Dark matter annual modulation and ANAIS-112 results: testing the DAMA/LIBRA positive signal
• Intro: Dark matter annual modulation
• DAMA/LIBRA positive signal
• Current NaI(Tl) experiments
• ANAIS-112
  - Experimental set-up
  - Detector performance
  - Results on annual modulation
  - ANAIS-112 sensitivity
• Summary
Intro: DARK MATTER
ANNUAL MODULATION
Evidence of Dark Matter

Zwicky (1933)

DM dominates all the structures of the Universe!

- Atoms: 4.9%
- Dark Energy: 68.3%
- Dark Matter: 26.8%

Gravitational lensing: Structure formation

Coma cluster

bullet cluster (1E0657-558)

Evidence of Dark Matter
DM candidates

What we know:
- lifetime $>>$ age of Universe
- No (or very very small) interaction with light
- Non baryonic
- Cold (or Warm) (Moving non-relativistically when galaxies started to form)
- Beyond the Standard Model
WIMPs

Weakly Interacting Massive Particles (WIMPs) very well motivated

- The relic abundance determined from the freeze-out mechanism matches the measured DM density for reasonable ranges of weak-scale annihilation cross section
- WIMPs arise spontaneously in many extensions of the Standard Model such as SUSY

Abundance of a thermal relic $\sim \frac{0.1 \text{ pb}}{\langle \sigma A \, v/c \rangle}$
WIMP direct detection

Dark Matter Halo
Density $\rho_0 \sim 0.4 \text{ GeV/cm}^3$

Earth
$V \sim 200 \text{ km/s}$

$\phi^{WIMP}_{earth} \sim 10^8 - 10^{10} \text{ s}^{-1} \text{ m}^{-2}$

Milky Way rotation curve

M. Martinez. F. ARAID & U. Zaragoza

CIEMAT, October 29, 2020
WIMP direct detection

WIMPs scatter elastically off nuclei
WIMP direct detection

WIMPs scatter elastically off nuclei

Expected rate @ Earth:

\[ \frac{dR}{dE_R} = \frac{\rho_0 M_{Det} \sigma_{WN}}{2m_W m_{WN}^2} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv^3 \]

MODEL DEPENDENT!

Naïve approximation: SHM
Isothermal sphere
Maxwellian distribution
\( v_o = 220 \text{ km/s} \)
Truncated at \( v_{esc} \sim 530 \text{ km/s} \)

Halo model

\( M_W = 100 \text{ GeV} \)
\( \sigma_{si} = 1e-46 \text{ cm}^2 \)

NO DISTINCTIVE SIGNAL 😞

\( c / \text{keV} / \text{ton / yr} \)

\( c / \text{keV} / \text{ton / yr} \)

- Xe
- Ar
- NaI

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DM Annual modulation

\[ v_0 = 220 \text{ km/s} \]

\[ \frac{dR}{dE_R} = \frac{\rho_0 M_{Det}}{2 m_w m_{WN}^2} \sigma_{WN} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv^3 \]
DM Annual modulation

\[ \frac{dR}{dE_R} = \frac{\rho_0 M_{Det}}{2m_W m^2_{WN}} \sigma_{WN} \int_{v_{min}}^{v_{max}} \frac{f(v, t)}{v} dv^3 \]

- \( v_{orbital} = 30 \text{ km/s} \)
- \( \alpha = 60^\circ \)
- \( v_0 = 220 \text{ km/s} \)

Detection rate

M. Martinez. F. ARAID & U. Zaragoza

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DM Annual modulation

Due to the Earth revolution around the Sun, the relative speed Earth-halo is cosine-like with 1 year periodicity and small amplitude ($\sim 7\%$), and that implies a modulation in the expected rate:

$$\frac{dR}{dE}(E, t) \approx S_0(E) + S_m(E)\cos \omega(t - t_0)$$

Where

$$S_m(E) = \frac{1}{2}\left(\frac{dR}{dE}(E, t_0) - \frac{dR}{dE}(E, t_0 + 182)\right)$$

A distinctive signal hard to mimic by background

- Cosine behaviour
- 1 year period
- Maximum around June 2nd
- Weak effect ($\frac{S_m}{S_0} \sim 0.01 - 0.1$)
- Only noticeable at low energy
- Phase reversal at low E
DAMA: an observatory for rare processes @LNGS

DAMA/LXe
DAMA/R&D
low bckg DAMA/Ge for sampling meas.
DAMA/NaI
DAMA/LIBRA
http://people.roma2.infn.it/dama
DAMA/NaI & DAMA/LIBRA (phase 1)


- 10 × 9.7 kg NaI(Tl)
  (3x3 matrix)
- 7 annual cycles
- Exposure : 0.29 ton × y

The data support the presence of a modulation
(1 y period, phase on May 20th) at 6.3σ CL

DAMA/NaI & DAMA/LIBRA (phase 1)

- 10 × 9.7 kg NaI(Tl)
  (3x3 matrix)
- 7 annual cycles
- Exposure : 0.29 ton × y


The data support the presence of a modulation
(1 y period, phase on May 20th) at \(6.3\sigma\) CL

DAMA / LIBRA (2003-2010)
- 25 × 9.7 kg NaI(Tl)
  (5x5 matrix)
- 7 annual cycles
- Exposure : 1.17 ton × y


The data support the presence of a modulation
(1 y period, phase on May 20th) at \(9.2\sigma\) CL
DAMA/NaI & DAMA/LIBRA (phase 1)

- 10 × 9.7 kg NaI(Tl)
  (3x3 matrix)
- 7 annual cycles
- Exposure : 0.29 ton × y

DAMA / LIBRA (2003-2010)
- 25 × 9.7 kg NaI(Tl)
  (5x5 matrix)
- 7 annual cycles
- Exposure : 1.17 ton × y

The signal satisfies all requirements for DM and can be interpreted as a WIMP:

- Na-dominated rate
- I-dominated rate

Solid line: $\cos \omega (t - t_0)$, with period 1 year and phase on June 2nd
Interpreting DAMA/LIBRA ph1 as WIMPs

DAMA clearly sees an annual modulation at $12.9 \sigma$

But the parameter’s region singled out by DAMA/LIBRA is excluded by most sensitive experiments, even assuming more general halo/interaction models!
Other annual modulation searches


“Search for Electronic Recoil Event Rate Modulation with 4 Years of XENON100 Data” PRL118, 101101 (2017)

“Search for annual modulation in low-energy CDMS-II data”, 1203.1309

None of them is compatible with DAMA/LIBRA
2011-2013 exciting times

One PPC HPGe @ SOUDAN
330 g Ge, 3.4 years
No $\beta/\gamma$ discrimination
(Sm 4-7 times larger than predicted in SHM)

Hint of annual modulation in one experiment
CoGeNT (2011-2014)

Excess of events in WIMP region in two experiments:
CRESST (2011)
One module (300 g CaWO$_4$)

SuperCDMS-Si (2013)

ArXiv:1401.3295
But since 2013 ...

- CRESST-II (2014-2015) with an upgraded detector did not confirm the excess
- CoGeNT’s signal significance decreased with time (3.4y by 2014) to below 2\(\sigma\).
  Different interpretations among the collaboration.
- CDMS-II-Si signal very small. No more data

CoGeNT modulation too large, but can be in agreement with DAMA/LIBRA for some non-SHM haloes
The data of DAMA/LIBRA phase1+phase2 favor the presence of a modulation with proper features at $11.9\sigma_{\text{CL}}$ (2.17 ton $\times$ yr)

- All PMTs replaced with new ones of higher Q.E.
- 6 annual cycles
- Exposure: 1.13 ton $\times$ y


M. Martinez, F. ARAID & U. Zaragoza
Interpretation of the 1 keV point

1804.01231, Baum, Freese, Kelso “Dark Matter implications of DAMA/LIBRA-phase2 results”

“the observed annual modulation signal is no longer well fitted by canonical (isospin conserving) spin-independent WIMP nucleon couplings”
1804.01231, Baum, Freese, Kelso “Dark Matter implications of DAMA/LIBRA-phase2 results”

“the observed annual modulation signal is no longer well fitted by canonical (isospin conserving) spin-independent WIMP nucleon couplings”

1907.06405, Bernabei et al. “Improved model-dependent corollary analyses after the first six annual cycles of DAMA/LIBRA-phase2”

“at present level of uncertainties the DAMA data, if interpreted in terms of DM particle inducing nuclear recoils through SI interaction, can account either for low and large DM particle mass and for a wide range of the ratio fn fp, even including the “standard” case fn fp = 1.”

“The purely SD scenarios are in good agreement with the DAMA results and can explain the different capability of detection among targets with different unpaired nucleon.”
Interpreting DAMA/LIBRA ph1 as WIMPs

DAMA clearly sees an annual modulation at $12.9\sigma$

TO AVOID ANY MODEL DEPENDENCE, WE NEED A PROOF/DISPROOF WITH THE SAME TARGET

Dark matter or systematics?
Model dependency

Expected rate @ Earth:

\[
\frac{dR}{dE_R} = \frac{\rho_0 M_{Det}}{2m_W m_W^2} \sigma_{WN} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv^3
\]

In order to compare experiments using different targets I have to assume:

- Only SI or SD coupling
- For SI: - Isospin conserving (couplings are identical for protons and neutrons)
  - A scaling law for the cross section
  \[
  \sigma_{SI} \propto \frac{m_{WN}^2}{m_{Wn}^2} A^2 F^2 \sigma_{nucleon}^{SI}
  \]
- A model for the WIMPs velocity distribution, usually the standard Halo Model (Maxwellian distribution)

\[
\nu_{min} = \sqrt{\frac{m_N E_{th}}{2 \mu_{NW}^2}}
\]

- A good knowledge of the NR quenching factor
Model dependency

Expected rate @ Earth:

\[
\frac{dR}{dE_R} = \rho_0 M_{Det} \frac{m^2_{WN}}{2m_W m^2_{WN}} \sigma_{WN} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dV^3
\]

In order to compare experiments using different targets I have to assume:

- Only SI or SD coupling
- For SI: - Isospin conserving (couplings are identical for protons and neutrons)
  - A scaling law for the cross section
    \[
    \sigma_{SI} \propto \frac{m^2_{WN}}{m^2_{Wn}} A^2 F^2 \sigma_{nucleon}^{SI}
    \]
- A model for the WIMPs velocity distribution, usually the standard Halo Model (Maxwellian distribution)
- A good knowledge of the NR quenching factor

That is the only that **could** remain when using the same target.
NR quenching factor

In a scintillator, an ER produces much more light than a NR of the same energy!

The spectra are calibrated with X/γ sources, so are given in keVee(*). In order to be interpreted as NR, $QF$ has to be measured to correct the energy scale:

$$QF = \frac{\text{signal}_{NR}/\text{keV}}{\text{signal}_{ER}/\text{keV}}$$

(* keVee: electron-equivalent keV

The “true” NR energy is: But I measure:

Mod Amplitude WIMP 50 GeV

I recoil

$QF_I = 0.09$
NR quenching factor measurements

DAMA uses (Spooner’94) NaI quenching factor measurements: $QF_{Na} = 0.3$ $QF_I = 0.09$

But recent measurements give lower values. Na quenching decreases when decreasing the energy.
NR quenching factor measurements

DAMA uses (Spooner’94) NaI quenching factor measurements: $Q_{FNa} = 0.3$  $Q_{FI} = 0.09$

But recent measurements give lower values. Na quenching decreases when decreasing the energy.

To answer this question,

Anais + Yale

QF measurements @ TUNL (Duke Univ.)
different NaI(Tl) crystals (ANAIS & COSINE)
in the same setup

Results soon!

Does the QF depend on the crystal?
- Impurities
- Tl level
- Crystal quality
- …
CURRENT NaI(Tl) experiments
Nal experiments around the World

ANAIS-112 (LSC)
SABRE NORTH (LNGS)
COSINE-100 (Y2L)
PICO-LON (Kamioka)
SABRE SOUTH (Stawell)
NaI experiments around the World

IN DATA-TAKING
Since Aug 2017
112 kg NaI(Tl)

ANAIS-112 (LSC)

IN DATA-TAKING
Since Sep 2016
∼60 kg NaI(Tl)

SABRE NORTH (LNGS)

COSINE-100 (Y2L)

SABRE SOUTH
(Stawell)

PICO-LON
(Kamioka)
Why took so long?

Sensitivity $\propto \sqrt{\frac{MT\epsilon}{B}}$

Large mass
Stable conditions over years
High efficiency at very low energy

Very low radioactive background!!

- The main contribution to the background comes from the crystal itself
- Long effort of ANAIS team looking for ultra pure NaI(Tl), R&D with Alpha Spectra → crystals now used by ANAIS-112 and COSINE-100
- However, up to the date, the quality of the DAMA crystals has not been reached by any group

<table>
<thead>
<tr>
<th></th>
<th>K (ppb)</th>
<th>$^{210}\text{Pb}$ (mBq/kg)</th>
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</thead>
<tbody>
<tr>
<td>DAMA</td>
<td>13</td>
<td>0.01-0.03</td>
</tr>
<tr>
<td>(Saint Gobain)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANAIS/COSINE (Alpha Spectra)</td>
<td>18-44</td>
<td>0.7-3</td>
</tr>
</tbody>
</table>
**COSINE-100**

- Data-taking started in Sep 2016, Y2L (South Korea)
- 8 ultra low-background NaI(Tl) crystals with 106 kg in total *(but only \(\sim 60\) kg usable for DM search)*
- Inside lead shielding and Liquid Scintillator tank to reject coincident events (\(^{40}\)K!)
- Muon veto & neutron monitoring

**NEXT STEP: COSINE-200 (2020?)**

Goal: Run 200 kg NaI(Tl) in the same set-up, with improved background (lower than DAMA/LIBRA)

Status: Power purification, crystal growing and handling facilities established, buy a factor 2 or more improvement in bkg is needed.

From G. Adhikari @ TAUP2019
COSINE-100 results

From Y. J. Ko @ TAUP2019

SET1 (59.5 days)

Background + WIMP signal is fit to data:

→ Model dependent exclusion of DAMA/LIBRA-phase1 (*)
  - Spin Independent interaction
  - Maxwellian velocity distribution

Nature 564 (2018) 83-86

(*) But not excluded in effective models (COSINE coll. & S. Scopel, JCAP 1906 (2019) 06, 048)

SET2 (1.7 y, 97.7 kg·year exposure)


At 68.3% C.L., result is consistent with both a null hypothesis and DAMA/LIBRA's best fit value.
Proof of Principle: one NaI crystal in LS vessel

- Ultra-clean NaI(Tl) (Princeton)
- Two sites (LNGS/ Stawell)

First crystal (3.5 kg) arrived @ LNGS on August 2019

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<th>$^{210}\text{Pb}$ (mBq/kg)</th>
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<tr>
<td>SABRE</td>
<td>4</td>
<td>0.4</td>
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<tr>
<td>DAMA</td>
<td>13</td>
<td>0.01-0.03</td>
</tr>
<tr>
<td>ANAIS</td>
<td>18-44</td>
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</tr>
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</table>
GOAL: Development of highly radiopure NaI(Tl) scintillator

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</thead>
<tbody>
<tr>
<td>Size</td>
<td>3”φX3”</td>
<td>4”φX3#</td>
<td>3”φX3”</td>
<td>5”φX4”(*)</td>
<td>5”φX5”</td>
</tr>
<tr>
<td>$^{40}$K (ppb)</td>
<td>2630</td>
<td>120</td>
<td>&lt;20</td>
<td>&lt;20</td>
<td>&lt;20</td>
</tr>
<tr>
<td>$^{232}$Th (ppt)</td>
<td>0.4±0.5</td>
<td>3.7±0.5</td>
<td>1.7±0.2</td>
<td>--</td>
<td>&lt;4</td>
</tr>
<tr>
<td>$^{238}$U (ppt)</td>
<td>4.7±0.3</td>
<td>5.9±0.3</td>
<td>9.7±0.8</td>
<td>4.4±0.2</td>
<td>&lt;10</td>
</tr>
<tr>
<td>$^{210}$Pb (μBq/kg)</td>
<td>30±7</td>
<td>2300</td>
<td>1076</td>
<td>~560</td>
<td>&lt;50</td>
</tr>
<tr>
<td>Method</td>
<td>Resin for Pb</td>
<td>I26+cation resin</td>
<td>double re- crystallization</td>
<td>Pb resin + double re- crystallization</td>
<td></td>
</tr>
</tbody>
</table>

From K.Fushimi @ TAUP2019
First NaI detector with particle discrimination
(Two channel approach: HEAT and LIGHT)

With a moderate exposure of few O(100) kg-days, can confirm or rule-out a nuclear recoil origin of the DAMA/LIBRA dark matter claim

https://doi.org/10.1007/s10909-018-1967-3

Present threshold: 8.26 keV$_{\text{NR}}$
(Goal: 1 keV$_{\text{NR}}$)
Annual Modulation with NaI Scintillators

GOAL:
Confirmation of DAMA-LIBRA modulation signal with the same target and technique (but different experimental approach and environmental conditions)

THE DETECTOR:
3x3 matrix of 12.5 kg NaI(Tl) cylindrical modules = 112.5 kg of active mass

taking data since August 2017
ANAIS-112: experimental setup

- 9 NaI(Tl) cylindrical crystals (12.5 kg each) in 3x3 matrix
- Ultrapure NaI powder (Alpha Spectra Inc)
- Each coupled to two Hamamatsu R12669SEL2 PMT (QE ~40%)

Muon veto: 16 plastic scintillators

20 cm lead
10 cm ancient lead
40 cm neutron shielding

Anti-Rn box

Neutron shielding (water tanks + polyethylene)

CIEMAT, October 29, 2020
Detectors equipped with a **Mylar window**!

Radon-free system for low energy calibration:

- **$^{109}\text{Cd}$ sources** on flexible wires (radon-free)
- Energies: 11.9, 22.6 and 88.0 keV
- Simultaneous calibration of the nine modules
- Performed every two weeks
In ANAIS we flag every muon that cross the shielding and set a (configurable) dead-time after every passage (DAMA/LIBRA has no muon veto)

The underground muon flux is annual-modulated!

DAMA reply:
• Modulation phase inconsistency
• Muons interacting directly in the detectors do not fulfill the DM requisites
• Not enough muon-induced fast neutrons to account for the signal

But still some open questions:
• (delayed) effect of muons in PMTs?
• slow phosphorescence in NaI?

ANAIS can test these hypotheses
- Individual PMT signals **digitized** and fully processed (14 bits, 2 GS/s)
- Trigger at phe level for each PMT signal
- AND coincidence in 200 ns window
- Redundant energy conversion by QDC
- Trigger in OR mode among modules
- Electronics at air-conditioned-room to decouple from temperature fluctuations
- Muon detection system: tag every muon event to offline processing
ANAIS-112: Slow control

- Monitoring **environmental parameters** since the start of DM run
  
  - Monitoring:
    
    Rn content, humidity, pressure, different temperatures, N$_2$ flux, PMT HV, muon rate, …
    
    Data saved every few minutes and alarm messages implemented
  
  - Stability checks:
    
    gain, trigger rate, …
DETECTOR PERFORMANCE

Detector Response: duty cycle & stability

- Excellent **duty cycle**
  - Live time: 94.4%
  - Down time (calibrations): 2.7%
  - Dead time: 2.9%

- Good **total rate and gain stability**

Evolution of $^{109}$Cd lines from calibrations along the whole data-taking (~ 2 year)

**ANAIS accumulated exposure vs time**

100% live time
Detector response: threshold

- Effectively **triggering below 1 keV$_{ee}$**

bulk $^{22}$Na and $^{40}$K events identified by coincidences with high energy gammas

---

Outstanding light collection of $\sim$15 phe/keV
Detector response: threshold

- Effectively triggering below 1 keV$_{ee}$

- Energy threshold limited by PMT noise filtering protocols efficiency

  - Multiparametric cuts to properly select events with pulse shapes from NaI(Tl) scintillation (efficiency computed on $^{109}$Cd calibration and $^{22}$Na and $^{40}$K coincidence populations)

  "Outstanding light collection of ~15 phe/keV"

![Graphs showing energy detector responses and event selection criteria]
Blinded analysis

**ANALYSIS STRATEGY**

- Multiplicity-1 events in the RoI (1-6 keV) **blinded**
- We use multiplicity-2 events in the RoI and calibration events to tune the filtering algorithms and calculate the cut efficiencies
- We unblind 10% (~30 days randomly distributed along the first year) data for background assessment

---


M. Martinez. F. ARAID & U. Zaragoza, 4th IBS-Multidark-IPPP Workshop, Daejeon (South Korea), October 7-11 2019
Event selection & efficiency

CUTS

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

2. We remove asymmetric events (<2 keVee) with origin in the PMT

3. Remove 1 s after a muon passage

4. Multiplicity = 1 (Reject events that deposit energy simultaneously in more than one crystal)

TOTAL EFFICIENCY

EFFICIENCY-CORRECTED BACKGROUND


M. Martinez. F. ARAID & U. Zaragoza, 4th IBS-Multidark-IPPP Workshop, Daejeon (South Korea), October 7-11 2019
Background


M. Martinez. F. ARAID & U. Zaragoza
Background model

At very low energy (<20 keV), main contamination in the crystal itself

- $^{40}$K and $^{22}$Na ($T_{1/2} = 2.6$ y) peaks
- $^{210}$Pb (bulk+surface) ($T_{1/2} = 22.3$ y)
- $^3$H ($T_{1/2} = 12.3$ y)

Very good agreement with data except between 1-2 keV

Cosmogenic isotopes ($^3$H, $^{22}$Na, ...) and $^{210}$Pb are decaying → prediction of the time dependence of the rate in the RoI

RESULTS ON ANNUAL MODULATION
Analysis strategy

Background decay rate in the RoI consistent with our background model (in green)

ANALYSIS STRATEGY

- Focus on model independent analysis searching from modulation
- In order to better compare with DAMA/LIBRA results, we use the same energy regions ([1-6] keV, [2-6] keV) and fit parameters
- Least square fit to

\[ R(t) = R_0 + R_1 \exp(-t/\tau) + S_m \cos(\omega(t + \phi)) \]

Fixed parameters:
- \( \tau \) (background model)
- \( \omega \) (freq. corresponding to a period of 1 year)
- \( \phi \) (maximum in June, 2\textsuperscript{nd})
Least squared fit to: $R(t) = R_0 + R_1 \exp(-t/\tau) + S_m \cos(\omega(t + \phi))$

**Fixed parameters:**

- $\tau$ (background model)
- $\omega$ (freq. corresponding to a period of 1 year)
- $\phi$ (maximum in June, 2\textsuperscript{nd})

**$S_m$** fixed to 0 in the null hypothesis and left unconstrained for the modulation hypothesis.


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

DAMA mod hyp: $S_m = (-0.0044 \pm 0.0058)$ (cpd/kg/keV)
\[ \chi^2/\text{NDF} = 47.4 / 52 \quad \text{[pval=0.65]} \]
null hyp $\rightarrow \chi^2/\text{NDF} = 48.0 / 53 \quad \text{[pval=0.67]}

DAMA mod hyp: $S_m = 0.0102$ (cpd/kg/keV)
\[ \chi^2/\text{NDF} = 62.0 / 52 \quad \text{[pval=0.16]} \]
null hyp $\rightarrow \chi^2/\text{NDF} = 62.0 / 53 \quad \text{[pval=0.18]}

DAMA mod hyp: $S_m = 0.0105$ (cpd/kg/keV)

1st Annual modulation results: 1.5 y
1st Annual modulation results

\[ [2-6] \text{ keV} \rightarrow S_m = -0.0044 \pm 0.0058 \text{ c/keV/kg/d} \quad (S_{m}^{DAMA} = 0.0102 \text{ cpd/kg/keV}) \]

\[ [1-6] \text{ keV} \rightarrow S_m = -0.0015 \pm 0.0063 \text{ c/keV/kg/d} \quad (S_{m}^{DAMA} = 0.0105 \text{ cpd/kg/keV}) \]

- Null hypothesis is well supported by the \( \chi^2 \) test (p-values=0.18, 0.67)
- Best fits for the modulation hypothesis have p-values slightly lower than for the null hypothesis
- Best fits are compatible with no modulation and incompatible at 2.5\( \sigma \) (2-6 keV) and 1.9\( \sigma \) (1-6 keV) with DAMA/LIBRA results.

Sensitivity (1.5 y) 1.8\( \sigma \)

\textbf{arXiv:1903.03973}
2 years results

M. L. Sarsa @ TAUP2019
J., Phys (Conference Series) 1468 (2020) 012014

mod hyp: Sm = (-0.0029 ± 0.0050) (cpd/kg/keV)
→ $\chi^2$/NDF = 67.0 / 71 [pval=0.61]
null hyp → $\chi^2$/NDF = 67.4 / 72 [pval=0.63]

DAMA mod hyp: Sm = 0.0102 (cpd/kg/keV) → $\chi^2$/NDF = 74.5 / 75 [pval=0.49]

mod hyp: Sm = (-0.0036 ± 0.0054) (cpd/kg/keV)
→ $\chi^2$/NDF = 88.0 / 71 [pval=0.08]
null hyp → $\chi^2$/NDF = 88.5 / 72 [pval=0.09]

DAMA mod hyp: Sm = 0.0105 (cpd/kg/keV) → $\chi^2$/NDF = 95.5 / 75 [pval=0.06]
Null hypothesis is well supported by the $\chi^2$ test (p-values=0.09, 0.63)

Best fits for the mod. hypothesis p-values slightly lower than for the null hypothesis

Best fits are compatible with no modulation and incompatible at $2.6\sigma$ with DAMA/LIBRA results. Present sensitivity $2\sigma$

$[2-6] \text{ keV} \rightarrow S_m = -0.0029 \pm 0.0050 \text{ c/keV/kg/d} \quad (S_m^{\text{DAMA}} = 0.0102 \text{ cpd/kg/keV})$

$[1-6] \text{ keV} \rightarrow S_m = -0.0036 \pm 0.0054 \text{ c/keV/kg/d} \quad (S_m^{\text{DAMA}} = 0.0105 \text{ cpd/kg/keV})$
Sm & phase free

M. L. Sarsa @ TAUP2019

\[ R(t) = R_0 + R_1 \exp(-t/\tau) + S_m \cos(\omega(t + \phi)) \]

Fixed parameters:
- \( \tau \) (background model)
- \( \omega \) (freq. corresponding to a period of 1 year)

Free parameters:
- \( R_0, R_1, S_m, \phi \)

\( 25 \text{ may} \)
3 years results

NEW!

- Preliminary sensitivity @ 3 years: 2.6σ
3 year results

PRELIMINARY

NEW!

M. Martinez. F. ARAID & U. Zaragoza

CIEMAT, October 29, 2020

313.6 kg x yr
ANAIS-112
SENSITIVITY

2-6 keV
DAMA/LIBRA = 250 kg (0.87 ton·yr)
Calculating the sensitivity

Least squared fit to: \[ R(t) = R_0 + R_1 \exp(-t/\tau) + S_m \cos(\omega(t + \phi)) \]

Three free parameters \((R_0, R_1, S_m)\)

The experimental sensitivity is given by the standard deviation of the modulation amplitude \(\sigma(S_m)\), that can be calculated analytically from:
- Updated background
- Efficiency estimate and its error
- Live time distribution

Expected sensitivity

We quote our sensitivity to DAMA/LIBRA result as the ratio $S_{m}^{DAMA}/\sigma(S_m)$
Experimental sensitivity

We quote our sensitivity to DAMA/LIBRA result as the ratio $S_m^{DAMA}/\sigma(S_m)$

- data confirm our sensitivity projection to DAMA/LIBRA result
  - Sensitivity @ 2 years: $2\sigma$
  - Preliminary sensitivity @ 3 years: $2.6\sigma$

$3\sigma$ sensitivity at reach in about 1 year from now!
Model dependent (SI interaction)

Likelihood 90% - 90%

90% probability of detecting an annual modulation signal at 90% C.L.

- Standard halo model
- Spin-independent interaction
- $\rho_0 = 0.3 \text{ GeV/cm}^3$

- $v_0 = 220 \text{ km/s}$
- $v_{esc} = 650 \text{ km/s}$
- $Q_{Na} = 0.30$, $Q_I = 0.09$

DAMA regions from:
C. Savage et al., JCAP04 (2009) 010
Summary

- Annual modulation is a distinctive signature of Dark Matter
- One positive signal (DAMA/LIBRA) for more than 20 years, in strong tension with other experiments
- Currently, many efforts trying to confirm / rule out DAMA/LIBRA signal with the same target. COSINE-100 and ANAIS-112 in data-taking
- ANAIS-112: is taking data in stable condition @ LSC since 3rd August 2017 with excellent performances. Up to now it has accumulated more than 300 kg×y exposure.
- **ANAIS-112 results** are compatible with absence of modulation and incompatible with DAMA/LIBRA at 2σ after 2 years of data-taking. Preliminary results for 3 years reach 2.6 sensitivity in [2-6] keV. **3σ sensitivity at reach in about 1 year from now!**
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¡GRACIAS!