Self-interacting Dark Matter via Right Handed Neutrino Portal

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(Ref.: arXiv:2110.00021 [hep-ph])
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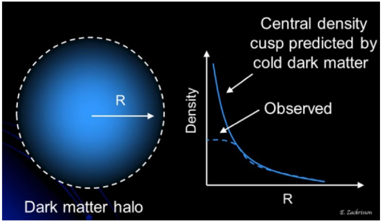
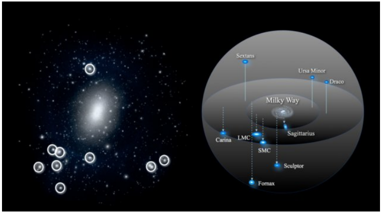
Issues with CDM

- **The cusp-core problem:**
  ΛCDM: Central densities of halos→ **Cuspy ($\rho \sim r^{-1}$)**
  Observation: Central densities of halos→ **Cored ($\rho \sim r^{0}$).**
  (S-H. Oh et al, Astron. J 149 180 (2015))
- **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.





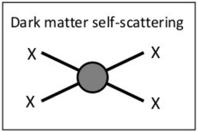
(Weinberg, Bullock, Governato, Kuzio de Naray, Peter(2013))

Self-interacting dark matter: a promising alternative

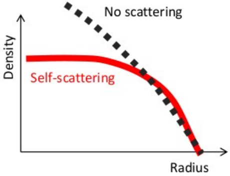
CDM structure problems can be resolved introducing dark matter self-interaction.
Dark matter particles in halos elastically scatter with other dark matter particles.

(D. N. Spergel and P. J. Steinhardt, Phys. Rev. Lett. 84 (2000) 3760–3763, arXiv:astro-ph/9909386)

SIDM: $\sigma/m \sim 1 cm^2/g \sim 10^{-24} cm^2/GeV$
Typical WIMP: $\sigma/m \sim 10^{-38} cm^2/GeV$.

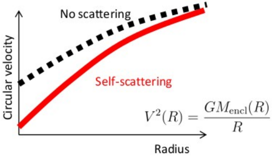


Cusp-Core Problem:



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 ~ 10^{-4})

Medium energies (v/c ~ 10^{-3})

High energies (v/c ~ 10^{-2})

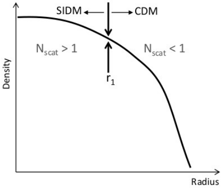
Stronger self-scattering needed for (dwarf-sized) halos.
$\sigma/m \sim 0.5 - 10 cm^2/g$ at dwarf-scale velocity $v \sim 10 km/s$.

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)

RHN assisted elastic SIDM and neutrino mass

Fields		$SU(3)_C$	$\otimes SU(2)_L$	$\otimes U(1)_Y$	$\otimes U(1)_D$
Fermion	N_R	1	1	0	0
	χ	1	1	0	1
Scalars	Φ	1	1	0	-1

$$\mathcal{L}_{DM} = i\,\overline{\chi}\,\gamma^{\mu}\,(\partial_{\mu} - ig_D Z'_{\mu})\,\chi - M\,\overline{\chi}\,\chi - M_{N_R}\overline{N_R^c}N_R - y\,\chi\,\Phi\,N_R + \frac{\epsilon}{2}B^{\alpha\beta}Y_{\alpha\beta}$$

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

Yukawa Potential:

$$V(r) = \pm\frac{\alpha_{\chi}}{r}e^{-m_{Z'}r}$$

Sean Tulin, Hai-Bo Yu and Kathryn M. Zurek

Parameter space for sufficient self-interaction

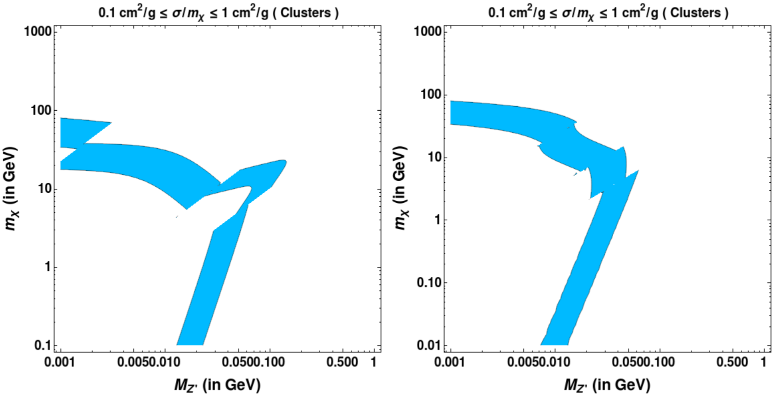


Figure: [Left]: Attractive; [Right]: Repulsive Self-interaction cross-section in the range $0.1 - 1\ \mathrm{cm}^2/\mathrm{g}$ for clusters ($v \sim 1000\ \mathrm{km/s}$). Sky blue colour represents regions of parameter space where $0.1\ \mathrm{cm}^2/\mathrm{g} < \sigma/m_\chi < 1\ \mathrm{cm}^2/\mathrm{g}$.

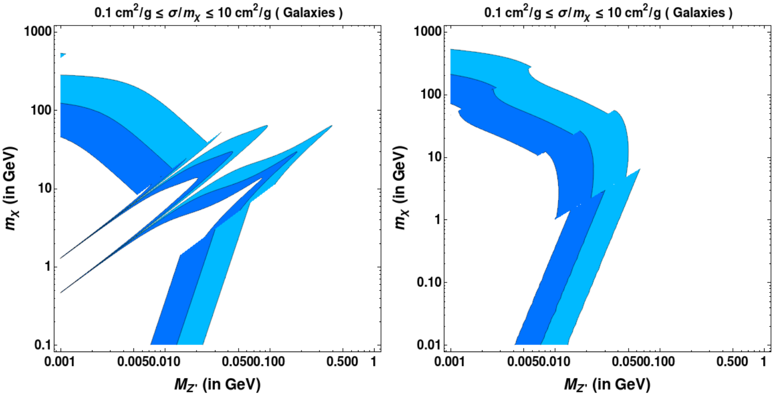


Figure: [Left]: Attractive; [Right]: Repulsive Self-interaction cross-section in the range $0.1 - 10\ \mathrm{cm}^2/\mathrm{g}$ for galaxies ($v \sim 200\ \mathrm{km/s}$). Blue colour represents regions of parameter space where $1\ \mathrm{cm}^2/\mathrm{g} < \sigma/m_\chi < 10\ \mathrm{cm}^2/\mathrm{g}$; Sky blue colour represents regions of parameter space where $0.1\ \mathrm{cm}^2/\mathrm{g} < \sigma/m_\chi < 1\ \mathrm{cm}^2/\mathrm{g}$.

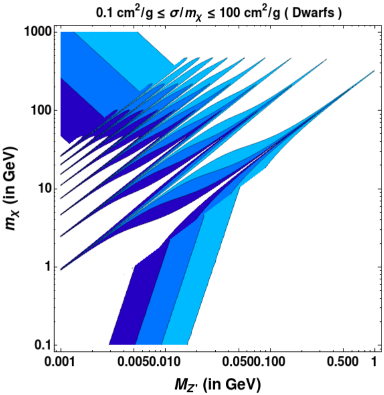


Figure: [Left]: Attractive; [Right]: Repulsive Self-interaction cross-section $0.1 - 100\ \mathrm{cm}^2/\mathrm{g}$ for dwarfs ($v \sim 10\ \mathrm{km/s}$). Dark blue colour represents regions of parameter space where $10\ \mathrm{cm}^2/\mathrm{g} < \sigma/m_\chi < 100\ \mathrm{cm}^2/\mathrm{g}$; Blue colour represents regions of parameter space where $1\ \mathrm{cm}^2/\mathrm{g} < \sigma/m_\chi < 10\ \mathrm{cm}^2/\mathrm{g}$; Sky blue colour represents regions of parameter space where $0.1\ \mathrm{cm}^2/\mathrm{g} < \sigma/m_\chi < 1\ \mathrm{cm}^2/\mathrm{g}$.

Velocity dependent self-interaction

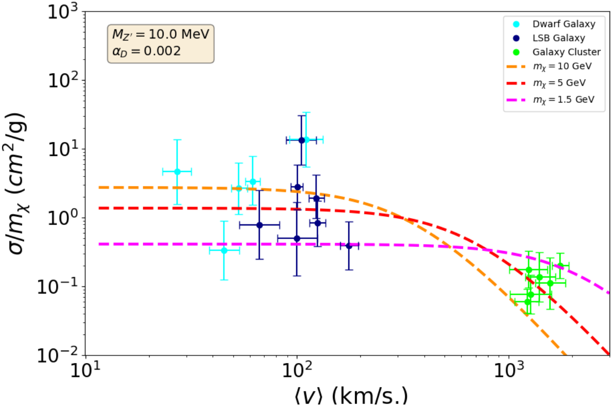
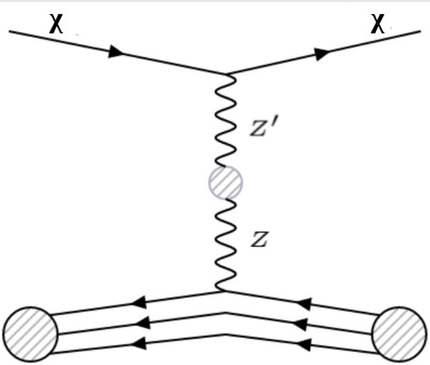
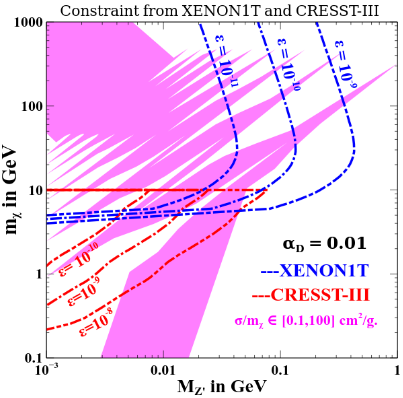


Figure: The self-interaction cross section per unit mass of DM as a function of average collision velocity.

Direct Search bound



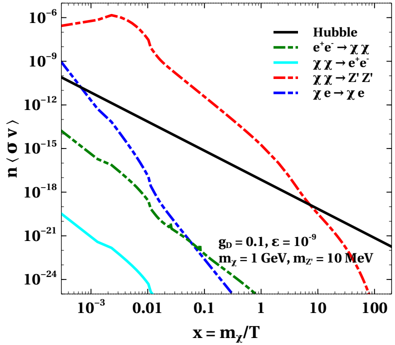
$$\sigma^{\rm SI}_{\chi N} = \frac{g^2 g_D^2 \epsilon^2}{\pi} \frac{\mu^2_{\chi N}}{M^4_{Z'}} \frac{(Zf_p + (A-Z)f_n)^2}{A^2}.$$



However, $\Gamma_{Z'} = \frac{\alpha_{em} m_{Z'} \epsilon^2}{3}$

$$\therefore \tau_{Z'} = 3 \;\; sec \left(\frac{\epsilon}{10^{-10}}\right)^{-2} \left(\frac{m_{Z'}}{10 MeV}\right)^{-1}$$

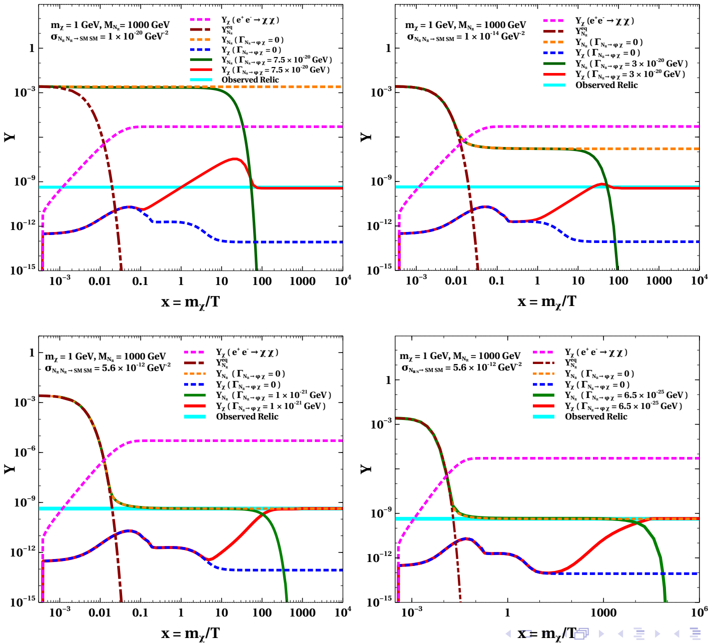
Production of dark matter



$$\frac{T'}{T} = \left(\frac{g_{*s}^{\rm SM}(T)}{g_{*s}^{\rm SM}(T_D)}\right)^{1/3}, \quad x' = \frac{m_\chi}{T'} = \left(\frac{T}{T'}\right)x$$

$$\frac{dY_{N_R}}{dx} = -\frac{s(m_\chi)}{x^2 H(m_\chi)\left(\frac{T'}{T}\right)}\langle\sigma(N_R N_R \to SMSM)v\rangle(Y_{N_R}^2 - (Y_{N_R}^{eq})^2) - \left(\frac{T'}{T}\right)^2 \frac{x}{H(m_\chi)}\langle\Gamma_{N_R\to\phi\chi}\rangle Y_{N_R} \quad ;$$

$$\frac{dY_\chi}{dx} = \left(\frac{T'}{T}\right)^2 \left[\frac{s(m_\chi)}{x^2 H(m_\chi)}\left(\langle\sigma(e^+e^- \to \chi\chi)v\rangle(Y_\chi^{eq})^2 - \langle\sigma(\chi\chi \to Z'Z')v\rangle Y_\chi^2\right) + \frac{x\left(\frac{g_{*s}(T_D)}{g'_{*s}(T_D)}\right)}{H(m_\chi)}\langle\Gamma_{N_R\to\phi\chi}\rangle Y_{N_R}\right]$$


m_χ = 1 GeV, M_NR = 1000 GeV
σ_NRNR→SM SM = 1 × 10^-20 GeV^-2
Y_χ (e+ e- → χ χ)
Y_NR^eq
Y_NR (Γ_NR→φχ = 0)
Y_χ (Γ_NR→φχ = 0)
Y_NR (Γ_NR→φχ = 7.5 × 10^-20 GeV)
Y_χ (Γ_NR→φχ = 7.5 × 10^-20 GeV)
Observed Relic
Y
x = m_χ/T
m_χ = 1 GeV, M_NR = 1000 GeV
σ_NRNR→SM SM = 1 × 10^-14 GeV^-2
Y_χ (e+e- → χ χ)
Y_NR^eq
Y_NR (Γ_NR→φχ = 0)
Y_χ (Γ_NR→φχ = 0)
Y_NR (Γ_NR→φχ = 3 × 10^-20 GeV)
Y_χ (Γ_NR→φχ = 3 × 10^-20 GeV)
Observed Relic
m_χ = 1 GeV, M_NR = 1000 GeV
σ_NRNR→SM SM = 5.6 × 10^-12 GeV^-2
Y_NR (Γ_NR→φχ = 1 × 10^-21 GeV)
Y_χ (Γ_NR→φχ = 1 × 10^-21 GeV)
σ_NR→SM SM = 5.6 × 10^-12 GeV^-2
Y_NR (Γ_NR→φχ = 6.5 × 10^-25 GeV)
Y_χ (Γ_NR→φχ = 6.5 × 10^-25 GeV)

Relic Density: Interplay between cross-section and decay rate

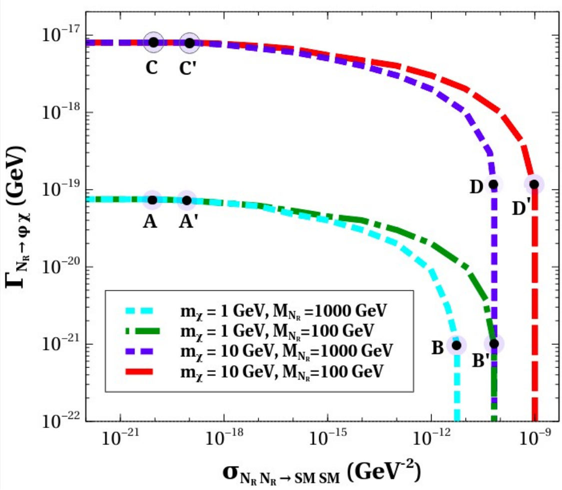


Figure: Contour of correct relic in the plane of $\sigma_{N_R N_R \to SMSM}$ versus $\Gamma_{N_R \to \phi\chi}$.

Final parameter space

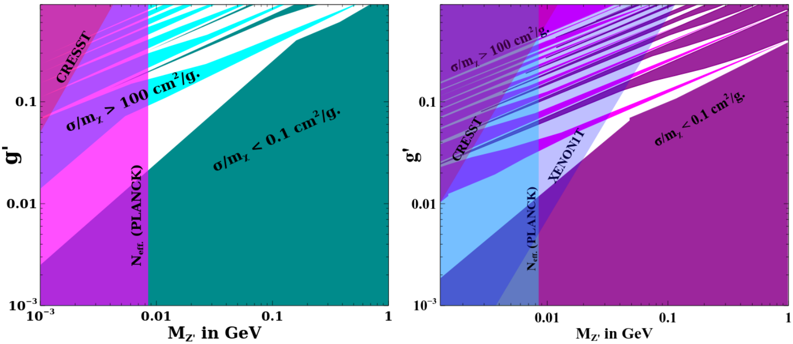


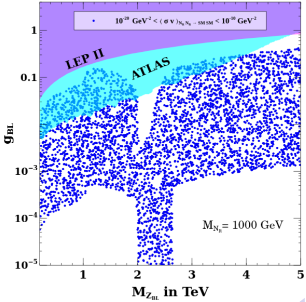
Figure: Summary plot showing the parameter space in $g' - M_{Z'}$ for $M_\chi = 1$ GeV (left) and $M_\chi = 10$ GeV (right).

Model-I: B-L model

Fields		$SU(3)_c$	$\otimes\ SU(2)_L$	$\otimes\ U(1)_Y$	$\otimes\ U(1)_{\rm B-L}$	$\otimes\ U(1)_D$
Fermion	N_R	1	1	0	-1	0
	χ	1	1	0	0	1
Scalars	Φ	1	1	0	1	-1
	ζ	1	1	0	2	0

$$\mathcal{L} \supset -\frac{1}{2} y' \zeta \overline{N_R^c} N_R - Y_\nu \overline{L} \widetilde{H} N_R - y\, \chi\, \Phi\, N_R + \text{h.c.}$$

The light neutrino mass matrix $M_\nu = -m_D M_R^{-1} m_D^T$.

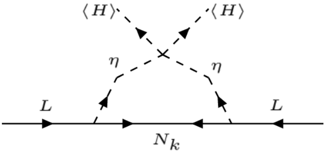


Model-II: Scotogenic model

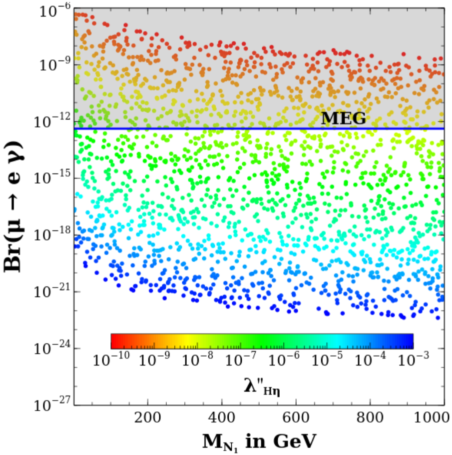
Fields		$SU(3)_c \otimes$	$SU(2)_L \otimes$	$U(1)_Y \otimes$	$U(1)_D \otimes$	Z_2
Fermion	N_R	1	1	0	0	-
	χ	1	1	0	1	-
Scalars	η	1	2	1	0	-
	Φ	1	1	0	-1	+

$$\mathcal{L} \supset -\frac{1}{2} M_{N_R} \overline{N_R^c} N_R - Y_N \bar{L} \tilde{\eta} N_R + \text{h.c.}$$

$$\begin{aligned} V(H,\eta) &= -\mu_H^2 H^\dagger H + \frac{\lambda_H}{2}(H^\dagger H)^2 + \mu_\eta^2 \eta^\dagger \eta + \frac{\lambda_\eta}{2}(\eta^\dagger \eta)^2 \\ &+ \lambda_{H\eta}(H^\dagger H)(\eta^\dagger \eta) + \lambda'_{H\eta}(H^\dagger \eta)(\eta^\dagger H) + \frac{\lambda''_{H\eta}}{2}\left[(H^\dagger \eta)^2 + (\eta^\dagger H)^2\right] \end{aligned}$$



Allowed parameter space



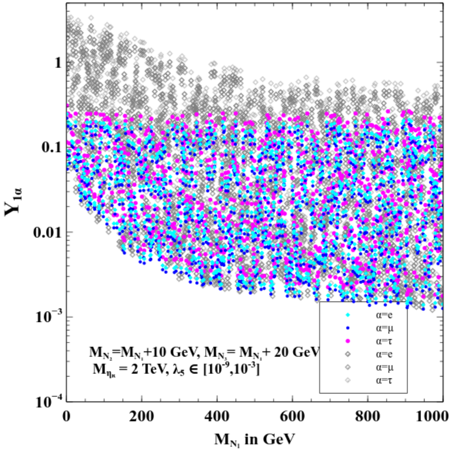


Figure: [Left]: Br($\mu \to e\gamma$) as a function of N_1 mass while keeping $M_{N_1} = M_{N_2} - 10\,\mathrm{GeV} = M_{N_3} - 20\,\mathrm{GeV}$, $M_{\eta^+} = 1$ TeV. [Right]: Parameter space for scotogenic model in the plane of N_1 Yukawa and its mass consistent with SIDM relic.

Summary and Conclusion

- We studied velocity dependent self-interacting DM with a light mediator as a possible resolution to the small scale anomalies associated with ΛCDM model.
- Thermal relic of SIDM is always under-abundant unless DM is at TeV scale, however higher masses are disfavoured from direct search even for very small kinetic mixing $\epsilon \sim 10^{-9}$.
- A hybrid set up of dark freeze-out and freeze-in is necessary to obtain the correct relic, which often needs extra particles which can decay to dark matter at a late time.
- We have also explored possible connection to the neutrino phenomenology in two different models.
- Future data from direct search experiments and complementary astrophysical searches will be able to further constrain such scenario.

Sincerely,
Manoranjan