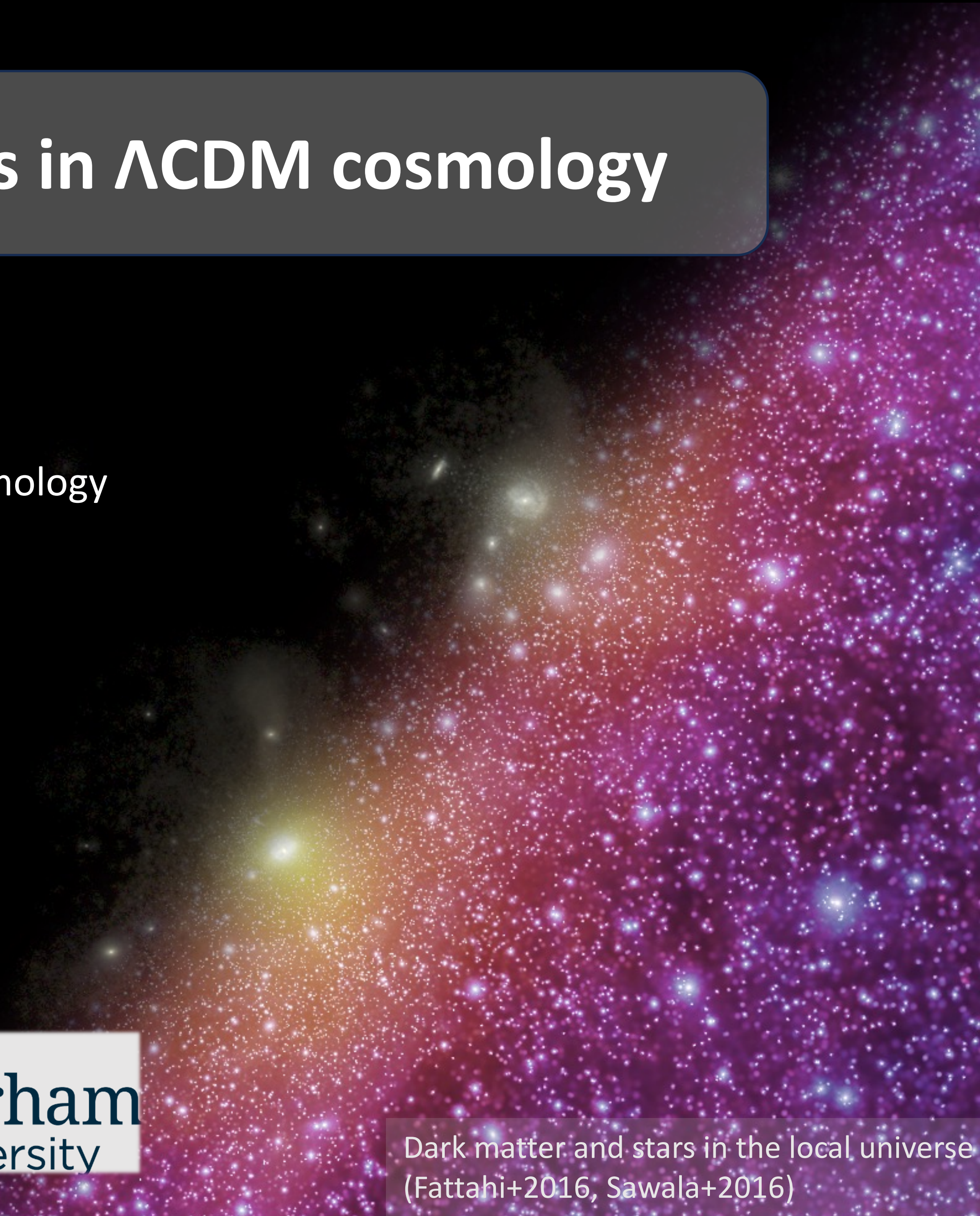
Small scale frictions in ΛCDM cosmology

Azadeh Fattahi
Institute for computational Cosmology
Durham University, UK

TeVPA 2023, Napoli



Dark matter and stars in the local universe
(Fattahi+2016, Sawala+2016)

Outline

- Background:

  the predictions of the standard model of cosmology

- Abundance of dwarf galaxies

  “missing satellites problem”
  cold vs warm dark matter

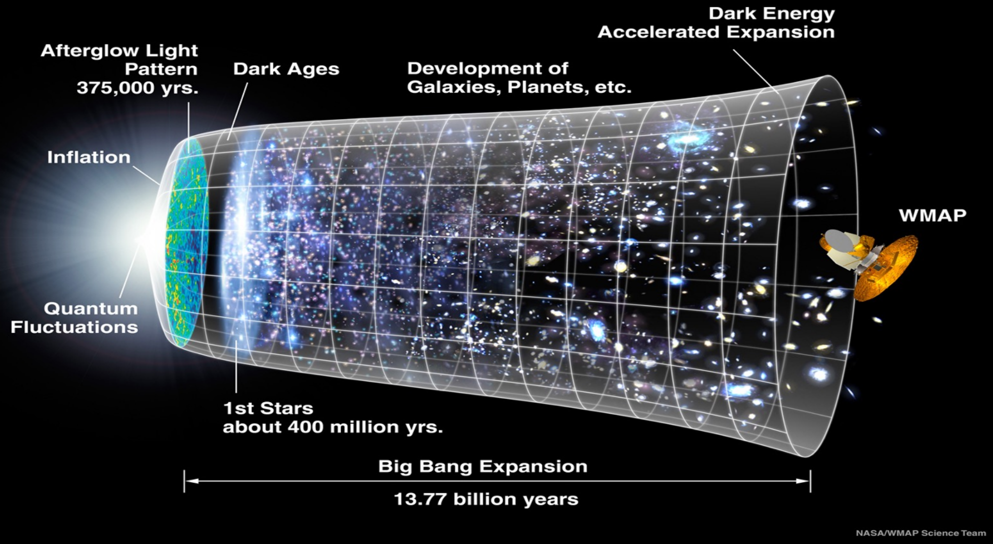
- Dark matter content of dwarf galaxies

  “too big to fail”

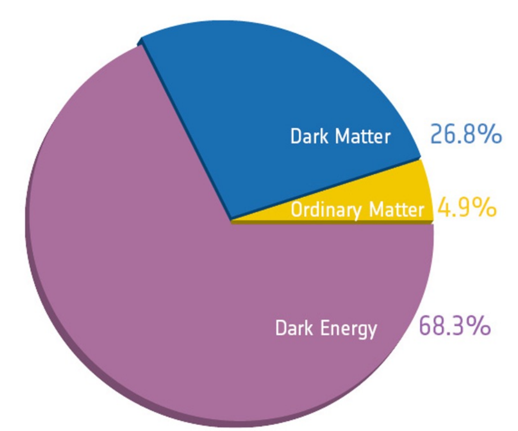
- Dark matter distribution inside dwarf galaxies

  core vs cusp problem
  diversity of rotation curves

Standard model of cosmology: LCDM
Lambda Cold Dark Matter



Credit: NASA/WMAP team



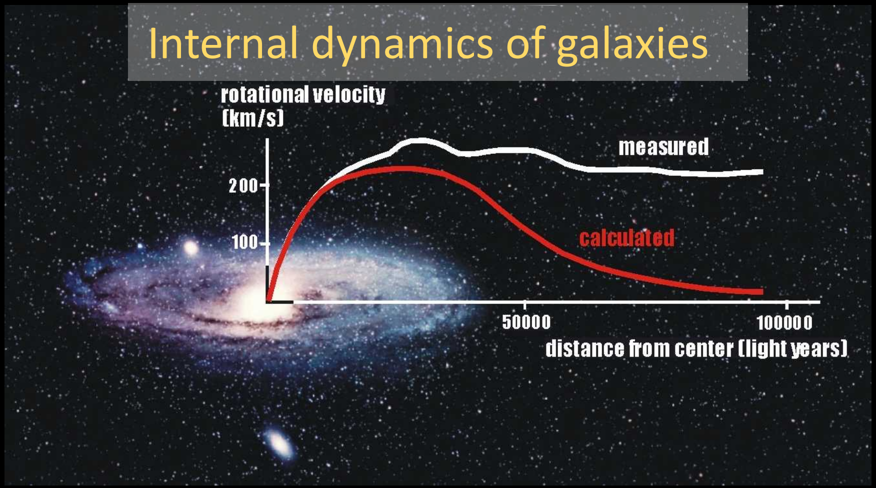
Credit: Planck collaboration

Ordinary Matter ~5%
(planets, stars, gas, galaxies, ...)

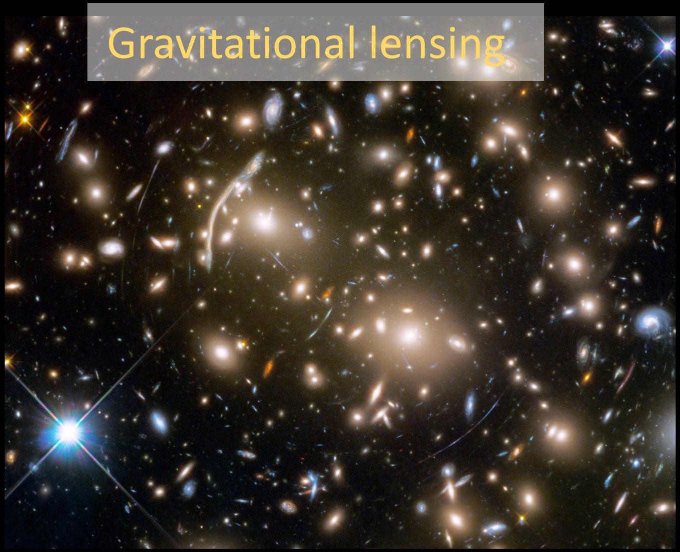
Dark Matter ~25%
Interacts gravitational with itself and ordinary matter

Dark energy ~70%
accelerating the expansion of the Universe

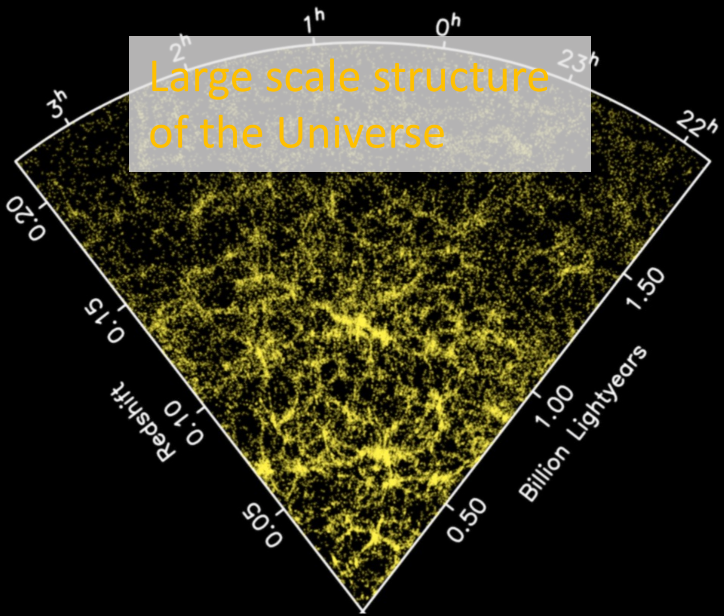
Where do we see evidence of dark matter ?



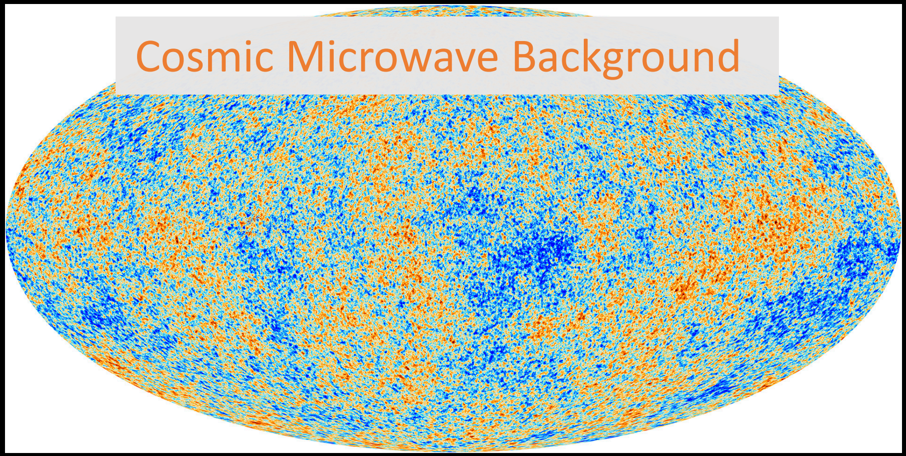
Internal dynamics of galaxies



Gravitational lensing



Large scale structure of the Universe

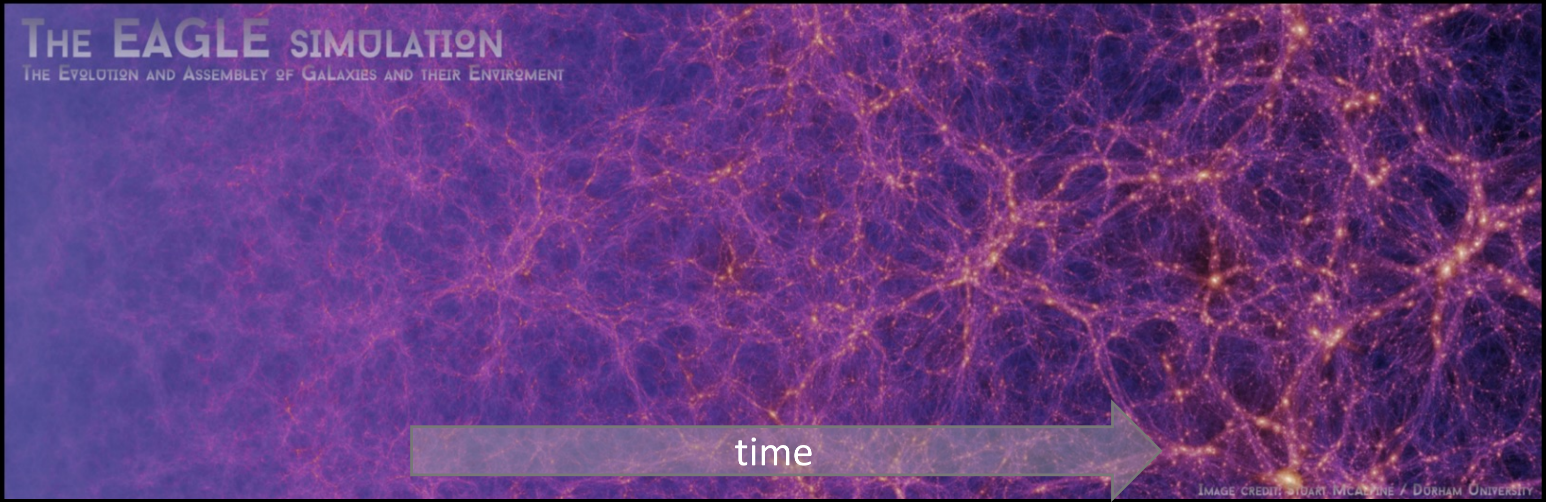


Cosmic Microwave Background

Predictive power of the model realised by numerical simulations

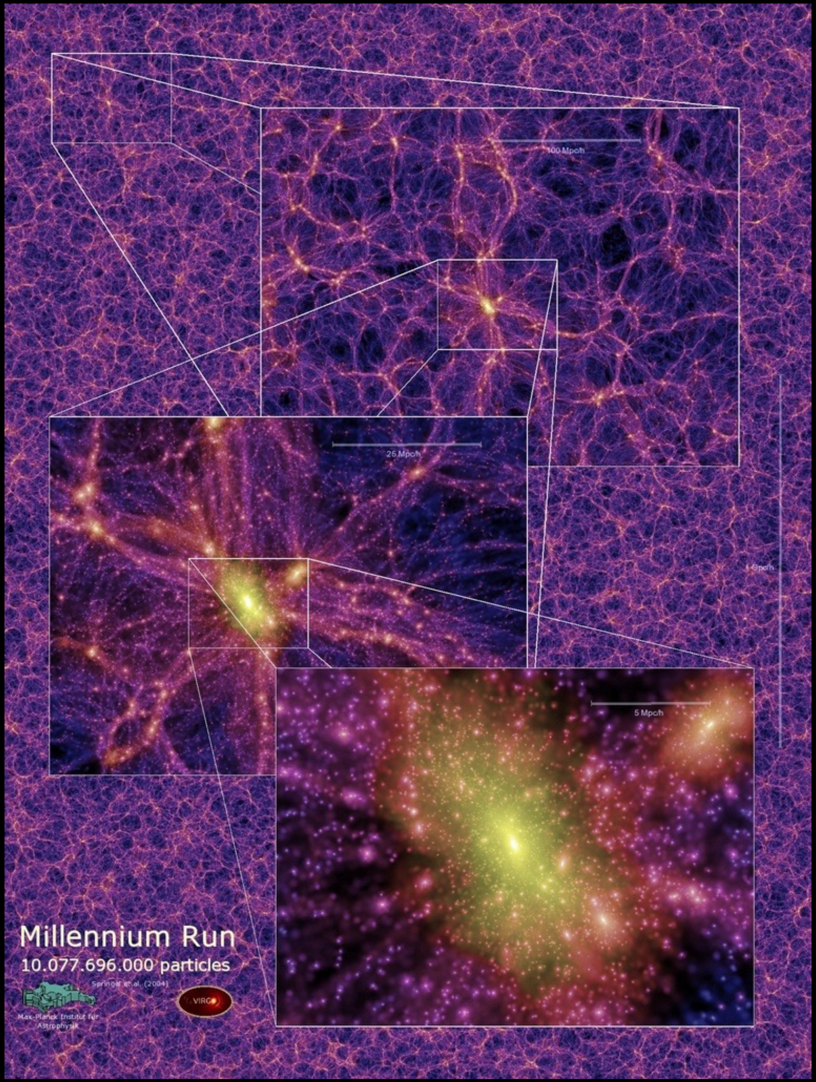
Numerical simulations are needed to follow the non-linear growth of structure.

Cosmological simulations:
- Starting from initial conditions motivated by CMB
- early efforts included dark matter only simulations (star formation, etc are neglected)



Credit: EAGLE project (Schaye et al. 2015 – S. McAlpine)

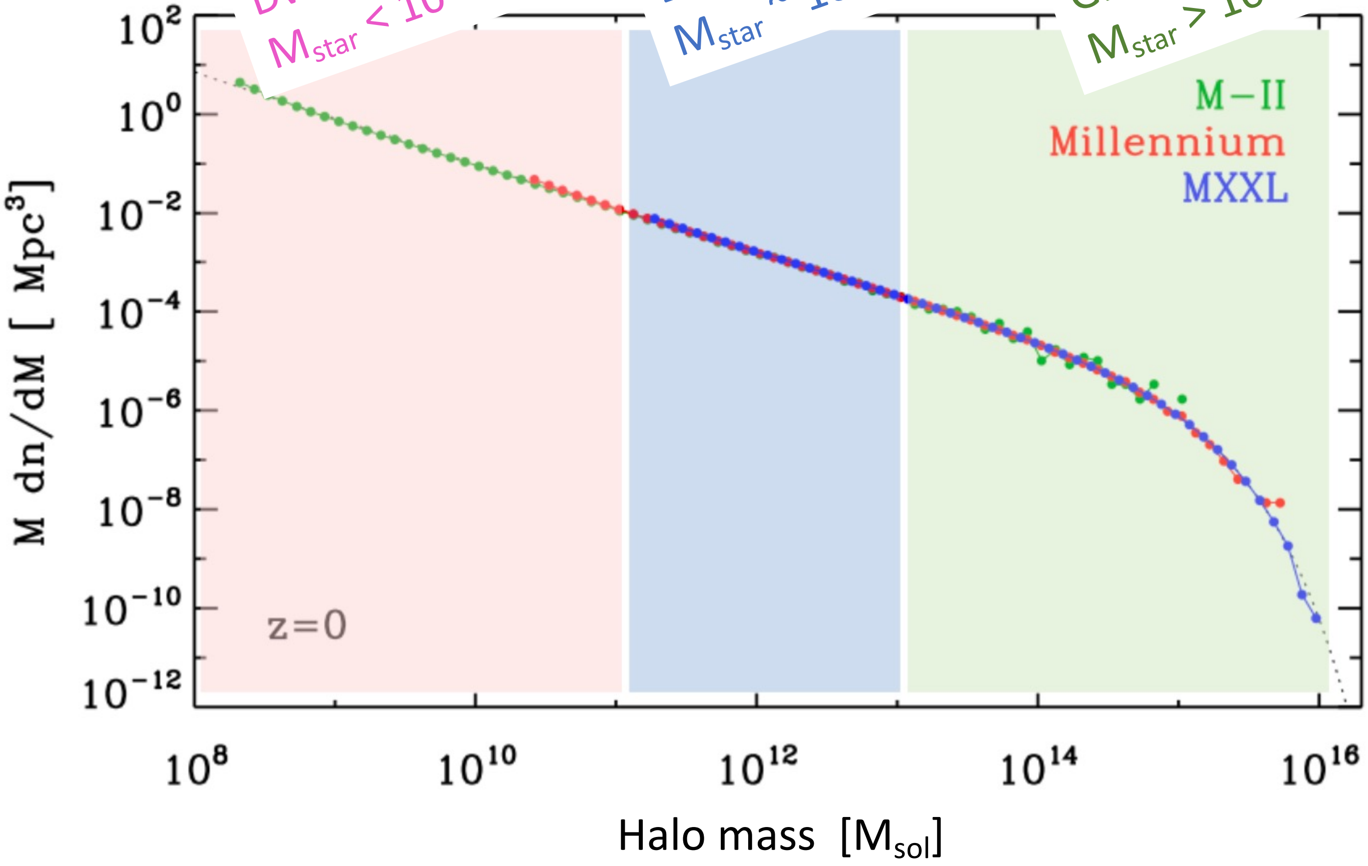
Predictions of the standard model of cosmology



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

Dark matter halo of a Milky Way-like galaxy

CDM and halo mass function



Dwarf galaxies and below
$M_{star} < 10^{9}\ M_{sol}$

Bright galaxies (e.g. MW)
$M_{star} \sim 10^{10}\ M_{sol}$

Groups and Clusters
$M_{star} > 10^{11}\ M_{sol}$

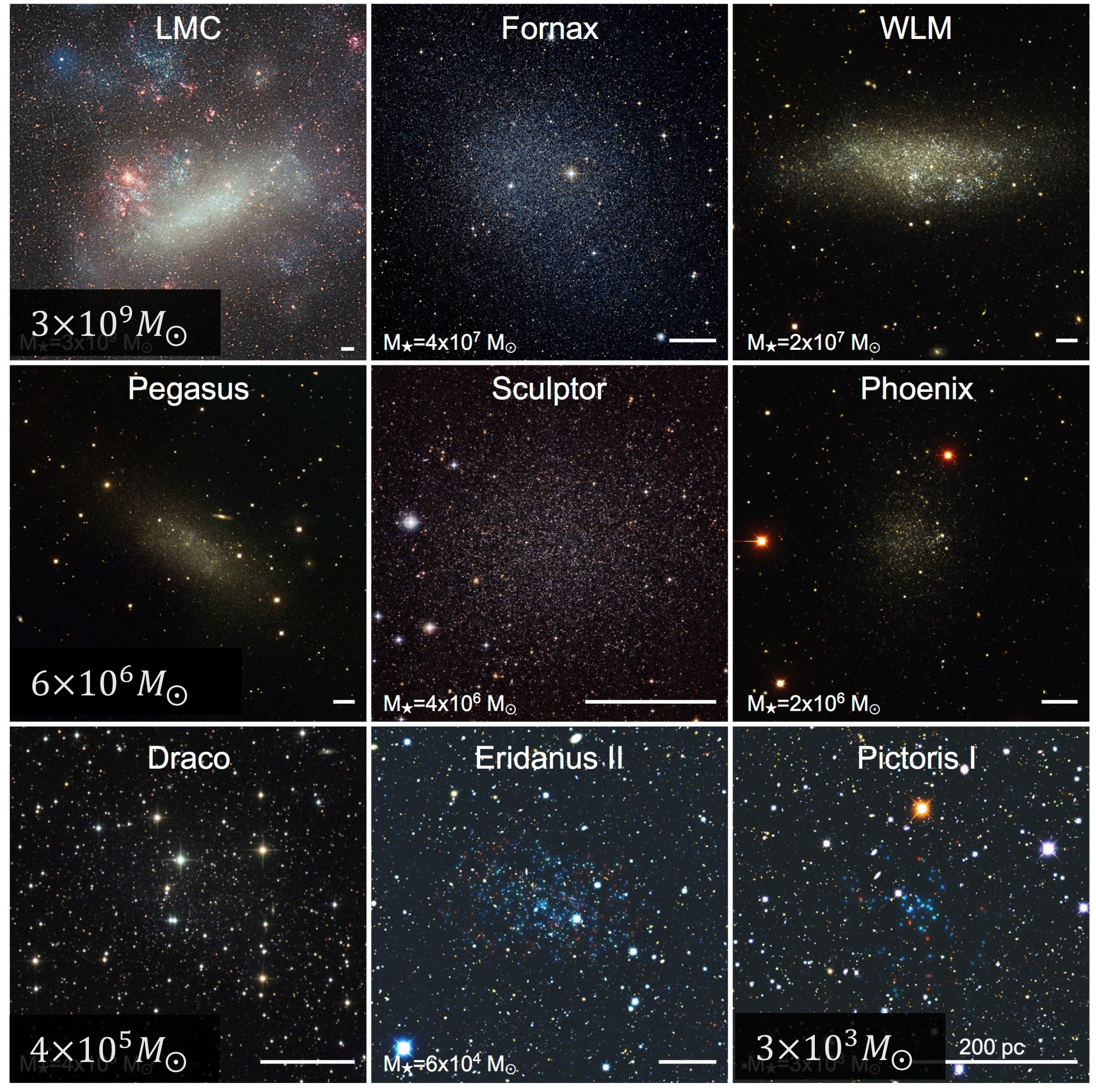
Jenkins+2001
Angulo+2012

Dwarf galaxies

Our Milky Way

$M_* \sim 5\times10^{10} M_\odot$

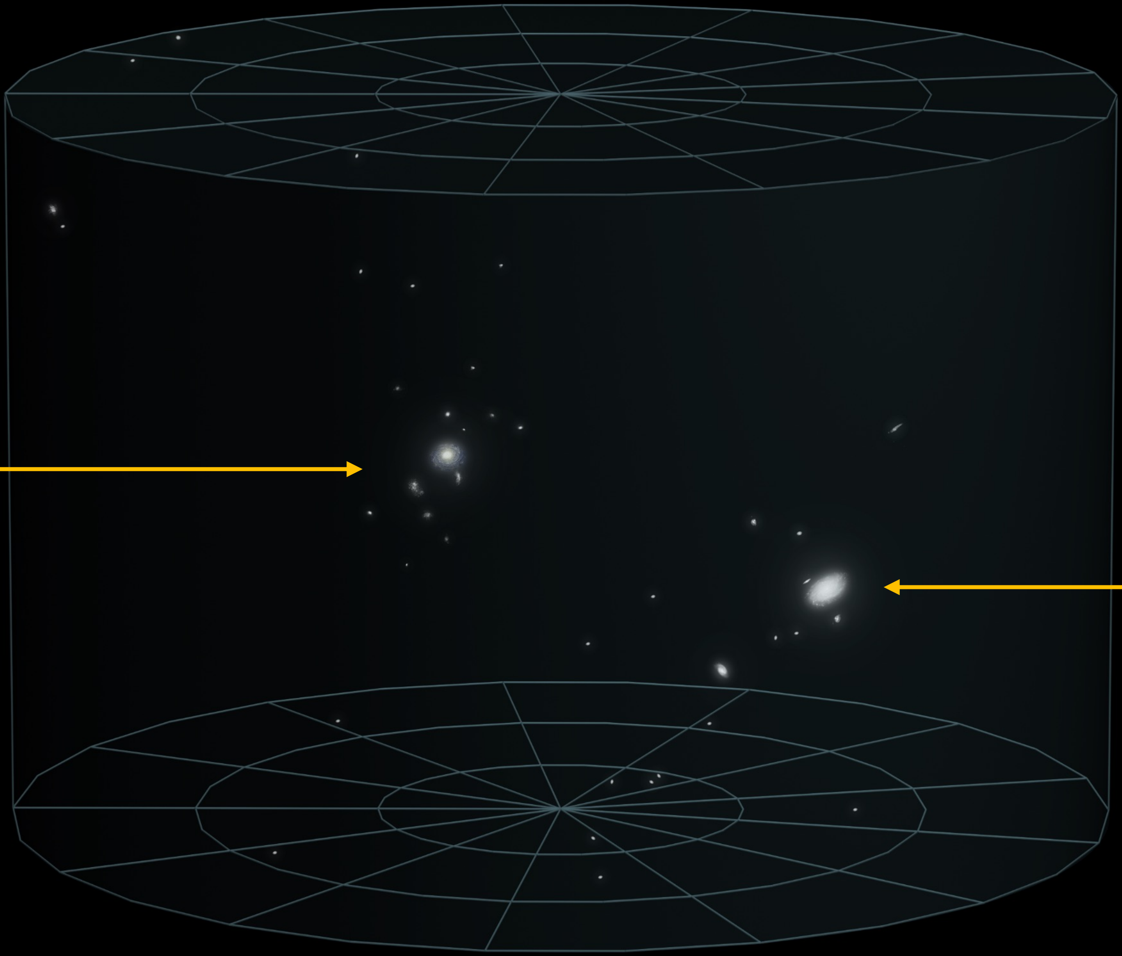
- ❖ Classical dwarfs: $M_* > 10^5 M_\odot$
- ❖ Ultra-faint dwarfs: $M_* < 10^5 M_\odot$



Bullock & Boylan-kolchin 2017

“the missing satellites” problem

Large number of low mass dark matter halos vs. number of dwarf galaxies



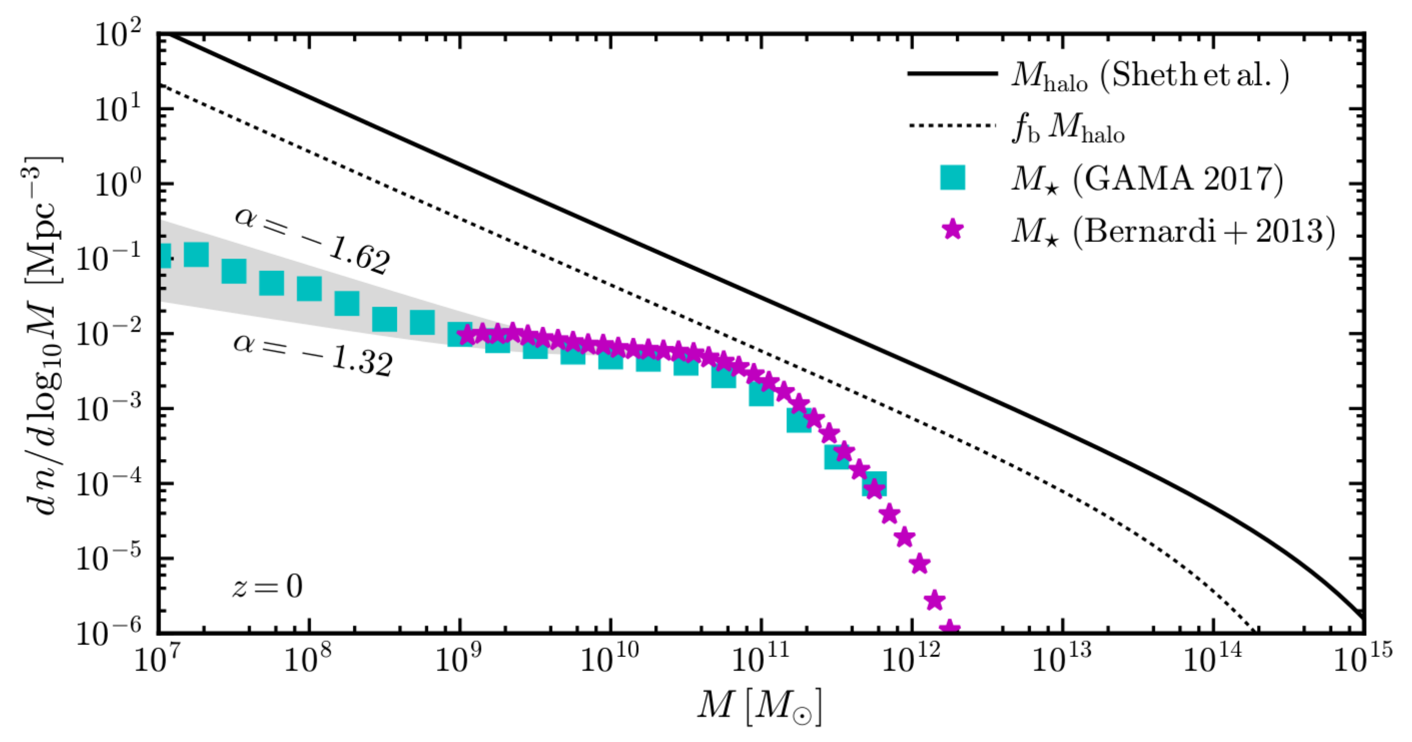
Milky Way + sats

Andromeda + sats

“the missing satellites” problem

Large number of low mass dark matter halos vs. number of dwarf galaxies

How do (faint) galaxies populate (low mass) dark matter halos ?



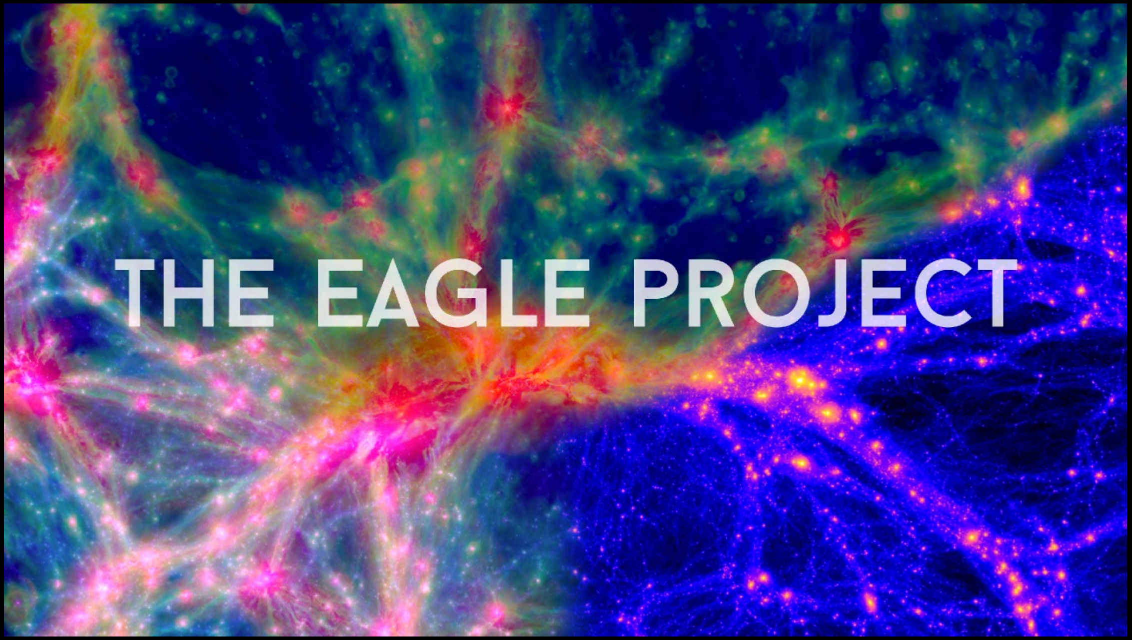
Bullock & Boylan-Kolchin 2017

Cosmological hydrodynamical simulations

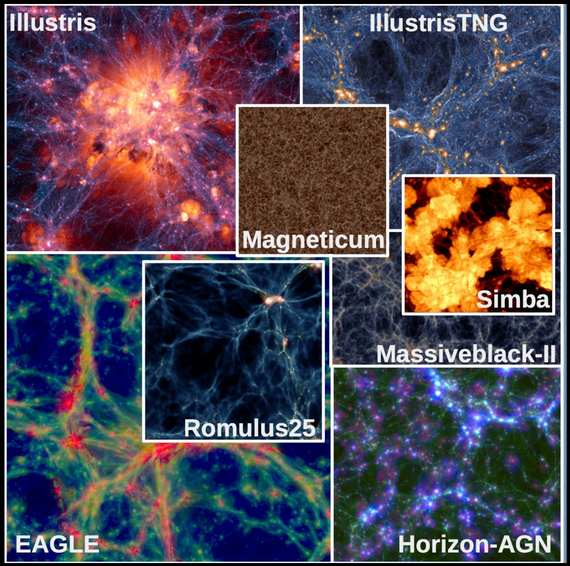
A major step forward in the field: large volume cosmological simulations which include gas hydrodynamics and complex physics of galaxy formation.

Physics included:

- Star formation
- cooling
- Stellar evolution
- Stellar and supernovae feedback
- UV radiation background
- AGN feedback
- …



EAGLE project (Schaye+2016)

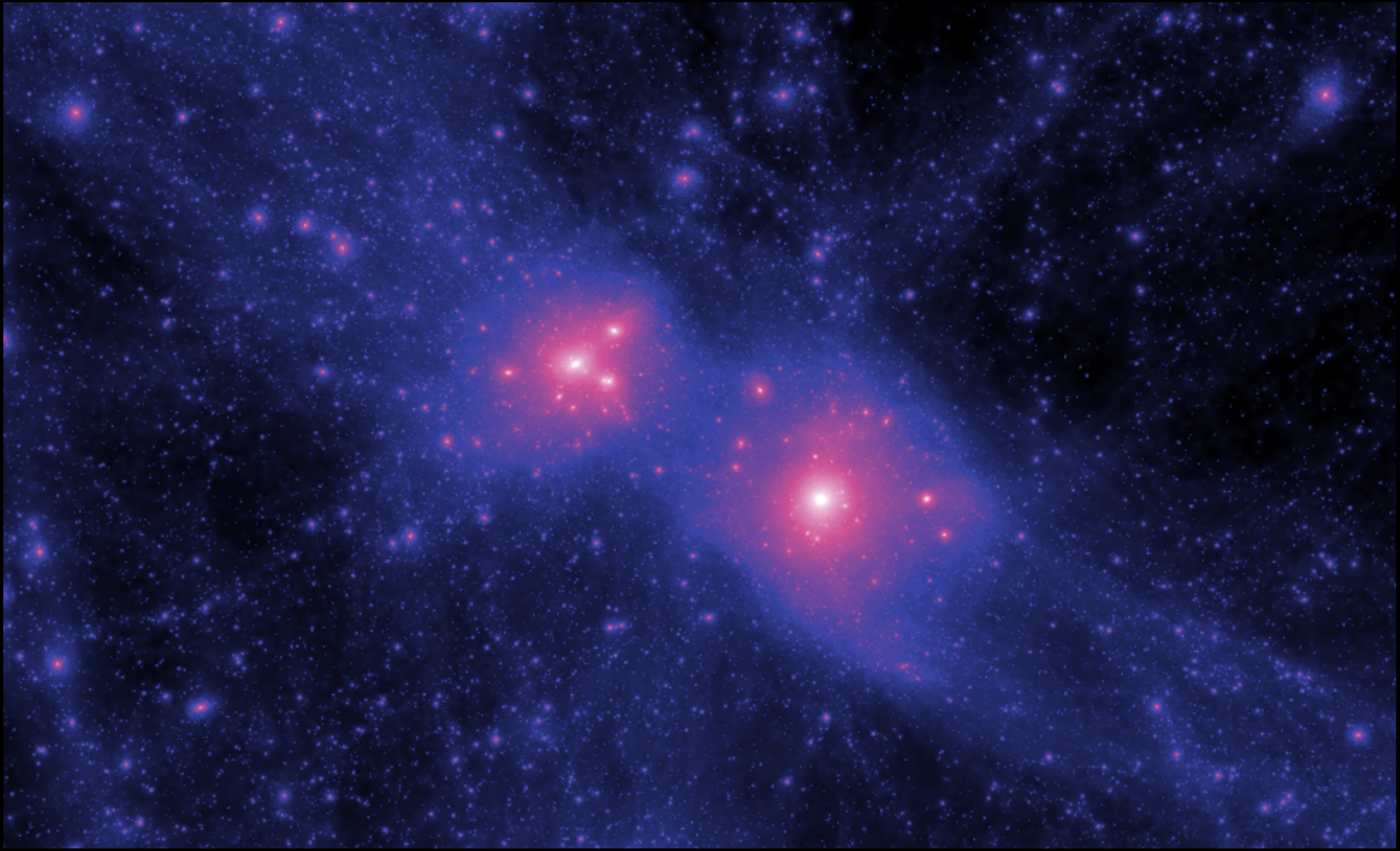


Cosmological hydrodynamical simulations

Face-on and edge-on images of Milky Way –like galaxies in simulations

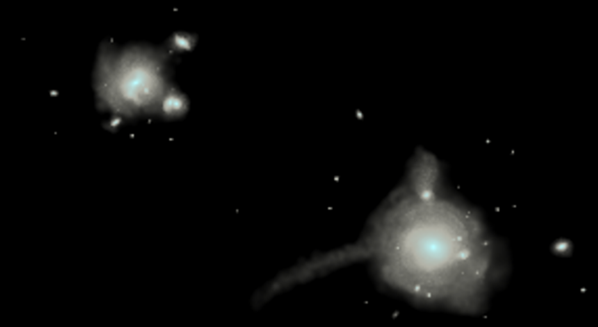
Auriga Project (Grand+2017)

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

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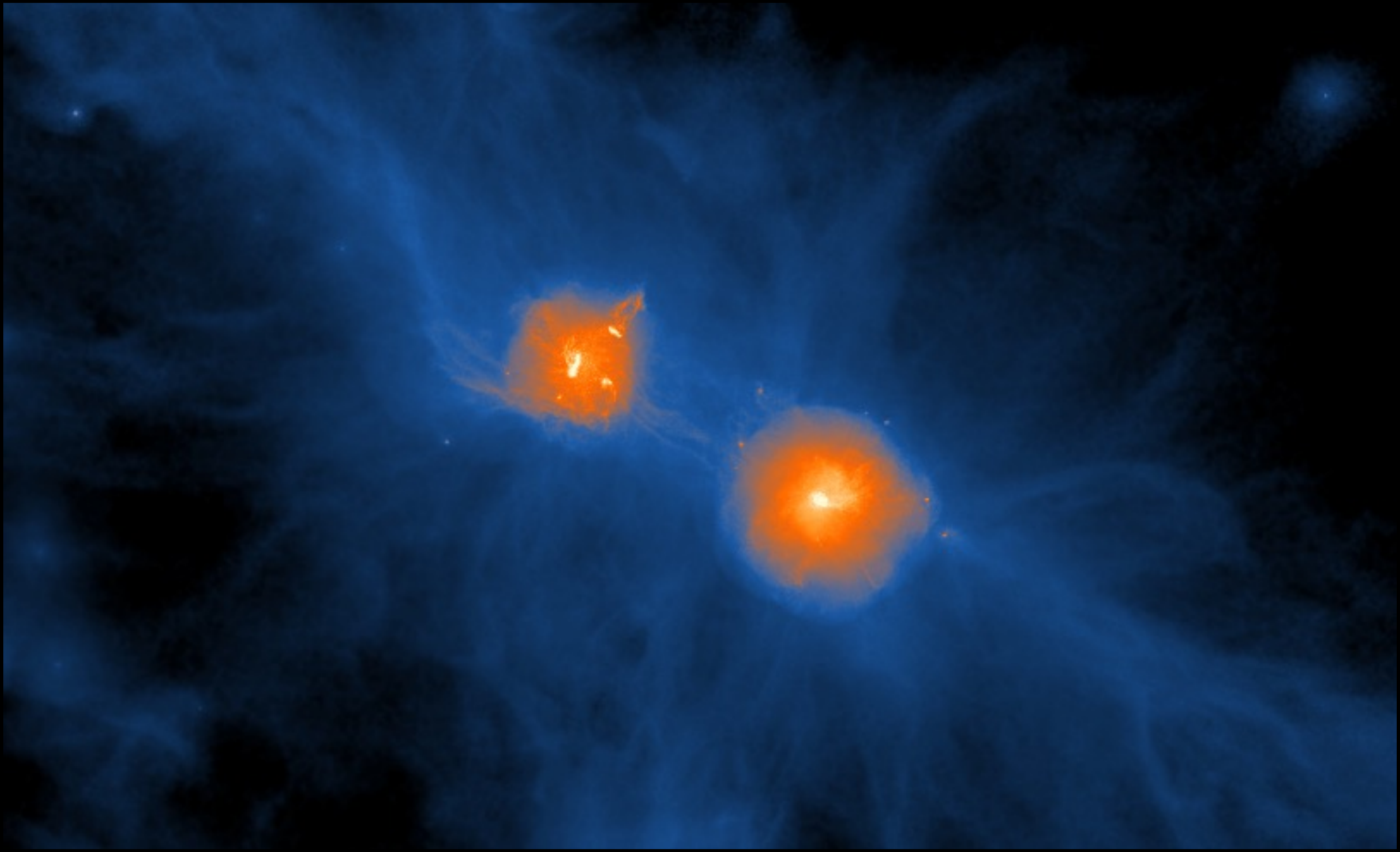


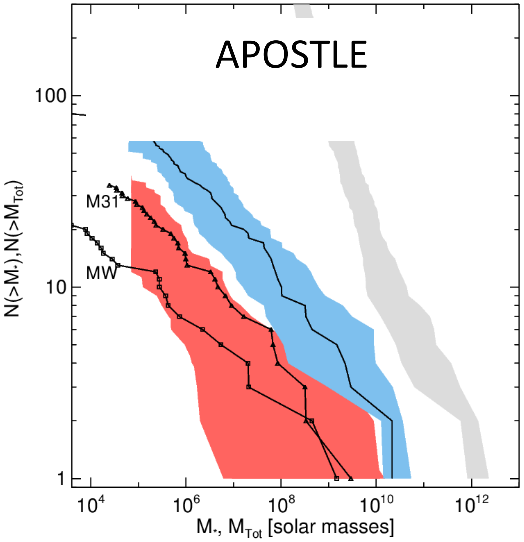
APOSTLE project - AF+2016, Sawala+2016

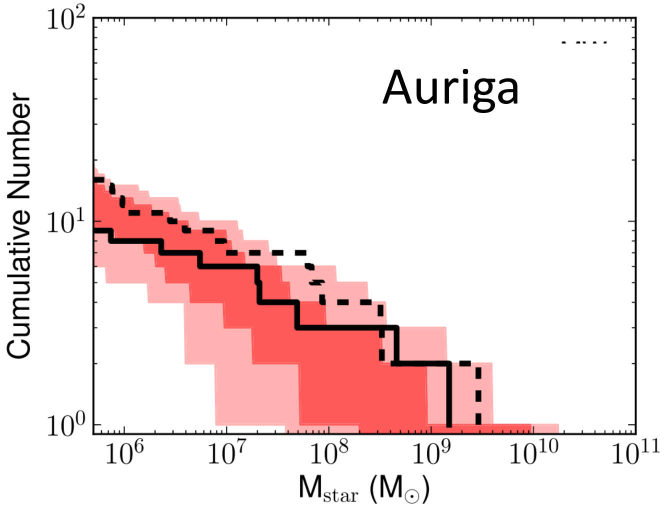
Abundance of dwarf galaxies

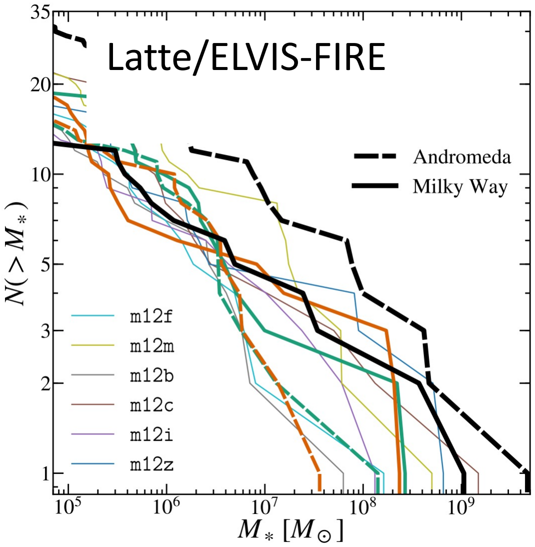
Current cosmological hydrodynamical simulation can produce realistic abundance of dwarf galaxies in the “classical regime”; i.e. > 10^5 M_{sun}

- 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+)



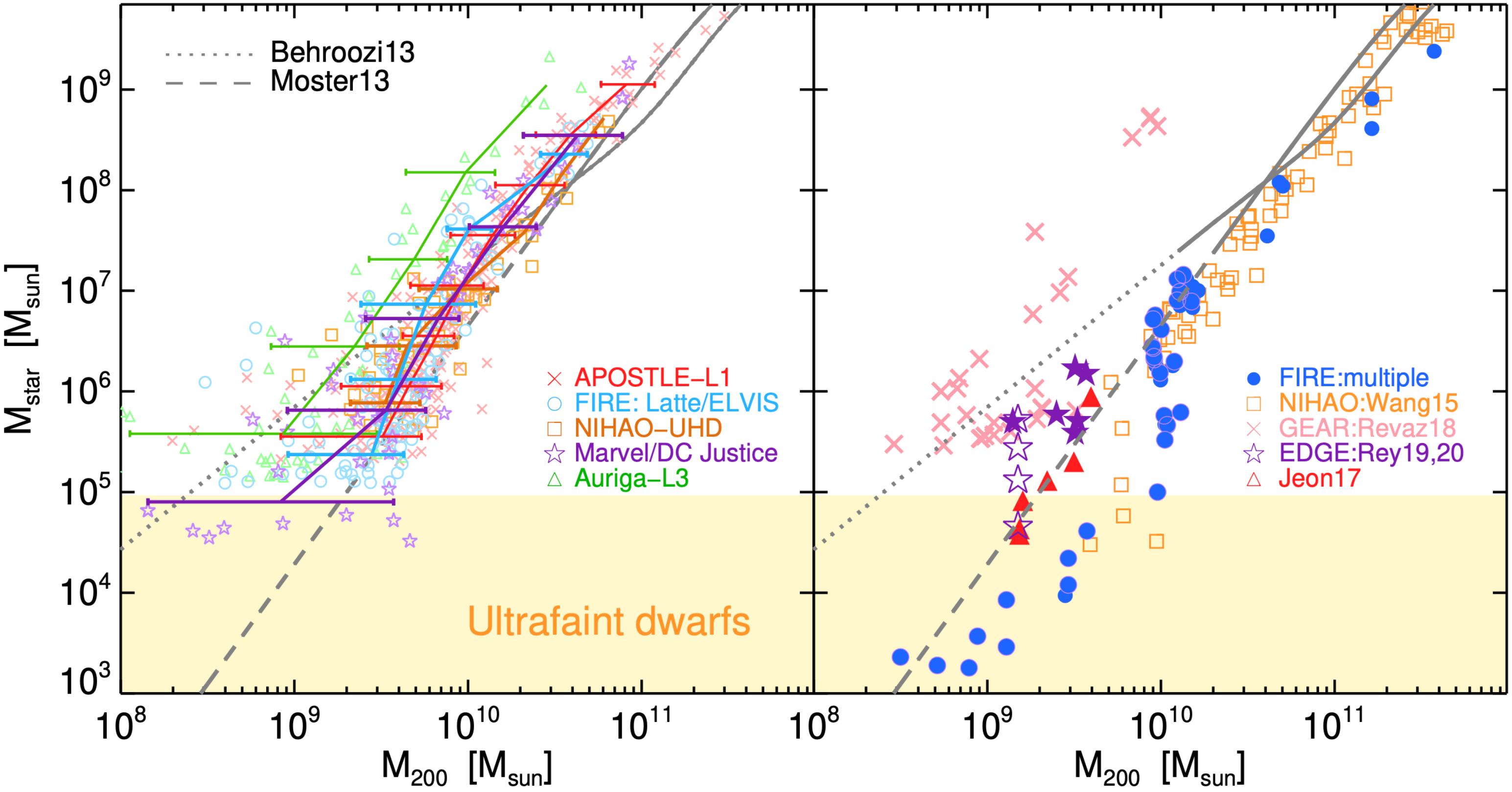




Stellar mass-halo mass relation at the faint end (dwarf galaxies) in hydrodynamical LCDM simulations

Field dwarf galaxies around MW-like halos

Simulations of isolated dwarf galaxies



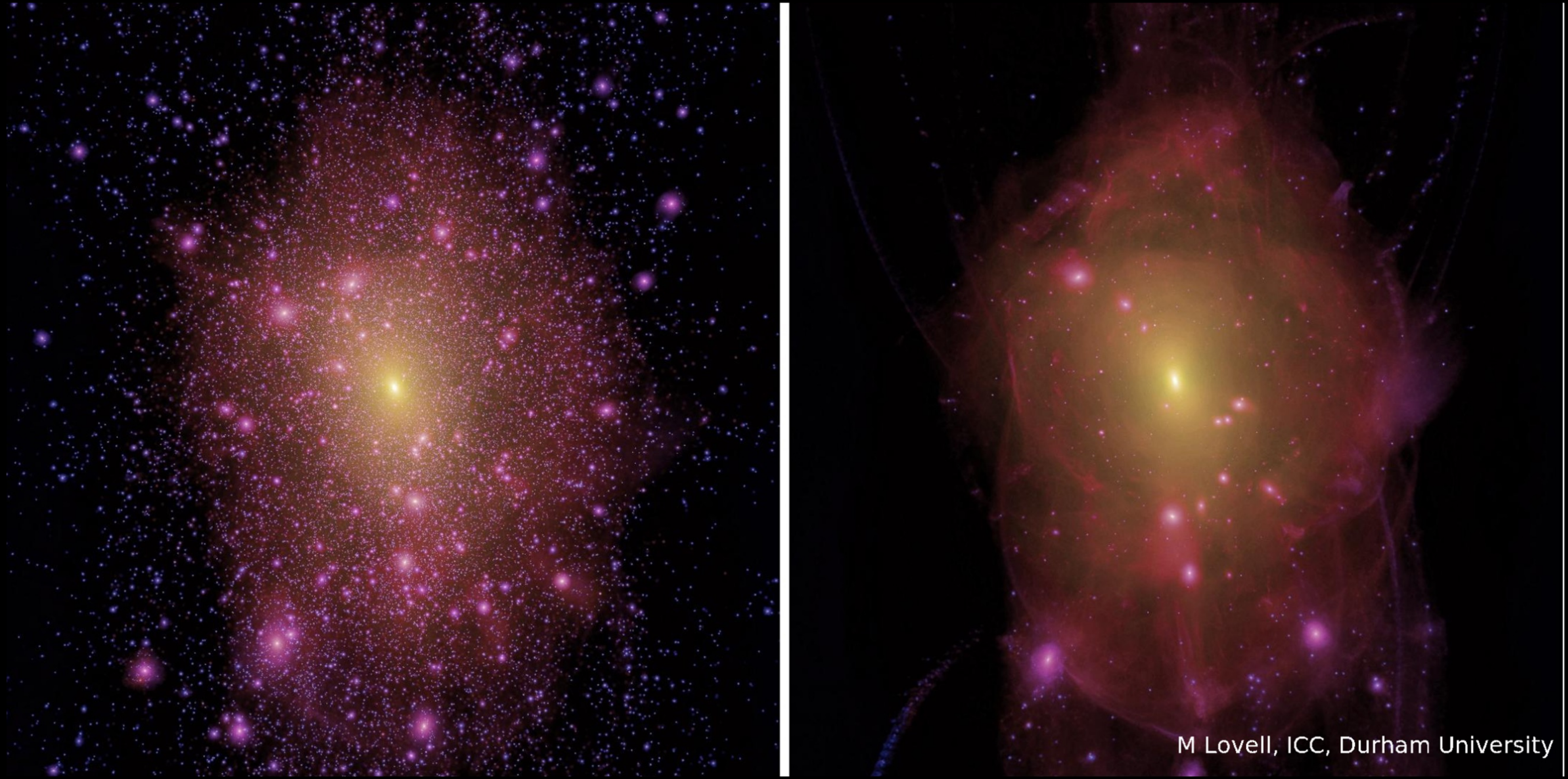
Sales, Wetzel & AF (2022)

Nature of dark matter

Dark matter halo of a Milky Way like galaxy in:

Cold dark matter

Warm dark matter



M Lovell, ICC, Durham University

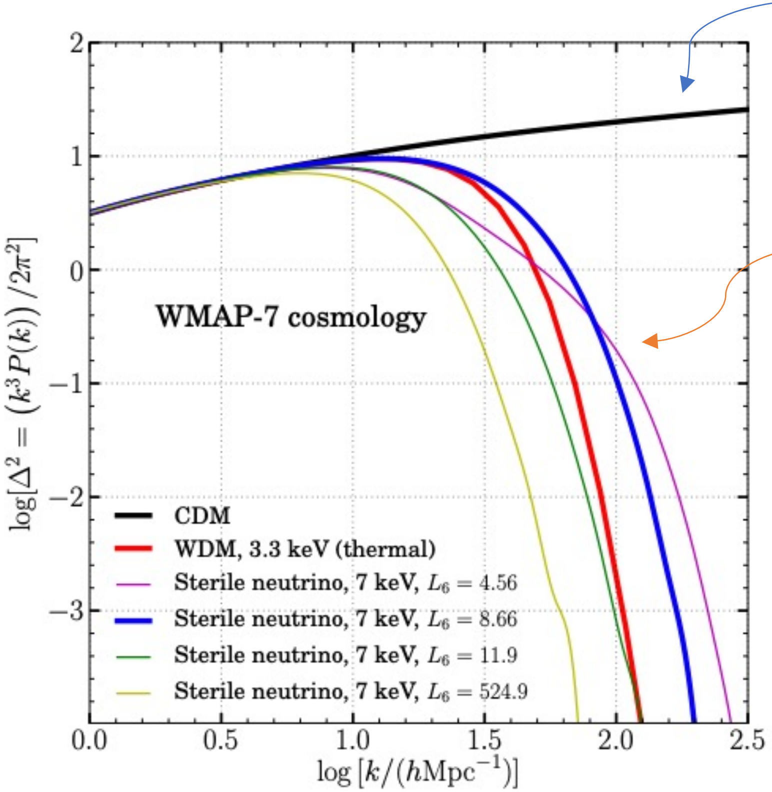
Cold vs Warm dark matter

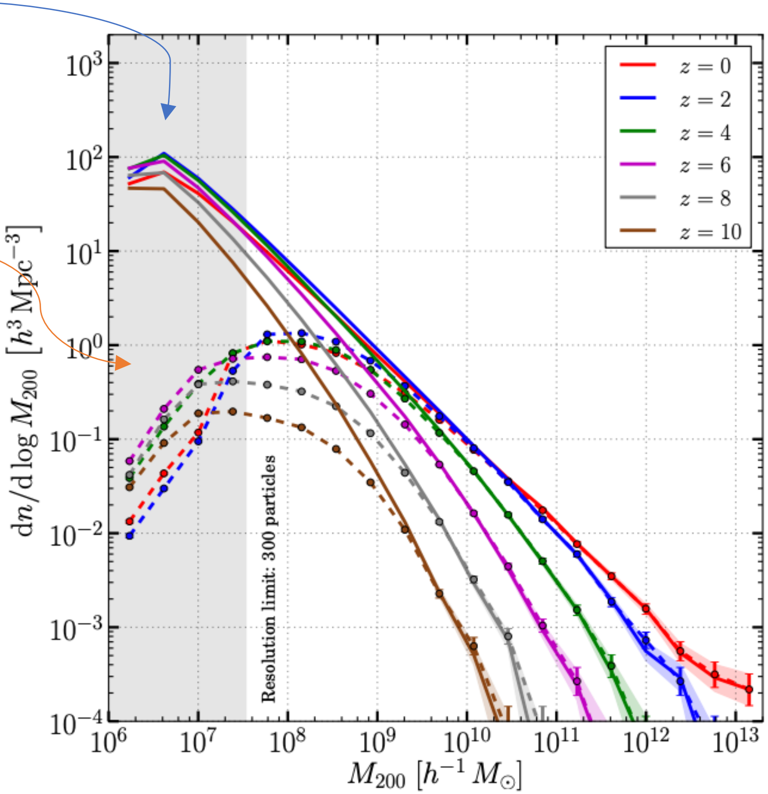
Suppression of power spectrum on small scale

Suppression of mass function at the low mass end

CDM

WDM





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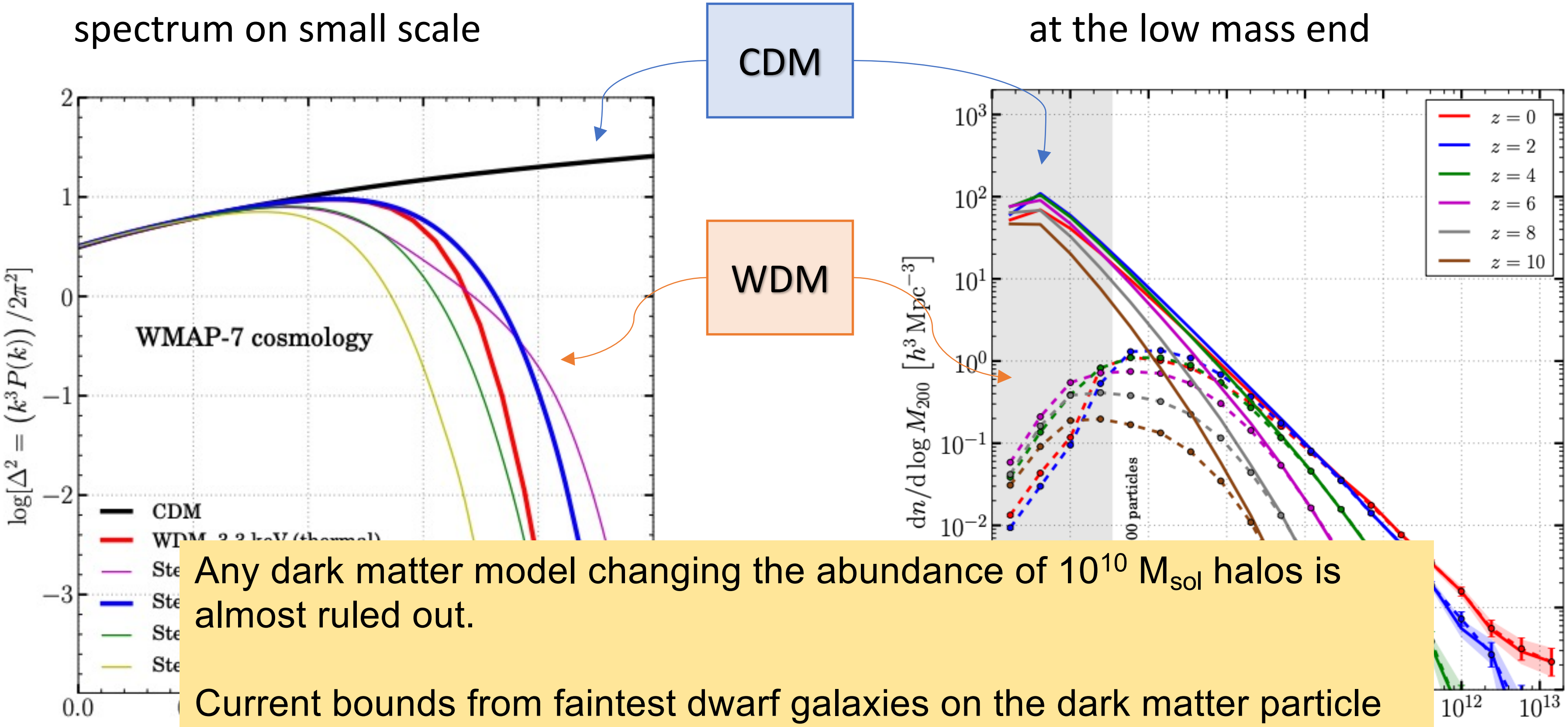


Any dark matter model changing the abundance of 10^{10} M_{sol} halos is almost ruled out.

Current bounds from faintest dwarf galaxies on the dark matter particle mass (thermal relic) > ~5 KeV

Take away points

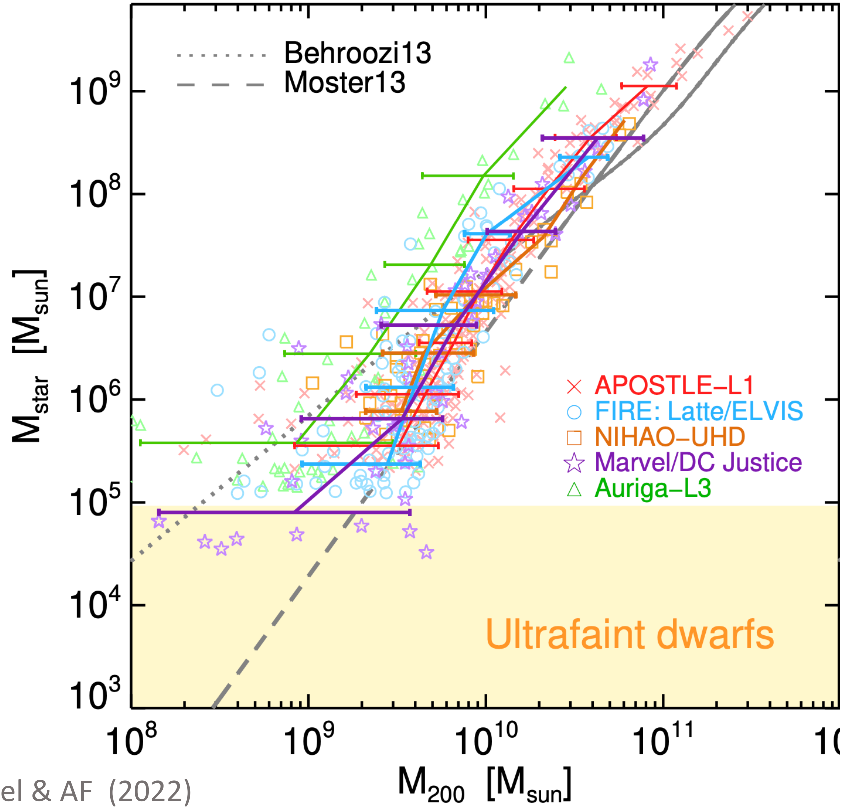
- Current models can explain/predict the correct abundance of dwarf galaxies in the “classical” regime ($M_{star} > 10^5\ M_{sol}$)

- Theoretical predictions and observation at the “ultra faint” regime is highly uncertain due to:
    - extremely faint nature of these objects have made their discovery challenging
    - galaxy formation physics in the first galaxies and lowest mass halos is not fully understood

- Warm dark matter models with thermal relic mass lower than ~5 keV are ruled out by abundance known ultra faint dwarf galaxies

Dark matter content of low mass dwarfs

“too big to fail” in its classical definition is considered a solved problem in LCDM. But the general question about dark matter content of observed dwarf galaxies is still debated.



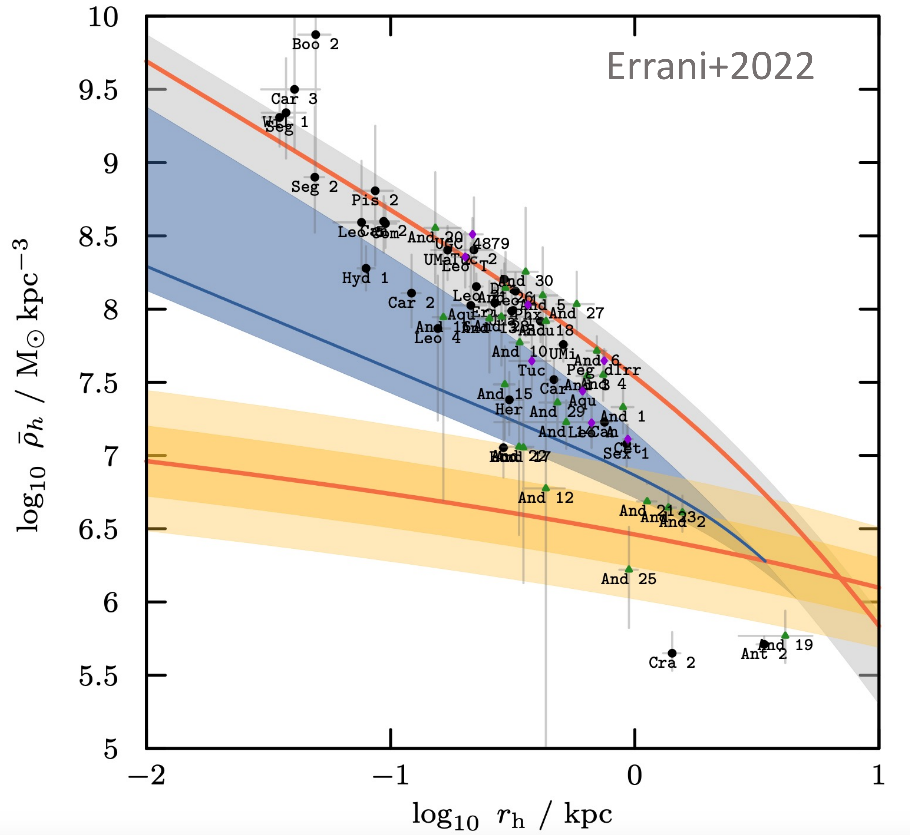
Sales, Wetzel & AF (2022)

Prediction: Dwarf galaxies with $M_{star} < 10^7 M_{sol}$ have a narrow range of halo mass.

What are the constraints from observations?

Dark matter content of Local Group dwarfs

Most Local Group dwarfs, which are the faintest known dwarfs, are spheroidals (i.e. dispersion dominated) and we can measure their mass reliably only at their half light radius.



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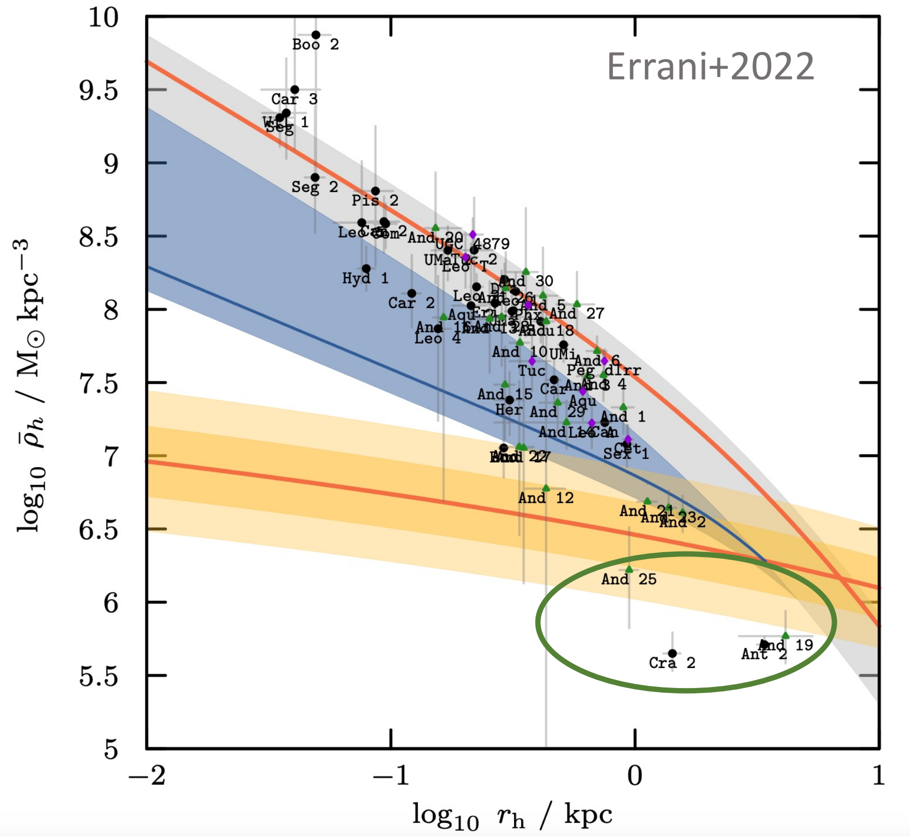

These extended low density dwarfs seem to be difficult to explain in LCDM.

see Errani+2022, Borukhovetskaya+(incl AF)2022

Dark matter content of Local Group dwarfs

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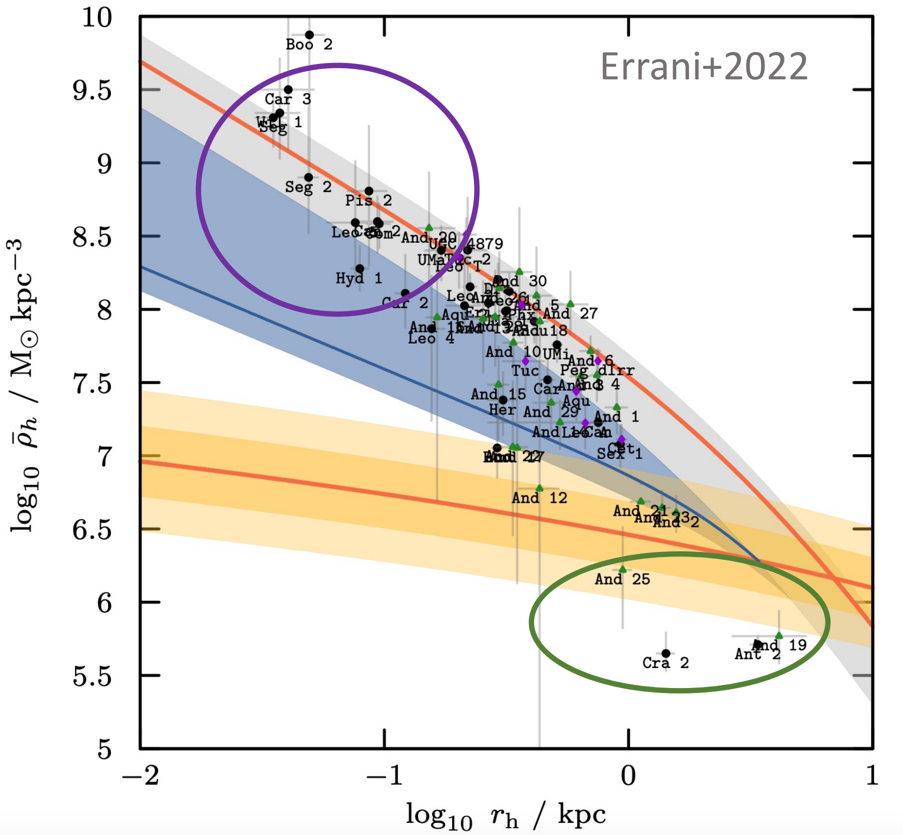
Ultra faint dwarf galaxies favour higher halo masses/central densities. They can rule out some DM models.



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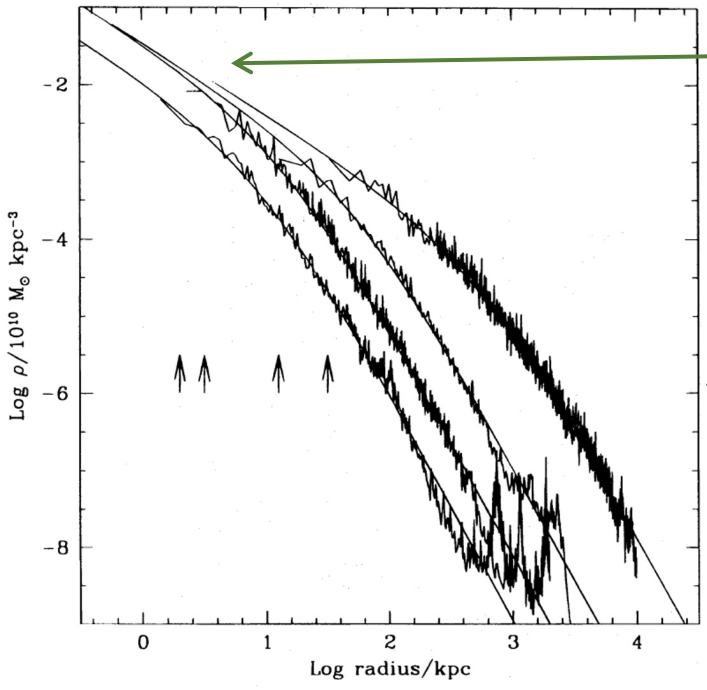
Dark matter distribution inside dark matter halos & The core-cusp problem (Flores & Primack 1994, Moore 1994)

Universal density profile of dark matter halos



cusp

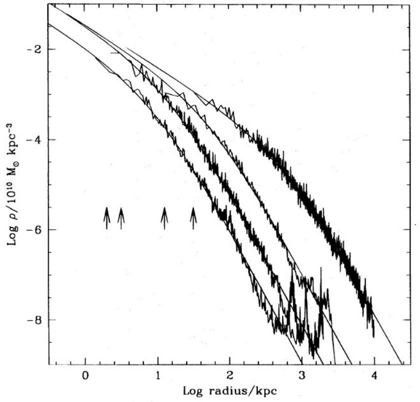
$$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

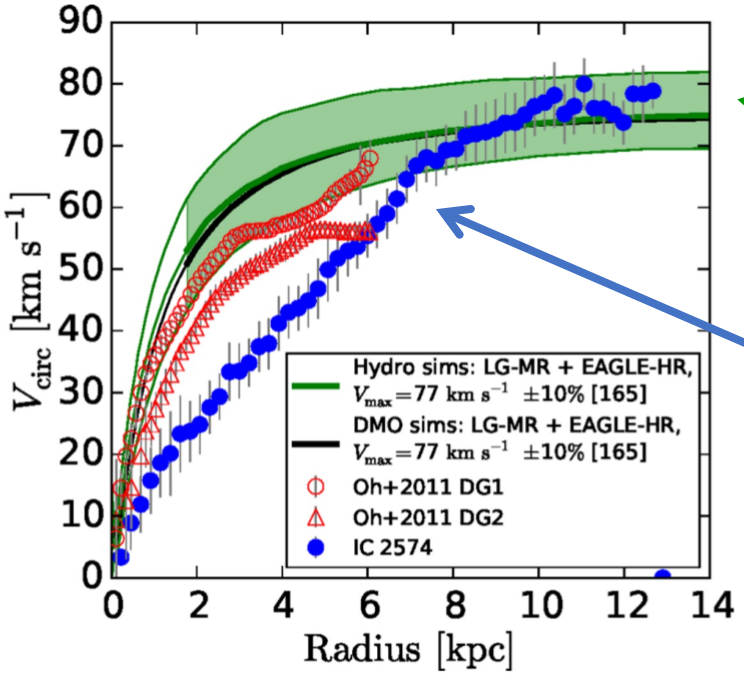
Navarro, Frenk & White (1996,97)

Log mass

Cusp vs. Core problem

(Flores & Primack 1994, Moore 1994)





CDM circular velocity

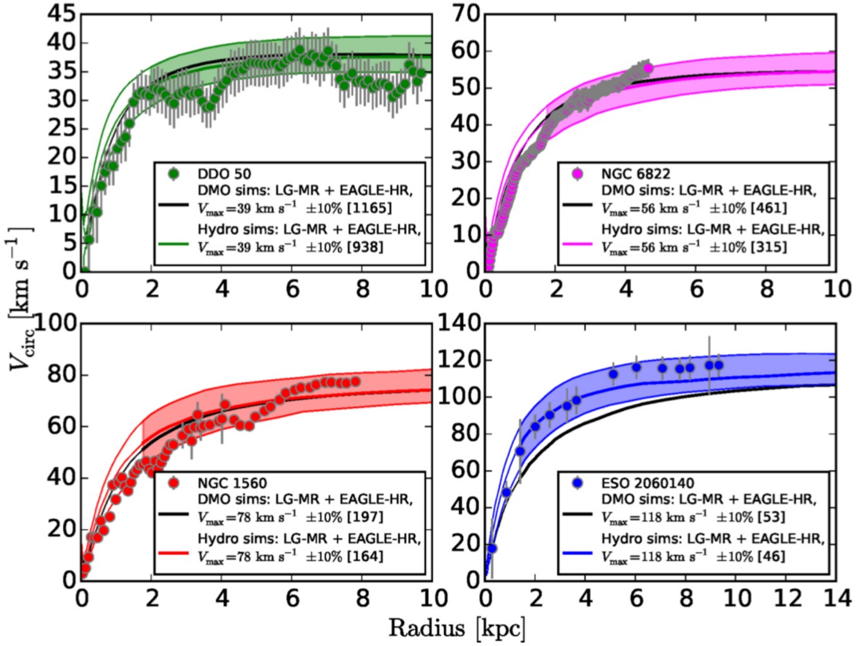
Observed rotation curve of IC-2574

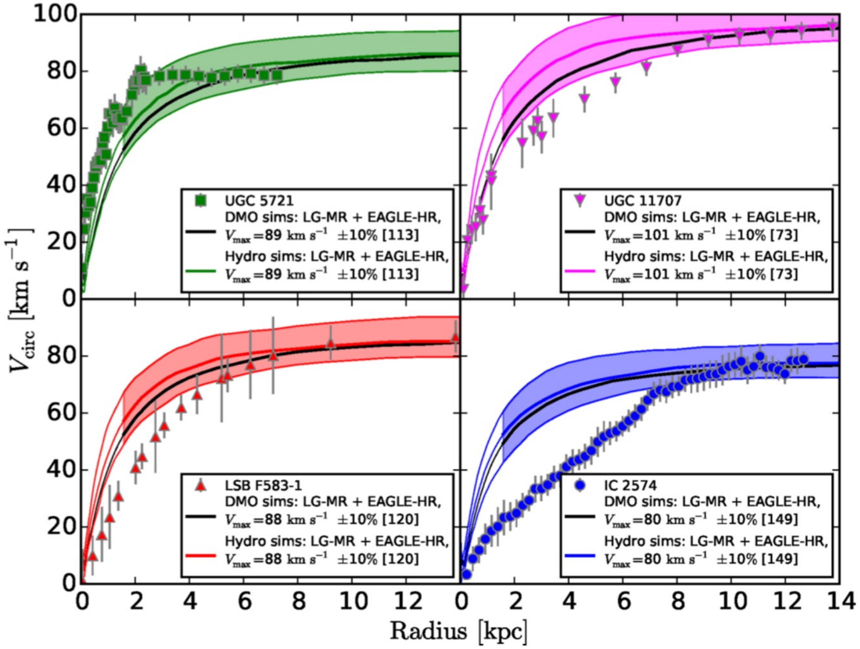
Linearly rising rotation curve ~ flat density profile (cored)

Oman+2015

The core-cusp problem or the diversity of rotation curves

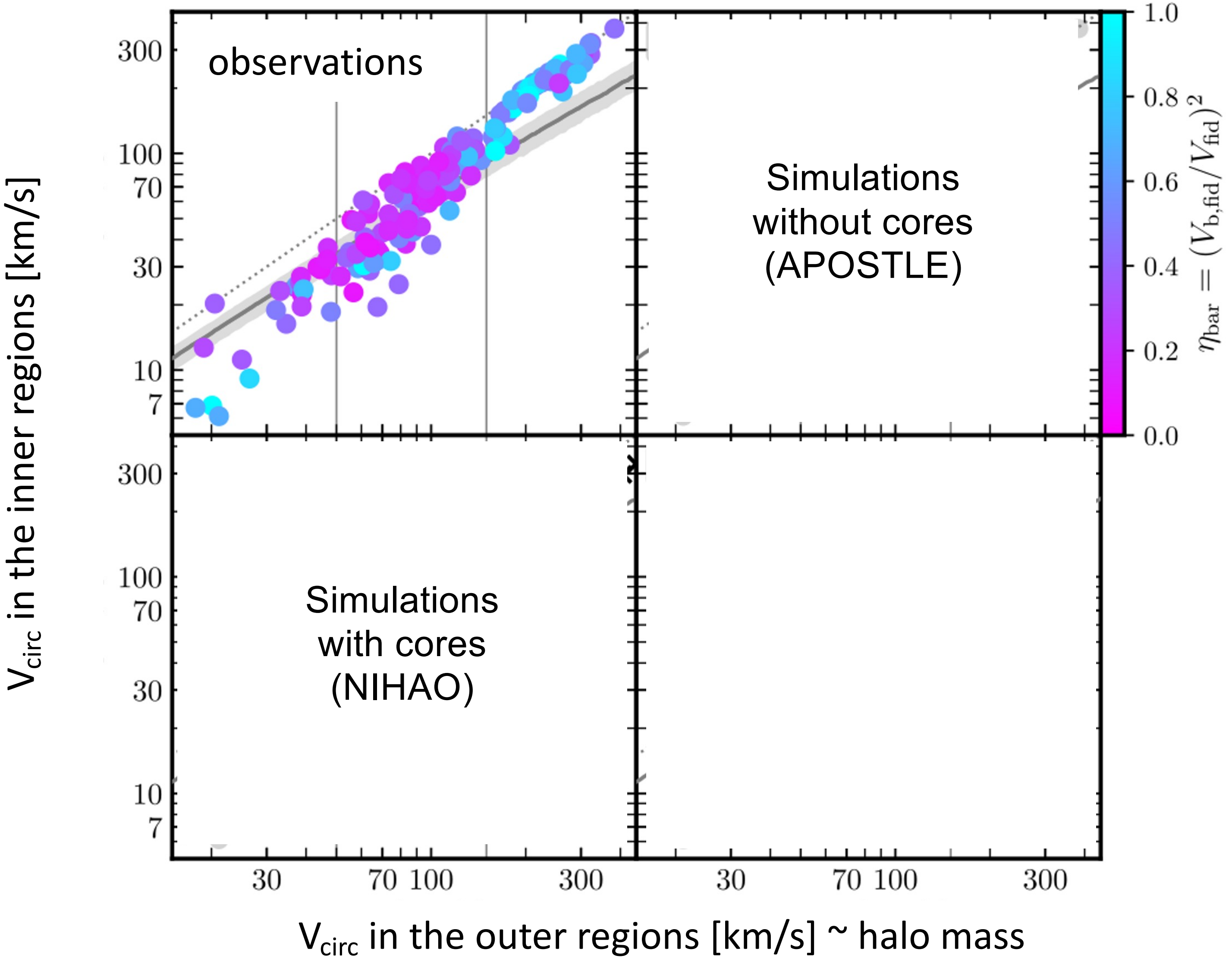
HI Rotation curves of field dwarf galaxies (THINGS and LITTLE THINGS) compared with cuspy rotation curves





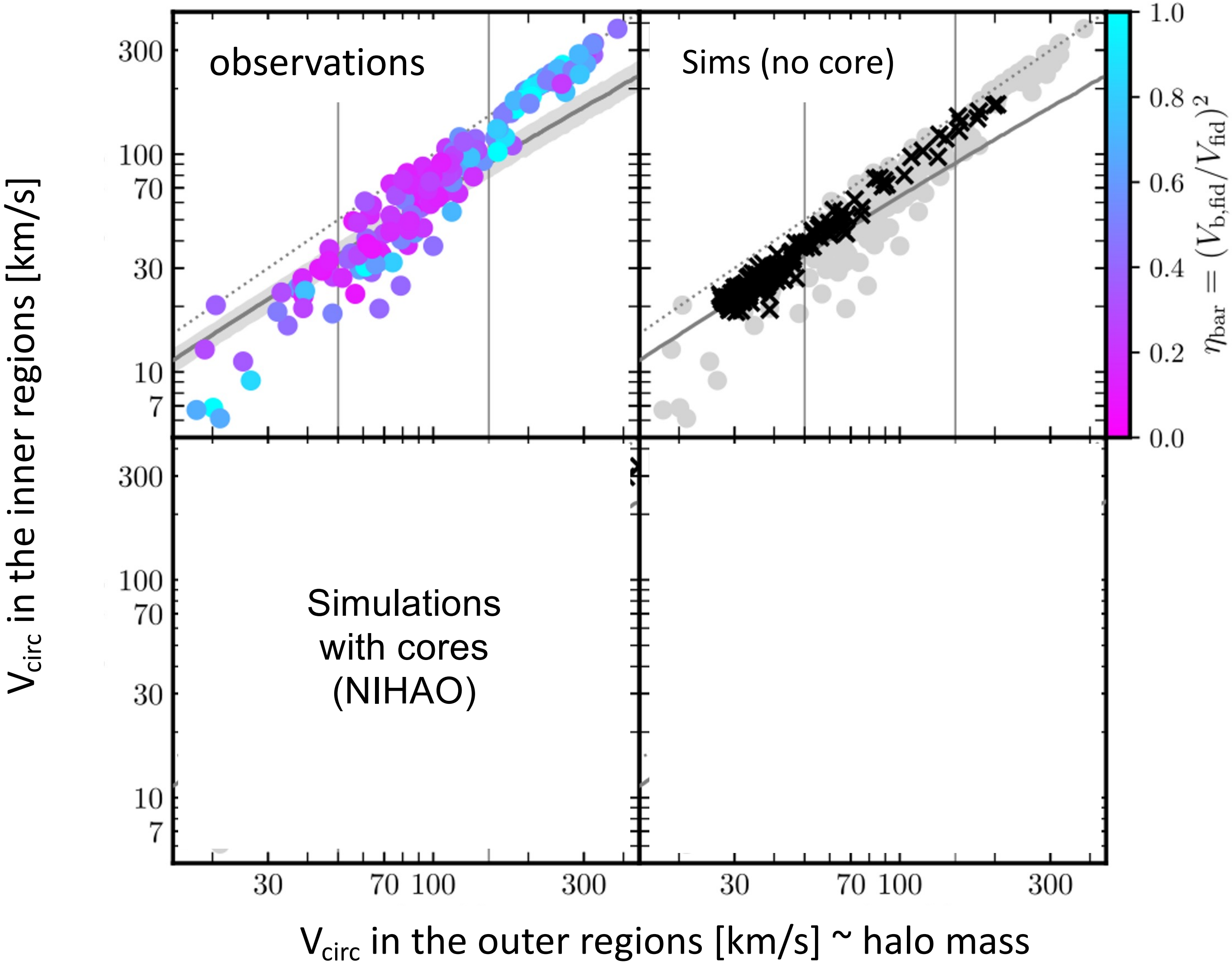
Oman+2015

The diversity of rotation curves



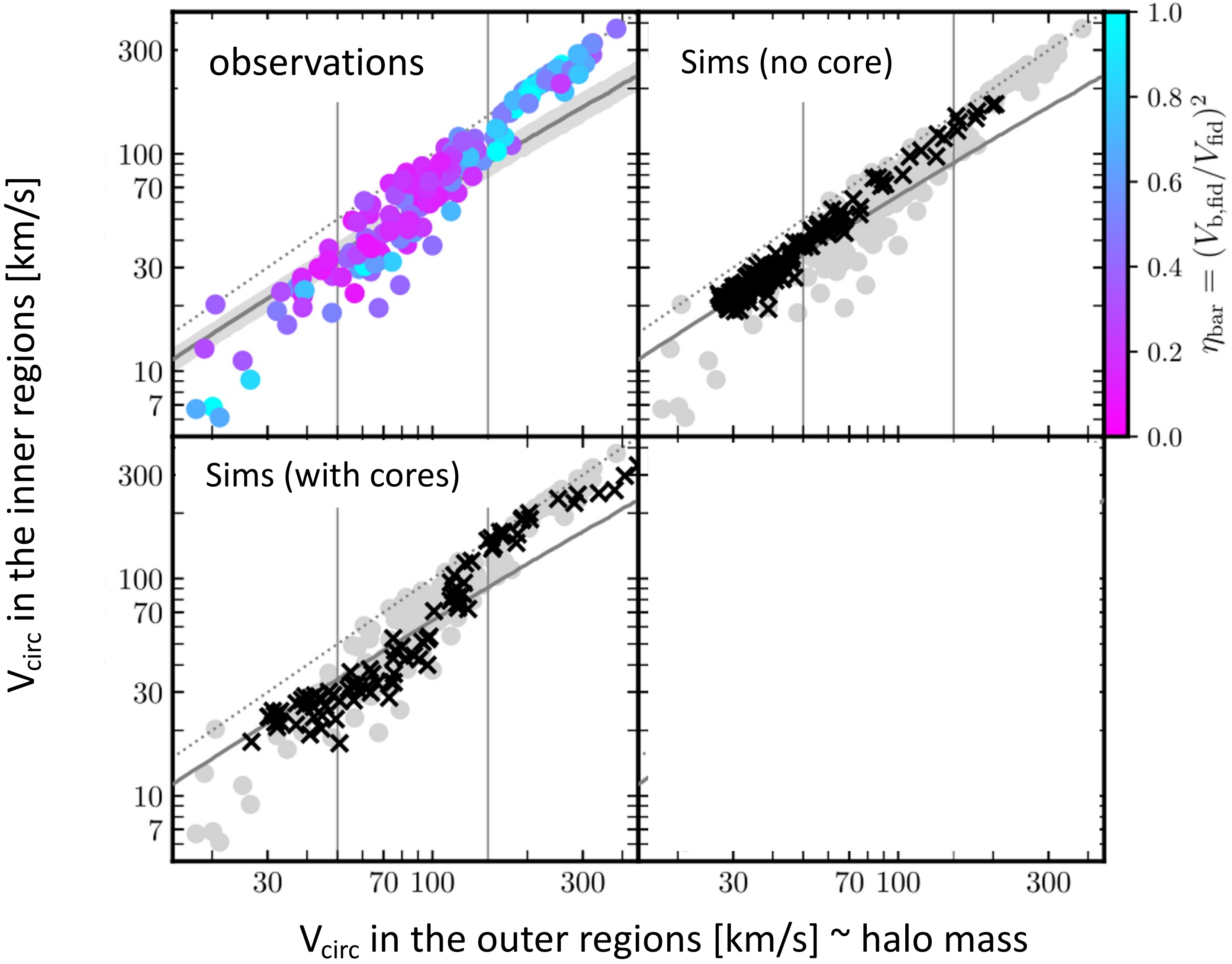
Santos-Santos+2020

The diversity of rotation curves



Santos-Santos+2020

The diversity of rotation curves

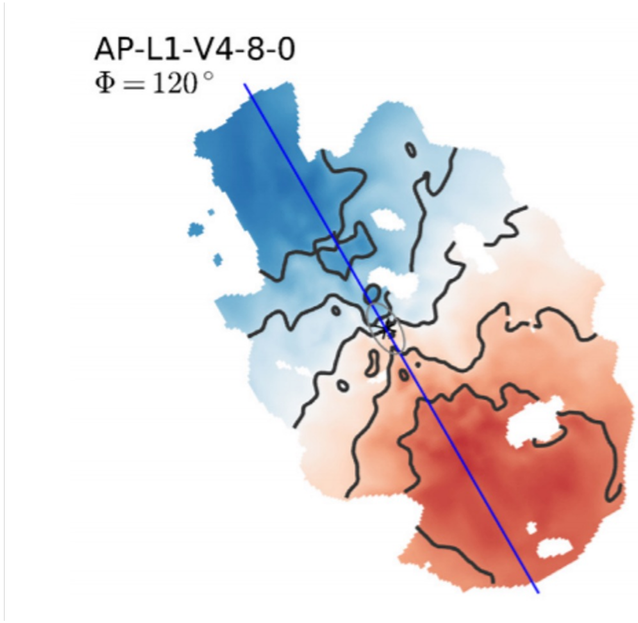


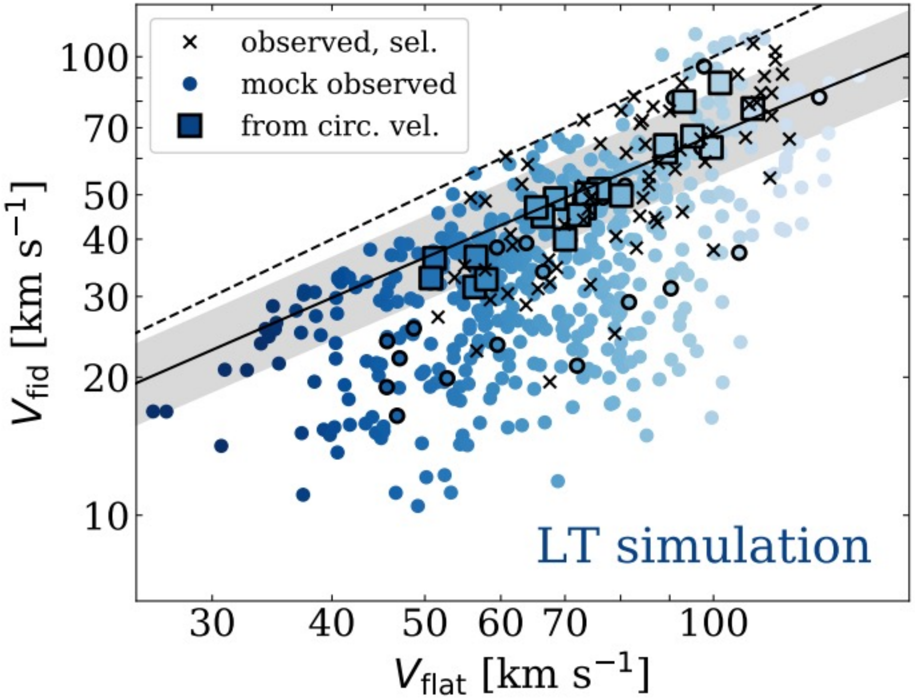
Santos-Santos+2020

The diversity of rotation curves

Have we understood all systematic uncertainties in deriving rotation curves?

To understand the above we should “mock observe” 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) – not very satisfactory

Uncertainties in the inferred total (or DM) mass from observational data and gas kinematics

Going beyond CDM: dark matter self-interaction (SIDM)

nature astronomy

REVIEW ARTICLE

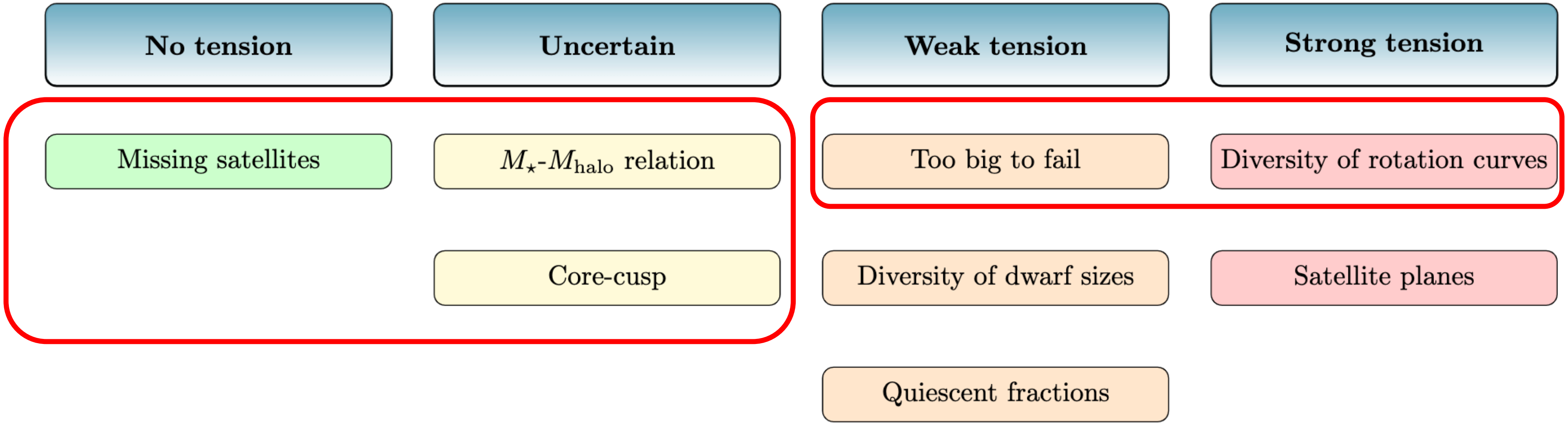
https://doi.org/10.1038/s41550-022-01689-w

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

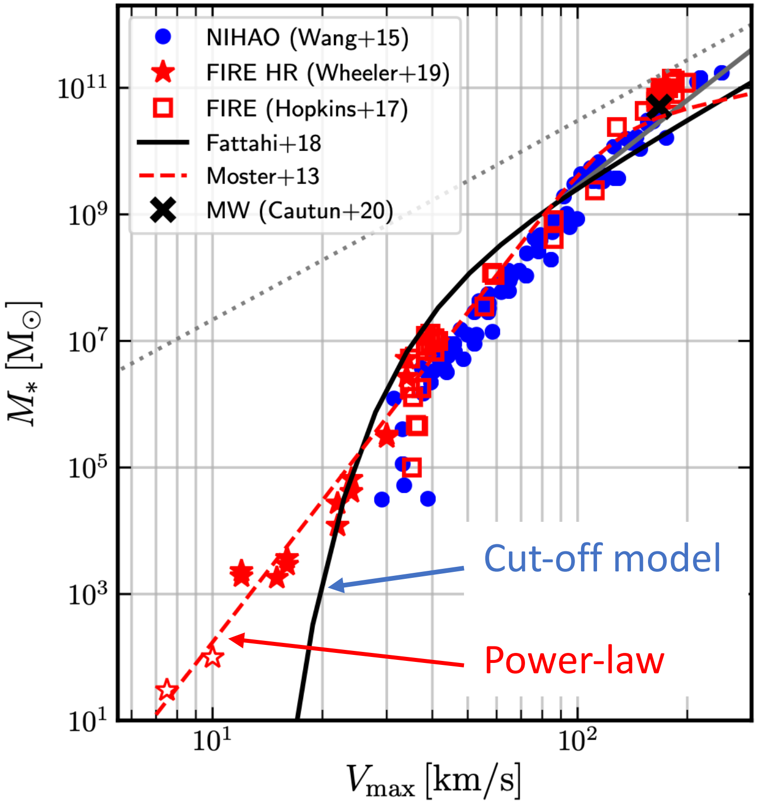


No tension	Uncertain	Weak tension	Strong tension
Missing satellites	$M_\star$-M_{halo} relation	Too big to fail	Diversity of rotation curves
	Core-cusp	Diversity of dwarf sizes	Satellite planes
		Quiescent fractions	

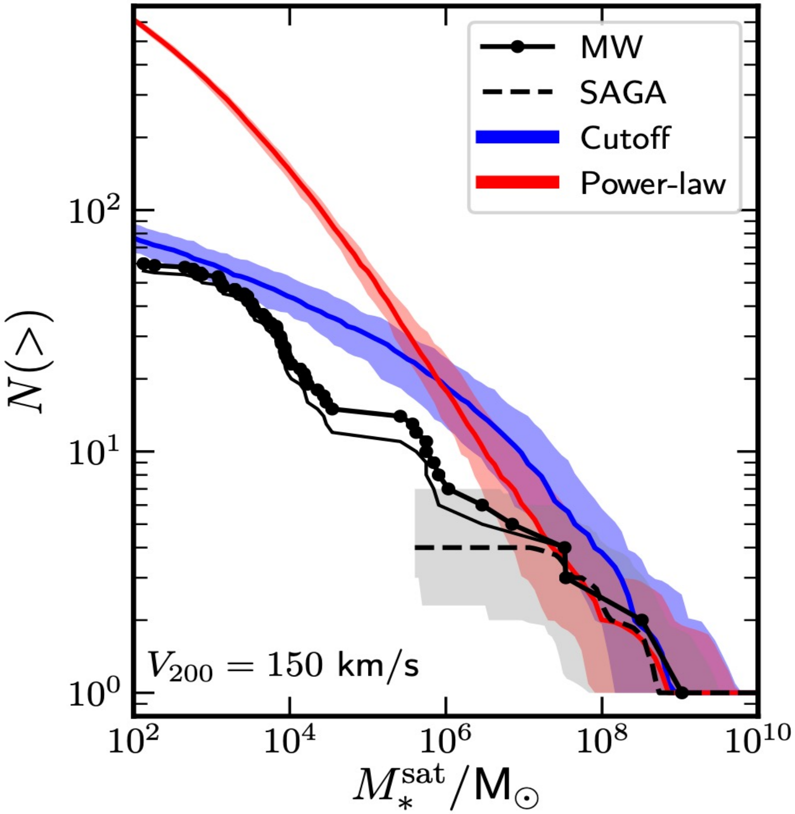
Stellar mass-halo mass relation at the faint end & the abundance of Milky Way satellites

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

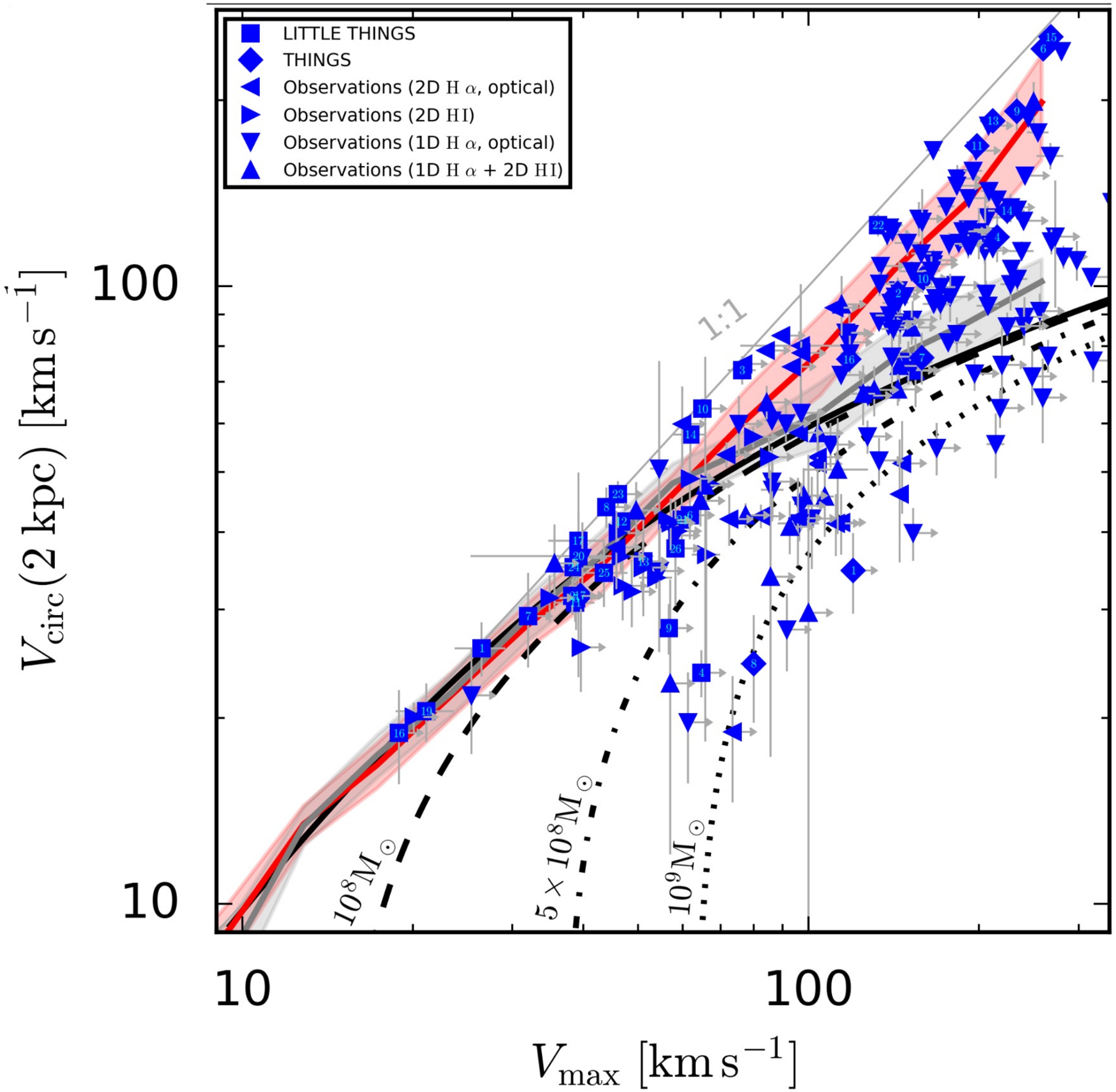
Santos-Santos et al. (+AF) 2022



~halo mass

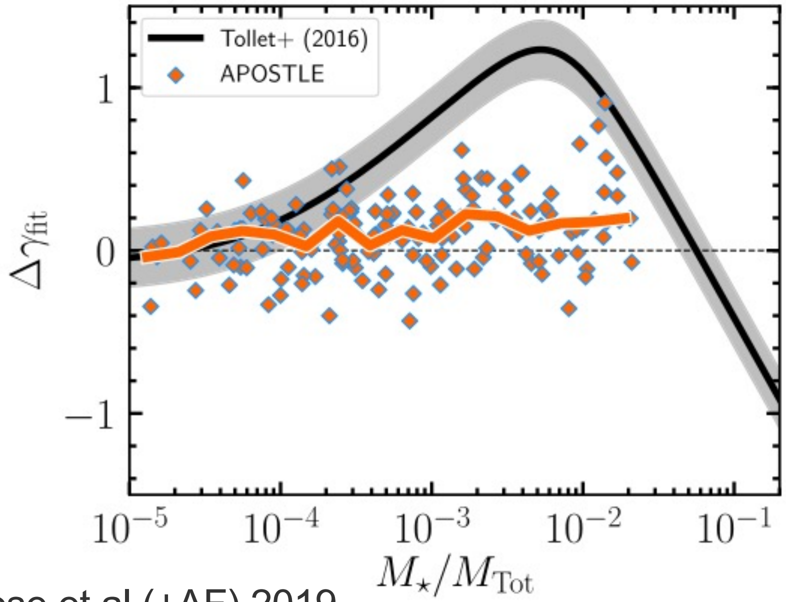


The diversity of rotation curves (Oman+2015)

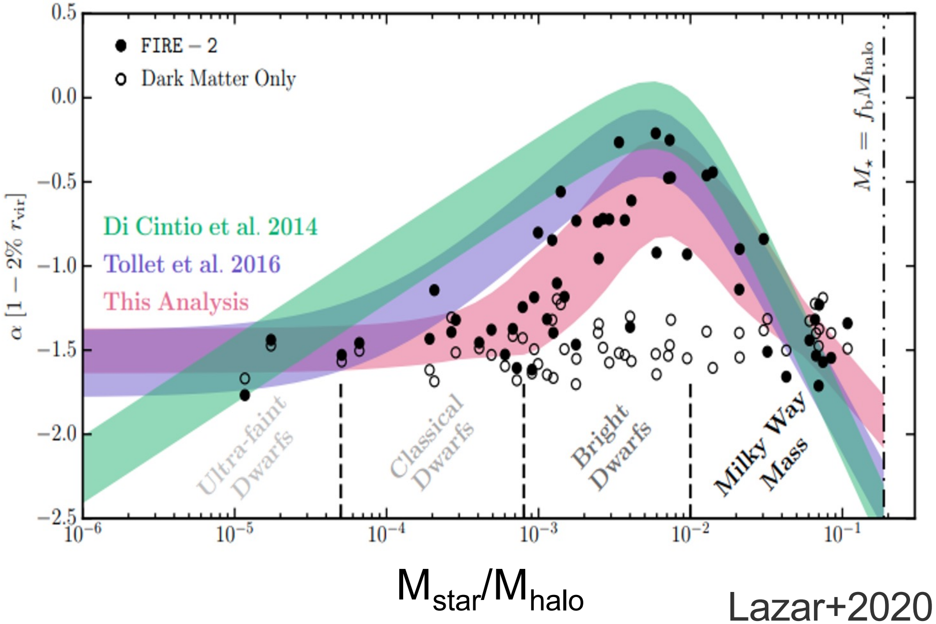


Core vs. Cusp in the simulations

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



Bose et al (+AF) 2019



Lazar+2020

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

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