Is CDM ruled out?

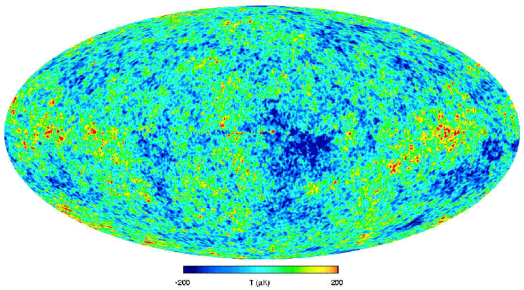
Carlos S. Frenk
Institute for Computational Cosmology,
Durham

Four problems for CDM on small scales?

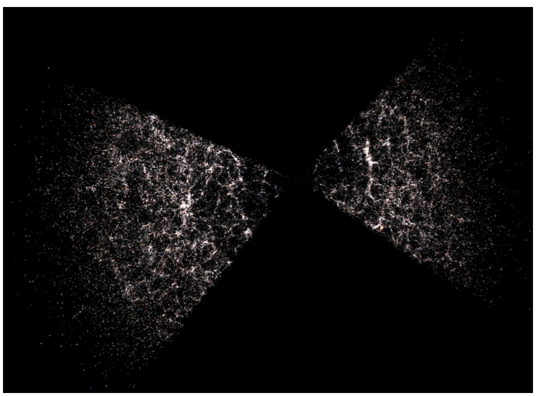
1. The “missing satellites” problem
2. The “too-big-to-fail” problem
3. The “core-cusp” problem
4. The “satellite disk” problem

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

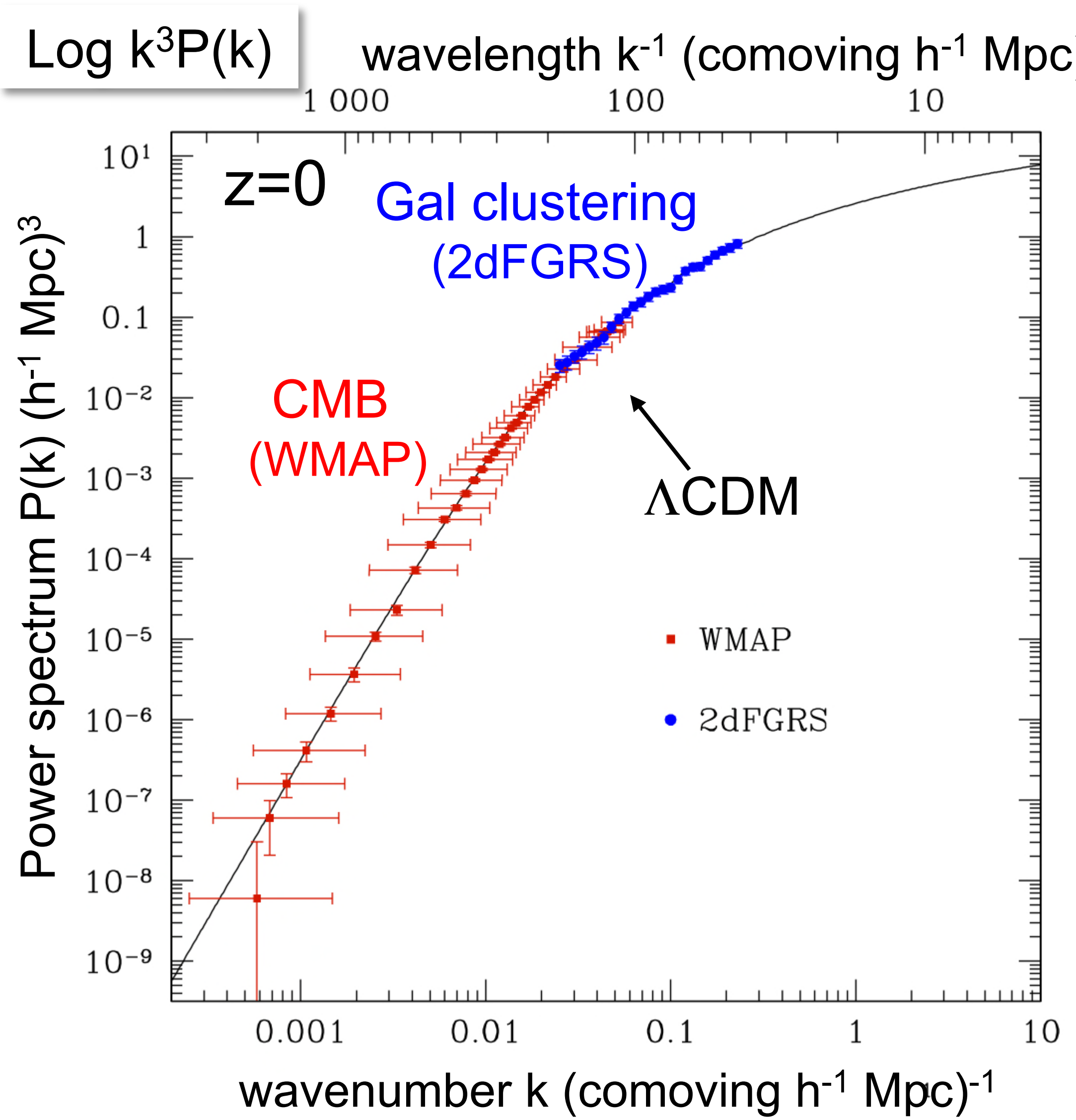
University of Durham



z~1000



z~0



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

Sanchez et al 06

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

University of Durham

Free streaming →

$\lambda_{cut} \alpha\, m_x^{-1}$

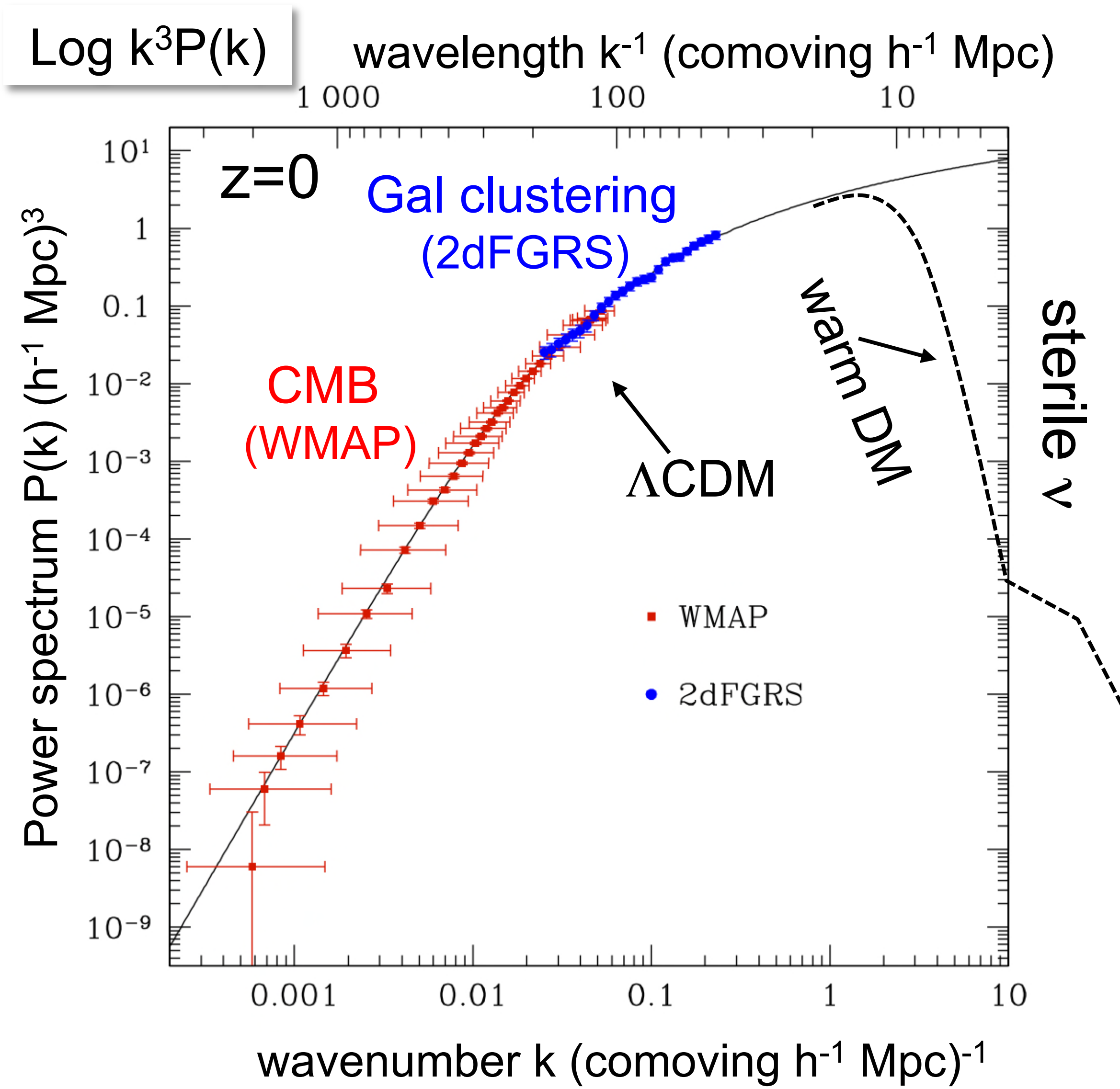
for thermal relic

$m_{CDM} \sim 100 GeV$

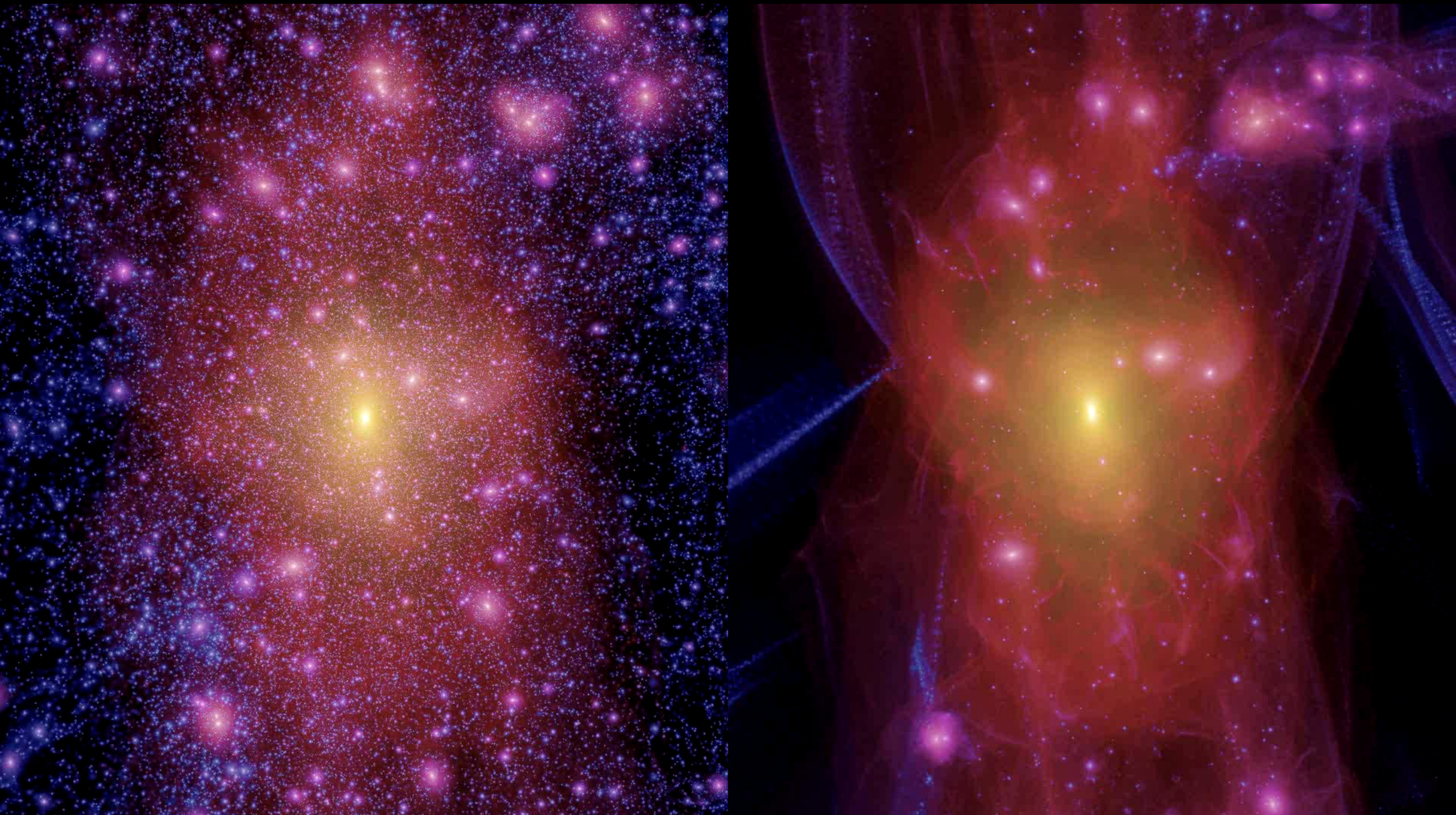
susy; $M_{cut} \sim 10^{-6} M_o$

$m_{WDM} \sim$ few keV

sterile ν; $M_{cut} \sim 10^9 M_o$



cold dark matter   warm dark matter



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

Four problems for CDM on small scales?

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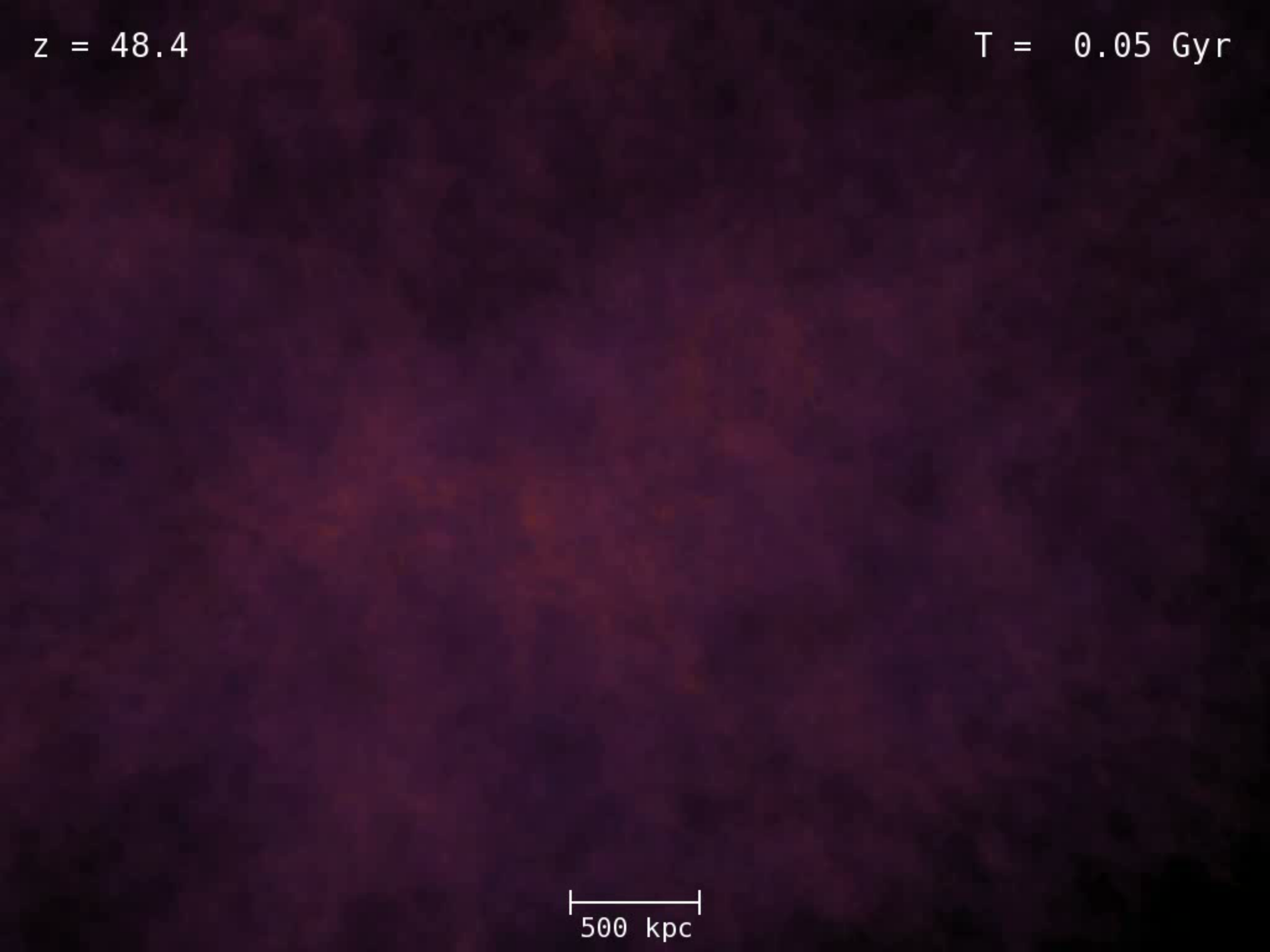
These problems have all been identified in N-body simulations that follow only dark matter

Need to consider "baryon effects"


z = 48.4
T = 0.05 Gyr
500 kpc

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.

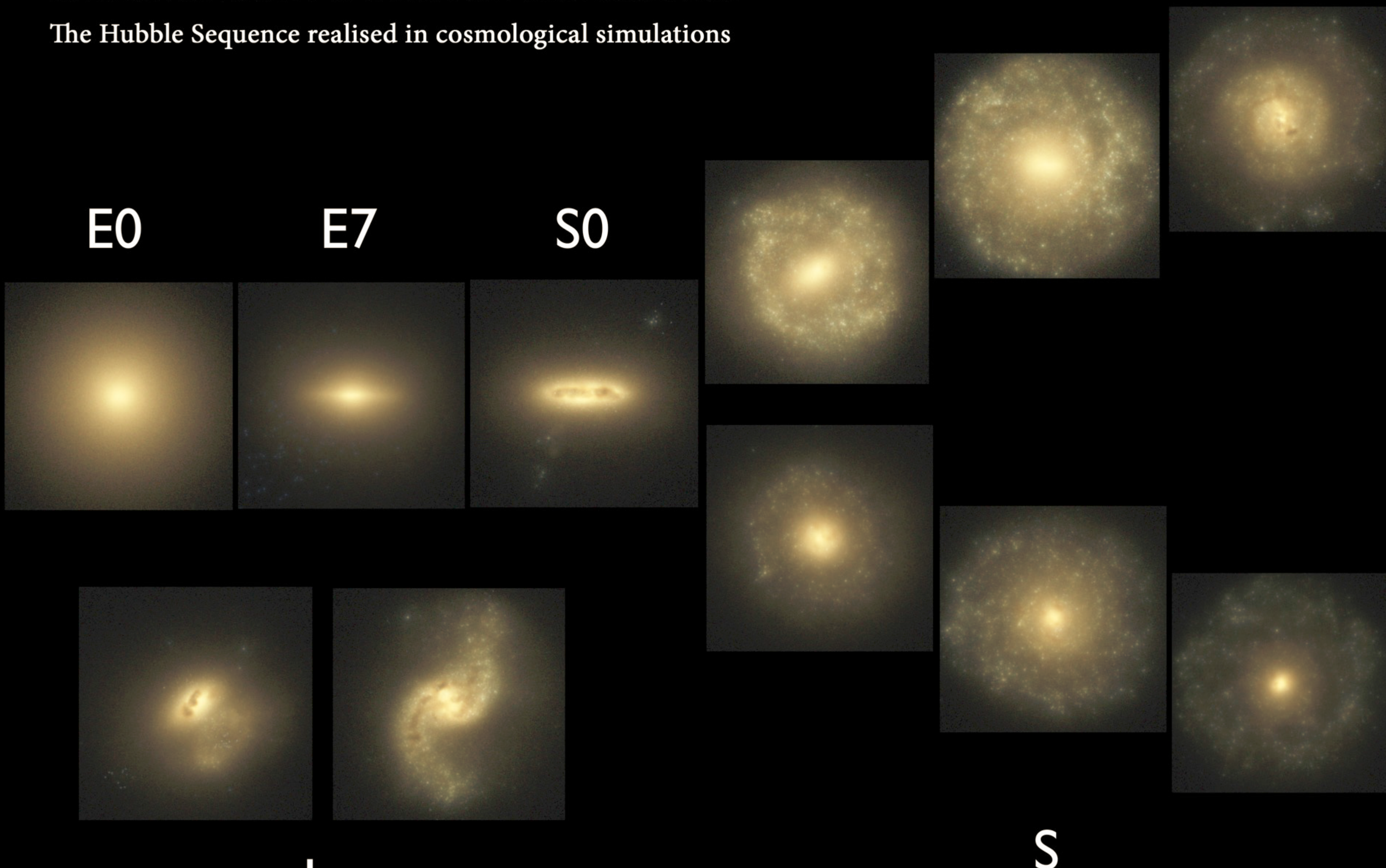
Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth…

The EAGLE simulation is a project by the Virgo Consortium.
Images courtesy of Richard Bower.

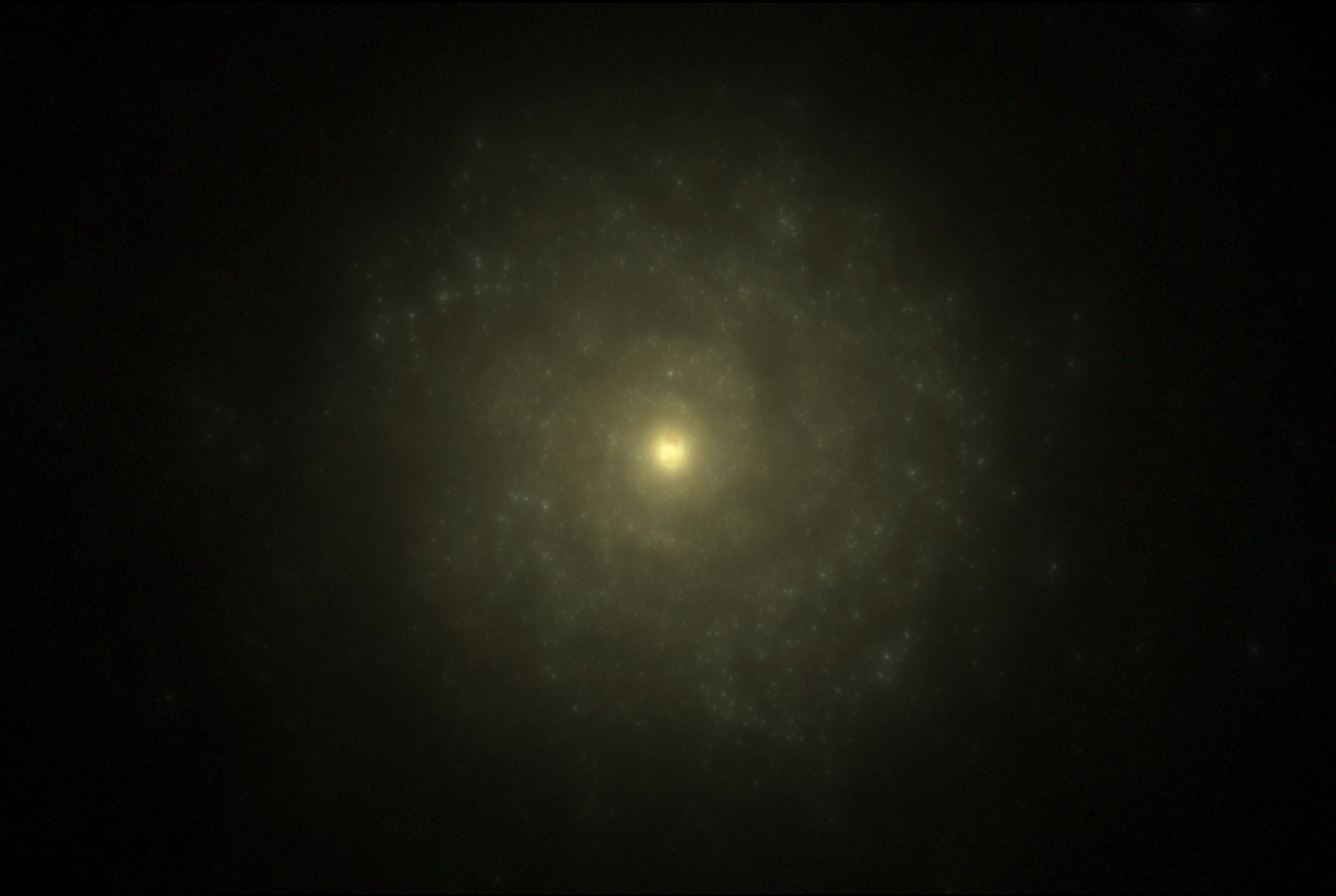
The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations

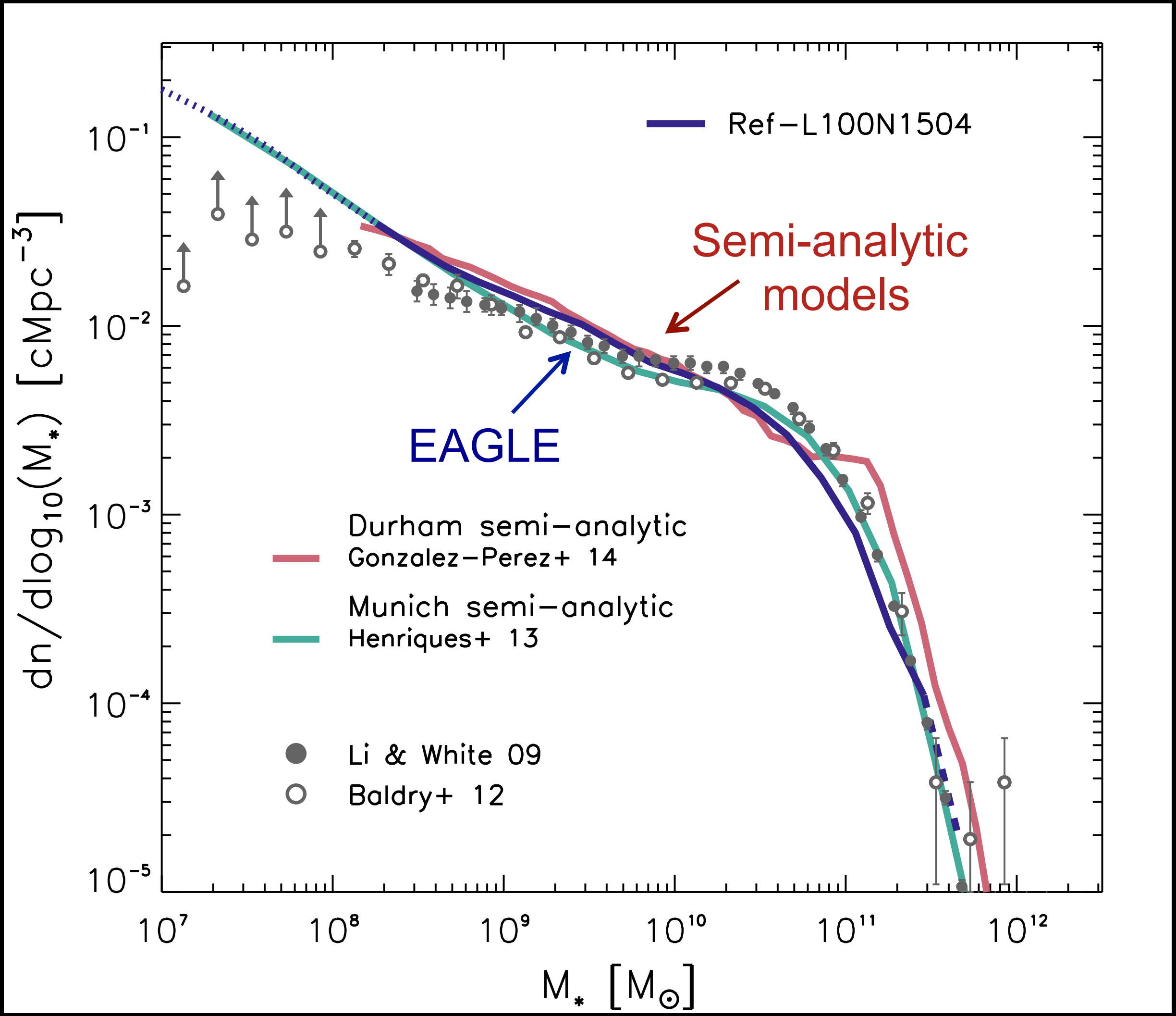


Trayford et al ‘14



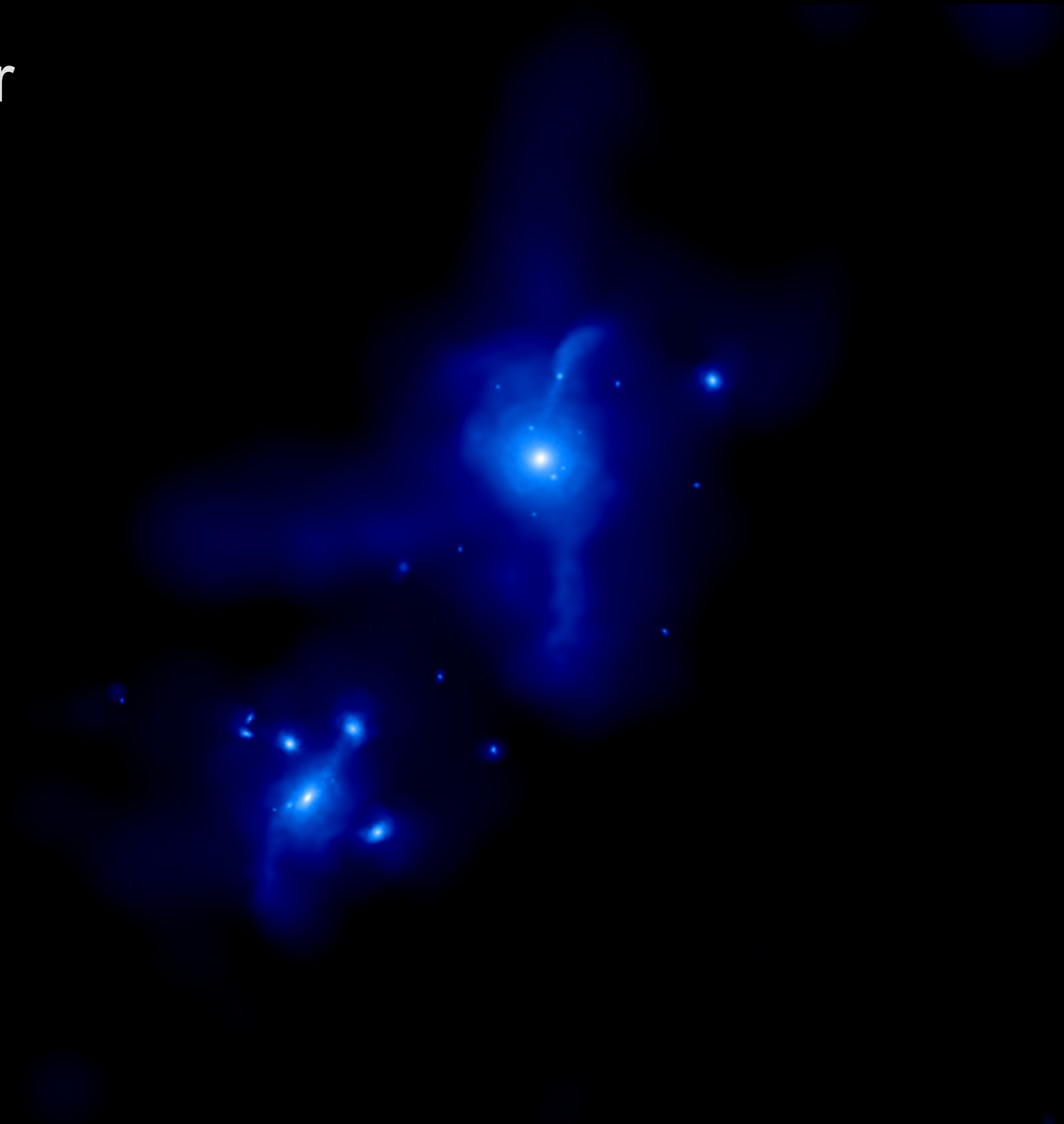
Galaxy stellar mass function

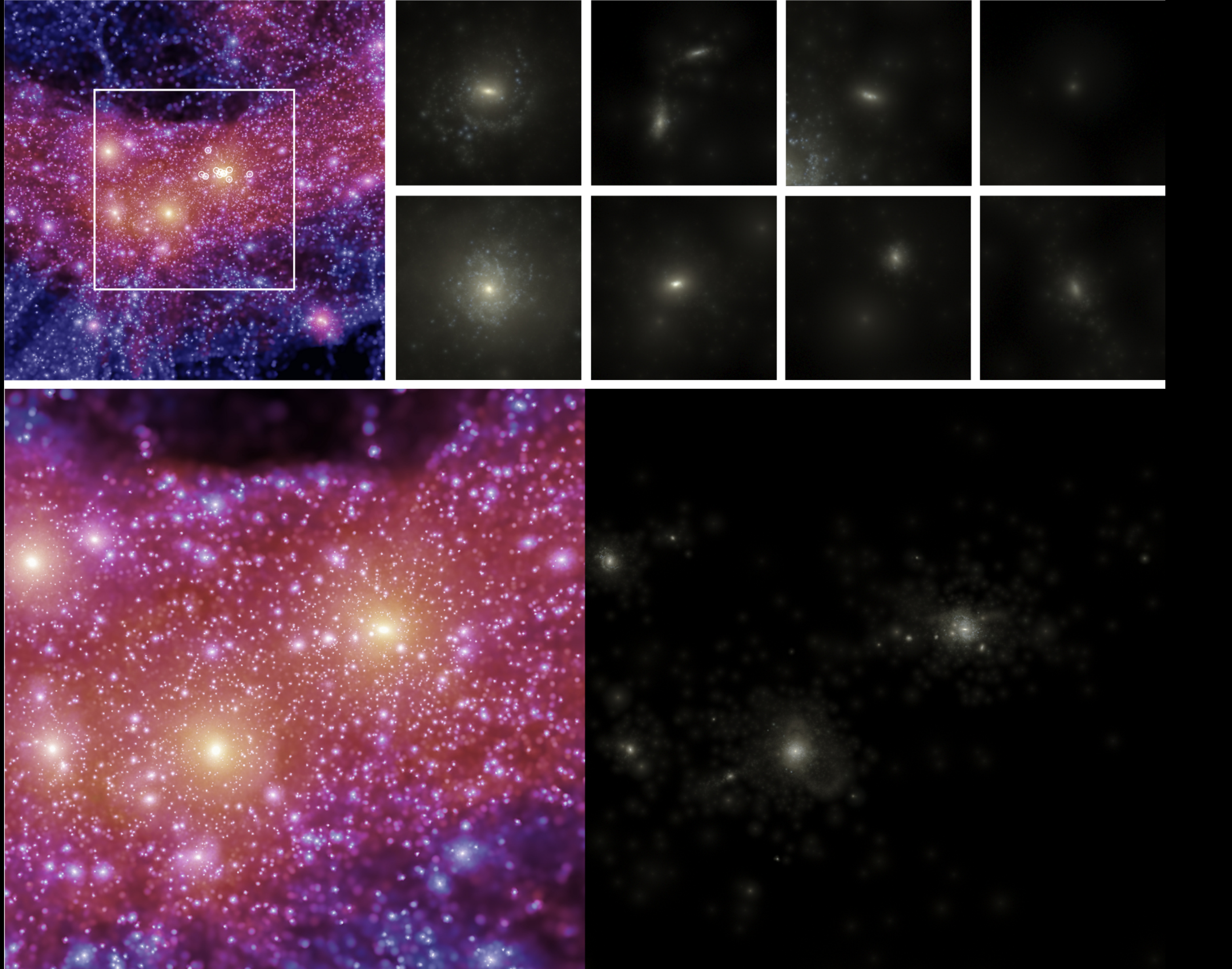
Eagle gives a good match to observed stellar mass fn over 5 orders of magnitude in stellar mass



EAGLE full hydro Local Group simulations

Dark Matter
Gas
Stars





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Four problems for CDM on small scales?

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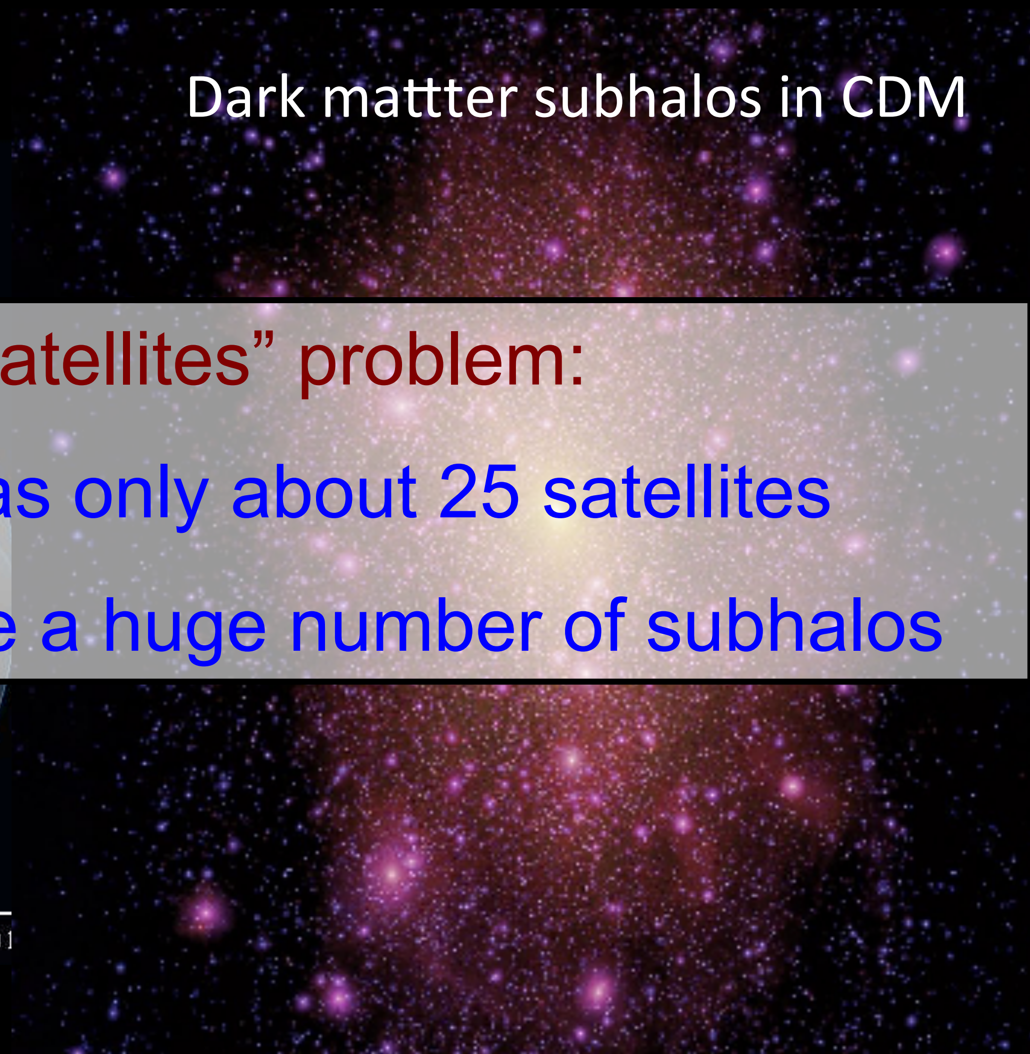
The "missing satellites" problem

The satellites of the MW

Dark matter subhalos in CDM



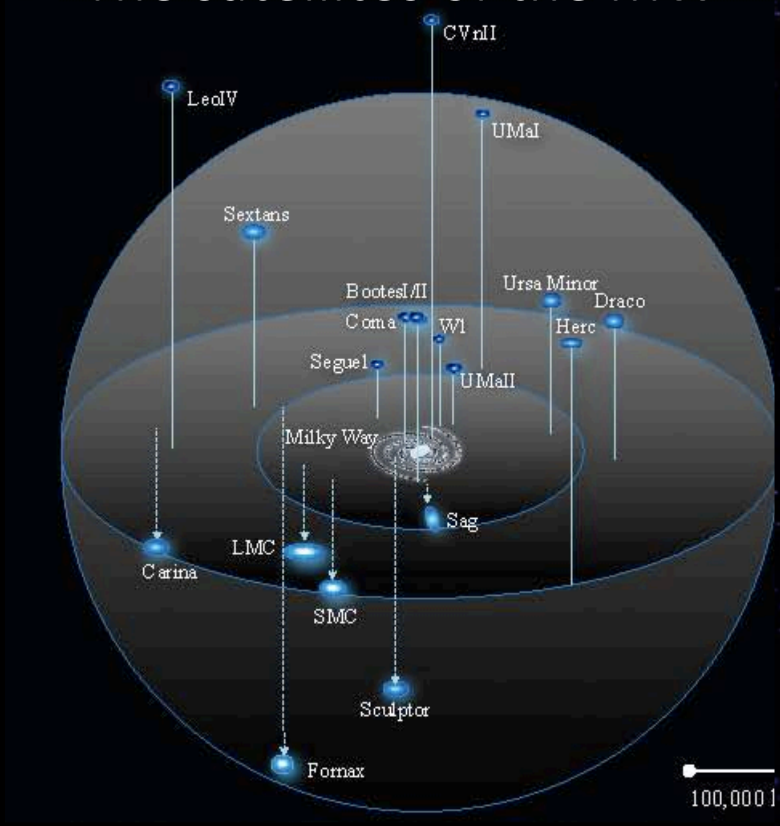
"Missing satellites" problem:

The Milky way has only about 25 satellites

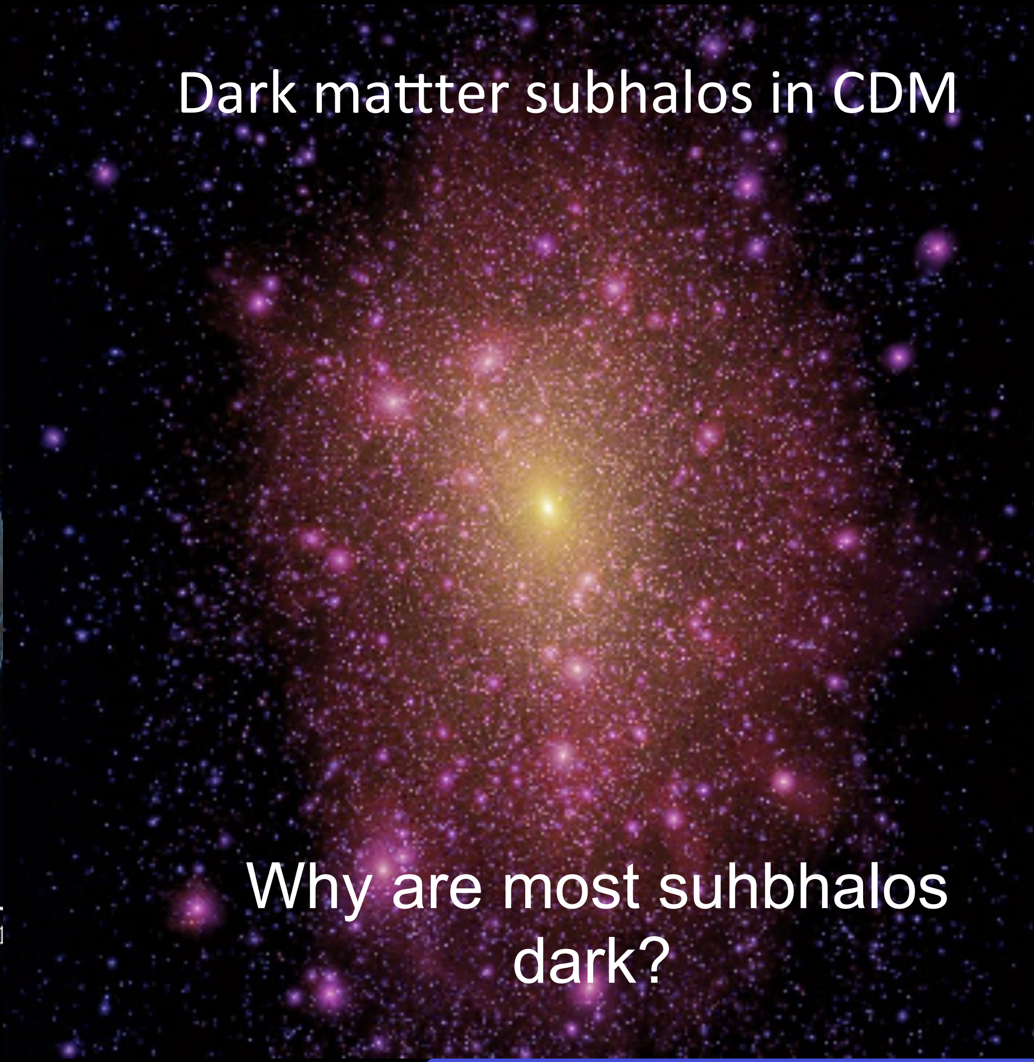
BUT: CDM halos have a huge number of subhalos

The “missing satellites” problem

The satellites of the MW



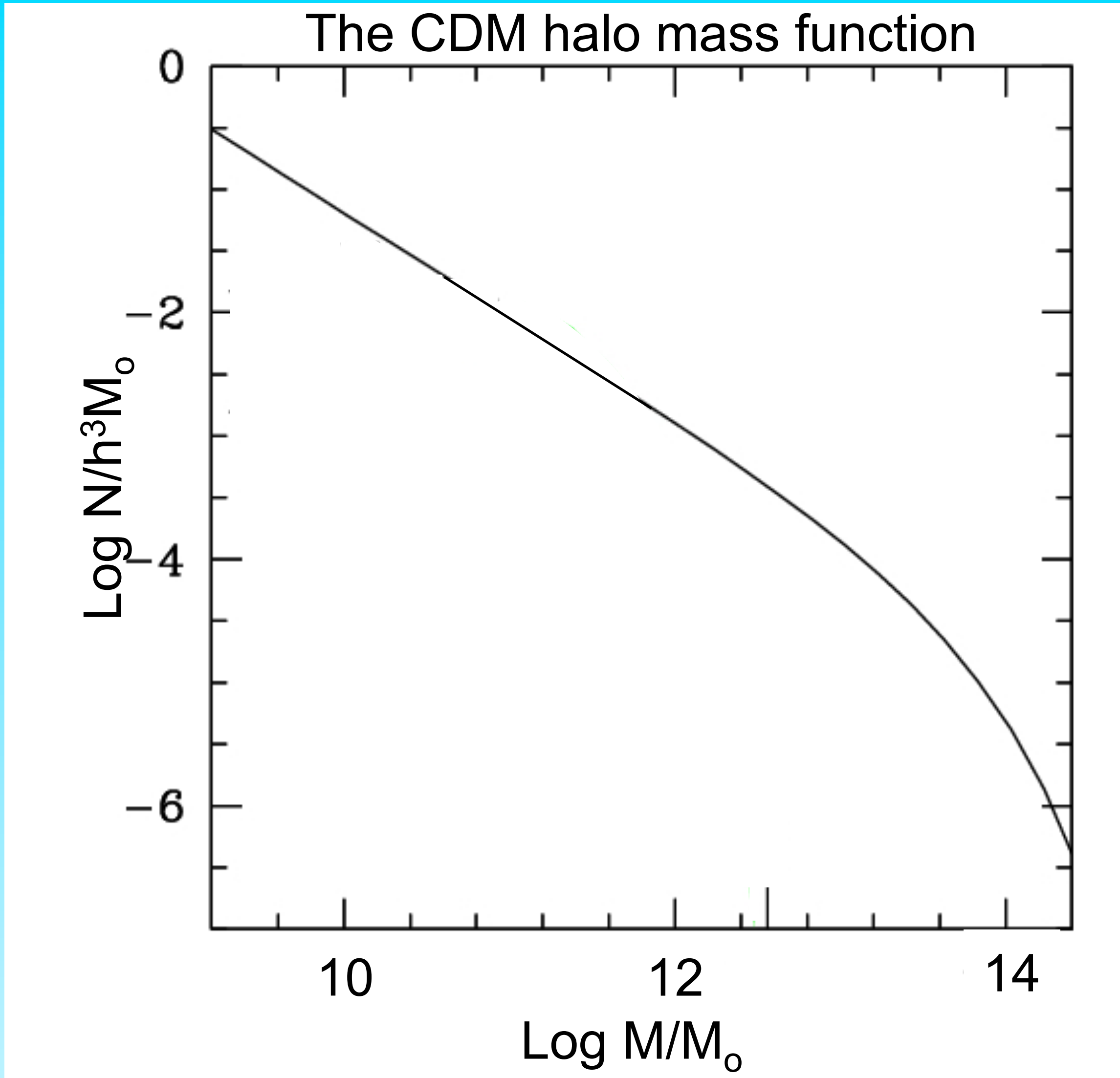
Dark mattter subhalos in CDM



Why are most suhbhalos dark?

The CDM halo mass function

Jenkins et al. ‘01



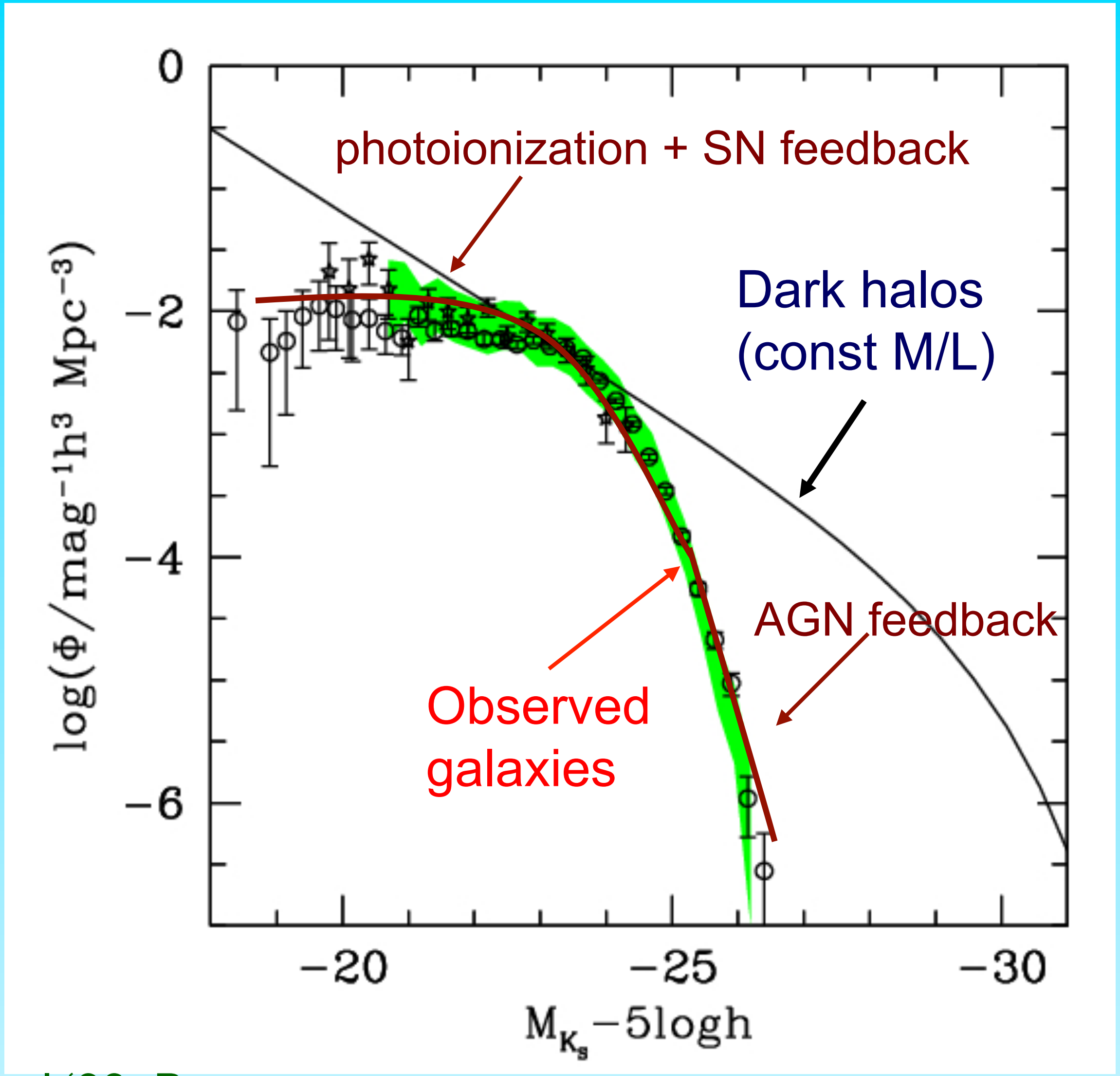
The galaxy luminosity function

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

⇨

Galaxy luminosity not just ∝ 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

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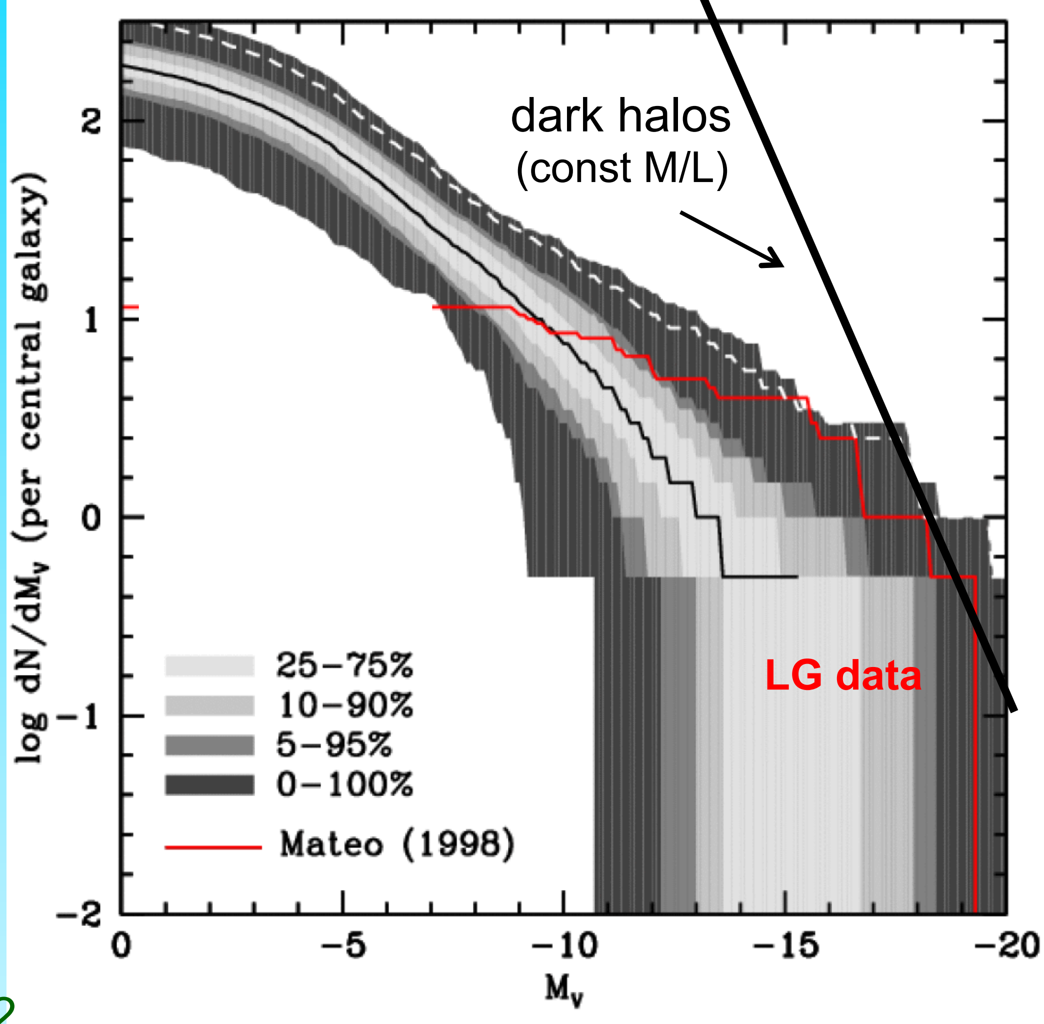
- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



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

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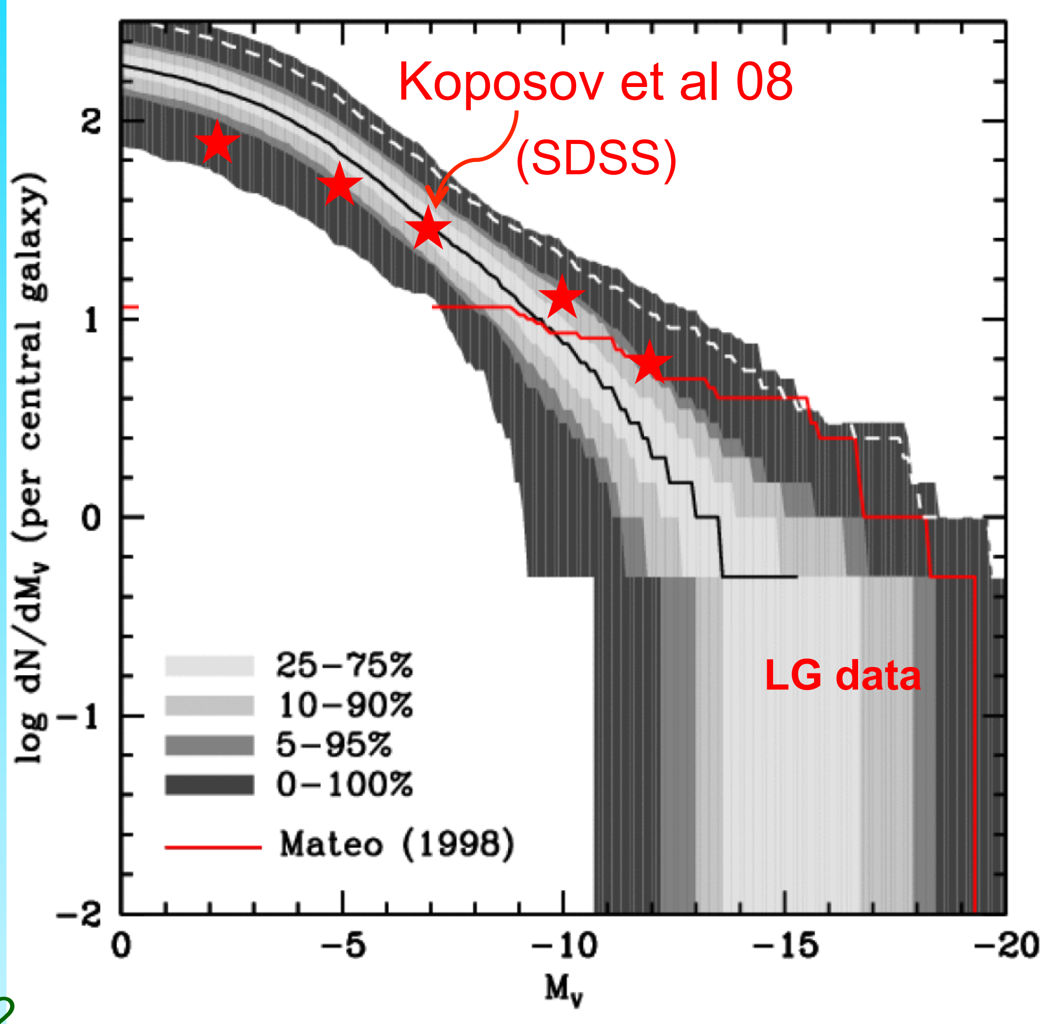

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EAGLE full hydro simulations

Local Group

Sawala et al ‘15

Far fewer satellite galaxies than CDM halos

EAGLE full hydro simulations

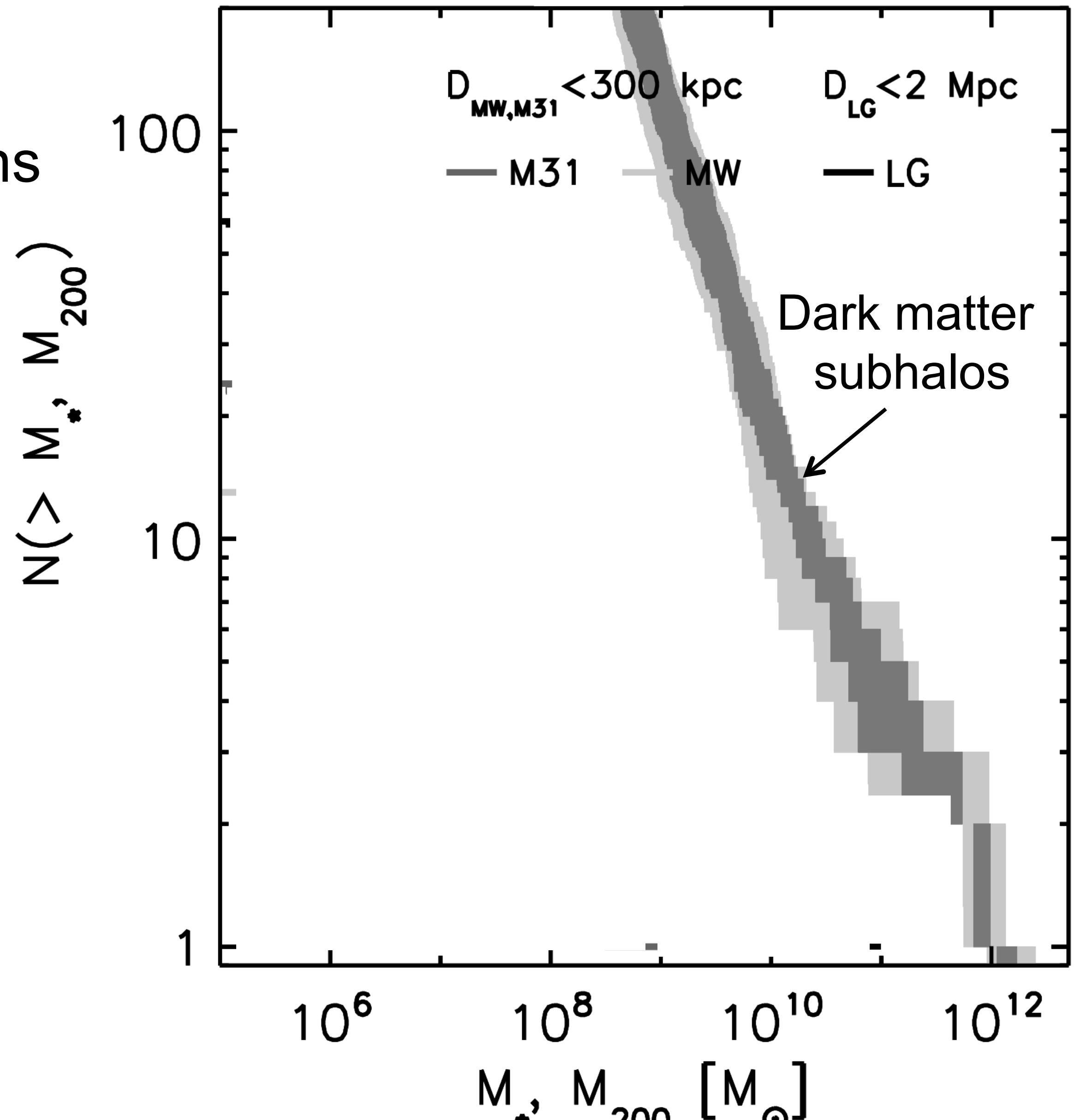
Local Group

Sawala et al ‘15

EAGLE Local Group simulation

University of Durham

Subhalo mass functions

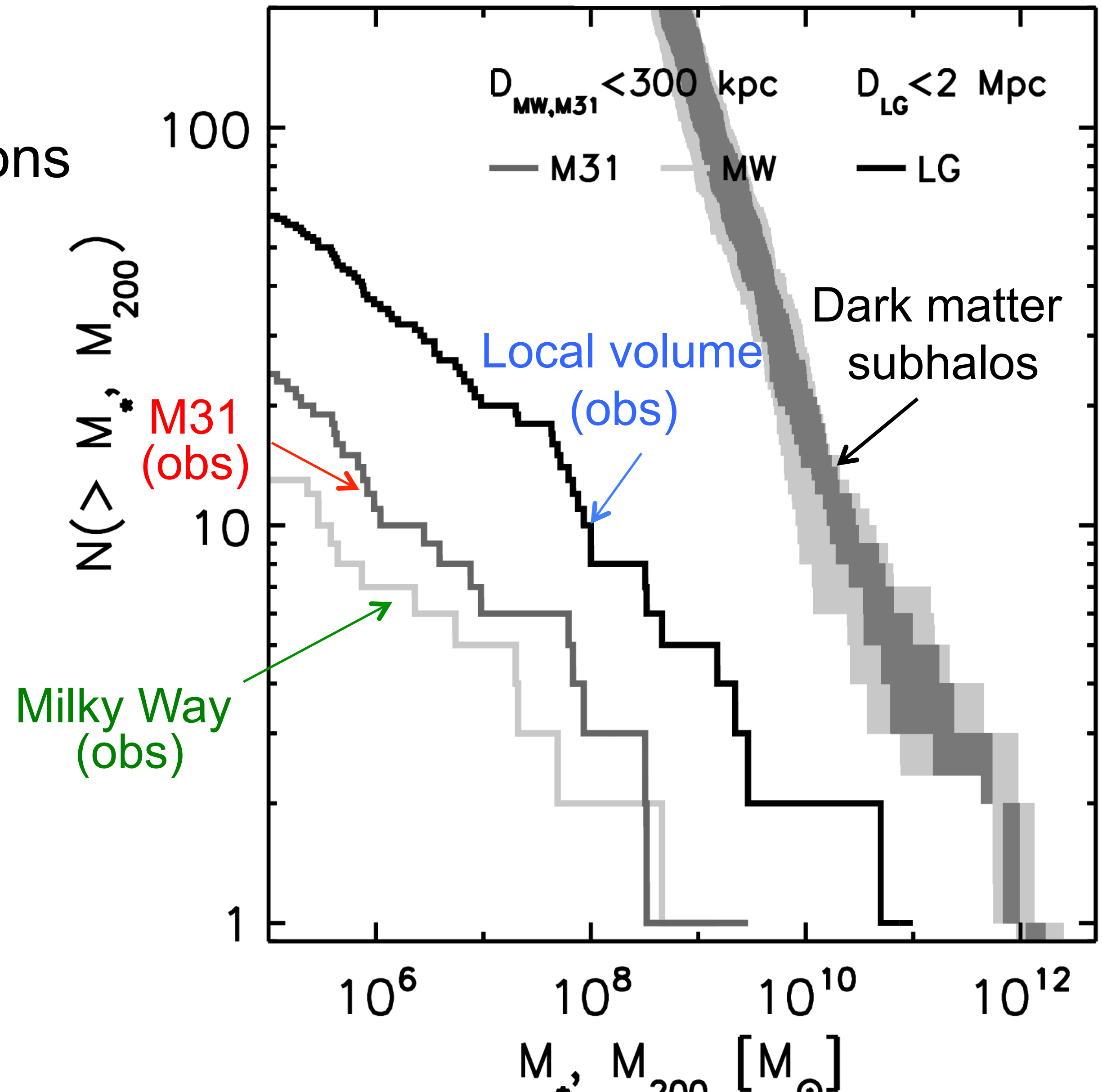


Sawala et al '15

EAGLE Local Group simulation

University of Durham

Stellar mass functions



Sawala et al '15

EAGLE Local Group simulation

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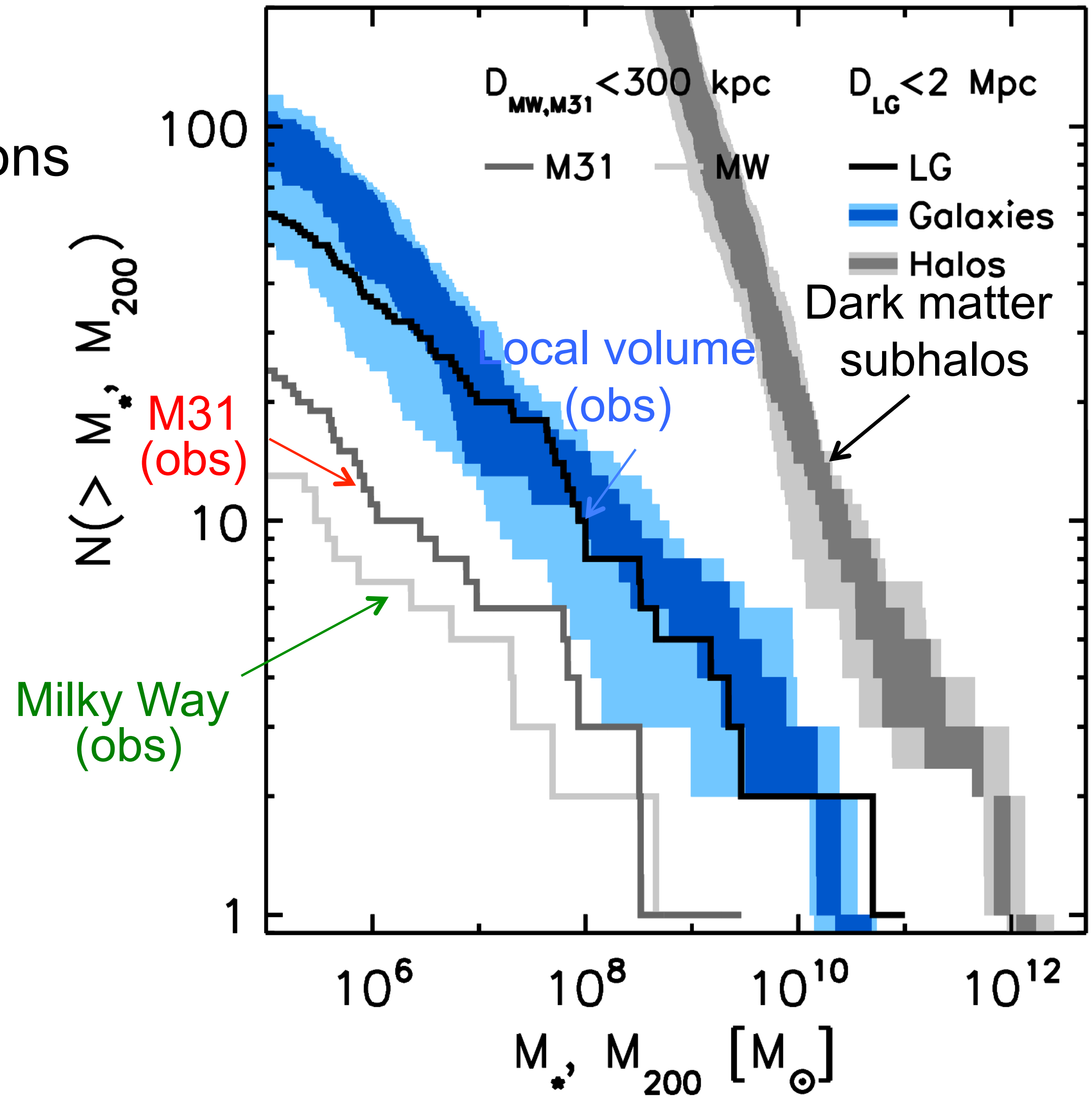
Stellar mass functions



Sawala et al '15

EAGLE Local Group simulation

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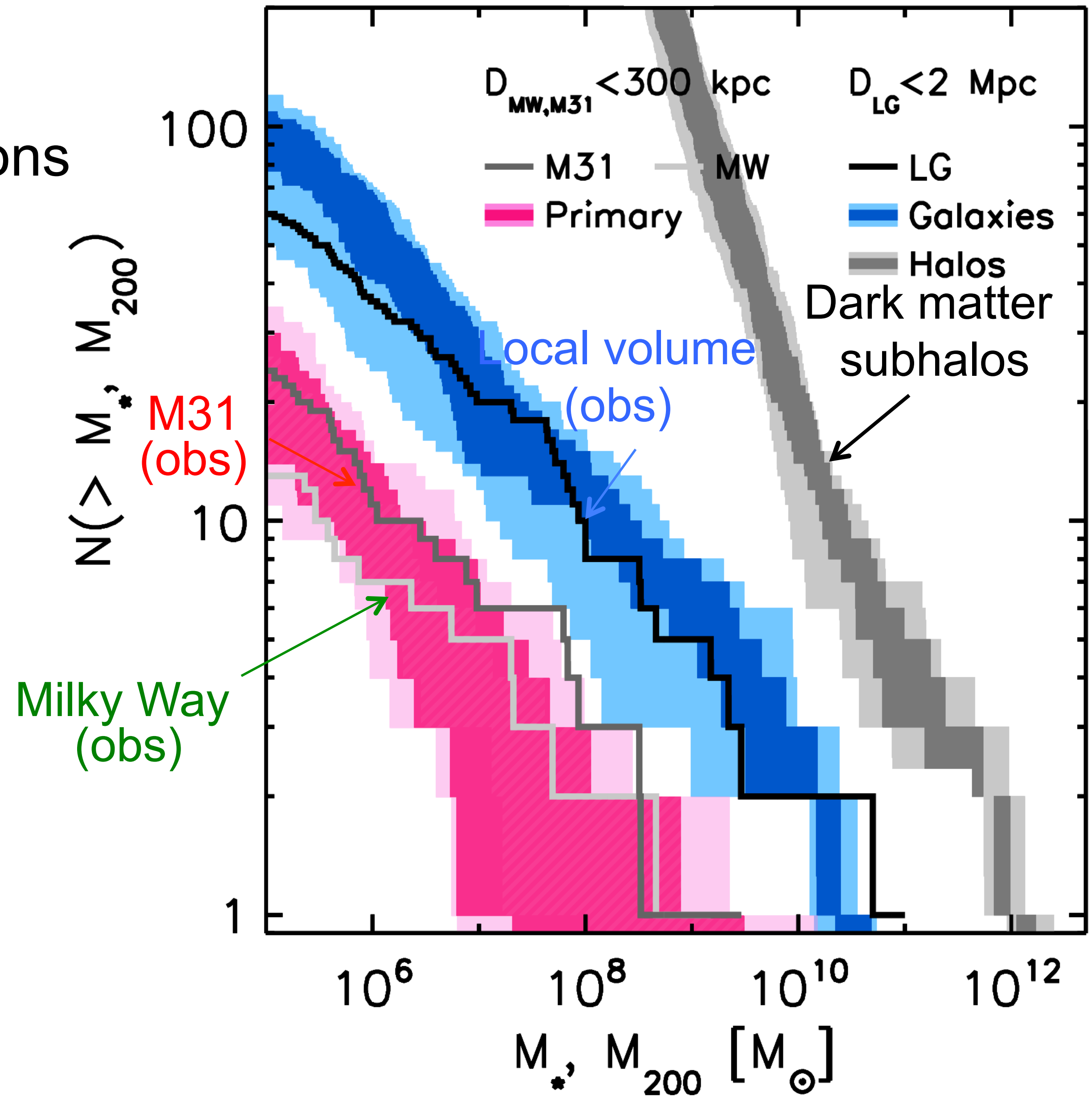
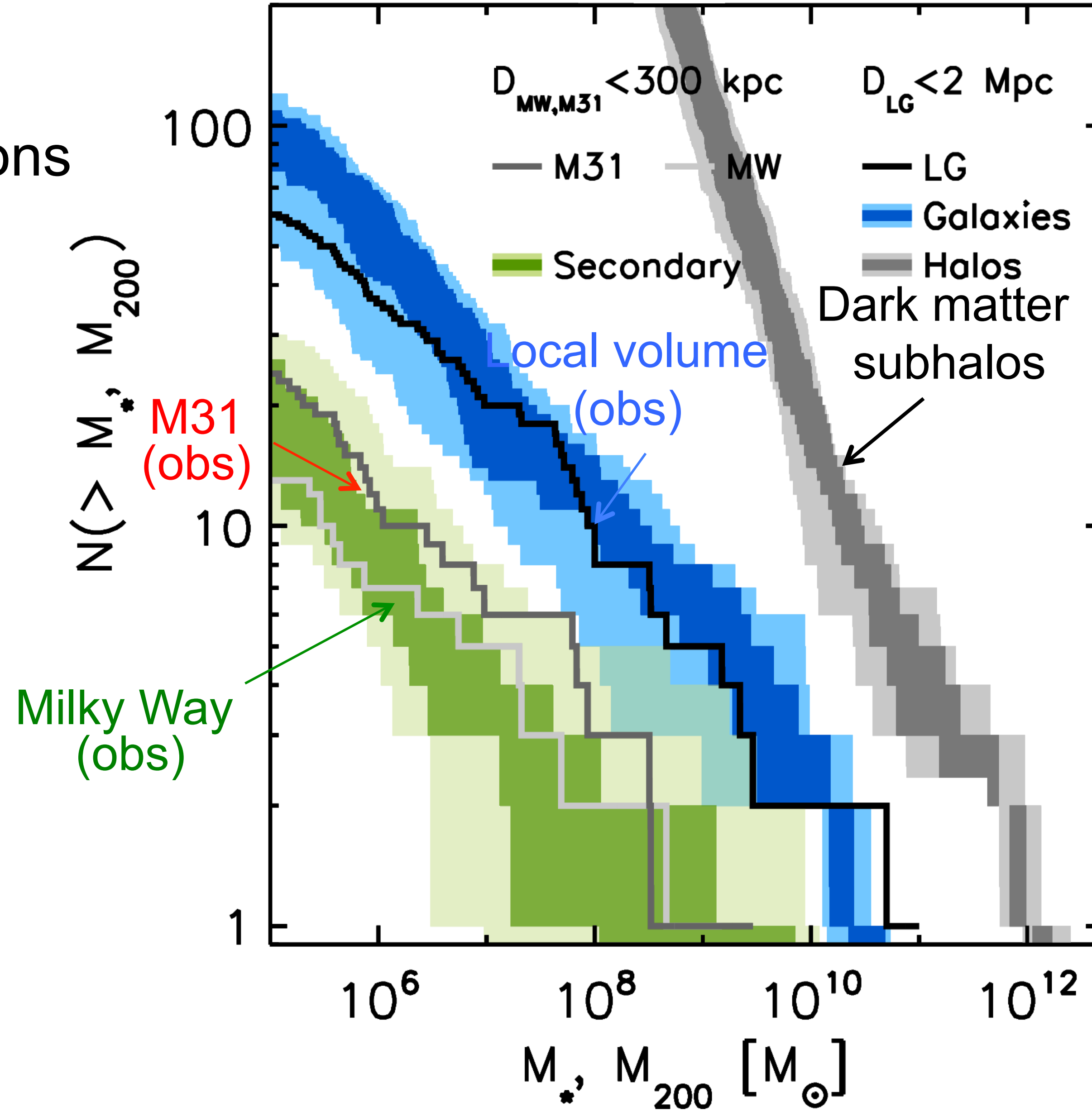
Stellar mass functions



Sawala et al ‘15

EAGLE Local Group simulation

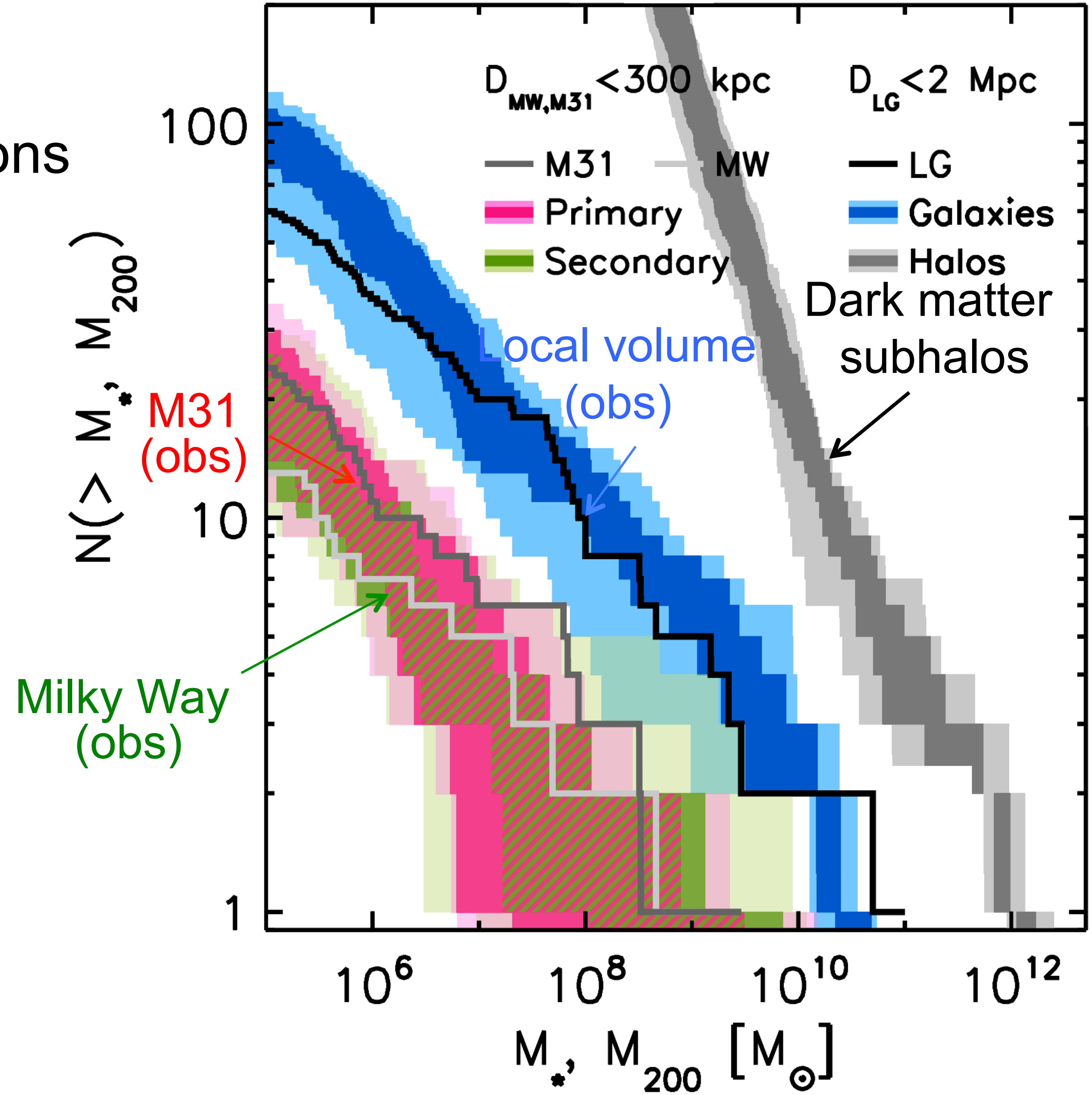
Stellar mass functions



Sawala et al '15

EAGLE Local Group simulation

Stellar mass functions



Sawala et al '15

Is there a "satellite problem" in CDM?

No, when galaxy formation is taken into account!

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Four problems for CDM on small scales?

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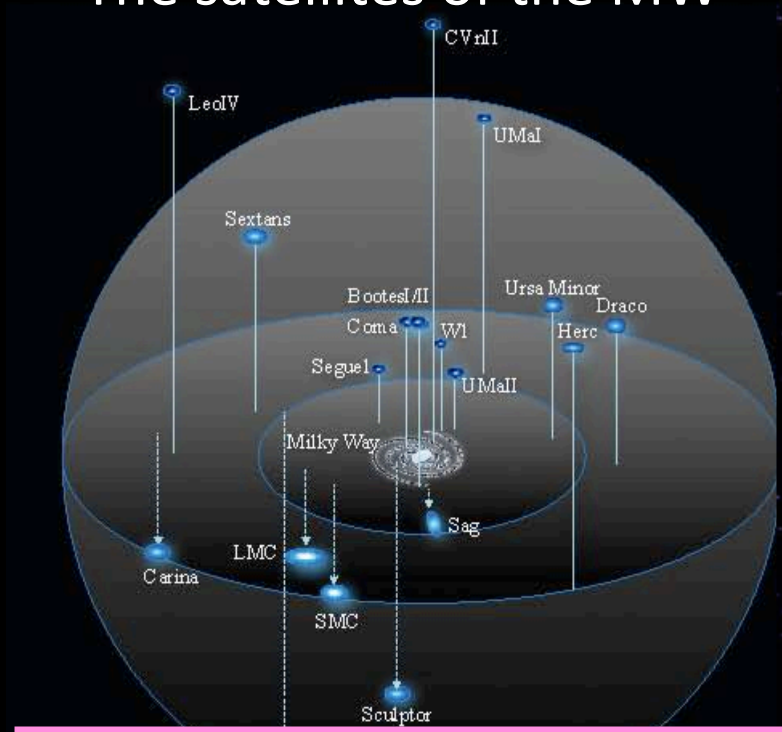
The "too-big-to-fail" problem

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

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

The satellites of the MW



MW has only 3 satellites with V_{max}>30 km/s

(LMC, SMC, Sgr)

Dark mattter subhalos in CDM

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

Why did these not make a galaxy?

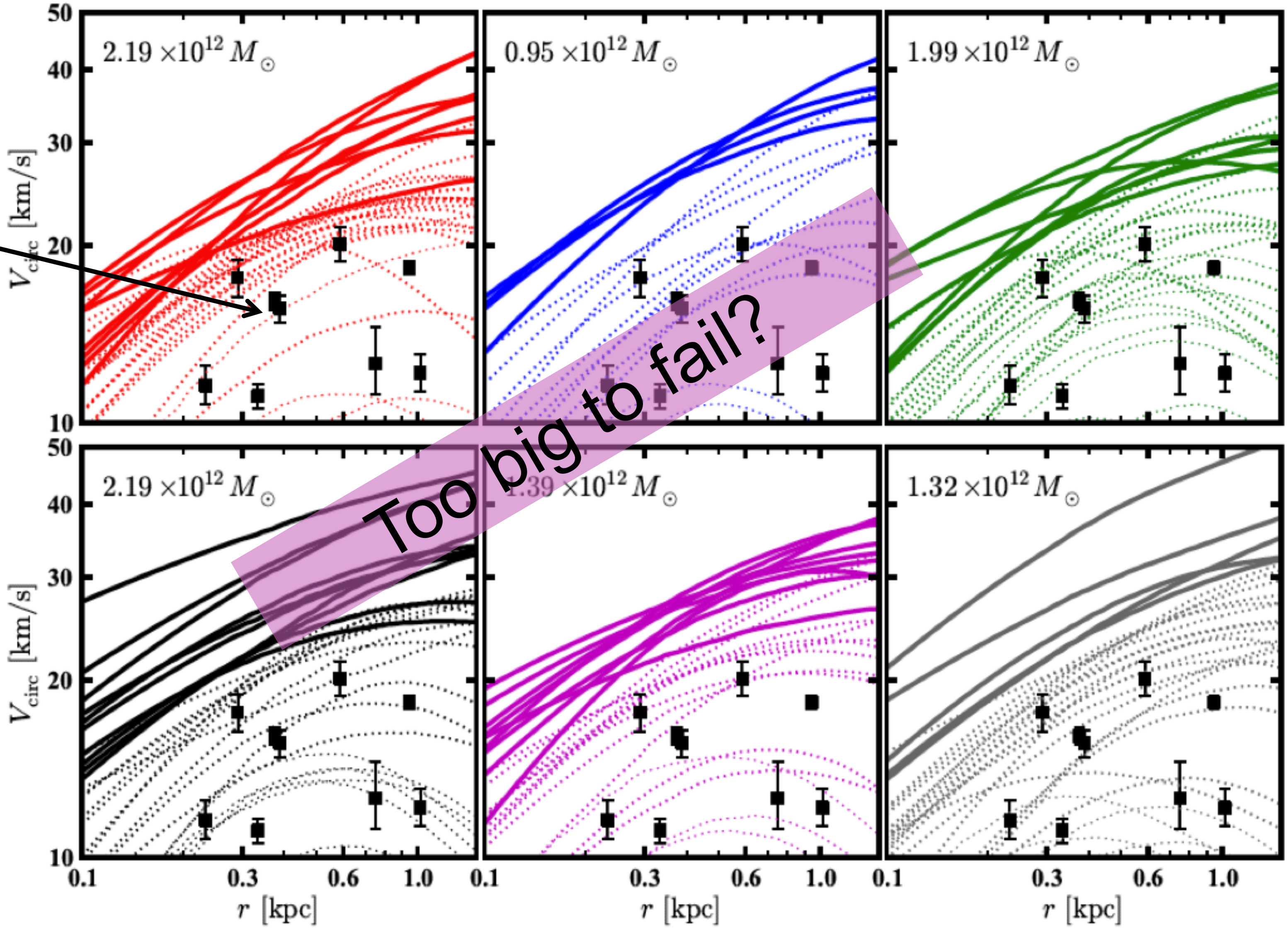
Rotation curves of Aquarius subhalos

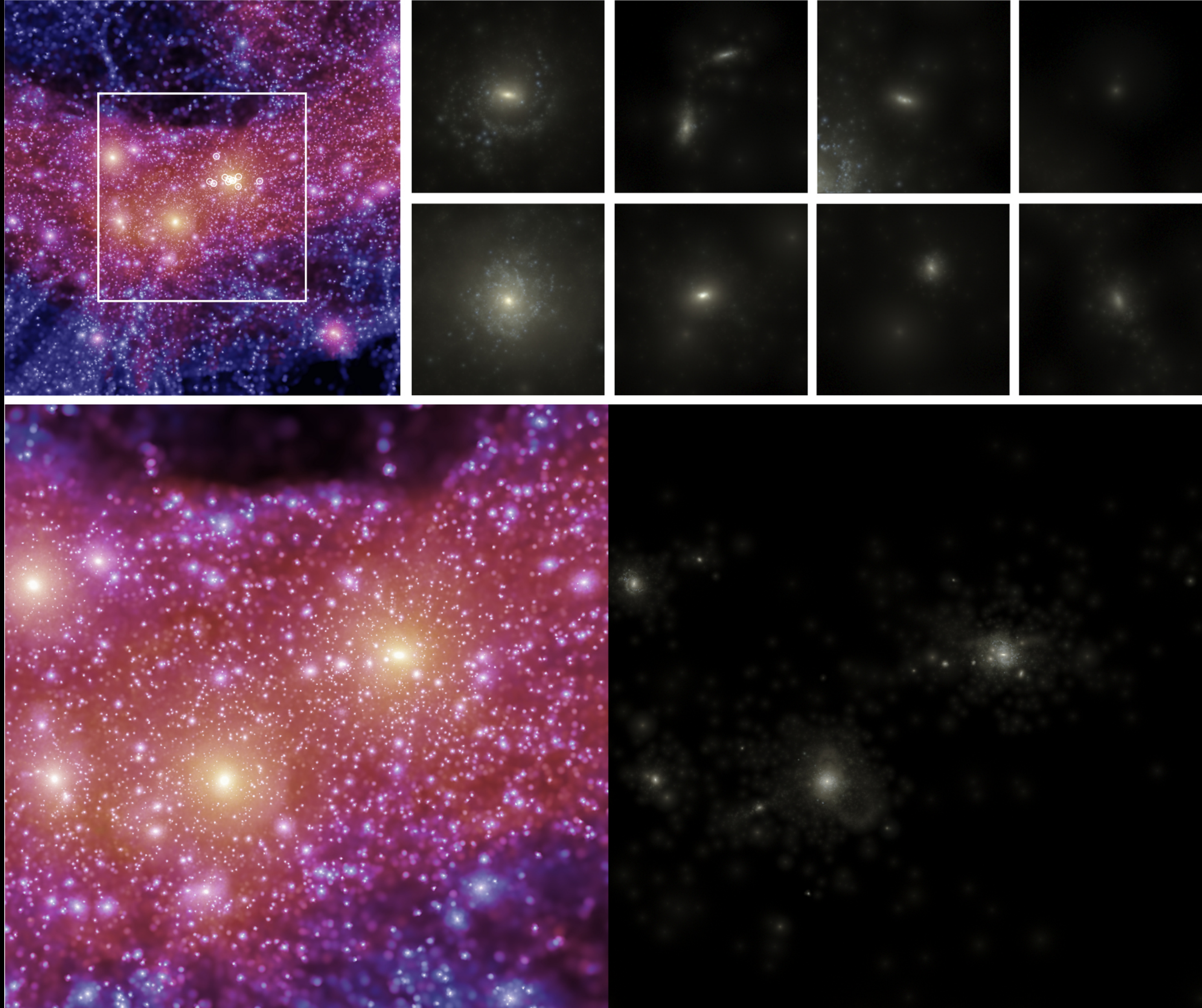
Boylan-Kolchin et al. '11

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

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

Excludes LMC, SMC, Sagittarius





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

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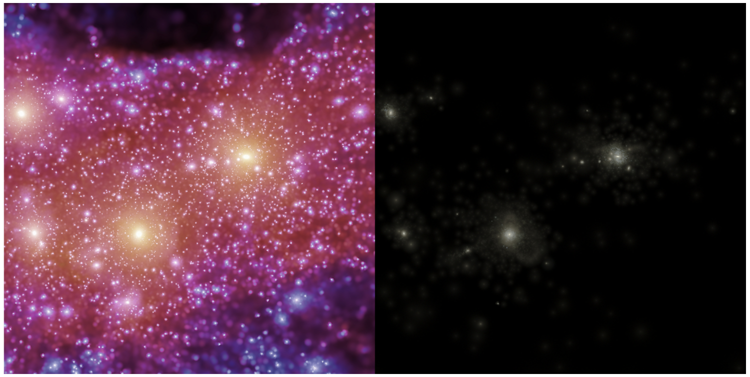
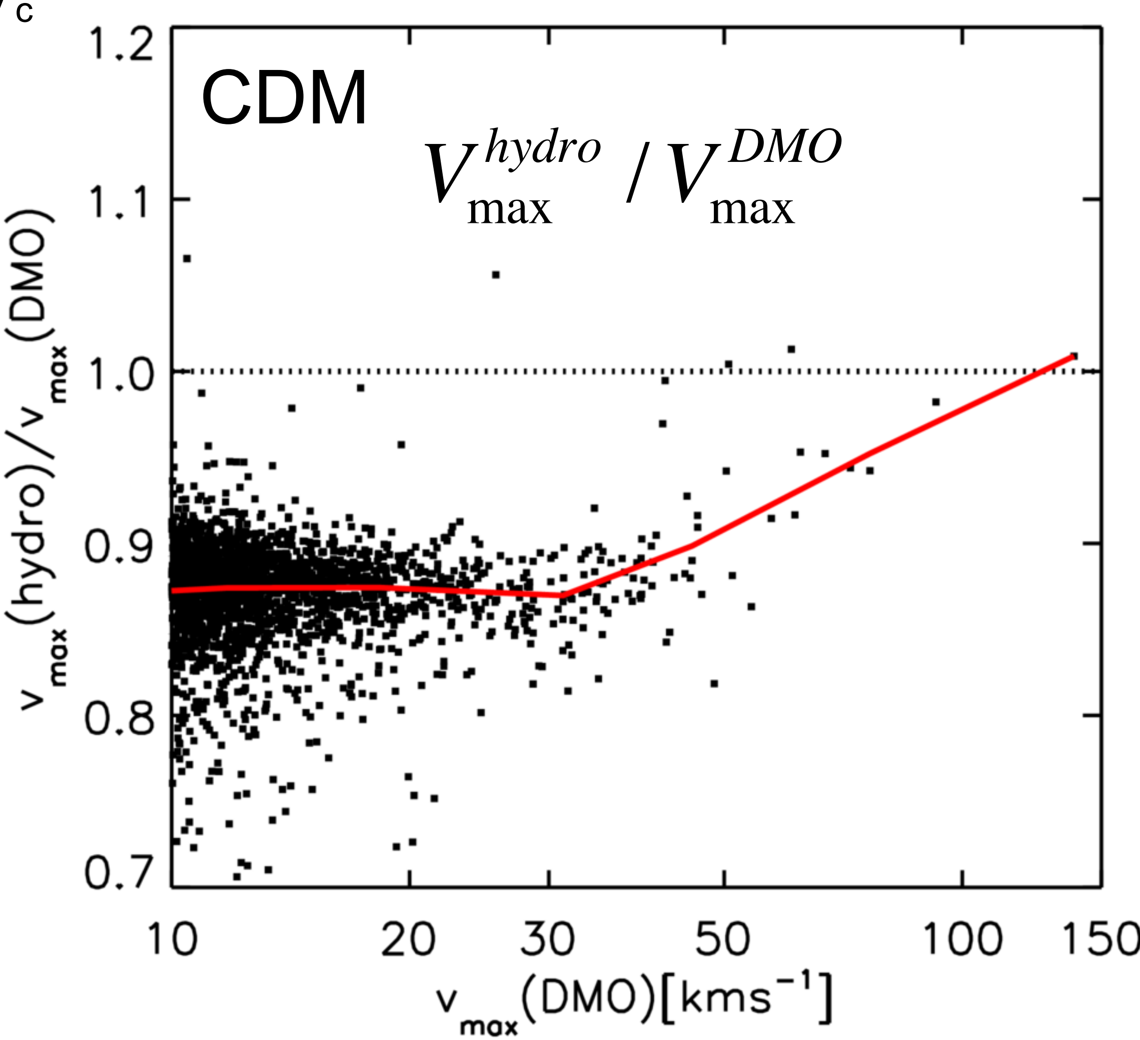
$$V_c = \sqrt{\frac{GM}{r}}$$

$V_{max} = \max V_c$

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate





Sawala et al. '13, '15

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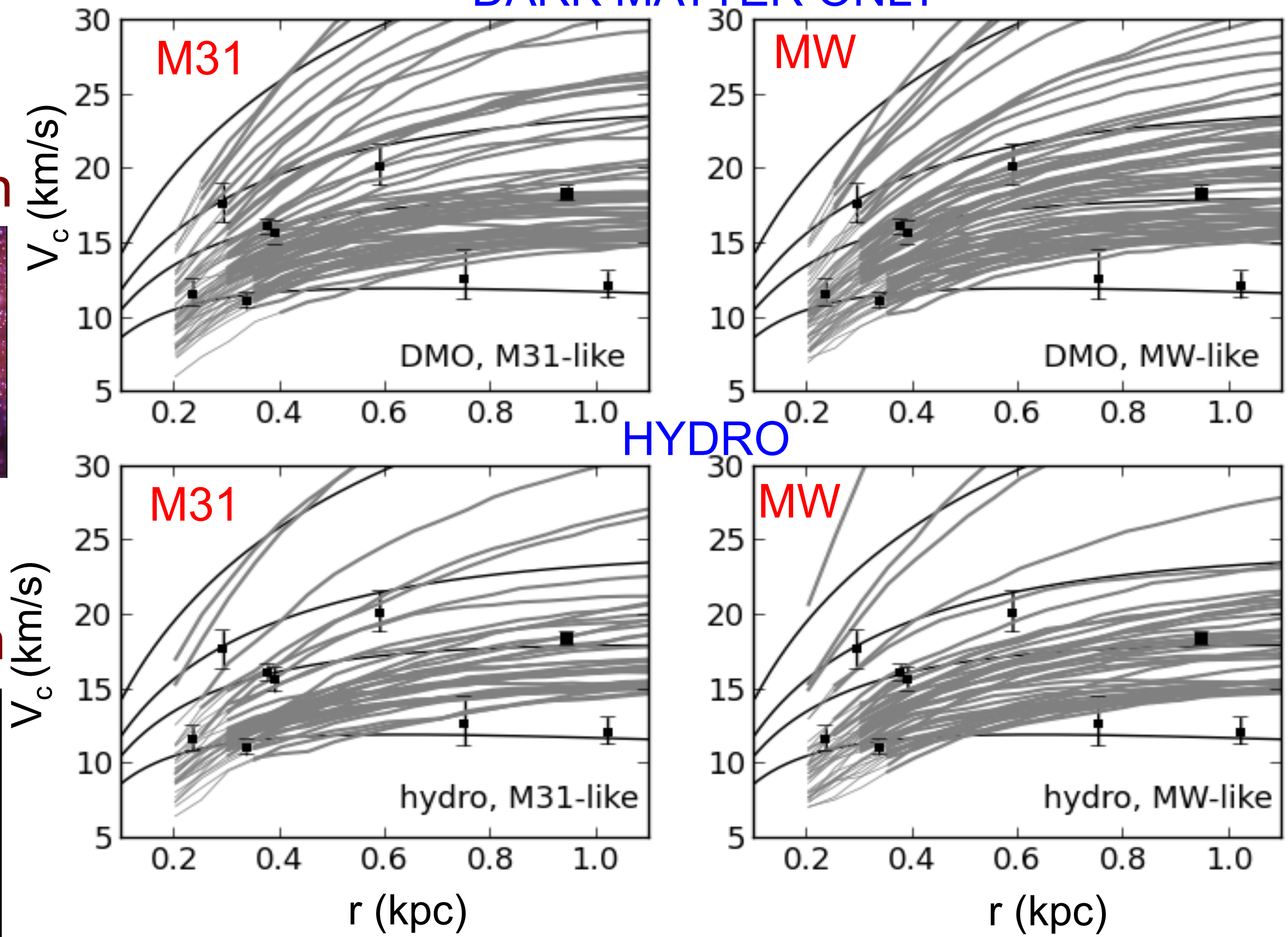
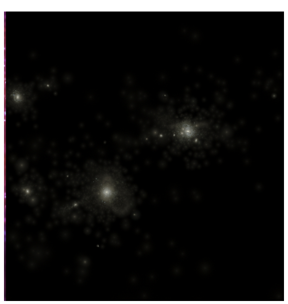
Too-big-to-fail: the baryon bailout

DM-only simulation

DARK MATTER ONLY



Gas simulation



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

Sawala et al. '15

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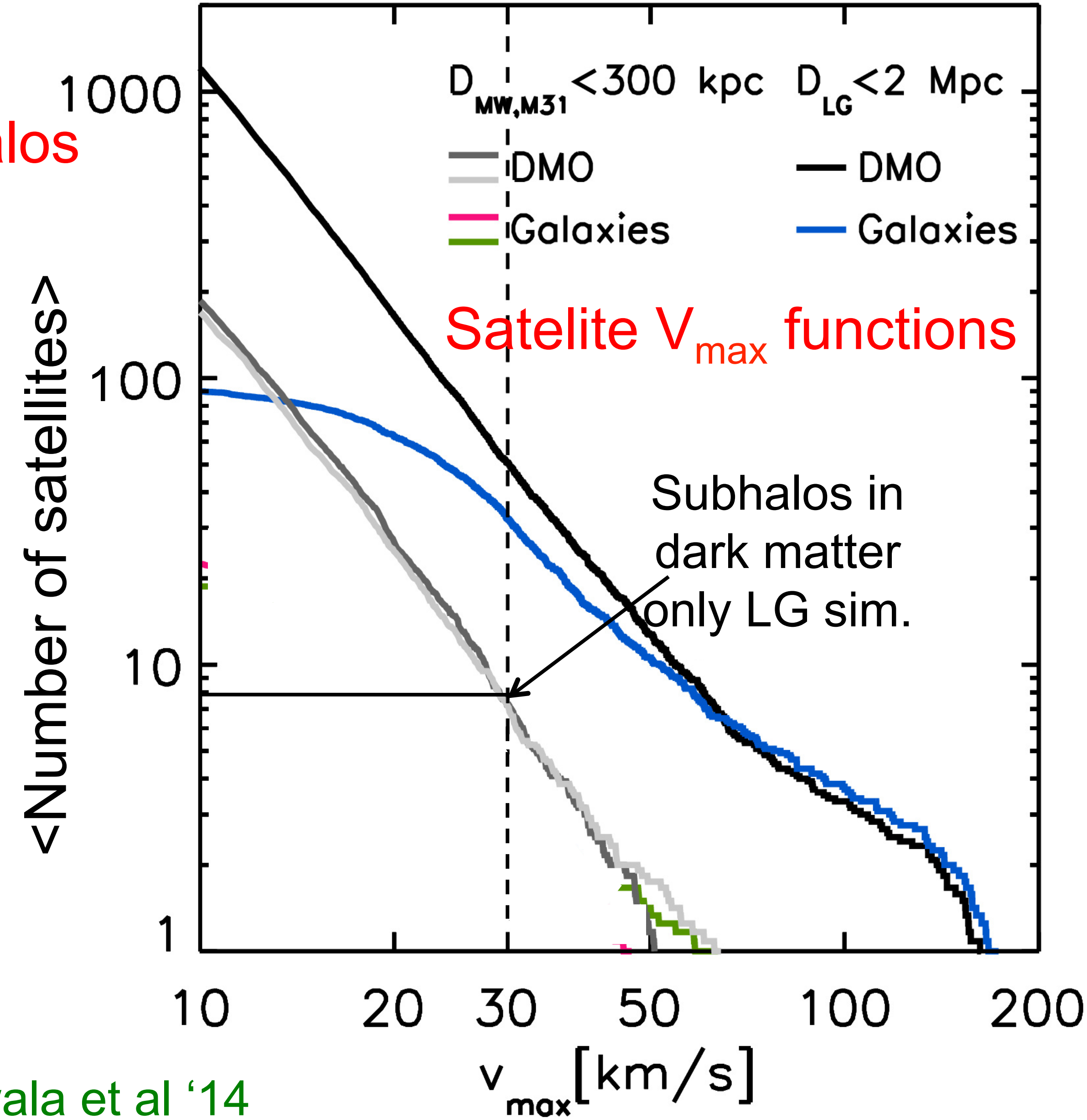
Too-big-to-fail: the baryon bailout

DM only sims → ~10 halos with V_{max}> 30 km/s



Sawala et al ‘14

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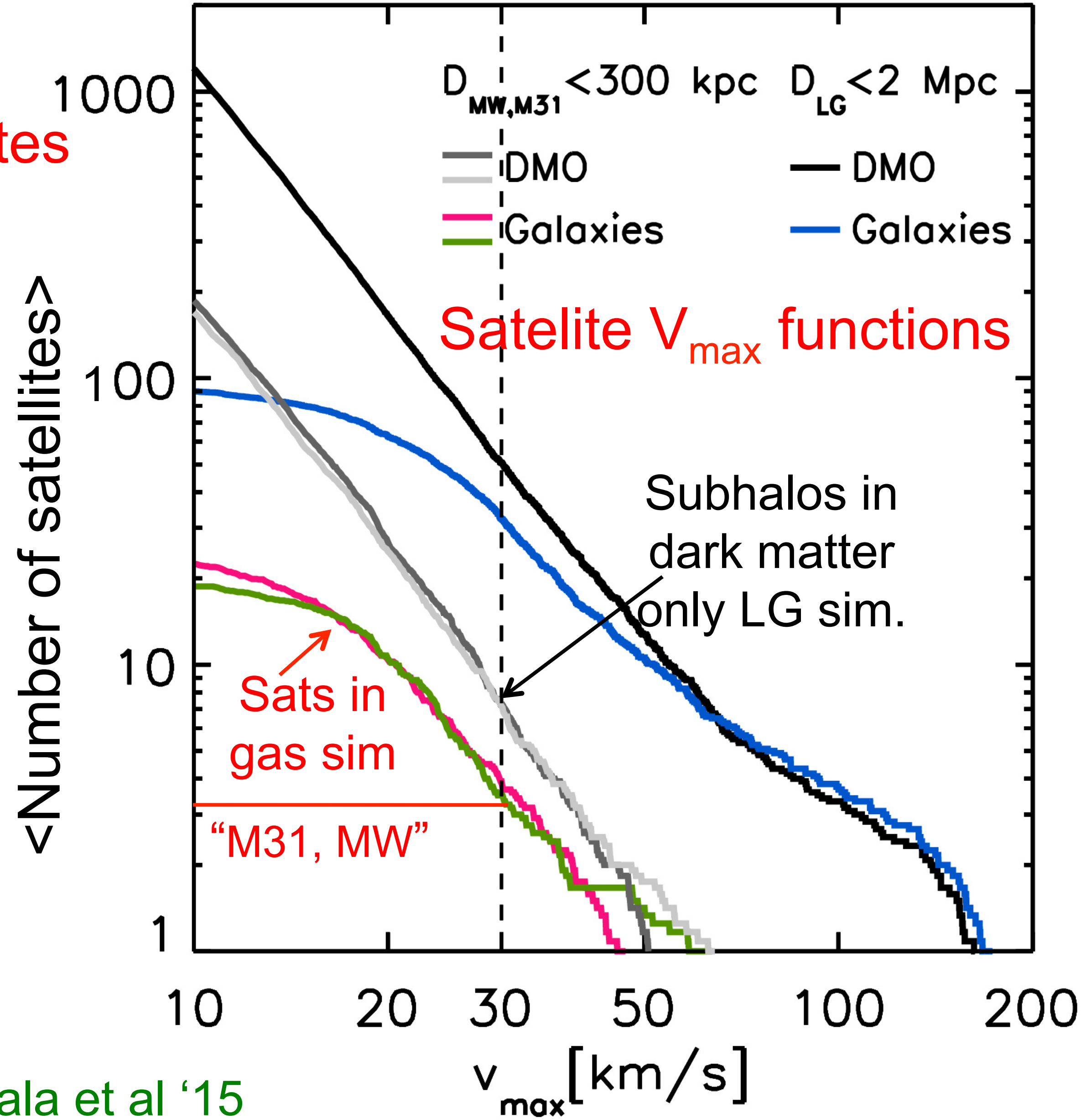
Too-big-to-fail: the baryon bailout

Hydro sims → ~3 satellites with V_{max}> 30 km/s



Sawala et al '15

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Too-big-to-fail: the baryon bailout

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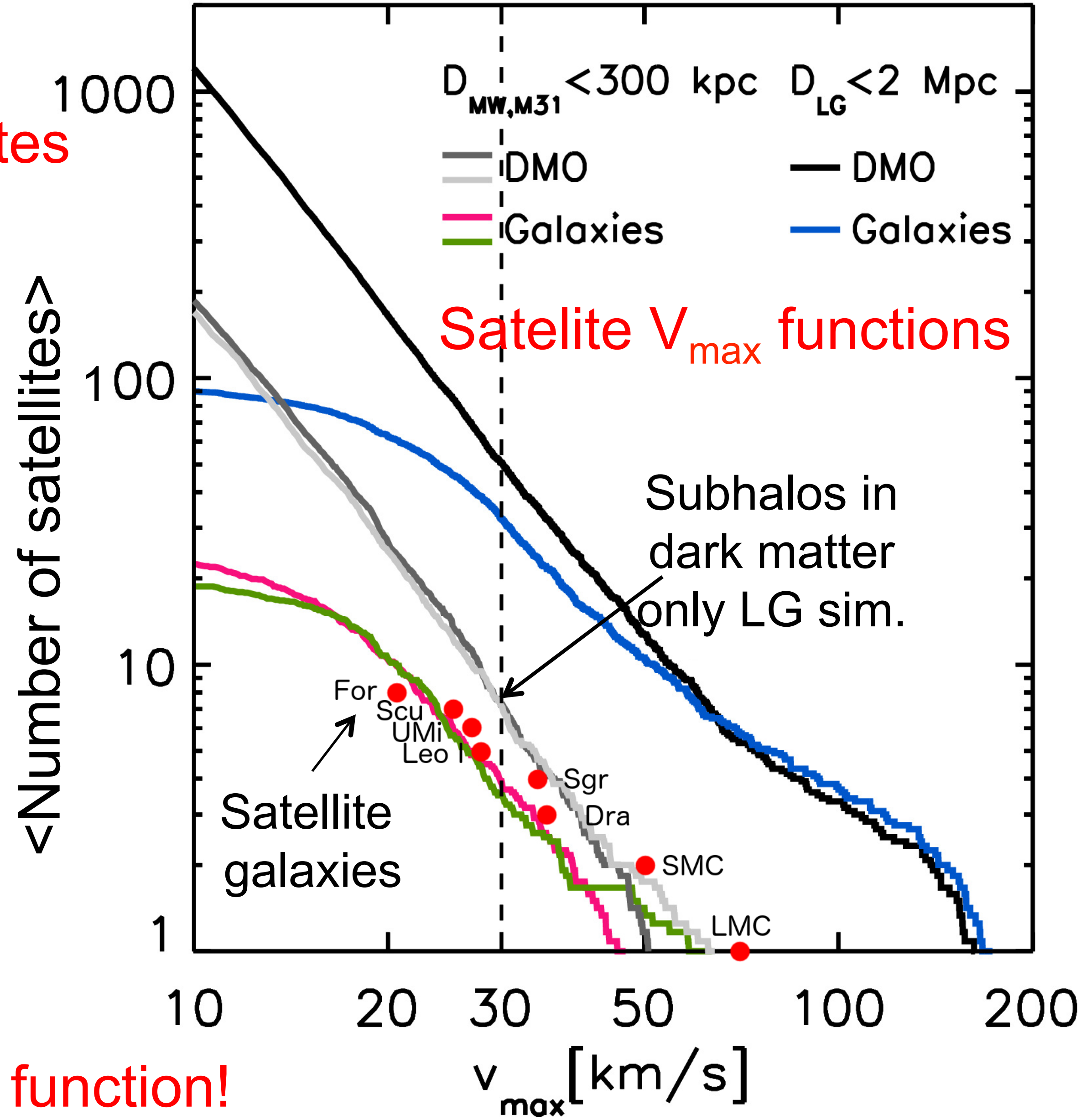

… and with correct V_{max} function!

Is there a "too-big-to-fail" problem in CDM?

No, when galaxy formation is taken into account!

Four problems for CDM on small scales?

1. The “missing satellites” problem
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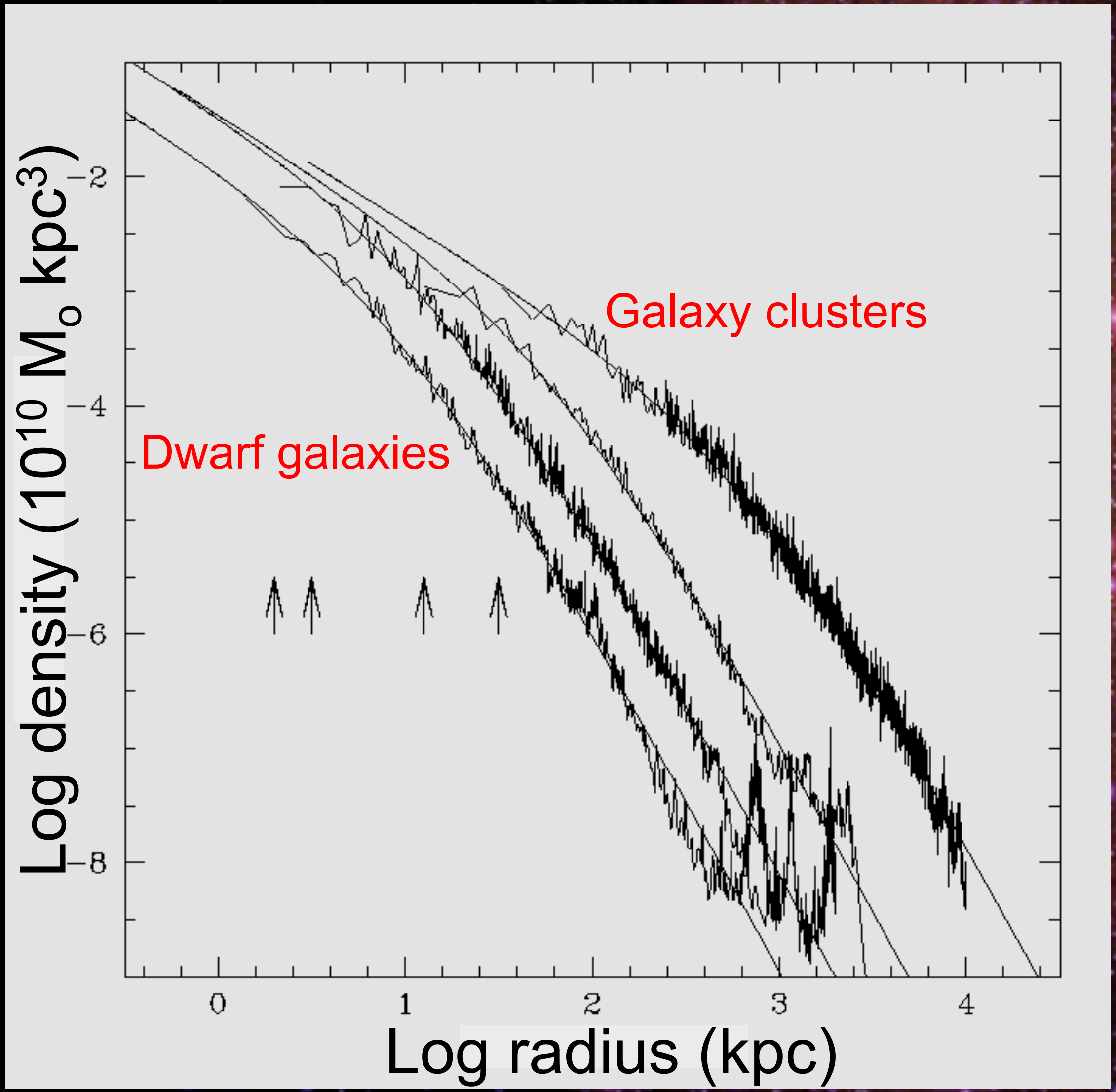
The Density Profile of Cold Dark Matter Halos



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

Density profiles are "cuspy" - no `core' near the centre

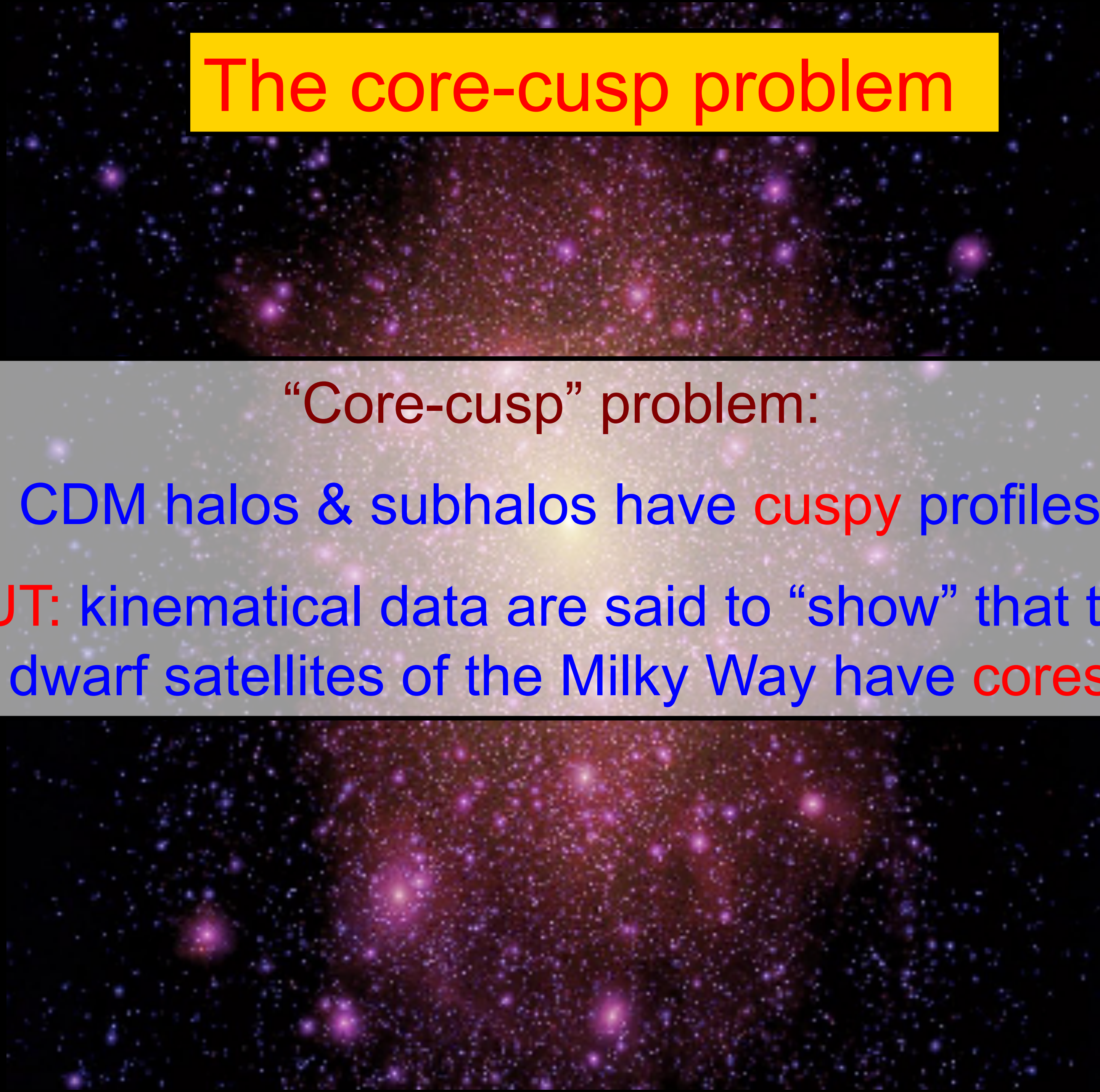
Fitted by simple formula:

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

(Navarro, Frenk & White '97)

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

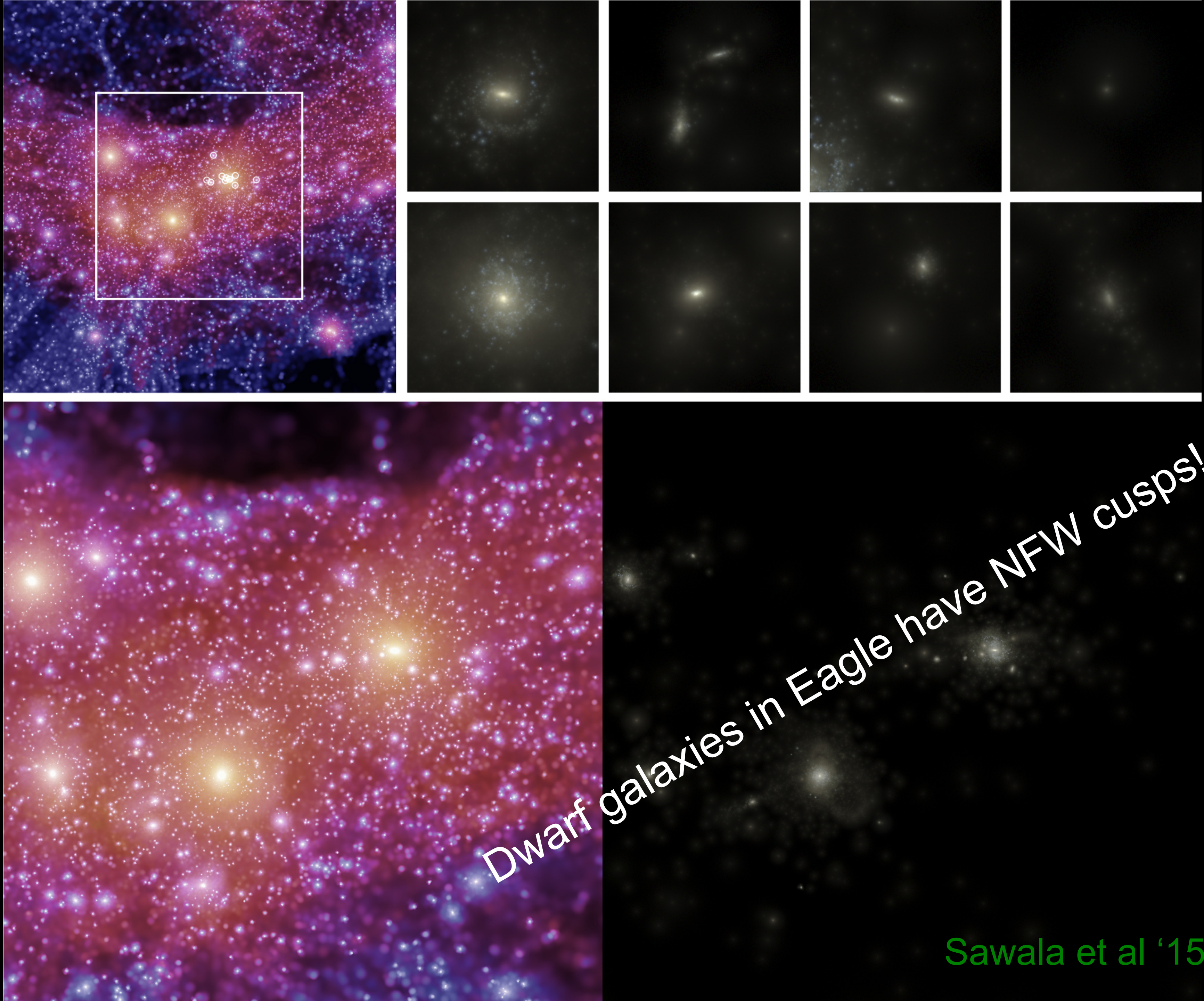
The core-cusp problem



"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 in Eagle have NFW cusps!
Sawala et al ‘15

Dwarf galaxies around the Milky Way

Many claims that dwarf spheroidal satellites have density cores

- e.g. Gilmore et al. '07, Kuzio de Naray '08 and many more

Fornax

Sculptor

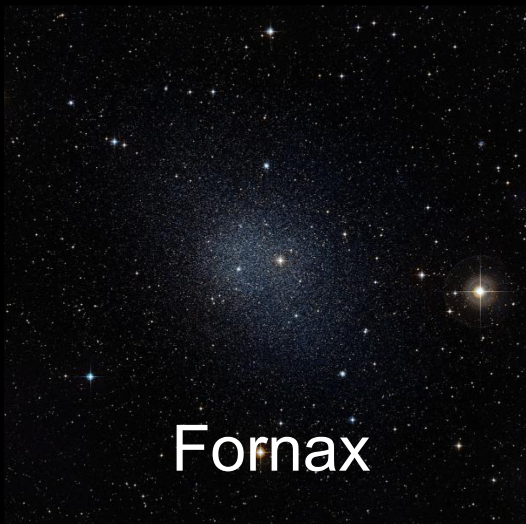
Leo I

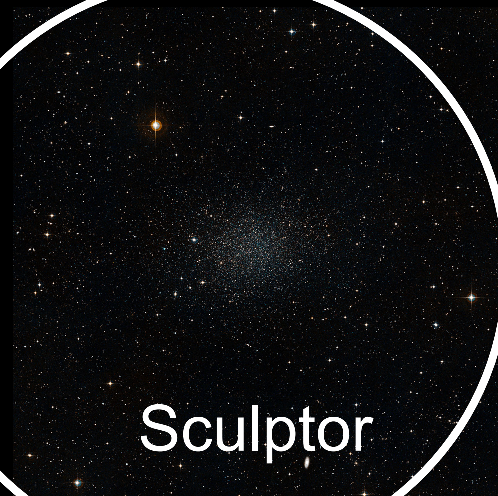
Sextans

Carina

Sagittarius

Dwarf galaxies around the Milky Way





Sextans

Carina

Sagittarius

University of Durham

The DM halo of the Sculptor dwarf

Sculptor has two stellar pops:

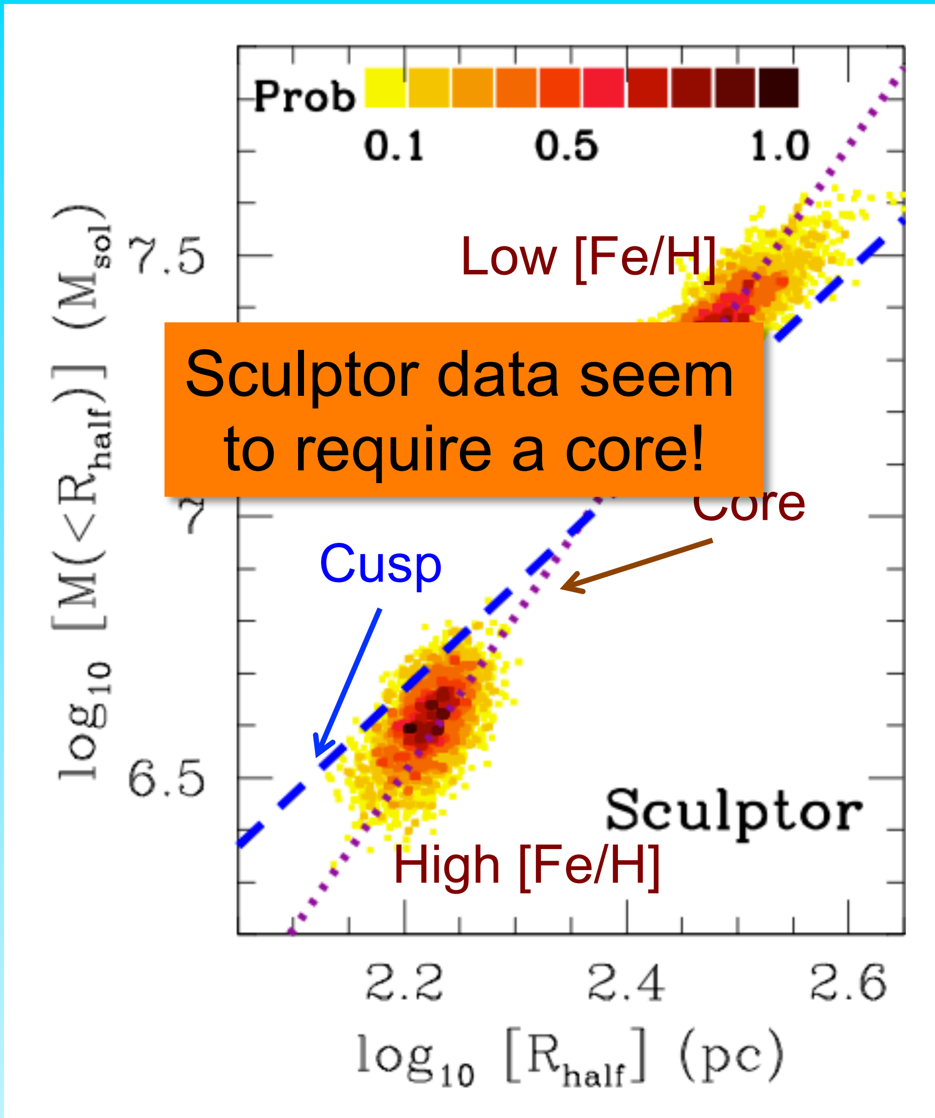
(i) centrally concentrated, high [Fe/H]

(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!



Walker & Peñarrubia '11

University of Durham

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

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

Find best-fit parameters using MCMC

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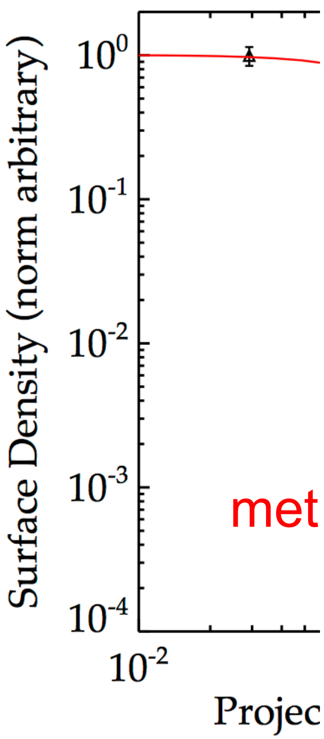
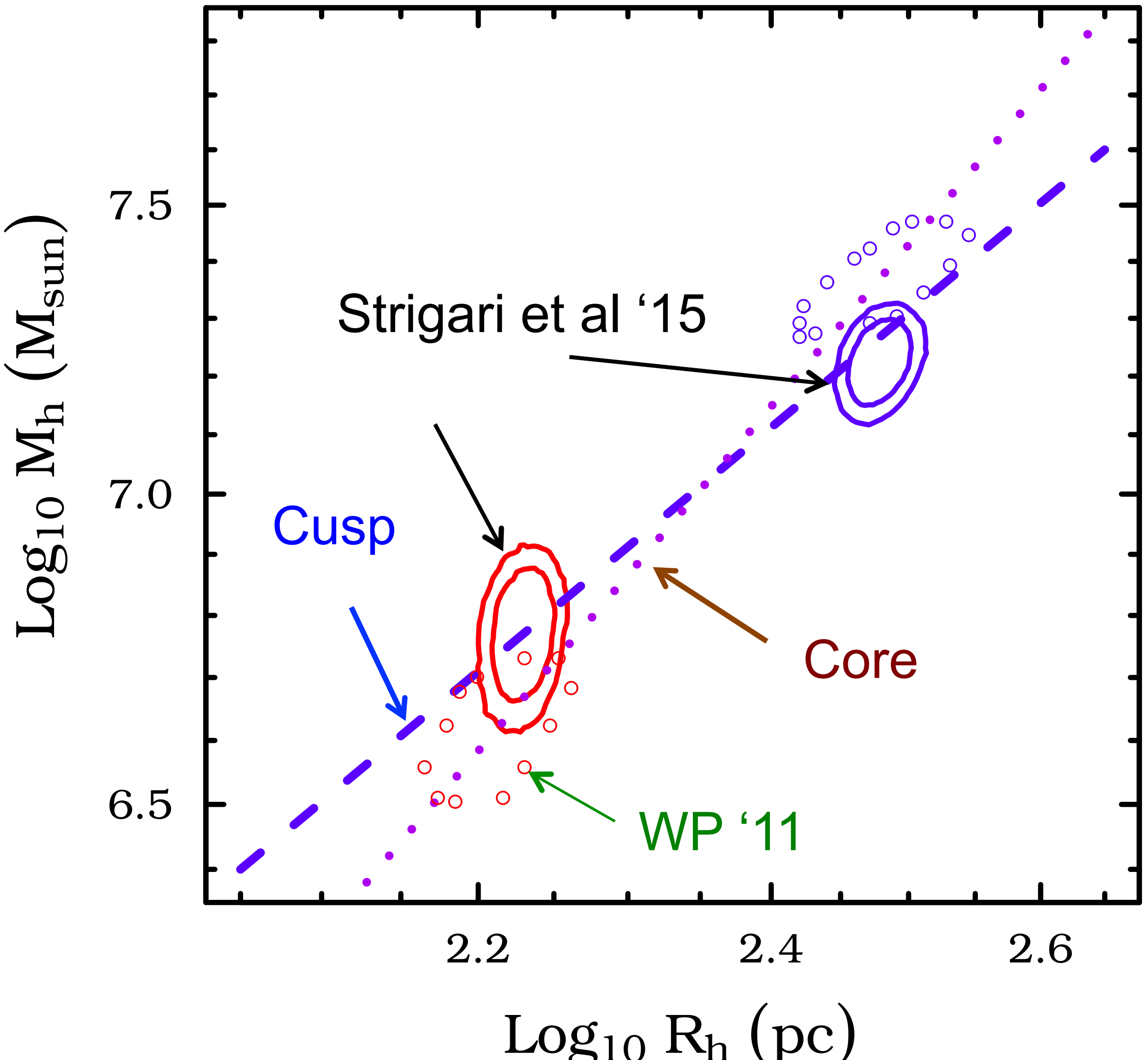
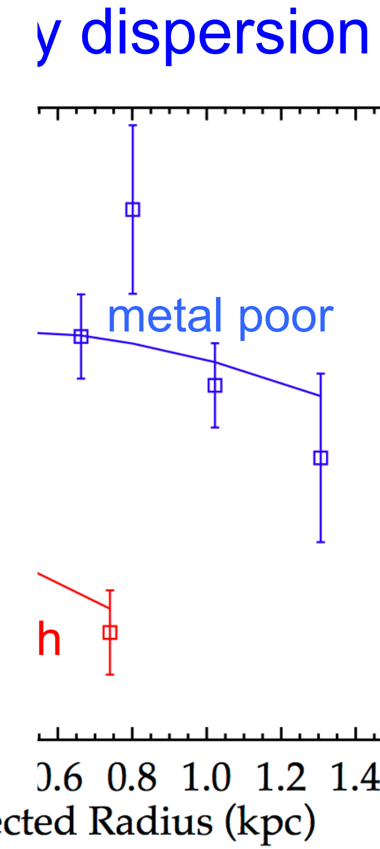
The DM halo of the Sculptor dwarf



Data cons
eq



Distribution function analysis



Strigari, Frenk & White '14

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

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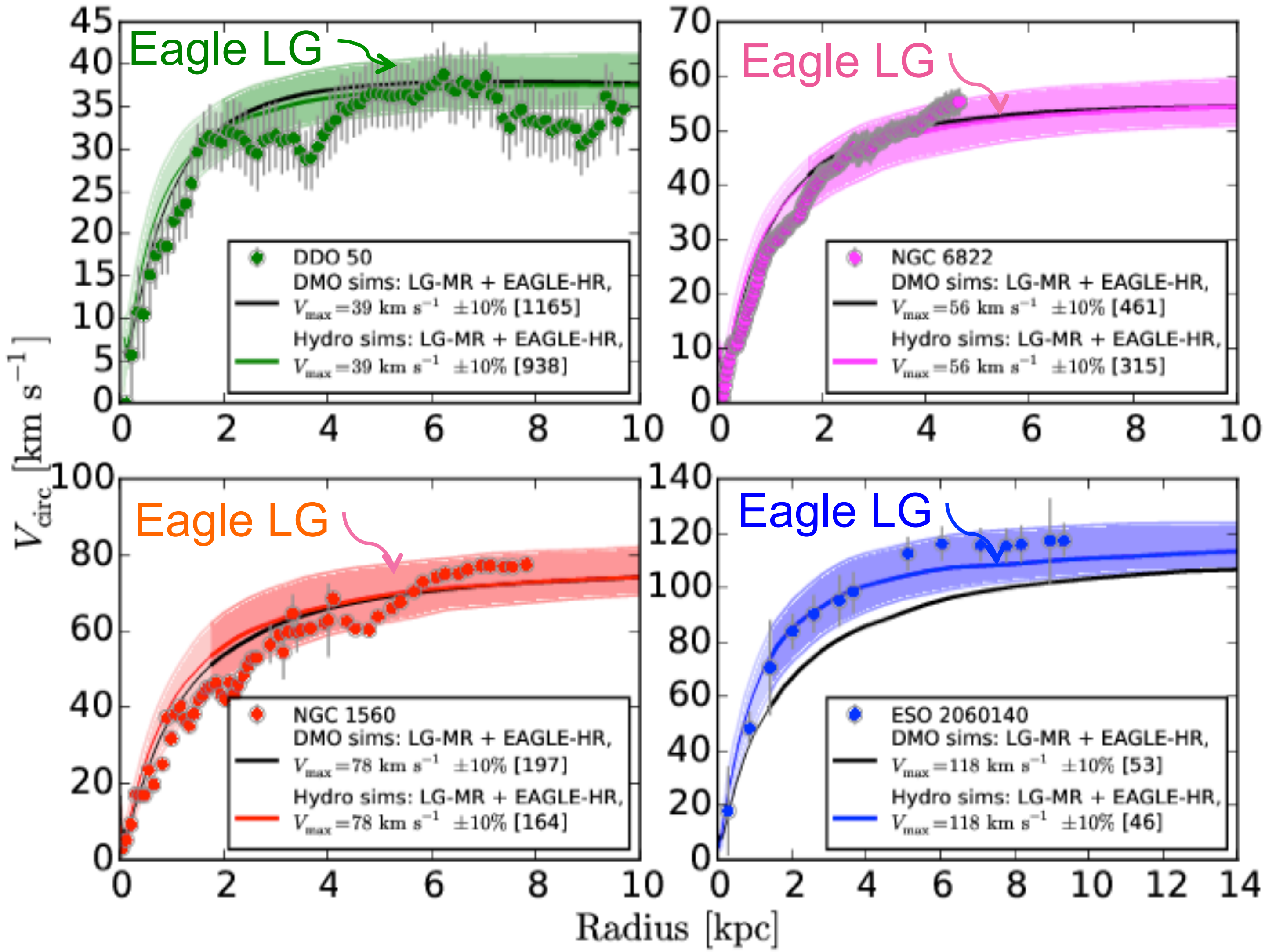
The diversity of gal rotation curves

Four rotation curves that are well fit by ΛCDM

(from dwarfs to ~L*)



Oman, Navarro, Frenk et al. ‘15

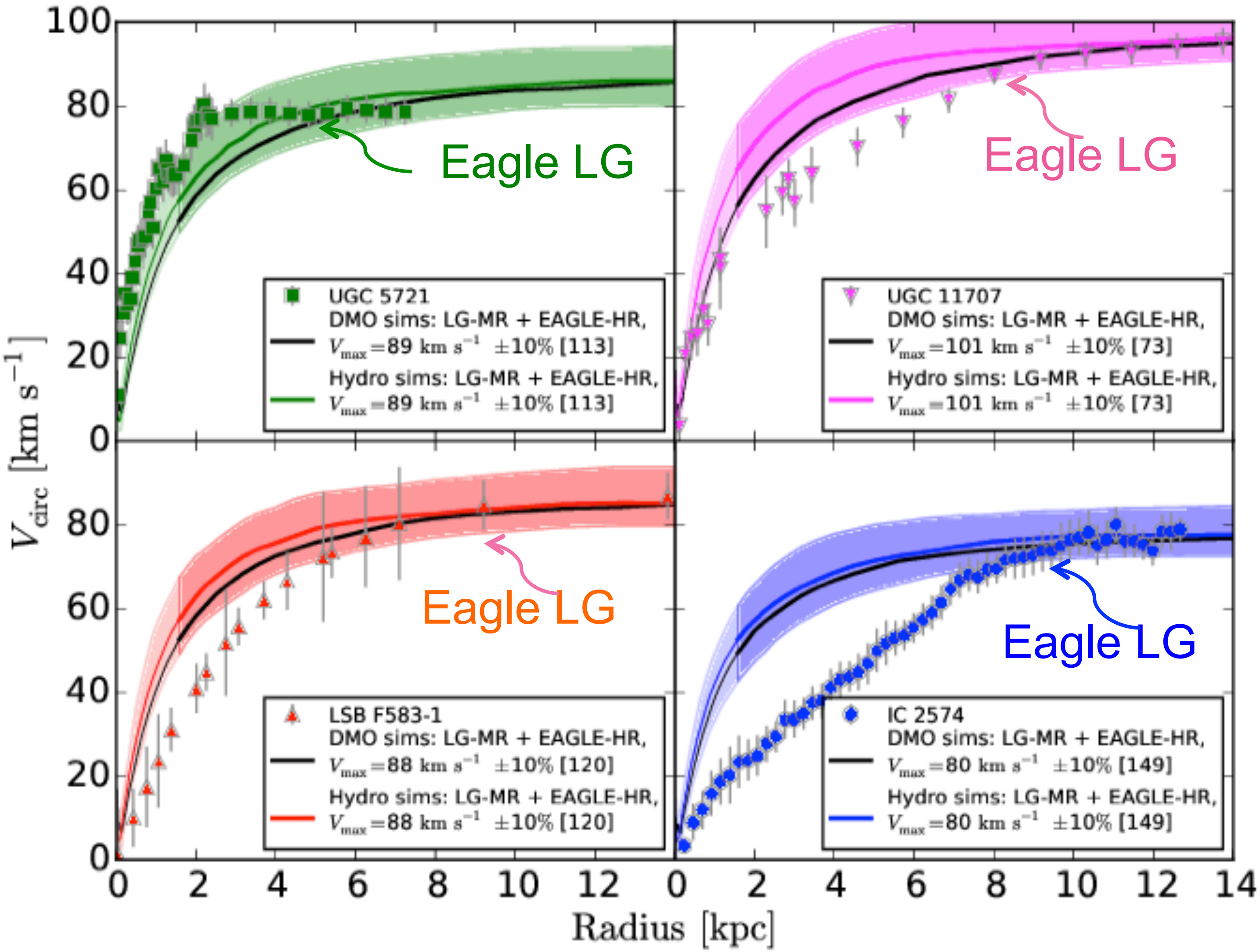
Institute for Computational Cosmology

University of Durham

The diversity of gal rotation curves

Four rotation curves that are NOT well fit by ΛCDM

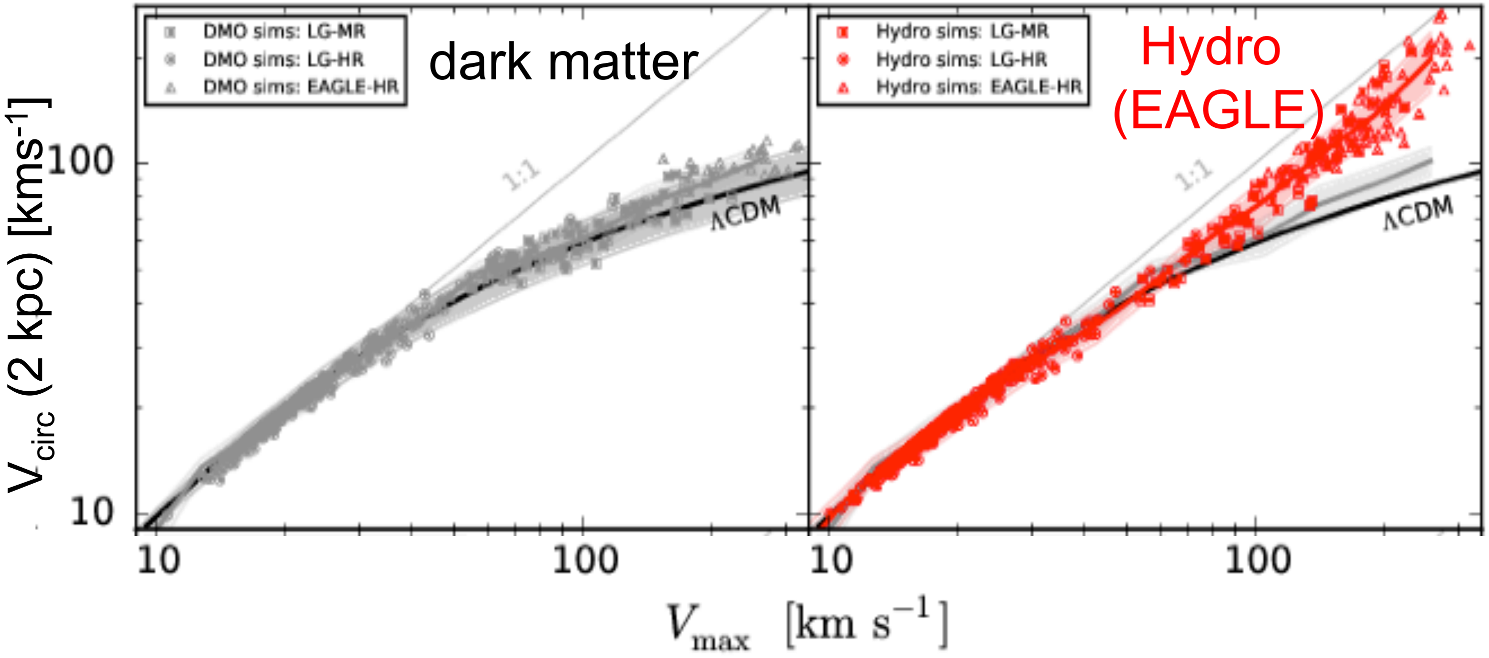
(from dwarfs to ~L_*)



Oman et al. '15

Institute for Computational Cosmology

The diversity of gal rotation curves



Oman et al. '15

The diversity of gal rotation curves

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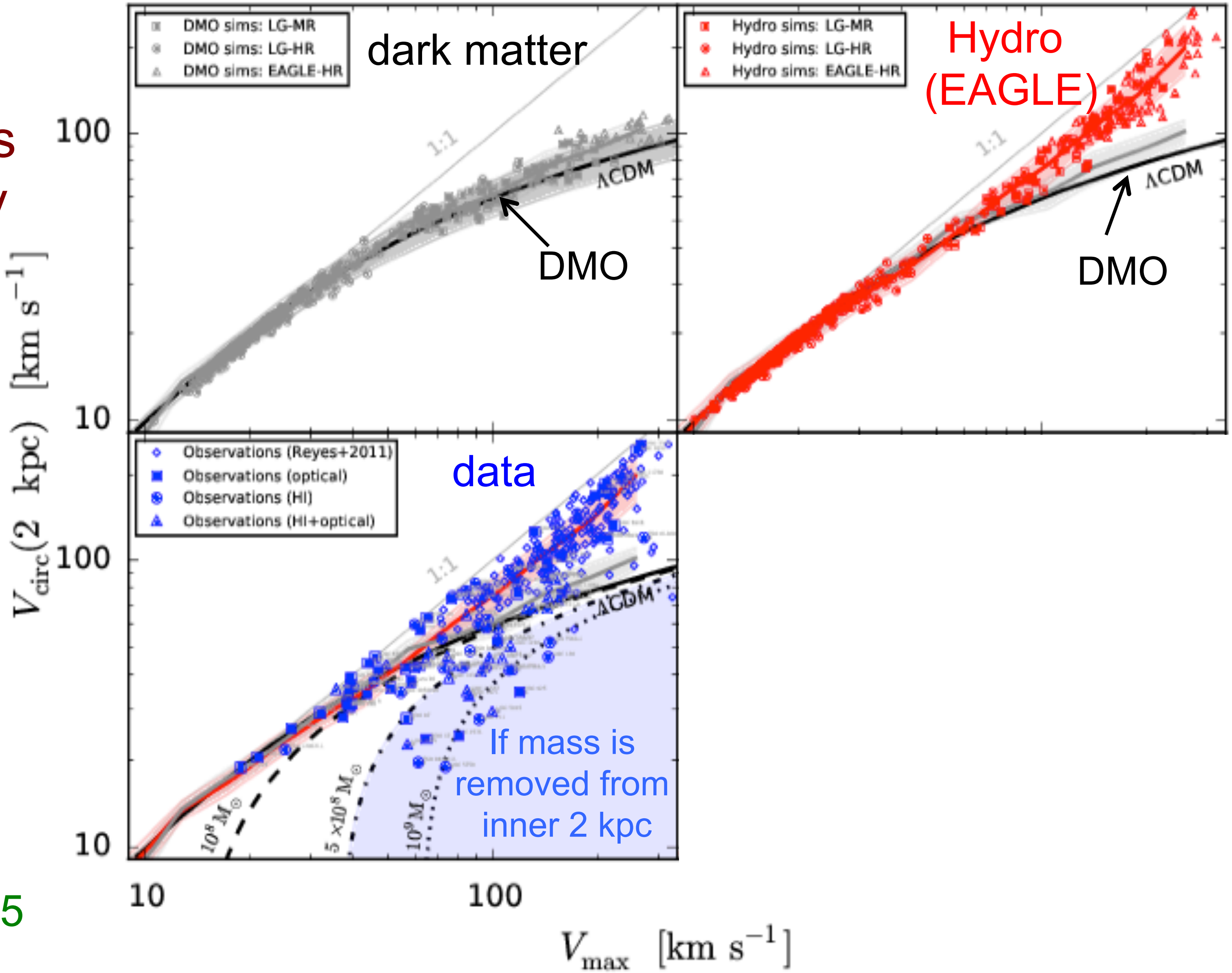
Most galaxies are well fit by EAGLE; others not fit by any simulation



Oman et al. '15

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

Mon. Not. R. Astron. Soc. **283**, L72–L78 (1996)

The cores of dwarf galaxy haloes

Julio F. Navarro,[1,2]★ Vincent R. Eke[2] and Carlos S. Frenk[2]

[1]*Steward Observatory, The University of Arizona, Tucson, AZ 85721, USA*
[2]*Physics Department, University of Durham, South Road, Durham DH1 3LE*

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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.

Baryon effects in the MW satellites

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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

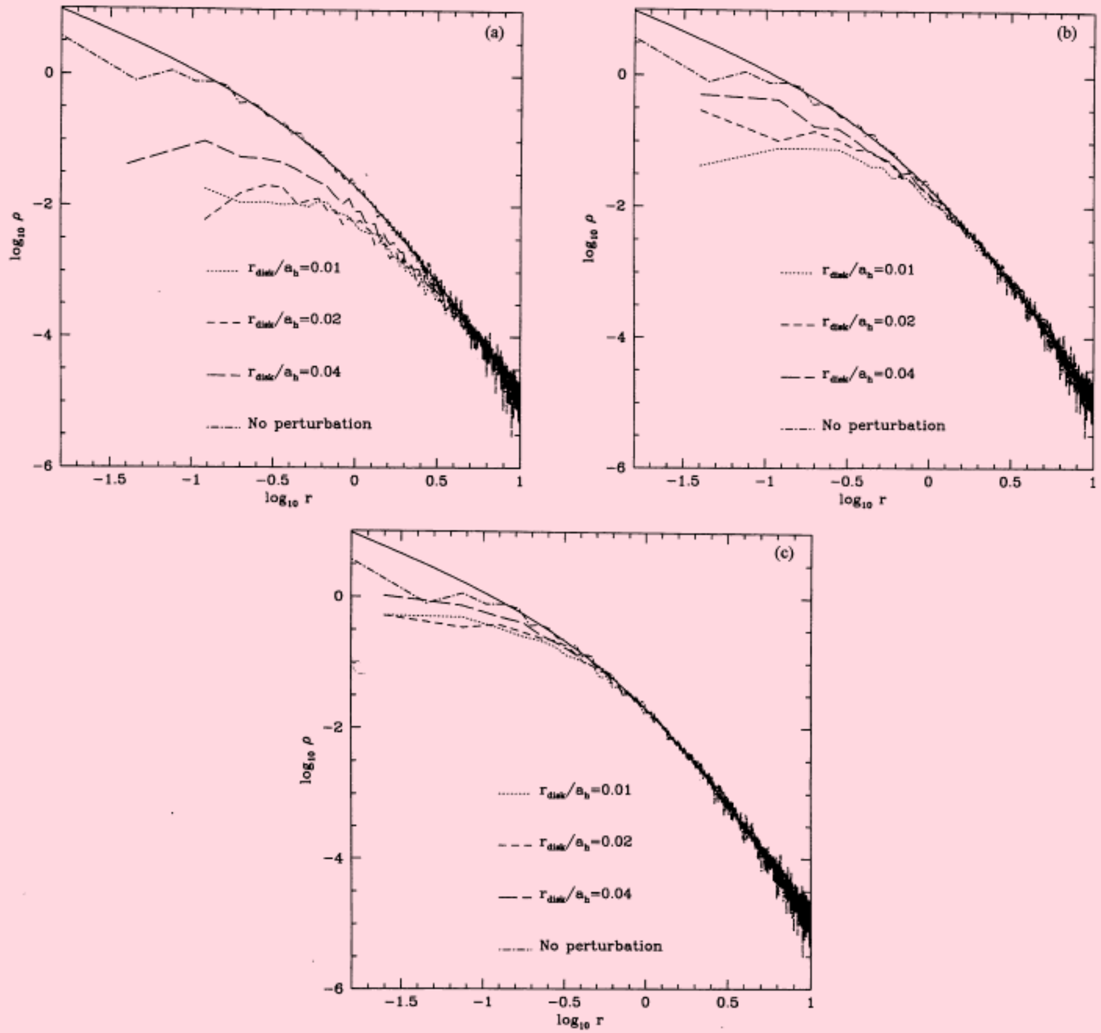


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t = 200$. (a) $M_{disc} = 0.2$.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

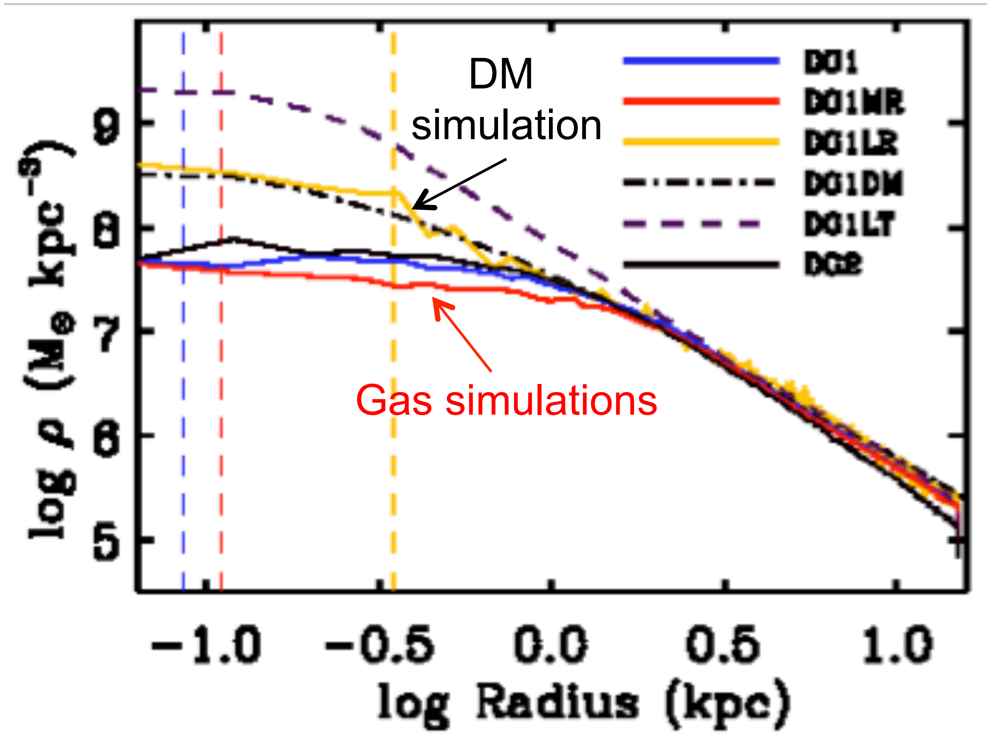
Cores in dwarf galaxy simulations

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

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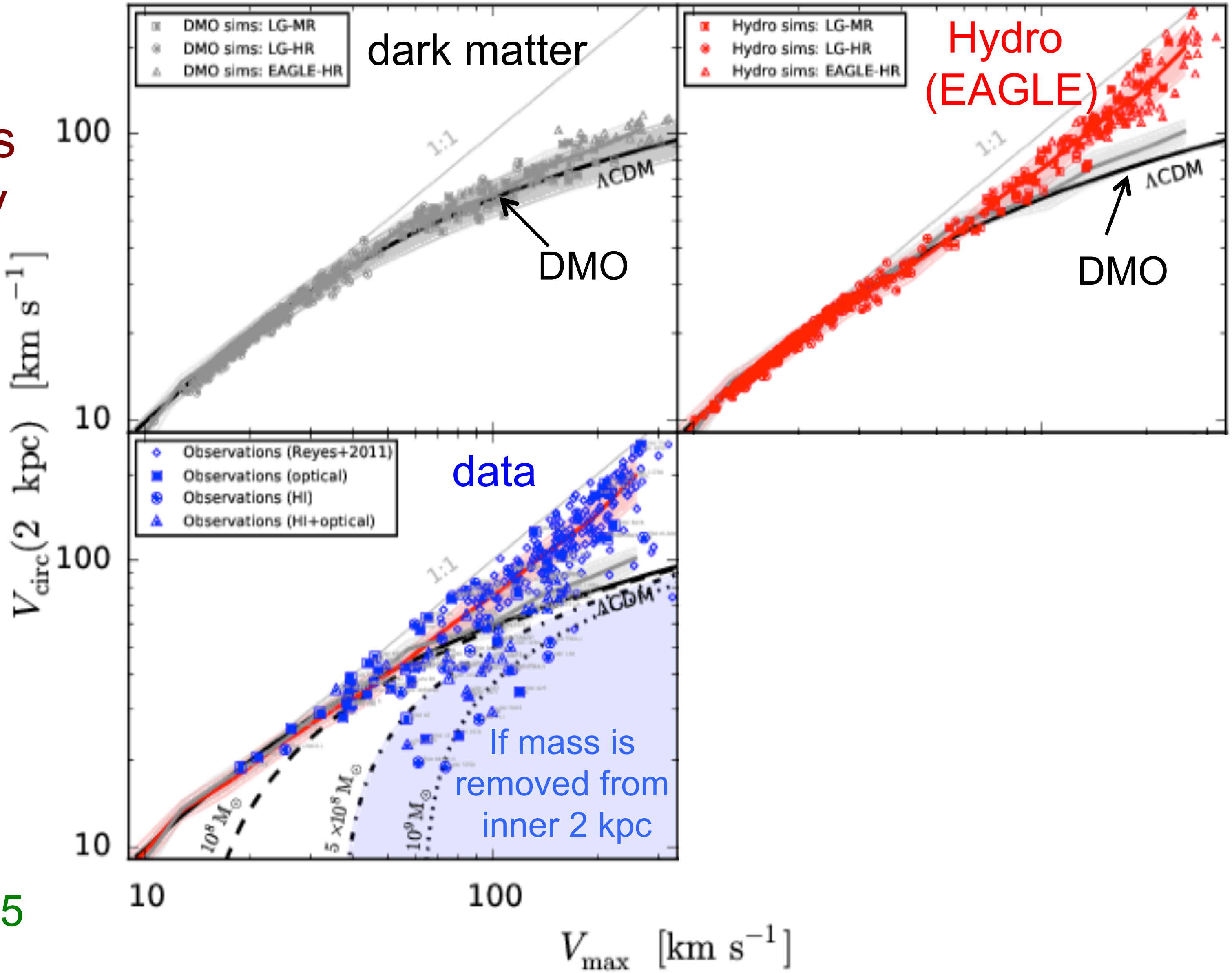
Most galaxies are well fit by EAGLE; others not fit by any simulation



Oman et al. '15

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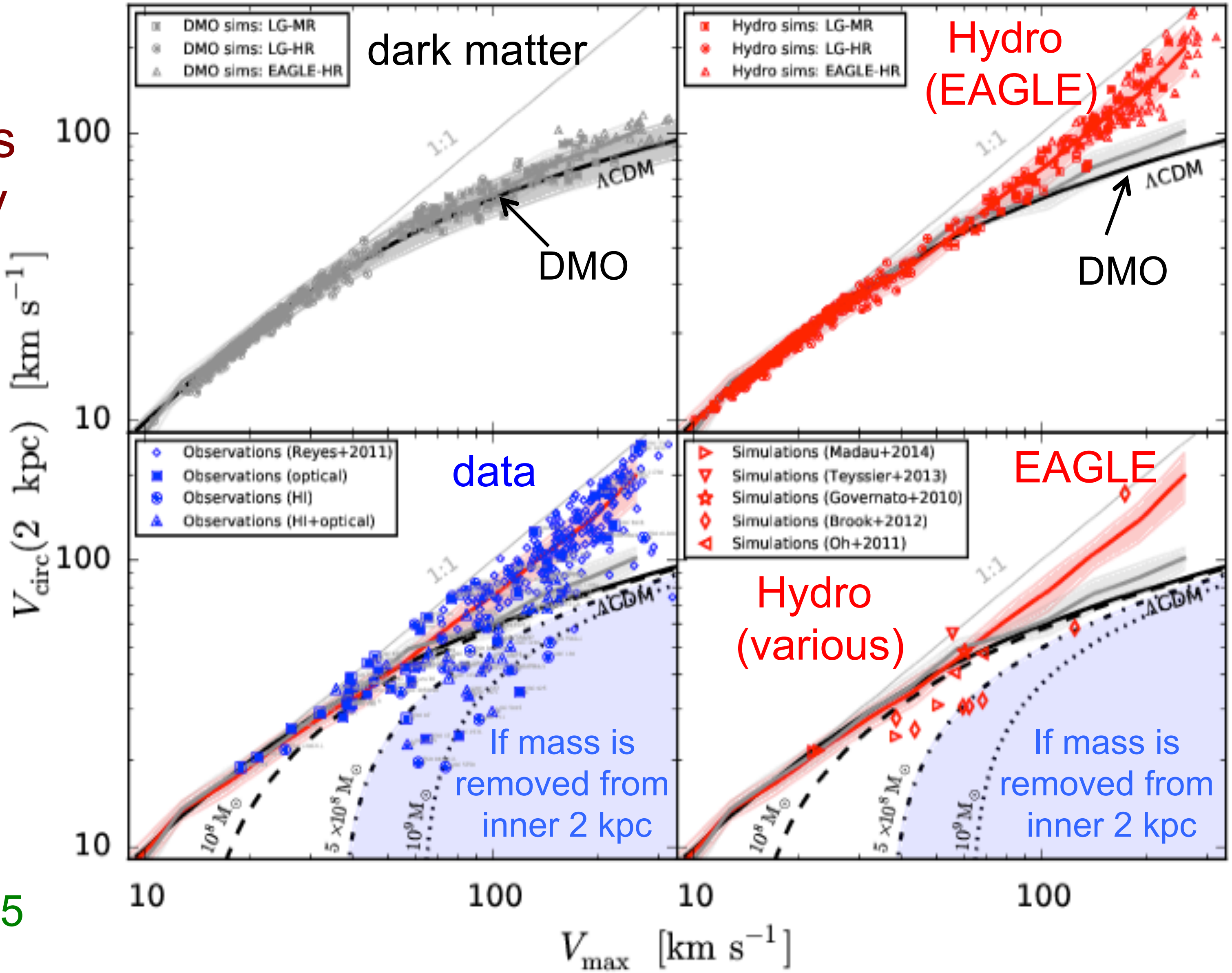

Oman et al. '15

Cores or cusps in dwarf gals?

- Some dwarfs have rotation curves that agree well with EAGLE
- Others have inner mass deficits compared to ΛCDM 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.

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

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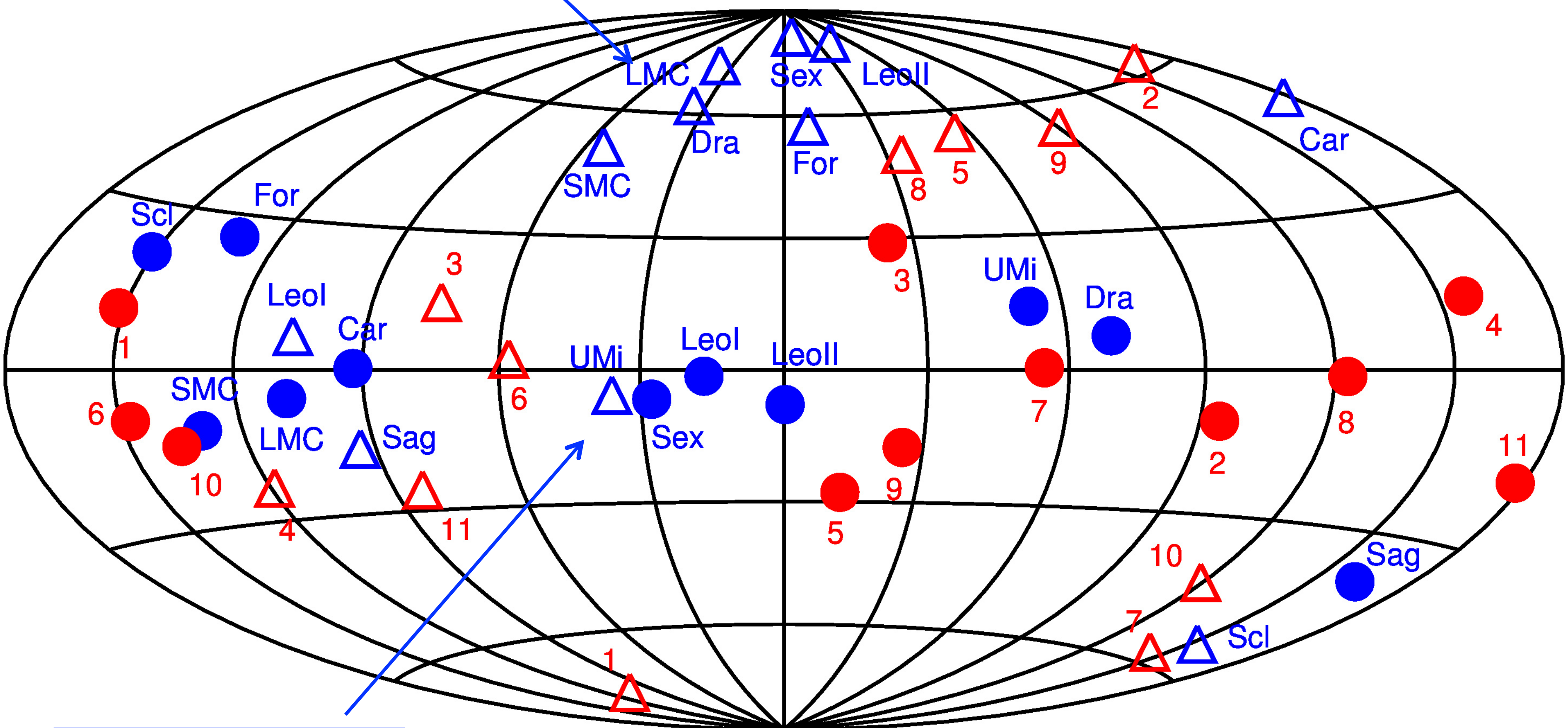
The "satellite disk" problem

Milky Way

Direction of ang. mom.



MW satellites

Lynden-Bell '76

Sawala et al '15

Institute for Computational Cosmology

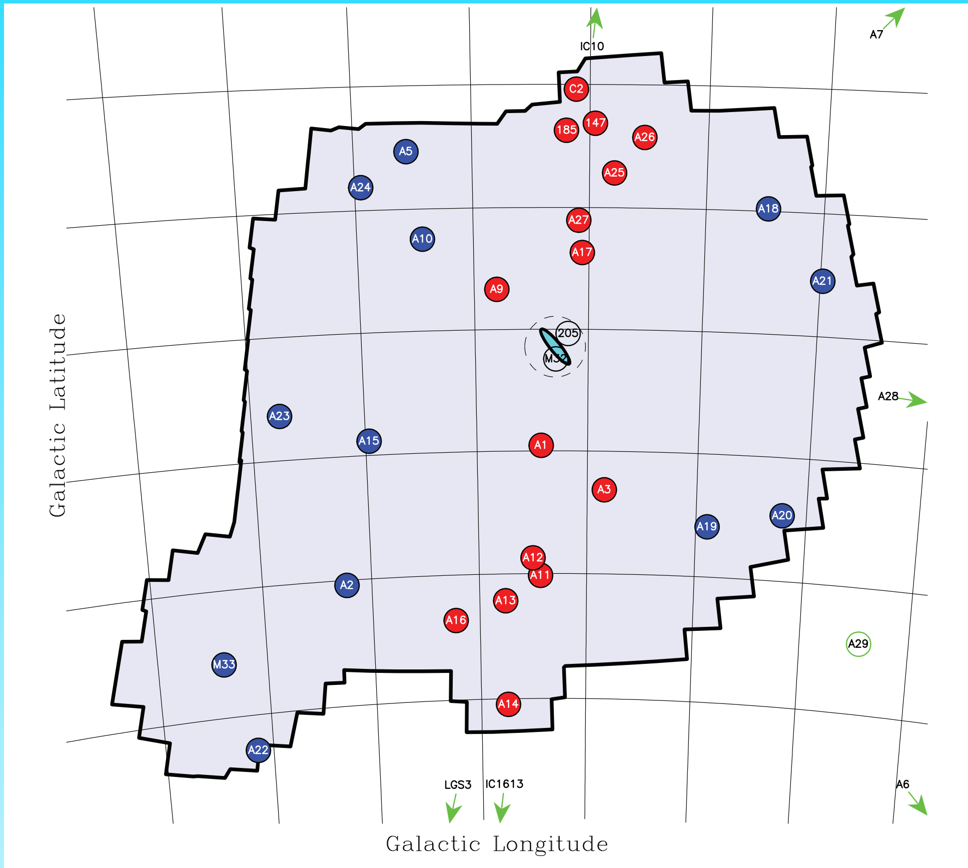
The curious case of a thin, "rotating" plane of sats in M31

University of Durham

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

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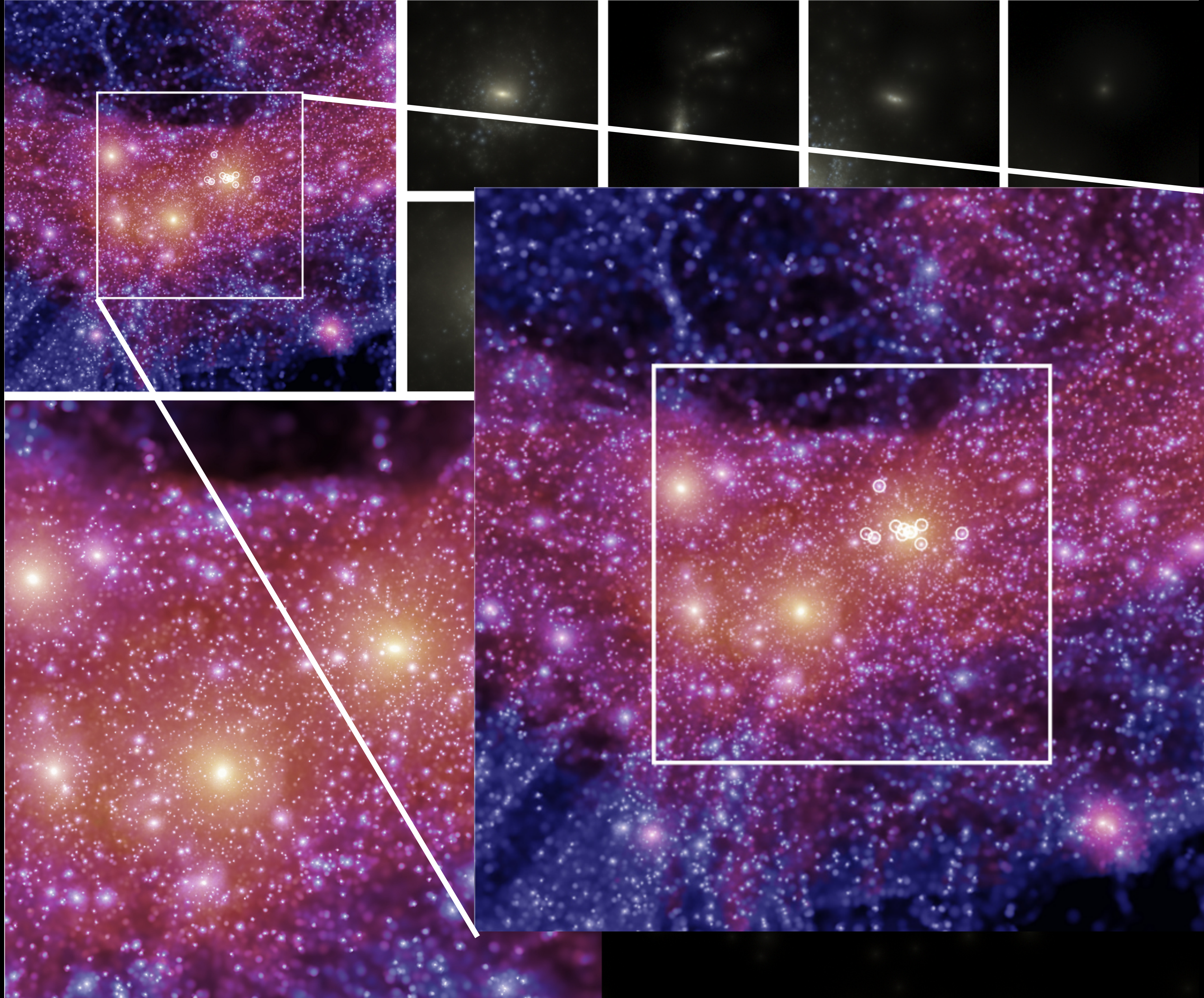

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The "satellite disk" problem

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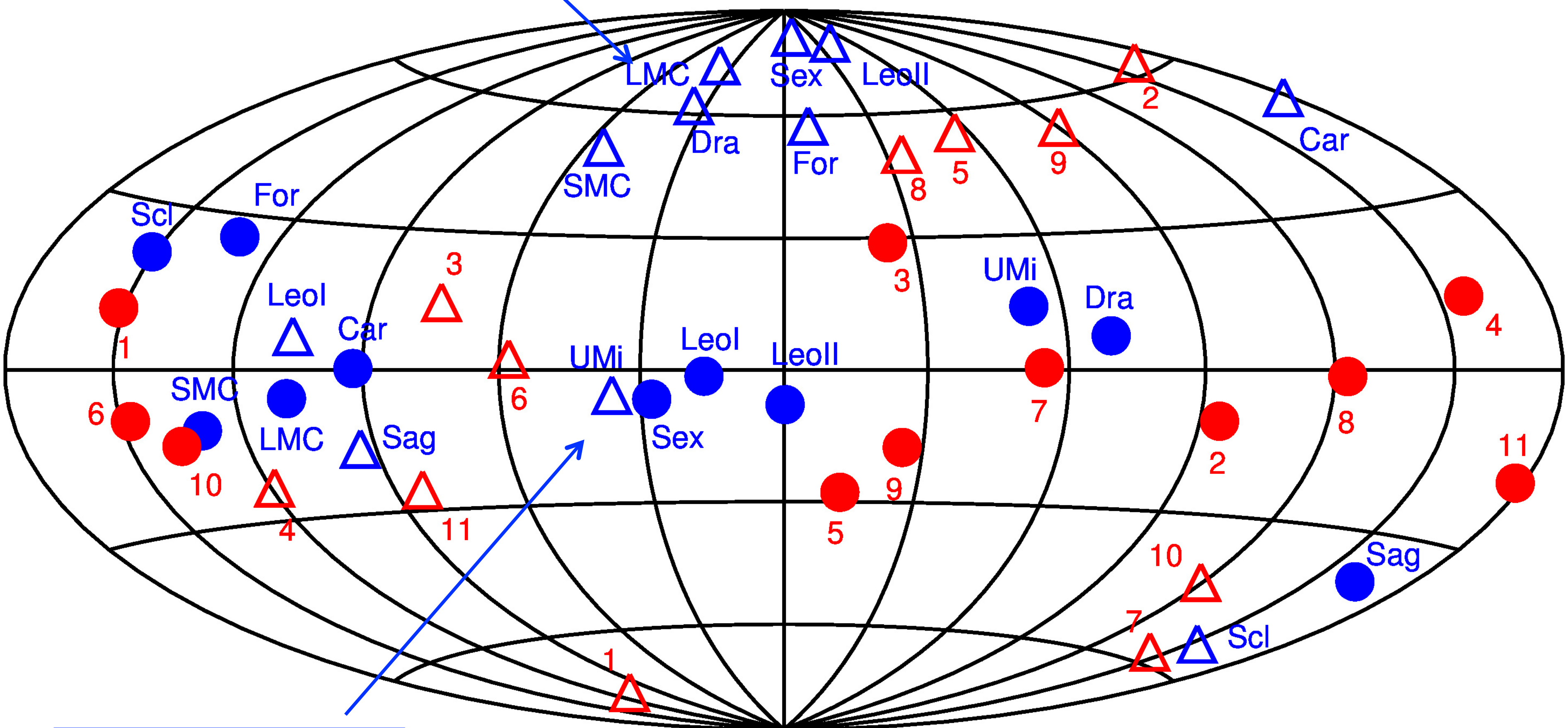
Direction of ang. mom.



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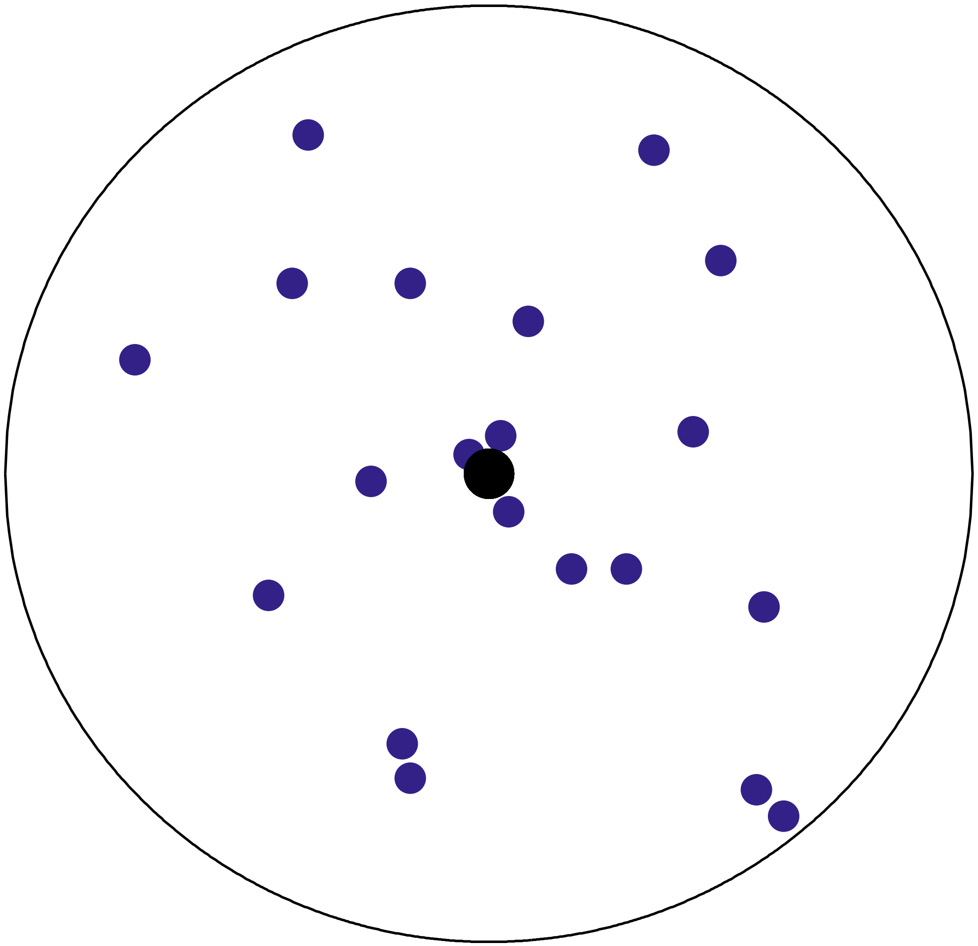
Finding disks of satellites



Cautun, Bose, CSF et al. '15

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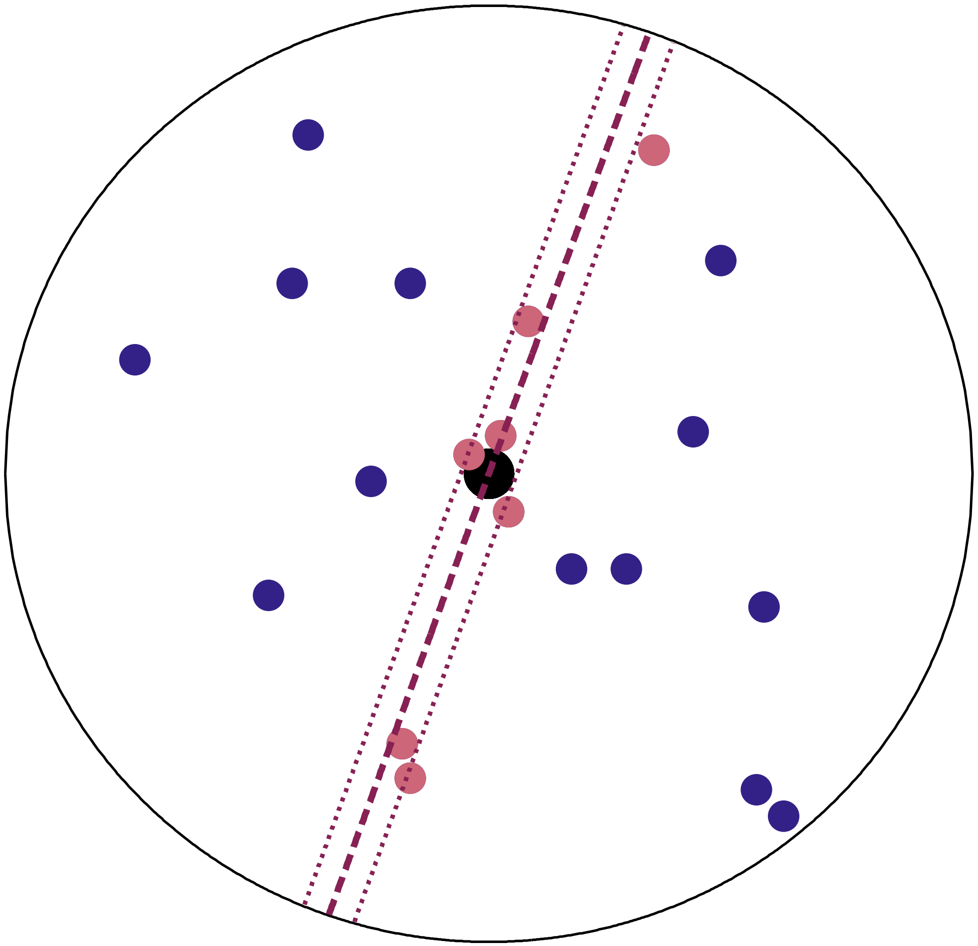
Finding disks of satellites

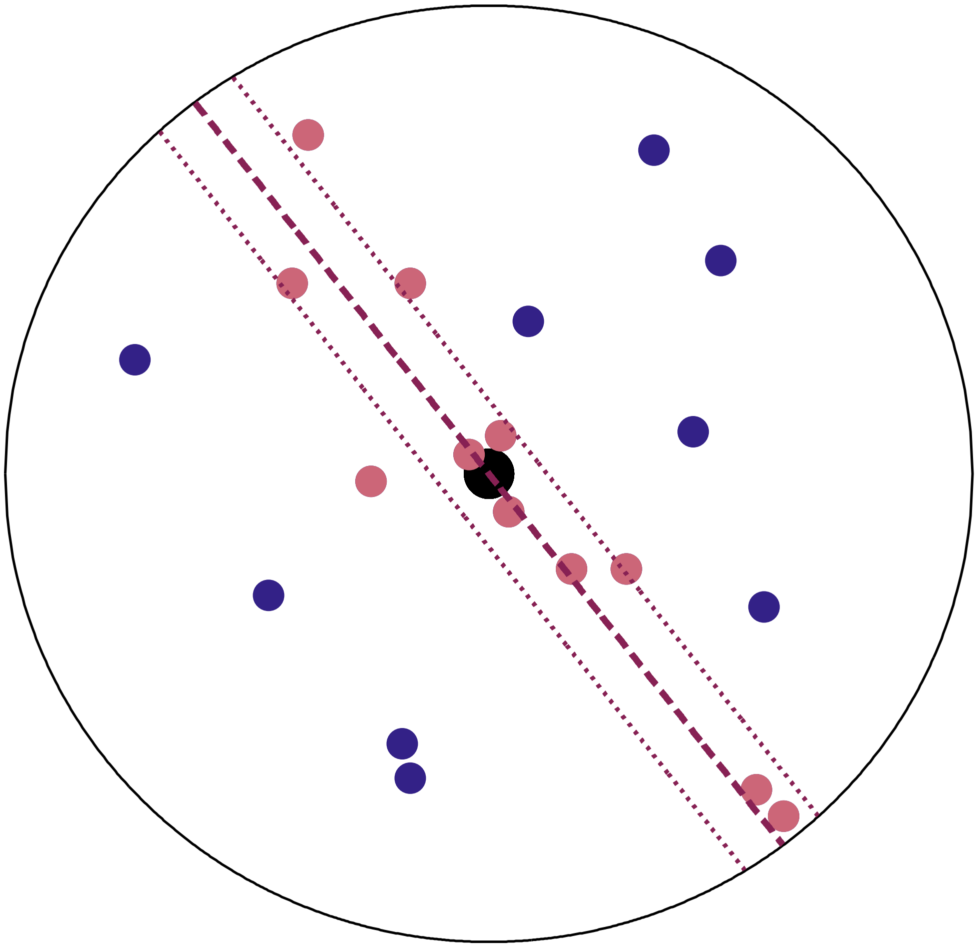
Plane 1: $N_{sat} = 7$, $\mathcal{P} = 410$



Cautun, Bose, CSF et al. '15

Finding disks of satellites

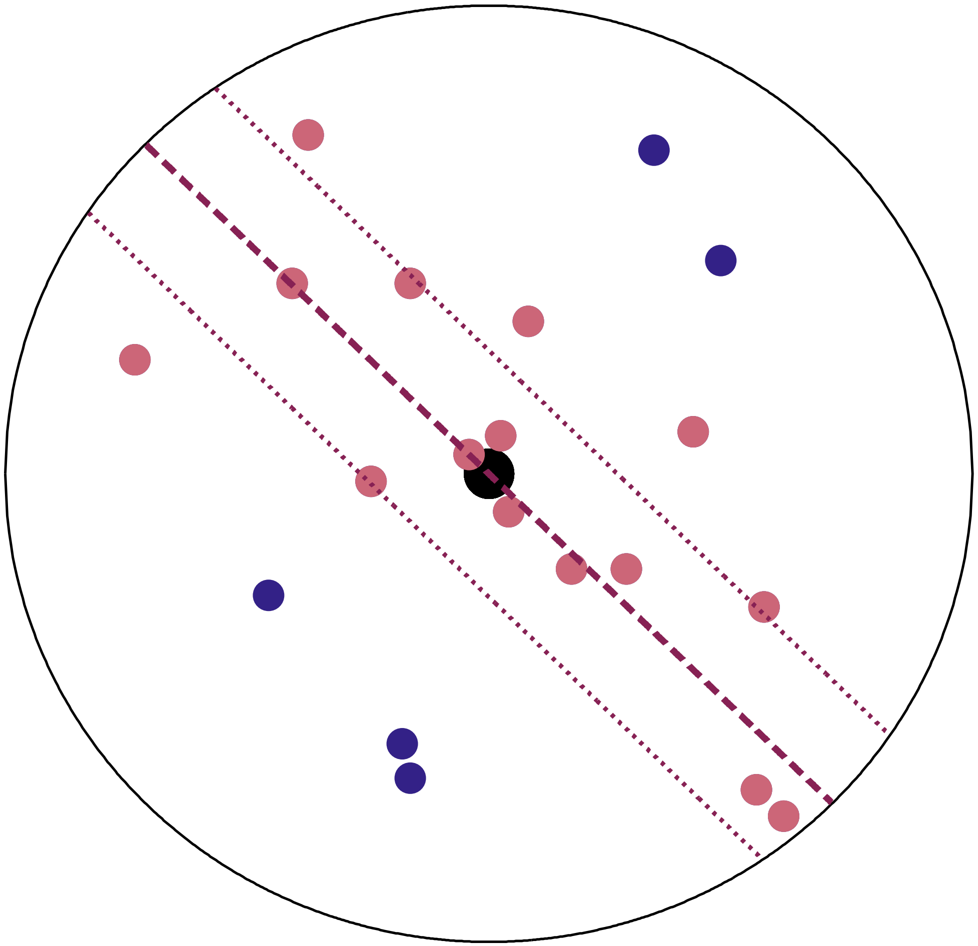
Plane 2: $N_{sat} = 11$, $\mathcal{P} = 660$



Cautun, Bose, CSF et al. '15

Finding disks of satellites

Plane 3: $N_{sat} = 15$, $\mathcal{P} = 450$



Cautun, Bose, CSF et al. '15

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The "satellite disk" problem

Prominence of a plane = $\dfrac{1}{\text{Probability of finding plane in random distr}}$

Prominence of plane thiner than $r_\perp$ having N_{sat} galaxies

$$\mathcal{P}^{\mathrm{plane\ i}}_{\mathrm{spatial}} = \frac{1}{p\left(\leqslant r_{\perp;\,i} \mid N_{\mathrm{sat;\,i}}\right)}$$

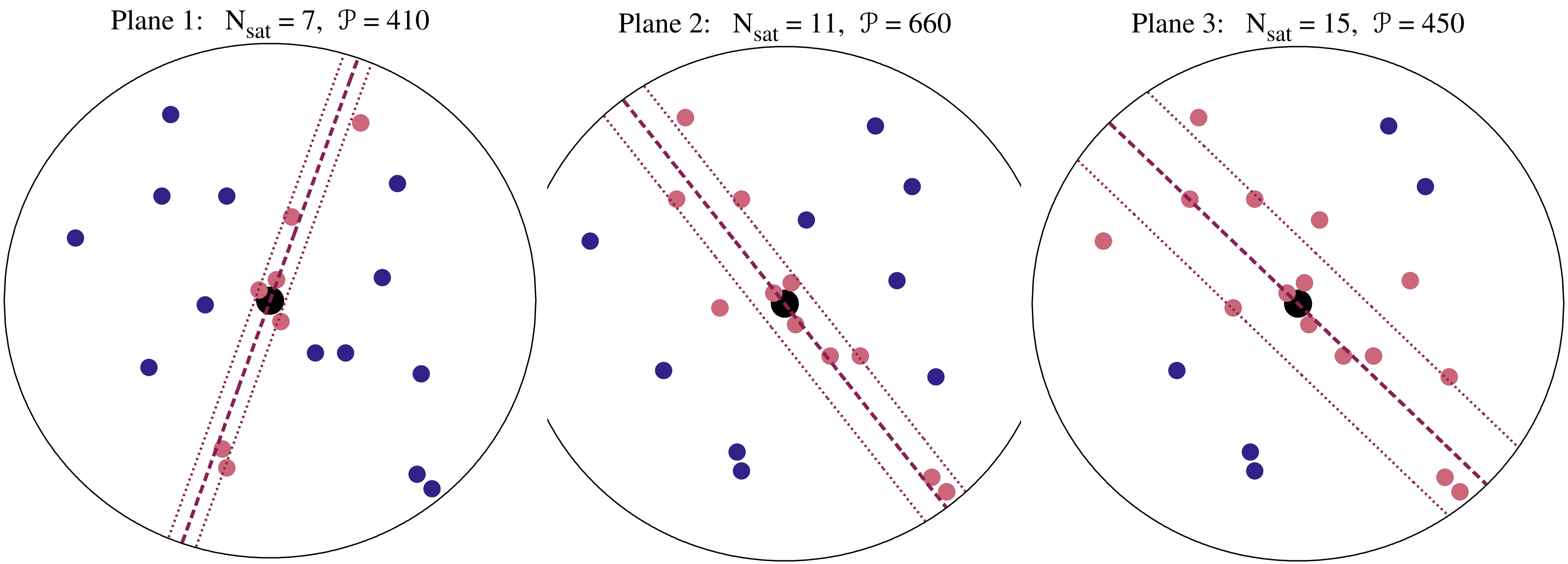
Prominence of plane of N_{sat} gals, N same sense of rotation

$$\mathcal{P}^{\mathrm{plane\ i}}_{\mathrm{2D-kin}} = \frac{1}{p\left(\geqslant N_{\mathrm{s.s.r.;\,i}} \mid N_{\mathrm{sat;\,i}}\right)}$$

$$\mathcal{P}^{\mathrm{rarest}}_{\mathrm{spatial}} = \max_{\mathrm{all\ planes\ i}} \left[\mathcal{P}^{\mathrm{plane\ i}}_{\mathrm{spatial}} \right] ;$$

Cautun et al '15

Finding disks of satellites



Cautun, Bose, Frenk et al '15

The significance of Ibata's plane

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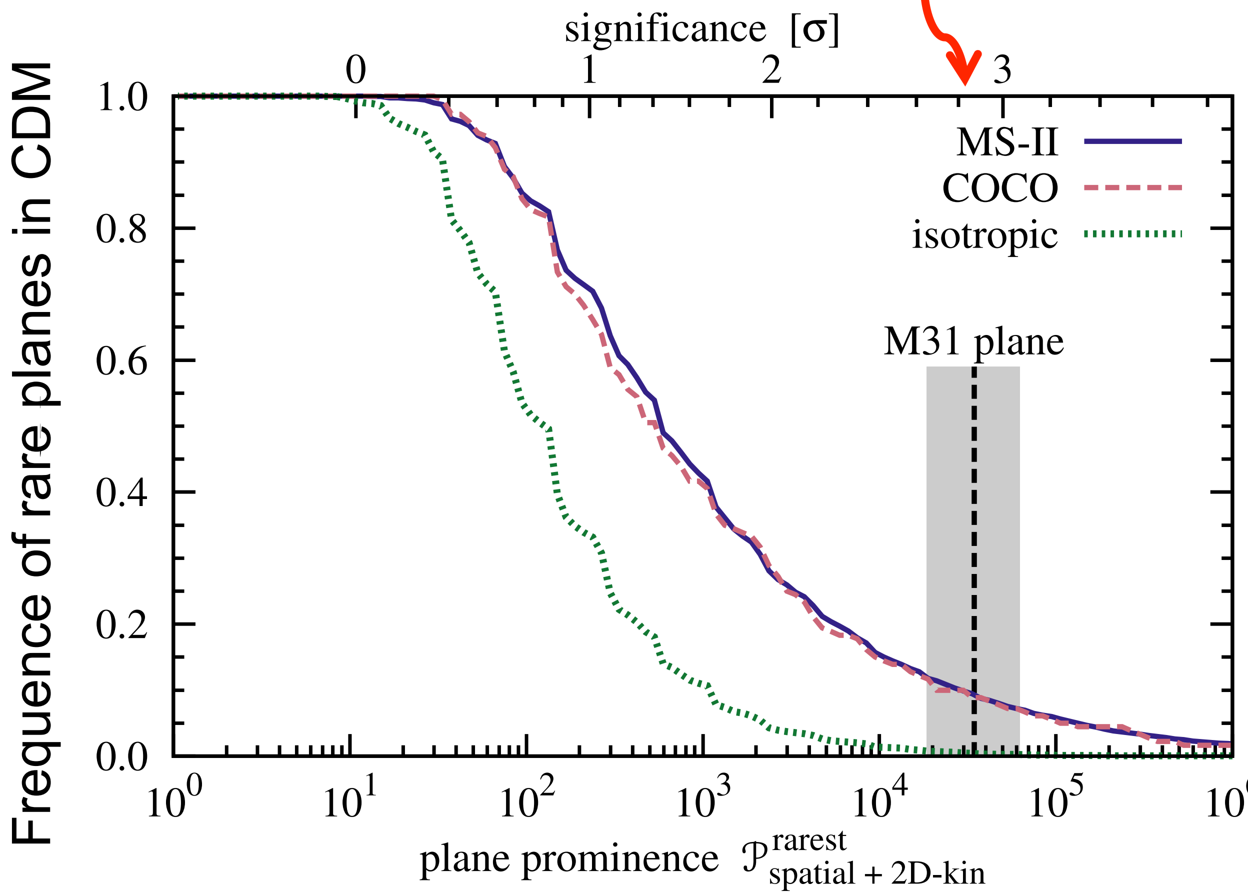
- Significance of Ibata's plane is reduced by x100 when trials factor is included
- 8.8% of halos in ΛCDM simulation have even more prominent disks than Ibata's

Including "trials factor"



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

Cautun et al '15

Is there a "satellite disks problem" in CDM?

No, when statistics are properly calculated

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

Conclusions

- ΛCDM: great success on scales > 1Mpc: CMB, LSS, gal evolution

Correct astrophysics → necessary for accurate cosmology

Four "problems" on small scales:

1. Abundance of sats
2. Too-big-to-fail
3. Core-cusp
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2. Too-big-to-fail: baryon effects lower V_{max} in dwarfs by ~15%
3. Core-cusp: no evidence for cores in satellites (baryon effects?)
4. Disk of satellites: incorrect claims of inconsistency w. ΛCDM

Is CDM ruled out?

No, but we'll keep trying!