Astrophysics-Independent Bounds on the Annual Modulation of Dark Matter Signals

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Astrophysics independent bounds on the annual modulation of dark matter signals

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We show how constraints on the time integrated event rate from a given dark matter (DM) direct detection experiment can be used to bound the amplitude of the annual modulation signal in another experiment. The method requires only mild assumptions about the properties of the local DM distribution: that it is temporally stable on the scale of months and spatially homogeneous on the ecliptic. We apply the method to the annual modulation signal in DAMA/LIBRA, which we compare to the bounds derived from XENON10, XENON100, CDMS, and SIMPLE data. Assuming a DM mass of 10 GeV, we show that under the above assumptions about the DM halo a DM interpretation of the DAMA/LIBRA signal is excluded for several classes of models: at 6.3σ (4.6σ) for elastic isospin conserving (violating) spin-independent interactions, and at 4.9σ for elastic spin-dependent interactions on protons.

Dark matter (DM) constitutes a significant fraction of the energy density in the universe, $\Omega_{\rm DM} = 0.229 \pm 0.015$ [1]. This conclusion is based entirely on gravitational effects of DM. A fundamental question is whether DM interacts also non-gravitationally. Direct detection experiments, for instance, are looking for the scattering of DM particles from the galactic halo in underground detectors. A characteristic feature of the signal is an annual modulation, because the Earth rotates around the Sun, while at the same time the Sun moves relative to the DM halo [2]. At present two experiments are reporting annually modulated signals, DAMA/LIBRA [3] (DAMA for short) and CoGeNT [4], with significances of 8.9σ and 2.8σ, respectively. Assuming the standard Maxwellian DM halo and elastic spin-independent DM scattering both claims are in tension [5, 6] with bounds on time integrated rates from other experiments such as XENON10 [7], XENON100 [8], or CDMS [9]. The situation may change in the case of non-Maxwellian DM halos, e.g., halos with anisotropic velocity distributions or with significant substructure, for instance DM streams or DM debris flows. Recently CDMS provided a direct bound on the modulation signal, which disfavors the CoGeNT modulation without referring to any halo or particle physics model [10]. Therefore we focus below on DAMA.

In this Letter we present a general method that avoids astrophysical uncertainties when comparing putative DM modulation signals with bounds on time averaged DM scattering rates from different experiments by combining the results from [11, 12] with bounds on the modulation derived by us in [13]. We are then able to translate the bound on the DM scattering rate in one experiment into a bound on the annual modulation amplitude in a different experiment. The resulting bounds present roughly an order of magnitude improvement over [11, 12] and [13].

The bounds are (almost completely) astrophysics independent. Only very mild assumptions about DM halo properties are used: (i) that it does not change on the time-scales of months, (ii) that the density of DM in the halo is constant on the scales of the Earth-Sun distance, and (iii) that the DM velocity distribution does not vary strongly on scales of the Earth velocity $v_e = 29.8$ km/s. If the modulation signal is due to DM, then the modulation amplitude has to obey the bounds. In the derivation an expansion in v_e over the typical DM velocity ~ 200 km/s is used. The validity of the expansion can be checked experimentally, by searching for the presence of higher harmonics in the time-stamped DM scattering data [13].

Bounds on the annual modulation. We focus on elastic scattering of DM χ off a nucleus (A, Z), depositing the nuclear recoil energy E_{nr}. The differential rate in events/keV/kg/day is

$$R_A(E_{nr}, t) = \frac{\rho_\chi \sigma_A^0}{2 m_\chi \mu_{\chi A}^2} F_A^2(E_{nr})\, \eta(v_m, t)\,, \qquad (1)$$

with ρ_χ the local DM density, σ_A^0 the total DM–nucleus scattering cross section at zero momentum transfer, m_χ the DM mass, $\mu_{\chi A}$ the DM–nucleus reduced mass, and $F_A(E_{nr})$ a nuclear form factor. For SI interactions, σ_A^0 can be written as $\sigma_A^{\rm SI} = \sigma_p [Z + (A-Z)(f_n/f_p)]^2 \mu_{\chi A}^2/\mu_{\chi p}^2$, where σ_p is the DM–proton cross-section and $f_{n,p}$ are coupling strengths to neutron and proton, respectively. Apart from ρ_χ, the astrophysics enters in Eq. (1) through the halo integral

$$\eta(v_m, t) \equiv \int_{v > v_m} d^3 v \frac{f_{\rm det}(\mathbf{v}, t)}{v}, \quad v_m = \sqrt{\frac{m_A E_{nr}}{2\mu_{\chi A}^2}}, \quad (2)$$

where v_m is the minimal velocity required for recoil energy E_{nr}, and $f_{\rm det}(\mathbf{v}, t)$ describes the distribution of DM particle velocities in the detector rest frame with $f_{\rm det}(\mathbf{v}, t) \geq 0$ and $\int d^3 v f_{\rm det}(\mathbf{v}, t) = 1$. The integral of

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the velocity distribution enters in $R_A(E_{nr},t)$ because DM scattering at different angles probes different DM velocities even for fixed E_{nr}. The velocity distributions in the rest frames of the detector and the Sun are related by $f_{\rm det}(\mathbf{v},t) = f_{\rm sun}(\mathbf{v}+\mathbf{v}_e(t))$, where $\mathbf{v}_e(t)$ is the velocity vector of the Earth. The rotation of the Earth around the Sun introduces a time dependence in the event rate through $\eta(v_m,t) = \overline{\eta}(v_m) + \delta\eta(v_m,t)$, where

$$\delta\eta(v_m,t) = A_\eta(v_m)\cos 2\pi[t - t_0(E_{nr})], \qquad (3)$$

when expanding to first order in $v_{\rm e} = 29.8$ km/s $\ll v_{\rm sun} \simeq 230$ km/s, and $A_\eta(v_m) \geq 0$. The expansion can be truncated, if $f_{\rm sun}(v)$ does not show large variations on the scale of v_e, i.e., $v_e|df(v)/dv| \ll f(v)$. We are also assuming that the only time dependence comes from the rotation of the Earth around the Sun and $f_{\rm sun}(v)$ itself is constant in time and space.

Under those assumptions we have schematically $\overline{\eta} \sim \int f(v)/v$ and $A_\eta \sim v_e \int f(v)/v^2$. After some algebra the modulation amplitude $A_\eta(v_m)$ can be shown to be bounded by the unmodulated halo integral $\overline{\eta}$ (see [13] for the derivation):

$$A_\eta(v_m) \leq v_e\left[-\frac{d\overline{\eta}}{dv_m} + \frac{\overline{\eta}(v_m)}{v_m} - \int_{v_m} dv\frac{\overline{\eta}(v)}{v^2}\right]. \qquad (4)$$

If we further assume that the DM velocity distribution obeys certain symmetry properties such that there is only one single direction related to the DM flow, independent of v_m (see [13] for details), then one obtains a more stringent constraint:

$$\int_{v_1}^{v_2} dv_m A_\eta(v_m) \leq \sin\alpha\, v_e\left[\overline{\eta}(v_1) - v_1\int_{v_1} dv\frac{\overline{\eta}(v)}{v^2}\right]. \qquad (5)$$

Here α is the angle between the DM flow and the direction orthogonal to the ecliptic. The most conservative bound is obtained for $\sin\alpha = 1$ (which would correspond to a DM stream parallel to the ecliptic). However, in many cases the DM flow will be aligned with the motion of the Sun within the galaxy. This holds for any isotropic velocity distribution and, up to a small correction due to the peculiar velocity of the Sun, also for tri-axial halos or a significant contribution from a possible dark-disc. In this case we have $\sin\alpha \simeq 0.5$.

In the following we will use time averaged rates from various experiments to derive an upper bound on $\overline{\eta}(v_m)$. In order to be able to apply this information we integrate Eq. (4) over v_m and drop the negative terms in Eqs. (4) and (5). This gives the bounds

$$\int_{v_1}^{v_2} dv_m A_\eta(v_m) \leq v_e\left[\overline{\eta}(v_1) + \int_{v_1}^{v_2} dv\frac{\overline{\eta}(v)}{v}\right], \qquad (6)$$

$$\int_{v_1}^{v_2} dv_m A_\eta(v_m) \leq \sin\alpha\, v_e\, \overline{\eta}(v_1), \qquad (7)$$

In practice the integrals on the l.h.s. are replaced by a sum over bins. Below we will refer to the relations (6) and (7) with $\sin\alpha = 0.5$ as the bounds for "general halo" and "symmetric halo", respectively. Here "symmetric" refers to the local velocity distribution according to the sentence before Eq. (5), not the spatial distribution of DM.

Bounds on the unmodulated halo integral. Let us first consider SI scattering with $f_n = f_p$. Generalization to isospin violating scattering with $f_n \neq f_p$ and to SD scattering is straightforward. The predicted number of events in an interval of observed energies $[E_1, E_2]$ is

$$N^{\rm pred}_{[E_1,E_2]} = MTA^2\int_0^\infty dE_{nr}F_A^2(E_{nr})G_{[E_1,E_2]}(E_{nr})\tilde{\eta}(v_m). \qquad (8)$$

Here $G_{[E_1,E_2]}(E_{nr})$ is the detector response function, which describes the contribution of events with true nuclear-recoil energy E_{nr} to the observed energy interval $[E_1,E_2]$. It may be non-zero outside the $E_{nr} \in [E_1,E_2]$ interval due to the finite energy resolution and includes also (possibly energy dependent) efficiencies. M and T are the detector mass and exposure time, respectively, and

$$\tilde{\eta} \equiv \frac{\sigma_p\rho_\chi}{2m_\chi\mu_{\chi p}^2}\overline{\eta}, \qquad (9)$$

where $\tilde{\eta}$ has units of events/kg/day/keV.

Now we can use the fact that $\tilde{\eta}$ is a monotonically decreasing function of v_m [11] (see also [14, 15]). Among all possible forms for $\tilde{\eta}$ such that they pass through $\tilde{\eta}(v_m)$ at v_m, the minimal number of events is obtained for $\tilde{\eta}$ constant and equal to $\tilde{\eta}(v_m)$ until v_m and zero afterwards. Therefore, for a given v_m we have a lower bound $N^{\rm pred}_{[E_1,E_2]}(v_m) \geq \mu(v_m)$ with

$$\mu(v_m) = MTA^2\tilde{\eta}(v_m)\int_0^{E(v_m)} dE_{nr}F_A^2(E_{nr})G_{[E_1,E_2]}(E_{nr}), \qquad (10)$$

where $E(v_m)$ is given in (2). Suppose an experiment observes $N^{\rm obs}_{[E_1,E_2]}$ events in the interval $[E_1,E_2]$. Then we can obtain an upper bound on $\tilde{\eta}$ for a fixed v_m at a confidence level CL by requiring that the probability of obtaining $N^{\rm obs}_{[E_1,E_2]}$ events or less for a Poisson mean of $\mu(v_m)$ is equal to 1−CL. Note that this is actually a lower bound on the CL, since Eq. (10) provides only a lower bound on the true Poisson mean. For the same reason we cannot use the commonly applied maximum-gap method to derive a bound on $\tilde{\eta}$. If several different nuclei are present, there will be a corresponding sum in Eqs. (8) and (10).

The limit on $\tilde{\eta}$ can then be used in the r.h.s. of Eq. (6) or (7) to constrain the modulation amplitude. For concreteness we first focus on the annual modulation in DAMA. If m_χ is around 10 GeV, then DM particles do not have enough energy to produce iodine recoils above the DAMA threshold. We can thus assume that the DAMA signal is entirely due to the scattering on sodium. We define $\tilde{A}_\eta \equiv \sigma_p\rho_\chi/(2m_\chi\mu_{\chi p}^2)A_\eta$, which is related to the observed modulation amplitude $A_i^{\rm obs}$ by

$$\tilde{A}_\eta^{\rm obs}(v_m^i) = \frac{A_i^{\rm obs} q_{\rm Na}}{A_{\rm Na}^2 \langle F_{\rm Na}^2 \rangle_i f_{\rm Na}} \,. \qquad (11)$$

Here $q_{\rm Na} = dE_{ee}/dE_{nr}$ is the sodium quenching factor, for which we take $q_{\rm Na} = 0.3$. The index i labels energy bins, with v_m^i given by the corresponding energy bin center using Eq. (2). Further, $\langle F_{\rm Na}^2 \rangle_i$ is the sodium form factor averaged over the bin width and $f_{\rm Na} = m_{\rm Na}/(m_{\rm Na} + m_{\rm I})$ is the sodium mass fraction. For the modulation amplitude in CoGeNT we proceed analogously. Note that the conversion factor from $\bar{\eta}$ to $\tilde{\eta}$ is the same as for A_η to $\tilde{A}_\eta$, and is not dependent on the nucleus. Therefore, the bounds (6) and (7) apply to $\tilde{\eta}$, $\tilde{A}_\eta$ without change, even if the l.h.s. and r.h.s. refer to different experiments.

Let us briefly describe the data we use to derive the upper bounds on $\tilde{\eta}$. We consider results from XENON10 [7] (XE10) and XENON100 [8] (XE100). In both cases we take into account the energy resolution due to Poisson fluctuations of single electrons. For XE100 we adopt the best-fit light-yield efficiency $L_{\rm eff}$ from [8]. The XE10 analysis is based on the so-called S2 ionization signal and we follow [7] imposing a sharp cut-off of the efficiency below threshold. From CDMS we use results from a low-threshold (LT) analysis [9] of Ge data, as well as data on Si [16]. For SIMPLE [17] we use the observed number of events and expected background events to calculate the combined Poisson probability for stage 1 and 2.

For all experiments we use the lower bound on the expected events, Eq. (10), to calculate the probability of obtaining less or equal events than observed. For XE100, CDMS Si, and SIMPLE we just use the total number of events in the entire reported energy range. For XE10 and CDMS LT the limit can be improved if data are binned and the probabilities for each bin are multiplied. This assumes that the bins are statistically independent, which requires to make bins larger than the energy resolution. For XE10 we only use two bins. For CDMS LT we combine the 36 bins from Fig. 1 of [9] into 9 bins of 2 keV where the energy resolution is 0.2 keV.

Results. In Fig. 1 we show the 3σ limits on $\tilde{\eta}$ compared to the modulation amplitudes $\tilde{A}_\eta$ from DAMA and CoGeNT for a DM mass of 10 GeV. Similar results have been presented in [14, 15]. The CoGeNT amplitude depends on whether the phase is let to vary freely in the fit or fixed at June 2nd [6], which applies to the "general" and "symmetric" halos, respectively. Already at this level XE100 is in tension with the modulation from DAMA (and to some extent also CoGeNT).

We now apply our method. As shown in Fig. 2 the null results become significantly more constraining after applying the bound Eq. (6). DAMA and GoGeNT are strongly excluded by XE100, XE10, CDMS LT already for the general halo, and even more assuming a symmetric halo. Then also CDMS Si excludes DAMA, and there is some tension with SIMPLE (not shown). In Fig. 3 we consider two variations of DM–nucleus interaction. The

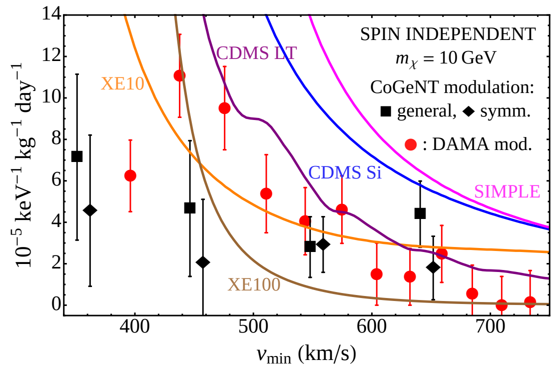

FIG. 1: 3σ upper bounds on $\tilde{\eta}$. The modulation amplitude $\tilde{A}_\eta$ is shown for DAMA (for $q_{Na} = 0.3$) and CoGeNT for both free phase fit (general) and fixing the phase to June 2nd (symmetric). We assume a DM mass of 10 GeV and SI interactions.

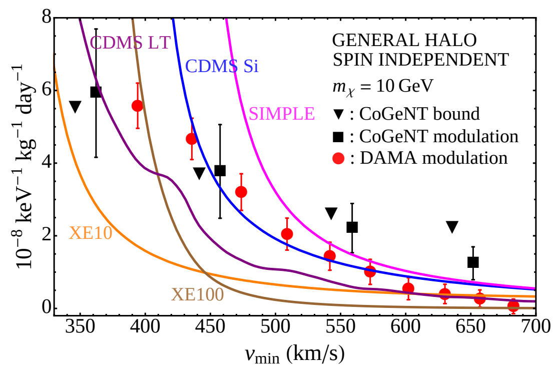

FIG. 2: Integrated modulation signals, $\int_{v_1}^{v_2} dv A_{\tilde{\eta}}$, from DAMA and CoGeNT compared to the 3σ upper bounds for the general halo, Eq. (6). We assume SI interactions and a DM mass of 10 GeV. The integral runs from $v_1 = v_{\rm min}$ till $v_2 = 743$ km/s (end of the 12th bin in DAMA).

upper panel is for SD interactions with the proton, where the bound from SIMPLE is in strong disagreement with the DAMA modulation, due to the presence of fluorine in their target. (A comparable limit has been published recently by PICASSO [18].) In the lower panel of Fig. 3 we show the case of SI isospin violating interactions with $f_n/f_p = -0.7$. This choice evades bounds from Xe, but now the DAMA modulation is excluded by the bounds from CDMS Si for the general halo and CDMS Si, LT, and SIMPLE for the symmetric halo.

Let us now quantify the disagreement between the observed DAMA modulation and the rate from another null-result experiment using our bounds. We first fix v_m. To each value of $\tilde{\eta}(v_m)$ Eq. (10) provides a Poisson mean $\mu(v_m)$. We can then calculate the probability p_η to obtain equal or less events than measured by the null-result experiment. Then we construct the bound on the modulation using the same value $\tilde{\eta}(v_m)$ on the r.h.s. of Eq. (6) or (7) (the integrand $\tilde{\eta}(v)$ in Eq. (6) is calculated using the same p_η but with $v > v_m$ in Eq. (10)). We calculate

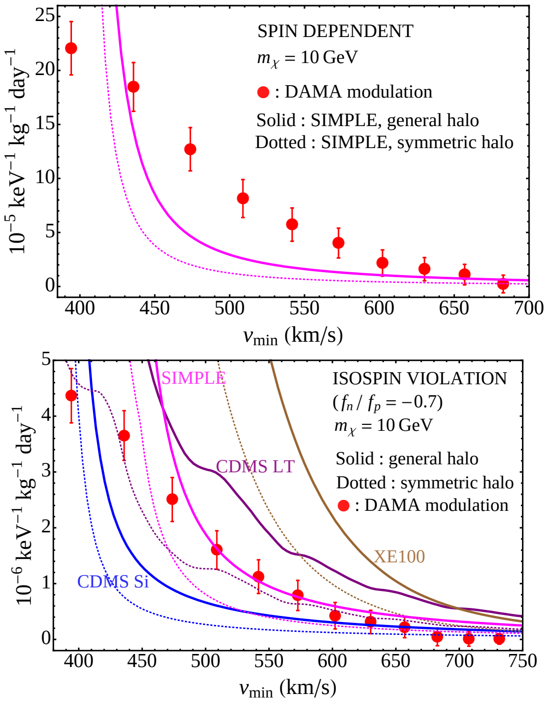

FIG. 3: Integrated modulation signal $\int_{v_{\rm min}}^{v_2} dv A_{\tilde\eta}$ from DAMA compared to the 3σ upper bounds for the general halo, Eq. (6) (solid), and symmetric halo, Eq. (7) with $\sin\alpha = 0.5$ (dotted). We assume a DM mass of 10 GeV, and SD interactions on protons (upper panel) and SI interactions with $f_n/f_p = -0.7$ (lower panel).

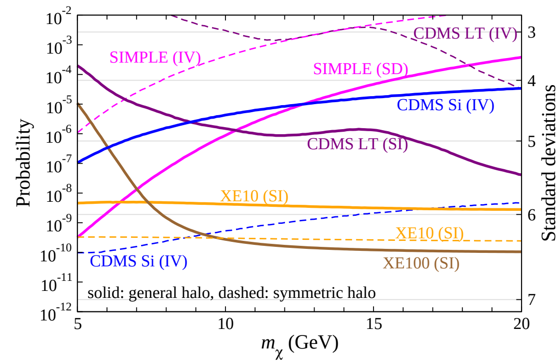

FIG. 4: The probability that the integrated modulation amplitude in DAMA (summed starting from the 3rd bin) is compatible with the bound derived from the constraints on $\tilde\eta$ for various experiments as a function of the DM mass. The label SI (SD), refers to spin-independent (spin-dependent) interactions with $f_n = f_p$ ($f_n = 0$), and IV refers to isospin-violating SI interactions with $f_n/f_p = -0.7$. For solid and dashed curves we use the bounds from Eqs. (6) and (7), respectively.

the probability p_A that the bound is not violated by assuming on the l.h.s. of Eq. (6) or (7) a Gaussian distribution for the DAMA modulation signal with the measured standard deviations in each bin. Then $p_{\rm joint}(\tilde\eta) = p_\eta p_A$ is the combined probability of obtaining the experimental result for the chosen value of $\tilde\eta$. Then we maximize $p_{\rm joint}(\tilde\eta)$ with respect to $\tilde\eta$ to obtain the highest possible joint probability.

The results of such an analysis are shown in Fig. 4. The analysis is performed at the fixed v_m corresponding to the 3rd modulation data point in DAMA, depending on the DM mass m_χ. We find that for all considered interaction types and $m_\chi \lesssim 15$ GeV at least one experiment disfavors a DM interpretation of the DAMA modulation at more than 4σ even under the very modest assumptions of the "general halo". In the case of SI interactions the tension with XE100 is at more than 6σ for $m_\chi \gtrsim 8$ GeV and saturates at the significance of the modulation data point itself at about 6.4σ for $m_\chi \gtrsim 13$ GeV. The exclusion from XE10 is nearly independent of the DM mass slightly below 6σ. We show also a few examples of the joint probability in case of a "symmetric halo".

As mentioned above, one requirement for our method to apply is that the DM velocity distribution $f(v)$ is smooth on scales $\lesssim v_e$. Results from N-body simulations [19] indicate that close to the galactic escape velocity $v_{\rm esc} \sim 550$ km/s fluctuations at such small scales can become significant due to the presence of cold unvirialized DM streams. Note however, that in all cases shown above the DAMA modulation signal is excluded already for $v_{\rm min}$ well below $v_{\rm esc}$, where $f(v)$ is expected to be sufficiently smooth [19]. Furthermore, since $\mathcal{O}(v_e^2)$ terms in the expansion of Eq. (1) lead to the appearance of a $[\cos(2\pi t)]^2$ time dependence, the validity of this approximation can be checked experimentally by searching for higher harmonics in the modulation.

While astrophysics uncertainties are avoided, the obtained bounds are still subject to nuclear, particle physics and experimental uncertainties. For instance, the tension between the DAMA signal and the bounds depends on the value of the Na quenching factor $q_{\rm Na}$, light yield or ionization yield efficiencies in Xe, upward fluctuations from below threshold, and so on. For example, if a value of $q_{Na} = 0.45$ is adopted instead of the fiducial value of 0.3 consistency for SD and isospin violating interactions can be achieved in the case of the general halo at around 3σ, while for SI interactions the XE10 bound still implies tension at more than 5σ for $m_\chi \gtrsim 10$ GeV. Hence, the precise CL of exclusion may depend on systematic uncertainties. We also stress that the above bounds apply to elastic scattering only.

In conclusion, we have presented a powerful method to check the consistency of an annual modulation signal in a DM direct detection experiment with bounds on the total DM scattering rate from other experiments, almost completely independent of astrophysics, for a given type of DM–nucleus interaction. While our bounds strongly disfavor a DM interpretation of present annually modulated signals for several models of DM interactions (SI and SD elastic scattering), the method will be an important test that any future modulated signal will have to pass before a DM interpretation can be accepted.

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