Small-scale Structure

Is it a valid motivation?

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Small Scale Structure Problems

<—>

All the reasons why “CDM is not it”

How did we get here?

- We are gravitationally sensitive to something sourcing $T_{\mu\nu}$
—> we are fairly certain that DM exists.

- An exception is MOND, which has issues of its own. However, the MOND community has been instrumental in pointing out some of the discrepancies with CDM.

- But how do we verify the picture?
—> NBODY simulations (disclaimer: I have never run a serious body simulation)

N-body Simulations

- Take N dark matter particles, optionally add baryon gas (which has to be treated differently because it is far from linear) and numerically solve for their motion.
- This implies a limit in resolution (finite N), but we also have to regulate the IR singularities (softening).
- The whole code has to be checked for convergence (changing unphysical parameters does not change physics on relevant scales)

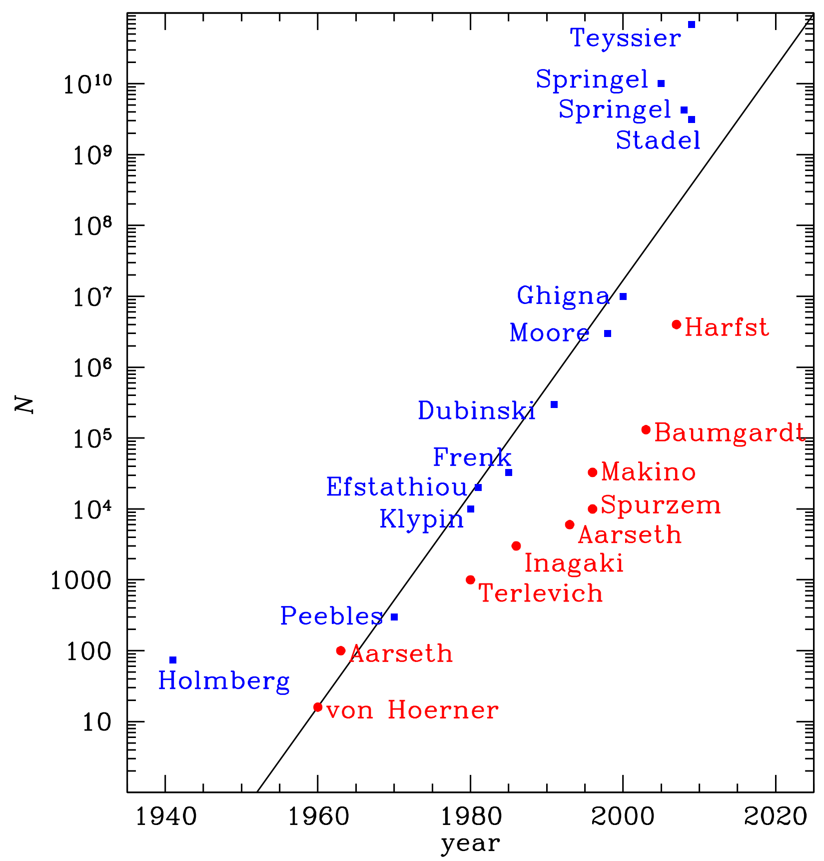


Fig. 1. The increase in particle number over the past 50 years for selected collisional (red, [4–6, 11–16] taken from [17]) and collisionless (blue, [3, 7–9, 18–24]) N-body simulations. The line shows the scaling $N = N_0 2^{(\text{year}-y_0)/2}$ expected from Moore's law if the costs scale $\propto N$.

[1105.1082]

Subgrid Physics

- Some physics is not known from first principles. Such as: star formation details, supernova feedback parameters.
- Or if it is known at certain scale (at the level of the molecular clouds), but the simulation cannot reach a resolution that can probe those scales.
- These processes can still have a important role and need to be included.
- Resolution: do it by hand. Ff a particular region reaches a low enough temperature and high enough density the code inserts stars by hand. If a star is old enough, the code turns into supernova and deposits some amount energy into the surrounding gas.
- This subgrid physics has to be validated: you sacrifice some output (such as stellar mass distribution), in order to set the unknown parameters correctly.

Possible small scale discrepancies

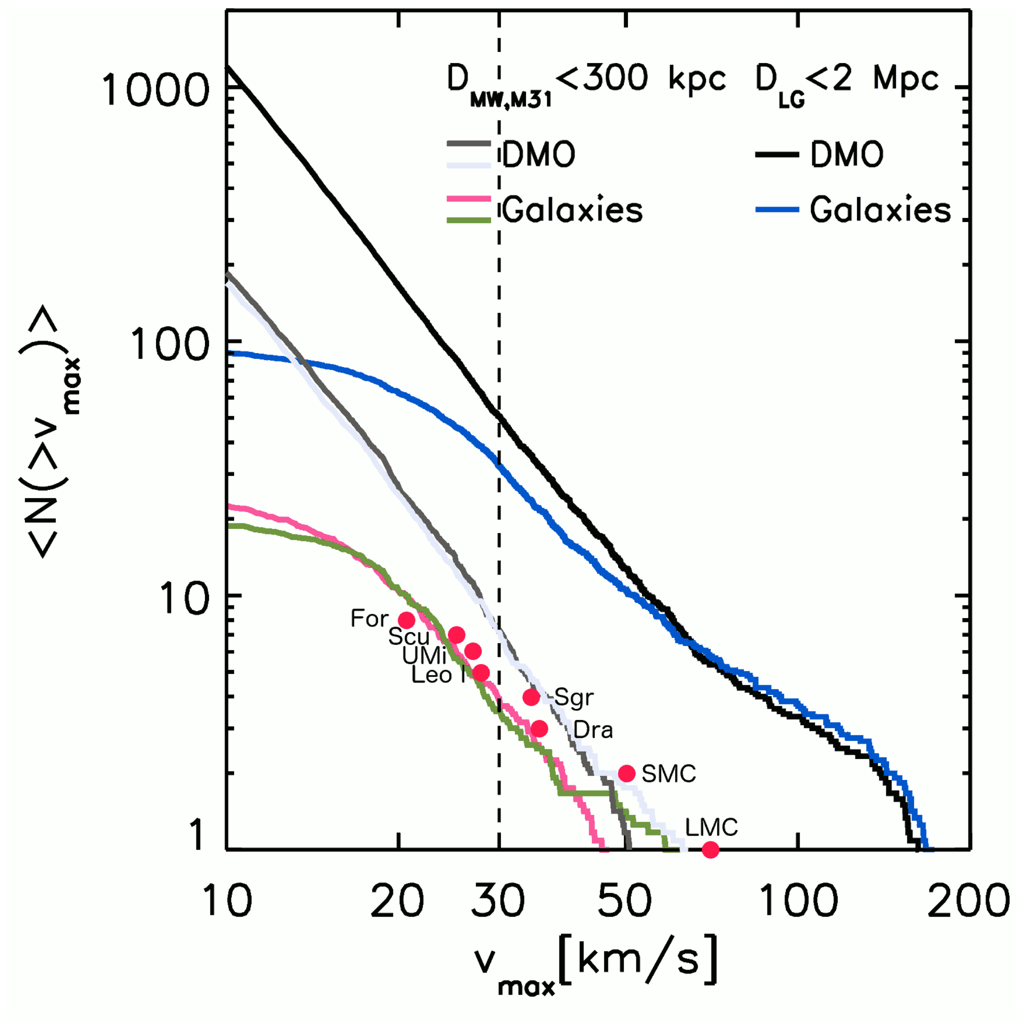
- Missing Satellites
- Too-big-to-fail
- Cores in Dwarf galaxies
- Diversity of Rotation Curves
- Planes of galaxy satellites

Probably not a problem
Maybe a problem
a problem

Missing Satellites and Too-big-to-fail

- Pure LCDM simulations made predictions on number of satellites as a function of their DM mass.
- This number does not match the observed number of satellites (in the observational footprint).
- However, once the baryons were included, this is significantly improved.
- Tidal stripping is also likely responsible [1707.03898]
- However, see [1807.07093]

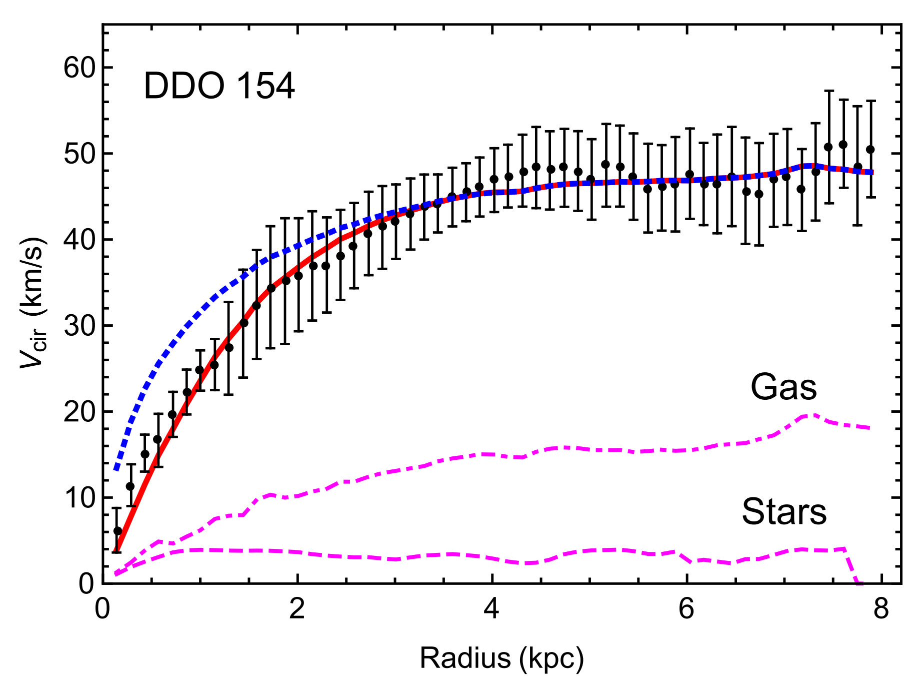
APOSTLE [1511.01098] [1611.00005]

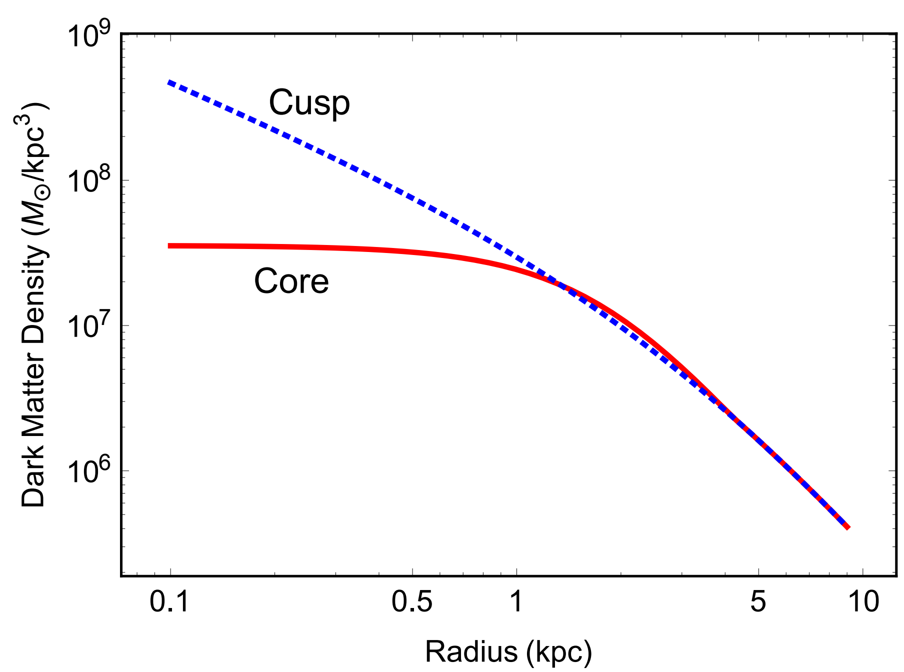


Cores-Cusp

- Started by Moore B., 1994, Nature, 370, 629, there were observations that show rotation curve that indicated that the central density profile was flat.

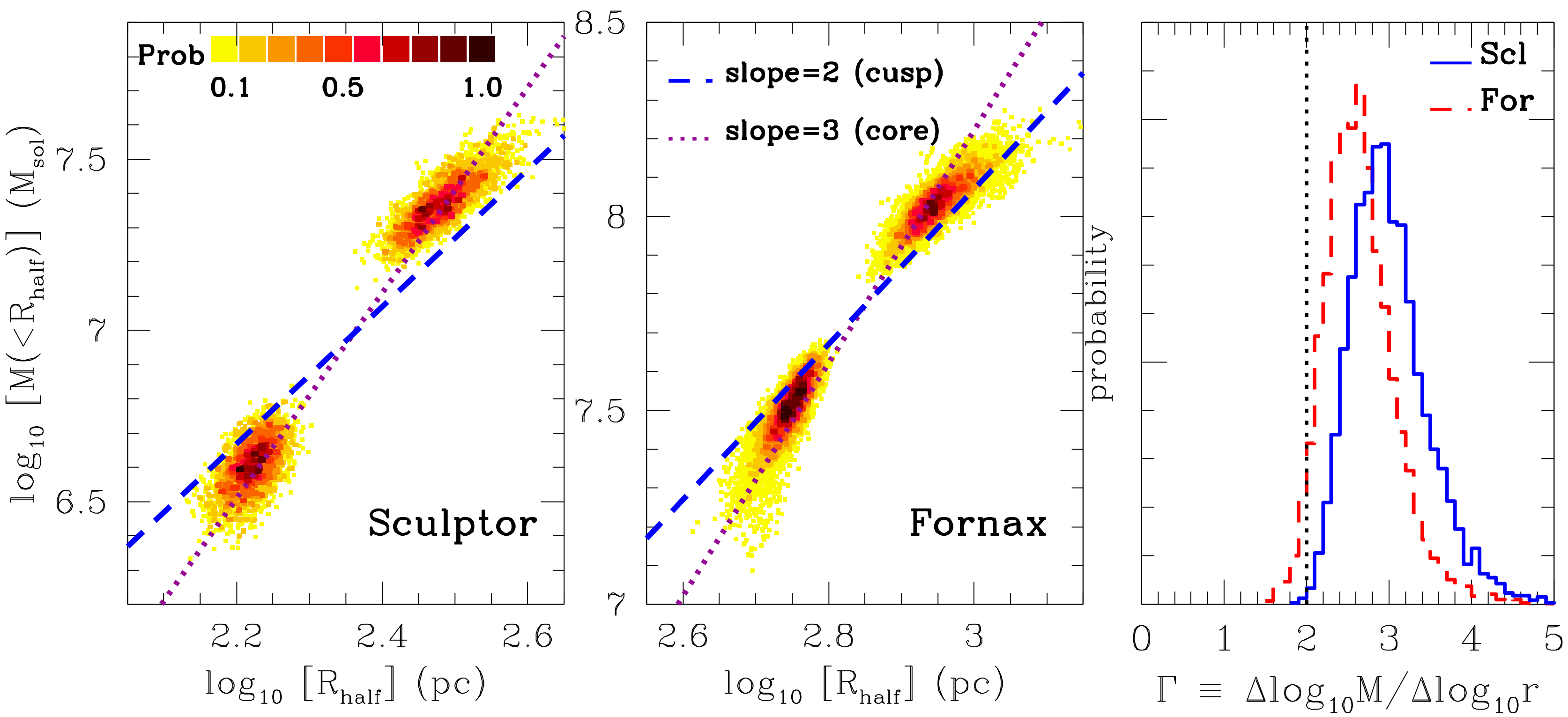
- This was in tension with the pure CDM simulations

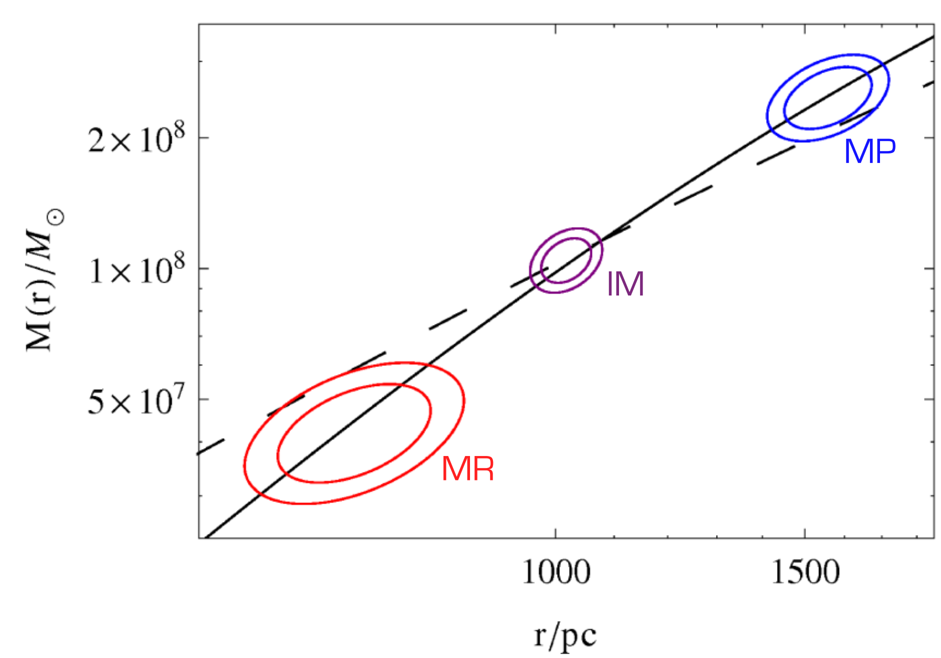




Core-Cusp: Extraction

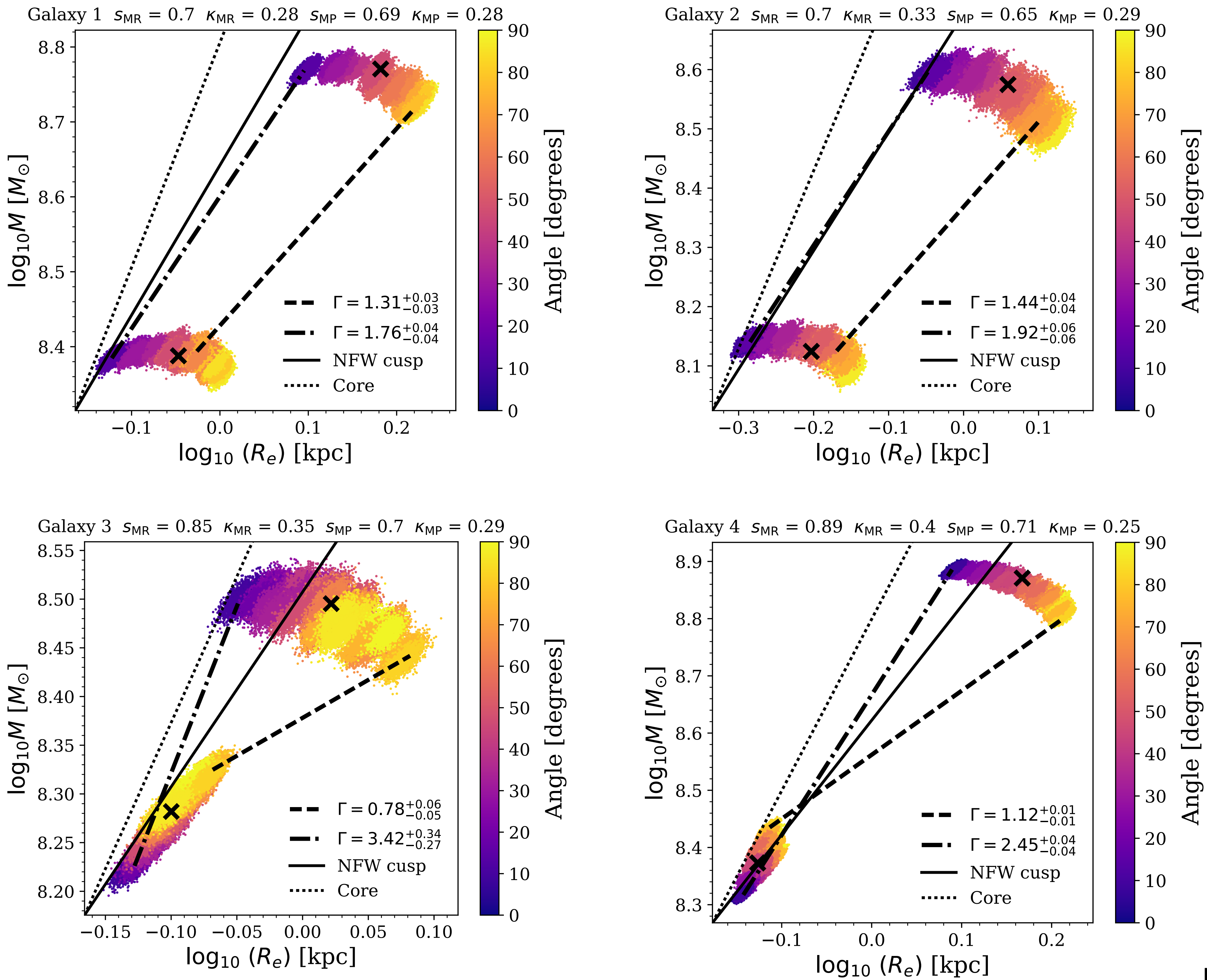
- When a galaxy contains gas, the rotation curve is accessible. However, really small galaxies do not contain much gas.
- Otherwise we need to use the dispersion velocity of the stars as a probe of the local gravitational potential.
- We only know one of the three components of the velocity: this degeneracy vastly complicates the problem





[1108.2404]
[1210.3157]

Core-Cusp: Warning

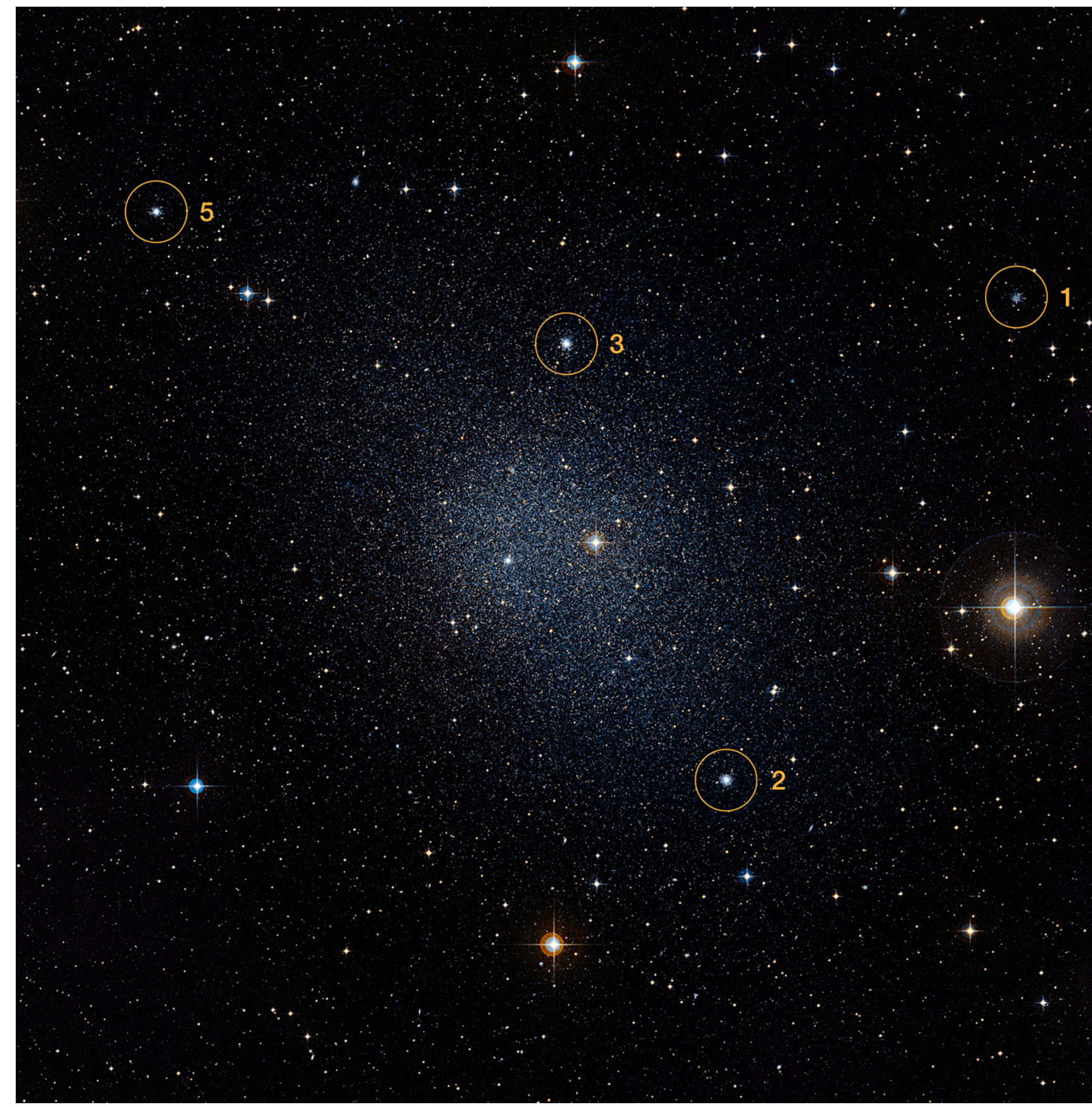


[1707.06303]

Globular Clusters

- In a cuspy (1/r) dark matter halo, we expect to see some globular clusters to spiral-in towards the centre due to dynamical friction.

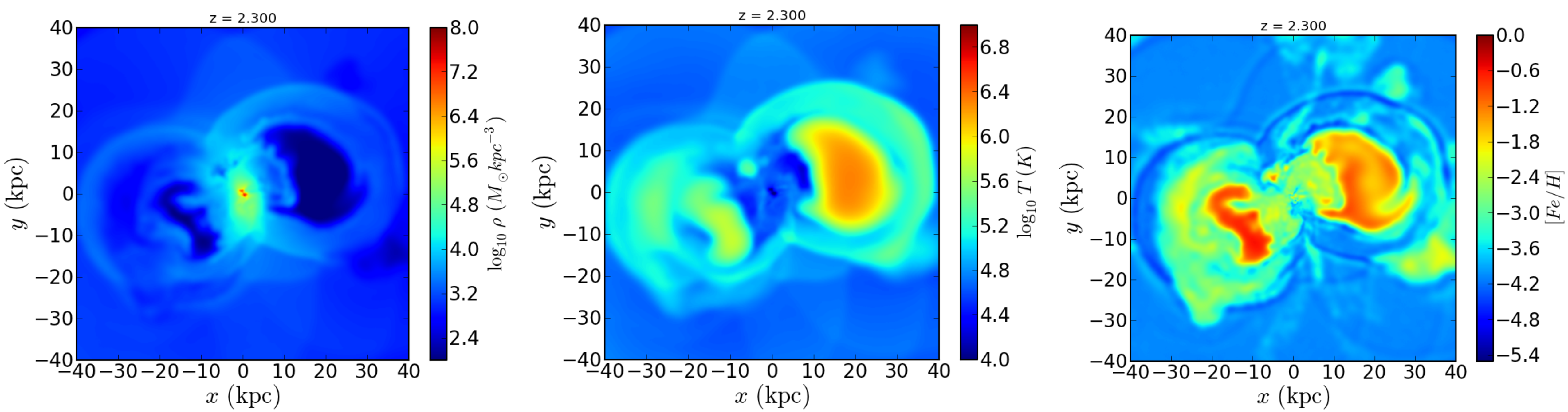
- Since we see a couple GCs in Fornax that have not spiralled-in yet, we can take this as a (rough) evidence for core in the Fornax



Fornax by Hubble Telescope

Core-Cusp: resolution?

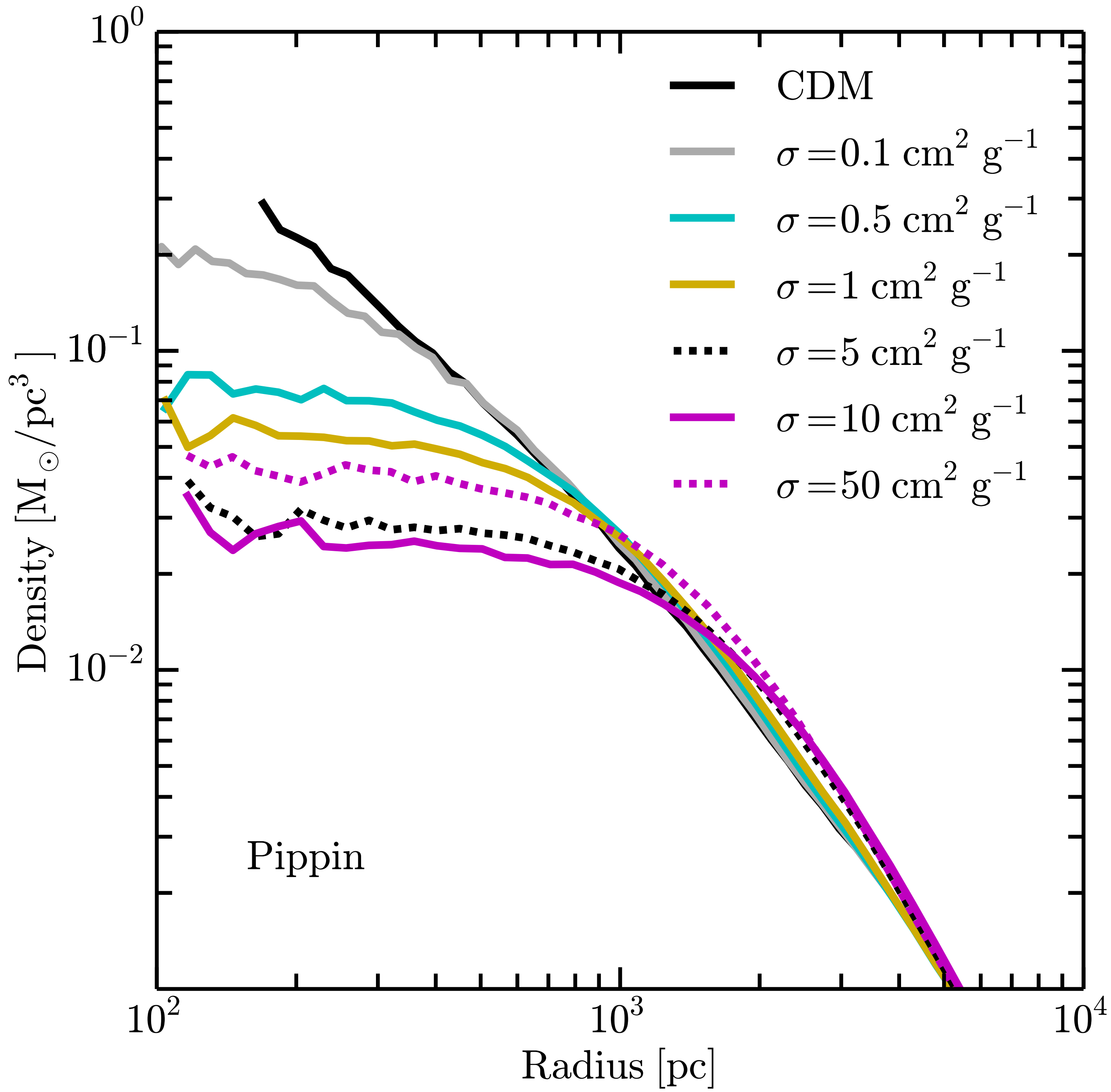
- Baryonic feedback seems to solve part of the problem: once a galaxy is big enough, the star formation inject energy into the gas. This leads to fluctuation of the gravitational potential and transfers energy to the dark matter, removing it from the central potential. These results are somewhat group dependent (depend on the burstiness of the star formation). There is a cutoff below which this mechanism does not work (10^5 M_sun).



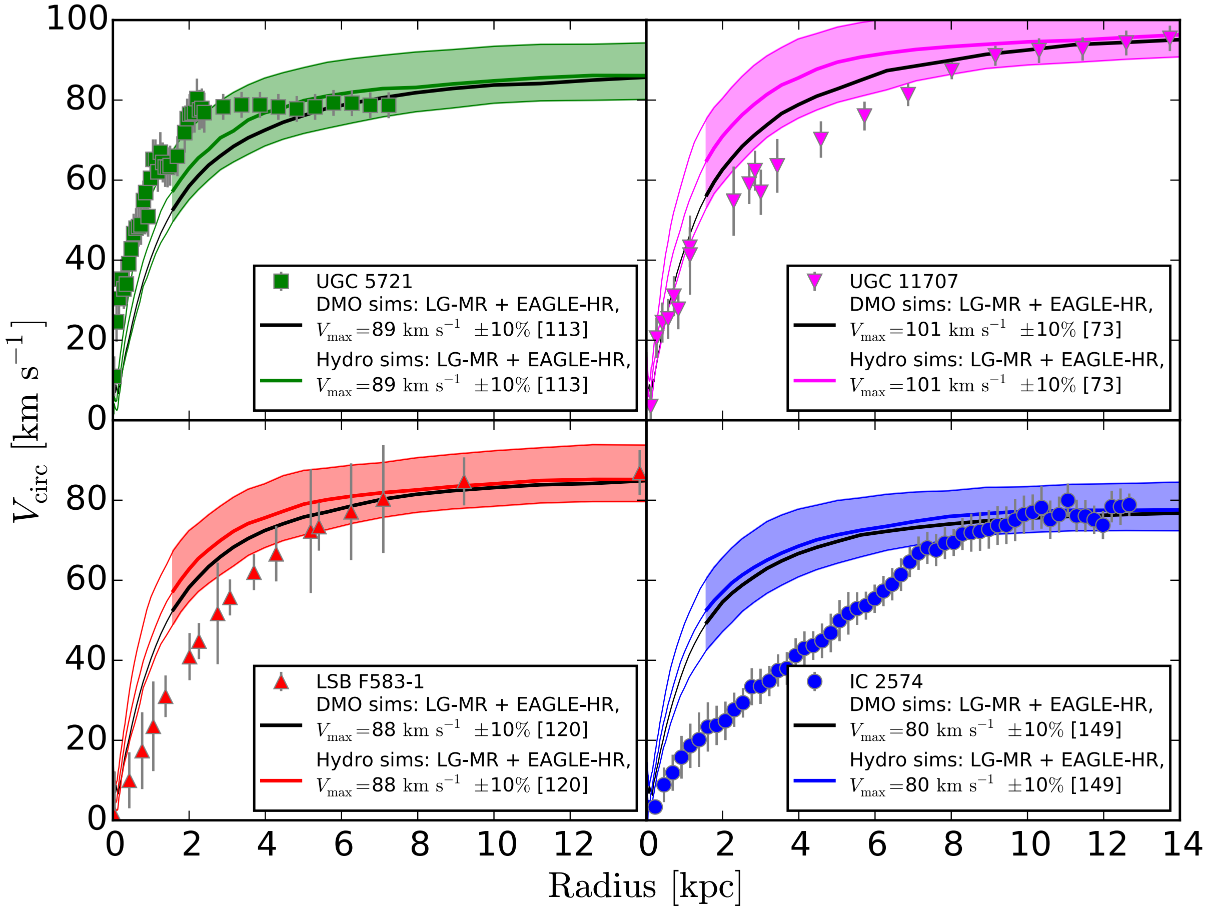
[1502.02036]

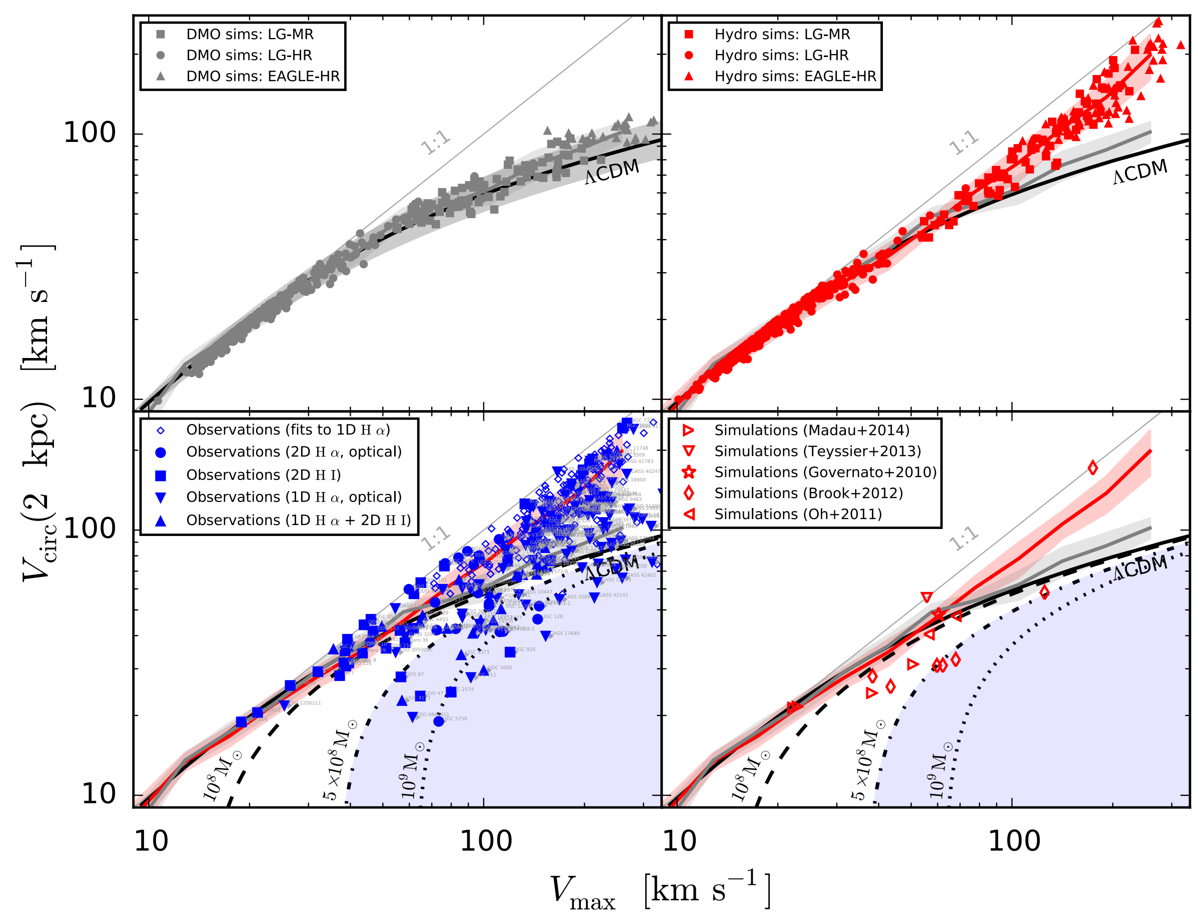
Core-Cusp: resolution?

- SIDM seems to do the job well [1412.1477]
- There is a variety of fun physics associated with this scenario: gravothermal collapse, strongly coupled systems become poor heat conductors, etc.



Diversity of Rotation Curves





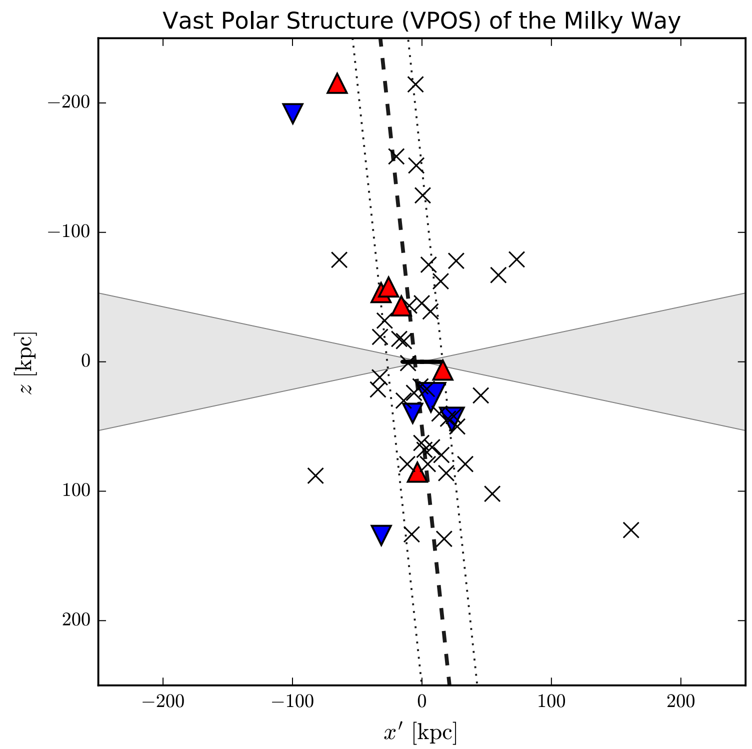
[1504.01437]

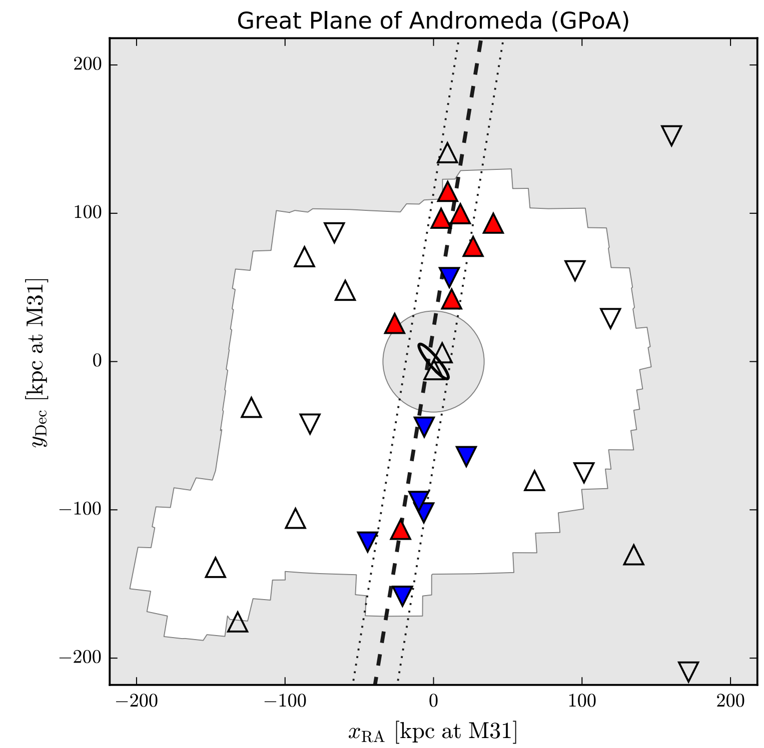
Solutions to the Diversity of Rotation Curve Problem

- [1601.05821] suggest deprojection: when we look at the galaxy, we might mis-measure rotational velocity due to the inclination

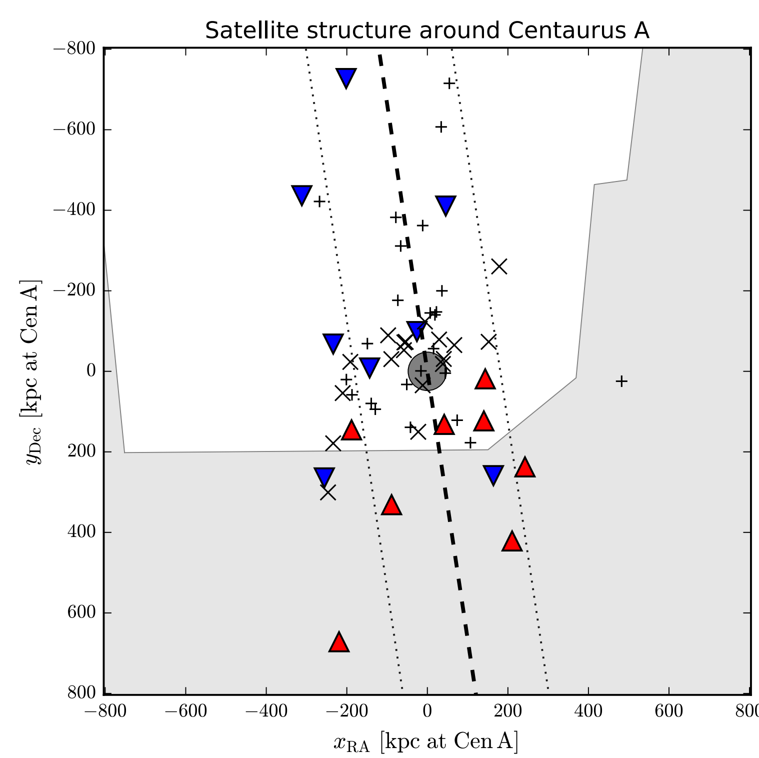
- SIDM provides a nice solution: the Baryons and the DM are strongly linked through their gravitational interactions because of the isothermally of SIDM. [1808.05695]

Planes of Satellite Galaxies



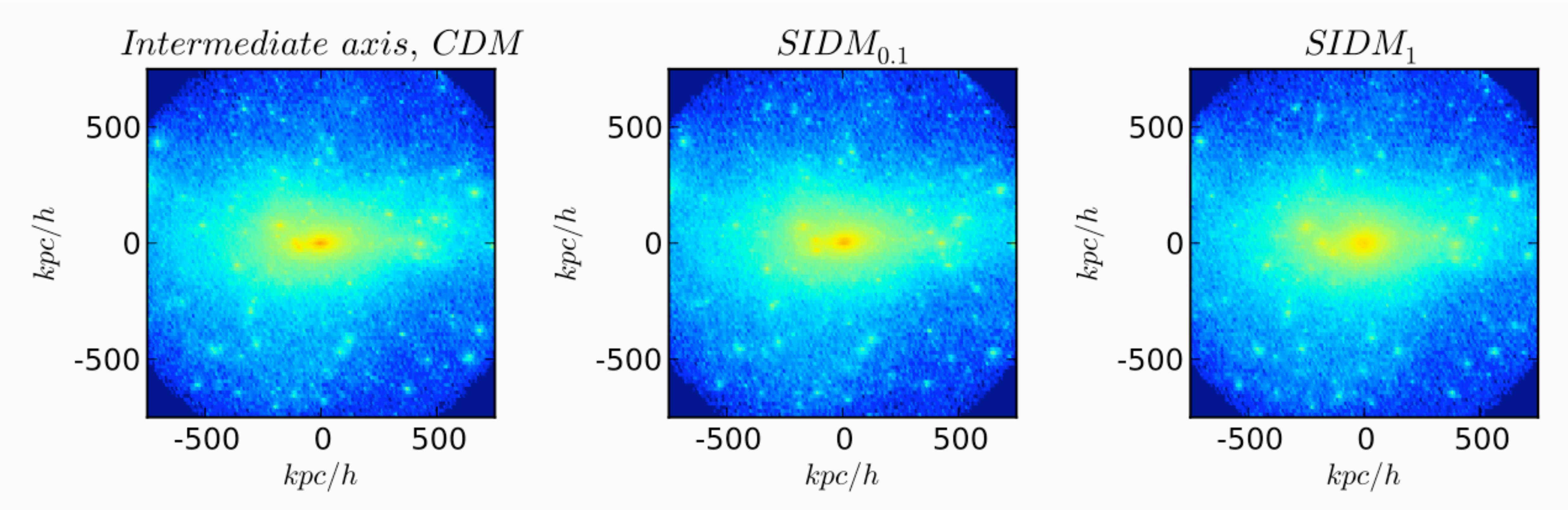


- The three large galaxies in the local neighbourhood seem to each have a planar subset of satellites galaxies. This is somewhat unlikely.



[1802.02579]

Self Interacting DM



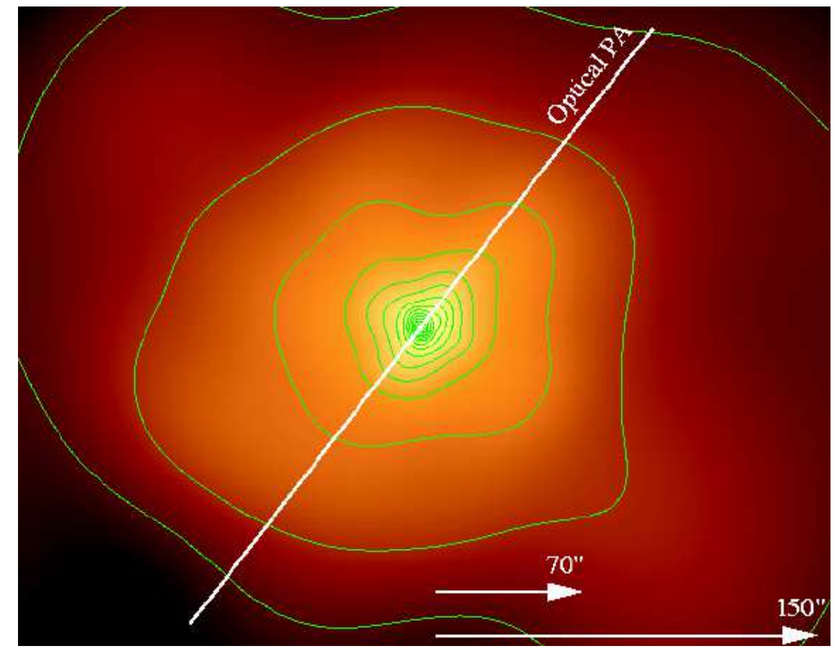
One is sensitive to:

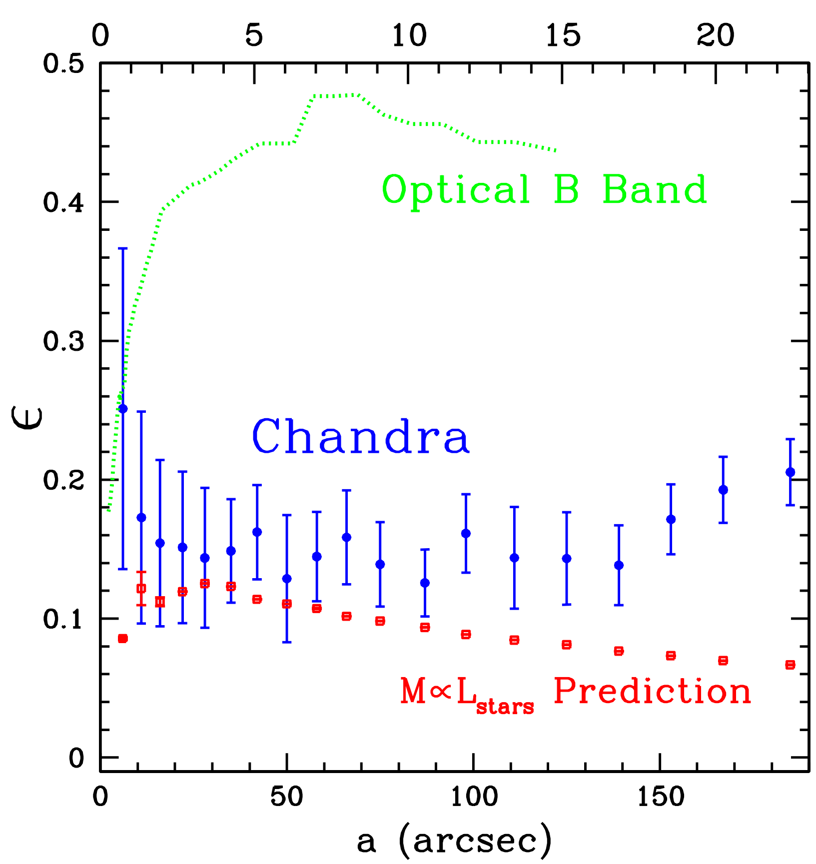
$$\Gamma = \langle \sigma v n \rangle = \langle \sigma v \rho / m \rangle \propto \langle \sigma v \rangle / m$$

Constraints: Shapes

- NGC 720: As observed by Chandra Telescope [astro-ph/0205469]
- It shows an elliptical gravitational potential
- This indicates that the DM has a triaxial distribution.
- This implies an upper bound on the scattering cross-section:

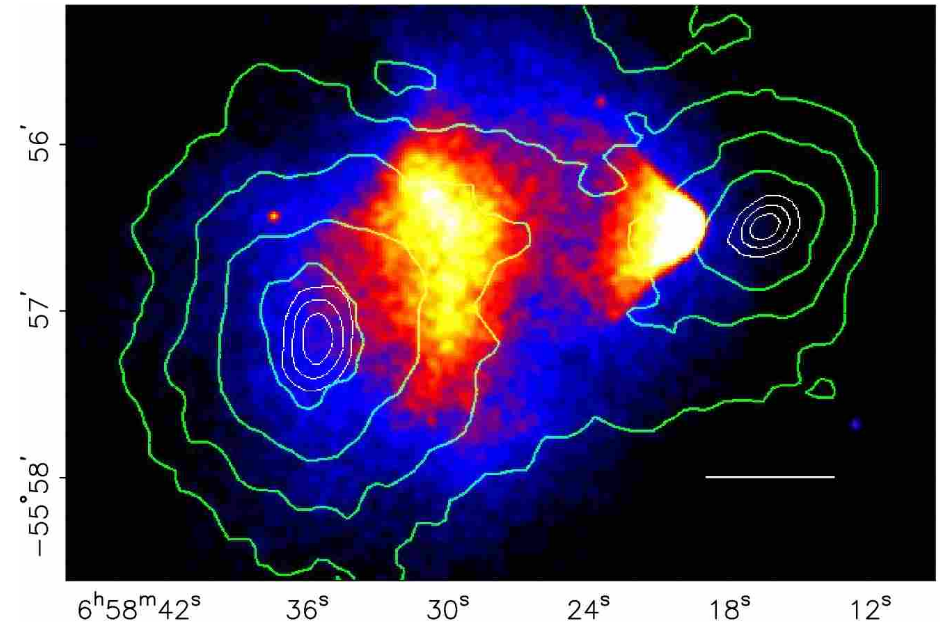
$$\langle \sigma v \rangle / m < 0.1 \mathrm{cm}^2/\mathrm{g}$$





Merging Clusters

- During the merger, SIDM would under go collision and heat up as well as slow down.

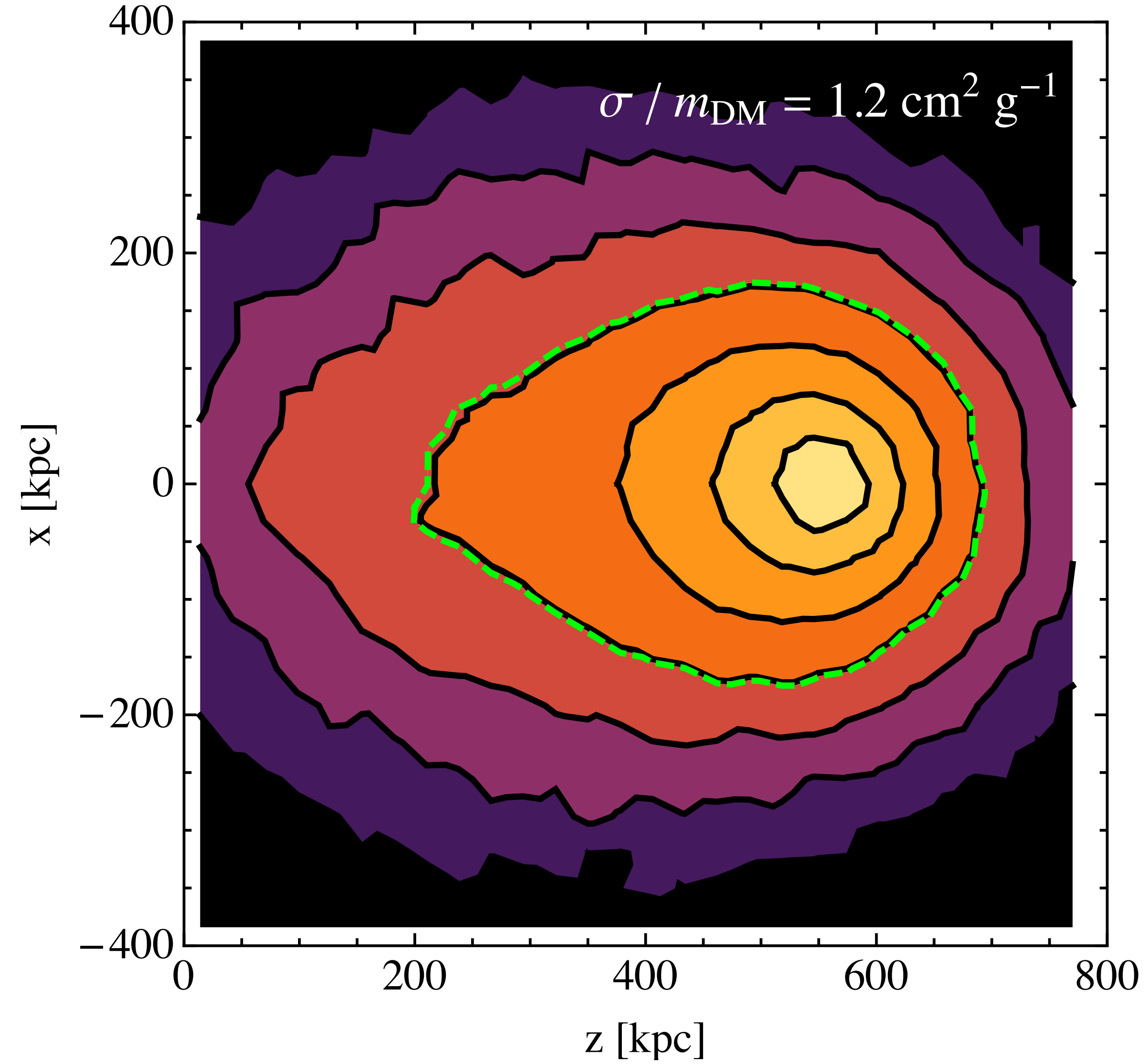


Cluster	σ/m	Method used	Ref.
Bullet Cluster	$< 3\ \mathrm{cm^2/g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.3\ \mathrm{cm^2/g}$)	[298]
(1E 0657-558)	$< 0.7\ \mathrm{cm^2/g}$	Mass loss $< 23\%$	[106]
	$< 1.25\ \mathrm{cm^2/g}$	DM-galaxy offset 25 ± 29 kpc	[106]
Abell 520	$3.8 \pm 1.1\ \mathrm{cm^2/g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.07\ \mathrm{cm^2/g}$)	[326]
	$0.94 \pm 0.06\ \mathrm{cm^2/g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.14\ \mathrm{cm^2/g}$)	[128]
Abell 2744	$< 1.28\ \mathrm{cm^2/g}$	Offset	[340]
	$< 3\ \mathrm{cm^2/g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.3\ \mathrm{cm^2/g}$)	[329]
Musket Ball Cluster (DLSCL J0916.2+2951)	$< 7\ \mathrm{cm^2/g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.15\ \mathrm{cm^2/g}$)	[316]
Baby Bullet (MACS J0025.4-1222)	$< 4\ \mathrm{cm^2/g}$	Scattering depth ($\Sigma_{\mathrm{dm}} \approx 0.25\ \mathrm{cm^2/g}$)	[318]
Abell 3827	$\sim 1.5\ \mathrm{cm^2/g}$	Offset	[127]

Taken from [1705.02358]

Dwarf Evaporation

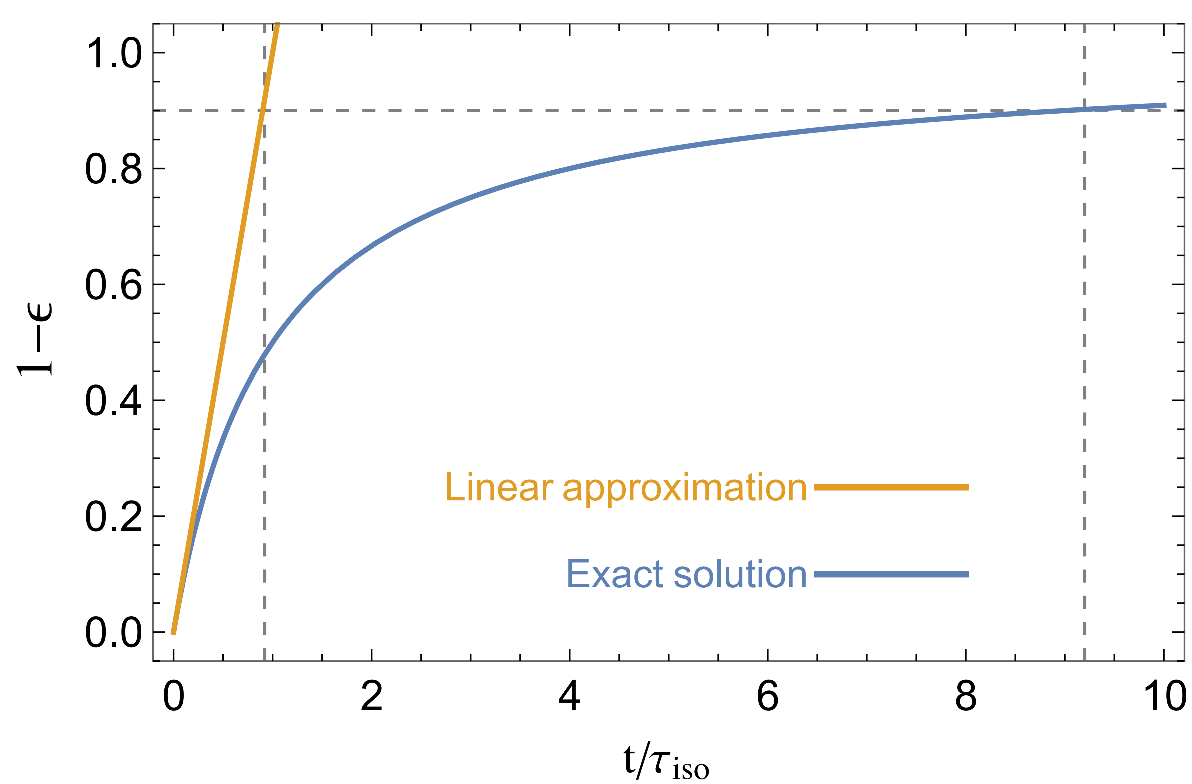
- As dwarf galaxies move in the halos of their host galaxies, the dark matter self interaction tends to strip and reshape the satellites halo.
- The constraints are derived from requiring that existing satellites such as Fornax do not disappear.
- However, this bound is subheading to triaxiality bound.
- Moreover, the literature does not quite treat this bound correctly: internal interactions are crucial
- N-body simulations do include this effect naturally.

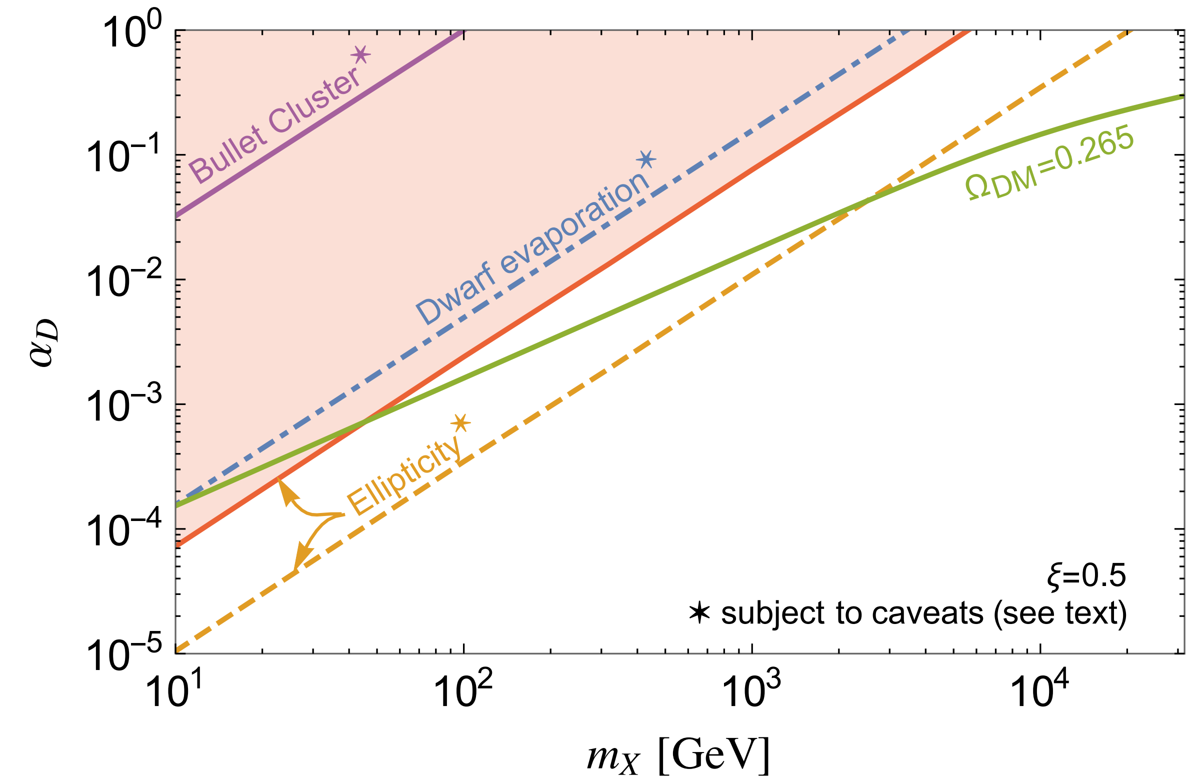


[1308.3419]

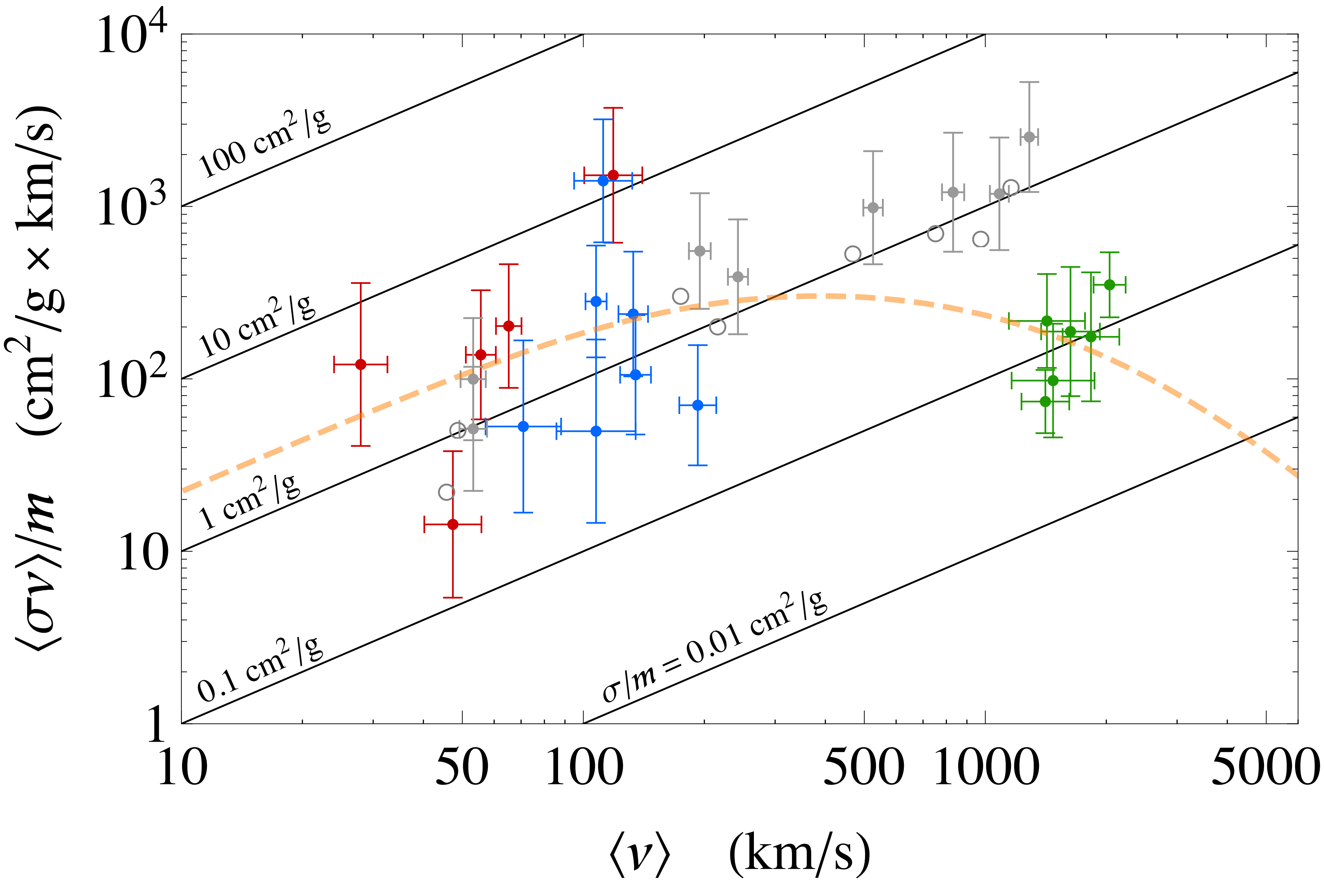
Warning!

- Most of the simulation community has focused on contact interactions.
- There are exceptions where 1/v^4 cross-sections were simulated. (But without the angular dependence)
- The following constraints are relevant for point like interactions. There are situations when “long-range” interactions lead to different results. [I am happy to talk about that]



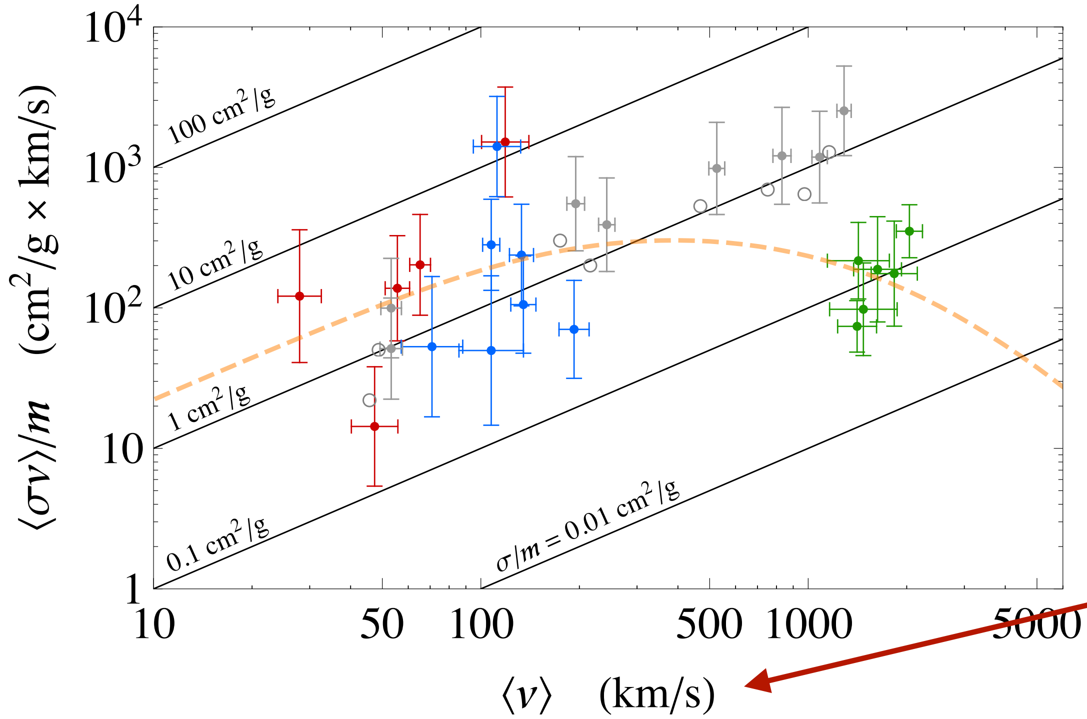


SIDM: Fits

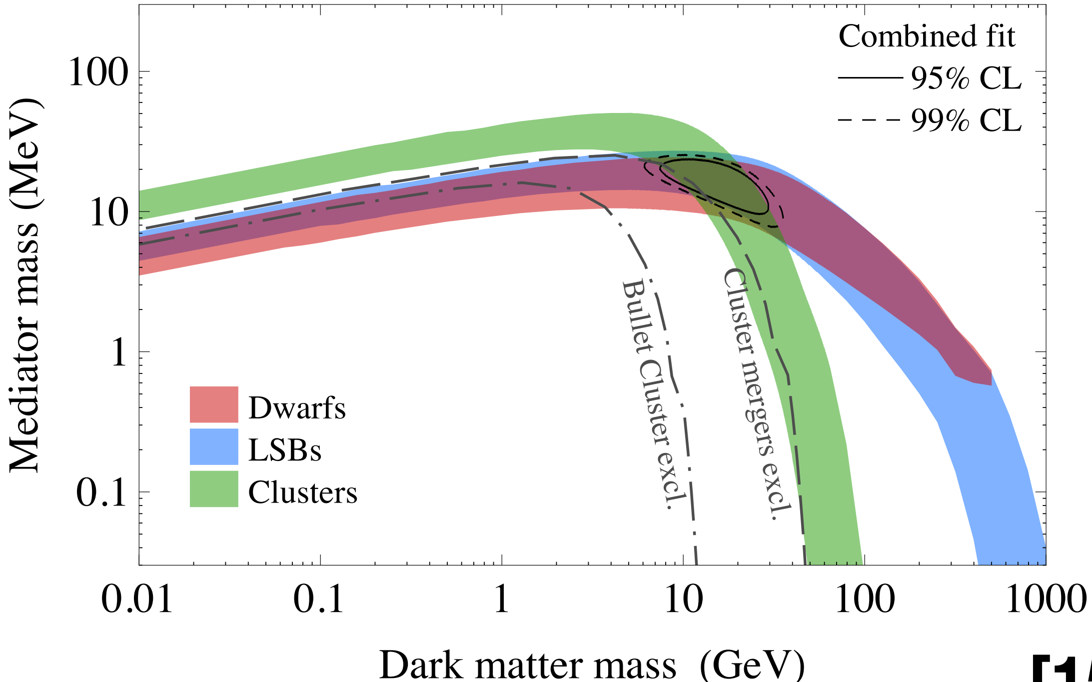


[1508.03339]

SIDM: Fits 2



$$\frac{d\sigma}{d\Omega} = \frac{\alpha_\chi^2 m_\chi^2}{\left[m_\chi^2 v_{\rm rel}^2 (1-\cos\theta)/2 + m_\phi^2\right]^2}$$



[1508.03339]

Strongly Coupled DM

- From the previous slide it is apparent we prefer two scales
- This suggests a simple strongly coupled model won't fly.
- Solutions:
  - Make some fermions become heavier than the strong scale, we are back in business.
  - Use glueballs and glueballinos
  - …

$$\sigma/m \sim 3\ \mathrm{cm}^2/\mathrm{g} \times \left(\frac{\Lambda_{\mathrm{DM}}}{m}\right)\left(\frac{\Lambda_{\mathrm{DM}}}{a^{-1}}\right)^2\left(\frac{100\ \mathrm{MeV}}{\Lambda_{\mathrm{DM}}}\right)^3$$

[1312.3325]
[1402.3629]
…

Conclusion

- Some small scale structure problems have gone away once baryons are included in the simulations (missing satellites, too-big-to-fail)
- Other problems arise (Diversity of rotation curves)
- And some are partially resolved, but not fully: Core-Cusp
- Some we are not so sure what they are: Planes of satellites
- However, one could take some of the anomalies as hints as to the nature of DM: Self Interacting
- Furthermore, if you like skating on thin ice, you could motivate some choices of your SIDM interaction parameters.
- If in doubt start consulting [1705.02358]