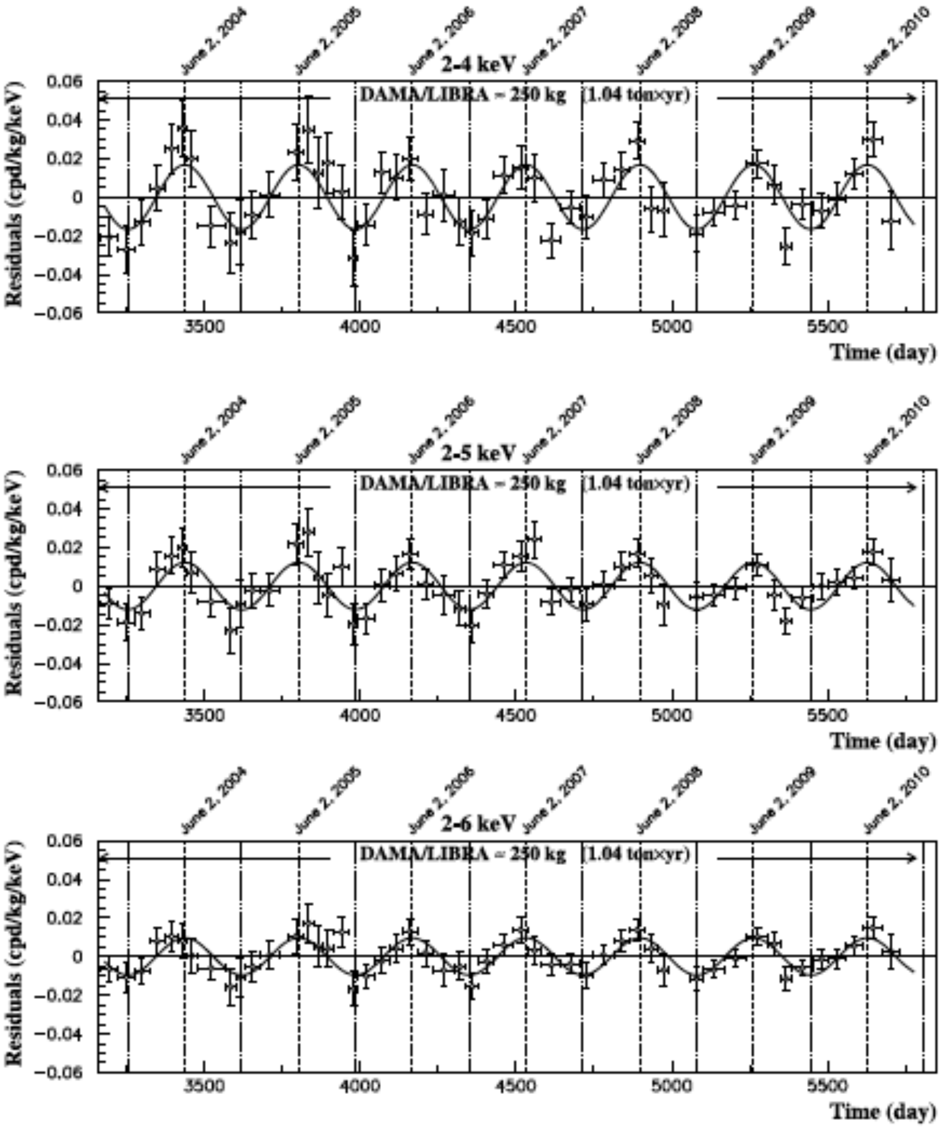
What can and cannot explain the DAMA data?

Joel Klinger and Vitaly A. Kudryavtsev

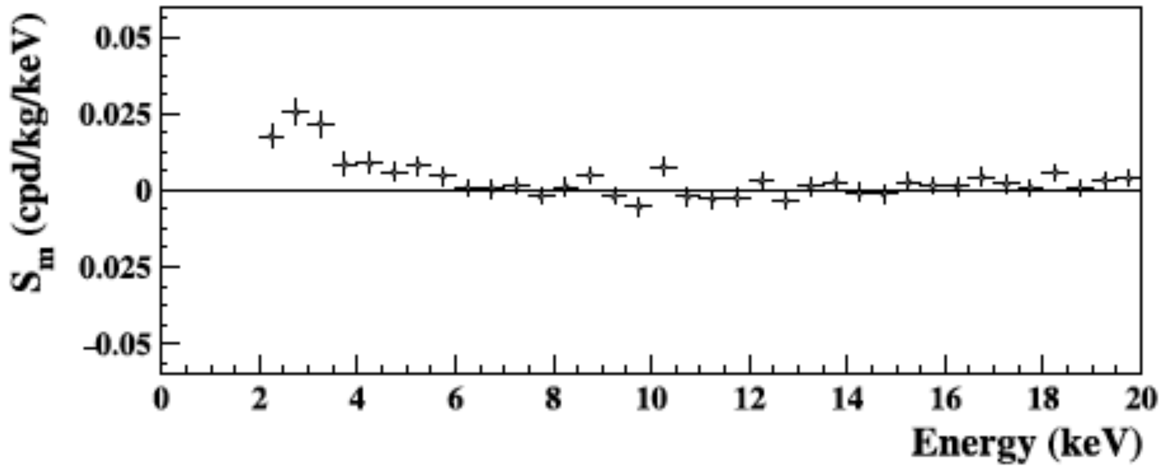
DAMA/LIBRA results



- Modulated signal detected at about 9σ.
- Signal seen only at 2-6 keV.
- Only in single-hit events.
- Variations consistent with dark matter signal in period and phase.
- No temperature variations.
- Radon under control.
- …
- See DAMA papers.
- Average modulation amplitude at 2-6 keV:

  0.0112 counts/kg/day/keV.

Modulation amplitude

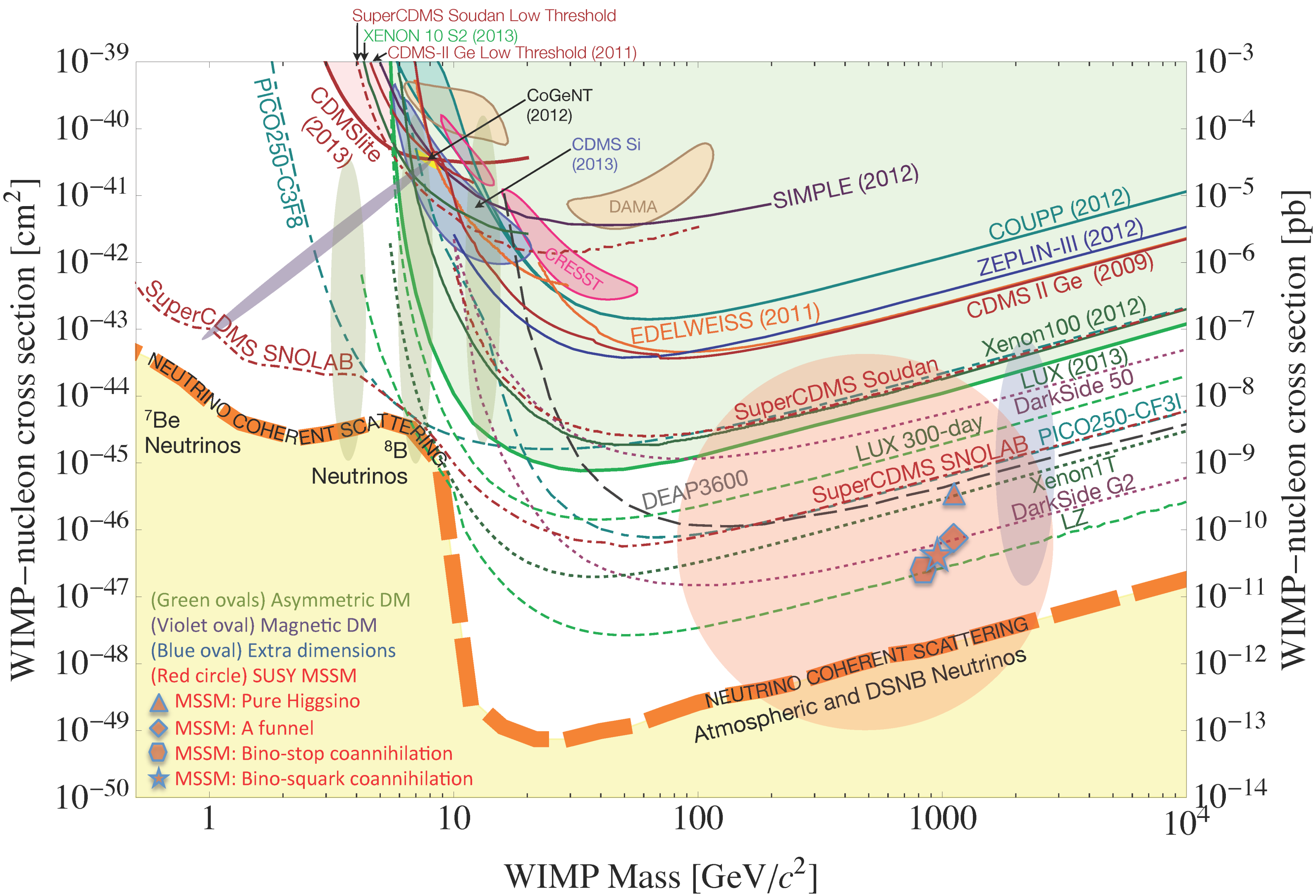


- Average modulation amplitude at 2-6 keV: 0.0112 events/ kg/day/keV.
- Modulation amplitude at 2-3 keV: 0.0190 events/ kg/day/keV.

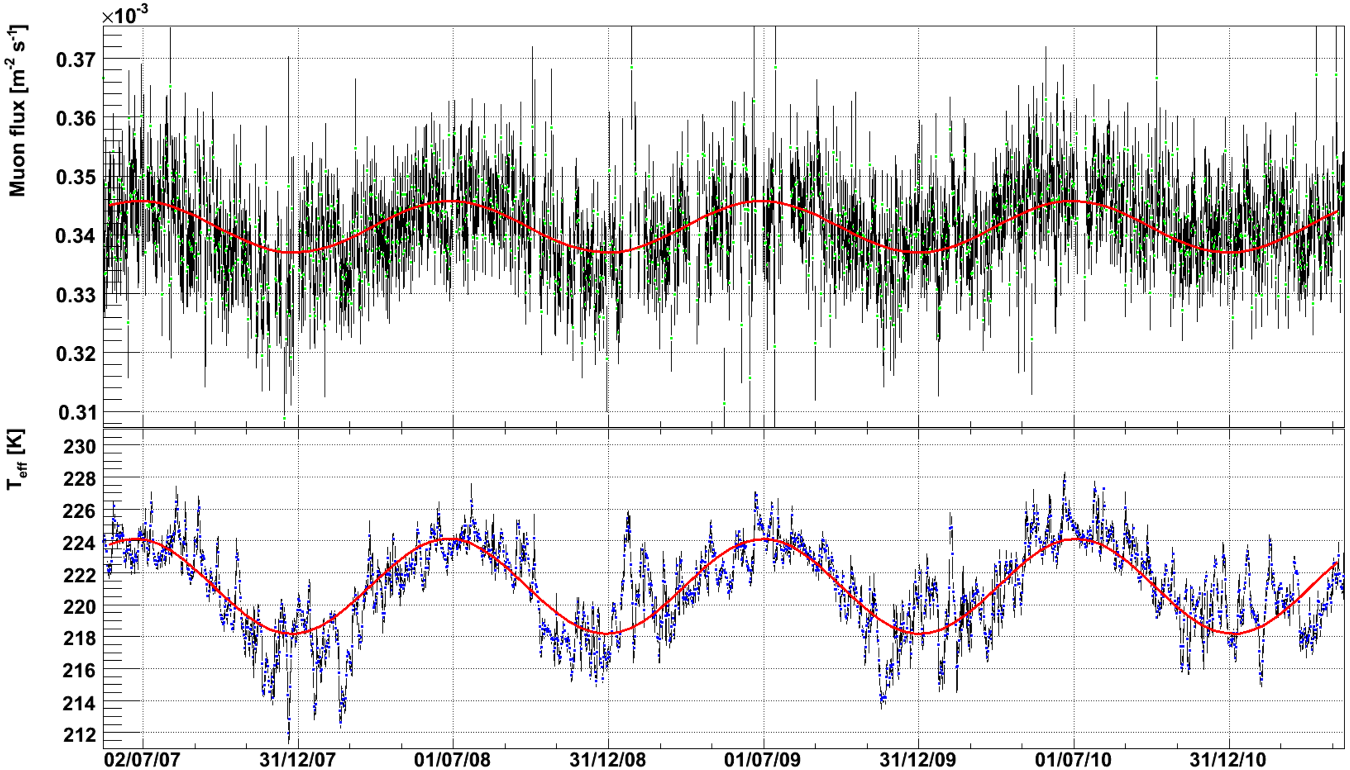
From Bernabei et al. EPJC, 73 (2013) 2648.

Very difficult (impossible?) to reconcile with other experiments

Comparison with other experiments



Can muons explain the DAMA signal?



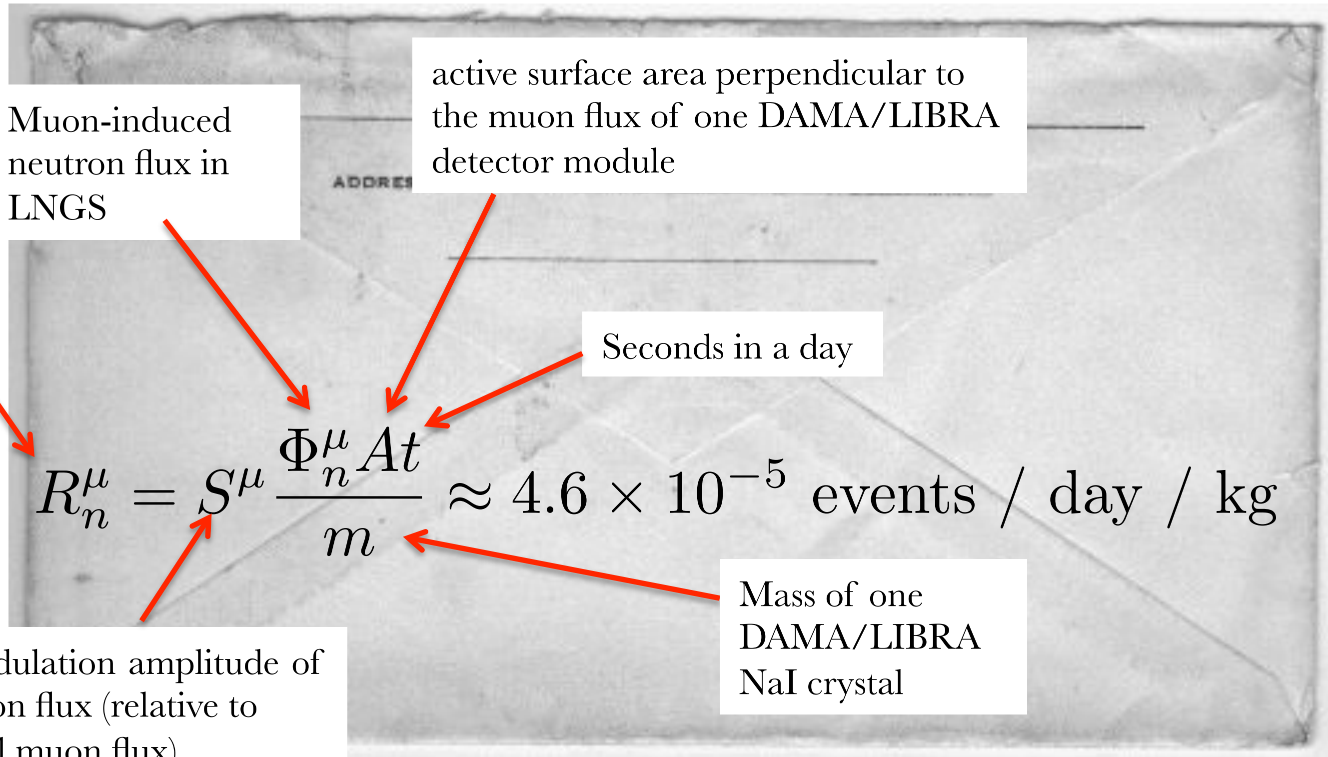
Borexino Collaboration, JCAP 1205 (2012), 015.

- Annual modulation of the muon rate has been observed by Borexino, LVD and MACRO.
- The modulation amplitude is about 1.4% of the average rate.

Can muons explain the DAMA signal?

- Several papers (mostly unpublished) suggest various models linked to muons and/or muon-induced neutrons:
  - Ralston, arXiv:1006.5255 [astro-ph].
  - Nygren, arXiv:1102.0815 [astro-ph].
  - Blum, arXiv:1110.0857 [astro-ph].
- Estimates by DAMA: Bernabei et al. EPJC 72 (2012) 2064, but no detailed simulations. Conclusion: expected neutron flux is several orders of magnitude too low.
- Statistical analysis focusing on phase only:
  - Chang et al. Phys. Rev. D 85 (2012), 063505.
  - Fernandez-Martinez and R. Mahbubani, JCAP, 07 (2012) 029.
- Main focus on the phase of the modulation signal, not the amplitude.

Back of the envelope calculation



$$R_n^\mu = S^\mu \frac{\Phi_n^\mu A t}{m} \approx 4.6 \times 10^{-5} \text{ events / day / kg}$$

The estimate neglects the efficiency of neutron detection and event selection (single hits, energy range). Also, neutron flux from rock only.

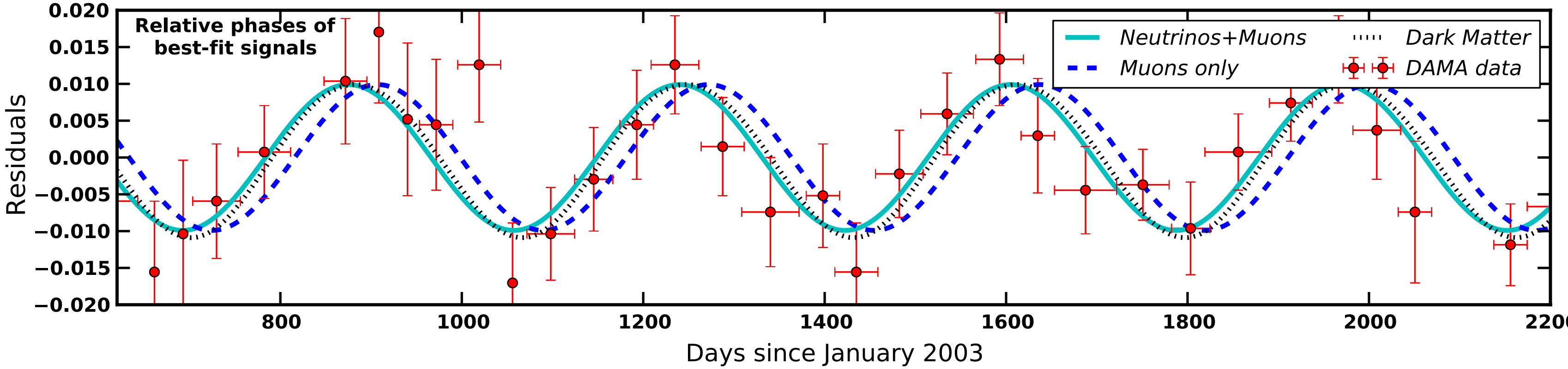
This simple estimate and a similar one, with more details, in Bernabei et al. EPJC 72 (2012) 2064, clearly show that muon-induced neutron rate is several orders of magnitude smaller than the DAMA modulation amplitude: 0.045 events/kg/day.

Recent publication

Davis, PRL, 113 (2014) 081302: combination of muon and solar-neutrino induced neutrons.

PRL **113,** 081302 (2014) PHYSICAL REVIEW LETTERS week ending 22 AUGUST 2014

Fitting the Annual Modulation in DAMA with Neutrons from Muons and Neutrinos



- The phase difference (30 days) between muons and DAMA can be shifted by a contribution to the total flux from **solar neutrino-induced neutrons.**
- Rough estimates of neutrino and muon induced neutron rates in DAMA do not contradict the DAMA signal.

Recent publication

- The calculation of the muon-induced background in this paper contradicts the back-of-the-envelope estimate.
- The calculation neglects the fact that most neutrons will be accompanied a showering muon, and would not be accepted by DAMA/LIBRA.
- The value of the neutron mean free path in rock that was used in the paper, was actually for liquid argon (half of the density of LNGS rock).
- Quick response from DAMA: Bernabei et al. EPJC 74 (2014) 3196. Estimate similar to the previous one in Bernabei et al. EPJC 72 (2012) 2064 show similar results: no neutrons can be responsible for such a modulation. (However, no full MC).
- Neutrino-induced neutron flux is in fact 6 orders of magnitude smaller: Barbeau et al. PRD, 113 (2014) 229001.

Recent publication

Davis, PRL, 113 (2014) 081302.

Despite of these criticisms, such publications attract a lot of attention:

PRL **113,** 081302 (2014) PHYSICAL REVIEW LETTERS week ending 22 AUGUST 2014

Fitting the Annual Modulation in DAMA with Neutrons from Muons and Neutrinos

physicsworld.com

Home | News | Blog | Multimedia | In depth | Events

News archive
- 2015
- 2014
  - December 2014
  - November 2014
  - October 2014
  - September 2014
  - August 2014
  - July 2014
  - June 2014
  - May 2014
  - April 2014
  - March 2014
  - February 2014
  - January 2014
- 2013
- 2012
- 2011
- 2010
- 2009

Scattered neutrons could mimic DAMA-LIBRA's 'dark matter' modulation

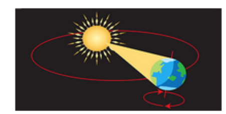
Jul 17, 2014 3 comments

On a high: do muons and neutrinos mimic DAMA's signal?

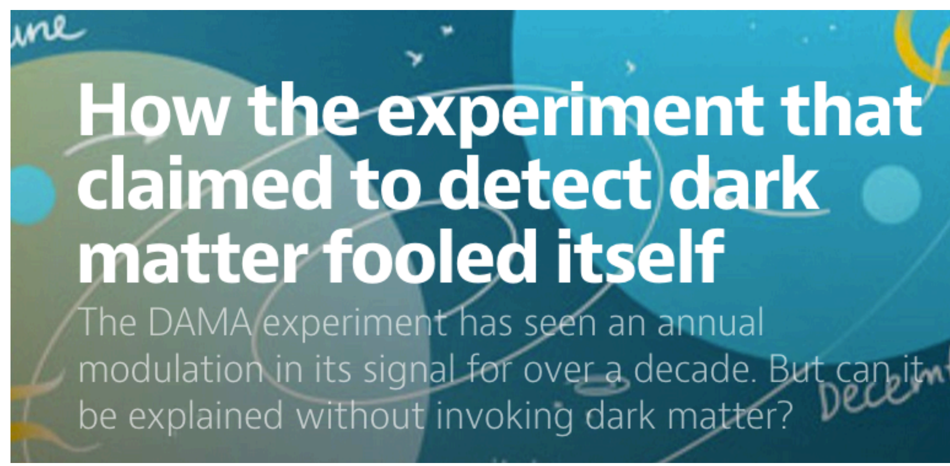
Physics
spotlighting exceptional research

Home | About | Browse | APS Journals

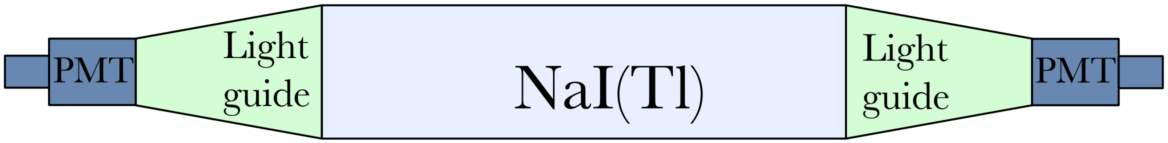
Synopsis: Dark Matter or Neutrons?

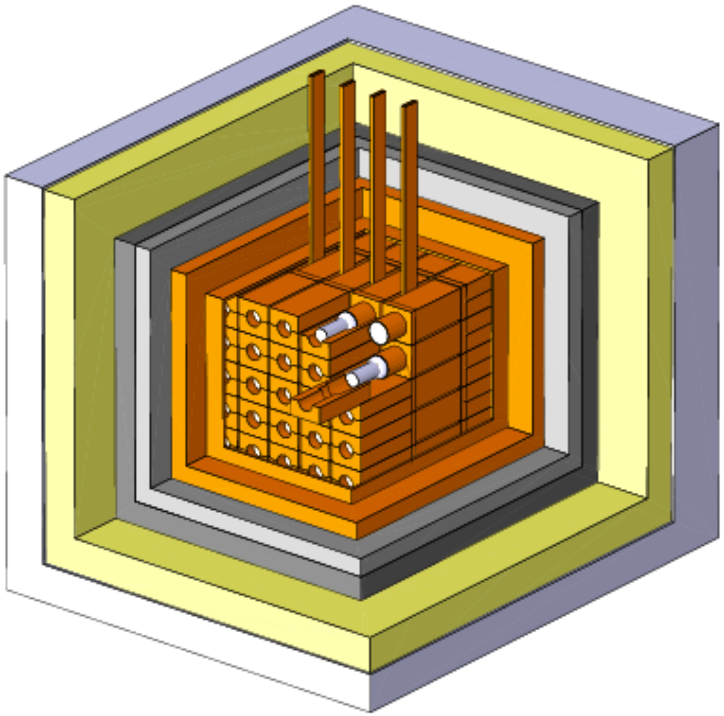


Fitting the Annual Modulation
Jonathan H. Davis
Phys. Rev. Lett. **113**, 08130
Published August 21, 2014



DAMA/NaI and DAMA/LIBRA

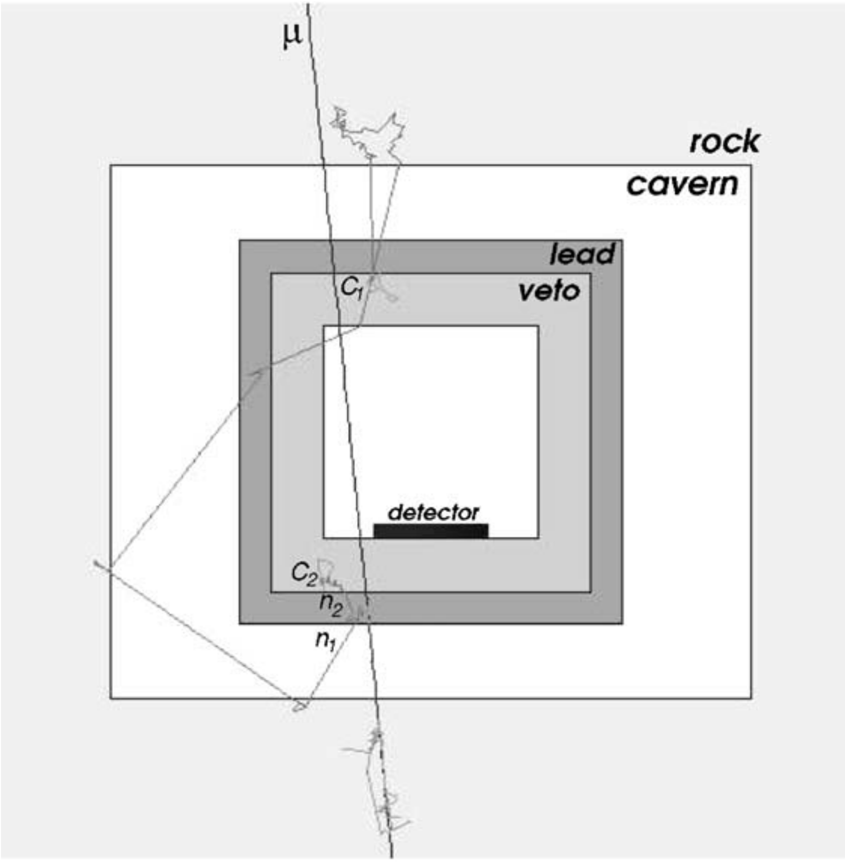


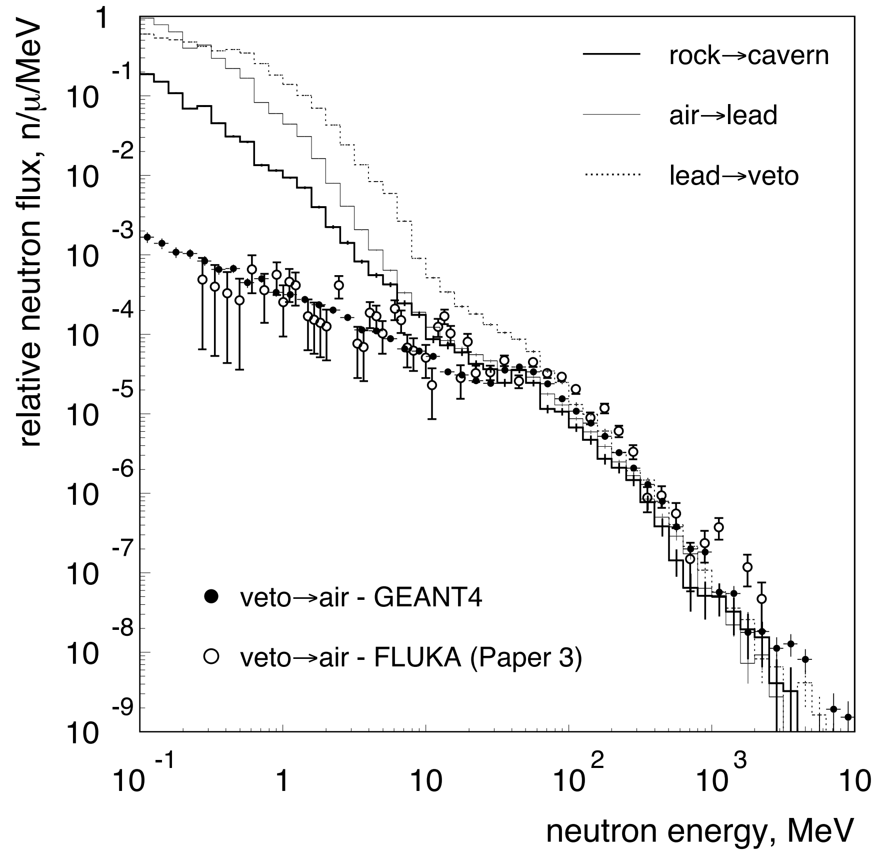


Bernabei et al. NIMA 592 (2008) 297.

- 25 NaI(Tl) crystals.
- 9.7 kg each.
- 242.5 kg total mass.
- Located at LNGS.
- 10 cm copper.
- 15 cm lead.
- 1.5 mm Cd.
- 50 cm of polyethylene.
- 1 m of concrete.
- Background from rock is suppressed by 5-6 orders of magnitude.
- No veto.
- Too much lead/copper around?

First simulations

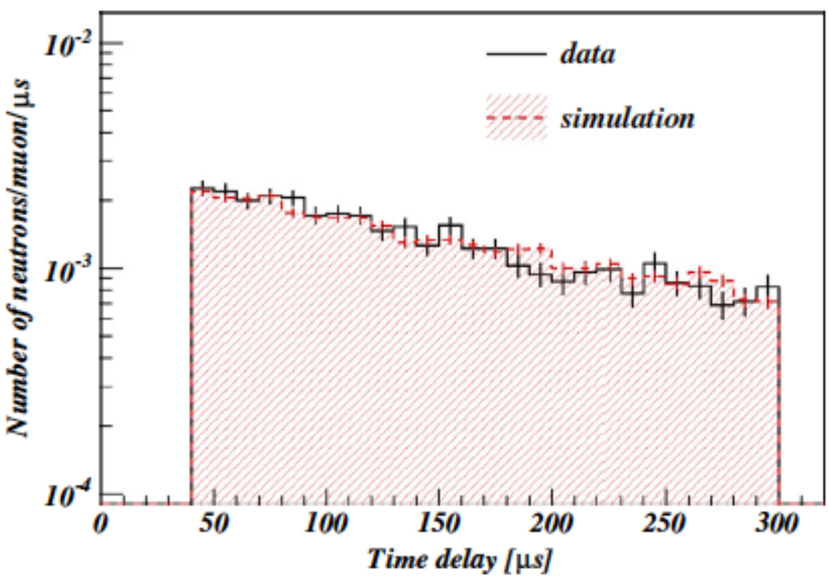


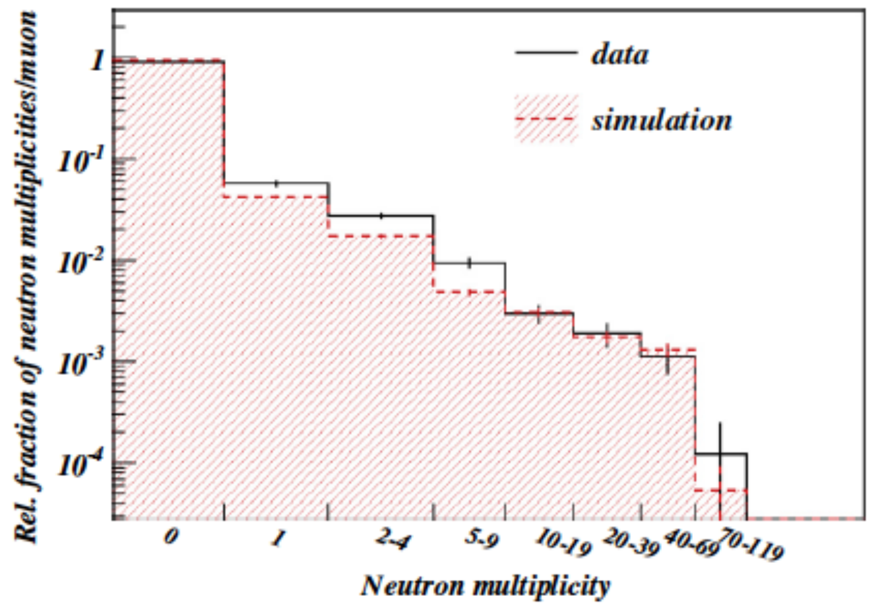


Our first simulations for a simplified geometry and a hypothetical xenon-based dark matter detector.

Araujo et al. NIMA, 545 (2005) 398

Neutrons in lead





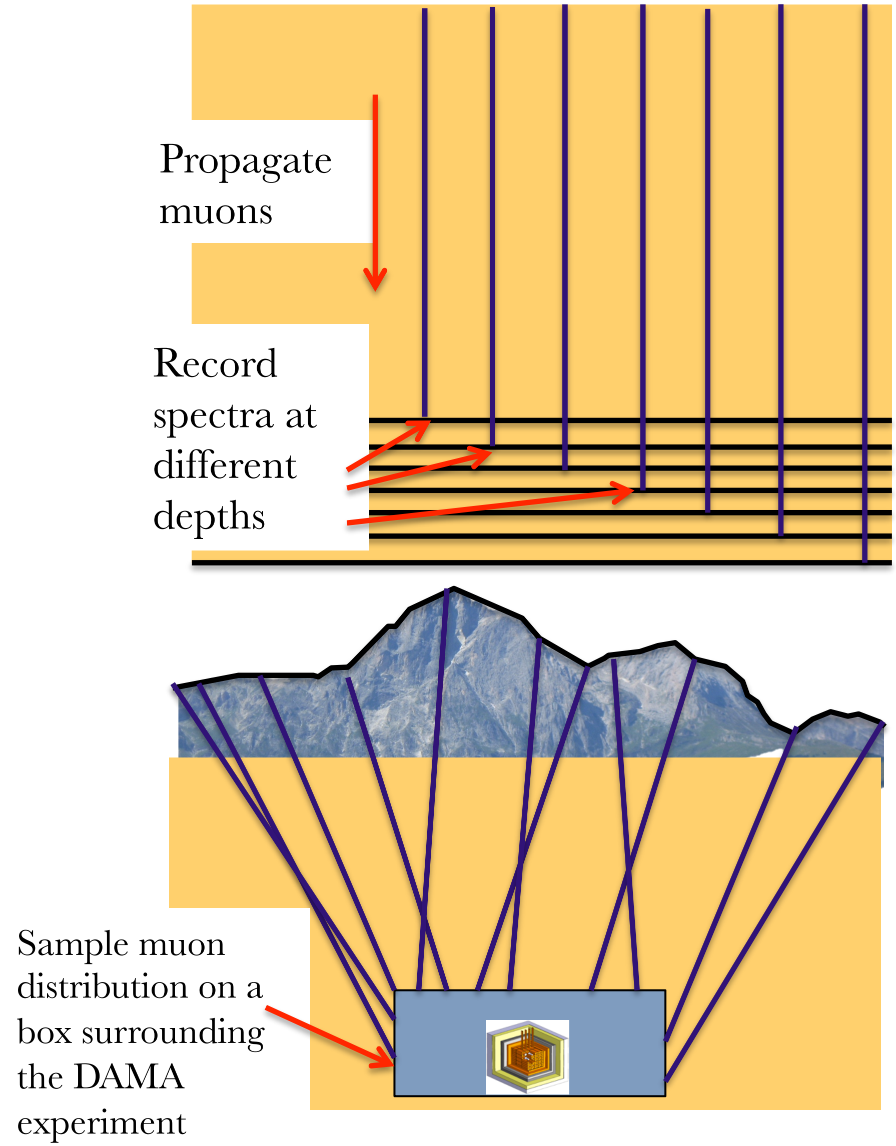
- ZEPLIN-III veto data vs GEANT4 simulations.
- GEANT4 predicts 20% lower neutron production rate.
- Data and plots: Reichhart et al. ApP, 47 (2013) 67.
- GEANT4: Agostinelli et al. NIMA, 506 (2003) 250.

Full MC

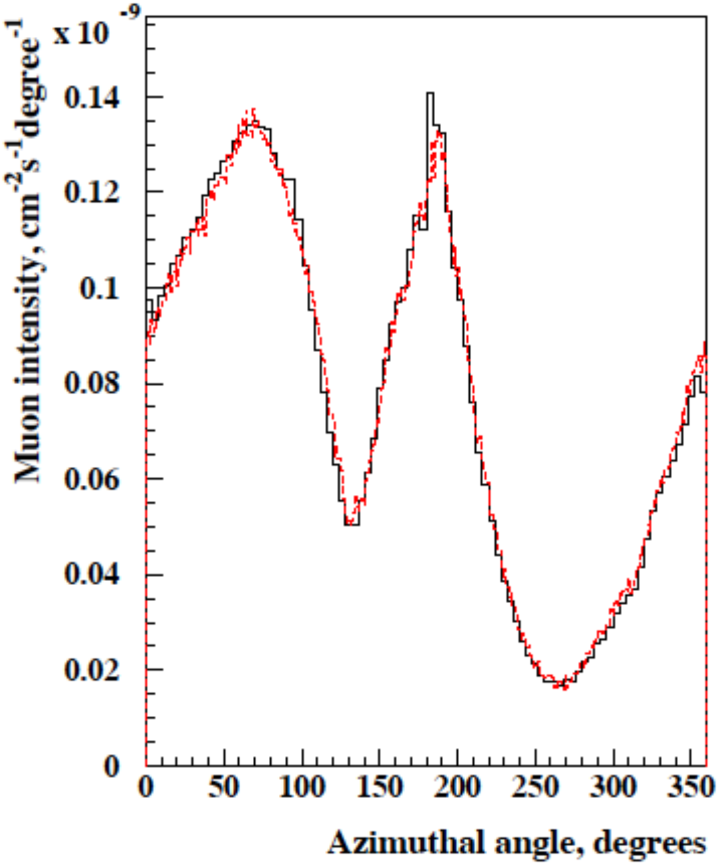
- Let's do this properly:
  - Fully modelled muon-induced neutrons.
  - Detector geometry, including high-Z shielding.
  - Event selection.
  - Do not care about the phase: enough of statistical analyses already.
- Simulation in two stages:
  - First stage: muon transport from the surface to the lab: MUSIC code (Antonioli et al., 7 (1997) 367; Kudryavtsev, CPC 180 (2009) 339). Only muons are transported and their losses are taken into account. Secondary particles are neglected.
  - Second stage: transport of all particles produced by muons, through rock near LNGS and DAMA setup as described in Bernabei et al. NIMA 592 (2008) 297.
- **Klinger and Kudryavtsev. Phys. Rev. Lett. 114 (2015) 151301**.

Muon transport

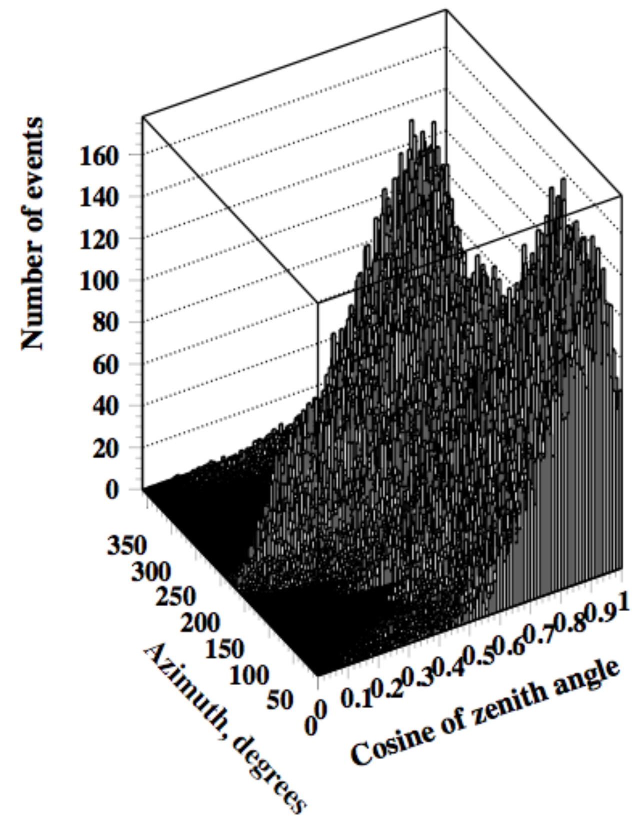
- Propagate muons with fixed energies through LNGS rock (no mountain profile) using MUSIC.
- Record energy distributions at different depths/distances.
- Convolute recorded energy distributions with muon spectrum at the surface using modified Gaisser's parameterisation which fits LVD and MACRO data. Take into account the surface profile.
- Use MUSUN to sample muons on a box around the LNGS lab (part of it where the DAMA detector is).



Muons at LNGS



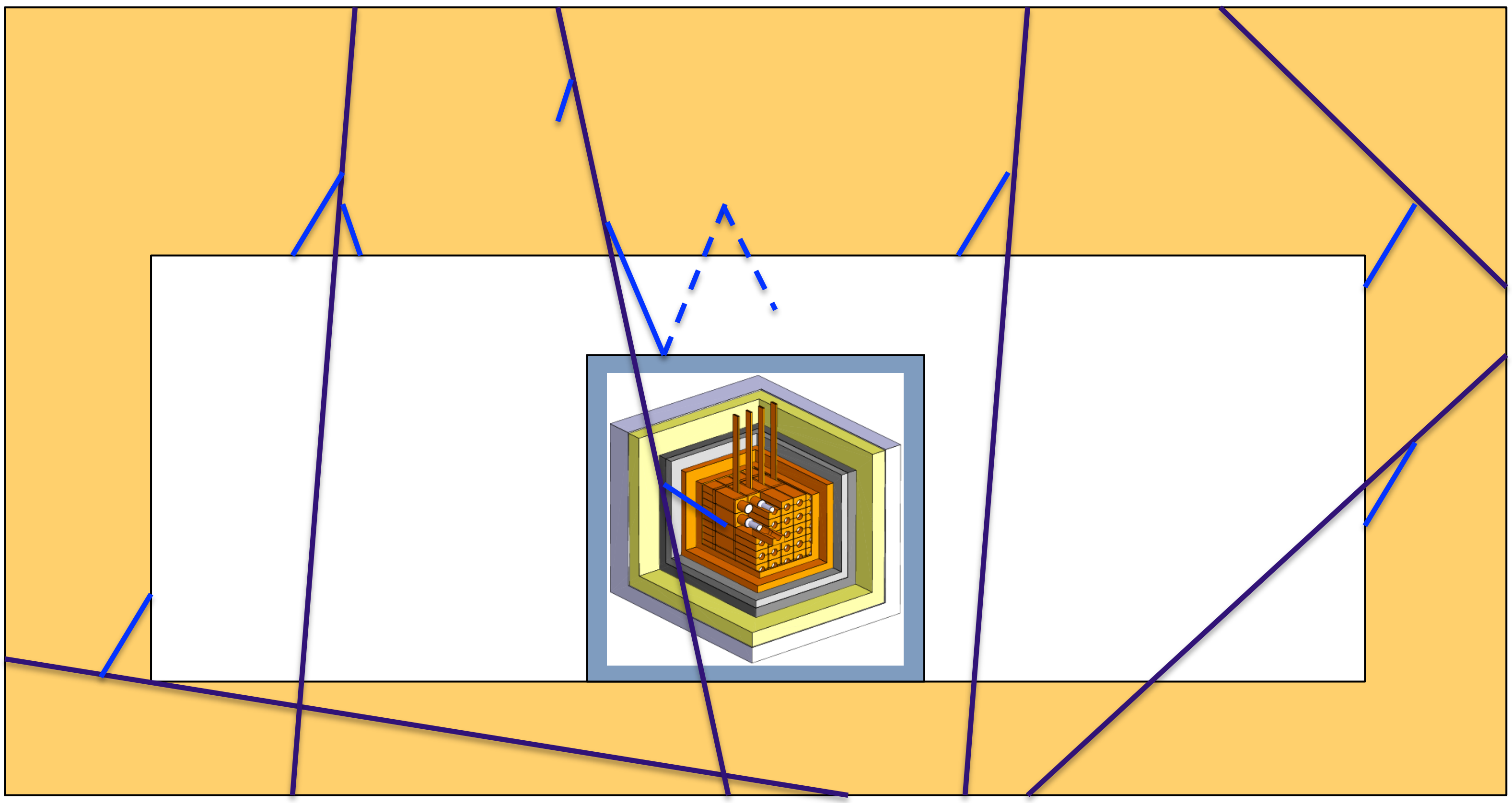
LVD data (LVD coordinate system (black) (Hall A) vs MUSIC/MUSUN simulations (red).
MUSIC: Antonioli et al. Astropart. Phys. 7 (1997) 357; Kudryavtsev, Comp. Phys. Comm., 180 (2009) 339.
MUSUN: Kudryavtsev, Comp. Phys. Comm., 180 (2009) 339.



- Data from LVD Collaboration, PRD 58 (1998) 092005; PRD 60 (1999) 112001.
- Graph from: Kudryavtsev et al. EPJA (2008) 1.

Neutron production and transport

- The box encompasses the lab and 5-7 m of rock around.
- All particles produced are transported with GEANT4.
- All hits in the crystals are recorded.



Comparison with other simulations

- Wulandari et al. arXiv: 0401032 [hep-ex]; Persiani, PhD Thesis, University of Bologna (2011).
- Agreement within 30% although different geometries give slightly different results.

Incl. backscattering

Different cavern geometries give different values of flux

	Cavern	> 0 MeV	> 1 MeV	> 1 MeV (*)
This study	(1)	10	4.0	5.0
This study	(2)	7.6	5.8	10
Wulandari et al.	(2)	No data	4.3	8.5
Persiani	(3)	7.2	2.7	No data

TABLE I. A comparison of Φ_n^μ (in units of 10^{-10} cm^{-2} s^{-1}) predicted by this study, Wulandari et al. [20] and Persiani [21]. Cavern geometries (1) - (3) indicate the dimensions used: (1) in this study; (2) by Wulandari et al. and (3) by Persiani. The range of considered neutron energies is shown, and '(*)' indicates that back-scattered neutrons are included.

Flux calculations are consistent within 30%

Neutron spectra

- High-Z shielding (lead, copper) leads to the enhancement of the neutron flux (no surprise).
- Simulations show that the flux increases by a factor of 2-40 depending on the energy (0.1-100 MeV).
- Is this enough to explain the modulation signal?

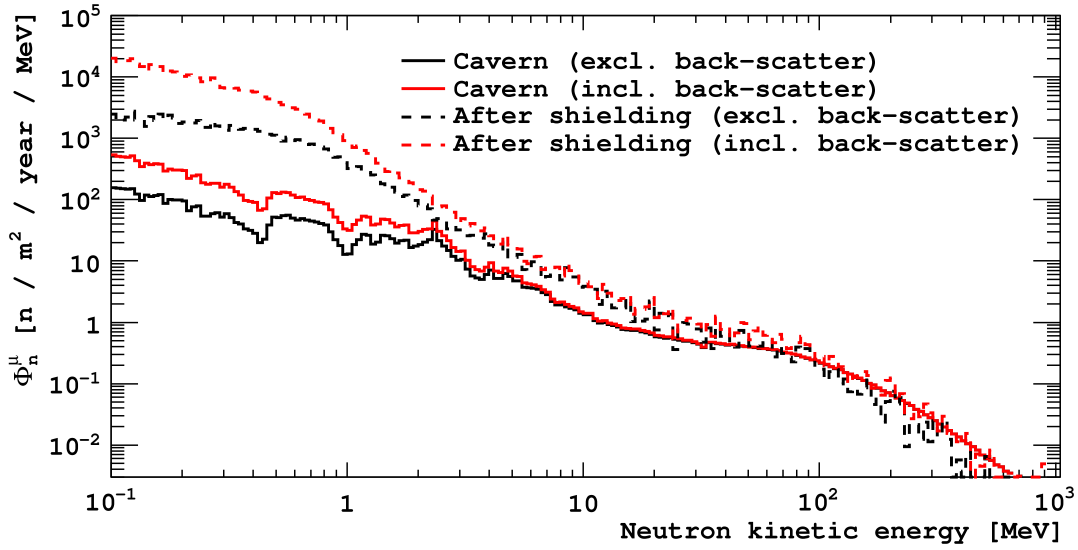
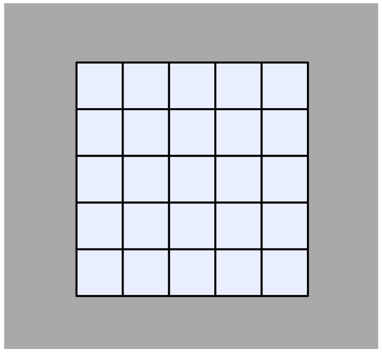
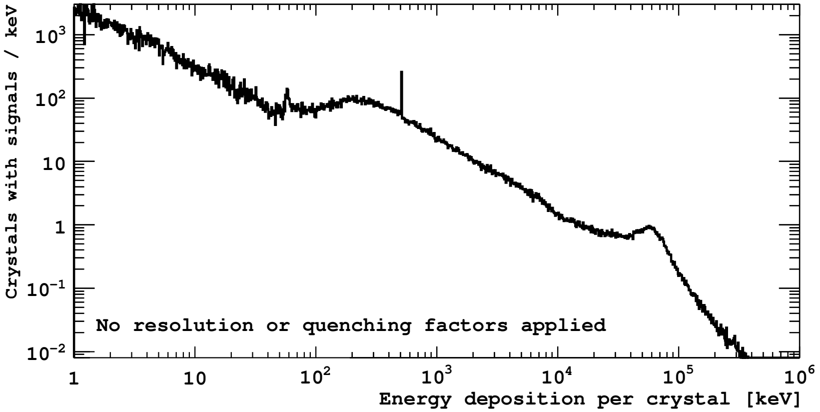


FIG. 1. The distribution of Φ_n^μ as a function of neutron energy for neutrons entering the cavern in which DAMA/LIBRA is situated (solid lines) and entering the DAMA/LIBRA detector modules after all shielding is traversed (dashed line). The distributions excluding and including back-scattered neutrons are shown in black and red respectively.

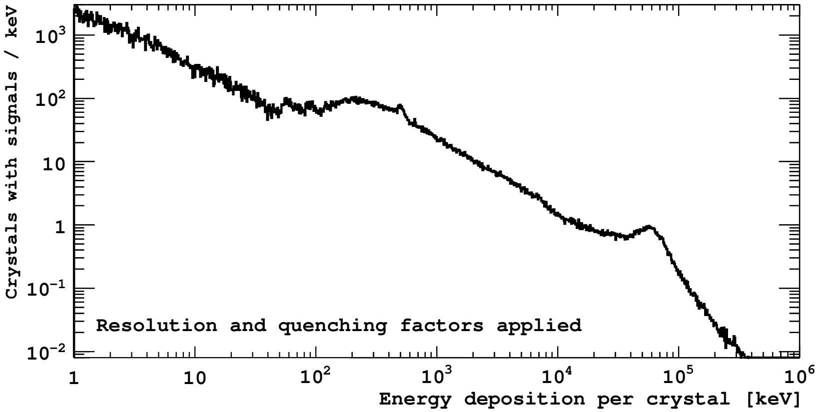
Event analysis

- Each crystal is treated independently.
- Event ID, energy deposition and crystal number are recorded, as well as the info about the initial muon.
- Energy resolution and quenching of scintillation light from nuclear recoils is taken into account.





(a)

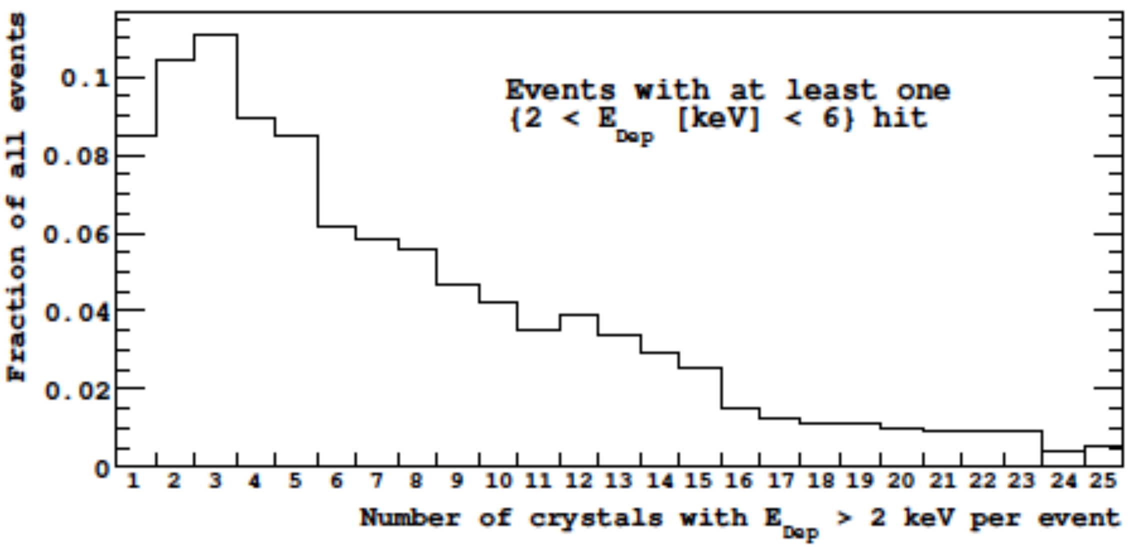


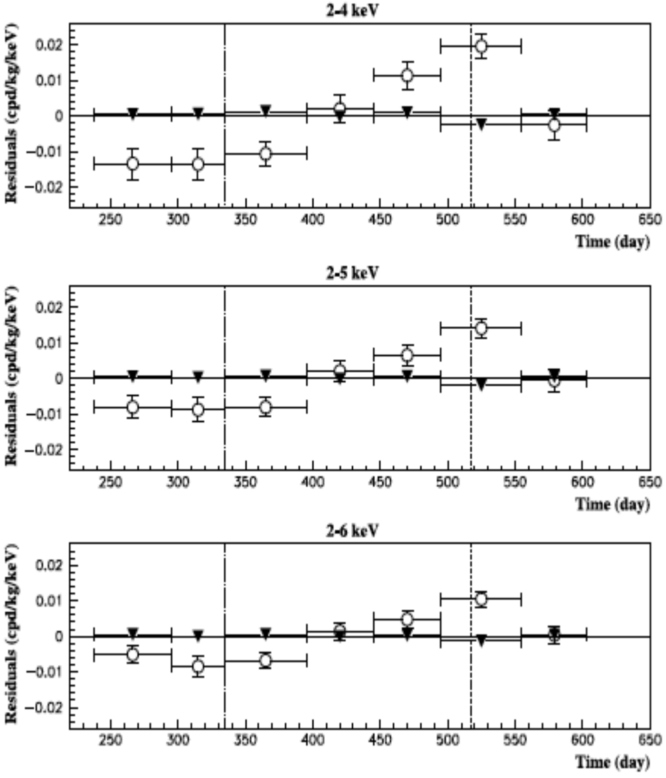
(b)

Figure 3: The energy spectrum of all crystals with energy depositions with (a) no correction factors applied and (b) resolution and nuclear recoil quenching factors applied. The equivalent of ten years of muon-induced data is presented.

Hit multiplicity

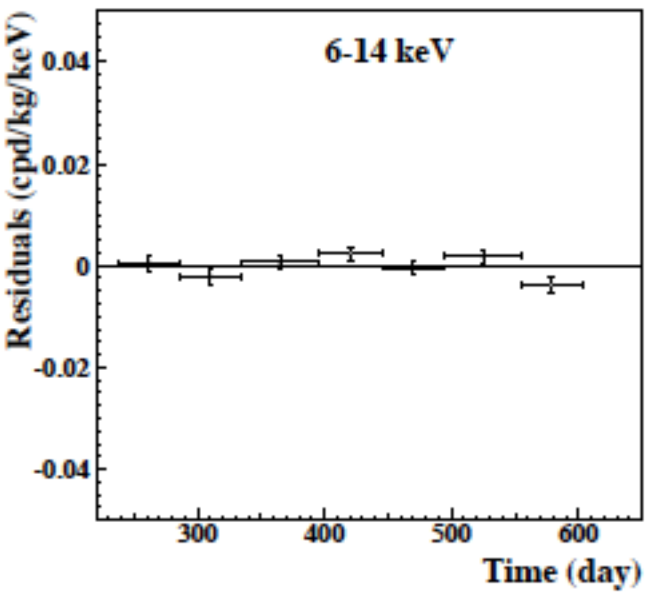
- Distribution of hit multiplicity for events with energy depositions above 2 keV. At least one hit is at 2 – 6 keV.
- Only 8% of events are single hit events.
- Definitely contradicts DAMA data.





Event energy spectrum

- Select only single hit events.
- Non-negligible contribution at >6 keV.
- Contradicts DAMA data.



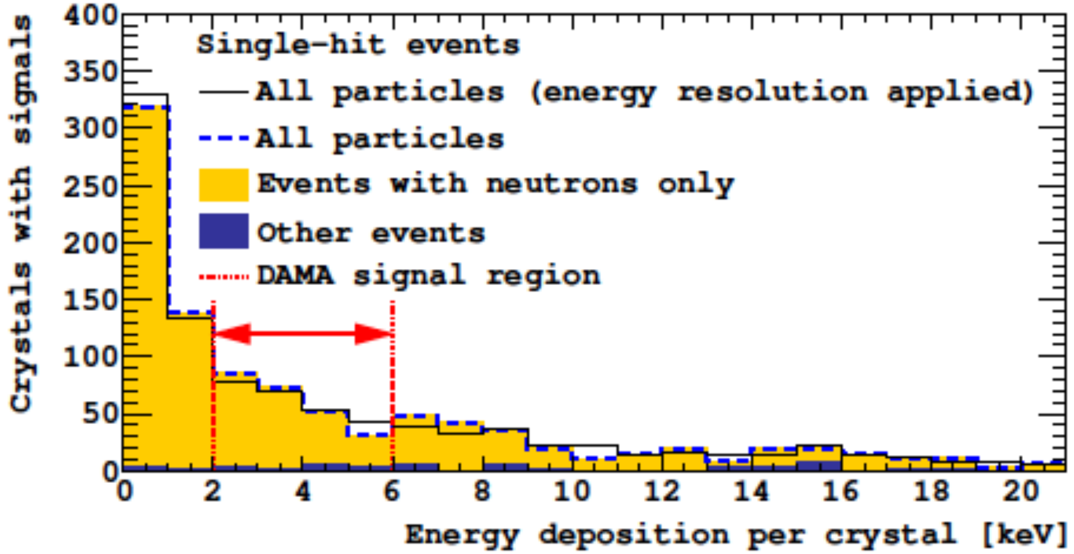


FIG. 4. The distribution of the total energy deposition in *single-hit* events. The blue dashed line and the black solid line show the sum of all energy depositions before and after energy resolution is considered, respectively. The stacked colored bars indicate the relative fraction of all events (before energy resolution is considered) attributed to events in which only neutrons deposit energy (yellow) and other events (blue). The equivalent of twenty years of muon-induced data is presented.

Conclusions so far

- Single-hit event rate (averaged over 2-6 keV): 3.5×10^{-5} counts/kg/day/keV, this is the TOTAL (AVERAGE) rate - 0.3% of the reported MODULATED AMPLITUDE.
- Muon-induced neutrons cannot explain the DAMA data.
- In agreement with all our previous estimates and DAMA calculations – no surprise.
- Any other muon-induced background/noise?

Energy spectrum

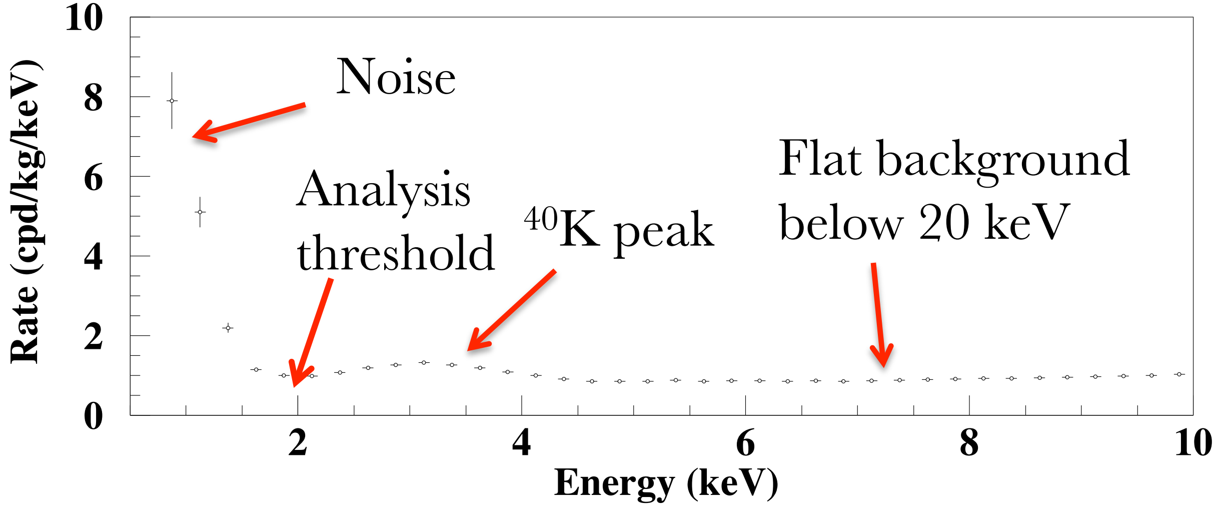
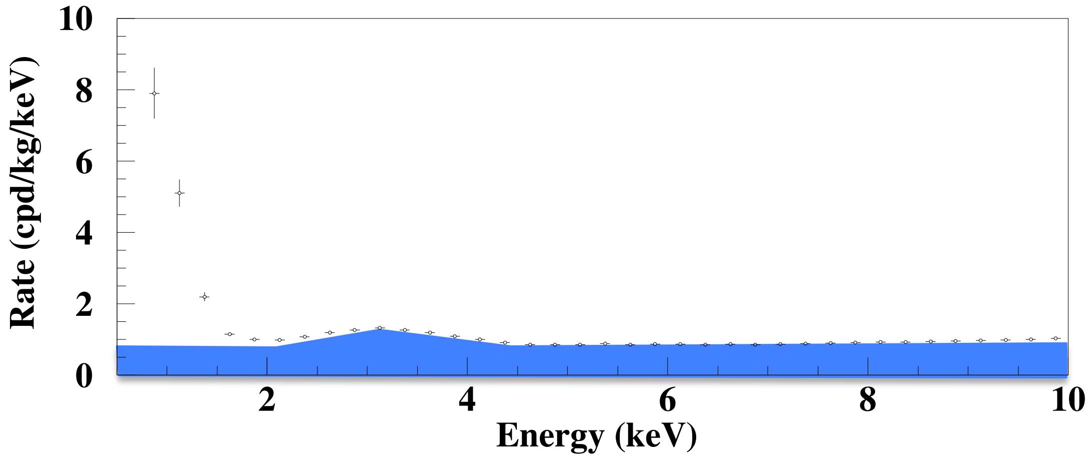


Figure 1: Cumulative low-energy distribution of the *single-hit* scintillation events (that is each detector has all the others as veto), as measured by the DAMA/LIBRA detectors in an exposure of 0.53 ton × yr. The energy threshold of the experiment is 2 keV and corrections for efficiencies are already applied.

- Bernabei et al. EPJC 56 (2008) 333.

Other options?

- Let's look at the energy spectrum.
- Measured energy spectrum consists of two components: background (whatever this background is) and the signal (whatever this signal is).
- Major background is known to come from radioactivity. Background from radioactivity (Compton electrons if external) is known to be flat below ~20 keV except some obvious lines (such as a peak at ~3 keV from ^{40}K).

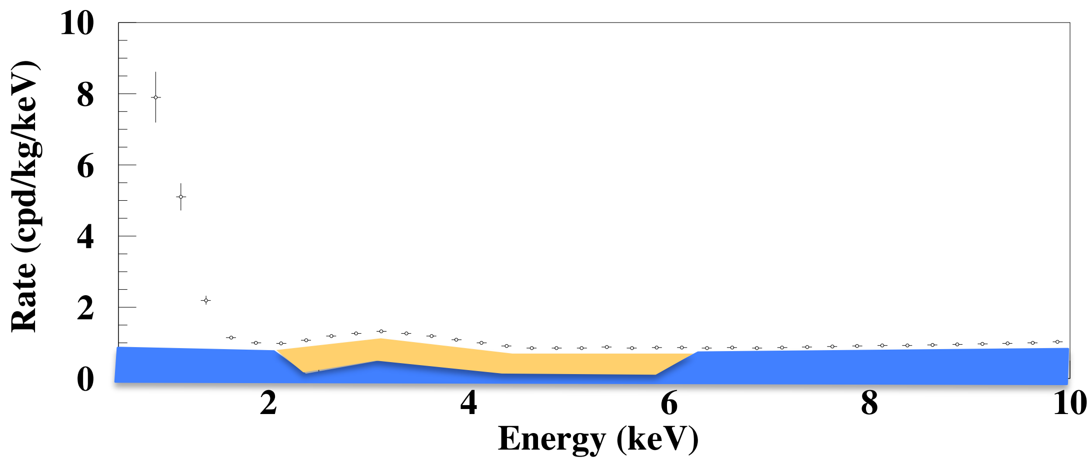


Muon-induced events

- Assume the signal has a 'flat' energy spectrum with the average modulation amplitude at 2 – 6 keV equal to 0.0112 counts/kg/day/keV (from DAMA).
- The measured muon flux modulation at LNGS (Borexino, LVD) is 1.4%, therefore (assuming this is muon-induced signal) the total (average) rate of muon-induced backgrounds should be:

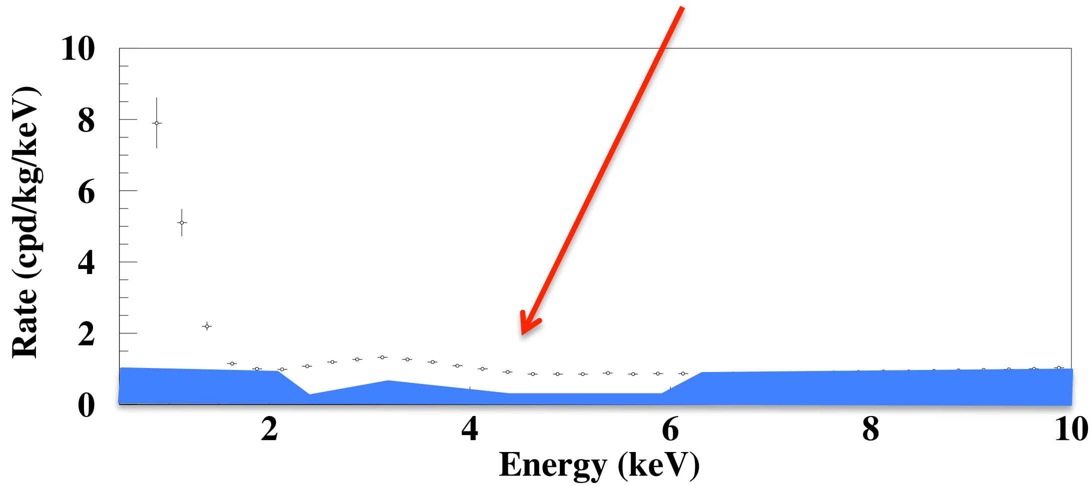
$$0.0112/0.014 \approx 0.8 \text{ counts / day / kg / keV.}$$

This accounts for almost all measured rate at this range!



Consequences for background model

- Radioactivity model does not predict such a dip.



The first energy bin 2-3 keV. DAMA modulation amplitude is:

$$0.0190 \ \ \text{counts} \ / \ \text{day} \ / \ \text{kg} \ / \ \text{keV}$$

Total (average) rate is then: $$\frac{0.0190}{0.014} = 1.4 \ \text{counts/kg/day/keV}$$

This is bigger than the measured rate!!!

Background from radioactivity

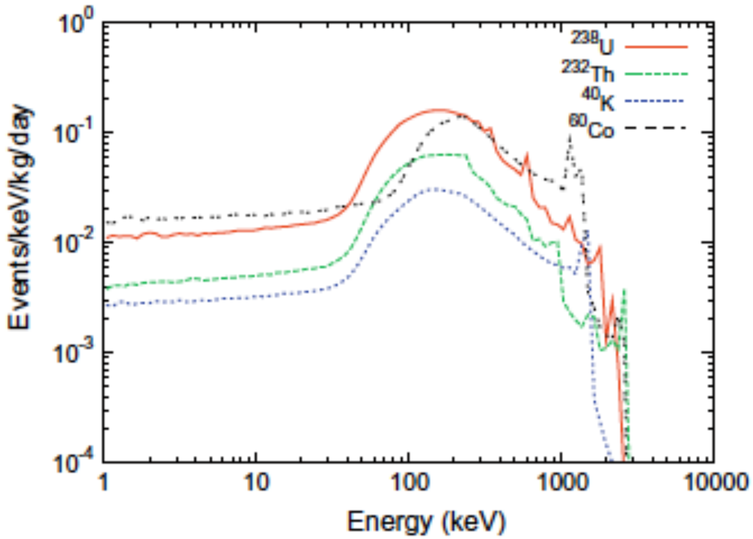


Fig. 1. Spectra of energy depositions from electron recoils in the NaI crystals from ^{238}U, ^{232}Th and ^{40}K decay chains in secular equilibrium. The source of radiation was the PMT envelopes (100 g each) attached to the light guides connected to the crystals. Also shown is the spectrum of ^{60}Co events from Cu. Only events in which a single crystal was hit, are included. See text for details.

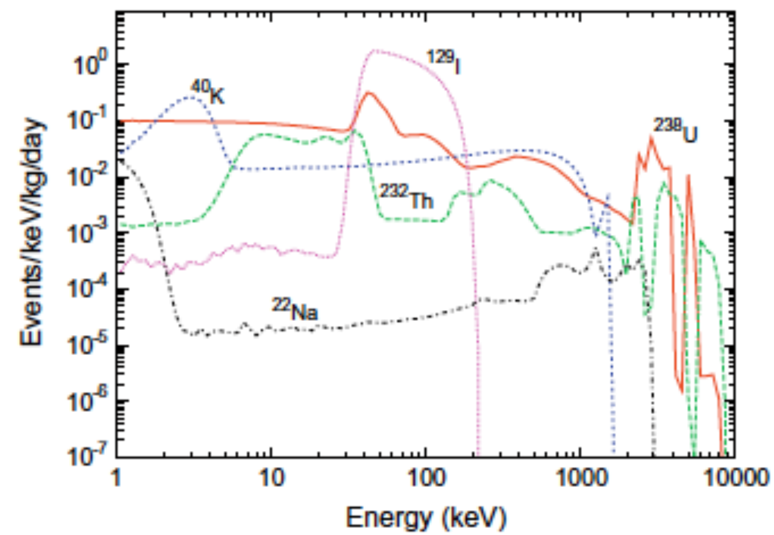


Fig. 2. Spectra of energy depositions in the NaI crystals from ^{238}U (solid curve), ^{232}Th (dashed curve) and ^{40}K (dotted curve) decay chains in secular equilibrium. The decays of ^{129}I and ^{22}Na are also shown. Only events in which a single crystal was hit, are included. The decays of isotopes occurred within the sensitive volume of the crystals. Spectra were normalised using the typical concentrations reported in Ref. [4].

- External background from Compton electrons (left) assumed to be from PMTs.
- Internal background in NaI crystals (right).
- Plots from: Kudryavtsev, Robinson and Spooner. ApP, 33 (2010) 91.

Background from radioactivity

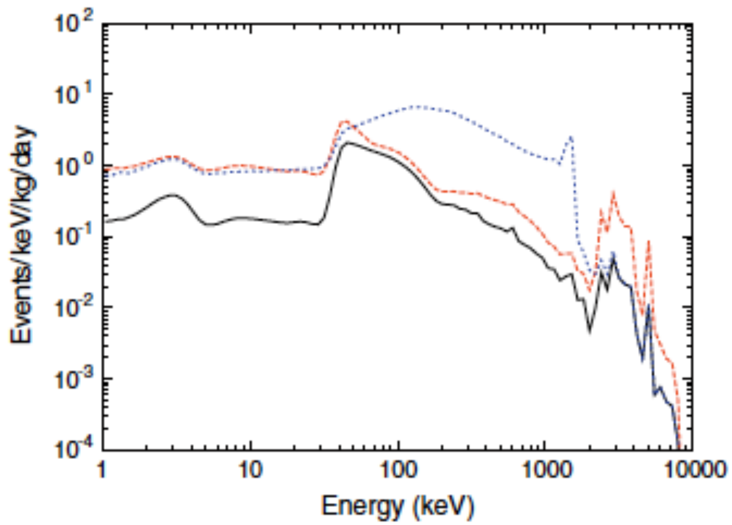


Fig. 4. Combined spectra of energy depositions in the NaI crystals from radioactive background originating in the crystals and in the PMTs. Solid curve: PMTs – 30 ppb of ^{238}U, 30 ppb of ^{232}Th, 60 ppm of natural potassium in 100 g of the PMT envelope; NaI – 5 ppt of ^{238}U, 5 ppt of ^{232}Th, 10 ppb of natural potassium, 0.2 ppt of ^{129}I and 6.46×10^{-14} ppb of ^{22}Na. Dotted curve: PMTs – U/Th – the same as for solid curve, 1.2% of K; NaI – U/Th – the same as for solid curve, 20 ppt of K. Dashed curve: PMTs – the same as for solid curve; NaI – 20 ppb of natural potassium, 40 ppt of ^{238}U, 20 ppt of ^{232}Th, other isotopes – the same as for solid curve.

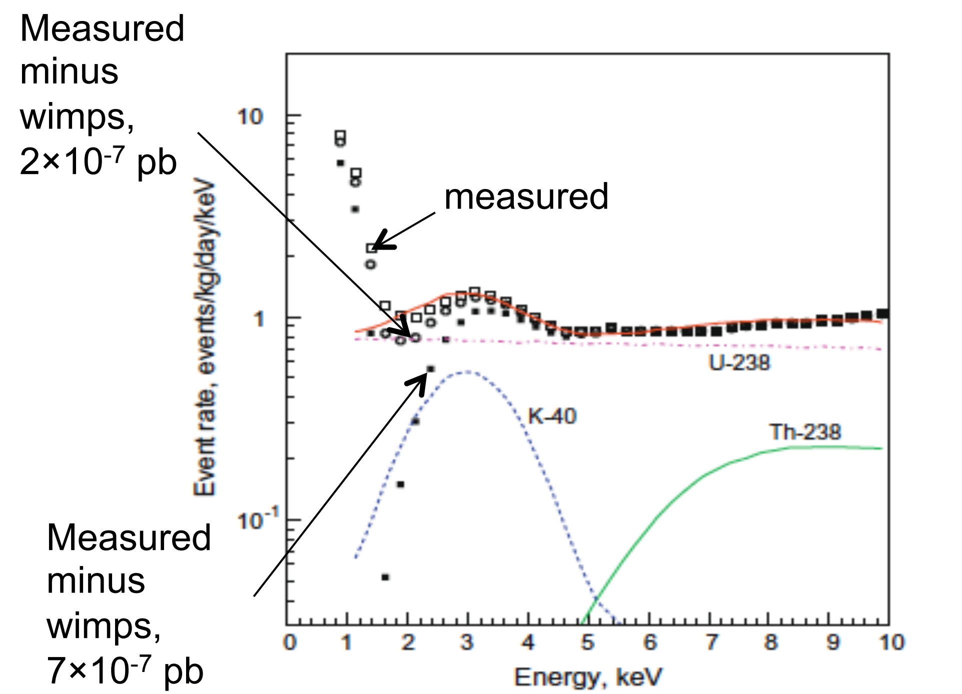


Fig. 5. Simulated spectra of energy depositions in the NaI crystals from internal sources at low energies assuming 'optimised' concentrations of isotopes in the crystals (solid curve): 40 ppt of ^{238}U (pink dashed-dotted curve), 20 ppt of ^{232}Th (green solid curve), 20 ppb of natural potassium (blue dashed curve), 0.2 ppt of ^{129}I (not seen on the graph). The measured spectrum of DAMA/LIBRA without signal subtraction (open squares) and with signal subtraction are also shown. For the latter case we assumed a signal from 60 GeV mass WIMPs with $\sigma_{SI} = 7 \times 10^{-6}$ pb (filled squares) and $\sigma_{SI} = 2 \times 10^{-6}$ pb (open circles) (see text for details).

- Combined spectra (internal + external) with various normalisations (left).
- Measured rate with signal subtracted (right). This must be equal to the radioactive background rate. Signal is assumed to be from WIMPs (no link to the measured modulation amplitude).

Requirements for any model

- The total (average) rate of the signal must be very small compared to the DAMA event rate.
- The modulation amplitude of the signal must not be much smaller than the average rate of this signal.
- Any effect not satisfying the latter two criteria implies that there is a new model of suppressed radioactivity in the region 2-6 keV, that does not apply above 6 keV.
- The modulation must only affect single-hit events, whilst disregarding multiple-hit events.
- The explanation must simultaneously predict the phase and the period of the modulation.
- An explanation which incorporates muon-induced backgrounds cannot satisfy these criteria.
- Any other model? Your call, but do not forget about radioactivity. The model should incorporate radioactivity.