# Studies on remoTES-based Cryogenic Calorimeters for the COSINUS Experiment

IMPRS Recruitment Workshop, 12.07.2023
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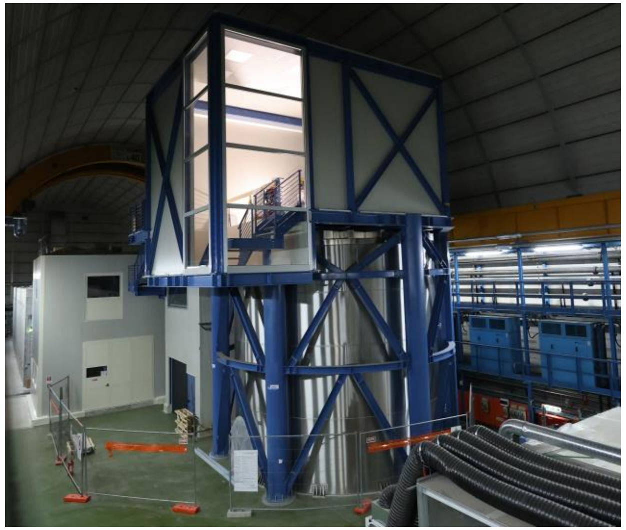
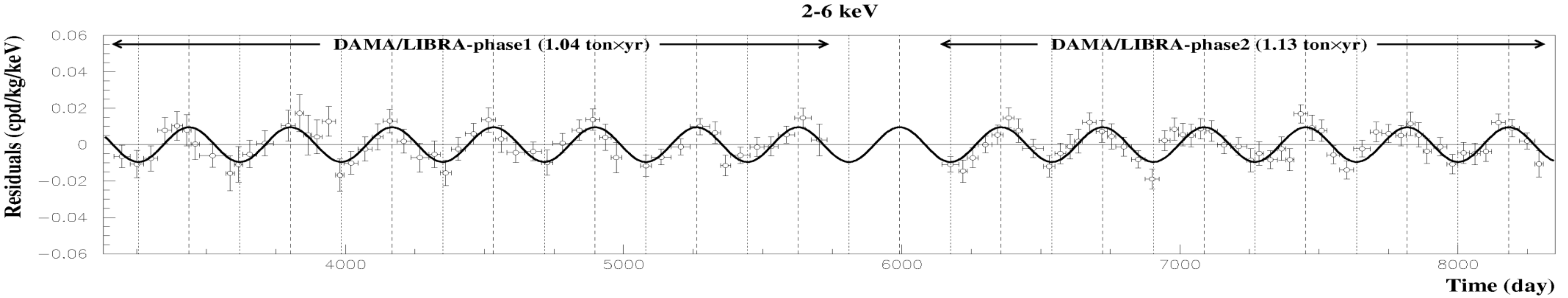
MAX-PLANCK-INSTITUT FÜR PHYSIK

COSINUS

# **C**ryogenic **O**bservatory for **SI**gnals seen in **N**ext **U**nderground **S**earches (COSINUS)

- Direct dark matter search operating NaI as a cryogenic calorimeter
- Primary objective: a model-independent cross-check of the modulation signal observed by the DAMA/LIBRA experiment
  https://iopscience.iop.org/article/10.1088/1475-7516/2018/05/074/pdf






DOI:10.3390/universe4110116

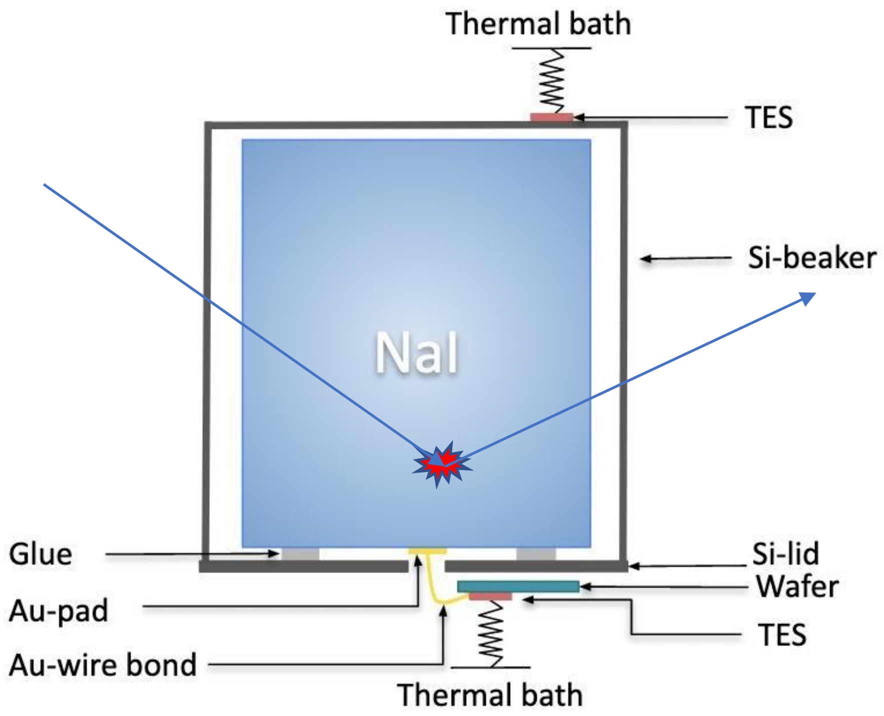
# COSINUS cryogenic detector module

**Phonon signal** + **Light signal**: dual channel readout technique

→ particle identification on an event-by-event basis

→ background discrimination

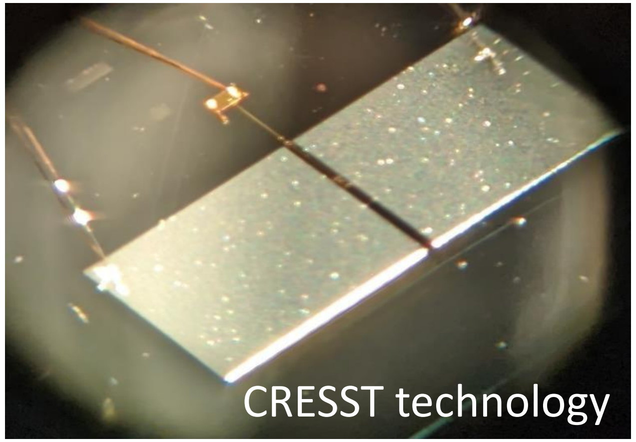
→ clarification of the modulation signal observed by DAMA/LIBRA

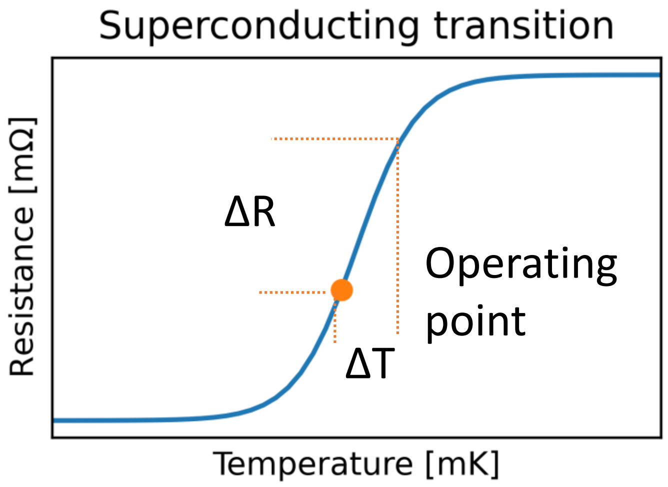


# Transition Edge Sensor (TES)

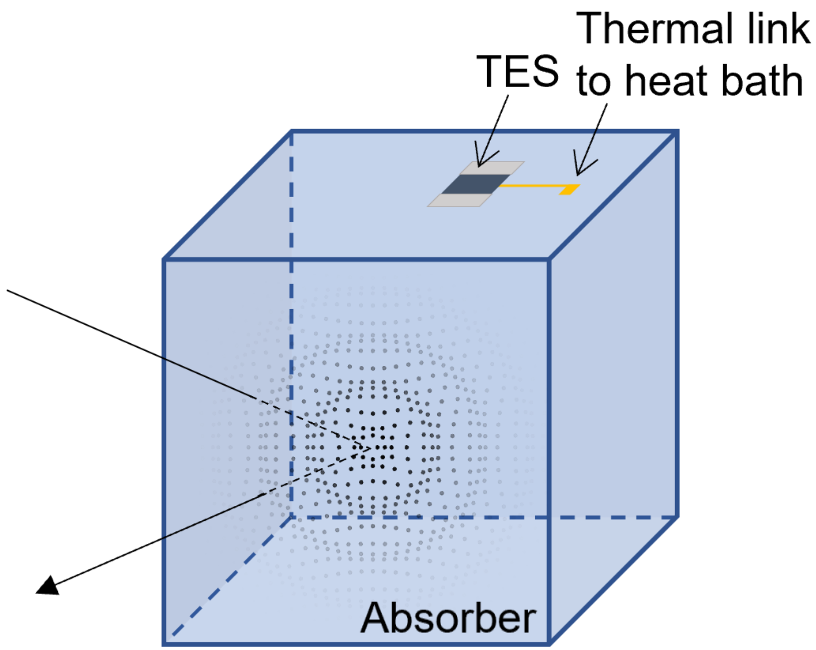
**Phonon channel** + **Light channel**: readout with Transition Edge Sensors

- Sensors made of superconducting tungsten thin film ($T_c$ = 15 mK)
- Operated in the transition between the normal conducting and the superconducting phase
- Small increase in the temperature $\mathcal{O}(\mu K)$ leads to a change in the resistance $\mathcal{O}(m\Omega)$



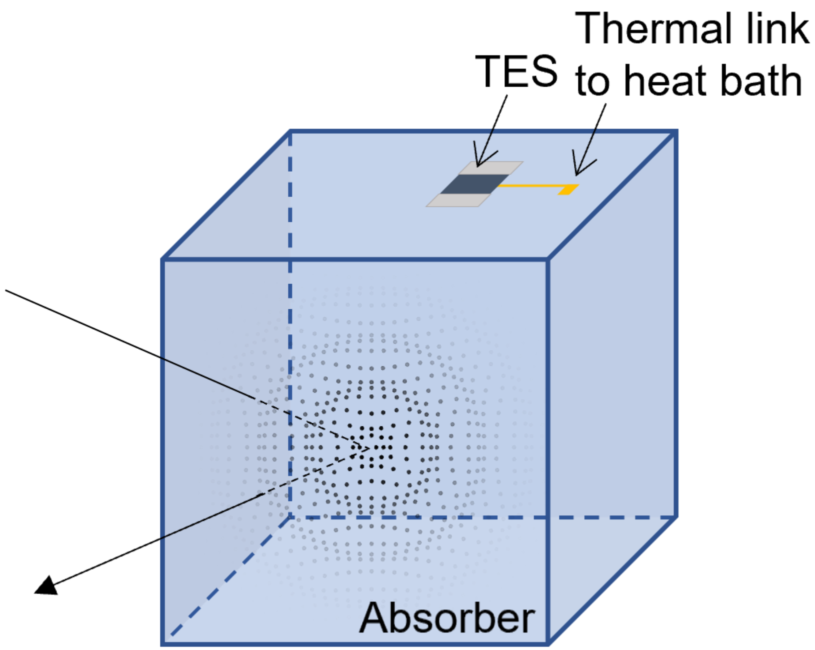



# TES



# TES and NaI

NaI:
- hygroscopic
- soft
- low melting point (662 °C)



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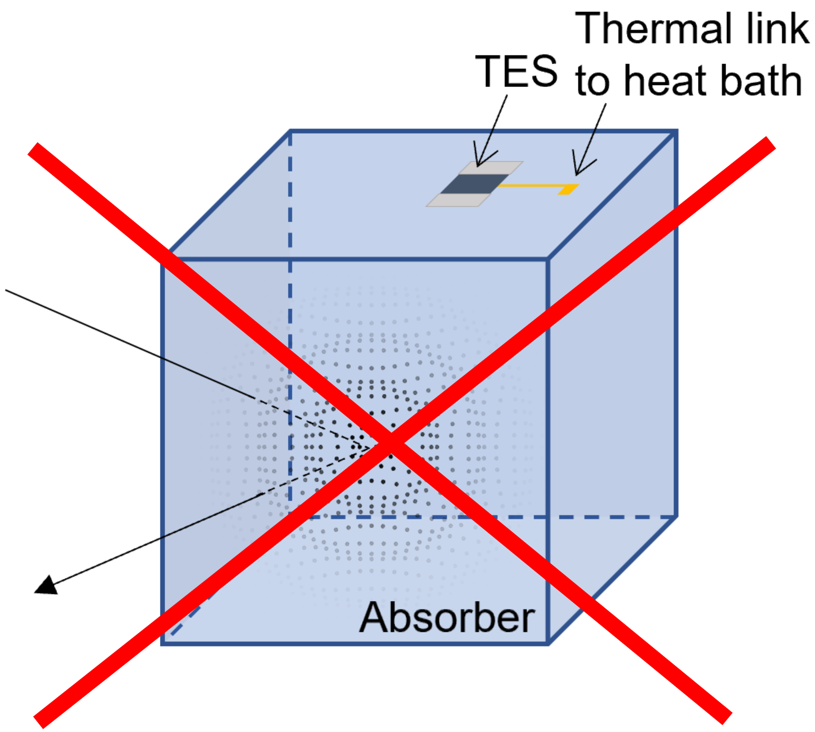

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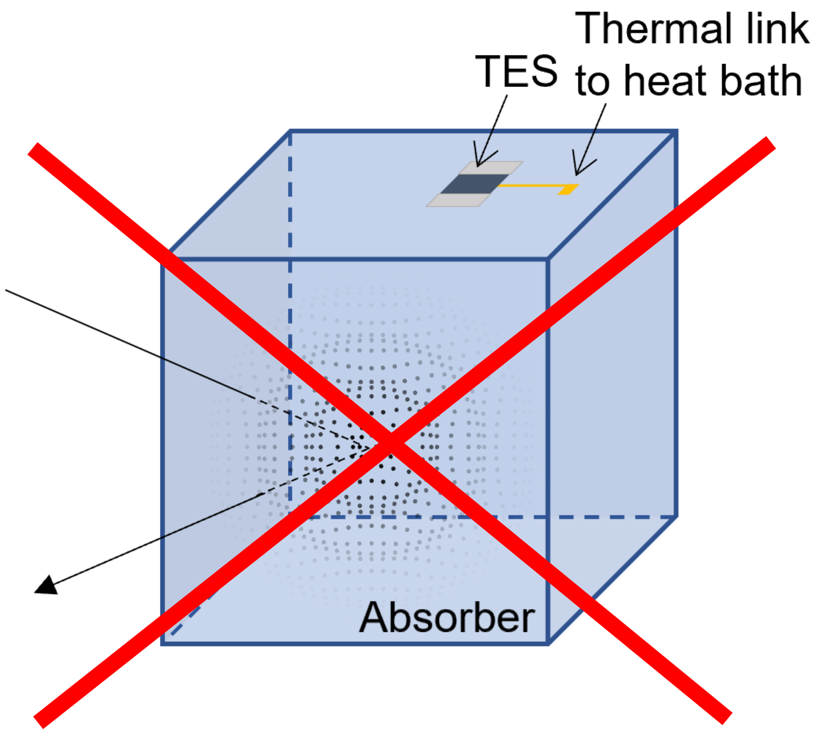
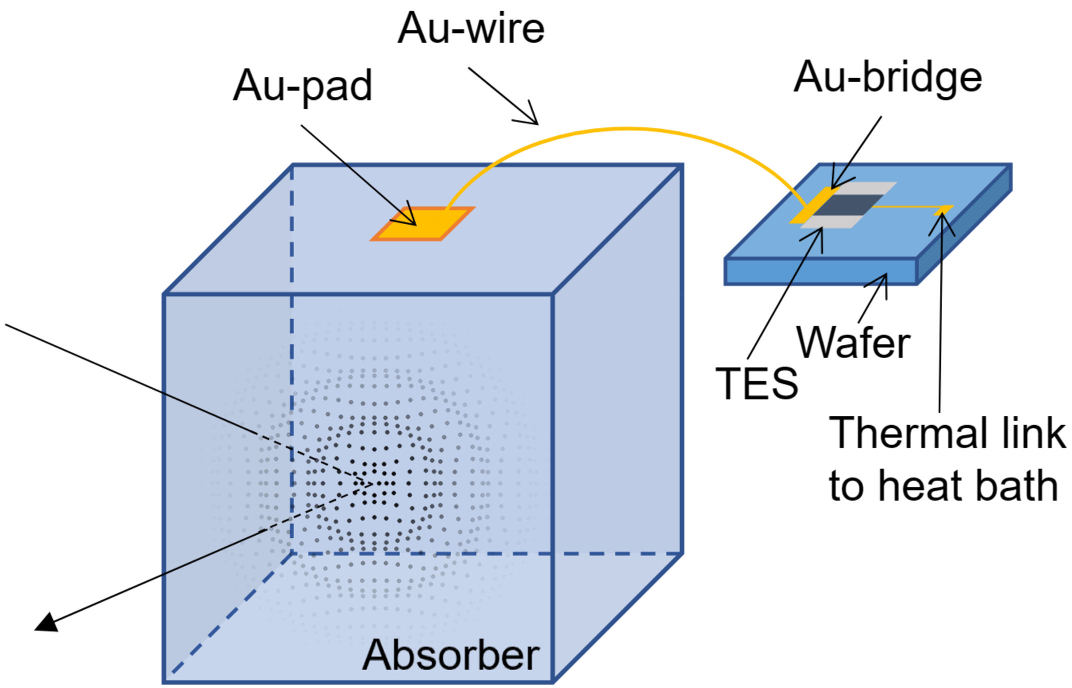



# remoTES

- TES deposited on a separate wafer

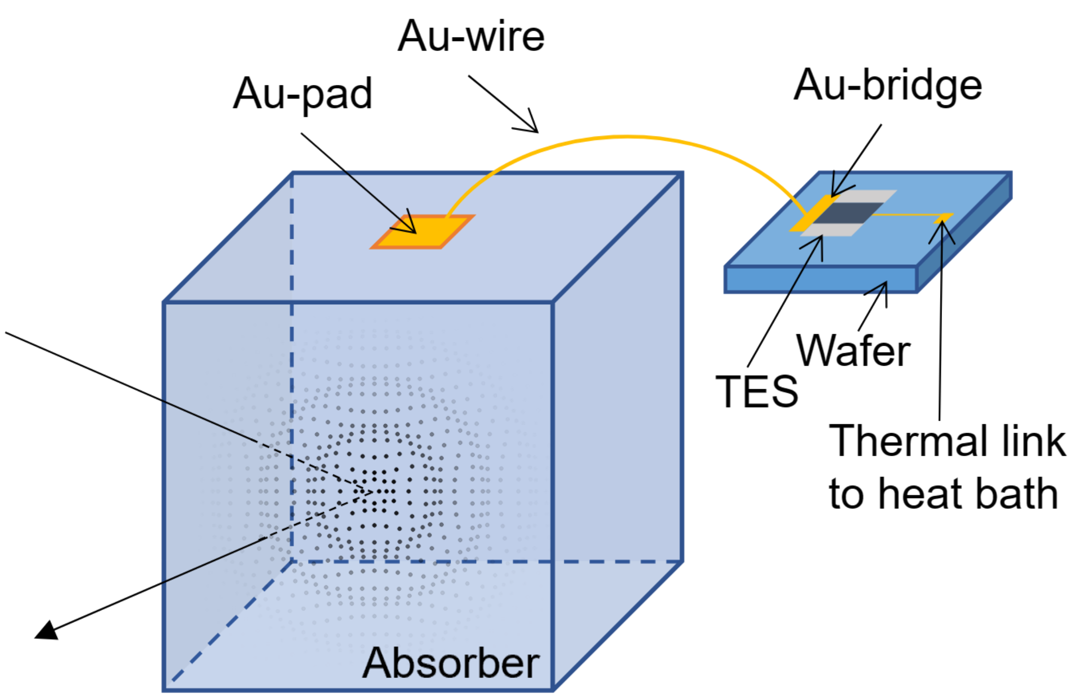
arXiv:1503.01200




https://doi.org/10.1016/j.nima.2022.167532

# Motivation for my work

- remoTES readout design crucial for COSINUS to achieve a threshold of 1 keV
- remoTES is a composite design
- goal: study systematically the impact of the different components on the overall performance



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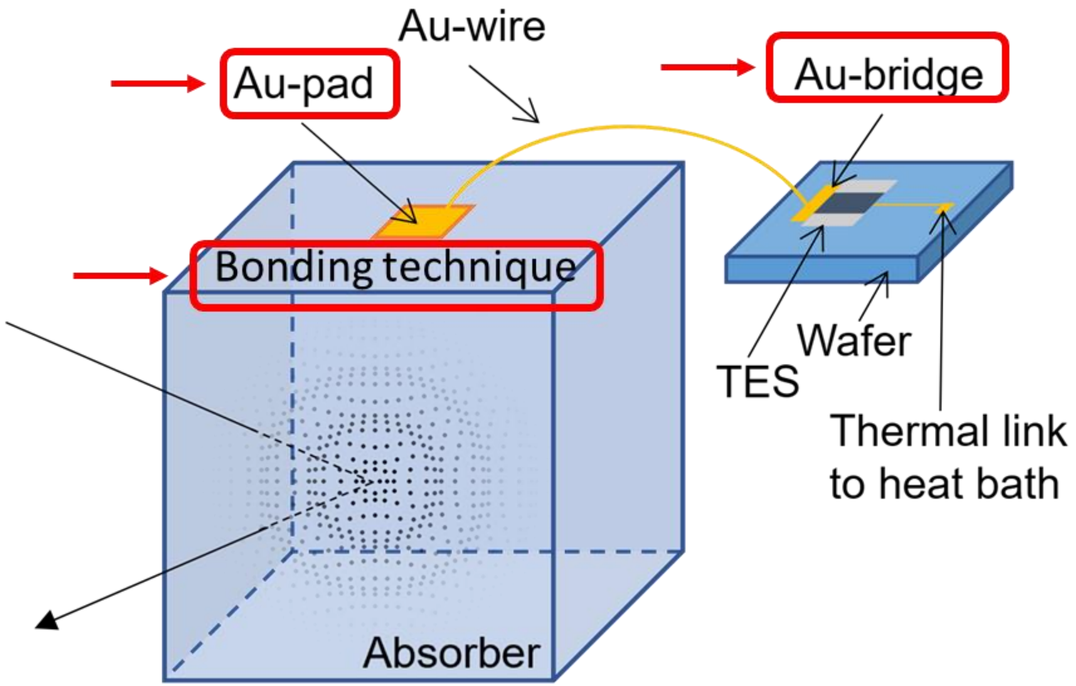
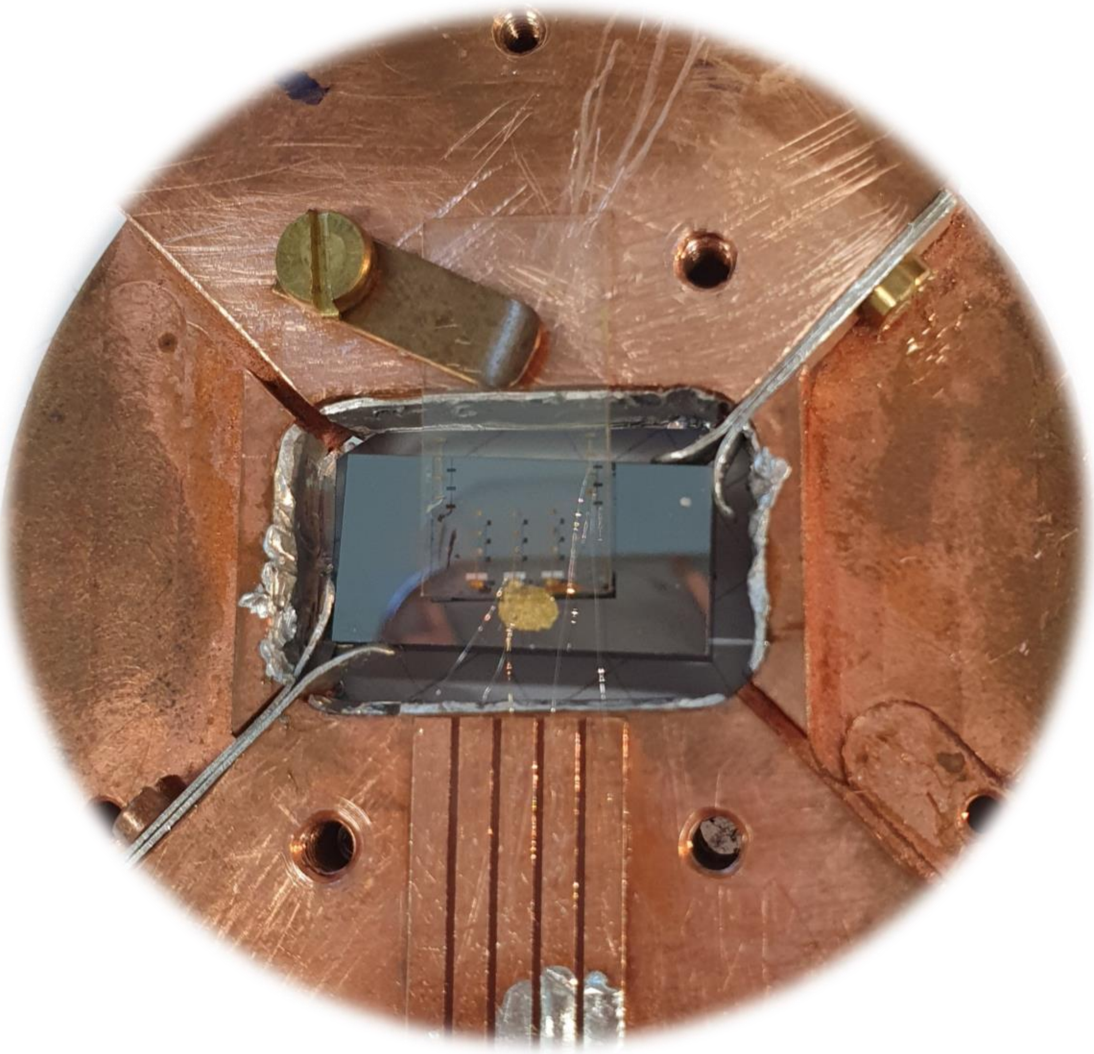


# Systematic studies on silicon(Si) remoTES cryogenic calorimeters



# Overview

| Overview of the different detector setups | | | | |
|---|---|---|---|---|
| **Run** | **Detector** | **Au-pad thickness** | **Bonding technique** | **Au-bridge/Au-island** |
| Run233 | Ψ | 1 µm (glued) | Wedge-bond | Au-bridge |
| | Φ | 1 µm (glued) | Wedge-bond | Au-bridge |
| Run595 | Electra | 200 nm (sputtered) | Ball-bond | Au-bridge |
| | Olympia | 8 µm (glued) | Ball-bond | Au-bridge |
| Run596 | Electra’ | 200 nm (sputtered) | Second ball-bond | Au-bridge |
| | Olympia’ | 8 µm (glued) | Ball-bond | Au-island |

→ CRESST R&D facility at MPP

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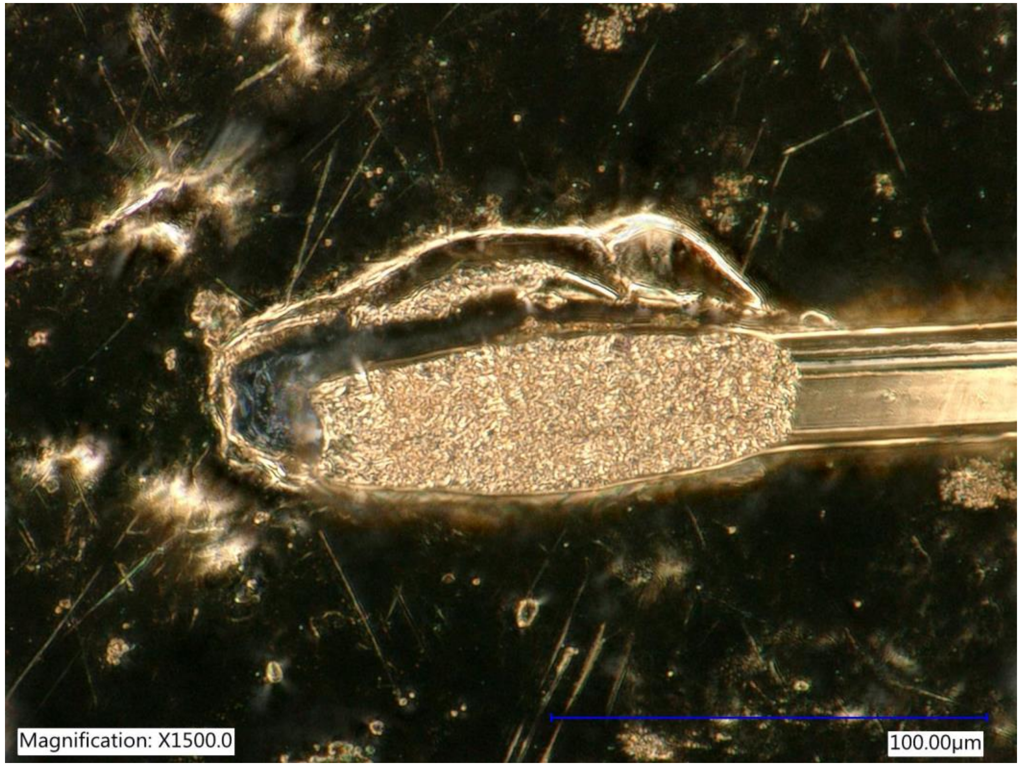
→ CRESST R&D facility at MPP

# Wedge-bond on 1 μm thick Au-foil

- The wedge bonding foot breaks the Au-pad
  → limitation of the surface area of the Au-pad available for phonon collection
- Wedge bond might be a bottleneck for signal transmission
- Microfractures are produced in the NaI crystal below the bond foot




Picture was taken in cooperation with **Miriam Modjesch (MPP)**

# Ball-bond

Pro:

- Less bonding force → less destructive for Au-pad and crystal (important for NaI)
- Might enable better signal transmission

# Ball-bond on 1 µm thick glued Au-foil

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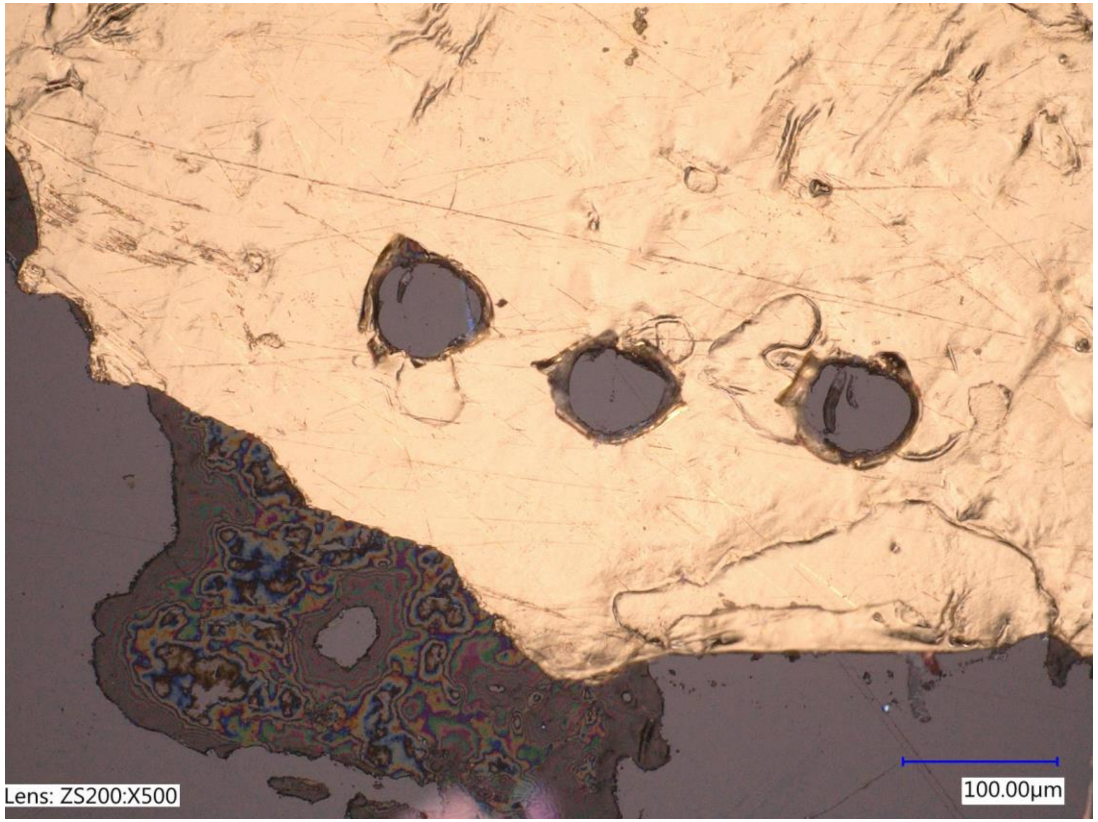
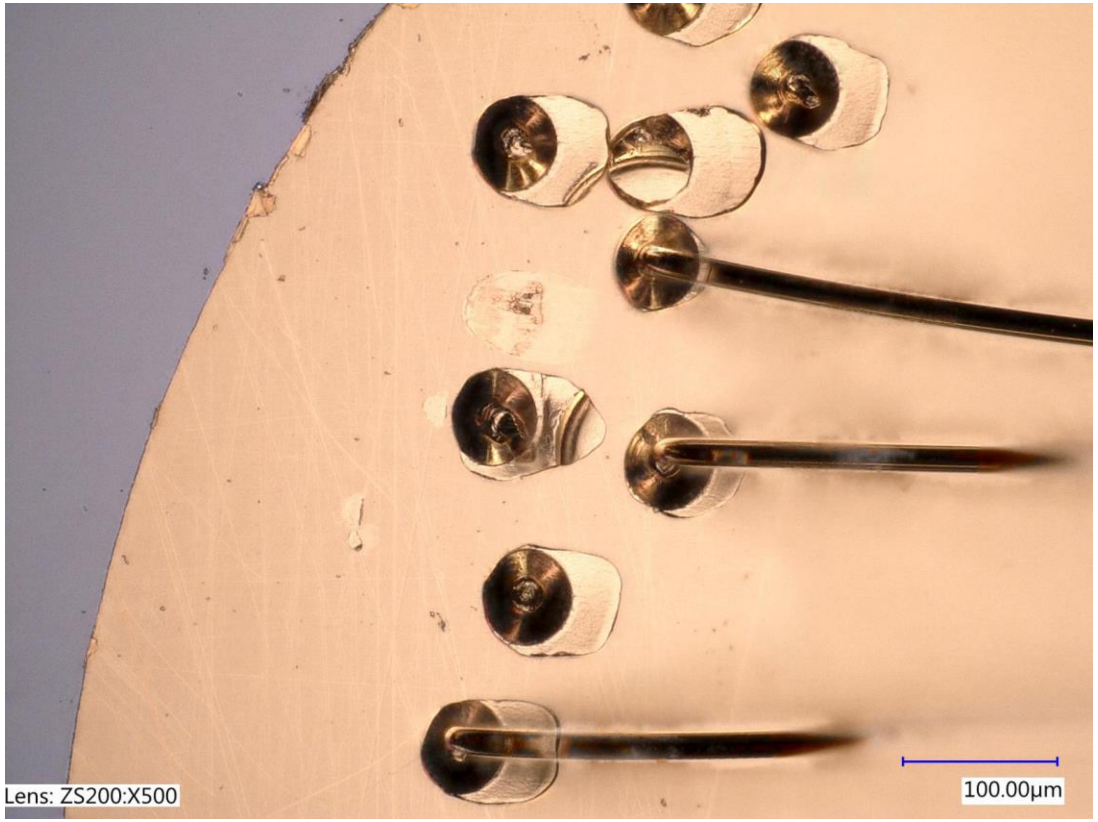


# Ball-bond on 200 nm thick sputtered Au-film

Pro:

- Less bonding force → less destructive for Au-pad and crystal (important for NaI)
- Might enable better signal transmission




Ball-bonds were performed by **Carina Schlammer (MPP)**

# Ball-bond on 8 μm thick glued Au-foil

Pro:

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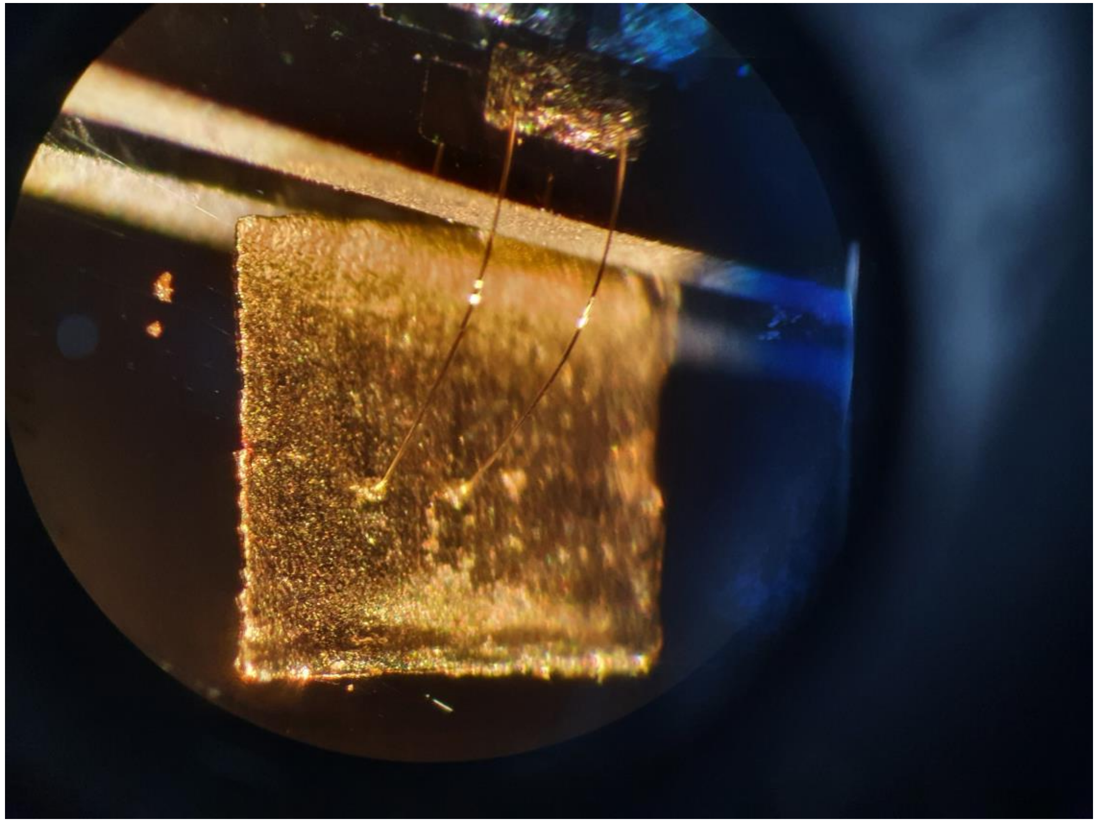
- Might enable better signal transmission



Ball-bonds were performed by **Carina Schlammer (MPP)**

# Performance comparison

| Detector | Au-pad | Baseline resolution (eV) |
|---|---|---|
| Ψ | 1 µm | 280±9 |
| Φ | 1 µm | 440±13 |
| Electra | 200 nm | 133±3 |
| Olympia | 8 µm | 89±2 |
| Electra’ | 200 nm | 167±8 |
| Olympia’ | 8 µm | 1159±134 |

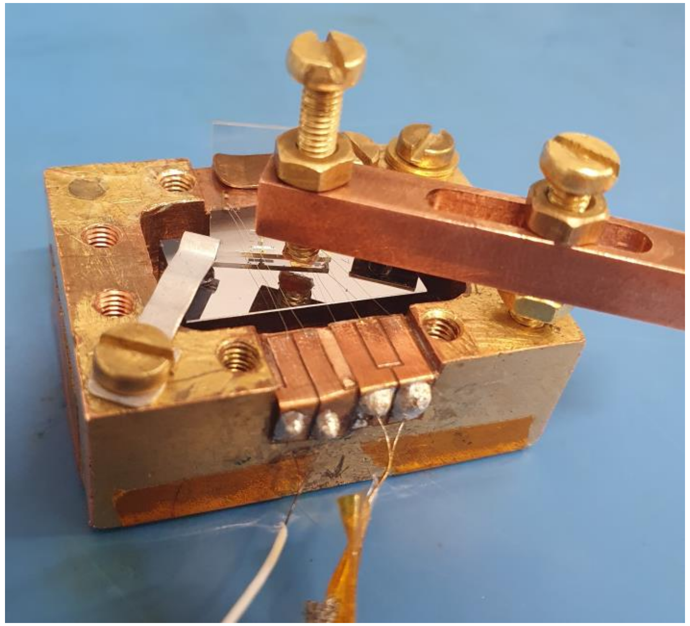
Wedge-bond (Ψ, Φ)

Ball-bond (Electra, Olympia)

Olympia: best performance → heat capacity not the limiting factor

# Detector Olympia

| Detector | Olympia |
|---|---|
| Absorber | Si (20×10×5) $mm^3$ |
| Au-pad | 8 µm thickness |
| Au-wire | 25 µm |
| Bonding technique | Ball-bond |
| TES | W-TES on $Al_2O_3$ |
| Calibration sources | $^{55}Fe$ |



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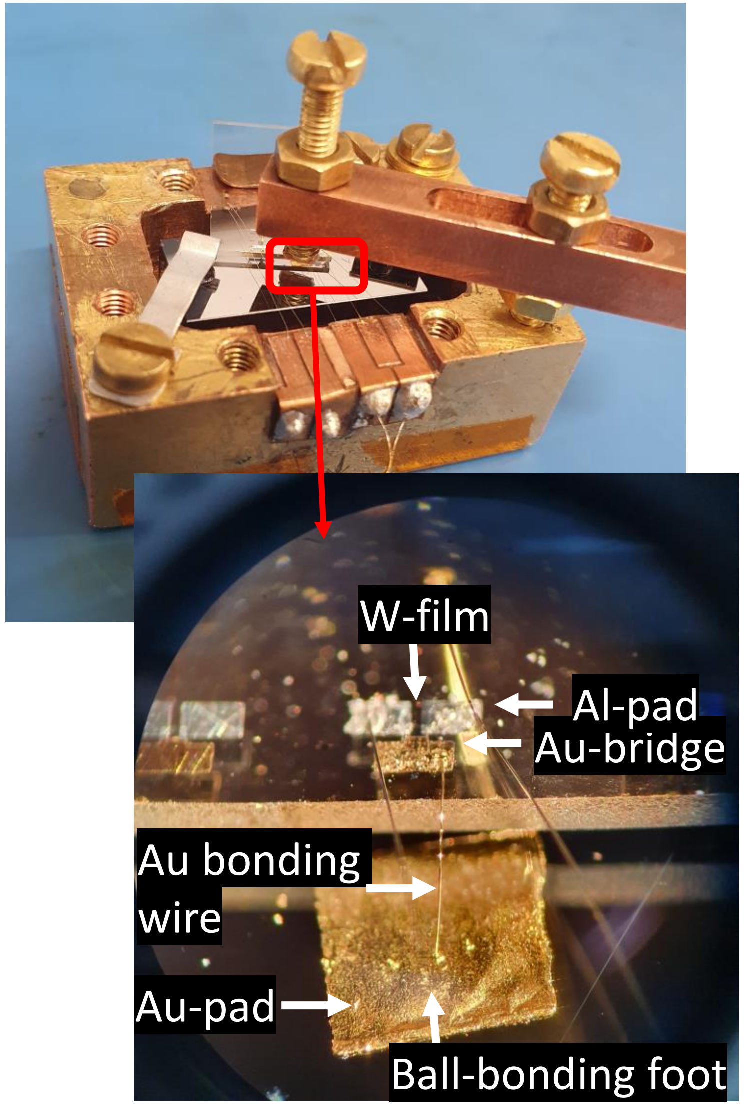

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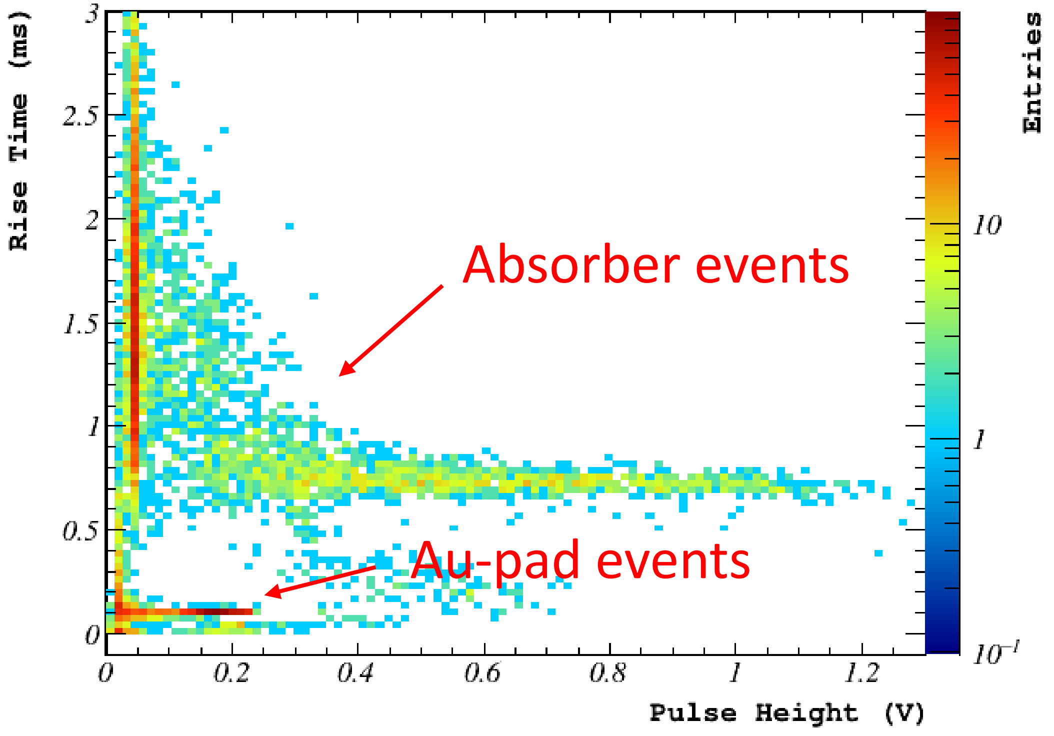
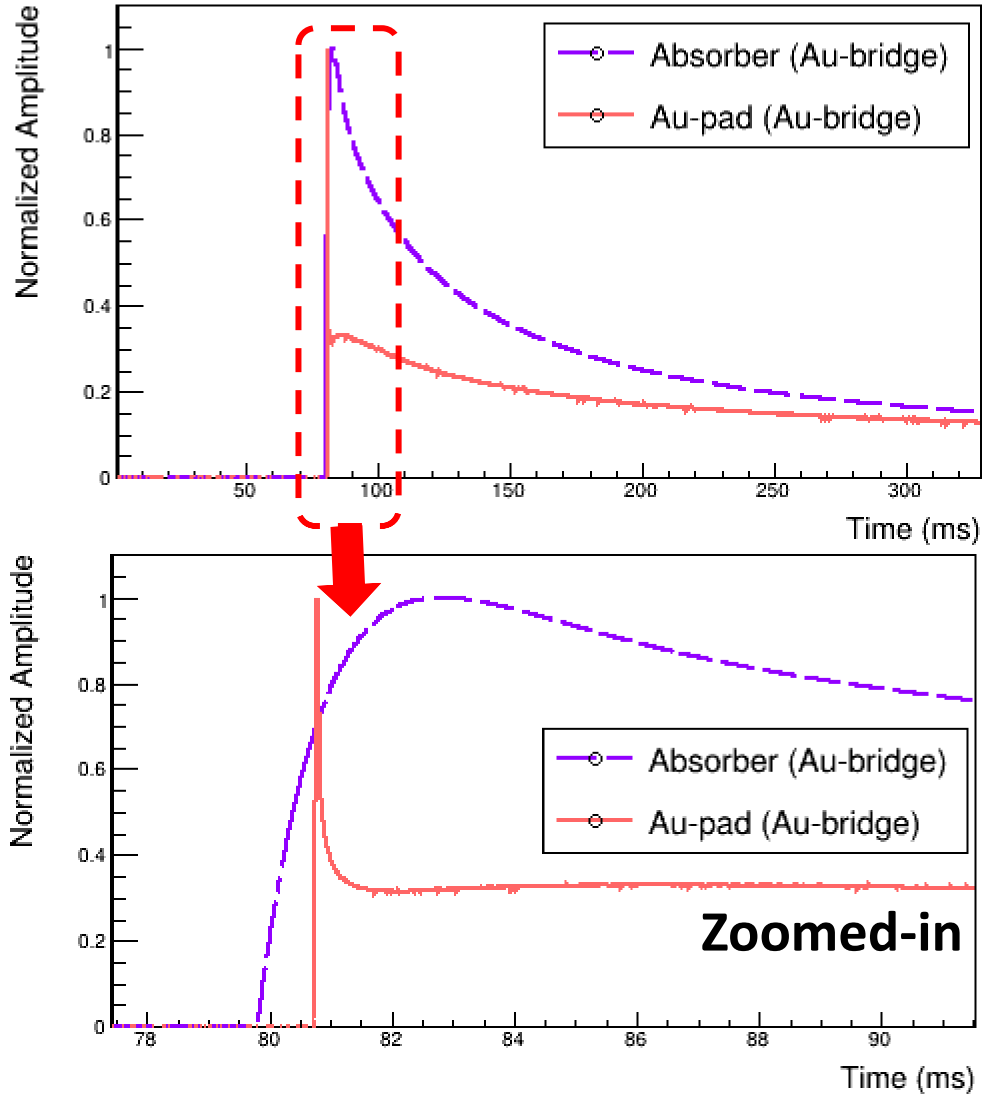
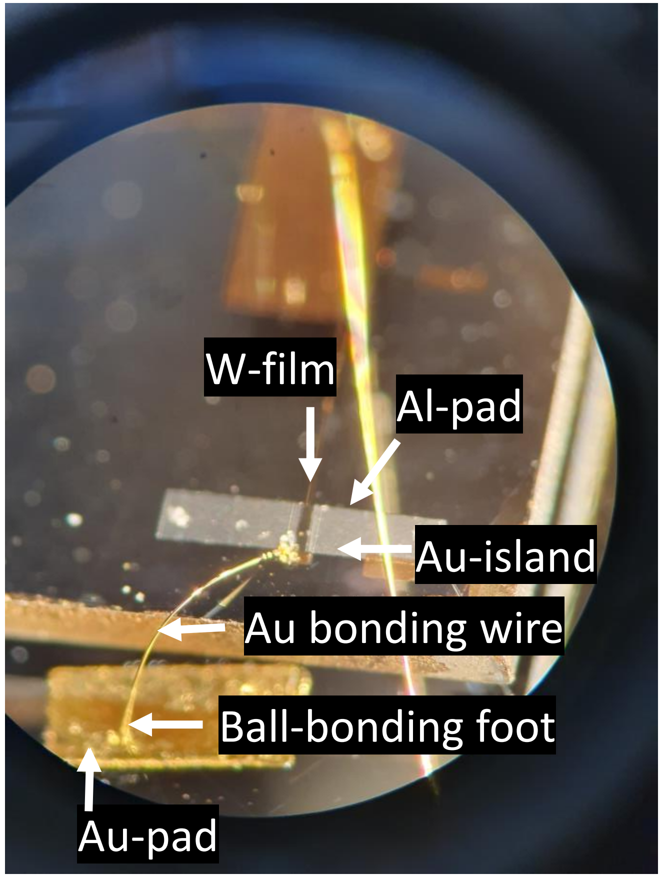


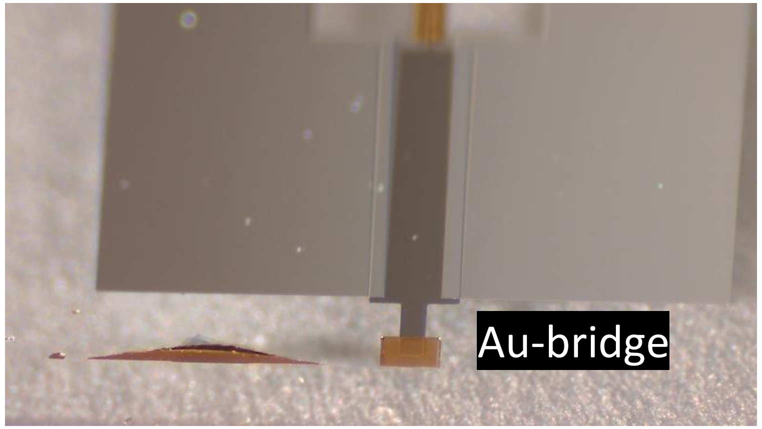



# Detector Olympia'

Modification: removal of the Au-bridge




Olympia

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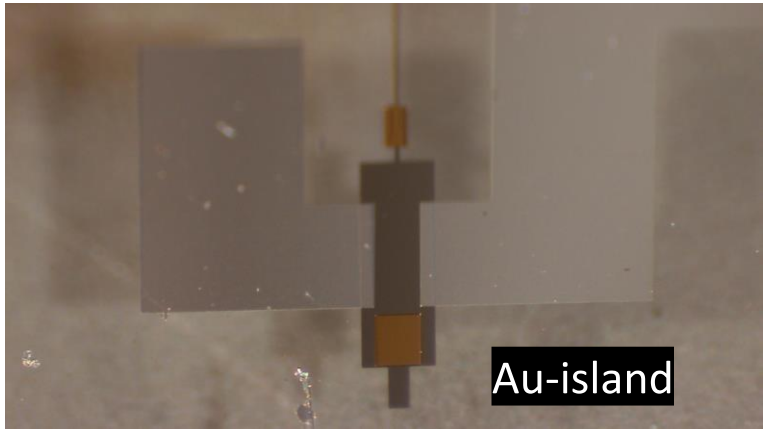

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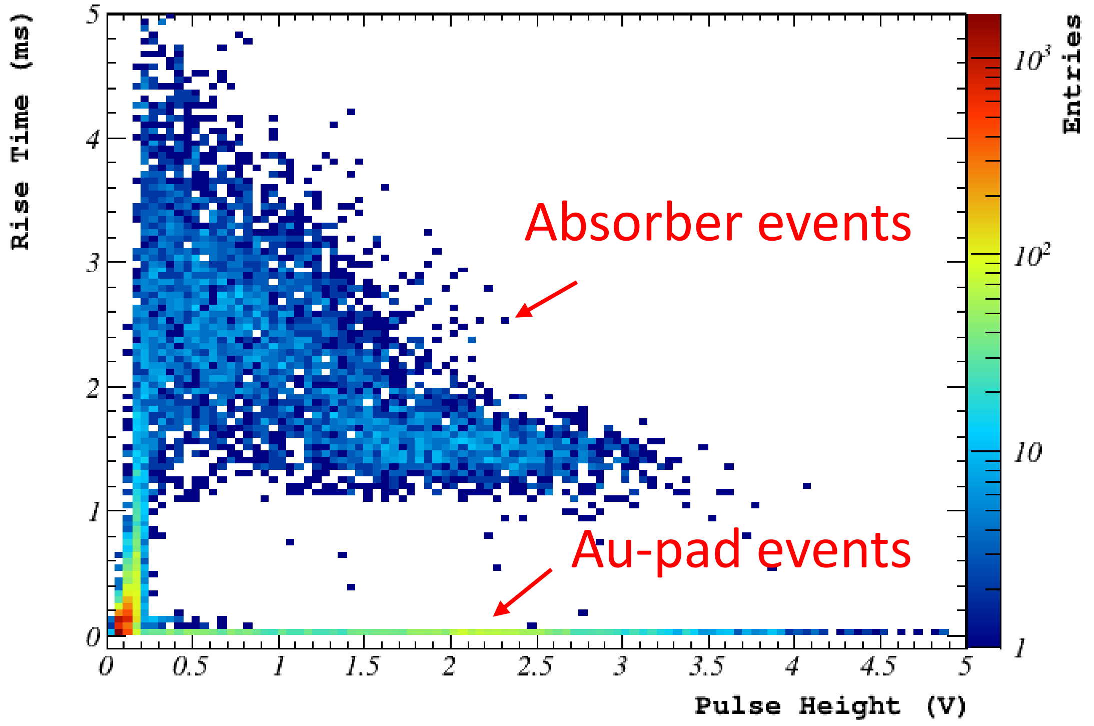
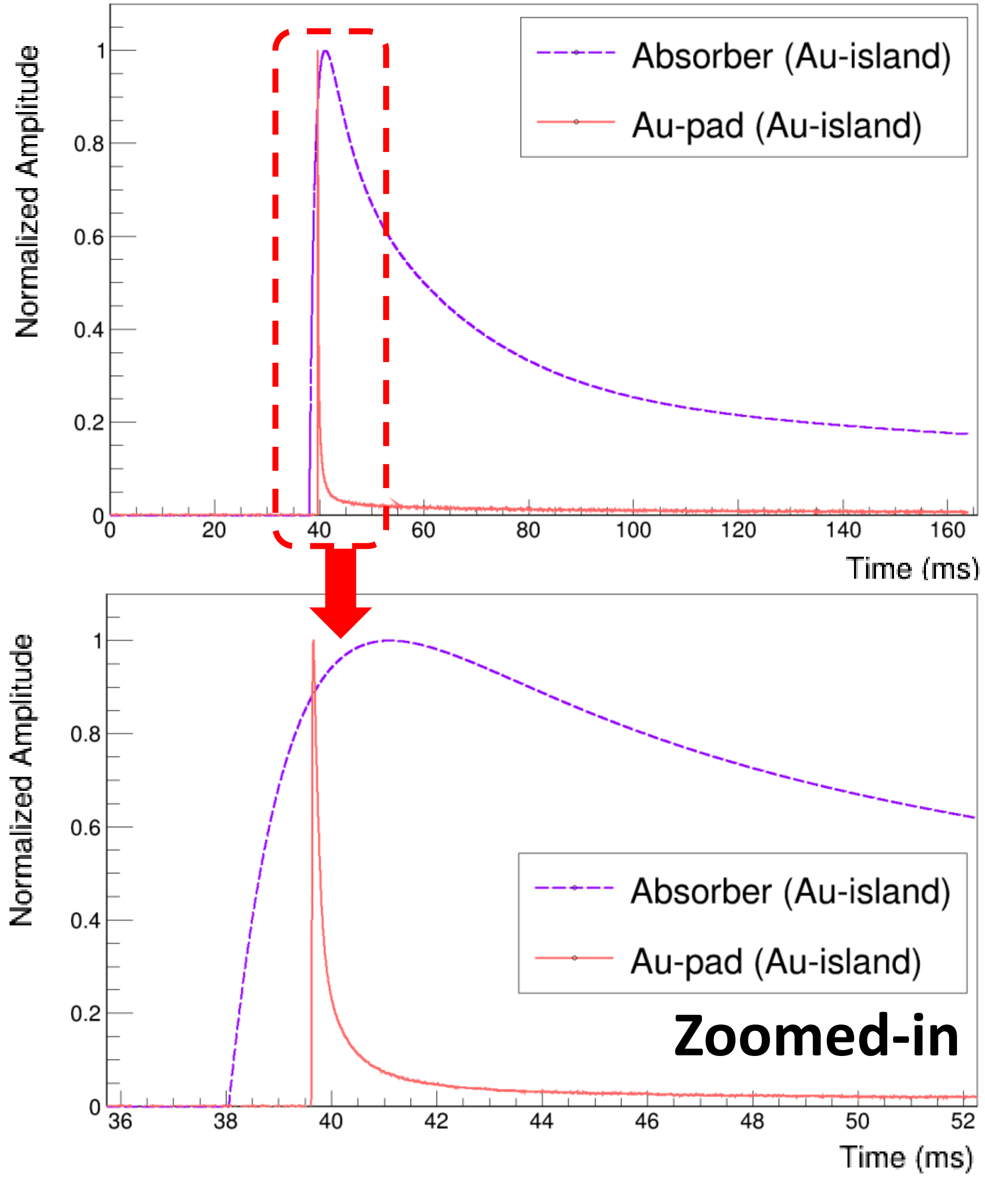
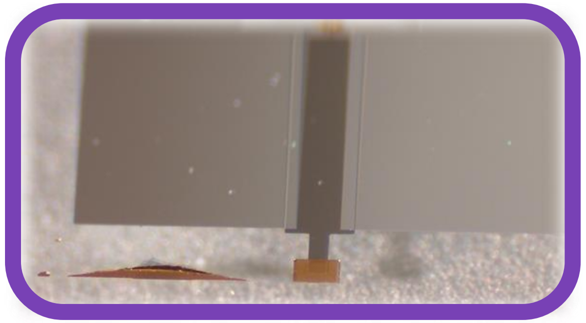


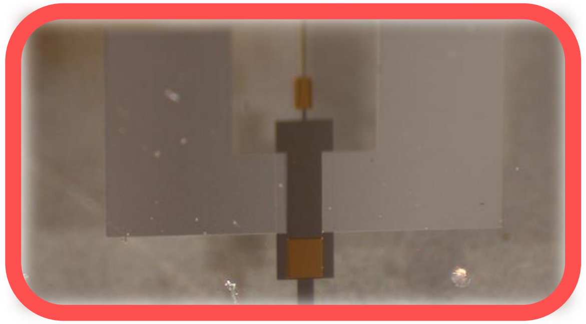



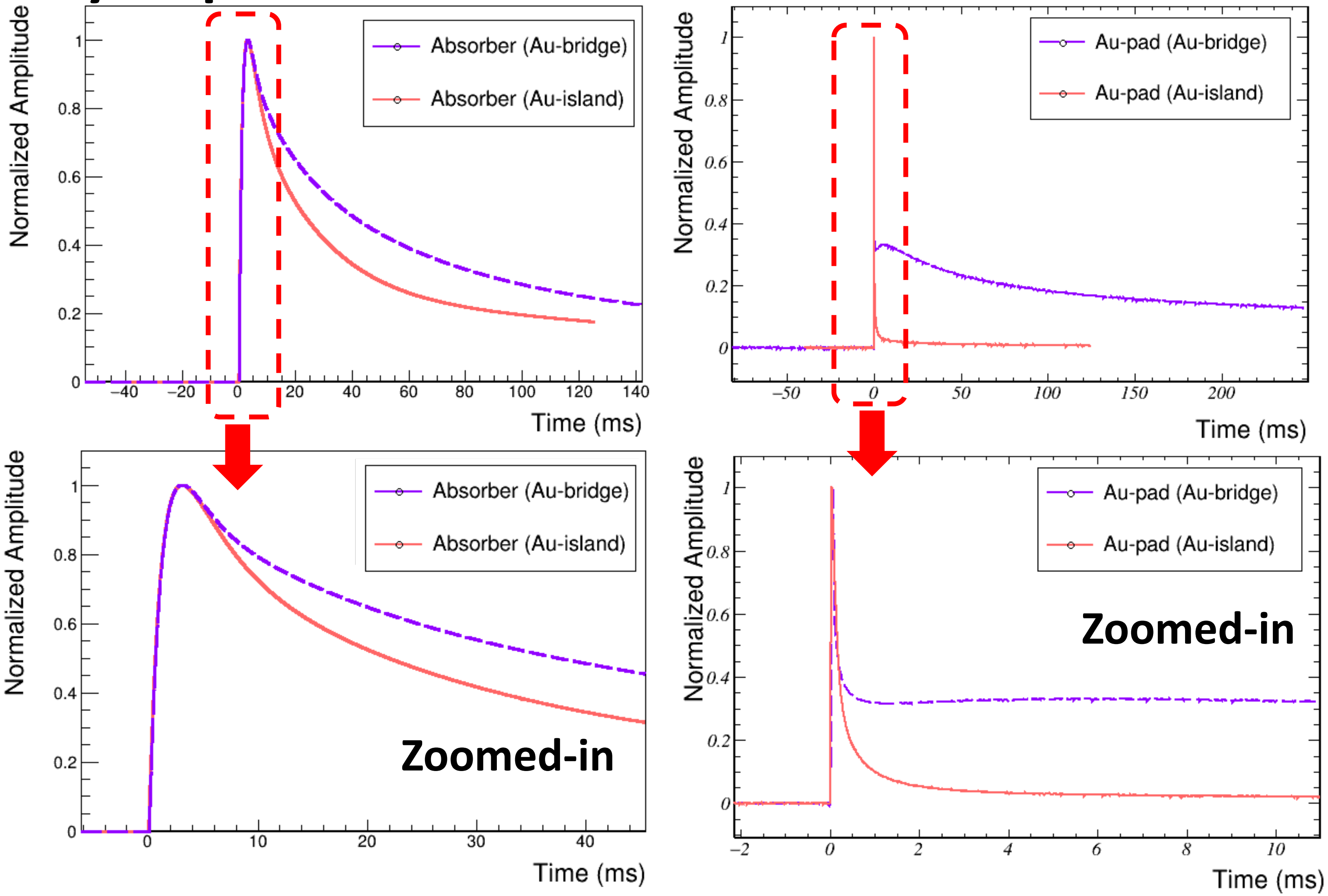
# Olympia VS Olympia’

Au-bridge



Au-island





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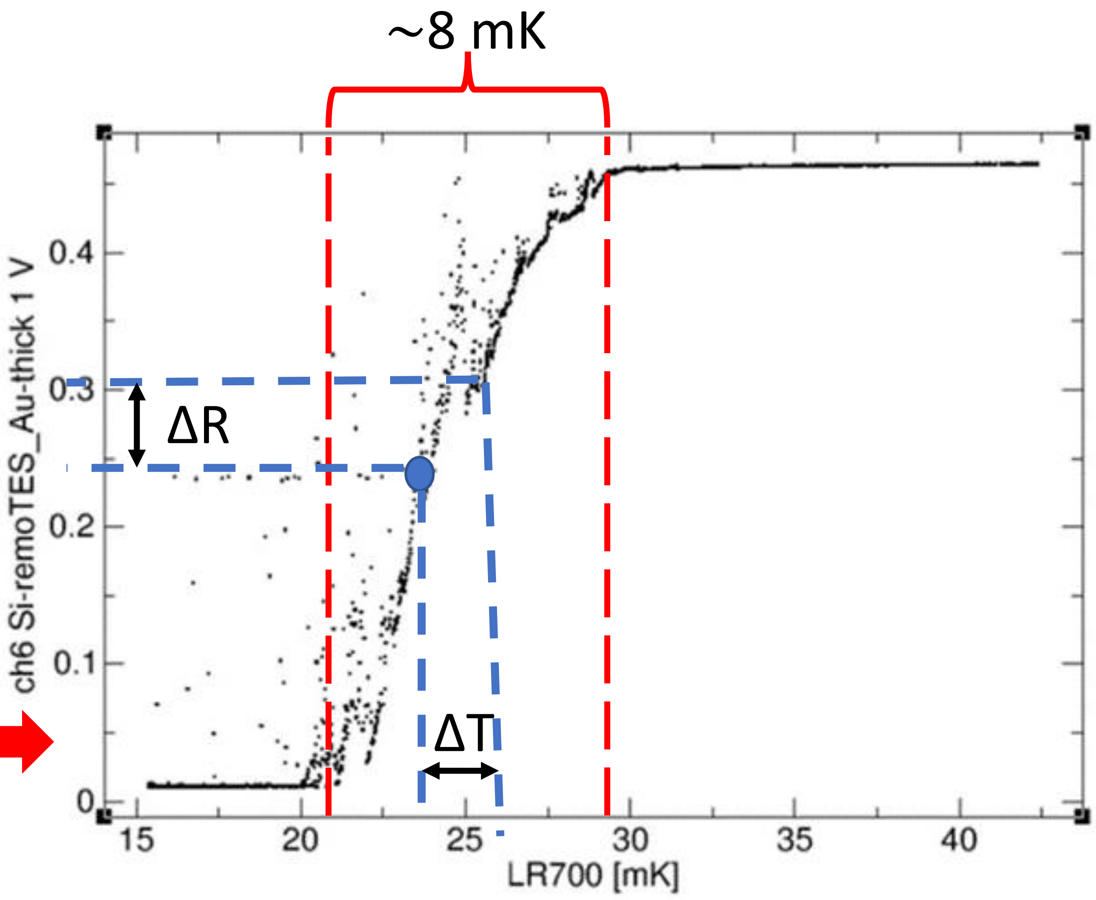

# Conclusion

The remoTES offers possibilities for NaI/COSINUS but also other absorbers. In these studies it was found that:

- Wedge bonding tears the thin Au-foil
- Ball bonding improves the performance of the detector
- Heat capacity is not the limiting factor for the present detector design → best-achieved performance by Olympia
- Au-island leads to faster-decaying pulses

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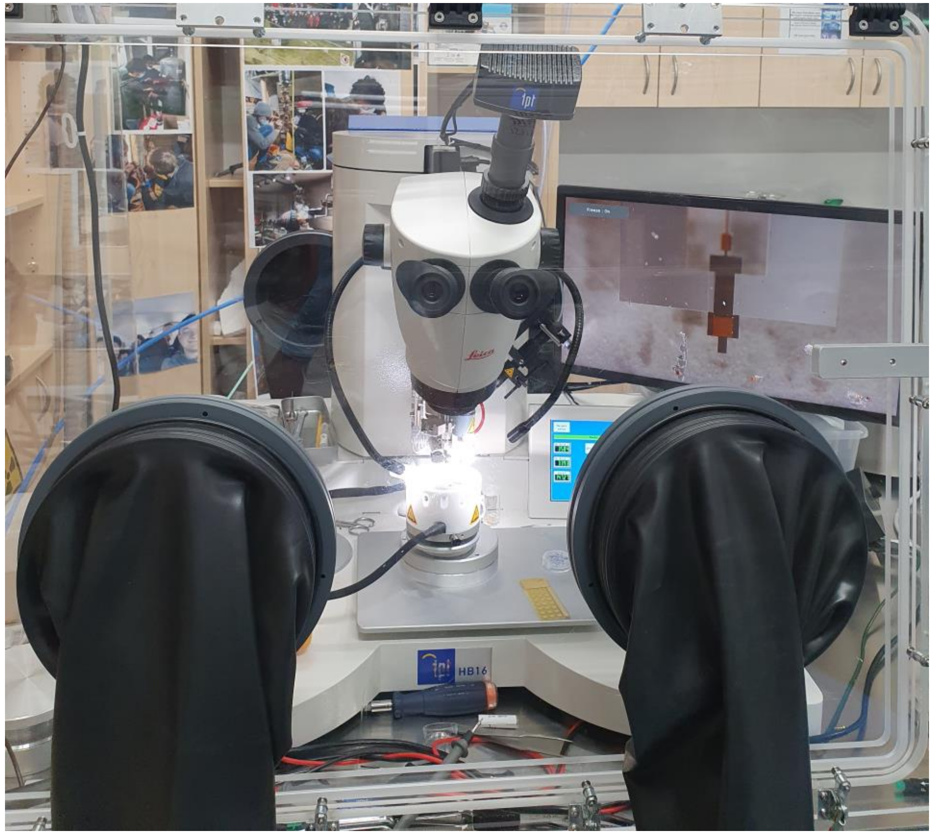
# Outlook

New COSINUS bonding machine!



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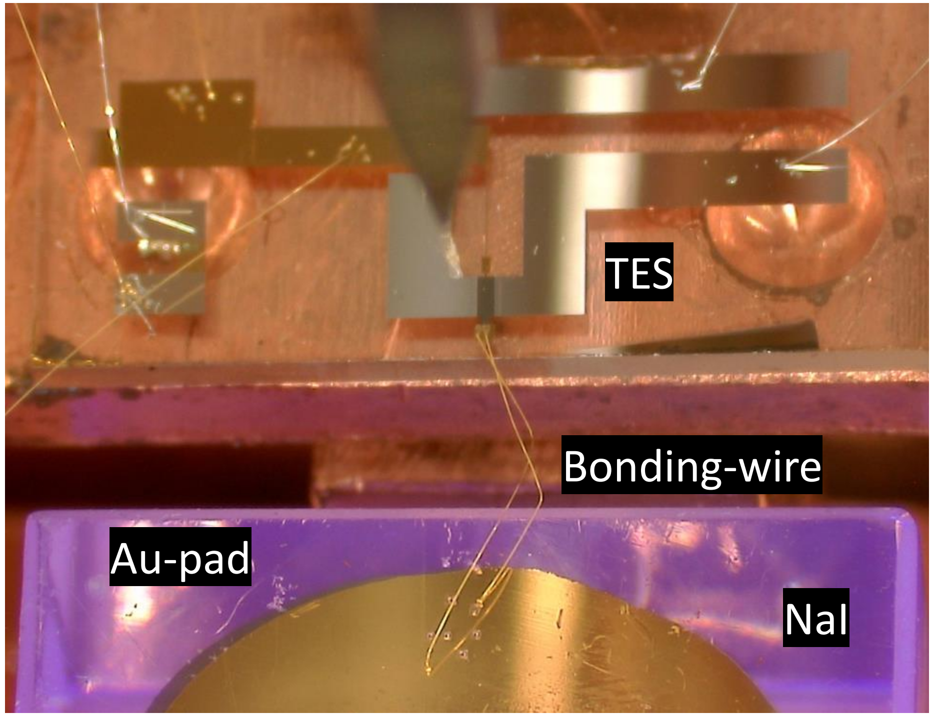


In collaboration with Rainer Götz, Aliaksandr Bandarenka
TUM, TUM School of Natural Sciences, Department of Physics, Physics of Energy Conversion and Storage

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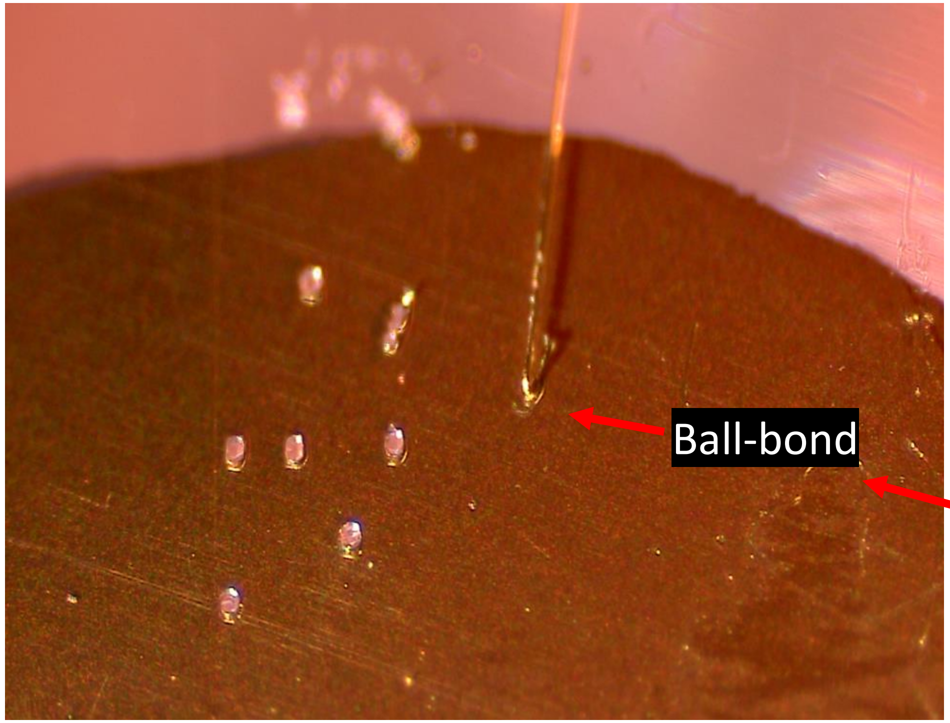


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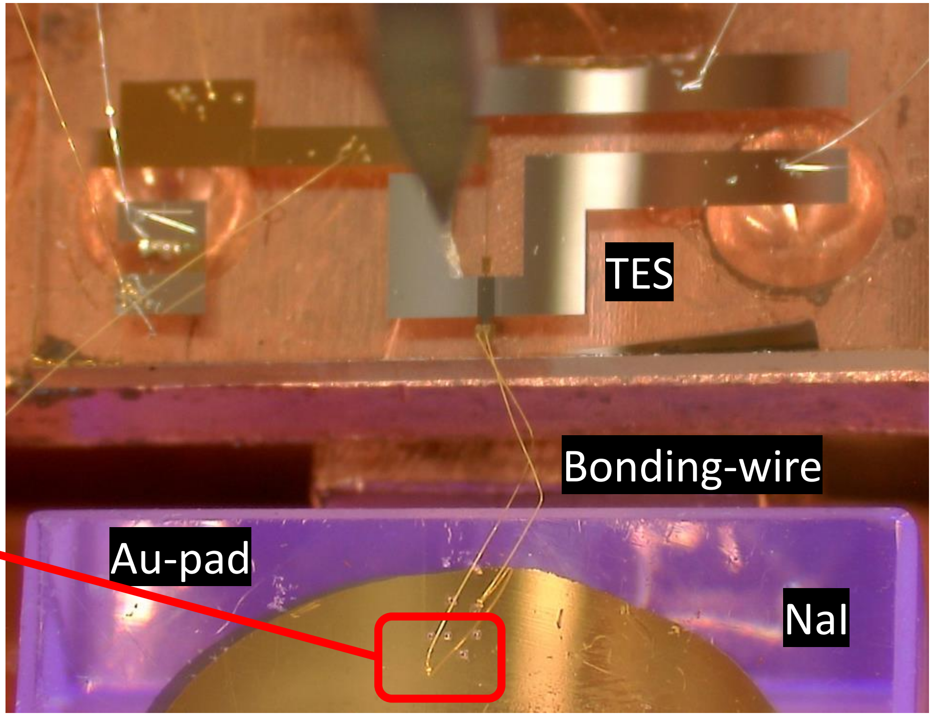


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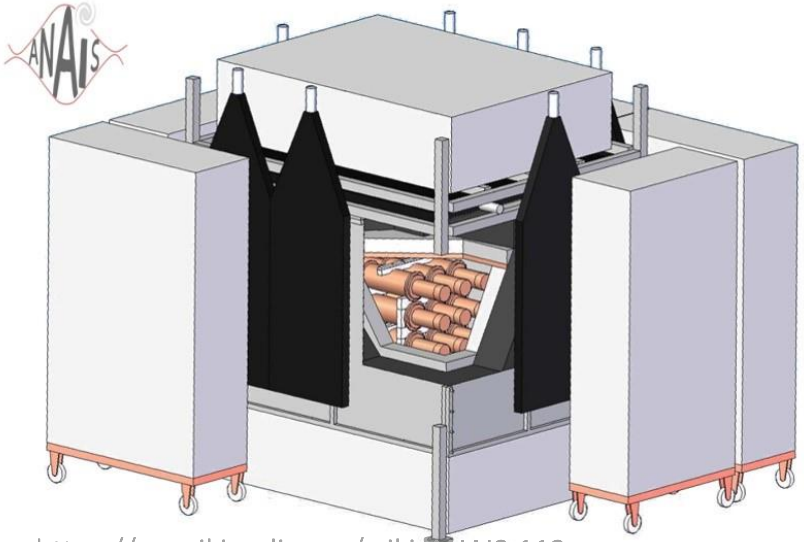
# Thank you!

# Other NaI experiments

## ANAIS-112

- Room-temperature scintillator experiment
- Three years of data taking→ exposure 313.95 kg × y
- No modulation observed
- Incompatible with DAMA/LIBRA results




https://en.wikipedia.org/wiki/ANAIS-112

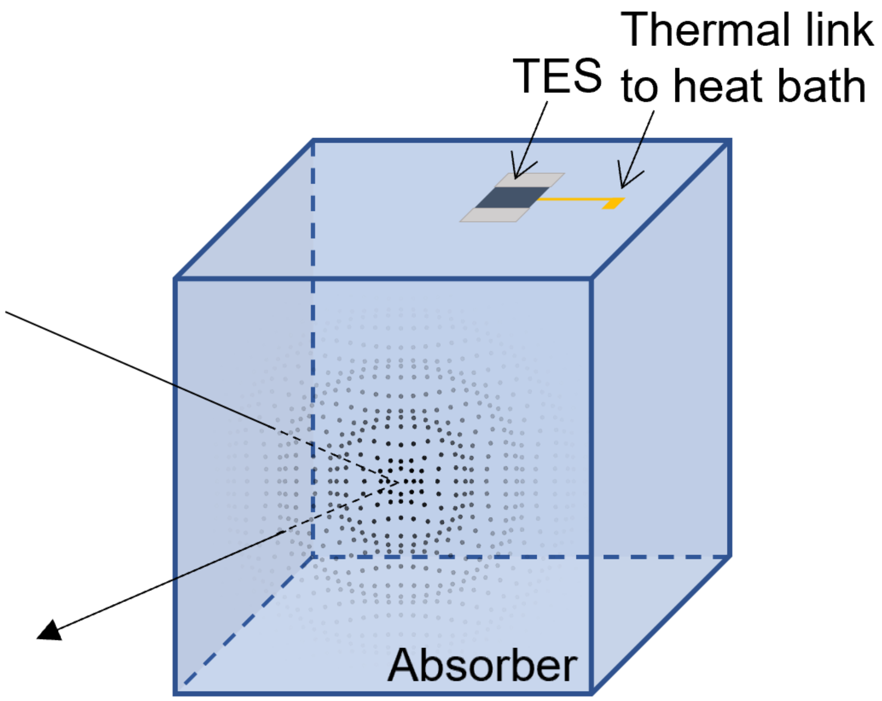
## COSINE-100

- Room-temperature scintillator experiment
- Three years of data taking →exposure 173 kg × y
- Results consistent with both the DAMA-observed modulation and the case of no observed modulation

https://cosine.yale.edu/about-us/cosine-100-experiment

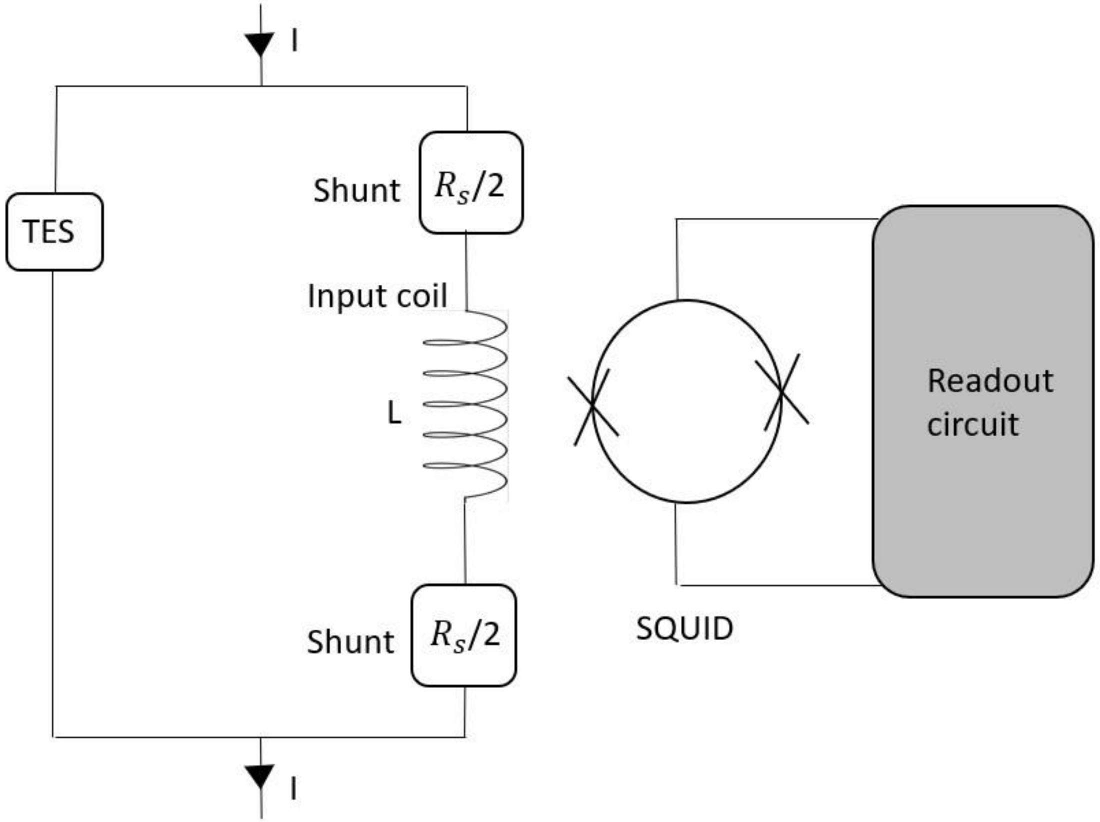
# Cryogenic detectors

- Absorber weakly coupled to a thermal bath + temperature sensor
- Particle interaction produces atomic lattice vibration (phonons)
- The lattice vibrations cause a temperature increase in the absorber
- $\Delta T = \frac{\Delta E}{C}$
- Few keV energy deposition would cause a temperature increase of μK



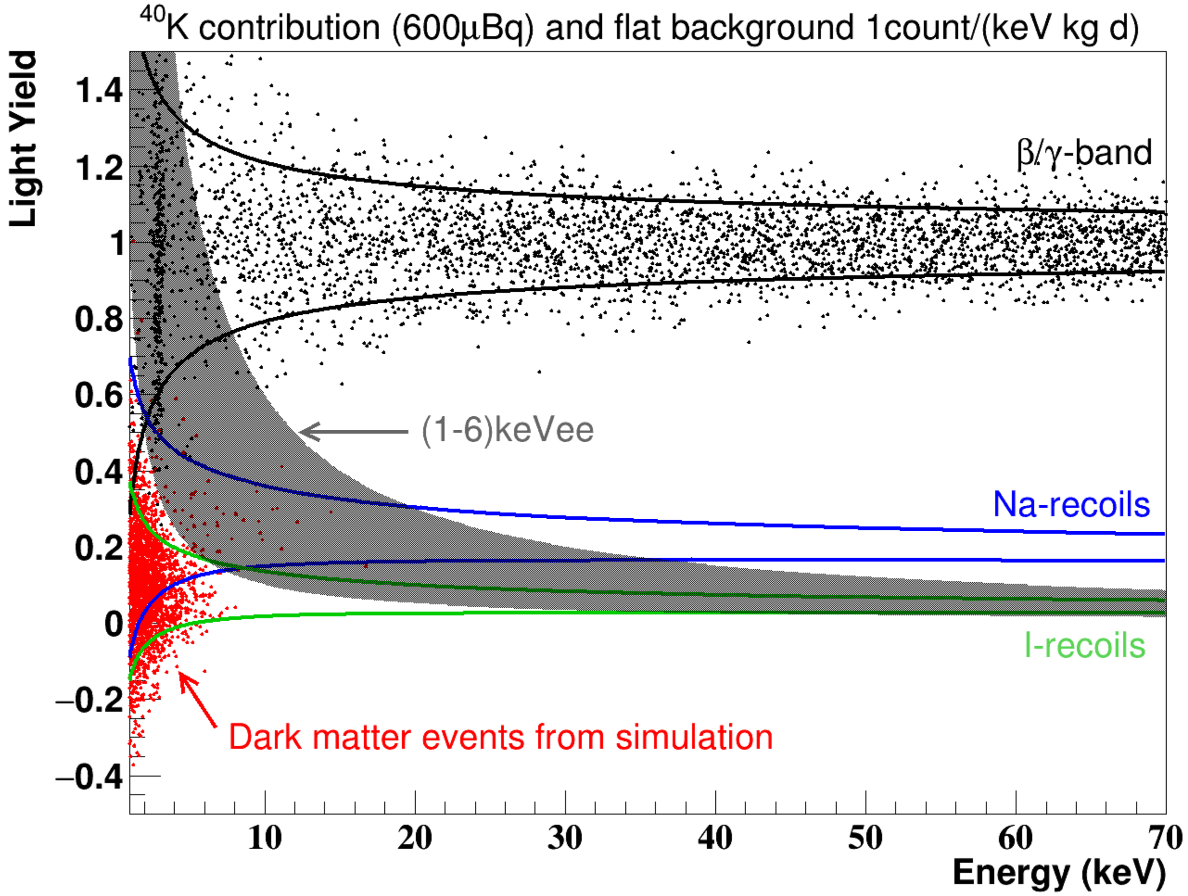
# Read out circuit

- The TES connected in parallel with two shunt resistances
- A energy deposition induces a change in the resistance of the TES→ change in the distribution of the current → change in the magnetic field induced by the input coil
- The change in the magnetic field is magnified and measured by the SQUID
- Output: pulse in voltage versus time

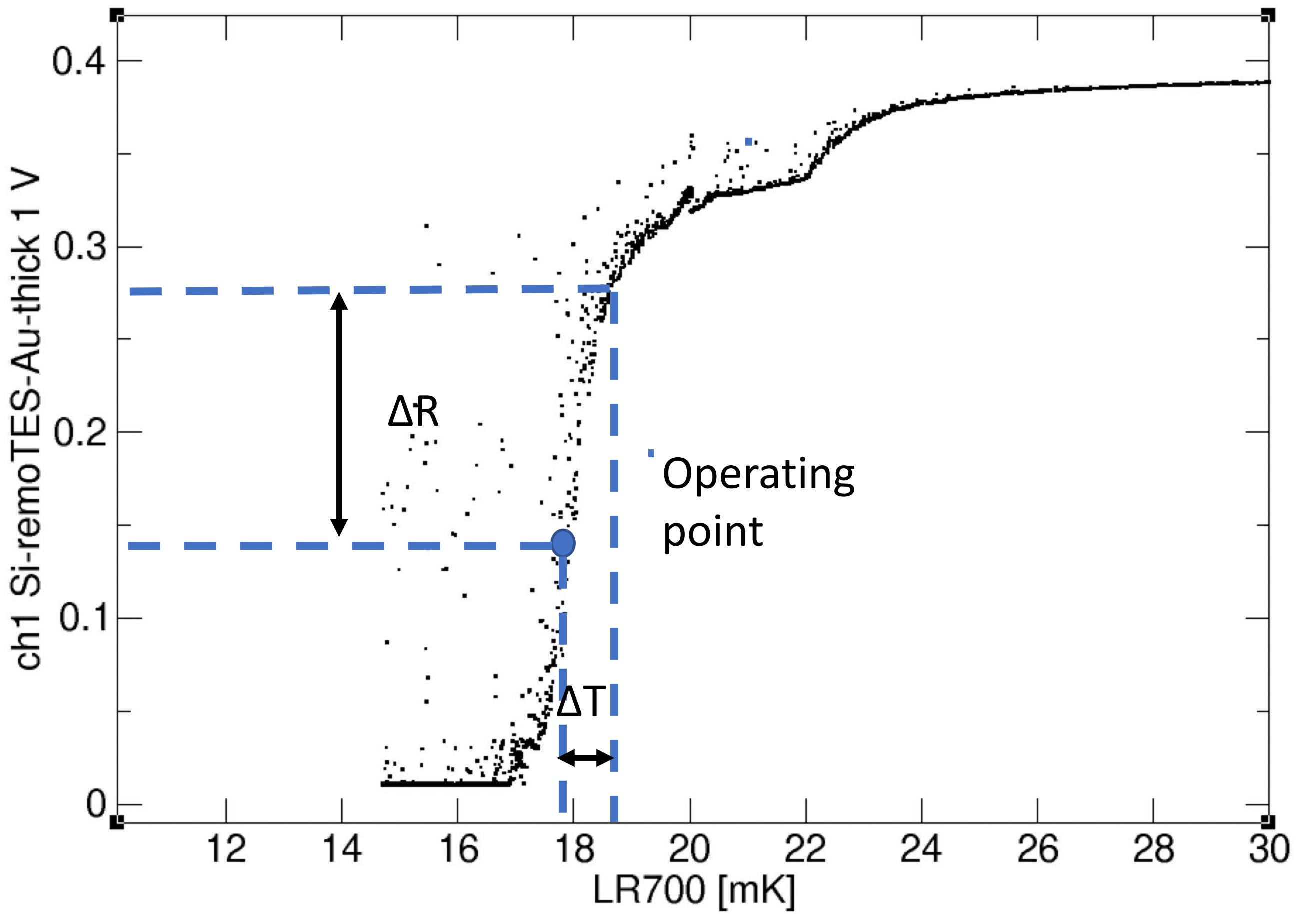


# Light Yield

LIGHT YIELD = $\frac{\text{LIGHT SIGNAL}}{\text{HEAT SIGNAL}}$



# Detector Olympia



# Pulse shape analysis

The temperature increase in the thermometer can be described as:

$$\Delta T_e(t) = \Theta(t)[A_n\left(e^{-\frac{t}{\tau_n}} - e^{-\frac{t}{\tau_{in}}}\right) + A_t\left(e^{-\frac{t}{\tau_t}} - e^{-\frac{t}{\tau_n}}\right)]$$

non-thermal component  thermal component

- $\tau_n$: lifetime of non-thermal phonons
- $\tau_{in}$: intrinsic thermal relaxation time of the thermometer
- $\tau_t$: relaxation time of the absorber

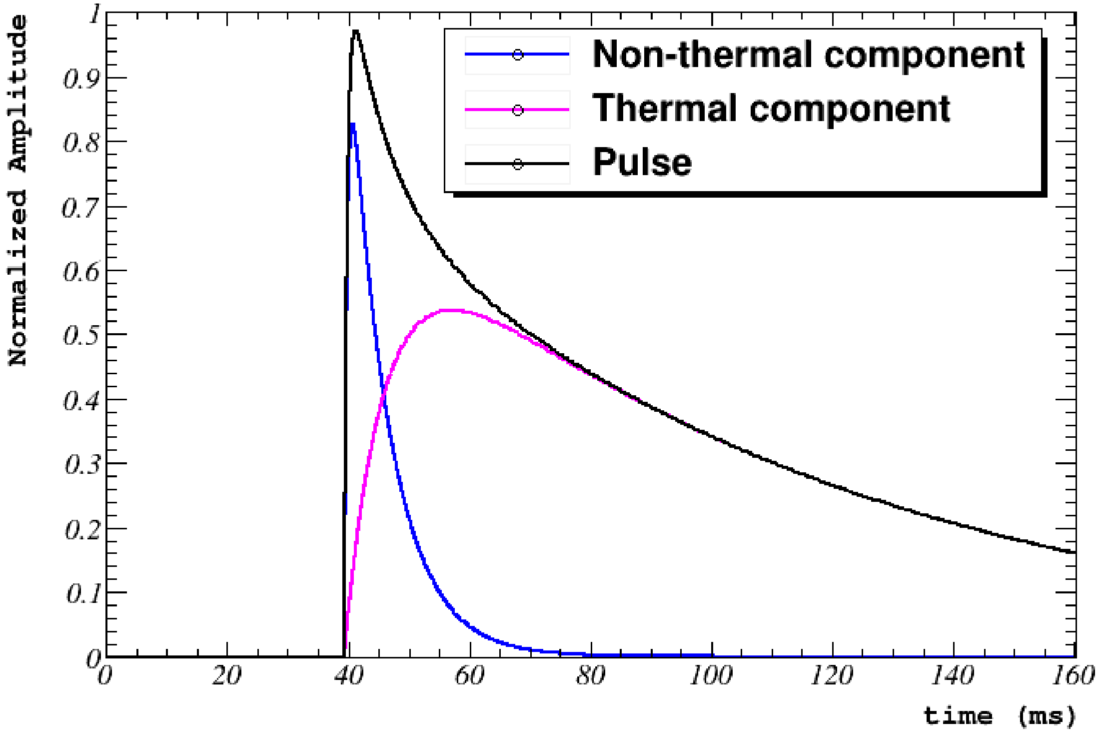
- **$\tau_{in}/\tau_n \ll 1$ → Bolometric Mode:**
  - $\tau_{in}$: rise time of non-thermal
  - $\tau_n$: decay time of non-thermal and rise time of thermal component
  - $\tau_t$: decay time of the thermal component

- **$\tau_n/\tau_{in} \ll 1$ → Calorimetric Mode:**
  - $\tau_{in}$: decay time of non-thermal
  - $\tau_n$: rise time of non-thermal and thermal component
  - $\tau_t$: decay time of the thermal component

# Pulse shape analysis

| Detector | Olympia |
|---|---|
| Event class | Absorber |
| $A_n$ | 1.11 |
| $A_t$ | 0.73 |
| $\tau_n$ | 6.55 |
| $\tau_{in}$ | 0.51 |
| $\tau_t$ | 79.59 |

- For both detectors it holds that $\tau_{in}/\tau_n \ll 1$
  → operated in the bolometric mode



# Heat capacities

| Detector | Electra (μJ/K) | Olympia (μJ/K) |
|---|---|---|
| Si crystal | $5.10 \cdot 10^{-6}$ | $5.10 \cdot 10^{-6}$ |
| Au-pad | $7.98 \cdot 10^{-6}$ | $4.06 \cdot 10^{-5}$ |
| Au-wire | $1.44 \cdot 10^{-6}$ | $1.44 \cdot 10^{-6}$ |
| Au-bond foot | $8.31 \cdot 10^{-8}$ | $8.31 \cdot 10^{-8}$ |
| Au-bridge/Au-island | $1.27 \cdot 10^{-6}$ | $1.27 \cdot 10^{-6}$ |
| TES | $9.78 \cdot 10^{-8}$ | $9.78 \cdot 10^{-8}$ |
| Total | $1.85 \cdot 10^{-5}$ | $4.85 \cdot 10^{-5}$ |