Illuminating the Invisible:
deep underground dark matter search with COSINUS

TeV Particle Astrophysics
Napoli, 2023

Mukund Bharadwaj | On behalf of the COSINUS collaboration
13.09.2023

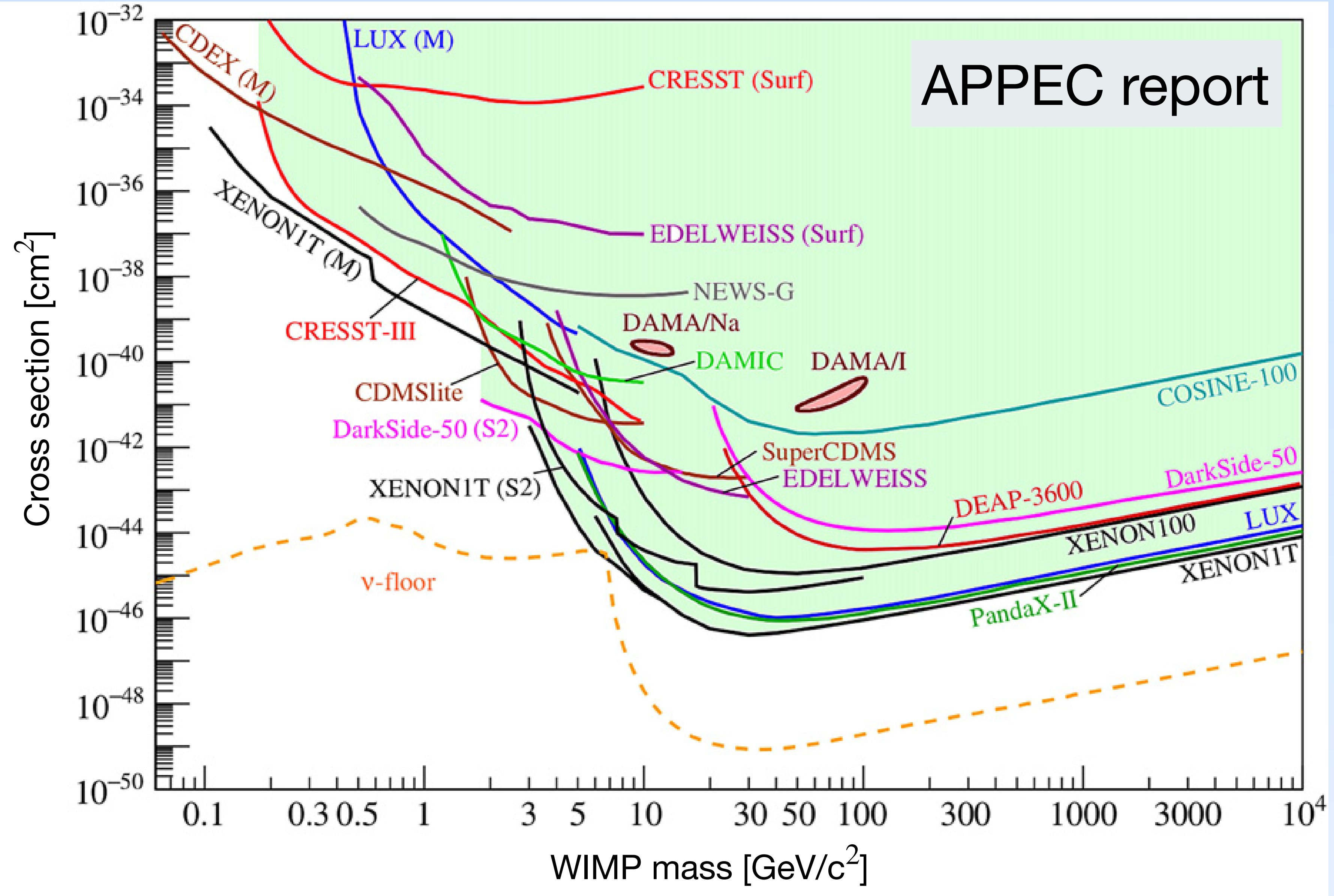
COSINUS

MAX-PLANCK-INSTITUT
FÜR PHYSIK

Direct DM searches

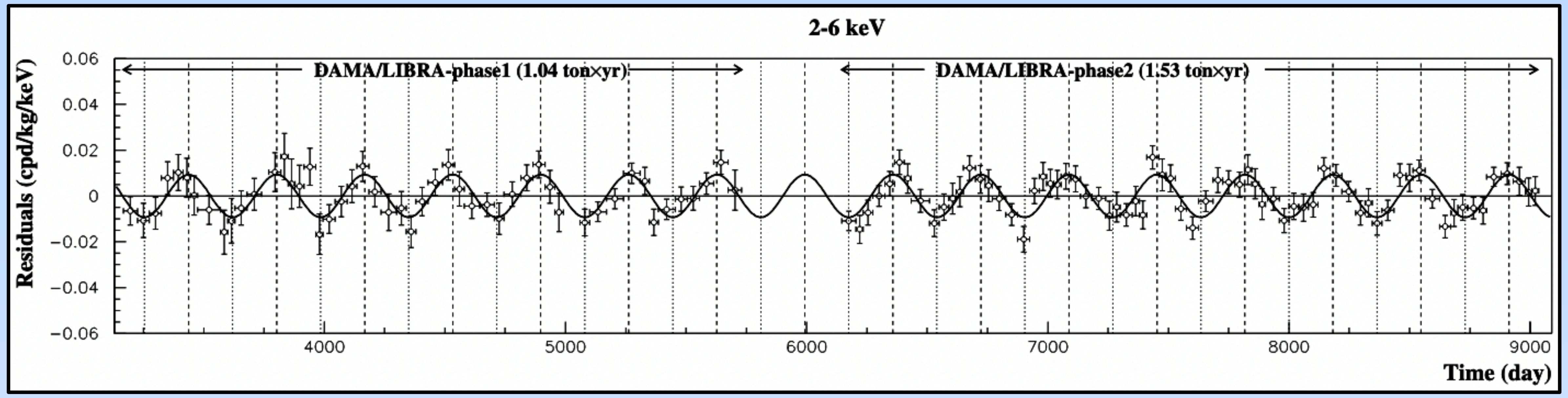
Primer

Julien Billard et al 2022 Rep. Prog. Phys. 85 056201



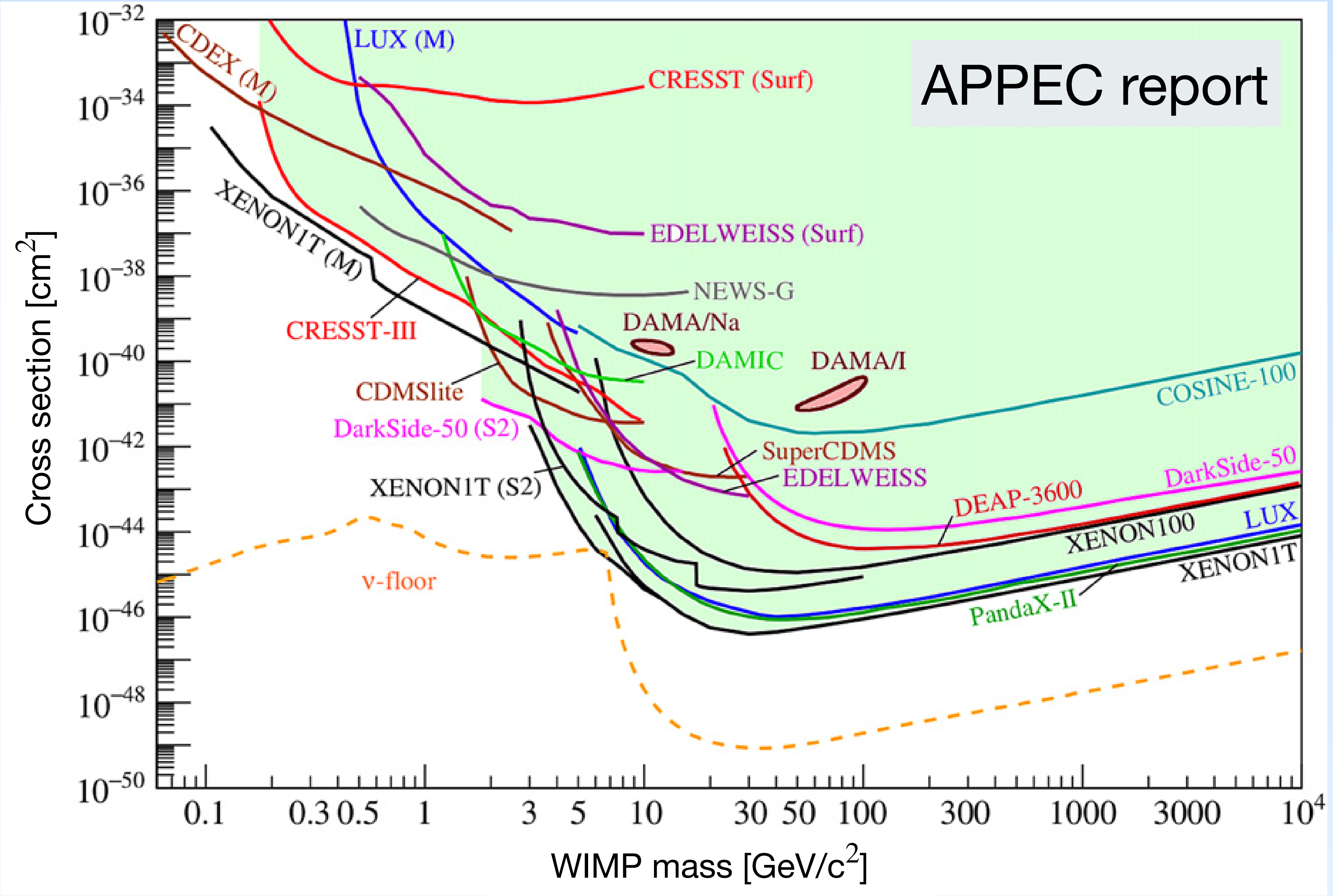
Direct DM searches

Primer



R. Bernabei et al., Nucl. Phys. At. Energy, 22(4):329–342, 2022.

Julien Billard et al 2022 Rep. Prog. Phys. 85 056201



- Target material: NaI
- Total exposure: 2.86 tonne years
- Energy threshold: 0.75 keV$_{ee}$
- C.L: 13.7 σ in (2-6 keV$_{ee}$)

  11.6 σ in (1-6 keV$_{ee}$)

Direct DM searches

Motivation

Why a model-independent check is necessary?

DM and target properties

DM interaction model

DM velocity distribution

$$\frac{dR}{dE_R} = N_T \frac{\rho}{m_\chi}\frac{\sigma_0 m_T}{2\mu_N^2}\sum_{i,j}\sum_{a,b=0,1}\hat{c}_i^{(a)}\hat{c}_j^{(b)}\left(F_{ij}^{(ab),1}(q)\int\frac{f_{lab}(\vec{v})}{v}d^3v + F_{ij}^{(ab),2}(q)\int v f_{lab}(\vec{v})d^3v\right).$$

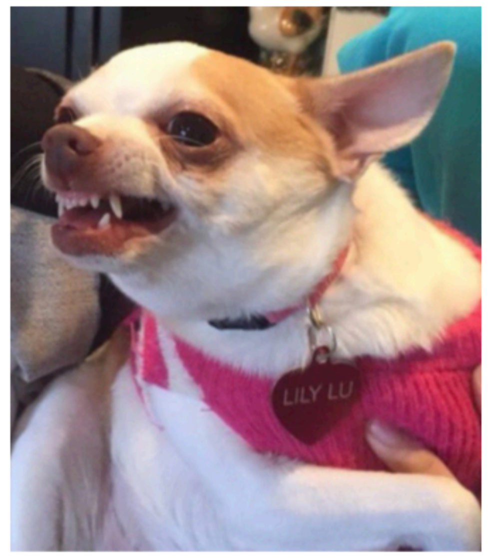
$$\frac{dR}{dE'} = \epsilon(E')\frac{1}{(2\pi)^{1/2}}\int_0^\infty \frac{dR}{dE_R}\frac{dE_R}{dE_{ee}}\frac{1}{\Delta E_{ee}}\exp\left[\frac{-(E'-E_{ee})^2}{2(\Delta E_{ee})^2}\right]dE_{ee}$$

Efficiency/threshold

Number of nuclear recoils

Quenching factor

Resolution

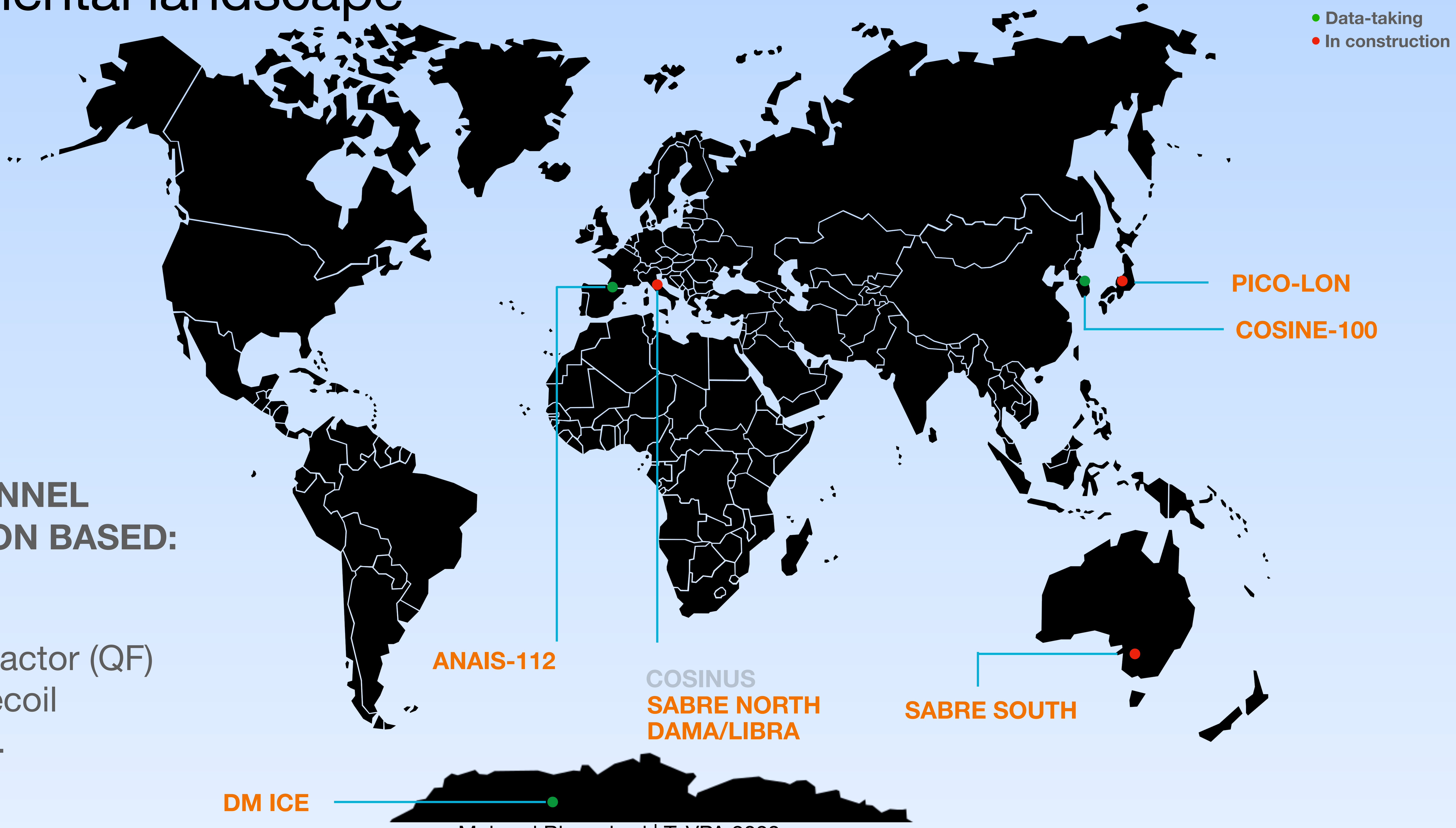


from M.J Zurowski, DSU 2022, Sydney

F. Kahlhöfer et al., JCAP 1805 (2018) no.05, 074

Direct DM searches

NaI experimental landscape



SINGLE-CHANNEL SCINTILLATION BASED:

- Influence of Quenching Factor (QF) on nuclear recoil energy scale.

Direct DM searches

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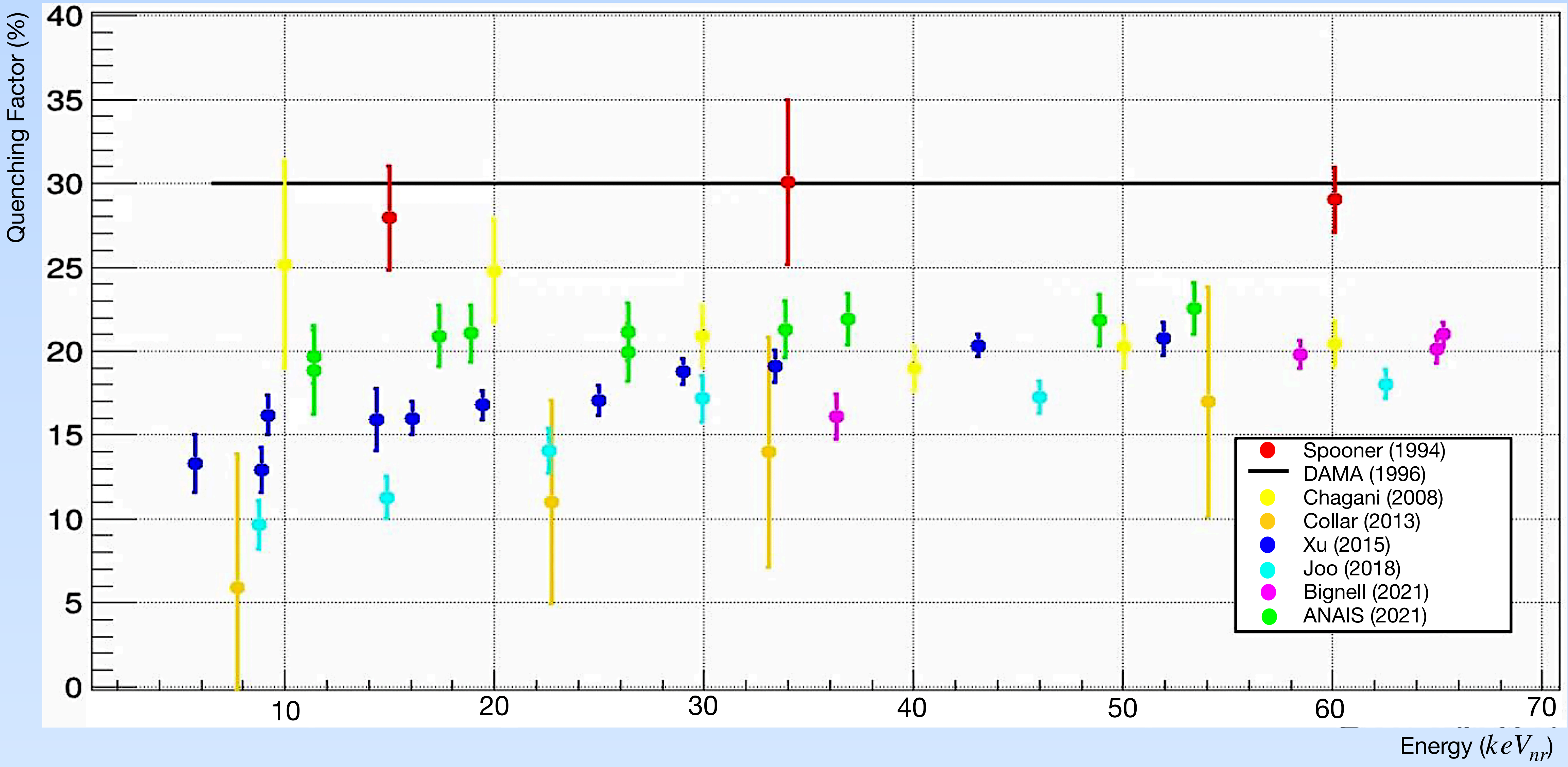
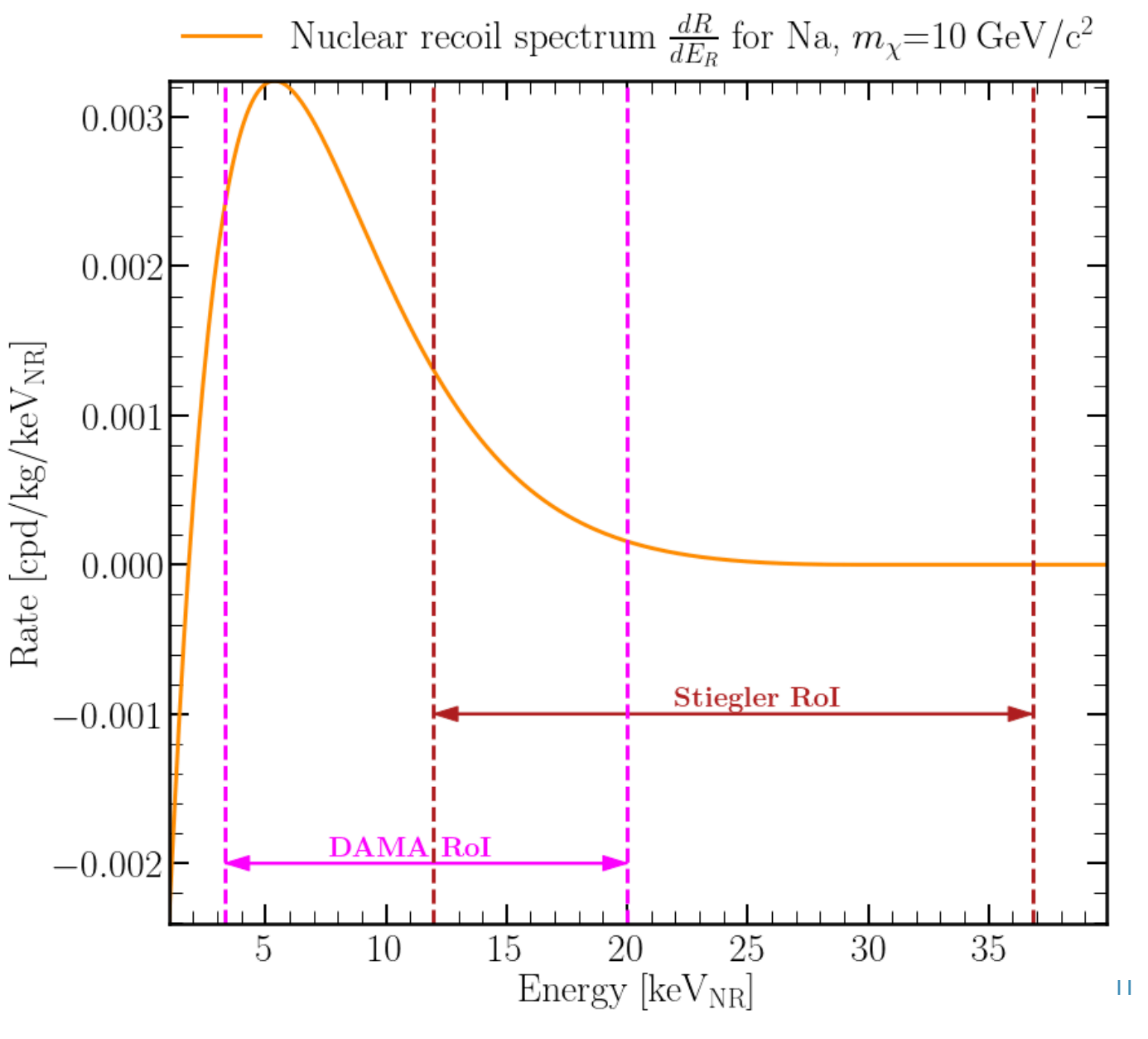
QF uncertainties in NaI



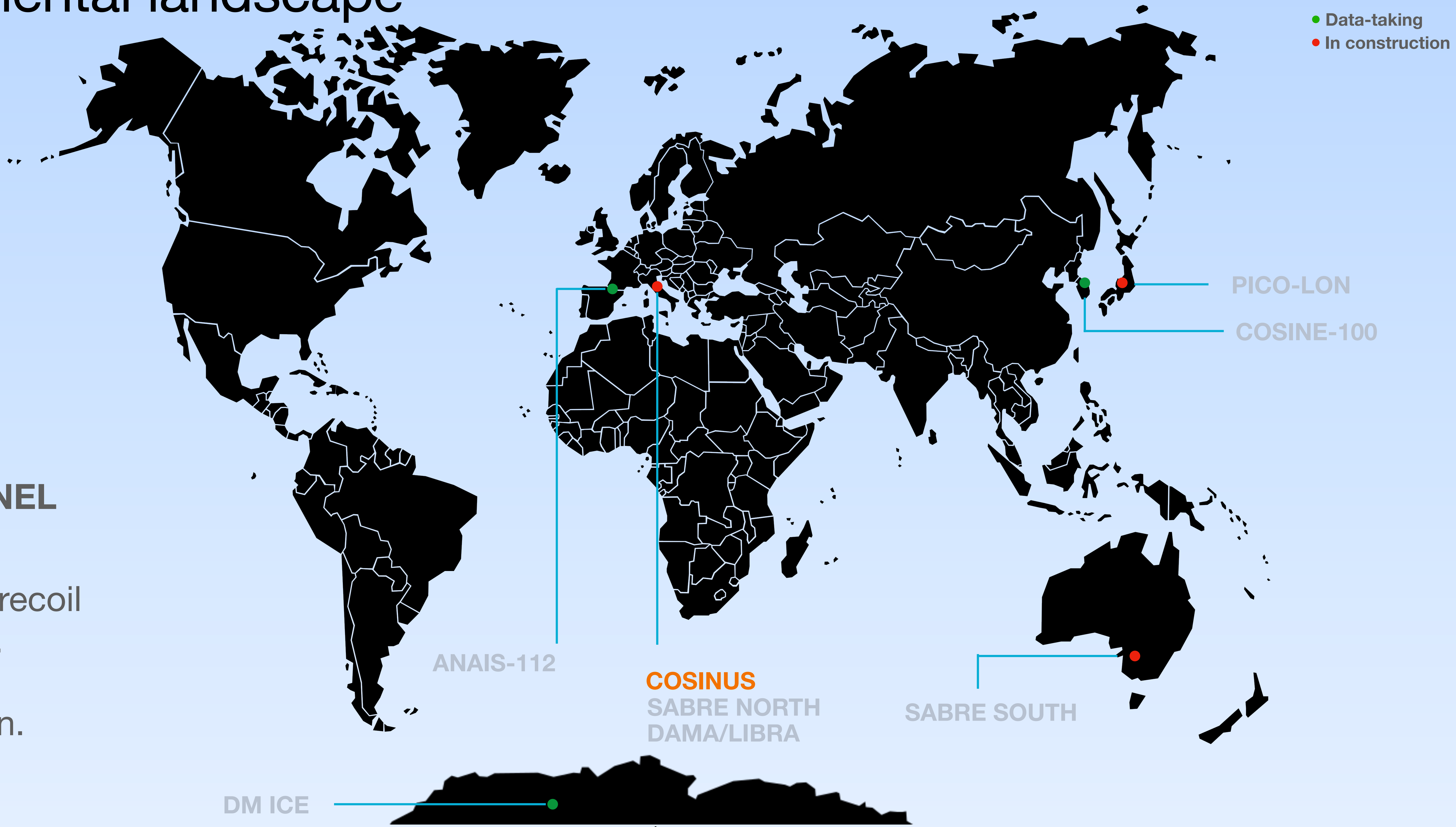
D. Cintas et al 2021 J. Phys.: Conf. Ser. **2156** 012065



- Measurements of quenching factor (QF) at room temperature disagree.
- Potential dependence on Tl dopant %
- Change of QF has a strong impact on observable rate.

Direct DM searches

NaI experimental landscape



DUAL-CHANNEL BASED:

- True nuclear recoil energy scale.
- Particle discrimination.

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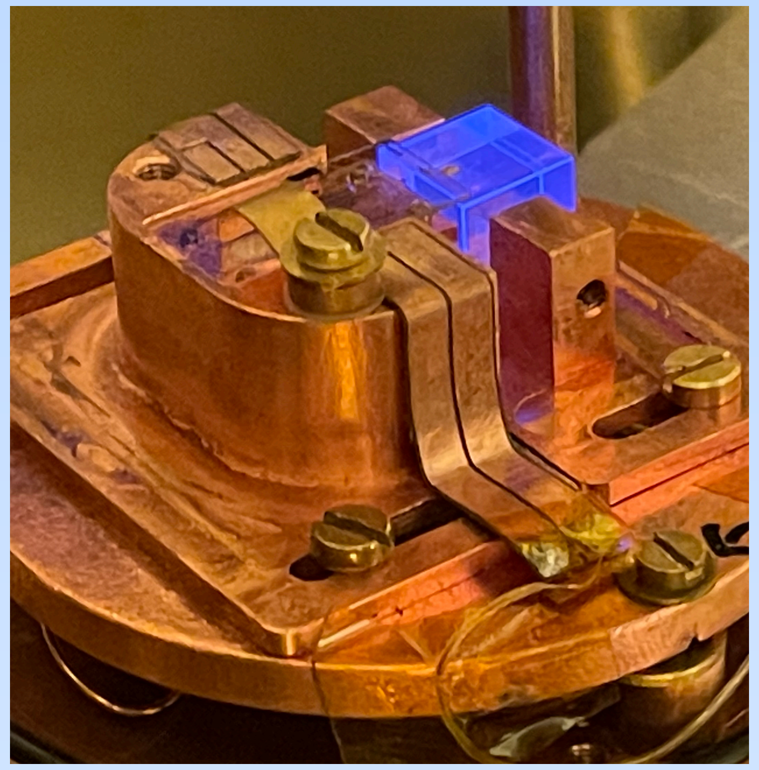
Cryogenic **O**bservatory for **SI**gnatures seen in **N**ext generation **U**nderground **S**earches

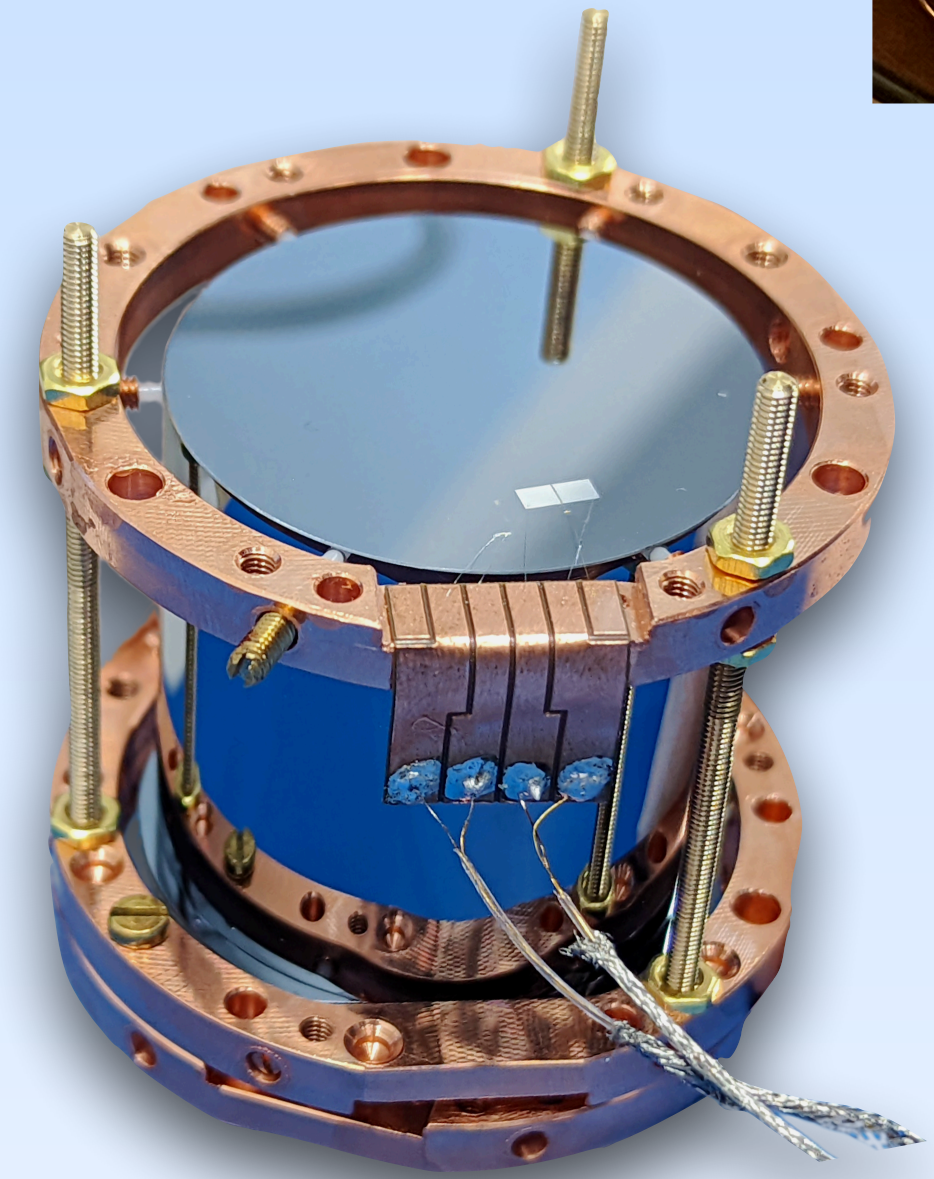
Design aspects:

Provide a model-independent cross-check of DAMA/LIBRA

Target detector material: NaI

Novel operation of radio-pure NaI at cryogenic temperatures. $\mathcal{O}(mK)$





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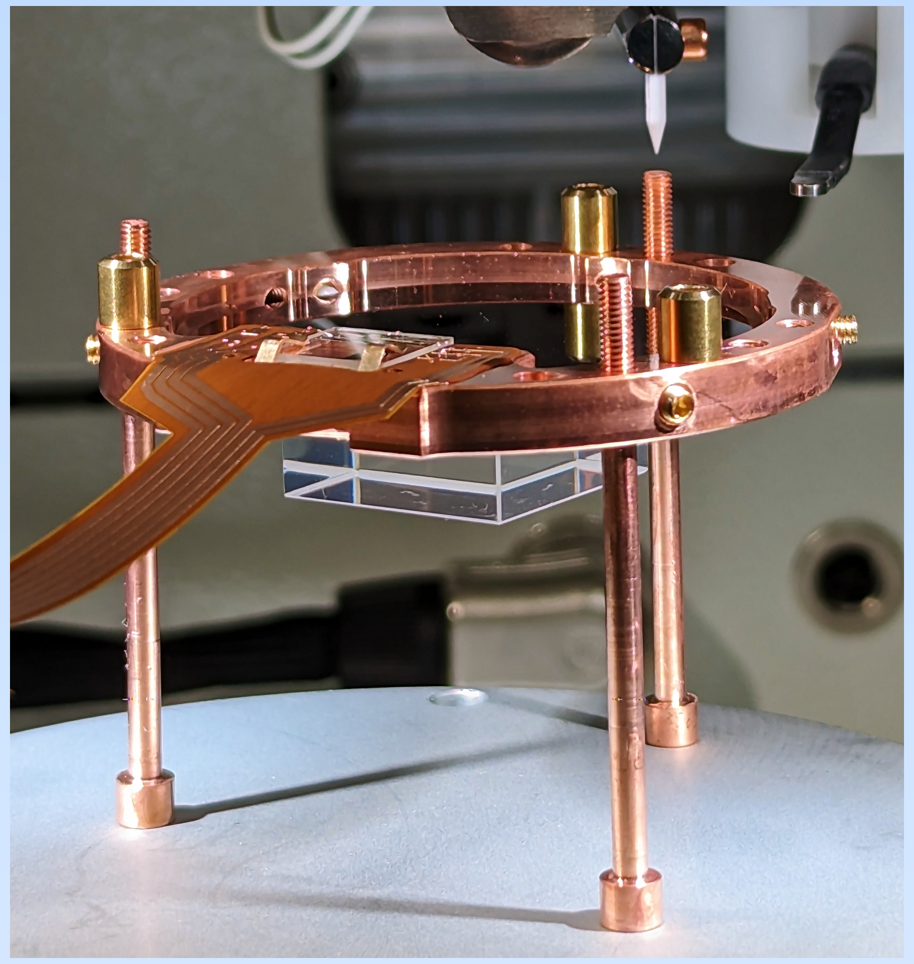
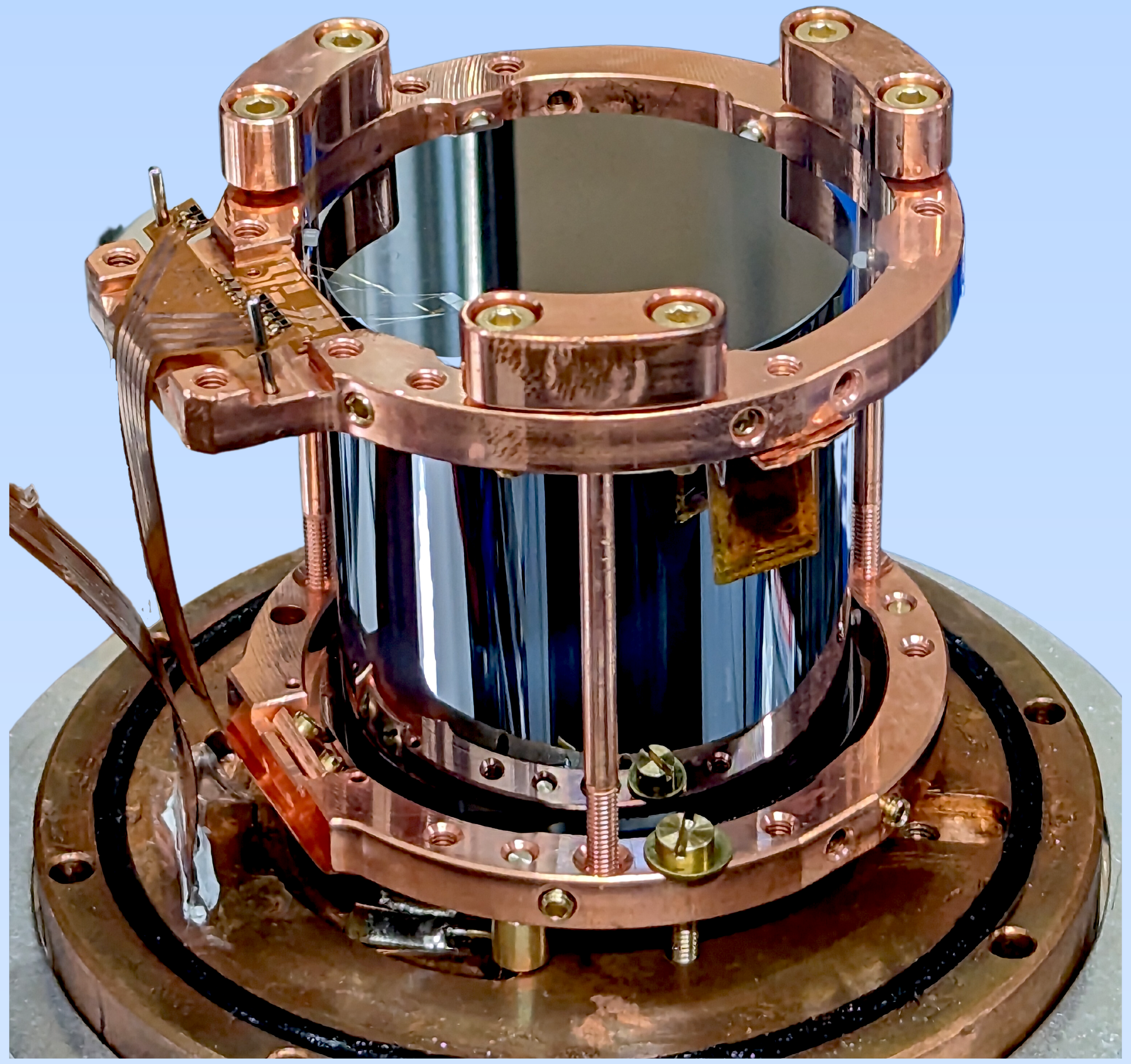
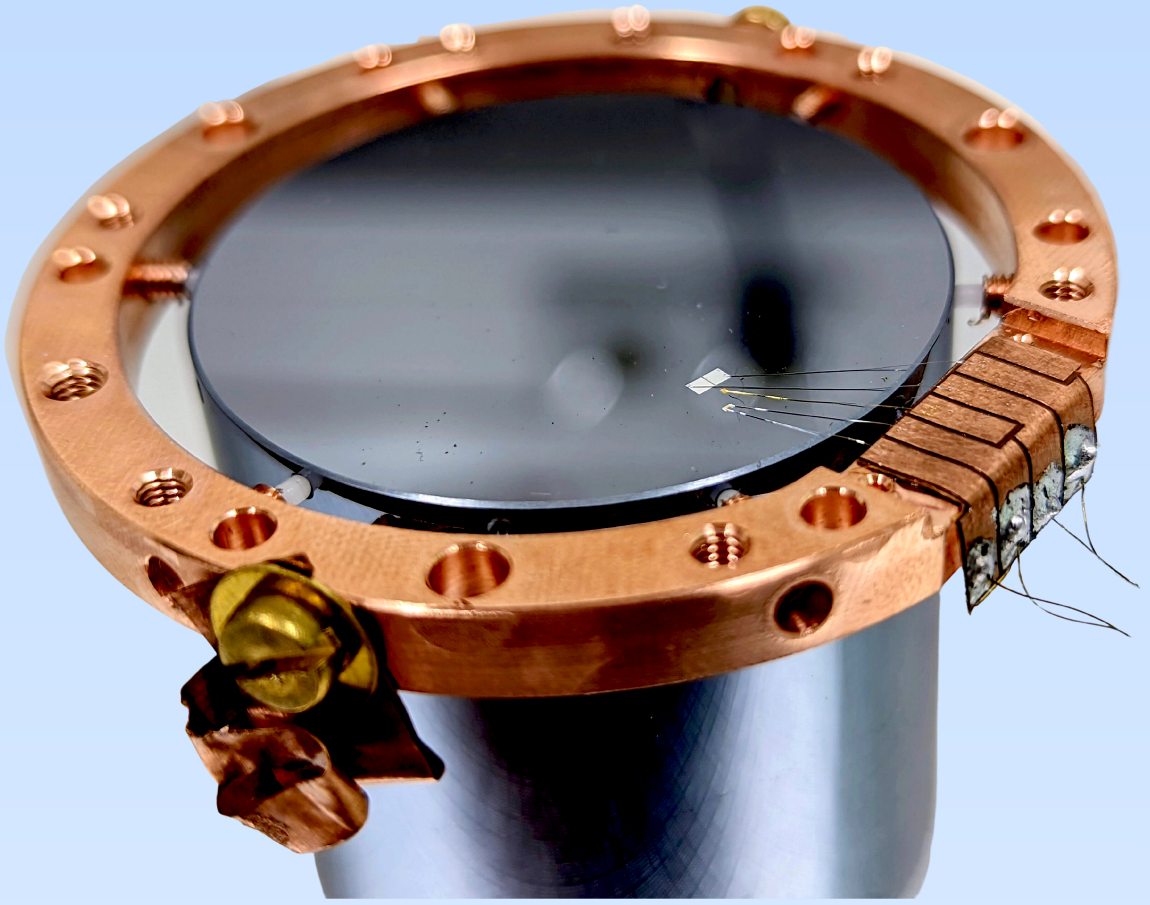
2 channel readout

CHANNEL - 1: PHONON DETECTOR





CHANNEL - 2: LIGHT DETECTOR



Phonon Signal

- (almost) independent of particle type

NaI + remoTES

Light Signal

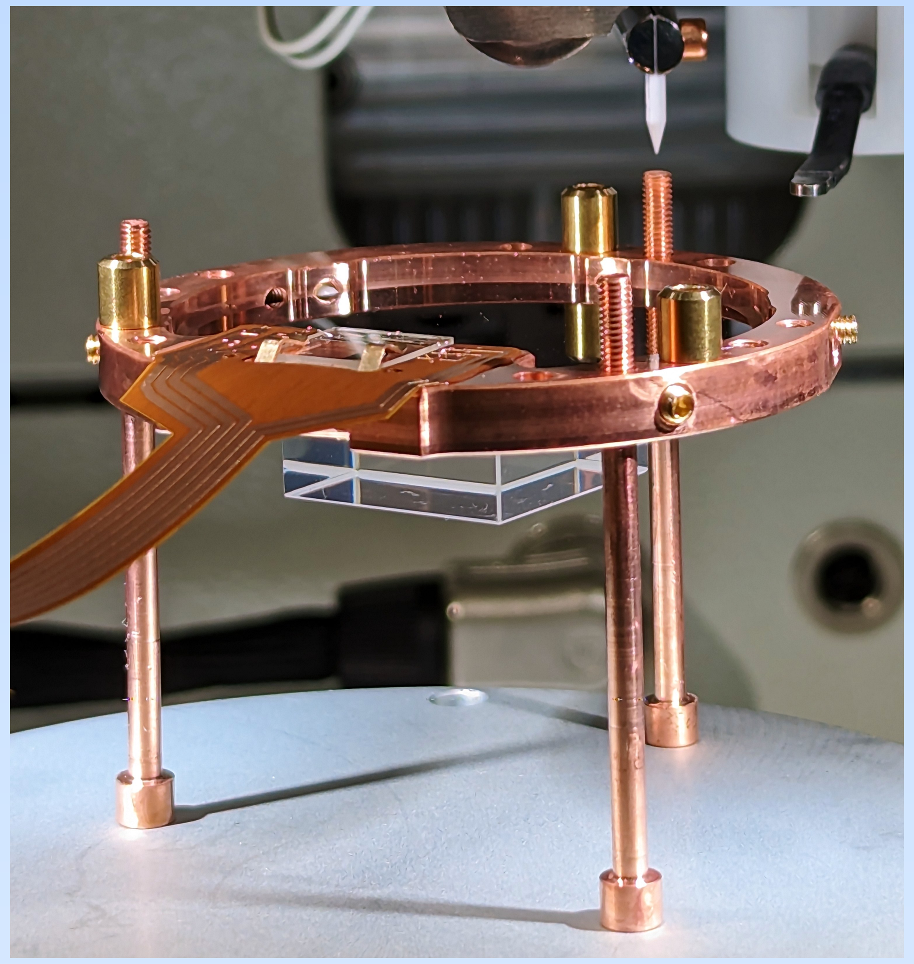
- Scintillation light strongly dependent on type of particle interaction

Si + TES

COSINUS

Advantages

CHANNEL - 1: PHONON DETECTOR



Phonon Signal

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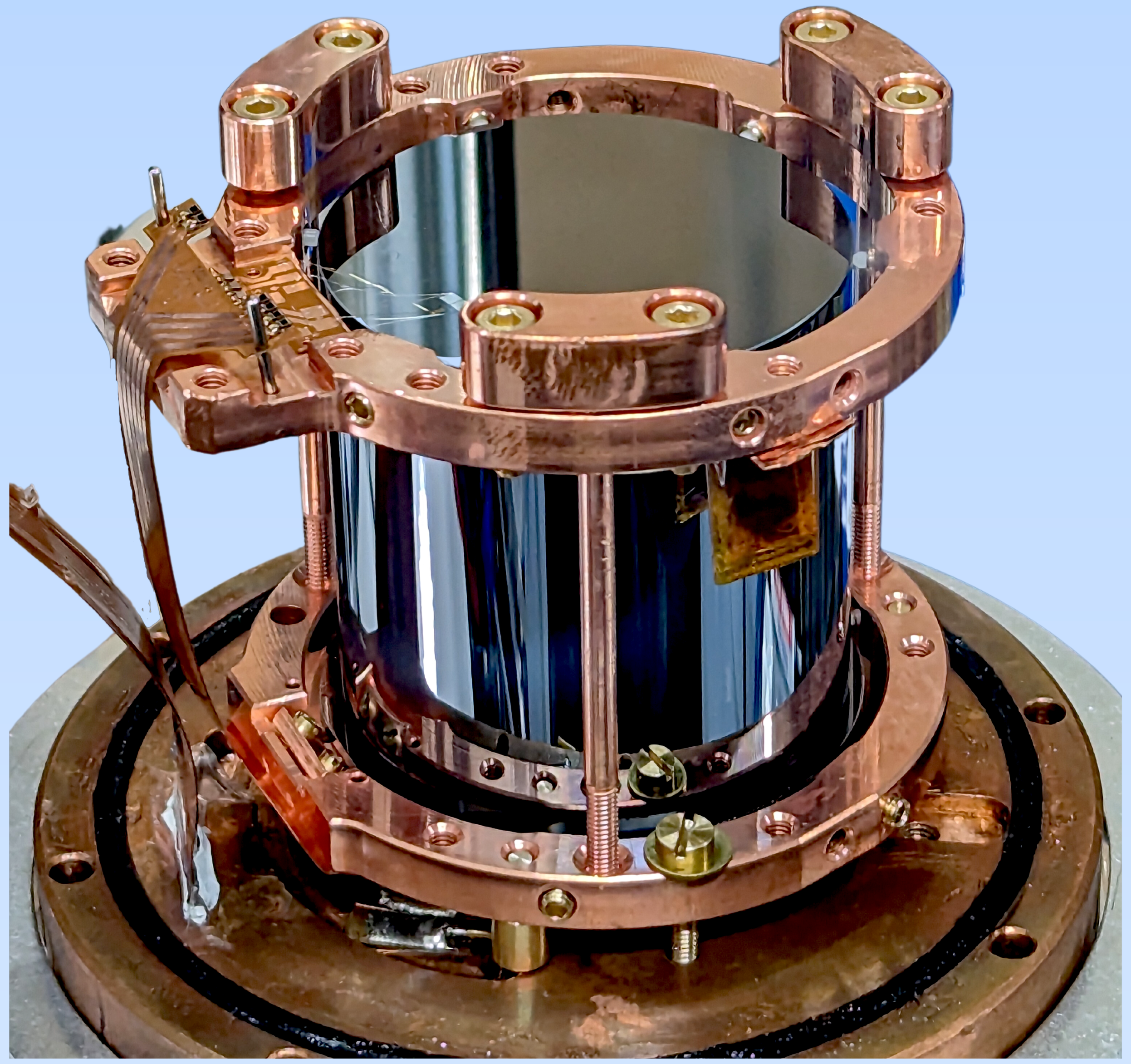
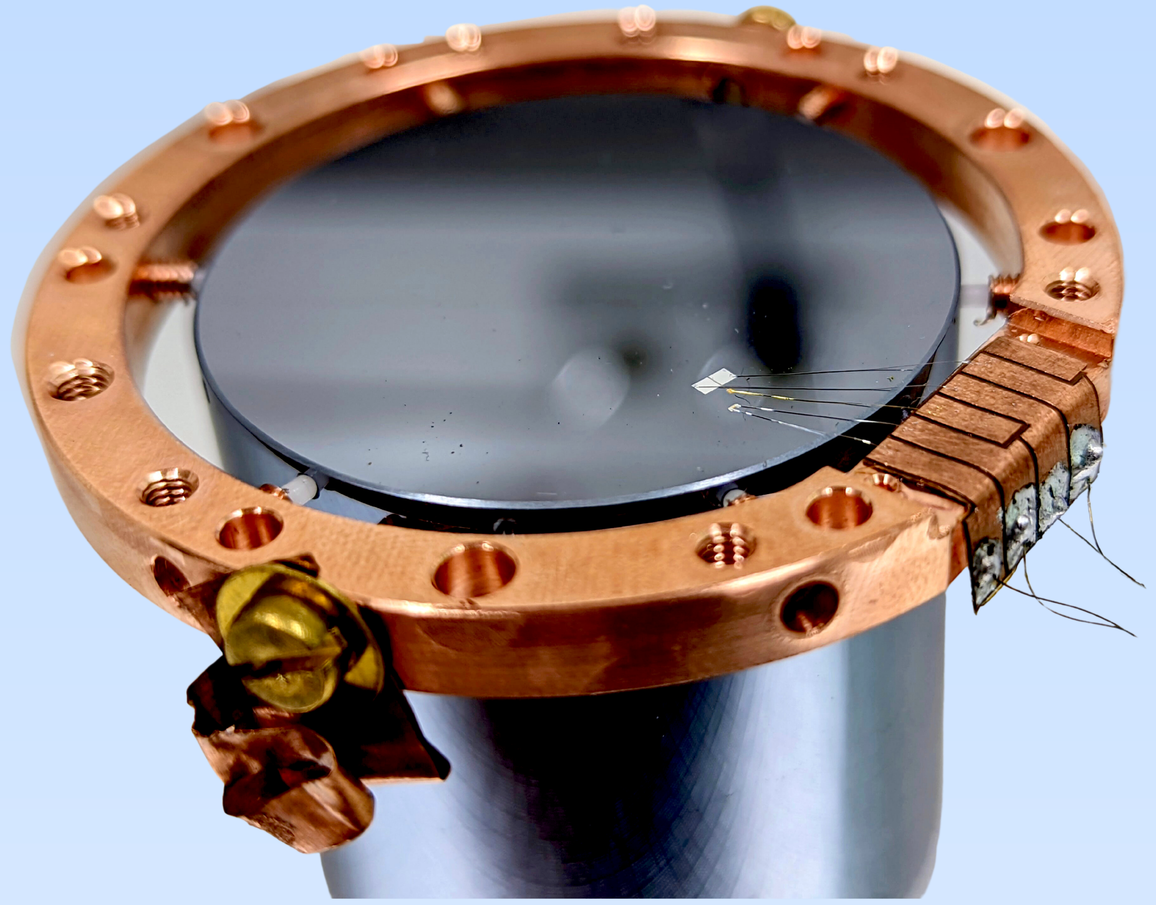
<u>NaI + remoTES</u>



- Particle discrimination on per-event basis!
- Low threshold for nuclear recoils (TES based readout)
- In-situ measurement of QF

CHANNEL - 2: LIGHT DETECTOR



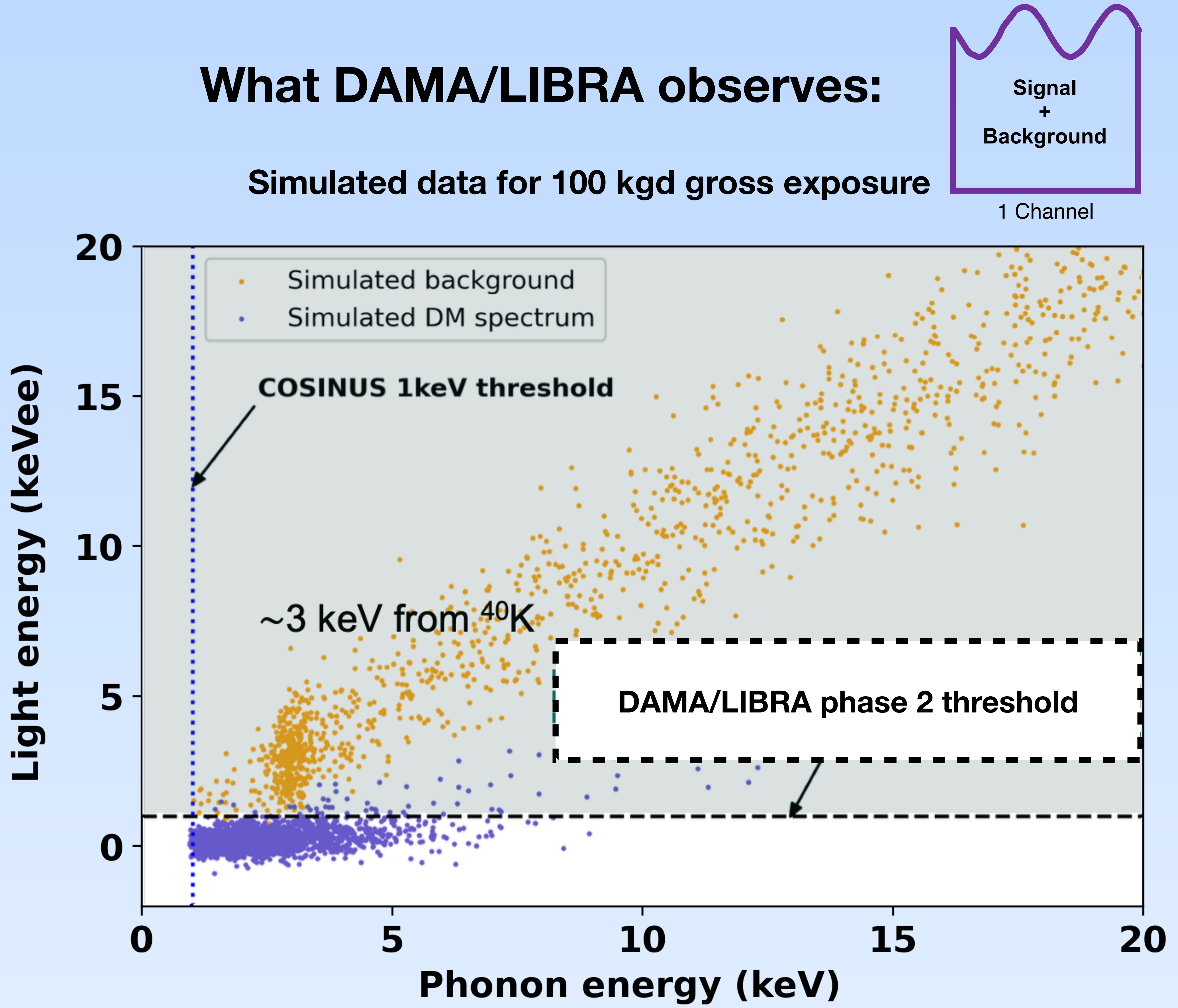
Light Signal

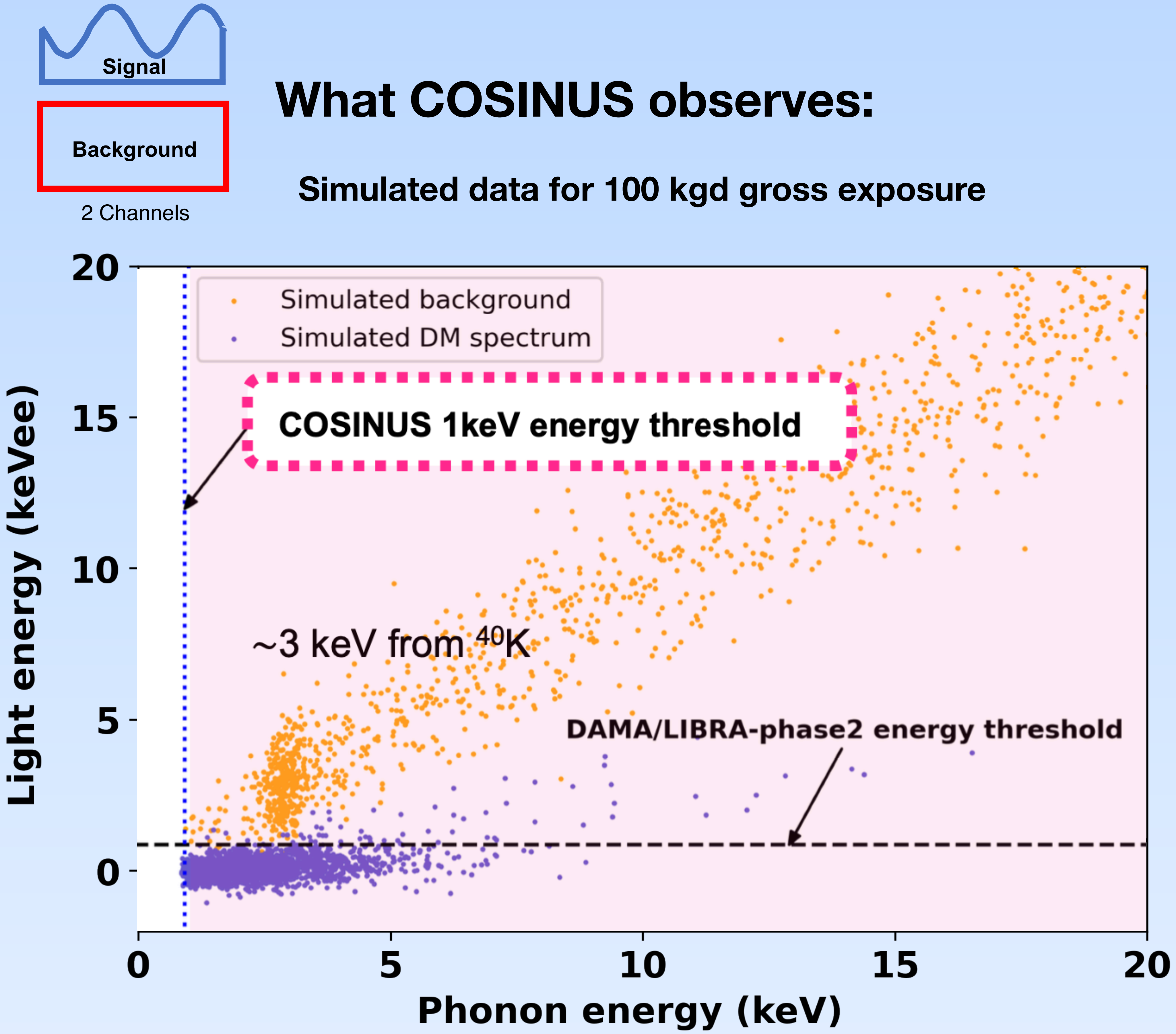
- Scintillation light strongly dependent on type of particle interaction

<u>Si + TES</u>

COSINUS

Advantages





background: 20ppb ^{40}K + flat bkg (1/ keV kg d)

σ^{SI}: 2x10^{-4} pb, M_{DM}: 10 GeV/c^2

Efficiency between 20-50% at 1-2 keV, 50% above 2 keV

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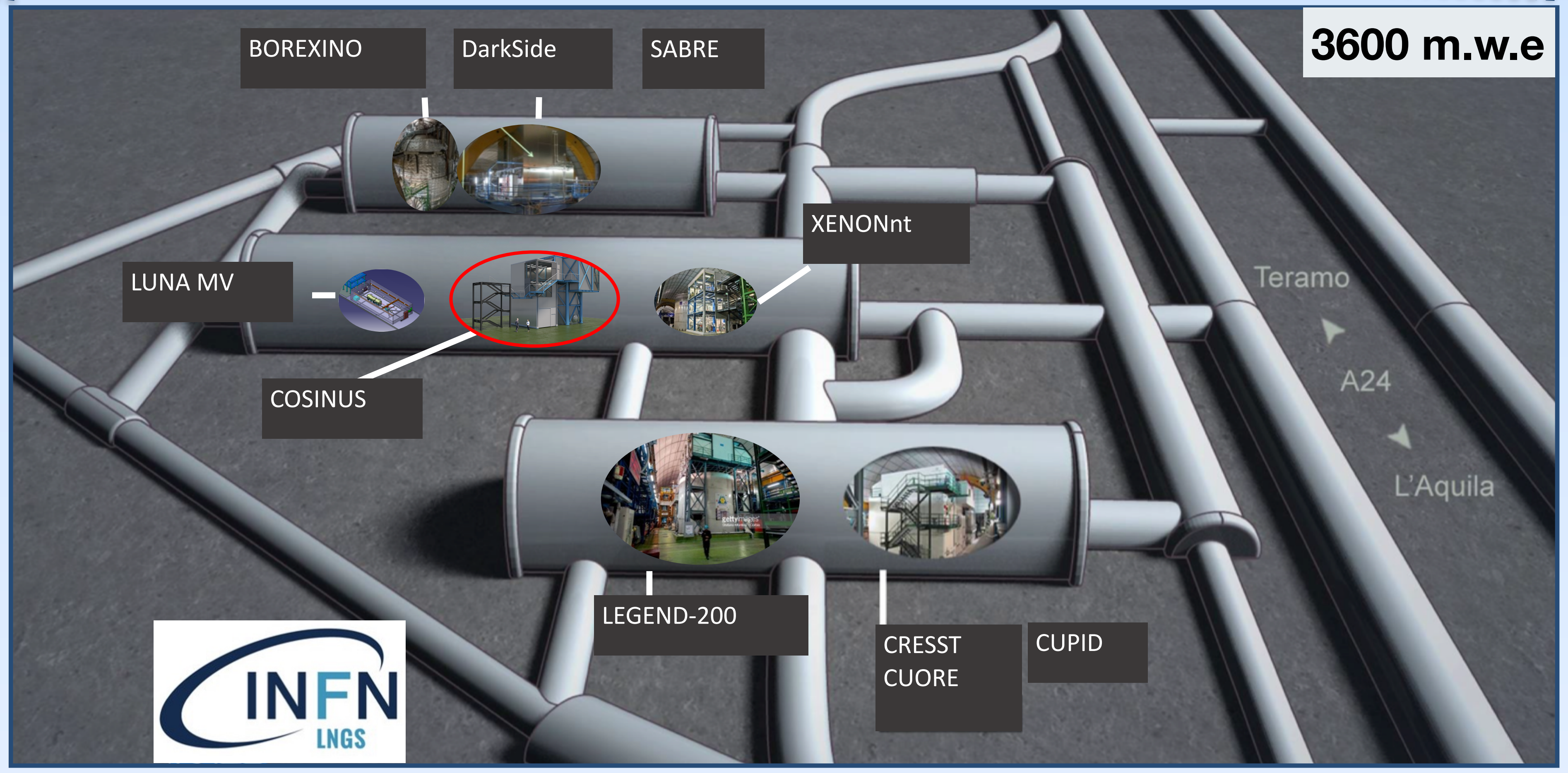
Low-background facility



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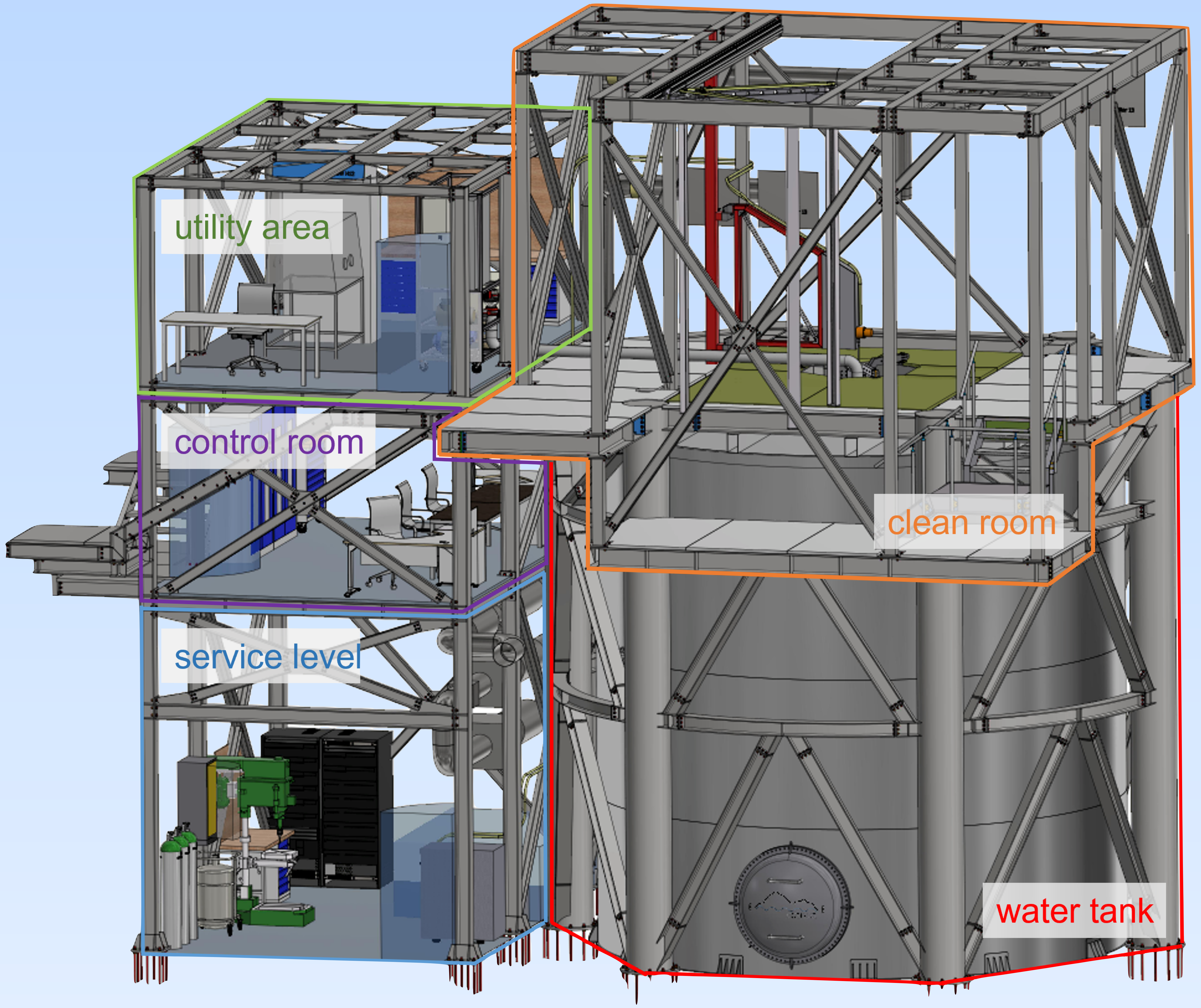
Low-background facility

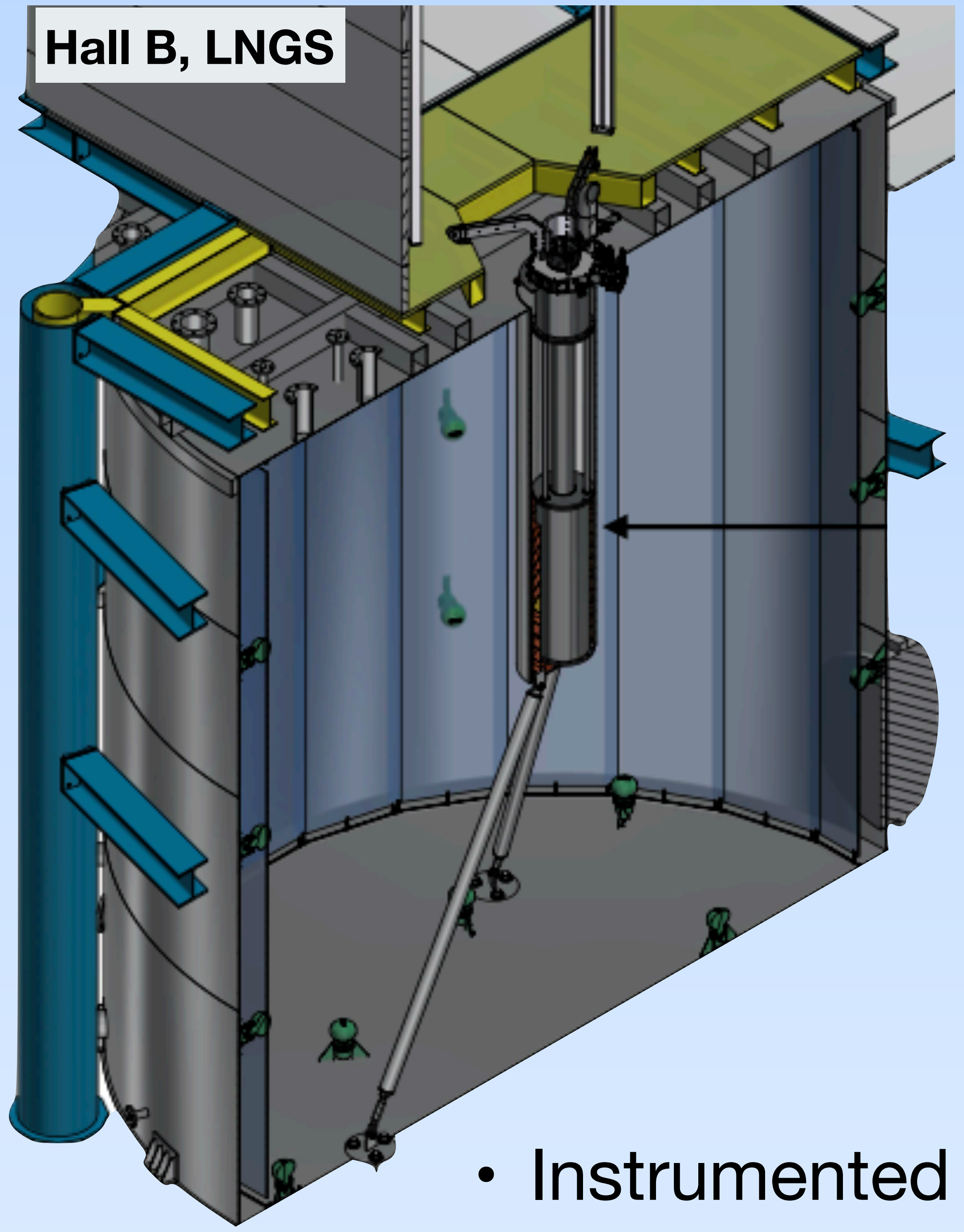
Eur. Phys. J. C (2022) 82: 248
Following work to be published



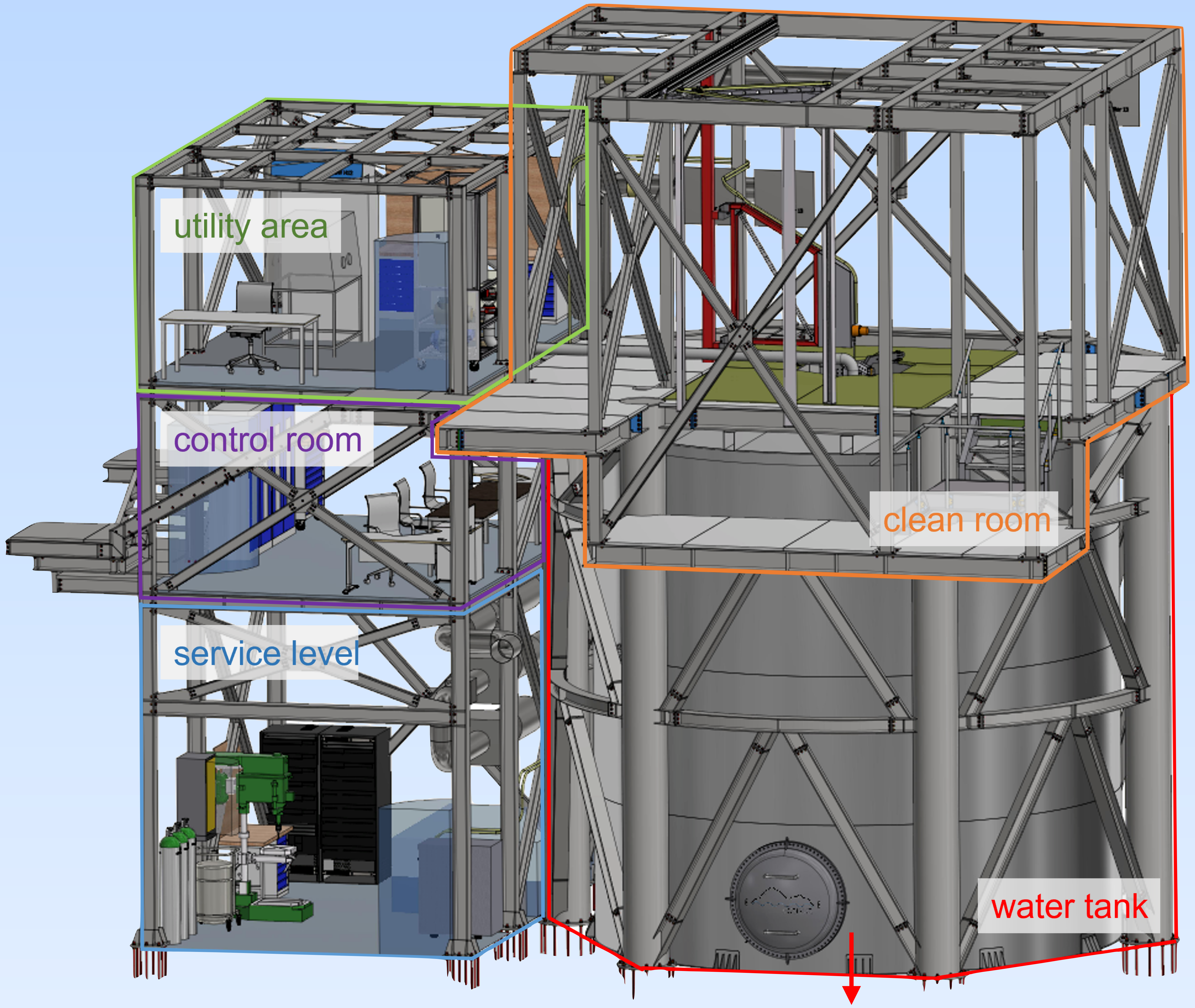
COSINUS

Low-background facility

Eur. Phys. J. C (2022) 82: 248
Follow-up work to be published



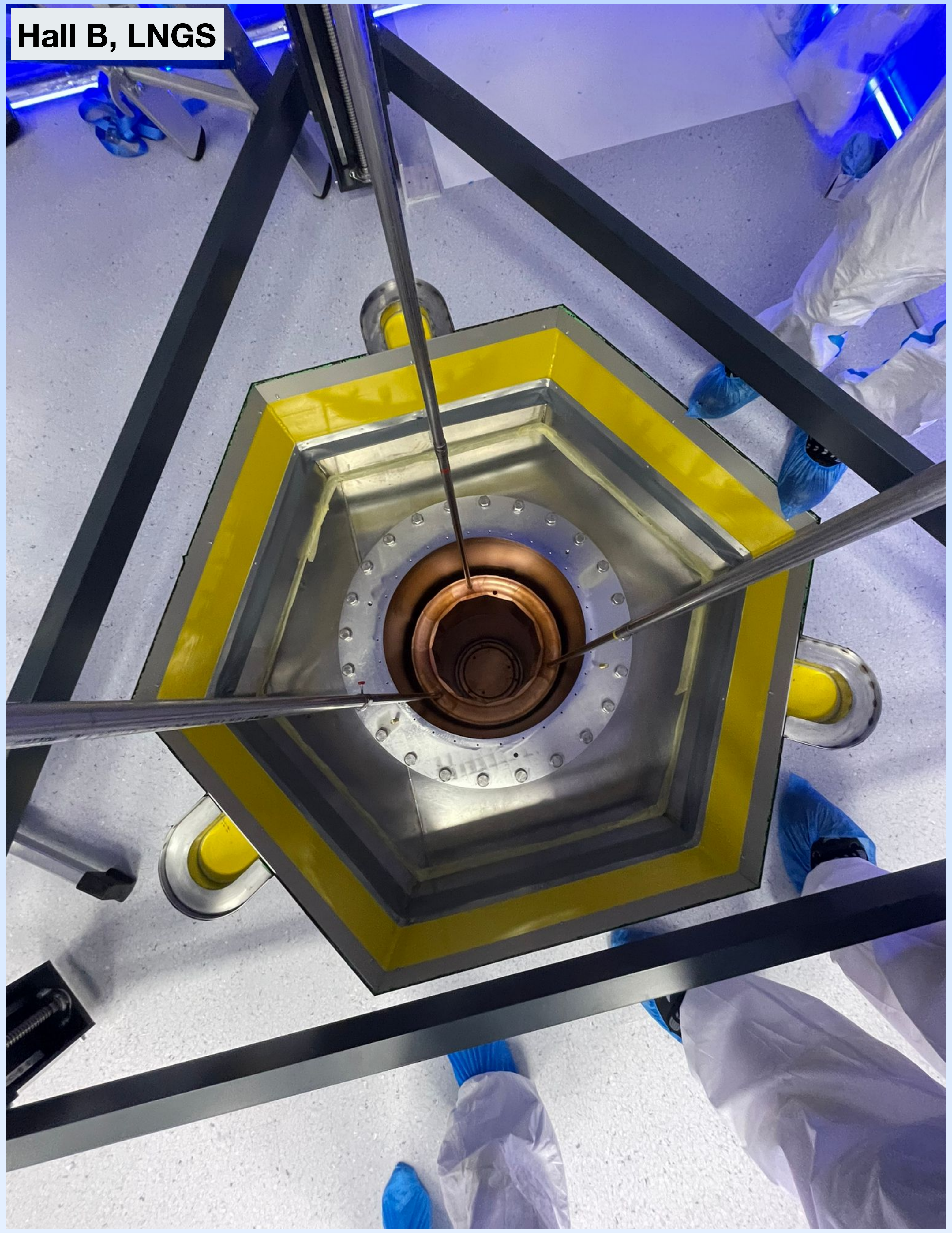
- Instrumented with 28 PMTs to reduce the cosmogenic neutron bkg.
- We simulate 99% muon event veto
  45% shower event veto
  97% of veto in total
- **no veto**: neutron rate (3.5 ± 0.7) cts kg^{-1} yr^{-1}
- **veto**: neutron rate (0.11 ± 0.08) cts kg^{-1} yr^{-1}

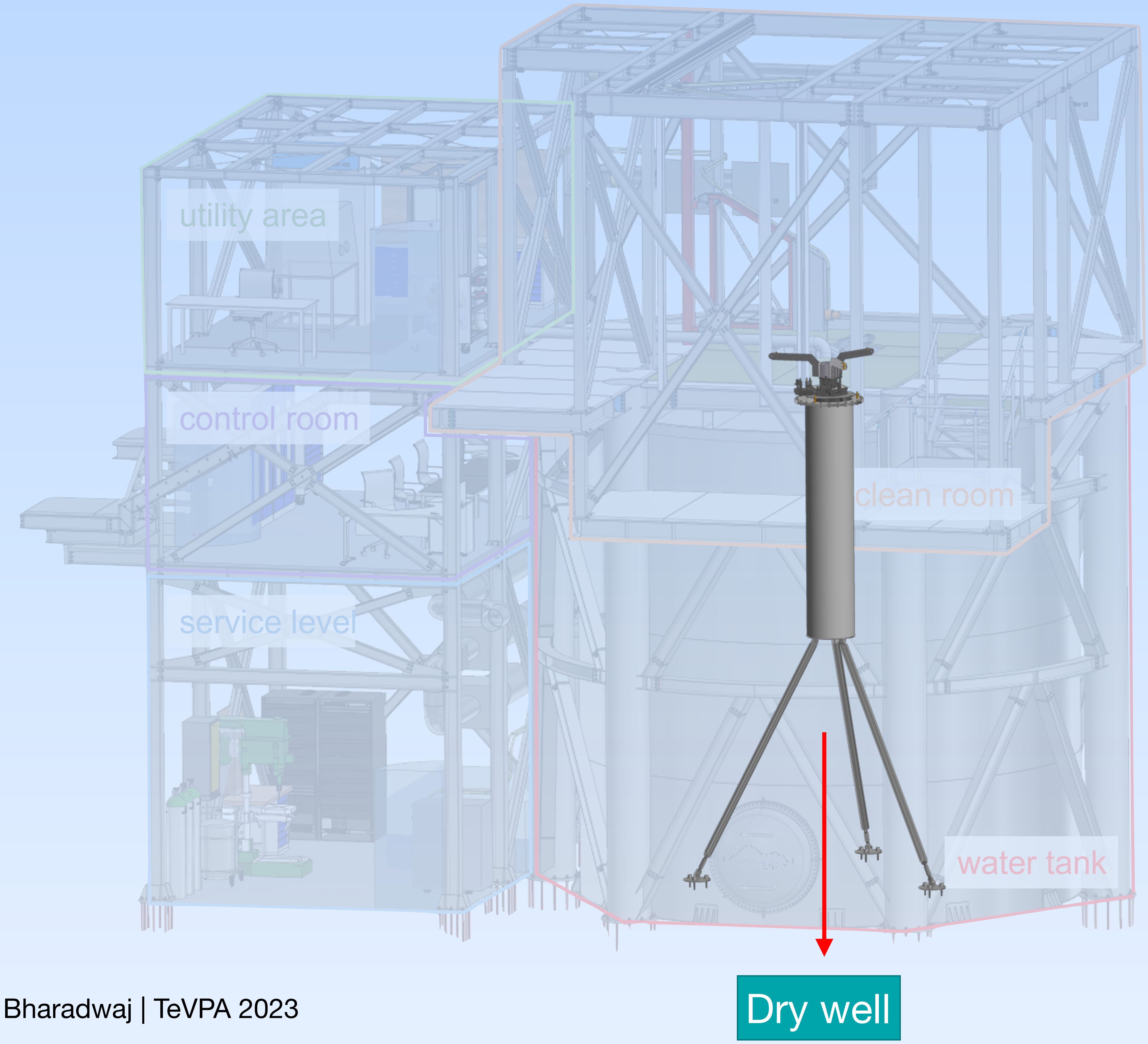


Water Cherenkov Muon Veto

COSINUS

Low-background facility





COSINUS

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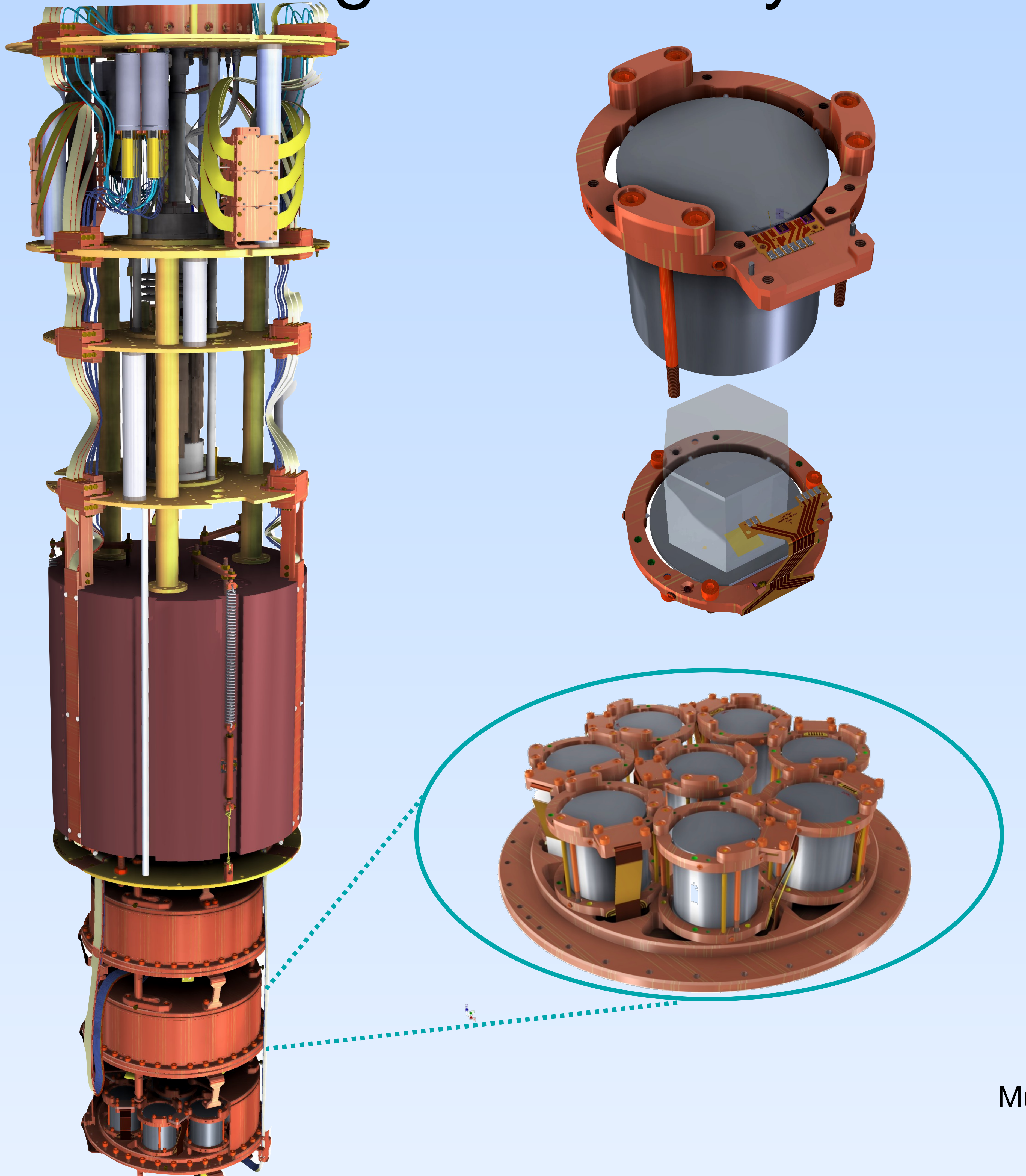
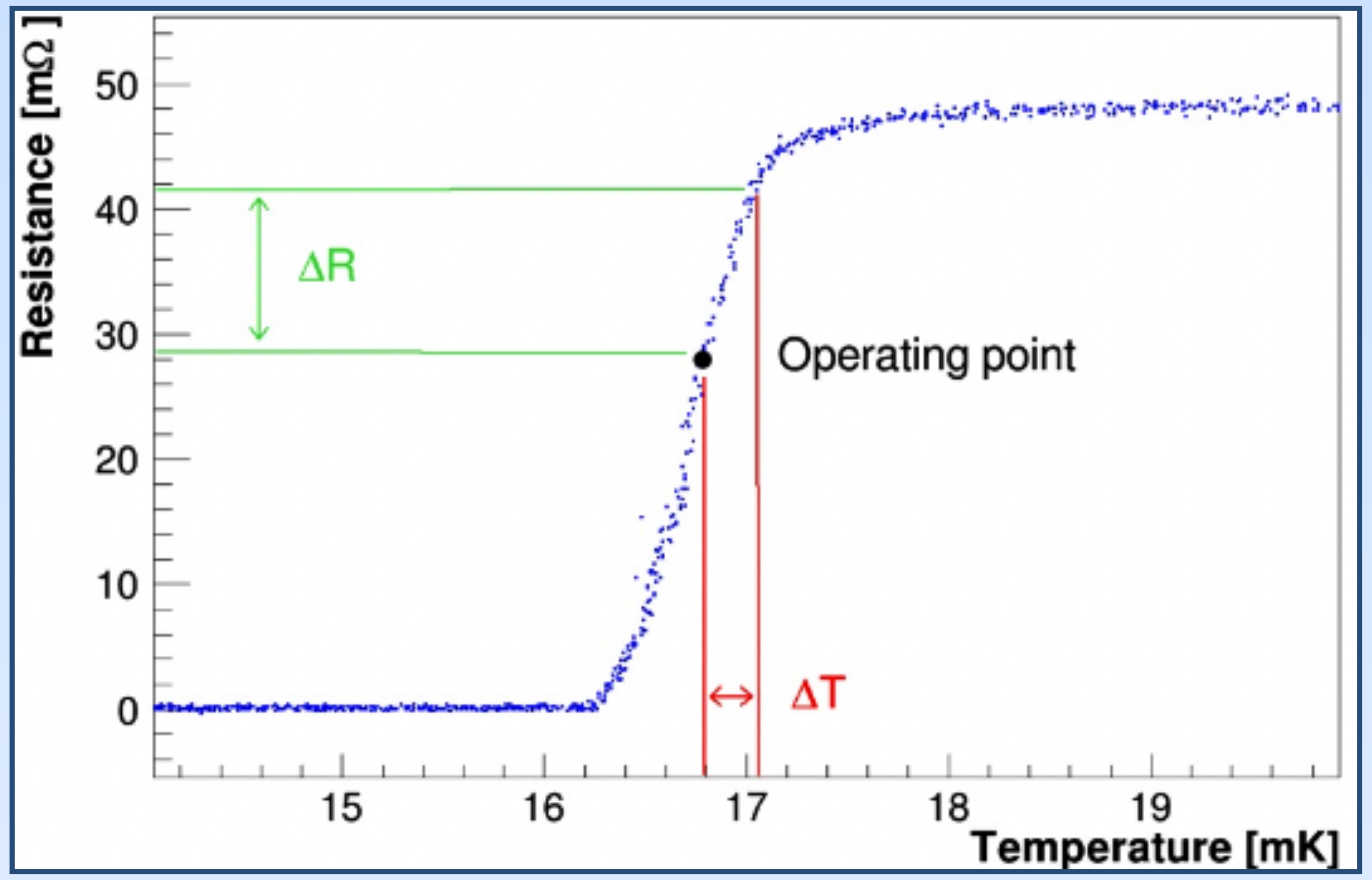


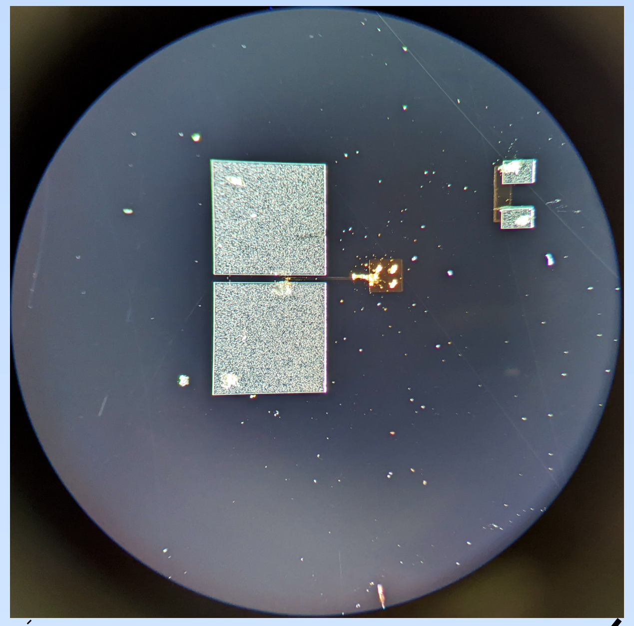
Detector design

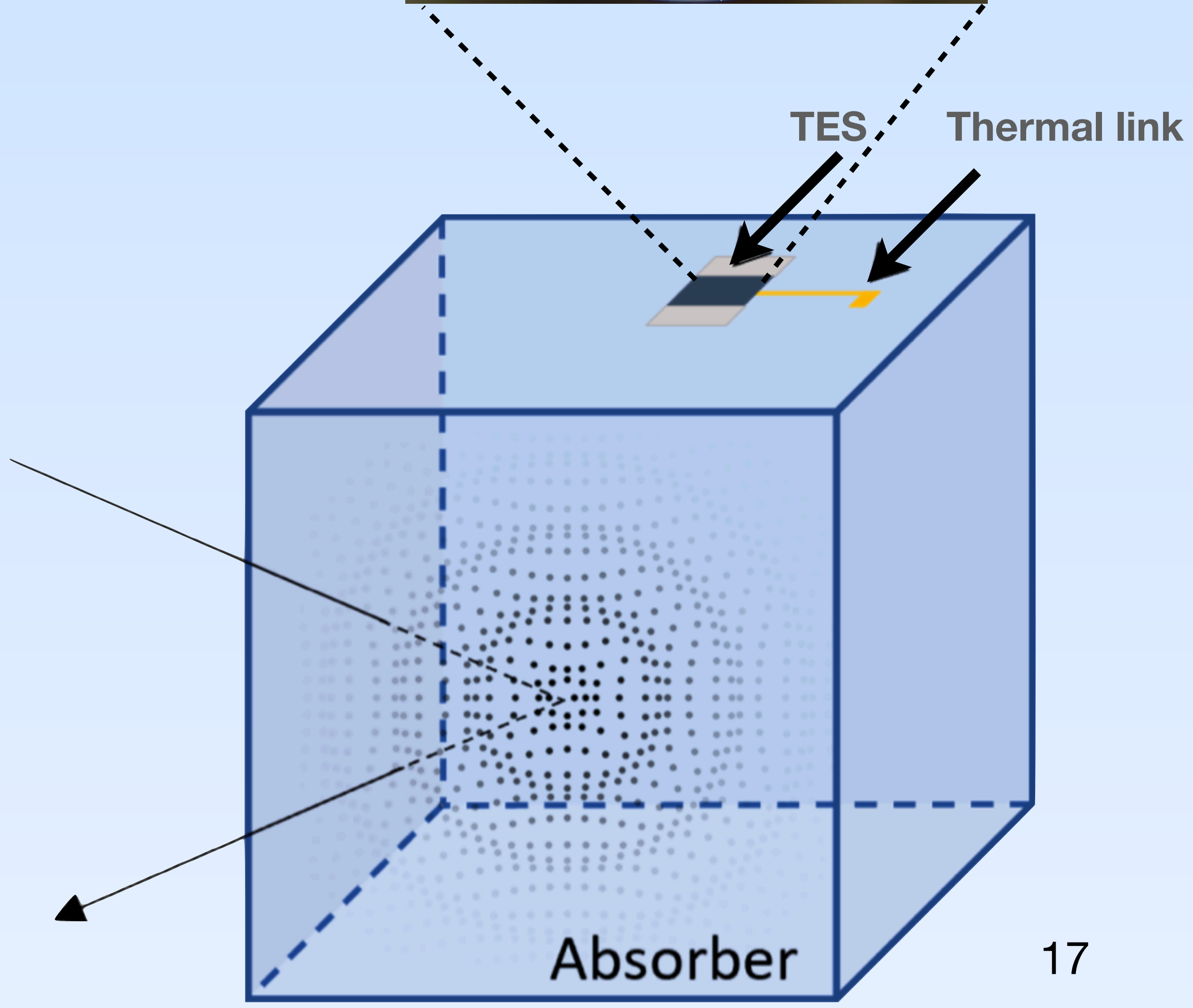
Working principle

- Transition Edge Sensors (TES): extremely sensitive phonon-mediated energy detectors.

Energy Deposition (keV) $\longrightarrow$ Temperature Change (μK) $\longrightarrow$ Resistance Change (mΩ)







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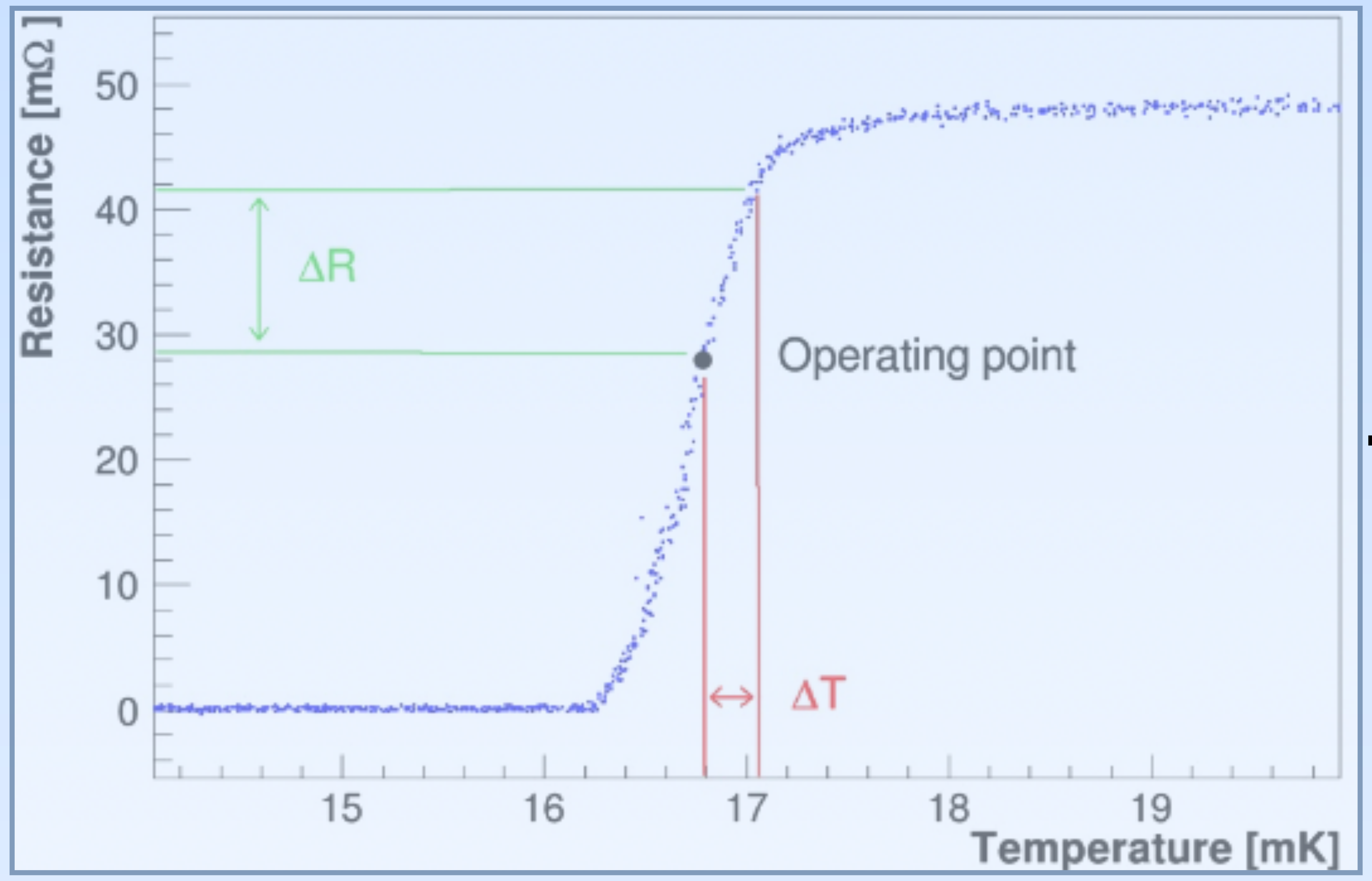
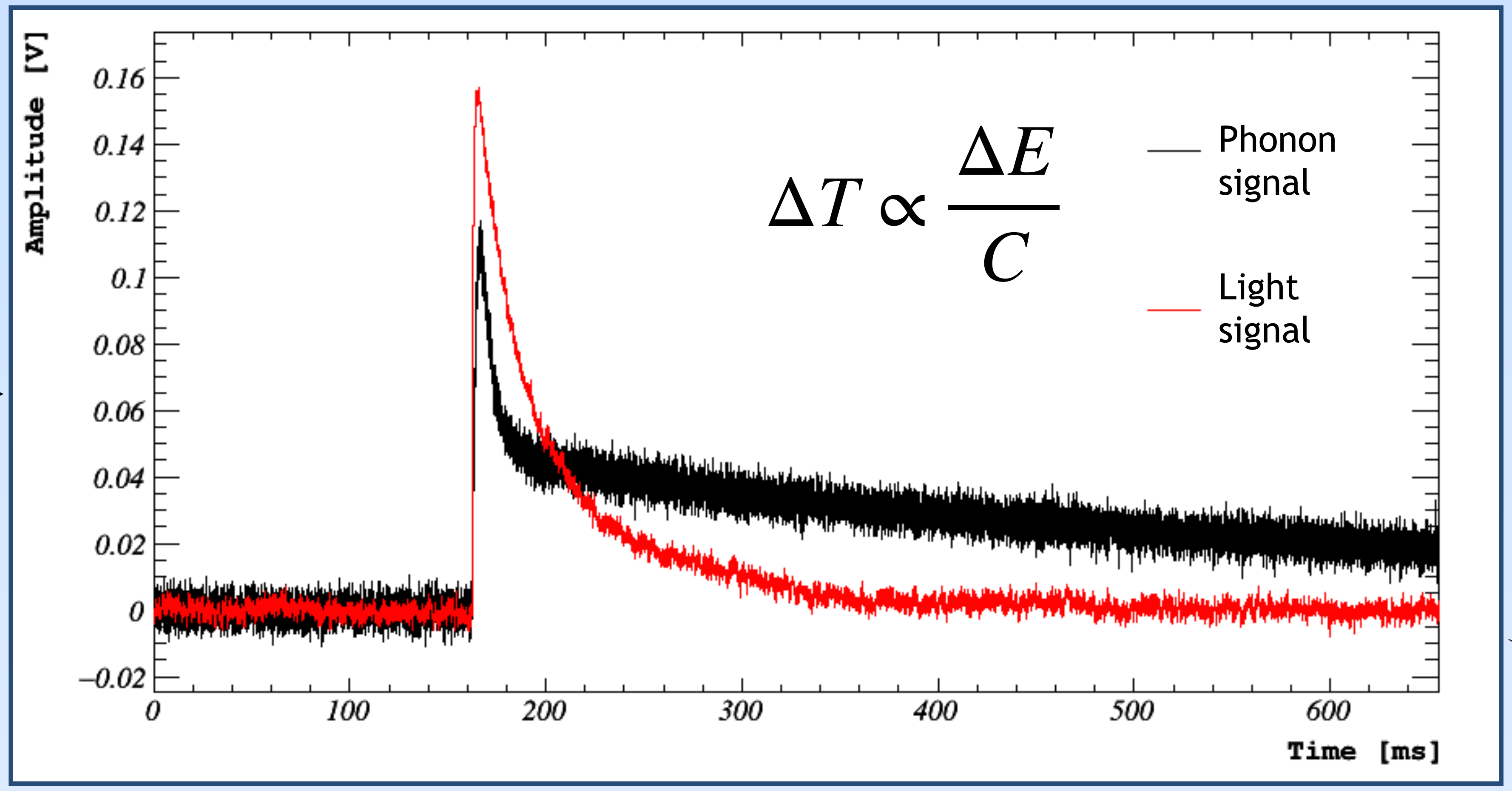
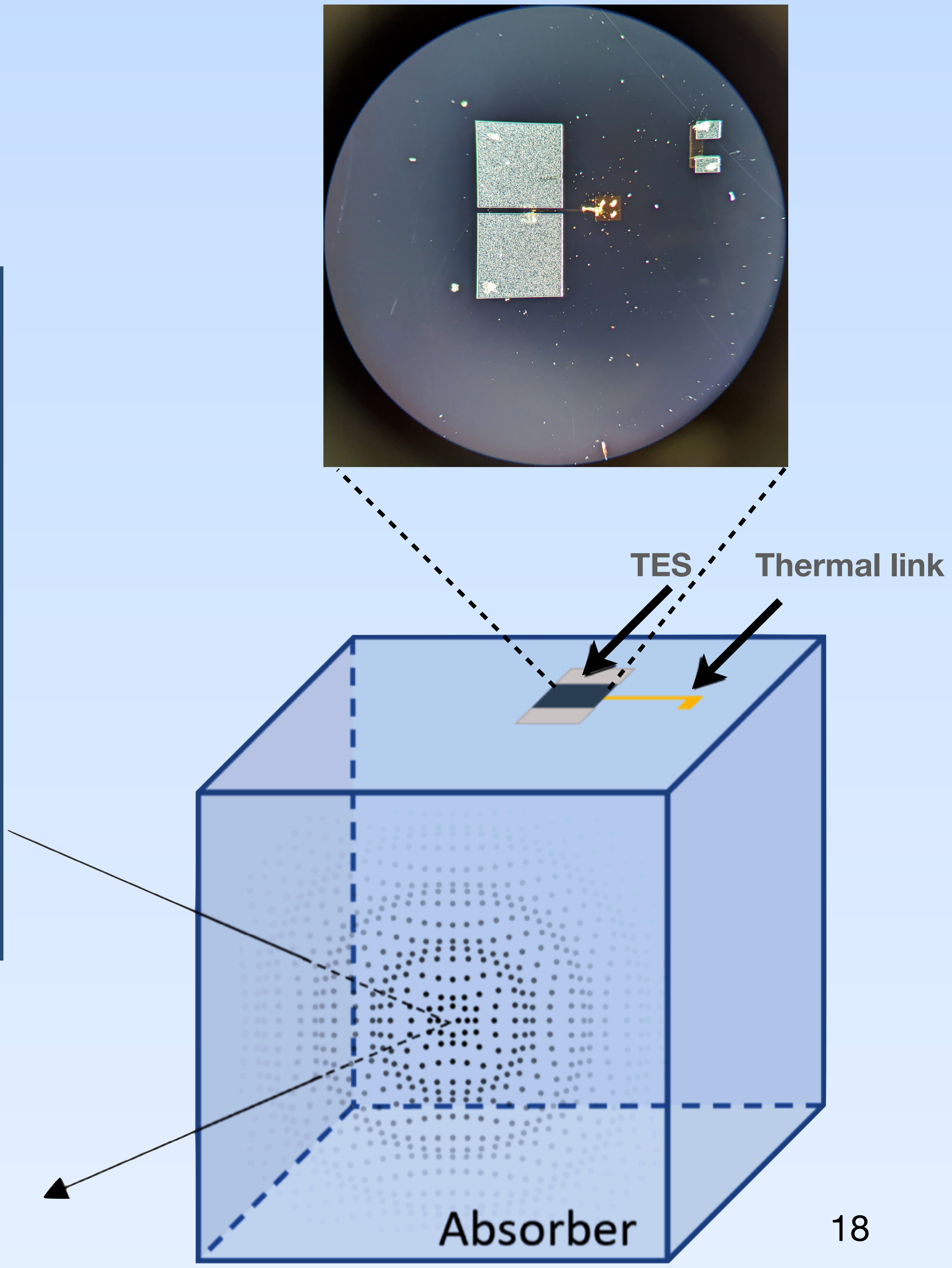
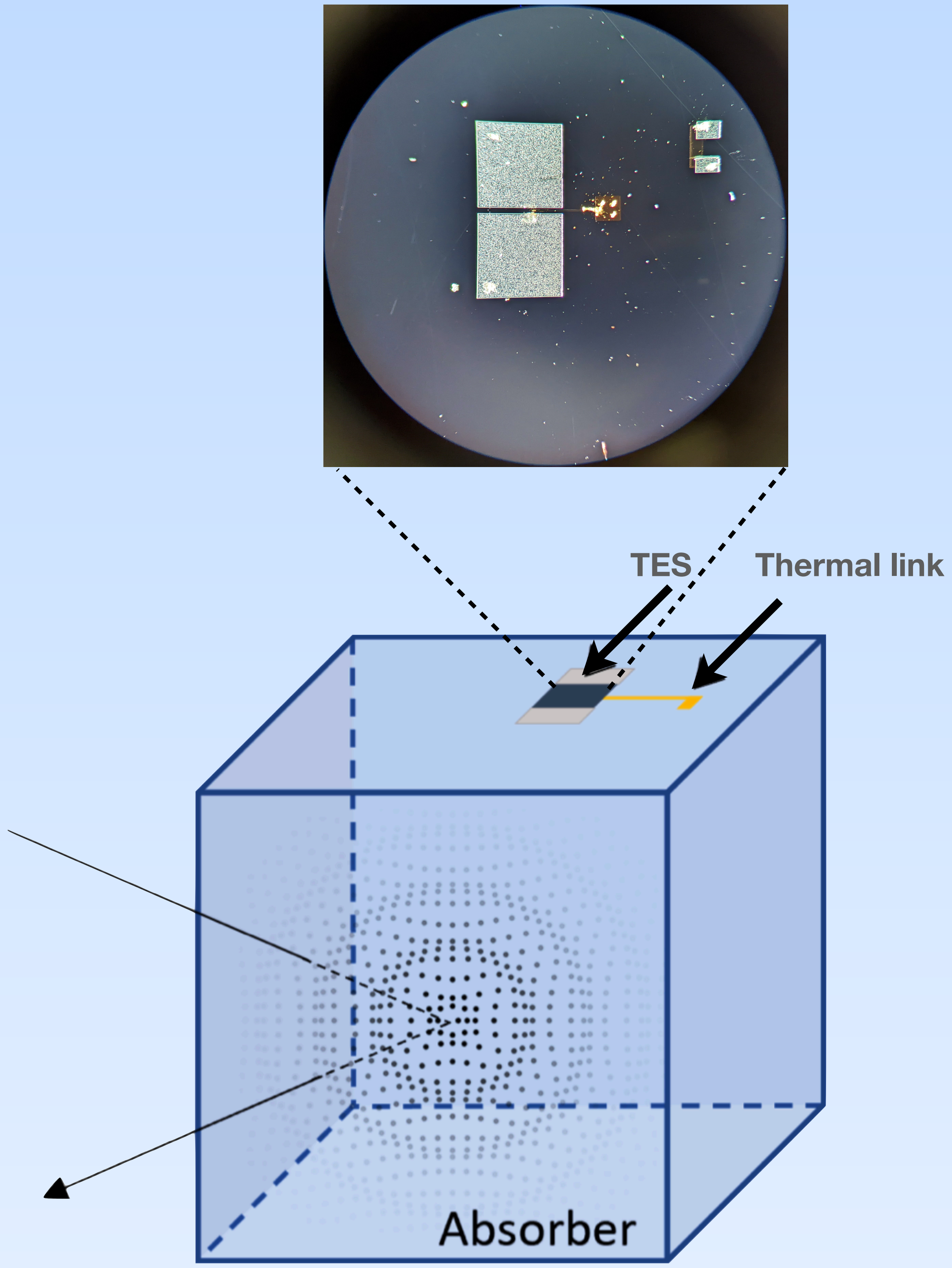






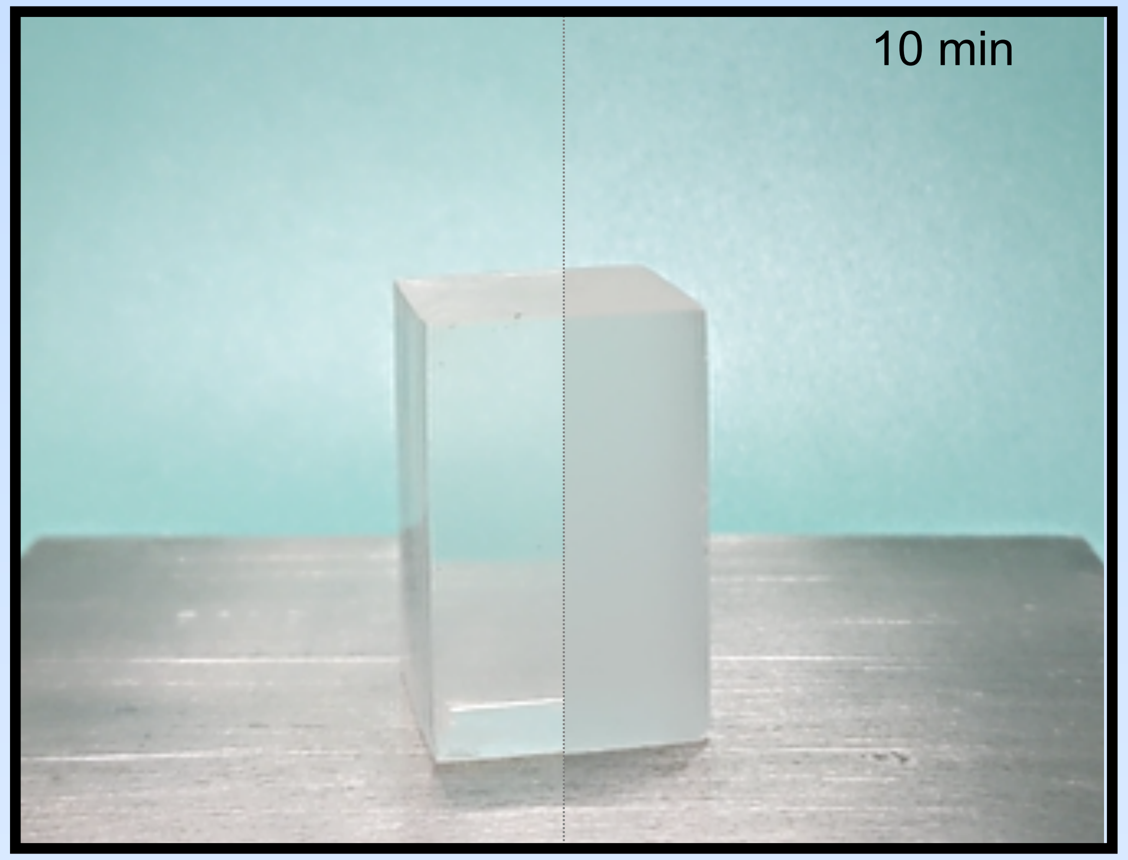
Detector design

Why *remo*TES?



Problem: Traditional TES deposition not possible on NaI

- Hygroscopic
- Soft
- Low melting point



Detector design

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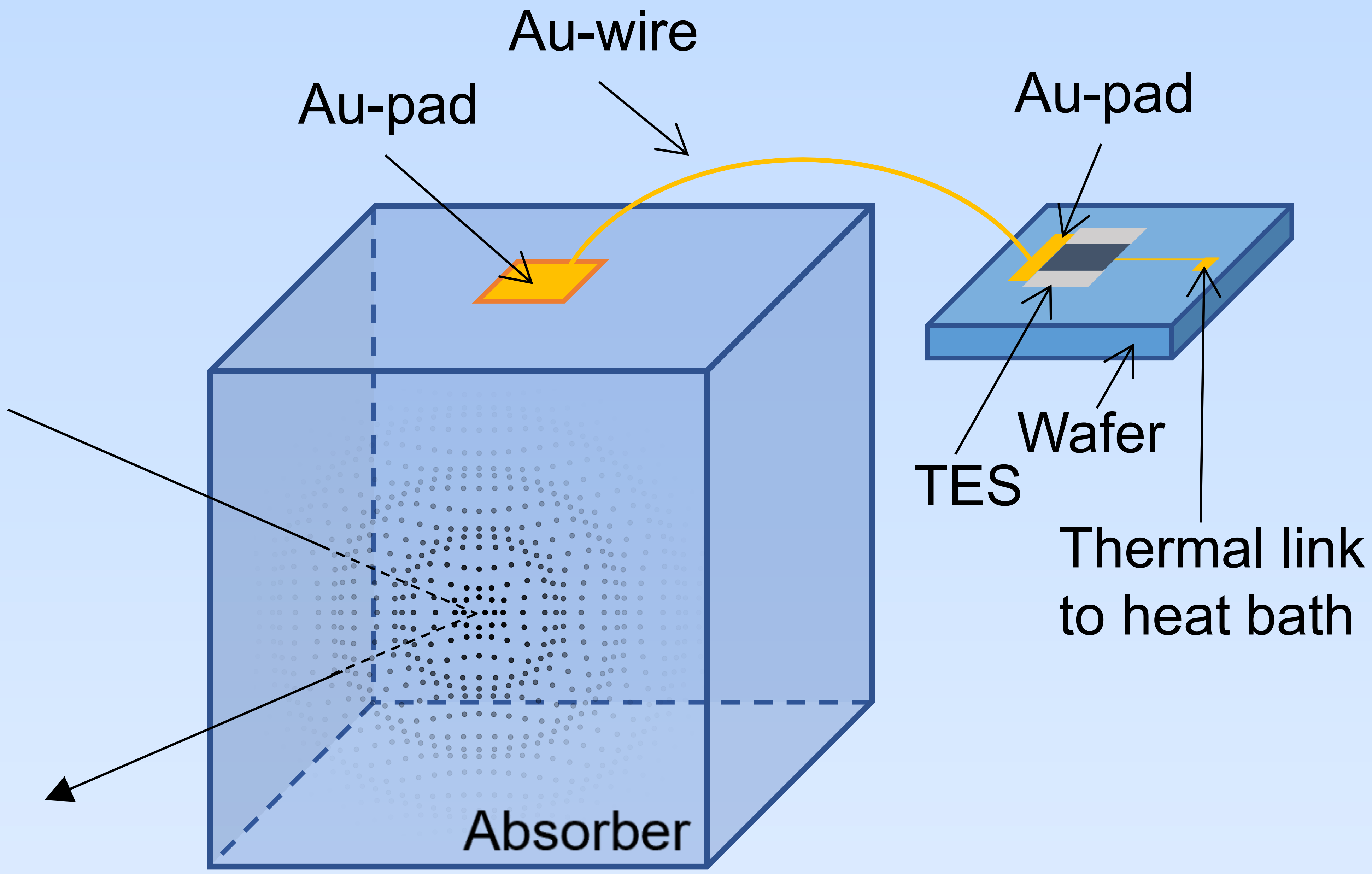

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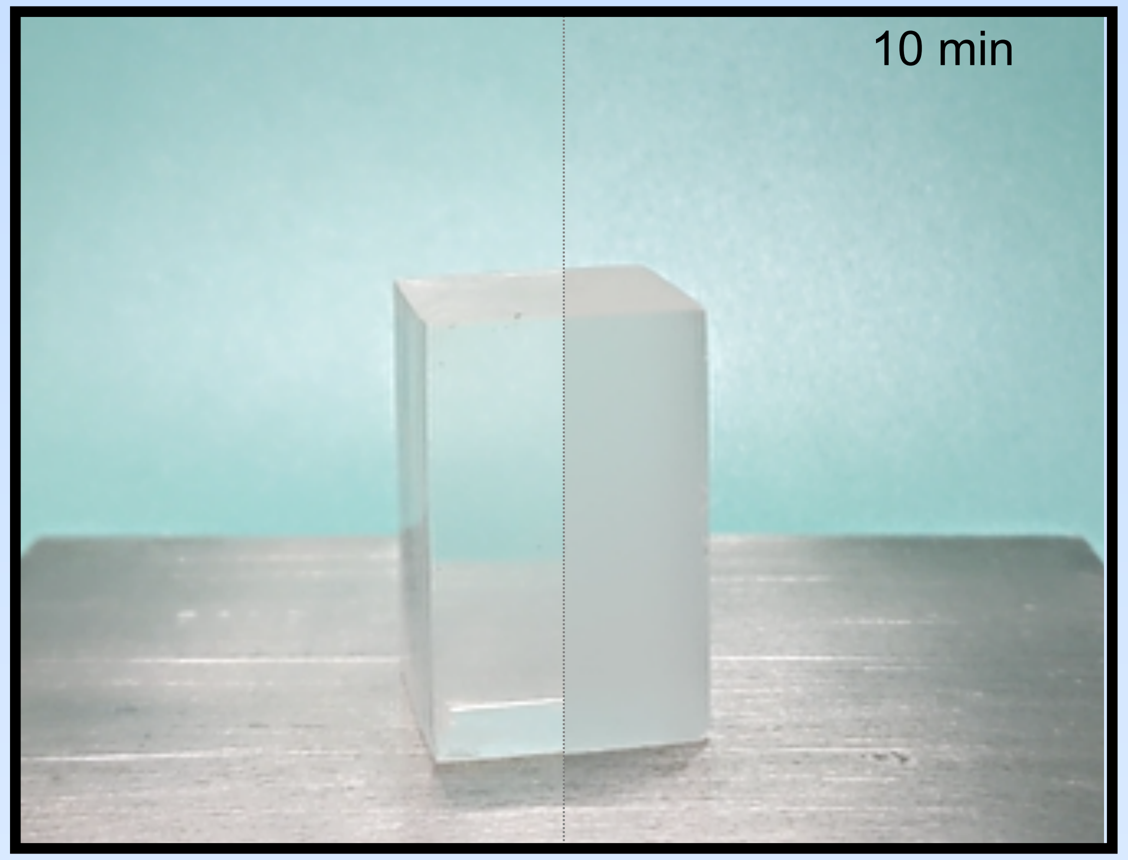
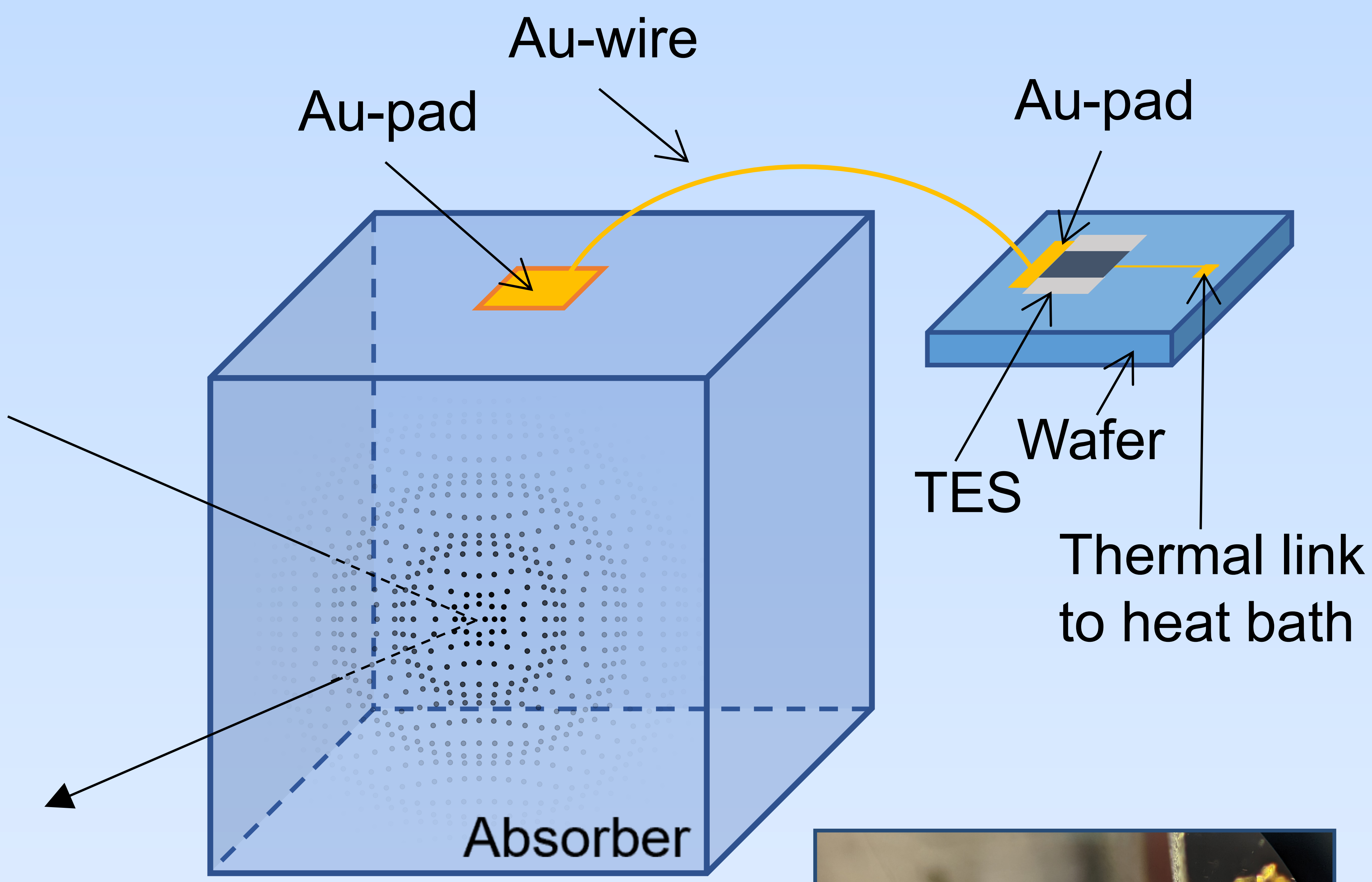


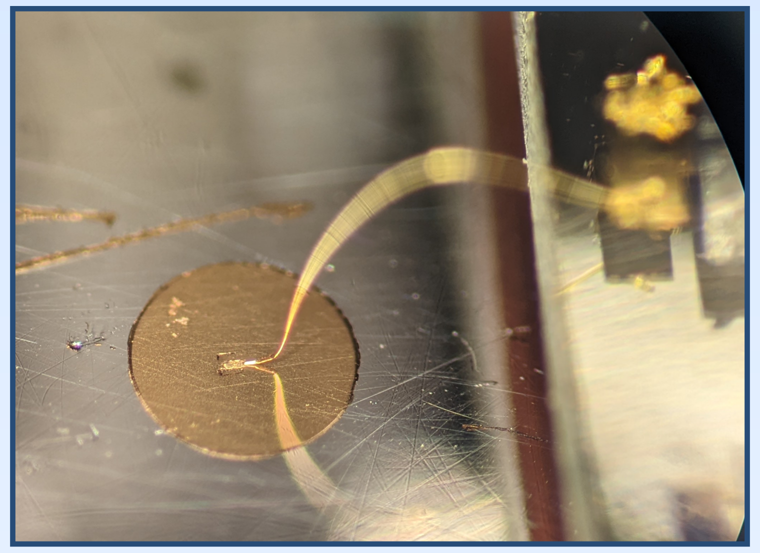
Solution: The remoTES design

First proposed in Matt Pyle *et al*, arxiv:1503.01200

Detector design

Why *remo*TES?



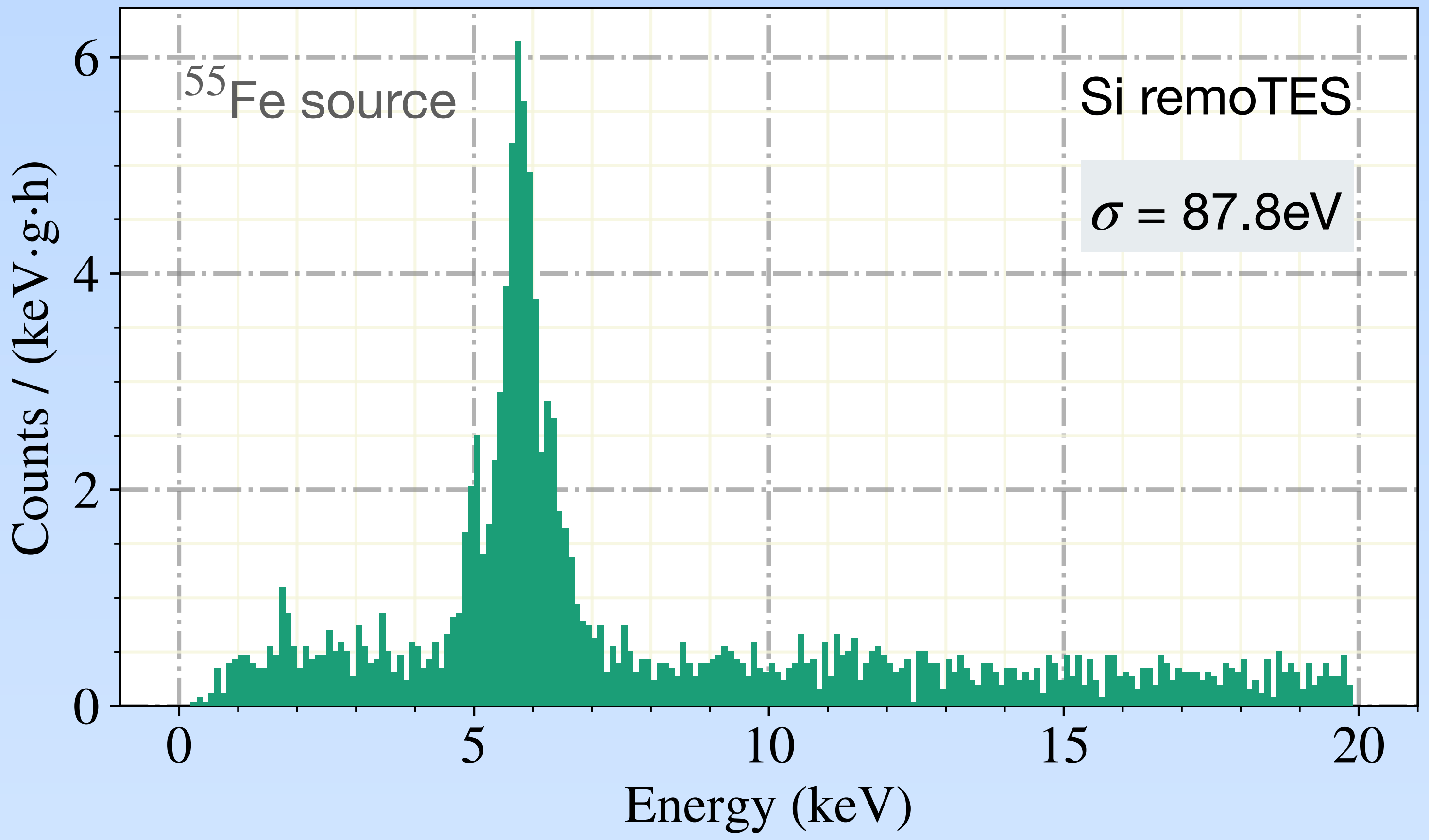


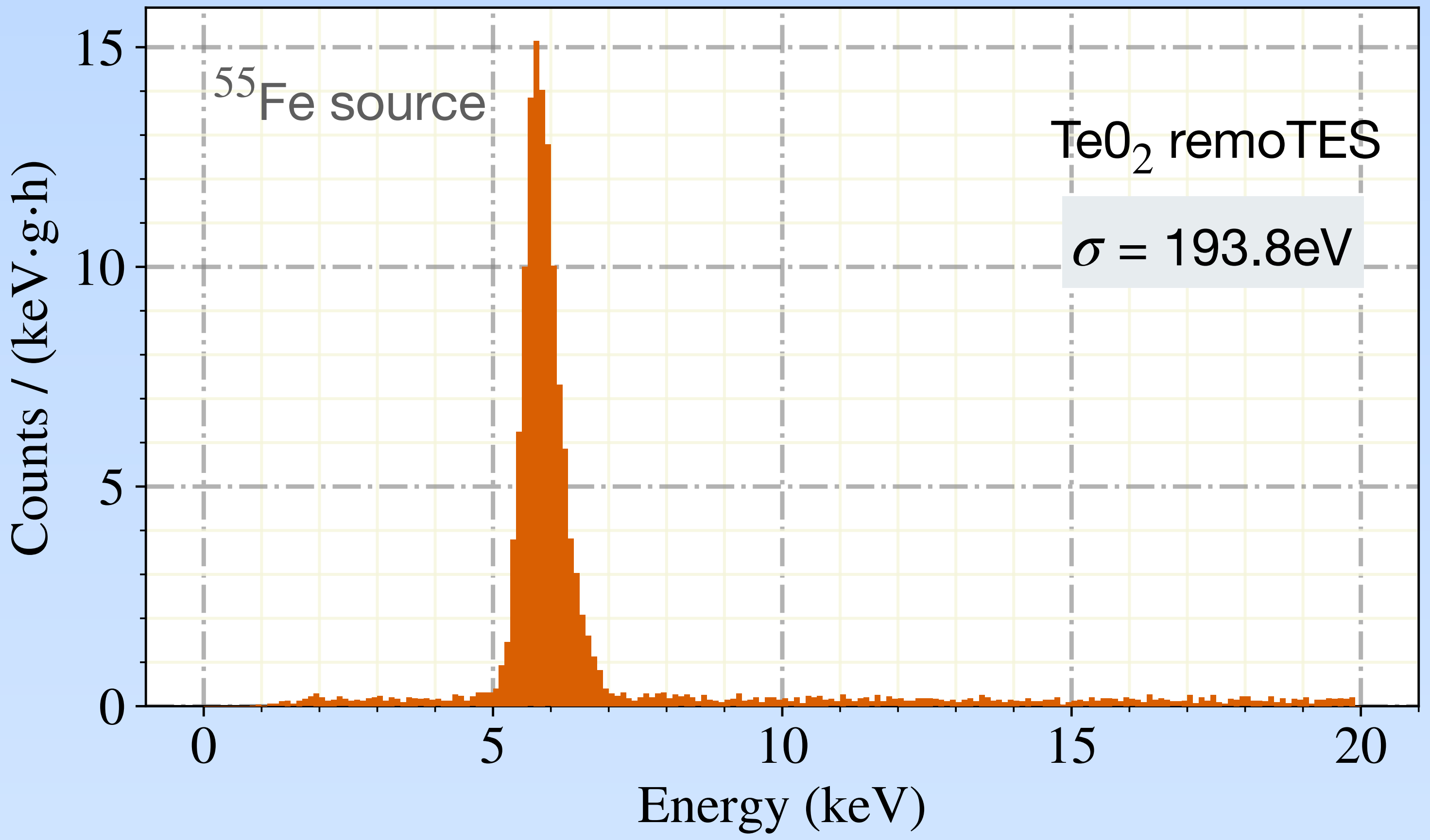
ADVANTAGES:

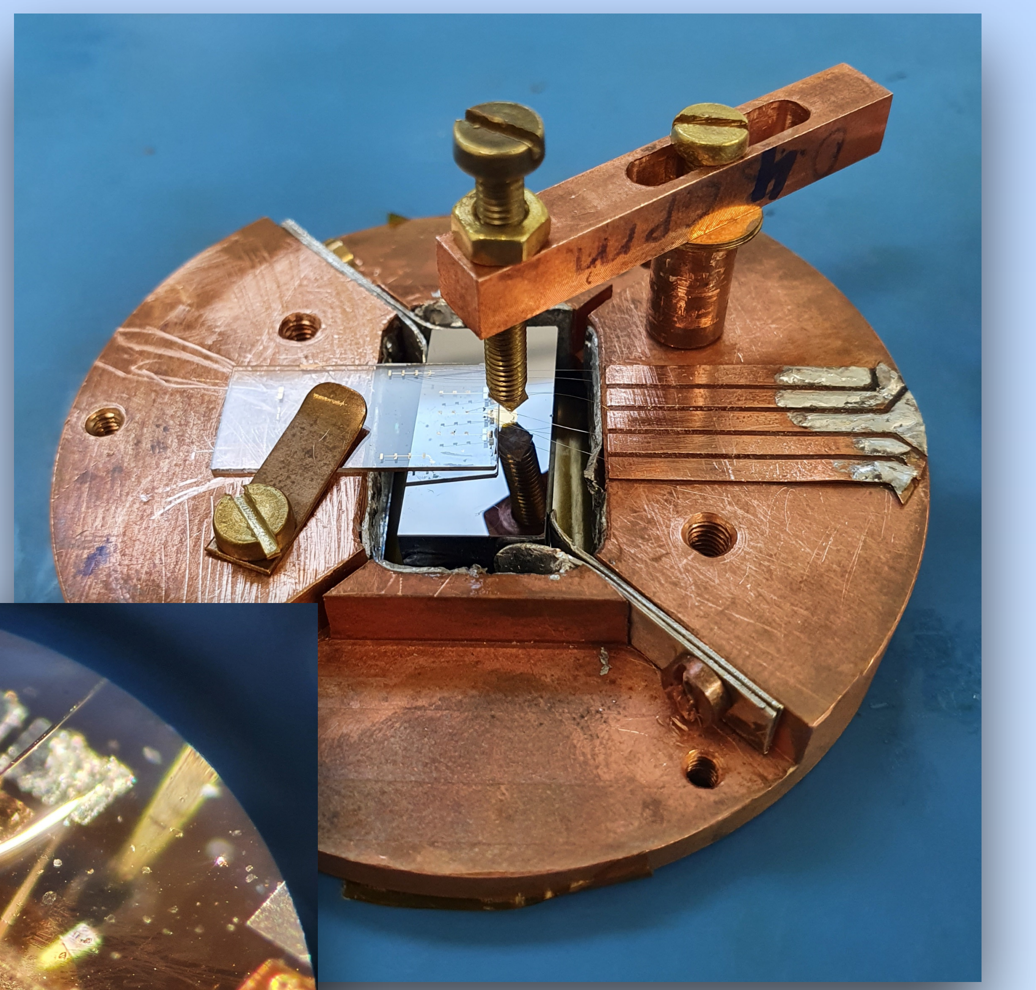
- Absorber is not subjected to manufacturing processing associated with TES fabrication.
- Opens possibility to test other non-standard absorbers as cryogenic calorimeters.
- Easier to fabricate large array of detectors with better reproducibility.

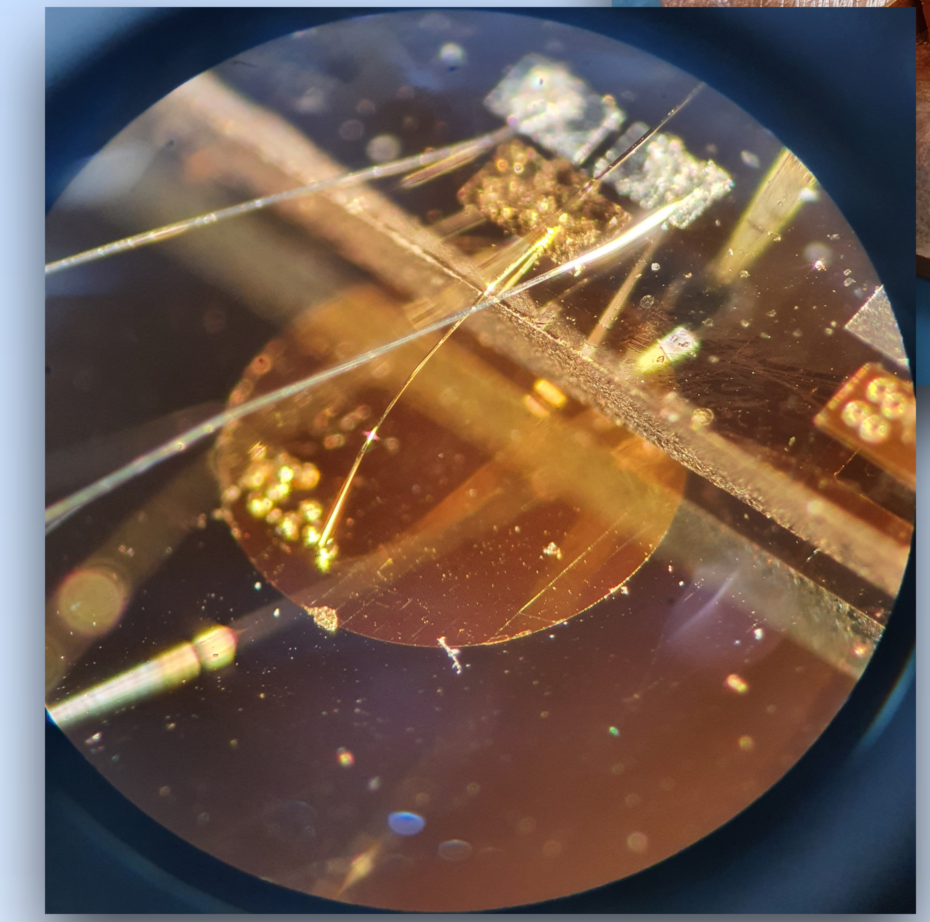
First prototypes

Proof-of-concept









G. Angloher et al. (COSINUS collaboration), Nucl. Instrum. Methods:A, 1045, 167532 (2023).

First prototypes

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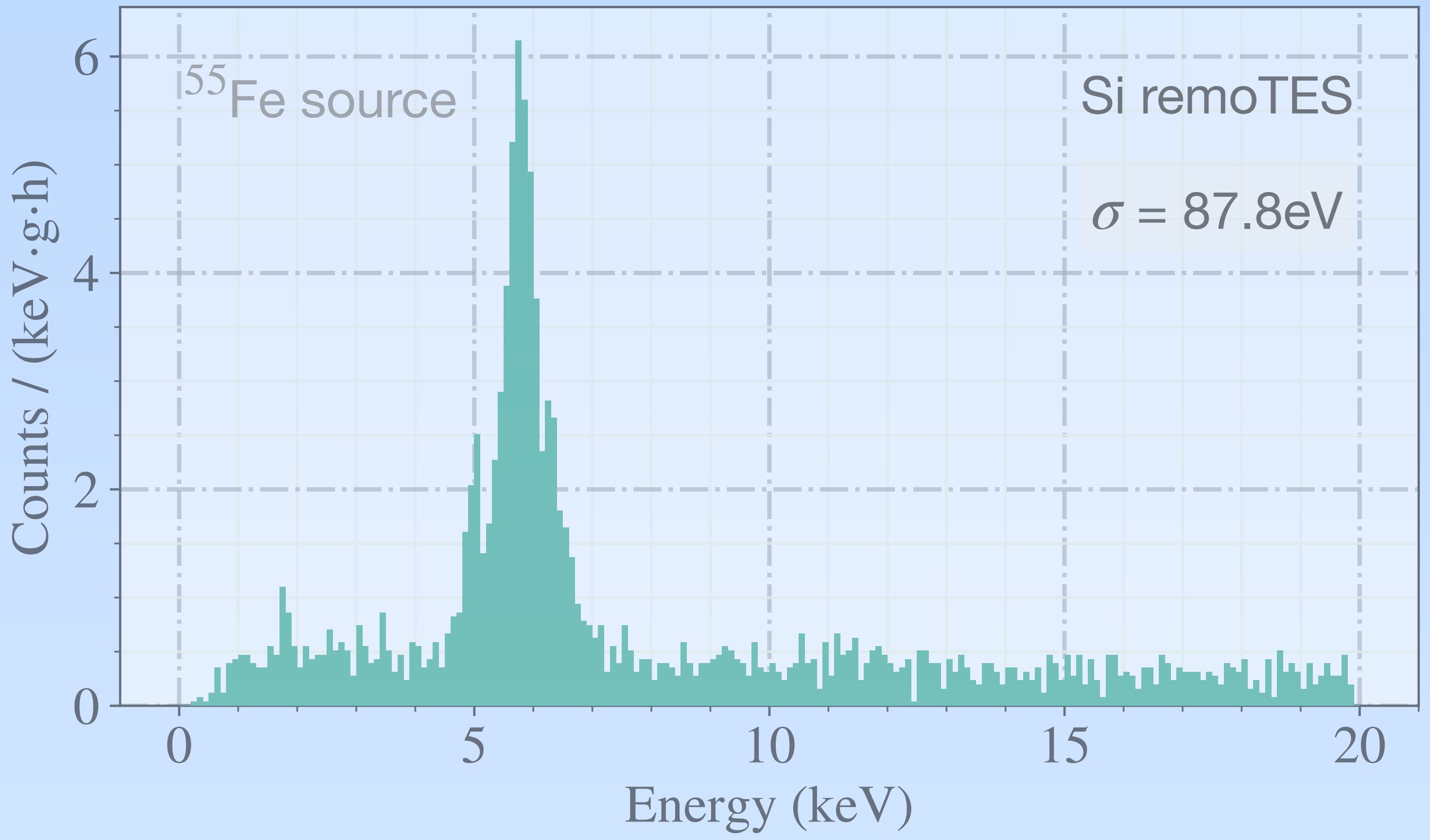

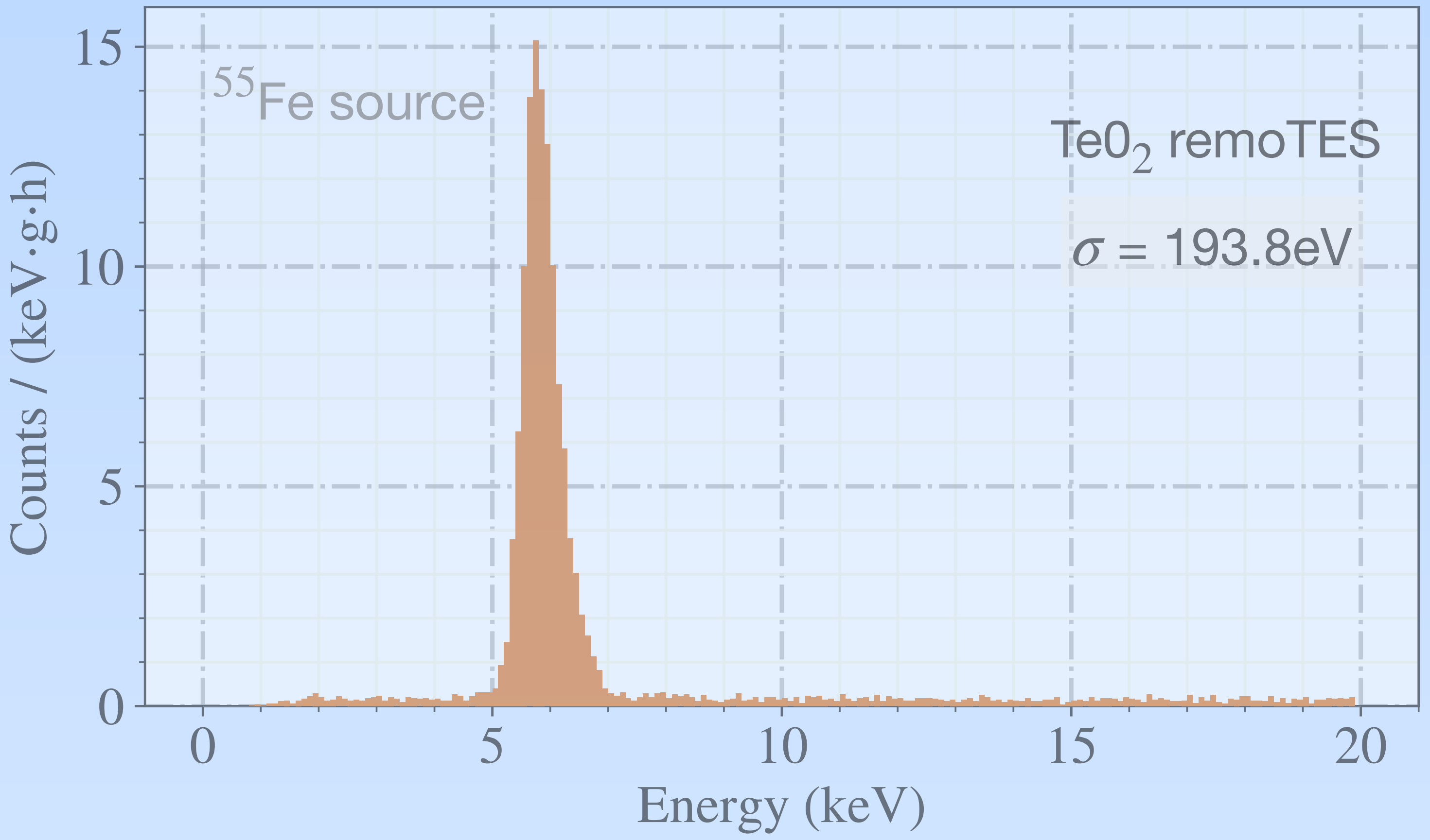

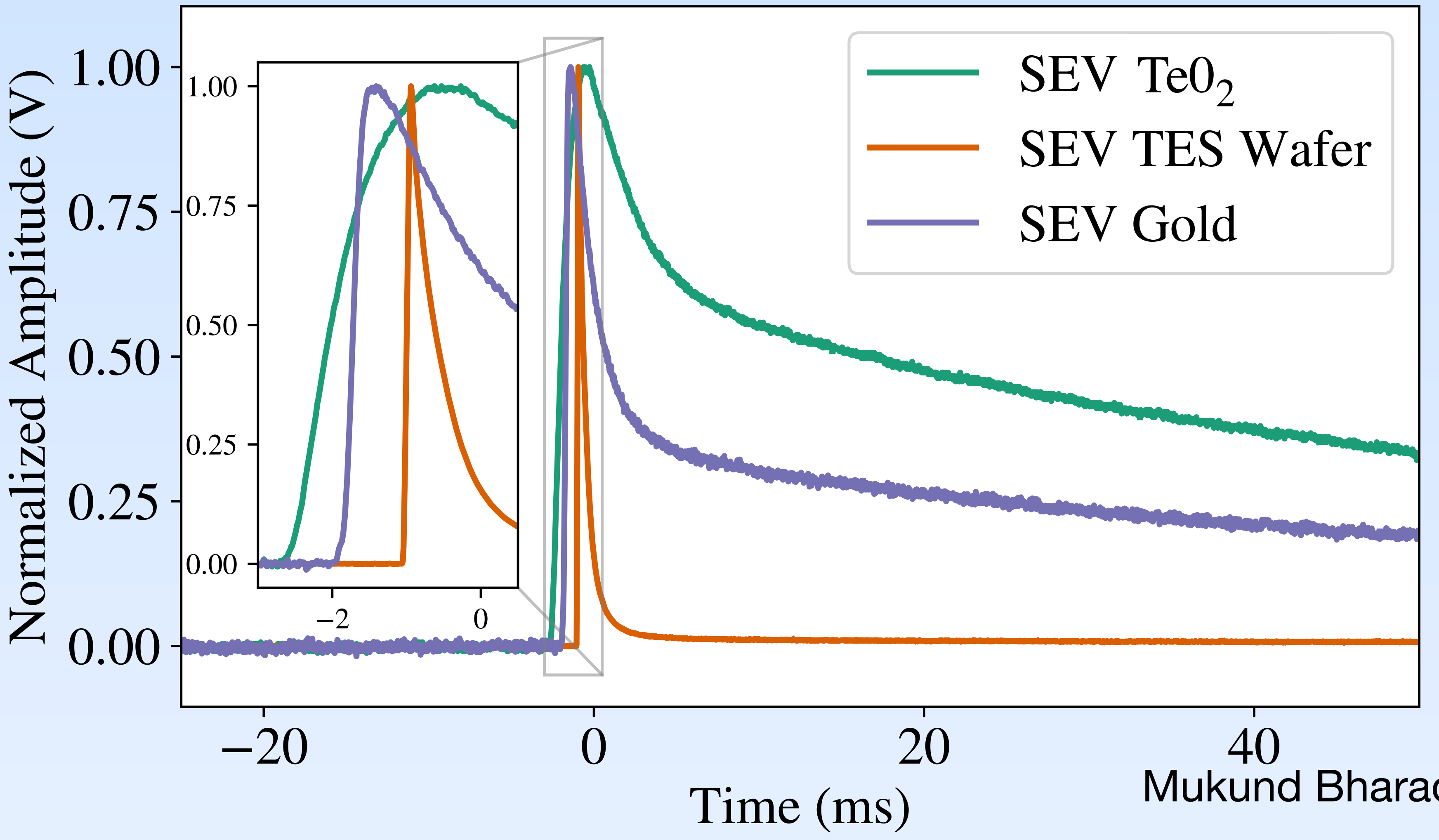

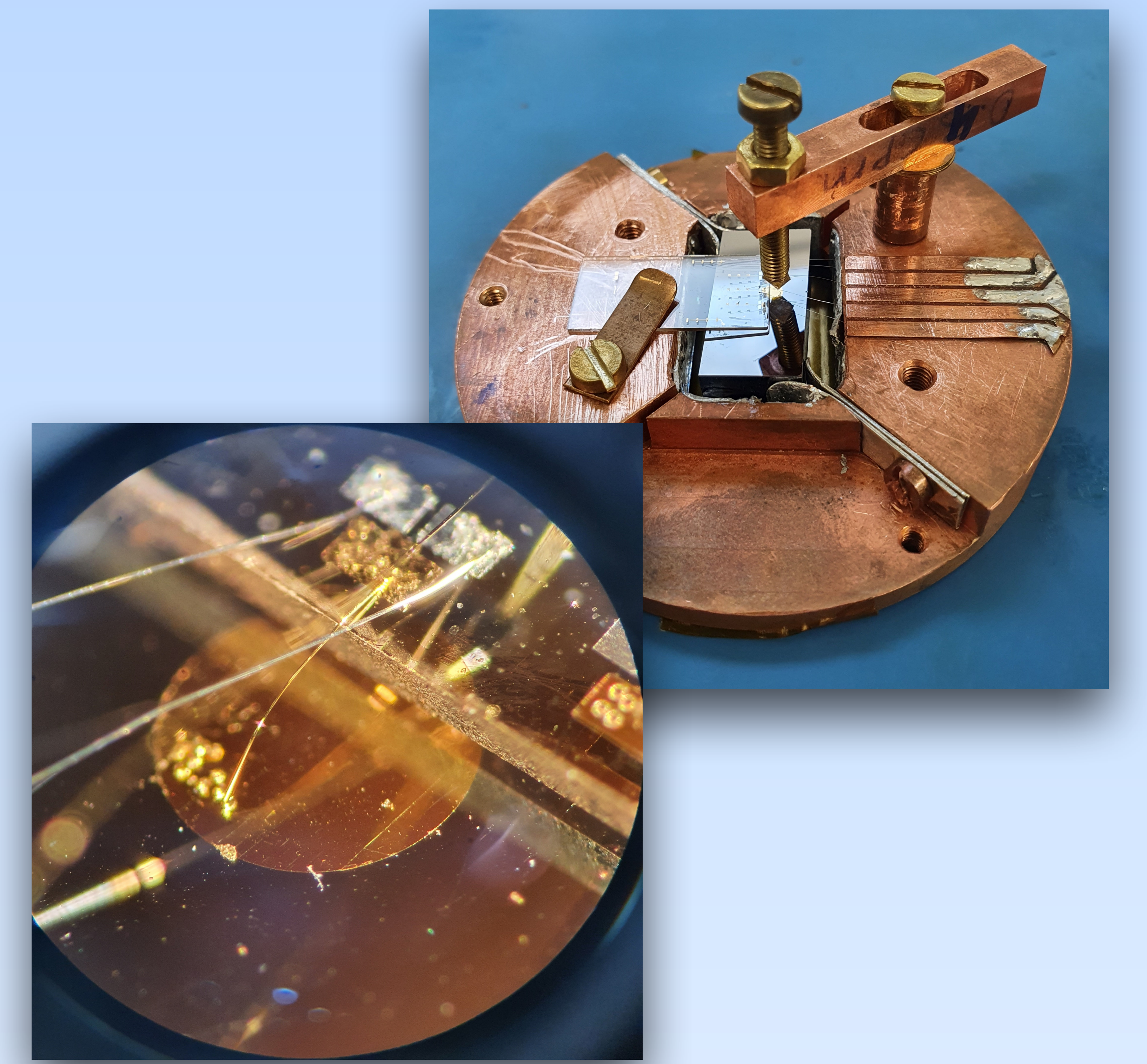

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Latest results

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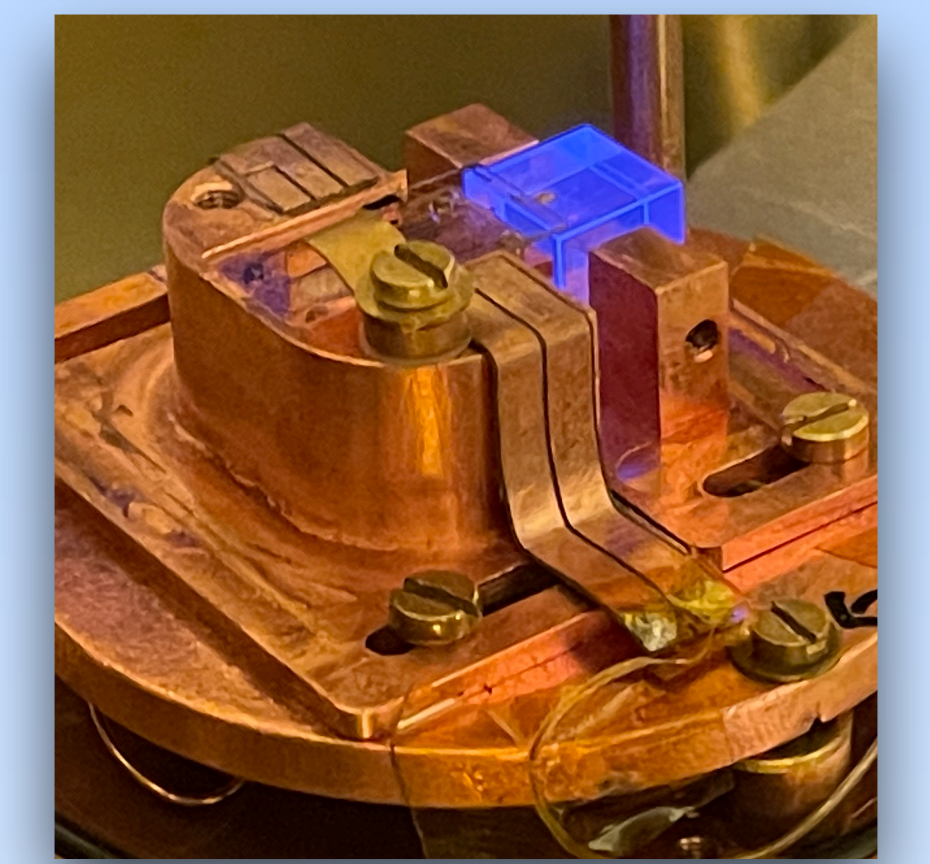
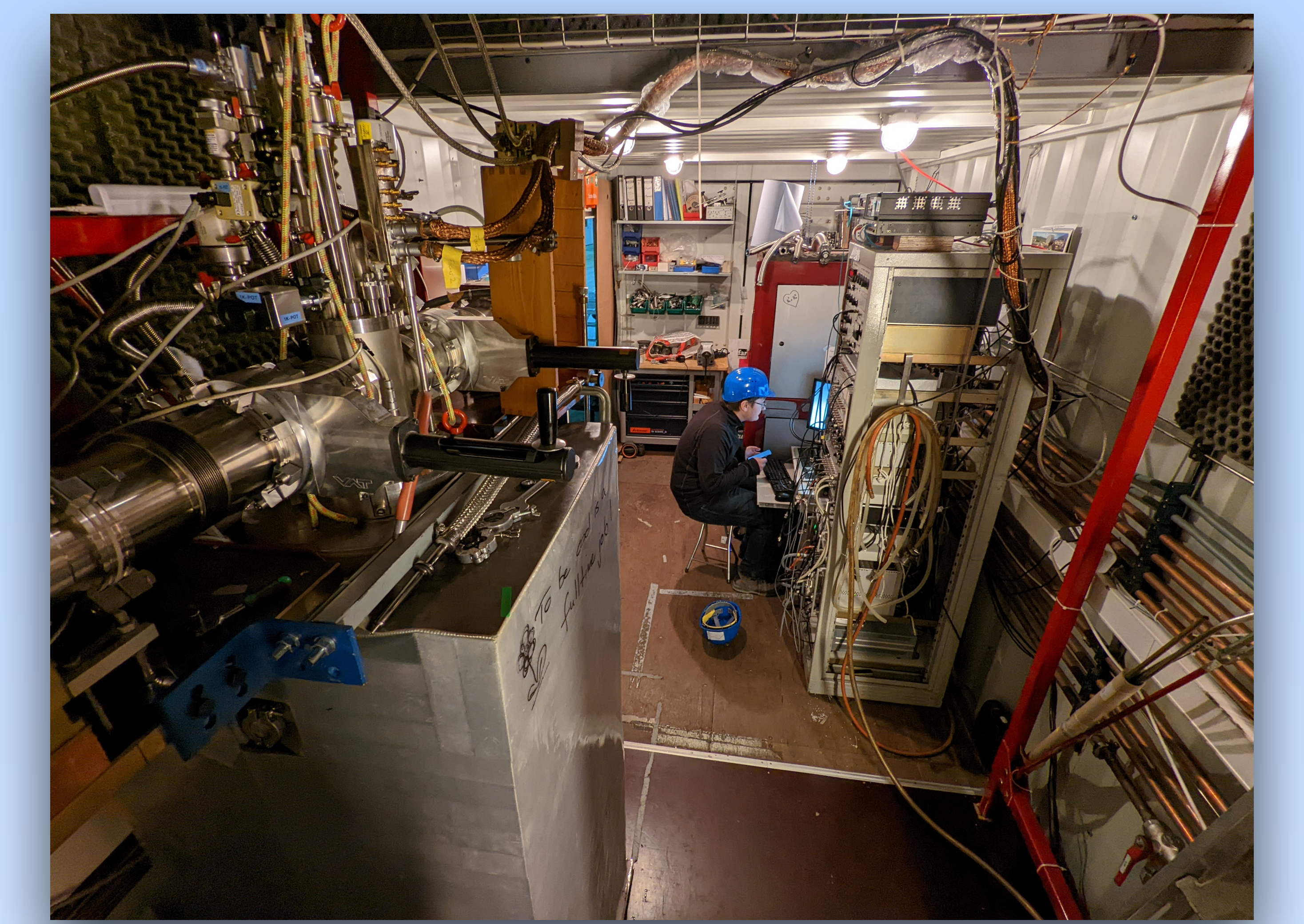
CHANNEL - 1: PHONON DETECTOR

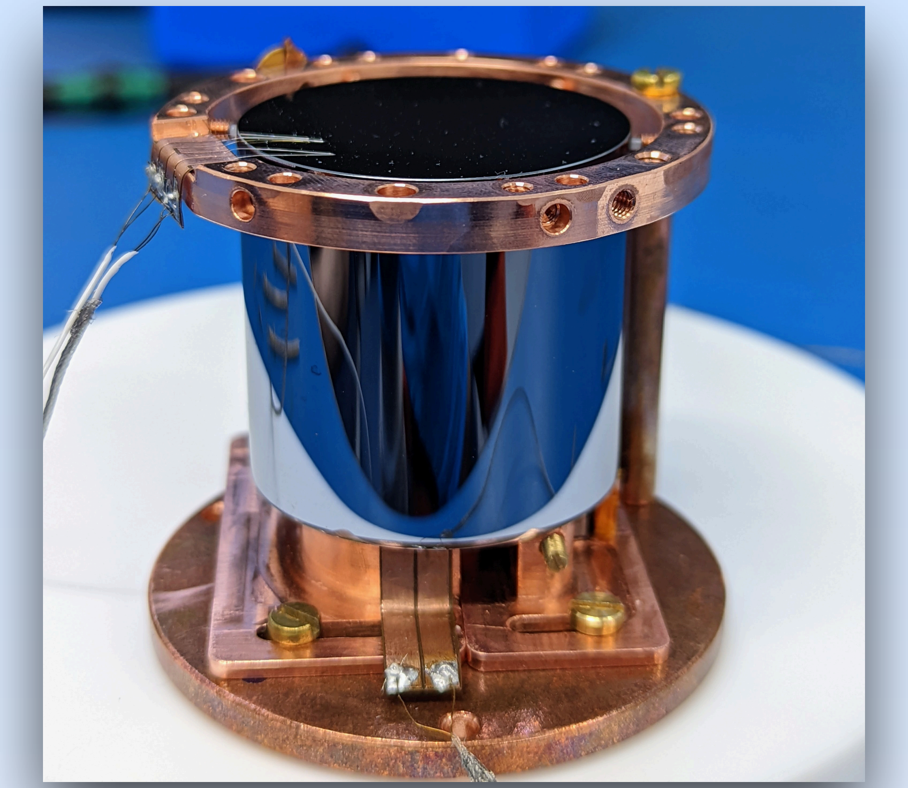




NaI-remoTES

- NaI grown by SICCAS Since 1928
- 6-22 ppb of ^{40}K
- 3.67 g, 1 cm^3
- 730 ± 73 ppm thallium
- <1ppb of ^{208}Th and ^{238}U (ICP-MS)

CHANNEL - 2: LIGHT DETECTOR



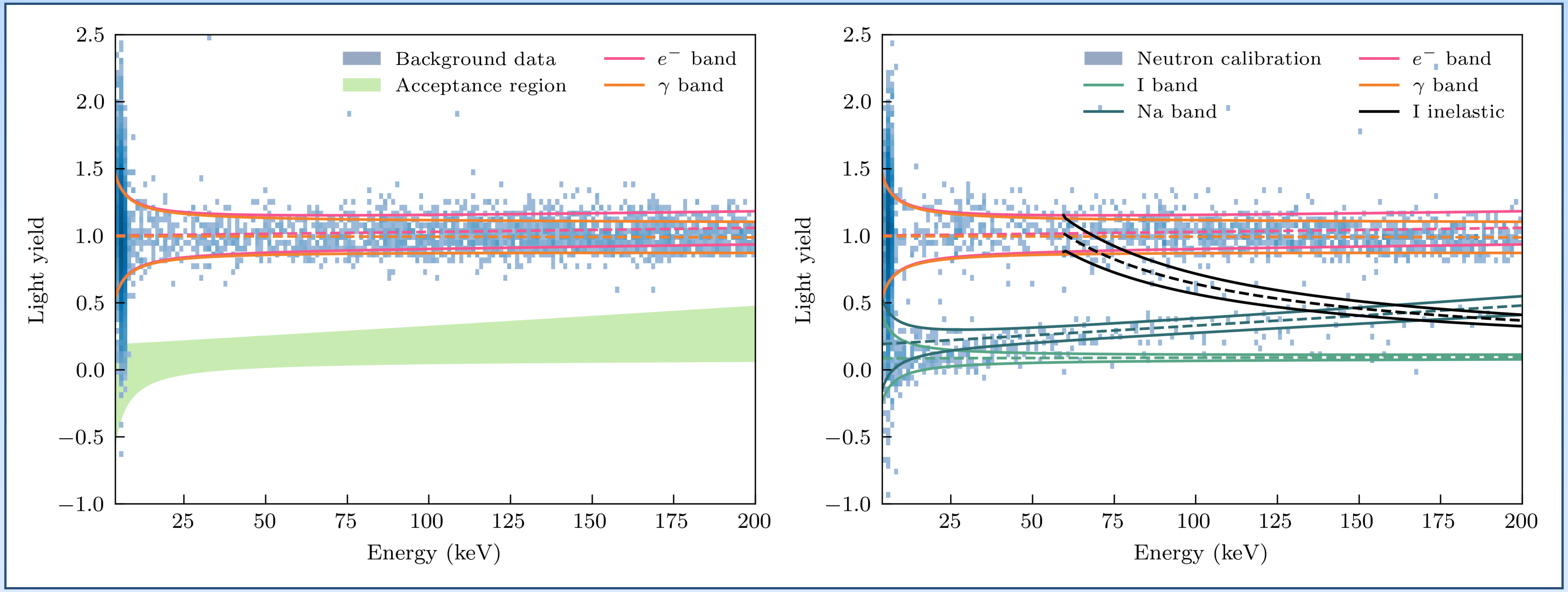
Silicon beaker

- 4 cm diameter and height
- 1 mm thickness
- 15.38 g
- Read out using W-TES evaporated on the surface

Latest results

COSINUS

Event-by-event particle discrimination demonstrated in NaI



https://arxiv.org/pdf/2307.11139.pdf

$$\mathrm{QF_{Na}}(10\,\mathrm{keV}) = 0.2002 \pm 0.0093$$

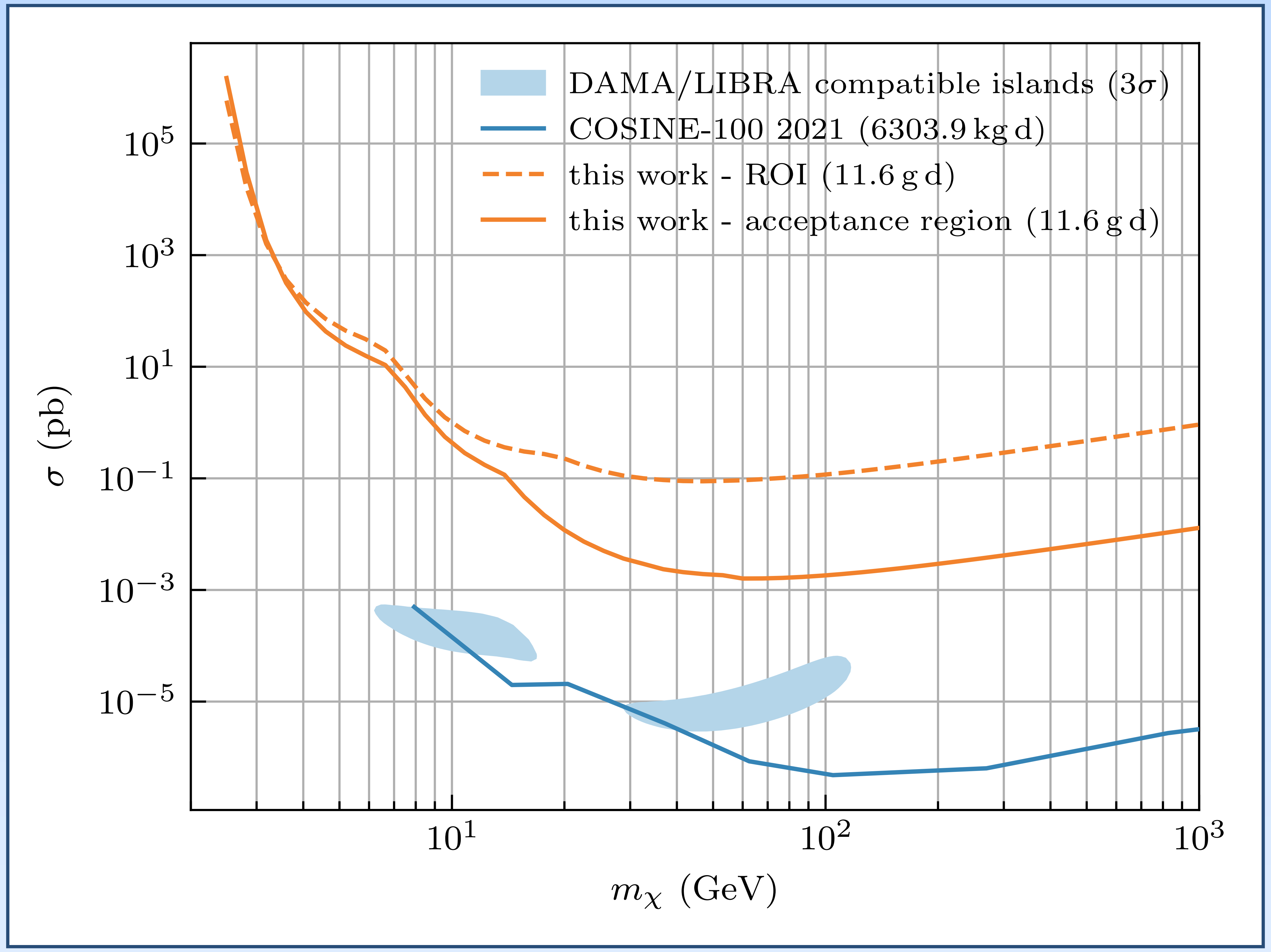
$$\mathrm{QF_{I}}(10\,\mathrm{keV}) = 0.0825 \pm 0.0034$$

Latest results

COSINUS

PERFORMANCE COMPARISON

σ_{NaI} = (0.441 ± 0.011 keV)



With 11.6 gd exposure

With 6303.9 kgd exposure

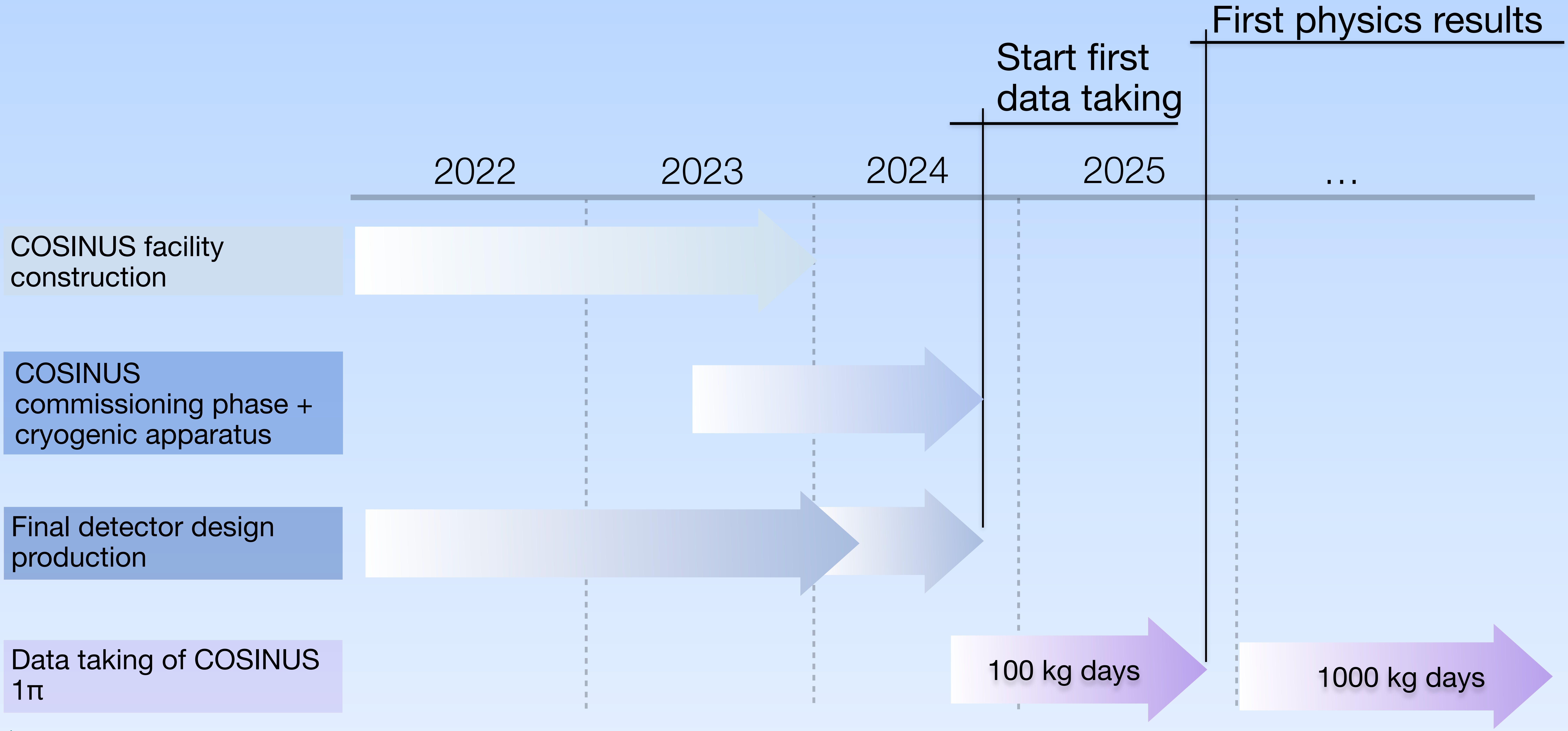
https://arxiv.org/pdf/2307.11139.pdf

Conclusion

COSINUS

- COSINUS operates NaI detectors at mK temperatures.
- First proof-of-concept tests with standard absorbers successfully carried out.
- A 2-channel readout system allows for particle discrimination on an event-by-event basis and better sensitivity.
- NaI calorimeters operated using the remoTES readout design achieved a baseline resolution of ~400eV for nuclear recoils.
- Updated NaI detector design with a 4π-veto currently under testing.

Outlook


First physics results
Start first data taking
2022
2023
2024
2025
...
COSINUS facility construction
COSINUS commissioning phase + cryogenic apparatus
Final detector design production
Data taking of COSINUS 1π
100 kg days
1000 kg days

Outlook

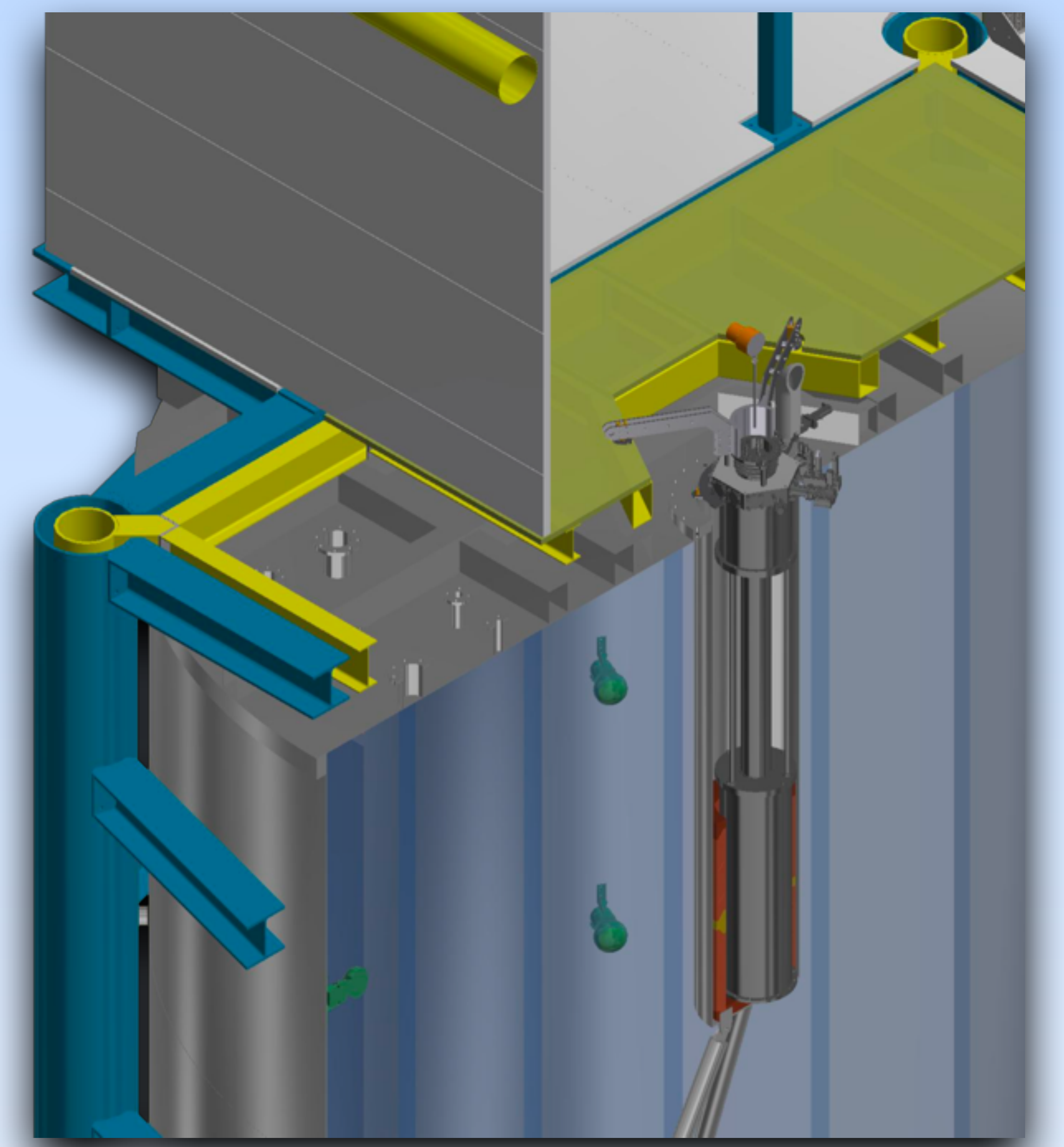
COSINUS

MAX-PLANCK-INSTITUT FÜR PHYSIK
TU WIEN
GSSI GRAN SASSO SCIENCE INSTITUTE SCHOOL OF ADVANCED STUDIES Scuola Universitaria Superiore
HEPHY INSTITUTE OF HIGH ENERGY PHYSICS
INFN Istituto Nazionale di Fisica Nucleare
HELSINKI INSTITUTE OF PHYSICS
SICCAS Since 1928

Appendix

Decoupling

Three stages of decoupling



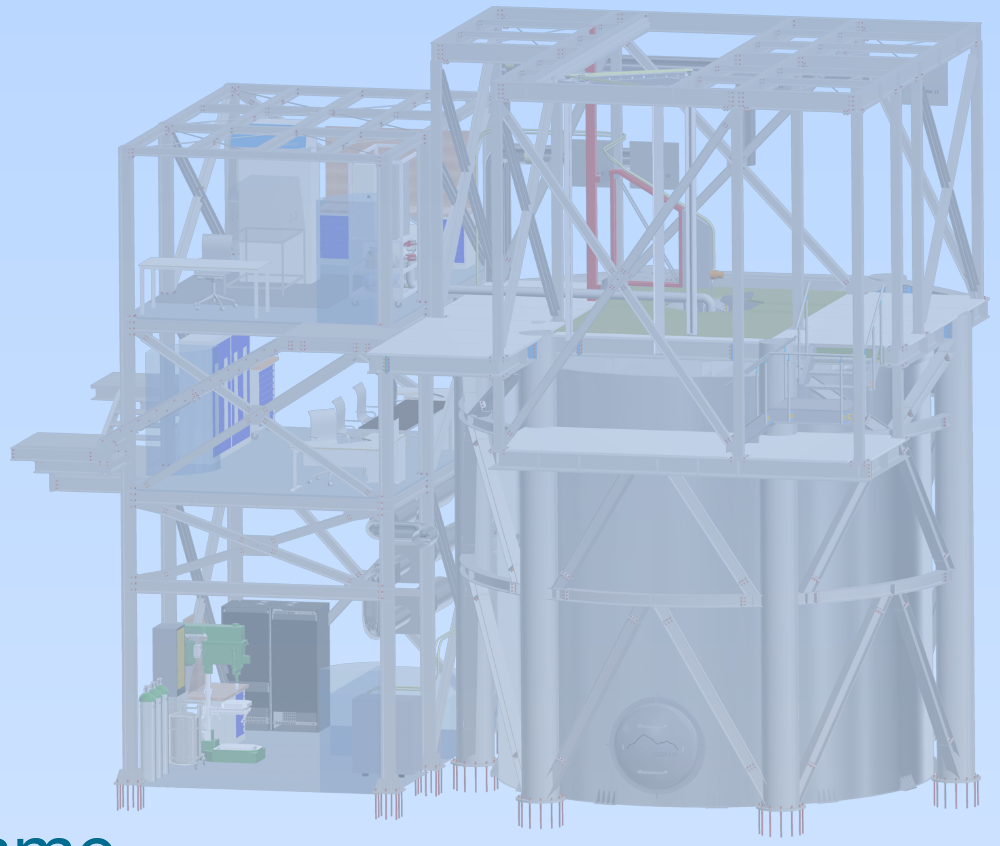
1. Global stage

<u>Double frame</u>

The infrastructure is built on the blue frame, subjected to most of the vibrations
The pulse tube on the yellow frame
The cryostat rests on the dry well, which is the most quiet part

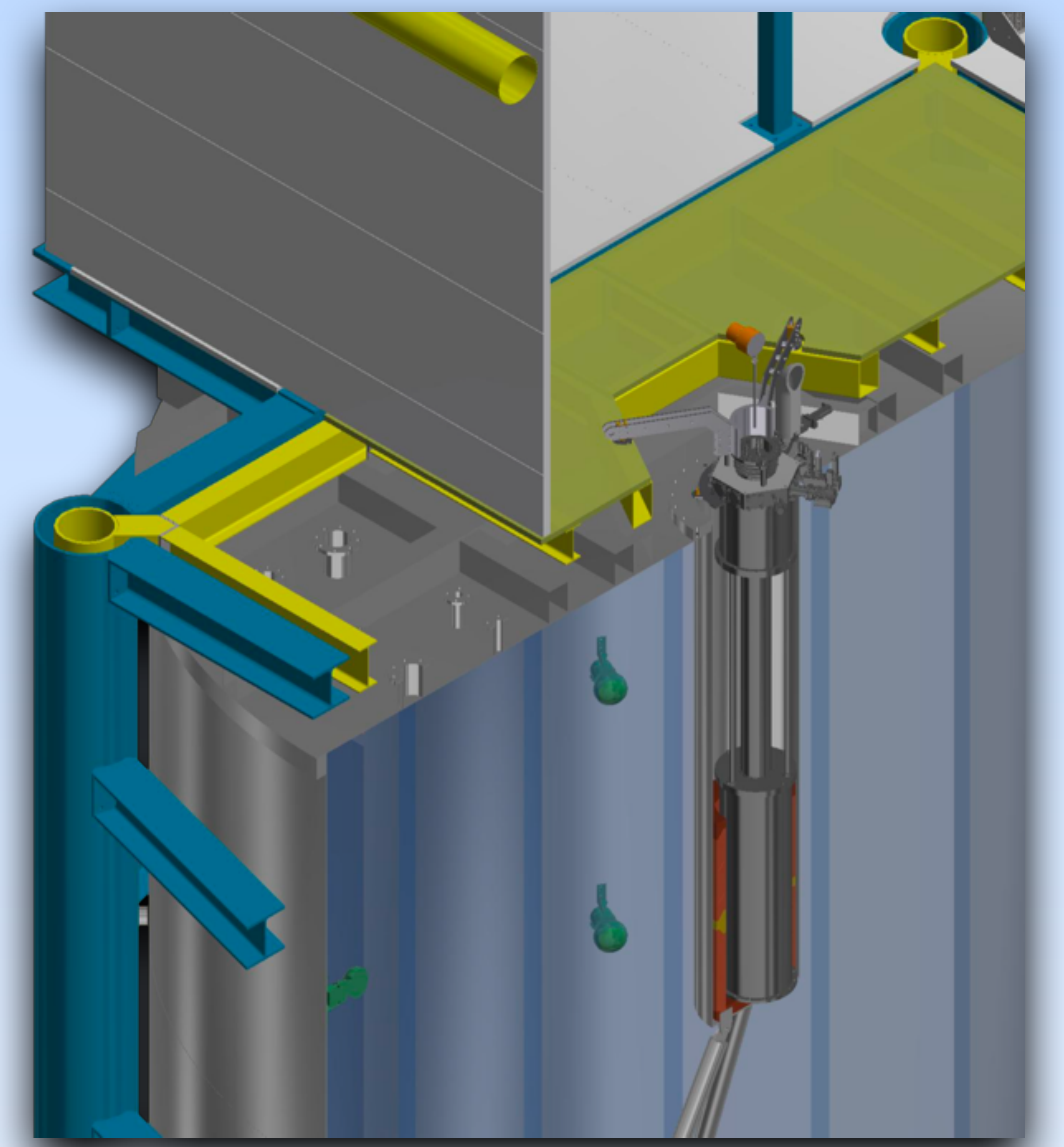
<u>Bellow</u>

The pulse tube is connected to a supple bellow which dumps the mechanical vibrations of the pulse tube

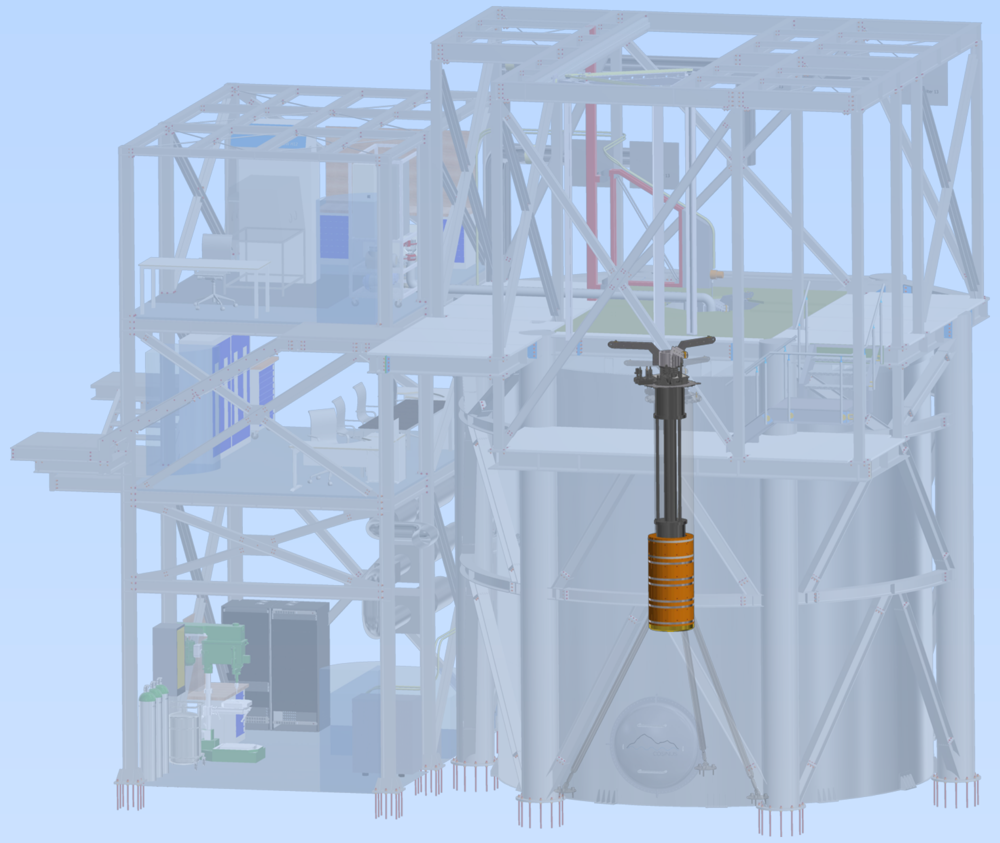


Appendix

Decoupling



2. Cryostat stage



<u>Pumping duct gas exchanger</u>

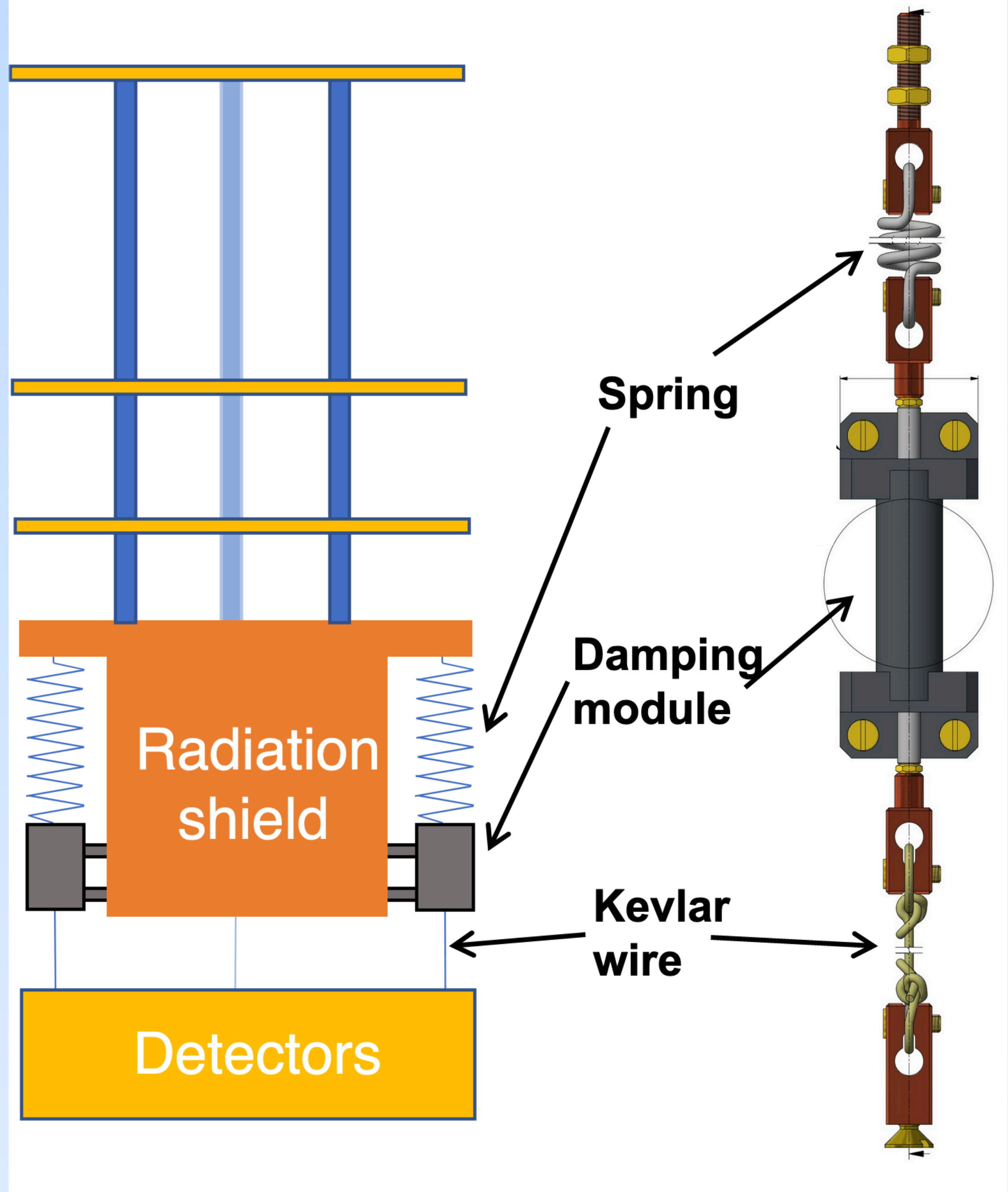
The heat exchange between pulse tube and cryostat occurs via gas, no mechanical contact

The Ultra-Quiet Technology™

https://cryoconcept.com/product/the-ultra-quiet-technology/

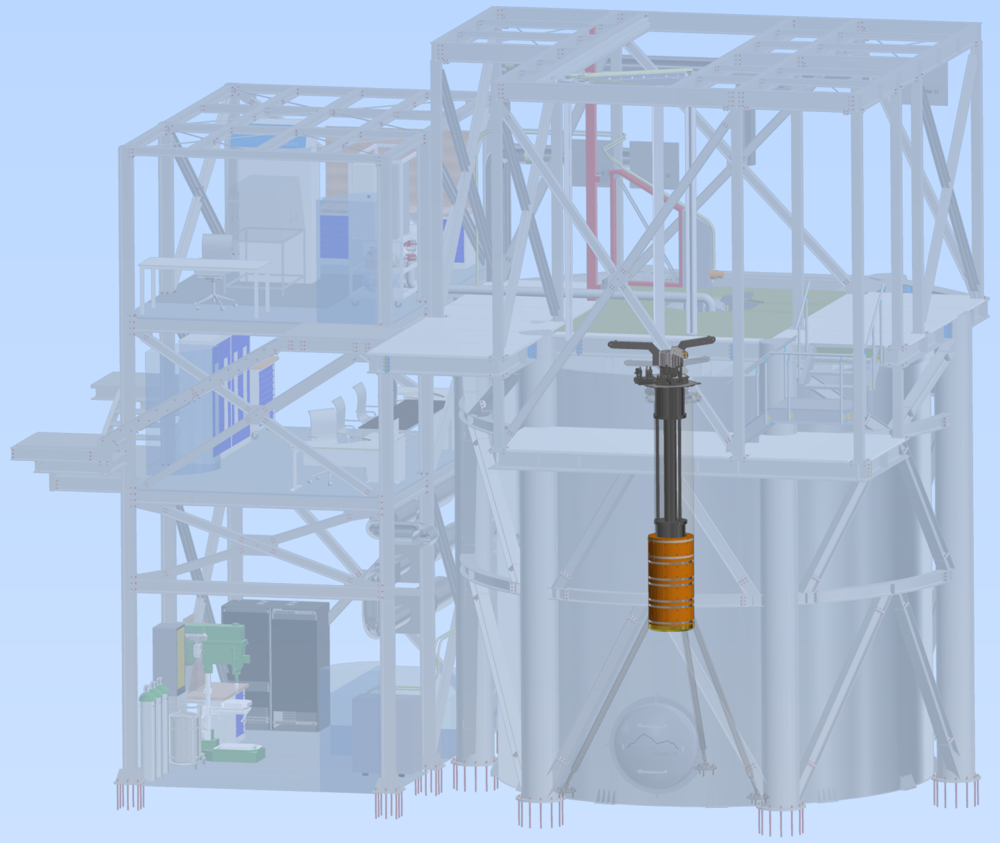
Appendix

Decoupling



3. Detector stage

- Spring and damping modules to decouple the detector plate
- Magnetic eddy current damping
- Studies ongoing

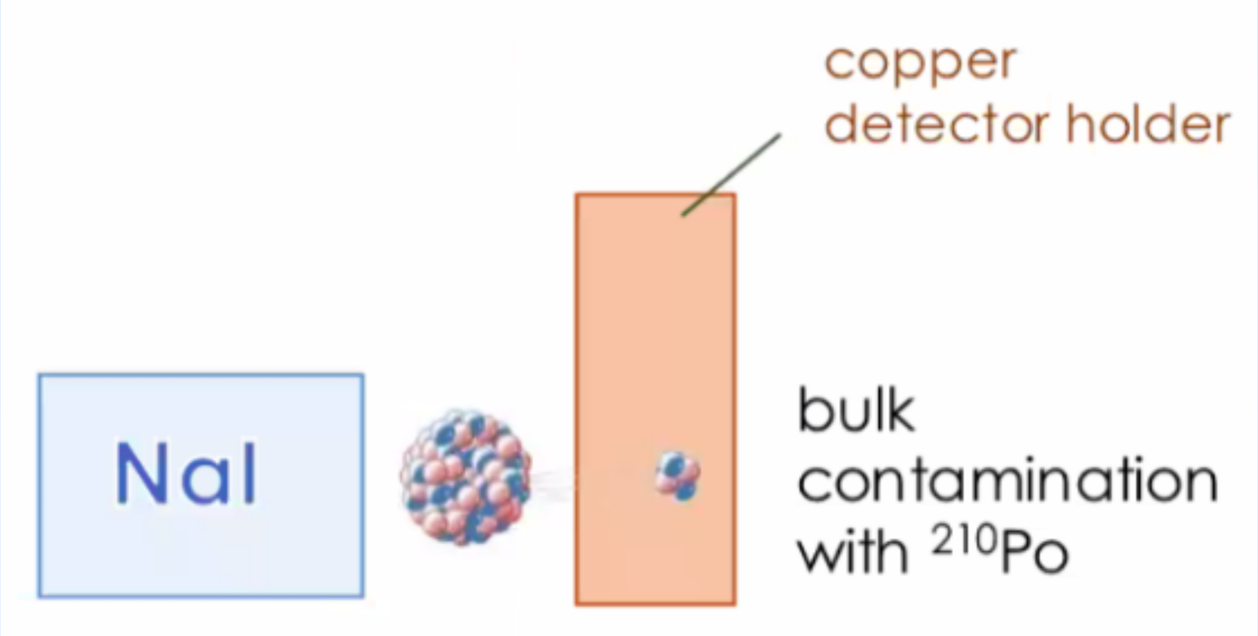


Appendix

COSINUS

The 4π design

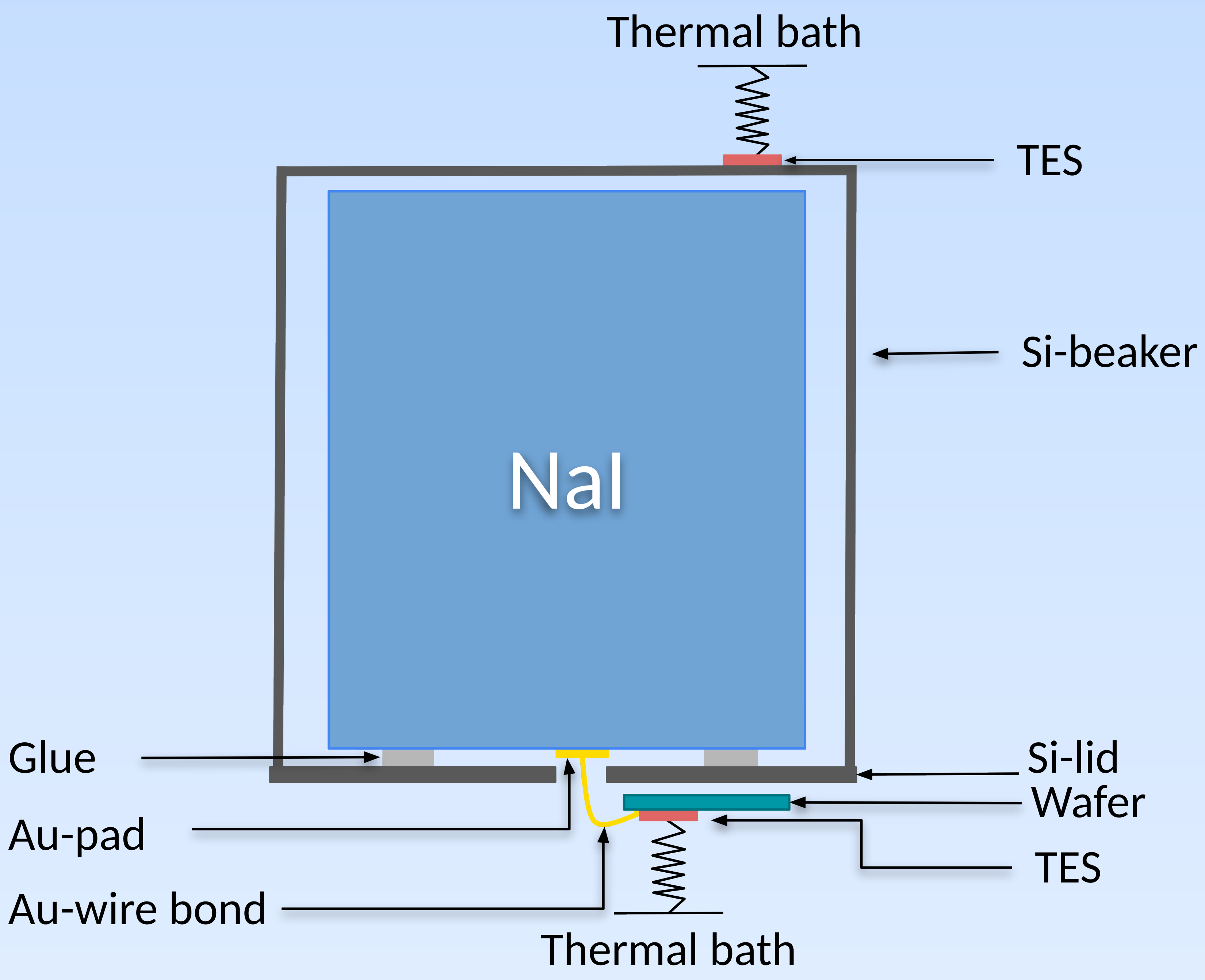
The problem



$$^{210}_{84}Po \rightarrow ^{206}_{82} Pb(103keV) + ^{4}_{2} He(5.3MeV)$$

Inefficient collection of scintillation light emitted by crystal

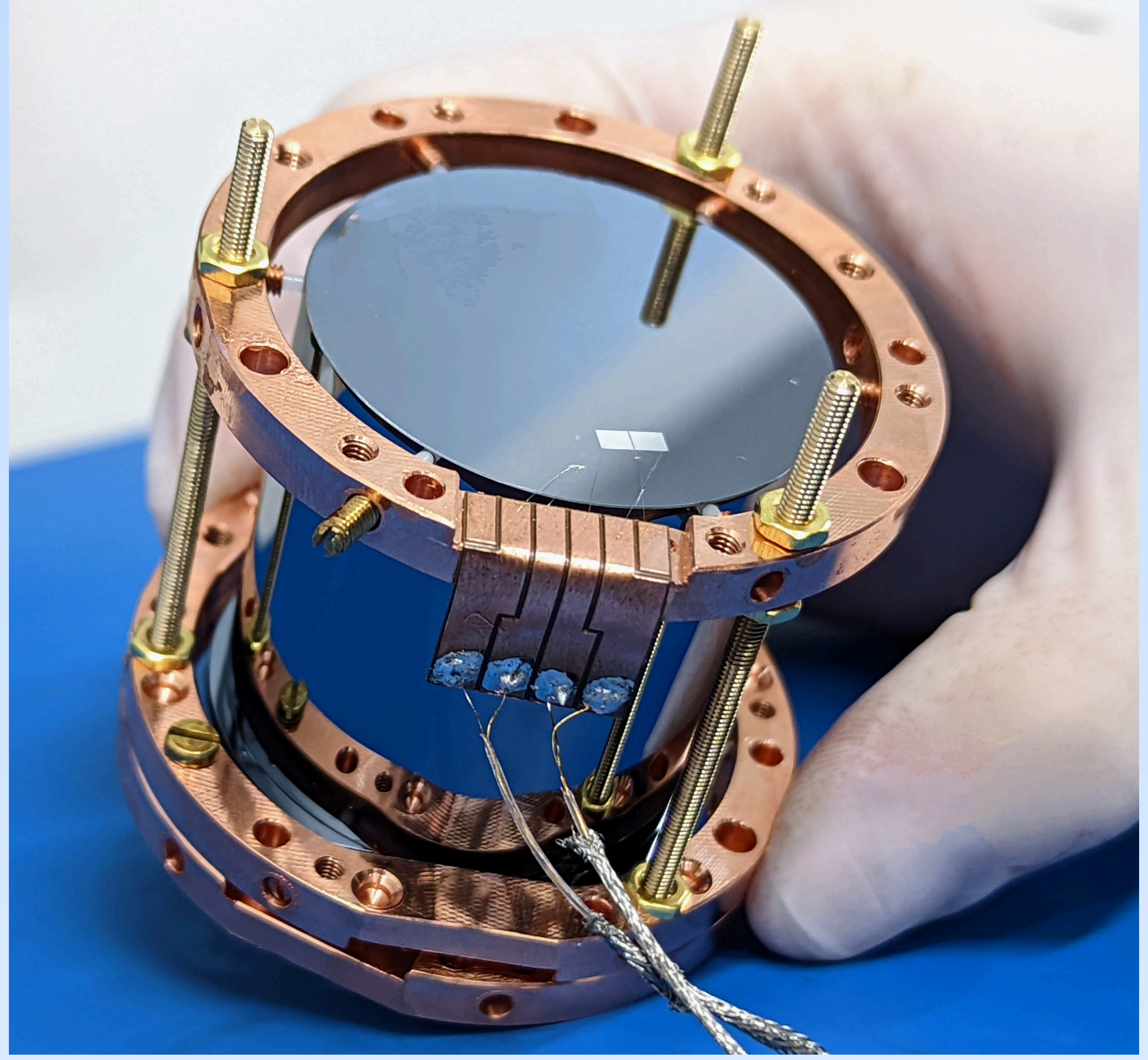
Proposed solution

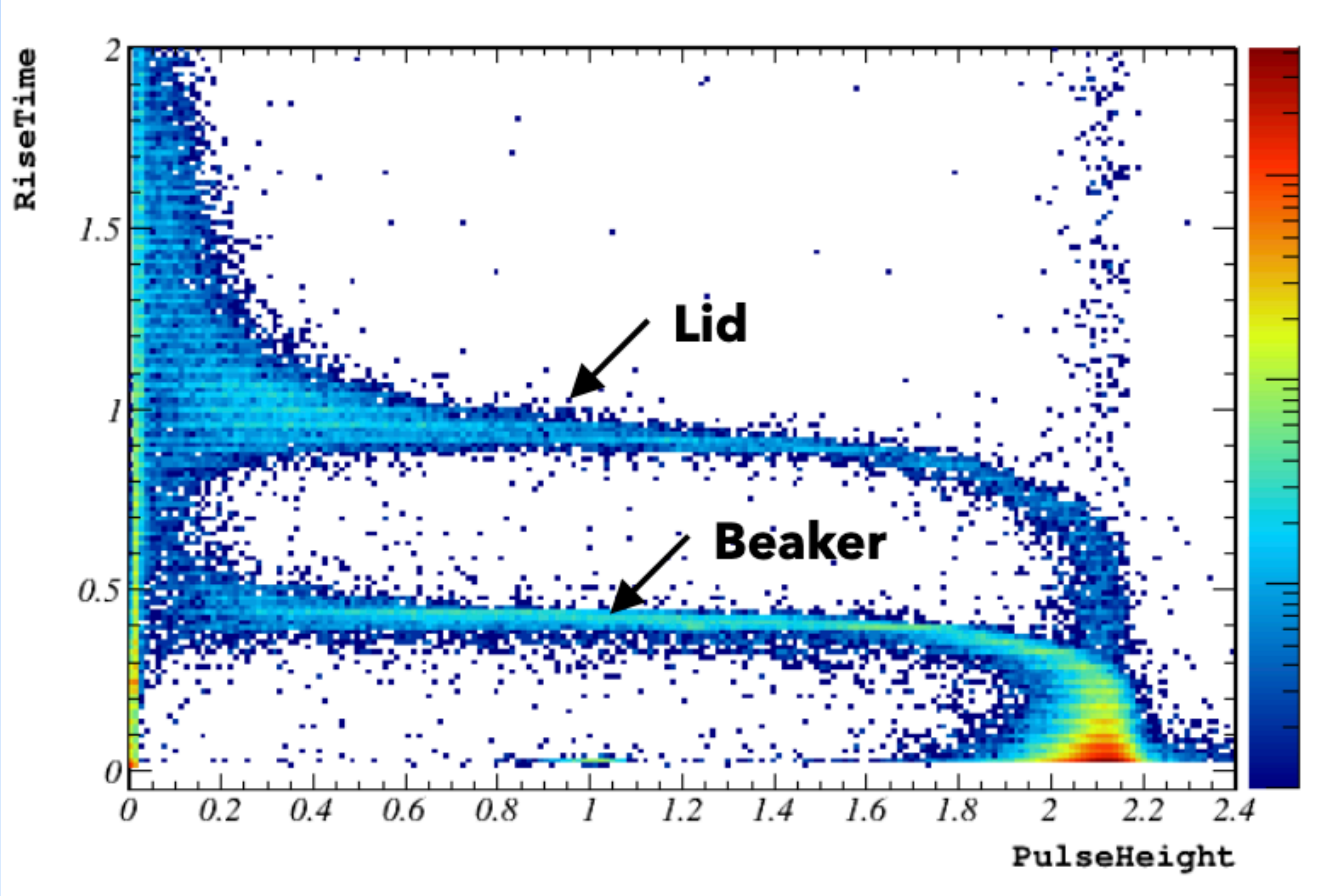


Appendix

COSINUS

The 4π design





Transmission factor: 54