Self-interacting Dark Matter

Status and Perspectives

Camilo A. Garcia Cely
Alexander von Humboldt fellow

SFB Colloquium

TU München

Feb 3, 2020

PHYSICAL REVIEW LETTERS **122,** 071103 (2019)

Velocity Dependence from Resonant Self-Interacting Dark Matter

Xiaoyong Chu,[1,*] Camilo Garcia-Cely,[2,†] and Hitoshi Murayama[3,4,5,2,‡]

PHYSICAL REVIEW LETTERS **124,** 041101 (2020)

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

Xiaoyong Chu [1,*] Camilo Garcia-Cely [2,†] and Hitoshi Murayama[3,4,5,2,‡]

A Practical and Consistent Parametrization of Dark Matter Self-Interactions

Xiaoyong Chu (Vienna, OAW), Camilo Garcia-Cely (DESY), Hitoshi Murayama (DESY & LBL, Berkeley & Tokyo U., IPMU & UC, Berkeley)

Aug 16, 2019

e-Print: arXiv:1908.06067 [hep-ph] | PDF

Dark Matter Self-interactions and Small Scale Structure

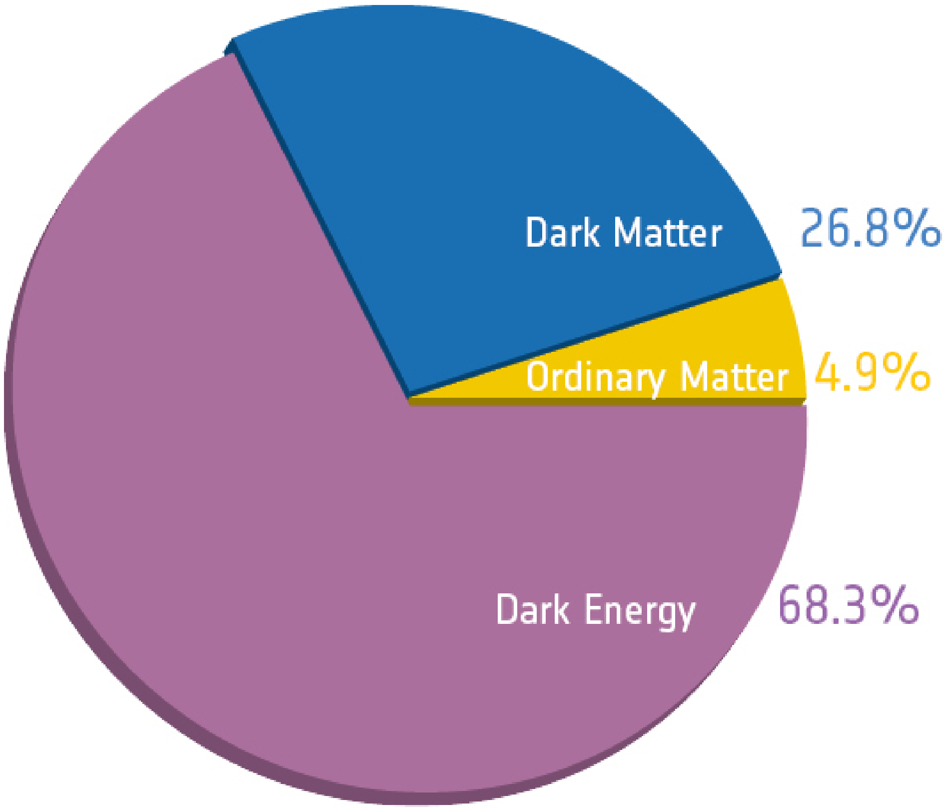
Sean Tulin (York U., Canada), Hai-Bo Yu (UC, Riverside)

May 5, 2017 - 57 pages

Phys.Rept. 730 (2018) 1-57

Lambda Cold Dark Matter model

Energy budget of the Universe



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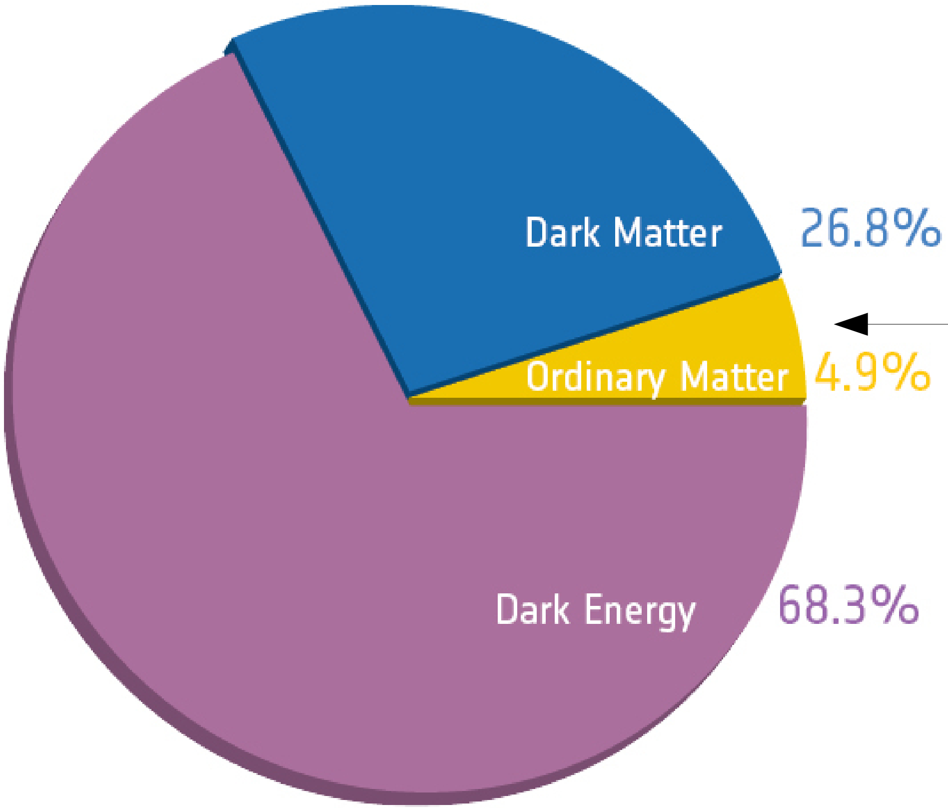

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Mostly protons, electrons, neutrinos and photons.

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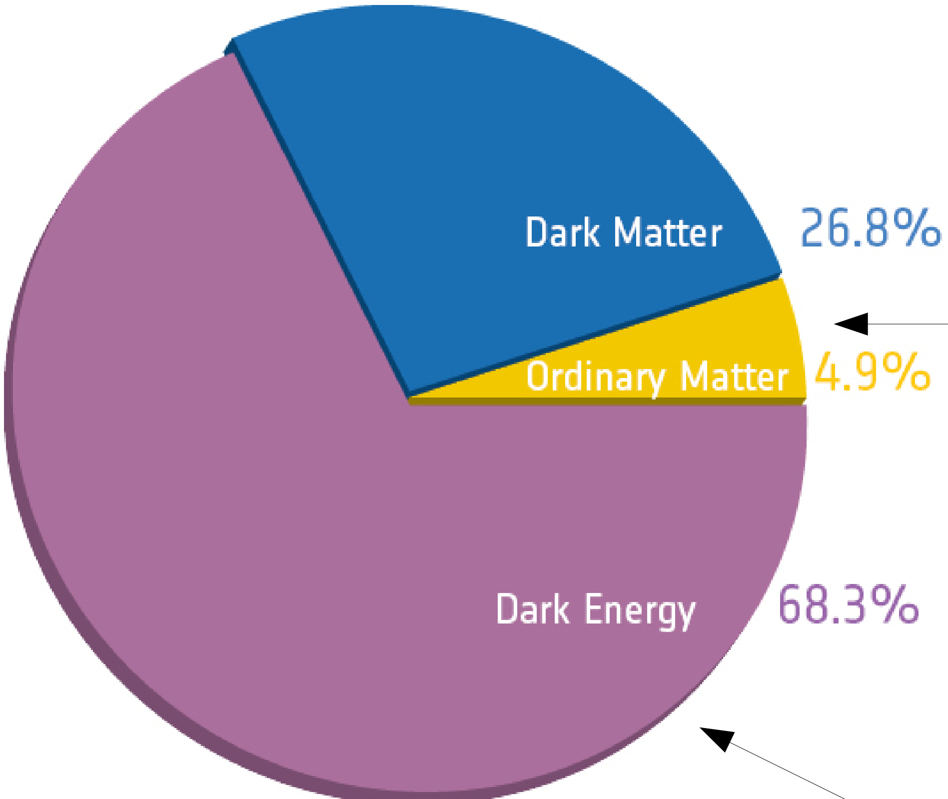

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$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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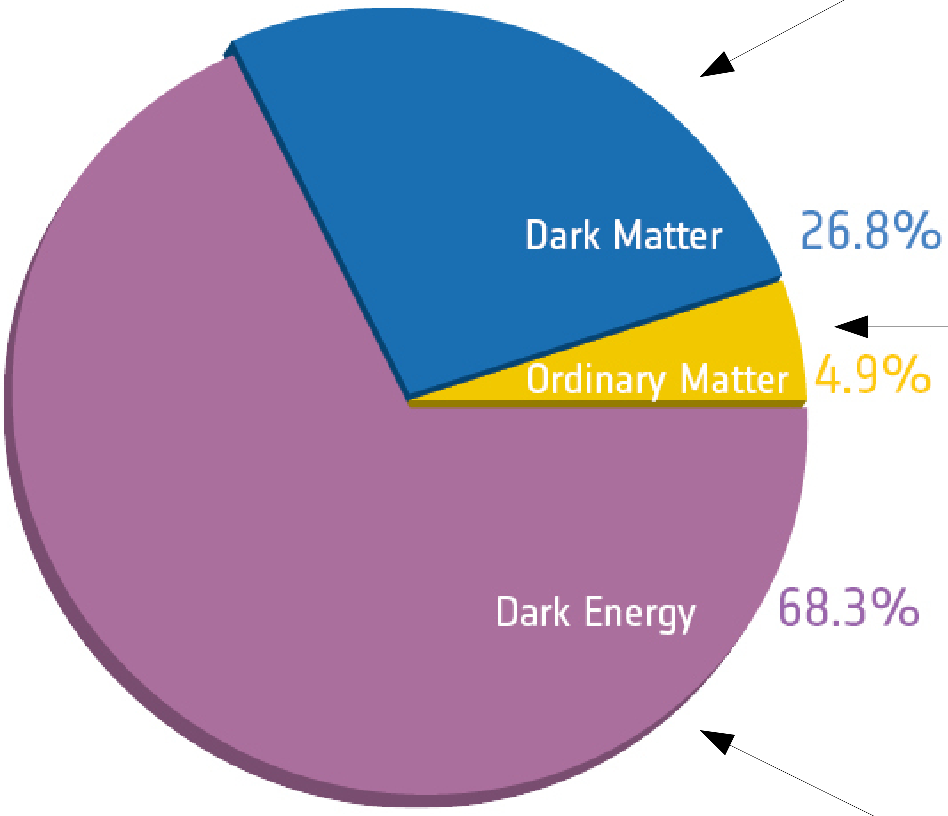

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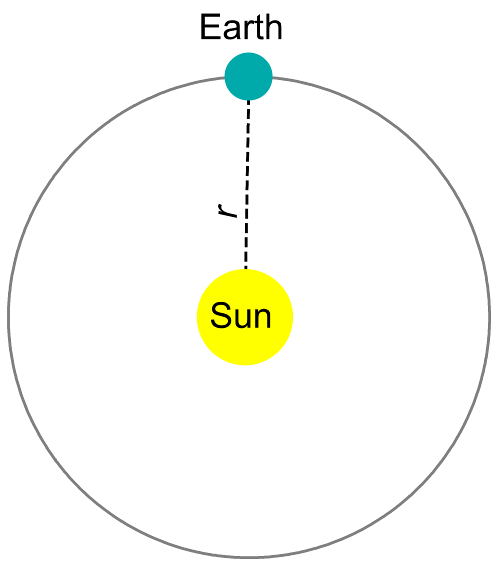
Kepler’s Laws for Planets



Third law

"I first believed I was dreaming… But it is absolutely certain and exact that the ratio which exists between the period times of any two planets is precisely the ratio of the 3/2th power of the mean distance." Kepler (1619)

Planet	r (AU)	T (days)	r^3/T^2 (10^{-6}AU^3/day^2)
Mercury	0.3871	87.9693	7.496
Venus	0.72333	224.701	7.496
Earth	1	365.256	7.496
Mars	1.52366	686.98	7.495
Jupiter	5.20336	4332.82	7.504
Saturn	9.53707	10775.6	7.498
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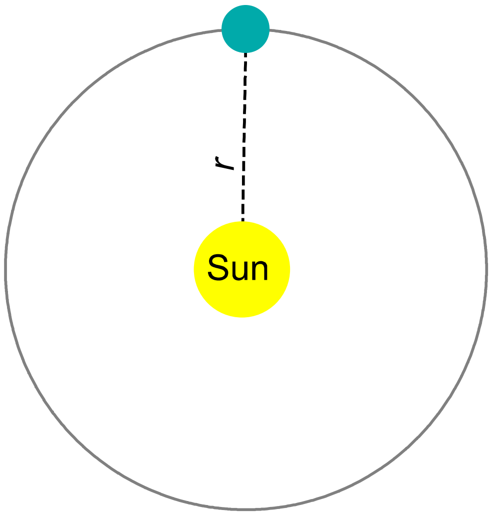

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$$\frac{GM_{\mathrm{Sun}}}{4\pi^2}$$

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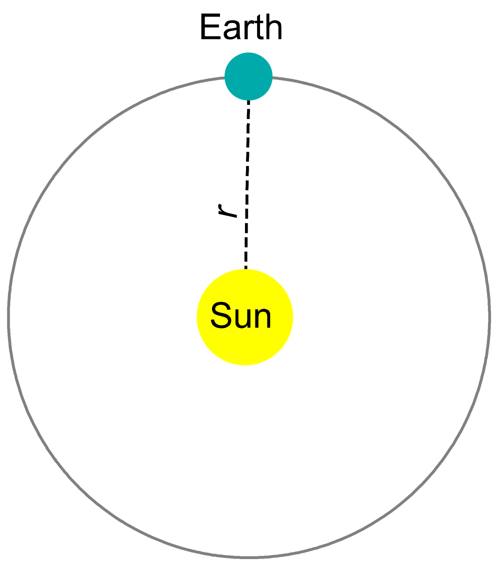

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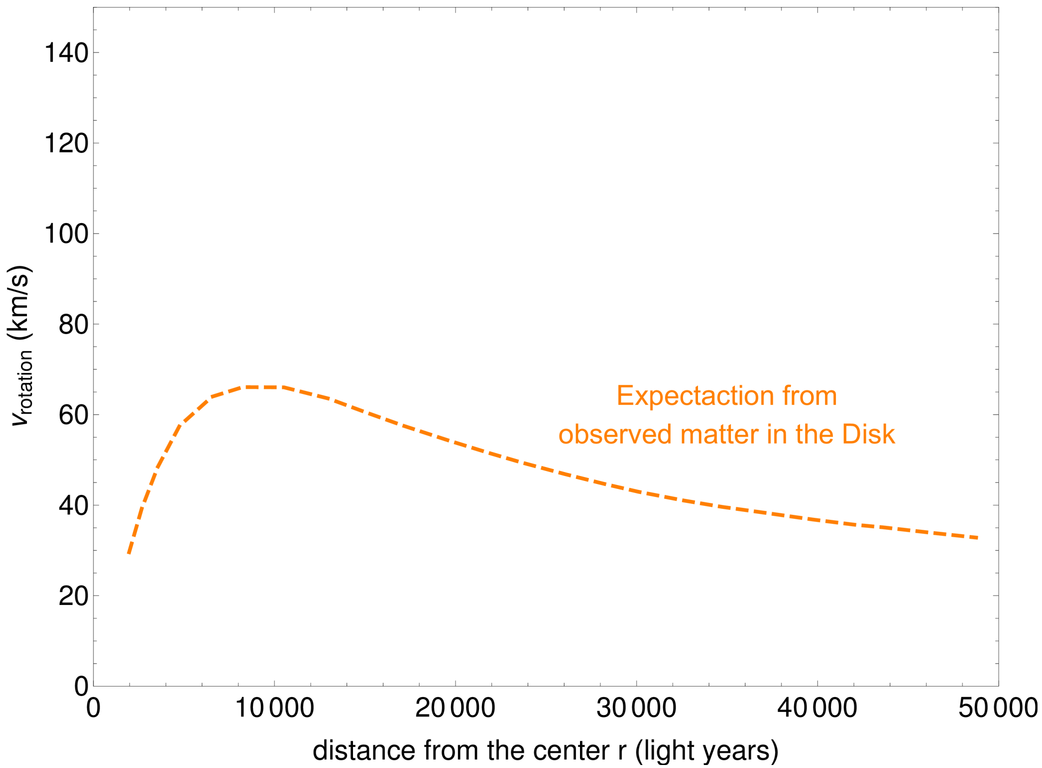
$$\frac{GM_{\mathrm{Sun}}}{4\pi^2}$$

For circular orbits this can be recast as

$$v_{\mathrm{rotation}}^2 = \frac{GM_{\mathrm{enclosed}}}{r}$$

Kepler's Laws for Galaxies?



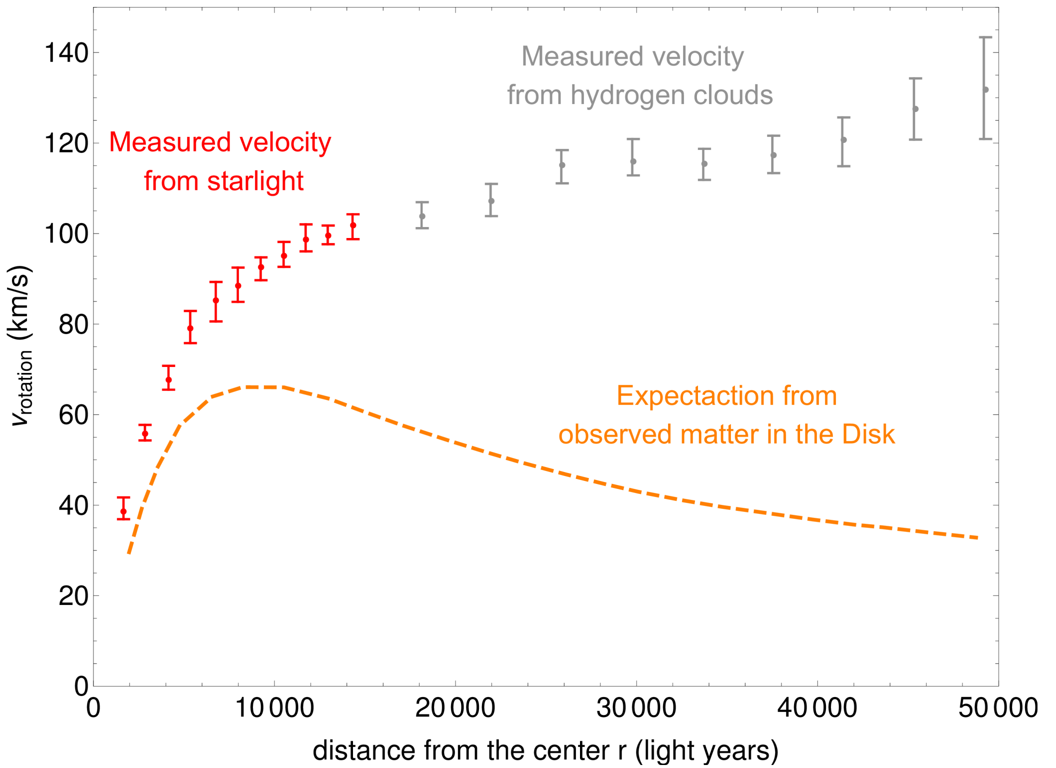
Triangulum Galaxy (M33)

$$v^2_{\rm rotation} = \frac{G M_{\rm enclosed}}{r}$$

Kepler's Laws for Galaxies?

There must be some matter that we don't see

or Kepler's Laws don't work in galaxies



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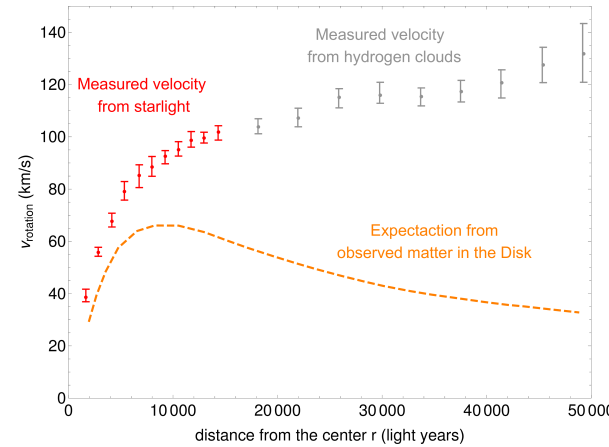
Dark Matter

The dark matter hypothesis is remarkably simple and explain observations at many other scales

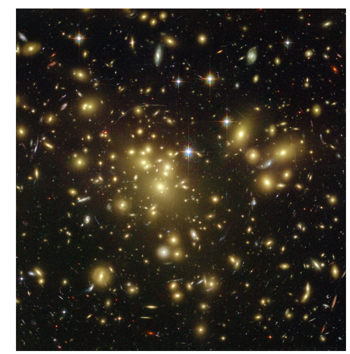


kpc

Velocity measurements

- Flat rotation curves of spiral galaxies
- Velocity dispersion of stars in giant elliptical and dwarf spheroidal galaxies
- Velocity dispersion of galaxies in clusters

Lensing



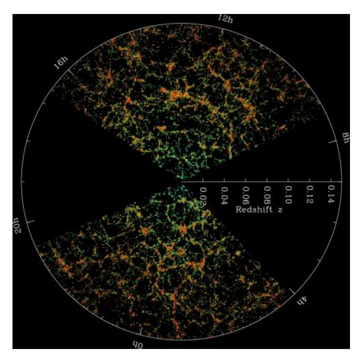
Mpc

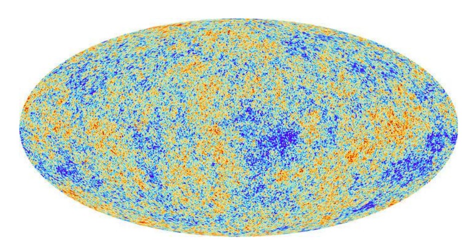
- Weak lensing by large-scale structure and cluster mergers
- Strong lensing by individual galaxies and clusters

Universe at large scales

Gpc

- Abundance of clusters
- Large-scale distribution of galaxies
- Power spectrum of CMB anisotropies





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

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

DOUGLAS CLOWE,[2] MARUŠA BRADAČ,[3] ANTHONY H. GONZALEZ,[4] MAXIM MARKEVITCH,[5,6]
SCOTT W. RANDALL,[5] CHRISTINE JONES,[5] AND DENNIS ZARITSKY[2]
Received 2006 June 6; accepted 2006 August 3; published 2006 August 30

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

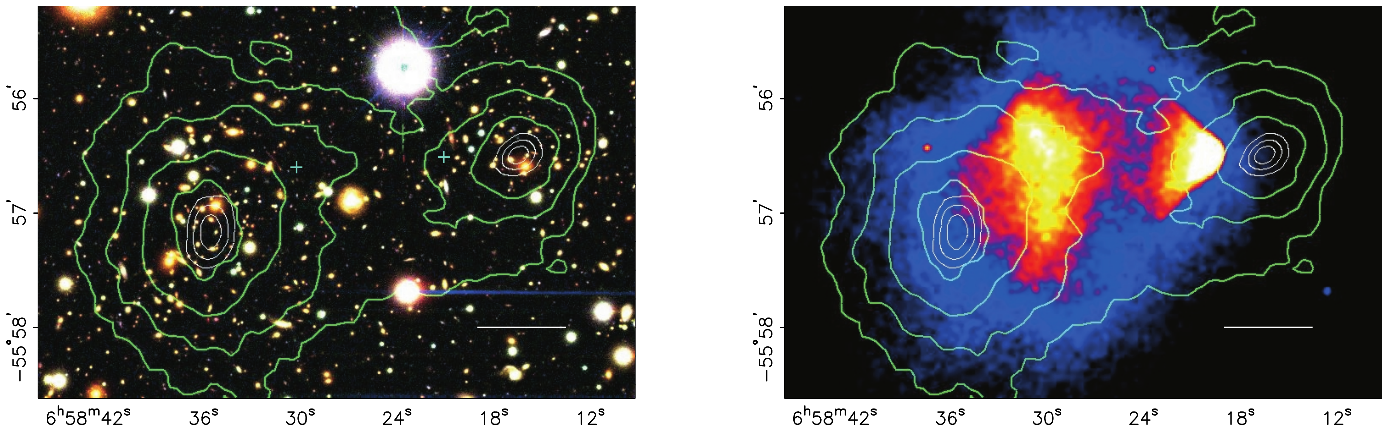


FIG. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with 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.

Camilo A. Garcia Cely (Alexander von Humboldt Fellow, DESY)

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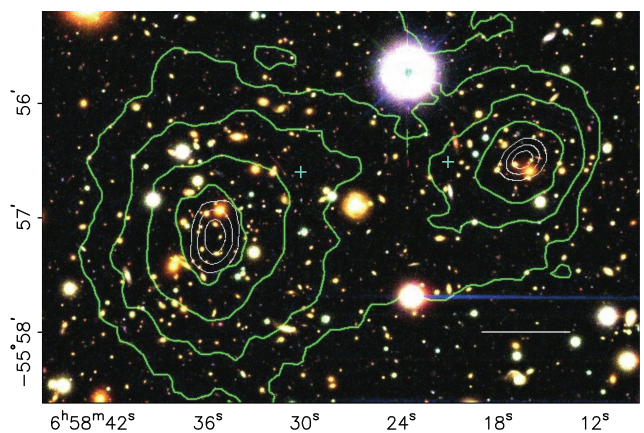

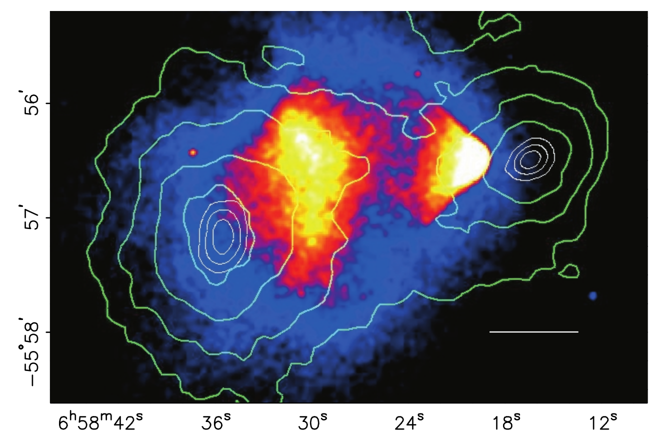

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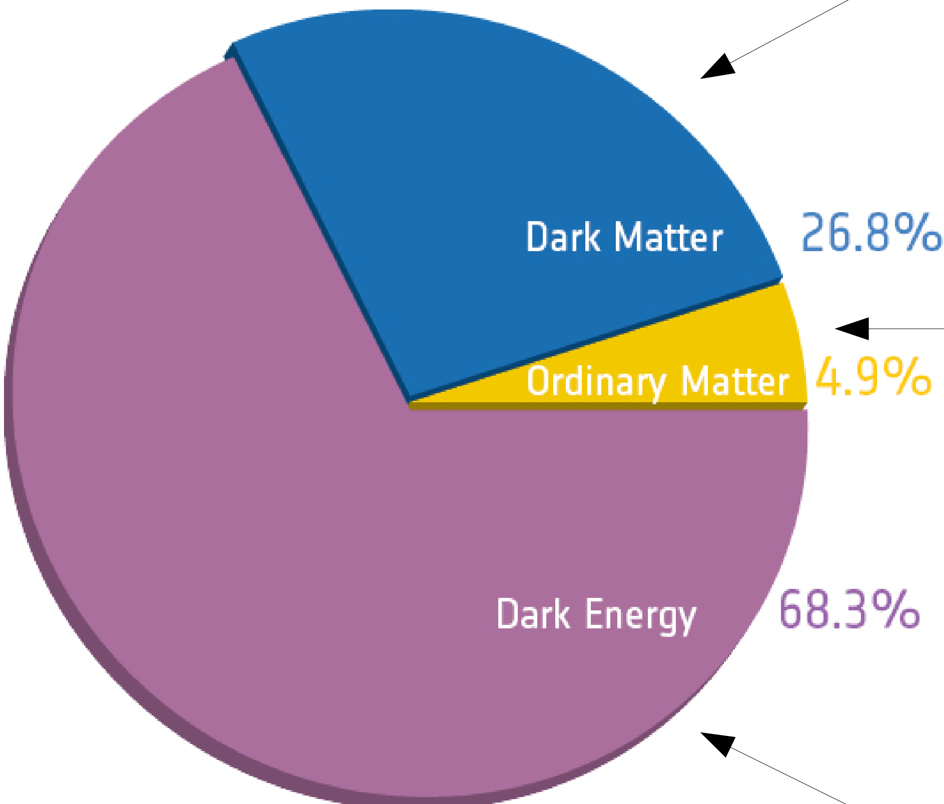

Collisionless Cold Dark Matter

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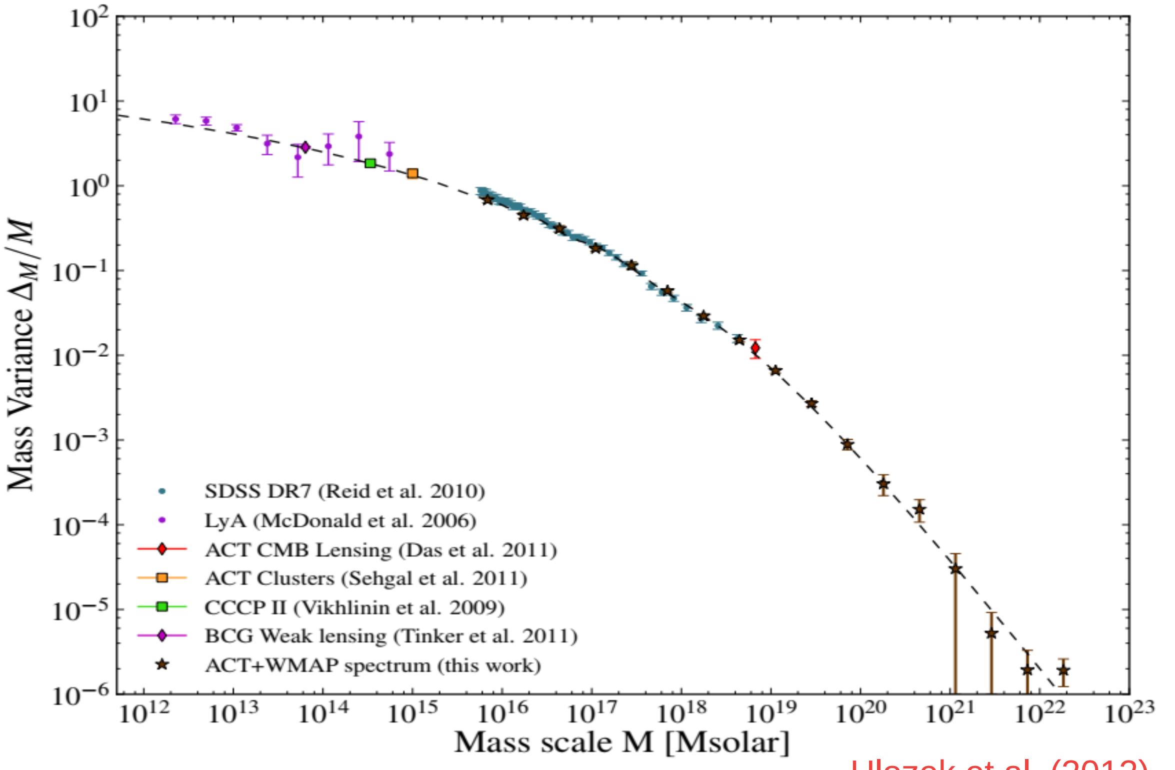
Remarkably successful
at large scales

At low scales
N-body simulations
are needed



Hlozek et al. (2012)

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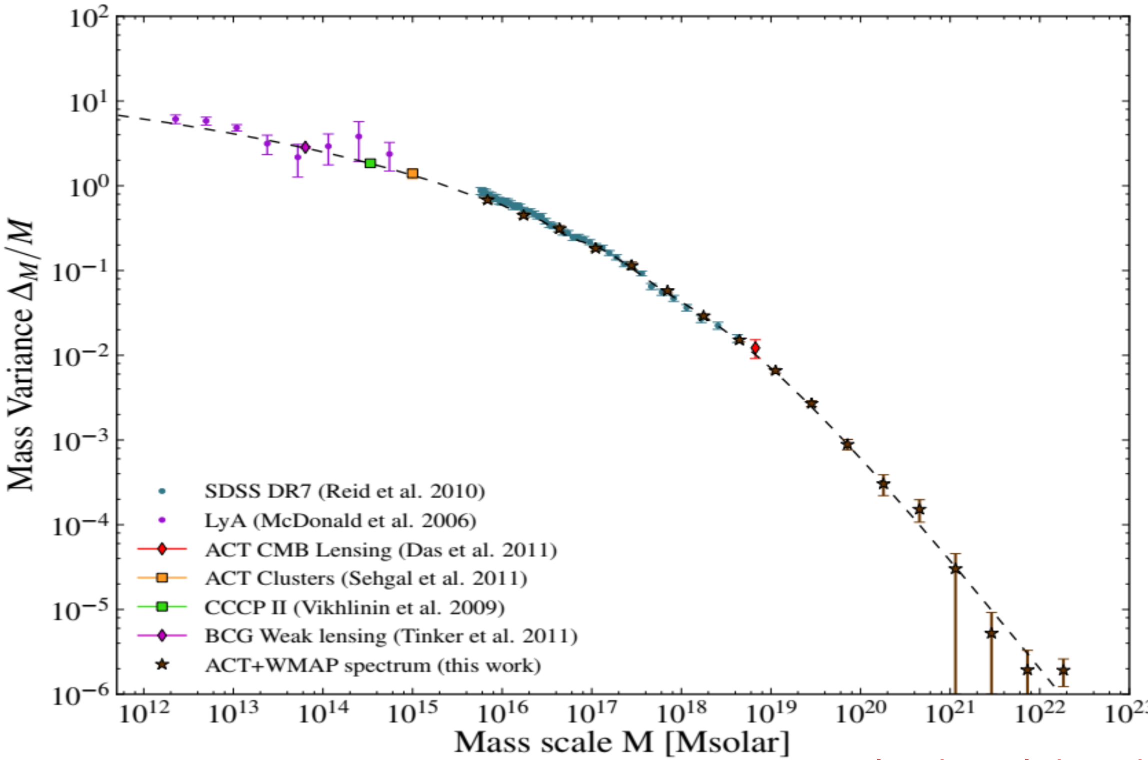


Hlozek et al. (2012)

Mass deficits at galactic scales

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

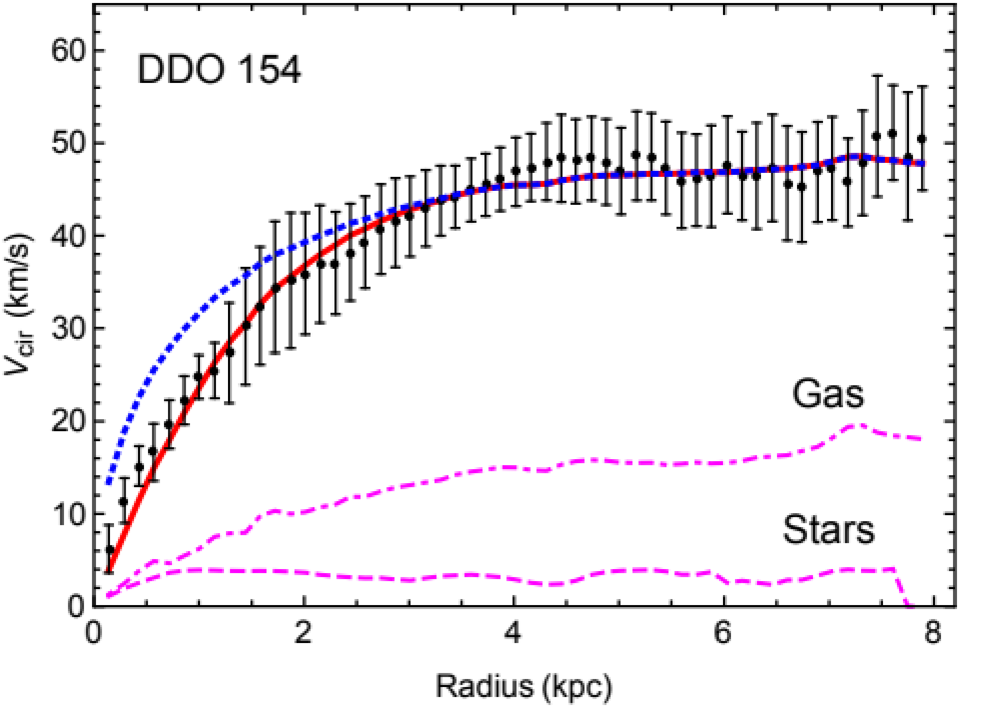
Heated debates!!!

Core vs. cusp problem

rotation curves again!

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)



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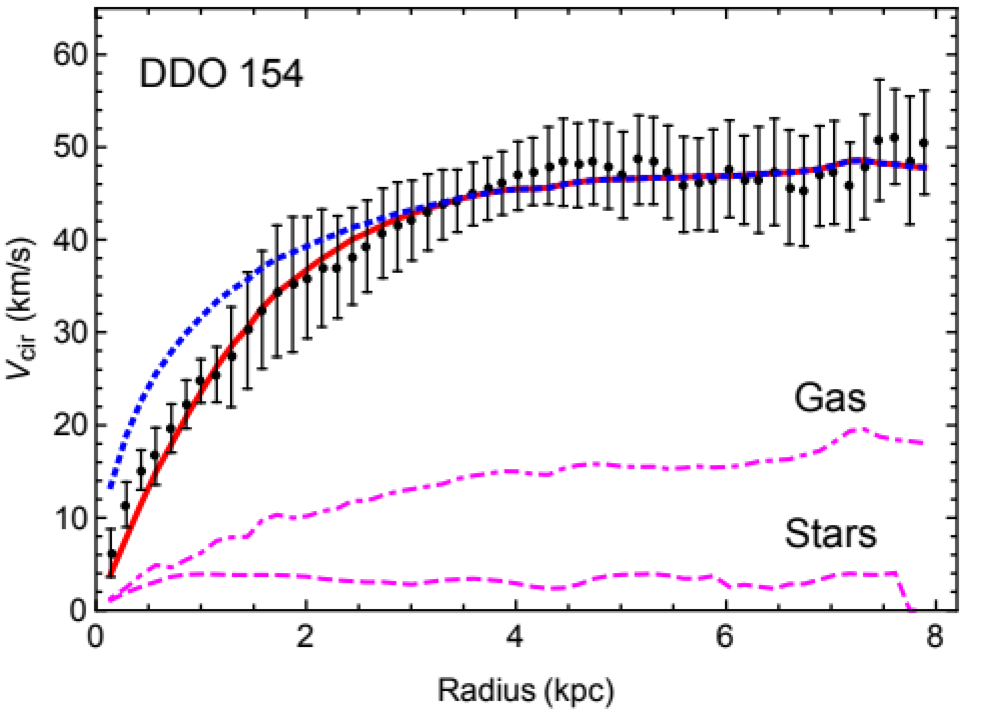
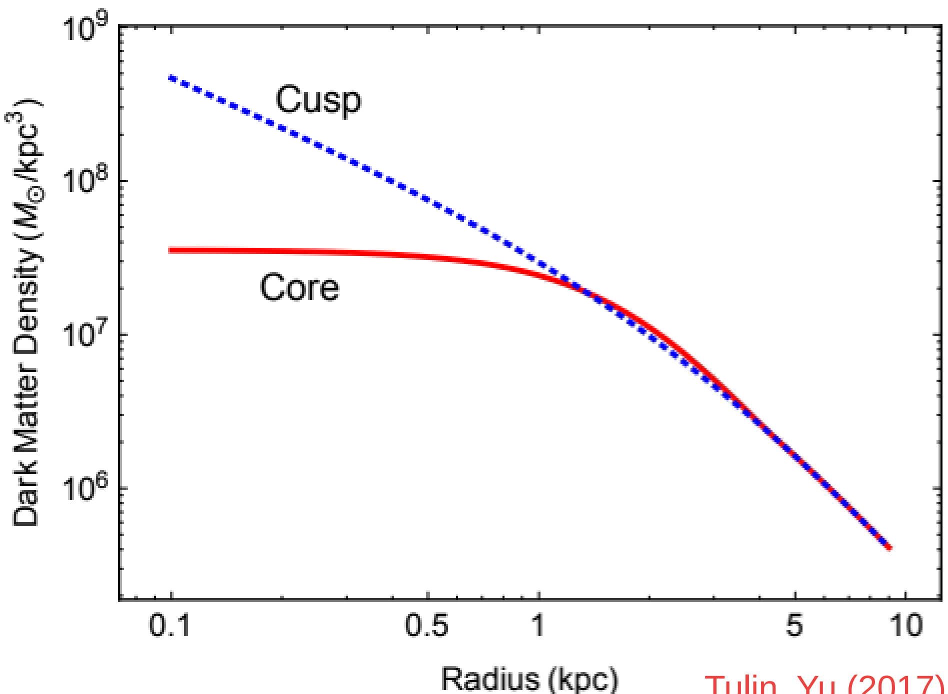




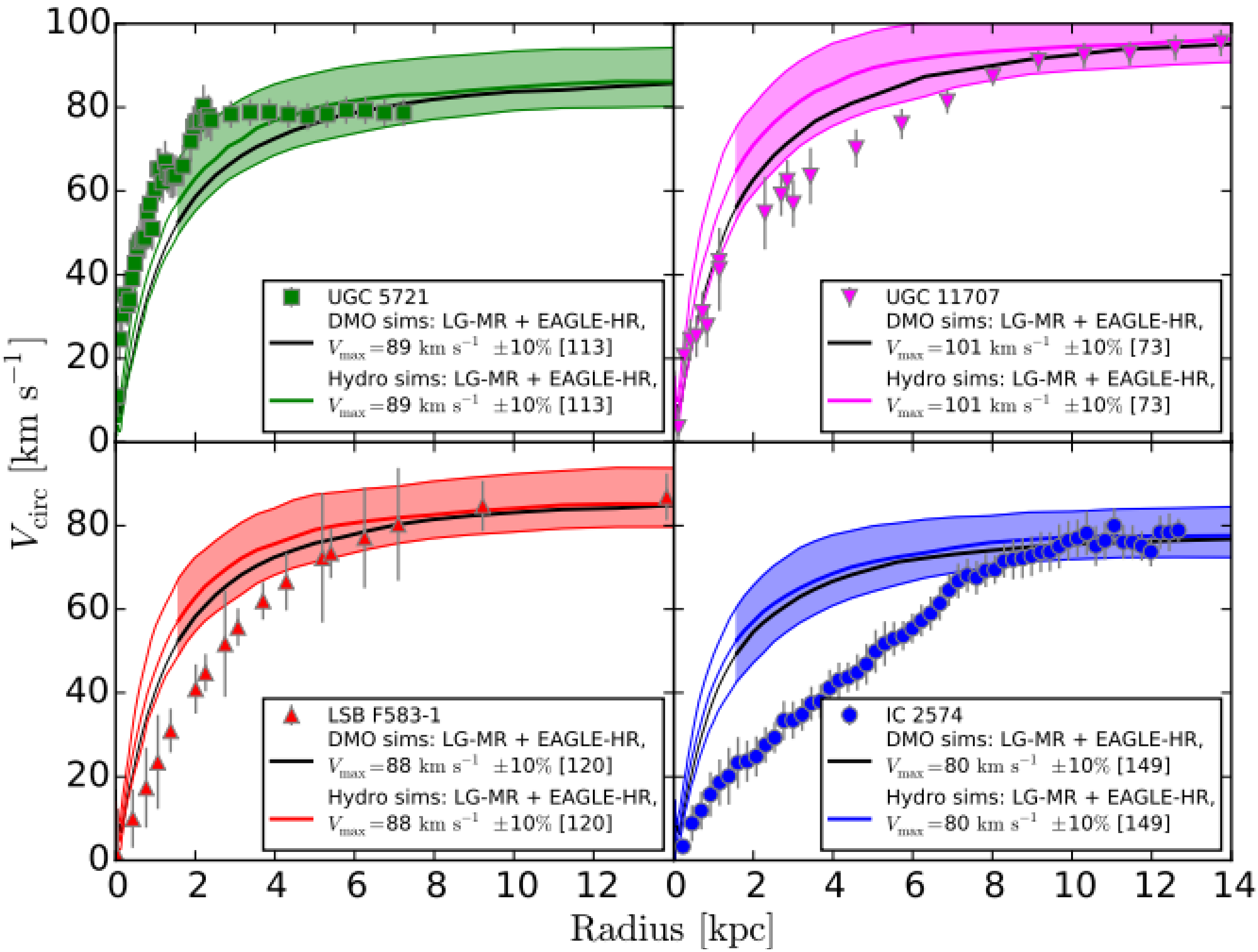
Tulin, Yu (2017)

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

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

Diversity Problem
diversity of rotation curves

Cosmological structure formation is predicted to be a self-similar process with a remarkably little scatter in density profiles for halos of a given mass. However, disk galaxies with the same maximal circular velocity exhibit a much larger scatter in their interiors and inferred core densities vary by a factor of order ten.



The unexpected diversity of dwarf galaxy rotation curves 2015

Kyle A. Oman, Julio F. Navarro, Azadeh Fattahi (Victoria U.), Carlos S. Frenk, Till Sawala (Durham U., ICC), Simon D. M. White (Garching, Max Planck Inst.), Richard Bower (Durham U., ICC), Robert A. Crain (Liverpool John Moores U., ARI), Michelle Furlong, Matthieu Schaller (Durham U., ICC), Joop Schaye (Leiden Observ.), Tom Theuns (Durham U., ICC) Hide

Debate

Plausible explanations

- Baryonic effects (supernovae, star formation,...)
- Non-circular motions
- Systematic errors in the modelling of the internal dynamics of galaxies

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

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"..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)

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

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

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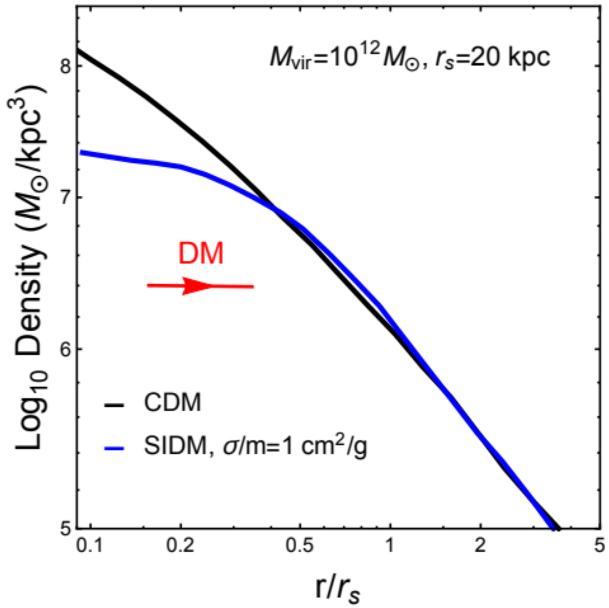
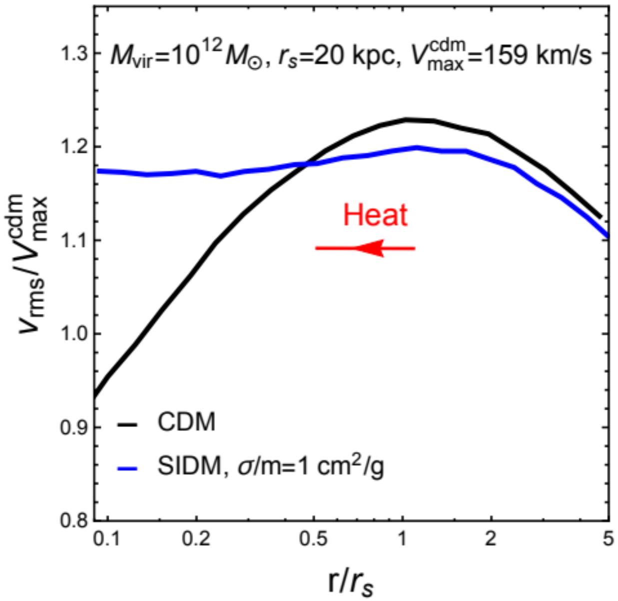
Simulations show that this is indeed a solution

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)
Creasey et al (2017)

How does self-interacting dark matter solve the problem?





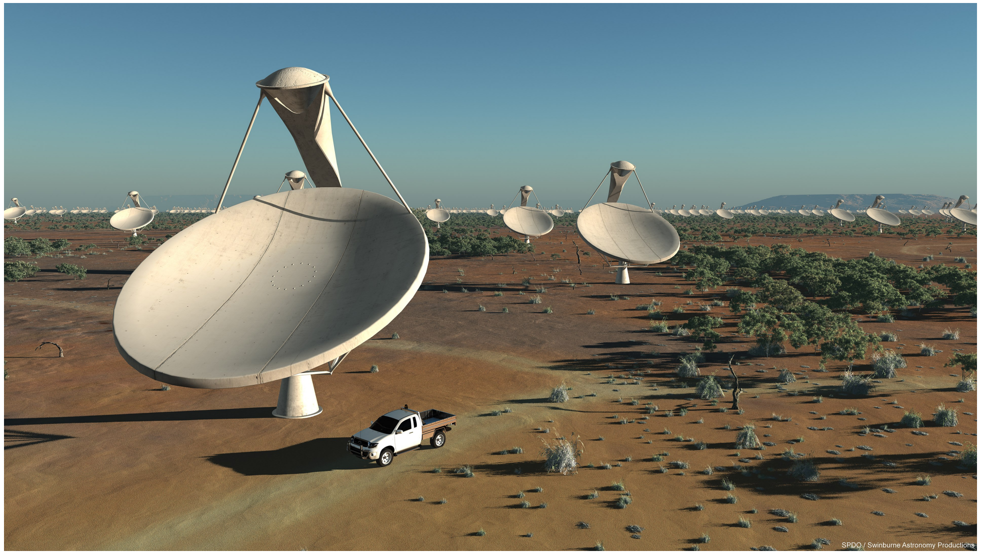
Tulin, Yu (2017)
Rocha et al (2013)

The future is data rich. For example...

The SKA will combine the signals received from thousands of small antennas spread over a distance of several thousand kilometres to simulate a single giant radio telescope

→ *extremely high sensitivity and angular resolution*

It has the potential to observe hundreds of nearby spiral galaxies at resolutions below 100 pc, providing a large and detailed sample of rotation curves.



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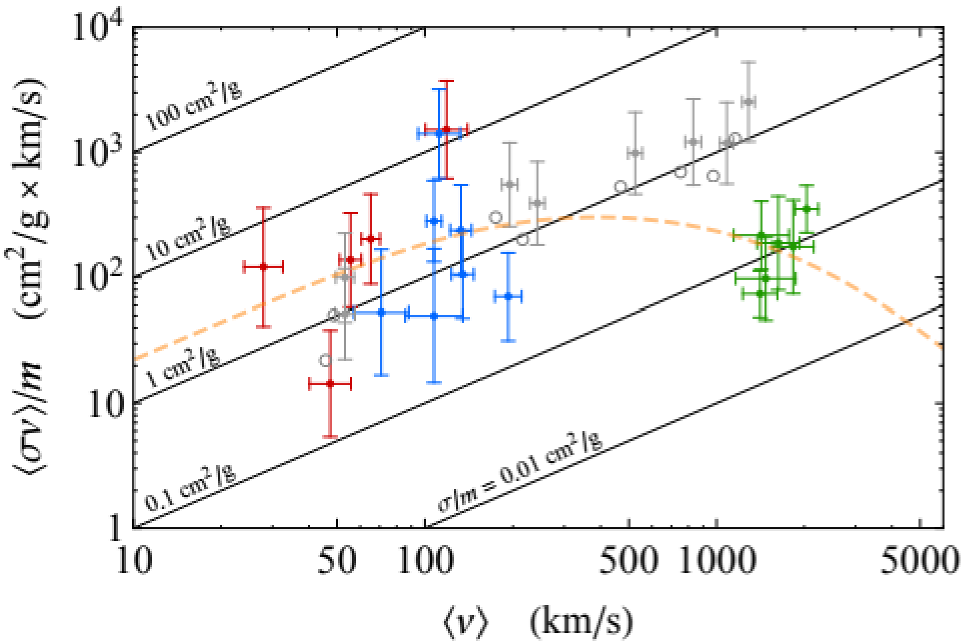
What does this tell us about the nature of the dark matter particle?

Dark matter halos as particle colliders

Kaplinghat ,Tulin, Yu (2017)



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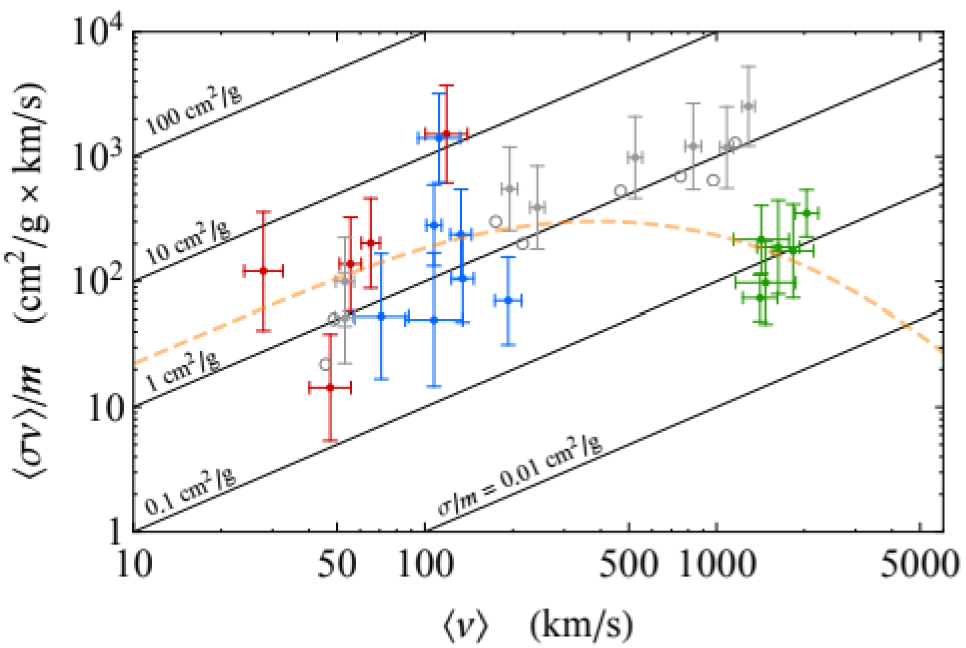
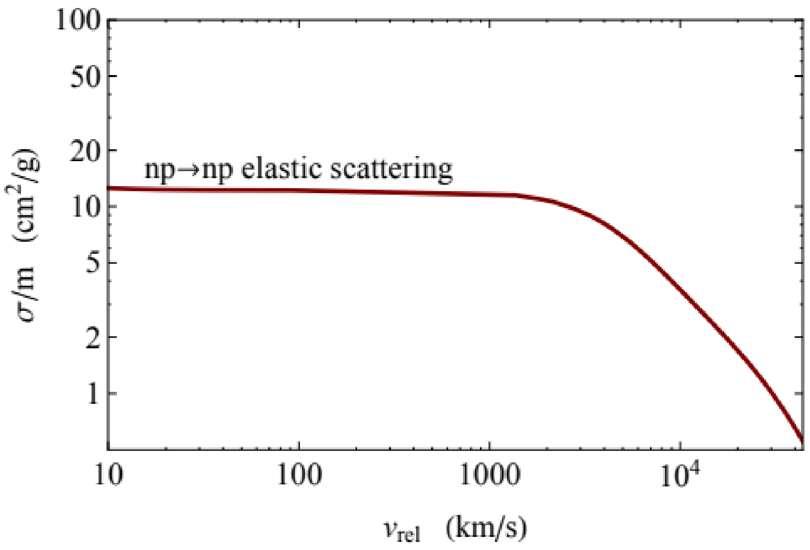


Tulin, Yu (2017)

How does that compare to nucleon-nucleon collisions?



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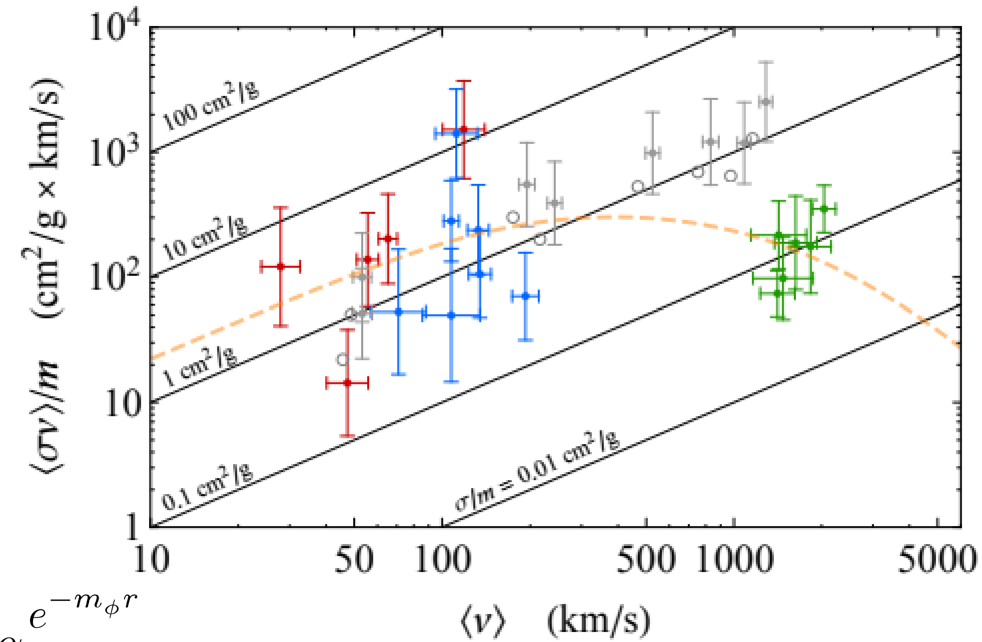
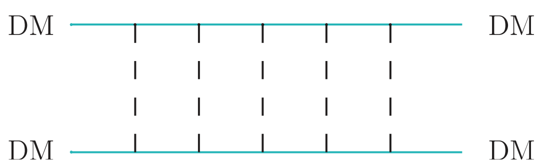


Light mediator



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

Tulin, Yu (2017)

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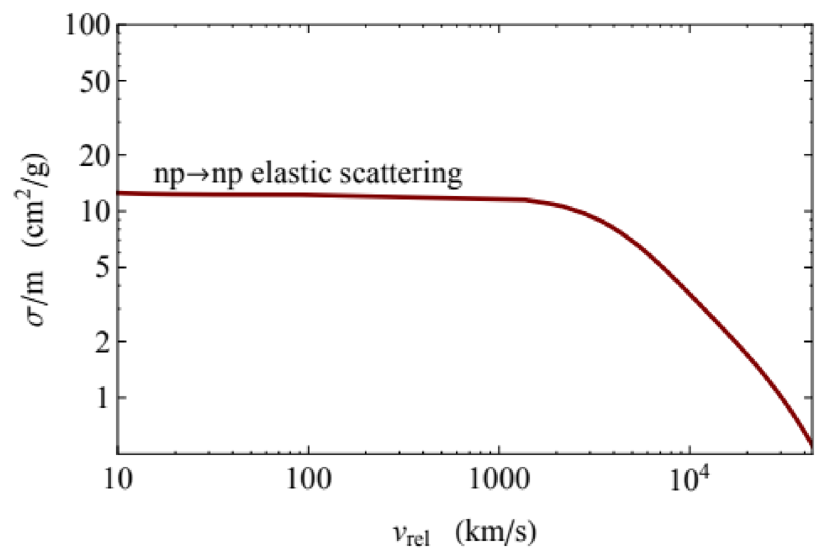
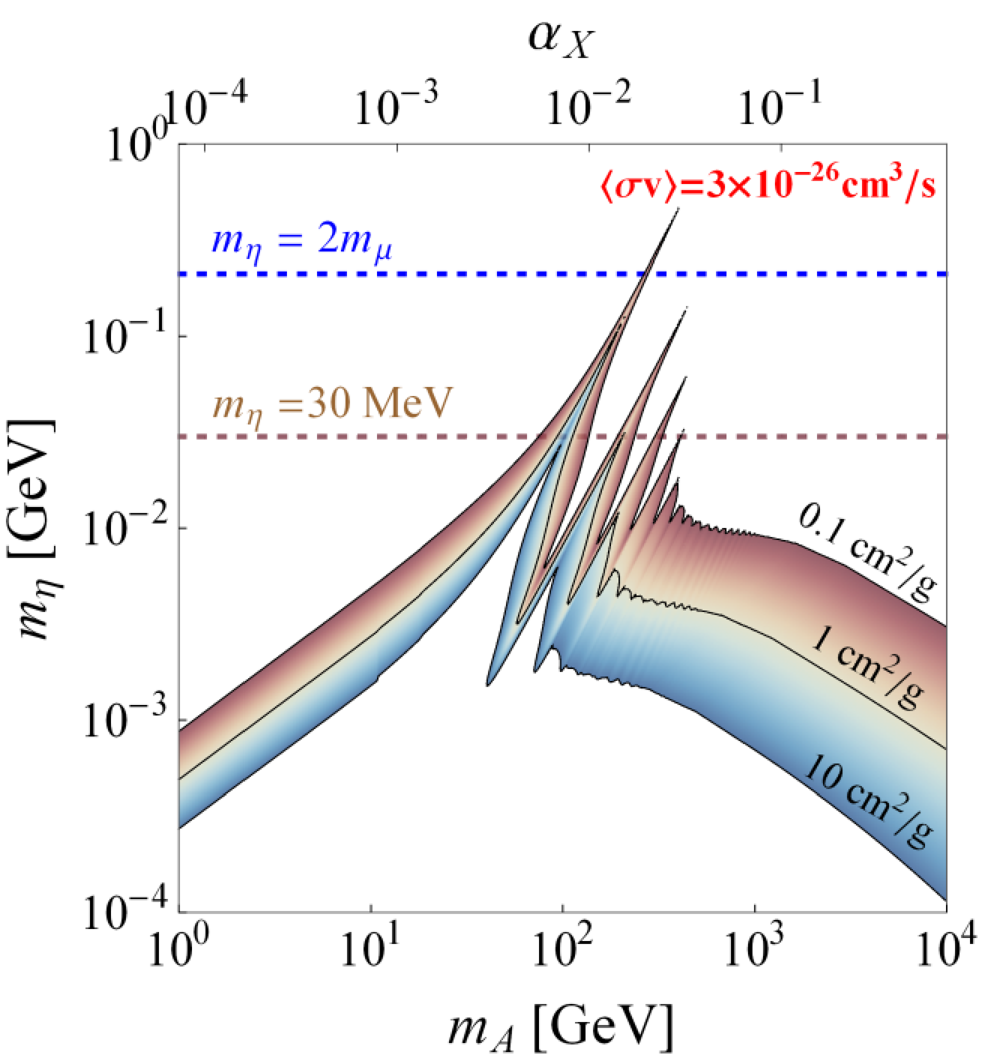


Camilo A. Garcia Cely (Alexander von Humboldt Fellow, DESY)

Light mediator in the dark sector?

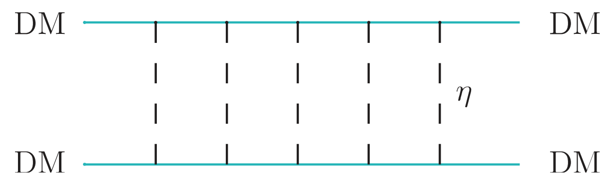
Concrete model



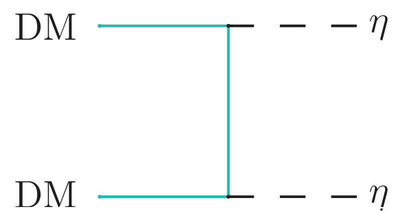
Concrete model

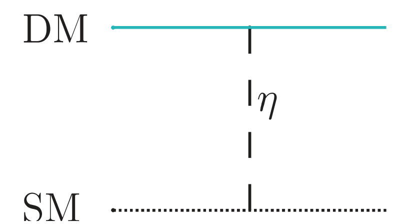
Light mediator η

- Long-range forces



- Freeze-out via $\sigma v_{\rm ann} \sim 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$

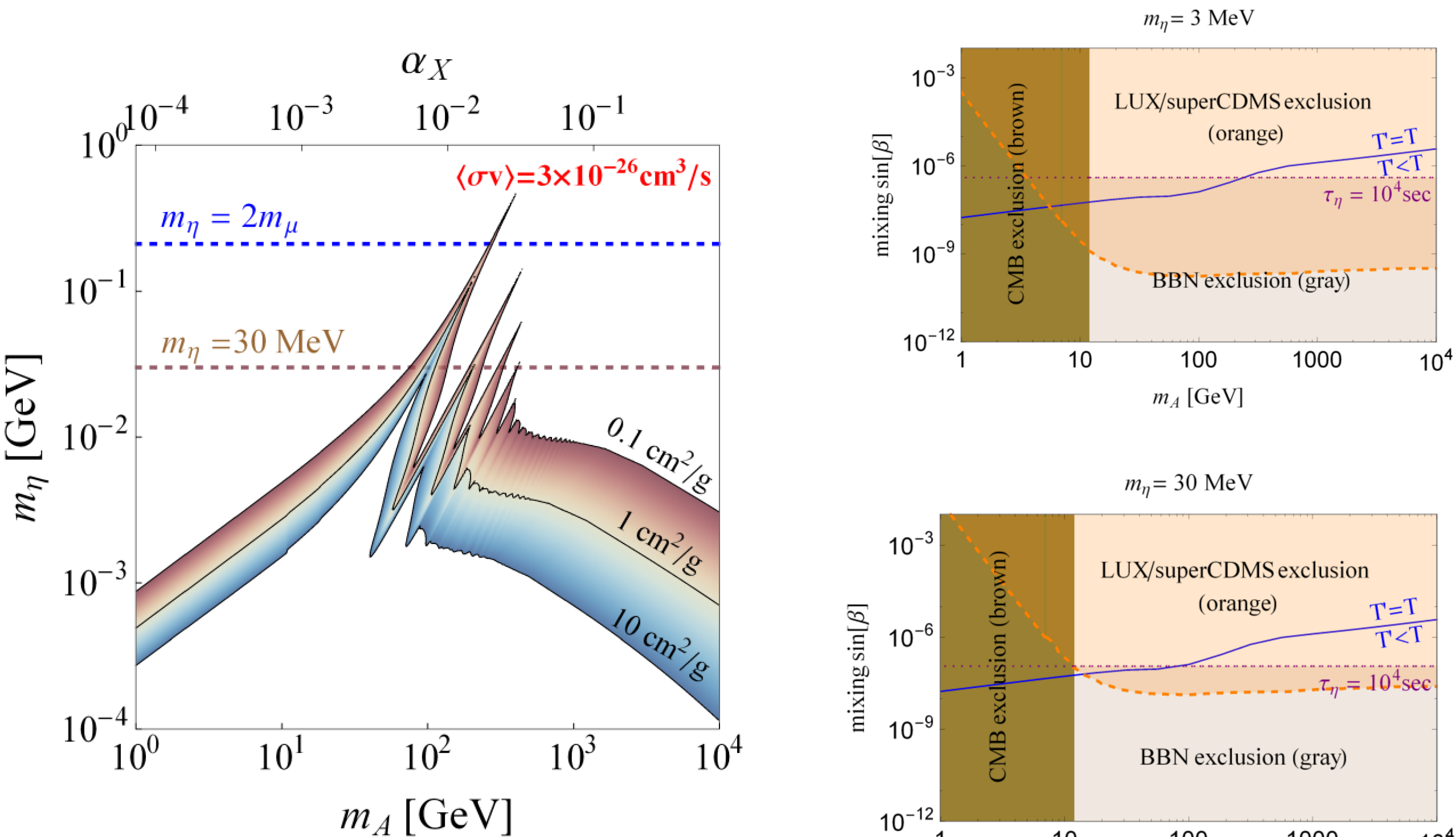




Implementing the freeze-out is challenging because thermal equilibrium between the SM and DM is needed, which leads to problems Bernal, Chu, CGC, Hambye, Zaldivar (2015)

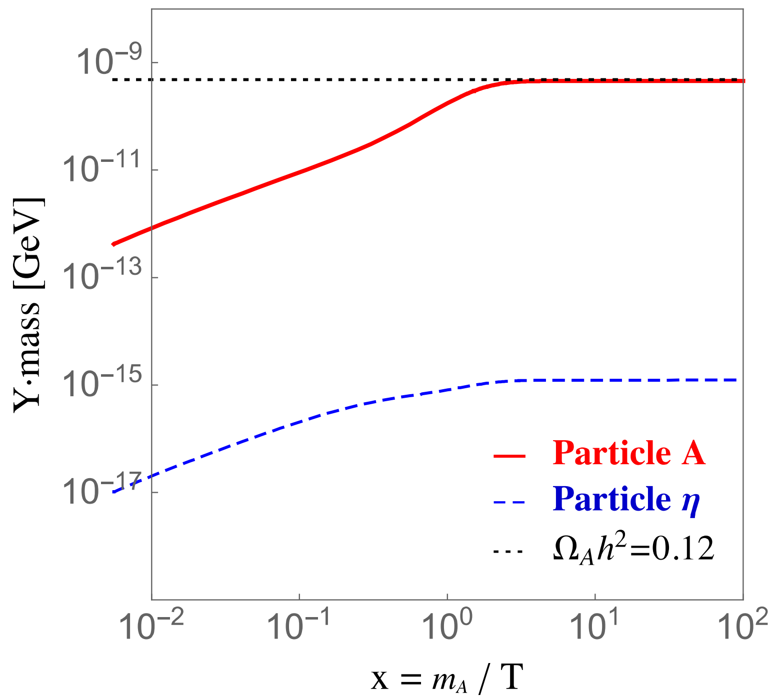
- In the early universe the mediator is produced in large amounts affecting the CMB and BBN.
- Large direct detection rates. Kaplinghat, Sean Tulin, Yu (2013)
- Large annihilation signals due to the Sommerfeld effect. Bringmann, Kahlhoefer, Schmidt-Hoberg, Walia (2016) Cirelli, Panci, Petraki, Sala, Taoso (2016)

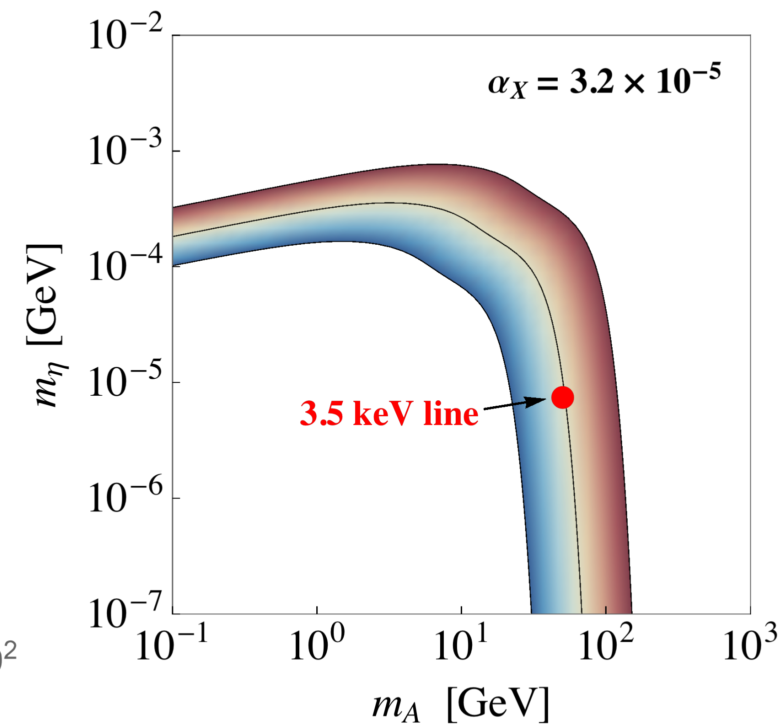
Concrete model



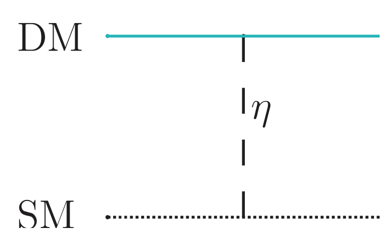
Standard freeze-out is not posible.
Freeze-in works

Freeze-in





Bernal, Chu, CGC, Hambye, Zaldivar (2015)



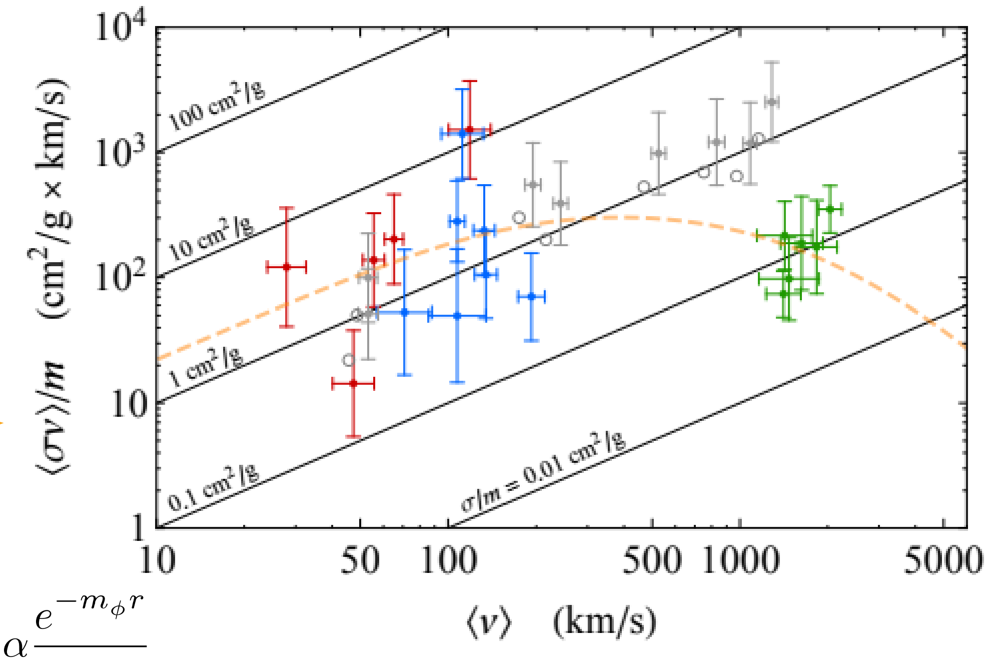
- Very small interactions between the DM sector and SM. There is never thermal equilibrium.
- Hard to probe by construction.

Is a light mediator the only possibility?

Velocity-dependent SIDM

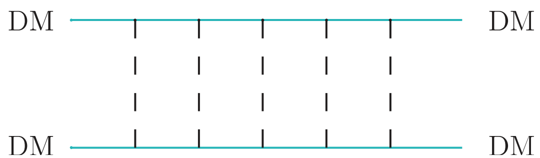
Dark matter halos as particle colliders

Kaplinghat ,Tulin, Yu (2017)



Tulin, Yu (2017)

Light mediator



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

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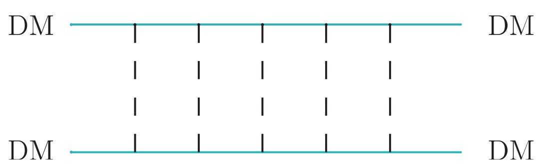

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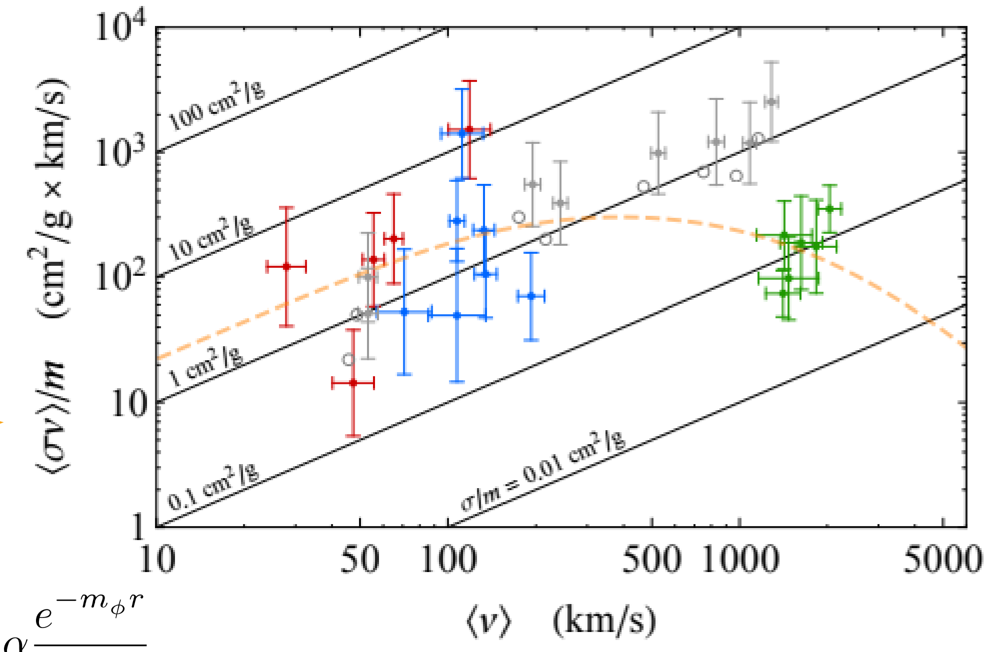


Tulin, Yu (2017)

Velocity dependent SIDM does not necessarily imply the existence of a light mediator!!!

From nuclear physics:

- *Light mediators (pions)*
- *Resonances (Breit-Wigner)*
- *Bound states (deuteron in p-n collisions)*

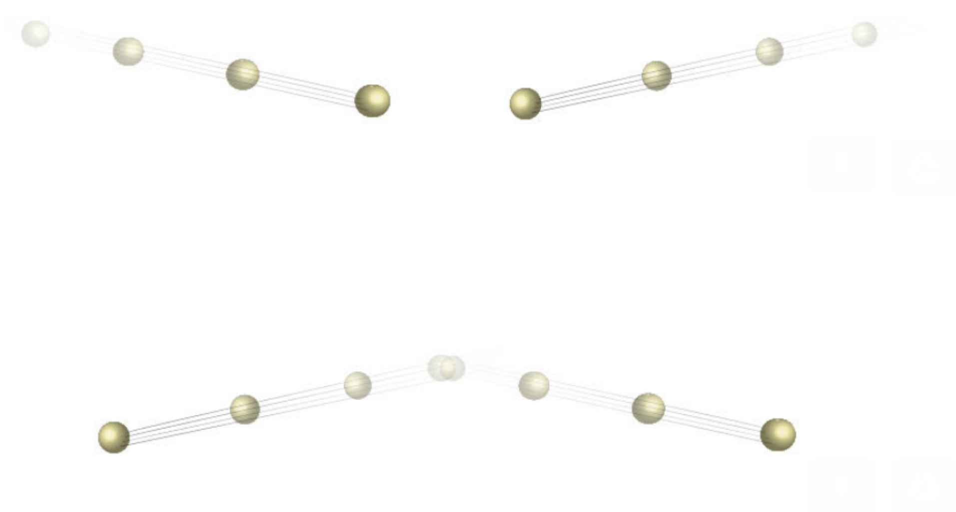
……

Resonant SIDM

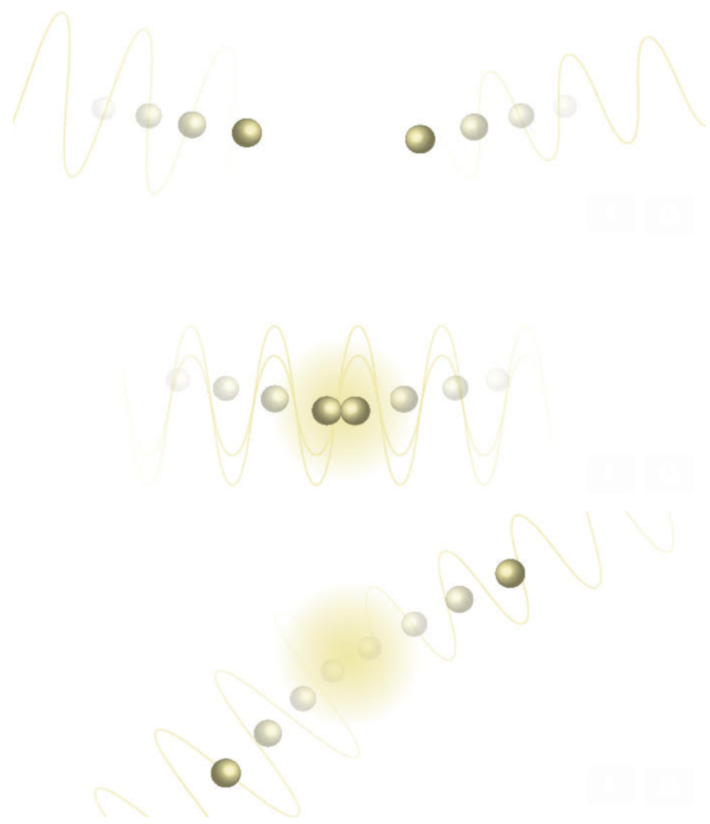
Chu, CGC, Murayama (2018)

“Resonance is a phenomenon that appears every day. To swirl wine in a glass to get it more oxygen so that it lets out more aroma and softens its taste, you need to find the right speed to circle the wine glass. Or you dial old analog radios to the right frequency to tune into your favorite station” Murayama https://www.ipmu.jp/en/20190227-DM_hittingNote

At clusters of galaxies



In galaxies



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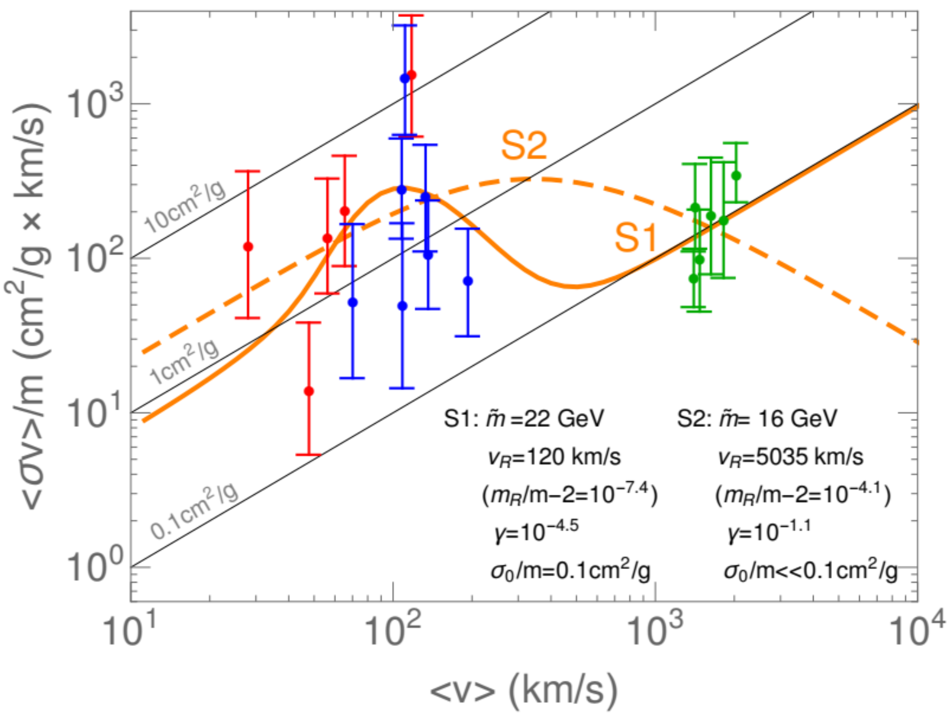
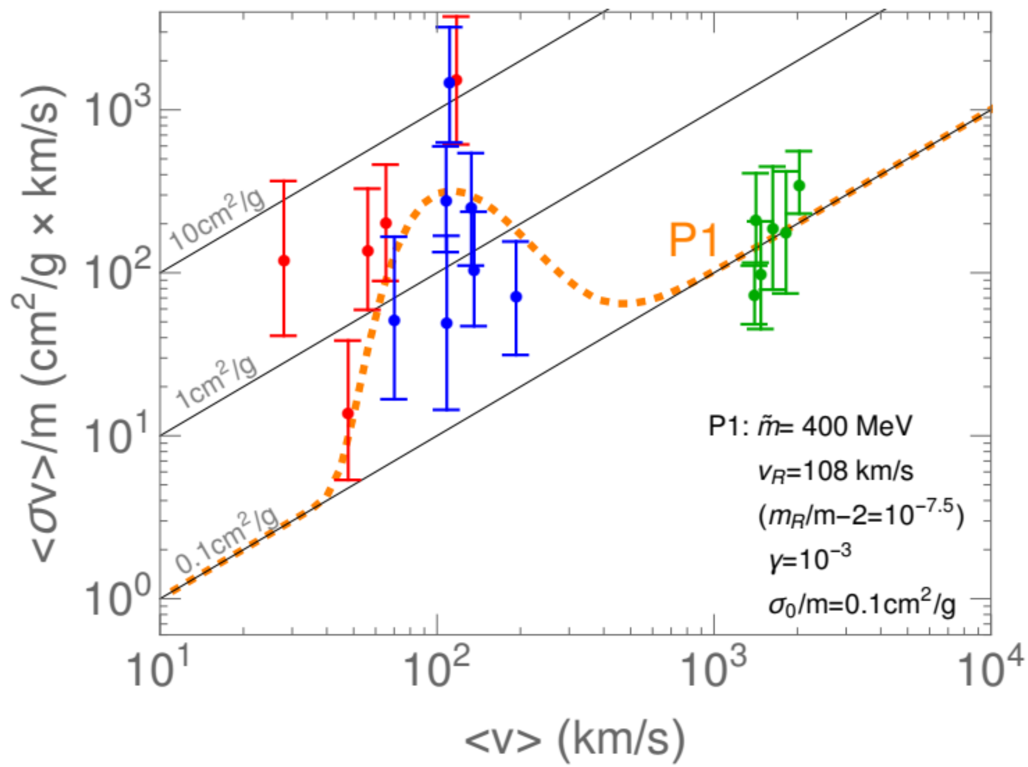


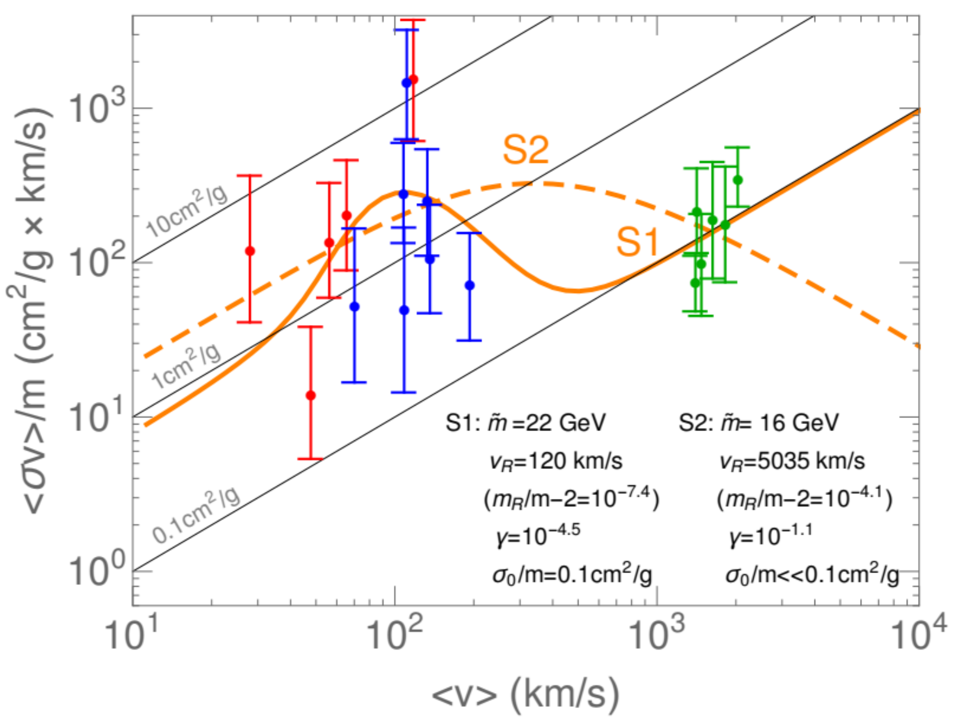


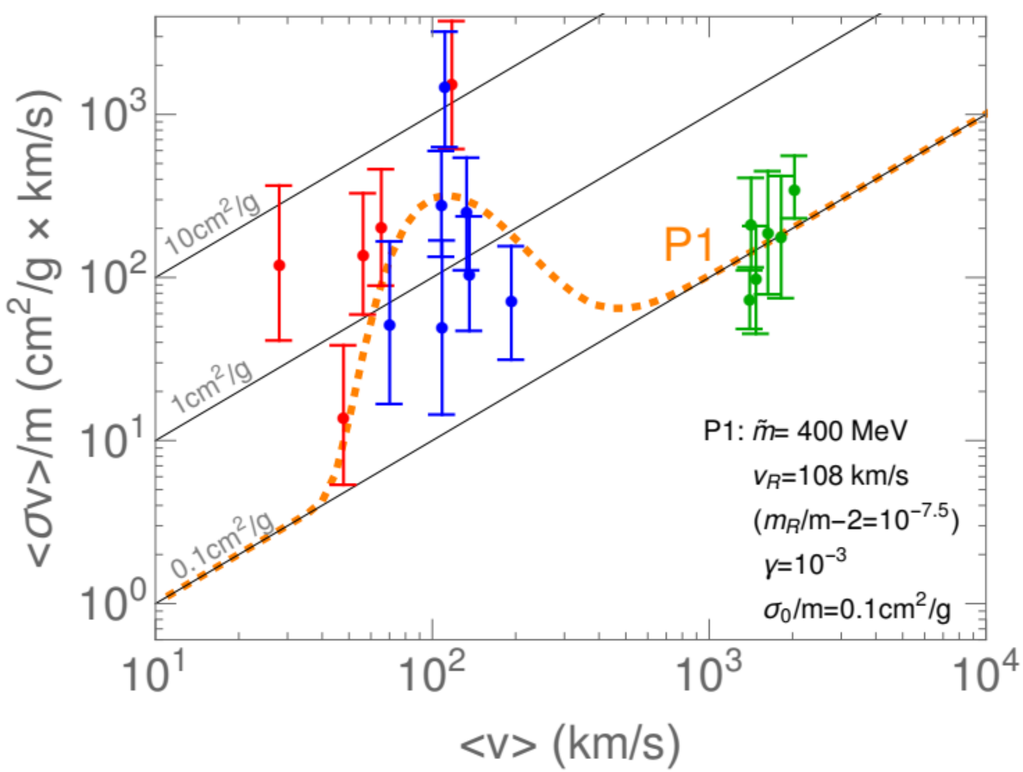
Resonant SIDM

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)





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	$\frac{m_R^2}{30720\pi\Lambda^2}$

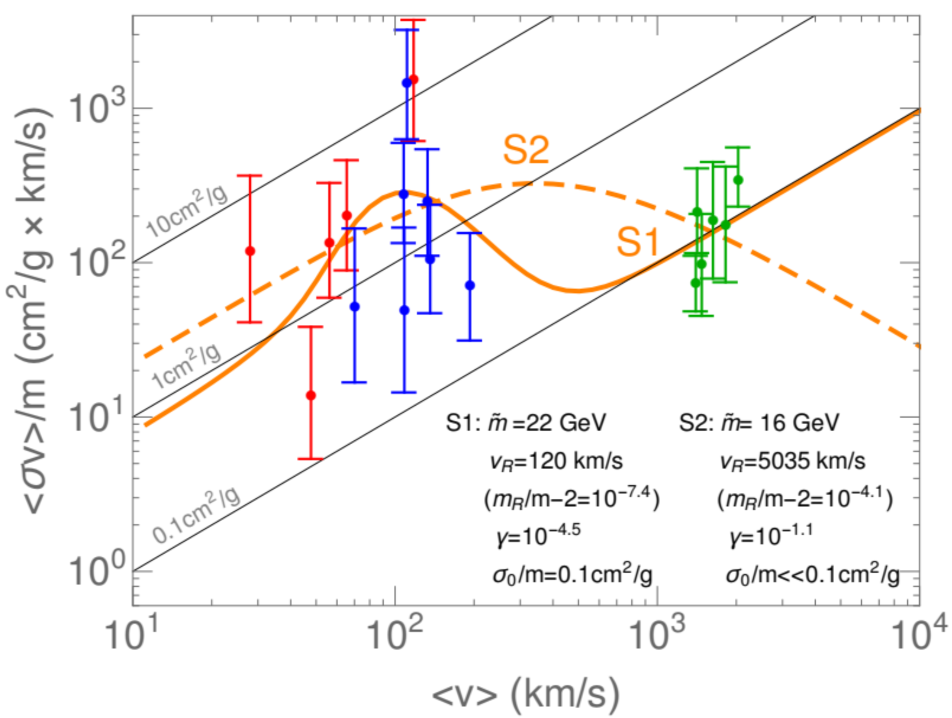
Table I: Benchmark RSIDM models.

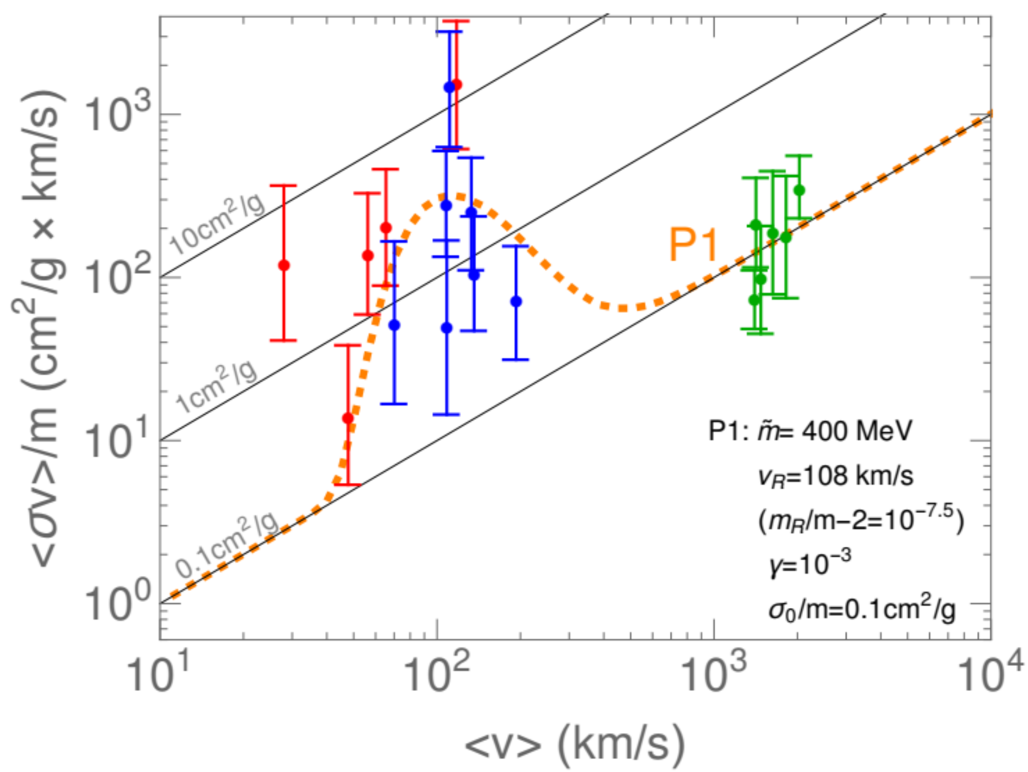
Pseudo-scalar mediator

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

Spin-two exchange

Chu, CGC, Murayama (2018)





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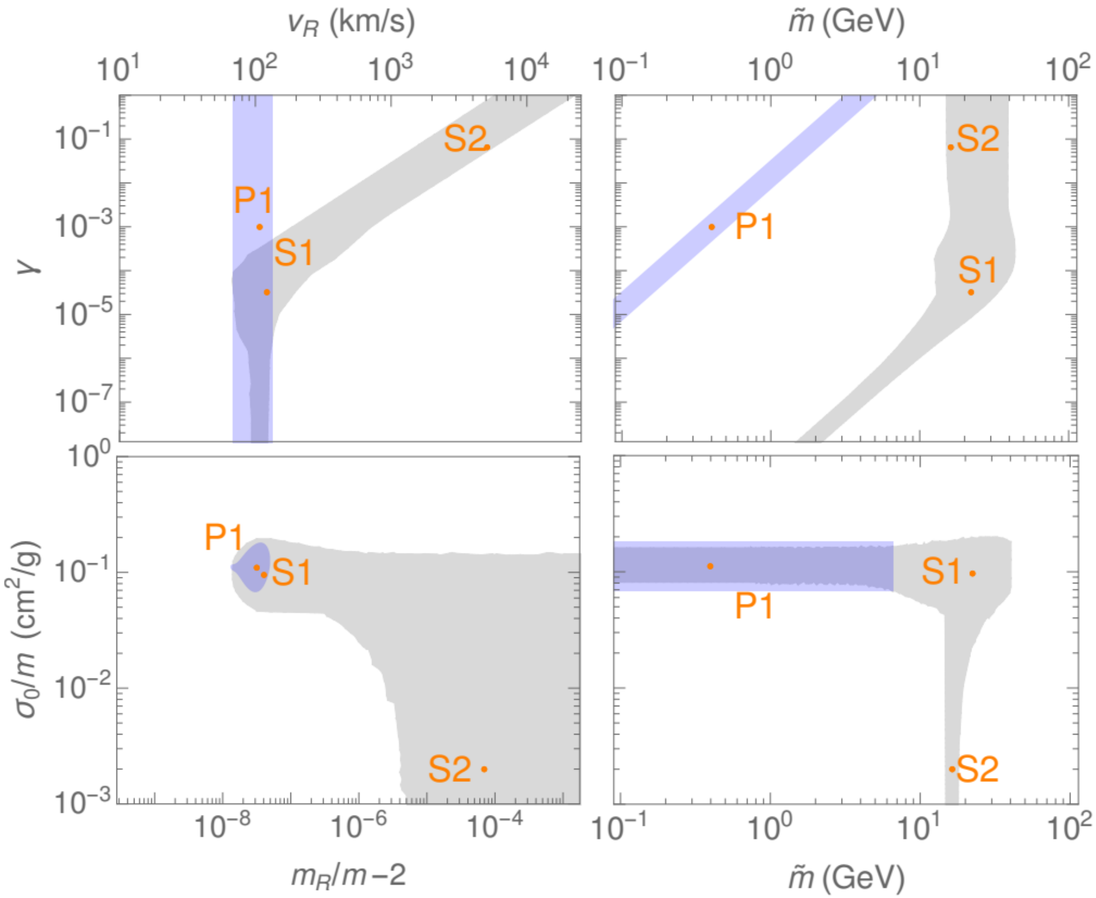
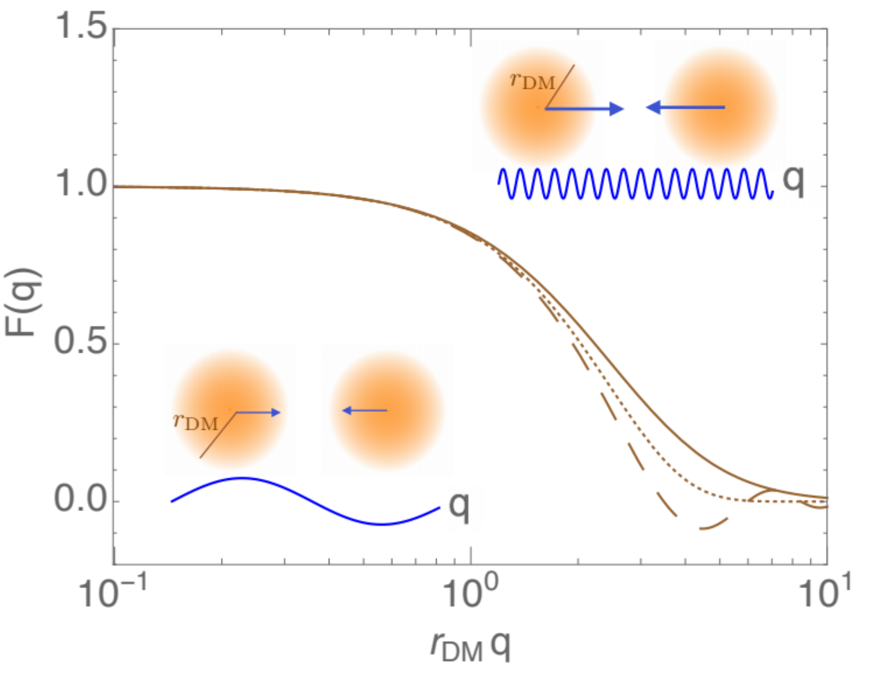


Chu, CGC, Murayama (2018)

Dark Matter with a finite size

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

Chu, CGC, Murayama (2019)



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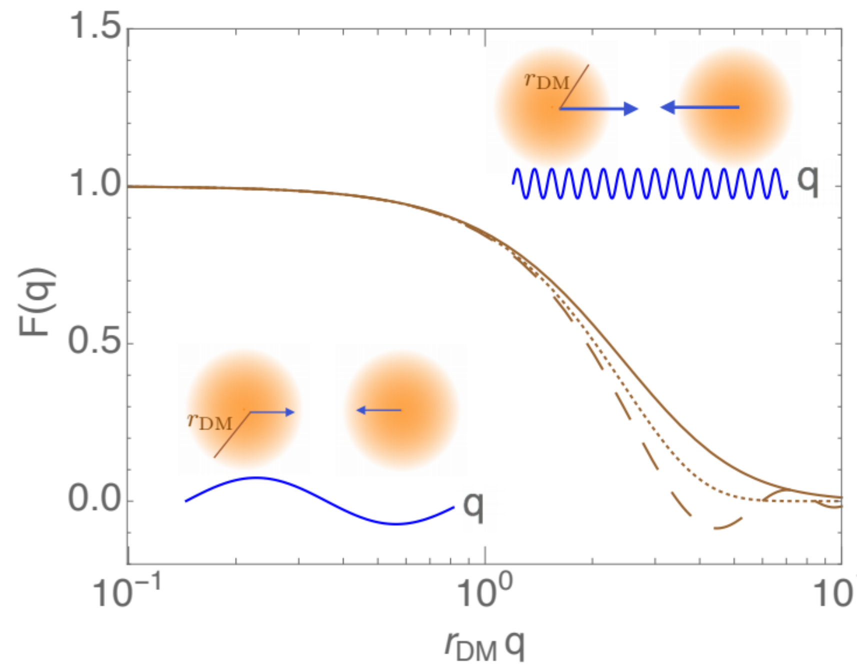
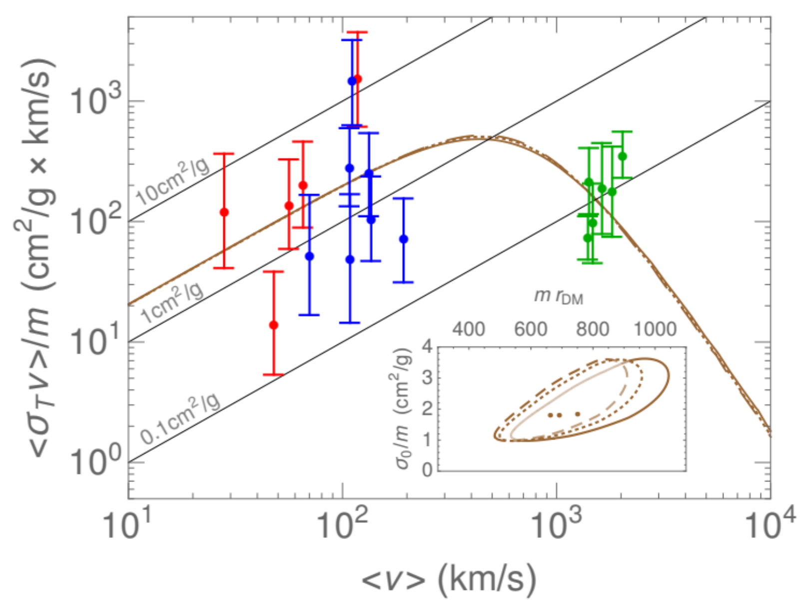
Chu, CGC, Murayama (2019)

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	$\frac{e^{-r/r_0}}{8\pi r_0^3}$	$\sqrt{3/5}r_0$	$\frac{1}{(1+r_0^2 q^2)^2}$
Gaussian	$\frac{1}{8 r_0^3 \pi^{3/2}} e^{-r^2/(4r_0^2)}$	$\sqrt{6}r_0$	$e^{-r_0^2 q^2}$

Table I: Form factors for different density distributions.





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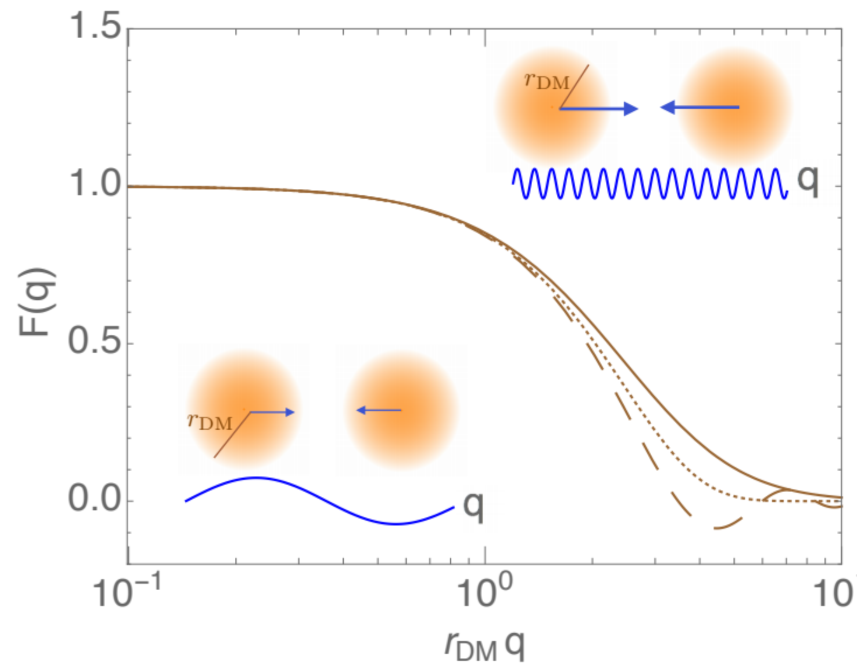

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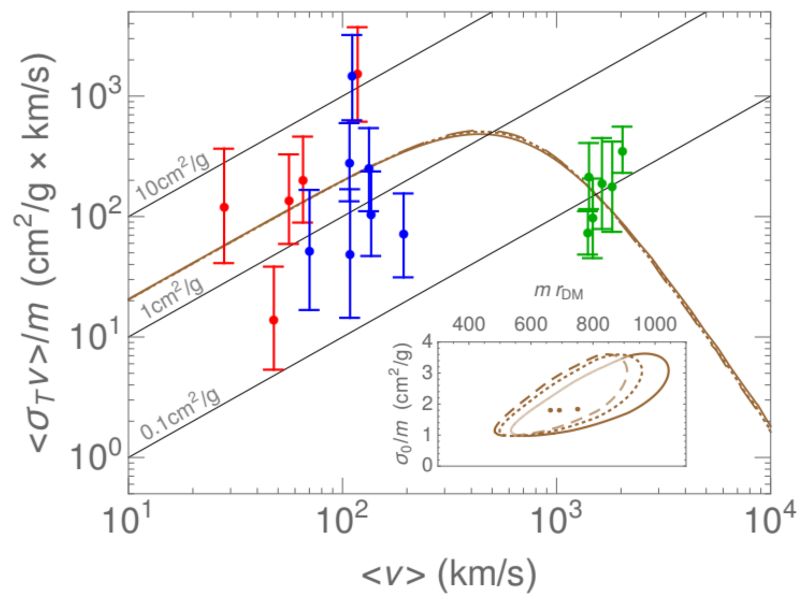

The way the non-relativistic cross section varies with the velocity is largely independent of the dark matter internal structure when the range of the mediating force is short.

Effective Range Theory

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

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

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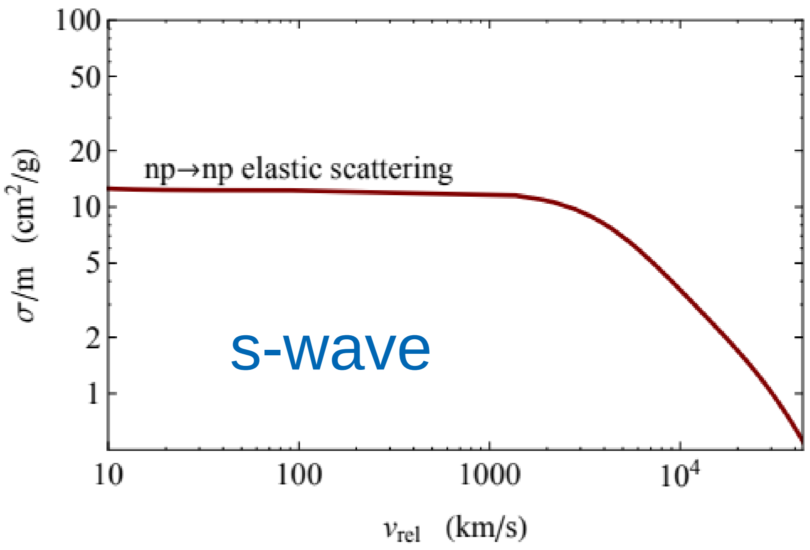

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https://www.youtube.com/watch?v=hbcQMG2XpTI

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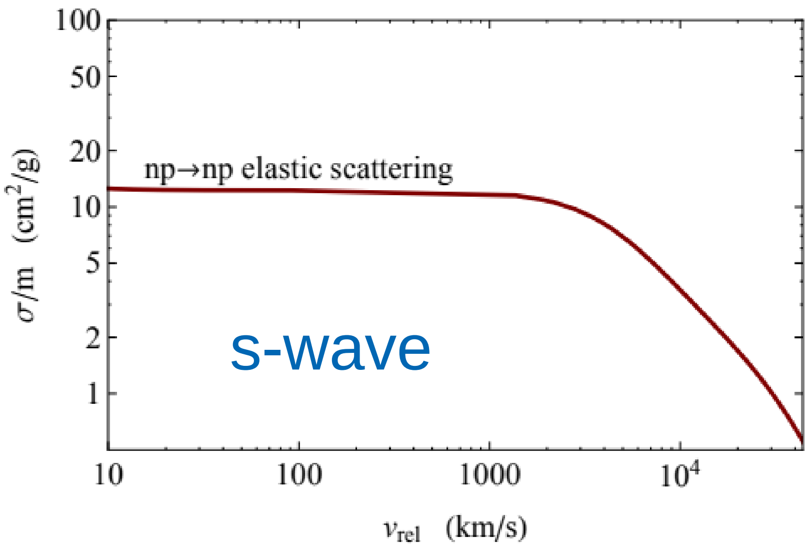

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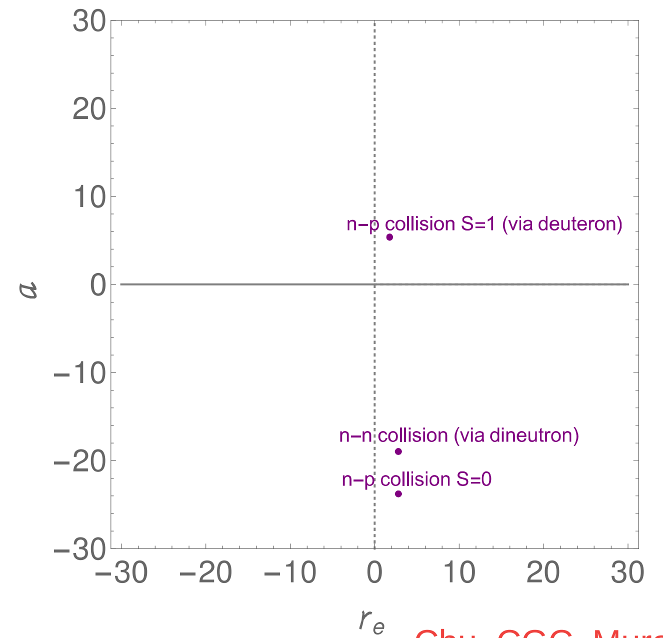
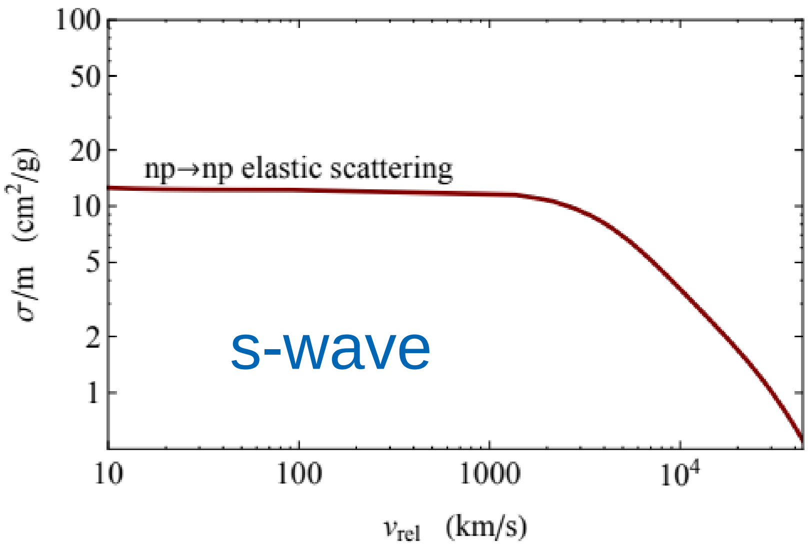


Chu, CGC, Murayama (2019)

Tulin, Yu (2017)



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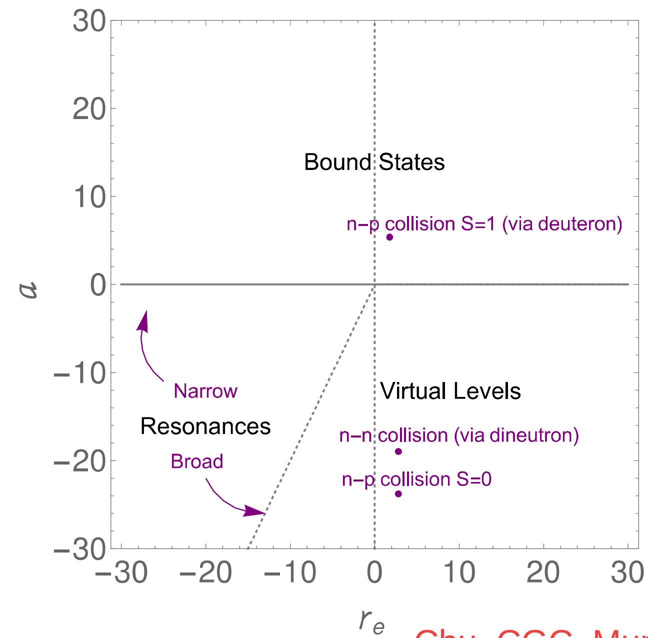

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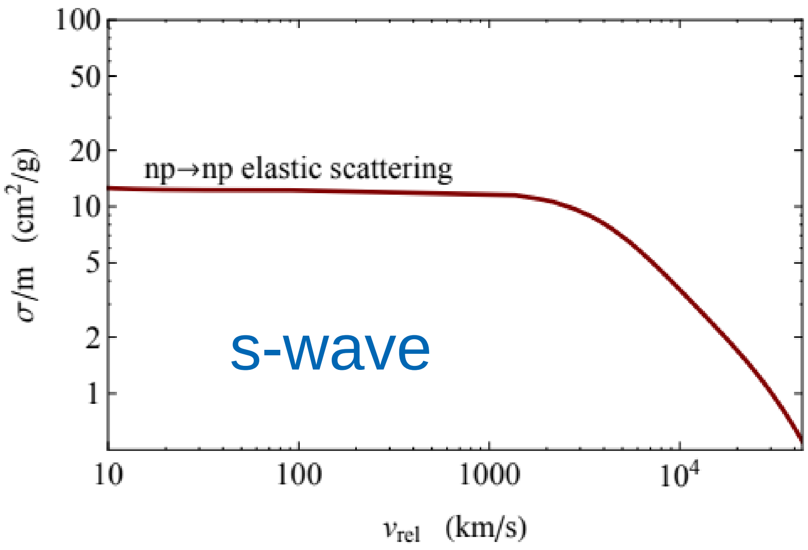

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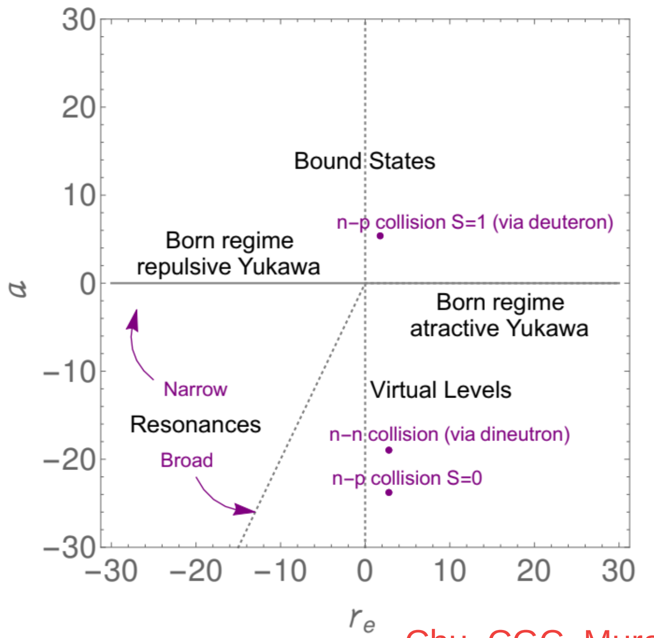

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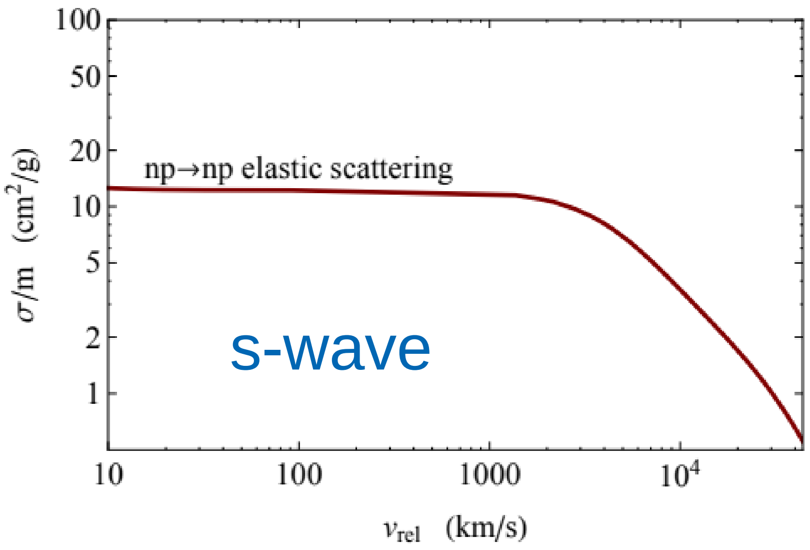

Camilo A. Garcia Cely (Alexander von Humboldt Fellow, DESY)

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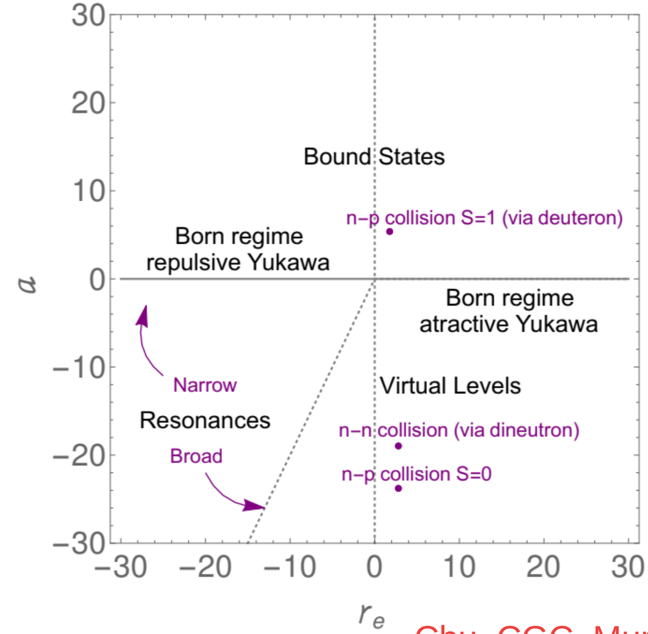

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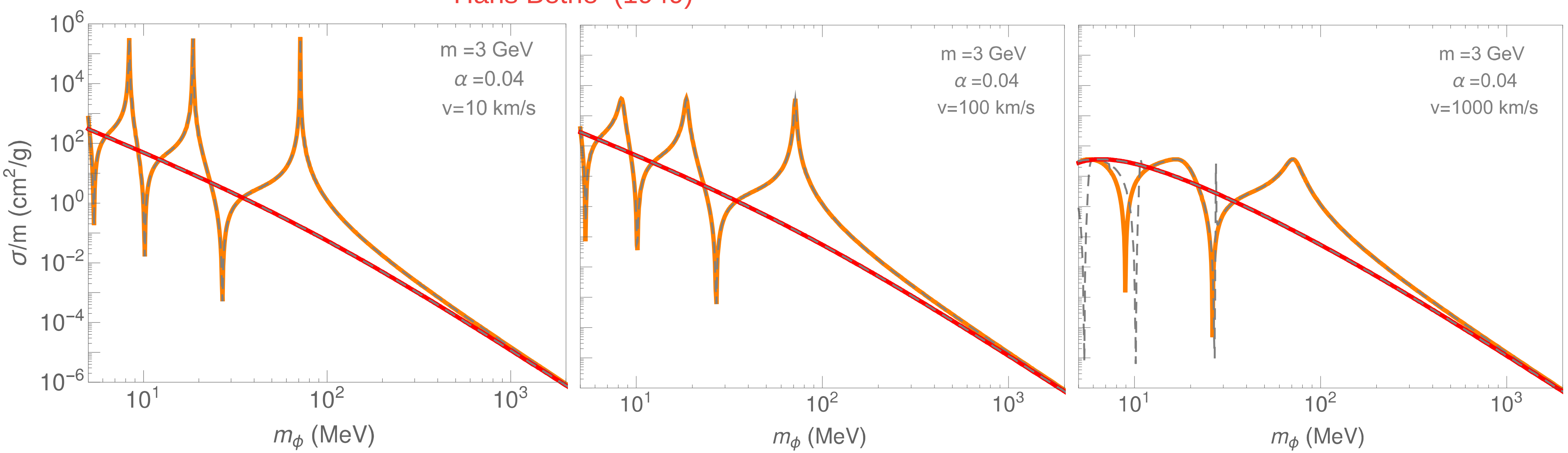

The case of light mediators

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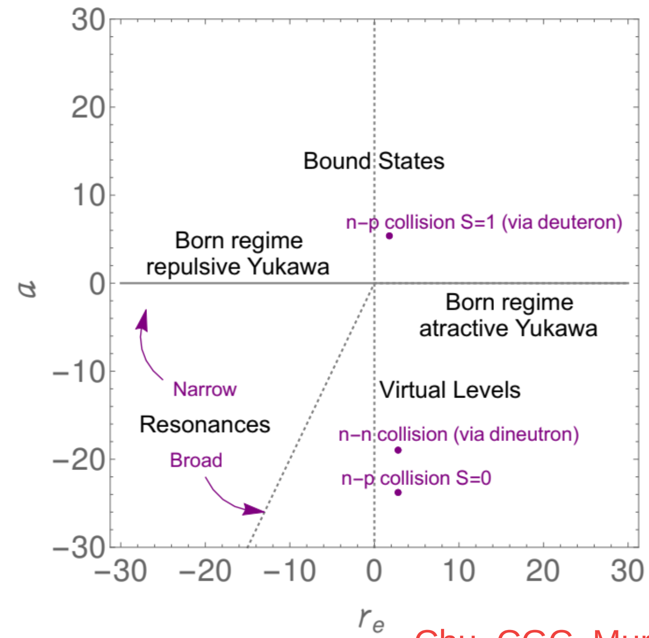

Chu, CGC, Murayama (2019)

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

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 has a finite size 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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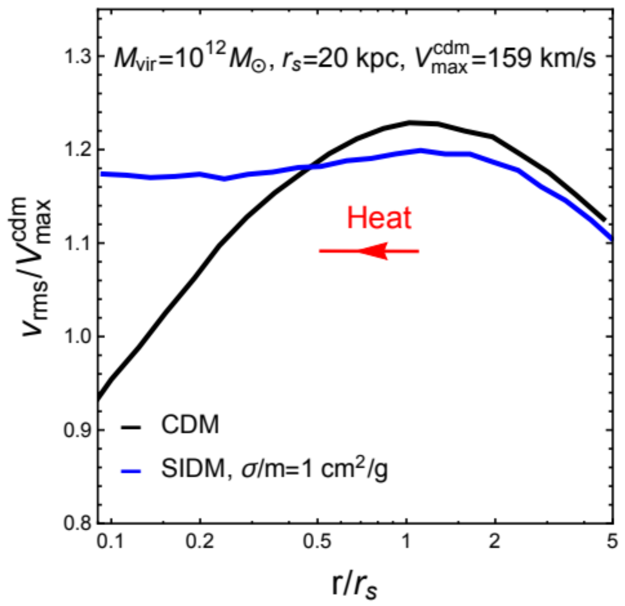
Thanks for your attention

How does self-interacting dark matter solve the problem?



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Rocha et al (2013)

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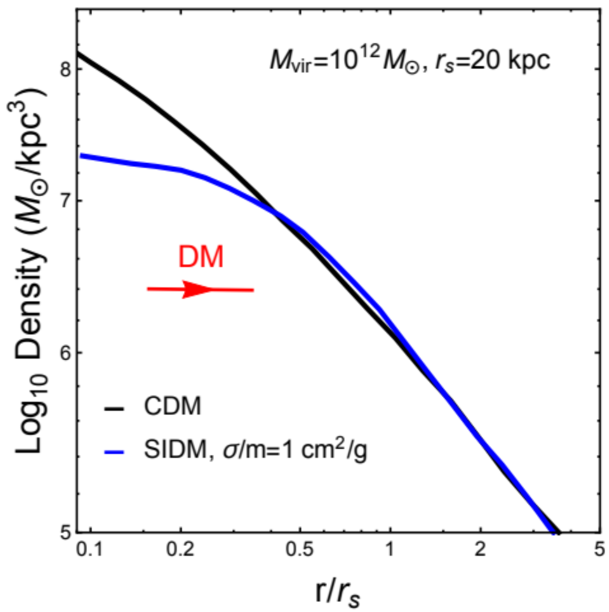

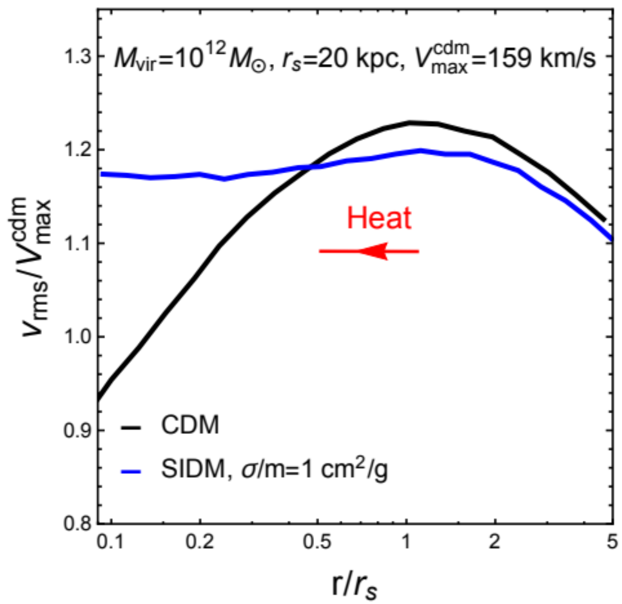

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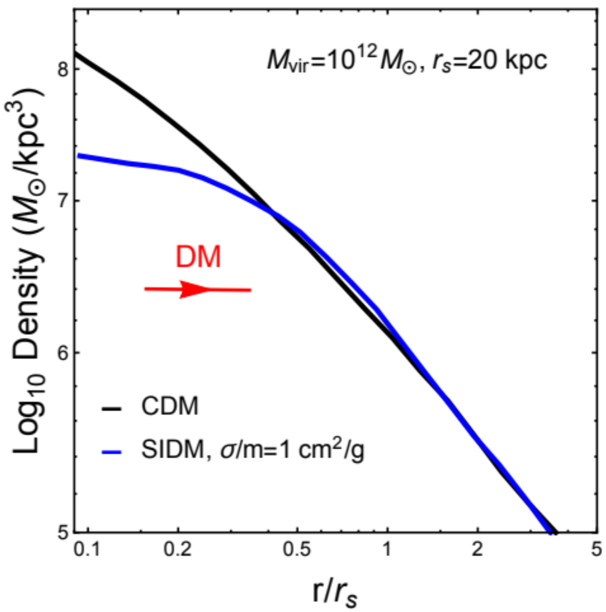

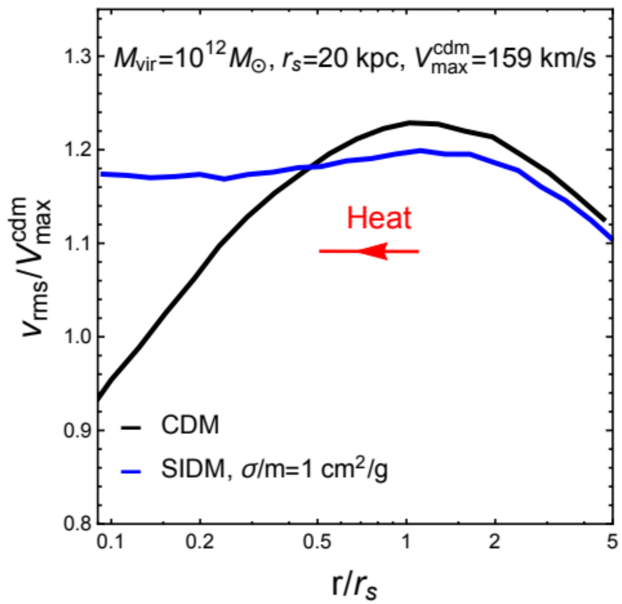

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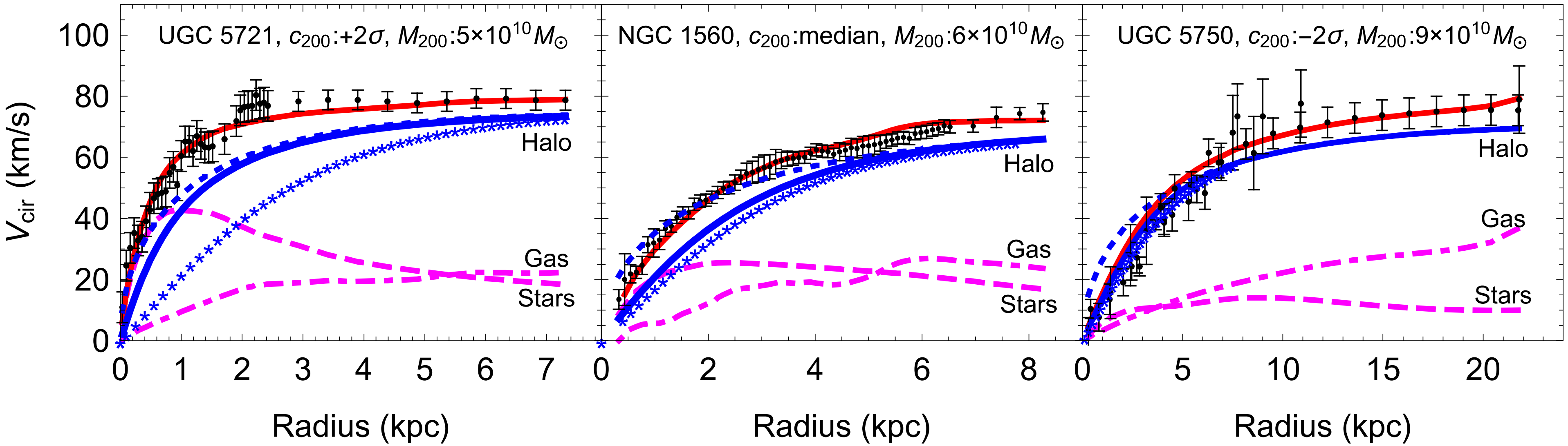


Kamada et al (2017)

Effective Range Theory

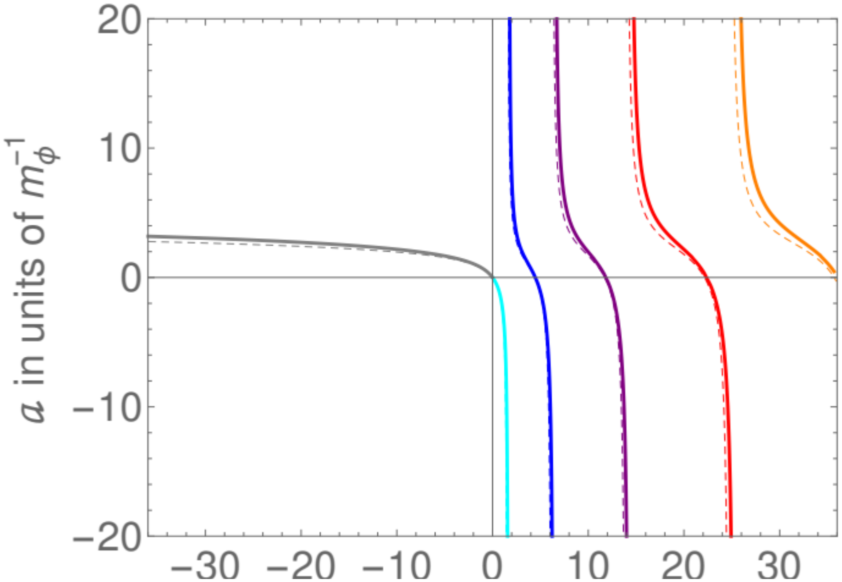
$$f(k,\theta) = \sum_{\ell=0}^{\infty}(2l+1)f_\ell(k)P_\ell\left(\cos\theta\right) \ ,$$

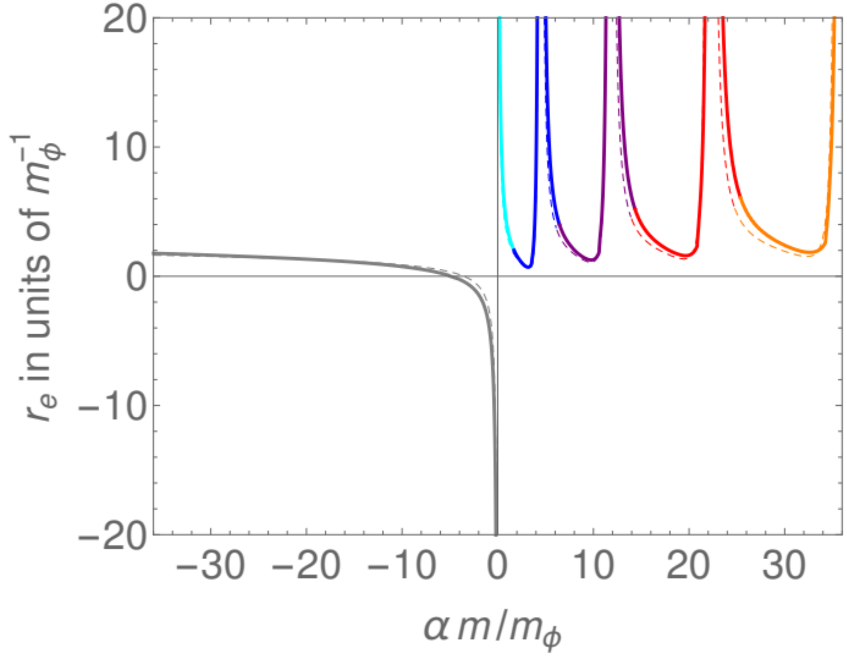
$$\text{with} \quad f_\ell(k) \equiv \frac{e^{2i\delta_\ell(k)}-1}{2ik} = \frac{1}{k\left(\cot\delta_\ell(k) - i\right)} \ .$$

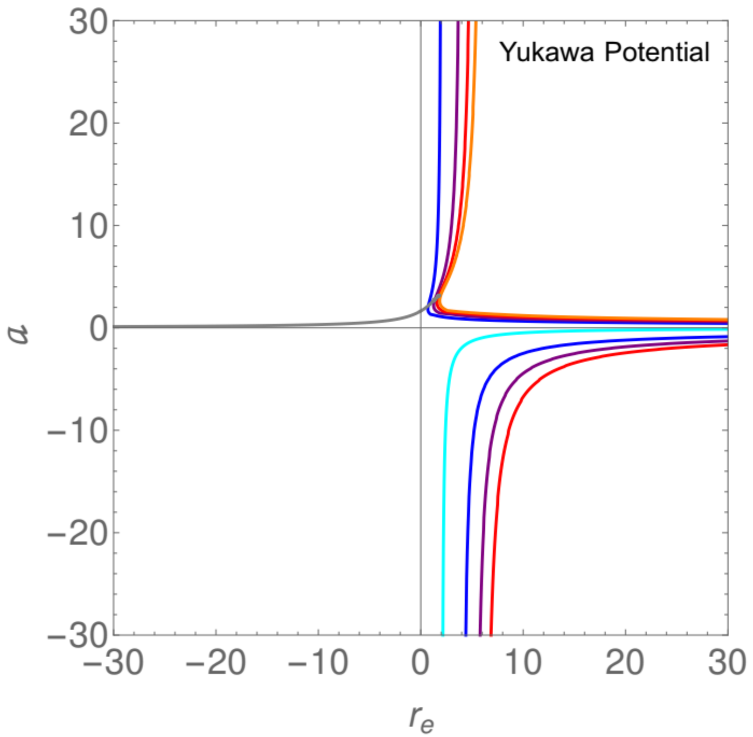
for finite-range interactions, the function $k^{2\ell+1}\cot\delta_\ell(k)$ must be analytic at $k = 0$

$$k^{2\ell+1}\cot\delta_\ell(k) \simeq -\frac{1}{a_\ell^{2\ell+1}} + \frac{1}{2r_{e,\ell}^{2\ell-1}}k^2 \ .$$

Effective Range Theory

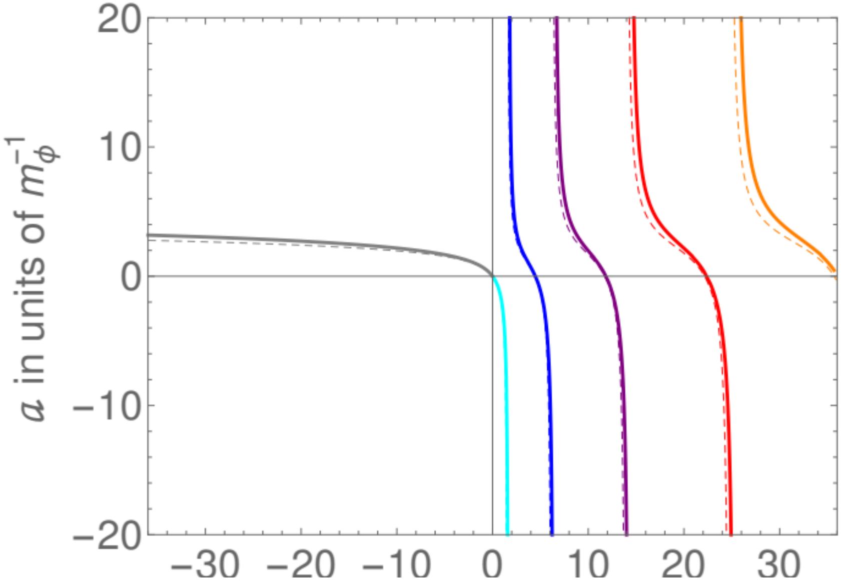


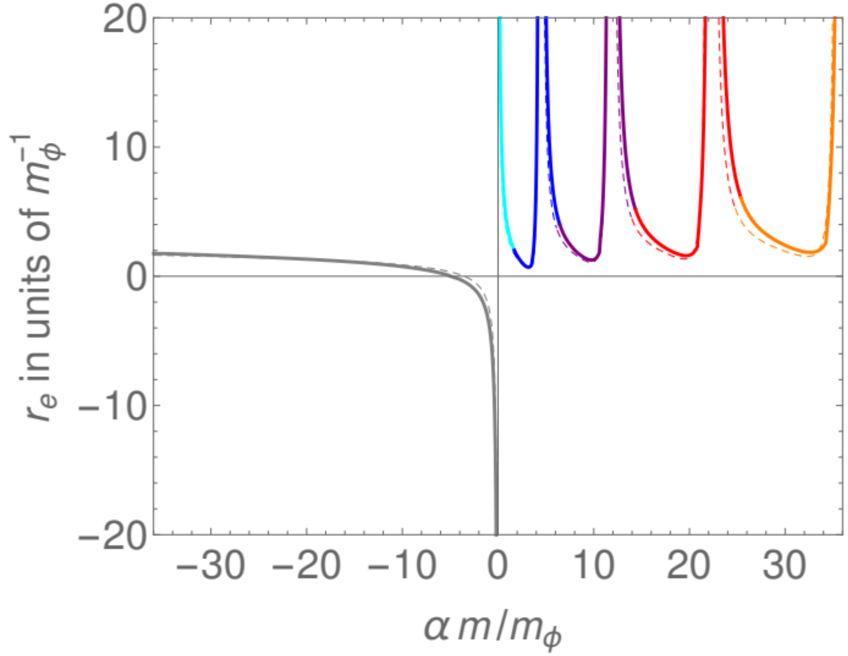


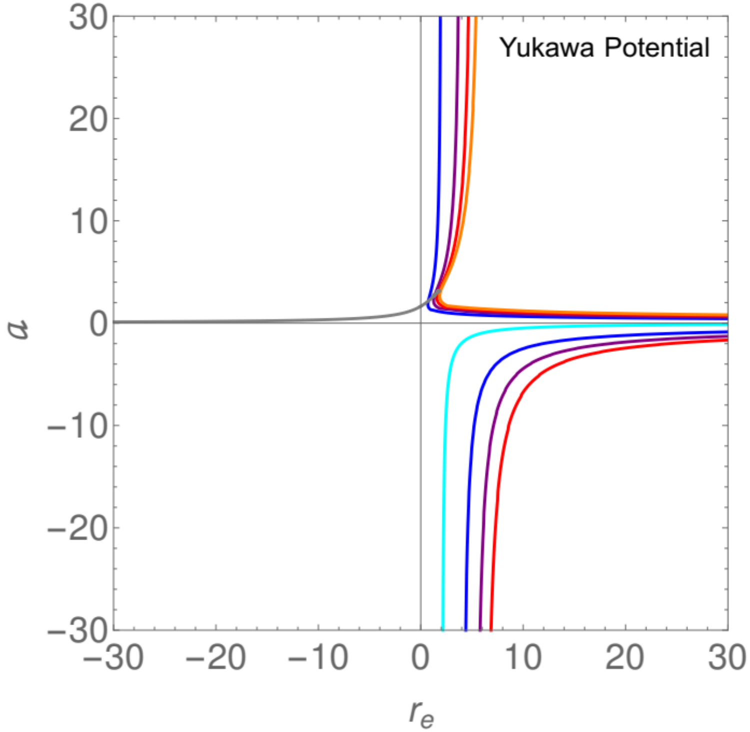


Chu, CGC, Murayama (2019)

Effective Range Theory







$$\frac{d\delta_{\ell,k}(r)}{dr} = -k\, m\, r^2 V(r)\ \mathrm{Re}\left[e^{i\delta_{\ell,k}(r)} h_\ell^{(1)}(kr)\right]^2$$

$$\delta_{\ell,k}(0) = 0 \qquad \text{and} \qquad \delta_{\ell,k}(r) \to \delta_\ell \quad \text{at} \quad r \to \infty$$

Chu, CGC, Murayama (2019)