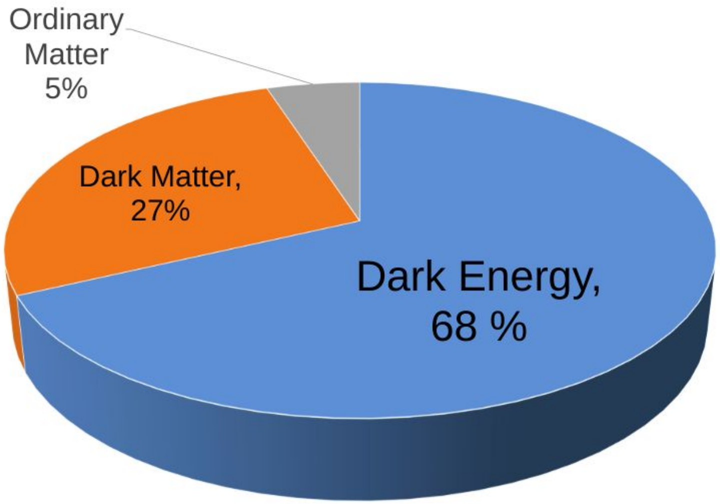
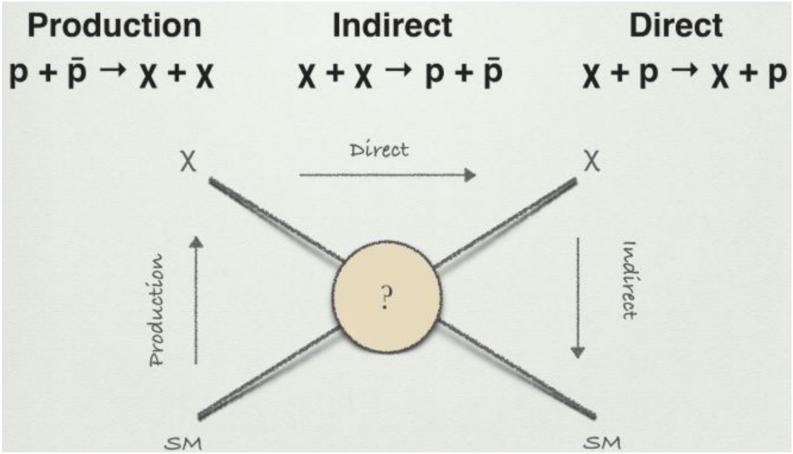
Optimization of the COSINUS experiment for background reduction using Monte Carlo simulations

By: Matthew Stukel
VIEWS 2024 workshop
2024/04/25

What is COSINUS?

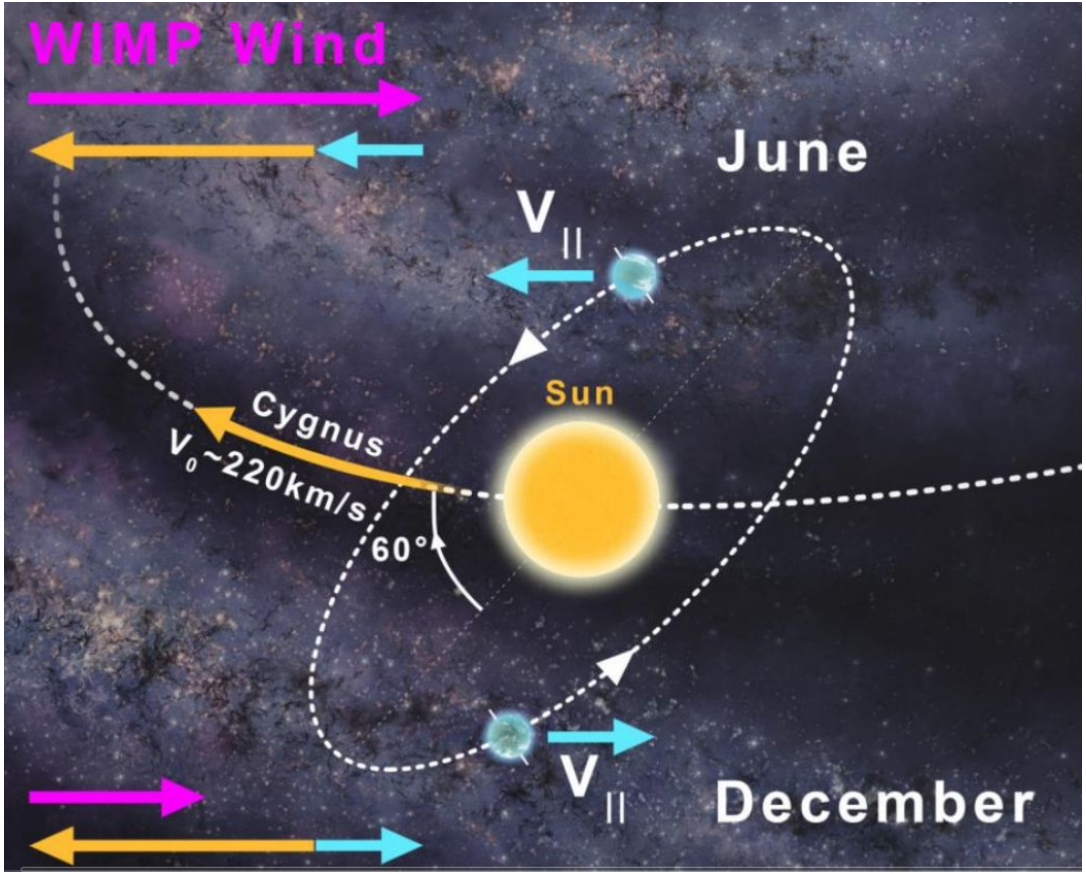
Dark Matter





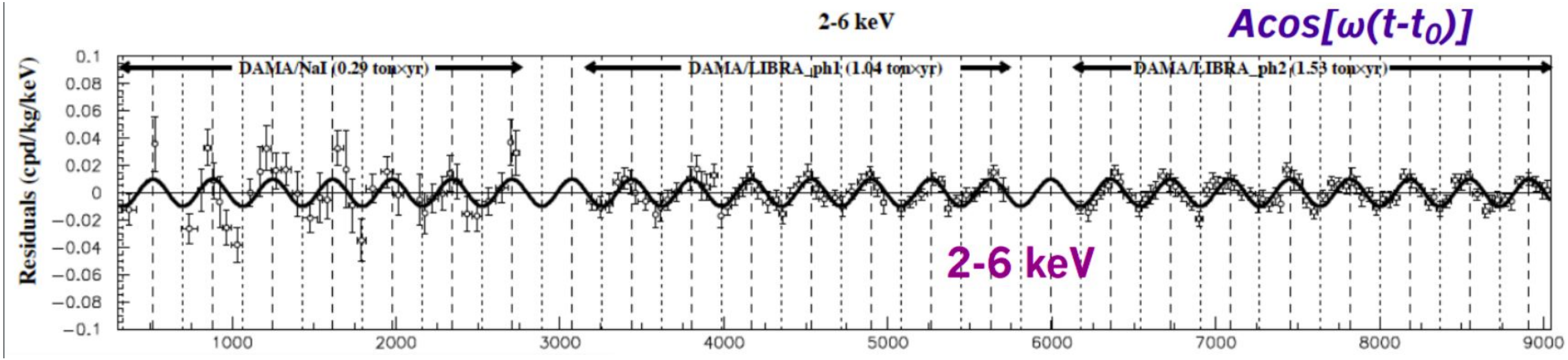
- Evidence includes: Weak gravitational lensing, rotational curves of galaxies, cosmological modeling
- Many experiment employ many techniques

Direct Detection: Annual Modulation



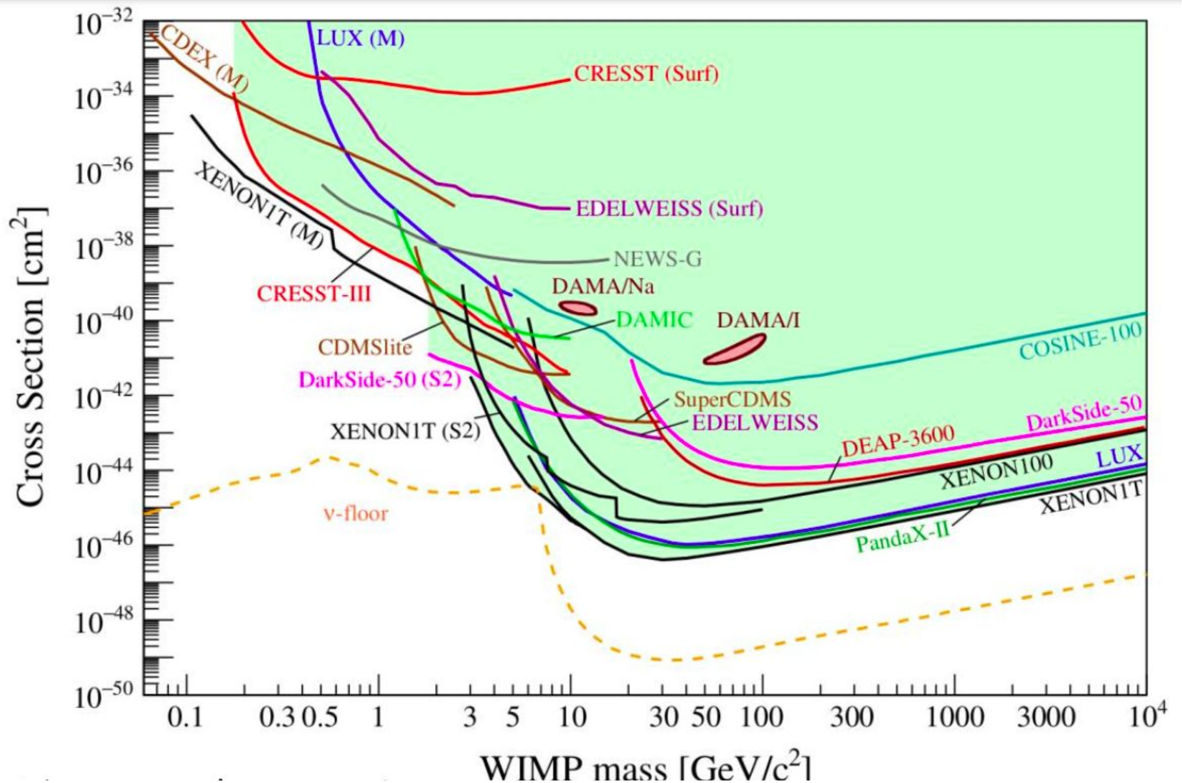
- The sun moves through the galactic dark matter halo
- The earth rotates around the sun inducing a change in the dark matter flux throughout the year
- Unique and detectable signal for dark matter
  - Period of one year
  - Peaks around June 2nd
  - Signal expected in low energy region (O(keV))

DAMA/LIBRA Results



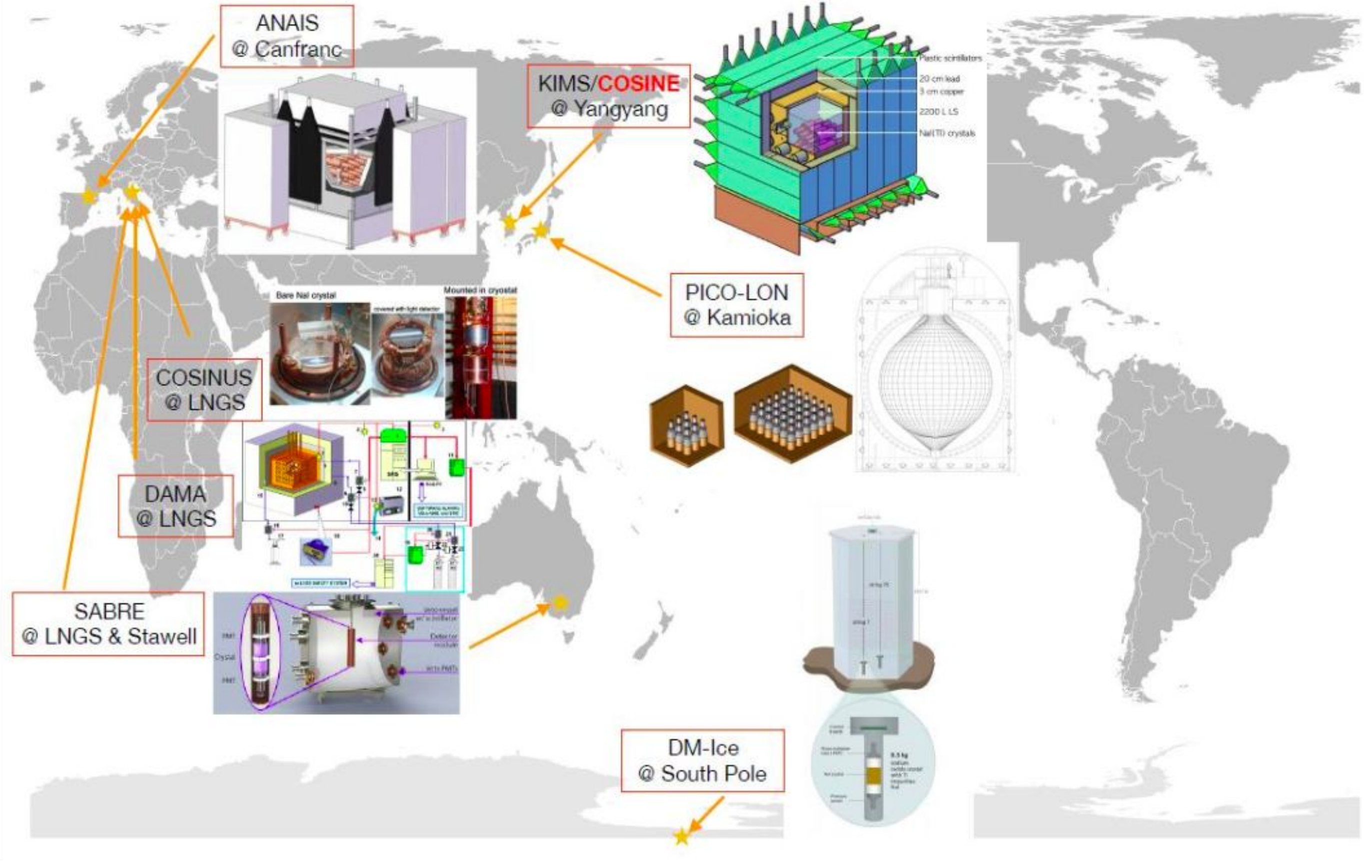
- The DAMA collaboration has detected a peculiar annual modulation signal since 1997
- Signal is consistent with WIMP dark matter halo predictions (0.75 keV threshold shown)
  - Statistics: >13σ
  - Period: 0.999 +/- 0.001
  - Phase: 25th May +/- 5 days
  - Non-dark matter explanation: No

Complications with DAMA



- Incompatible with every other experiment in a model dependent way

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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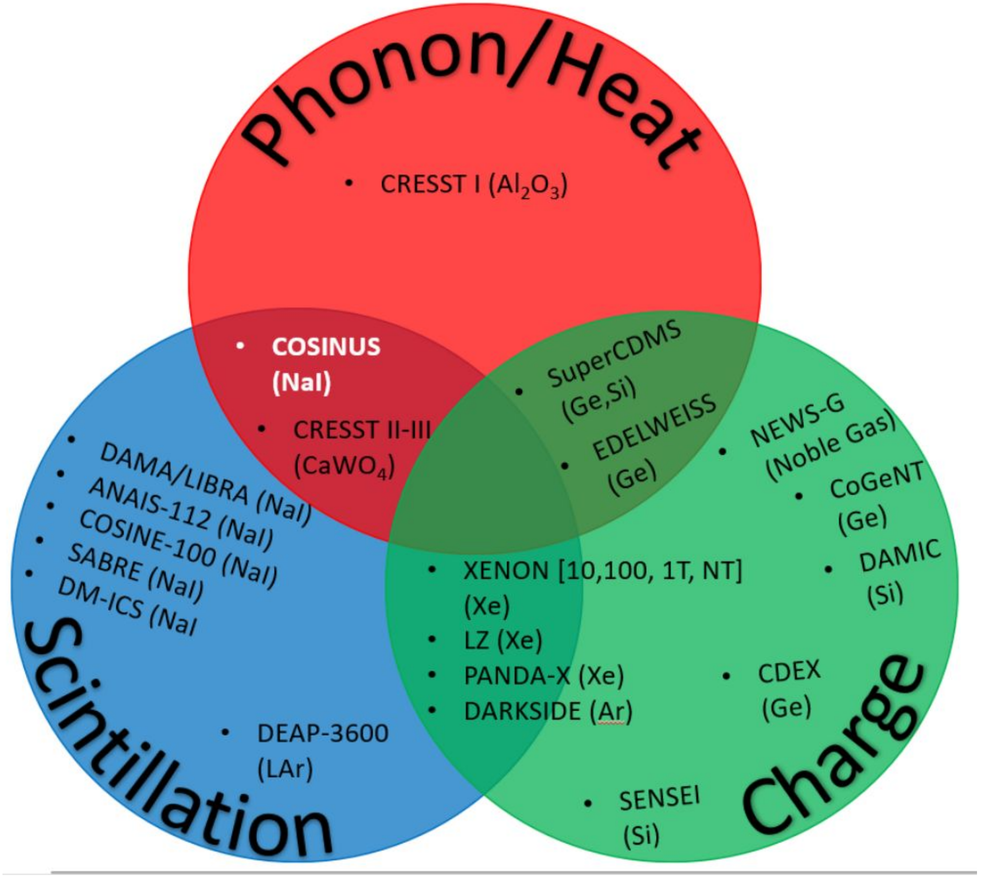
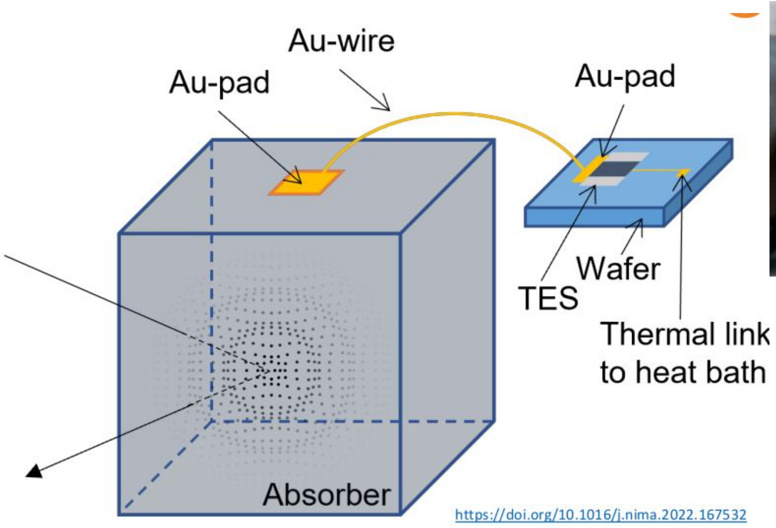
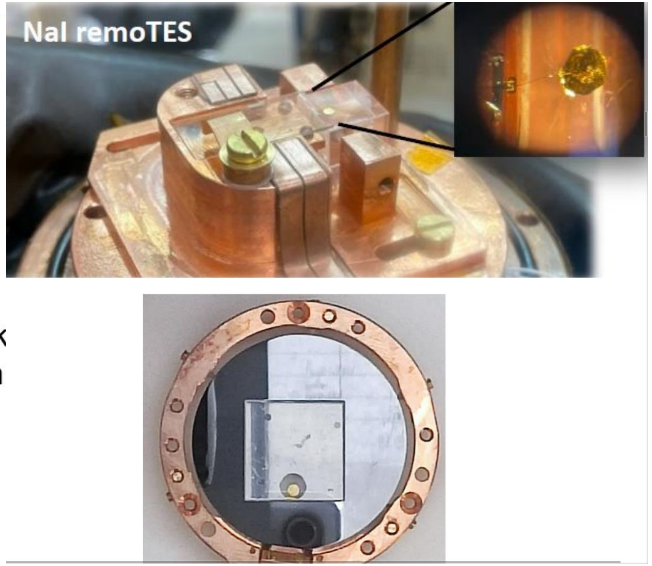
COSINUS Detection Technique

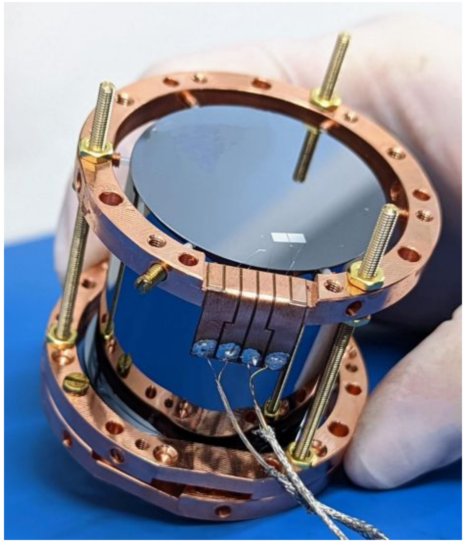


- **COSINUS Goal:** Aims at a model independent test of the DAMA/LIBRA experiment
  - Same material (NaI)
  - Same location (LNGS)
  - Need 1000 kg days
- **Unique Technique:** Operate NaI as a cryogenic detector (First ever!!)
  - Dual Channel: Phonon (~90%) and Light (~10%) signal for event-by-event particle discrimination

COSINUS Detection Principle

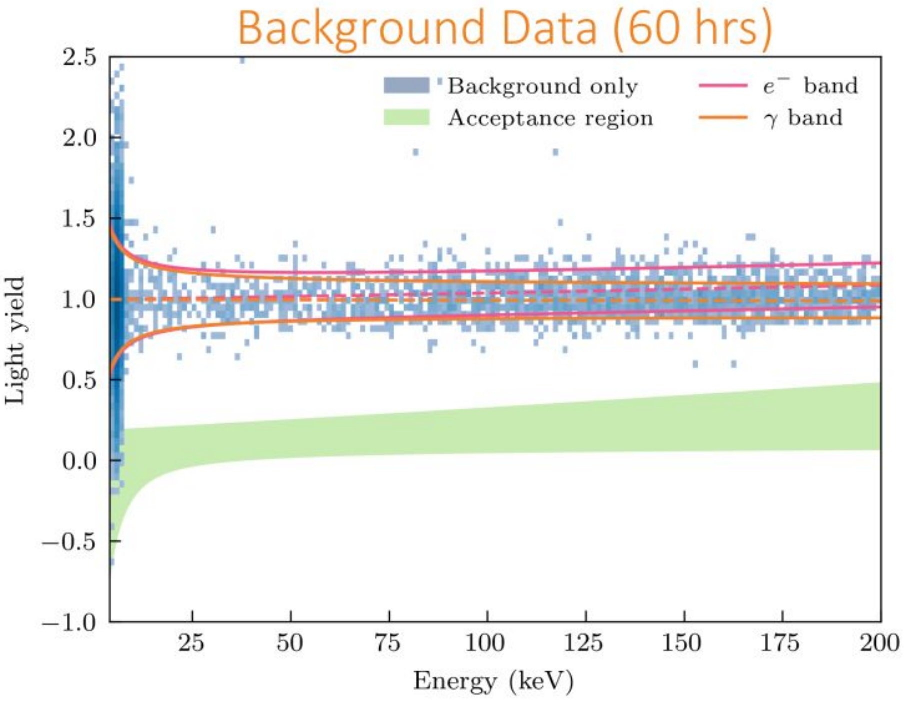


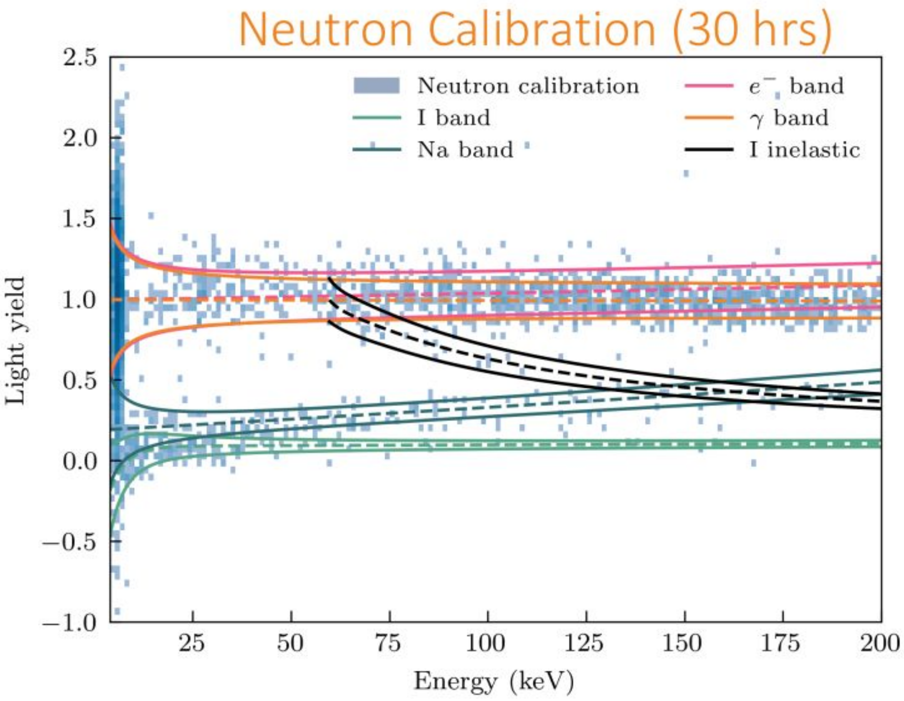




- NaI is hygroscopic (should not come into contact with humid air)
- Very soft and low melting point (easy to damage when handling)
- Separate wafer that holds the TES-Wafer:
- Scintillation light is detected by a surrounding silicon beaker
    - 1mm thick, 40mm in diameter
    - 4π coverage to maximize light collection

Particle Discrimination

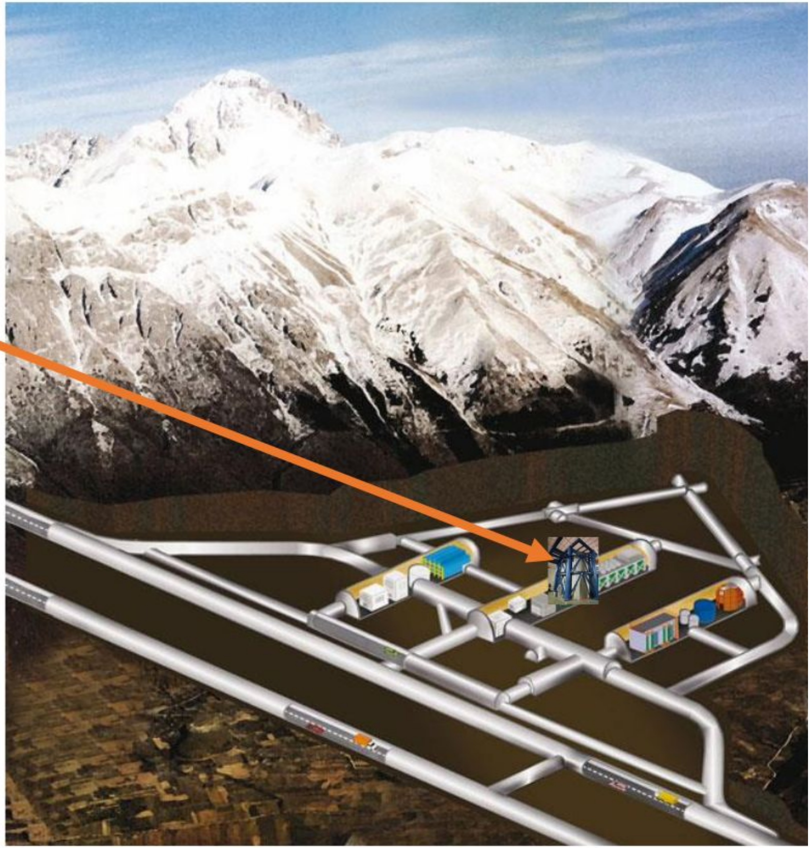




- December 2021: Demonstrated the first particle discrimination in NaI at a surface setup
- June 2022: Measurement was carried out using a CRESST test facility at the Gran Sasso National Laboratory (underground)
- NaI phonon resolution: 440 eV nr, proof of particle discrimination in NaI

Gran Sasso National Laboratory

COSINUS
Location



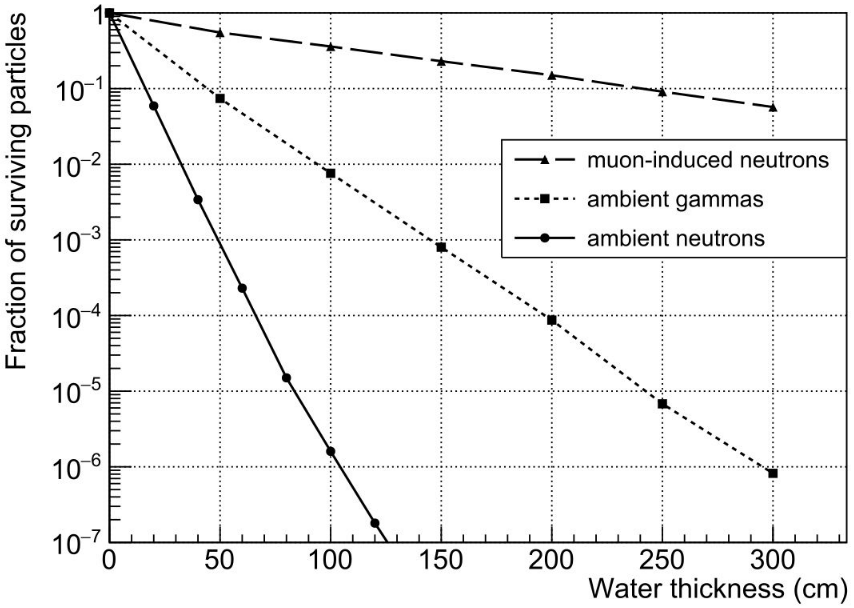
https://www.appec.org/news/hands-on-experimental-underground-physics-at-lngs

How simulations helped built the shielding of the experiment

COSINUS simulation group

- A simulation toolkit used in the CRESST, COSINUS and NUCLEUS experiment
- Geant4 (v10) and Root (v6 based)
- Paper to cite if used: DOI:10.1140/epjc/s10052-019-7385-0
- COSINUS adapted ImpCRESST to design the shielding for the experiment and model the background
- Used in conjunction with external programs such as MUSUN and SOURCES-4C

Shielding for COSINUS

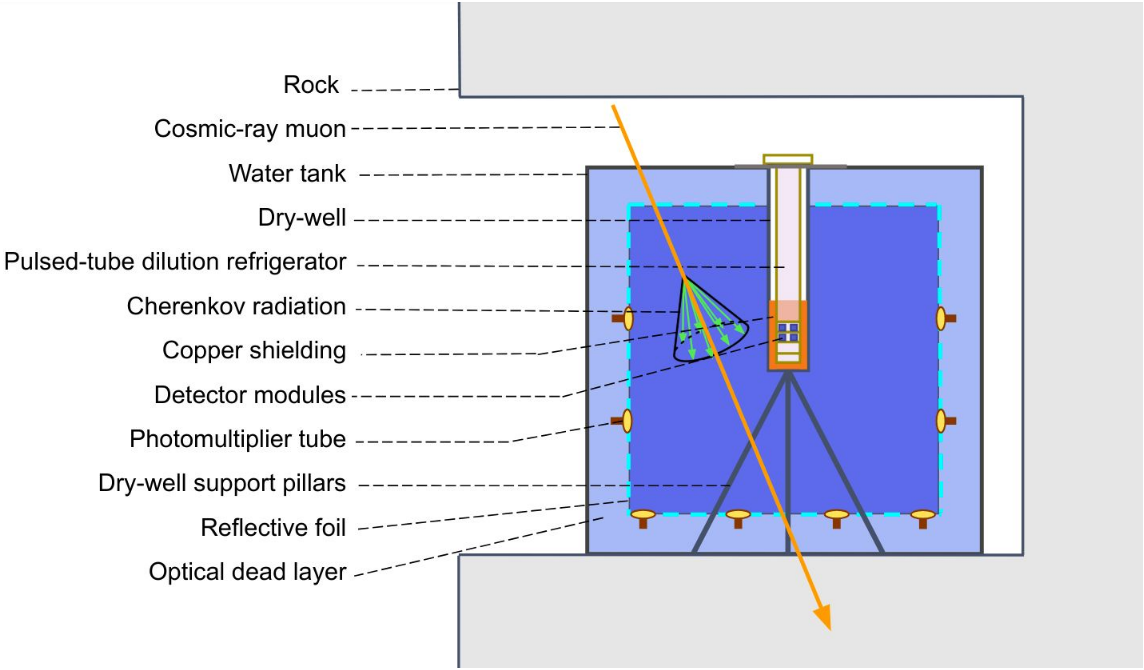


- Major backgrounds
  - Ambient radiation (gamma/neutrons)
  - Radiogenic (gamma/neutrons)
  - Cosmogenic (neutrons)
- Ambient radiation in Gran Sasso can be significantly reduced by a **3 m radius water tank**
- Radiogenic backgrounds are reduced through proper material selection
  - Detailed material screening campaign performed at LNGS
- Cosmogenic neutron background will give **3.5 cts/kg/yr,** needs an active veto

Angloher,
experime

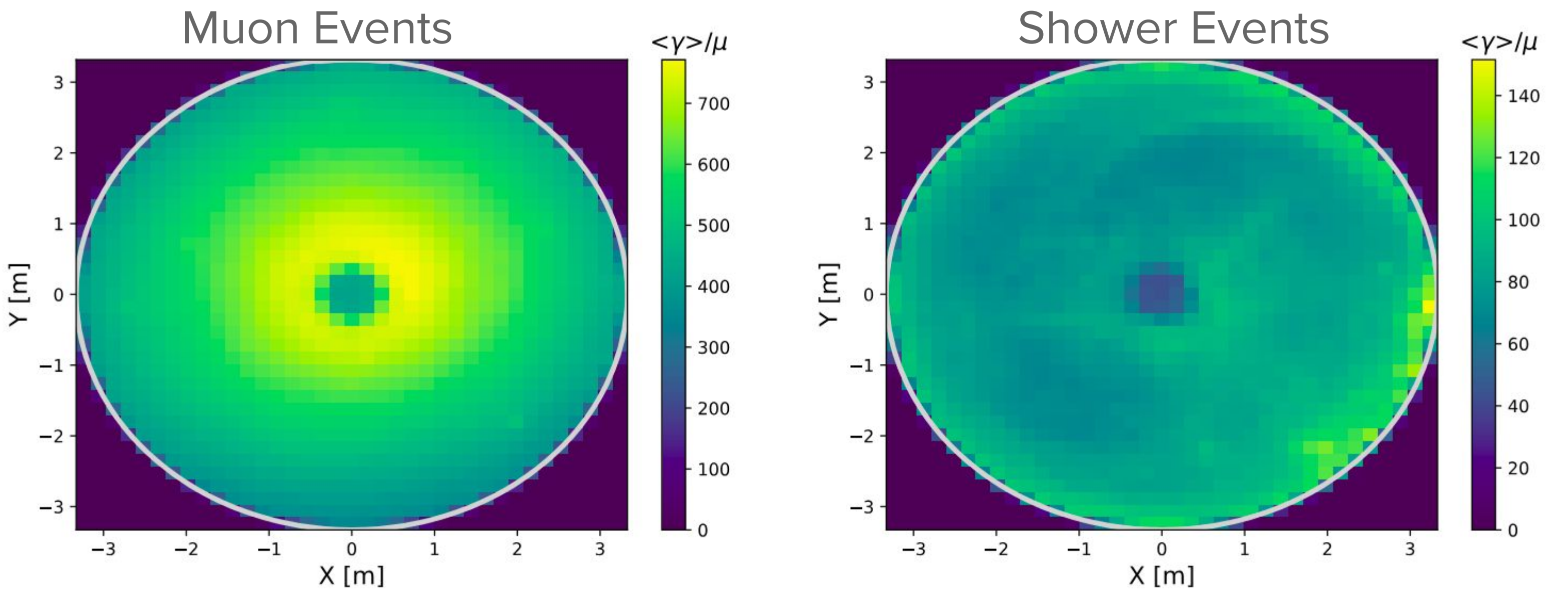
Material	Method	^{232}Th		^{238}U			^{235}U	^{40}K
		^{228}Ra	^{228}Th	^{226}Ra	^{234}Th	^{234m}Pa		
Stainless Steel	HPGe	< 1.1	< 1.3	0.9(4)	< 84	< 26	< 1.5	< 5
Copper	HPGe	< 0.2	< 0.11	0.15(4)	< 7.2	< 3.8	< 0.14	< 1.7
NaI Powder	HR-ICP-MS	Th: < 10 ppt		U: < 10 ppt				< 15 ppb

Active Water Cherenkov Muon Veto



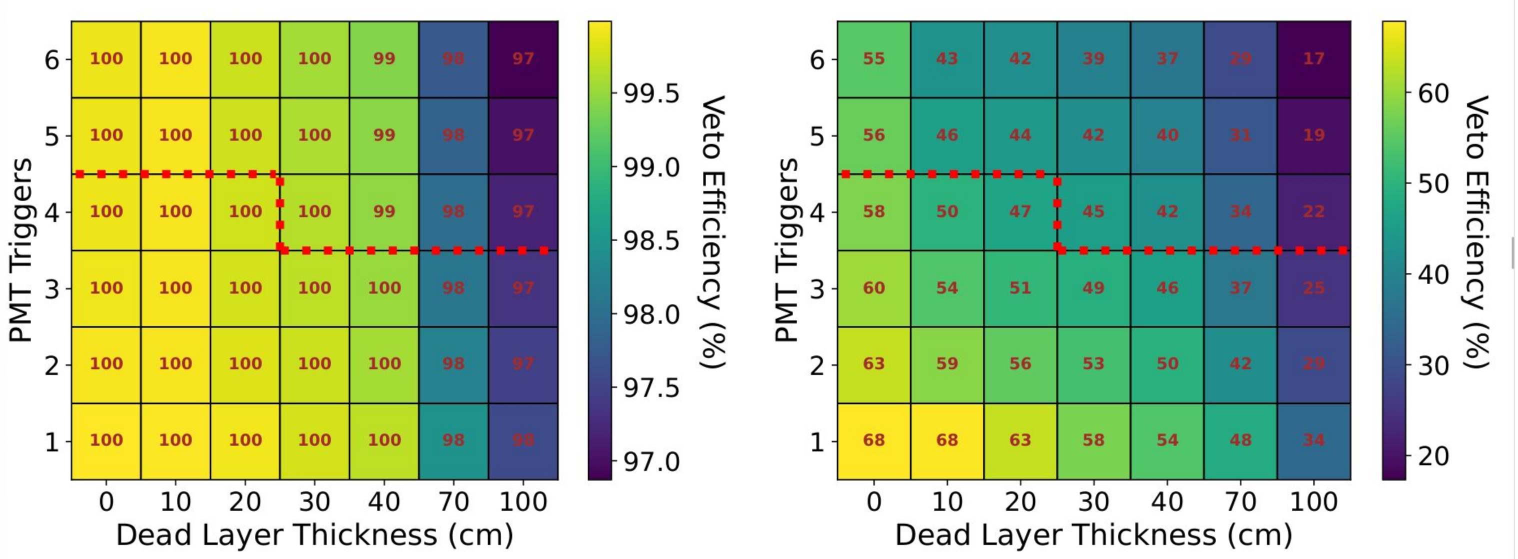
- 230 tonne water tank (7mx7m cylinder)
- Optical dead layer for the muon veto
  - Reduce the spurious triggers of PMT from ambient background and triggers
- Need a trigger rate **less than 1 Hz to be viable**
- Detailed optical simulation created with ImpCRESST to optimize PMT placement, detector efficiency and background rate

Muon Veto PMT Placement



- Photon illumination plots of muon and shower events give clues on where to place the limited amount of PMTs
- Muon events make lots of Cherenkov radiation near the centre so can be detected by a circle of PMTs at a radius of 1m
- Shower events produce Cherenkov radiation near the edge so another ring at radius 2.7 m should be placed

Optical Dead Layer and PMT Triggering



- Ambient gammas can trigger PMTs, but this can be reduced by creating an optical dead layer in the water tank
- Optical dead layer will also reduce veto efficiency
- Final Configuration:
  - 30 PMTs, 30cm optical dead layer, 99% muon efficiency, 44% shower efficiency
  - Cosmogenic neutron background reduced to: **0.11 ± 0.02 cts/kg/yr**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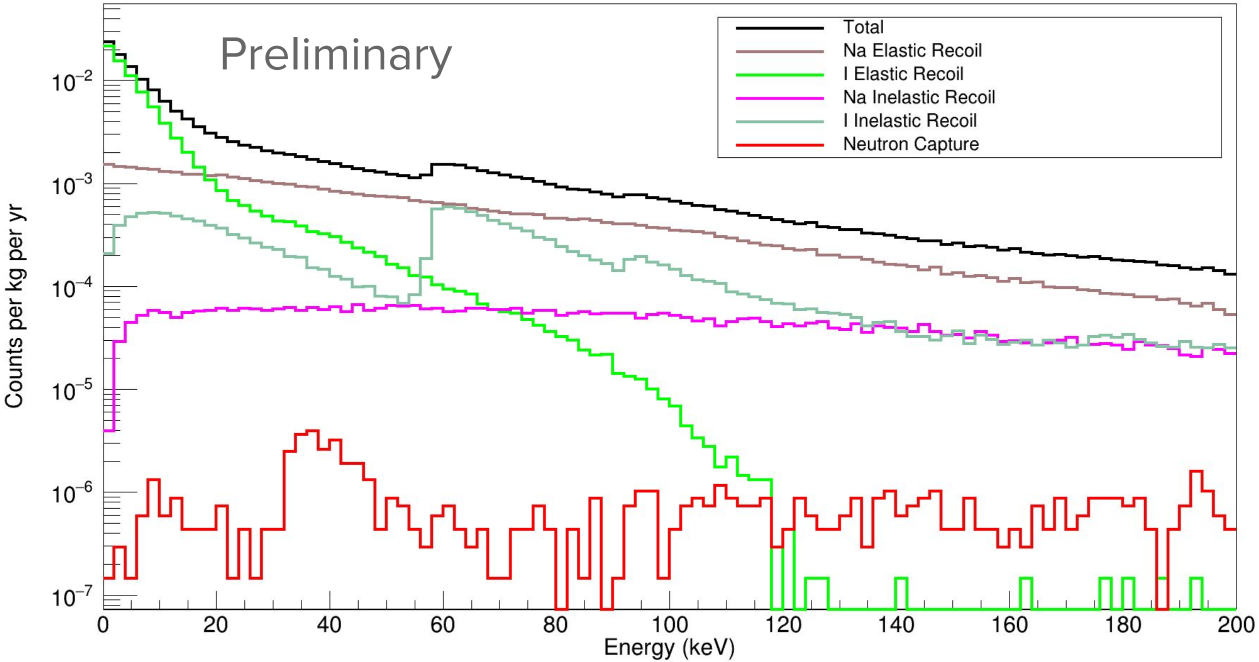
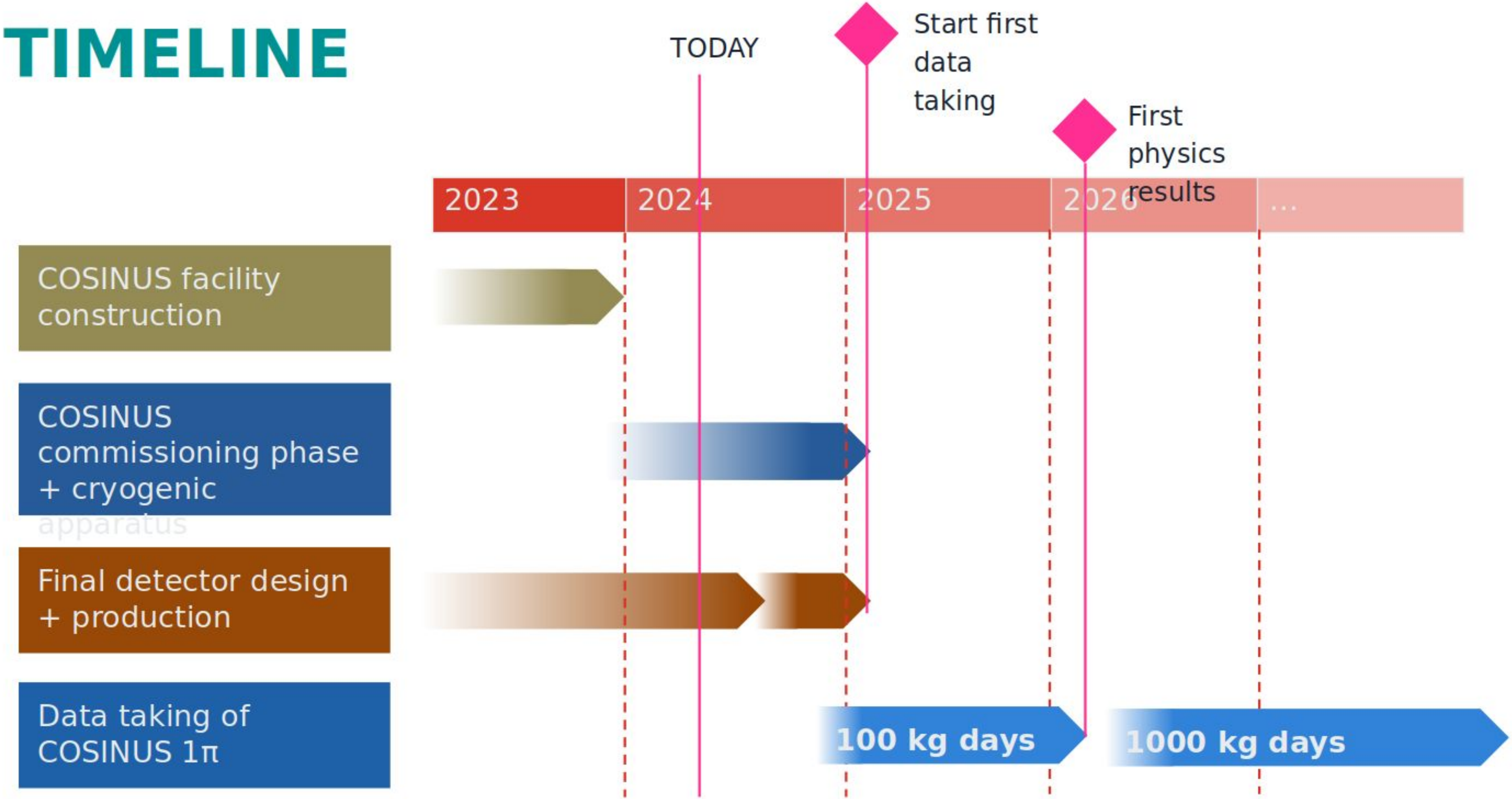
Intrinsic Nuclear Recoil Background in NaI



- Background modeling has just begun for the COSINUS experiment
- Most important background will be intrinsic nuclear recoil backgrounds of the crystals
- NaI astrograde powder: 15 ppb K-40, 0.01 ppb Th, and 0.01 ppb U
- **1- 10 keV: 0.066 +/- 0.024 cts / kg /yr (Preliminary)**
    - Does not include resolution or light yield leakage effects

TIMELINE


TODAY
Start first data taking
First physics results
2023
2024
2025
2026
...
COSINUS facility construction
COSINUS commissioning phase + cryogenic apparatus
Final detector design + production
Data taking of COSINUS 1π
100 kg days
1000 kg days

Summary

- COSINUS is a NaI-based dark matter search whose goal is to check the longstanding DAMA/LIBRA claim
- Cryogenic NaI calorimeters have demonstrated the ability to discriminate particle interaction types
- **Facility completed and recently celebrated the inauguration of the experiment!!**
- Data taking is expected to begin by the end of the year
- Simulations have played a large role so far in the design of the experiment so far (shielding and muon veto)
- Next step is the background model

Extra Slides

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?
- ...

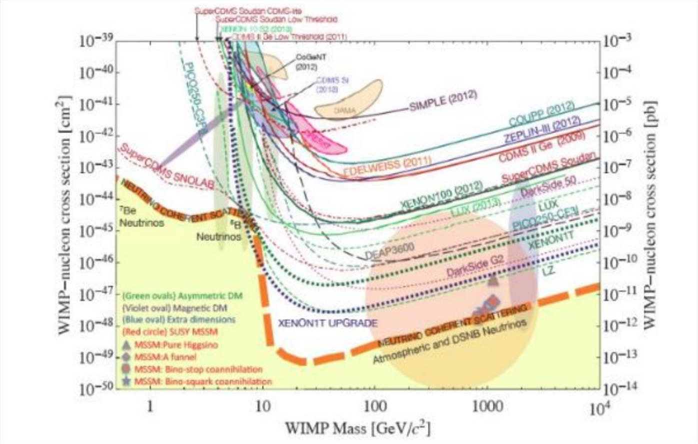
...and experimental aspects...

- 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

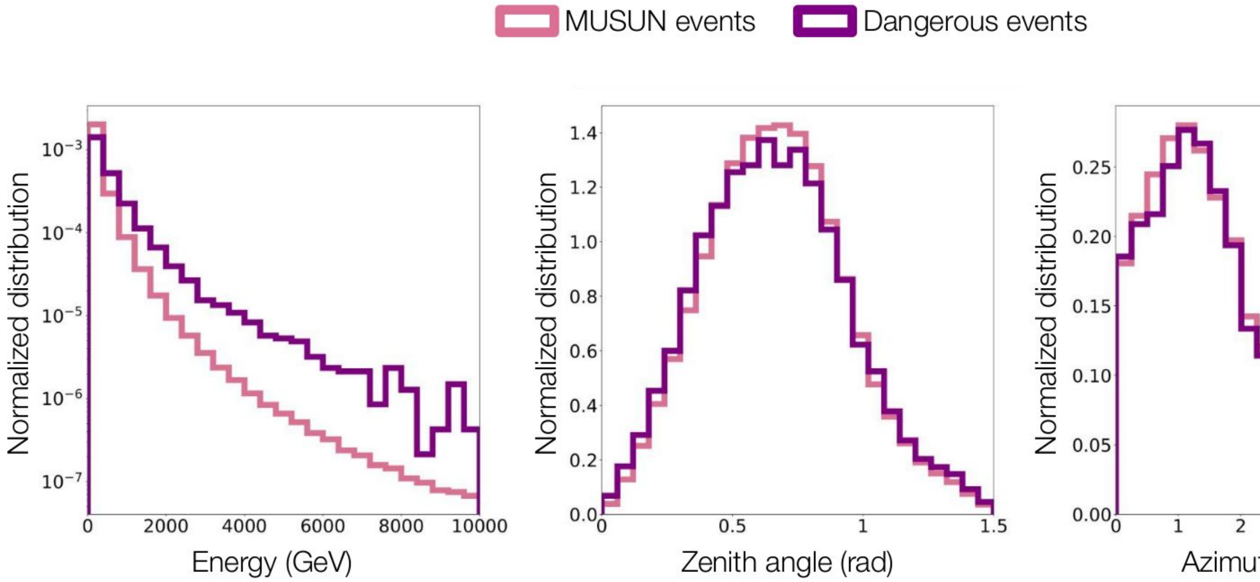
Is it an "universal" and "correct" way to approach the problem of DM and comparisons?



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

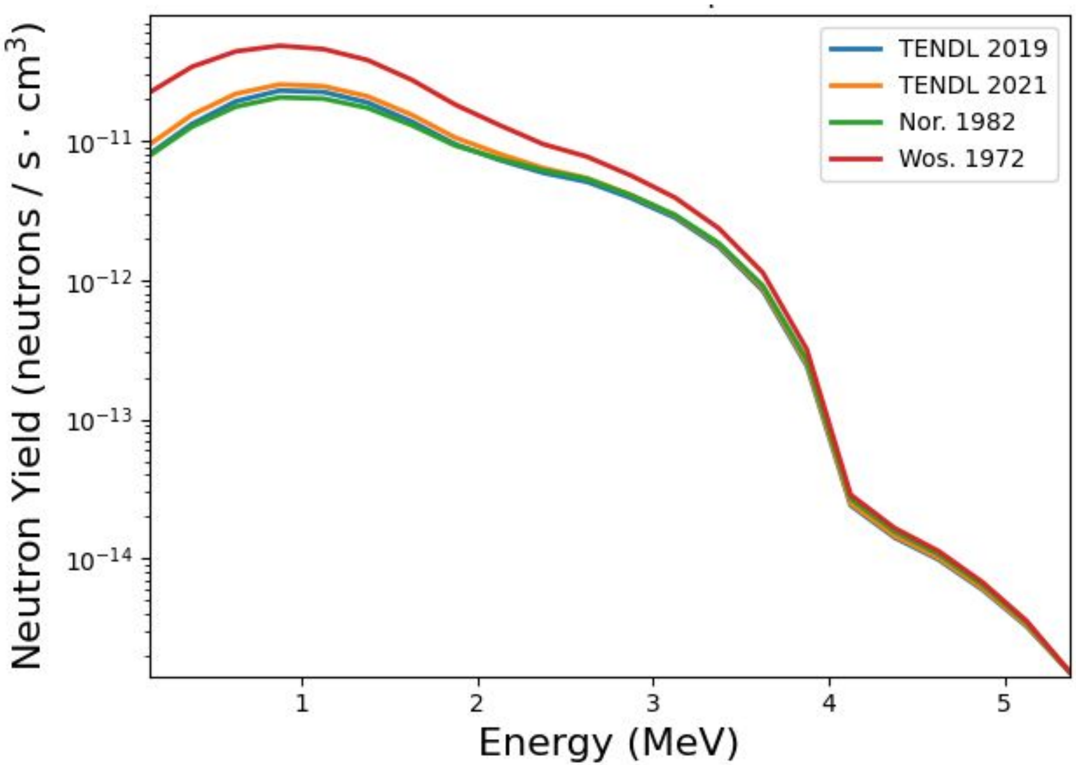
https://agenda.infn.it/getFile.py/access?contribId=34&sessionId=1&resId=0&materialId=slides&confId=15474

MUSUN: MUons Simulated UNderground



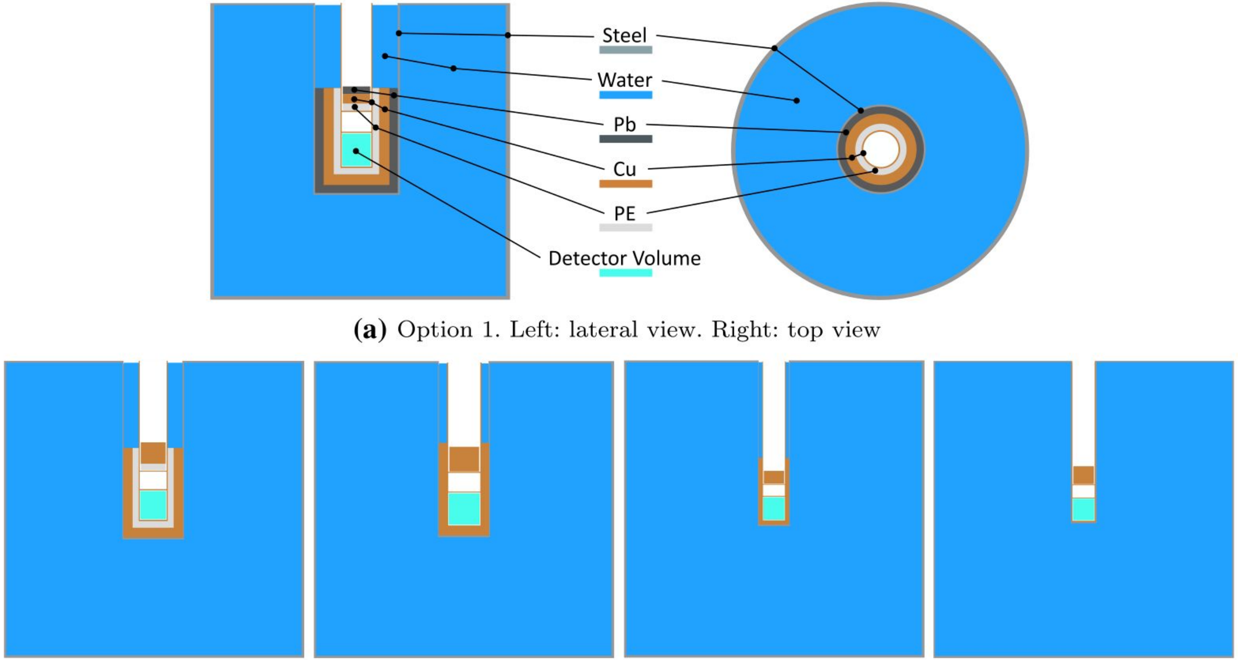
- MUSUN simulates the muon flux at LNGS, using the topographical layout of the mountains
- 30 million muons where simulated in the COSINUS geometry
- Events that generate neutrons in the dry-well are classified as “dangerous” and simulated with the optical physics turned on

SOURCES-4C



- SOURCES-4C is a fortran based code that calculates the (α,n) interaction from spontaneous fission of primordial radionuclides

COSINUS Shielding Evaluation from simulations



(a) Option 1. Left: lateral view. Right: top view

(b) Option 2. **(c)** Option 3. **(d)** Option 4. **(e)** Option 5.

Background source		Estimated number of particles entering the detector volume (yr^{-1}) Option 1	Option 2	Option 3	Option 4	Option 5
Neutrons	Ambient	$< 3.50 \cdot 10^{-2}$	$< 3.50 \cdot 10^{-2}$	$< 3.50 \cdot 10^{-2}$	$< 3.50 \cdot 10^{-2}$	$< 3.50 \cdot 10^{-2}$
	Radiogenic	$(9.17 \pm 0.01) \cdot 10^{0}$	$(9.18 \pm 0.01) \cdot 10^{0}$	$(2.17 \pm 0.01) \cdot 10^{0}$	$(9.31 \pm 0.07) \cdot 10^{-1}$	$(4.22 \pm 0.05) \cdot 10^{-1}$
	Cosmogenic	$(2.10 \pm 0.03) \cdot 10^{2}$	$(1.15 \pm 0.02) \cdot 10^{2}$	$(3.36 \pm 0.04) \cdot 10^{2}$	$(2.22 \pm 0.03) \cdot 10^{2}$	$(1.11 \pm 0.02) \cdot 10^{2}$
Gammas	Ambient	$(3.15 \pm 1.41) \cdot 10^{3}$	$(6.81 \pm 1.15) \cdot 10^{4}$	$(7.88 \pm 1.05) \cdot 10^{4}$	$(1.71 \pm 0.57) \cdot 10^{4}$	$(4.94 \pm 0.47) \cdot 10^{5}$
	Radiogenic	$(5.68 \pm 0.14) \cdot 10^{6}$	$(5.68 \pm 0.14) \cdot 10^{6}$	$(4.08 \pm 0.13) \cdot 10^{5}$	$(4.46 \pm 0.14) \cdot 10^{5}$	$(2.09 \pm 0.04) \cdot 10^{6}$

Ambient Gamma in LNGS

Energy Region (keV)	Flux ($\gamma \cdot cm^{-2} \cdot s^{-1}$)
7.4 - 249.8	0.137
250.2 - 500.4	4.24×10^{-2}
500.8 - 1005.2	2.99×10^{-2}
1005.6 - 1555.8	1.46×10^{-2}
1556.2 - 2055.8	3.50×10^{-3}
2056.2 - 2734.2	2.02×10^{-3}

Table 1: Ambient gamma flux as a function of energy in Hall B of LNGS. Adopted from [32].