ANAIS–112 experiment in the search for dark matter annual modulation: two years results

Iván Coarasa on behalf of the ANAIS team

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Outline

- Dark matter annual modulation
- DAMA/NaI and DAMA/LIBRA positive signal
- Other NaI experiments around the world
- ANAIS–112 experiment
  - Performance
  - Background model
  - Results on annual modulation
  - Sensitivity prospects
Dark matter annual modulation
Dark matter annual modulation

June

Maximum

December

Minimum
Dark matter annual modulation

Detection rate would have a cosine behaviour with a yearly period and maximum around June 2\textsuperscript{nd}

\[ R(t) = S_0 + S_m \cdot \cos \left( 2\pi \frac{t - t_0}{T} \right) \]

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Dark matter annual modulation

Detection rate would have a cosine behaviour with a yearly period and maximum around June 2nd

Only at low energy

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Dark matter annual modulation

Detection rate would have a cosine behaviour with a yearly period and maximum around June 2\textsuperscript{nd}

Only at low energy

Single-hit events

\[ R(t) = S_0 + S_m \cdot \cos\left(2\pi \frac{t - t_0}{T}\right) \]

June

December

Maximum

Minimum

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DAMA/NaI and DAMA/LIBRA positive signal

- 9 × 9.7 kg NaI(Tl)
- 7 annual cycles
- Exp: 0.29 t × yr

DAMA/LIBRA phase 1 (2003-2010)
- 25 × 9.7 kg NaI(Tl)
- 7 annual cycles
- Exp: 1.04 t × yr

DAMA/LIBRA phase 2 (2011-2018)
- 25 × 9.7 kg NaI(Tl)
- 6 annual cycles
- Exp: 1.13 t × yr
- Higher QE PMTs

DAMA/LIBRA-ph1 interpreted as WIMPs

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DAMA/LIBRA-ph1 interpreted as WIMPs

Strong tension

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DAMA/LIBRA-ph1 interpreted as WIMPs

- Its result has neither been reproduced by any other experiment,
- nor ruled out in a model independent way
- Its compatibility in most conventional WIMP scenarios is actually disclaimed
Composición del universo

DAMA/LIBRA-ph1 interpreted as WIMPs

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- nor ruled out in a model independent way
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Need to test the DAMA/LIBRA positive signal with the same target
Other NaI experiments around the world
Other NaI experiments around the world

Target: NaI

Borrowed from Jay Hyun Jo @15th MultiDark Workshop

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Other NaI experiments around the world

Target: NaI

In data taking

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Other NaI experiments around the world

Target: NaI

Exposure: 112.5 kg × 2.0 y

In data taking

Borrowed from Jay Hyun Jo @15th MultiDark Workshop

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COSINE–100 experiment

- Start: Sep 2016 at Y2L (South Korea)
- 8 ultra low-background NaI(Tl) crystals with 106 kg in total, but only 61.4 kg are useful for DM search
- Inside lead shielding and Liquid Scintillator tank to reject coincident events ($^{40}$K)
- Muon veto and neutron monitoring
COSINE–100 experiment

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- 8 ultra low-background NaI(Tl) crystals with 106 kg in total, but only 61.4 kg are useful for DM search
- Inside lead shielding and Liquid Scintillator tank to reject coincident events ($^{40}$K)
- Muon veto and neutron monitoring

SET1 (59.5 days): model dependent exclusion of DAMA/LIBRA-phase 1

SET2 (1.7 yr, 97.7 kg × yr exposure) used for annual modulation analysis: consistent with both null hypothesis and DAMA/LIBRA best fit at 1σ

SET3 analysis is still underway
ANAIS–112 experiment

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ANAIS−112 experiment

Goal

ANAIS (Annual modulation with NaI(Tl) scintillators) intends to provide a model independent test of the signal reported by DAMA/LIBRA, using the same target and technique at the Canfranc Underground Laboratory (Spain)

Experimental goals

- Energy threshold at 1 keV
- Background level below 10 keV at a few cpd/kg/keV
- Very stable operation conditions
EXPERIMENTAL SET-UP

9 ultrapure NaI(Tl) cylindrical crystals (12.5 kg each) in 3×3 matrix coupled to two Hamamatsu R12669SEL2 PMTs ($QE \sim 40\%$)
ANAIS–112 experiment: Performance

EXPERIMENTAL SET-UP

9 ultrapure NaI(Tl) cylindrical crystals (12.5 kg each) in 3×3 matrix coupled to two Hamamatsu R12669SEL2 PMTs (QE ~ 40%)

LOW ENERGY CALIBRATION

Low energy calibration with \(^{109}\text{Cd}\) sources every two weeks to monitor/correct possible gain drifts
- Mylar window
- Energies: 11.9, 22.6 and 88.0 keV
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**DUTY CYCLE**

Excellent duty cycle: 94.5% (1st year) and 95.6% (2nd) of Live Time

- 1st year: 341.72 days
- 2nd year: 374.30 days
- TOTAL: 716.02 days

Greater than DAMA/LIBRA:
- phase 1: 61% $L_T$
- phase 2: 78% $L_T$

ANAIS−112 experiment: Performance

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LIGHT COLLECTION

Outstanding light collection of ~ 15 phe/keV stable over time
Larger and more homogeneous than the reported light collection for DAMA/LIBRA detectors:
- phase 1: 5.5-7.5 phe/keV
- phase 2: 6-10 phe/keV

ANAIS–112 experiment: Calibration at low energy

11.9 and 22.6 keV $^{109}$Cd lines

Bulk $^{22}$Na (0.87 keV) and $^{40}$K (3.20 keV) events identified by coincidences with high energy $\gamma$
ANAIS−112 experiment: Calibration at low energy

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ENERGY RESOLUTION

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ANAIS–112 experiment: Event selection

0. Raw data below 10 keV

1. Pulse shape cut to select pulses with NaI(Tl) scintillation constant

2. We remove asymmetric events (<2 keV\(_{ee}\)) with origin in the PMT

3. Remove 1 s after a muon passage

4. Multiplicity = 1 (single-hit events)

We unblind 10% data for background assessment (~30 days randomly distributed along the first year)

**ANAIS–112 experiment:** Background and efficiency

**Total efficiency** at detector $d$, energy $E$:

$$\varepsilon(d, E) = \varepsilon_{trg}(d, E) \times \varepsilon_{PSA}(d, E) \times \varepsilon_{asy}(d, E)$$

- $\varepsilon_{trg}$: **Trigger efficiency** evaluated by a MC “scintillation” simulation
- $\varepsilon_{PSA}$: **Pulse Shape efficiency** calculated from $^{22}\text{Na}$ and $^{40}\text{K}$ events
- $\varepsilon_{asy}$: **Asymmetry efficiency** calculated from $^{109}\text{Cd}$ calibration events

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Effectively triggering below 1 keV$_{ee}$

**BUT** Energy threshold is limited by the efficiency of the PMT noise filtering protocols

Analysis threshold at 1 keV$_{ee}$

0.87 keV from $^{22}$Na is actually below our analysis threshold

Full First Year Data selected by coincidence with high energy $\gamma$

Fit:
Detailed background models based on:

- Geant4 Monte Carlo simulation
- Accurate quantification of background sources

1. External components screening with HPGe at LSC
2. Internal activity directly assessed: $^{40}$K, $^{210}$Pb
3. Cosmogenic activity: short-lived Te and I isotopes, $^3$H, $^{22}$Na, $^{109}$Cd, $^{113}$Sn

**Good agreement at high energy (> 250 keV)**
- 5% average deviation (1.5 years of data)

**Good agreement at low energy (< 100 keV)**
- 8% average deviation

**At very low energy (< 20 keV)**
- 8% average deviation in [2,6] keV
- 50% average deviation between 1 and 2 keV
- Most significant contributions: $^{22}$Na, $^{40}$K, $^{210}$Pb, $^3$H
ANAIS—112 experiment: Background model

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**Guaranteed agreement at high energy ($>250$ keV)**
- 5% average deviation (1.5 years of data)

**Guaranteed agreement at low energy ($<100$ keV)**
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- 8% average deviation in [2,6] keV
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- Most significant contributions: $^{22}$Na, $^{40}$K, $^{210}$Pb, $^{3}$H

\[c/(keV/kgd)\] vs. energy (keV)
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Most significant contributions: $^{22}$Na, $^{40}$K, $^{210}$Pb, $^{3}$H

**High energy**
- D6 sim
- D6 data

**Low energy**
- D3 sim
- D3 data

**Very low energy**
- D2 sim
- D2 data

**Time evolution**
- Days after 2nd August, 2017

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ANAIS–112 experiment: Results on annual modulation
Analysis strategy

- Focus on model independent analysis searching for modulation
- Same energy regions than DAMA/LIBRA for suitable comparison

**Fit function:**

\[ R(t) = R_0 + R_1 \exp(-t/\tau) \]

**Fixed parameter:**
- \( \tau \): from background model

**Free parameters:**
- \( R_0 \)
- \( R_1 \)
Least-squares fit to: \( R(t) = R_0 + R_1 \exp(-t/\tau) + S_m \cos(\omega(t + \phi)) \)

Fixed parameters:
- \( \tau \): from background model
- \( \omega \): 1 year period
- \( \phi \): maximum in June, 2\(^{nd}\)

\( S_m \) is fixed to 0 to analyze the null hypothesis and left unconstrained for the modulation hypothesis.

DAMA/LIBRA result with 1—free parameter is shown for comparison.

[2,6] keV: \( S_m^{DAMA} = 0.0102 \pm 0.0008 \text{ cpd/kg/keV} \)

[1,6] keV: \( S_m^{DAMA} = 0.0105 \pm 0.0011 \text{ cpd/kg/keV} \)
Best fits ANAIS−112:

[2,6] keV: $S_m = -0.0044 \pm 0.0058 \text{ cpd/kg/keV}$

[1,6] keV: $S_m = -0.0015 \pm 0.0063 \text{ cpd/kg/keV}$

$(S_{m}^{\text{DAMA}} = 0.0102 \pm 0.0008 \text{ cpd/kg/keV})$

$(S_{m}^{\text{DAMA}} = 0.0105 \pm 0.0011 \text{ cpd/kg/keV})$

Null hypothesis is well supported by the $\chi^2$ test (p-values of 0.67 and 0.18 for [2,6] and [1,6] keV energy regions)

Best fits for the modulation hypothesis have p-values slightly lower than for the null hypothesis

Best fits are incompatible at 2.5$\sigma$ (2-6 keV) and 1.9$\sigma$ (1-6 keV) with DAMA/LIBRA results.

Sensitivity (1.5 yr): 1.8$\sigma$
**Least-squares fit to:** \[ R(t) = R_0 + R_1 \exp(-t/\tau) + S_m \cos(\omega(t + \phi)) \]  

**Fixed parameters:**
- \( \tau \): from background model
- \( \omega \): 1 year period
- \( \phi \): maximum in June, 2\textsuperscript{nd}

**Least-squares fit to:**

- **[2-6] keV**
  - mod hyp: \( S_m = (-0.0033 \pm 0.0049) \) (cpd/kg/keV) \( \rightarrow \chi^2/\text{NDF} = 66.9/70 \) [pval=0.58]
  - null hyp \( \rightarrow \chi^2/\text{NDF} = 67.4/72 \) [pval=0.63]
  - DAMA mod hyp: \( S_m = 0.0102 \) (cpd/kg/keV) \( \rightarrow \chi^2/\text{NDF} = 74.5/75 \) [pval=0.49]

- **[1-6] keV**
  - mod hyp: \( S_m = (0.0049 \pm 0.0054) \) (cpd/kg/keV) \( \rightarrow \chi^2/\text{NDF} = 87.7/70 \) [pval=0.08]
  - null hyp \( \rightarrow \chi^2/\text{NDF} = 88.5/72 \) [pval=0.09]
  - DAMA mod hyp: \( S_m = 0.0105 \) (cpd/kg/keV) \( \rightarrow \chi^2/\text{NDF} = 95.5/75 \) [pval=0.06]

**NEW!!!**

*Preliminary*

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Best fits ANAIS−112:

[2,6] keV: $S_m = -0.0029 \pm 0.0050 \text{ cpd/kg/keV}$  

[1,6] keV: $S_m = -0.0036 \pm 0.0054 \text{ cpd/kg/keV}$  

($S_{m\text{ DAMA}} = 0.0102 \pm 0.0008 \text{ cpd/kg/keV}$)  

($S_{m\text{ DAMA}} = 0.0105 \pm 0.0011 \text{ cpd/kg/keV}$)

Null hypothesis is well supported by the $\chi^2$ test  
(p-values of 0.63 and 0.09 for [2,6] and [1,6] keV energy regions)

Best fits for the modulation hypothesis have p-values slightly lower than for the null hypothesis

**Best fits** are incompatible at $2.6\sigma$ with DAMA/LIBRA results.  
Present sensitivity: $2\sigma$
The absence of modulation is also well supported when we consider 1 keV bins in the RoI.
**ANAIS−112 experiment: 2 years results**

**Least-squares fit to:**

\[ R(t) = R_0 + R_1 \exp\left(-\frac{t}{\tau}\right) + S_m \cos(\omega(t + \phi)) \]

**Fixed parameters:**
- \( \tau \): from background model
- \( \omega \): 1 year period

**Free parameters:**
- \( R_0, R_1 \): background
- \( S_m \): annual modulation amplitude
- \( \phi \): phase (days)

**NEW!!! Preliminary**

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ANAIS–112 experiment: Sensitivity prospects

Sensitivity prospects of ANAIS–112
Sensitivity estimate based on the decay of efficiency corrected background in the RoI

Standard deviation of the modulation amplitude

\[ \sigma(S_m) \] is the estimator of sensitivity. Estimated from:

- updated background
- efficiency estimates and its errors
- live time distribution
Sensitivity to DAMA/LIBRA result as $S_{m}^{DAMA}/\sigma(S_{m})$

- [2,6] keV: $S_{m}^{DAMA} = 0.0102 \pm 0.0008$ cpd/kg/keV
- [1,6] keV: $S_{m}^{DAMA} = 0.0105 \pm 0.0011$ cpd/kg/keV

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The 1.5 and 2.1 yr data confirmed our sensitivity projection to the DAMA/LIBRA result. 

3σ sensitivity will be reached in 2 years from now.

Best fits are incompatible at 2.6σ with DAMA/LIBRA results.

Present sensitivity: 2σ.

\[ S_m^{\text{DAMA}} = 0.0102 \pm 0.0008 \text{ cpd/kg/keV} \]

\[ S_m^{\text{DAMA}} = 0.0105 \pm 0.0011 \text{ cpd/kg/keV} \]
**ANAIS—112 experiment: Sensitivity prospects**

**Likelihood 90%—90%**

- Standard halo model
- Spin-independent interaction
- $\rho_0 = 0.3 \text{ GeV/cm}^3$
- $\nu_0 = 220 \text{ km/s}$
- $\nu_{\text{esc}} = 650 \text{ km/s}$
- $Q_{Na} = 0.30, Q_I = 0.09$

DAMA regions from:

*C. Savage et al., JCAP04 (2009) 010*

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Summary and outlook

ANAIS—112 is taking data at LSC with 112.5 kg NaI(Tl)

- 2.22 years of data so far with very high duty cycle (> 95% live time)
- Low energy calibrations in the RoI every 15 days
- Excellent light collection (∼ 15 phe/keV), threshold at 1 keV
- Good background understanding, but from 1 to 2 keV

Analysis for model independent annual modulation of 2 yr of data taking

- Consistent with the absence of modulation
- Confirmed sensitivity of 3σ to DAMA/LIBRA result for 5 yr of data

Next future

- Data taking is going on in the same conditions for 3 years more
- Working to improve PMT-related events rejection procedures with new strategies
- Blank module is already taking data at LSC to understand the noise events population
- Analysis of Quenching Factor for scintillation in ANAIS crystals measured at TUNL is underway
- Preliminary conversations to combine ANAIS-112 and COSINE-100 data to reach 3σ sensitivity sooner
Acknowledgements

Thank you for your attention!

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Combined sensitivity projection

Sensitivity to DAMA/LIBRA result as $S_{mDAMA}^{DAMA}/\sigma(S_m)$

**NEW!!!**

Preliminary

Model Independent

- **ANAIS—112 mass**: 112.5 kg
- **COSINE—100 effective mass**: 61.4 kg

- **3σ combined sensitivity** will be reached in 4 months from now
- **4σ combined sensitivity** will be reached in 2 years from now

**ANAIS—112 start**

03/08/2017:

<table>
<thead>
<tr>
<th>Window: [2,6] keVee</th>
<th>ANAIS-112</th>
<th>COSINE-100</th>
<th>Combined sensitivity</th>
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<tr>
<td>C.L. (σ)</td>
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<td>2</td>
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<tr>
<td>real time (yr)</td>
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<td>1.2 yr</td>
<td>2 yr</td>
</tr>
</tbody>
</table>


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