DAMA and CoGeNT - muon background and higher harmonics

Josef Pradler
Perimeter Institute

with Spencer Chang and Itay Yavin


Moriond EW, March 5, 2012
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
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
“take home message”

- 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

- there is more than “one modulation”
signal modulation in direct detection

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

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

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

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

\[
\downarrow
\]

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

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

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

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

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

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

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

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

[annual modulation]

[using \(f(v)\) from Lisanti et al, 2010]
\[
\sim 3\% \\
\]

DAMA/LIBRA 0.87 ton \times yr

\begin{itemize}
\item scintillation from NaI-crystals
\item 8\sigma+ modulation
\item phase consistent as expected from WIMPs
\end{itemize}

\[ t_0 \approx 2 \text{ June} \]
\[ = 152.5 \text{ days} \]

[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

\[
\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{\text{eff}}}{T_{\text{eff}}}
\]

\[
T_{\text{eff}} = \int_0^\infty dX T(X)W(X)
\]

- 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

\[ \bar{I}_\mu \sim 30/\text{day/m}^2 \] @ DAMA site [Selvi, 2009]
LVD and DAMA

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

- very recent response by DAMA [Bernabei, 2012]
LVD and DAMA

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

very recent response by DAMA [Bernabei, 2012]
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

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

- invariant to shifts in time origin

- if $d_i$ is pure noise (with unit variance)

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

99% (one freq)

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

\[ P(\omega) = LS(\omega)/\sigma^2 \]

- 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

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

- two studies suggest that phase can potentially in agreement

1. Selvi for LVD collaboration finds

\[ t_0(LVD)_{LVD\text{-collab}} = (185 \pm 15) \text{ days} \]

\[ \chi^2/dof = 577/362 \]

adopting this procedure we find

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

suspecting that Selvi used reduced \( \chi^2 \) for construction of confidence region => confidence interval overestimated

[Selvi for LVD, 2009]
The phase of DAMA vs the “phase” of LVD

- two studies suggest that phase can potentially in agreement

2. Blum, 2011:
nice observation that direct hits by muons induce produce too large spread in signal, BUT

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

\[y = \text{signal counts / muon}\]

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

\[\Rightarrow \text{used to generate DAMA mock data}\]
The phase of DAMA vs the “phase” of LVD

- two studies suggest that phase can potentially in agreement

2. Blum, 2011:
   nice observation that direct hits by muons induce produce too large spread in signal, BUT

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

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

=> used to generate DAMA mock data
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

Mean = 187
S.D. = 27

$t_0$ from Jan 1, 1995

VS.

since period floats in fit => $t_0$ loses 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

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

Q: how significant is the difference between these two?

Correlation coefficient $r$
correlation study

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

correlation
$r(muon,mock)$

Model excluded $\gtrsim 99\% \text{ C.L.}$
- 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]
CoGeNT vs. MINOS published days since Dec 3, 2009

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

MINOS published

CoGeNT

days since Dec 3, 2009

$146 \text{ kg-day}$

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

$0.5-3.0 \text{ keV}_{\nu}$

VS.
CoGeNT correlation study

no correlation with high significance!

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

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

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

[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]
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
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

$\Rightarrow$ phase shifts between different harmonics

$\Rightarrow$ new signature

- detection is likely to require large exposure

DAMA/LIBRA:

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

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

• 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

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