Using XENON100 Data to Probe Electronic Recoils as an Explanation of the DAMA/LIBRA Anomaly

Luke Walker Goetzke
Columbia University
On behalf of the XENON Collaboration
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21 institutions, ~130 scientists
XENON Program

XENON10

2005-2007
25 kg
15 cm drift
\( \sigma_{SI} = 8.8 \times 10^{-44} \text{ cm}^2 \)

XENON100

2008-2015
161 kg
30 cm drift
\( \sigma_{SI} = 2.0 \times 10^{-45} \text{ cm}^2 \)

XENON1T/XENONnT

2012-2018 / 2016-2022
3300 kg / 7000 kg
96 cm drift
\( \sigma_{SI} \approx 2 \times 10^{-47} \text{ cm}^2 / \sigma_{SI} \approx 3 \times 10^{-48} \text{ cm}^2 \)
DAMA/LIBRA Annual Modulation

- **2-6 keV, single-hit**
- **Peak phase 144 ± 7 days (May 24)**
- **9.3σ confidence level**
- **Could be from DM halo**

Expected annual modulation signal

- **peak phase ~152 days**
  (~June 1)
- **~6% change in flux**

235 km/s

30 km/s


Freese et al., Rev. Mod. Phys. 85, 1561 (2013)
Null results from many experiments more sensitive than DAMA/LIBRA
First LXe DM detector with single run > 1 year

Can discriminate ER from NR

Average ER rate ~155x lower than DAMA/LIBRA average, and ~2x lower than modulation amplitude

First detector at LNGS to study annual modulation after DAMA/LIBRA

Annual Modulation in XENON100

Annual Modulation in DAMA/LIBRA from ERs?

Study Overview

Data: 225 live-days used for DM Search

- 397 days total (Feb 28, 2011 – March 31, 2012)
- ERs: ~ 6.6 events/(keV · tonne · day)
- NRs: expected 1±0.2; detected 2
- $\sigma_{\text{SI}} = 2 \times 10^{-45}$ cm$^2$ for $m_\chi = 55$ GeV/c$^2$

Electronic recoil study

- Time evolution of single-scatter events
- S1-based energy scale:
  
  3-14 pe = 2.0-5.8 keV (DAMA/LIBRA range)

Current Status

- Mean from NEST v0.98, assume 500V/cm, weighted fit of uncertainties (4% NEST + spread in)
  
  Szydagis et al., J. Instrum. 6, P10002 (2011)

- Based on dedicated calibration measurements of light yield (S1 [pe/keV])


New measurements of light and charge yield and field dependence to improve uncertainty
Results forthcoming!

Energy Scale

\[ 3 - 14 \text{ pe} = (2.0 \pm 0.3) - (5.8 \pm 0.5) \text{ keV} \]

\[ [\pm 14\%] \quad [\pm 9\%] \]
Detector Stability

- Detailed stability and correlation analysis of **detector parameters**
- Variations small, no significant impact on ER rate

◊ Absolute detector pressure
◊ Relative detector pressure
◊ Room pressure
◊ LXe temperatures (4)
◊ PTR temperature
◊ Room temperature
◊ Purification flow
◊ $N_2$ purge flow
◊ LXe levels (2)
◊ PMT gain
◊ Rn level (2)

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Detector Stability

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ER Rate Model

- Detector parameters
- Radioactive backgrounds from measurement or MC: $^{85}$Kr, $^{222}$Rn, $^{60}$Co
- Test for periodic component

Cut acceptance

$^{222}$Rn, $^{60}$Co, ...

$f(t) = \epsilon(t) \left[ C + Kt + A \cos \left( 2\pi \frac{(t - \phi)}{P} \right) \right]$

$^{85}$Kr background from air leak:
$K = 2.54\pm0.53\times10^{-3}$
(events/(keV \cdot \text{tonne} \cdot \text{day}))/day

Null hypothesis ($L_0$):
$A=0$

Signal hypothesis ($L_1$):
any $P$, $P = 1$ year


Single-scatter rate
2.0 - 5.8 keV

± RMS/Mean
51%
Periodicity Test

- **Unbinned** profile likelihood analysis
- Most significant uncertainties *constrained by data*: cut acceptance, Kr level, energy scale
- Binned cross checks: $\chi^2$, Lomb-Scargle

\[
f(t) = \epsilon(t) \left[ C + Kt + A \cos \left( \frac{2\pi (t - \phi)}{P} \right) \right]
\]

\[
\mathcal{L} = \left( \prod_{i=1}^{n} f(t_i) \right) \text{Poiss}[n|N_{\text{exp}}(E)] \mathcal{L}_e \mathcal{L}_K \mathcal{L}_E
\]

Unbinned profile likelihood analysis

 constraints


Normalized

Total observed events

Constraints

\( \Delta \text{RMS/Mean} \)

51%
Discovery Potential

- Simulate synthetic signals, \( n = 153 \) events
- Follow time distribution of actual data
- Fix \( C, A \) at best-fit values for \( P = 365 \) days
- Local significance from null hypothesis test
PL Results

- Global sig < 1σ for all periods
- Local sig rise at long periods for signal and control
- Binned cross checks in agreement

Simulated Modulation

SS = single scatters
MS = multiple scatters (coincident signal in veto)
PL Results: \( P = 365.25 \) days

- Local sig rise at long periods for signal \textit{and} control
- Best-fit SS and MS phases \textit{in agreement}
- Standard DM halo phase \textit{disfavored at 2.5}\( \sigma \)

Hint of annual modulation...

...but in strong tension with DM interpretation

Uncertainty on best-fit values from scan of \( \mathcal{L}_1/\mathcal{L}_{\text{max}} \)

Annual modulation best-fit:
\[
C = (5.5 \pm 0.6) \text{ events/(keV} \cdot \text{tonne} \cdot \text{day)}
\]
\[
A = (2.7 \pm 0.8) \text{ events/(keV} \cdot \text{tonne} \cdot \text{day)}
\]
\[
\phi = (112 \pm 15) \text{ days (April 22)}
\]
Signal Conversion

- Assume axial-vector coupling of WIMPs to electrons, compute relative rate in Xe and NaI
  - Also considers Luminous and Mirror DM models

- Find expected spectrum in XENON100 from DAMA/LIBRA observation, accounting for
  - Relative rate and energy scale conversion
  - S1 generation (Poisson process)
  - PMT single pe resolution
  - Measured cut acceptance
  - DAMA/LIBRA stat. uncert. and XENON100 uncert.

- DAMA/LIBRA expected (axial-vector): 11.5 ± 1.2 stat ± 0.7 sys

DAMA/LIBRA Comparison

![Graph of Ratio of Rates (Xe/NaI) vs. Energy (keV)]

- Xenon and iodine have nearly identical electronic structure

![Graph of Mean electronic recoil energy (keV) vs. Rate (counts/PE/tonne/day)]

- DAMA/LIBRA annually modulated spectrum (2-6)keV interpreted as
  - Leptophilic DM, axial-vector coupling
  - Mirror DM
  - XENON100 70 summer live days
Exclusion – Average Rate

- Assume all events in XENON100 are signal
- Average rate in XENON100 ~2x lower than DAMA/LIBRA modulation fraction
- Integrate rate during optimized time window around June 2, and use for exclusion:

  ◇ Mirror Dark Matter: 3.6σ
  ◇ Luminous Dark Matter: 4.6σ
  ◇ Axial-vector coupling to electrons: 4.4σ

>3σ even assuming ~4.5σ downward deviation of yield measurements or zero light yield below 2.9 keV (in contradiction with direct measurement)

DAMA/LIBRA Comparison

PL method to compute discrepancy of expected DAMA/LIBRA $A$ with XENON100 best-fit

- Fix $P = 365.25$ days, $\phi = 144 \pm 7$ days (May 24)
- Uncertainties constrained by data
- Add constraint term to likelihood, $L_\phi$

Interpretation of DAMA/LIBRA signal as ERs (axial-vector coupling) excluded at $4.8\sigma$

DAMA/LIBRA Comparison

Summary

- Best-fit annual modulation amplitude >4x lower than DAMA/LIBRA modulation
- *Phase shifted* ~1 month from DAMA/LIBRA
- Local significance comparable for single *and* multiple scatter events (and *phases in agreement*)
- Interpretation of DAMA/LIBRA as WIMP-induced ERs strongly challenged

**Models Excluded**

<table>
<thead>
<tr>
<th>Model</th>
<th>Significance</th>
<th>Reference</th>
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<tr>
<td>Luminous Dark Matter (4.6σ)</td>
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**Conclusion**

- Benchmark for stability of LXe dark matter detectors
- Challenges interpretation of DAMA/LIBRA modulation as ERs from WIMPs

| Luminous Dark Matter (4.6σ) |

**Improvements in progress**

- *More* XENON100 data (153 additional live days)
- *Lower uncertainty* on energy scale (new calibration measurements)
- *More* diagnostic tools for Kr contamination
- and...
Conclusion

... an even bigger, better detector - XENON1T!
Detector Stability

Rn-Kr Correlation

Air leak \( \sim 10^{-5} \) torr*l/s

\(^{85}\text{Kr} \): \( t_{1/2} = 10.8 \) years builds up
decays away

\(^{222}\text{Rn} \): \( t_{1/2} = 3.82 \) days

\[ K = 2.54 \pm 0.53 \times 10^{-3} \text{ (events/(keV\cdot tonne\cdot day))/day} \]

\[ f(t) = c(t) \left[ C + K t + A \cos \left( \frac{2\pi (t - \phi)}{P} \right) \right] \]
Expected rate from WIMP-induced ER

- keV recoils from inelastic scatter of >1GeV WIMPS with momentum ~MeV
- Interaction rate from Kopp et al. (x2 to account for electron spin) [Kopp et al., Phys. Rev. D 80, 083502 (2009)]
- Sum contribution from each atomic shell (integrate momentum wave function)
- Largest rate from 3s shell of Iodine (Na 100x smaller)
- Xe and I overall very similar electron structure
- Negligible dependence on WIMP mass

Other Models Considered

- **Mirror Dark Matter**: scale by ratio of (number of loosely bound electrons · number of target atoms)
- **Luminous Dark Matter**: scale by target density ratio

PL Method Details

**Basic method:** Olive et al., Chin. Phys., C38 (2014), 090001

**Rate**

\[ f(t) = e(t) \left[ C + Kt + A \cos \left( \frac{2\pi (t - \phi)}{P} \right) \right] \]

Normalized by \( D \)

**Normalization factor**

\[ D = C \times \sum_{j=1}^{m} (T_{E}^j - T_{S}^j) \times \epsilon \left( \frac{T_{S}^j + T_{E}^j}{2} \right) + \frac{K}{2} \times \sum_{j=1}^{m} (T_{S}^{j2} - T_{S}^2) \times \epsilon \left( \frac{T_{S}^j + T_{E}^j}{2} \right) + \frac{A \times P}{2\pi} \sum_{j=1}^{m} \epsilon \left( \frac{T_{S}^j + T_{E}^j}{2} \right) \times \sin \left( \frac{2\pi}{P} \times (T_{E}^j - \phi) \right) - \frac{A \times P}{2\pi} \sum_{j=1}^{m} \epsilon \left( \frac{T_{S}^j + T_{E}^j}{2} \right) \times \sin \left( \frac{2\pi}{P} \times (T_{S}^j - \phi) \right) \]

**Likelihood function**

\[ \mathcal{L} = \left( \prod_{i=1}^{n} \tilde{f}(t_i) \right) \text{ Poiss}[n|N_{\exp}(E)] \mathcal{L}_E \mathcal{L}_K \]

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**Local significance, 500 days**

- **MC Distribution**
- **χ² Distribution**

2 d.o.f. = 7 total parameters – 4 constraints – 1 fixed parameter

\((\epsilon, \phi, C, K, A, P, E)\) (likelihood factors)

\((P)\)

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**Global significance**

- **MC Distribution**

\(1\sigma\) (global)