On the DM annual modulation signal

(in collaboration with Thomas Schwetz and Jure Zupan)

[JCAP03(2012)005, 1112.1627 [hep-ph]]

J. Herrero-García

IFIC, Universidad de Valencia - CSIC

Invisibles ITN pre-meeting

Madrid, March 2012

Introduction and goal

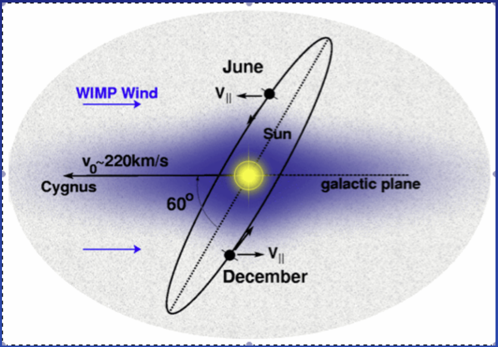
- A very distinctive signature of DM is its annual modulation.
- DAMA reports a significance of 8.9σ and CoGeNT of 2.8σ.
- Typical ratio modulation over constant rate:

$\longrightarrow \sim 0.02$ (DAMA), $\sim 0.1 - 0.3$ (CoGENT).

- Assuming the observed modulated signal is DM and with very mild assumptions about the halo, we establish a consistency check between the *modulated* rate and the *constant* rate, that must be fulfilled within an experiment.
- We also treat the case of an unknown background that contributes *only* to the constant rate (*NOT modulated*).

Annual modulation

- Depending on the time of the year, we should *receive* more or less DM flux.



- Typical velocities involved:

$$\bar{v} \simeq 220\,\text{km/s},\ v_S \simeq 220\,\text{km/s},\ v_e \simeq 30\,\text{km/s},\ v_{esc} \simeq 550\,\text{km/s}.$$

Direct detection: event rate

- Differential event rate (♯ counts/ keV/ kg/ day):

$$R(E_r, t) = \frac{\rho_\chi}{m_\chi m_A} \int_{v_m} d^3v \, \frac{d\sigma_\chi}{dE_r} \, v \, f_{det}(\vec{v}, t)$$

where $v_m = \sqrt{m_A E_r / (2\mu_{\chi A}^2)}$ and the velocity distribution fulfills:

$$f_{det}(\vec{v}, t) \geq 0 \;\; \text{and} \;\; \int d^3v \, f_{det}(\vec{v}, t) = 1$$

- For SI we have that

$$R(E_r, t) \equiv C \, F^2(E_r) \, \eta(v_m, t) \quad \text{with} \quad C \equiv \frac{\rho_\chi \sigma_A^0}{2 m_\chi \mu_{\chi A}^2}$$

and with the velocity integral defined by:

$$\eta(v_m, t) \equiv \int_{v_m} d^3v \, \frac{f_{det}(\vec{v}, t)}{v}$$

Relating the modulation with the rate

- For typical recoil energies $E_r \sim 10$ KeV, and for Na, I, Ge, $v_m \gg v_e$, so we expand $\eta(v_m, t)$ to first order in $v_e/v \ll 1$.
- So the total rate can be divided into a time-ind. and a time-dep. part:

$$R(E_r, t) \equiv \overline{R}(E_r) + \delta R(E_r, t) \equiv$$

$$\equiv C\, F^2(E_r)\, \eta(v_m, t) \equiv$$

$$\equiv C\, F^2(E_r)\ [\bar{\eta}(v_m) + A_\eta(v_m) \cos 2\pi(t - t_0)]$$

- We derive a relation between A_η and $\bar{\eta}$, and we translate it into observable quantities A_R and $\overline{R}$, with:

$$\overline{R} \equiv CF^2(E_r)\bar{\eta}(v_m) \text{ and } A_R \equiv CF^2(E_r)A_\eta$$

The general bound

1. Smooth halo: spikes in $v < 30\,\mathrm{km/s}$ may not be covered.
2. Only time dependence comes from $v_e(t)$. No explicit time dependence in f_{Sun} (no change on time-scales of months).
3. DM halo spatially constant at scale Sun-Earth.

$$A_\eta(v_m) \leqslant v_e \left[-\frac{d\bar{\eta}}{dv_m} + \frac{\bar{\eta}(v_m)}{v_m} - \int_{v_m} dv \frac{\bar{\eta}(v)}{v^2} \right]$$

- It allows an arbitrary halo structure, including several streams from different directions.

Symmetric bounds

1. There is some preferred constant direction $\hat{v}_{HALO}$ (independent of v_m) governing the shape of the DM velocity distribution in the Sun's rest frame.

$$\int_{vm1}^{vm2} dv_m \, A_\eta(v_m) \leqslant v_e \left[\bar{\eta}(v_{m1}) - v_{m1} \int_{v_{m1}} dv \, \frac{\bar{\eta}(v)}{v^2} \right]$$

- It is fulfilled for isotropic halos (Maxwellian), tri-axial ones (up to peculiar velocity), streams parallel to the motion of the Sun like a dark disc co-rotating with the stellar one...
- In general, natural cases like the above ones have $\hat{v}_{HALO}$ aligned with $\hat{v}_{SUN}$. In this case we get:

$$\int_{vm1}^{vm2} dv_m \, A_\eta(v_m) \leqslant 0.5 \, v_e \left[\bar{\eta}(v_{m1}) - v_{m1} \int_{v_{m1}} dv \, \frac{\bar{\eta}(v)}{v^2} \right]$$

Applying the bounds to real data

- Experimental data is binned: We have to average over each bin and convert integrals to sums... etc.
- For bin i, bounds look like $A_i \leq v_e \left(R_i\alpha_i - R_{i+1}\alpha_{i+1}\ldots\right) \equiv B_i$.
- They vary depending on whether we have single detector (Ge in CoGeNT) or multi-target (Na, I in DAMA).
- The dependence on ρ_χ, σ_χ, v_{esc} drops from the bounds.
- They are valid for SI and SD (we only analyze SI).
- They depend on m_χ, $Q(E_r)$ and $F^2(E_r)$. m_X appears when translating v_m to E_e ($E_e = Q(E_r)E_r$).

Methods to study the consistency between M and R

Conservative approach: only a fraction ω_i ($0 \leq \omega_i \leq 1$) of R_i is due to DM, the rest being an unknown background. Assume NO modulated background.

- ***Method 1.*** Drop the negative term and set $\omega_i = 1$. No background present.
- ***Method 2.*** Build a “Chi square”:

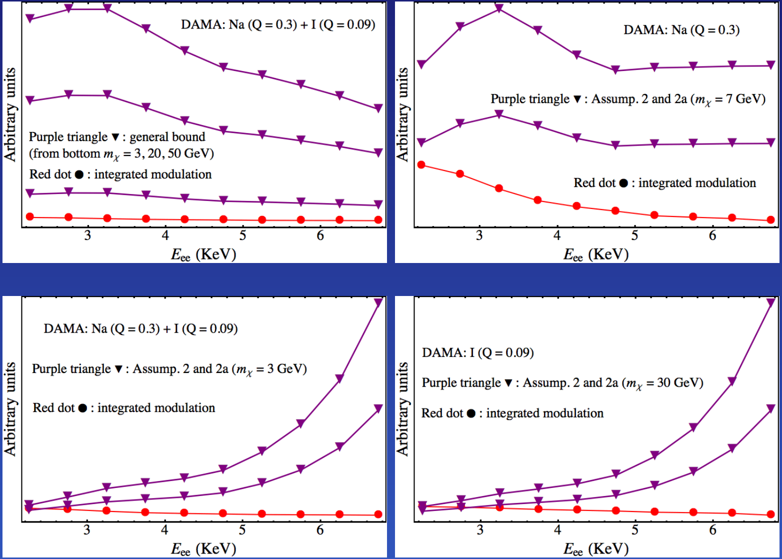
$$\Delta X^2 = \sum_i^N \left(\frac{A_i - B_i}{\sigma_i^A} \right)^2 \Theta(A_i - B_i)$$

and minimize w.r.t the ω_i.
There is only a contribution to it when the bound is violated.
Approximately Chi-square distributed with 1 d.o.f., m_χ.

- ***Method 3.***

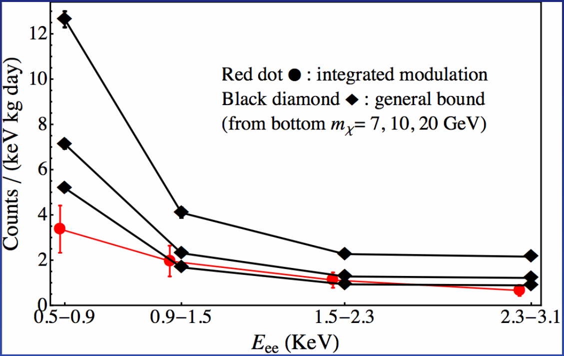
1. For each m_χ, compute the less constraining set of ω_i by minimizing the X^2.
2. With this set of ω_i, suppose the bound is saturated (conservative) and simulate pseudo-data (for the modulation) taking the upper bounds (r.h.s.) as the mean value for a Gaussian, with σ_i = error of the true A_i.
3. For each random data set, calculate the X^2 value and obtain its distribution.
4. Compare it with the X^2_{obs} of the real data and calculate the probability of obtaining a $X^2 > X^2_{obs}$.

DAMA

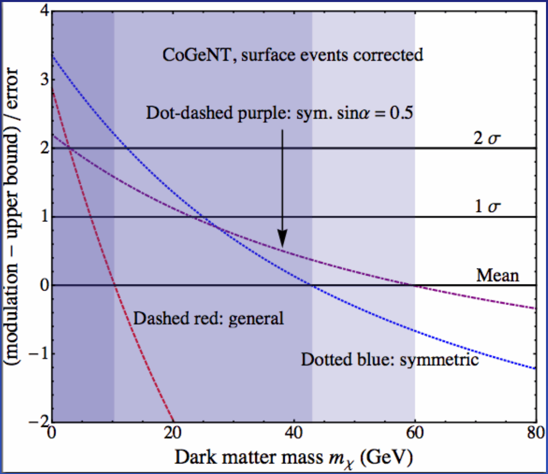


DAMA: Na (Q = 0.3) + I (Q = 0.09)
Purple triangle ▼ : general bound
(from bottom m_χ = 3, 20, 50 GeV)
Red dot ● : integrated modulation
Arbitrary units
E_{ee} (KeV)
3
4
5
6
DAMA: Na (Q = 0.3)
Purple triangle ▼ : Assump. 2 and 2a (m_χ = 7 GeV)
Red dot ● : integrated modulation
Arbitrary units
E_{ee} (KeV)
DAMA: Na (Q = 0.3) + I (Q = 0.09)
Purple triangle ▼ : Assump. 2 and 2a (m_χ = 3 GeV)
Red dot ● : integrated modulation
Arbitrary units
E_{ee} (KeV)
DAMA: I (Q = 0.09)
Purple triangle ▼ : Assump. 2 and 2a (m_χ = 30 GeV)
Red dot ● : integrated modulation
Arbitrary units
E_{ee} (KeV)

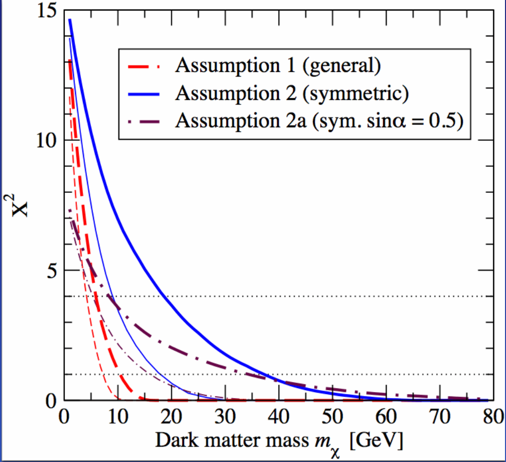
CoGeNT


Red dot ● : integrated modulation
Black diamond ◆ : general bound
(from bottom m_χ= 7, 10, 20 GeV)
Counts / (keV kg day)
12
10
8
6
4
2
0
0.5−0.9
0.9−1.5
1.5−2.3
2.3−3.1
E_{ee} (KeV)

CoGENT (with surface events subtracted)

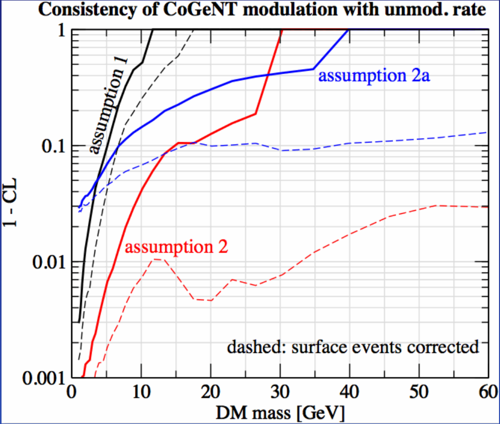


X^2 method (with/out surface events subtracted)



Montecarlo bounds

Probability to obtain $X^2 > X^2_{obs} \equiv P_{\textit{bound is fulfilled}}$:



If preliminary surface events are confirmed, under ass. 2 and 2a data is inconsistent with DM at the 97% and 90% C.L. resp.

Conclusions

- We have derived a consistency check between the modulation and the constant rate, under very mild assumptions about the DM halo.
- A violation of it suggests a non-DM origin or exotic properties which should have other striking signatures.
- We have applied it to DAMA and CoGeNT (elastic, SI):

1. DAMA is consistent.
2. Very strong tensions exist for CoGENT, with typical DM haloes excluded at $>90\%$ C.L.

BACK-UP

Notation

- Local DM density:

$$\rho_\chi = n_\chi m_\chi \approx 0.3\,\mathrm{GeV/cm^3}$$

- Flux (♯ particles/ area/ time):

$$\phi_\chi = n_\chi v = \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right) 10^5 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- Rate (♯ counts/ time):

$$R = \phi_\chi\, \sigma_\chi\, N_{target} = \frac{\rho_\chi v}{m_\chi} \cdot \sigma_\chi \cdot \frac{\text{target mass}}{m_A}$$

- By kinematics there is a minimum velocity (elastic scatt.):

$$v_m = \sqrt{\frac{m_A E_r}{2\mu_{\chi A}^2}}$$

Expansion of $\eta(v_m, t)$

$$\eta(v_m, t) = \int_{v_m} d^3v \, \frac{f_{det}(\vec{v})}{v} =$$

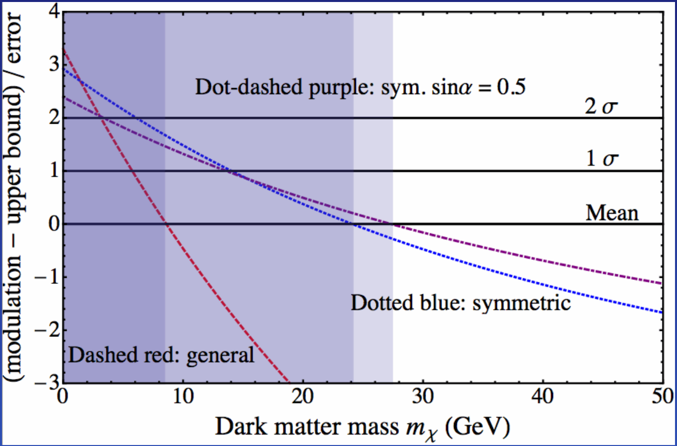
$$= \int_{v_m} d^3v \, \frac{f_{Sun}(\vec{v})}{v} +$$

$$+ \int d^3v \, f_{Sun}(\vec{v}) \, \frac{\vec{v}\cdot\vec{v}_e(t)}{v^3} [\Theta(v - v_m) - \delta(v - v_m) \, v_m] \equiv$$

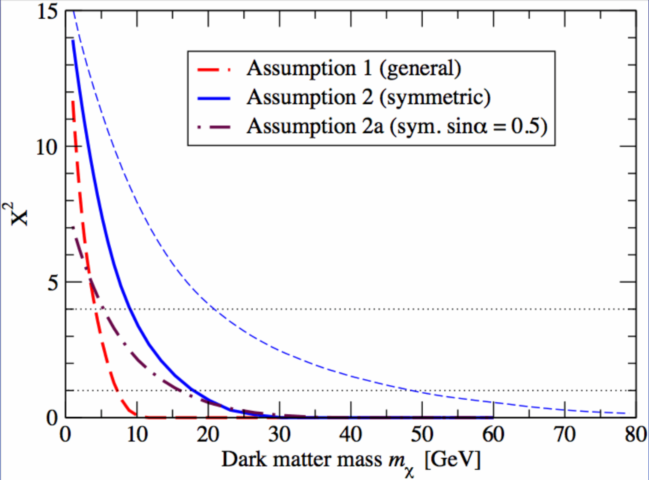
$$\equiv \bar{\eta}(v_m) + A_\eta(v_m) \cos 2\pi(t - t_0)$$

- $v_e(t) \propto v_e \cos 2\pi(t - t_0)$, so the first terms is just the constant part $\bar{\eta}(v_m)$ and the second one is the modulated part $A_\eta(v_m) \cos 2\pi(t - t_0)$.

CoGENT (without subtraction of surface events)



Chi square minimization



CoGENT bounds on the DM mass

	Proc. 1	Proc. 1	Proc. 2	Proc. 2
Mean mass (GeV)	Normal	Surface	Normal	Surface
General bound	8.5	10	7.3	10
Symmetric bound	24	43	18	37
Sym. $\alpha = \pi/6$	27.5	59.5	16	35

Iterative method

- ***Method 4.*** For each bin i, the inequality depends only on ω_j, with $j \geq i$. The most conservative option is to have ω_i (ω_j with $j > i$) as large (small) as possible.

Iterative prescription to find the set of ω_i corresponding to the most conservative choice of background:

1. Saturate the bounds ($\leq \to =$). System of N ($\sharp$ bins) linear equations in ω_i.
2. Starting with the highest bin $j = N$, solve for the ω_N that saturates the bound. If $\omega_N \leq 1$, it will be the smallest allowed value, so the bound for $N - 1$ will be the weakest. If $\omega_N \geq 1$, i it is violated & we set it to one.
3. Then go to the bin $j = N - 1$ with that value of ω_N and look for the ω_{N-1} that saturates the bound, and so on...

Iterative method bounds

	Proc. 4	Proc. 4
Mean mass (GeV)	Normal	Surface
General bound	10	12.5
Symmetric bound	29.5	63
Sym. $\alpha = \pi/6$	37.5	94.5