Bound states and dark matter

Camilo A. Garcia Cely
Alexander von Humboldt fellow

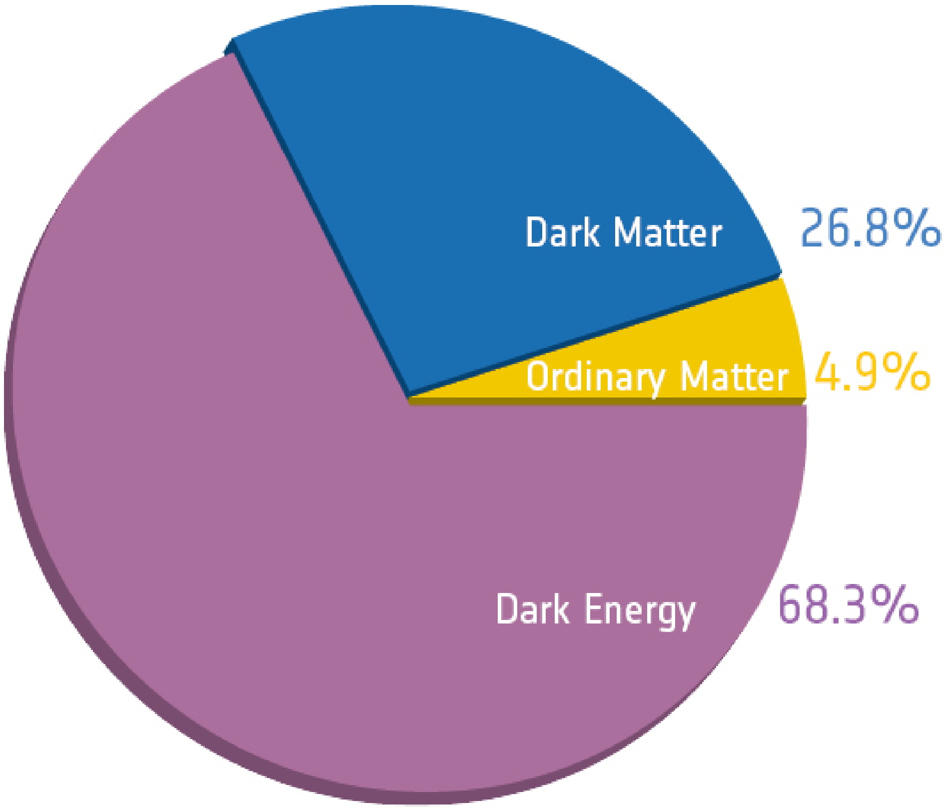
Theory Seminar

Universitetet i Oslo

March 4, 2020

Lambda Cold Dark Matter model

Energy budget of the Universe



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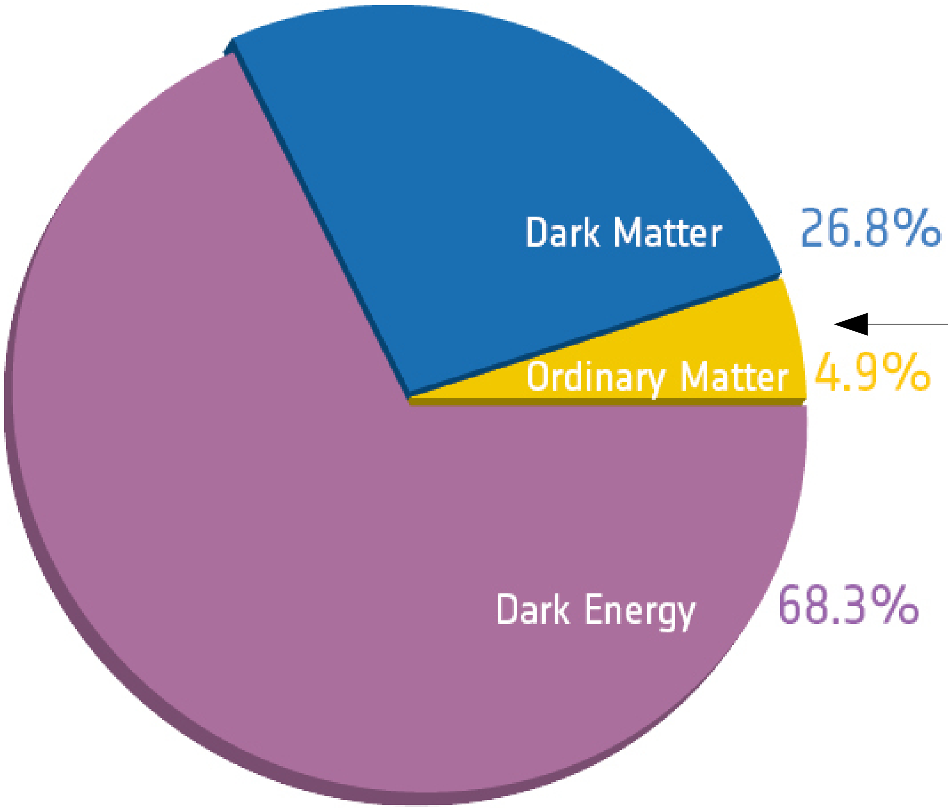

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Mostly protons, electrons, neutrinos and photons.

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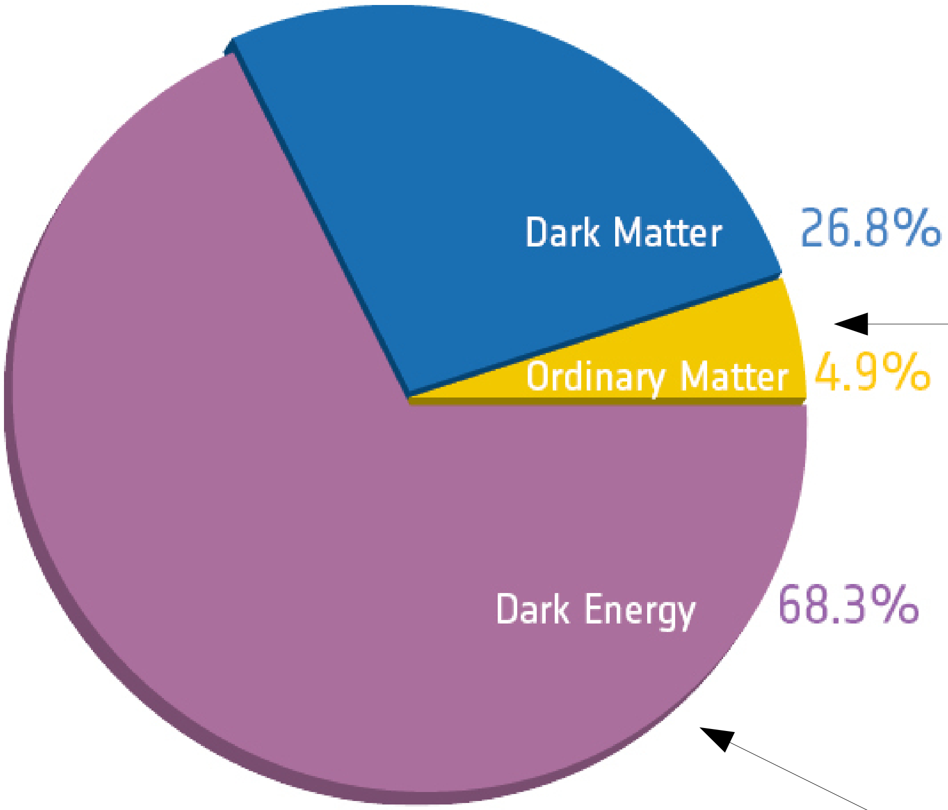

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$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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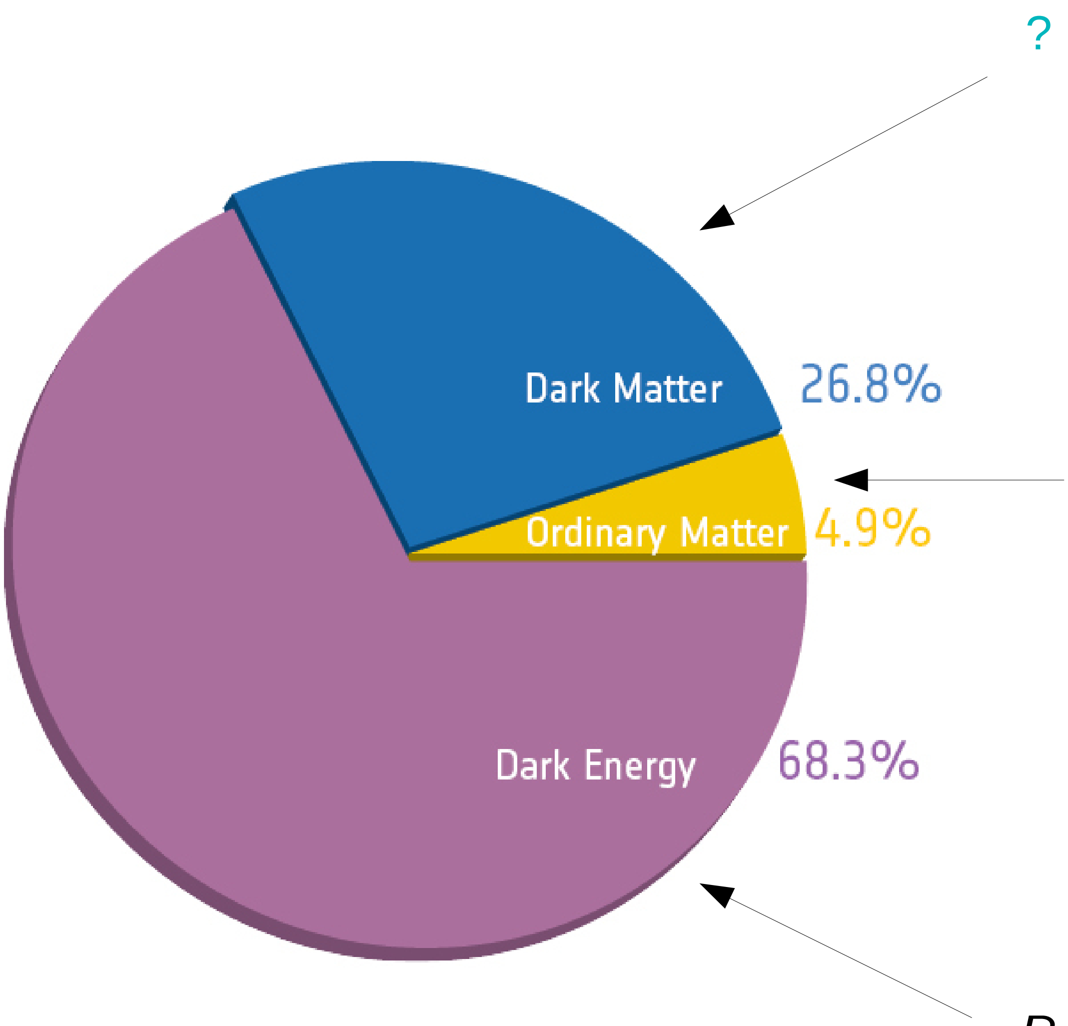

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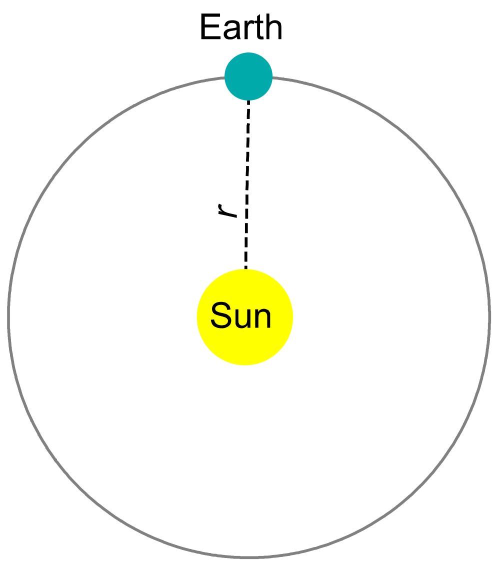
Kepler's Laws for Planets



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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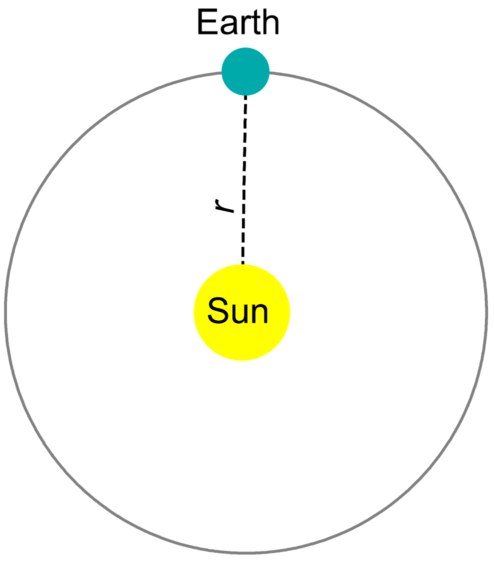

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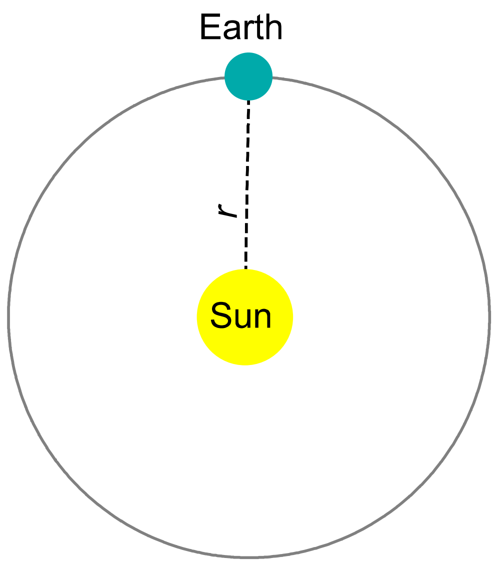
$$\frac{GM_{\text{Sun}}}{4\pi^2}$$

Kepler's Laws for Planets



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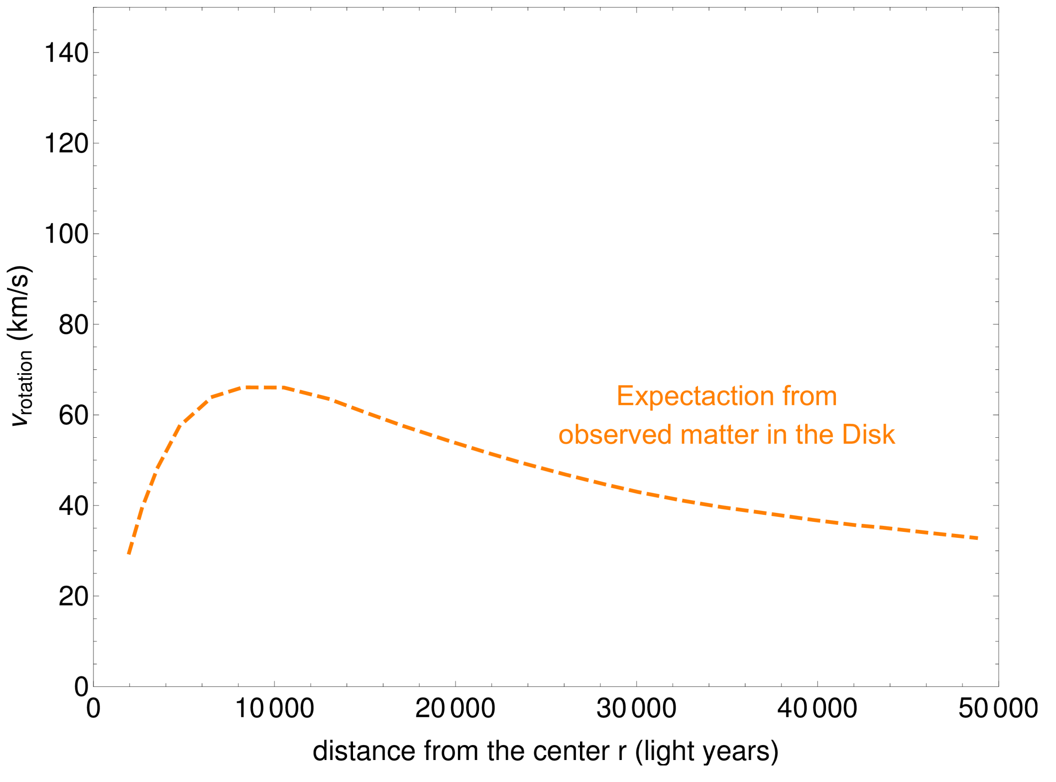
$$\frac{GM_{\text{Sun}}}{4\pi^2}$$

For circular orbits this can be recast as

$$v^2_{\text{rotation}} = \frac{GM_{\text{enclosed}}}{r}$$

Kepler's Laws for Galaxies?



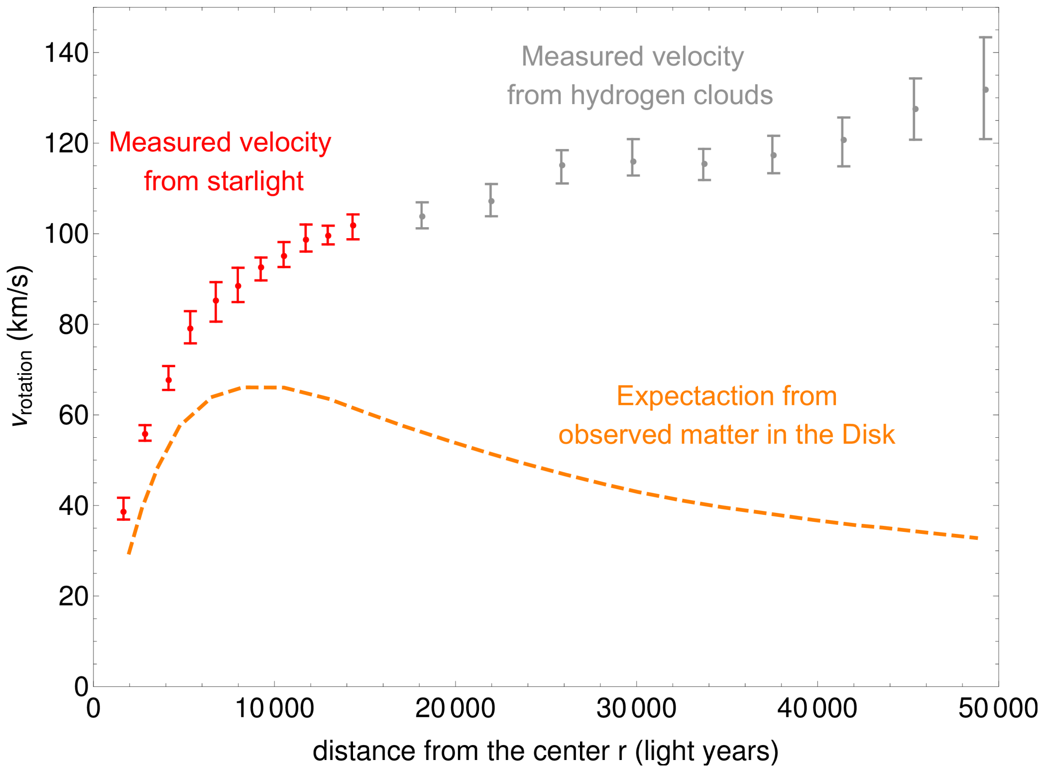
Triangulum Galaxy (M33)

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

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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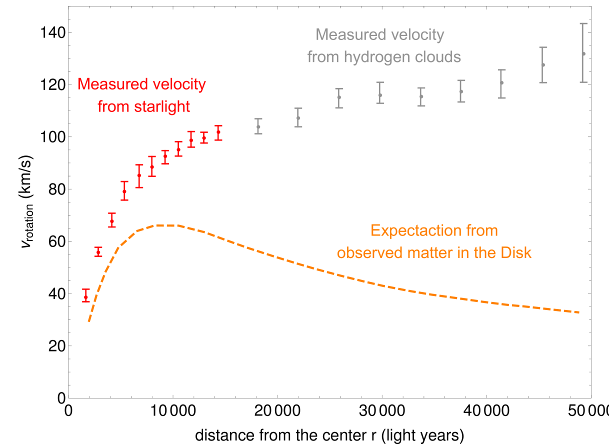
Dark Matter

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



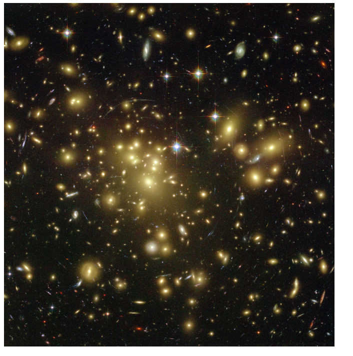
Velocity measurements

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

kpc

Lensing

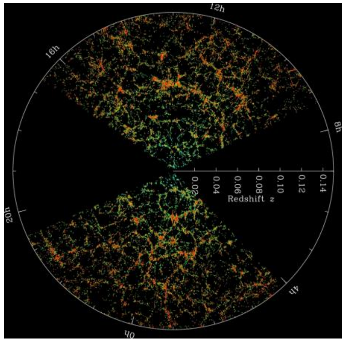
- Weak lensing by large-scale structure and cluster mergers
- Strong lensing by individual galaxies and clusters



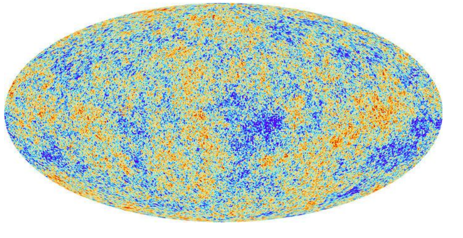
Mpc

Universe at large scales

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



Gpc



The Astrophysical Journal, 648:L109–L113, 2006 September 10

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Douglas Clowe,[2] Maruša Bradač,[3] Anthony H. Gonzalez,[4] Maxim Markevitch,[5,6]
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Received 2006 June 6; accepted 2006 August 3; published 2006 August 30

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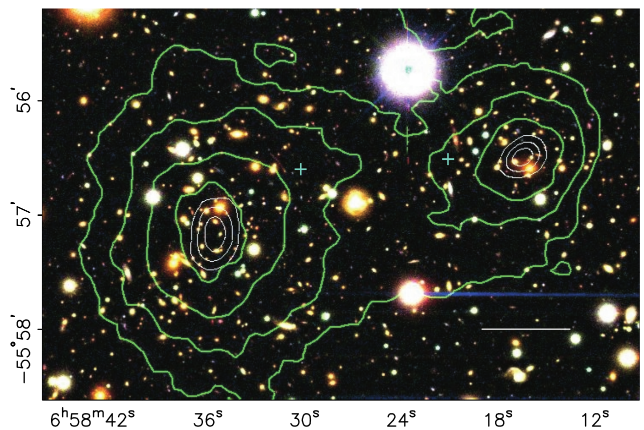

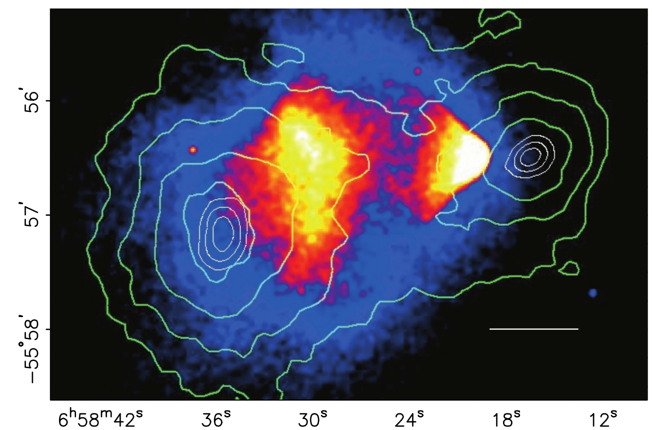

Fig. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with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

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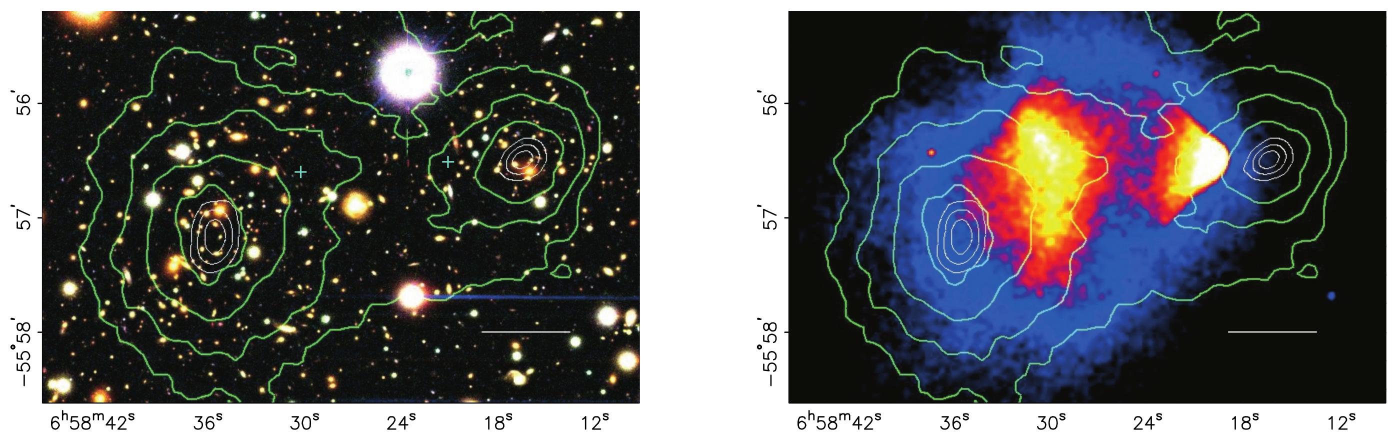

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$$\sigma_{\text{scattering}}/m_{\text{DM}} \lesssim 1\ \text{cm}^2/\text{g}$$

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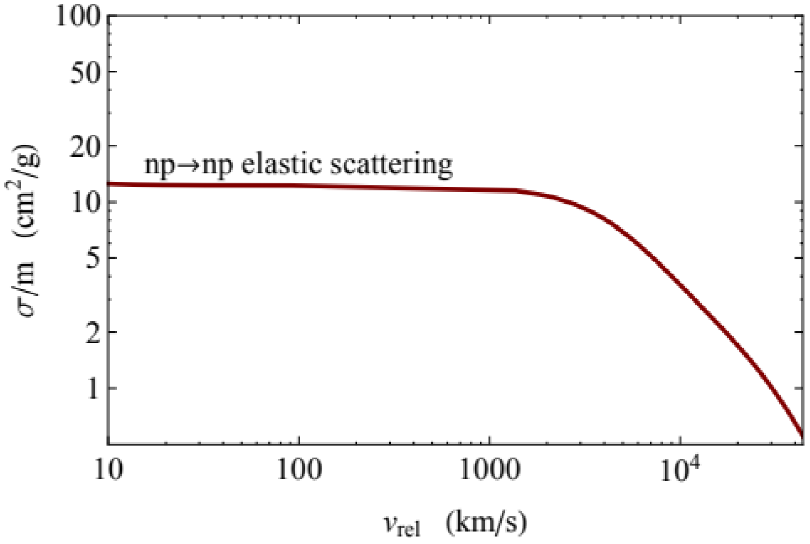
What does this tell us about the nature of the dark matter particle?

How does that compare to nucleon-nucleon collisions?

Tulin, Yu (2017)



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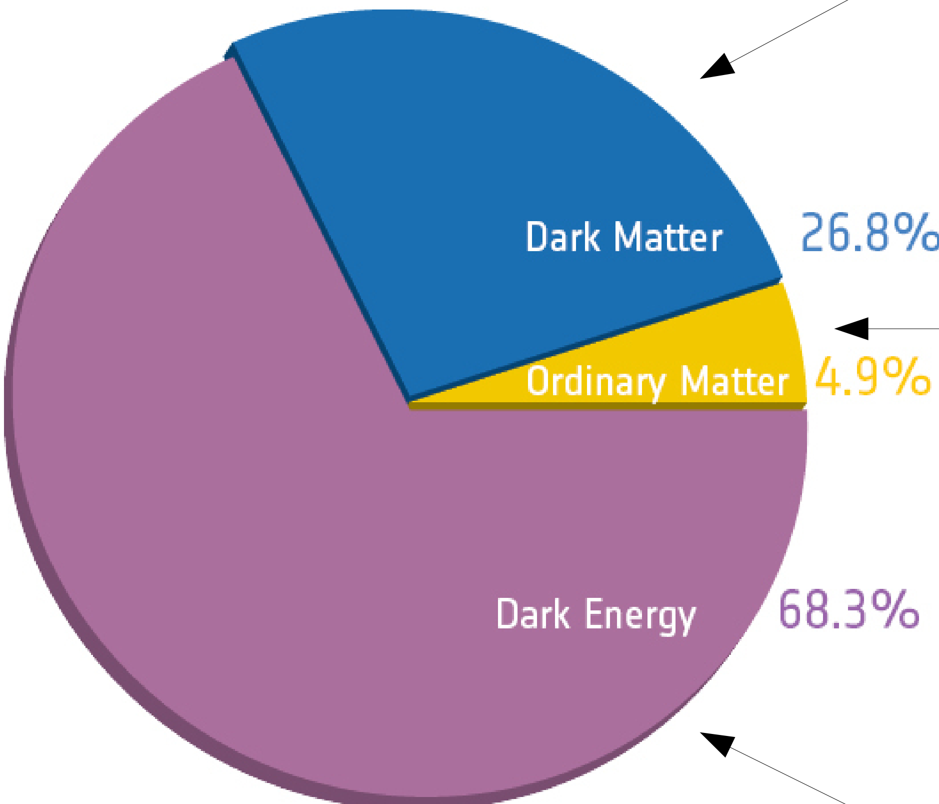

Collisionless Cold Dark Matter

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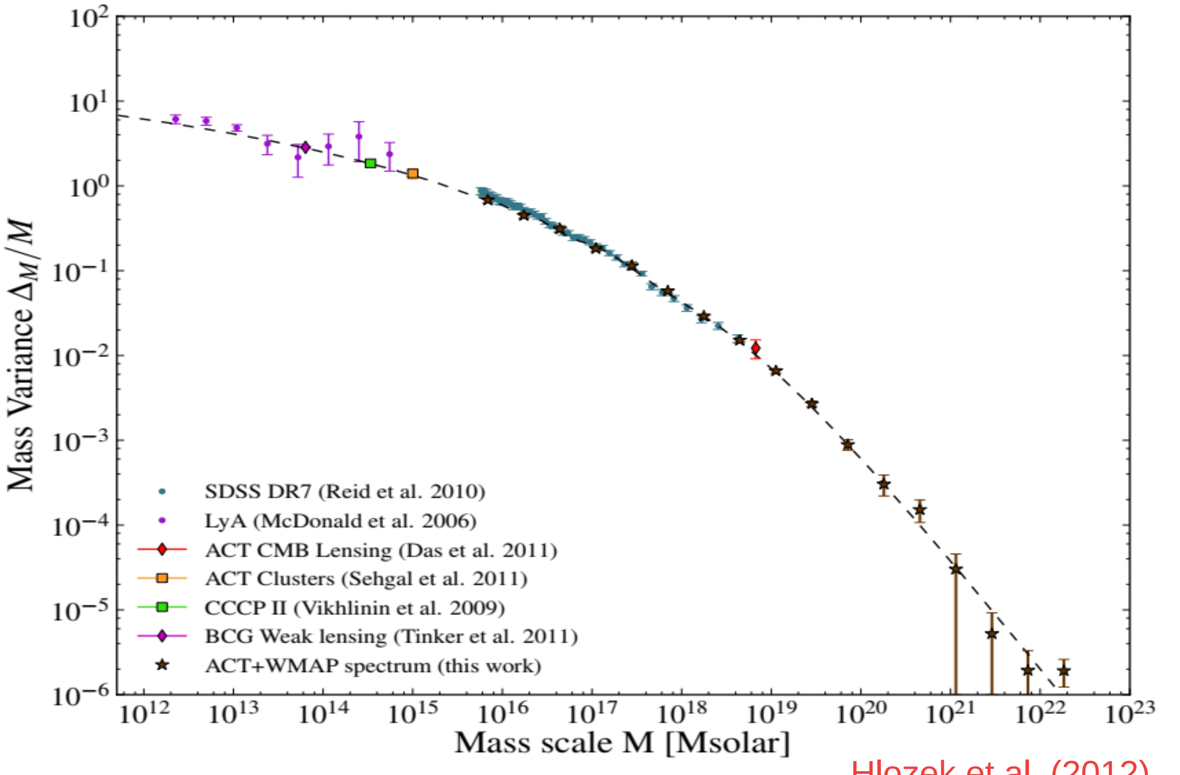
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Lambda Cold Dark Matter model

Remarkably successful
at large scales

At low scales
N-body simulations
are needed



Hlozek et al. (2012)

I. Dark matter as a bound state

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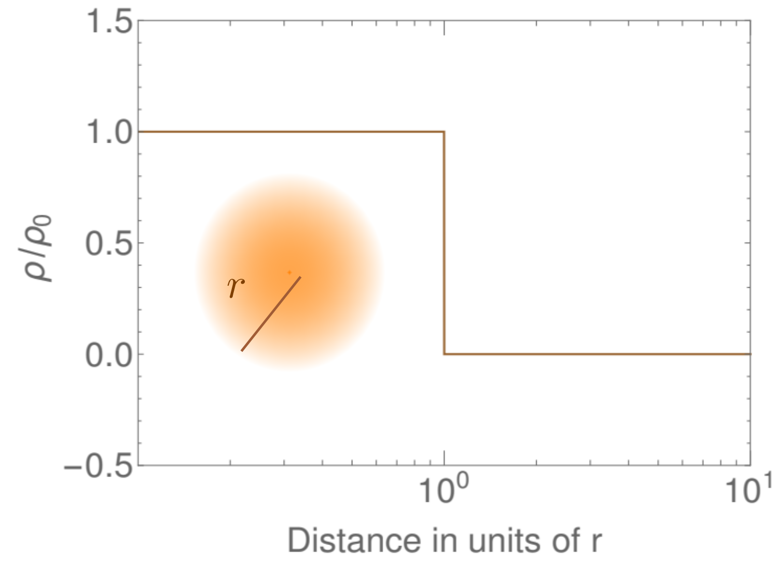
Based on

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,‡]

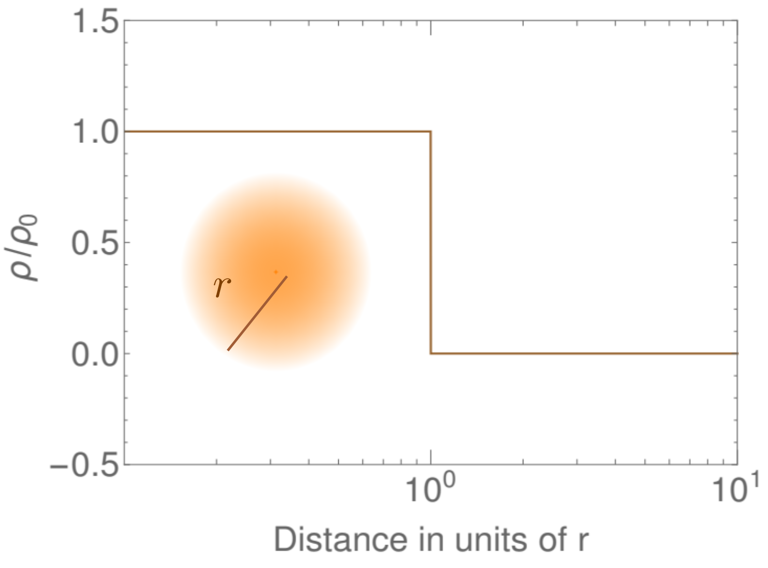
How do we know something has a finite size?

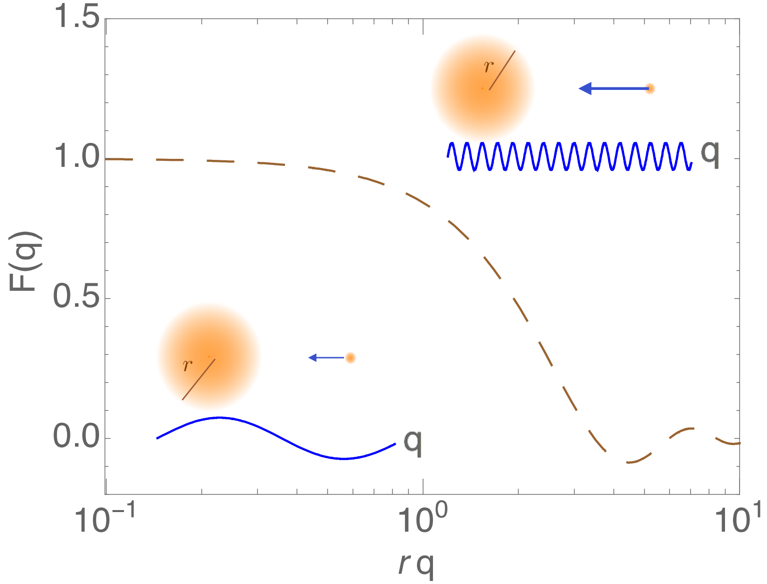


How do we know something has a finite size?

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}\bigg|_{\text{pointlike}} |F(q)|^2.$$

Fourier Transform
of the density





Realistic example

VOLUME 19, NUMBER 9 PHYSICAL REVIEW LETTERS 28 AUGUST 1967

SCATTERING OF 750-MeV ELECTRONS BY CALCIUM ISOTOPES*

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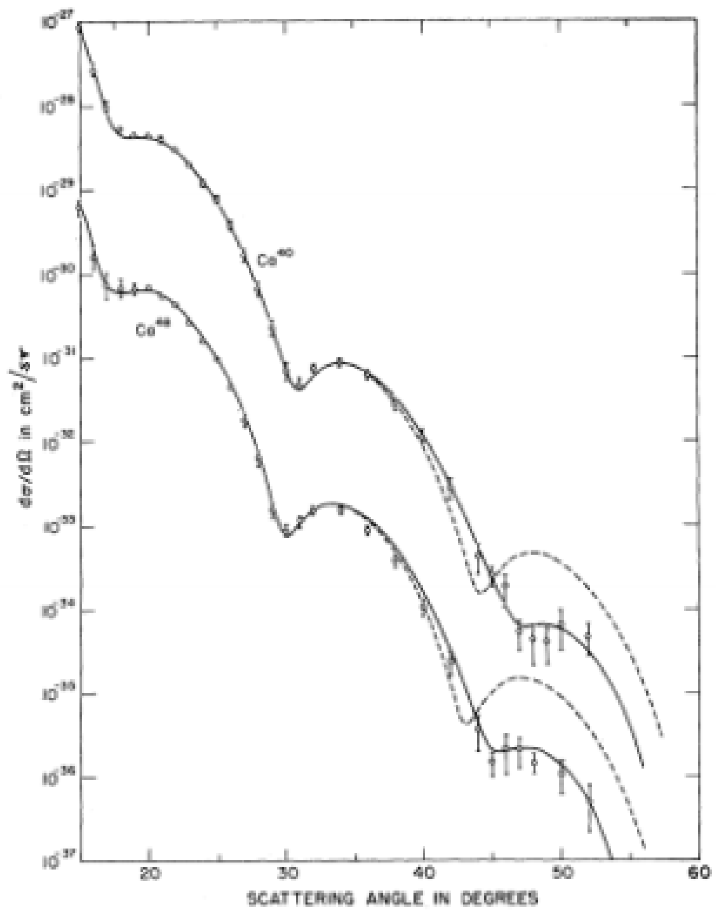
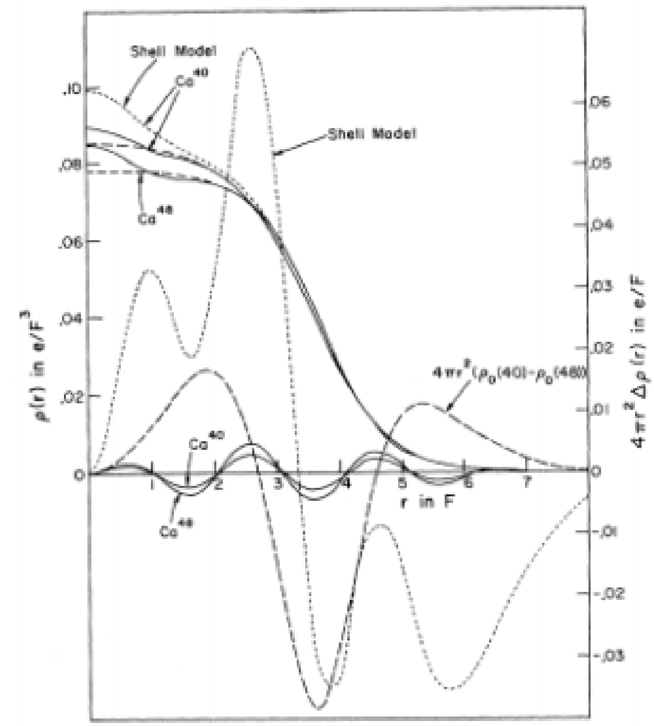
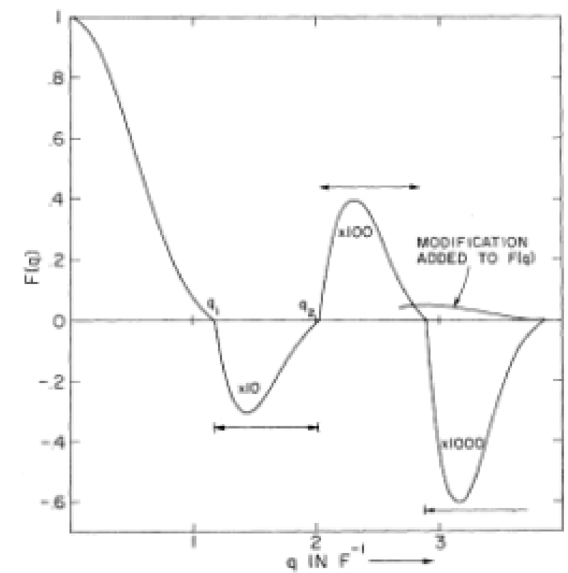


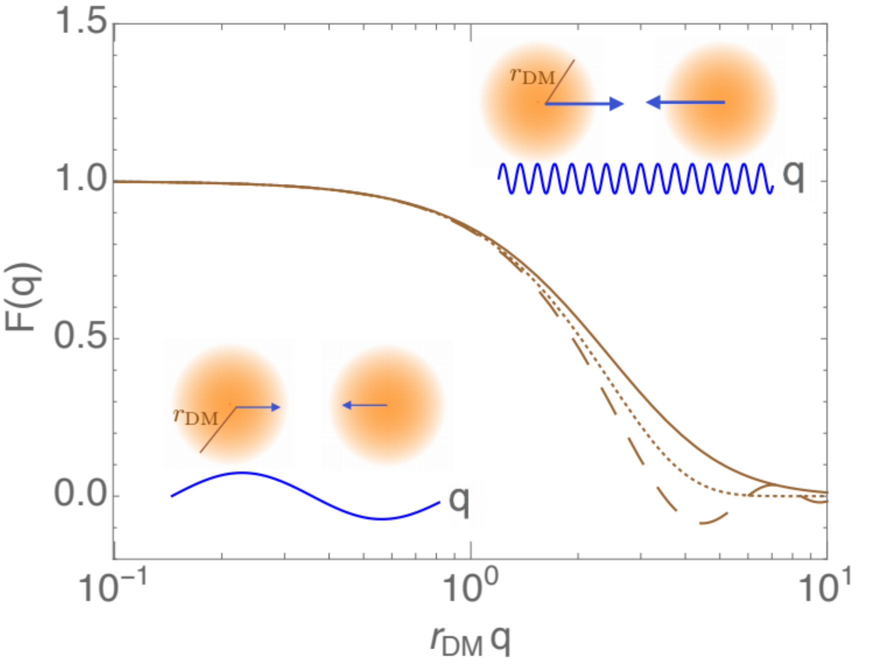




Dark Matter with a finite size

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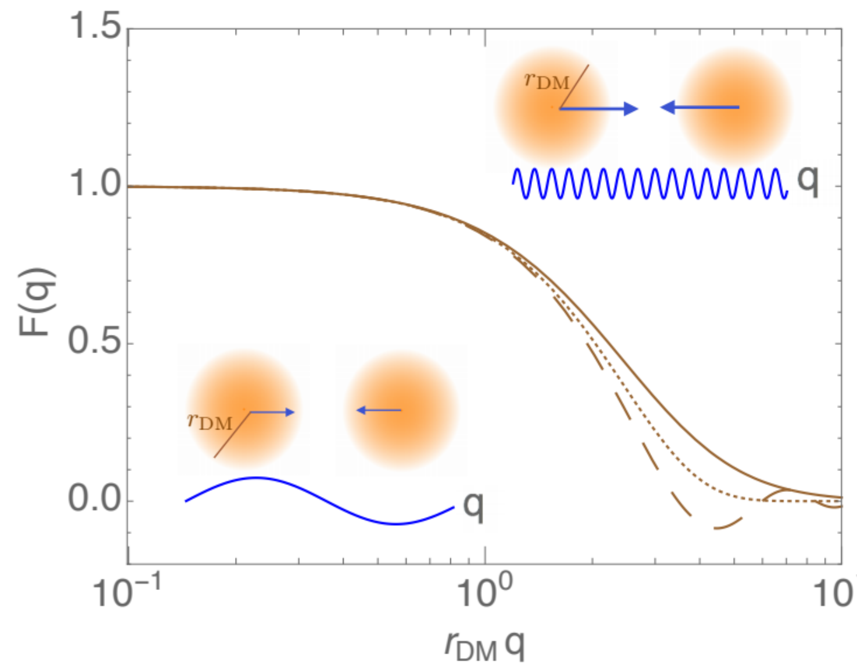
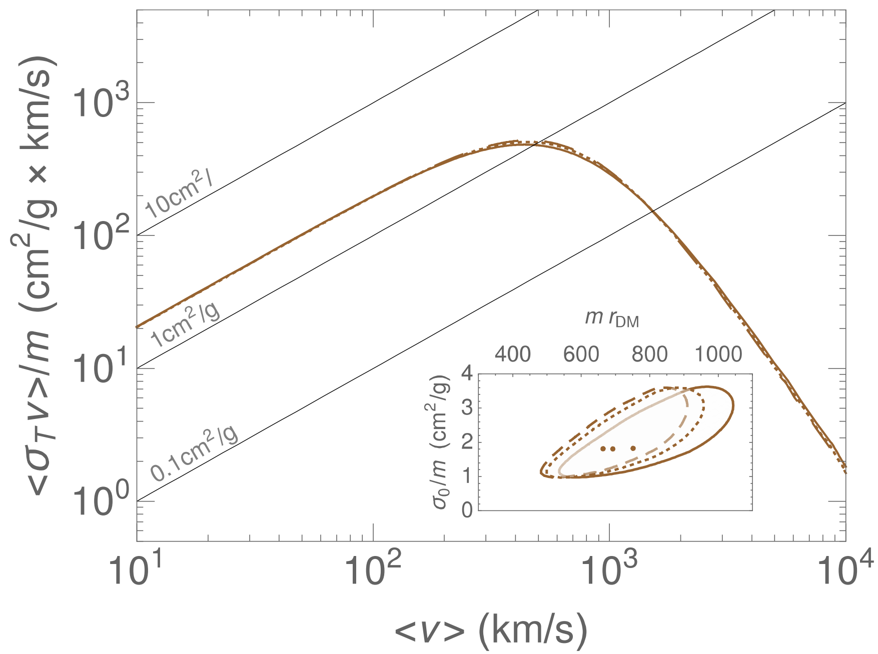
Shape	$\rho(r)$	$r_{\rm DM}$	$F(q)$
tophat	$\frac{3}{4\pi r_0^3}\theta(r_0-r)$	$2\sqrt{3}r_0$	$\frac{3(\sin(r_0q)-r_0q\cos(r_0q))}{r_0^3q^3}$
dipole	$\frac{e^{-r/r_0}}{8\pi r_0^3}$	$\sqrt{3/5}r_0$	$\frac{1}{(1+r_0^2q^2)^2}$
Gaussian	$\frac{1}{8r_0^3\pi^{3/2}}e^{-r^2/(4r_0^2)}$	$\sqrt{6}r_0$	$e^{-r_0^2q^2}$

Table I: Form factors for different density distributions.

It is possible to obtain small cross section at cluster (v~ 1000 km/s) but small cross section in smaller objects (galaxies)





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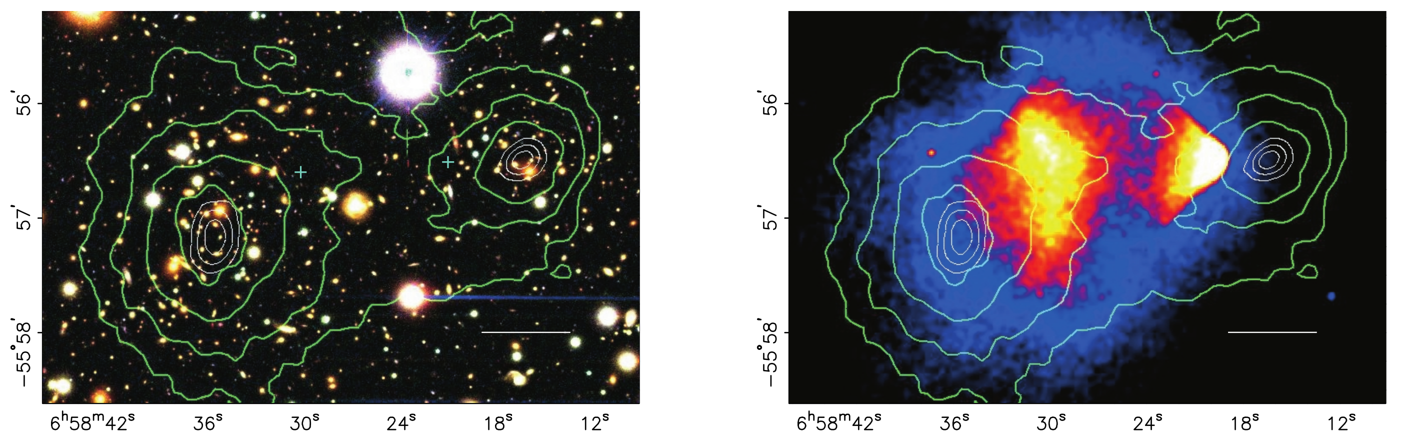

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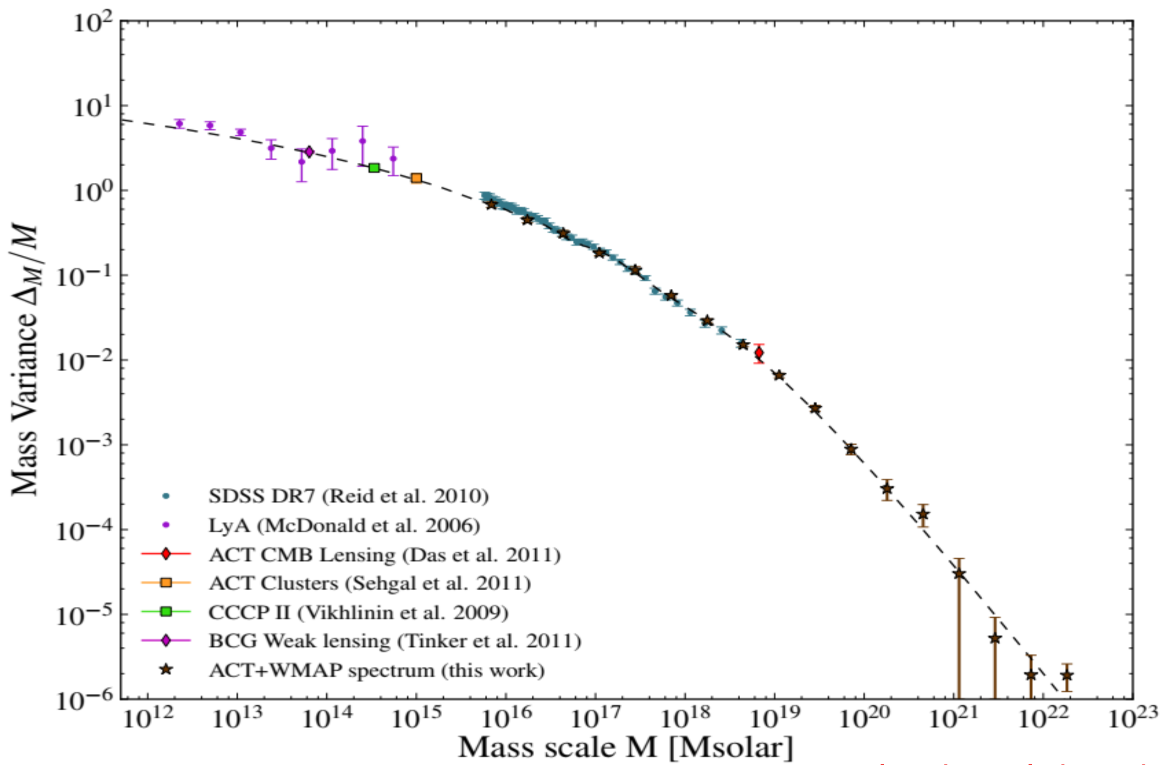
Is this useful?



Hlozek et al. (2012)

Remarkably successful at large scales

At low scales N-body simulations are needed

Mass deficits at galactic scales

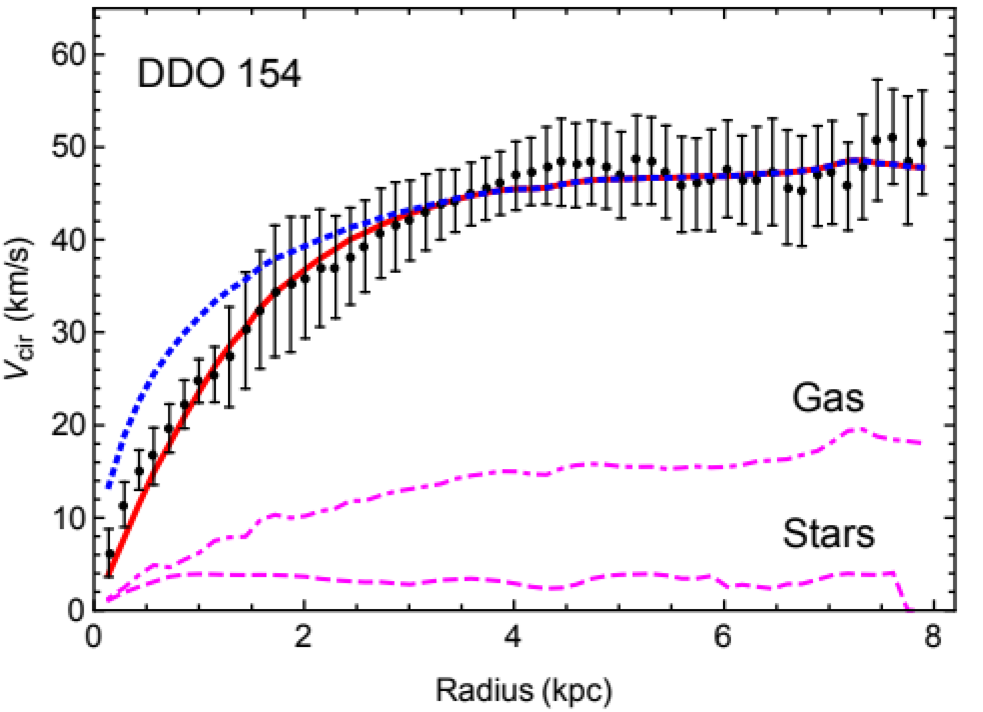
- Core vs. cusp problem
- Diversity problem
- Too-big-to-fail problem
- Missing satellites

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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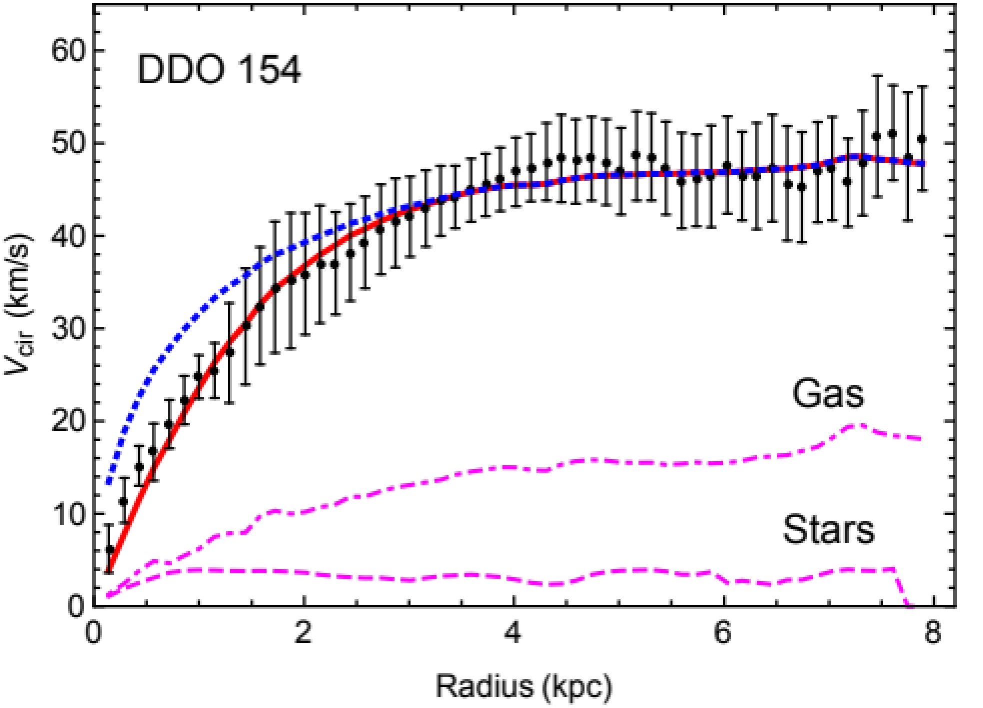
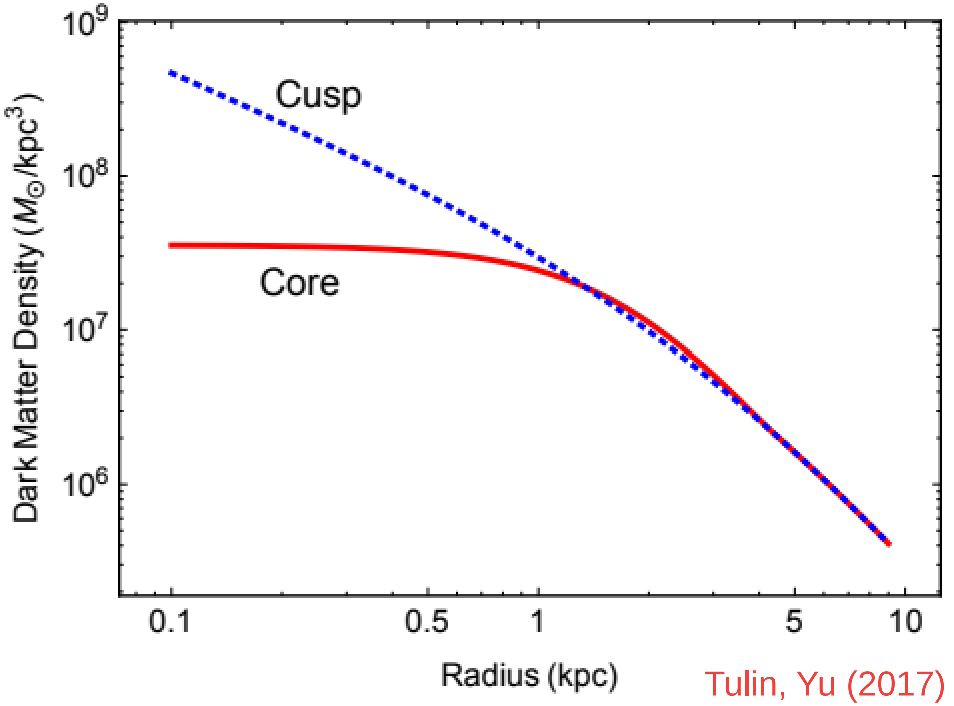




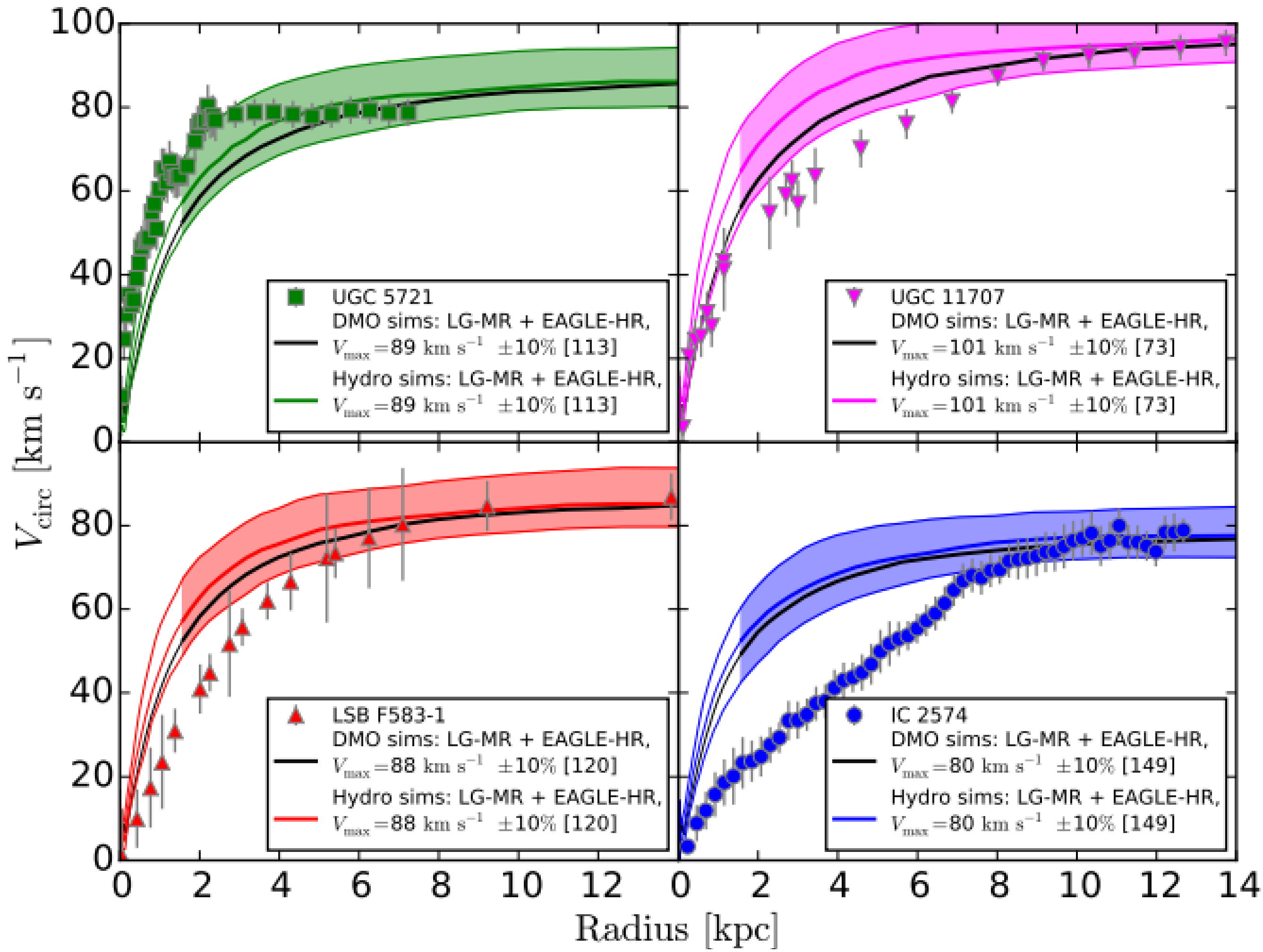
Tulin, Yu (2017)

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

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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Dark matter 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)

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

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

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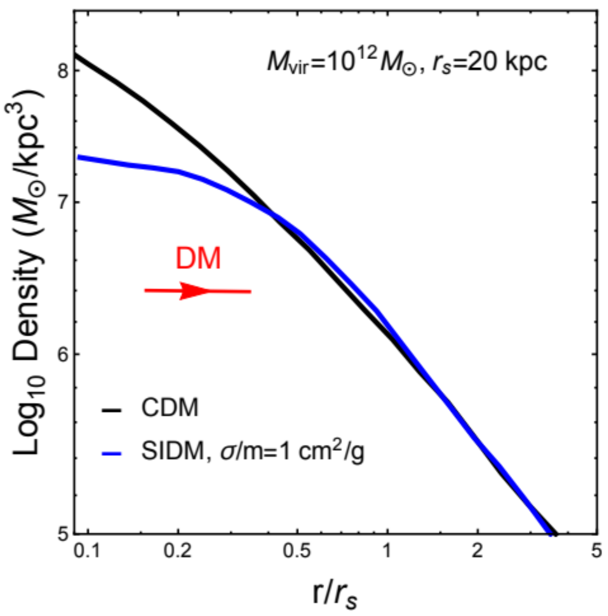
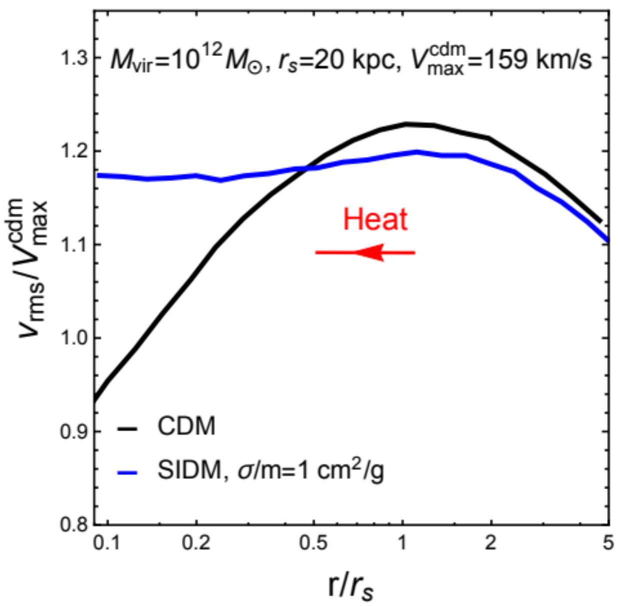
Simulations show that this is indeed a solution

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)

Debate

Plausible explanations

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

Dark matter solution?

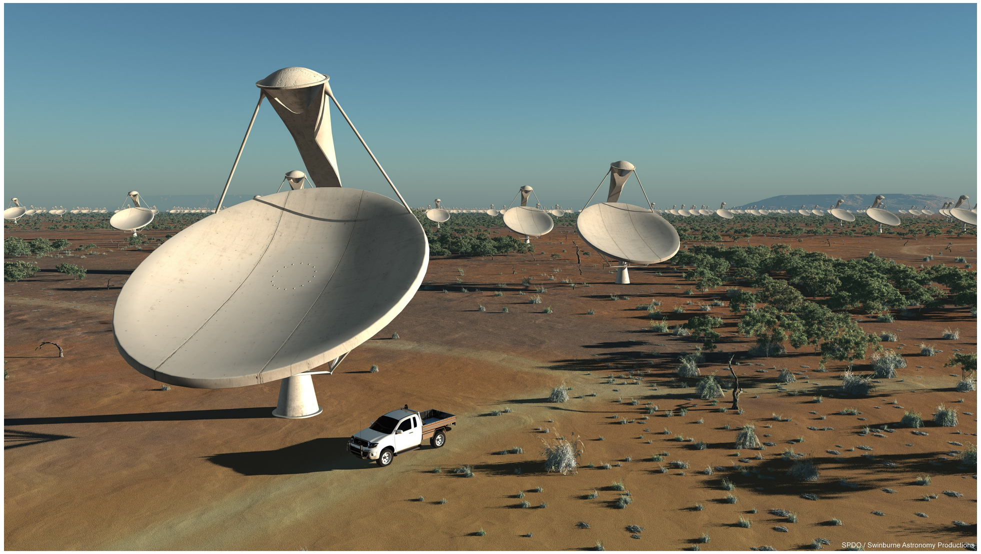
- postulate dark matter interactions that become relevant at small scales, without modifying the physics at large scales.

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*

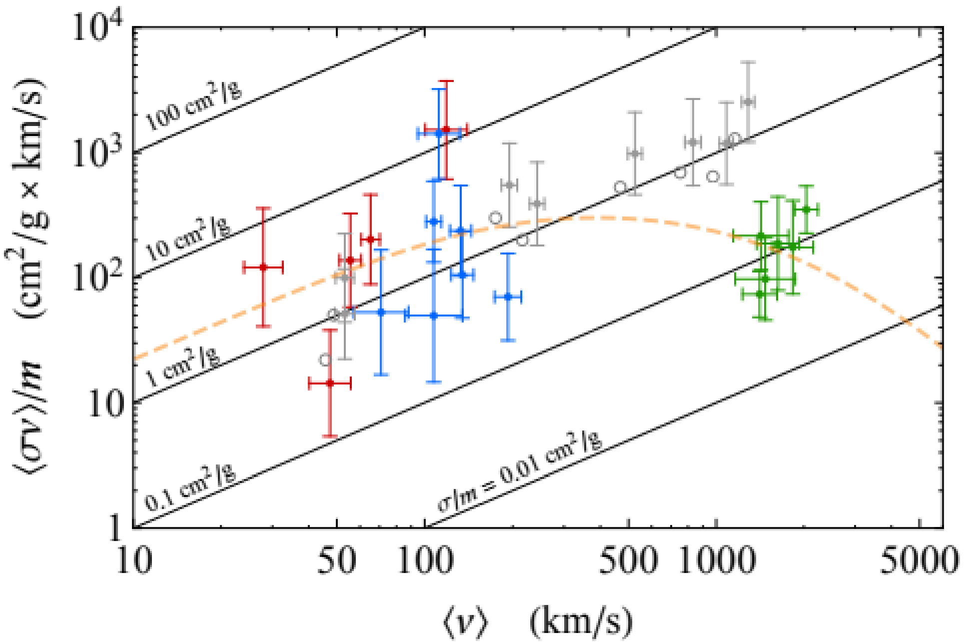
It has the potential to observe hundreds of nearby spiral galaxies at resolutions below 100 pc, providing a large and detailed sample of rotation curves.



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

Dark matter halos as particle colliders

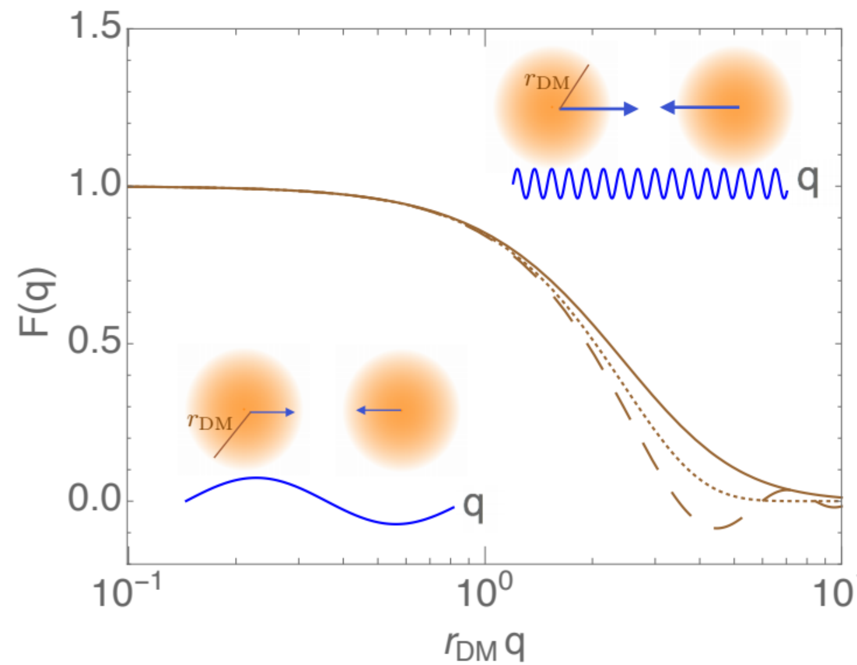
Kaplinghat ,Tulin, Yu (2017)



Maybe dark matter is a bound state

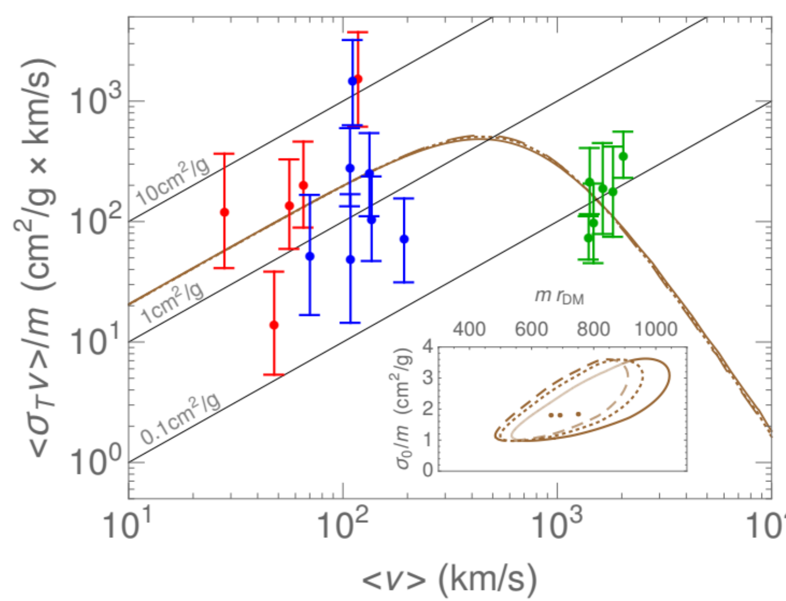
Suppose that dark matter has a finite size that is larger than its Compton wavelength: Puffy DM

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.



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

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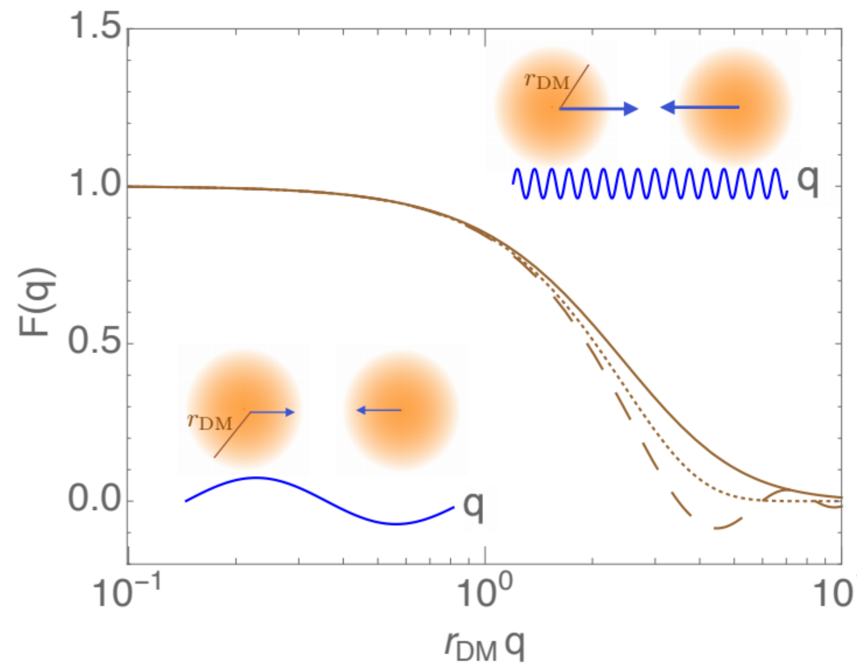
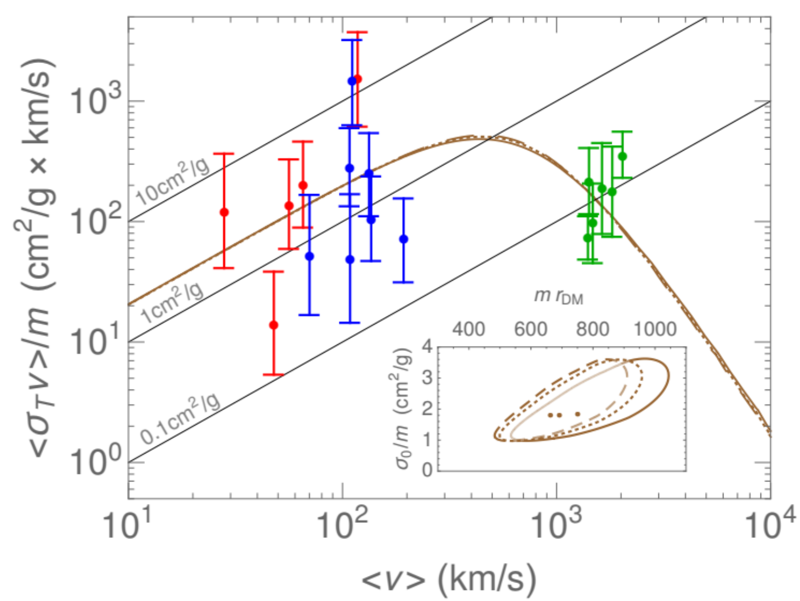
Table I: Form factors for different density distributions.

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.





Why is that?

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

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

Effective Range Theory

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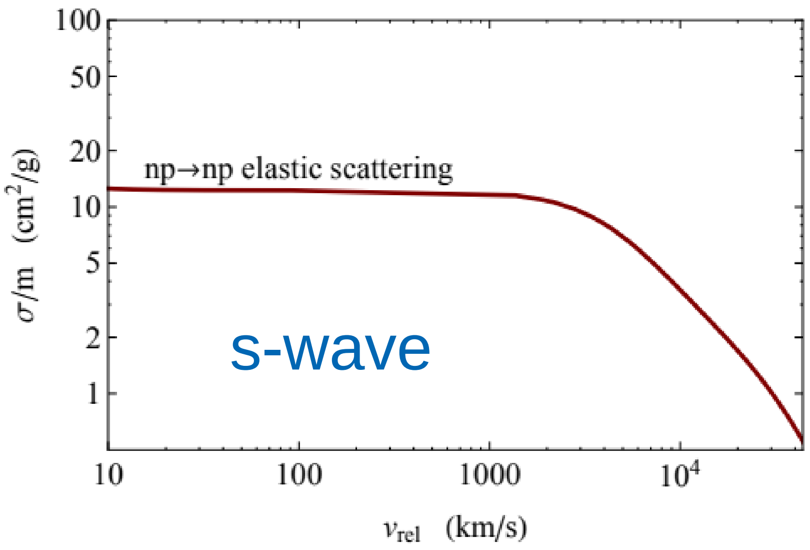
Tulin, Yu (2017)



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Hans Bethe (1949)

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

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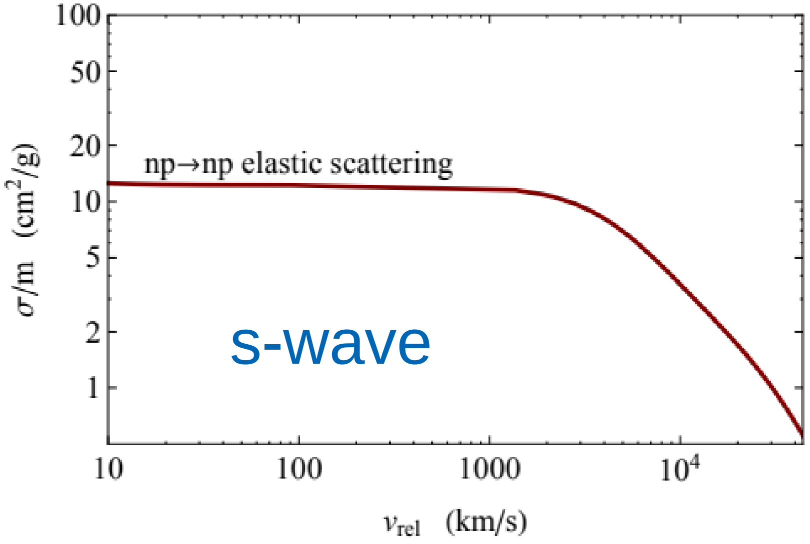

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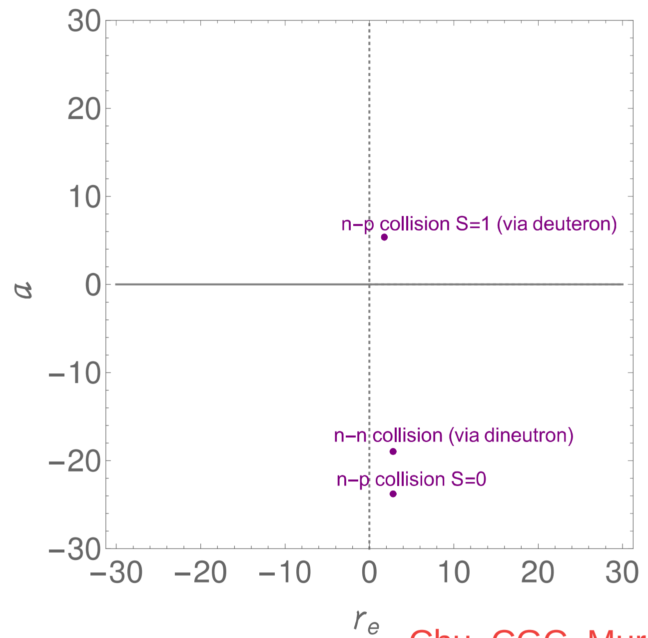

Chu, CGC, Murayama (2019)

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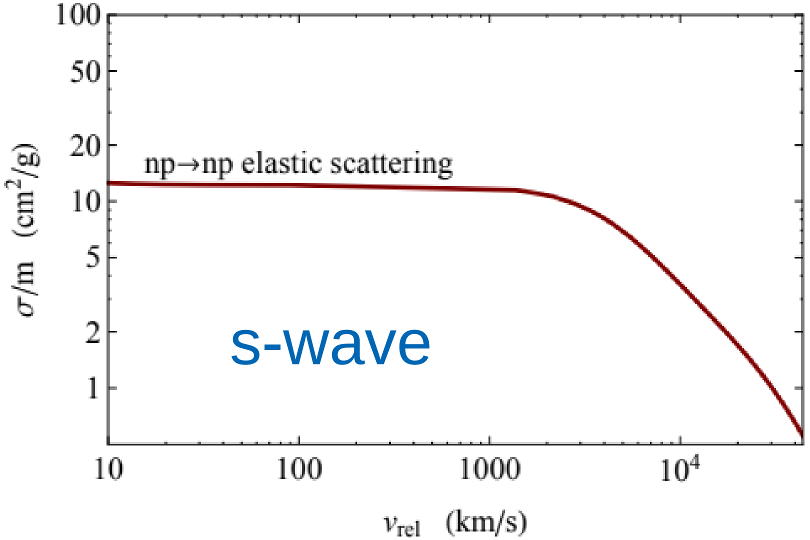

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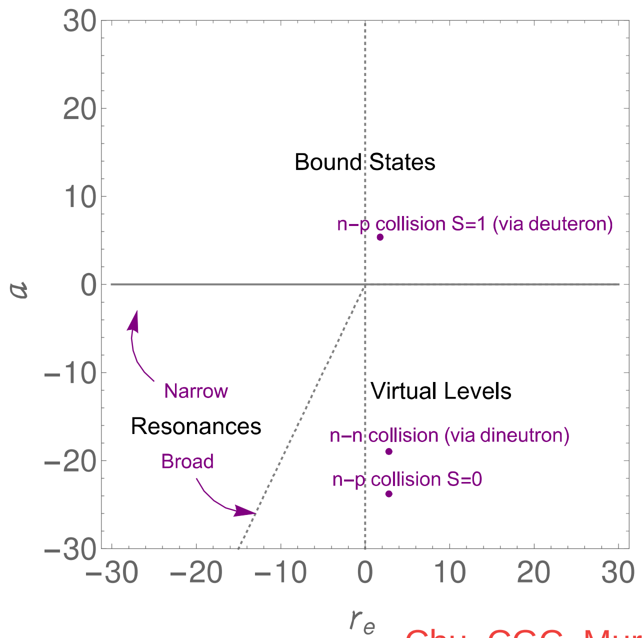

Chu, CGC, Murayama (2019)

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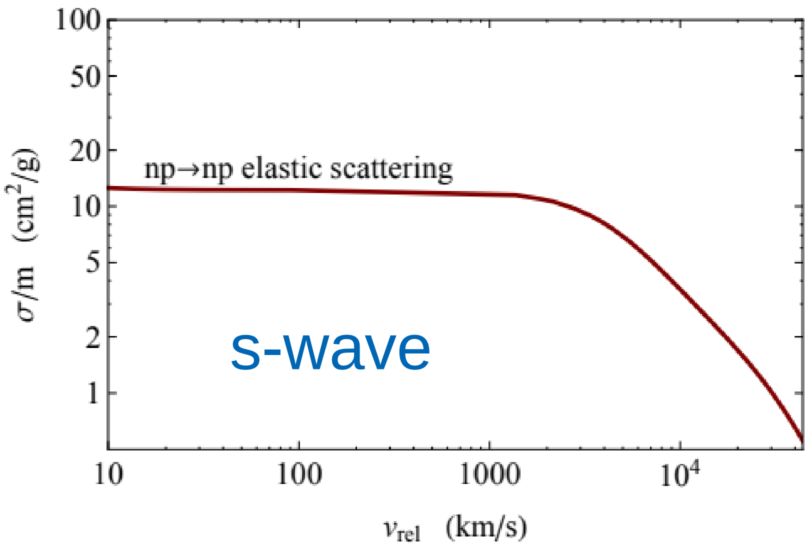
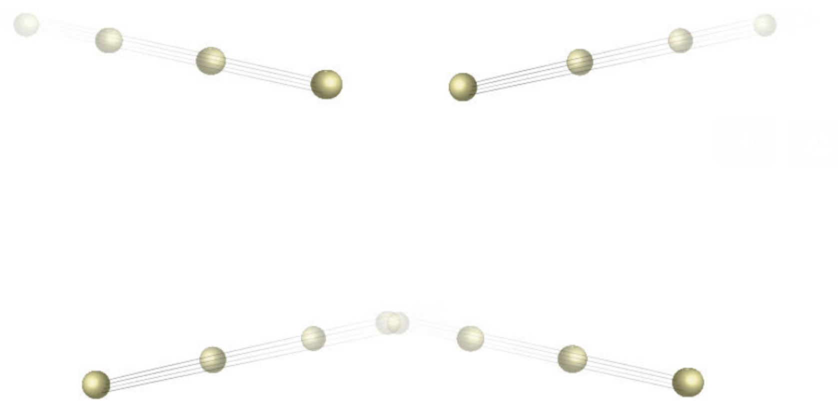


Resonant SIDM

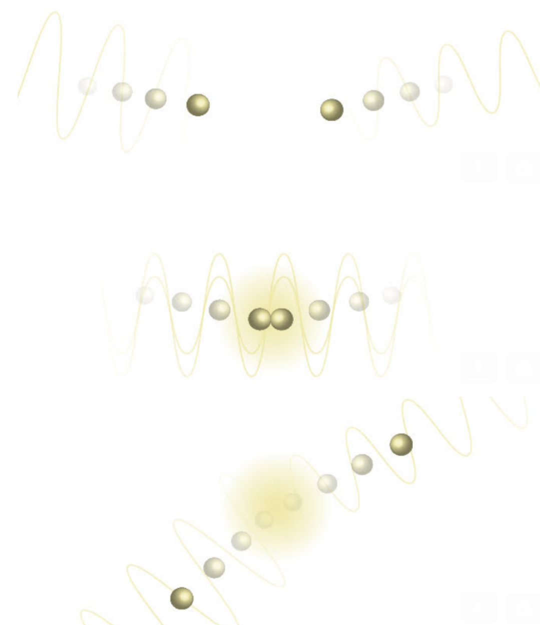
"Resonance is a phenomenon that appears every day. To swirl wine in a glass to get it more oxygen so that it lets out more aroma and softens its taste, you need to find the right speed to circle the wine glass. Or you dial old analog radios to the right frequency to tune into your favorite station" Murayama

https://www.ipmu.jp/en/20190227-DM_hittingNote

At clusters of galaxies



In galaxies



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,‡]

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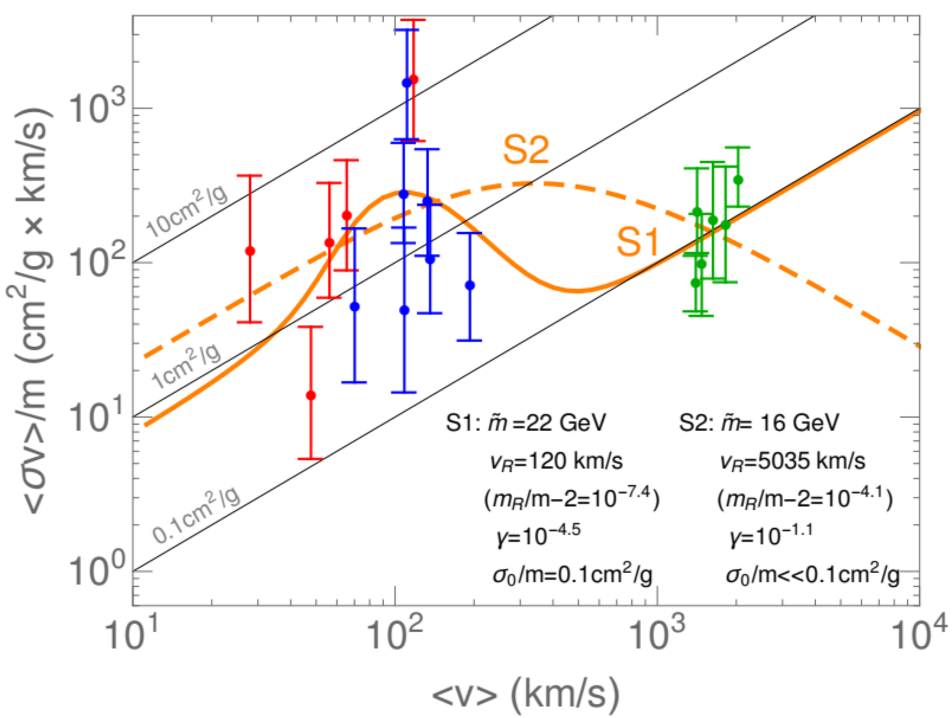

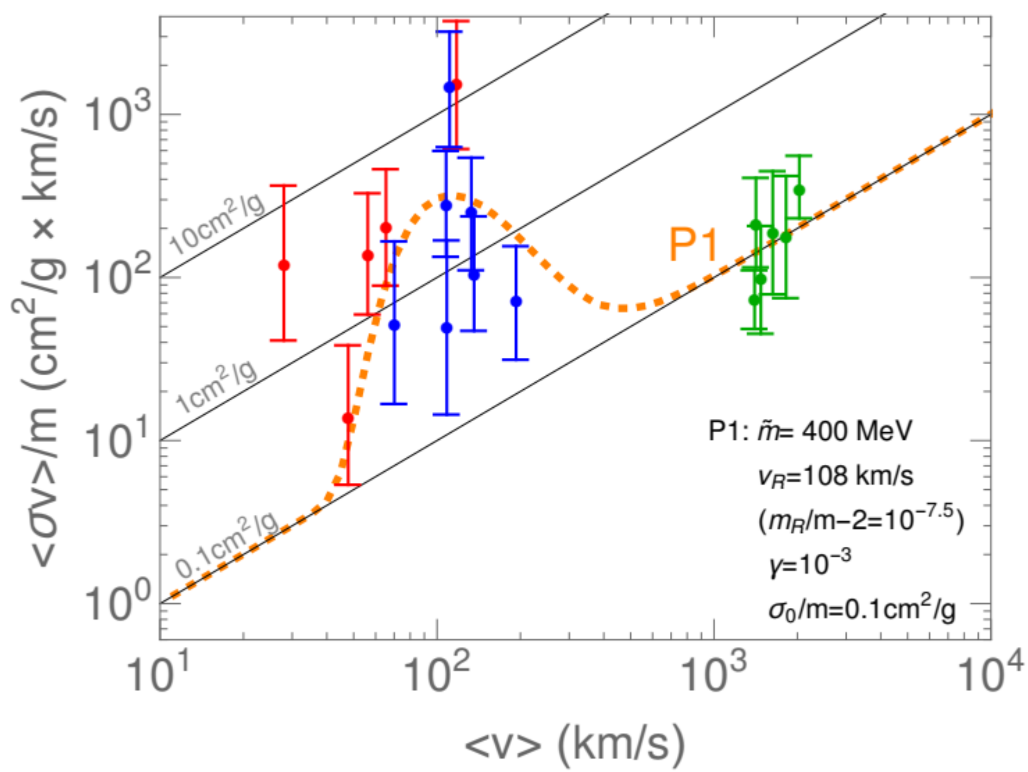

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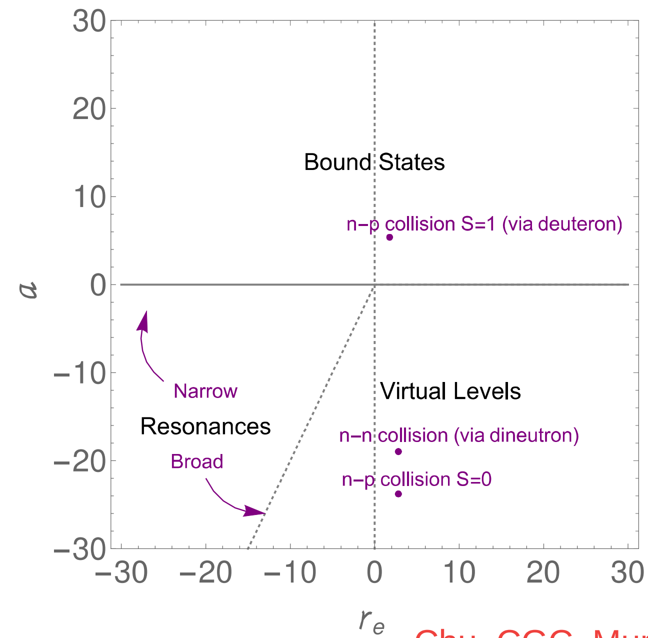

Chu, CGC, Murayama (2019)

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

A model of puffy dark matter

a QCD-like theory of dark matter

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

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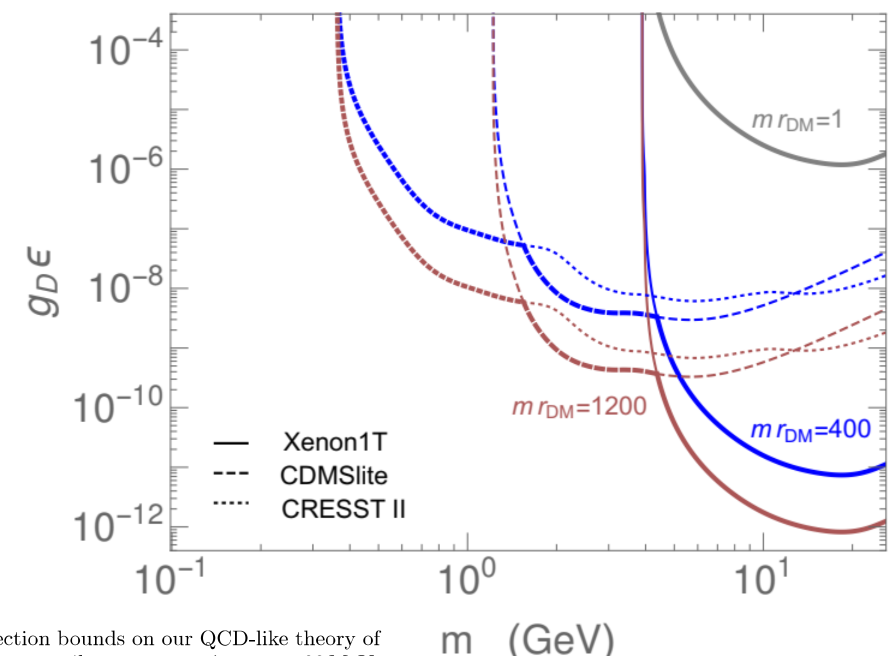
Chu, CGC, Murayama (2018)

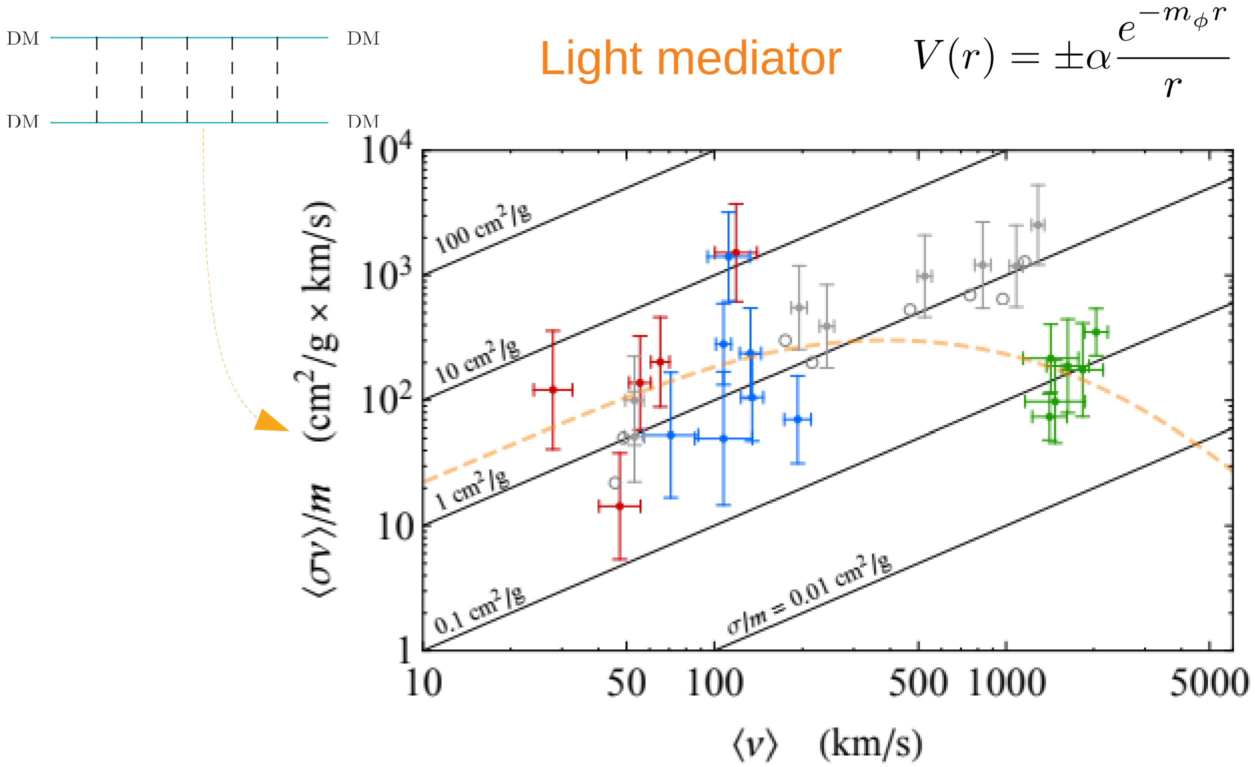
low-threshold direct detection experiments have the potential to probe Puffy Dark Matter.



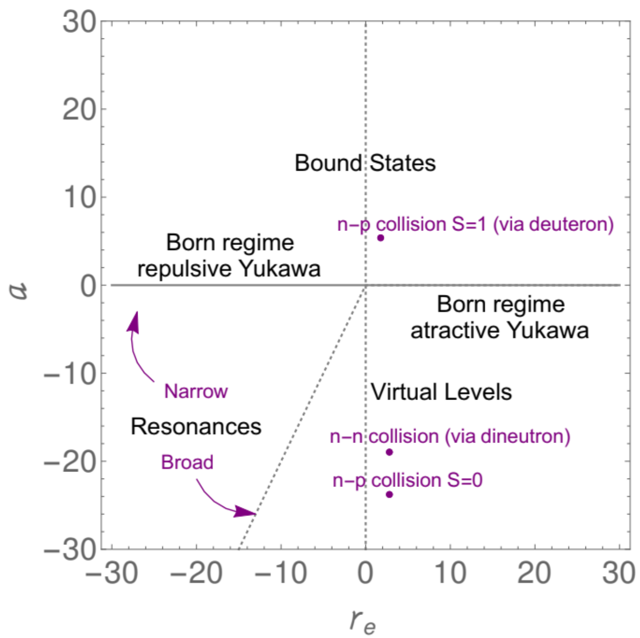
Direct detection bounds on our QCD-like theory of Puffy DM from nucleon recoil events assuming $m_{\gamma_D} = 20$ MeV. For a heavier dark photon, this bound scales with $m^2_{\gamma_D}$.

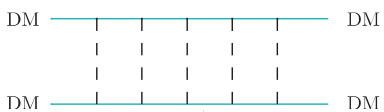
II. Dark matter forming bound states

Light mediator

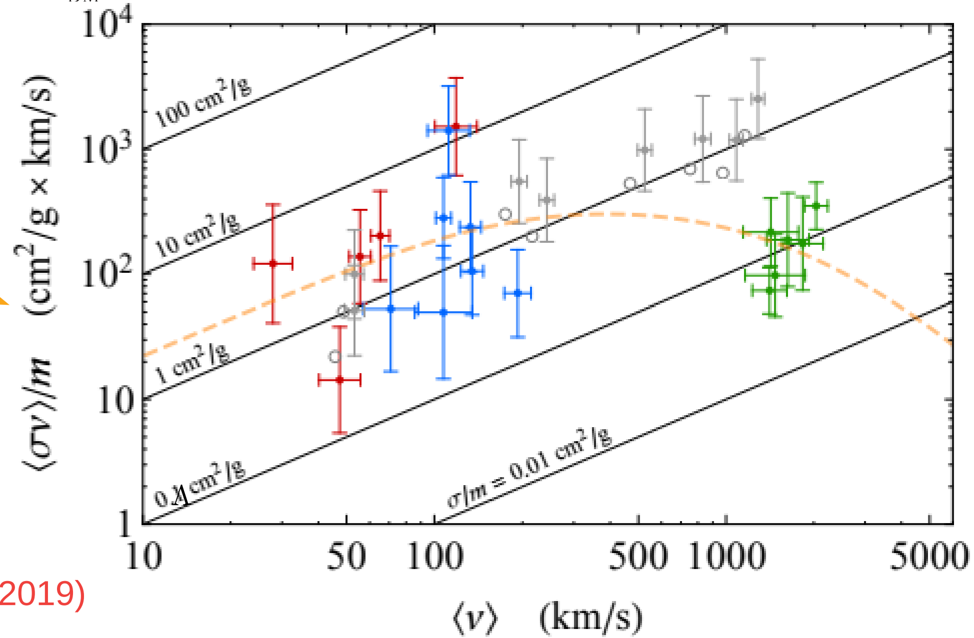


Light mediator

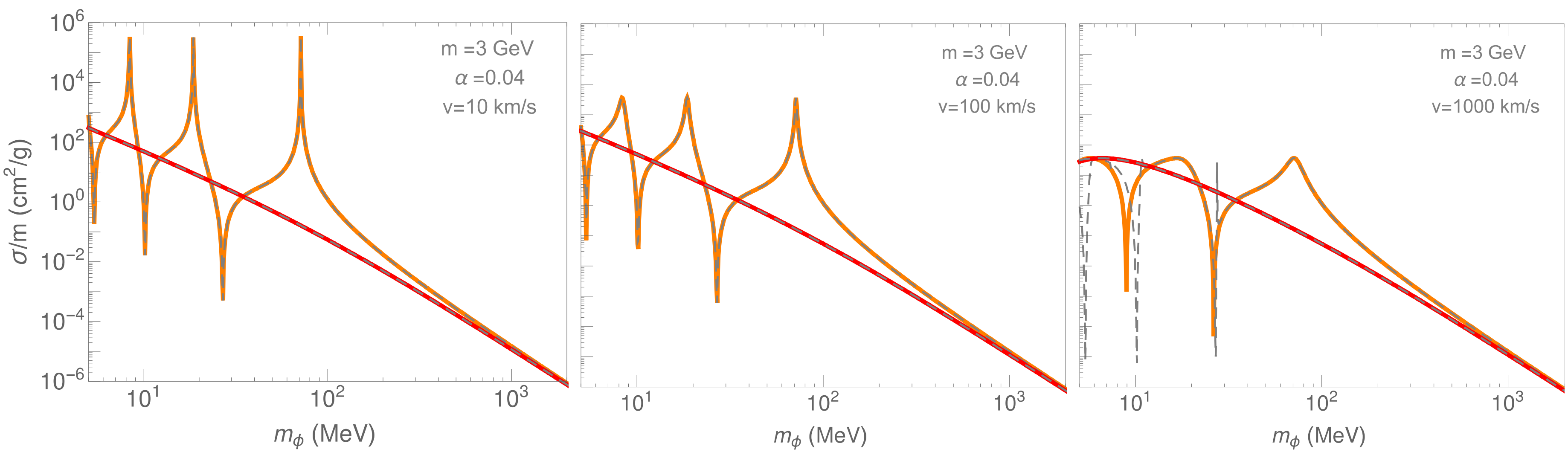




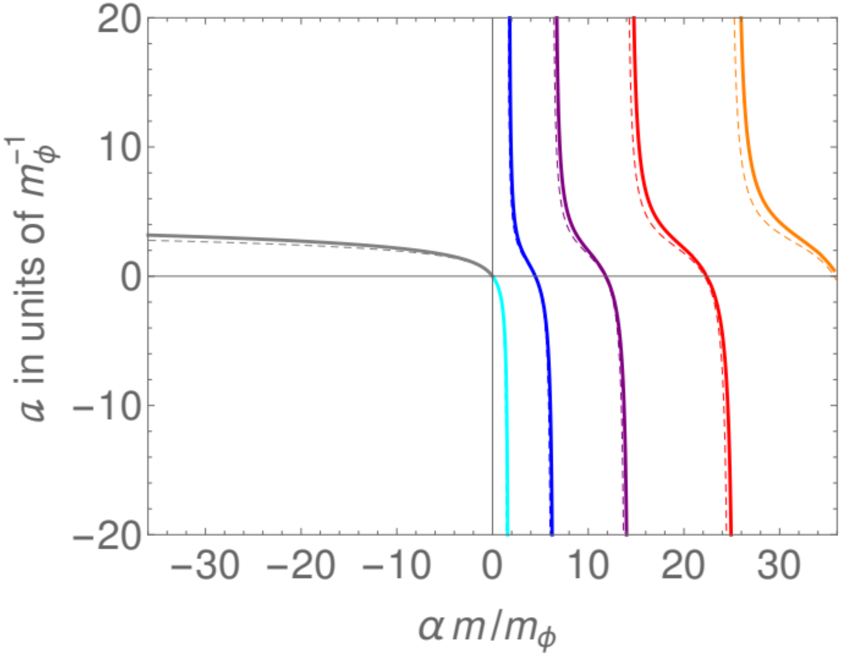
Light mediator $V(r) = \pm\alpha \frac{e^{-m_\phi r}}{r}$

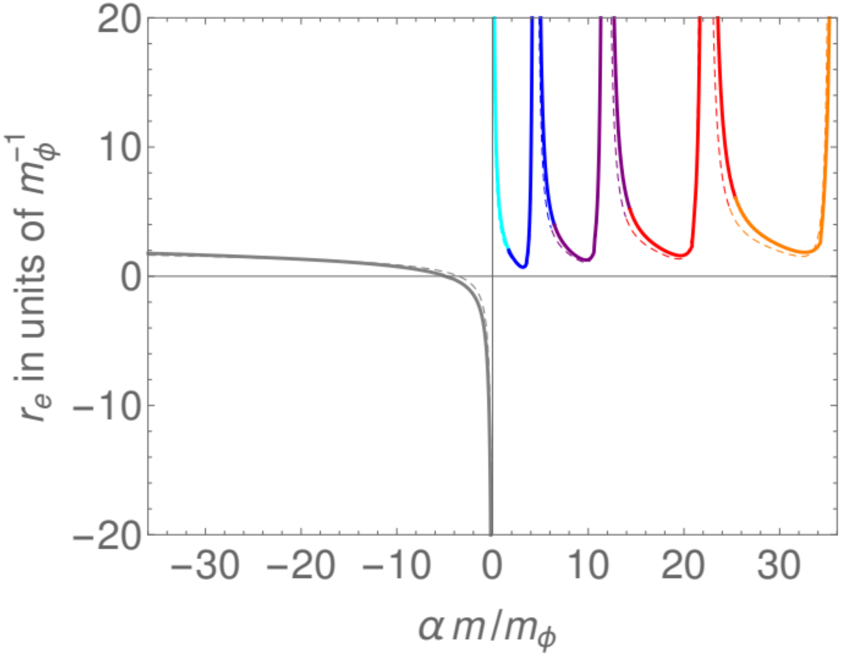


Chu, CGC, Murayama (2019)



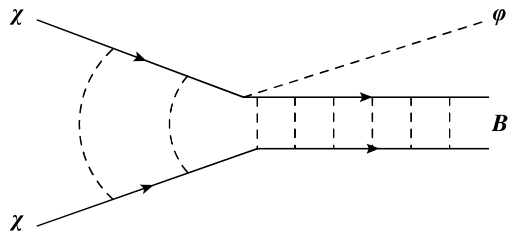
Bound states via a light mediator



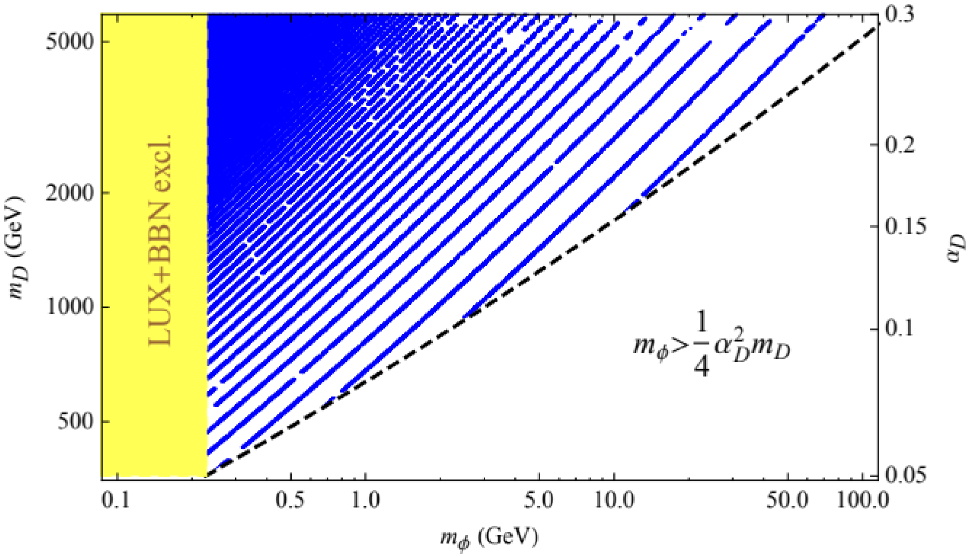


Chu, CGC, Murayama (2019)

Scalar mediator



Wise and Zhang (2016)



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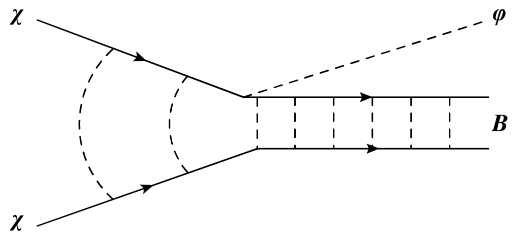

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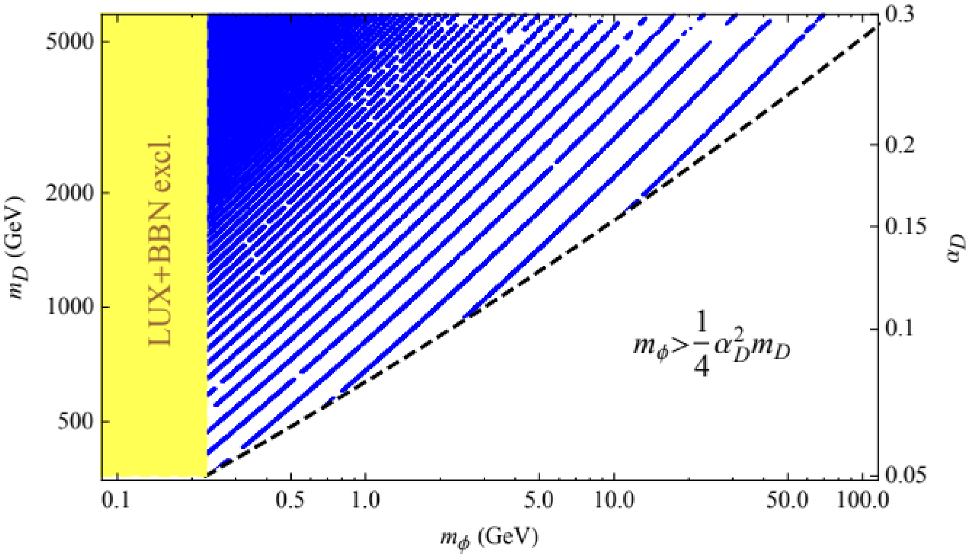

- *The Sun can capture dark matter and the bound state formation can happen in the Sun. Search for mediator decays.*
- *Neutron stars?*

Preliminary work

Chu, CGC and Garani

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.*

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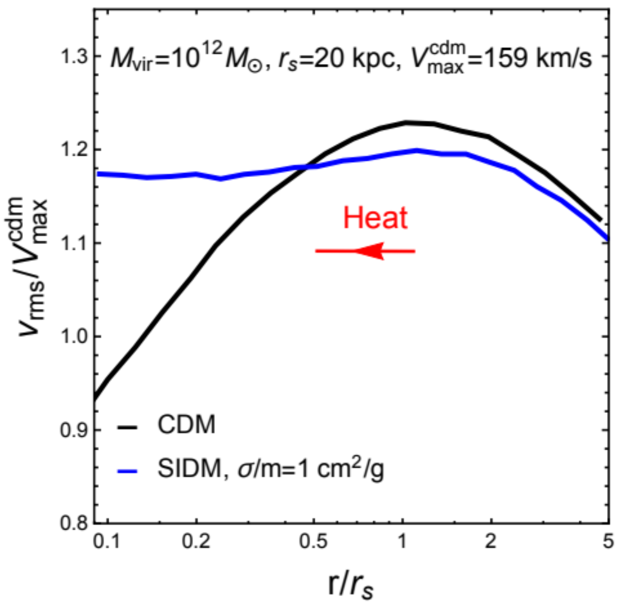
Thanks for your attention

How does self-interacting dark matter solve the problem?



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

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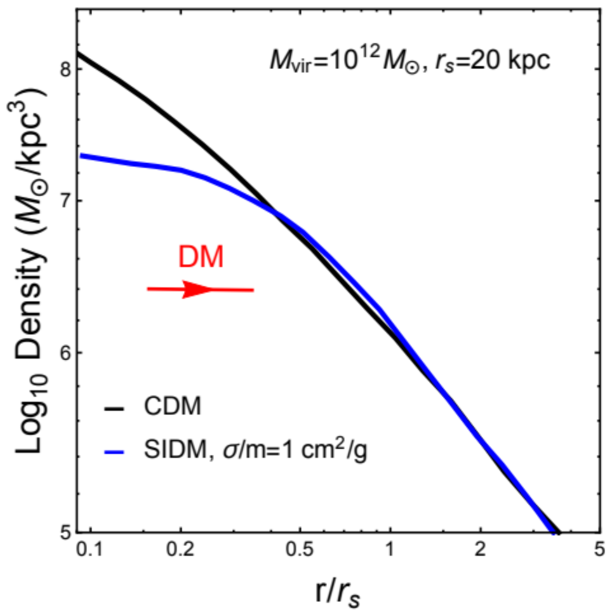

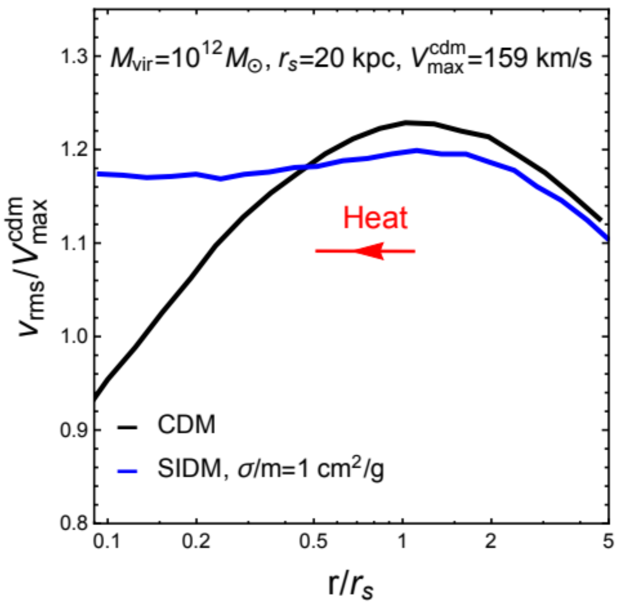

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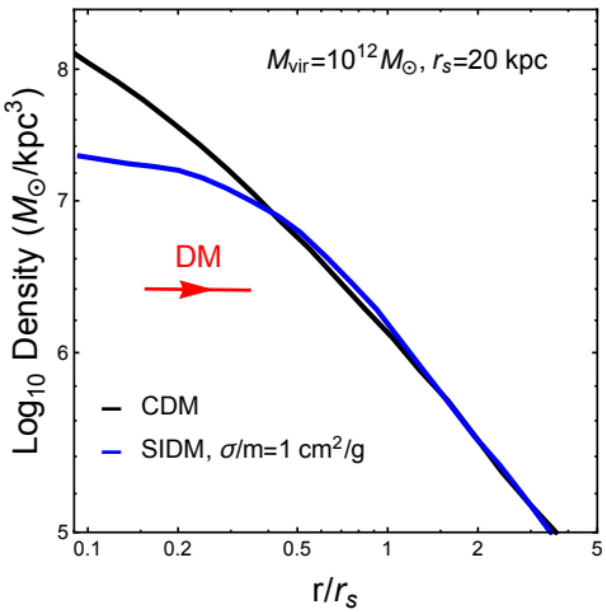

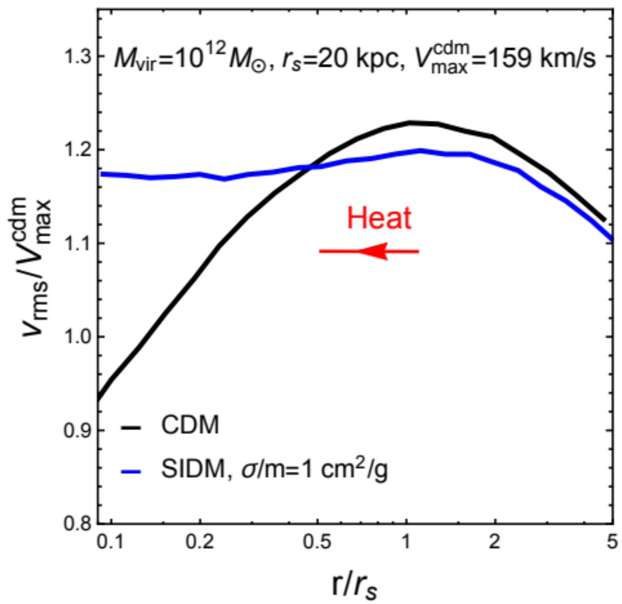

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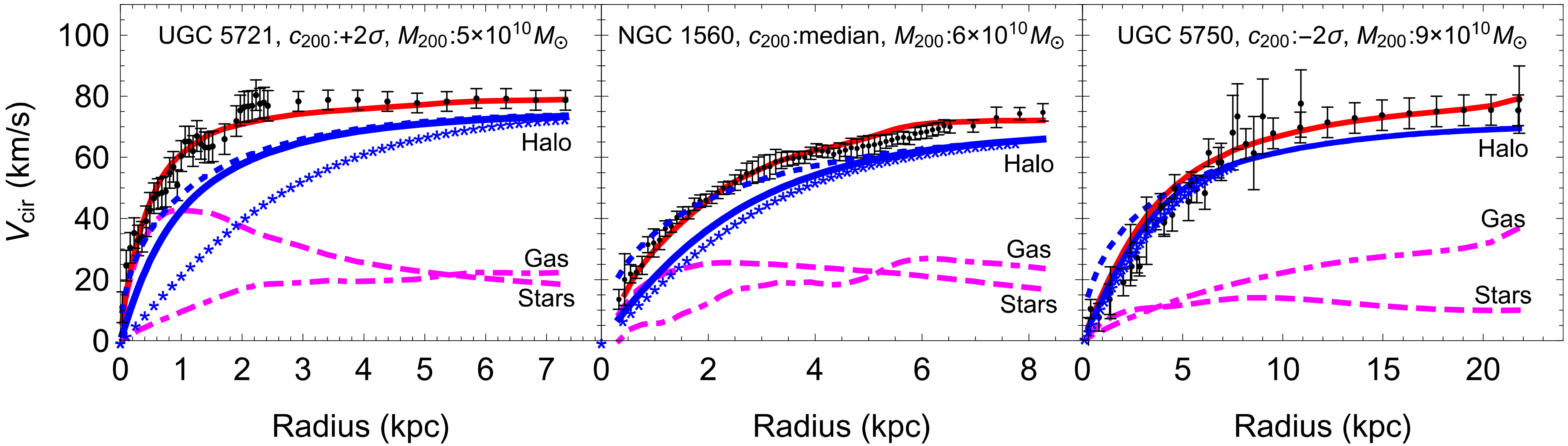

Kamada et al (2017)

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 $k = 0$

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

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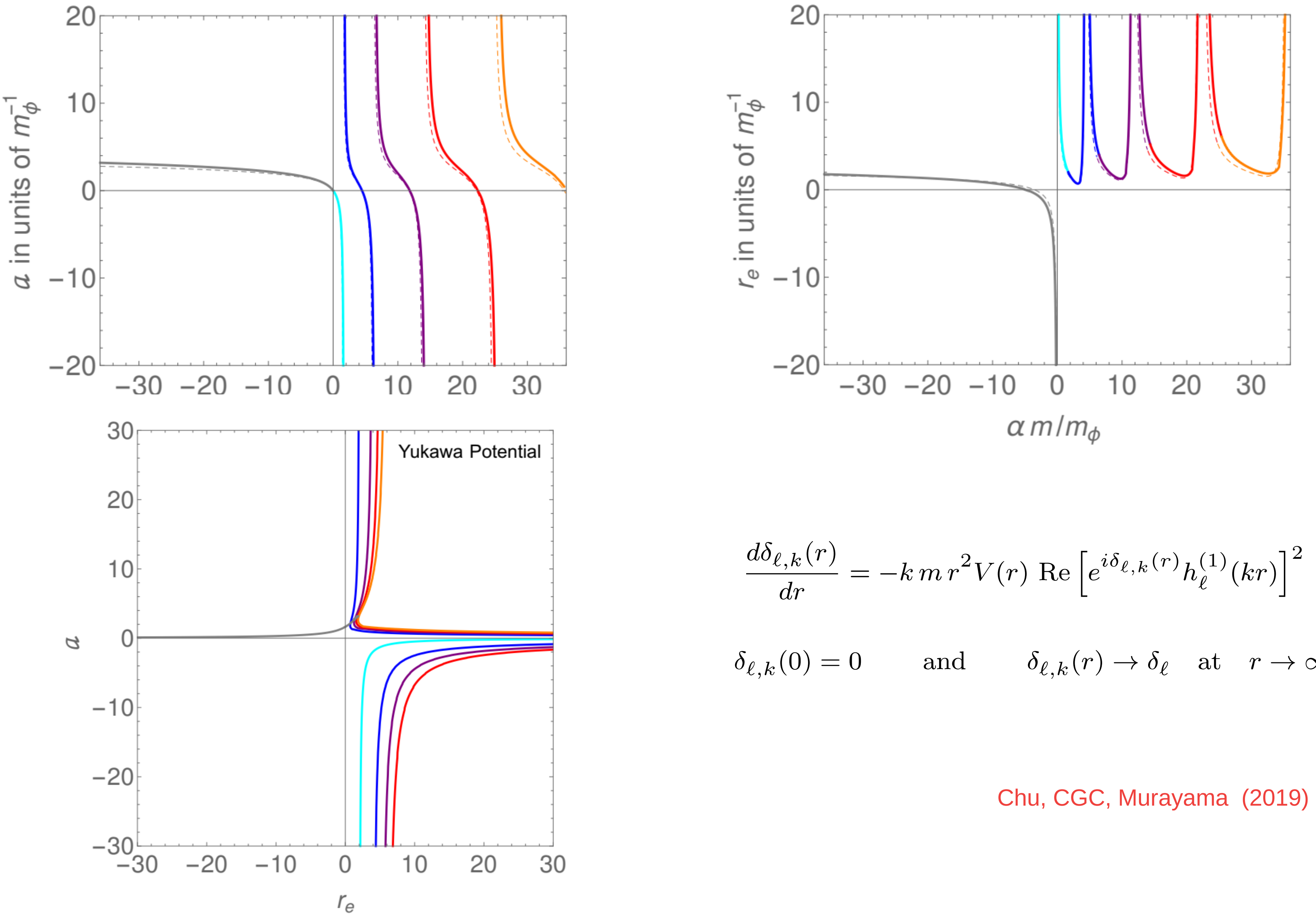

$$\frac{d\delta_{\ell,k}(r)}{dr} = -k\, m\, r^2 V(r)\ \mathrm{Re}\left[e^{i\delta_{\ell,k}(r)} h_\ell^{(1)}(kr)\right]^2$$

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

Chu, CGC, Murayama (2019)