

Is CDM ruled out?

Carlos S. Frenk
Institute for Computational Cosmology,
Durham



Is CDM ruled out?

Four problems for CDM on small scales?

1. The “missing satellites” problem
2. The “too-big-to-fail” problem
3. The “core-cusp” problem
4. The “satellite disk” problem

The “missing satellites” problem in CDM

The satellites of the MW

Dark matter subhalos in CDM

“Missing satellites” problem:

The Milky Way has only about 25 satellites

BUT: CDM halos have a very large number of subhalos

Why are most subhalos dark?

100,000



The “too-big-to-fail” problem

$$V_c = \sqrt{\frac{GM}{r}}$$

$$V_{\max} = \max V_c$$

The satellites of the MW

Dark matter subhalos in CDM

“Too-big-to-fail” problem:

Milky way has only 3 satellites with $V_{\max} > 30$ km/s

BUT: CDM has ~ 10 subhalos with $V_{\max} > 30$ km/s

Why did these not make a galaxy?



The core-cusp problem

cold dark matter

warm dark matter

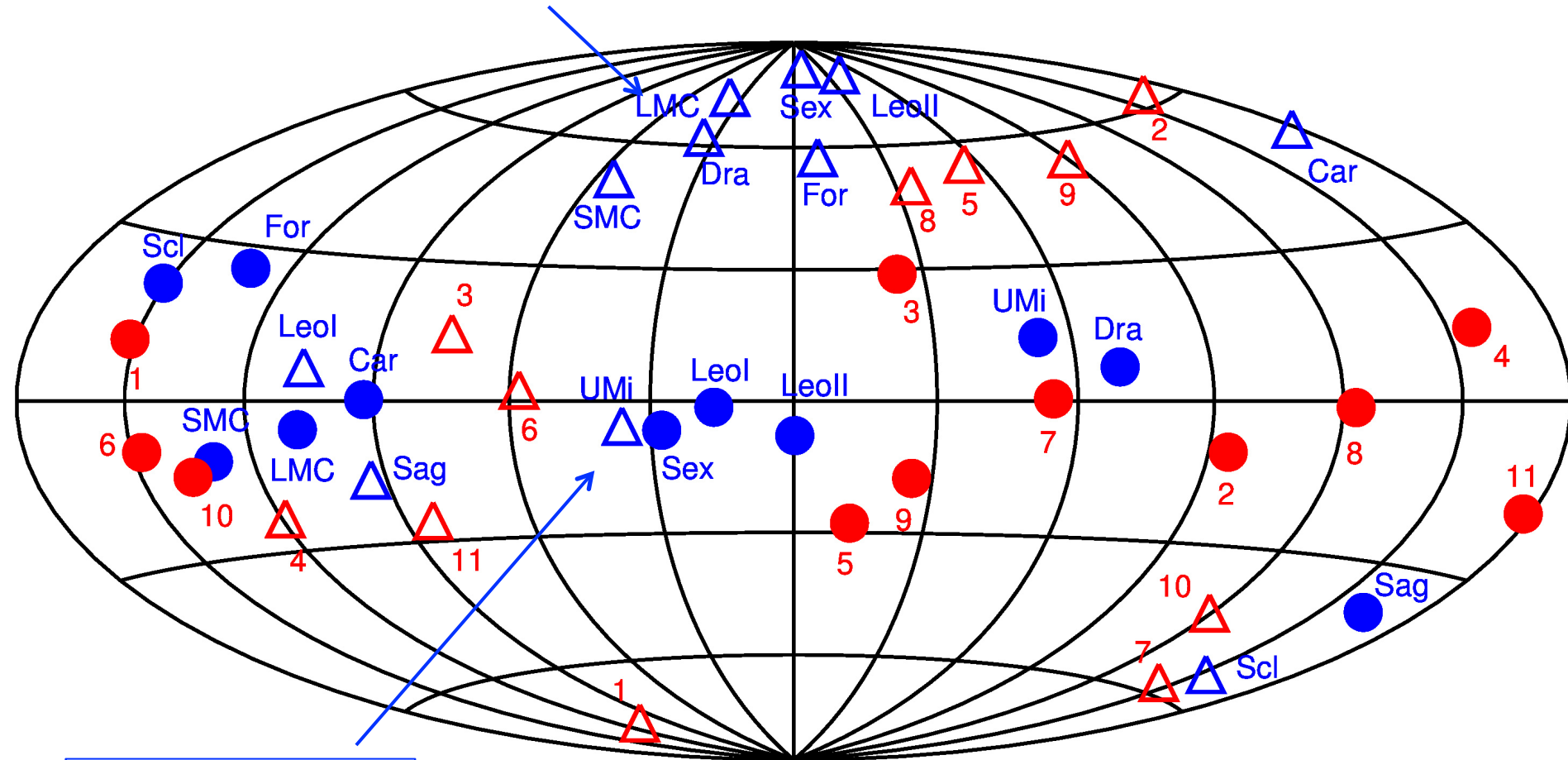
“Core-cusp” problem:

CDM halos & subhalos have **cuspy** density profiles

BUT: kinematical data are said to “show” that the dwarf satellites of the Milky Way have **cores**

The “satellite disk” problem

Direction of ang. mom. Milky Way



MW satellites

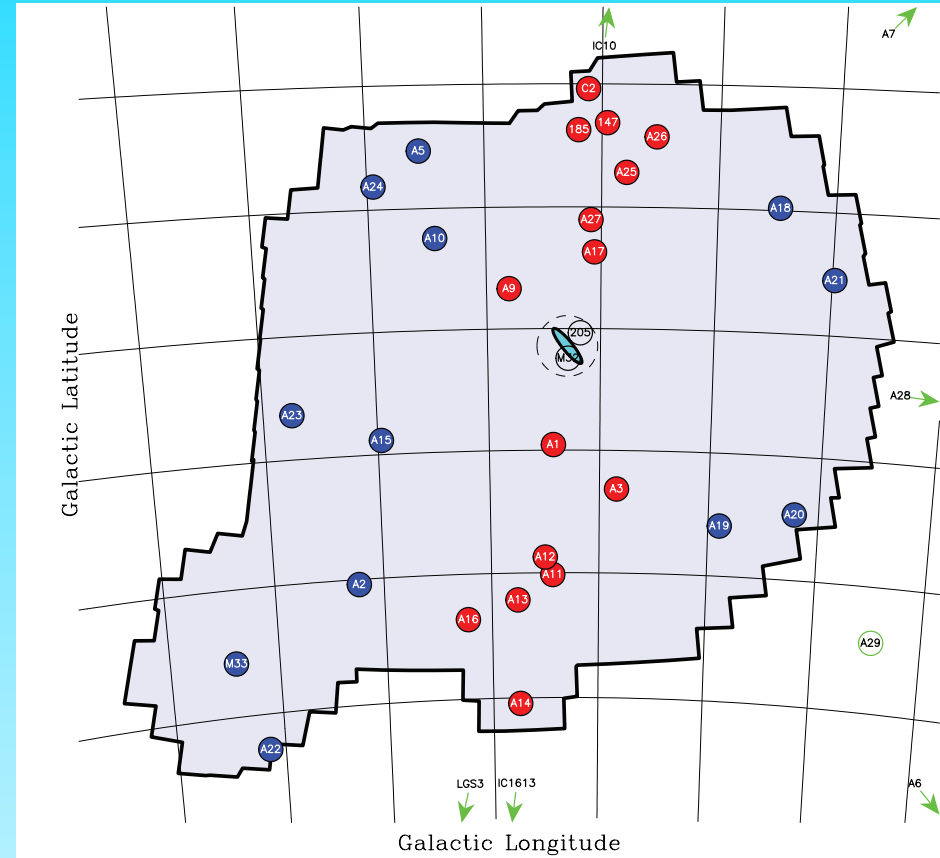
Lynden-Bell '76

The curious case of a thin, “rotating” plane of sats in M31

Ibata et al '13 found a **plane** of **15 satellites** in Andromeda (out of 27) of which **13** have the same sense of **rotation**

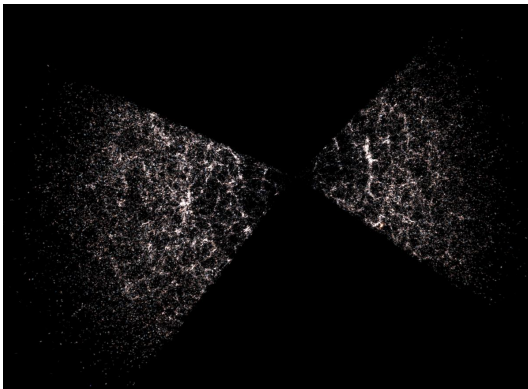
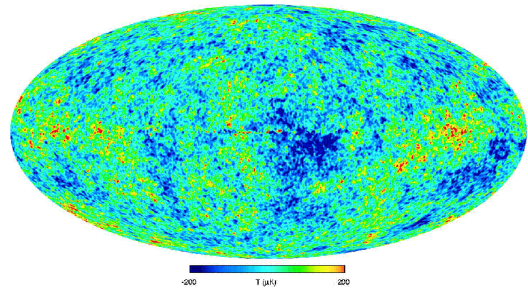
They claim a 4.3σ detection

“We find that 0.04% of host galaxies [in Millennium II] display satellite alignments that are at least as extreme as the observations, when we consider their extent, thickness, and number of members rotating in the same sense.”



Ibata et al '13

The cosmic power spectrum: from the CMB to the 2dFGRS



⇒ Λ CDM provides an excellent description of mass power spectrum from 10-1000 Mpc

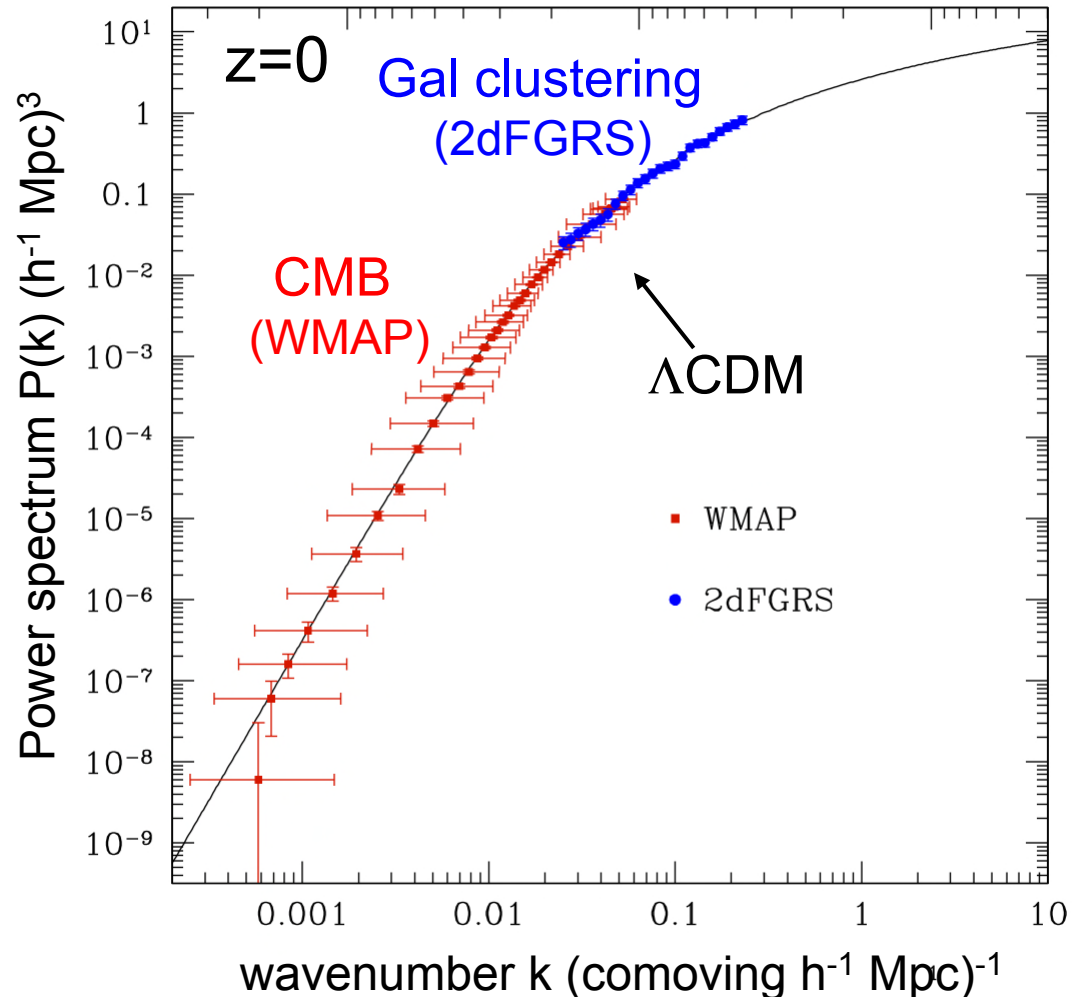
Sanchez et al 06

$z \sim 1000$

$\text{Log } k^3 P(k)$

wavelength k^{-1} (comoving h^{-1} Mpc)

1 000 100 10



The cosmic power spectrum: from the CMB to the 2dFGRS

Free streaming $\rightarrow$

$$\lambda_{\text{cut}} \propto m_x^{-1}$$

for thermal relic

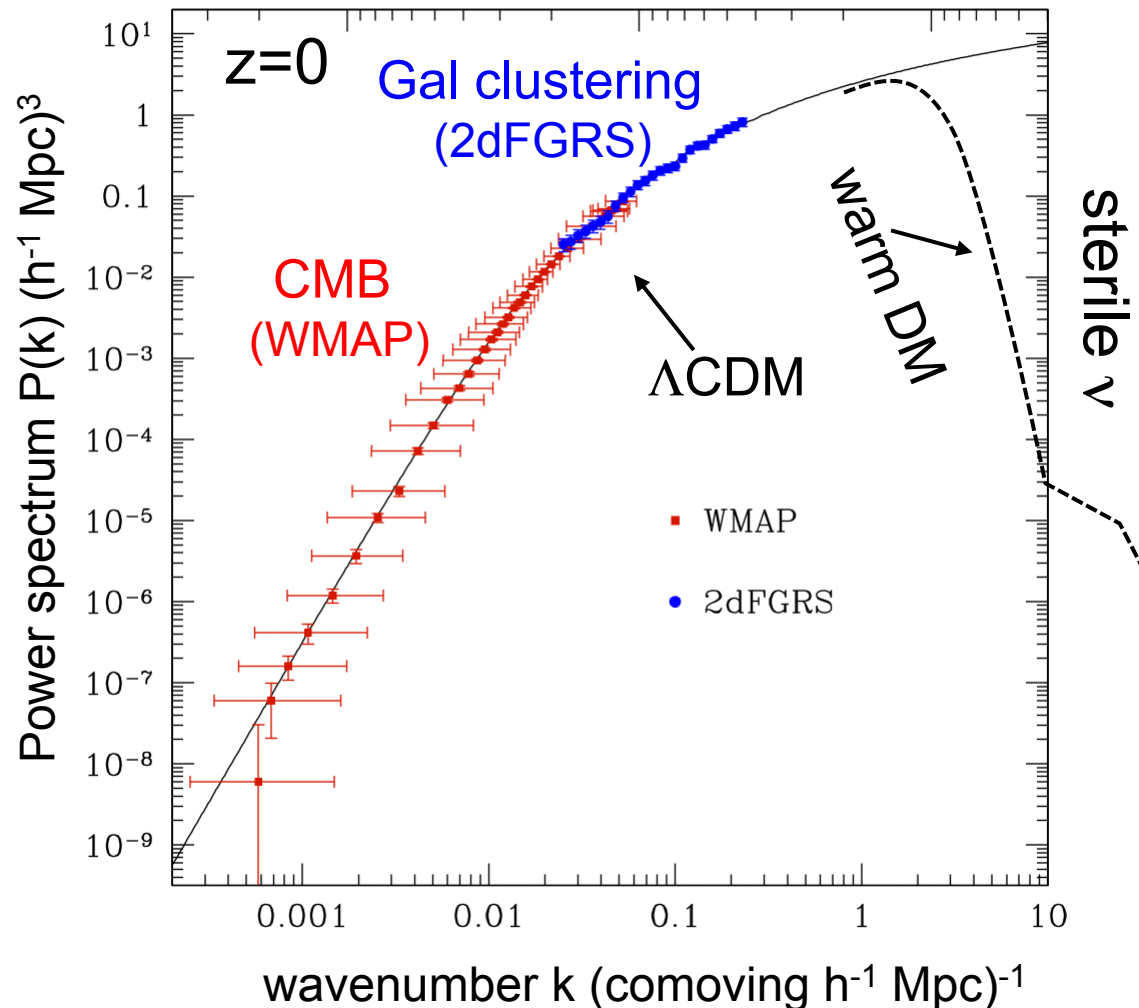
$$m_{\text{CDM}} \sim 100 \text{ GeV}$$

$$\text{susy}; M_{\text{cut}} \sim 10^{-6} M_{\odot}$$

$$m_{\text{WDM}} \sim \text{few keV}$$

$$\text{sterile } \nu; M_{\text{cut}} \sim 10^9 M_{\odot}$$

Log $k^3 P(k)$ wavelength k^{-1} (comoving $h^{-1} \text{ Mpc}$)



cold dark matter



warm dark matter



Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy '12

Four problems on small scales

Traditionally ascribed to CDM:

Different in WDM

- 1. The “missing satellites” problem
- 2. The “too-big-to-fail” problem

The same in WDM

- 3. The “core-cusp” problem
- 4. The “satellite disk” problem

Can these help distinguish between CDM & WDM?

Four problems for CDM on small scales?

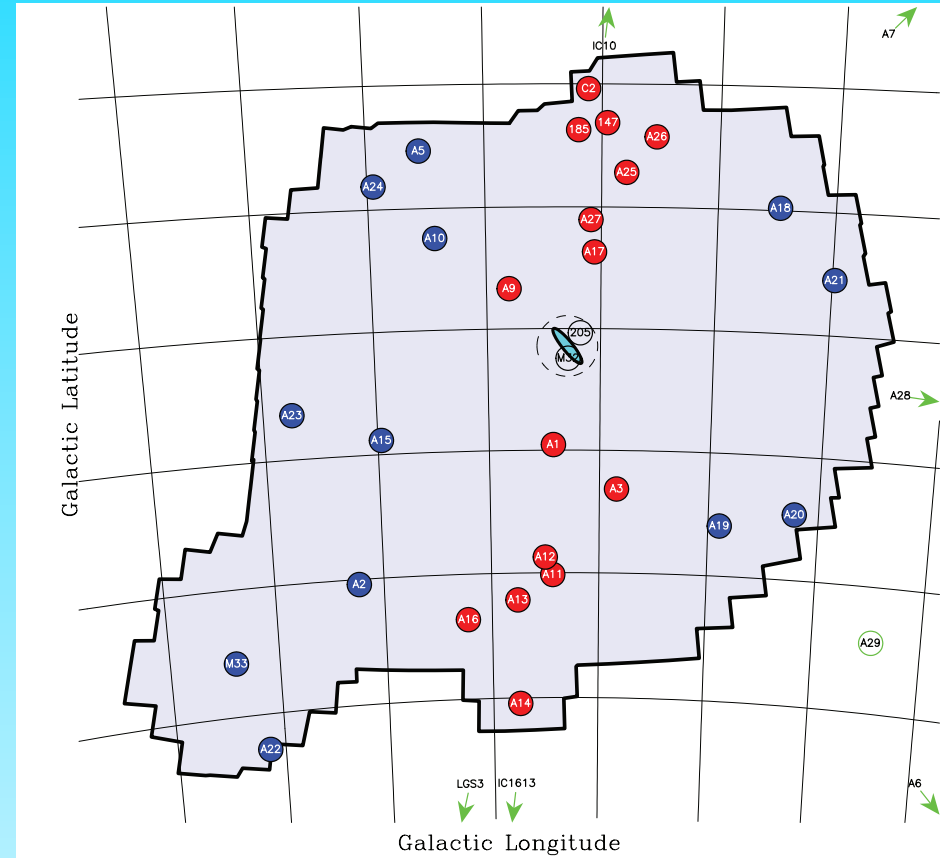
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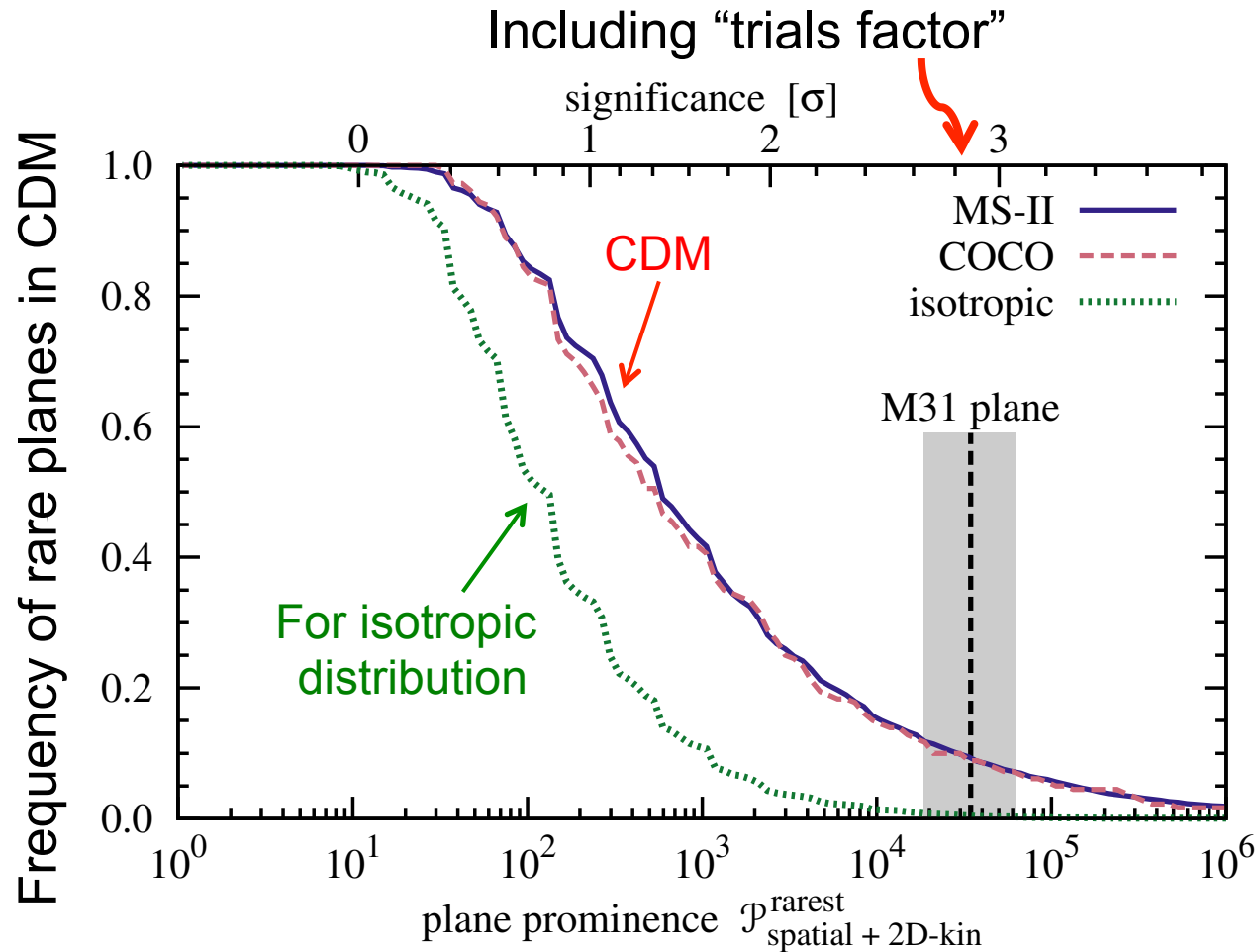
“We find that **0.04%** of host galaxies [in **Millennium II**] display satellite alignments that are at least as extreme as the observations, when we consider their extent, thickness, and number of members rotating in the same sense.”



Ibata et al ‘13

The significance of Ibata's plane

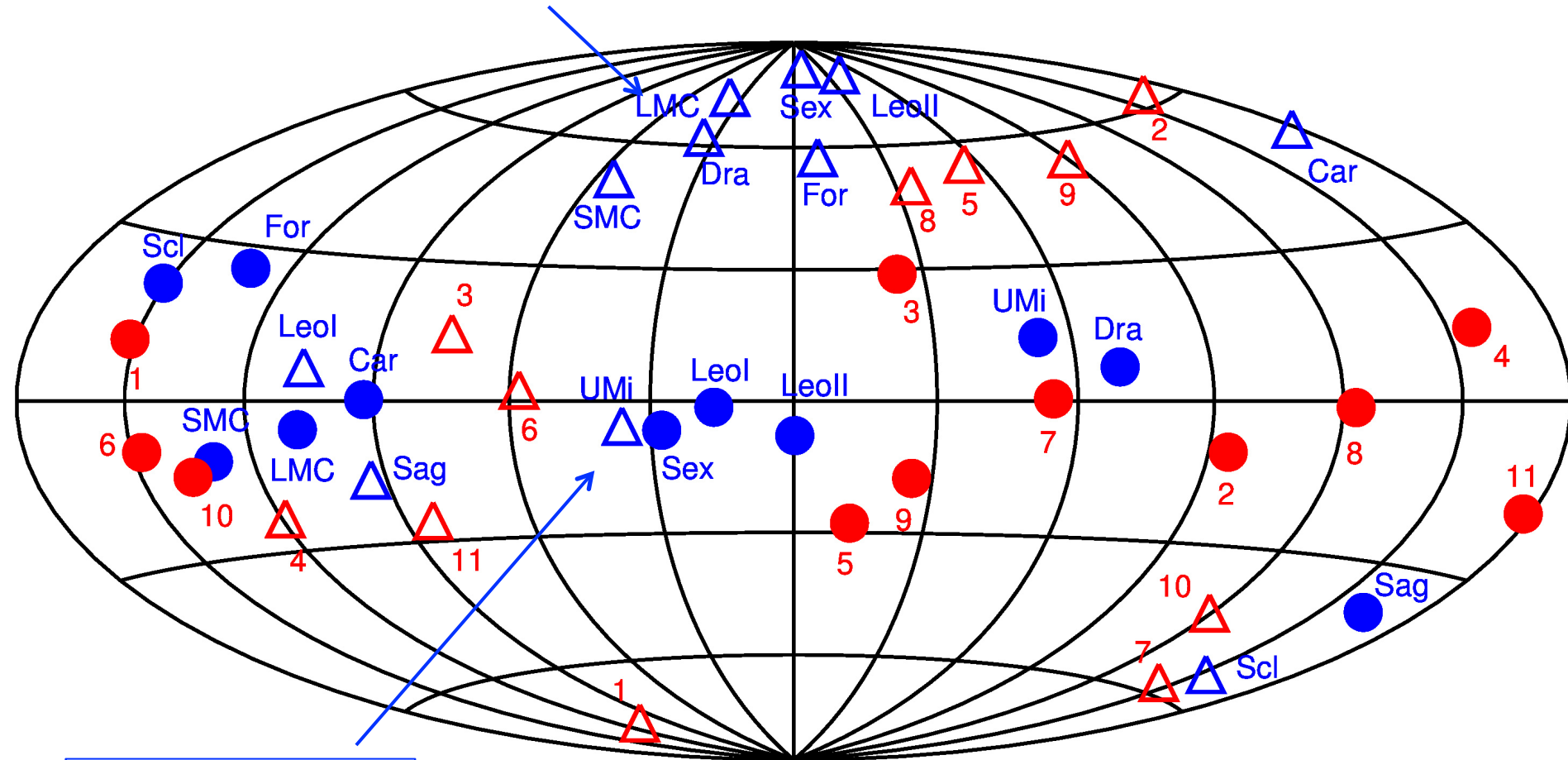
- Significance of Ibata's plane is reduced by x100 when trials factor is included
- 8.8% of halos in Λ CDM simulation have even more prominent disks than Ibata's



In random distribution, 1 in 30,000 chance of finding a plane of 15 sats (out of 27) as thin found by Ibata et al., with at least 13 having same sense of rotation

The “satellite disk” problem

Direction of ang. mom. Milky Way

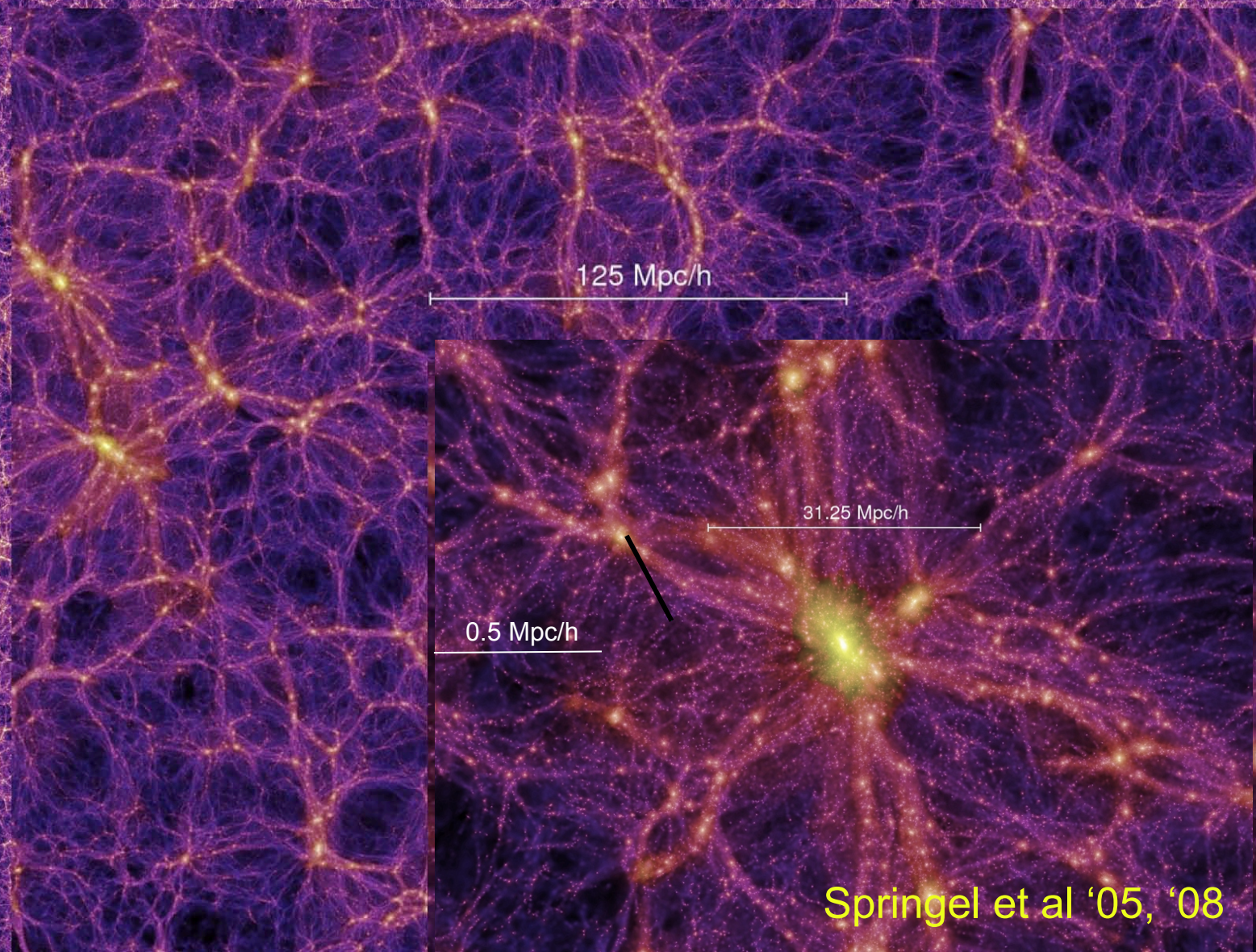


MW satellites

Lynden-Bell '76

VIRGO

The Millennium/Aquarius simulation series





Is there a “satellite disks problem” in CDM?

No, when statistics are properly calculated

Satellite planes are v. common in Λ CDM: 5 & 9% of halos have even more prominent planes than Milky Way and Andromeda

Four problems for CDM on small scales?

1. The “missing satellites” problem
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These problems have all been identified in N-body simulations that follow only dark matter

Need to consider “baryon effects”

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The “missing satellites” problem

The satellites of the MW



Dark matter subhalos in CDM

“Missing satellites” problem:

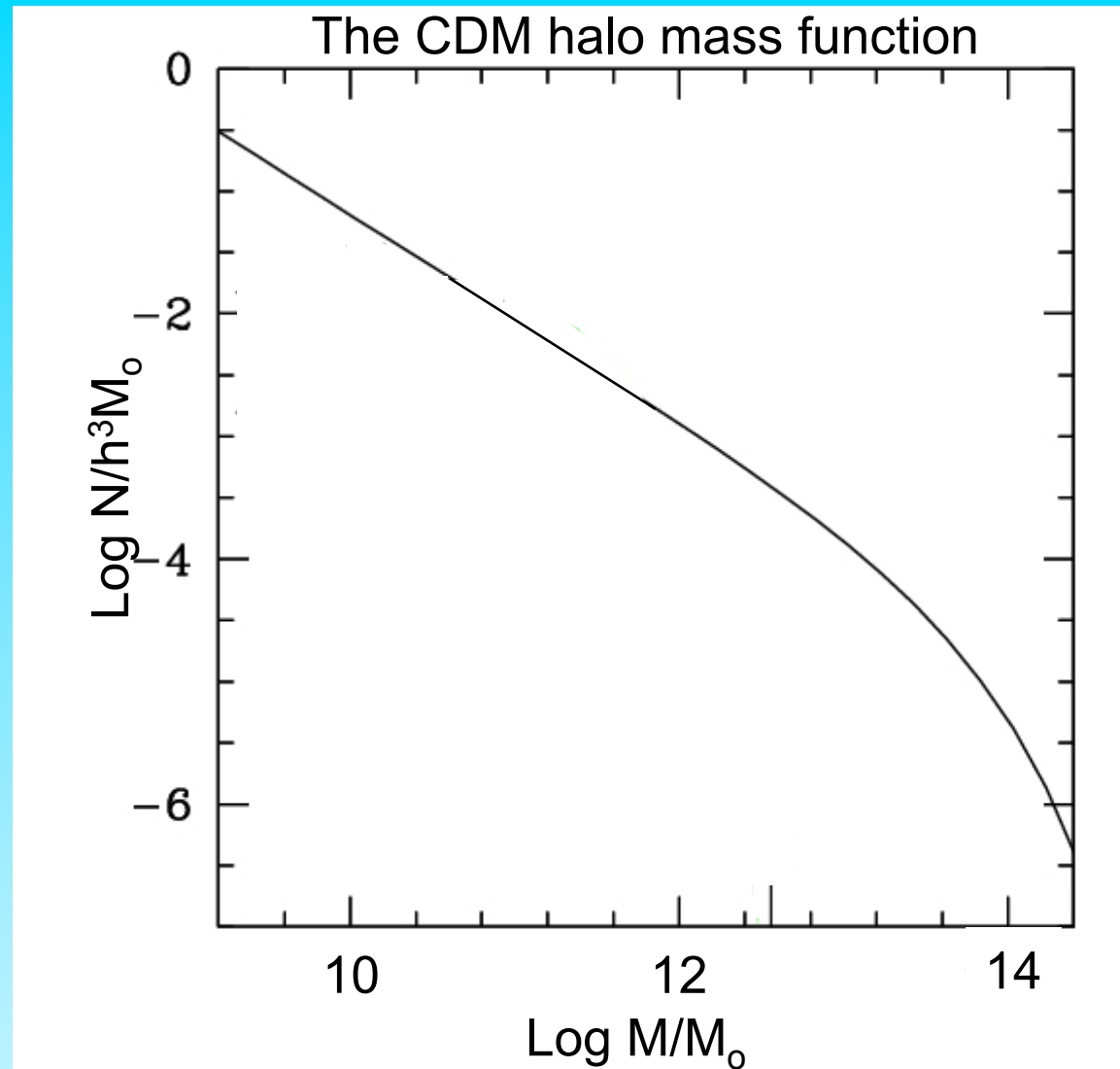
The Milky way has only about 25 satellites

BUT: CDM halos have a huge number of subhalos

Why are most subhalos dark?

The CDM halo mass function

Jenkins et al. '01



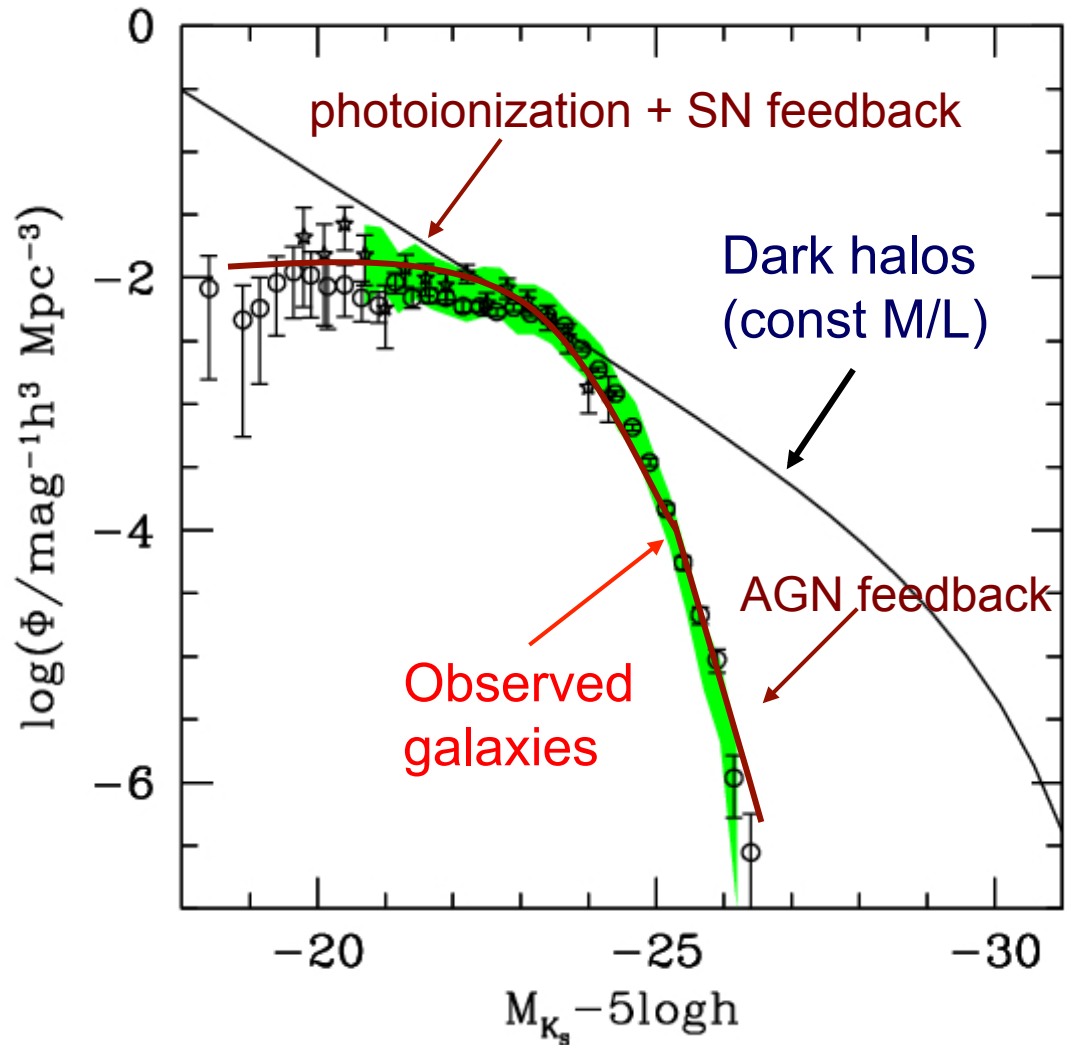
The galaxy luminosity function

The halo mass function and the galaxy luminosity function have different shapes



Galaxy luminosity not just $\propto$ halo mass

Complicated variation of M/L with halo mass



White & Frenk '91; Kauffmann et al '93; Benson et al '03; Croton et al '06; Bower et al. '06

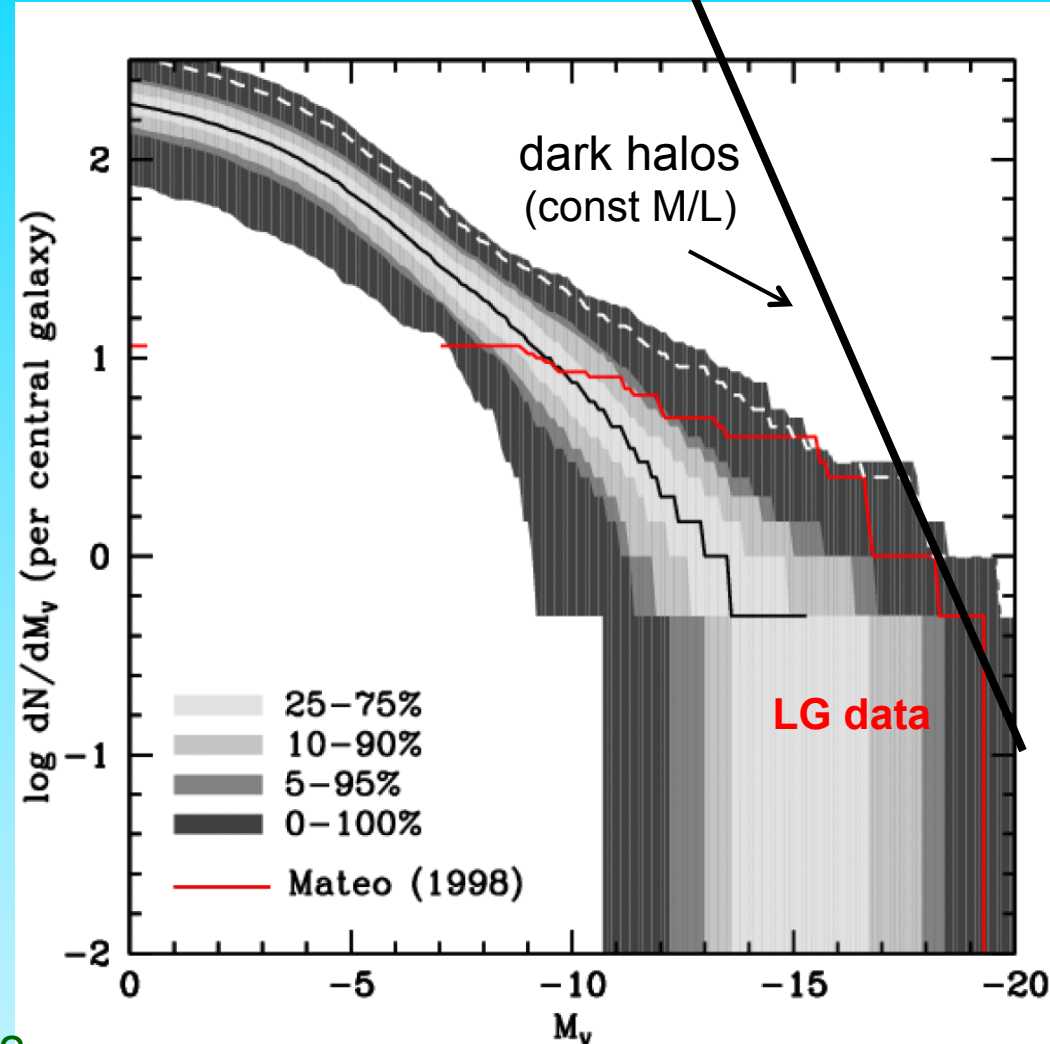
Making a galaxy in a small halo is hard because:

- Reionization heats gas above T_{vir} , preventing it from cooling and forming stars in small halos
- Supernovae feedback expels residual gas

Most subhalos never make a galaxy!

Luminosity Function of Local Group Satellites

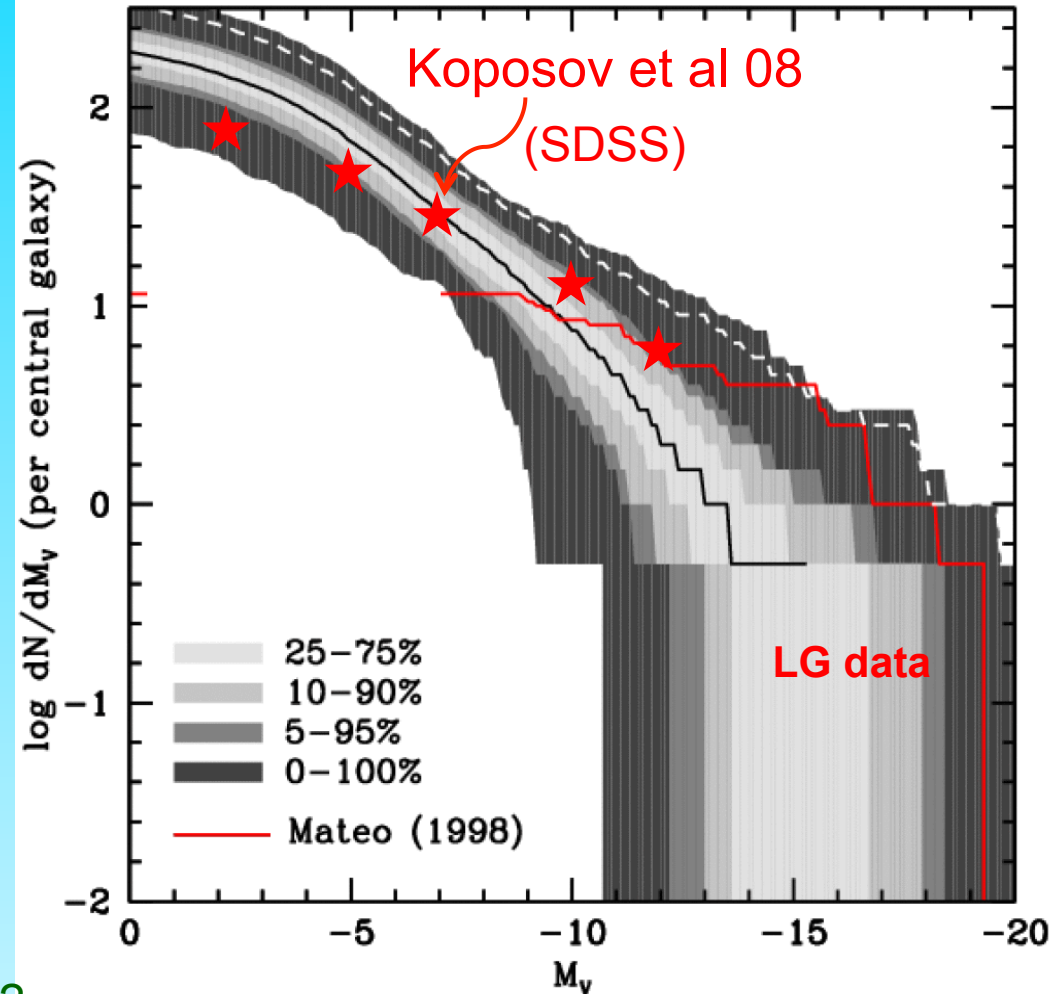
- Median model → correct abund. of sats brighter than $M_V = -9$ and $V_{\text{cir}} > 12$ km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock et al '01)

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VIRGO

icc.dur.ac.uk/Eagle

“Evolution and assembly of galaxies and
their environment”

THE EAGLE PROJECT

Virgo Consortium

Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

Leiden: Rob Crain, Joop Schaye.

Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth...

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

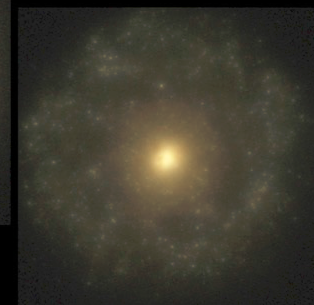
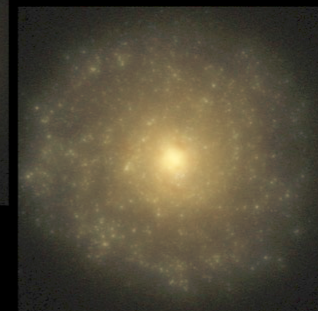
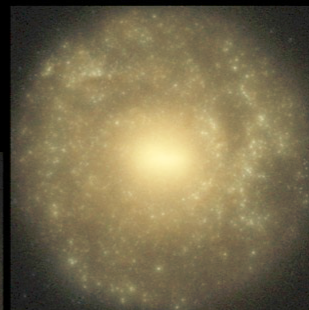
The Hubble Sequence realised in cosmological simulations

SB

E0

E7

S0



S

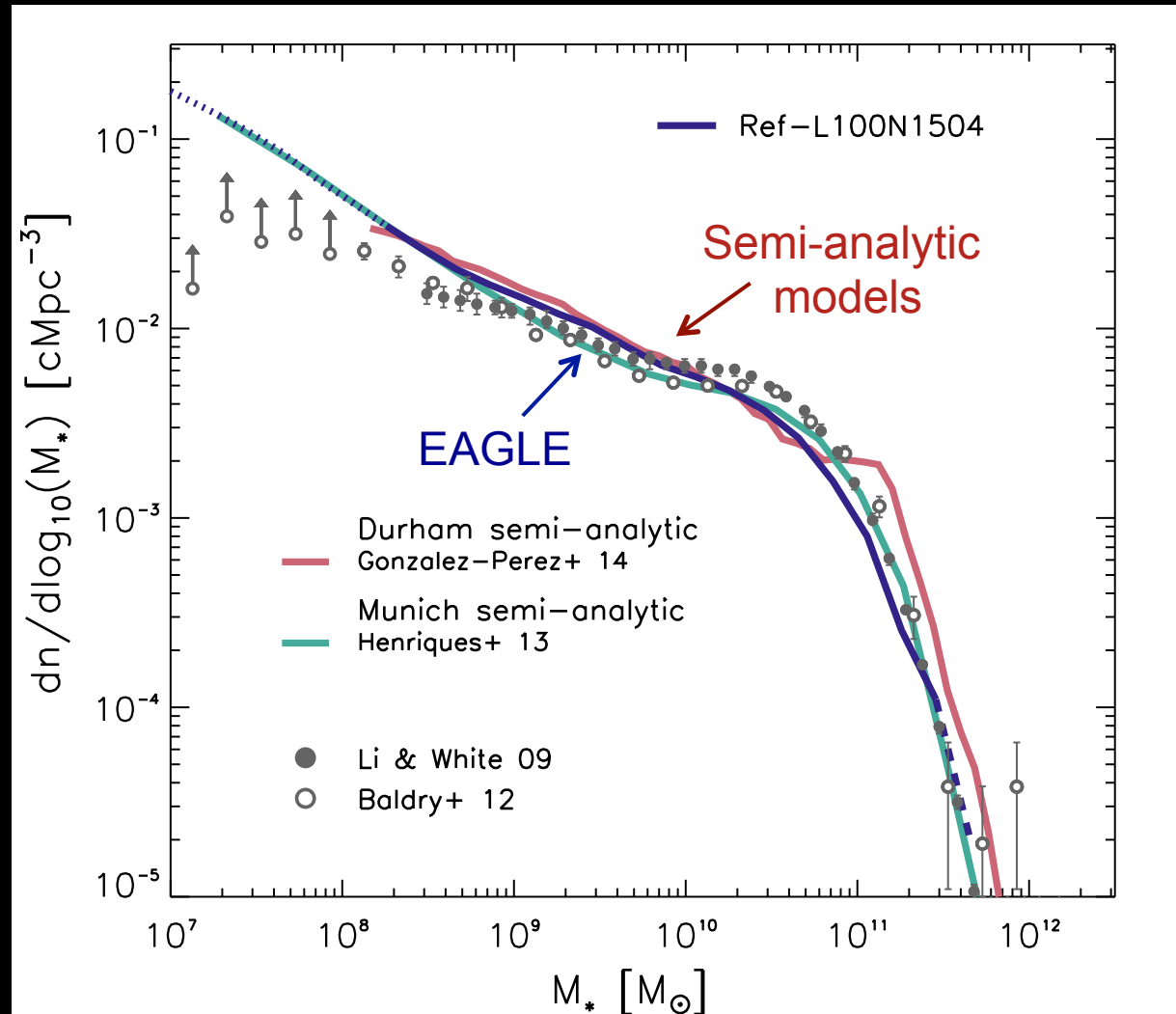


Irr

Trayford et al '14

Galaxy stellar mass function

Eagle gives a good match to observed stellar mass fn over 5 orders of magnitude in stellar mass



VIRG

Dark matter

APOSTLE
project

Local
Group
hydro sims
w. EAGLE

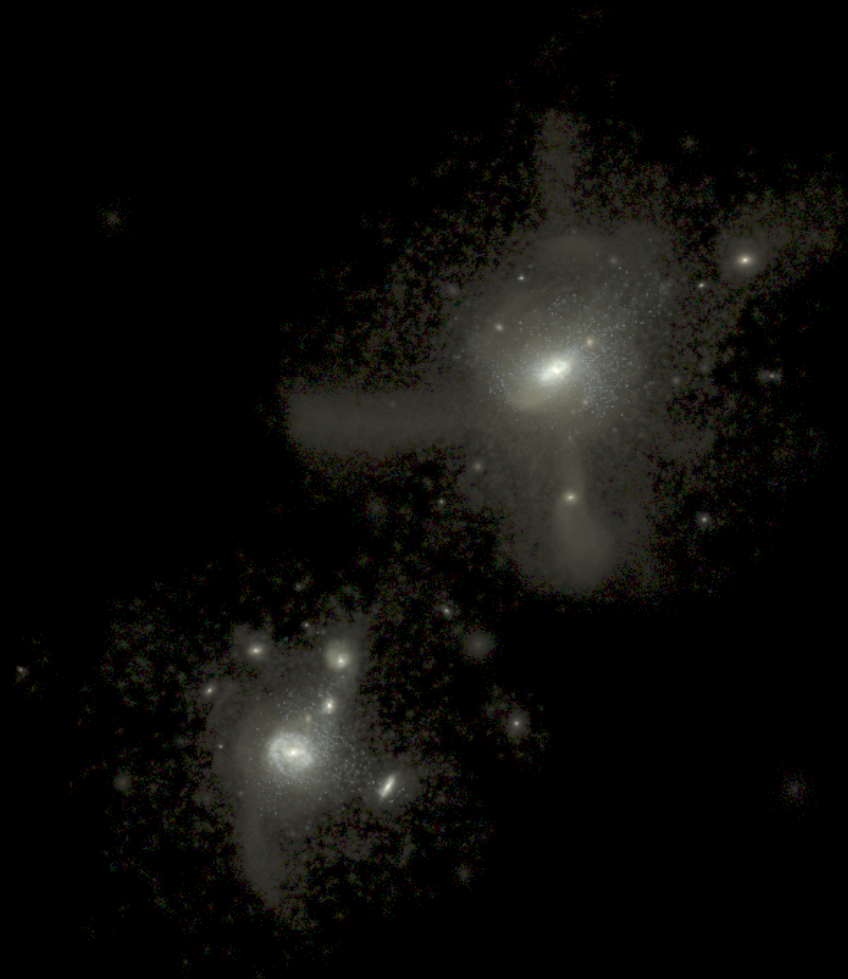
Sawala et al '15



Stars

APOSTLE
project

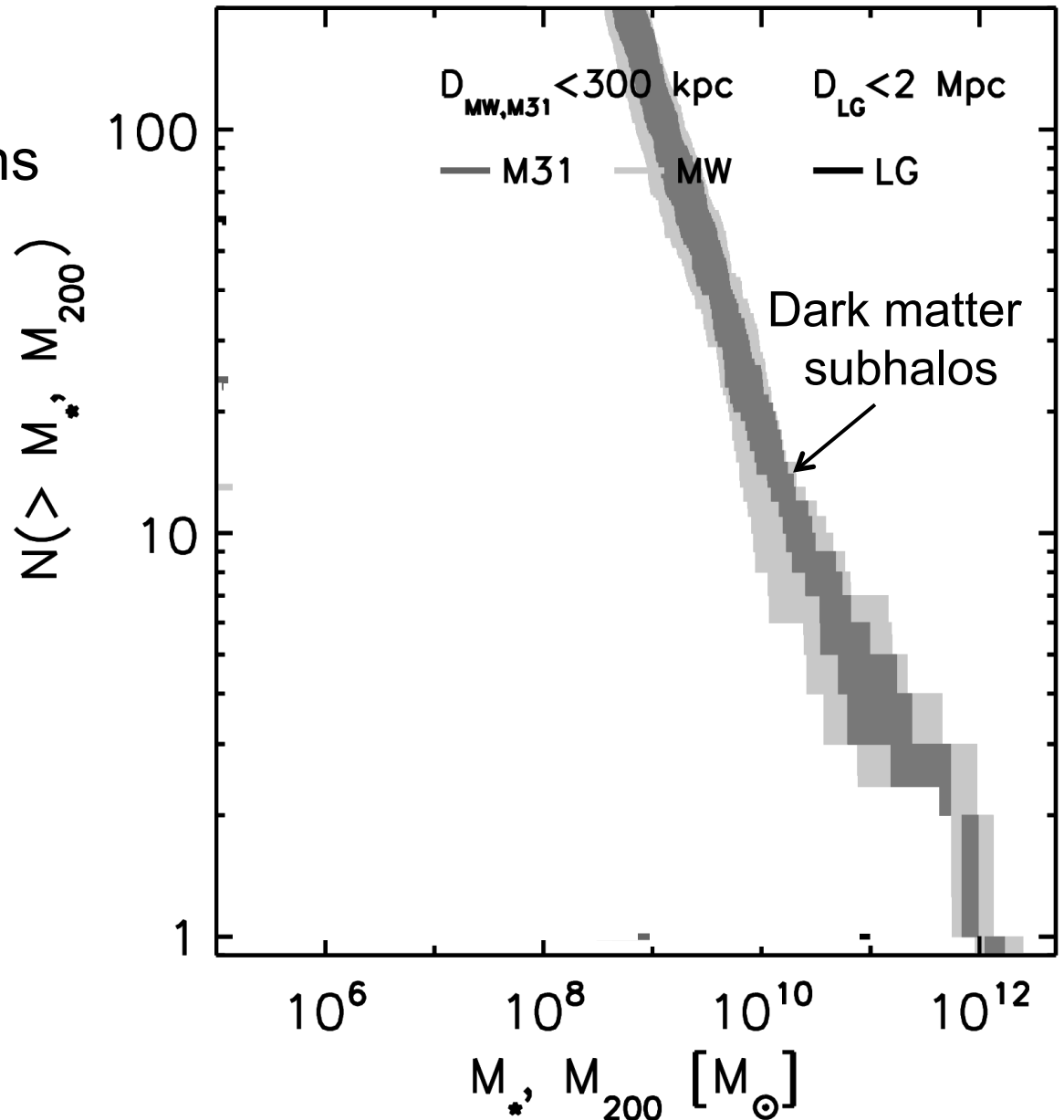
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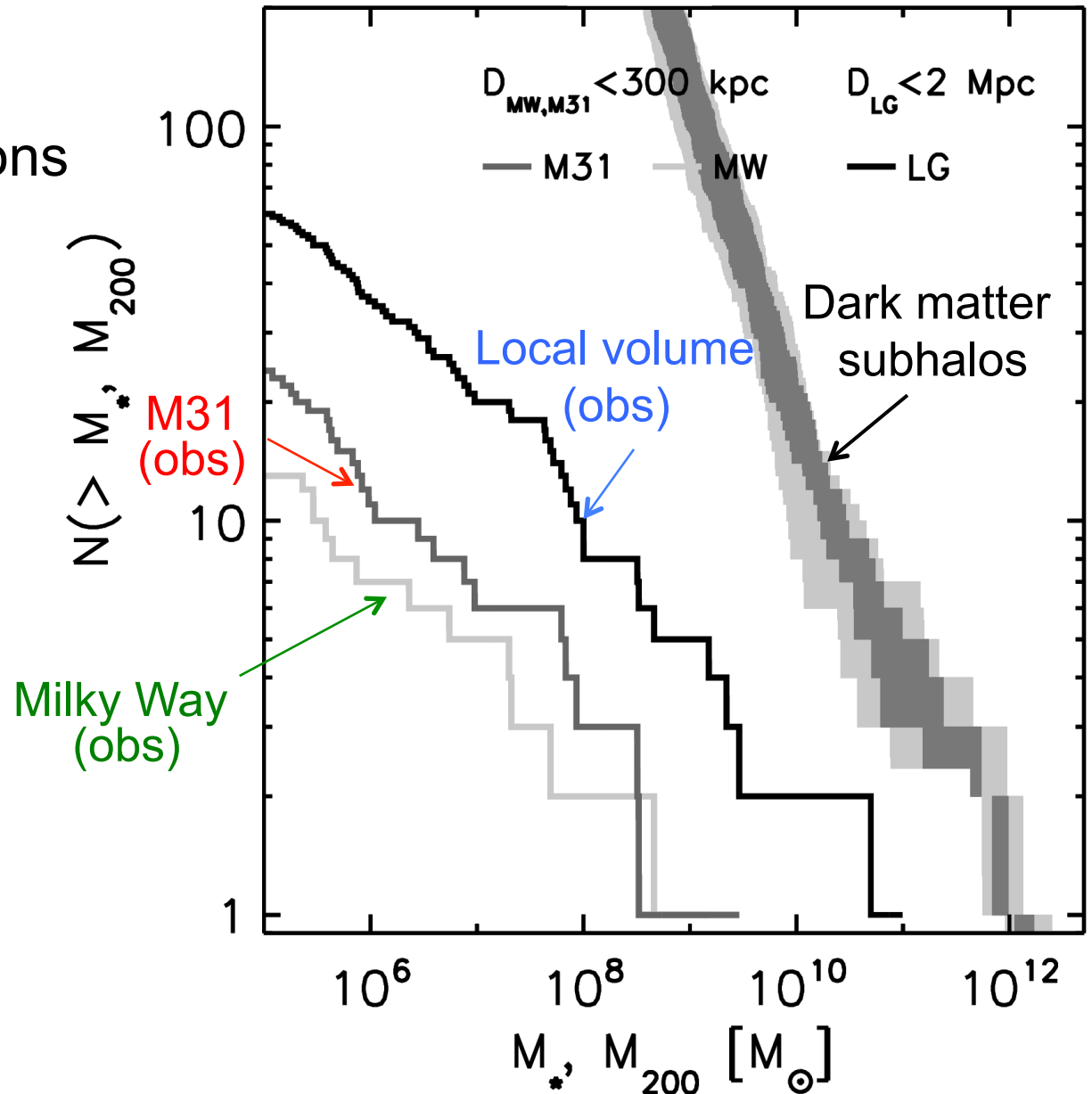
Far fewer satellite galaxies than CDM halos

Sawala et al '15

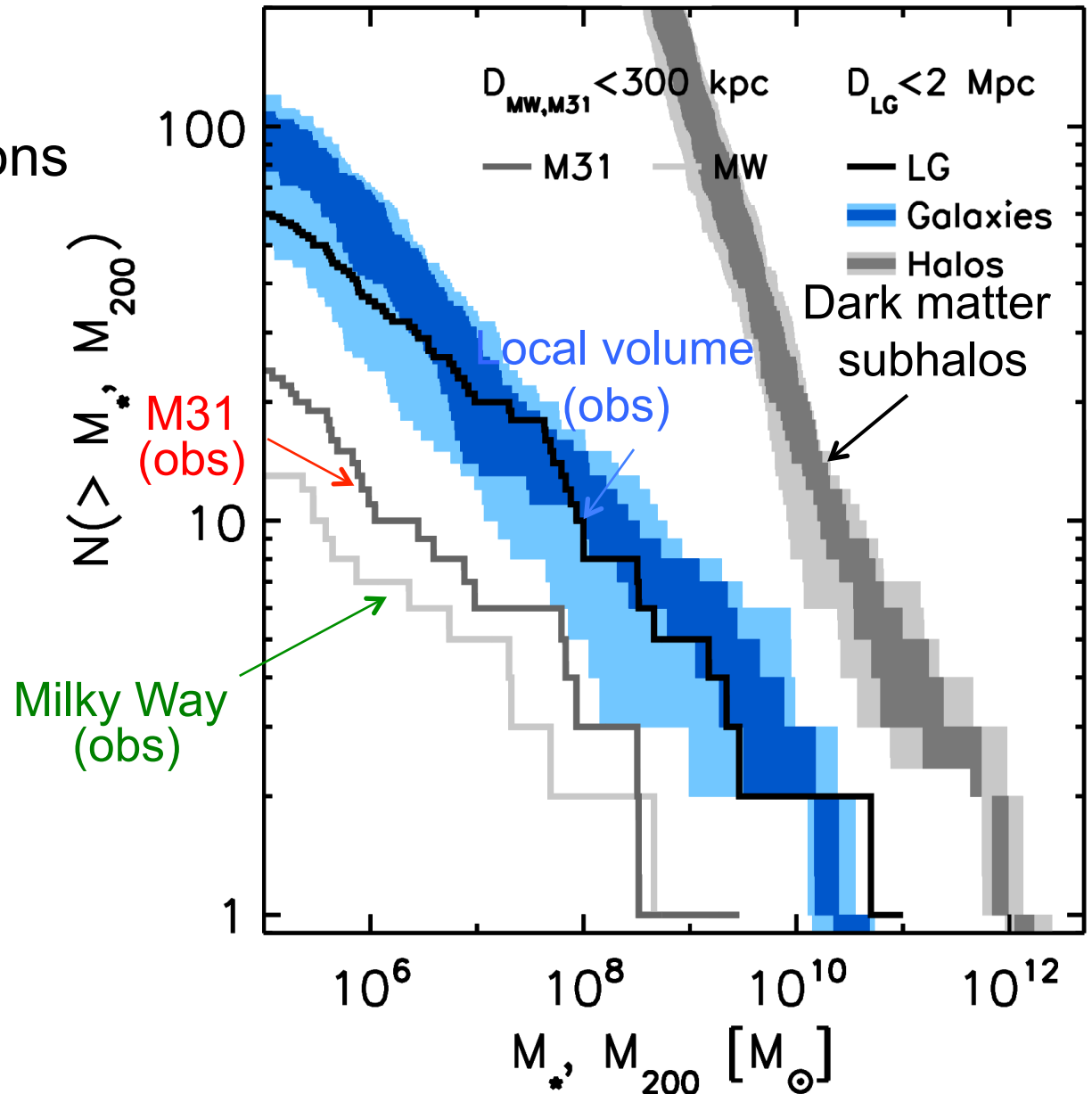
Subhalo mass functions



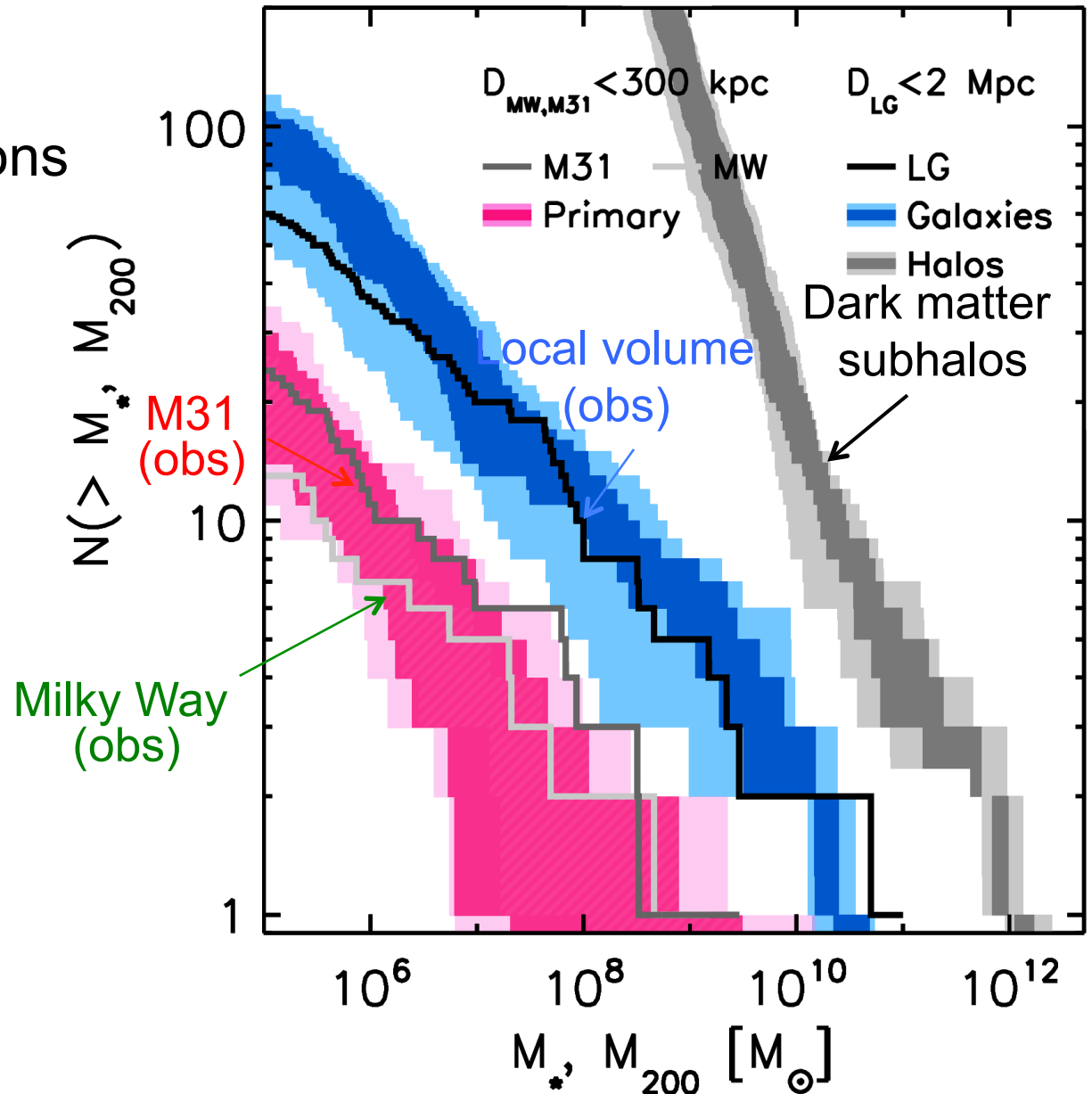
Stellar mass functions



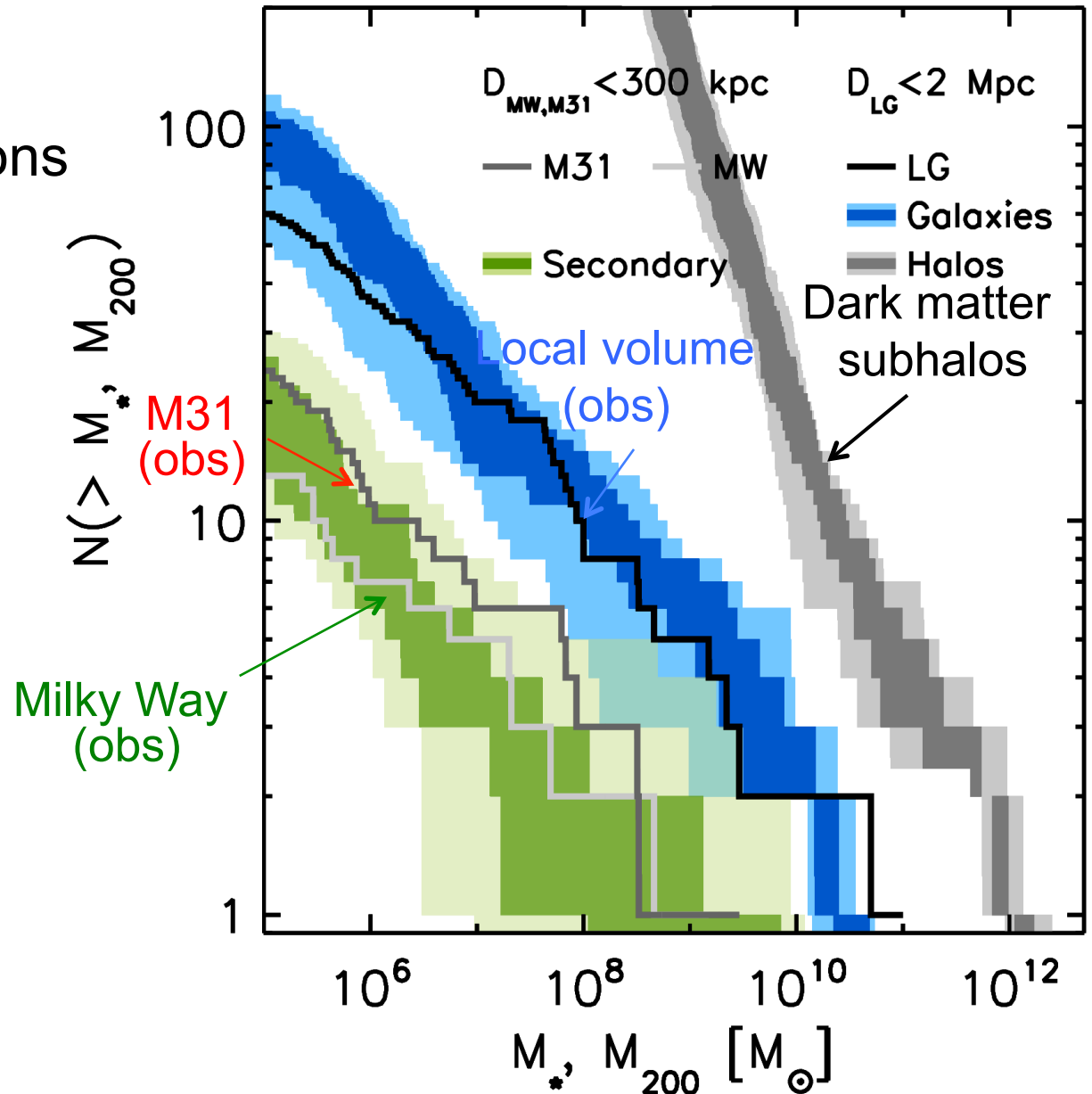
Stellar mass functions



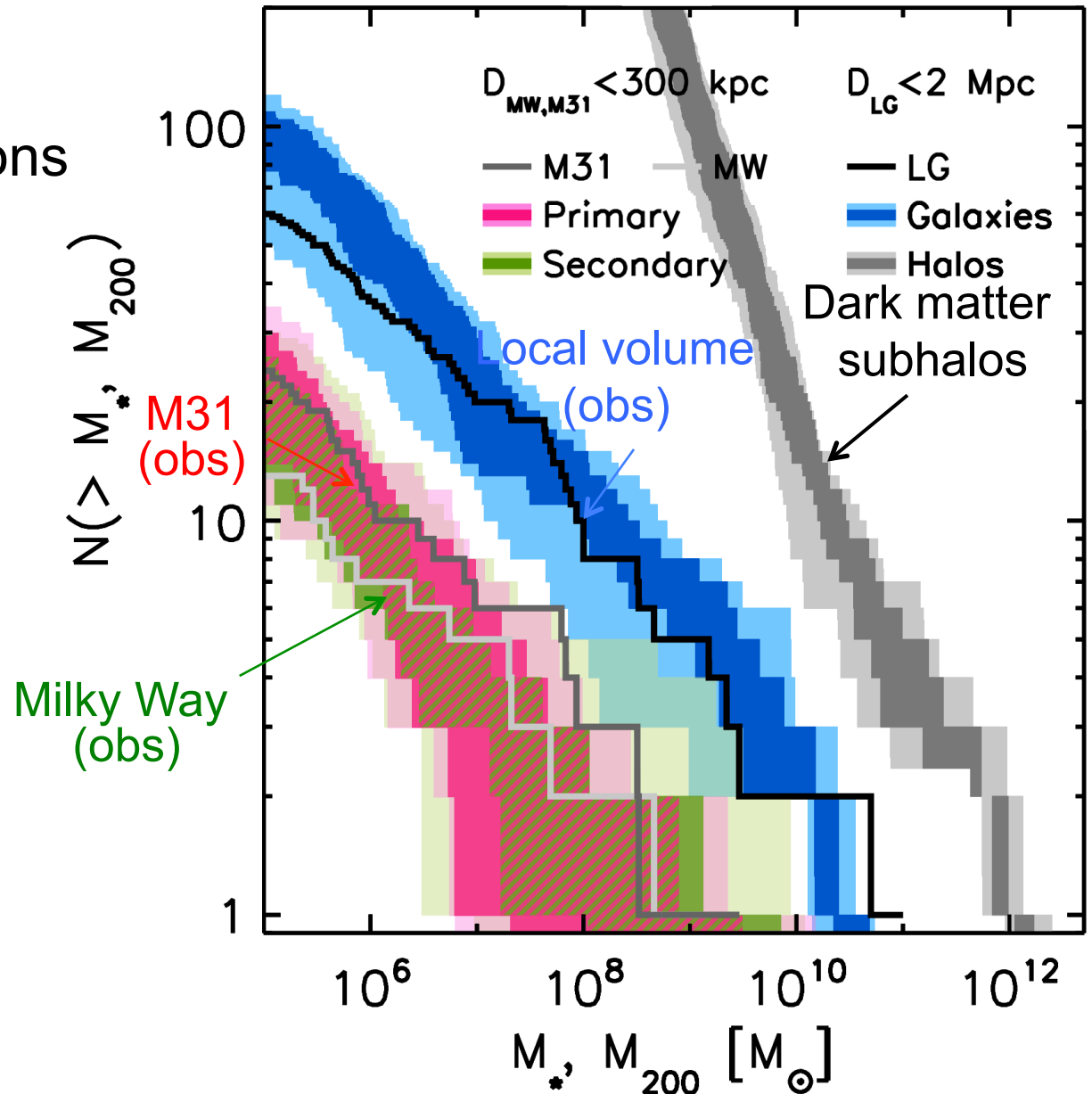
Stellar mass functions



Stellar mass functions



Stellar mass functions





Is there a “satellite problem” in CDM?

No, when galaxy formation is taken into account!

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$$V_c = \sqrt{\frac{GM}{r}}$$

$$V_{\max} = \max V_c$$

The satellites of the MW



CDM has ~ 10 subhalos with $V_{\text{max}} > 30$ km/s

MW has only 3 satellites
with $V_{\text{max}} > 30 \text{ km/s}$
(LMC, SMC, Sgr)

Why did these not make a galaxy?

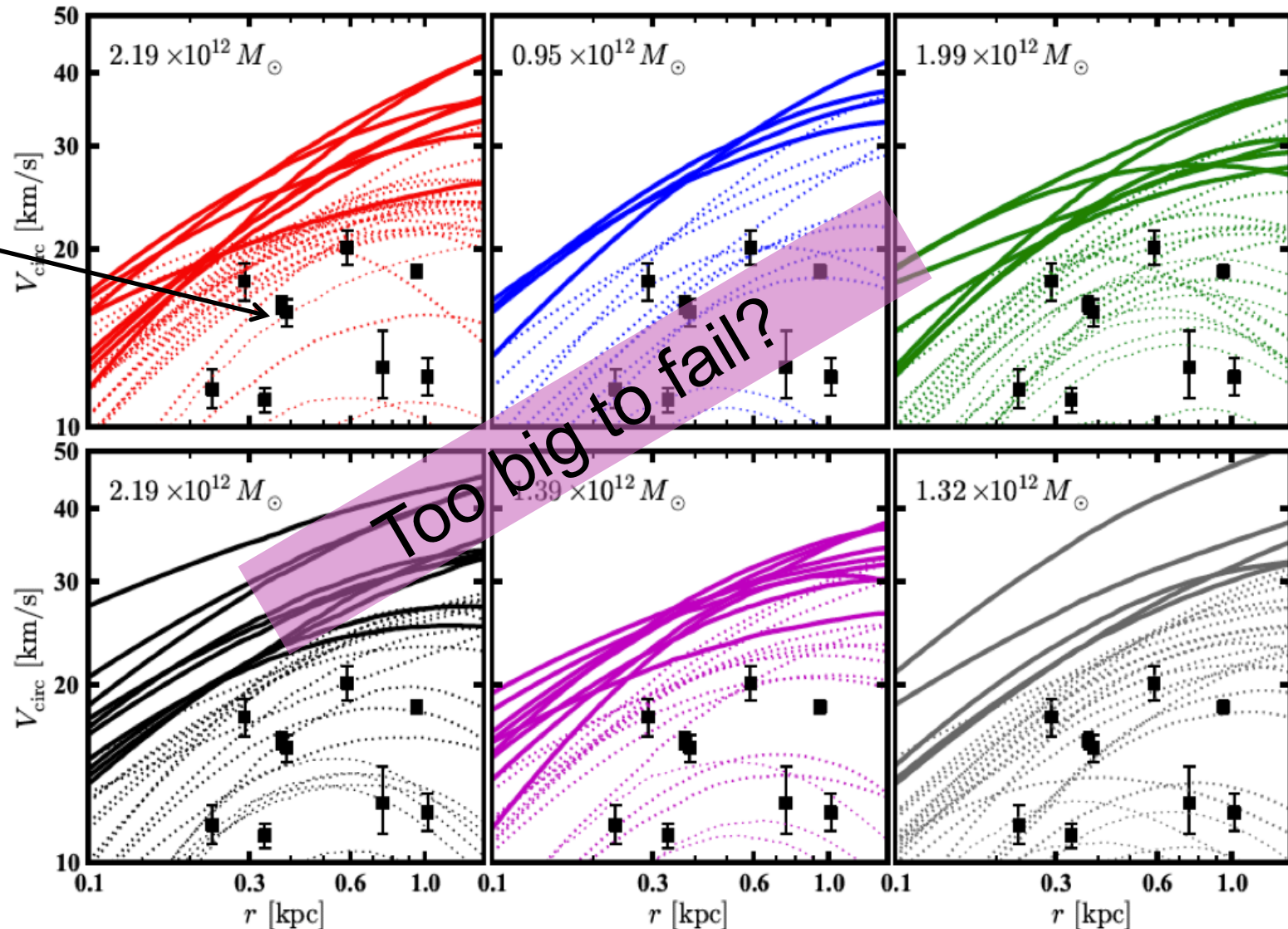
Rotation curves of Aquarius subhalos

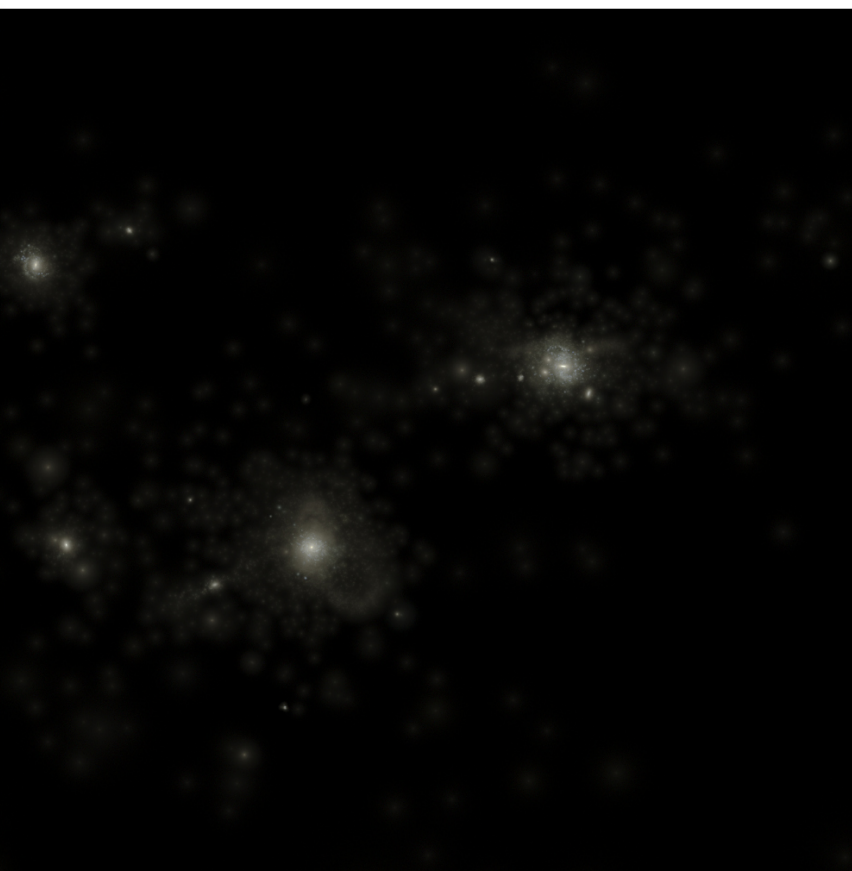
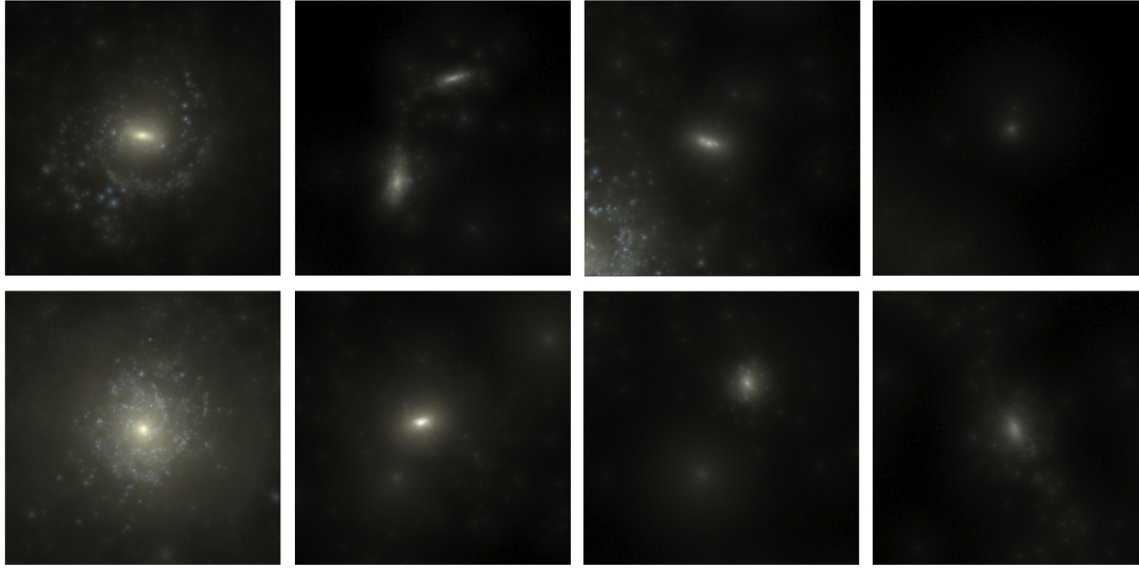
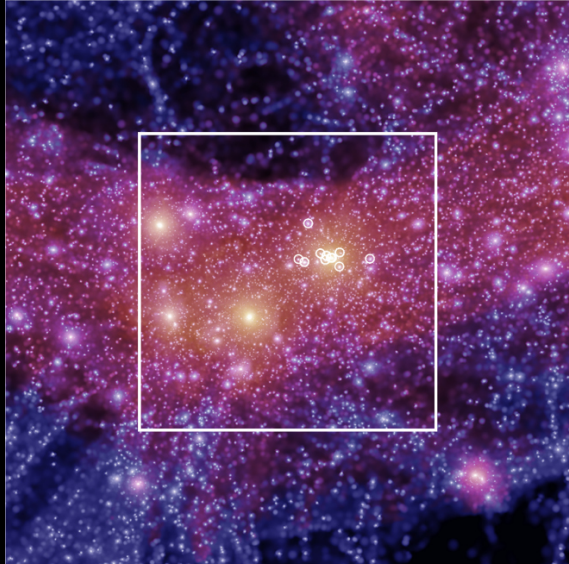
Boylan-Kolchin et al. '11

$$V_c = \sqrt{\frac{GM}{r}}$$

9 dwarf
satellites of
Milky Way:
mass within
half-light
radius

Excludes
LMC, SMC,
Sagittarius



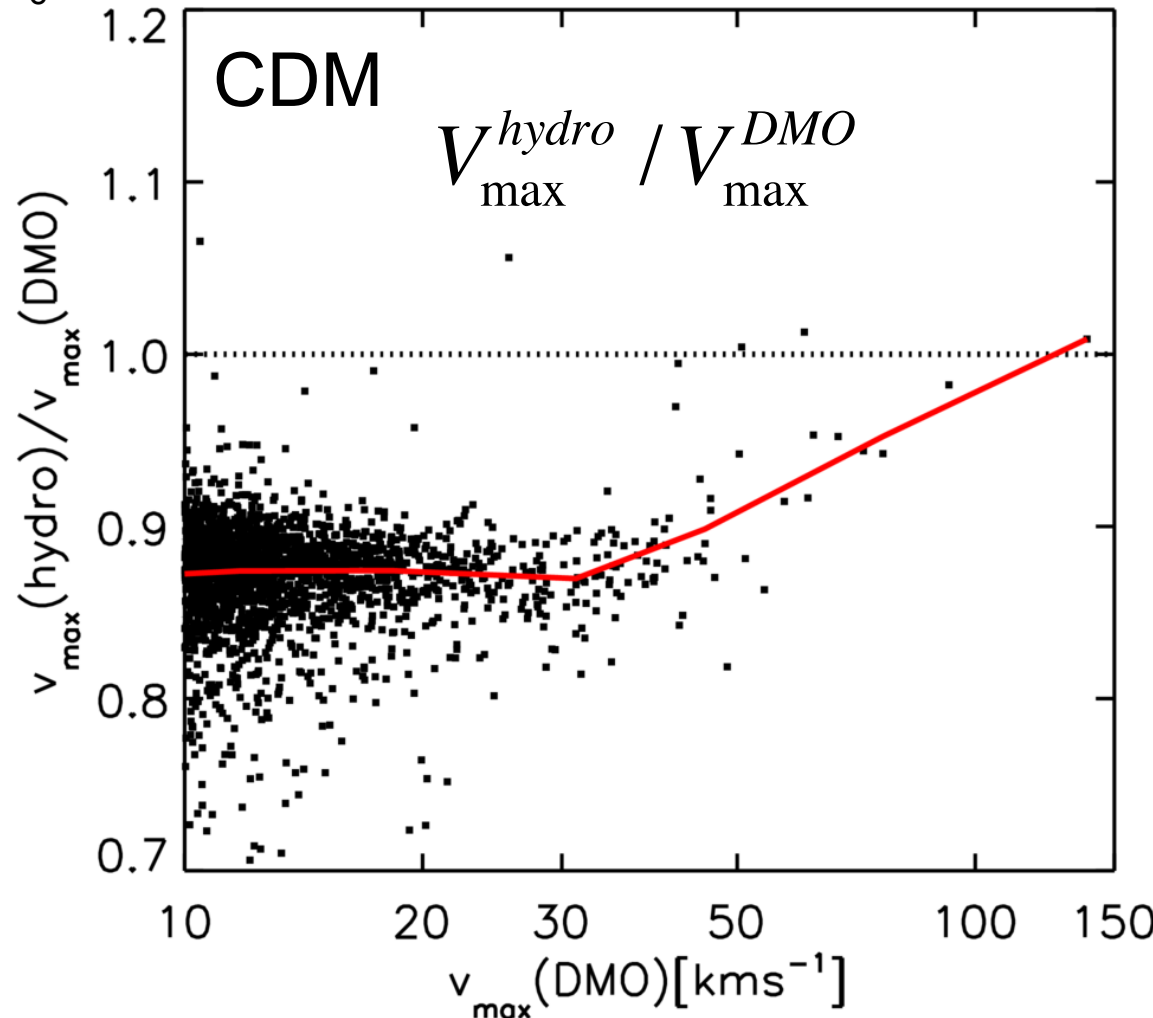
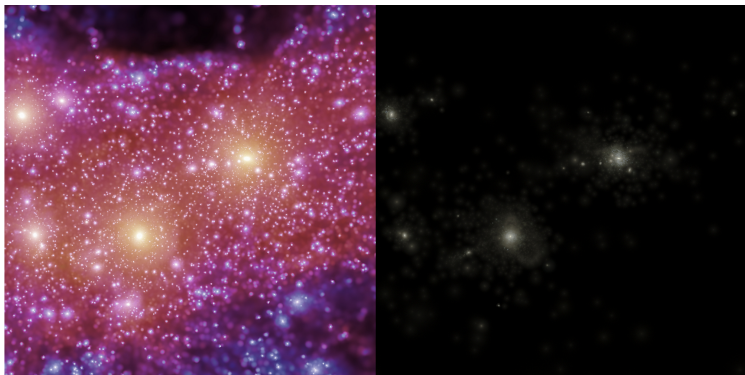


Too-big-to-fail in CDM: baryon effects

$$V_c = \sqrt{\frac{GM}{r}} \quad V_{\max} = \max V_c$$

Reduction in $V_{\max}$ due to
SN feedback:

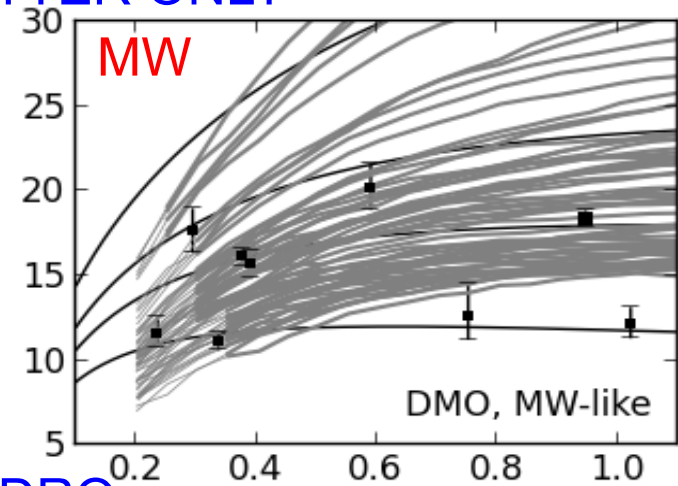
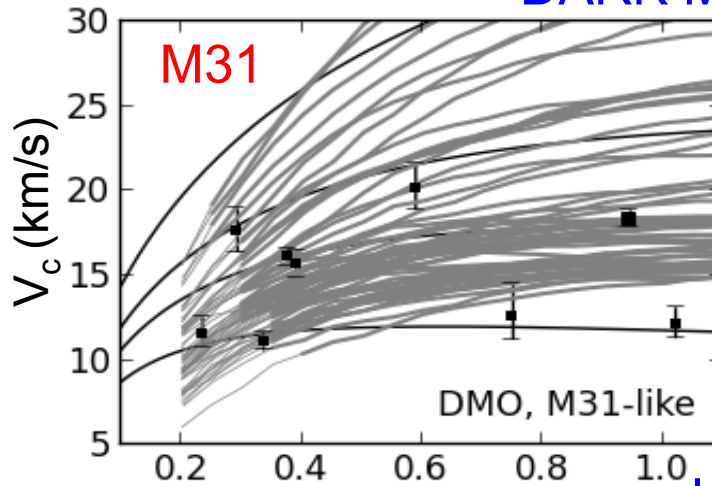
→ Lowers halo mass &
thus halo growth rate



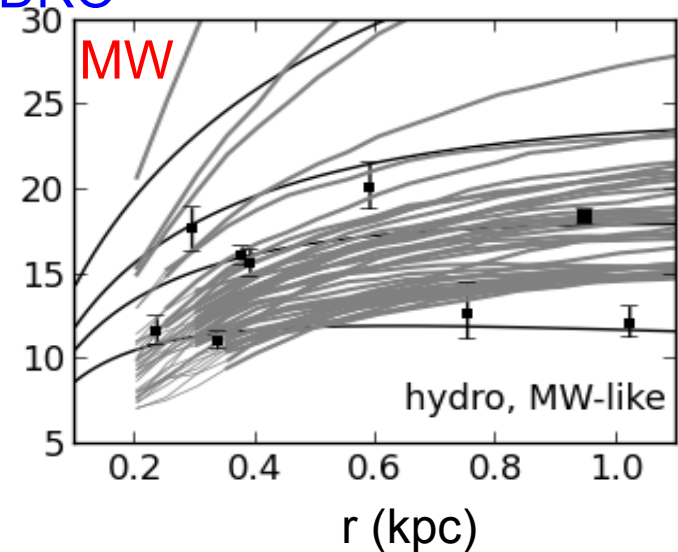
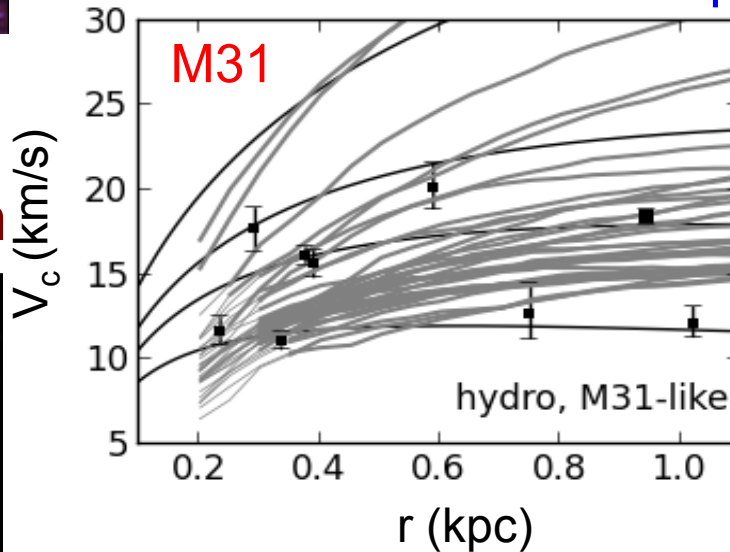
Sawala et al. '13, '15

Too-big-to-fail: the baryon bailout

DARK MATTER ONLY



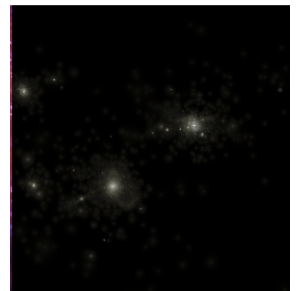
HYDRO



DM-only
simulation



Gas
simulation

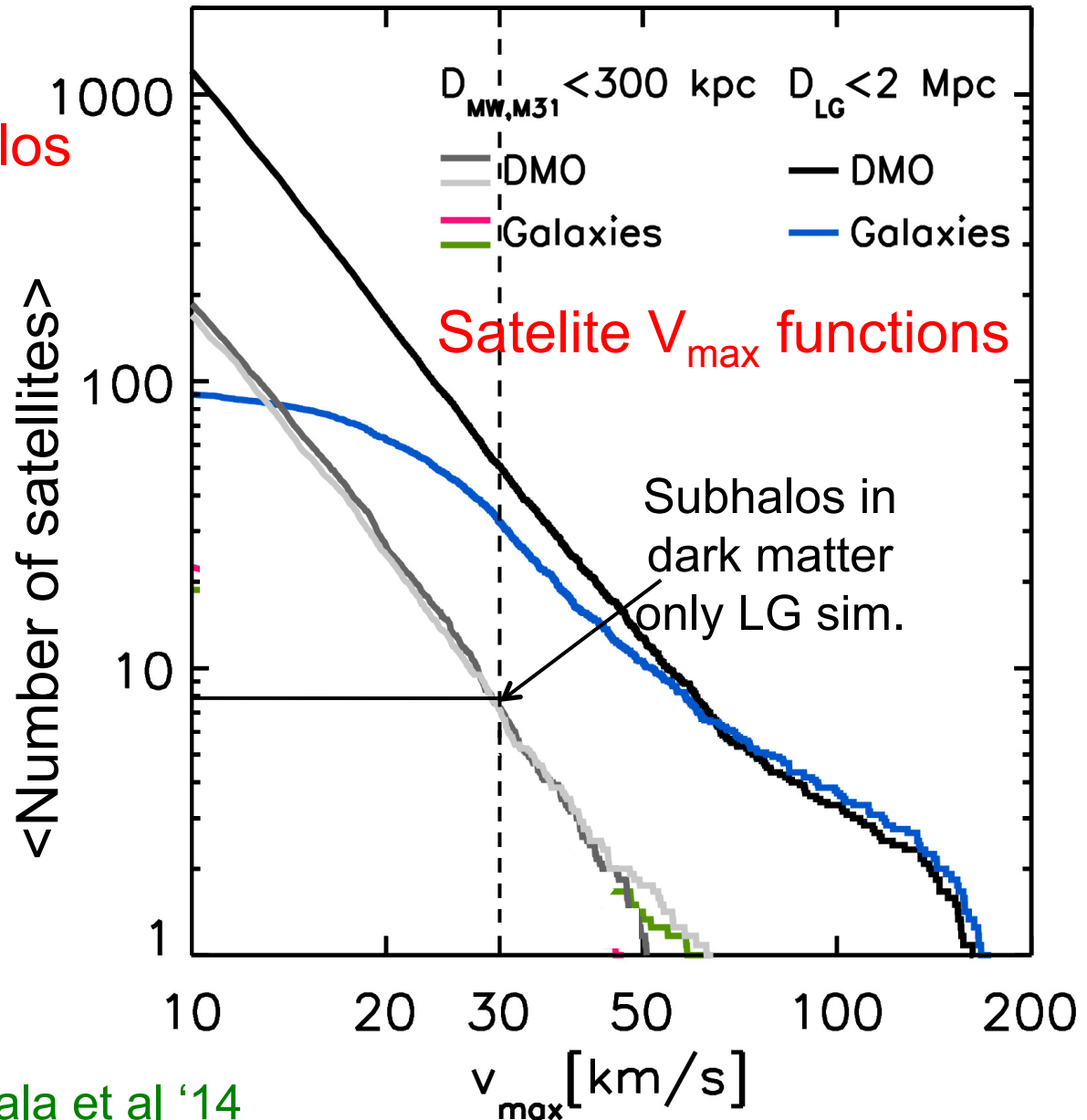


Number of subhalos of given $V_{\max}$ is greatly reduced in gas simulations

Sawala et al. '15

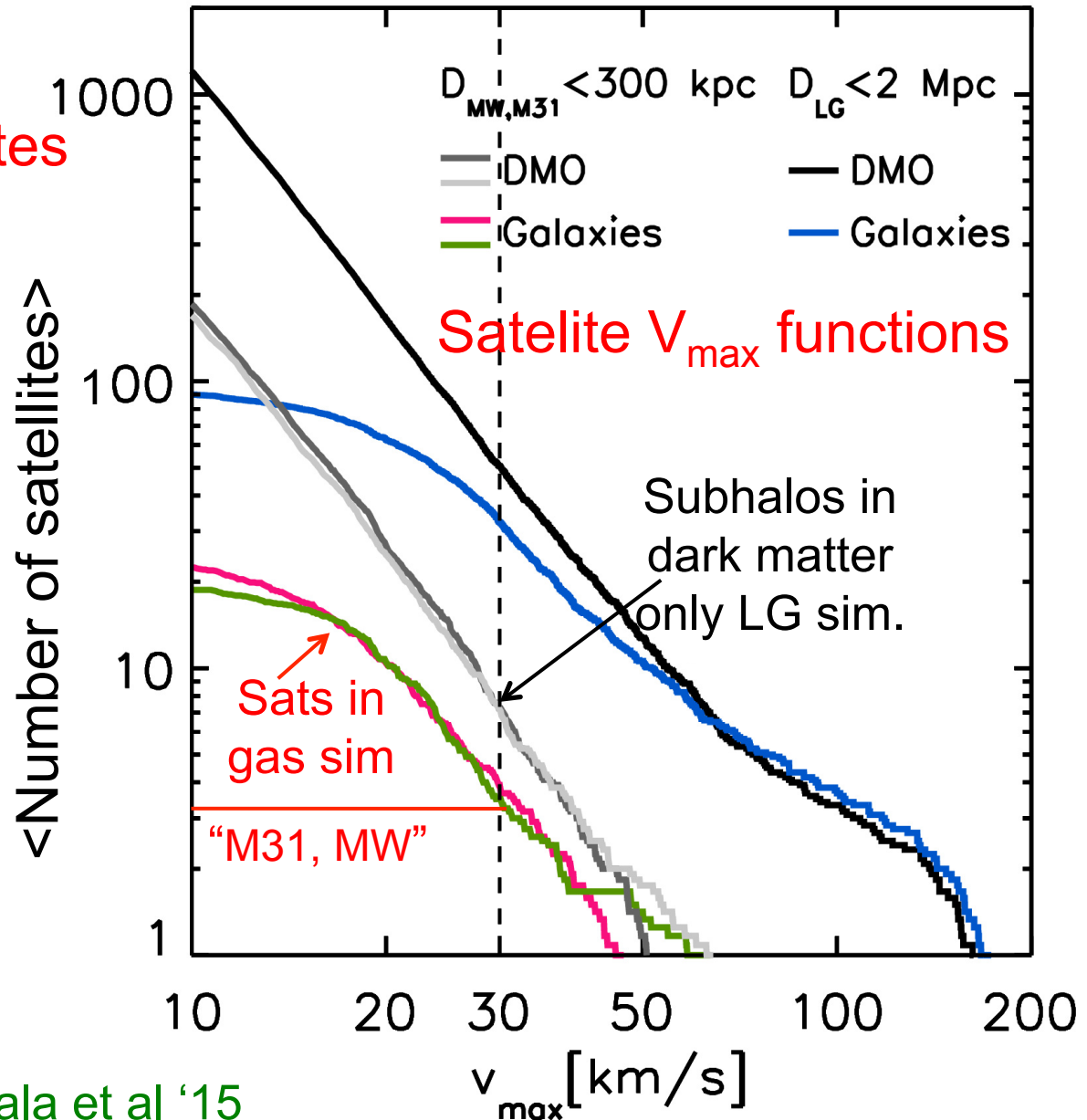
Too-big-to-fail: the baryon bailout

DM only sims $\rightarrow$ **~ 10 halos**
with $V_{\max} > 30$ km/s



Too-big-to-fail: the baryon bailout

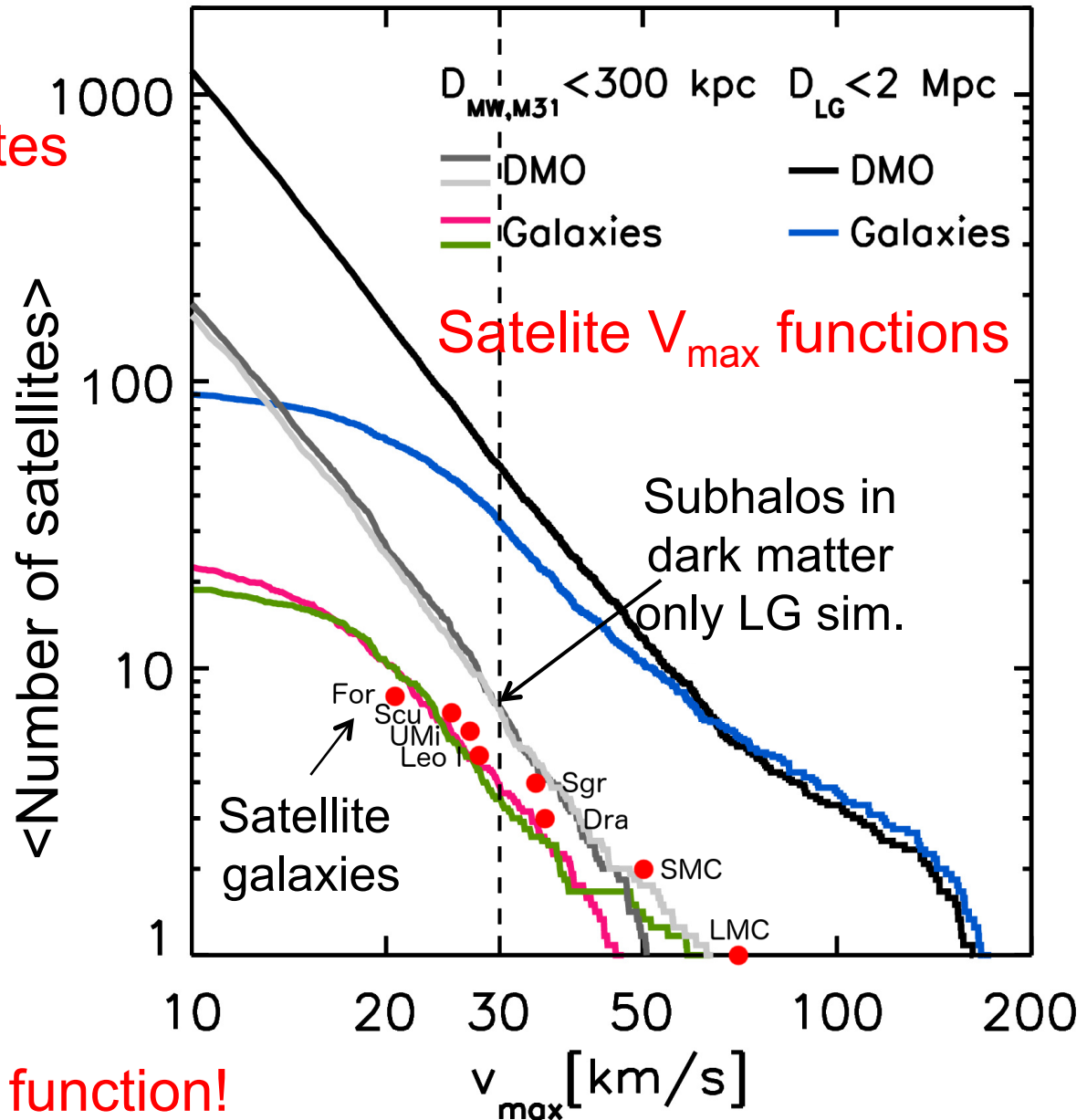
Hydro sims $\rightarrow$ **~3 satellites**
with $V_{\max} > 30$ km/s



Sawala et al '15

Too-big-to-fail: the baryon bailout

Hydro sims $\rightarrow$ **~ 3 satellites**
with $V_{\max} > 30$ km/s



... and with correct $V_{\max}$ function!



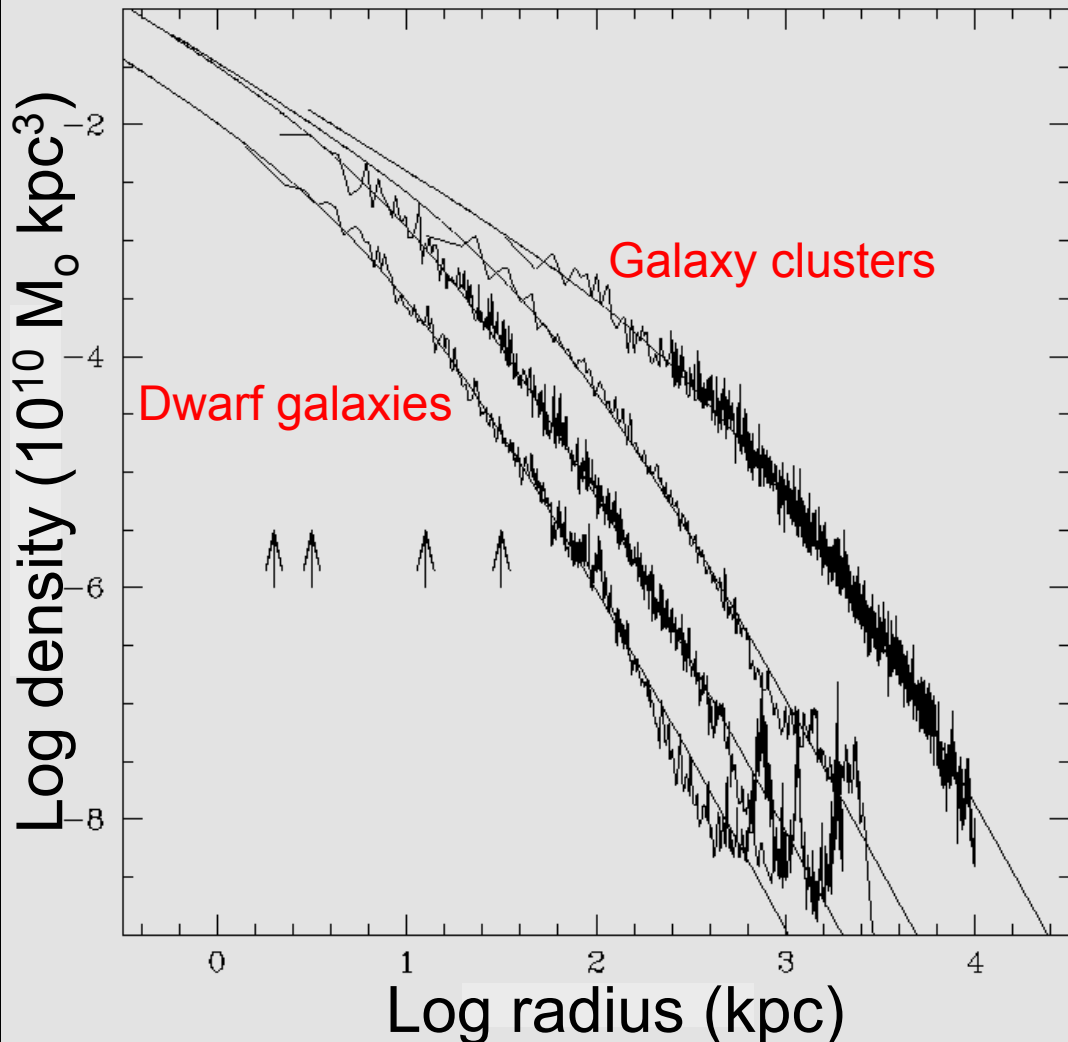
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No, when galaxy formation is taken into account!

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The Density Profile of Cold Dark Matter Halos



Shape of halo profiles
~independent of halo mass &
cosmological parameters

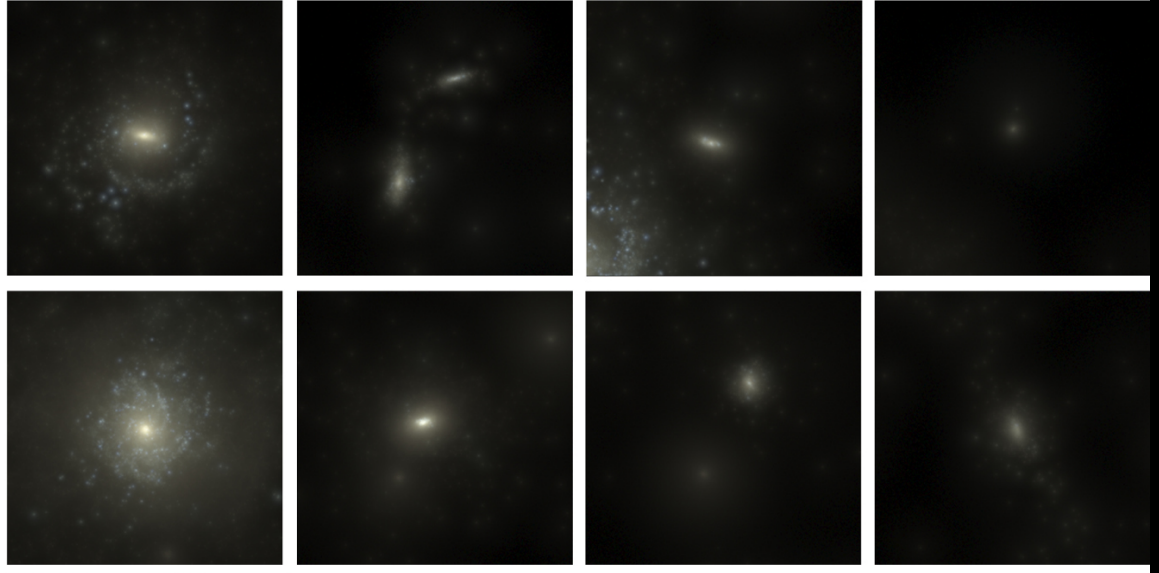
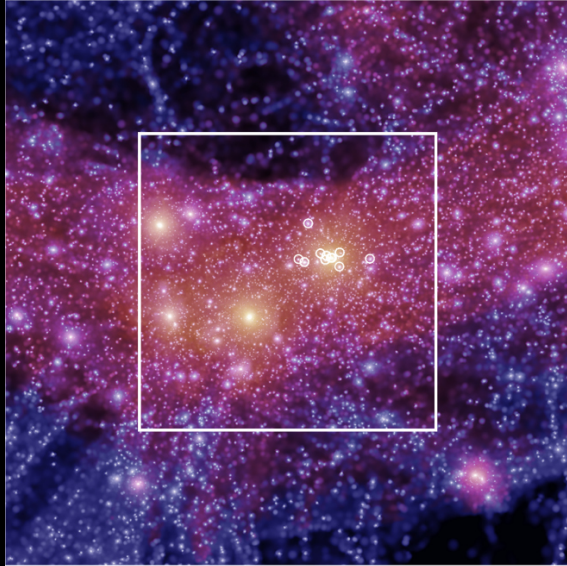
Density profiles are “cuspy” -
no ‘core’ near the centre

Fitted by simple formula:

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

(Navarro, Frenk & White '97)

More massive halos and
halos that form earlier have
higher densities (bigger δ)



Dwarf galaxies in Eagle have NFW cusps!

Sawala et al '15

The core-cusp problem

“Core-cusp” problem:

CDM halos & subhalos have **cuspy** profiles

BUT: kinematical data are said to “show” that the dwarf satellites of the Milky Way have **cores**



Dwarf galaxies around the Milky Way

Fornax

Sculptor

Leo I

© Anglo-Australian Observatory

Carina

Sextans

Sagittarius

The DM halo of the Sculptor dwarf

Sculptor has two stellar pops:

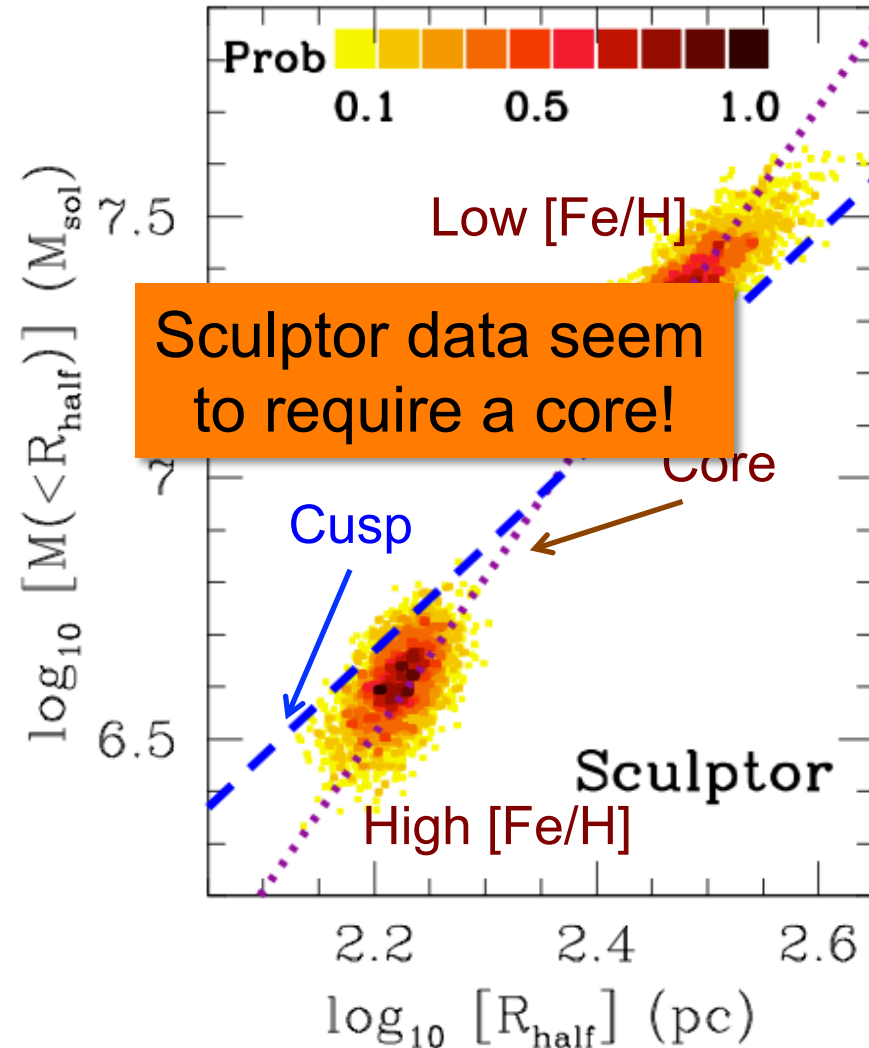
(i) centrally concentrated, high [Fe/H]

(ii) extended, low [Fe/H]

$$M(< r) = \mu \frac{r < \sigma_{los}^2 >}{G}$$

Walker '10; Wolf et al '10 →

if $r=r_{1/2}$, $\mu=2.5$, independently of model assumptions!



The DM halo of the Sculptor dwarf

Strigari, Frenk & White '14

Distribution function analysis of 2 metallicity pop. data of Battaglia et al.

Assume pops in equil. in NFW halo: $\rho(r) = \frac{\rho_s}{x(1+x)^2}$

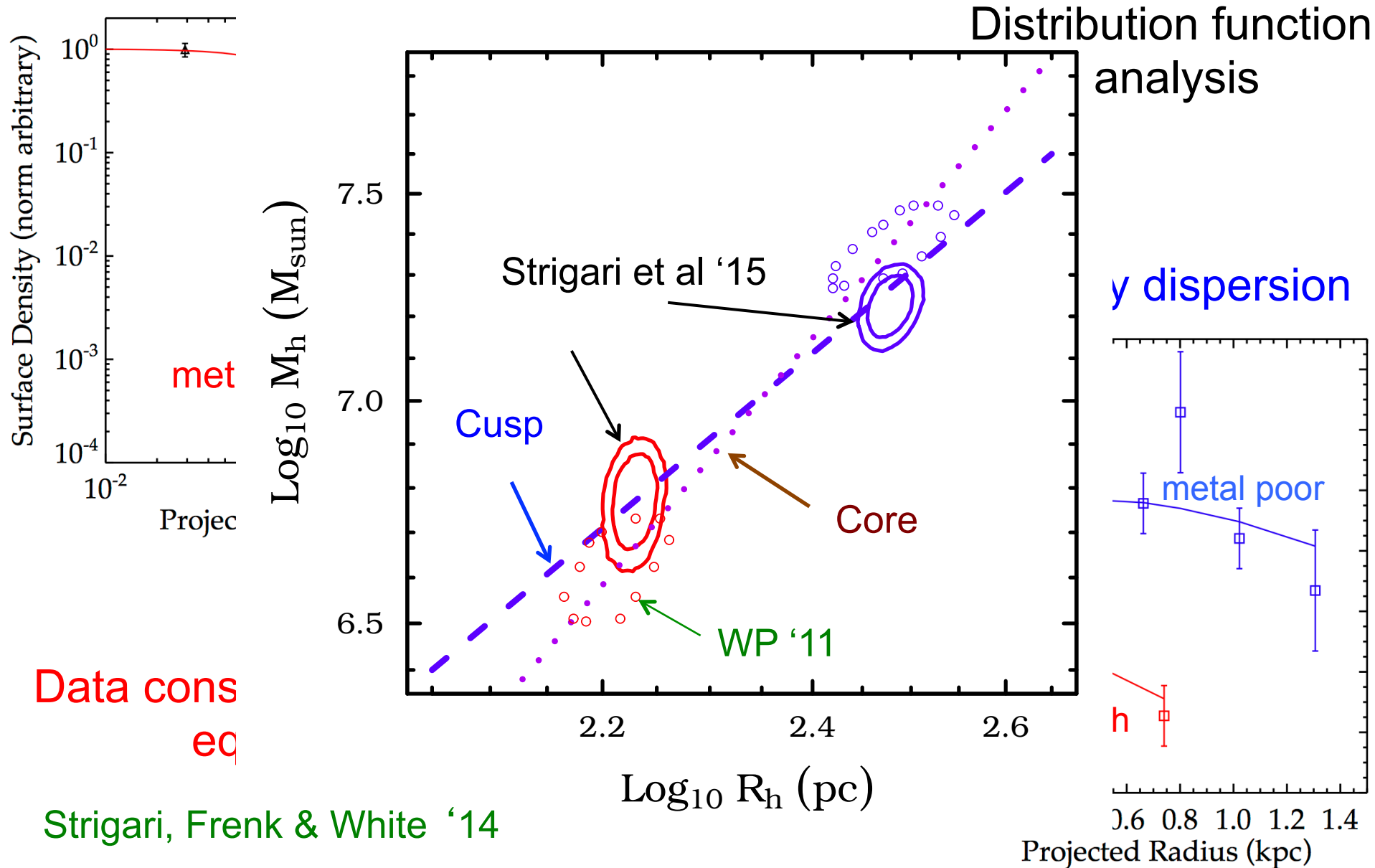
For each population: $f(E, J) = g(J)h(E)$,

Parametrize: $g(J) = \left[\left(\frac{J}{J_\beta} \right)^{\frac{b_0}{\alpha}} + \left(\frac{J}{J_\beta} \right)^{\frac{b_1}{\alpha}} \right]^\alpha$

$$h(E) = \begin{cases} N E^a (E^q + E_c^q)^{d/q} (\Phi_{lim} - E)^e & \text{for } E < \Phi_{lim} \\ 0 & \text{for } E \geq \Phi_{lim}, \end{cases}$$

Find best-fit parameters using MCMC

The DM halo of the Sculptor dwarf





Cores or cusps in the dwarf sph. satellites of the MW?

When sufficiently general models are considered, even best kinematical data cannot distinguish cores from NFW cusps in the dwarf spheroidal satellites of the Milky Way

How about in field dwarf galaxies?

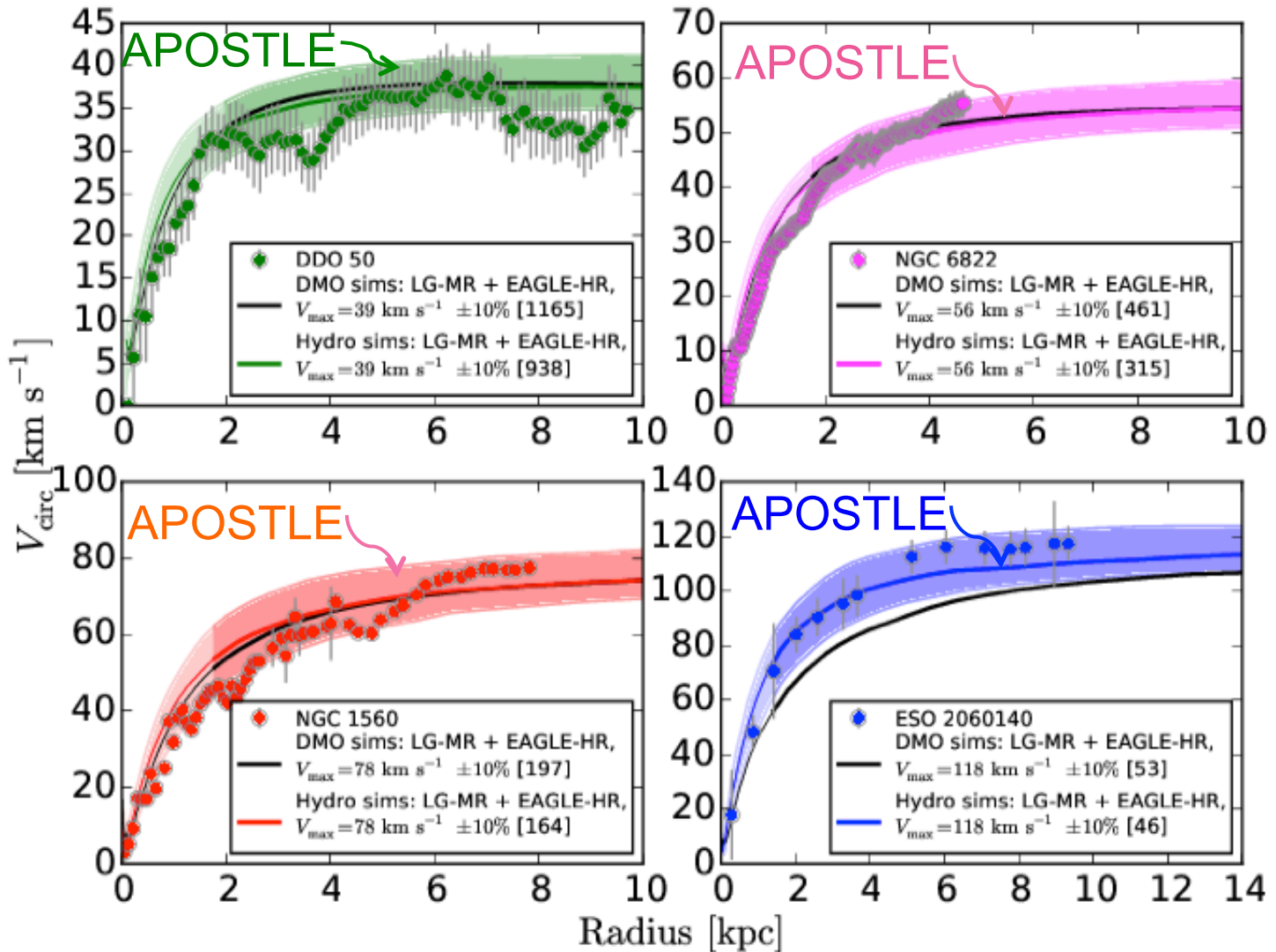
Data are not as detailed, but some dwarfs have disks:

- (i) Rotation curves
- (ii) 2D velocity fields

The diversity of gal rotation curves

Four rotation curves that are well fit by Λ CDM

(from dwarfs to $\sim L_*$)

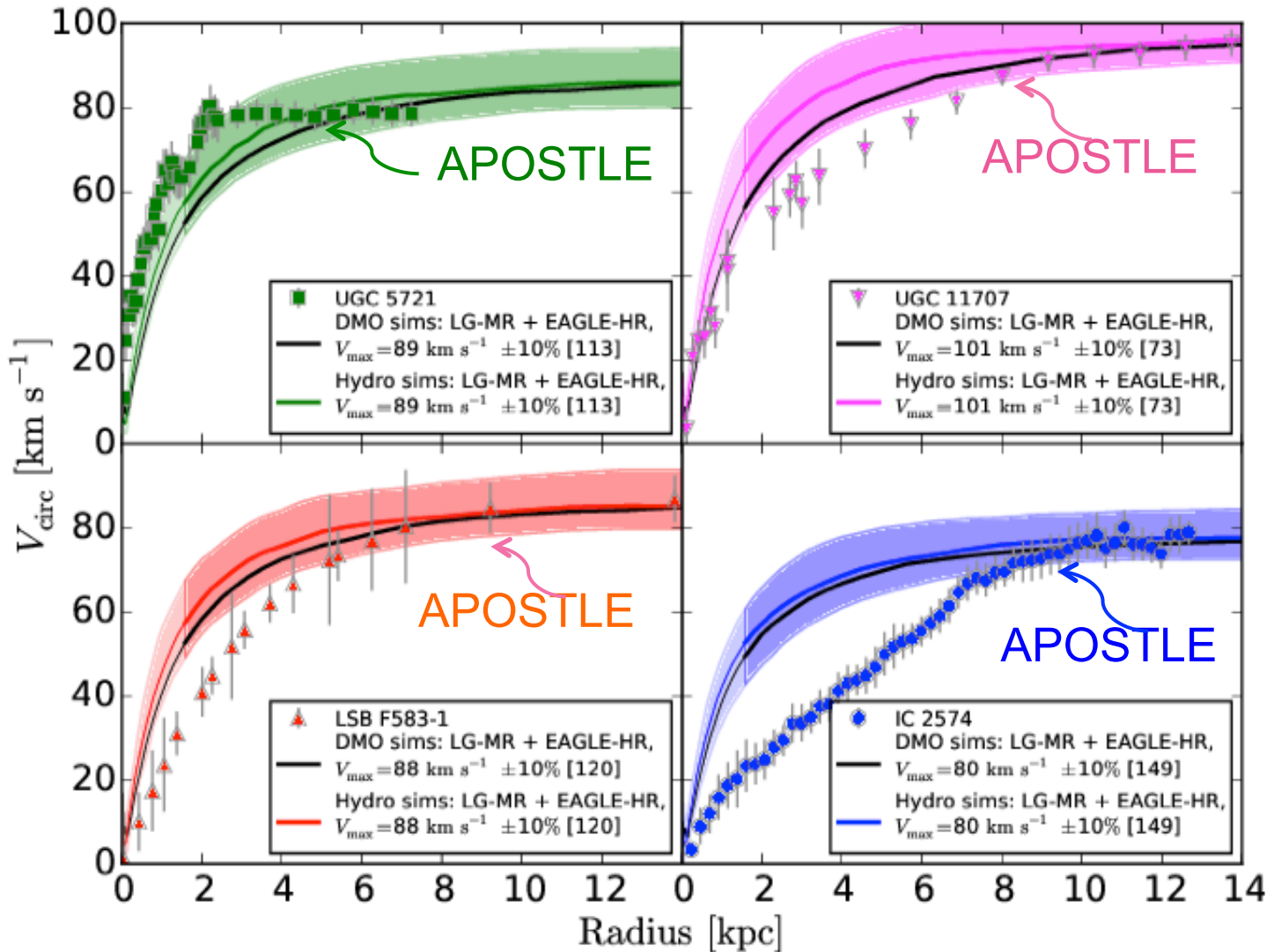


Oman, Navarro, Frenk et al. '15

The diversity of gal rotation curves

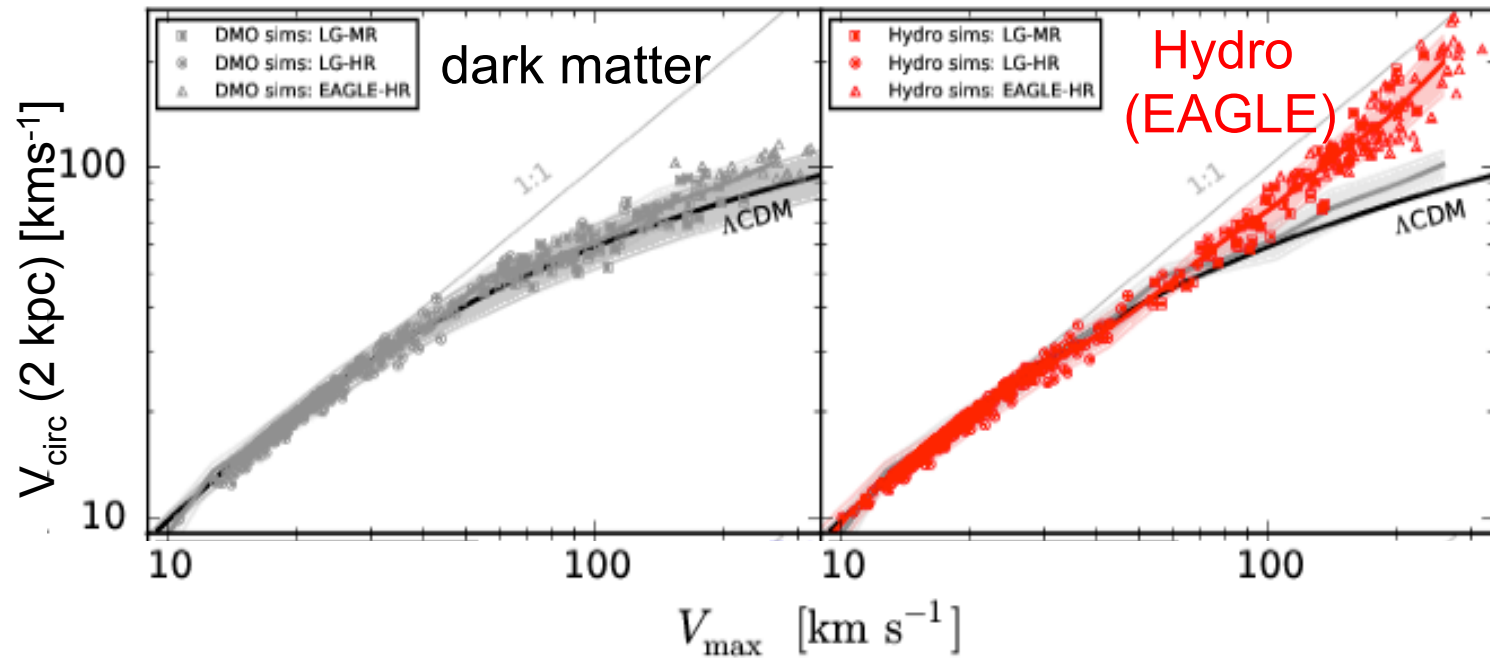
Four rotation curves that are NOT well fit by Λ CDM

(from dwarfs to $\sim L_*$)



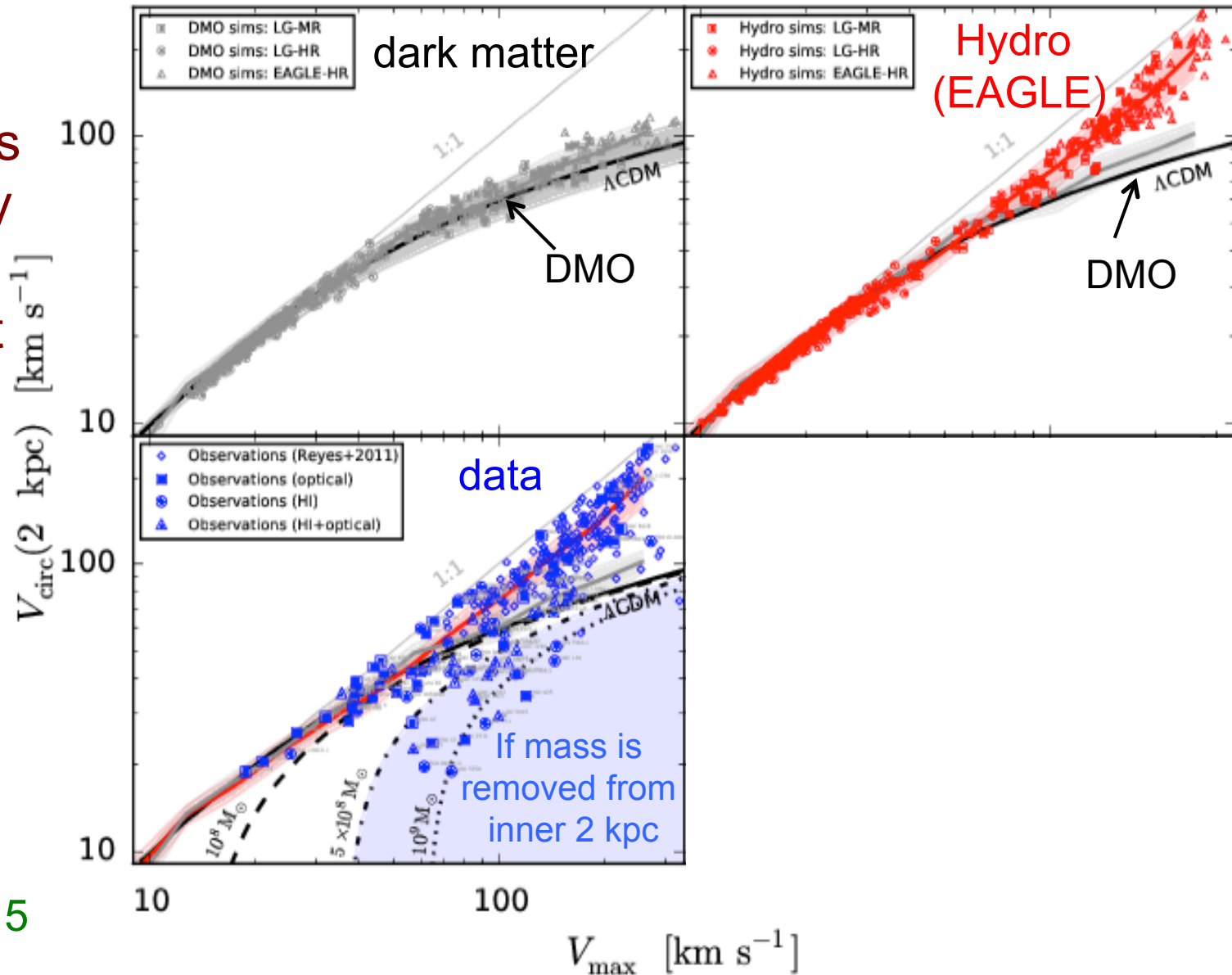
Oman et al. '15

The diversity of gal rotation curves



The diversity of gal rotation curves

Most galaxies are well fit by EAGLE; others not fit by any simulation





Are there other baryon effects that could make cores but are not present in Eagle?

The cores of dwarf galaxy haloes

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Accepted 1996 September 2. Received 1996 August 28; in original form 1996 June 26

ABSTRACT

We use N -body simulations to examine the effects of mass outflows on the density profiles of cold dark matter (CDM) haloes surrounding dwarf galaxies. In particular, we investigate the consequences of supernova-driven winds that expel a large fraction of the baryonic component from a dwarf galaxy disc after a vigorous episode of star formation. We show that this sudden loss of mass leads to the formation of a core in the dark matter density profile, although the original halo is modelled by a coreless (Hernquist) profile. The core radius thus created is a sensitive function of the mass and radius of the baryonic disc being blown up. The loss of a disc with mass and size consistent with primordial nucleosynthesis constraints and angular momentum considerations imprints a core radius that is only a small fraction of the original scalelength of the halo. These small perturbations are, however, enough to reconcile the rotation curves of dwarf irregulars with the density profiles of haloes formed in the standard CDM scenario.

Let gas cool and condense to the galactic centre

→ gas self-gravitating
→ star formation/burst

Rapid ejection of gas during starburst → a core in the halo dark matter density profile

Navarro, Eke, Frenk '96

Governato et al. '12

Pontzen & Governato '12

Brooks et al. '12

Navarro, Eke, Frenk '96

The cores of dwarf galaxy haloes L75

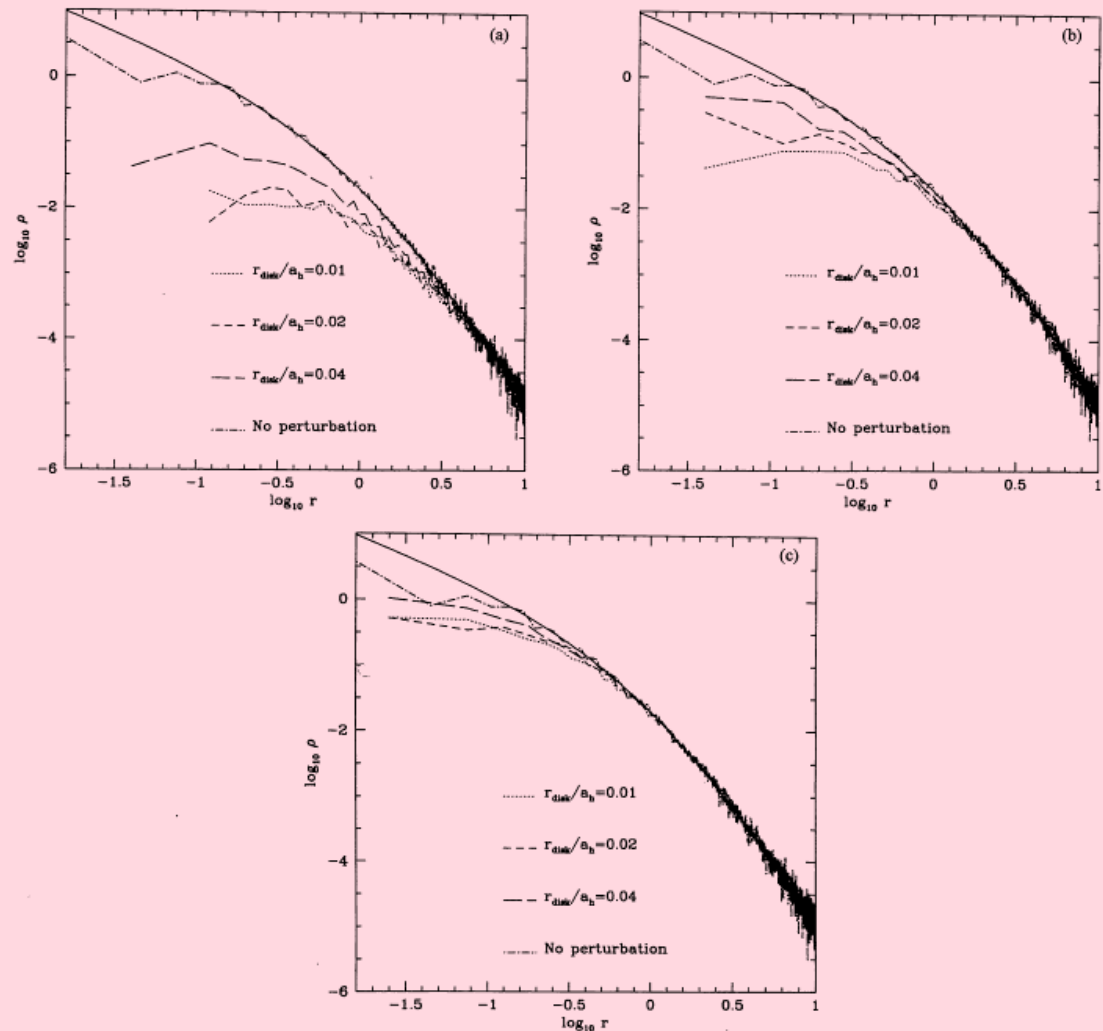


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot-dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{\text{disc}}=0.2$. (b) $M_{\text{disc}}=0.1$. (c) $M_{\text{disc}}=0.05$.

For **core formation** to happen need:

- Accumulate **large gas mass** in **central** region of halo
- **Sudden removal** of most of the gas

Governato et al.
assume **large density** threshold for star formation.

EAGLE does not

Navarro, Eke, Frenk '96

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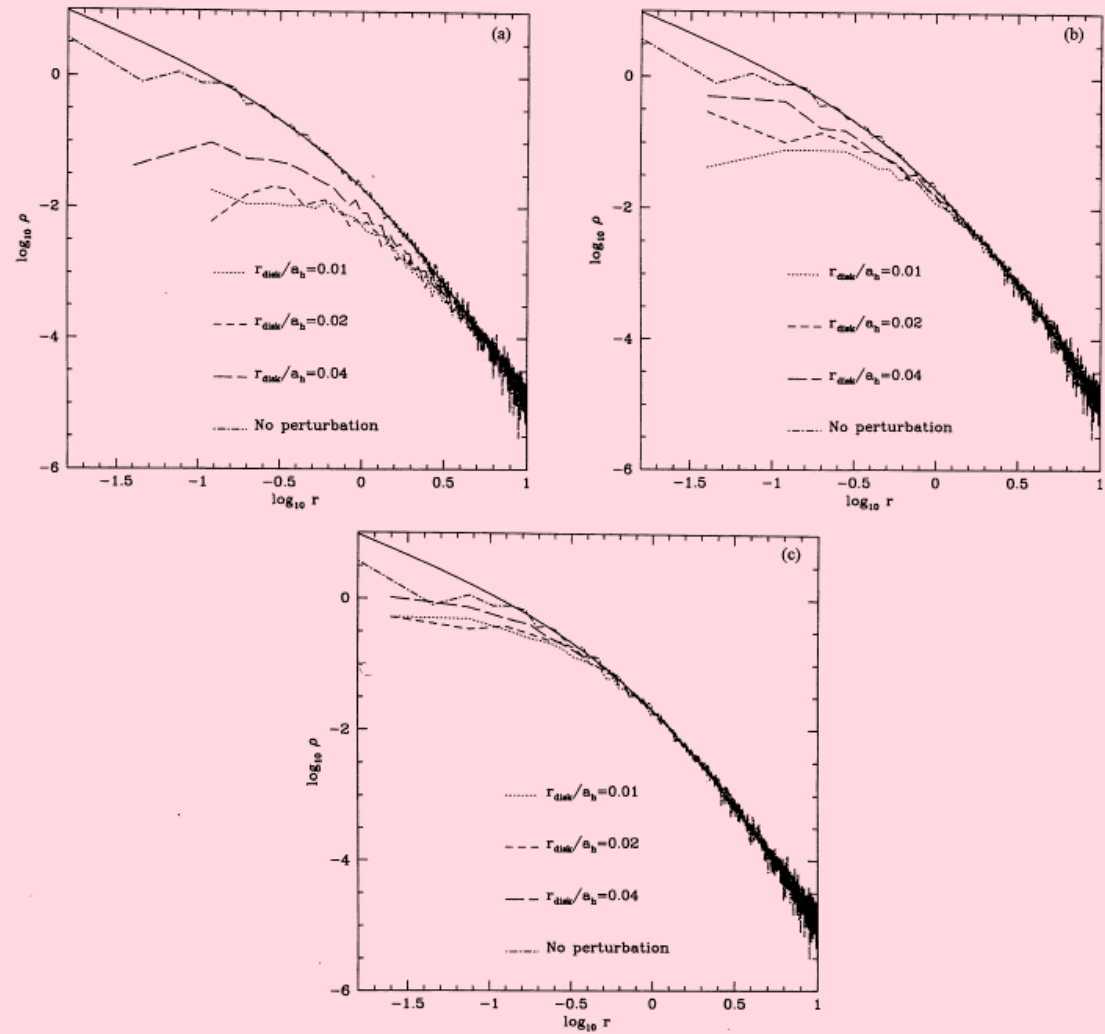


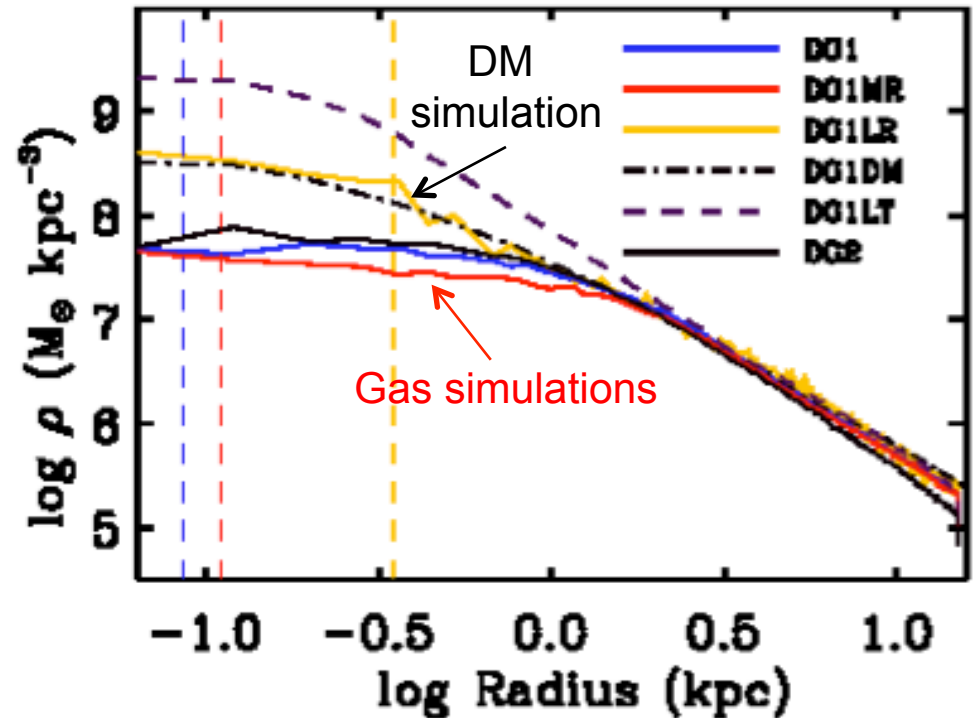
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Cores in dwarf galaxy simulations

Governato et al. assume
high density threshold for
star formation

EAGLE does not

- High threshold allows
large gas mass to
accumulate in centre
- Sudden repeated
removal of gas transfers
binding energy

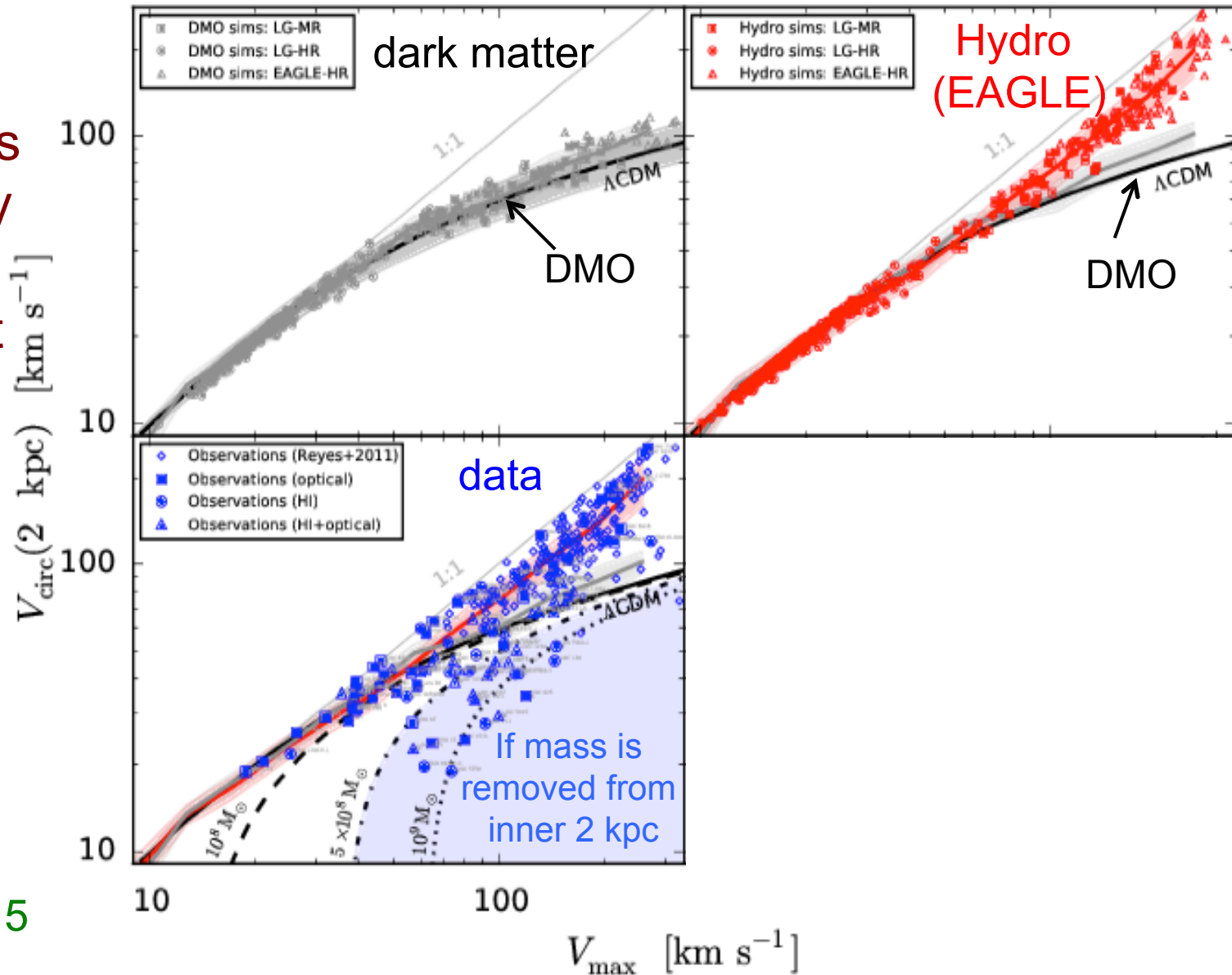


Governato et al. '10

Pontzen et al. '11

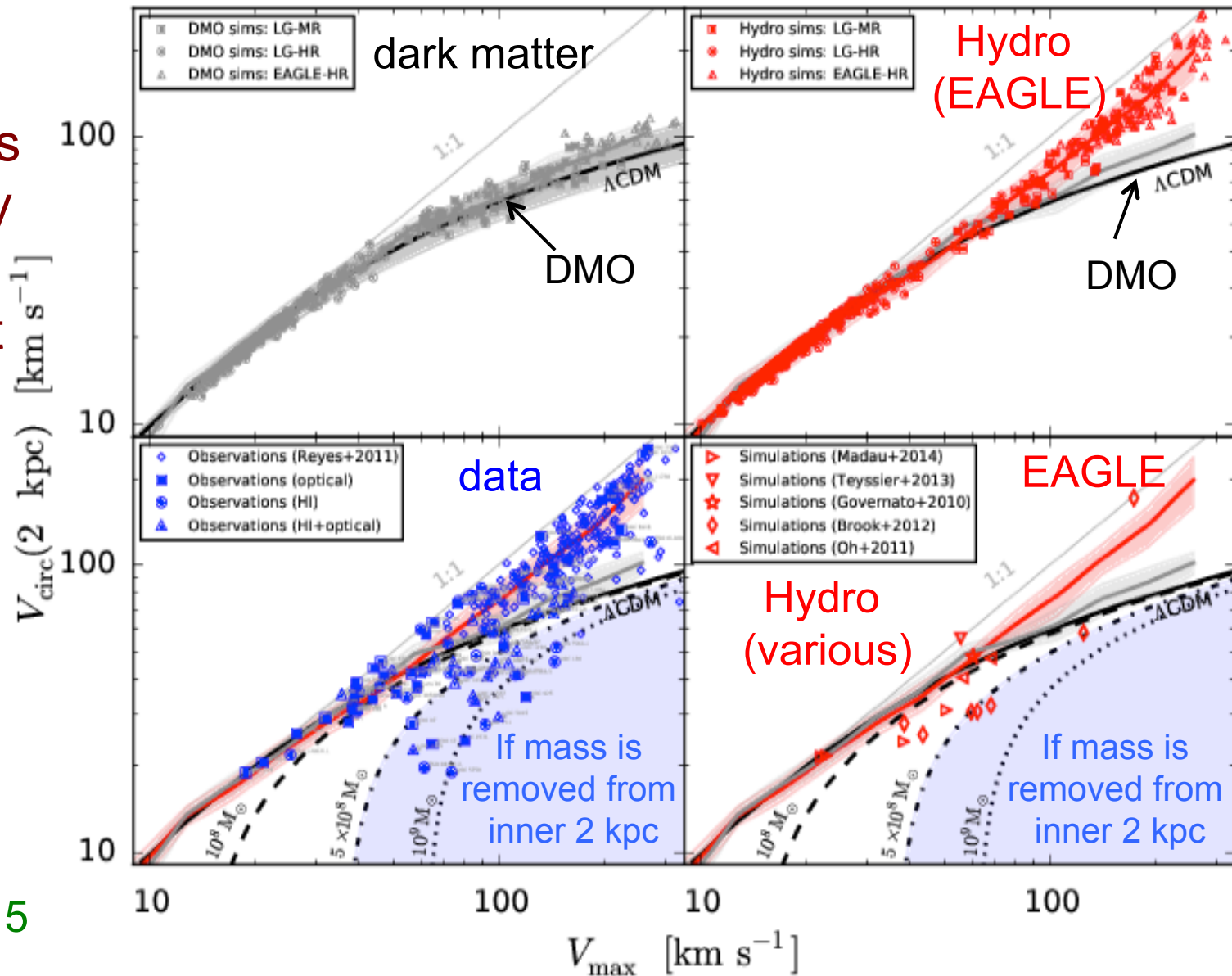
The diversity of gal rotation curves

Most galaxies are well fit by EAGLE; others not fit by any simulation



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Cores or cusps in dwarf gals?

- Some dwarfs have rotation curves that agree well with EAGLE
- Others have inner mass deficits compared to Λ CDM expectation
- In many cases, inner deficit much larger than seen in simulations that make cores

EITHER (i) dark matter more complex than in any current model

OR (ii) current simulations fail to reproduce effects of baryons on inner regions of dwarfs

AND/OR (iii) the mass profiles of “inner mass deficit” galaxies inferred from kinematic data are incorrect.



Conclusions

- Λ CDM: great **success** on scales $> 1\text{Mpc}$: CMB, LSS, gal evolution

Four “problems” on small scales:

1. Abundance of sats
2. Too-big-to-fail
3. Core-cusp
4. Disk of satellites



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3. Core-cusp: **no evidence** for cores in satellites (**baryon effects?**)
4. Disk of satellites: **incorrect claims** of inconsistency w. Λ CDM



Is CDM ruled out?

Not yet, but we'll keep
trying!

