A halo-independent lower bound on the DM capture rate in the Sun from a DD signal

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Outline

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3 A halo-independent (HI) lower bound on $C_{\rm Sun}$
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Motivation

Motivation: derive a new HI framework for DD and capture

Uncertainties on $f(v)$, ρ are crucial on interpretation of DM signals.

1. Many studies:
   - For DD [McCabe, Frandsen, Drees, Savage...]. Talk by N. Bozorgnia.
   - For $C_{\rm Sun}$ [Bruch, Choi...].
2. Also halo-independent (HI) methods:
   - For DD: for fixed m_χ, compare $\tilde{\eta}(v_m, t)$ (detector independent) in same v_m range [Fox, Del Nobile, Bozorgnia, Feldstein, JHG...]. Talk by P. Gondolo.
   - HI upper bounds from DD and $\Gamma_{\rm Sun}$ [Ferrer...]. Talks by S. Wild.
   - New HI framework to compare DD with ρ_χ, LHC, Ω_χ, and indirect detection [Blennow, JHG, Ferrer]. Talk by S. Vogl.

Here new HI framework for comparing a positive DD signal with $\Gamma_{\rm Sun}$:

- We use that both the DD signal and $C_{\rm Sun}$ depend on $\sigma_{\rm SI/SD}$.
- However, the velocities probed by both are very different.

Direct detection and the capture rate in the Sun

Direct detection: there is a minimum velocity v_m

Goodman, Drukier, Freese...

- For elastic SI interactions the event rate can be expressed as

$$\mathcal{R}(E_R, t) = A^2 F_A^2(E_R)\tilde{\eta}(v_m, t),$$

where

$$\tilde{\eta}(v_m, t) \equiv \mathcal{C} \int_{v_m}^{\infty} dv v \tilde{f}_{\rm det}(v, t), \qquad \text{with} \qquad \mathcal{C} \equiv \frac{\rho_\chi \sigma_{\rm SI/SD}}{2 m_\chi \mu_{\chi p}^2} .$$

- $v > v_m$ by kinematics, with:

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

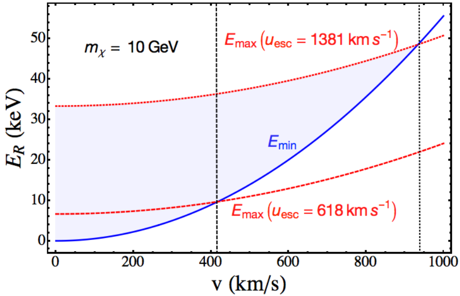
Capture: there is a maximum velocity $v_{\rm cross}$ (shown H, SD)

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

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

These define the maximum velocity to be trapped:

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



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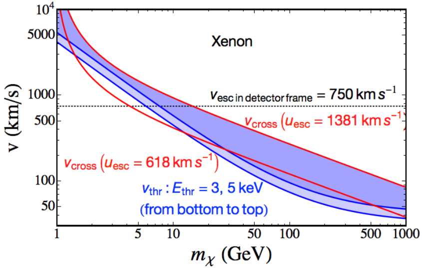
Overlap in velocity (H, SD) and assumptions of the bound

Gould, Edsjo, Kavanagh, Blennow...

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

- DD is sensitive to $v > v_{\rm thr}$.
- Capture for $v < v^A_{\rm cross}(r)$.



We can derive a lower bound on the capture, assuming:

1. We use that $v_e \approx 29\,{\rm km/s} \ll v_m$ so that:

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

2. $f(v)$, ρ_χ constant so they are equal for the capture and for DD.

A lower bound on the capture

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

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

From a perfectly measured 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 $f(v)$, $v_{\rm esc}$, $\sigma_{\rm SI/SD}$ and ρ_χ.

Equilibrium between capture and annihilations in the Sun

- DM obeys ($A_{\rm Sun}$ annihilation rate, no evaporation for $m_\chi \gtrsim 3.5$ GeV):

$$\frac{dN}{dt} = C_{\rm Sun} - A_{\rm Sun} N^2\,.$$

- Equilibrium ($dN/dt = 0$) occurs for $t_{\rm eq} \ll t_{\rm Sun} \sim 4.5\,{\rm Gyr}$, where:

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

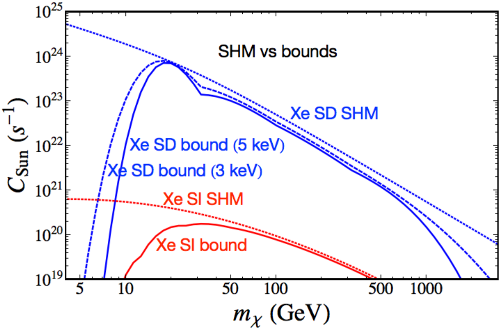
$$\approx 0.5\,{\rm Gyr} \left(\frac{10^{21}\,{\rm s}^{-1}}{C_{\rm Sun}}\right)^{1/2} \left(\frac{3\cdot 10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}}{\langle\sigma v\rangle_{\rm ann}}\right)^{1/2} \left(\frac{100\,{\rm GeV}}{m_\chi}\right)^{3/4},$$

  where $\langle\sigma v\rangle_{\rm ann}$ is the thermally-averaged annihilation cross section.
- For $C_{\rm Sun} \lesssim 10^{21}\,{\rm s}^{-1}$, no equilibrium reached if $\langle\sigma v\rangle_{\rm ann} < \langle\sigma v\rangle_{\rm fo}$.
- If it is reached $\Gamma_{\rm Sun}$ given solely in terms of $C_{\rm Sun}$:

$$\Gamma^{\rm eq}_{\rm Sun} = \frac{N^2}{2} A_{\rm Sun} = \frac{C_{\rm Sun}}{2}.$$

Numerical analysis

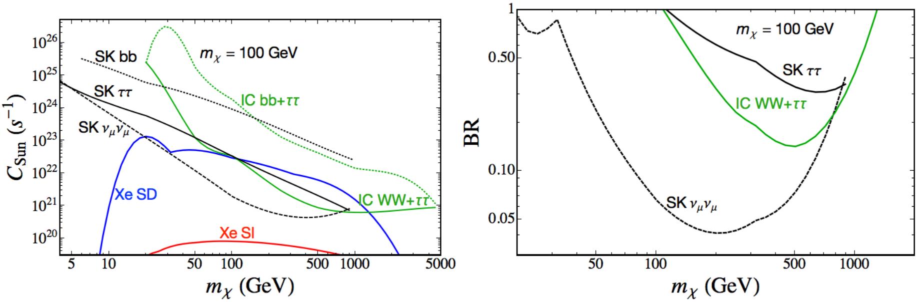
Comparison with the SHM



Our bounds are strongest:

- For Xe in $20 \lesssim m_\chi \lesssim 1000$ GeV (SD) and $m_\chi \gtrsim 50$ GeV (SI).

$C_{\rm Sun}$ and upper bounds on BR for Xe mock signal

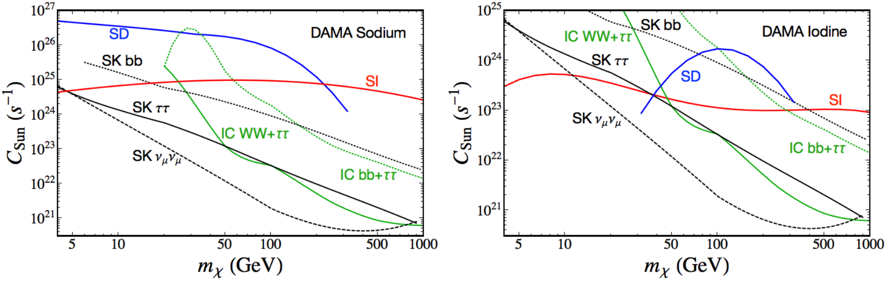


Results:

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

DAMA (already strongly disfavored HI by DD)

Using HI bounds on modulation: $A_\eta(v_m) \leq -v_e s_\alpha \frac{d\overline{\eta}}{dv_m}$ [Schwetz, Zupan, JHG].



DAMA in strong tension:

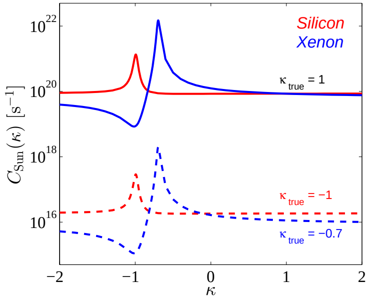
- Na: for SI annihilation into $\nu\nu$, $\tau\tau$ (bb) are strongly constrained for $m_\chi \gtrsim 5\,(15)$ GeV, while SD is excluded for all channels.
- I: for SI, strong bounds for $m_\chi \gtrsim 10, 35$ GeV for $\nu\nu$, $\tau\tau$. For SD $m_\chi \gtrsim 40\,(80)$ GeV excluded for $\nu\nu$, $\tau\tau$ (bb).

Unknown couplings to n and p, and uncertainties in SD FF

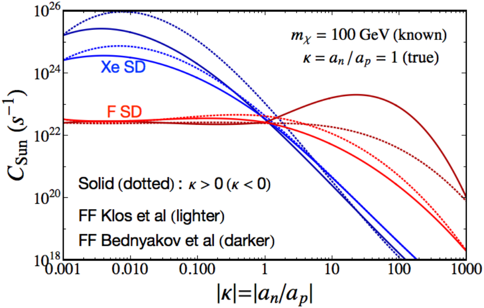
The extracted $f(v)$ depends on couplings to n and p, and FF:

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

Isospin violation (IV), $\kappa \equiv f_n/f_p$:



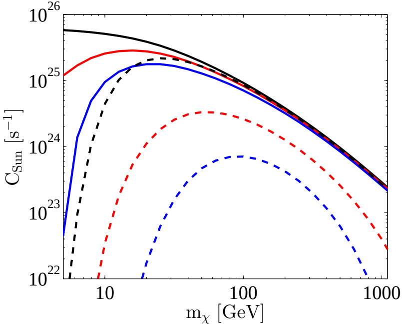
SD Xe (n) & F (p), $\kappa \equiv a_n/a_p$:

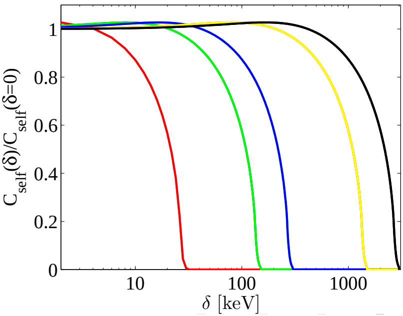


Preliminary: inelastic ($m_\chi^* - m_\chi = \delta$), self-interactions

Blennow, Clementz, JHG: in preparation.

- Left) $C_{\rm Sun}$ for inelastic scattering (solid) and bounds (dashed) δ (keV) black: 0, red: 25, blue: 50.
- Right) $C_{\rm Sun}$ for inelastic self-interactions (solid) [no bounds possible] m_χ (GeV) red: 10, green: 50, blue: 100, yellow: 500, black: 1000.





Summary and conclusions

Summary

- We derived a lower bound on $C_{\rm Sun}$ in terms of a positive DD signal that is independent of $f(v)$, $v_{\rm esc}$, $\sigma_{\rm SI/SD}$ and ρ_χ.
- We assumed $f(v)$, ρ_χ constant on $t_{\rm eq}$ and equal in DD and $C_{\rm Sun}$.
- If equilibrium between capture-annihilations is reached (otherwise need $\sigma_{\rm ann}$) one can derive upper bounds on BR from no ν signal.
- It is strong for SD and channels to $\nu\nu$, $\tau\tau$ and $m_\chi \gtrsim 100$ GeV.
- Extension to inelastic scattering, isospin-violation and self-interactions in preparation [Blennow, Clementz, JHG].

Concluding remarks: complementarity of the signals

DD	Γ_{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, JHG (in preparation)...] IV? Inelastic? [Nussinov, Menon, Shu, JHG (in preparation)...]
Yes	No	$\rightarrow$ HI upper bounds on BRs [this work]. SD dominated by neutrons? Asymmetric DM with suppressed Γ? [Kaplan, Nussinov...] p-wave suppressed σ_{ann}? [Kappl...] Channels without ν (or not energetic enough)? IV? Inelastic? [Nussinov, Menon, Shu, JHG (in preparation)...]
Yes	Yes	Check if the lower bounds here derived are fulfilled. If so, extract DM properties by a fit [Arina, Serpico, Kavanagh...].

Back-up slides

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:

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

A lower bound on the capture

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

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

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

Features:

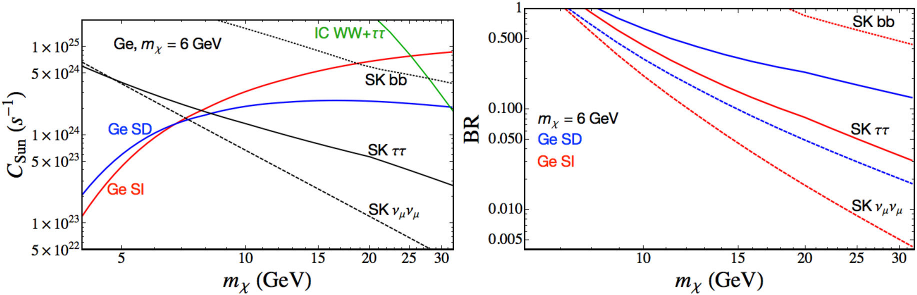
- Either the derivative or the function $\tilde{\eta}(v)$, including its value at the threshold, have to be determined from DD.
- The bound is independent of the DM velocity distribution, the galactic escape velocity, the scattering cross section and the local DM density.

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%.

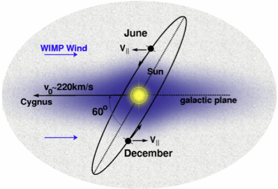
$C_{\rm Sun}$ and BR assuming equilibrium ($\Gamma_{\rm Sun} = C_{\rm Sun}/2$) for Ge



Results:

- For Ge, 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.

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 $\bar{\eta}(v_m)$ (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:

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

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

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

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:

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

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

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

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

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

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).

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

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

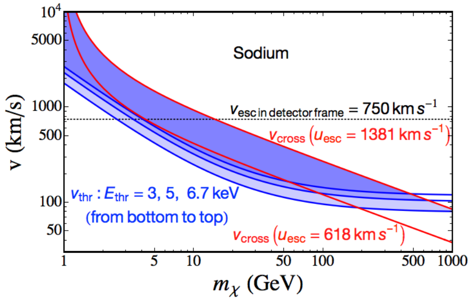
$$\int_{v_{m1}}^{v_{m2}} dv_m\, A_\eta(v_m) \leqslant \sin\alpha\, v_e\, \bar{\eta}(v_{m1})$$

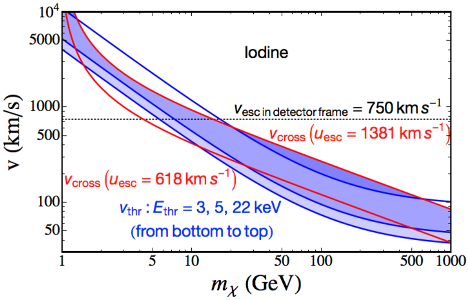
where:

- in general $\sin\alpha$ can be set to 1.
- $\sin\alpha \simeq 0.5$ when $\hat{v}_{HALO} \propto \hat{v}_{SUN}$ (isotropic, SHM, DD...). And phase $t_0 =$ June 2nd.

DAMA results

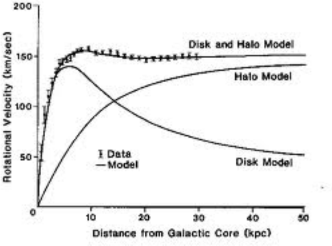
- Na dominates for DM masses $m_\chi \lesssim 20$ GeV.
- I is relevant for larger DM masses.
- Small overlap for I for H (SD).





Evidence for dark matter

Rotation curves of spiral galaxies:



Bullet cluster (X-rays + grav. lensing):

- CMB spectrum alone: $\Omega_{DE} \approx 0.69$, $\Omega_B \approx 0.05$, $\Omega_{DM} \approx 0.26$
- Combination of data from CMB, SN IA, BBN and clusters.
- M/L ratio in galaxy clusters (virial theorem to gas).
- Growth of structure (N-body simulations).
- Globular clusters in galaxies...

Properties of a DM particle (or particles)

1. Interacts gravitationally.
2. With the observed density (long-lived/ stable).
3. Neutral.
4. Cold (or warm), otherwise small scales would have been erased.
5. Collisionless: it does not dissipate, it forms haloes.

We assume DM is a Weakly Interacting Massive Particle (WIMP):

- weak-scale cross-section with the SM.
- mass $m_\chi \sim \mathcal{O}(1 - 10^3)$ GeV.

which yield right relic abundance (WIMP miracle) and make DD possible.