COSINUS dark matter direct detection experiment

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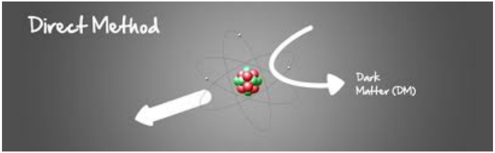
Direct detection

- Direct detection experiments look for DM scattering off the nucleus of the target material, by detecting the nuclear recoil (typically via scintillation light, ionization or phonons).
- The event rate depends on the DM-nucleus scattering cross section, and the velocity distribution of DM:

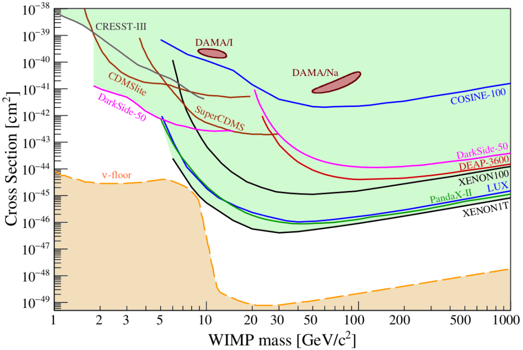
$$\frac{dR}{dE_r}(t) = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{\rm min}}^{v_{\rm esc}} v f(v,t) \frac{d\sigma}{dE_r} dv, \qquad v_{\rm min} = \sqrt{\frac{E_r m_N}{2\mu_{N\chi}^2}}.$$

- $f(v,t)$: DM velocity distribution in the laboratory frame, depends on the DM halo model.
- $\frac{d\sigma}{dE_r}$: DM-nucleus scattering cross section, depends on the particle physics model of DM, and on the target nucleus.



Direct detection

- The exclusion limit is typically presented in the $(m_\chi, \sigma_{\chi n})$-plane, where the cross section refers to a given scattering operator.
- The simplest operator is the scalar (Spin-Independent) operator. Arising from e.g. $\bar{\chi}\chi\bar{q}q$: $\frac{d\sigma}{dE_r} = \sigma_{\chi n}\frac{A^2 m_N}{2v^2\mu_{n\chi}^2}F^2(E_r)$.
- The interpretation of this limit, and the comparison between different experiments depends strongly on the assumptions made on the DM halo and DM-nucleus interaction.



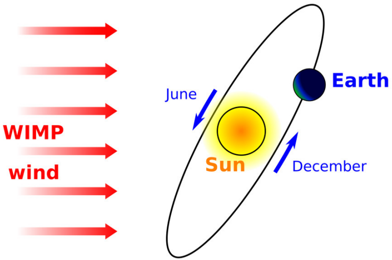
Modulation experiments

- Separation of the DM signal from the background can be achieved via the modulation of the DM scattering event rate due to the motion of the earth in the Galactic rest frame.

$$\vec{v}_{\rm lab} = \vec{v}_{\rm circ} + \vec{v}_{\rm sol} + \vec{v}_{\rm rev} + \vec{v}_{\rm rot}\,,$$

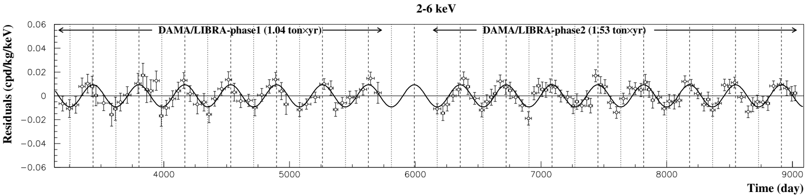
  $v_{\rm circ} \sim 220\,{\rm km\,s^{-1}}$, $v_{\rm sol} \sim 18\,{\rm km\,s^{-1}}$, $v_{\rm rev} \sim 30\,{\rm km\,s^{-1}}$, $v_{\rm rot} \sim 0.5\,{\rm km\,s^{-1}}$.

- Annual modulation is expected due to the variation in $v_{\rm lab}$ as $\vec{v}_{\rm rev}$ and $\vec{v}_{\rm circ}$ are aligned/antialigned during the year.



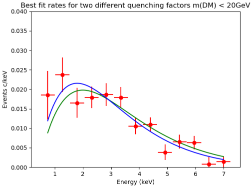
DAMA modulation signal

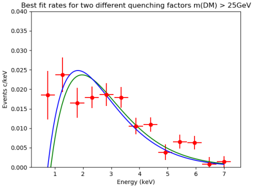
- For more than 20 years, the DAMA/LIBRA experiment has observed a modulation signal, with phase and frequency matching that predicted for a DM signal.
- The statistical significance for a non-zero modulation amplitude in the observed event rate is 13.7σ [arXiv:2110.04734].
- However, at least under the standard assumptions on the Halo model and DM-nucleon couplings, the DM signal responsible for the DAMA modulation should be visible in several other experiments.



DAMA modulation signal

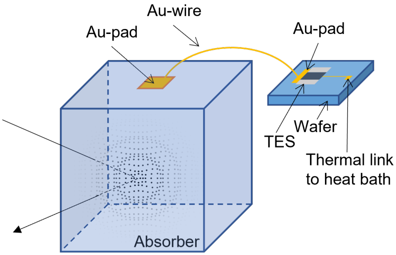
- DAMA observes the scintillation light from the scattering events in NaI target crystals.
- The amount of light emitted after a nuclear recoil event is smaller than that from an electron recoil with the same deposited energy.
- The ratio of the light yields from nuclear/electron recoils is called the quenching factor. Uncertainty in the quenching factor results in uncertainty in the absolute recoil energy of the observed events.
- The interpretation of the DAMA signal in terms of a DM model (mass, interaction strength) is only possible under fixed assumptions on the halo model, DM-nucleon coupling operator and the quenching factor.
- The comparison to other experiments is only possible under similar assumptions for both experiments.

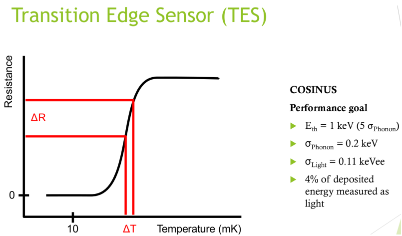




COSINUS experiment

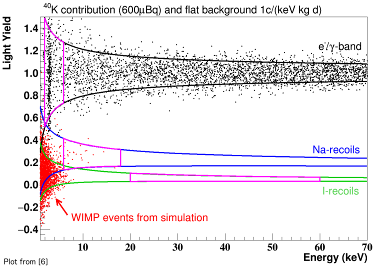
- COSINUS is a direct detection experiment under construction in the LNGS underground laboratory.
- COSINUS will use NaI crystals as scintillating calorimeters operated at cryogenic ($\sim$ 10 mK) temperature.
- The cryogenic operation allows for direct measurement of the nuclear recoil energy via the phonon channel, in addition to the measurement of the scintillation light.





COSINUS experiment

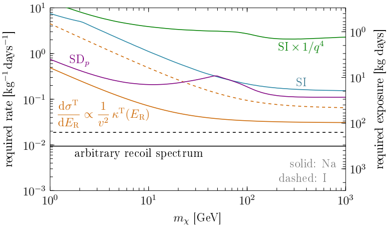
- The two-channel measurement mode carries several benefits, allowing for:
- Discrimination between nuclear and electron recoils, and even between nuclear recoils from Na or I due to their different light yields.
- Unambiguous calibration of the recoil energy, and for an in-situ determination of the quenching factor of the crystal.
- Better energy resolution and lower detection threshold.

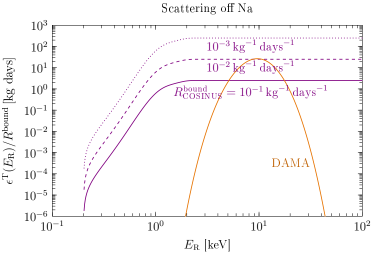


Plot from [6]

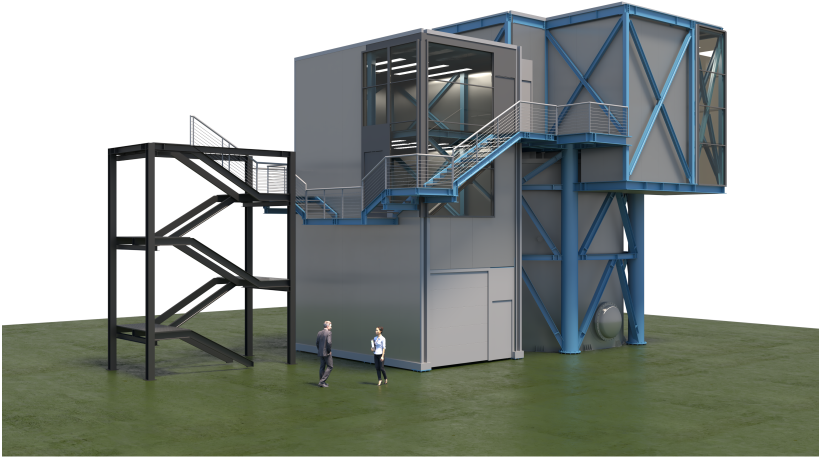
Model-independent comparison to the DAMA signal

- Because COSINUS and DAMA use the same target material, a non-observation of events in COSINUS can be used to exclude the DM-origin of the DAMA modulation signal, independent of the assumptions on the halo model or DM-nucleon interaction [arXiv:1802:10175].
- Under some standard assumptions, the same limit can be reached with less exposure.



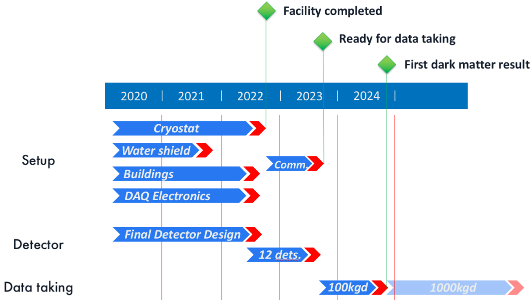


Cosinus facility



Schedule

Time schedule



Status of other NaI experiments

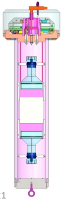
NAI EXPERIMENTS

DM-Ice17

South pole
17 kg NaI

threshold: 4 keV_{ee}

3.5 y physics run
no hint

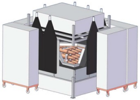


ANAIS-112

LSC - Spain
112.5 kg NaI

threshold: < 1 keV_{ee}

since spring 2017



COSINE-100

Y2L Korea
KIMS NaI + DM-Ice
106 kg

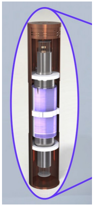
threshold: $\sim_1$ keV_{ee}

since Sept. 2016

SABRE

Gran Sasso/Australia
40-50 kg NaI

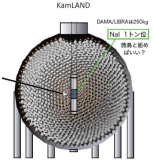
construction phase



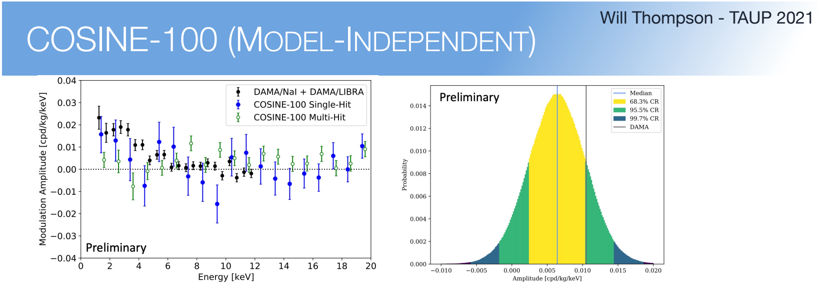
KamLand-PICO

KamLand/Japan
1t NaI

planning/
prototyping phase



Status of other NaI experiments



3-years result are not sensitive enough to test DAMA

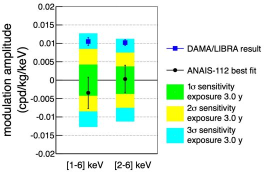
Will continue data taking until end 2022 → Upgrade to COSINE-200 afterwards
- Lower background (< 1 cts / (kg keV d))
- Higher light collection

Status of other NaI experiments

ANAIS-112

PHYS. REV. D 103, 102005 (2021)

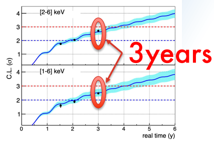
No modulation observed



3 years of data = 314 kg year

3σ sensitivity: ~autumn 2022

Sensitivity as a function of measurement time



Quenching factors introduce systematic uncertainty in comparison of DAMA-like setups

"However, the poor knowledge of some sodium iodide properties can introduce a model-dependent uncertainty in the comparison. In particular, for WIMP dark matter candidates, the possibility that sodium and iodine quenching factors for the conversion of nuclear recoil energies into electron equivalent ones are dependent on specific crystal properties, introduces a systematic uncertainty in the comparison for such candidates."

Status of other NaI experiments

SABRE

South (Stawell – Australia)

Experimental space to be finished in 12/2021

Installation of SABRE (50kg) and commissioning in early 2022

Background goal: 0.36 cts / (keV kg day)
Threshold goal: 1keVee

For DAMA like signal:
- 5σ Discovery power in 2 years
- 5σ Exclusion within 5 years

North (LNGS - Italy)

To our knowledge: Start of data taking ~2024/25

Status of other NaI experiments: summary

- ANAIS is expected to reach 3σ sensitivity (exclusion) to the DAMA signal in 2022.
- However there is still some uncertainty regarding the comparison of the QFs of DAMA and ANAIS crystals.
- Several other experiments, including COSINUS should reach 3σ sensitivity in a few years.
- COSINUS is unique in its capability for the direct measurement of the nuclear recoil energy in the phonon channel.

HIP activities in COSINUS

- Currently members of the collaboration: Katri Huitu, Matti Heikinheimo and Alex Stendahl.
- Current activities include:
  - Data analysis.
  - Design of magnetic field shielding/stabilization.
  - Improved studies for sensitivity/exclusion reach, accounting for QF uncertainties and latest DAMA release of modulation data down to 0.75 keV.
- Planned activities: Molecular dynamics simulations for improved understanding of the detector response to nuclear recoils and the phonon signal shape:
  - Defect creation and recombination.
  - Phonon propagation, effects of impurities and defects.
  - Dependence on the recoil direction ('channeling', energy loss as a function of direction)