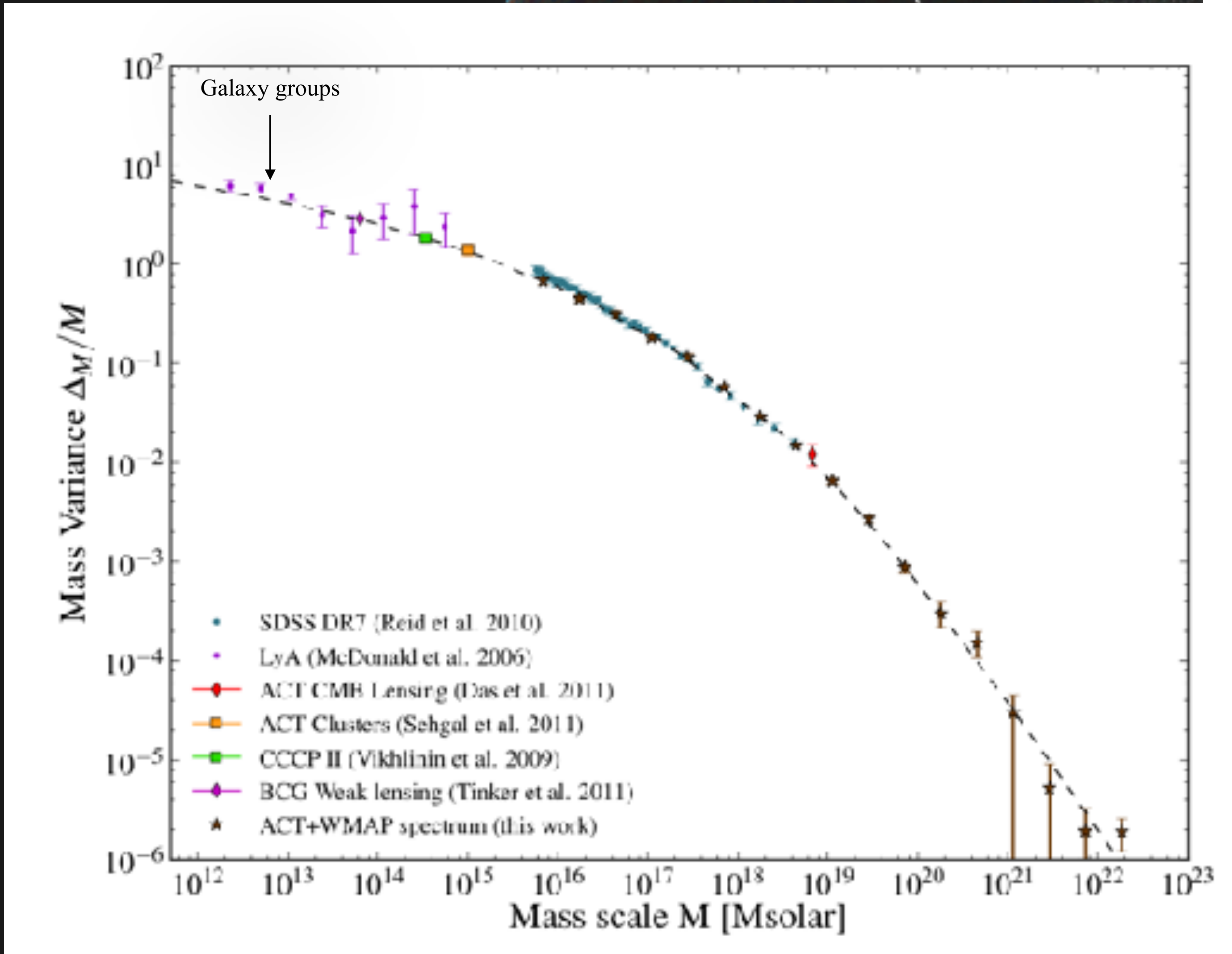
Galaxy Structure and Lambda Cold Dark Matter

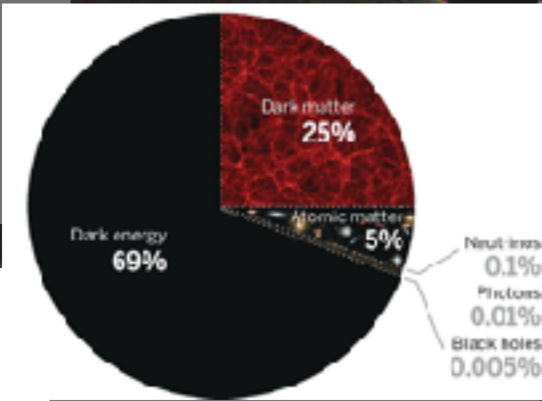
Julio F. Navarro

- Lecture 1: Basic Cosmological Facts
- Lecture 2: Non-Linear Structures in LCDM
- Lecture 3: Galaxy Structure and LCDM
- Lecture 4: Small Scale Constraints to LCDM

The LCDM paradigm: Structure in the Universe in the Linear Regime



Hlozek et al 2012

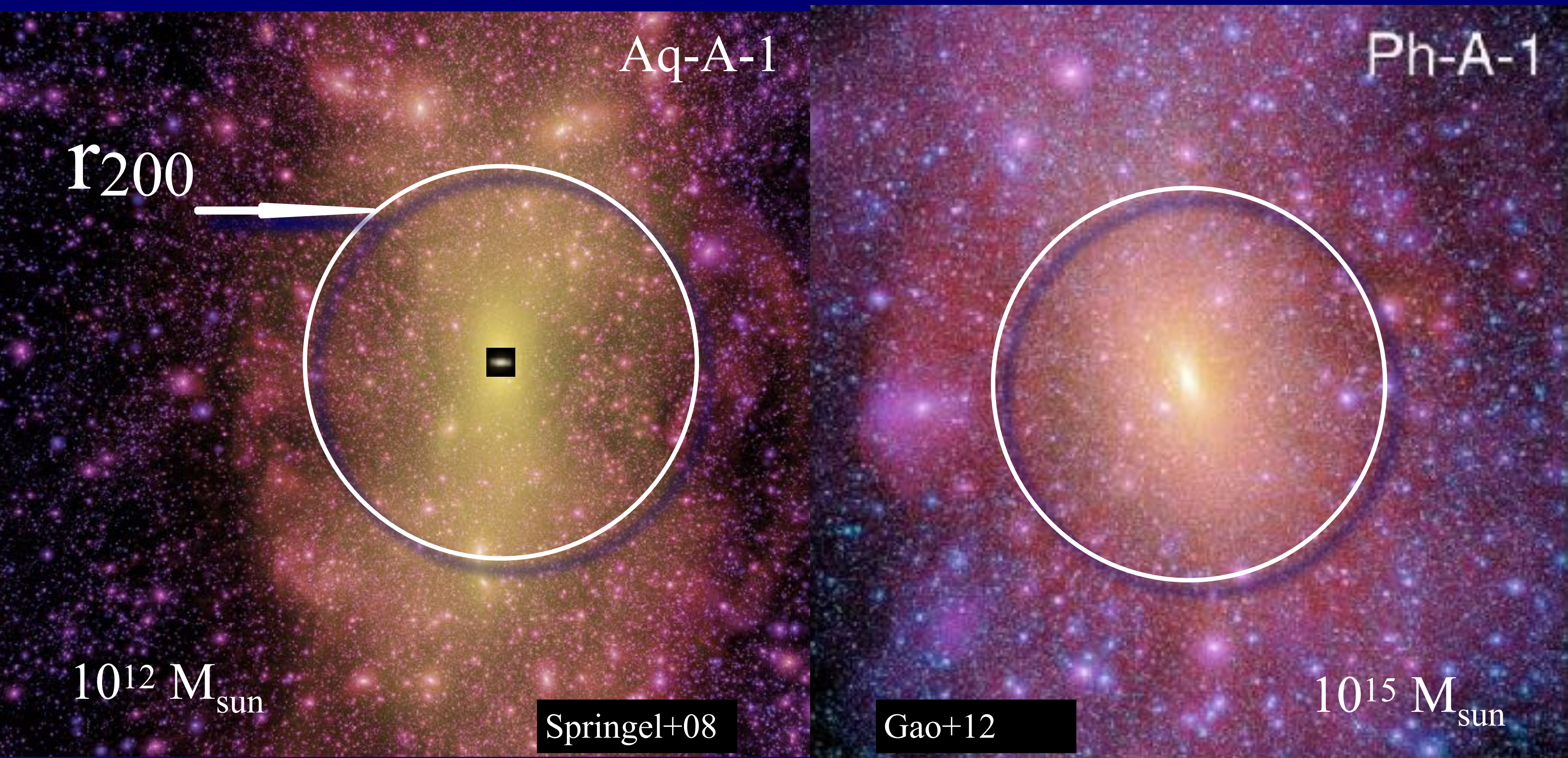


The power spectrum of density fluctuations in the linear regime is matched by
Cold Dark Matter (CDM)

The normalization of this spectrum specifies the collapse time of a given mass scale

The spectrum shape specifies the relation between potential well depth (velocity) and mass

The self-similar nature of LCDM halos

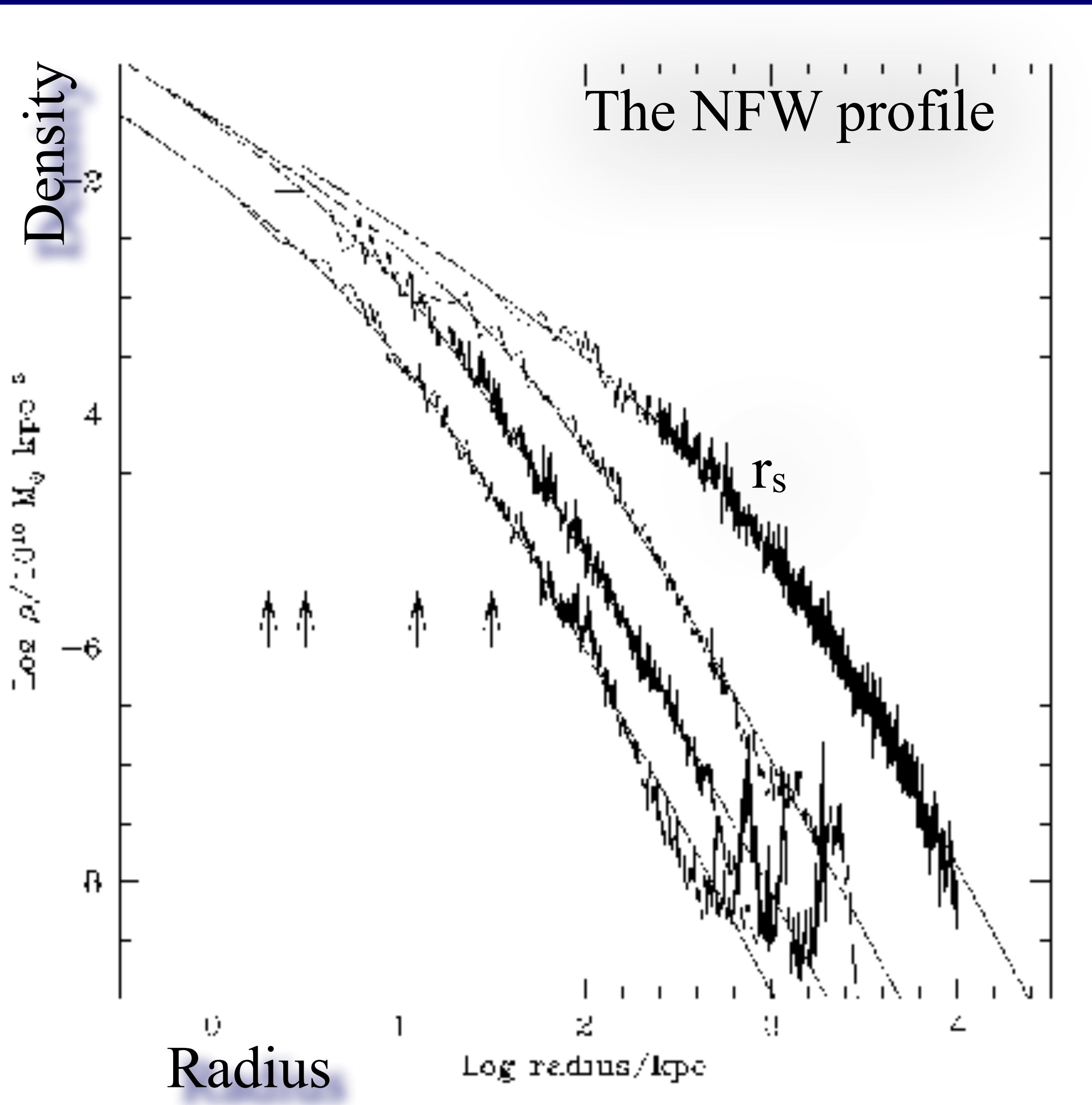


DM halos: self-similar structures linked by the age of the Universe

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**"

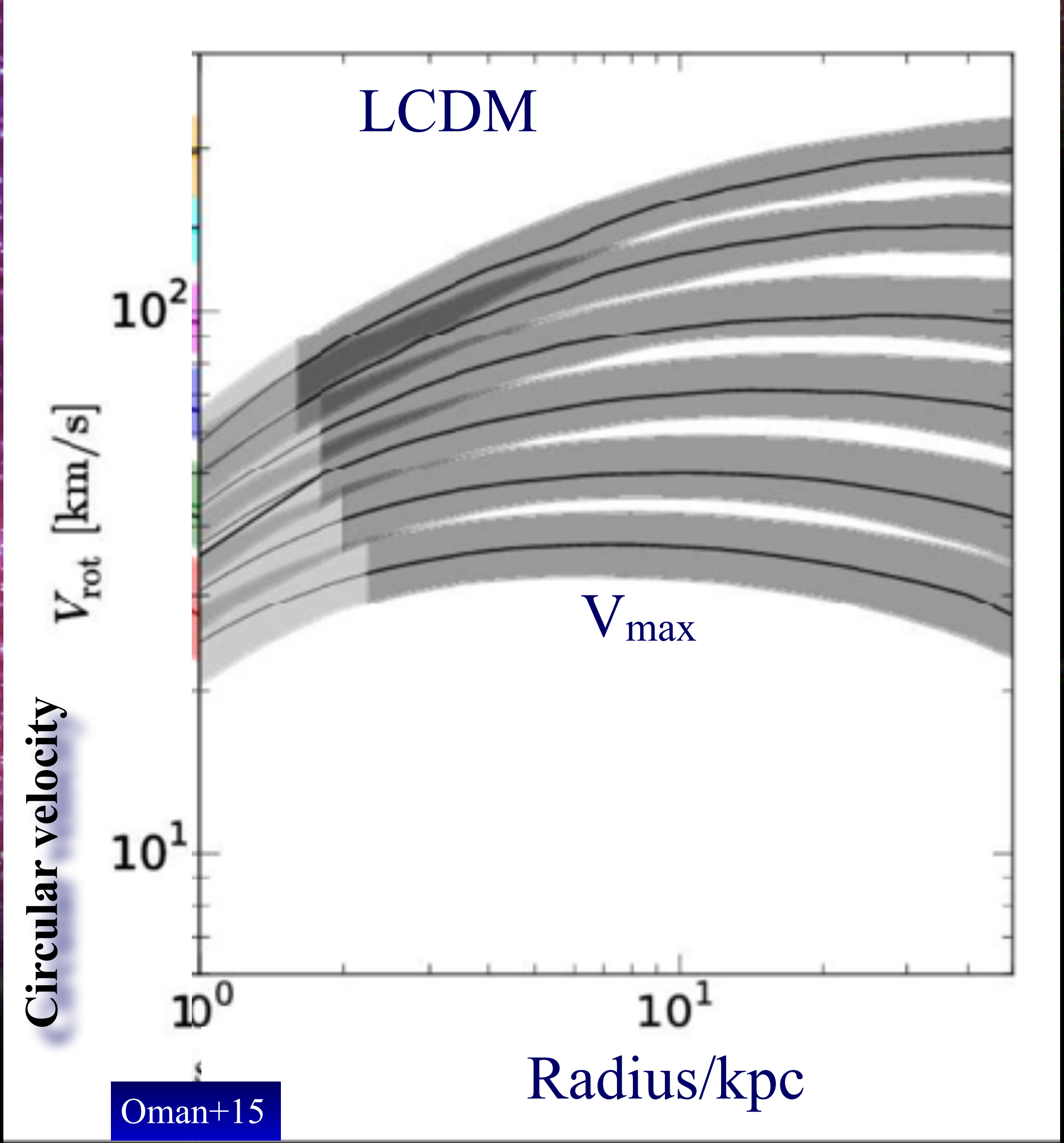
$$\rho/\rho_{crit}=\delta_c/[(r/r_s)(1+r/r_s)^2]$$

- 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" $c=r_{200}/r_s$

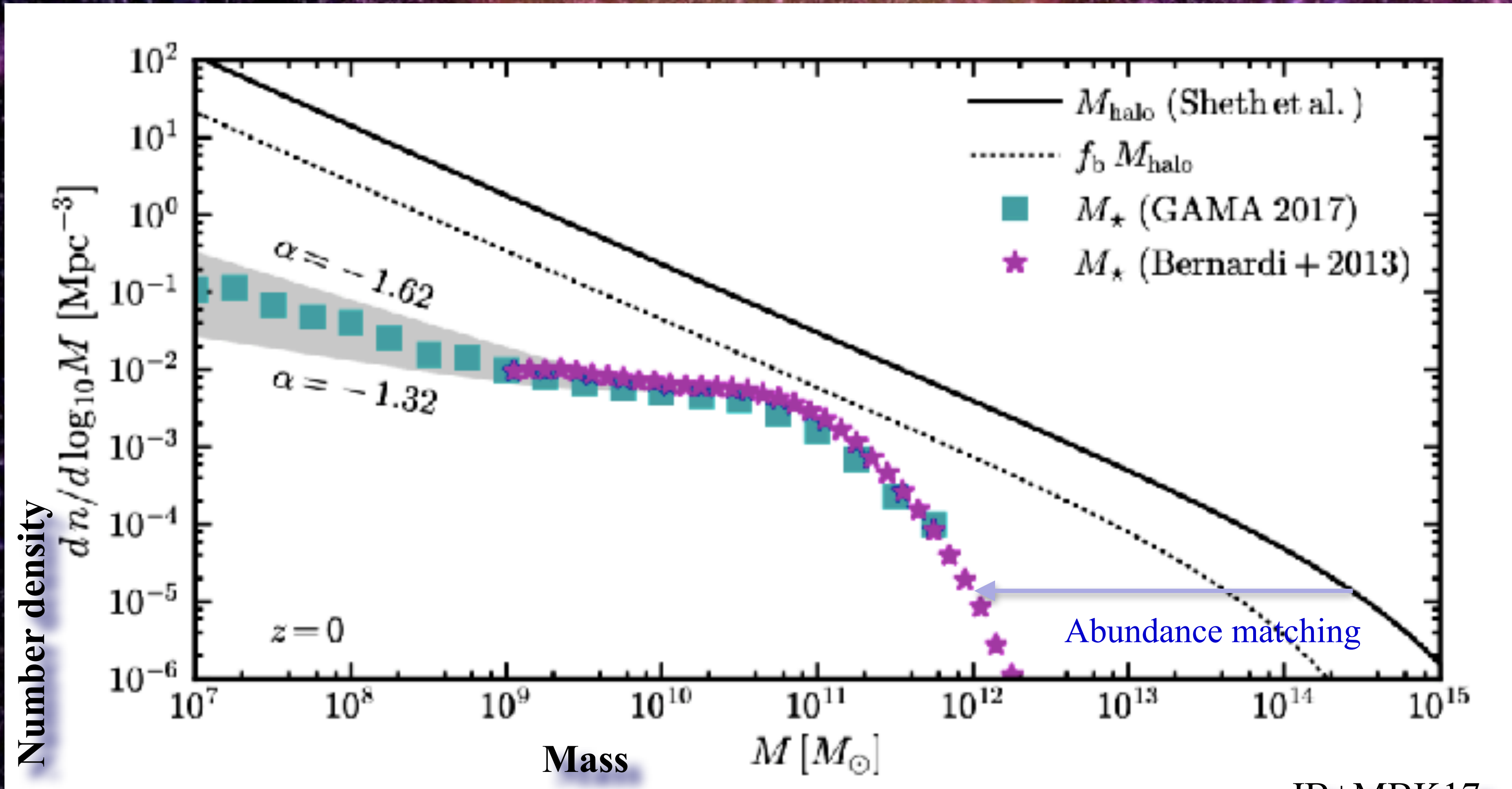
NFW+1996, 1997

LCDM predicted circular velocity profiles



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

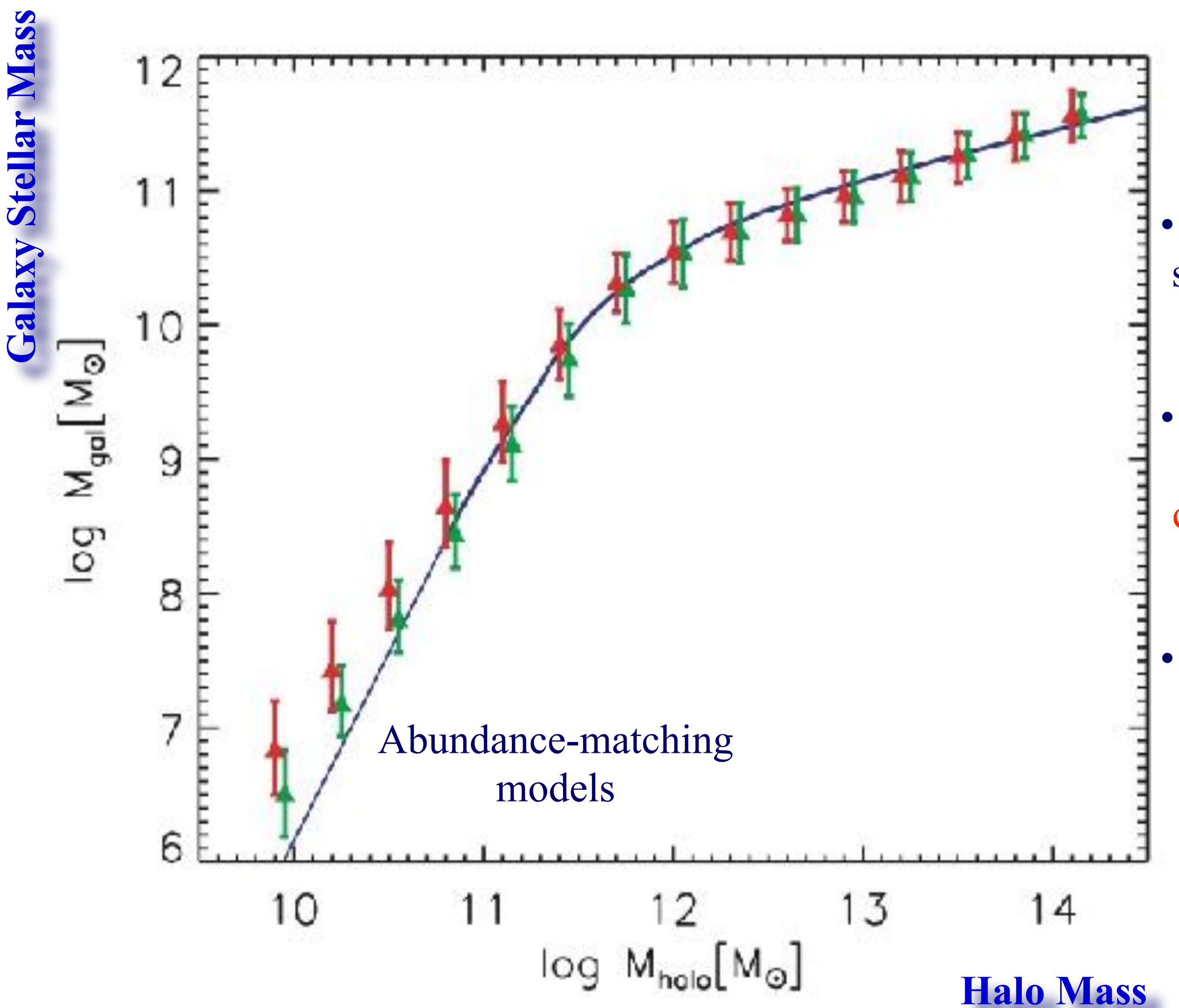
Galaxies and dark matter halos



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 similar mass. Galaxy formation efficiency declines in low mass halos

Abundance Matching: Galaxy Stellar Mass vs Halo Mass



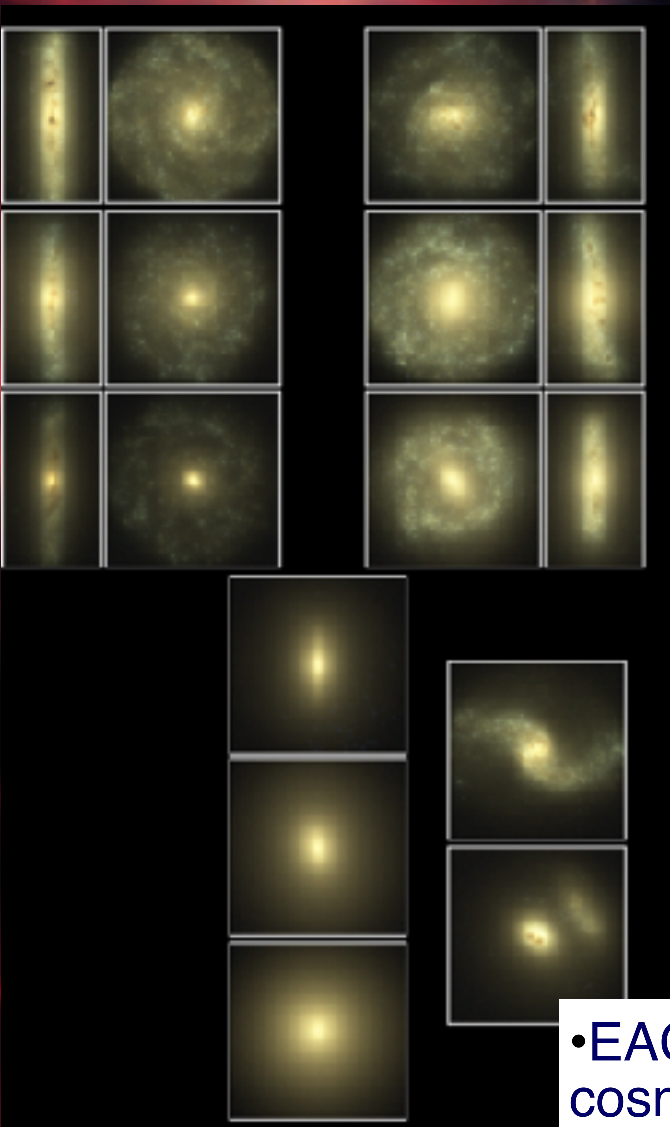
- Galaxy masses are **not** simply proportional to halo masses
- Also recall that halo masses and their characteristic velocities are strongly correlated.
- Note the approximate “threshold” halo mass for galaxy formation, just below 10^{10} M_{sun}

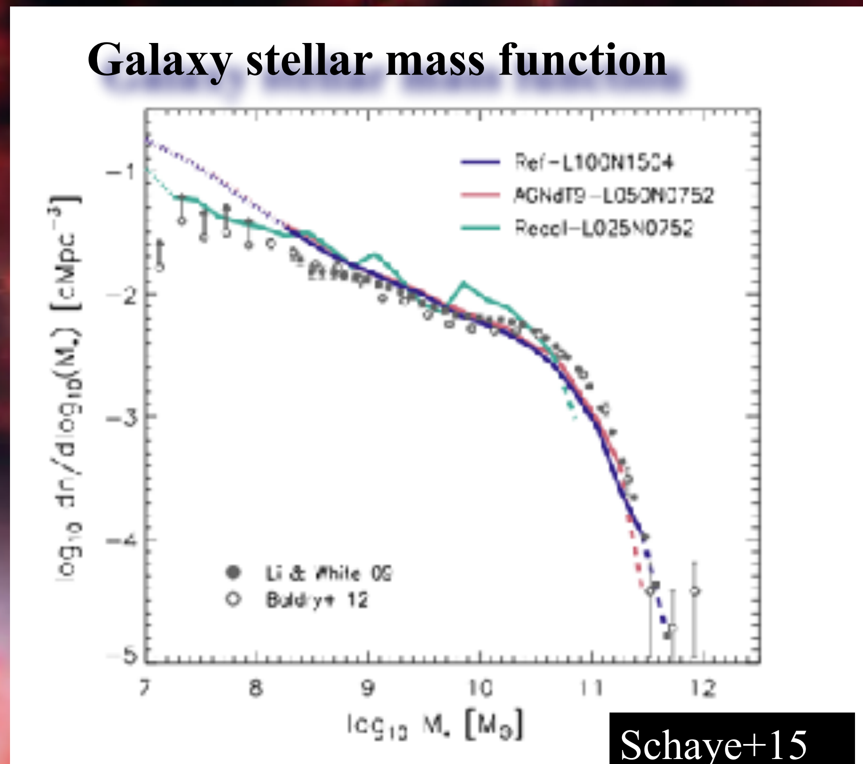
Guo+2011

The Eagle simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

A project of the Virgo Consortium





•EAGLE: Large hydrodynamical simulations of cosmologically representative volumes (~100 Mpc box)

The Eagle simulations

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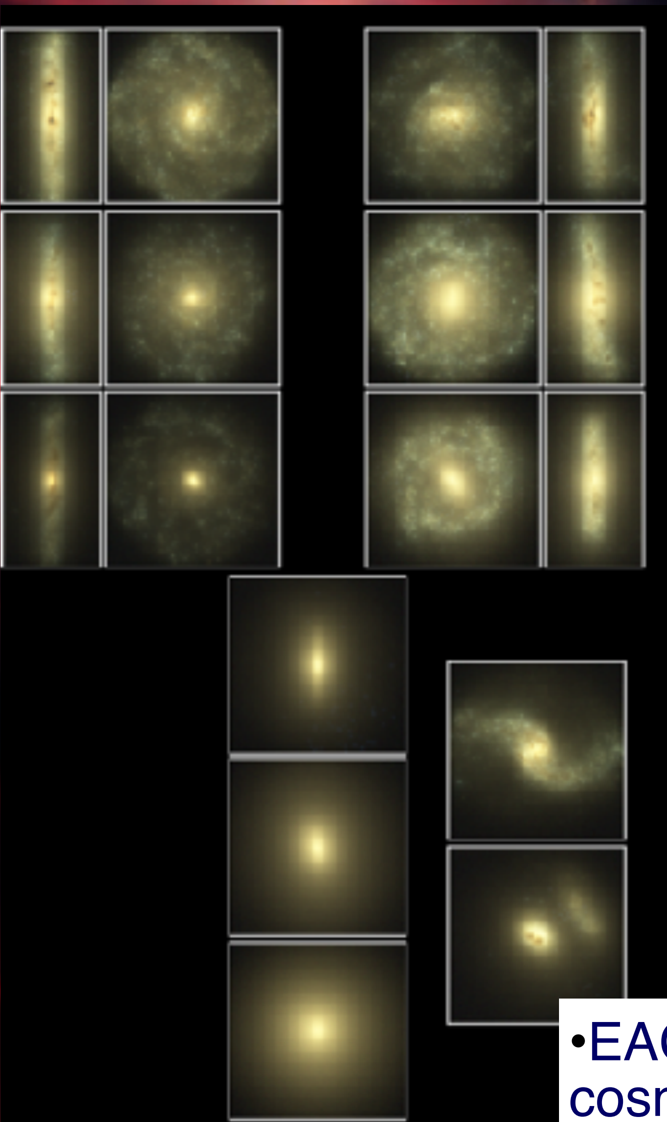
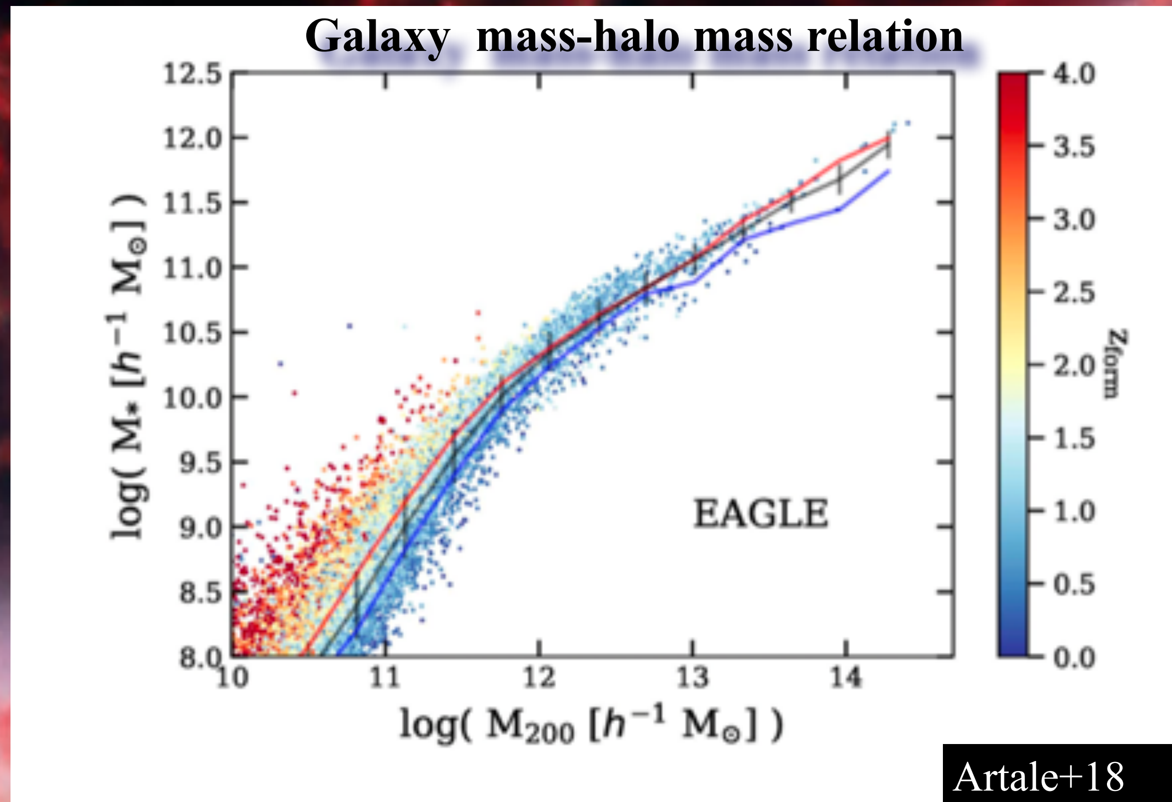




•EAGLE: Large hydrodynamical simulations of cosmologically representative volumes (~100 Mpc box)

Cosmological Puzzles and Galaxy Structure

I. The Tully-Fisher relation of spirals and the Fundamental Plane of ellipticals

II. The Mass Discrepancy-Acceleration Relation (MDAR)

LCDM and Dwarf Galaxy Rotation Curves

The "cusp-core problem" or "the rotation curve diversity problem" of disk galaxies

Cosmological Puzzles in the Local Group of Galaxies

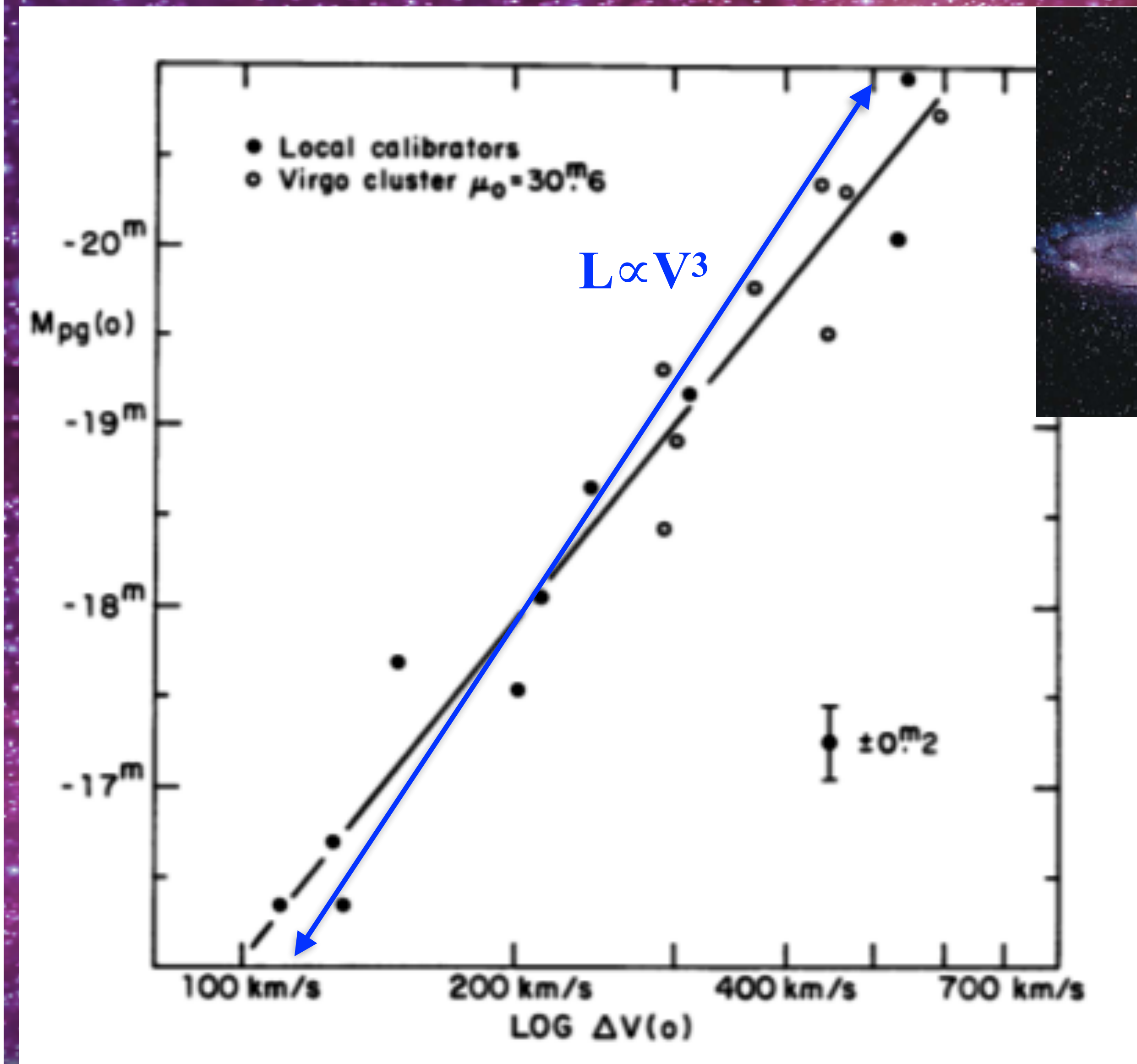
- ”Missing satellites” problem
- “Satellite alignment” problem
- “Too big to fail” problem

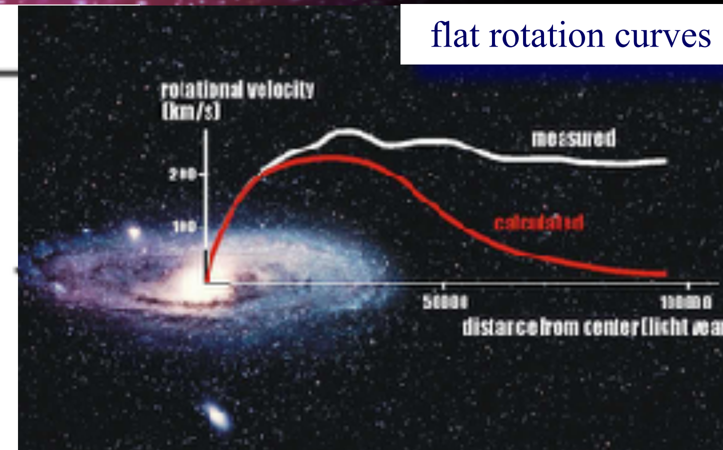
Galaxy Structure in LCDM

I.The Tully-Fisher relation of spirals and the Fundamental Plane of ellipticals

The Tully-Fisher relation of spirals

Absolute magnitude=Luminosity=Stellar mass





flat rotation curves

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

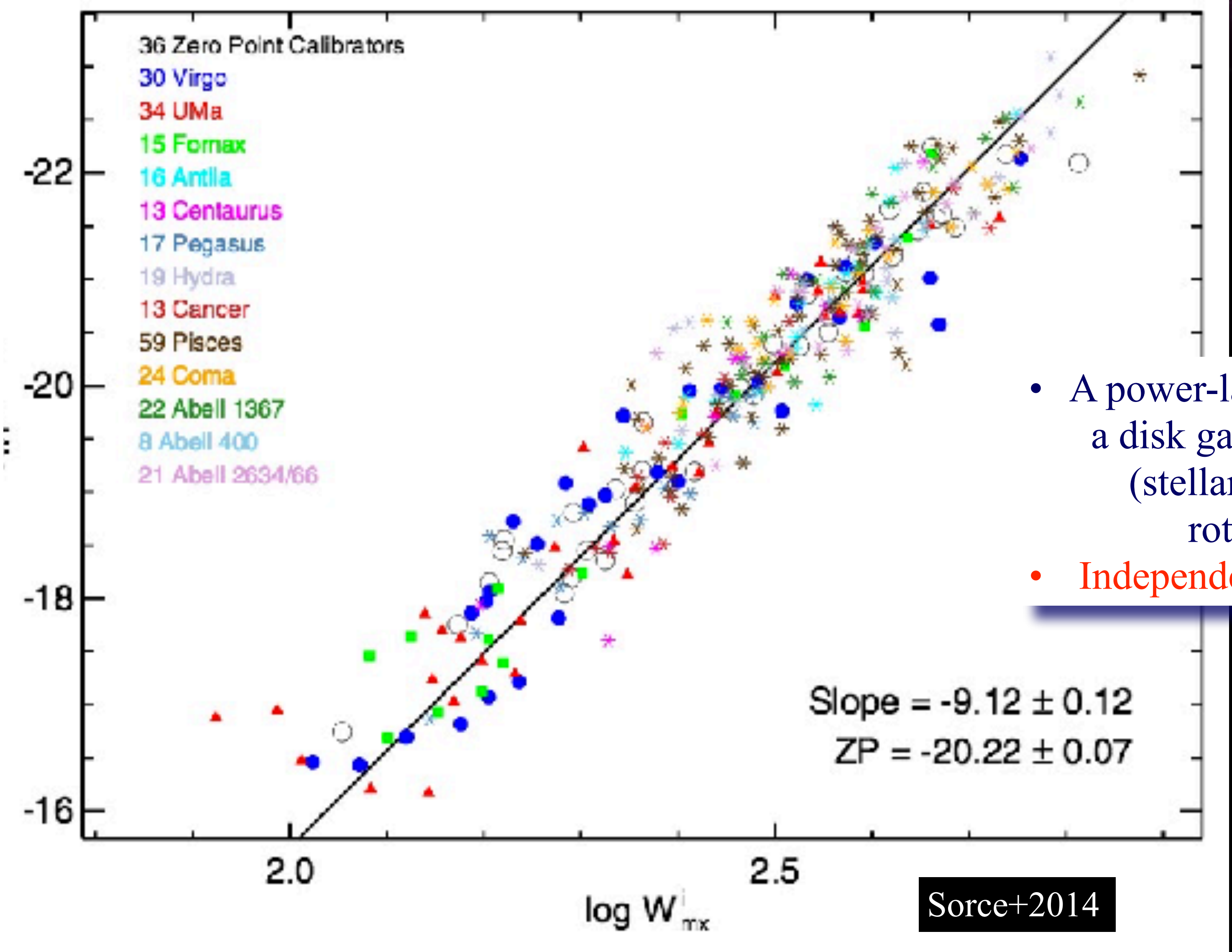
Recall that halos follow the relation: mass-circular velocity

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

Velocity width~2*V_{rot}

Tully & Fisher 1977

The Tully-Fisher relation of spirals

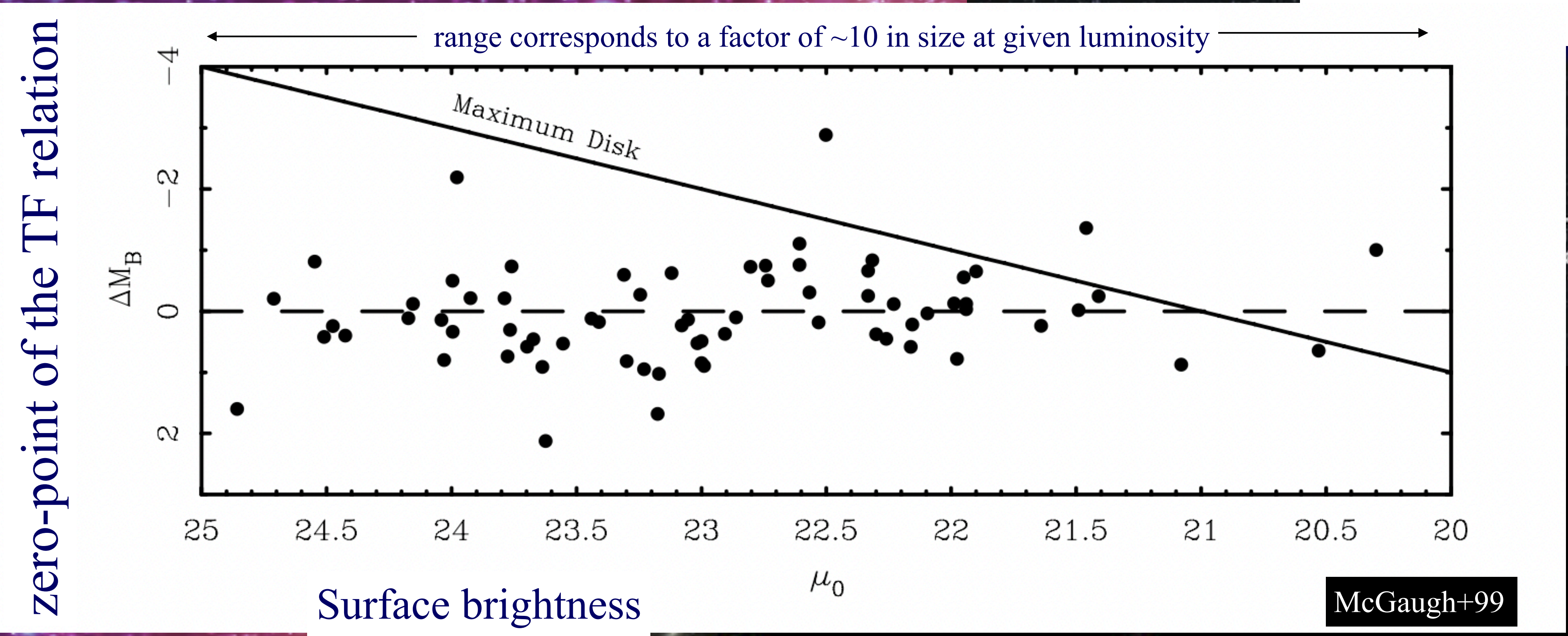


Absolute magnitude=Luminosity=Stellar mass

Velocity width~2*V_{rot}

- A power-law scaling relating a disk galaxy's luminosity (stellar mass) with its rotation speed
- Independent of galaxy size!

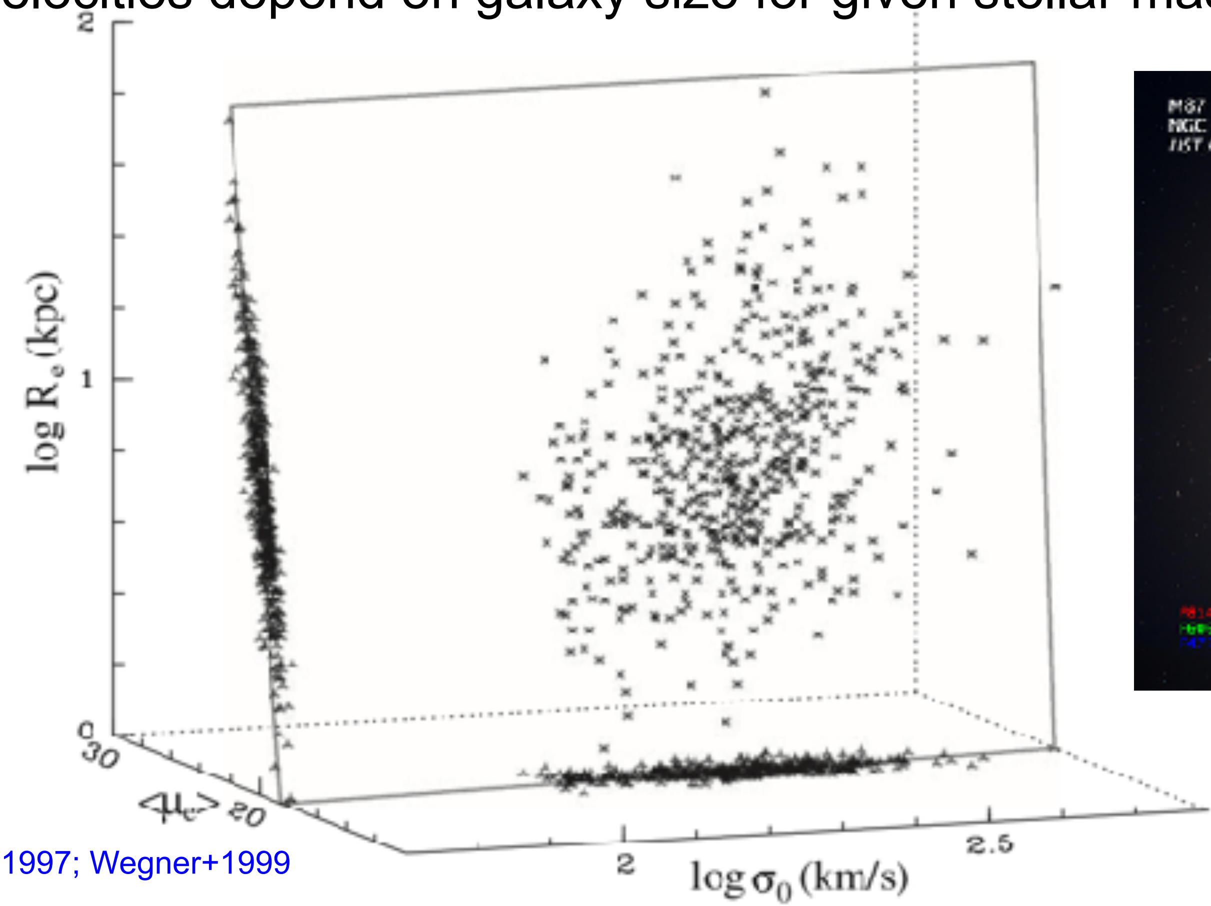
The Tully-Fisher relation of spirals

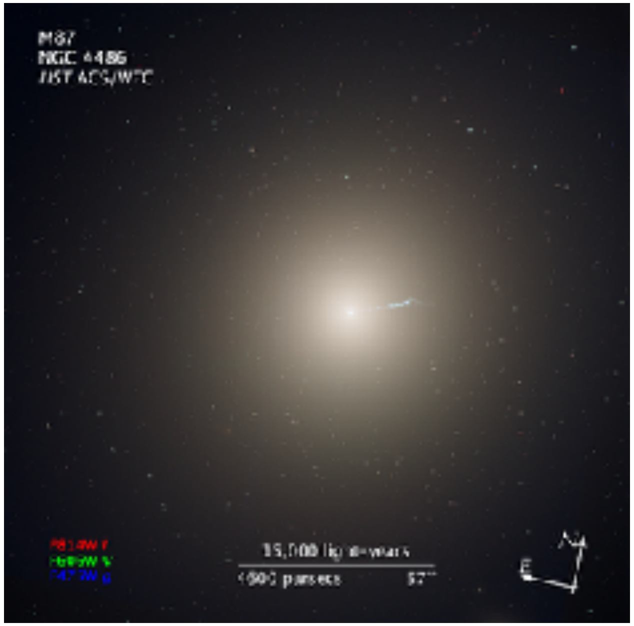


- Zero-point of the TF relation independent of galaxy size (surface brightness).
- But $M_{tot} \sim V_{rot}^2 * r$!
- Implies at fixed galaxy stellar mass, the total enclosed mass increases with size

The “Fundamental Plane” of Ellipticals

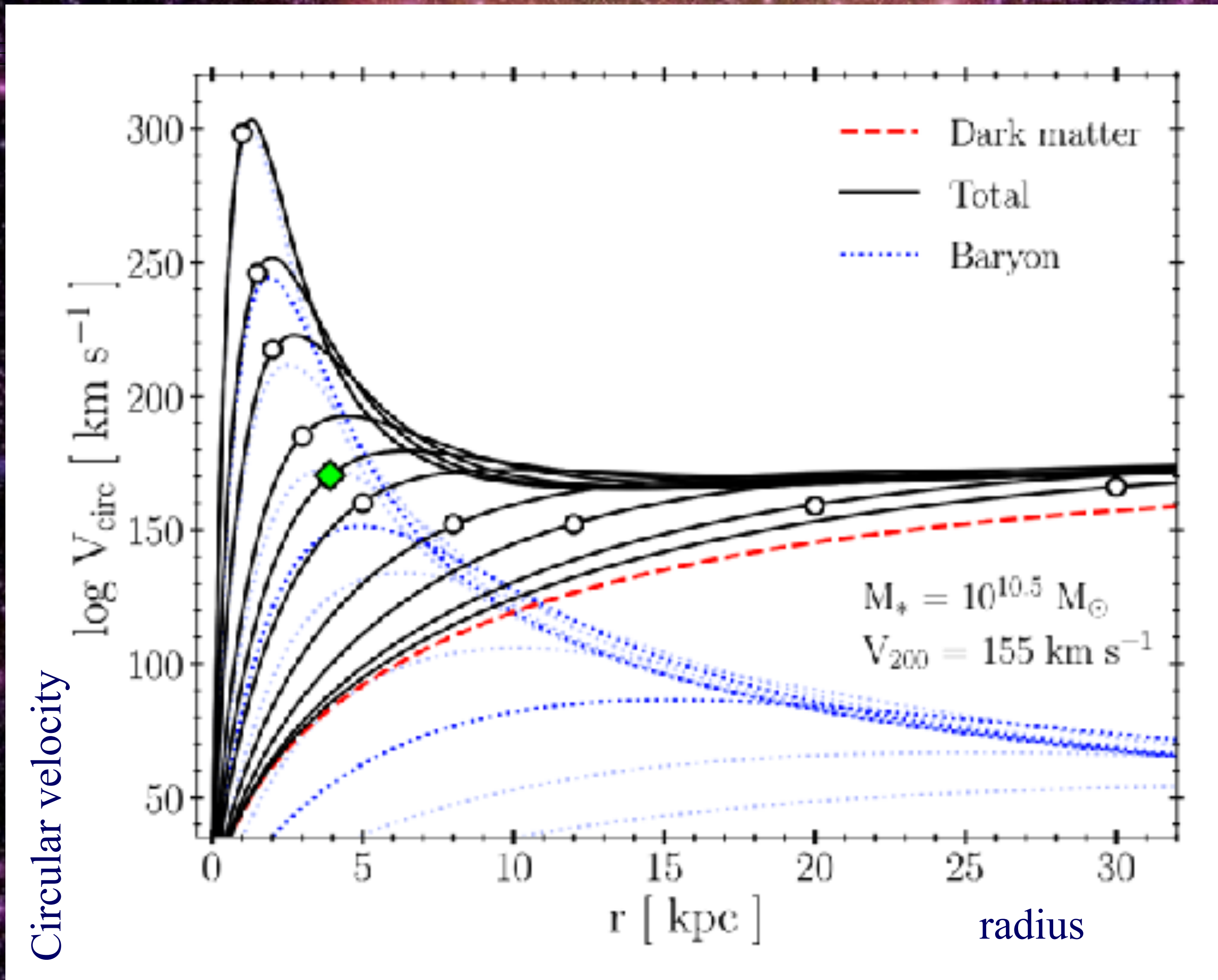
- Luminosity (stellar mass), size, and <u>velocity dispersion</u> of E gx are correlated and lie close to a plane.
    - $A*\log R_e + B*\log \langle I \rangle_e + C*\log \sigma_0 = \text{constant}$, where $\langle I \rangle_e = L/\pi R_e^2$
- Similar, *but not identical*, to what is expected from the virial theorem $M \sim \sigma^2 R$
- Velocities depend on galaxy size for given stellar mass!





Saglia+1997; Wegner+1999

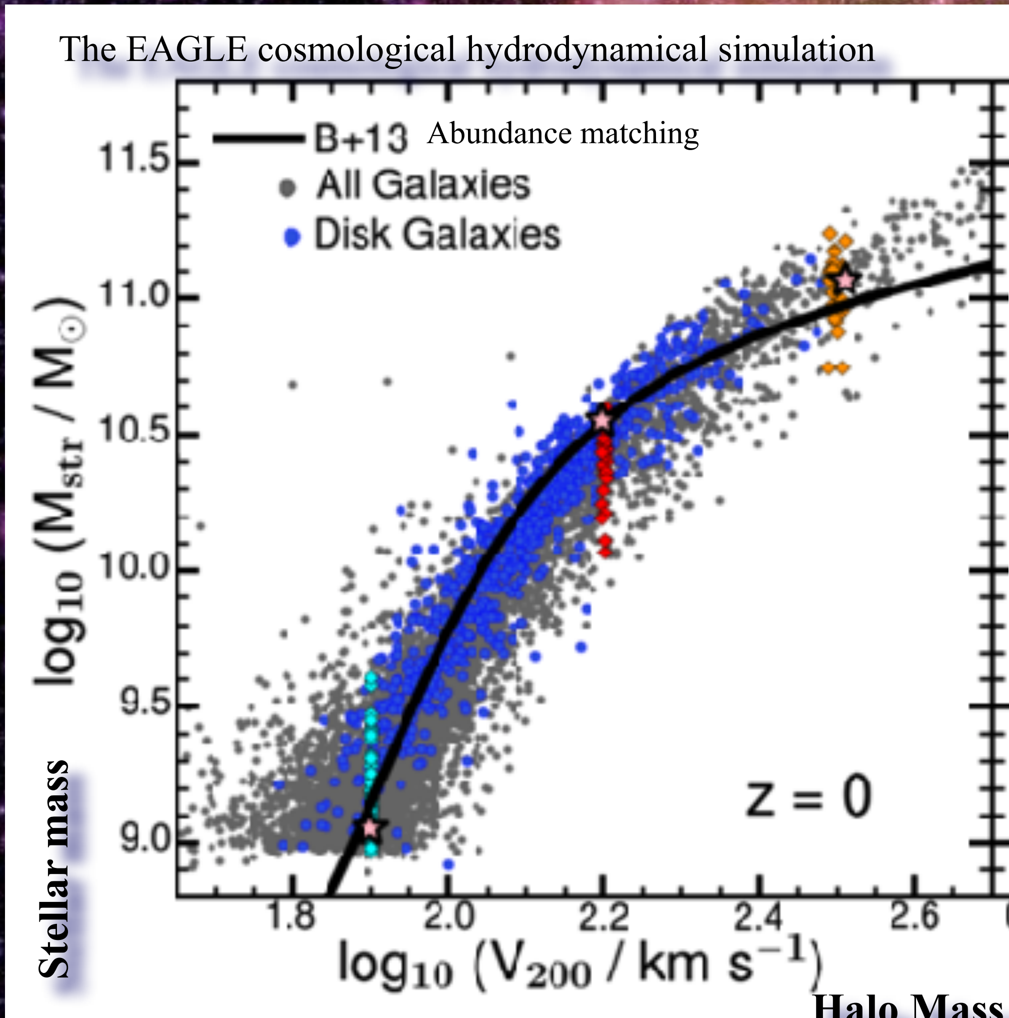
Disk rotation curves in LCDM

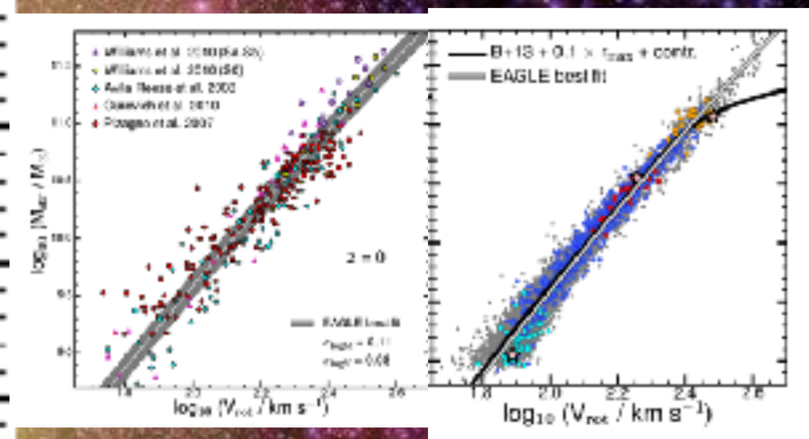


- Flat rotation curves result from the combined contribution of baryons and dark matter
- This provides strong support for the NFW-like structure of CDM halos
- Rotation velocity is roughly independent of radius for galaxies that are "large enough"
- Velocity does depend on galaxy size if galaxy is "small enough"—> "Fundamental Plane"

Ferrero+2020

The TFR in EAGLE



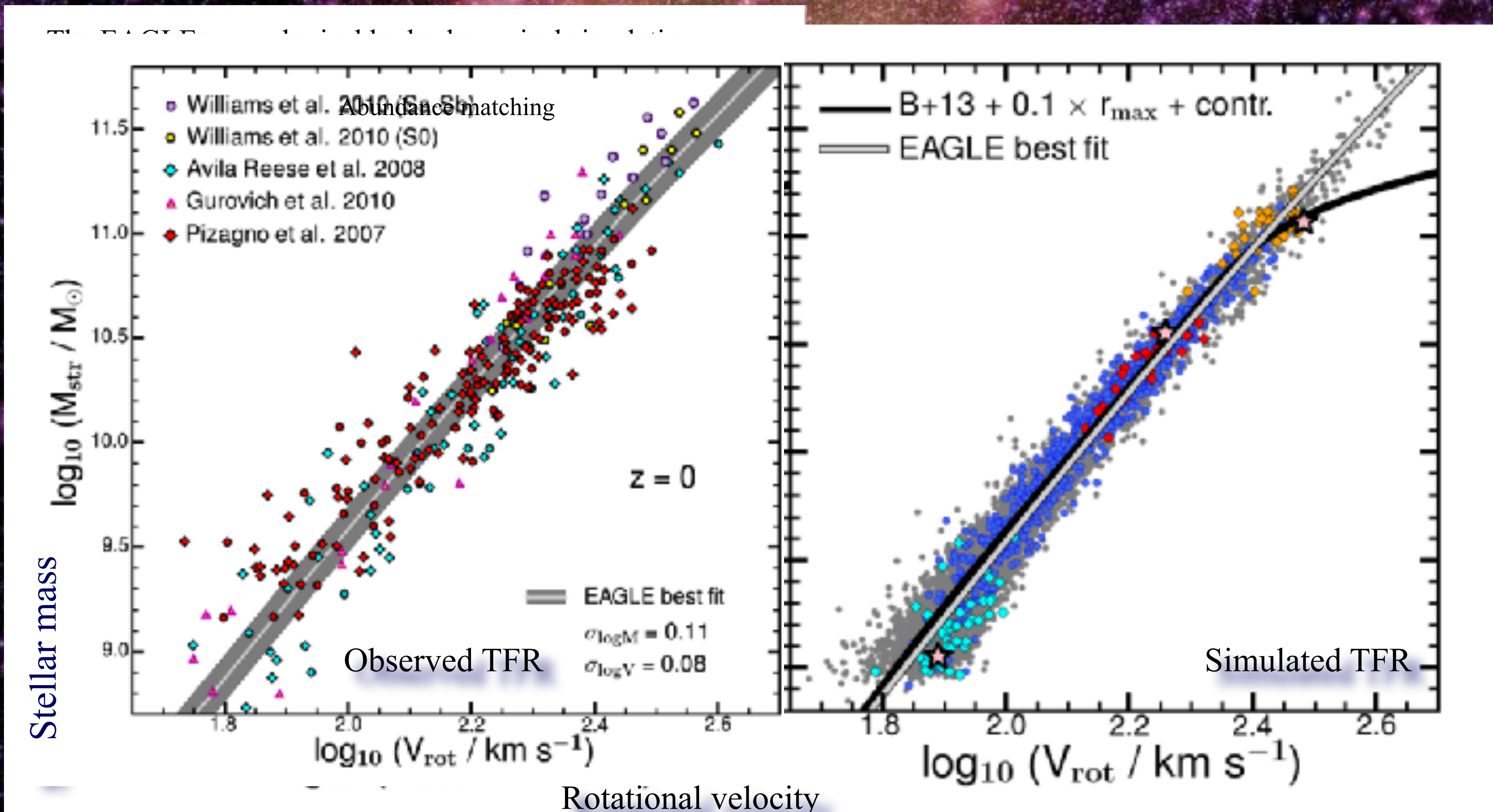


Ferrero+2016

JB+MBK17

- The same "abundance-matching" relation accounts well for galaxy scaling laws such as the "Tully-Fisher relation" linking stellar mass and rotation speed of galaxy discs
- This provides strong support for the NFW-like structure of CDM halos
- Same galaxy mass-halo mass relation applies to both ellipticals and spirals

The TFR in EAGLE



- The same "abundance-matching" relation accounts well for galaxy scaling laws such as the "Tully-Fisher relation" linking stellar mass and rotation speed of galaxy discs
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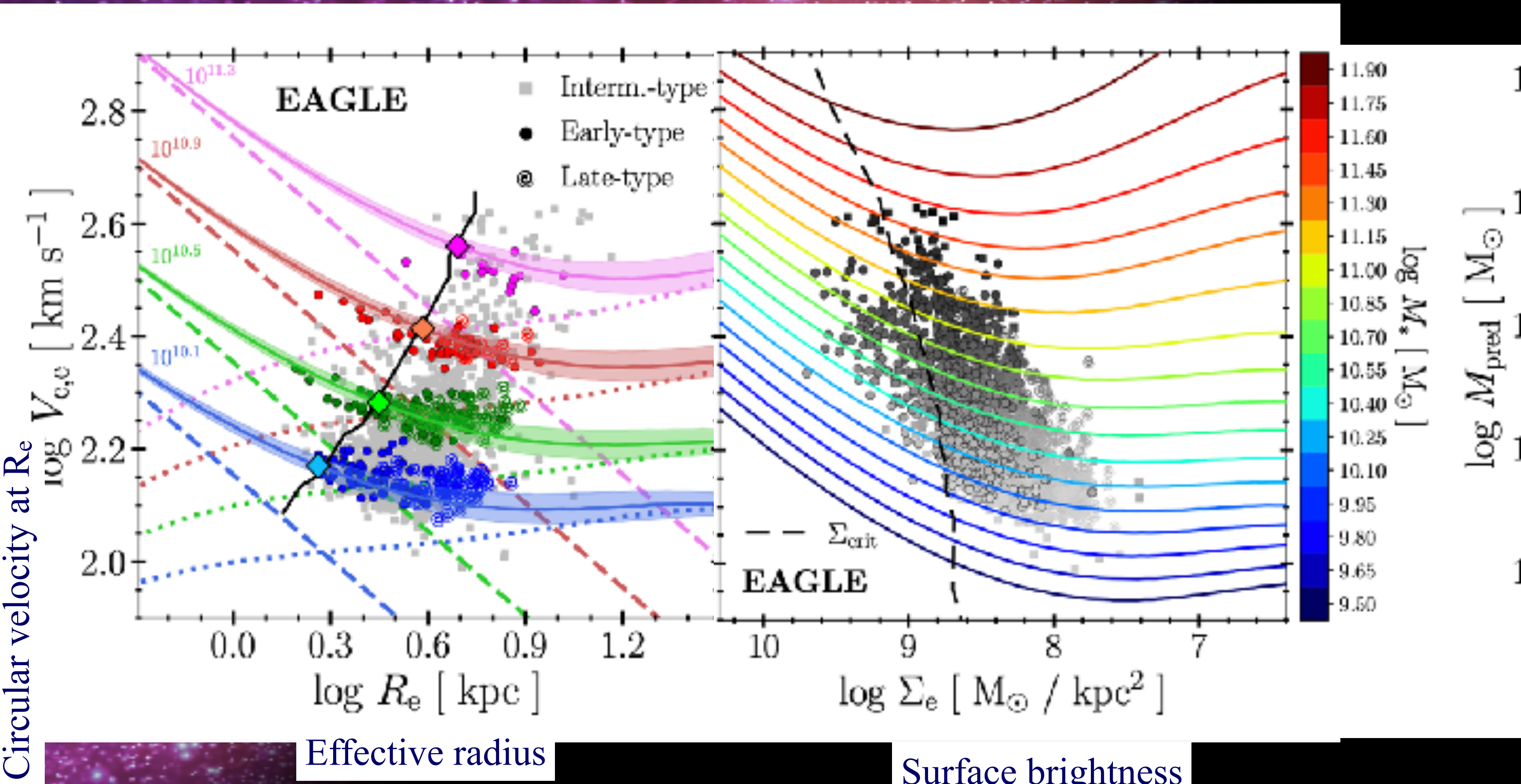
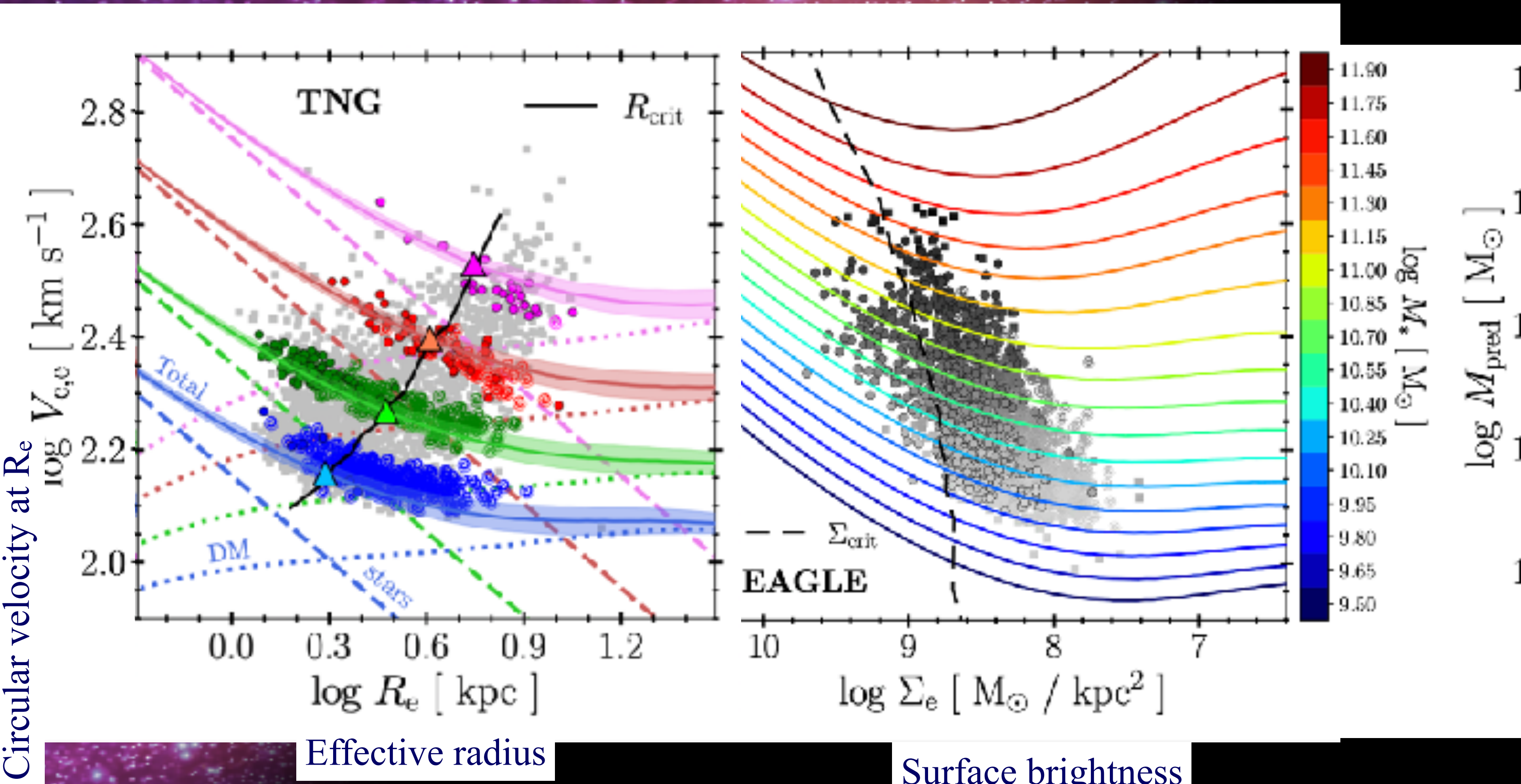
Circular velocity-radius-surface brightness relation



- Ellipticals and spirals live in halos of similar mass and therefore their characteristic velocity depends on radius and stellar mass
- This is sensitive only to the galaxy mass-halo mass relation

Ferrero+2020

Circular velocity-radius-surface brightness relation



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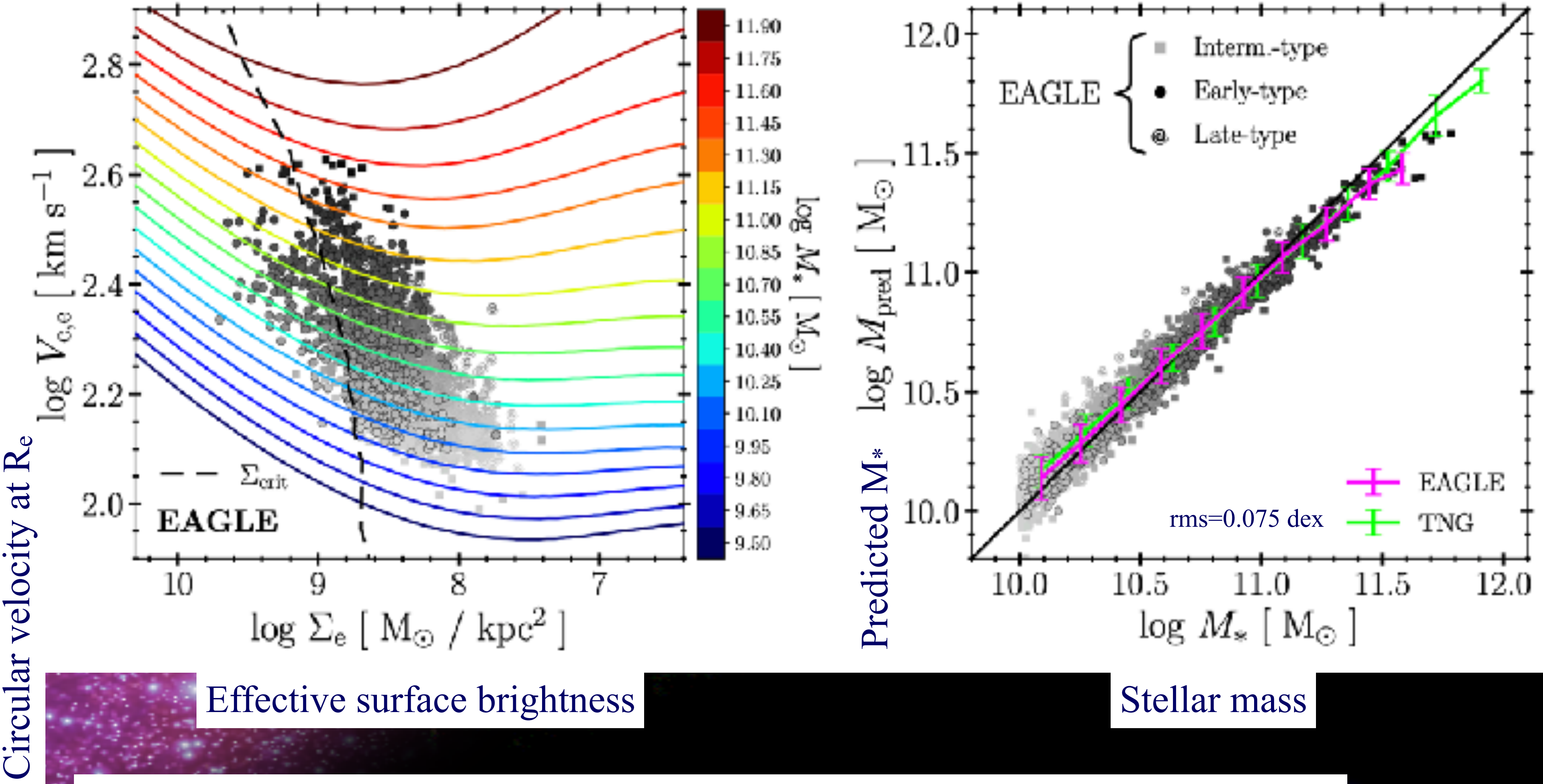
Ferrero+2020

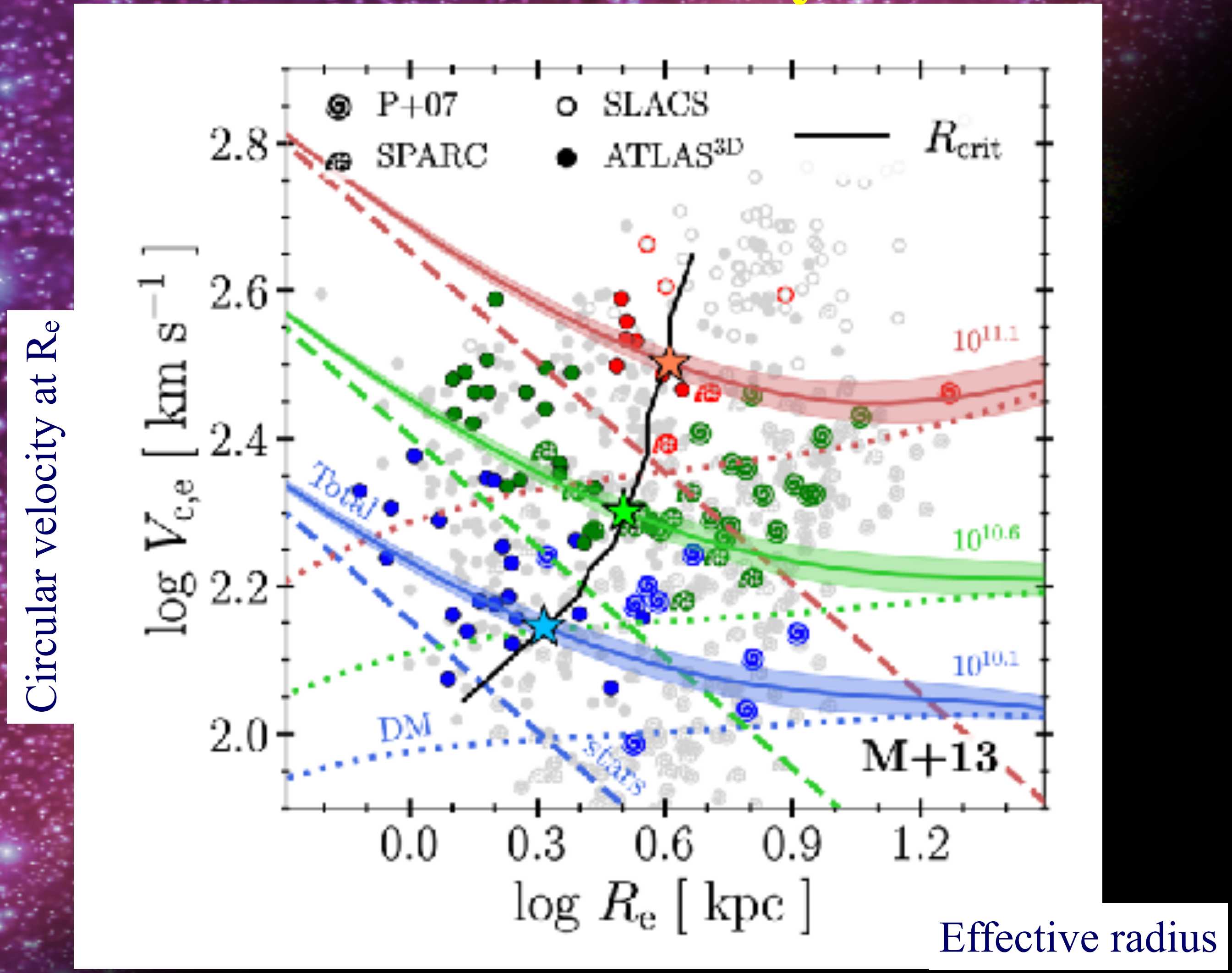
A new distance indicator?



- Surface brightness and circular velocity may be used to predict stellar masses with no other information
- This may be used as a secondary distance indicator that effectively combines the Tully-Fisher relation and the Fundamental Plane

Ferrero+2020

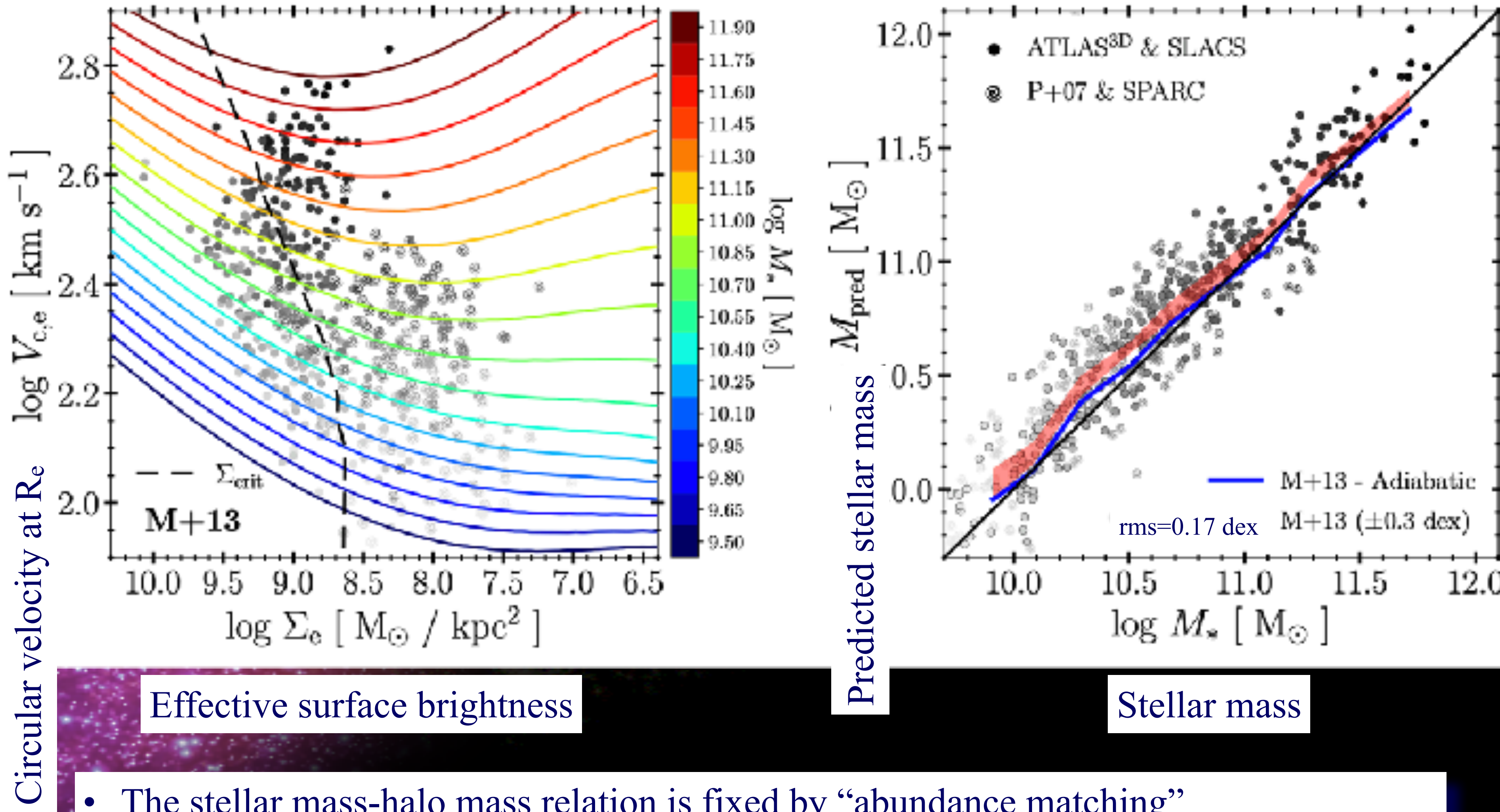
Observed circular velocity-radius relation



- The same results apply to <u>observed</u> samples of galaxies of all morphological types

Ferrero+2020

The Tully-Fisher relation in EAGLE



- The stellar mass-halo mass relation is fixed by "abundance matching"
- Surface brightness and circular velocity may be used to predict stellar masses
- This may be used as a secondary distance indicator that effectively combines the Tully-Fisher relation and the Fundamental Plane and has competitive scatter

Ferrero+2020

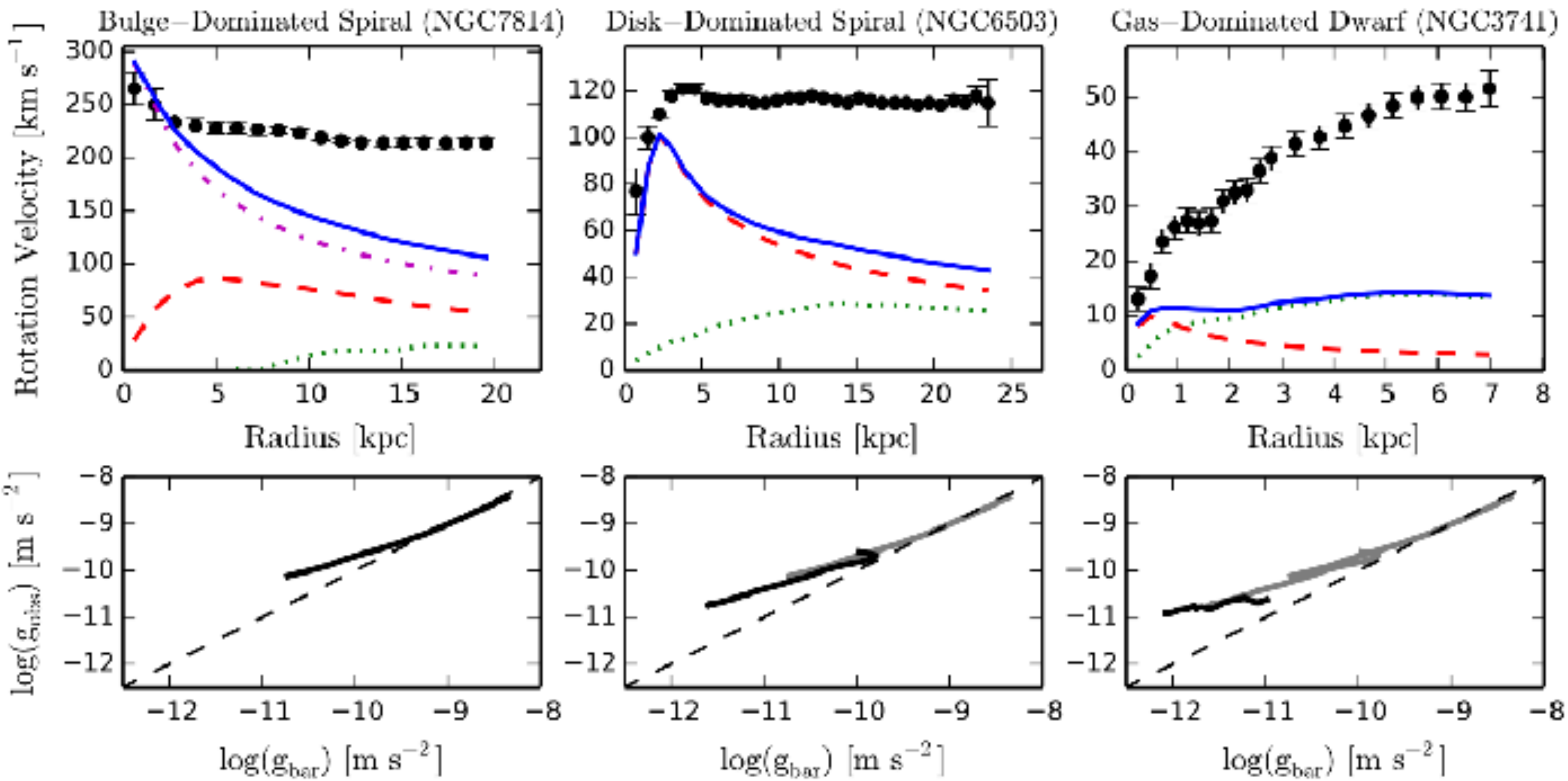
Galaxy Scaling Laws in LCDM

II.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

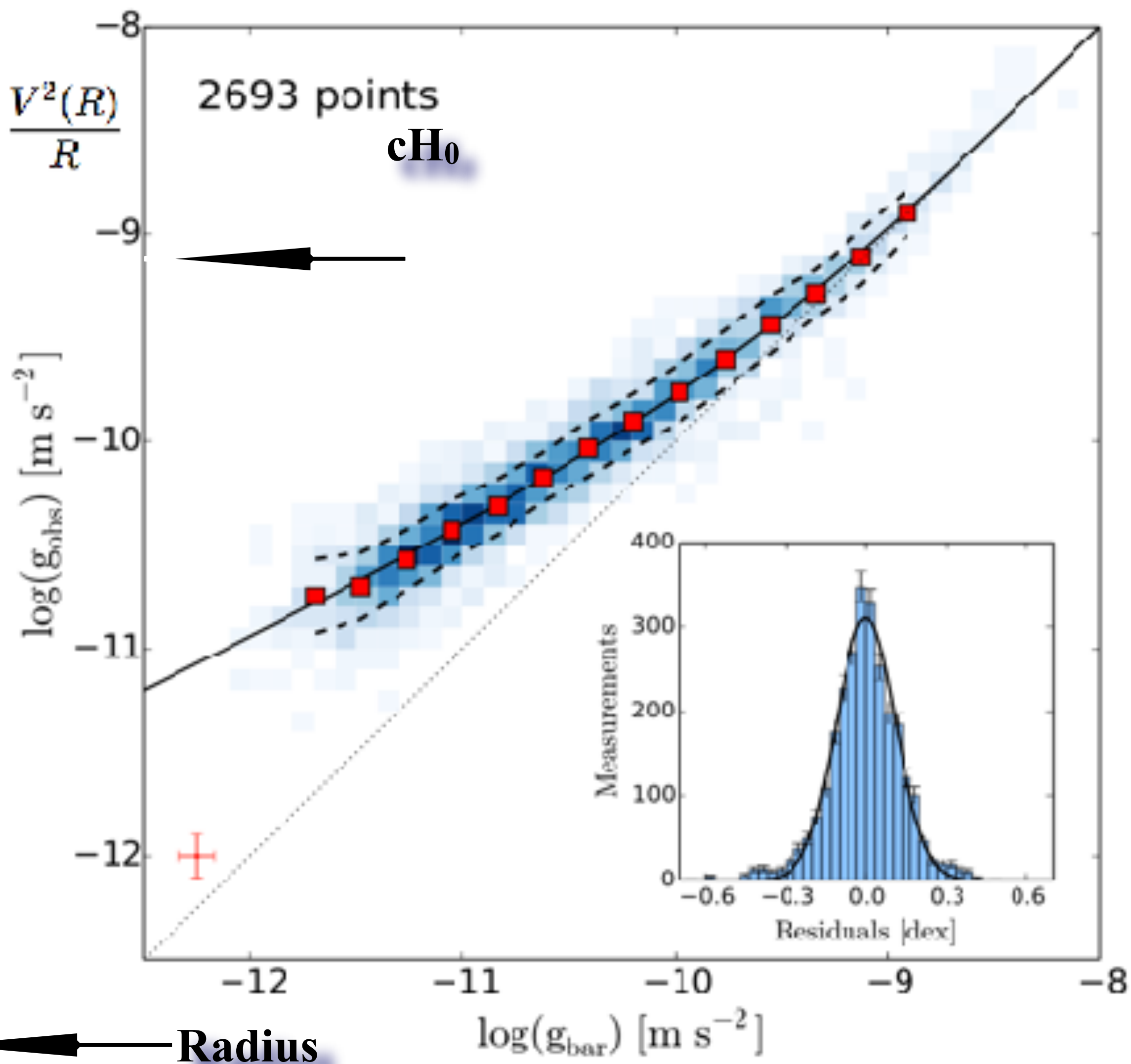
$$g_{\rm bar}(r) = GM_{\rm bar}(<r)/r^2$$

(to first order a proxy for surface brightness)

McGaugh+16 in PRL

The mass discrepancy-acceleration relation

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



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

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: a "minimum" acceleration probed by galaxies

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

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

At the solar circle is ~2 10^{-10} m/s^2

McGaugh+16 in PRL

The mass discrepancy-acceleration relation

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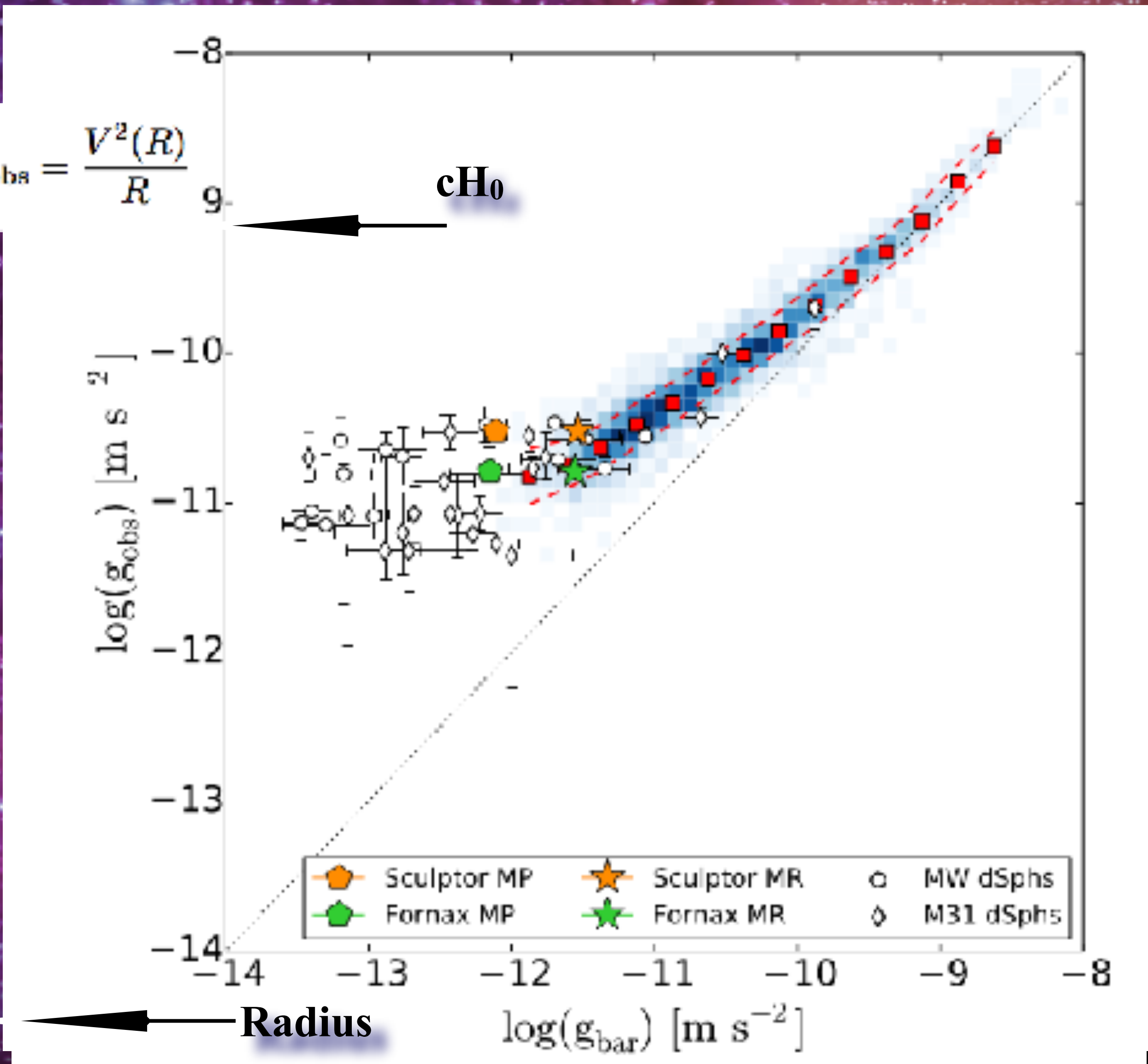

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Two characteristic accelerations:

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

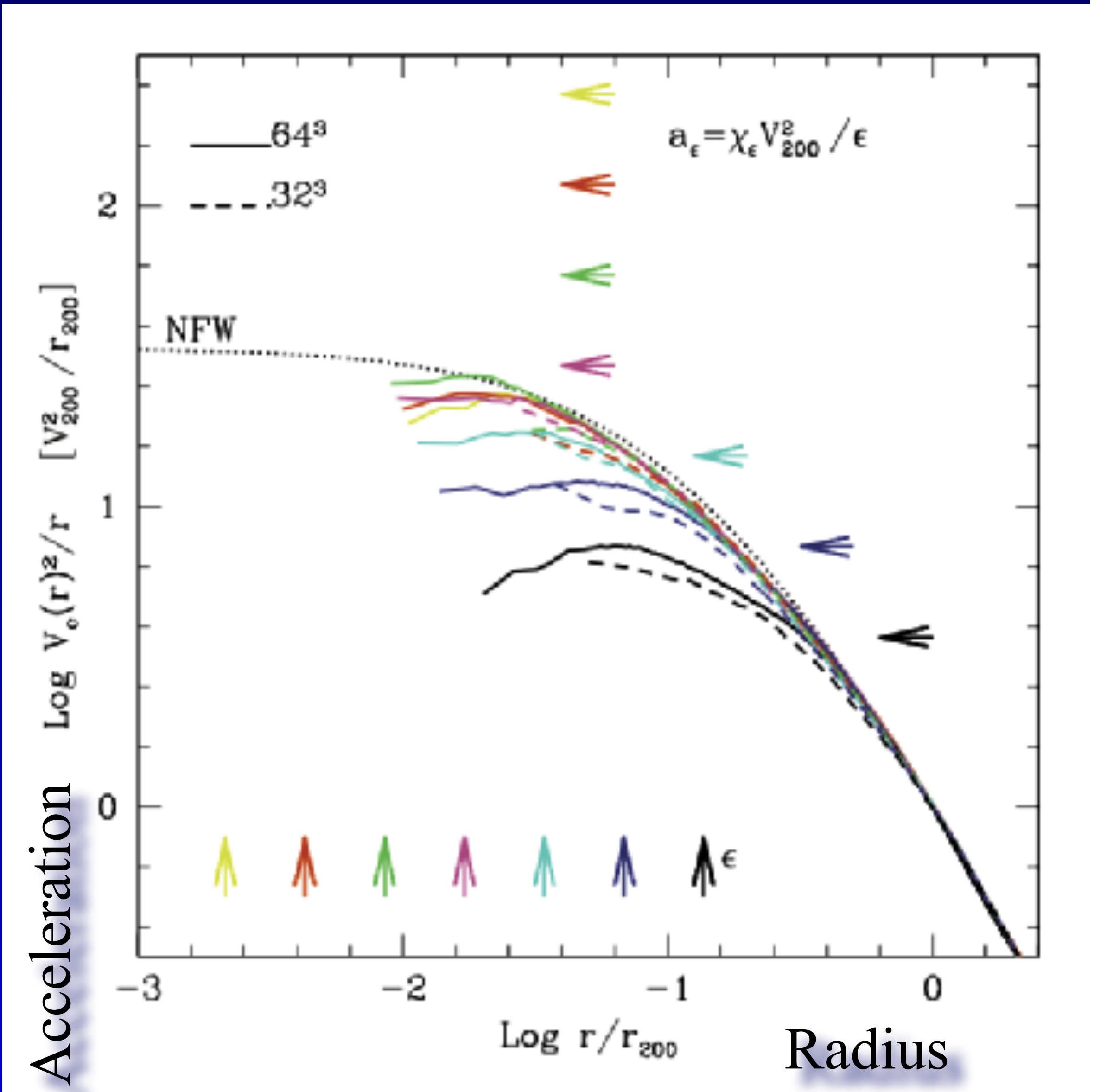
For reference: Earth's acceleration around the Sun is $\sim 6\ 10^{-3}$ m/s^2

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

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

Lelli+16

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

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

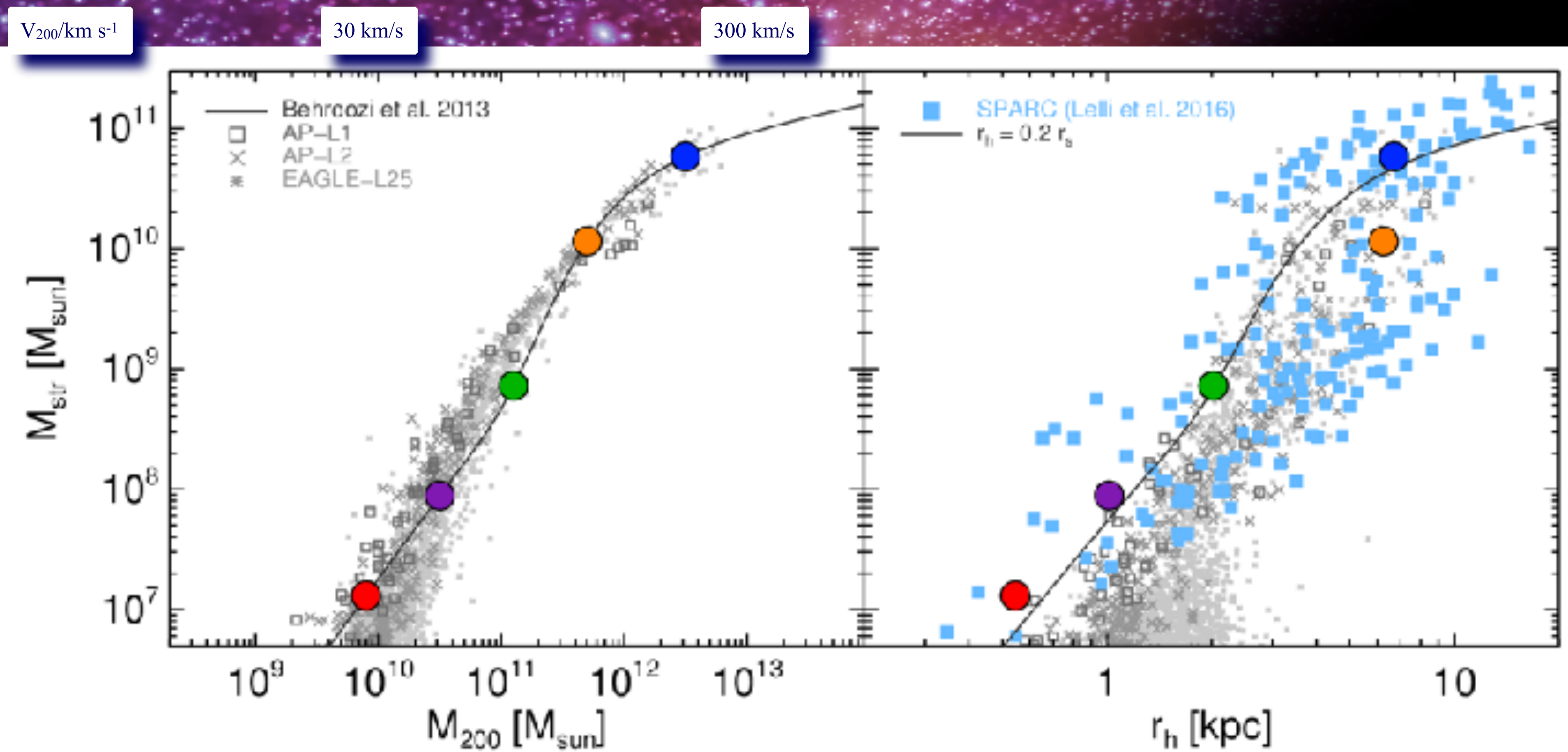
$$a_{max} = a(0) = const * V_{200}^2/r_{200}$$

$$a_{max}(V_{200} = 300 \text{ km/s}) = (cH_0/10) \sim \sim 10^{-10} \text{ m/s}^2$$

$$a_{max}(V_{200} = 30 \text{ km/s}) = (cH_0/100) \sim 10^{-11} \text{ m/s}^2$$

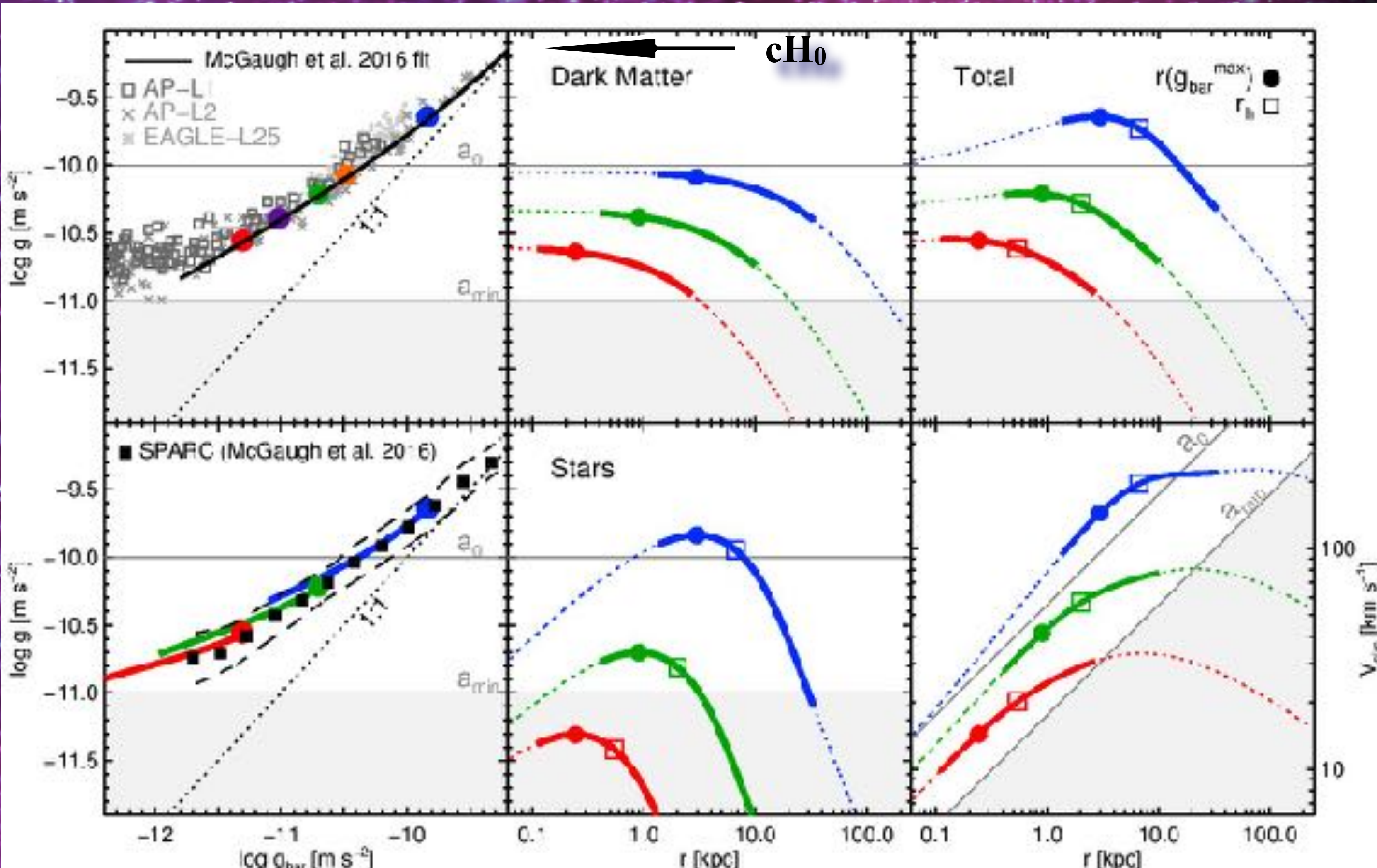
- Note that the DM acceleration contribution in halos likely to host disk galaxies (i.e., V_{200}<300 km/s) should not exceed a certain maximum. Baryons must dominate in regions where $a > 0.1cH_0$

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



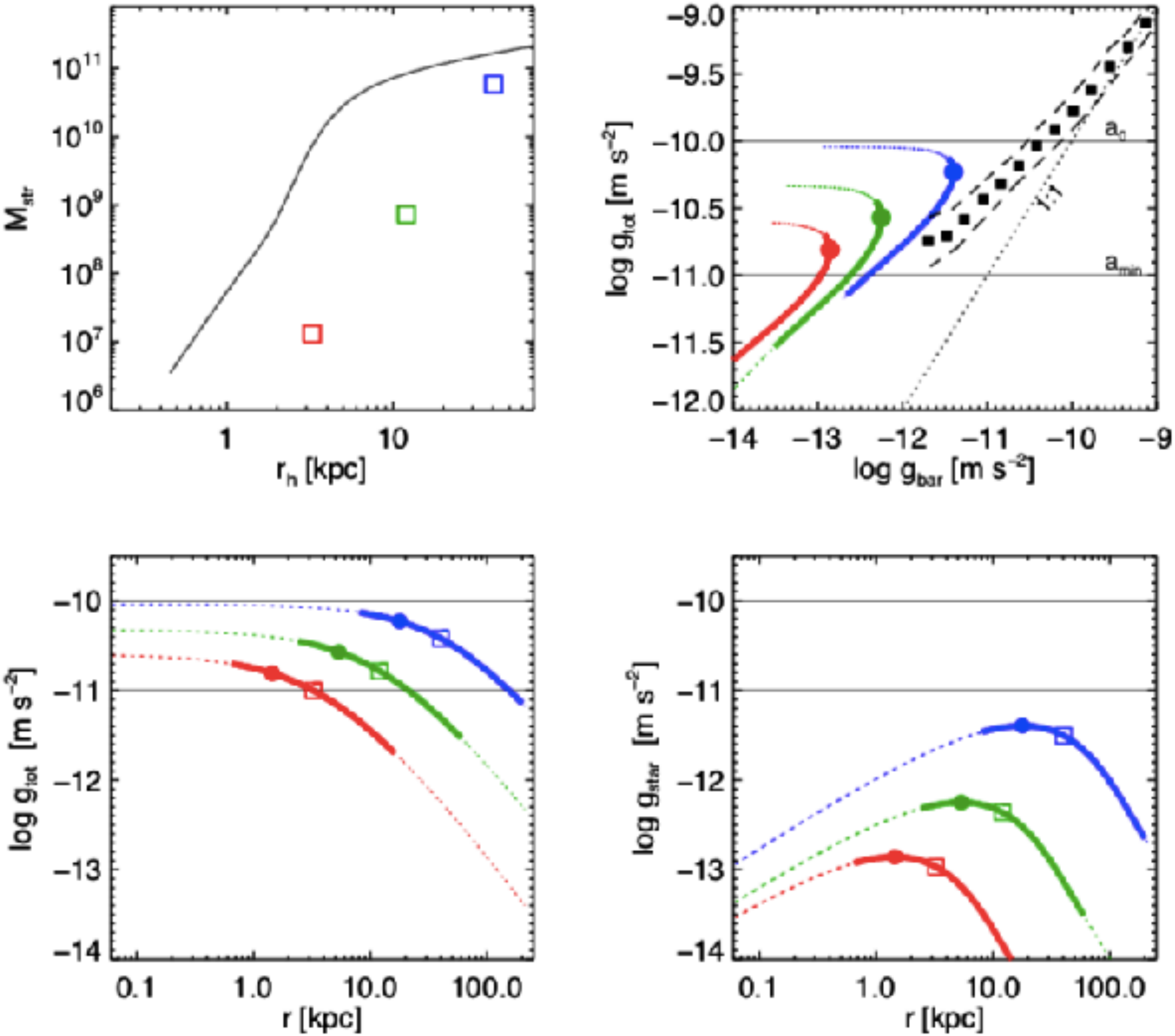
MDAR in LCDM

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)

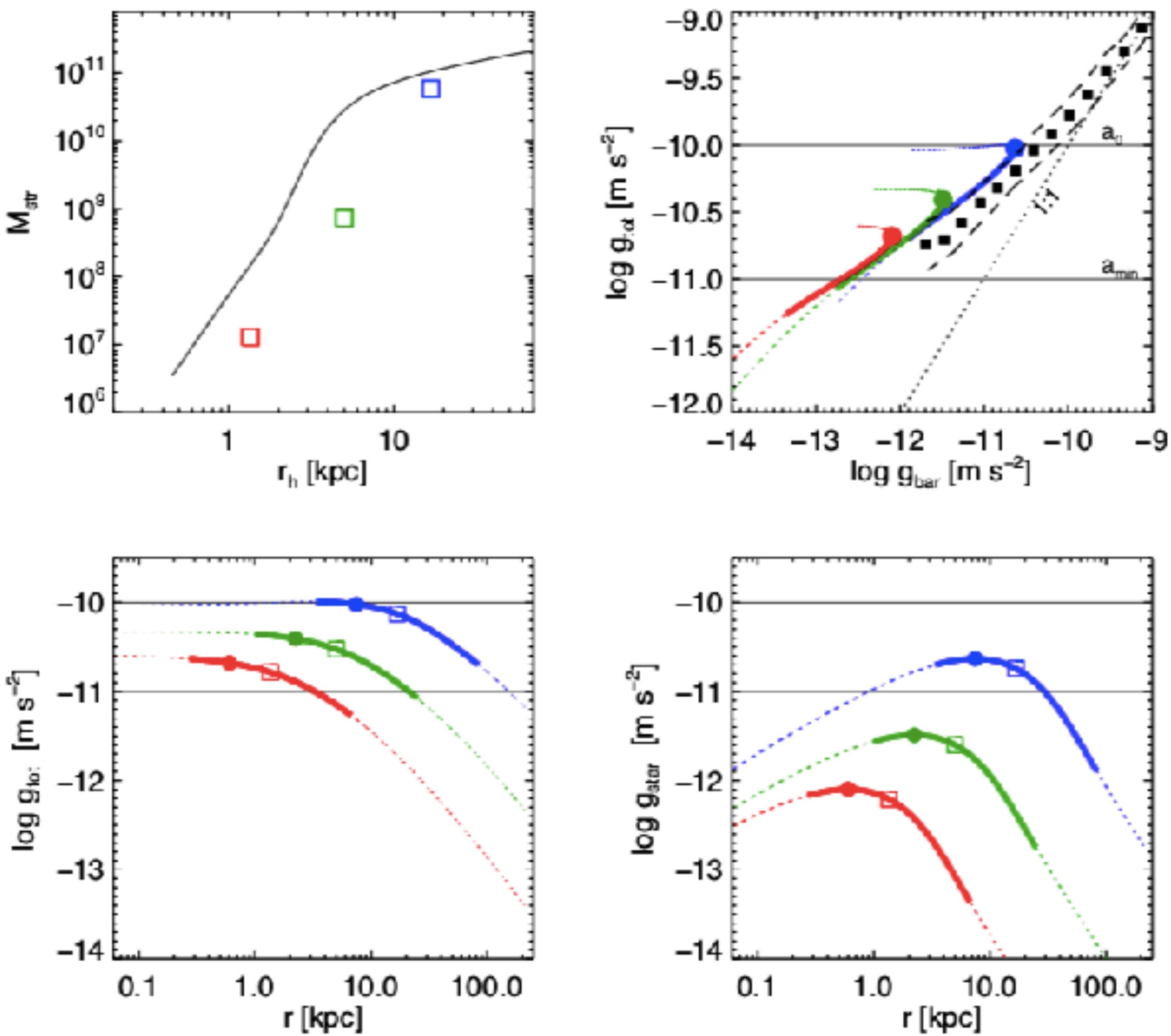
$a_{min} \sim 10^{-11}$ m/s^2: is roughly the acceleration of the least massive halo able to host a luminous galaxy ($V_{max} \sim$20-30 km/s)

Navarro+18



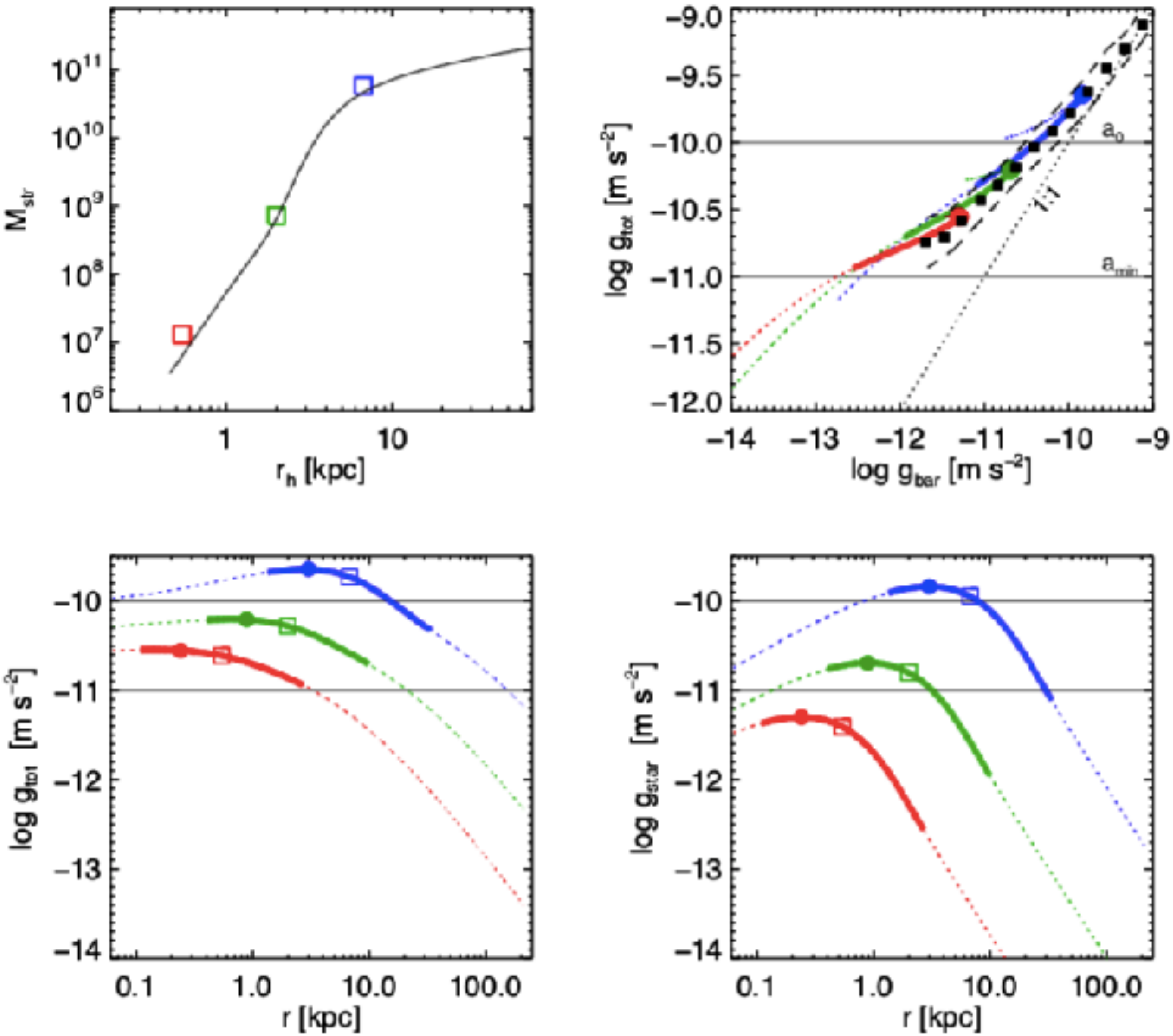
MDAR in LCDM

Navarro+17



MDAR in LCDM

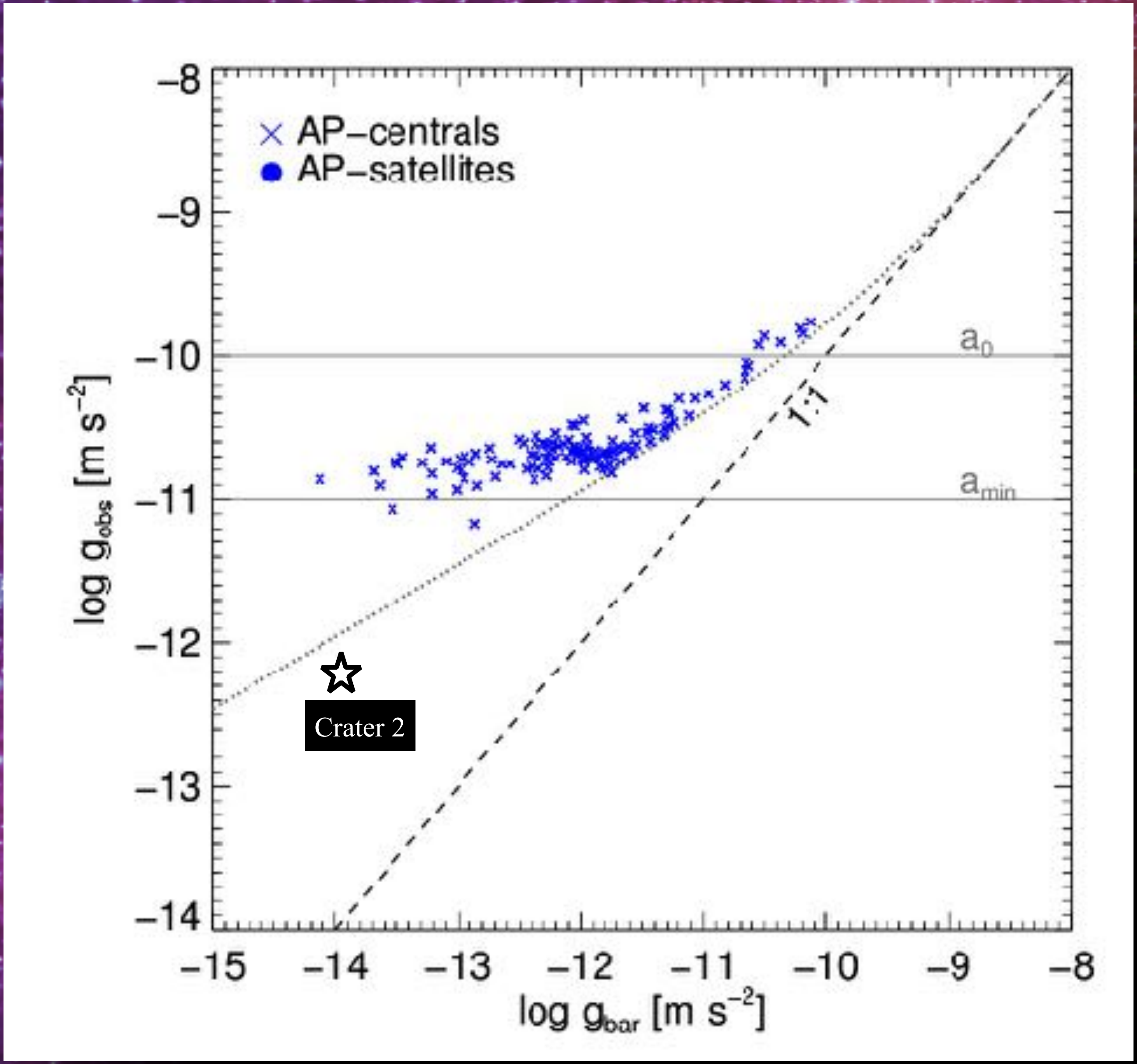
Navarro+17



MDAR in LCDM

Navarro+17

Dwarfs with anomalously low acceleration



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

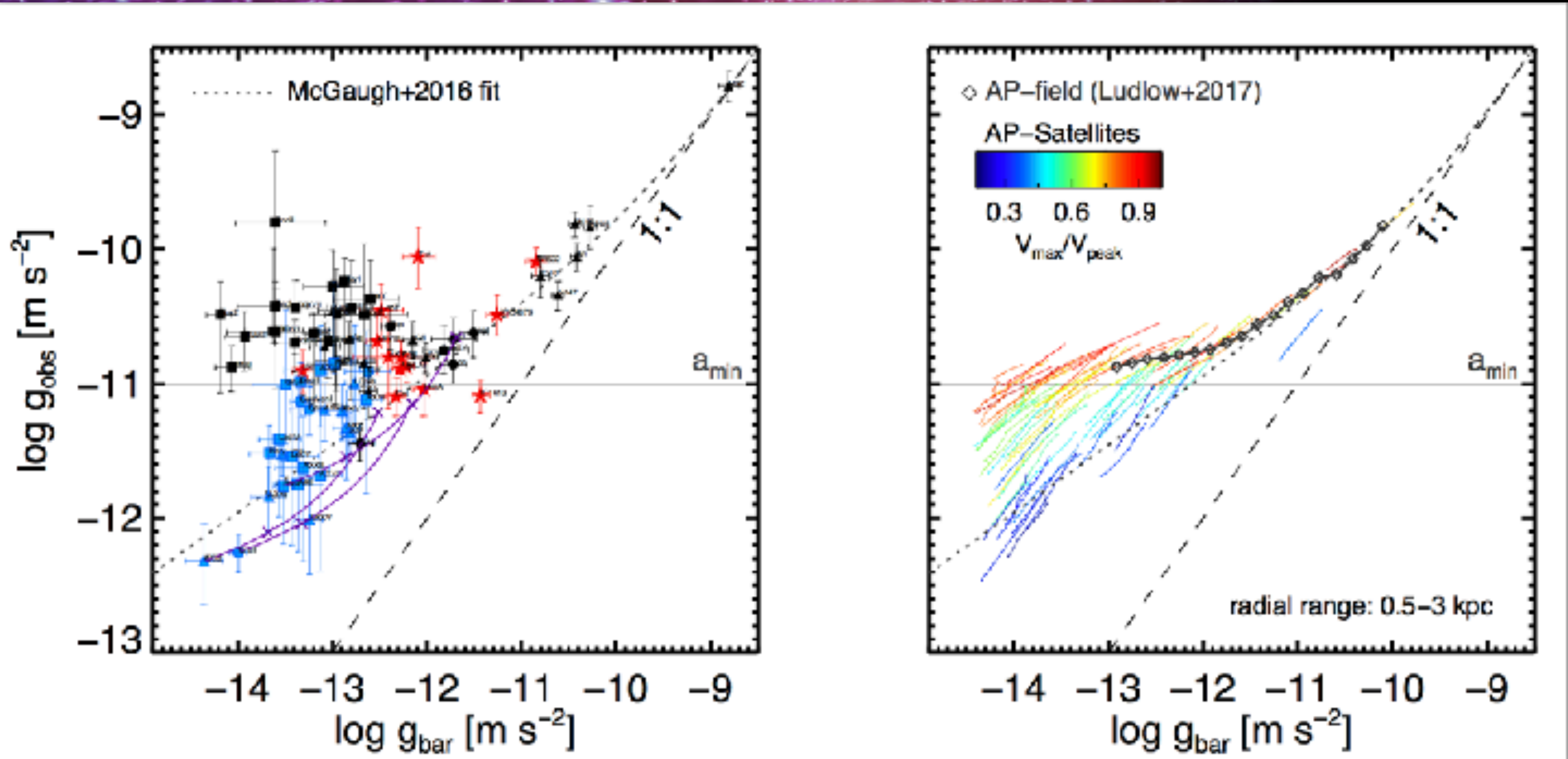
A further prediction of LCDM is that some *satellite* galaxies should deviate from the general trend and probe accelerations below a_{min}.

This is because tidal stripping removes dark matter from satellites, reducing their central accelerations

Could Crater 2 be the remnant of a once much more luminous galaxy?

Fattahi+17

MDAR in LCDM

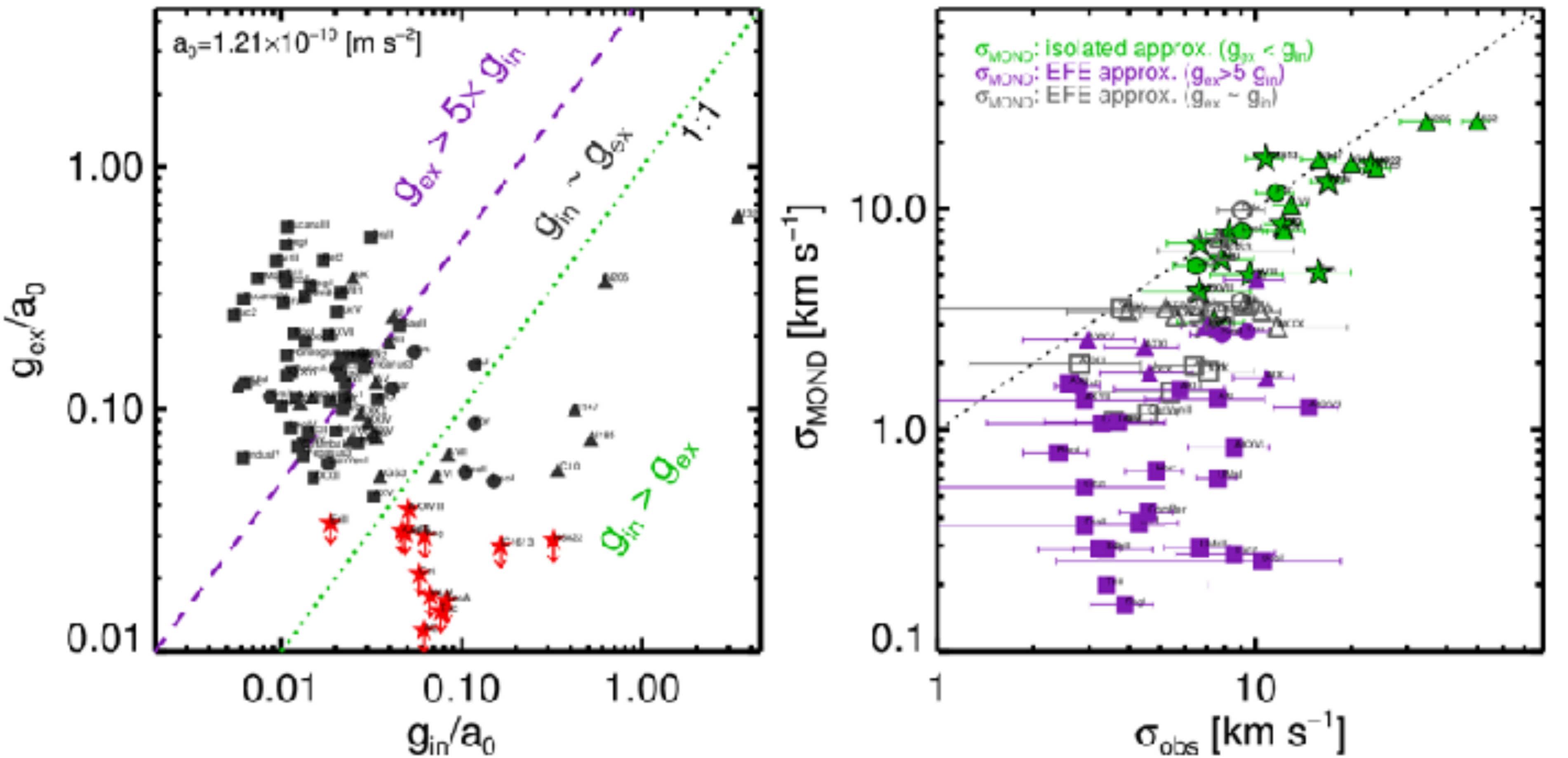


This large scatter at fixed g_{bar} is at odds with the predictions of alternative theories of gravity, like MOND

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

Fattahi+17

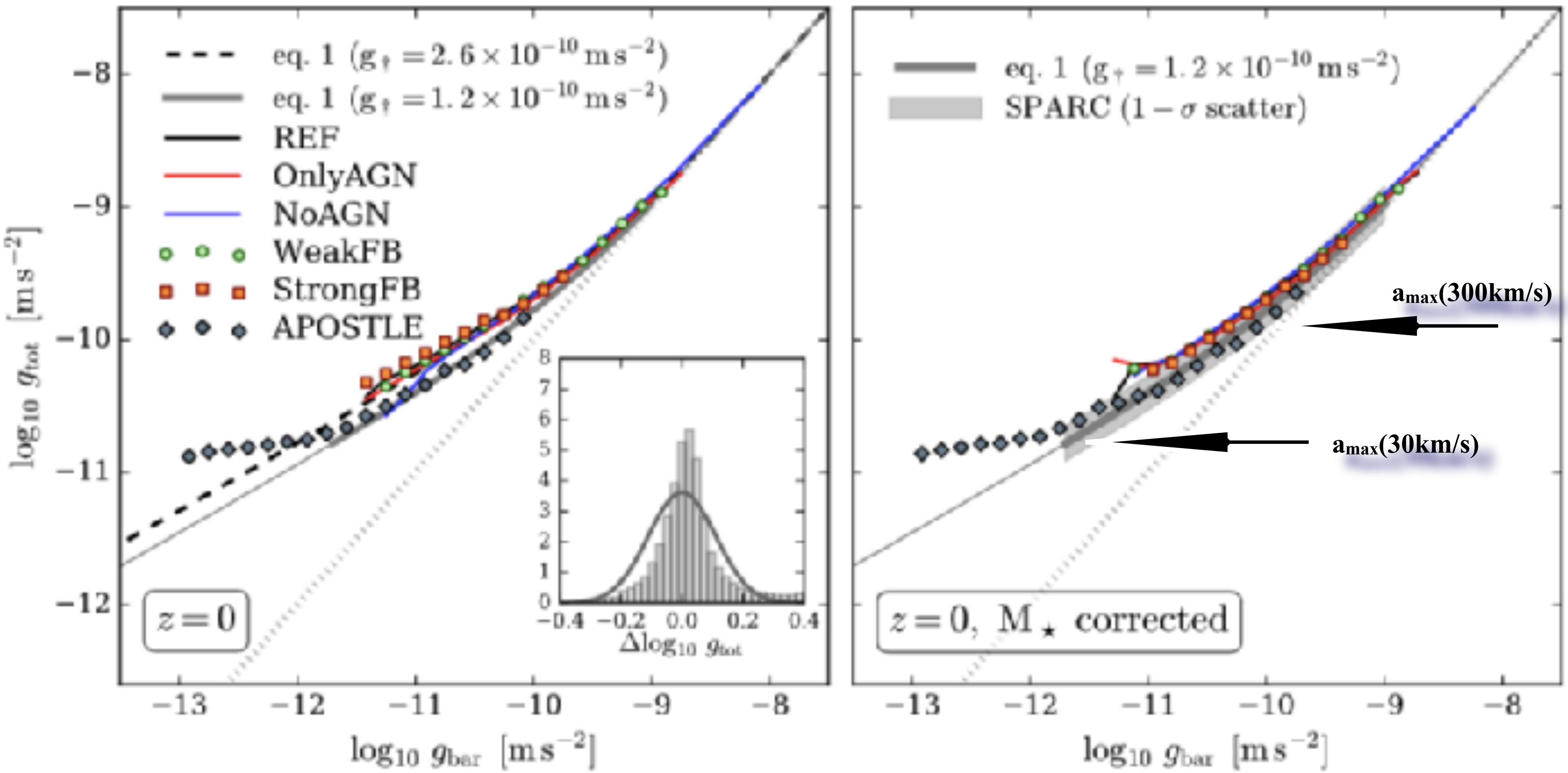
MDAR and MOND



The velocity dispersion of most ultra-faint dwarf spheroidals is at odds with the predictions of alternative theories of gravity, like MOND

Fattahi+17

The mass discrepancy-acceleration relation in EAGLE/APOSTLE



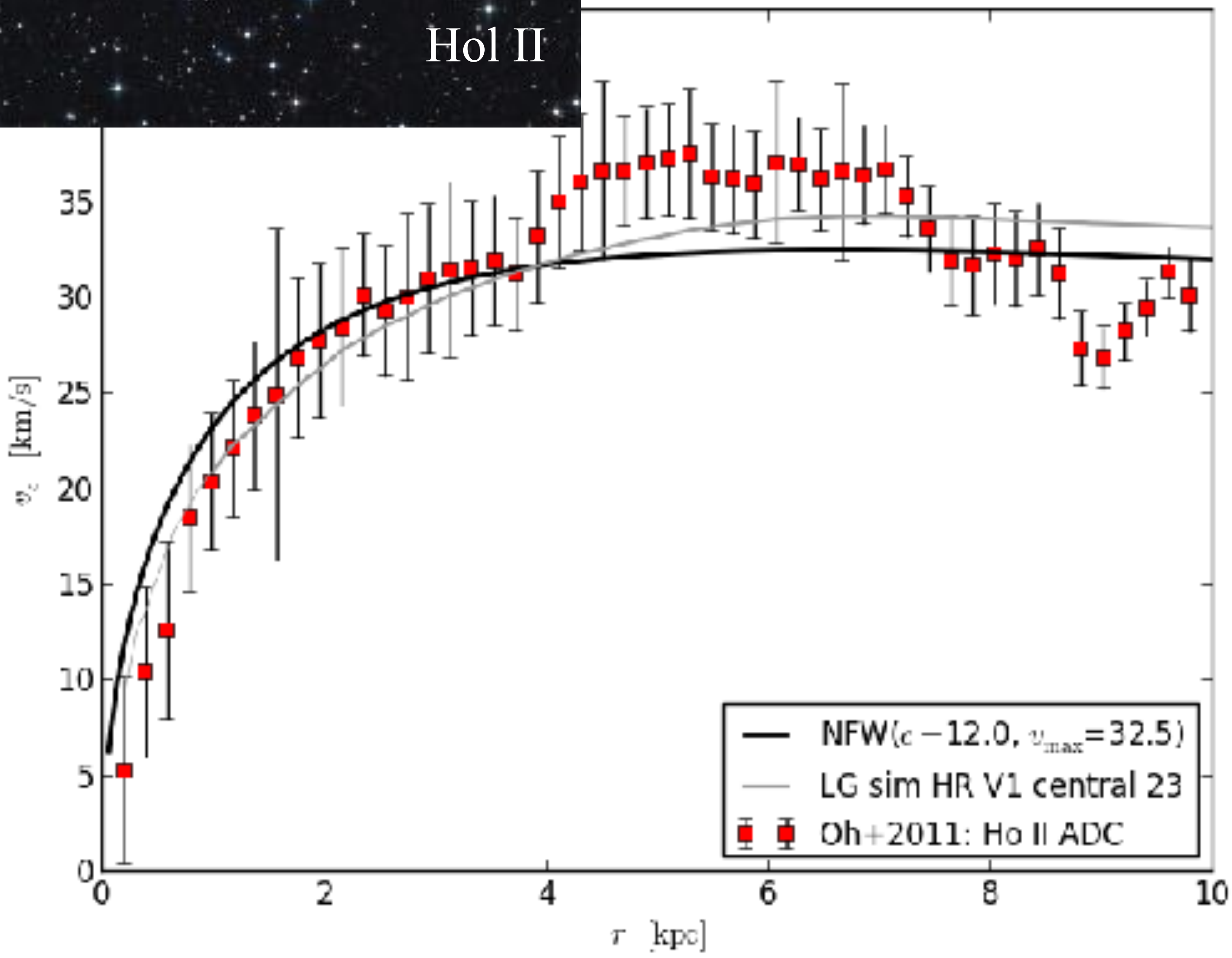
$$g_{\rm bar}(r) = GM_{\rm bar}(< r)/r^2$$

(to first order a proxy for surface brightness)

Ludlow+16 in PRL
Navarro+18 in MNRAS

The "cusp-core problem" or "the rotation curve diversity problem" of disk galaxies

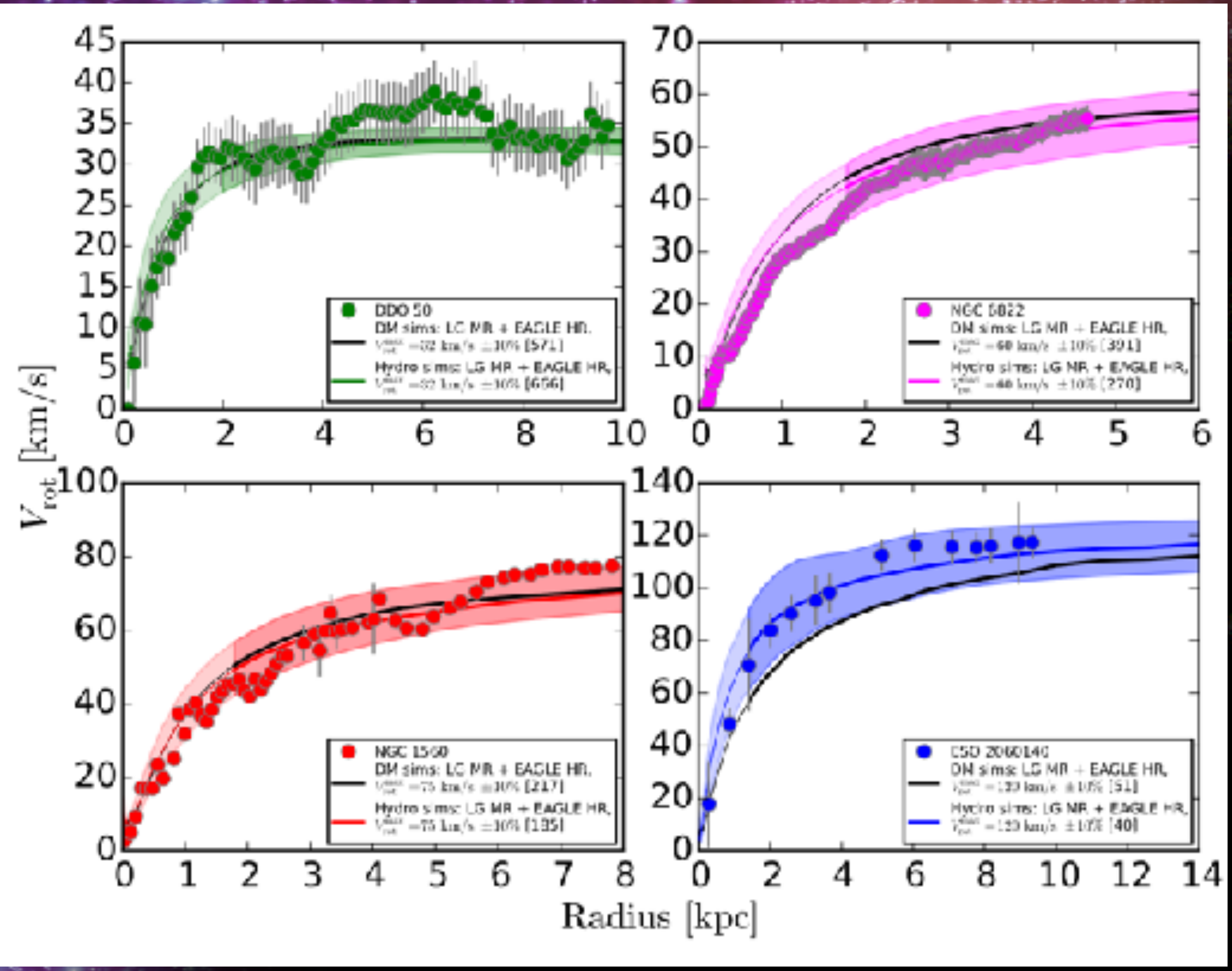
The rotation curve problem



- Some galaxies have rotation curves that agree with simulation predictions

Oman+15

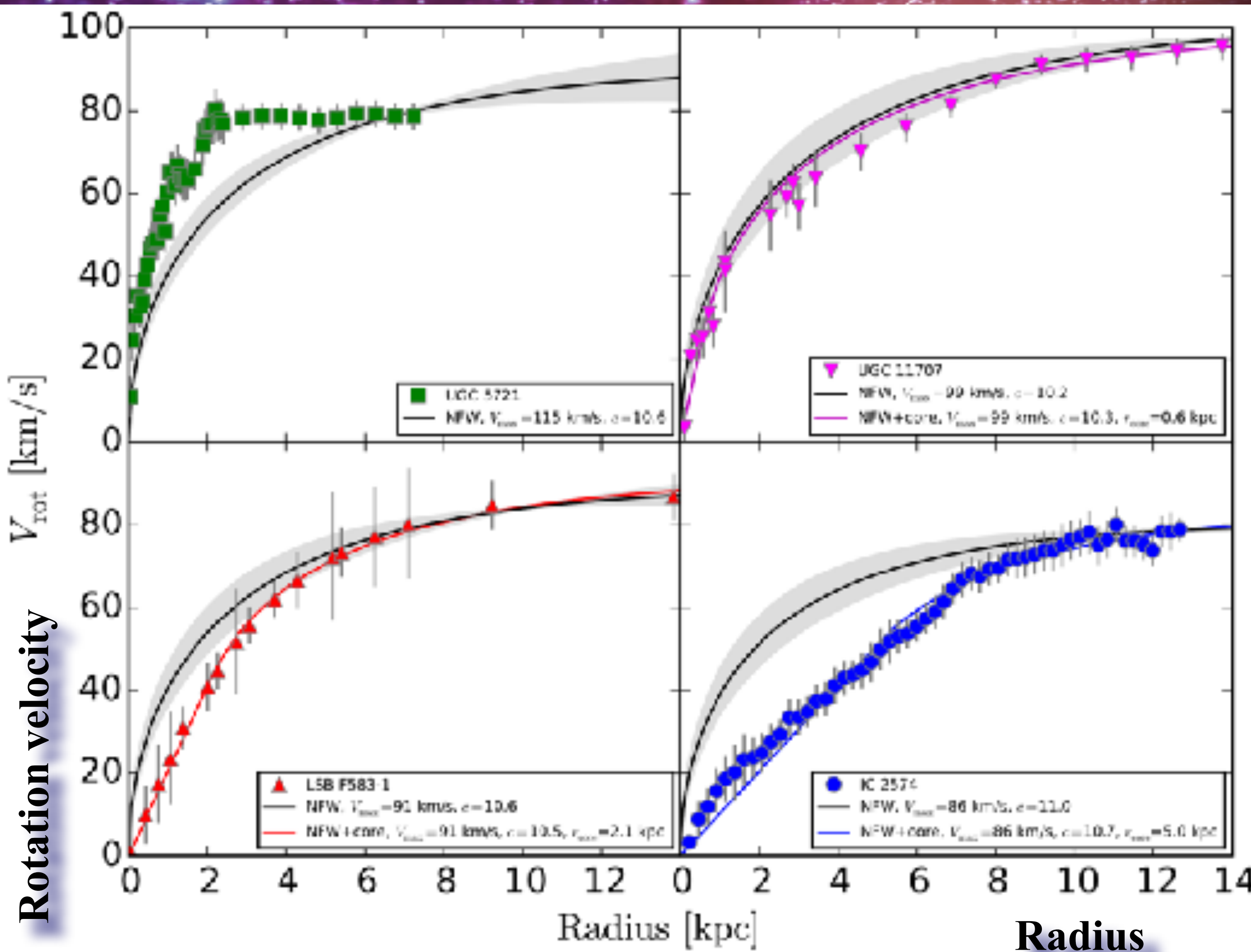
The rotation curve problem



- Some galaxies have rotation curves that agree with simulation predictions
- Others do not.

Oman+15

The rotation curve diversity problem

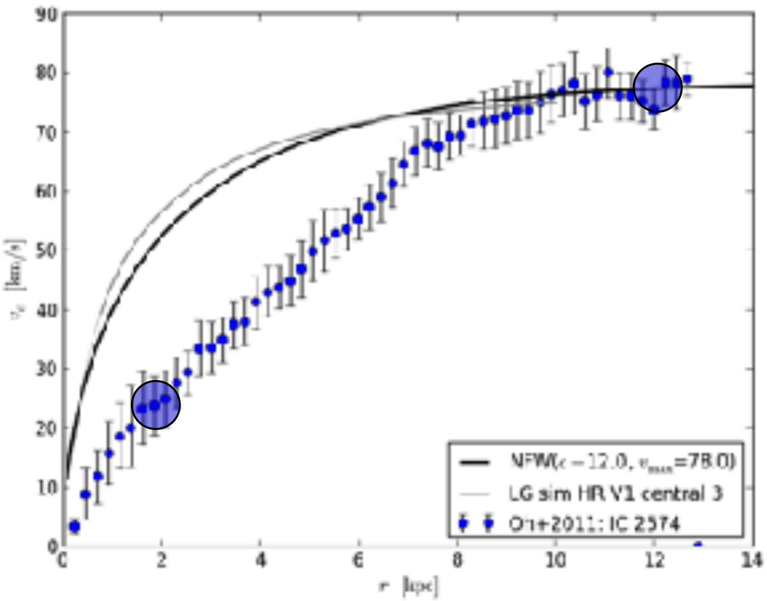


•The rotation curve problem is one of **diversity**.

•In dark matter-dominated galaxies, CDM predicts a **single** profile for a given velocity scale, *unlike* observed rotation curves

Oman'15

The “inner dark matter deficit” problem



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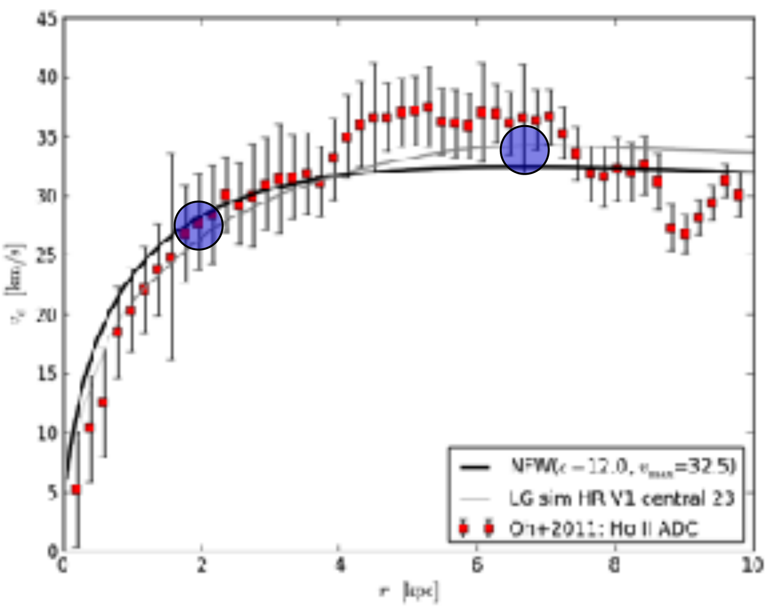


Hol II

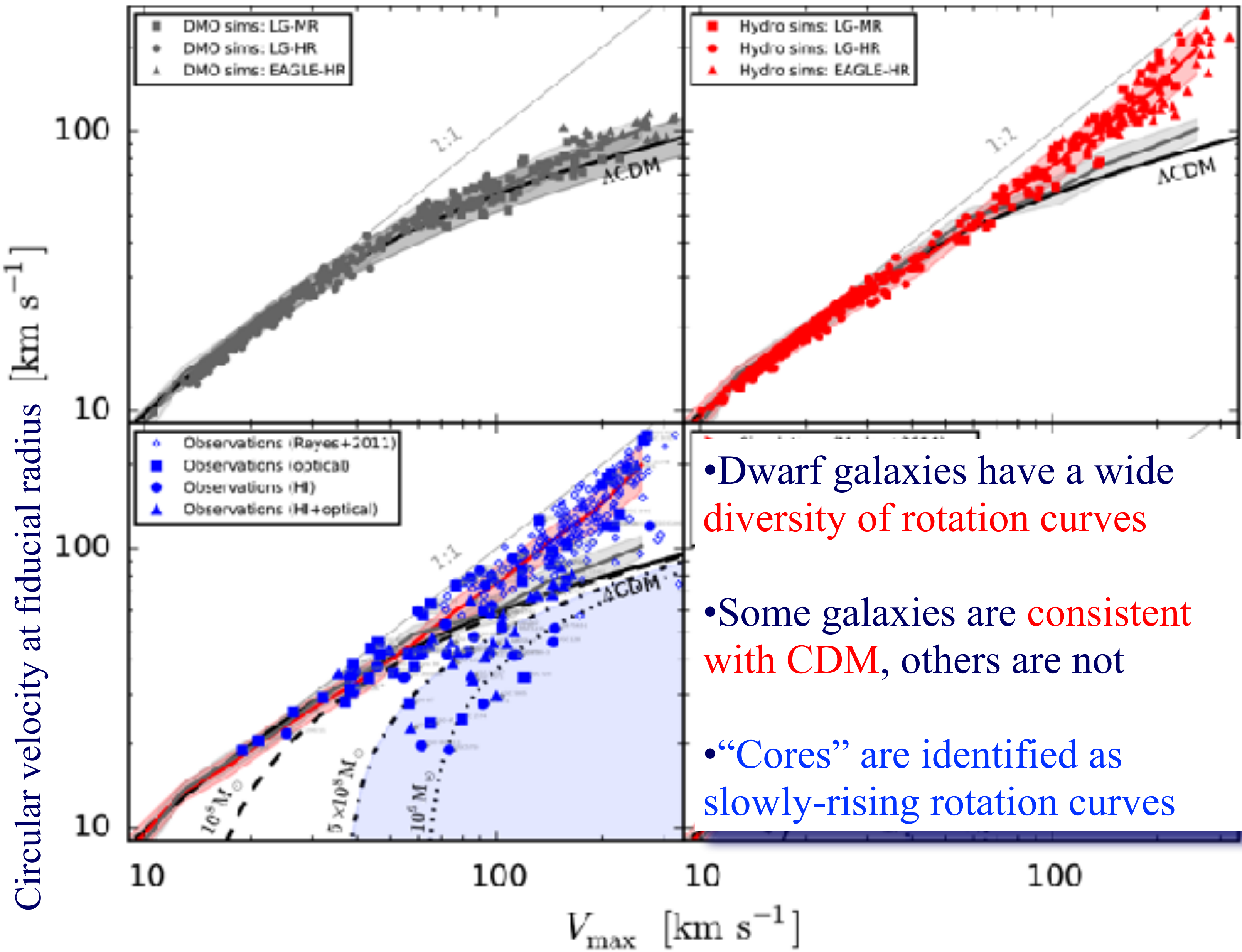
•The *cusp vs core* problem is best thought of as an “*inner mass deficit*” problem

•It does **not** affect all galaxies

•Note that **this disfavours 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" are identified as slowly-rising rotation curves

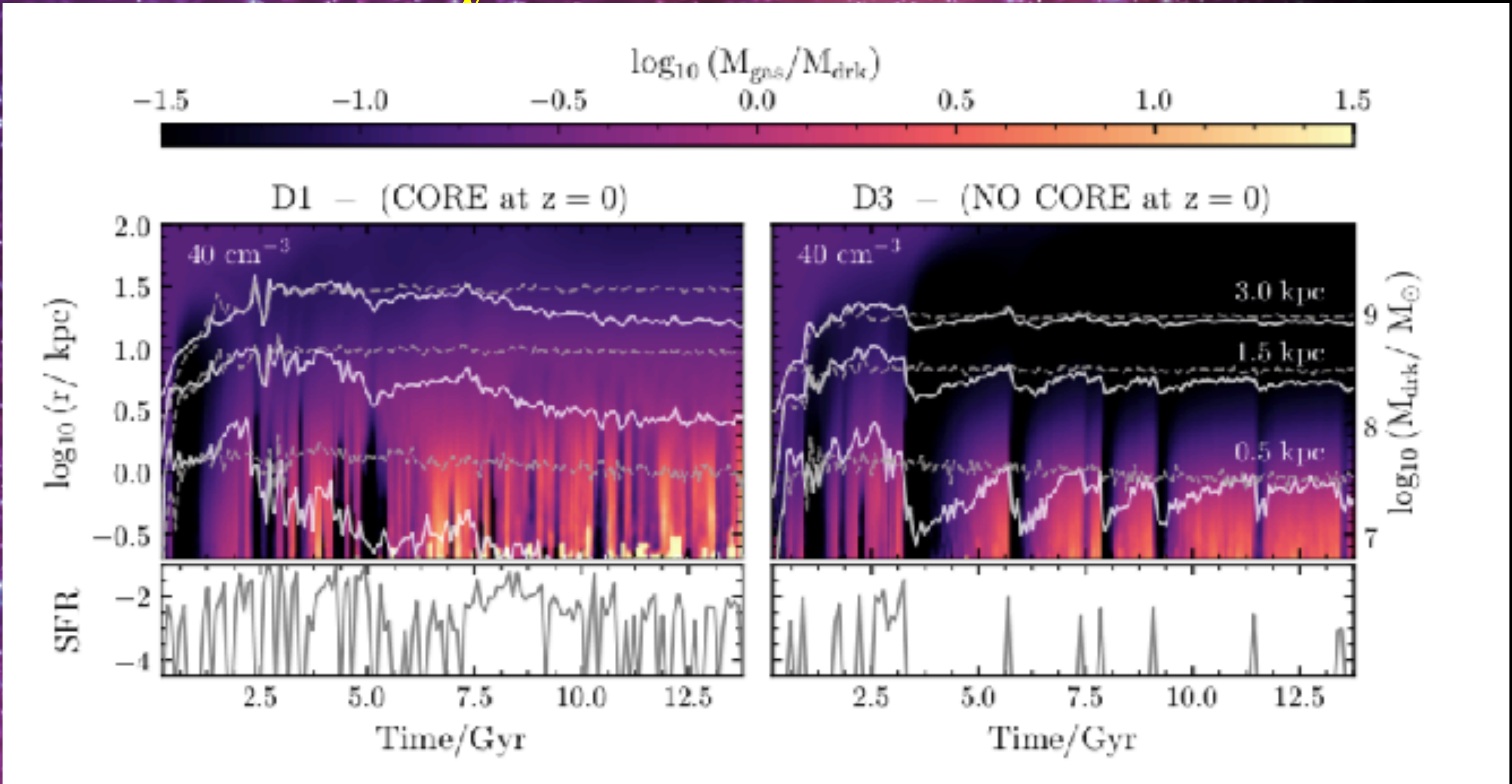
Oman+15

The rotation curve diversity problem

Possible solutions

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

Galaxy formation-induced cores

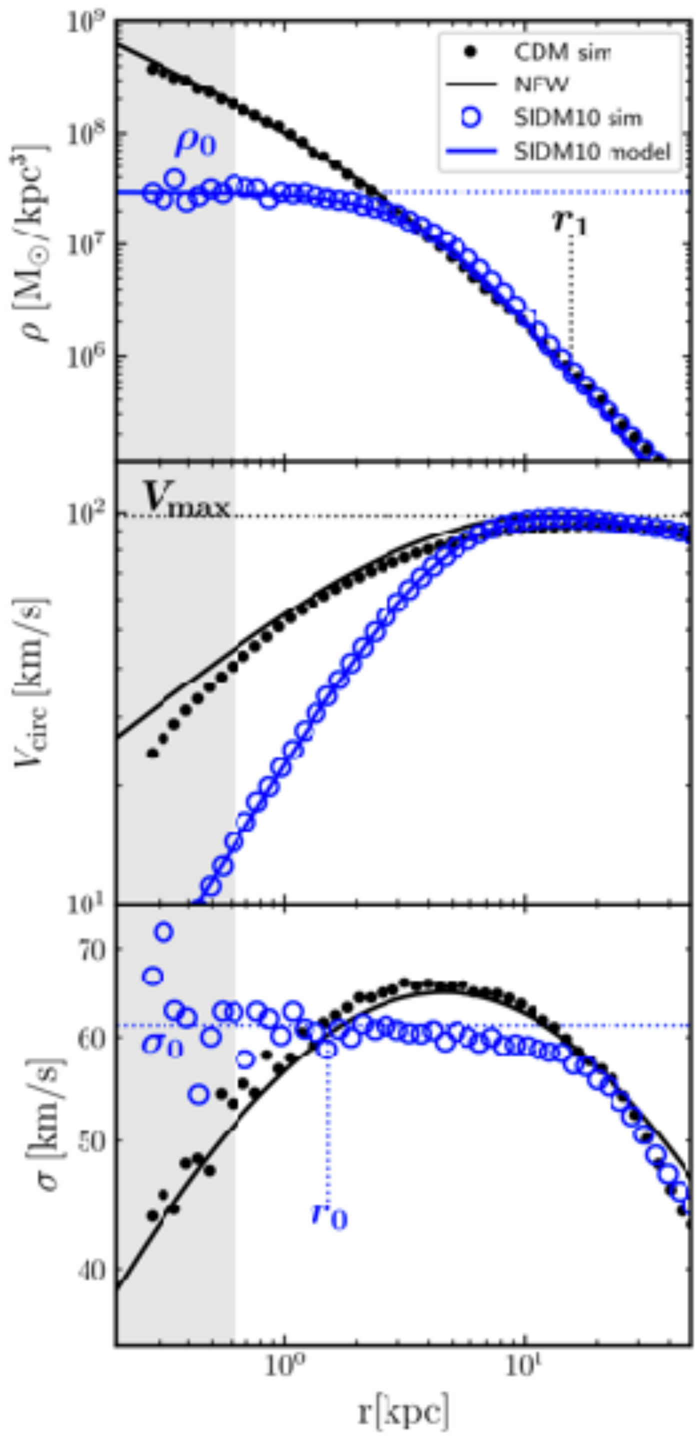


•Supernova explosions produce massive gas outflows that lead to variations in the gravitational potential and the reduction of dark matter in the inner regions (Navarro+1996, Pontzen & Governato 2012).

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

•It may lead to large rotation curve diversity, and predicts that galaxies without cores should be baryon-dominated in the inner regions

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.

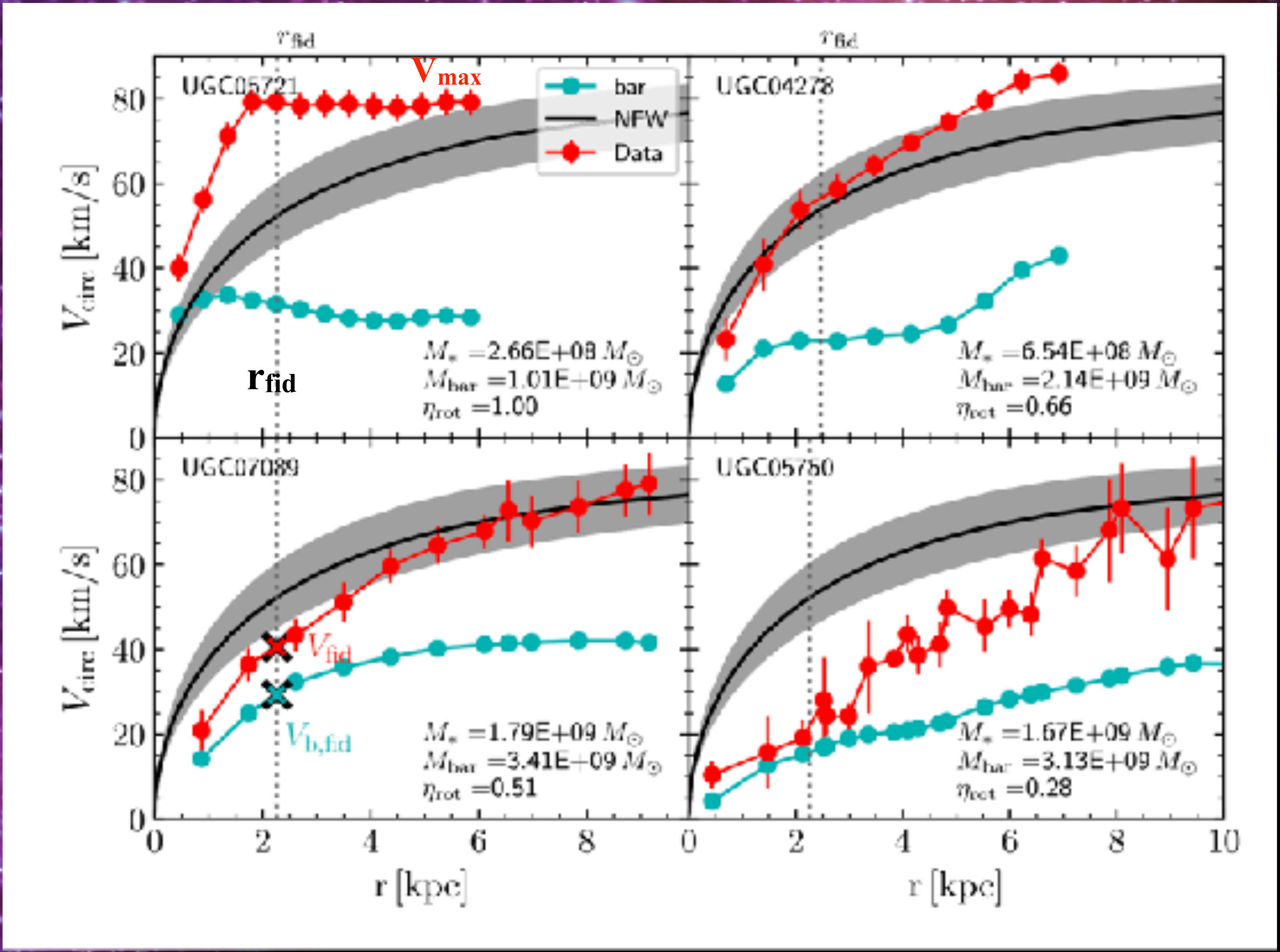
•It may in principle lead to the formation of large cores, which should exist in all galaxies

•The "cusp" may be restored if the accretion of baryons leads to the deepening of the central gravitational potential.

•This scenario also predicts that baryons should dominate the inner regions of galaxies with "cores"

Santos-Santos+20

Baryonic clues to rotation curve diversity



- Two parameters may be used to discriminate between models

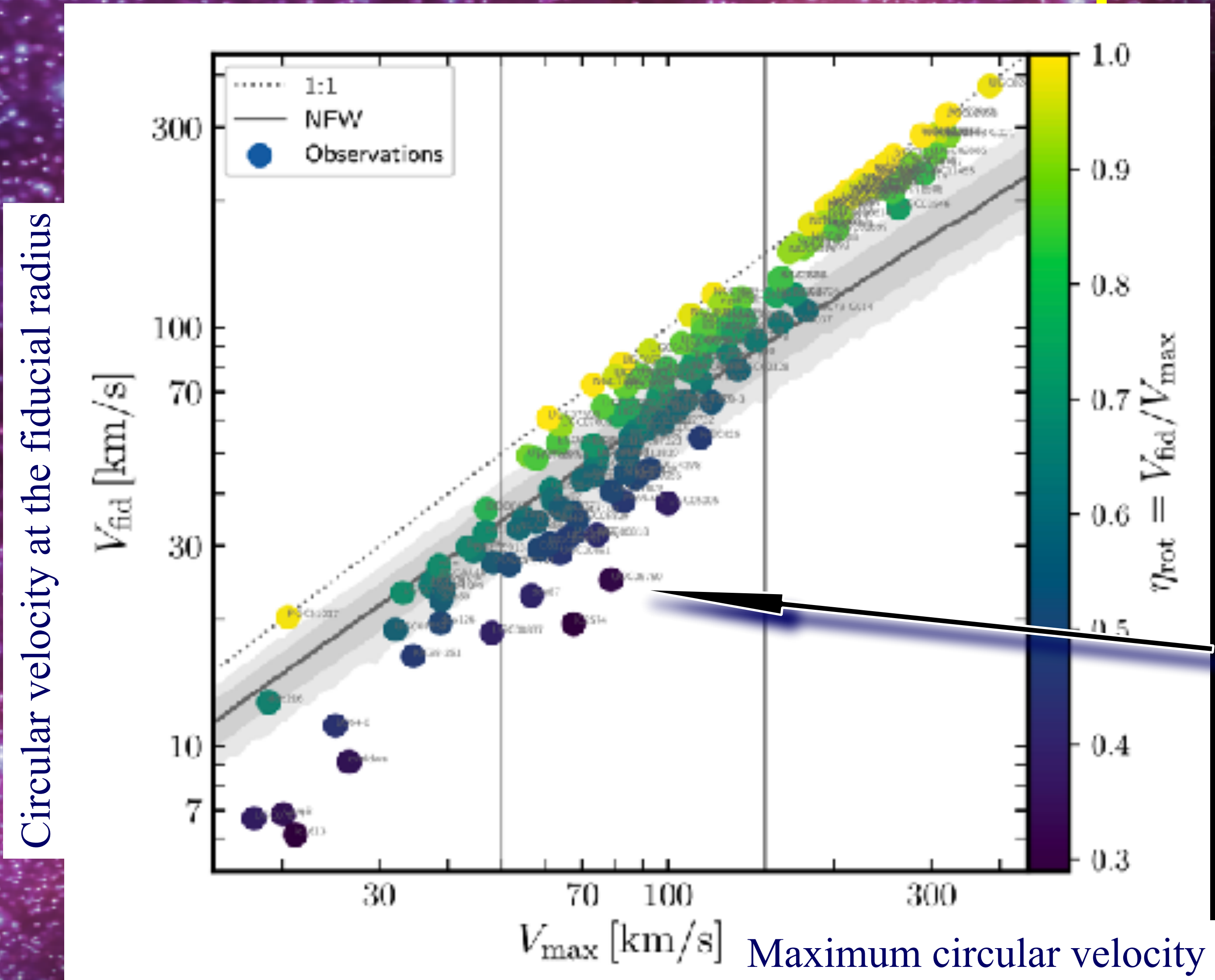
- $\eta_{bar} = V_{b,fid}/V_{fid}$ **measures the importance of baryons in the inner regions**

- $\eta_{rot} = V_{fid}/V_{max}$ **measures how rapidly the rotation curve rises**

- There are extra correlations that qualify the "diversity" of rotation curves.

Santos-Santos+20

How to tell these scenarios apart?



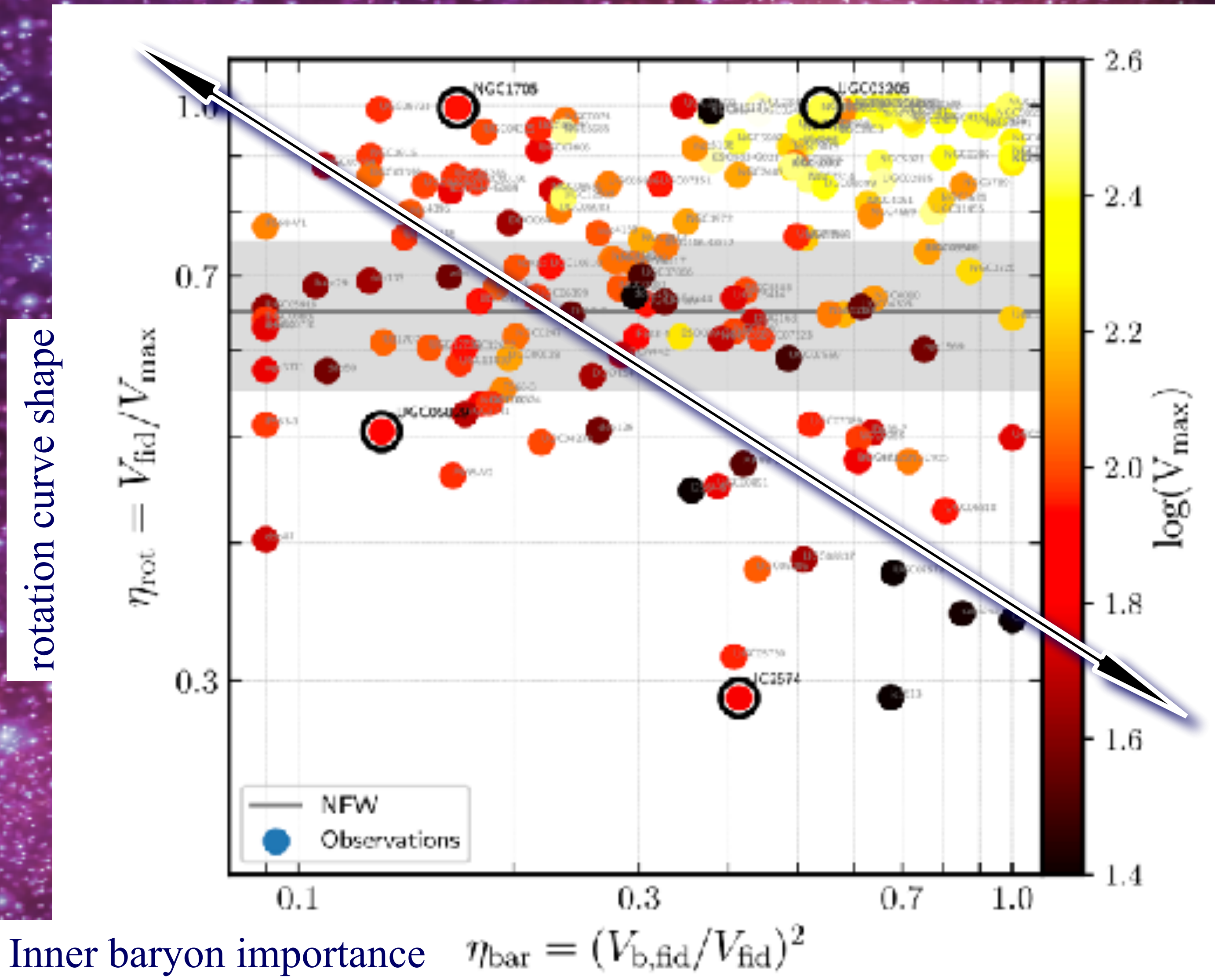
• $\eta_{rot}=V_{fid}/V_{max}$ measures how rapidly the rotation curve rises

• Low values of η_{rot} imply "cores"

• There are extra correlations that qualify the "diversity" of rotation curves.

Santos-Santos+20

How to tell these scenarios apart?

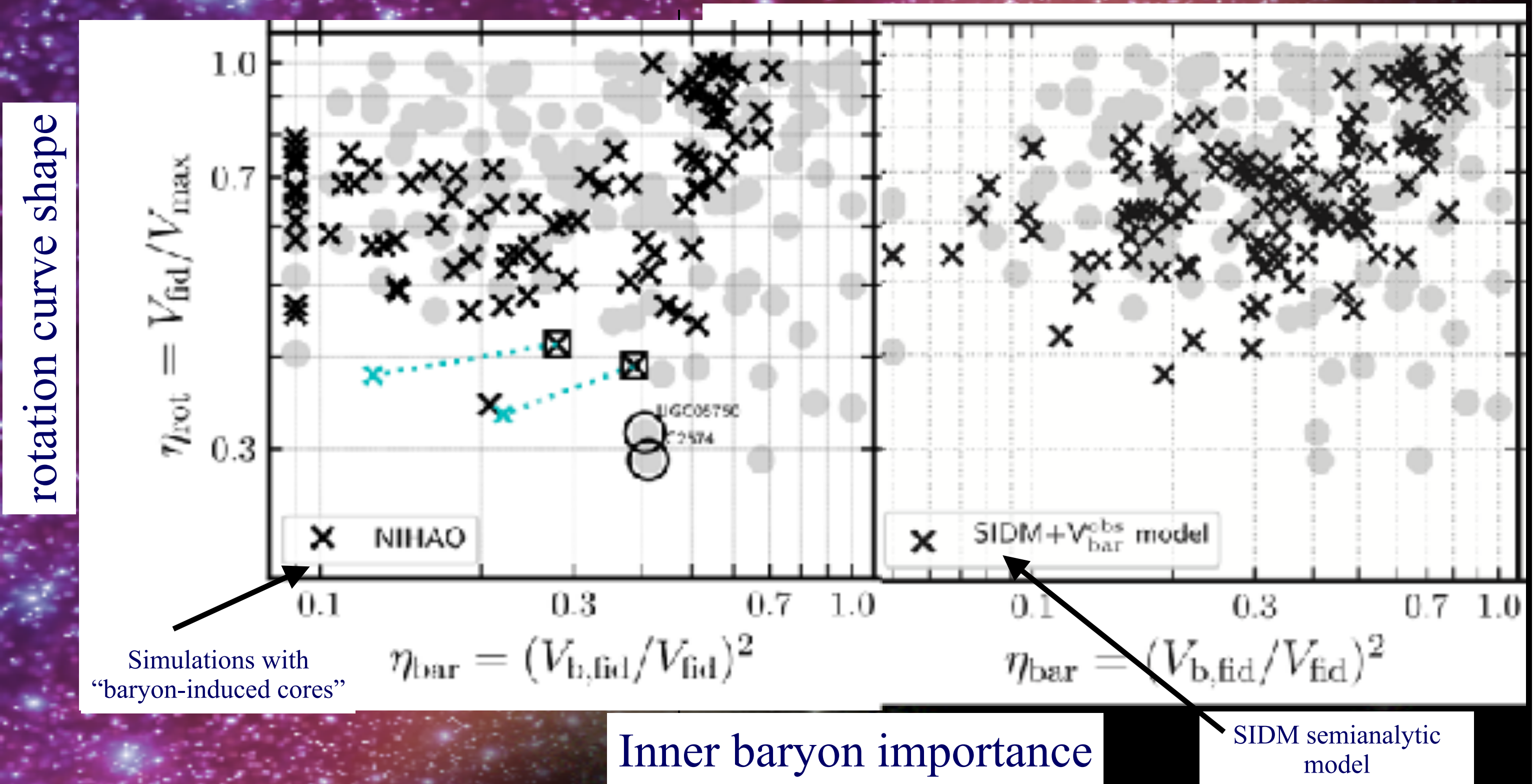


- Baryons dominate the inner regions of galaxies with largest cores
- Baryons are unimportant in the inner regions of galaxies without obvious cores
- Neither behaviour is predicted by the scenarios mentioned above

- The importance of the baryons at the fiducial radius correlates with the shape of the rotation curve

Santos-Santos+20

How to tell these scenarios apart?



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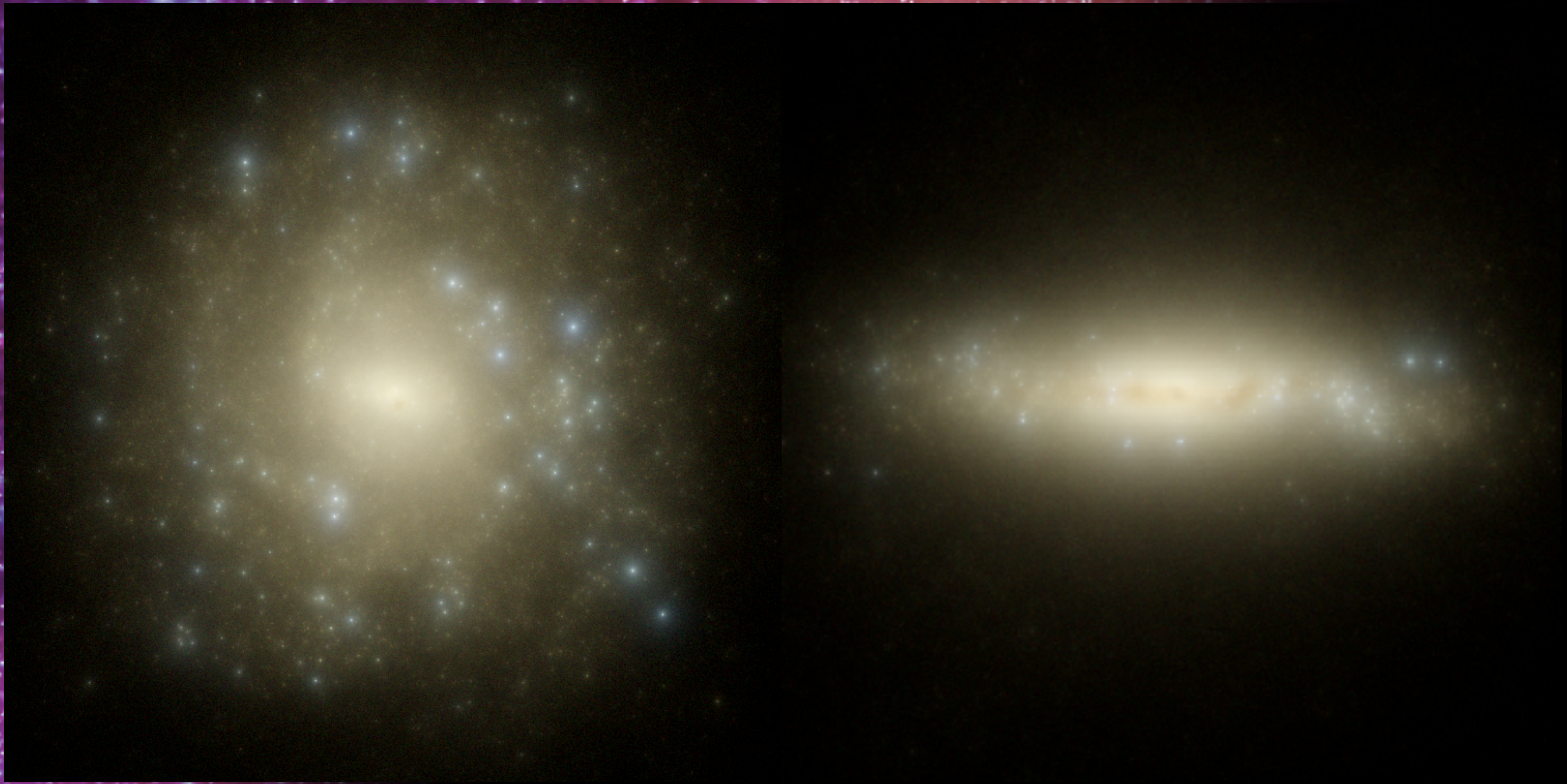
Santos-Santos+20

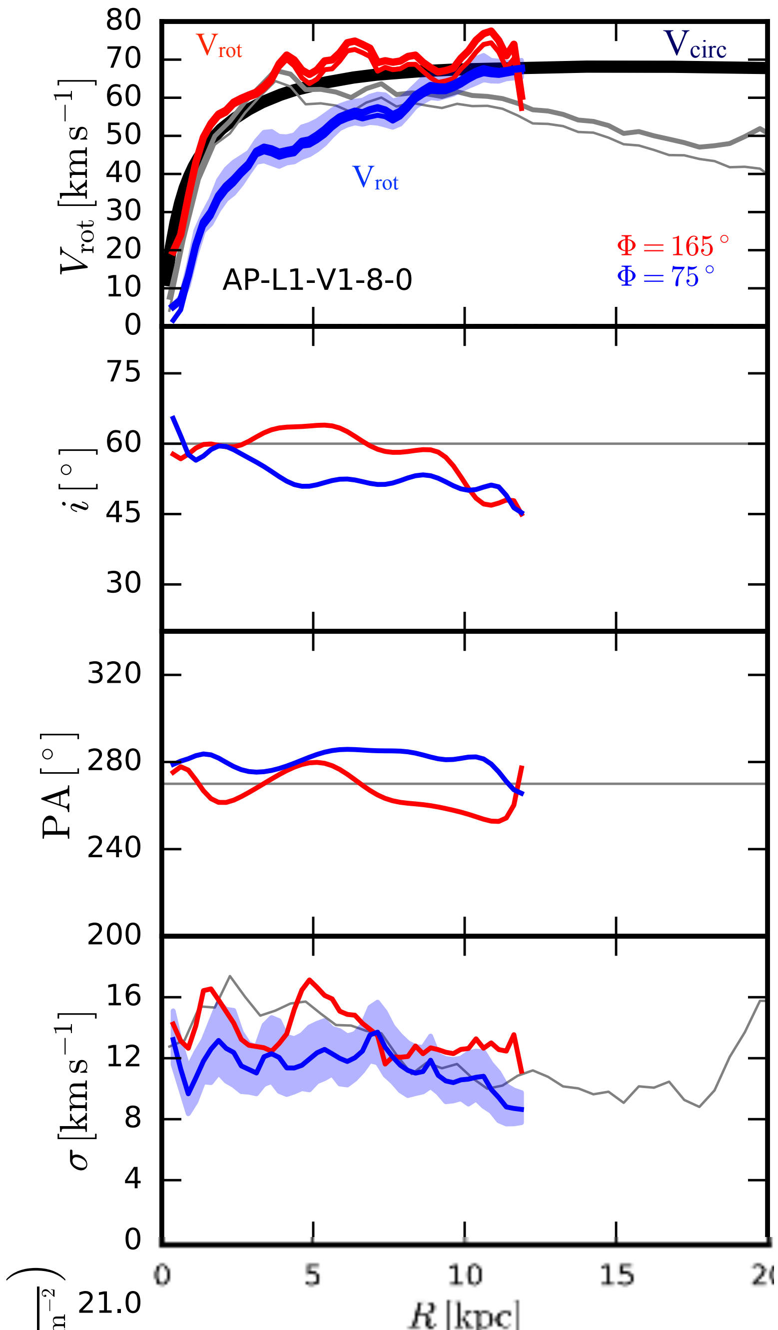
Non-circular motions and rotation curves of simulated galaxies

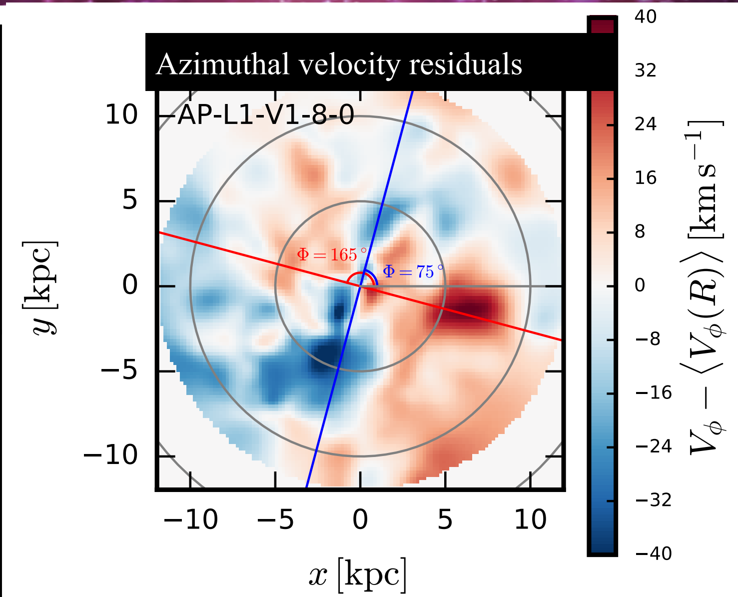


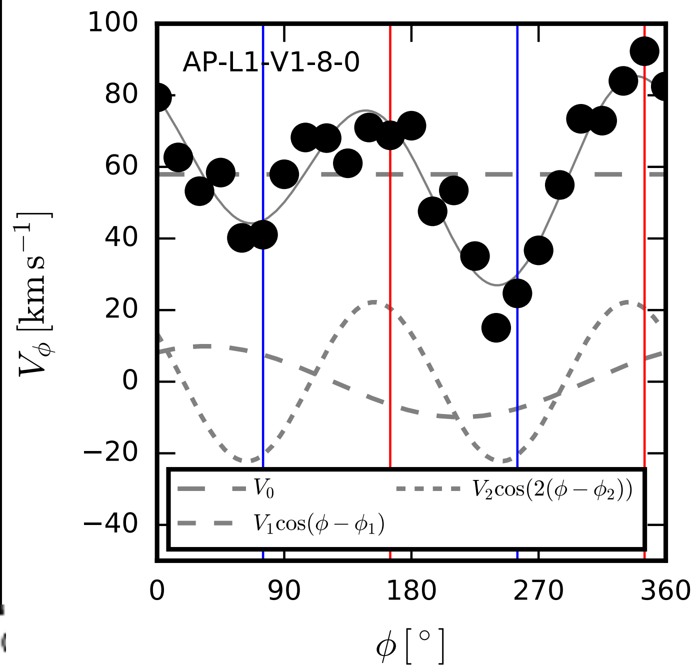
- HI velocity fields used to derive rotation curves using the same tools as in observations
- HI data cubes are built after assuming a favourable inclination and distance
- Rotation curves derived using BAROLO^{3D}, one of the latest version of “tilted-ring”models
- Procedure tested on galaxies from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

Oman+17

Non-circular motions and rotation curves



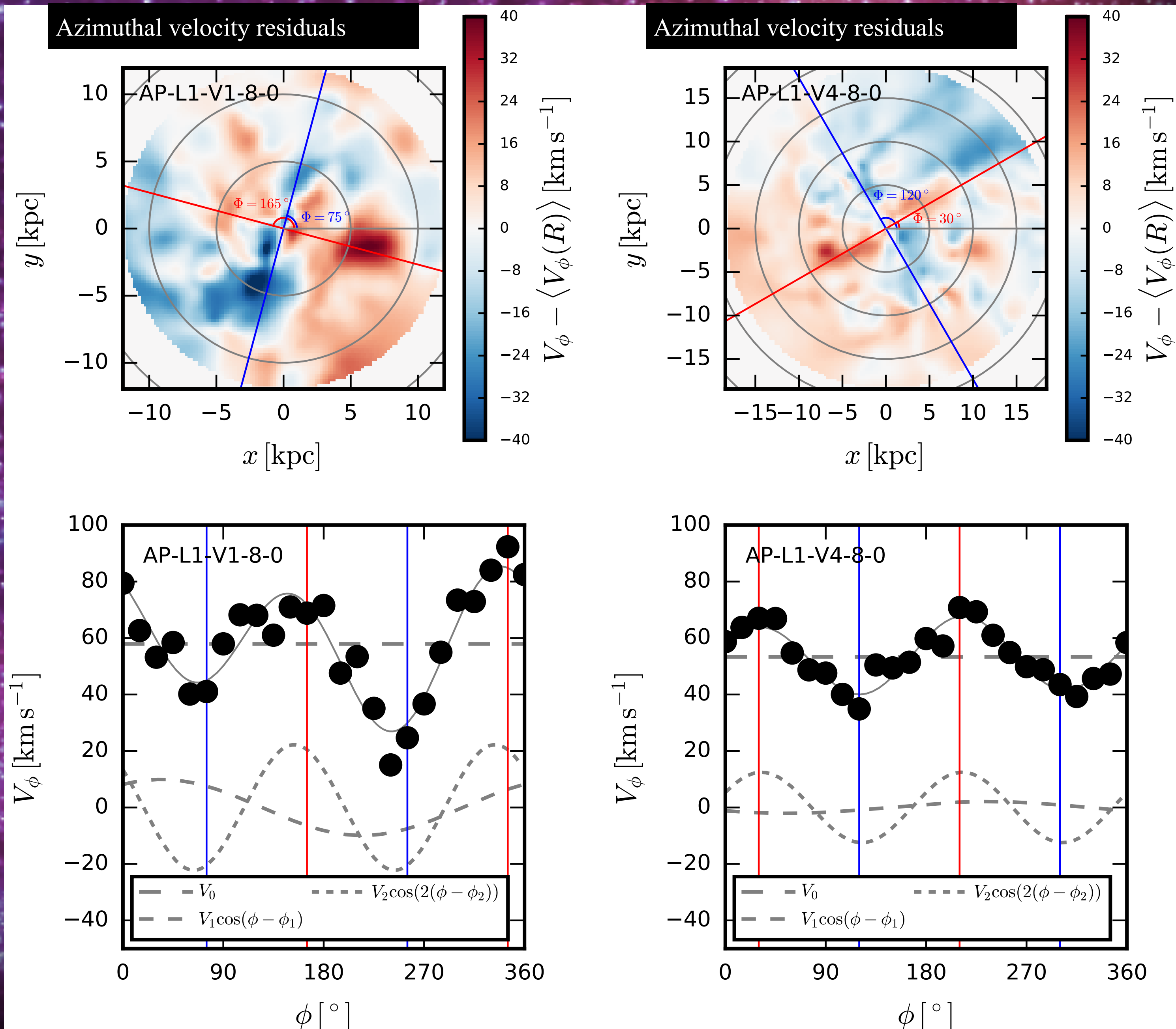




- Rotation curves recovered using a tilted-ring model
- **Blue** and **red** correspond to two different orientations for the *same* inclination
- The orientation dependence of the recovered rotation curves is due to non-circular motions in the galaxy plane
- This can ***in principle*** reproduce the diversity

Oman+17

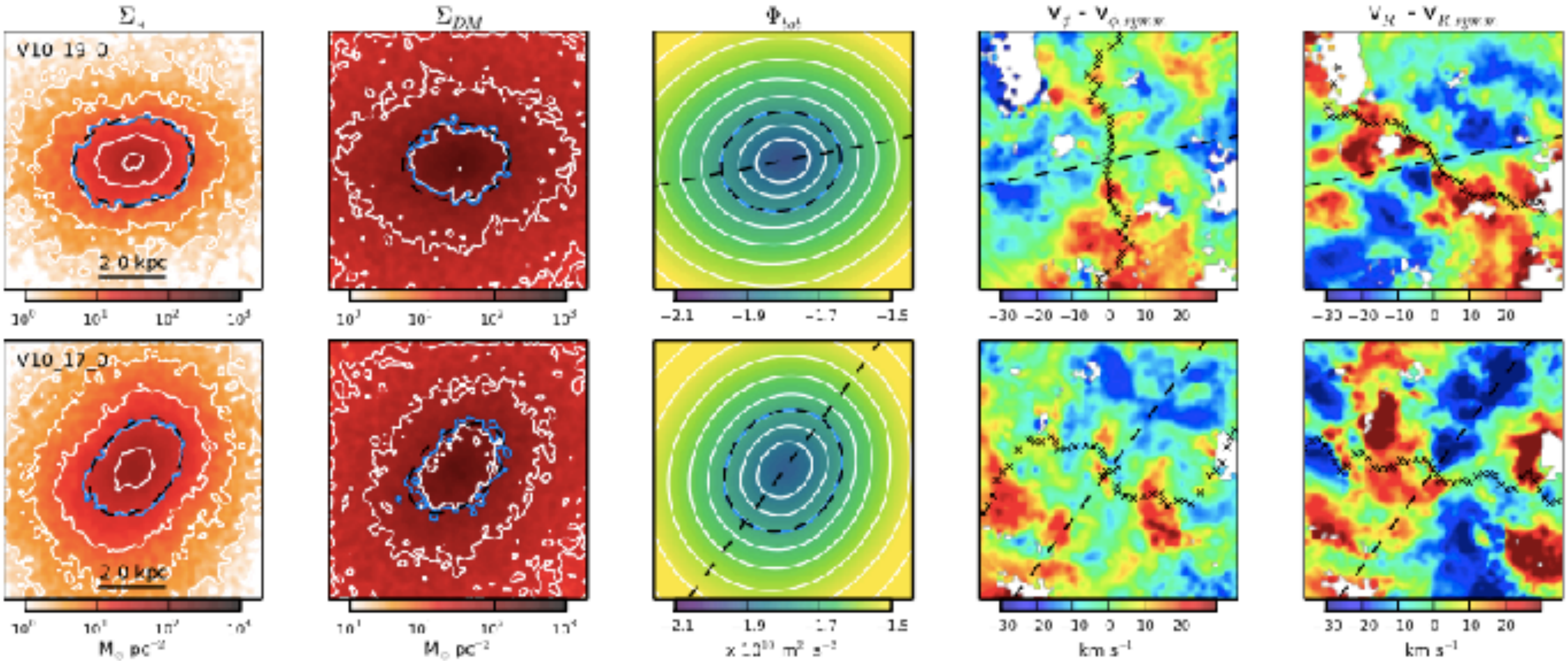
HI Velocity fields of APOSTLE galaxies



- The orientation dependence of the recovered rotation curves is due to non-circular motions in the galaxy plane
- Although the average V_ϕ is close to V_{circ}, there is a strong m=2 modulation in the velocity field

Oman+17

HI Velocity fields of APOSTLE galaxies

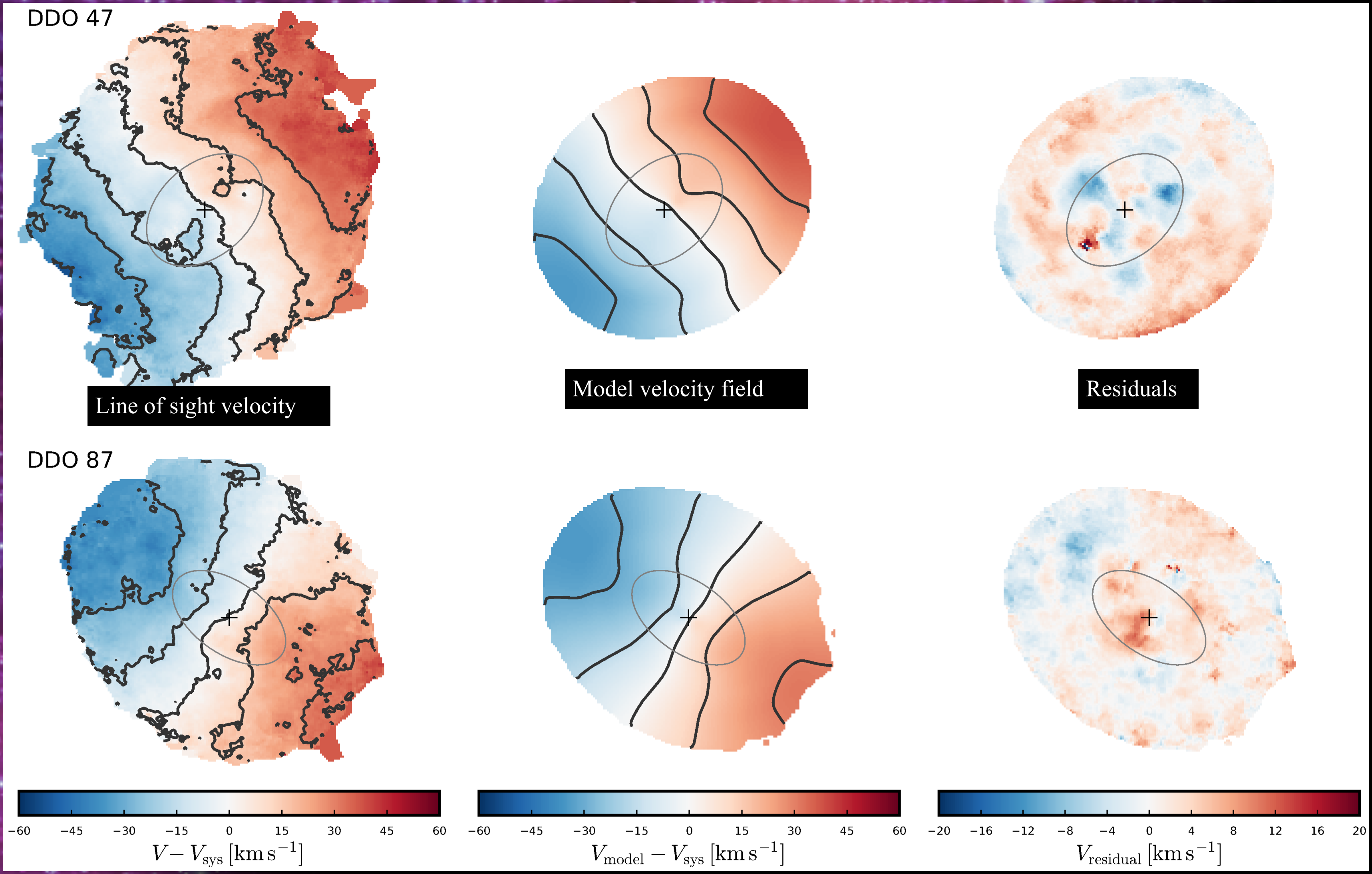


Star surface density | Dark matter surface density | Gravitational potential | Azimuthal velocity | Radial velocity

- The gravitational potential is dominated by the dark matter
- Bar-like features in dwarf galaxy disks are due to the slowly tumbling triaxial nature of their dark matter halos.

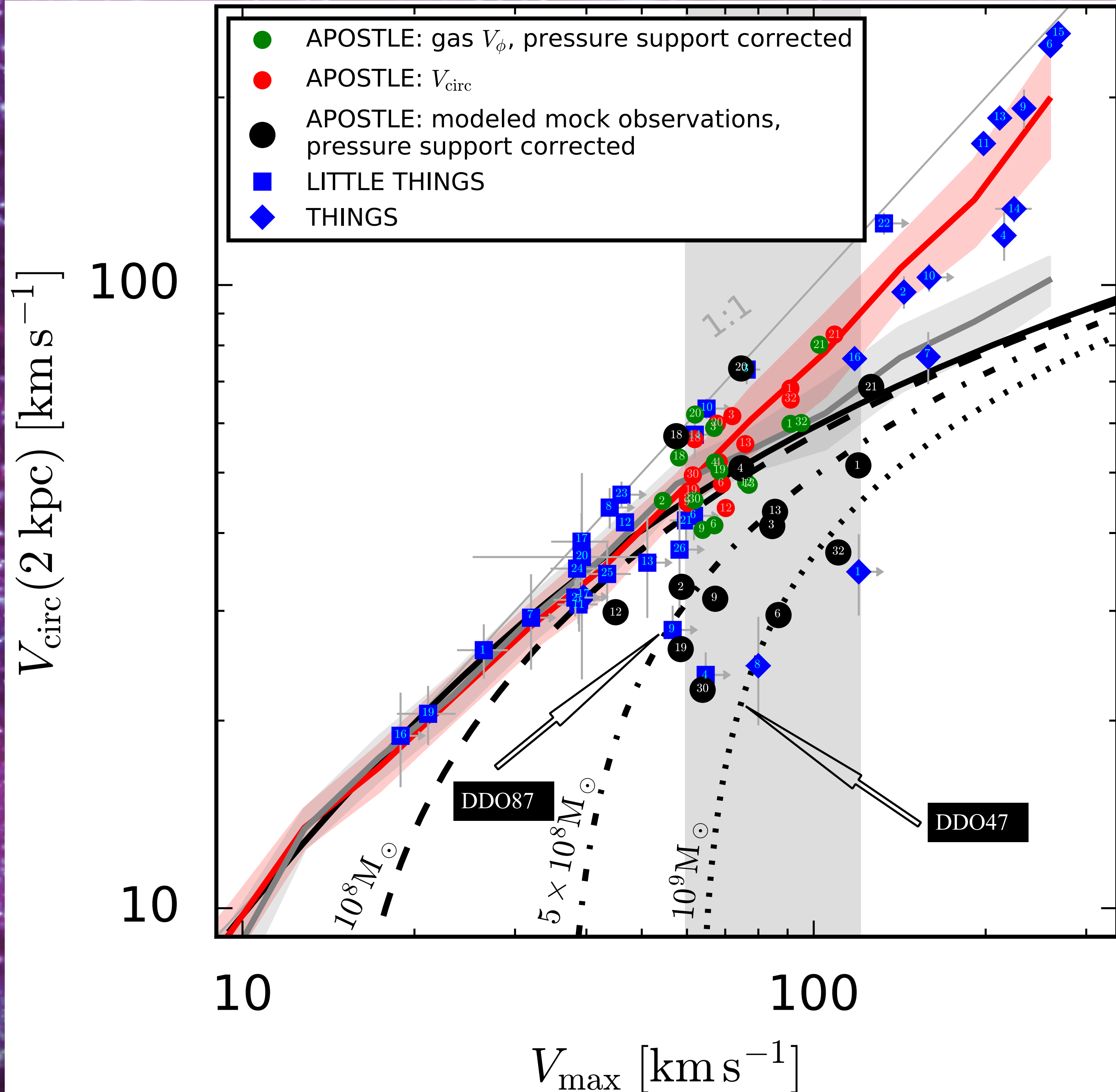
Marasco+17

HI Velocity fields of LITTLE THINGS galaxies



•The m=3 mode in projection is clearly present in two galaxies with slowly rising rotation curves reminiscent of constant density "cores"

Oman+17

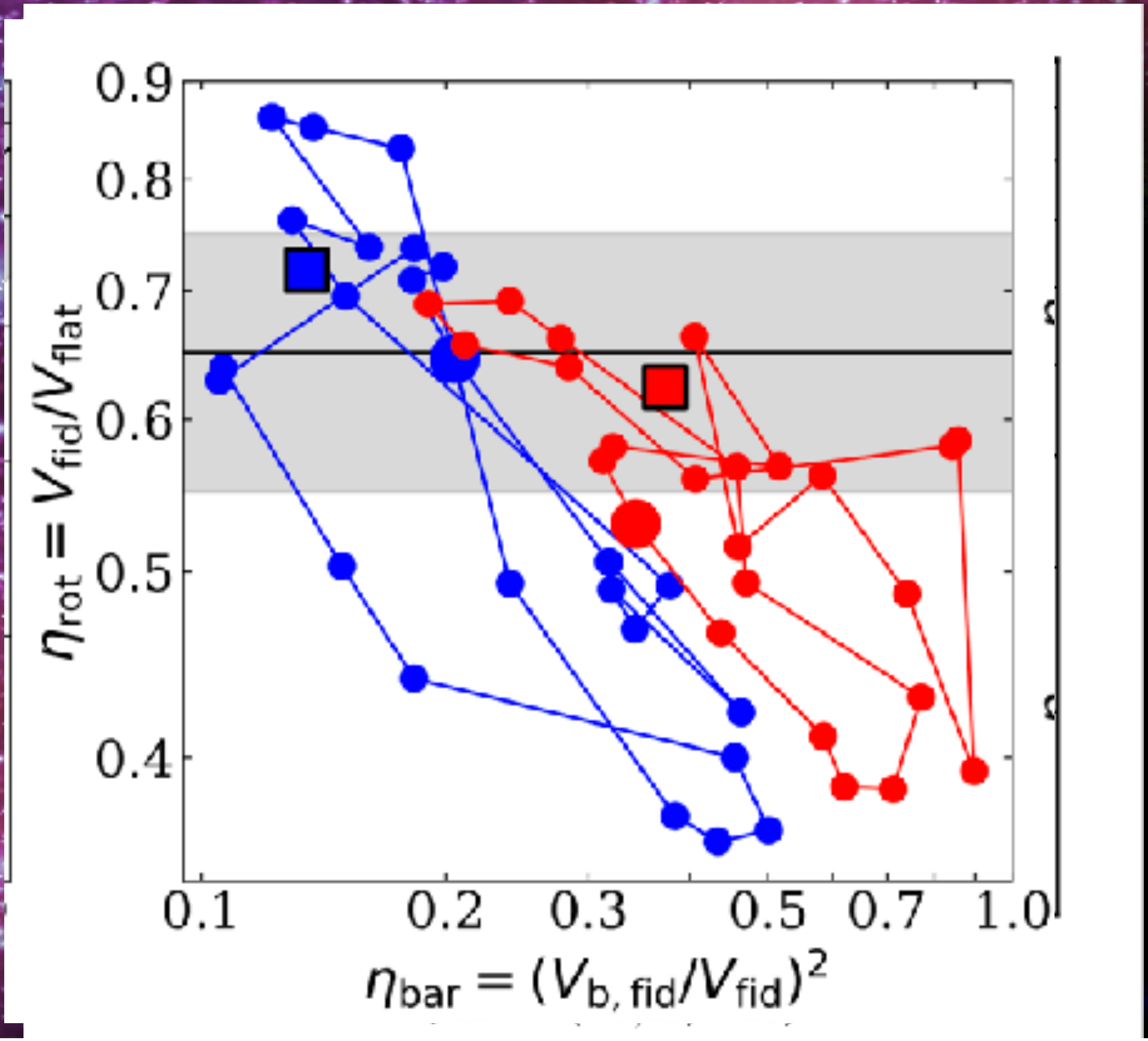


"Inner mass discrepancy" or non-circular motions?

- Two galaxies that deviate from LCDM predictions have velocity estimates clearly affected by non-circular motions
- Others may very well be affected too
- The "cusp vs core" issue may have just be caused by systematic uncertainties associated with tilted-ring models

Oman+17

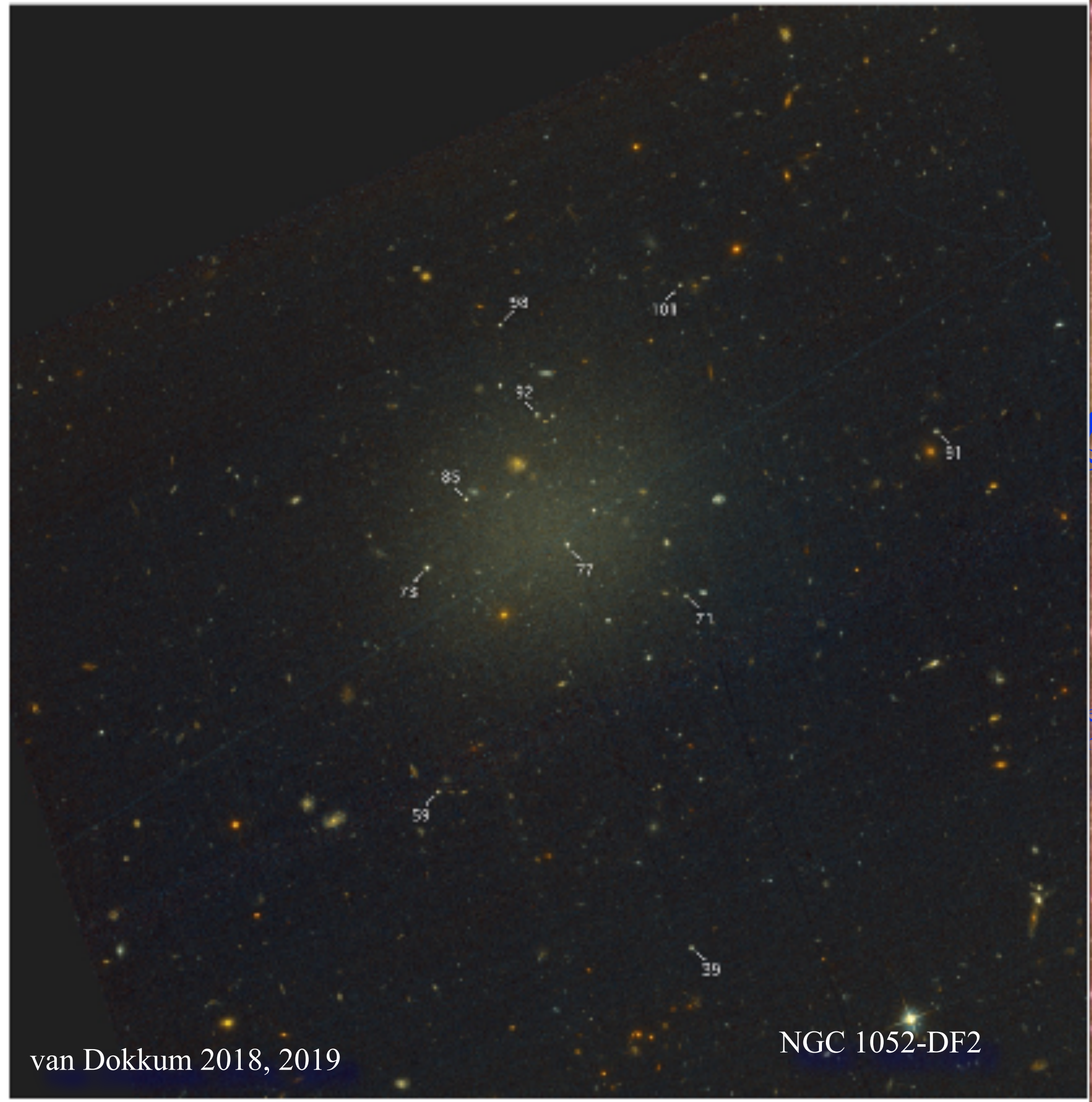
How to tell these scenarios apart?

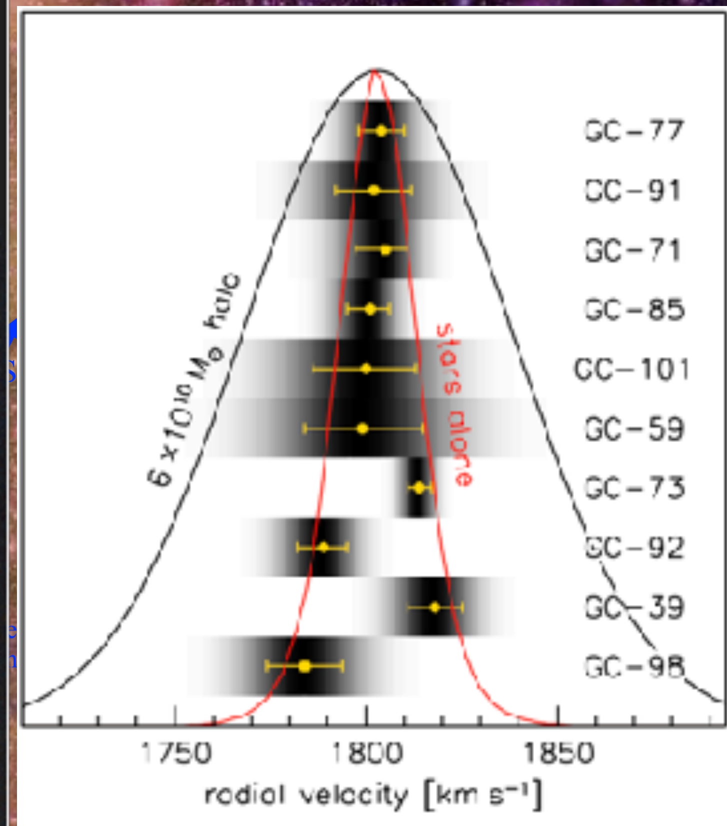


- Non-circular motions may explain naturally why the importance of the baryons at the fiducial radius correlates with the shape of the rotation curve

Roper+2022

Missing dark matter galaxies? NGC 1052-DF2





• Globular clusters in the “ultra-diffuse” galaxy companion of the elliptical NGC 1052 have vey low velocity dispersion, consistent with little or no dark matter content.

End of Lecture 3