Cosmic Duologue: Dark matter and MOND

Azadeh (Azi) Fattahi

Postdoc fellow
Institute for Computational Cosmology
Durham University, UK

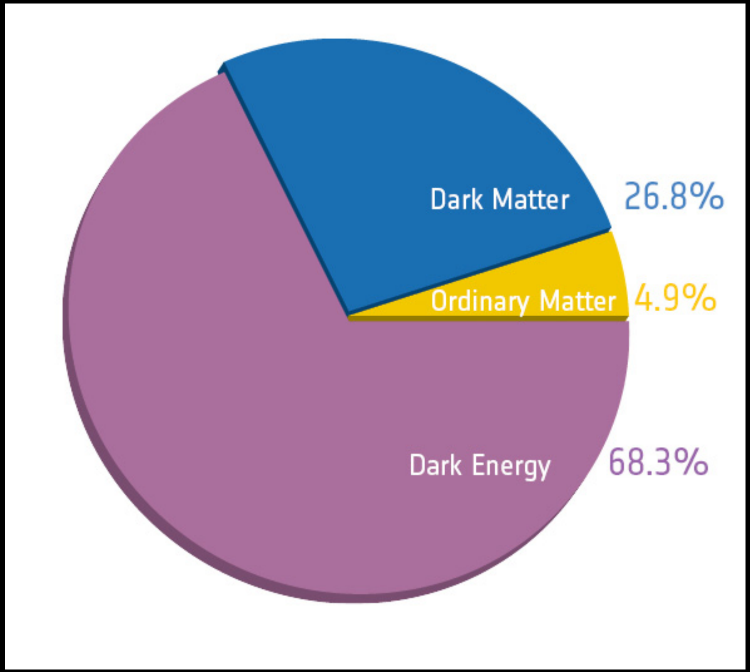
Durham castle and cathedral – credit: Durham University student blog

Disclaimer

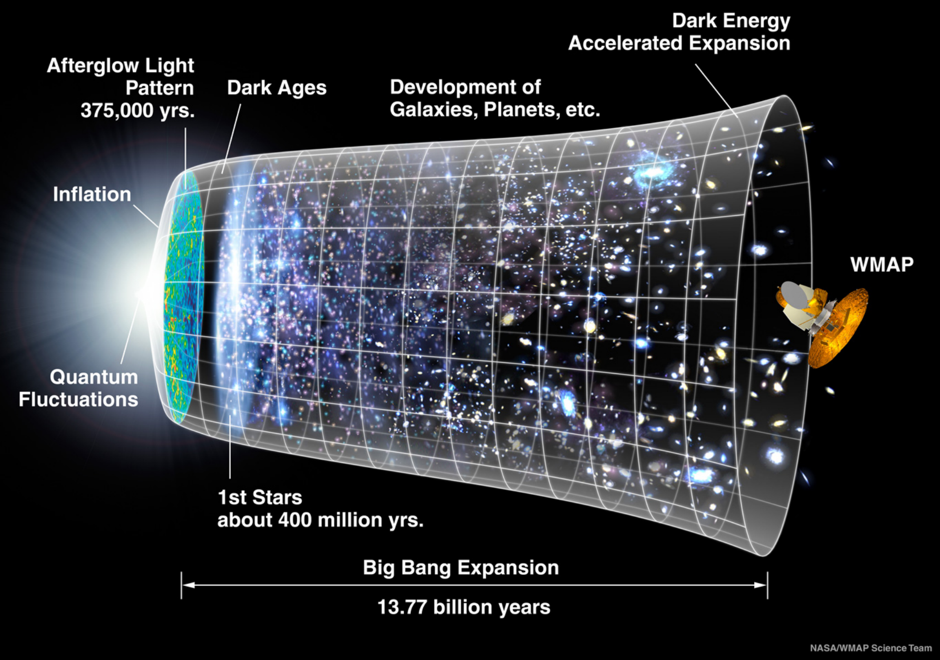
I will **NOT** discuss cold dark matter vs. other flavours of dark matter (such as warm dark matter and self-interacting dark matter). Where relevant, I mention them.

Apologies in advance to my colleagues and fellow researchers if I do not mention your work. The references throughout the talk are by no means complete.

Standard model of cosmology:
Lambda-Cold Dark Matter (LCDM)



Credit: Planck collaboration

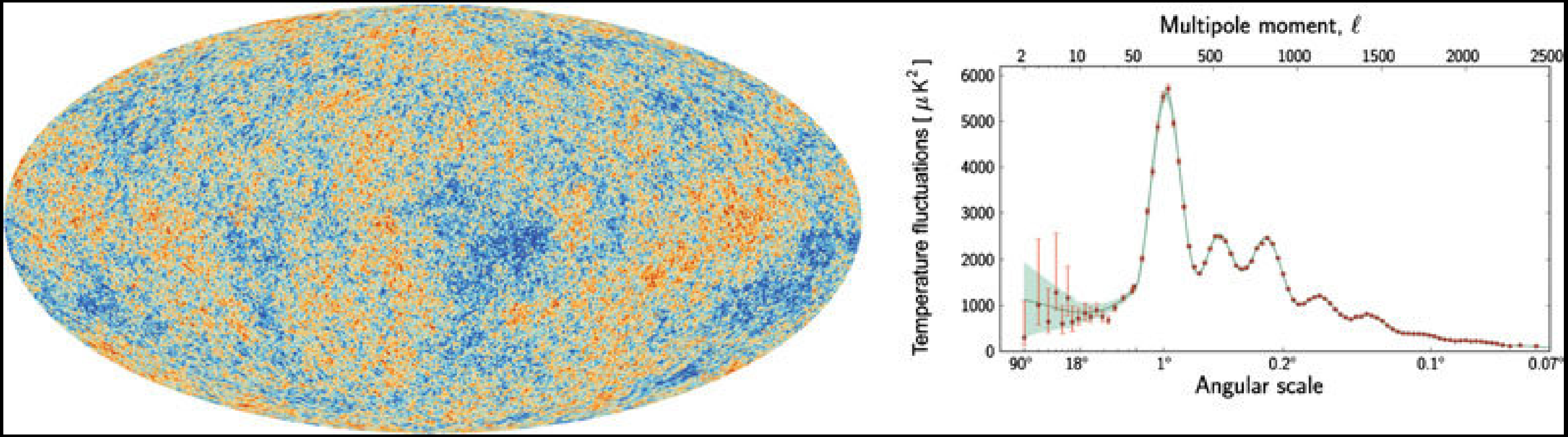


Credit: NASA/WMAP team

The need for dark matter is beyond the “missing mass” inferred from internal dynamics of galaxies and clusters.

The need for dark matter is beyond "the missing matter"

i) Cosmic Microwave Background fluctuations



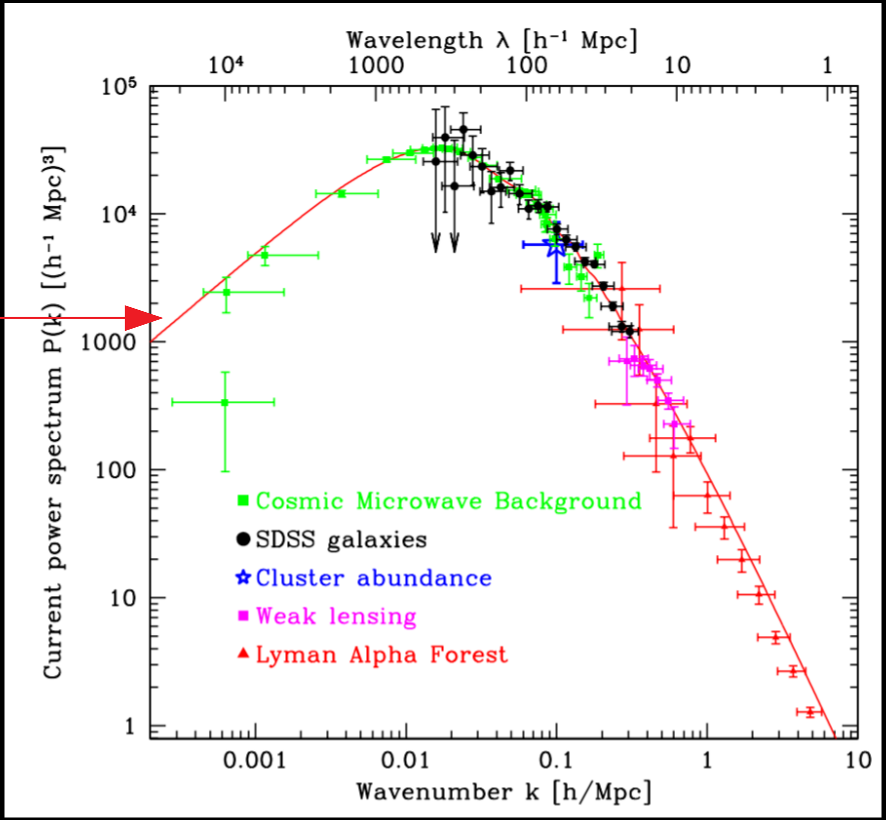
Planck Collaboration

The need for dark matter is beyond "the missing matter"

ii) Large scale distribution of matter in the Universe

- Distribution of galaxies
- Lyman-alpha forest
- Baryonic acoustic oscillation
- ...

LCDM prediction



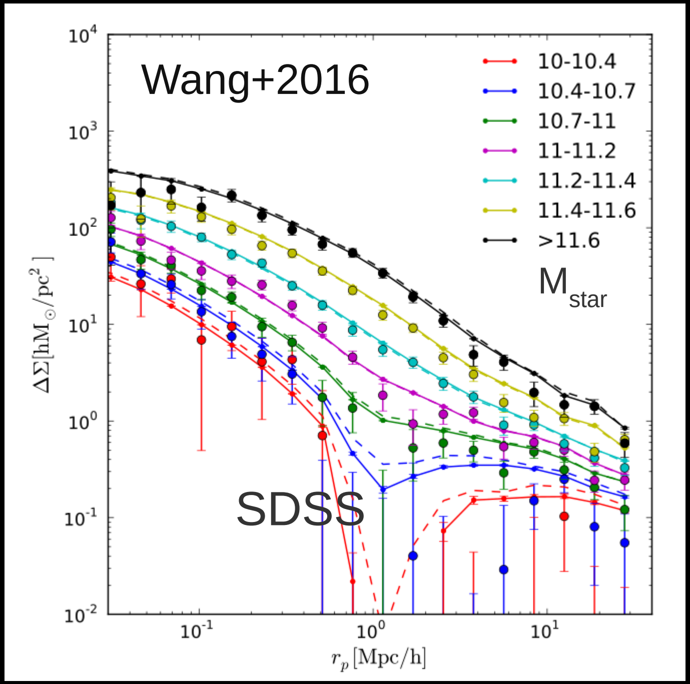
Matter power spectrum probed by various observations, from the largest scales, ~1000Mpc to ~1Mpc

Tegmark et al. 2004

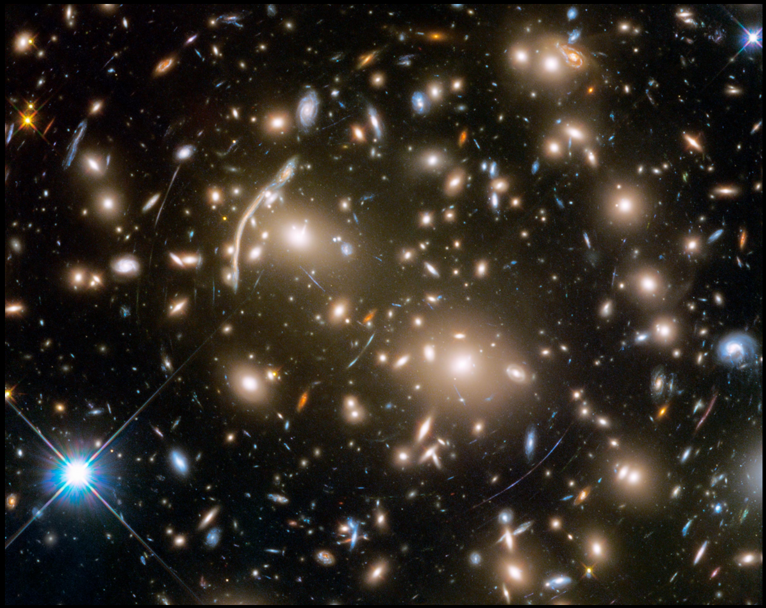
The need for dark matter is beyond “the missing matter”

iii) Gravitational Lensing

Gives an independent measure of mass for clusters and galaxies
(strong lensing from single galaxies, weak lensing from clusters, bullet cluster)



Projected mass around galaxies and clusters from weak lensing lensing, compared to LCDM predictions. Note, they probe regions where there is no light.



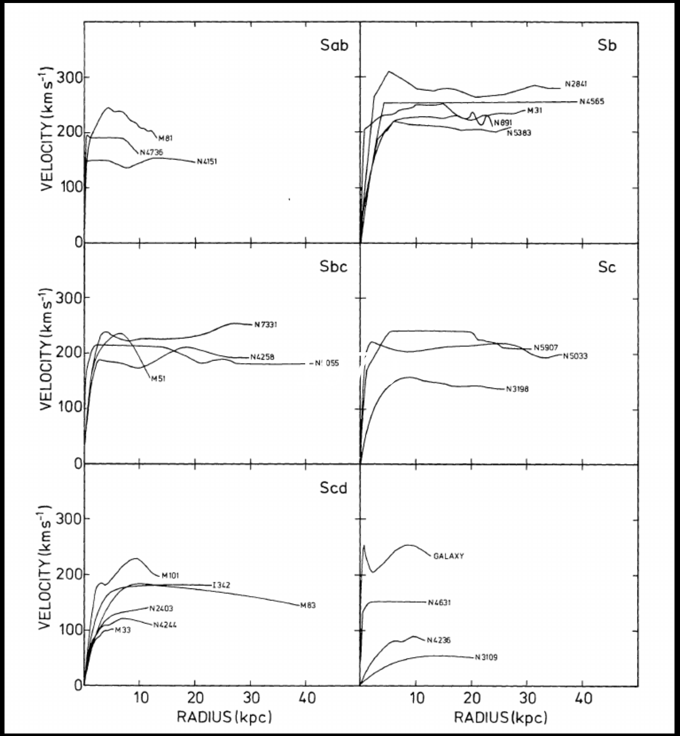
Credit: NASA, ESA, and J. Lotz and the HFF Team

The need for dark matter is beyond “the missing matter”

iv) Dynamics of galaxies, groups and clusters

- internal dynamics of clusters and galaxy groups
- internal dynamics of galaxies (including rotation curve data)
- Mass of the Local Group: MW and M31 will be unbound without dark matter

- Galaxy disks with bar structures are unstable without extra mass



Review by Faber & Gallagher 1979

Success of the dark matter model:

Fixing the model to fit CMB → **all** the other mentioned observations are explained **for free.**

Things yet to be understood on the small scales (centre of galaxies or the smallest galaxies). To be continued …

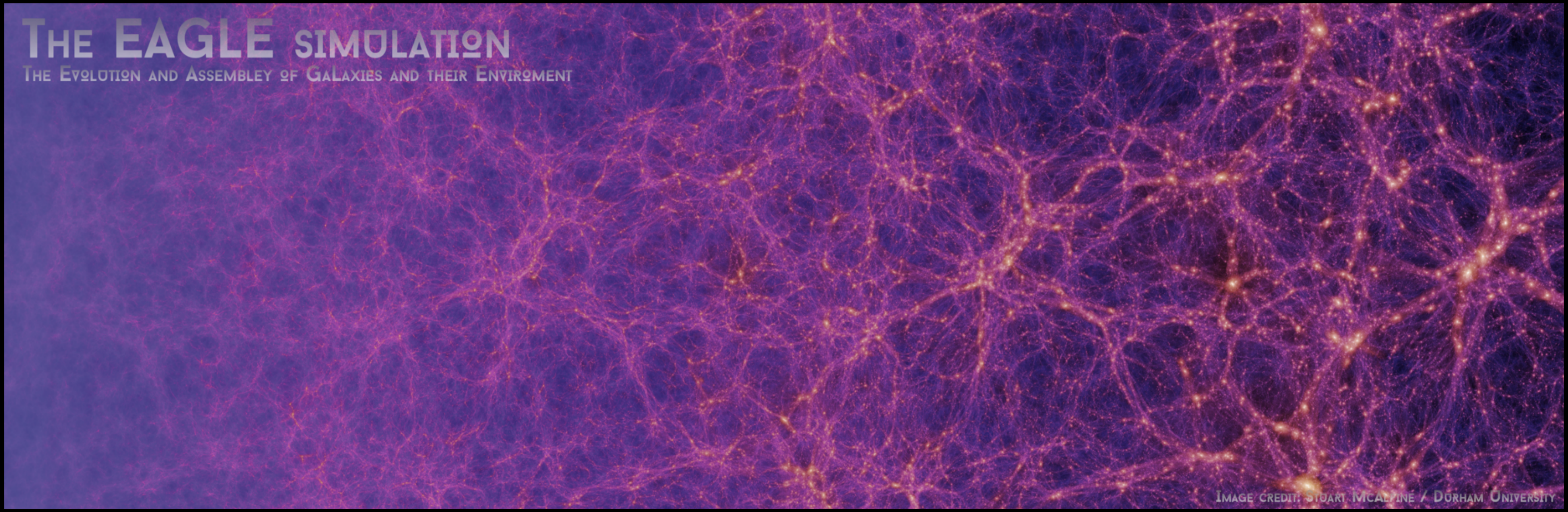
Predictive power of the model realised by numerical simulations

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)

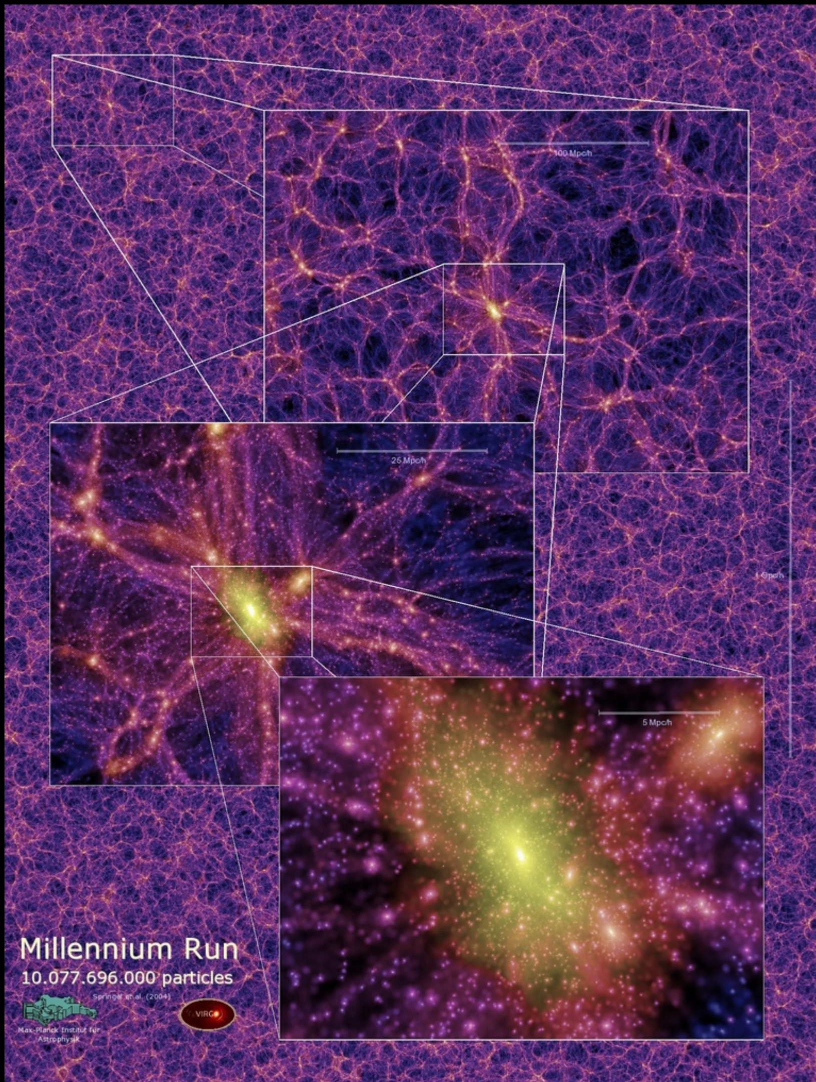
COSMA supercomputers, Durham

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



Big Bang → today

Predictive power of the model realised by numerical simulations

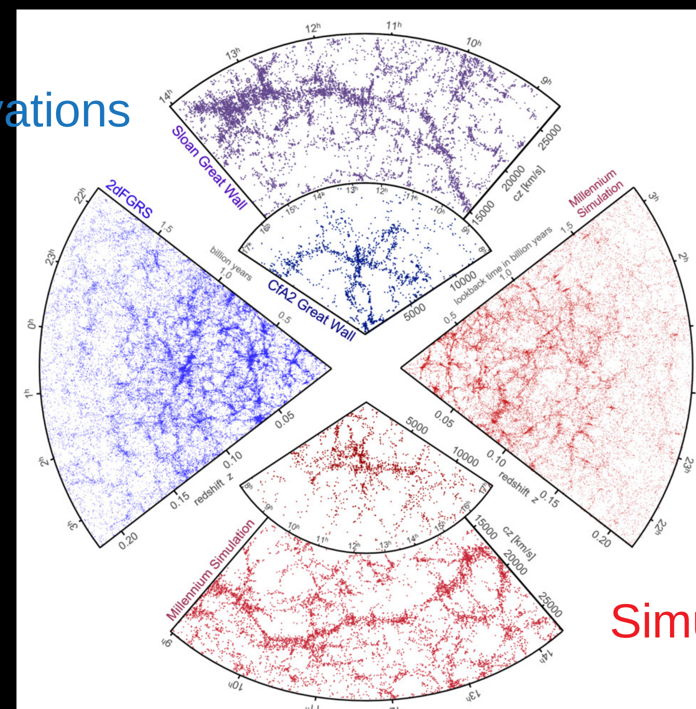


Millennium Simulation – Virgo Consortium

Predictions of the standard model of cosmology:

- cosmic web structure
- Hierarchical growth
- “Clumpiness”
- Dark matter halo mass function
- Distribution of dark matter inside halos

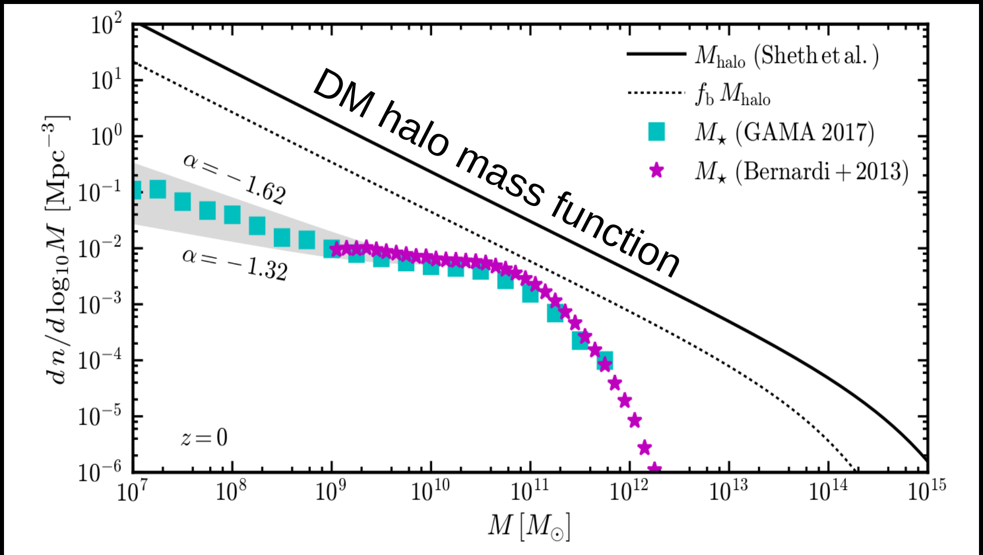
Observations



Simulations

Springel et al. 2005

CDM predictions (i) : dark halo mass function and galaxy formation

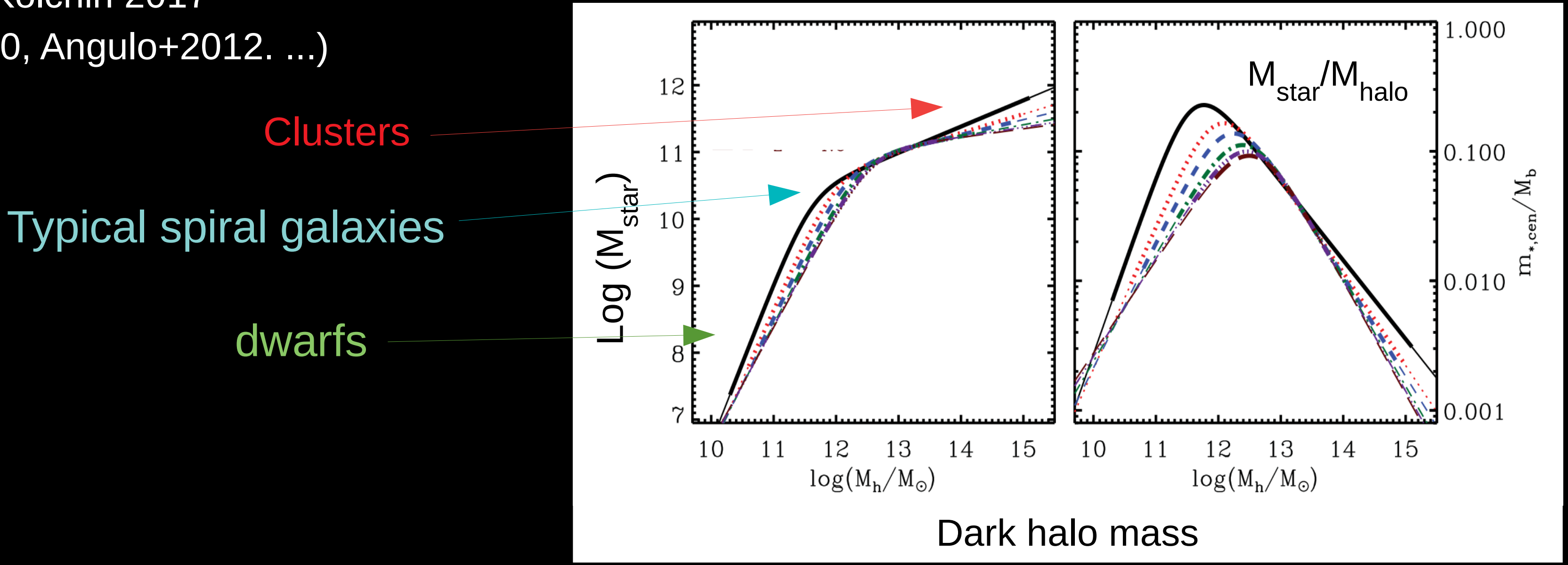


Bullock & Boylan-Kolchin 2017
(also Jenkins+2010, Angulo+2012. ...)

"Abundance Matching" : assuming there is a one-to-one and monotonic relation between stellar mass and halo mass

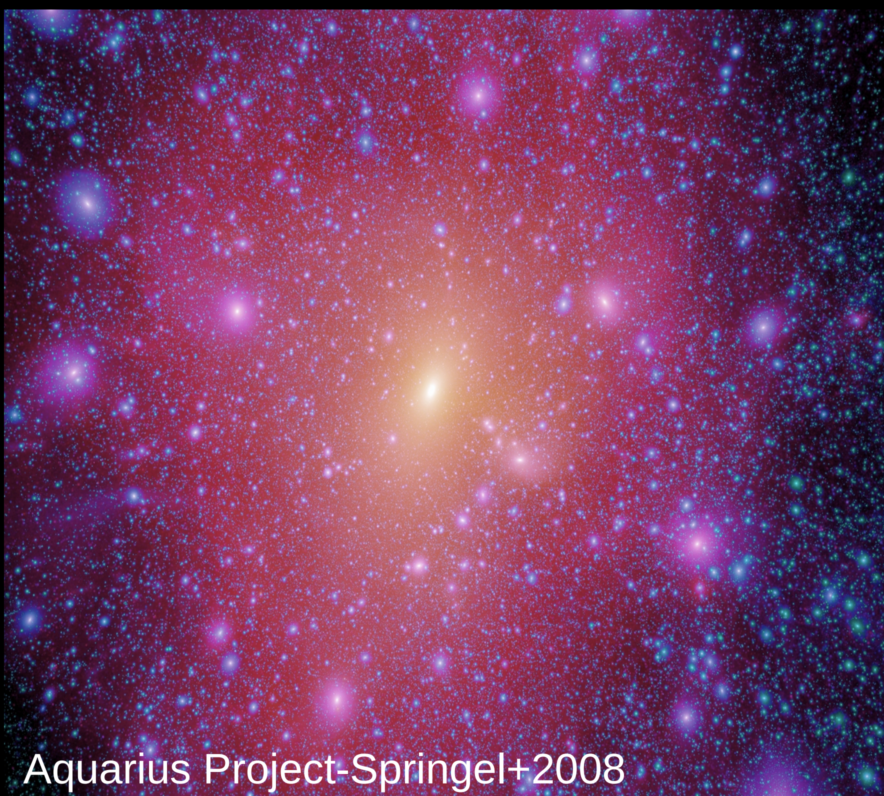
(Frenk+1988, Guo+2010, Wang & Jing 2010, Behroozi+2013, Moster+2013, ...)

Moster+2013

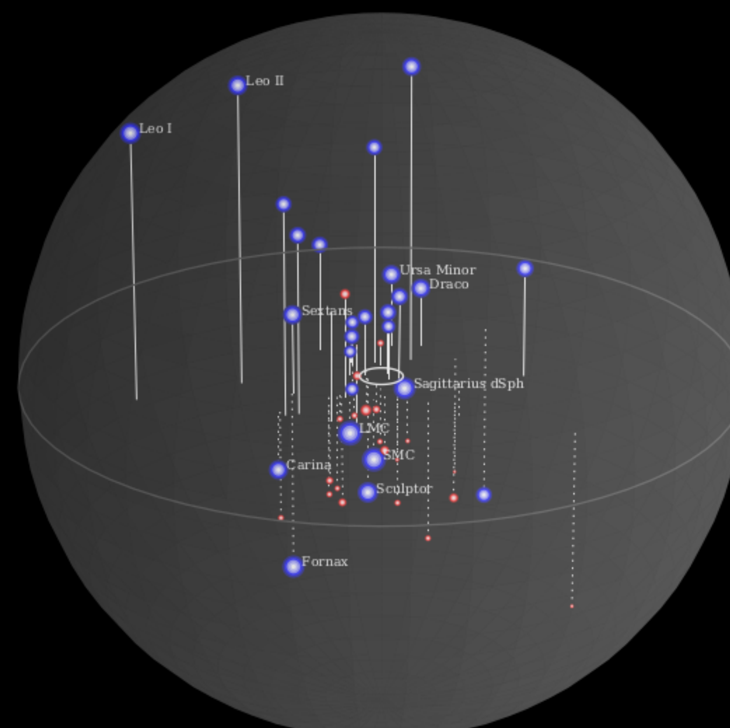


Large number of dark matter clumps vs number of dwarf galaxies
the missing satellites problem
(Moore+1998, Klypin+1999)

Dark matter halo a MW size halo in
cold dark matter universe.
Consequence of the hierarchical growth + steep shape of the halo mass function


Aquarius Project-Springel+2008

Observed dwarf galaxies around the Milky Way



Pawlowski/Bullock/Boylan-Kolchin

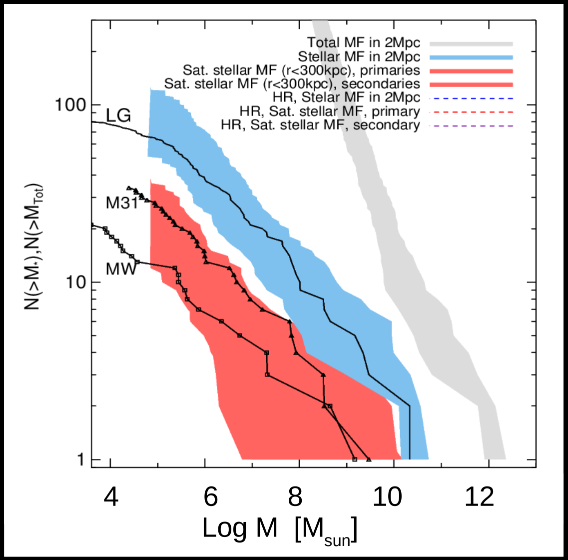
How do galaxies populate dark matter halos?

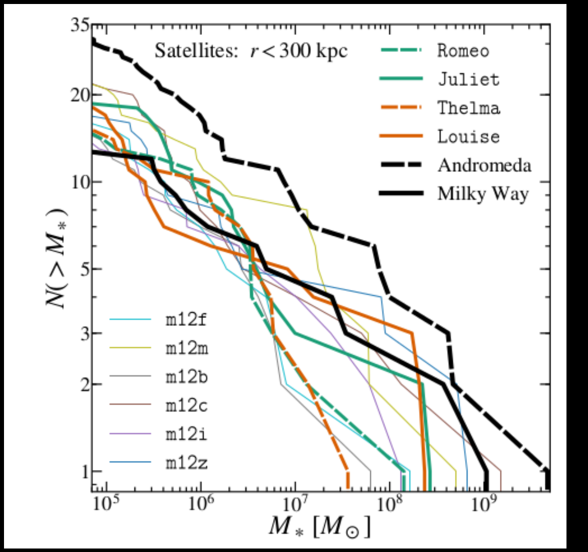
Current hydrodynamical cosmological simulations produce the right number of dwarfs galaxies (satellites and field).

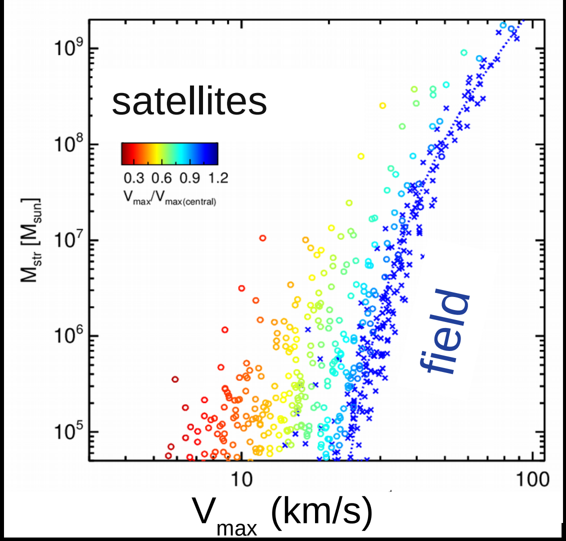
Reionisation and supernovae feedback keep the smallest DM clumps empty of stars.

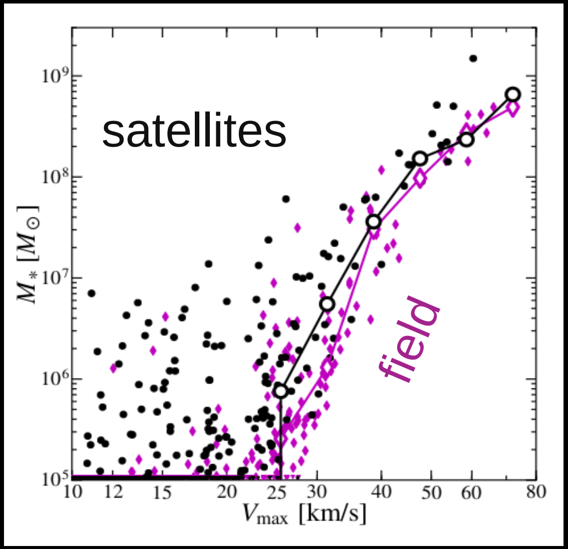
As a consequence: steep shape of the stellar mass-halo mass relation

Also, other works by: C Scannapieco et al; A. Brooks et al; Auriga simulations; NIHAO project; MaGICC simulations; Revaz et al., …









Sawala+2016; AF+2016 (APOSTLE)

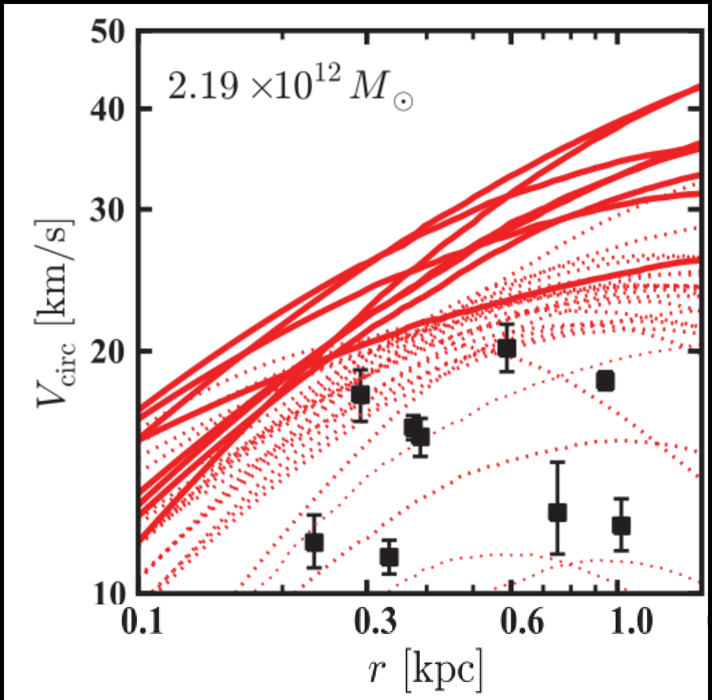
Garrison-Kimmel+2019, Wetzel+2016 (FIRE)

Dark matter content of dwarf galaxies and the too-big-to-fail (TBTF) problem

Dwarf galaxies appear to live in lower mass halos than predicted

Boylan-Kolchin+2012
Based on **dark matter-only simulations** of the Milky Way size halos

~enclosed mass



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

Is the “too-big-to-fail” problem a challenge for dark matter?

Current cosmological hydrodynamical simulations can address it and the solution(s) have various aspects:

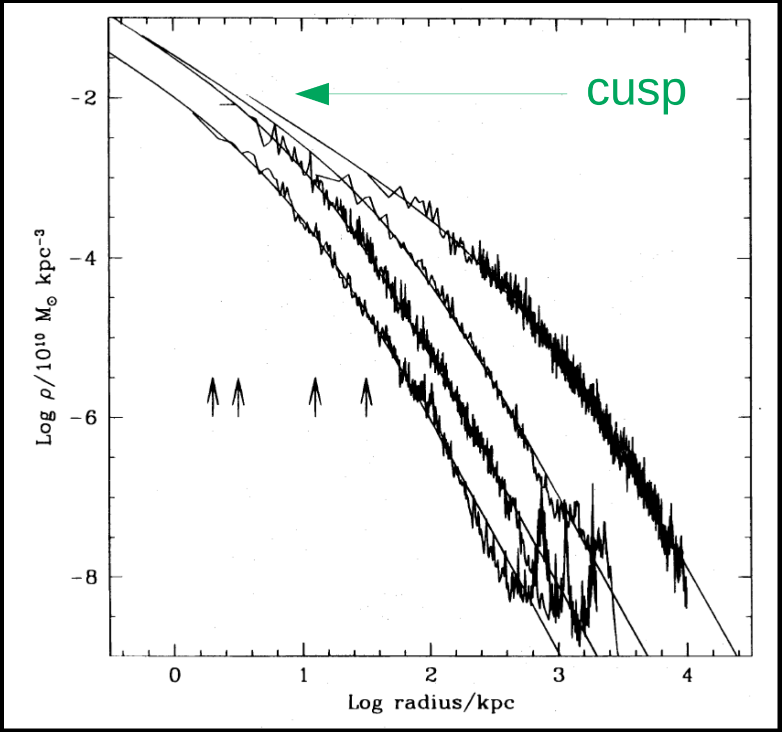
- (i) Abundance matching principles, i.e. monotonic and one-to-one relation between halos and galaxies, do not hold at the lowest masses. “Dark halos” are predicted by simulations (e.g., Sawala+2015, Maccio+2018, Fits+2018; Munshi+2018)
- (ii) Dark matter halos in hydrodynamical simulations have lower masses than their matched counterparts in DMO simulations at the dwarf galaxies regime (e.g., Sawala+2013, Wetzel+2016, Garrison-Kimmel+2019)
- (iii) baryonic feedback processes ***can*** alter the density of the DM in the inner regions (not in all simulations) - to be continued! (e.g., Zolotov+2011, Brook+2015; Dutton+2016; Wetzel+2016; Garrison-Kimmel+2019)
- Also, warm DM and self-interacting DM models can address the problem by lowering the concentration or inner slope of the density profile (e.g., Lovell+2012; Maccio+2012, Elbert+2015; Robels+2019)

The **slope** of the stellar mass-halo mass relation, as well as the **scatter** around the relation is uncertain in the regime of low mass dwarf galaxies (and ultra faint dwarfs).

Internal structure of cold dark matter (CDM) halos & Cusp vs. Core problem
(Flores & Primack 1994, Moore 1994)

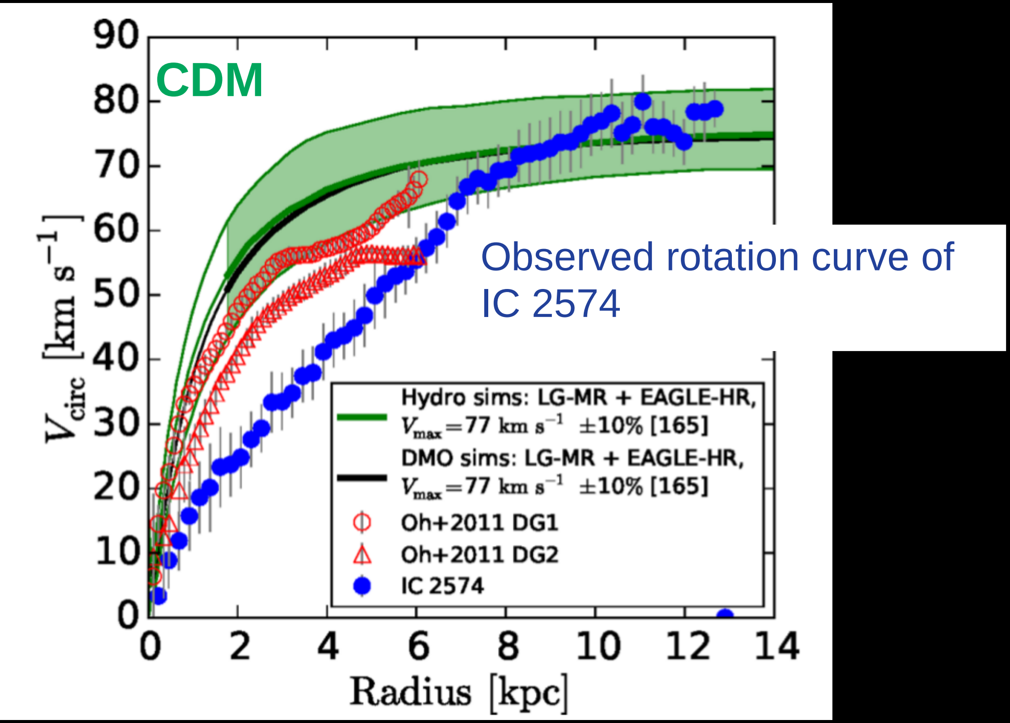
Universal dark matter density profiles of halos in CDM

These halos span 4 orders of magnitude in mass



Navarro, Frenk & White (1996,97)

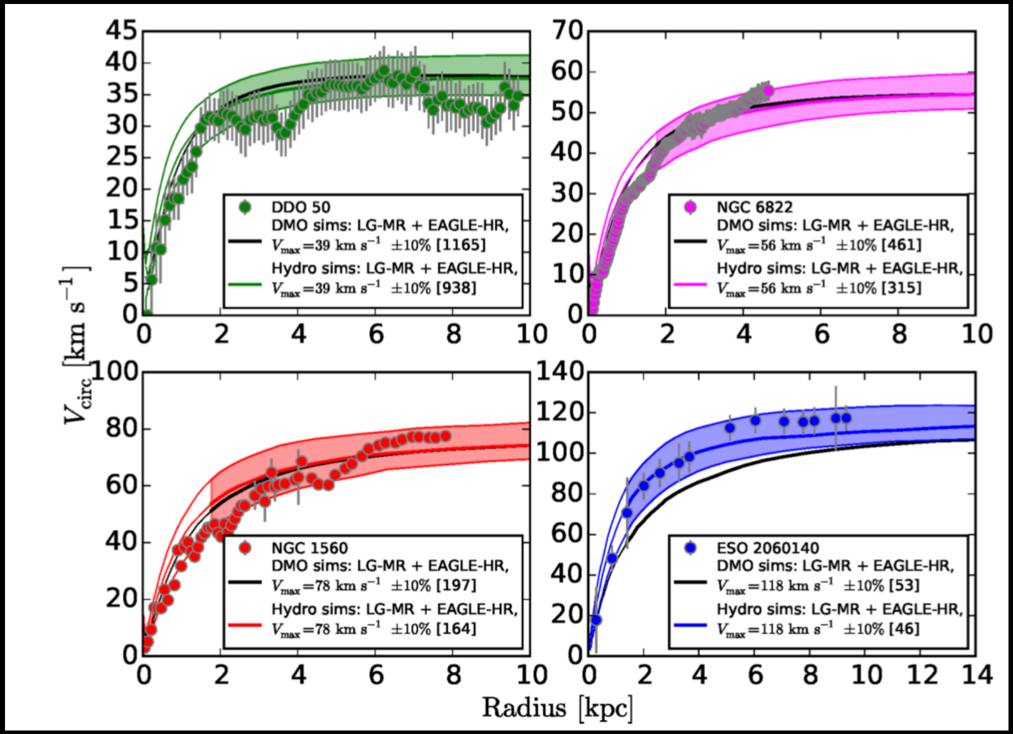
Rotation curve of some galaxies indicate a shallower (cored) dark matter density profile

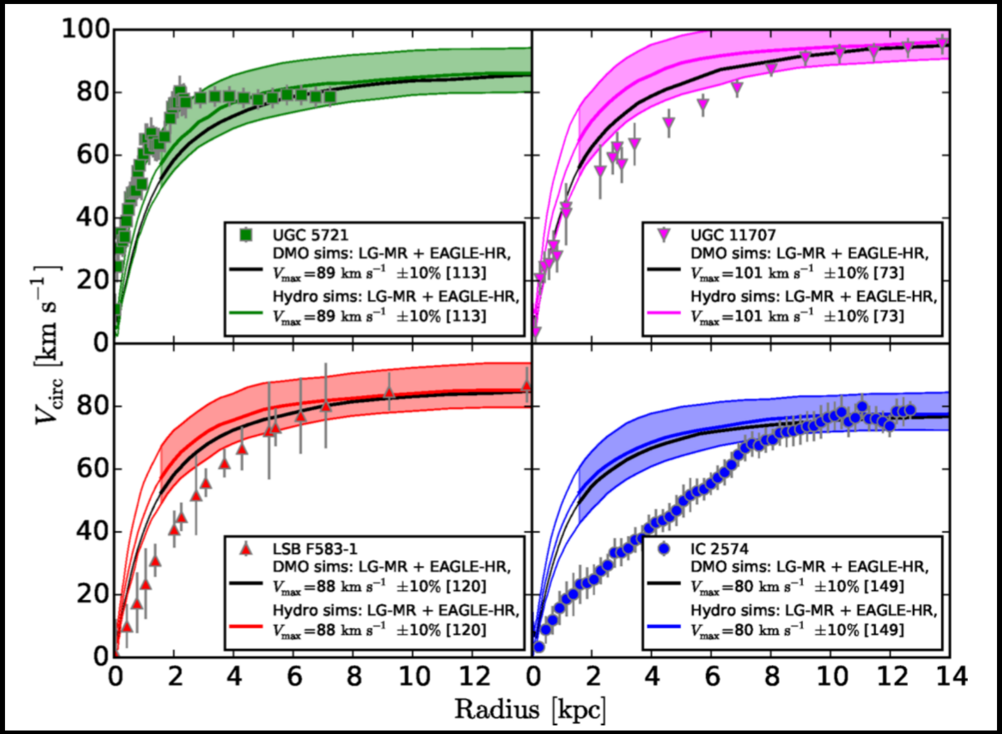


Oman et al. 2015

The core-cusp problem or diversity of rotation curves

Rotation curve of galaxies indicate a larger diversity compared to pure CDM halos





Oman+2015

Oh+2015

The core-cusp problem or diversity of rotation curves

Possible solutions

within LCDM	Alternatives to Cold DM

within LCDM

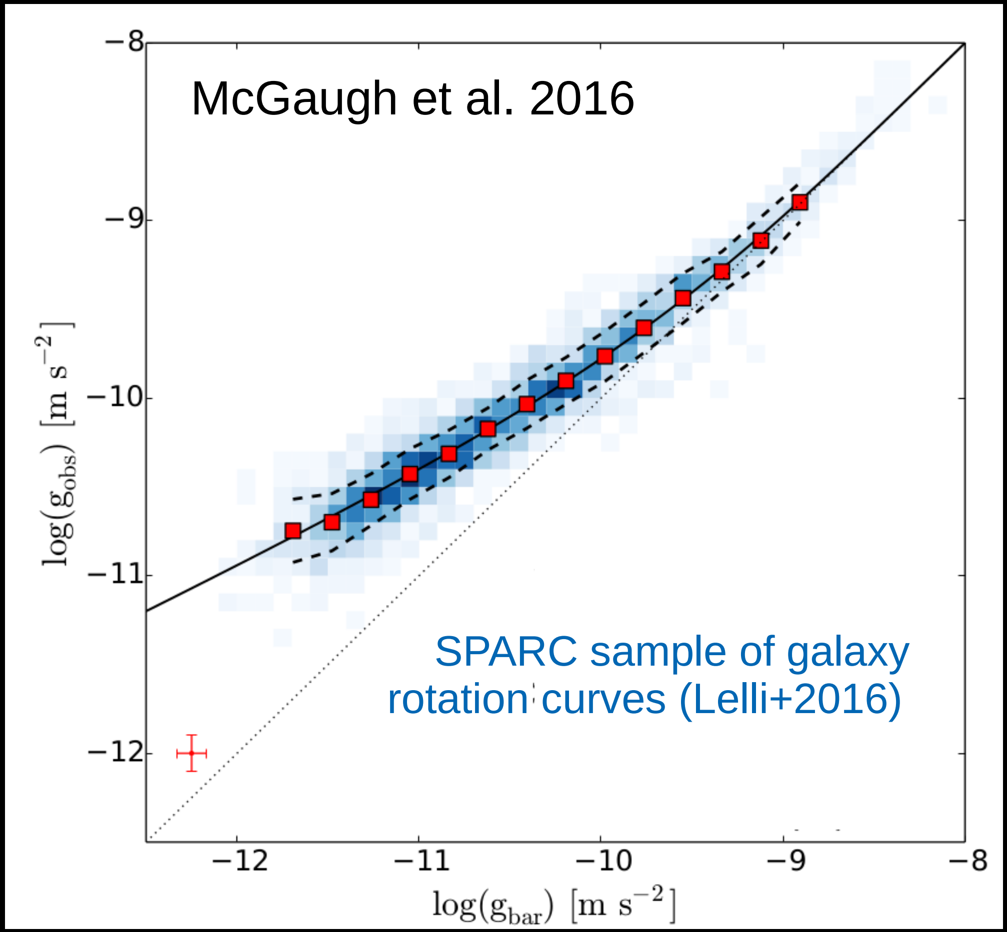
- Data; gas rotation curve is not giving us accurate estimate of the enclosed mass (e.g. Read+2016, Verbeke+2017, Oman+2019)
- baryon-induced cores: Fluctuations of potential, e.g. caused by bursts of star formation, *can* modify the shape of the density profile.
  (Navarro+1996; Gnedin+2002; Read+2005; Governato+2010; Brooks+2012; Pontzen+2014; DiCintio+2014; Brook+2016 Onorbe+2015;…)
  Also, Santos-Santos et al. 2020

Alternatives to Cold DM

- Warm Dark Matter (WDM): WDM halos have lower central densities (e.g. Lovell+2012; Maccio+2012)
- Self-interacting dark matter (SIDM) (e.g. Spergel+2000; Vogelsberger+2012; Rocha+2013; Elbert+2014; Creasey+2017; Ren+2019; Kaplinghat+2019...)

Radial Acceleration Relation (RAR)

There is a tight correlation between the surface brightness and rotation speed of galaxies

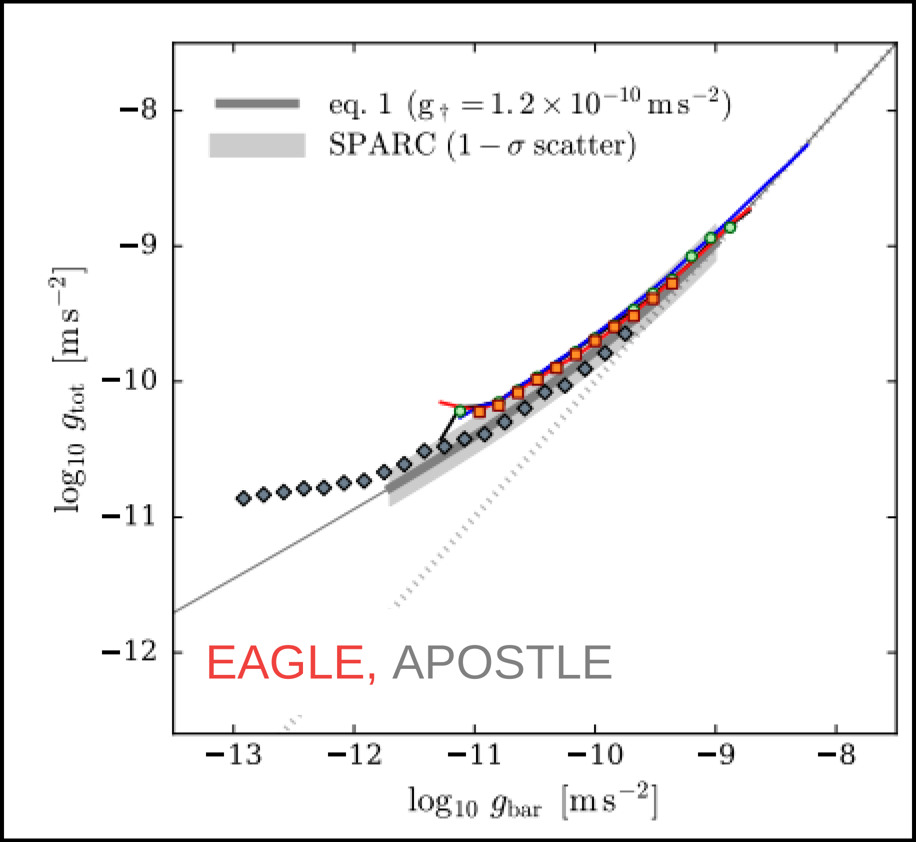


Observed (total) acceleration ~ v^2/r

Surface brightness

Radial Acceleration Relation (RAR) & LCDM

- Galaxies from LCDM simulations (EAGLE and APOSTLE) follow the SPARC sample on RAR
- They deviate from MOND prediction at low accelerations
- The relation naturally rises in LCDM(even with toy models) due to scaling rela tions:
  stellar mass-halo mass relation +
  stellar mass-size relation
- See Ren+2019 for self-Interacting DM and RAR

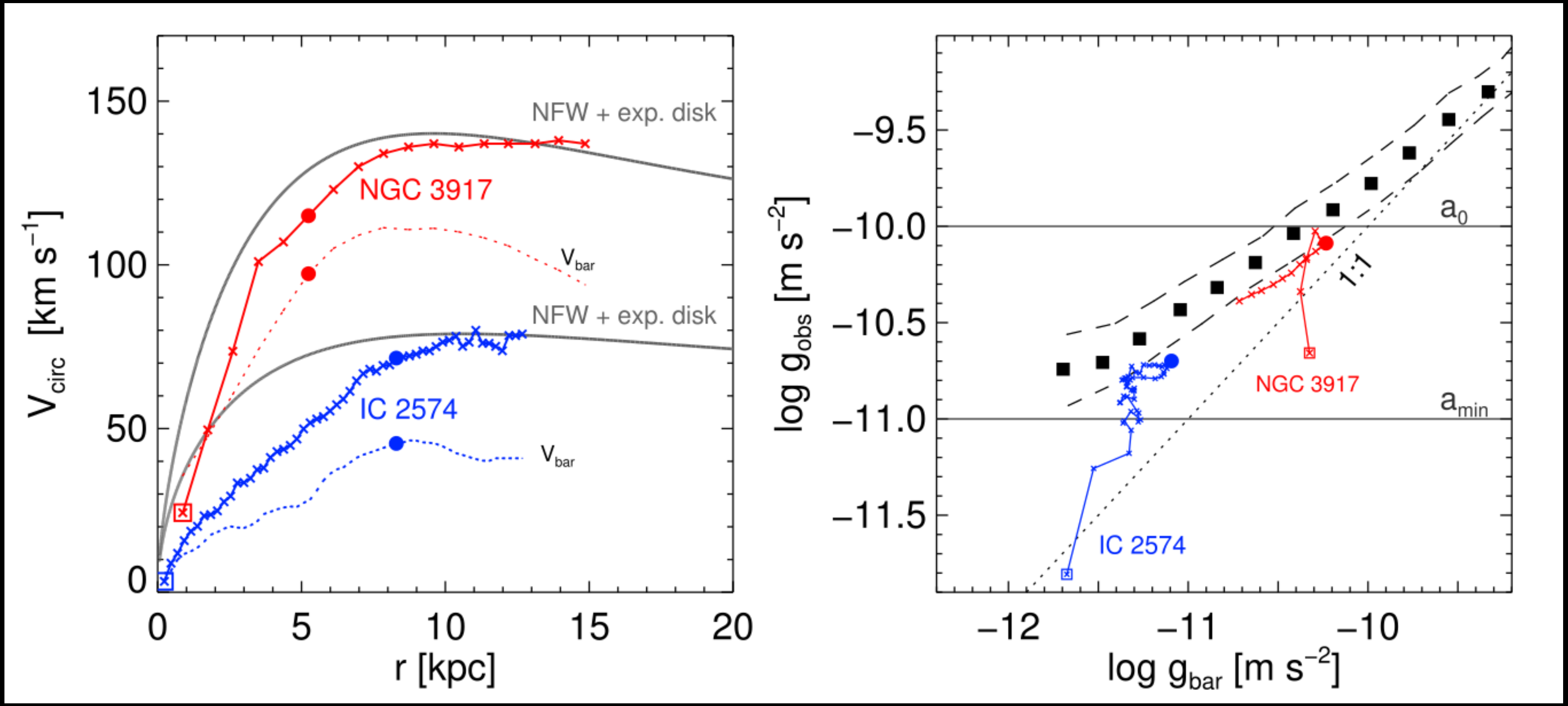


Ludlow et al. 2017

See, also, Navarro et al. 2017; Di Cintio & Lelli 2016, Keller et al. 2017;

Radial Acceleration Relation (RAR) & LCDM

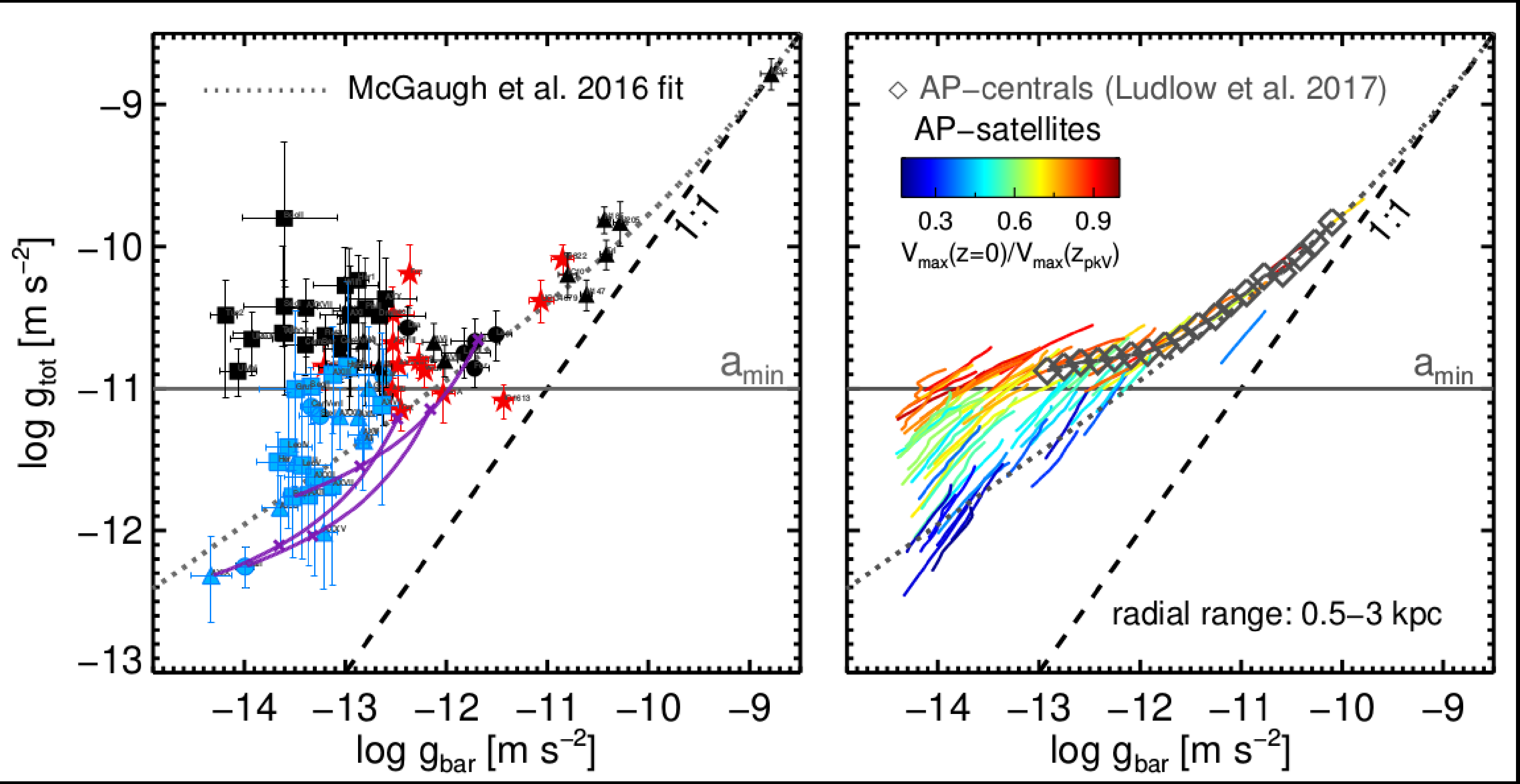
Galaxies that are "troublesome" for LCDM due to shallow DM profiles, do not follow the RAR either



Navarro, Benitez-Llambay, AF, et al. 2017
(see, also, Ren et al. 2019; Santos-santos et al. 2020)

Radial Acceleration Relation (RAR) & dwarf galaxies

Dwarf galaxies in the Local Group with
velocity dispersion measurement



AF et al. 2018

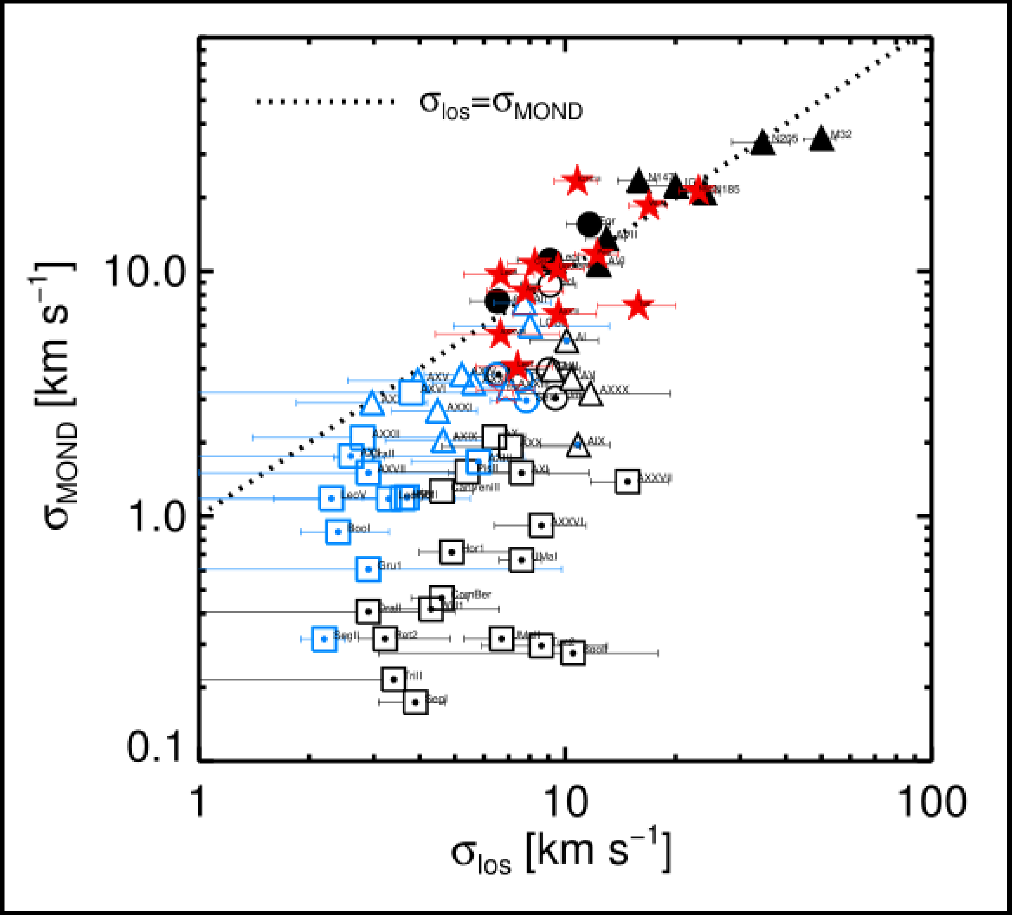
Is the mass of dwarf galaxies consistent with MOND?

Predicted velocity dispersion of dwarf galaxies by MOND using the formalism in McGaugh et al 2013

including external field effect (EFE) approximation

Squares: ultra faint dwarfs
dotted symbols: dominated by EFE

Predicted velocity dispersion



Observed velocity dispersion

AF et al. 2018

Looking into the future: (some) big questions and challenges

In LCDM (or WDM or SIDM flavours)
- The origin of diversity of rotation curves (or core-cusp problem) in dwarf galaxies
    - do cores exist in the observed galaxies? If so,
    - are they due to baryonic effects or other dark matter models?

- the stellar mass-halo mass relation at the faint end

- detection of dark subhalos around galaxies, in particular Milky Way

- Plane(s) of satellites around Milky Way-like galaxies

- Existence of compact galaxy group

In MOND:

- Dwarf spheroidal galaxies in MOND

- predictions for large scale structure, lensing, CMB, etc

Success of the dark matter model in the cosmological context
very much worth trying to understand the details better :)