Halo-independent tests of dark matter direct detection signals

Juan Herrero García

Department of Theoretical Physics
Royal Institute of Technology (KTH)

In collaboration with Mattias Blennow, Thomas Schwetz and Stefan Vogl

arXiv [hep-ph]: 1502.03342, 1505.05710, 1506.03503

Invisibles Meets Visibles

Madrid, 23^th of June 2015

Outline

1 DM direct detection (DD)
2 A halo-independent (HI) lower bound on the DM capture rate in the Sun ($C_{\rm Sun}$) from a DD signal
3 A HI lower bound on $\rho_\chi \sigma_{\rm SI/SD}$ for constant rates
4 A HI lower bound on $\rho_\chi \sigma_{\rm SI/SD}$ for annual modulations
5 Summary and conclusions

DM direct detection (DD)

The direct detection event rate

Goodman, Drukier, Freese...

- For elastic SI interactions the rate can be written as

$$\mathcal{R}(E_R, t) = A^2 F_A^2(E_R)\tilde{\eta}(v_m, t), \quad \text{with} \quad \tilde{\eta}(v_m, t) \equiv \mathcal{C}\int_{v_m}^{\infty} dv v \tilde{f}_{\rm det}(v, t)$$

where

$$\tilde{f}(v) \equiv \int d\Omega f(v, \Omega) \quad \text{and} \quad \mathcal{C} \equiv \frac{\rho_\chi \sigma_{\rm SI}}{2 m_\chi \mu_{\chi p}^2},$$

and by kinematics $v > v_m$,

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

- For fixed m_χ, one can translate $\mathcal{R}(E_R, t)$ in E_R space into v_m space, and $\tilde{\eta}(v_m, t)$ is detector independent [Fox, Gondolo, HG, Bozorgnia...].

A HI lower bound on DM $C_{\rm Sun}$ from a DD signal

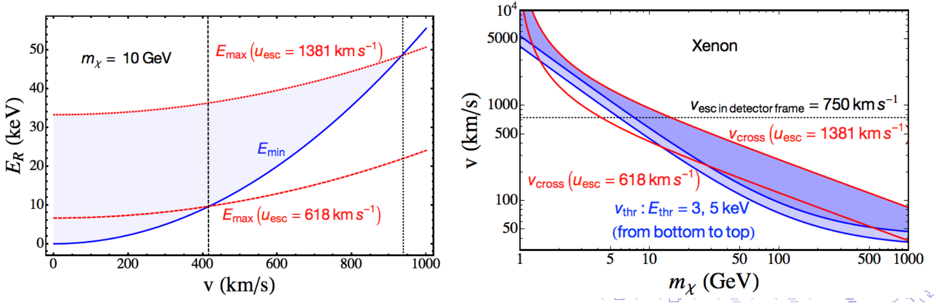
JCAP 1505 (2015) 05, 036; arXiv [hep-ph]: 1502.03342

The overlap in velocity space for $C_{\rm Sun}$ and DD

Gould, Edsjo, Kavanagh, Blennow JHG...

Overlap for $v_{\rm thr} < v < v^A_{\rm cross}(r)$:

- Capture range: $\frac{m_\chi}{2} v^2 \equiv E_{\rm m} < E_R < E_{\rm M} \equiv \frac{2\mu^2_{\chi A}}{m_A}(v^2 + u^2_{\rm esc}(r))$
- Maximum velocity: $v < v^A_{\rm cross}(r) = \frac{\sqrt{4 m_A m_\chi}}{|m_\chi - m_A|} u_{\rm esc}(r)$



Assumptions for the lower bound

1. We neglect $v_e \approx 29\,\mathrm{km/s} \ll v_{\mathrm{Sun}}$

$$\tilde{f}_{\mathrm{det}}(v) = \tilde{f}_{\mathrm{Sun}}(v + v_e) \approx \tilde{f}_{\mathrm{Sun}}(v) \equiv \tilde{f}(v)\,.$$

2. $f(v)$ and ρ_χ are constant on time scales of equilibration, so they are the same for the capture and for DD.

A lower bound on the capture

$$C_{\rm Sun} = 4\pi\,\mathcal{C}\sum_A A^2 \int_0^{R_{\rm S}} dr r^2 \rho_A(r) \int_0^{v^A_{\rm cross}} dv \tilde{f}(v)\, v\, \mathcal{F}_A(v,r)$$

$$\geq 4\pi \sum_A A^2 \mathcal{C} \int_0^{R_{\rm S}} dr r^2 \rho_A(r) \int_{v_{\rm thr}}^{v^A_{\rm cross}} dv\, \tilde{f}(v)\, v\, \mathcal{F}_A(v,r).$$

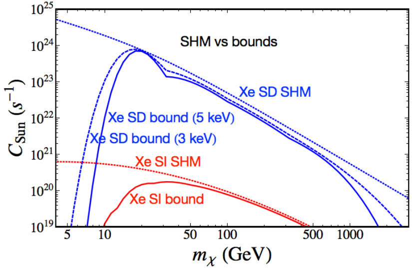
with $\mathcal{F}_A(v,r) \equiv \int_{E_{\rm min}(v)}^{E_{\rm max}(v)} F_A^2(E_R) dE_R$.

From the DD spectrum one can extract:

$$\mathcal{C}\tilde{f}(v) = -\frac{1}{vA^2}\frac{d}{dv}\left(\frac{\mathcal{R}(E_R)}{F_A^2(E_R)}\right)$$

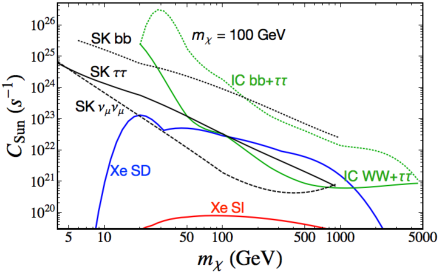
- The bound on $C_{\rm Sun}$ can be expressed in terms of DD quantities.
- It is independent of $f(v)$, $v_{\rm esc}$, σ_χ and ρ_χ.

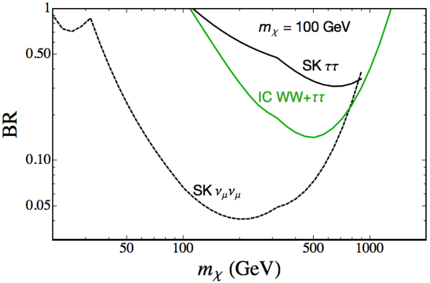
Xe mock data: bound vs SHM. BR: equil., $\Gamma_{\rm Sun} = C_{\rm Sun}/2$



Xe bounds are strongest:

- Xe: for SD in the range $20 \lesssim m_\chi \lesssim 1000$ GeV
- For SI $m_\chi \gtrsim 50$ GeV.





A HI lower bound on $\rho_\chi \sigma_{\rm SI/SD}$ for constant rates

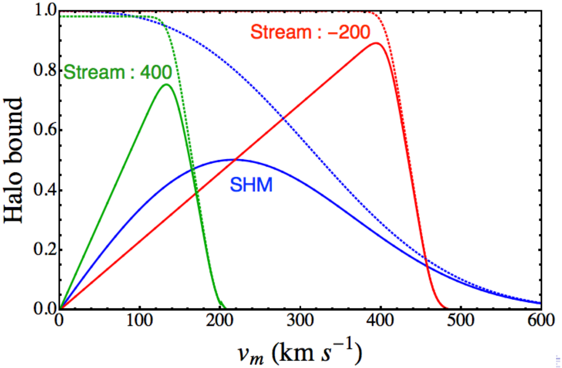
arXiv [hep-ph]: 1505.05710

Lower bound on the halo function

Feldstein, Kavanagh, Blennow...

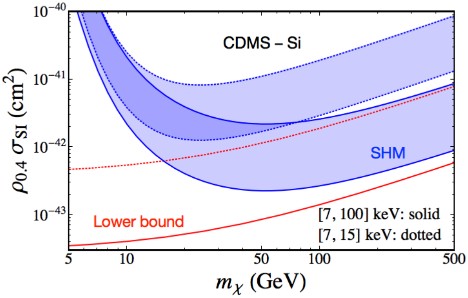
$$1 \equiv \int_0^\infty d^3v\, f_{\rm det}(\vec{v}) \equiv \int_0^\infty \overline{\eta}(v) dv \quad \geq \overline{\eta}(v_1)\, v_1 + \int_{v_1}^{v_2} dv\, \overline{\eta}(v) \quad B_1\,(\text{dotted})$$

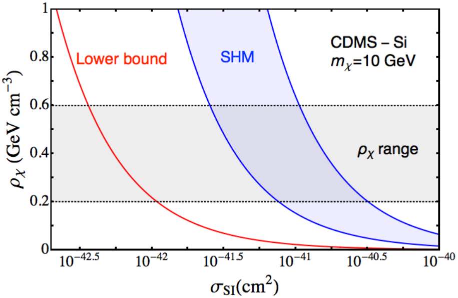
$$\geq \overline{\eta}(v_1)\, v_1 \quad B_2\,(\text{solid})$$



Lower bound on $\rho_\chi \sigma_{\rm SI/SD}$ from # of events (CDMS-Si)

$$B_2 \longrightarrow \rho_\chi \sigma_{\rm SI} \geq \frac{2\, m_\chi\, \mu_p^2}{MT\, \langle 1/v_m^A \rangle_{E_1}^{E_2}} N_{[E_1,E_2]} \qquad \text{“Events bound”}$$





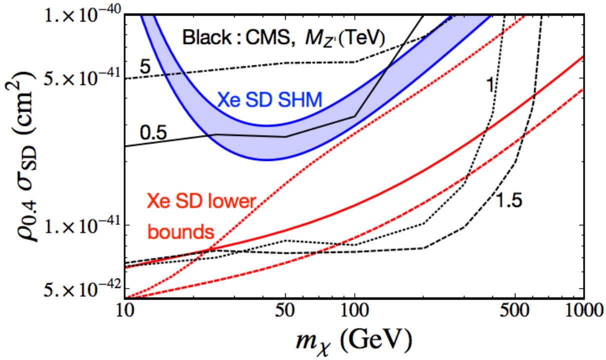
$\longrightarrow \sigma_{\rm SI} \lesssim 3 \cdot 10^{-43}\,{\rm cm}^2$ are disfavoured.

Lower bound on $\rho_\chi \sigma_{\rm SI/SD}$ from a spectrum (Xe SD mock)

$$B_1 \to \rho_\chi \sigma_{\rm SI} \geq \frac{2 m_\chi \mu_{\chi p}^2}{A^2} \left(v_1 \frac{\mathcal{R}(E_1)}{F_A^2(E_1)} + \int_{v_1}^{v_2} dv \frac{\mathcal{R}(E_R)}{F_A^2(E_R)} \right)$$ "Spectrum bound"

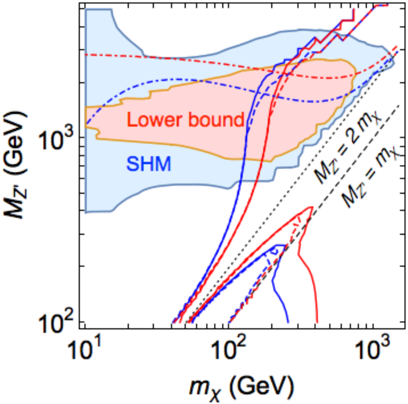
Simplified model: Majorana fermion χ, equal couplings to u, d, s, c:

$$\mathcal{L}_{\rm int} = g_\chi \bar{\chi} \gamma_\mu \gamma^5 \chi Z'^\mu + g_q \bar{q} \gamma_\mu \gamma^5 q Z'^\mu$$



Constraints from LHC and relic abundance ($\rho_\chi = 0.4$)

- Shaded area: LHC limits. $\Gamma_{Z'} > M_{Z'}/2$ (dotted-dashed).
- $\Omega_{\text{bound/SHM}} < \Omega_{\text{obs}}$ in red/blue for $g_\chi = 1\,(10)\,g_q$ dashed (solid).
- Ω bound also valid for multi-component if DD given by one species, and $\rho_\chi \propto \Omega_\chi$ (CDM). Conservative: more channels make it stronger.



A HI lower bound on $\rho_\chi \sigma_{\rm SI/SD}$ for annual modulations

arXiv [hep-ph]: 1506.03503

Lower bounds on $\rho_\chi \sigma_{\rm SI/SD}$ from a modulated spectrum [JHG]

Bounds based on an expansion of $\eta(v_m, t)$ on $v_e(t)$ [Schwetz, Zupan, JHG (2011, 2012)]

1. General bound (only time-dependence in $v_e(t)$, f constant):

$$\rho_\chi \sigma_{\rm SI} \geq \frac{2\, m_\chi\, \mu_p^2}{A^2} \frac{1}{v_e} \left(\frac{1}{v_1} + \int_{v_1}^{v_2} dv \frac{1}{v^2} \right)^{-1} \int_{v_1}^{v_2} dv \frac{\mathcal{M}(v)}{F_A^2(E_R)} \qquad \text{“General”}$$

   - Phase free.

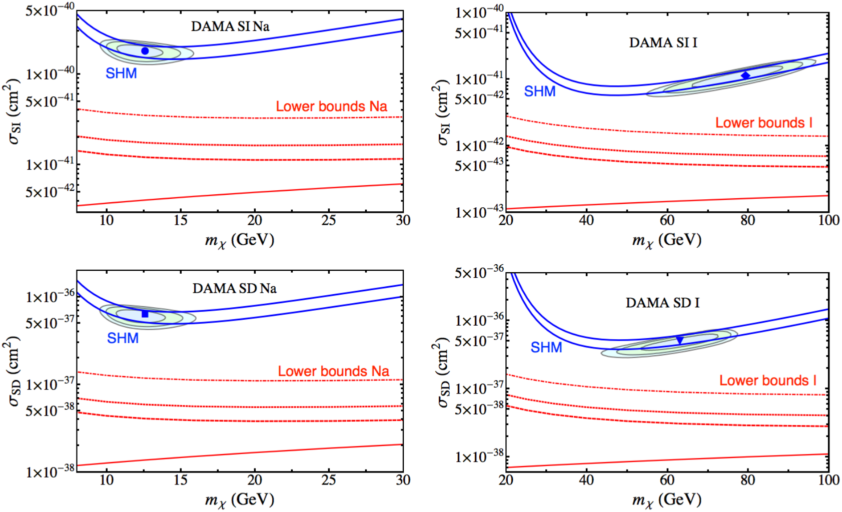
2. Symmetric bound (preferred direction of the DM flow):

$$\rho_\chi \sigma_{\rm SI} \geq \frac{2\, m_\chi\, \mu_p^2}{A^2} \left(\frac{1}{v_1} \right)^{-1} \frac{1}{\sin\alpha\, v_e} \int_{v_1}^{v_2} dv \frac{\mathcal{M}(v)}{F_A^2(E_R)} \qquad \text{“Symmetric”}$$

   - Phase constant.
   - $\sin\alpha = 0.5$: DM flow $\propto v_{\rm Sun}$, $t_0 =$June 2nd (isotropic, SHM, DD).

Example: DAMA (already strongly disfavoured HI by DD)

Blue: SHM. Red: from bottom “Spectrum” solid, “General” dashed and "Symmetric” dotted ($\sin\alpha = 1$), dotted-dashed ($\sin\alpha = 0.5$).



Summary and conclusions

Summary and conclusions

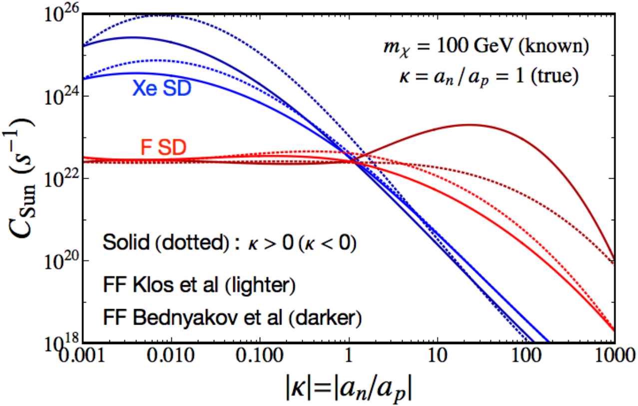
1. We derived a lower bound on the capture rate in the Sun in terms of a positive DD signal that is independent of $f(v)$, $v_{\rm esc}$, $\sigma_{\rm scatt}$ and ρ_χ.
   - We assumed that $f(v)$ and ρ_χ are constant on time scales relevant for equilibration in the Sun and the same in both DD and $C_{\rm Sun}$.
   - It is strong for SD and channels to $\nu\nu$, $\tau\tau$ and $m_\chi \gtrsim 100$ GeV.
2. We have derived a HI lower bound on $\rho_\chi \, \sigma_\chi$ for constant rates
   - It allows to restrict particle physics models by comparison with local density measurements, LHC, relic abundance or indirect detection.
3. We have extended it to annual modulations
   - Using previous works based on an expansion on the Earth's velocity.
   - We illustrate them with DAMA data.

Back-up slides

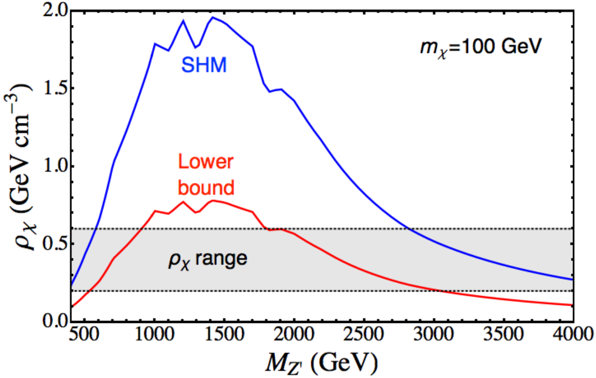
SD FF uncertainties, Xe (n), F (p). $\kappa \equiv a_n/a_p$

$$\mathcal{C}\tilde{f}_{\text{extr}}(v) = \mathcal{C}\tilde{f}(v)\frac{F^2_{\text{true}}(E_R)}{F^2_{\text{wrong}}(E_R)} - \frac{\tilde{\eta}(v)}{v}\frac{d}{dv}\left(\frac{F^2_{\text{true}}(E_R)}{F^2_{\text{wrong}}(E_R)}\right).$$

$$F^2_{\text{SD}}(E_R) = \Big(1+\kappa\Big)^2 S_{00}(E_R) + \Big(1-\kappa^2\Big) S_{01}(E_R) + \Big(1-\kappa\Big)^2 S_{11}(E_R)$$



Lower bound on ρ_χ for Xe SD from LHC limits



Complementarity of the signals

DD	$\Gamma_{\rm Sun}$	Lesson
No	No	Keep trying... Axions? Eventually, does DM interact non-gravitationally?
No	Yes	There is no halo-independent lower bound on $\mathcal{R}$ from a ν signal Dark disk? [Bruch, Choi...] Self-interactions? [Zentner...] Inelastic? [Nussinov, Menon, Shu...]
Yes	No	Halo-independent lower bound on capture. $\to$ Upper bounds on branching ratios [this work]. SD dominated by neutrons? Asymmetric DM with suppressed Γ? [Kaplan, Nussinov...]
Yes	Yes	Check if the lower bounds here derived are fulfilled. If so, extract DM properties by a fit [Arina, Serpico, Kavanagh...].

A halo-independent framework for DD and capture

Previous works have studied:

- The astrophysical uncertainties in DD [McCabe, Frandsen, Drees, Savage...].
- The astrophysical uncertainties in the capture rate [Bruch, Choi...].
- The complementarity of both signals [Arina, Serpico, Kavanagh...].
- Also a halo-independent framework for DD is well-established and extensively used [Fox, Del Nobile, Bozorgnia, Feldstein, JHG...].

In this work we establish a halo-independent framework for comparing a positive DD signal with the capture rate in the Sun:

- We use that $\sigma_{\rm scatt}$ enters in both the DD signal and the capture rate.
- However, the velocities probed by both are very different.

A lower bound on the capture

$$C_{\rm Sun} \geq 4\pi \sum_A A^2 \int_0^{R_{\rm S}} dr r^2 \rho_A(r) \int_{v_{\rm thr}}^{v_{\rm cross}^A} dv \left(-\frac{d\tilde{\eta}(v)}{dv} \right) \mathcal{F}_A(v,r)$$

$$= 4\pi \sum_A A^2 \int_0^{R_{\rm S}} dr r^2 \rho_A(r) \left[\tilde{\eta}_{\rm thr} \mathcal{F}_A(v_{\rm thr}, r) + \int_{v_{\rm thr}}^{v_{\rm cross}^A} dv \, \tilde{\eta}(v) \, \mathcal{F}'_A(v,r) \right],$$

where in the last line we integrated by parts, with $\mathcal{F}_A(v_{\rm cross}^A, r) = 0$.

Features:

- Either the derivative or the function $\tilde{\eta}(v)$, including its value at the threshold, have to be determined from DD.
- The bound is independent of the DM velocity distribution, the galactic escape velocity, the scattering cross section and the local DM density.

Numerical examples

We simulate mock data motivated by future experiments:

- Xenon, with $\sigma_{\rm SI} = 10^{-45}\,{\rm cm}^2$ and $\sigma_{\rm SD} = 2 \cdot 10^{-40}\,{\rm cm}^2$. Assuming $m_\chi = 100$ GeV, for an exposure of 1 ton yr, about 154 (267) events in the range $5 - 45$ keV for SI (SD) are predicted.
- Germanium, with $E_{\rm thr} = 1$ keV, focusing on low DM masses. Assuming $m_\chi = 6$ GeV and $\sigma_{\rm SI} = 5 \cdot 10^{-42}\,{\rm cm}^2$ and $\sigma_{\rm SD} = 2 \cdot 10^{-40}\,{\rm cm}^2$, 1.5×10^4 (2–3) events for SI (SD) predicted in the range 1–10 keV for an exposure of 100 kg yr with energy resolution of 30%.

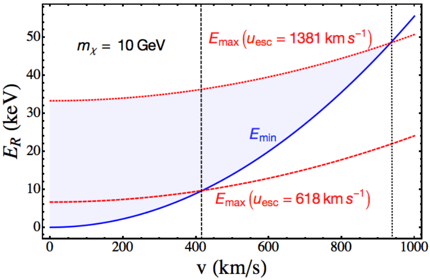
Maximum velocity for capture (shown for hydrogen, SD)

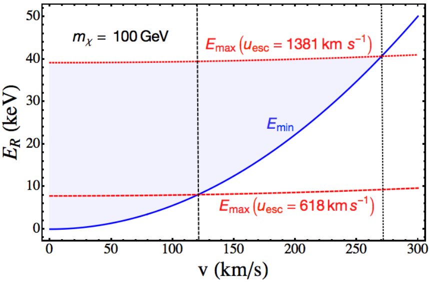
For the DM to be captured there is a minimal and maximal E_R:

$$E_{\min} = \frac{m_\chi}{2} v^2 \,, \qquad E_{\max} = \frac{2\mu_{\chi A}^2}{m_A} \left(v^2 + u_{\rm esc}^2(r)\right) .$$

These define the maximum velocity to be trapped:

$$v_{\rm cross}^A(r) = \frac{\sqrt{4 m_A m_\chi}}{|m_\chi - m_A|} u_{\rm esc}(r)$$





Capture rate in the Sun [Press, Griest, Gould, Bergstrom, Edsjo, Blennow...]

- The DM velocity inside the gravitational potential of the Sun $w^2 = v^2 + u_{\rm esc}^2(r)$, with $u_{\rm esc}^2(r)$ the escape velocity from the Sun.
- The capture rete is given by (notice that $wdw = vdv$)

$$C_{\rm Sun} = 4\pi \frac{\rho_\chi}{m_\chi} \sum_A \int_0^{R_{\rm S}} dr\, r^2 \int_0^\infty dv\, \tilde{f}(v)\, v\, w\, \Omega_A(w,r)\,,$$

with

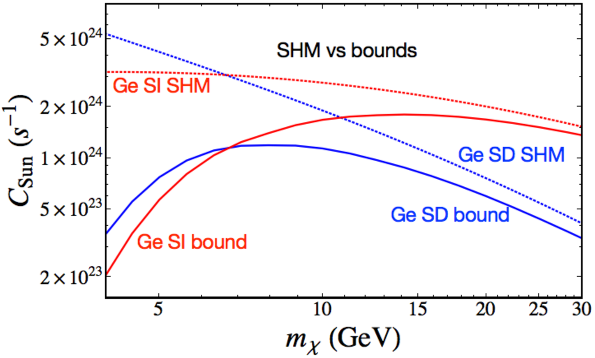
$$\Omega_A(w,r) = w\, \frac{\rho_A}{m_A} \int_{E_{\rm min}(w)}^{E_{\rm max}(w)} dE_R \frac{d\sigma_A}{dE_R}(w)\,,$$

where E_R is the nuclear recoil energy.

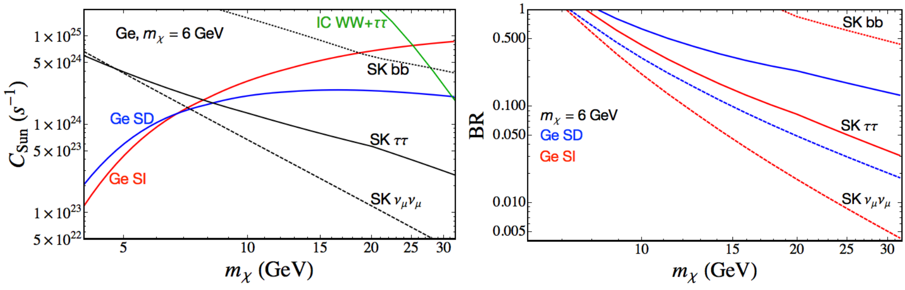
If equilibrium between capture and annihilation is reached:

$$\Gamma_{\rm Sun} = \frac{1}{2} C_{\rm Sun}$$

C_{Sun} for Ge



Results for Ge



Results:

- For xenon, for SD, annihilations into ν would be constrained to BR at the few % level. $\tau\tau, WW$ at the 10% level.
- For germanium, for both SD and SI direct annihilations into ν would be constrained to BR at the few % level. $\tau\tau$ are at *wrong* m_χ.
- Strong dependence on m_χ. Stronger bounds at the *wrong* m_χ.

Equilibrum

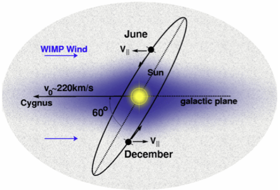
$t_{\text{eq}} \ll t_{\text{Sun}} \sim 4.5\,\text{Gyr}$, where:

$$t_{\text{eq}} = \frac{1}{\sqrt{C_{\text{Sun}}\,A_{\text{Sun}}}} \approx$$

$$\approx 0.5\,\text{Gyr}\left(\frac{10^{21}\,\text{s}^{-1}}{C_{\text{Sun}}}\right)^{1/2}\left(\frac{3\cdot 10^{-26}\,\text{cm}^3\,\text{s}^{-1}}{\langle\sigma v\rangle}\right)^{1/2}\left(\frac{100\,\text{GeV}}{m_\chi}\right)^{3/4}.$$

- A_{Sun} is the annihilation rate in the Sun
- $\langle\sigma v\rangle$ the thermal average of the annihilation cross section.
- Above $C_{\text{Sun}} \gtrsim 10^{21}\,\text{s}^{-1}$ in all cases except for SI interactions in Xe ($\sigma_{\text{SI}} = 10^{-45}\,\text{cm}^2$).
- In this case, equilibrium may not be reached for annihilation cross sections smaller or equal than the freeze-out one.

Halo-independent bounds on annual modulation in DD



Annual modulation [Freese et al]:

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

- The annual modulation $A_\eta(v_m)$ can be constrained in terms of the constant rate $\overline{\eta}(v_m)$ (almost) halo-independently [JHG, Schwetz, Zupan], by expanding $\eta(v,t)$ in $v_e/v \ll 1$, with $v_e \simeq 30\,\text{km/s}$.
- If there is a preferred direction in the DM velocity:

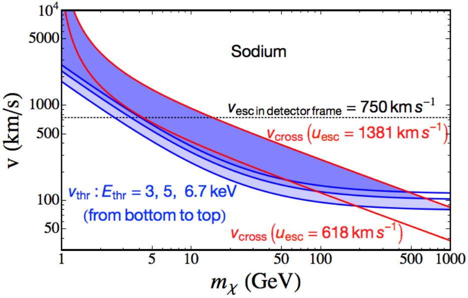
$$A_\eta(v_m) \leq -v_e \sin\alpha_{\text{halo}} \frac{d\overline{\eta}}{dv_m}.$$

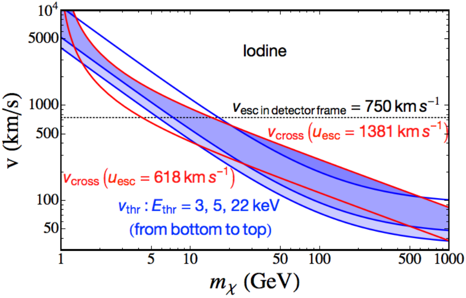
- Therefore there is also a lower bound on the capture for $A_\eta(v_m)$:

$$C_{\text{Sun}} \geq 4\pi \sum_A A^2 \int_0^{R_{\text{Sun}}} dr r^2 \rho_A(r) \int_{v_{\text{thr}}}^{v^A_{\text{cross}}} dv \, \frac{\tilde{A}_\eta(v)}{\sin\alpha_{\text{halo}}\, v_e} \mathcal{F}_A(v).$$

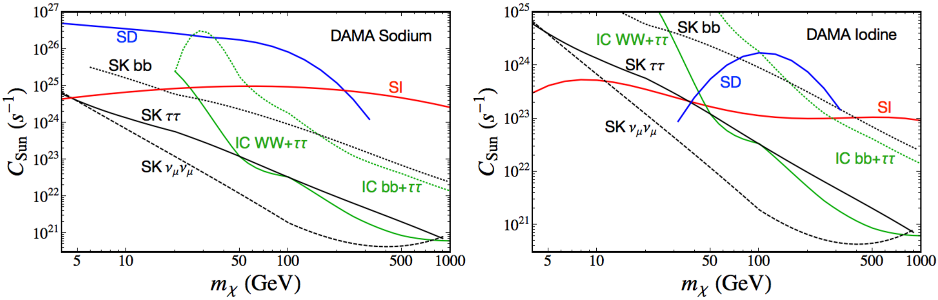
DAMA results

- Na dominates for DM masses $m_\chi \lesssim 20$ GeV.
- Iodine is relevant for larger DM masses.
- Small overlap for iodine for hydrogen (SD).





DAMA (already excluded halo-independently by DD)



DAMA in strong tension:

- For Na, for SI DM annihilation into ν, $\tau\tau$, bb are strongly constrained for $m_\chi \gtrsim 5, 10, 30$ GeV, respectively, while SD is excluded for $\nu\nu$ and $\tau\tau$, and also into bb for $m_\chi \gtrsim 8$ GeV.
- For I and SI, strong bounds for $m_\chi \gtrsim 10, 50$ GeV for $\nu\nu$ and $\tau\tau$.

Expansion of $\eta(v_m, t)$ in v_e/v

$v_{esc} \gg \langle v \rangle > v_m \gg v_e$, so we can expand $\eta(v_m, t)$ to first order in v_e:

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

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

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

- $\overline{\eta}(v_m)$ is constant, A_η is modulated, with observed rates:

$$\overline{R} \equiv \mathcal{C} F^2(E_r) \overline{\eta}(v_m) \;\; \text{and} \;\; A_R \equiv \mathcal{C} F^2(E_r) A_\eta$$

The general bound on the annual modulation

1. Halo "smooth" on $\lesssim v_e \sim 30\,\text{km/s}$.
2. Only time dependence in $v_e(t)$, not in f_{Sun} (no change on months).

$$\int_{v_{m1}}^{v_{m2}} dv_m\, A_\eta(v_m) \leqslant v_e \left[\overline{\eta}(v_{m1}) + \int_{v_{m1}} dv\, \frac{\overline{\eta}(v)}{v} \right]$$

3. If there is a constant $\hat{v}_{HALO}$ governing the modulation:

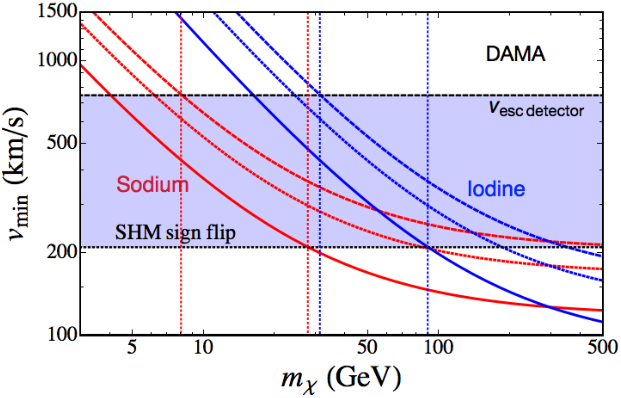
$$\int_{v_{m1}}^{v_{m2}} dv_m\, A_\eta(v_m) \leqslant \sin\alpha\, v_e\, \overline{\eta}(v_{m1})$$

where:

- in general $\sin\alpha$ can be set to 1.
- $\sin\alpha = 0.5$ when $\hat{v}_{HALO} \propto \hat{v}_{SUN}$ (isotropic, SHM, DD...). Then $t_0 =$ June 1st.

DAMA signal in the SHM

- Sodium (red) and iodine (blue) for $E_R = 2,\ 4\,,6\,\mathrm{keVee}$ (from bottom to top as solid, dotted and dashed curves).
- Dotted black below which $\mathcal{M} < 0$, and as dashed black the typical escape velocity in the detector rest frame.
- SHM: $8 \lesssim m_\chi\,(\mathrm{GeV}) \lesssim 30$ ($30 \lesssim m_\chi\,(\mathrm{GeV}) \lesssim 90$) for Na (I)

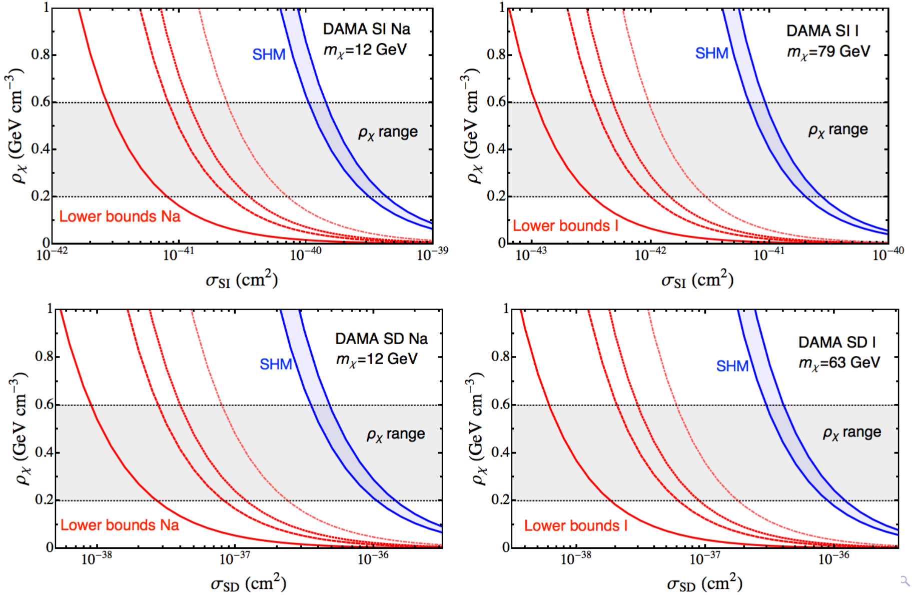


DAMA fit to the SHM

$v_{esc} = 550$ km/s, $\rho_\chi = 0.4\,\mathrm{GeV\,cm^{-3}}$, $q_{Na} = 0.3$ and $q_I = 0.09$. Equal couplings to protons and neutrons

	I			**Na**		
	m_χ (GeV)	$\sigma_{SI/SD}$ (cm^2)	χ^2_{min}/dof	m_χ (GeV)	$\sigma_{SI/SD}$ (cm^2)	χ^2_{min}/dof
SI	79.4	$1.1 \cdot 10^{-41}$	7.7/6	12.6	$1.8 \cdot 10^{-40}$	8.3/6
SD	63.1	$5.0 \cdot 10^{-37}$	7.9/6	12.6	$6.3 \cdot 10^{-37}$	8.7/6

Local energy density



Multi-target bounds

Bounds (in black) for DAMA modulation for SI (top) and SD (bottom)