Self-interacting Inelastic Dark Matter in the Light of XENON1T Excess

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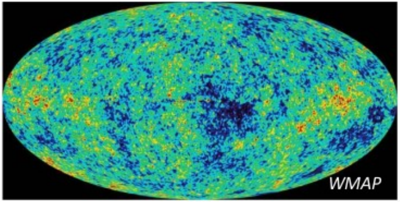
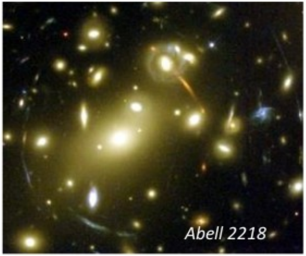
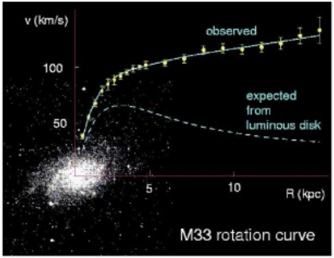
ΛCDM: Cold-Collisionless Dark Matter



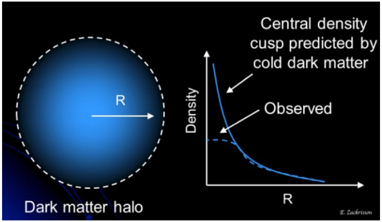




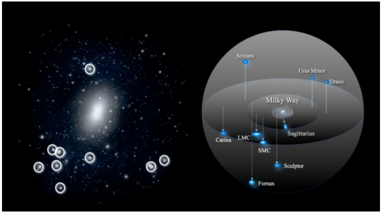
Courtesy: Sean Tulin (frascati'15)

Issues with ΛCDM

- **The cusp-core problem:**
  ΛCDM /NFW: Central densities of halos→ **Cuspy** ($\rho \sim r^{-1}$)
  Observation: Central densities of halos→ **Cored** ($\rho \sim r^{0}$).



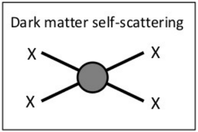
- **The missing satellite Problem:** ΛCDM Simulations predict more satellites than those observed.
- **Too big to fail Problem:** Observed satellites of the MW are not massive enough to be consistent with predictions of ΛCDM.



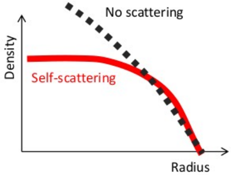
(Weinberg, Bullock, Governato, Kuzio de Naray, Peter(2013))

Self-interacting dark matter : a promising alternative

CDM structure problems can be resolved introducing dark matter self-interaction.
Dark matter particles in halos elastically scatter with other dark matter particles. *(Spergel and Steinhardt (2000)*.

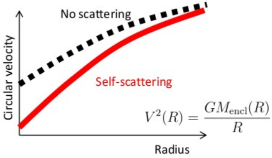


Cusp-Core Problem:



Particles get scattered out of dense halo centers.

The Missing Satellite Problem :



Rotation curves reduced (less enclosed mass)
Simulated satellites matched to observations.

Courtesy: Sean Tulin (frascati'15)

Velocity dependent self- scattering

Low energies ($v/c \sim 10^{-4}$)

Medium energies ($v/c \sim 10^{-3}$)

High energies ($v/c \sim 10^{-2}$)

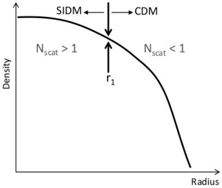
Stronger self-scattering needed for (dwarf-sized) halos.
$\sigma/m \sim 0.5 - 10 cm^2/g$ at dwarf-scale velocity $v \sim 10 km/s$.

Weaker self-scattering favoured by cluster merging/halo profiles.
$\sigma/m \sim 0.1 - 1 cm^2/g$ at cluster-scale velocity $v \sim 1000 km/s$.

A velocity-dependent DM self-scattering.

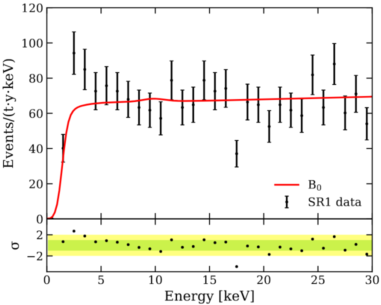
$$\sigma \sim \frac{g^4 m_{DM}^2}{m_{mediator}^4}$$

Popular choice: a light mediator ($m_{mediator} << m_{DM}$) with mass 1-100 MeV.



Courtesy: Sean Tulin (frascati'15)

XENON1T Excess



The XENON1T detector. Visible is the bottom array of photomultiplier tubes, and the copper structure that creates the electric drift field.

The excess observed in XENON1T in the electronic recoil background at low energies, compared to the level expected from known backgrounds indicated as the red line.

Courtesy: XENON1T Collaboation

The model for inelastic self-interacting dark matter

Fields		$\underbrace{SU(3)_C \otimes SU(2)_L \otimes U(1)_Y} \otimes U(1)_X$			
Dirac Singlet	Ψ	1	2	-1	1
Scalar Singlet	$\Phi = \left(\frac{h+v+iz}{\sqrt{2}}\right)$	1	1	1	-2

The Model Lagrangian:

$$\mathcal{L}_{DM} = i\overline{\Psi}\gamma^{\mu} D_{\mu}\Psi - M(\overline{\Psi}_L\Psi_R + \overline{\Psi}_R\Psi_L) - (y_L\Phi\overline{(\Psi_L)^c}\Psi_L) + (y_R\Phi\overline{(\Psi_R)^c}\Psi_R + h.c.) + \frac{\epsilon}{2}B^{\alpha\beta}Y_{\alpha\beta}$$

where $D_{\mu} = \partial_{\mu} + ig'Z'_{\mu}$ and

$$\mathcal{L}_{\Phi} = (D_{\mu}\Phi)^{\dagger}(D^{\mu}\Phi) + m^2_{\Phi}\Phi^{\dagger}\Phi - \lambda_{\phi}(\Phi^{\dagger}\Phi)^2 - \lambda_{\Phi H}(\Phi^{\dagger}\Phi)(H^{\dagger}H)$$

After spontaneous symmetry breaking:

$$\begin{aligned}\mathcal{L}_{DM} = &\frac{1}{2}\overline{\psi_1}\gamma^{\mu}\partial_{\mu}\psi_1 + \frac{1}{2}\overline{\psi_2}\gamma^{\mu}\partial_{\mu}\psi_2 - \frac{1}{2}M_1\overline{\psi_1}\psi_1 - \frac{1}{2}M_2\overline{\psi_2}\psi_2 + \frac{\epsilon}{2}B^{\alpha\beta}Y_{\alpha\beta}\\ &+ ig'Z'_{\mu}\overline{\psi_1}\gamma^{\mu}\psi_2 + \frac{1}{2}g'Z'_{\mu}\frac{m_-}{M}(\overline{\psi_2}\gamma^{\mu}\gamma^5\psi_2 - \overline{\psi_1}\gamma^{\mu}\gamma^5\psi_1)\\ &+ \frac{1}{2}(y_L\cos^2\theta - y_R\sin^2\theta)\overline{\psi_1}\psi_1\phi + \frac{1}{2}(y_R\cos^2\theta - y_L\sin^2\theta)\overline{\psi_2}\psi_2\phi\end{aligned}$$

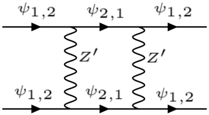
where $\sin\theta \approx m_-/M$.

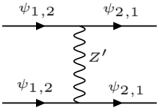
Very light Z' to explain velocity dependent self-interaction.

The mass splitting $\Delta m \sim 2$ keV to explain XENON1T excess.

Dark Matter Self-scattering

Relevant Feynman diagrams:





The relevant Lagrangian terms for self-scattering:

$$\mathcal{L} = ig' Z'_\mu \overline{\psi_1}\gamma^\mu \psi_2 + \frac{1}{2} g' Z'_\mu \frac{m_-}{M} (\overline{\psi_2}\gamma^\mu \gamma^5 \psi_2 - \overline{\psi_1}\gamma^\mu\gamma^5\psi_1).$$

Potential for two Majorana fermion DM with a light mediator:

$$V(r) = \begin{pmatrix} 0 & -\alpha e^{M'_Z r} \\ -\alpha e^{M'_Z r} & 2\Delta m \end{pmatrix}.$$

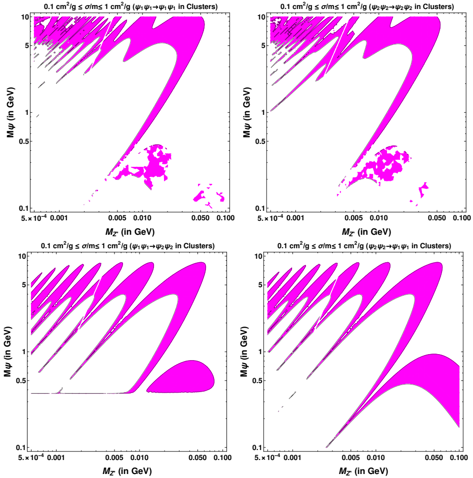
The two body Schrodinger equation for relative motion is

$$\frac{1}{M_\psi} \nabla^2 \Psi(\vec{r}) = (V(r) - M_\psi v^2)\Psi(\vec{r})$$

Low energy phenomenology $\rightarrow$ needs to solve the Schroedinger equation!

(Ref: K. Schutz and T. R. Slatyer, JCAP 01 (2015) 021, [arXiv:1409.2867].)

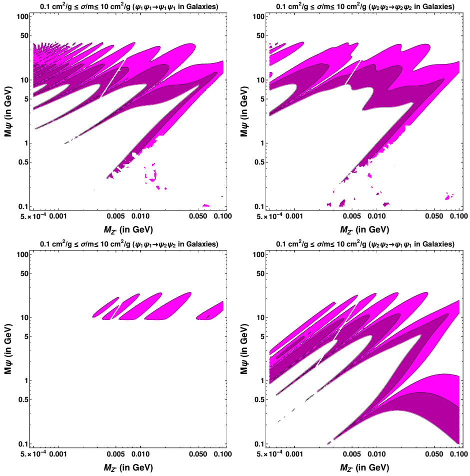
Self-interaction in Clusters



Self-interaction cross-section (σ/m) in the range $0.1 - 1\mathrm{cm}^2/\mathrm{g}$ (light pink coloured region) for clusters ($v \sim 1000 km/s$).

- Top left (right) panel: elastic scattering of ground (excited) to ground (excited) state.
- Bottom left (right) panel: up (down) scattering of ground (excited) to excited (ground) state.

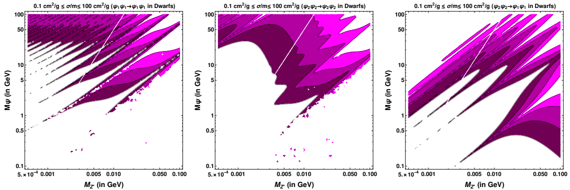
Self-interaction in Galaxies



Self-interaction cross-section (σ/m) in the range 0.1 – 10 cm^2/g for galaxies ($v \sim 200$ $\mathrm{km/s}$).

- Light pink coloured region represents the parameter space where 0.1 $\mathrm{cm}^2/\mathrm{g} < \sigma/m <$ 1 cm^2/g.
- dark pink colour represents regions of parameter space where 1 $\mathrm{cm}^2/\mathrm{g} < \sigma/m <$ 10 cm^2/g.

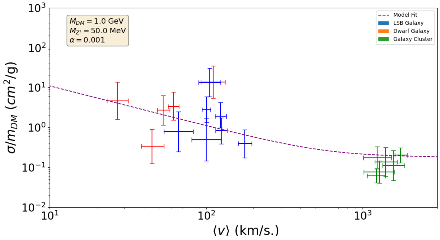
Self-interaction in Dwarfs



Light pink: $0.1\ \mathrm{cm}^2/\mathrm{g} < \sigma/m < 1\ \mathrm{cm}^2/\mathrm{g}$
Dark pink: $1\ \mathrm{cm}^2/\mathrm{g} < \sigma/m < 10\ \mathrm{cm}^2/\mathrm{g}$
Maroon: $10\ \mathrm{cm}^2/\mathrm{g} < \sigma/m < 100\ \mathrm{cm}^2/\mathrm{g}$.

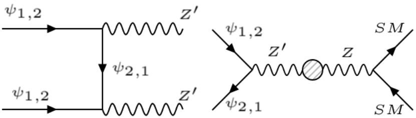
Velocity dependent cross-section

- Our model gives velocity dependent self-interacting cross-section.
- Maximum self-scattering at dwarf scale while retains CDM behaviour at large scales.
- Fig: σ/m_{DM} as function of average collision velocity.



Dark matter relic density: Issues with thermal relic

Relevant Feynman diagrams:



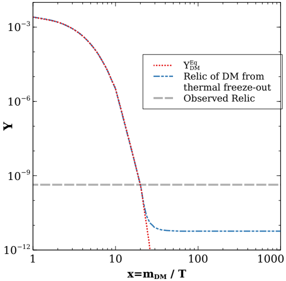
Dominant contribution from the left diagram: $\langle \sigma v \rangle \sim \frac{\pi \alpha_X^2}{M_\psi^2}$

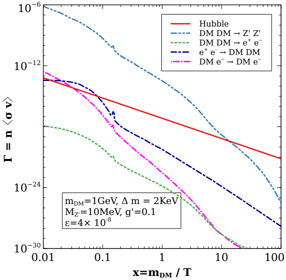
Too much annihilation of DM to Z' Z'.

Thermal relic is under-abundant !!

$\rightarrow$ go for freeze-in production.

but dark sector thermalizes within itself!





DM Production : A hybrid set-up of freeze-in and freeze-out

- The epoch of reaching kinetic equilibrium between DM-SM sectors (*i.e.,*T'=T) till $x < 0.03$.
- One with $0.03 < x < 100$ where the dark sector is decoupled from the thermal bath and its temperature evolves as $\frac{T'}{T} = \left(\frac{g_{*s}^{\rm SM}(T)}{g_{*s}^{\rm SM}(T_D)}\right)^{1/3}$.
- Introduce extra singlet scalar η to rescue the relic!

$$\frac{dY_\eta}{dx'} = -\frac{s(M_\psi)}{x'^2 H(M_\psi)\left(\frac{T'}{T}\right)} \langle\sigma v\rangle_{\eta\eta\to HH}(Y_\eta^2 - (Y_\eta^{eq})^2) - \frac{x'\left(\frac{T'}{T}\right)^2(\langle\Gamma_{\eta\to\overline{\psi_1}\psi_1}\rangle + \langle\Gamma_{\eta\to\overline{\psi_2}\psi_2}\rangle)}{H(M_\psi)} Y_\eta;$$

$$\frac{dY_{\psi_1}}{dx'} = \left(\frac{T'}{T}\right)^2\left[\frac{s(M_\psi)}{x'^2 H(M_\psi)}\left(\frac{g'_{*s}(T_D)}{g_{*s}(T_D)}\right)\left(\langle\sigma v\rangle_{e^+e^-\to\psi_1\psi_1}(Y_{\psi_1}^{eq})^2 - \langle\sigma v\rangle_{\psi_1\psi_1\to Z'Z'}Y_{\psi_1}^2 + \langle\sigma v\rangle_{\psi_2\psi_2\to\psi_1\psi_1}\left(Y_{\psi_2}^2 - \frac{(Y_{\psi_2}^{eq})^2}{(Y_{\psi_1}^{eq})^2}Y_{\psi_1}^2\right)\right) + \frac{x'\left(\frac{g_{*s}(T_D)}{g'_{*s}(T_D)}\right)\langle\Gamma_{\eta\to\overline{\psi_1}\psi_1}\rangle}{H(M_\psi)}Y_\eta\right];$$

$$\frac{dY_{\psi_2}}{dx'} = \left(\frac{T'}{T}\right)^2\left[\frac{s(M_\psi)}{x'^2 H(M_\psi)}\left(\frac{g'_{*s}(T_D)}{g_{*s}(T_D)}\right)\left(\langle\sigma v\rangle_{e^+e^-\to\psi_2\psi_2}(Y_{\psi_2}^{eq})^2 - \langle\sigma v\rangle_{\psi_2\psi_2\to Z'Z'}Y_{\psi_2}^2 - \langle\sigma v\rangle_{\psi_2\psi_2\to\psi_1\psi_1}\left(Y_{\psi_2}^2 - \frac{(Y_{\psi_2}^{eq})^2}{(Y_{\psi_1}^{eq})^2}Y_{\psi_1}^2\right)\right) + \frac{x'\left(\frac{g_{*s}(T_D)}{g'_{*s}(T_D)}\right)\langle\Gamma_{\eta\to\overline{\psi_2}\psi_2}\rangle}{H(M_\psi)}Y_\eta\right]$$

where, $x' = \frac{m_{\rm DM}}{T'} = \frac{M_\psi}{T'}$, $s(M_\psi) = \frac{2\pi^2}{45}g_{*s}M_\psi^3$ and $H(M_\psi) = 1.67 g_*^{1/2}\frac{M_\psi^2}{M_{Pl}}$. Here $M_\psi \approx M_1 \approx M_2$.

DM relic density

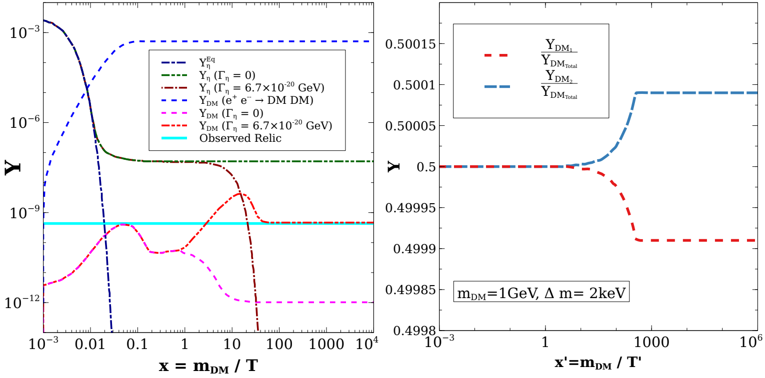
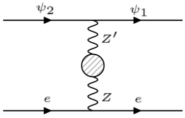


Figure: Left: Comoving number densities of DM and scalar singlet for different cases. Right: Fractional contributions $Y_{\mathrm{DM}_1}/Y_{\mathrm{DM}_{\mathrm{Total}}}$ and $Y_{\mathrm{DM}_2}/Y_{\mathrm{DM}_{\mathrm{Total}}}$ to DM relic density for $\Delta m = 2 \times 10^{-6}$ GeV

Recent XENON1T excess: An electron recoil event

DM-electron scattering:

$$\sigma(\psi_2 e \to \psi_1 e) = \frac{16\pi\alpha_Z\alpha^{'}\epsilon^2 m_e^2}{M_{Z'}^4}$$



For fixed velocity v of heavier DM χ_2:

$$\frac{d\langle\sigma v\rangle}{dE_r} = \frac{\sigma_e}{2m_e v}\int_{q-}^{q+} a_0^2 q dq |F(q)|^2 K(E_r, q) \,,$$

with velocity dispersion: $f(v) = Av\mathrm{Exp}[-3(v - v_m)^2/2\sigma_v^2]$, where A is the normalisation constant such that $\int f(v)dv = 1$;

$$\frac{d\langle\sigma v\rangle}{dE_r} = \frac{\sigma_e}{2m_e}\int_0^{v_{esc}} dv \frac{f(v)}{v}\int_{q-}^{q+} a_0^2 q dq |F(q)|^2 K(E_r, q) \,.$$

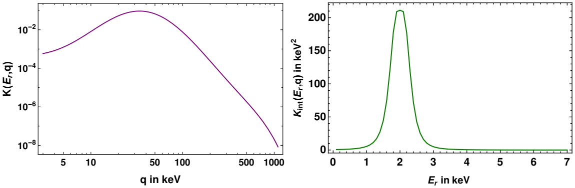


Figure: Left panel: Atomic excitation factor is shown as a function of momentum transferred. Right panel: The atomic excitation factor after being integrated over the transferred momentum, is shown as a function of the transferred recoil energy E_r.

Fit to XENON1T excess

Parameters fixed for the fit:

m_{DM} = 1 GeV, $\Delta m = 2$ keV.

$\sigma_v = \sqrt{3/2} v_m$ with $v_m = 1 \times 10^{-3}$

$g' = 0.1$, $M_{Z'} = 10$MeV, $\epsilon = 4 \times 10^{-8}$

$\sigma(\psi_2 e \to \psi_1 e) = 1.9 \times 10^{-17}\ \mathrm{GeV}^{-2}$.

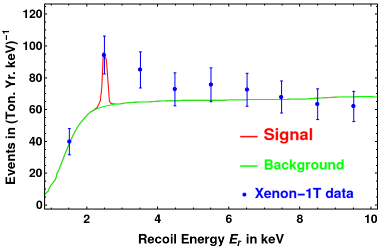
The differential event rate for $\psi_2 e \to \psi_1 e$:

$$\frac{dR}{dE_r} = n_T n_{\mathrm{DM}} \frac{d\langle \sigma v \rangle}{dE_r}$$

where $n_T = 4 \times 10^{27}\ \mathrm{Ton}^{-1}$ is the number density of Xenon atoms and n_{DM} is the number density of the dark matter particle.

Detected recoil energy spectrum is given by:

$$\frac{dR_{\mathrm{det}}}{dE_r} = \frac{n_T n_{\mathrm{DM}} \sigma_e a_0^2}{2 m_e} \int dE\ \ \zeta(E, E_r) \left[\int_0^{v_{esc}} dv \frac{f(v)}{v} \int_{q-}^{q+} dq\ \ qK(E_r, q) \right]$$



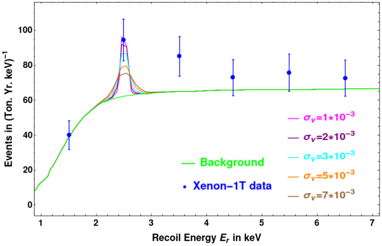


Figure: Fit to XENON1T electron recoil excess with the self interacting inelastic DM in our model.

Summary

- We studied the possibility of self-interacting DM as a possible explanation of the recently reported XENON1T excess.
- XENON1T excess can arise due to inelastic nature of DM so that the heavier DM can undergo a down scattering with electrons.
- If the mediator is sufficiently light compared to DM, it gives rise to the required self-interaction cross section σ/m required to solve the small scale structure problems associated with cold dark matter.
- After applying all relevant bounds, there exists only a tiny parameter space (the blue shaded region not overlapped with other regions) that can give rise to the required XENON1T excess, DM self-interactions for 1 GeV inelastic DM with mass splitting of 2 keV while being consistent with all other bounds.
- Future data from XENON1T and others should be able to further constrain or confirm this predictive scenario.

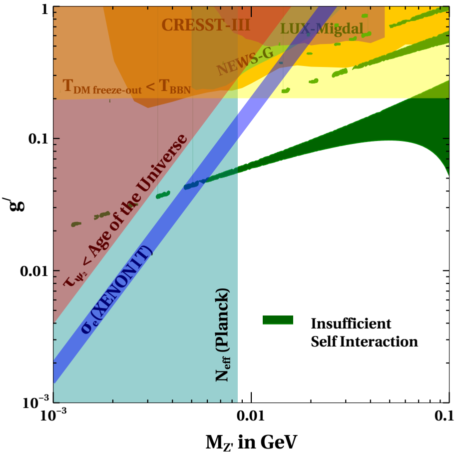


Figure: Summary plot for inelastic self-interacting DM showing the final parameter space from relevant constraints.

Sincerely,
Manoranjan