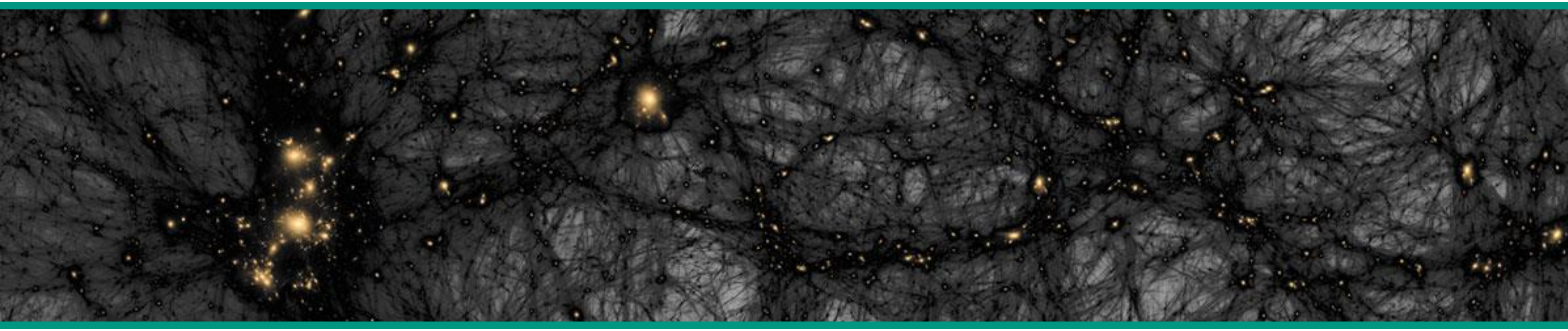
Karlsruhe Institute of Technology

Astroparticle physics *I* – Dark Matter

Winter term 23/24 Lecture 19 Jan. 31, 2024



Recap of Lecture 18

- **Liquid noble gas experiments: $\mathbf{2-}$ phase read−out as leading technology**

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

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

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

  - $\boldsymbol{xenon}$: cryo−distillation to purify, $\mathbf{3}$ large suites of experiments:
    $\boldsymbol{LZ}$ in the $\boldsymbol{US}$, $\boldsymbol{XENON}(-\boldsymbol{1T}, -\boldsymbol{nT})$, $\boldsymbol{DARWIN}$ at $\boldsymbol{LNGS}$, $\boldsymbol{PANDA}$ in $\boldsymbol{Ch}$

  } down to $\boldsymbol{\nu}$ – floor

$4.5.3$ Cryogenic bolometers

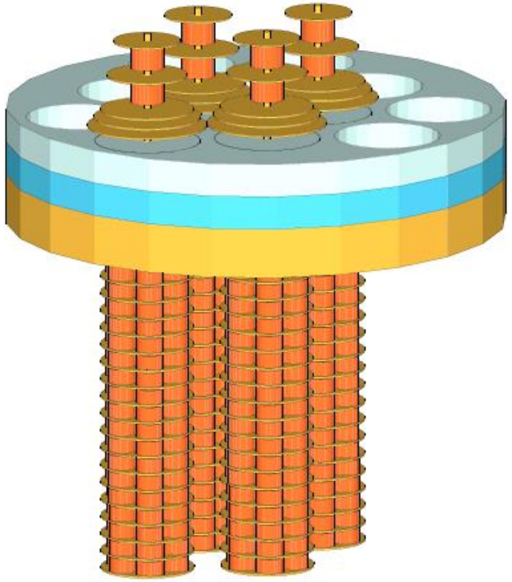
- **Going down to the mK – scale: using phonons in a hunt for light $WIMPs$**

cryo–bolometers: $Ge, Si, CaWO_4$

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

energy threshold:
very small $< 1\ keV$

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

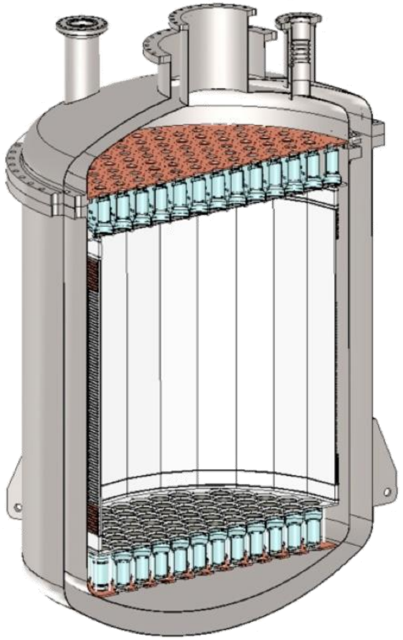


2 – phase noble gas $TPCs$: Xe, Ar

TPC with large volume
total mass: up to $50\ t$
⇨ small relative 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 $\boldsymbol{\Phi_{DM}}$

energy threshold:
$< 100\ eV$ ...

sensitivity to very
small $xsecs$ (down to $\nu -$ floor)

2 – phase noble gas $TPCs$: Xe, Ar

$\boldsymbol{TPC}$ with large volume
large $\varnothing =\ 2 \ldots 3\ m$
for small fluxes $\boldsymbol{\Phi_{DM}}$

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

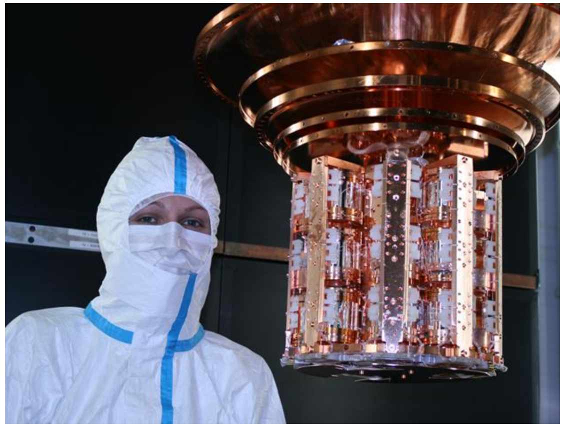
sensitivity to very
small $xsecs$ (down to $\nu -$ floor)

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 read–out



sensitivity to very
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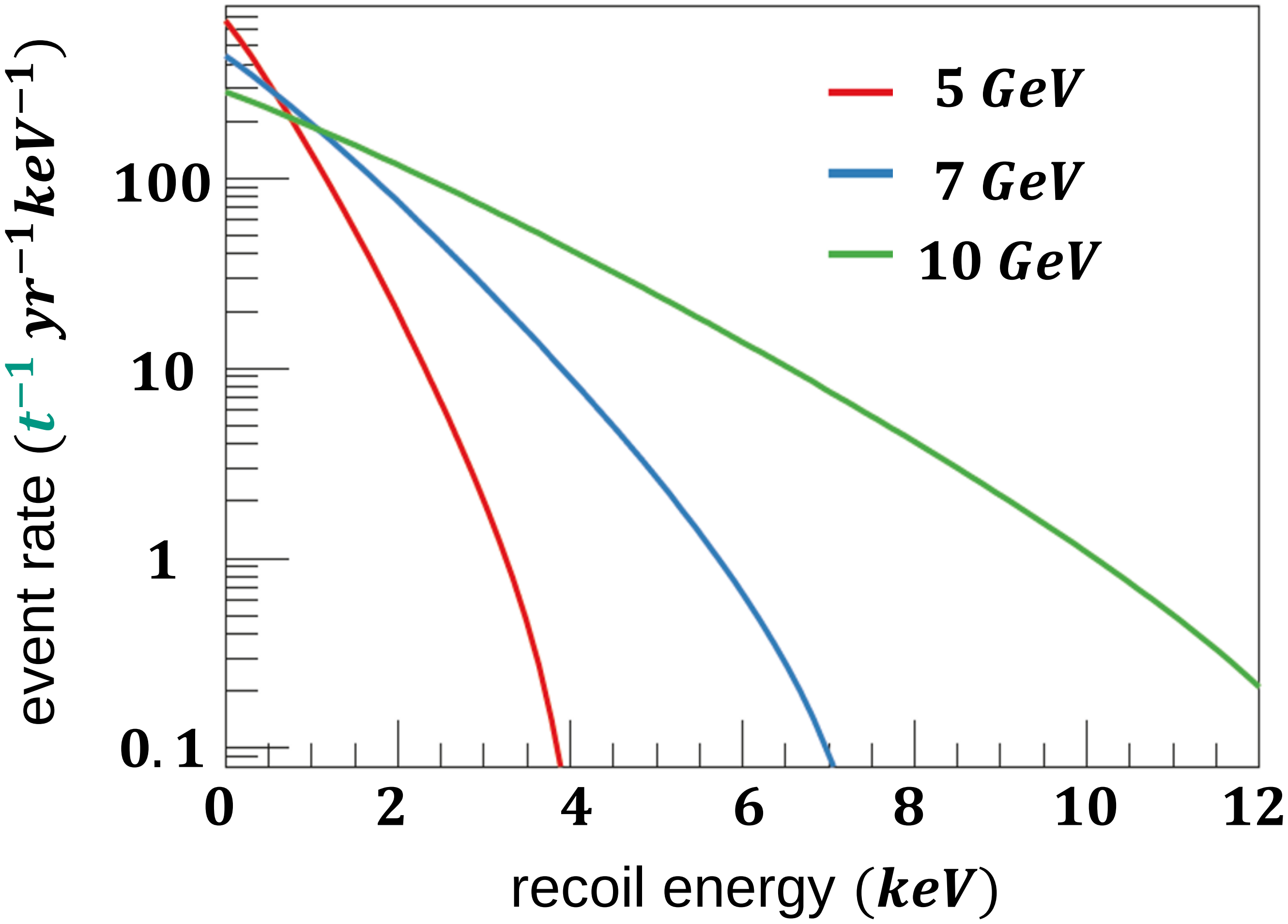
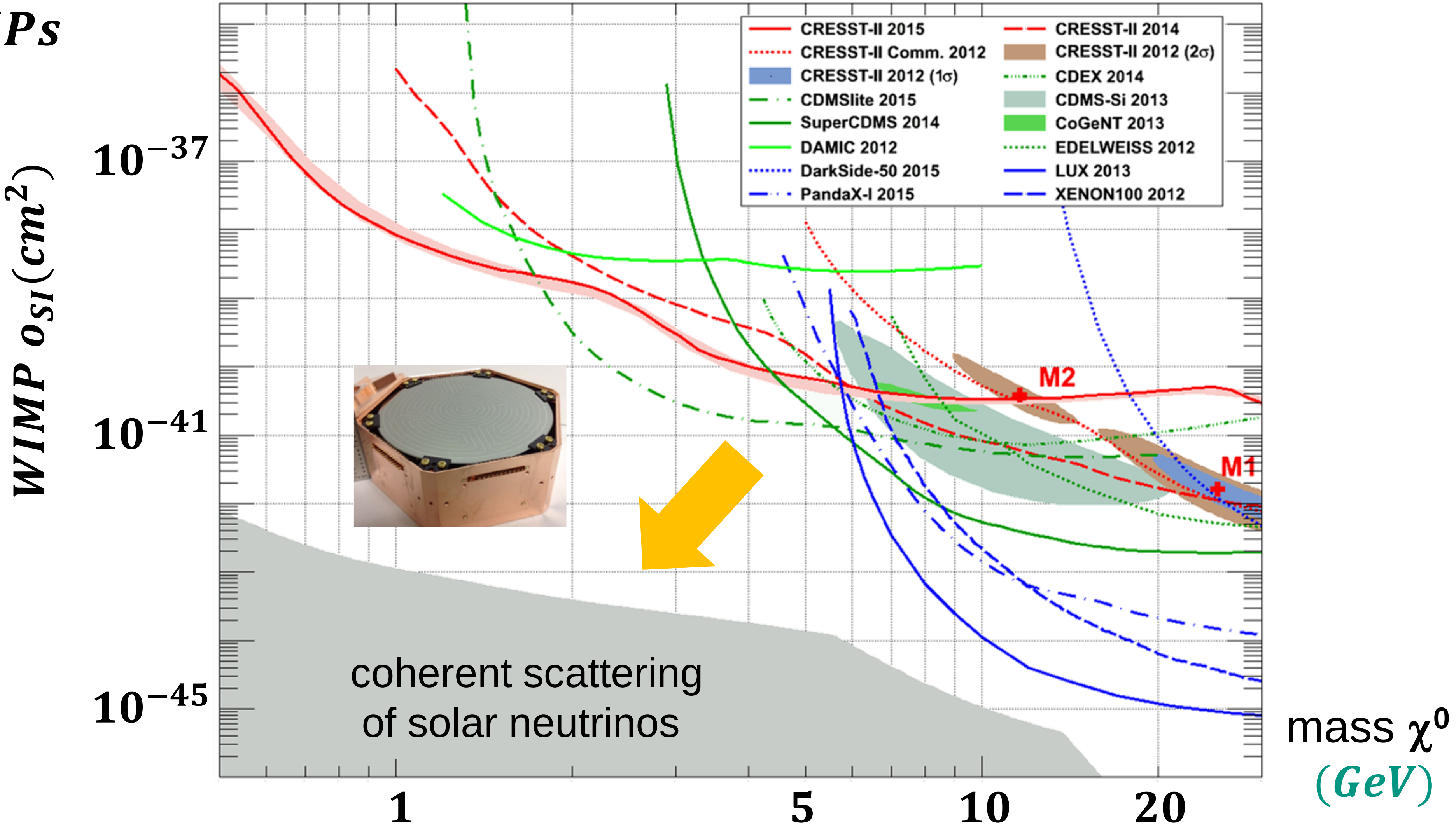


Cryogenic bolometers: explore low–mass $WIMPs$

- low–mass $WIMPs$

- 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 ν – **floor**



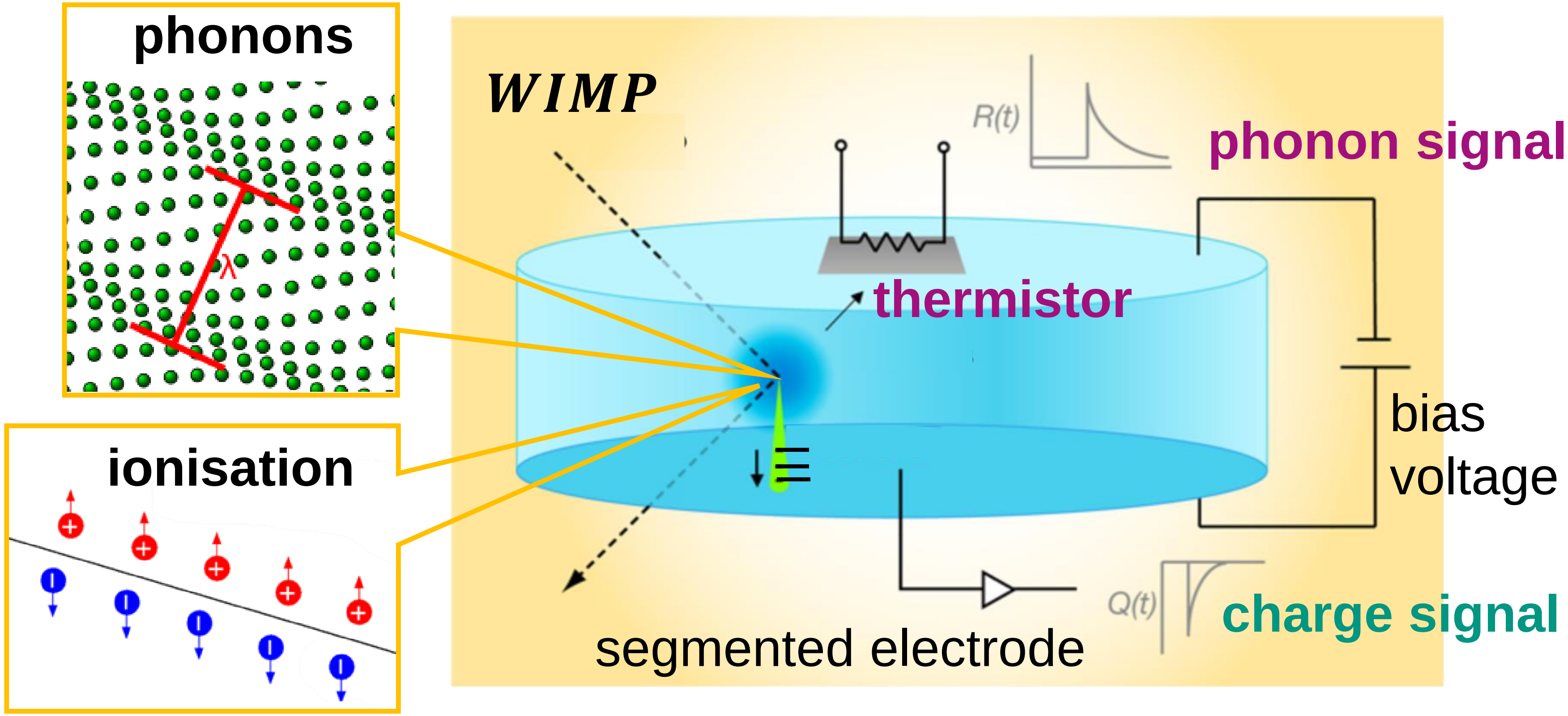
Cryogenic bolometers: fundamental principle

- **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



Cryogenic bolometers: fundamental principle

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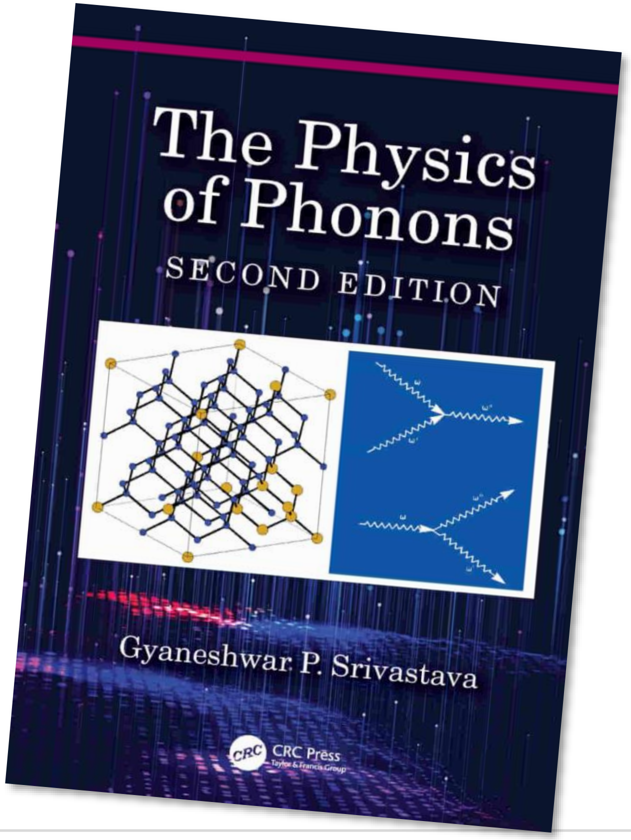
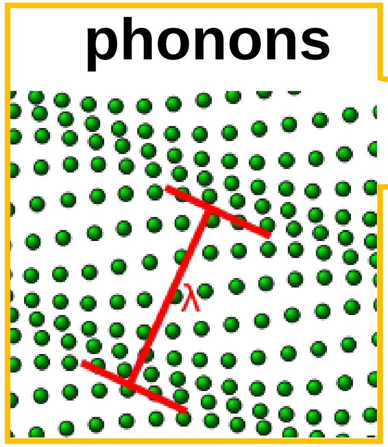
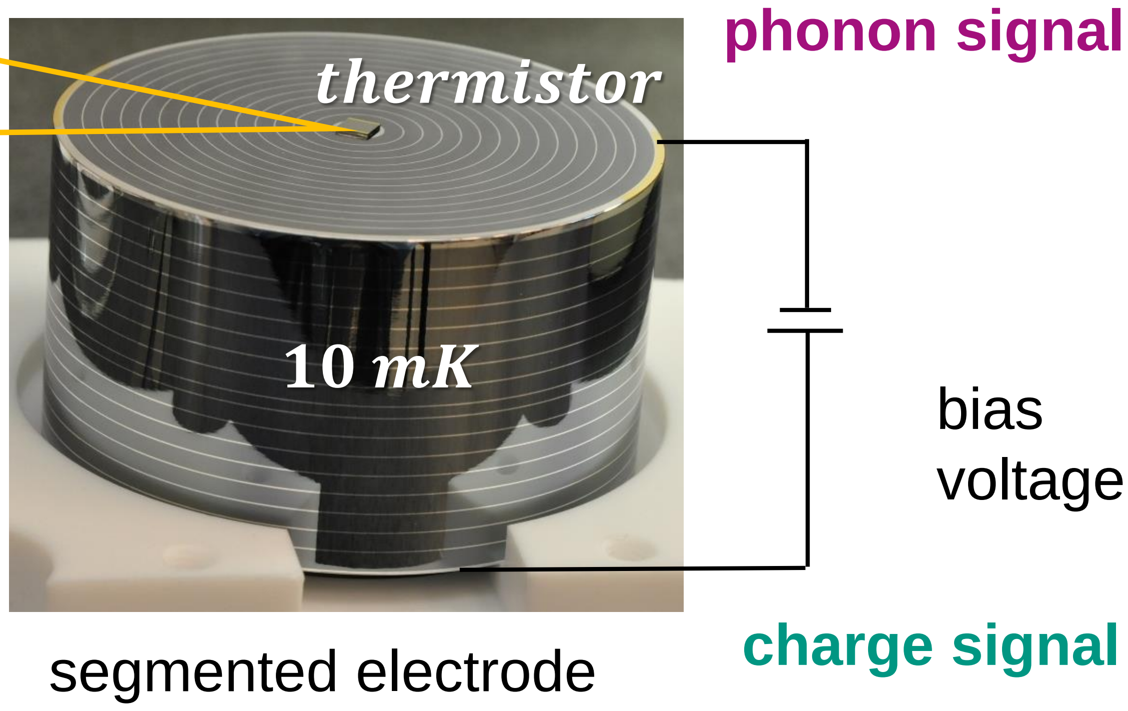
  - **phonon signal**: read–out of **nuclear recoil energy E_R** via a **thermistor**







Cryogenic bolometers: properties for $DM -$ search

Advantages of bolometers of Ge, Si or $CaWO_4$

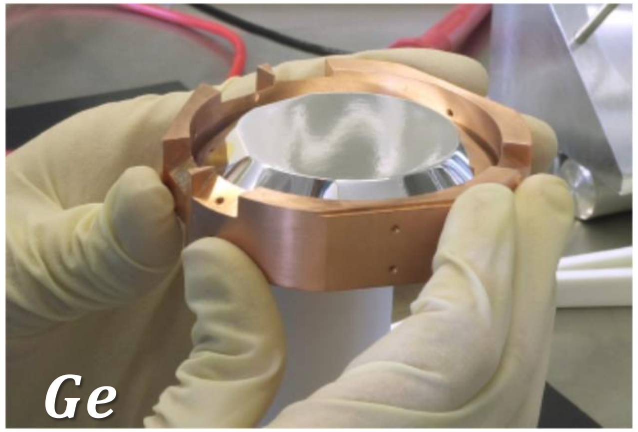
- only $\Delta E \sim 10\ meV$ to produce a **primary phonon**

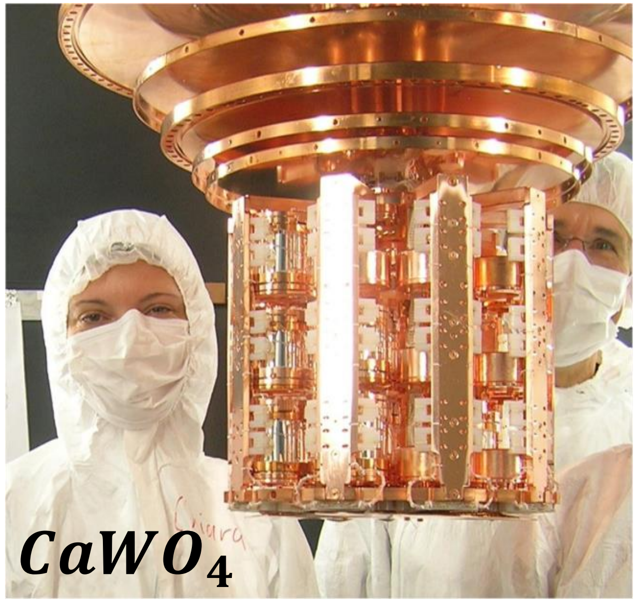
- result: exceedingly **low−energy threshold** (light $WIMPs$)

- 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 feed–out from $mK \rightarrow RT$

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

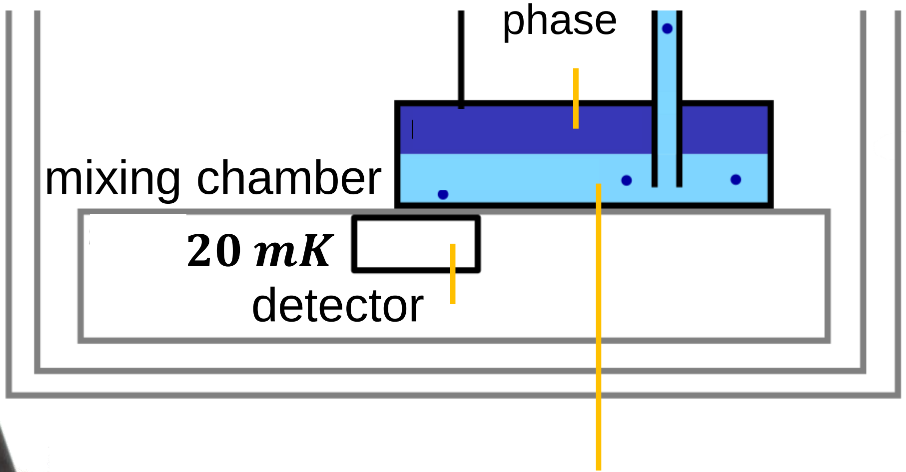
- modular set–up implies a **substantial mass** for holding structures & read–out cables (**potential bg – sources**)

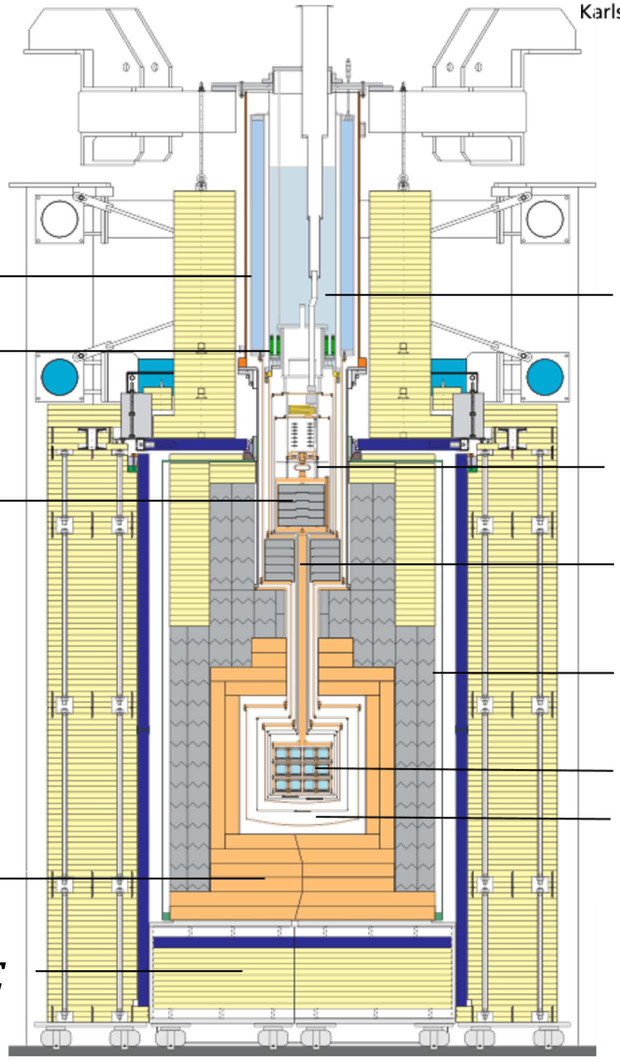
RT = Room Temperature

Cryogenic bolometers: mixing cryostats for mK

Commercial dilution refrigerators

- ^3He / ^4He mixing−cryostats are essential infrastructures for the operation of cryo−bolometers





Cryogenic bolometers: *phonon* signal

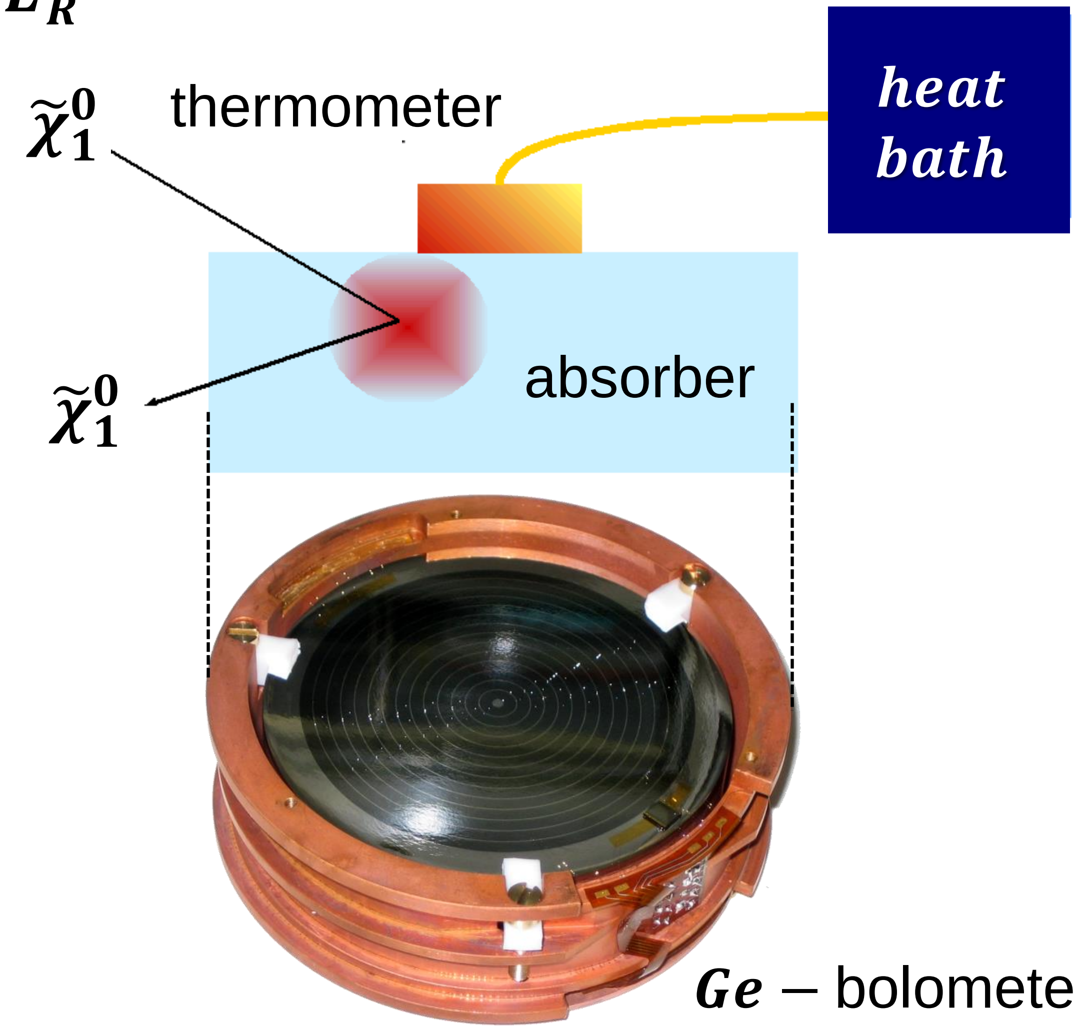
- **How to read out the nuclear recoil signal E_R**

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

- parameters of modern bolometers

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

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



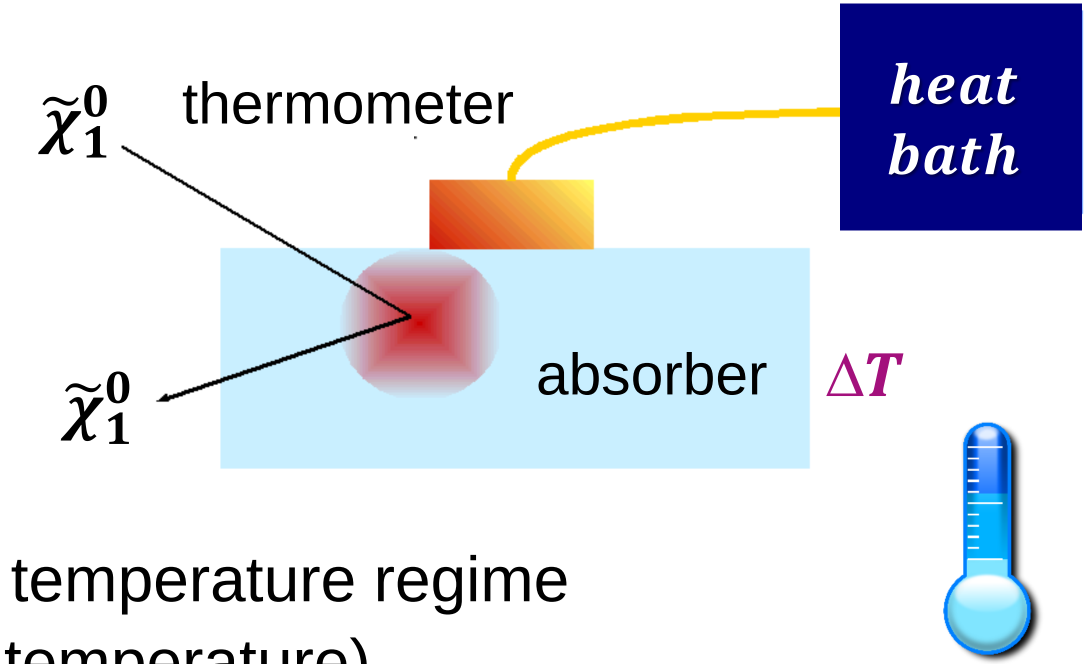
Ge – bolometer

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

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



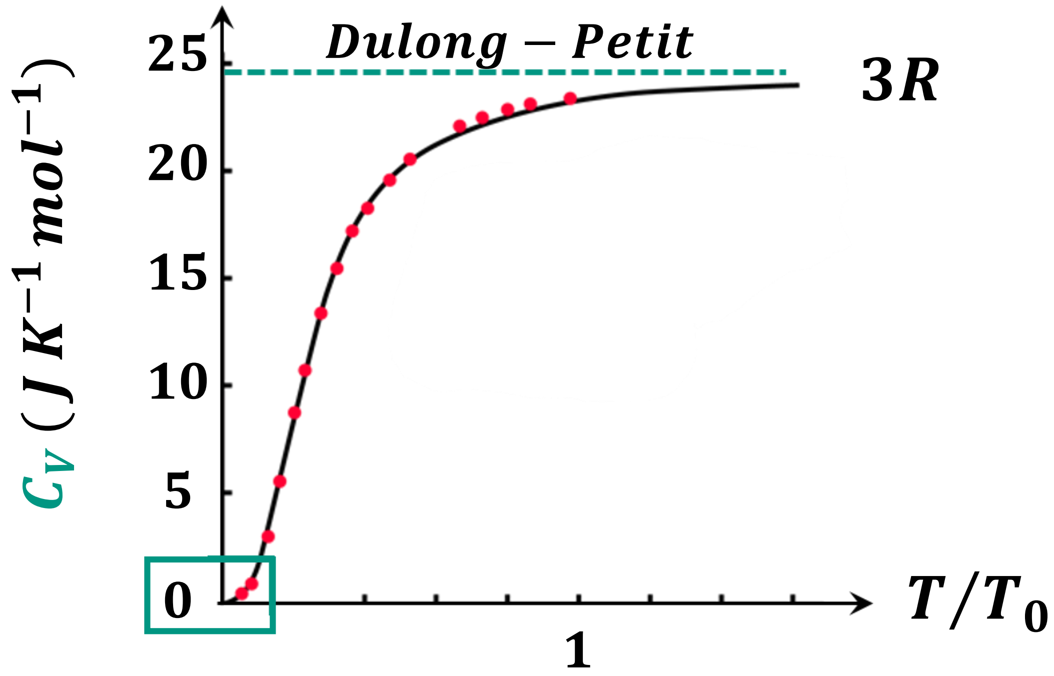
- we recall ***Debye´s* law** for C_V in the very low temperature regime where bolometers operate: $T \ll T_\Theta$ (*Debye* temperature)

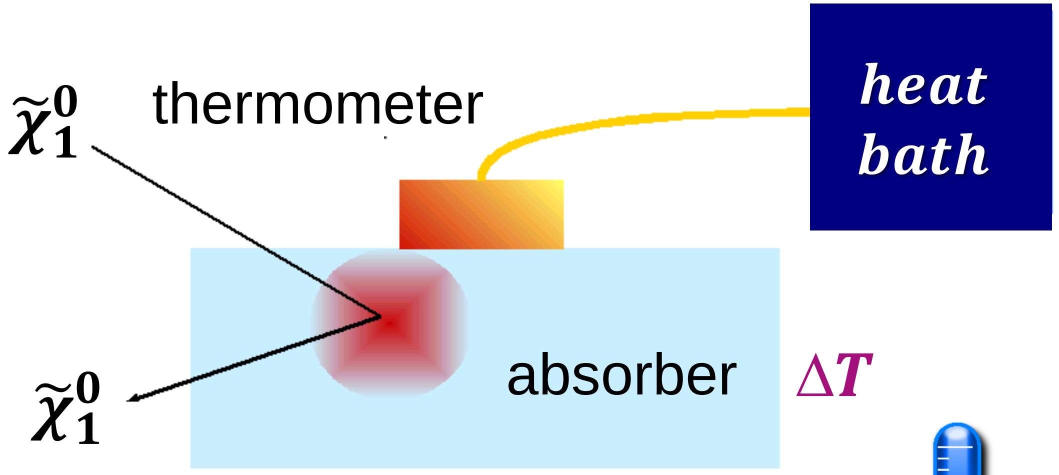
$$C_V \approx 10^{18} \cdot \left(\frac{T}{T_\theta}\right)^3 \frac{keV}{cm^3 \cdot K}$$

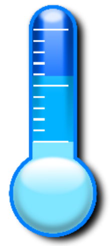
→ operate bolometer at lowest T possible to minimise value of C_V

Cryogenic bolometers: specific heat C_V

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







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

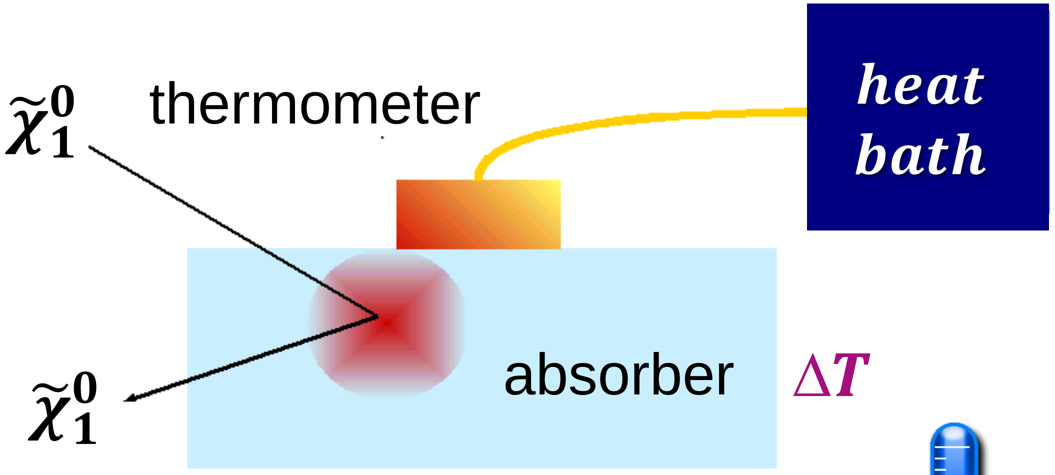
T_θ = material–specific *Debye* temperature (*Ge*: 374 *K*, *Si*: 645 *K*)

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



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

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**

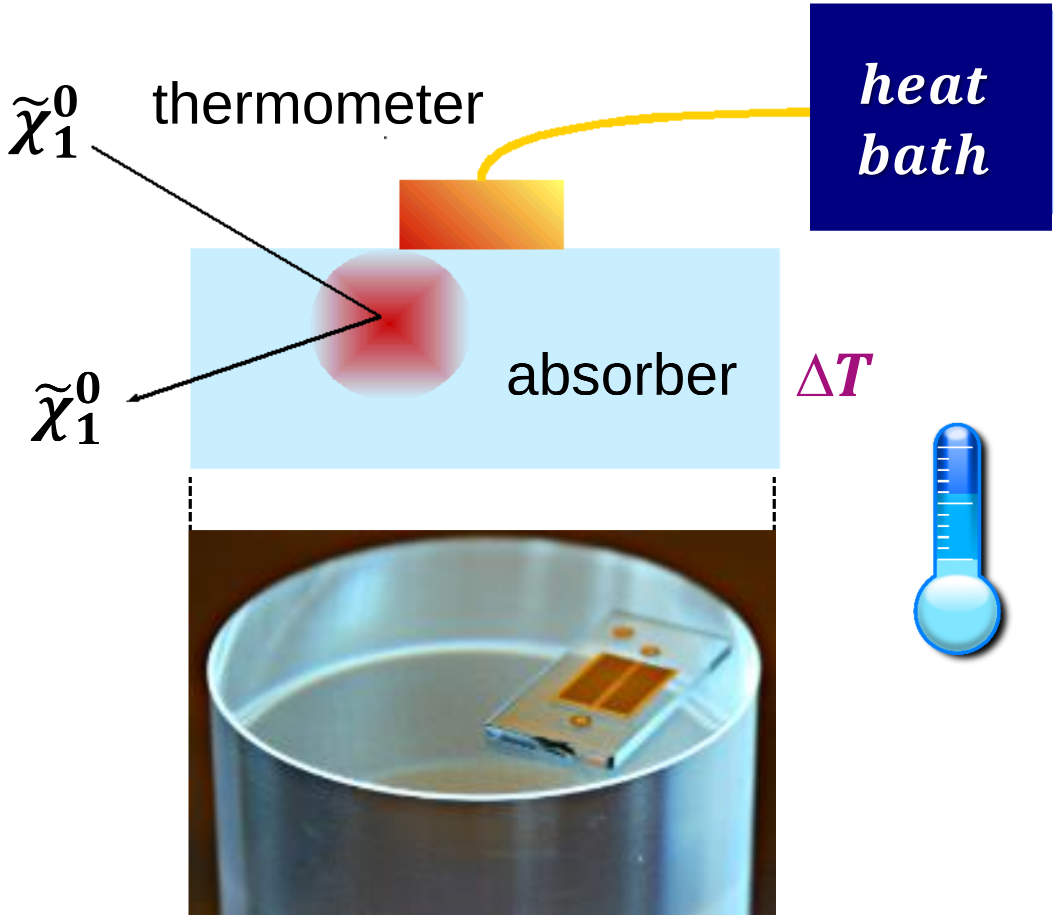
- additional sensors required for read–out of

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



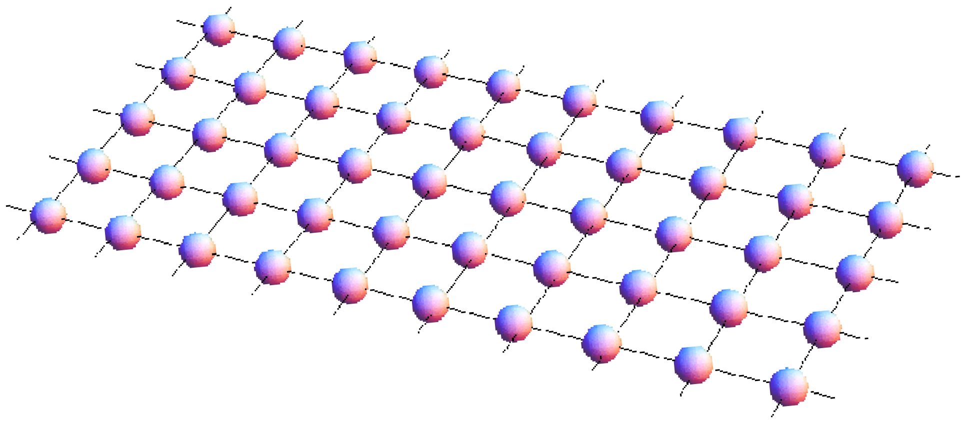
$CaWO_4$-bolometer

Cryogenic bolometers: properties of phonons

Propagation of a spherical phonon wave in the bolometer

- $\mathbf{3D}$ **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	$\mathbf{1 \ldots 10\ meV}$	$E_{ph} \gg k_B \cdot T \ \ (T > 10\ K)$	**not** in equilibrium
thermal	$< \mathbf{0.1\ meV}$	$E_{ph} \sim k_B \cdot T \ \ (T < 1\ K)$	**in** equilibrium

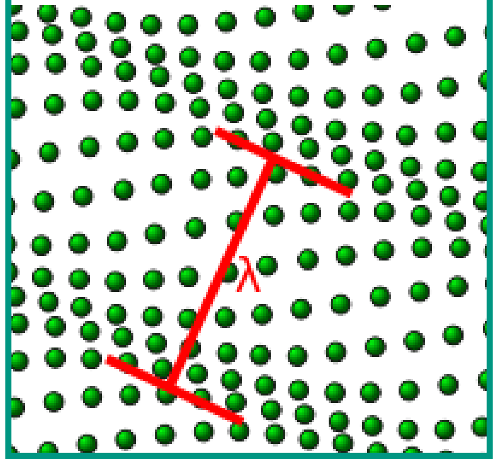
*conversion factor $\mathbf{1\ K \sim 0.1\ meV}$

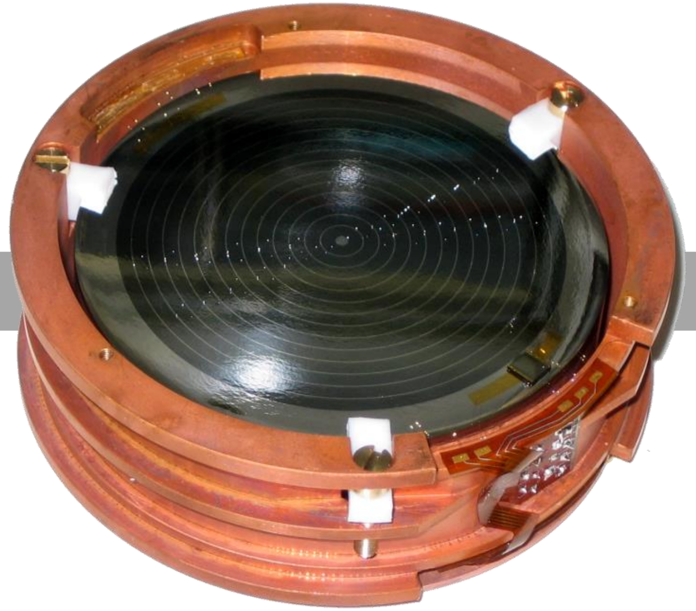
Cryogenic bolometers vs. ionisation

- Comparing energies of phonons to electron–hole pairs

phonons

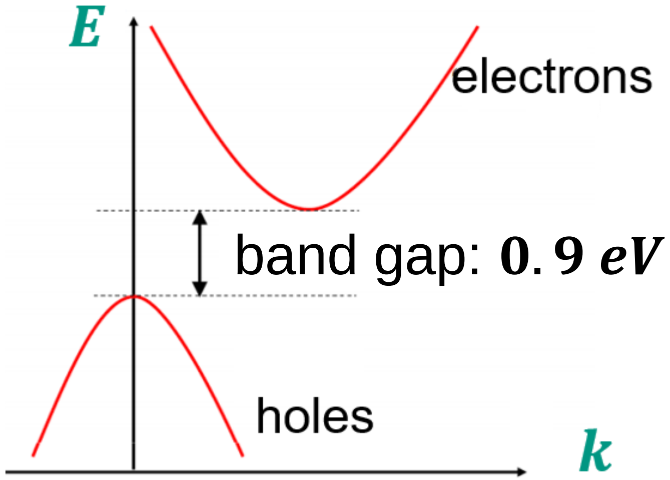
$\Delta E < 1\,meV$





electron–hole pairs

$\Delta E \sim 2.9\ eV$



Cryogenic bolometers: thermistor read–out

- ***THERMISTOR****: 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 μK – **scale**

  - optimisation: **small ΔT** → 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

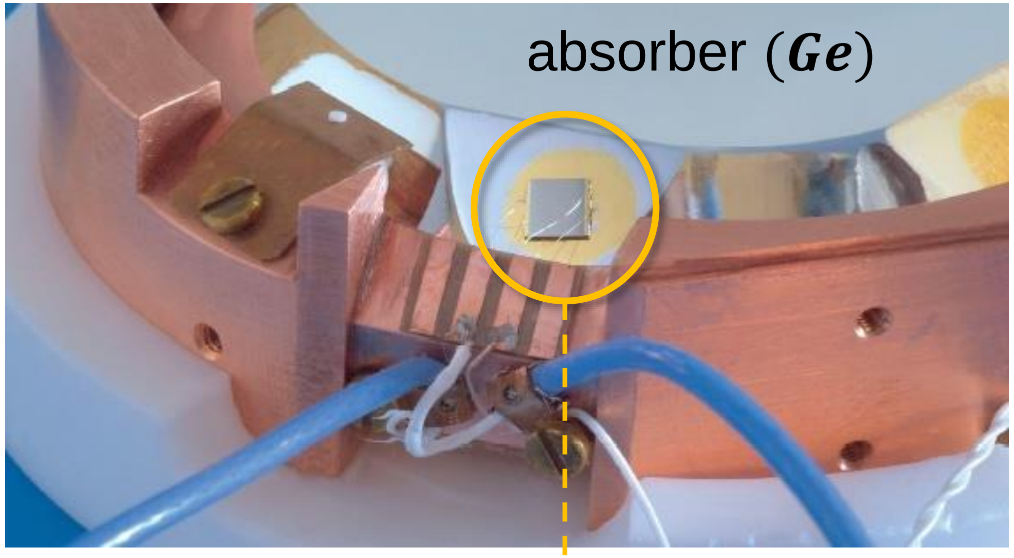
*THERMally sensitive resISTOR

Thermistors: high impedance NTD sensors

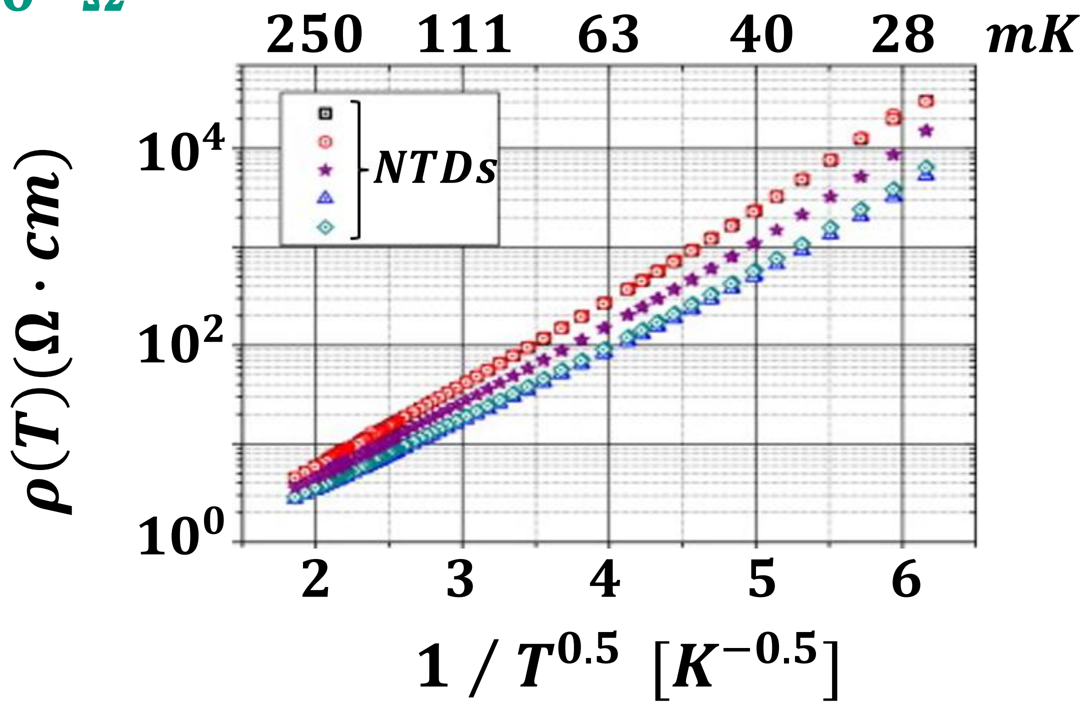
- ***N*eutron *T*ransmutation *D*oped (NTD) germanium sensors**

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

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



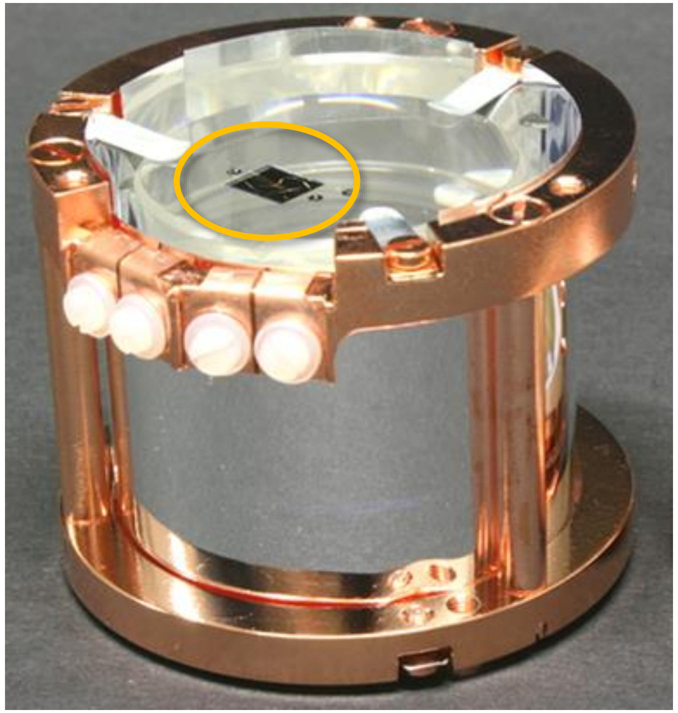
NTD – thermistor for phonon read–out



Thermistors: low impedance TES sensors

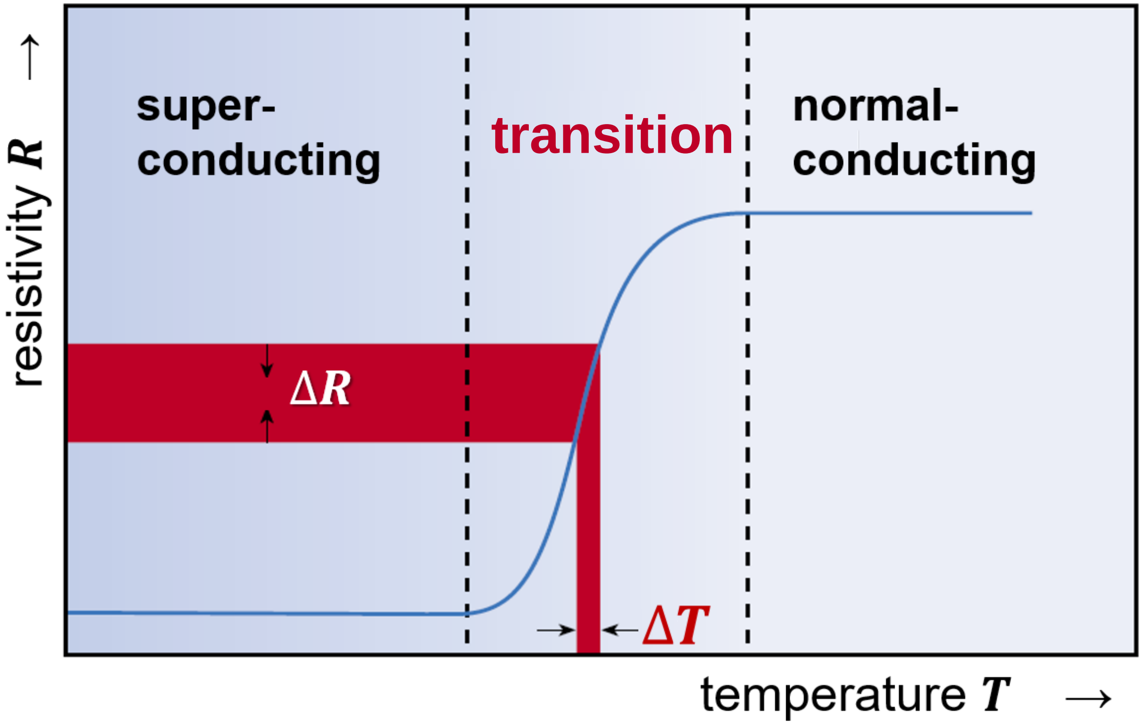
- **Superconducting Transition Edge Sensors (TES)**

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



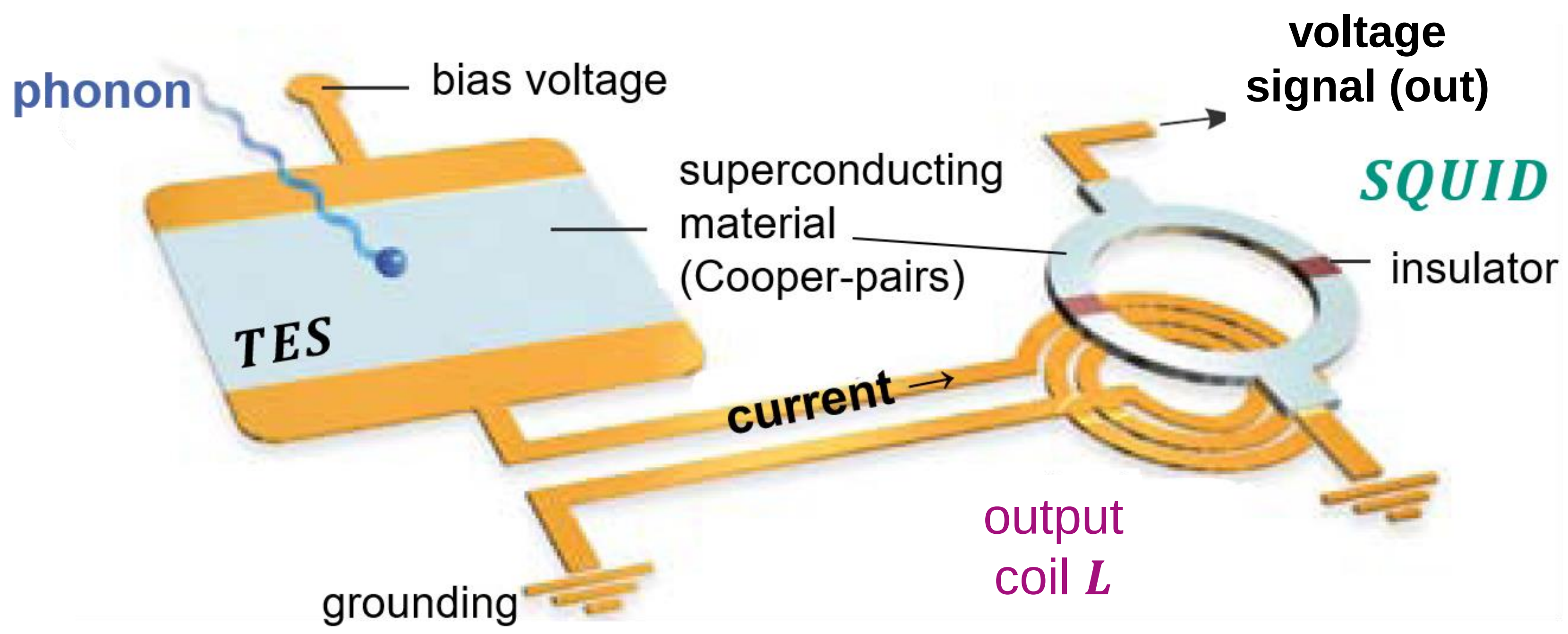
TES: tungsten–based thermistor

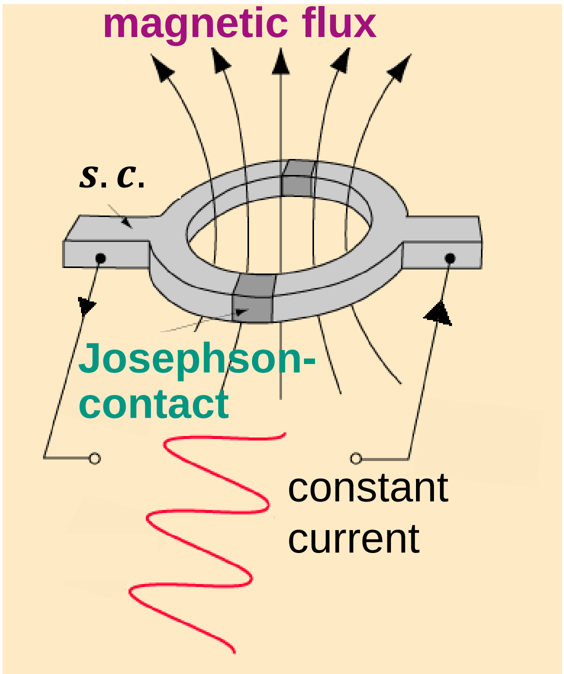
small ΔT
large ΔR



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





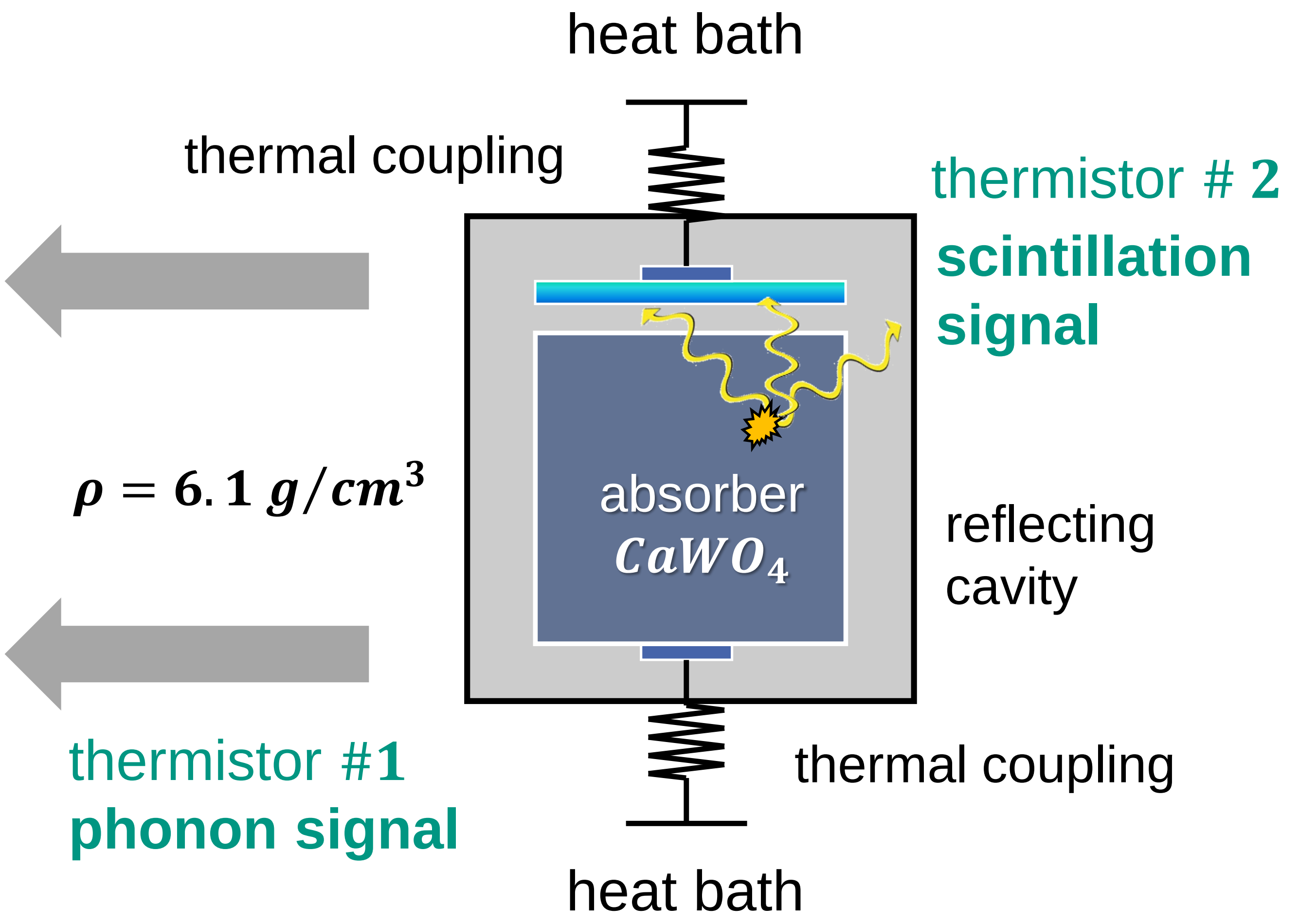
*Superconducting Quantum Interference Device

$CRESST$* experiment: phonons & photons

- **Hunting low mass $WIMPs$: 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**)



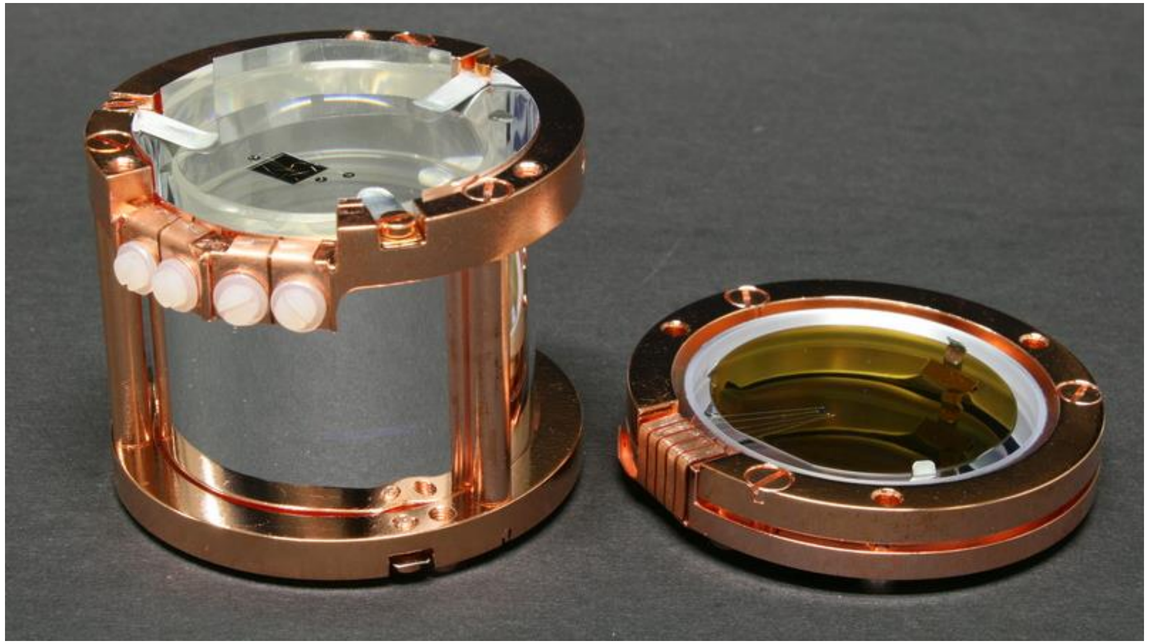
*Cryogenic $R$are Event Search with Superconducting Thermometers

$CRESST$ experiment: phonons & photons

- Hunting low mass $WIMPs$: 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 $CaWO_4$

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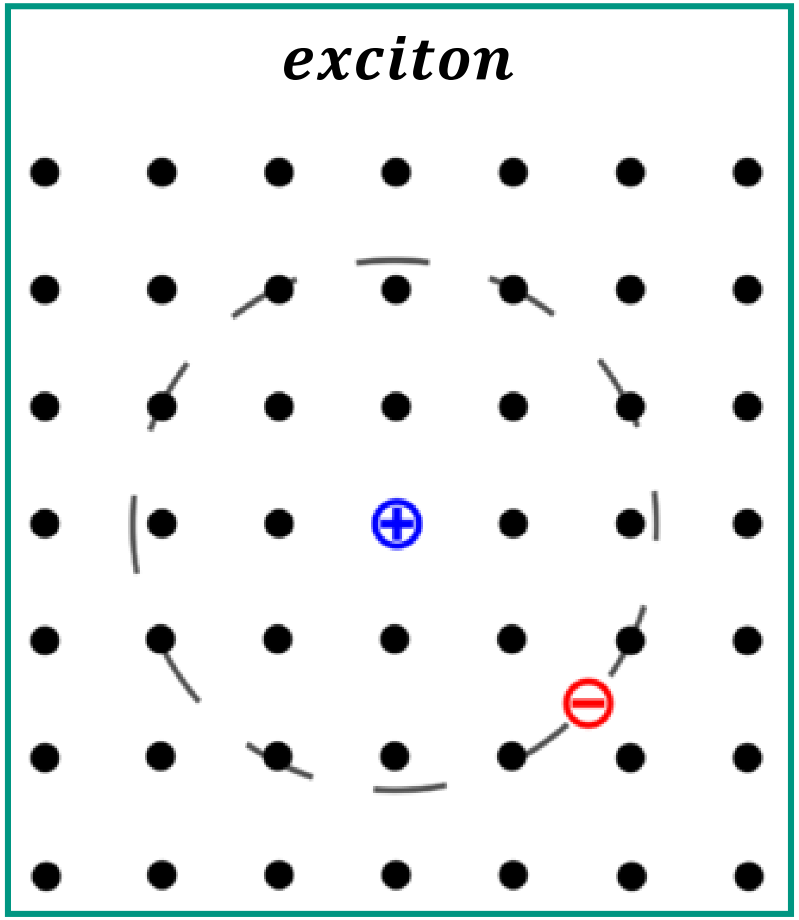
- **Primary particle interaction: generation of an $exciton$**

  - primary particle interaction:
    generation of $\boldsymbol{excitons}$
    $=$ **bound** states of electron – hole pairs
    with binding energies $\mathbf{10}\ \boldsymbol{meV}$ &
    large radii

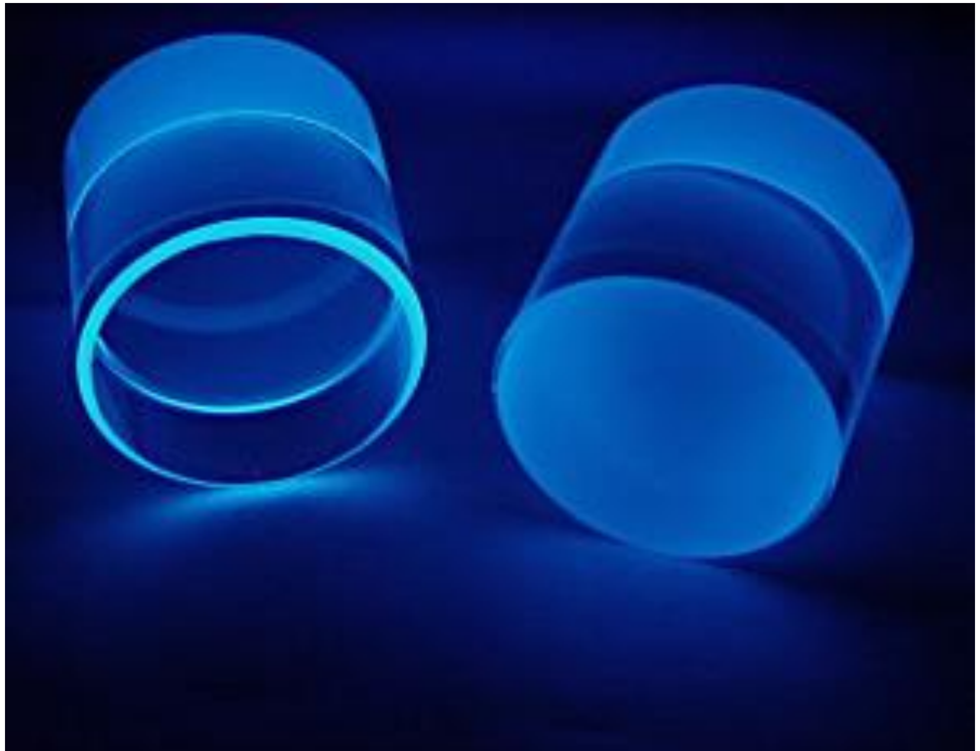


$CRESST$ experiment: scintillation of $CaWO_4$

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

- primary particle interaction:
  generation of $excitons$
  = **bound** states of **electron – hole pairs**
  with binding energies $10\ meV$ &
  large radii

- **recombination** of an exciton:
  will generate **scintillation light**
  with constant decay time $\tau \approx 1\ \mu s$ for
  temperature regime $T = 20\ mK \ldots\ 4.2\ K$


scintillation light from $CaWO_4$

$CRESST$ experiment: good PID in $CaWO_4$

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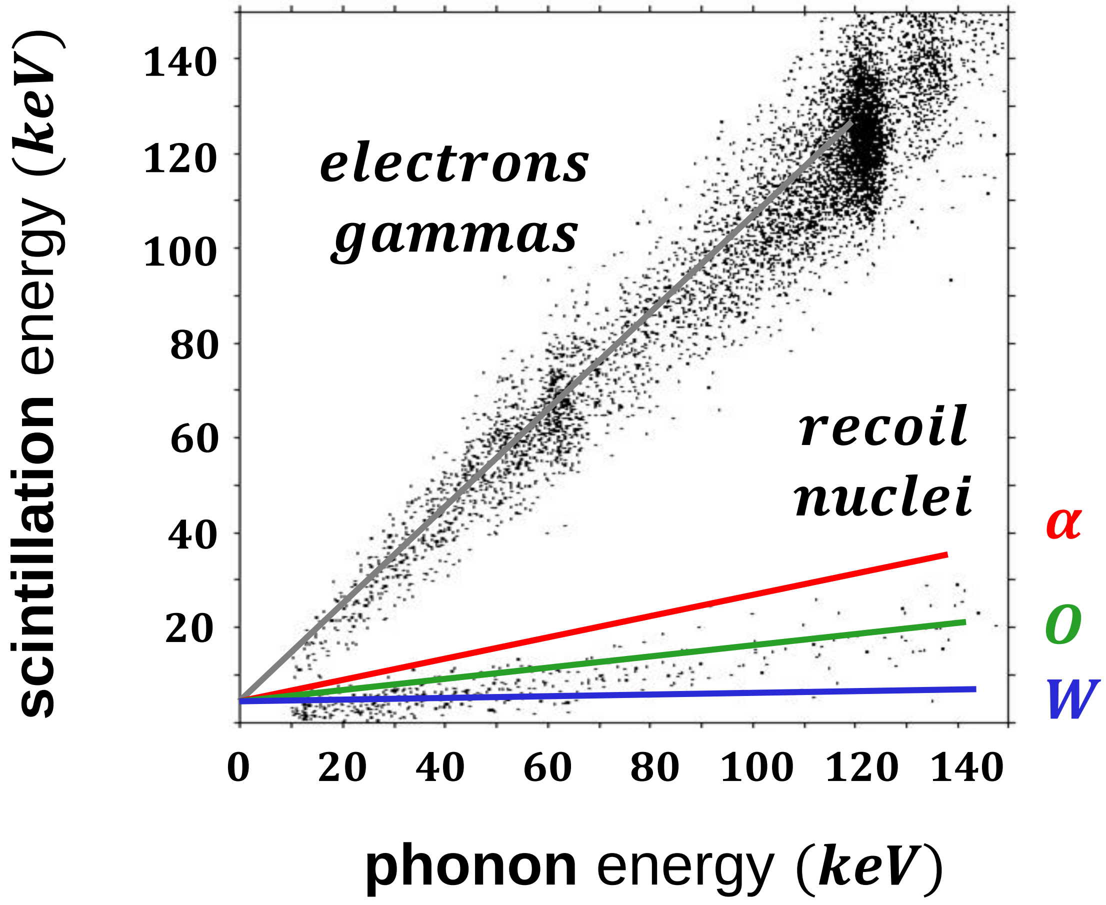
- **Light signal from exciton recombination is quenched for nuclear recoils**

- nuclear recoils

  - due to the **high energy loss dE/dx** of the recoil nucleus: excitons will undergo **non−radiative recombination** ⇨ quenching

  - amount of **quenching** (see picture) is verified by experimental studies



$CRESST$ experiment: good PID in $CaWO_4$

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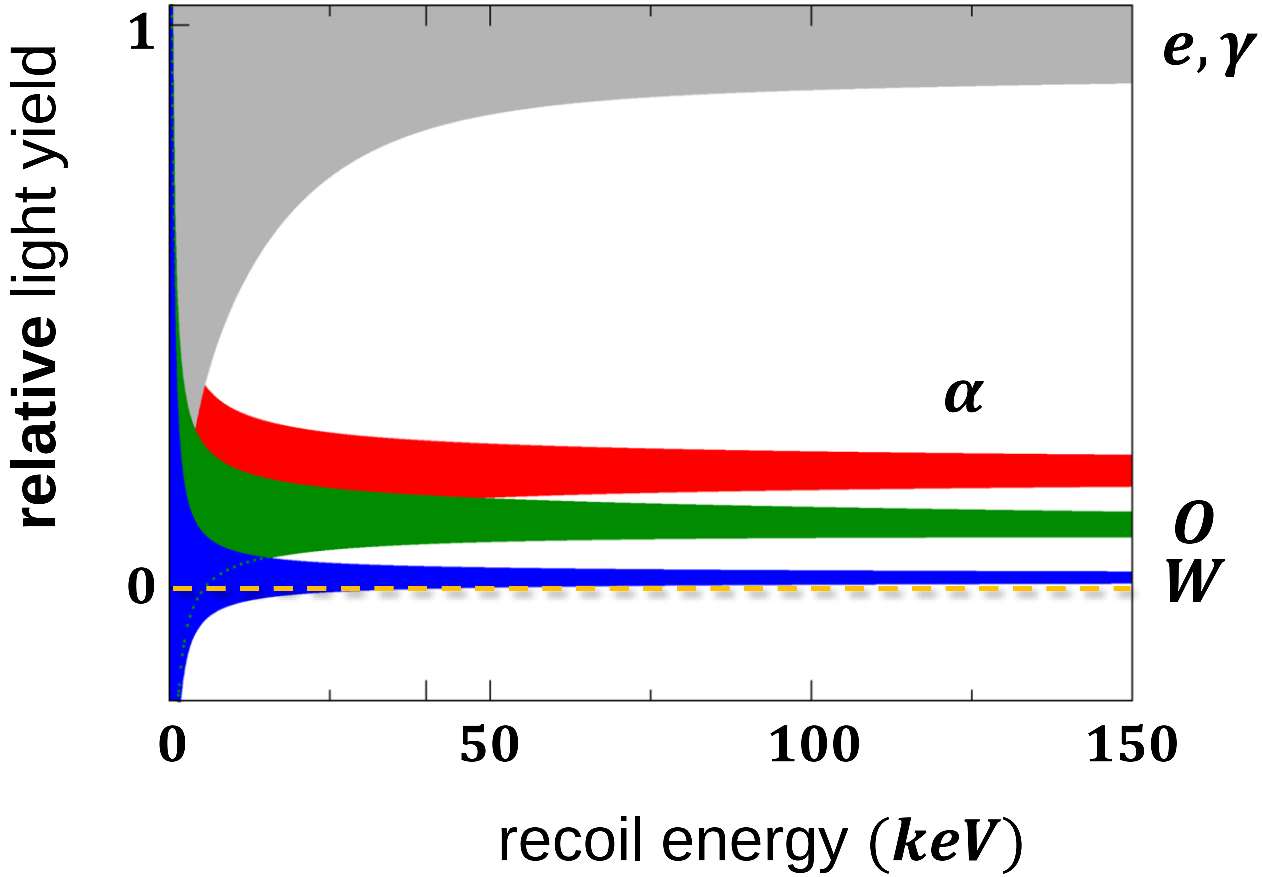
- **Light signal from exciton recombination is quenched for nuclear recoils**

- nuclear recoils

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

  - amount of **quenching** (see picture) is verified by theoretical studies

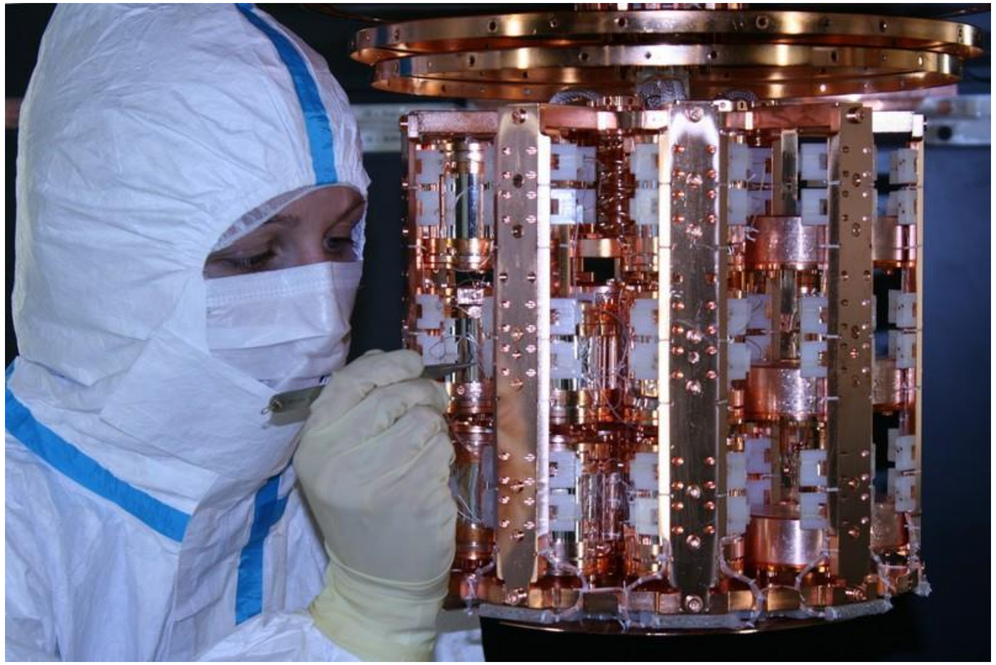


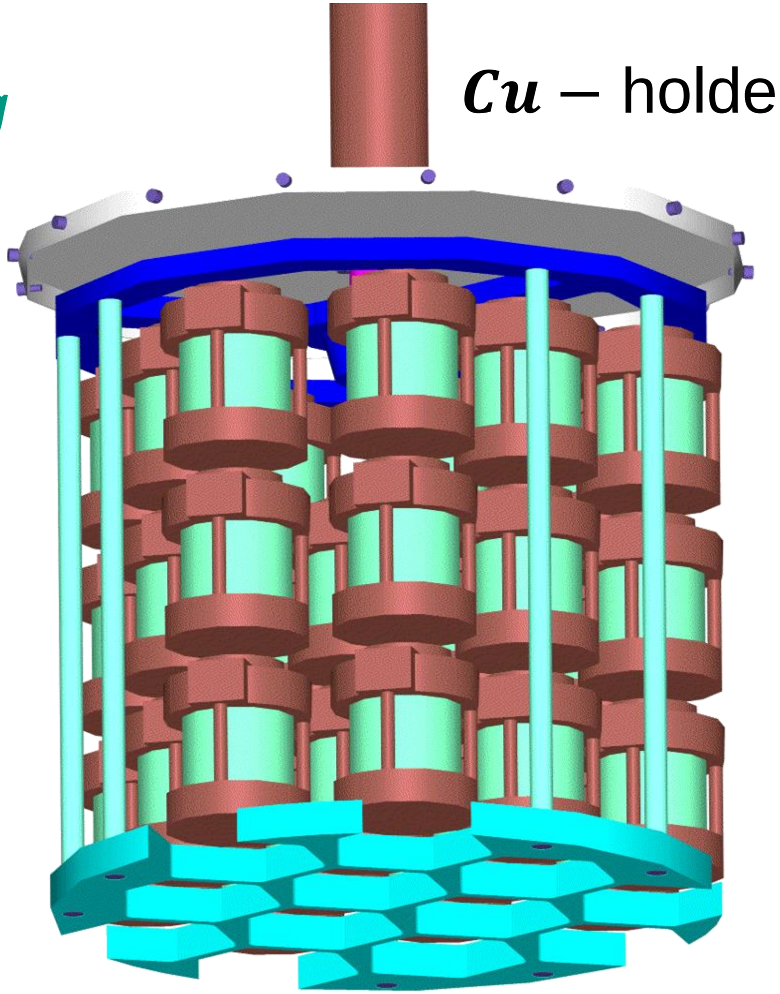
$CRESST$ experiment: set–up at $LNGS$

- **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

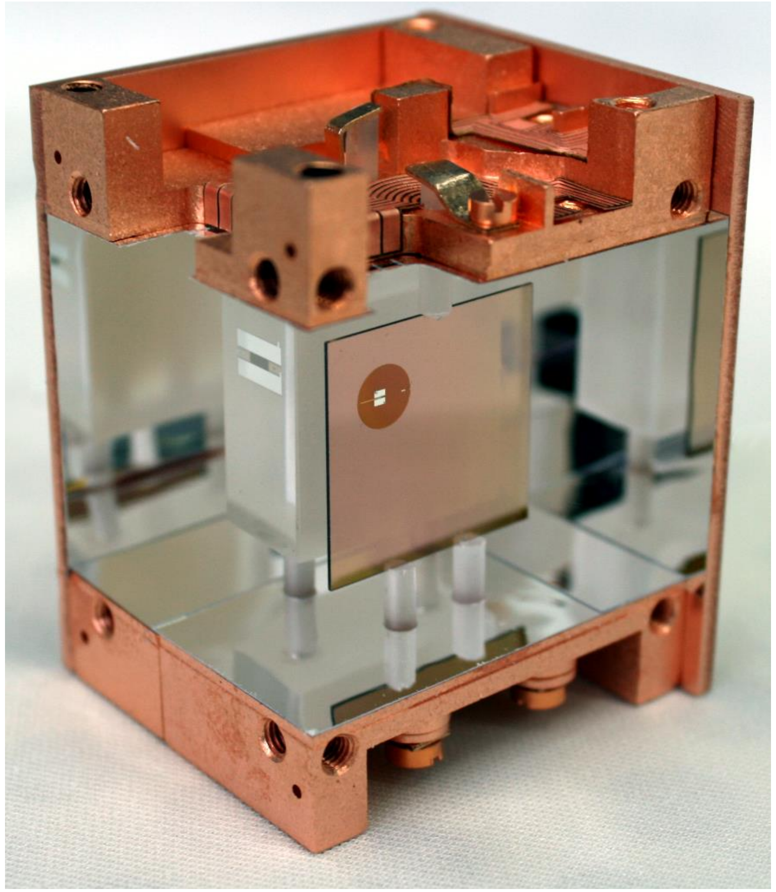
- **Reducing the mass of single bolometers to reduce the energy threshold**

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

- advantage: **very low threshold**, as more scintillation photons will reach **thermistor #2**

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

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



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

*in honour of $Lise\ Meitner$

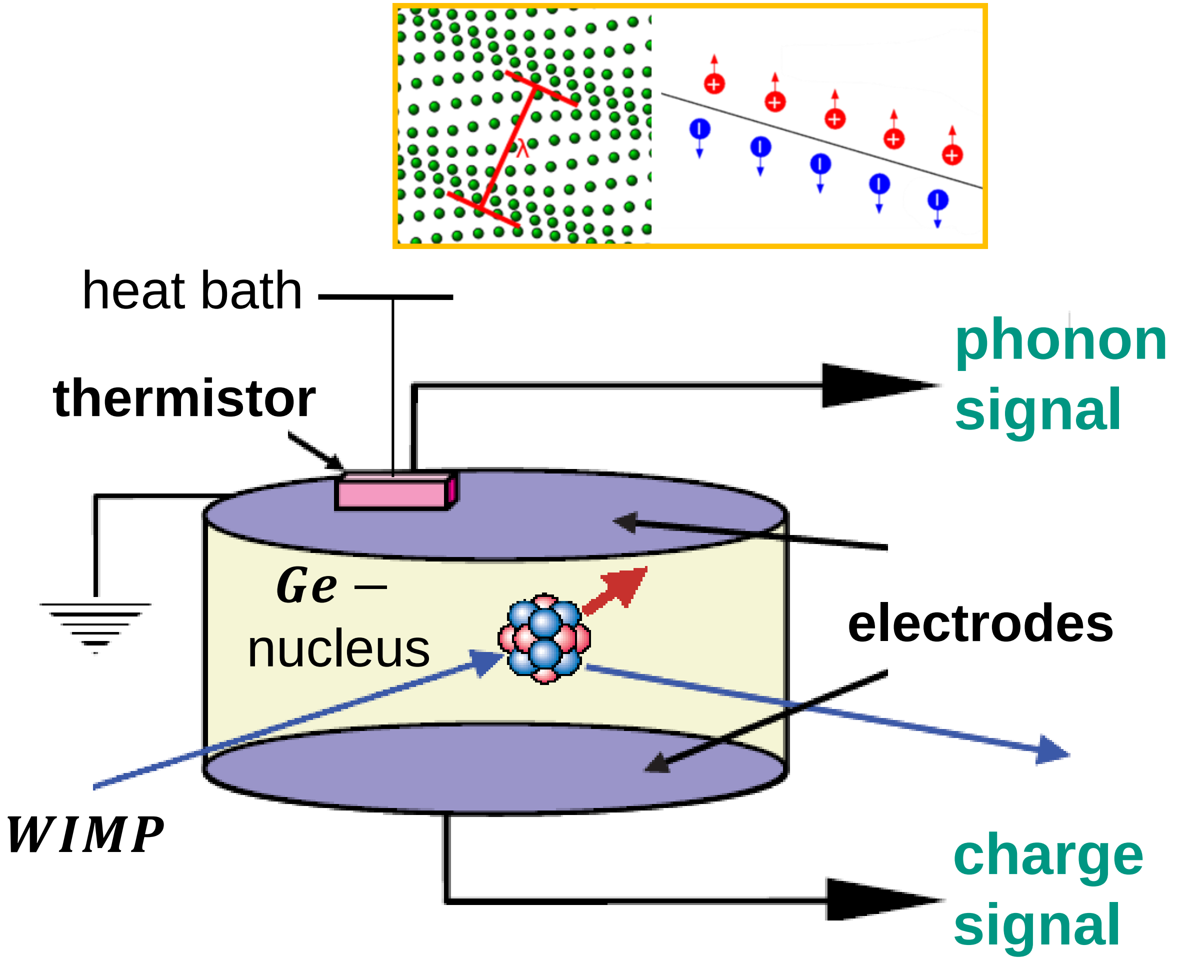
Cryogenic bolometers: phonons & ionisation

- $\boldsymbol{Ge}$ – **bolometers at the** $\boldsymbol{mK}$ – **scale with charge and phonon read–out**

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

  - read–out of **slow** (**fast**) **phonons** via either a $\boldsymbol{NTD}$ ($\boldsymbol{TES}$) thermistor
    ⇨ determine **recoil energy** $\boldsymbol{E_R}$

  - read–out of **electron** & **hole signals** via electric field at **2 electrodes**
    ⇨ determine the $\boldsymbol{PID}$ on the basis of **quenching**



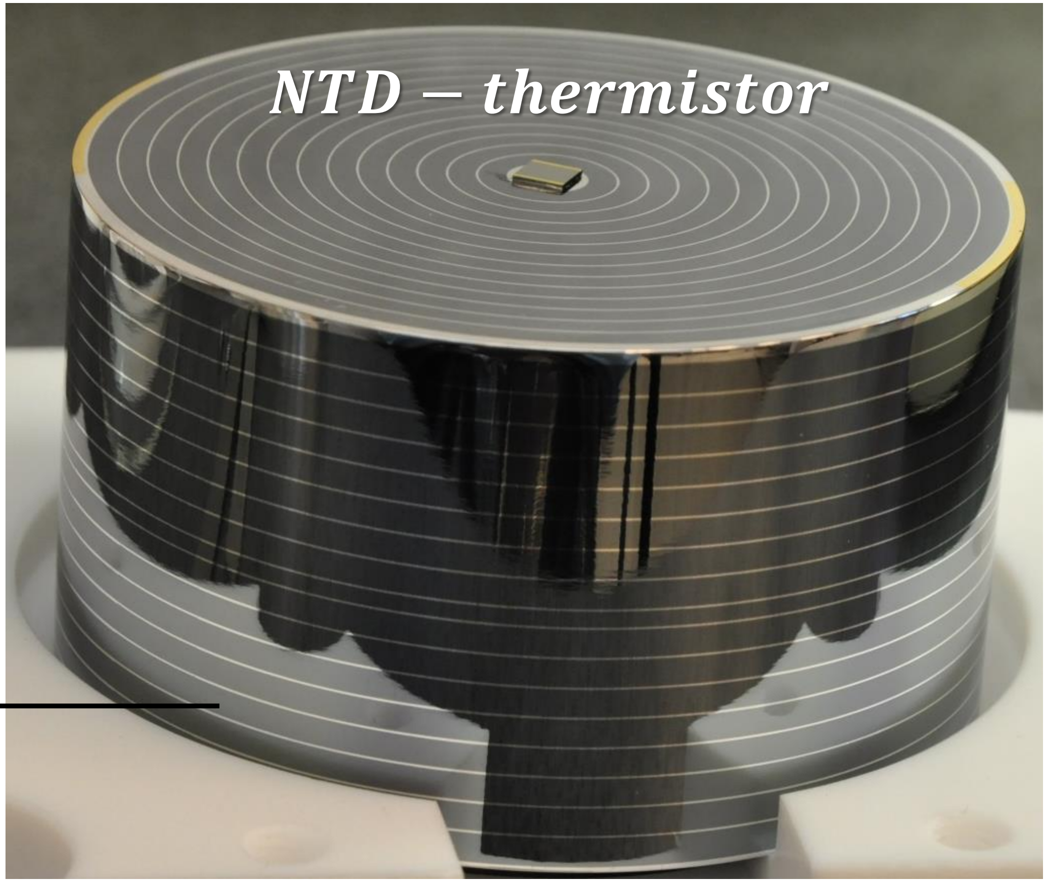
Cryogenic bolometers: phonons & ionisation

- 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: ionisation

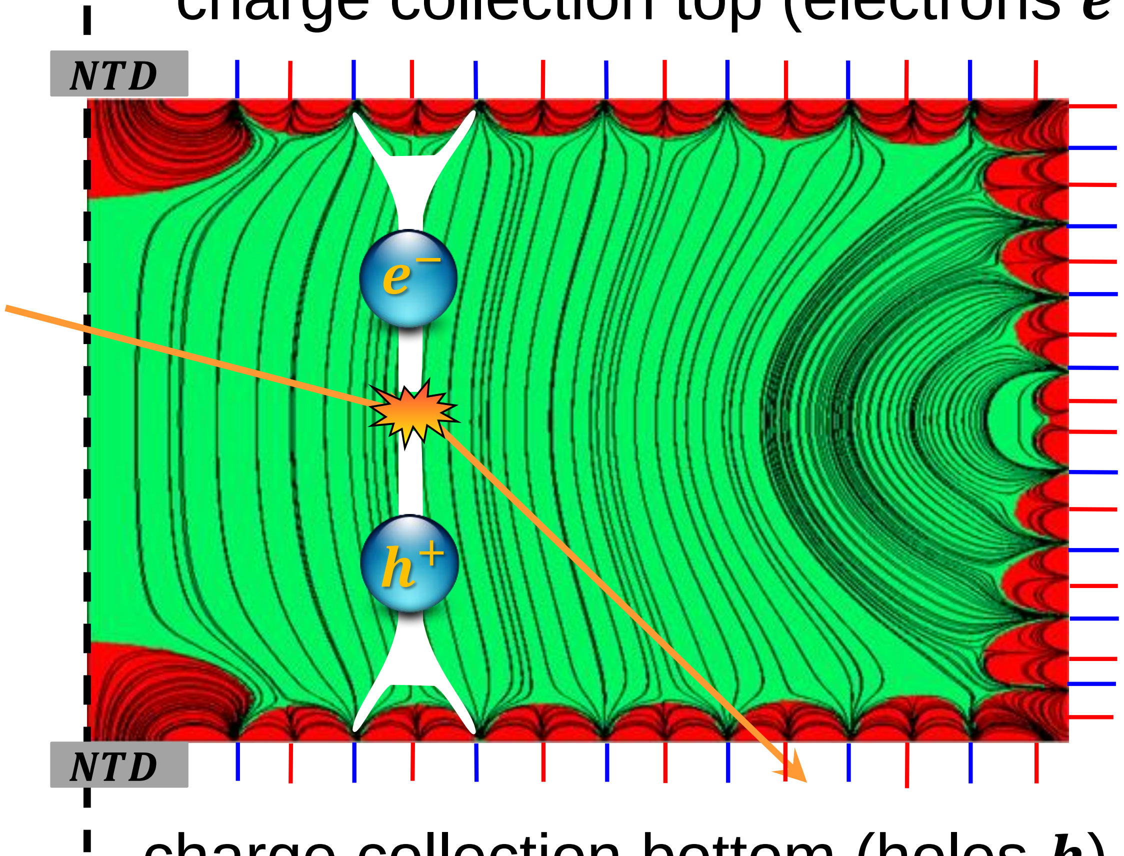
- Ge – **bolometers at the** mK – **scale:** **read–out of the charge signal**

  - 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 e^-)



charge collection bottom (holes h)

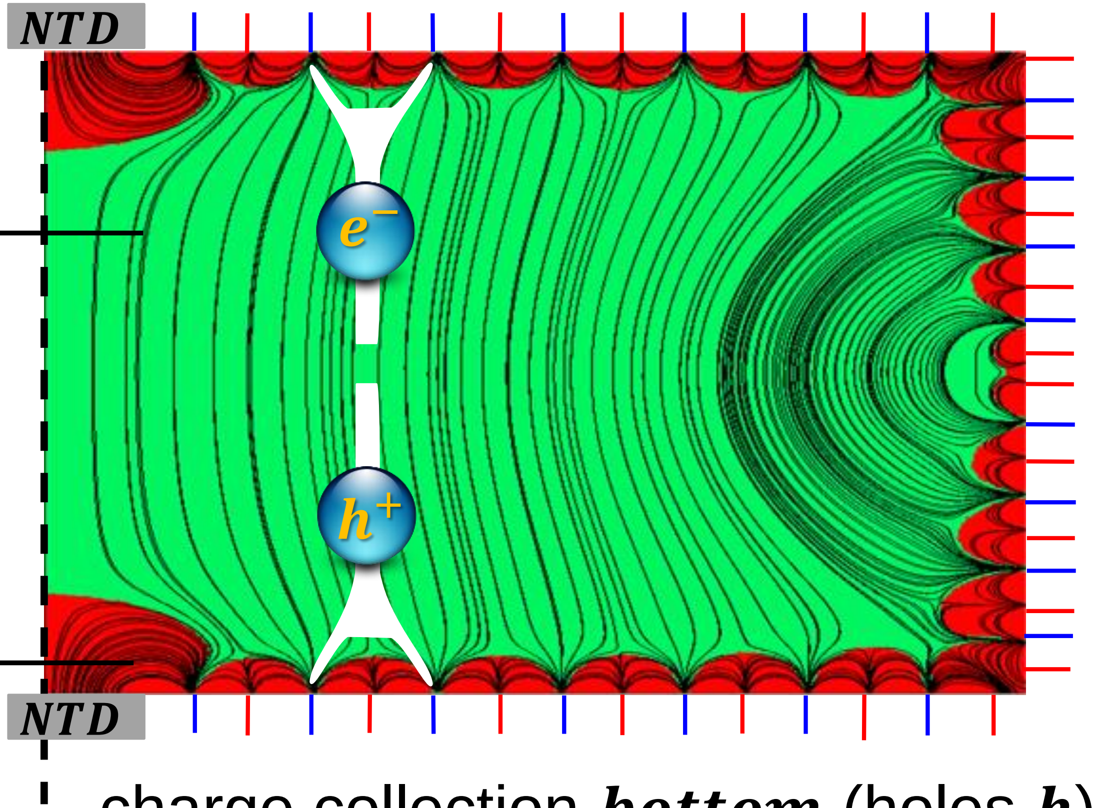
Cryogenic bolometers: ionisation

- 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**



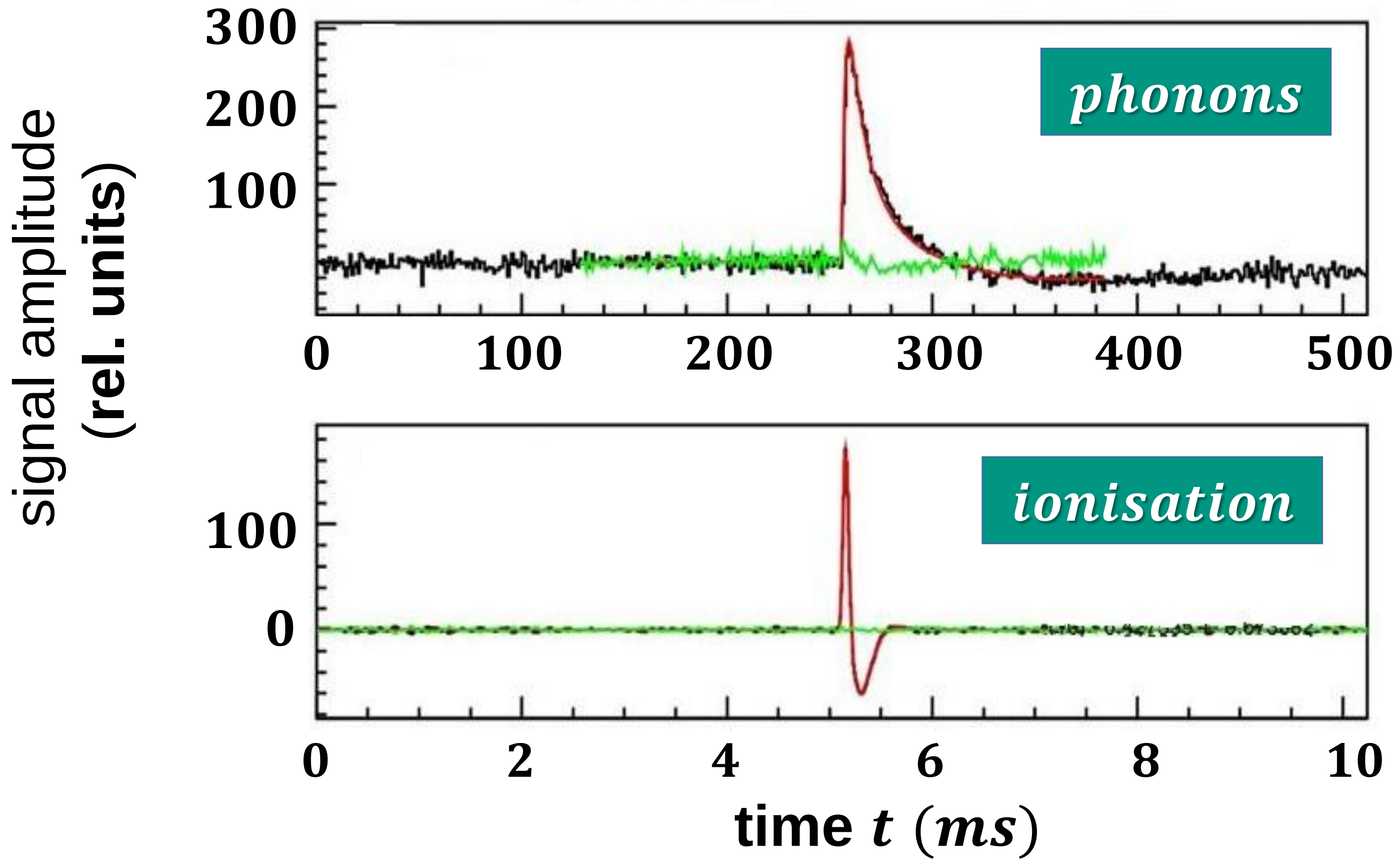
Cryogenic bolometers: phonons & ionisation

- 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 surface of a bolometer – this would look like a $WIMP$

coincidence: $phonons$ & $ionisation$

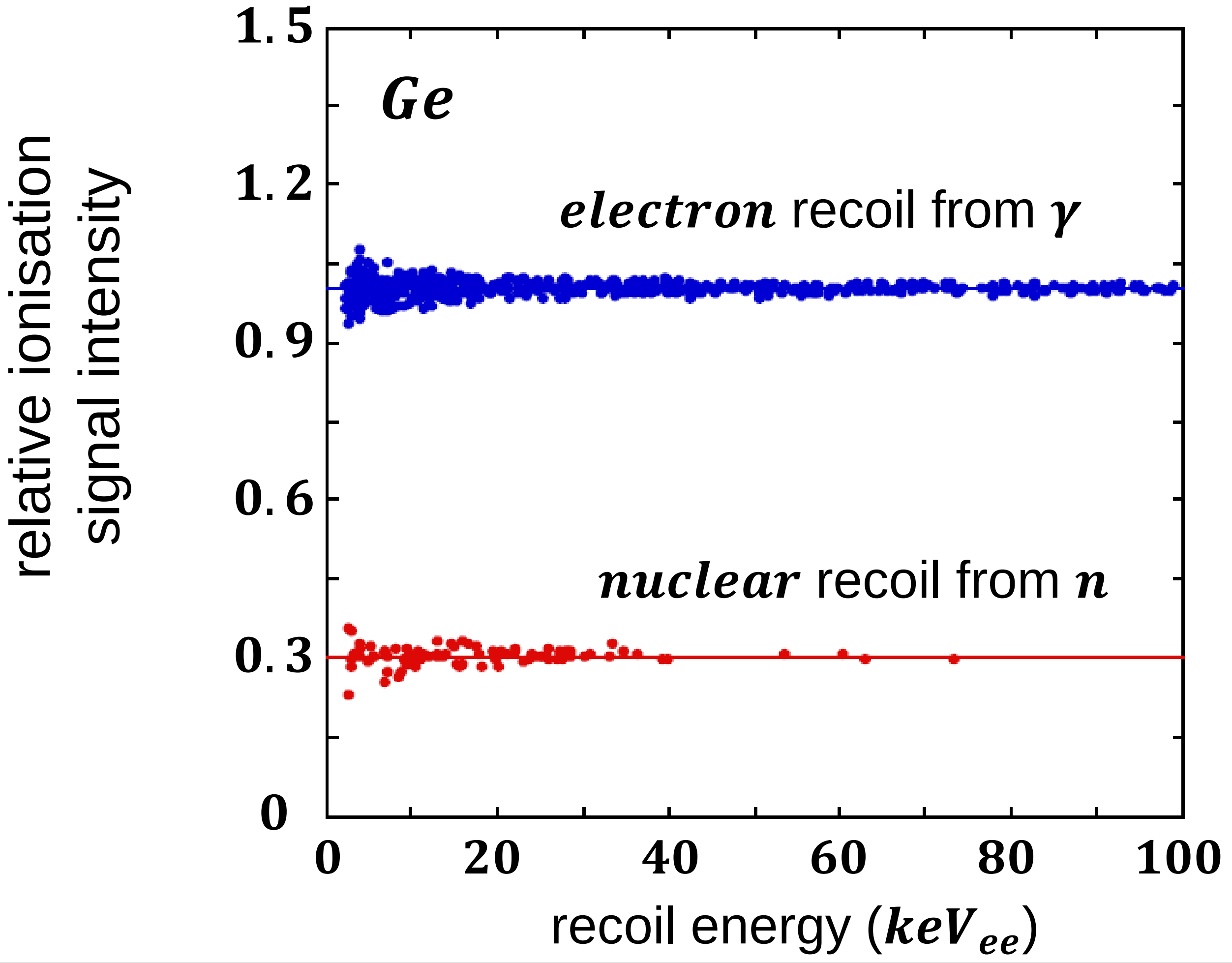


Cryogenic bolometers: phonons & ionisation

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

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

ionisation signal
$\cong 1/3$ of
phonon signal

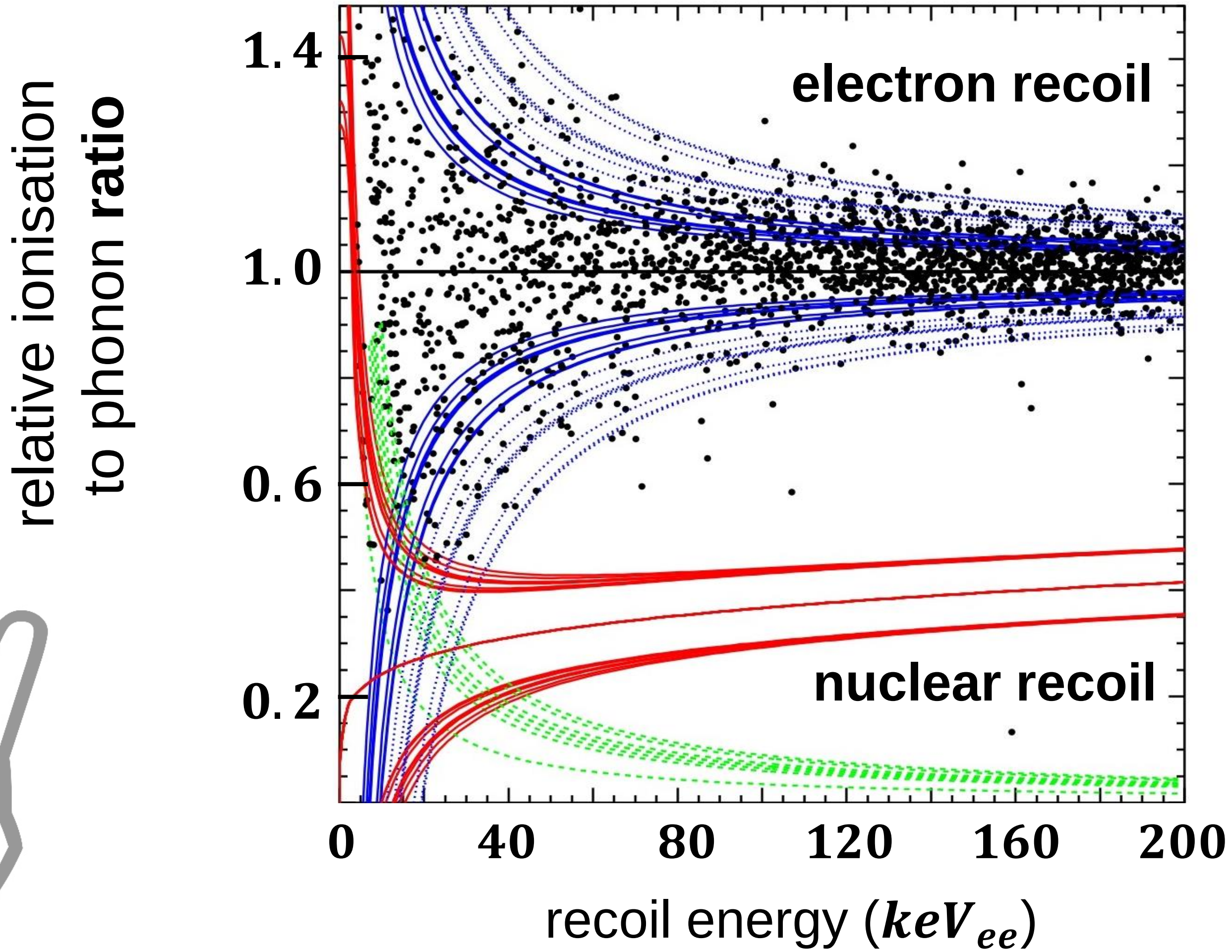


Cryogenic bolometers: phonons & ionisation

- $Ge-$ 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*

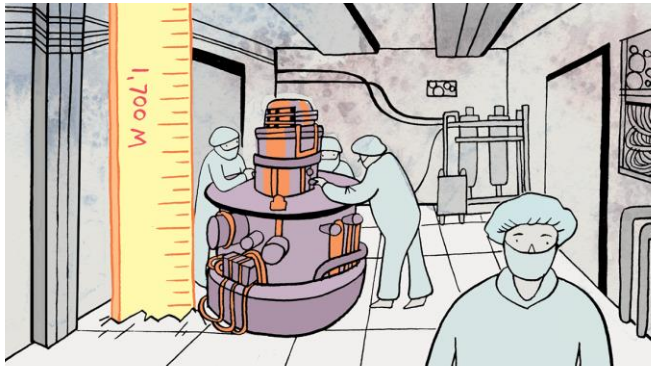
Karlsruhe Institute of Technology

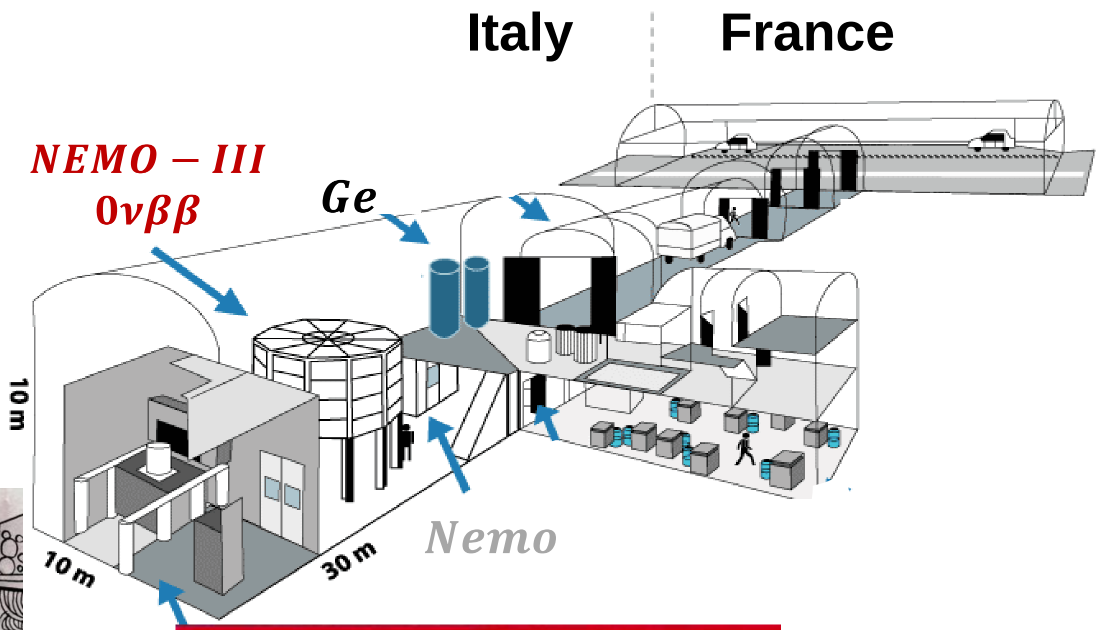
- *Ge* – bolometer array for light *WIMPs* at *L*aboratoire *S*outerrain de *M*odane

LABORATOIRE SOUTERRAIN DE MODANE

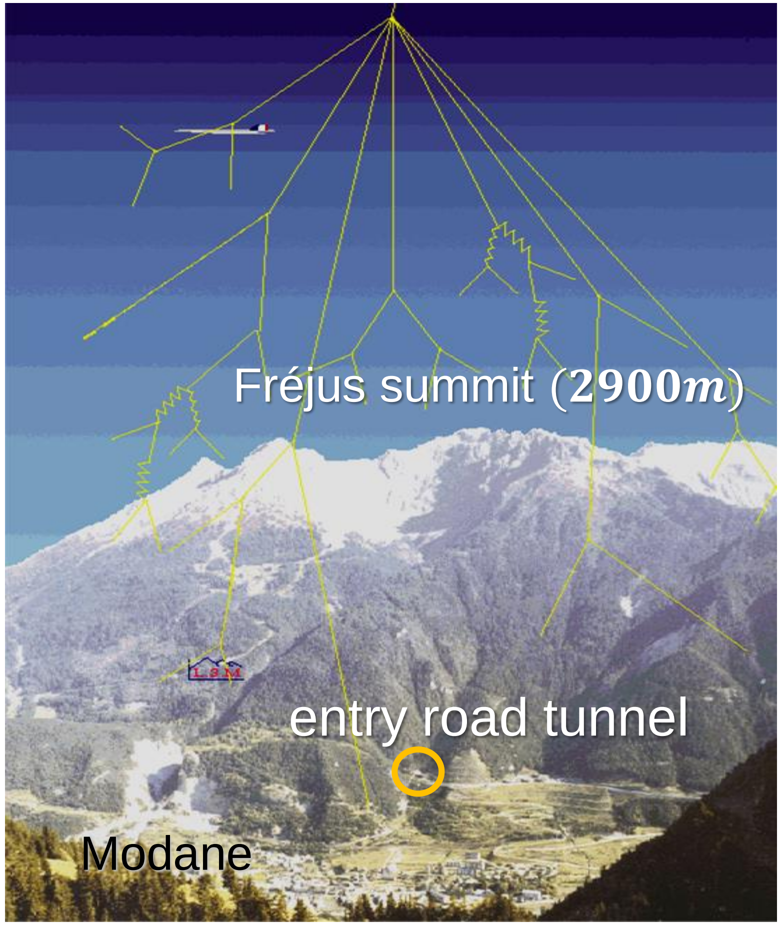
$4800\ m.w.e.$

$4\ \mu's\ m^{-2}\ day^{-1}$





Expérience pour DEtecter Les WIMPs En Site Souterrain



*Expérience pour $dé$tecter $l$es WIMPs en Site Souterrain

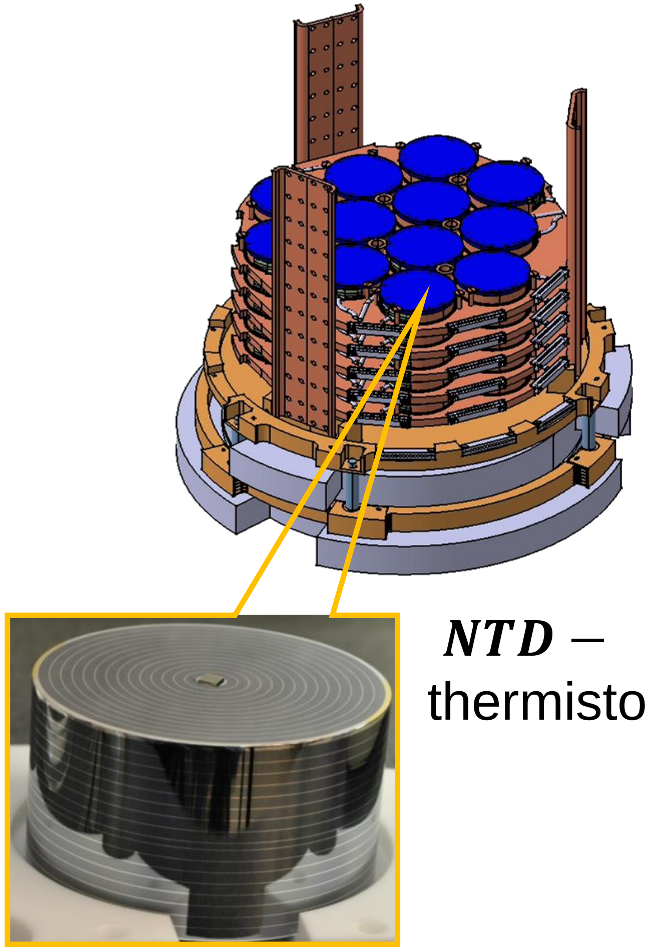
$EDELWEISS$ experiment at the LSM

- $20\ yr$ – long search for light $WIMPs$: set–up & history (KIT participated)

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

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

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



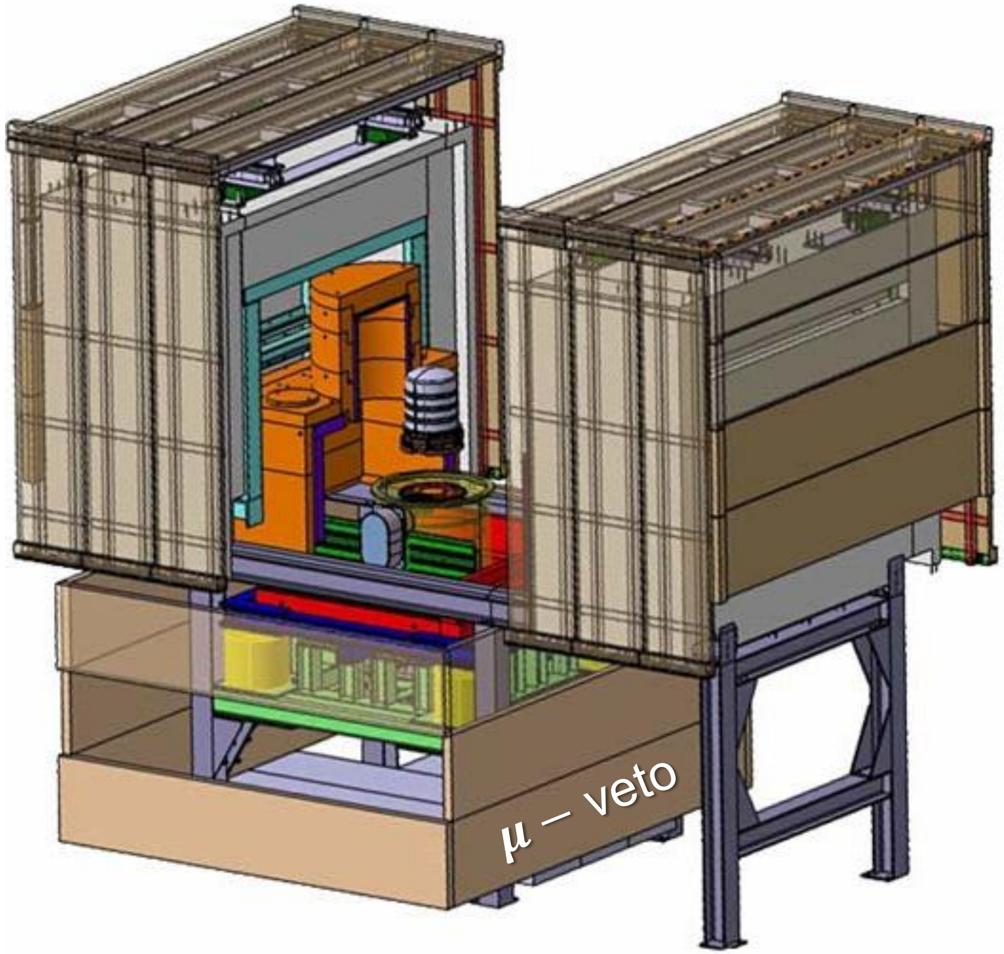
$EDELWEISS$ experiment at the LSM

- **$20\ yr$ –long search for light $WIMPs$: results & impact**

- **no $WIMP$** signal observed in $Edelweiss - III$

- **no further increase** of the target mass
  ⇨ focus is now on a very **low threshold E_R**
  ⇨ hunt **extremly light $WIMPs$**

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

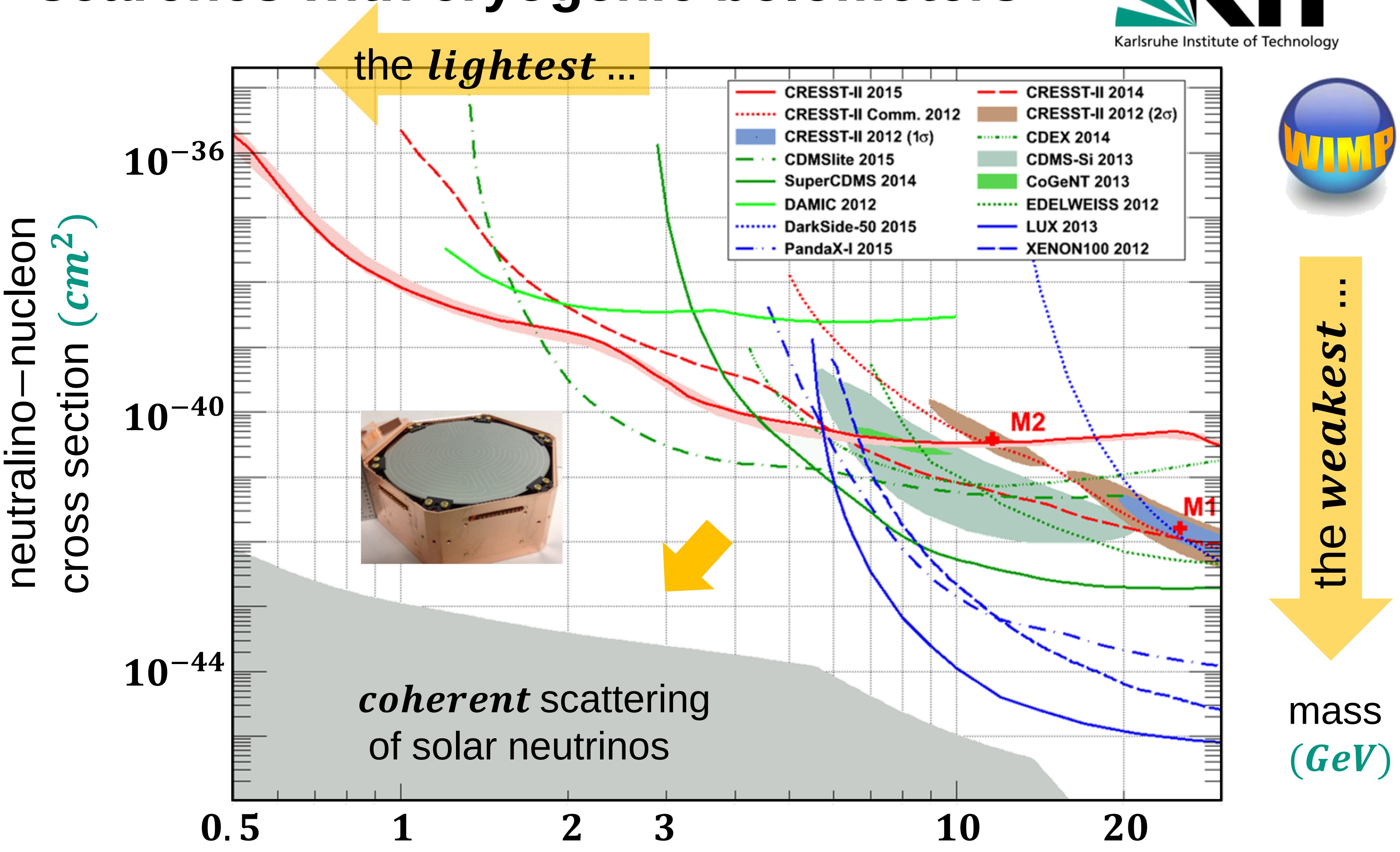


$Edelweiss - III$ setup: veto–scintillator & cryostat

Status of DM – searches with cryogenic bolometers

- $WIMPs$:
  how light?
  how weak?

- 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

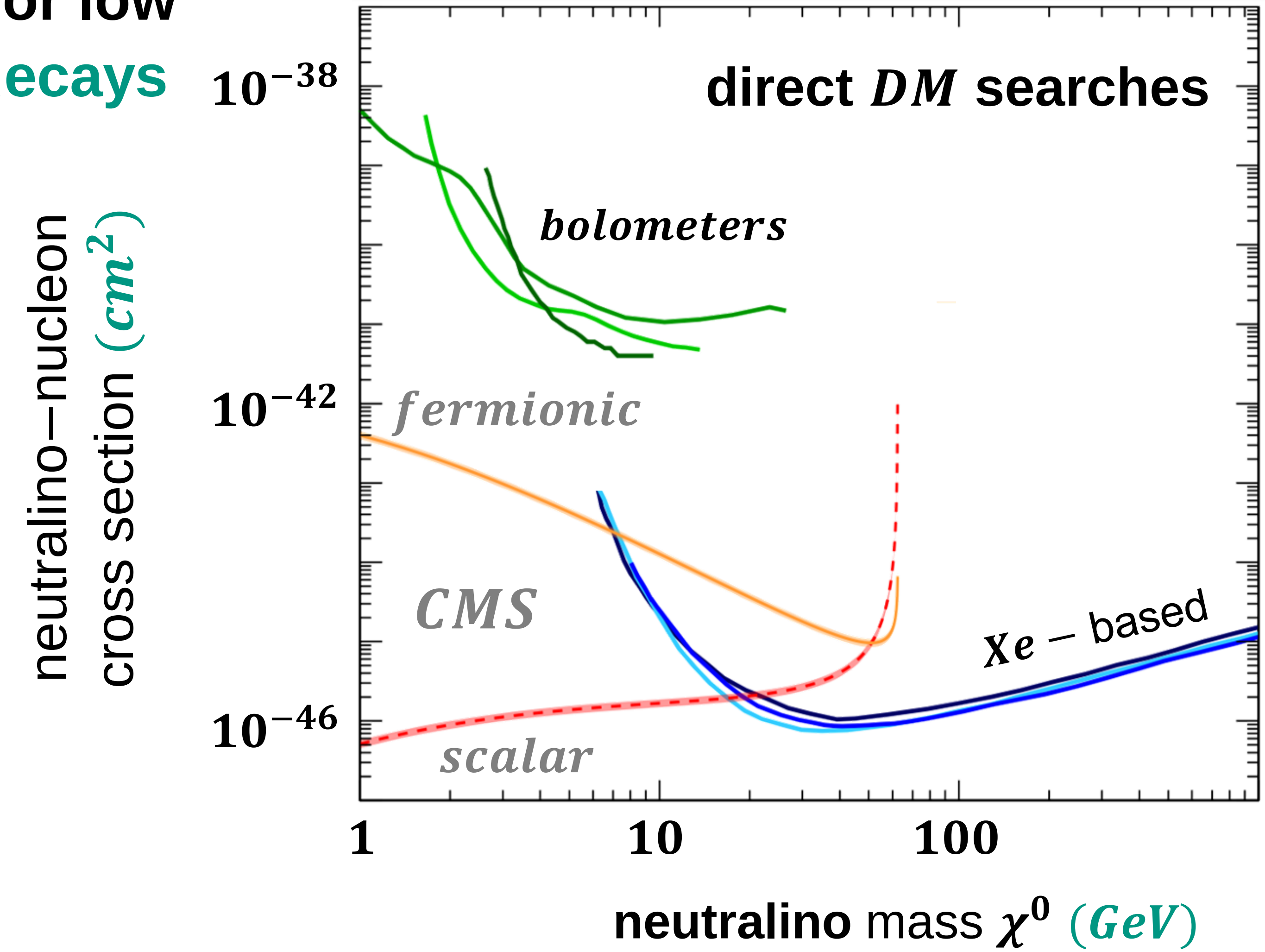


Comparing limits from LHC with direct searches

- **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 the $Higgs$ (⇨ $fermionic/scalar\ DM$)



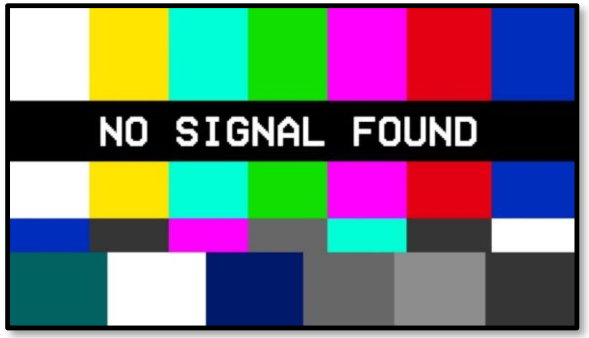
Comparing limits from LHC with direct searches

Karlsruhe Institute of Technology

- **No undisputed signals: 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 $\boldsymbol{sub-GeV}$ masses are upcoming…



* *Did you manage to finally find this Dark Matter?*
Or, do I first need to get angry?

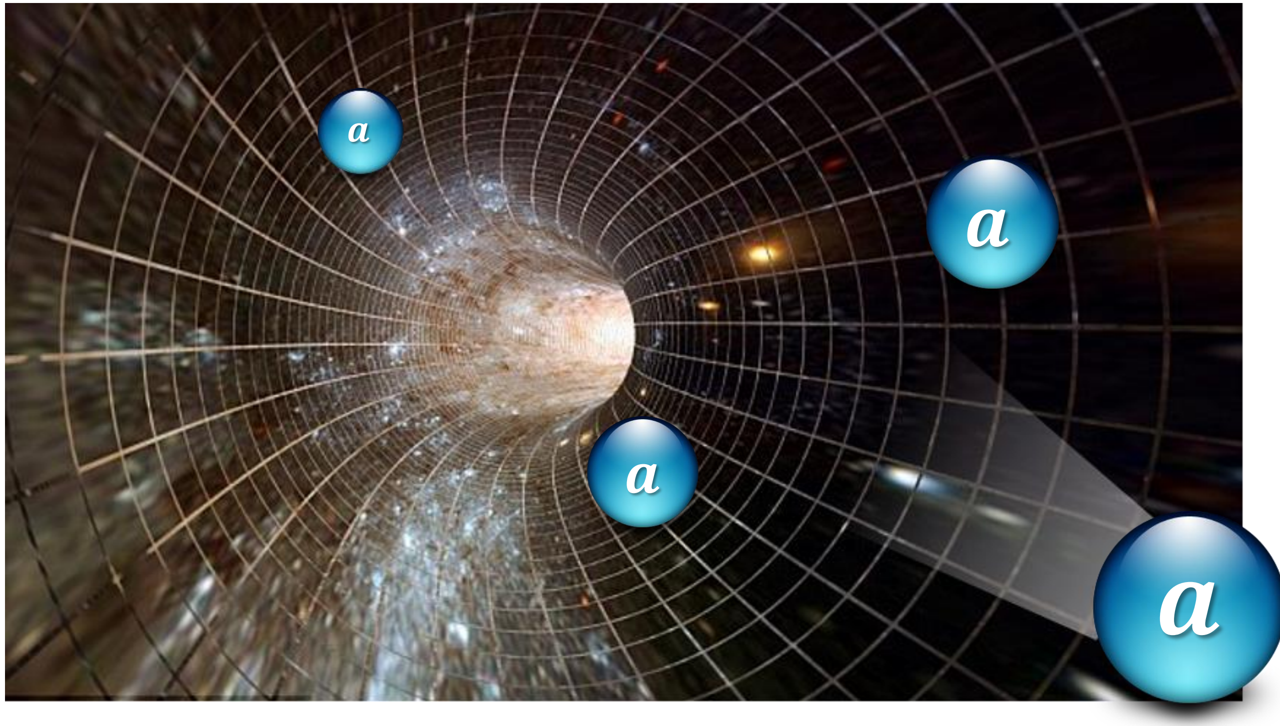
Is Dark Matter super–symmetric, or, is it from …

- **Dark Matter could arise due to other symmetries in nature that also require a (now completely different) extension of the Standard Model**

  - supersymmetric $\boldsymbol{WIMP}$s – or a completely different $\boldsymbol{DM}$ – candidate

enter the

axion



MONTY PYTHON'S FLYING CIRCUS