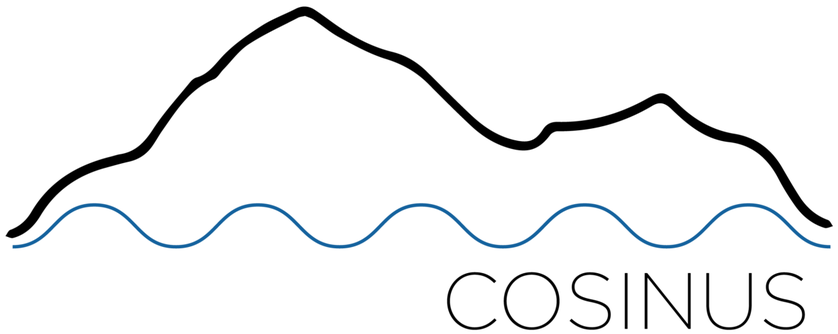
Dark matter modulation and the COSINUS experiment

Presented by: Matthew Stukel (He/Him)
For the Summer Particle (Astro) Physics Workshop 2022



GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Overview

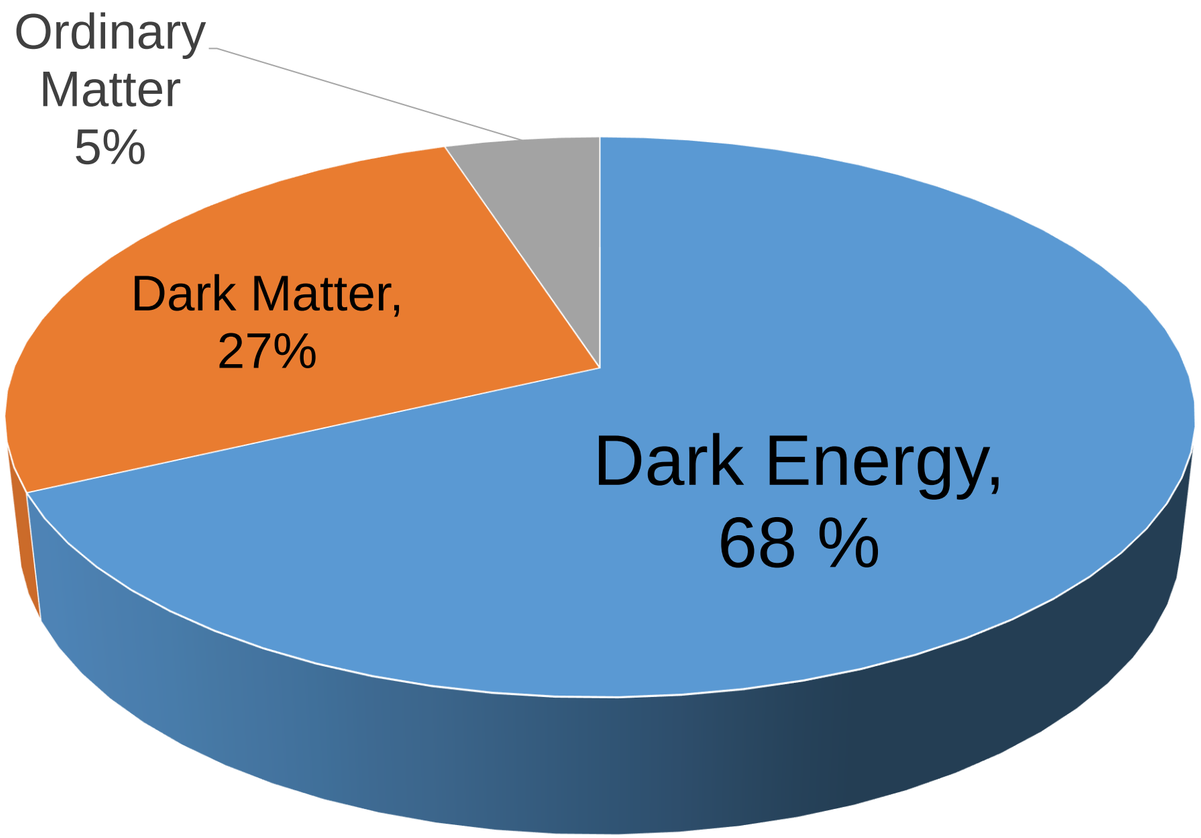
1. Introduction
2. Dark Matter and its annual modulation
3. DAMA/LIBRA experiment
4. Global NaI dark matter searches
5. COSINUS
6. Conclusion

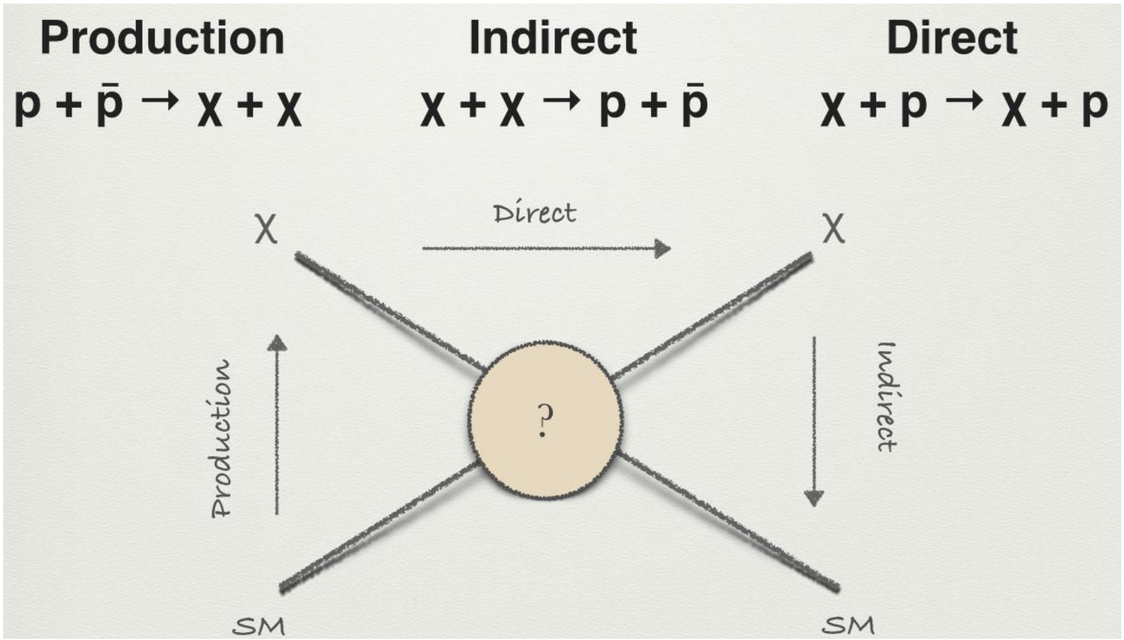
Who am I?

- Physics Postdoc at Gran Sasso Science Institute (GSSI)
  - L’Aquila, Italy
- Bio:
  - BSc : Applied Physics @ Carleton University
  - Worked 1 year at TRIUMF
  - MSc and Ph.D.:@ Queen’s University
- Big Formula 1 Fan (Forza Ferrari!)
- Probably the second best Twilight Imperium Player @ Queen’s

Dark Matter

Dark Matter

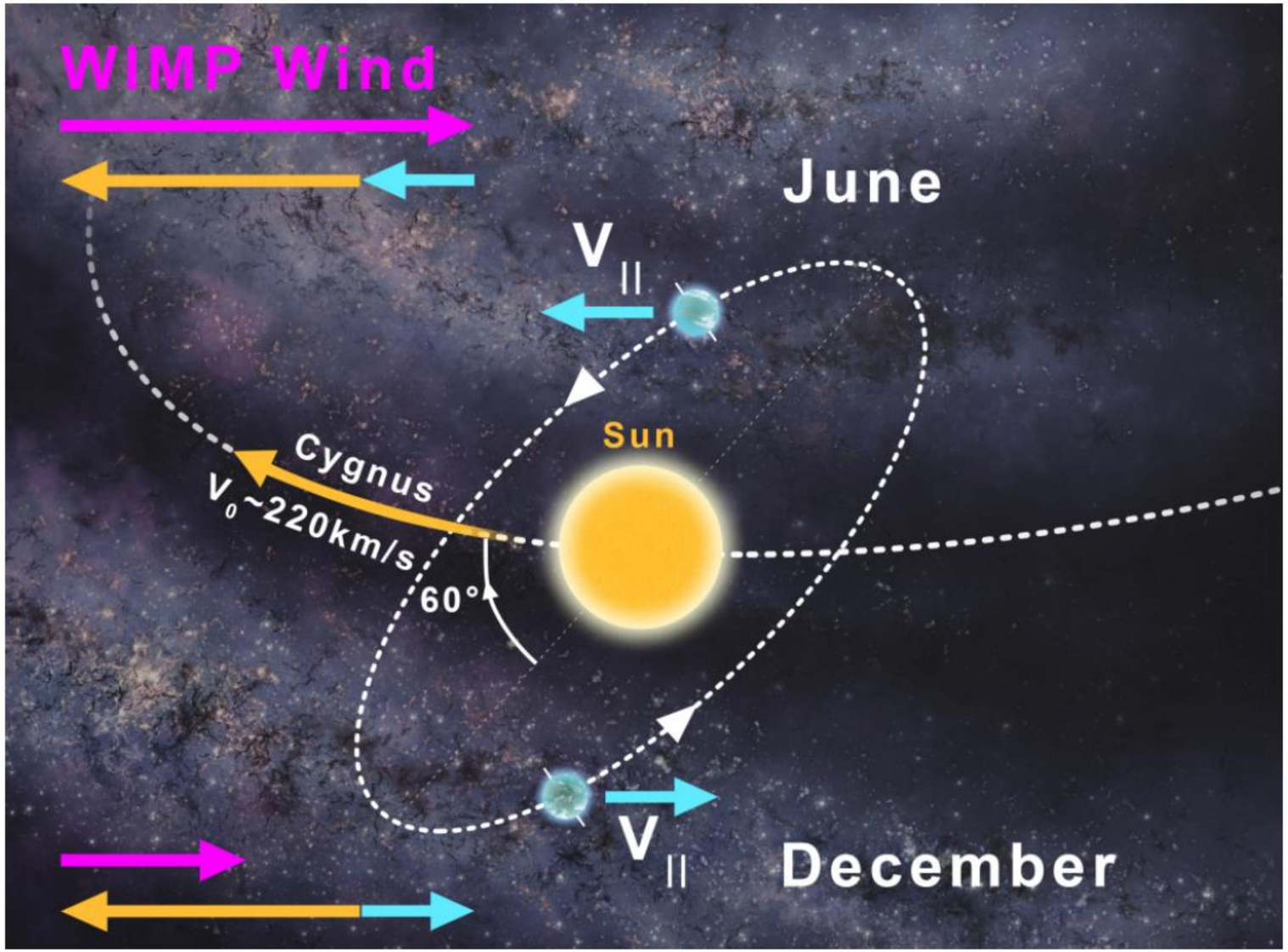




https://www.quantumdiaries.org/2014/10/22/have-we-detected-dark-matter-axions/

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

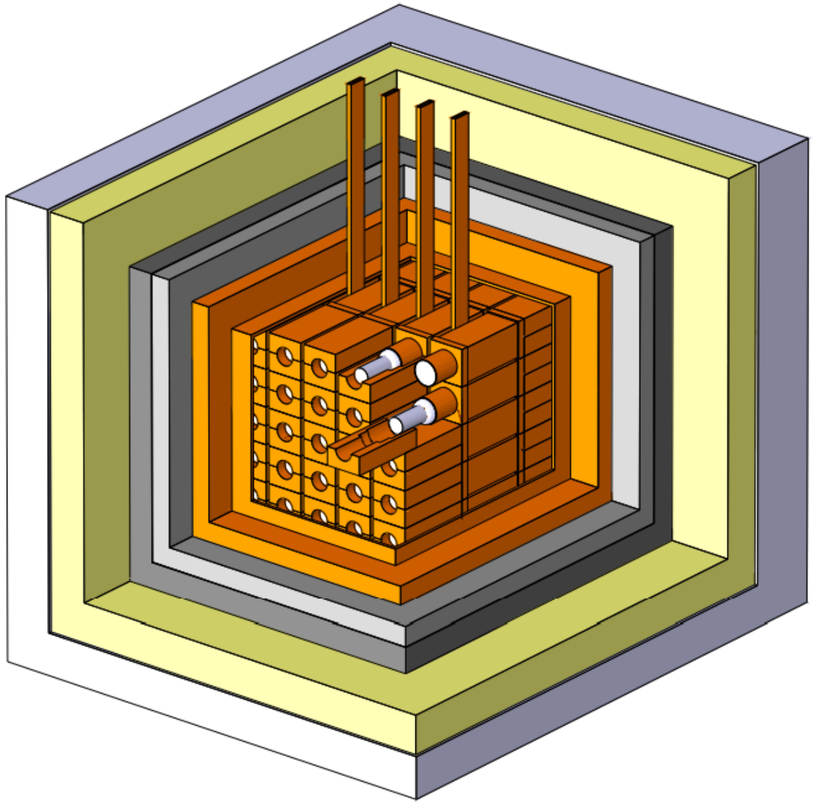
Direct Detection: Annual Modulation



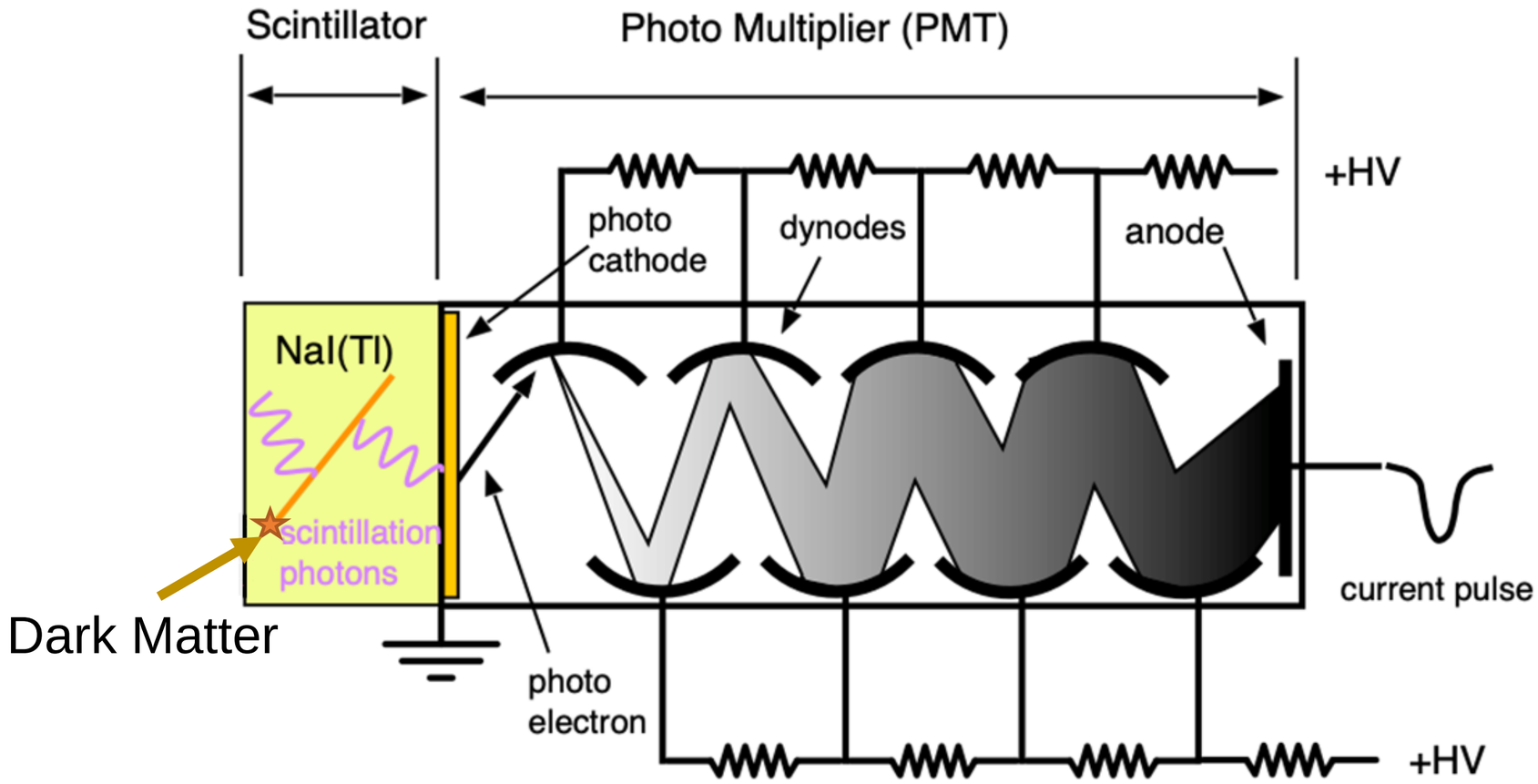
https://iopscience.iop.org/article/10.1088/1361-6471/ab8e93/meta

- 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
- **Unique** and **detectable** signal for dark matter
  - Period of one year
  - Peaks around June 2nd
  - Signal expected in low energy region (O(keV))

DAMA/LIBRA Experiment



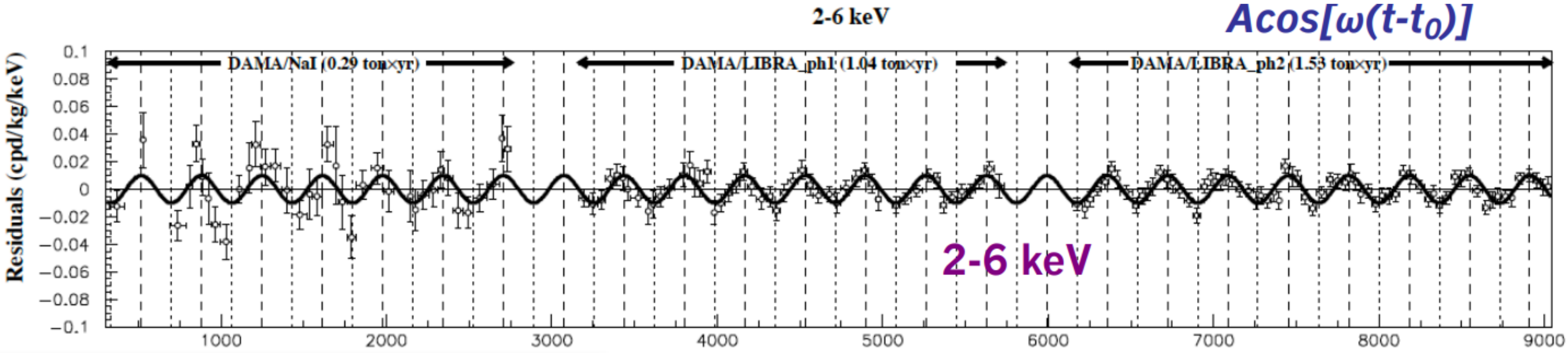
Bernabei, R., et al. "The dama/libra apparatus." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 592.3 (2008): 297-315.



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
- **Single-channel Experiment** -> Scintillation light from NaI(Tl)

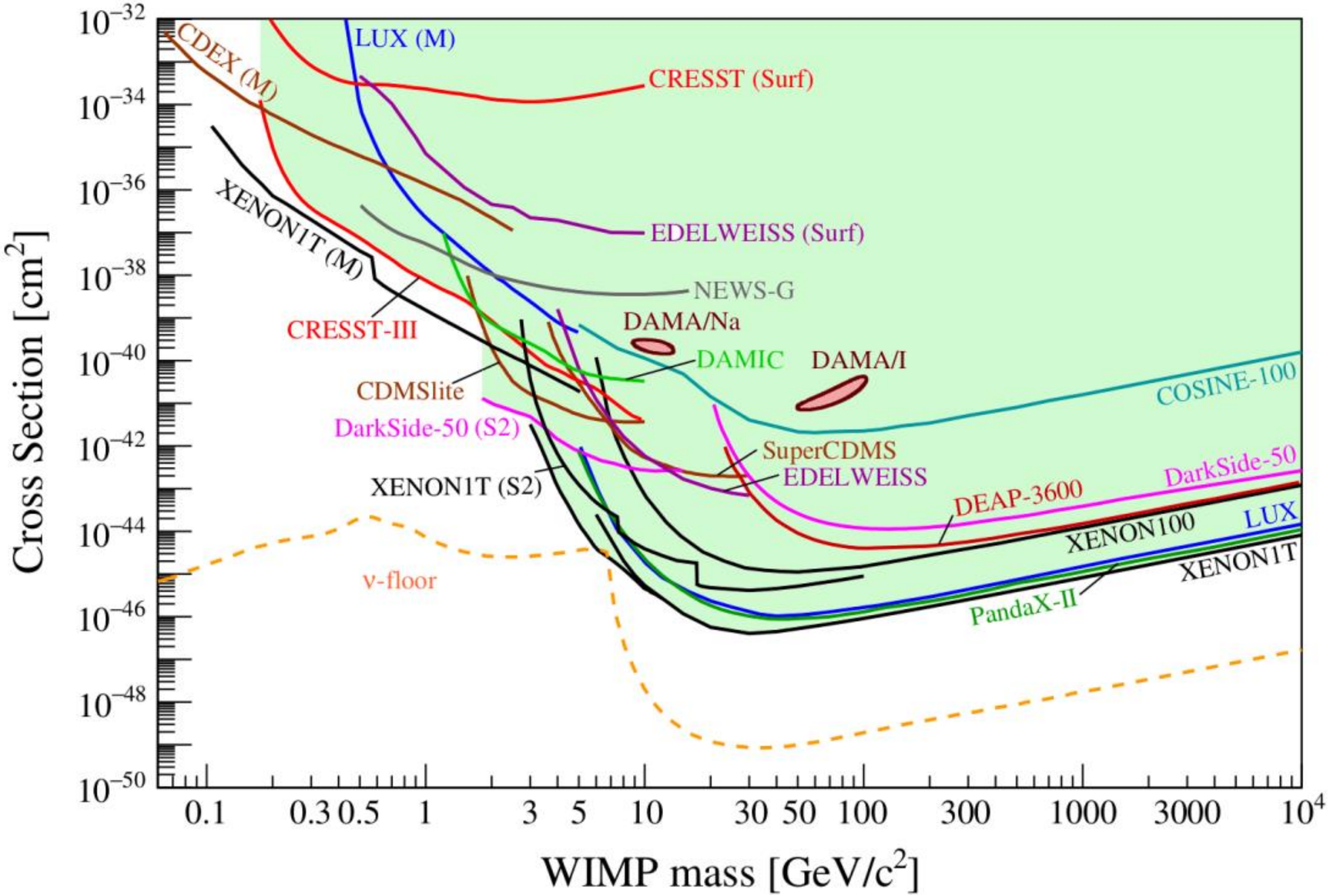
DAMA/LIBRA Results



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 **every other experiment**

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?
- ...

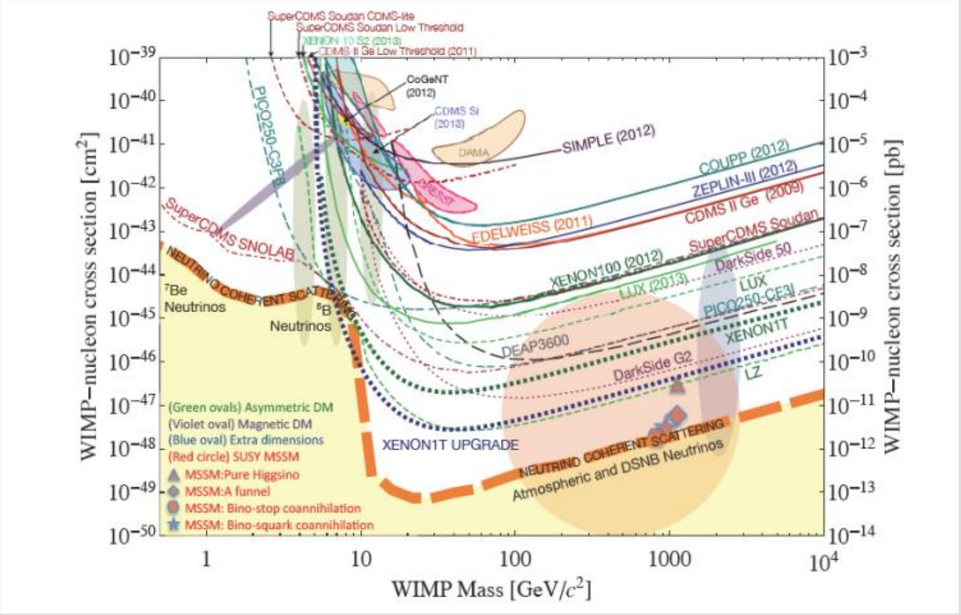
...and experimental aspects...

- 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

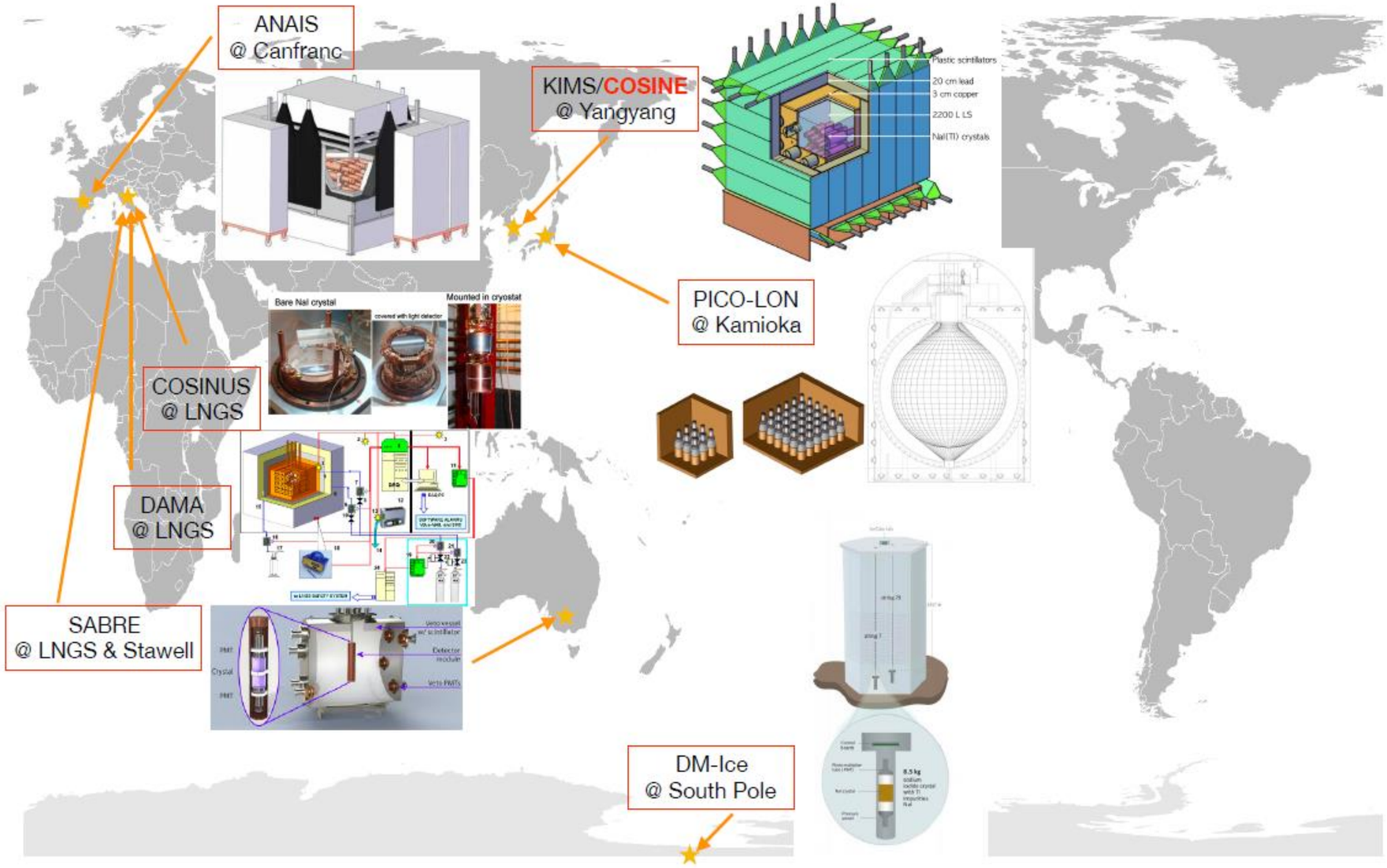
Is it an "universal" and "correct" way to approach the problem of DM and comparisons?



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

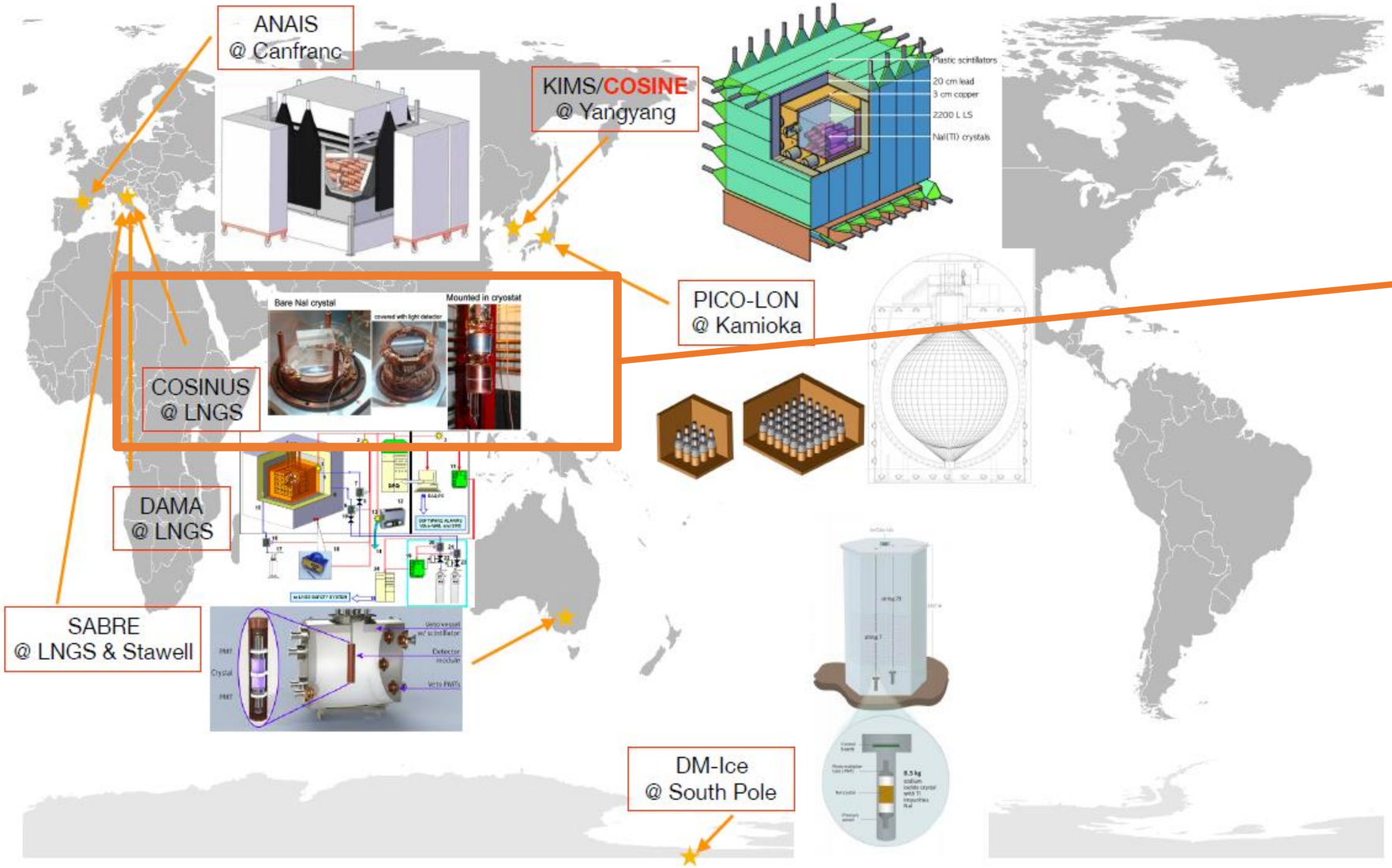
Global Efforts using NaI(Tl)



Astroparticle Physics European Consortium (APPEC) Recommendation:

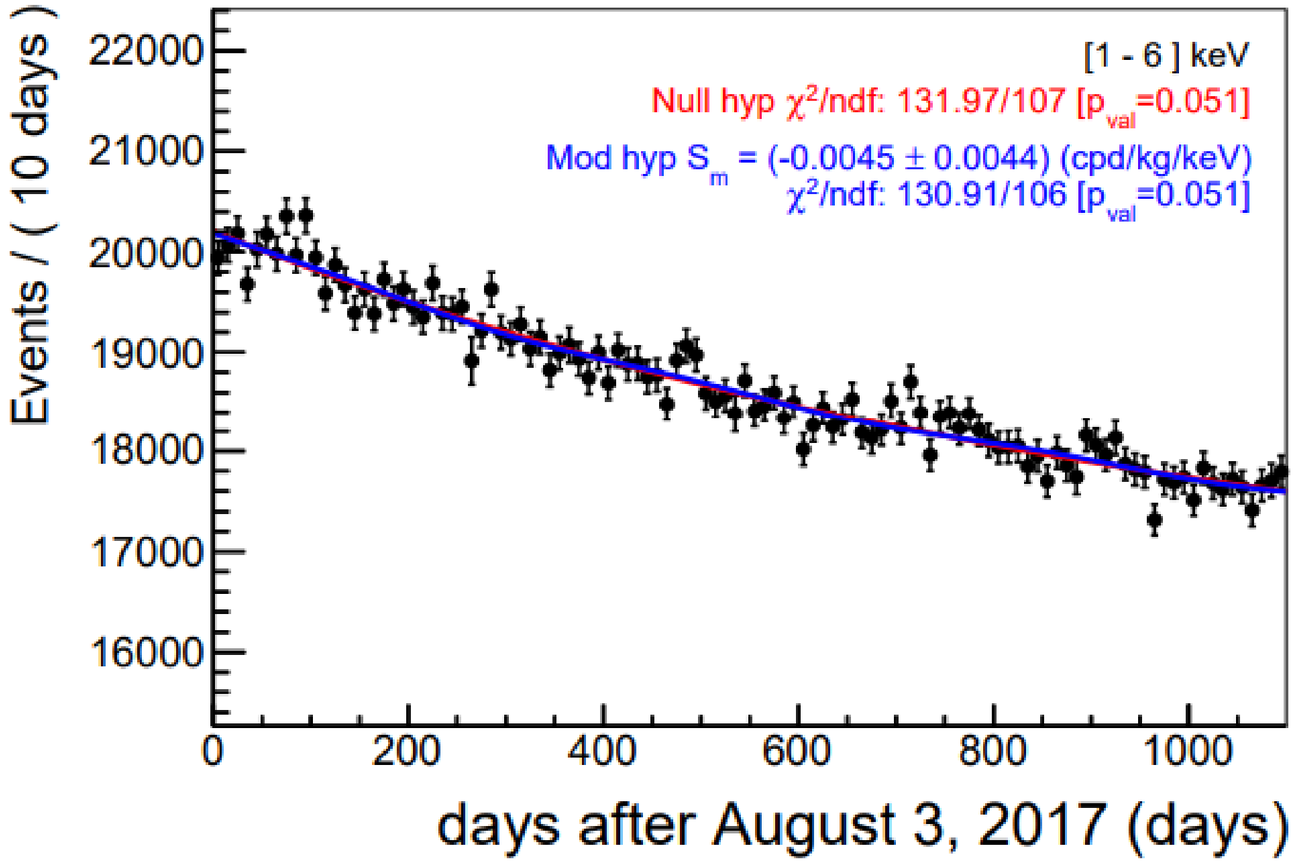
- “The long-standing claim from DAMA/LIBRA […] needs to be independently verified using the same target material.”

Global Efforts using NaI(Tl)

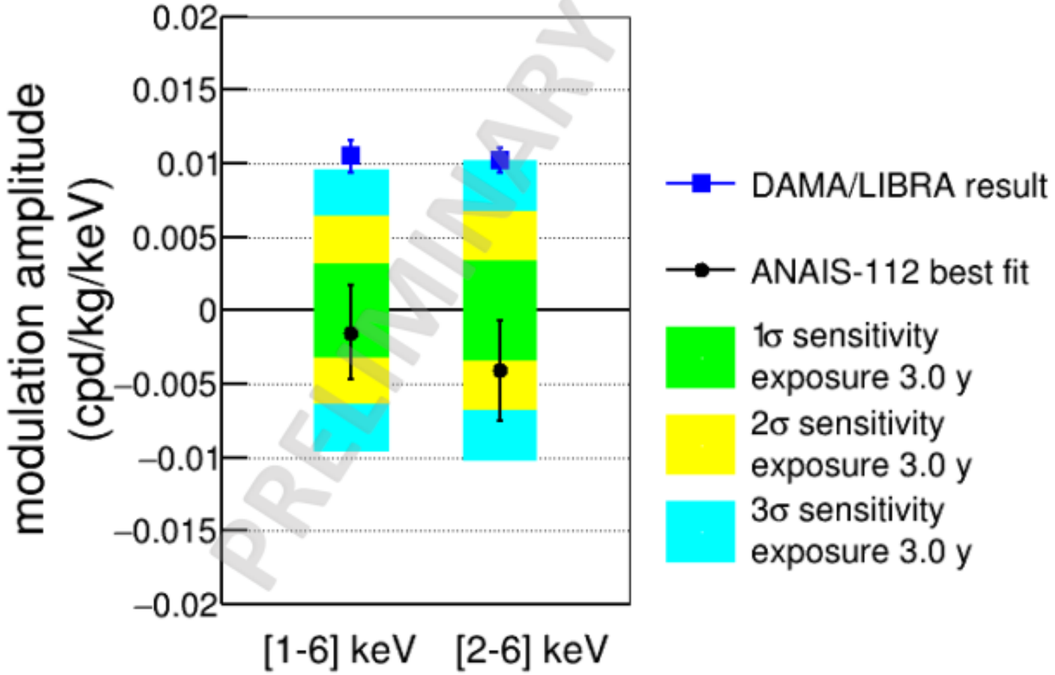


The best one

ANAIS-112: 3 Years of Data Taking



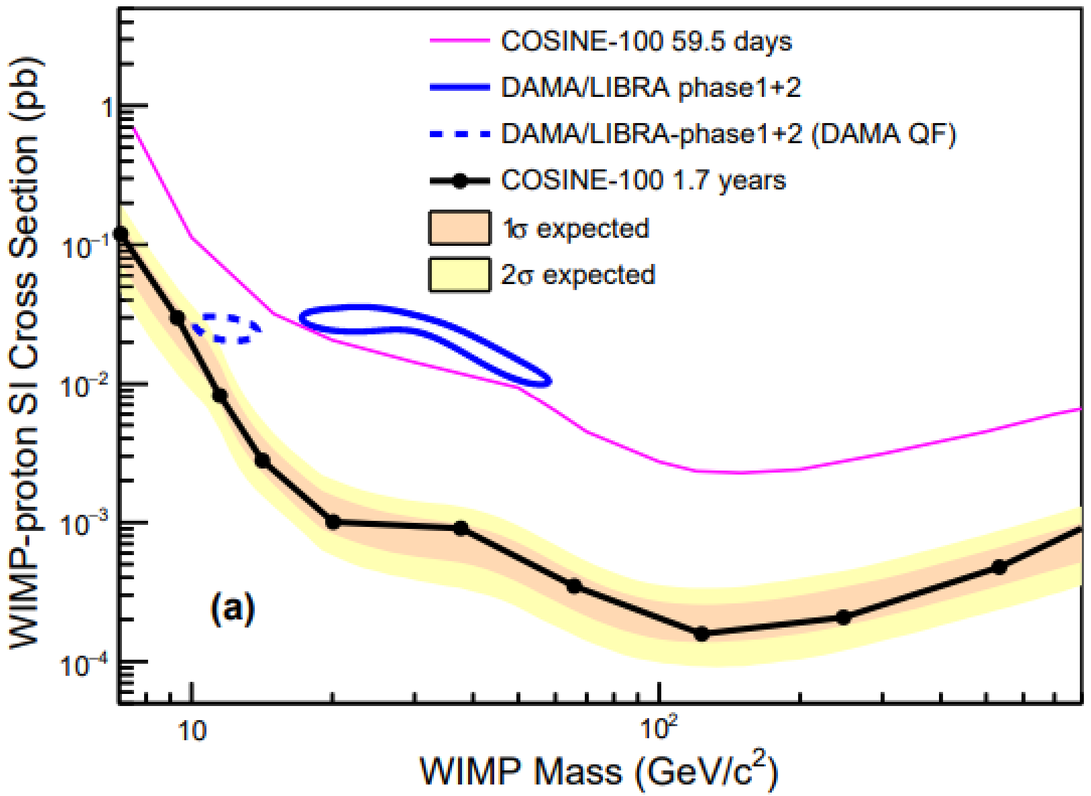
Amare, J., et al. "Annual Modulation Results from Three Years Exposure of ANAIS-112." *arXiv preprint arXiv:2103.01175* (2021).

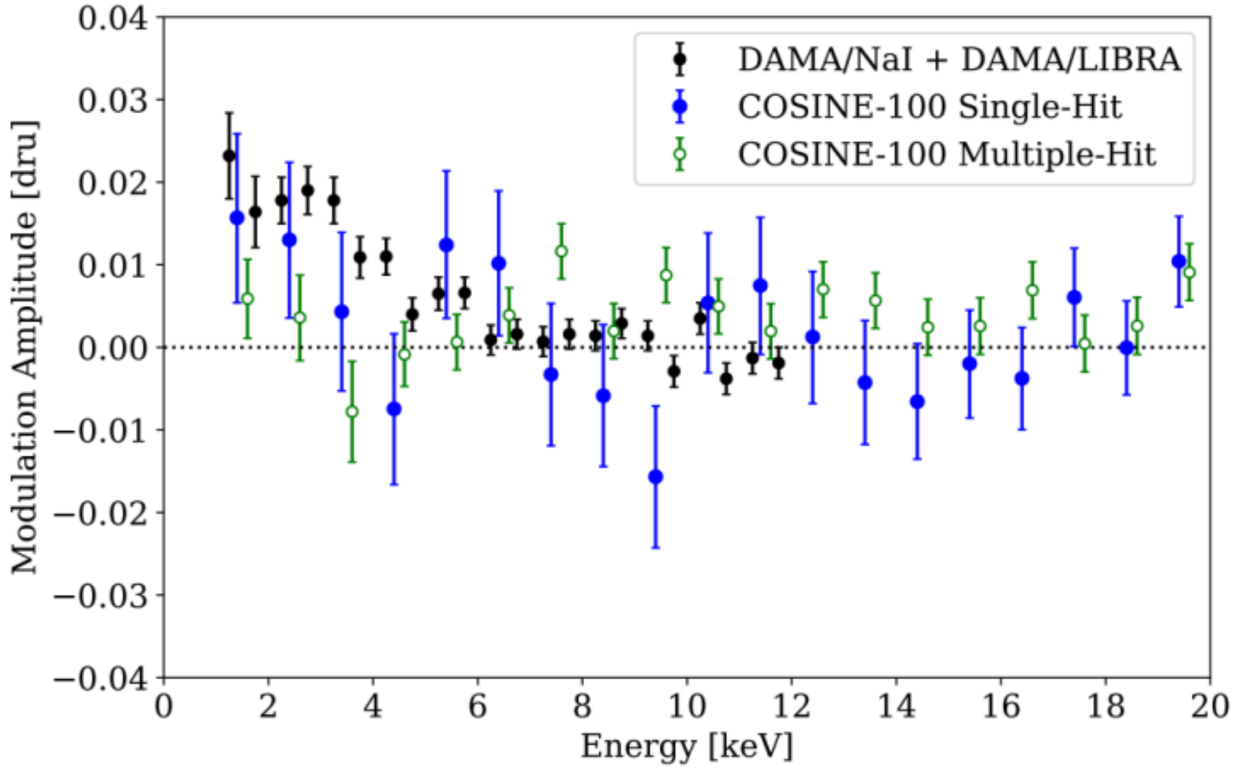


https://indico.cern.ch/event/1188759/contributions/5222288/attachments/2622529/4534685/UCLADM_23_MMartinez.pdf

- 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

COSINE-100





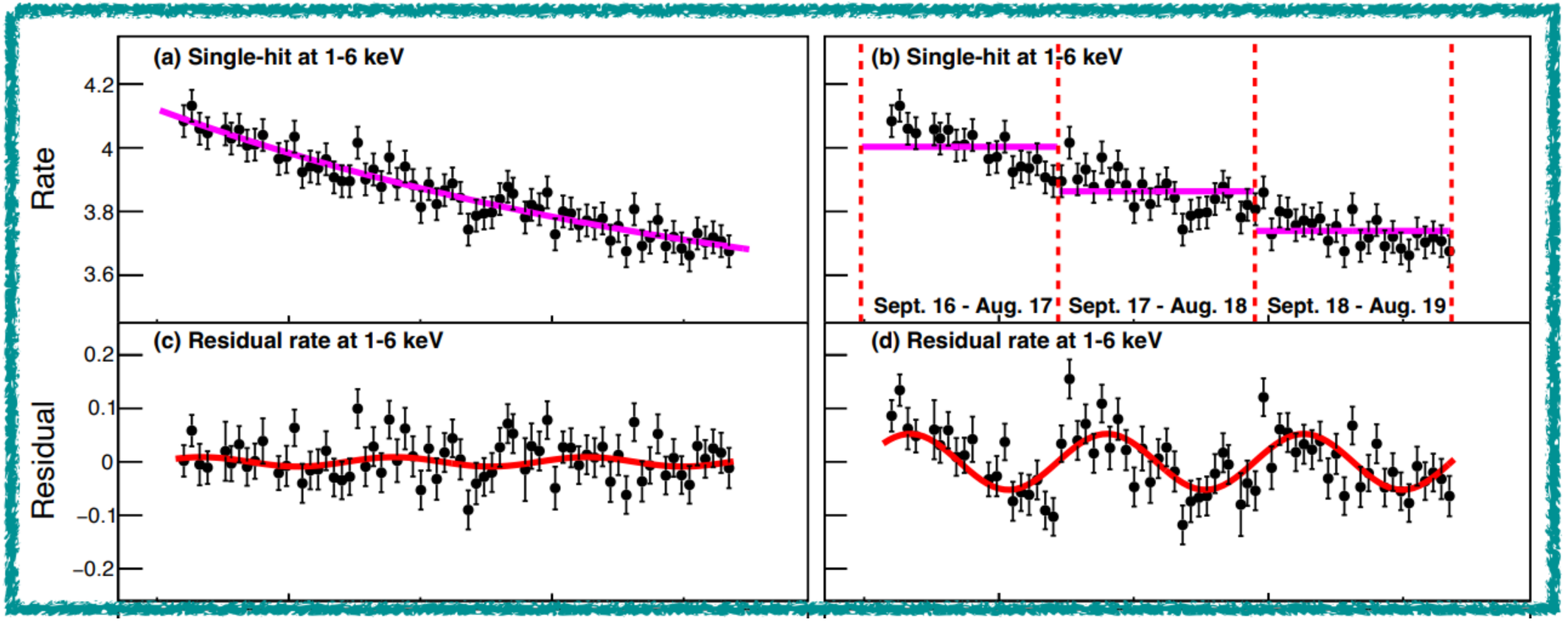
Adhikari, G., et al. "Three-year annual modulation search with COSINE-100." *Physical Review D* 106.5 (2022): 052005.

- COSINE-100 strongly constrains the DAMA result as a signal of dark matter origin
- But the modulation amplitude they measure is compatible with the DAMA result (also compatible with zero)
- It almost splits the difference between ANAIS and DAMA measurement

COSINE Modulation introduction with DAMA-like analysis

Single exponential model

DAMA/LIBRA method

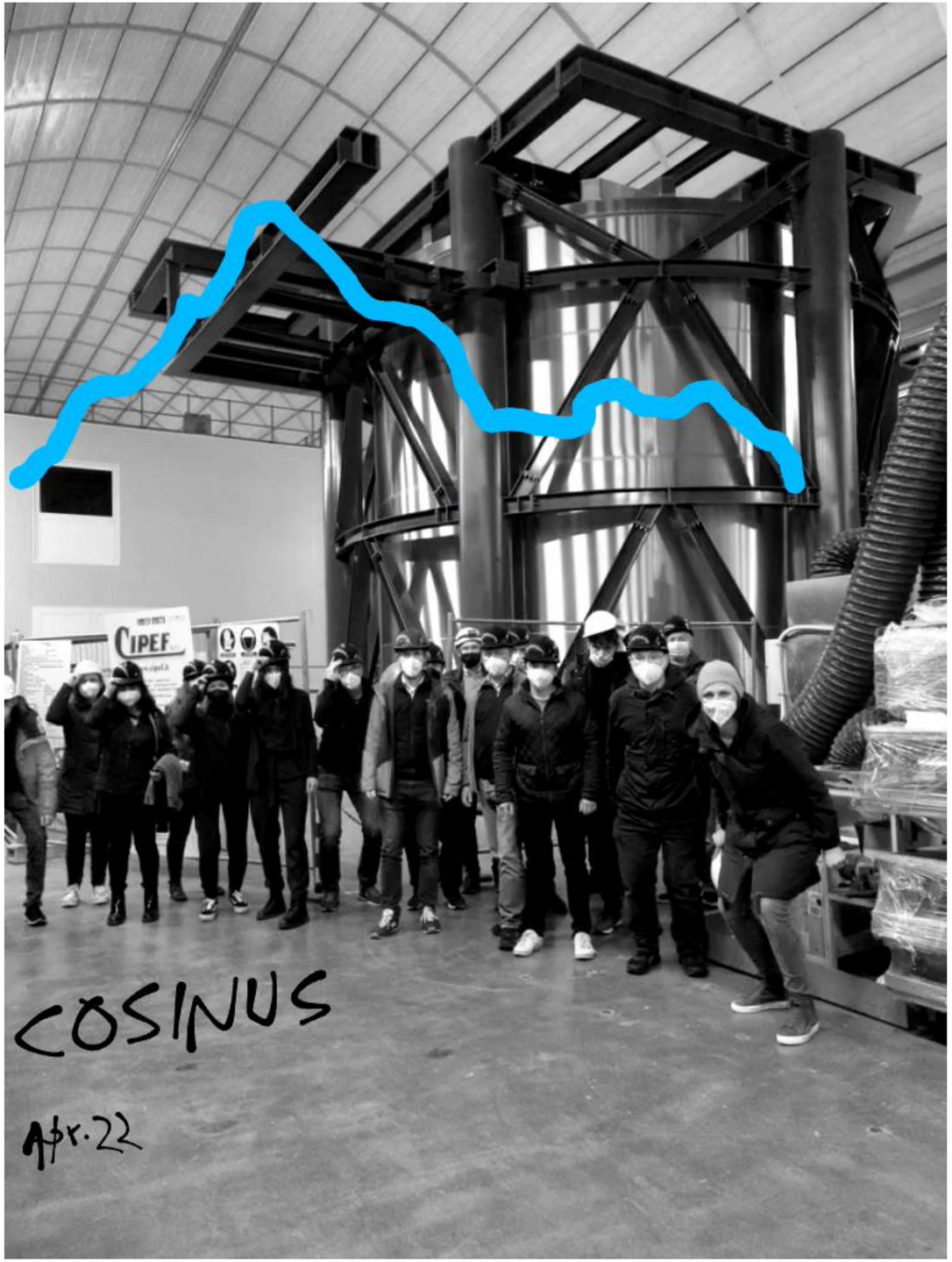


https://indico.cern.ch/event/1188759/contributions/5235240/attachments/2622453/4534541/UCLA_cosine_stattus_govinda.pdf

- Impossible to confirm without DAMA rate vs. time data.
- This analysis gives the wrong phase. To replicate DAMA would need and increasing rate (which would be strange)

COSINUS

Cryogenic Observatory for SIgnatures seen in Next-generation Underground Searches



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

$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

The Group

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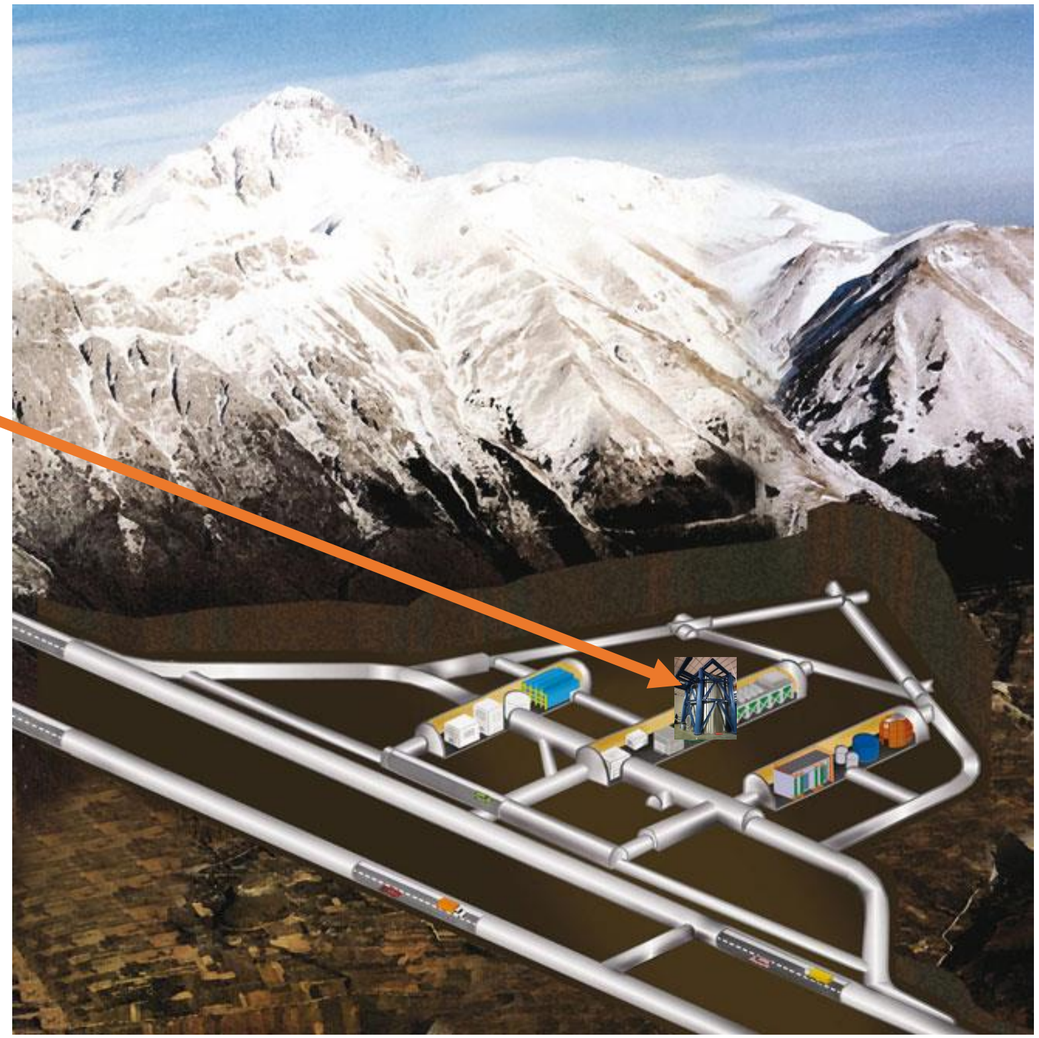
Gran Sasso National Laboratory (LNGS)

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

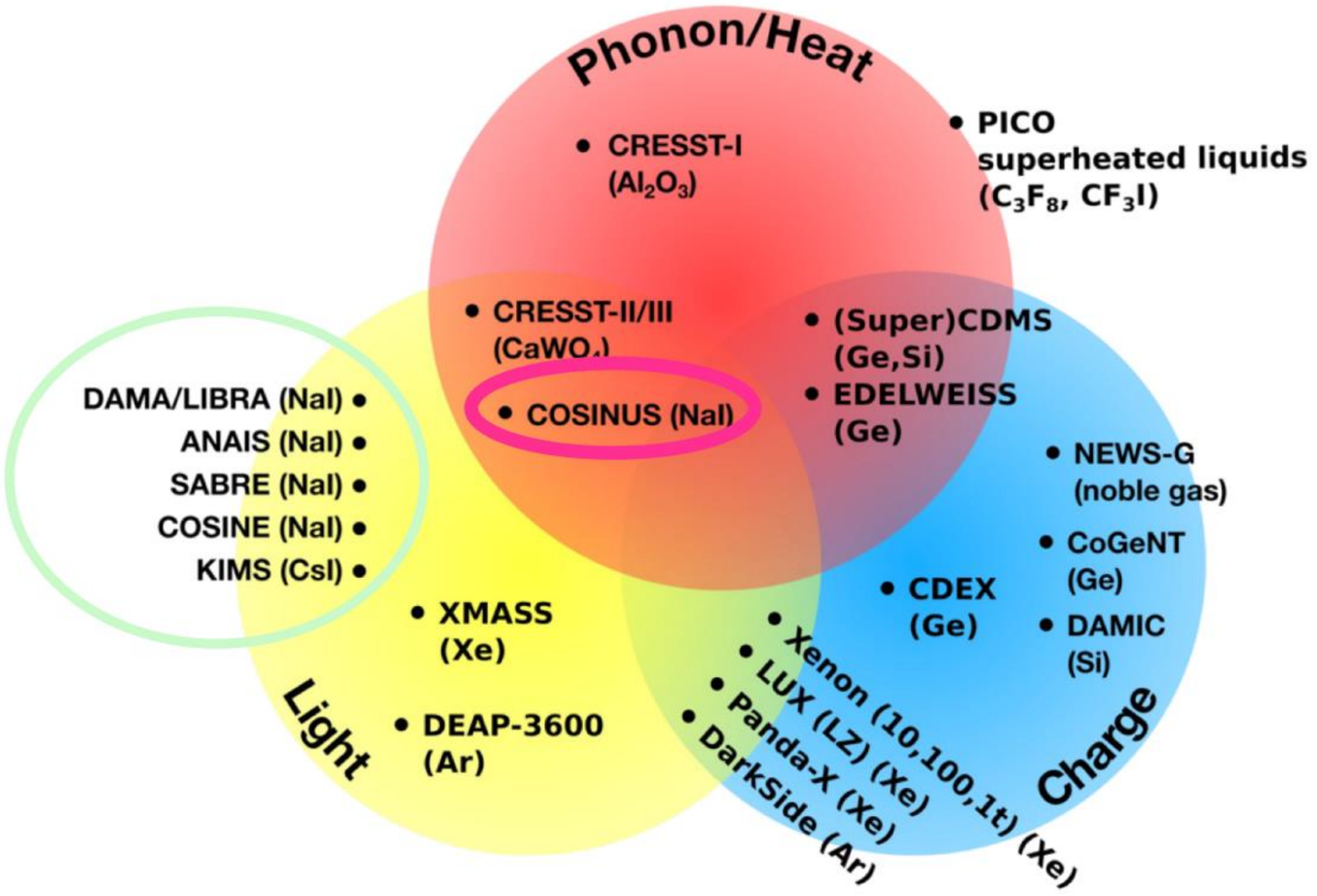
COSINUS Location



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

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

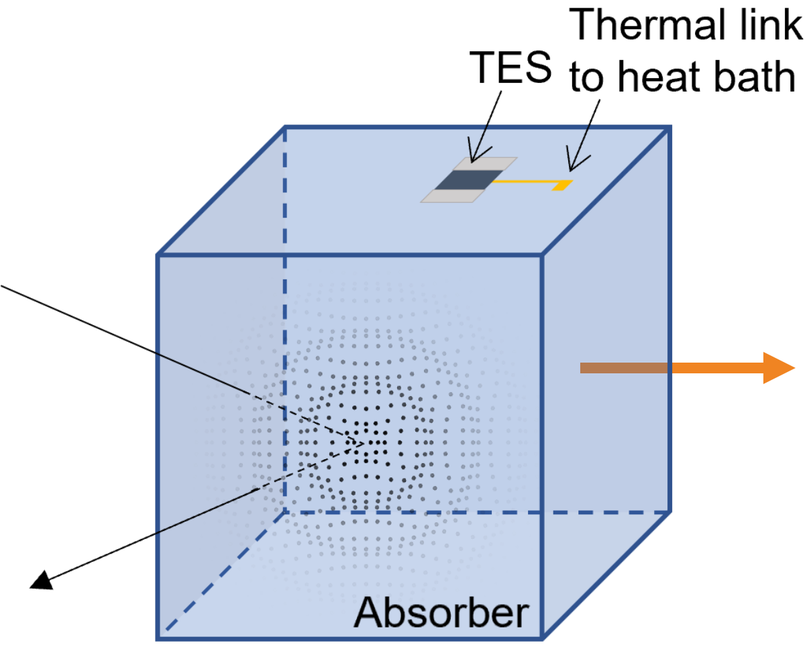
Landscape of Dark Matter Experiments

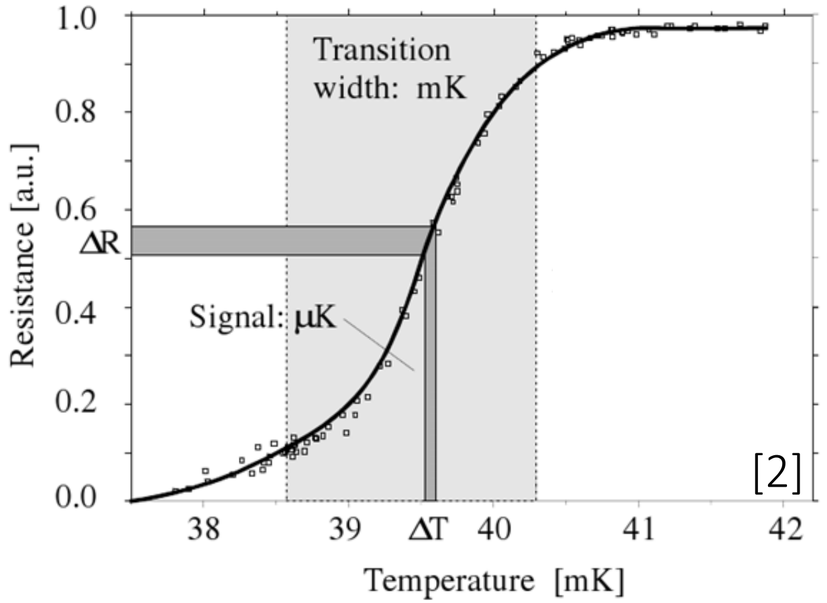


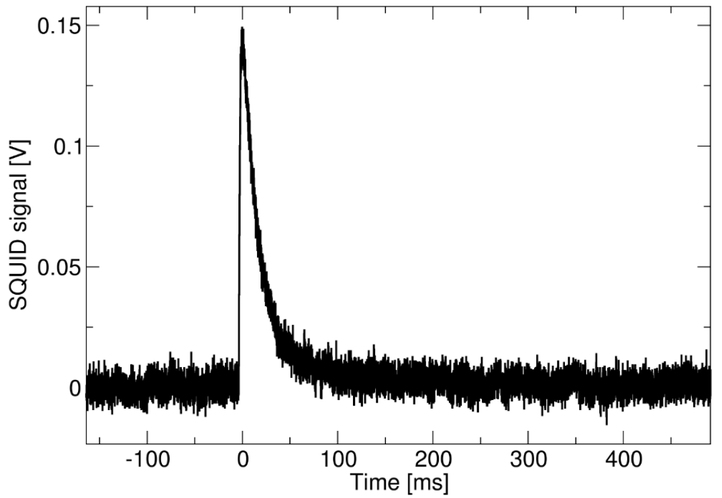
Credits to: F. Reindl

- **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!!)
  - Dual Channel: Phonon (90%) and Light (10%) signal for **event-by-event particle discrimination**

NaI - Phonon Signal Measurement



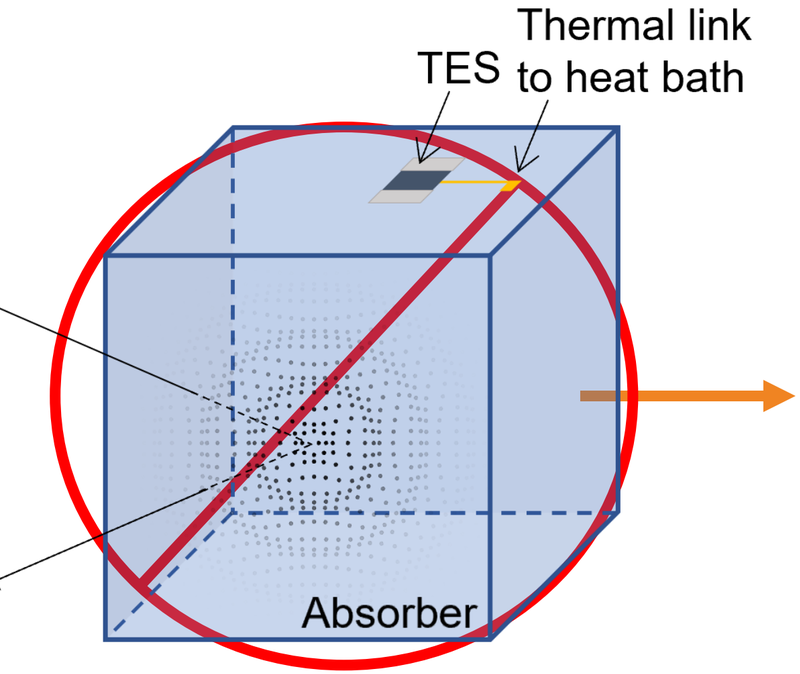


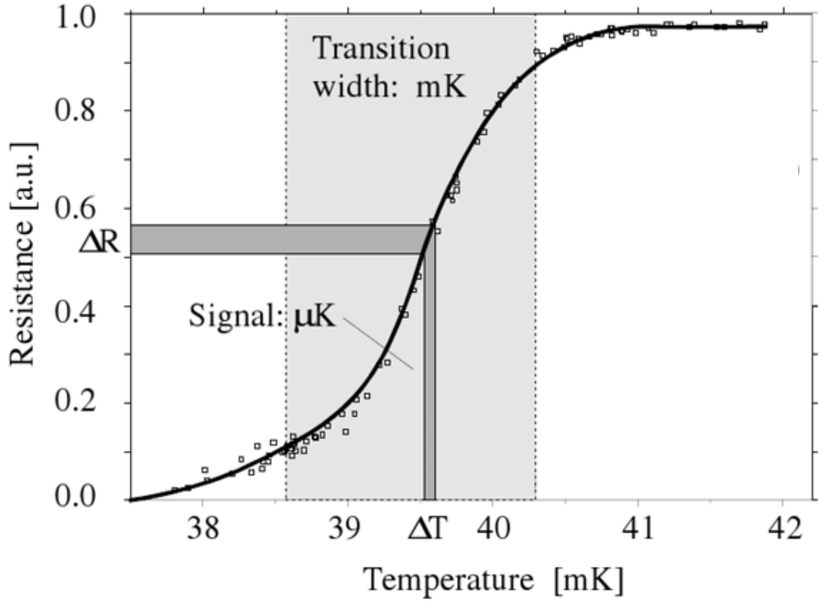


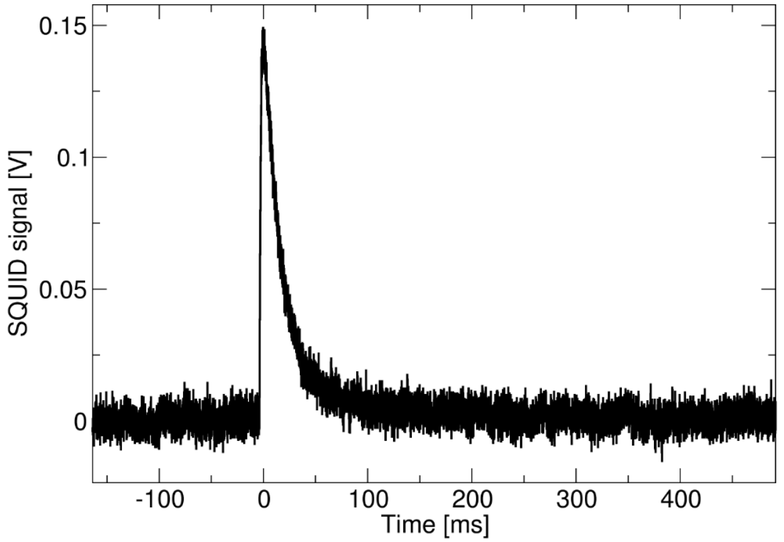
[3]

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

NaI not so NICE

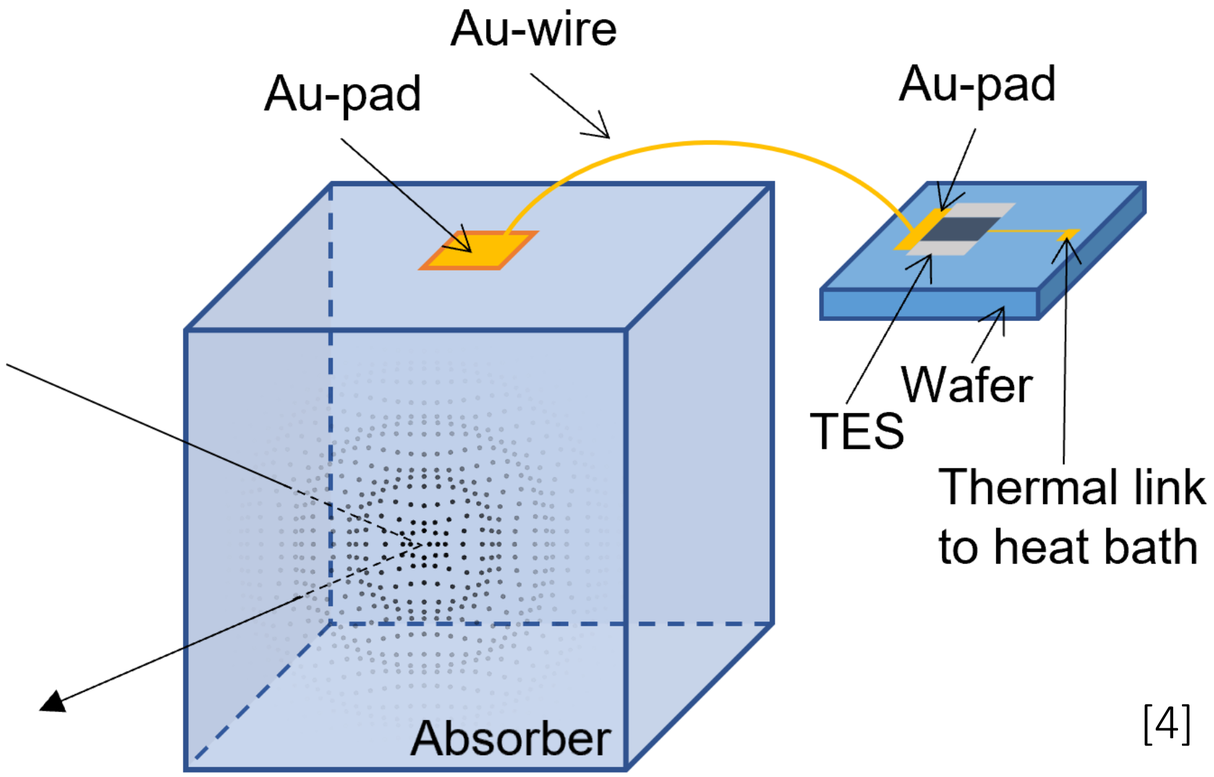






- Difficulties with attaching TES directly to NaI
  - NaI is hygroscopic (cannot come into contact with humid air)
  - Very soft and low melting point (easy to damage when handling)
- Solution: **remoTES**

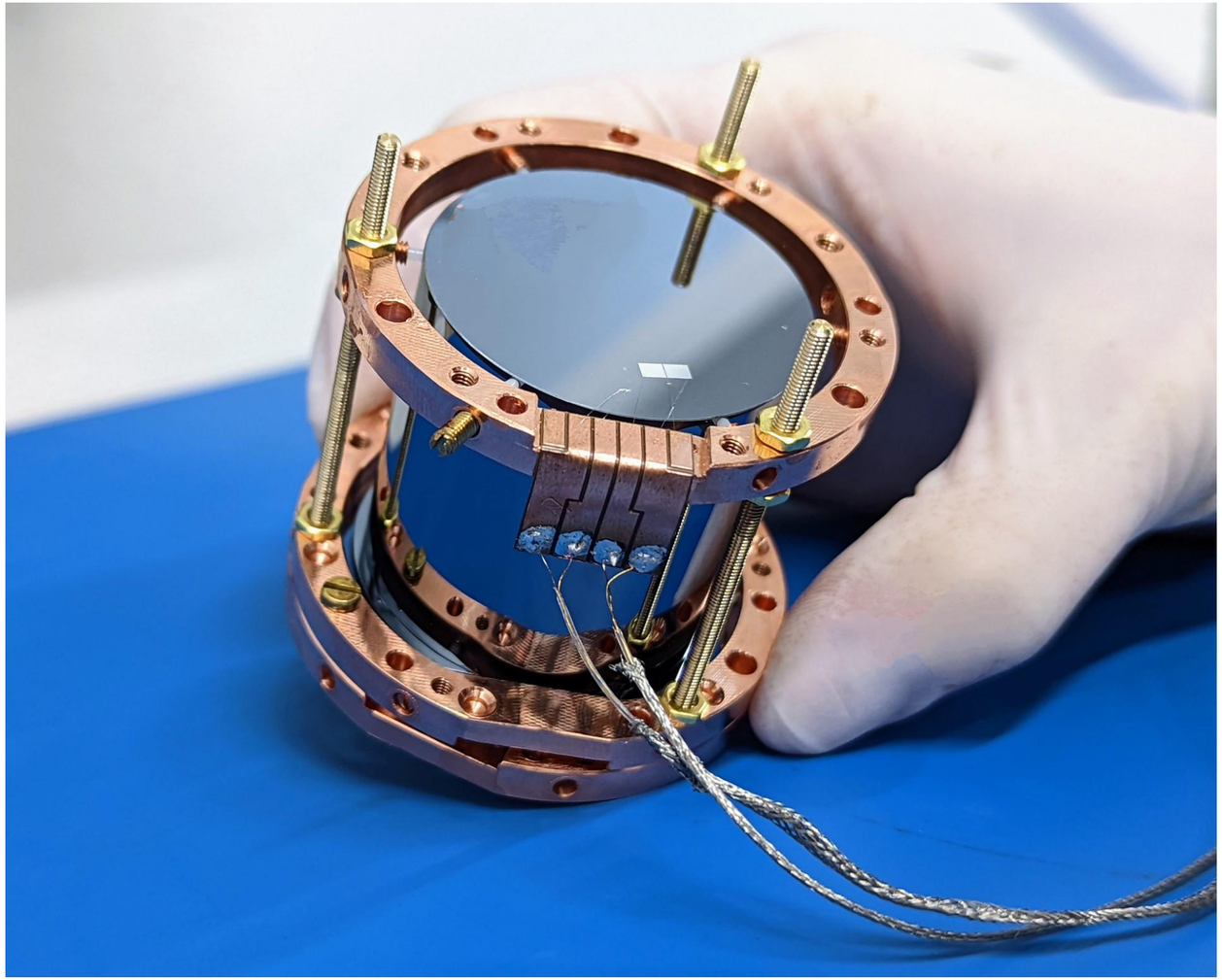
NaI- remoTES design



[4]

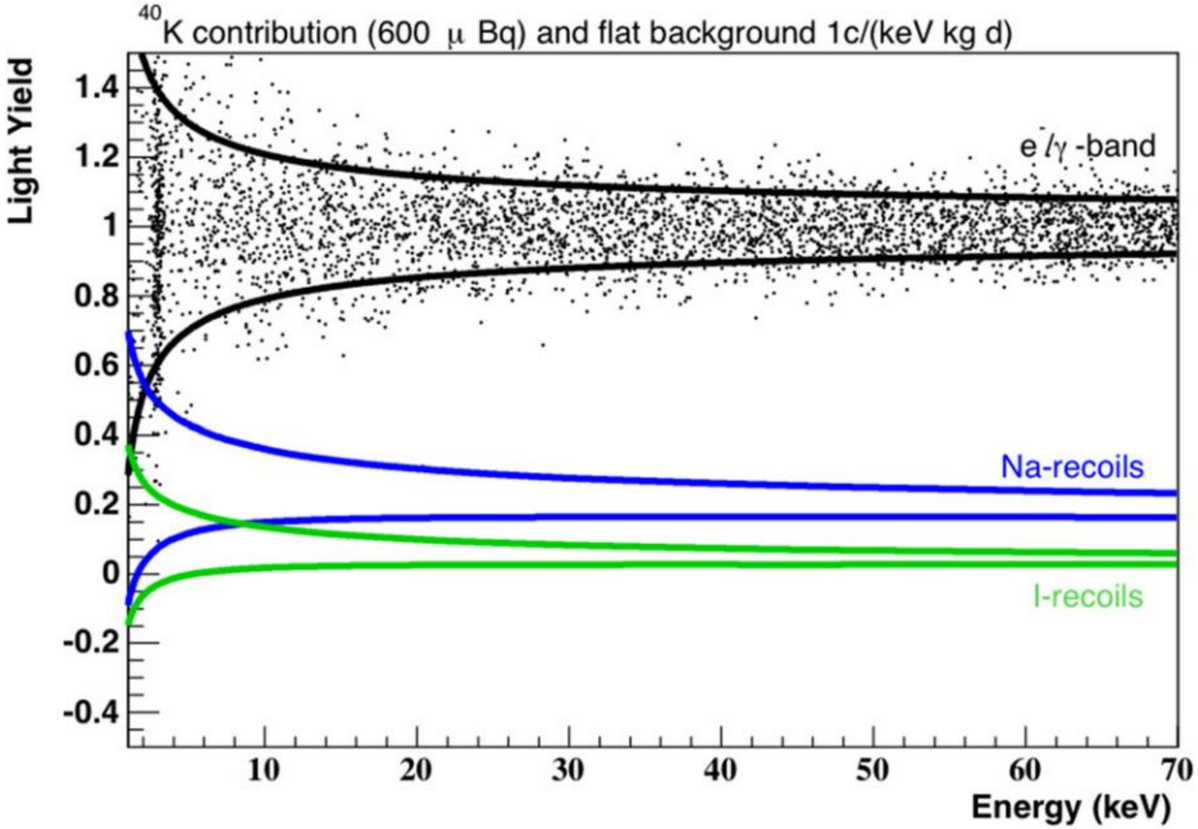
- Implement **remoTES** design, first proposed by Matt Pyle [4]
- Separate wafer that holds the TES: Wafer: Al_2O_3
- Gold pad on absorber with a gold bonding wire connected to TES
- Wafer and TES setup is constructed separately then attached to the NaI

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



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

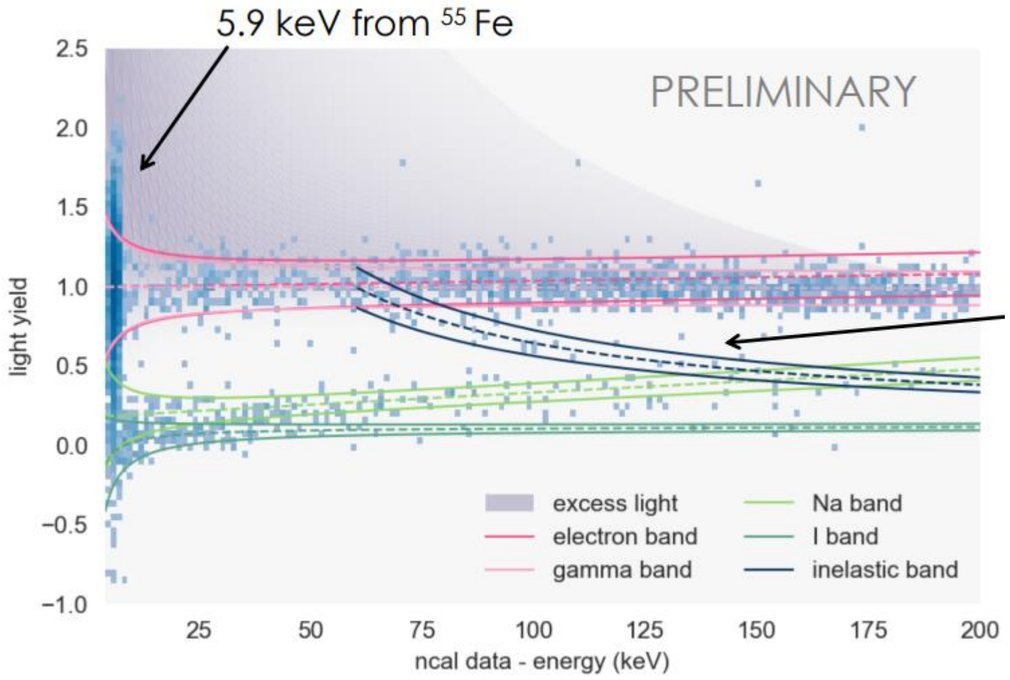
- Particle discrimination is the COSINUS advantage

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

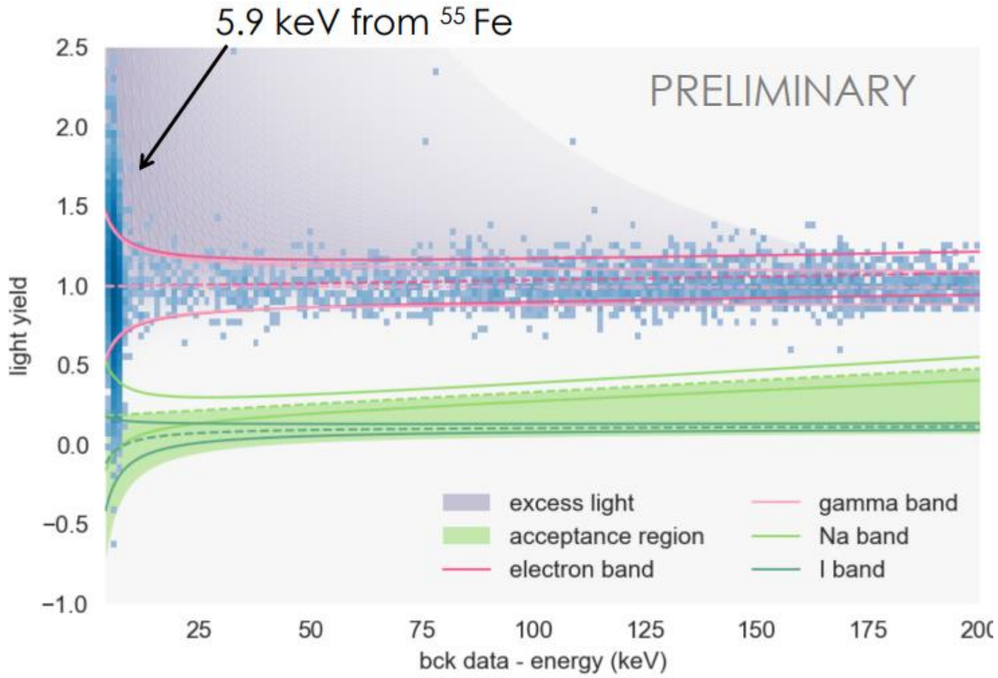
- Electromagnetic interactions will emit more light than nuclear recoils
- Use for **particle discrimination** on an event-by-event basis
- Left is simulated data
- Position of the bands is very dependent on the quenching factor (QF)
  - Dedicated QF performed at TUNL (See backup slide)

COSINUS: Particle Discrimination

Neutron Calibration (30 hrs)

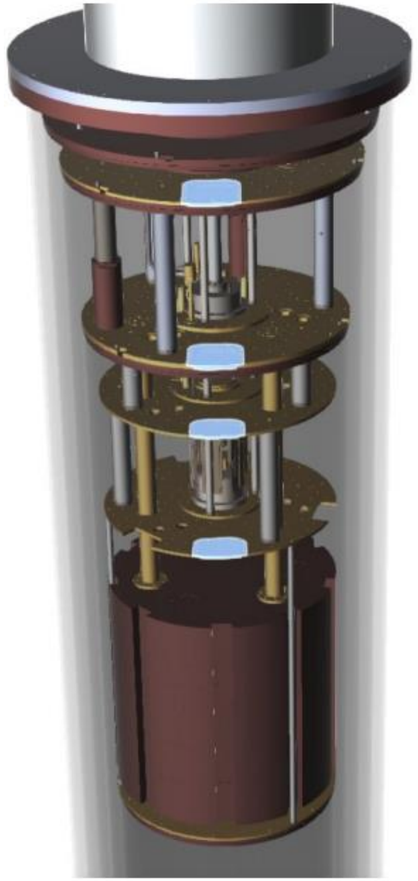


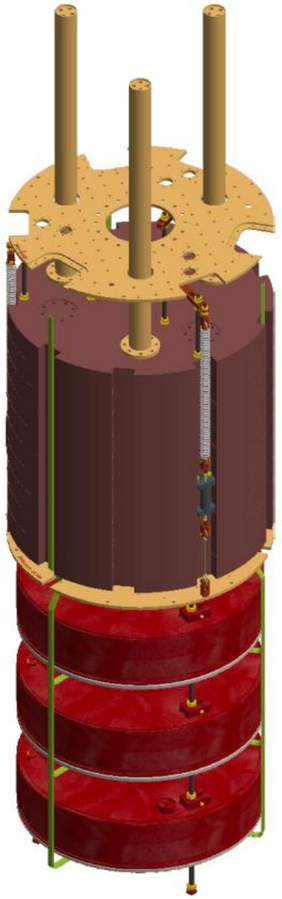
Background Data (60 hrs)

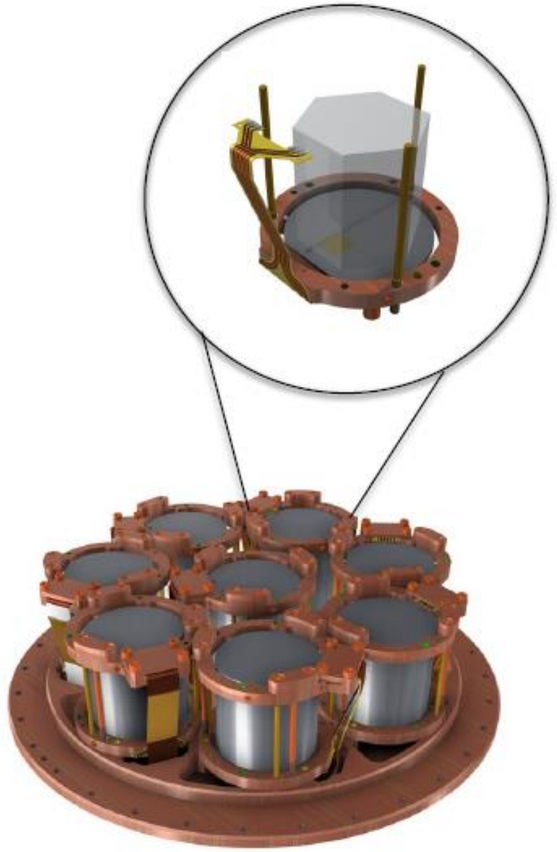


- December 2021: Demonstrated the first particle discrimination in NaI at a surface setup
- June 2022: Measurement was carried out using a CRESST test facility at the Gran Sasso National Laboratory (underground)
  - NaI baseline resolution: 0.39 keV (< 2 keV threshold)
  - Silicon Beaker baseline resolution: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

COSINUS – Dry Dilution Refrigerator



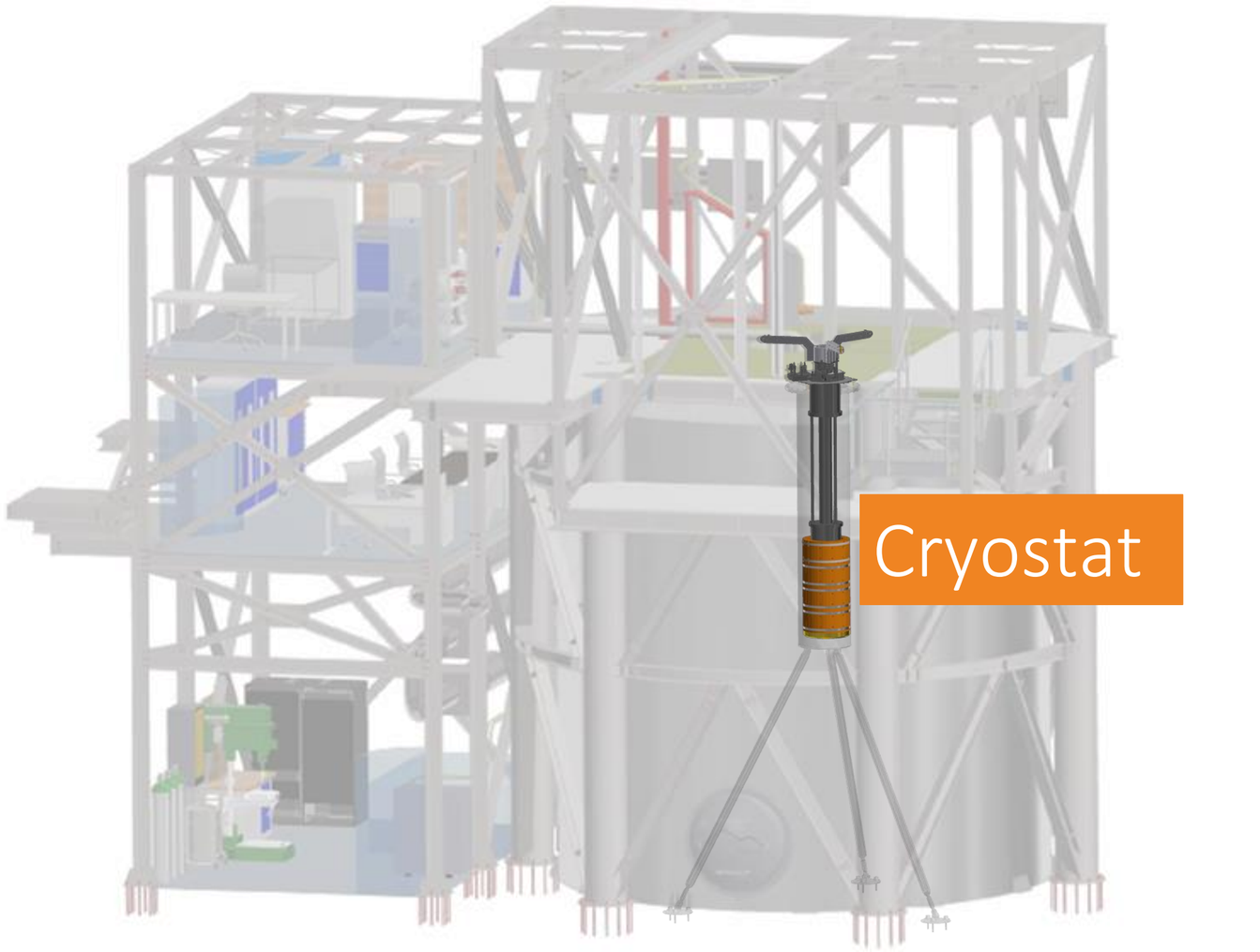




- Crystals are grown in collaboration with SICCAS using Astrograde (MERCK) powder in a modified Bridgeman technique

- 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

Experimental Setup I



Cryostat

June 2022

Experimental Setup II

Dry Well

June 2022

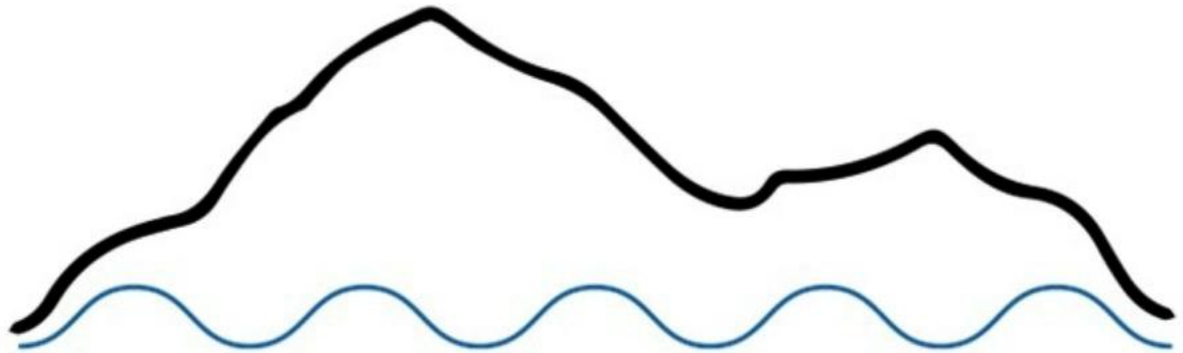
Experimental Setup III

Control Room

Clean Room

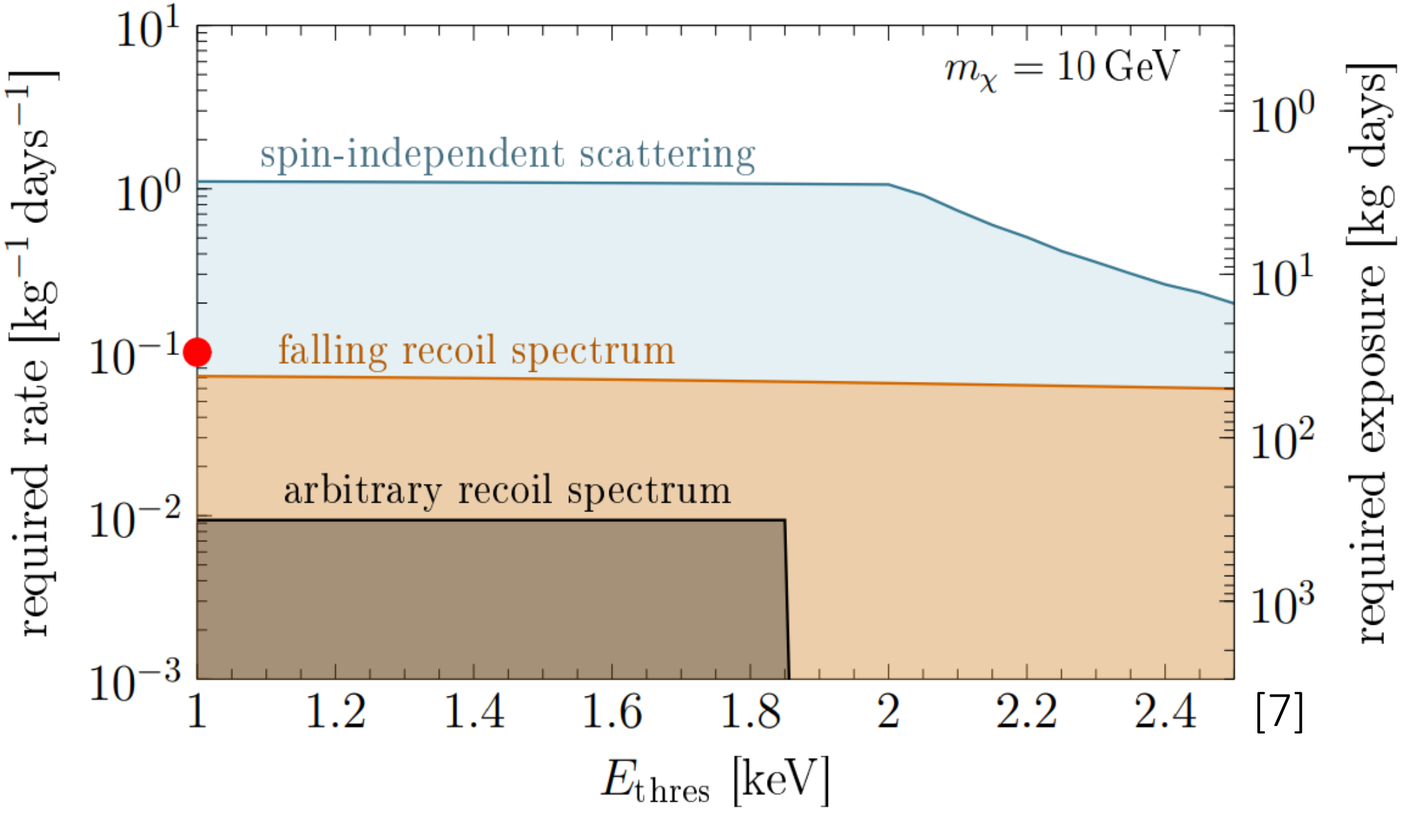
Water Tank

June 2022



COSINUS Productions™(pending)

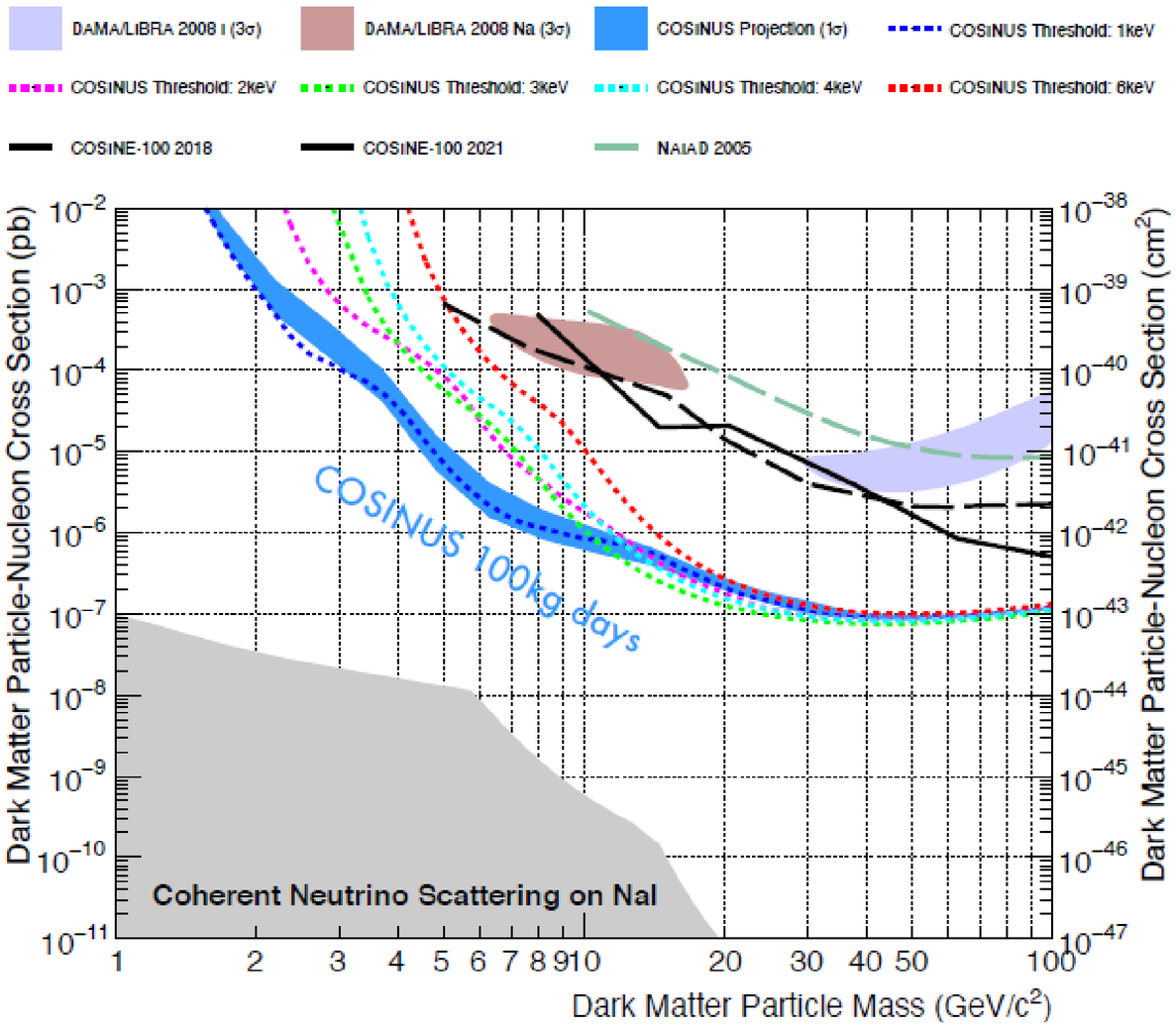
COSINUS Physics Goals I



*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>
  - <u>Model independent exclusion</u>
- COSINUS-2π
  - Annual modulation signal
  - Increase target mass capability, more than double the number of detectors

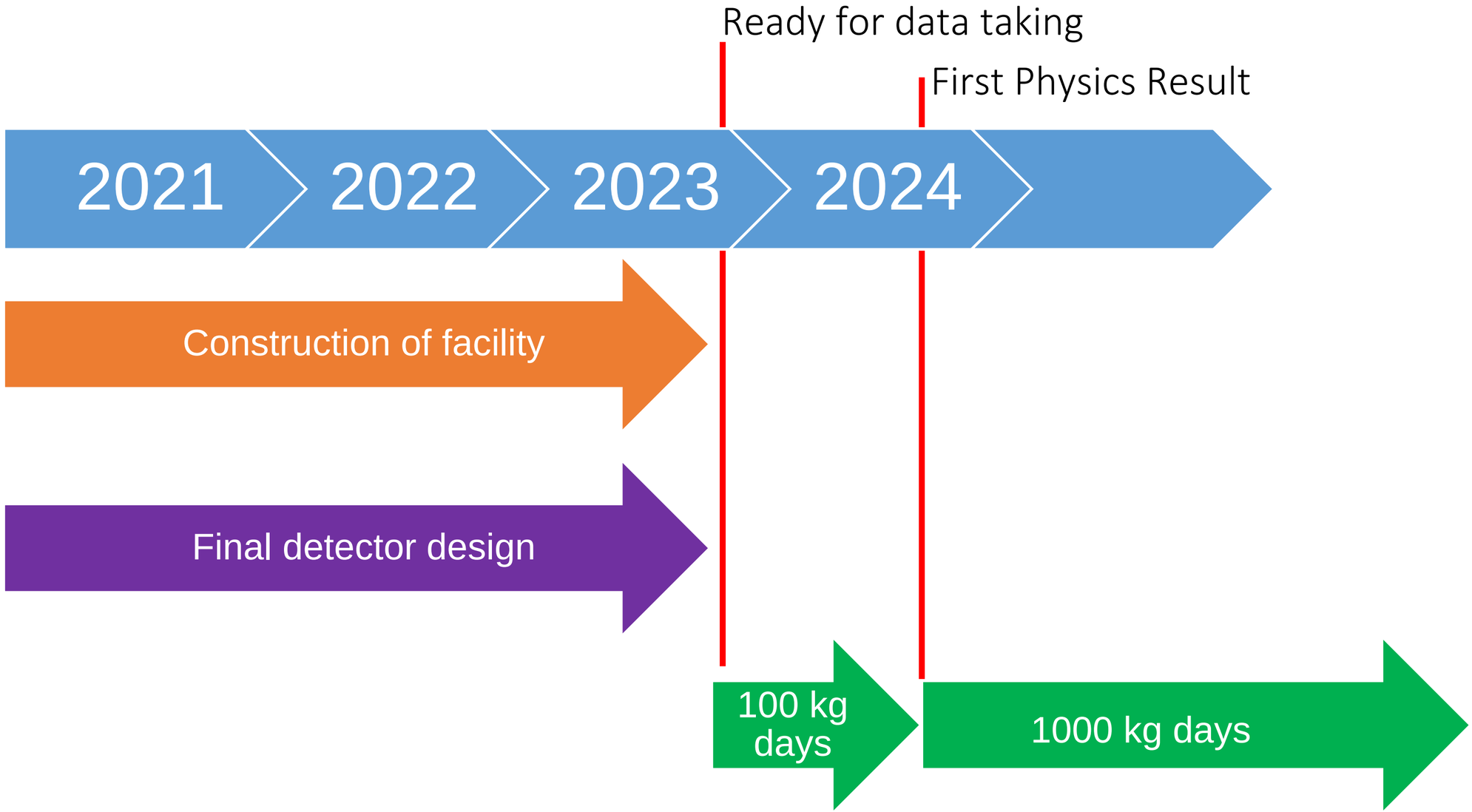
COSINUS Physics Goals II



*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

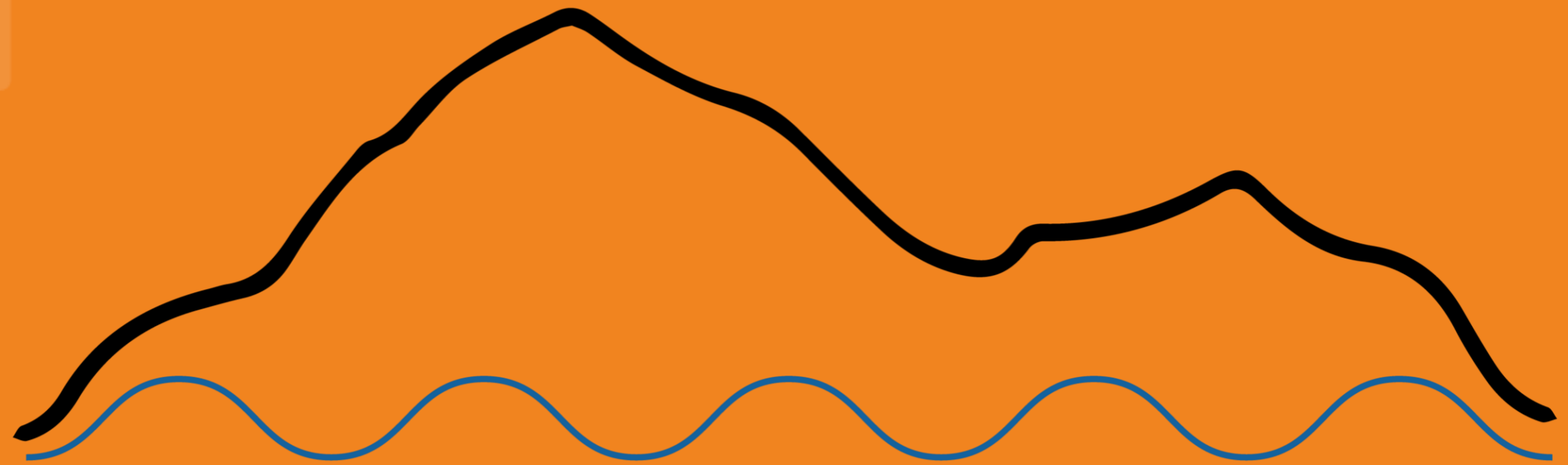
COSINUS Timeline



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!



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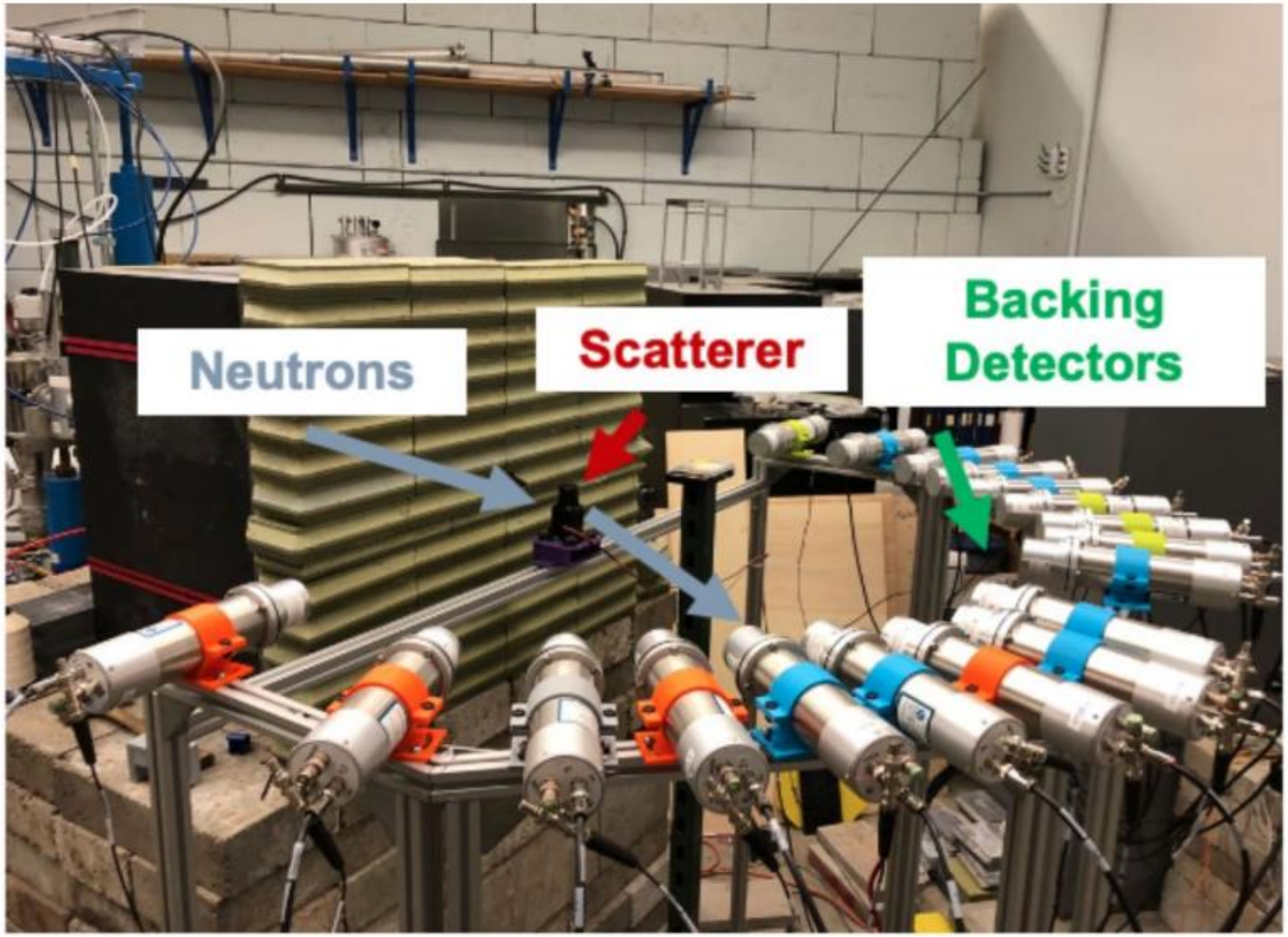
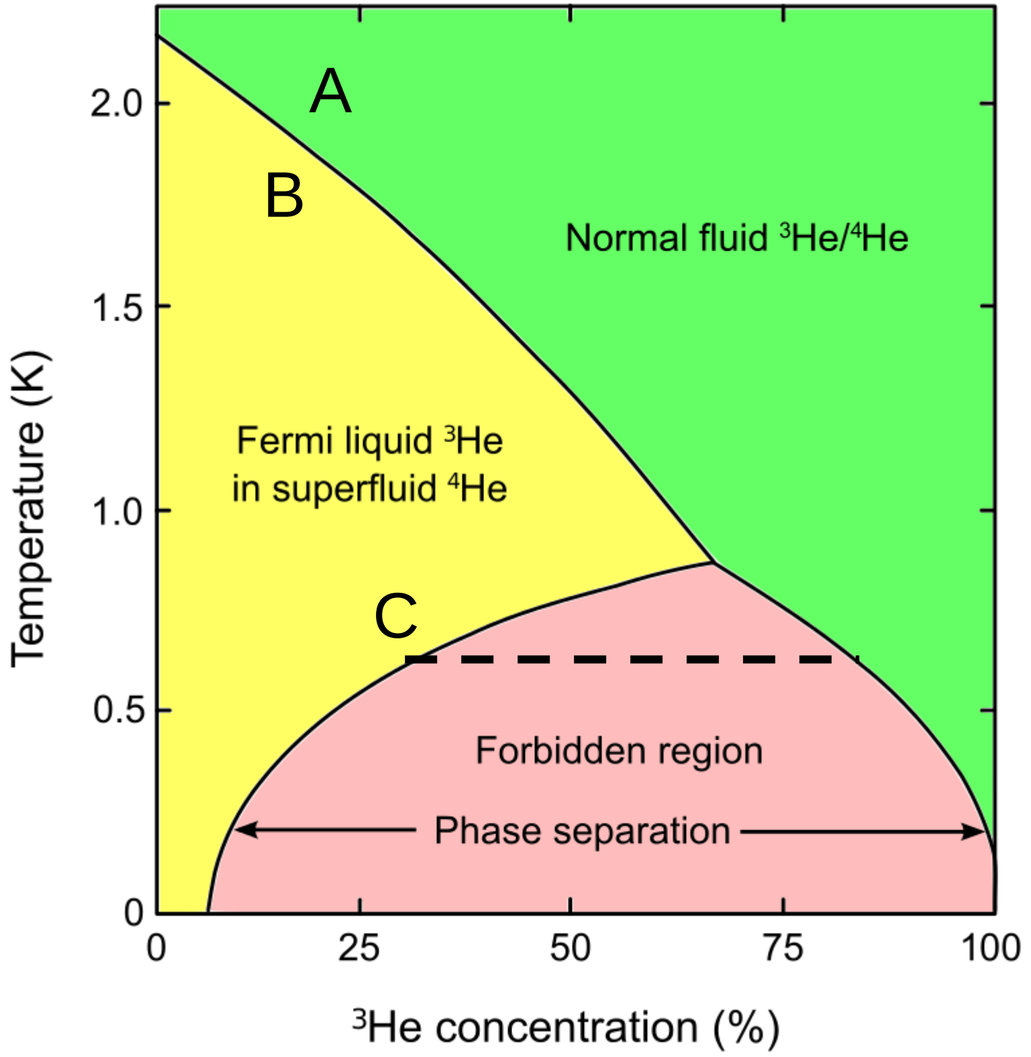
Quenching Factor Measurement



- 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 <u>QF!!</u>

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

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