Statistical test of noise and harmony in Dark Matter modulation signals

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one species - three signals?

- **DAMA**: 250kg of scintillating NaI crystals, running since 1995, exposure in excess of 1 ton x year, no discrimination

- **CoGeNT**: 440 gram Ge crystal, 442 live days; ionization only, no discrimination

- **CRESST**: scintillation and phonons; 730 kg days, multi-target
some conclusions first

- cosmic muons as origin for DAMA modulation strongly disfavoured
  - different in phase
  - different in correlation
  - possibly different in power
  - possibly different in amplitude

- similar conclusions hold for CoGeNT modulation

- more on DAMA vs the muon hypothesis tomorrow

  => talk by Kfir Blum

  => talk by Pierluigi Belli
signal modulation in direct detection

\[ \frac{dR}{dE_R} = N_T n_{DM} \int_{v \geq v_{min}} d^3v \, v \, f_{LAB}(v) \frac{d\sigma}{dE_R} \]

\[ f_{GAL}(v_{obs} + v) \]

see e.g. [Druiker et al, 1986; Freese et al, 1988; Savage et al, 2009]
signal modulation in direct detection

\[ \frac{dR}{dE_R} = N_T n_{DM} \int_{v \geq v_{min}} d^3 v \, v f_{LAB}(v) \frac{d\sigma}{dE_R} \quad [\text{cpd/kg/keV}] \]

\[ f_{\text{GAL}}(v_{\text{obs}} + v) \]

\[ v_{\text{obs}} = v_\odot + V_\odot [\varepsilon_1 \cos \omega (t - t_1) + \varepsilon_2 \sin \omega (t - t_1)] \]

\[ |v_{\text{obs}}| = |v_\odot| + \frac{1}{2} V_\odot \cos \omega (t - t_0) \]

\[ t_0 \simeq 152 \text{ days} \quad (\text{June 2nd}) \]

see e.g. [Druiker et al, 1986; Freese et al, 1988; Savage et al, 2009]
signal modulation in direct detection

\[
\frac{dR(t)}{dE_R} \propto \int_{v_{min}}^{\infty} \frac{f(v)}{v} dv \approx c_0(v_{min}) + c_1(v_{min}) \cos [\omega(t - t_0)]
\]

\[v_{min} = \frac{1}{\sqrt{2m_NE_R}} \left( \frac{m_NE_R}{\mu N\chi} + \delta \right)\]

\[t_0 \approx 152 \text{ days} \quad \text{(June 2nd)}\]

[using \(f(v)\) from Lisanti et al, 2010]
DAMA/LIBRA 0.87 ton × yr

- scintillation from NaI-crystals
- 8σ+ modulation
- phase consistent as expected from WIMPs
  \[ t_0 \simeq 2 \text{ June} \]
  \[ = 152.5 \text{ days} \]

[Bernabei et al. 2010]
Muon Flux underground

--- modulates too ---

- underground flux sourced mainly by primary meson decays (pions, kaons,...) => muons need to be TeV-like to reach underground

- competition between secondary meson interactions vs. decay depends on air-density

=> muon flux correlated with temperature

\[
\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{\text{eff}}}{T_{\text{eff}}} \quad \quad T_{\text{eff}} = \int_0^\infty dX T(X) W(X)
\]

- flux peaks in Summer (on northern hemisphere)
Muon Flux underground

- many measurements available, correlation with $T_{\text{eff}}$ firmly established

- LNGS: Macro, LVD, Borexino (DAMA location)
- Soudan Mine: MINOS (CoGeNT location)
- South Pole: Icecube

[Borexino 2011]
LVD and DAMA

- Large Volume liquid scintillator Detector (LVD) reports underground muon-flux at LNGS => temporal overlap with DAMA data

[Selvi, 2009]
LVD and DAMA

LVD and DAMA

(digitized from LVD data)
LVD and DAMA

percent residuals

days since Jan 1, 2001

2–4 keV
muons

2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-400
-600
0
-2
-4
-6
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
LVD and DAMA

- recent renewed interest in muons as DAMA background, see e.g. [Ralston, 2010], [Nygren, 2011], [Blum, 2011]

- DAMA’s response on arXiv this Monday.

see also tomorrow’s talks
LVD and DAMA

• muons can either directly hit the detector or indirectly, by spallation of nuclei which leads to neutron flux

=> guaranteed source of background

• in this talk we will base our analysis exclusively on the time-series of events in both data sets

=> we are ignorant to how the signal formation process concretely happens

=> but if we can make firm statements already it means that this approach is very model-independent and thus conservative
detecting periodicities

- evenly spaced data $d_i = d(t_i)$ discrete FT

$$P(\omega) \propto \left| \sum_i d_i \exp(-i \omega t_i) \right|^2 = \left[ \left( \sum_i d_i \cos(\omega t_i) \right)^2 + \left( \sum_i d_i \sin(\omega t_i) \right)^2 \right]$$

- unevenly spaced data: Lomb-Scargle Periodogram

$$\text{LS}(\omega) = \frac{1}{2} \left\{ \frac{1}{\sum_i \cos^2(\omega \tilde{t}_i)} \left[ \sum_i d_i \cos(\omega \tilde{t}_i) \right]^2 + \frac{1}{\sum_i \sin^2(\omega \tilde{t}_i)} \left[ \sum_i d_i \sin(\omega \tilde{t}_i) \right]^2 \right\}$$

  - invariant to shifts in time origin
  - if $d_i$ is pure noise (with unit variance)

$$\tilde{t}_i \equiv t_i - \tau$$

$$\Pr(P > p) = e^{-p}$$
detecting periodicities

DAMA/LIBRA

LVD muons

no power on timescales > 1 yr

BUT

adopting DAMA’s procedure of subtracting baseline on each cycle suppresses power on timescales longer than 1 yr (see also Blum, 2011)
detecting periodicities

DAMA/LIBRA, 2012

LS of baselines
O(10) data points, no significant power!
detecting periodicities

DAMA/LIBRA, 2012

LVD muons

LS of baselines
O(10) data points, no significant power!

LS of muon baselines
O(10) data points
no significant power neither!
detecting periodicities

DAMA/LIBRA, 2012

• with a small dataset it is hard to achieve statistical significance

\[ P(\omega) = \frac{LS(\omega)}{\sigma^2} \]

• power spectrum of baselines alone does **NOT** convincingly show that there is indeed no long term modulation in DAMA

=> DAMA should provide baseline rates
The phase of DAMA vs the “phase” of LVD

- interpret data as sinusoidal variations
- phase of DAMA/LIBRA incompatible with muons

@ \omega = 2\pi/1\text{yr}:

\[ t_0(\text{DAMA}) = (131 \pm 13) \text{ days} \]
\[ t_0(\text{LVD}) = (187 \pm 2) \text{ days} \]
The phase of DAMA vs the “phase” of LVD

- two studies suggest that phase can potentially in agreement

1. Selvi for LVD collaboration finds

\[ t_0(\text{LVD})_{\text{LVD-collab}} = (185 \pm 15) \text{ days} \]
\[ \chi^2 / \text{dof} = 577 / 362 \]

adopting this procedure we find

\[ t_0(\text{LVD}) = (186 \pm 2) \text{ days} \]

[Selvi for LVD, 2009]
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suspecting that Selvi used reduced \( \chi^2 \) for construction of confidence region \( \Rightarrow \) confidence interval overestimated
The phase of DAMA vs the “phase” of LVD

- Two studies suggest that phase can potentially be in agreement.

2. Blum, 2011: Direct hits by muons induce a produce too large spread in signal, but

\[ s_i = \frac{yN_{\mu,i}}{M \Delta E \epsilon_i t_i} \]  

\[ \langle N_{\mu,i} \rangle = A_{\text{eff}} I_{\mu,i} \epsilon_i t_i \]

\( y \) = signal counts / muon

\( \langle \rangle \) mean of Poisson distributed \( N_{\mu,i} \)

\( \Rightarrow \) used to generate mock data
The phase of DAMA vs the “phase” of LVD

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The phase of DAMA vs the “phase” of LVD

=> redo Blum’s analysis:

(one representative out of a sample of 10k)
The phase of DAMA vs the “phase” of LVD

$t_0$ from Jan 1, 2003

$t_0$ from Jan 1, 1995

since period floats in fit => $t_0$ looses its absolute meaning!
lessons learned

1. distribution in $t_0$ depends on time origin

   $=>$ frequentist fits to mock-data do not define a good test statistic

2. we need better ways to quantify agreement/disagreement of DAMA with the Muon hypothesis

   $=>$ preferentially without reliance on sinusoidal function

   $=>$ look at the correlation coefficient $r \in [-1, 1]$

$$r_{XY} = \frac{\sum_i (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_i (X_i - \bar{X})^2} \sqrt{\sum_i (Y_i - \bar{Y})^2}}$$
correlation study

Q: how significant is the difference between these two?
correlation study

correlation

\( r(\text{muon, mock} = \text{DAMA}) \)

\[ Z = 0.47 \]

Mean = 0.95
S.D. = 0.13

Model excluded \( \gtrsim 99\% \) C.L.
- 442 kg live-days
- Ge-target, ionization
- potential exponential rise toward low energies
- cosmogenic peaks
- modulation too

[Aalseth et al, 2011]
• muon measurements at CoGeNT site (Soudan Mine, MN) from MINOS experiment exist---but only for earlier time period

[Adamson et al, 2010]
muon measurements at CoGeNT site (Soudan Mine, MN) from MINOS experiment exist---but only for earlier time period

=> use available climate data to predict muon flux!

[Adamson et al, 2010]
vs.

CoGeNT vs. MINOS published days since Dec 3, 2009

$T_{\text{eff}} (K)$

MINOS published  CoGeNT

days since Dec 3, 2009

$146 \text{ kg-day}$

$0.5-0.9 \text{ keV}_{\nu}$

$0.5-3.0 \text{ keV}_{\nu}$
CoGeNT correlation study

no correlation with high significance!

=> CoGeNT’s modulation not muon-induced
higher harmonics in DM modulation

\[
\frac{dR(t)}{dE_R} \propto \int_{v_{min}}^{\infty} \frac{f(v)}{v} dv \simeq c_0(v_{min}) + c_1(v_{min}) \cos [\omega(t - t_0)]
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v_{min} = \frac{1}{\sqrt{2m_N E_R}} \left( \frac{m_N E_R}{\mu_N \chi} + \delta \right)
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[using \( f(v) \) from Lisanti et al, 2010]
higher harmonics in DM modulation

\[
\frac{dR(t)}{dE_R} \propto \int_{v_{min}}^{\infty} \frac{f(v)}{v} dv = \sum_{n=0,1,...} c_n(v_{min}) \cos [n\omega(t - t_n)]
\]

\[
v_{min} = \frac{1}{\sqrt{2m_N E_R}} \left( \frac{m_N E_R}{\mu_N \chi} + \delta \right)
\]

- biannual mode
- triannual mode
- ...

[using \(f(v)\) from Lisanti et al, 2010]
can be thought of as an expansion in $V_\oplus/v_\odot$

once ellipticity of earth’s orbit is included

=>$phase shifts between different harmonics

=>$ new signature

detection is likely to require large exposure
higher harmonics in DM modulation

- can be thought of as an expansion in $V_\oplus/v_\odot$
- once ellipticity of earth’s orbit is included

=> phase shifts between different harmonics

=> new signature

- detection is likely to require large exposure

**DAMA/LIBRA:**

$P_{\text{obs}}(\text{biann}) = 0.57$

$P_{\text{obs}}(\text{triann}) = 1.8$
conclusions

- cosmic muons as origin for DAMA modulation strongly disfavoured
  - different in phase
  - different in correlation
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- similar conclusions hold for CoGeNT modulation

- higher harmonics in the modulation signal may provide additional handles in discriminating signal from background