# DAMA and the Search for Dark Matter with Annually Modulating Signals

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# Outline

- Using annually modulating signals to search for dark matter
- The DAMA/LIBRA apparatus
- DAMA results
- Proposed alternative explanations
- Future experiments

# Direct Detection of Dark Matter

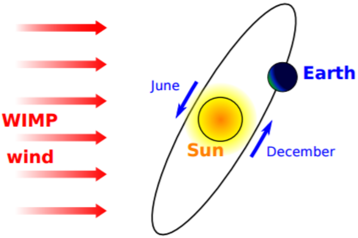
- When a WIMP scatters off a nucleus of mass M in a detector, it imparts some recoil energy $E_{nr}$ onto the nucleus
- The differential cross-section for the most commonly assumed couplings is

$$\frac{dR}{dE_{nr}} = \frac{1}{2m_\chi \mu^2}\sigma(q)\rho_\chi \eta(v_{min}(E_{nr}), t)$$

- $\eta(v_{min}, t)$ is the mean inverse velocity, and $v_{min}$ is the minimum WIMP velocity needed to result in a recoil $E_{nr}$

# Annual Modulation

- Our solar system moves through the galactic halo of dark matter with some relative velocity
- The Earth moves relative to the sun with an annually modulating relative velocity



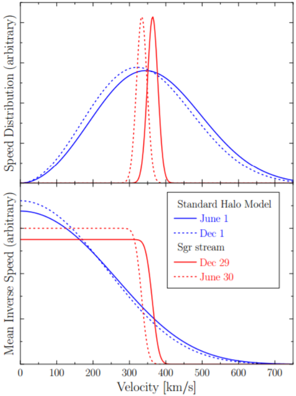

Perceived WIMP "wind" from motion through the galactic halo

arxiv:1209.3339v3

# The Galactic Halo

- Dark matter halo in local neighborhood believed to be dominated by a smooth, well-mixed component with average density $\rho_\chi \approx 0.4$ GeV / cm$^3$.
- Standard Halo Model models it as an isothermal sphere with an isotropic, Maxwellian velocity distribution, given by

$$\tilde{f}(\mathbf{v}) = \begin{cases} \frac{1}{N_{esc}} \left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2} e^{-3\mathbf{v}^2/2\sigma_v^2} & |\mathbf{v}| < v_{esc} \\ 0 & \text{otherwise} \end{cases}$$




Top: Velocity distributions from our solar system's reference frame. Bottom: mean inverse speed $\eta$ as a function of $v_{min}$

arxiv:1209.3339v3

# Annual Modulation

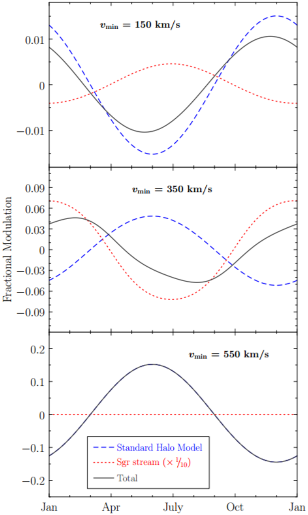
- For $\boldsymbol{v}_{obs}$ = velocity of Earth relative to the dark matter's rest frame, the dark matter's velocity distribution in Earth's frame is given by $f(\boldsymbol{v}, t) = \tilde{f}(\boldsymbol{v}_{obs}(t) + \boldsymbol{v})$
- For an Earth orbit velocity ¡¡ the sun's velocity relative to the halo, we can approximate $v_{obs}(t) \approx v_{sun} + b * v_{Earth} \cos \omega(t - t_0)$
  - $b$ is a factor associated with the direction of $v_{obs}$ relative to the Earth's orbital plane ($|b| << 1$)
  - $t_0$ is the time of year at which $v_{obs}$ is maximized
- The recoil rate per unit detector mass can then be approximated as

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

- There is also a modulation effect from the Earth's daily rotation, but this is on the order of 0.5 km/s, much smaller than the orbital velocity of 30 km/s, and so is normally ignored

# Annual Modulation Effect

- Sample plot of expected fractional modulation in detected recoil events for different $v_{min}$, the minimum velocity a dark matter candidate would need to produce detectable recoil energy in the detector
- Depicts effects from both the Standard Halo Model and from a stream whose density is 1/10 that of the SHM
- Max around June 2, min around December 2



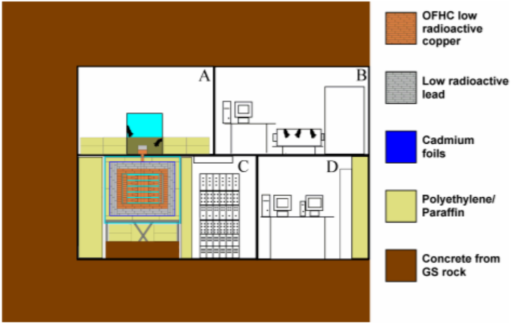
# The DAMA Apparatus

- DAMA/NaI (1995-2002) was the first iteration of the DAMA experiment, and which first reported an annual modulation in its signal
- DAMA/LIBRA (Large sodium Iodide Bulk for RAre processes) (2003-2010) is the successor experiment, using similar but improved technologies, and using the same location
    - This experiment's apparatus will be the focus of this section

# The Detector

- The detector uses highly radiopure NaI(TI) (sodium iodide activated with thallium) scintillation detectors
  - NaI(TI) is one of the most used scintillators (making it well-understood), with a very high luminescence
  - Sensitive to both high WIMP masses through the iodine target, and low WIMP masses through the Na target
- Total 250 kg of detector split into 25 individual detectors of 9.7 kg each, arranged in a 5x5 grid, with each detector having 2 PMT's
  - Allows additional rejection of background since a dark matter event should have a hit in only one detector at a time
  - Response of 5.5-7.5 photoelectrons/keV

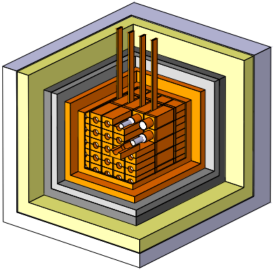
# The Setup




Room A holds glove box for calibrations. Room C holds the actual detectors and sensitive parts of the apparatus, as well as the shielding and electronics for these parts. Room D holds the computer for DAQ. arxiv: 0804.2738

# Shielding

- Materials selected for low radioactivity with a Ge detector, mass spectrometry, and/or atomic absorption spectroscopy
- Room with the detector sealed off from external air, with environmental radon monitors
- Detector sealed in purified Cu box constantly flushed with high purity $N_2$ stored underground
- Rest of the shielding consists of 10 cm of copper, 15 cm of lead, 1.5 mm of cadmium, 10-40 cm polyethylene/paraffin, and 1 m of concrete around the room



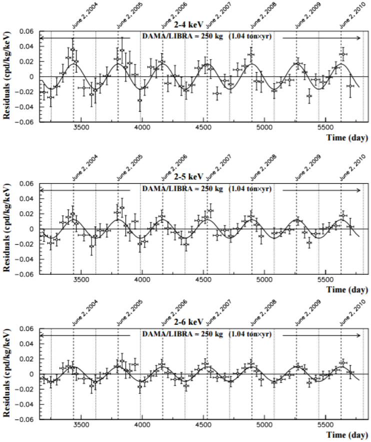
The layers of the DAMA detector and shielding.

arxiv:1308.5109v2

# Backgrounds

- The NaI(TI) crytals are grown through a confidential, non-disclosed method, but that ensures high radiopurity. They are then further purified by various chemical/physical methods
- Primary contamination is from $^{232}$Th, $^{238}$U, and $^{nat}$K
  - Estimates of the first two can be found by looking at peaks in the energy spectra from the $\alpha$ particles that result from their decay chains
  - The K abundance can be estimated by looking at double coincidence events, as $^{40}$K decays to $^{40}$Ar, which then decays to X-rays/Auger electrons that are almost all contained within the detector, plus a 1461 keV $\gamma$ that tends to escape into another detector
- $^{125}$I, $^{129}$I, $^{210}$Pb, $^{22}$Na, $^{24}$Na are also possible backgrounds due to activation from either cosmic rays before reaching the underground facility or from environmental neutrons

# DAMA Results




arxiv:1308.5109v2

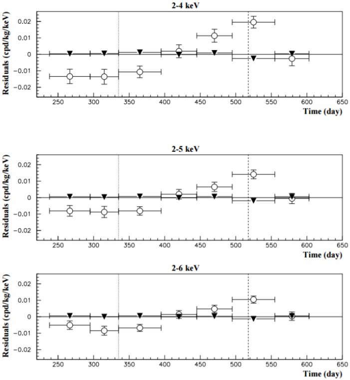
- Residual rates of single-hit scintillation events in the 2-4, 2-5, and 2-6 keV ranges shown. The curves are fitted functions $A \cos \omega(t - t_0)$ with period 1 year, phase $t_0$=152.5 days (June 2nd).

# DAMA Results

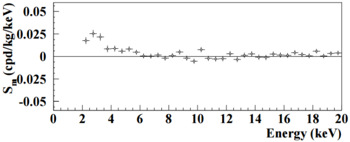
| | $A$ (cpd/kg/keV) | $T = \frac{2\pi}{\omega}$ (yr) | $t_0$ (days) | C.L. |
|---|---|---|---|---|
| DAMA/LIBRA–phase1 | | | | |
| 2-4 keV | (0.0178±0.0022) | (0.996±0.002) | 134±7 | 8.1 $\sigma$ |
| 2-5 keV | (0.0127±0.0016) | (0.996±0.002) | 137±8 | 7.9 $\sigma$ |
| 2-6 keV | (0.0097±0.0013) | (0.998±0.002) | 144±8 | 7.5 $\sigma$ |
| DAMA/NaI & DAMA/LIBRA–phase1 | | | | |
| 2-4 keV | (0.0190±0.0020) | (0.996±0.002) | 134±6 | 9.5 $\sigma$ |
| 2-5 keV | (0.0140±0.0015) | (0.996±0.002) | 140±6 | 9.3 $\sigma$ |
| 2-6 keV | (0.0112±0.0012) | (0.998±0.002) | 144±7 | 9.3 $\sigma$ |

Fitted amplitude (A), period (T), phase ($t_0$), and confidence levels for the annual modulation in signal. arxiv:1308.5109v2

# DAMA Results

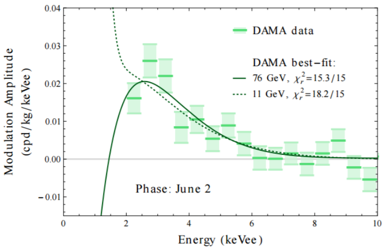



Triangles: residual rates for multi-hit events. Circles: residual rates for single-hit events.




Modulation amplitude $S_m$ in the scattering cross-section for different recoil energies in bins of 0.5 keV

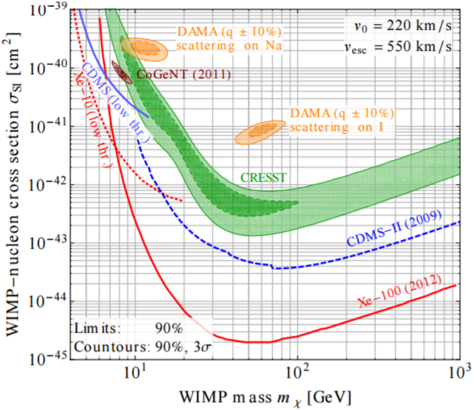
# DAMA Results




arxiv:1209.3339v3

- Bin-averaged modulation amplitudes for each detected energy are shown
- The calculated curves for WIMP masses of 76 GeV and 11 GeV are shown, which correspond to iodine recoils being dominant and sodium recoils being dominant, respectively

# WIMP Search Results




Composite of the boundaries set by experiments that failed to detect any annual modulation, as well as the locations in phase space of the anomalies that have been detected. arxiv:1209.3339v3

# Possible Alternative Explanations

- DAMA claims that all alternative explanations of the annual modulation in their signal have been ruled out
  - A background would have to also have a period of 1 year and a peak around June 2 to explain the signal
- The most prominent alternative explanation was background from the muon flux, which could either directly cause hits in the detector or induce reactions from environmental neutrons

# Muon Flux

- A number of experiments (MACRO, LVD, Borexino) have reported an annual modulation in the muon flux at Gran Sasso lab of 1.3%-2%, with a phase around the beginning of July
- This has been ruled out because muons would:
  - induce a variation in the signals across the energy spectra
  - induce a variation in the multiple-hit events as well
- The phase of the muon flux also varies year-by-year depending on $T_{eff}$ in the atmosphere above the site, but the DAMA signal's phase was consistent year-by-year
- The effect from muon-induced environmental neutrons can also be estimated and accounted for by looking for the presence of $^{24}$Na from activation of $^{23}$Na
  - $^{24}$Na decay has a distinct triple-hit signature from a $\beta$ in one detector and a $\gamma$ in each of the adjacent ones

# Future Prospects

- The KIMS experiment using CsI(TI) crystals in Yangyang, South Korea and the ANAIS experiment using NaI(TI) cryatls at Canfrac, Spain attempt to replicate the annual modulation found by DAMA
- DM-Ice is an ongoing experiment embedded deep in the ice at the South Pole using the same target material as DAMA
  - Backgrounds should be very different at the south pole, due to being on the other hemisphere and due to different environmental conditions
  - Finding the same annual modulation here would likely confirm DAMA's results

# References


- The DAMA/LIBRA Apparatus. arxiv:0804.2738
- Final model independent result of DAMA/LIBRA-phase1. arxiv:1308.5109v2
- No role for muons in the DAMA annual modulation results. arxiv:1202.4179v3
- Annual Modulation of Dark Matter: A Review. arxiv:1209.3339v3