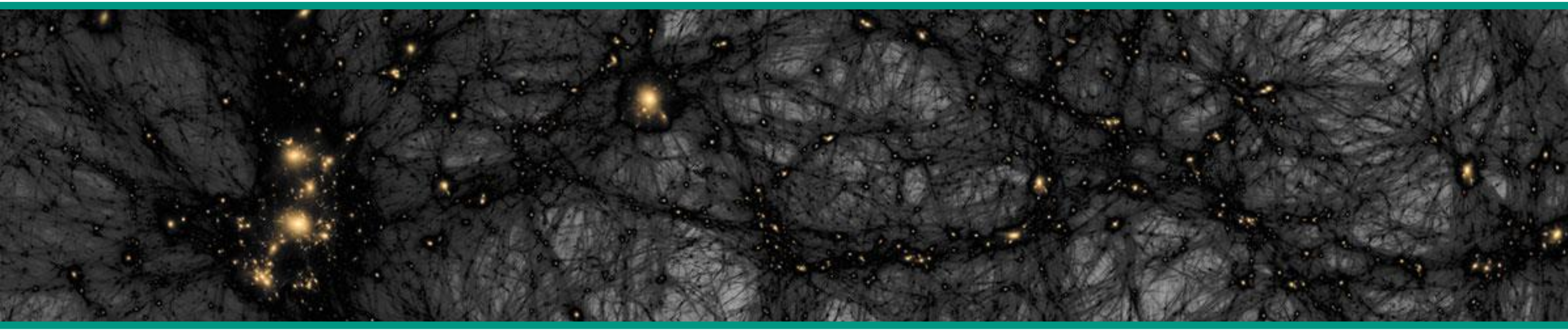
Astroparticle physics I – Dark Matter

WS22/23 Lecture 19 Feb. 2, 2023



Recap of Lecture 18

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Liquid noble gas experiments: 2-phase readout down to the neutrino floor

- $\boldsymbol{TPC}$-setup: liquid & gaseous phase with constant, homogeneous drift field with top & bottom PMT-array
  $\boldsymbol{S1}$: prompt scintillation in $\boldsymbol{VUV}$ – range, $\boldsymbol{S2}$: delayed electroluminescence after drift of $\boldsymbol{e^-}$ & extraction into gas phase

- excellent $\boldsymbol{PID}$ from ration $\boldsymbol{S1/S2}$, also: $\boldsymbol{3D}$-position reconstruction & shielding

- **argon**: use of underground argon & $\boldsymbol{PSD}$ (fraction of early light) current (global) experiment: $\boldsymbol{DarkSide\ 20k}$ at $\boldsymbol{LNGS}$

- **xenon**: cryodistillation to purify, 3 large series of experiments: $\boldsymbol{LZ}$ in the US, $\boldsymbol{XENON}(\boldsymbol{1T, nT})$, $\boldsymbol{DARWIN}$ at $\boldsymbol{LNGS}$, $\boldsymbol{PANDA}$ in Ch

} down to ν – floor

4.5.3 Cryogenic bolometers

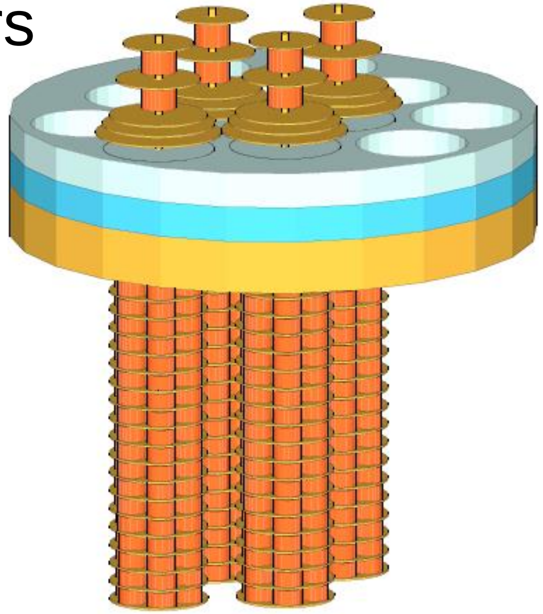
- **Going down to the mK – scale: using phonons in a hunt for light WIMPs**

cryo-bolometers: $Ge, Si, CaWO_4$

many single bolometers
total mass: $< 100\ kg$
⇨ large rel. surface

energy threshold:
very small $< 1\ keV$

sensitivity to very
light WIMPs (MeV ... GeV scale)

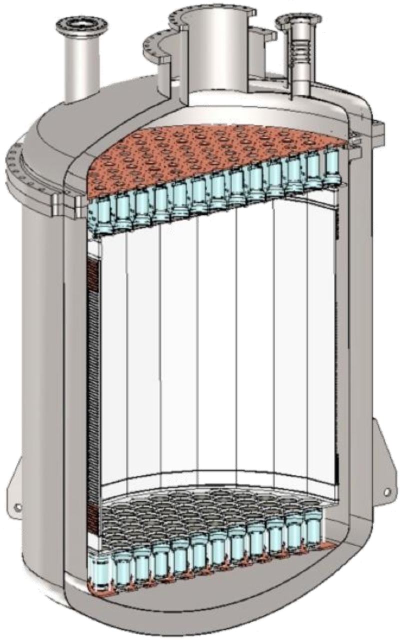


2-phase noble gas TPCs: Xe, Ar

TPC with large volume
total mass: up to $50\ t$
⇨ small rel. surface

energy threshold:
rather high $\sim 4 - 10\ keV$

sensitivity to very
heavy WIMPs (GeV ... TeV scale)



Cryogenic bolometers vs. liquid noble gas

- **Going down to the mass $m = g -$ scale: profiting from a large WIMP flux**

cryo-bolometers: $Ge, Si, CaWO_4$

many single bolometers

total mass: $kg \rightarrow g$ **scale**

for high fluxes Φ_{DM}

energy threshold:

$< 100\ eV$ ...

sensitivity to very

small xsecs (down to ν –floor)

2-phase noble gas TPCs: Xe, Ar

TPC with large volume

large $\varnothing = 2 \ldots 3\ m$

for small fluxes Φ_{DM}

energy threshold:

rather high $\sim 4 - 10\ keV$

sensitivity to very

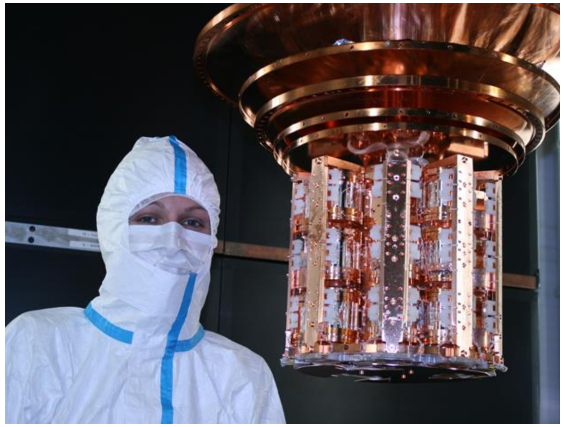
small xsecs (down to ν –floor)

Cryogenic bolometers: WIMP recoil spectra

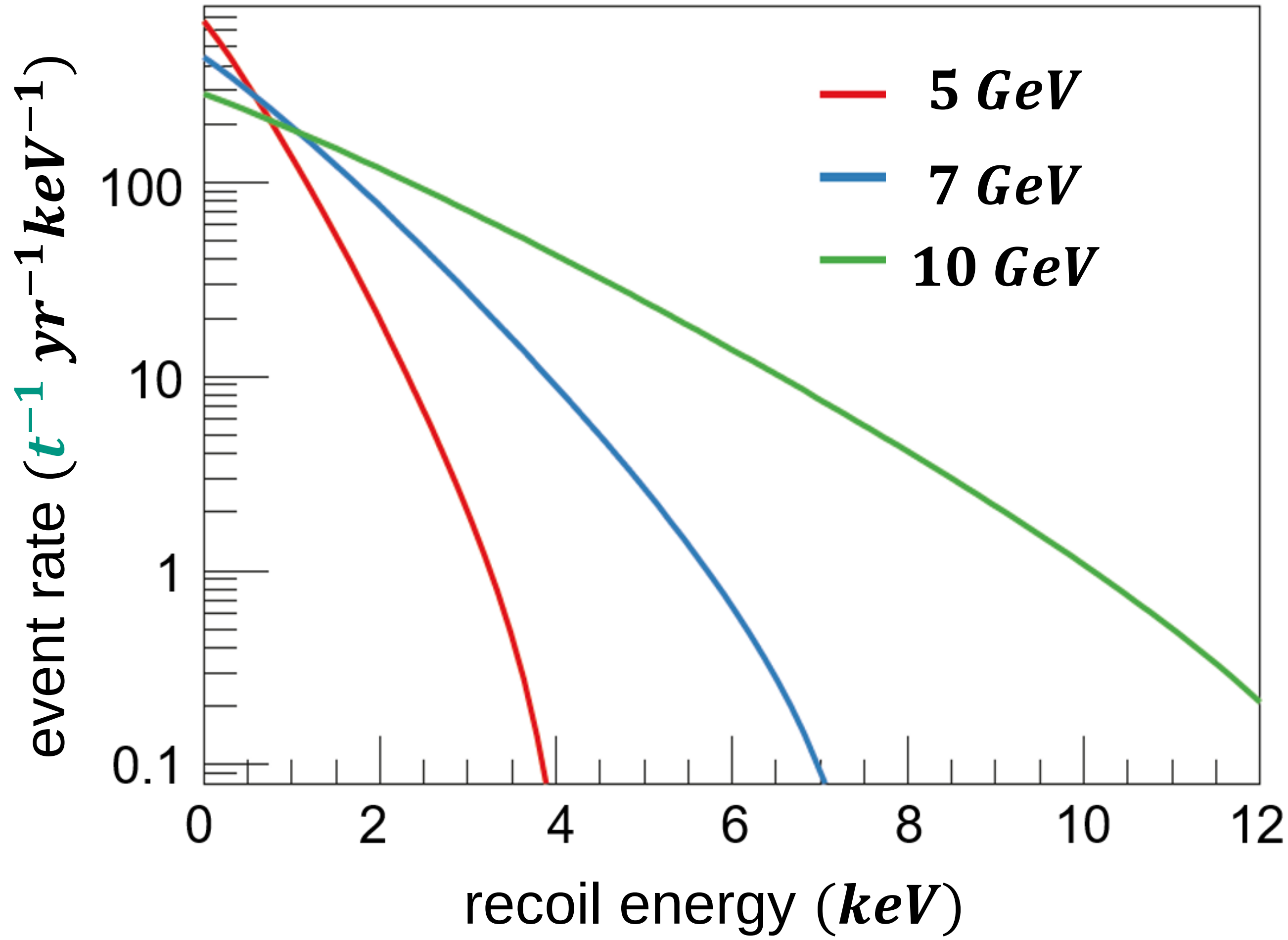
- Hunting very light WIMPs: a very low energy threshold is important

cryo-bolometers: $Ge, Si, CaWO_4$

⇨ improve charge/light readout



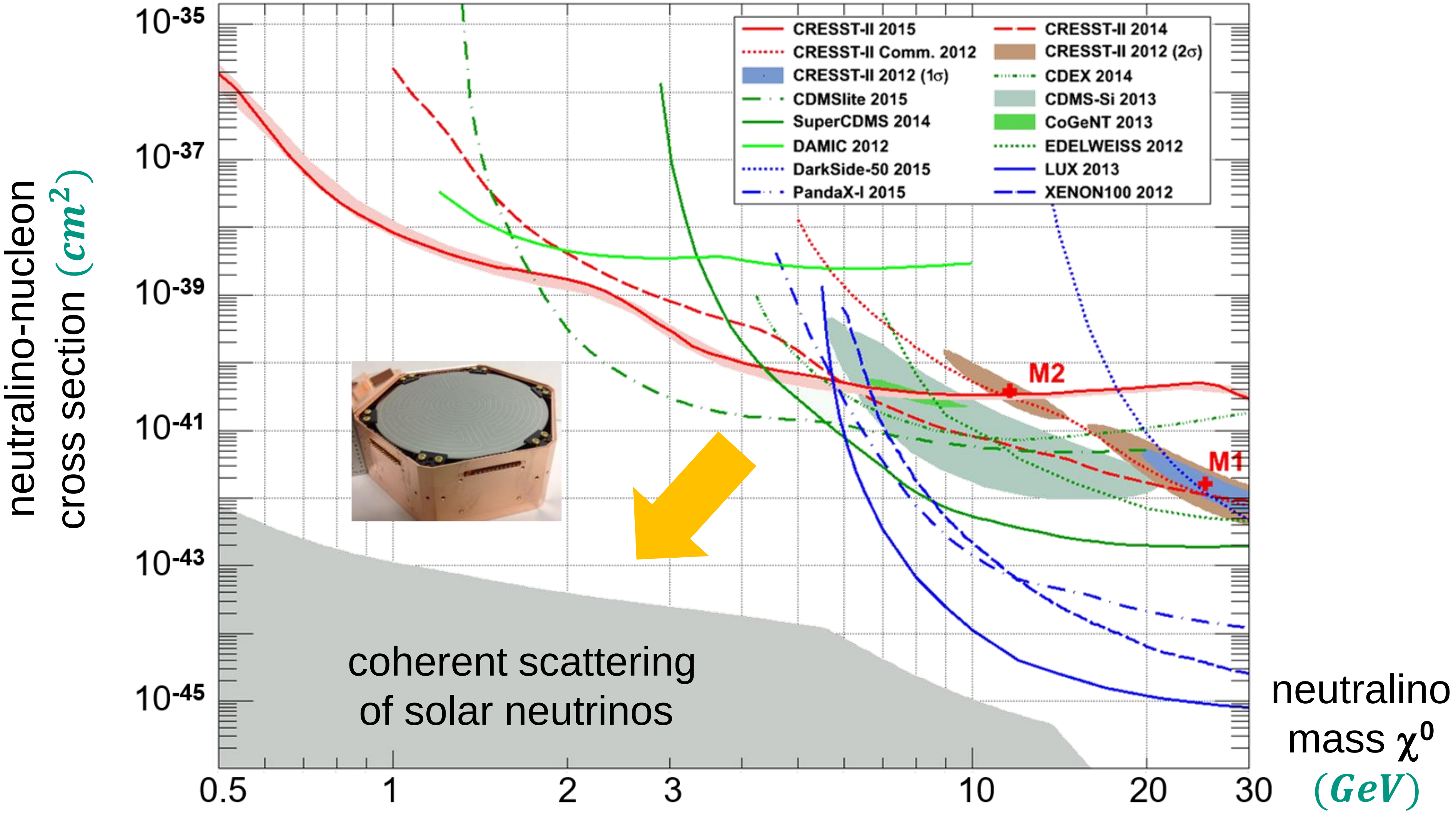
sensitivity to very
light WIMPs (MeV … GeV scale)



Cryogenic bolometers: explore low mass WIMPs

- **Light WIMPs**

  - development of novel, small scale bolometers with an extremely low threshold to push forward deep into the $sub-GeV$ mass region of WIMPs down to $\nu-$ **floor**



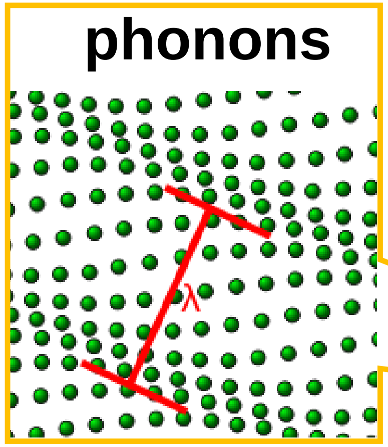
Cryogenic bolometers: fundamental principle

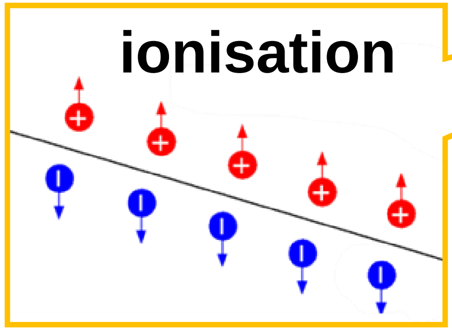
- **How does a low temperature bolometer detect WIMP recoils?**

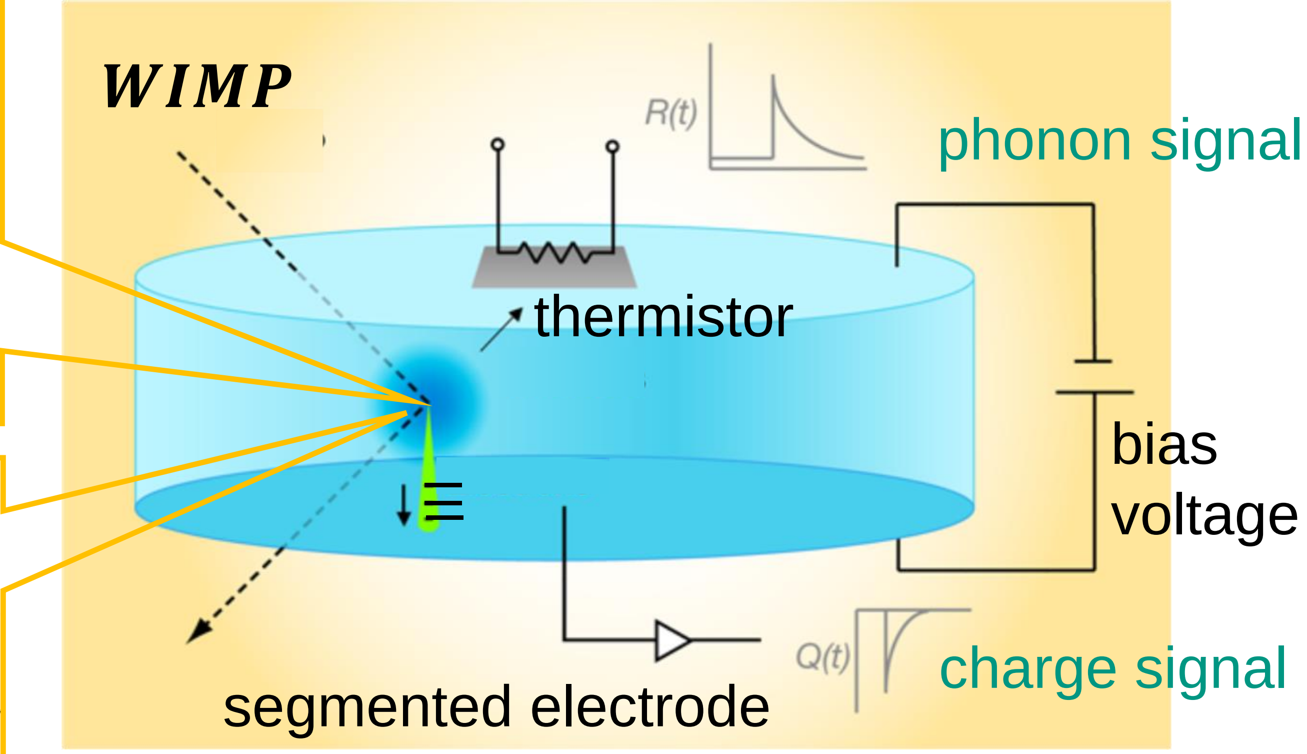
- **phonon signal**: read-out of **nuclear recoil energy** E_R via a **thermistor**

- PID:
  via **light signal** or
  via **charge signal**

quenching







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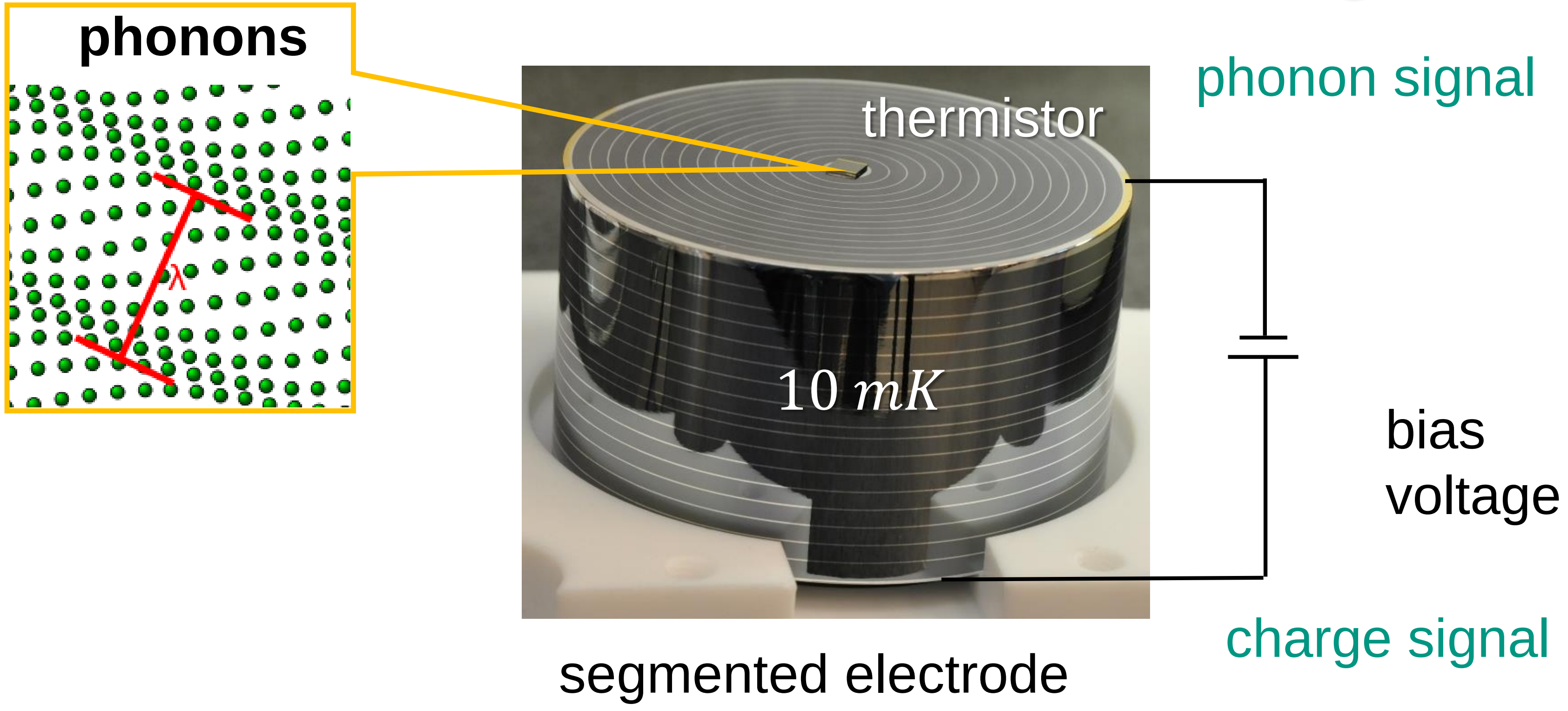


Cryogenic bolometers: phonons & ionisation

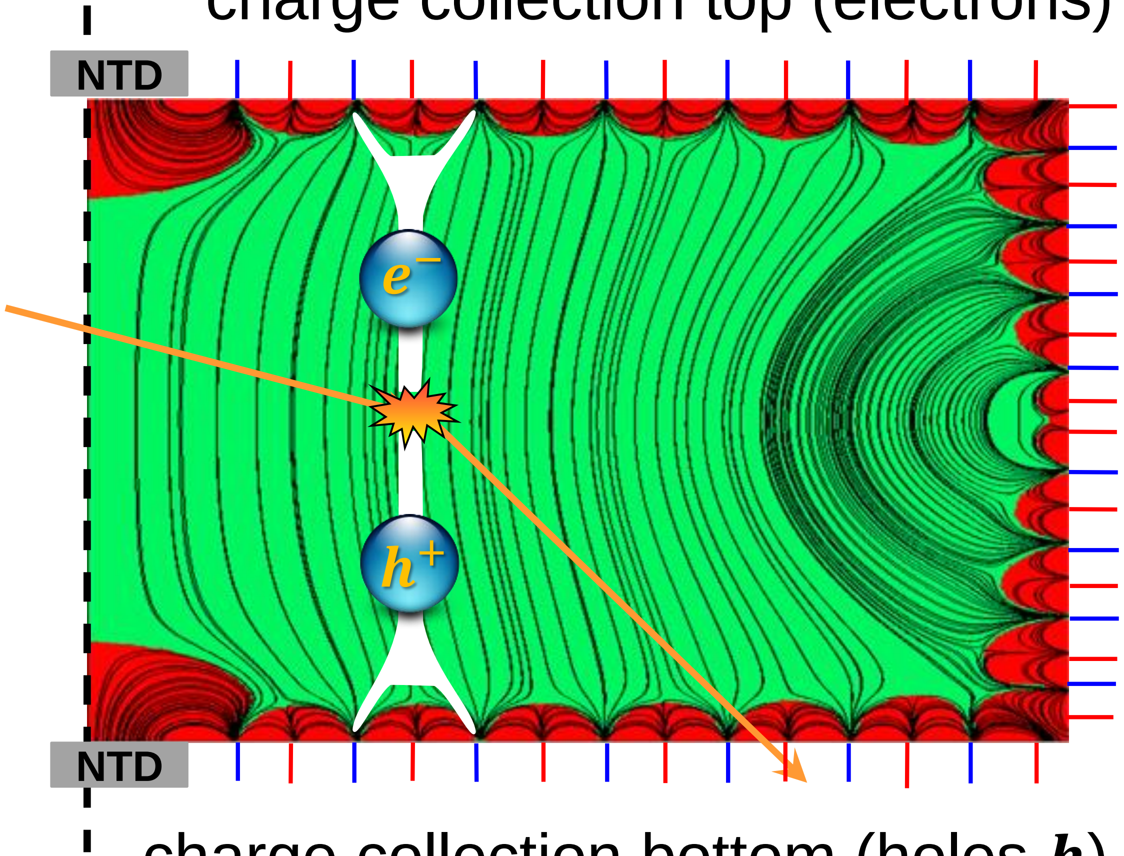
- Ge – bolometers at the mK – scale: read-out of the charge signal

  - detector mass $m < 1\ kg$
    ⇨ low E_{thres} for light WIMPs

  - electrodes are optimized for charge transport as well as for reduction of background

  - segmented electrodes with different potentials allow to fine-form the drift field E_D

charge collection top (electrons)



charge collection bottom (holes h)

Cryogenic bolometers: properties for DM-search

- **Advantages of bolometers of Ge, Si or $CaWO_4$**

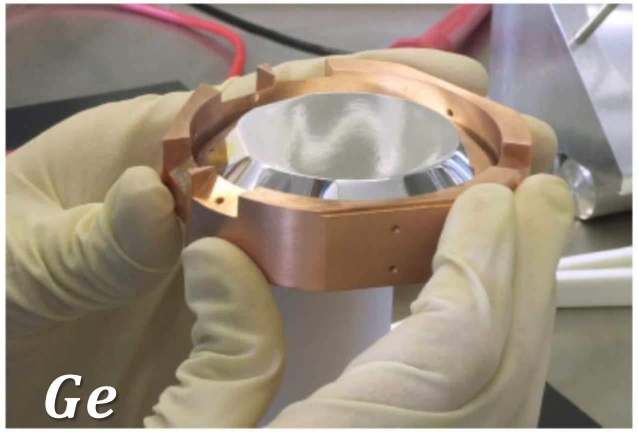
  - only $\Delta E \sim 10\ meV$ to produce a primary phonon

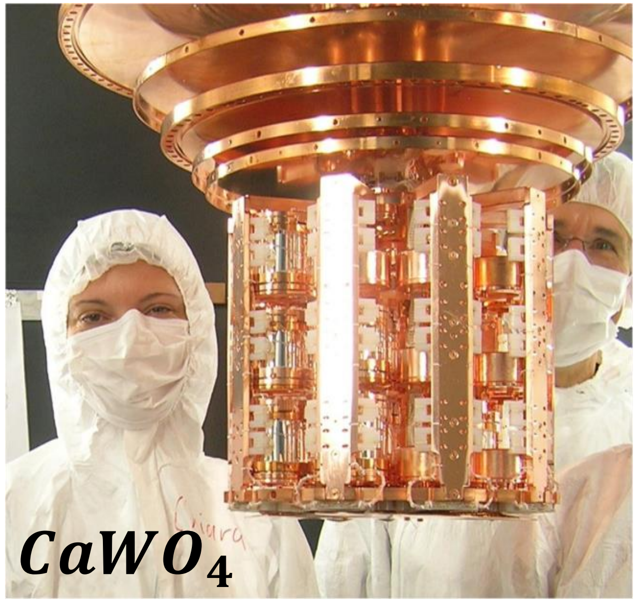
  - result: exceedingly low energy threshold (light WIMPs)

  - good energy resolution ($\sim 150\ eV\ @\ 6\ keV$)

  - combining phonons with ionisation or scintillation:
    ⇨ **quenching** for nuclear recoils
    ⇨ suppression of gammas & electrons

  - **modular setup**:
    ⇘ can be scaled up & expanded at later times
    if necessary: single detectors can be exchanged





Cryogenic bolometers: properties for DM-search

- **Disadvantages of bolometers of Ge, Si or $CaWO_4$**

- read-out of phonon signal requires laborious cryogenic technology to maintain operating temperature of $T \sim 10\ mK$

- read-out is technologically challenging, also signal feedout from $mK \rightarrow RT$

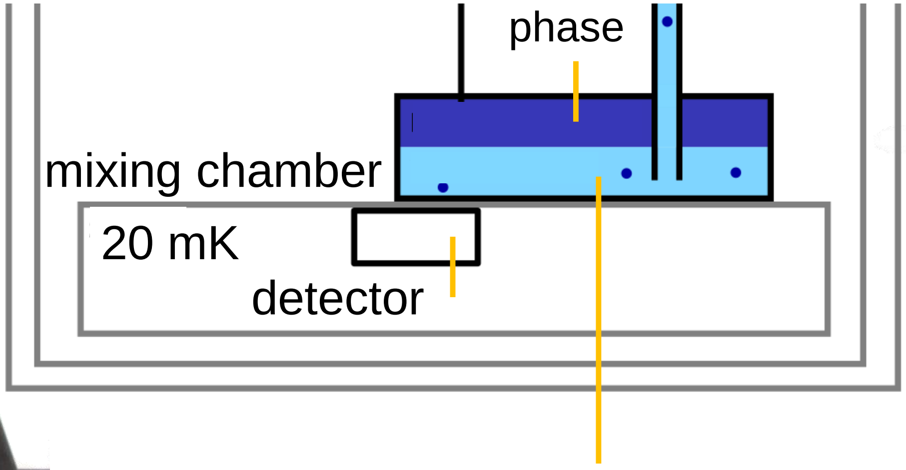
- large number of small bolometers: fiducial volume cut has to be applied to each detector unit individually

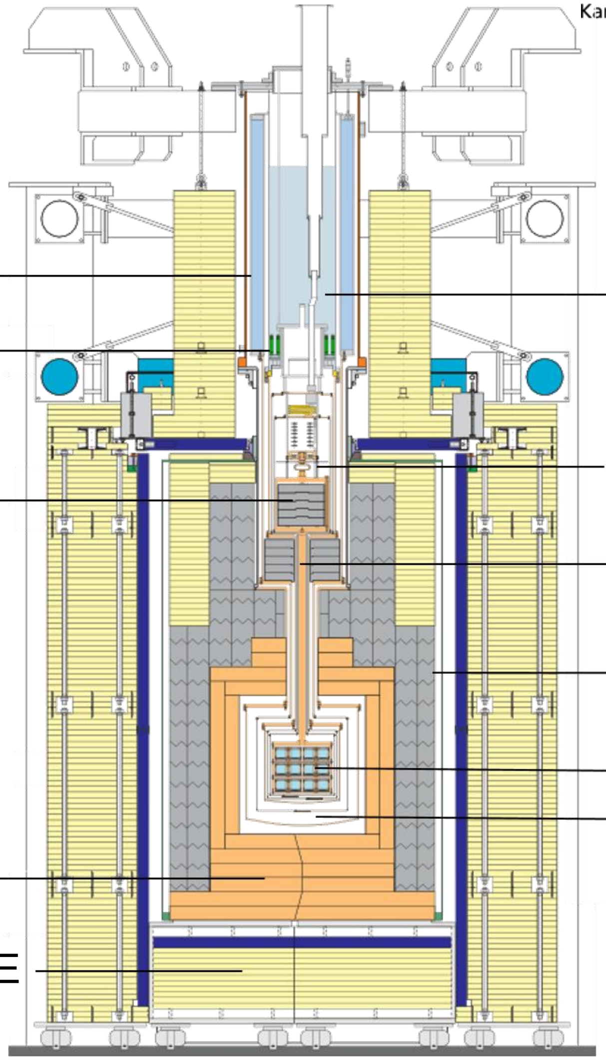
- modular set-up implies a substantial mass for holding structures & read-out cables (potential bg-sources)

RT = Room Temperature

Cryogenic bolometers: mixing cryostats for mK

- **Commercial dilution refrigerators**
  - ^{3}He / ^{4}He mixing-cryostats are essential infrastructures for the operation of cryobolometers





Cryogenic bolometers: phonon signal

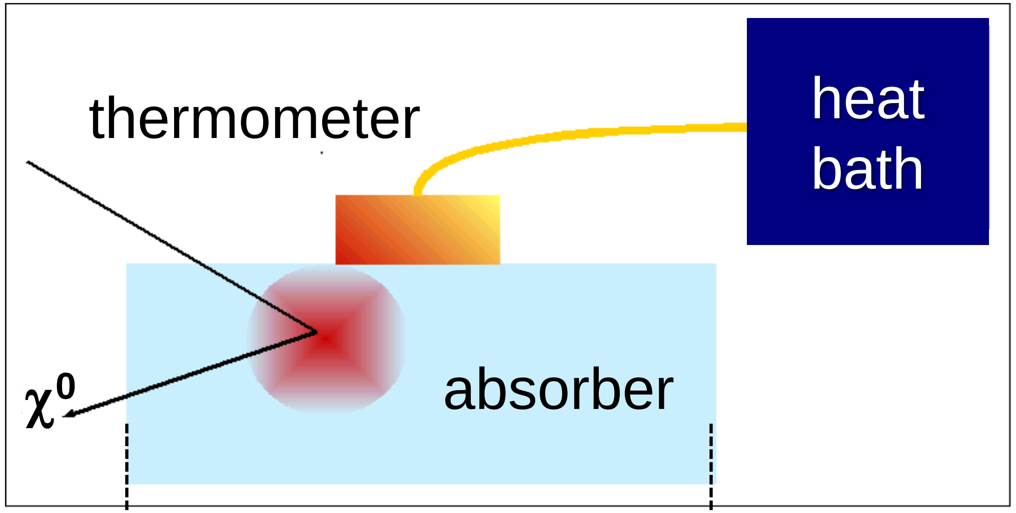
- **How to read out the nuclear recoil signal E_R**

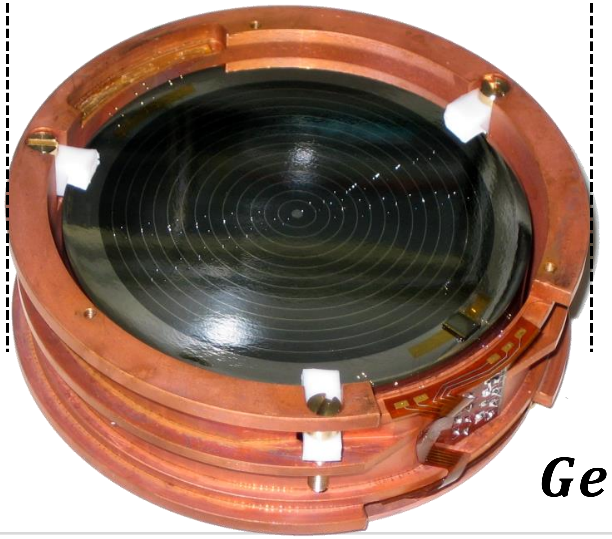
- recoil energy E_R is deposited in bulk material
  ⇨ tiny increase of temperature (μK) of absorber mass m

- parameters of modern bolometers

  mass $m = 100 \ldots 300\ \mathrm{g}$
  temperature $T = 10 \ldots 20\ mK$

- thermometer (´thermistor´):
  ⇨ measures increase of ΔT
  ⇨ weakly coupled to **heat bath** to restore base temperature



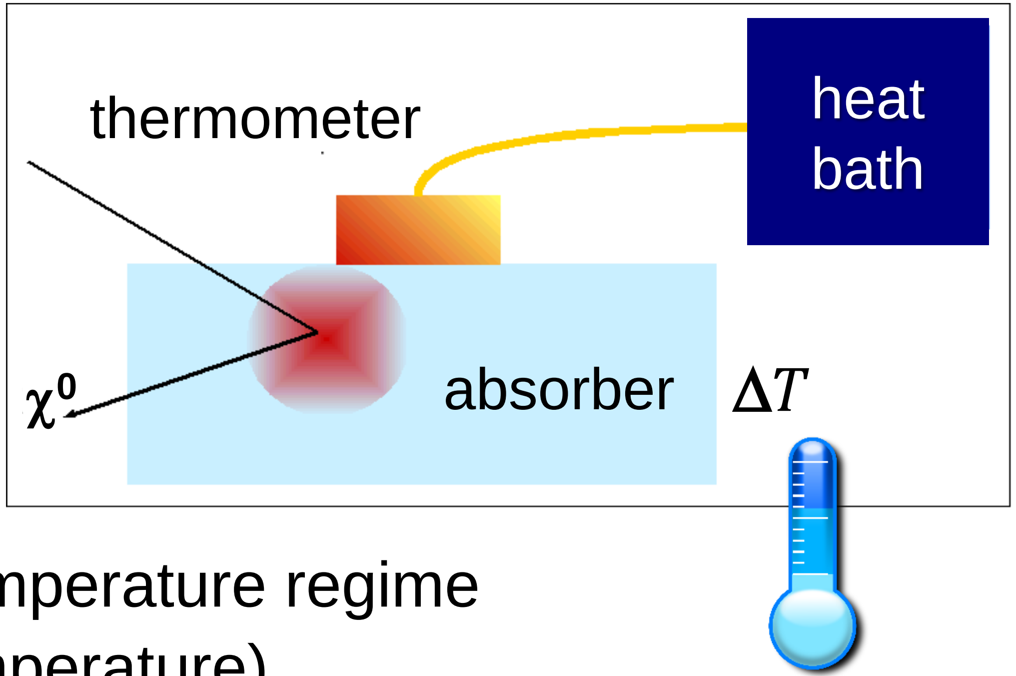


Ge-bolometer

Cryogenic bolometers: specific heat C_V

- **A key task: minimize specific heat C_V**

- we now calculate the temperature increase ΔT of the absorber of volume V



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

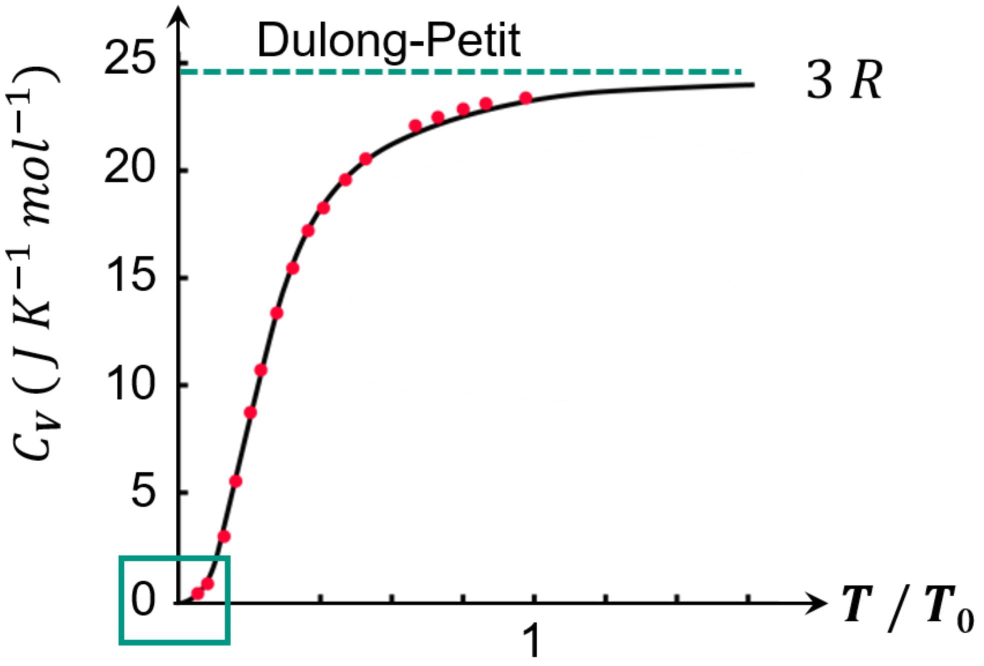
- we recall **Debye´s law** for C_V in the very low temperature regime where bolometers operate: $T \ll T_\Theta$ (Debye temperature)

$$C_V \approx 1 \cdot 10^{18} \frac{\text{keV}}{\text{cm}^3\,\text{K}} \cdot \left(\frac{T}{T_\Theta}\right)^3$$

→ operate bolometer at lowest T possible to minimise value of C_V

Cryogenic bolometers: specific heat C_V

- **A key task: minimize specific heat C_V**



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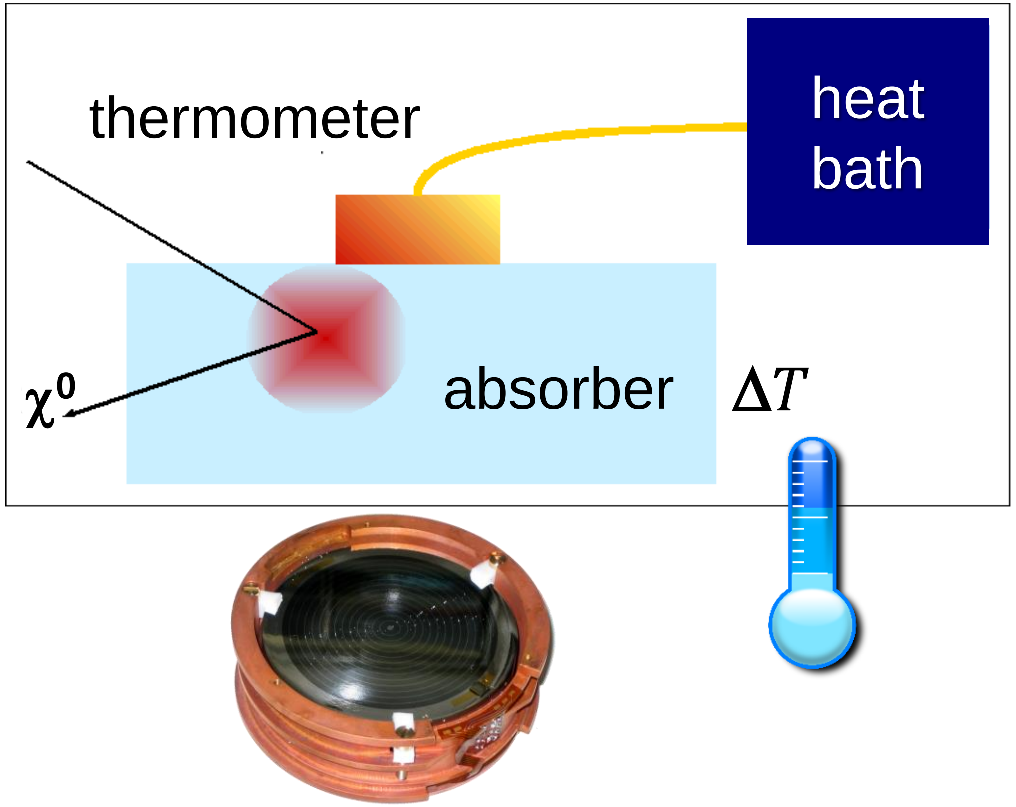


T_Θ = material-specific Debye temperature (Ge: $374\ K$, Si: $645\ K$)

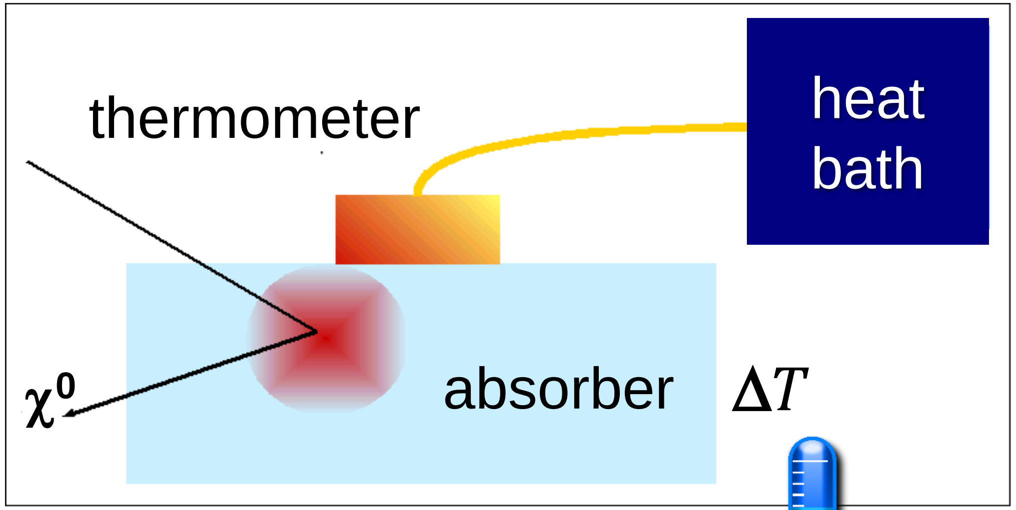
Cryogenic bolometers: specific heat C_V

- **Example for a bolometer with $m = 100\ g$**

$T = 1\ K$	$C_V = 130\ MeV\ \mu K^{-1}$ ✗
$T = 25\ mK$	$C_V = 2\ keV\ \mu K^{-1}$ ✓

- due to the very low recoil energies $E_R \sim keV$
  a bolometer cannot be massive ($m < 1\ kg$)
  & must be operated at the mK – regime

$$C_V \approx 1 \cdot 10^{18} \frac{\text{keV}}{\text{cm}^3\,\text{K}} \cdot \left(\frac{T}{T_\Theta}\right)^3$$



T_Θ = material-specific Debye temperature (Ge: $374\ K$, Si: $645\ K$)

Cryogenic bolometers: charge or light signal

- **perform PID by read-out of second signal**

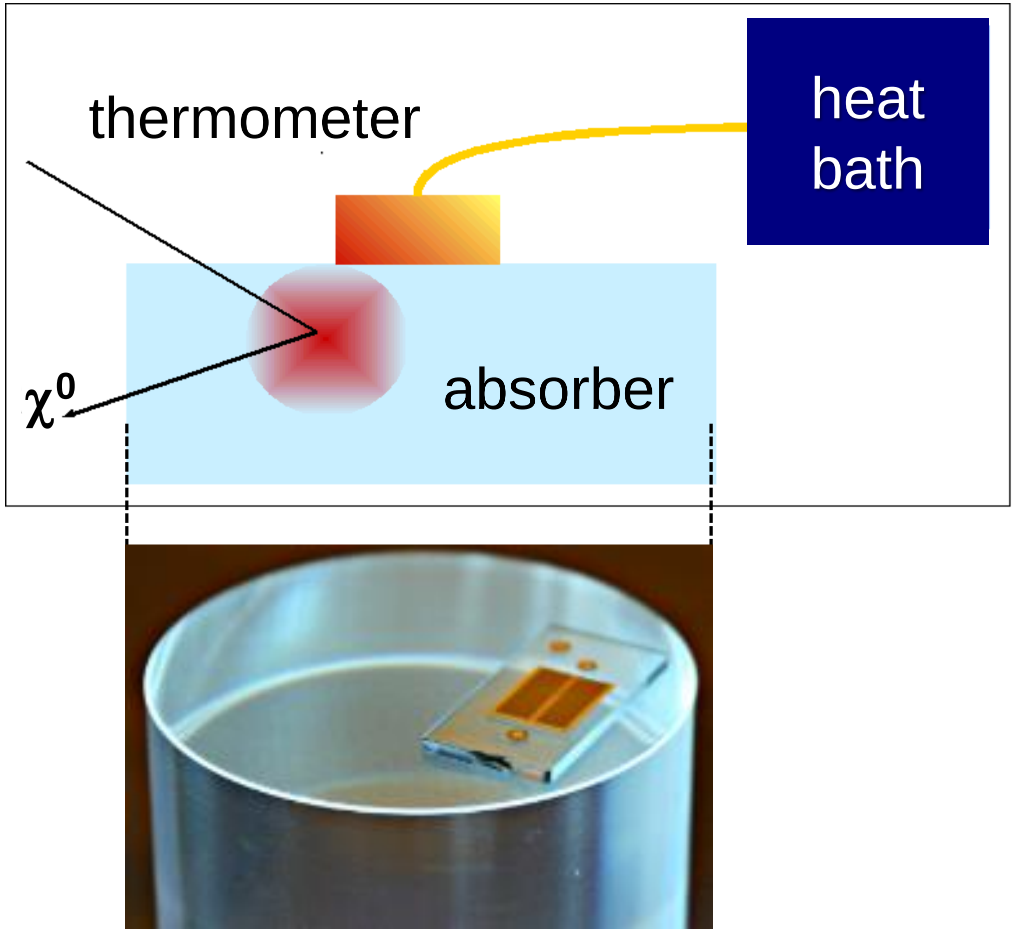
- additional sensors required for read-out of

ionisation

apply bias voltage to generate
electric drift field $\vec{E}_D$
amplify charge signal in amplifier

scintillation

generation of light signal proceeds
via excitons (pseudo-particles)
read-out: often via second thermistor



$CaWO_4$-bolometer

Cryogenic bolometers: properties of phonons

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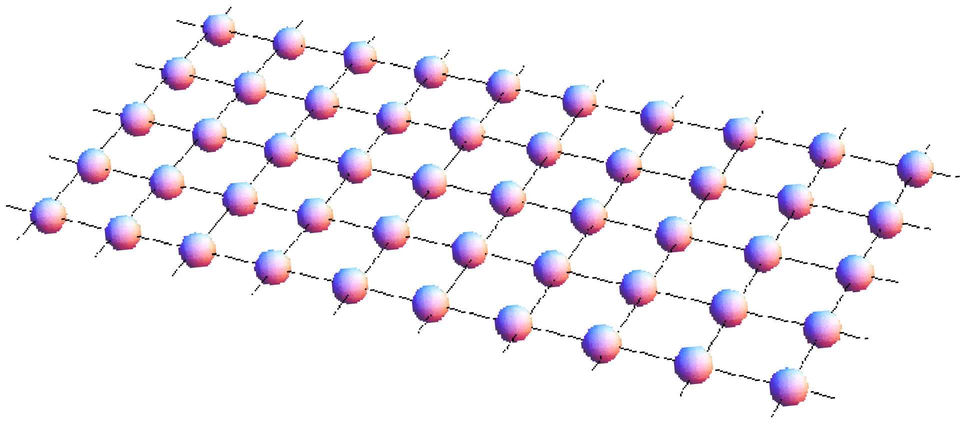
Propagation of a spherical phonon wave in the bolometer

- **3D phonon wave** propagates outward from interaction point at speed of sound

- phonons: elementary lattice vibration
  modes: acoustic / optical
  phonons are **quasi-particles**



- quasi-ballistic phonons: can decay into ballistic phonons

phonon type	energy	thermodyamics*	
quasi-ballistic	$1 \dots 10\ meV$	$E_{ph} \gg k_B \cdot T\ \ (T > 10\ K)$	not in equilibrium
thermal	$< 0.1\ meV$	$E_{ph} \sim k_B \cdot T\ \ (T < 1\ K)$	in equilibrium

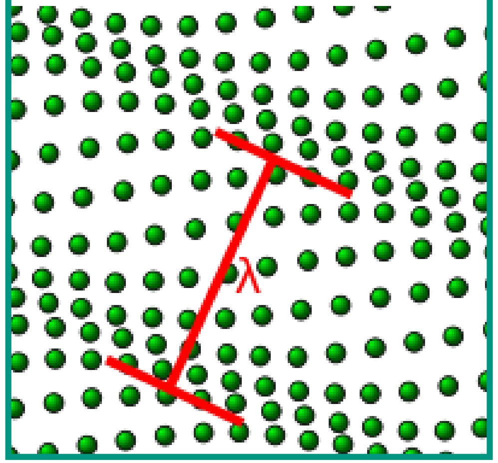
*conversion factor $1\ K \sim 0.1\ meV$

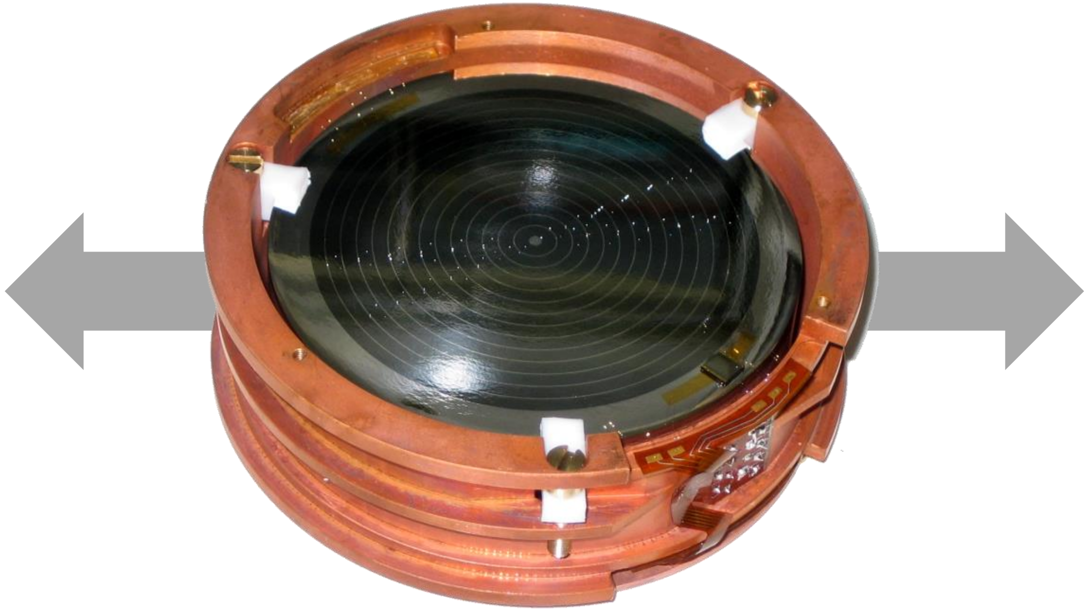
Cryogenic bolometers vs. ionisation

- Comparing energies of phonons to electron-hole pairs

phonons

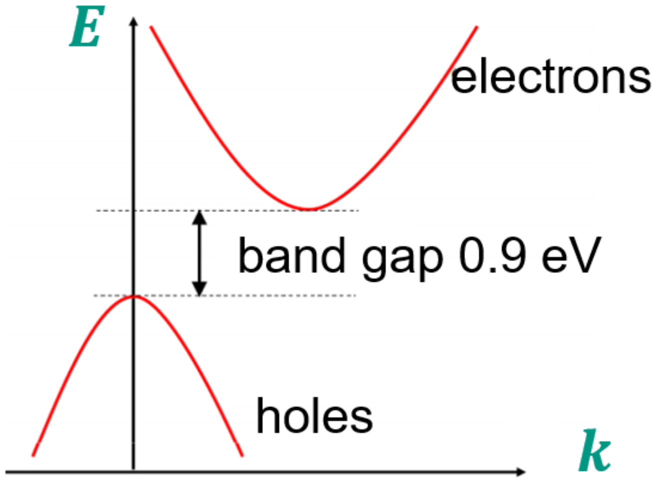
$\Delta E < 1\, meV$





electron-hole pairs

$\Delta E \sim 2.9\, eV$



Cryogenic bolometers: thermistor read-out

- **Thermistors*: a resistor which strongly changes (ΔR) for a small ΔT**

  - a sensor to measure the temperature increase of the absorber material with sensitivity on the $\mu K -$ **scale**

  - optimisation: small $\Delta T \rightarrow$ large sensor signal in the form of a large change ΔR in resistivity

  - phonon read-out via coupling into thermistor

  - high impedance sensors (NTD) for thermal (**slow**) phonons

  - low impedance sensors (TES) for ballistic (**fast**) phonons

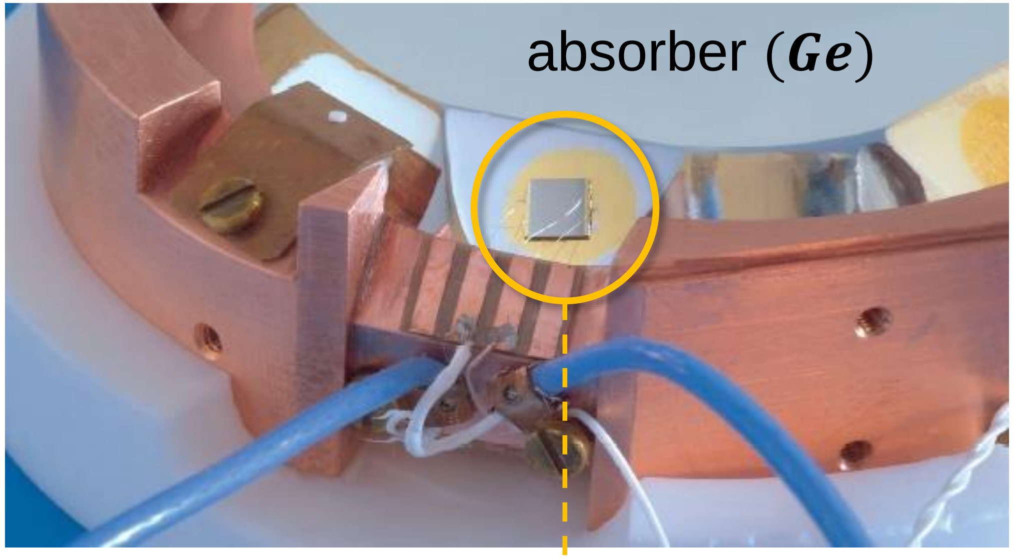
***THERM**ally sensitive res**ISTOR**

Thermistors: high impedance NTD sensors

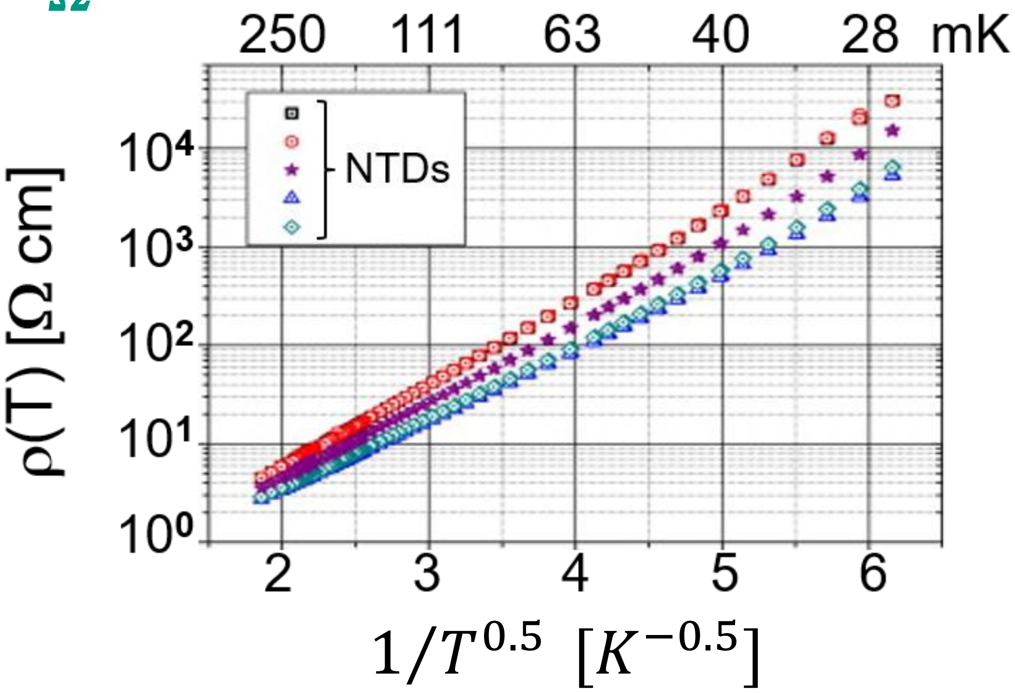
Neutron Transmutation Doped (NTD) germanium sensors

- precise doping of Ge is achieved by multiple **neutron irradiation** campaigns at research reactor: ⇨ optimise performance of high impedance sensors

- $NTD - Ge$ at $30\ mK$: resistivity $R = 10^5 \ldots 10^6\ \Omega$



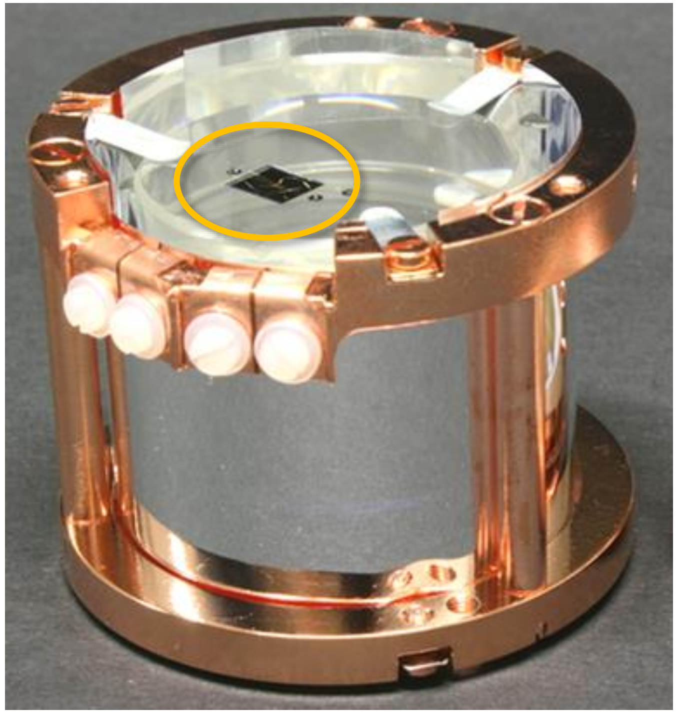
NTD-thermistor for phonon read-out



Thermistors: low impedance TES sensors

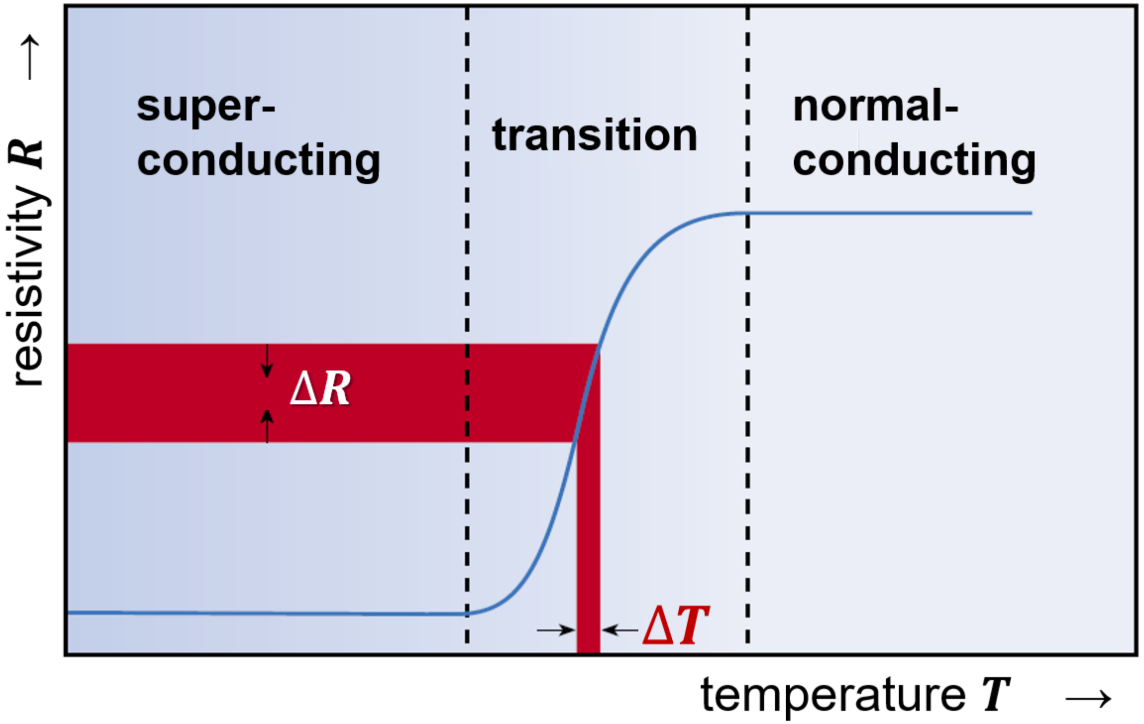
- **Superconducting Transition Edge Sensors (TES)**

  - read-out of (fast) ballistic phonons: operation at the centre of the small (few mK only) transition region in between the s.c. & normal conducting state



TES: tungsten-based thermistor

small ΔT
large ΔR

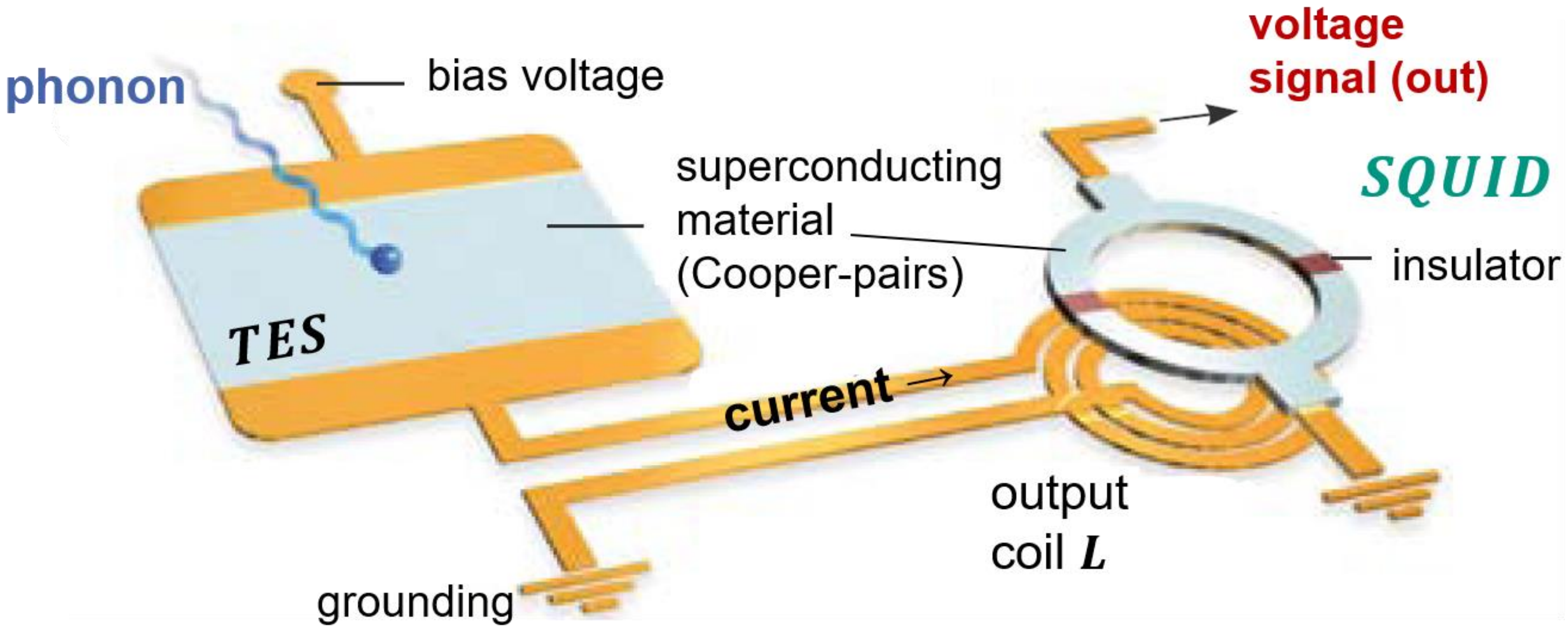


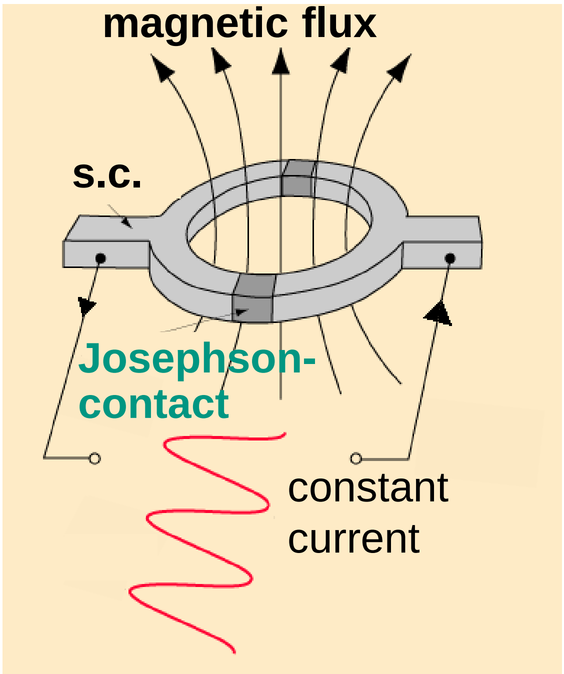
TES – thermistors with $SQUID$ read-out

- a $SQUID$* for TES –readout is based on 2 Josephson contacts

  - formed by a thin niobium ring & 2 Josephson contacts (sensitive to $\Delta B \sim 10^{-18} T$)

  - absorbed phonon in TES: change of current in coil L ⇨ $\Delta\Phi$ of magnetic flux





 *Superconducting Quantum Interference Device

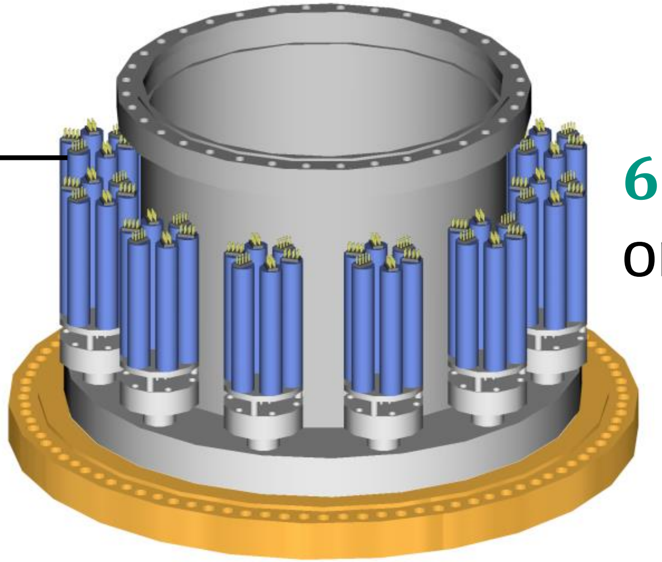
TES – thermistors with $SQUID$ read-out

- **SQUIDs for TES-readout: how is it implemented ?**

  - cooling via suprafluid He

  - technically challenging signal output:
    TES (mK) ⇨ $SQUID$ (LHe) ⇨ electronics (RT)

TES –thermistor
on a crystal



66 $SQUID$s
on He –flange

$SQUID$s

$CRESST$* experiment: phonons & photons

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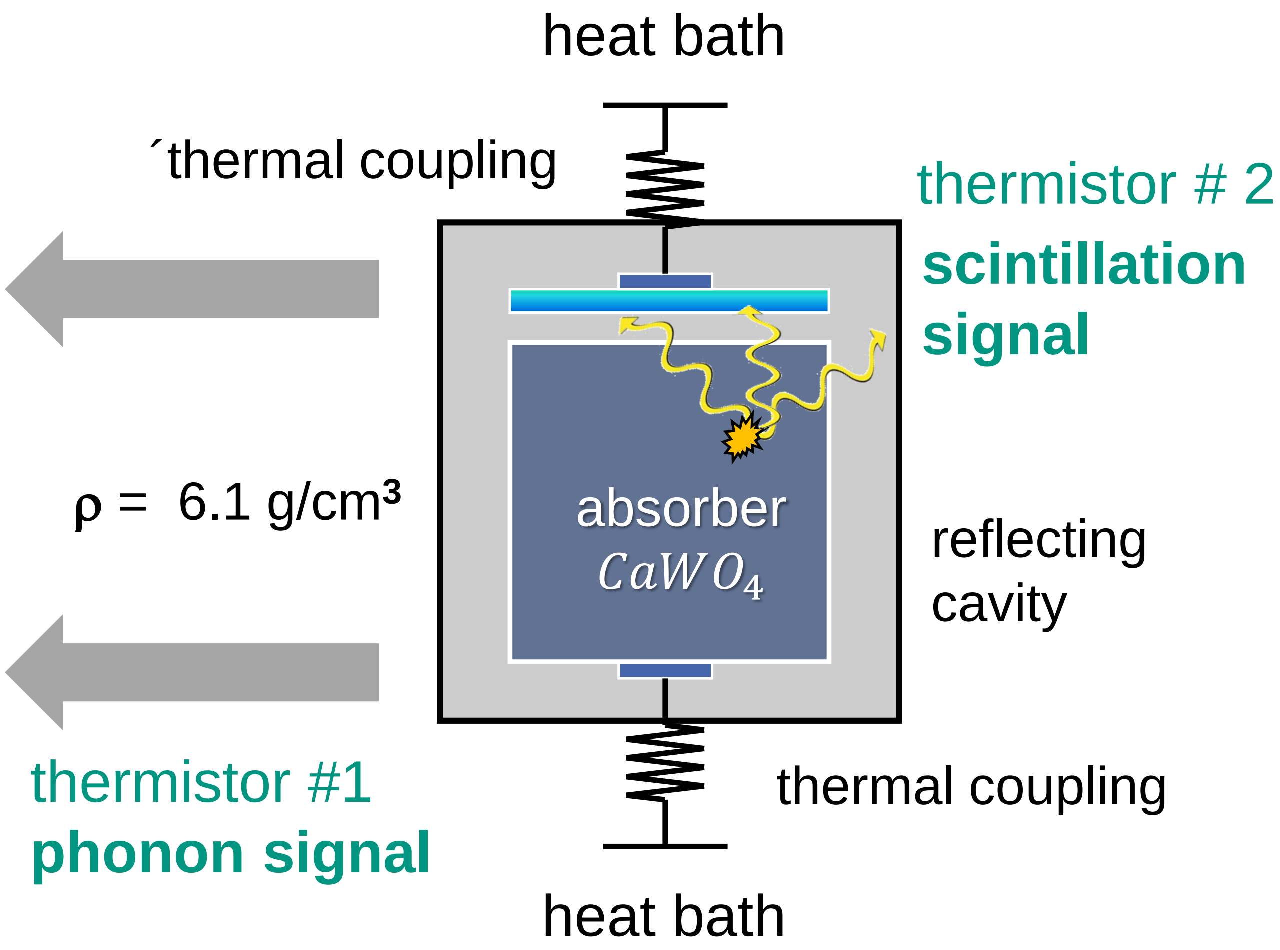
- **Hunting low mass WIMPs with scintillating bolometer crystals of $CaWO_4$**

- scintillation light:
  light emitted from **transparent absorber** is detected via light absorption in thermistor #2 (TES)

- phonon signal:
  ballistic phonons are detected via absorption in thermistor #1 (TES)



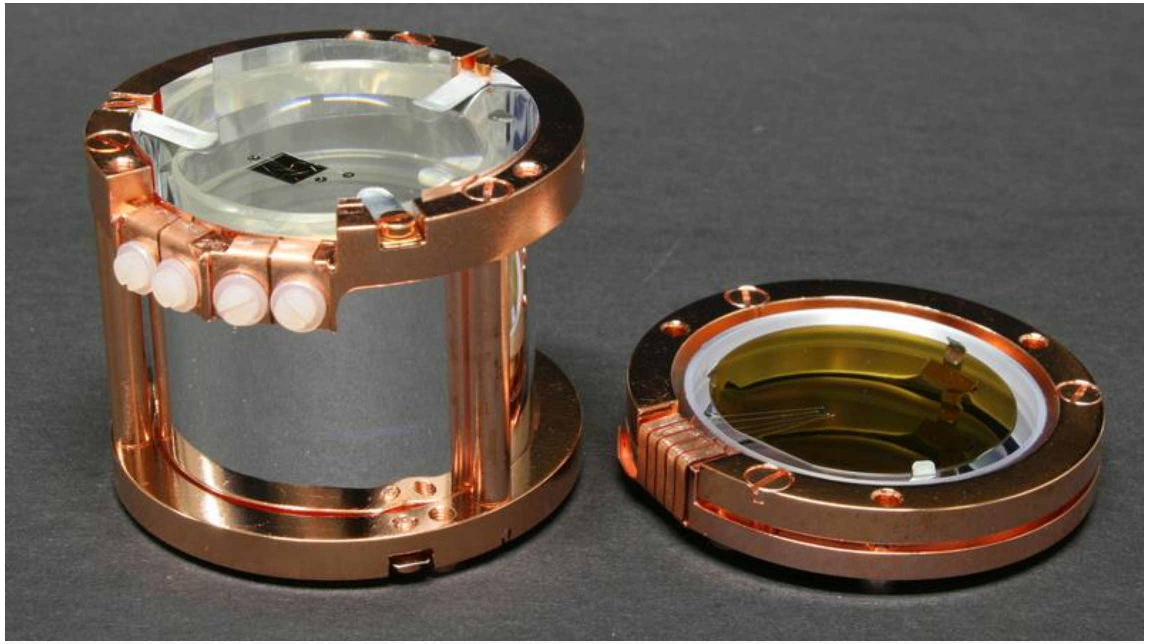
*Cryogenic Rare Event Search with Superconducting Thermometers

$CRESST$ experiment: phonons & photons

- **Hunting low mass WIMPs with scintillating bolometer crystals of $CaWO_4$**

- **scintillation light** from absorber:
  read-out via separate, thin $\boldsymbol{CaWO_4}$ bolometer
  with glued-on $\boldsymbol{TES}$-thermistor

- **phonon signal**
  from absorber:
  read-out via
  with glued-on
  $\boldsymbol{TES}$-thermistor



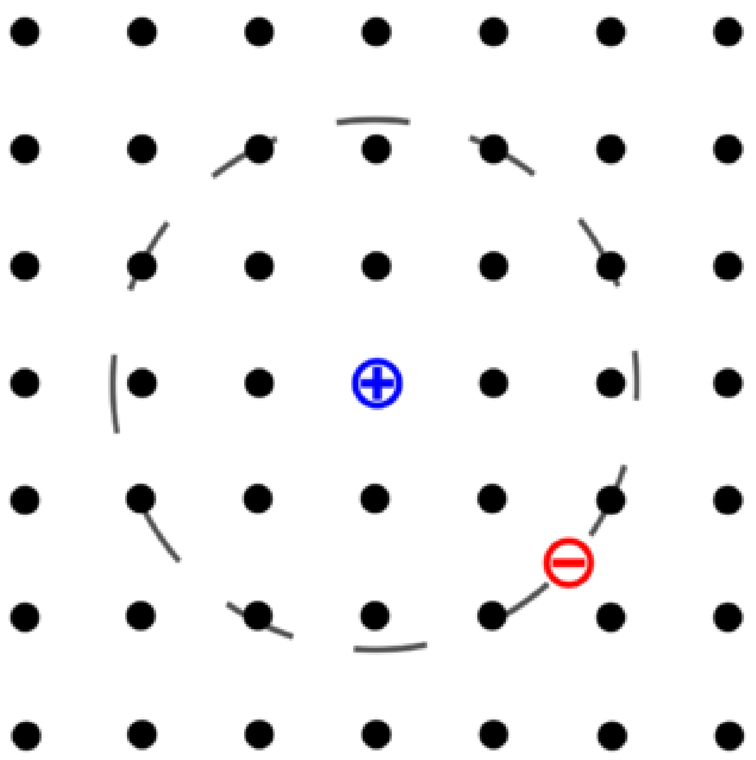
$CRESST$ experiment: scintillation of $CaWO_4$

- **Light emission following the radiative recombination of an exciton**

  - primary particle interaction generates excitons (bound states of electron – hole pairs with binding energy $\mathbf{10}\ \boldsymbol{meV}$ & large radii)

  - **recombination** generates **scintillation light** with constant decay times $\boldsymbol{\tau \approx 1 \mu s}$ for temperature regime $\boldsymbol{T = 20\ mK \ldots\ 4.2\ K}$

exciton



$CRESST$ experiment: scintillation of $CaWO_4$

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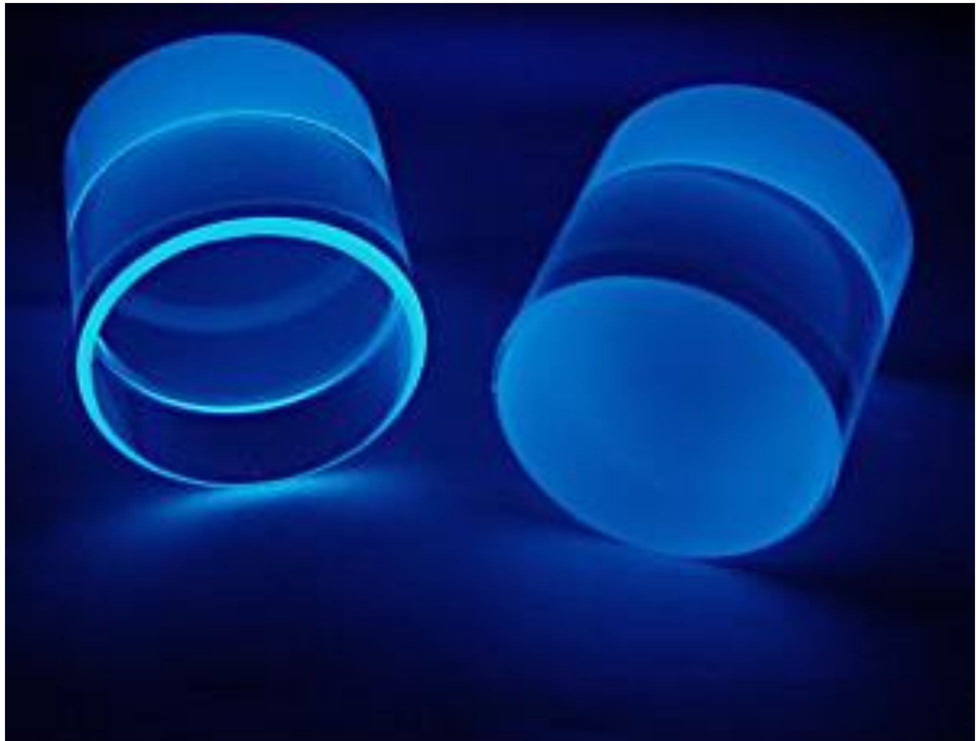
- **Light emission following the radiative recombination of an exciton: ~1% of recoil energy is detected as light with $\lambda_{max} = 420\ nm$**

- primary particle interaction generates excitons (bound states of electron – hole pairs with binding energy $\mathbf{10\ meV}$ & large radii)

- **recombination** generates **scintillation light** with constant decay times $\boldsymbol{\tau \approx 1\mu s}$ for temperature regime $\boldsymbol{T = 20\ mK}$ ... $\mathbf{4.2\ K}$



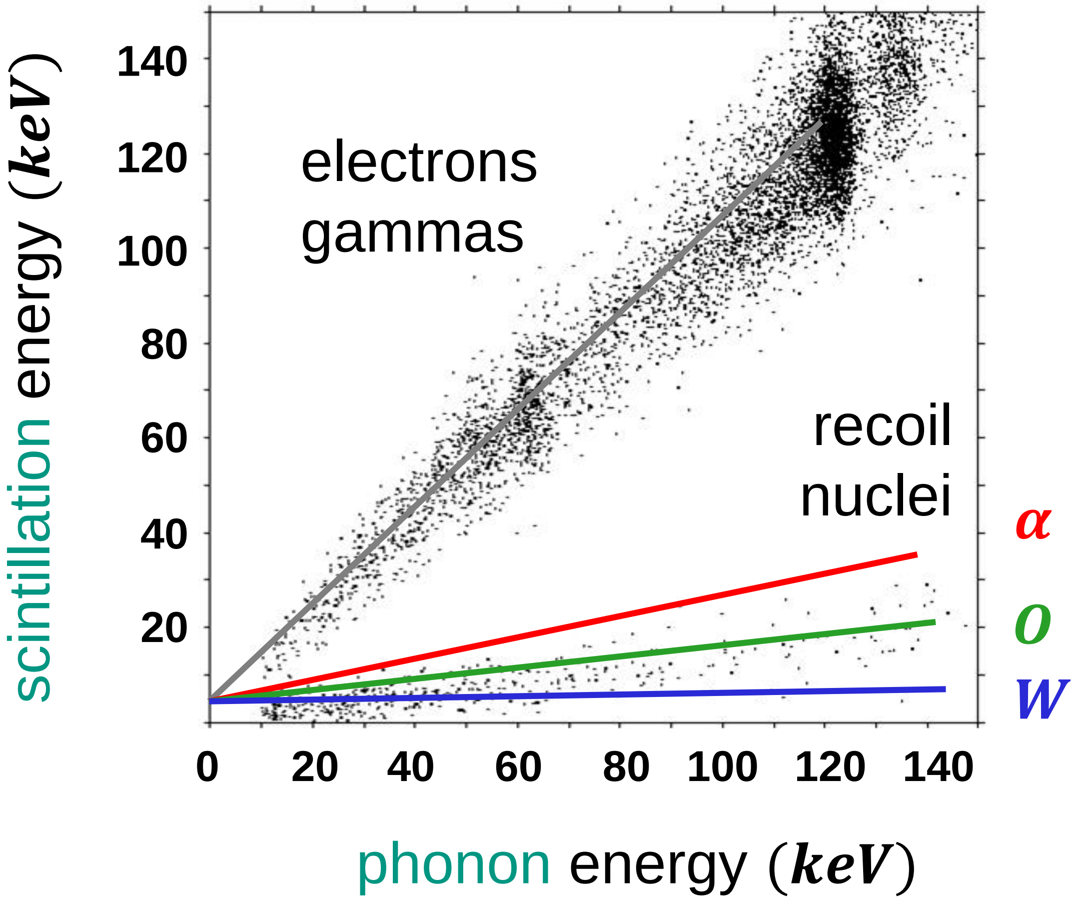
scintillation light from $CaWO_4$

$CRESST$ experiment: good PID in $CaWO_4$

■ **Light signal from exciton recombination is quenched for nuclear recoils**

- nuclear recoils:
  due to the **high energy loss dE/dx**
  excitons will undergo non-radiative recombination ⇨ **quenching**

- nuclear recoils:
  amount of quenching (see picture) verified by experimental studies



$CRESST$ experiment: good PID in $CaWO_4$

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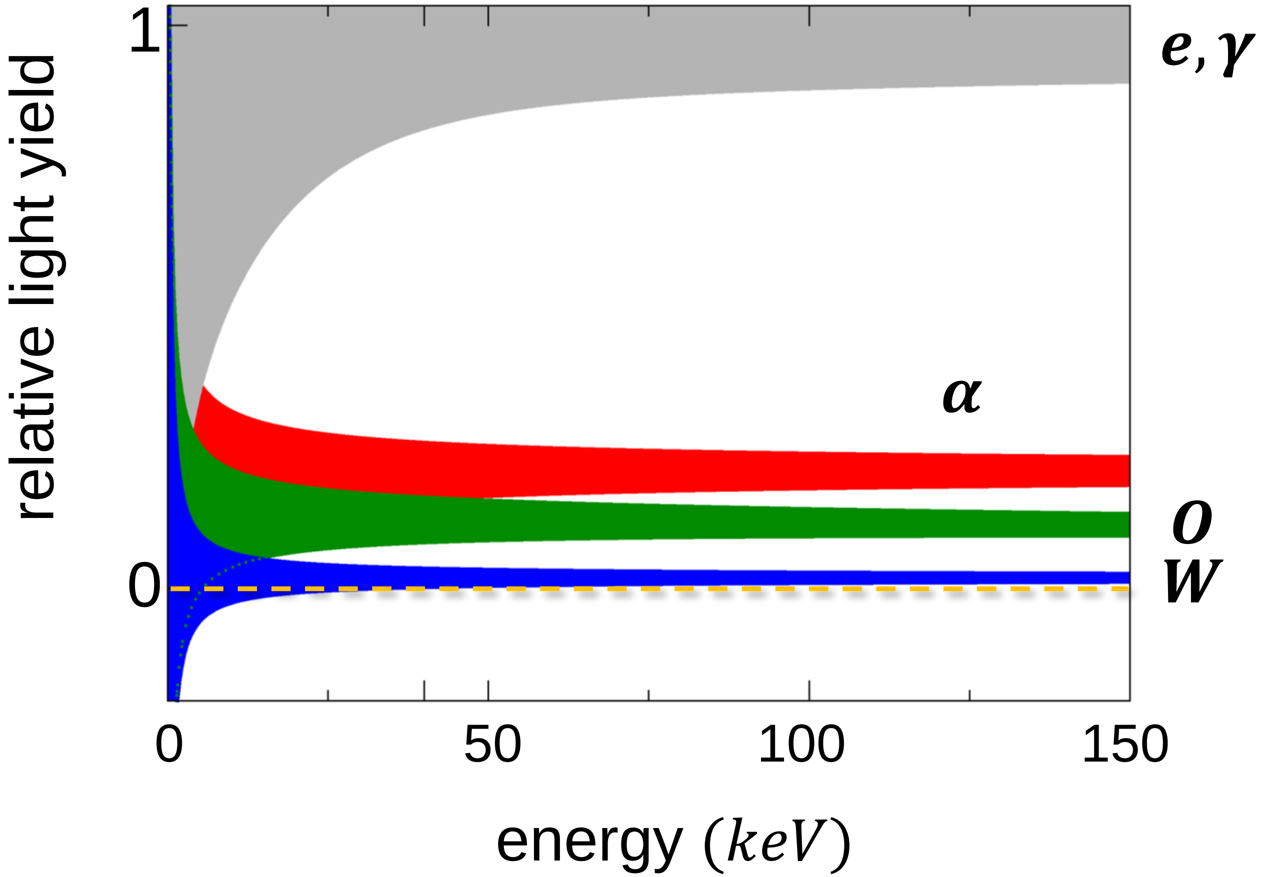
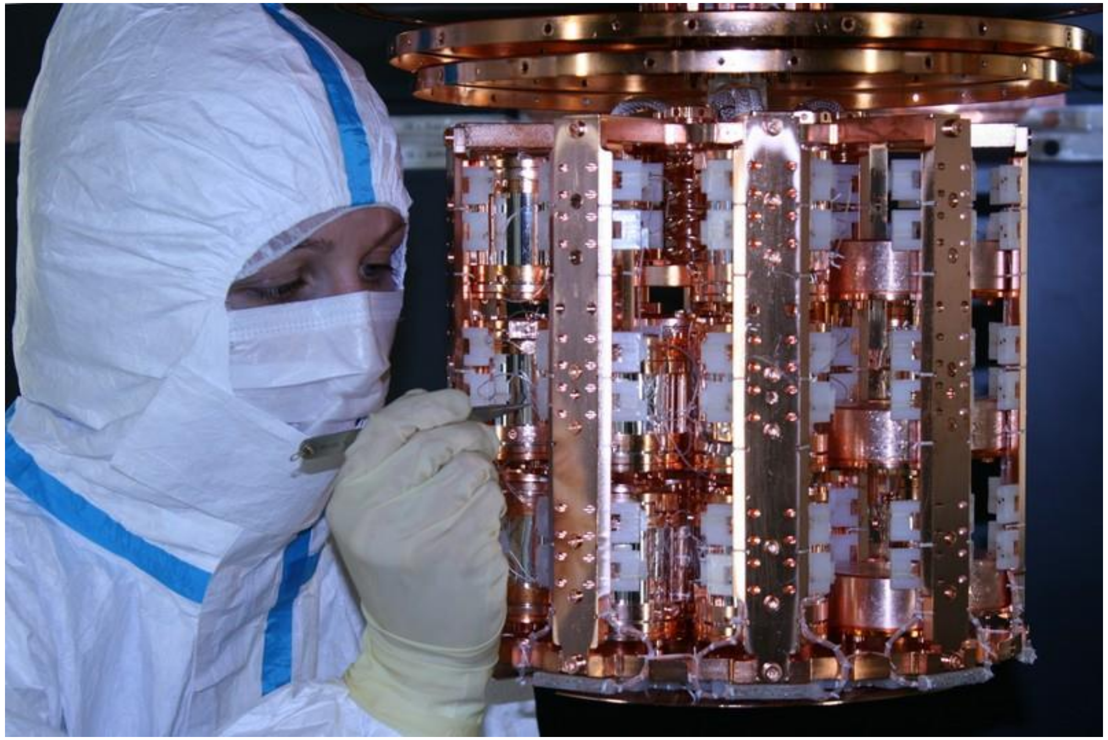
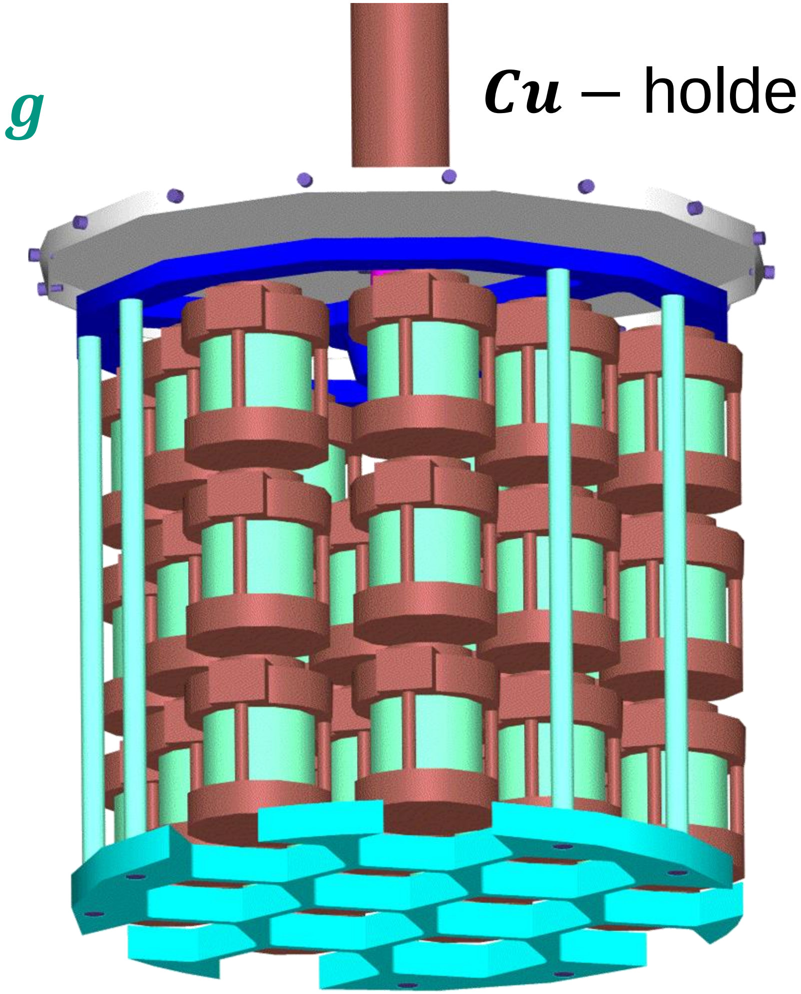


$CRESST$ experiment: set-up at $LNGS$

- **Array of bolometers inside a mK – cryostat**

  - single $CaWO_4$ bolometer with mass $m = 100 \dots 300\ g$
  - WIMP-induced nuclear recoils of $^{184}W, ^{40}Ca, ^{16}O$





$CRESST$: hunting WIMPs at the $sub - GeV$ scale

Reducing the mass of single bolometers to reduce the energy threshold

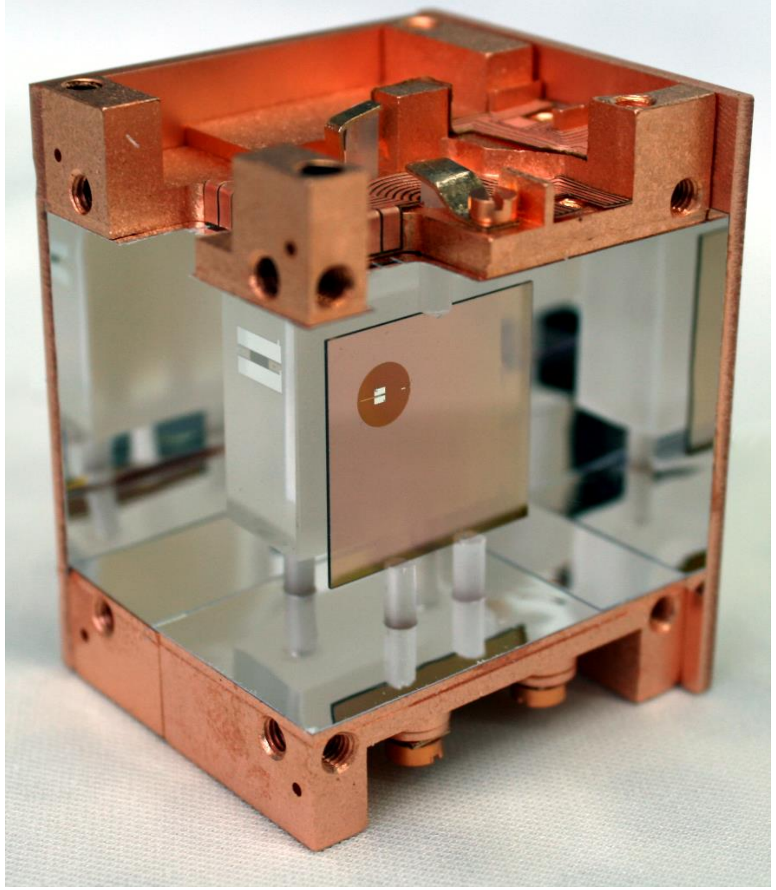
- development of $CaWO_4$ bolometers of small size: module ´Lise´* with $m = 24\ g$

- advantage: **lower threshold**, more scintillation photons reach thermistor #2

- goal: reach an energy threshold of $E_{thres} \sim 100\ eV$

↓

- push forward into WIMP masses in $sub - GeV$ range



$2 \times 2 \times 1\ cm^3$

*in honour of Lise Meitner

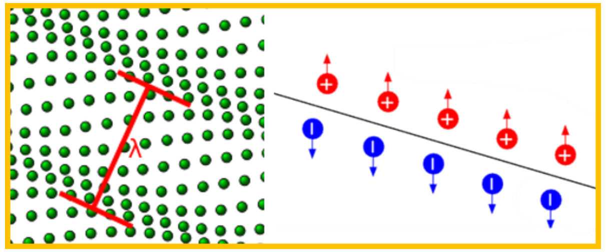
Cryogenic bolometers: phonons & ionisation

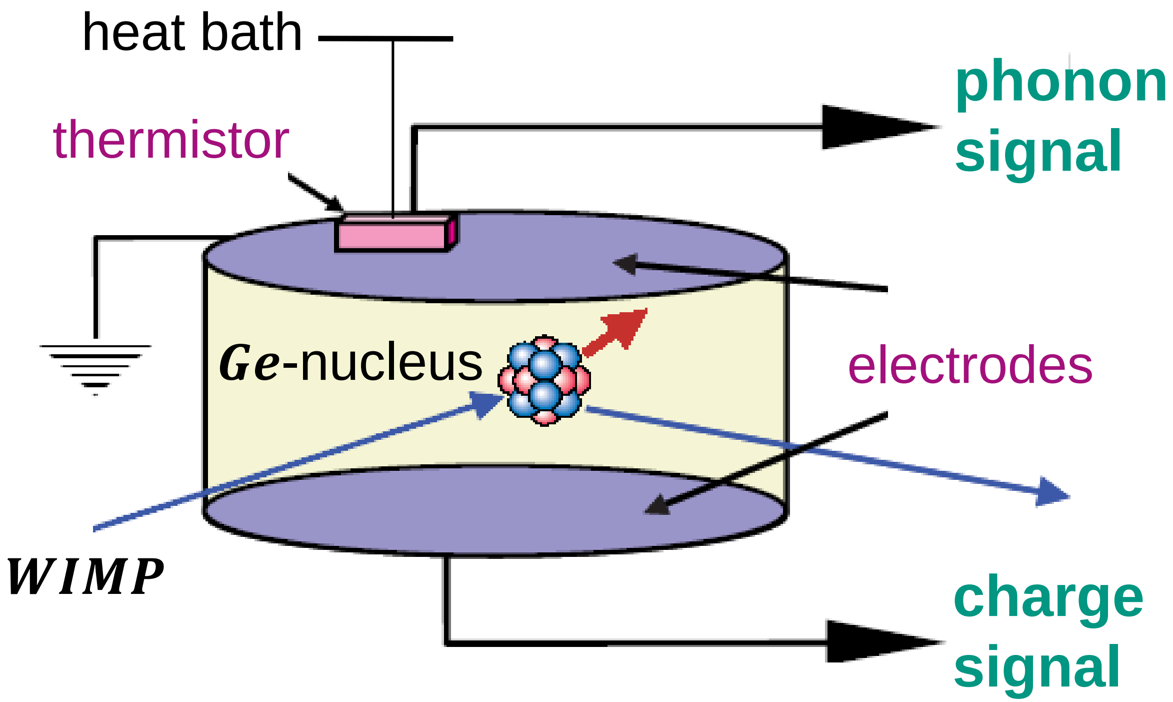
- Ge – **bolometers at the** mK – **scale with charge and phonon read-out**

  - detector mass $m < 1\ kg$
    ⇨ low E_{thres} for light WIMPs

  - read-out of slow (fast) phonons
    via NTD (TES) thermistor
    ⇨ determine **recoil energy** E_R

  - read-out of electron & hole signals
    via electric field at 2 electrodes
    ⇨ determine the PID on the
    basis of quenching





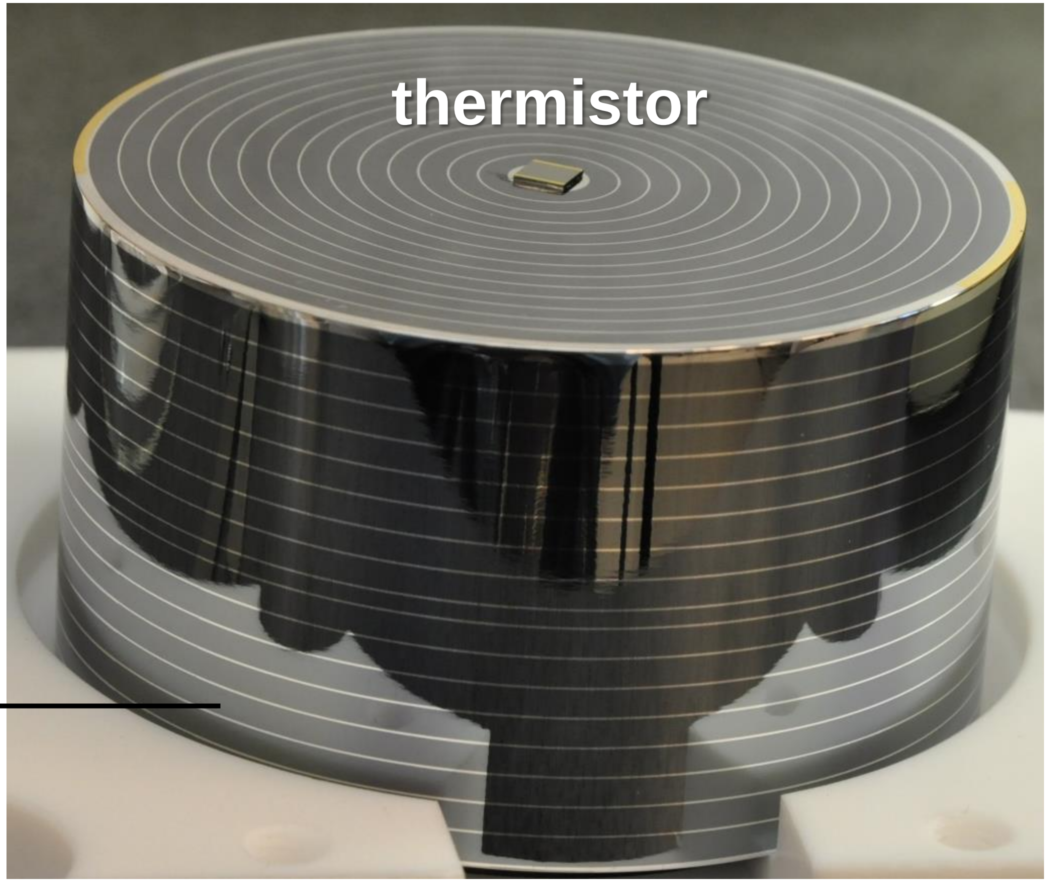
Cryogenic bolometers: phonons & ionisation

- Ge – bolometers at the mK – scale: read-out of the charge signal

  - detector mass $m < 1\ kg$
    ⇨ low E_{thres} for light WIMPs

  - electrodes are optimized for charge transport as well as for reduction of background

  - segmented electrodes with different potentials allow to fine-form the drift field E_D



Cryogenic bolometers: phonons & ionisation

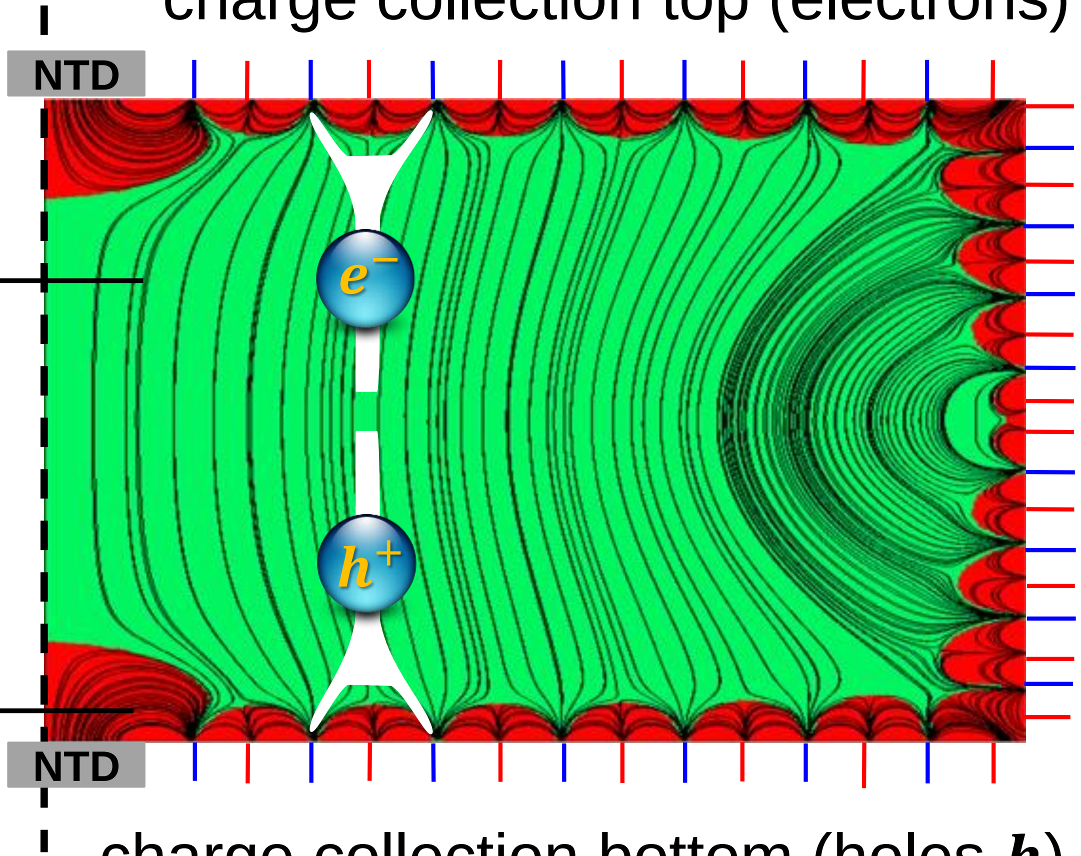
- Ge – bolometers at the mK – scale: read-out of the charge signal

  - read-out of both electrons & holes

  - **green**: **active volume** - here the two charge carriers are being collected

  - **red**: **inactive volume** - here the two charge carriers are NOT being collected, coincides with **areas of high background**

charge collection top (electrons)



charge collection bottom (holes h)

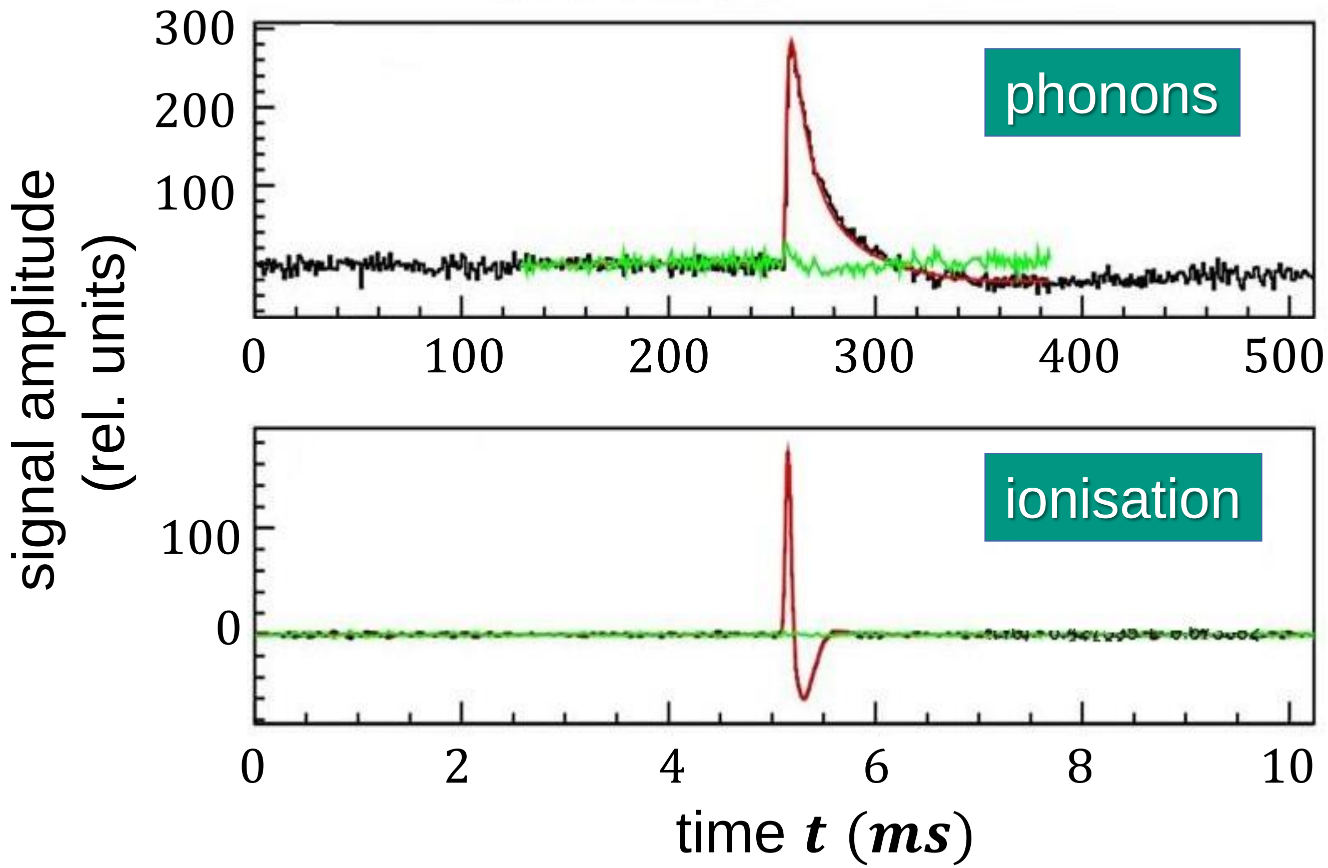
Cryogenic bolometers: phonons & ionisation

- Ge – bolometers at the mK – scale: charge and phonon signals

- key to a successful PID:
  measure quenching of
  the charge signal

- challenge: avoid partial
  charge collection close to
  the surfaces (looks like WIMPs)

coincidence: phonons & ionisation

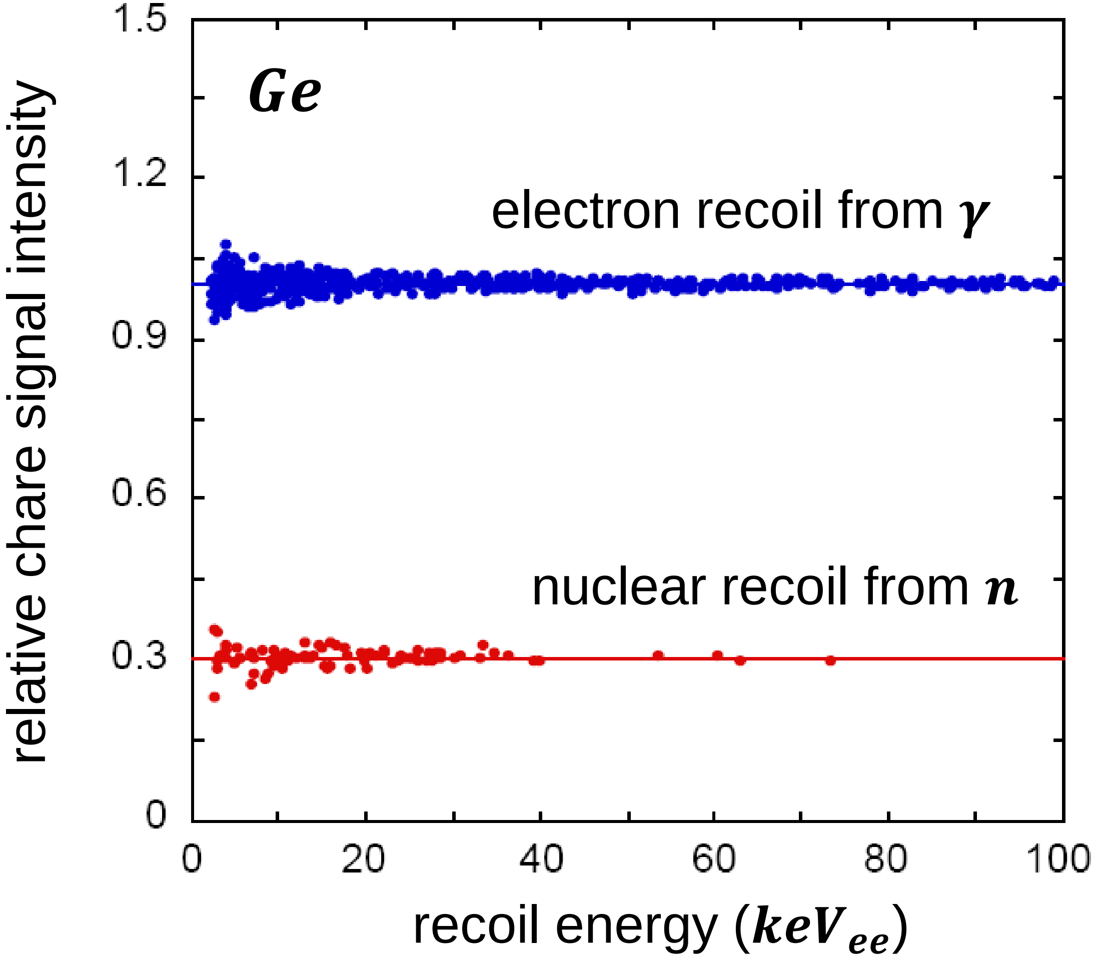


Cryogenic bolometers: phonons & ionisation

- Ge – **bolometers at the** mK – **scale: charge and phonon signals**

\- key to a successful PID:
measure quenching of
the charge signal

ionisation signal
= 1/3 of
phonon signal

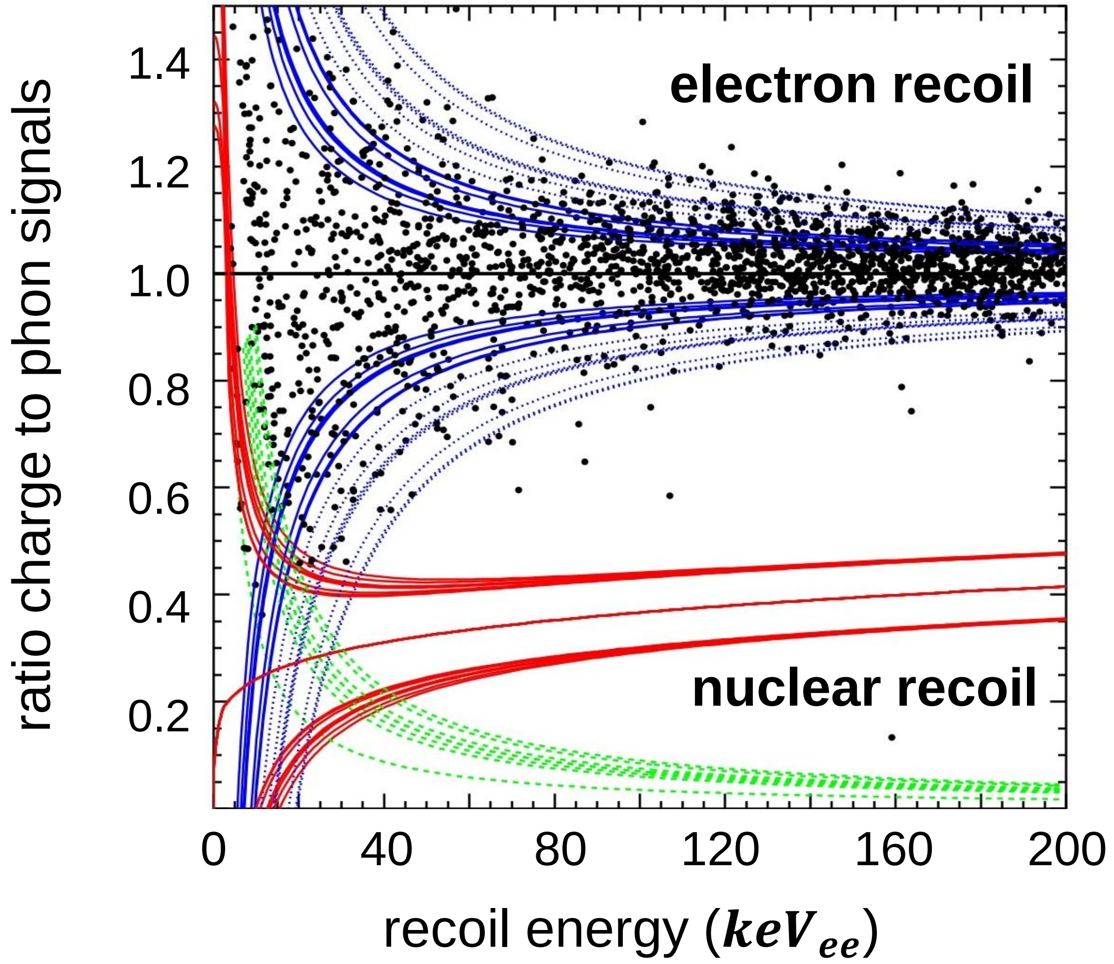


Cryogenic bolometers: phonons & ionisation

- Ge – bolometers at the mK – scale: charge and phonon signals

- key to a successful PID: measure quenching of the charge signal

no events
in the
nuclear recoil band
(i.e. background-free)

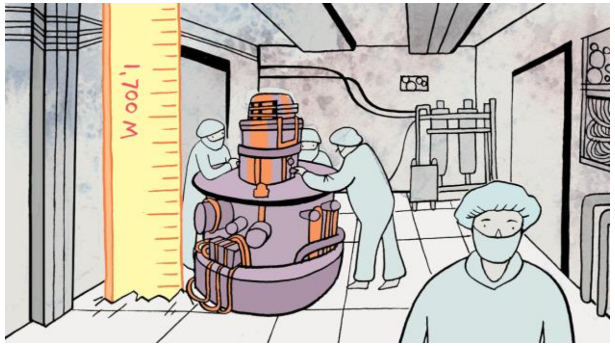


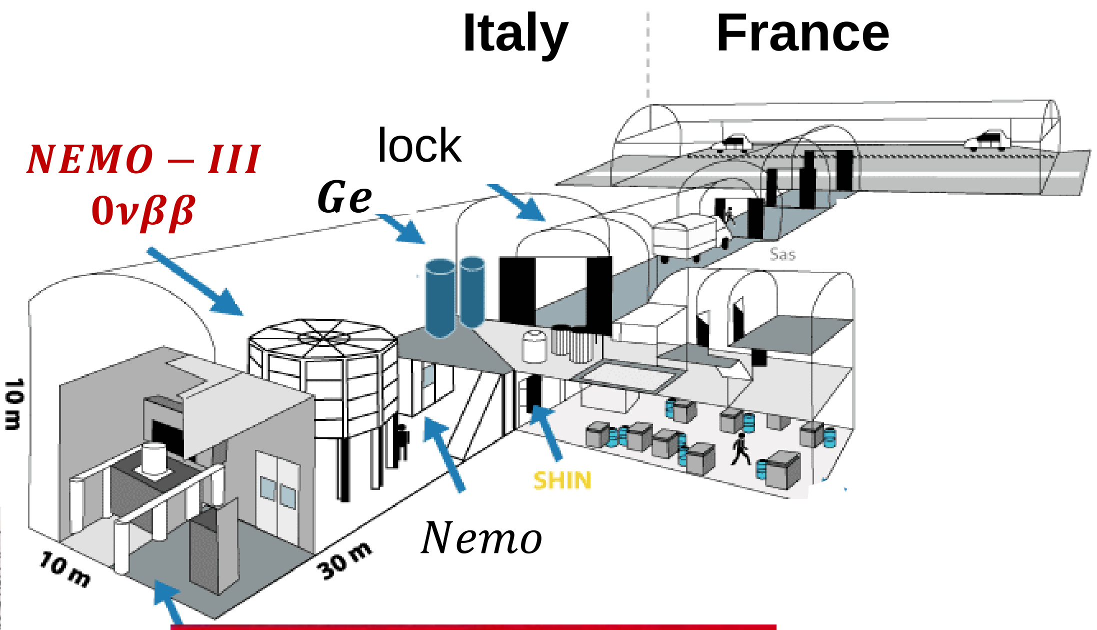
*EDELWEISS** experiment at the *LSM*

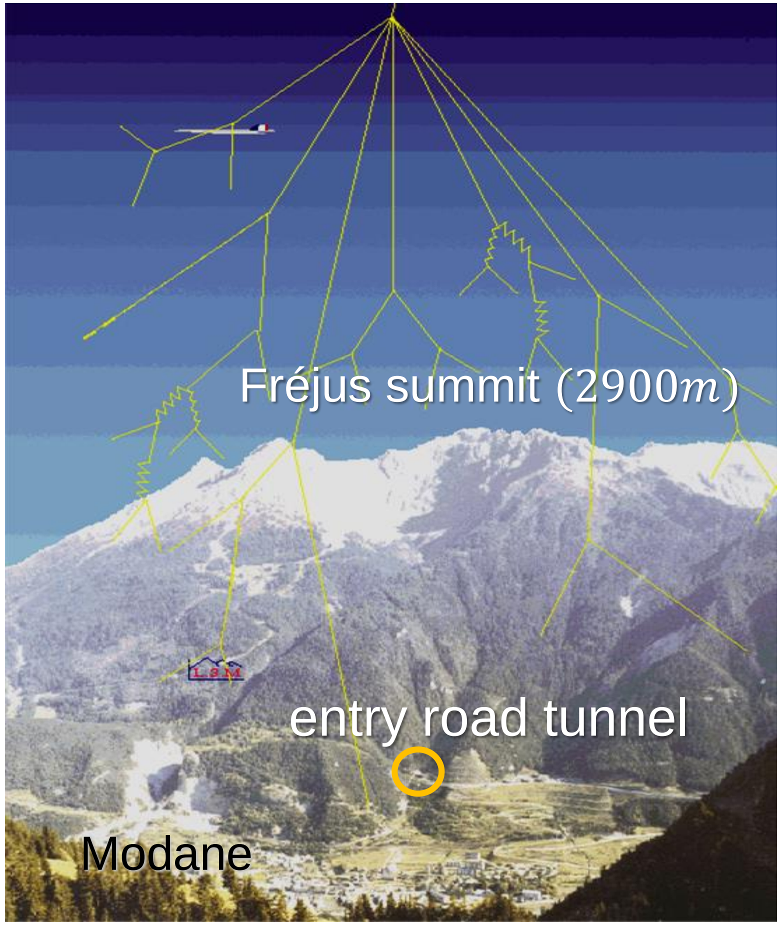
- A Ge – bolometer array for light $WIMP$s at Laboratoire Souterrain de Modane

$4800\ m.w.e.$

$4\ \mu\text{´}s\ m^{-2}\ day^{-1}$







*Expérience pour détecter les WIMPs en Site Souterrain

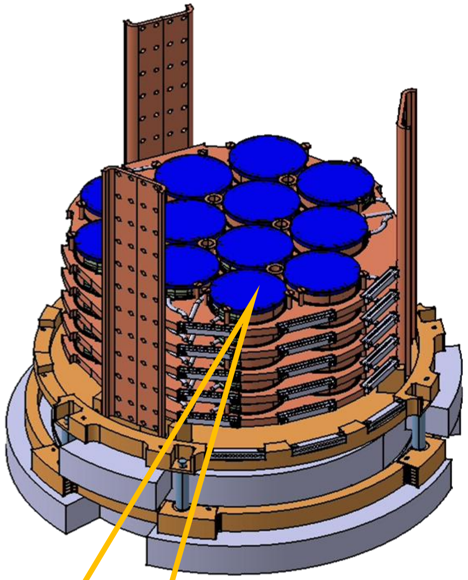
$\boldsymbol{EDELWEISS}$ experiment at the $\boldsymbol{LSM}$

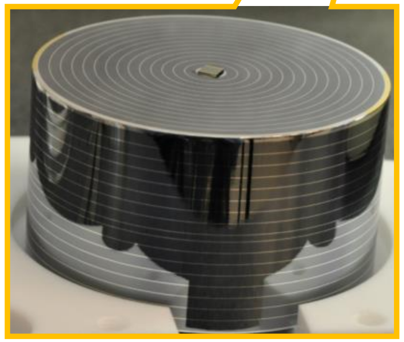
- **A $\mathbf{20}\ \boldsymbol{yr}$ –long search for light $\boldsymbol{WIMP}$s: set-up & history (KIT participated)**

- 2000-2003:
  $\boldsymbol{Edelweiss - I}$ with $\boldsymbol{m} = \mathbf{1}\ \boldsymbol{kg}$
  3 bolometers

- 2008-2010:
  $\boldsymbol{Edelweiss - II}$ with $\boldsymbol{m} = \mathbf{4}\ \boldsymbol{kg}$
  10 bolometers, each $\mathbf{400}\ \boldsymbol{g}$

- 2011-2019:
  $\boldsymbol{Edelweiss - III}$ with $\boldsymbol{m} = \mathbf{32}\ \boldsymbol{kg}$
  40 bolometers, each $\mathbf{800}\ \boldsymbol{g}$





$\boldsymbol{NTD}$ –
thermistor

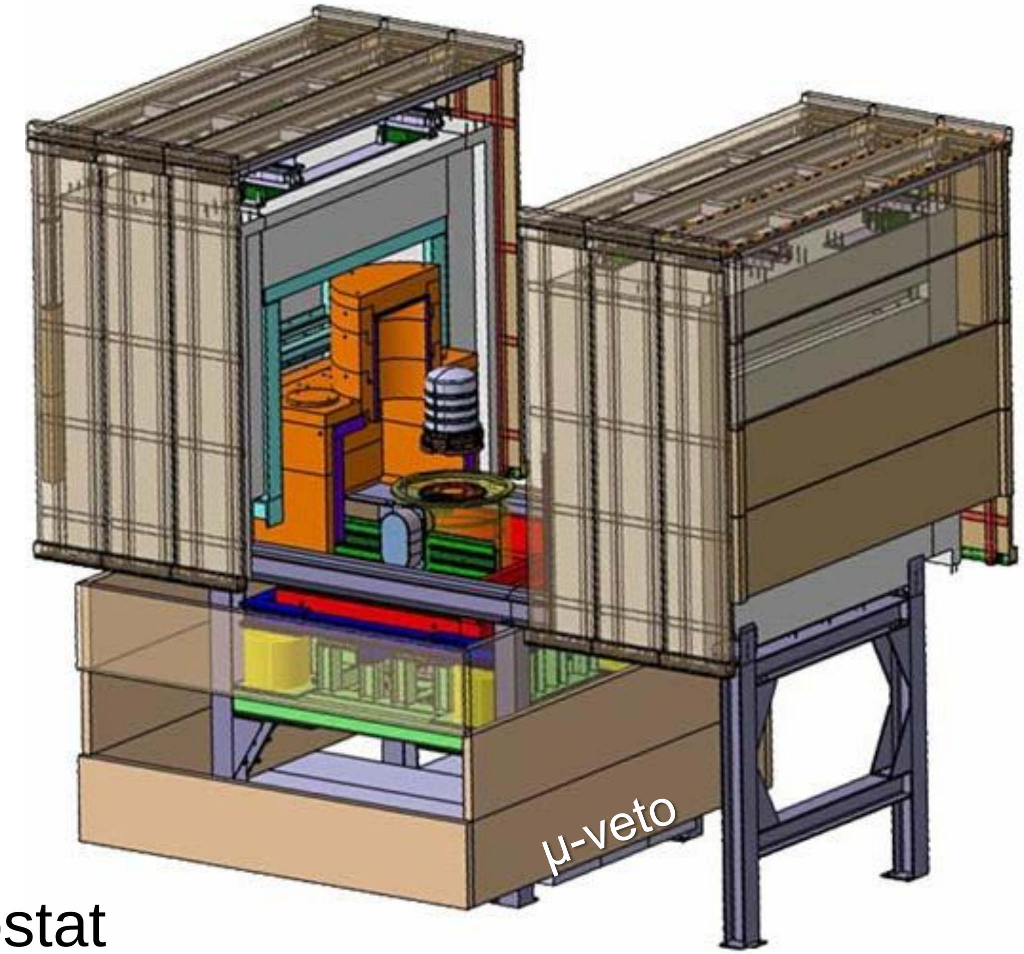
$\boldsymbol{EDELWEISS}$ experiment at the $\boldsymbol{LSM}$

- **A $\mathbf{20}\ \boldsymbol{yr}$ –long search for light $\boldsymbol{WIMP}$s: set-up & history (KIT participated)**

- no $\boldsymbol{WIMP}$ signal observed in $\boldsymbol{Edelweiss - III}$

- no further increase of the target mass
  ⇨ focus is now on a very **low threshold $\boldsymbol{E_R}$**
  ⇨ hunt extremly light $\boldsymbol{WIMP}$s

- a very dynamic field of work with many new detector ideas & new projects starting targeting mass regime $\boldsymbol{m_{WIMP} < 1\,GeV}$

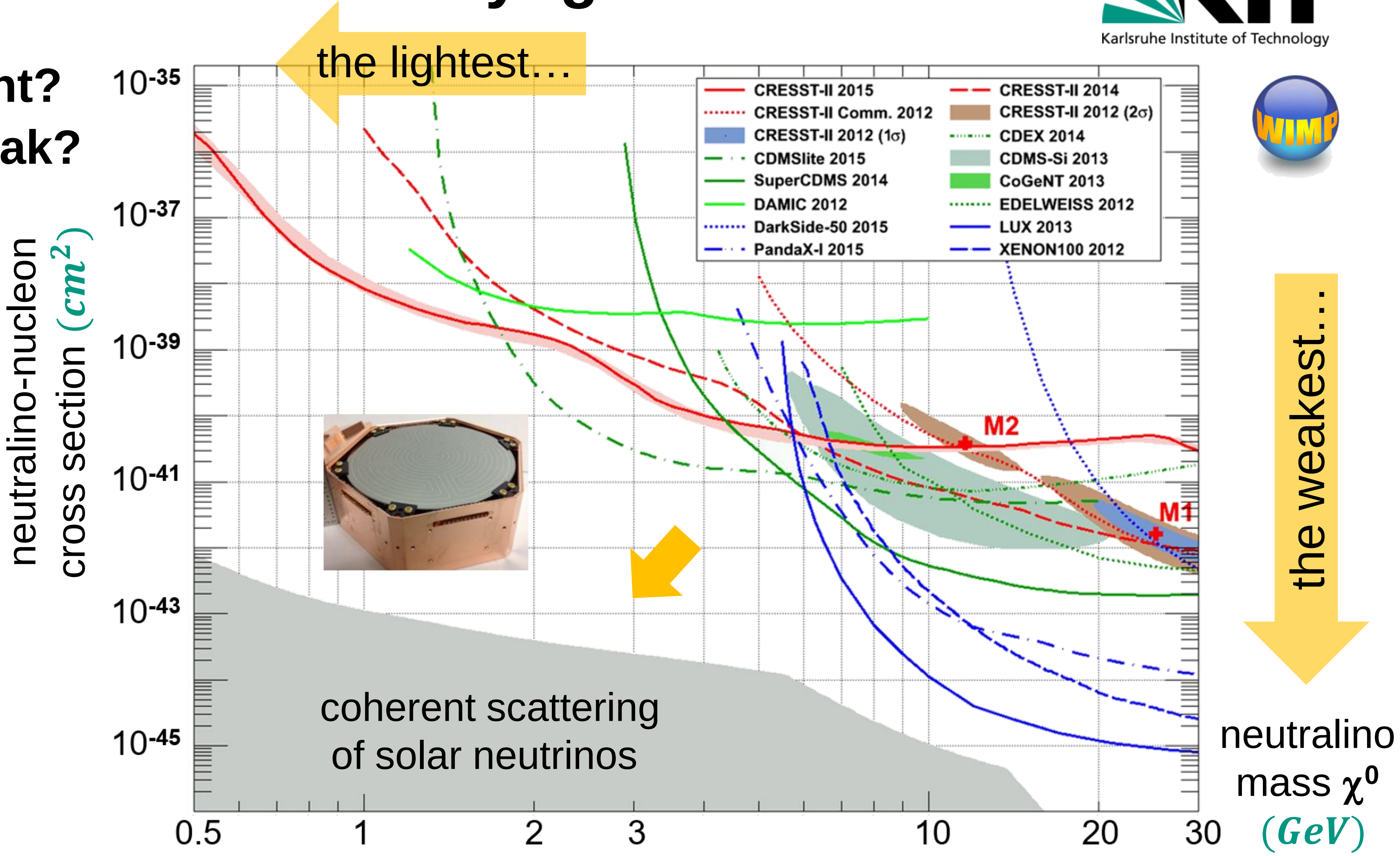


$\boldsymbol{Edelweiss - III}$ setup with veto-scintillator & cryostat

Status of DM-searches with cryogenic bolometers

- **WIMPs: how light?**
  how weak?

\- development of novel, small scale bolometers with an extremely low threshold to push forward deep into the ***sub – GeV*** mass region of WIMPs down to ***ν – floor***



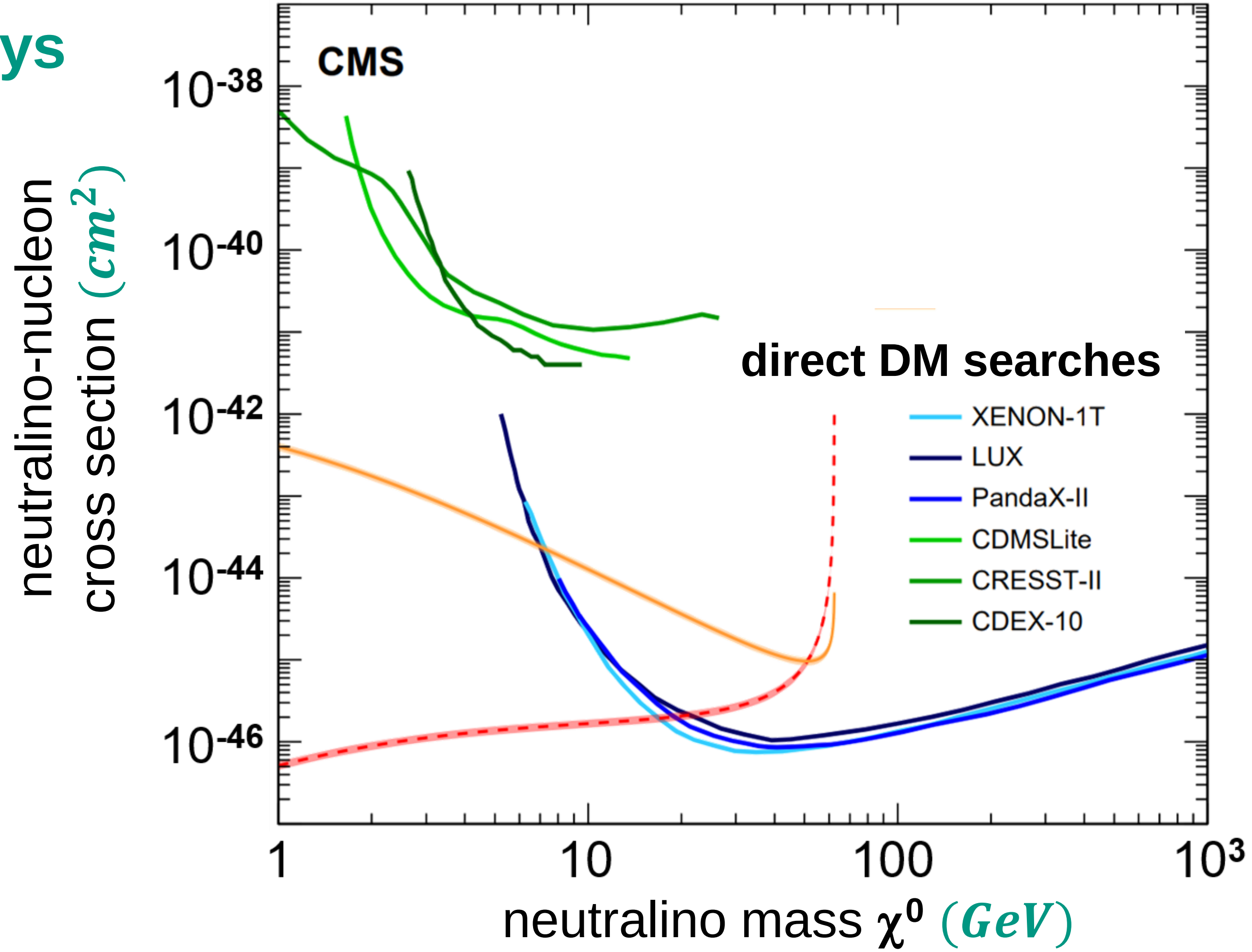
Comparing limits from LHC with direct searches

- **A new method for LHC to look for low mass WIMPs: study of Higgs decays**

- DM searches at LHC & direct searches are complementary

- **Higgs portal to DM**: invisible width of Higgs (⇨ fermionic/scalar DM)

sensitivities compared



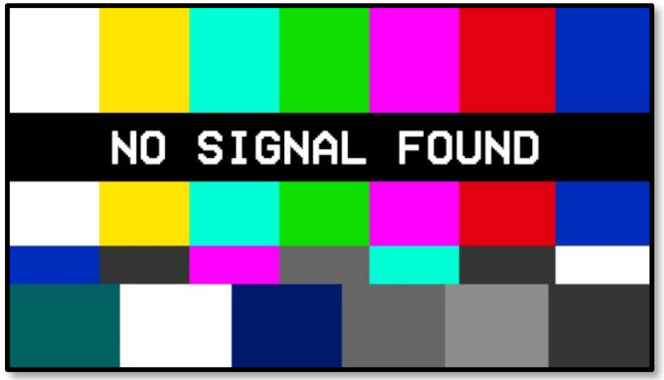
Comparing limits from LHC with direct searches

Karlsruhe Institute of Technology

- **No undisputed signal at the LHC, in indirect searches with gammas, neutrinos & positrons & in direct searches in underground labs**

- supersymmetric $\boldsymbol{WIMP}$s have evaded detection so far

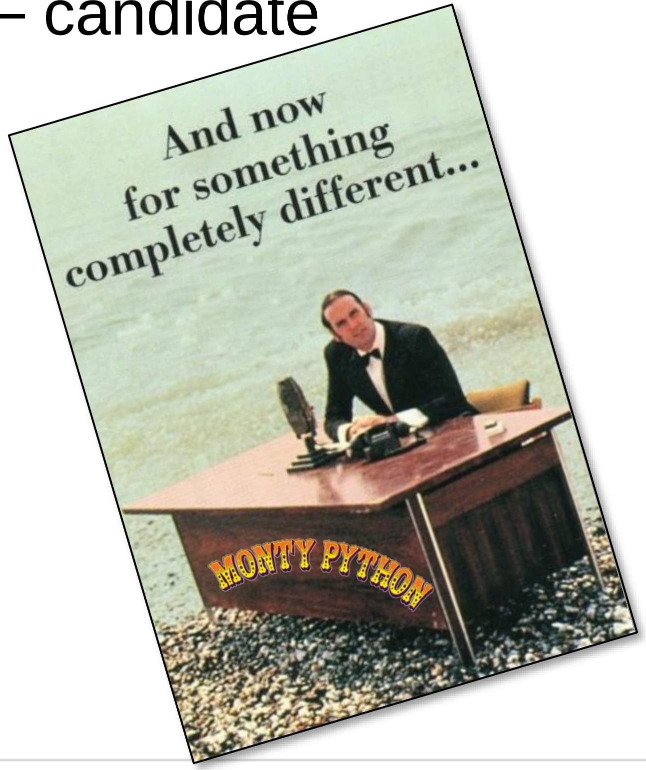
- new experiments ($\boldsymbol{DARWIN}$) & novel methods for sub-GeV masses…



Is Dark Matter super-symmetric, or follows from …

- **Dark Matter could arise due to other symmetries in nature that also require an extension of the Standard Model**

- supersymmetric $\boldsymbol{WIMP}$s or
another $\boldsymbol{DM}$ – candidate



enter the
axion