

Cryogenic detectors for dark matter search and neutrinoless double beta decay

Thanks to:

Oliviero Cremonesi

Xavier Defay

Klaus Eitel

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Andrea Giuliani

Federica Petricca

Stefano Pirro

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Raimund Strauss

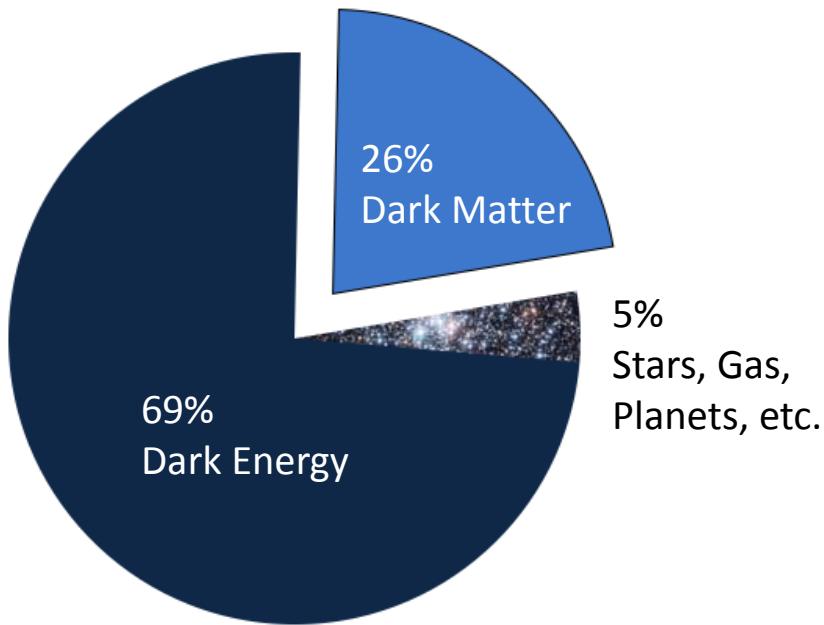
Mike Willers

14th Vienna Conference on Instrumentation

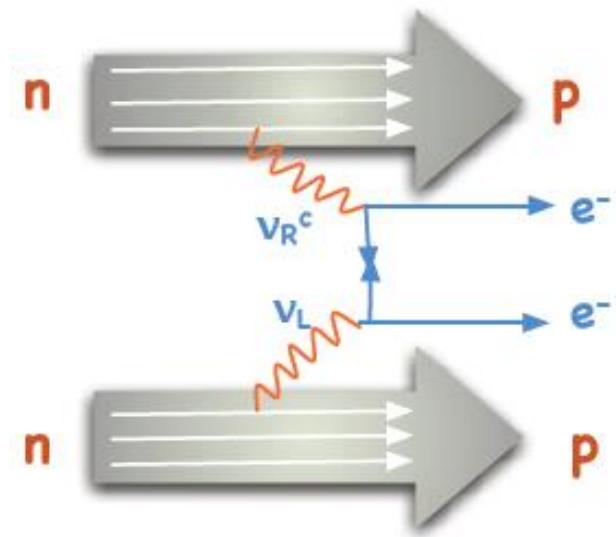
Stefan Schönert

TU München

The physics drivers



What is the nature of Dark Matter?

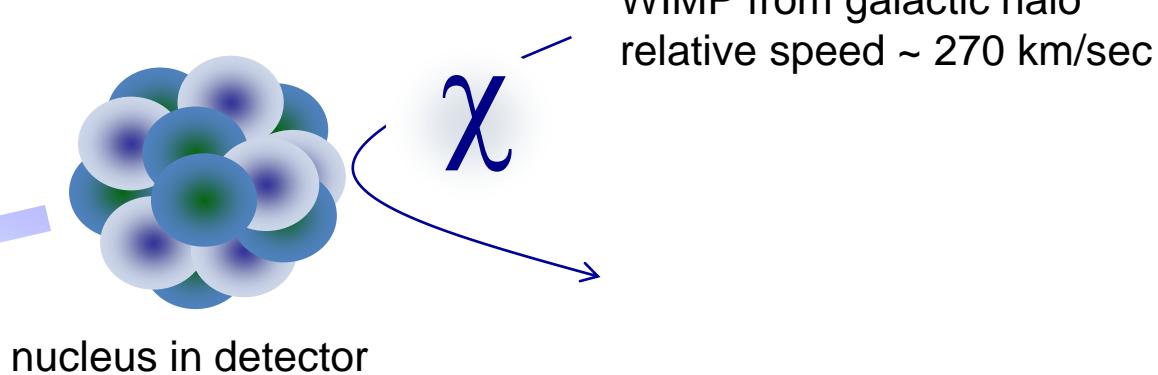


Are neutrinos their own anti-particles?

Why cryogenic detectors?

Direct Dark Matter Search:

- ⇒ Nuclear recoil generate primarily phonon signal
- ⇒ Low threshold
- ⇒ Large choice of target materials

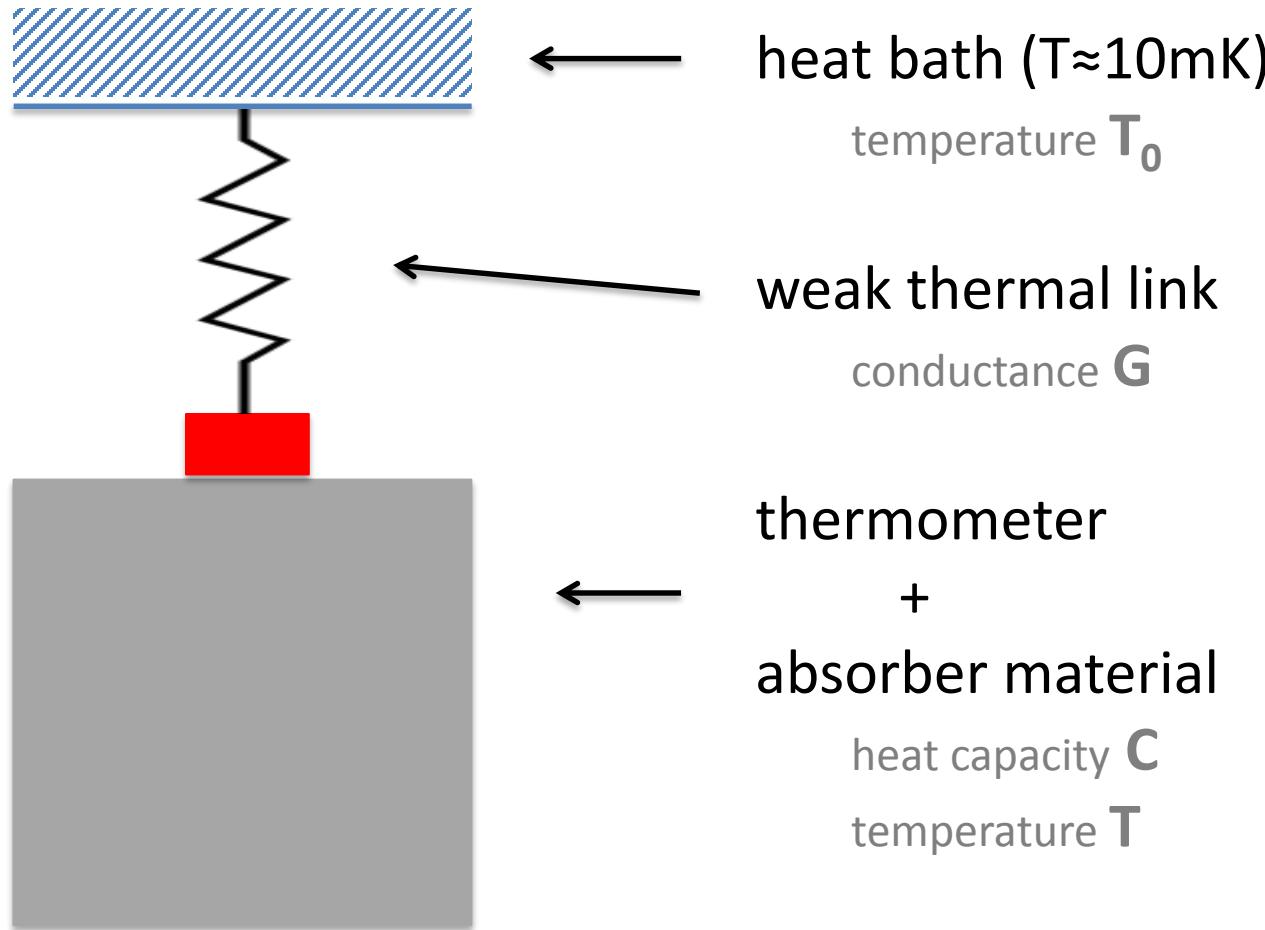


Neutrinoless double beta decay:

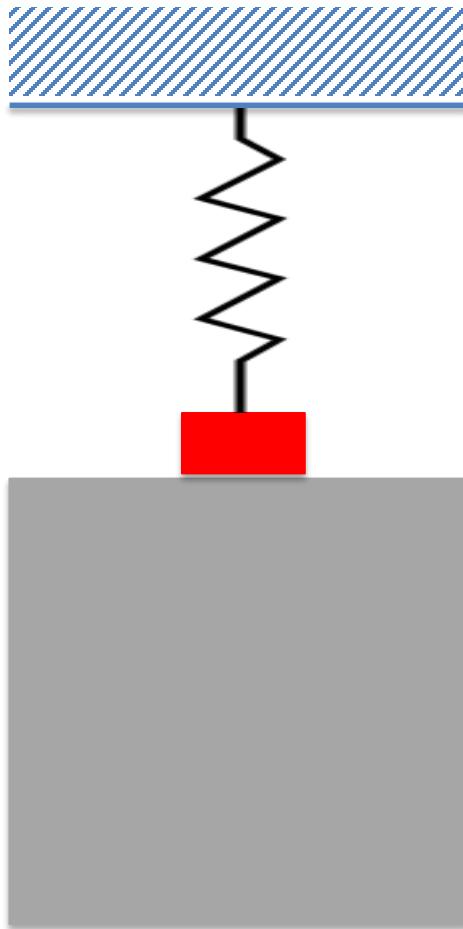
- ⇒ Excellent energy resolution
- ⇒ Background suppression
- ⇒ Choice of different isotopes and crystals



Cryogenic Detector



Cryogenic Detector



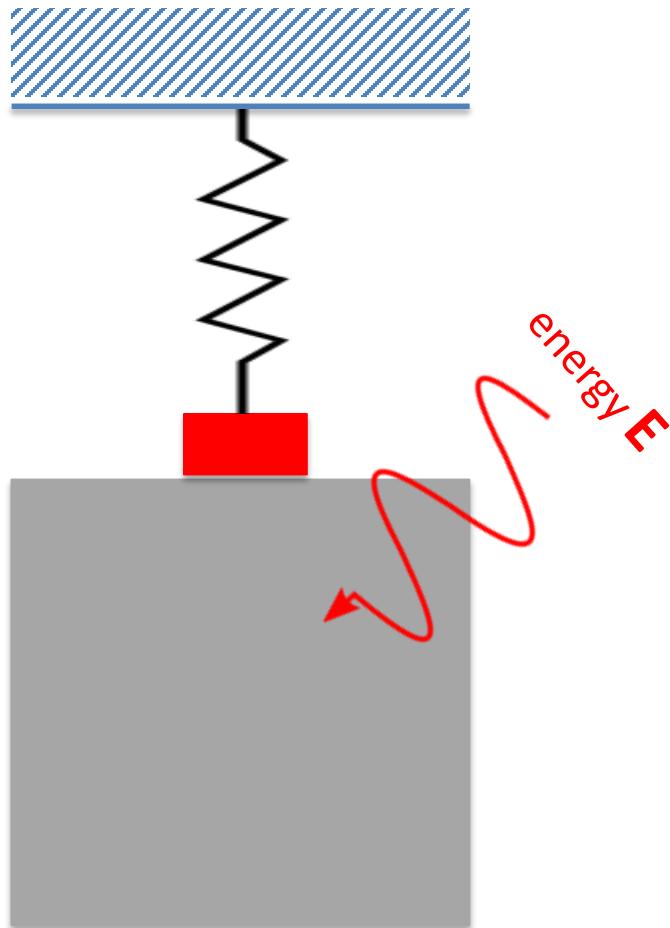
Irreducible thermal fluctuations:

$$\langle \Delta E^2 \rangle = k_B T^2 C$$

Need:

- Low temperature
- Low heat capacity

Cryogenic Detector



Irreducible thermal fluctuations:

$$\langle \Delta E^2 \rangle = k_B T^2 C$$

Need:

- Low temperature
- Low heat capacity

Operation at mK:

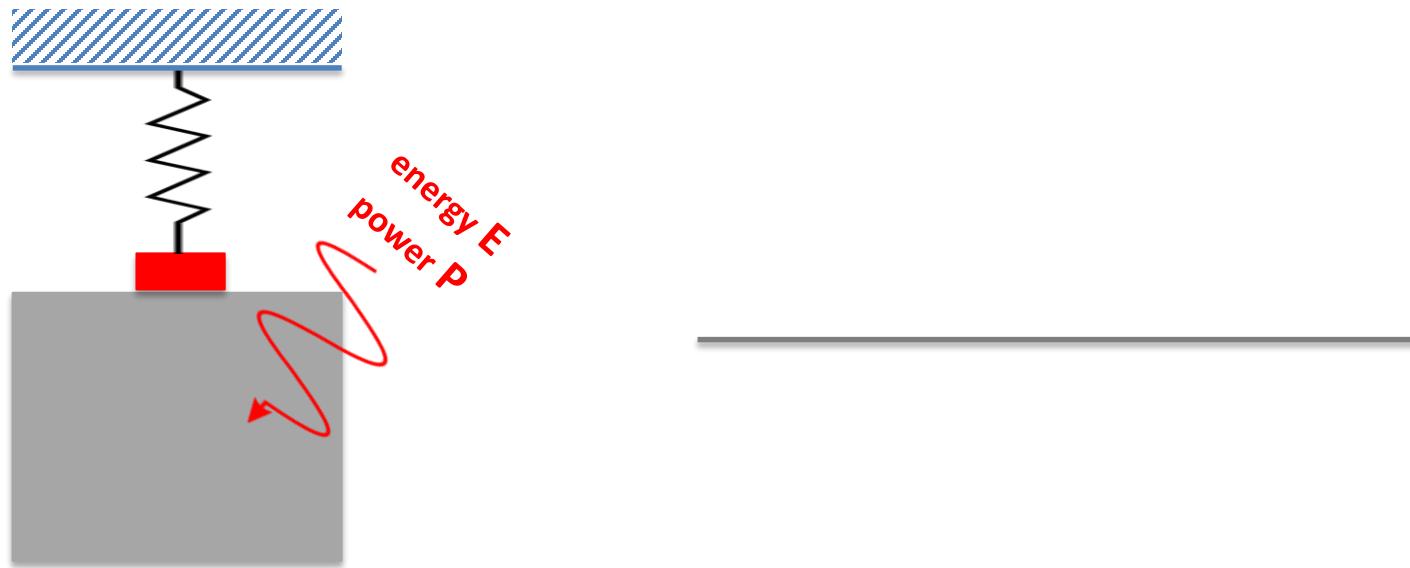
Temperature increase from particles interactions can be measured!

$$\Delta T \propto \frac{E}{C}$$

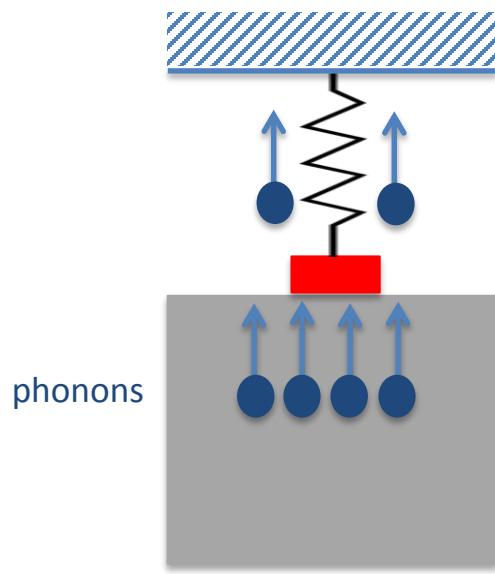
$$C(T) \propto T^3$$

$$(1 \text{ keV} \rightarrow \mu\text{K})$$

Calorimetric Mode

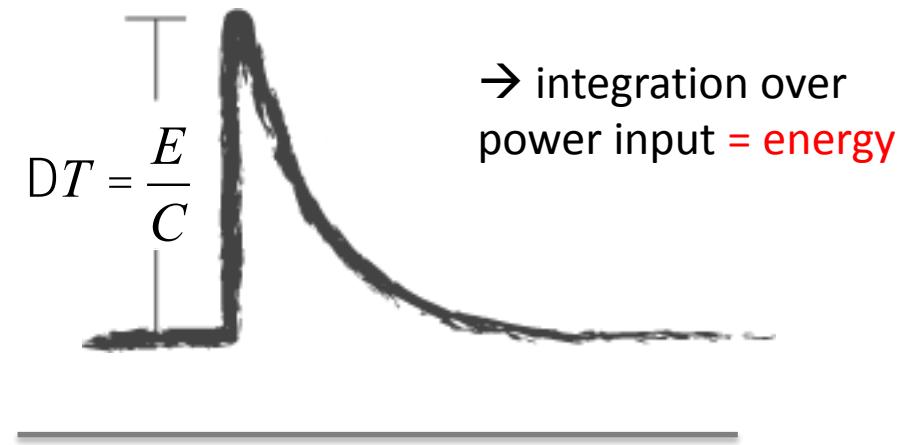


Calorimetric Mode

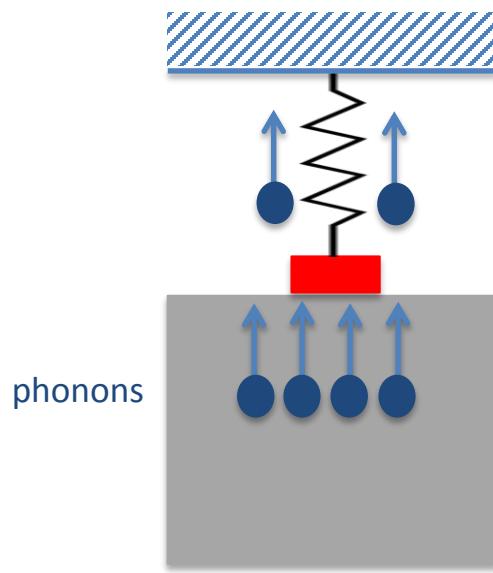


phonons

“phonons flow into the thermometer more **quickly** than out of it !”

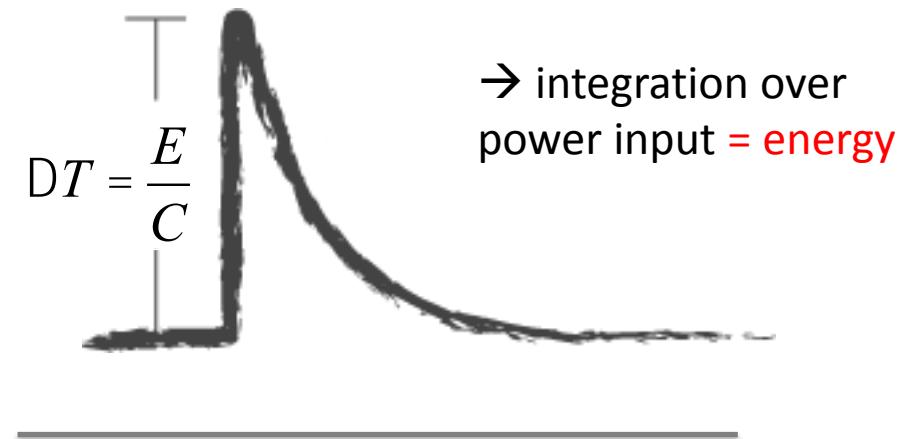


Calorimetric Mode



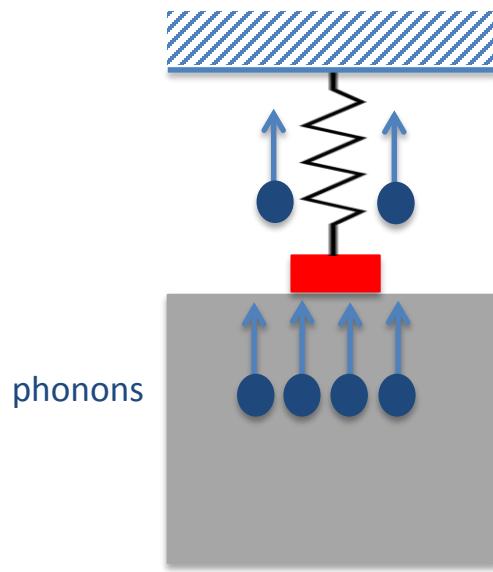
phonons

“phonons flow into the thermometer more **quickly** than out of it !”



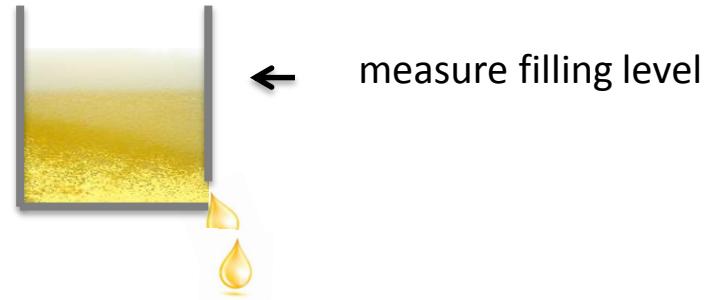
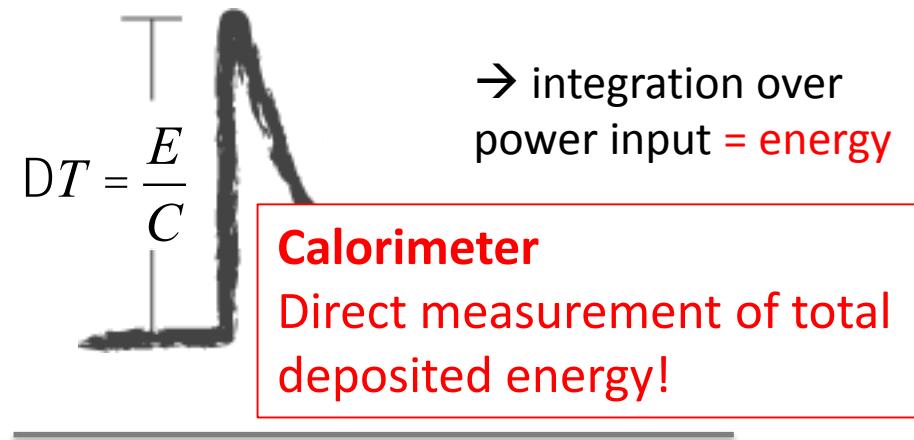
← measure filling level

Calorimetric Mode



phonons

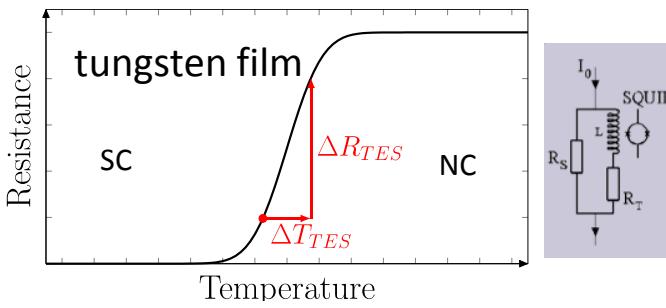
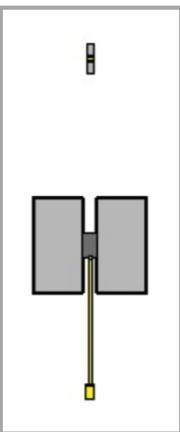
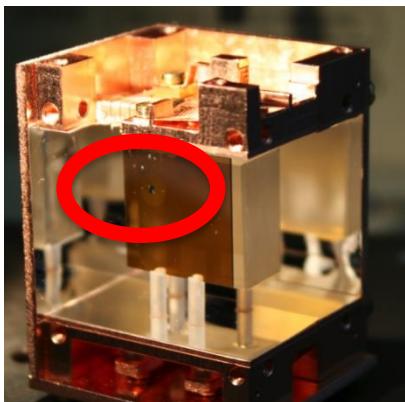
“phonons flow into the thermometer more quickly than out of it !”



← measure filling level

Thermal sensors for cryogenic detectors

Transition Edge Thermistors (TES)



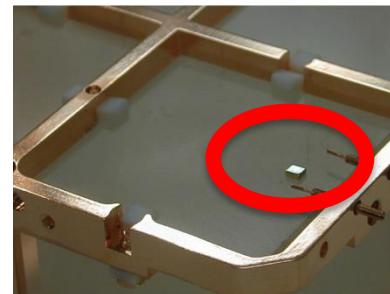
$$\eta = \left| \frac{d \log R(T)}{dT} \right| \quad \eta_{TES} \approx 100$$

Op. temp range: narrow

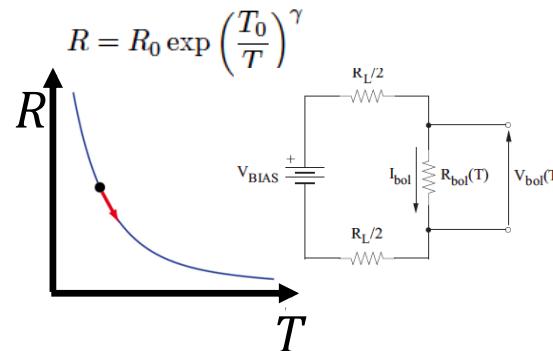
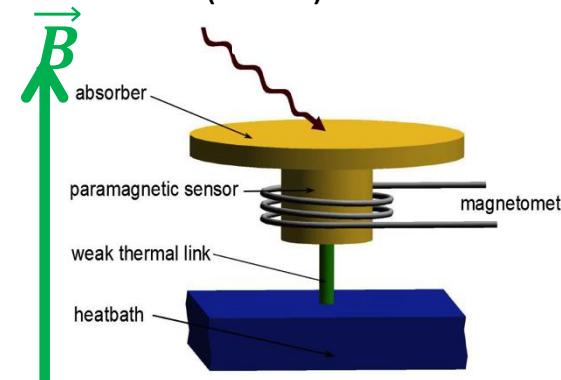
Response time: μ sec

Read out: SQUID

Neutron Transmutation Doped (NTD) germanium thermistor



Magnetic Micro-Calorimeters (MMC)

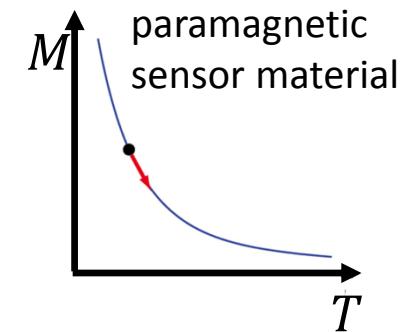


$$\eta_{NTD} \approx 10$$

wide

msec

Convent. voltage amplification



$$\frac{d(\log M)}{dT} = \alpha_{MMC} = 1 \quad (\text{but no Johnson noise!})$$

wide

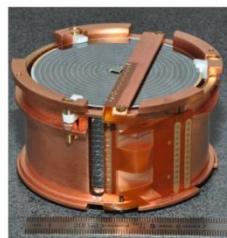
100 nec

SQUID

Signal channels and particle identification

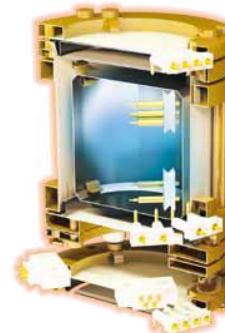
DM:

- CDMS
- Edelweiss



Phonons

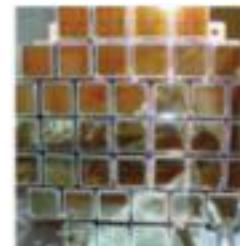
Interaction:
- Nucl. Recoil
- EM interaction



Charge

DBD:

- GERDA
- Majorana



Light
(Scintillation,
Cherenkov,
Flourescence)

DM:

- CRESST
- Rosebud

DBD:

- Lucifer
- Lumineu
- Amore
- CUPID

(Liquefied) noble gas detectors:
DM: Xenon, LUX, Darkside
DBD: EXO200, NEXT

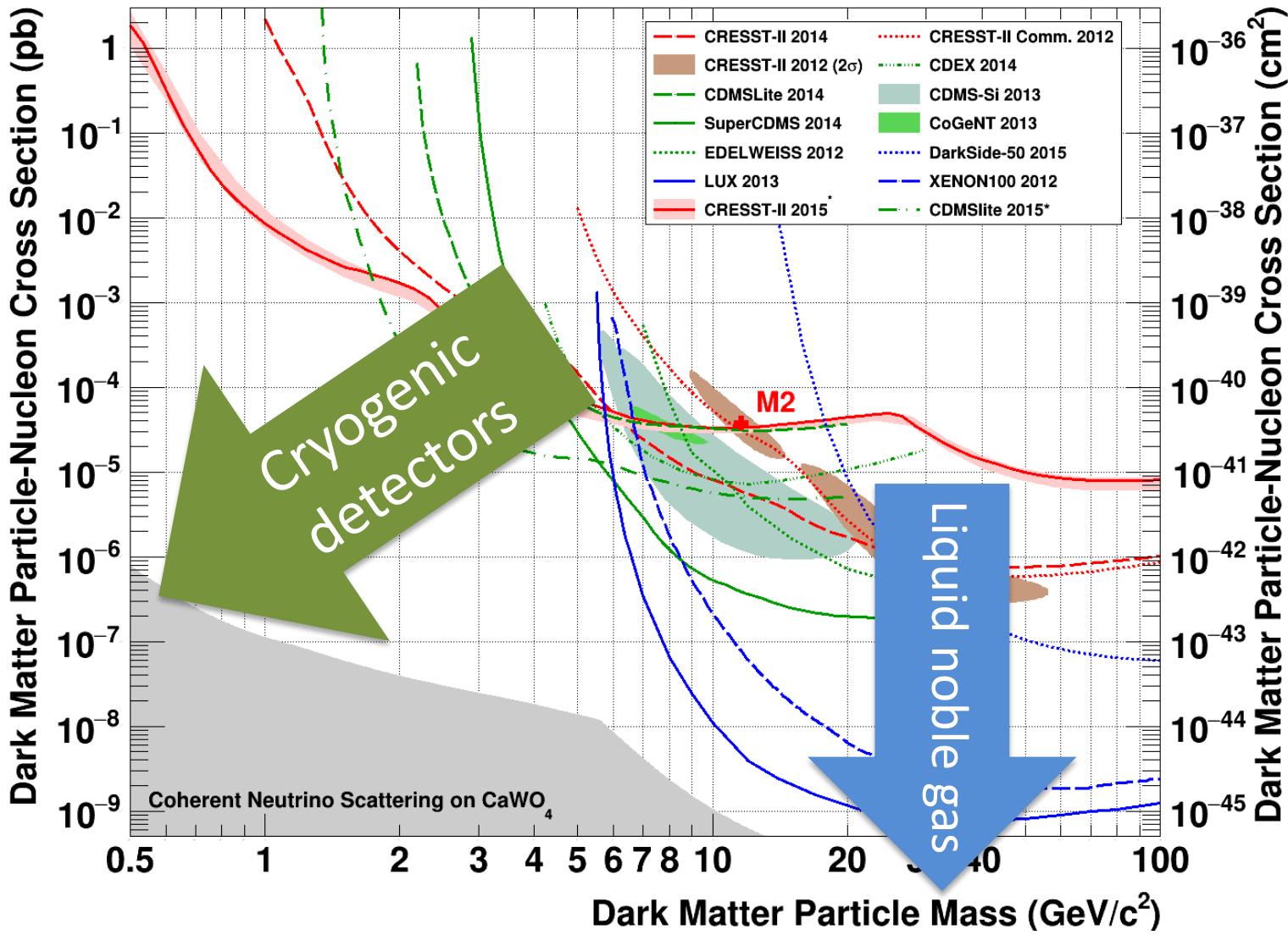
DM:

- DEAP
- XMASS

DBD:

- SNO+

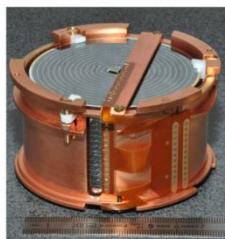
Direct Dark Matter Search experiments



Signal channels and particle identification

DM:

- CDMS
- Edelweiss

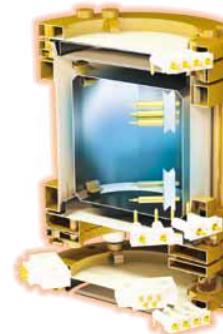


Phonons



Interaction:

- Nucl. Recoil
- EM interaction



Charge



Light
(Scintillation,
Cherenkov,
Flourescence)

DM:

- CRESST
- Rosebud

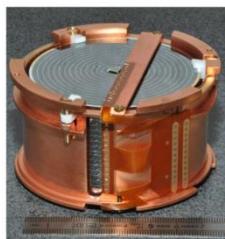
DBD:

- Lucifer
- Lumineu
- Amore
- CUPID

Signal channels and particle identification

DM:

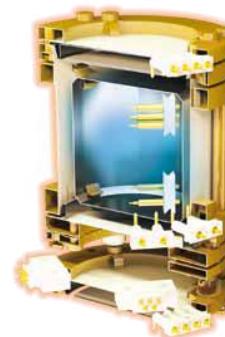
- CDMS
- Edelweiss



Phonons

Interaction:
- Nucl. Recoil
- **EM interaction**

Charge



Light
(Scintillation,
Cherenkov,
Flourescence)

DM:

- CRESST
- Rosebud

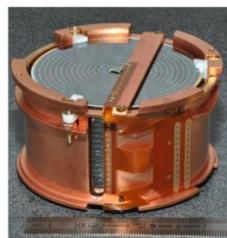
DBD:

- Lucifer
- Lumineu
- Amore
- CUPID

Signal channels and particle identification

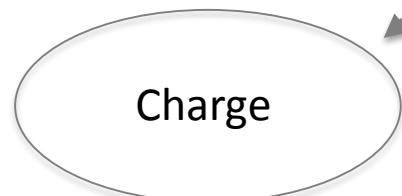
DM:

- CDMS
- Edelweiss



DBD:

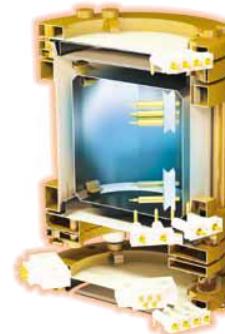
- GERDA
- Majorana



Phonons



Interaction:
- Nucl. Recoil
- EM interaction



DM:

- CRESST
- Rosebud

DBD:

- Lucifer
- Lumineu
- Amore
- CUPID

Light
(Scintillation,
Cherenkov,
Flourescence)

Particle identification
by comparing
• phonon/light
• phonon/charge
• charge/light
• pulse shape of
charge or light only

DM: Xenon, LUX, Darkside
DBD: EXO200, NEXT

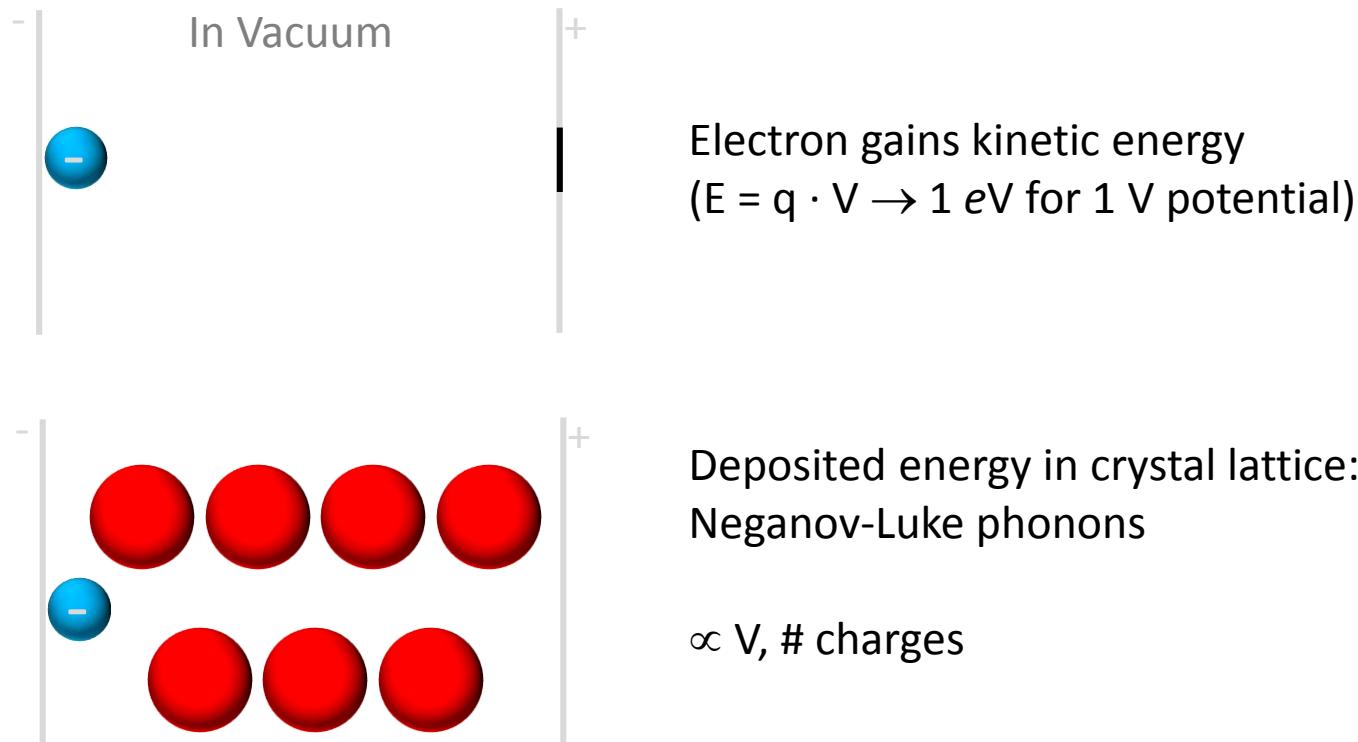
DM:

- DEAP
- XMASS

DBD:

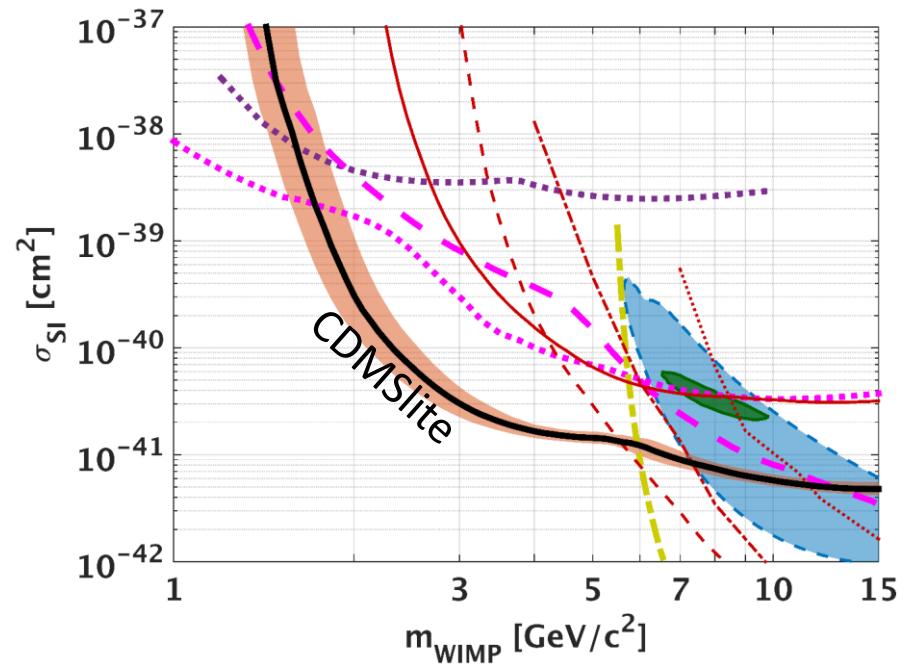
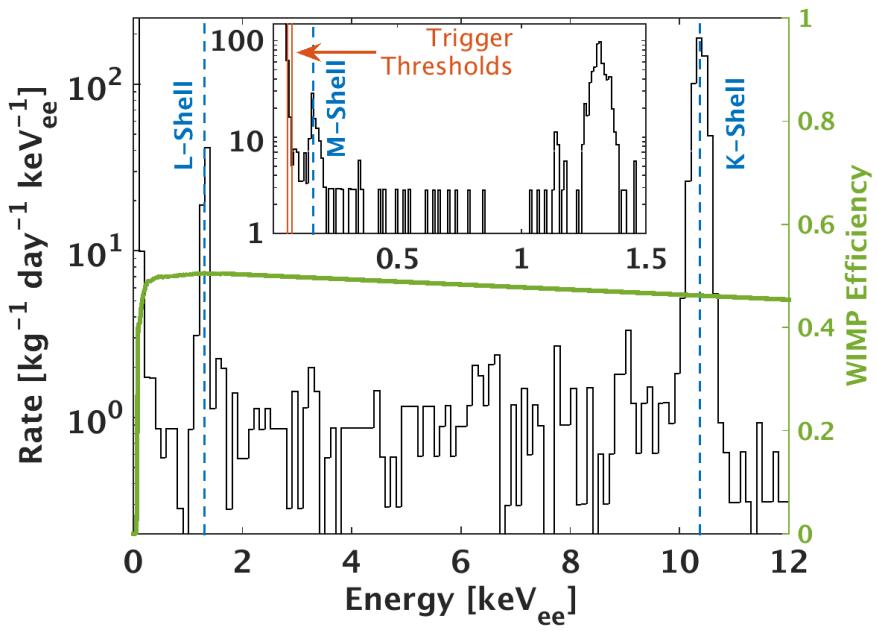
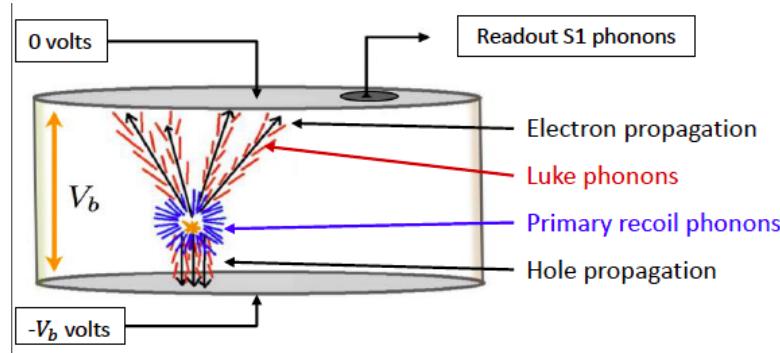
- SNO+

Neganov-Trofimov-Luke (NTL) Effect



- NTL phonons mix charge and phonon signal → reduced discrimination
- Apply high voltage → large final phonon signal, measures charge!!
- EM interaction much more amplified than nuclear recoil
→ gain in threshold AND dilute background from EM interations

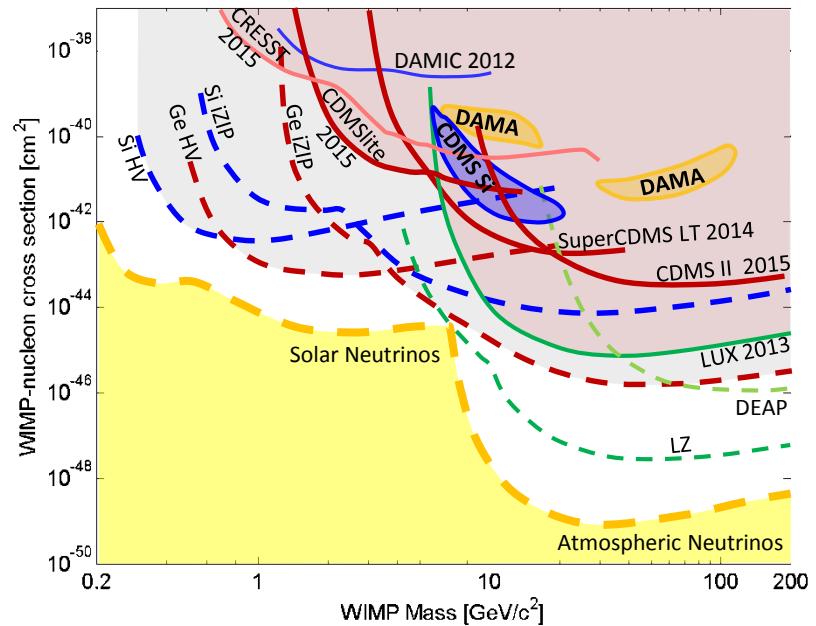
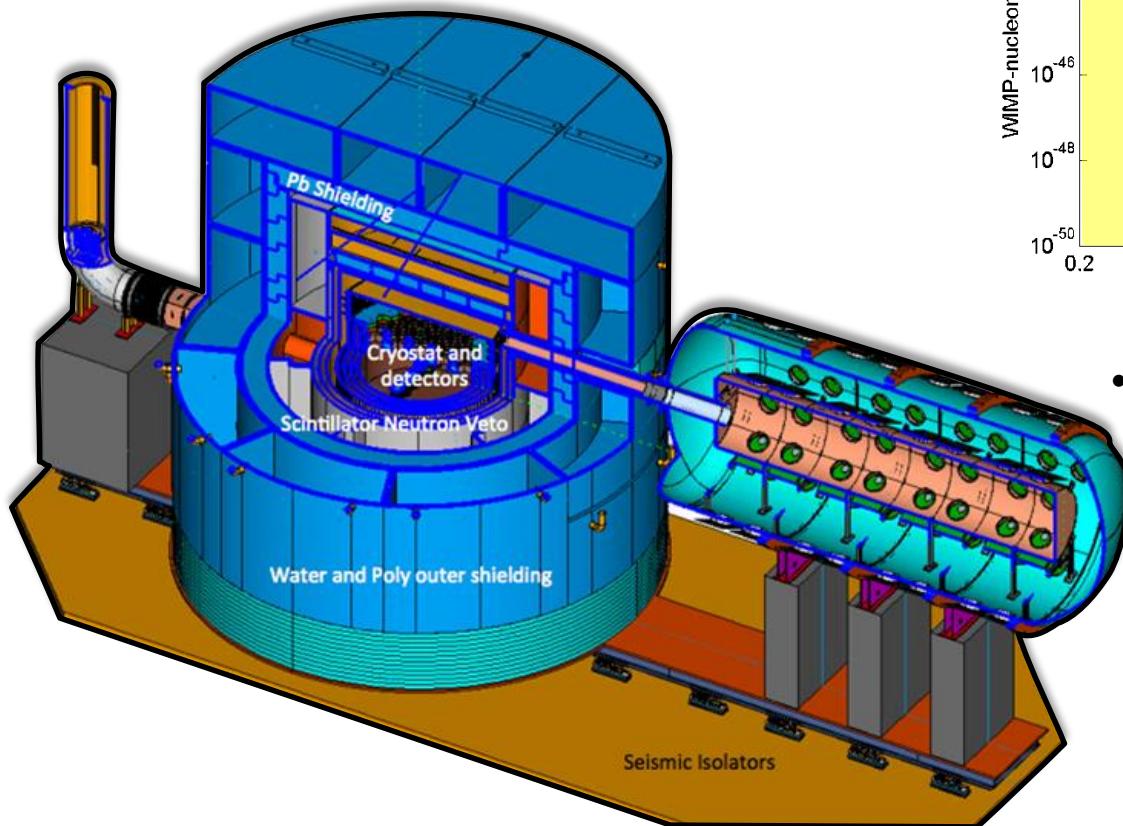
CDMSlite: low-mass DM search with NTL detector



From Pepin - TAUP 2015 & W. Rau – Munich 2015

SuperCDMS at SNOLAB

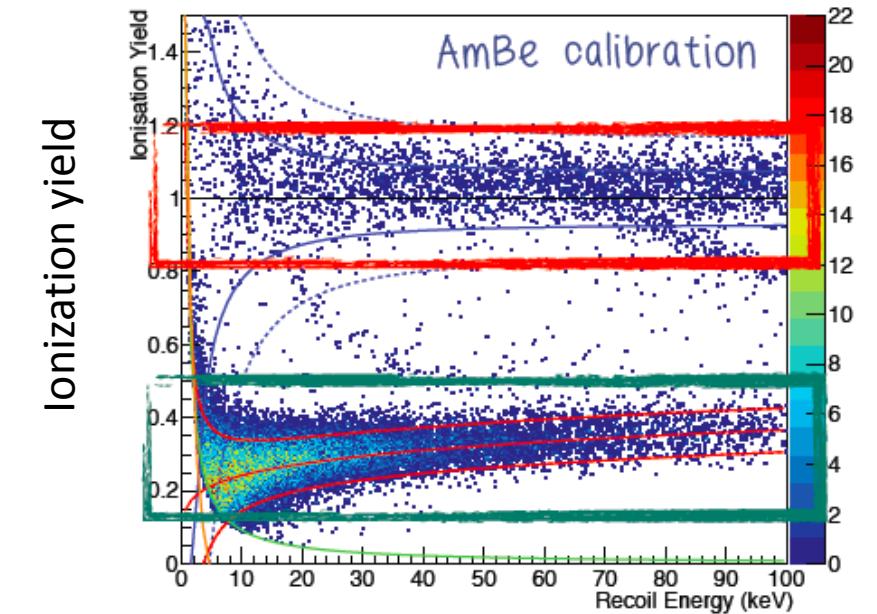
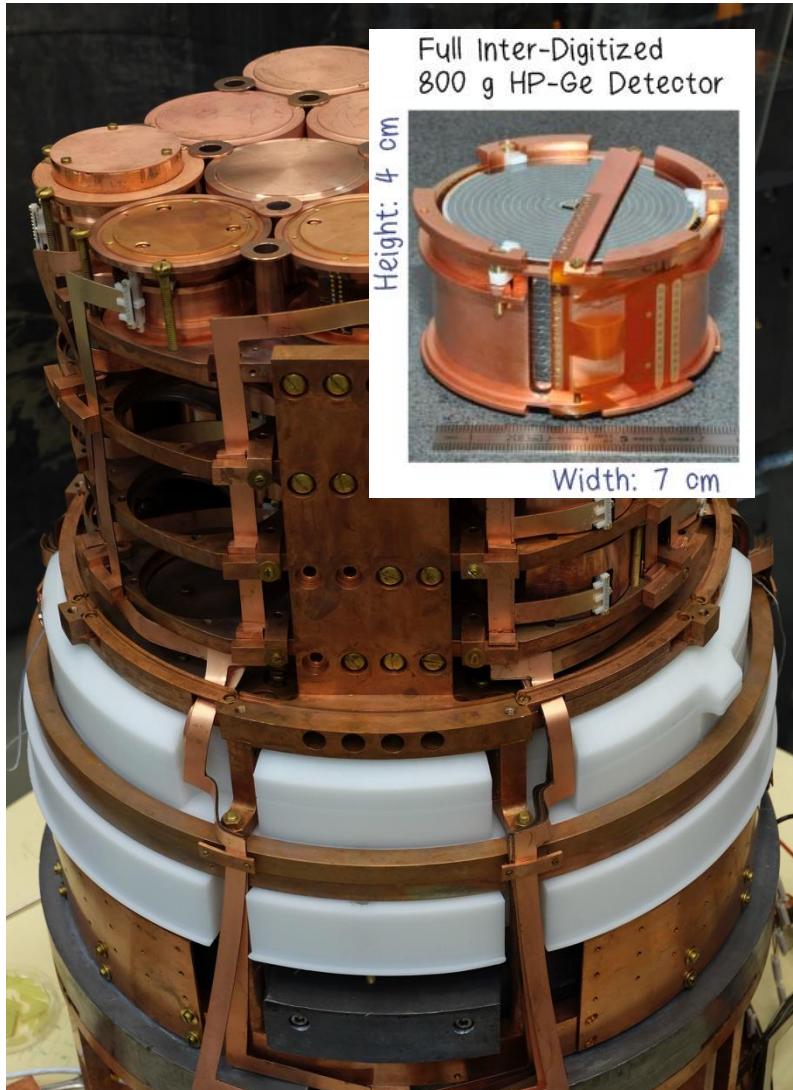
- Setup holds up to ~260 kg detectors
- Shielding includes water tanks (n), lead (γ), poly (n from inner parts)



- Initial payload includes mix of standard and HV detectors (Ge, Si)
Room for significant additional payload e.g. from EURECA (CRESST, EDELWEISS) or advanced HV dets.

Edelweiss: phonon and charge detection

Phonon read out with NTD's



Most backgrounds (e, γ) produce electron recoils \rightarrow Yield (Ionization/recoil) ~ 1

WIMPs (and neutrons) produce nuclear recoils \rightarrow Yield (Ionization/recoil) ~ 0.3

^{133}Ba Gamma Calibration:
no event in $4.1 \times 10^5 \gamma$ leaks below ionization yield of 0.5
 \rightarrow FID gamma's rejection factor $< 6 \times 10^{-6}$

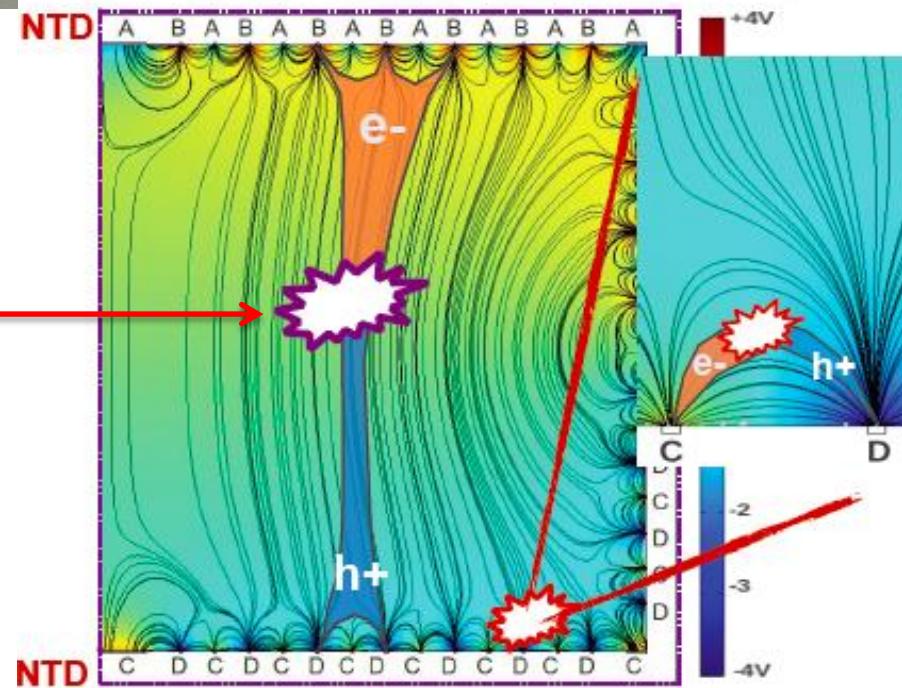
Edelweiss: phonon and charge detection



Discrimination of surface from bulk events with
fully Inter-Digitized 800 g HP-Ge Detector

Bulk Event:

Charge collected on fiducial
electrodes B & D

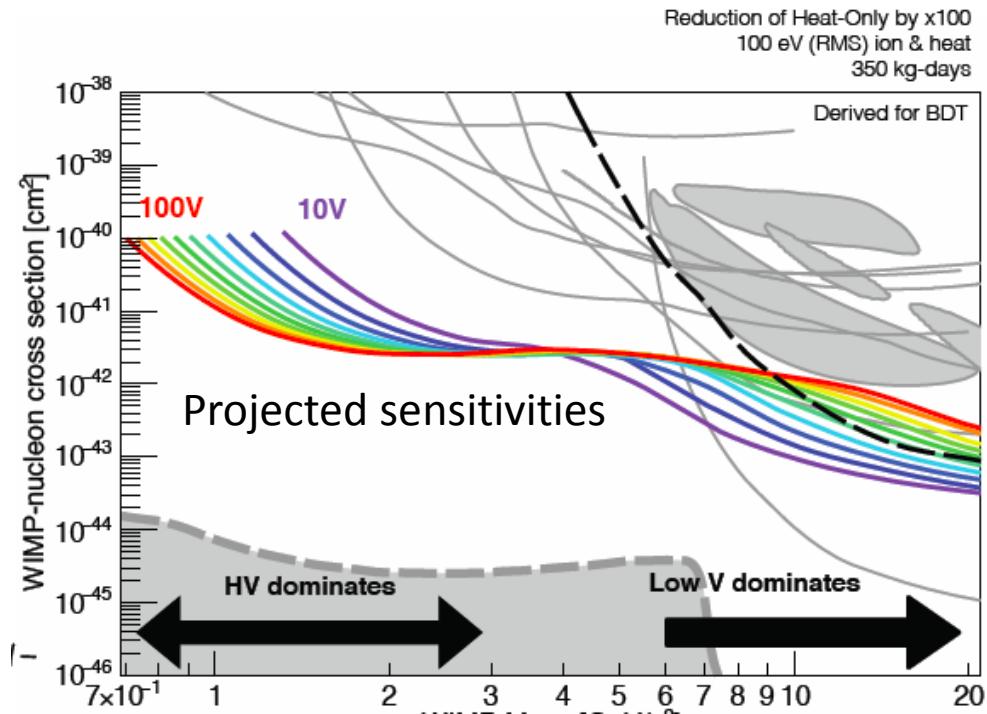
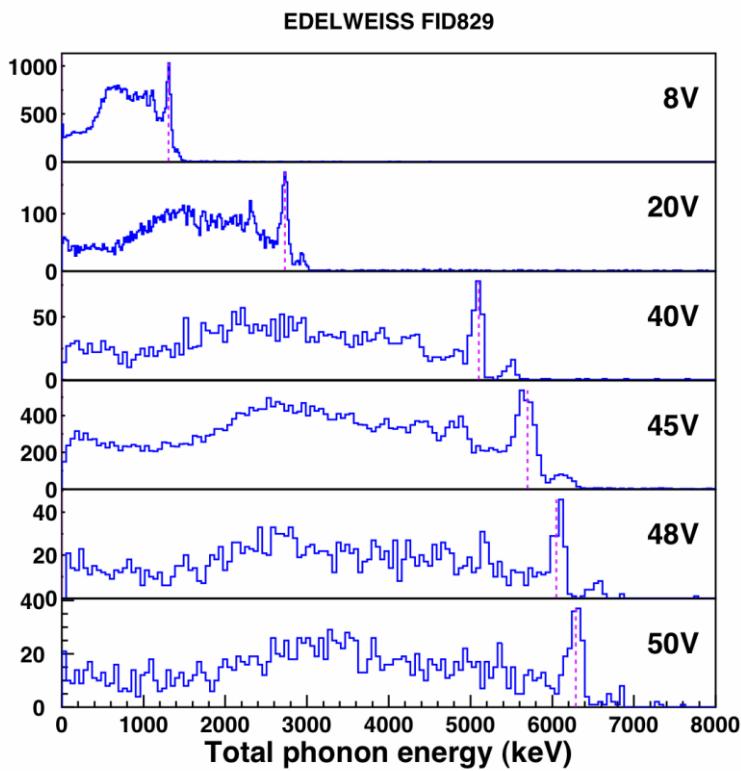


Surface Events:
Charge collection
shared between
one veto and its
neighbor fiducial
electrodes, e.g. C
& D

Edelweiss: future low-mass DM search

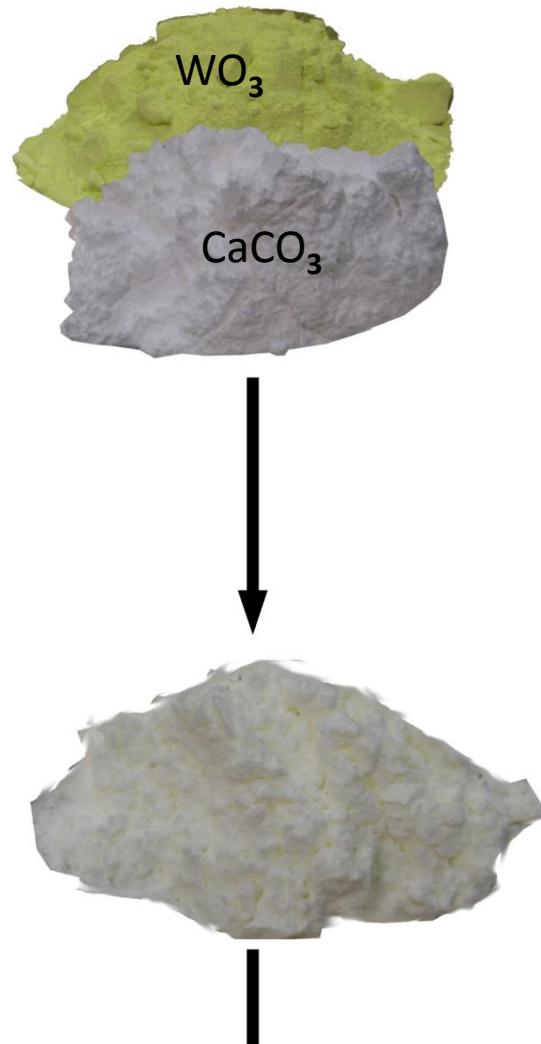
First Neganov-Trofimov-Luke (NTL) boosted data at LSM with 800 g FIDs

- Heat signal boosted by NTL effect
- Loss of ionization based bgd discrimination

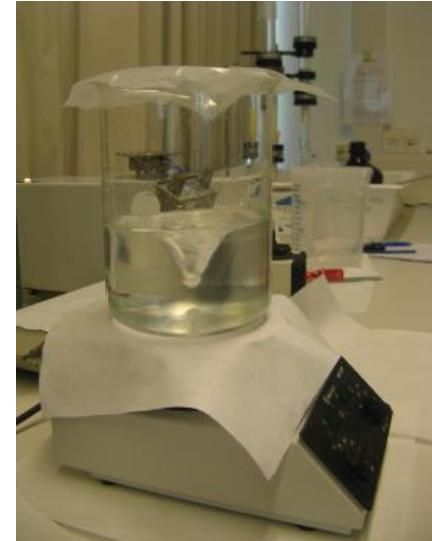


- Background and mass limitations at LSM
- Future at SNOLAB within the EDELWEISS-EURECA-SuperCDMS collaboration

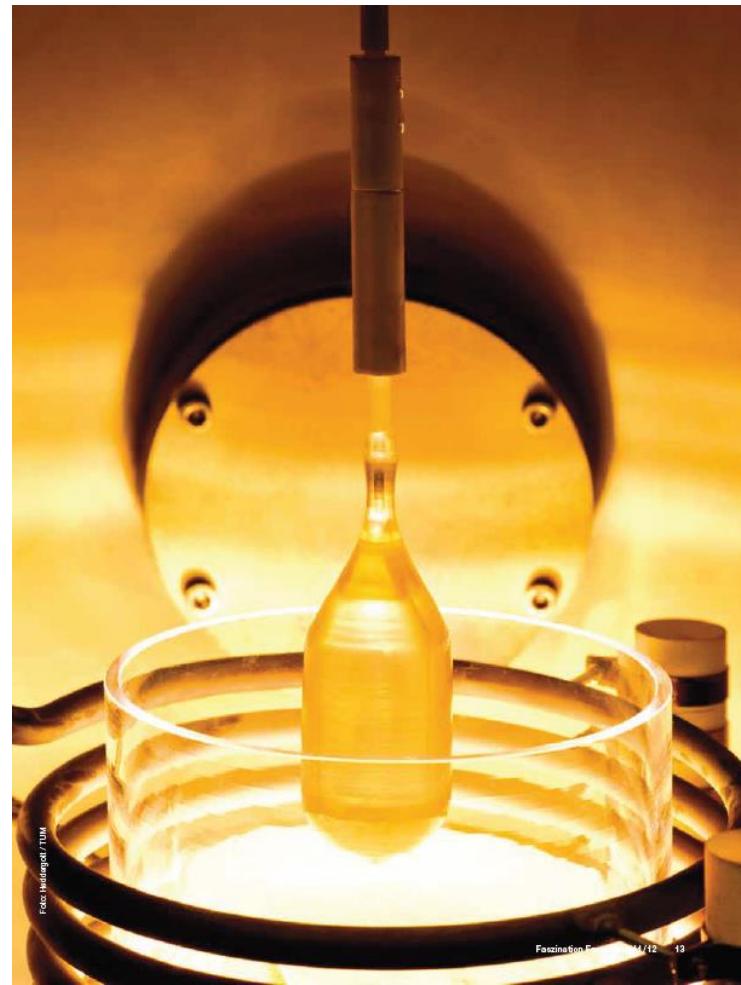
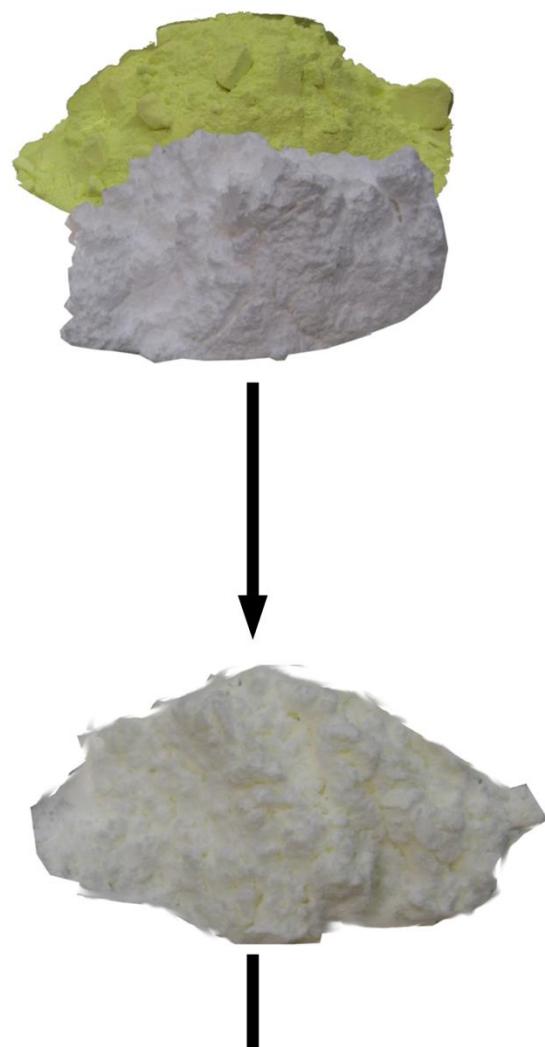
CRESST: phonon and light – from raw materials to final CaWO_4 cryogenic detectors



- Shipment of raw material by sea / road transport
- Underground storage to minimize cosmic activation
- Chemical purification of raw material

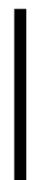
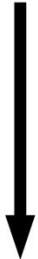


CRESST: phonon and light – from raw materials to final CaWO_4 cryogenic detectors

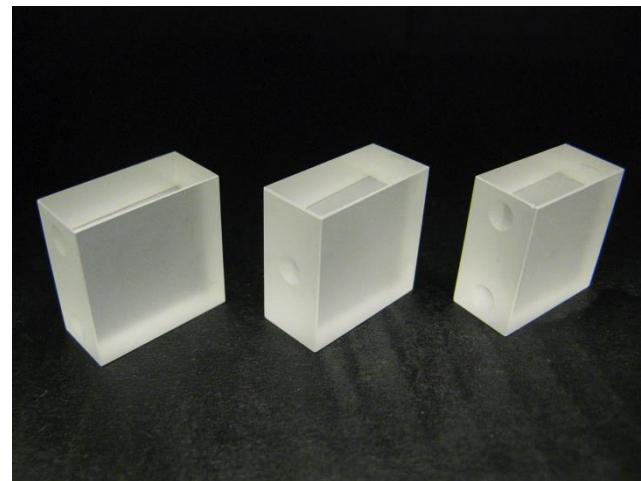


Czochralski crystal pulling at TUM

CRESST: phonon and light – from raw materials to final CaWO_4 cryogenic detectors

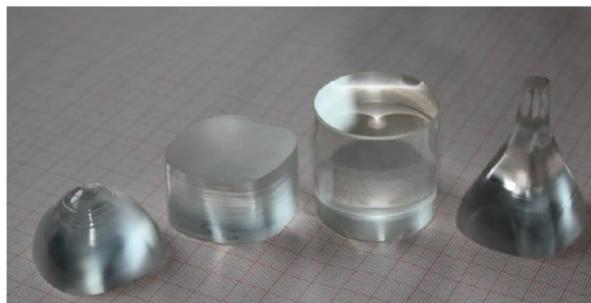


In house crystal cutting, machining
and polishing



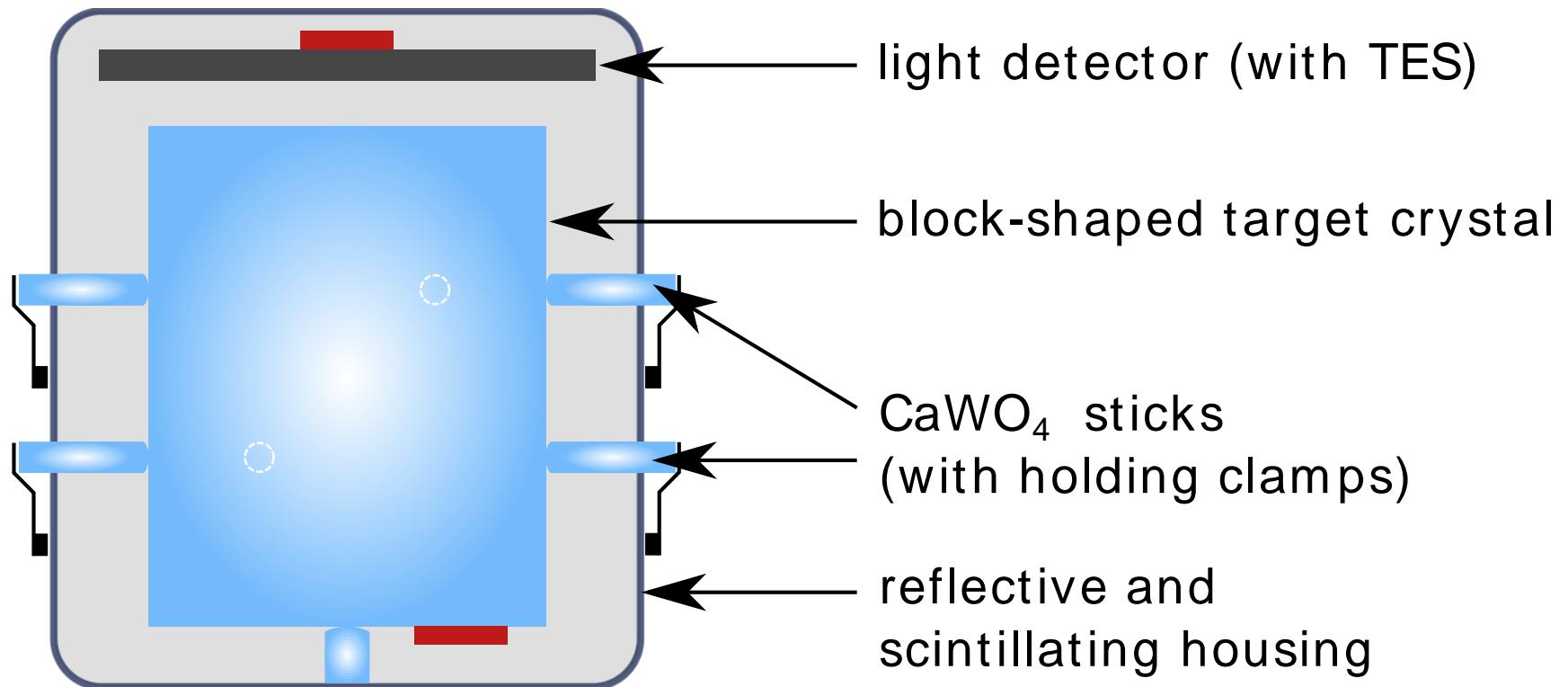
(New crystals for CRESST-III Phase 1)

CRESST: phonon and light – from raw materials to final CaWO_4 cryogenic detectors

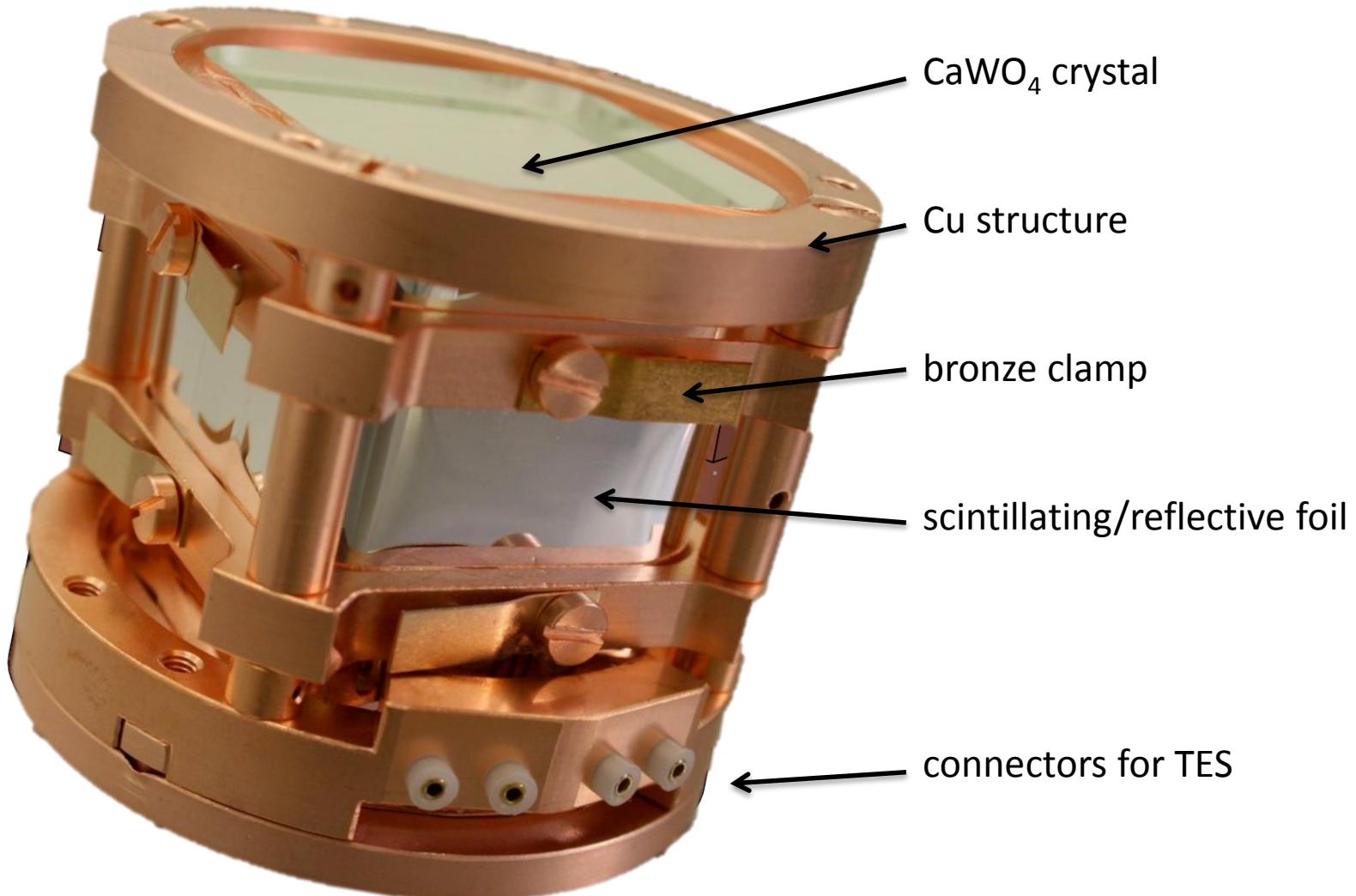


Detector production:
TES evaporation on CaWO_4 and on
SOS light detector

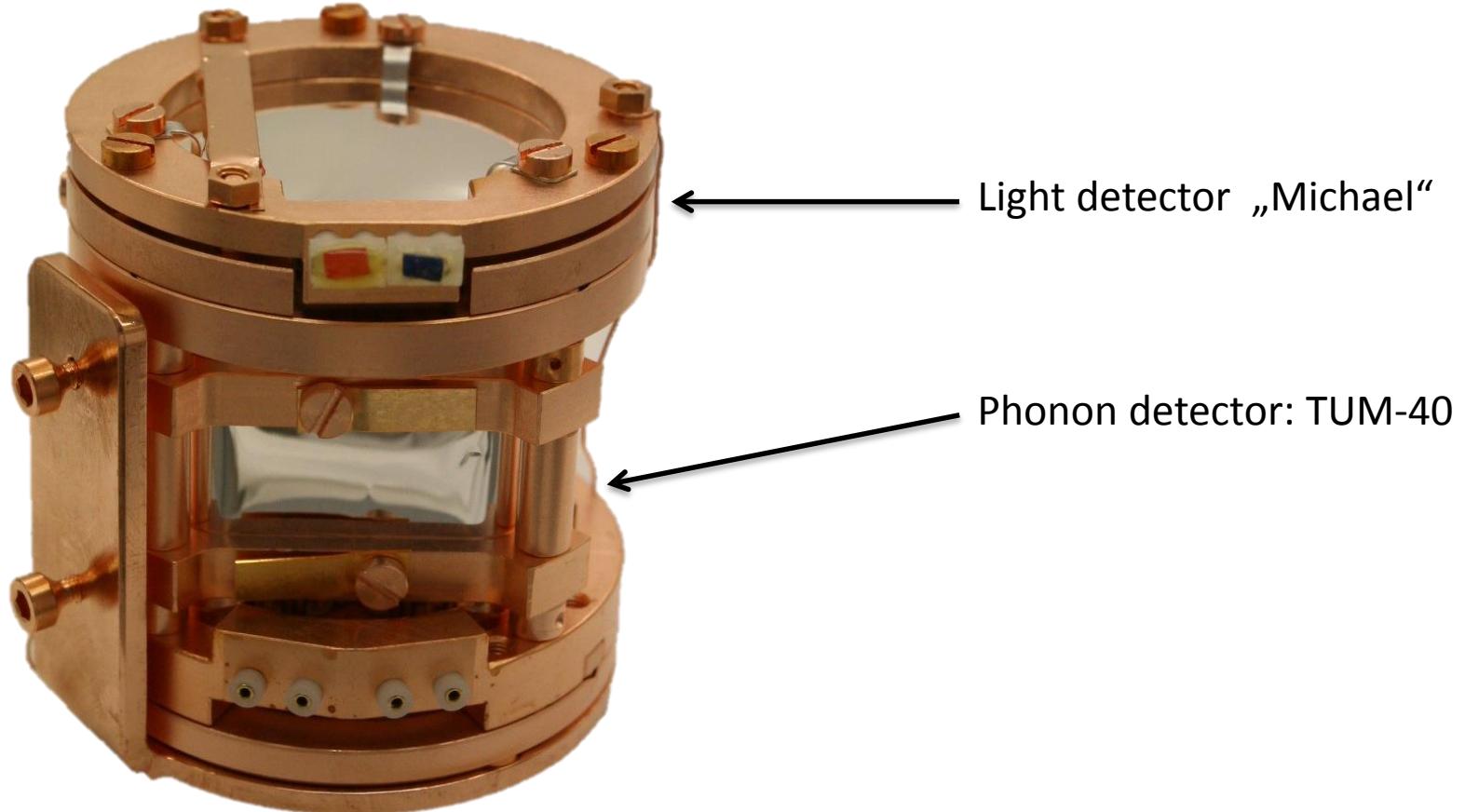
CRESST: phonon and light – fully scintillating design



CRESST: phonon and light



CRESST: phonon and light



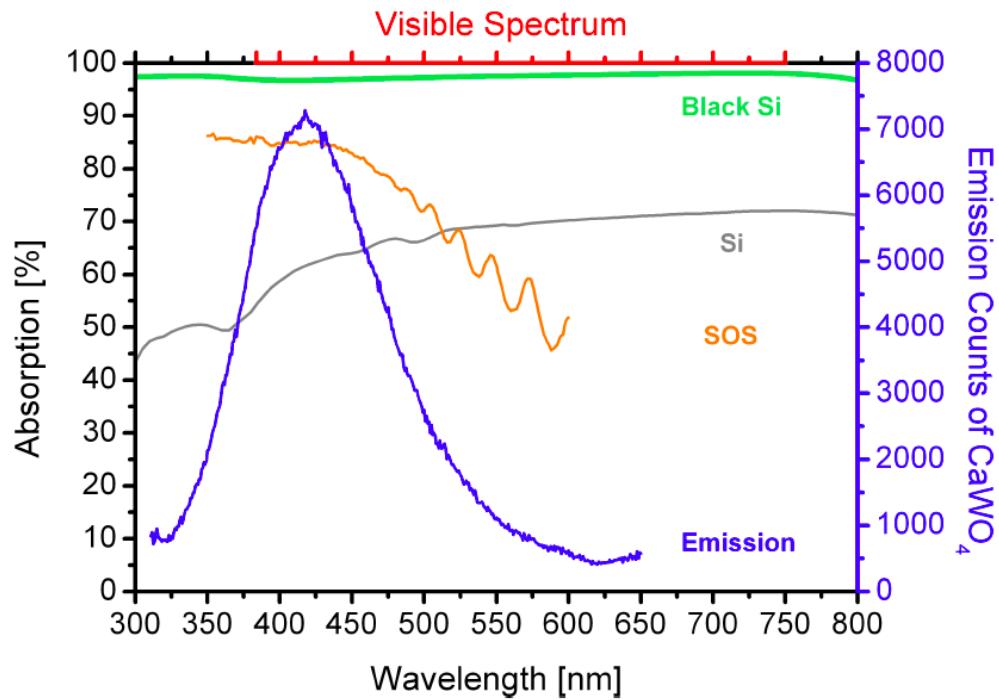
R. Strauss et al. arxiv:1410.1753 EPJ-C (2015)

CRESST light detectors

Silicon on sapphire (SOS)
with evaporated TES



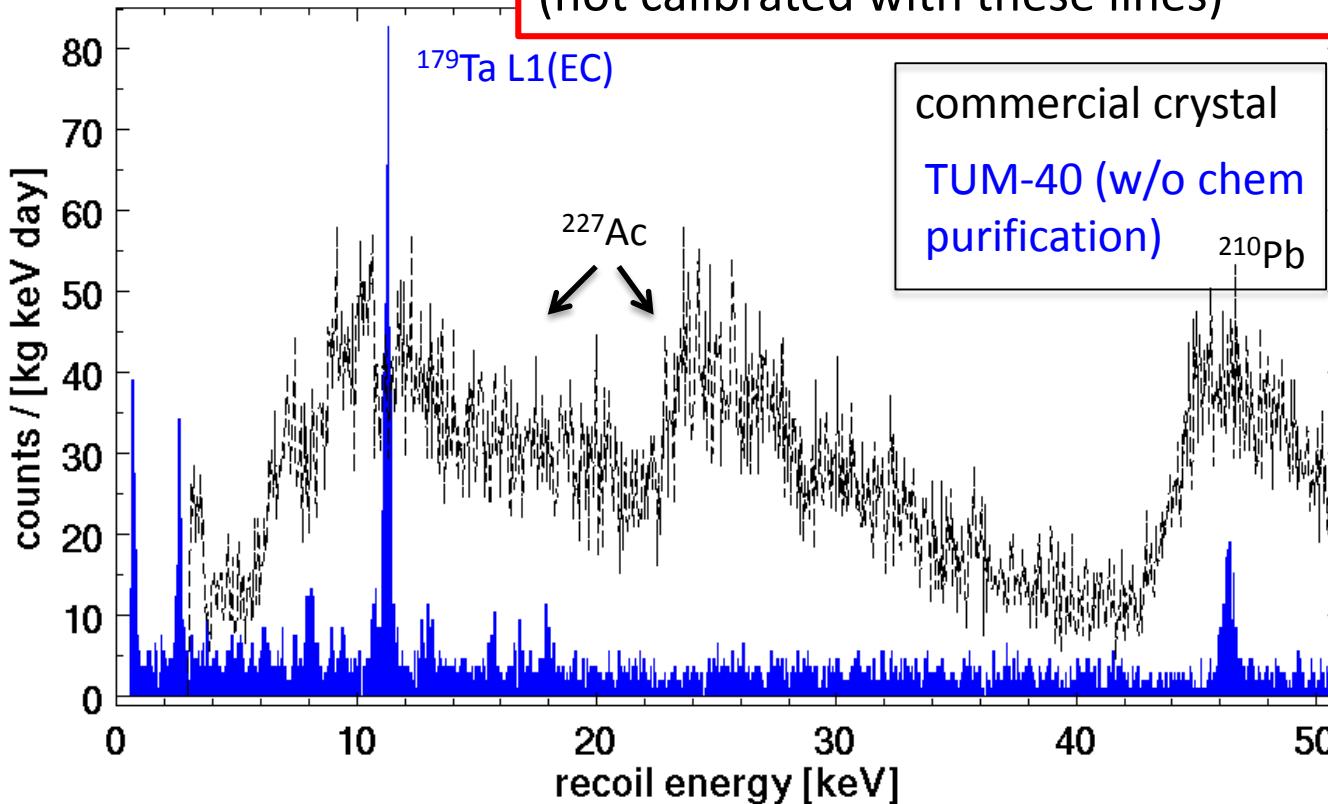
- diameter: 40mm
- thickness: 500 μ m
- baseline noise: 5 eV
- (cf. 420 nm photon \approx 3 eV)



CRESST: phonon and light

TUM-40: Radiopurity

All gamma lines agree within < 5eV
with tabulated values !!
(not calibrated with these lines)

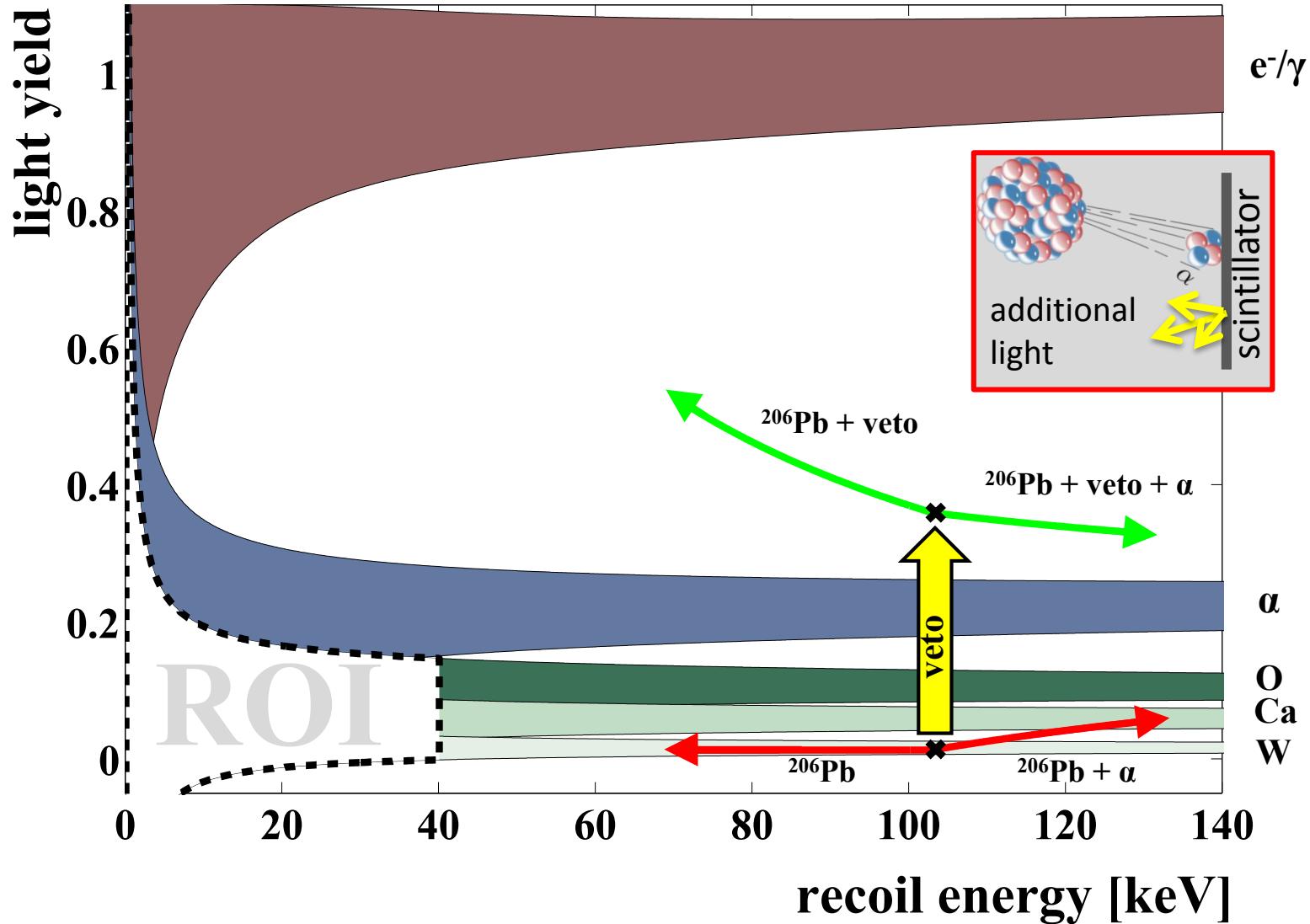


See: CRESST collab. G. Angloher et al. arXiv:1407.3146, EPJ-C (2014) 74
CRESST collab. R. Strauss et al. arxiv:1410.4188, JCAP 06(2015)030

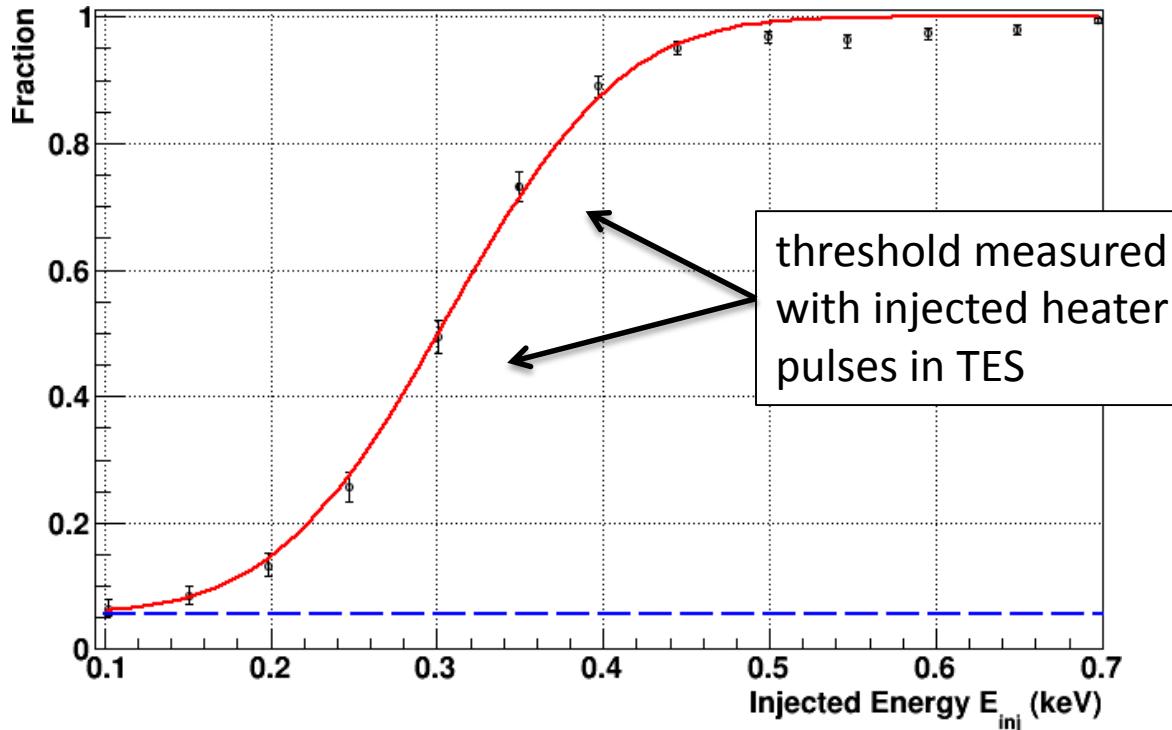
Gamma-lines
from **cosmogenic**
activation

Excellent
resolution:
 $\sigma \approx 100\text{eV}$

CRESST: phonon and light Efficient Veto of Surface Backgrounds



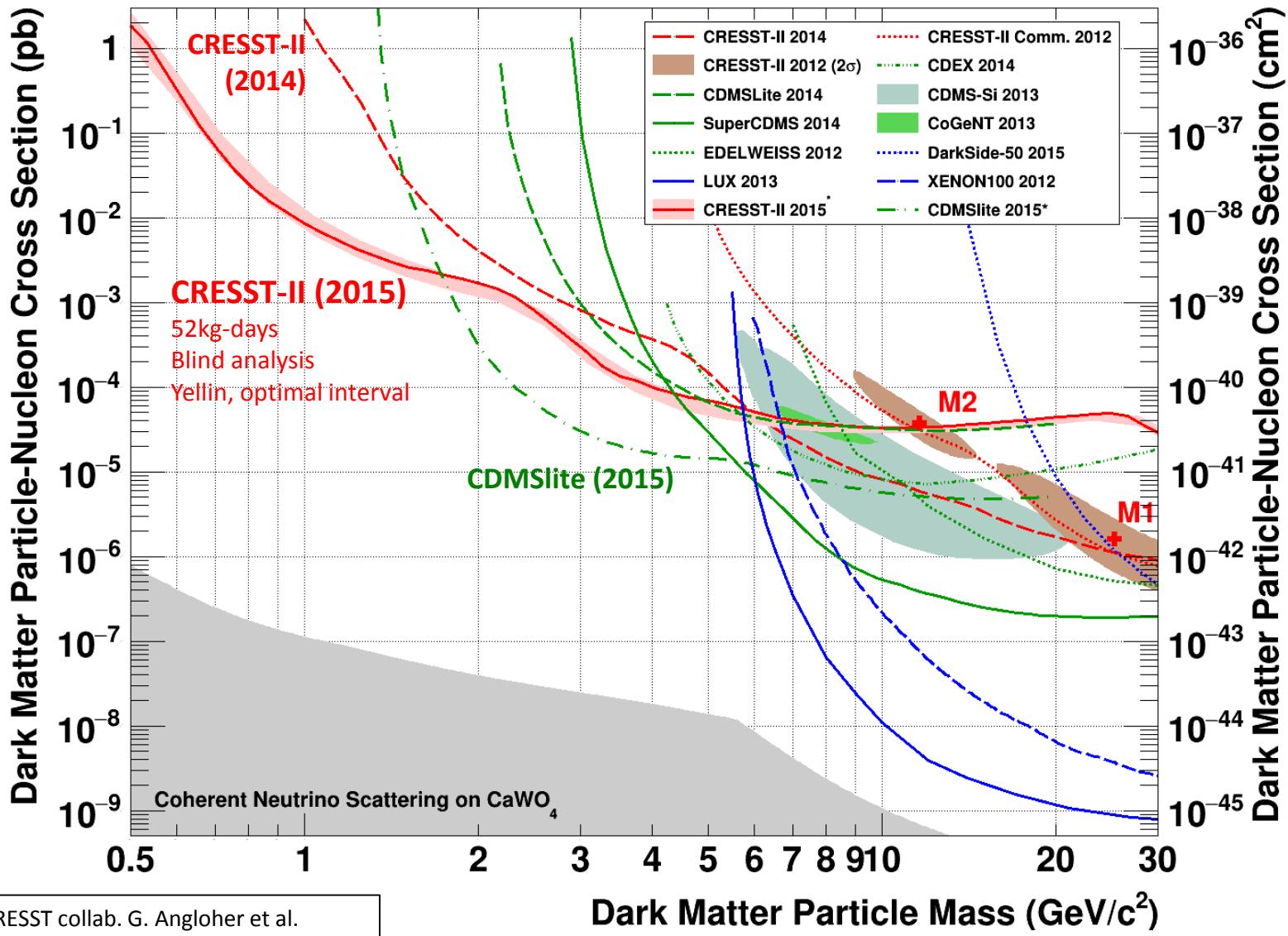
CRESST: phonon and light “Lise”: Trigger Threshold



Lowest trigger threshold among all Dark Matter searches!

Direct measurement of nuclear-recoil energy with calorimetric detector!

CRESST: phonon and light “Lise”: Results 2015



See: CRESST collab. G. Angloher et al.
arXiv1509.01515

CRESST-III: Low-Mass Dark Matter Search

Straight-forward approach for near future: **CRESST-III Phase 1**

Status quo

$m = 250\text{g}$

$V = 32 \times 32 \times 40 \text{ mm}^3$



Scale down size by factor 10

$m=24\text{g}$



Phonon threshold: $E_{\text{th}} \lesssim 500\text{eV}$

improvement by a factor of 5-10

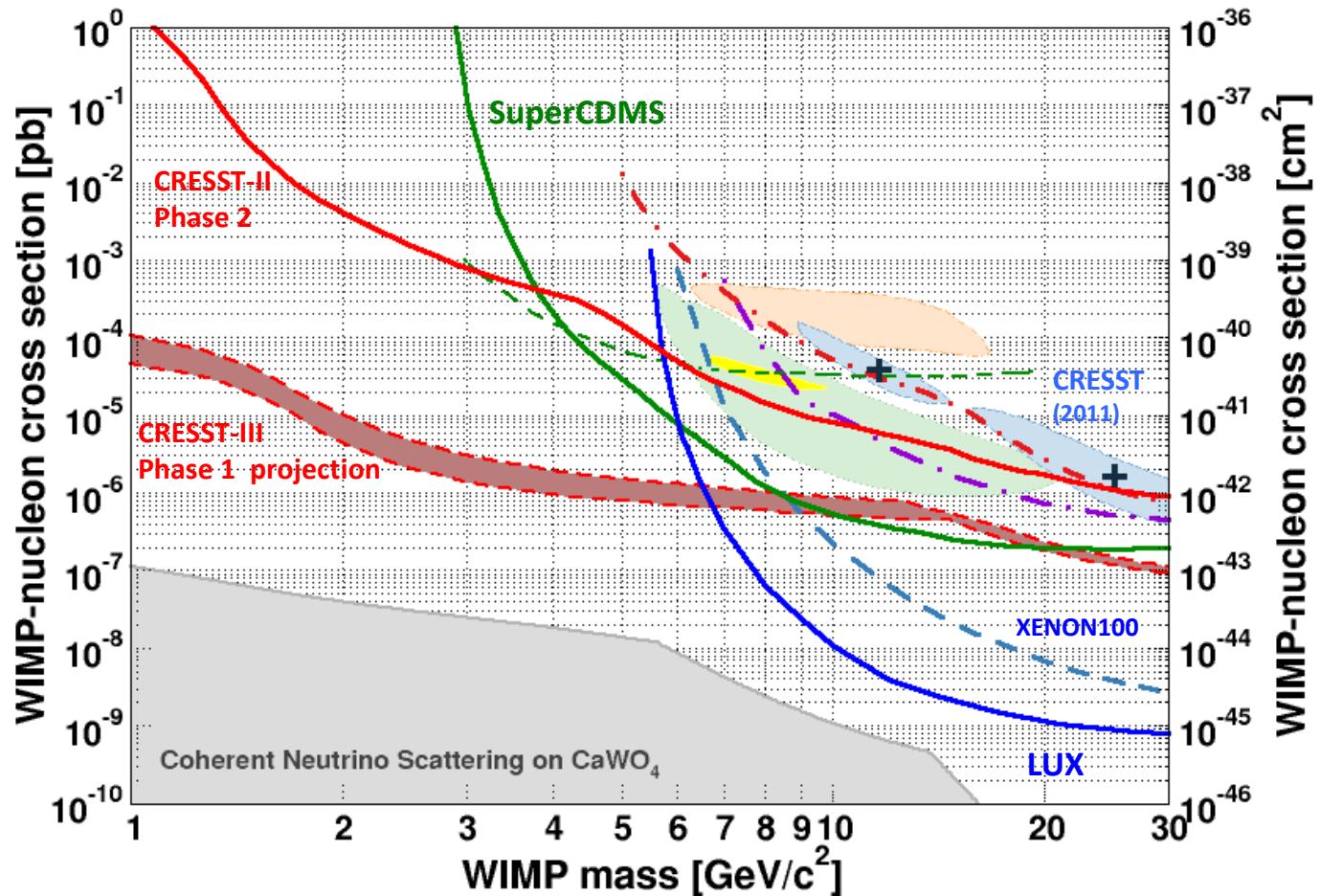
Light-detector res.: $\sigma \approx 5 \text{ eV}$

improvement by a factor of 2

CRESST-III Phase 1

Assumptions:

- 24g CaWO₄ crystal
- $E_{th} = 100\text{eV}$
- Light detector improved by factor 2 (due to smaller volume)
- 2x more detected light: due to thin crystal
- CRESST-II radiopurity

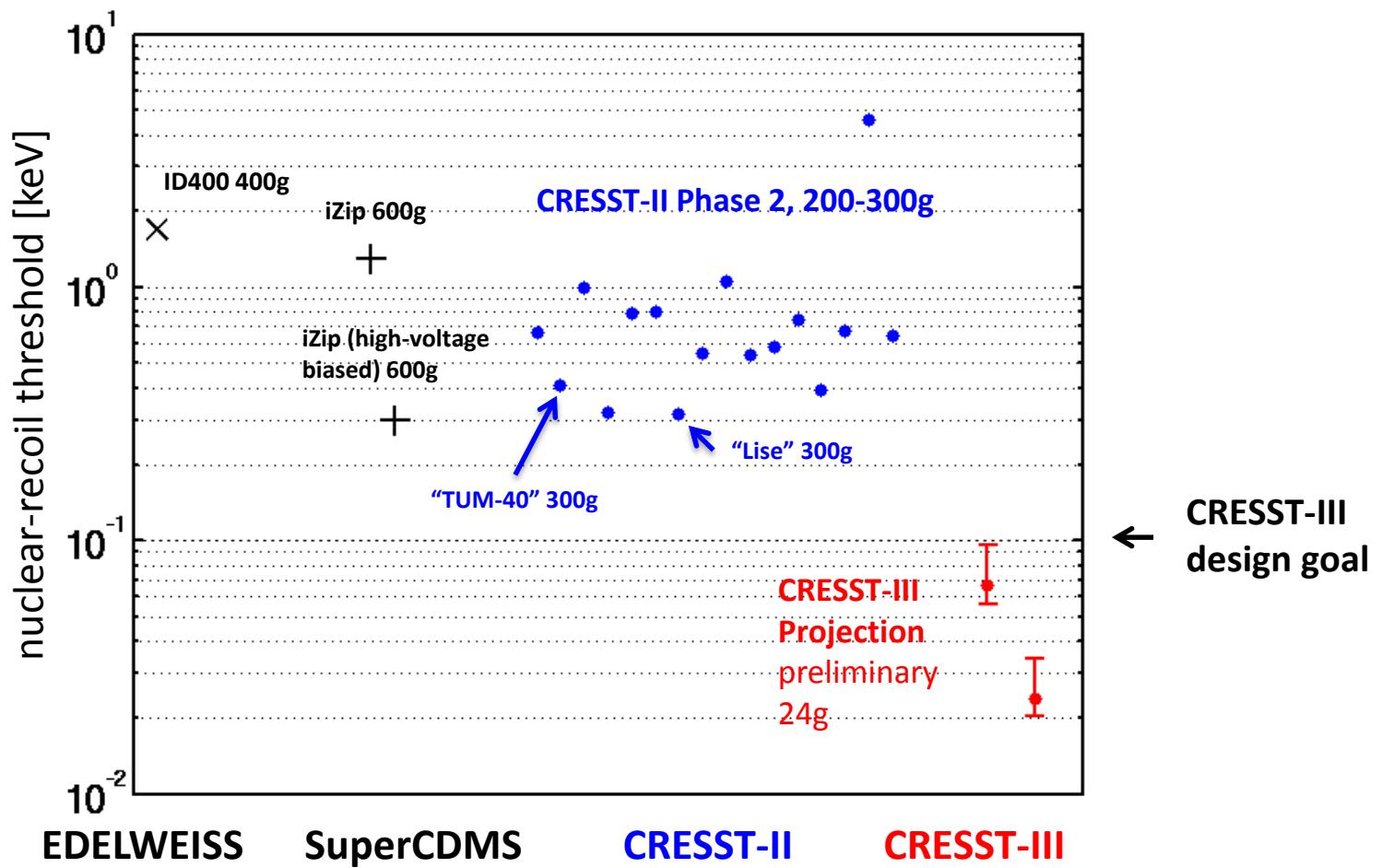


CRESST collab. G. Angloher et al.
arXiv:1503.08065

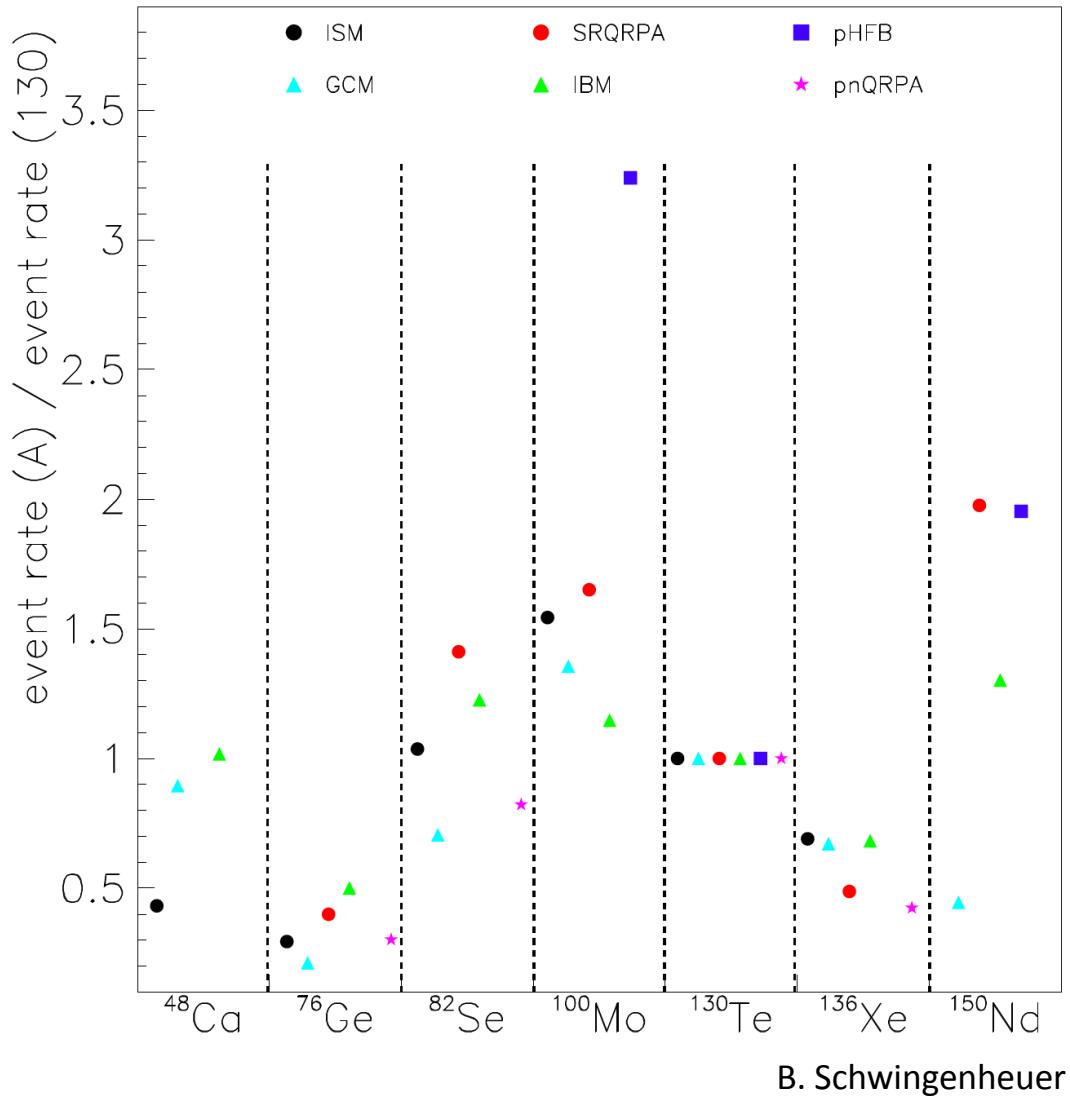
10 x 24g detectors operated for one year $\approx 50 \text{ kg-days (net)}$

See details R. Strauss' talk on Thursday

Thresholds of Cryogenic Experiments

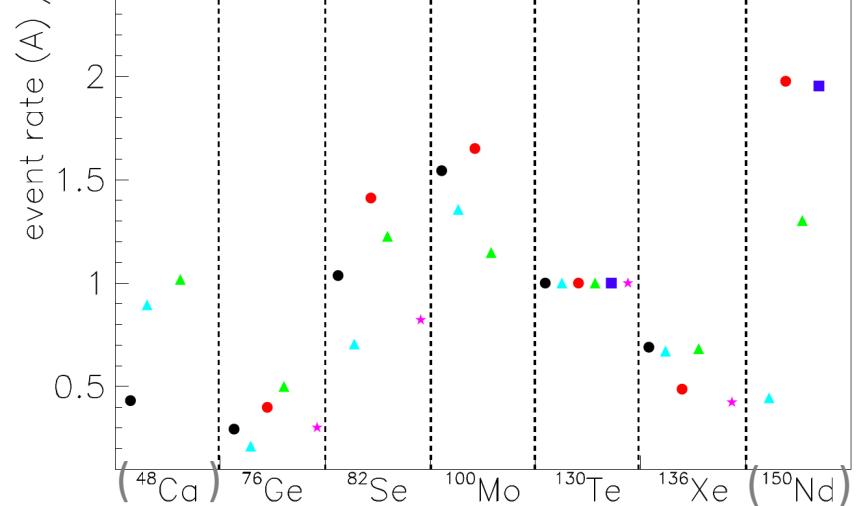


Isotopes for neutrinoless double beta decay ($0\nu\beta\beta$) search



Choice of isotopes driven by experimental considerations:

- Detector technology
- Background at $Q_{\beta\beta}$
- Isotope enrichment
- Costs (not only of enrichment!)
-



Experimentalist's choice

⁴⁸Ca, ¹⁵⁰Nd currently can not be enriched in large quantities

LXe TPC: **(n)EXO**
 gas-Xe TPC: **NEXT**
 Xe-loaded LS: **KL-Zen**

Te-bolometers: **Cuore**
 Te-loaded LS: **SNO+**

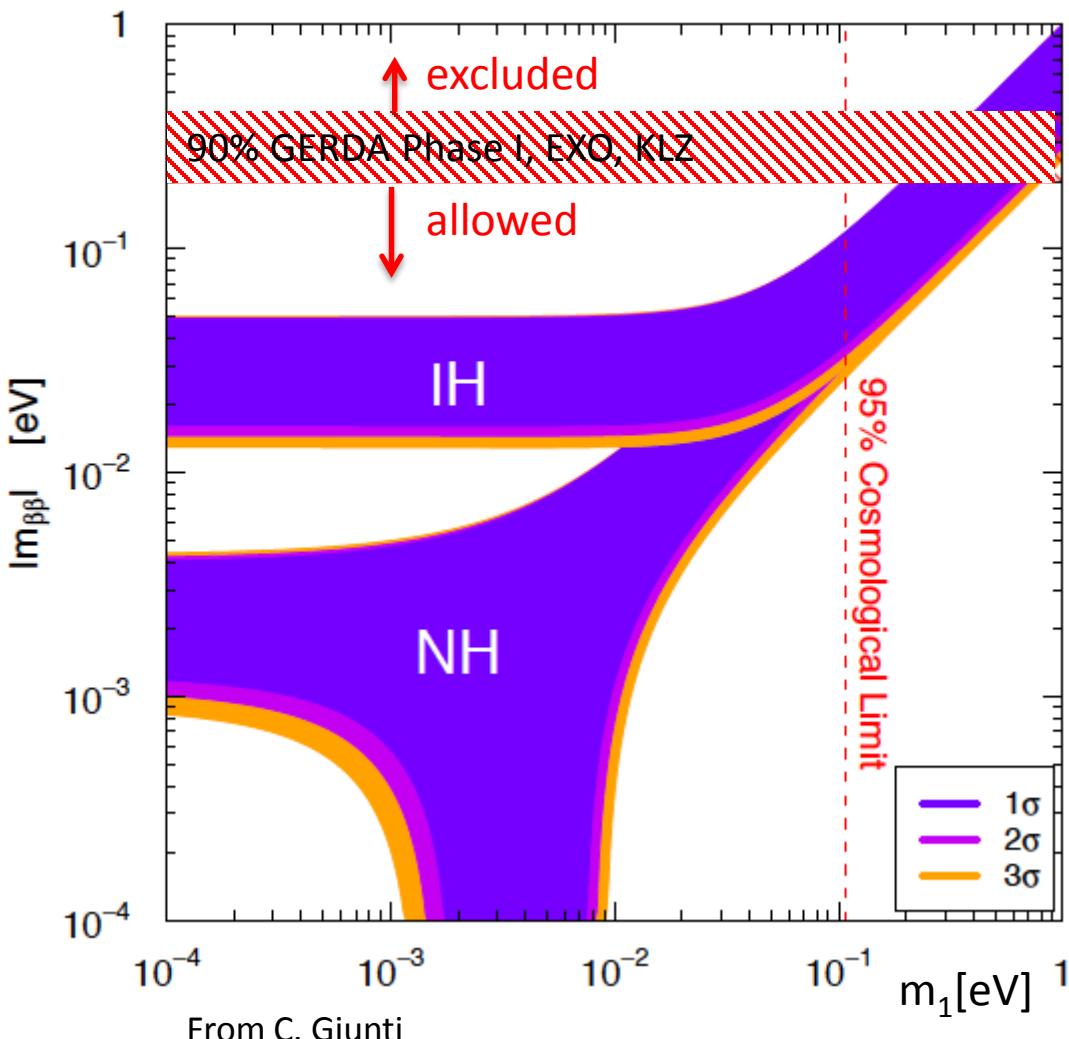
Mo-bolometers: **Lumineu (CUPID), Amore**

Se-bolometers: **Lucifer (CUPID)**
 Se-calorimeter: **SuperNemo**

Ge-semiconductor: **GERDA, MJD**

& other interesting, but less advanced R&D

next generation $0\nu\beta\beta$ experiments

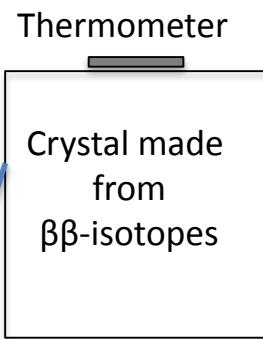


3v-paradigm:

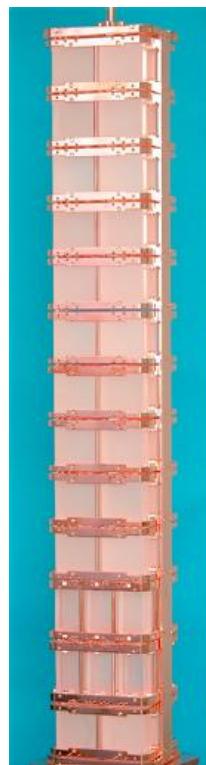
- Next generation of experiments should probe mass range predicted for **IH**
- 10 meV mass range
- $0\nu\beta\beta$: $T_{1/2} \sim 10^{27} - 10^{28}$ years
- $(2\nu\beta\beta: T_{1/2} \sim 10^{19} - 10^{21}$ years)
- **1 ton scale of isotope required**
- **BI < 1E-3 cts/(kg keV yr)**

$0\nu\beta\beta$ cryogenic experiments: Cuore (^{130}Te)

Heatsink



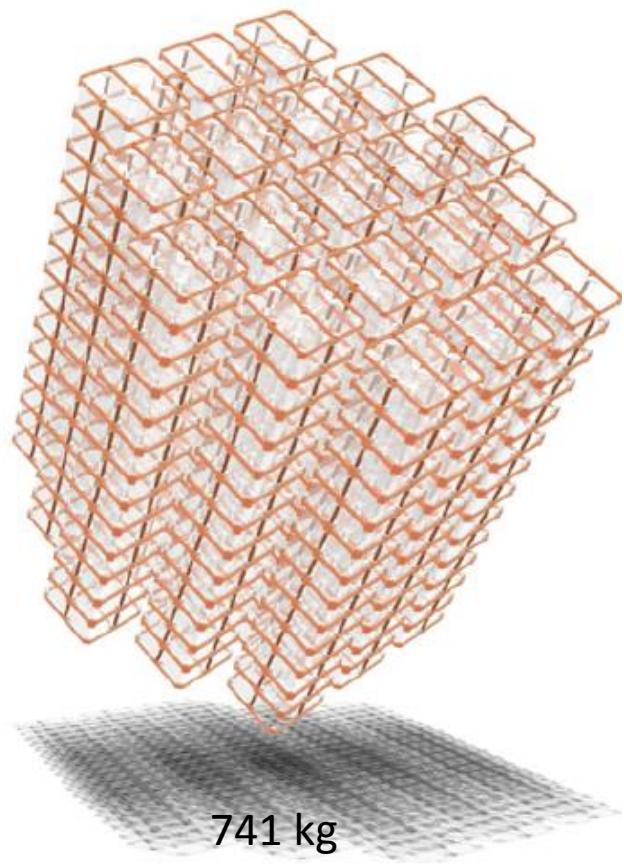
Cuoricino
2003-2008



Cuore-0
2013-2015



Cuore
2016-2020

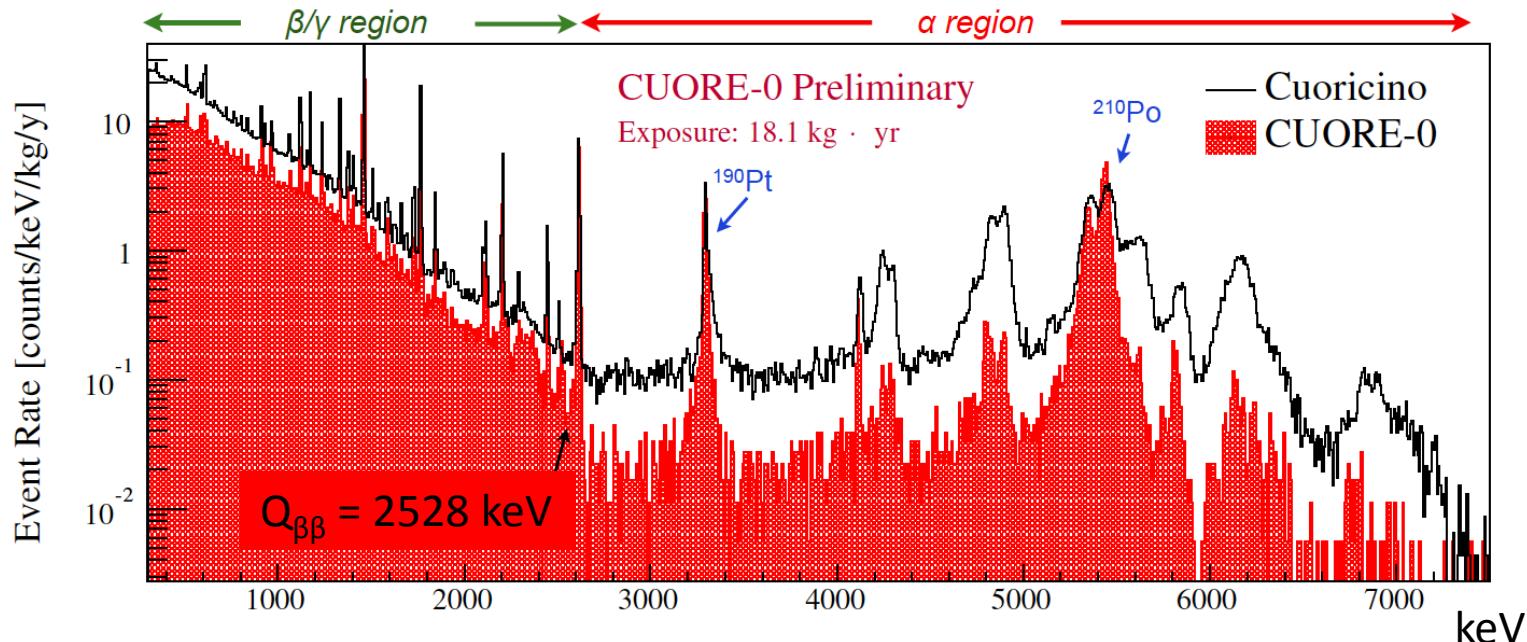


39 kg
(11 kg ^{130}Te)

741 kg
(206 kg ^{130}Te)

$0\nu\beta\beta$: Cuore-0/Cuore (^{130}Te)

Cuore-0: operation of Cuore detector-tower in Couricino cryostat



α -, γ -Backgrounds from nearby surfaces and bulk. Reduction w.r. to Cuoricino:

- 5.5x in alpha energy range
- 2.4x at $Q_{\beta\beta}$
- bgd in Cuore $\approx 0.01 \text{ cts}/(\text{keV kg y})$
- Cuore: $9.5 \times 10^{25} \text{ yr} / 40\text{-}100 \text{ meV}$

	$0\nu\beta\beta$ region cnts/(keV kg y)	2700-3900 keV	$\varepsilon(\%)$
Cuoricino	0.153 ± 0.006	0.110 ± 0.001	83
CUORE-0	0.063 ± 0.006	0.020 ± 0.001	78

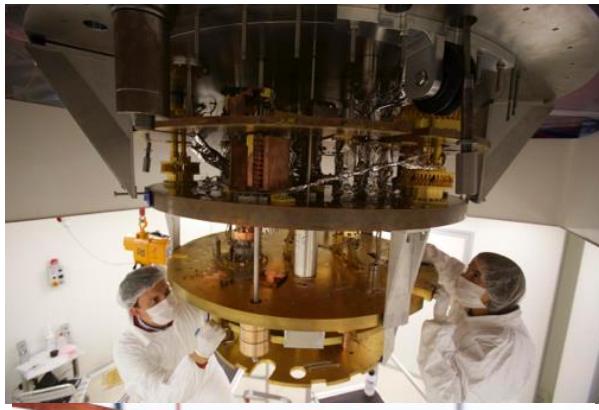
From O. Cremonesi, Nu2014

Combined CUORE-0 + Cuoricino: $T_{1/2}^{0\nu\beta\beta}(^{130}\text{Te}) > 4.0 \times 10^{24} \text{ yr}$ (90% C.L.) arXiv:1504.02454

$0\nu\beta\beta$: status of Cuore (^{130}Te)



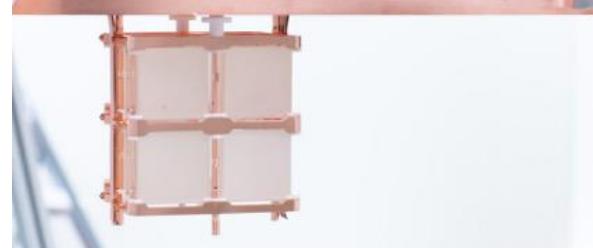
- 19 towers complete, stored under constant N₂ flux



- Successful cool-down with 6t Pb and operation at 6.5 mK



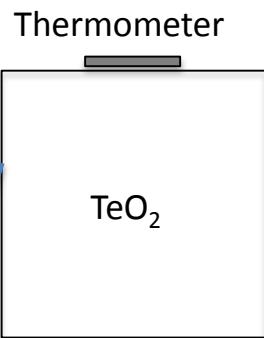
- Final phase of cryostat commissioning ongoing with MiniTower test in progress (8 CUORE-like TeO₂ bolometers)



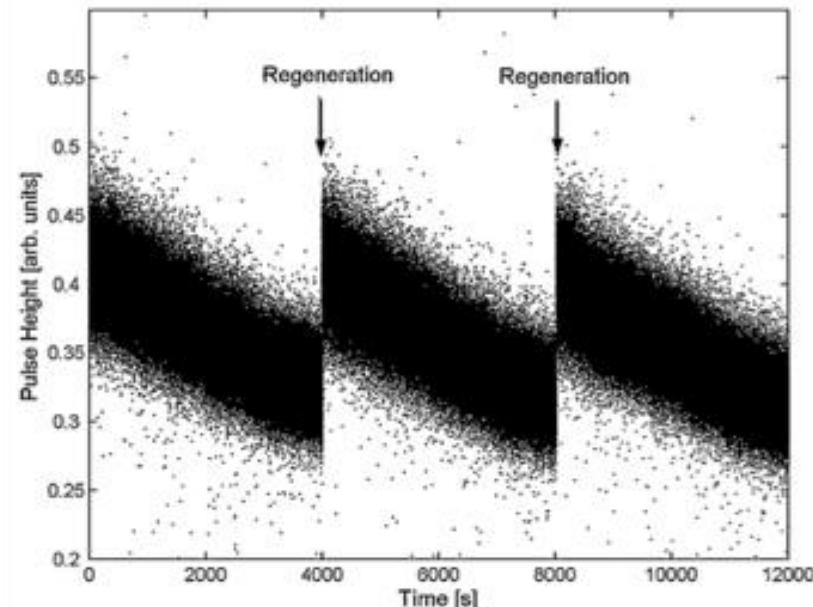
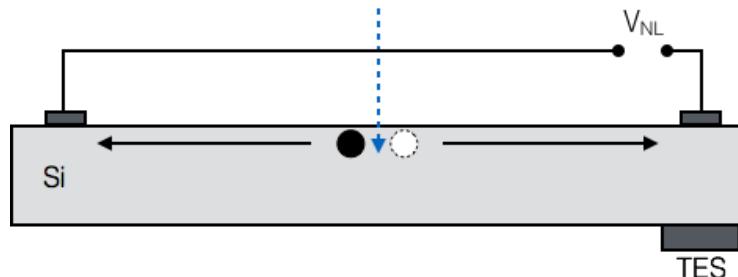
Courtesy O. Cremonesi

Possible future: enriched TeO_2 with coincident Cherenkov detection

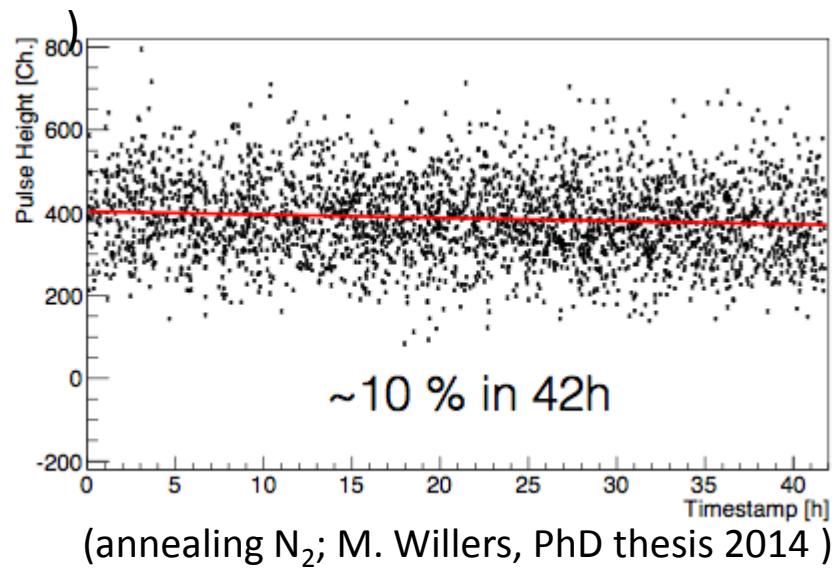
Heatsink



Few-MeV α -particles do
not generate Cherenkov
light while $\beta\beta$ (and γ 's) do
→ Measure Cherenkov
light in coinc. with heat
T.Tabarelli de Fatis, EPJ C65, 2010

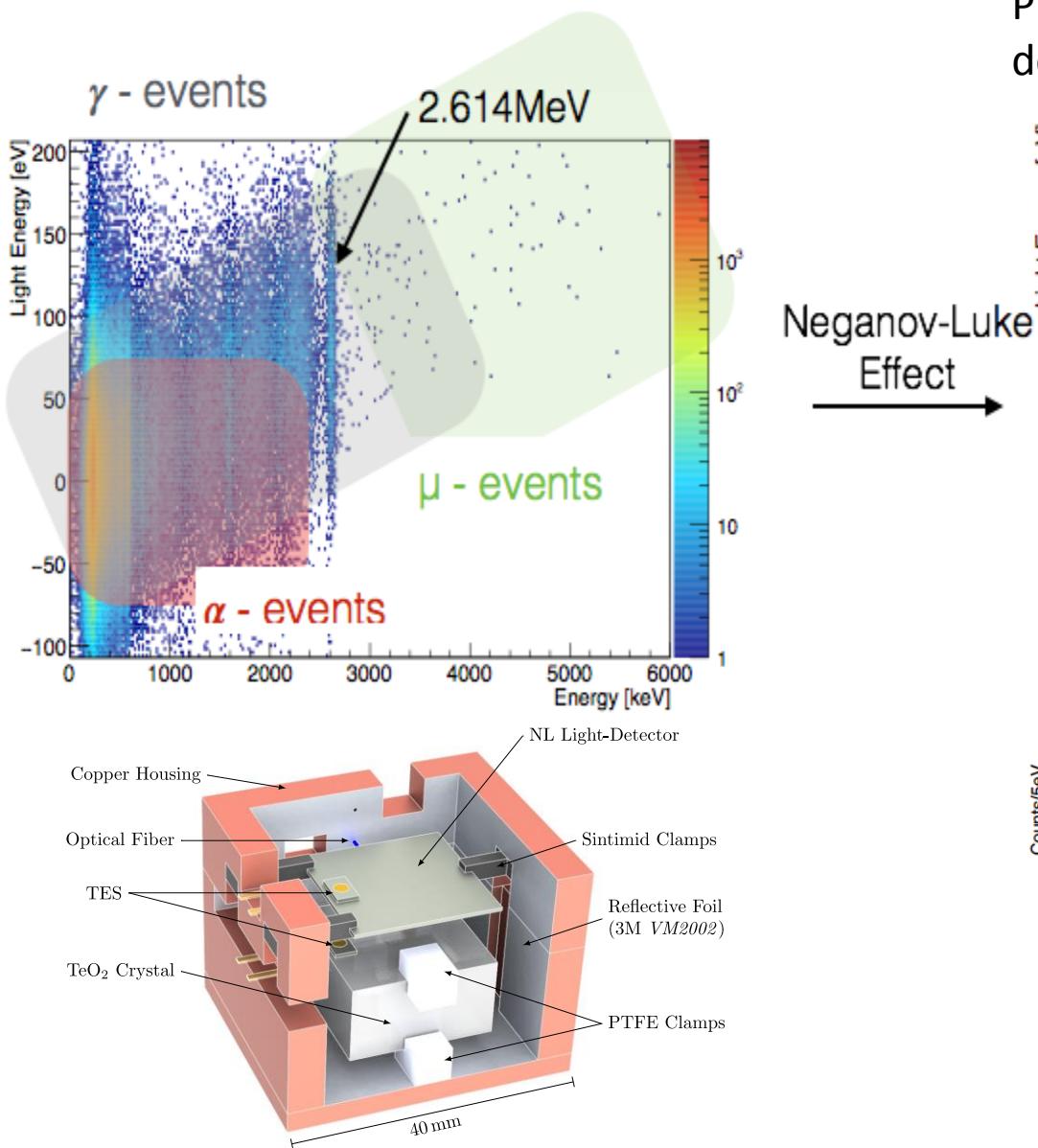


(no annealing, Isaila et al., arXiv:1106.0167)

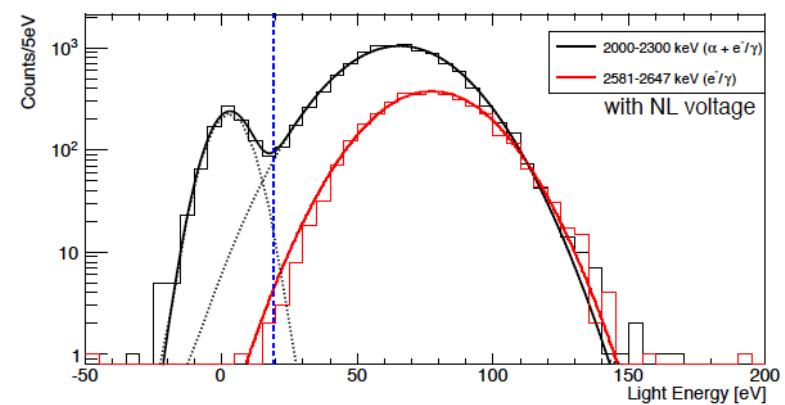
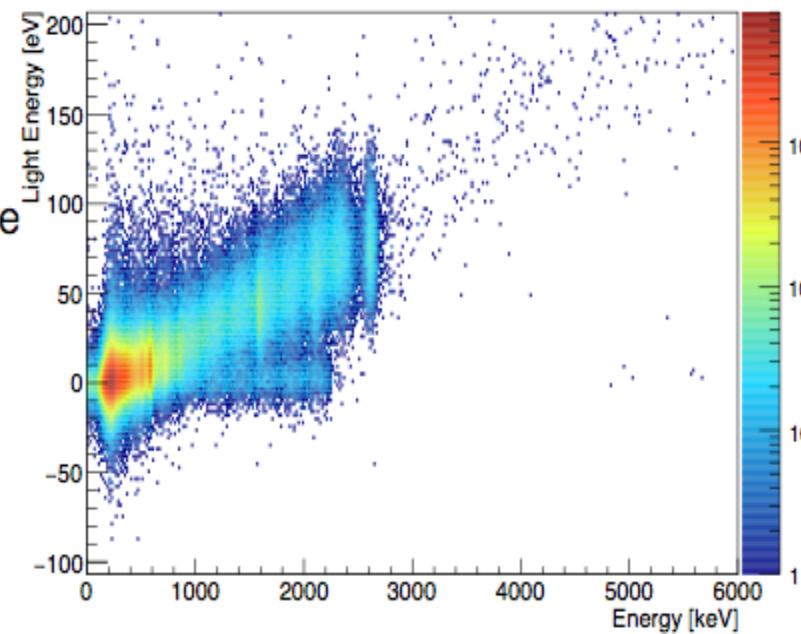


(annealing N_2 ; M. Willers, PhD thesis 2014)

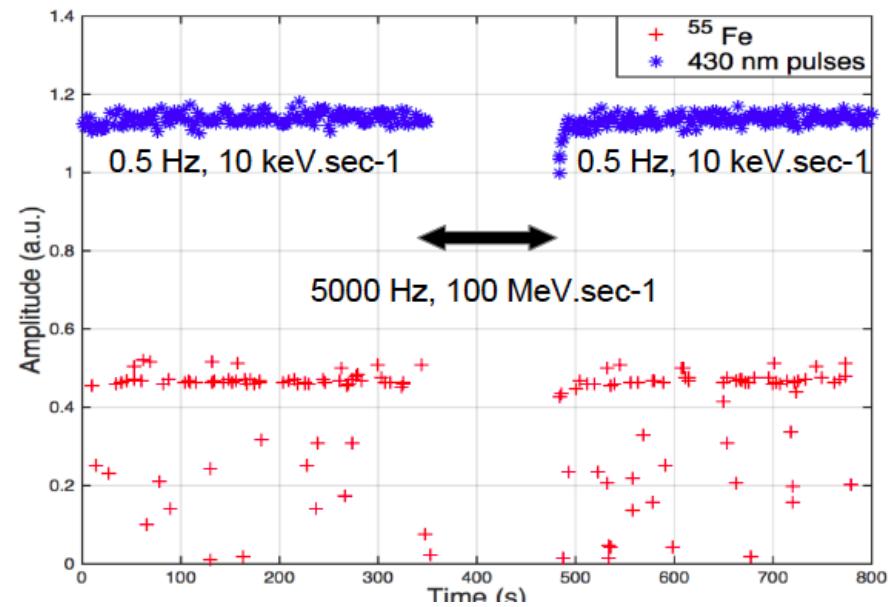
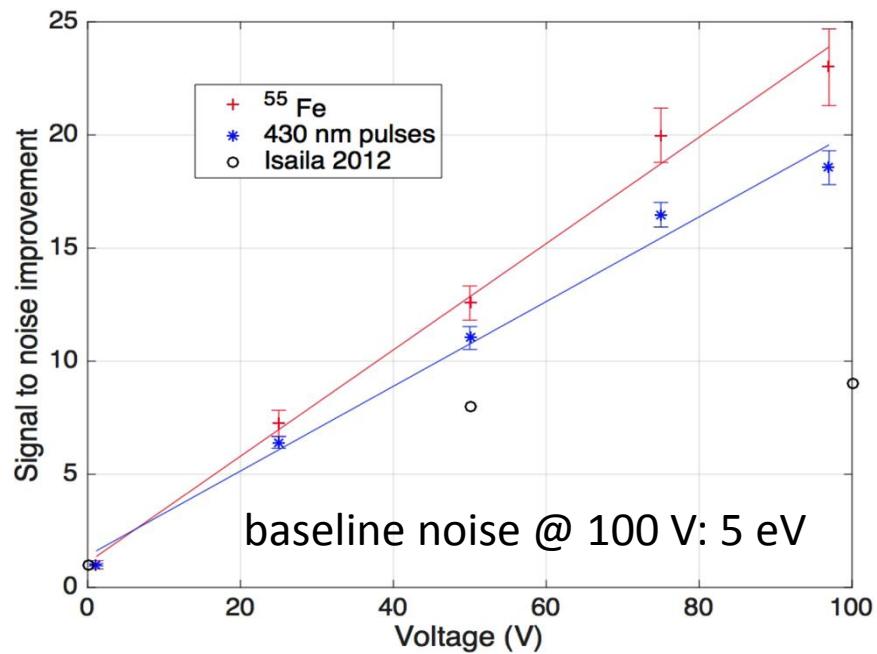
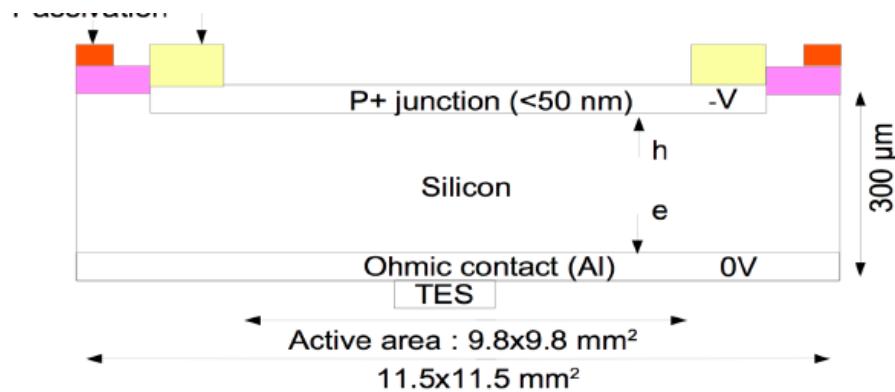
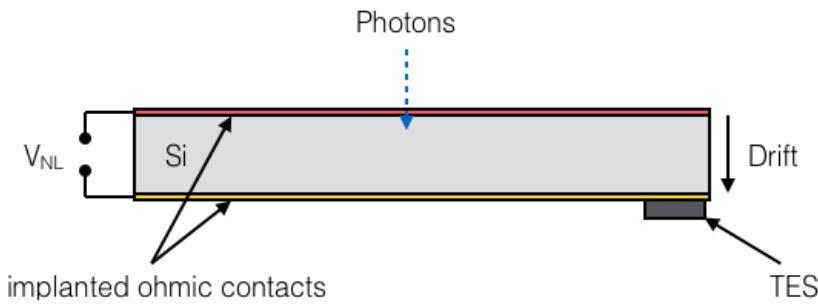
Possible future: enriched TeO_2 with coincident Cherenkov detection



Proof of principle: TES/Neganov-Luke light detector with event-by-event separation



First planar NTL light detector



LUCIFER- CUPID-0 Demonstrator: phonon and scintillation light

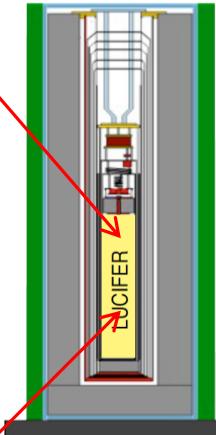
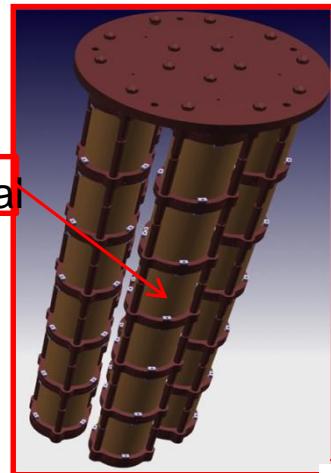
LUCIFER (**CUPID-0**): 25÷30 **Zn⁸²Se** scintillating crystal bolometers (95% enriched), 440 g each (total ~7 kg of ⁸²Se),.



Ge-Light
detector

ZnSe Crystal

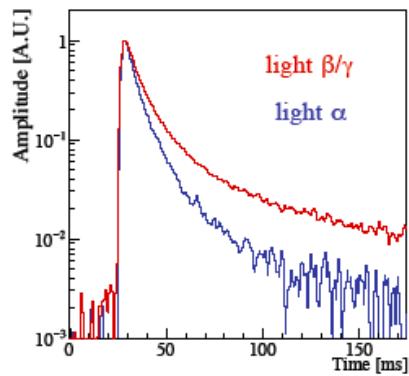
LUCIFER TOWER



CUORE-0 cryostat

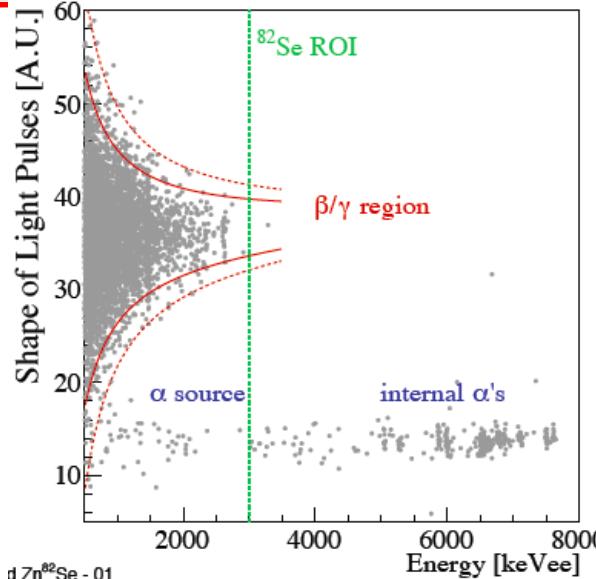
- Inner shield:
 - 1cm Roman Pb A (²¹⁰Pb) < 4 mBq/Kg
- External shield:
 - 20 cm Pb
 - 10 cm Borated polyethylene
- Nitrogen flushing to avoid Rn contamination.

(new shields, new wiring)



Powerful bkg
discrimination by

- phonon/light
- Light pulse
shape



Cool down of CUPID-0 by June 2016

See Poster of Nicola Casali

d Zn⁸²Se - 01

Energy [keVee]

Courtesy S. Pirro

R&D of Mo-containing scintillators

Precursors grown by LTG Cz @ NIIC

Funct. Mat. 17(2010)504; NIMA 729(2013)856; Crystallogr. Rep. 59(2014)288

2010 Purification



2011

$\text{ZnMoO}_4 \sim 1 \text{ kg}$



First LUMINEU crystals - ZMO

JINST 9(2014)P06004

2013 Adopted purification



W-doped ZMO

Opt. Mat. 49(2015)67

2014



First enriched ZMO

EPJC 74(2014)3133



First large ZMO

JINST 10 (2015) P05007

2013



First large LMO

Astropart. Phys. 72(2016)38

$\text{Li}_2\text{MoO}_4 \sim 0.3 \text{ kg}$

2014



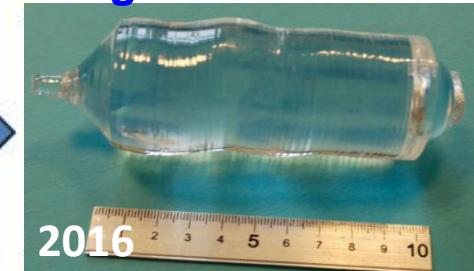
First large enriched ZMO

AIP Conf. Proc. 1672(2015)040003

2015



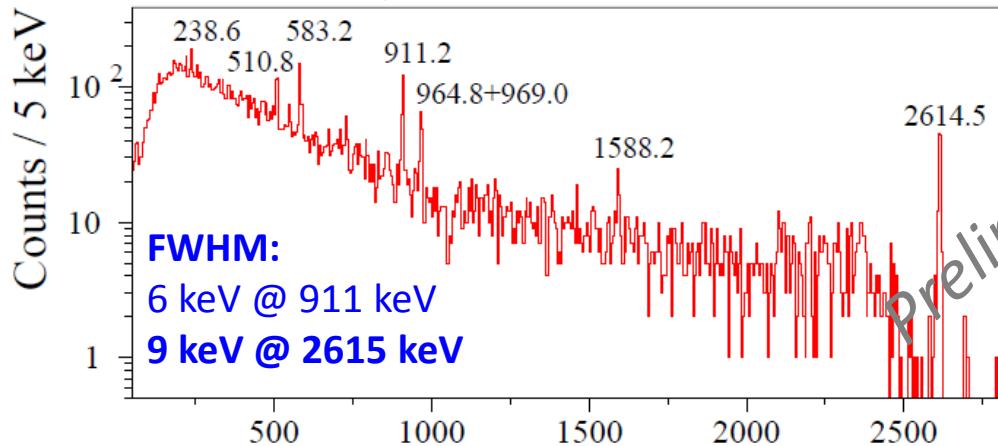
First large enriched LMO



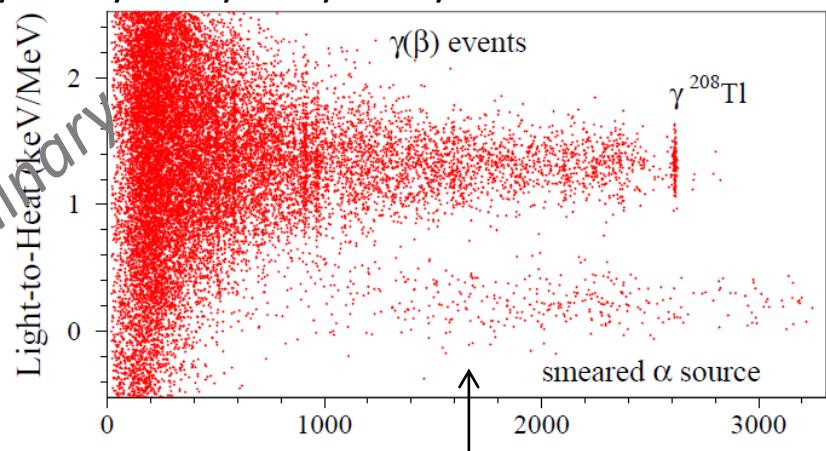
Courtesy A. Giuliani

Tests at LNGS: Excellent performance of large enriched Zn¹⁰⁰MoO₄ and large natural Li₂MoO₄ scintillating bolometers

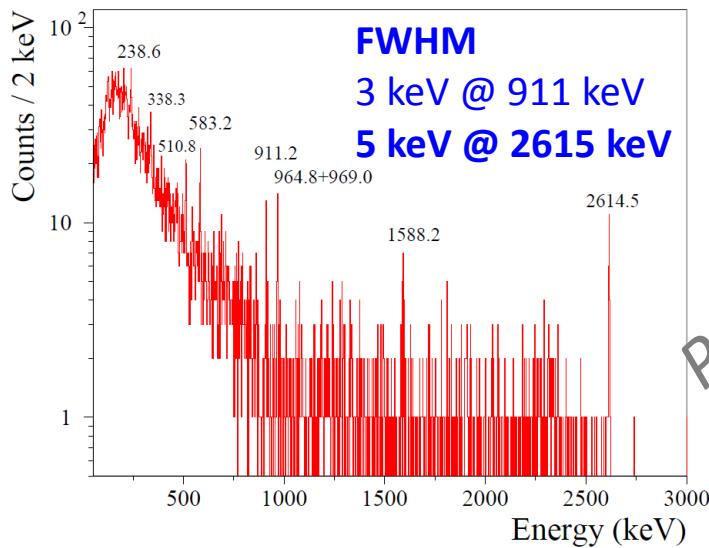
Enriched ZMO – M ~380 g



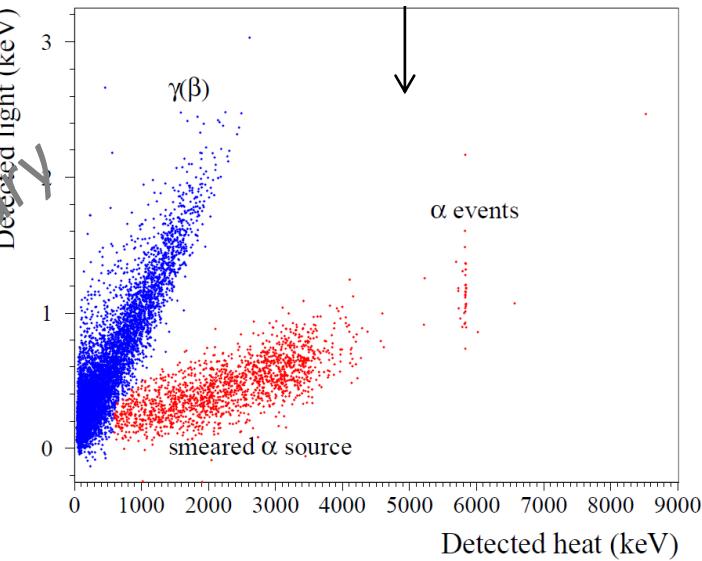
CNRS/INFN/IRFU/ITEP/KINR/NIIC collaboration
 CNRS/INFN/IRFU/ITEP/KINR/NIIC collaboration



Natural LMO – M ~240 g (Enriched LMO test imminent)



Excellent rejection of α background



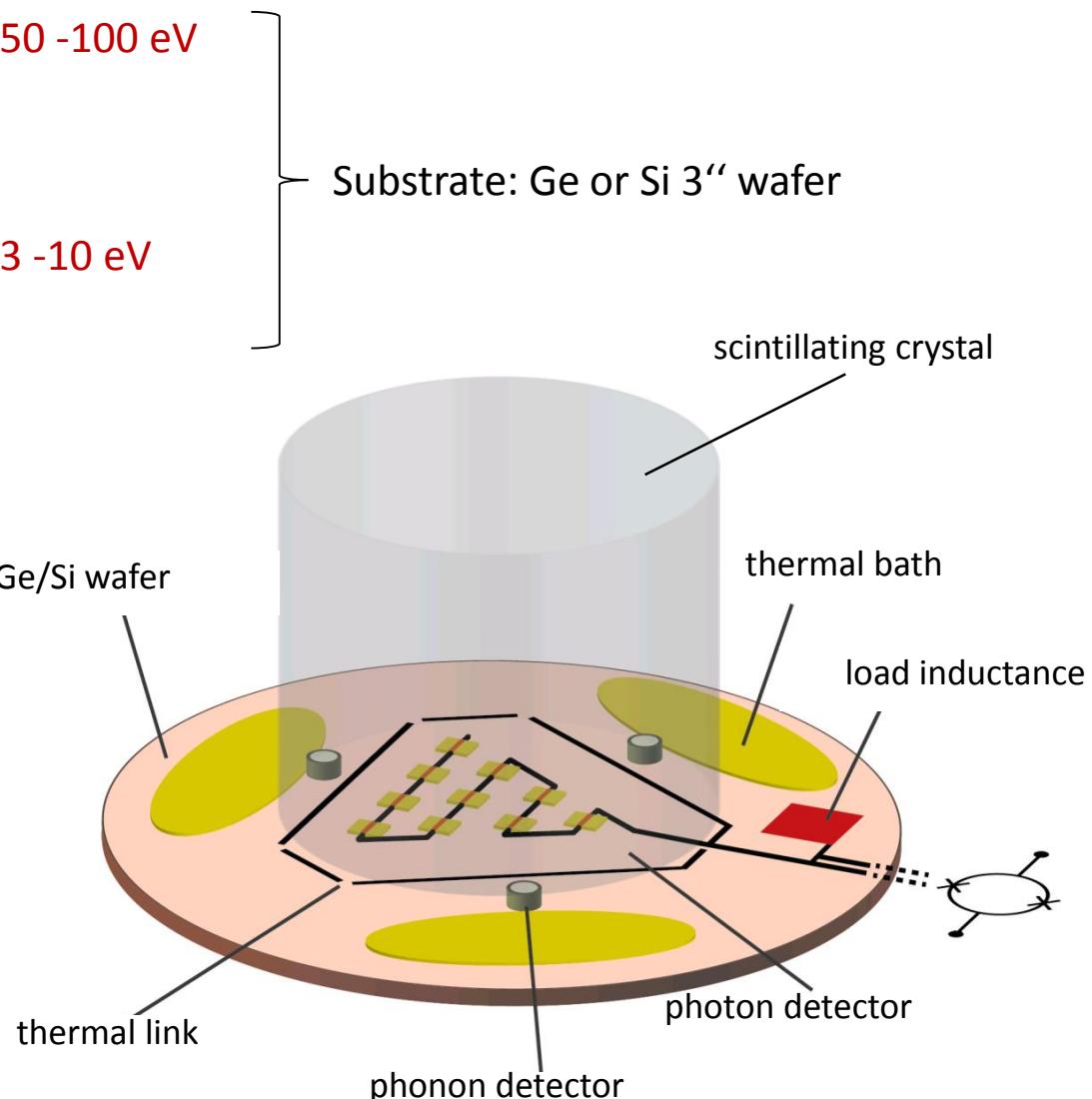
Courtesy A. Giuliani

7 kg ¹⁰⁰Mo zero-background run in preparation (40 crystals) $\rightarrow M_{\beta\beta} < 80\text{-}230 \text{ meV in } 2.5 \text{ y}$

Combined Photon and Phonon Detector with MMC's

- Phonon detector:
 - energy resolution $\Delta E_{FWHM} = 50 - 100 \text{ eV}$
 - rise time $\tau < 200 \mu\text{s}$
- Photon detector:
 - energy resolution $\Delta E_{FWHM} = 3 - 10 \text{ eV}$
 - rise time $\tau < 50 \mu\text{s}$
- A minimum of (contaminated?) parts
- Position sensitivity, if wanted
- Two light detectors per crystal

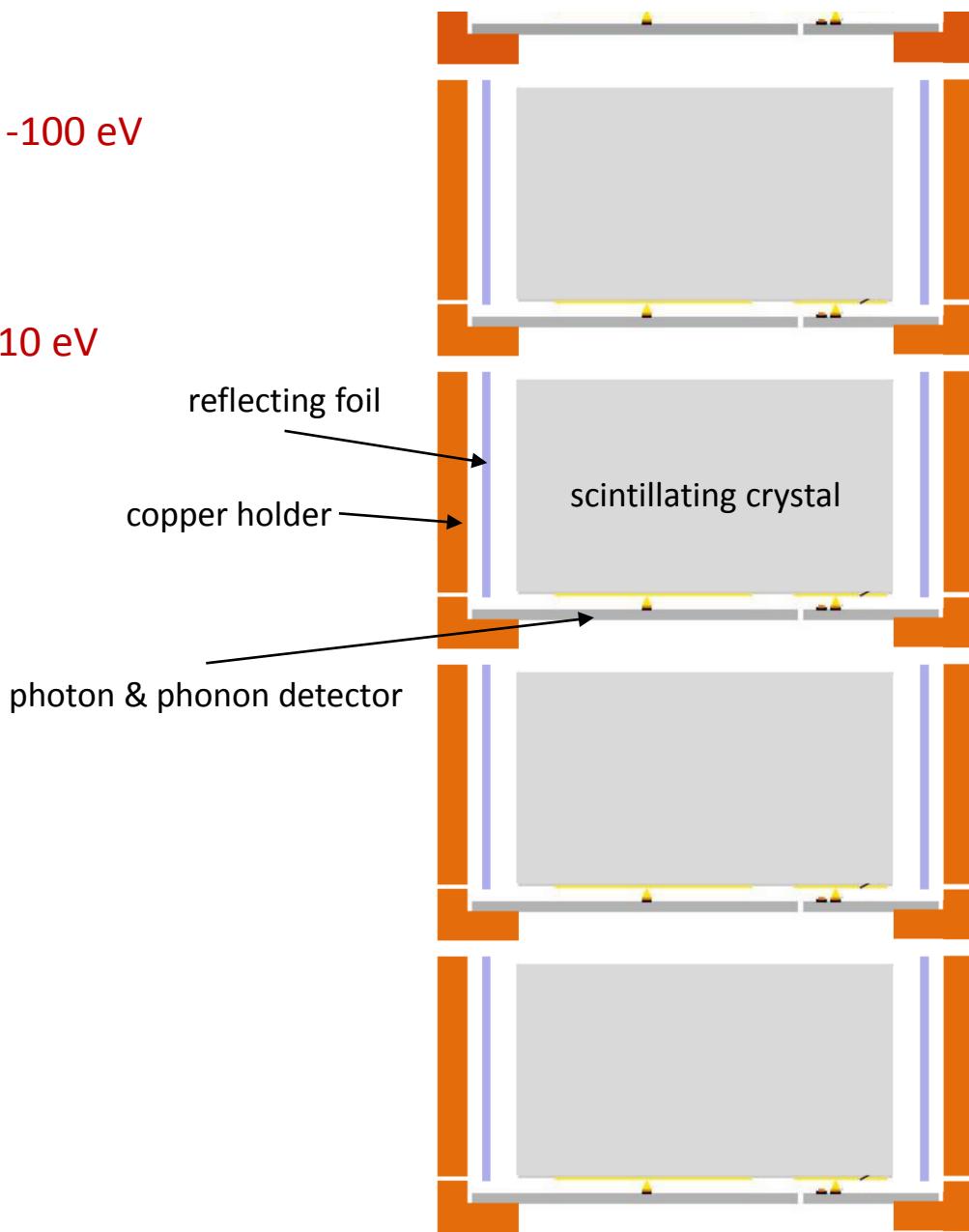
→ reduce and discriminate
intrinsic contamination background



Combined Photon and Phonon Detector with MMC's

- Phonon detector:
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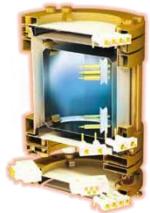
→ reduce and discriminate
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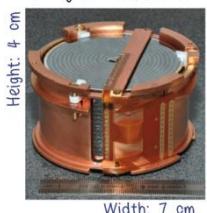
Summary & Conclusions

DM with cryogenic detectors:

- Unique opportunity to explore low-mass dark matter down to neutrino floor with multiple target materials (CaWO_4 , **Ge**, ...)
- Thresholds for nuclear recoils of 300 eV reached for large detectors achieved
- Upcoming generation: few 10's – 100 eV
- Radio purity of crystals, mount and shielding critical
- **N.B.:** Large mass WIMP search dominated by liquefied noble gas detectors (Xenon, LUX, DEAP, Darkside)



Full Inter-Digitized
800 g HP-Ge Detector



DBD with cryogenic detectors:

- Choice of interesting isotopes: ^{130}Te , ^{82}Se , ^{100}Mo , (^{48}Ca)
- Cuoricino/Cuore-0/Cuore pioneering experiments
- Interesting, because most cost efficient: enriched TeO with Cherenkov read out for alpha background suppression
- Major progress by Lucifer (^{82}Se), Lumineu (^{100}Mo) projects – part of CUPID R&D; also Amore (^{100}Mo)
- Plan to use Cuore experimental infrastructure for future CUPID
- **N.B.:** strong concurrence by Ge (GERDA, Majorana), Xe (EXO, nEXO, KLZ, NEXT) and other exp.



Strong synergies between DM and DBD cryogenic communities

- Thermal sensor developments
- light detector developments
- High-purity crystal production

