Constraining Self-interacting Dark Matter: Hints of the Dark force and Beyond

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Introduction

WIMP dark matter

Typical weak-scale cross section for self-scattering

$\sigma_T \sim 10^{-36} cm^2$

DM elastic scattering cross section must be

$\sigma_T \sim 1 cm^2 (m_X/g) \approx 2x10^{-24} cm^2 (m_X/GeV)$

Weak-scale cross section *too small* to affect structure formation

Invoke strong self-interaction in dark matter particles?

Cusp/Core Anomaly

Collisionless cold dark matter halos in dwarfs

Appears to be centrally cuspy in simulations

Observations exhibit cored profiles

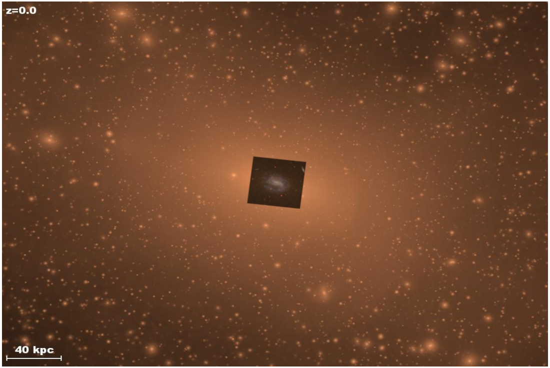


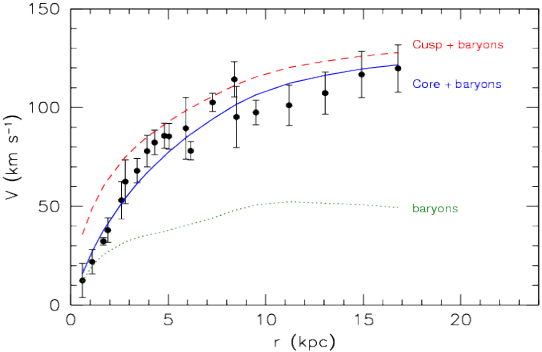
Image of galaxy F568-3 superposed on Via Lactea CDM simulation of MW-sized halo

Cusp/Core Anomaly

- Galactic rotation curves
- Cluster observations

Prospective resolutions

- Include baryonic feedback mechanisms that steepen the inner profile

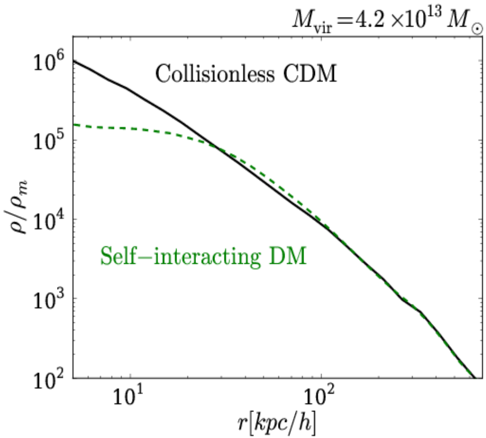


Weinberg et al., 2013

- New DM physics (SIDM, WDM)

Cusp/Core Anomaly

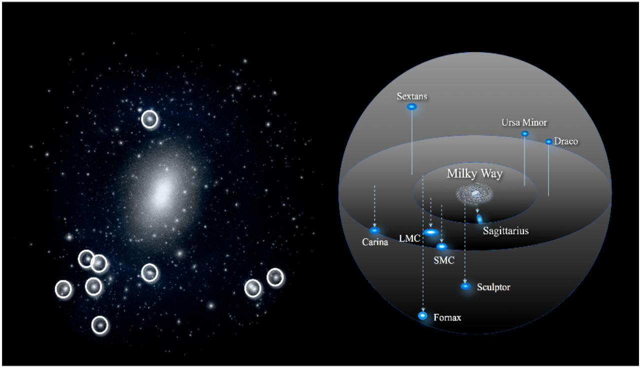
Self-interaction in collisional DM makes halos rounder, less dense at center



From simulations by Rocha et al., 2013

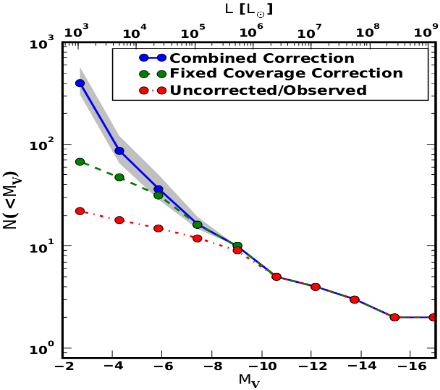
Missing Satellites Problem

Simulations predict orders of magnitude of more dwarf galaxies than observation



Yniguez et al. (2013), Garrison-Kimmel et al. (2014)

Missing Satellites Problem



Bullock (2013)

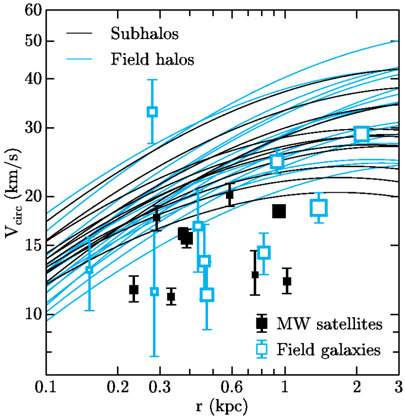
Missing Satellites Problem

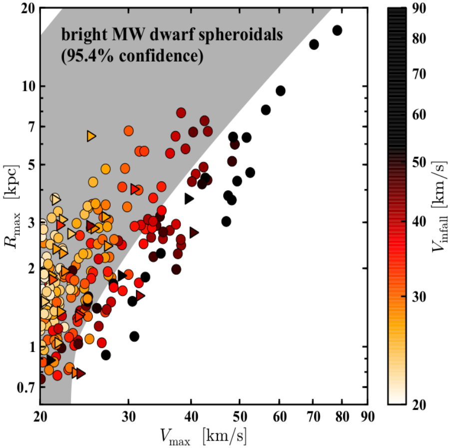
Potential solution

- Star formation suppressed due to photo-ionization and heating. Up to 5-20 times of the known dwarfs may have gone undetected because of luminosity bias, limited sky coverage, surface brightness limits etc.
- Tidal stripping and supernova feedback may have destroyed the subhaloes
- New DM physics (SIDM, WDM)

Problem within the Milky Way

Subhaloes too massive to host observed bright satellites!





Garrison-Kimmel et al. 2014 (left) & figure from Via Lactea II and

"Too Big to Fail"

Problem is not limited to the Milky Way!

Extragalactic observations

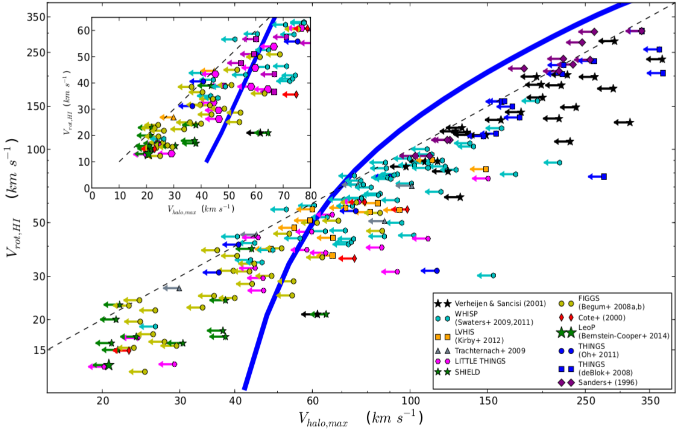
Twofold trouble with the hosts

- Dwarfs are hosted by less massive halos than predicted by CCDM simulations
- If smaller halos are allowed to host them observations come up with higher galactic number density

Three problems are linked: A Common Resolution?

"Too Big to Fail"

Hosts are too massive to be accommodated into the galactic rotation curve



ALFALFA Experiment, Papastergis et al., 2015

"Too Big to Fail"

Possible way-outs

- Feedback from star formation and supernovae, ram pressure and tidal stripping in hosts
- Uncertainty in MW halo mass
- Statistical uncertainties in formation of MW-sized halos
- New DM physics

Baryonic feedback mechanisms are not enough to fix the abundance of halos *or* the galactic rotation curves (projected masses)

Time to look into new possibilities on the dark matter front?

Alternatives

What are the viable routes out of the messy small-scale anomalies?

Collisional self-interacting DM candidate: e.g. hidden dark matter (with dark gauge boson as mediators: scalars, dark photons)

Warm dark matter candidate: e.g. decaying 7.1 keV sterile neutrinos

Both offer resolutions to problems with the small-scale structure without violating astrophysical bounds

Dark Matter Candidate and Mediators

Yukawa potential at work:

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

Dark fine structure constant $\alpha_X = g_X^2/4\pi$

Interactions

$\mathcal{L}_{int} = g_X \overline{X} \gamma_\mu X \phi_\mu$ vector mediator
$\mathcal{L}_{int} = g_X \overline{X} X \phi$ scalar mediator

Scalar interactions: purely attractive
Vector interactions: both attractive and repulsive

Scattering

Repulsive: $\chi\chi \to \chi\chi$
Attractive: $\chi\overline{\chi} \to \chi\overline{\chi}$

Mometum-transfer cross section

Transfer Cross Section

$\sigma_T = \int d\Omega (1 - \cos\theta) \frac{d\sigma}{d\Omega}$

- Weighted by fractional longitudinal momentum transfer
- Regulates forward scattering divergence

Viscosity Cross Section

$\sigma_V = \int d\Omega \sin^2\theta \frac{d\sigma}{d\Omega}$

- Weighted by energy transfer in the transverse direction
- Regulates forward and backward scattering divergence evenly

Difference between σ_T and σ_V will be small
Angular dependence in full scale N-body simulation is taken care of through angular information in $\frac{d\sigma}{d\Omega}$
σ_T widely used in DM literature

Born regime

The Born limit: $\frac{\alpha_X m_X}{m_\phi} \ll 1$

Cross section calculated perturbatively in α_X

For both attractive and repulsive potential

$$\sigma_T^{Born} = \frac{8\pi\alpha_X^2}{m_X^2 v^4}(log(1 + \frac{m_X^2 v^2}{m_\phi^2}) - \frac{m_X^2 v^2}{m_\phi^2 + m_X^2 v^2})$$

Differential cross section: $\frac{d\sigma}{d\Omega} = \frac{\alpha_X^2 m_X^2}{(m_\phi^2 + m_X^2 v^2 (1 - cos\theta)/2)^2}$

Classical regime

The classical limit: $\frac{m_\chi v}{m_\phi} \gg 1$

Cross-sections computed in the non-perturbative regime

For attractive potential

$$\sigma_T^{clas} = \begin{cases} \frac{4\pi}{m_\phi^2}\beta^2 ln(1+\beta^{-1}) & \beta \lesssim 10^{-1} \\ \frac{8\pi}{m_\phi^2}\beta^2/(1+1.5\beta^{1.65}) & 10^{-1} \lesssim \beta \lesssim 10^3 \\ \frac{\pi}{m_\phi^2}(ln\beta + 1 - \frac{1}{2}ln^{-1}\beta)^2 & \beta \gtrsim 10^3 \end{cases}$$

For repulsive potential

$$\sigma_T^{clas} = \begin{cases} \frac{2\pi}{m_\phi^2}\beta^2 ln(1+\beta^{-2}) & \beta \lesssim 1 \\ \frac{\pi}{m_\phi^2}(ln2\beta - lnln2\beta)^2 & \beta \gtrsim 1 \end{cases}$$

With $\beta \equiv \frac{2\alpha_\chi m_\phi}{m_\chi v^2}$

Classical regime

Differential cross section

For $\beta \lesssim 1$

- $\frac{d\sigma}{d\Omega} \approx \frac{\sigma_T}{4\pi}$
- Remains approximately constant

For $\beta \gtrsim 1$

- $\frac{d\sigma}{d\Omega} \approx \frac{\alpha_X^2}{m_X^2 \upsilon^4 sin^4 \frac{\theta}{2}}$
- Approaches Rutherford scattering formula

Resonant regime

Onset of both quantum mechanical and non-perturbative effects

Regime is defined by

$$\frac{\alpha_\chi m_\chi}{m_\phi} \geq 1 \qquad \textit{and} \qquad \frac{m_\chi v}{m_\phi} \leq 1$$

A significant chunk of the parameter space!

No analytic formula for σ_T

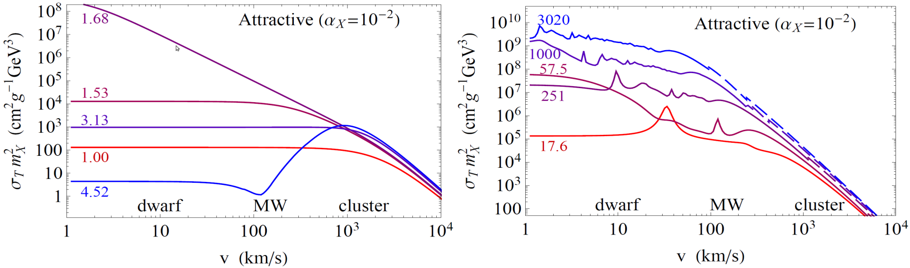
Resonant regime

σ_T computed by solving the Schroedinger equation using partial wave analysis

Velocity dependence within the resonant regime

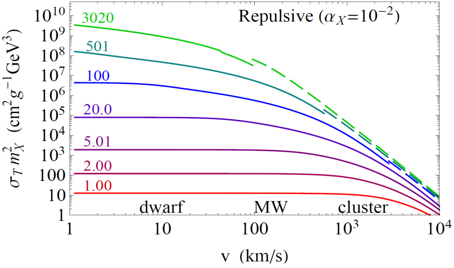
Curves parametrized with $\alpha_X m_X / m_\phi$

For attractive potential



Resonant regime

For repulsive potential



Tulin et al., 2013

The analytic path

The Hulthen potential

$$V(r) = \pm \frac{\alpha_X \delta e^{-\delta r}}{1 - e^{-\delta r}}$$

Serves as an excellent approximation to the Yukawa potential

The analytic path

Transfer cross-section in Hulthen potential:

$$\sigma_T^{Hulthen} = \frac{16\pi}{m_X^2 \upsilon^2} sin^2\delta_0$$

Differential cross-section:

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_T}{4\pi}$$

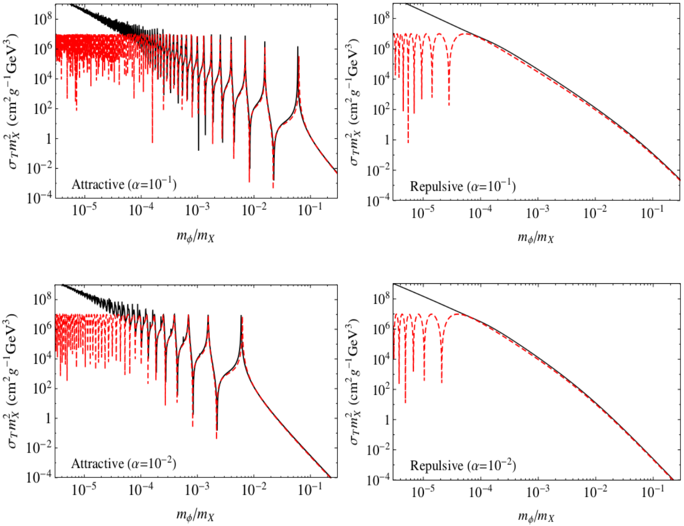
where

$$\delta_0 = arg\left(\frac{i\Gamma(\frac{im_X\upsilon}{\kappa m_\phi})}{\Gamma(\lambda_+)\Gamma(\lambda_-)}\right)$$

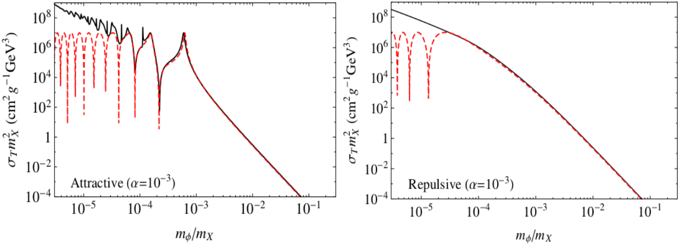
with κ ≈1.6 and

$$\lambda_\pm \equiv \begin{cases} 1 + \frac{im_X\upsilon}{2\kappa m_\phi} \pm \sqrt{\frac{\alpha_X m_X}{\kappa m_\phi} - \frac{m_X^2\upsilon^2}{4\kappa^2 m_\phi^2}} & \text{attractive} \\ 1 + \frac{im_X\upsilon}{2\kappa m_\phi} \pm i\sqrt{\frac{\alpha_X m_X}{\kappa m_\phi} + \frac{m_X^2\upsilon^2}{4\kappa^2 m_\phi^2}} & \text{repulsive} \end{cases}$$

A comparison between the numerical and analytic results



The resonant regime



Tulin et al., 2013

Phenomenology

Transfer cross-section

Cross section averaged over relative velocities of incoming DM

$\langle \sigma_T \rangle = \int \frac{d^3 \upsilon}{(2\pi \upsilon_0^2)^{3/2}} e^{-\frac{1}{2}\upsilon^2/\upsilon_0^2} \sigma_T(\upsilon)$

Uses exponential weight

$\upsilon_0 \longrightarrow$ most probable velocity

Similarly, the thermally averaged cross section in non-relativistic limit is

$\langle \sigma_{an} \upsilon \rangle = \int \frac{d^3 \upsilon}{(2\pi \upsilon_0^2)^{3/2}} e^{-\frac{1}{2}\upsilon^2/\upsilon_0^2} \sigma_{an} \upsilon$

$\upsilon_0 \longrightarrow \sqrt{2/x_X}$

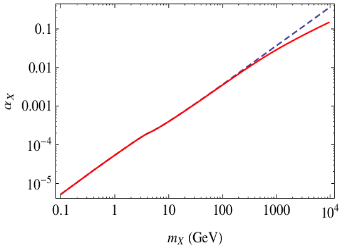
where $x_X = m_X/T_X$ and DM temperature T_X is $T_X = T^2/T_{kd}$

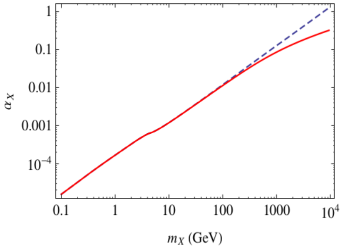
Light mediators $\longrightarrow$ *Enhancement*

Thermally averaged enhanced cross section

Multiply the Sommerfeld enhancement factor S with the tree level cross-section $(\sigma_{an}\upsilon)^{tree}$ to get $\sigma_{an}\upsilon$

$$\langle \sigma_{an\upsilon} \rangle = \frac{x_X^{3/2}}{2\sqrt{\pi}} \int S(\sigma_{an}\upsilon)^{tree} \upsilon^2 e^{-x_X \upsilon^2/4} d\upsilon$$



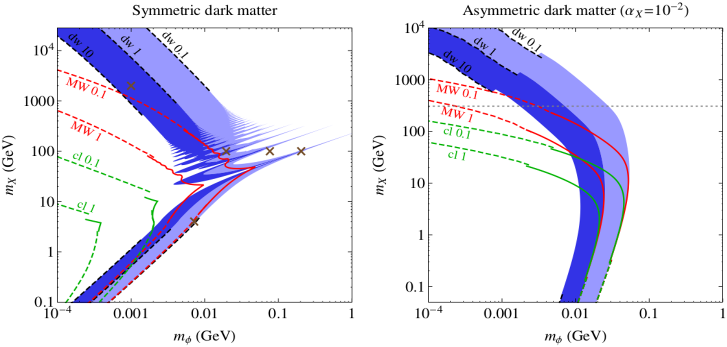


Tulin et al., 2013

Parameter space

For symmetric dark matter *(both X and $\overline{X}$ abundance)* we use $\sigma_T = (\sigma_T^{att} + \sigma_T^{rep})/2$

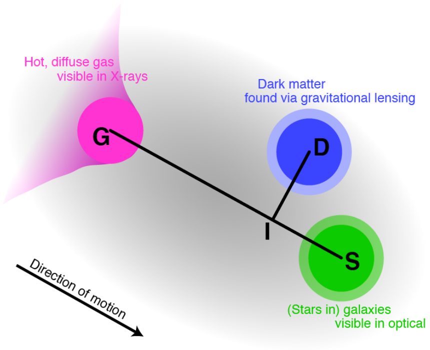
For asymmetric dark matter *(purely X or $\overline{X}$)* scattering is repulsive



Tulin et al., 2012

Cluster collisions

Collision between galactic clusters

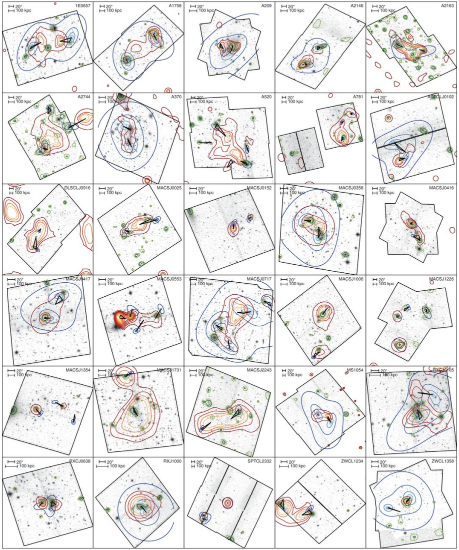


Harvey et al., 2015

72 collisions studied including major and minor mergers

- Confirms the existence of dark mass at 7.6σ significance
- Poses strong hints towards nongravitational self-interaction in DM

Cluster collisions

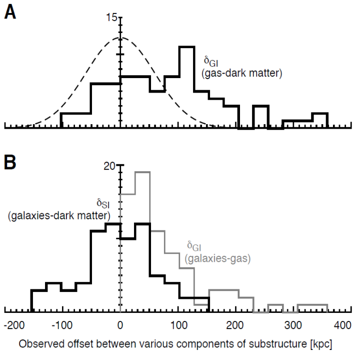


Hubble Space Telescope Data Release, 2015

Cluster collisions

Hubble Space Telescope: optical imaging
Chandra Observatory data: x-ray imaging

30 systems picked within the redshift $0.2 < z < 0.6$ + *2 systems* at $z > 0.8$
Contains 72 pieces of substructure



Harvey et al., 2015

Making a case for self-interaction

Mean DM lag

$\langle\delta_{SI}\rangle = -5.8 \pm 8.2 kpc$ in the direction of motion

$\langle\delta_{DI}\rangle = -1.8 \pm 7.0 kpc$ perpendicularly

Constraints on interaction cross section

Limits derived from *Bullet cluster* collision

- Test for drag $\longrightarrow$ $\sigma_{DM}/m < 1.25 cm^2/g [68\% CL]$
- Test for mass loss $\longrightarrow$ $\sigma_{DM}/m < 0.7 cm^2/g [68\% CL]$

Define dimensionless $\beta \equiv \frac{\delta_{SI}}{\delta_{SG}} = B\{1 - e^{[\frac{-(\sigma_{DM} - \sigma_{gal})}{\sigma^*}]}\}$

HST and Chandra observation on colliding clusters

Fractional lag of DM relative to gas $\langle\beta\rangle = -0.04 \pm 0.07 [68\% CL]$

- $\sigma_{DM}/m = -0.25^{+0.42}_{-0.43} cm^2/g [68\% CL, two - tailed]$
- $\sigma_{DM}/m < 0.47 cm^2/g [95\% CL, one - tailed]$

Detection prospects

If charged both under hidden gauge group U'(1) and the Standard Model, dark matter can couple to SM through the mediator

Spin-independent/dependent effective coupling cross section

$\sigma^{SI}_{\chi n} \approx 10^{-24} cm^2 x \epsilon^2_{eff} (\frac{30MeV}{m_\phi})^4 x \frac{\alpha_X}{10^{-2}}$ asymmetric DM

$\sigma^{SI}_{\chi n} \approx 10^{-24} cm^2 x \epsilon^2_{eff} (\frac{30MeV}{m_\phi})^4 x \frac{m_X}{200GeV}$ symmetric DM

Direct detection constraints via LUX and XENON1T

Attempt at looking into indirect detection prospects.

Line searches with Fermi-LAT, antimatter fraction from AMS-02 etc.

Collider searches in the light of LHC

Conclusion

Conclusion

- Astrophysical observations DOES NOT exclude Hidden Dark Matter
- Favours light DM in self-interacting framework
- Indicates long-range interaction
- Emphasizes light mediator (Yukawa scalars, *not-so-massive* vector bosons)

Possibilities

- Employing tighter astrophysical bounds to narrow down on self-interaction
- N-body simulations to investigate the accuracy of complementarity
- Prospective limits from detectors to confine the parameter space

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The End