COSINUS – Search for dark matter with cryogenic NaI detectors

Presented by: Matthew Stukel (He/Him)
For the Interplay between Particle and Astroparticle Physics 2022

COSINUS

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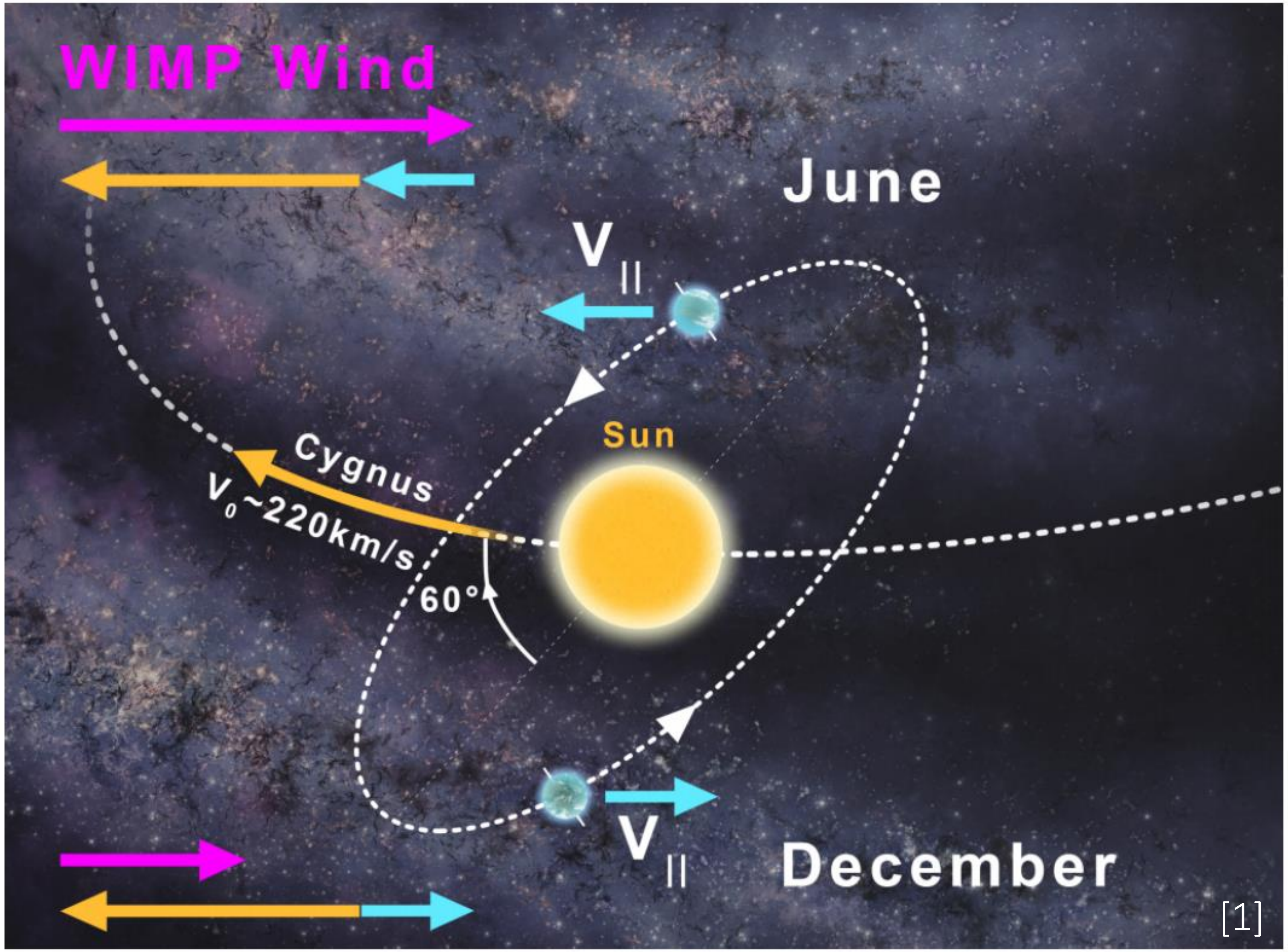
Scuola Universitaria Superiore

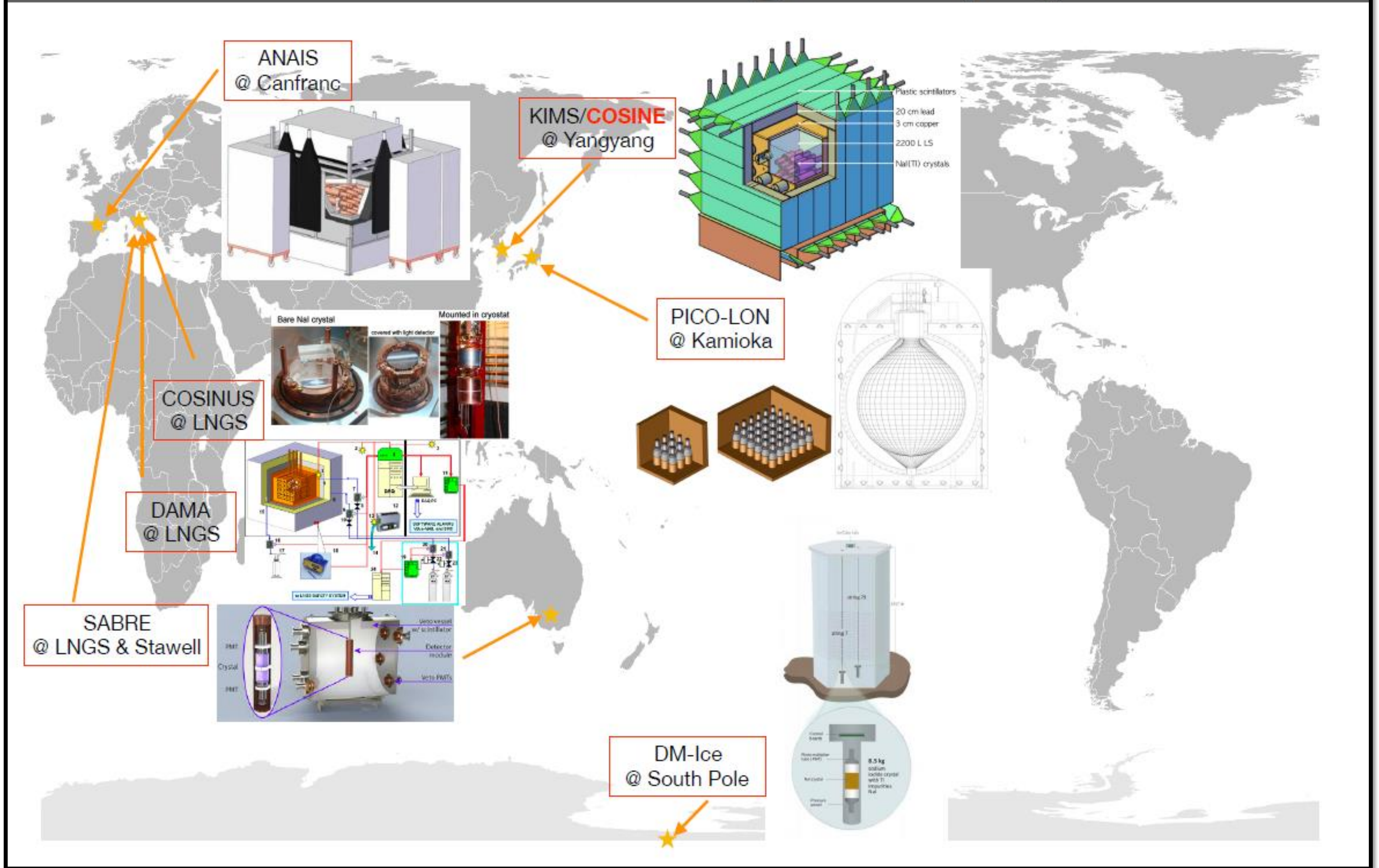
Direct Detection: Annual Modulation



- The celestial dance of the sun and earth through our galaxy induces a change in the dark matter flux throughout the year
- DAMA\LIBRA experiment observes an annual modulation consistent with dark matter
  - Period of one year
  - Peaks around June 2nd
  - Signal expected in low energy region (O(keV))

[TAUP 2019]

Global Efforts using NaI(Tl)



Astroparticle Physics European Consortium (APPEC) Recommendation:

- "The long-standing claim from DAMA/LIBRA […] needs to be independently verified using the same target material."

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Cryogenic Observatory for SIgnatures seen in Next-generation Underground Searches

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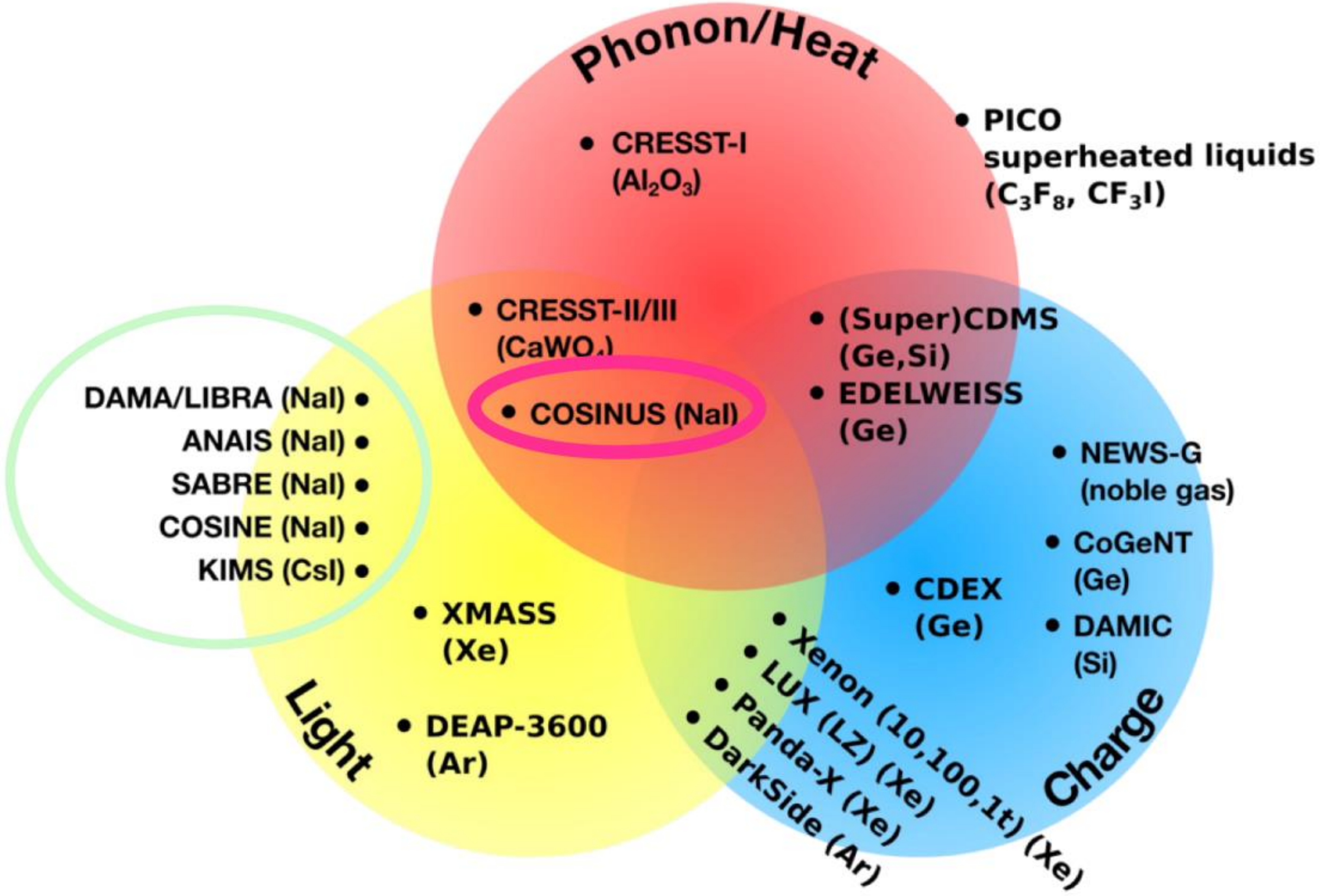
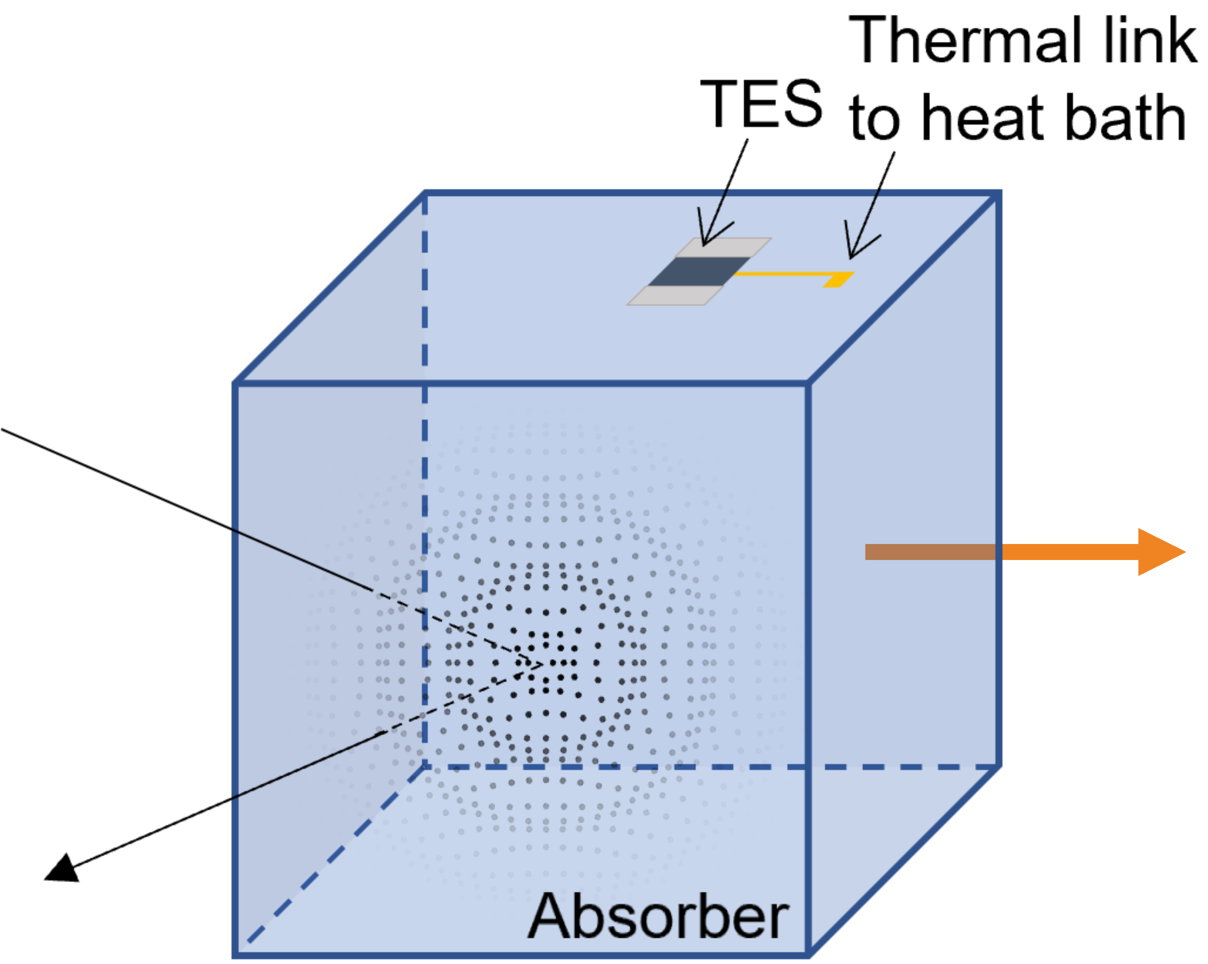
Landscape of Dark Matter Experiments

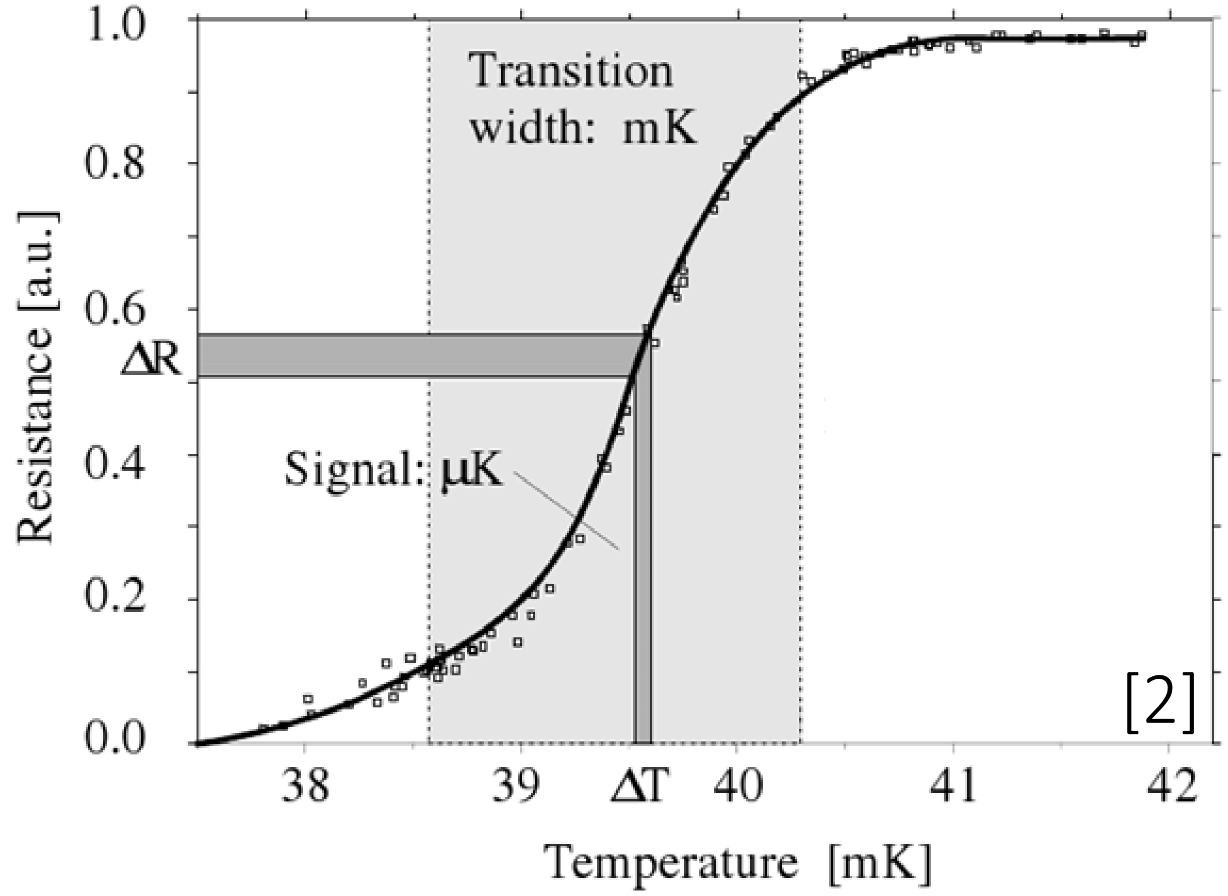


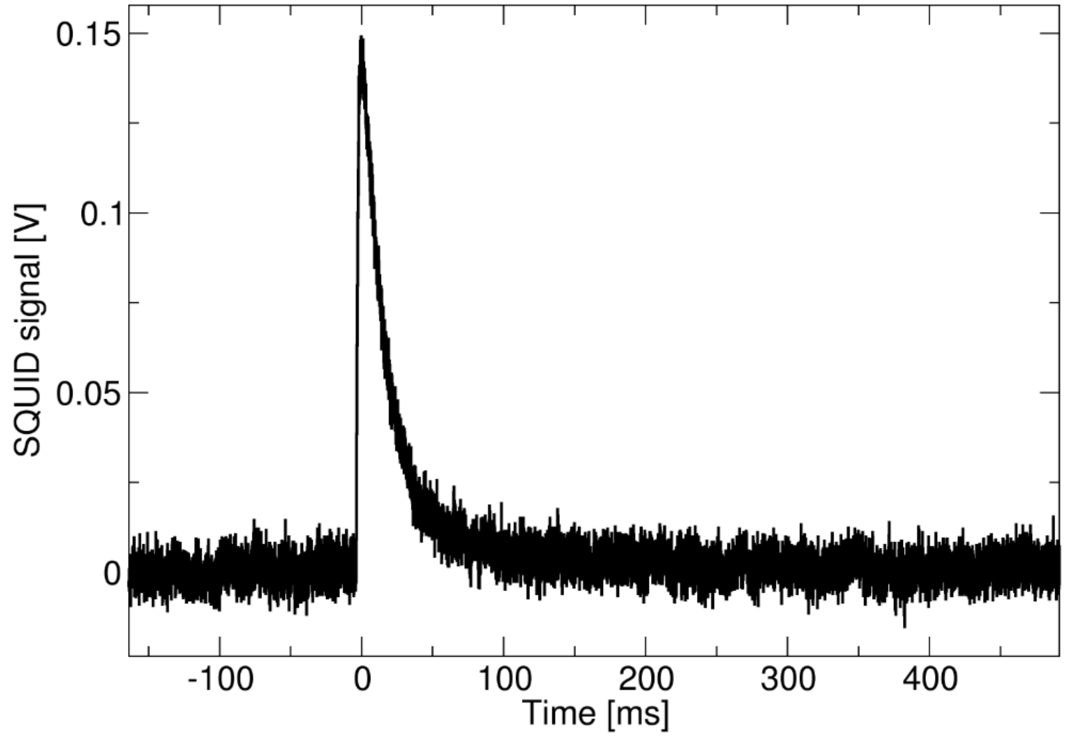
Credits to: F. Reindl

- **Goal:** Aims at a model independent test of the DAMA/LIBRA experiment
  - Same material (NaI)
  - Same location (LNGS)
- **Unique Technique:** Operate NaI as a cryogenic detector (First ever!!)
  - Use established technology from CRESST
  - Dual Channel: Phonon (90%) and Light (10%) signal for **event-by-event particle discrimination**

NaI - Phonon Signal Measurement



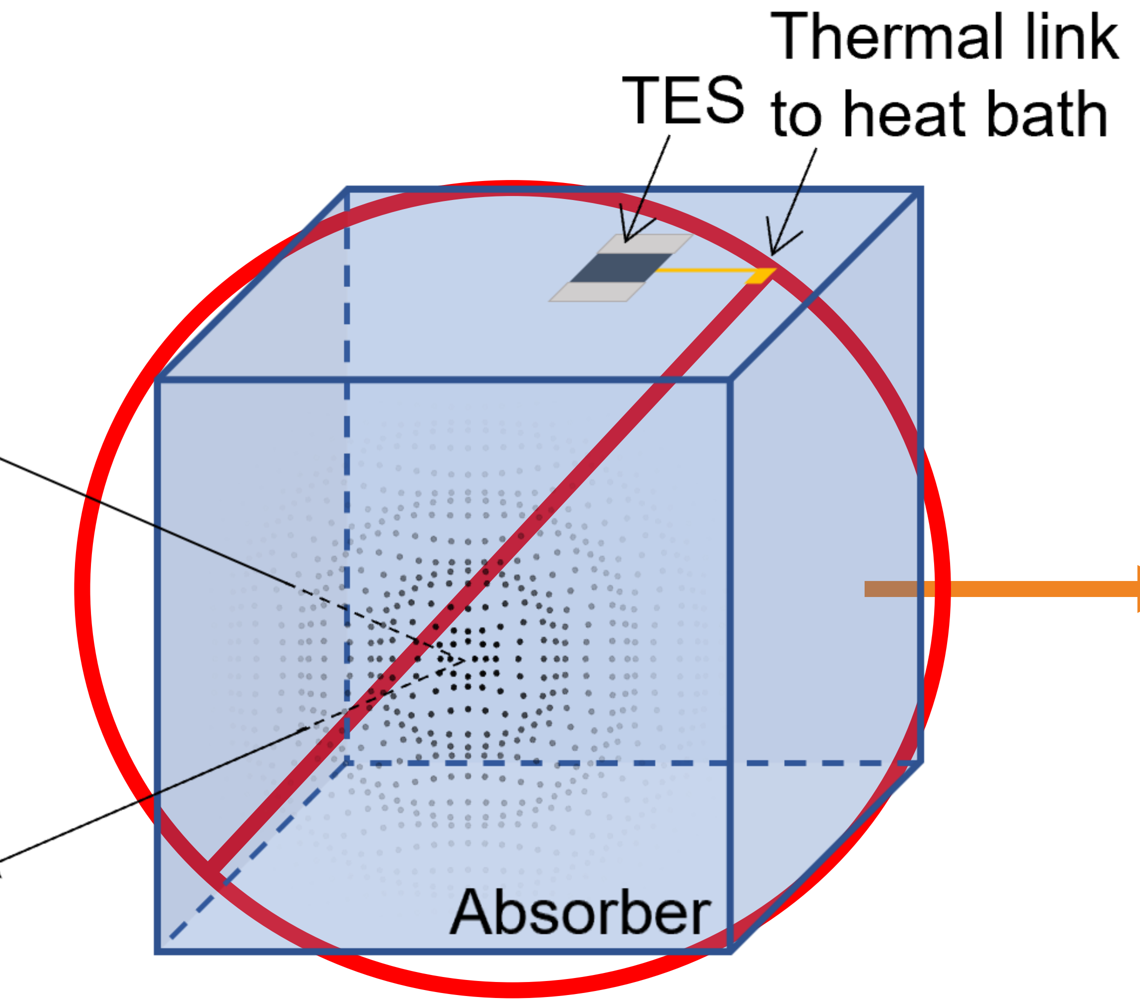


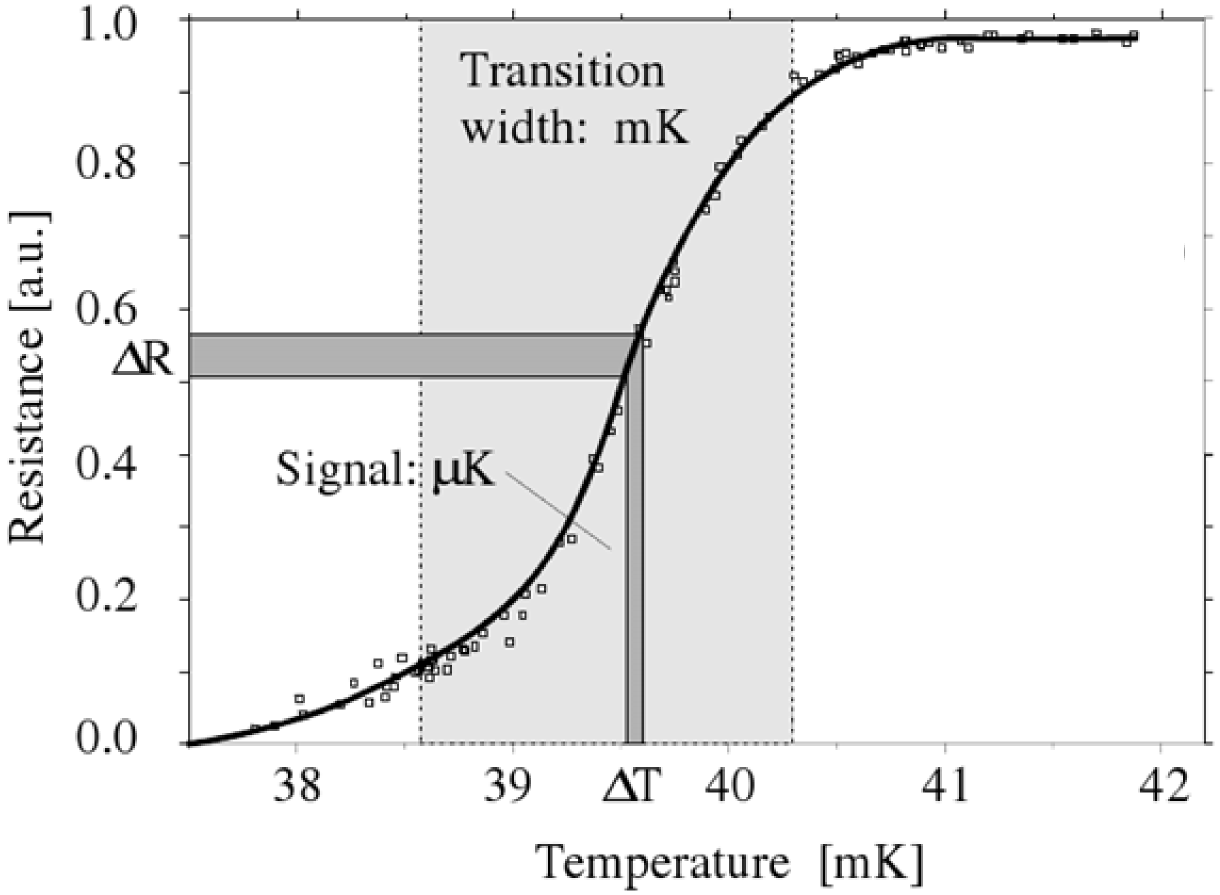


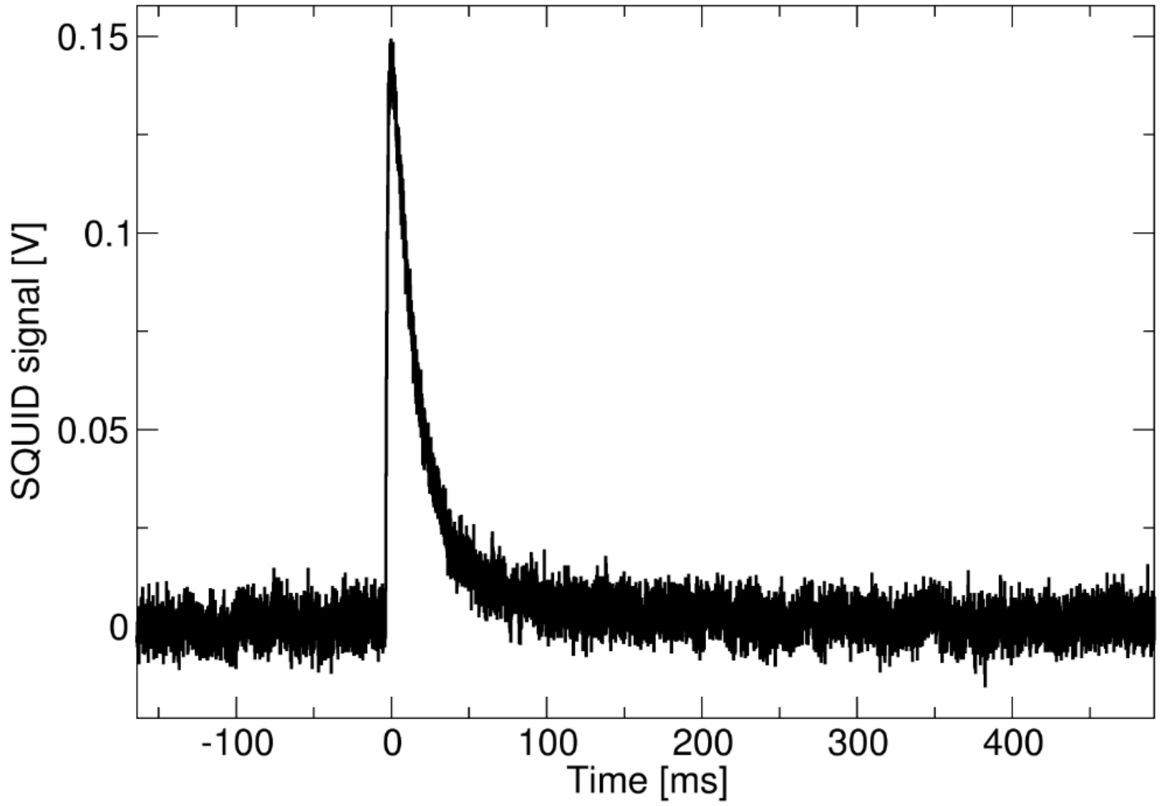
[3]

- Deposition of energy → Lattice vibrations (**<u>Phonons)</u>** → Change of temperature → Change in resistance → Signal
- Thermometer: Transition Edge Sensor (TES)
  - TES is Tungsten superconducting film operated at **<u>mK</u>** temperatures
  - TES readout technology developed and used by CRESST

NaI with TES

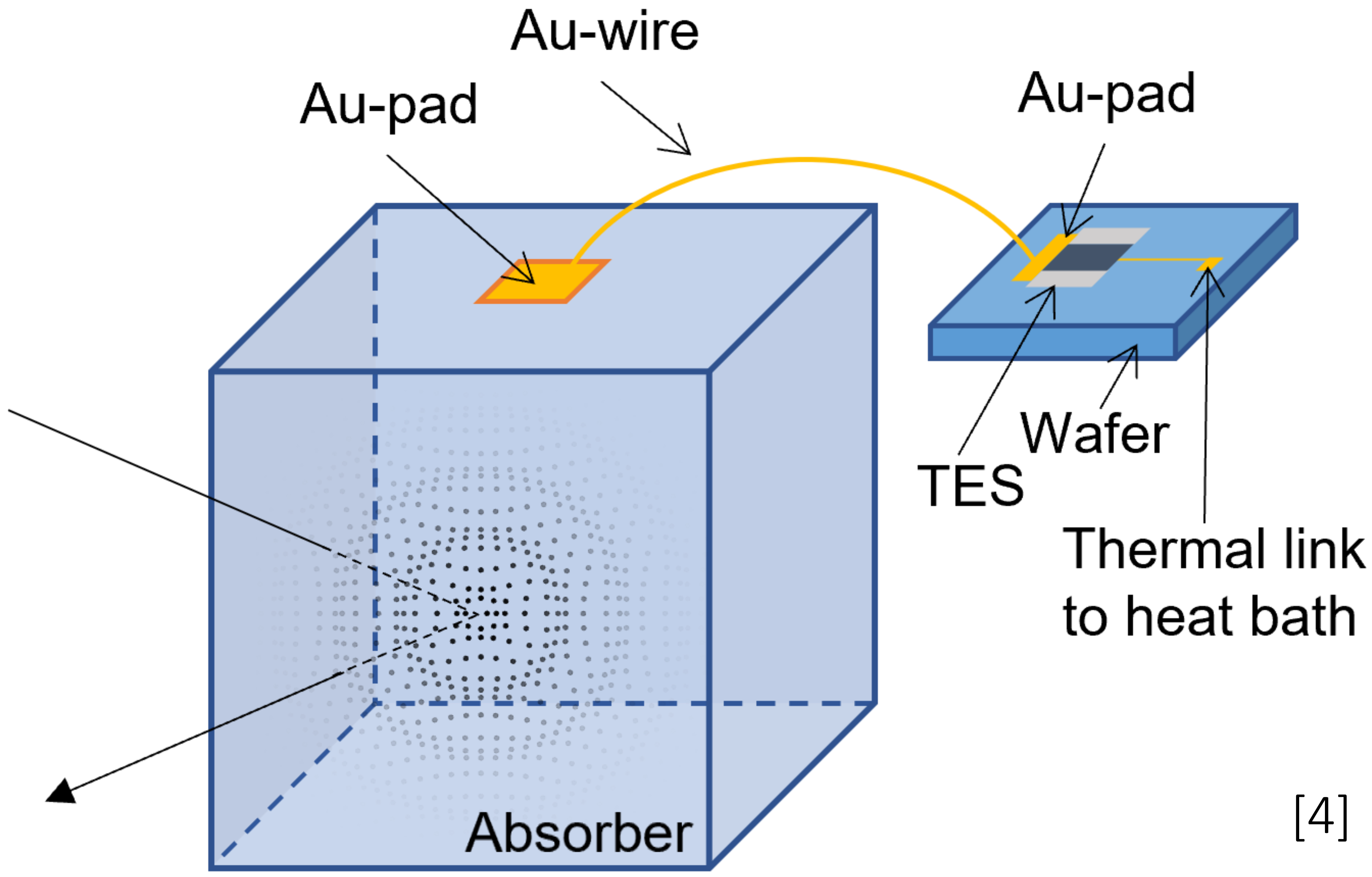






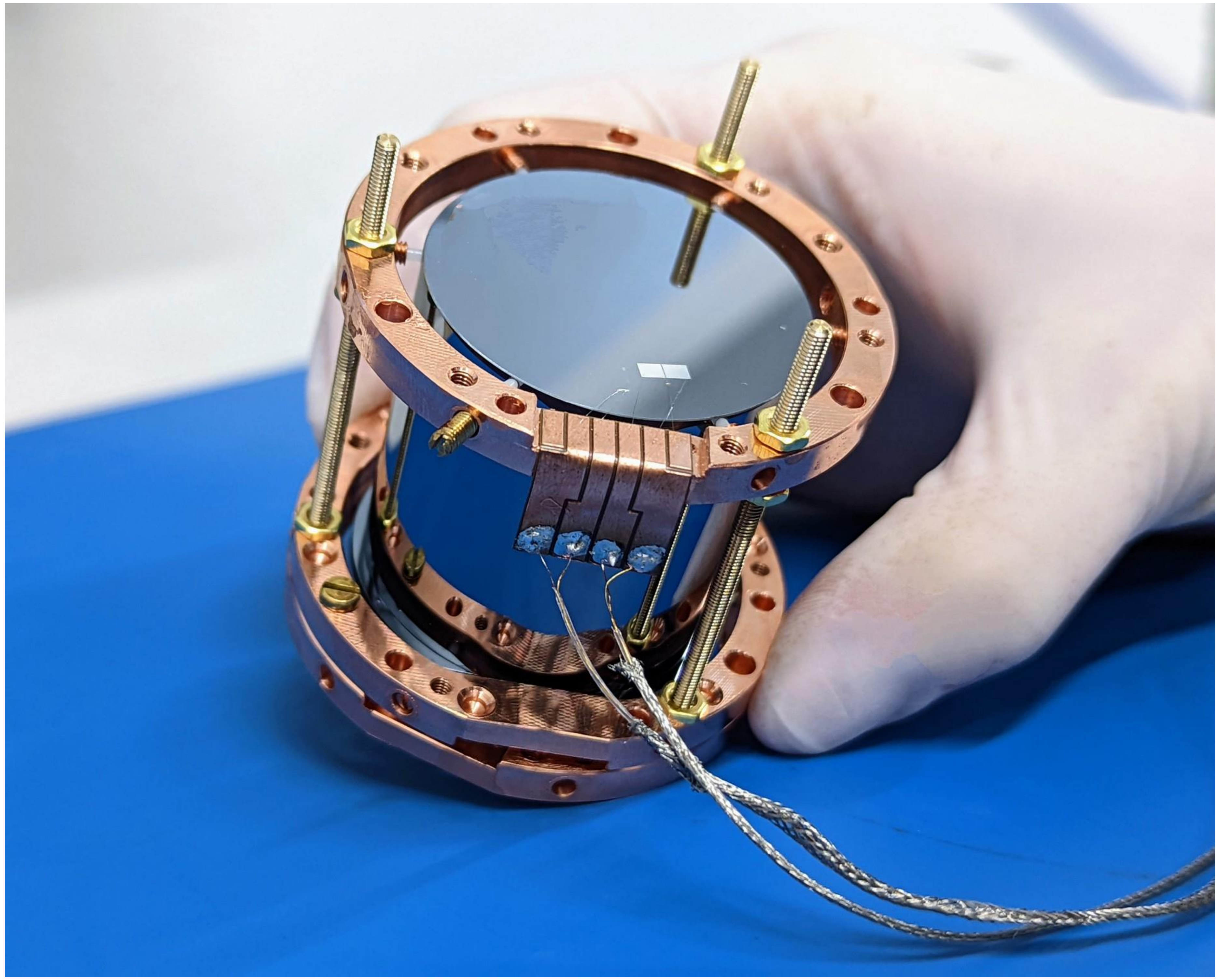
- Difficulties with attaching TES directly to NaI
  - NaI is hygroscopic (cannot come into contact with humid air)
  - Very soft and low melting point (easy to damage when handling)
- Solution: **remoTES**

NaI- remoTES design



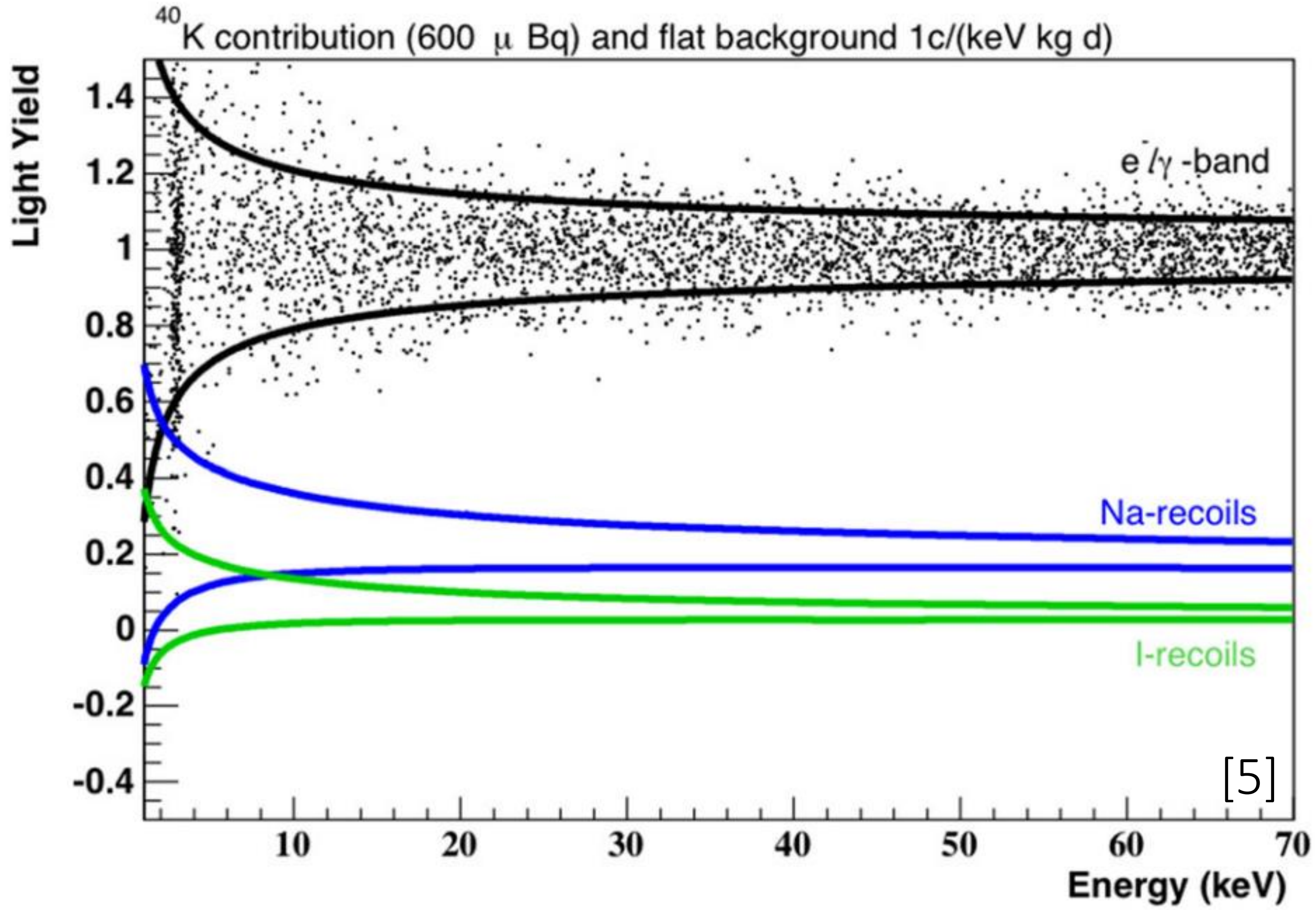
- Implement **remoTES** design, first proposed by Matt Pyle [4]
- Separate wafer that holds the TES: Wafer: Al_2O_3
- Gold pad on absorber with a gold bonding wire connected to TES
- Wafer and TES setup is constructed separately then attached to the NaI

NaI – Light Detector



- Scintillation light is detected by a surrounding silicon beaker
  - 1mm thick, 40mm in diameter
- 4π coverage to maximize light collection
- TES is evaporated directly onto the silicon

COSINUS: Particle Discrimination



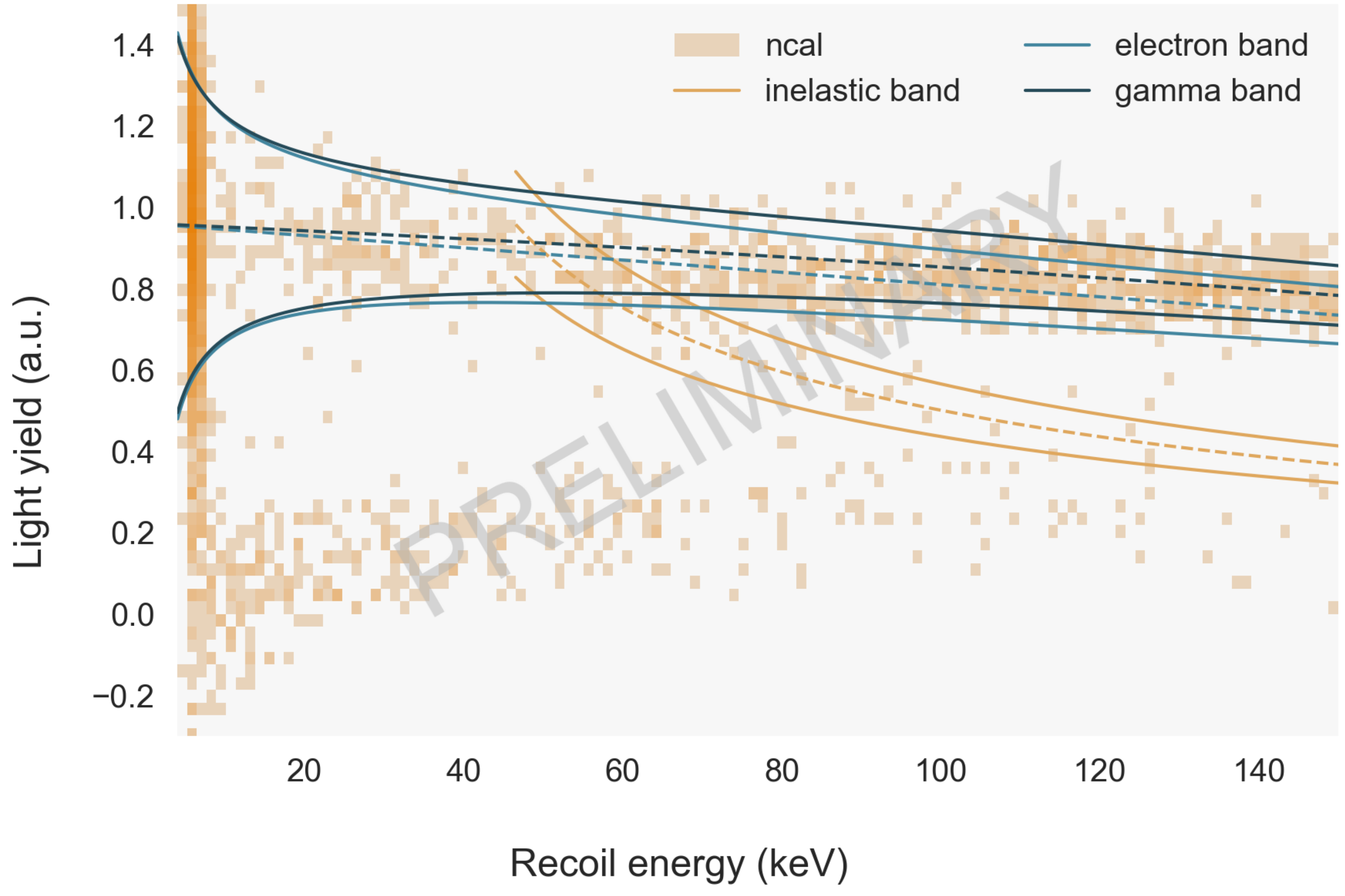
- Particle discrimination is the COSINUS advantage

$$\text{Light Yield} = \frac{\text{Light Energy}}{\text{Phonon Energy}}$$

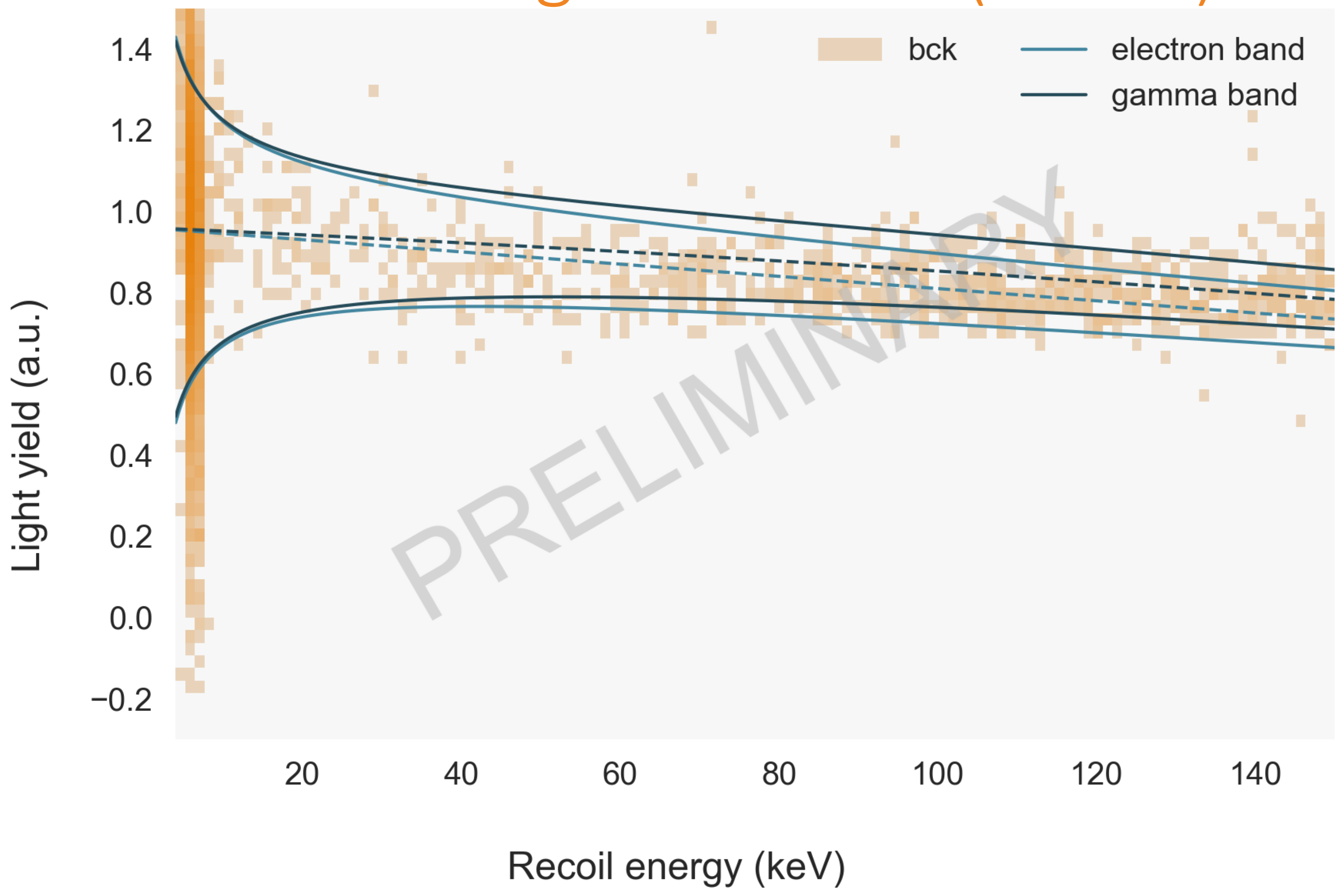
- Electromagnetic interactions will emit more light than nuclear recoils
- Use for <u>**particle discrimination**</u> on an event-by-event basis
- Left is simulated data [5]
- Position of the bands is very dependent on the quenching factor (QF)
  - Dedicated QF performed at TUNL (See backup slide)

COSINUS: R&D Results from June 2022

Neutron Calibration (30 hrs)



Background Data (60 hrs)



- December 2021: Demonstrated the first particle discrimination in NaI at a surface setup
- June 2022: Measurement was carried out using a CRESST test facility at the Gran Sasso National Laboratory (underground)
  - Energy calibration: ^{55}Fe & ^{57}Co
  - NaI baseline resolution: 0.39 keV (< 2 keV threshold)
  - Silicon Beaker baseline resolution: 0.58 keV_{ee}
  - Silicon Beaker direct hit resolution: 20 eV
- Neutron band is clearly visible, <u>proof of particle discrimination in NaI</u>

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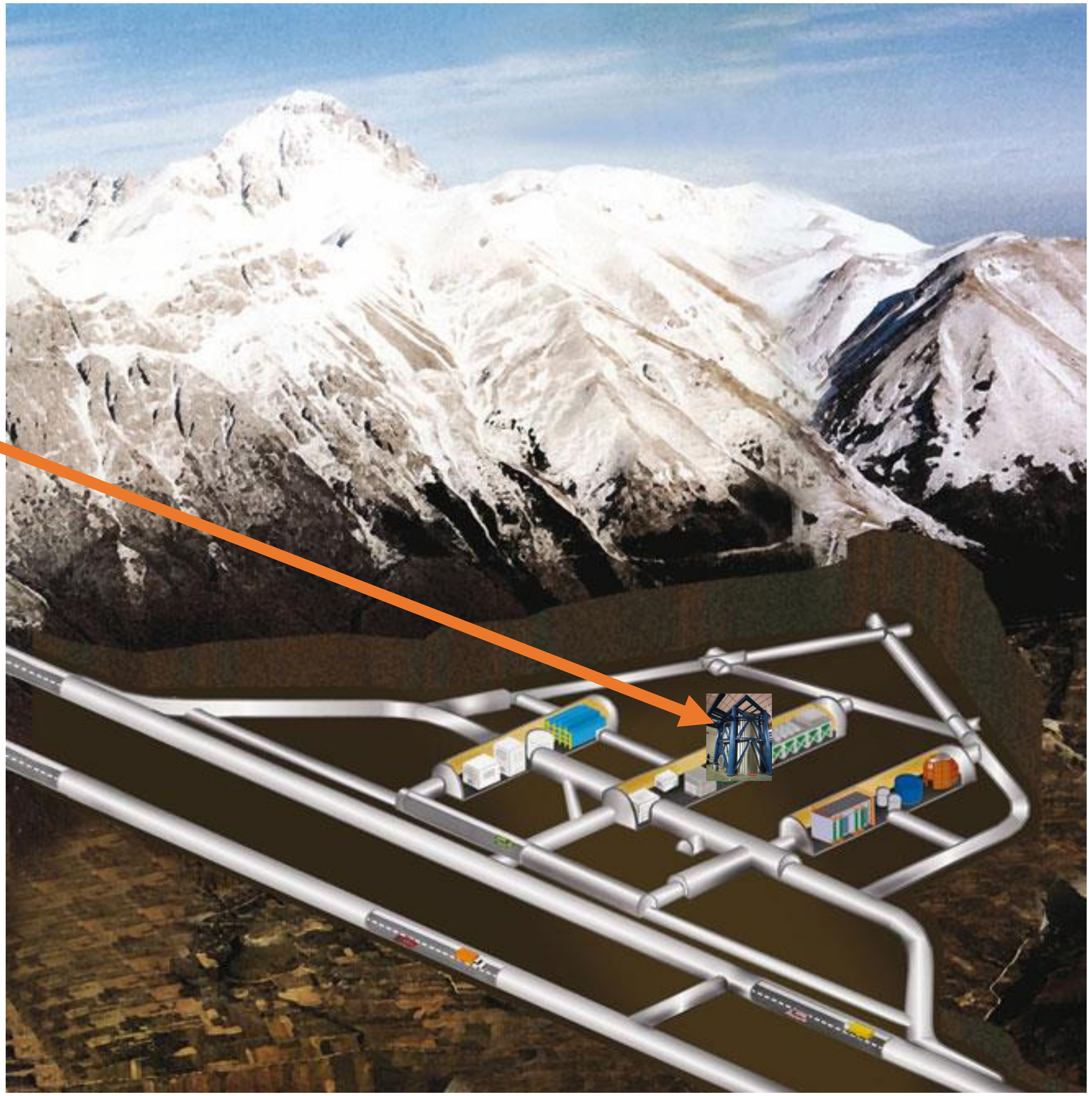
Experimental Facility and Prospective

Gran Sasso National Laboratory (LNGS)

https://www.planetware.com/map/italy-italy-republic-map-i-i37.htm

COSINUS Location



https://www.appec.org/news/hands-on-experimental-underground-physics-at-lngs

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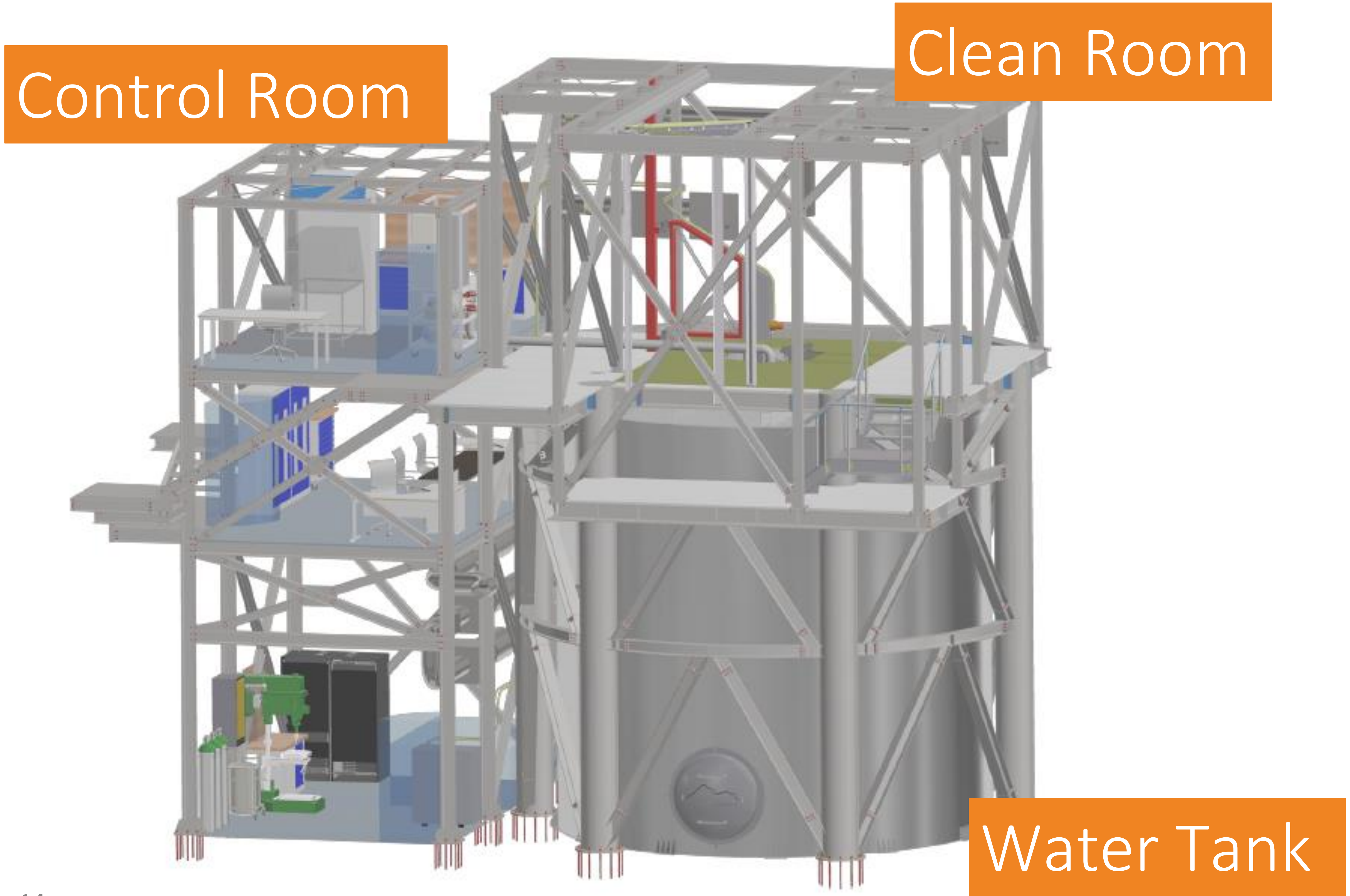
- LNGS provides 3500 m of water equivalent shielding from cosmic radiation

Experimental Setup I



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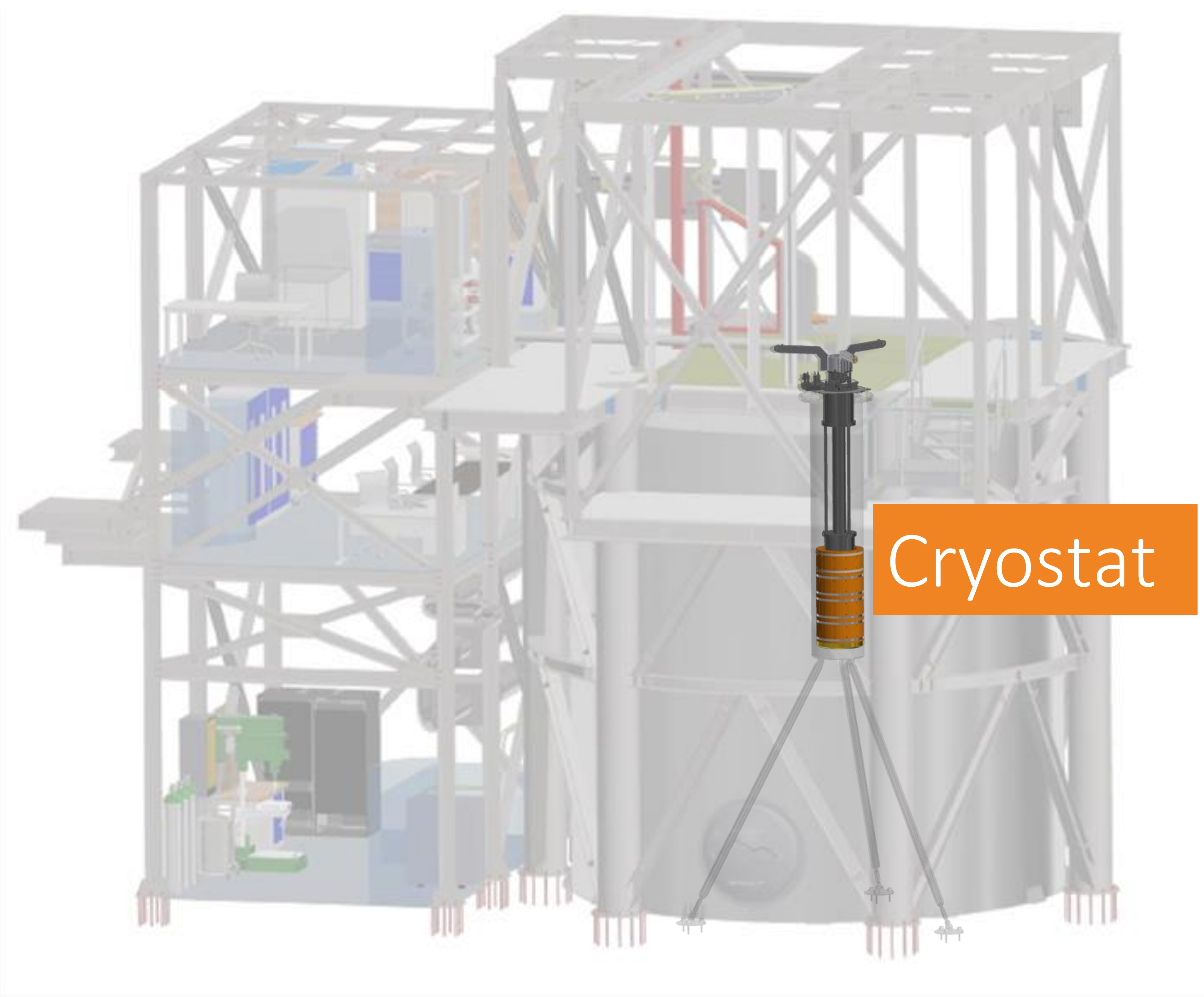
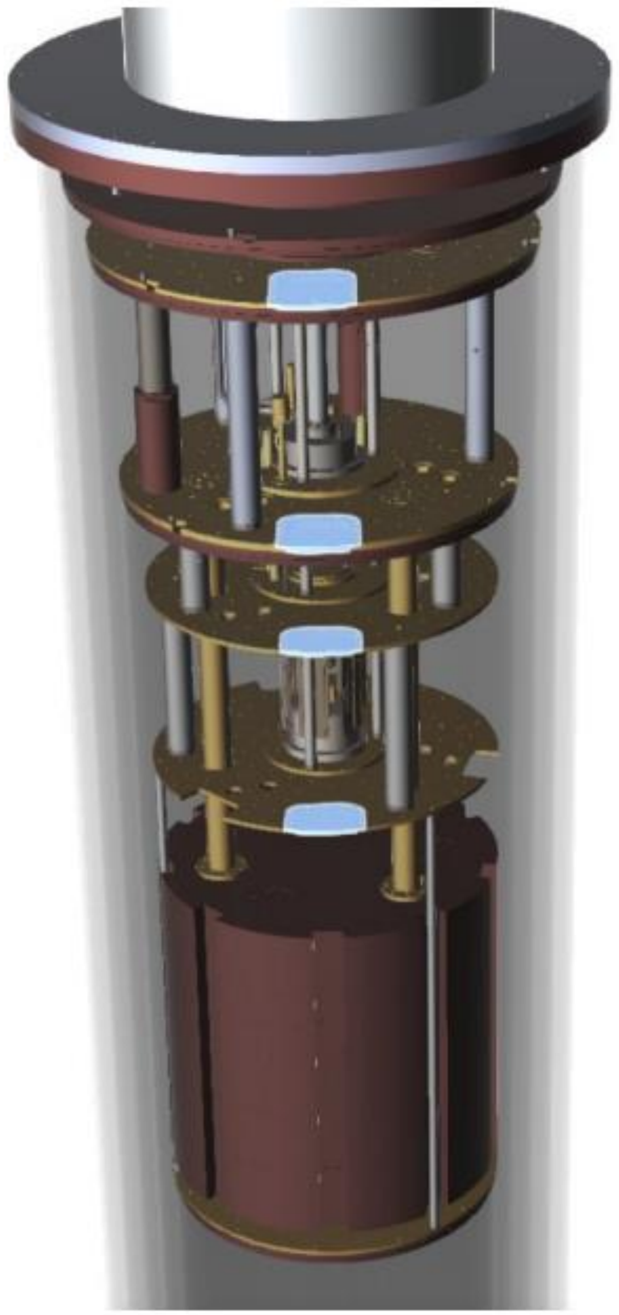
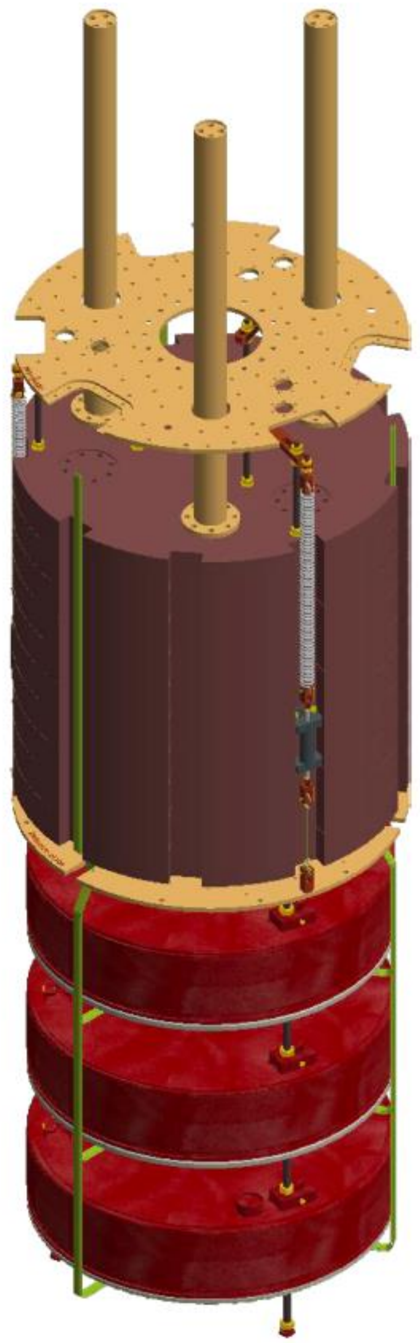
Experimental Setup II

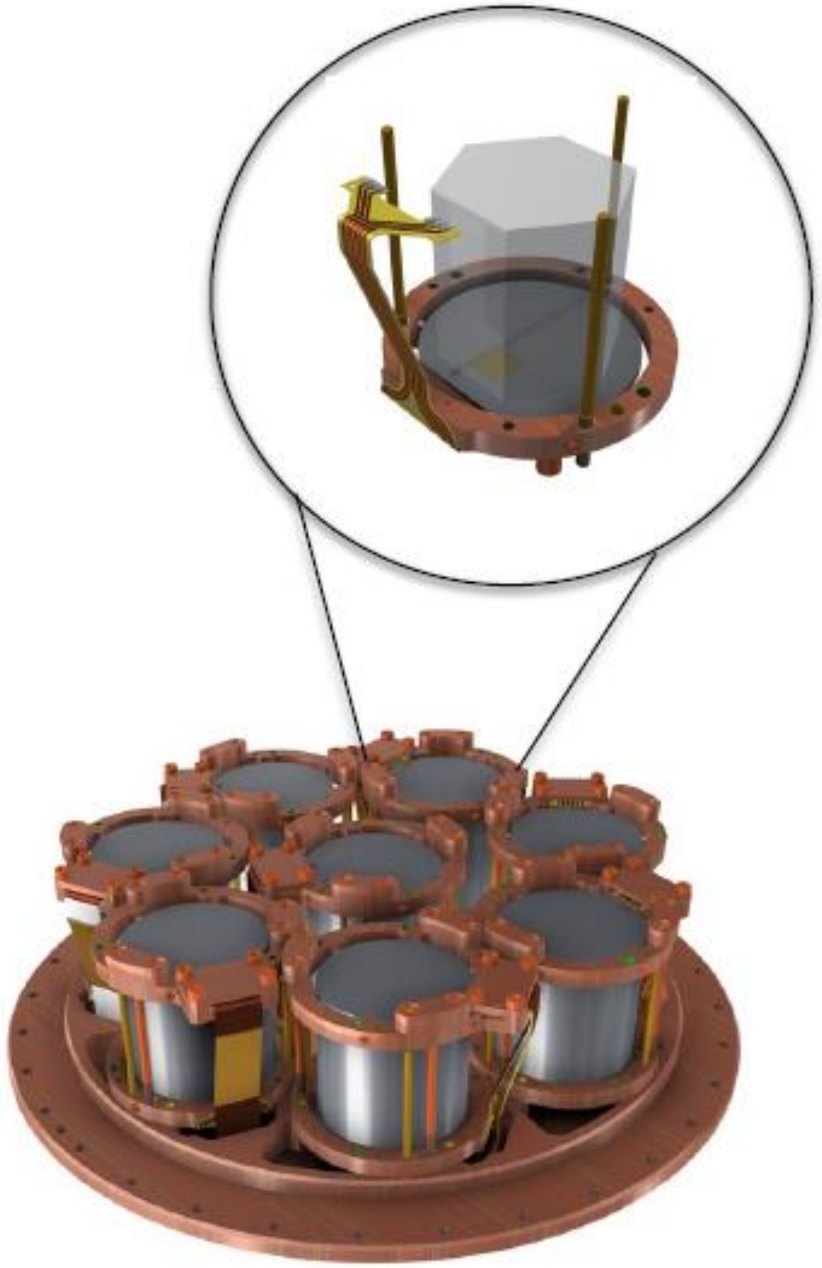
Experimental Setup III



COSINUS – Dry Dilution Refrigerator



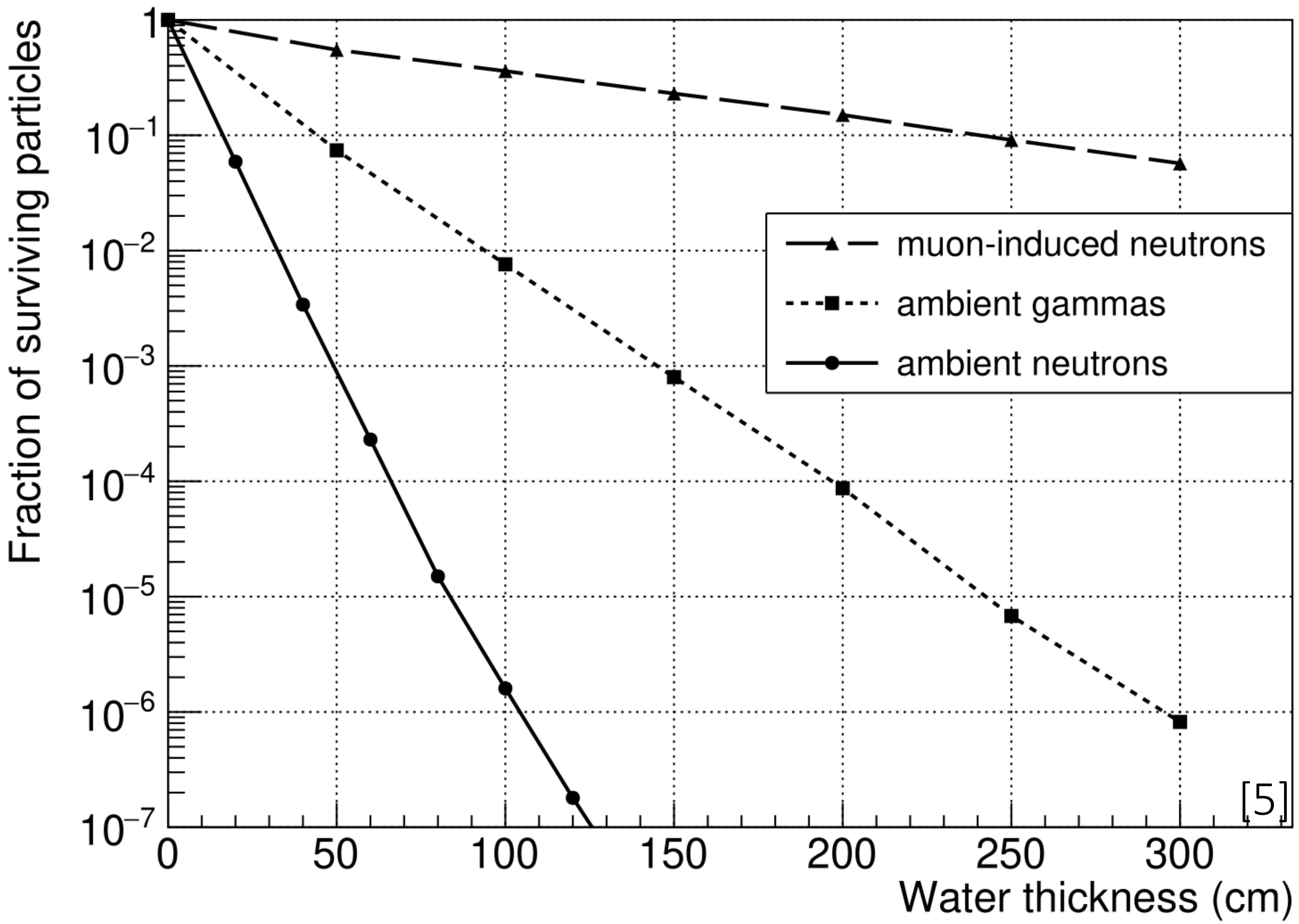


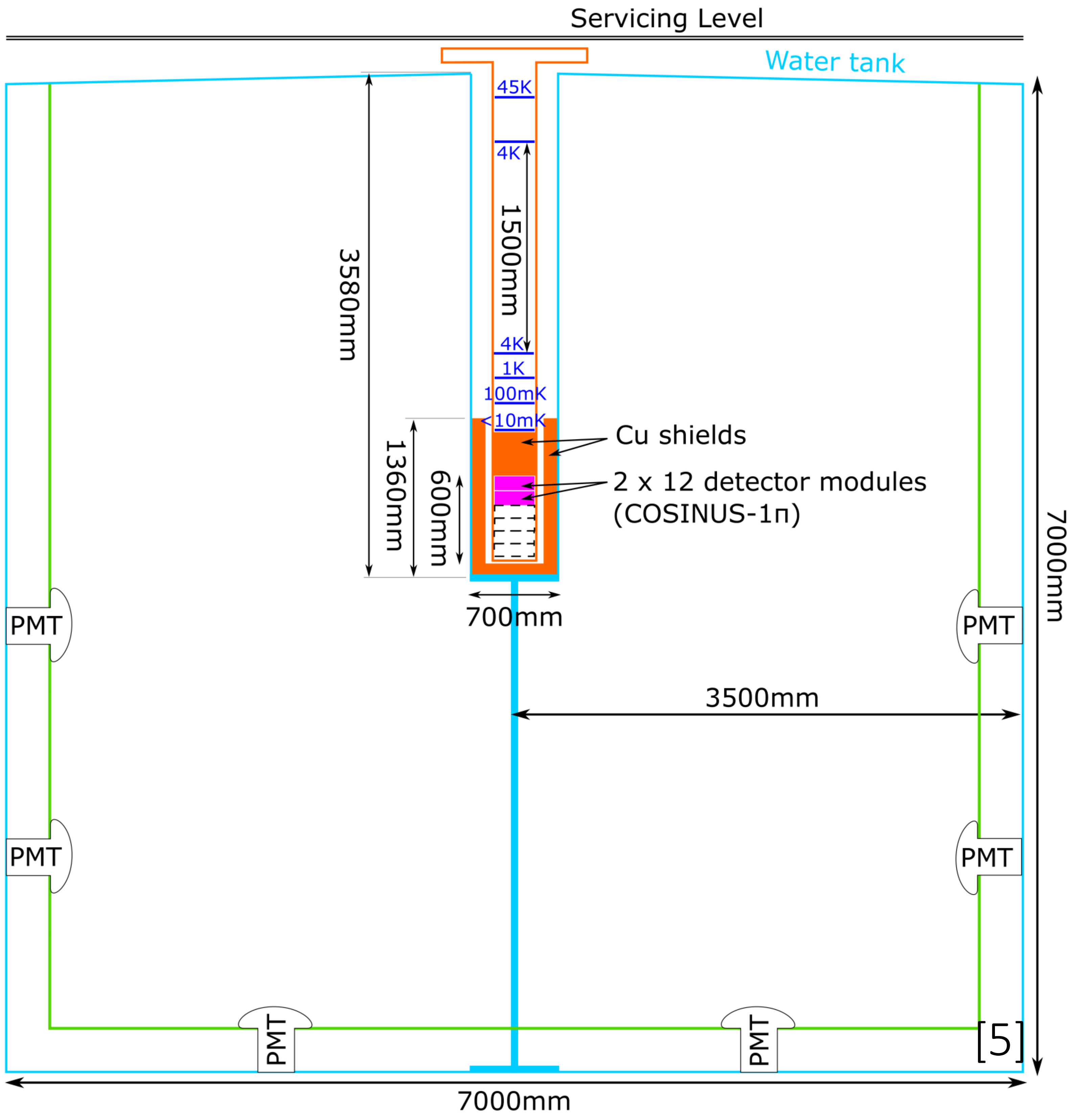


- Crystals are grown in collaboration with SICCAS using Astrograde (MERCK) powder in a modified Bridgeman technique

- Detectors housed in a pulse tubed assisted dilution refrigerator (mK)
- Three stage vibration decoupling: Global, Cryostat and Detector
- Ultra-pure copper for shielding the detectors from cryostat radiogenics

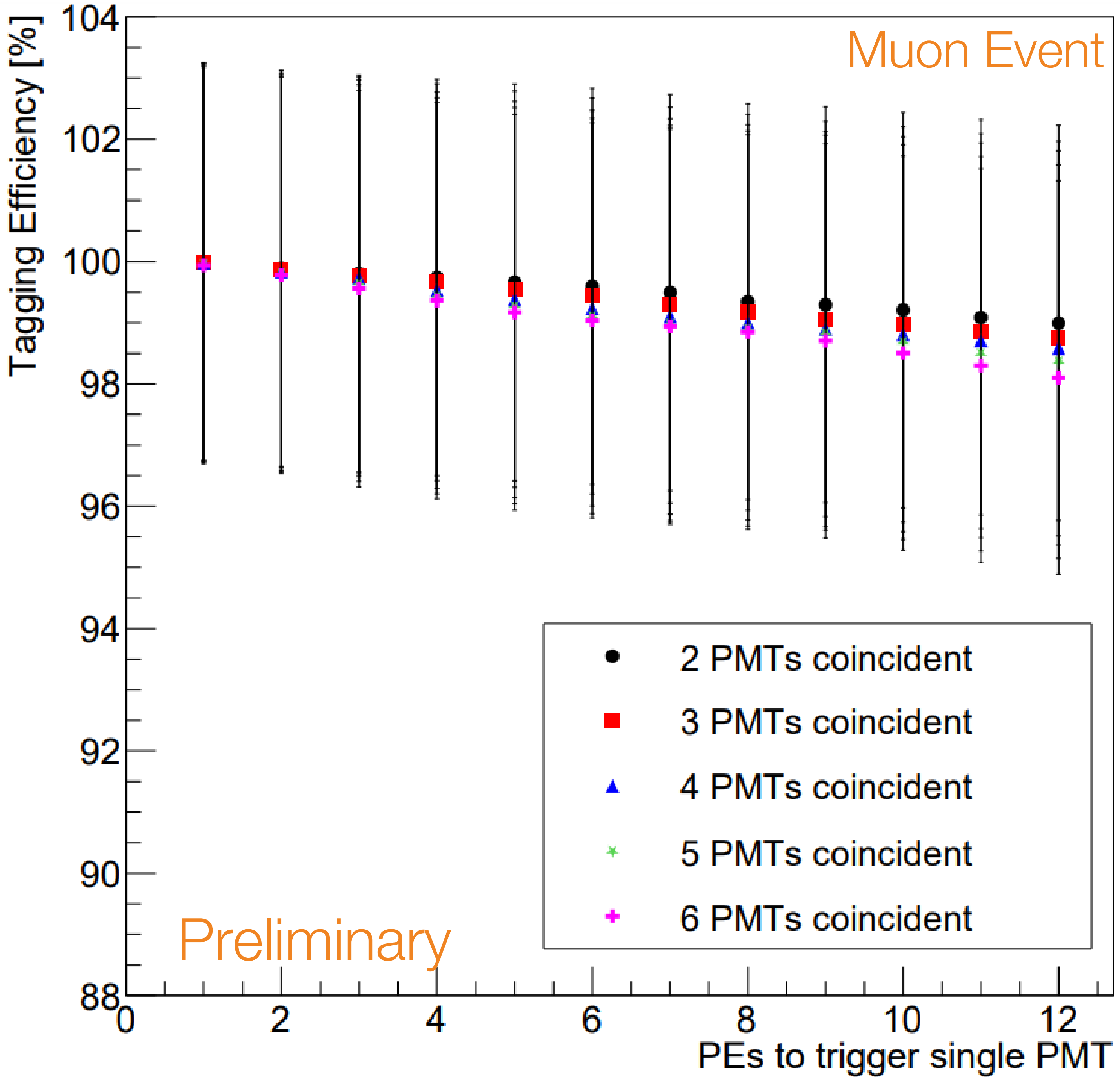
Passive Shielding

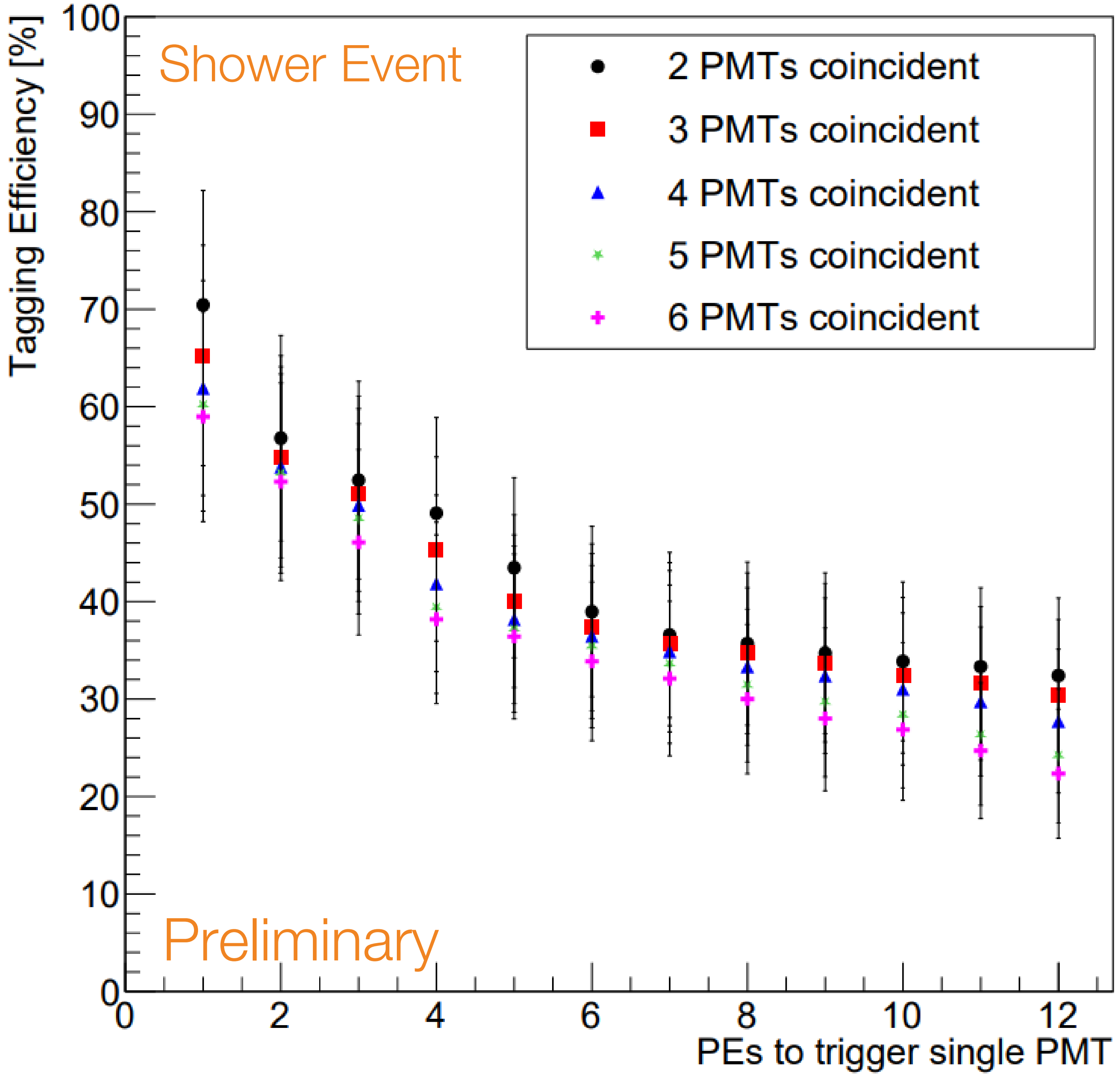




- Water tank acts as a passive shield for radiogenic and ambient gammas and neutrons
- Factor 10^6 reduction in ambient neutrons

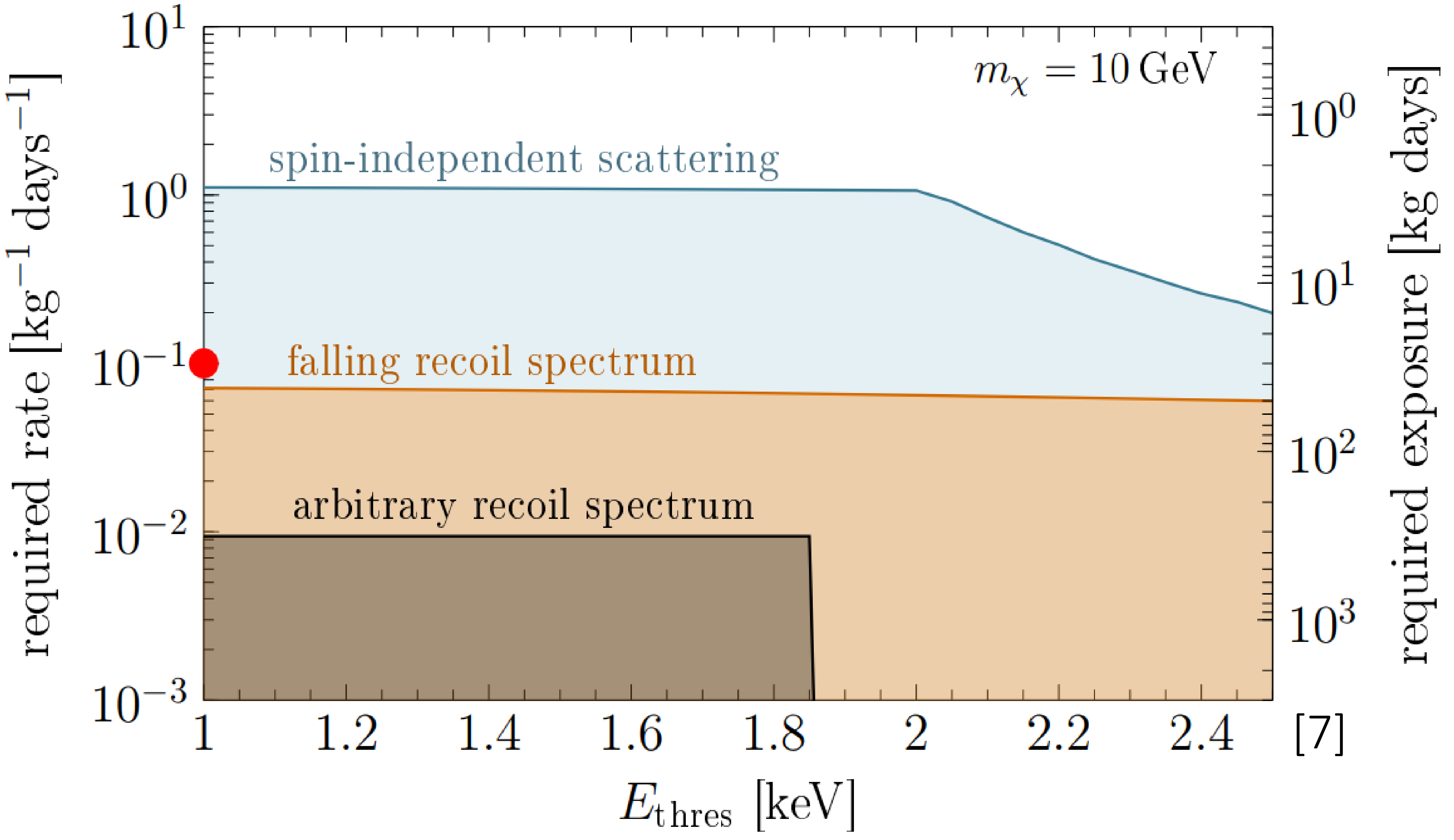
Active Muon Veto





- After internal radiogenics cosmogenic neutrons will be the largest background
- Cosmogenic neutrons: 3.5 +/- 0.7 cts kg^{-1} $year^{-1}$
- Tank will be instrumented with PMTs to make a water Cherenkov muon veto
- Simulations performed with ImpCRESST [6]

COSINUS Physics Goals I

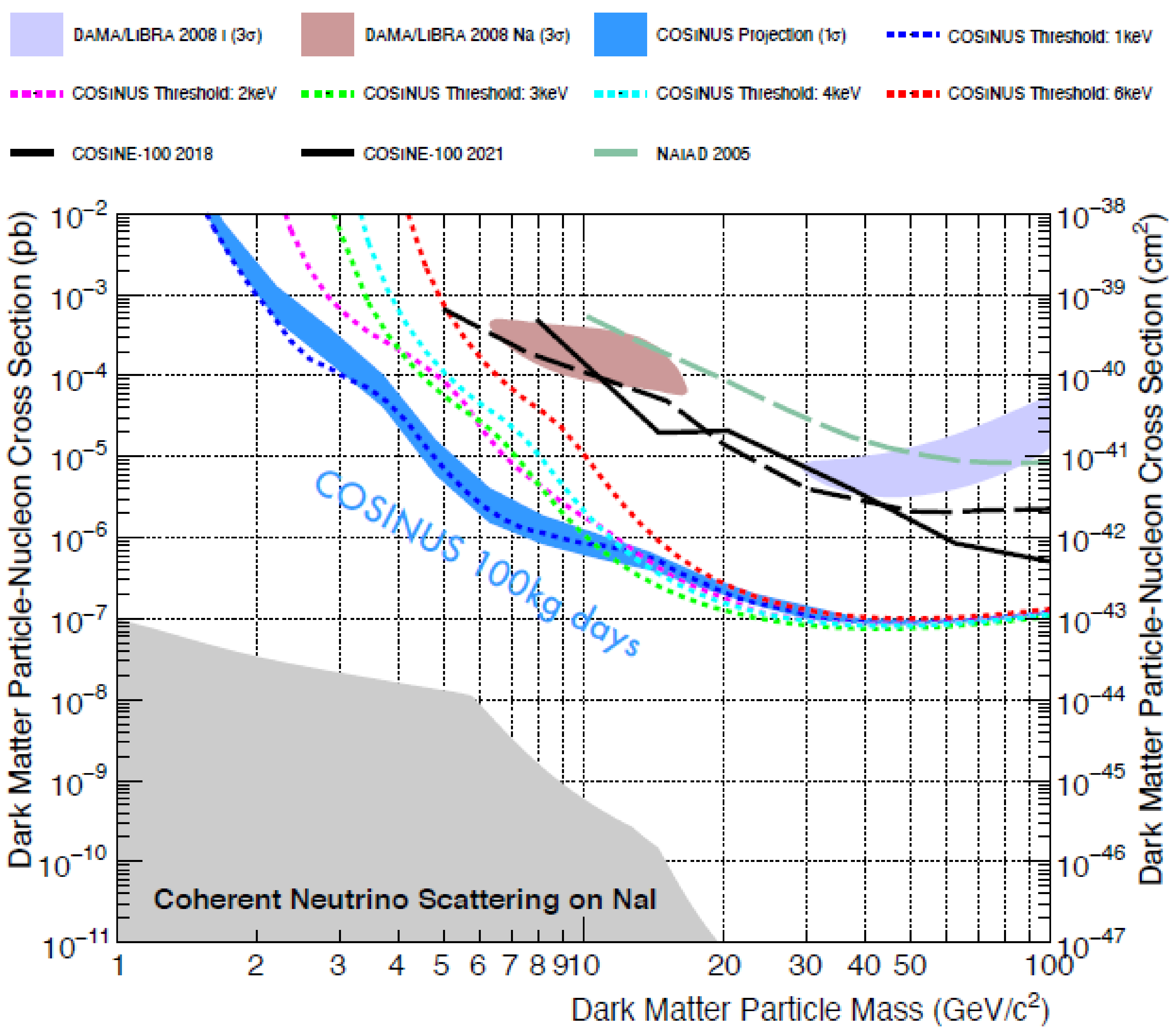


[7]

*Not Updated for DAMA <1 keV_{ee} result

- COSINUS-1π: 1000 kg•days
  - Run time of 1-3 years
  - <u>Exclude or confirm a nuclear recoil origin of the DAMA\LIBRA result</u>
- COSINUS-2π
  - Annual modulation signal
  - Increase target mass capability, more than double the number of detectors

COSINUS Physics Goals II



*Not Updated for DAMA <1 keV_{ee} result

- COSINUS-1π: 1000 kg•days
  - Run time of 1-3 years
  - Exclude or confirm a nuclear recoil origin of the DAMA\LIBRA result
  - **100 kg•days: Exclude an elastic scattering scenario independent of DM halo**
- COSINUS-2π
  - Annual modulation signal
  - Increase target mass capability, more then double the number of detectors

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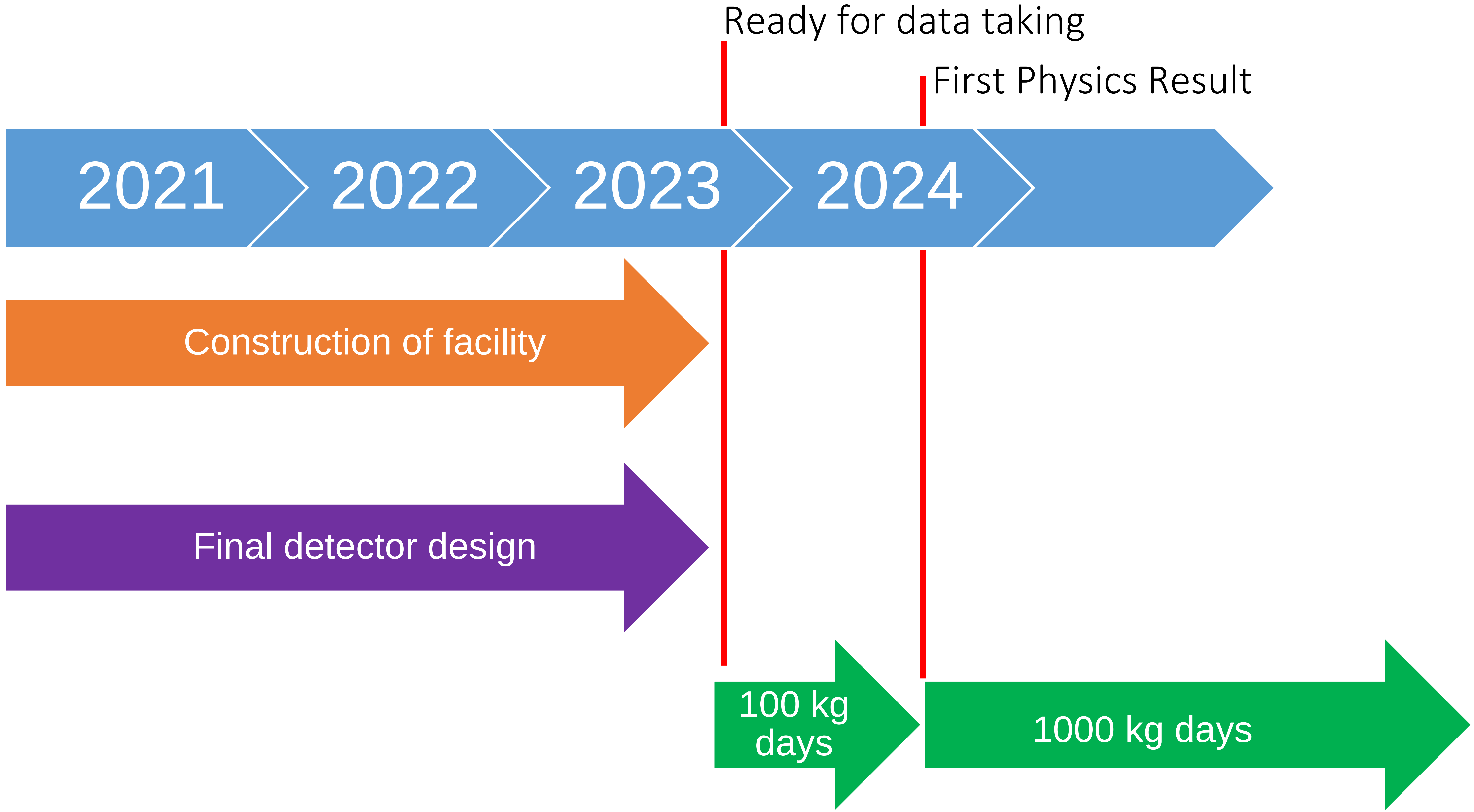
COSINUS Timeline



Conclusion/ Summary

- The search for dark matter is on the forefront of modern particle physics
- Effective annual modulation of dark matter is a unique and important way to continue this search
- COSINUS is a cryogenic NaI dark matter experiment whose goal is to verify the longstanding DAMA/LIBRA dark matter claim
  - Unique capability for particle discrimination (Proven!!)
- COSINUS will begin commissioning in 2023 and we look forward to great results!!

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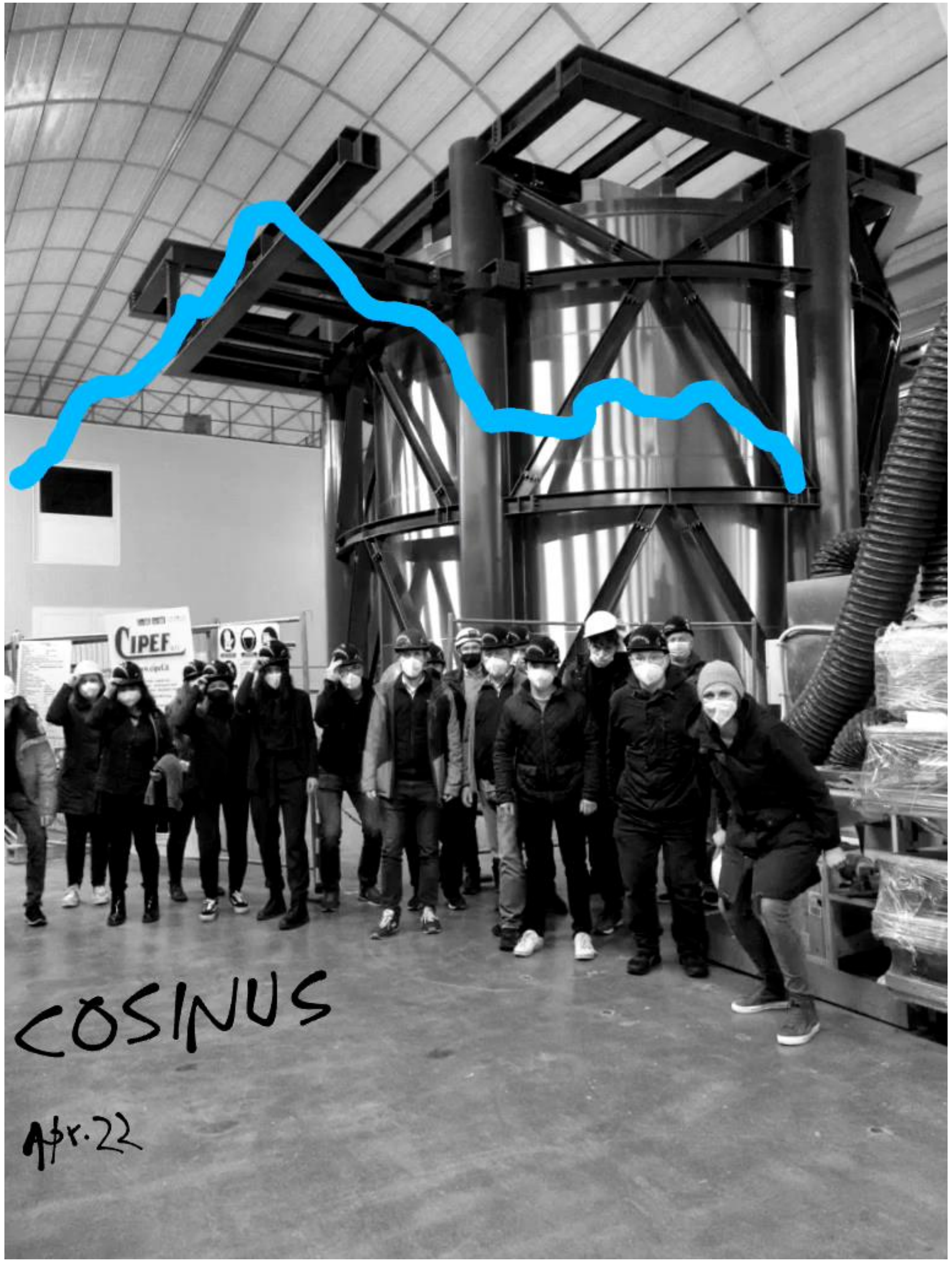

INFN
LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

Since 1928
SICCAS

TU WIEN

HEPHY
INSTITUTE OF HIGH ENERGY PHYSICS

HELSINKI INSTITUTE OF PHYSICS

Max-Planck-Institut für Physik
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Thank You!

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References

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2. Demers, Hendrix. "Two facets of the x-ray microanalysis at low voltage: the secondary fluorescence x-rays emission and the microcalorimeter energy-dispersive spectrometer." (2008).
3. https://www.cresst.de/CRESSTIIIPhase1.php
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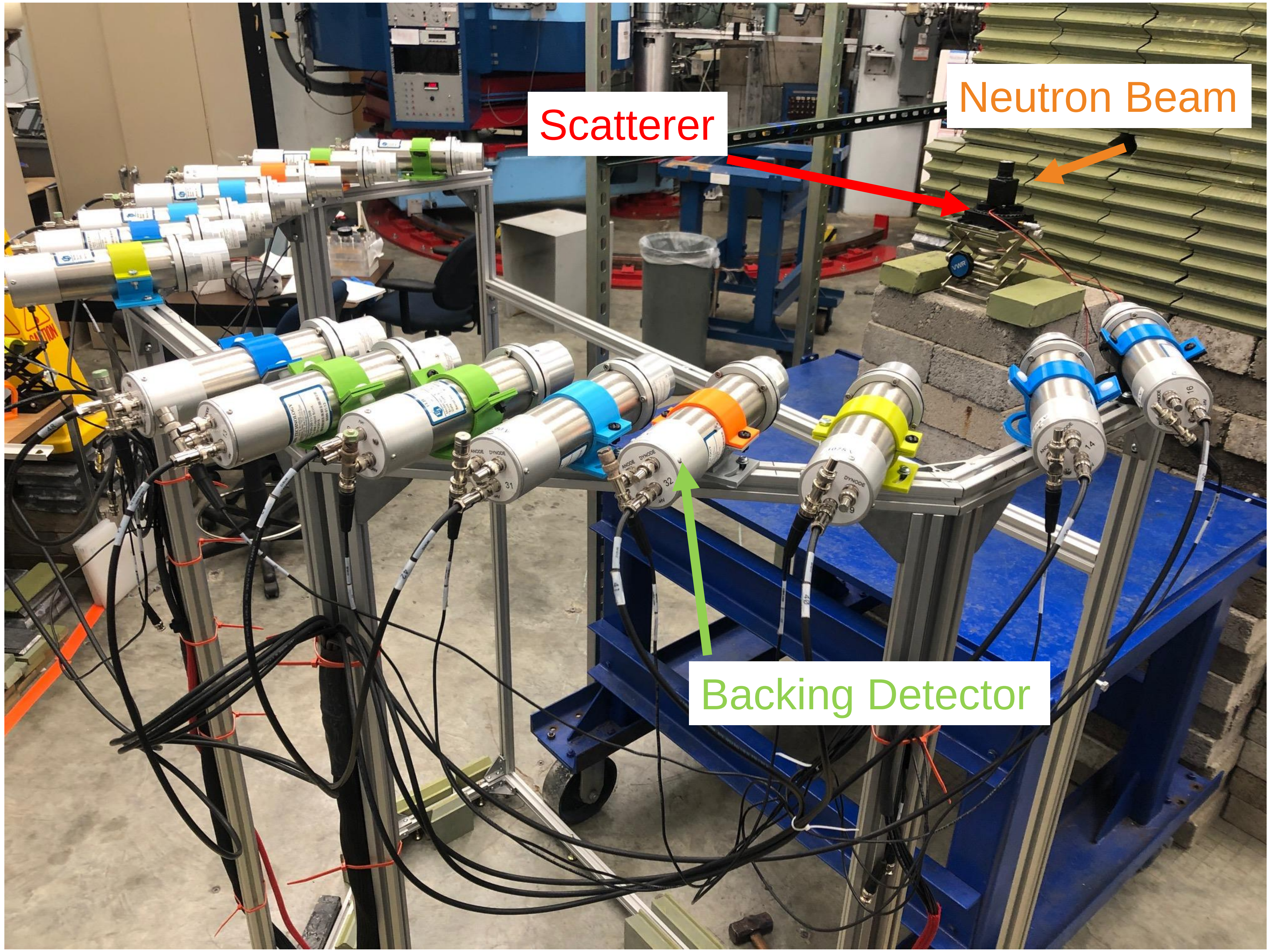
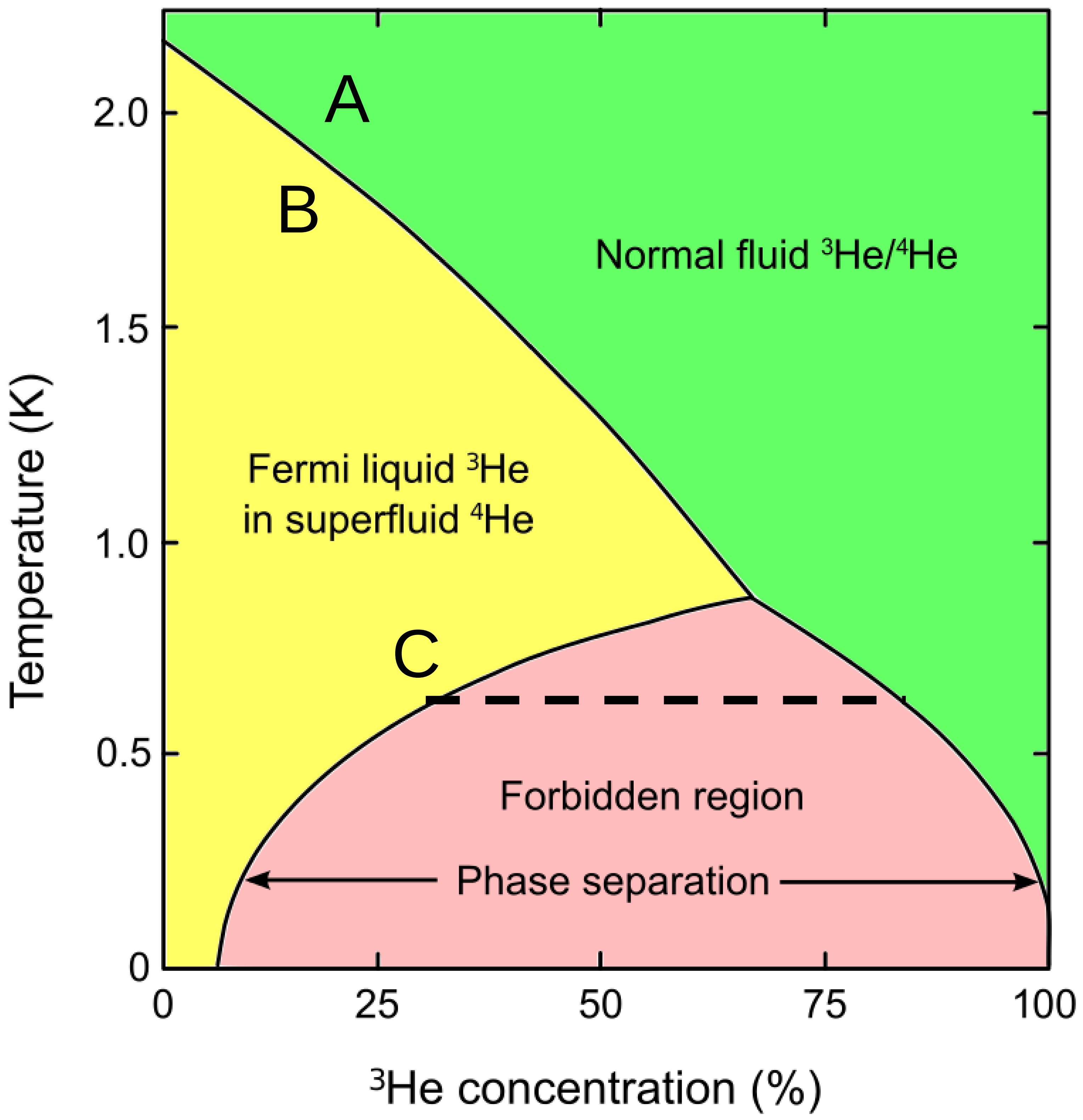
5. Angloher, G., et al. "Simulation-based design study for the passive shielding of the COSINUS dark matter experiment." *The European Physical Journal C* 82.3 (2022): 1-11.
6. Abdelhameed, A. H., et al. "Geant4-based electromagnetic background model for the CRESST dark matter experiment." *The European Physical Journal C* 79.10 (2019): 1-18.
7. Kahlhoefer, Felix, et al. "Model-independent comparison of annual modulation and total rate with direct detection experiments." *Journal of Cosmology and Astroparticle Physics* 2018.05 (2018): 074.

Quenching Factor Measurement



- Performed at TUNL (Triangle Universities Nuclear Laboratory)
- 5 NaI crystals with different Tl doping (0.1-0.9%)
- Neutron beam scatters in the crystal and arrives at backing detector
- Based on the angle we know the actual energy of the recoil
- Can then compare to energy measured and determine the **QF!!**

Dilution refrigerator



- Pure ^{4}He obeys boson statistics (T_c= 2.17 K)
- Pure ^{3}He obeys fermi statistics (no superfluid until very, very low temperature)
- When a fluid at point A is cooled to point B it undergoes superfluid transition
- At point C it separates into the ^{3}He and ^{4}He (‘dilute phase’) rich phase
- ^{3}He will float on top of the ^{4}He phase in the ‘mixing chamber’
- If we remove ^{3}He atoms from the dilute phase ^{3}He from the concentrated phase will cross the phase boundary to occupy the vacant state
- Cooling power = T^2 x Flow rate of ^{3}He