Recent ideas for models of self-interacting dark matter

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DESY

European Research Council

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Max-Planck-Institut fuer Kernphysik
Heidelberg, May 27

Outline

1. Small-scale problems of the Lambda-CDM model

2. Dark Matter sectors with a light mediator

3. New ideas : resonant scattering and puffy dark matter

Based on

Production Regimes for Self-Interacting Dark Matter

Nicolas Bernal (ICTP-SAIFR, Sao Paulo & Sao Paulo, IFT), Xiaoyong Chu (ICTP, Trieste), Camilo Garcia-Cely, Thomas Hambye (Brussels U.), Bryan Zaldivar (Annecy, LAPTH & Brussels U.)

Oct 27, 2015 - 40 pages

JCAP 1603 (2016) no.03, 018
(2016-03-08)

Velocity Dependence from Resonant Self-Interacting Dark Matter

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

Oct 10, 2018 - 8 pages

Phys.Rev.Lett. 122 (2019) no.7, 071103
(2019-02-22)

Puffy Dark Matter

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

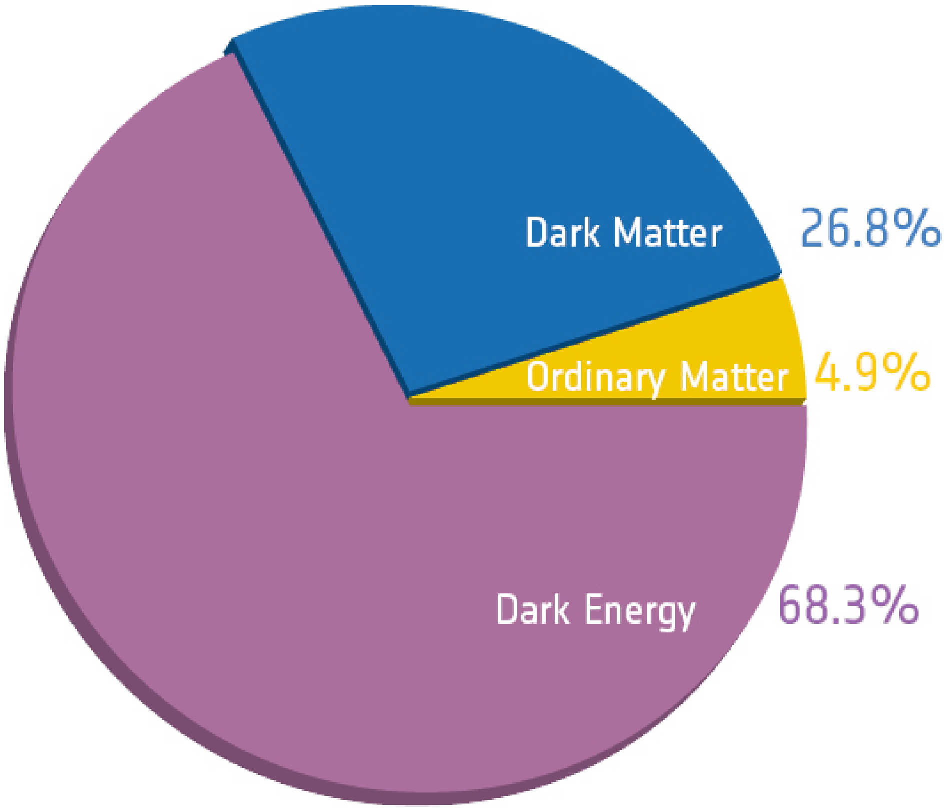
Dec 31, 2018 - 7 pages

DESY-18-225, IPMU18-0207
e-Print: arXiv:1901.00075 [hep-ph] | PDF

Small-scale problems

Lambda Cold Dark Matter model

Energy budget of the Universe



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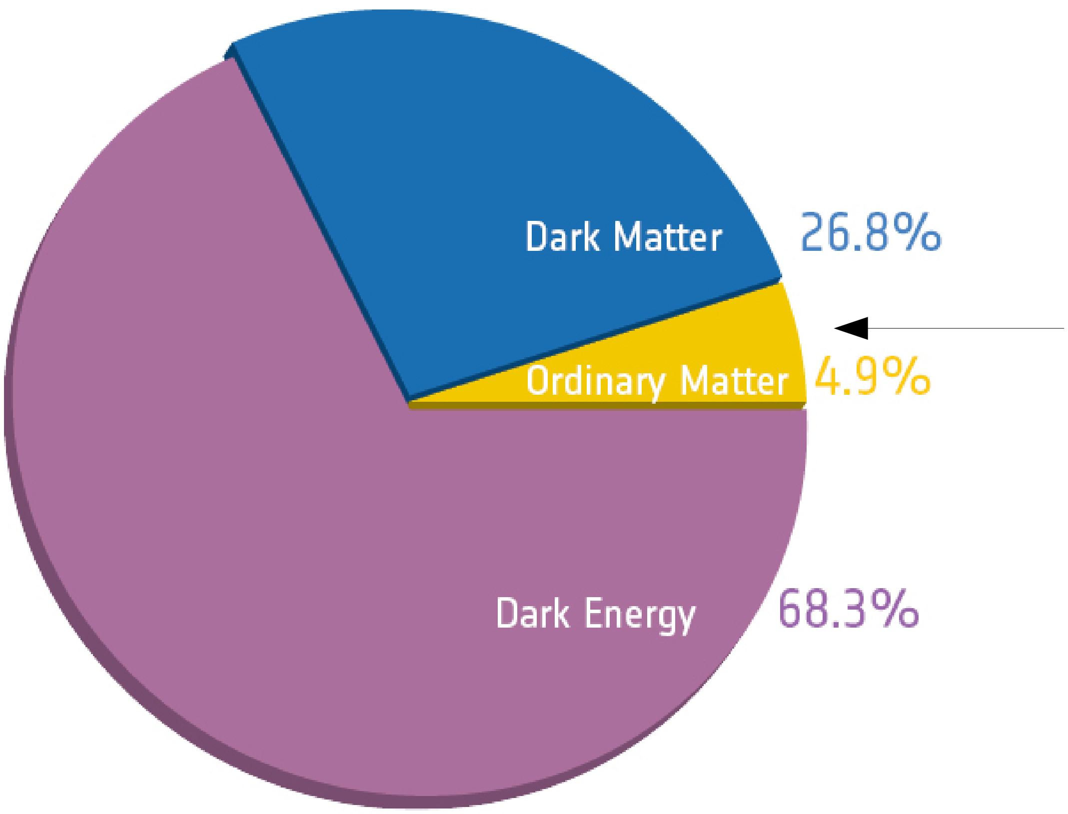

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Mostly protons, electrons, neutrinos and photons.

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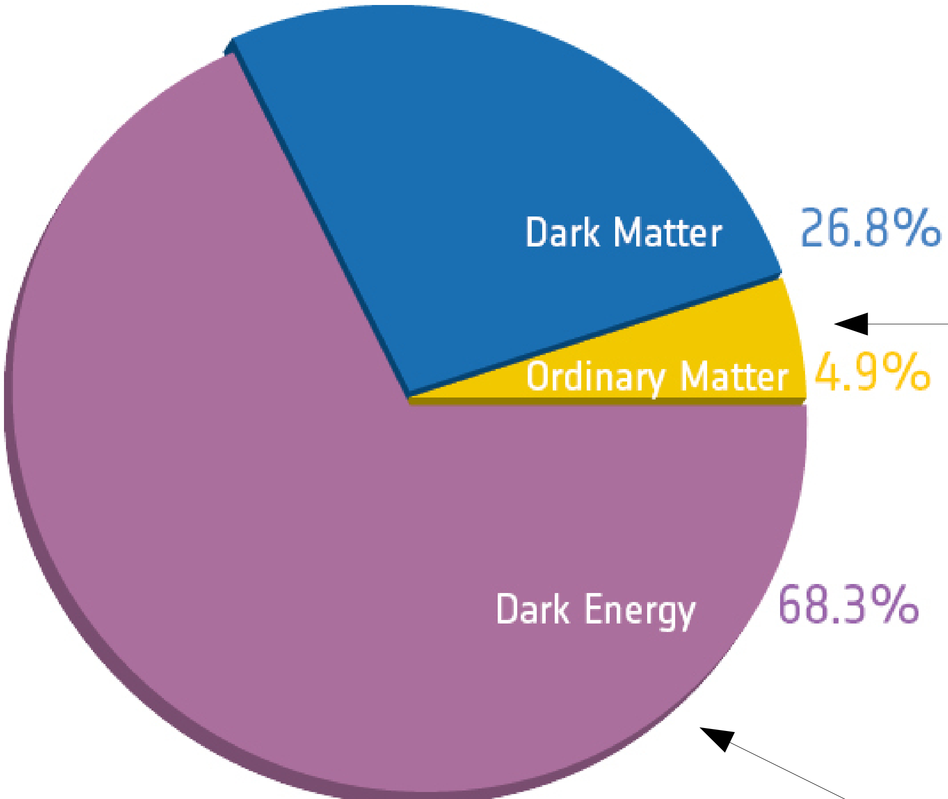

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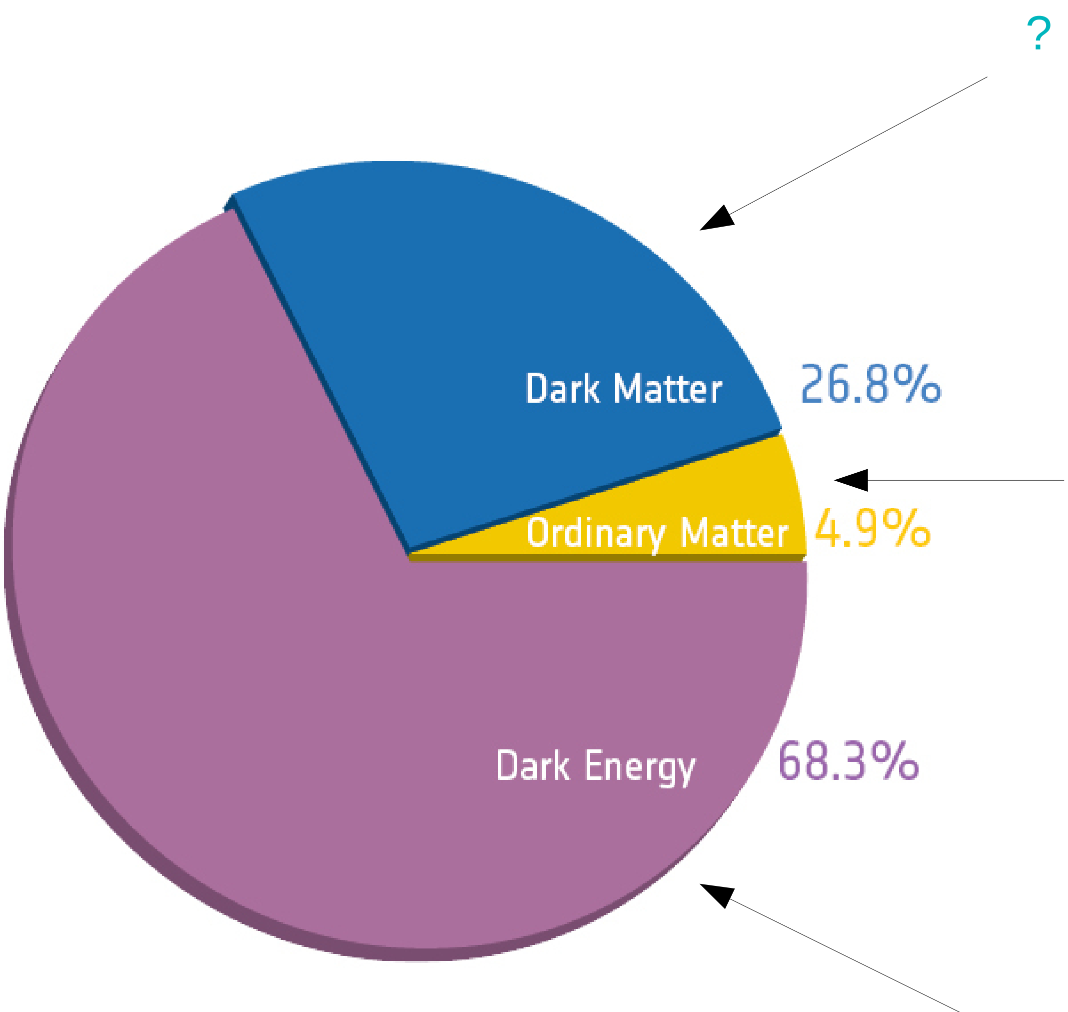

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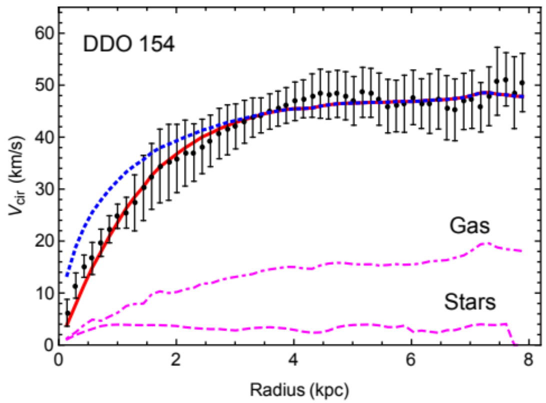
Evidence of Dark Matter



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

- Weak lensing by large-scale structure and cluster mergers
- Strong lensing by individual galaxies and clusters (SN Refsdal!)

Universe at large scales

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

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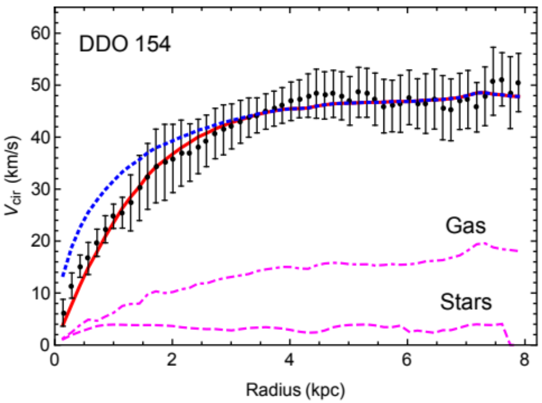

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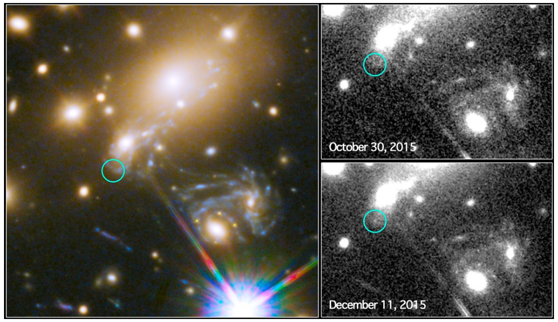

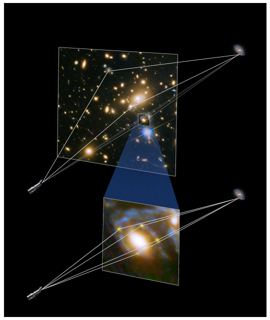

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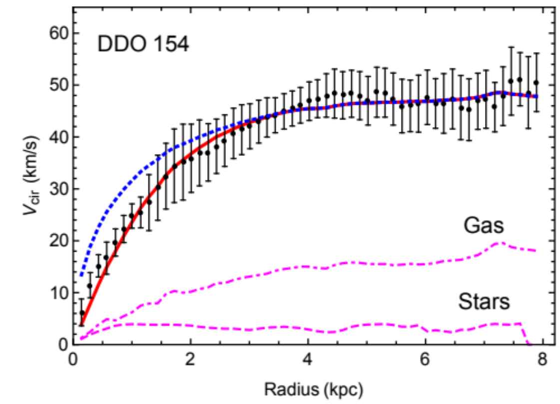

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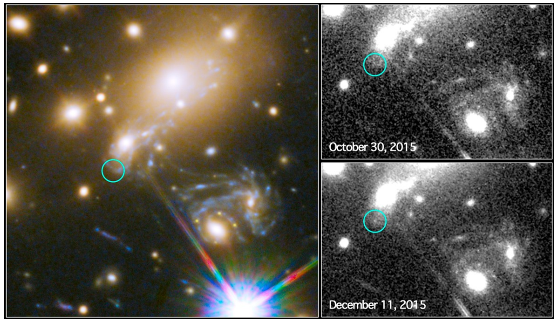

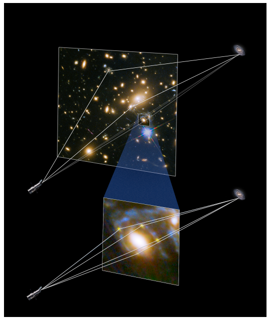

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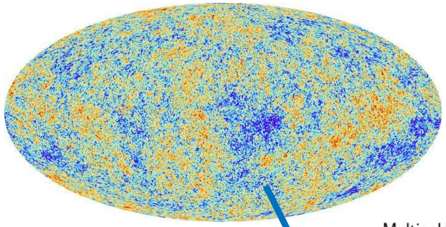

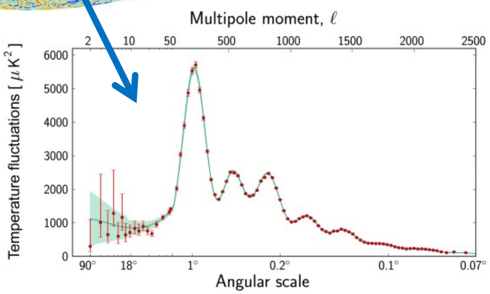

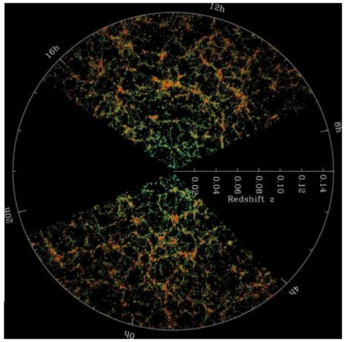

THE ASTROPHYSICAL JOURNAL, 648:L109–L113, 2006 September 10

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

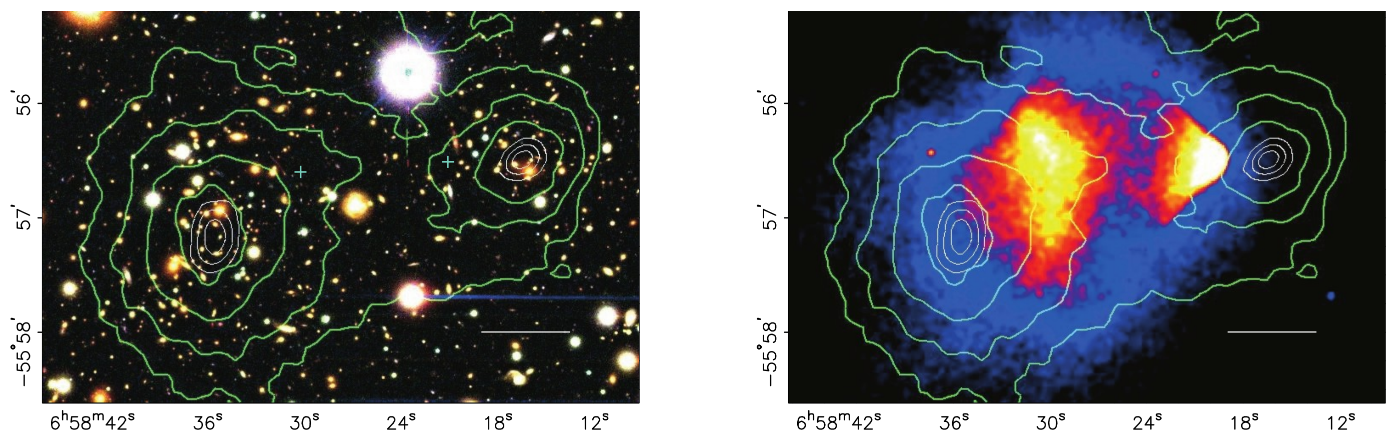

FIG. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with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

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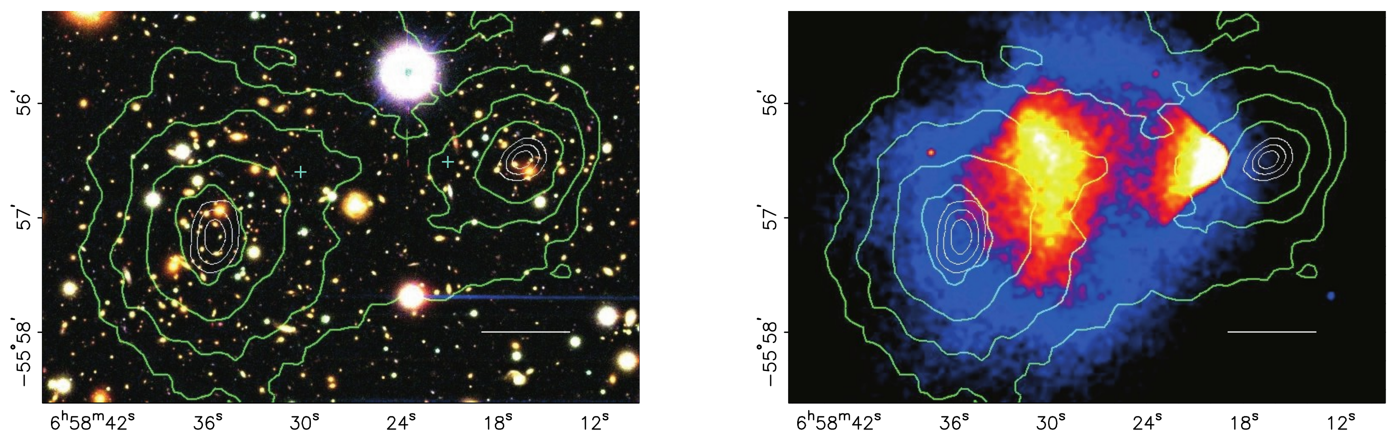

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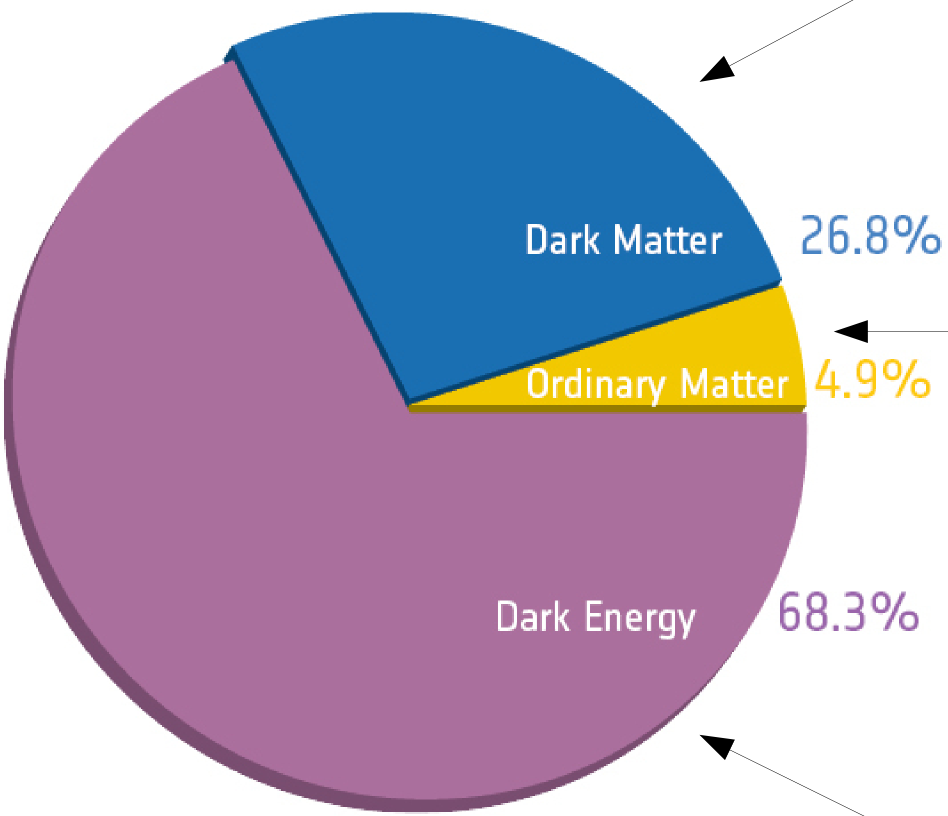

Collisionless Cold Dark Matter

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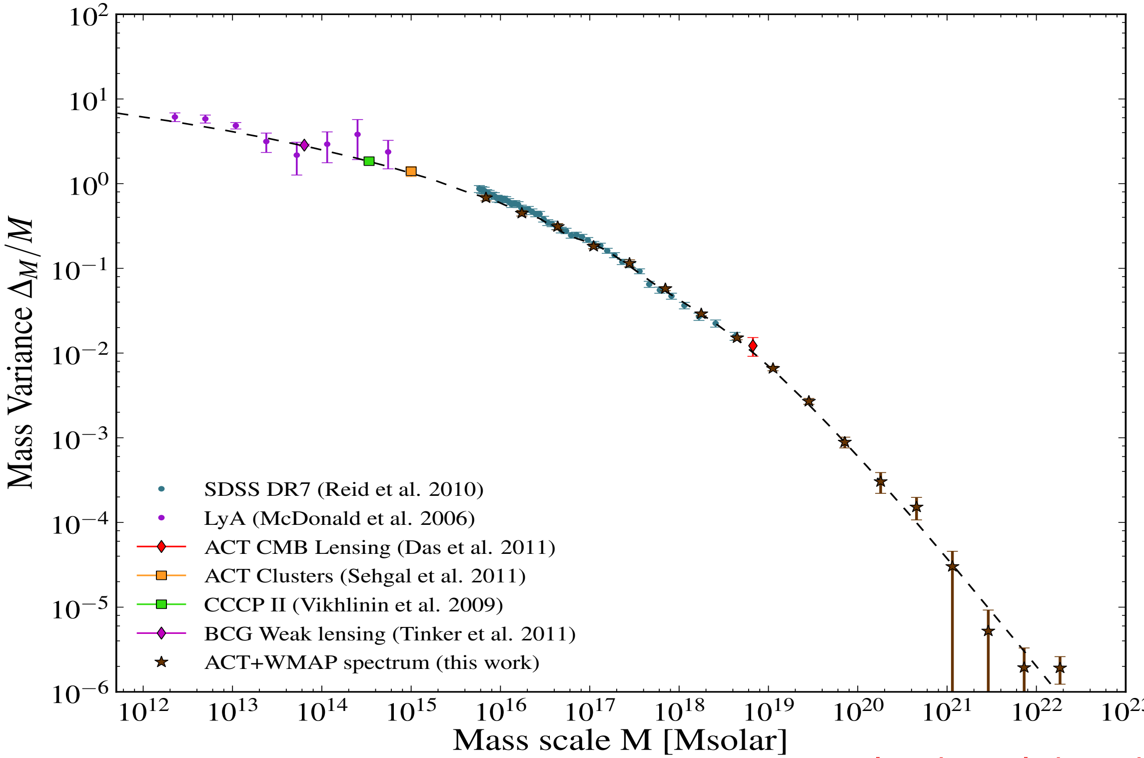
Remarkably successful
at large scales

At low scales
N-body simulations
are needed



Hlozek et al. (2012)

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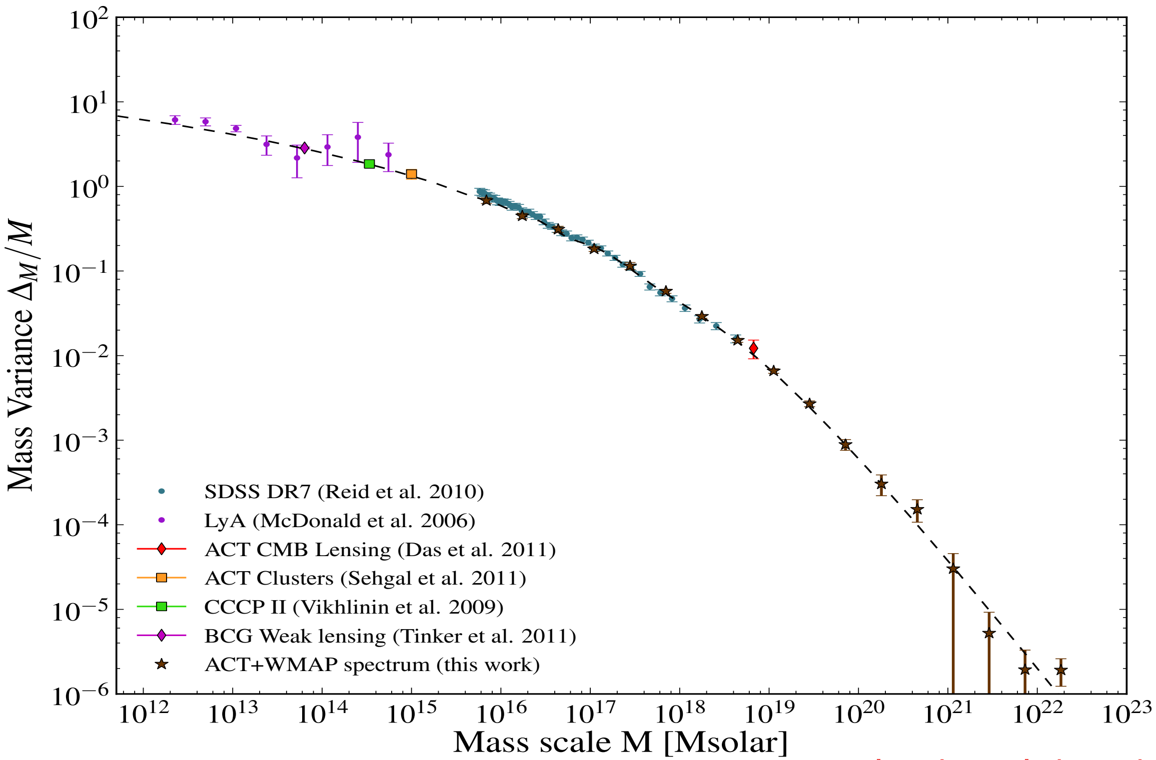


Hlozek et al. (2012)

Mass deficits at galactic scales

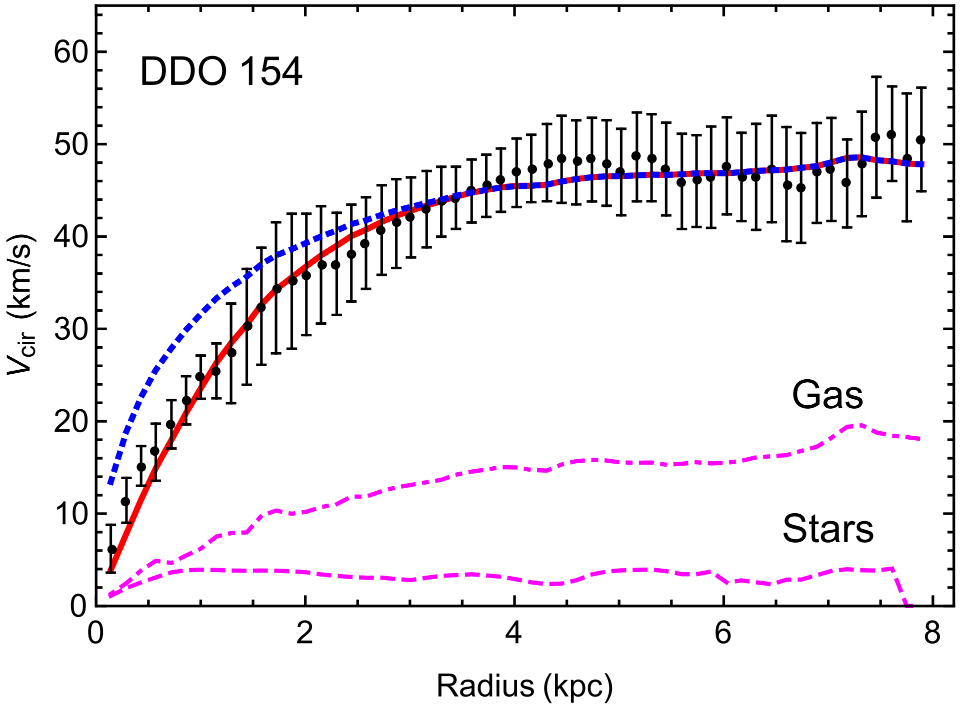
- Core vs. cusp problem
- Diversity problem
- Too-big-to-fail problem
- Missing satellites

Heated debates!!!

Core vs. cusp problem

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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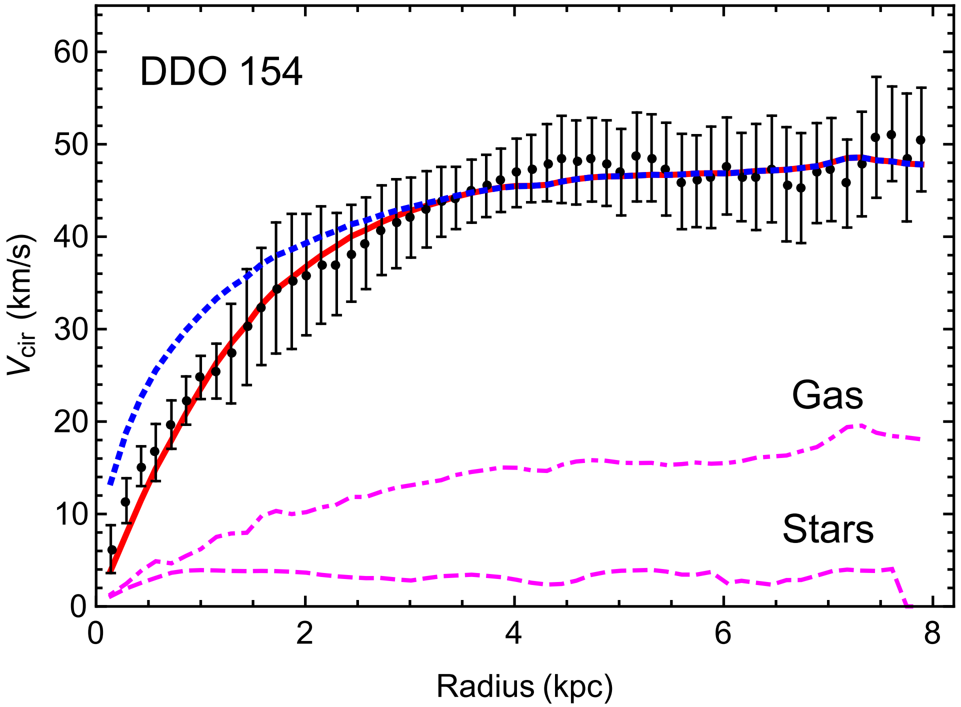
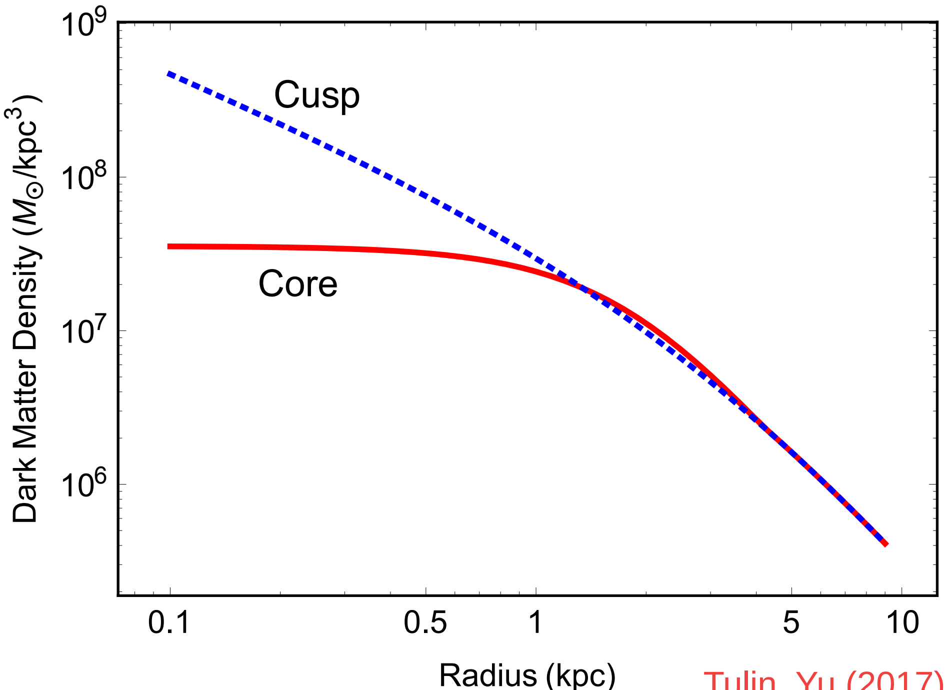




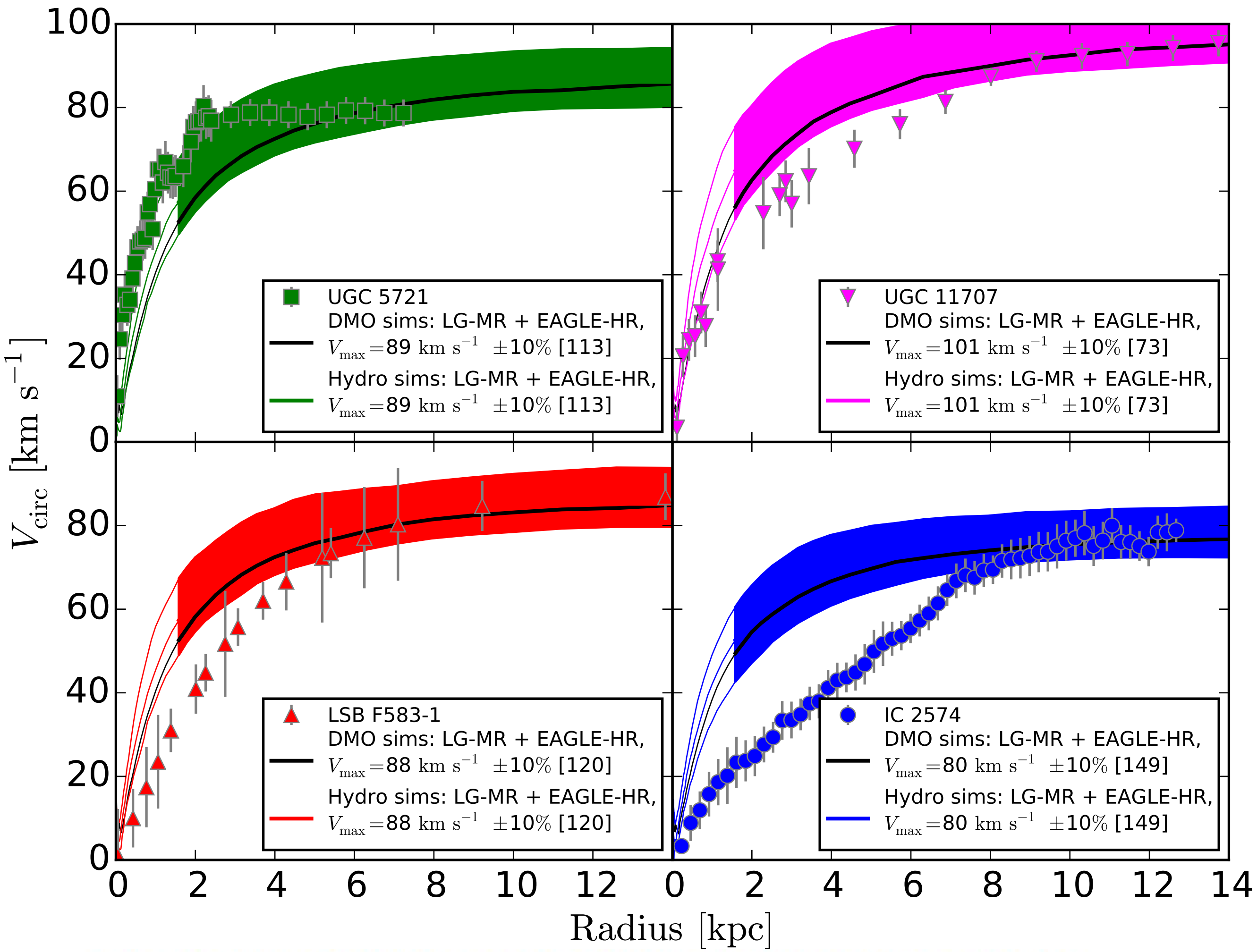
Tulin, Yu (2017)

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

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

Diversity Problem

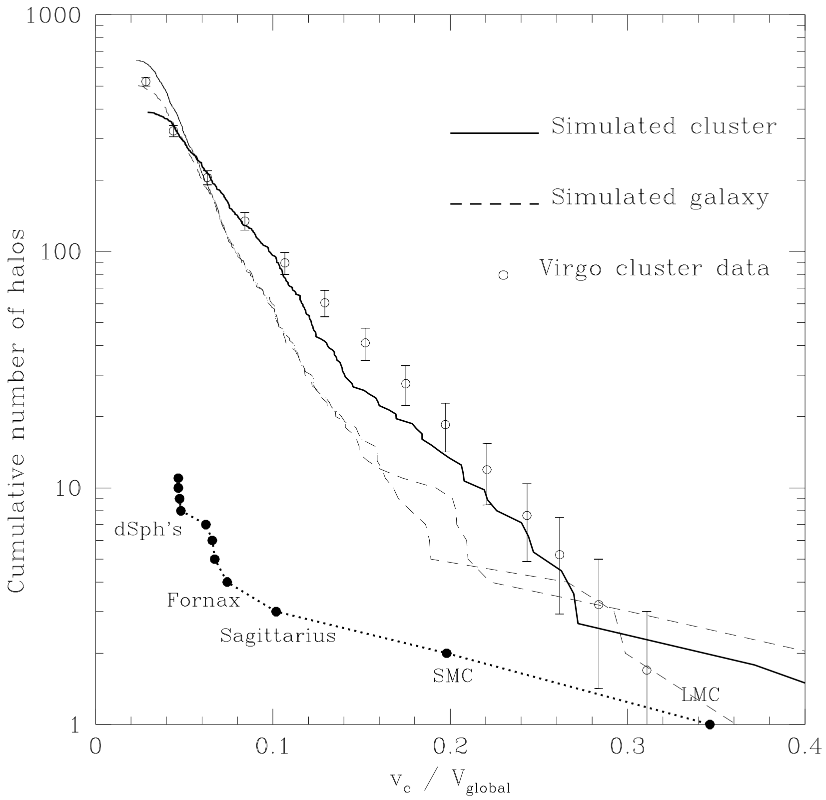
Cosmological structure formation is predicted to be a self-similar process with a remarkably little scatter in density profiles for halos of a given mass. However, disk galaxies with the same maximal circular velocity exhibit a much larger scatter in their interiors and inferred core densities vary by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

Missing Satellites

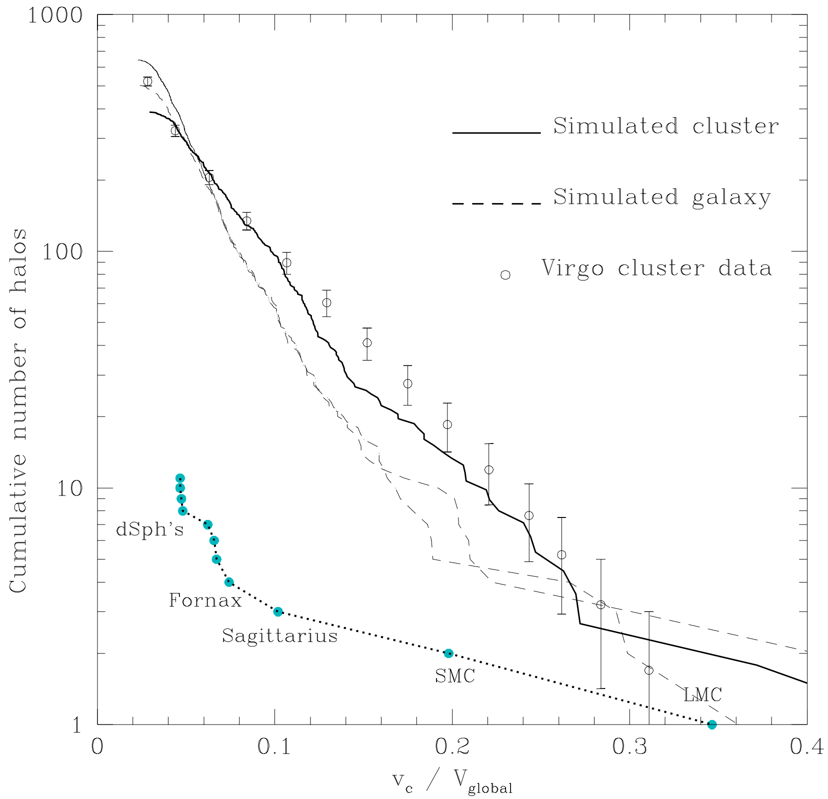


Moore et al (1999)

Simulations of the Milky Way predict a large number of subhalos that are not observed

Missing Satellites

Too-Big-To-Fail Problem



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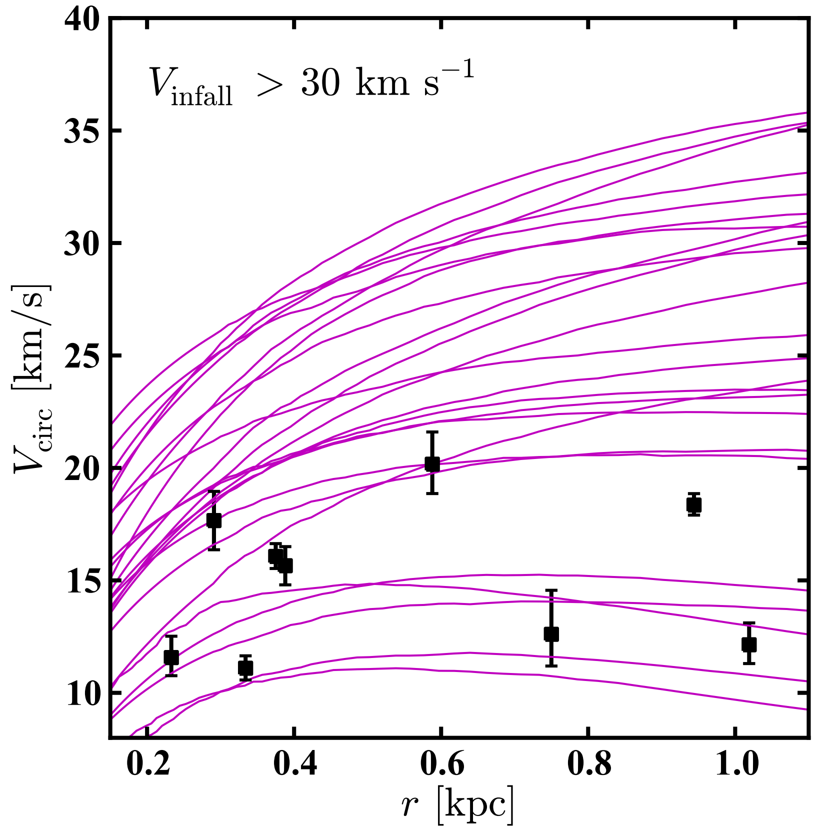

Simulations of the Milky Way predict a large number of subhalos that are not observed

Simulations of the Milky Way predict subhalos too massive and too dense to host the brightest observed satellites

Boylan-Kolchin et al.(2011)
Ferrero et al. (2014)

Debate

Astrophysical possible solutions:

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

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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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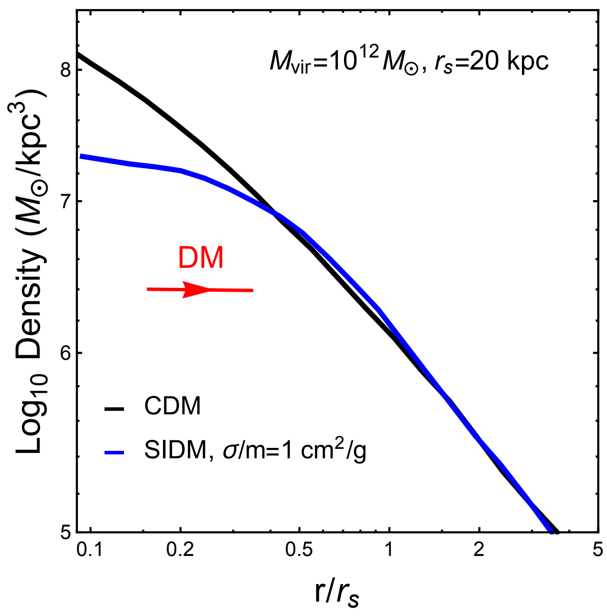
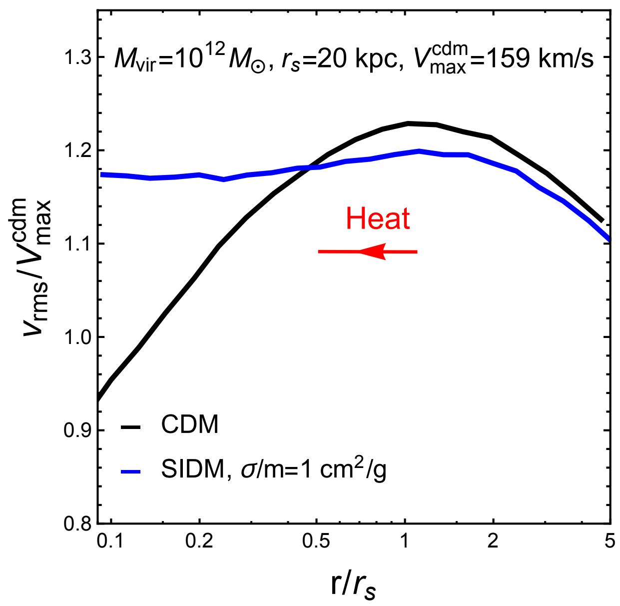
Simulations show that this is indeed a solution

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)

Self-interacting Dark Matter (SIDM)





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

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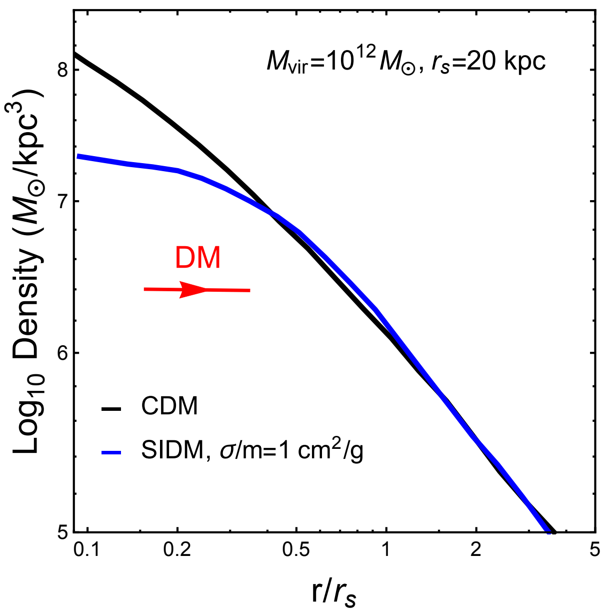

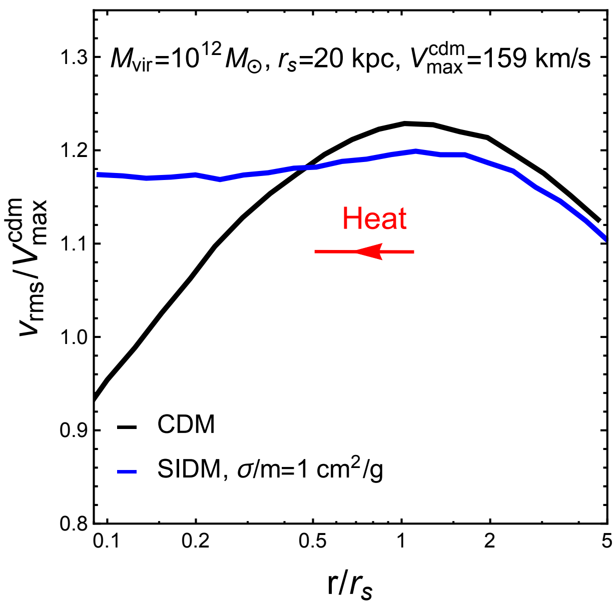

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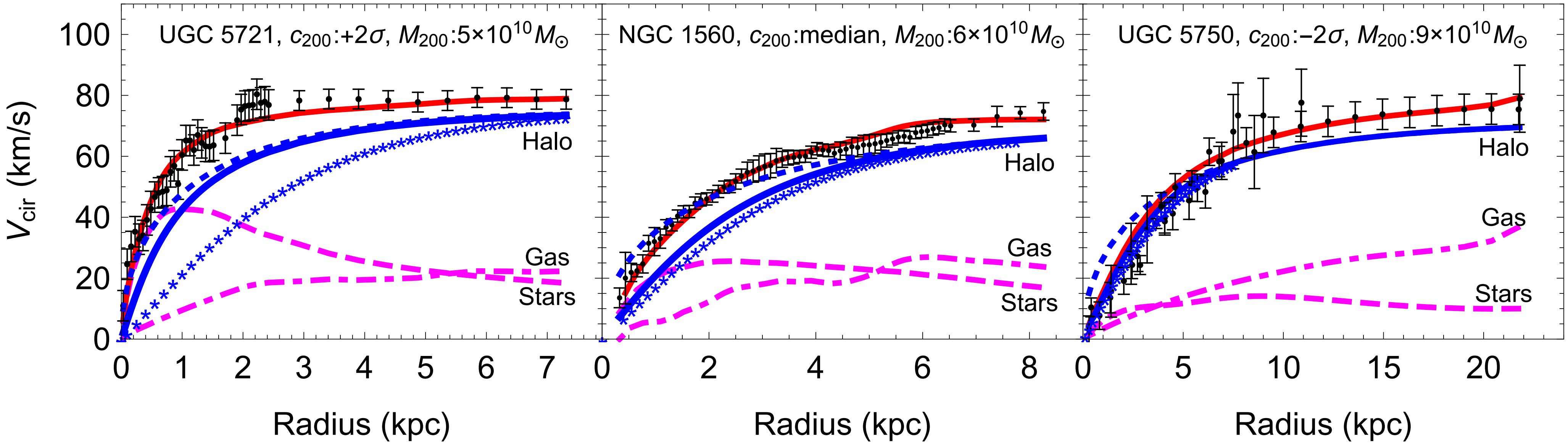


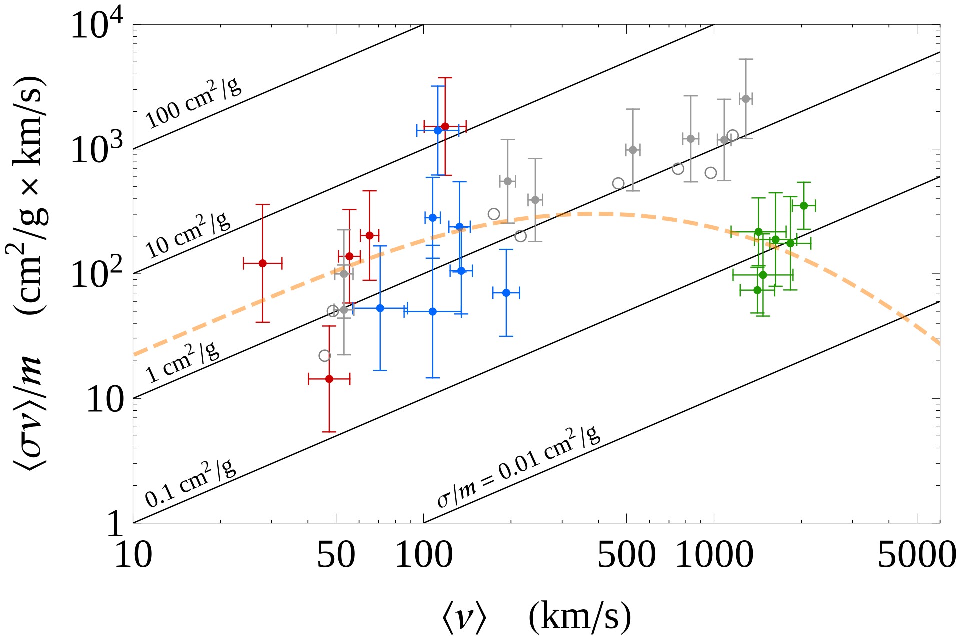
Kamada et al (2017)

$$\rho_0 \exp[-\Phi_{\rm tot}(\vec{r})/\sigma_{\rm v0}^2]$$

Cross sections

Dark matter halos as particle colliders

Kaplinghat ,Tulin, Yu (2017)



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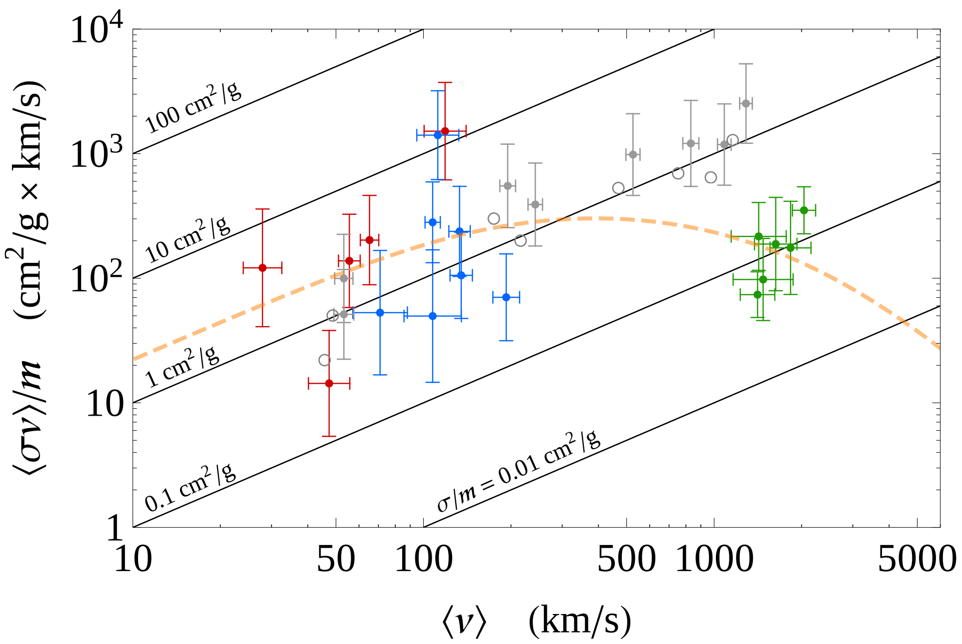
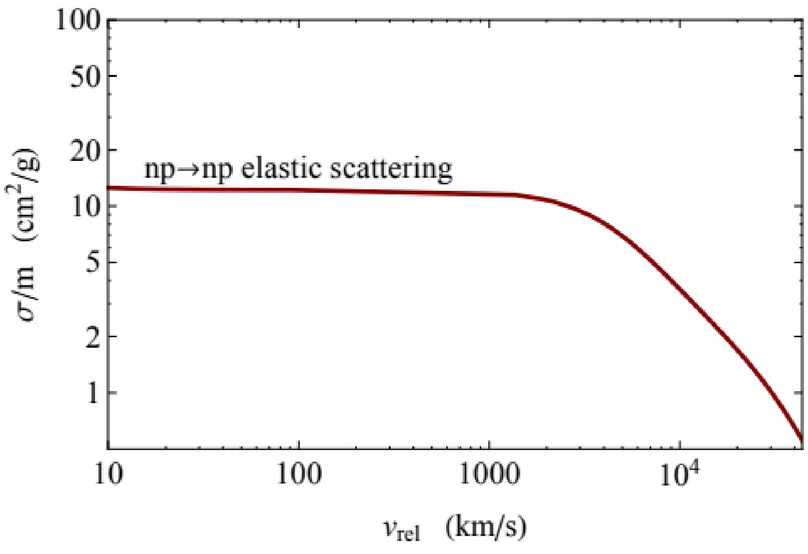


Tulin, Yu (2017)

How does that compare to nucleon-nucleon collisions?



Similar processes found in nature

- scattering of nucleons
  $\rightarrow$ pions act as light mediators.
- scattering of alpha particles

  $$He\,He \rightarrow Be \rightarrow He\,He$$

  $\rightarrow$ Resonant scattering.
- Inelastic scatterings

  $\rightarrow$ Exothermic reactions

SIDM models with light mediators

Light mediators

Solution to small-scale problems: $\frac{\sigma_{\text{SI}}}{m_{\text{DM}}} \sim 0.1 - 10\,\text{cm}^2/\text{g}$

$$\sigma_{\text{SI}} \sim 10^{11}\text{-}10^{13} \text{ pb for } m_{\text{DM}} \sim 1\,\text{GeV}$$

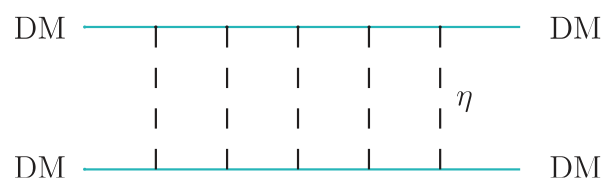
If $\sigma v_{\text{annihilation}} \sim 1$ pb : $\Omega_{\text{DM}} h^2 \sim 0.1$ (WIMP miracle)
If $\sigma v_{\text{annihilation}} \sim \sigma_{\text{SI}}$: $\Omega_{\text{DM}} h^2 \ll 1$

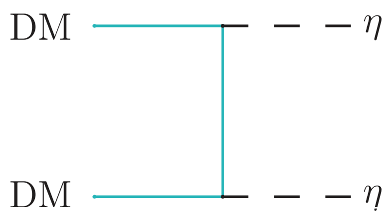
Keep pb cross sections in the Early Universe but enhance the interactions in DM halos today

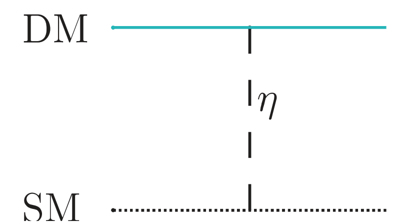
- Invoke a light mediator and consider non-perturbative effects

Light mediators

Light mediator η $\begin{cases} \text{Long-range forces} \\ \text{Freeze-out via } \sigma v_{\text{ann}} \sim 3 \times 10^{-26} \text{cm}^3/\text{s} \end{cases}$







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 example

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$SU(2)_X$
H	1	2	$\frac{1}{2}$	0
ϕ	1	1	0	2
A'_μ	1	1	0	3

Local $SU(2)_X$	$\rightarrow$	Global $SO(3)$	
Gauge Fields A'_μ	$\rightarrow$	Massive Fields A_μ	Stable (DM Candidate)
Doublet ϕ	$\rightarrow$	Higgs-like η	It mixes with the Higgs

Hambye (JHEP 2009)

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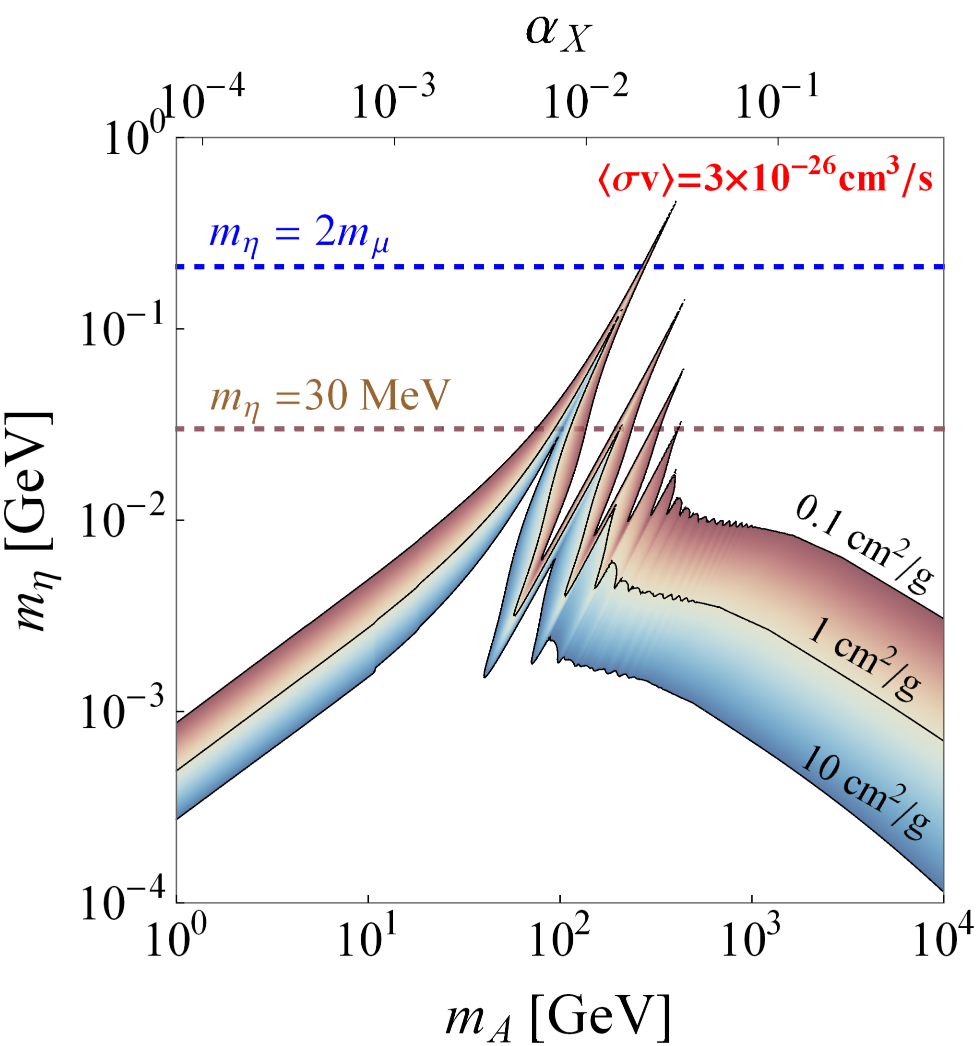
Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$SU(2)_X$
H	1	2	$\frac{1}{2}$	0
ϕ	1	1	0	2
A'_μ	1	1	0	3

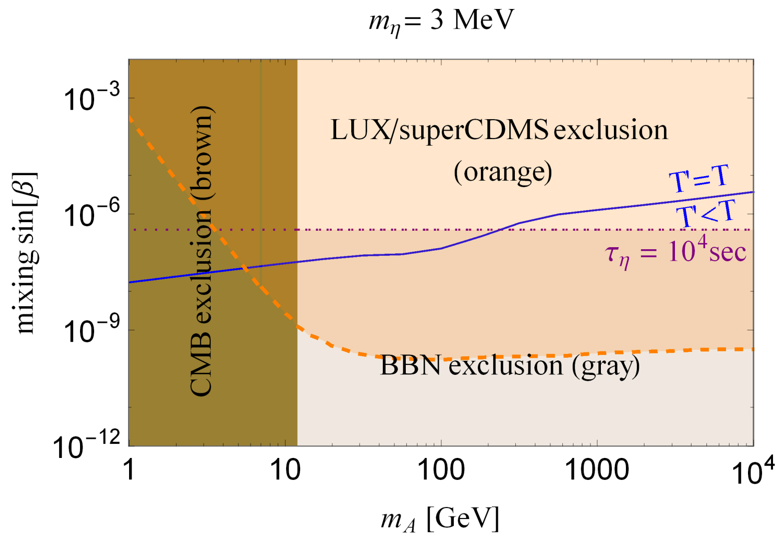
Local $SU(2)_X$	$\rightarrow$	Global $SO(3)$	
Gauge Fields A'_μ	$\rightarrow$	Massive Fields A_μ	Stable (DM Candidate)
Doublet ϕ	$\rightarrow$	Higgs-like η	It mixes with the Higgs

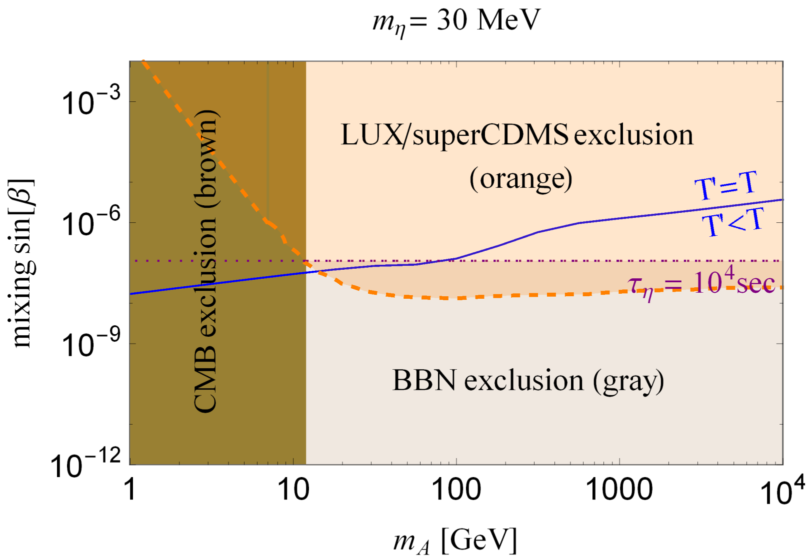
Hambye (JHEP 2009)

This scenario produces Gravitational Waves
in the Early Universe (Baldes Garcia-Cely 2018)

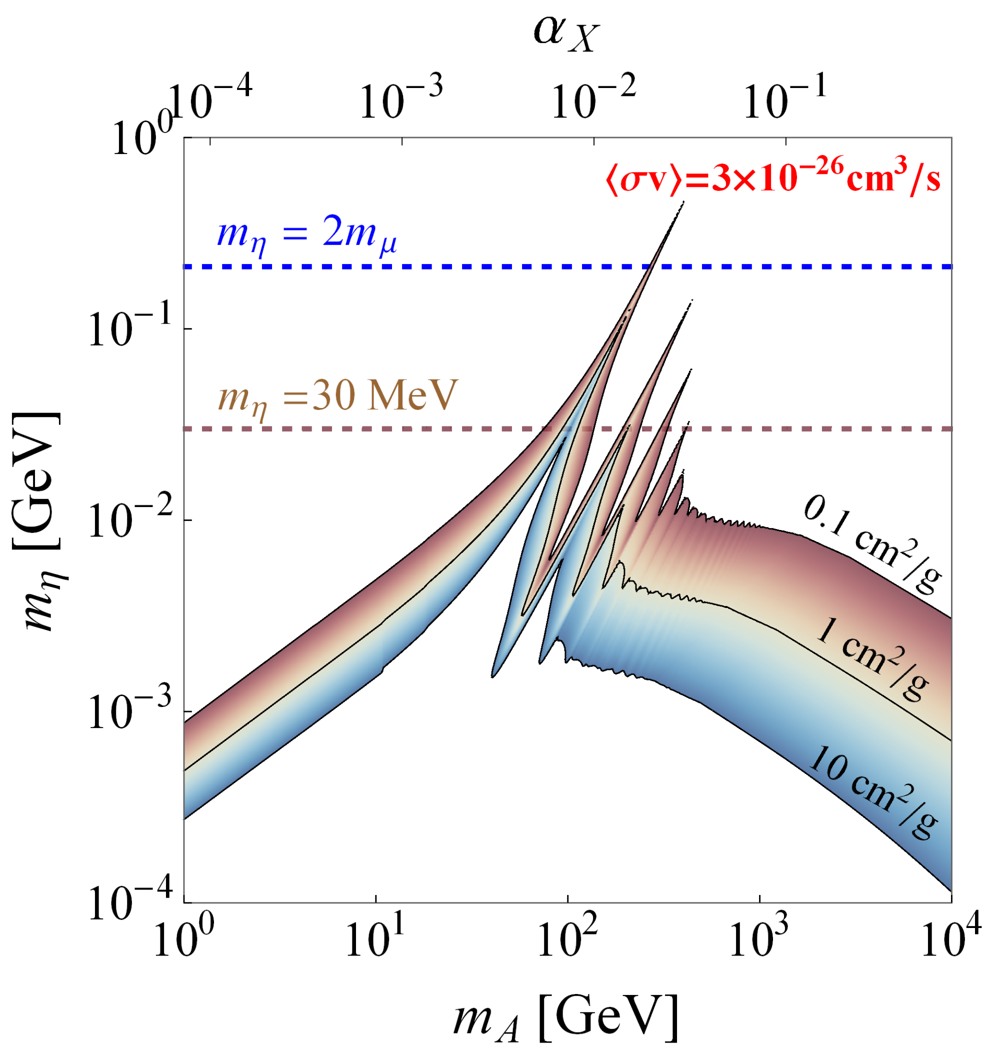
Concrete example

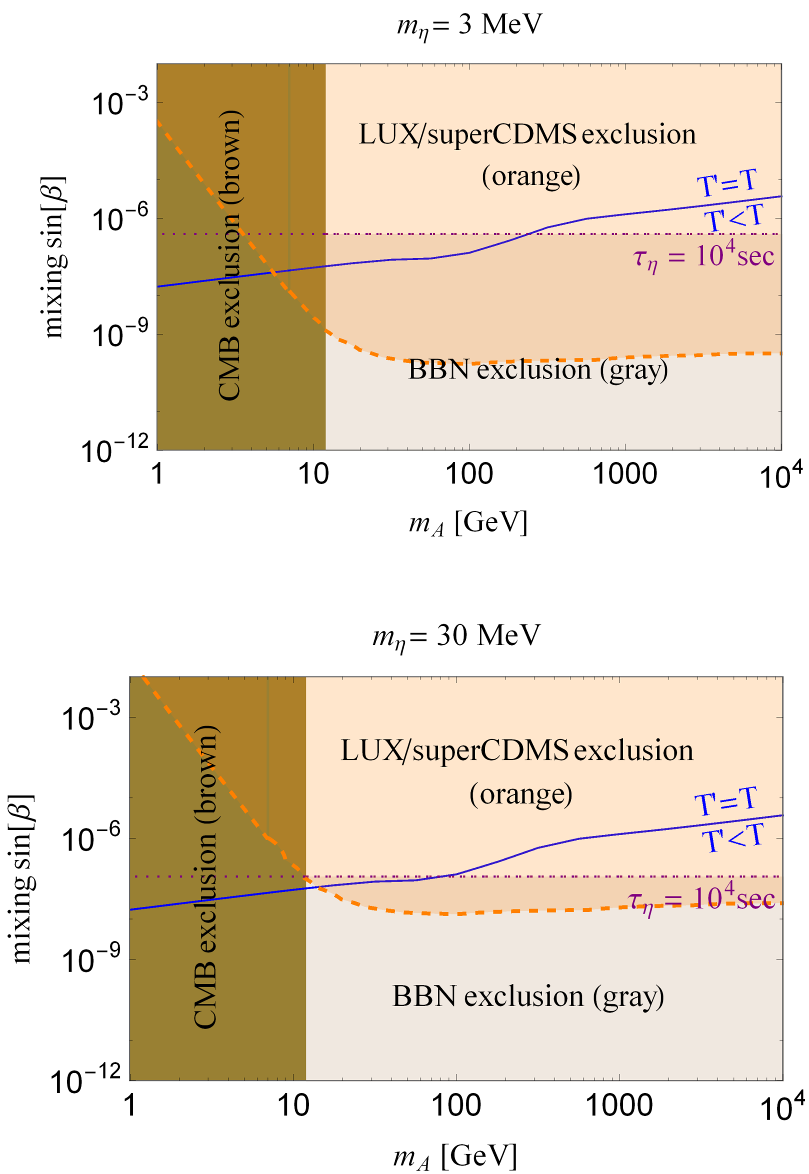






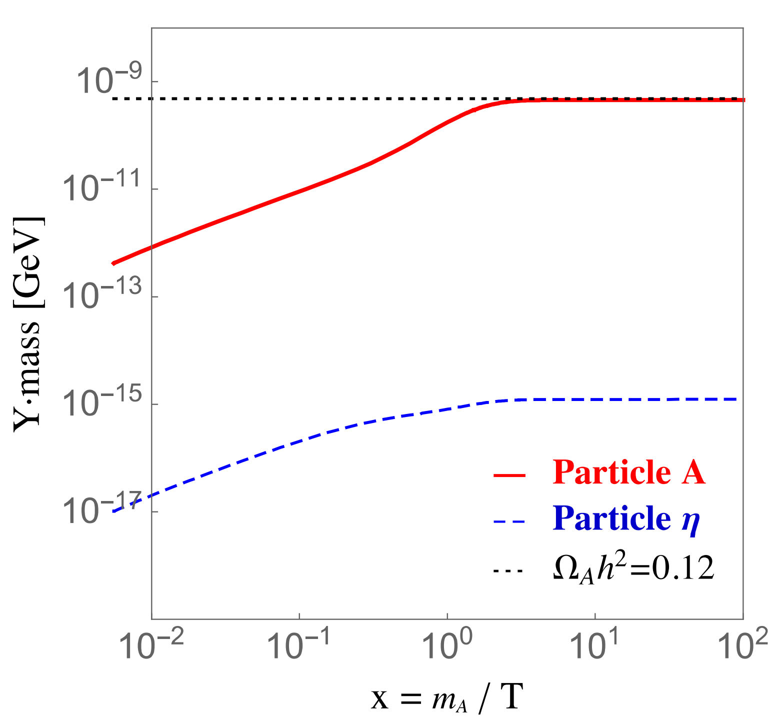
Concrete example

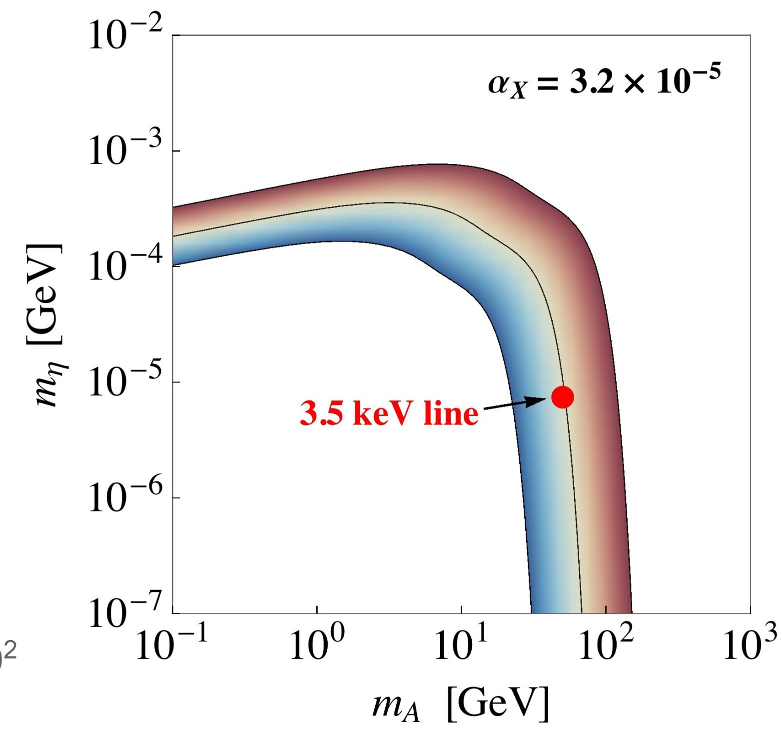




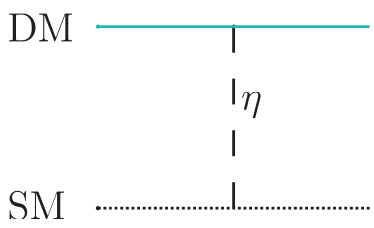
Standard freeze-out is not posible.
Freeze-in works

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.

New ideas

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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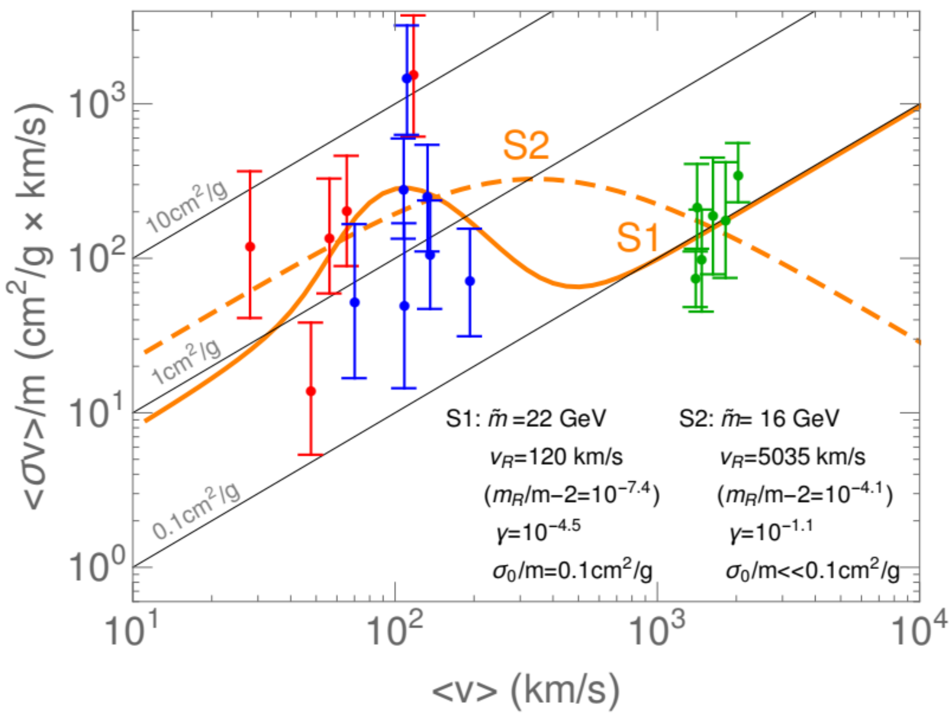

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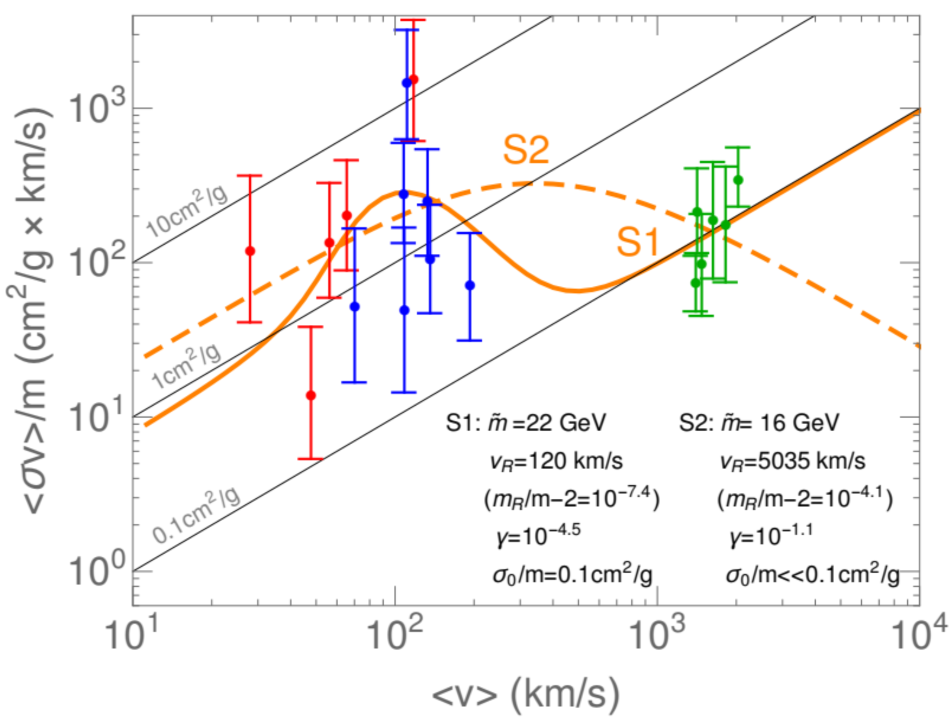
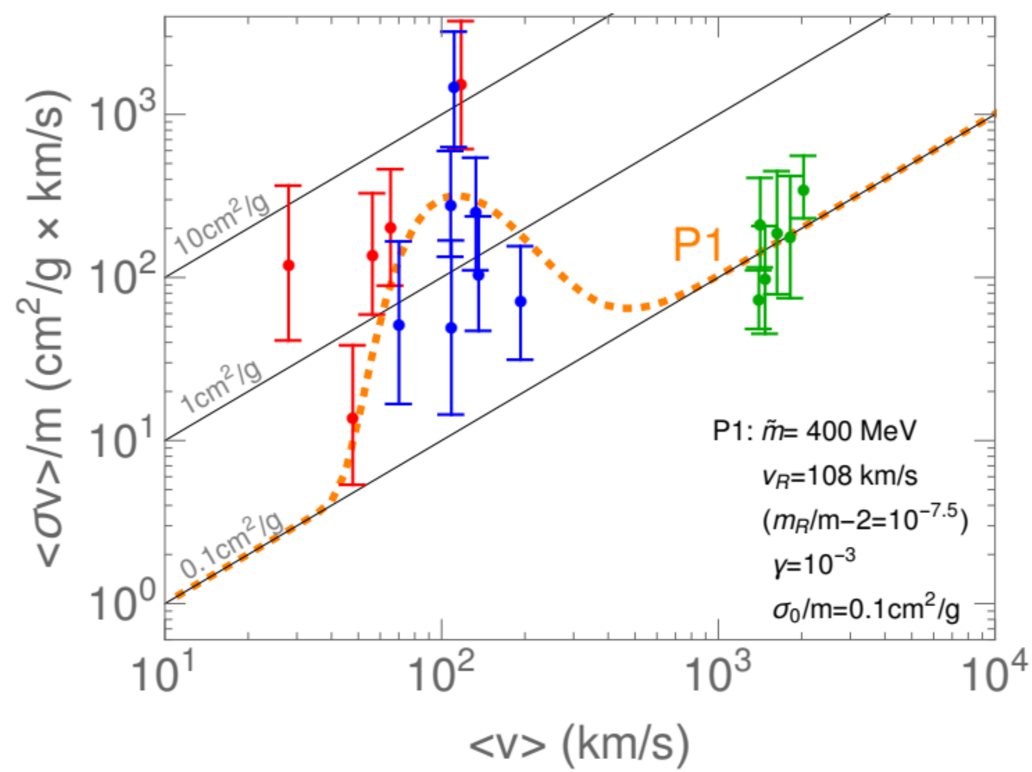




Concrete examples

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

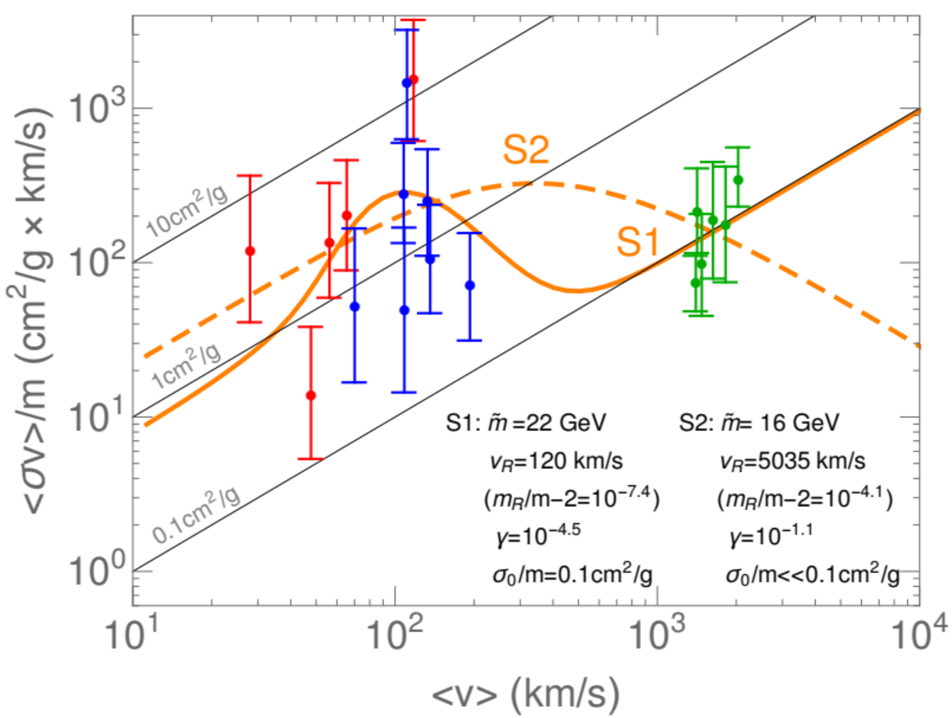
Table I: Benchmark RSIDM models.

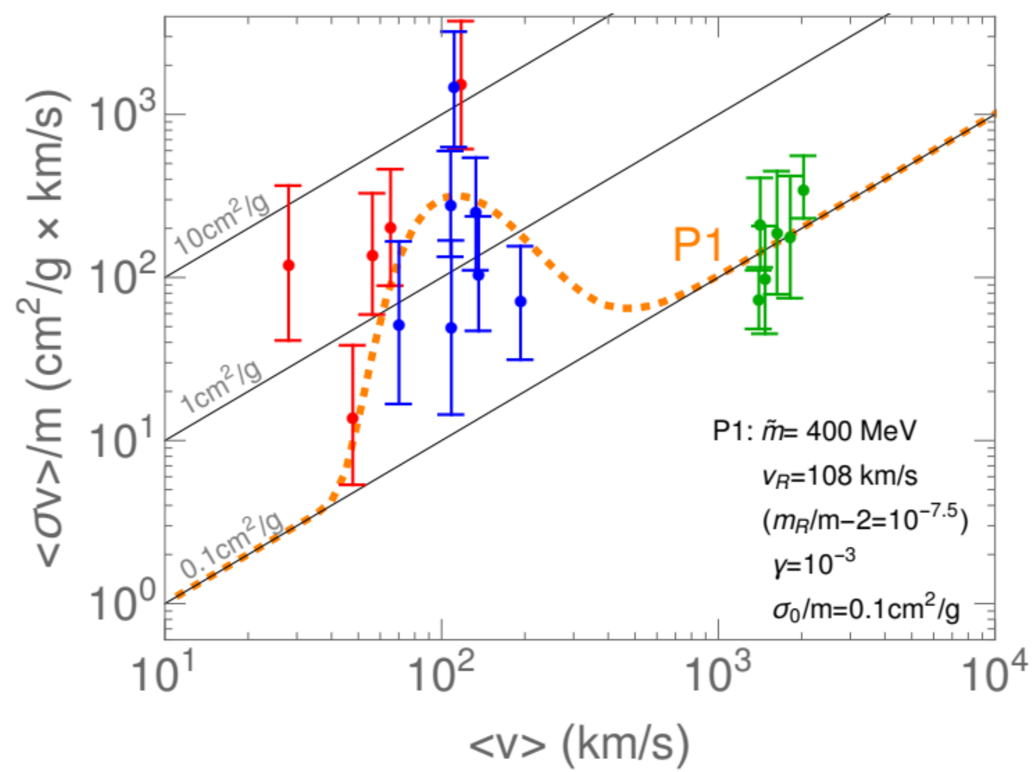
Pseudo-scalar mediator

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

Spin-two exchange

Chu, CGC, Murayama (2018)





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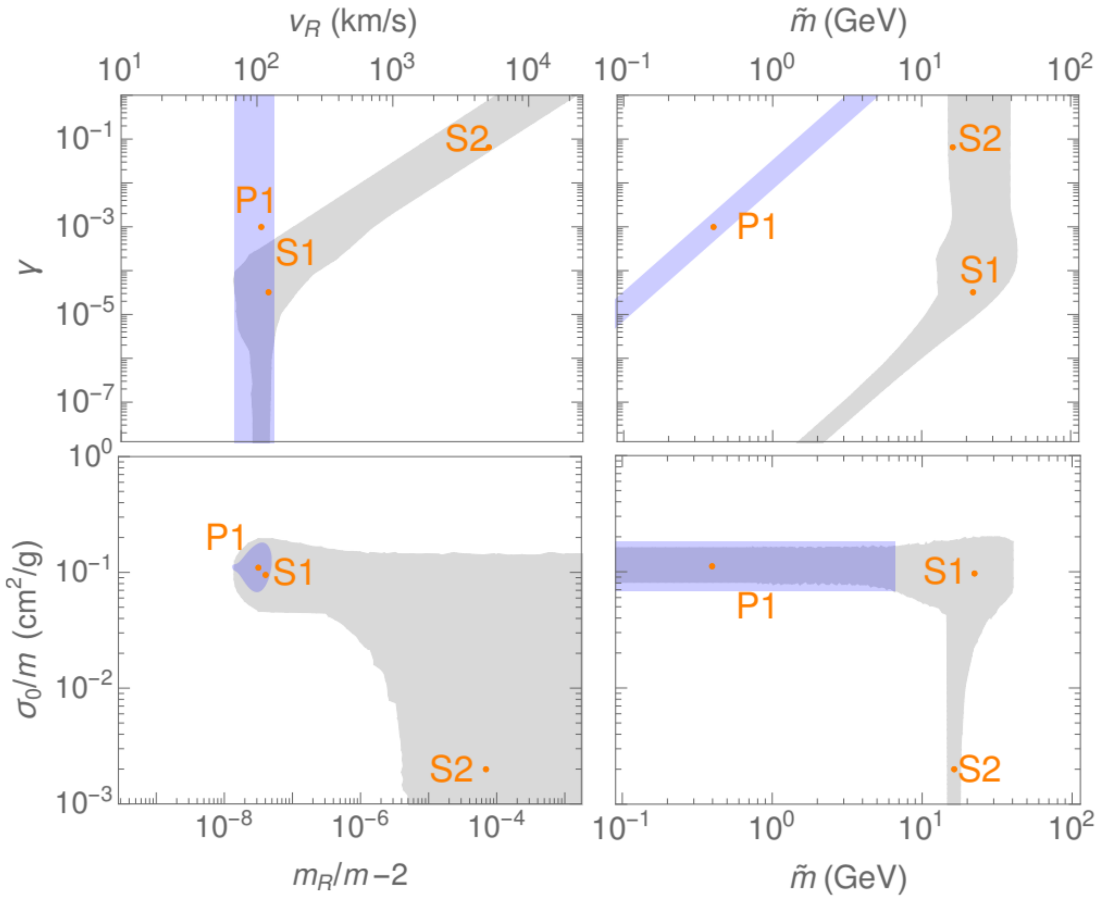


Chu, CGC, Murayama (2018)

Puffy DM

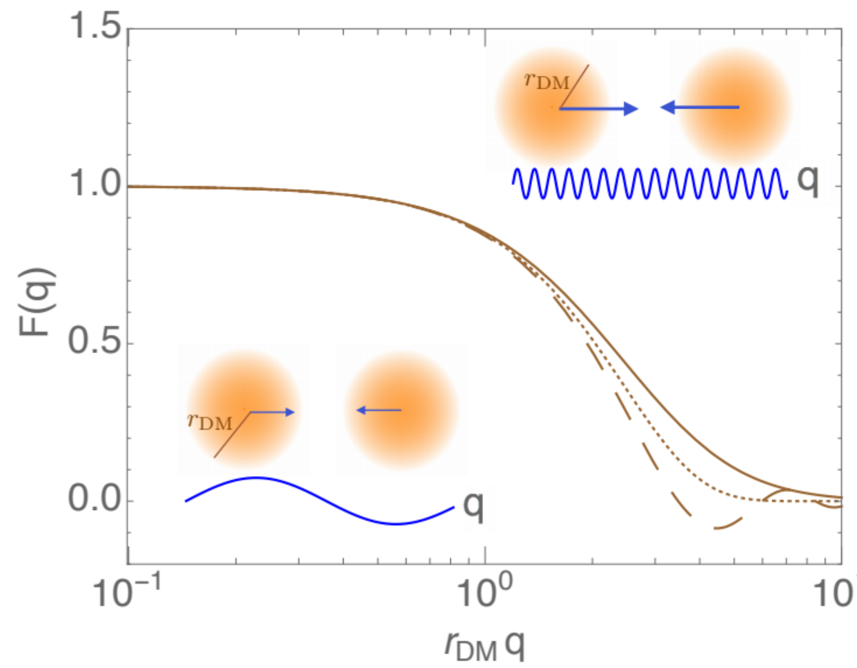
Supposed that dark matter has a finite size that is larger than its Compton wavelength: Puffy DM

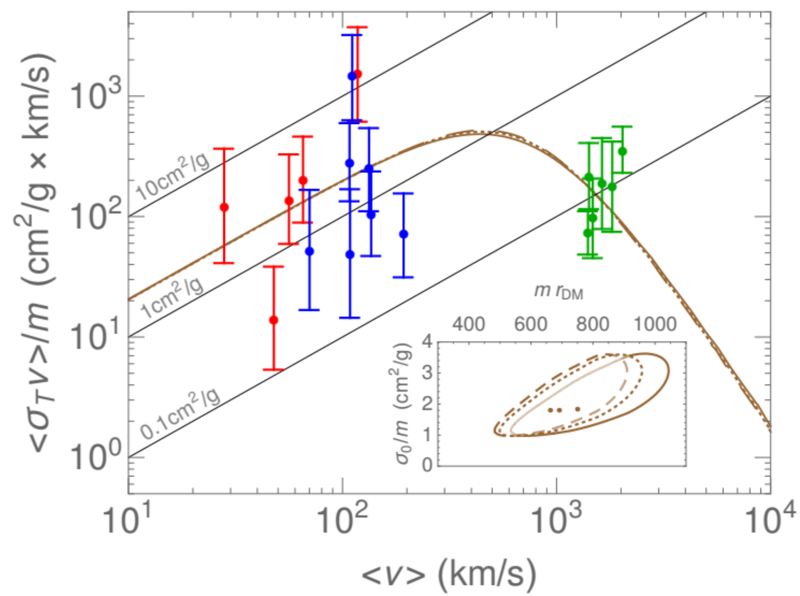
Chu, CGC, Murayama (2018)

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

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.





Direct Detection of Puffy DM

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
Δ^-	$\mathbf{1}$	-1	Dark baryon ddd
DM	$\mathbf{1}$	0	Bound state of A Σ_c baryons

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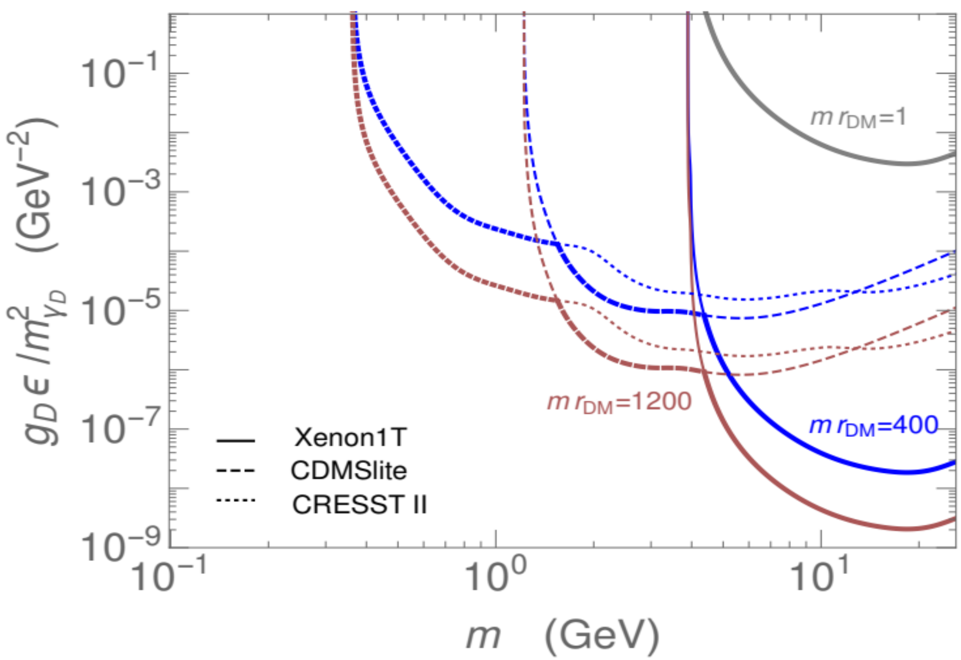
DM	**1**	0	Bound state of A Σ_c baryons

Chu, CGC, Murayama (2018)

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



Conclusions

- Self-interacting dark matter (SIDM) is a well-motivated solution to the problems encountered at small scales.
- Multiple observations severely constrain the production of self-interacting DM via the freeze-out mechanism with a light mediator.
- A viable scenario is freeze-in. It provides a candidate for the 3.5 keV line.
- Another possibility is the case of resonant dark matter
- Dark matter particles with a finite size (Puffy DM) constitute another viable candidate of self-interacting dark matter