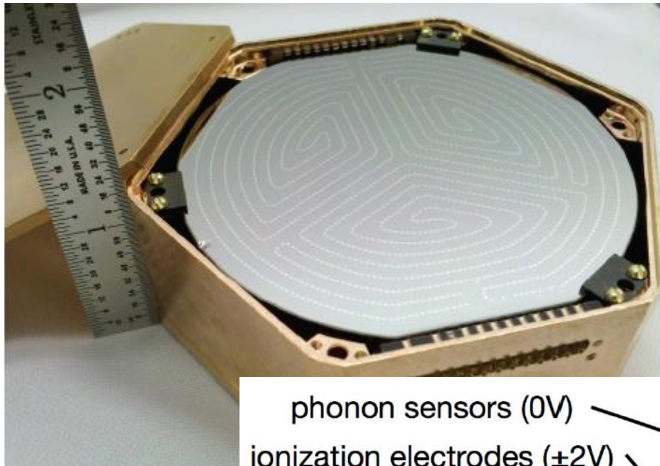
Reduction x100 of intrinsic bgd of crystals required!
reach 10^{-2} cts/(kg.keV.d)

- Growth of $CaWO_4$ crystals in-house
- All production steps under control
- Improvement x10 already achieved
- Cleaning procedure e.g. by re-crystallization, chemical purification of raw materials

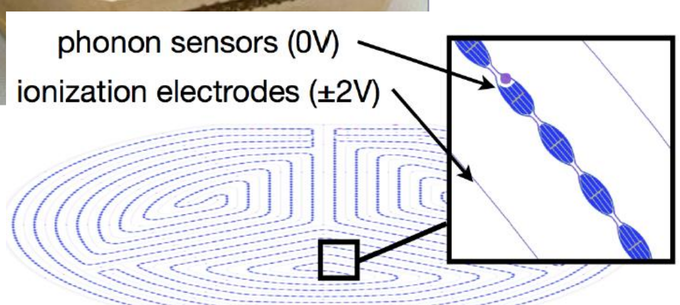
100 x 24g detectors operated for 2 years
≈ **1000 kg-days** (net)

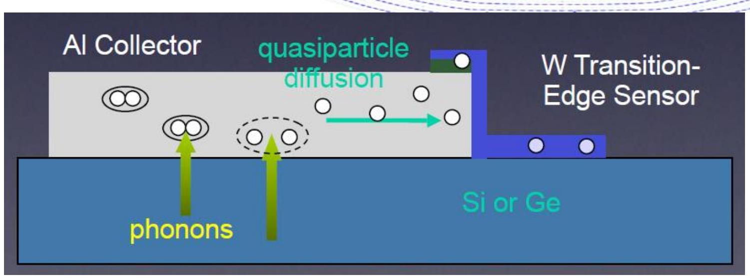
R. Strauss, Direct Dark Matter Detection: Experiment meets Theory, March 6-8, 2017, Munich

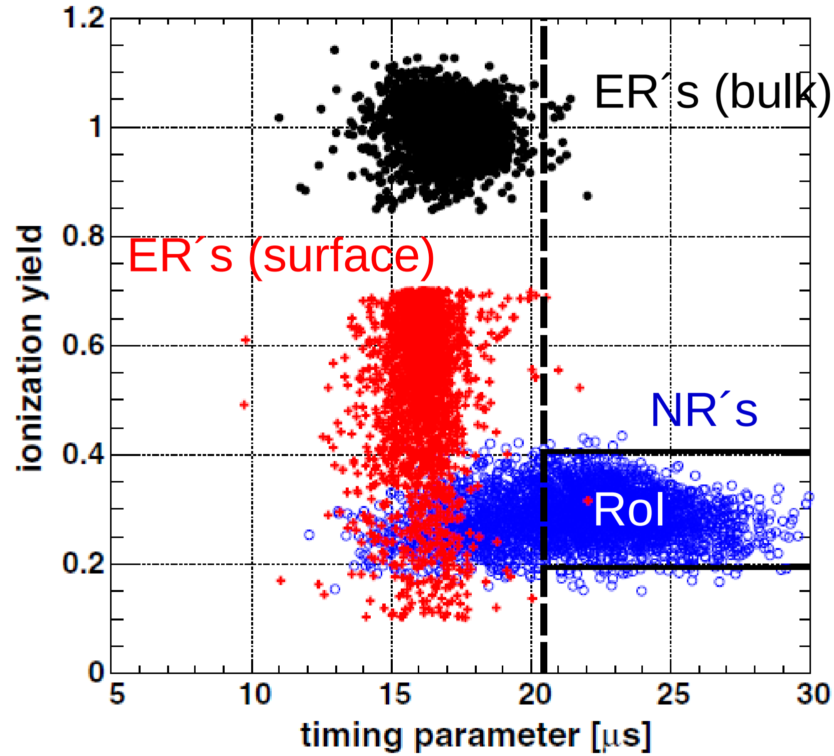
SuperCDMS @ Soudan (2090mwe)



15 HPGe monocrystals (Ø=3“, h=1“ → m=600g)
interleaved **Z**-sensitive
Ionization and
Phonon detectors (**iZIP**)



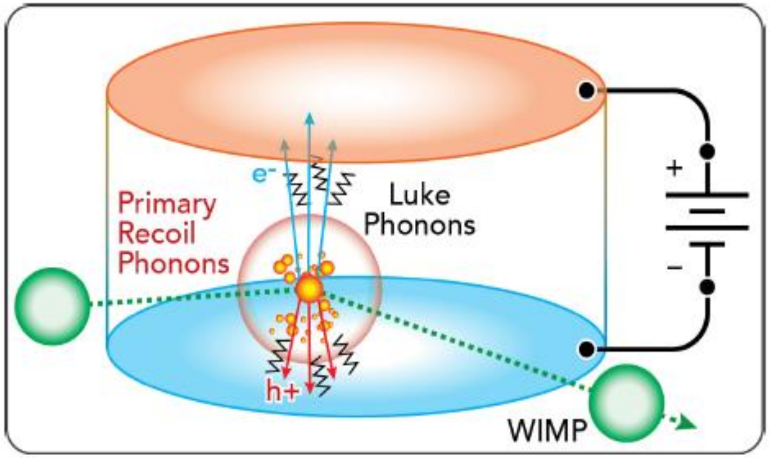




PRD 92, 072003 (2015)

T_{op} ~ 50mK; low impedance SQUID readout
t(phonon) + Δ(ionis.) → surface rejection

CDMS lite @ Soudan



making use of Neganov-Luke effect:

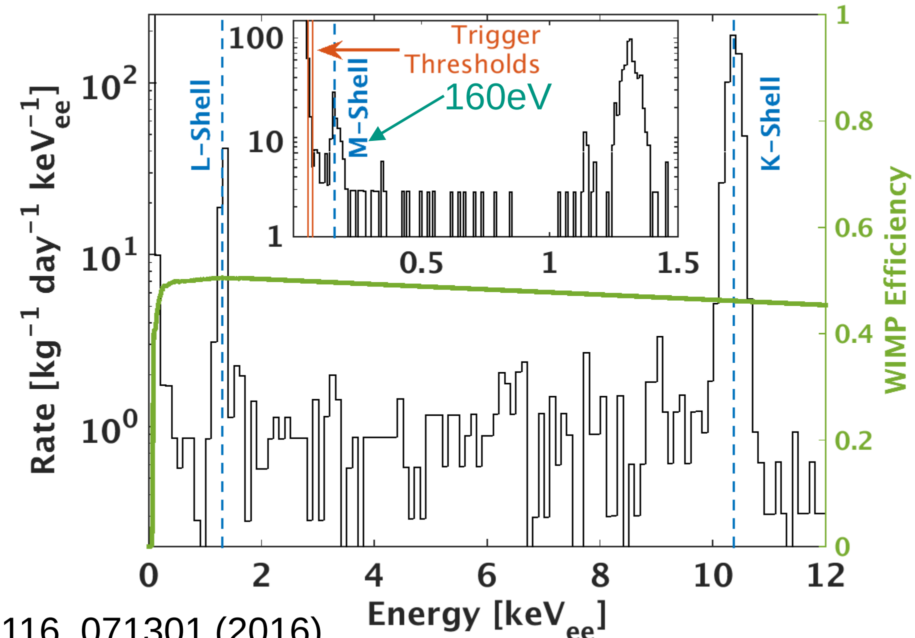
$$E_t = E_r + \frac{1}{3\,eV} E_Q \Delta V$$

with V=70V amplification of heat signal ~24
→ effective lowering the threshold

NL amplification:

- allows $E_{thr} \approx 50eV$
- opens window into ~GeV range

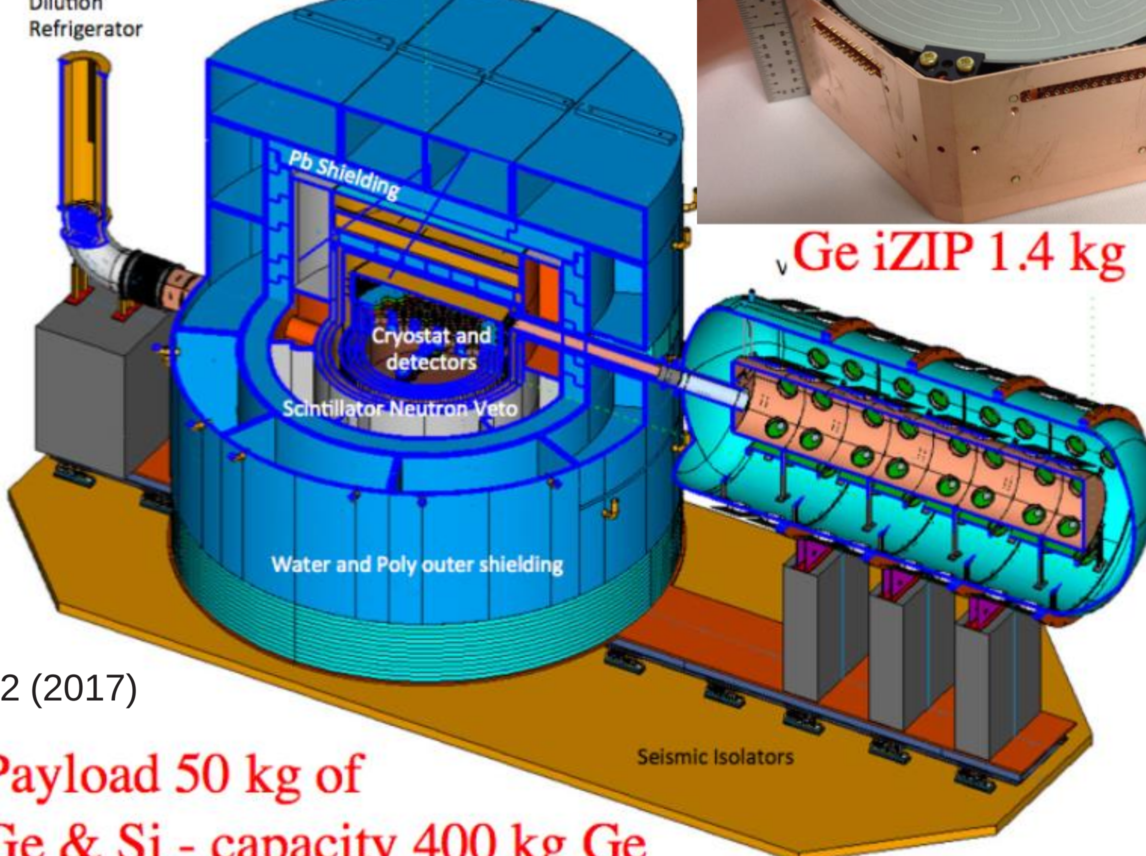
- loss of PID
- needs careful energy calib.

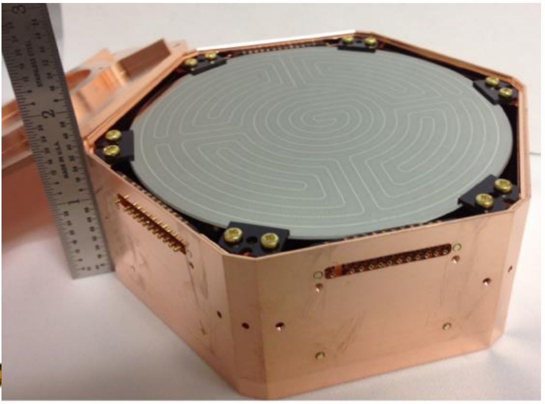


PRL 116, 071301 (2016)

SuperCDMS Soudan (2090mwe) → SNOLAB (6010mwe)

G2 experiment (2020+), 1st stage:
2 towers with Ge → $m_\chi \geq 5$ GeV (bgd for NL)
2 towers Ge+Si → $m_\chi \geq 0.3$ GeV (NL)





Ge iZIP 1.4 kg

Ge Tower 8.4 kg

PRD 95, 082002 (2017)

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

EDELWEISS @ LSM

Collaboration

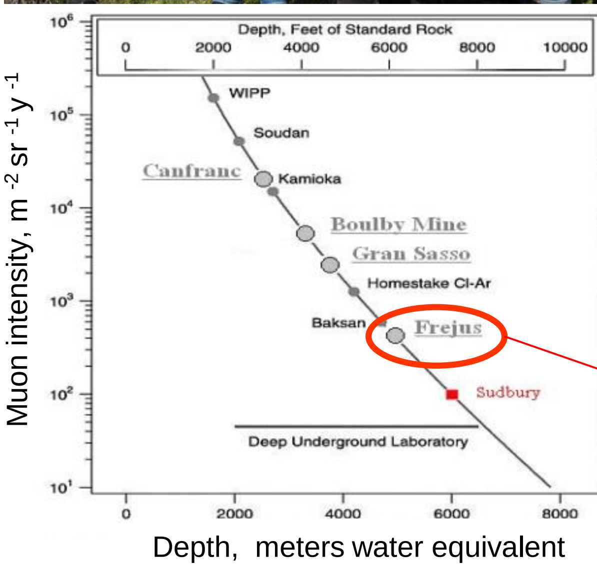
CEA Irfu/Iramis (Saclay)
CSNSM (Orsay)
Institut Néel (Grenoble)
IPNL (Lyon)
LPN (Marcoussis)

KIT (Karlsruhe)

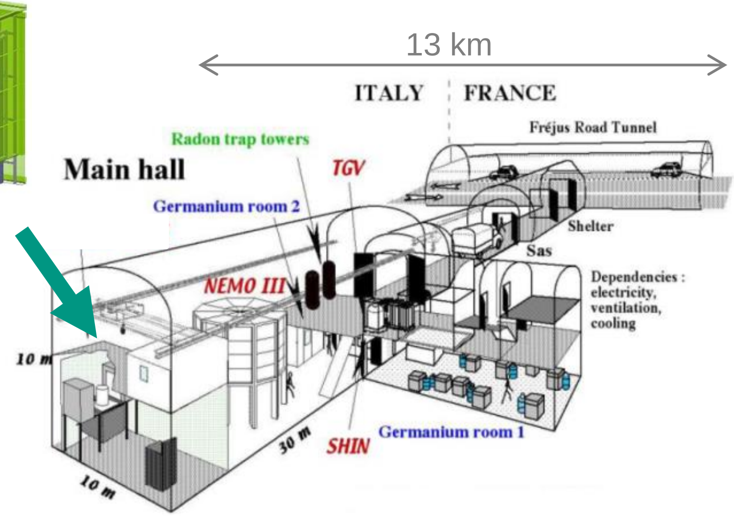
JINR (Dubna)

University of Oxford
University of Sheffield

LSM

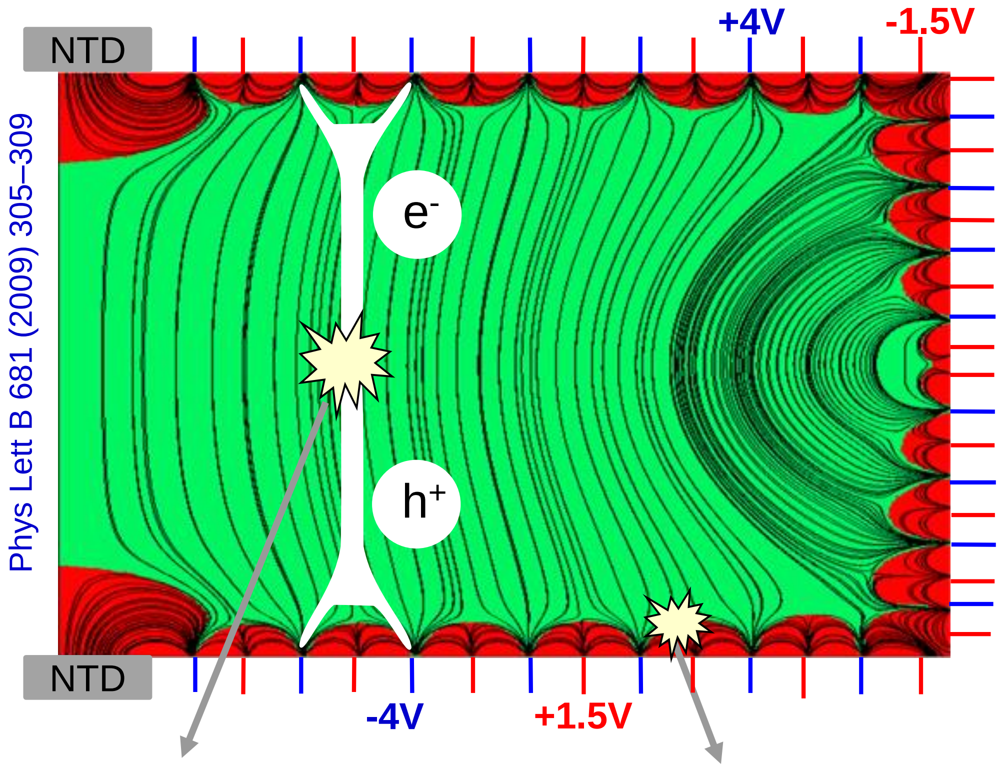


5 μ/m²/day
4800 mwe
(deepest in Europe)



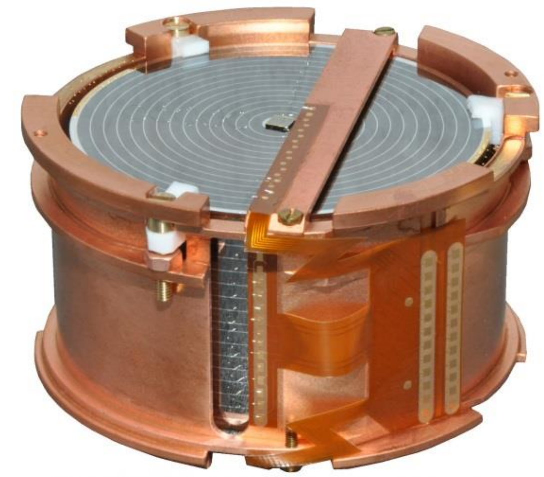
EDELWEISS-III FID800 detectors

Fully **I**nter**D**igitized ~870g HPGe detectors
T_{op}=18mK → heat & ionisation



Bulk/Fiducial event
Charge collected on
electrodes C_{top}&C_{bott}

Surface event
Charge collected on
electrodes C_{bott}&V_{bott}



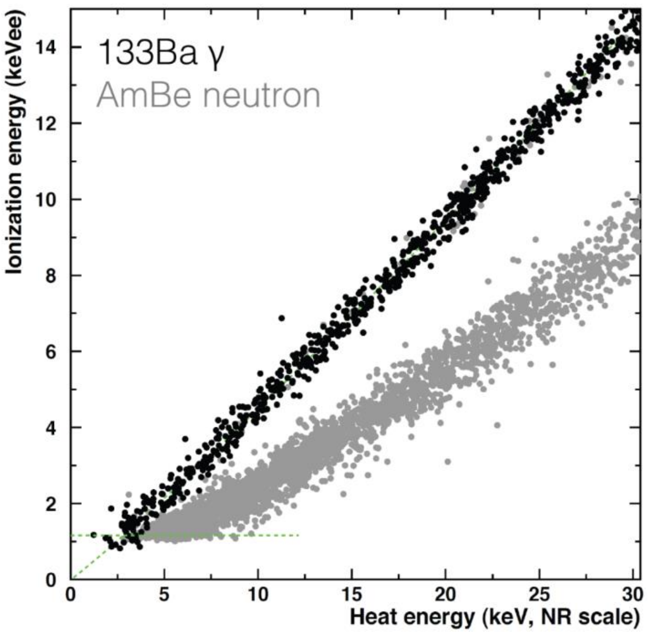
Ø=70mm, h=40 mm
2 GeNTDs heat sensors

Electrodes:
concentric Al rings (2mm spacing)
covering all faces
XeF_2 surface treatment
to ensure low leakage current (<1 fA)
between adjacent electrodes

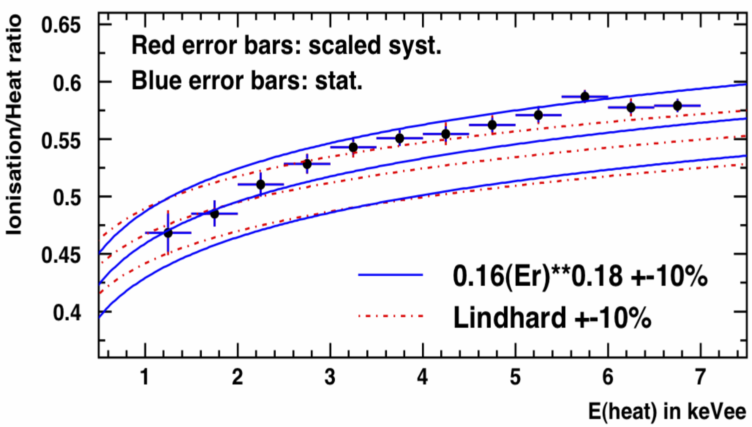
J Low Temp Phys (2014) 176: 182-187

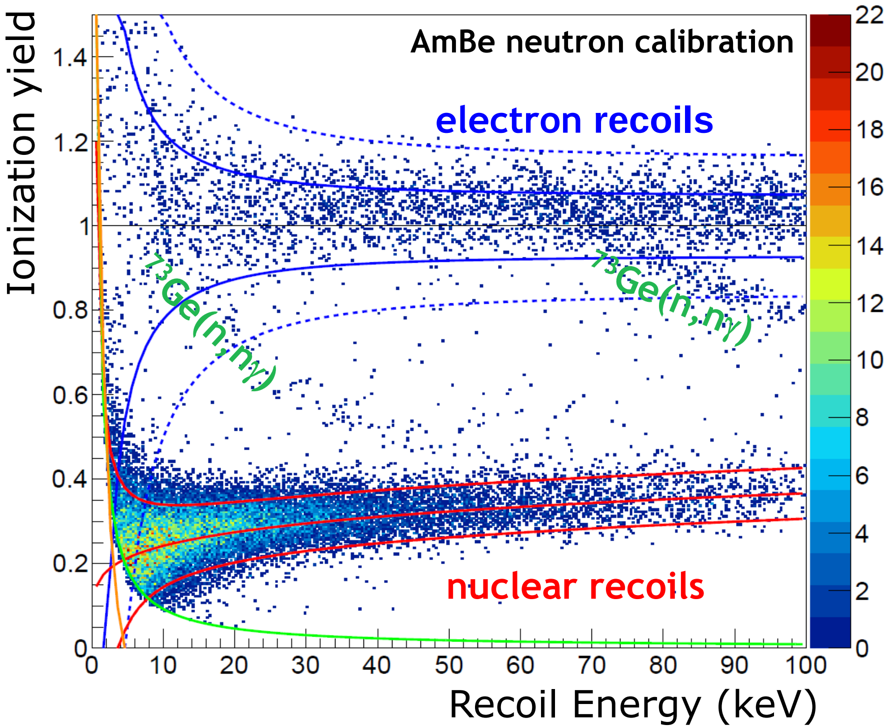
"Performance of the EDW-III experiment for direct dark matter searches"
arXiv:1706.01070 (subm. to JINST)

Nuclear recoil calibration + discrimination



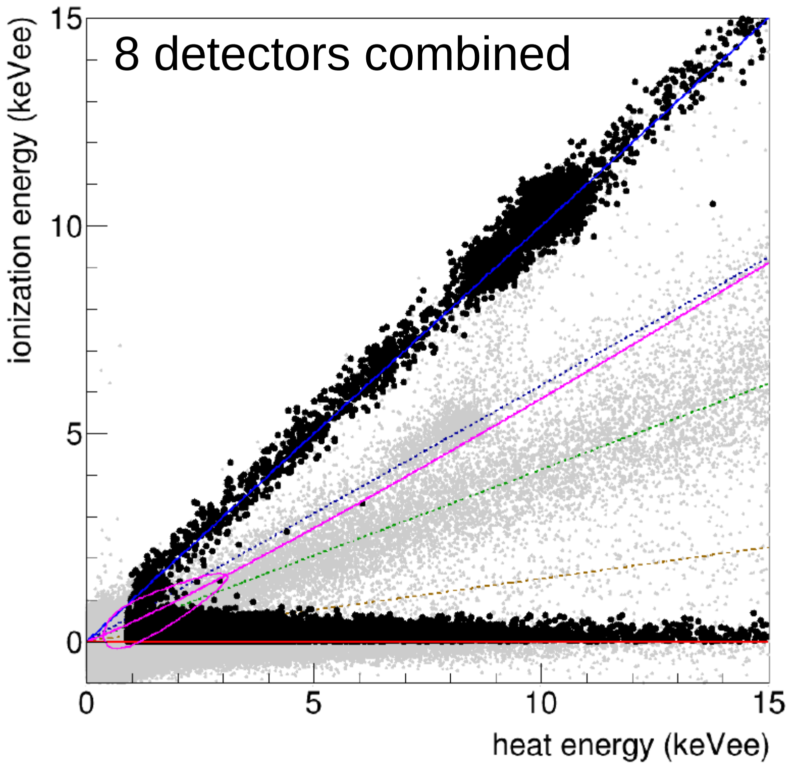
- Clear event-by-event separation down to 5 keV energy (nuclear recoils)
- Response to nuclear recoils calibrated down to the analysis threshold for low-mass WIMP searches *(1 keV$_{ee}$ heat = 2.5 keV nuclear rec.)*



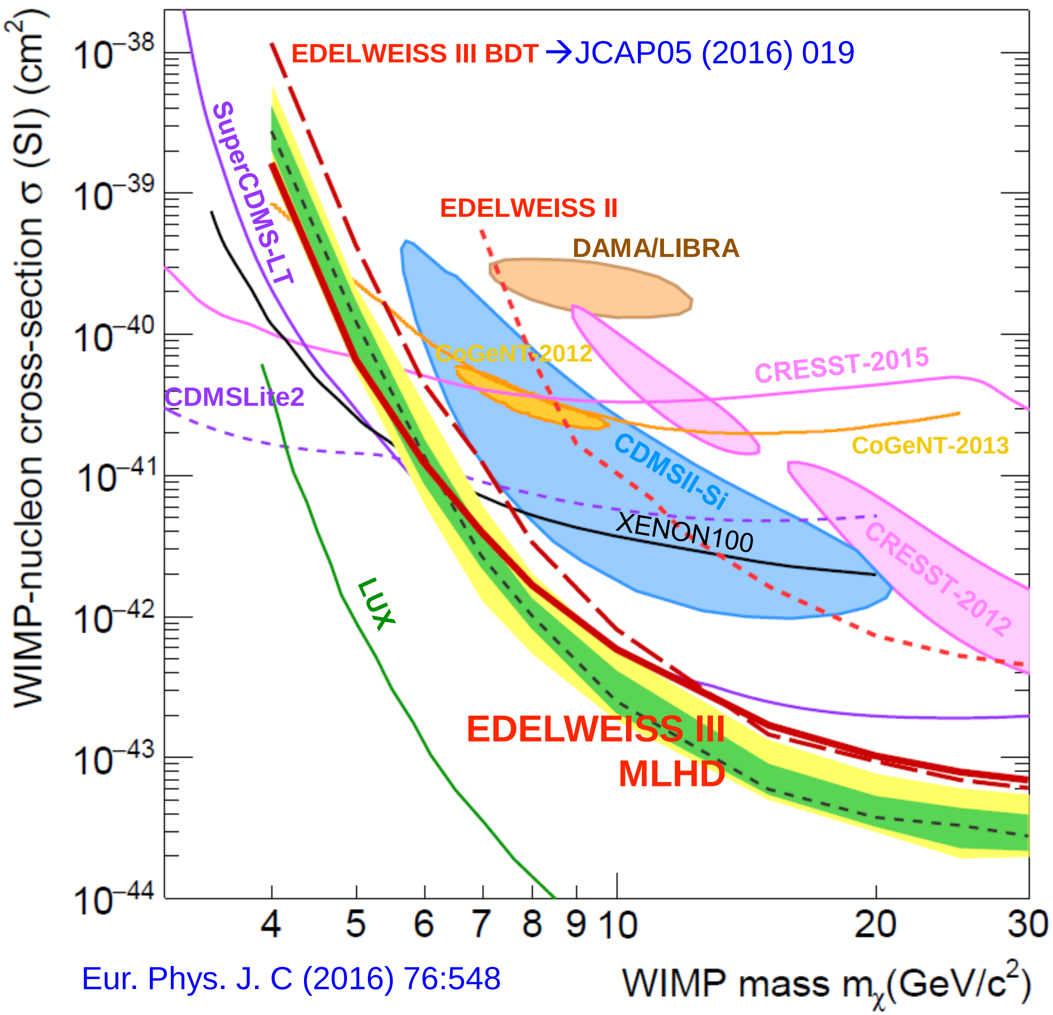


EDELWEISS-III 2014—2015 WIMP search

161 days of physics data with 8 FIDs: ~500 kg.d total



profile likelihood analysis



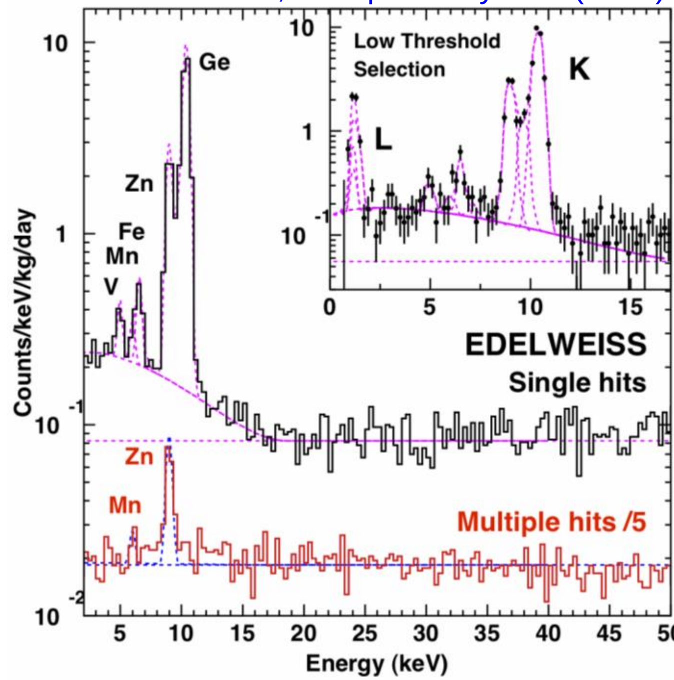
Eur. Phys. J. C (2016) 76:548

EDELWEISS-III 2014—2015 WIMP search

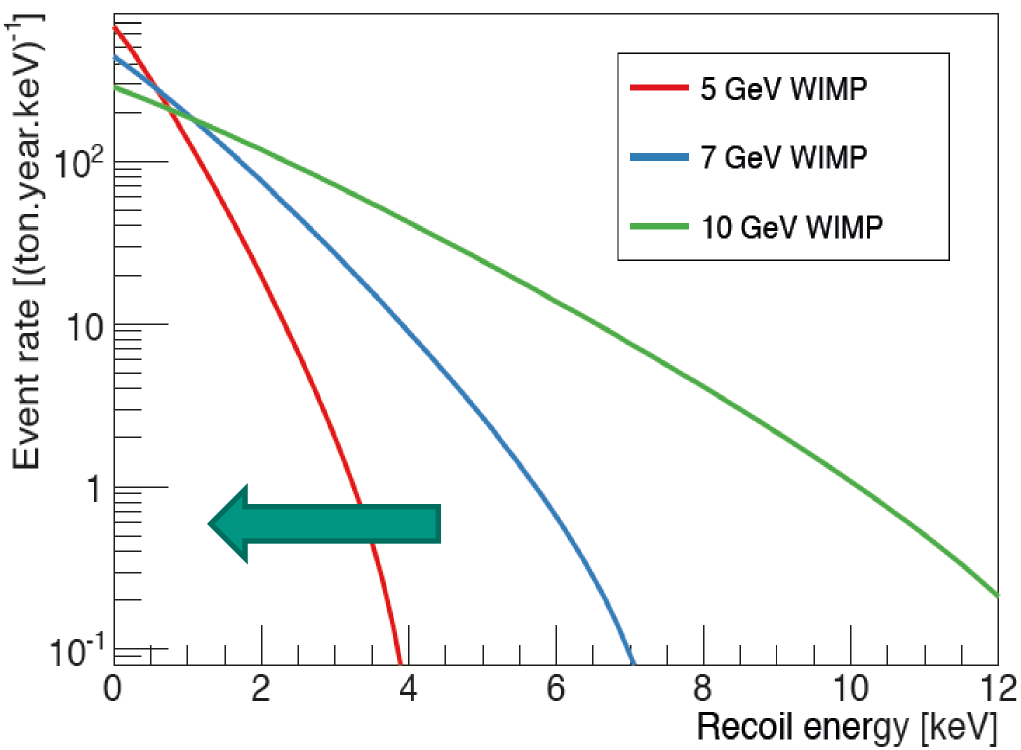
161 days of physics data with 24 FIDs: >3000 kg.d total

- first measurement of cosmogenic ^3H in Ge

arXiv:1607.04560, Astropart. Phys. 91 (2017) 51



Search for light WIMPs
→ lower threshold, better resolution



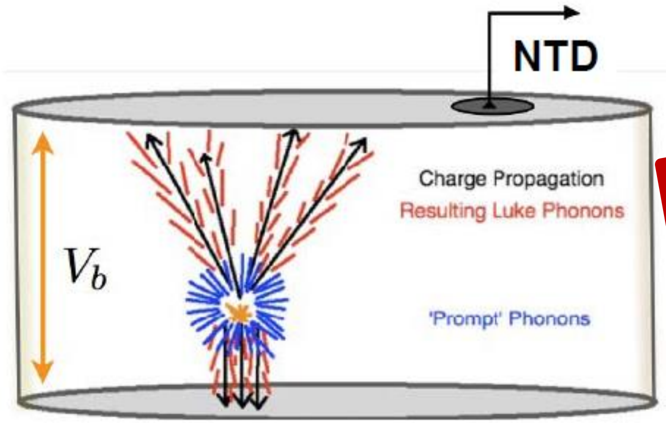
EDELWEISS R&D targets:

- Use High Voltage:
  Amplification of heat signal
  to reduce effective threshold
  8V → **100V**
- Optimize sensors:
  Improve energy resolutions
  on heat (thr) & ionization (ID)
  → **σ_{heat}=100eV, σ_{ion}=100eV**
- Reduce Heat-only events
  reduction by 100

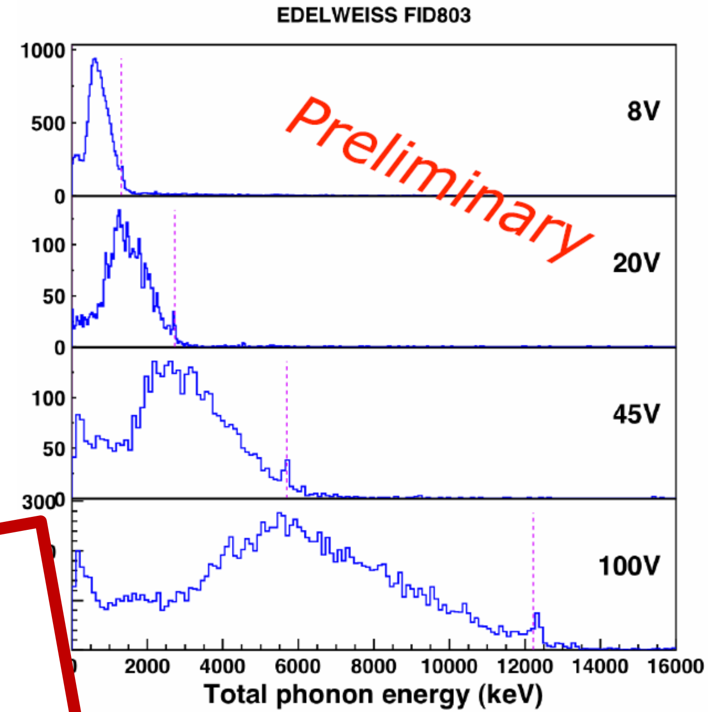
Applying high voltage

Neganov-Luke:

$$E_t = E_r + \frac{1}{3\ eV} E_Q \Delta V$$



first measurements
in LSM with FID800
in NL-mode
^{133}Ba calib 356keV line



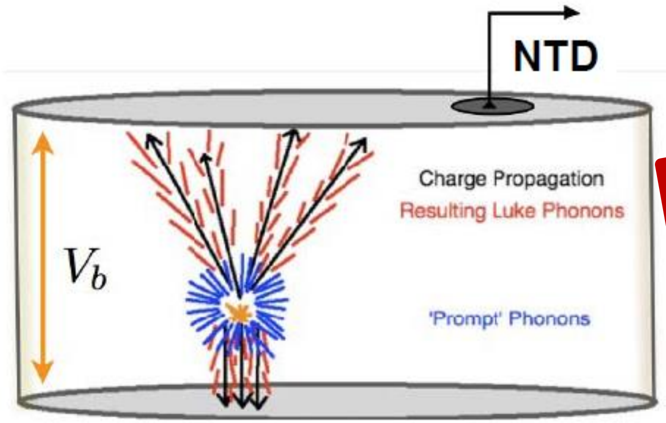
→ up to 100V working → NL boost 35
→ sensitivity to low mass WIMPs (~1GeV/c^2)

→ BUT: no electron/gamma suppression

Applying high voltage

Neganov-Luke:

$$E_t = E_r + \frac{1}{3\,eV} E_Q \Delta V$$



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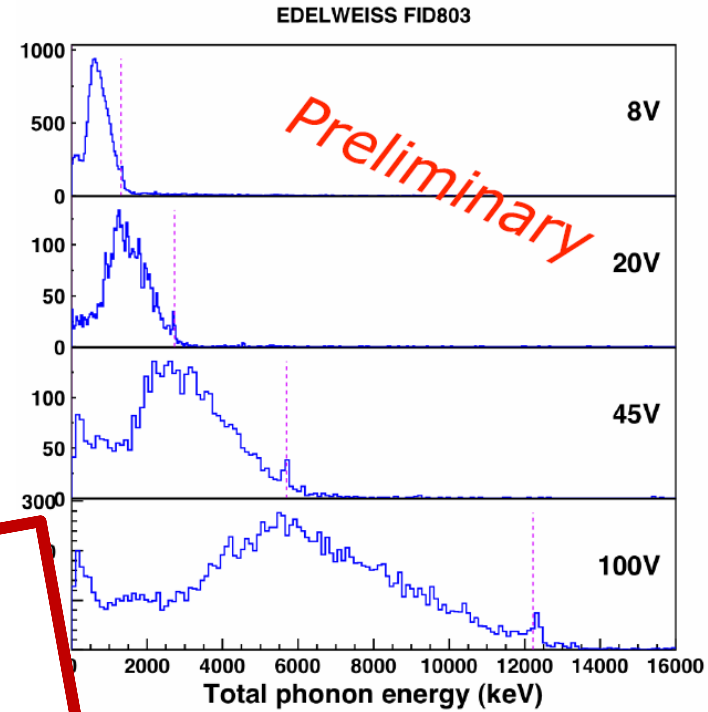
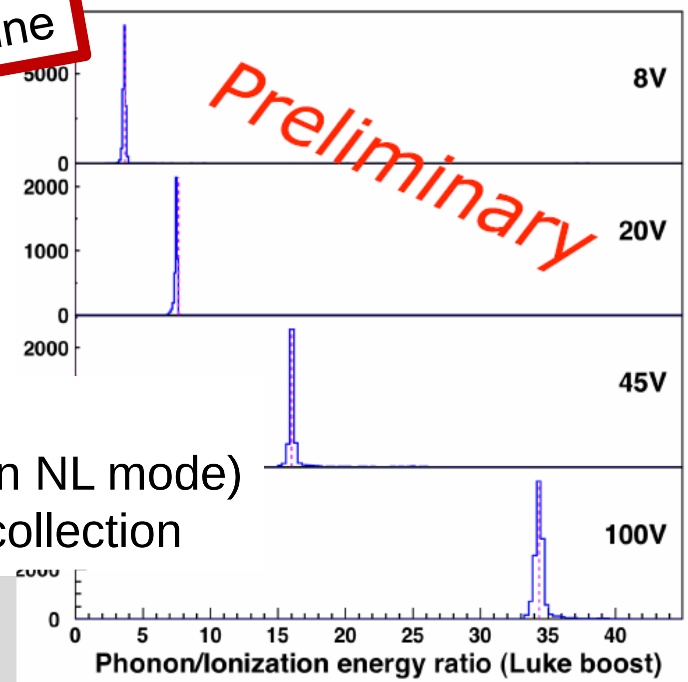
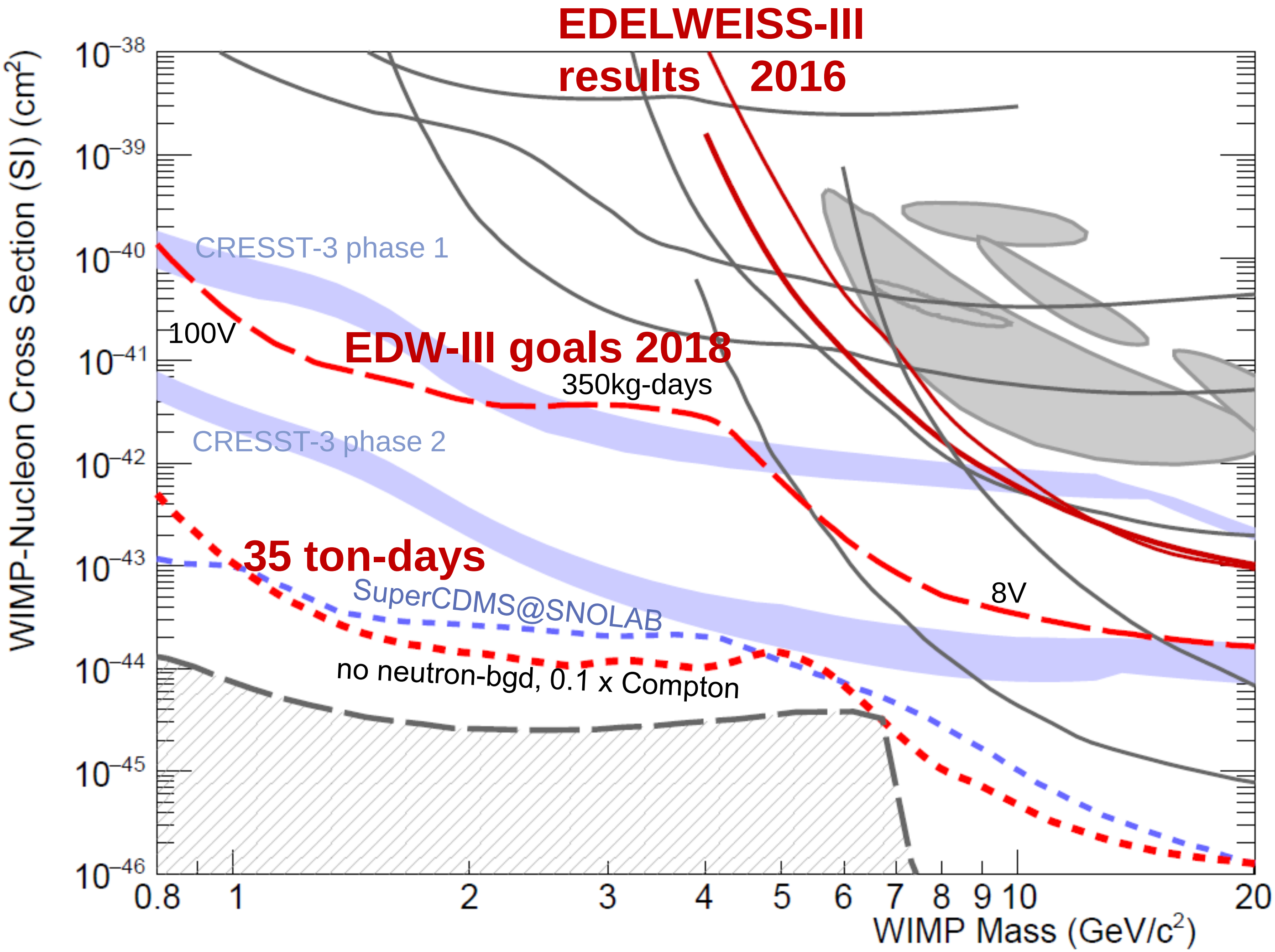




→ up to 100V working → NL boost 35
→ sensitivity to low mass WIMPs (~1GeV/c^2)

→ BUT: no electron/gamma suppression
→ BUT: both ionization and phonon signals (even in NL mode)
  → continuous + detailed diagnostics of charge collection

EDELWEISS-III 2018



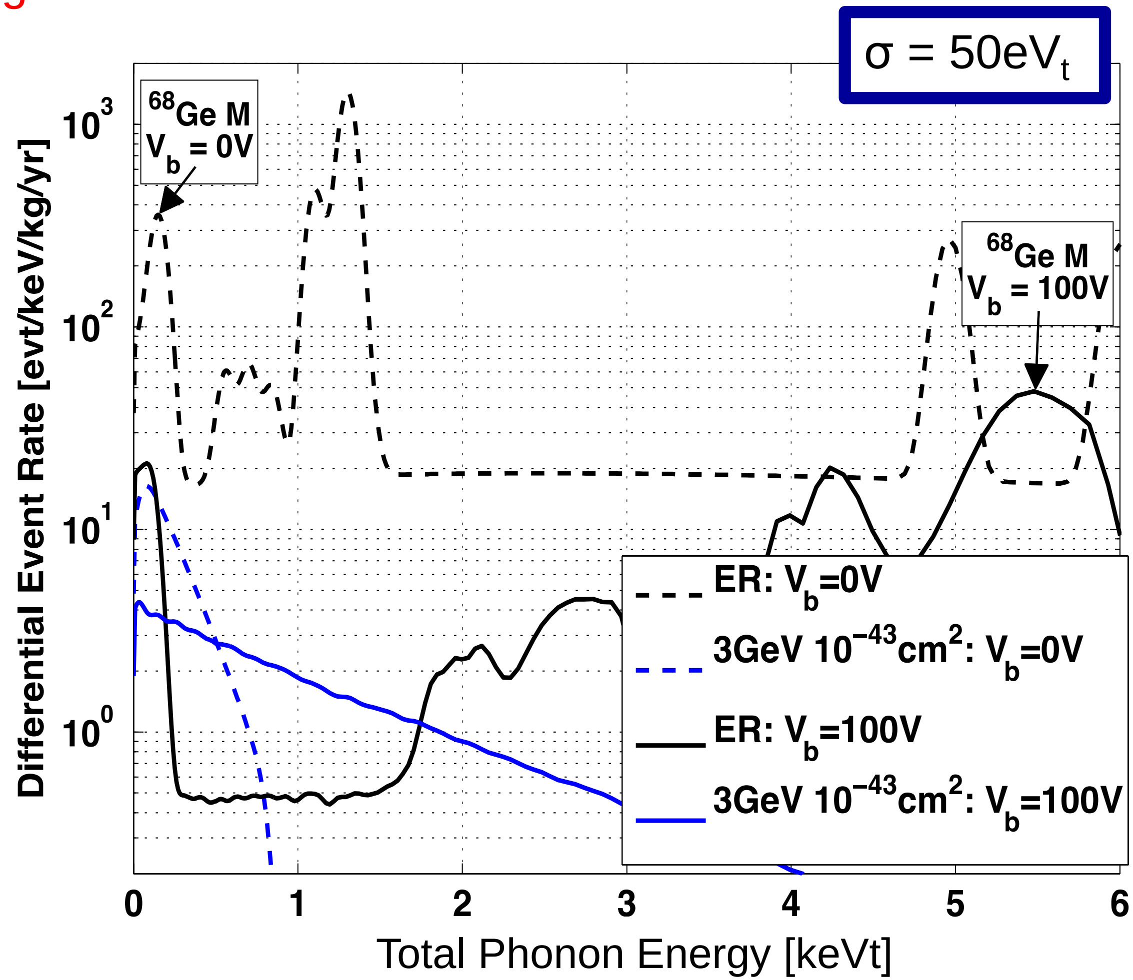
CNRS/IN2P3
CNRS/IN2P3
CNRS/INP
CNRS
CEA/IRFU
CEA/IRAMIS
IKP EKP IPE
JINR DUBNA
Univ. OXFORD
Univ. SHEFFIELD

CDMS with large NL amplification g_L

Quenching factor

$$E_{tot} = E_r \left(1 + \frac{Y(E_r)}{e_g} eV_b \right)$$

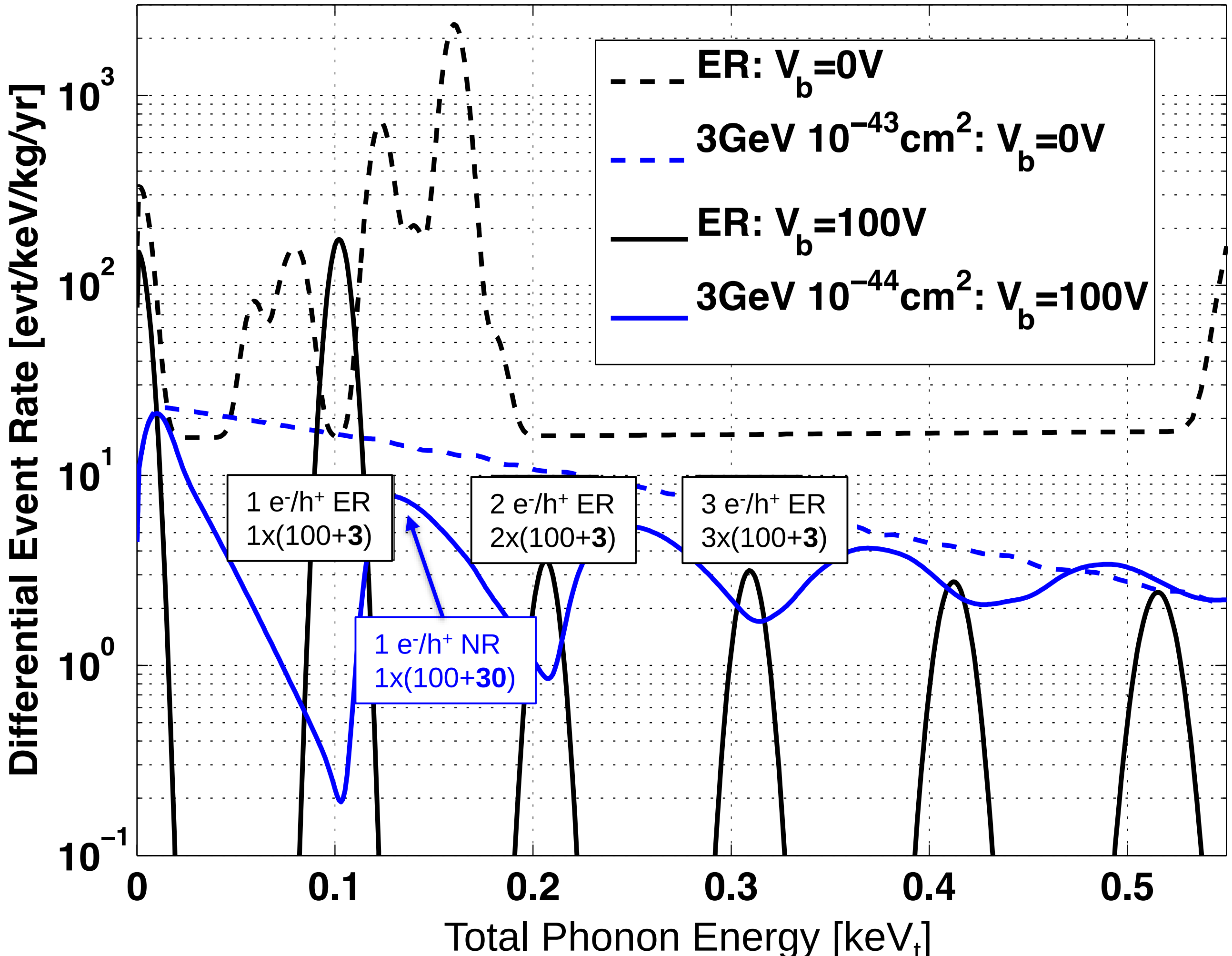
Since Y(ER) > Y(NR)
ER have larger g_L



P. Cushman, IDM 2016, Sheffield

CDMS towards single e- detection

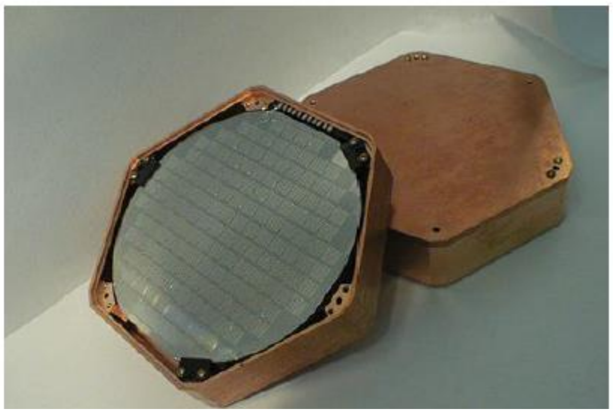
σ = 5eV$_t$
Single e$^-$/h$^+$ sensitivity
ER/NR discrimination

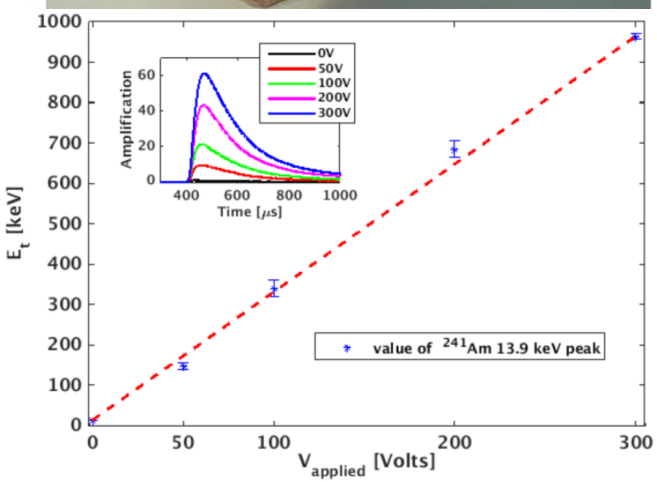


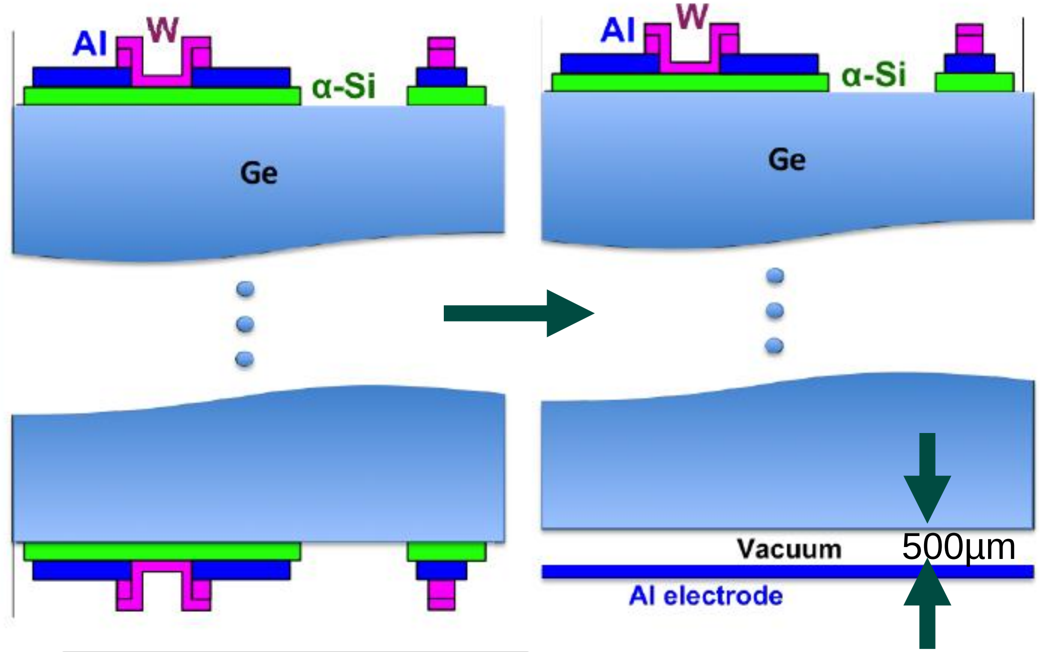
P. Cushman, IDM 2016, Sheffield

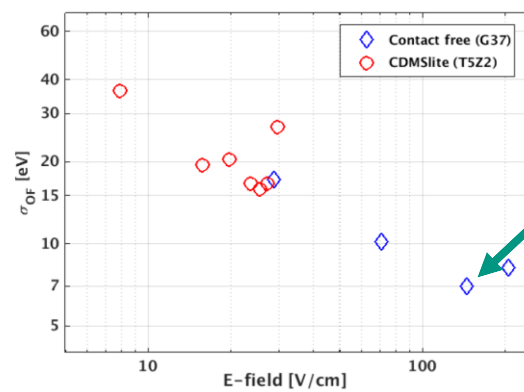
CDMS towards single e- detection

iZIP detectector with h=1cm
& vacuum electrode





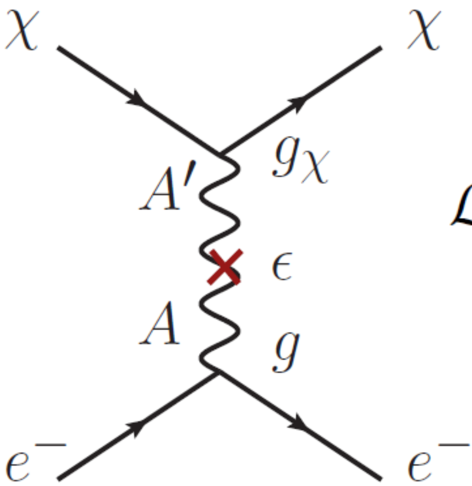




baseline resol. of σ=7eV
achieved with 250g Ge

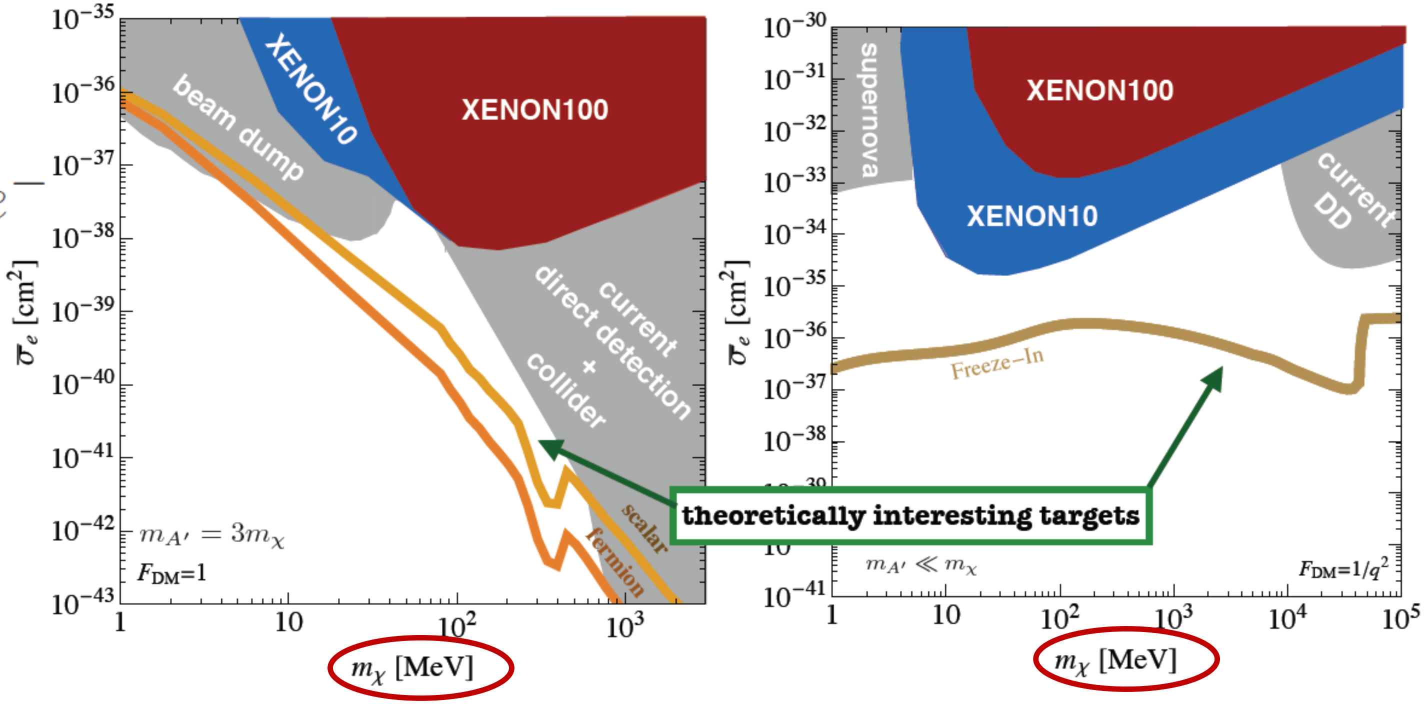
N. Mirabolfathi et al., 1510.00999

light DM with m_{DM}~MeV—GeV ?



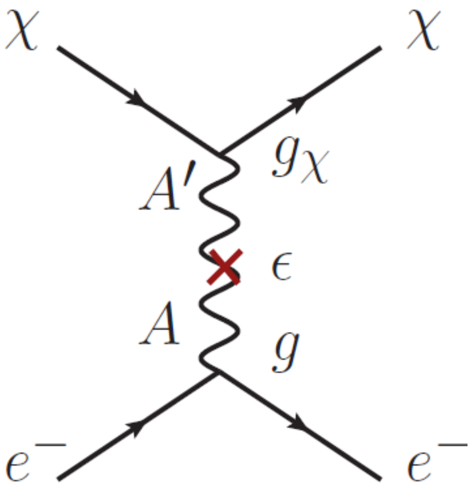
Dark Sector with Hidden Photon A´ and coupling ε

$$\mathcal{L} = F_{\mu\nu}^2 + F'^2_{\mu\nu} + m^2_{A'} A'^2_\mu + g_\chi J^\mu_\chi A'_\mu + g J^\mu_e (A_\mu + \epsilon A'_\mu)$$

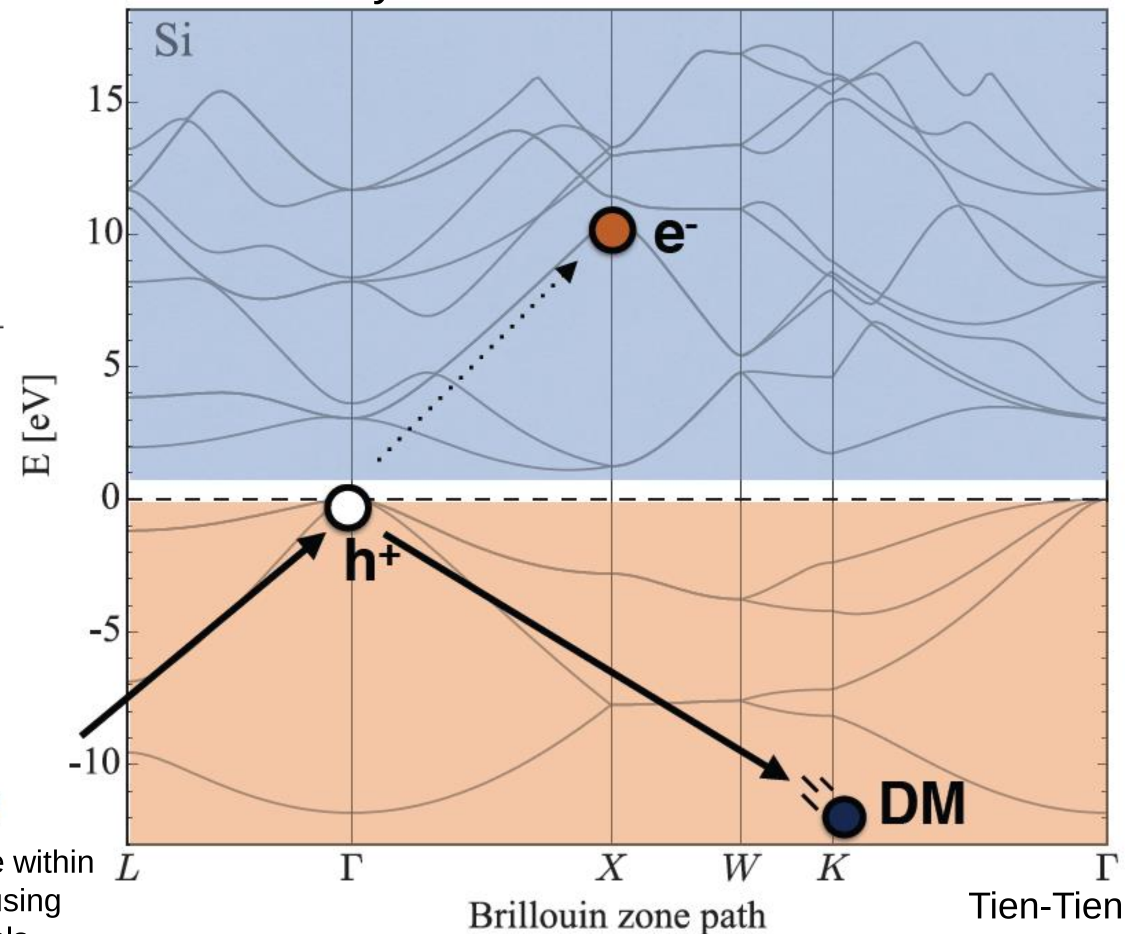


Essig et al., JHEP05(2016)046
Essig, Volansky, Yu 1703.00910

light DM with m_{DM}~MeV—GeV ?



very small energy thresh needed in semiconductors
→ sensitivity to MeV DM



band gap [eV]	
Ge	0.67
Si	1.1
GaAs	1.5
NaI	5.9
CsI	6.4

QUANTUM ESPRESSO

http://www.quantum-espresso.org/

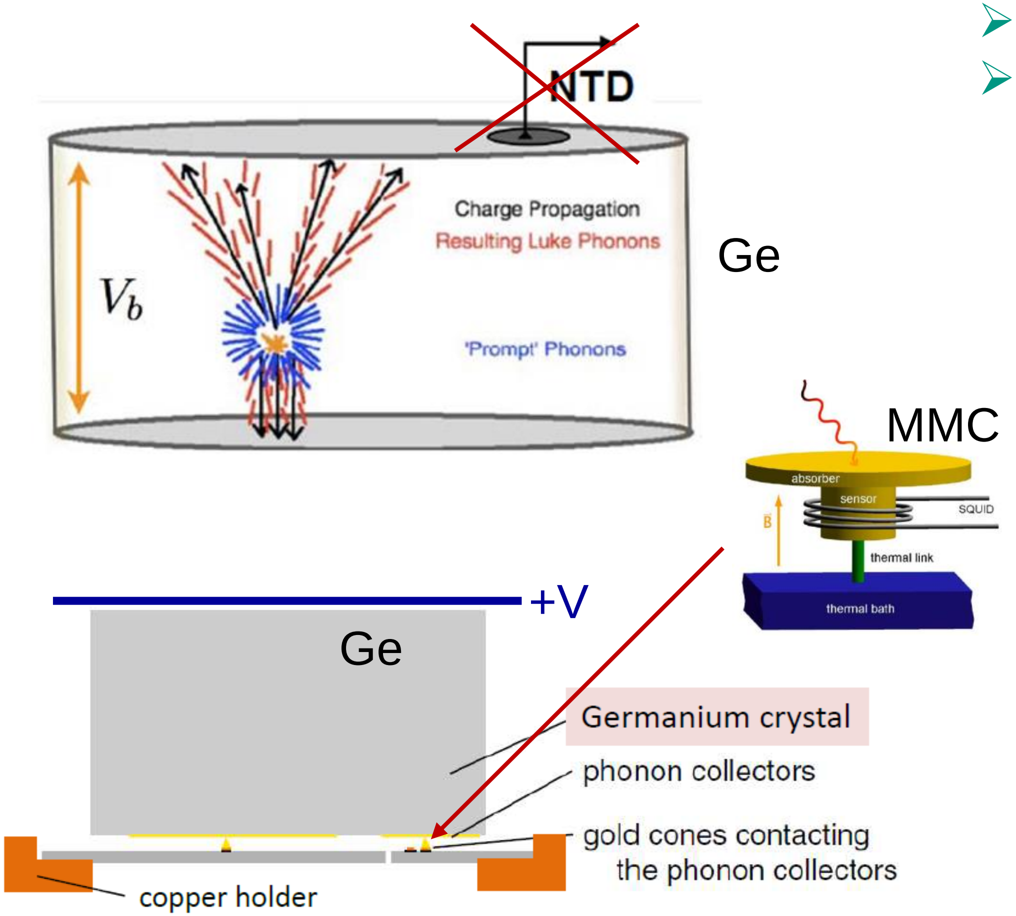
calculation of electronic structure within density functional theory (DFT) using plane waves and pseudopotentials

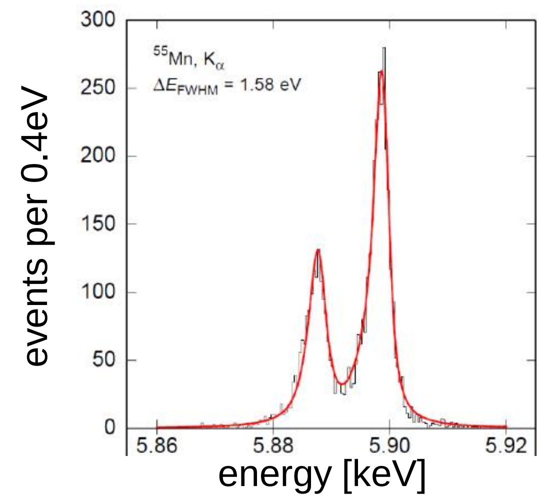
Tien-Tien Yu (CERN), seminar at KIT, May 2017

Search for light DM with GeMMC

combine EDW Ge technology (KIT) with high resol. MMC´s (U HD)

- DM-e⁻ scattering → e⁻/h⁺ pairs
- charge drift in high E-field @ 20mK
- amplification of phonon signal
- phonon readout with MMC

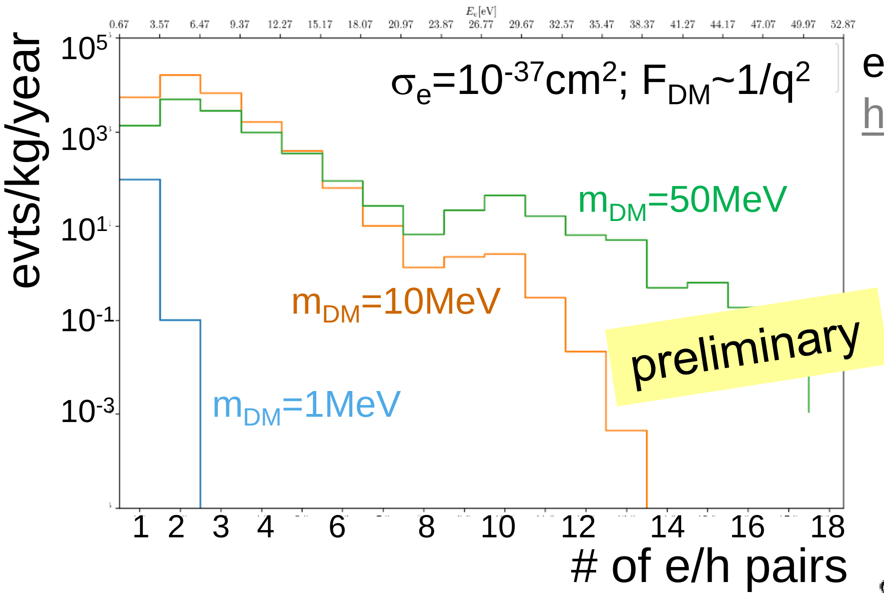




best achieved resolution with MMC (maXs20): ΔE_{FWHM}=1.6eV

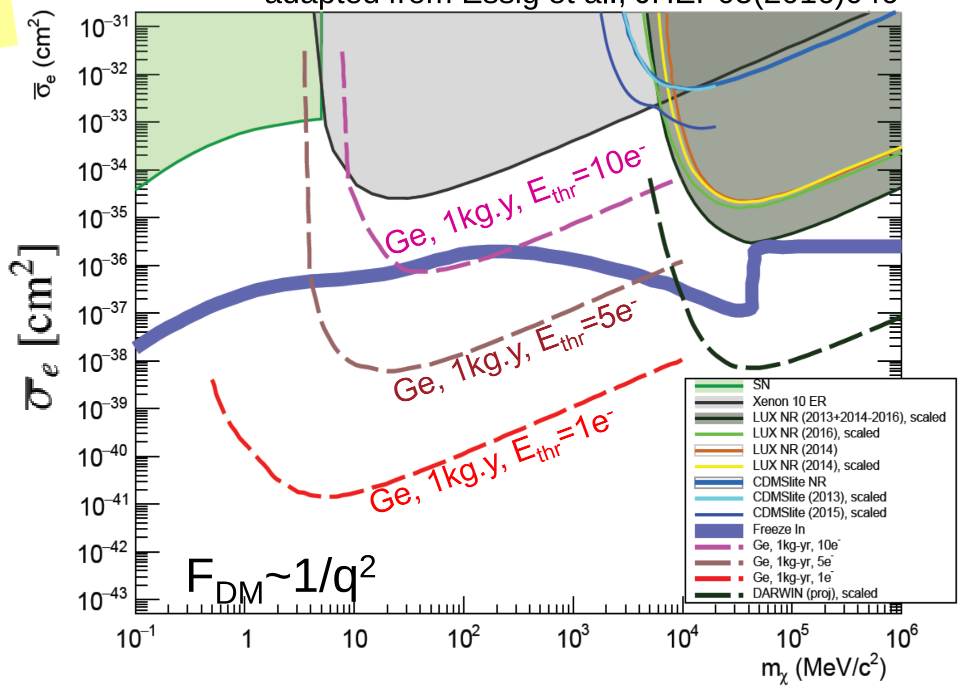
A. Fleischmann et al., *AIP Conference Proceedings*, **1185** (2009) 571

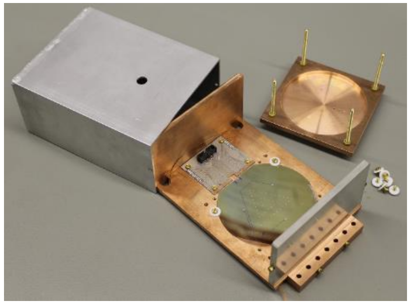
Search for light DM with GeMMC



electron signal calculated using QEdark:
http://ddldm.physics.sunysb.edu/ (T.-T. Yu et al)

adapted from Essig et al., JHEP05(2016)046





first tests in July/Aug

Conclusions

low thresh crystal detectors complementary to „standard WIMP“ searches by Xe, Ar
low mass WIMP search: expect major results within next 2—24 months
(CRESST, CDMS-lite, EDW-NL, DAMIC)

stay open-minded about nature of DM:
-> asymmetric DM, light DM, dark sector

approaches towards „single electron detection“
low thresh crystal detectors complementary to beam stop expts
many new ideas (→ Cosmic Visions workshop etc)

tests at surface/shallow sites, but „final“ expts in underground lab
~table top → midsize (few m^3) setup with shielding

not covered here: Ge diodes (GERDA, Majorana, CDEX, TEXONO,…)