COSINUS: A cryogenic NaI dark matter detector using the novel "remoTES" design

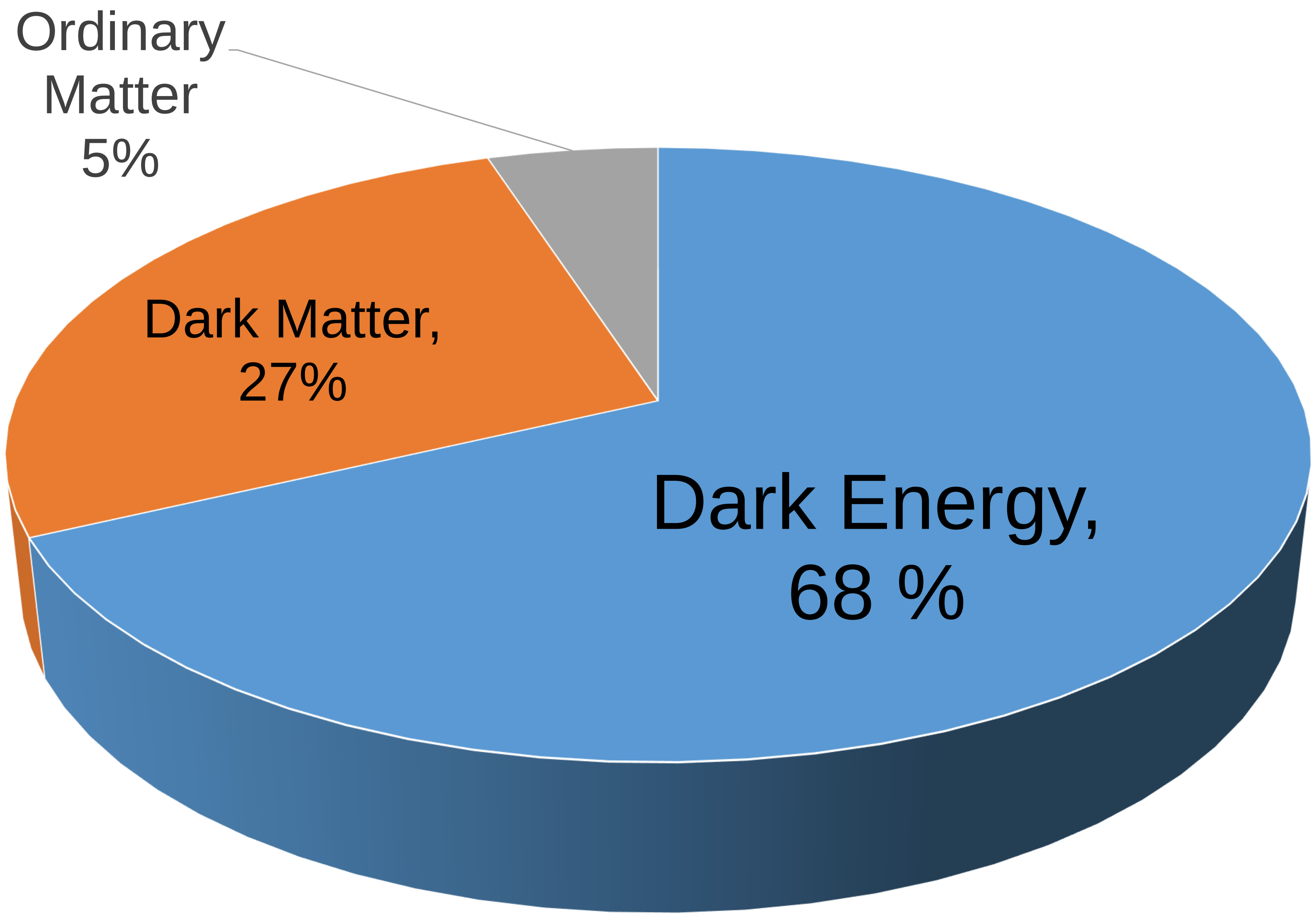
Presented by: Matthew Stukel
For the 24th International Workshop On Radiation Imaging Detectors

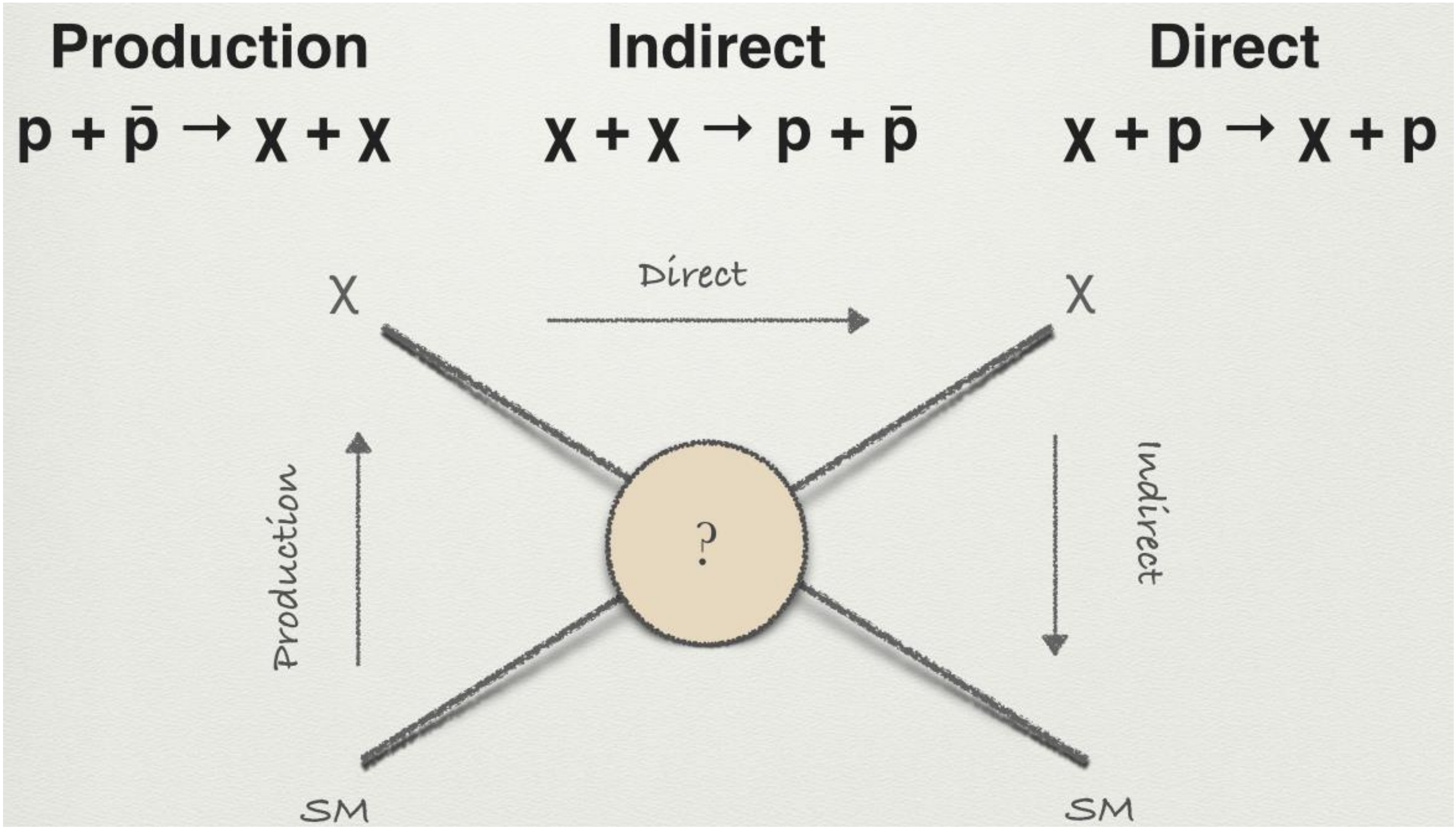
COSINUS

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Dark Matter

Dark Matter

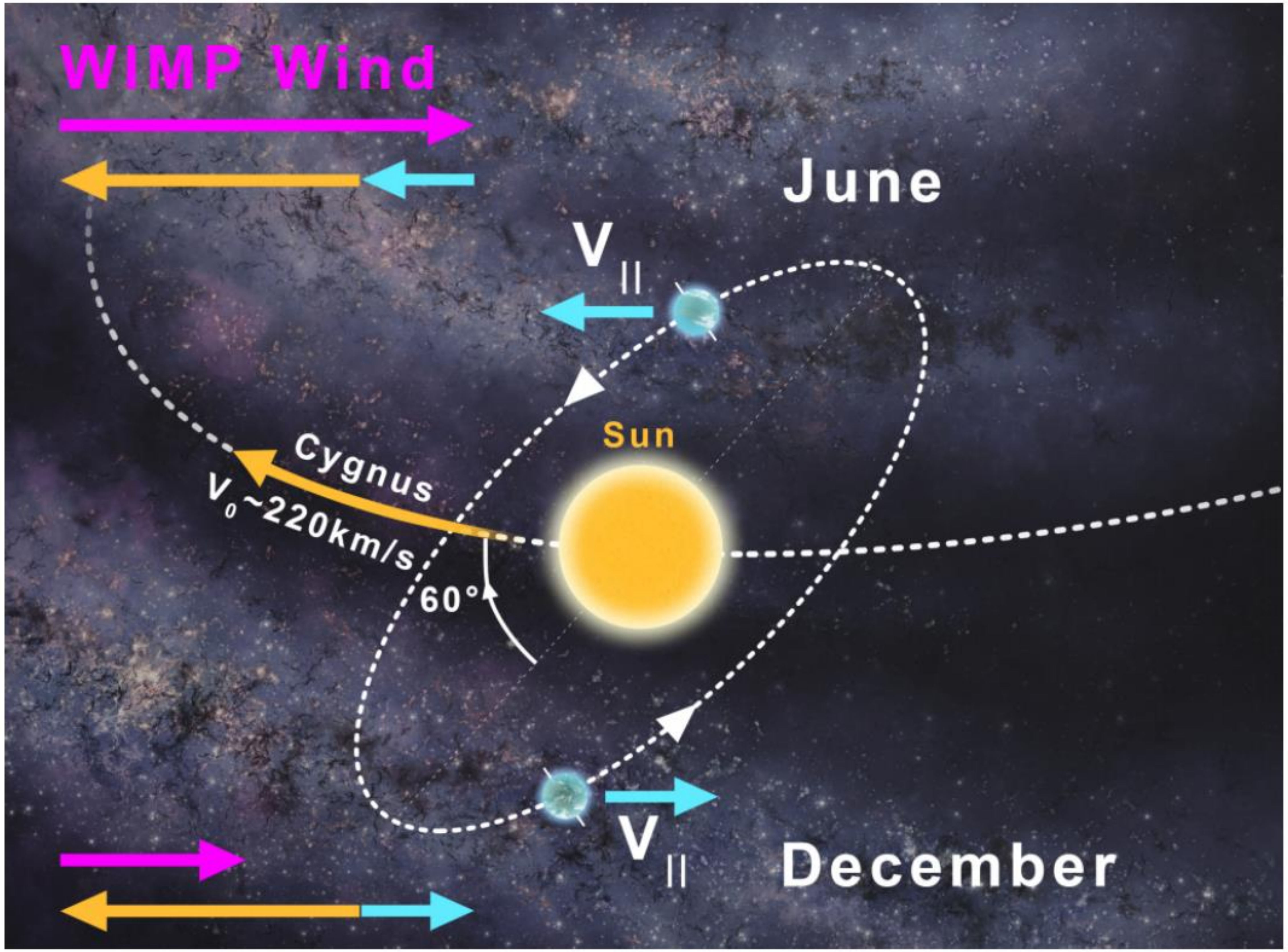




https://www.quantumdiaries.org/2014/10/22/have-we-detected-dark-matter-axions/

- Evidence includes: Rotation curves of galaxies, weak gravitational lensing, cosmological modelling
- Many experiments that employ many techniques!
- Direct Detection: Nuclear or electric recoils

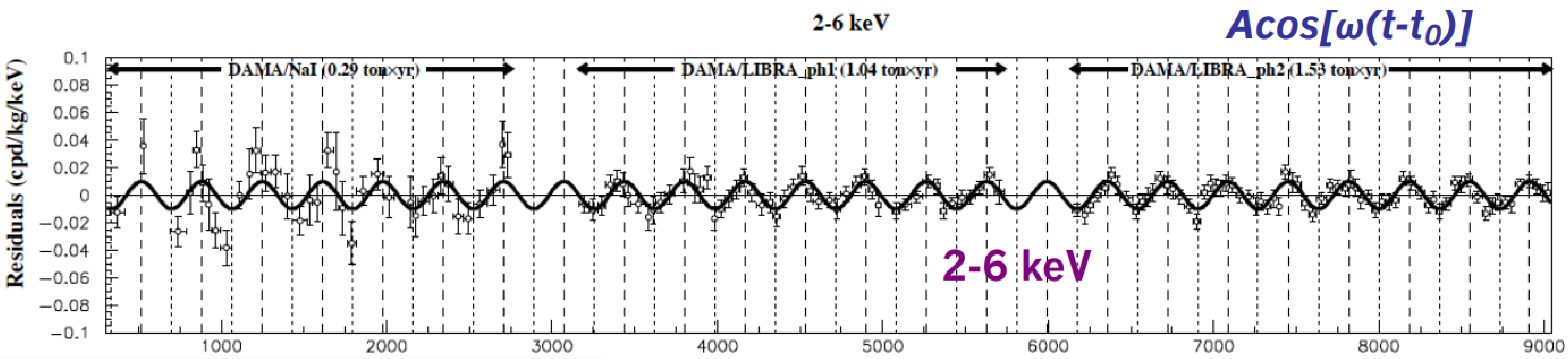
Direct Detection: Annual Modulation



https://iopscience.iop.org/article/10.1088/1361-6471/ab8e93/meta

- The sun moves through the galactic dark matter halo
- The earths rotates around the sun
- Induces a change in the dark matter flux throughout the year
- <u>Unique</u> and <u>detectable</u> signal for dark matter
  - Period of one year
  - Peaks around June 2nd
  - Signal expected in low energy region (O(keV))

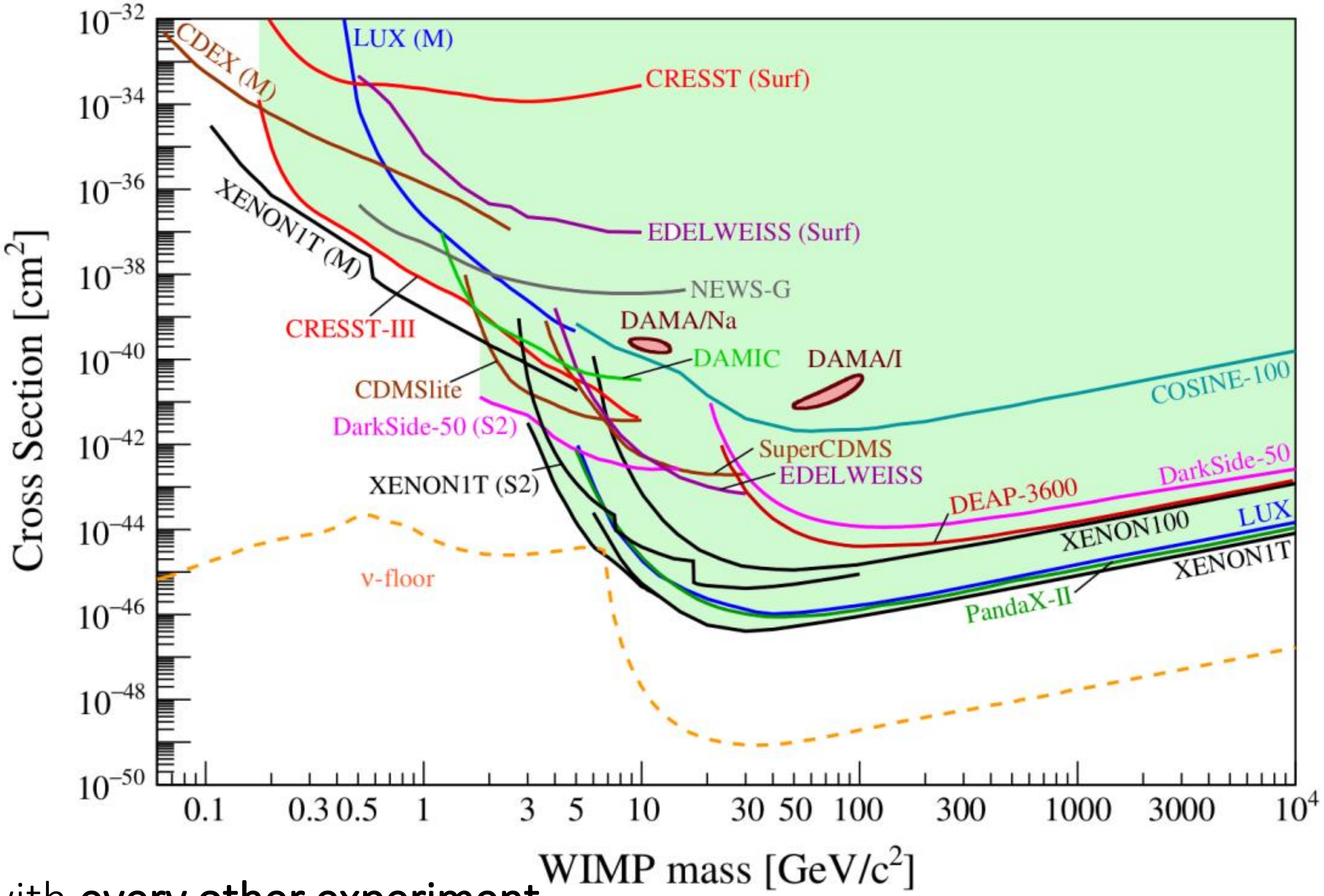
DAMA/LIBRA Results



https://indico.cern.ch/event/1188759/contributions/5230561/attachments/2622519/4534672/belli_DM2023_web.pdf

- The DAMA collaboration has detected a peculiar annual modulation signal since 1997
- Signal is consistent with WIMP dark matter halo predictions (0.75 keV threshold shown)
  - ✓ Statistics: >13σ
  - ✓ Period: 0.999 +/- 0.001
  - ✓ Phase: 25th May +/- 5 days
  - ✓ Non-dark matter explanation: No

Complications with DAMA



- Incompatibility with <u>every other experiment</u>

https://arxiv.org/abs/2104.07634

Response of DAMA

About interpretation and comparisons

See e.g.: Riv.N.Cim.26 ono.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, JMPA28(2013)1330022

...models...

- Which particle?
- Which interaction coupling?
- Which EFT operators contribute?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

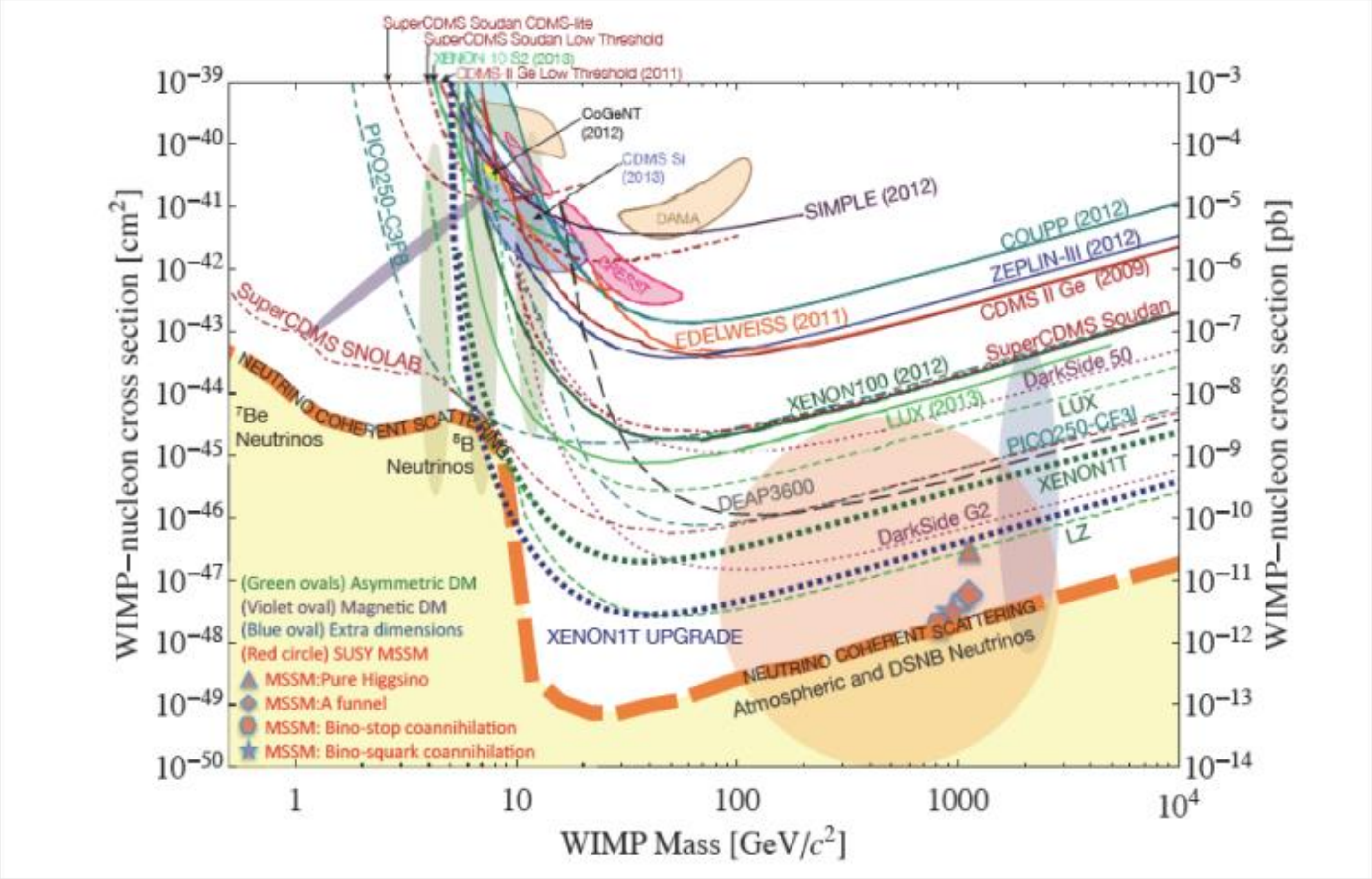
...and experimental aspects...

- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling
- ...

Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

No experiment can – at least in principle – be directly compared in a model independent way with DAMA so far

Is it an "universal" and "correct" way to approach the problem of DM and comparisons?

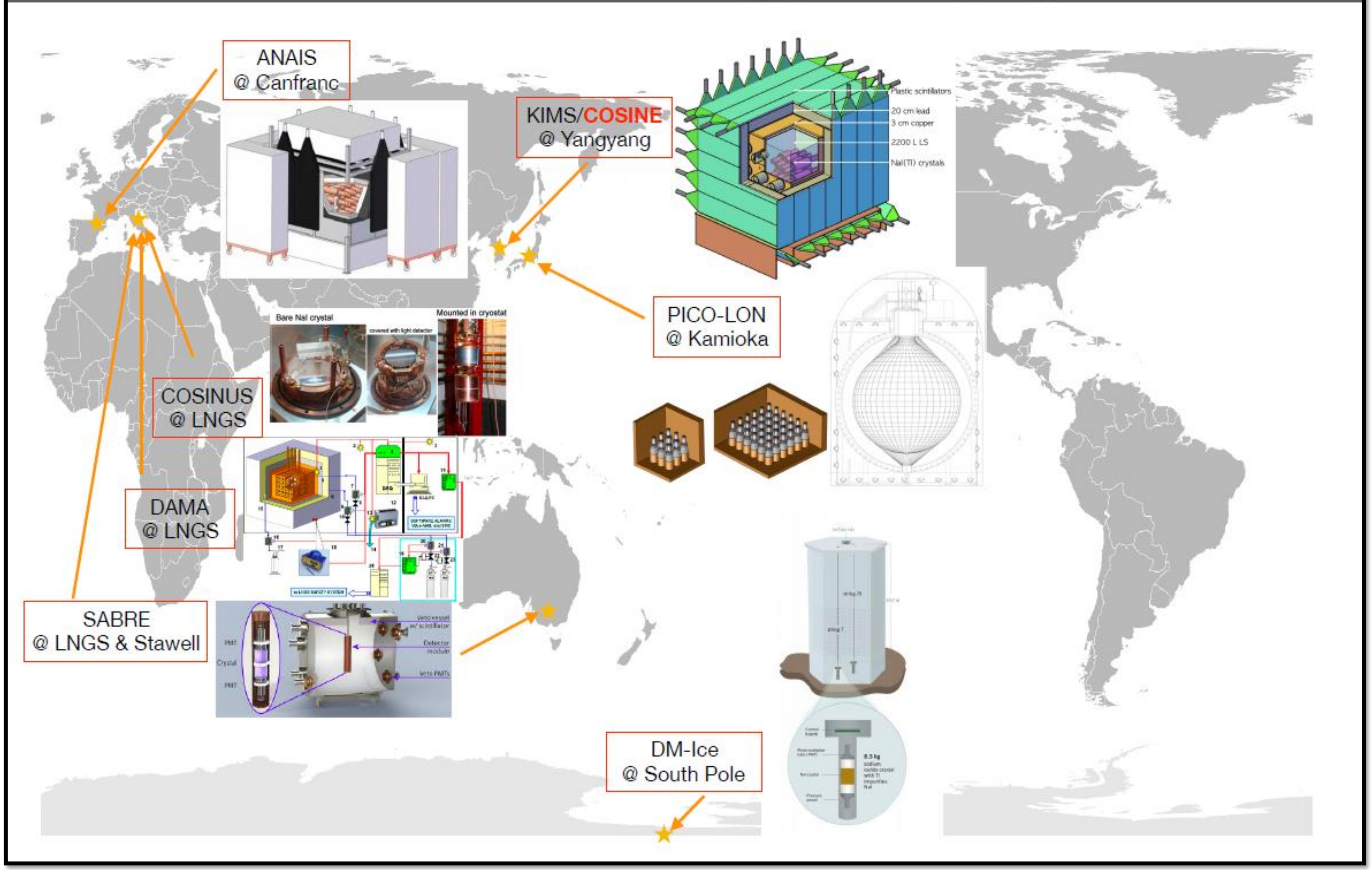


No, it isn't. This is just a largely arbitrary/partial/incorrect exercise

https://agenda.infn.it/getFile.py/access?contribId=34&sessionId=1&resId=0&materialId=slides&confId=15474

G S S I

Global Efforts using NaI(Tl)



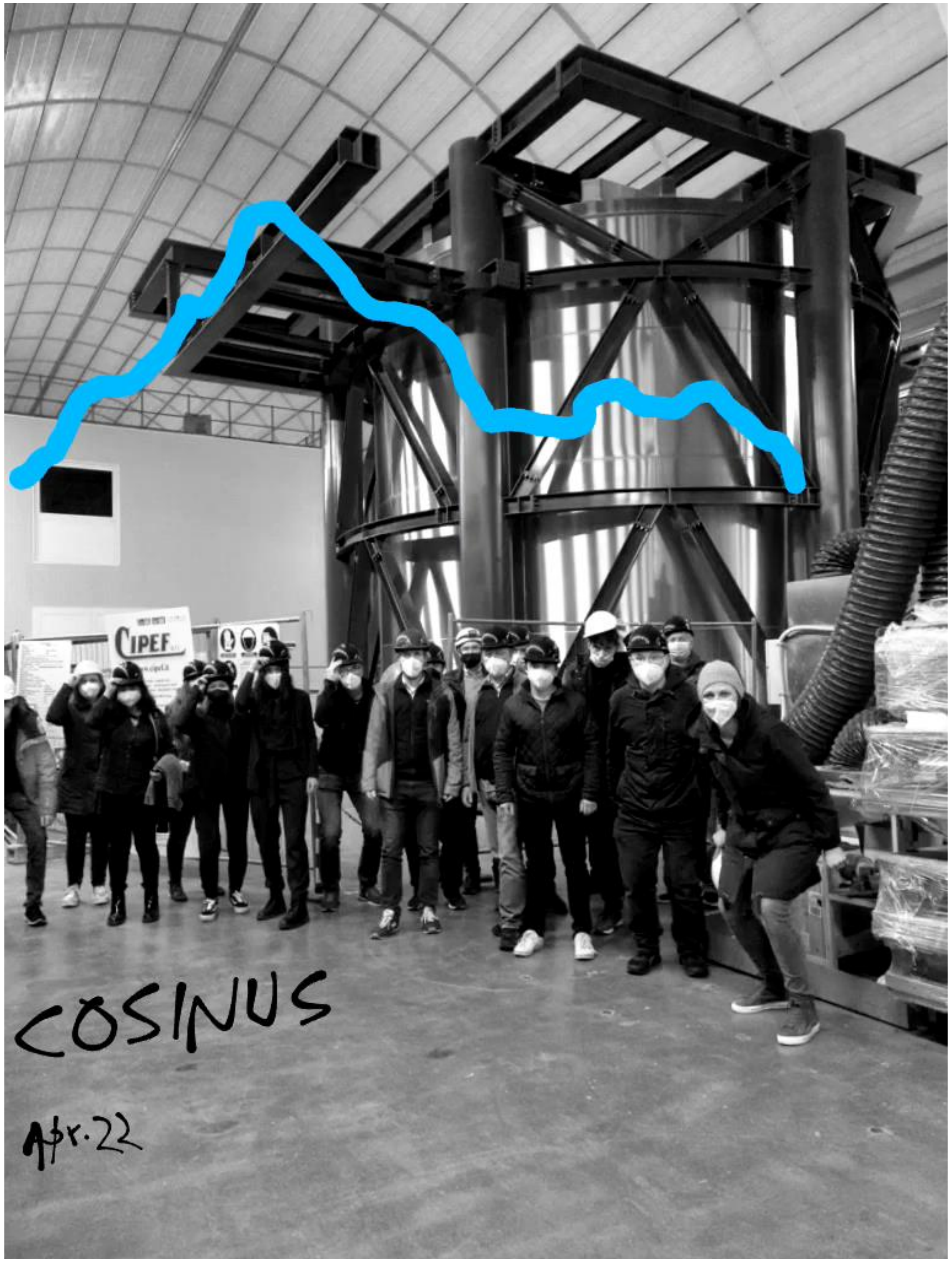
Astroparticle Physics European Consortium (APPEC) Recommendation:

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

COSINUS

Cryogenic Observatory for SIgnatures seen in Next-generation Underground Searches

GSSI



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

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SICCAS

TU WIEN

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INSTITUTE OF HIGH ENERGY PHYSICS

HELSINKI INSTITUTE OF PHYSICS

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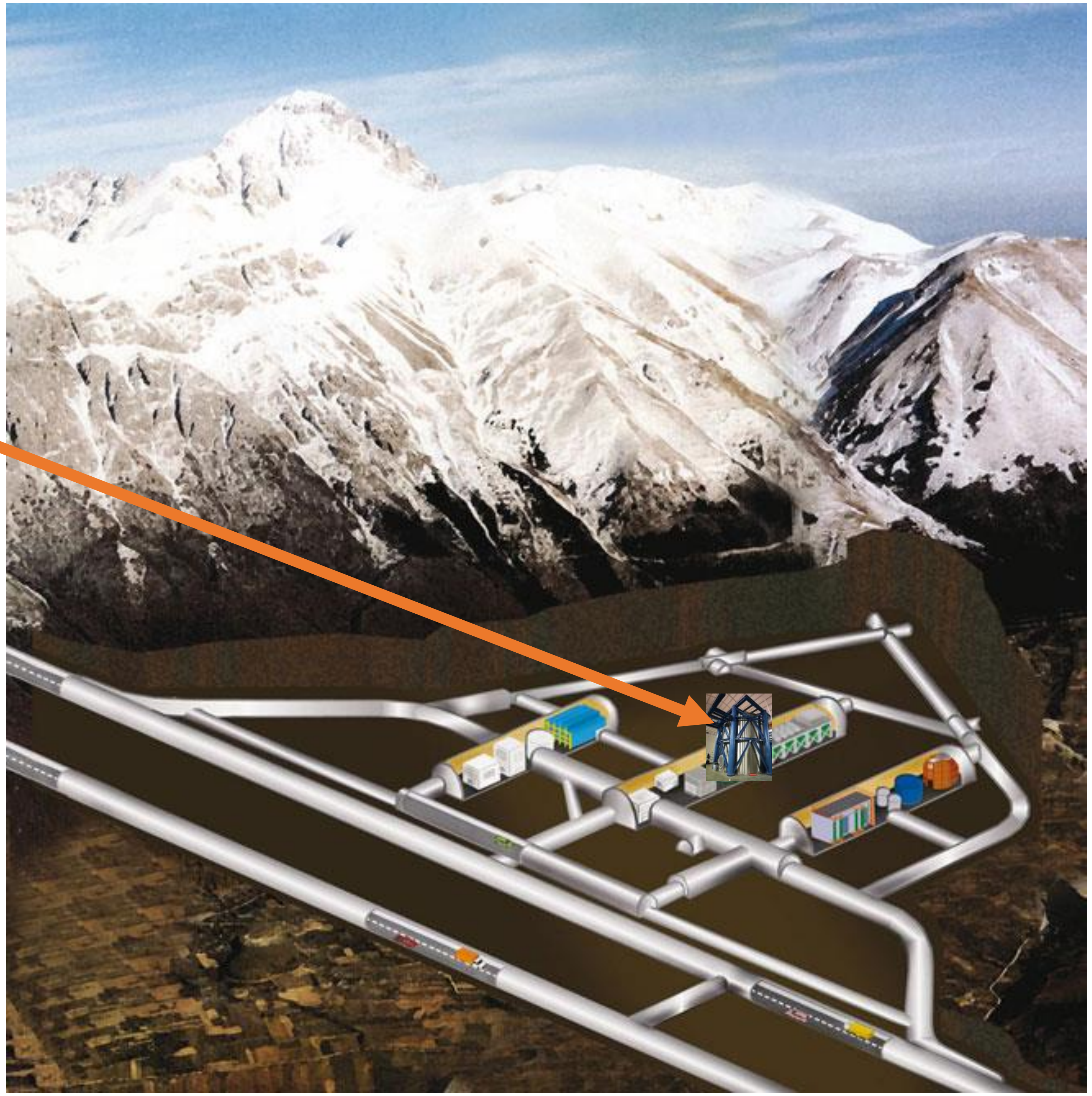
Gran Sasso National Laboratory (LNGS)

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

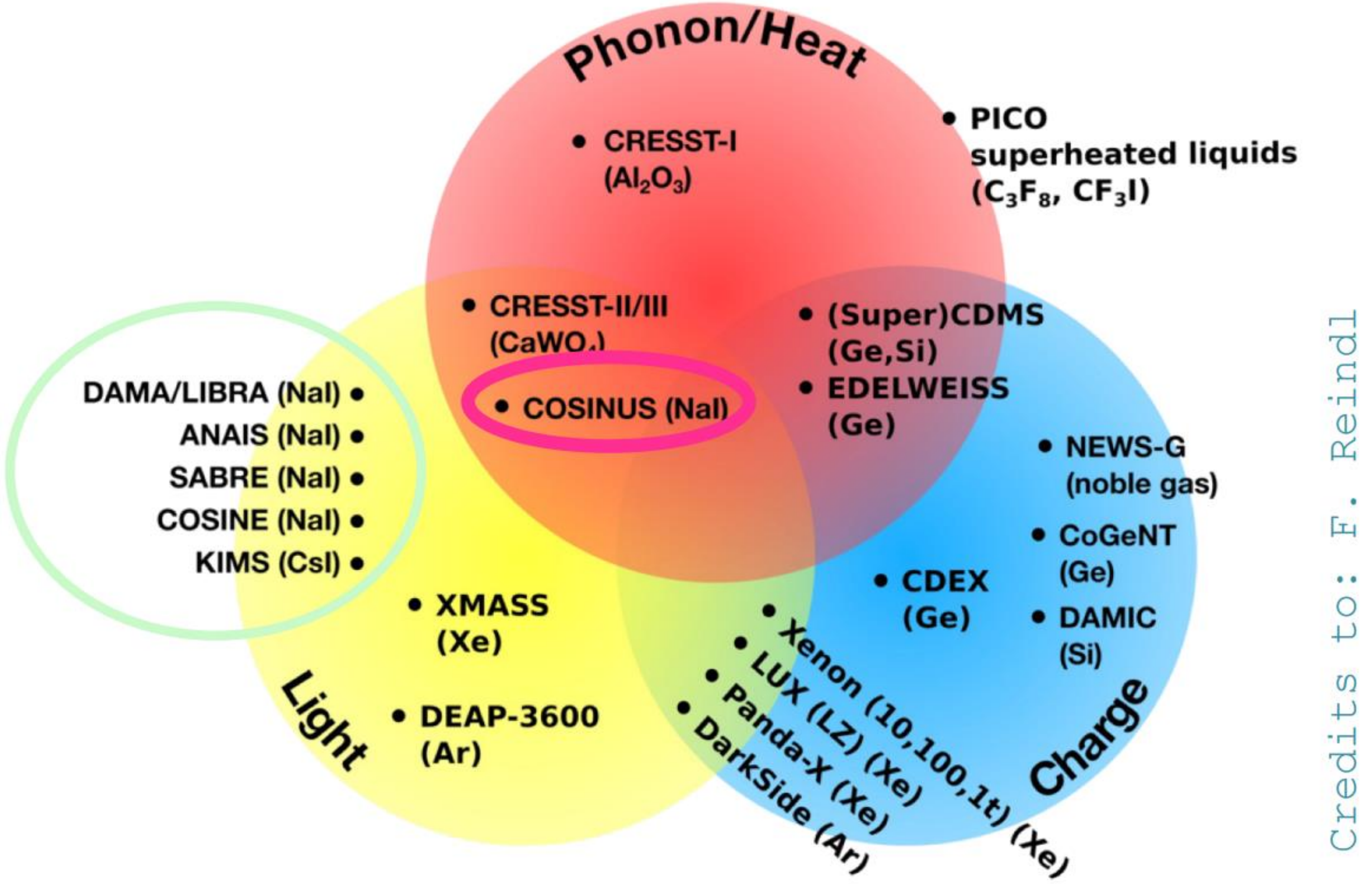
COSINUS Location



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

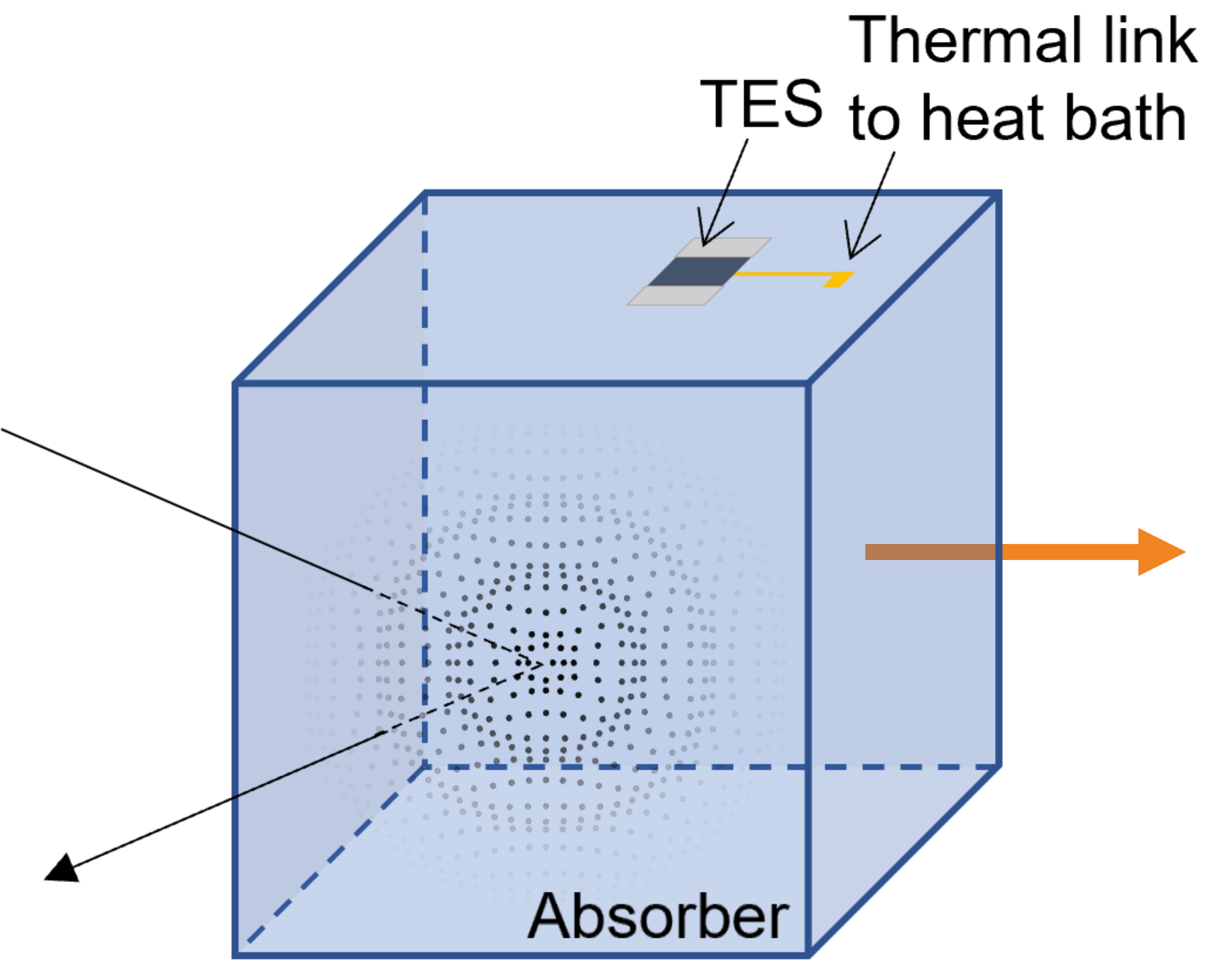
- LNGS provides 3500 m of water equivalent shielding from cosmic radiation

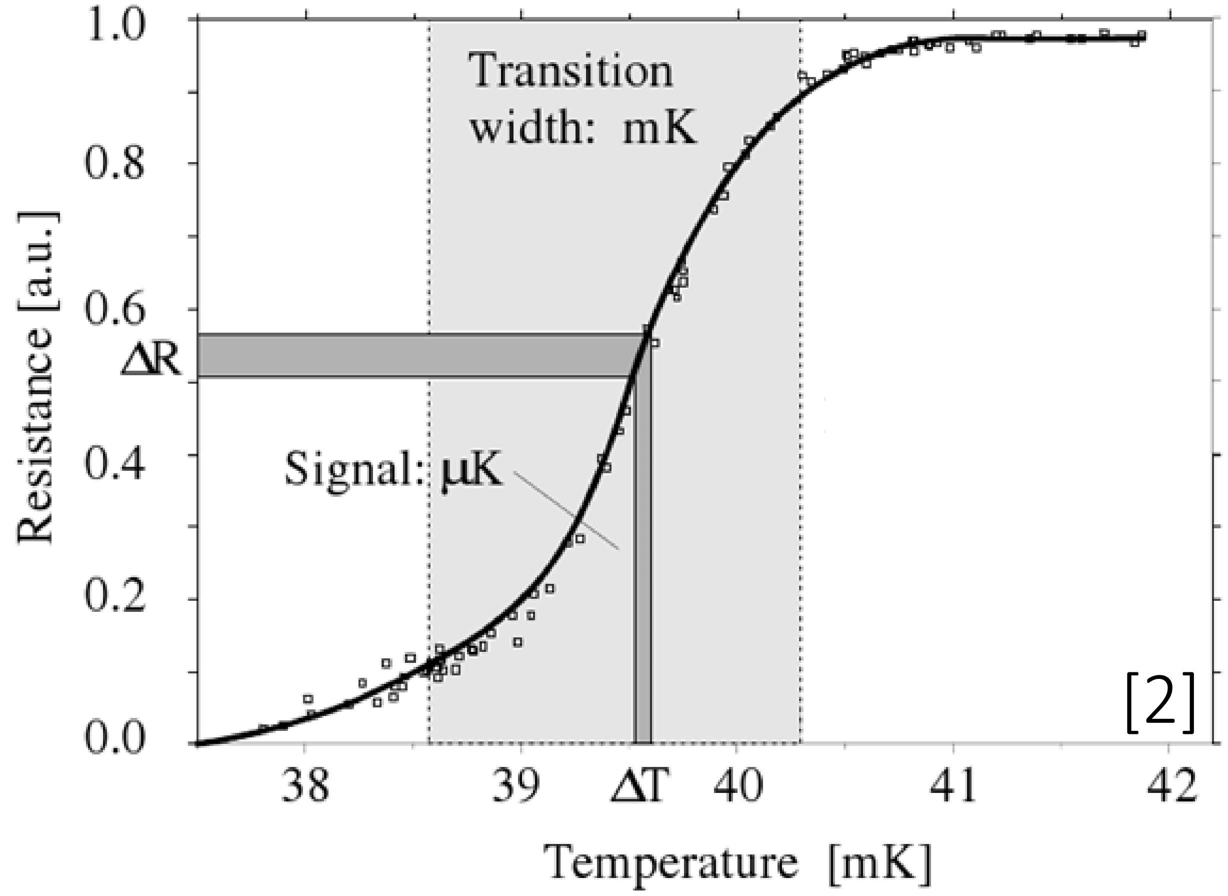
Landscape of Dark Matter Experiments

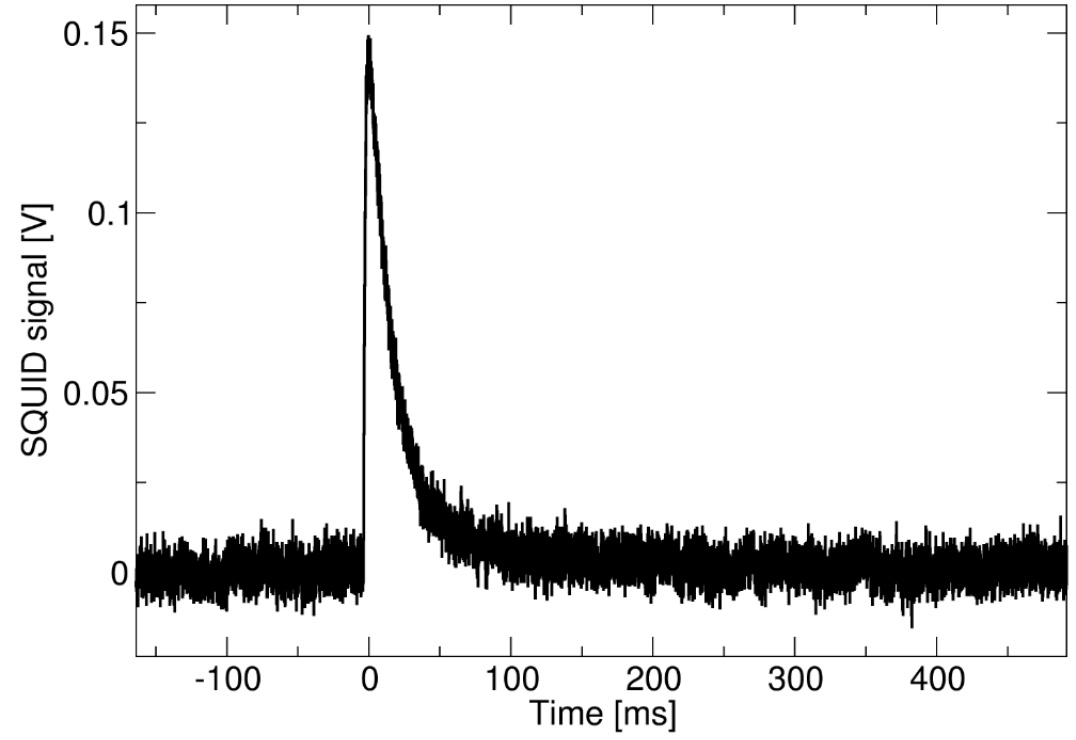


- **<u>Goal:</u>** Aims at a model independent test of the DAMA/LIBRA experiment
  - Same material (NaI)
  - Same location (LNGS)
- **<u>Unique Technique:</u>** Operate NaI as a cryogenic detector (First ever!!)
  - Dual Channel: Phonon (90%) and Light (10%) signal for **<u>event-by-event particle discrimination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

NaI - Phonon Signal Measurement



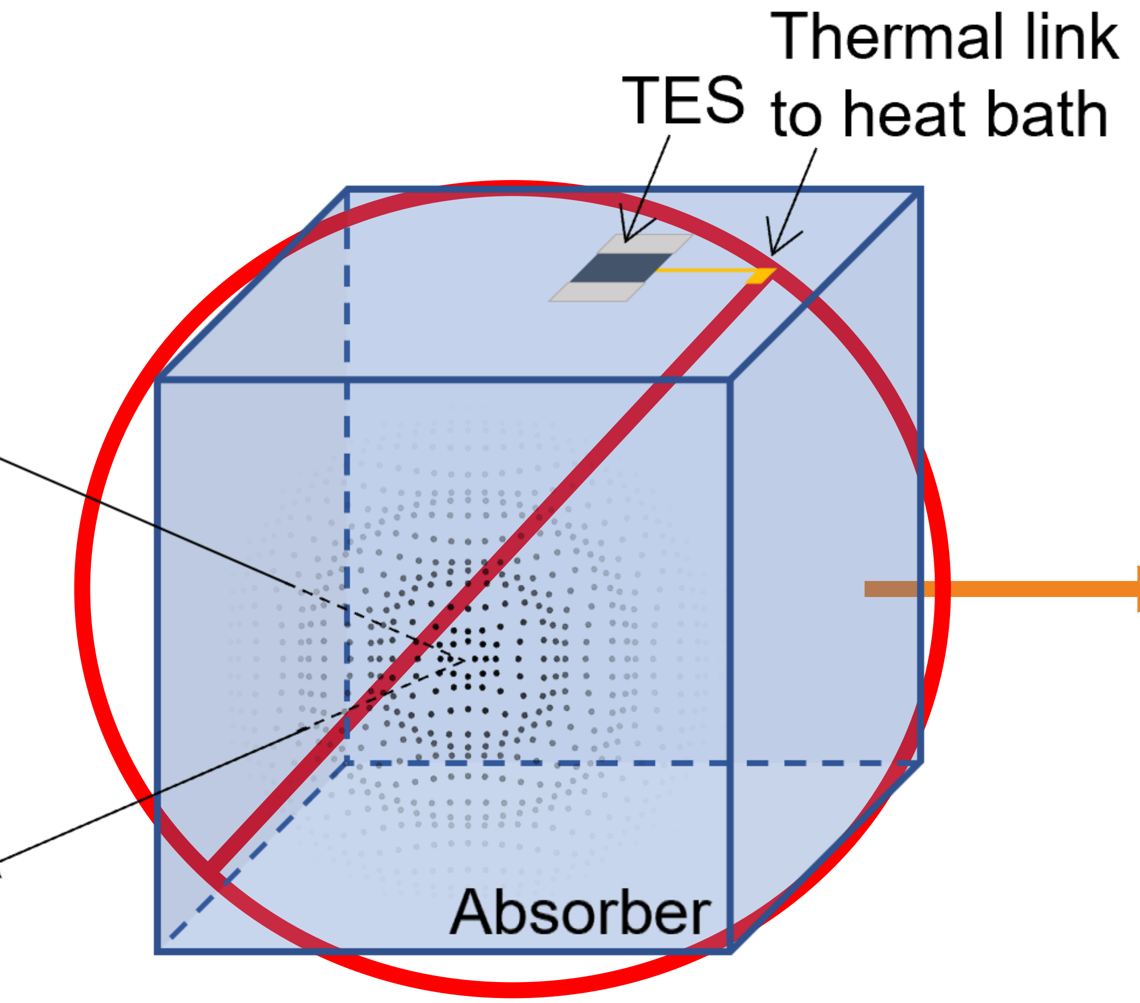


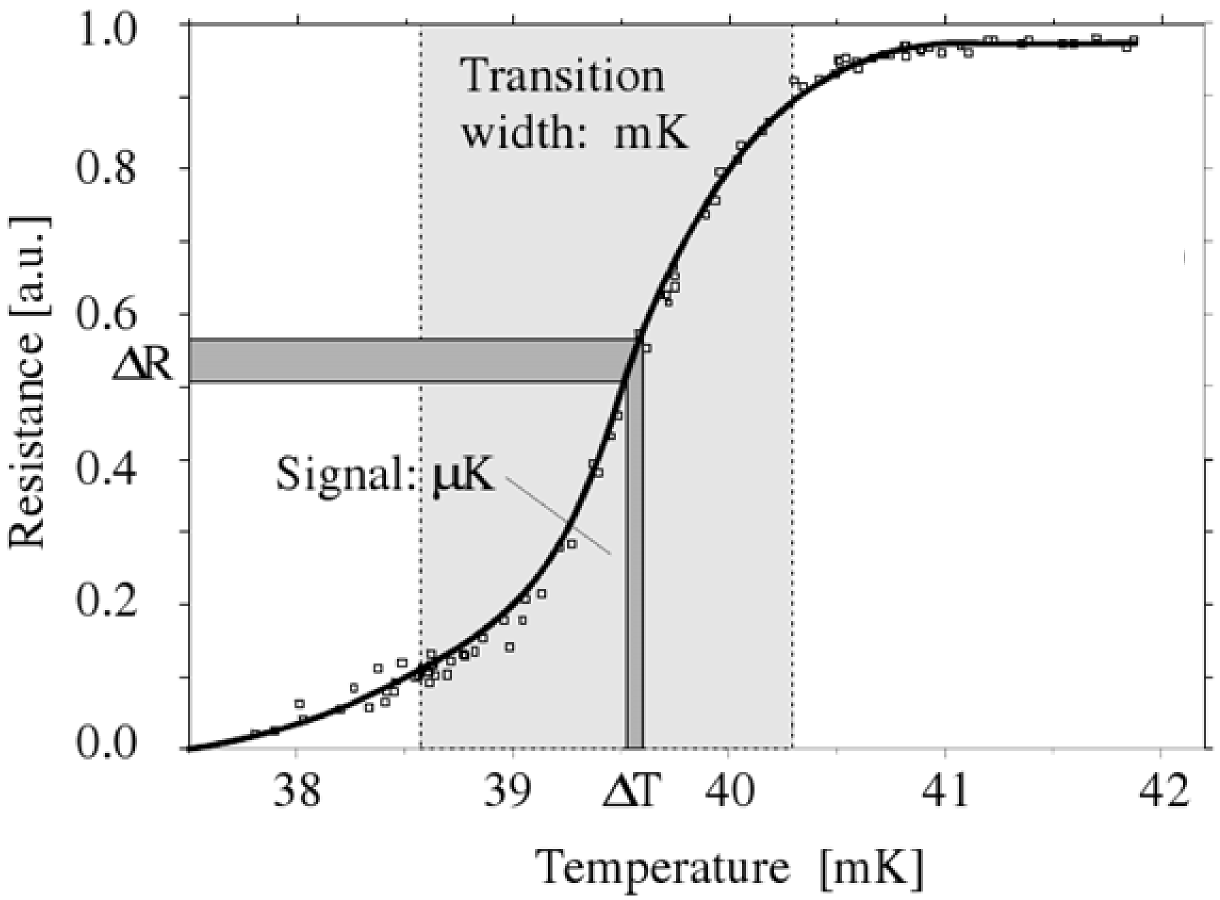


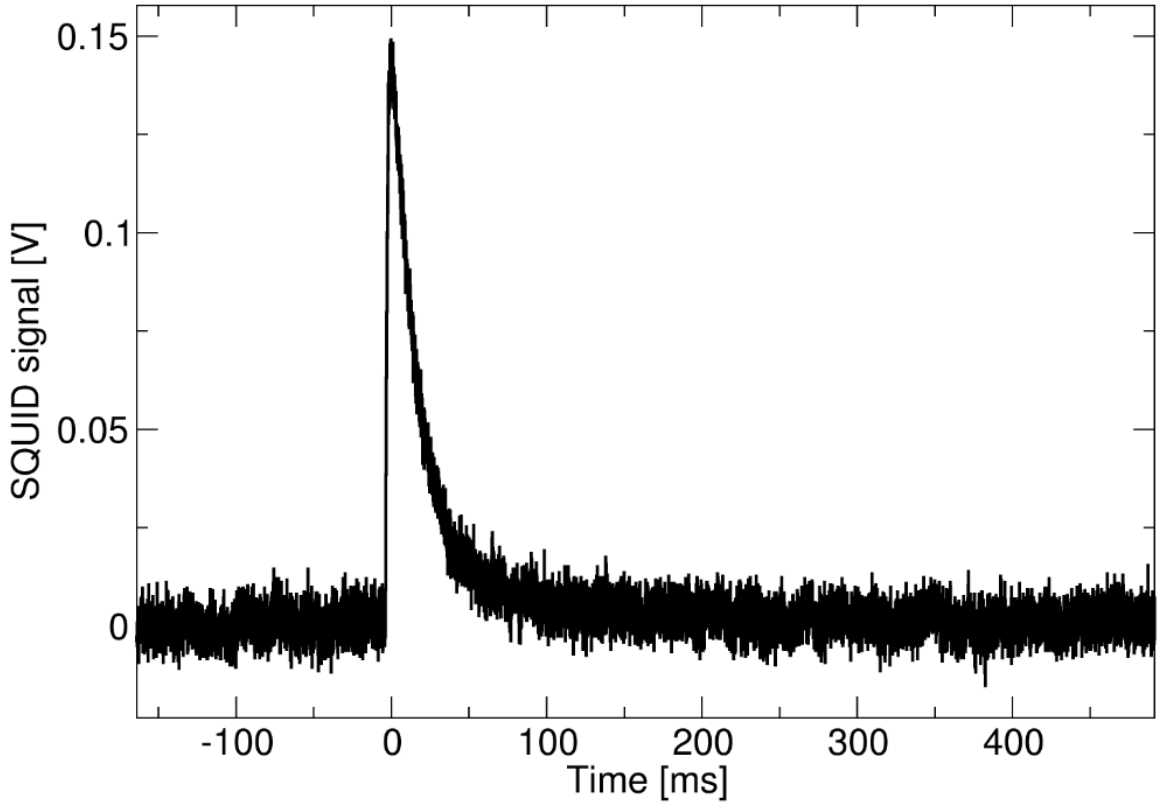
[3]

- 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 not so NICE

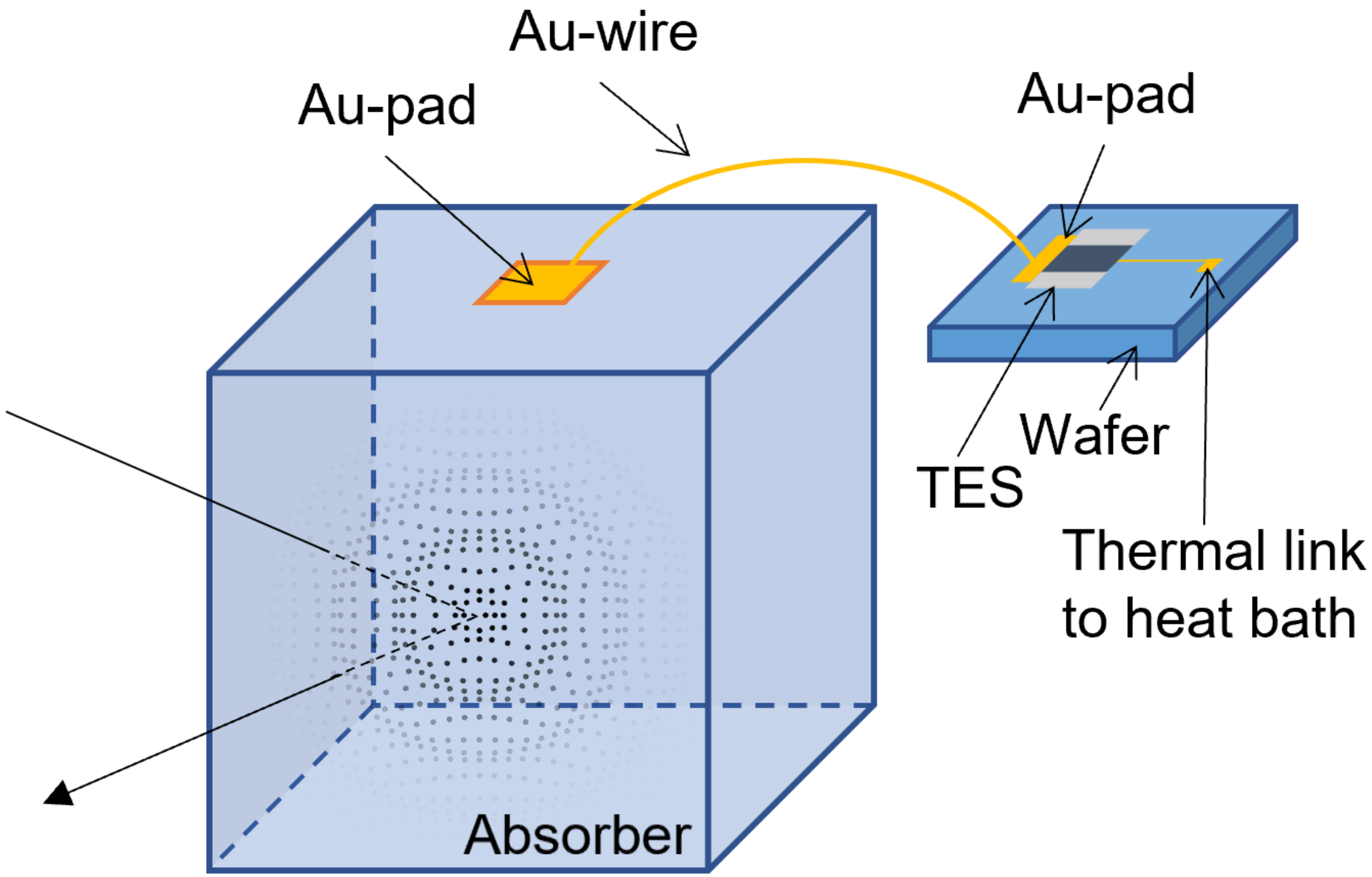






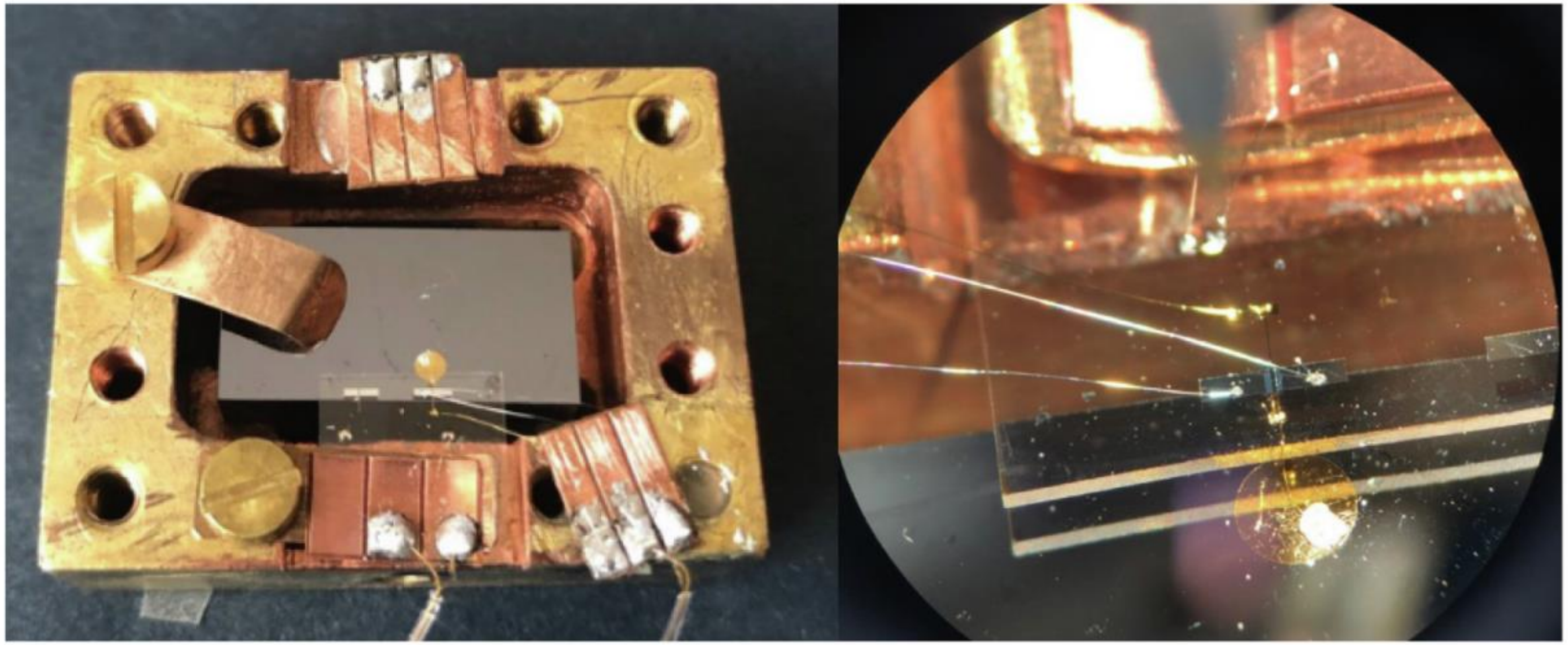
- Difficulties with attaching TES directly to NaI
  - NaI is hygroscopic (cannot come into contact with humid air)
  - Very soft and low melting point (easy to damage when handling)
  - Not suited for traditional thin film deposition
- Solution: **remoTES**

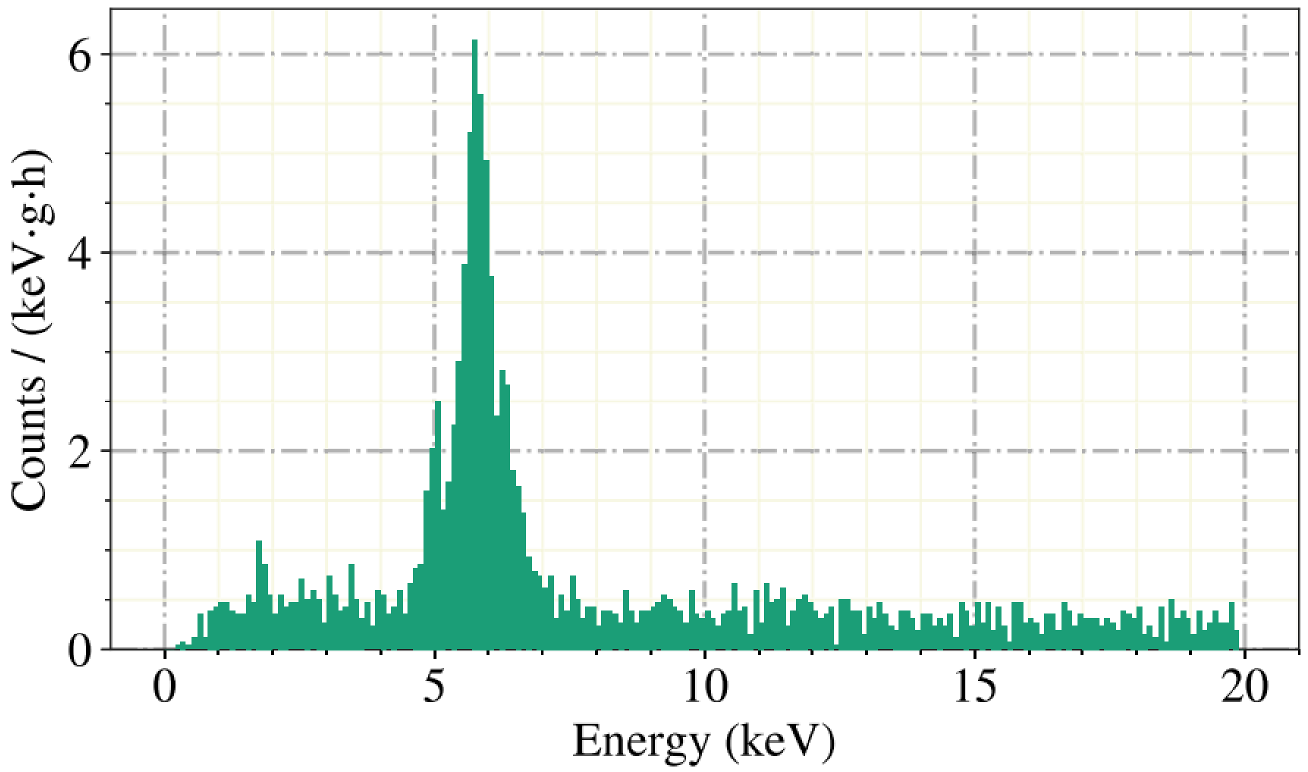
NaI- remoTES design



- Implement <u>**remoTES**</u> design, first proposed by Matt Pyle
- 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

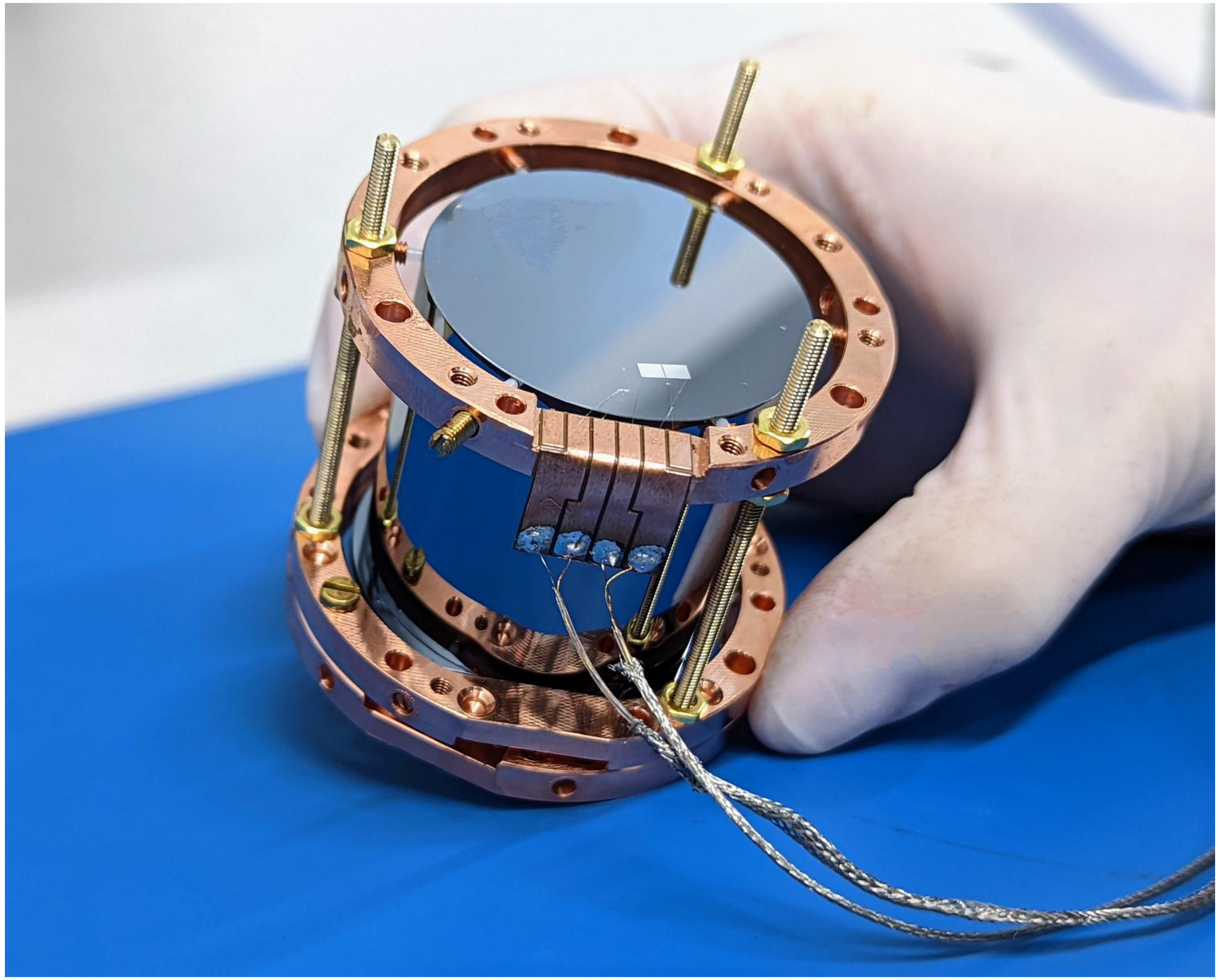
First measurement of remoTES





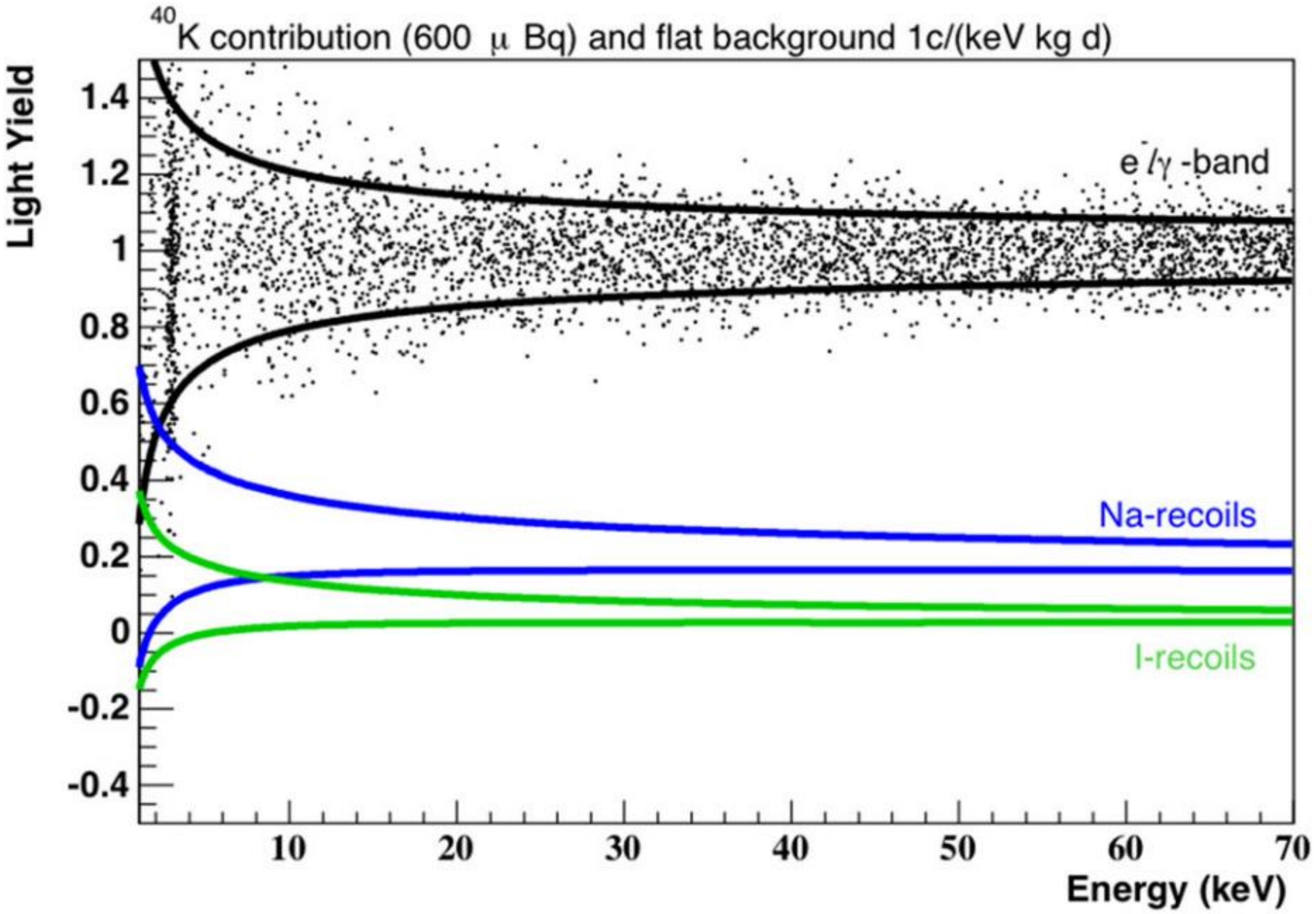
- Although ideal for NaI the first measurements of the novel remoTES idea was performed on Si and TeO_2
  - Si is highly studied for low temperature detectors
  - TeO_2 is thermally very similar to NaI
- Si resolution achieved was 88 eV
- TeO_2 resolution achieved as 193 eV
- Baseline threshold is 5 times lower then quoted resolution

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
- Resolution: 990 eV_{ee}

COSINUS: Particle Discrimination



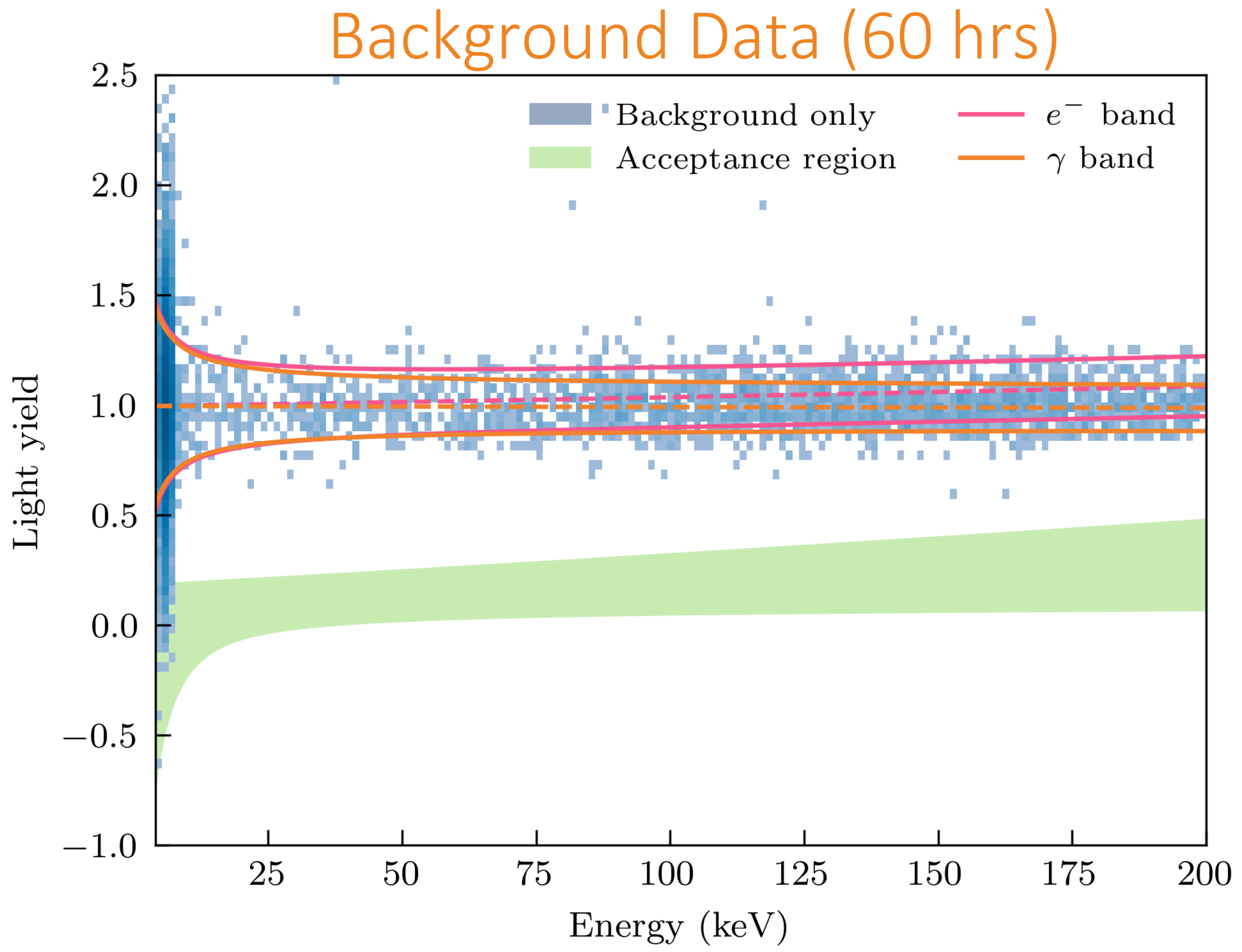
Angloher, G., et al. "Simulation-based design study for the passive shielding of the COSINUS dark matter experiment." *The European Physical Journal C* 82.3 (2022): 1-11

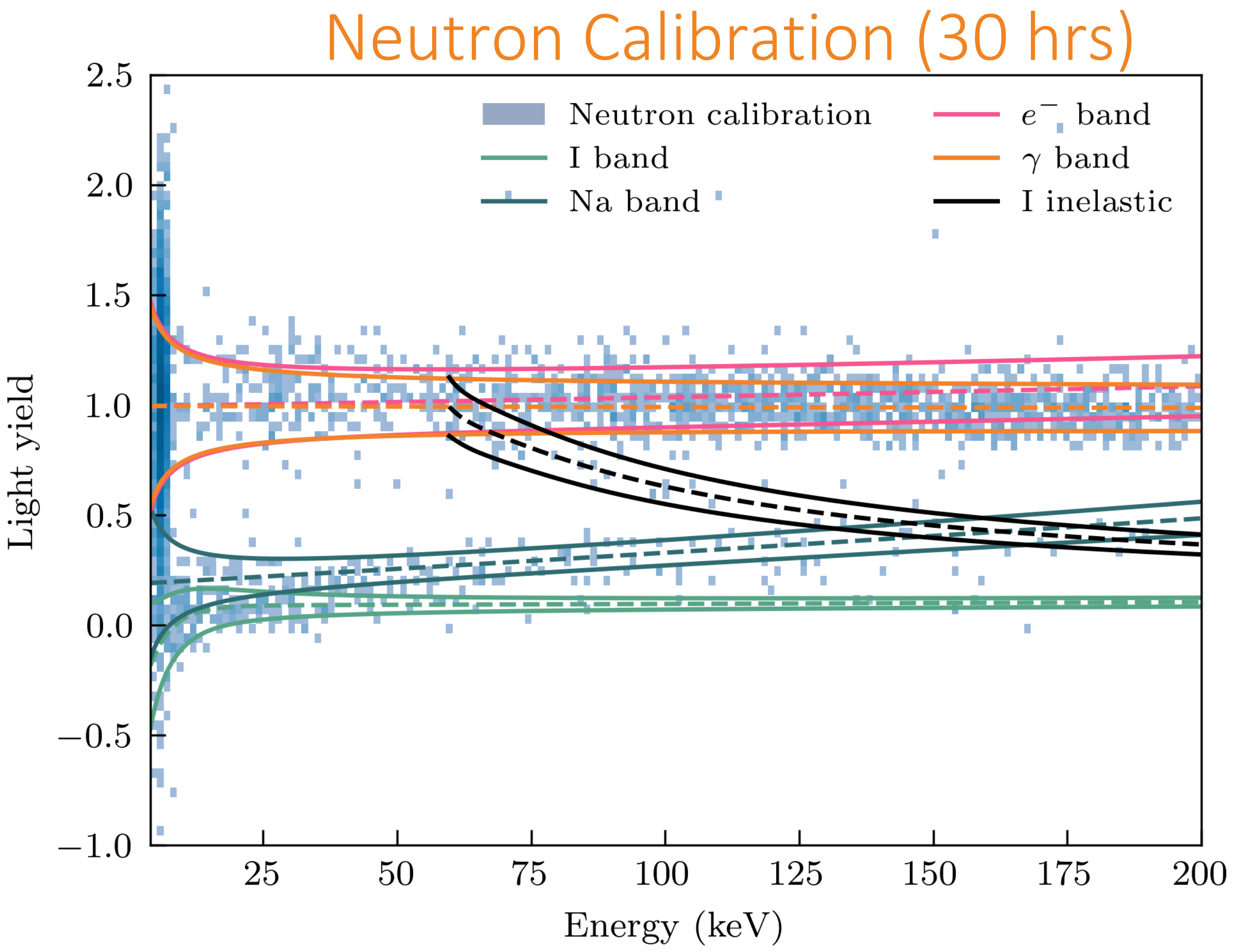
- Particle discrimination is the COSINUS advantage

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

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

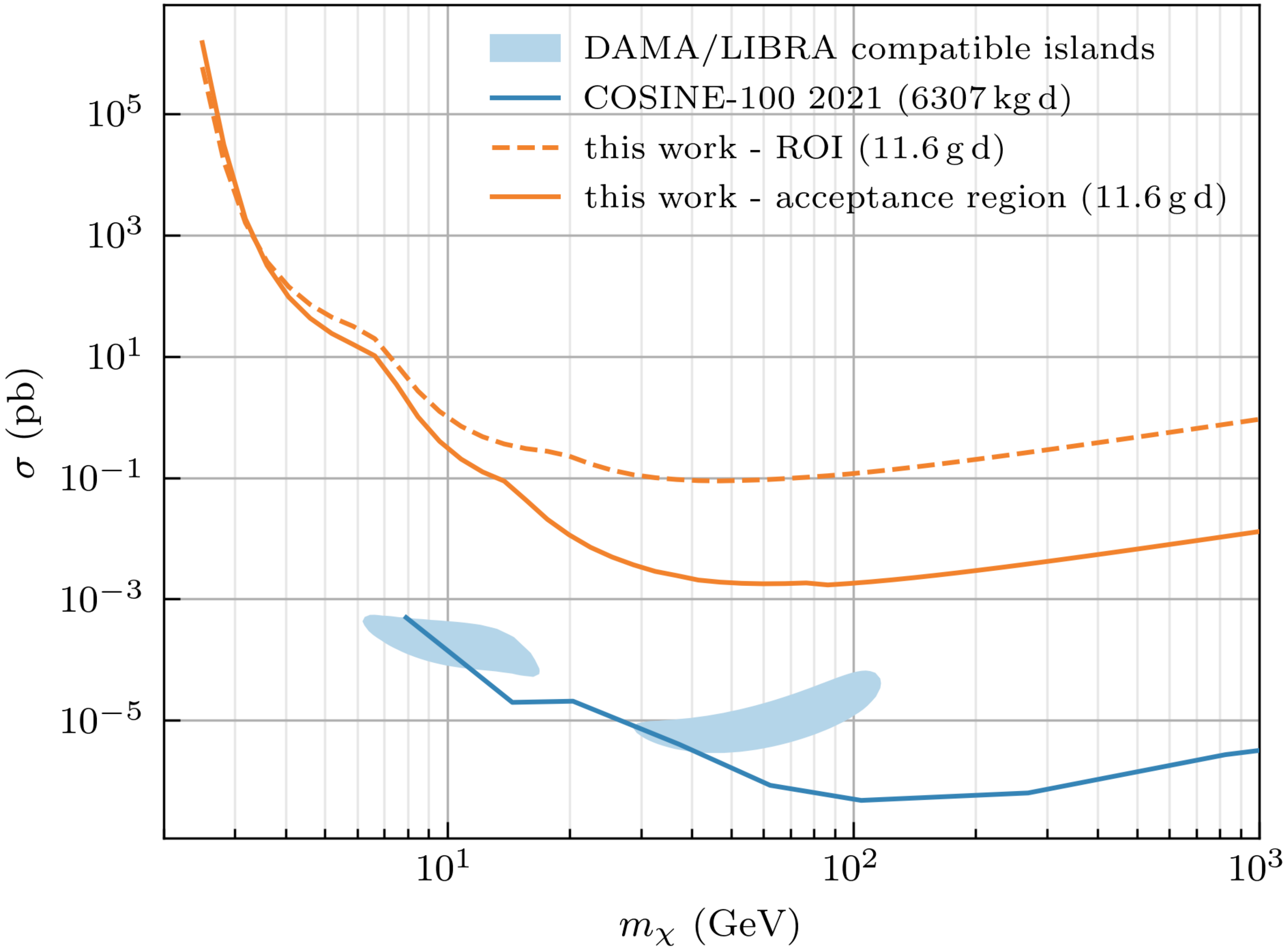
COSINUS: Particle Discrimination





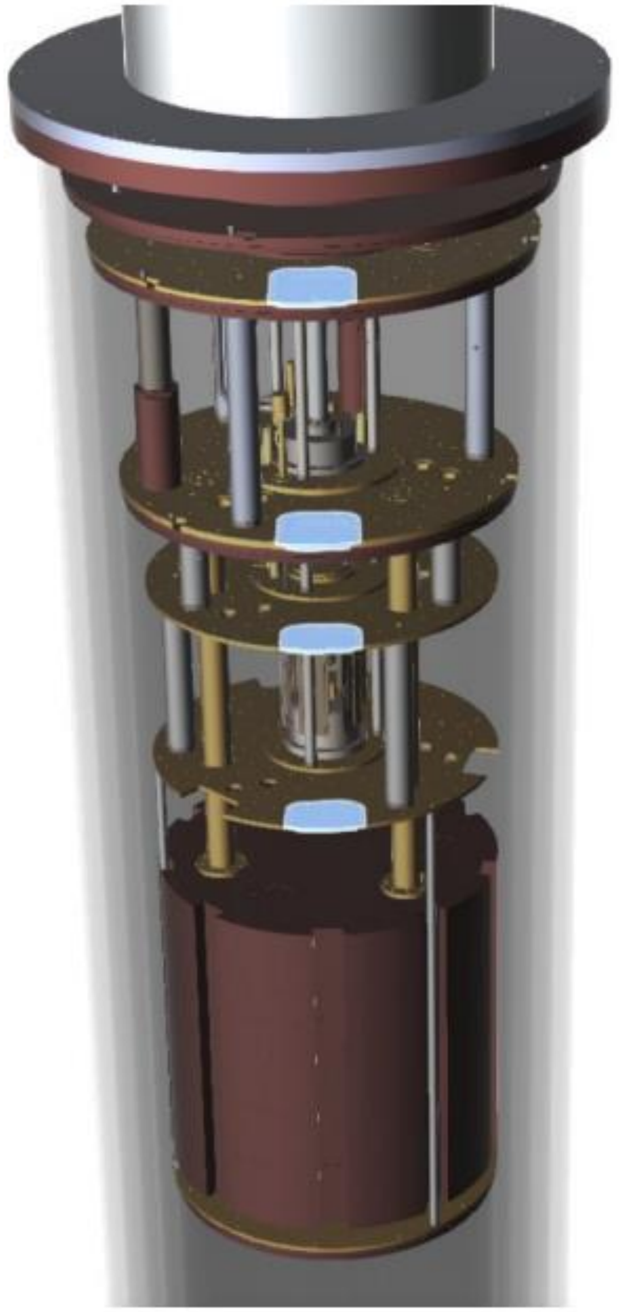
- December 2021: Demonstrated the first particle discrimination in NaI at a surface setup
- June 2022: Measurement was carried out using a CRESST test facility at the Gran Sasso National Laboratory (underground)
- Plots by Leonie Einfalt, publication in preparation
- NaI phonon resolution: 440 eV_{nr}
- Neutron band is clearly visible, <u>proof of particle discrimination in NaI</u>

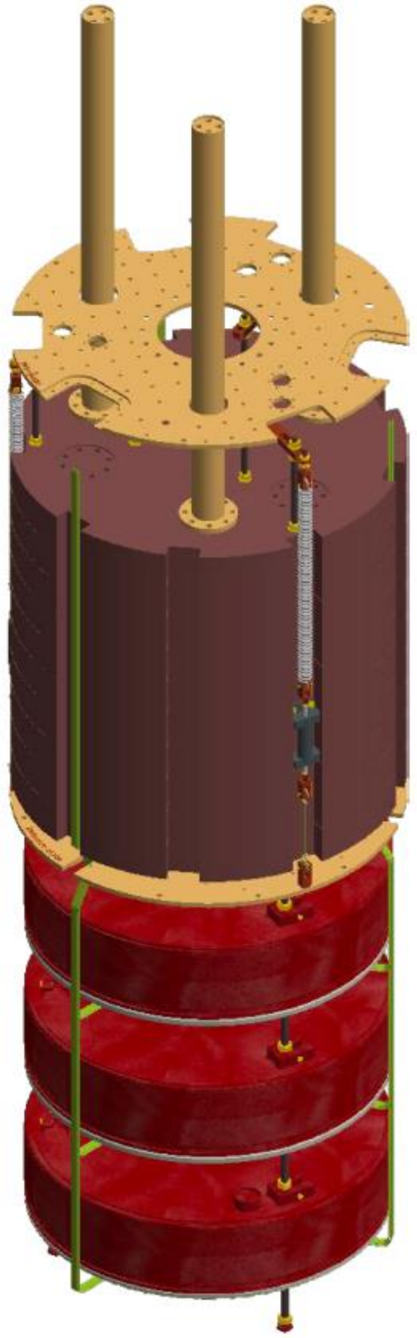
COSINUS: Current Status

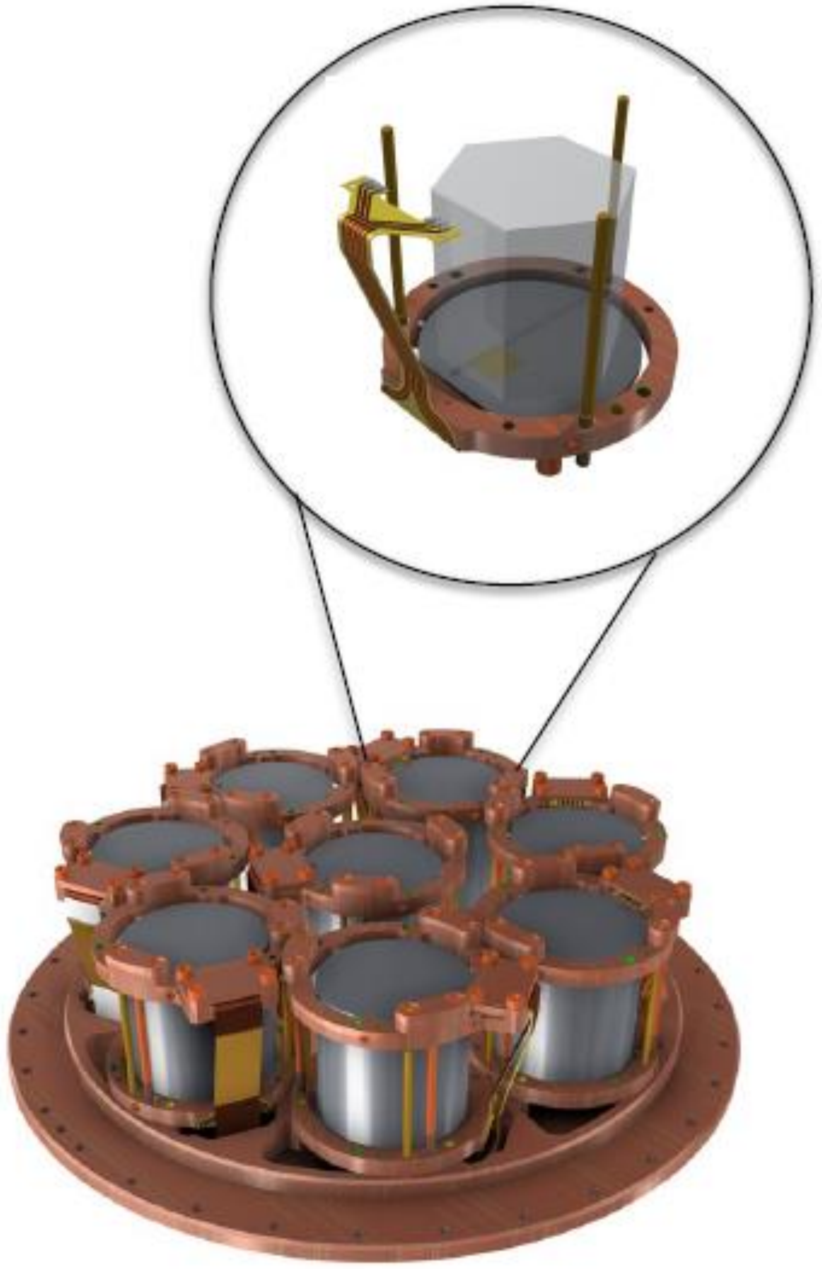


- 1 module (3.6g) of NaI
- 11.6 g·d exposure
- 1 order of magnitude away from DAMA/LIBRA
- 3 order of magnitude lower then COSINE-100
  - They have 10^5 times larger exposure

COSINUS: Dry Dilution Refrigerator





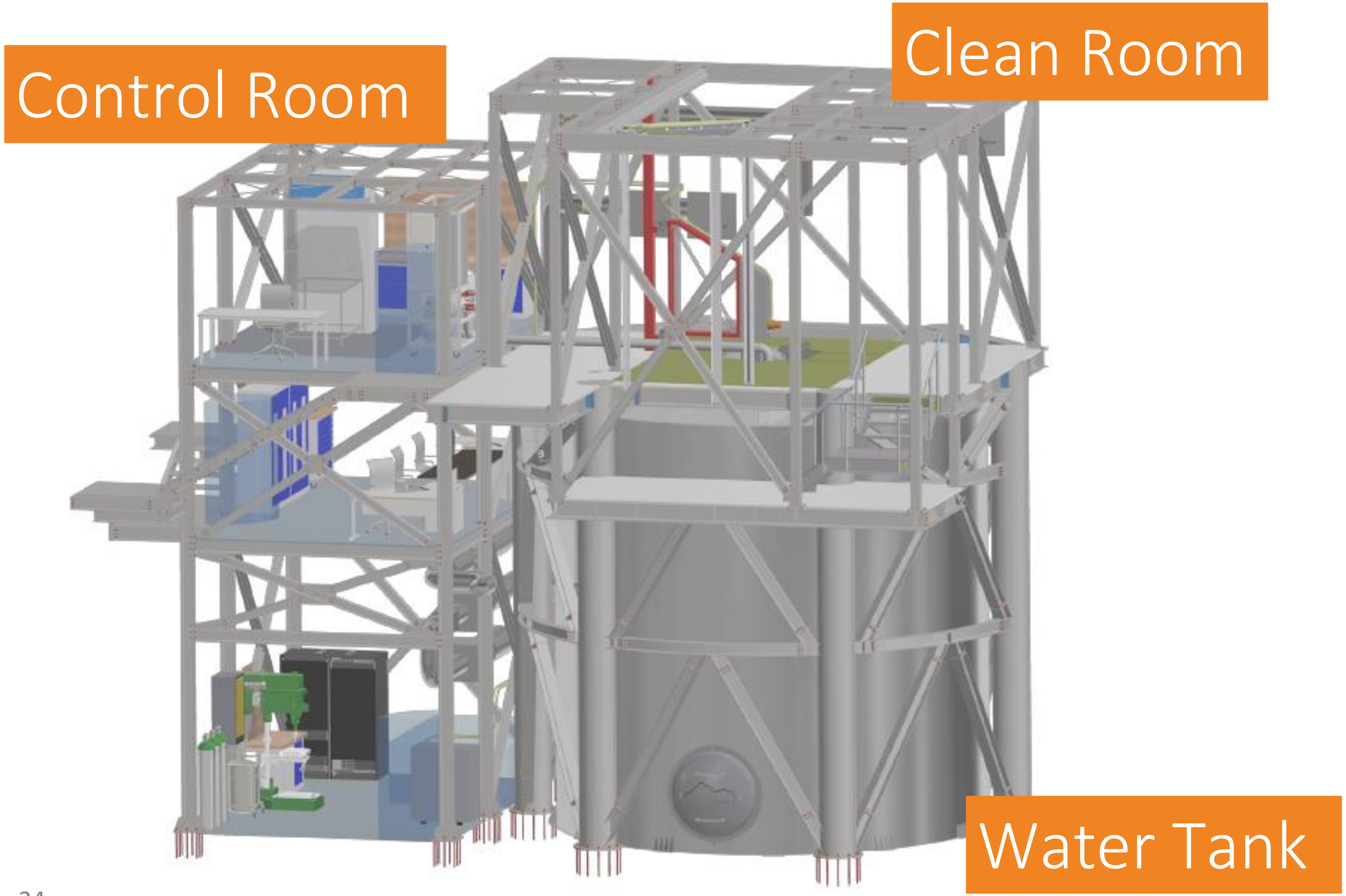


- Detectors housed in a pulse tubed assisted dilution refrigerator (mK)
- Three stage vibration decoupling: Global, Cryostat and Detector
- Ultra-pure copper for shielding the detectors from cryostat radiogenics

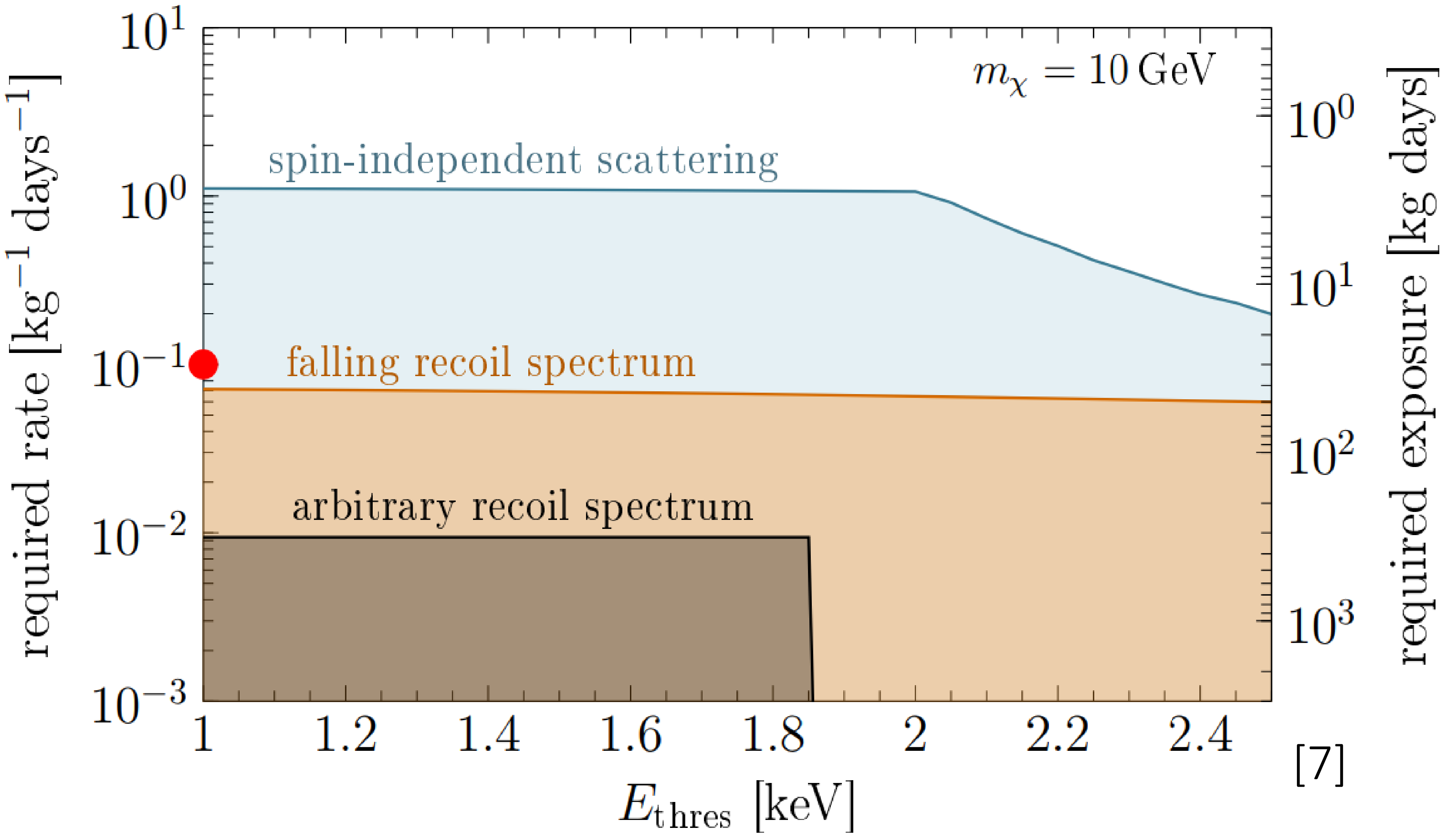
Experimental Setup I

Experimental Setup II

Experimental Setup III



COSINUS Physics Goals I

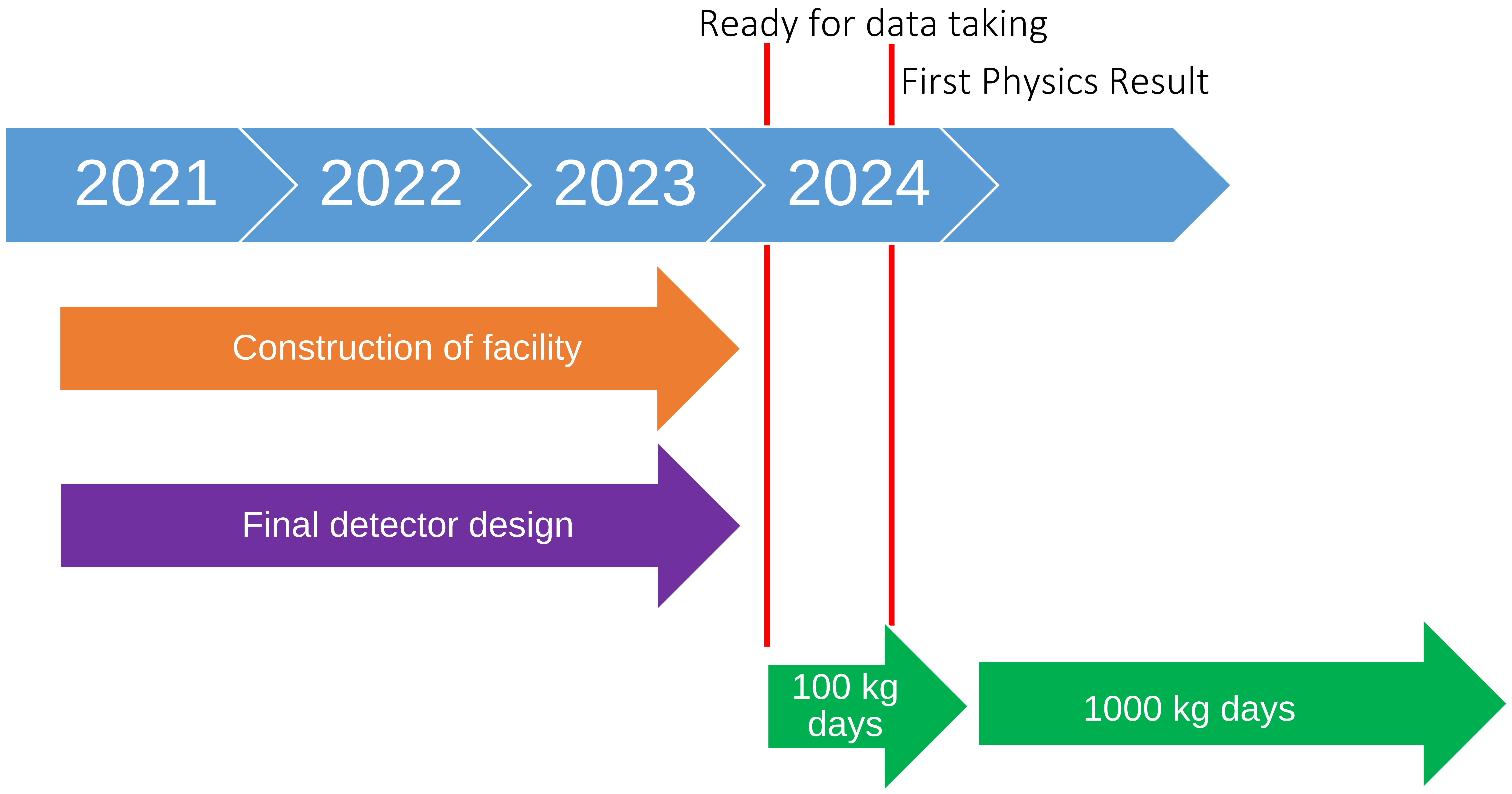


[7]

*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
  - Model independent exclusion
  - 100 kg•days: Exclude an elastic scattering scenario independent of DM halo
- COSINUS-2π
  - Annual modulation signal
  - Increase target mass capability, more than double the number of detectors

COSINUS Timeline



Conclusion/ Summary

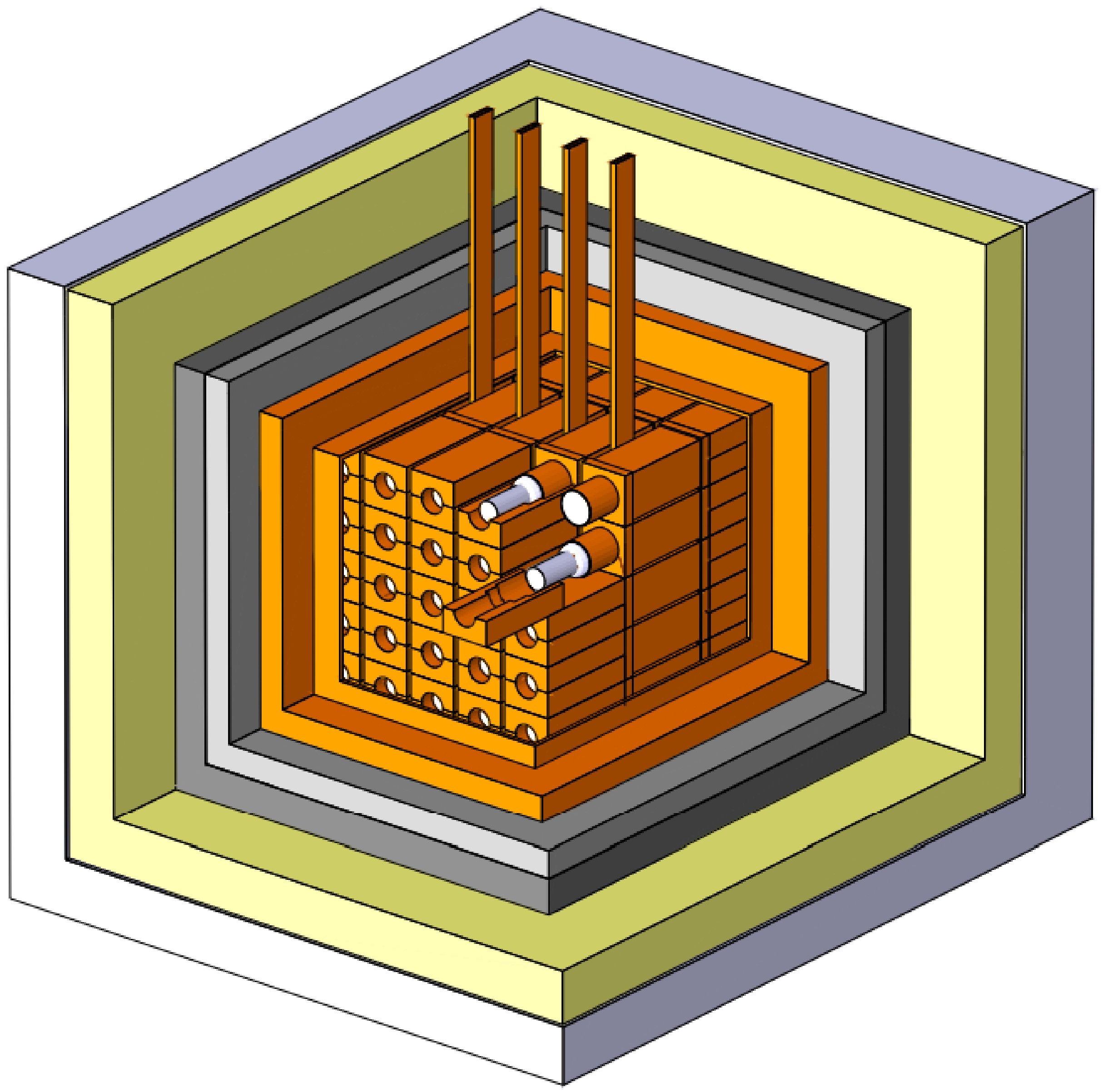
- The search for dark matter is on the forefront of modern particle physics
- Effective annual modulation of dark matter is a unique and important way to continue this search
- COSINUS is a cryogenic NaI dark matter experiment whose goal is to verify the longstanding DAMA/LIBRA dark matter claim
- COSINUS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

Thank You!

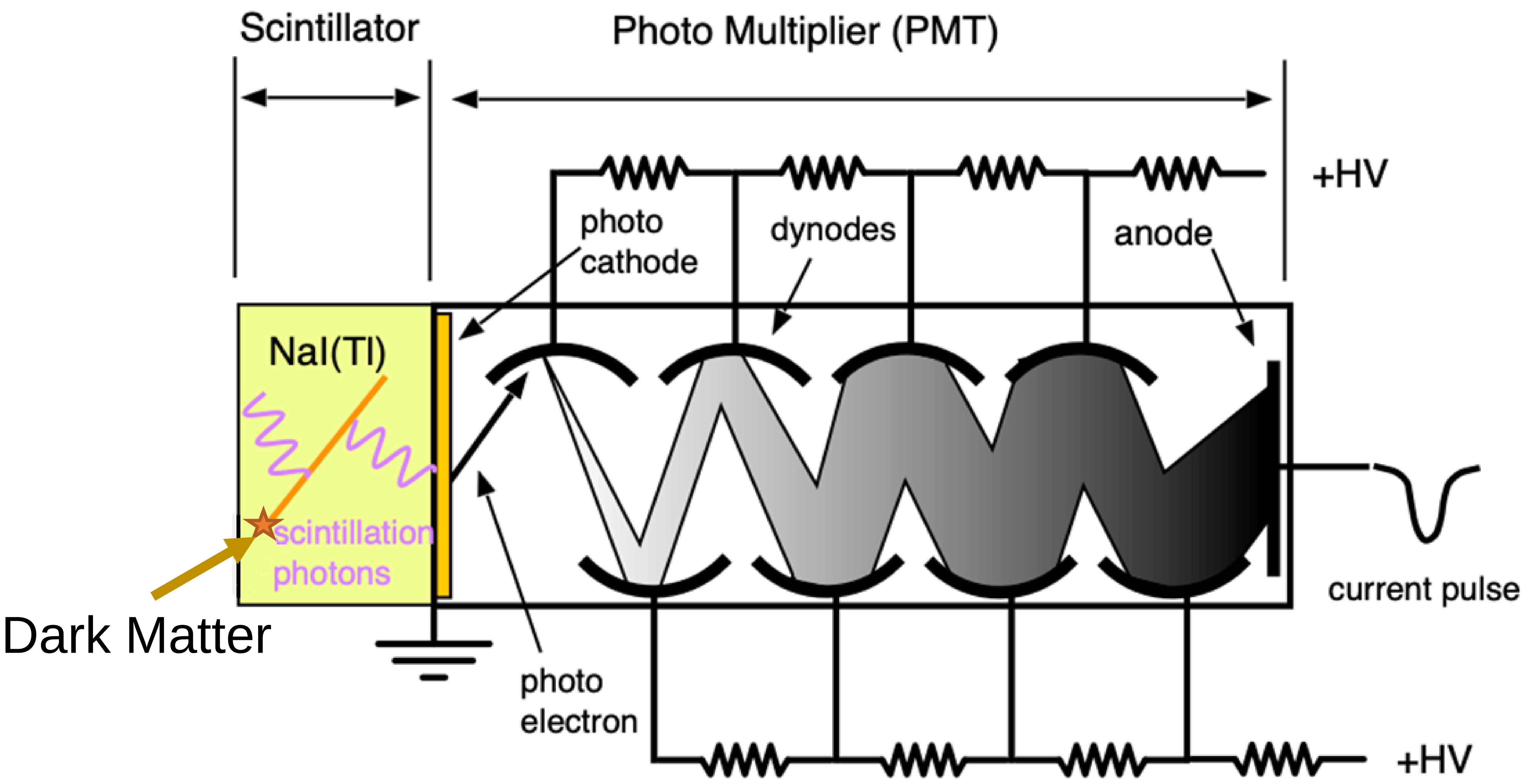
COSINUS

GSSI

DAMA/LIBRA Experiment



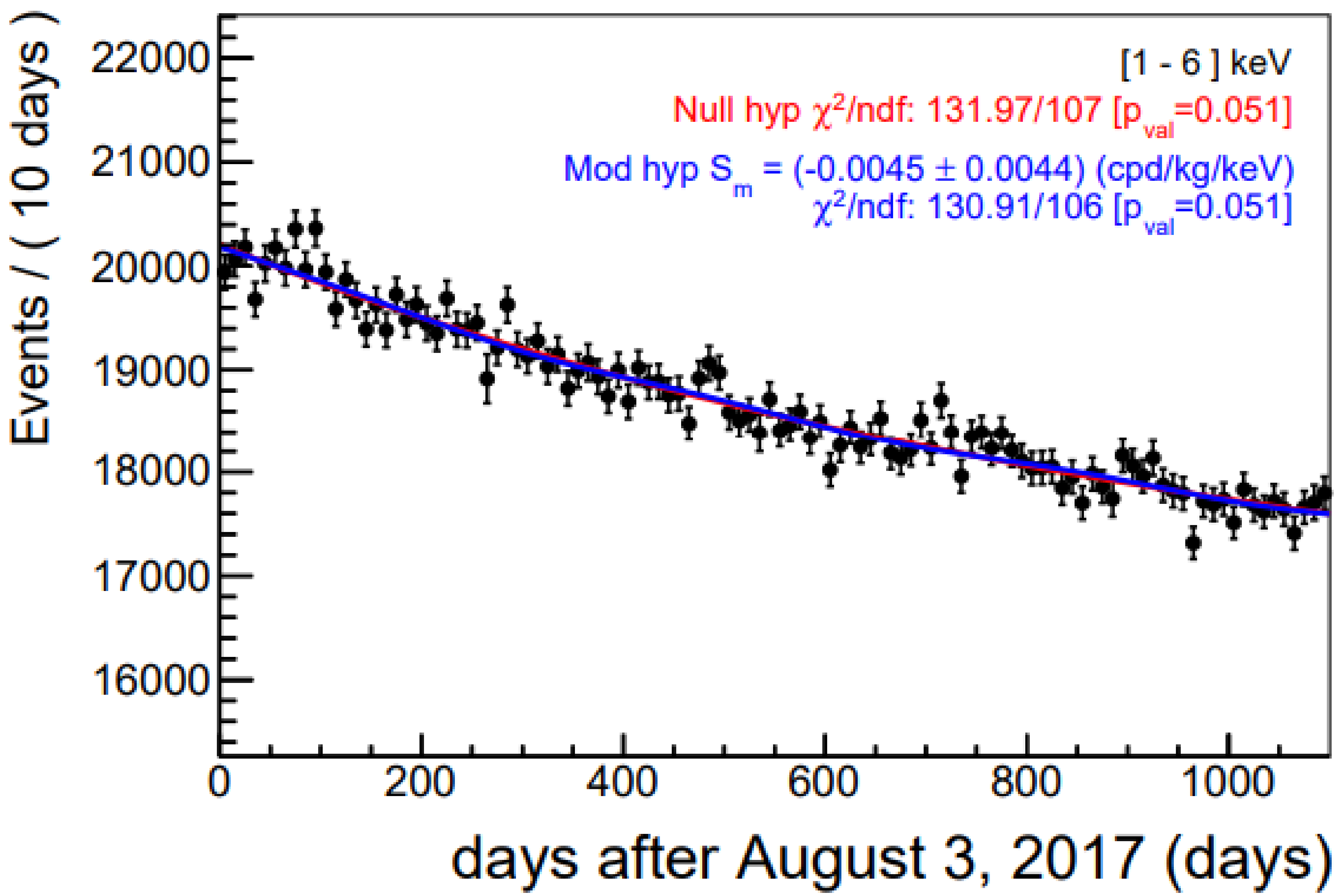
Bernabei, R., et al. "The dama/libra apparatus." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 592.3 (2008): 297-315.



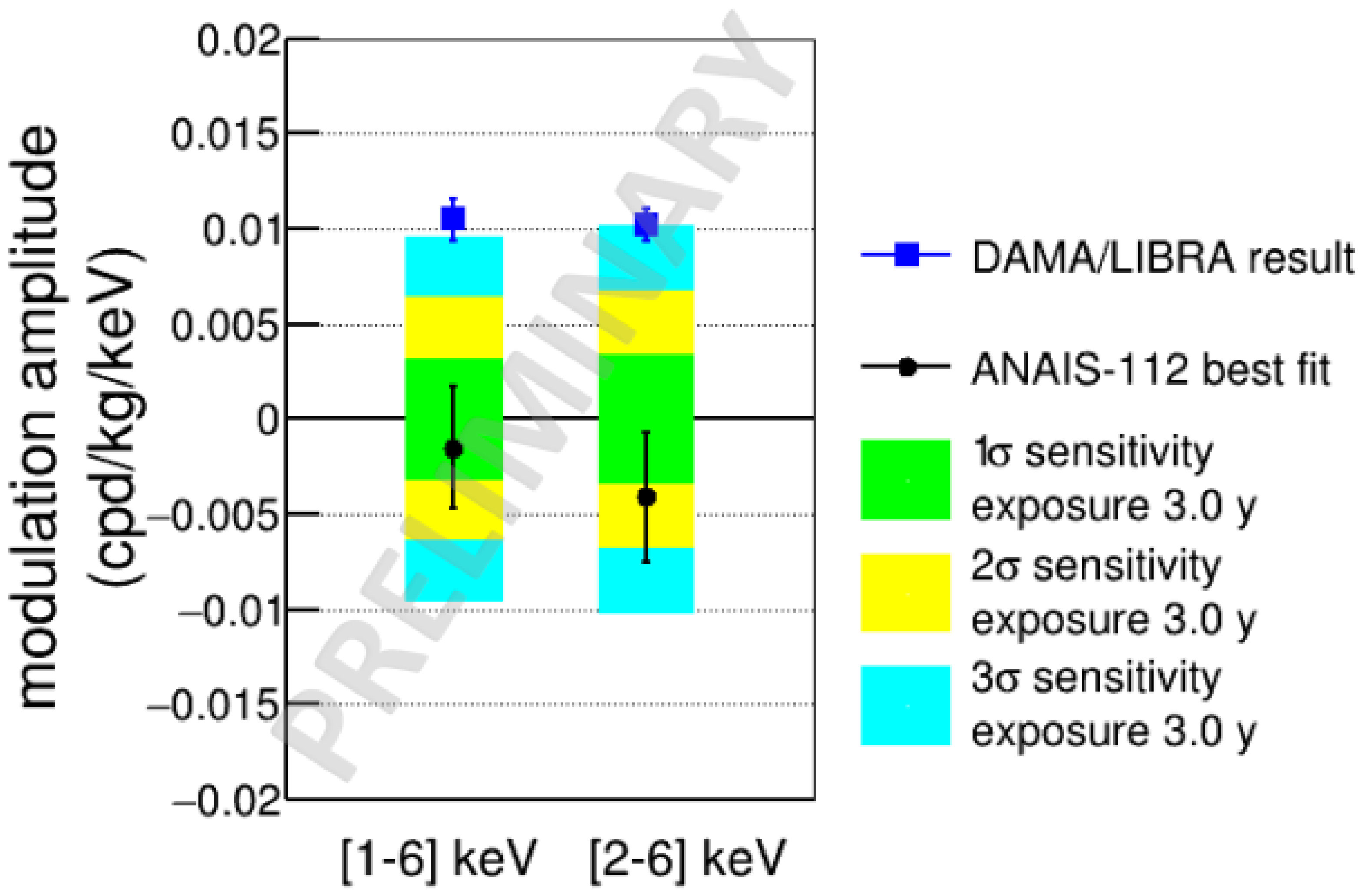
Based On: https://wanda.fiu.edu/boeglinw/courses/Modern_lab_manual3/scintillator.html

- The DAMA detector consists of 25 highly radiopure NaI(Tl) crystals. (~10 kg each)
- Search for dark matter model-independent annual modulation signature
- <u>Single-channel Experiment</u> -> Scintillation light from NaI(Tl)

ANAIS-112: 3 Years of Data Taking



Amare, J., et al. "Annual Modulation Results from Three Years Exposure of ANAIS-112." *arXiv preprint arXiv:2103.01175* (2021).



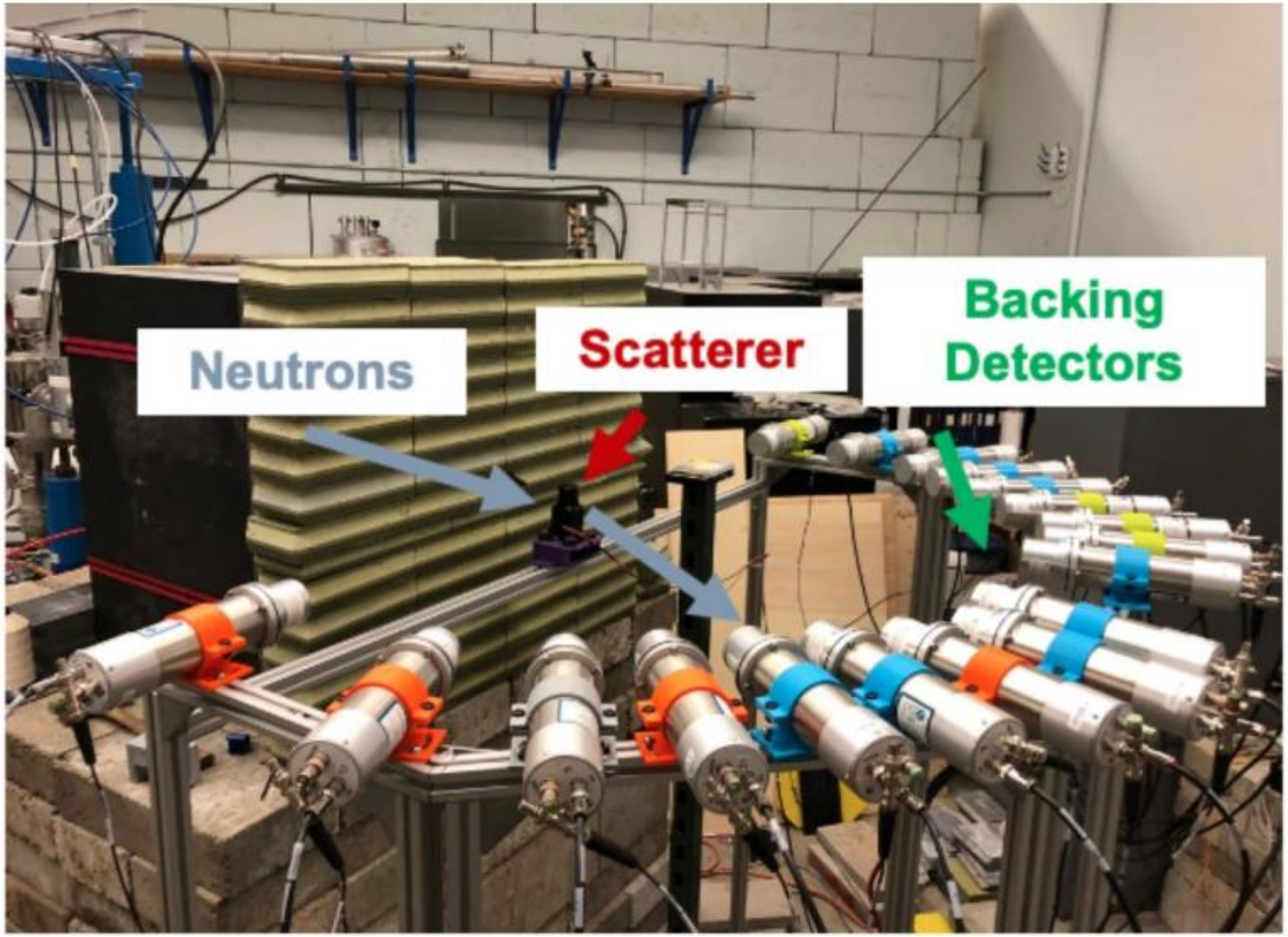
https://indico.cern.ch/event/1188759/contributions/5222288/attachments/2622529/4534685/UCLADM_23_MMartinez.pdf

- Incompatible with the DAMA results at 3.7 (4.2)σ , for a sensitivity of 3.3(3.0) σ for [1-6] ([2-6]) keV energy region

GSSI

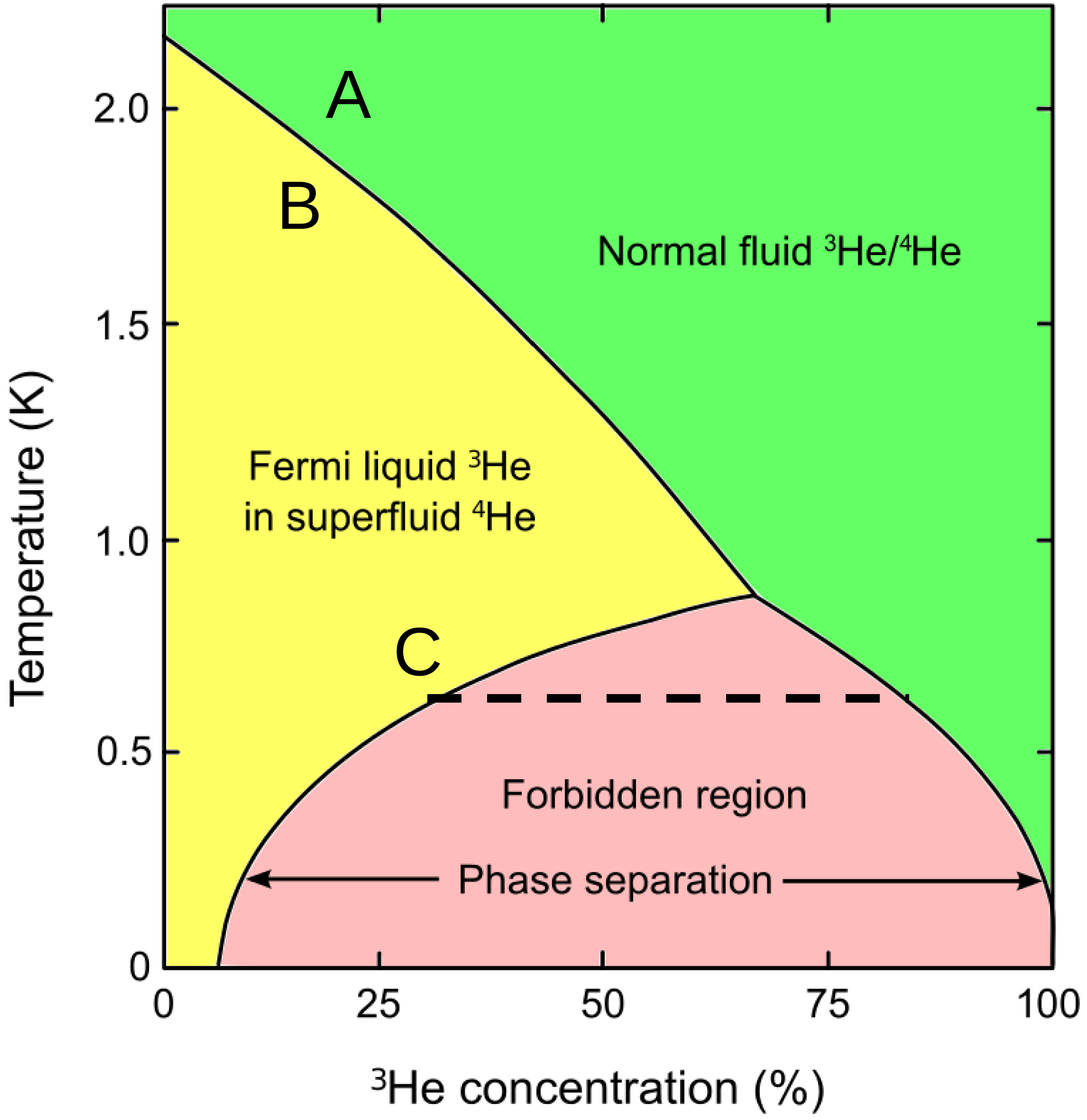
COSINUS Productions™(pending)

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 ^4He obeys boson statistics (T_c= 2.17 K)
- Pure ^3He 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 ^3He and ^4He (‘dilute phase’) rich phase
- ^3He will float on top of the ^4He phase in the ‘mixing chamber’
- If we remove ^3He atoms from the dilute phase ^3He from the concentrated phase will cross the phase boundary to occupy the vacant state
- Cooling power = T^2 x Flow rate of ^3He

Crystal Growth

- Crystals are grown in collaboration with SICCAS using Astrograde (MERCK) powder in a modified Bridgeman technique
- Keep isotope contamination down (K, Th, U)
- First sample hexagonal crystals have been made and will be tested soon