New avenues for Self-Interacting Dark Matter

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DESY.

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Outline

1. Motivation

2. Resonant SIDM *PRL 122 (2019) no.7, 071103*

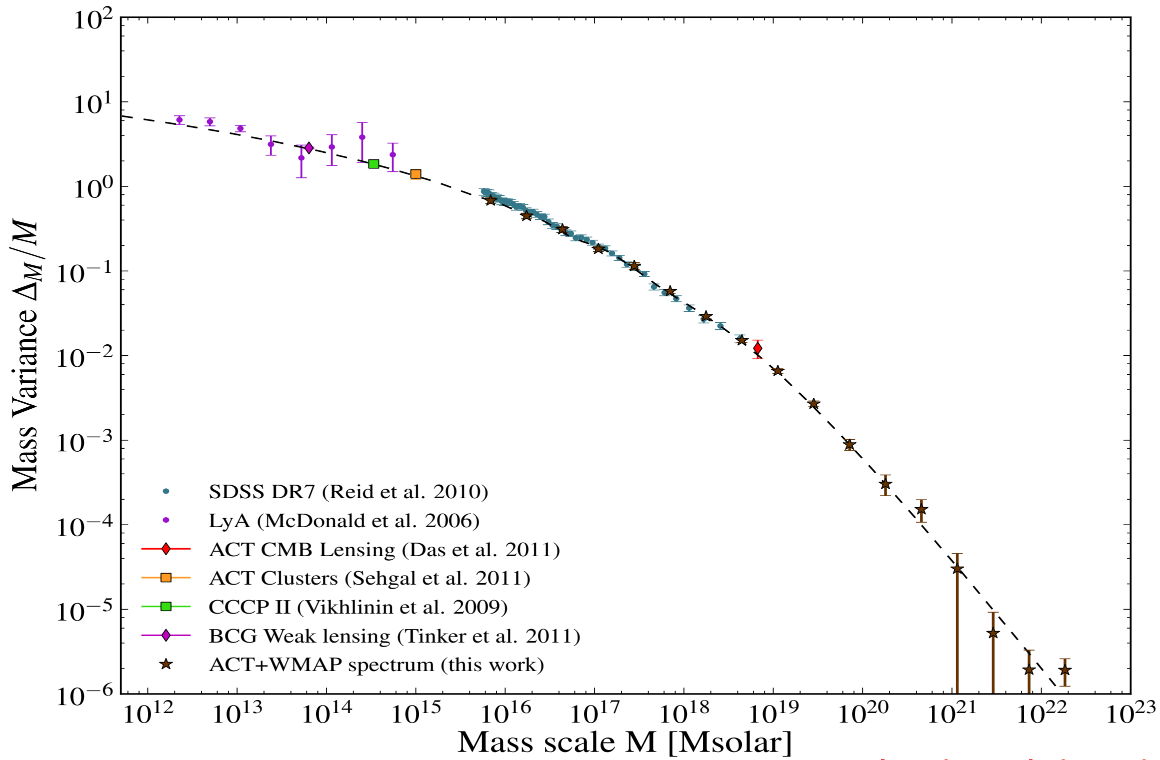
3. Puffy dark matter *arXiv:1901.00075*

4. Effective range theory. *arXiv:1908.06067*

5. Conclusions

Lambda Cold Dark Matter model

Remarkably successful at large scales



Hlozek et al. (2012)

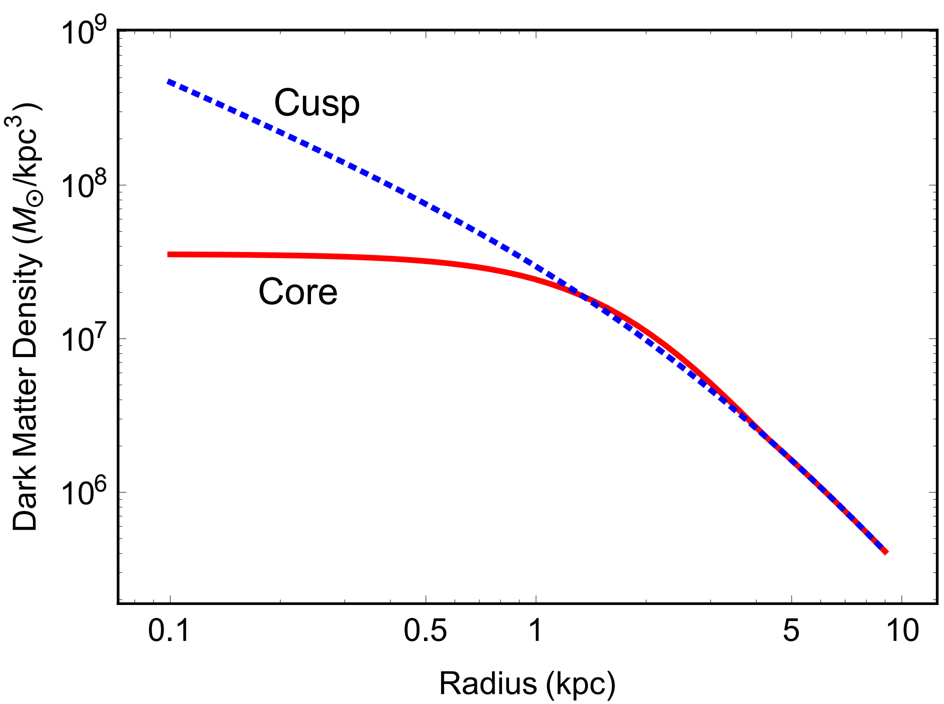
Mass deficits at galactic scales

- Core vs. cusp problem
- Diversity problem
- Too-big-to-fail problem
- Missing satellites

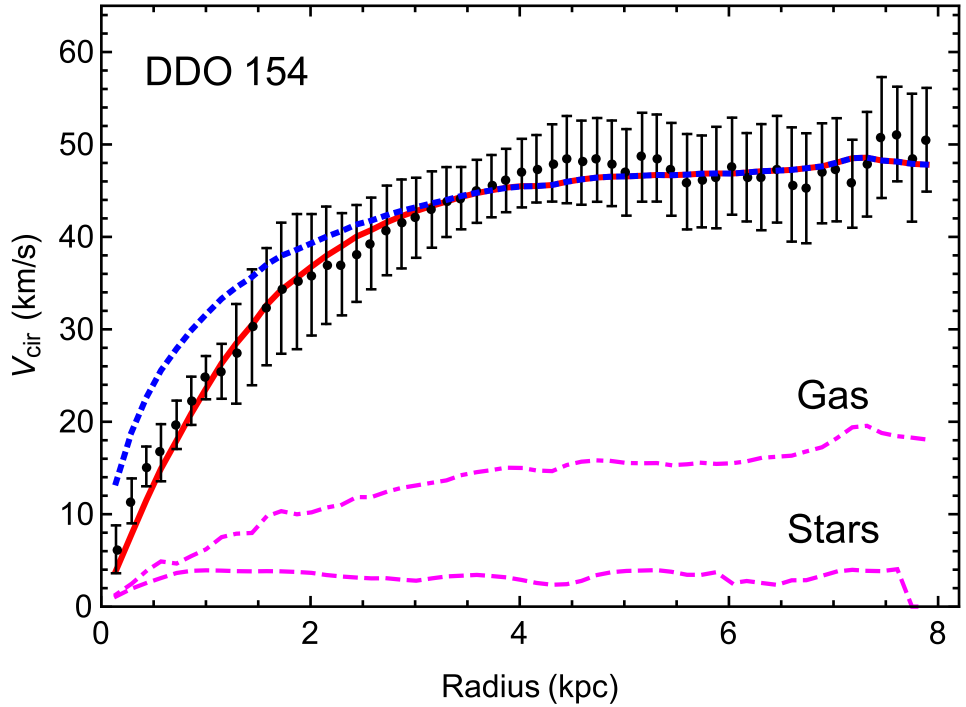
Core vs. cusp problem

This is the seemingly mass deficit observed in objects such as dwarf galaxies when compared to the predictions of collisionless dark matter

Moore (1994)
Flores et al. (1994)
Naray et al. (2011)



Tulin, Yu (2017)



$$\rho_{\rm NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2},$$

J. F. Navarro, C. S. Frenk, and S. D. M. White (1997)

Debate

Astrophysical possible solutions:

- Including baryons on the simulations
- Supernova feedback
- Tidal effects
- Low star-formation rates

Particle physics solution:

- postulate dark matter interactions that become relevant at small scales, without modifying the physics at large scales.

“..To be more specific, we suggest that the dark matter particles should have a mean free path between 1 kpc to 1 Mpc at the solar radius in a typical galaxy.”

Spergel, Steinhardt (1999)

$$\text{Mean Free Path} \sim \left(\frac{\rho}{m_{\text{DM}}}\sigma_{\text{scattering}}\right)^{-1}$$

$\frac{\sigma_{\text{scattering}}}{m_{\text{DM}}} \sim 1\text{cm}^2/g$ at the scale of galaxies ($v \sim$ 10 - 100 km/s)

Simulations show that this is indeed a solution

Wandelt, et.al (2000), Vogelsberger et.al (2012)
Peter et.al (2012), Rocha et.al (2013),Zavala et.al (2012)
Elbert et.al (2014), Kaplinghat (2015), Vogelsberger et.al (2015)
Francis-Yan Cyr-Racine (2015)

THE ASTROPHYSICAL JOURNAL, 648:L109–L113, 2006 September 10

A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER[1]

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SCOTT W. RANDALL,[5] CHRISTINE JONES,[5] AND DENNIS ZARITSKY[2]
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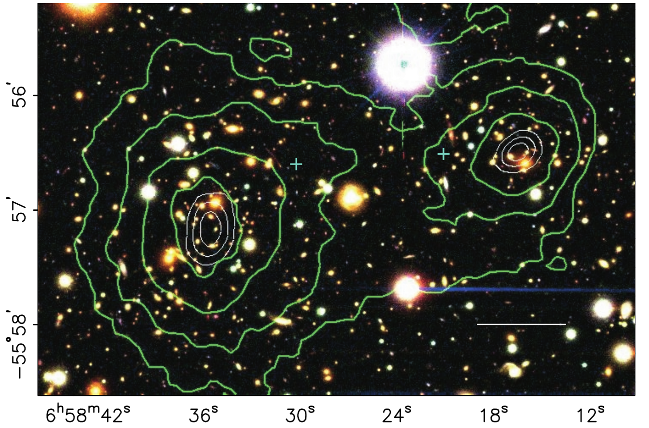
ABSTRACT

We present new weak-lensing observations of 1E 0657−558 ($z = 0.296$), a unique cluster merger, that enable a direct detection of dark matter, independent of assumptions regarding the nature of the gravitational force law. Due to the collision of two clusters, the dissipationless stellar component and the fluid-like X-ray–emitting plasma are spatially segregated. By using both wide-field ground-based images and *HST*/ACS images of the cluster cores, we create gravitational lensing maps showing that the gravitational potential does not trace the plasma distribution, the dominant baryonic mass component, but rather approximately traces the distribution of galaxies. An 8 σ significance spatial offset of the center of the total mass from the center of the baryonic mass peaks cannot be explained with an alteration of the gravitational force law and thus proves that the majority of the matter in the system is unseen.

Subject headings: dark matter — galaxies: clusters: individual (1E 0657−558) — gravitational lensing



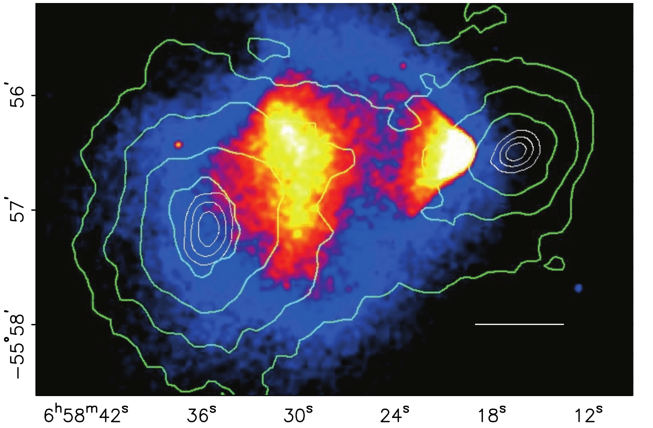


FIG. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with the outer contour levels at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the κ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue plus signs show the locations of the centers used to measure the masses of the plasma clouds in Table 2.

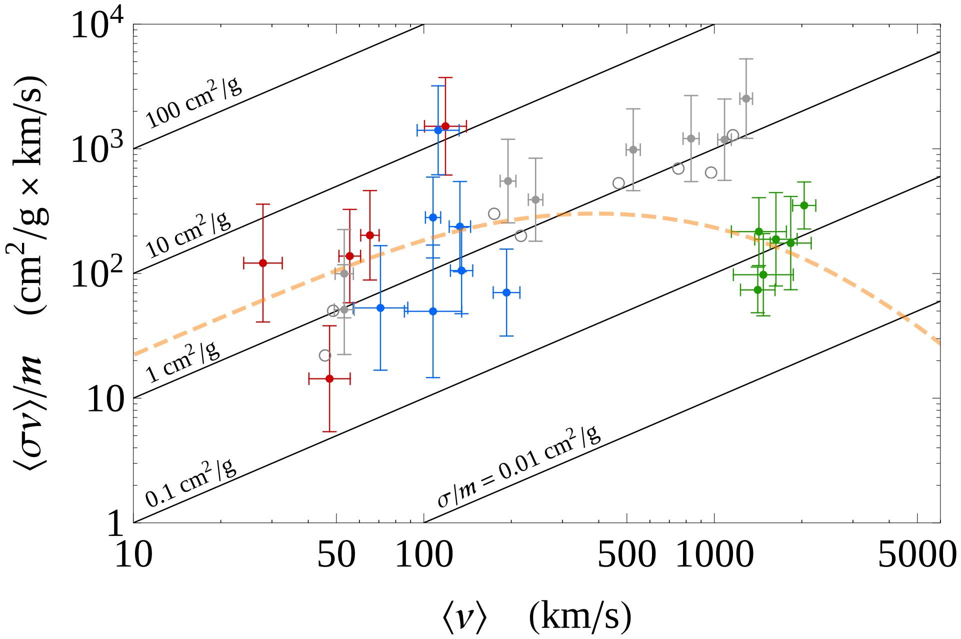
$$\sigma_{\rm scattering}/m_{\rm DM} \lesssim 1\ {\rm cm^2/g}$$

Randall et al (2008)
Robertson et al (2016)

Cross sections

Dark matter halos as particle colliders

Kaplinghat ,Tulin, Yu (2017)



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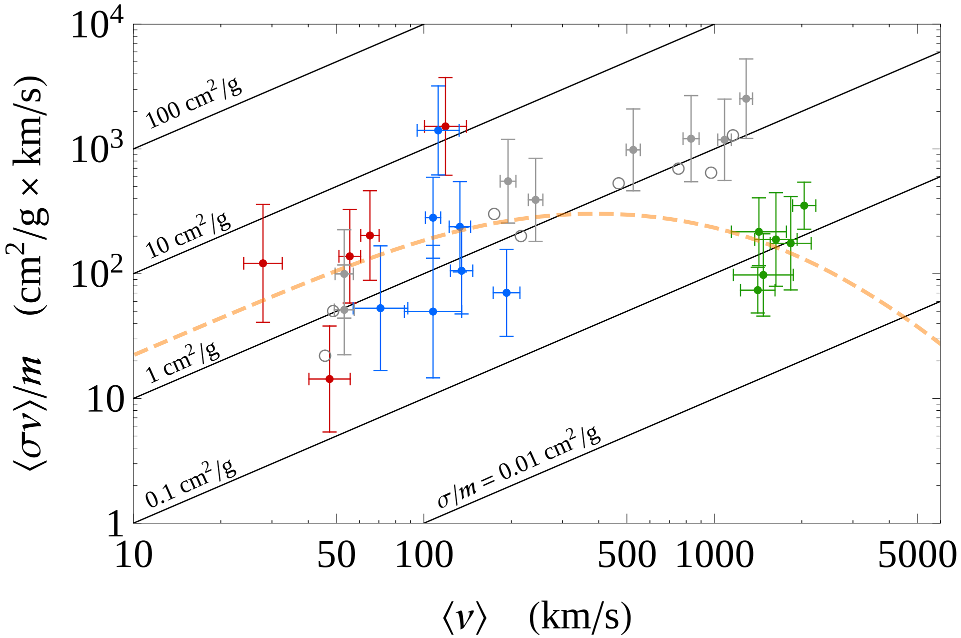
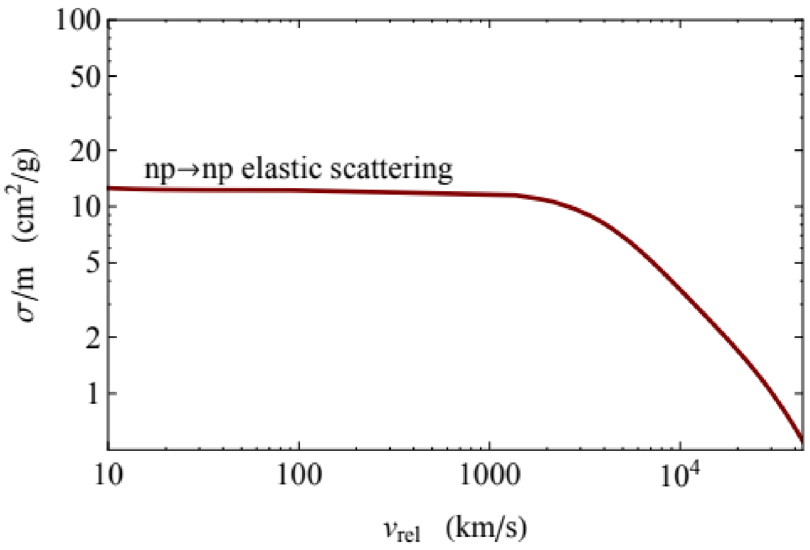


Tulin, Yu (2017)

How does that compare to nucleon-nucleon collisions?



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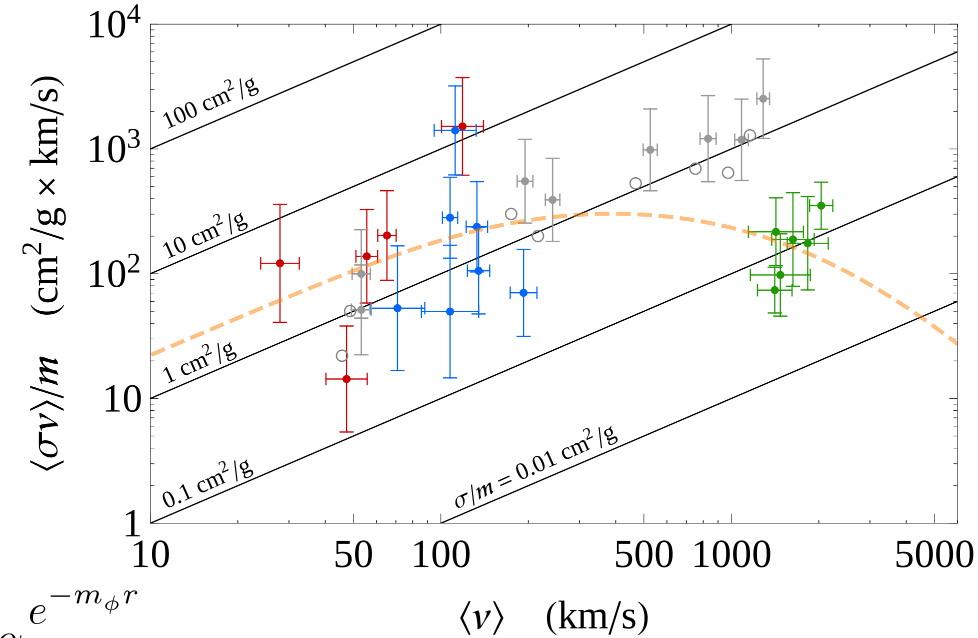
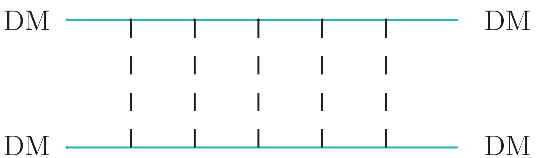


Light mediator



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

Tulin, Yu (2017)

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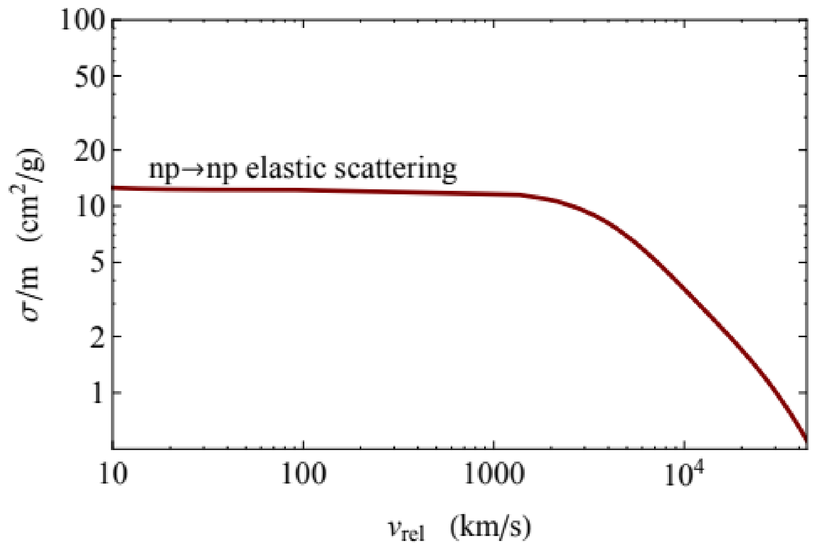

Resonant SIDM

Resonances can be studied in a model independent way (Breit-Wigner)

$$\sigma = \sigma_0 + \frac{4\pi\, S}{mE(v)} \cdot \frac{\Gamma(v)^2/4}{(E(v) - E(v_R))^2 + \Gamma(v)^2/4}\,, \quad \Gamma(v) = m_R \gamma v^{2L+1}\,.$$

Chu, CGC, Murayama (2018)

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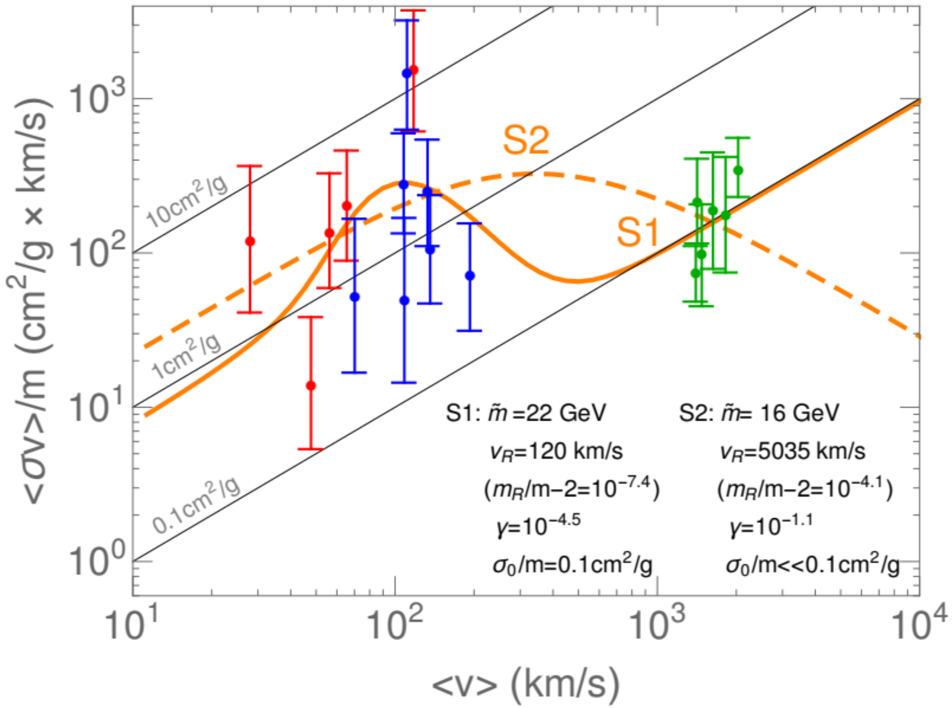

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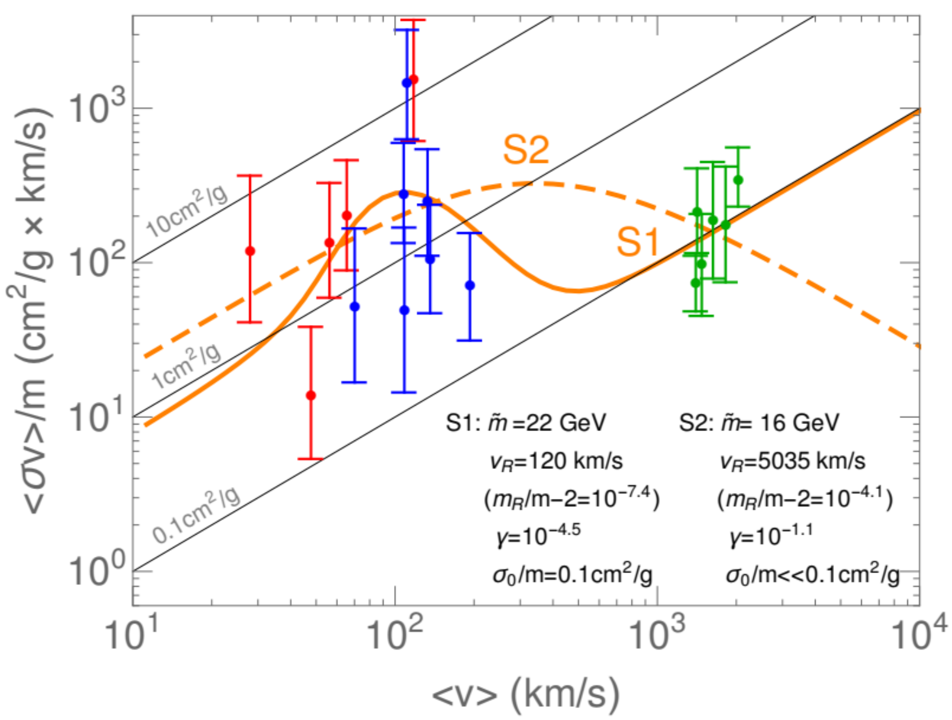
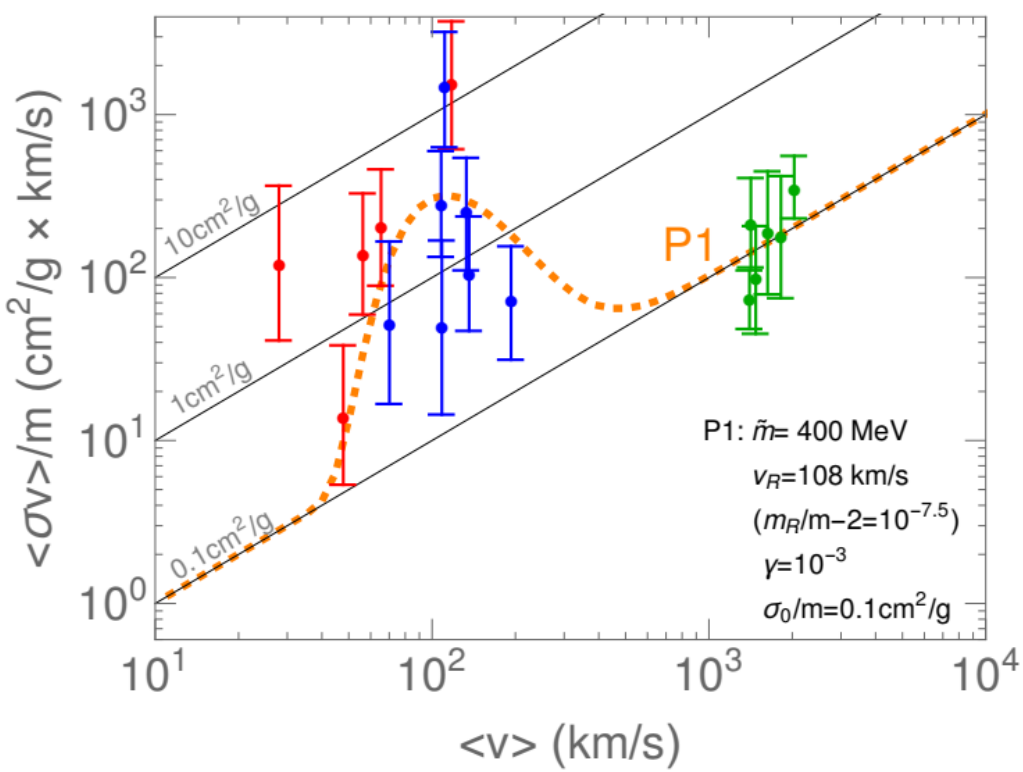




Concrete examples

Scenario	Interaction Lagrangian	L	$J_{\rm DM}$	J_R^P	S	γ
I	$g\,R\,\overline{\rm DM}\gamma^5{\rm DM}$	0	$\frac{1}{2}$	0^-	$\frac{1}{4}$	$\frac{g^2}{32\pi}$
IIa	$gR\,{\rm DM}^i{\rm DM}^i$	0	0	0^+	$\frac{1}{3}$	$\frac{g^2}{16\pi\, m_R^2}$
IIb	$g\,\epsilon_{ijk}\,R^i_\mu\,{\rm DM}^j\partial^\mu{\rm DM}^k$	1	0	1^-	1	$\frac{g^2}{384\pi}$
III	$\frac{1}{\Lambda}R_{\mu\nu}\,\mathcal{T}^{\mu\nu}_{\rm DM}$	2	0	2^+	5	$\frac{m_R^2}{30720\pi\Lambda^2}$

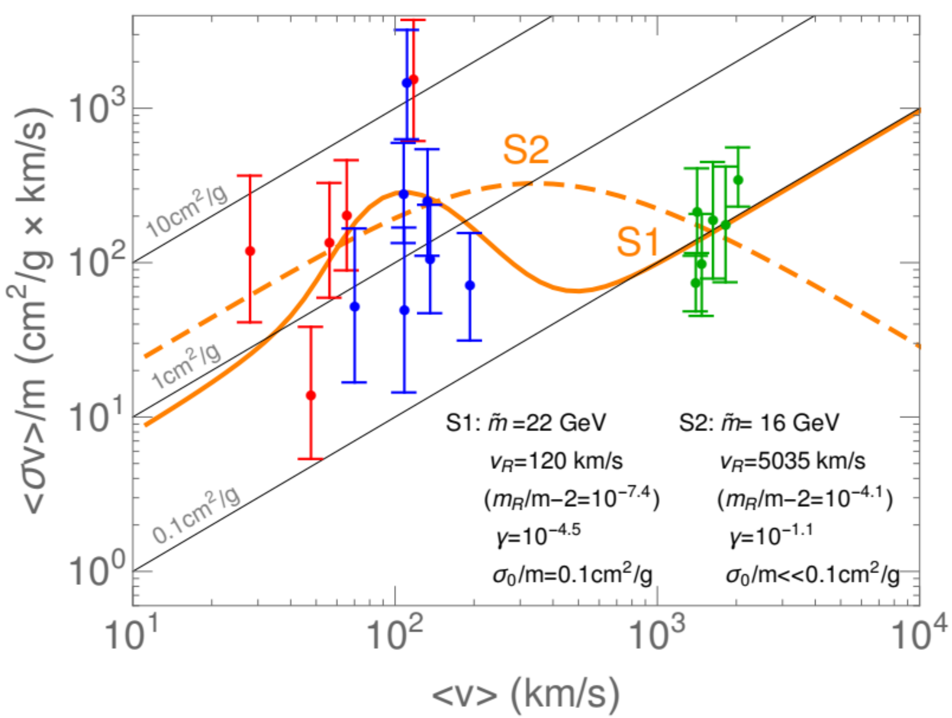
Table I: Benchmark RSIDM models.

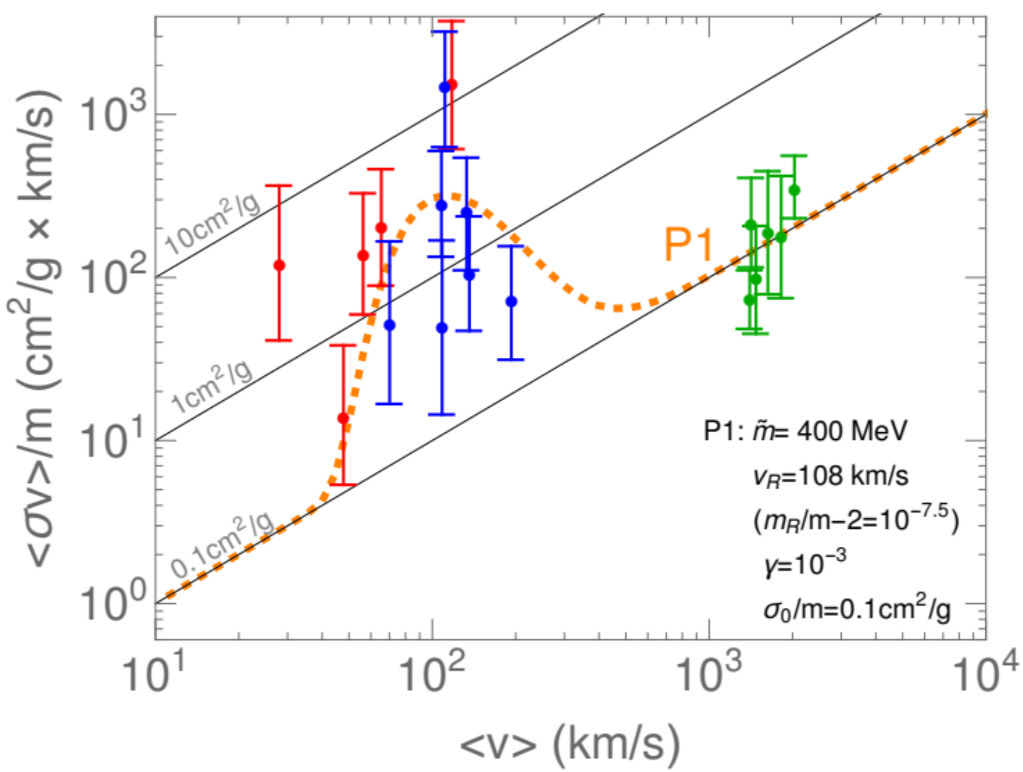
Pseudo-scalar mediator

Dark pions interacting with a dark sigma (IIa) or a rho (IIb) resonance

Spin-two exchange

Chu, CGC, Murayama (2018)





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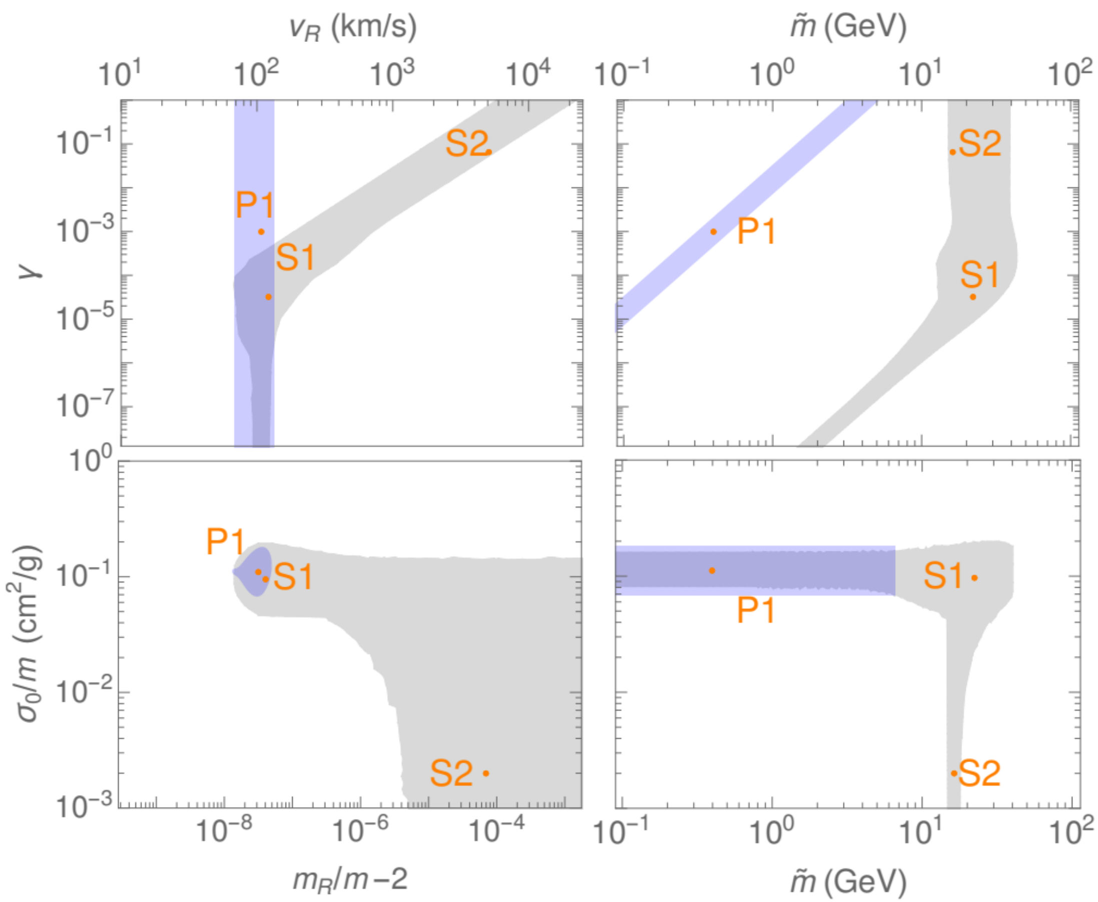


Chu, CGC, Murayama (2018)

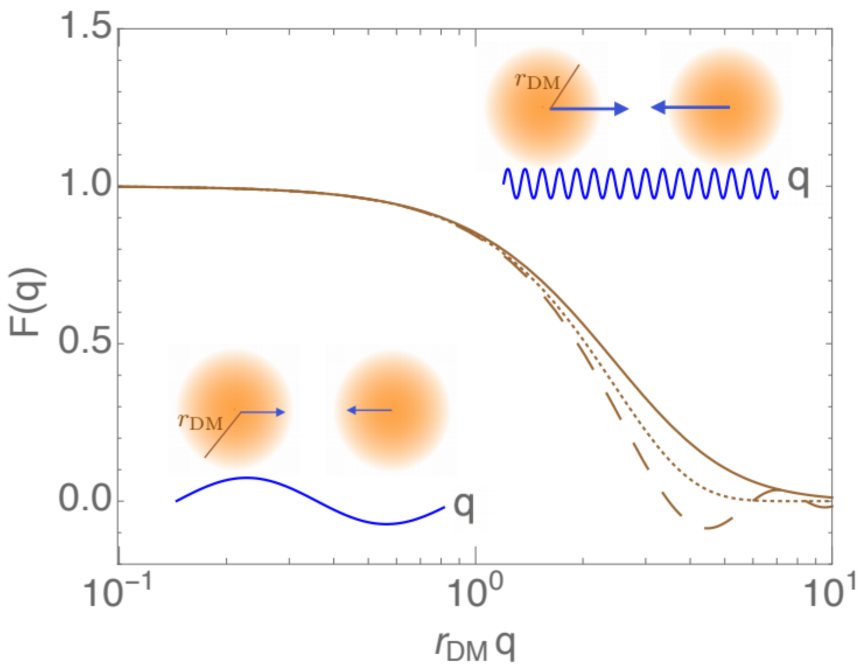
Puffy DM

Suppose that dark matter has a finite size that is larger than its Compton wavelength: Puffy DM

Chu, CGC, Murayama (2018)

Shape	$\rho(r)$	$r_{\rm DM}$	$F(q)$
tophat	$\frac{3}{4\pi r_0^3}\theta(r_0-r)$	$2\sqrt{3}r_0$	$\frac{3(\sin(r_0 q)-r_0 q\cos(r_0 q))}{r_0^3 q^3}$
dipole	$\frac{e^{-r/r_0}}{8\pi r_0^3}$	$\sqrt{3/5}r_0$	$\frac{1}{\left(1+r_0^2q^2\right)^2}$
Gaussian	$\frac{1}{8r_0^3\pi^{3/2}}e^{-r^2/(4r_0^2)}$	$\sqrt{6}r_0$	$e^{-r_0^2q^2}$

Table I: Form factors for different density distributions.



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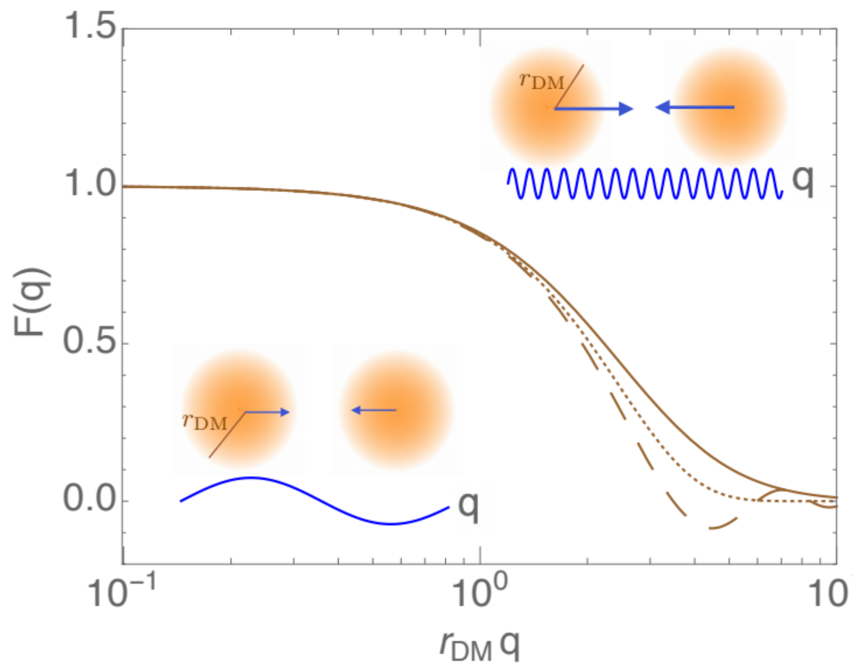

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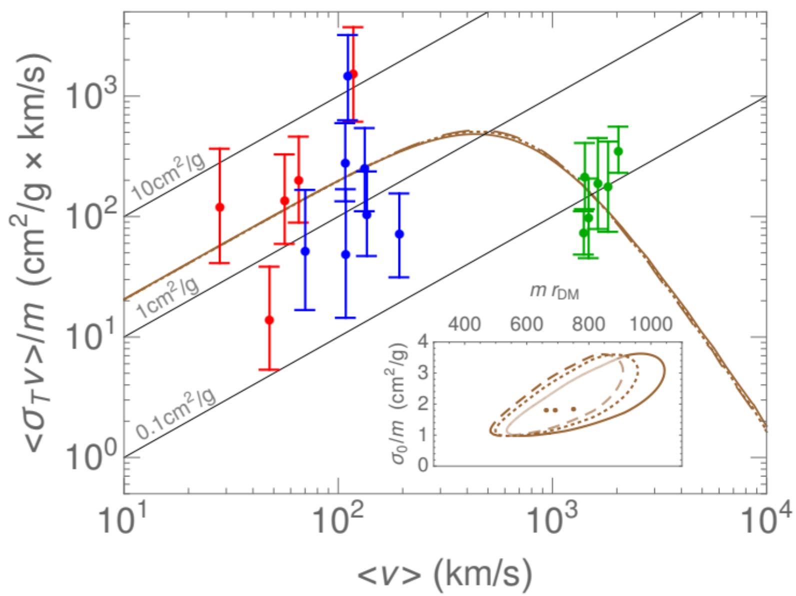
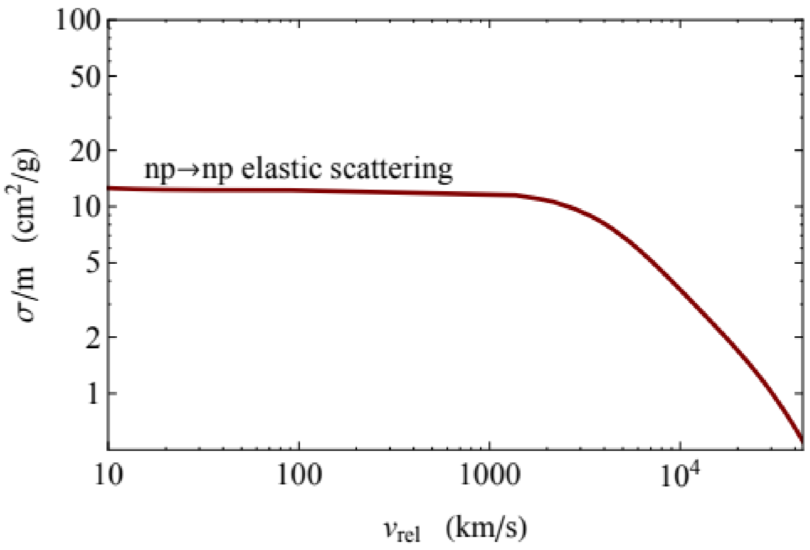
The way the non-relativistic cross section varies with the velocity is largely independent of the dark matter internal structure when the range of the mediating force is very short.



Effective Range Theory

Tulin, Yu (2017)



Effective Range Theory

For short-range interactions, regardless of the potential, the non-relativistic scattering cross section can be approximated by means of

$$\sigma(v) = 4\pi a^2 \left(\left(1 - \frac{1}{8}\frac{r_e}{a}(mav)^2\right)^2 + \frac{1}{4}(mav)^2 \right)^{-1}$$

"practically no information could be obtained, from classical scattering experiments, on the shape of the potential."

Hans Bethe (1949)

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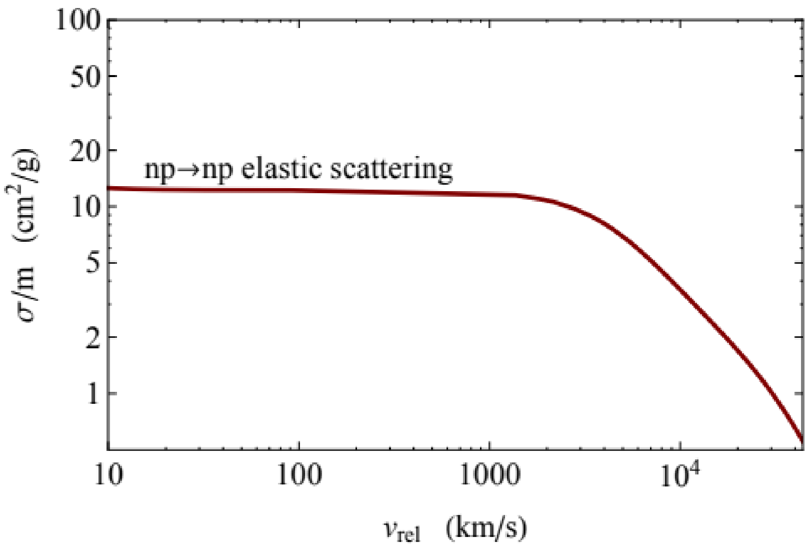

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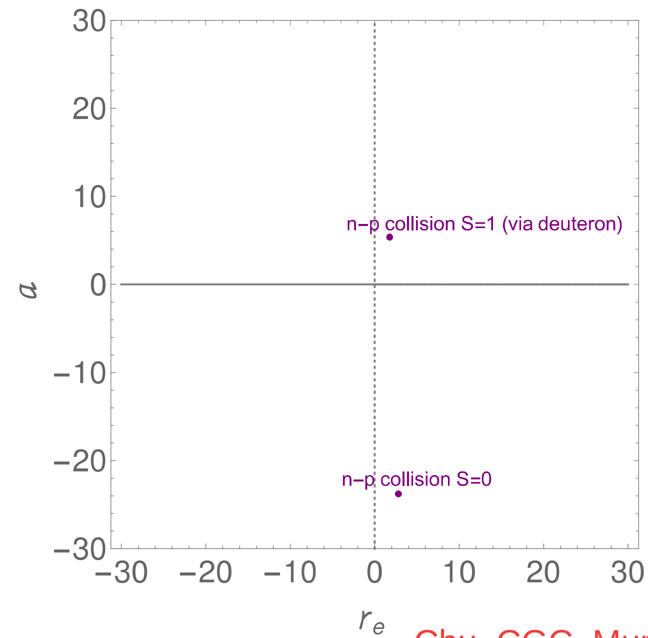

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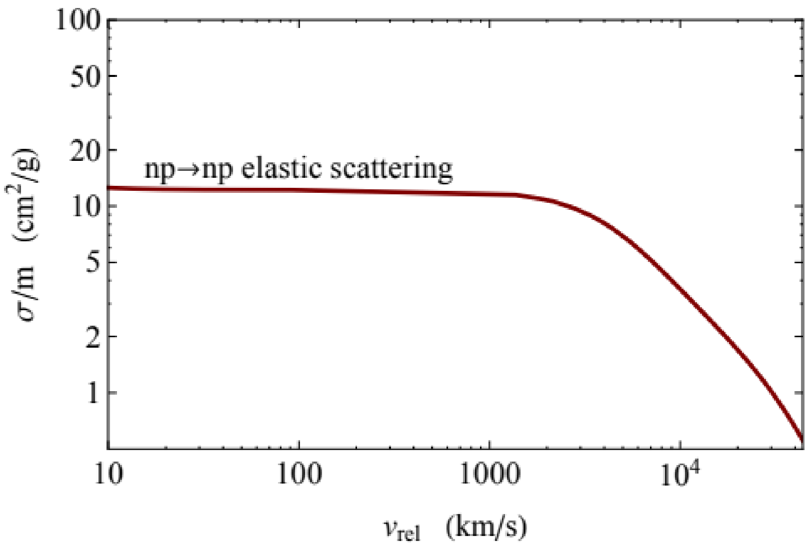

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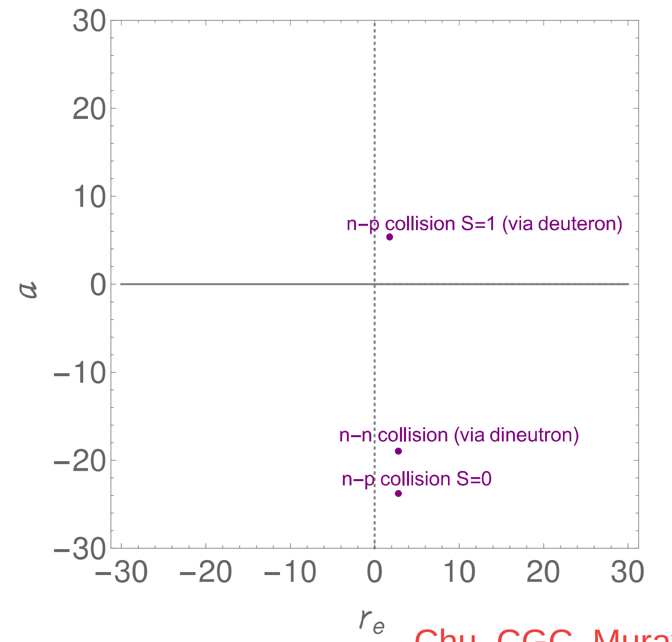

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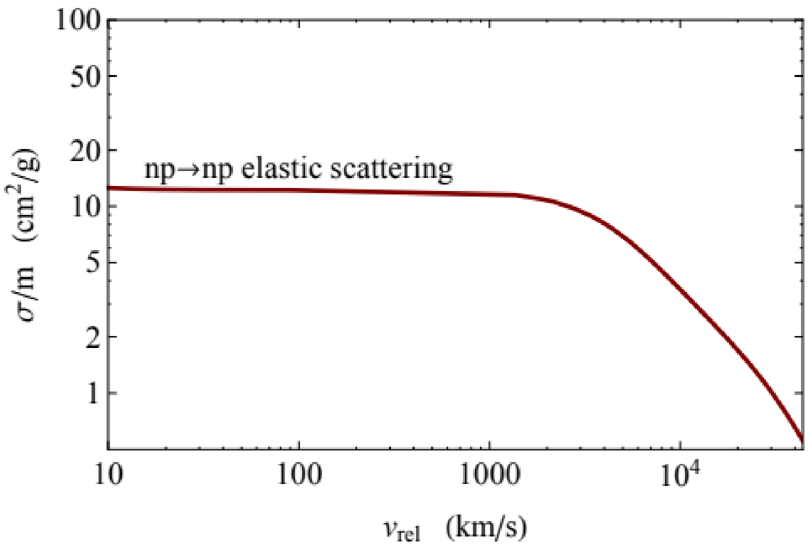

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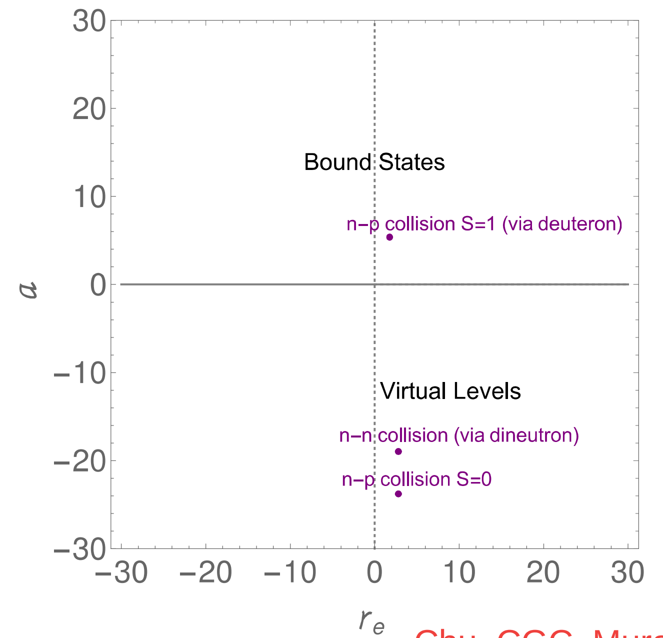

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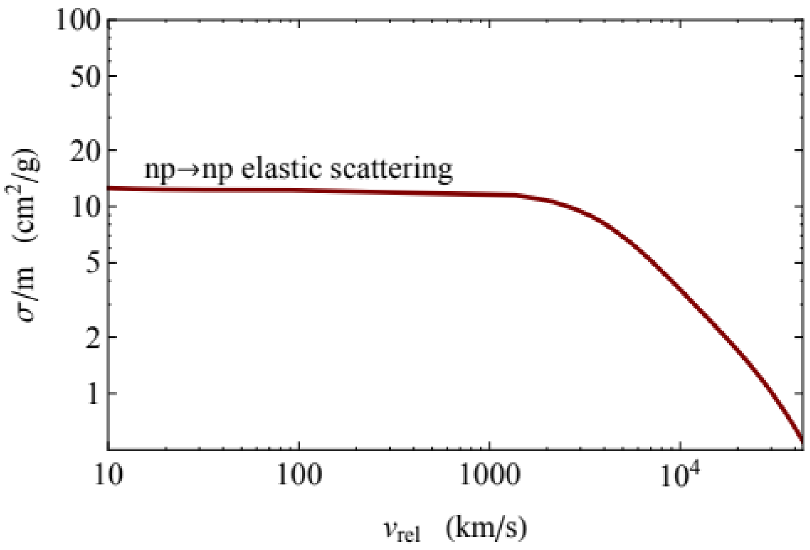

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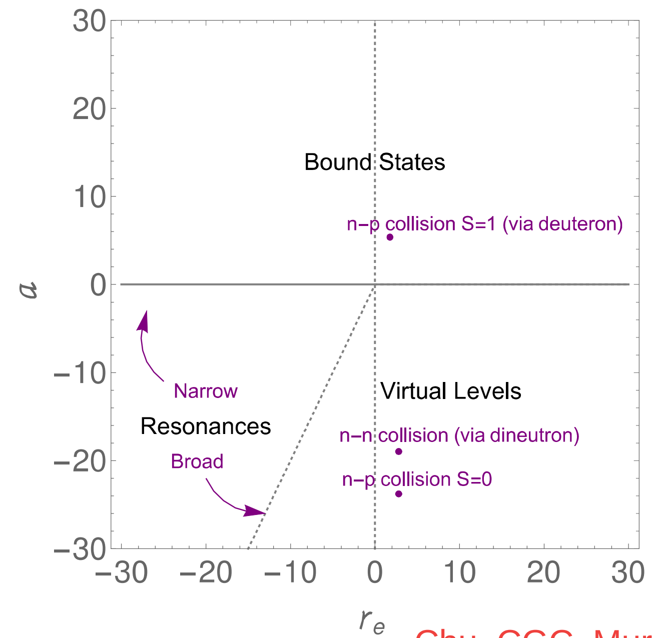

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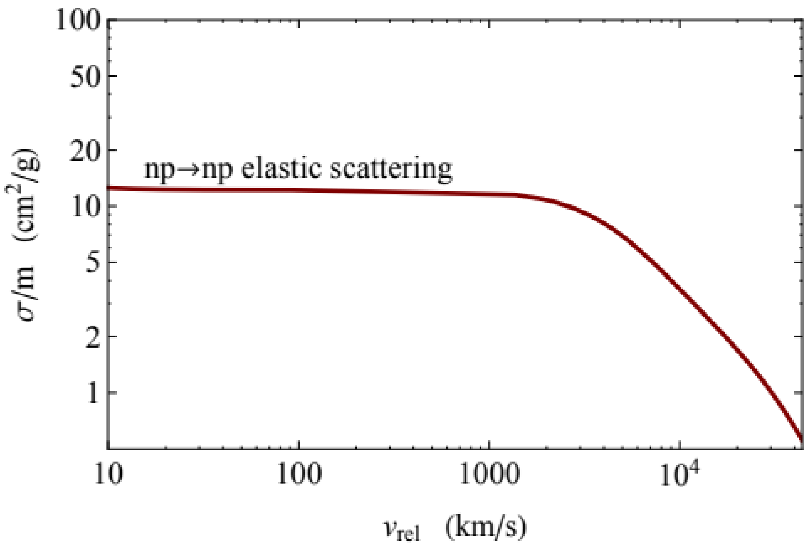

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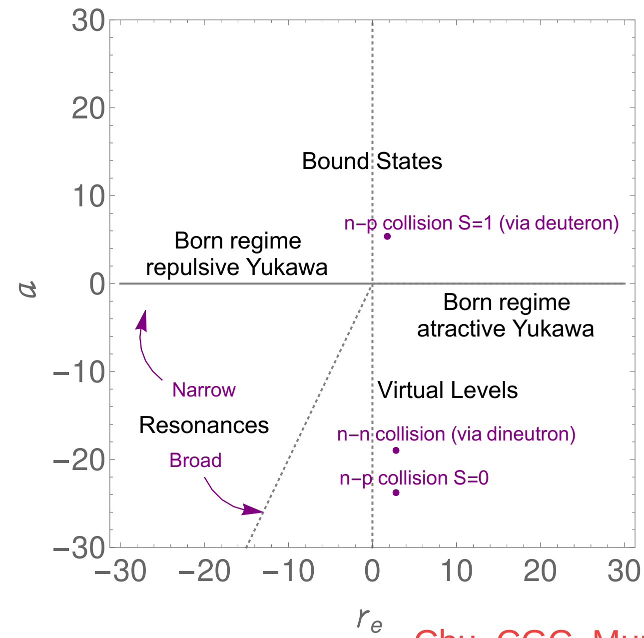

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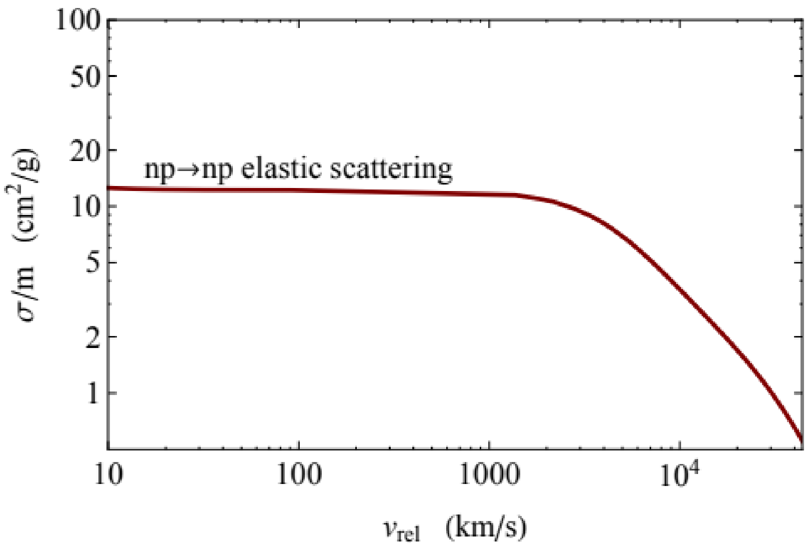

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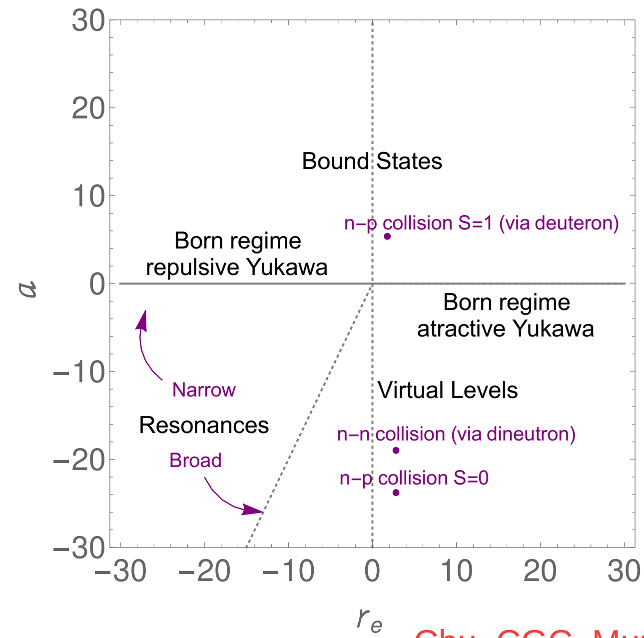

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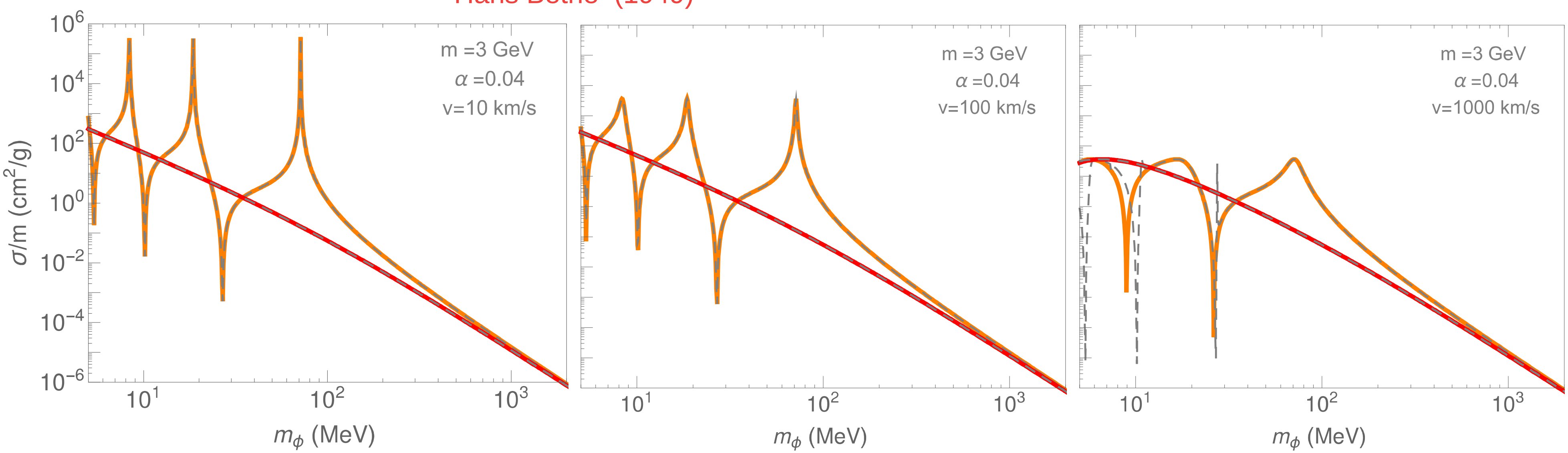

The case of light mediators

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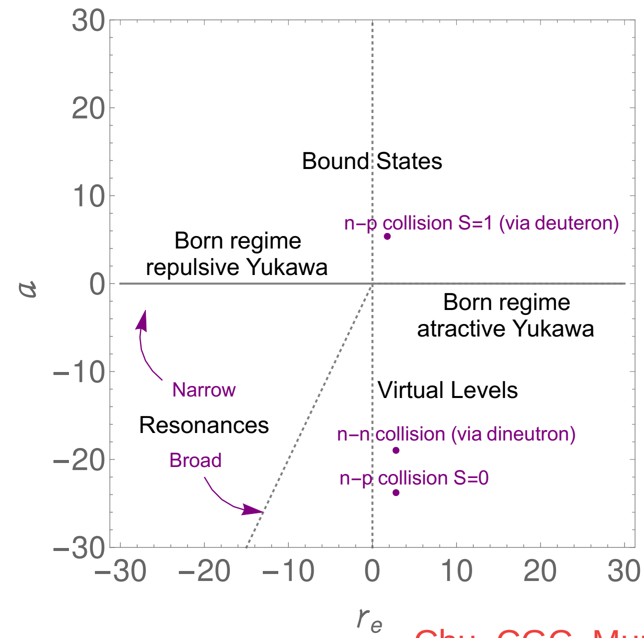

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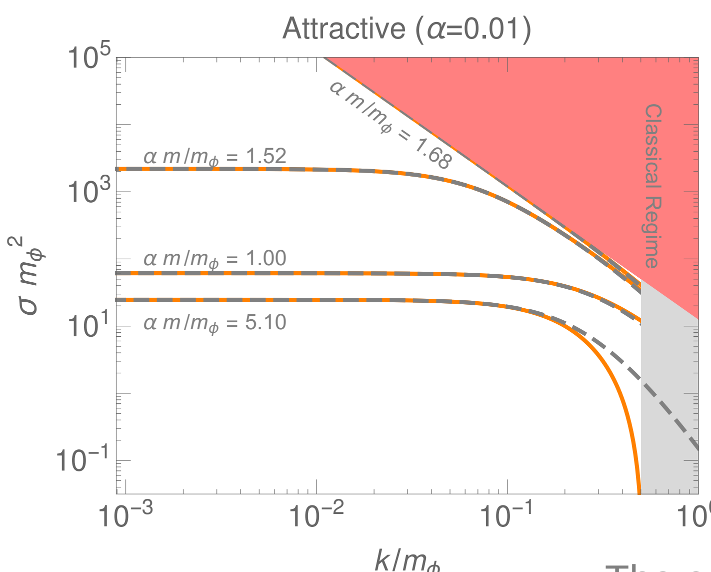

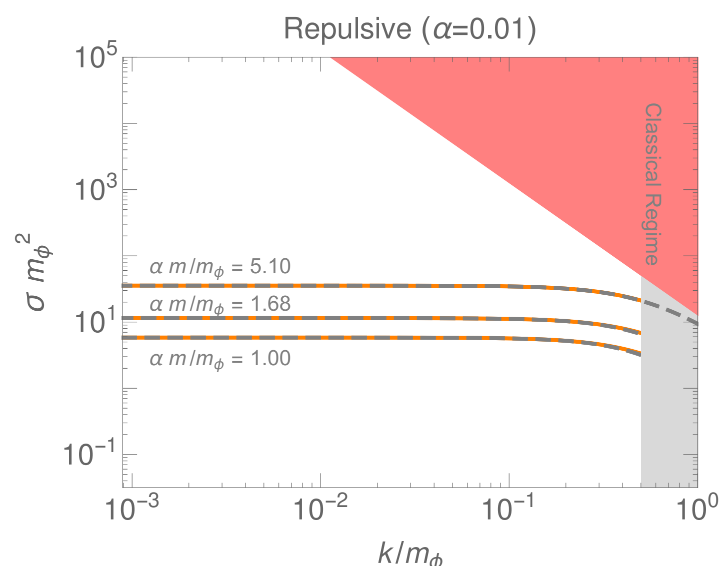

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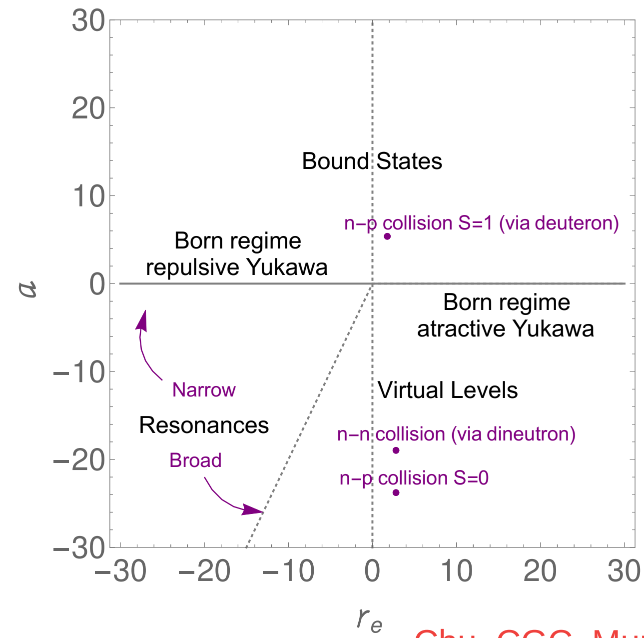
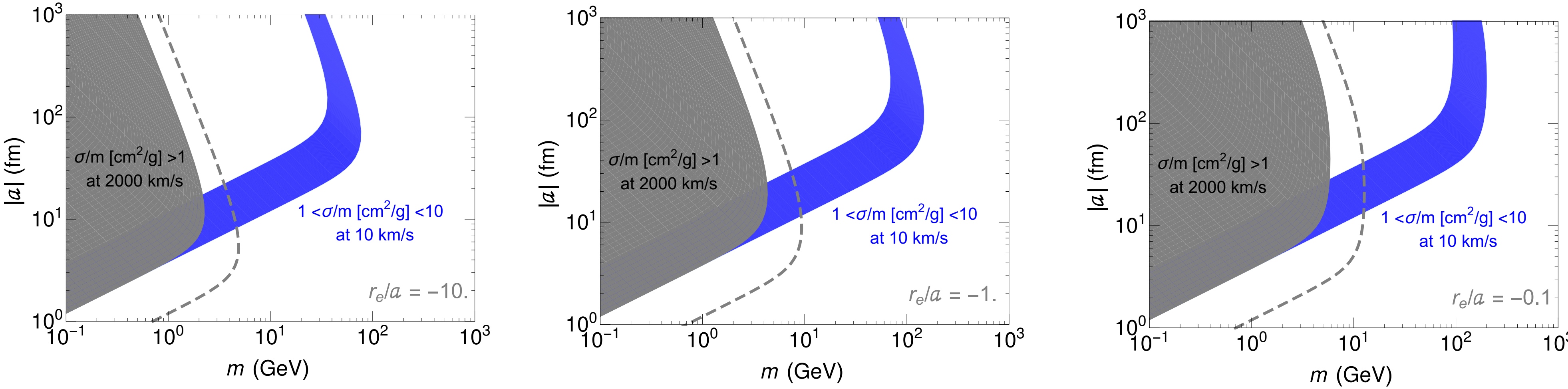


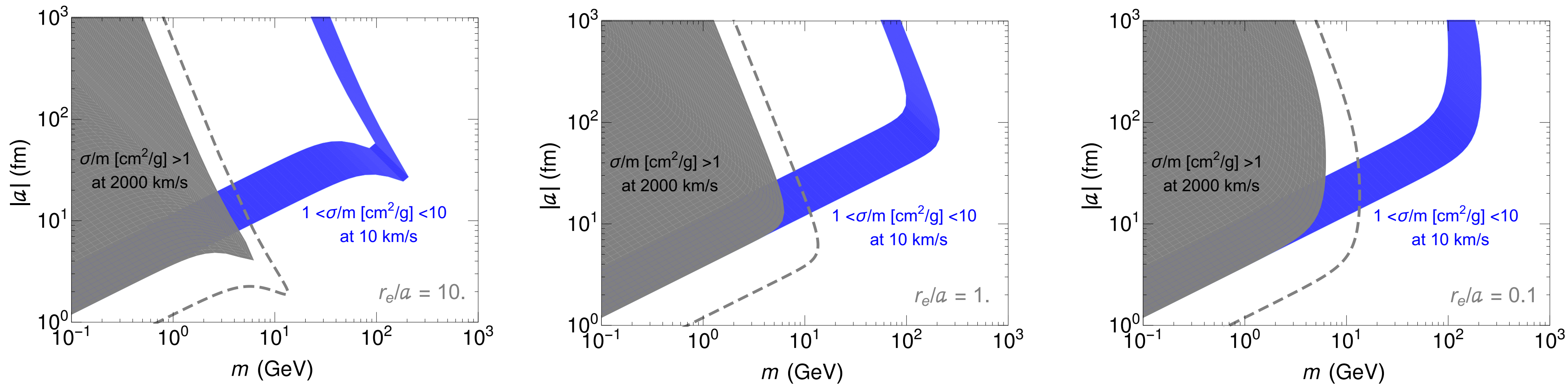
Chu, CGC, Murayama (2019)

This allows for a model-independent approach to SIDM!!

Effective Range Theory



Chu, CGC, Murayama (2019)



Conclusions

- *Self-interacting dark matter (SIDM) is a well-motivated solution to the problems encountered at small scales.*
- *Resonant SIDM is a viable model giving velocity-dependent scattering cross sections.*
- *Scenarios in which DM is puffy are another alternative.*
- *The velocity dependence of the scattering cross section is largely model independent and given by the effective range theory.*
- *This theory is able to simultaneously describe resonances, light mediators and DM bound states. As a result, we advocate its use in future SIDM studies.*

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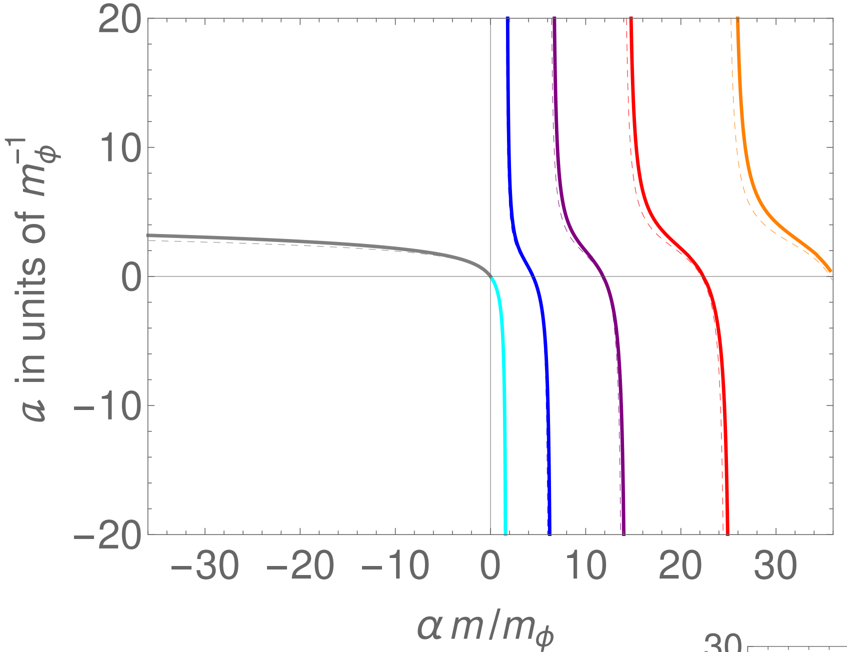
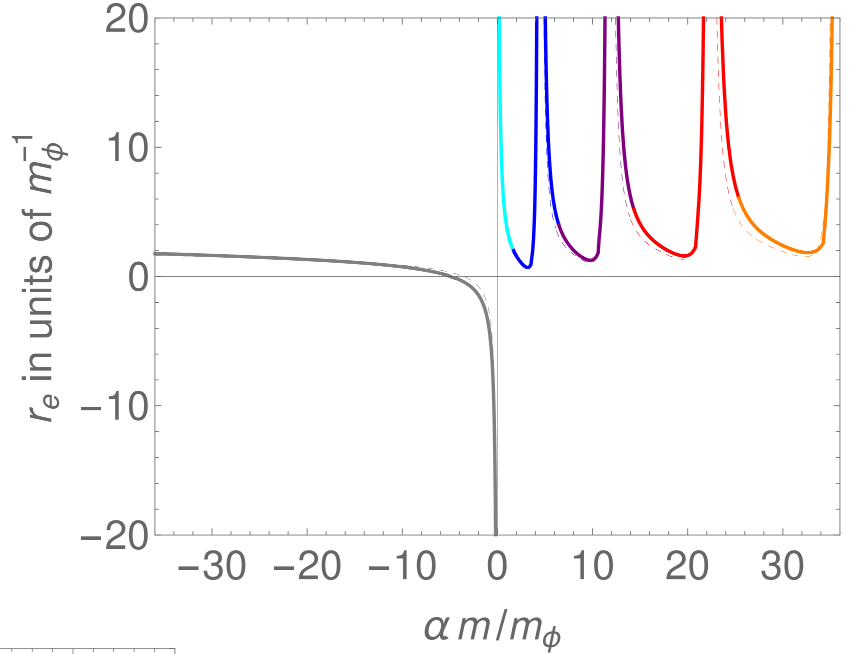
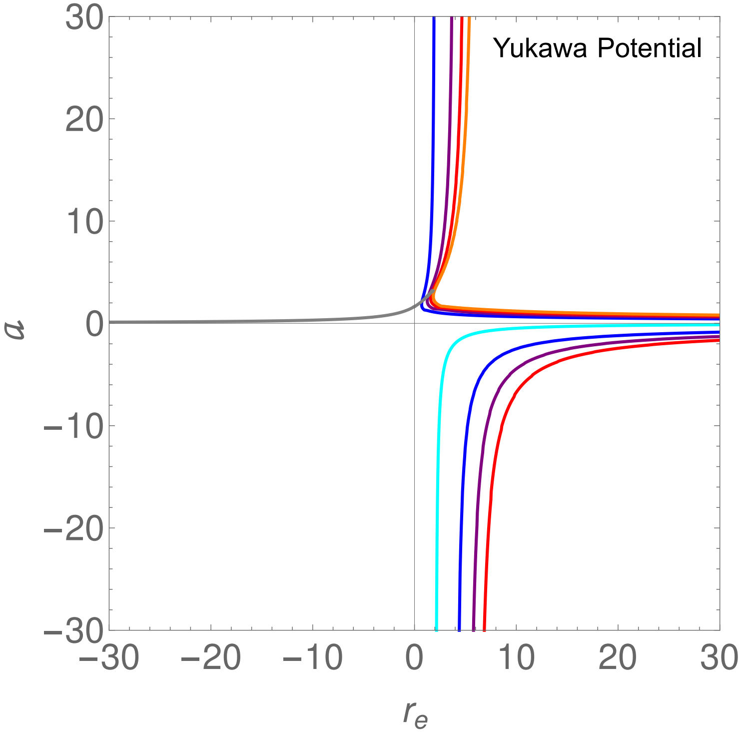
Thanks for your attention

Back-up slides







Back-up slides

a QCD-like theory of dark matter

Particle	$SU(3)_D$	$U(1)_D$	Description
c	**3**	2/3	Dark charm quark
d	**3**	-1/3	Dark down quark
γ_D	**1**	0	Dark photon
η	**1**	0	Pseudoscalar meson $d\bar{d}$
D^+	**1**	1	Pseudoscalar meson $c\bar{d}$
ρ	**1**	0	Vector meson $d\bar{d}$
Σ_c	**1**	0	Dark baryon cdd
Δ^-	**1**	-1	Dark baryon ddd
DM	**1**	0	Bound state of A Σ_c baryons

Chu, CGC, Murayama (2018)

low-threshold direct detection experiments have the potential to probe Puffy Dark Matter.