Galaxy Scaling Relations in LCDM

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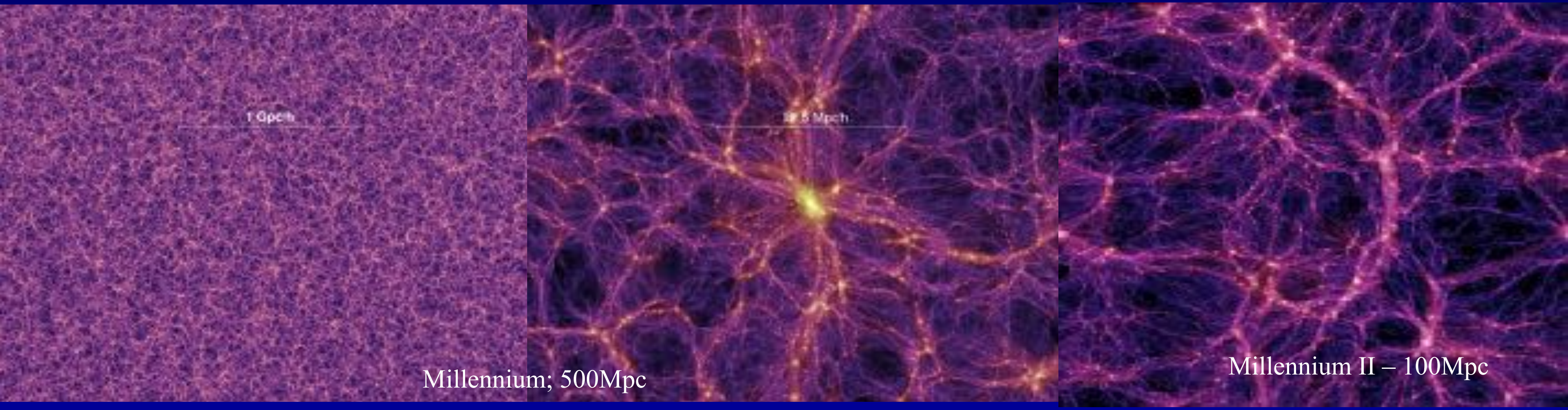
The Clustering of Dark Matter

The Millennium Simulation Series



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 on large and small scales.

- 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

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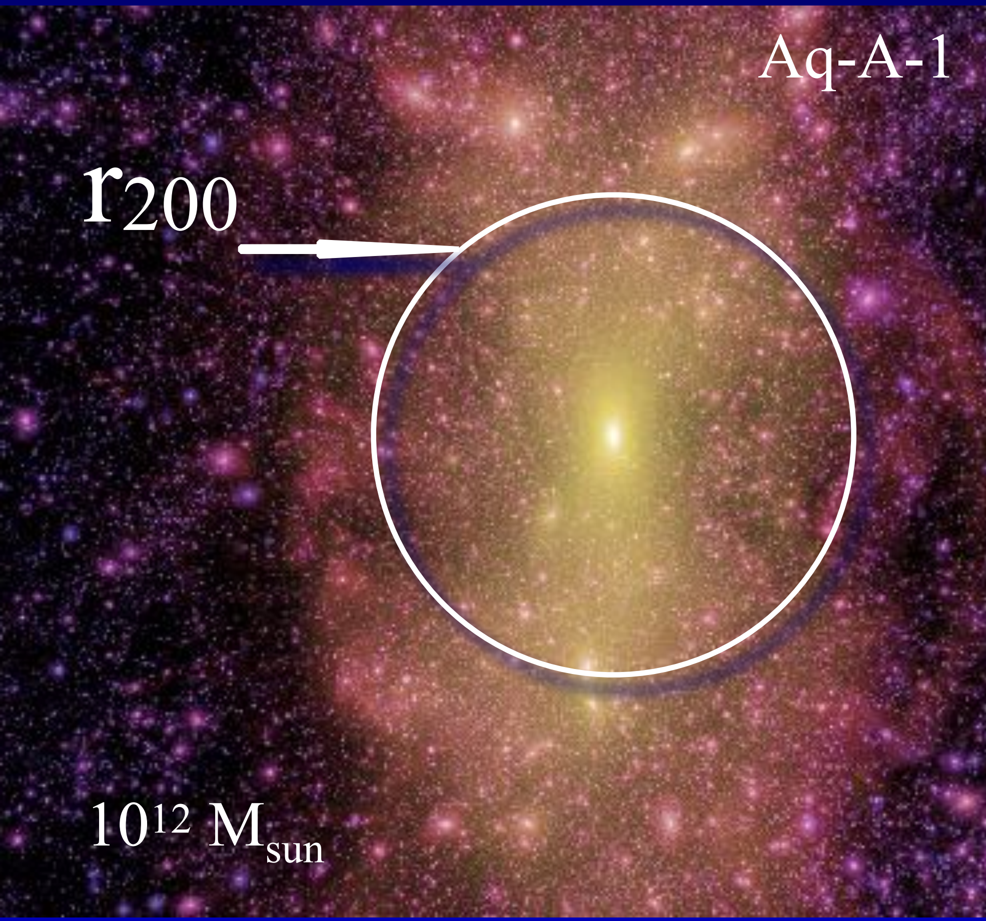
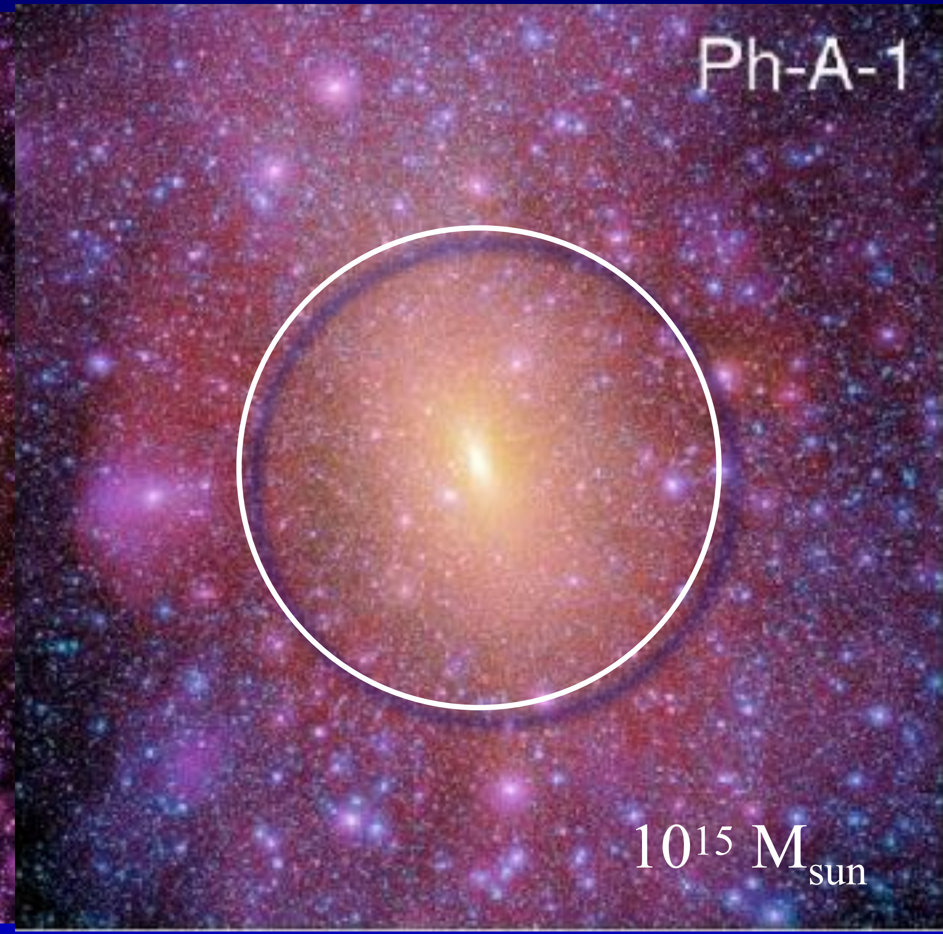
Dark matter halos in LCDM

The self-similar nature of LCDM halos

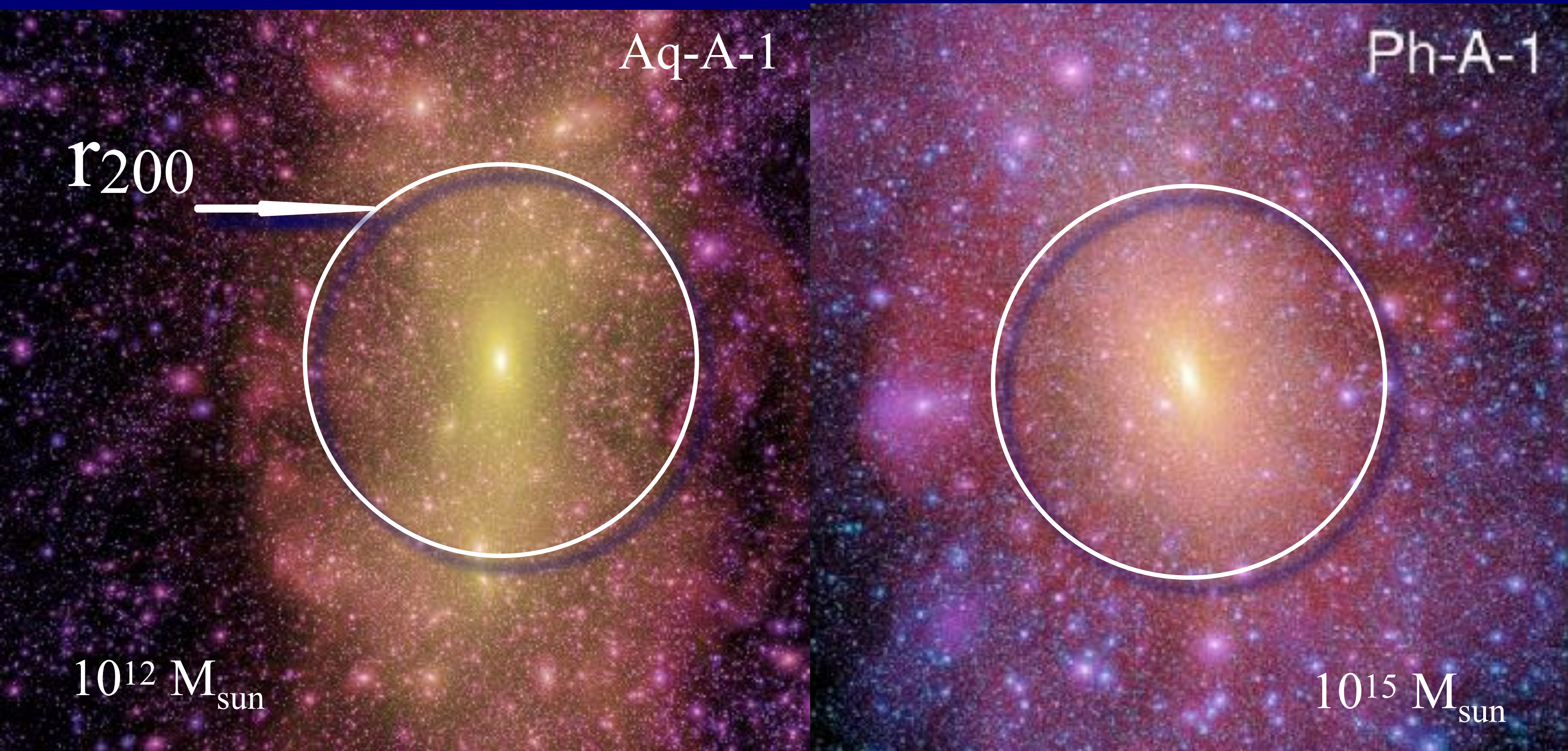




DM halos: self-similar structures linked by the age of the Universe

M/R^3=constant

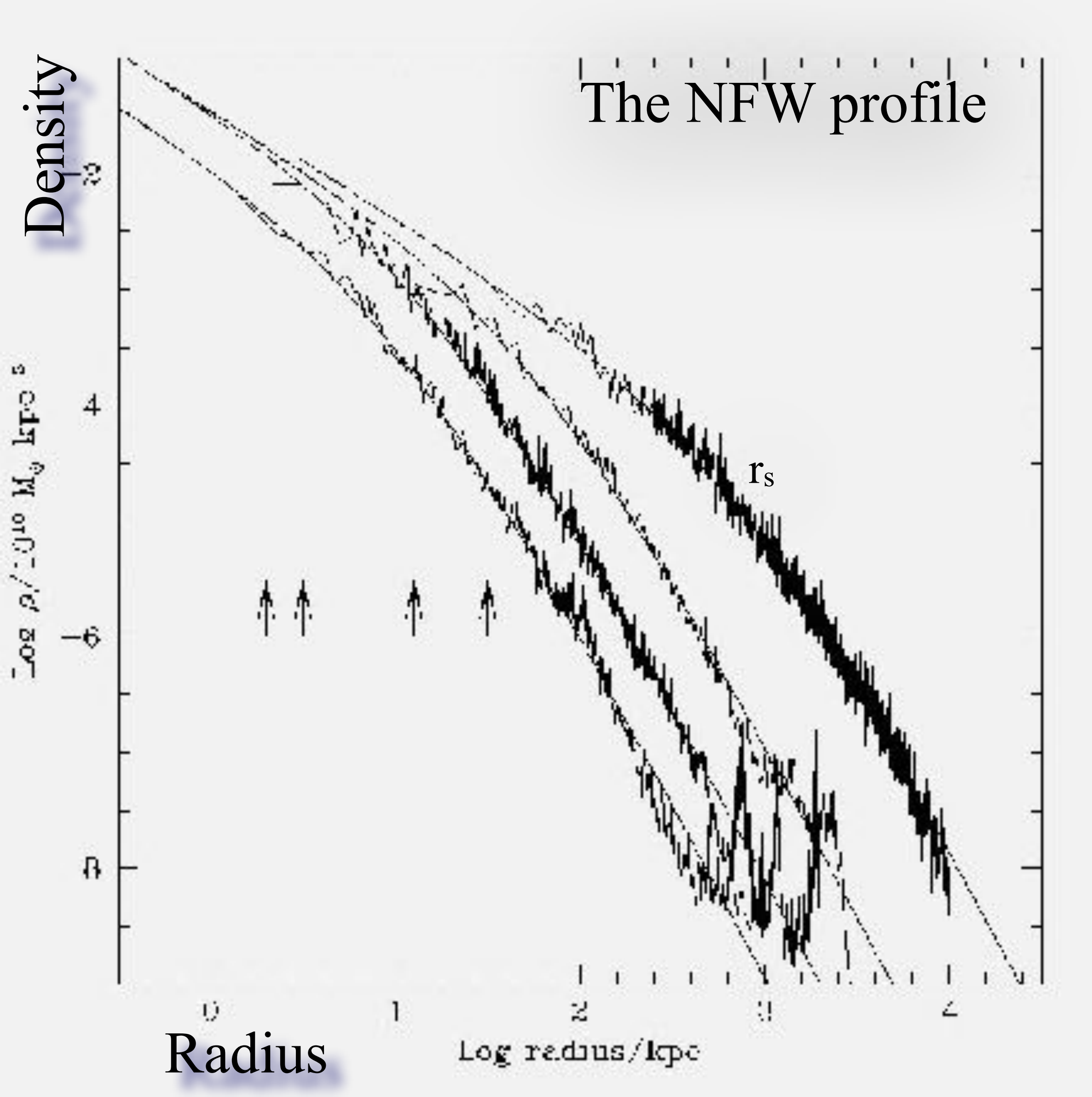
The self-similar nature of LCDM halos



M_{200}/r_{200}^3=constant $\quad$ $M_{200} \propto V_{200}^3$

acceleration:$(V_{200}^2/r_{200})/(cH_0)=10*(V_{200}/c)=0.01*(V_{200}/300\ \mathrm{km/s})$

The Mass Profile of Cold Dark Matter halos

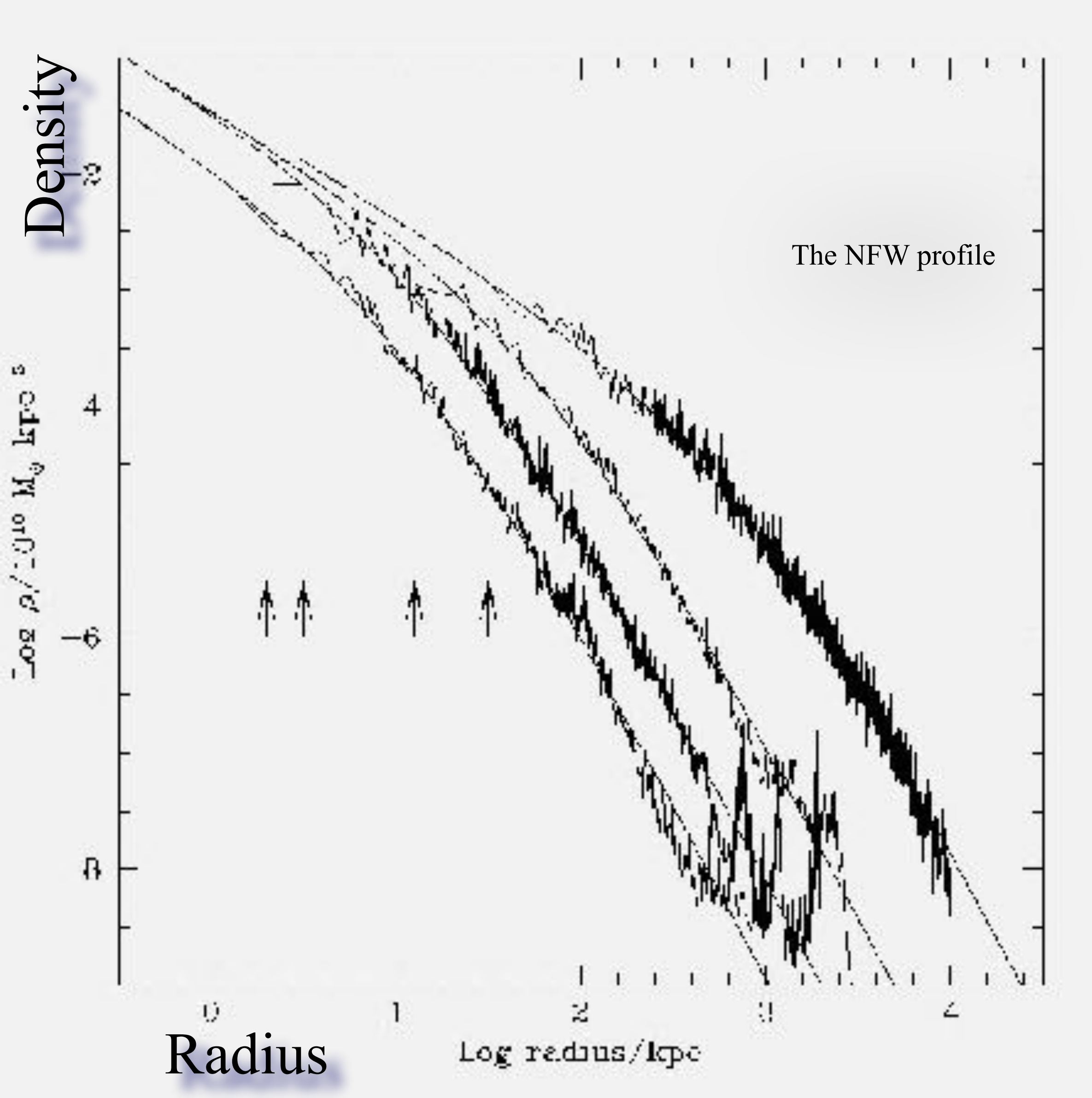


- The shape of the mass profiles of dark mater halos is roughly independent of halo mass and cosmological parameters

- Density profiles are “**cuspy**”

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

The Mass Profile of Cold Dark Matter halos



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

- At fixed mass, the only radial scale is given by the scale radius, r_s

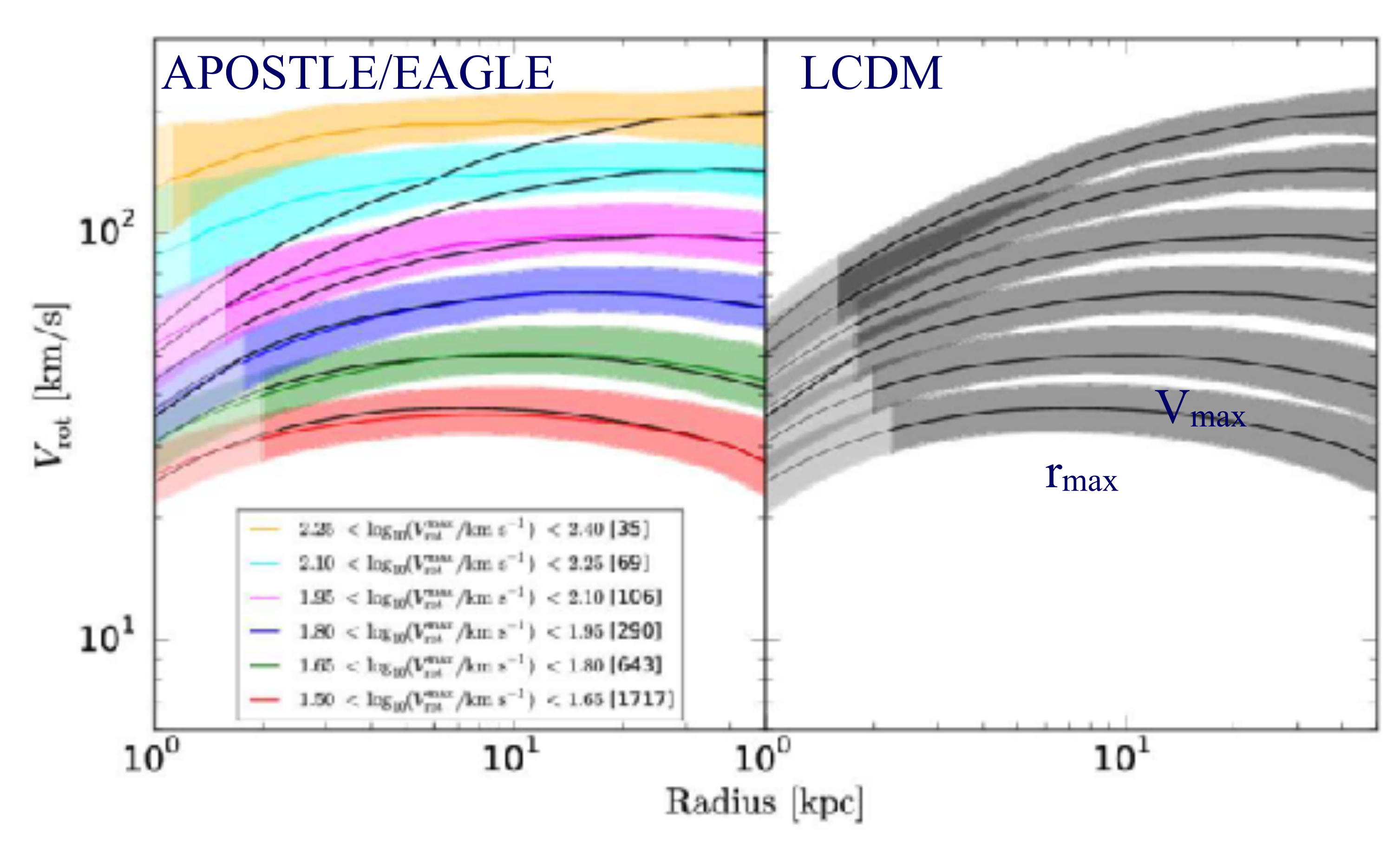
- The $\boldsymbol{\rho \propto r^{-1}}$ central cusp implies **constant acceleration**: galaxies form in regions where the DM acceleration varies little with radius

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

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

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

LCDM predicted circular velocity profiles



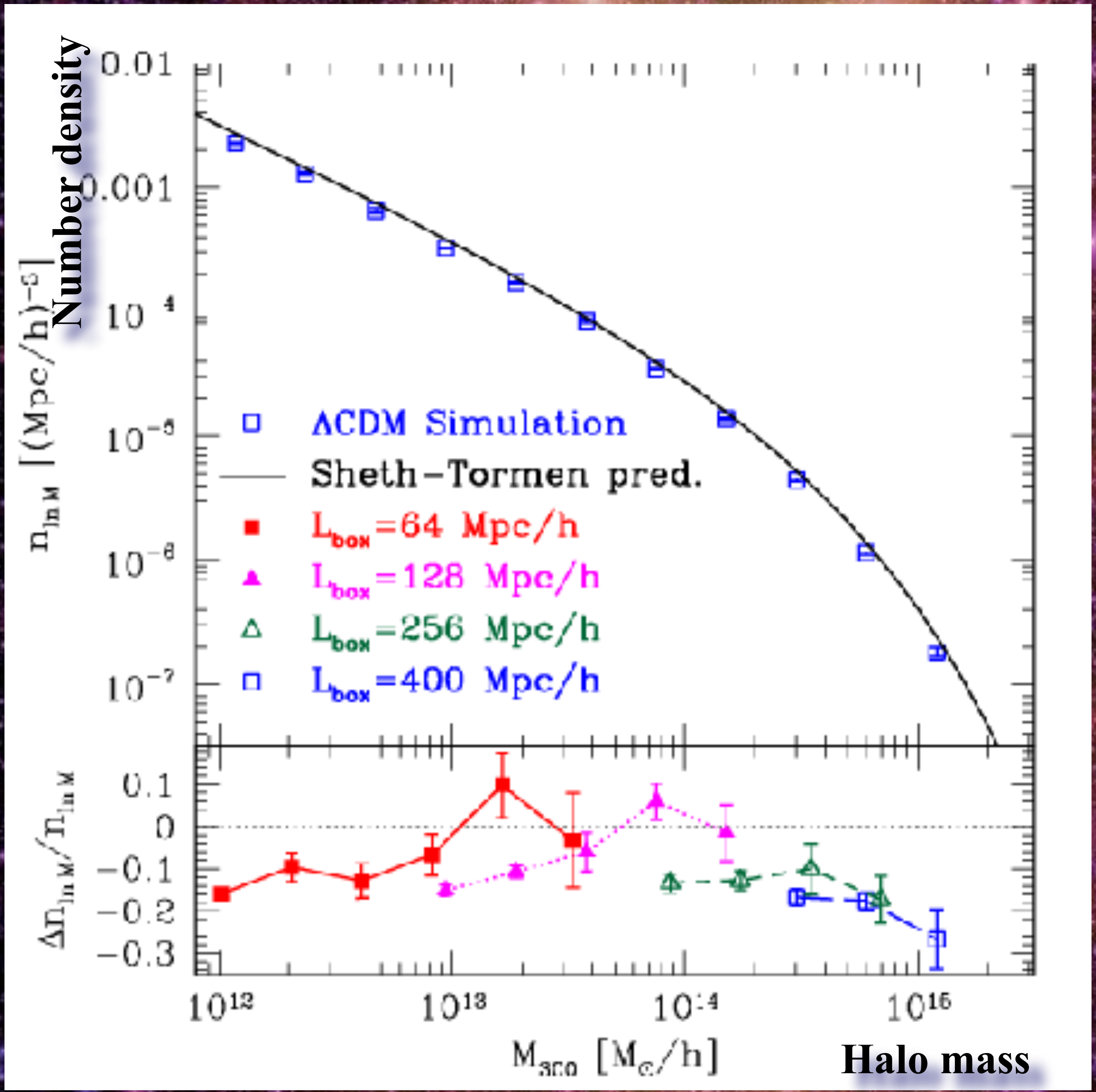
- CDM predicts a **single** mass/ circular velocity profile for a given velocity scale
- "Rotation curves" would be rising, not flat, without the contribution of baryons
- V_{max} and r_{max} are another way of specifying the mass/size of the halo

Oman+15

Galaxy Scaling Laws in LCDM

- Halo mass-galaxy mass relation
- Galaxy mass-size relation
- Tully-Fisher relation
- Mass discrepancy-acceleration relation

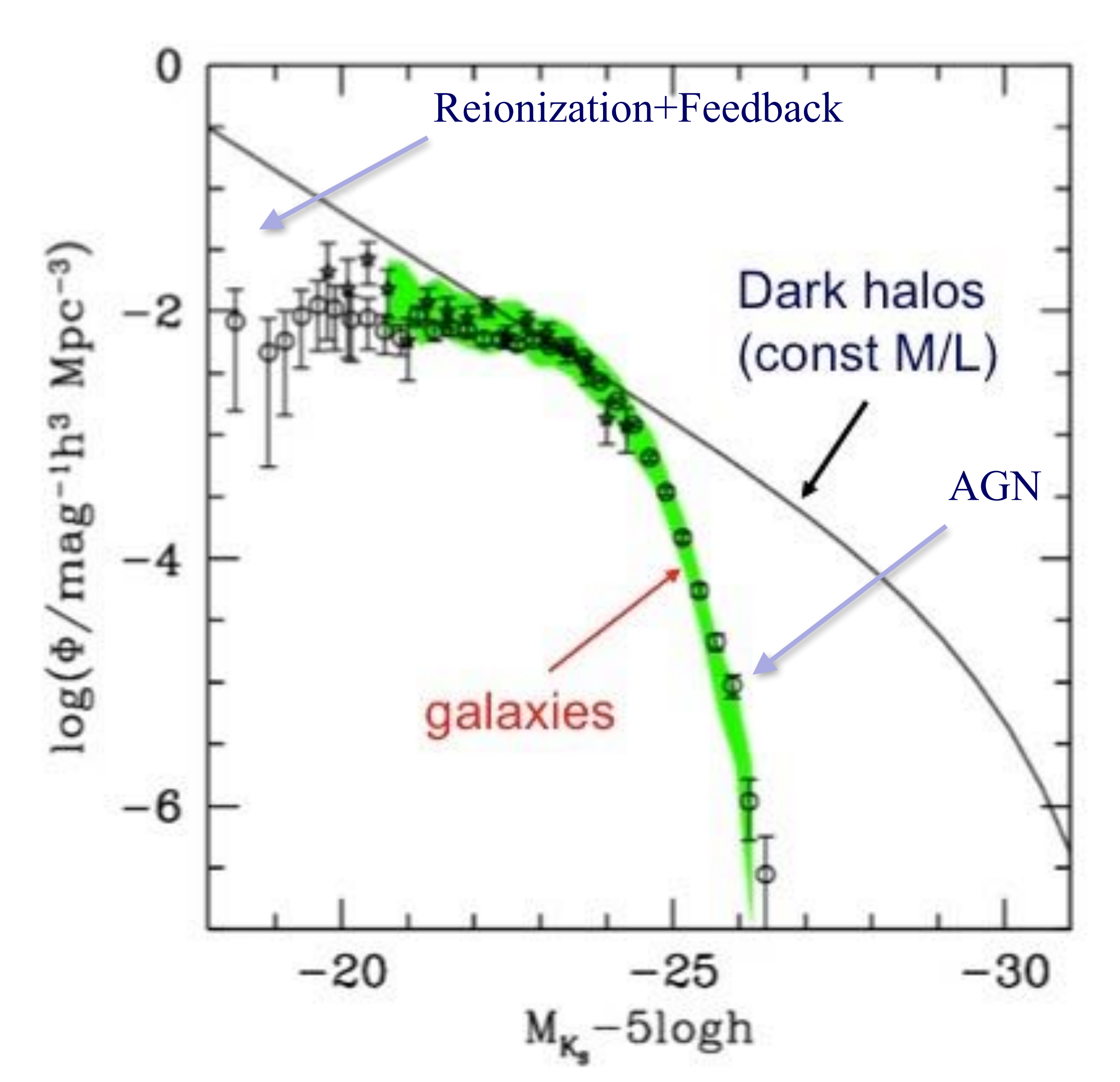
CDM halo mass function



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

Schmidt et al 2009

CDM halo mass function vs galaxy luminosity function



- CDM halo mass function *much steeper* than the galaxy luminosity function at the faint end

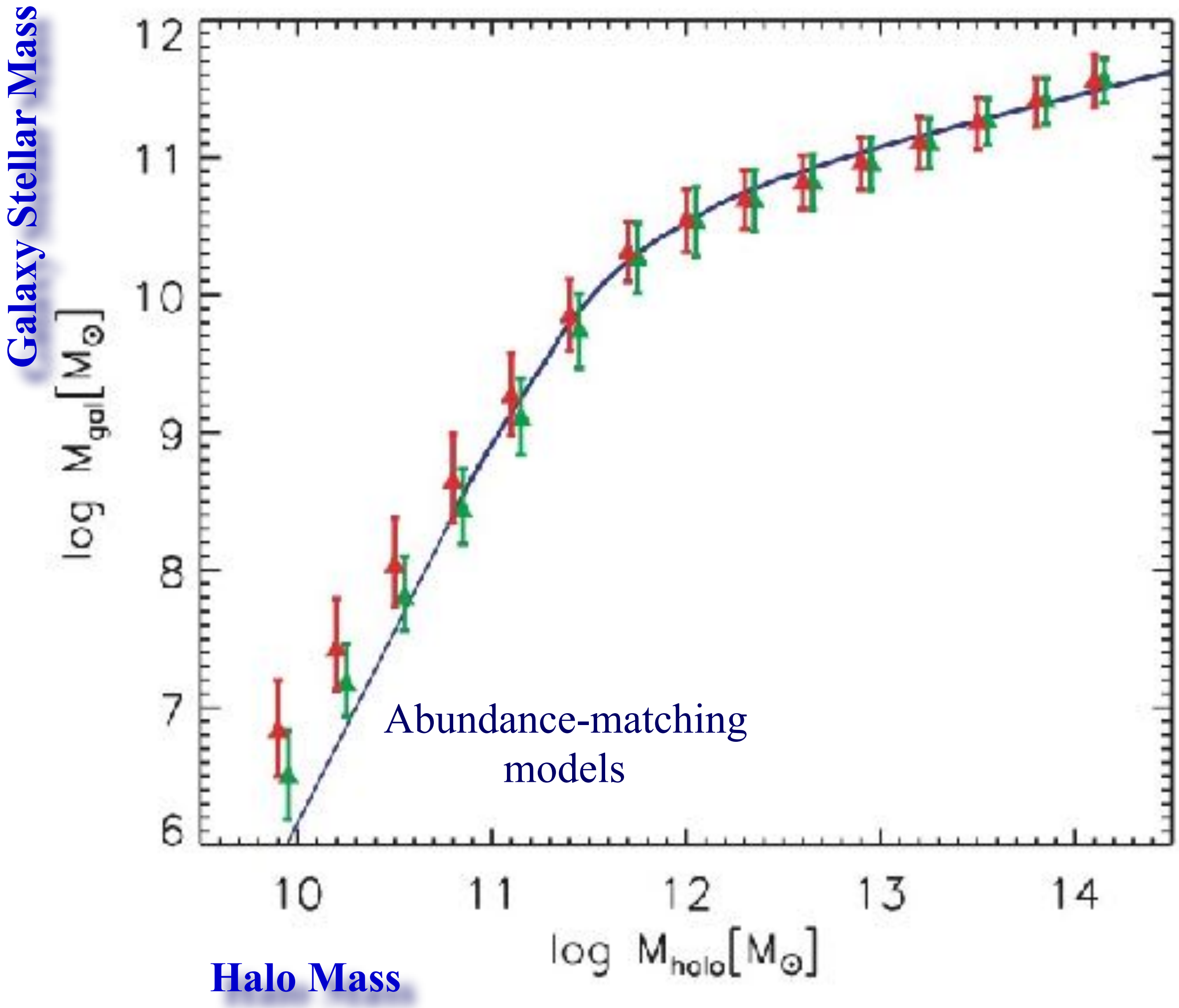
- Reconciling the two requires a highly non-linear dependence between galaxy and halo mass

- 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 should decline in low mass halos

Benson+2000

Abundance Matching: Galaxy Stellar Mass vs Halo Mass



- Galaxy formation efficiencies are very low, peak at 15% for Milky Way-like galaxies
- Steep dependence at low halo mass--a fundamental result of galaxy formation models.
- Most dwarfs form in halos of similar mass and hence similar properties—-what is the origin of their diversity then?
- Very few luminous galaxies should form in halos with mass below a “threshold” of 10^{10} M_{sun}

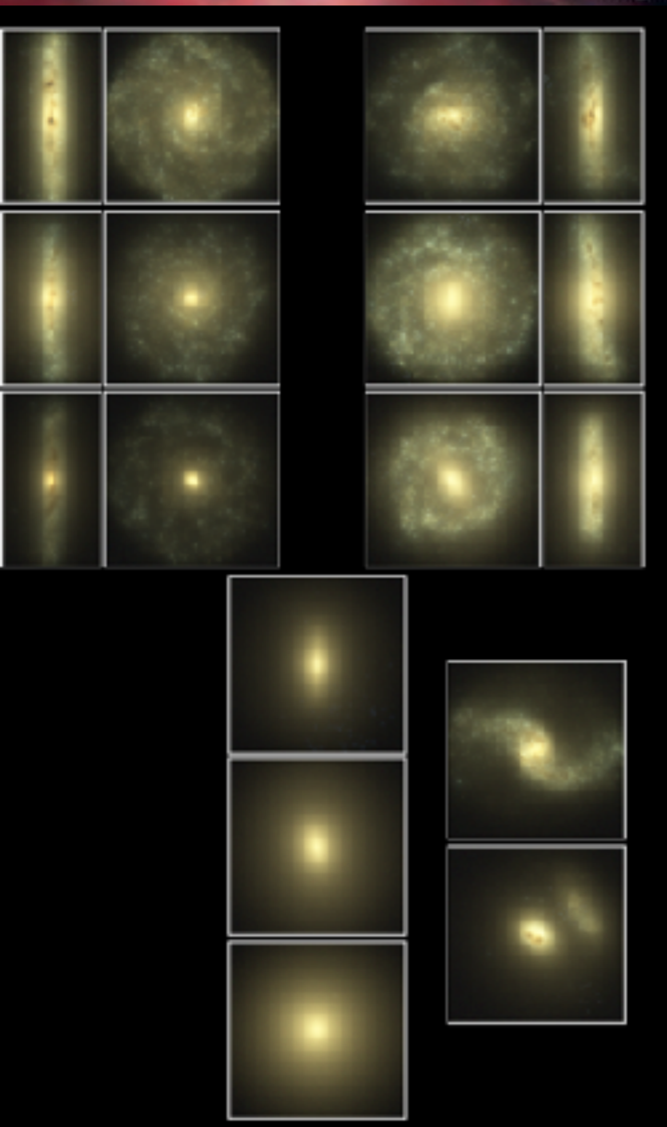
Guo+2011

The Eagle simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

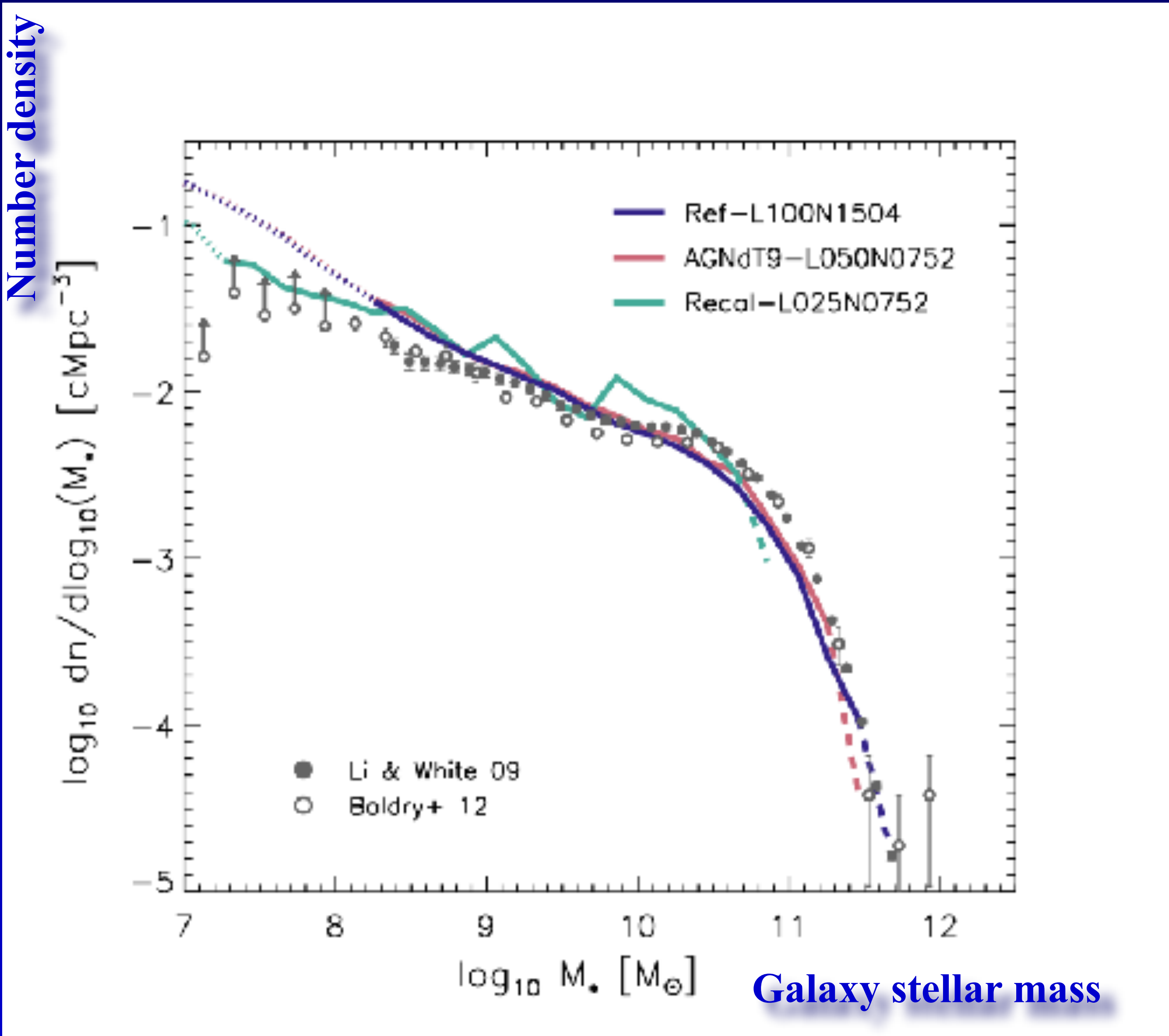
A project of the Virgo Consortium

VIRGO



•Large hydrodynamical simulations of cosmologically representative volumes (~100 Mpc box) have recently been completed (see; e.g., results from the Illustrius Project)

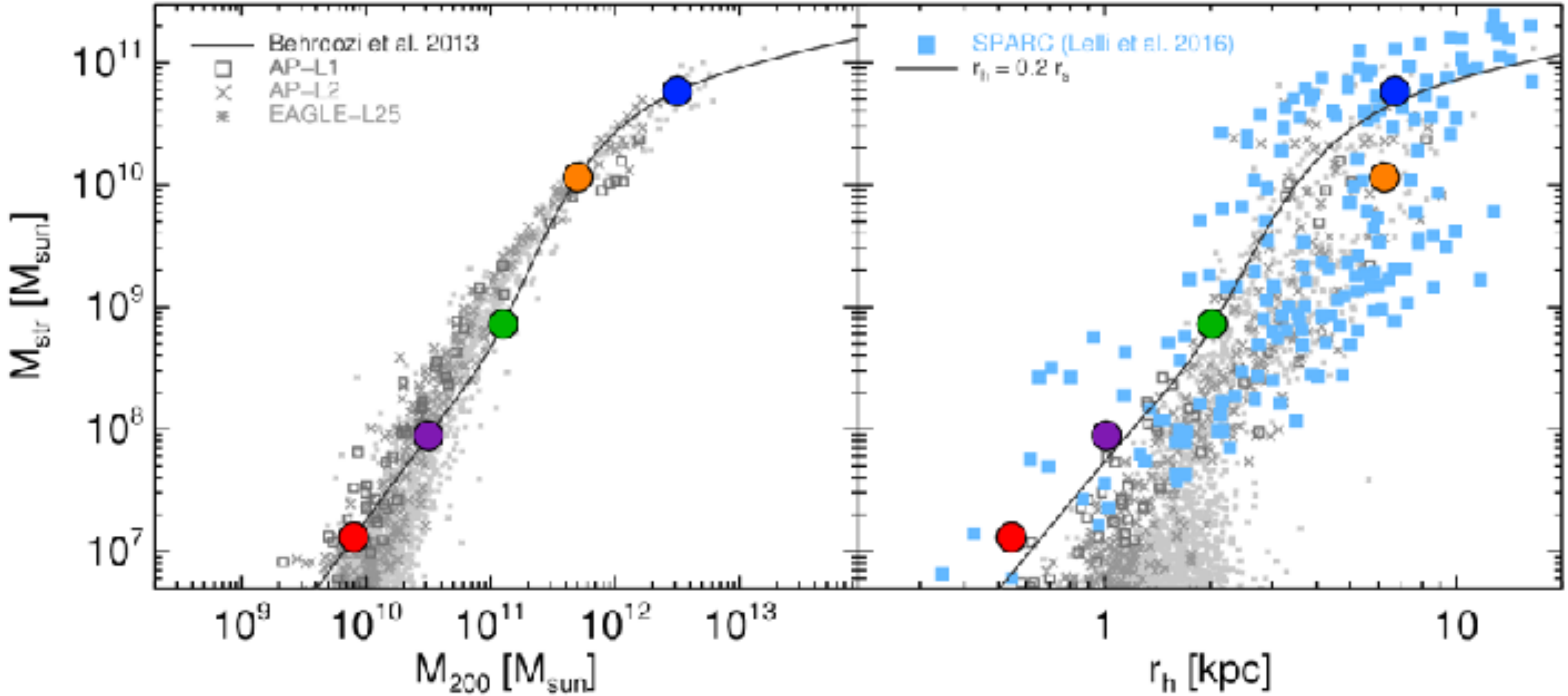
EAGLE Galaxy Stellar Mass Function



- Recent simulations have been able to include reionization and feedback effects to reproduce the galaxy stellar mass function down to galaxies of M_{*}~10^8 solar masses in stars
- They also match reasonably well other properties of the observed galaxy population

Schaye et al 2015

Galaxy mass vs halo mass and size



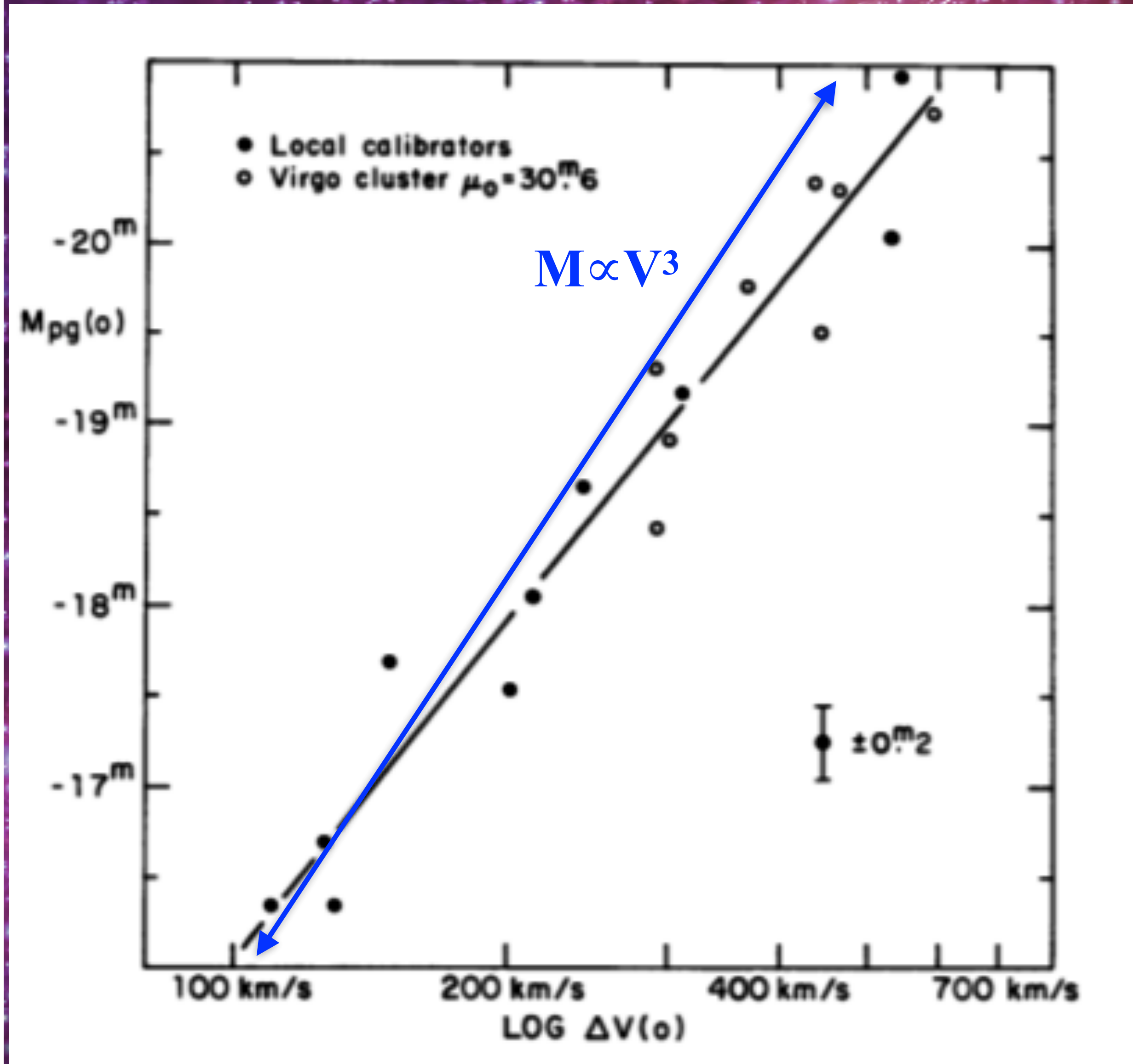
Galaxy mass-halo mass scaling is essentially that of abundance matching
Galaxy mass-size relation parallels the halo mass-size relation

Navarro+17

The Tully-Fisher relation

The Tully-Fisher relation

Absolute magnitude=Luminosity=Stellar mass

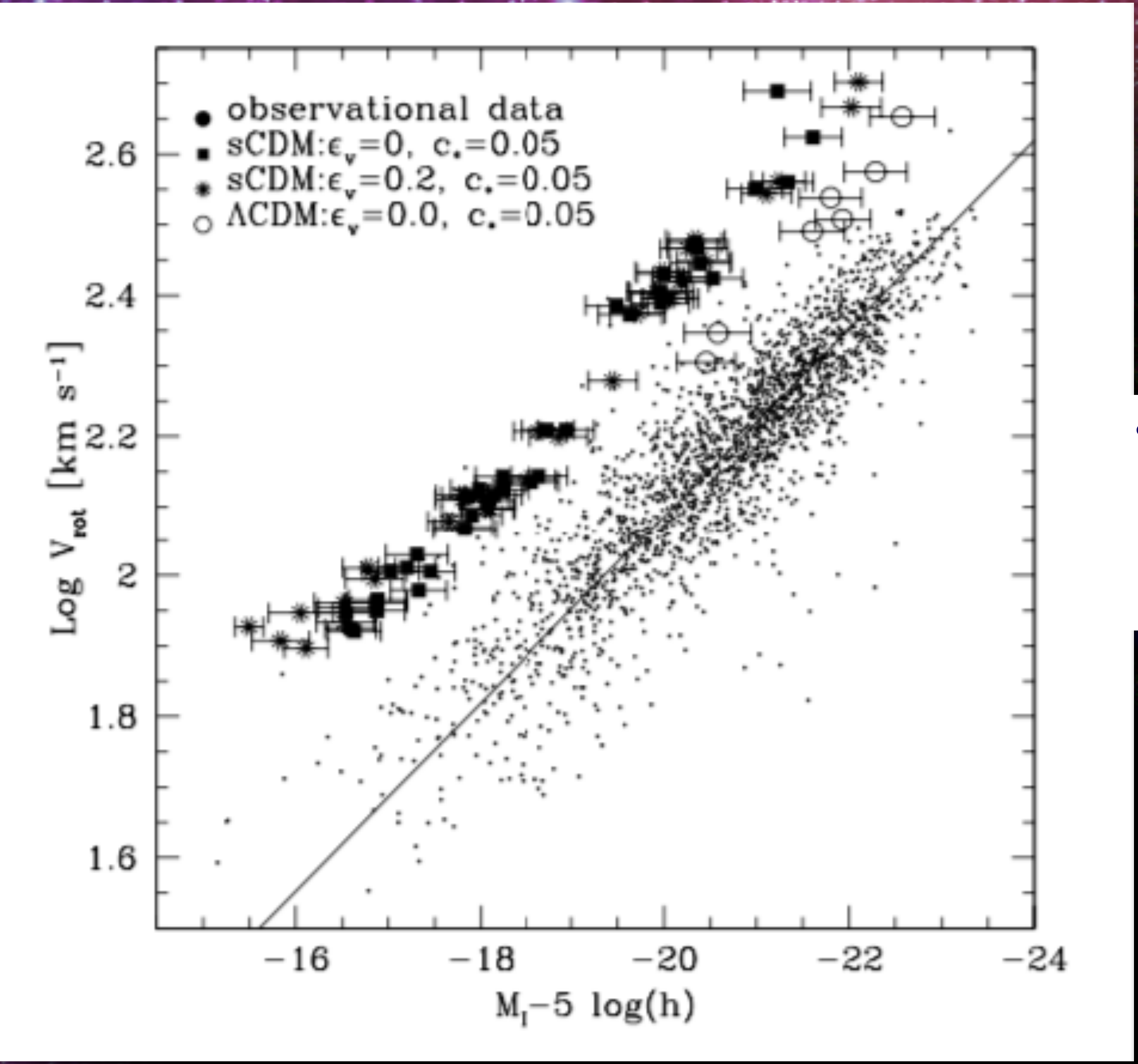


Velocity width~2*V_{rot}

- A power-law scaling relating a disk galaxy's luminosity (stellar mass) with its rotation speed
- A powerful secondary distance indicator

Tully & Fisher 1977

The Tully-Fisher relation



Rotation velocity

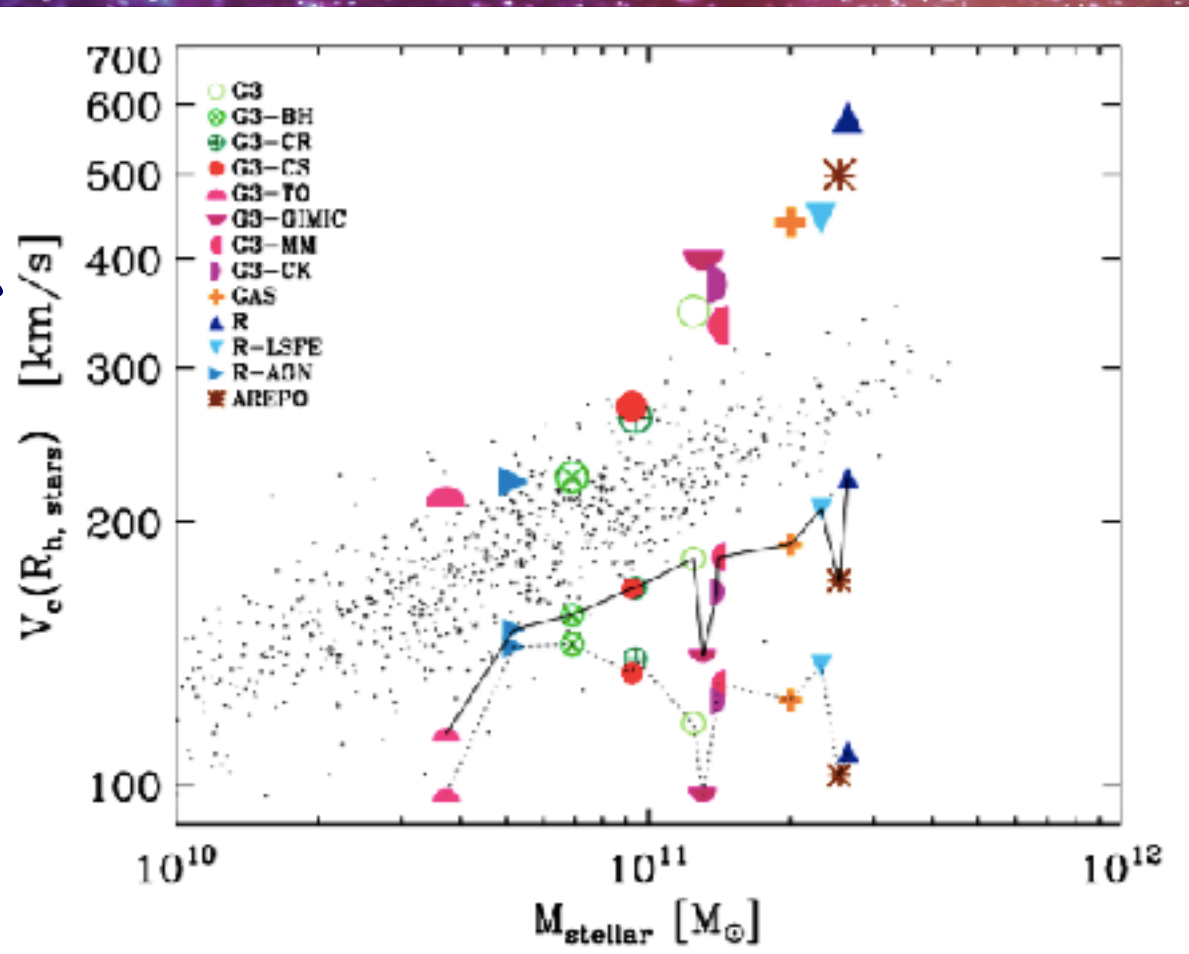
Absolute Magnitude

- Zero-point and slope difficult to reproduce in early cosmological simulations

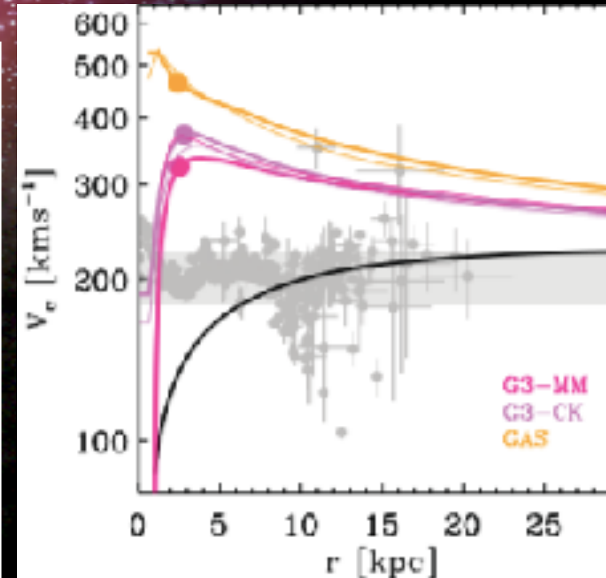
Navarro & Steinmetz 2000

The Tully-Fisher relation

Rotation velocity



Stellar mass

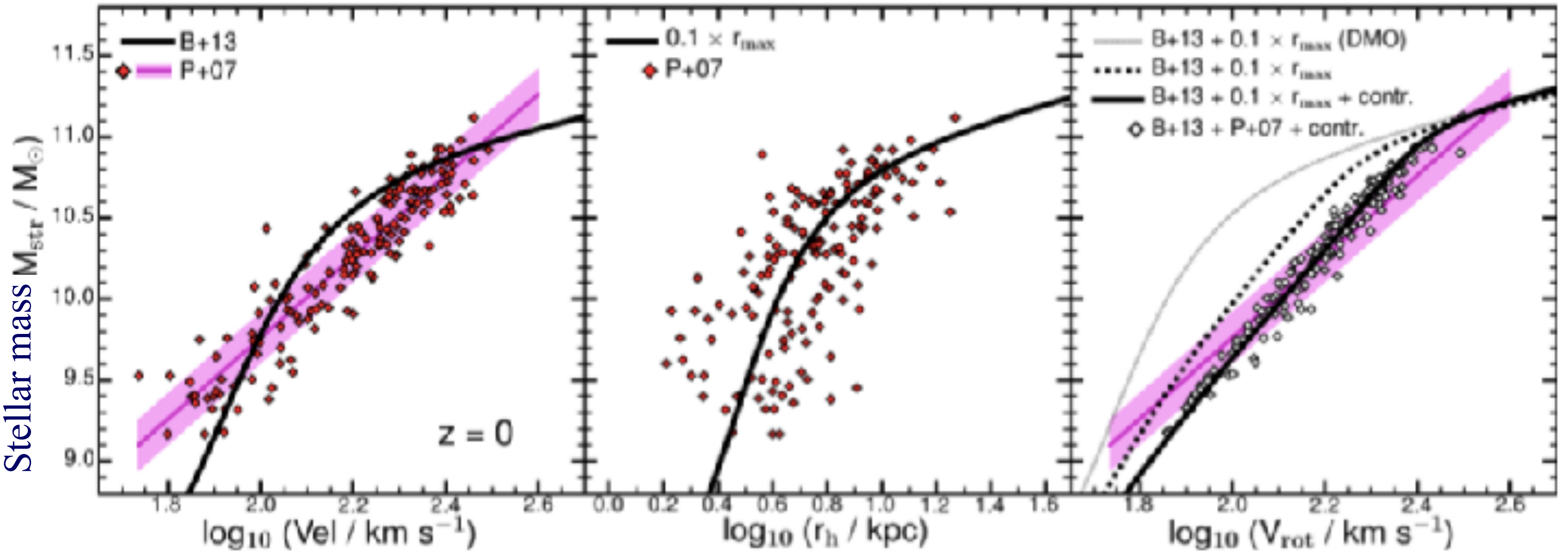


Galaxies too massive and centrally concentrated to give "flat rotation curves"

Zero-point and slope difficult to reproduce in early cosmological simulations

Scannapieco+2012

The Tully-Fisher relation in LCDM

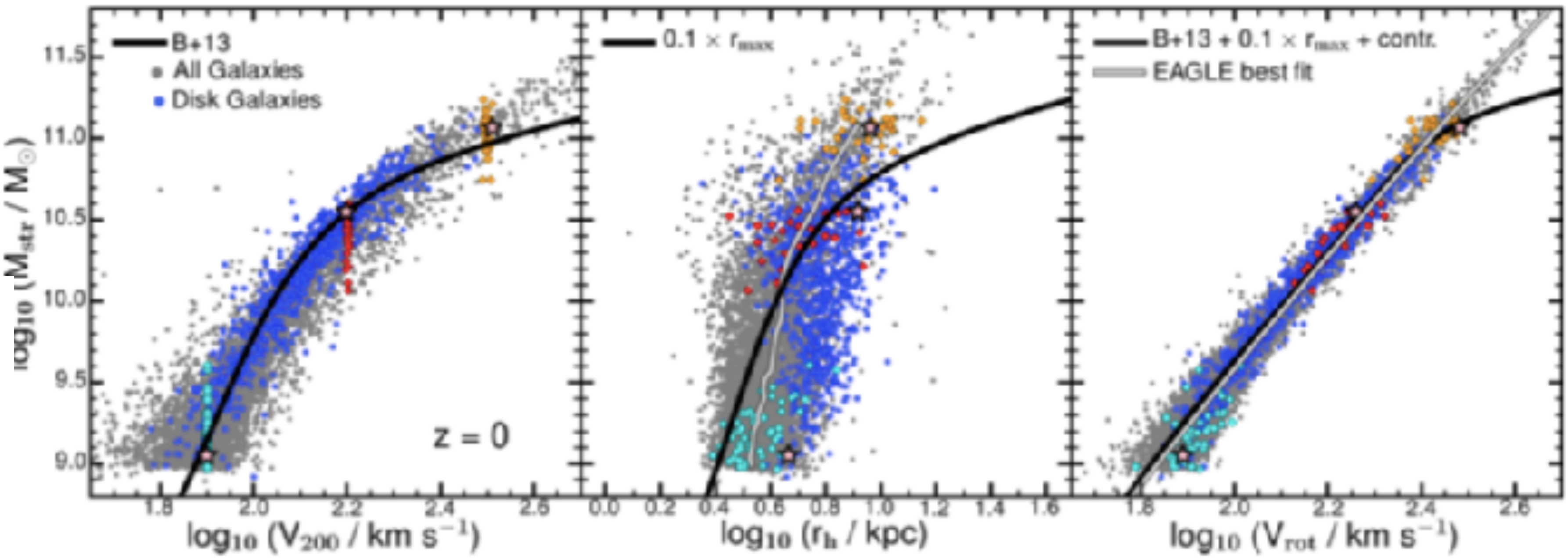


Rotation velocity | Half-mass radius | Disk rotation velocity

- TFR does *not* just reflect the mass-velocity ($M \propto V^3$) scaling of dark matter halos.
- Galaxy masses are *not* proportional to halo masses. Rotation velocities are a function of the galaxy mass, size, and the dark matter contribution within the galaxy half-mass radius
- Need galaxies that are important gravitationally, and halos that "contract" as a result of galaxy assembly

Ferrero+2016

The Tully-Fisher relation in EAGLE



Stellar mass

Halo virial velocity

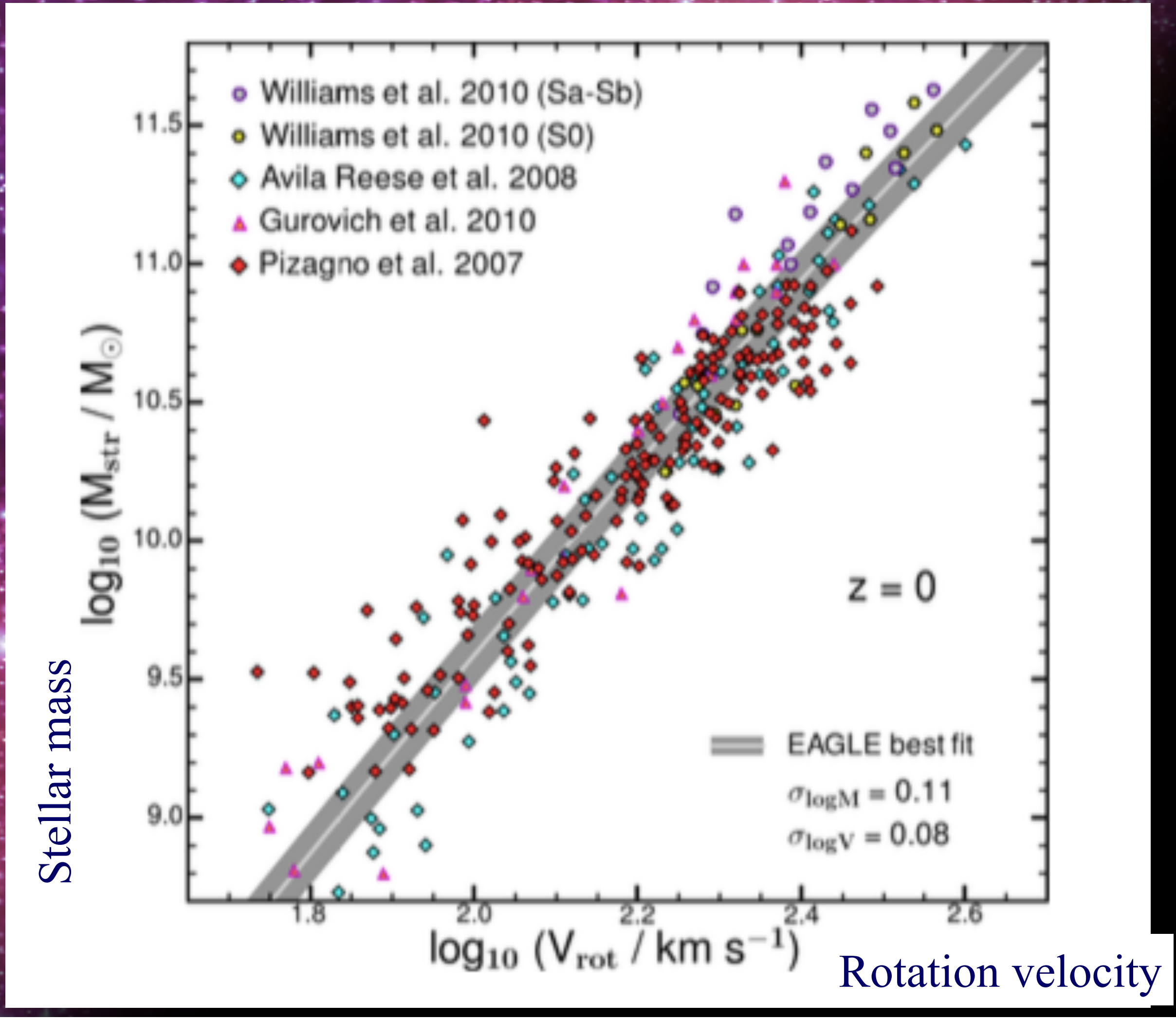
Half-mass radius

Disk rotation velocity

- Need galaxies that are important gravitationally (need to have the right size), and halos that “contract” as a result of the galaxy assembly
- At fixed halo mass, galaxies that are more massive than the average rotate faster than the average, and vice versa—the scatter spreads *along* the Tully-Fisher relation, leading to small dispersion in the relation

Ferrero+2016

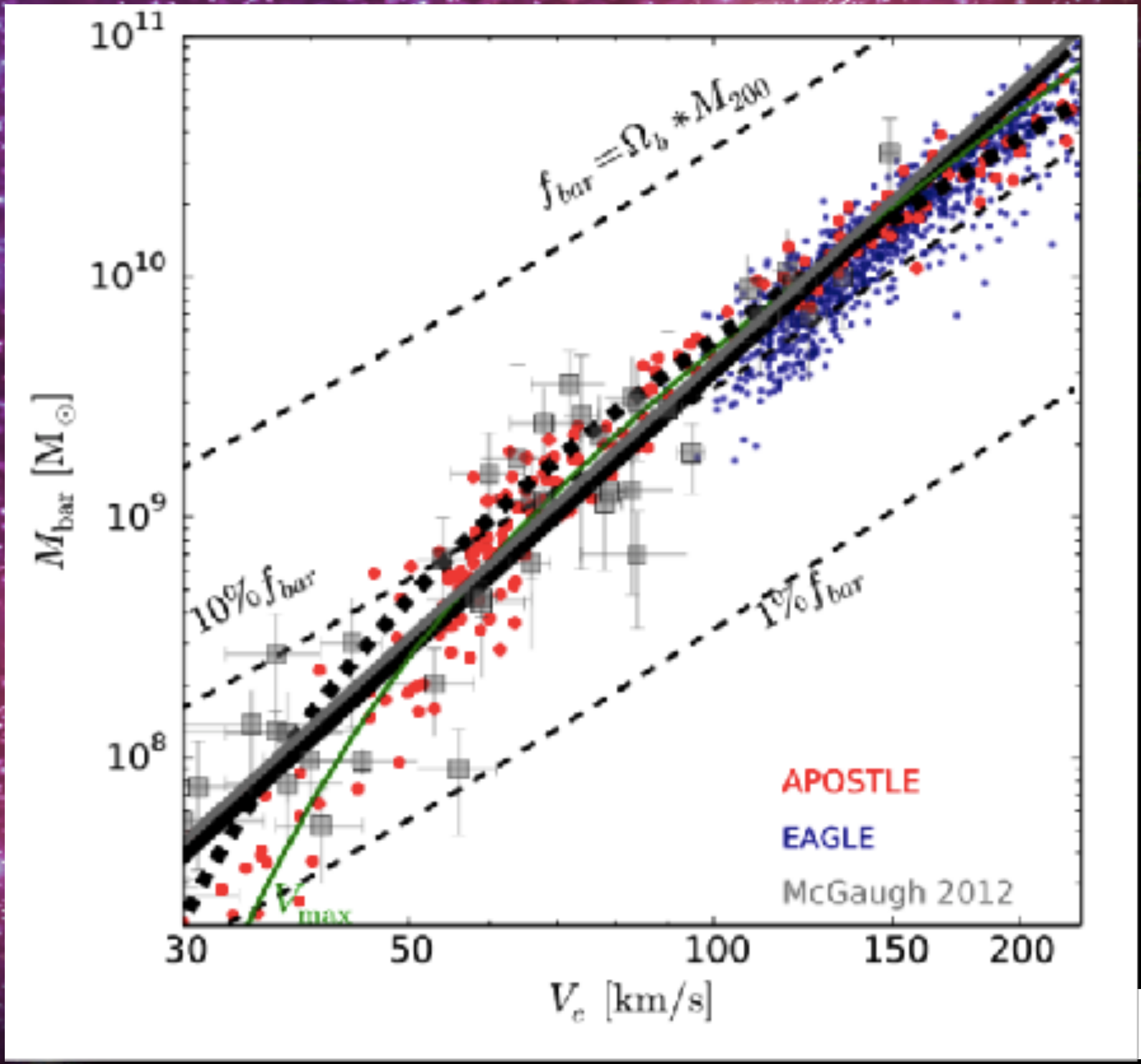
The Tully-Fisher relation in EAGLE



- The resulting relation is in excellent agreement with the observed Tully-Fisher relation, including its redshift evolution

Ferrero+2016

The Baryonic Tully-Fisher relation



Baryonic mass

Rotation velocity

- The low-mass baryonic TF relation also seems to agree with observations

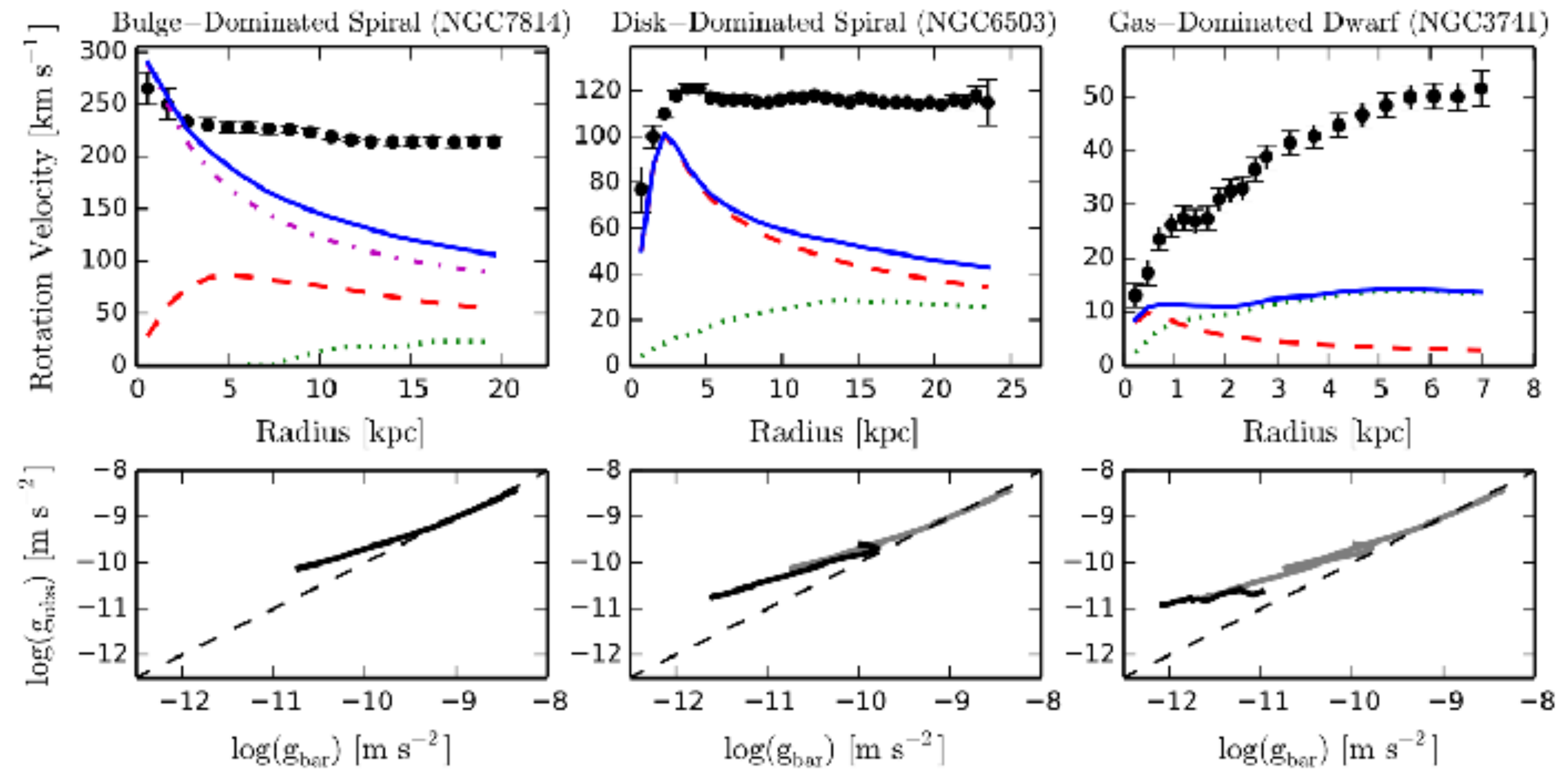
Sales+2016

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



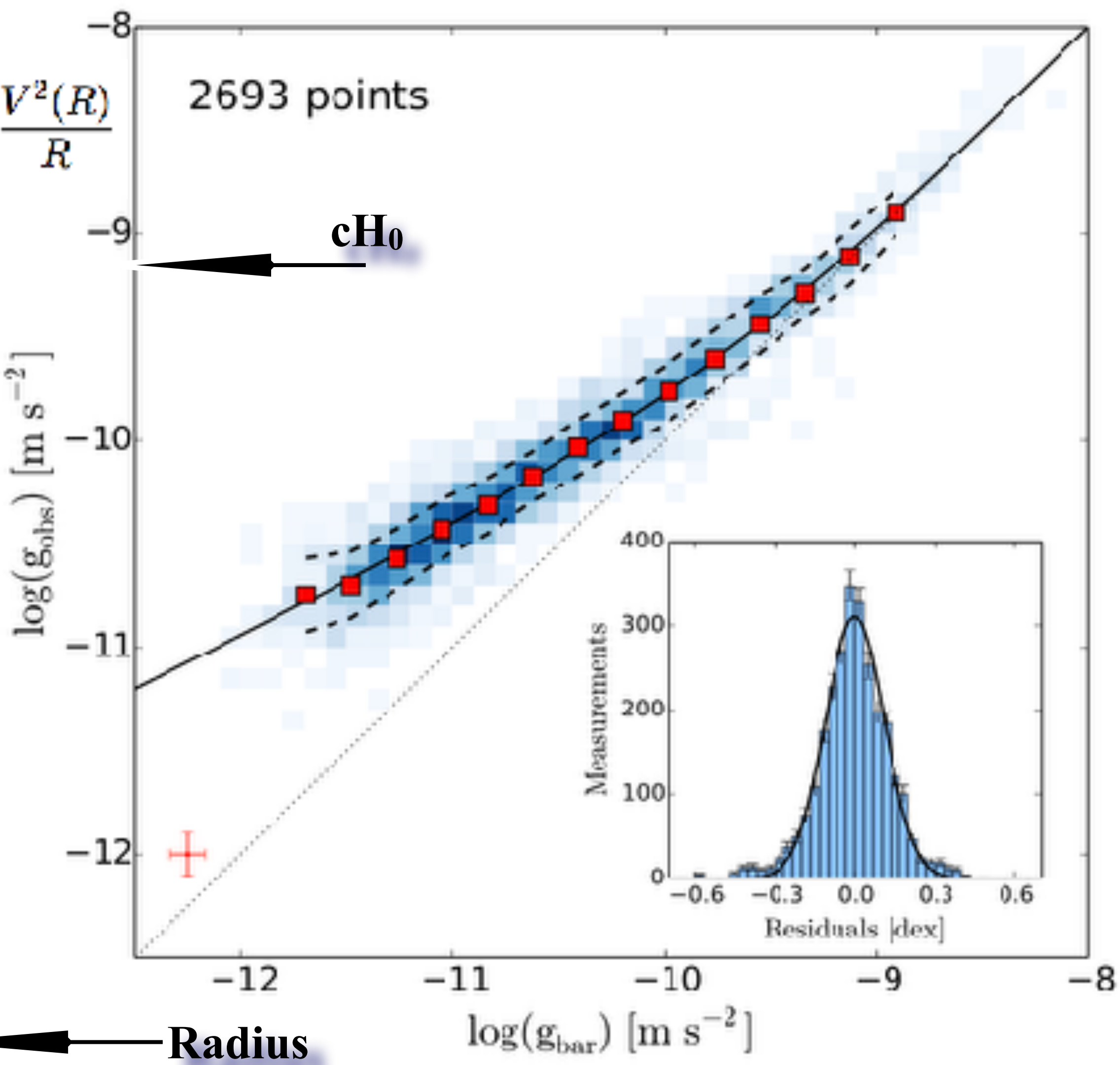
Radius

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

McGaugh+16 in PRL

The mass discrepancy-acceleration relation

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



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

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

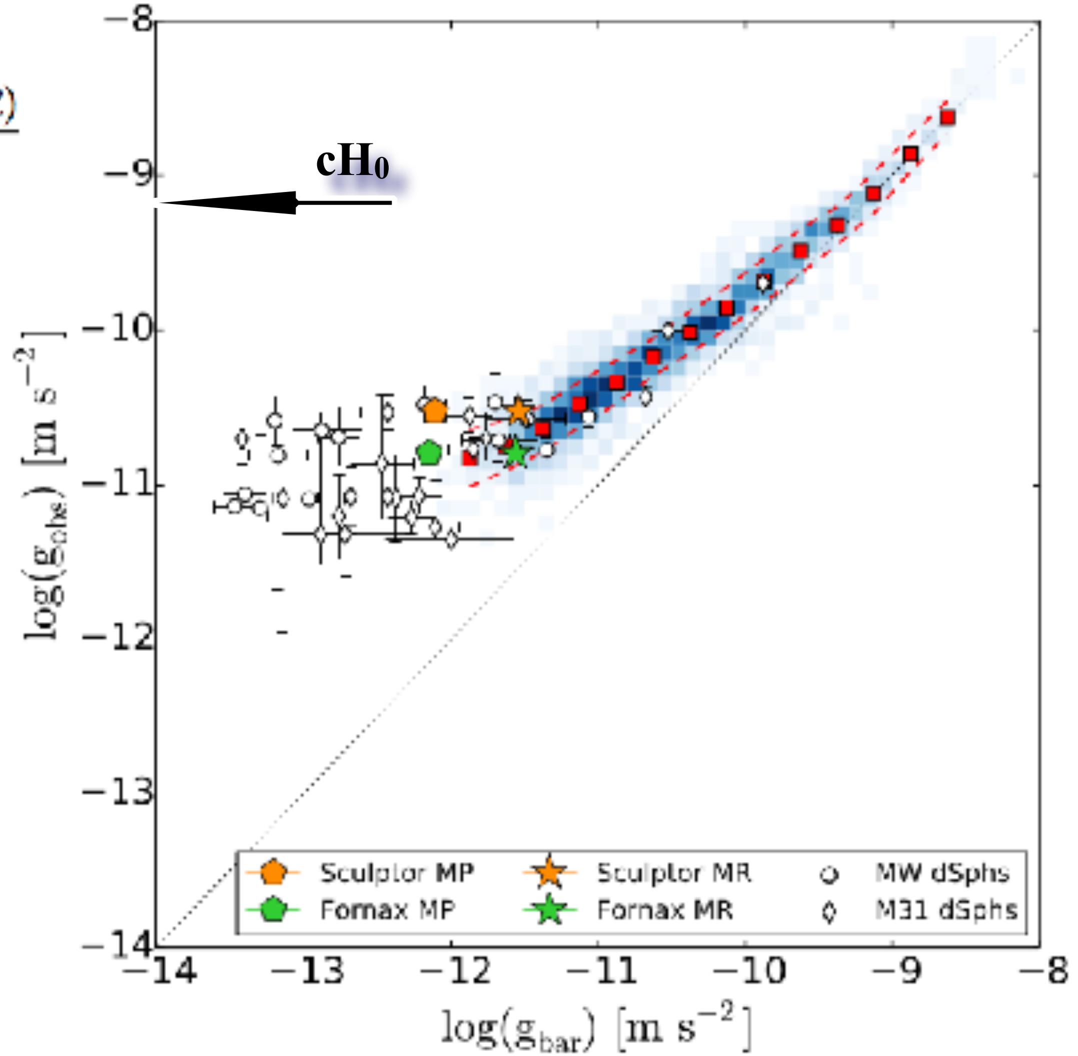
c^*H_0 is $\sim 7.2\ 10^{-10}$ m/s^2

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

McGaugh+16 in PRL

The mass discrepancy-acceleration relation

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



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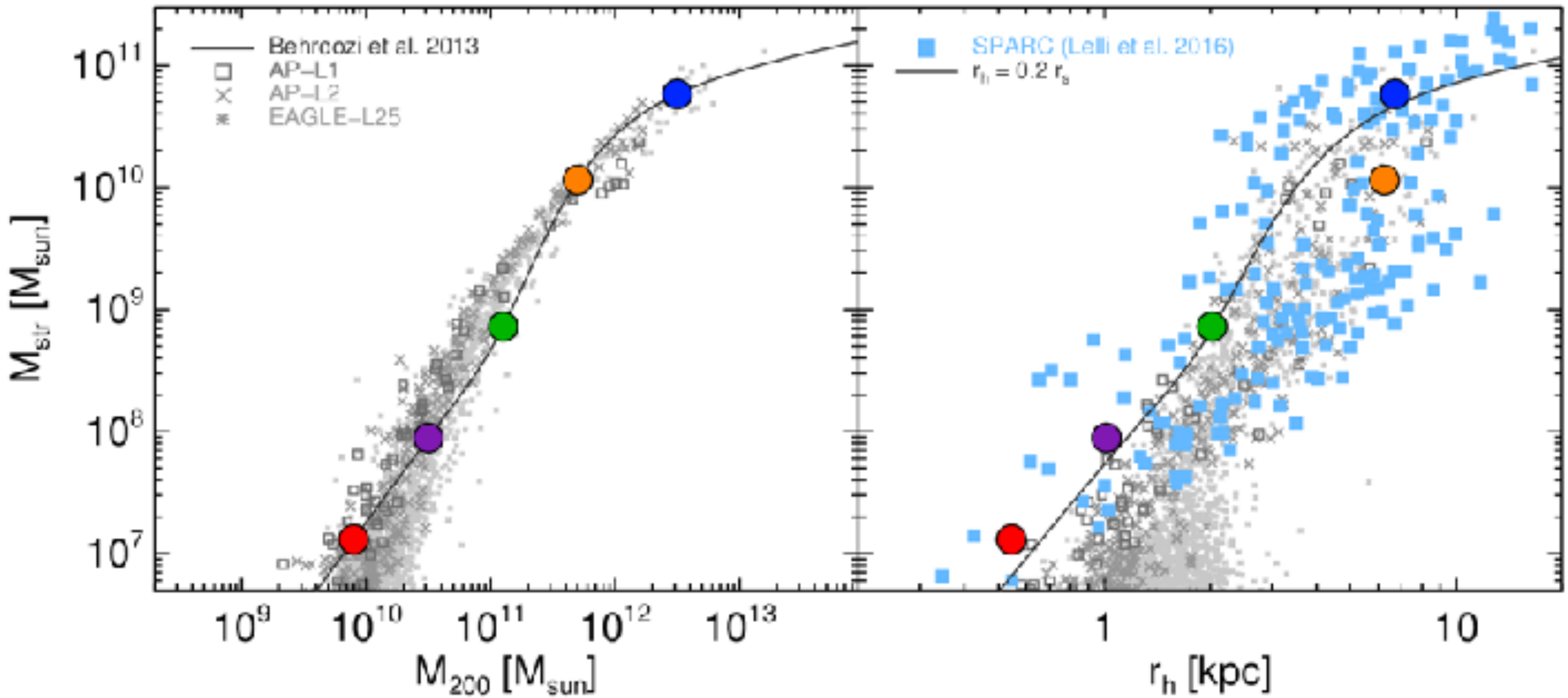
$c*H_0$ is ~7.2 10^{-10} m/s^2

Lelli+16

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

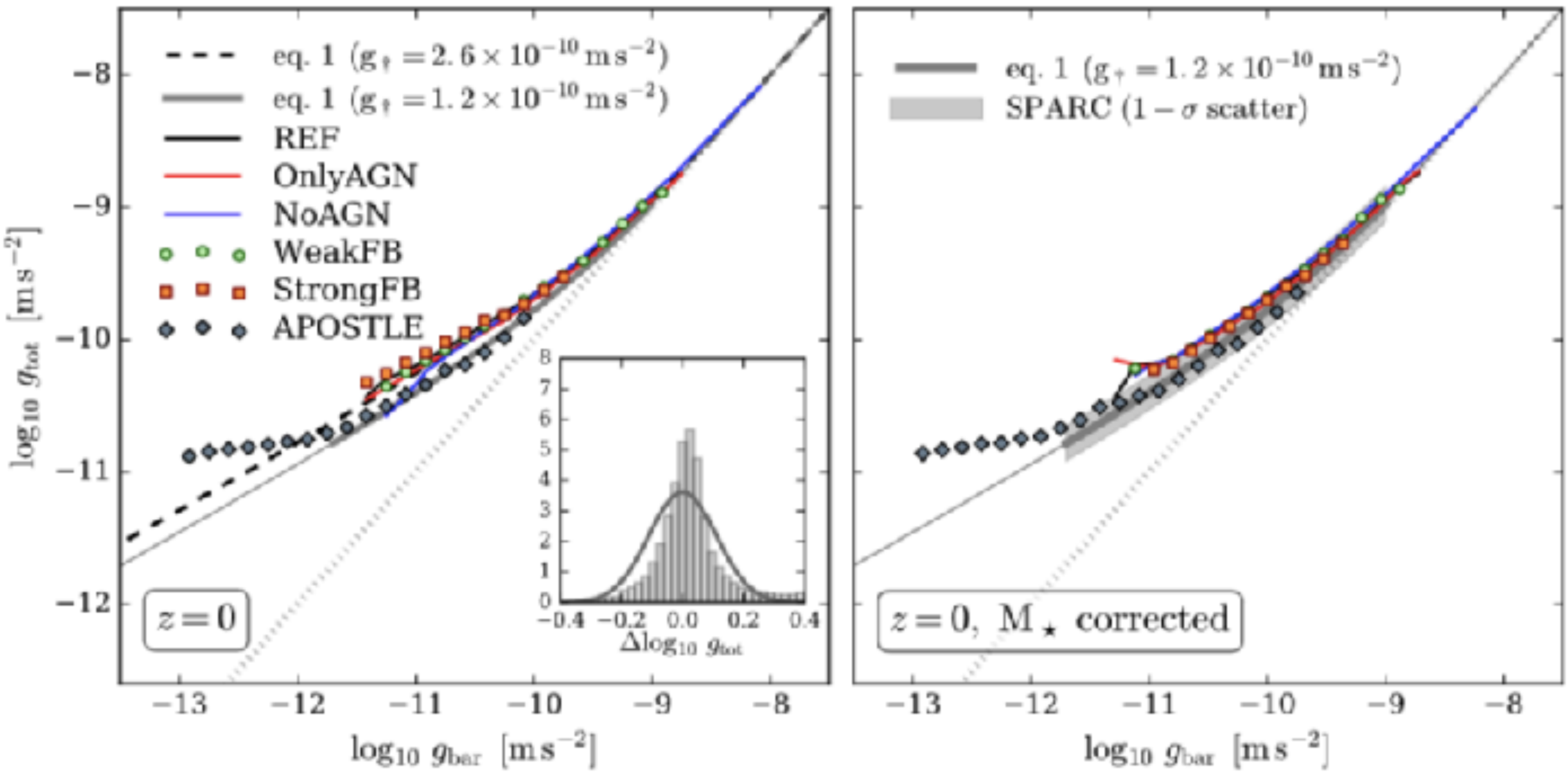
Where does MDAR come from in LCDM?



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

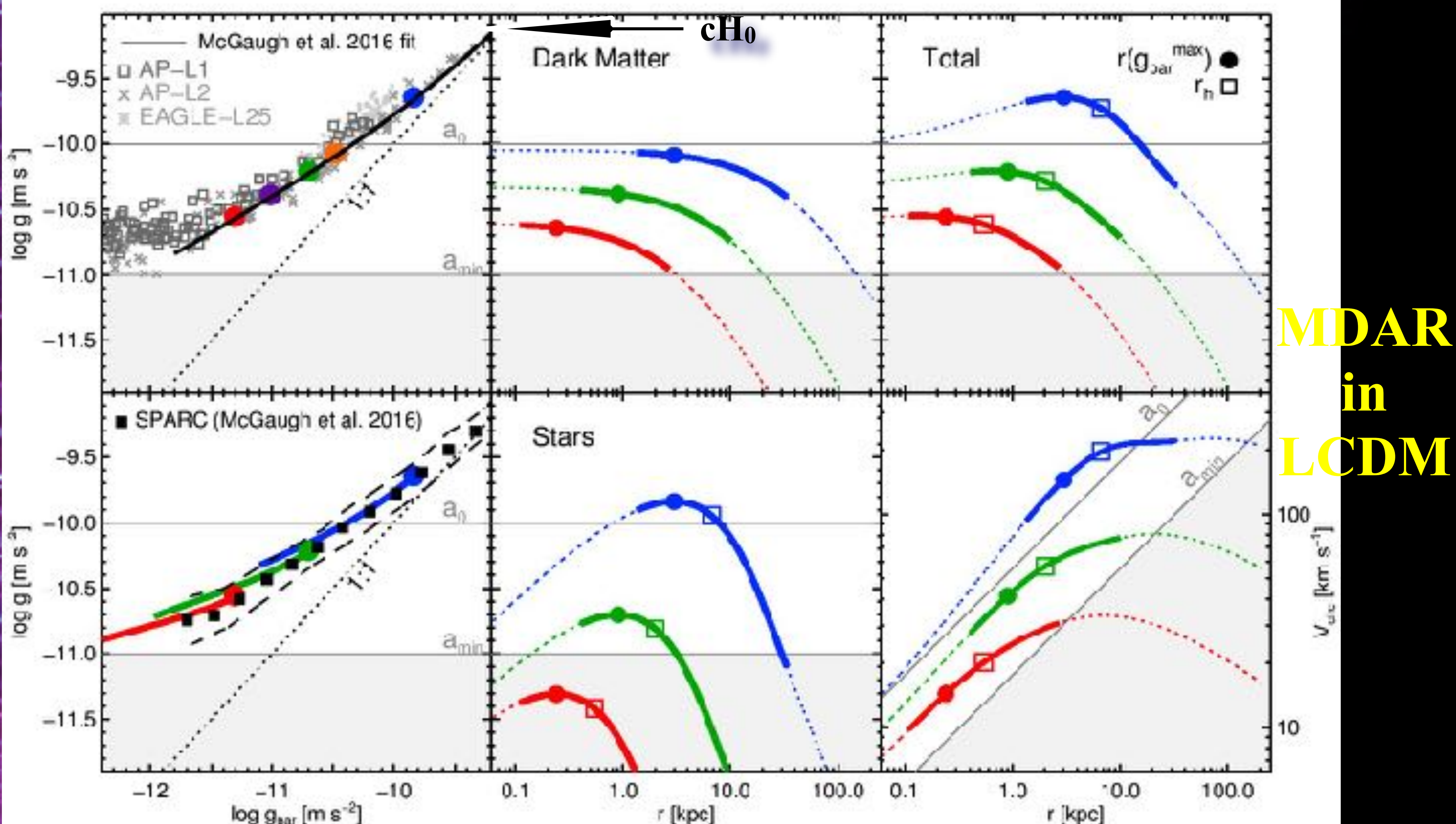
The mass discrepancy-acceleration relation in EAGLE/APOSTLE



Ludlow+16 in PRL

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

(a proxy for surface brightness)



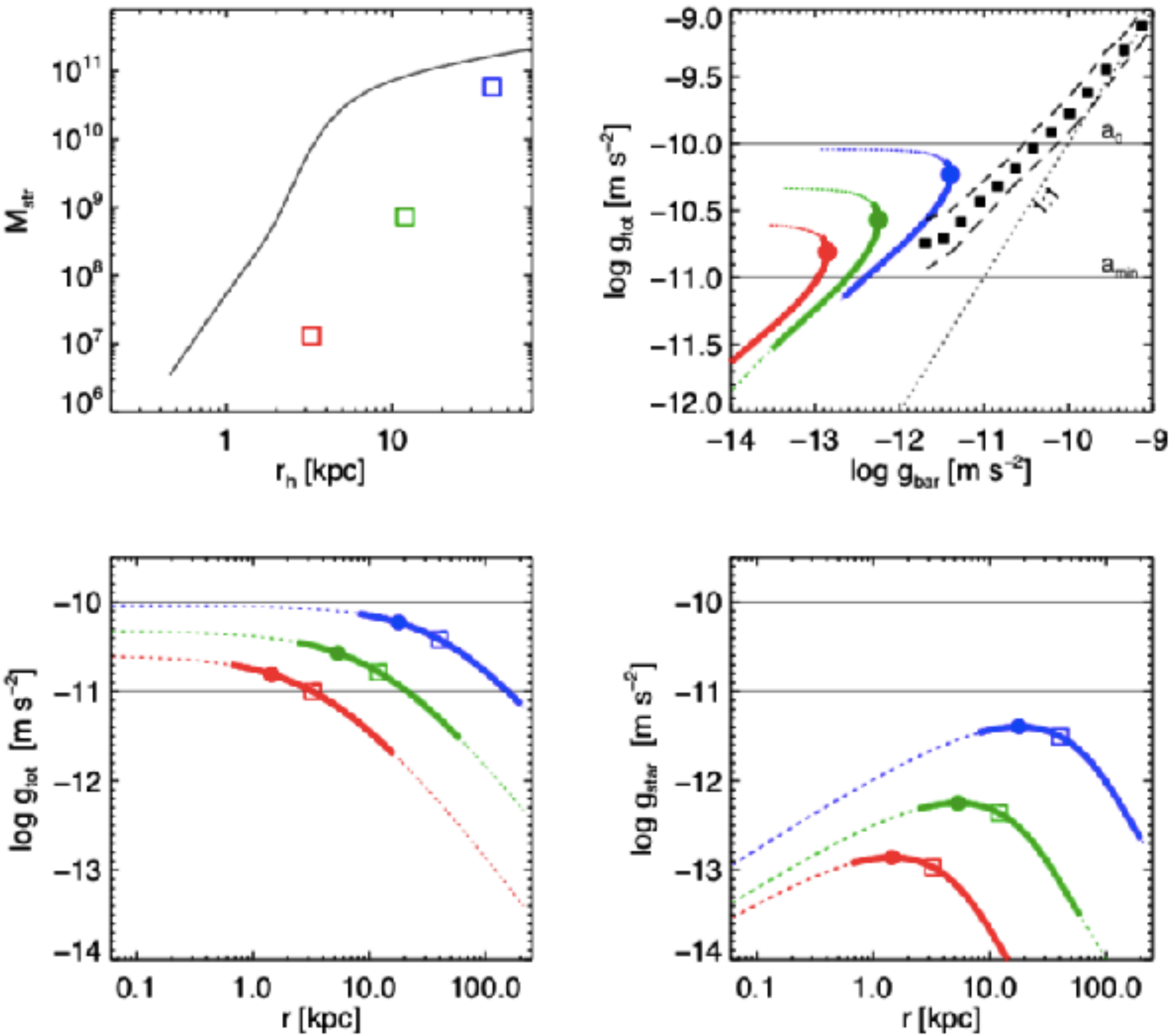
LCDM halos have a well-defined maximum central acceleration

$a_0 \sim 10^{-10}$ m/s^2 is the central acceleration of the most massive halo that may host a disk galaxy ($V_{max} \sim$ 200-300 km/s)

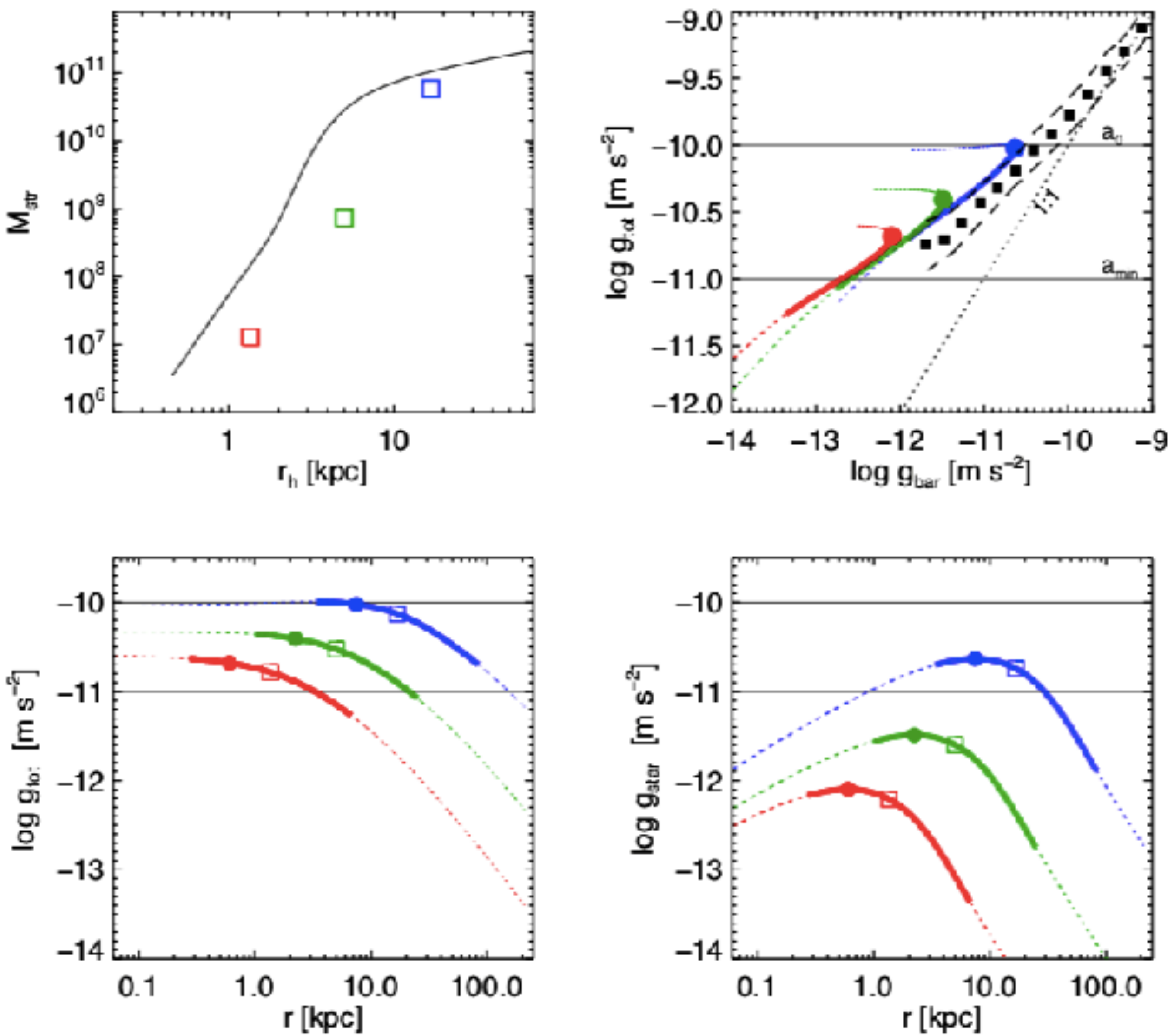
$a_{min} \sim 10^{-11}$ m/s^2: is roughly the acceleration of the least massive halo able to host a luminous galaxy ($V_{max} \sim$20-30 km/s)

Navarro+17

MDAR in LCDM

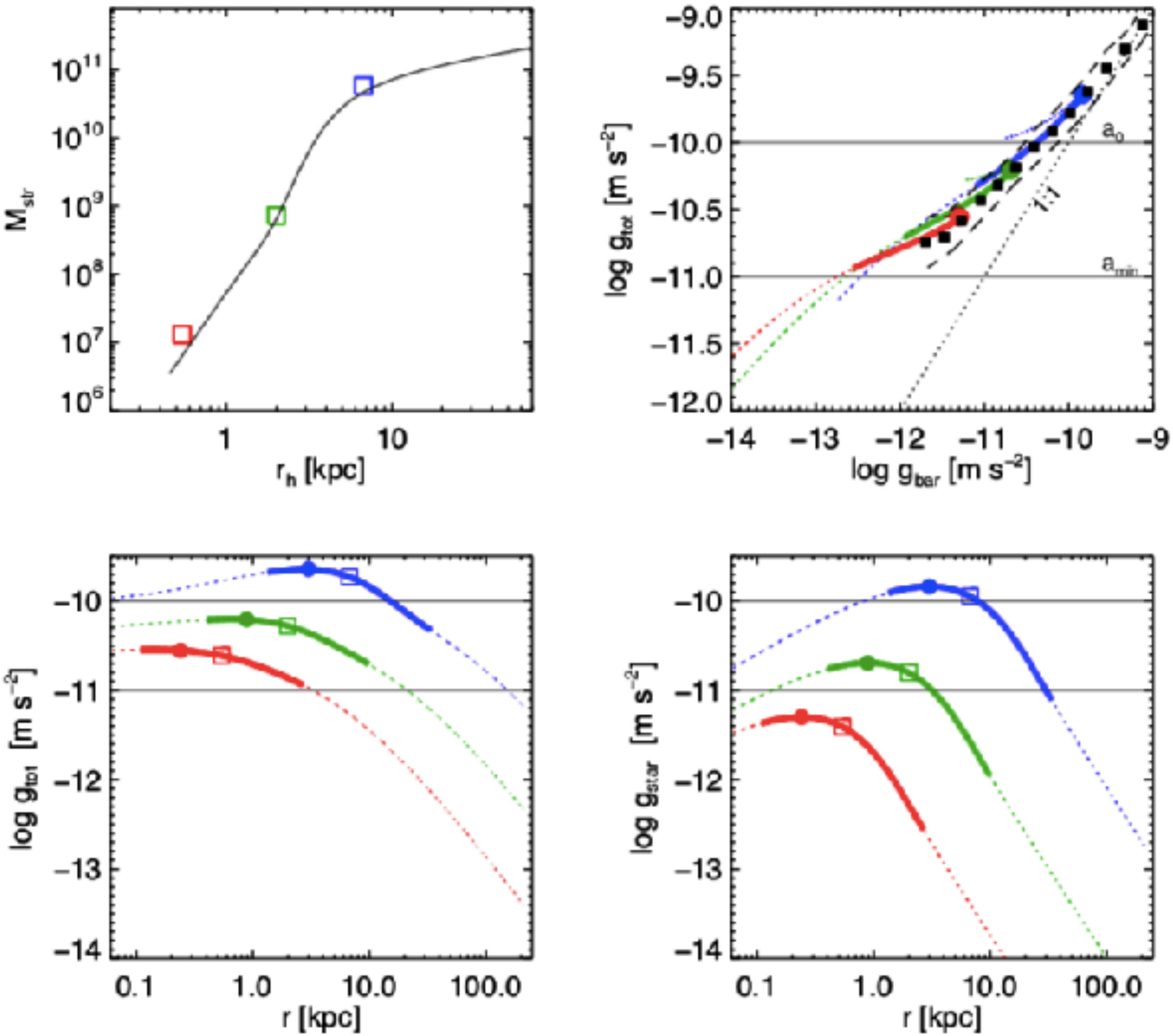


Navarro+17



MDAR in LCDM

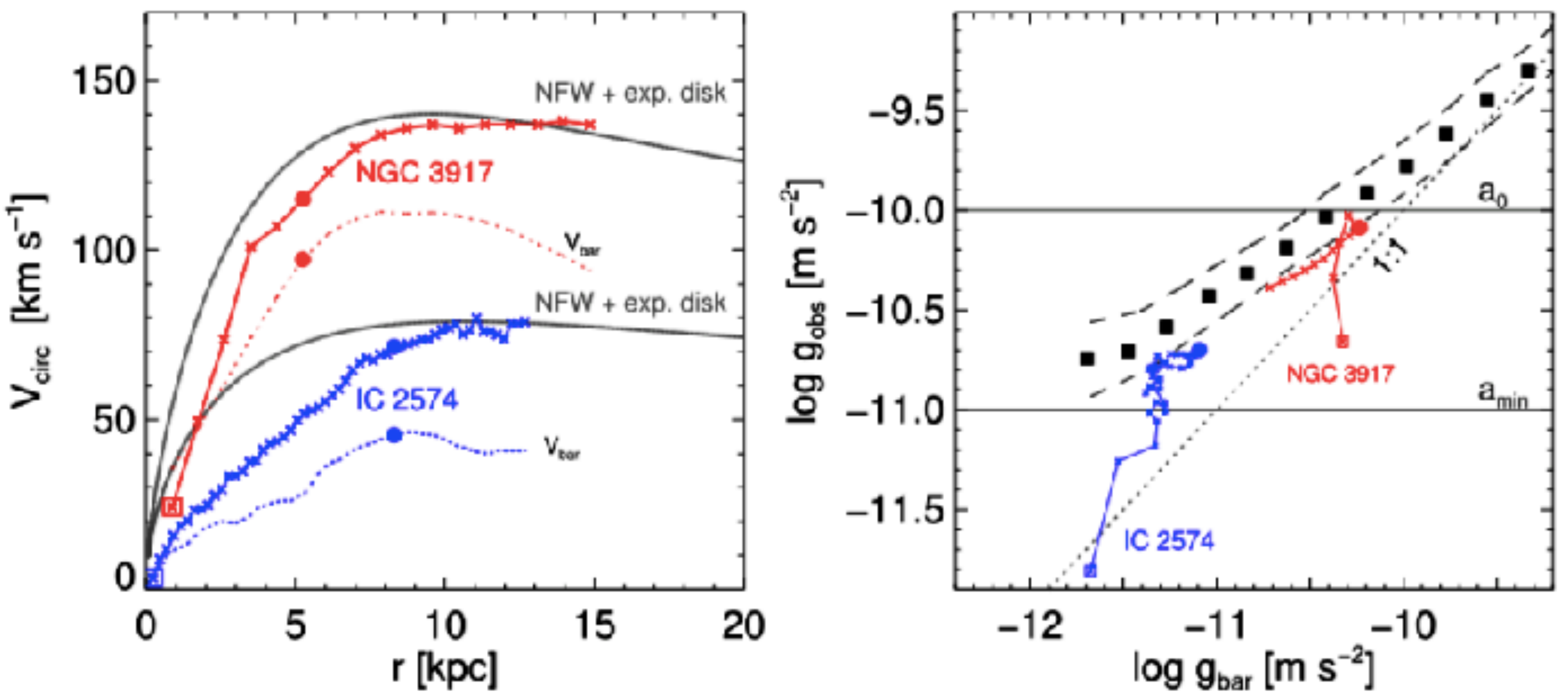
Navarro+17



MDAR in LCDM

Navarro+17

MDAR in LCDM



The small scatter in the relation is partly due to the mass modelling adopted in the SPARC papers, together with the LINEAR sampling of the rotation curves. Note also that various points in a same galaxy are NOT independent from each other so it is unclear what the rms actually means.

Navarro+17