The Small Scale Structure of Cold Dark Matter

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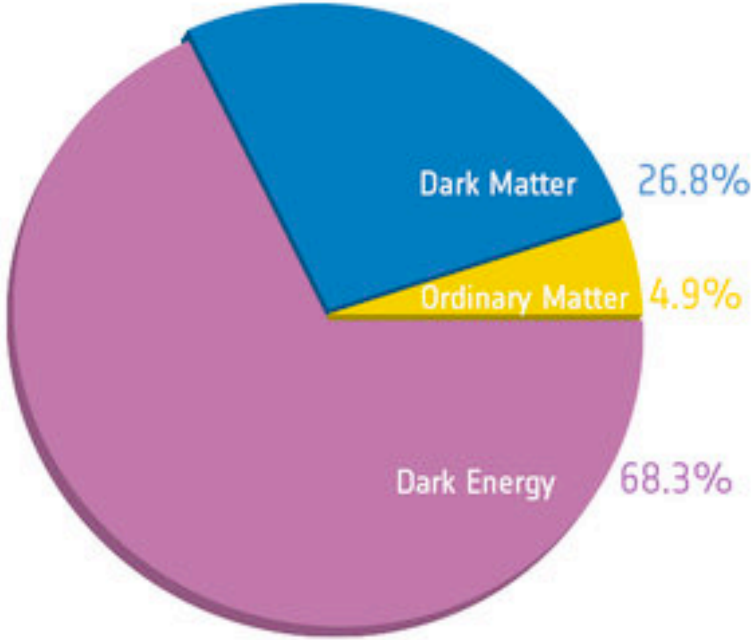
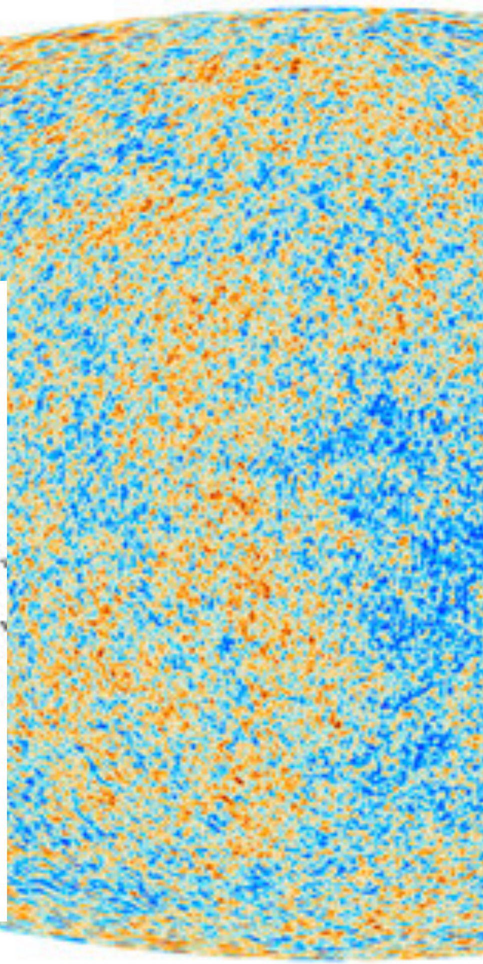
UVic

VIRGO

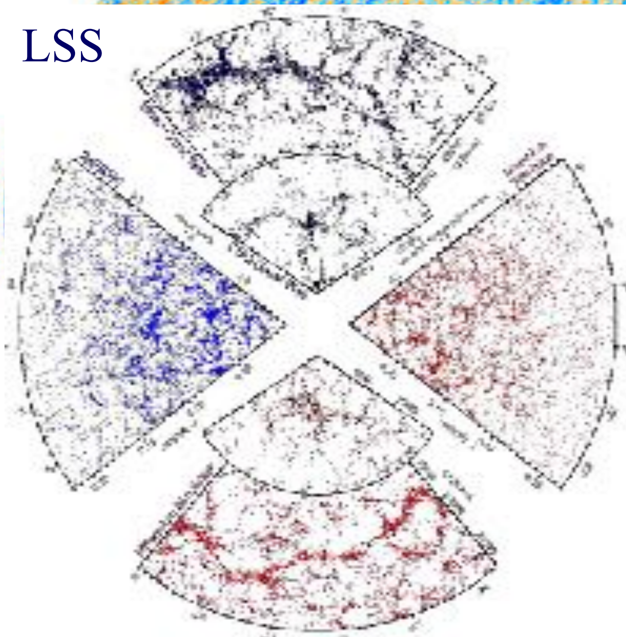
The Standard Model of Cosmology



CMB

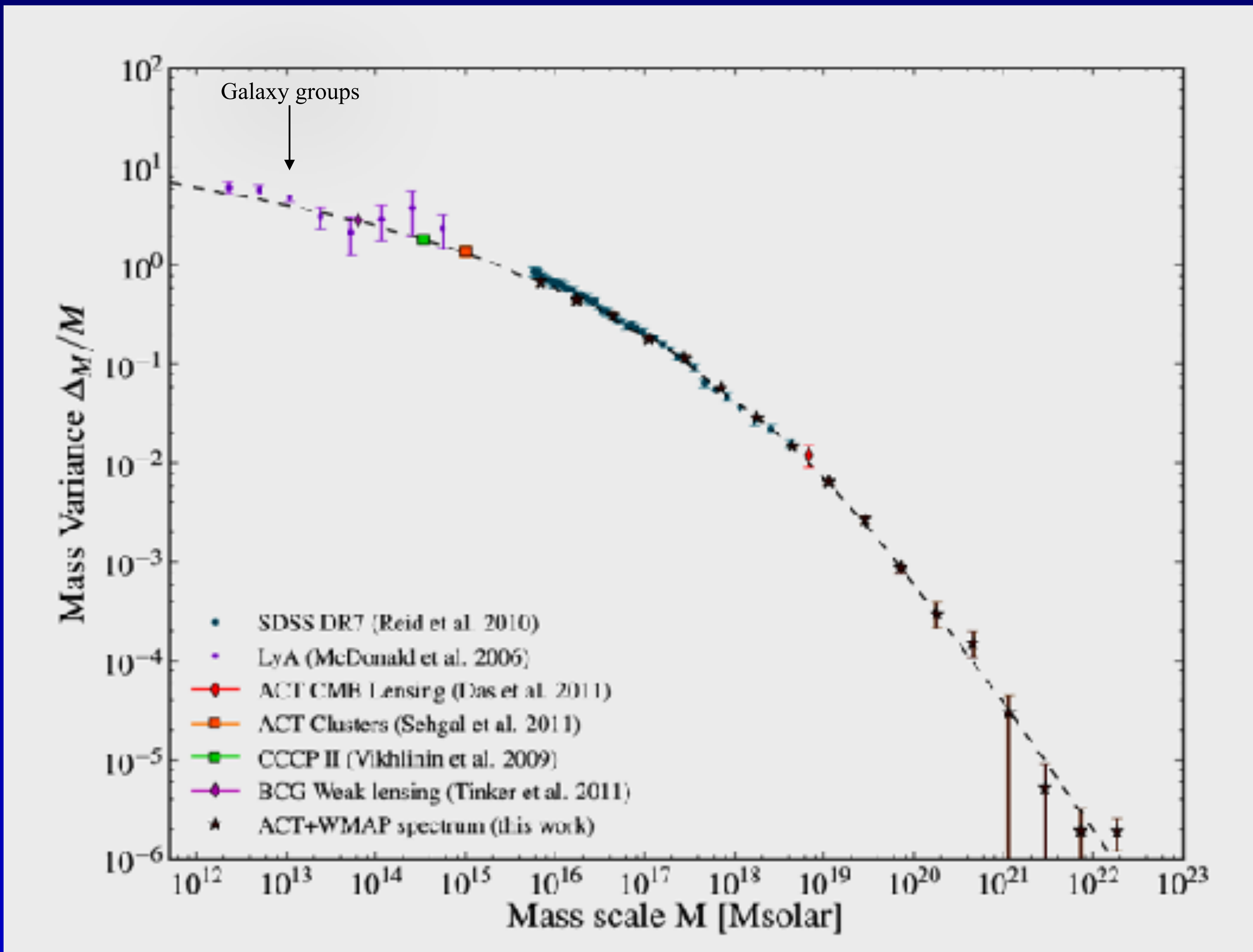


LSS



Wedded to LCDM

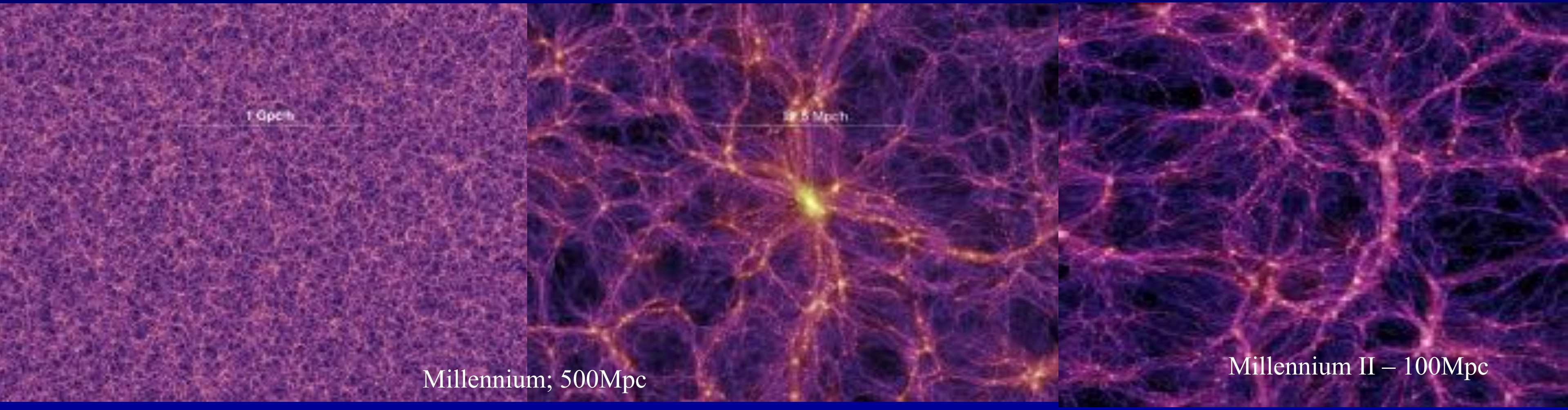
The LCDM paradigm: Dark Matter Clustering in the Linear Regime



The power spectrum of density fluctuations in the linear regime is very well matched by assuming that the initial density fluctuations are Gaussian and that the Universe is dominated by collisionless **Cold Dark Matter (CDM)**

Hlozek et al 2012

The Clustering of Dark Matter



Millennium; 500Mpc

Millennium II – 100Mpc

Aquarius: a galaxy halo

Phoenix: a galaxy cluster halo

Simulations have enabled a full characterization of the (hierarchical) clustering of cold dark matter in the non-linear regime

- Dark matter halos are self-similar in structure
- Mass function well constrained and understood

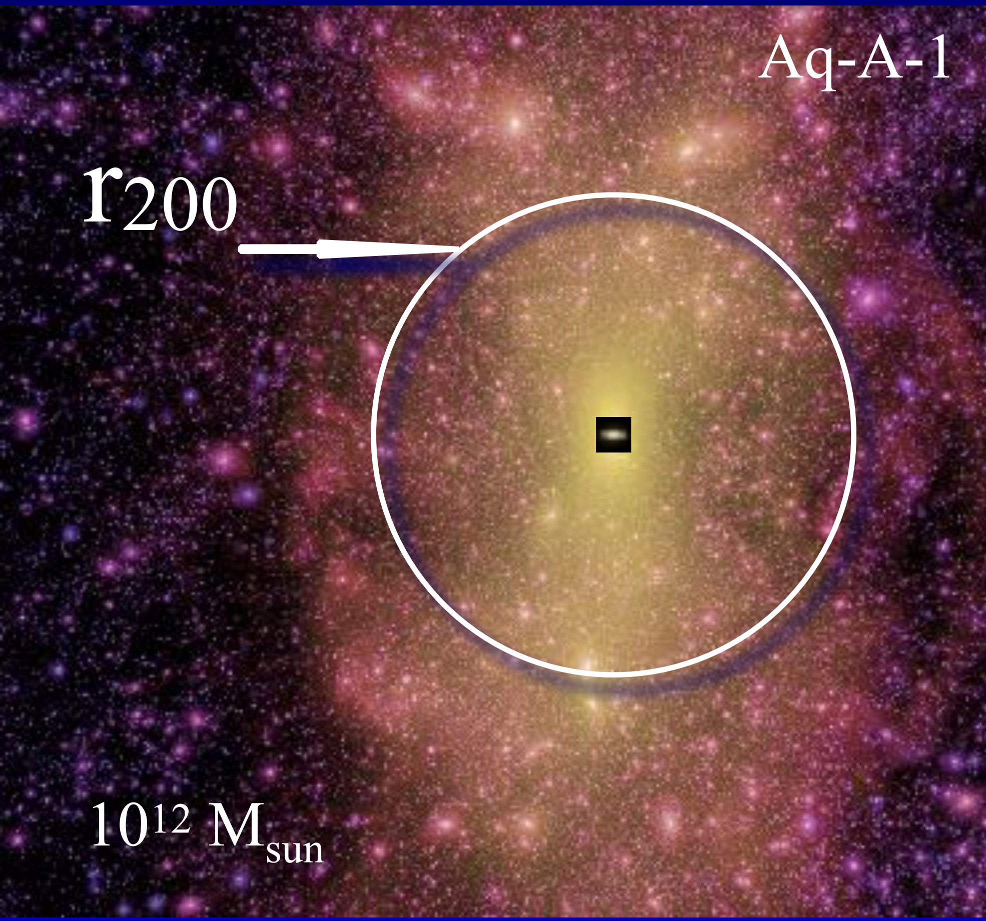
Spinger et al 2005, Boylan-Kolchin et al 2009, Angulo et al 2012

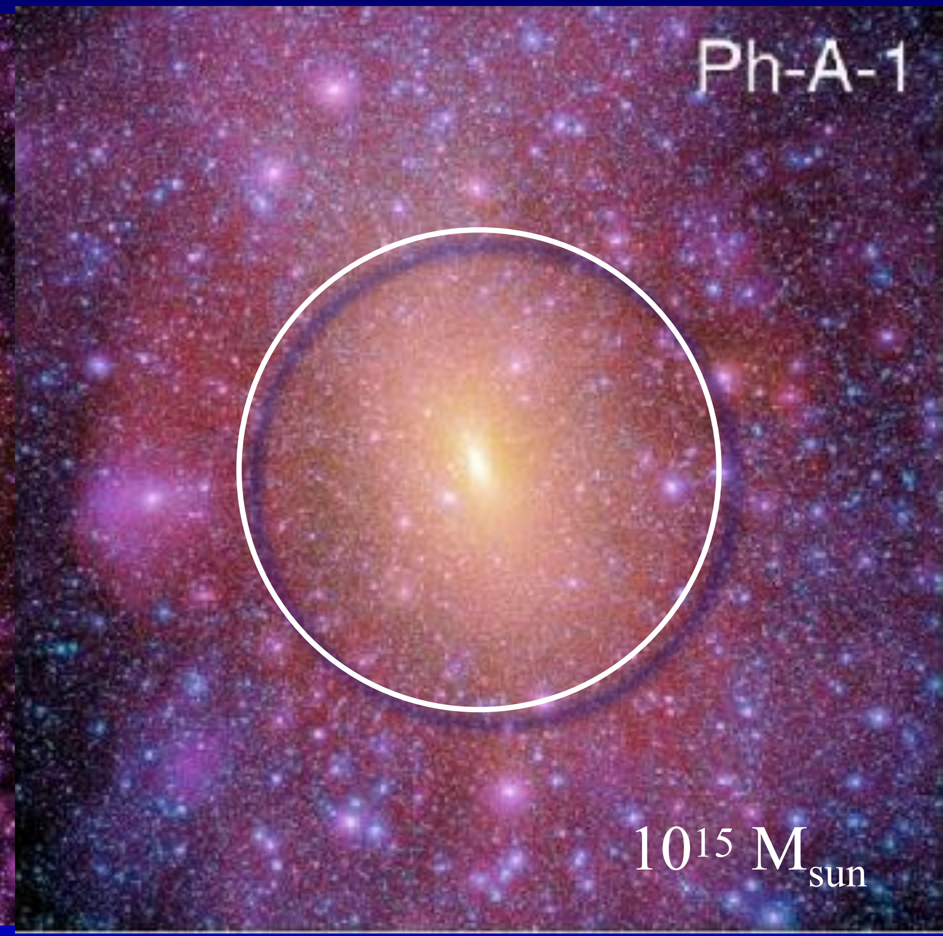
Small Scale Challenges to LCDM

- The ”missing satellites” problem
- The “too-big-to-fail” problem
- The mass discrepancy-acceleration relation
- The “cusp vs core” problem
- The “satellite alignment” problem
- “Missing dark matter” galaxies

Dark matter halos: the basic non-linear structures in LCDM

The self-similar nature of LCDM halos



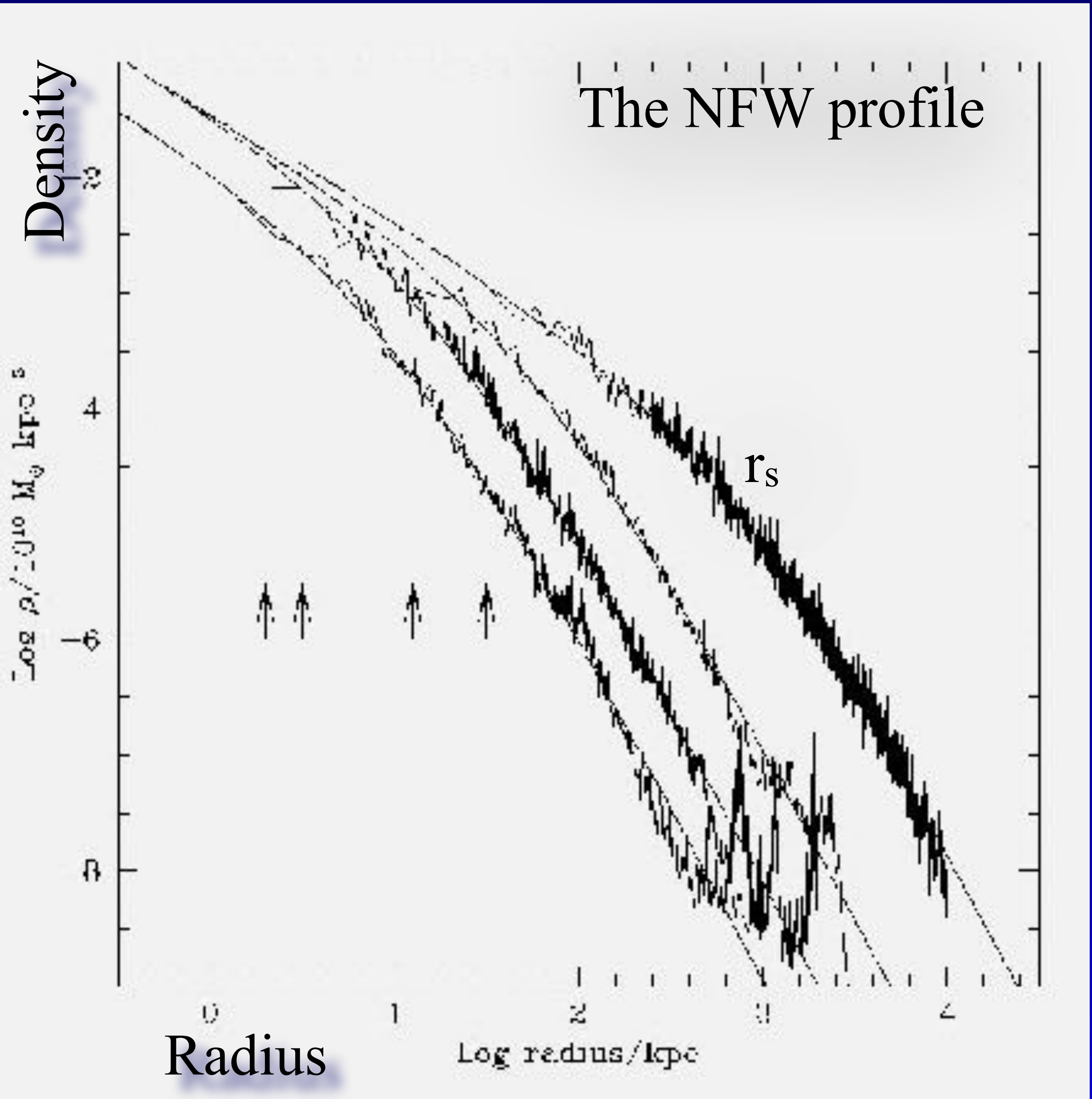


DM halos: self-similar structures linked by the age of the Universe

M_{200}/r_{200}^3=constant

$M_{200} \propto V_{200}^3$

The Mass Profile of Cold Dark Matter halos



- The shape of the mass profiles of dark mater halos is roughly independent of halo mass and cosmological parameters

- Density profiles are "**cuspy**"

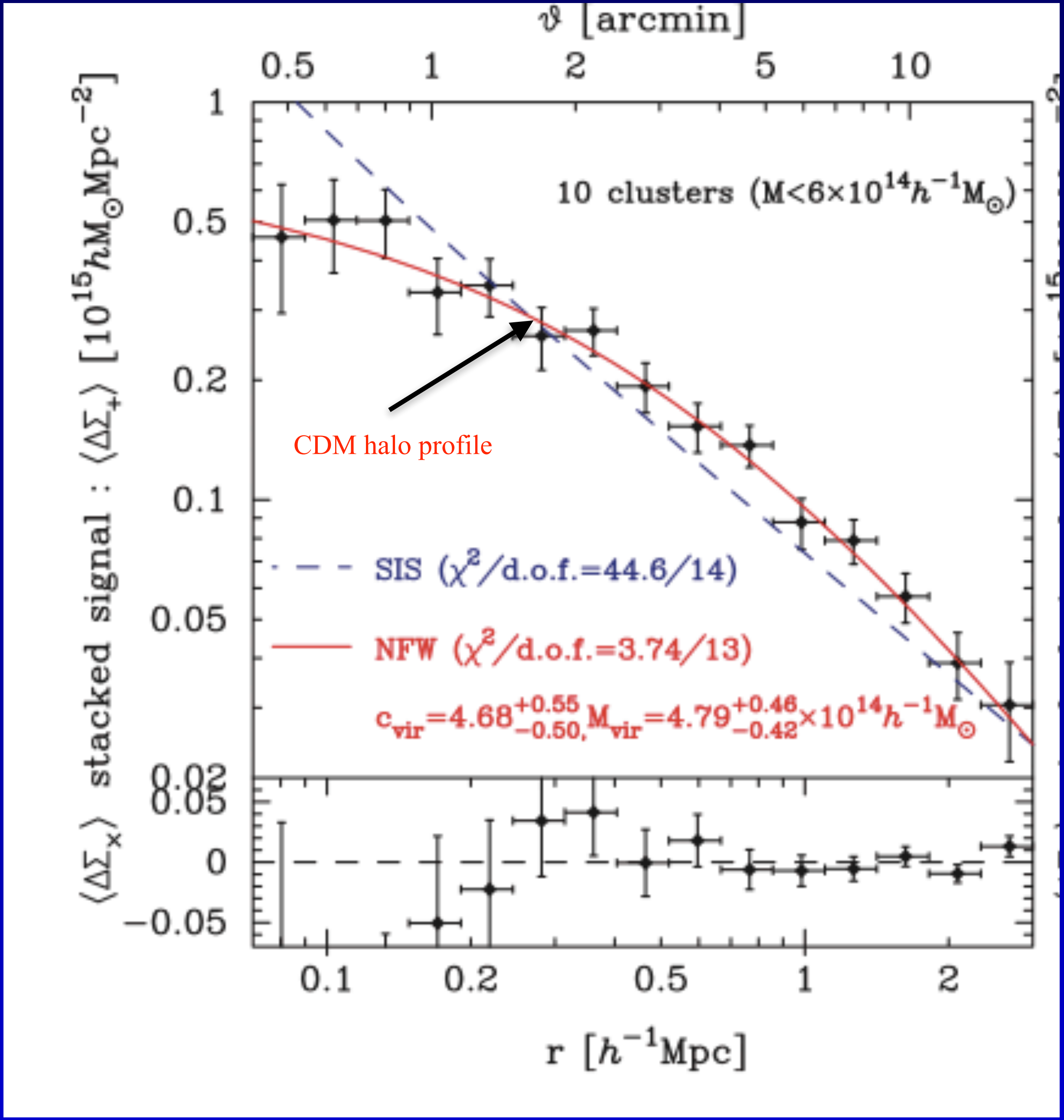
$$\rho/\rho_{crit}=\delta_c/[(r/r_s)(1+r/r_s)^2]$$

- At fixed mass, the *only* parameter is a radial scale set by the scale radius, r_s

- Halos are usually parameterized by the virial mass, M_{200}, and a "concentration" $c=r_{200}/r_s$

NFW+1996, 1997

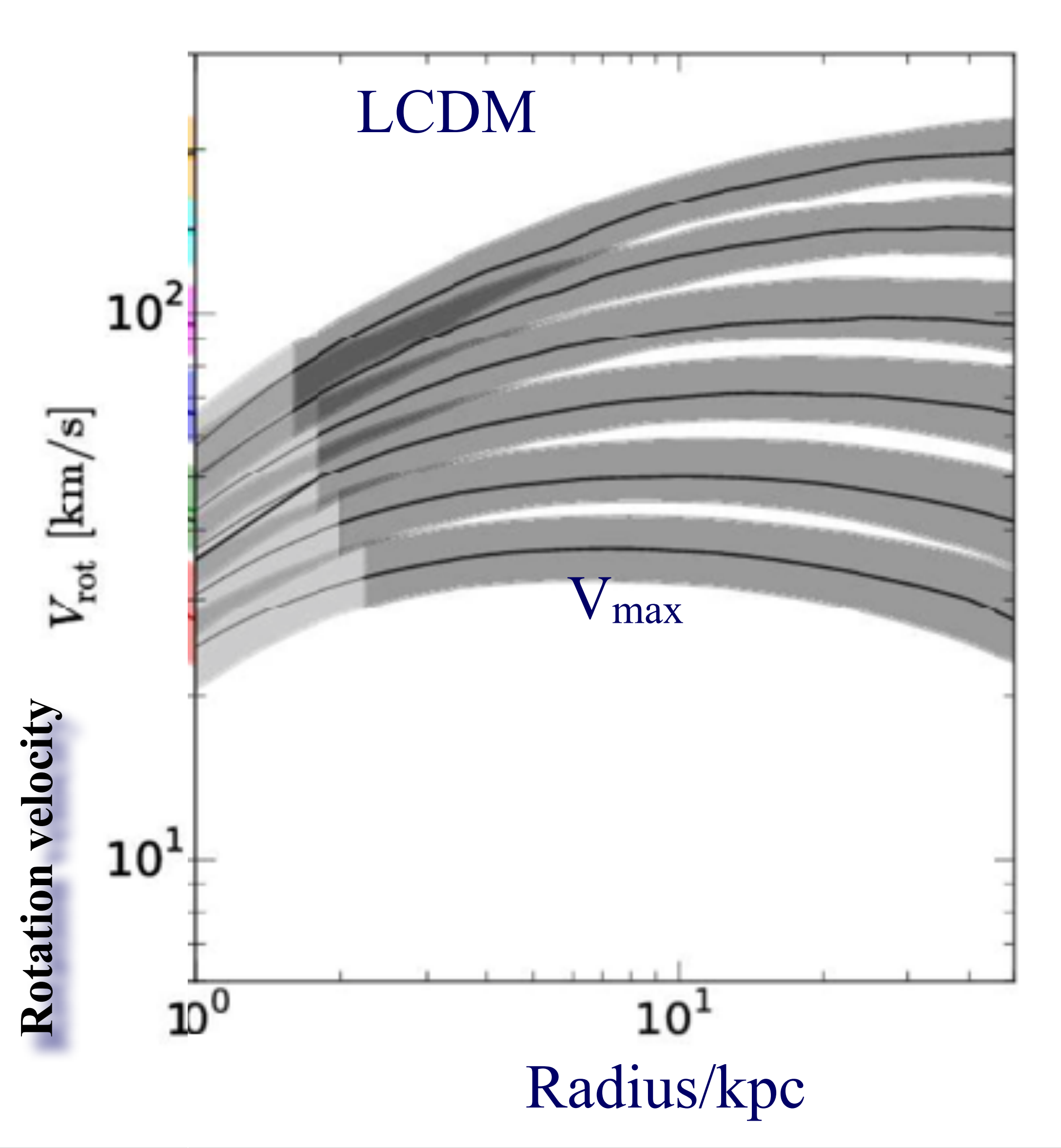
The dark matter profile of massive galaxy clusters



- There is good agreement between the mass profiles of a galaxy clusters (measured via gravitational lensing or X-ray emission profiles) and those of CDM halos

Okabe+2010, Umetsu+2011

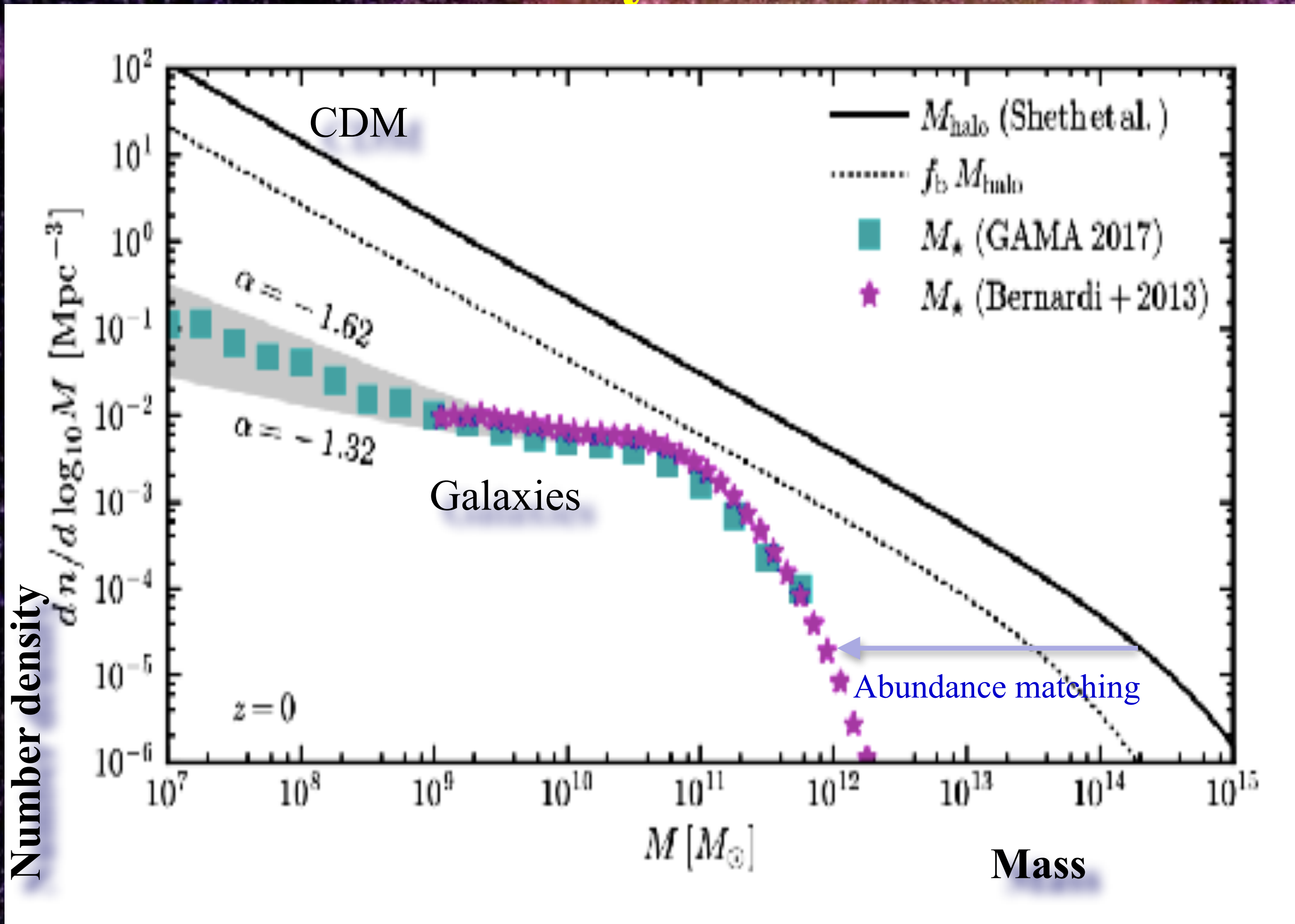
LCDM predicted circular velocity profiles



- CDM predicts a **single** mass/circular velocity profile for a given velocity scale
- The maximum circular velocity is an alternative measure of halo mass
- Curves do not cross—need only one measurement to characterize the full halo

Oman+15

Galaxy mass vs halo mass



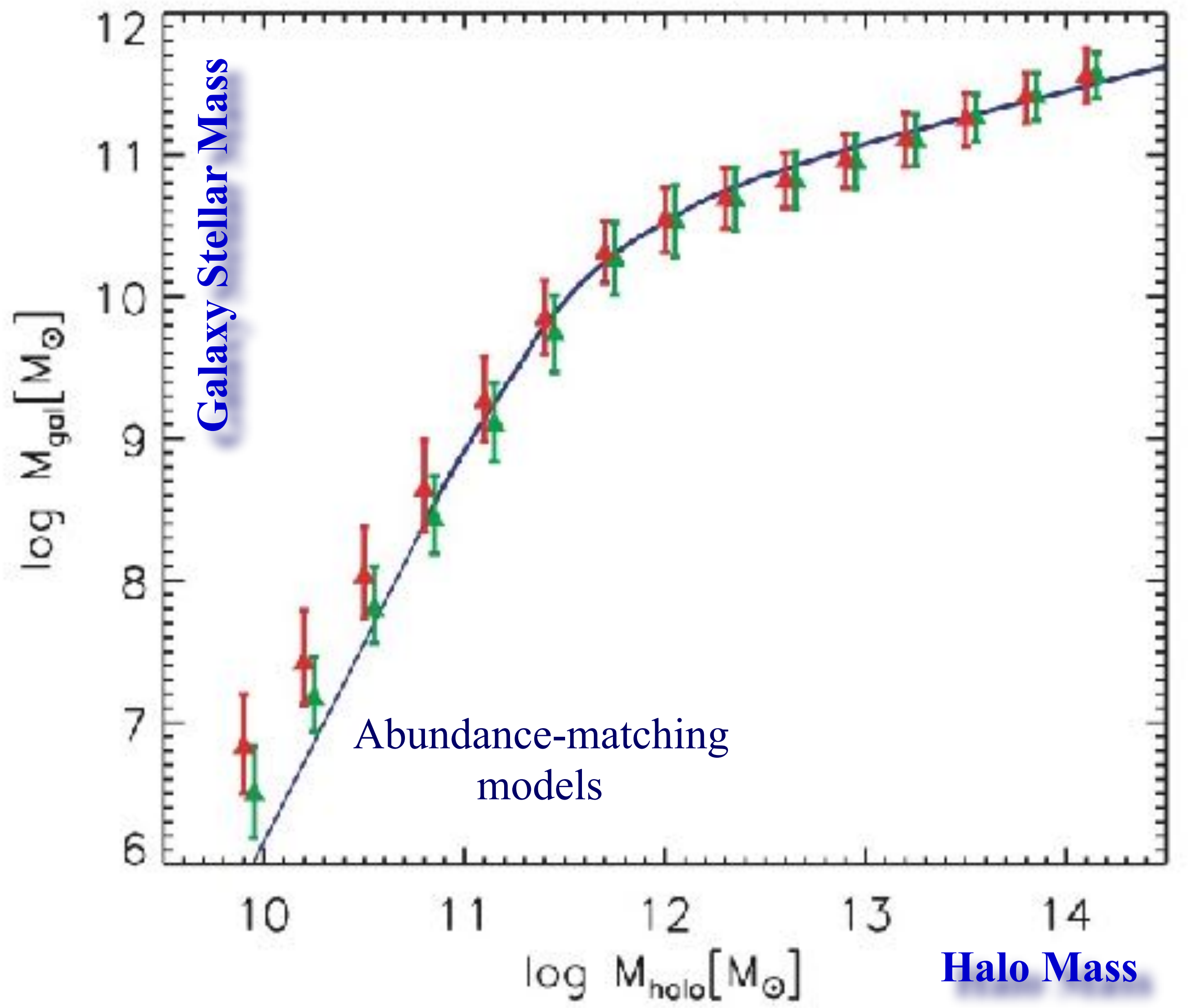
CDM halo mass function is now well understood in all mass scales relevant to galaxy formation.

JB+MBK17

- CDM halo mass function *much steeper* than the galaxy luminosity function at the faint end
- Reconciling the two requires a highly non-linear dependence between galaxy and halo mass
- At low halo masses reionization, as well as feedback from evolving stars, are thought to be responsible
- Most dwarf galaxies live in halos of the same mass. Galaxy formation efficiency declines in low mass halos

Bullock&Boylan-Kolchin 2017

Abundance Matching: Galaxy Stellar Mass vs Halo Mass



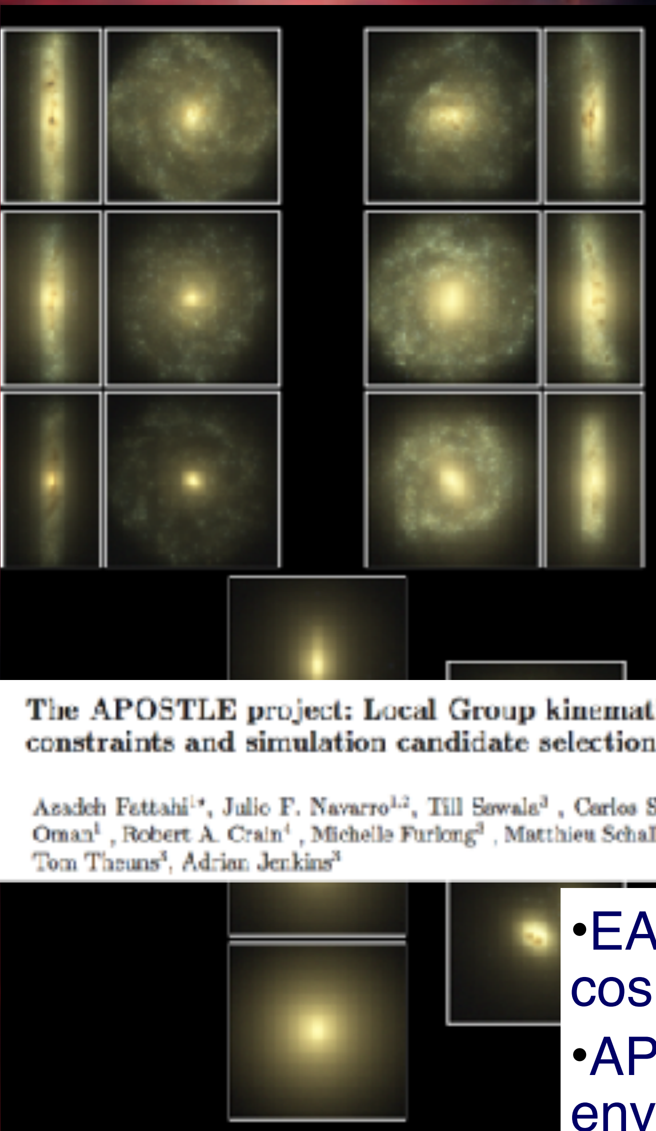
- Galaxy formation efficiencies are very low; peak at 15% for Milky Way-like galaxies
- Galaxy masses are **not** simply proportional to halo masses
- Note the approximate "threshold" halo mass for galaxy formation, just below 10^{10} M_{sun}

Guo+2011

The Eagle simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

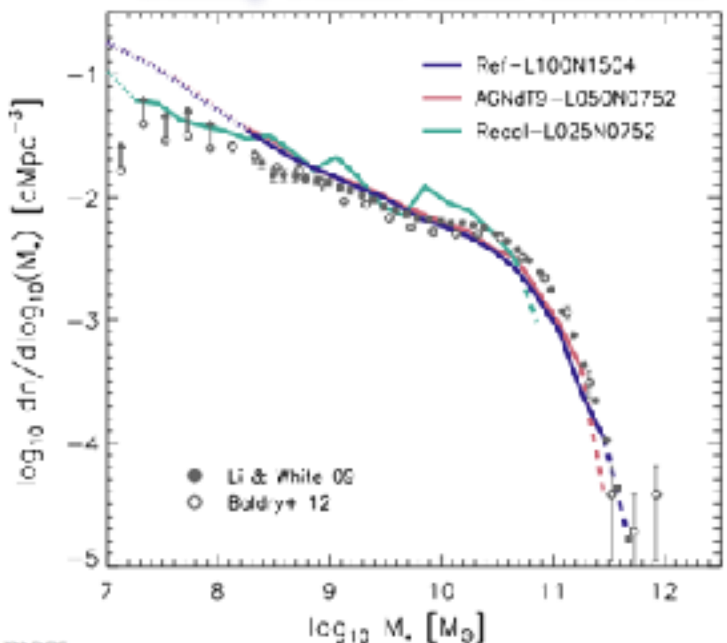
A project of the Virgo Consortium



The APOSTLE project: Local Group kinematic mass constraints and simulation candidate selection

Azadeh Fattahi[1,*], Julio F. Navarro[1,2], Till Sawala[3], Carlos S. Frenk[3], Kyle A. Oman[1], Robert A. Crain[4], Michelle Furlong[3], Matthieu Schaller[3], Joop Schaye[5], Tom Theuns[3], Adrian Jenkins[3]

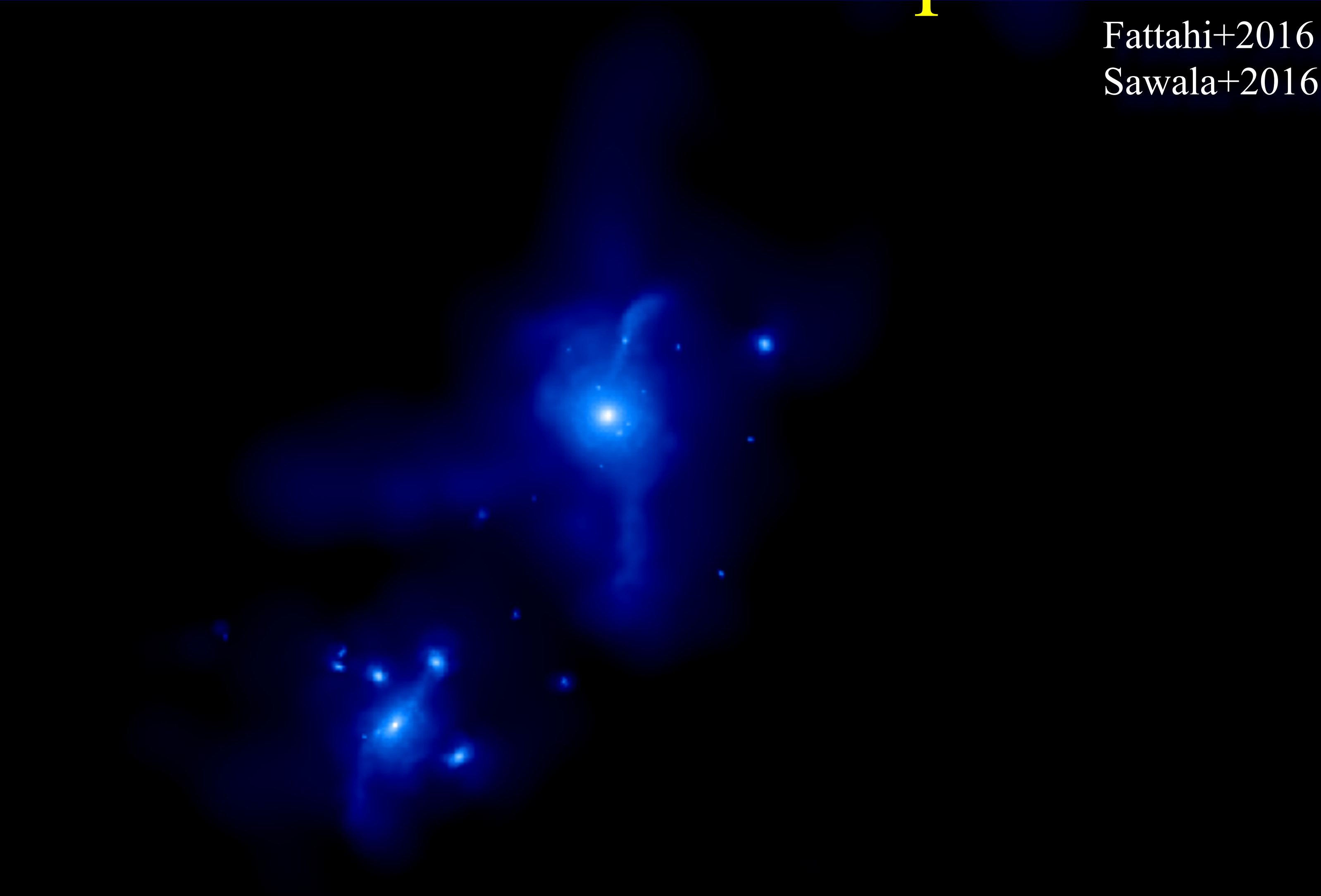
Galaxy stellar mass function



- EAGLE: Large hydrodynamical simulations of cosmologically representative volumes (~100 Mpc box)
- APOSTLE: Same as EAGLE but for a Local Group environment

Simulated Local Groups

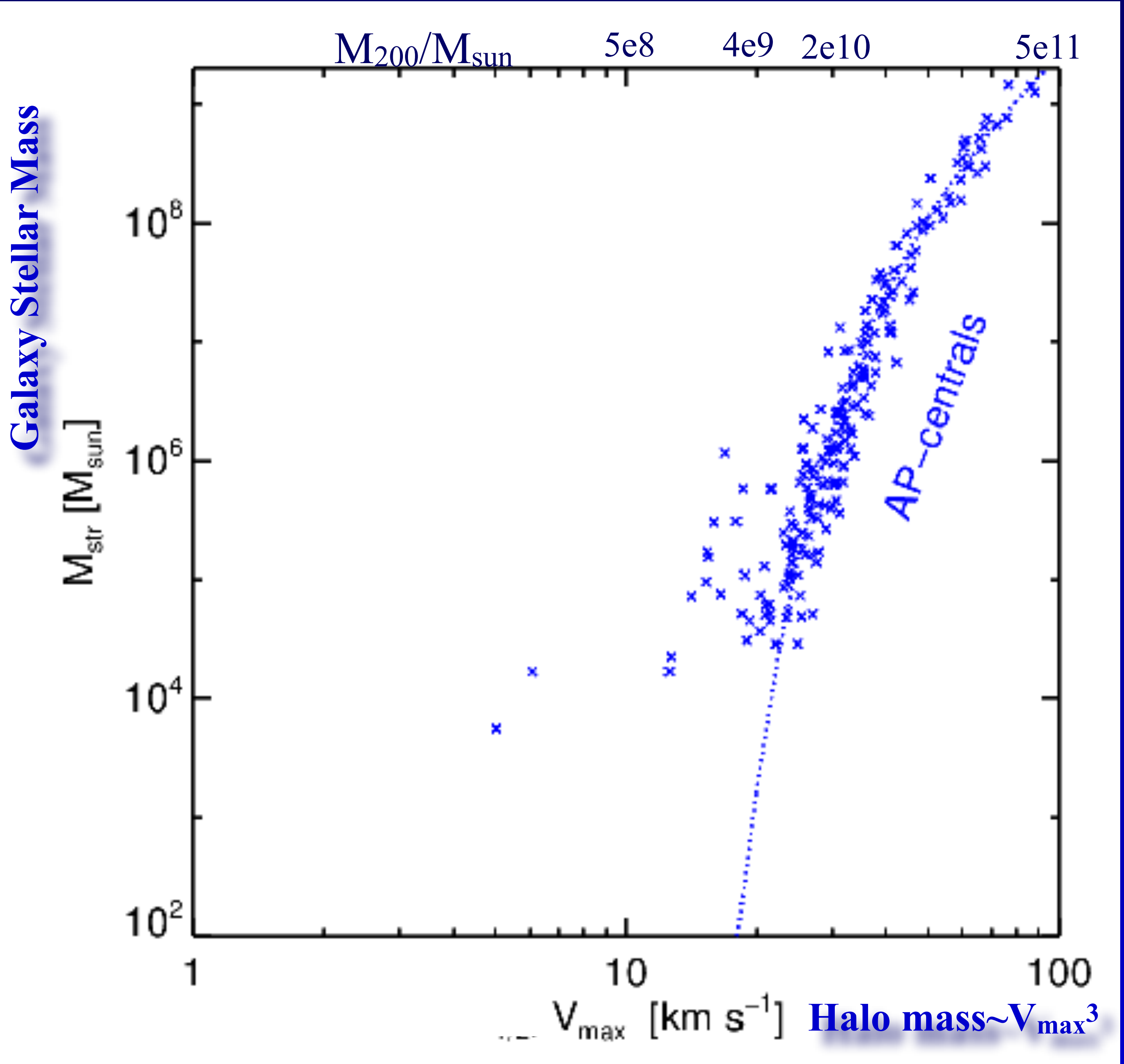
APOSTLE
Collaboration



Fattahi+2016
Sawala+2016

- Twelve LG candidates have been re-simulated using the *same* code used for the EAGLE project
- MW and M31 halos have combined mass of $2x10^{12}$ M_{sun}

Halo mass-stellar mass in APOSTLE/EAGLE

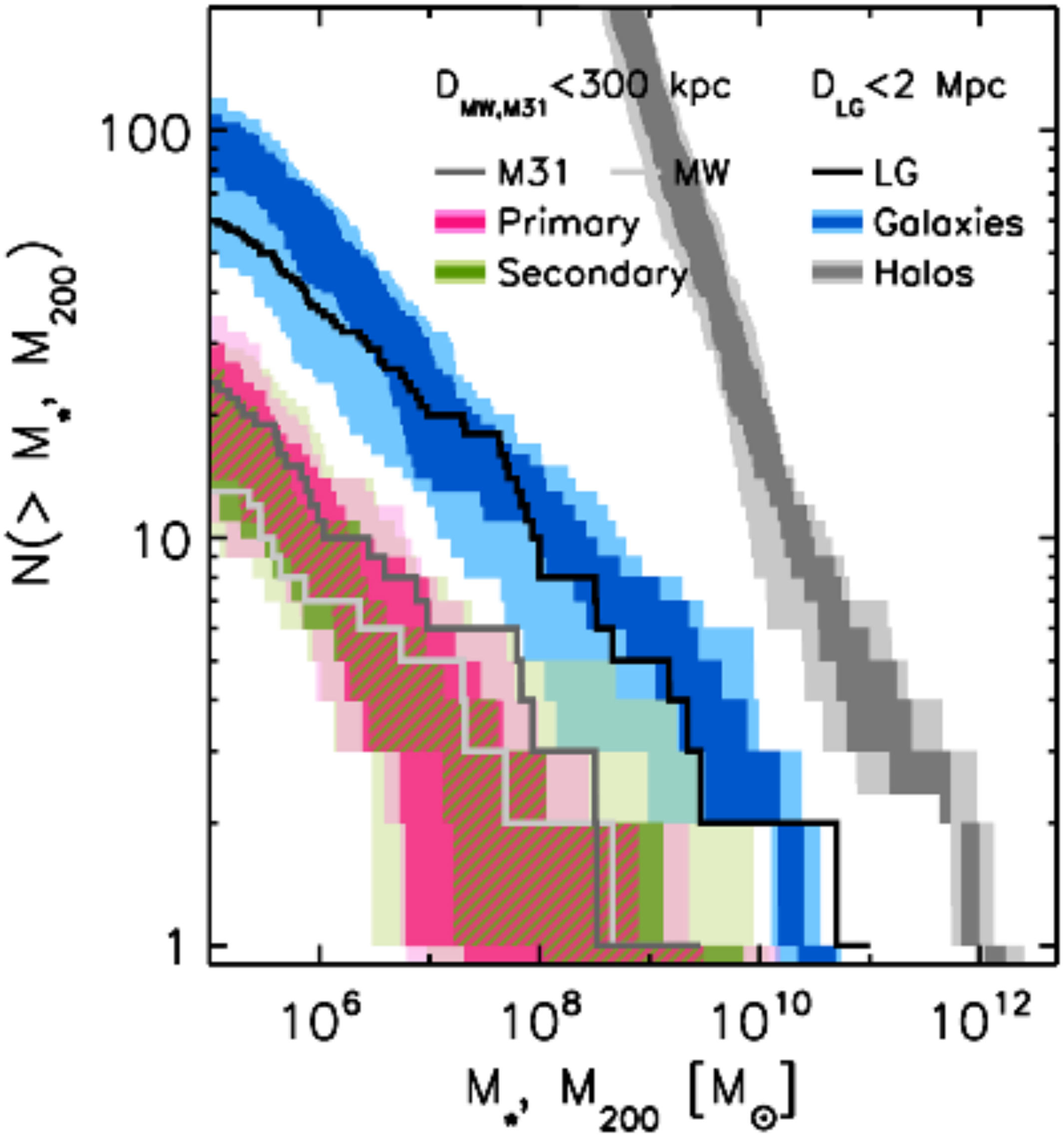


- Cosmic **reionization** imposes a sharp cutoff in the mass of halos that can host luminous galaxies
- Most **faint isolated galaxies** should form in halos of similar mass with V_{max}~20-30 km/s
- Note large scatter at fixed V_{max}

Fattahi+17

The “**missing satellites**” problem

The “missing satellites” problem



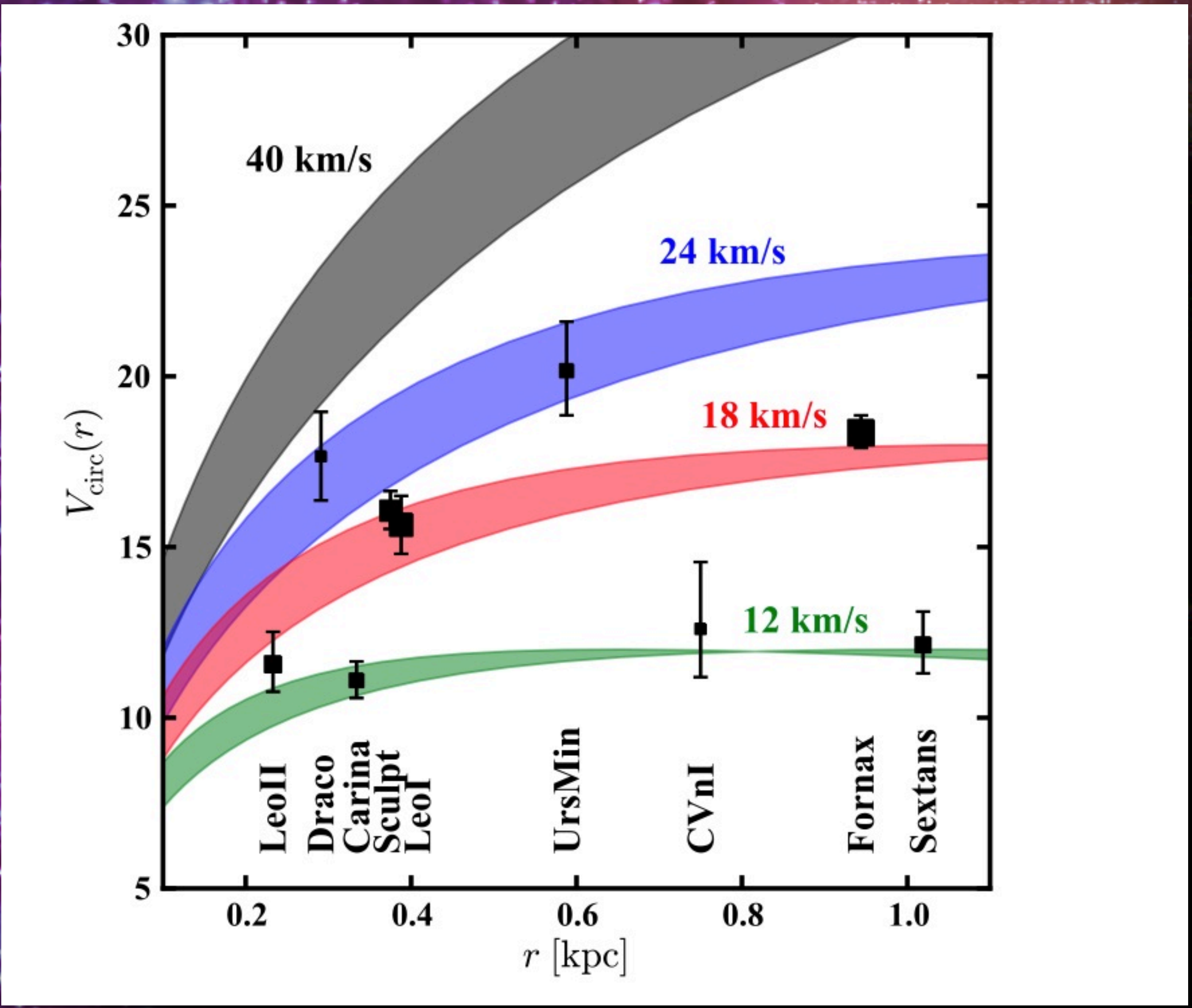
- The Local Group re-simulations match quite well the observed number of satellites of each primary and the number of dwarfs within ~2 Mpc from the LG barycentre, down to stellar masses of order ~10^5 M_{sun} **if the MW halo mass is ~10^{12} M_{sun}**

- Numbers depend *critically* on the total mass of the MW, M31, and the Local Group

Sawala et al 2016

The “too-big-to-fail” problem

Do satellites form in the "right" halos?



- Stellar velocity dispersions allow estimates of the total mass at the half-light radius—imply very low V_{max}

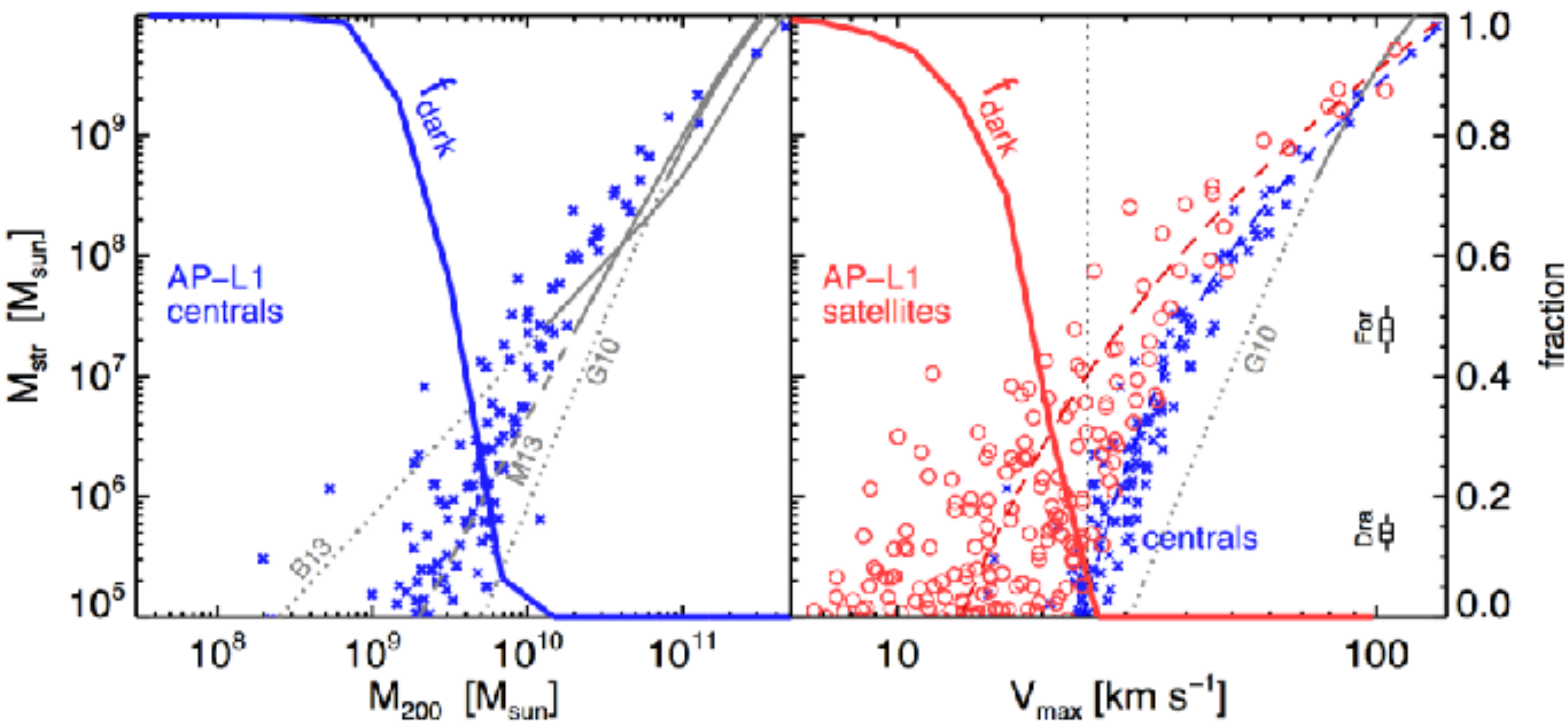
- Some low-luminosity satellites seem to inhabit more massive halos than luminous ones (cf. Fornax vs Draco)

- There seem to exist some massive sub halos without luminous satellites?

- Evidence for 'cores'?

Boylan-Kolchin et al '12

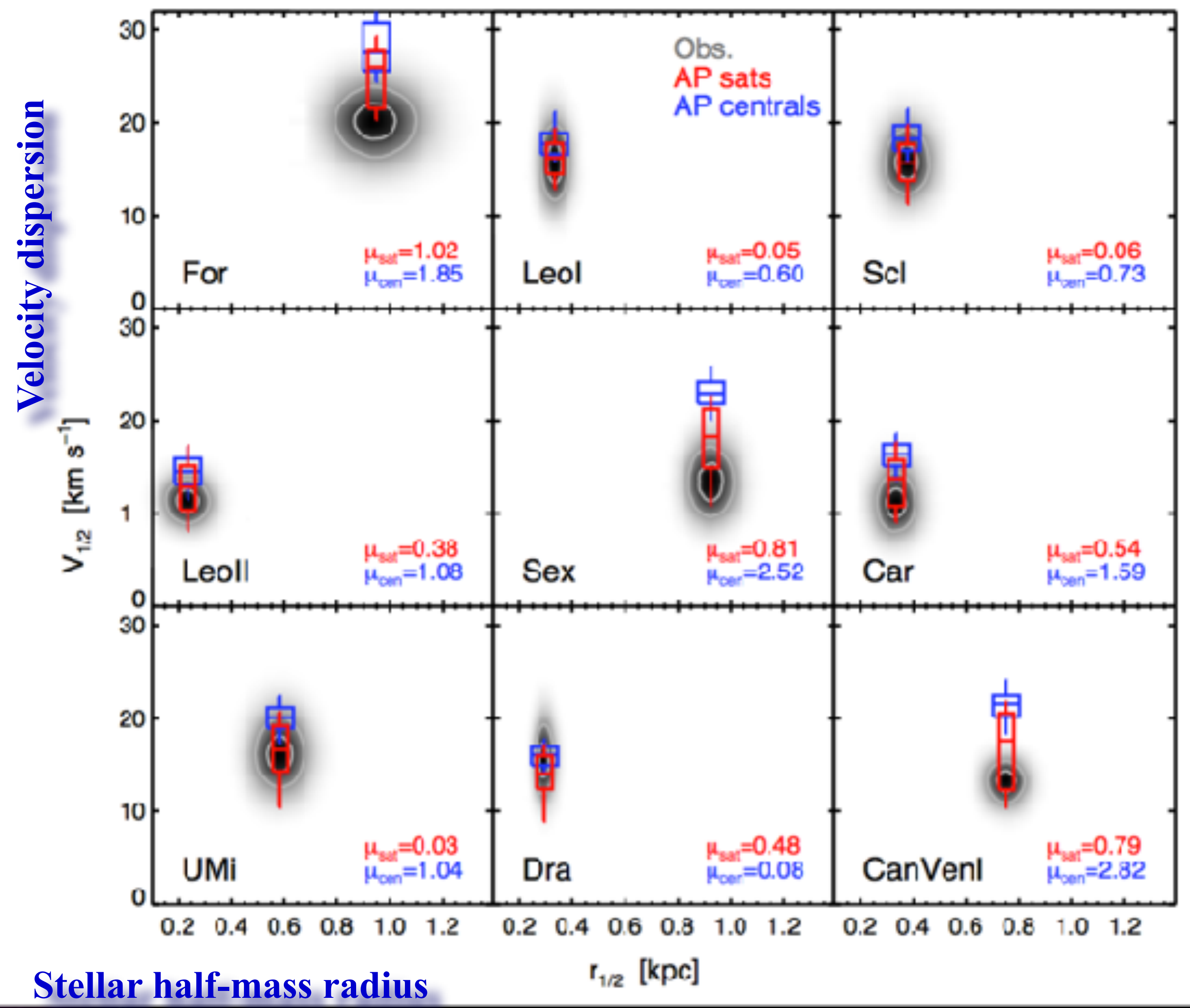
The importance of tidal stripping



- V_{max} can be severely affected by tidal stripping in satellites—this affects mass ranking (low L satellite may inhabit more massive halos than high-L satellites)
- Below M_{200}~10^{10} M_{sun} many halos are “dark”—**abundance matching is not applicable**

Fattahi+2016

The DM content of APOSTLE and MW satellites



- Given a stellar mass and half-light radius, we can predict the dark matter content of a MW satellite in APOSTLE
- Predicted dark masses are in good agreement with observational estimates

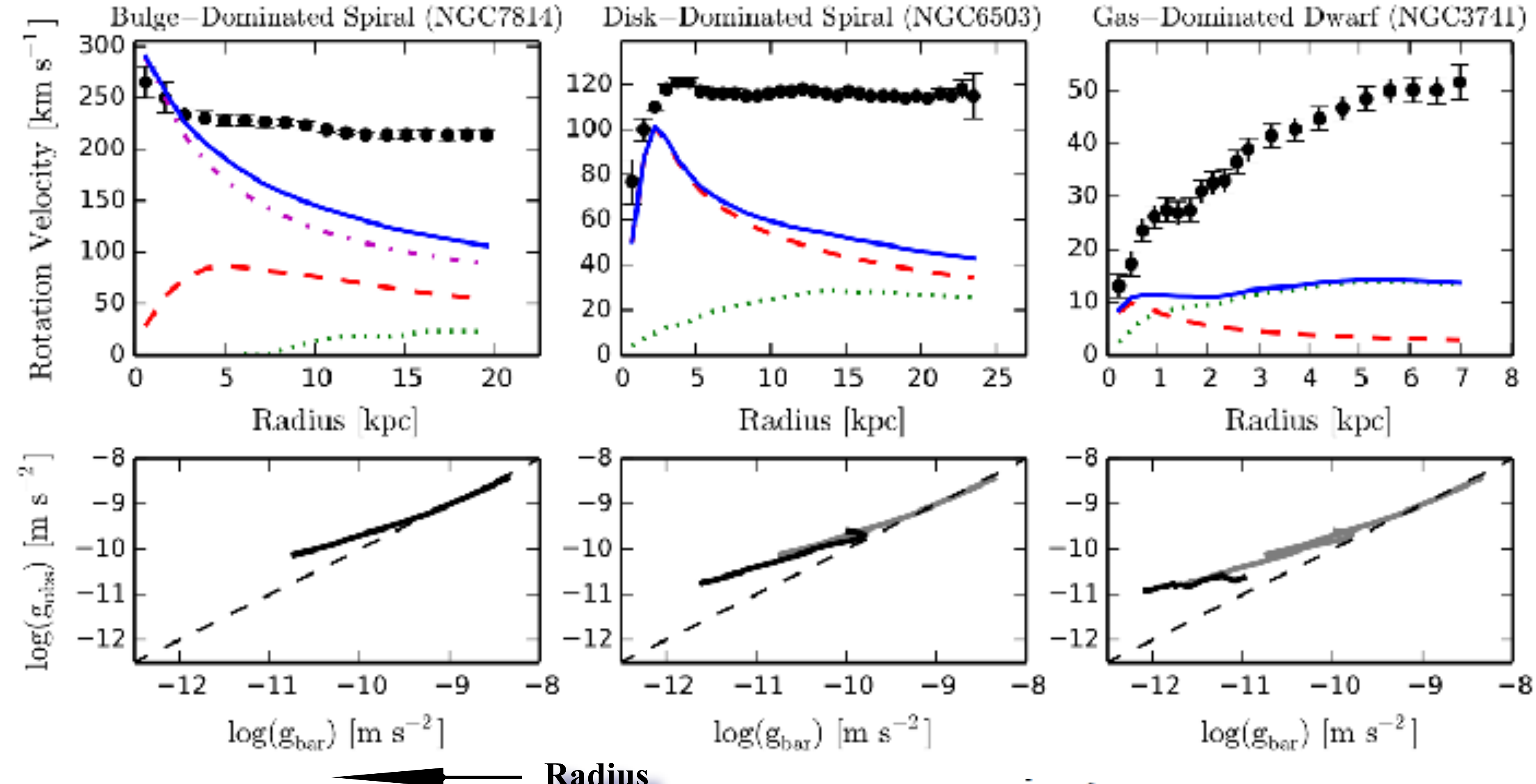
Fattahi+2016

The Mass Discrepancy-Acceleration Relation (MDAR)

The mass discrepancy-acceleration relation (MDAR)

$$g_{obs} = \frac{V^2(R)}{R}$$

Disk galaxy rotation velocities may be "predicted" from the distribution of luminous matter

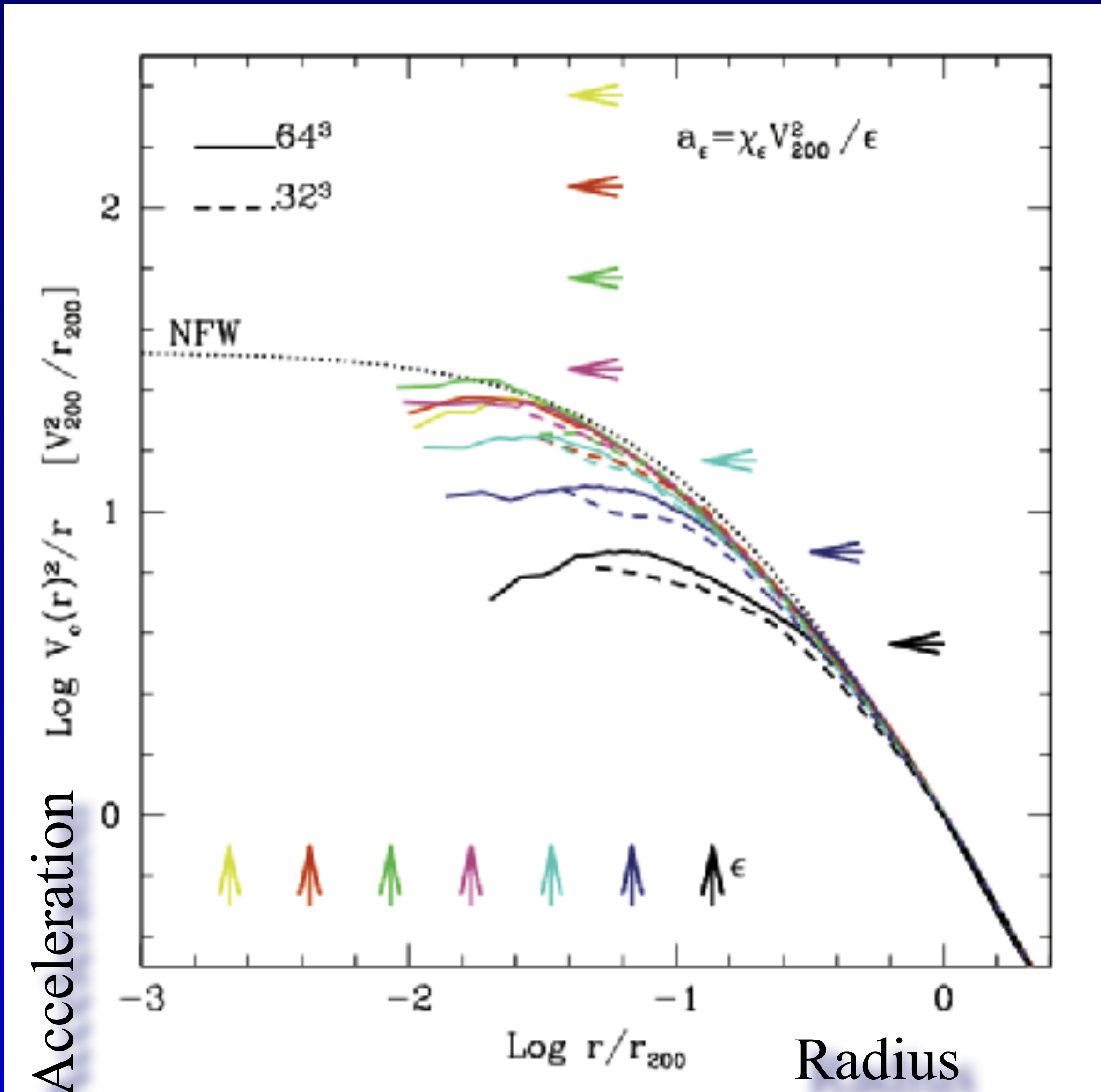


$$g_{bar}(r) = GM_{bar}(< r)/r^2$$

(to first order a proxy for surface brightness)

McGaugh+16 in PRL

The Acceleration Profile of CDM halos



- The $\rho \propto r^{-1}$ central cusp implies **constant central acceleration**: galaxies form in regions where the DM acceleration varies little with radius

$$a \propto GM(r)/r^2$$

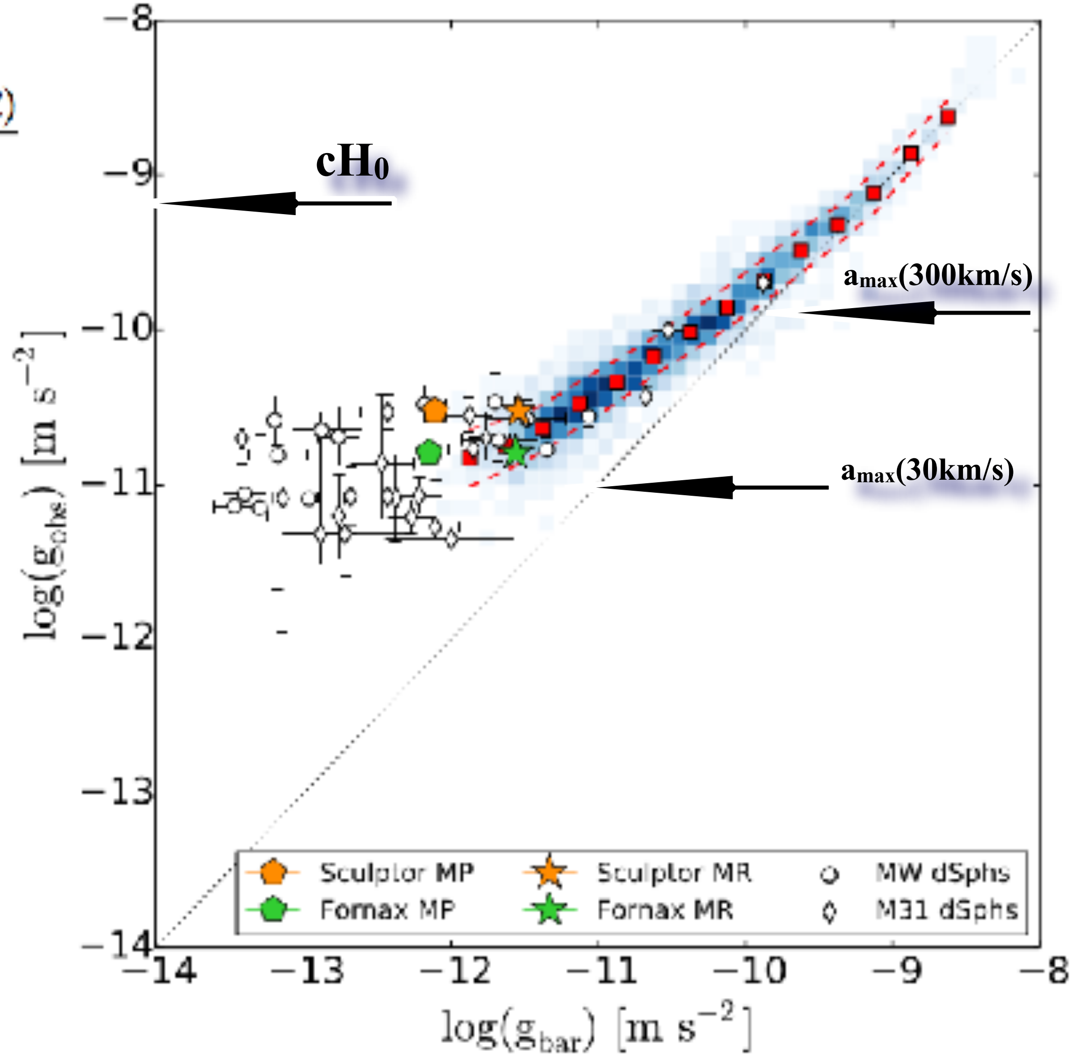
$$a_{max} = a(0) = const * V_{200}^2/r_{200}$$

$$a_{max}/(cH_0) \sim (1/10)(V_{200}/300\ km/s)$$

- Note that the DM acceleration contribution in halos likely to host disk galaxies (i.e., V_{200}<300 km/s) should not exceed a certain maximum. Baryons must dominate in regions where $a > 0.1cH_0$

The mass discrepancy-acceleration relation

$$g_{obs} = \frac{V^2(R)}{R}$$



Two characteristic accelerations:

$a_0 \sim 10^{-10}$ m/s^2: above which there is little need for dark matter, and

$a_{min} \sim 10^{-11}$ m/s$^2 \sim cH_0$: a "minimum" acceleration probed by galaxies

For reference: Earth's acceleration around the Sun is $\sim 6\ 10^{-3}$ m/s^2

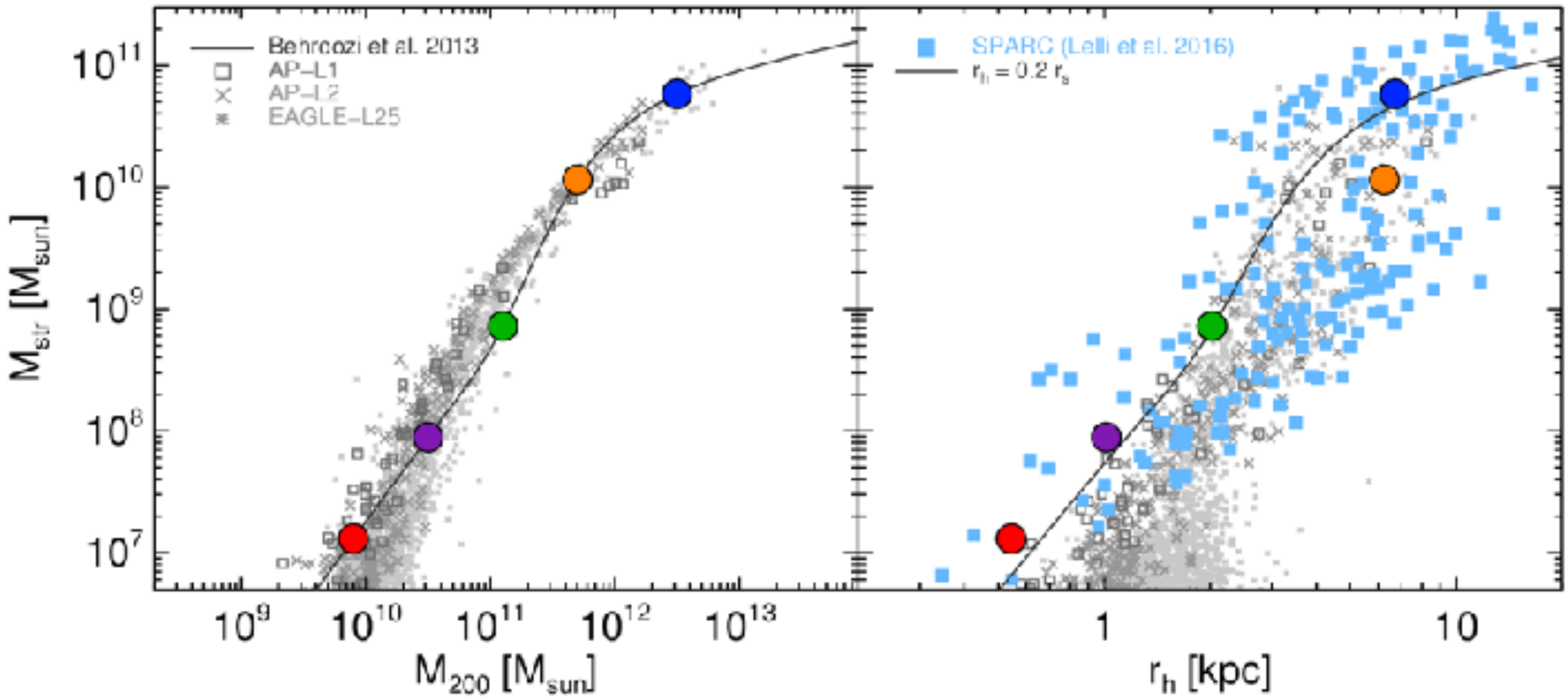
c^*H_0 is $\sim 7.2\ 10^{-10}$ m/s^2

At the solar circle is $\sim 2\ 10^{-10}$ m/s^2

Lelli+16

$g_{bar}(r) = GM_{bar}(< r)/r^2$ (a proxy for surface brightness)

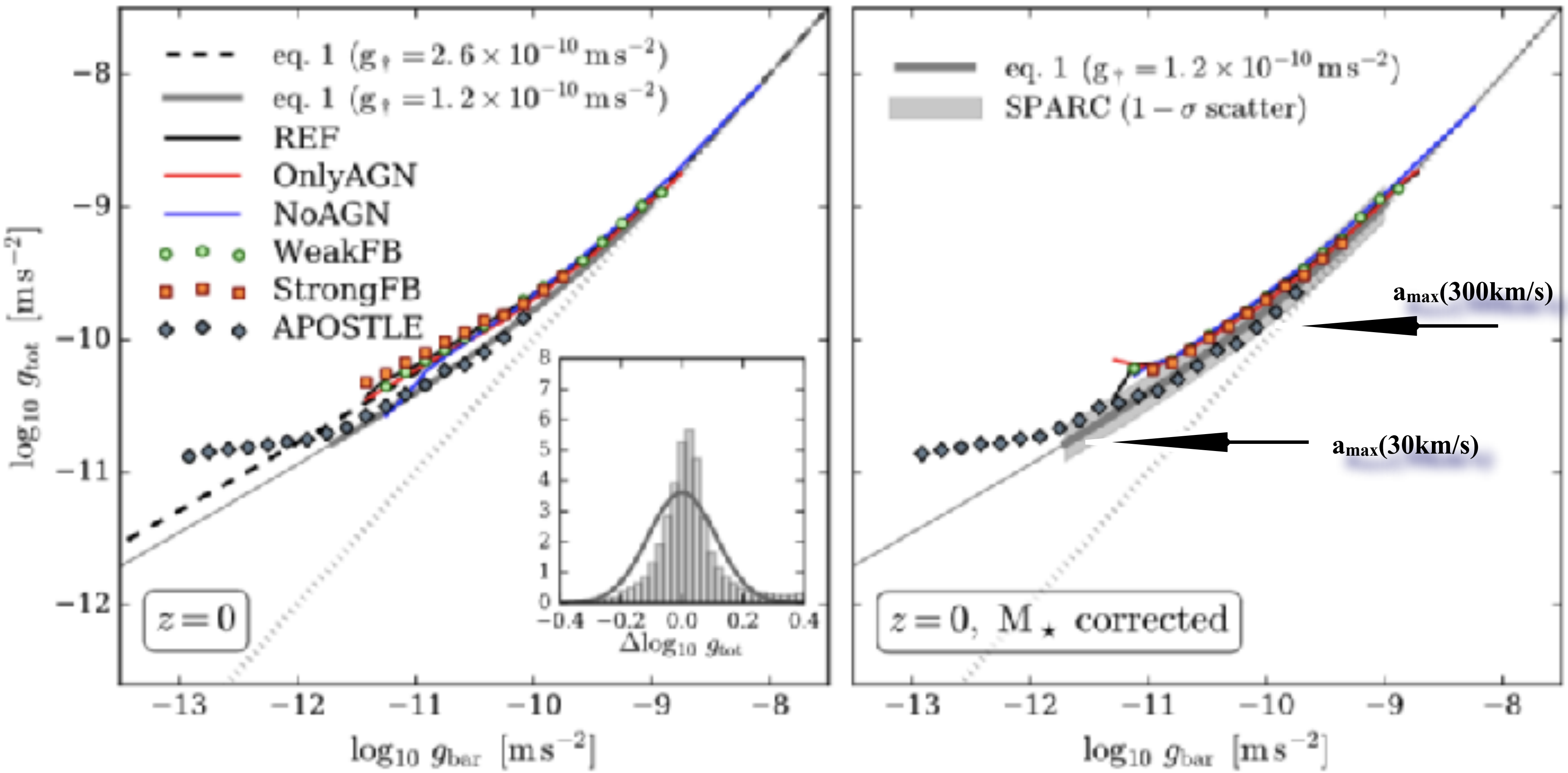
Where does MDAR come from in LCDM?



Where do the characteristic accelerations come from?
Every galaxy has a characteristic baryonic acceleration (“g_{bar}”) which depends on how its stellar mass and size correlate. This, together with the characteristic acceleration of the halo, which depends on its virial mass and concentration, imply a tight relation between g_{tot} and g_{bar} in LCDM

Navarro+17

The mass discrepancy-acceleration relation in EAGLE/APOSTLE



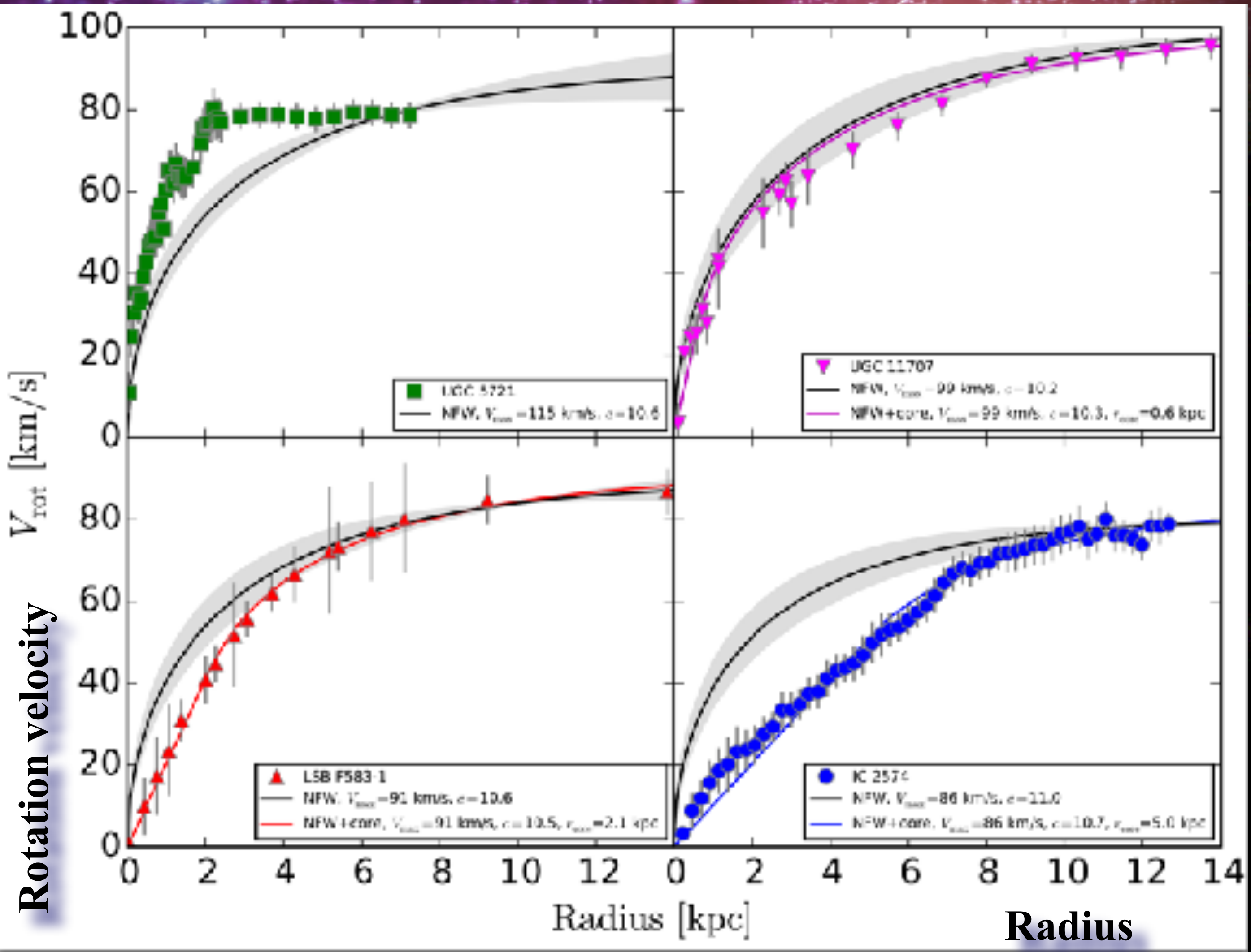
$$g_{\mathrm{bar}}(r) = G M_{\mathrm{bar}}(< r)/r^2$$

(to first order a proxy for surface brightness)

Ludlow+16 in PRL
Navarro+18 in MNRAS

The cusp-core problem or the diversity of disk galaxy rotation curves

The rotation curve diversity problem

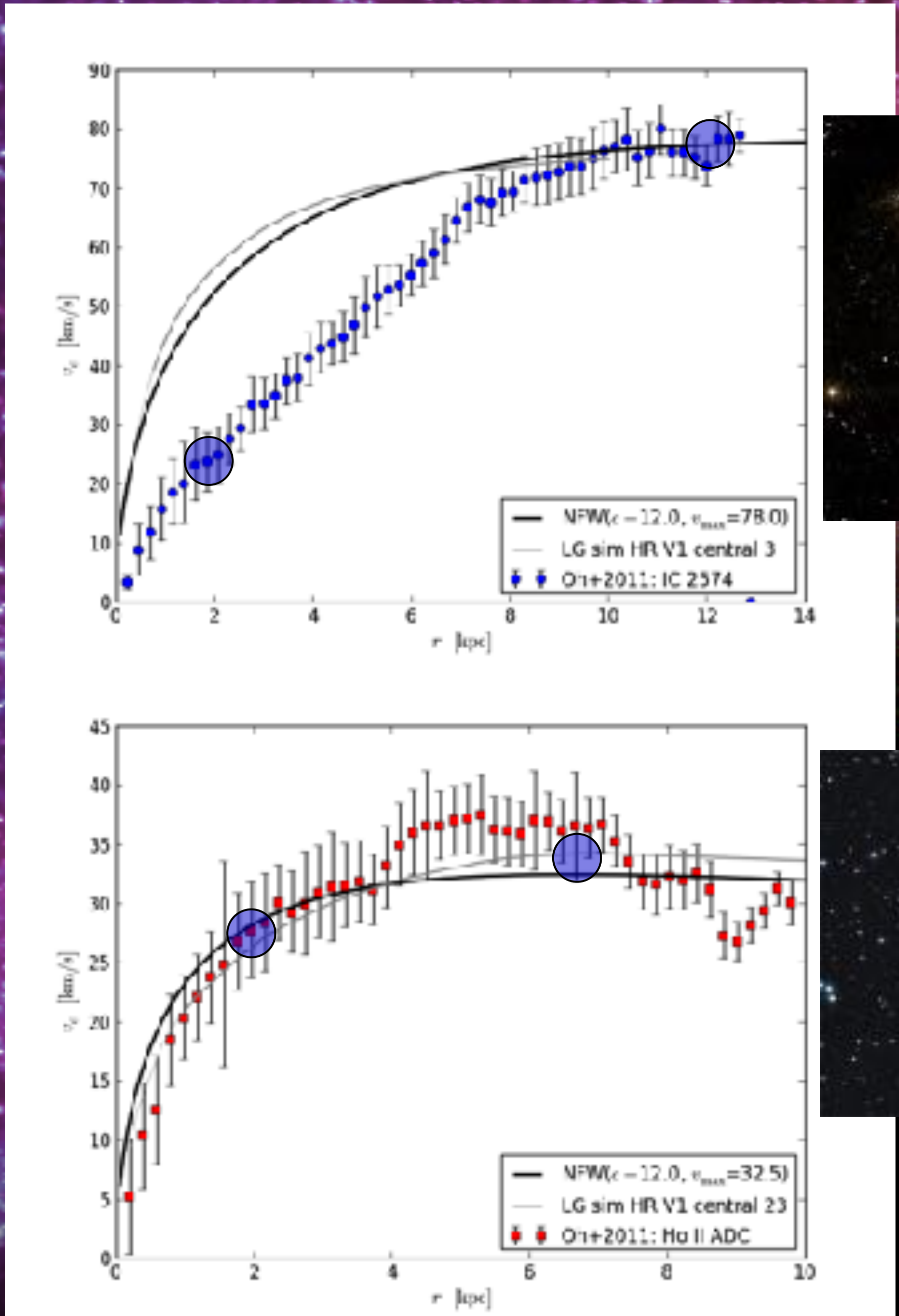


- The rotation curve problem is one of **diversity**.

- CDM predicts a **single** profile for a given velocity scale, *unlike* observed rotation curves

Oman'15

The "inner dark matter deficit" problem



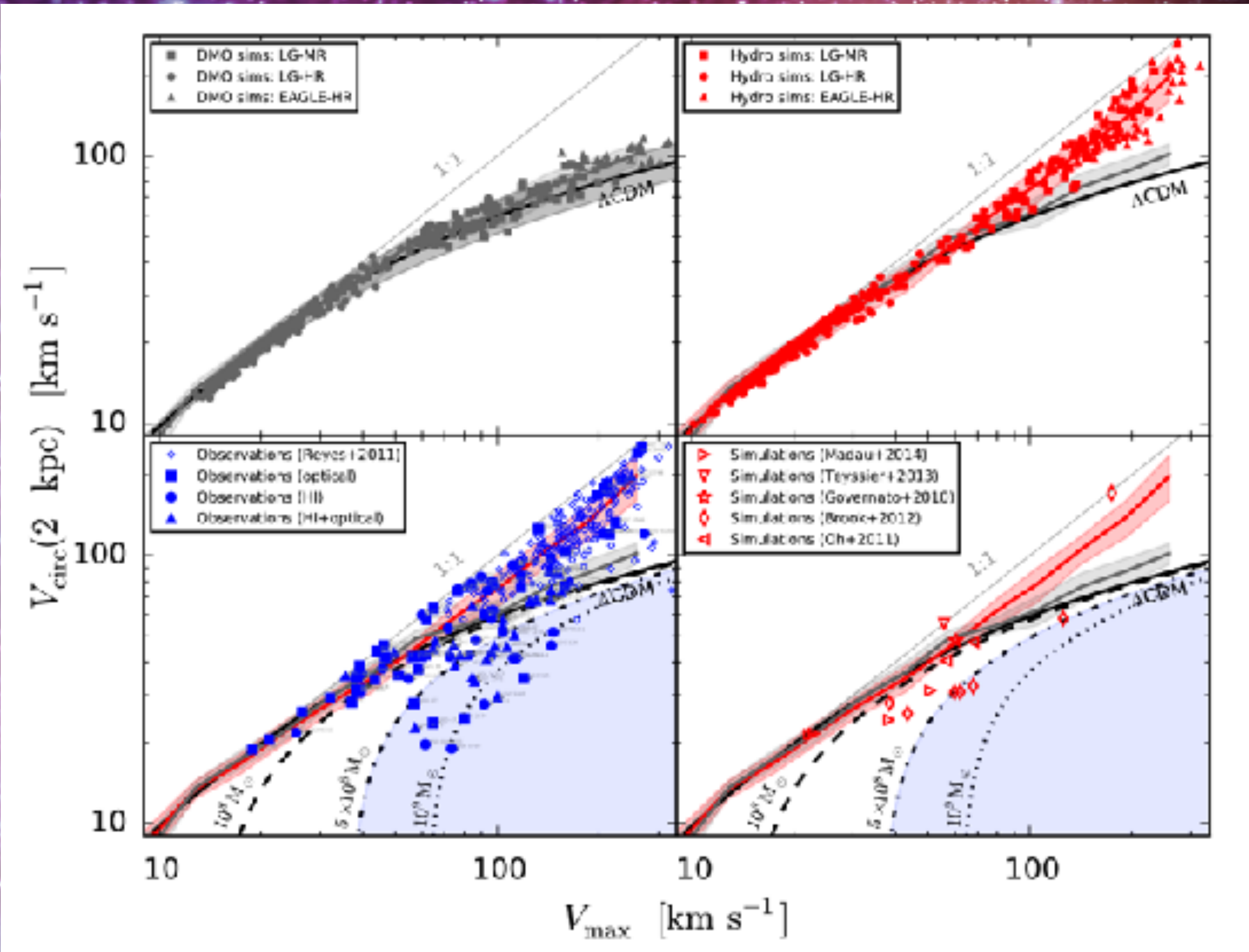
IC 2574

Hol II

- The *cusp vs core* problem is best thought of as an "*inner mass deficit*" problem
- It does not affect all galaxies
- Note that **this precludes a simple particle physics solution** to the problem (e.g, "self-interacting" or "warm" dark matter).

Oman+15

"Cores" as an inner mass deficit problem



- Dwarf galaxies have a wide diversity of rotation curves
- Some galaxies are consistent with CDM, others are not
- "Cores" seem present in galaxies up to ~200 km/s
- Some core radii are larger than simulations can produce
- Is the interpretation of the data reliable?

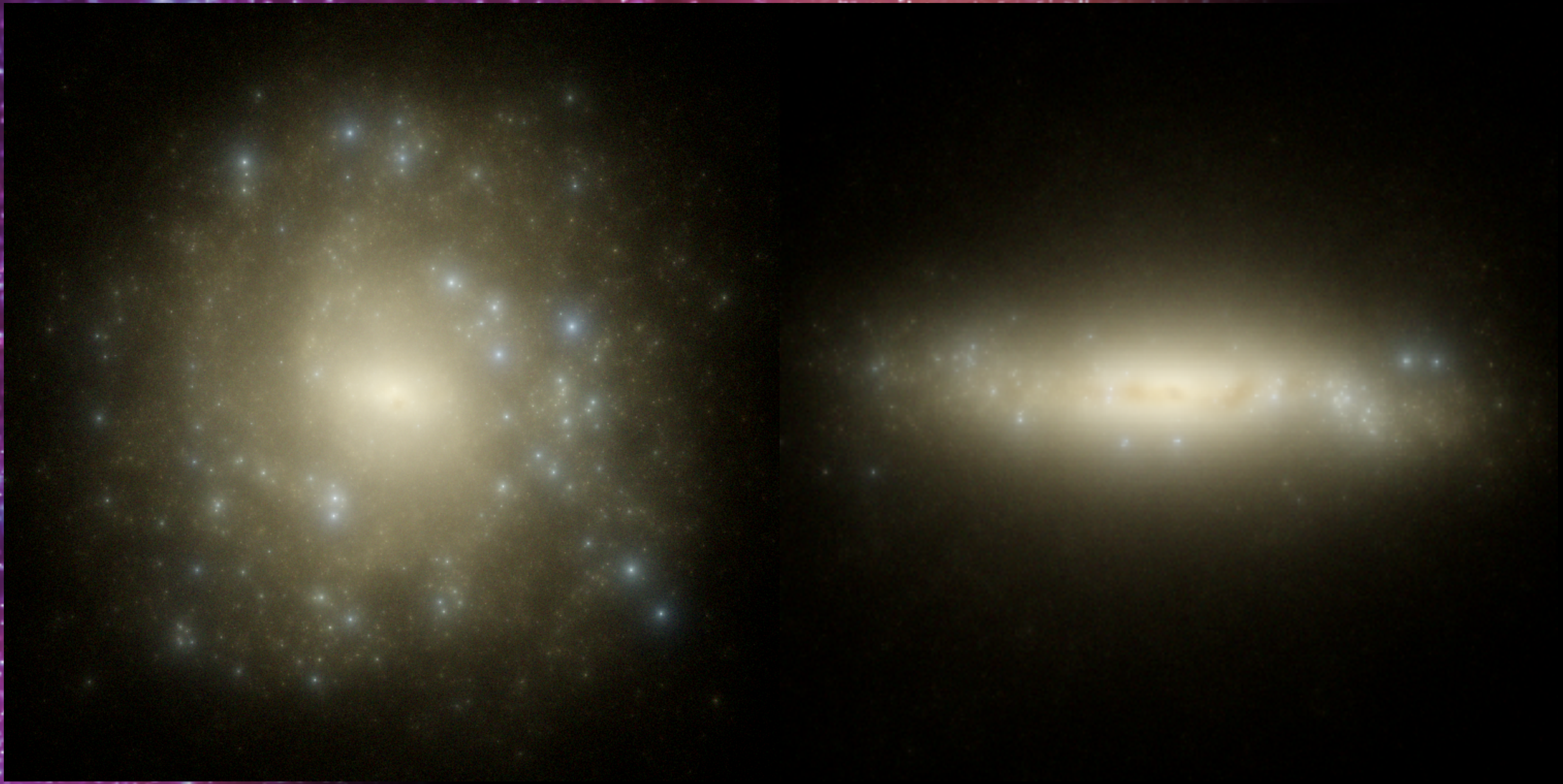
Oman+15

The rotation curve diversity problem

Possible solutions

- Uncertainties in data modeling and gas non-circular motions?
- Galaxy formation can modify DM mass profiles?
- DM is not CDM (e.g., self-interacting, SIDM)?

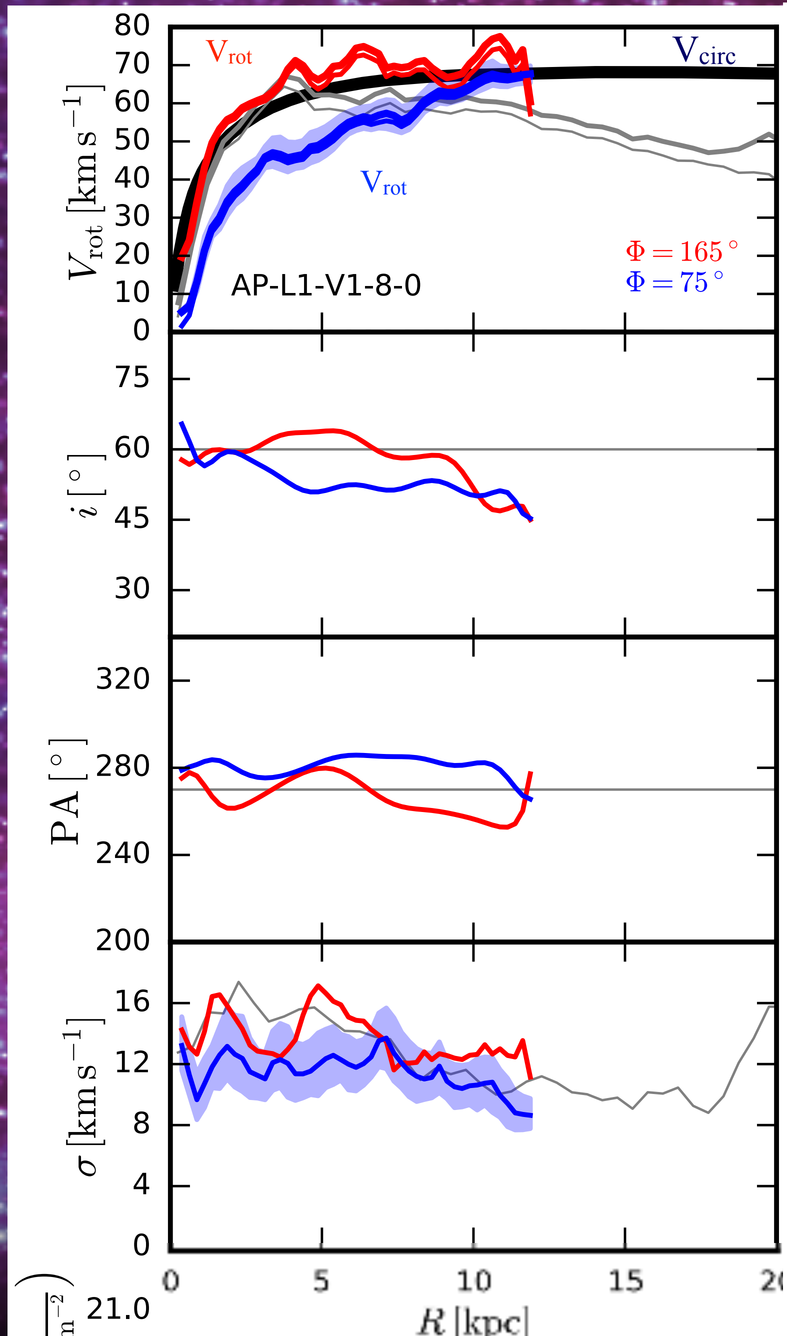
Non-circular motions and rotation curves of simulated galaxies

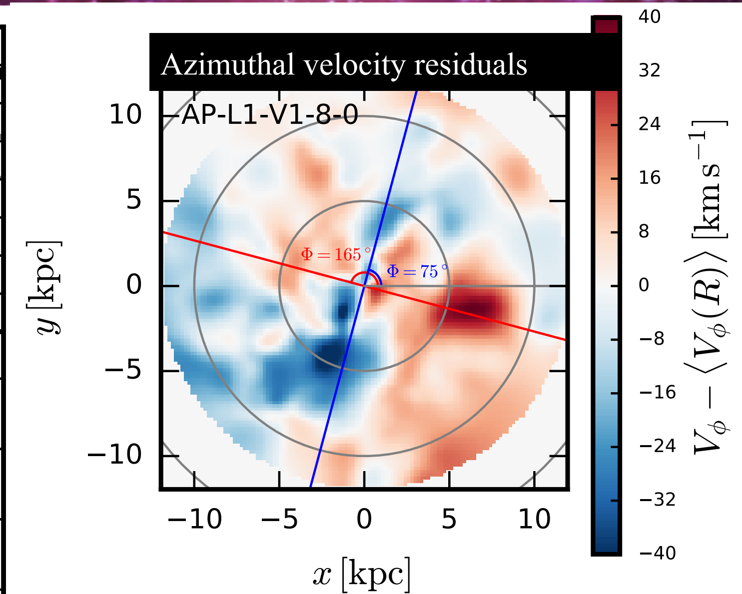


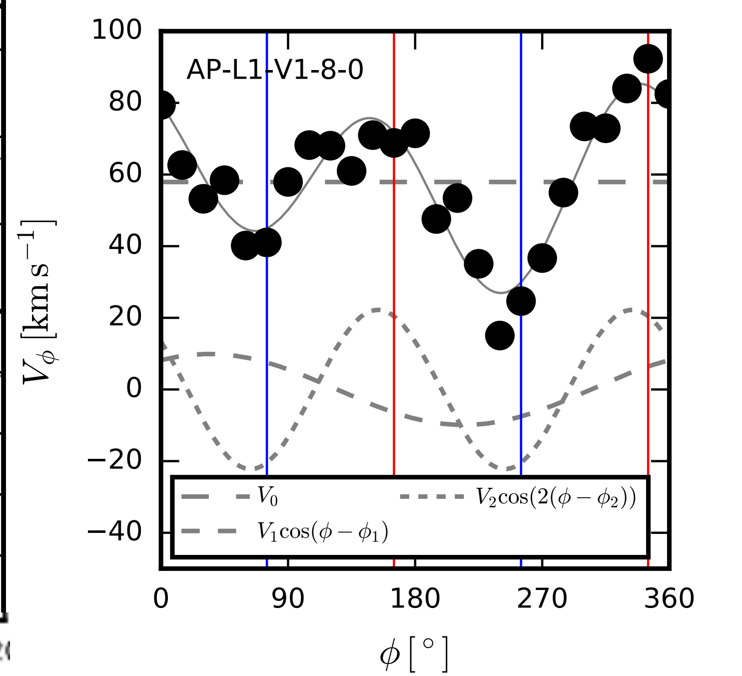
- HI velocity fields used to derive rotation curves using the same tools as in observations
- HI data cubes are built after assuming a favourable inclination and distance
- Rotation curves derived using BAROLO^{3D}, one of the latest version of "tilted-ring"models
- Procedure tested on galaxies from the THINGS and LITTLE THINGS datasets

Oman+17

Non-circular motions and rotation curves







- Rotation curves recovered using a tilted-ring model

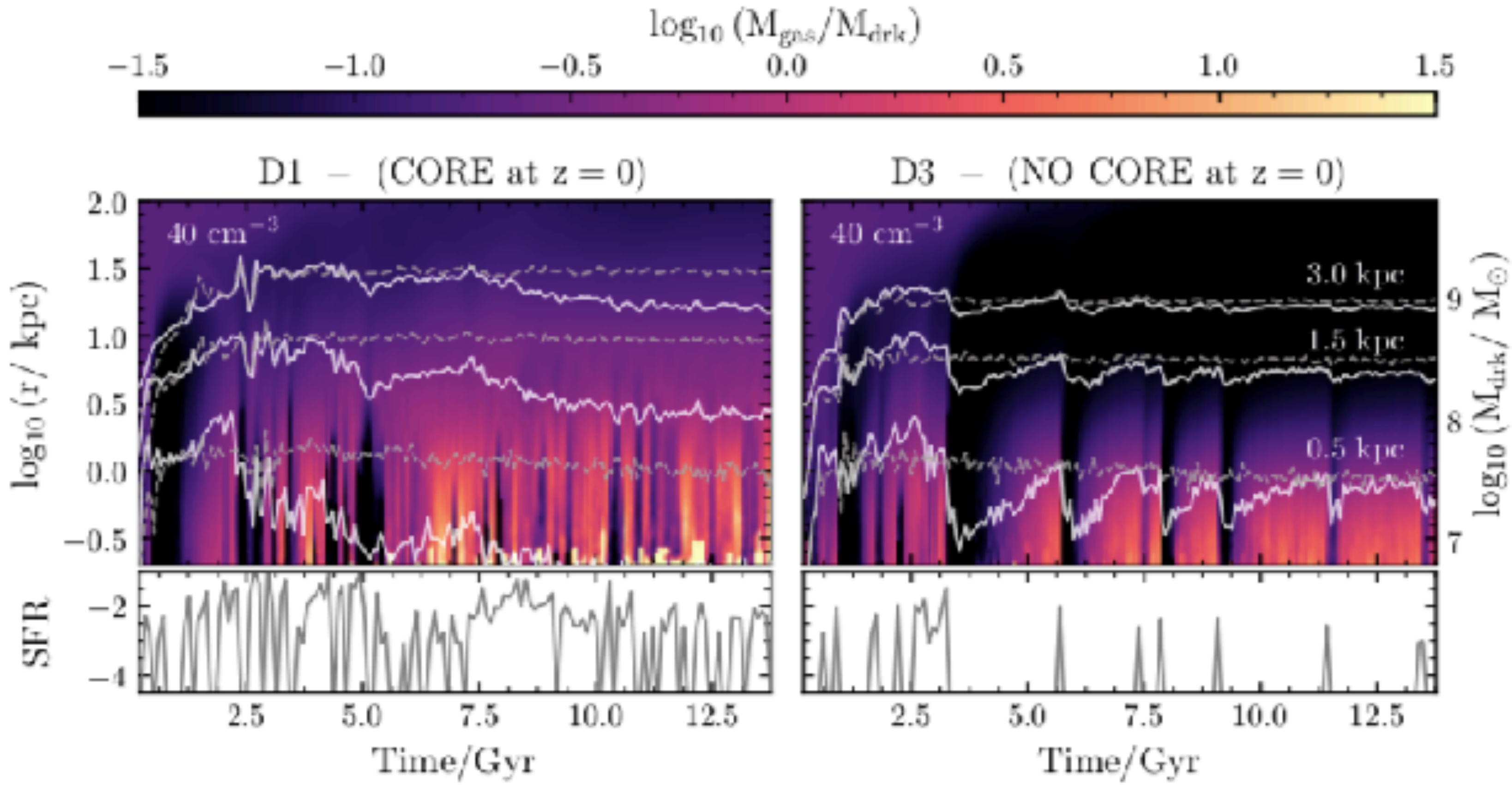
- **Blue** and **red** correspond to two different orientations for the *same* inclination

- The orientation dependence of the recovered rotation curves is due to non-circular motions in the galaxy plane

- This can ***in principle*** reproduce the diversity

Oman+17

Galaxy formation-induced cores



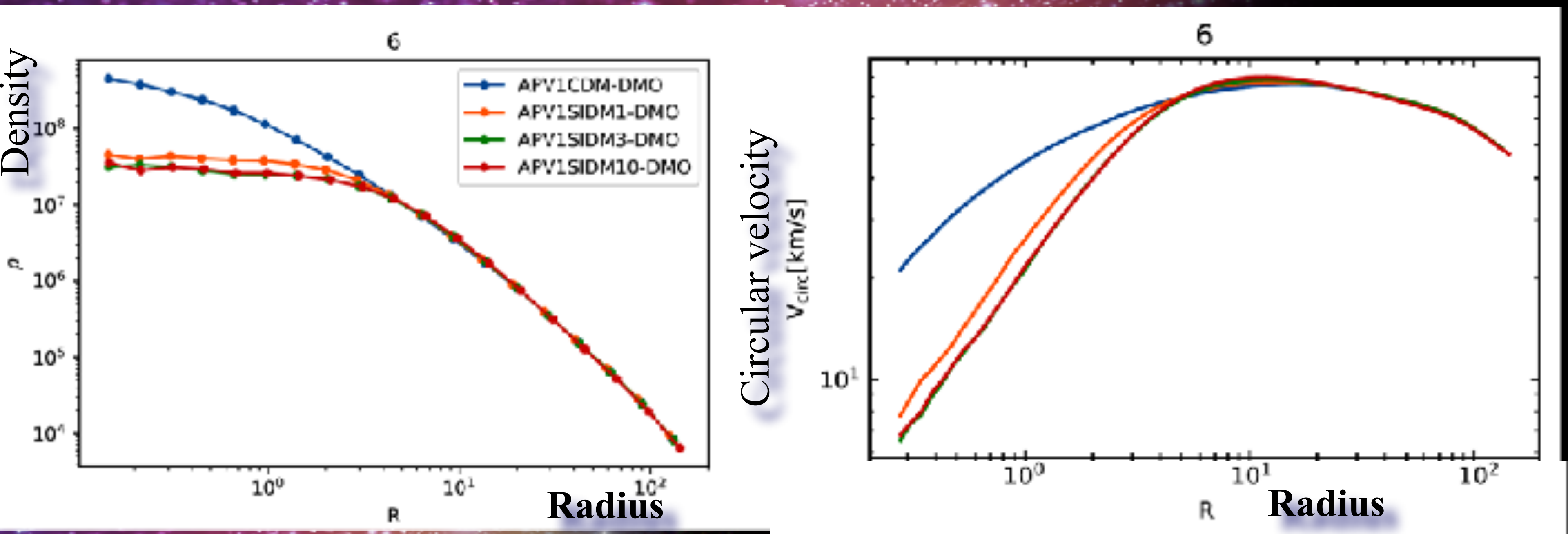
•Supernova explosions may lead to massive gas outflows that lead to variations in the gravitational potential and the reduction of dark matter in the inner regions (Navarro+1996, Pontzen & Governato 2012).

•This creates “cores” in the dark matter that may be reversed if baryons are re-accreted

•It may lead to large rotation curve diversity

Benítez-Llambay+19

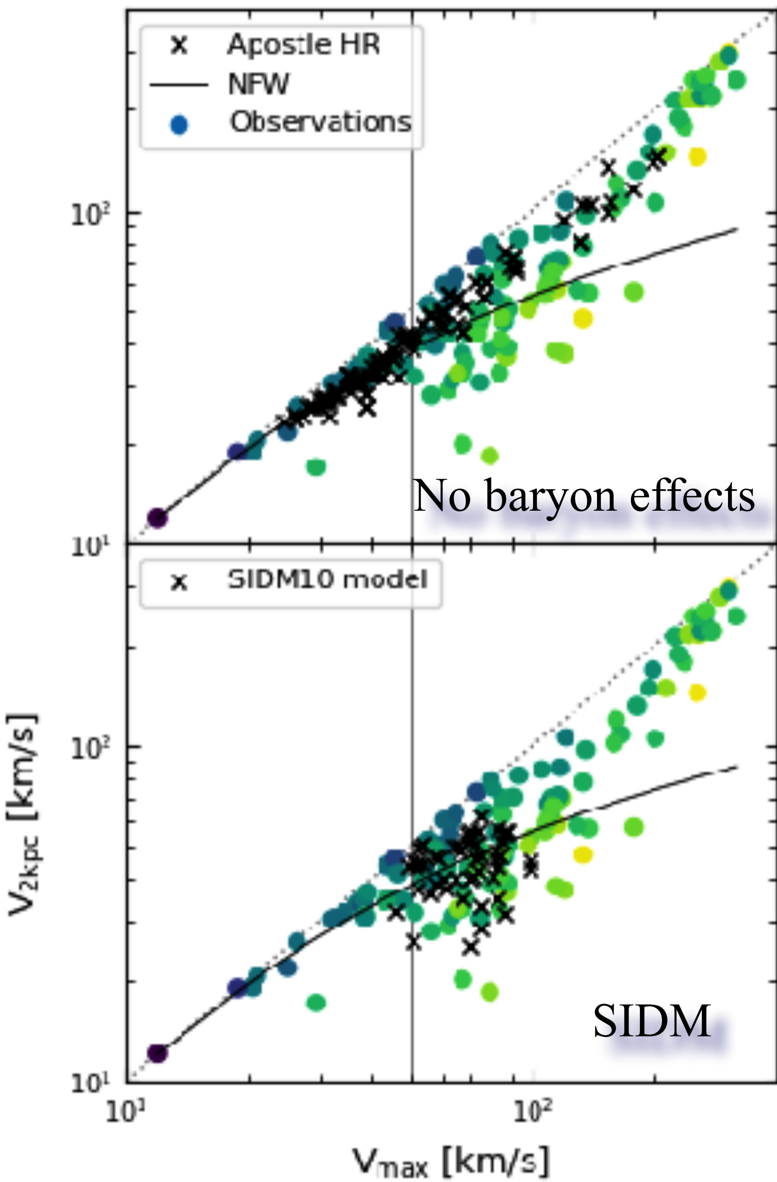
Cores and self-interacting dark matter (SIDM)



- A finite self-interacting cross section leads to “heat transfer” from the outside in and to the reduction of dark matter in the inner regions.
- It may in principle lead to the formation of large cores, which should exist in all galaxies
- The “size” of the core may be reduced if the accretion of baryons leads to the deepening of the central gravitational potential.

Santos-Santos+19

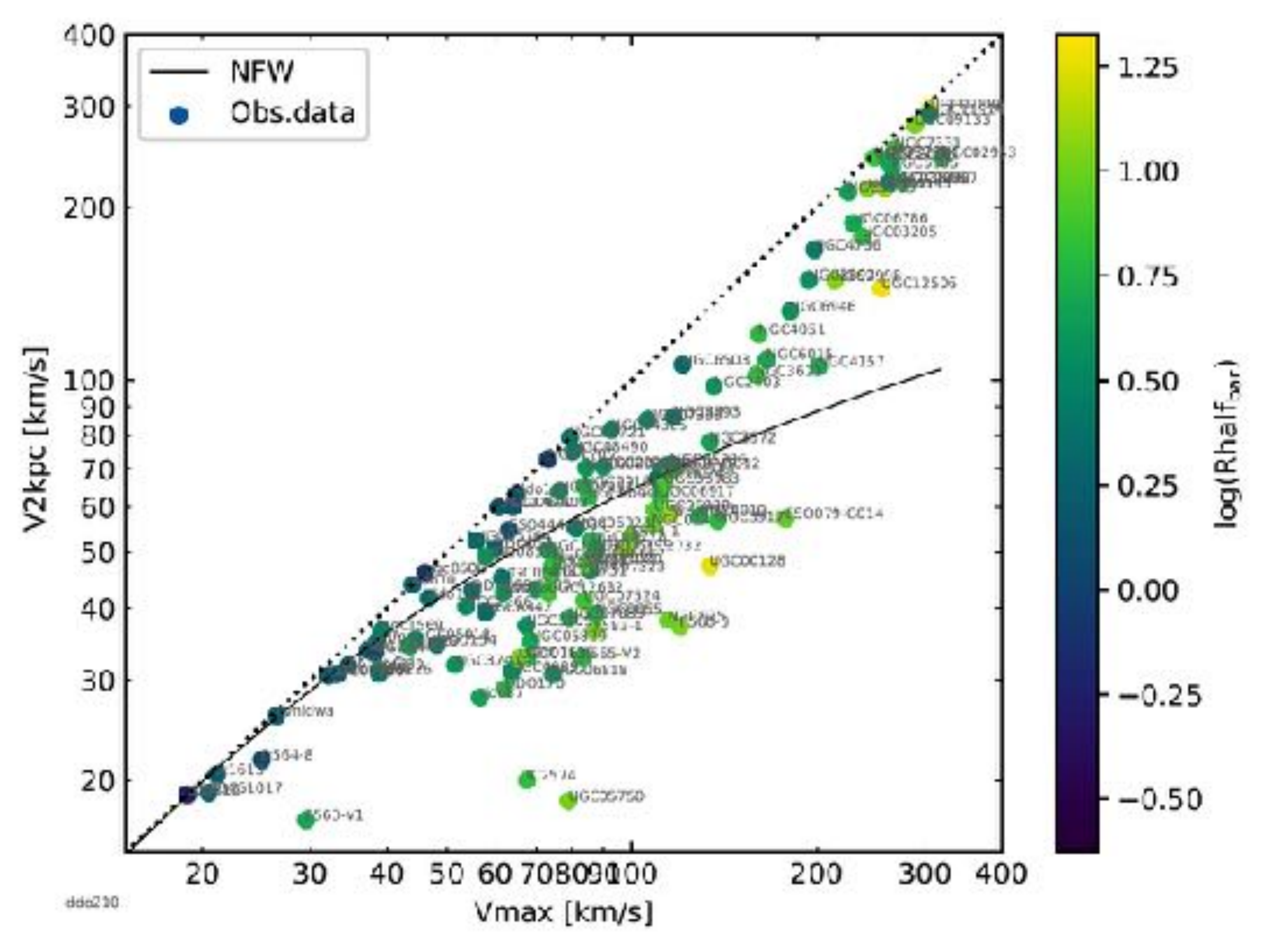
Rotation curve diversity



- These processes can create diversity in the rotation curves, although perhaps not as pronounced as observed.

Santos-Santos+19

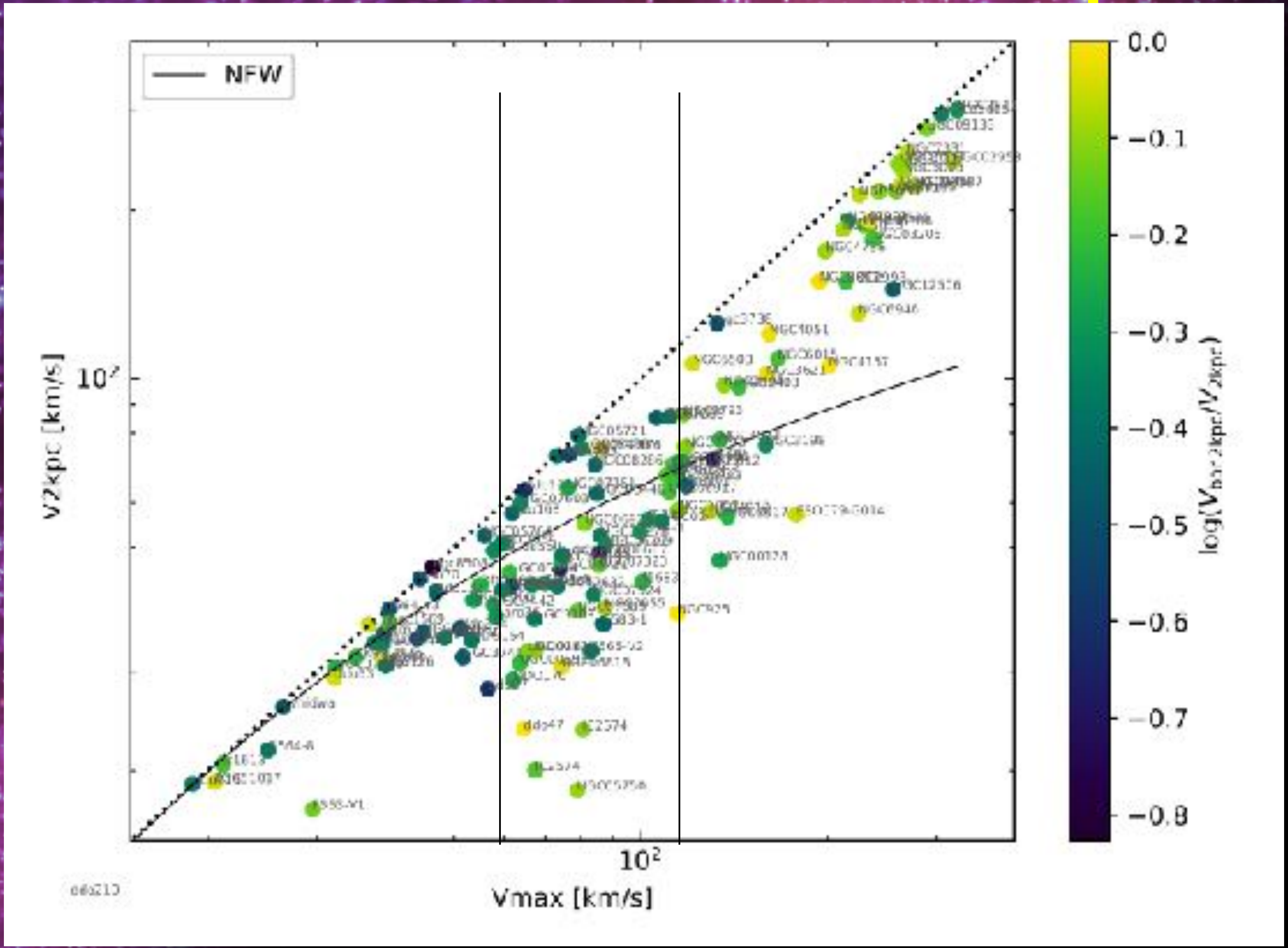
How to tell these scenarios apart?



• There are extra correlations that qualify the "diversity" of rotation curves.
• The size of the baryonic component correlates with the inner mass deficit

Santos-Santos+19

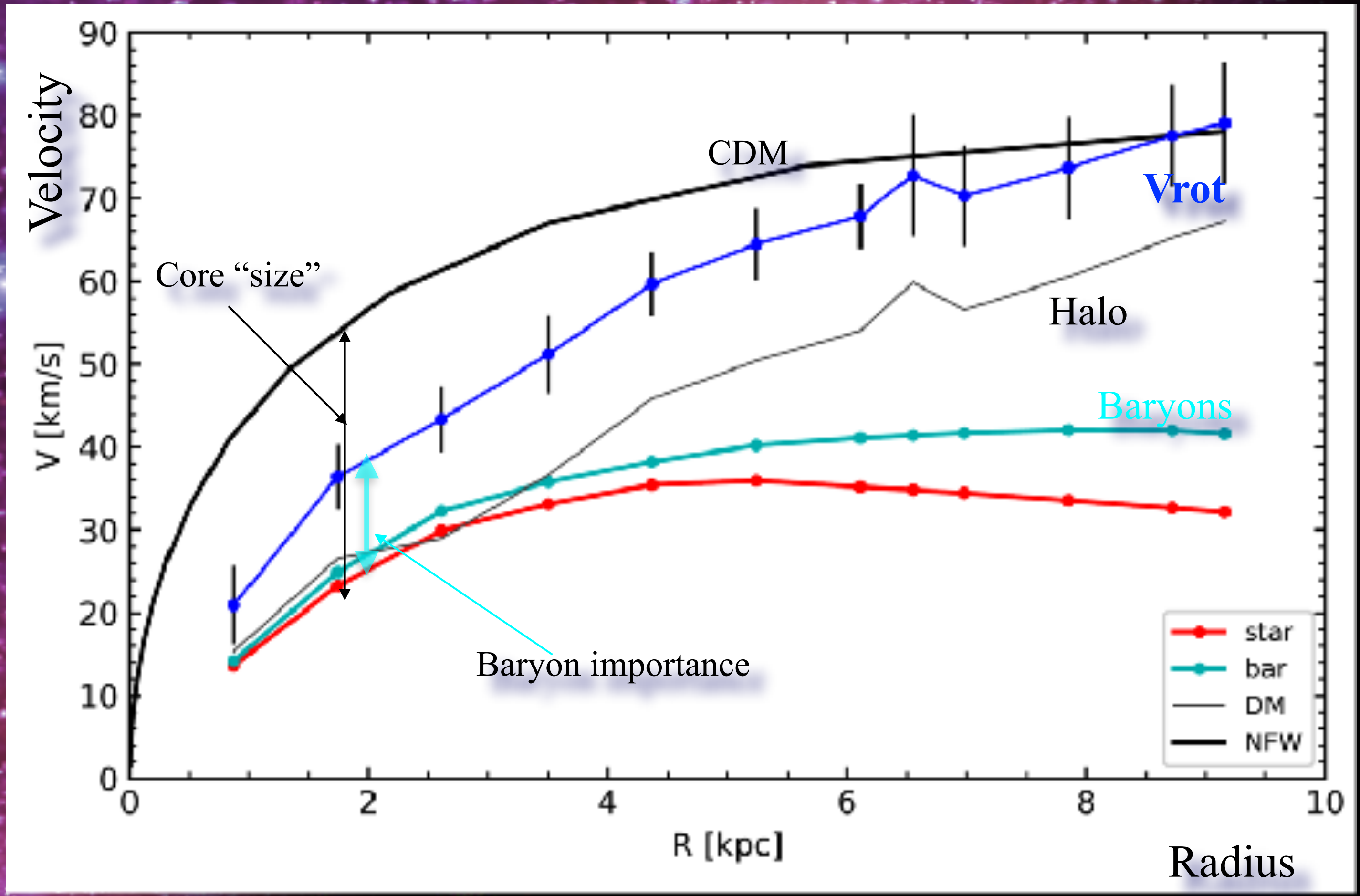
How to tell these scenarios apart?



- There are extra correlations that qualify the “diversity” of rotation curves.
- The importance of the baryons at 2kpc also correlate with the inner mass deficit.

Santos-Santos+19

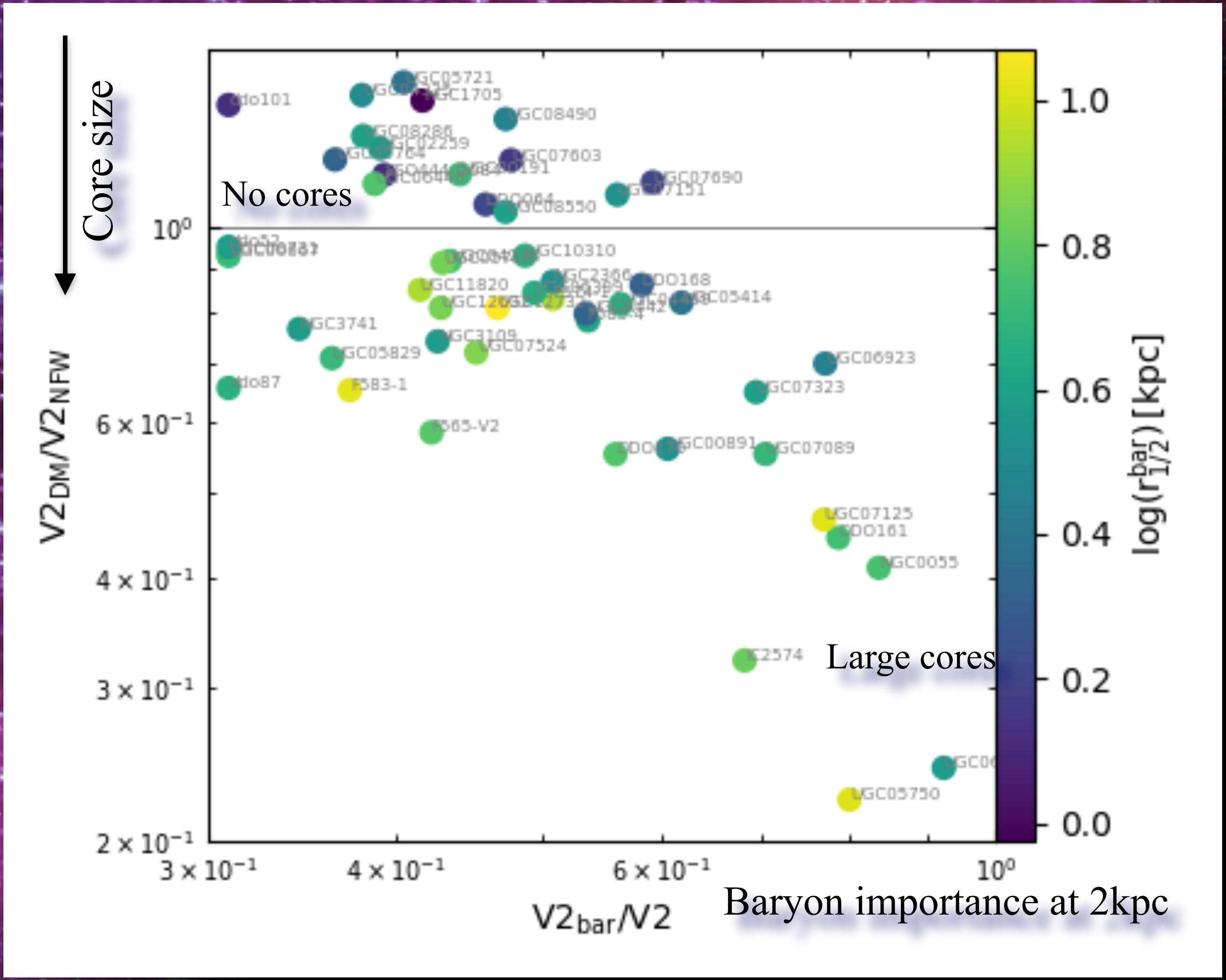
How to tell these scenarios apart?



The baryon importance at the fiducial radius of ~2 kpc correlates with the "size" of the core, measured by the dark matter mass deficit at that radius.

Santos-Santos+19

How to tell these scenarios apart?



•The larger the core, the more baryon-dominated the galaxy is at 2kpc

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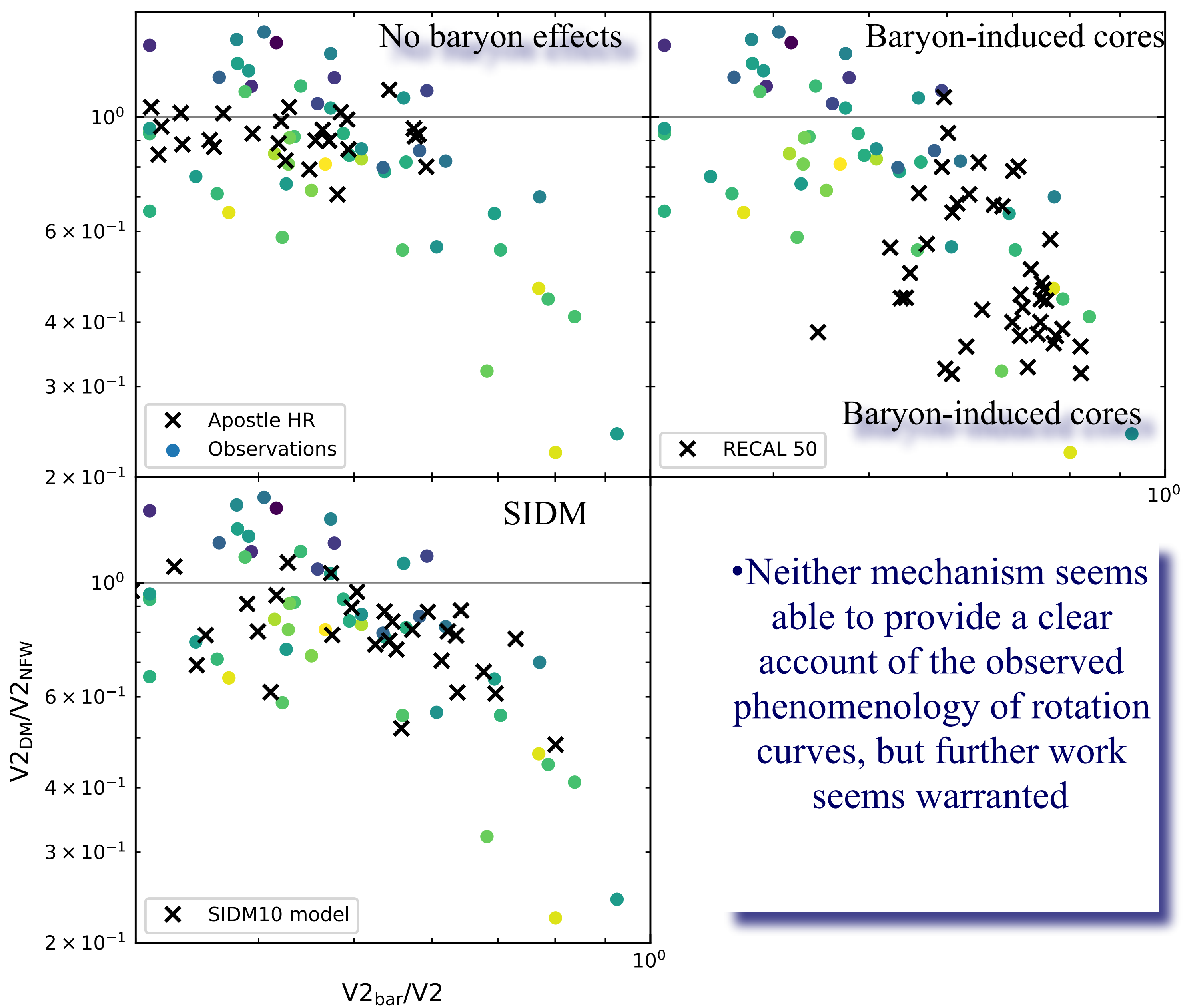
How to tell these scenarios apart?



- Neither mechanism seems able to provide a clear account of the observed phenomenology of rotation curves, but further work seems warranted

Santos-Santos+19

Summary

- Most small-scale “challenges” to LCDM are readily explained by physical effects (reionization, feedback) that govern the formation of galaxies.
- Galaxy scalings such as the mass discrepancy-acceleration relation probe the non-linear clustering of cold dark matter.
  - They are a “natural” consequence of the self-similar halo structure and the tight relations between galaxy mass, size, and halo mass.
- The one outstanding challenge is the diversity of dwarf galaxy rotation curves, characterized by apparent *deficit* of dark matter in the inner regions of *some* galaxies.
  - Some may be explained by uncertainties in the observations, others may signal galaxy-induced modifications to the CDM mass profile, or perhaps new dark matter physics.