The Milky Way, satellite galaxies, the Local Group; CDM predictions vs observations

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REVIEW ARTICLE

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Check for updates

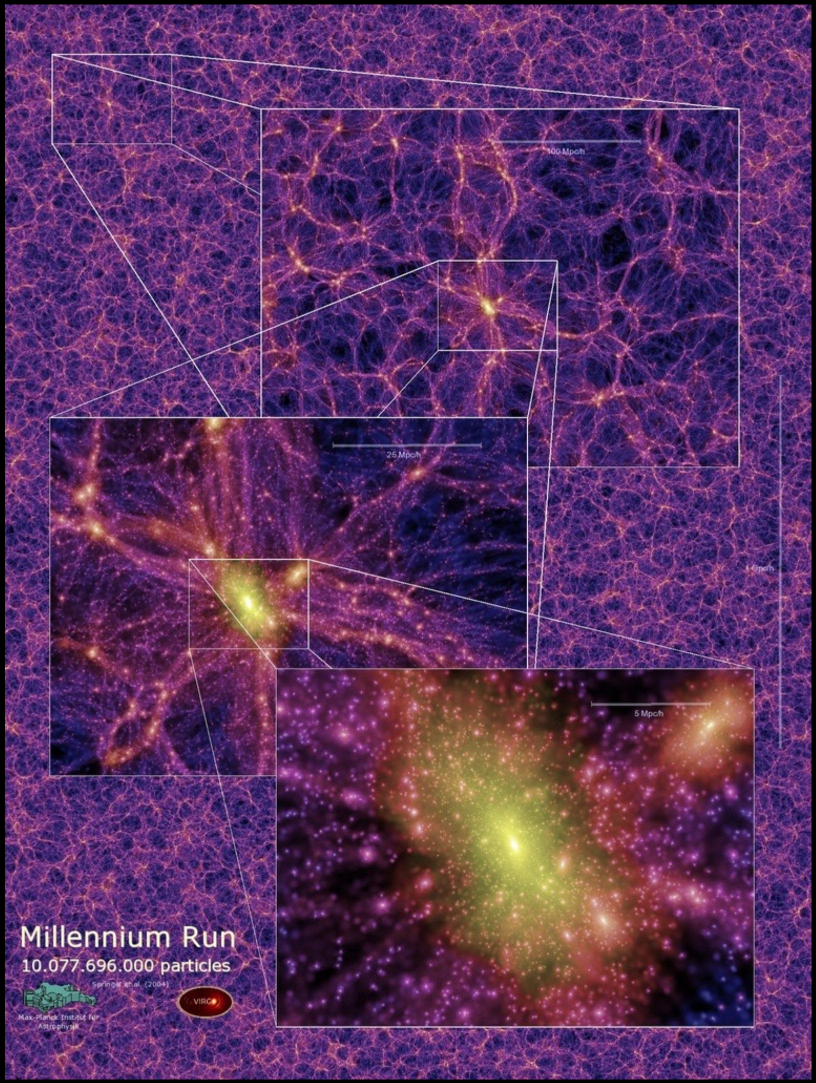
Baryonic solutions and challenges for cosmological models of dwarf galaxies

Laura V. Sales [1], Andrew Wetzel [2] and Azadeh Fattahi [3]

arXiv: 2206.05295

No tension	Uncertain	Weak tension	Strong tension
Missing satellites	$M_\star$-$M_{\rm halo}$ relation	Too big to fail	Diversity of rotation curves
	Core-cusp	Diversity of dwarf sizes	Satellite planes
		Quiescent fractions	

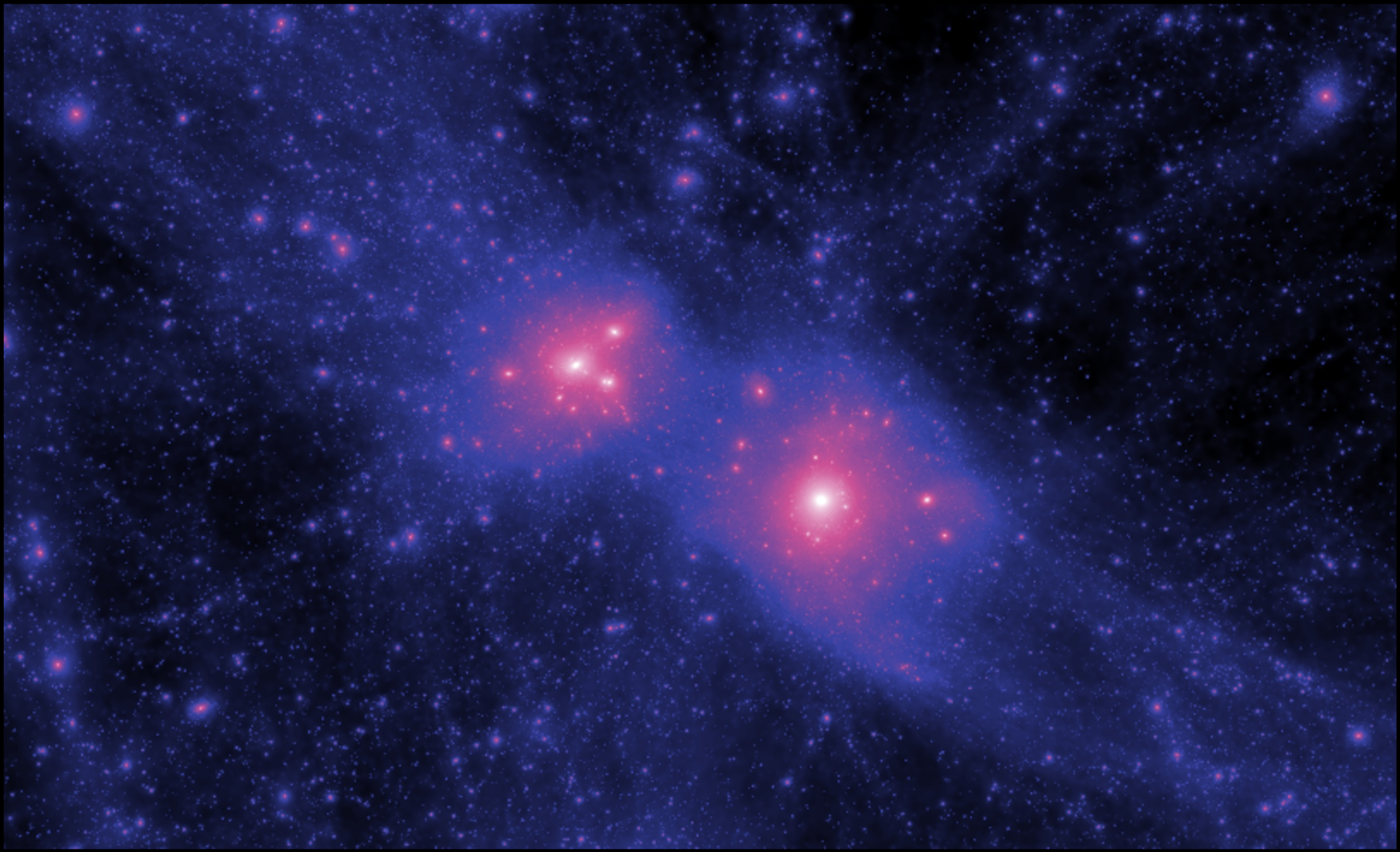
Predictions of the standard model of cosmology



- Cosmic web structure
- Hierarchical growth of structure
- “clumpiness”
- Self-similarity of dark matter halos

Dark matter halo of a Milky Way-like galaxy

Dark matter distribution in the local volume



APOSTLE project - AF+2016, Sawala+2016

Dark matter distribution in the local volume

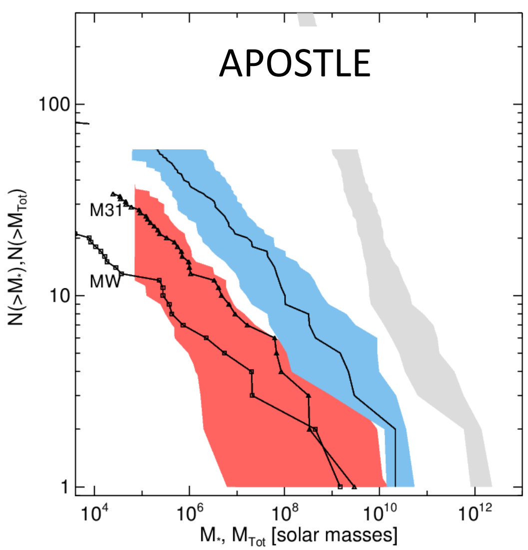
APOSTLE project - AF+2016, Sawala+2016

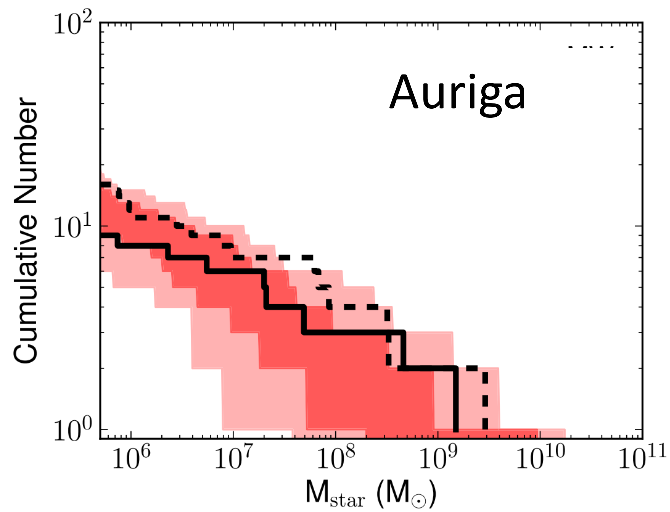
Abundance of satellite dwarf galaxies around Milky Way-like halos

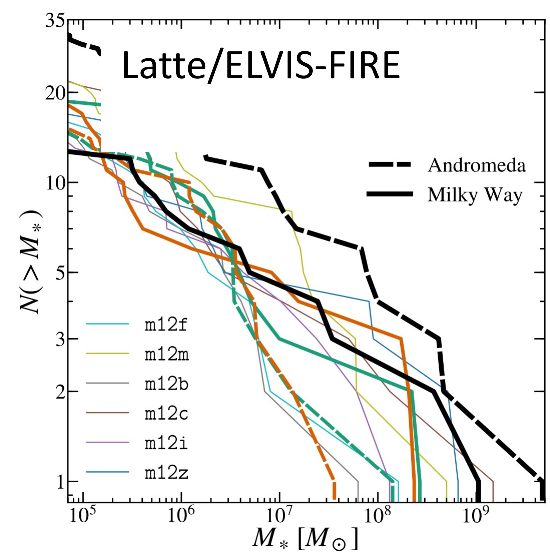
Current cosmological hydrodynamical simulation can produce realistic abundance of dwarf galaxies in the "classical regime"; i.e. > 10^5 M_{sun}

- supernovae feedback and reionisation (due cosmic UV/Xray background radiation) play key roles in getting the right abundance of low mass galaxies
- reionisation keeps the lowest mass halos free of stars/galaxies

see, also, NIHAO-UHD (Buck+), ARTEMIS (Font+)



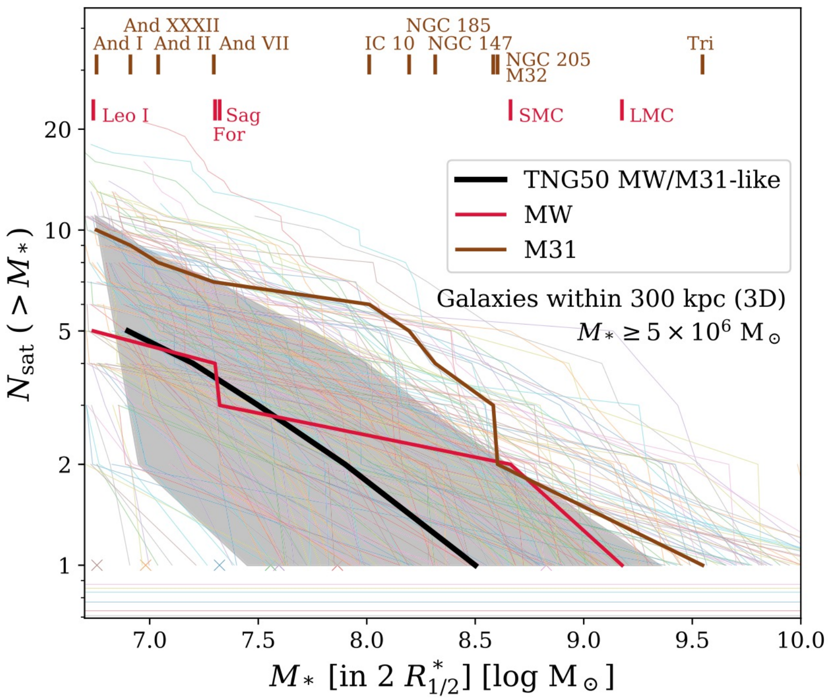




Abundance of satellite dwarf galaxies beyond the Milky Way

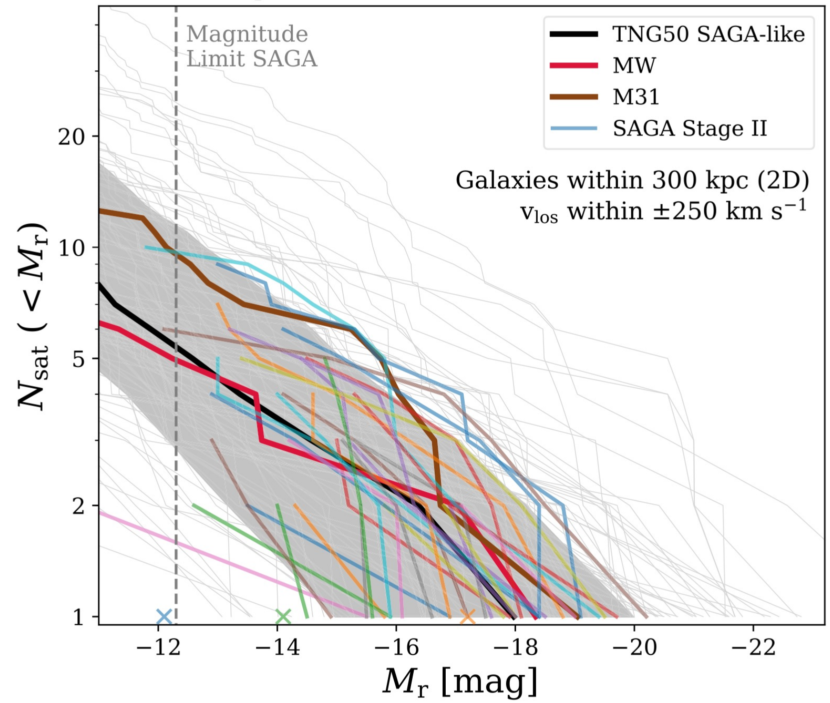
Engler+2021

~200 MW/M31-like hosts in TNG50



Beyond MW: SAGA satellites

(YY Mao & M. Geha)

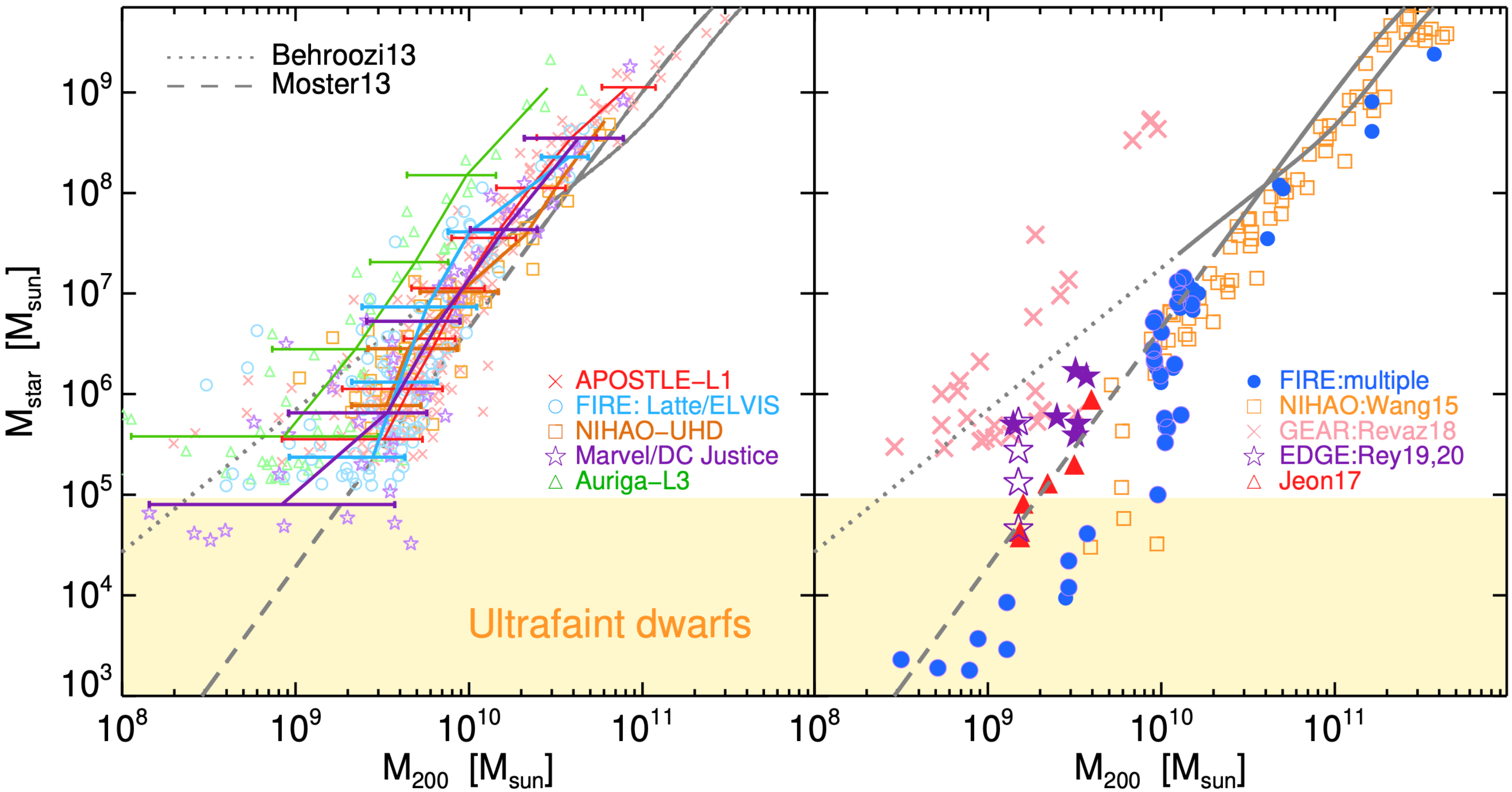


Also, Font+2021 (ARTEMIS simulations)

Stellar mass-halo mass relation at the faint end (dwarf galaxies) in hydrodynamical simulations

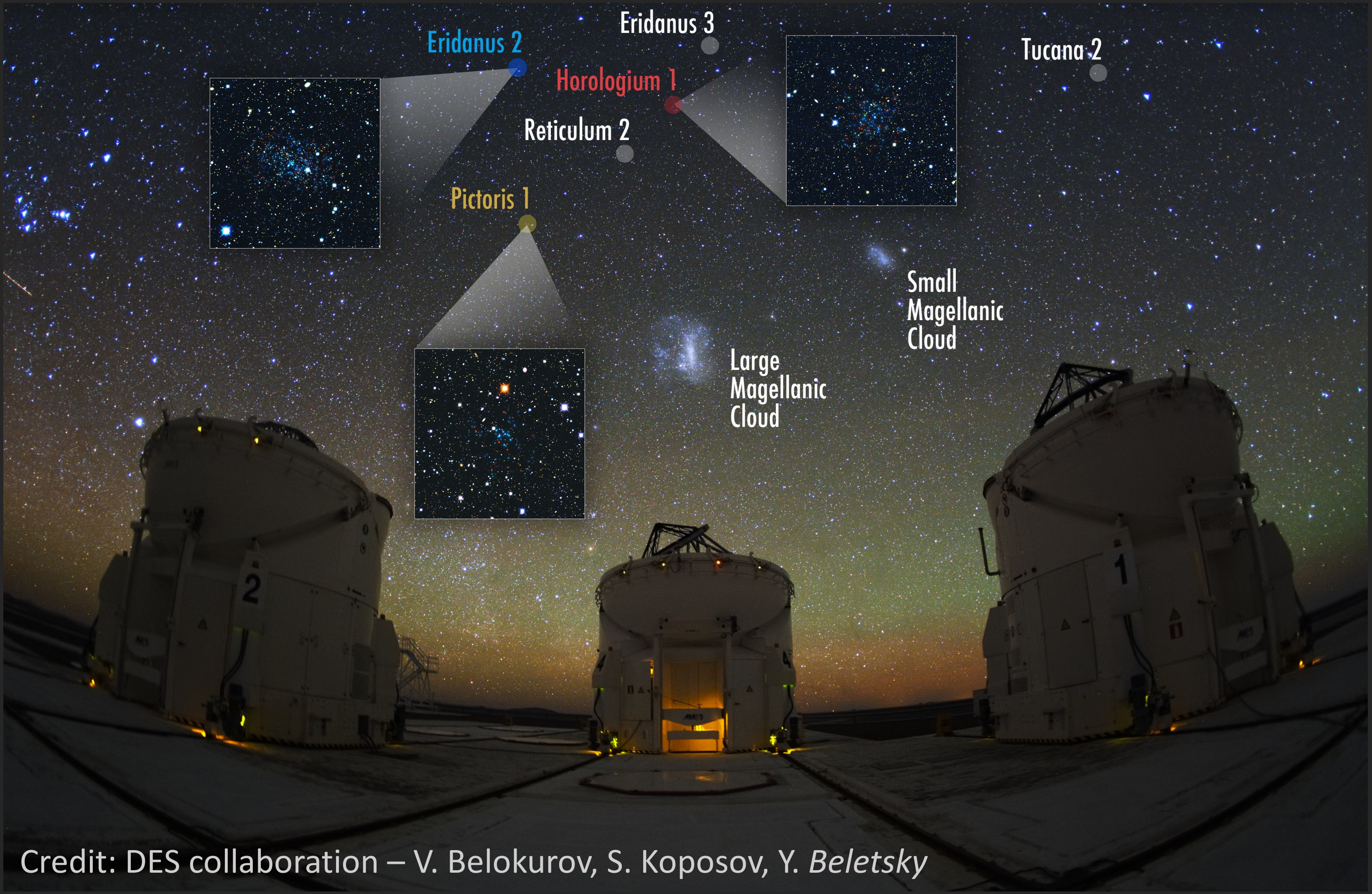
Field dwarf galaxies around MW-like halos

Simulations of isolated dwarf galaxies



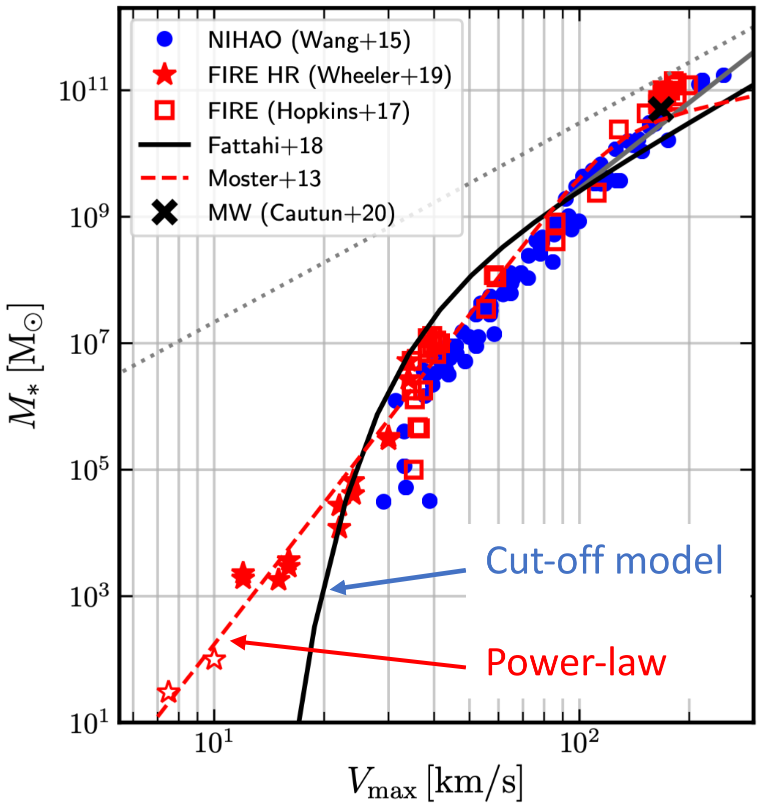
Sales, Wetzel & AF (2022)

(ultra faint) dwarf galaxies

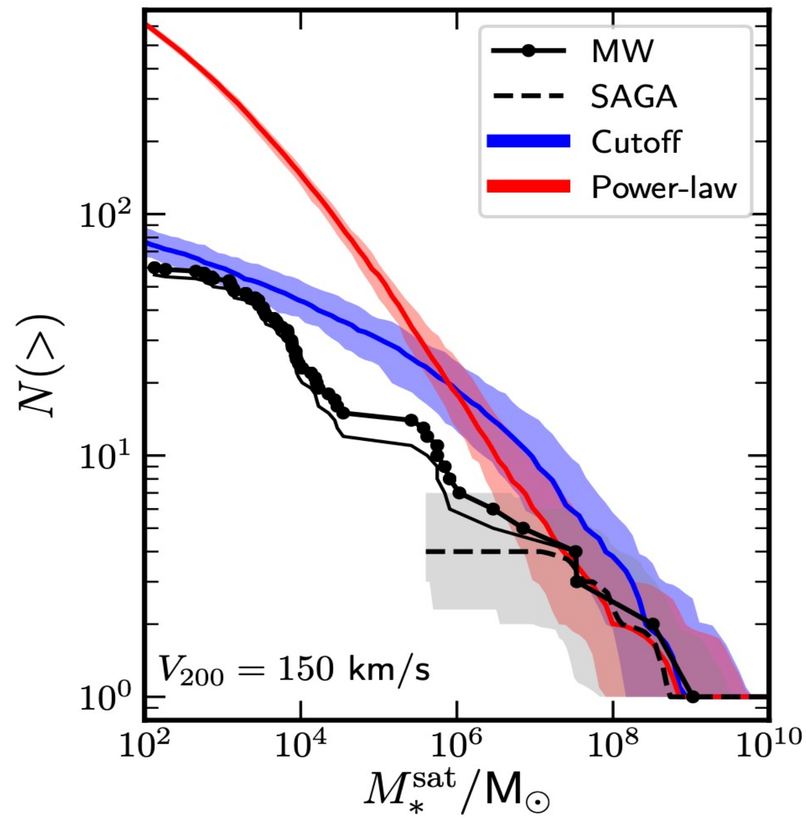


Stellar mass-halo mass relation at the faint end & the abundance of Milky Way satellites

Abundance of "ultra faint" dwarf galaxies is strongly dependent on the stellar mass-halo mass relation



~halo mass

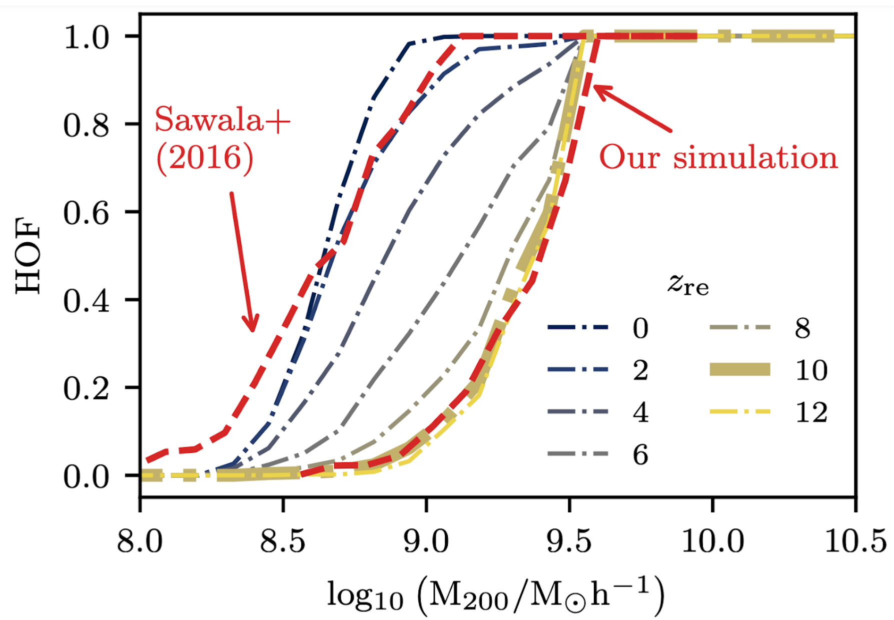


Santos-Santos+(incl. AF)2022

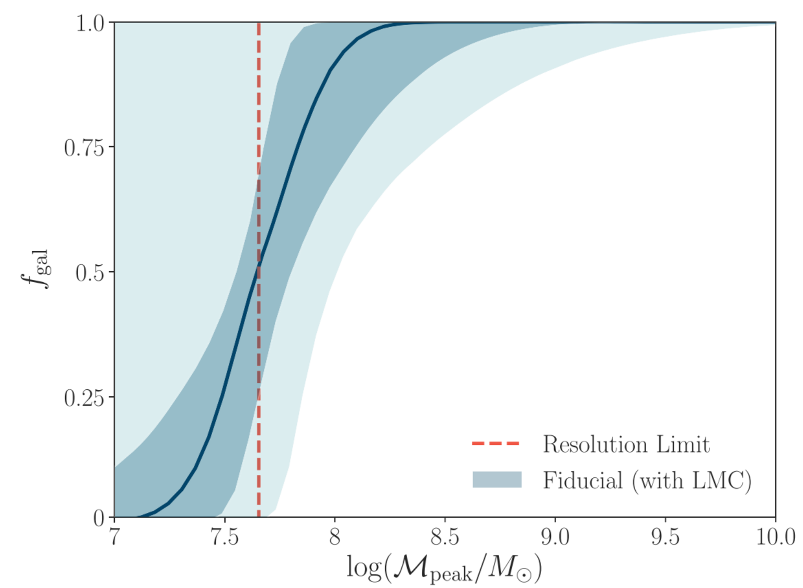
Stellar mass-halo mass relation at the faint end

Extra complication: halo occupation fraction (HOF) – not all low mass dark matter halos host stars/galaxies (because of reionisation and the the ability of gas to cool and form stars)

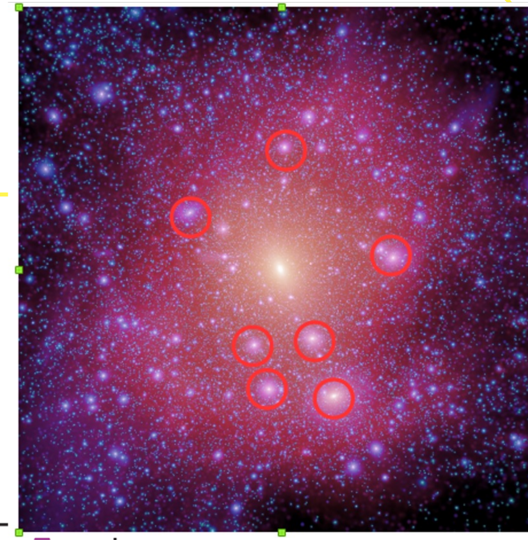
Simulations & semi-empirical modelling
Benitez-llambay & Frenk (2020)



Observations & semi-empirical modelling
Nadler + 2020

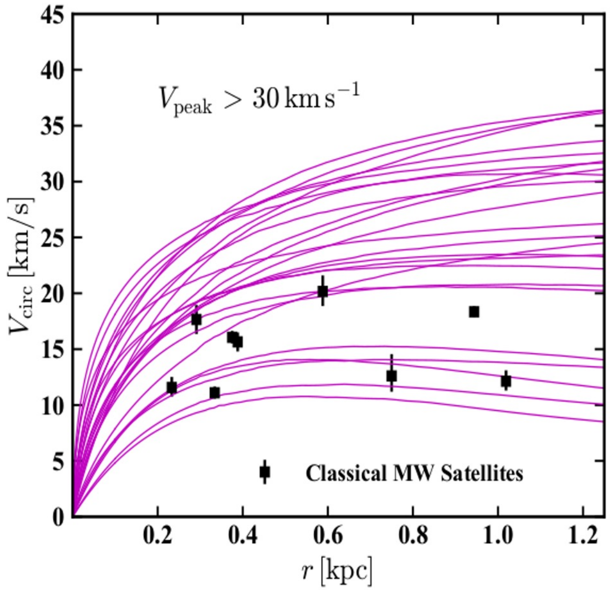


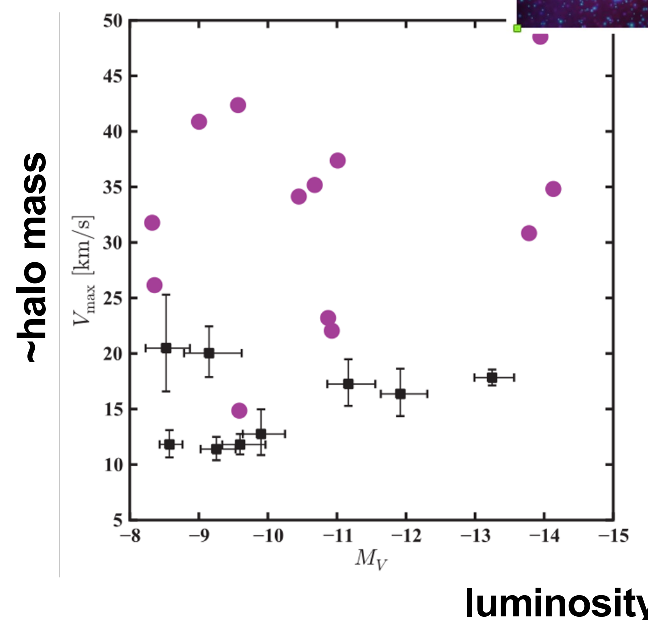
The too-big-to-fail problem for satellites
(Boylan-kolchin+2012)



Based on dark matter-only simulations from Aquarius project

Where are the most massive subhalos of the Milky Way?
They are “too big to fail” forming stars.



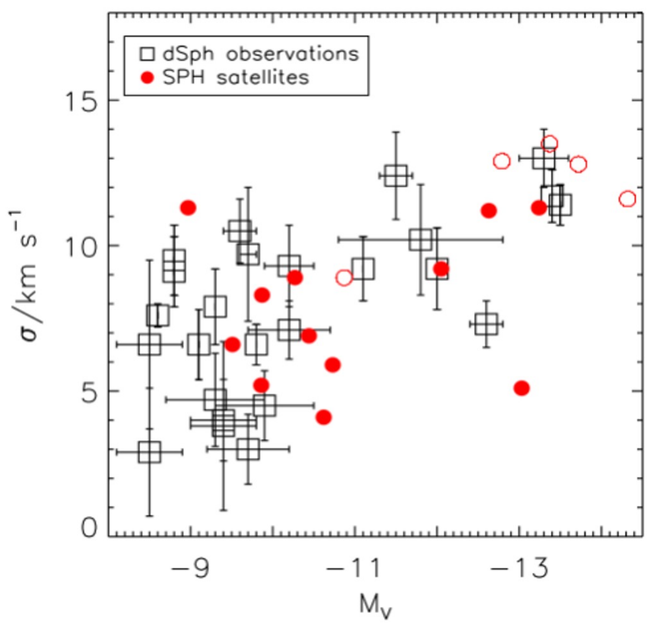


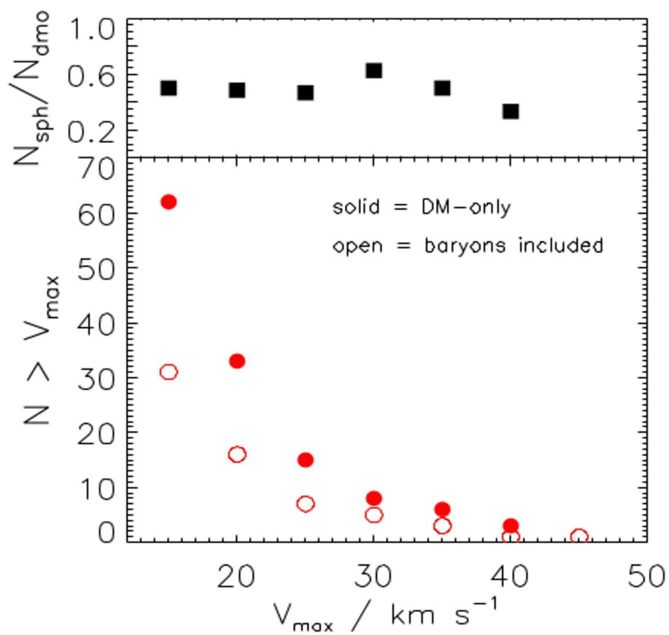
- Dwarf galaxies seem to live in halos less massive than predicted
- DM subhalos are denser than observed.

Solutions to the TBTF (for satellites)

Brooks et al. 2014 :
(hydro simulations with cored DM profile)

- Shallow (cored) dark matter density profiles bring down enclosed mass
- Fewer number of massive subhalos due to
  - enhanced tidal stripping due to DM cores and due to the baryons in the centre of host
  - enhanced disruption





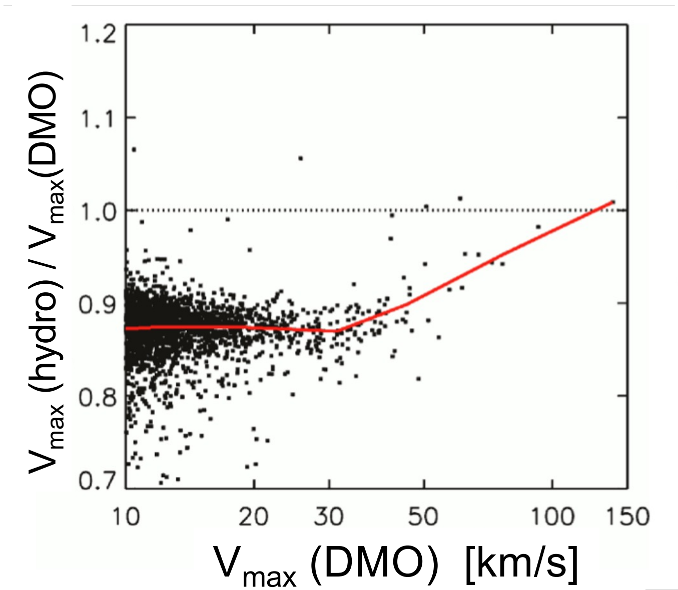
Solutions to the TBTF (for satellites)

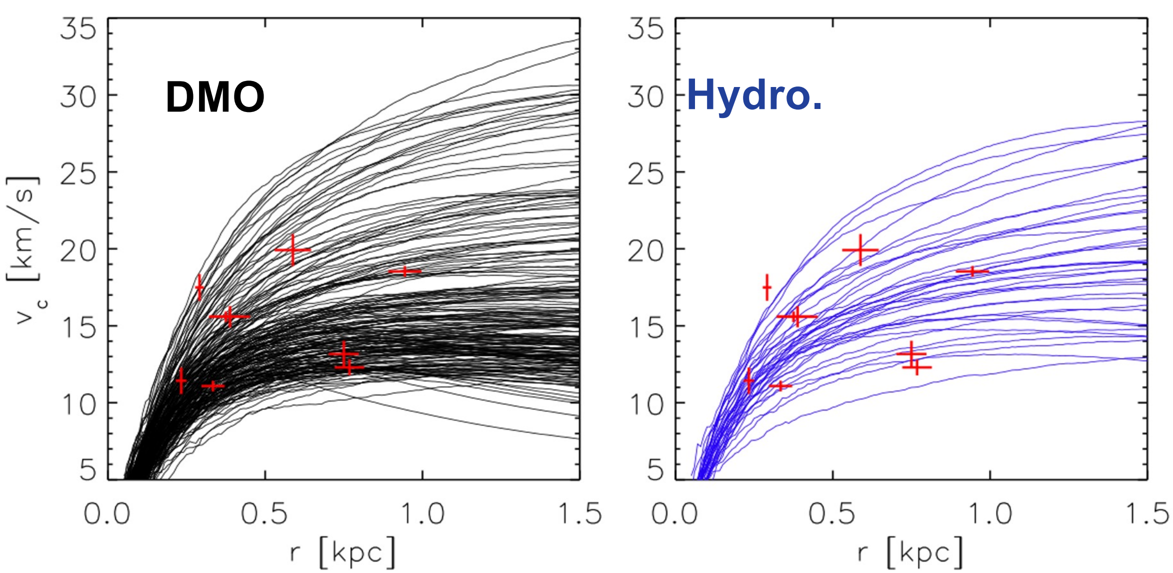
APOSTLE hydrodynamical simulations (with cuspy DM profiles):

Number of massive subhalos is reduced in hydrodynamical simulations compared to DMO simulations

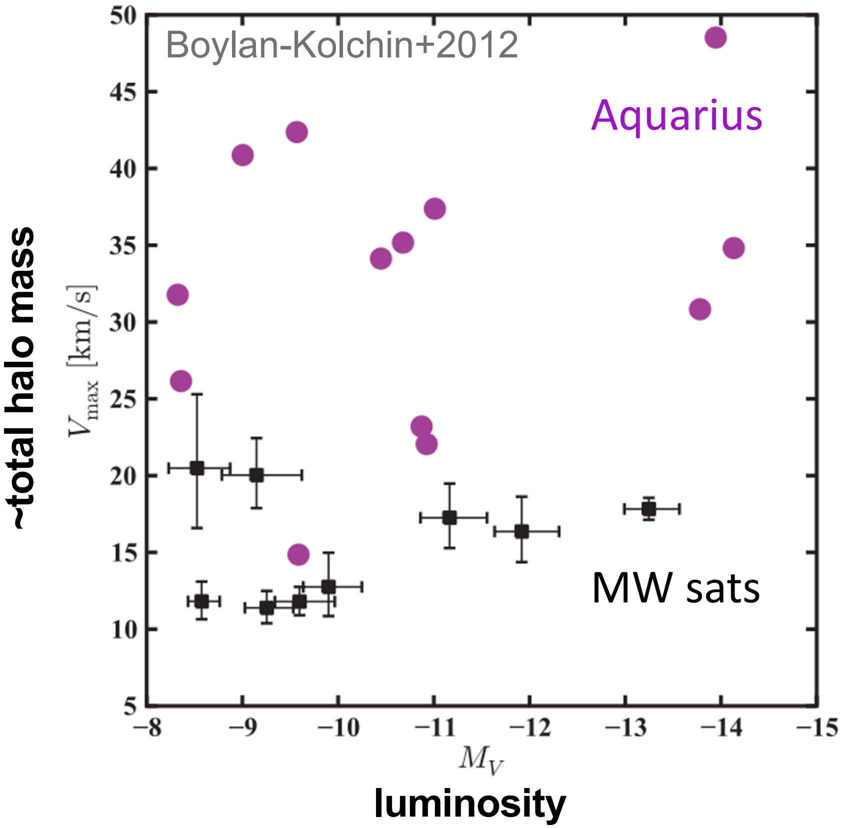
- Objects have lower (total) mass in hydro simulations compared to their DMO counterparts

- Host disk can disrupt subhalos quicker





Solutions to the TBTF (for satellites)



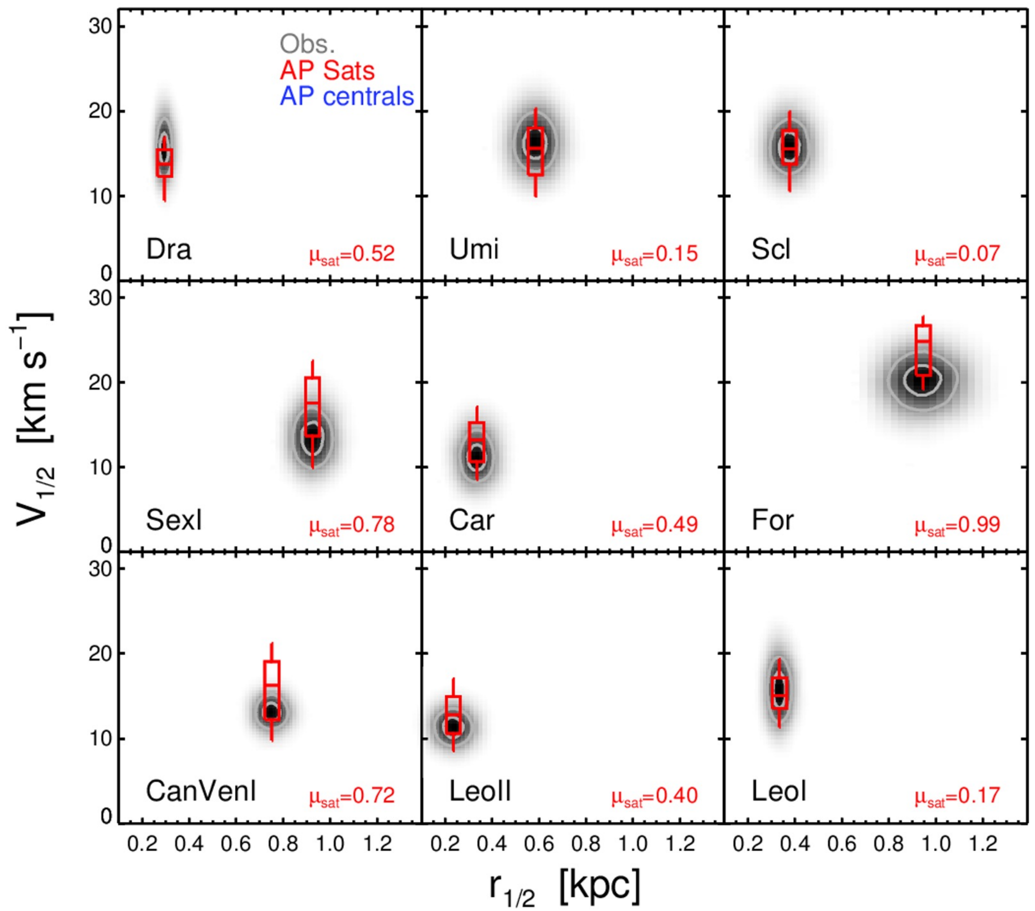
Issues with such comparison:

- Simulation: abundance matching does not work at the lowest mass end (see, e.g. Sawala+2014)
- Observation: V_{max} (or halo mass) is not directly observable. It is always an extrapolation for these galaxies.
  What is measurable more robustly is the mass (i.e. circular velocity) inside half light radius (see e.g. Wolf+2010)

Solutions to the TBTF (of satellites)

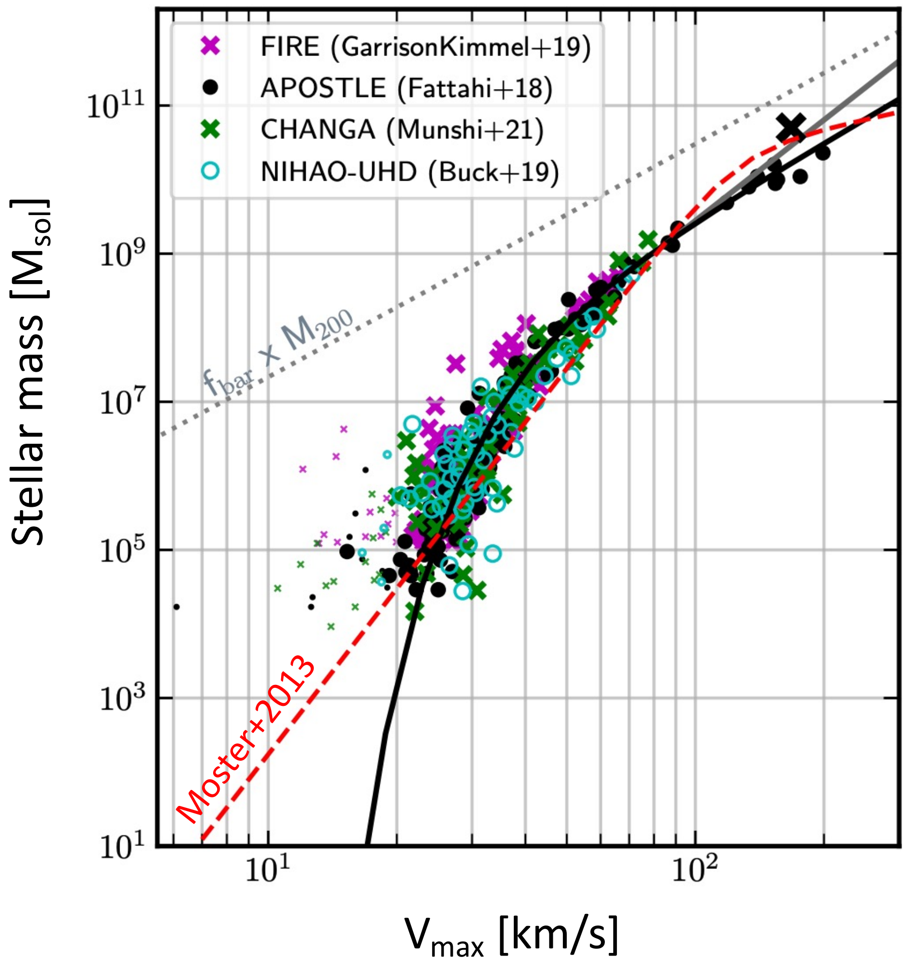
APOSTLE hydrodynamical simulations (with cuspy DM profiles):

Mass (inside half ligh radius) of the classical satellites of the MW compared to APOSTLE satellites of similar mass.



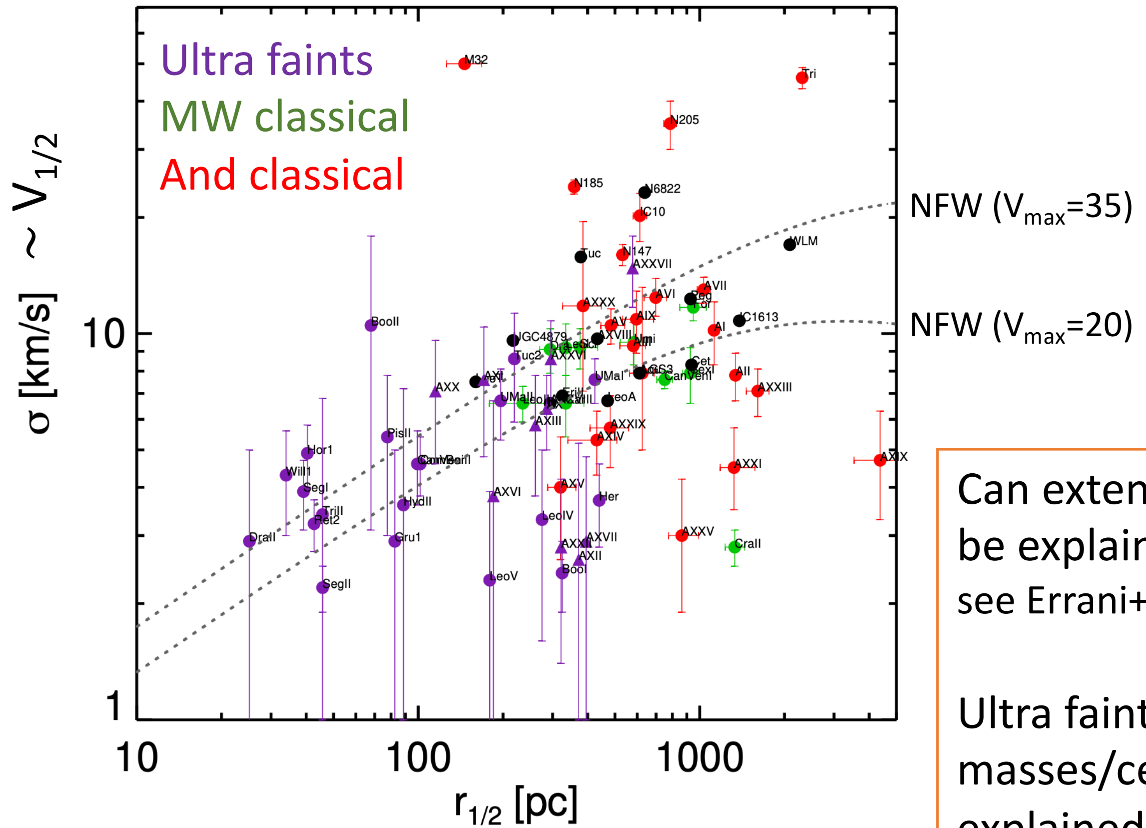
AF+2016

Dark matter content of Local Group dwarfs



Prediction: Dwarf galaxies with $M_{star} < 10^7 M_{sol}$ have a narrow range of halo mass.
(based on APOSTLE: $V_{max} \sim$ 20-40 km/s)

Dark matter content of Local Group dwarfs



AF+2018

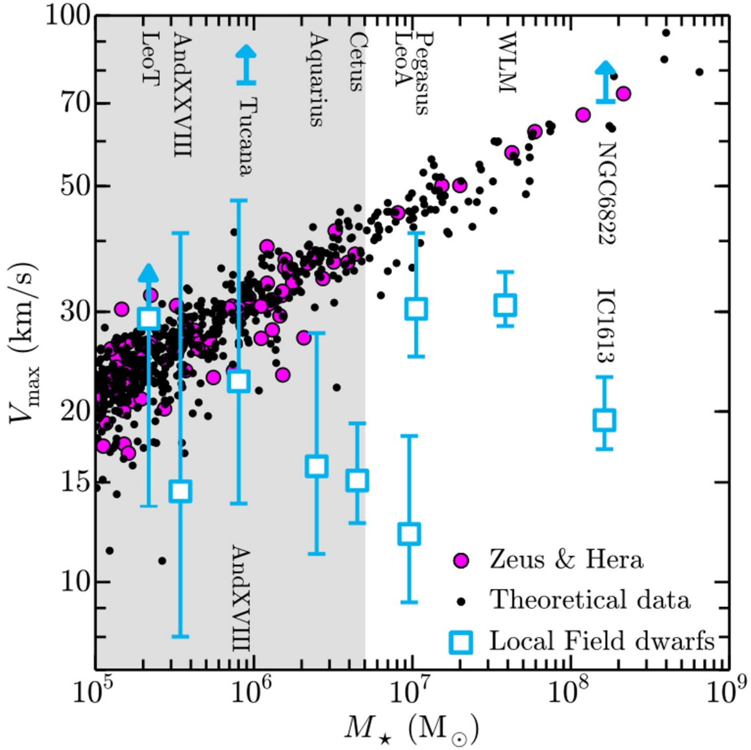
Can extended low density dwarfs (like Cra 2) be explained by tidal stripping?
see Errani+2022, Borukhovetskaya+(incl AF)2022

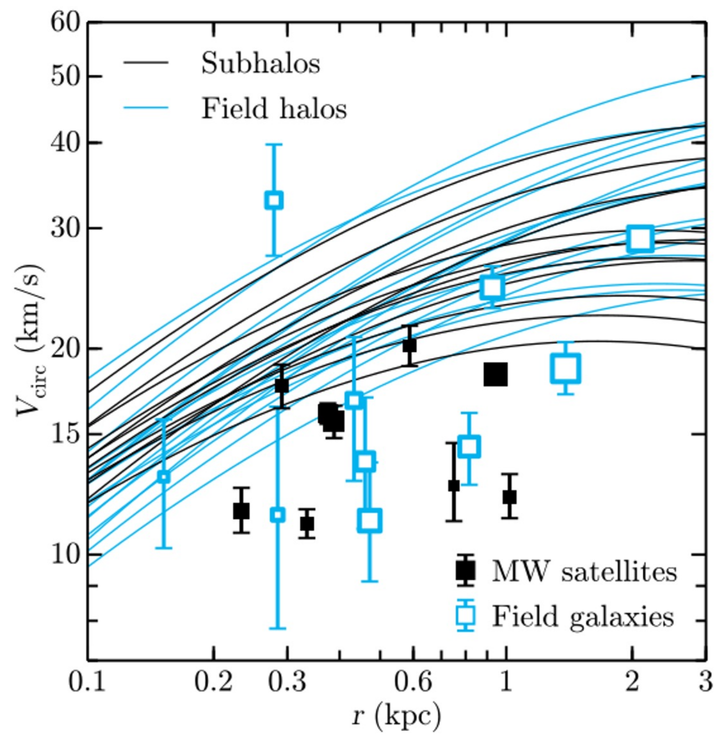
Ultra faint dwarf galaxies favour higher halo masses/central densities. Could they be explained in SIDM models?

Dwarf galaxies and the too-big-to-fail problem in the field

Garrison-Kimmel+2014
Based on ELVIS dark-matter only simulations of Local Group-like volumes

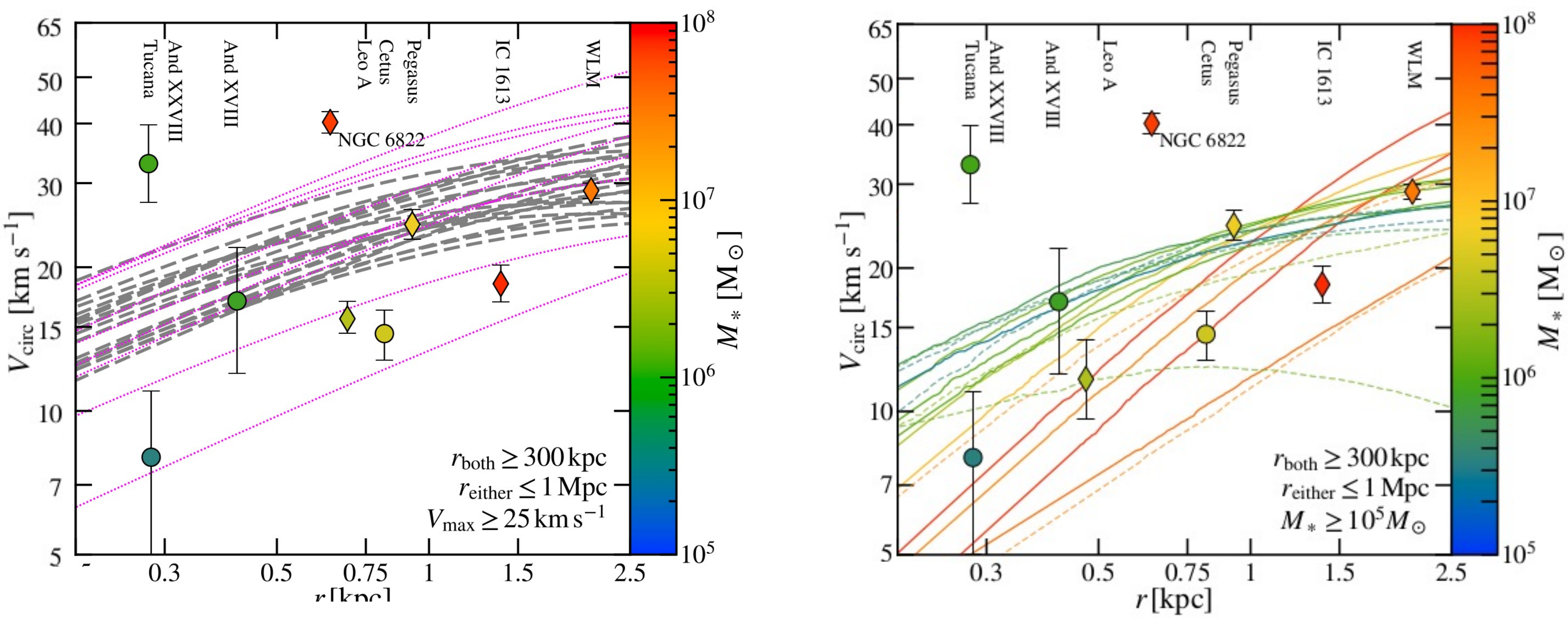
- filed dwarf galaxies around the LG have lower mass than "predicted"
- there are about 10-20 "unaccounted for" halos around the simulated LGs





Solutions to the TBTF (in the field)

Local Group simulations from the “ELVIS on FIRE”
Garrison-Kimmel+2018

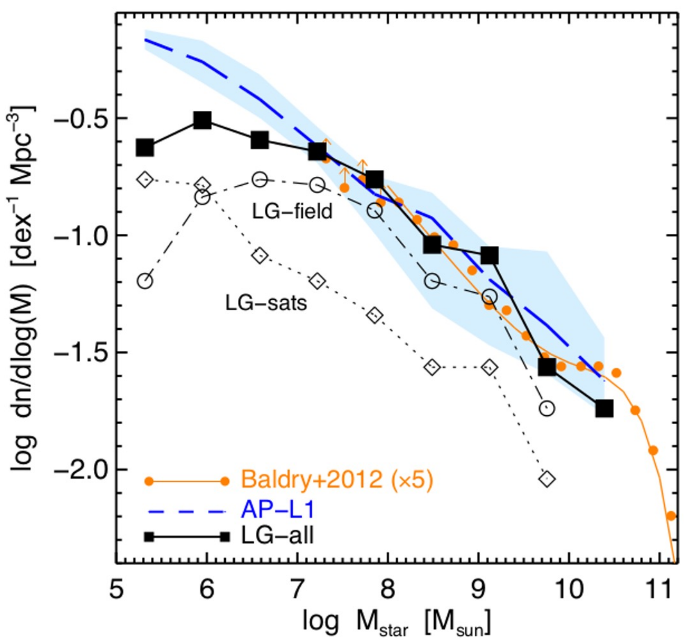


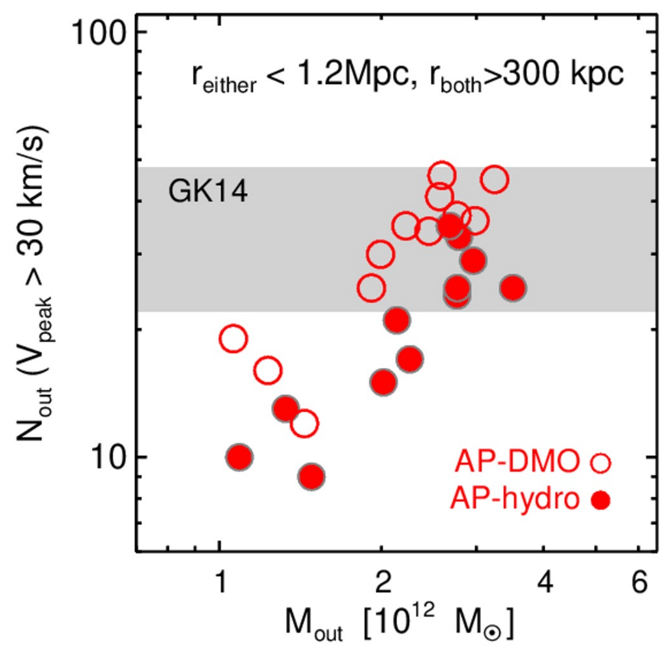
Solutions to the TBTF (in the field)

- Halos have lower mass in hydro simulations

- Number of halos around the Local Group depends on how much mass is in the environment

- Sample of dwarf galaxies (as bright as classical satellites of the MW) is incomplete.





AF+2020

Can we address the Too-big-to-fail problem?

Current cosmological hydrodynamical simulations (*with and without central DM cores*) can address it and the solutions have various aspects:

(i) Halos in hydrodynamical simulations have lower masses than their matched counterparts in DMO simulations

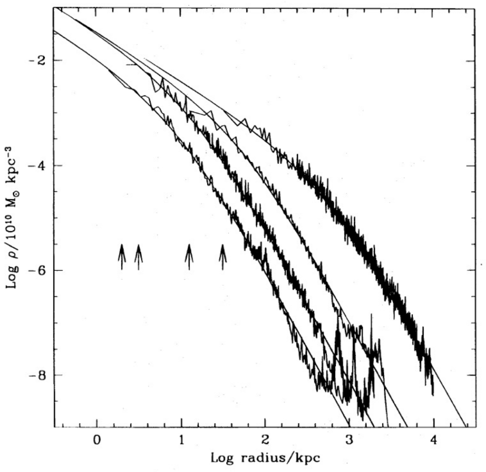
(ii) baryonic feedback processes ***may*** bring down the density of the DM in the inner regions (not in all simulations) – to be continued

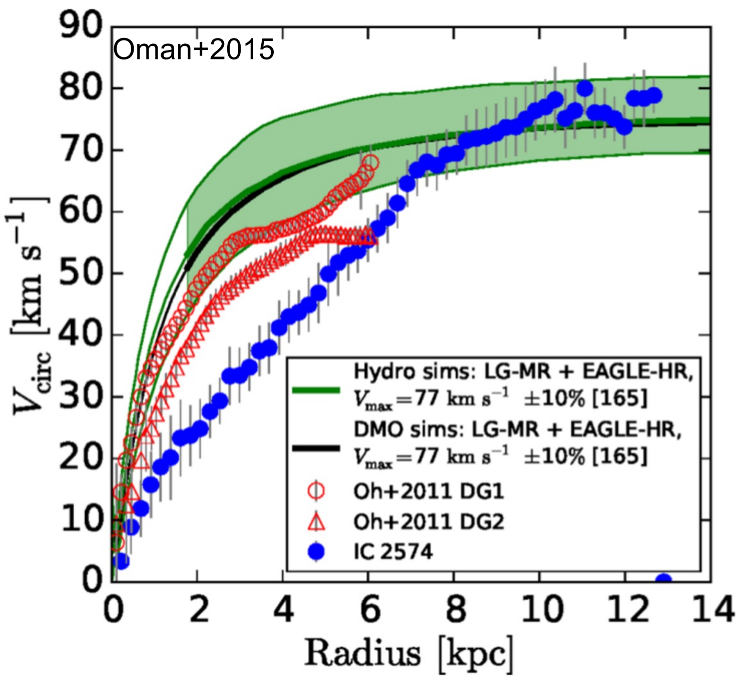
(iii) There is a large halo-to-halo scatter in number of subhalos

- (iv-a) For satellites: enhanced disruption of subhalos by Galactic disks, especially in simulations with cored DM pofiles
- (iv-b) for field: sample of dwarf galaxies is far from complete – mass of the Local Group is not well constrained

What is the dark matter content of dwarf galaxies and can it be explained in current models?

Cusp vs. Core problem
(Flores & Primack 1994, Moore 1994)





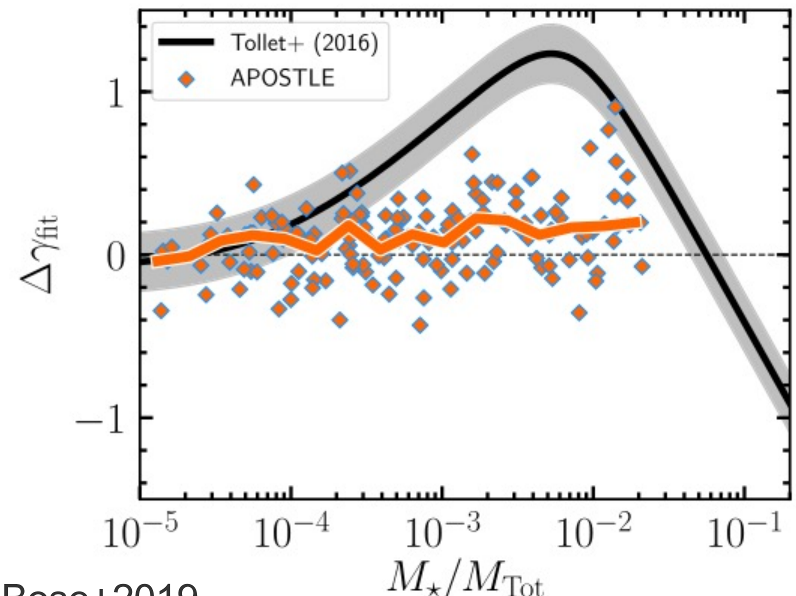
CDM circular velocity

Observed rotation curve of IC-2574

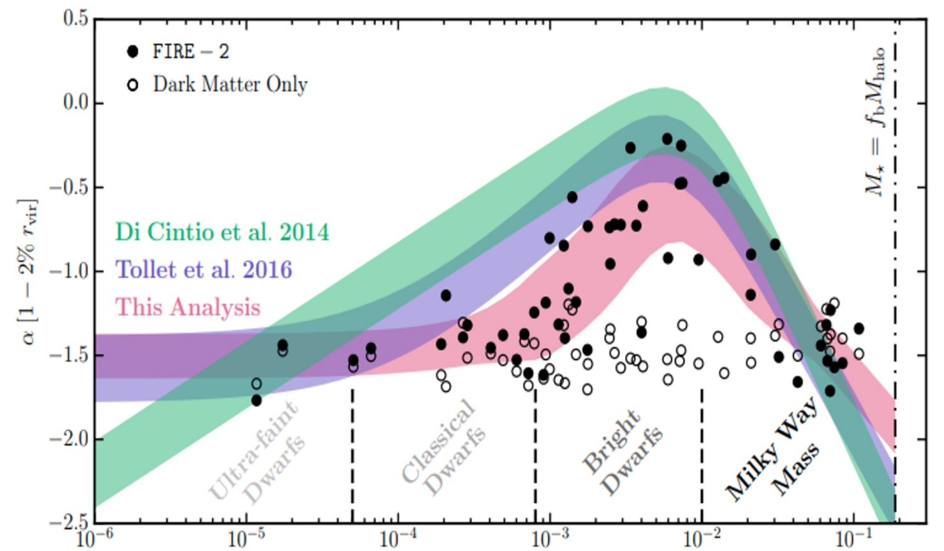
Linearly rising rotation curve ~ flat density profile (cored)

Navarro+1996 and Pontzen & Governato 2011: fluctuation in the potential due to supernovae feedback can change the density in the inner regions.

Core vs. Cusp in the simulations



Bose+2019



M_{star}/M_{halo}

Lazar+2020

No cores in APOSTLE (EAGLE) or Auriga or (Illustris-TNG)

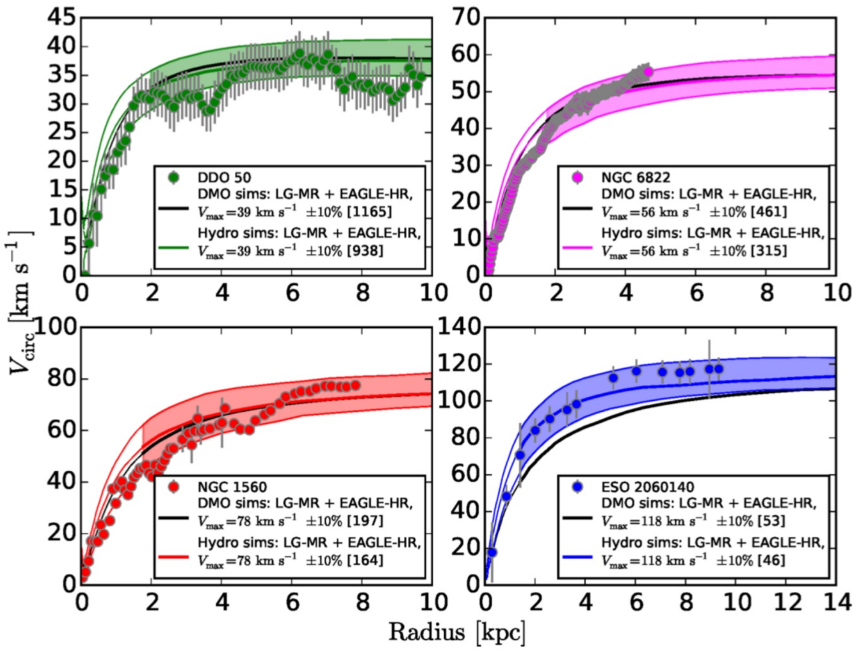
Resolution: (0.5-1)*10^4 M_{sol} for baryon mass elements

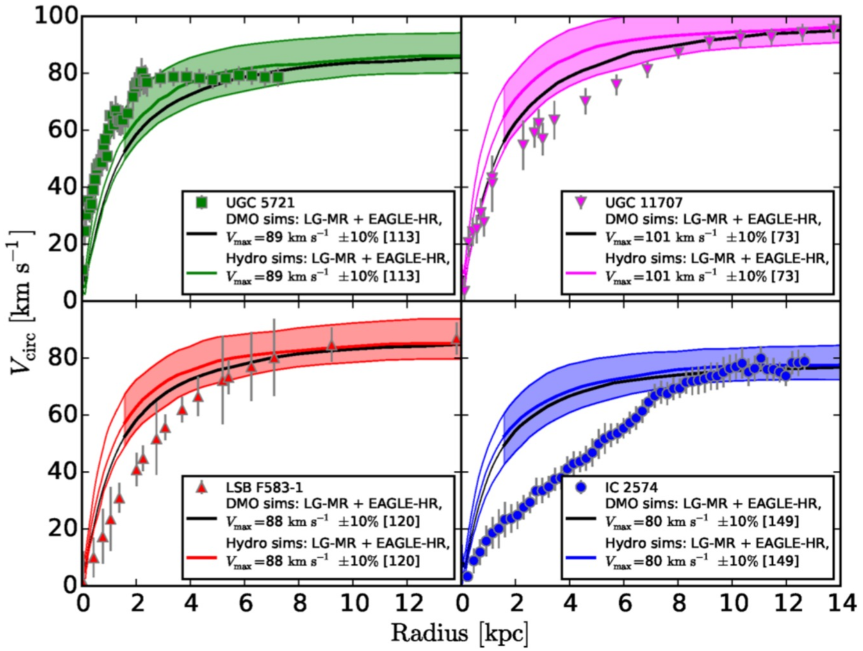
Cores in FIRE, NIHAO, sims. of J. Reads, A. Brooks, ..

Resolution of “Late” or “ELVIS on FIRE: (0.4-0.7)*10^4 M_{sol} baryon mass elements

The core-cusp problem or the diversity of rotation curves

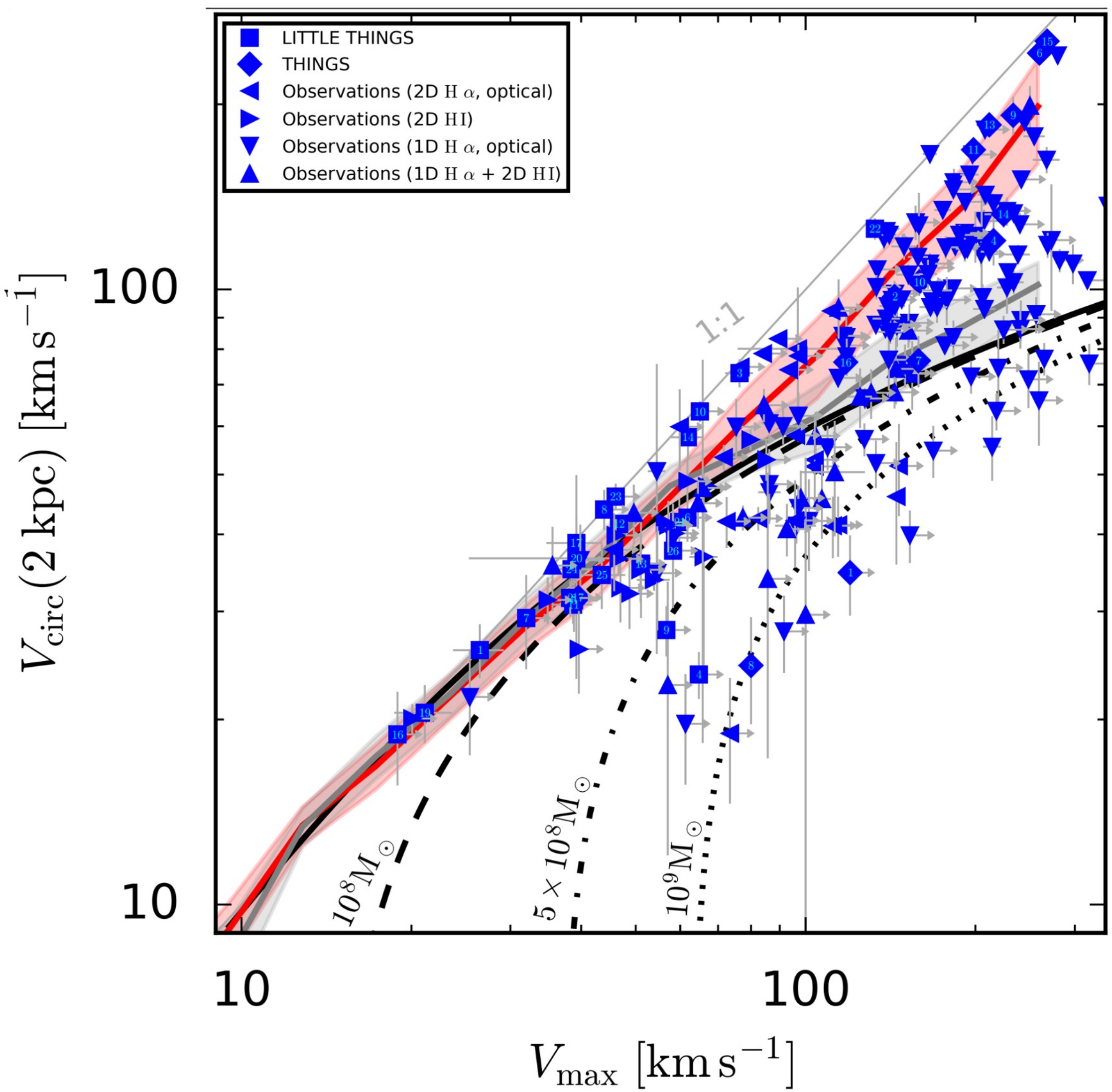
HI Rotation curves of field dwarf galaxies (THINGS and LITTLE THINGS) compared with cuspy rotation curves of similar V_{out}



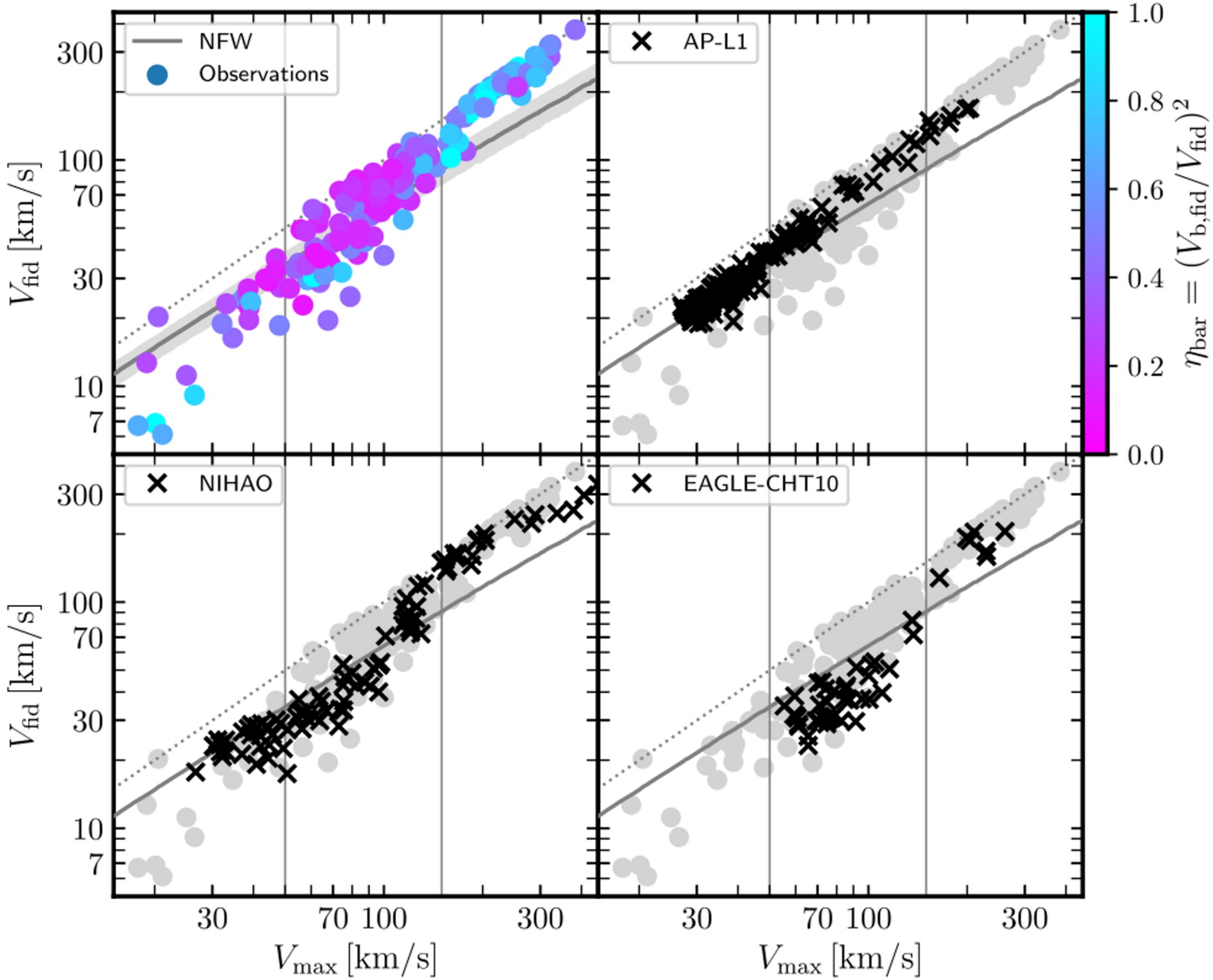


Oman+2015

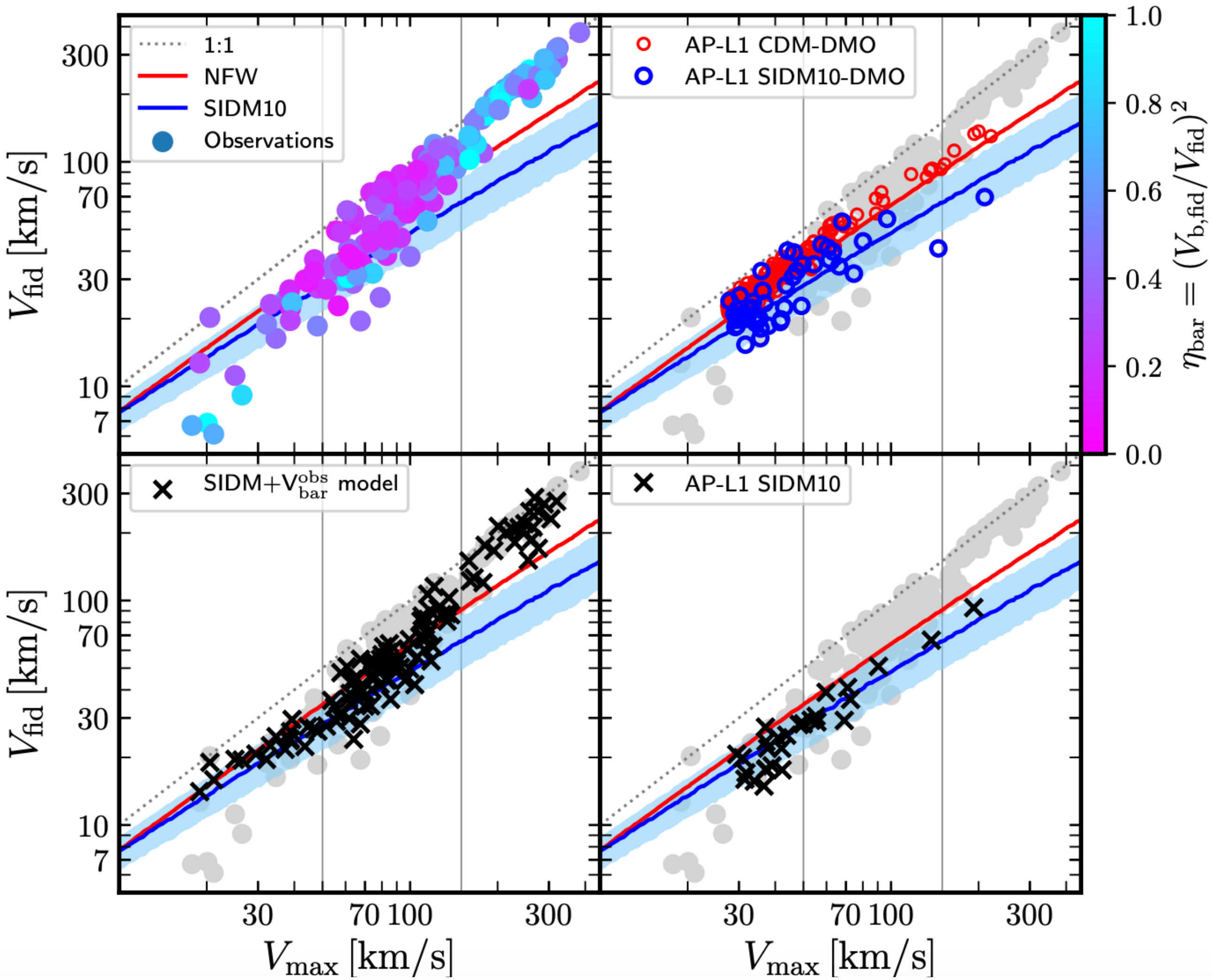
The diversity of rotation curves (Oman+2015)



The diversity of rotation curves



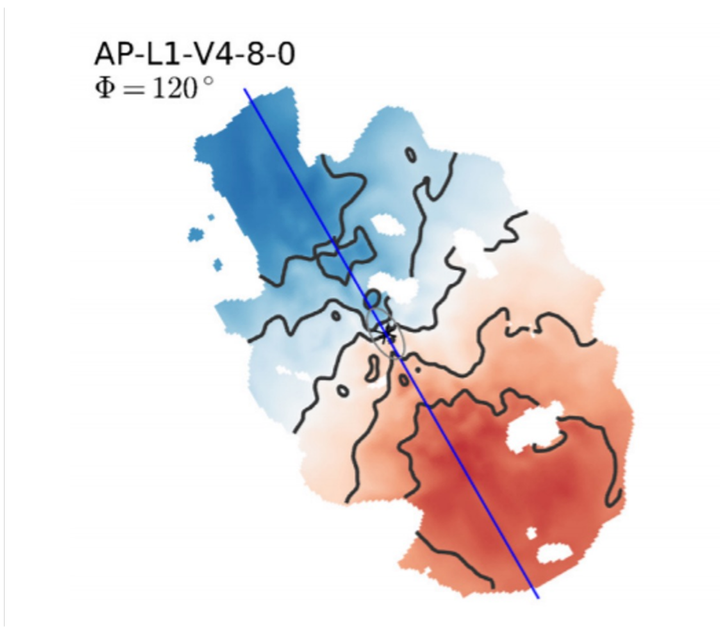
The diversity of rotation curves

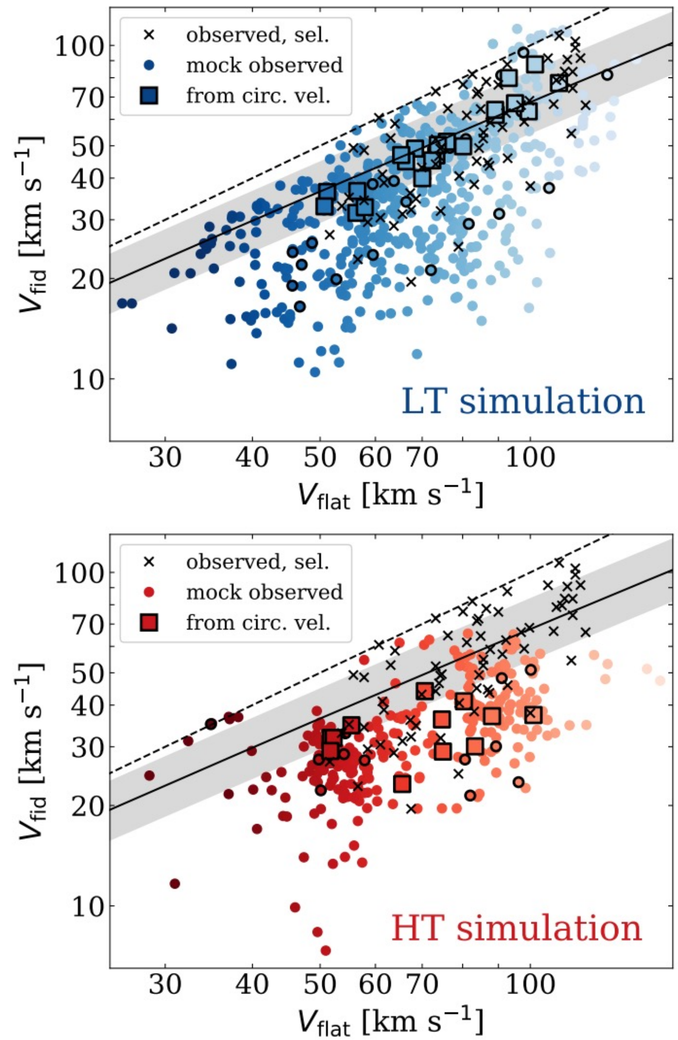


The diversity of rotation curves

Maybe systematic uncertainties?

Mock observing simulated dwarf galaxies





Oman+2018; Roper, Oman+2022

Proposed solutions to the diversity of rotation curves problem

- Baryonic processes altering the dark matter distribution in the inner regions of halos (e.g. creating cores)
- Uncertainties in the inferred total (or DM) mass from observational data and gas kinematics
- Dark matter self-interaction (SIDM) altering the shape of DM density profiles

Summary

No tension	Uncertain	Weak tension	Strong tension
Missing satellites	$M_\star$-M_{halo} relation	Too big to fail	Diversity of rotation curves
	Core-cusp	Diversity of dwarf sizes	Satellite planes
		Quiescent fractions	