Velocity-Dependent Self-Interactions of Dark Matter and their Astrophysical Implications

Beijing Normal University

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Excelencia Severo Ochoa

Outline

- Velocity-dependent dark matter scatterings.
- Specific benchmark predicting large cross sections
- Astrophysical implications?
- Conclusions

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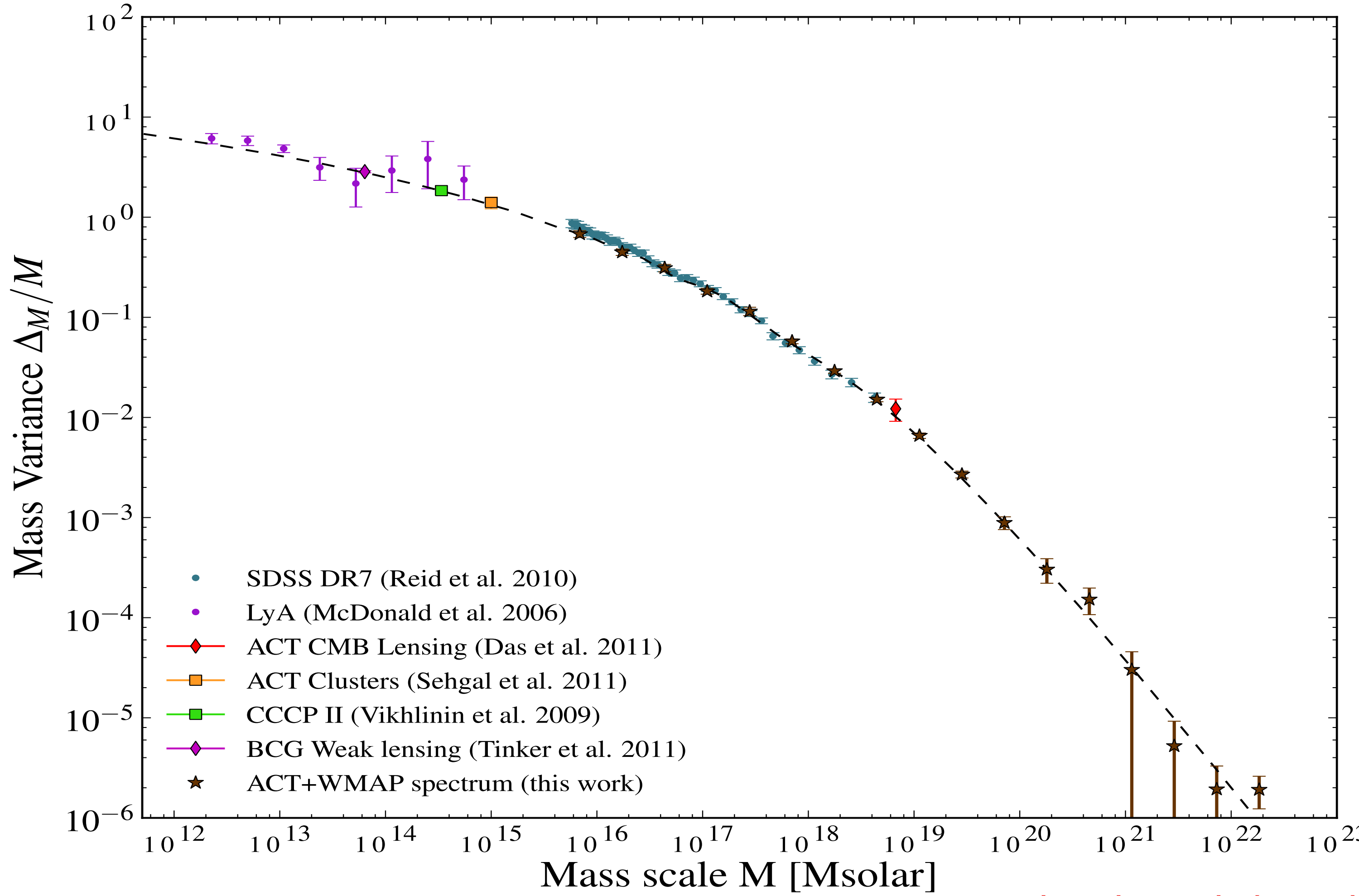
Cold Dark Matter



Hlozek et al. (2012)

Remarkably successful at large scales

At low scales N-body simulations are needed

Mass deficits at galactic scales

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

Heated debates!!!

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Self-interacting dark matter hypothesis

To be more specific, we suggest that the dark matter particles should have a mean free path between $\sim$1 kpc to 1 Mpc at the solar radius in a typical galaxy (mean density 0.4 GeV/cm^3), for reasons to be explained below. For a particle of mass m_x, this implies an elastic scattering cross section of

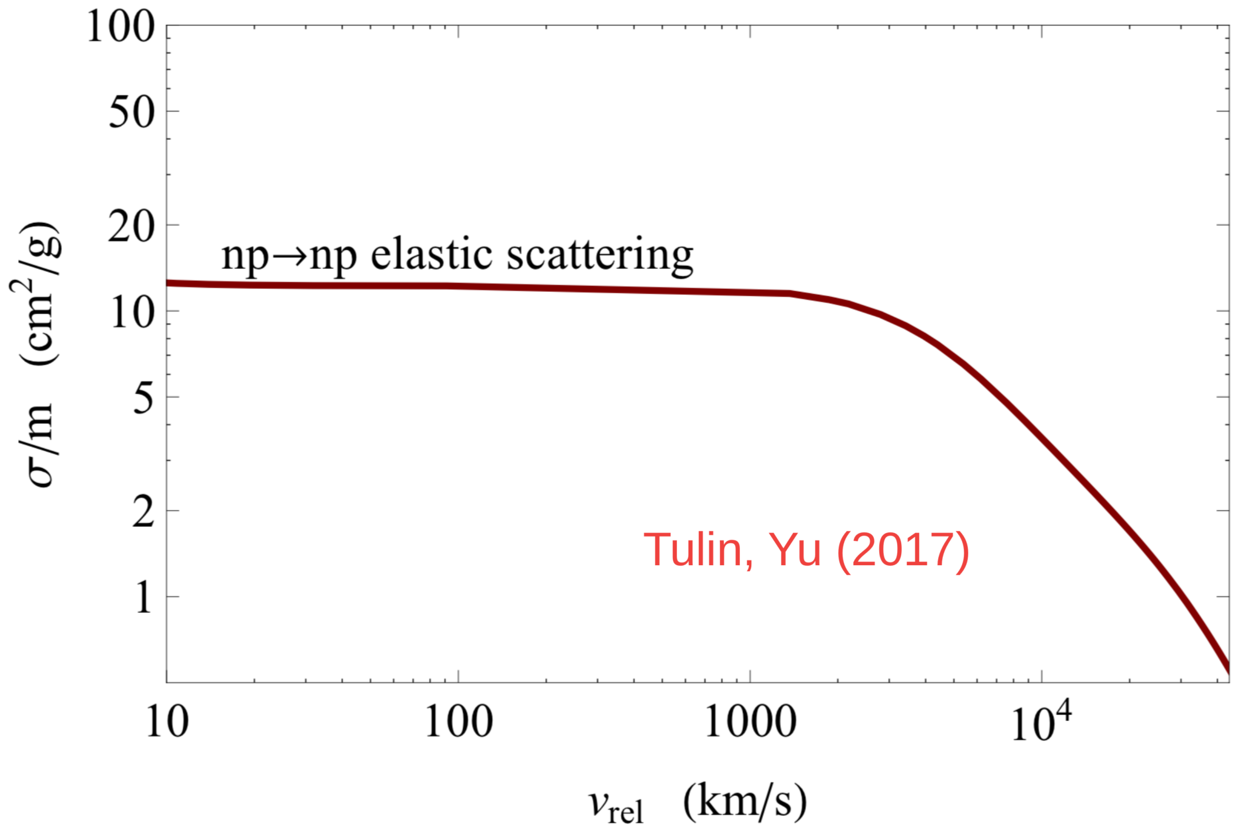
$$\sigma/m \sim 1 \text{ cm}^2/\text{g} \tag{1}$$

intriguingly similar to that of an ordinary hadron.

Observational Evidence for Self-Interacting Cold Dark Matter

David N. Spergel and Paul J. Steinhardt

Phys. Rev. Lett. **84**, 3760 – Published 24 April 2000



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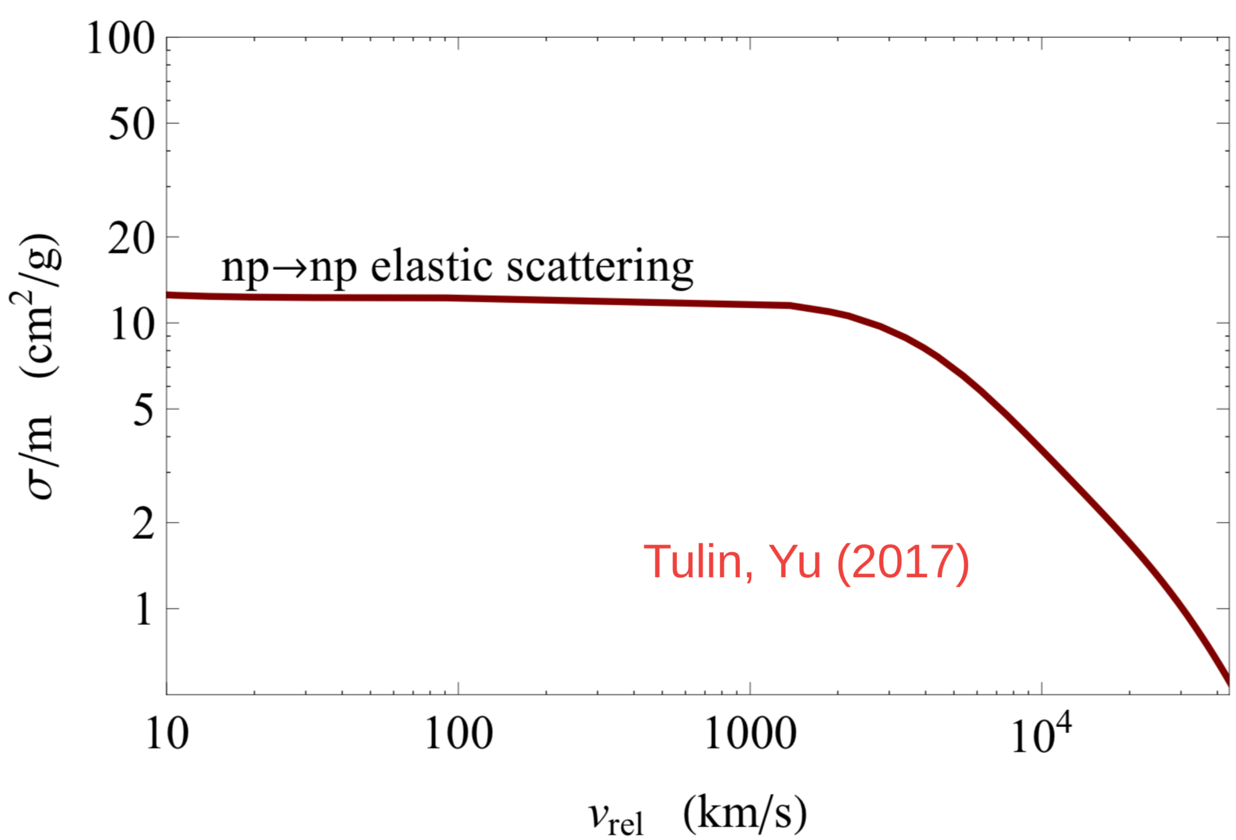
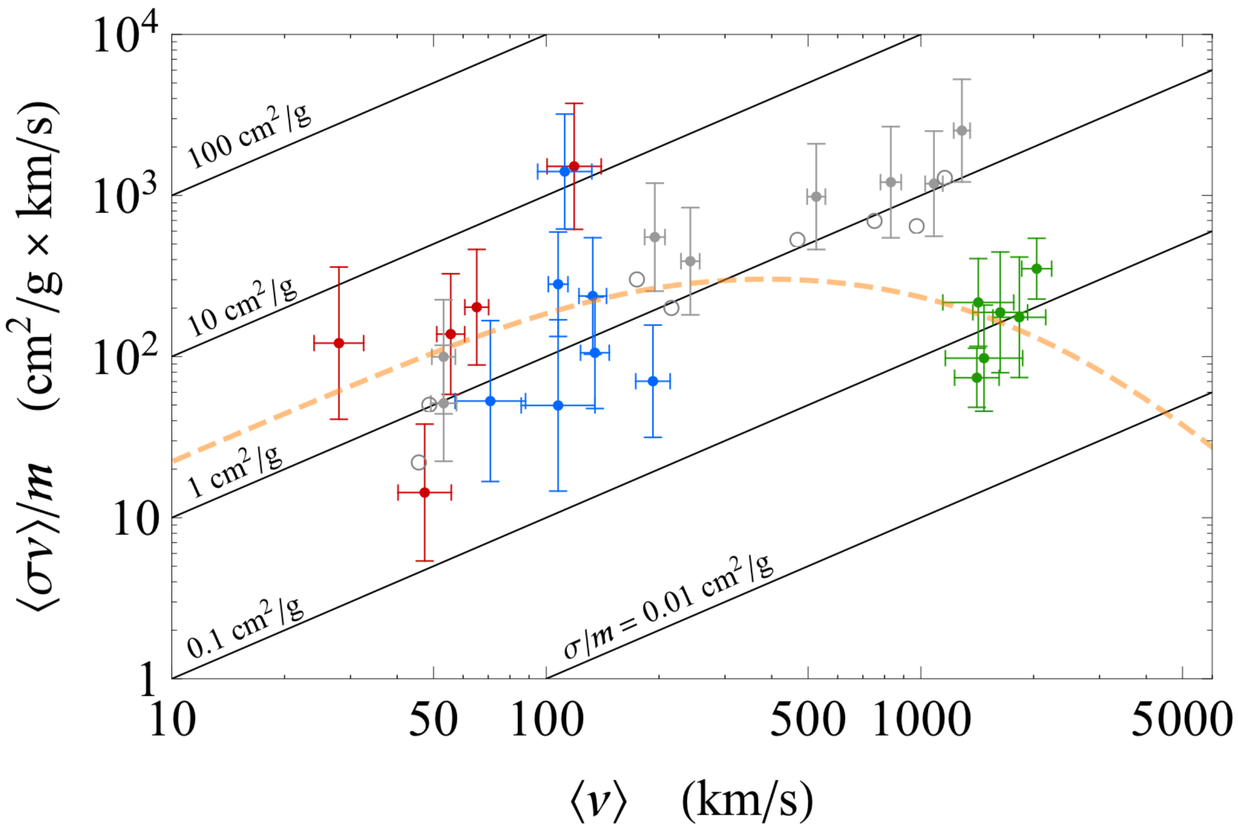


Dark Matter Halos as Particle Colliders: Unified Solution to Small-Scale Structure Puzzles from Dwarfs to Clusters

Manoj Kaplinghat, Sean Tulin, and Hai-Bo Yu
Phys. Rev. Lett. **116**, 041302 – Published 28 January 2016



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Light mediator

On the Interaction of Elementary Particles. I.

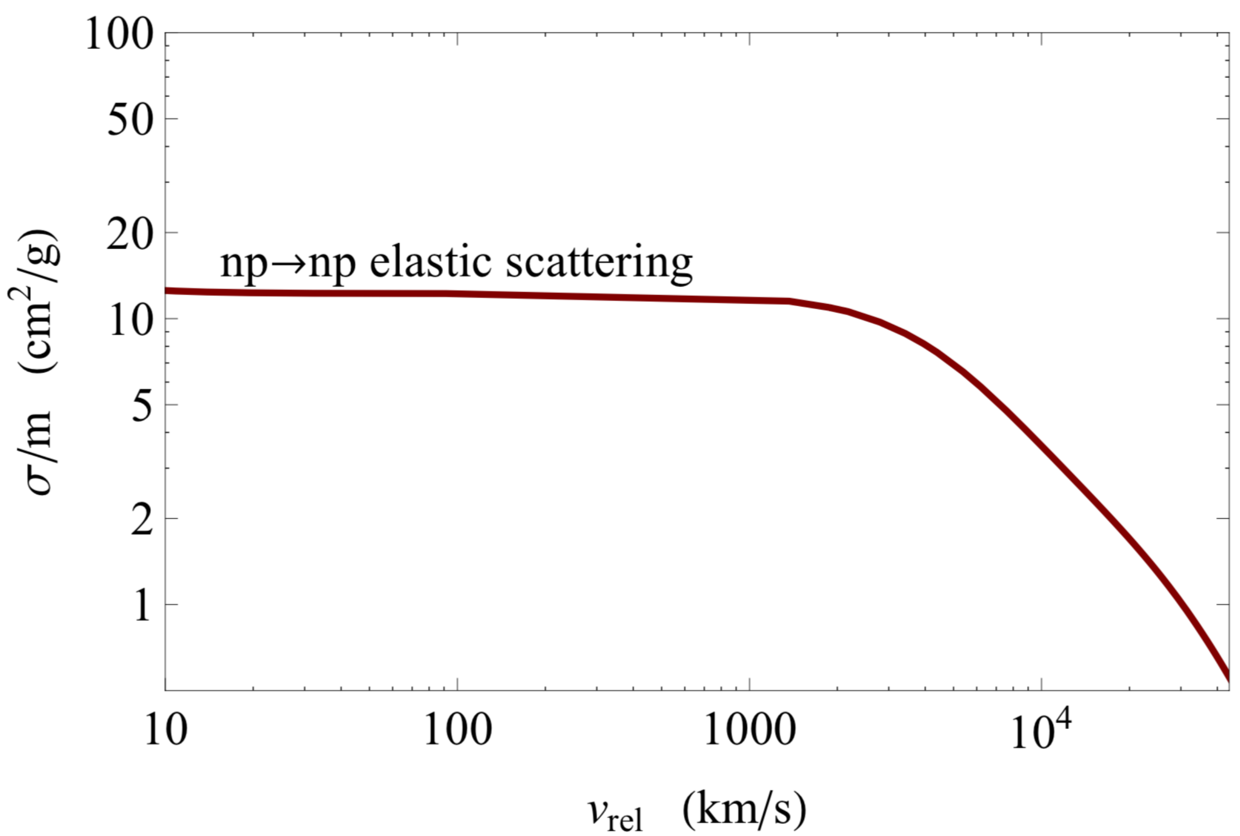
By Hideki YUKAWA.

(Read Nov. 17, 1934)

The potential of force between the neutron and the proton should, however, not be of Coulomb type, but decrease more rapidly with distance. It can be expressed, for example, by

$$+ \text{ or } -g^2\frac{e^{-\lambda r}}{r}, \tag{2}$$

so that the quantum accompanying the field has the proper mass $m_U = \frac{\lambda h}{c}$.



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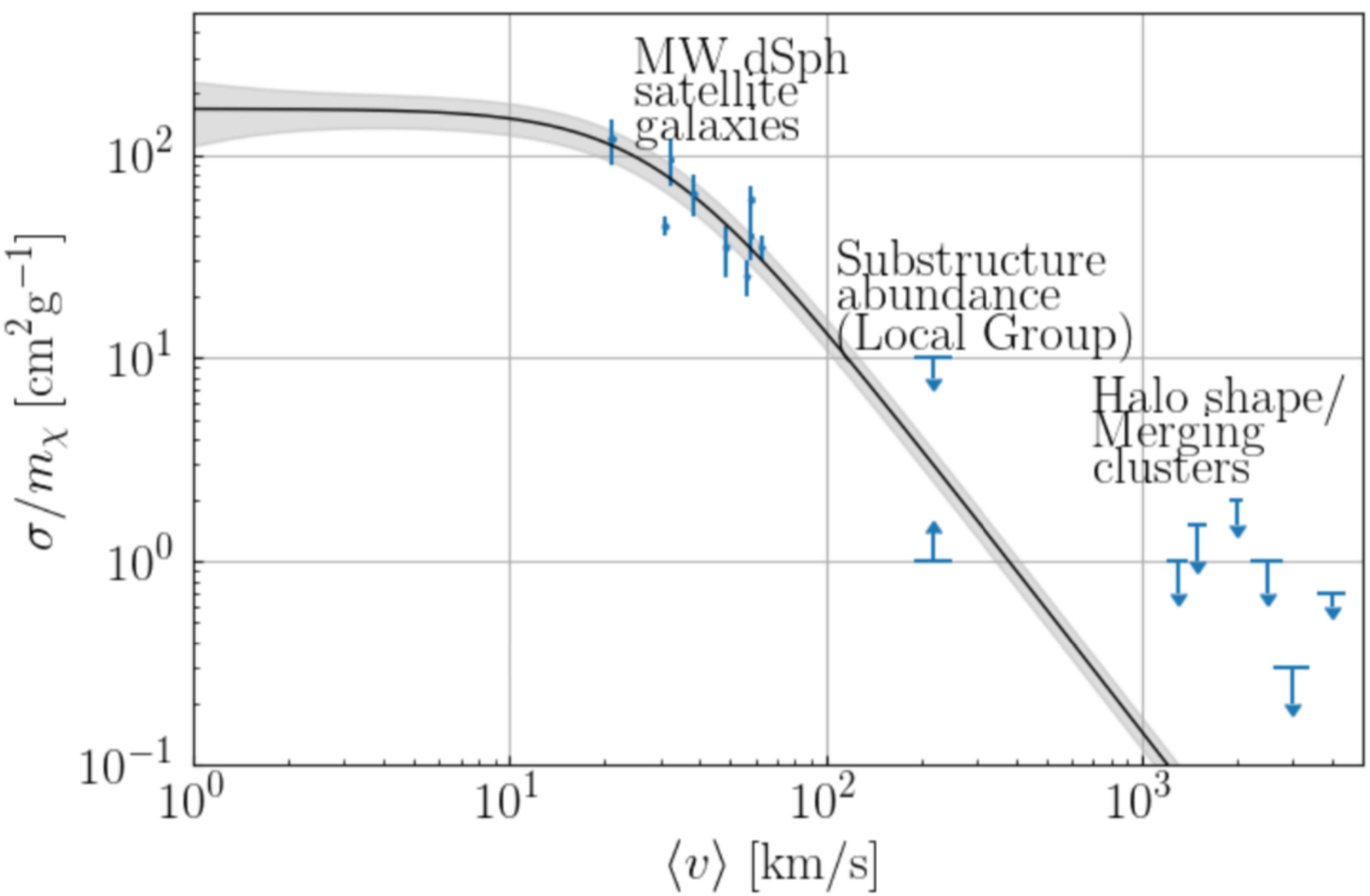
Light mediator

Constraining Velocity-dependent Self-Interacting Dark Matter with the Milky Way's dwarf spheroidal galaxies

Camila A. Correa[1]*



Born approximation of the Yukawa potential

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_0}{4\pi}\left[1 + \frac{v^2}{w^2}\sin^2\left(\frac{\theta}{2}\right)\right]^{-2},$$

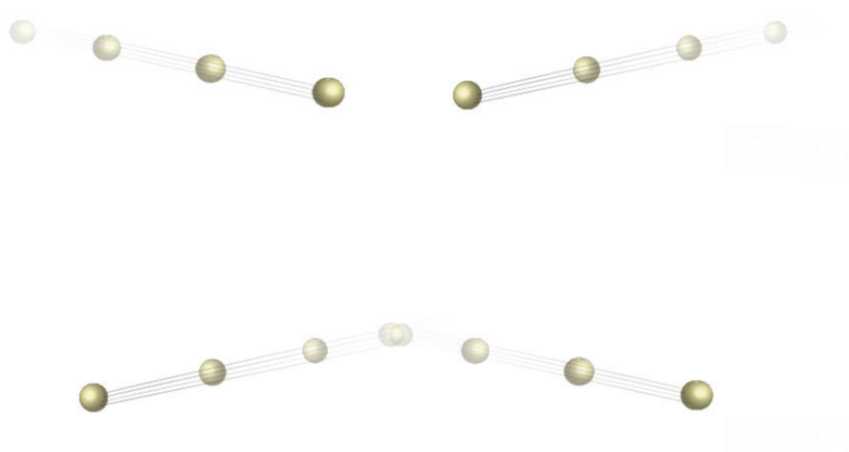
Resonant self-interacting dark matter

Velocity Dependence from Resonant Self-Interacting Dark Matter

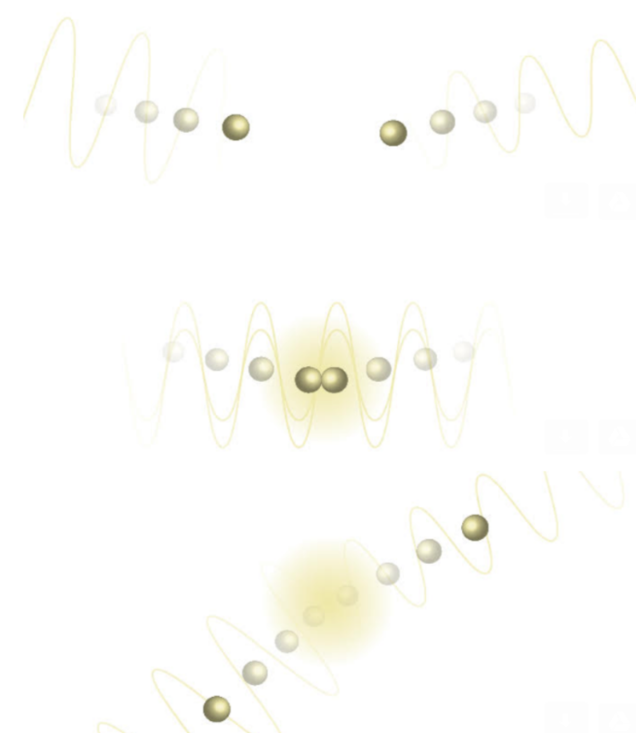
Xiaoyong Chu, Camilo Garcia-Cely, and Hitoshi Murayama
Phys. Rev. Lett. **122**, 071103 – Published 22 February 2019

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

At clusters of galaxies



In galaxies



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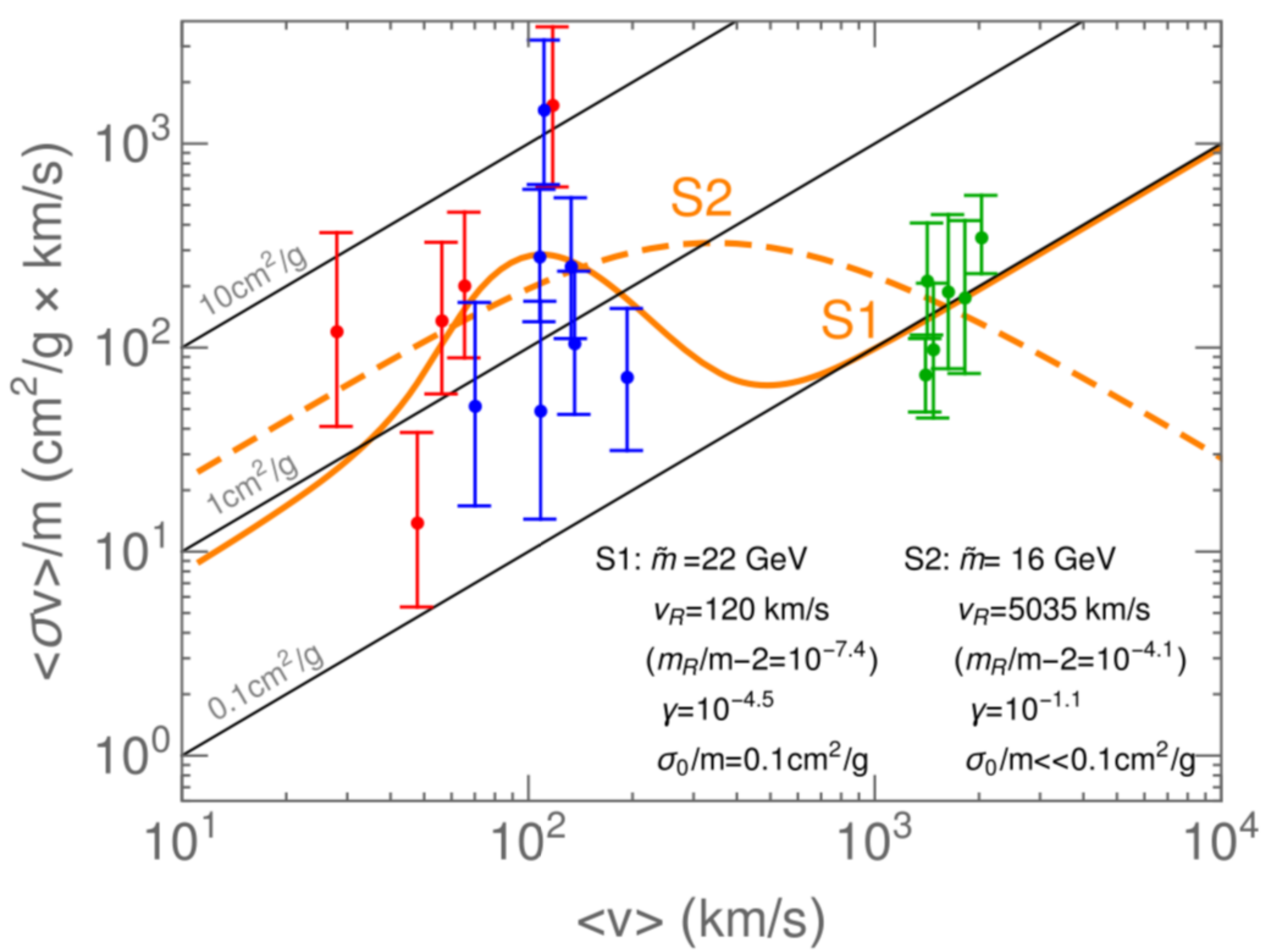

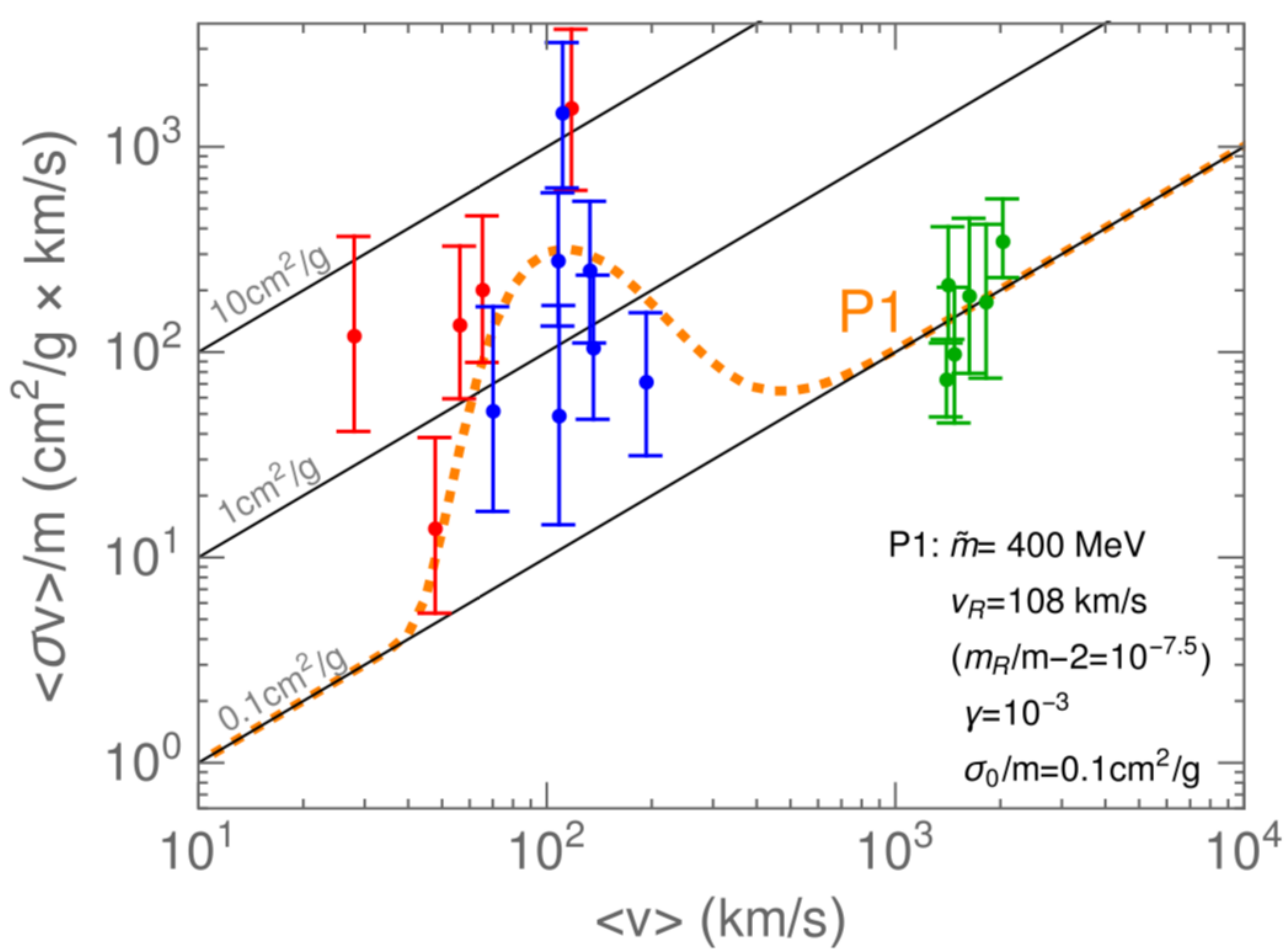

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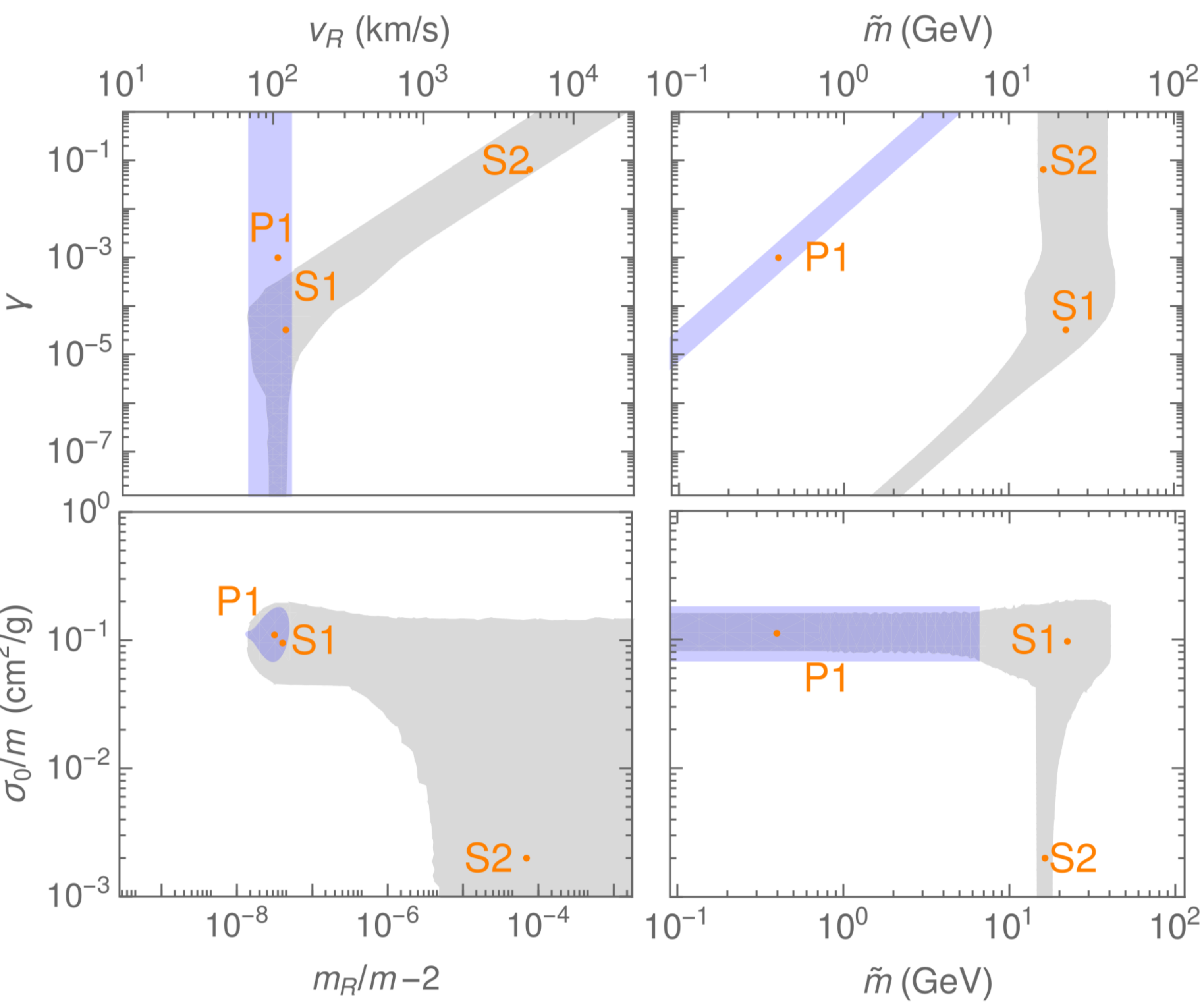


Scenario	Interaction Lagrangian	L	$J_{\rm DM}$	J_R^P	S	γ
I	$gR\overline{\rm DM}\gamma^5{\rm DM}$	0	$\frac{1}{2}$	0^-	$\frac{1}{4}$	$g^2/32\pi$
IIa	$gR{\rm DM}^i{\rm DM}^i$	0	0	0^+	$\frac{1}{3}$	$g^2/16\pi m_R^2$
IIb	$g\epsilon_{ijk}R^i_\mu{\rm DM}^j\partial^\mu{\rm DM}^k$	1	0	1^-	1	$g^2/384\pi$
III	$(1/\Lambda)R_{\mu\nu}\mathcal{T}^{\mu\nu}_{\rm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

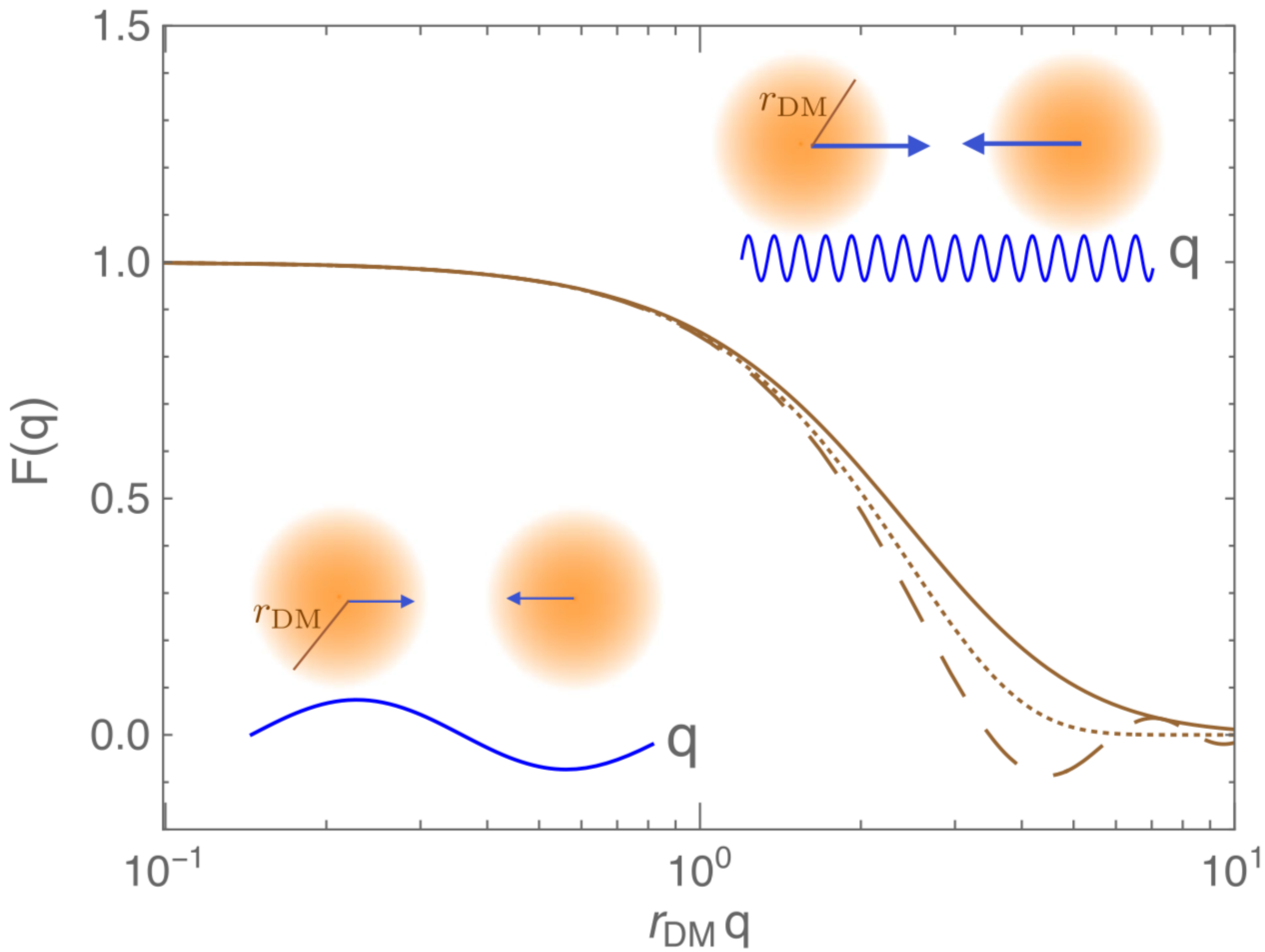
The way the non-relativistic cross section varies with the velocity is largely independent of the internal structure

Simple parametrization

Finite-size dark matter

Finite-Size Dark Matter and its Effect on Small-Scale Structure

Xiaoyong Chu, Camilo Garcia-Cely, and Hitoshi Murayama
Phys. Rev. Lett. **124**, 041101 – Published 28 January 2020



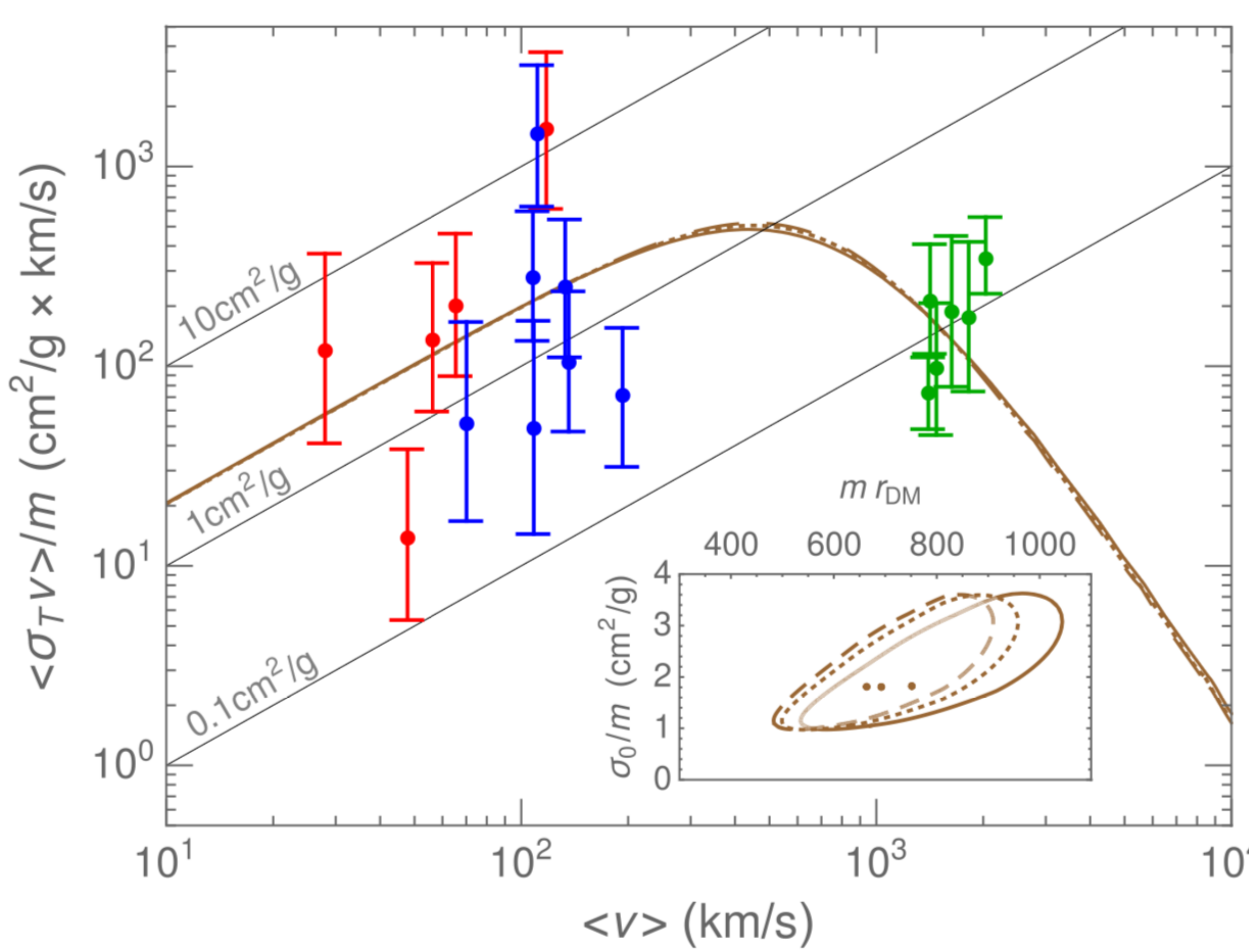


TABLE I. Form factors for different density distributions.

Shape	$\rho(r)$	$r_{\rm DM}$	$F(q)$
Top hat	$(3/4\pi r_0^3)\theta(r_0-r)$	$2\sqrt{3}r_0$	$\{(3[\sin(r_0q)-r_0q\cos(r_0q)])/(r_0^3q^3)\}$
Dipole	$[(e^{-r/r_0})/8\pi r_0^3]$	$\sqrt{3/5}r_0$	$\{1/[(1+r_0^2q^2)^2]\}$
Gaussian	$[1/(8r_0^3\pi^{3/2})]e^{-r^2/(4r_0^2)}$	$\sqrt{6}r_0$	$e^{-r_0^2q^2}$

The way the non-relativistic cross section varies with the velocity is largely independent of the internal structure

Simple parametrization

Lessons

- From this point of view, models based on light mediators are as well motivated as those arising from strongly coupled sectors.
- Studies based of light mediators can be adapted to other models .

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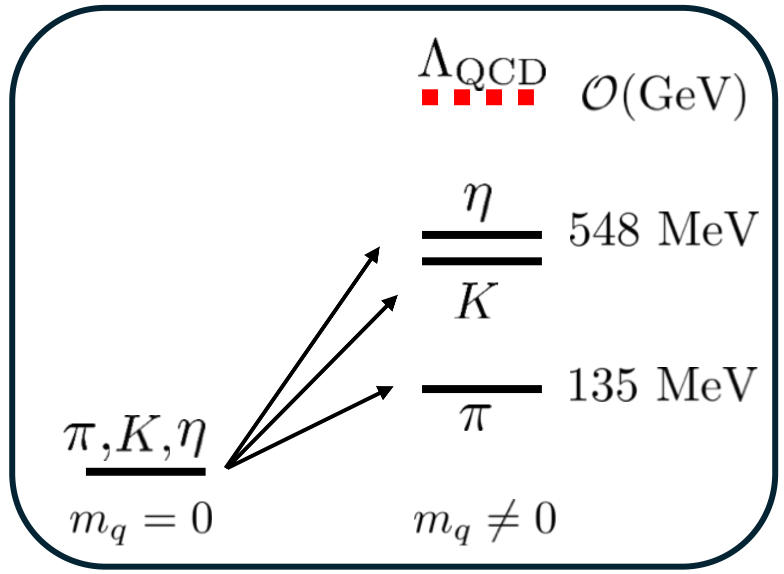
Strong interactions in the Standard Model

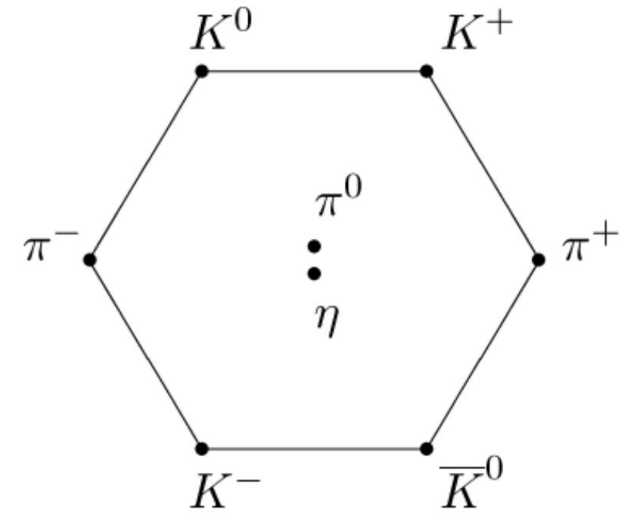
QCD sector of the Standard Model

$$\mathcal{L} = -\frac{1}{4}F^2 + \bar{q}i\not{D}q - (\bar{q}_L M q_R + h.c.)$$

$$M = \mathrm{diag}(m_u, m_d, m_s)$$

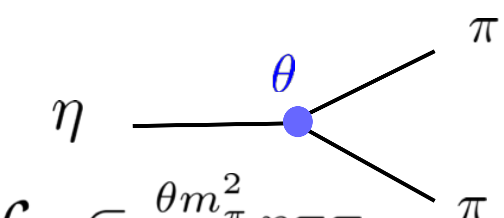
$$m_u < m_d < m_s$$





Low-energy Lagrangian $\mathcal{L}_\chi \subset \frac{1}{2}m_\pi^2\pi^2 + \frac{\mathcal{O}(\pi^4)}{f_\pi^2}$

$$\mathcal{L}_\theta = \frac{g^2\theta^2}{32\pi^2}F\widetilde{F}$$ topological term



$$\Gamma(\eta \to \pi\pi) \sim \frac{\theta^2 m_\pi^4}{\pi f_\pi^2 m_\eta}\sqrt{1 - \frac{4m_\pi^2}{m_\eta^2}}$$

$$\mathcal{L}_\chi \subset \frac{\theta m_\pi^2}{f_\pi}\eta\pi\pi$$

However in the SM $\theta_{\mathrm{SM}} < 10^{-10}$ **(Strong CP problem)**

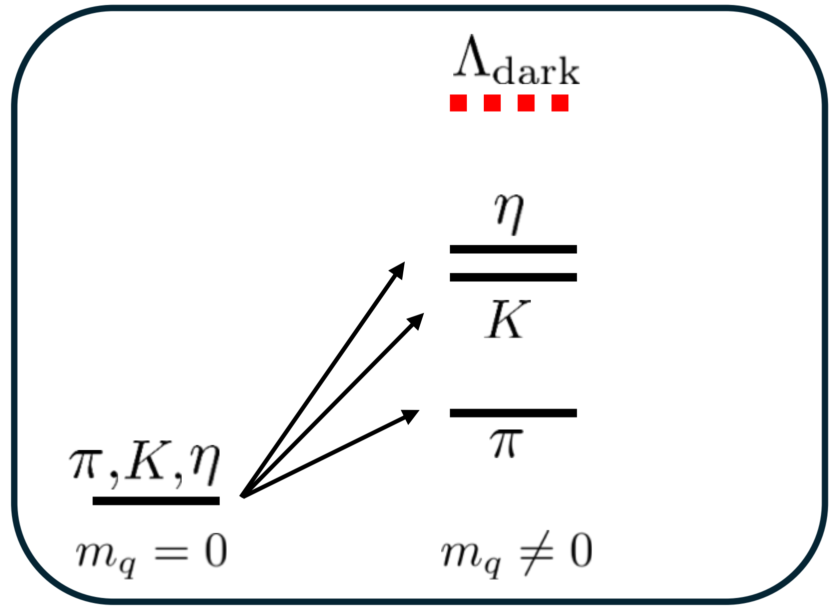
Suppose the dark matter sector is the same

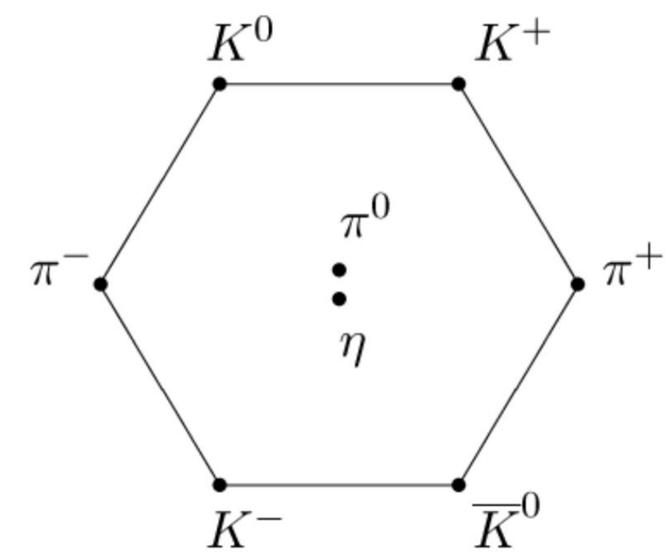
García-Cely, Landini, Zapata, 2024

Minimal SIMP model: same as SM

$$\mathcal{L} = -\frac{1}{4}F^2 + \bar{q}i\not{D}q - (\bar{q}_L M q_R + h.c.)$$

$$M = \mathrm{diag}(m_1, m_2, m_3)$$
$$m_1 < m_2 < m_3$$





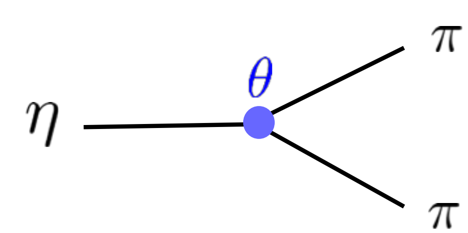
Resonance: $m_\eta = \left(2 + \frac{v_R^2}{4}\right) m_\pi$

with $v_R \lesssim 0.1$

Low-energy Lagrangian $\mathcal{L}_\chi \subset \frac{1}{2}m_\pi^2\pi^2 + \frac{\mathcal{O}(\pi^4)}{f_\pi^2}$

$\mathcal{L}_\theta = \frac{g^2\theta^2}{32\pi^2}F\widetilde{F}$ topological term **is** present in the **minimal** model (most papers $\theta = 0$)

Generally $\theta \sim \mathcal{O}(1)$ ➡ ✓ new interactions among dark mesons



$$\mathcal{L}_\chi \subset \frac{\theta m_\pi^2}{f_\pi}\eta\pi\pi$$

Specific benchmark with a Breit-Wigner resonance

PHYSICAL REVIEW D **111**, 063044 (2025)

Dark matter in QCD-like theories with a theta vacuum: Cosmological and astrophysical implications

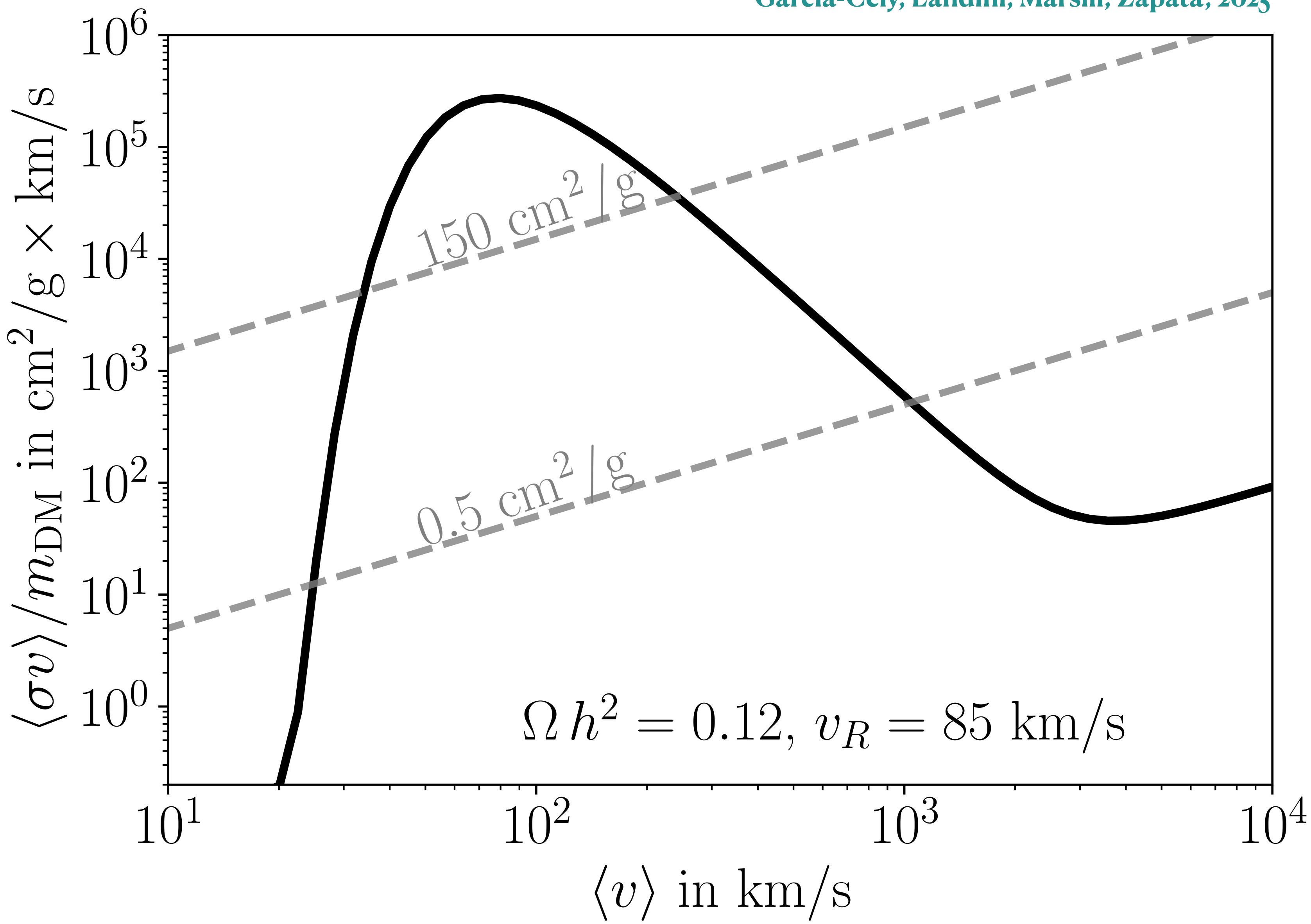
Camilo García-Cely,[1] Giacomo Landini,[1] and Óscar Zapata[2]

Pion dark matter in a θ vacuum: a thermal relic with sharp velocity-dependent self-interactions

Camilo García-Cely,[a] Giacomo Landini,[b] Luca Marsili,[c] Óscar Zapata [d]

Specific benchmark with a Breit-Wigner resonance

García-Cely, Landini, Marsili, Zapata, 2025



Camilo García-Cely

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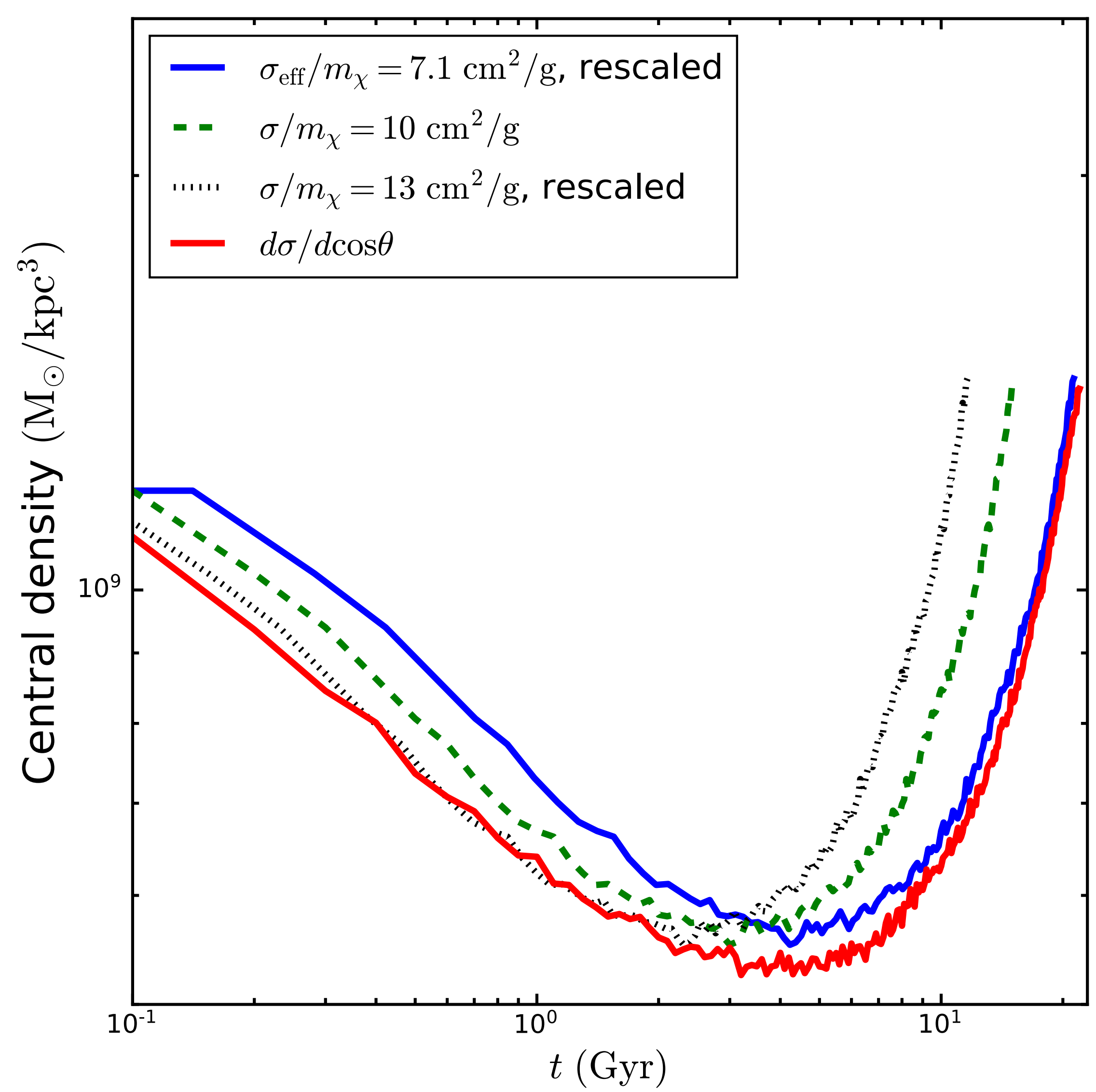
Gravothermal collapse



Daneng Yang, Hai-Bo Yu, 2022

The Jackpot – SDSS J0946+1006

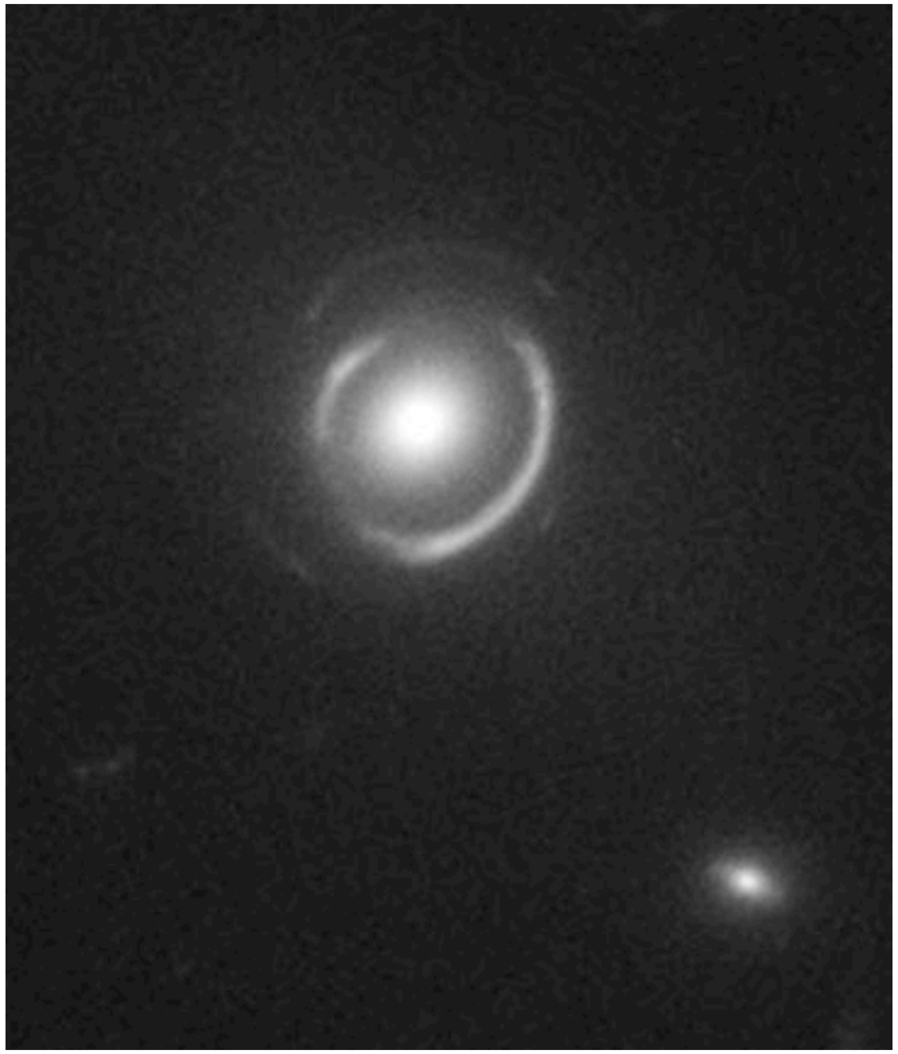


Image Credit: NASA, ESA, N. Benítez (IAA, Spain), T. Treu (UCLA), et al

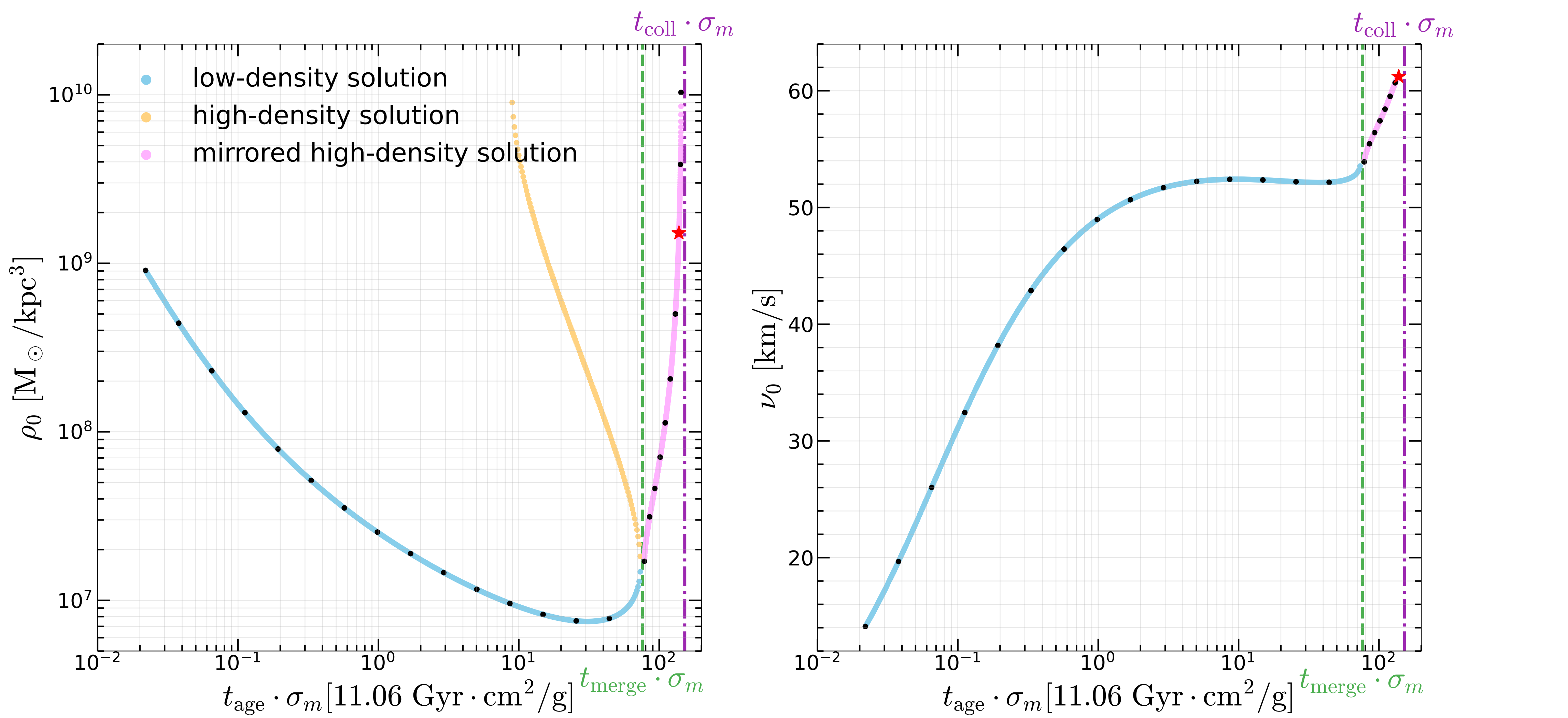
Why important?

- Nicknamed 'Jackpot' because if has multiple lensed sources.
- It is the first strong lens with a detected dark subhalo (~3×10^9 M$\odot$)
- Subhalo density exceeds CDM expectations.
- It could signal a core-collapsed halo of SIDM.

The Jackpot – SDSS J0946+1006

The "Little Dark Dot": Evidence for Self-Interacting Dark Matter in the Strong Lens SDSSJ0946+1006?

Shubo Li,[1,2,3] Ran Li,[1,3] Kaihao Wang,[1,2,3] Zixiang Jia,[4] Xiaoyue Cao,[3,2,1] Carlos S. Frenk,[5] Fangzhou Jiang,[6] Aristeidis Amvrosiadis,[5] Shaun Cole,[5] Qiuhan He,[5] Samuel C. Lange,[5] Richard Massey,[5] James W. Nightingale,[7,5,8] Andrew Robertson,[9] Maximilian von Wietersheim-Kramsta,[5,8] and Xianghao Ma[1,2,3]



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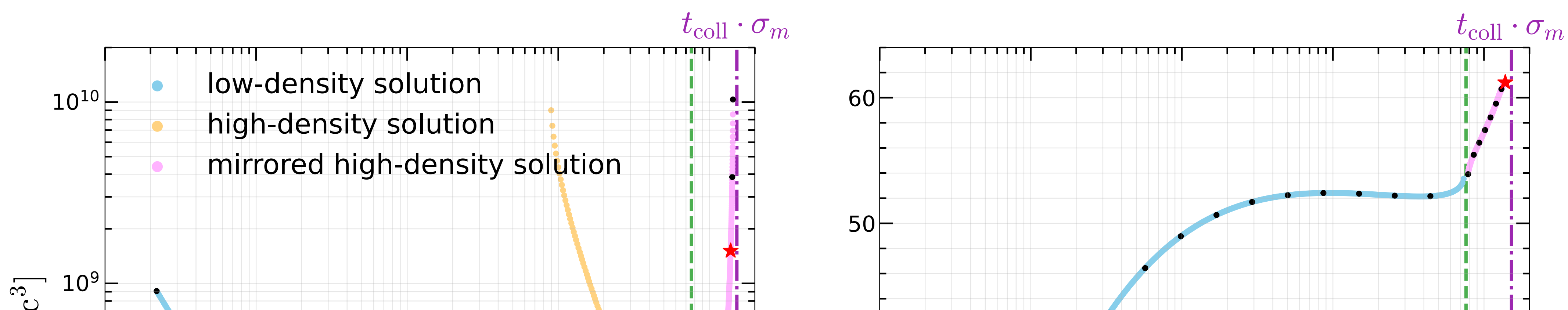
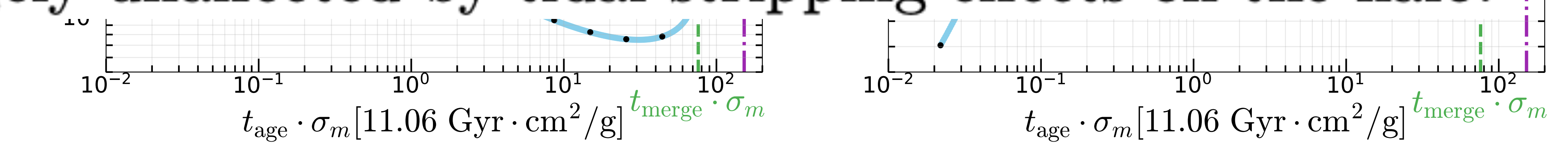
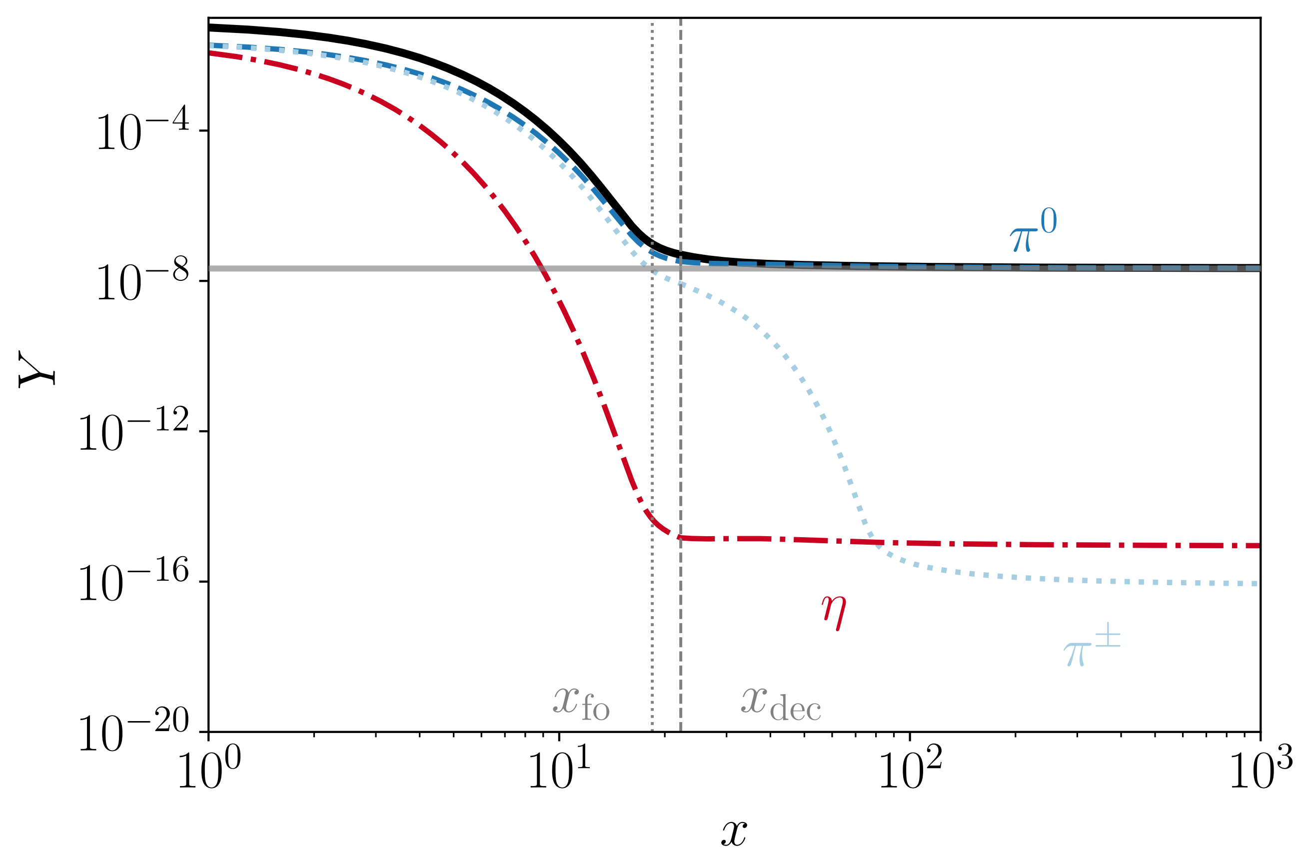


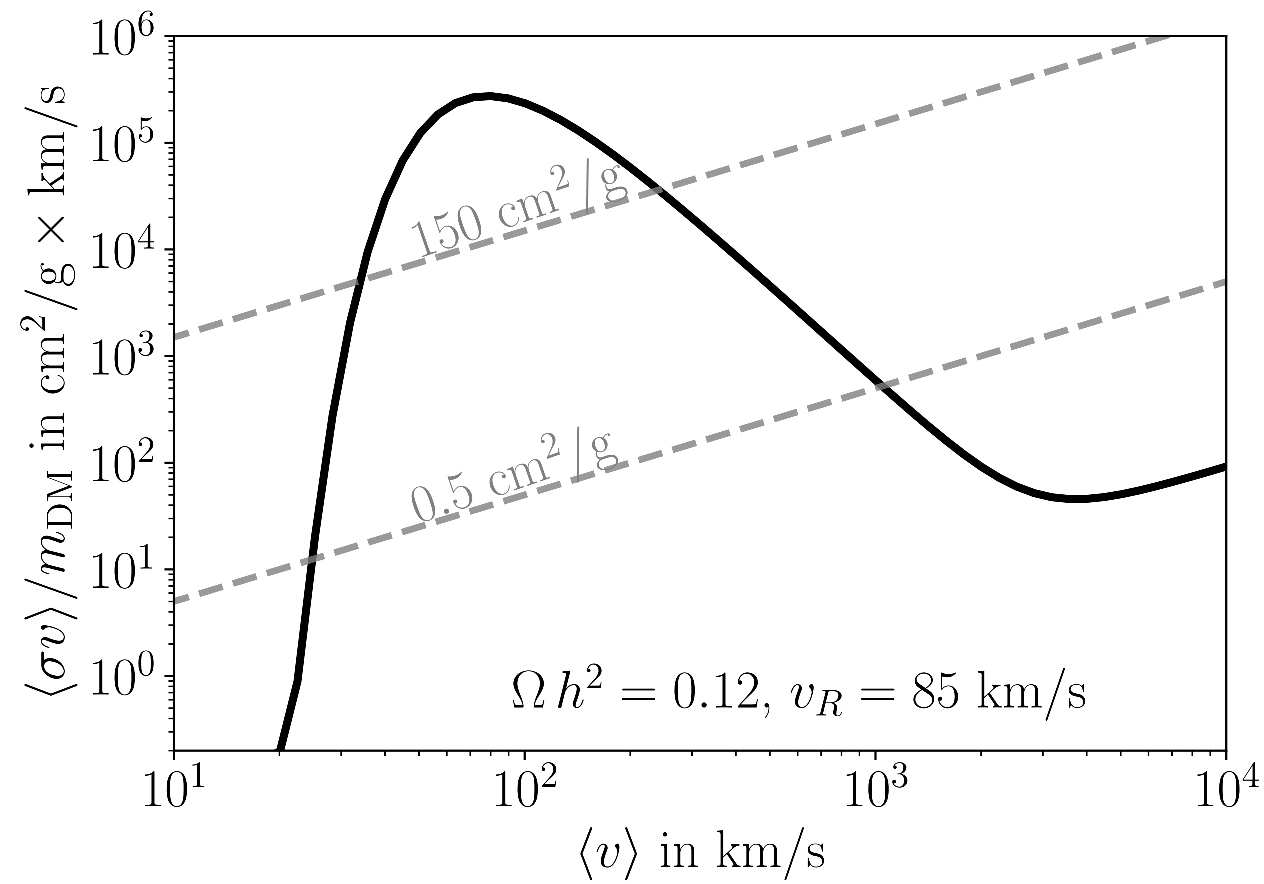
By setting the formation time of a $10^{11}\,\mathrm{M}_\odot$ halo equal to the cosmic time, we derive a lower bound on the SIDM cross-section of $\sigma_m = 138\,\mathrm{cm}^2/\mathrm{g}$. This conclusion is largely unaffected by tidal stripping effects on the halo.



Specific benchmark with a Breit-Wigner resonance

García-Cely, Landini, Marsili, Zapata, 2025





Conclusions

- Resonant SIDM is a viable model giving velocity-dependent scattering cross sections.

- It remains to be seen whether it can explain the Jackpot while explaining the relic density.