On the DM annual modulation signal

(in collaboration with Thomas Schwetz and Jure Zupan)

[JCAP 03 (2012) 005, 1112.1627; PRL 109 (2012) 141301, 1205.0134]

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Invisibles Journal Club

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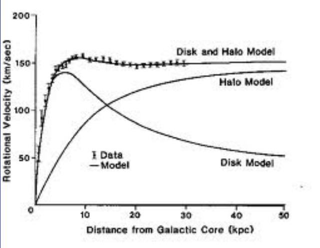
Outline

1. Evidence and properties of dark matter
2. Annual modulation in direct searches
3. Bounds on the annual modulation and results
4. Bounds between different experiments and results
5. Final remarks and conclusions

EVIDENCE AND PROPERTIES OF DARK MATTER

Evidence for dark matter

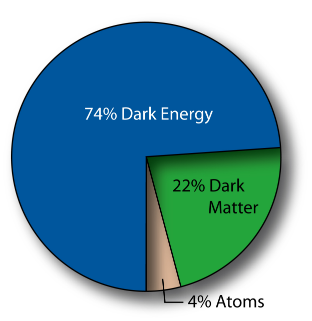
1. Rotation curves

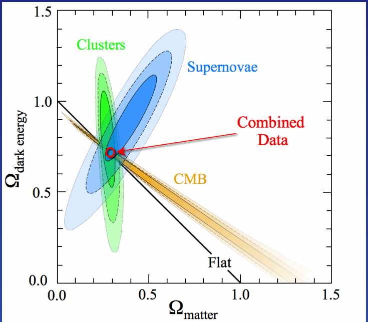


2. Bullet cluster (X-rays + gravitational lensing)

More evidence...

3. Concordance Model: cosmology + CMB ($\Omega_{TOTAL} = 1$) + SNIA ($\Omega_{DE} = 0.73$) + BBN ($\Omega_B = 0.04$) $\longrightarrow$ $\Omega_{DM} = 0.23$.





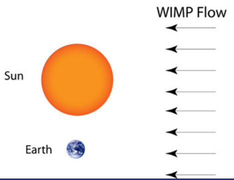
4. M/L ratio in galaxy clusters (virial theorem to gas).
5. Anisotropies of the CMB.
6. Growth of structure (verified by N-body simulations).
7. Globular clusters... etc.

Properties of a DM particle (or particles)

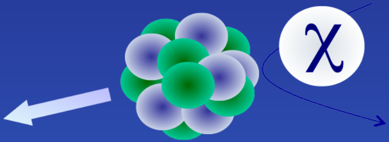
1. It interacts gravitationally.
2. It has to be present today with the observed abundance (long-lived or stable).
3. It is *Invisible:* electrically neutral and colourless (no e.m./ strong at tree level).
4. It may act weakly ($SU(2)_L$ or with an unknown "weak" int.).
5. It is cold (or warm), otherwise would have free-streamed erasing small scales.
6. It is collisionless: it does not dissipate, it forms haloes.

ANNUAL MODULATION
IN DIRECT SEARCHES

Direct detection



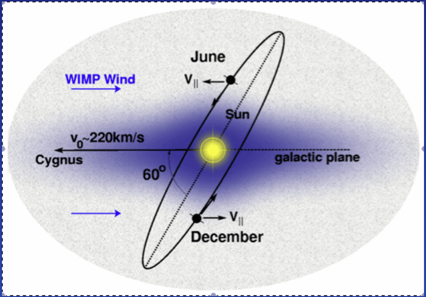
- IF DM interacts weakly, it can produce nuclear recoils.



1. Extremely difficult experiments.
2. Underground to reduce background.
3. Energy deposited via ionization, heat &/or light.

Annual modulation in direct searches

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



- Nice DM signature, as backgrounds (radioactivity) are not expected to show this time dependence.
- Typical velocities involved (apart from $v_{esc} \simeq 550$ km/s):

$\bar{v} \simeq v_{Sun} \approx 220$ km/s & $v_e(t) \propto v_e \cos 2\pi(t - t_0)$ [$v_e \simeq 30$ km/s].

Direct detection event rate: notation

- Local DM density:

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

- Flux (♯ particles/ area/ time):

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

- Hand - waving rate (♯ counts/ time):

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

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

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

where $v_m = \sqrt{m_A E_r / 2\mu_{\chi A}^2}$ is the minimum velocity (for elastic scattering) to produce a recoil of energy E_r (kinematics).

Event rate final: simple expression

- The velocity distribution fulfills ($\int d^3v\, f_{det}(\vec{v},t) = 1$):

$$f_{det}\,(\vec{v},t) = f_{Sun}(\vec{v}+\vec{v_e}(t)) = f_{gal}(\vec{v}+\vec{v}_S+\vec{v_e}(t)) \geq 0.$$

- The final rate can be simplified as ($C \equiv \rho_\chi \sigma_A^0 / 2 m_\chi \mu_{\chi A}^2$):

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

with:

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

- We have used for spin-independent (SI):

$$\frac{d\sigma_\chi}{dE_r} = \frac{m_A}{2\mu_{\chi A}^2 v^2} F^2(E_r)\sigma_A^0,$$

where $\sigma_A^0 = \sigma_p[Z + (A-Z)(f_n/f_p)]^2 \mu_{\chi A}^2/\mu_{\chi p}^2$.

Typical speed distributions $f(v)$ and $\eta(v_m)$

- Typical SHM - isothermal sphere with isotropic, Maxwellian $f(\vec{v})$ in the galactic frame (motivated at low velocities, with DM in equilibrium giving rise to a smooth halo):

$$f^{gal}_{SHM}(\vec{v}) \propto e^{-\vec{v}^2/\bar{v}^2}$$

- Therefore, spectrum is exponential (even in the lab. frame):

$$R \sim e^{-E_r/E_0} \text{ with } E_0 \sim \mathcal{O}(10\,\text{KeV})$$

There can be unvirialized components at high v (N-body sim.):

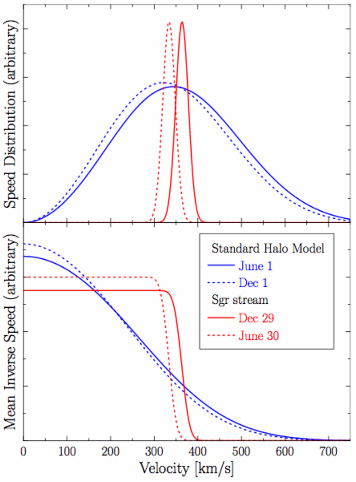
- 1. Streams - DM stripped from infalling substructures with small velocity dispersion, has not had time to spatially mix:

$$f^{gal}_{STREAM}(\vec{v}) \propto \delta^3(\vec{v} - \vec{v}_{stream})$$

- 2. Debris flows - spatially homogeneous velocity substr. from overlapping shells of subhaloes falling into the M.W.:

$$f^{gal}_{FLOW}(\vec{v}) \propto \delta(|\vec{v}| - v_{flow})$$

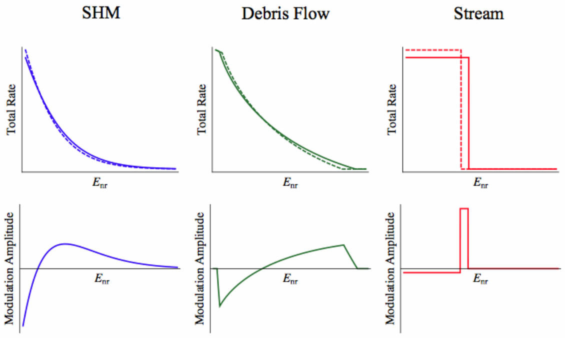
$f(v)$ and $\eta(v_m)$ (next figures from Freese et al.)



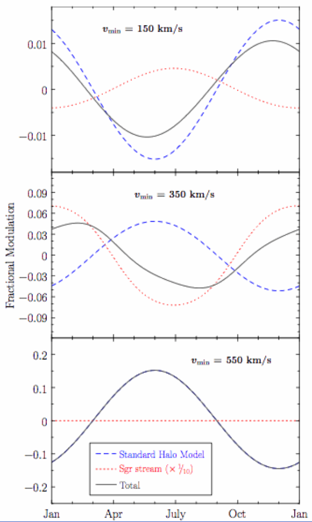
Typical rates and annual modulations

- The amplitude of the modulation is (for SHM):

$$A_R(E_r) \approx \frac{1}{2}[R(E_r, \text{June}) - R(E_r, \text{December})]$$



Modulation / rate versus time

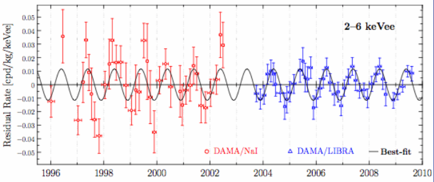


Modulation features of SHM and streams

- SHM: sinusoidal, phase in June, $\mathcal{O}(10\%)$ modulation (except for large v_{min}), phase reversal at $v_{min} \approx 200$ km/s.
- At large v_m, modulation fraction grows, but normally detectors not sensitive, except for low enough m_χ.
- The E_R at which the modulation changes phase constrains m_χ (only a lower limit on m_χ can be set, as, for large m_χ, E_R approaches a fixed value).
- Streams: modulation significant for $v_m \approx v_{stream}$, below is small and above it is negligible, like the rate. Possibly non-sinusoidal. Phase can vary.

DAMA's and CoGENT's annual modulation

- DAMA (NaI): 8.9 σ, consistent with SHM phase at June 1.



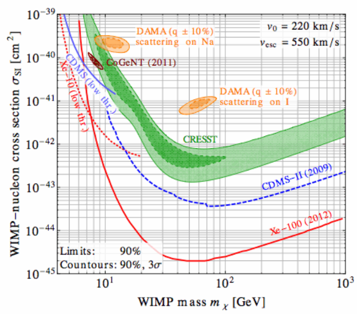
$\longrightarrow$ Fits typical modulation cosine function, with $T = 1$ year.
$\longrightarrow$ Two possible solutions:

$$m_\chi \sim 10 \text{ GeV (Na) and } m_\chi \sim 80 \text{ GeV } (I)$$

- CoGeNT (Ge): 2.8 σ, best fit phase at April 16.

$\longrightarrow$ Possible solution $m_\chi \sim 10\ \mathrm{GeV}$.

DAMA and CoGENT versus other experiments (Kopp)



- Discrepancy between DAMA and CDMS, XENON...
- XENON: most stringent constraint on σ_{SI} for $m_\chi > 10$ GeV.
- $m_\chi \sim 80$ GeV (I) DAMA solution seems to be ruled-out for SI and SD by XENON, CDMS, COUPP.
- However it assumes a particular velocity distribution (SHM), local density and escape velocity (550 km/s).

BOUNDS ON THE ANNUAL MODULATION AND RESULTS

[JCAP 03 (2012) 005, 1112.1627]

Our goal: is the annual modulation seen due to DM?

- Observed modulation fraction $\equiv$ modulation/constant rate:

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

1. First part: establish a consistency check between the *modulated* signal and the *constant* rate, that must be fulfilled *within an experiment* by dark matter, by making very mild assumptions about the DM halo. [JCAP03(2012)005, 1112.1627 [hep-ph]]
2. Second part: translate the bound on the rate of one experiment into a bound on the annual modulation in a *different experiment*. [PRL, 1205.0134 [hep-ph]]

Expansion of $\eta(v_m, t)$ to first order

- For typical $E_r \sim 10$ KeV and for Na, I, Ge: $v > v_m \gg v_e$, so we can expand $\eta(v_m, t)$ to first order in $v_e/v \ll 1$:

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

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

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

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

- So the 1st term is just the constant part $\bar{\eta}(v_m)$ and the 2nd one is the modulated part. Can check experimentally for convergence by searching for higher order terms.

Splitting the total rate

- So the total rate can be divided into a time-independent and a time-dependent part:

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

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

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

- 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 on the annual modulation

Assumptions:

1. "Smooth" halo, i.e., spikes in $v < 30$ km/s not 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 (constant ρ).

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

Integrating it over v_m and dropping the negative term, we get:

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

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

Symmetric bounds

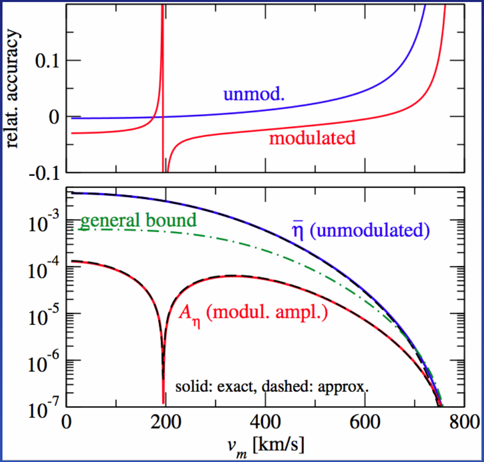
1. There is some preferred constant direction $\hat{v}_{HALO}$ (independent of v_m) governing the shape of the DM velocity distribution in the Sun's rest frame. We get (dropping a negative term):

$$\int_{vm1}^{vm2} dv_m \, A_\eta(v_m) \leqslant v_e \, \bar{\eta}(v_{m1})$$

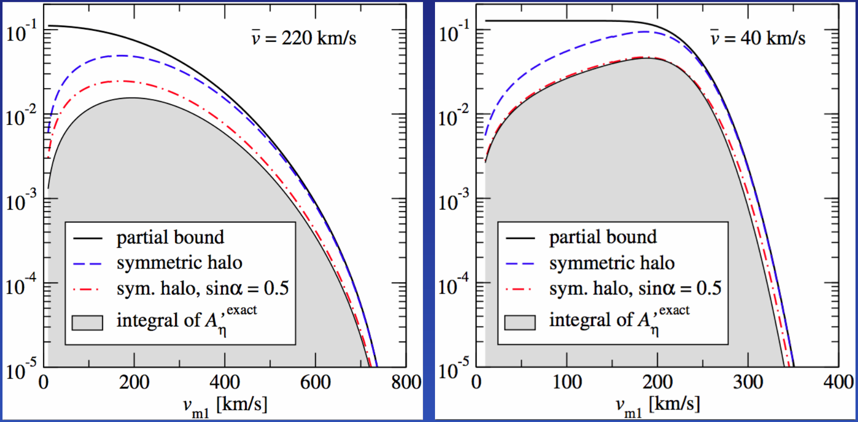
- It is fulfilled for isotropic halos (Maxwellian), tri-axial ones (up to peculiar velocity), streams parallel to the motion of the Sun like a dark disc... Phase constant (up to sign flip).
- In general, natural cases like the above ones have $\hat{v}_{HALO}$ aligned with $\hat{v}_{SUN}$. Phase fixed at June 1st. We get:

$$\int_{vm1}^{vm2} dv_m \, A_\eta(v_m) \leqslant 0.5 \, v_e \, \bar{\eta}(v_{m1})$$

Checking the general bound for the Maxwellian halo



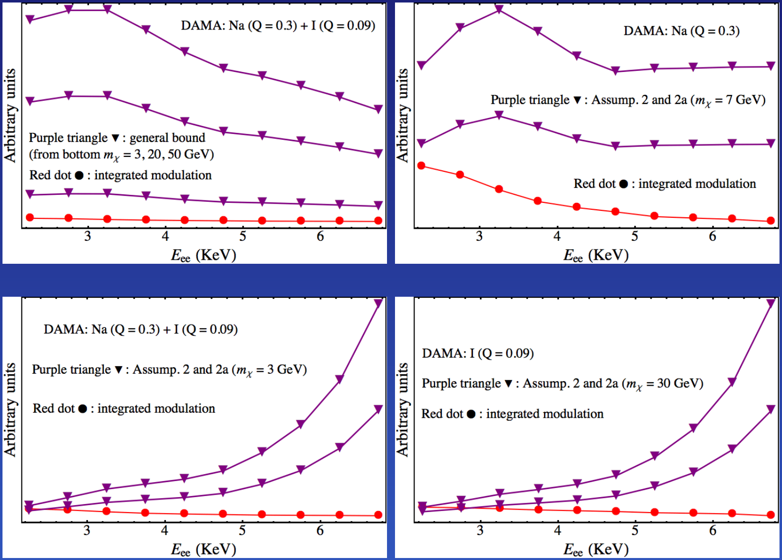
Checking the symmetric bounds



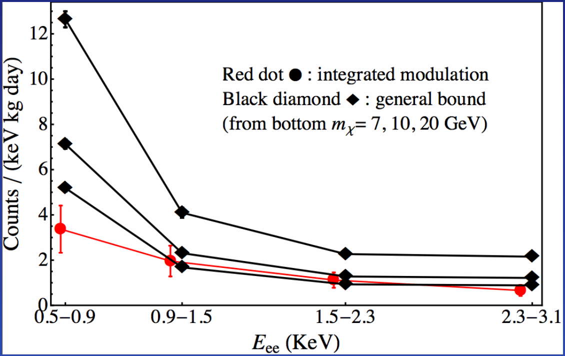
Applying the bounds to real data

- Experimental data is binned: We have to average over each bin and convert integrals to sums... etc.
- They vary depending on whether we have single-target detector (Ge in CoGeNT) or multi-target (Na & I in DAMA).
- The dependence on ρ_χ, σ_p, v_{esc} drops from the bounds.
- They depend on m_χ, $q(E_r)$ and $F^2(E_r)$.
- They are valid for SI, SD and IV.
- We also treat the case of an unknown background that contributes *only* to the constant rate (*NOT-modulated*).

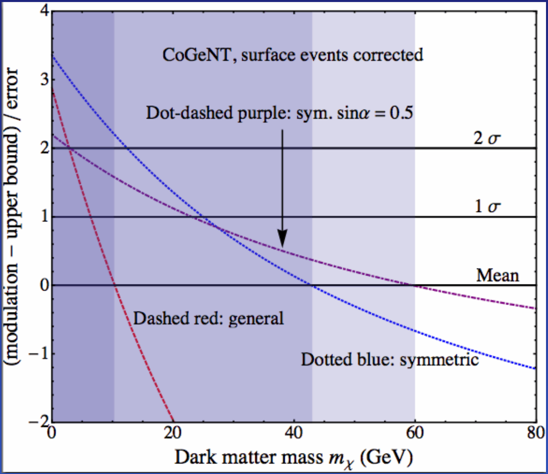
Results for DAMA



Results for CoGeNT



CoGeNT (with surface events subtracted)



To study the consistency between A and R

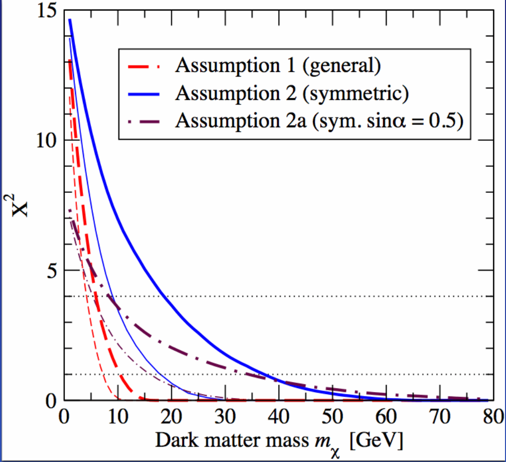
- Conservative approach: only a fraction ω_i ($0 \leq \omega_i \leq 1$) of R_i is due to DM, the rest being an unknown background.
- Build a "χ^2-like" function:

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

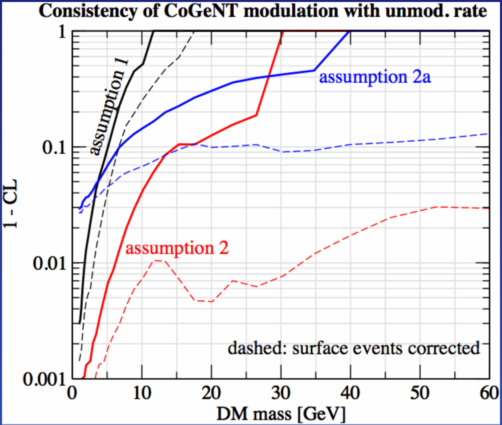
and minimize w.r.t the ω_i.

- There is only a contribution to it when the bound is violated.
- Approximately χ^2 distributed with 1 d.o.f., m_χ.

X^2 for CoGeNT (with & without surface events subtr.)



Probability that the bound is fulfilled



- If surface events are confirmed, under ass. 2 (2a) data is inconsistent with any m_χ at $\gtrsim 97\%$ ($\gtrsim 90\%$ C.L.) resp.

Results up to now:

- We have applied our bounds to DAMA and CoGeNT (elastic, SI):

1. DAMA annual modulation is consistent with its rate.
2. Very strong tensions exist for CoGeNT, with typical DM haloes excluded at $\gtrsim$ 90% C.L.

BOUNDS BETWEEN DIFFERENT EXPERIMENTS AND RESULTS

[PRL 109 (2012) 141301, 1205.0134]

The bounds are detector independent!

- The quantity

$$\tilde{\eta}(v_m) \equiv \tilde{C}\,\bar{\eta}(v_m), \quad \text{with} \quad \tilde{C} \equiv \frac{\rho_\chi \sigma_p}{2 m_\chi \mu_{\chi p}^2},$$

is detector independent (Fox et al.).

- The same happens to $\tilde{A}(v_m) \equiv \tilde{C}\,A(v_m)$.
- So the bounds apply to $\tilde{\eta}$ and $\tilde{A}$, even if the l.h.s. and r.h.s. of the bounds refer to different experiments!
- So we can have bounds that look like:

$$\int_{vm1}^{vm2} dv_m\, \tilde{A}_\eta^{DAMA}(v_m) \leqslant v_e\, \tilde{\eta}^{XENON}(v_{m1})$$

Upper bounds on $\tilde{\eta}(v_m)$ for null-result experiments

- The predicted number of events in an interval $[E_1, E_2]$ is:

$$N^{pred}_{[E_1,E_2]} = MTA^2 \int_0^\infty dE_{nr} F_A^2(E_{nr}) G_{[E_1,E_2]}(E_{nr}) \tilde{\eta}(v_m)$$

with G the detector response, M the mass and T the exp. time.

- As $\tilde{\eta}(v_m)$ is a falling function, the minimum number of events is obtained for $\tilde{\eta}(v) \equiv \tilde{\eta}(v_m)\Theta(v_m - v)$. So, for a given v_m, there is a lower bound $N^{pred}_{[E_1,E_2]} \geq \mu(v_m)$, with

$$\mu(v_m) = MTA^2 \tilde{\eta}(v_m) \int_0^{E(v_m)} dE_{nr} F_A^2(E_{nr}) G_{[E_1,E_2]}(E_{nr})$$

- So we can obtain an upper bound of $\tilde{\eta}(v_m)$ at a given C.L. by requiring that the probability of obtaining $N^{obs}_{[E_1,E_2]}$ events or less for a Poisson mean of $\mu(v_m)$ is equal to 1-C.L.

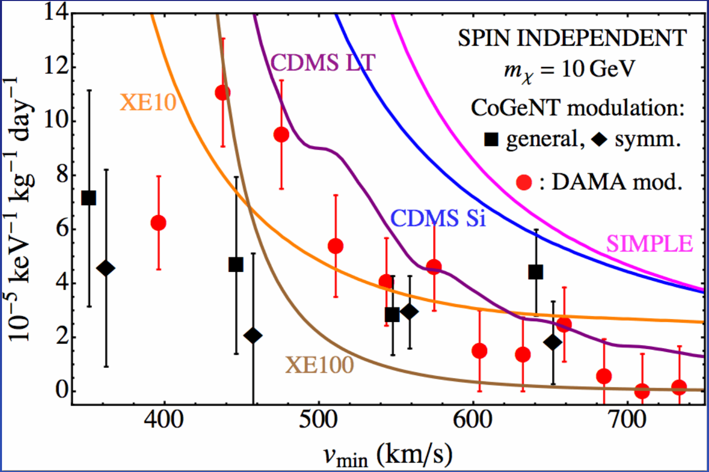
Computing the modulation for DAMA

- By assuming scattering on Na (for low mass DM particles), $\tilde{A}^i_\eta$ is related to the observed modulation in bin i, A^i_R, by:

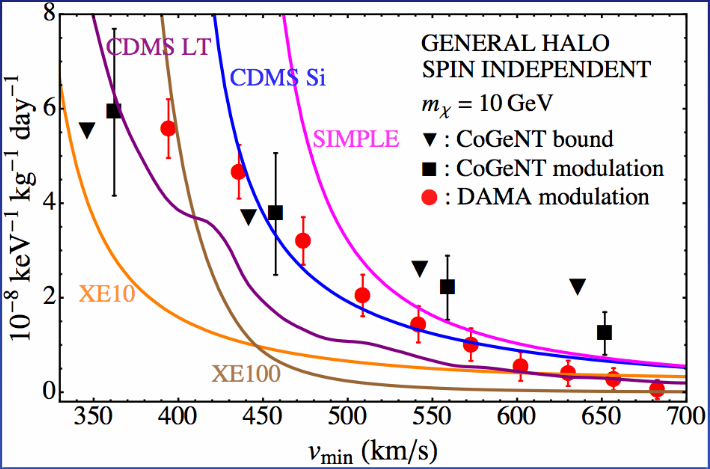
$$\tilde{A}^i_\eta(v^i_m) = \frac{A^i_R q_{Na}}{A^2_{Na} \left\langle F^2_{Na} \right\rangle_i f_{Na}}$$

where $q_{Na} = 0.3$ is the Na quenching factor, $F_{Na}(E_r)$ is the Na form factor and $f_{Na} = m_{Na}/(m_{Na} + m_I)$ is the Na mass fraction.

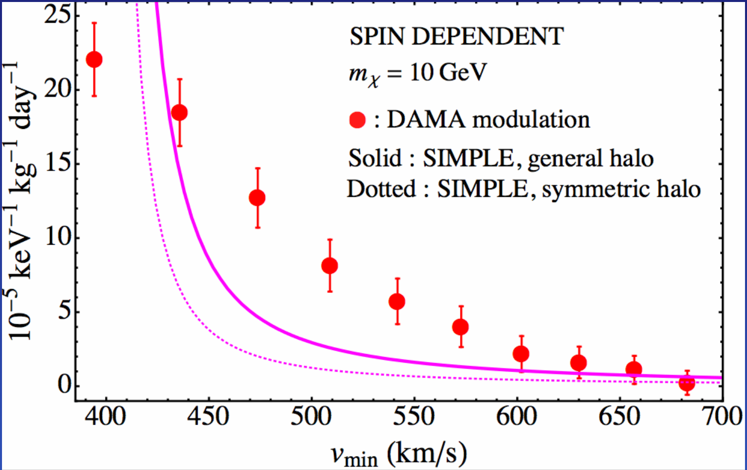
Modulations and upper bounds on the rates



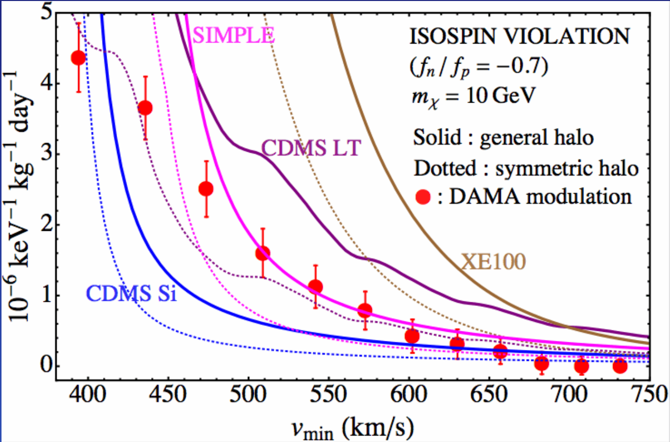
General bound, spin independent



Spin dependent



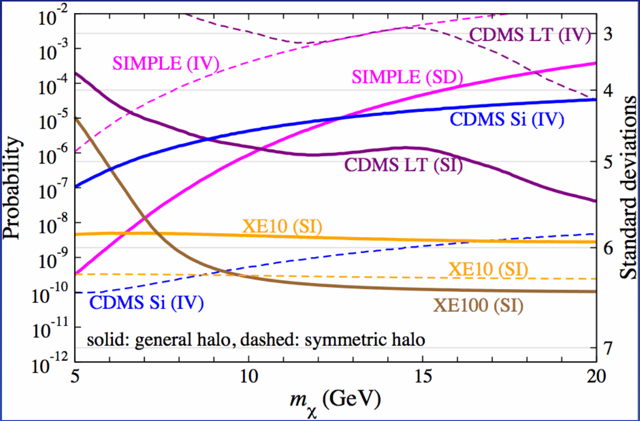
Isospin violation



Quantifying DAMA's modulation discrepancy

- We fix v_m (or m_χ). For each $\tilde{\eta}(v_m)$ there is a Poisson mean $\mu(v_m)$. We calculate the probability p_η to obtain equal or less events than measured by the null-result experiment.
- We construct the bound (r.h.s.) using the same $\tilde{\eta}(v_m)$.
- We calculate the probability p_A that the bound is not violated by assuming on the l.h.s of the bounds a Gaussian distribution for the modulation in each bin.
- Then $p_{joint} = p_\eta \, p_A$ is the combined probability of obtaining the experimental result for that $\tilde{\eta}$. Then we maximize it w.r.t. $\tilde{\eta}$ to obtain the highest joint probability.

Probability of compatibility of DAMA's modulation with the other null-result experiments



- $m_\chi \lesssim 15$ GeV, is disfavoured by ≥ 1 experiment at $\geq 4\sigma$.
- XE100 excludes at $> 6\sigma$ for $m_\chi \gtrsim 8$ GeV (SI).
- C.L. depends on systematic uncertainties, such as q_{Na}.

FINAL REMARKS AND CONCLUSIONS

Final remarks and conclusions

- 1) We have derived bounds (almost completely) astrophysics independent between the annual modulation signal and the constant rate.

$\longrightarrow$ DAMA was consistent, while CoGeNT's modulation was incompatible with its own rate at $\gtrsim 90\,\%$ C.L.

- 2) We have extended the bounds to the case of comparing between the modulation in one experiment and the null result of a different experiment.

$\longrightarrow$ DAMA, for all interactions (elastic) and with a DM mass $m_\chi \lesssim 15$ GeV, is disfavoured by ≥ 1 experiment at $\geq 4\sigma$.

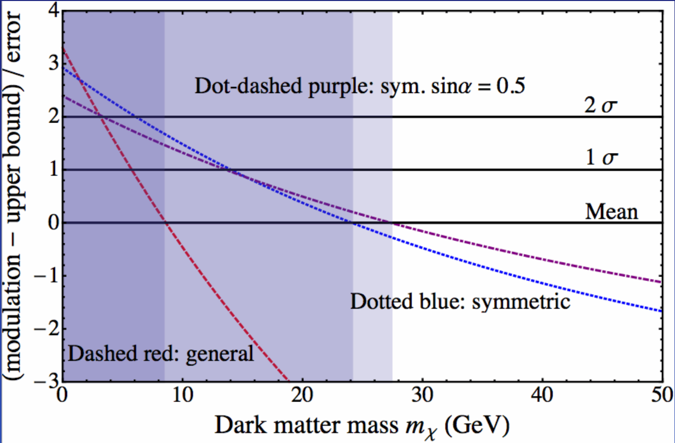
The method will be an important test that any DM annually modulated signal will have to pass in the future.

THANKS

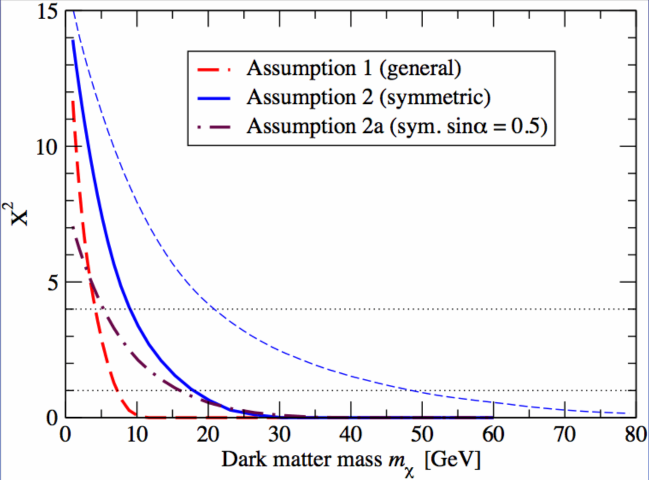
FOR YOUR ATTENTION!

BACK-UP

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

- ***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 $X^2 > X^2_{obs}$.

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

Na quenching factor $q_{Na} = 0.45$

- SI: excluded at $> 5\sigma$ for $m_\chi \gtrsim 10$ GeV (general halo).
- SD a IV can achieve a consistency at $\approx 3\sigma$ (general halo).

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