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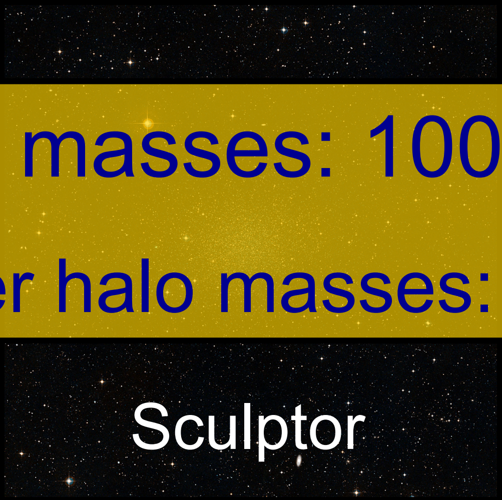
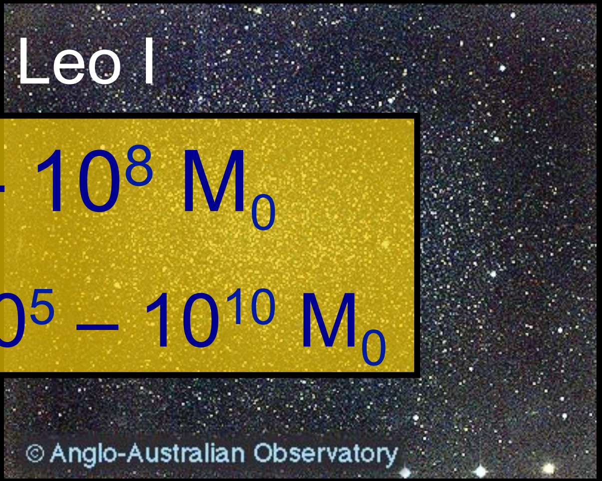
Cosmology with dwarf galaxies

Examples of dwarf galaxies (orbiting the Milky Way)

Stellar masses: 100 – 10^8 M_0

Dark matter halo masses: 10^5 – 10^{10} M_0






Sextans

Carina


Sagittarius

Cosmology with dwarfs?

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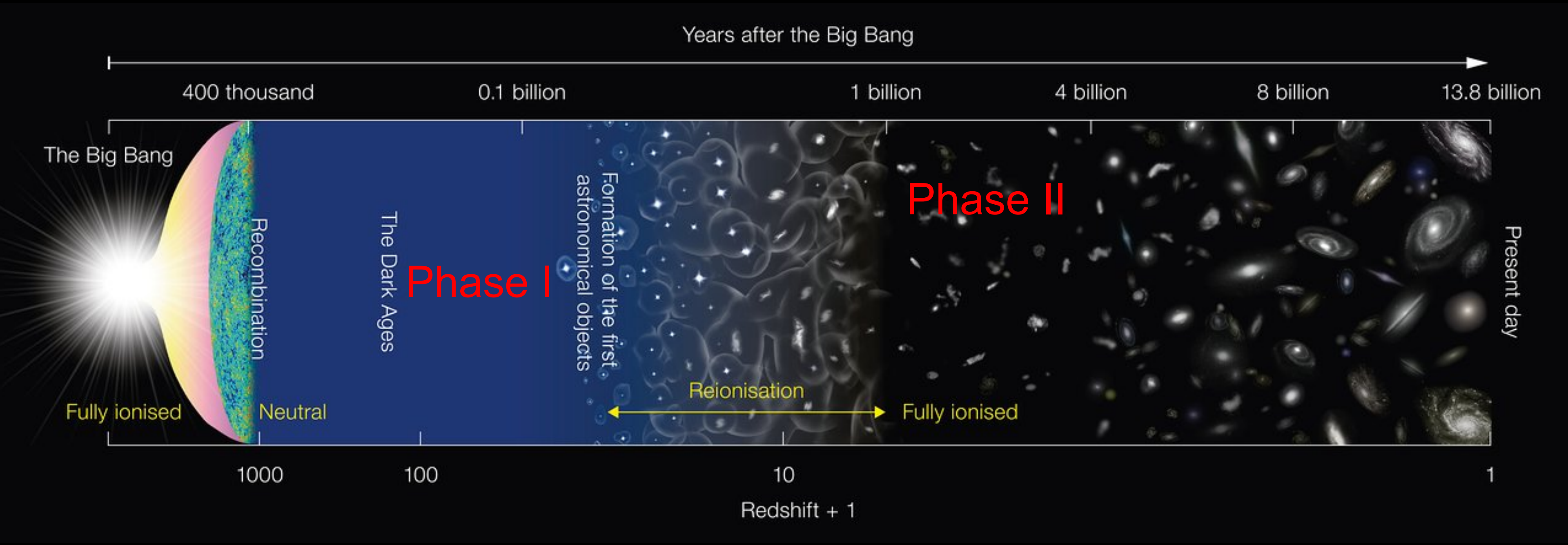
Dwarfs are key to:

1. Galaxy formation: in ΛCDM, small galaxies from first, so some dwarfs may be amongst the first galaxies that formed
2. Dark matter: dwarfs are mostly dark matter – M/L~100-1000

This talk:

1. The first galaxies
2. The abundance and structure of the dark matter halos of dwarfs and the identity of the dark matter

The two phases of galaxy formation



Phase I: Galaxies begin to form during the "dark ages"

First stars reionize H and heat it up to 10^4K → prevents gas from cooling in halos of "T_{vir}" < 10^4K – galaxy formation is interrupted

Phase II: Halos with "T_{vir}" > 10^4K form → galaxy formation resumes

The first galaxies

We may expect two populations of dwarf galaxies:

those that formed

- Before reionization (Phase I − very faint)
- After reionization (Phase II − less faint)

The faintest galaxies we can observe are the satellites of the Milky Way

The MW satellite luminosity function

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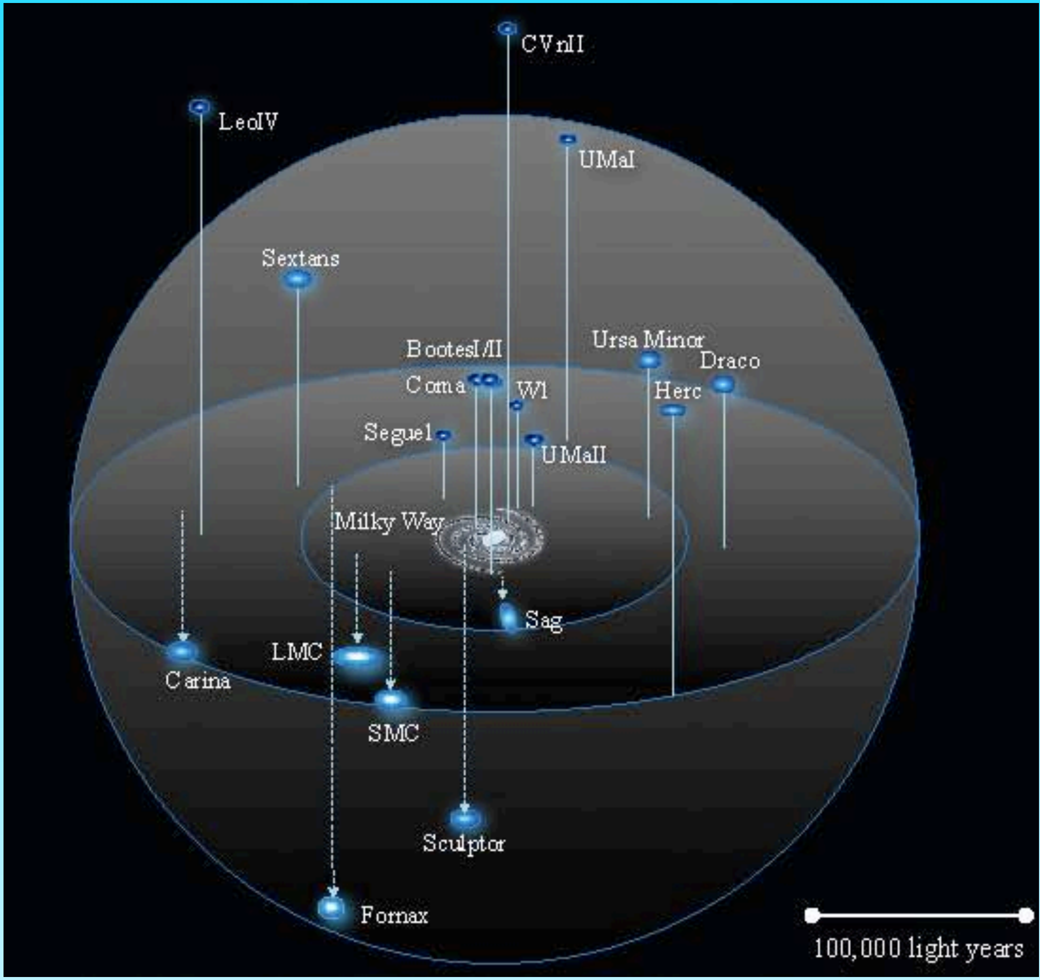
~55 satellites discovered so far in MW



About 55 satellites known in the MW so far from partial surveys (e.g. SDSS, Pan-STARRS, DES)

Can infer total population from survey selection function, assuming a radial distribution (from simulations)

(Newton+18, Koposov+08, Tollerud+08, Hargis+14)

The MW satellite luminosity function

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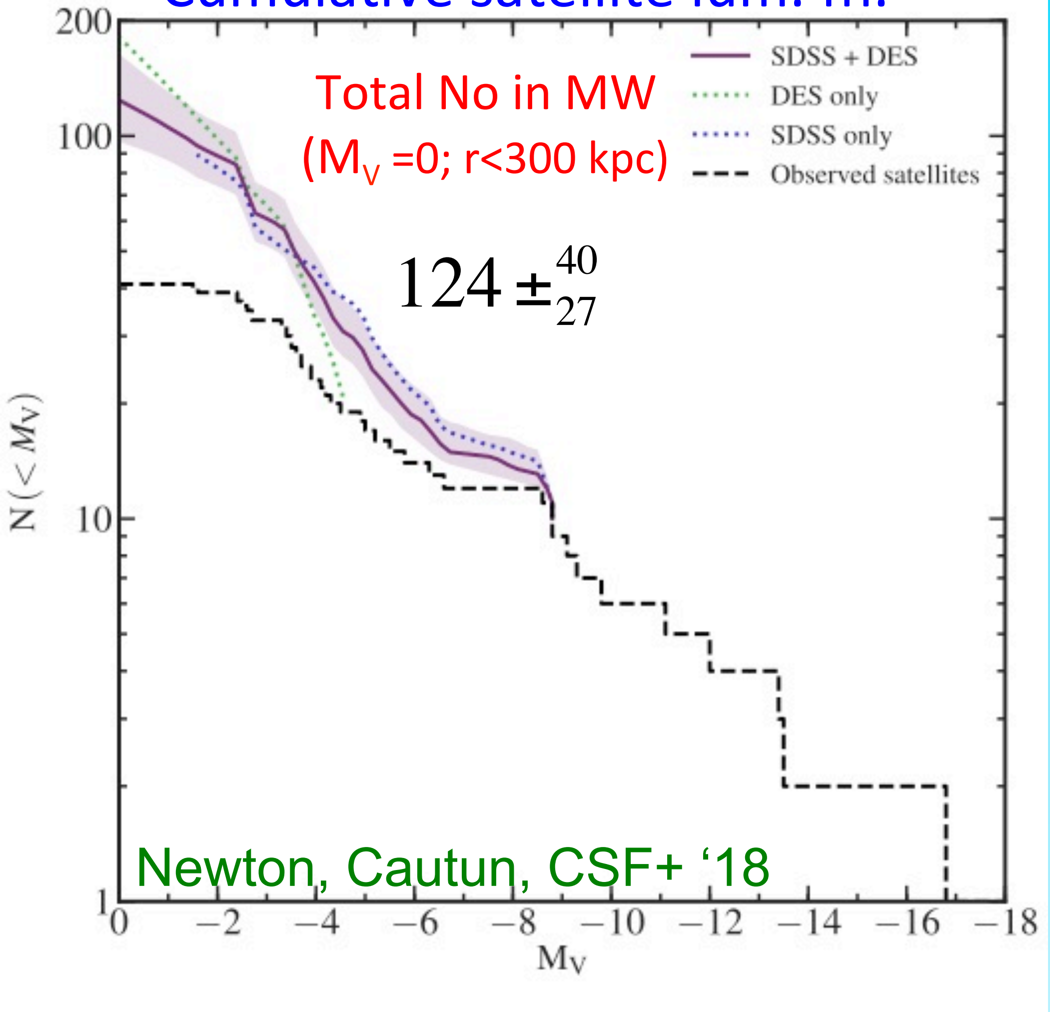
Can infer total population from survey selection function, assuming a radial distribution (from simulations)

(Newton+18, Koposov+08, Tollerud+08, Hargis+14)

Cumulative satellite lum. fn.

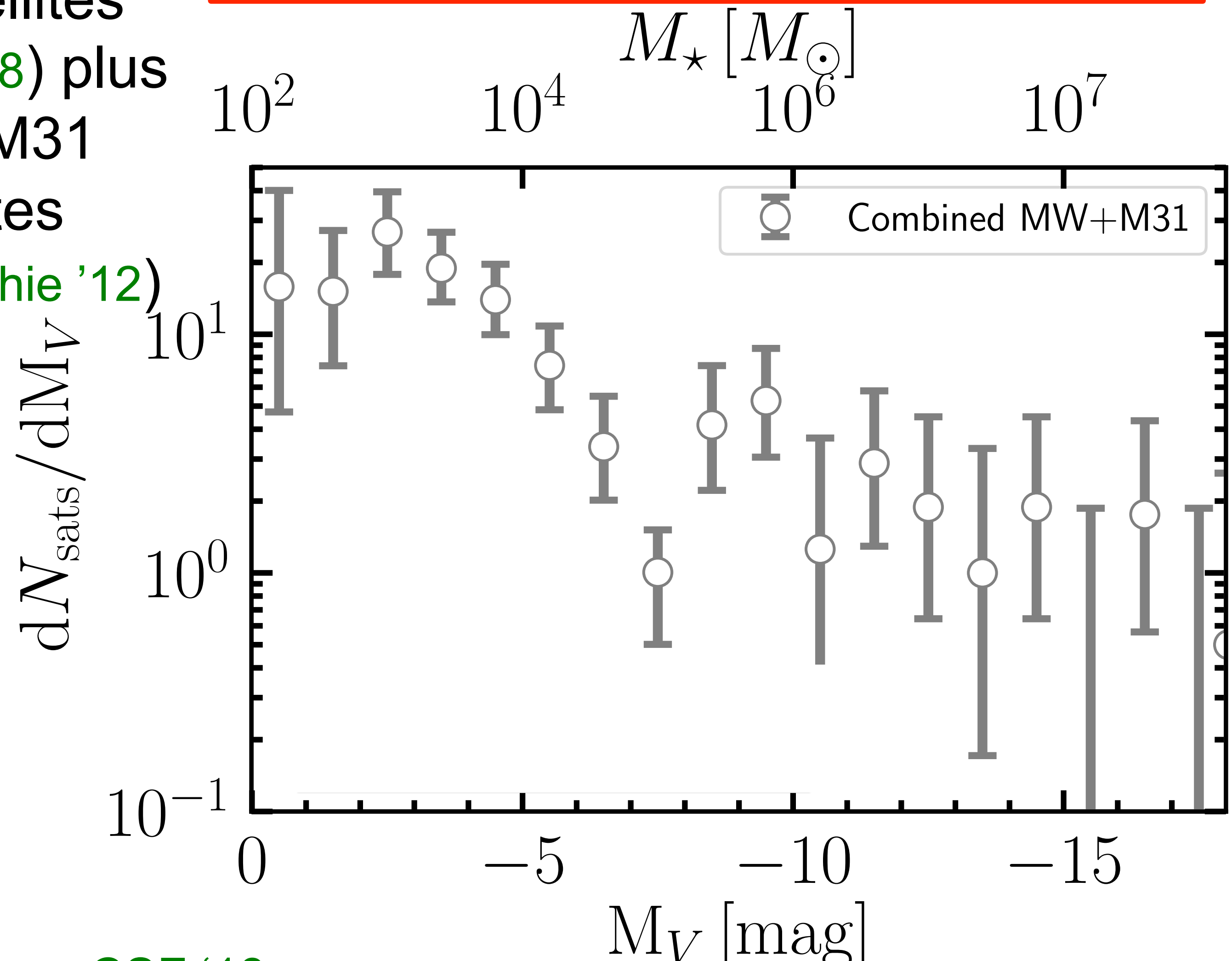


The MW/M31 sat. luminosity function

University of Durham

MW satellites (Newton+ '18) plus M_V<-8 M31 satellites (Mcconnachie '12)

Differential satellite luminosity function



Bose, Deason, CSF '18

Institute for Computational Cosmology

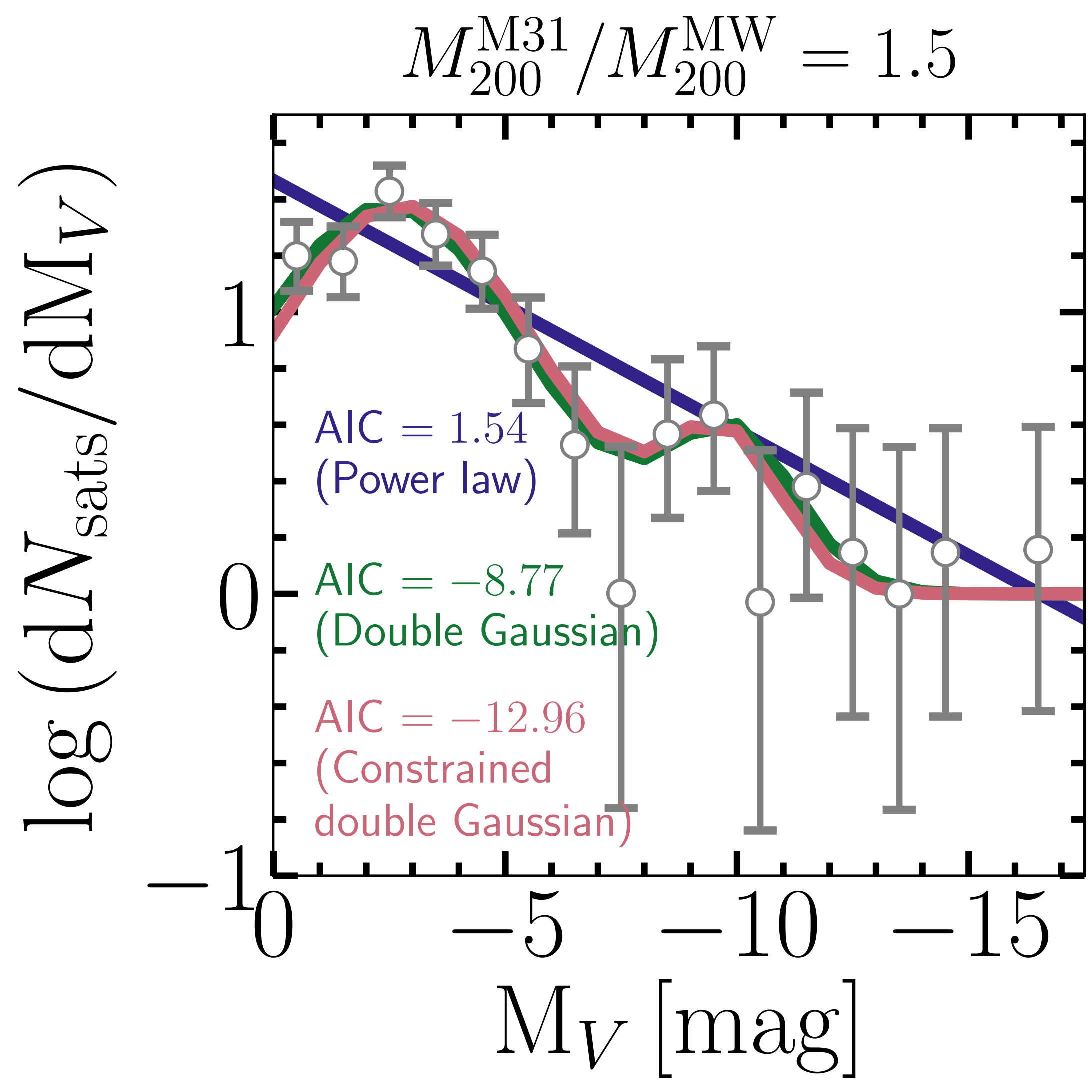
Two populations of galactic satellites

Fit 3 models and compare using Akaike Information Criterion (AIC)

Model	AIC
Power law	-1.5
Double Gaussian	-8.8
Constrained DG*	-13.0

*Assumes V_{cut}=30 km/s

Bose, Deason, CSF '18



The first galaxies

What do we expect from galaxy formation theory

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Galaxy formation theory

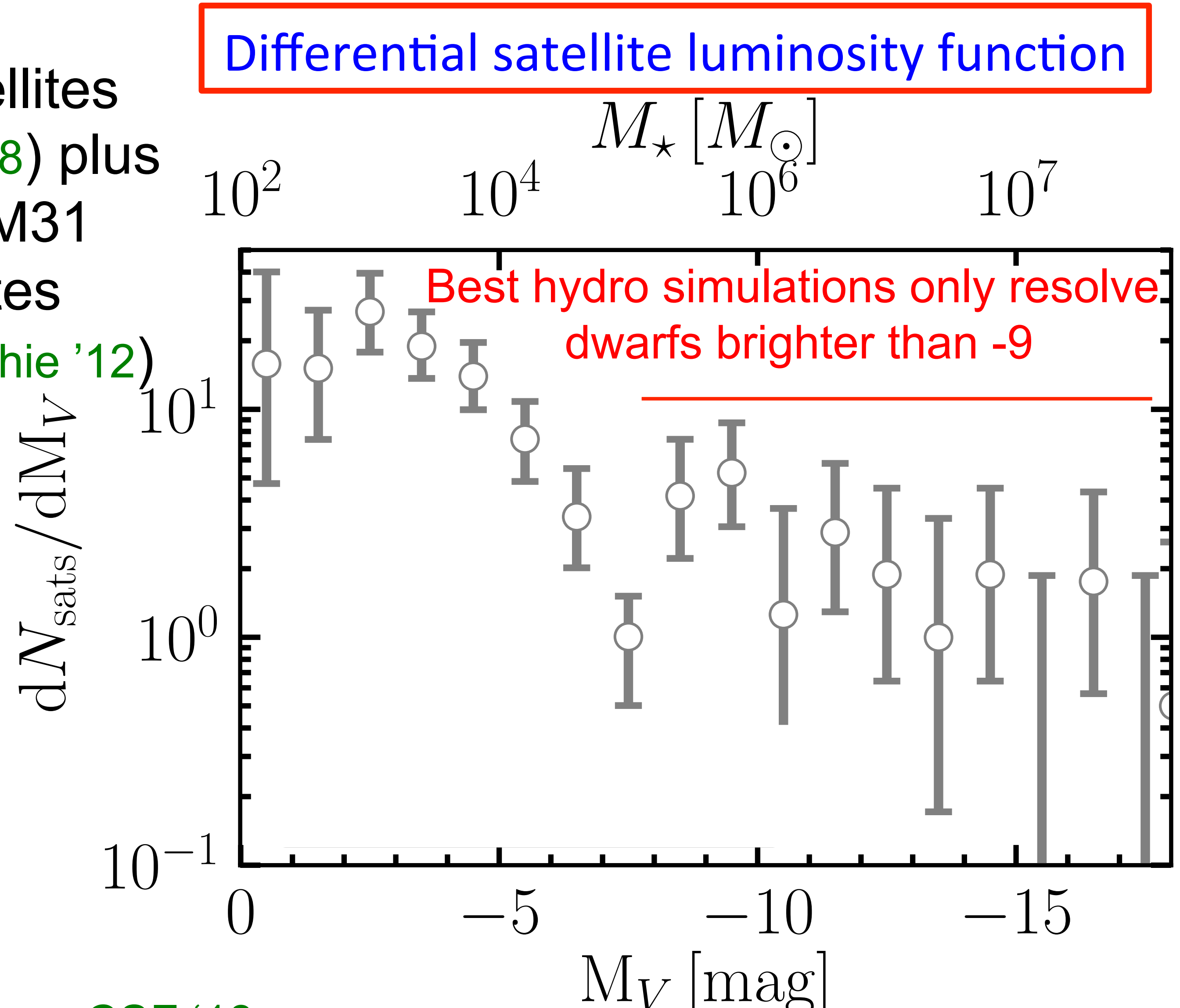
Two approaches:

1. Cosmological hydrodynamic simulations
2. Semi-analytic modelling

Hydro simulations cannot resolve the ultrafaints (yet)

The MW/M31 sat. luminosity function

MW satellites (Newton+ '18) plus M_V<-8 M31 satellites (Mcconnachie '12)



Bose, Deason, CSF '18

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Evolution of baryons

Basic differential equations of Durham SA model:

Mass conservation

$$
\begin{aligned}
\dot{M}_\star &= (1-R)\psi \\
\dot{M}_{\rm hot} &= -\dot{M}_{\rm cool} + \beta\psi \\
\dot{M}_{\rm cold} &= \dot{M}_{\rm cool} - (1-R+\beta)\psi
\end{aligned}
$$

Conservation of metals

$$
\begin{aligned}
\dot{M}^Z_\star &= (1-R)Z_{\rm cold}\psi \\
\dot{M}^Z_{\rm hot} &= -\dot{M}_{\rm cool}Z_{\rm hot} + (pe + \beta Z_{\rm cold})\psi \\
\dot{M}^Z_{\rm cold} &= \dot{M}_{\rm cool}Z_{\rm hot} \\
&+ (p(1-e) - (1+\beta-R)Z_{\rm cold})\psi,
\end{aligned}
$$

R = recycled fraction

ψ = star formation rate

β = SN feedback parameter

p = metal yield

e = fraction of metals ejected

White & Frenk '91

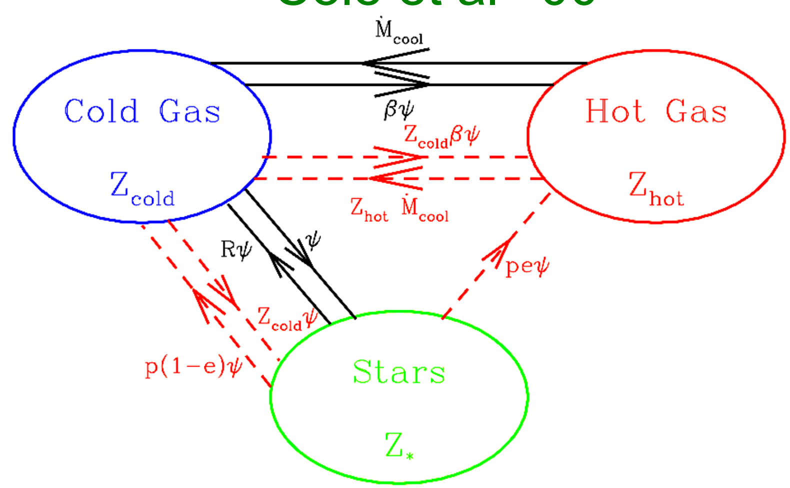
Cole et al '00

SFR & mass ejection

SFR $$\psi = \frac{M_{\rm cold}}{\tau_\star(r_{\rm disk}, V_{\rm disk})}$$

SN feedback $$\dot{M}_{\rm eject} = \beta(V_{\rm disk})\,\psi$$

AGN feedback $$\dot{M}_{BH} = f_{BH}\psi_{burst} + \frac{L_{cool}}{c^2\varepsilon_{SMBH}}$$



Photoionization & the filtering mass

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Linear theory for the growth of a baryonic perturbation (Gnedin & Hui 98)

$$\ddot{\delta}_b + 2H(a)\dot{\delta}_b = 4\pi G\bar{\rho}(f_{DM}\delta_{DM} + f_b\delta_b) - \frac{c_S^2}{a^2}k^2\delta_b$$

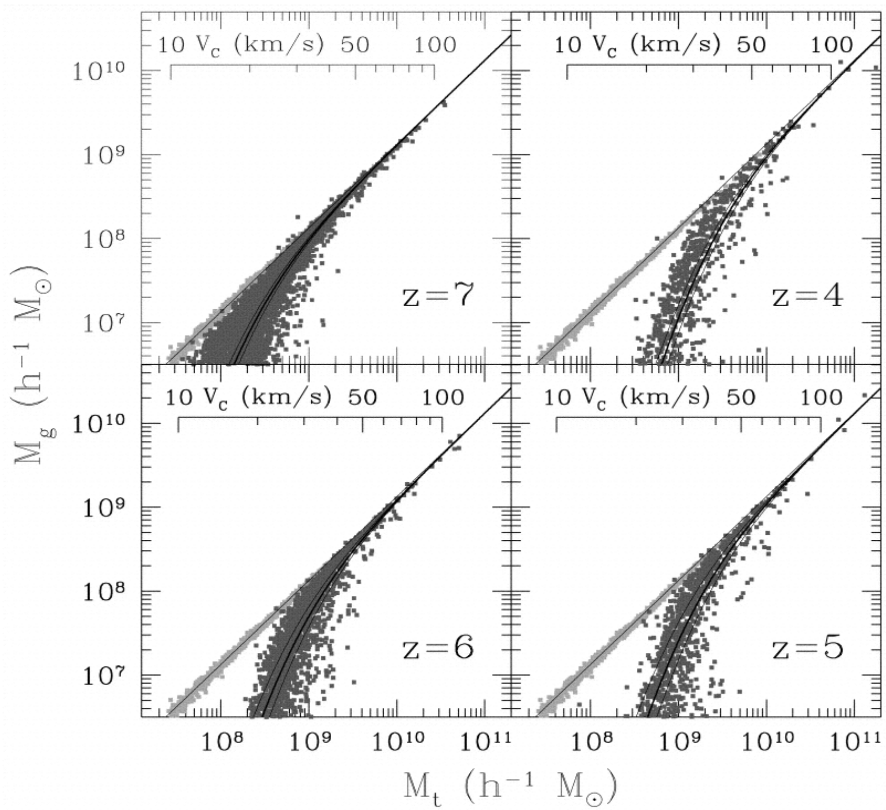
Instantaneous Jeans wavenumber given by $k_J = \frac{a}{c_S}\sqrt{4\pi G\bar{\rho}}$

Expand baryonic overdensity in wavenumber:

$$\frac{\delta_b(t,k)}{\delta_{DM}(t,k)} = 1 - \frac{k^2}{k_F^2}$$

$$\frac{1}{k_F^2}(t) = \frac{1}{D_+(t)}\int_0^t dt' a^2(t')\frac{\ddot{D}_+(t') + 2H(t')\dot{D}_+(t')}{k_J^2(t')}\int_{t'}^t \frac{dt''}{a^2(t'')}$$

Benson, CSF+ '02



Filtering mass used in fitting formula for total mass of gas accreted by halos (Gnedin '00):

$$M_{gas} = \frac{f_b M_{total}}{[1 + (2^{1/3} - 1)M_F(z)/M_{total}]^3}$$

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The GALFORM model

Modelling reionization: full model well approximated by:

Turn off cooling in halos of circular velocity V_c for:

$V_c < V_{cut}$ at $z < z_{cut}$ z_{cut}

Controls the characteristic scale below which reionisation is effective

[fiducial value: $V_{cut} = 30$ kms^{-1}]

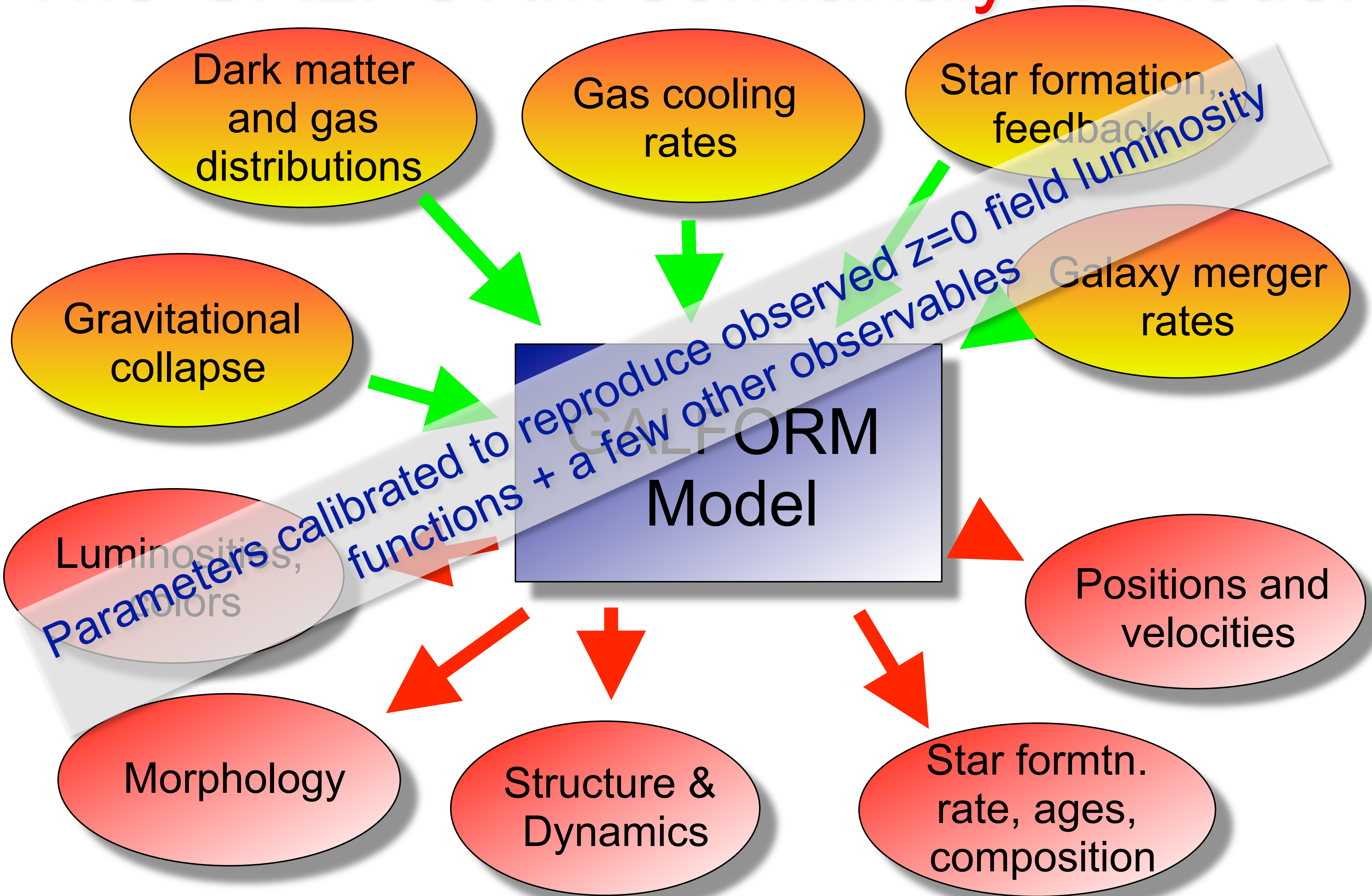
Controls when reionisation happens

[fiducial value: $z_{cut} = 6$]

[calibrated by hydrodynamical sims. of Okamoto+ '08]

[c.f. a full, self-consistent calculation of reionisation by Benson+ (2002a); also employed by Bullock+ 00; Somerville '0 etc.]

The GALFORM semianalytic model



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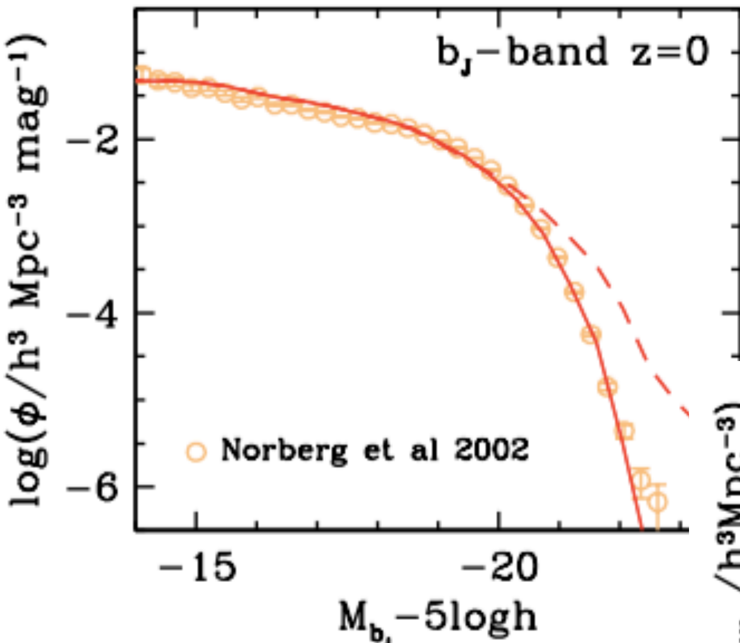
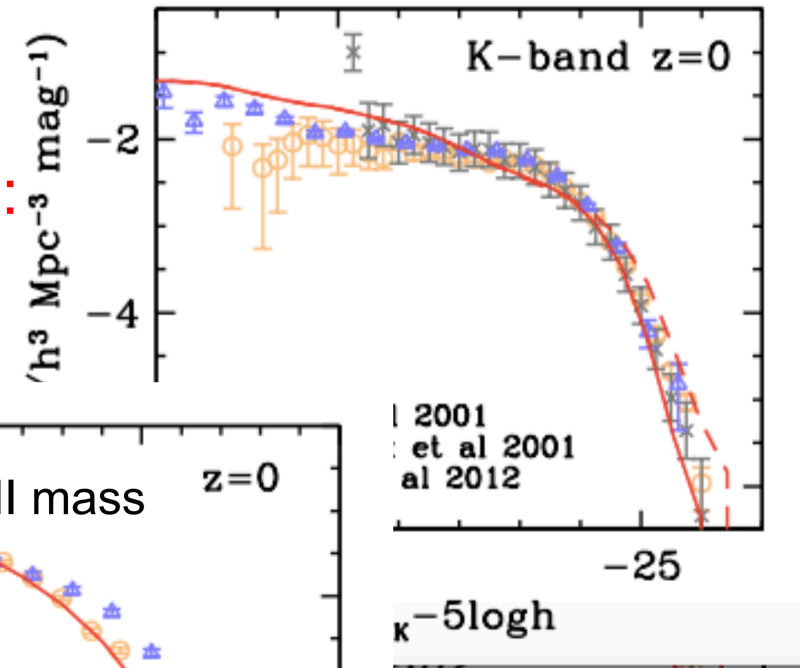
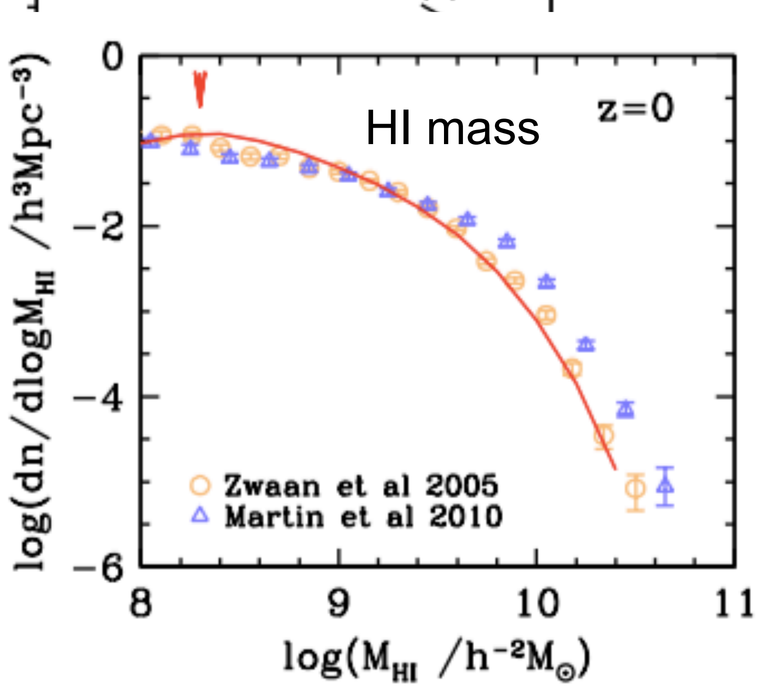
The GALFORM model

Durham semi-analytic model of galaxy formation: follows all physical processes thought to be relevant for galaxy formation



Example predictions: z=0 LFs



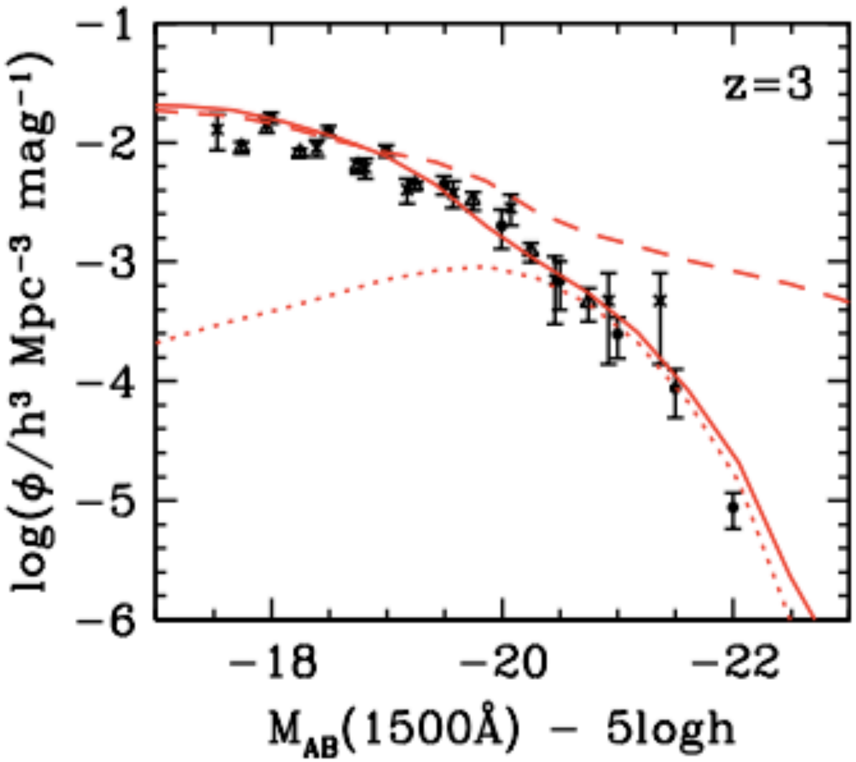


Lacey et al. ‘16

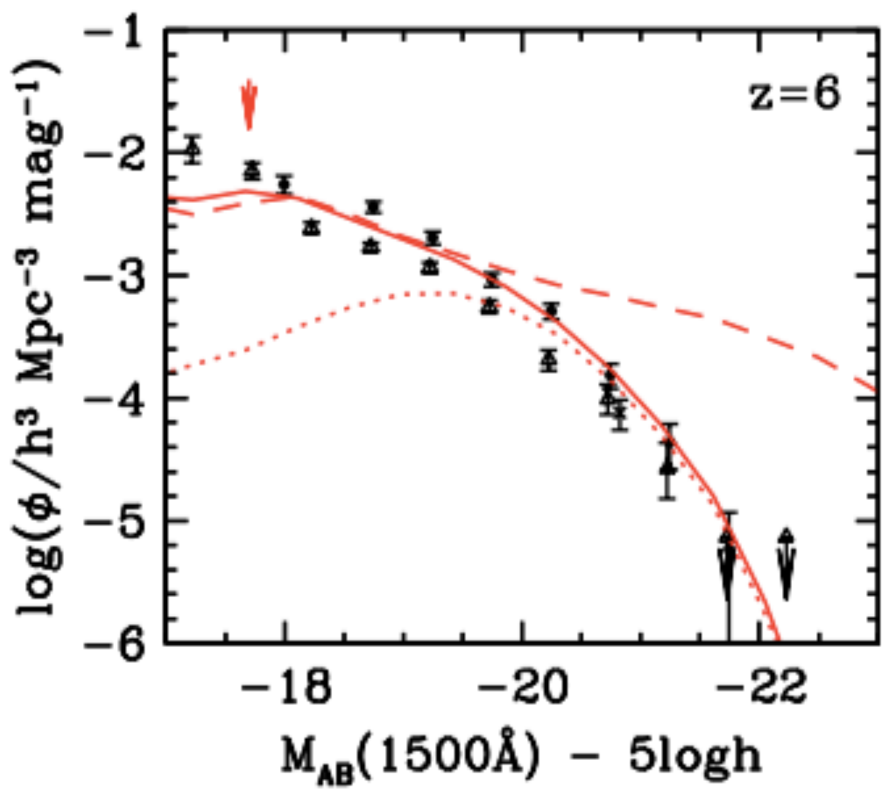
The GALFORM model

University of Durham

Durham semi-analytic model of galaxy formation: follows all physical processes thought to be relevant for galaxy formation



Example predictions: rest-frame far-UV LF at hi-z



Lacey et al. ‘16

Copernicus Complexio (COCO) simulation

Dark matter only

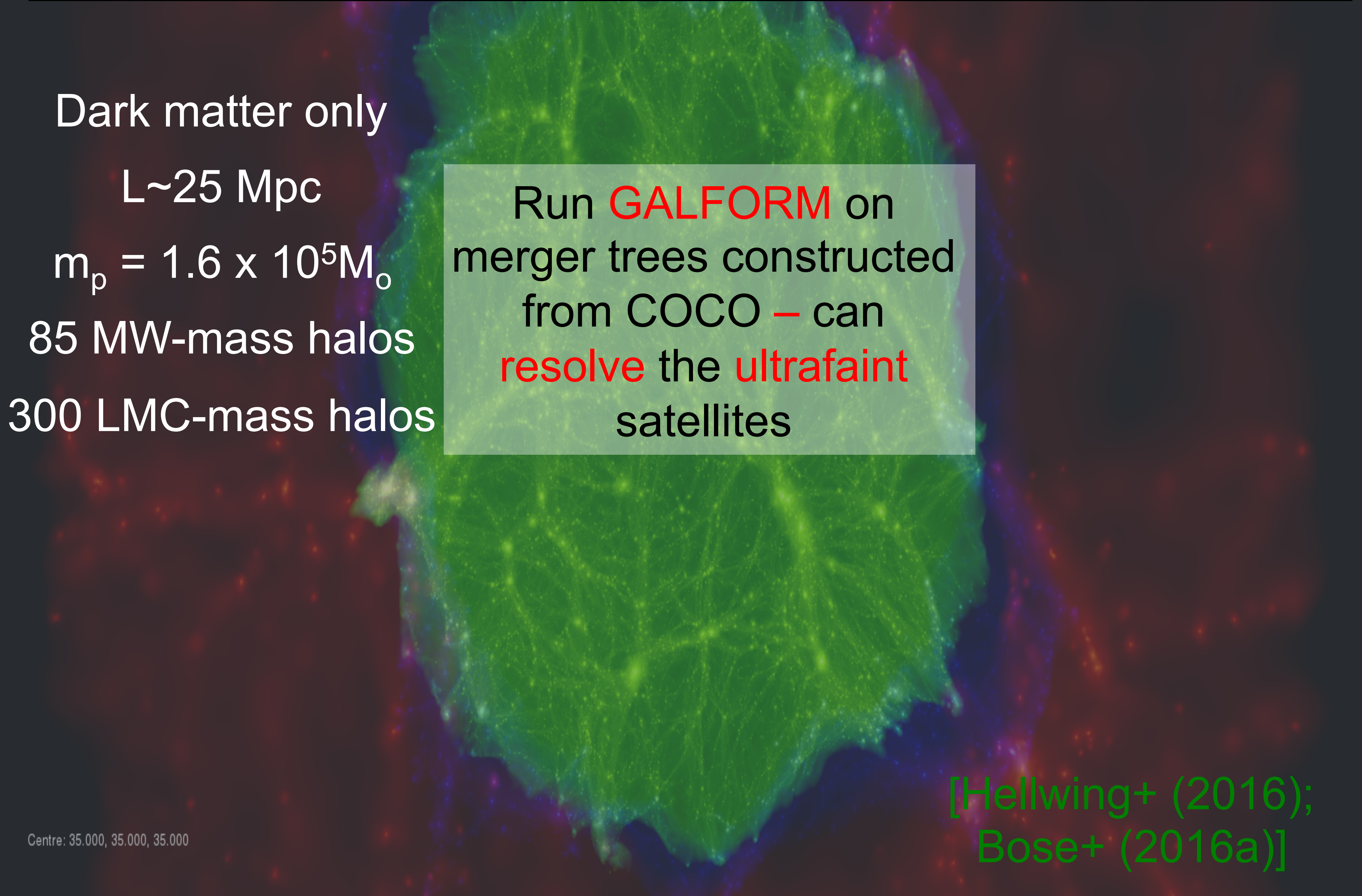
L~25 Mpc

$m_p = 1.6 \times 10^5 M_o$

85 MW-mass halos

300 LMC-mass halos

Run GALFORM on merger trees constructed from COCO – can resolve the ultrafaint satellites

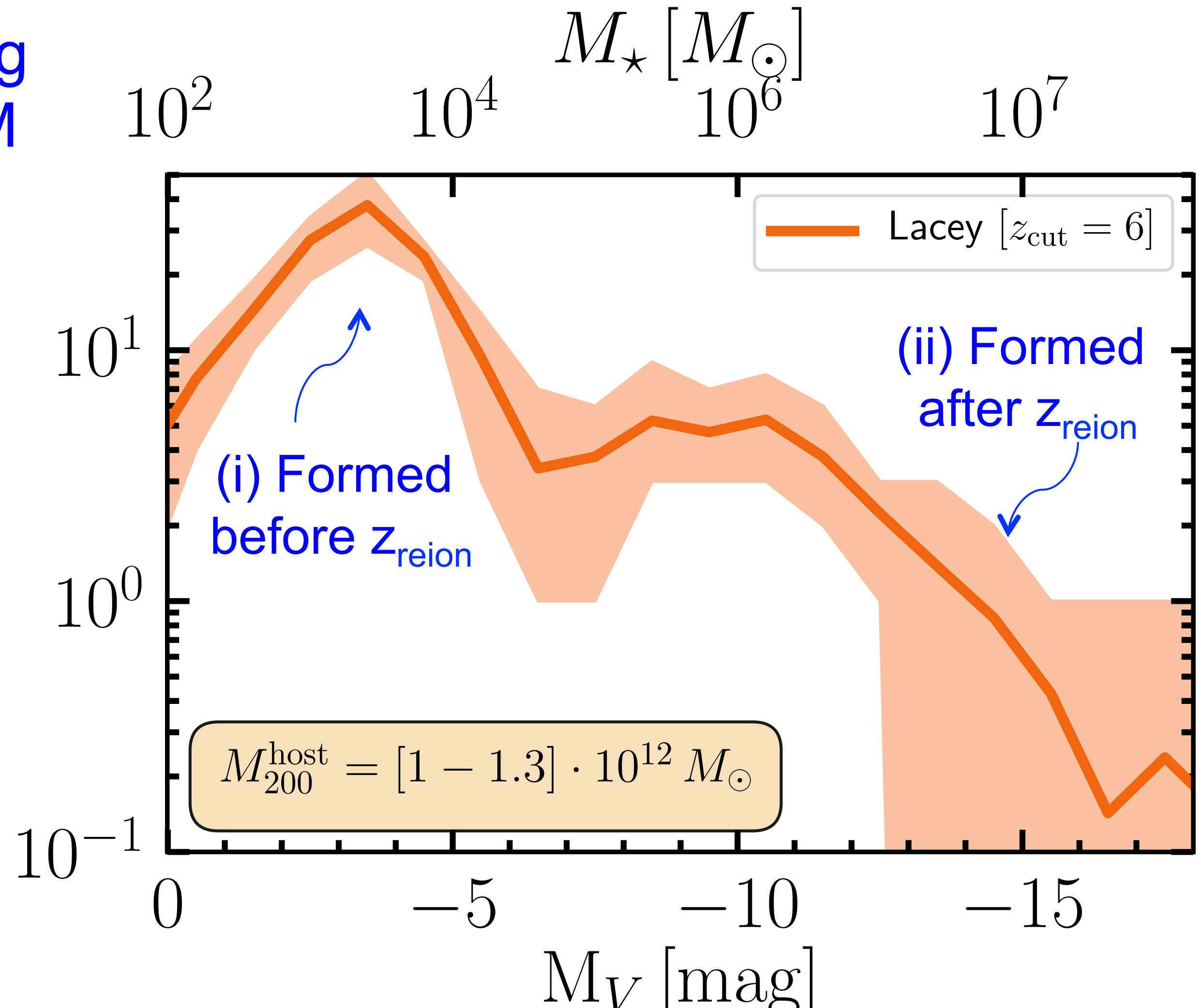


[Hellwing+ (2016); Bose+ (2016a)]

The satellite luminosity function

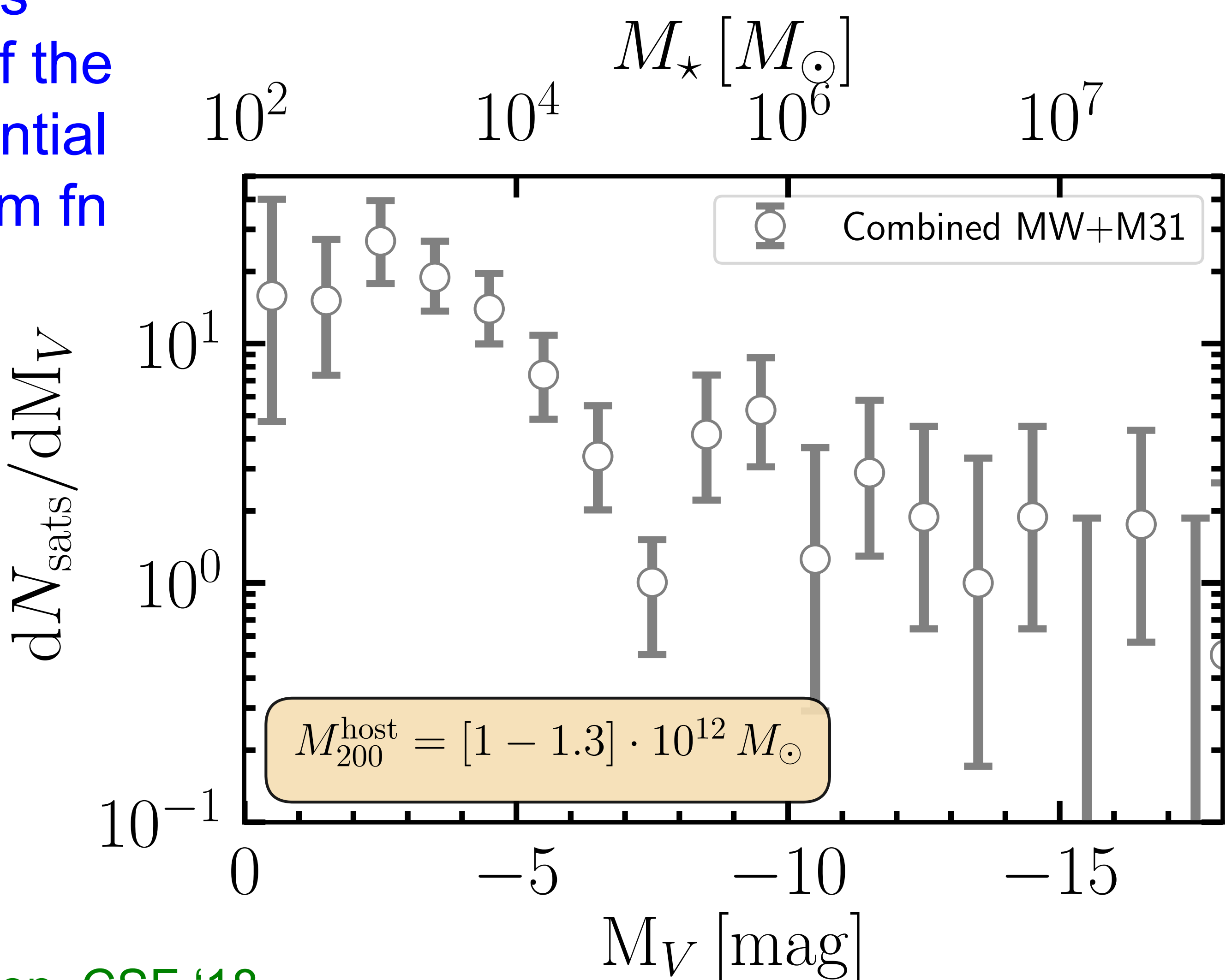
Two populations of sats formed: (i) before and (ii) after reionization

Pre-existing GALFORM model



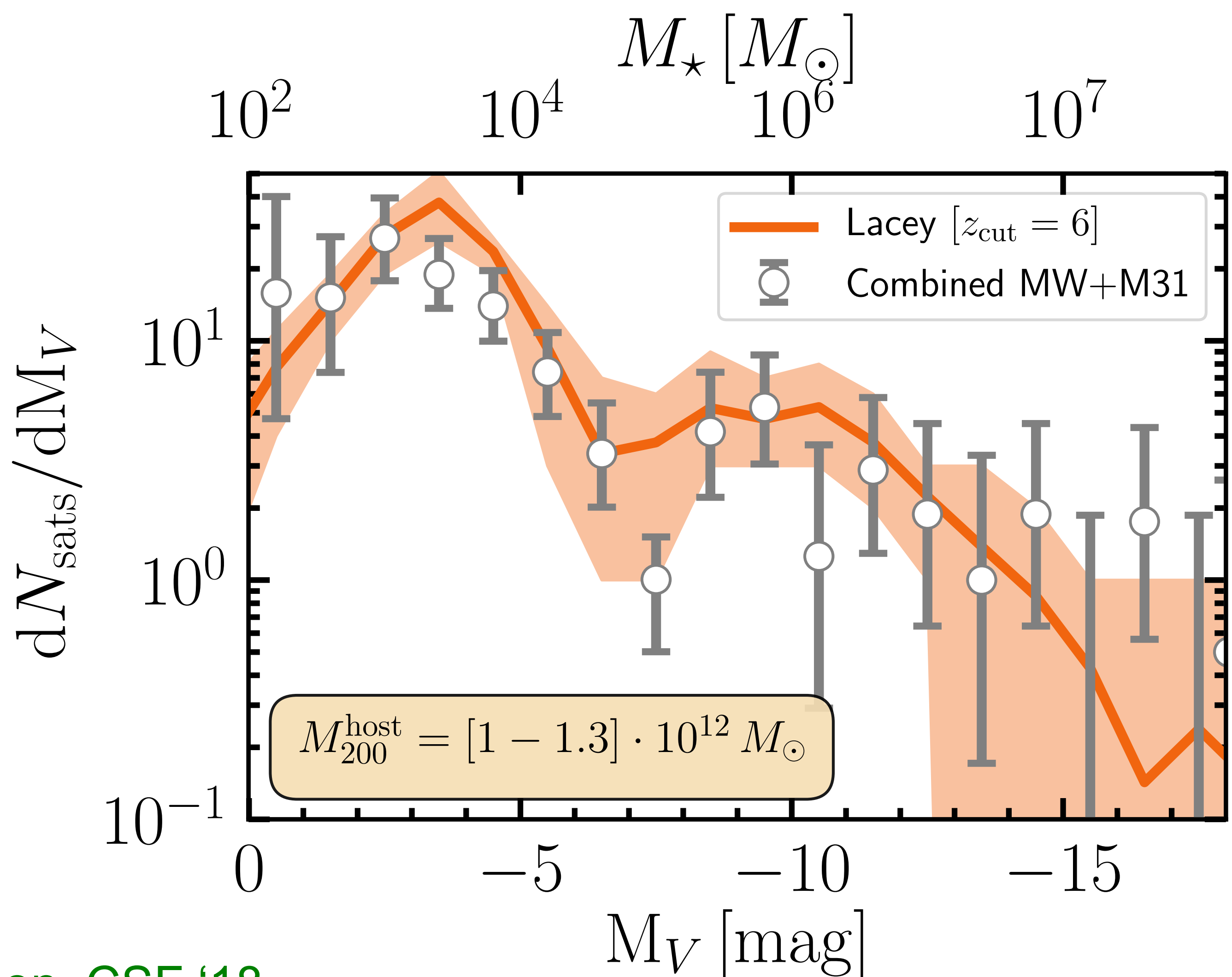
Theory *vs* data

Newtons' estimate of the MW differential satellite lum fn



Bose, Deason, CSF '18

Theory *vs* data



Bose, Deason, CSF '18

Stars formed before reionisation

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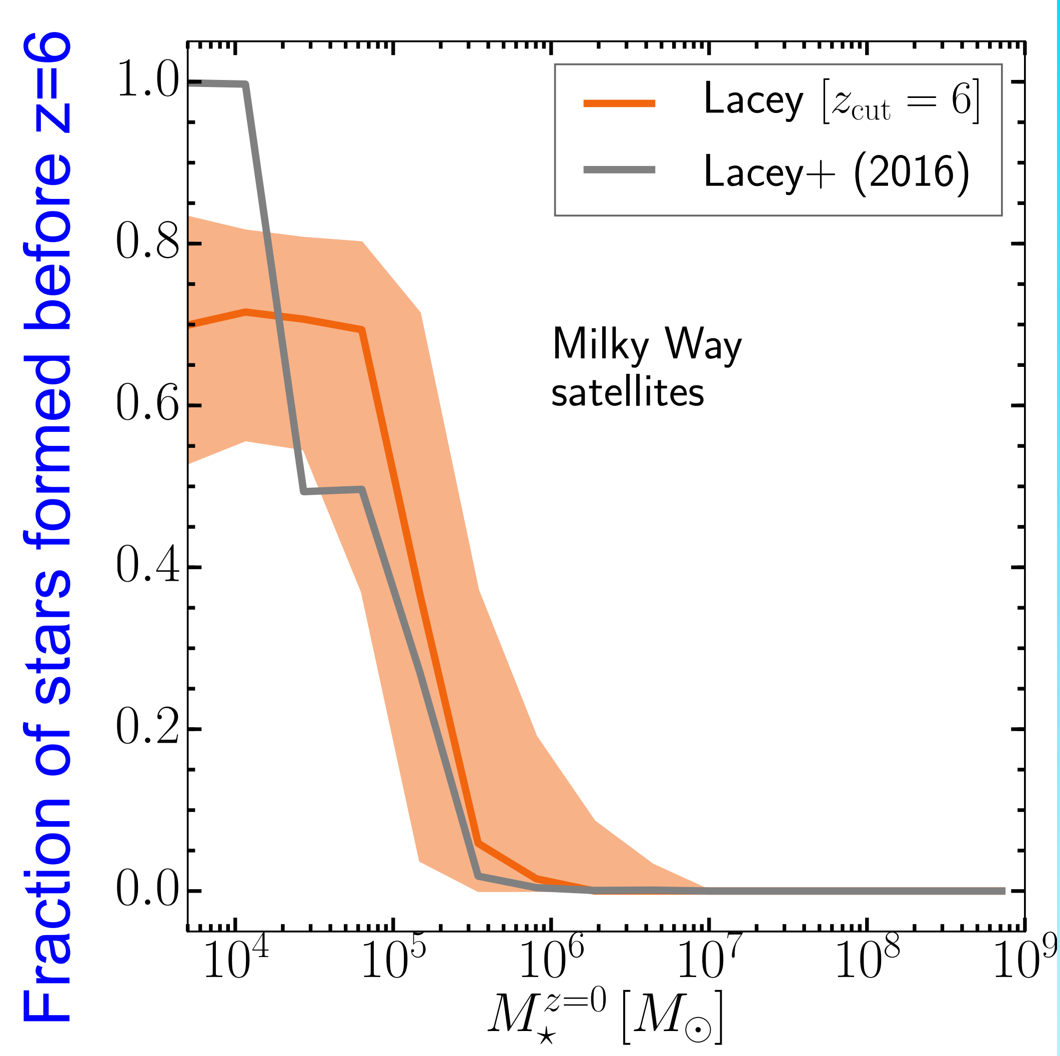
Ultra-faint satellites ($M_* < 10^5 M_o$) (e.g. Segue-2, Cannes Venatici 1 and 2, Bootes 1, etc) form ~70% of their stars before reionization

Bright galaxies assemble much later: they know nothing about reionisation.



Bose, Deason, CSF '18

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The satellite luminosity function

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How does the predicted satellite luminosity function depend on:

z_{cut} and V_{cut}

Controls when reionisation happens

[fiducial value: $z_{cut} = 10$]

Controls the characteristic scale below which reionisation is effective

[fiducial value: $V_{cut} = 30$ kms^{-1}]

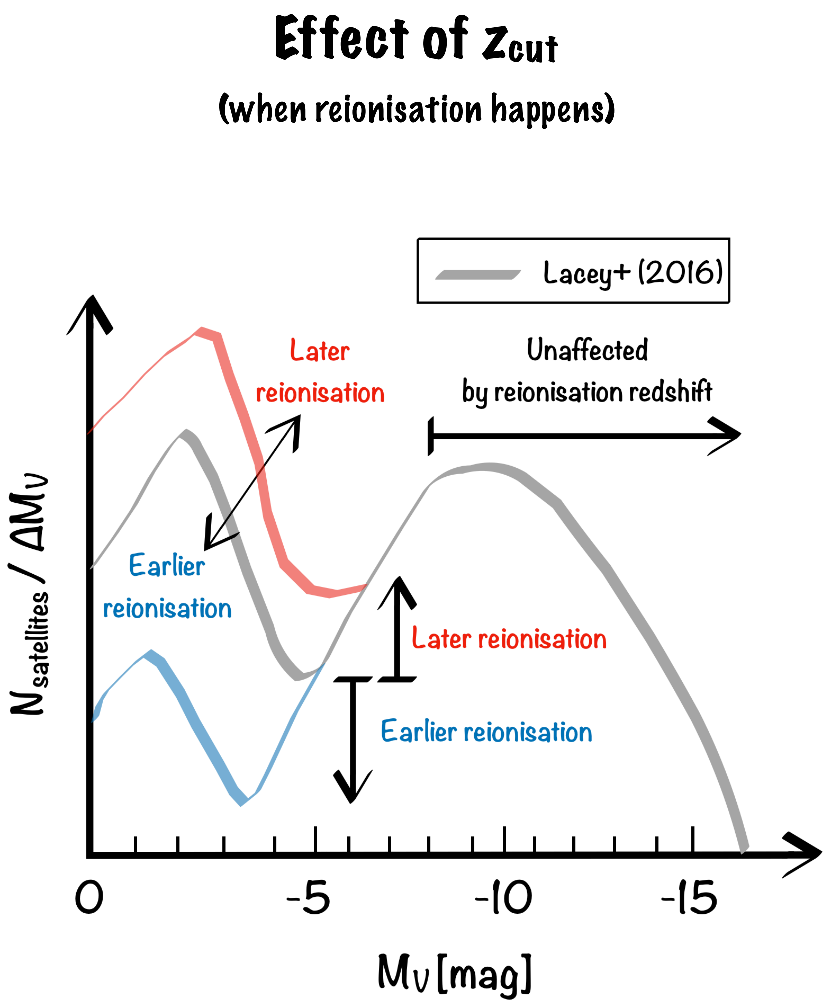
[calibrated by hydrodynamical sims. of Okamoto+ '08]

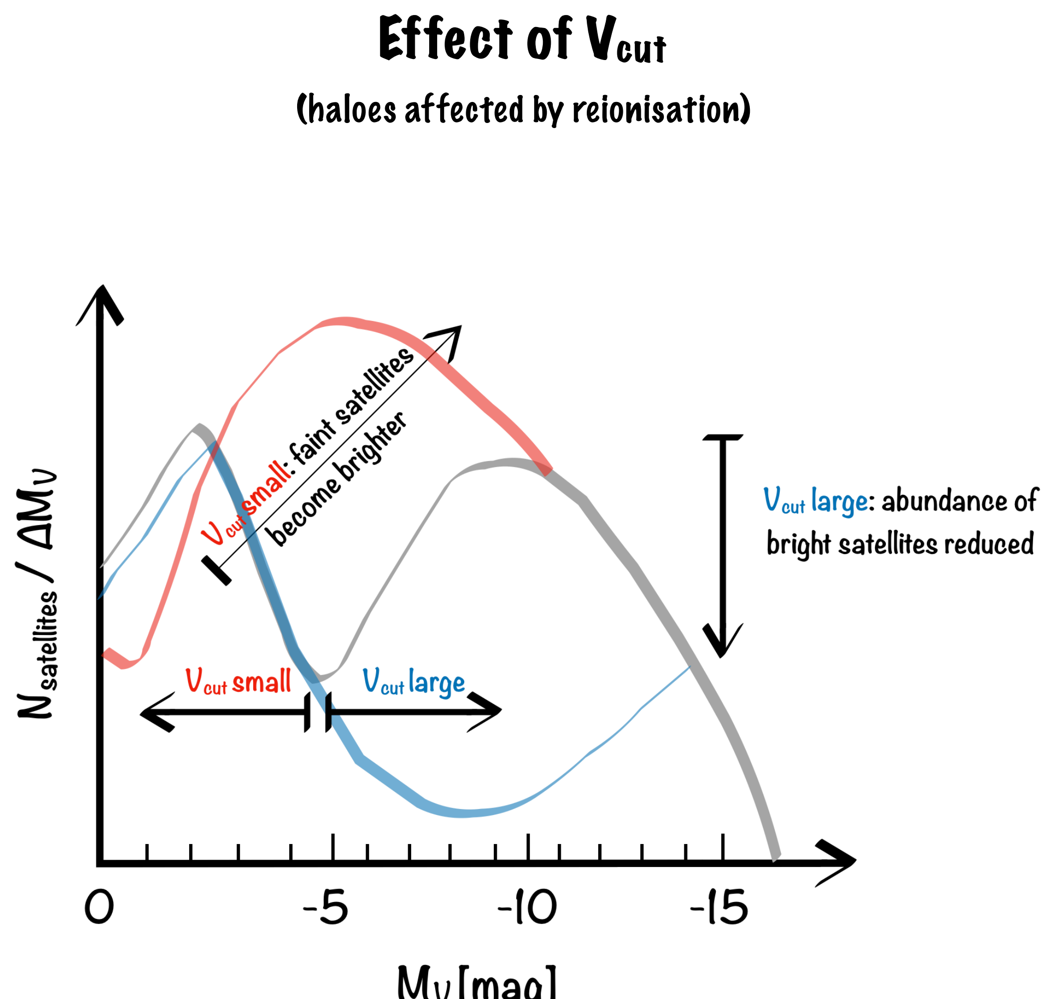
The satellite luminosity function

University of Durham

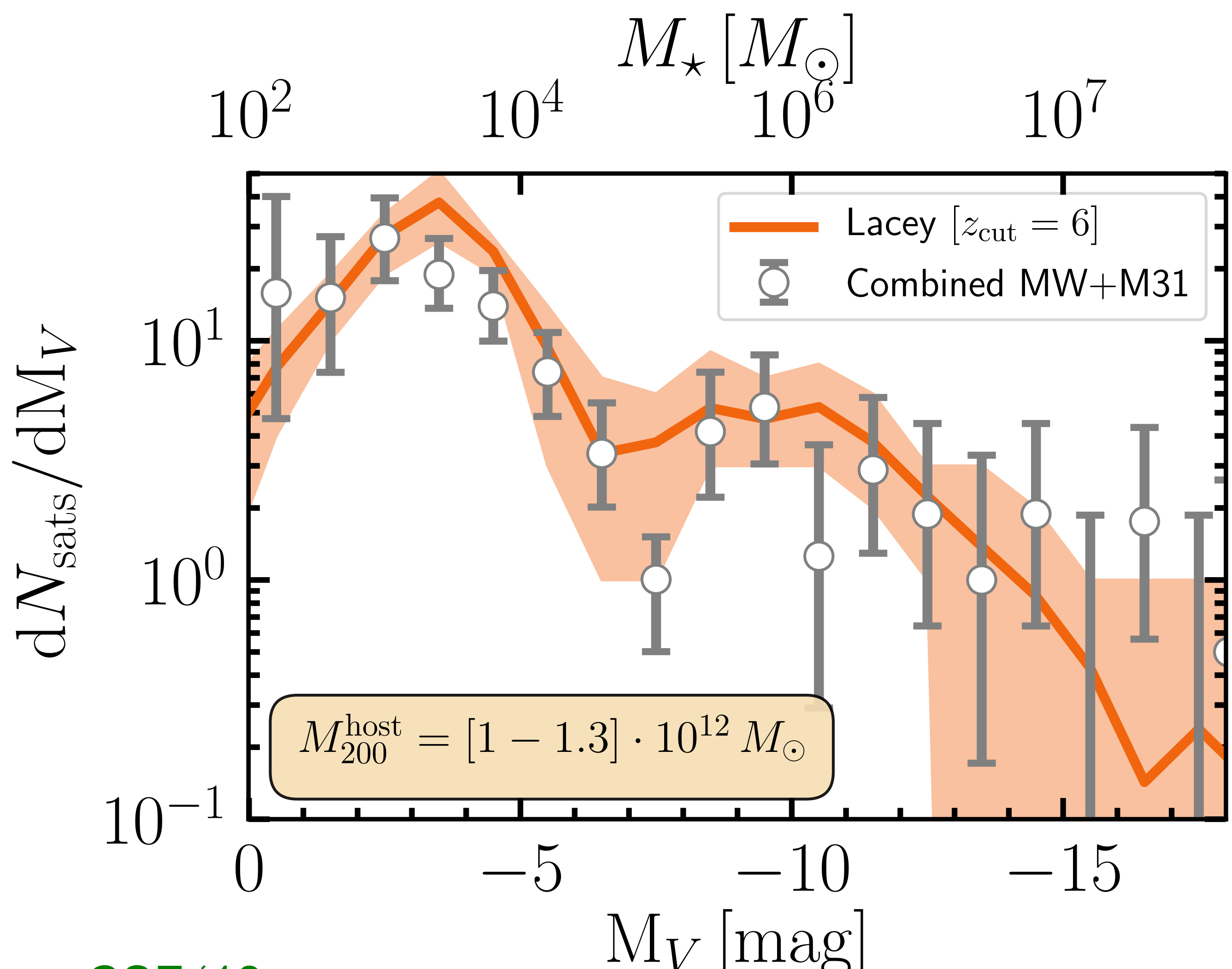
GALFORM predicts:

Two populations of sats formed: (i) before and (ii) after reionization





Theory vs data



Bose, Deason, CSF '18

The MW/M31 sat. luminosity function

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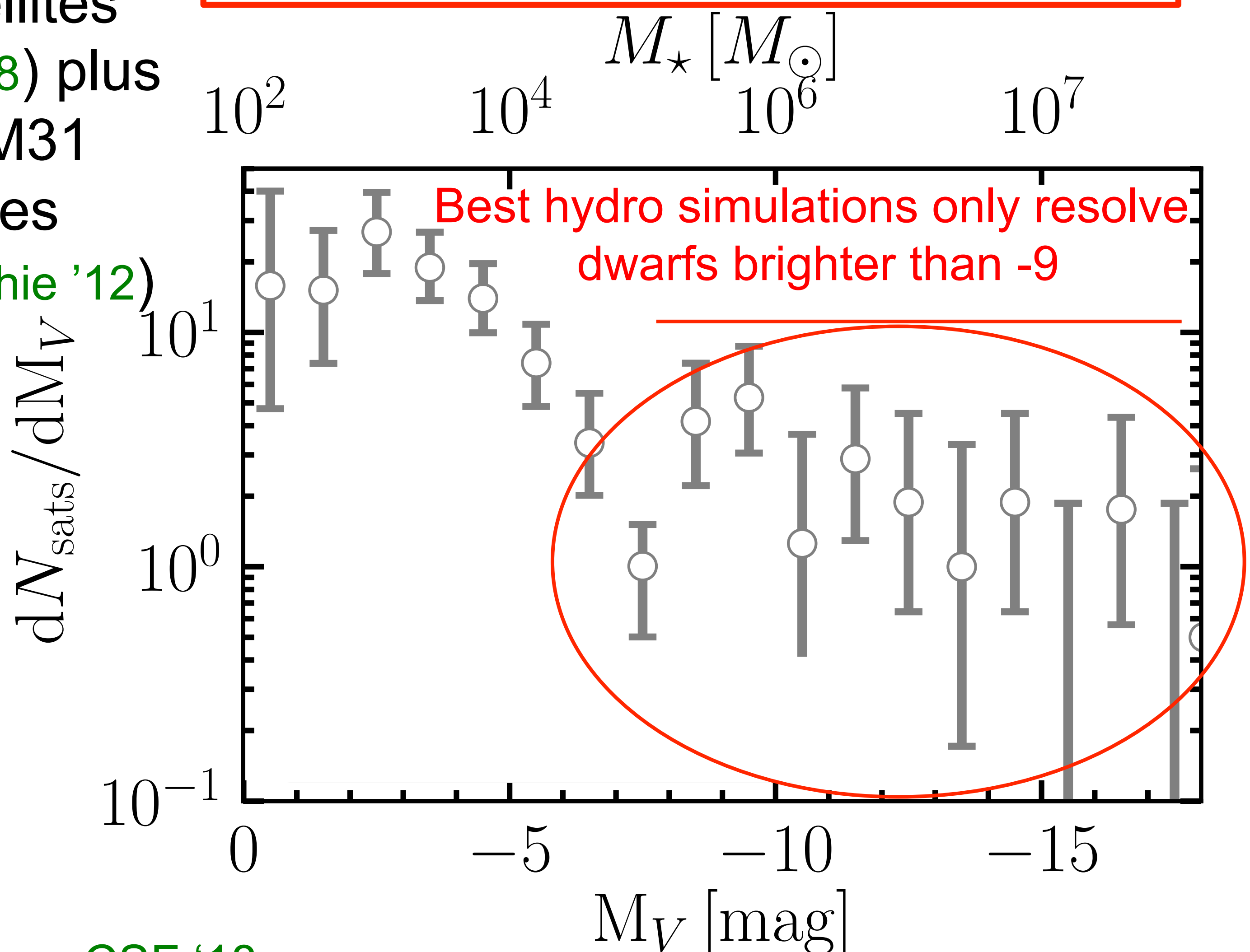
MW satellites (Newton+ '18) plus M_V<-8 M31 satellites (Mcconnachie '12)

Differential satellite luminosity function



Bose, Deason, CSF '18

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ΛCDM in crisis?

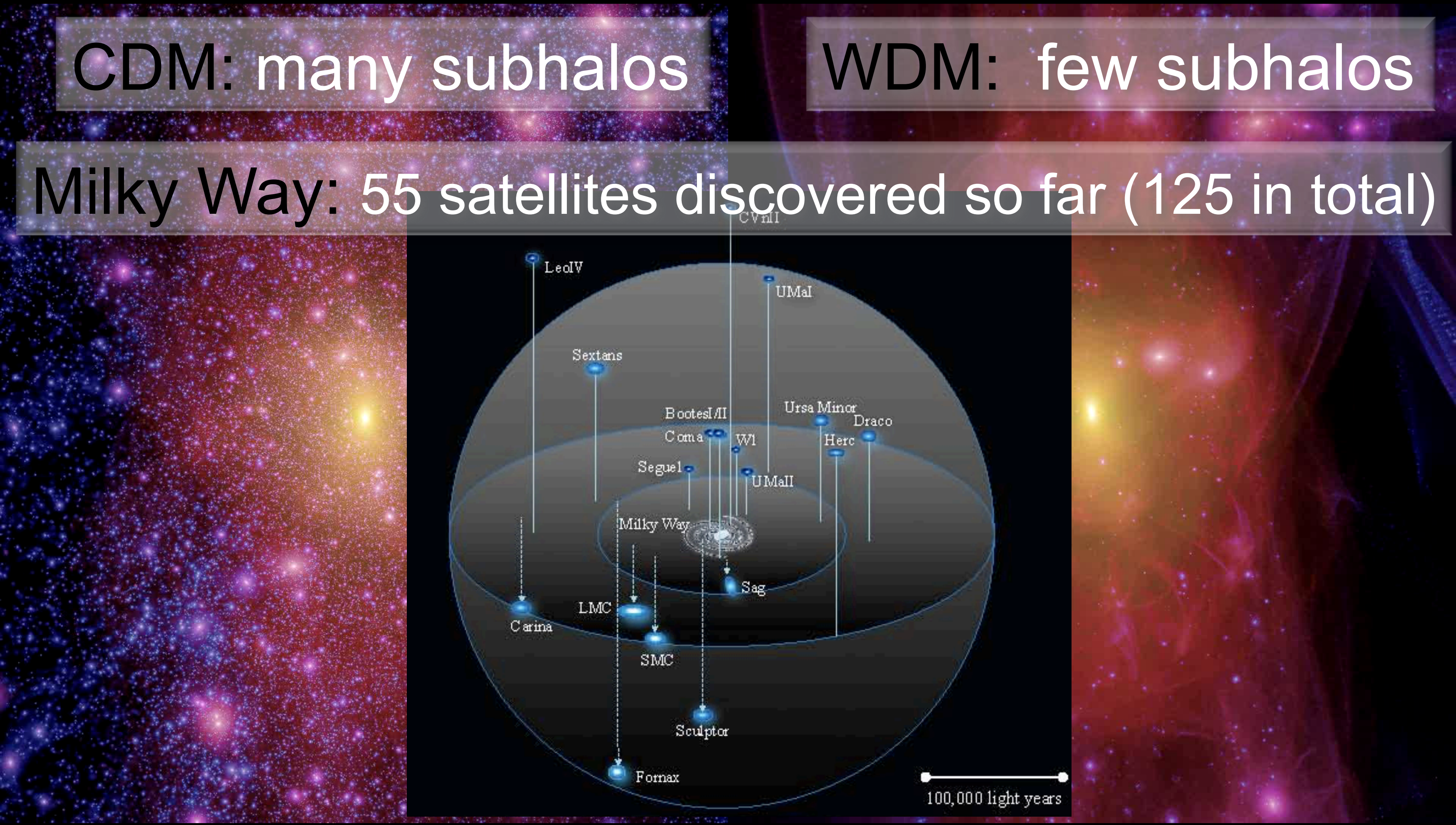
Two problems for ΛCDM on dwarf galaxy scales”

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

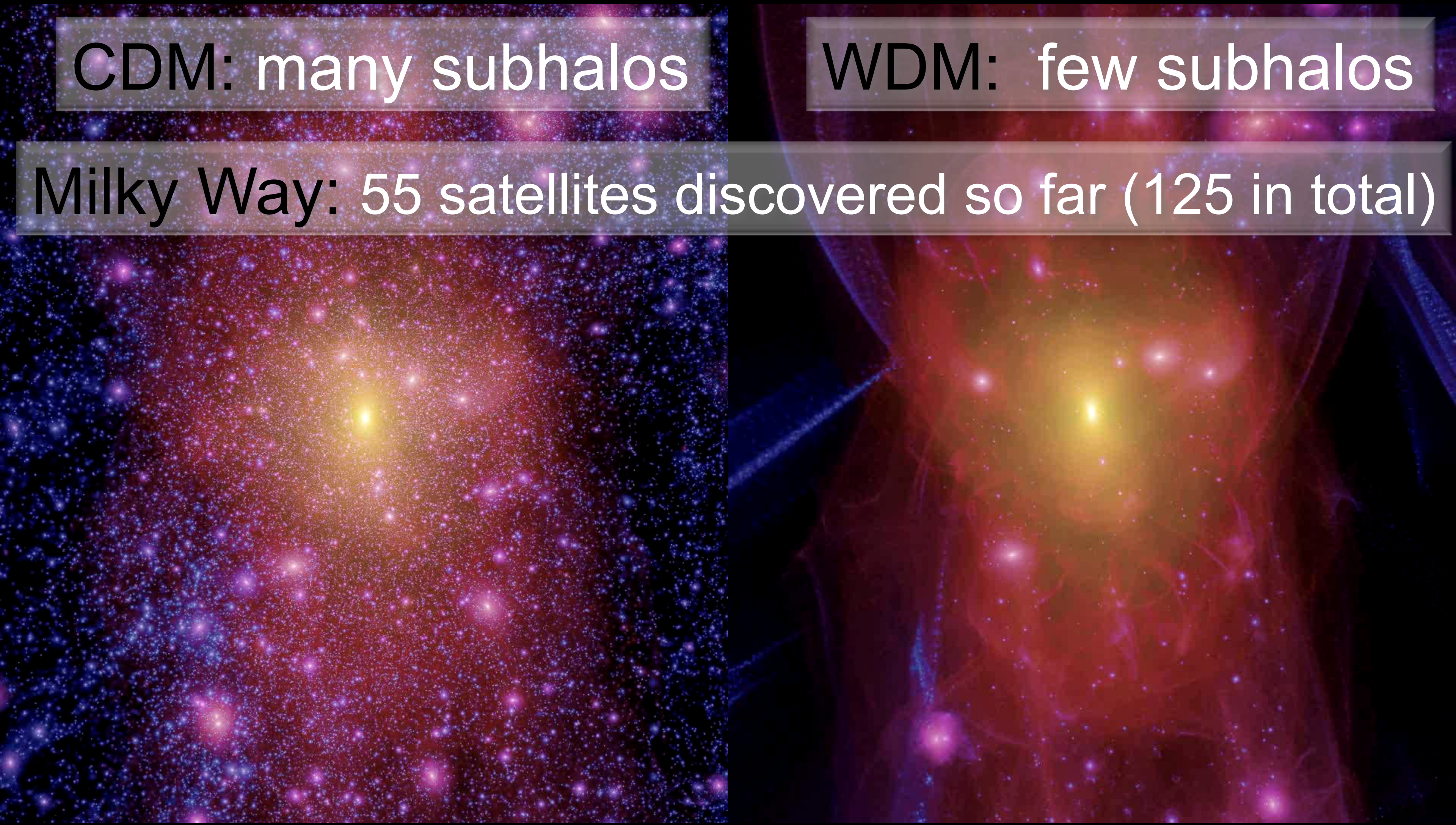
problems

cold dark matter

warm dark matter



Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12 cold dark matter | warm dark matter



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

cold dark matter

warm dark matter

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

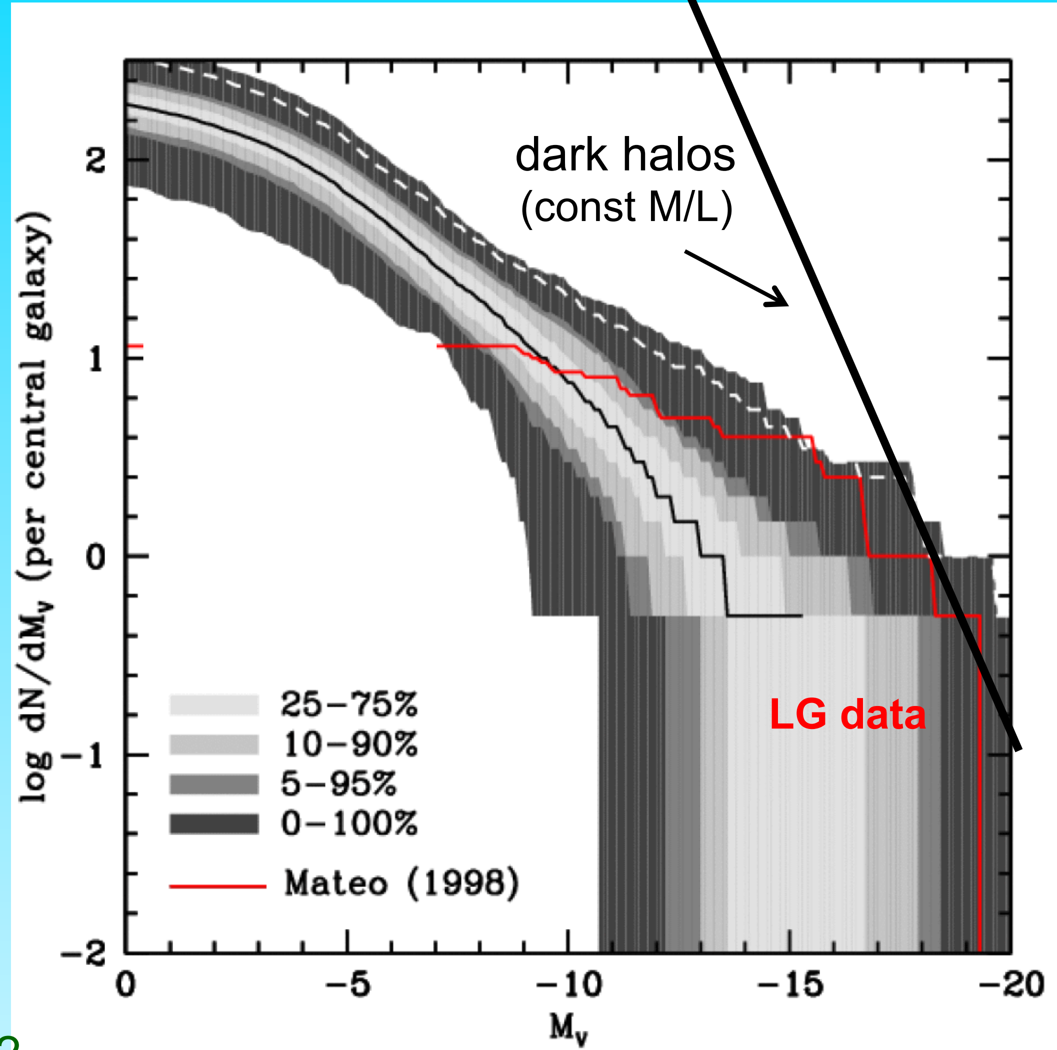
Most subhalos never make a galaxy!

Because:

- Reionization heats gas to ~10^4K, preventing it from cooling and forming stars in small halos
- Supernovae feedback expels any residual gas

Luminosity Function of Local Group Satellites

- 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 et al '93, Bullock et al '00)

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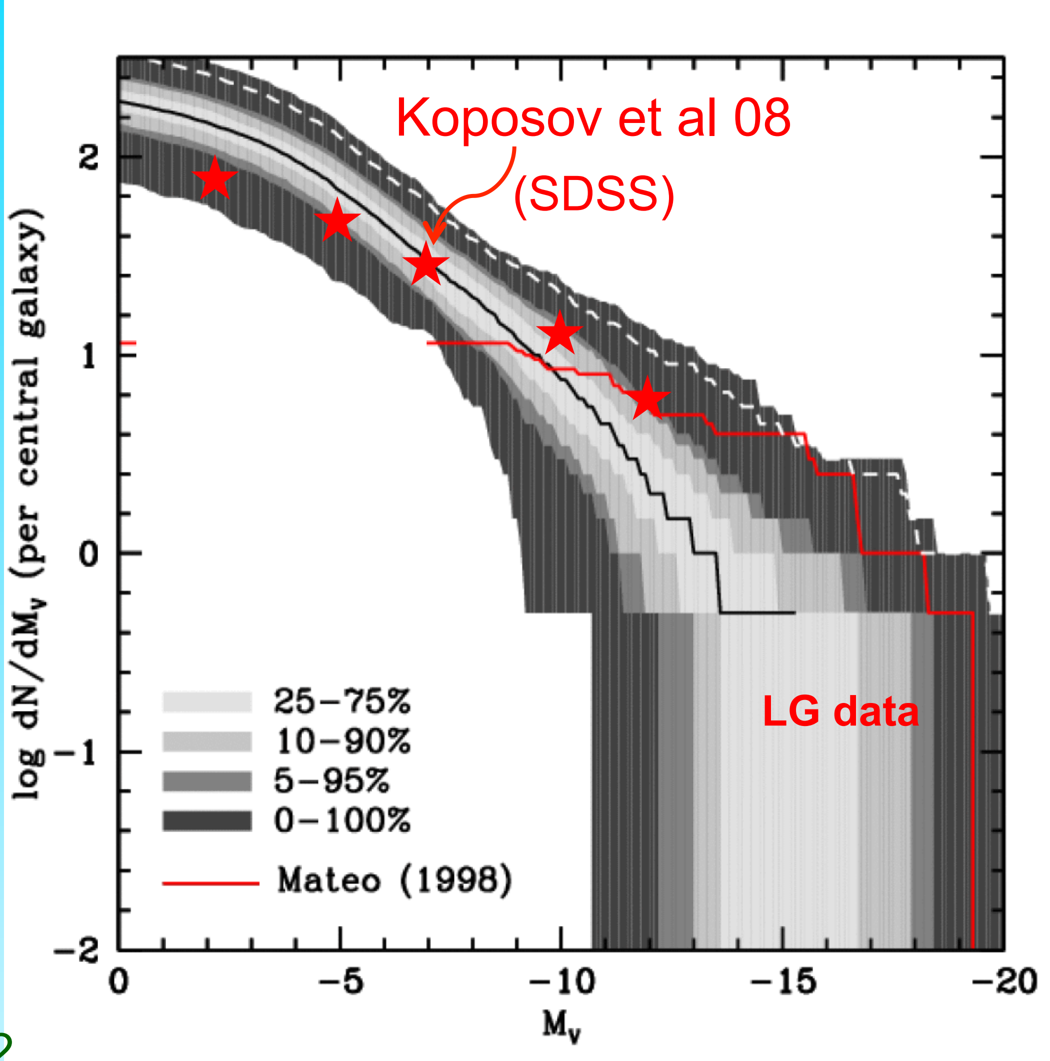


Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock et al '01)

Institute for Computational Cosmology

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…

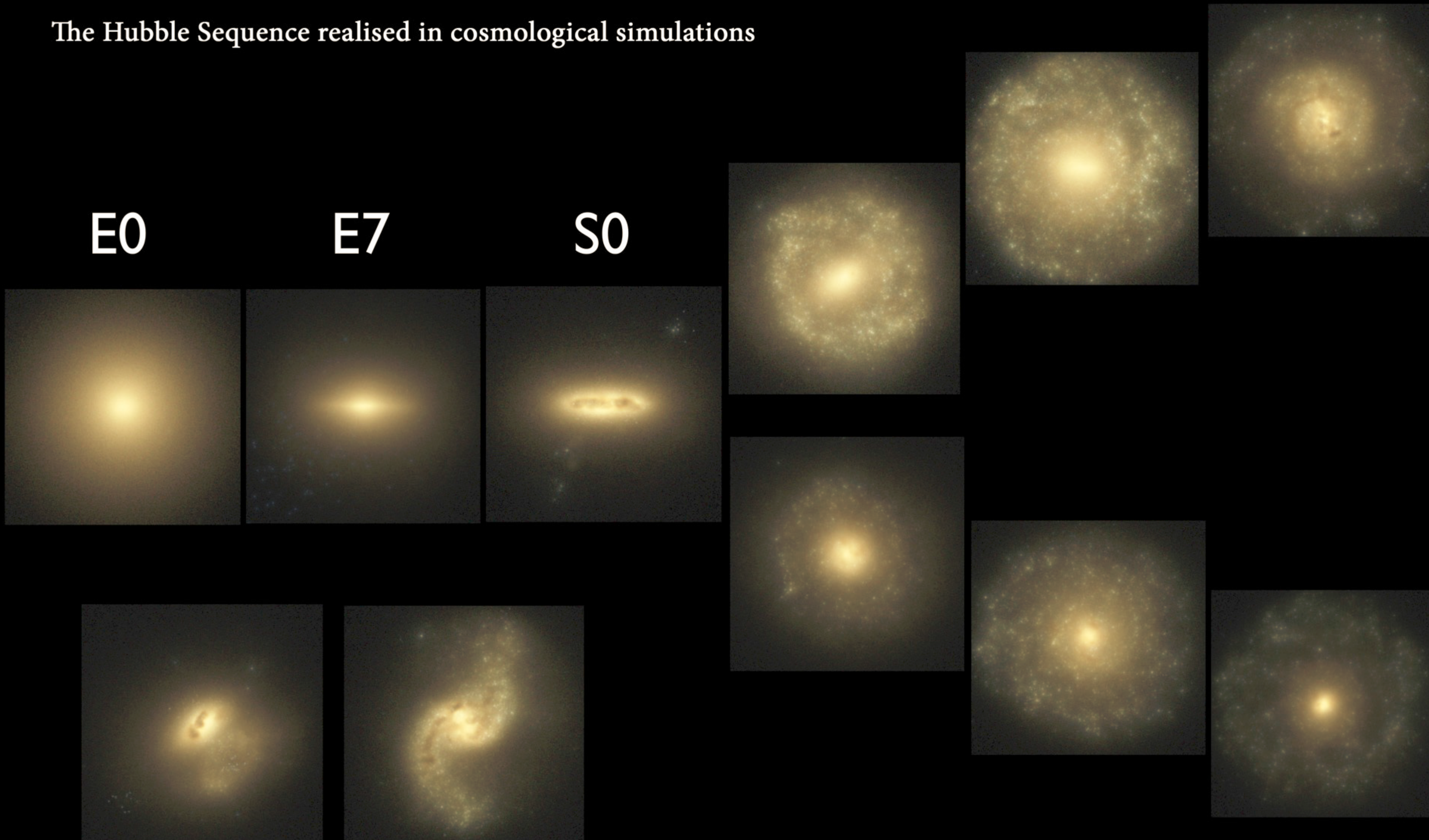
Durham University VIRGO ICC DiRAC PRACE

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 '15

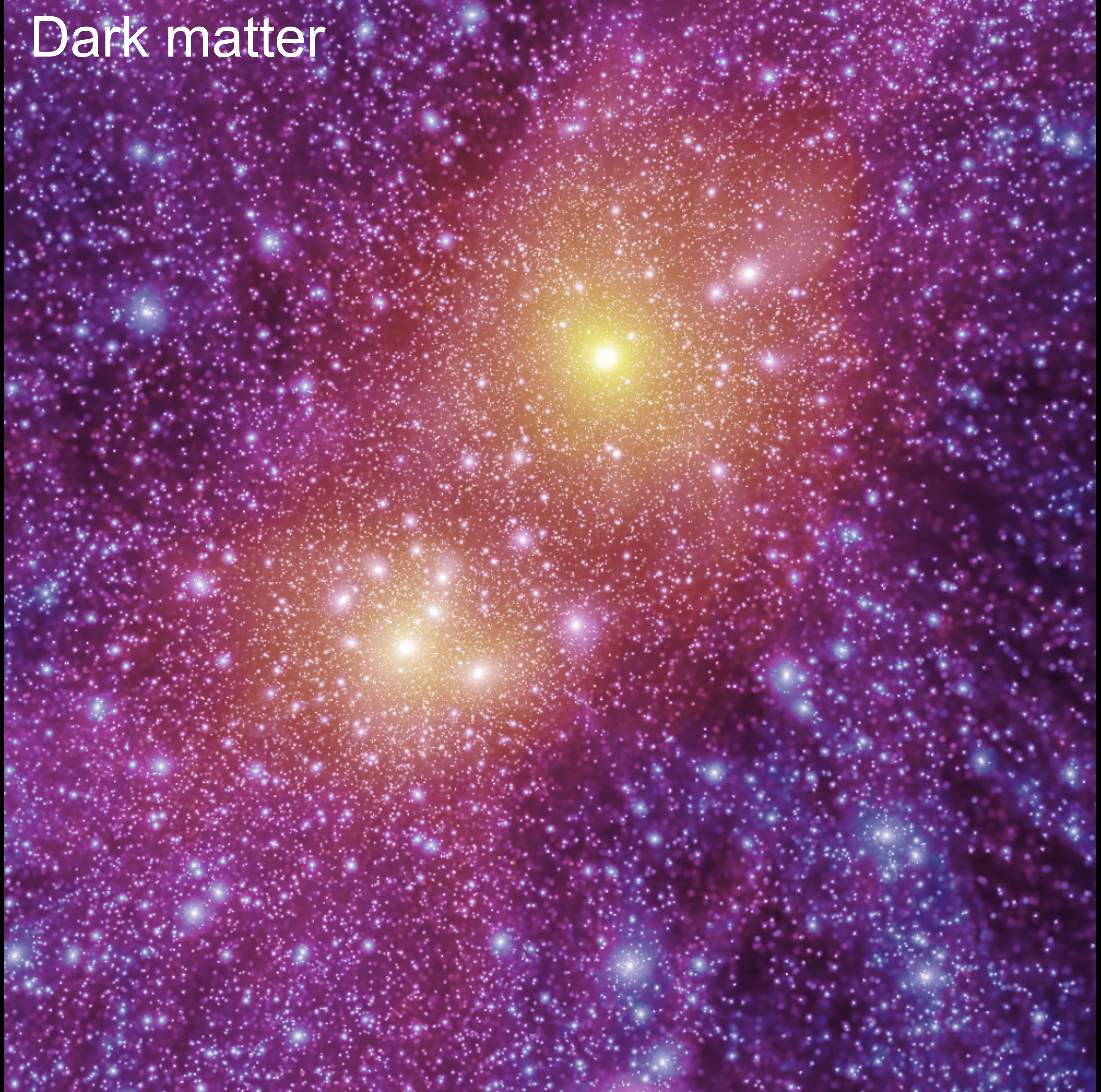
VIRGO

APOSTLE EAGLE full hydro simulations

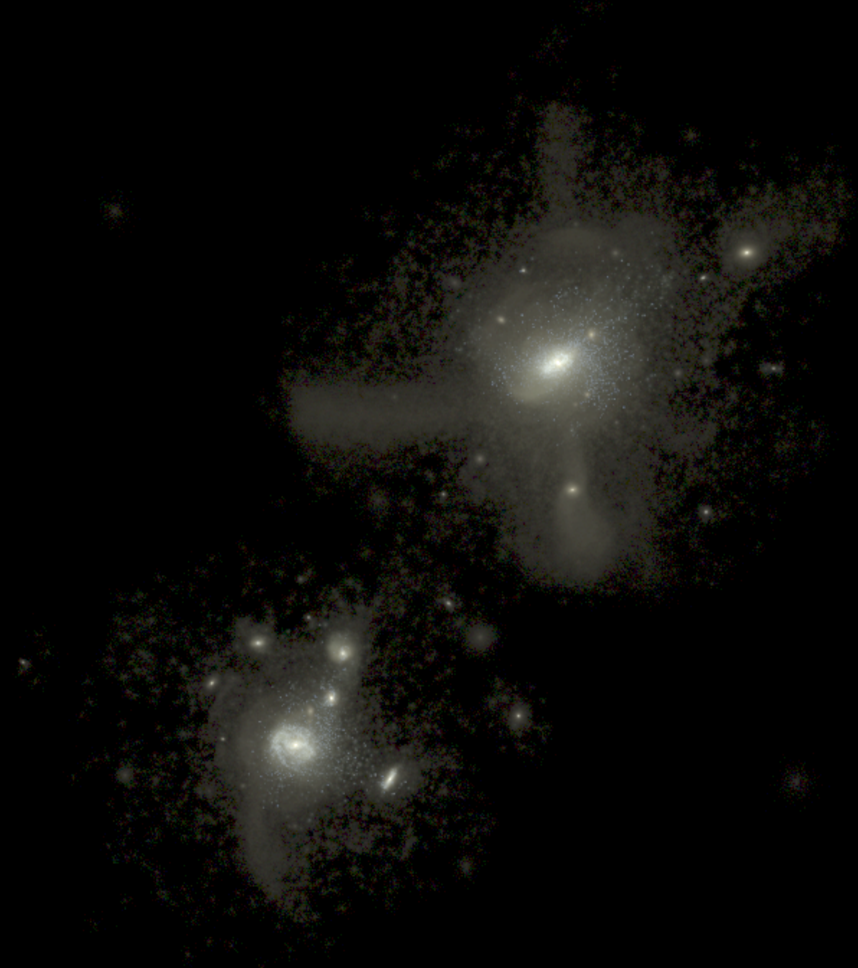
Local Group

CDM

Sawala et al ‘16



Stars



APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM

Far fewer satellite galaxies than CDM halos

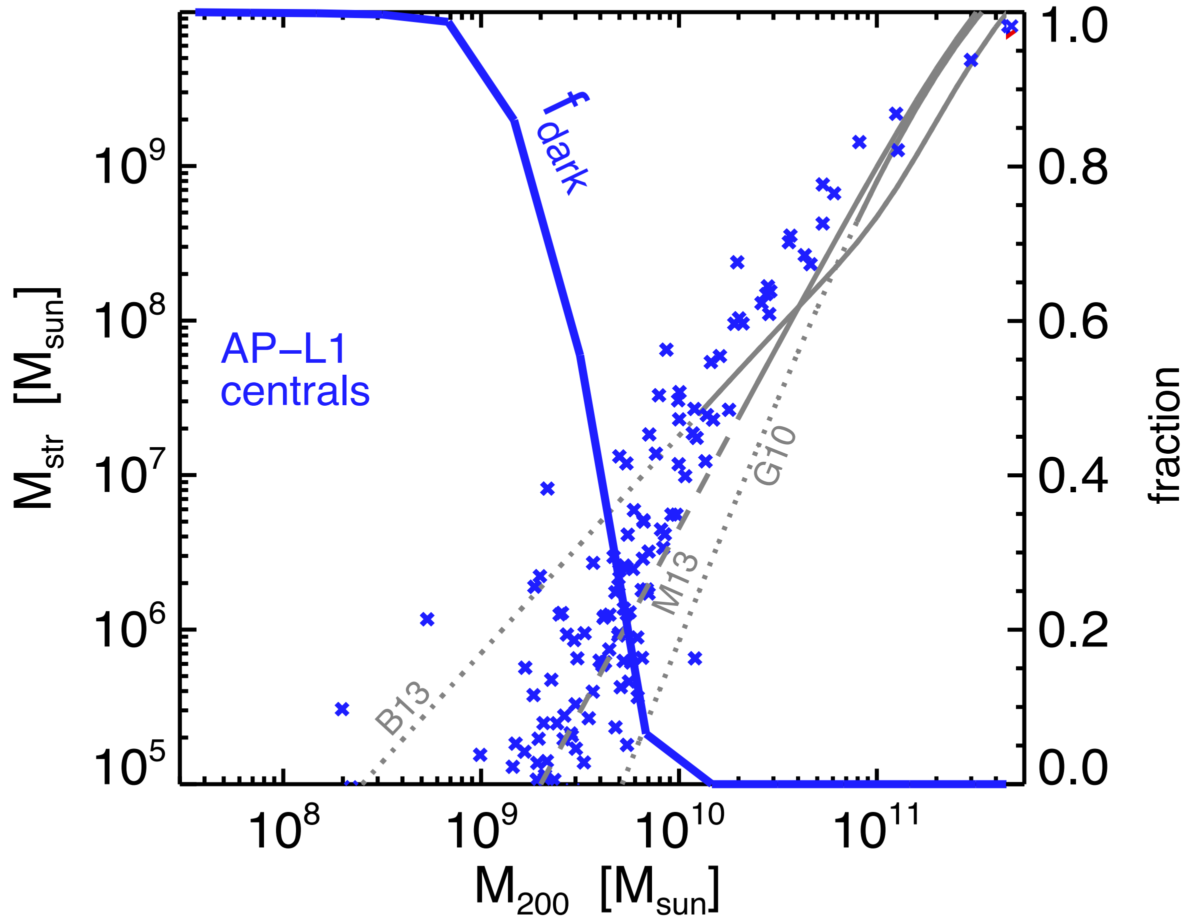
Sawala et al ‘16

University of Durham

Fraction of dark subhalos

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

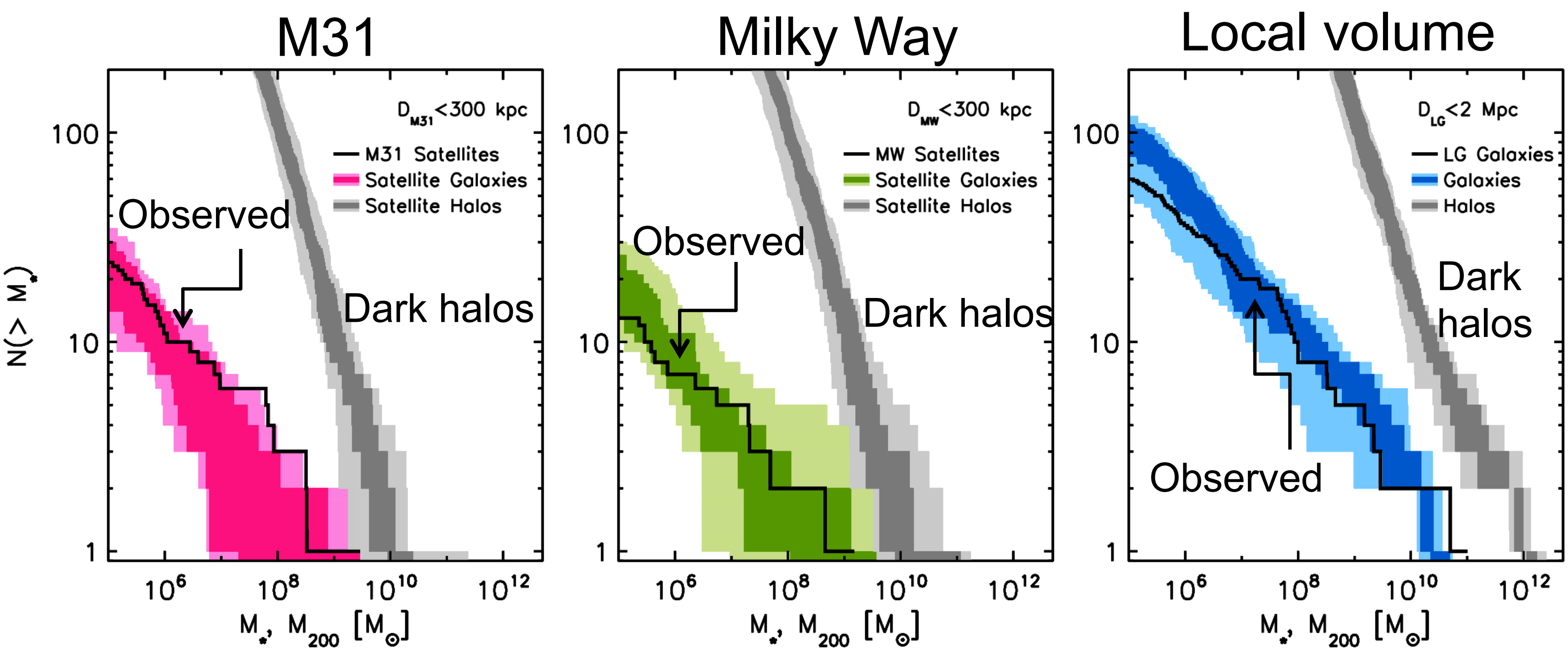
$$V_{max} = \max V_c$$



All halos of mass < $5\times10^8 M_o$ or V_{max} < 7 km/s are dark ($m_* < 10^4 M_o$)

Fattahi et al '16

EAGLE Local Group simulation



Sawala et al '16

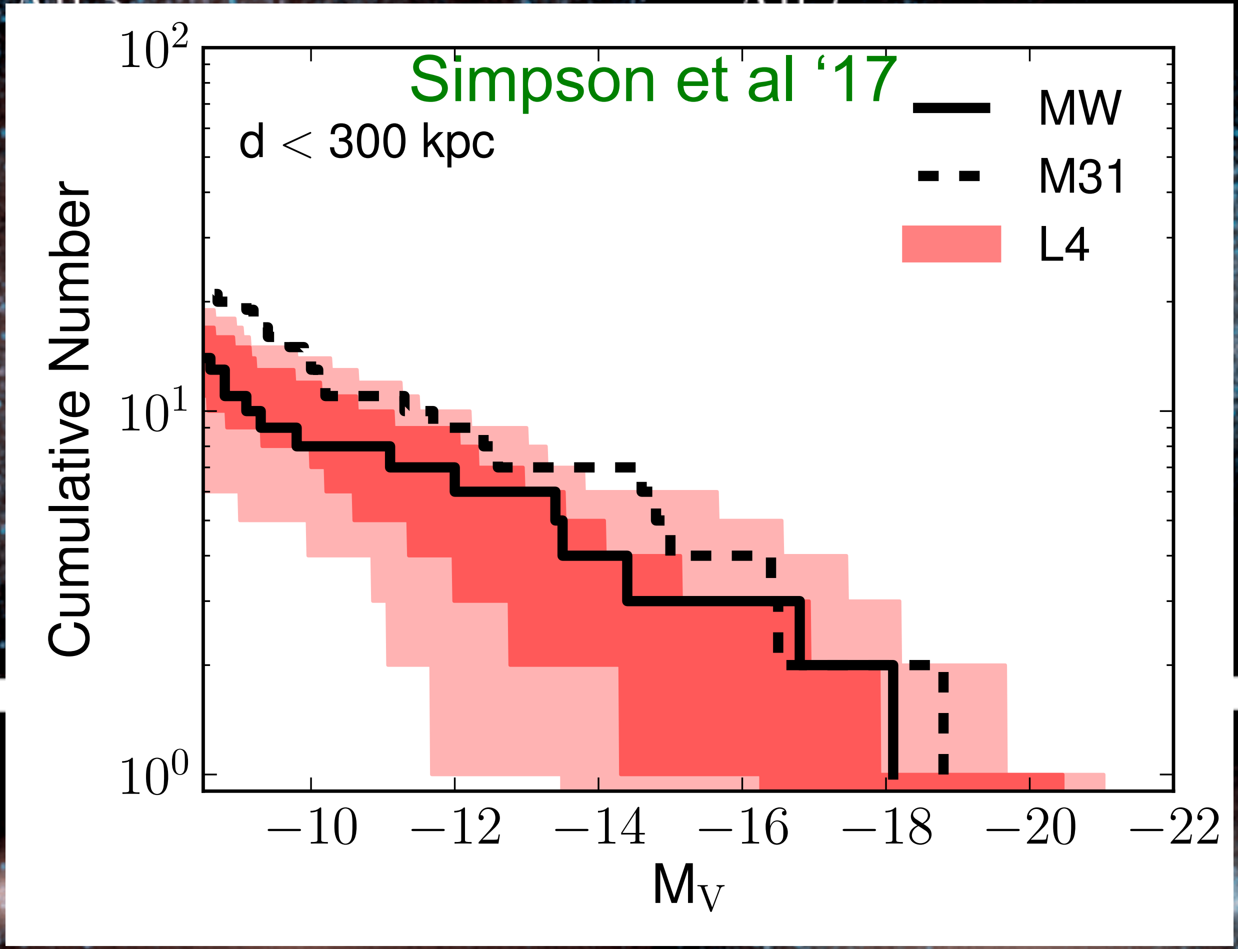
The Auriga MW-like galaxies

Grand et al '16

30 very high res Arepo sims

6 even higher res sims

D. Campbell
C. Frenk
F. Gomez
R. Grand
A. Jenkins
F. Marinacci
R. Pakmor
V. Springel
S. White



When "baryon effects" are taken into account

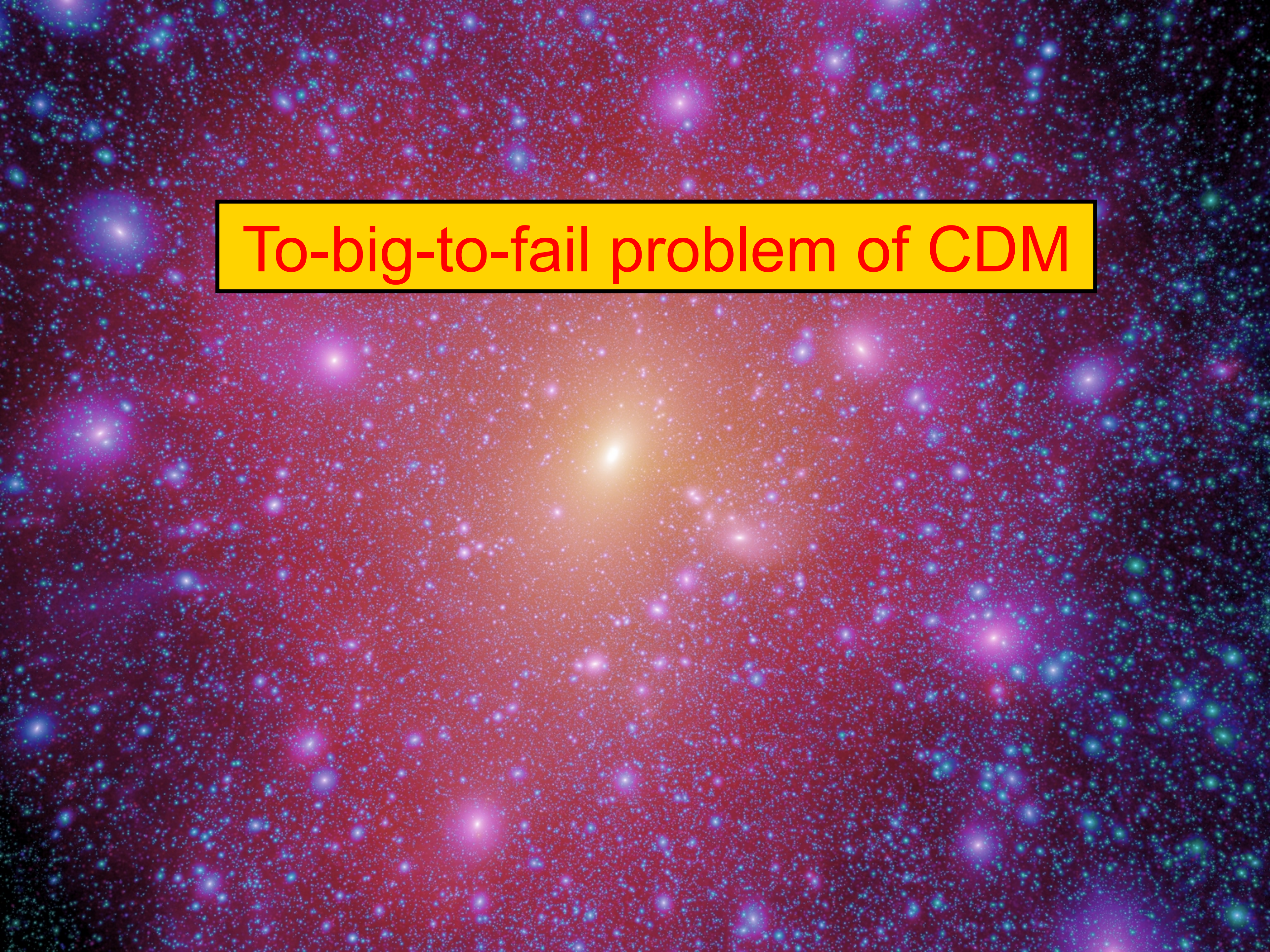
→

Observed abundance of satellites is compatible with CDM

→

There is no such thing as the "satellite problem" in CDM!

To-big-to-fail problem of CDM

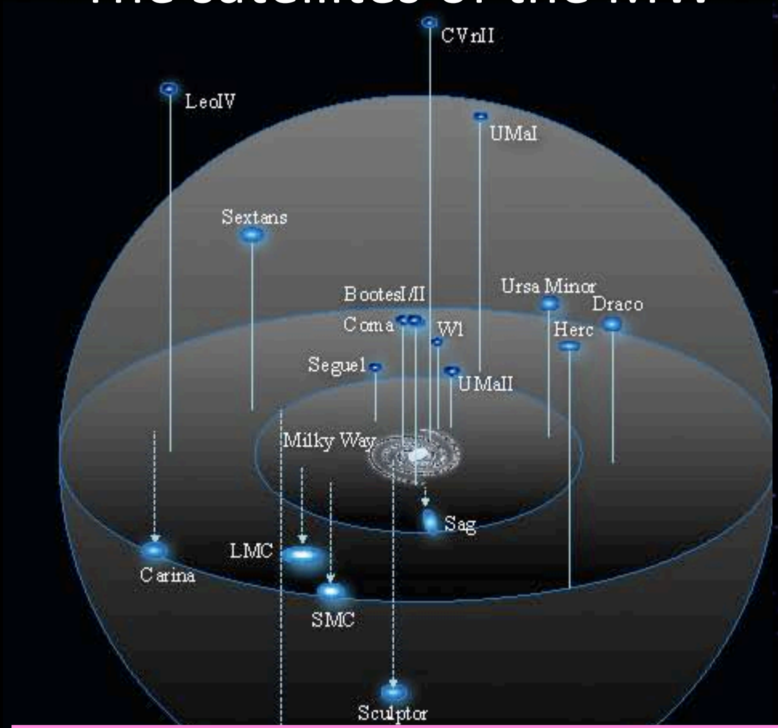


The "too-big-to-fail" problem

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

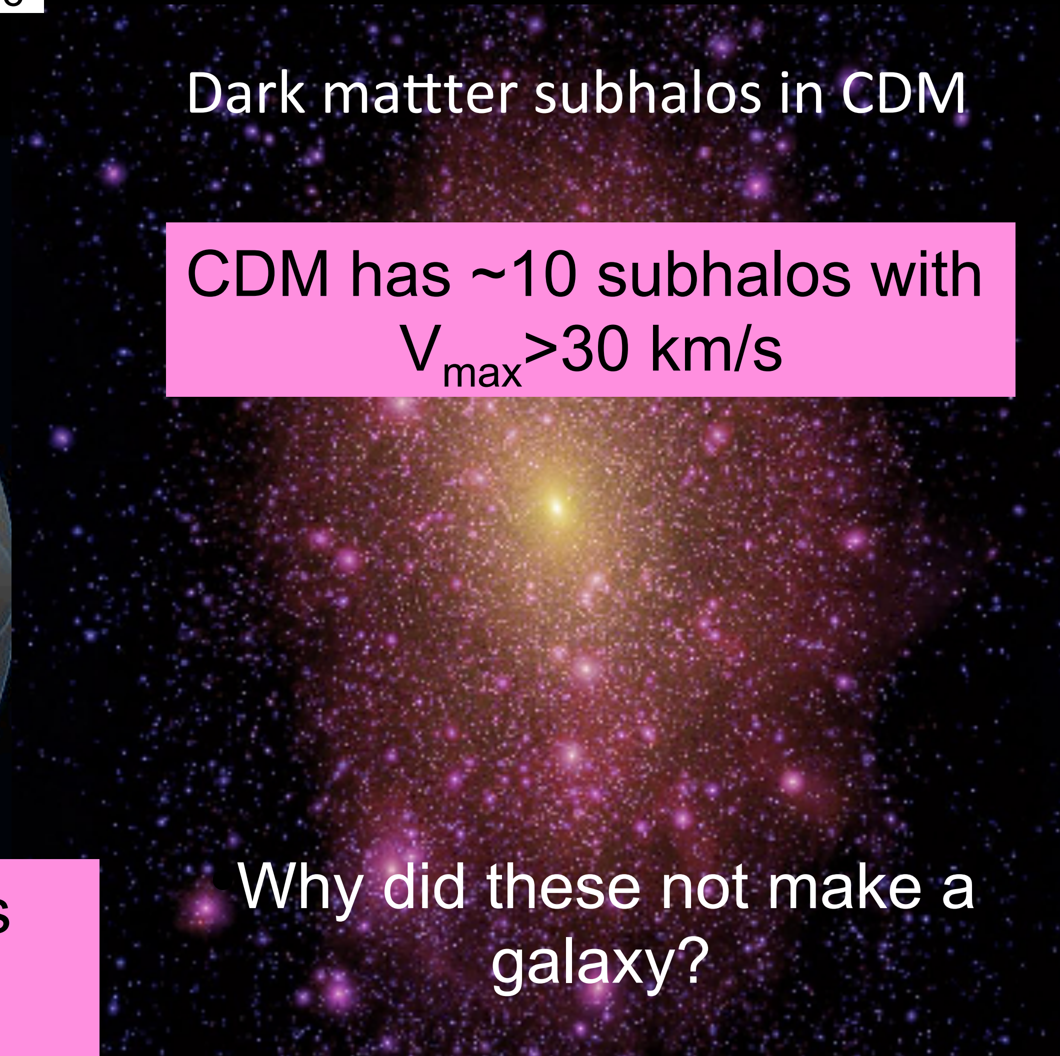
$$V_{max} = \max V_c$$

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?

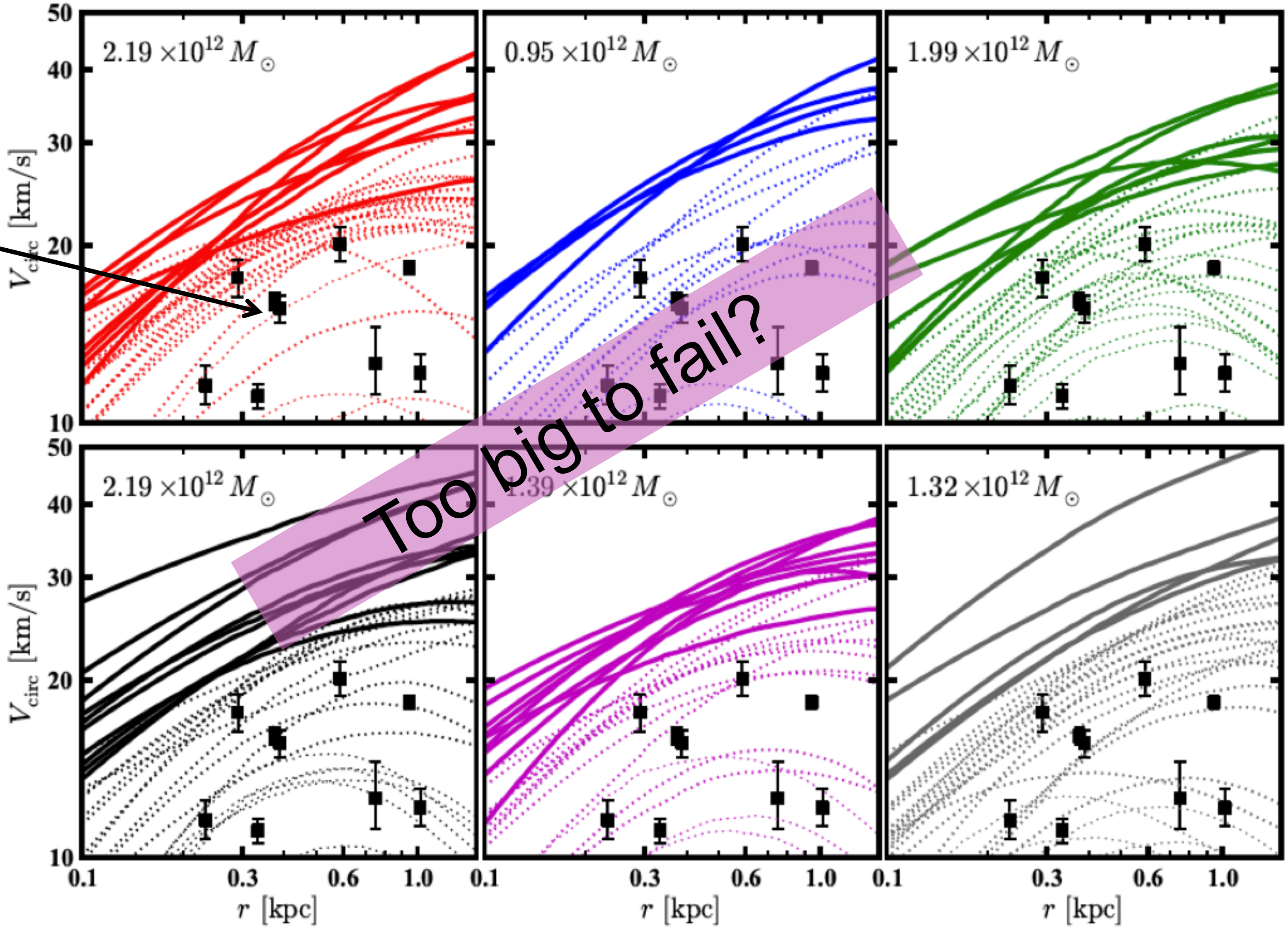
Rotation curves of Aquarius subhalos

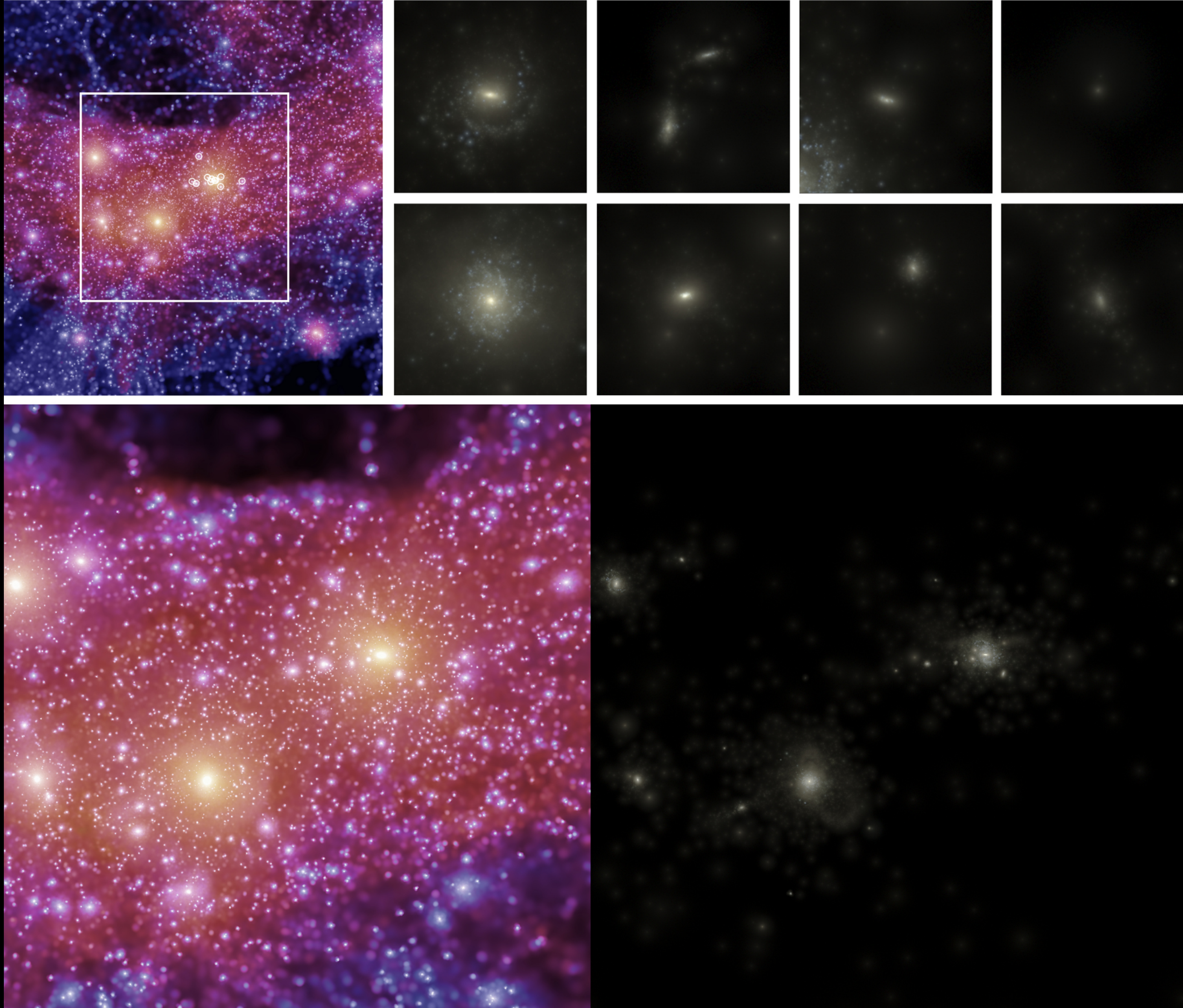
Boylan-Kolchin et al. '11

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

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

Excludes LMC, SMC, Sagittarius





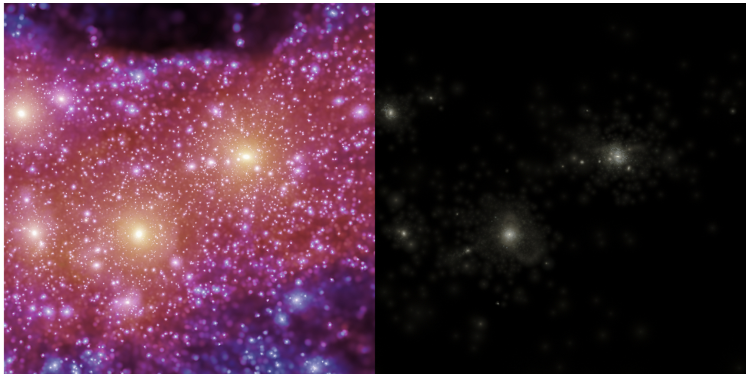
Too-big-to-fail in CDM: baryon effects

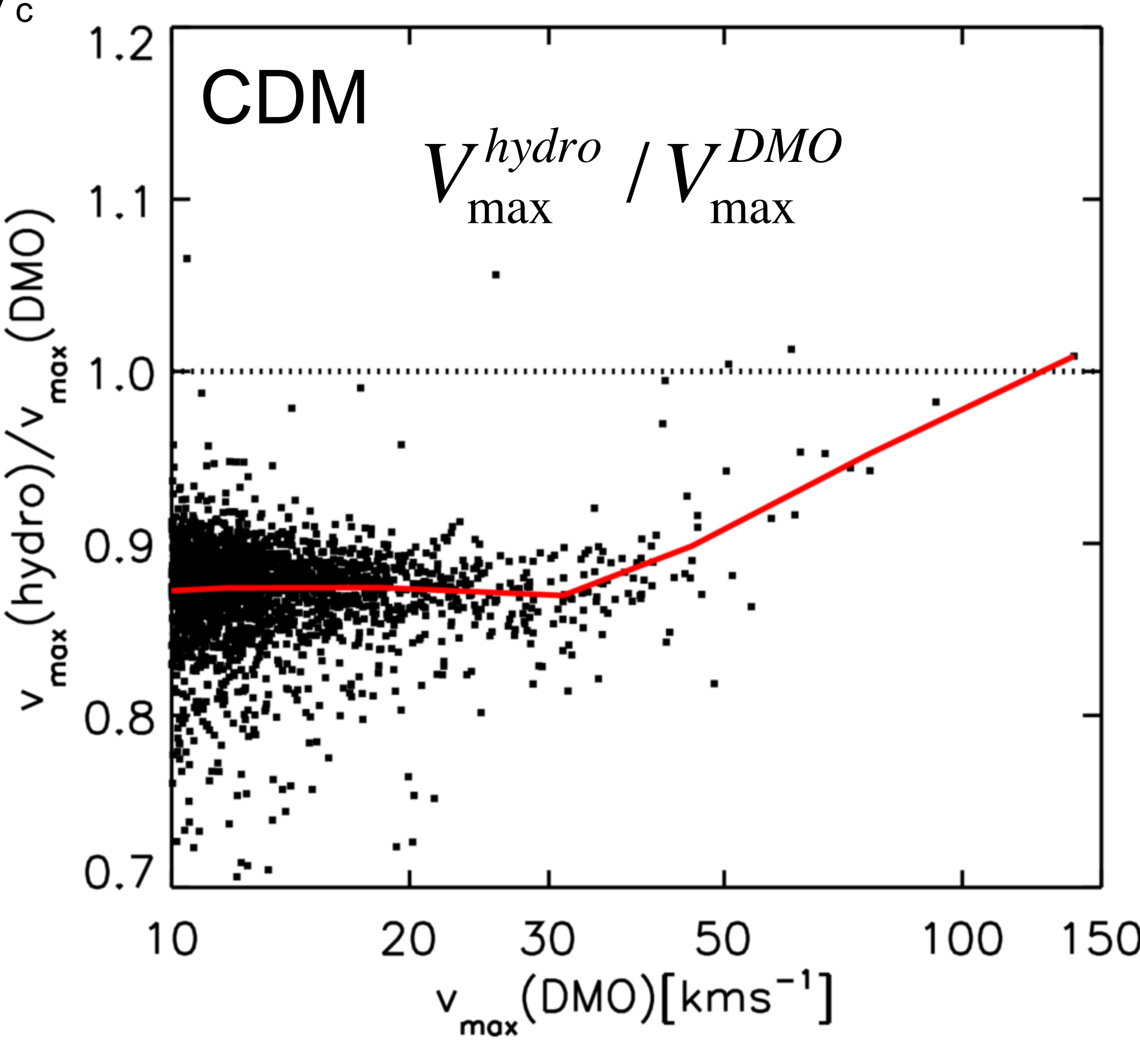
University of Durham

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

Reduction in V_{max} due to SN feedback:

→ Lowers halo mass & thus halo growth rate





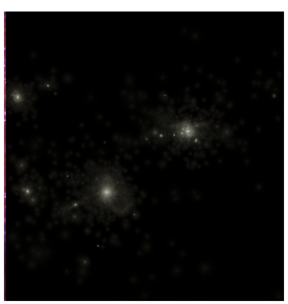
Sawala et al. '13, '15

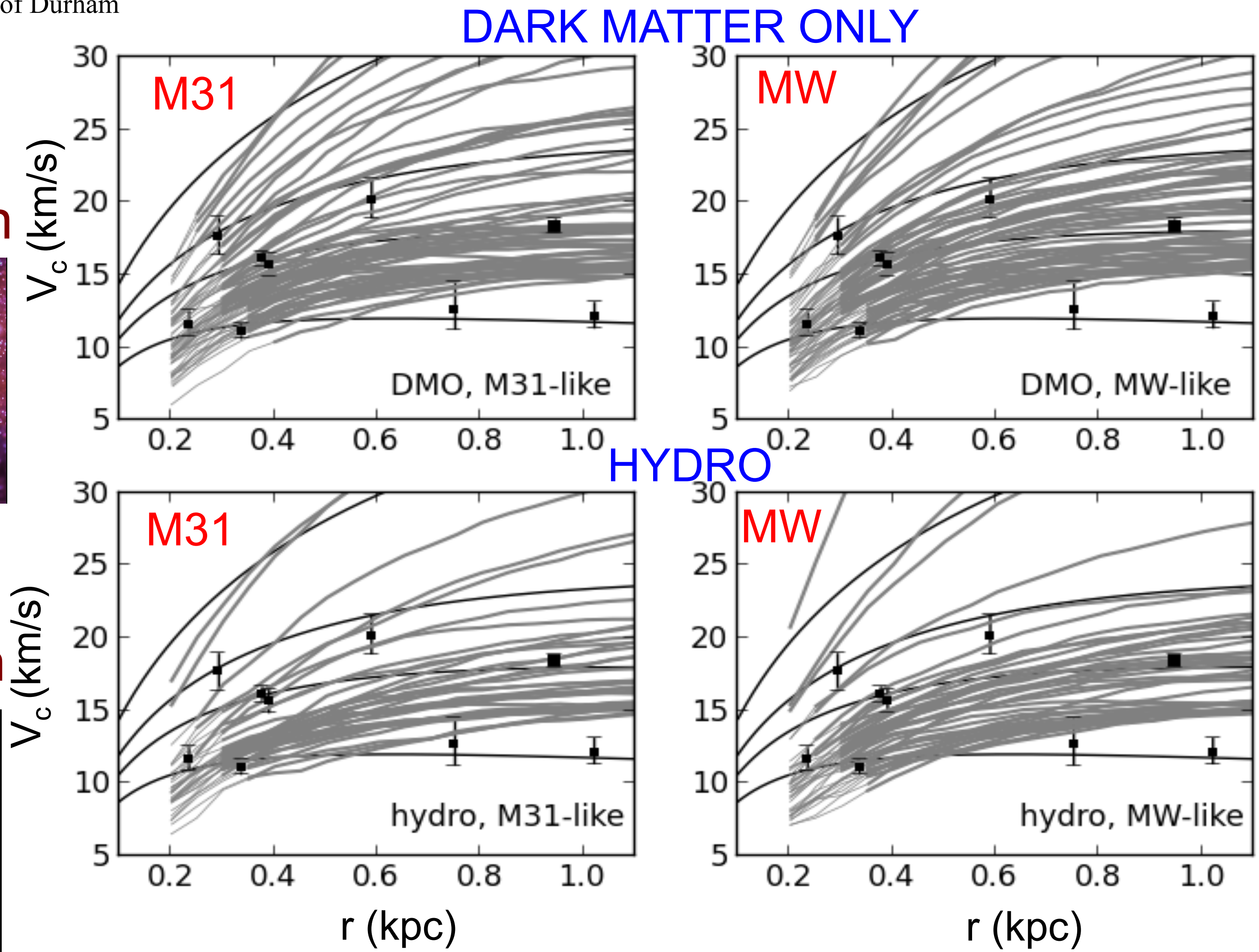
Too-big-to-fail: the baryon bailout

University of Durham

DM-only simulation

Gas simulation





Sawala et al. '15

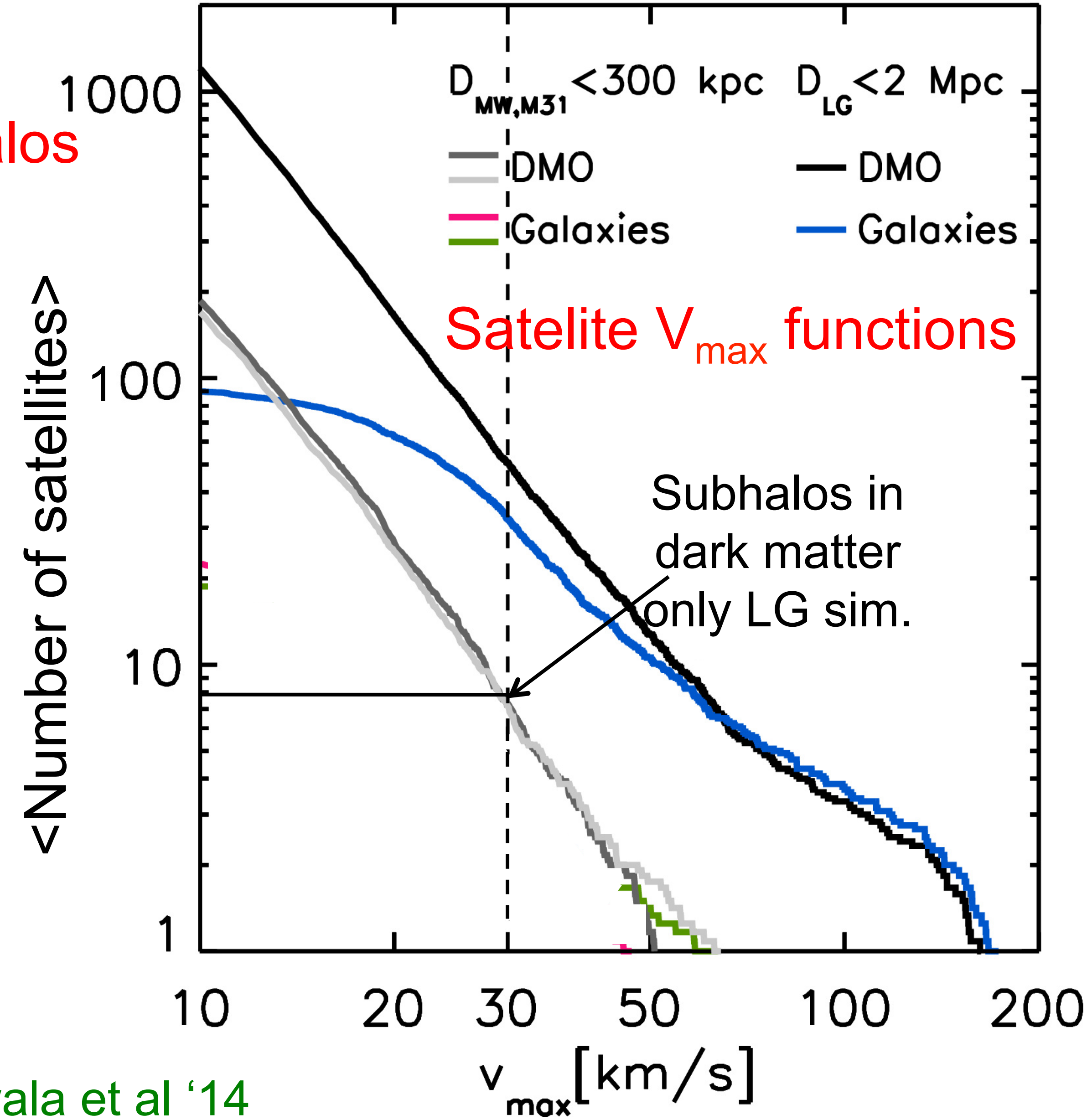
Number of subhalos of given V_{max} is greatly reduced in gas simulations

Institute for Computational Cosmology

Too-big-to-fail: the baryon bailout

University of Durham

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

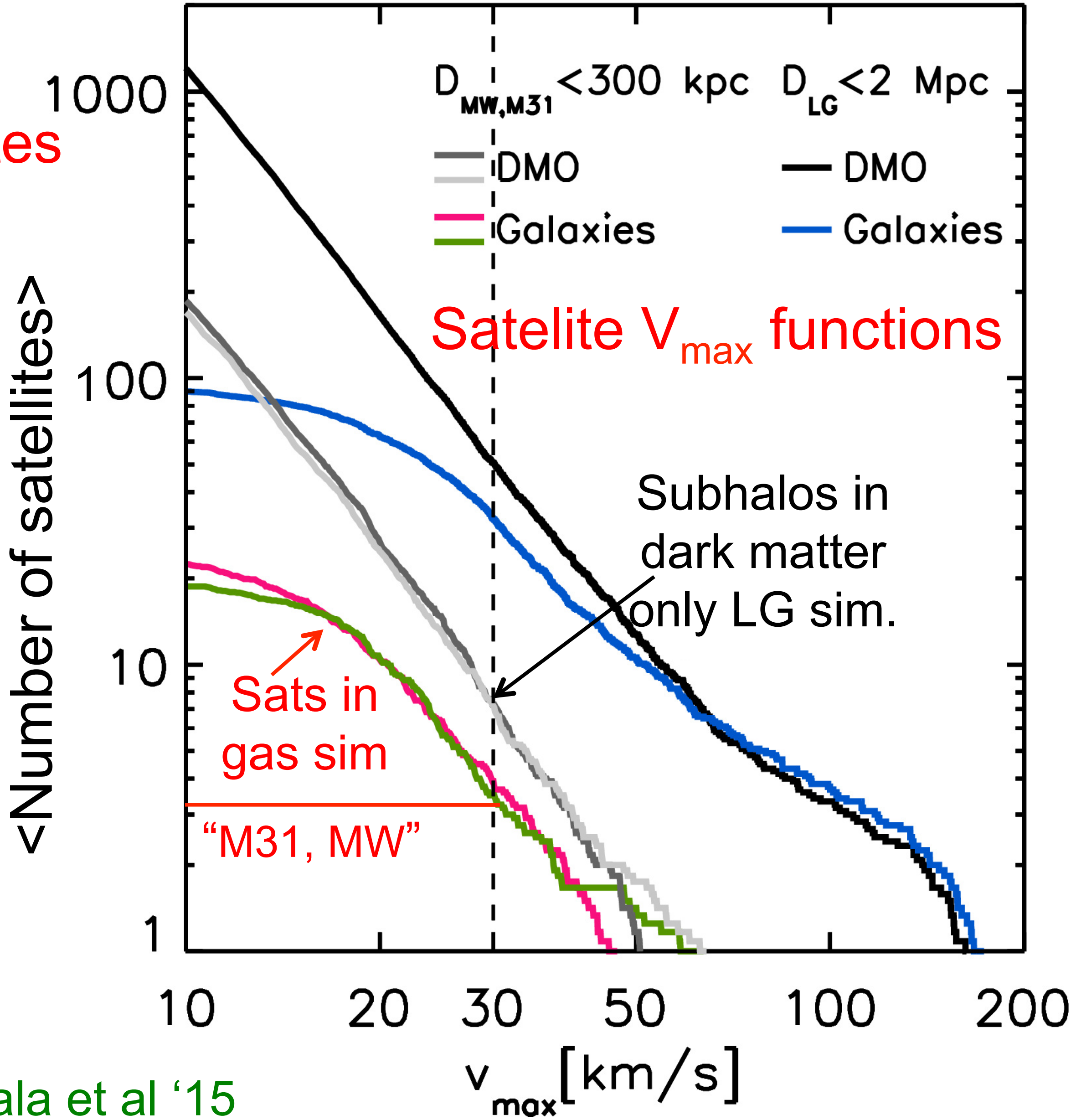


Sawala et al '14

University of Durham

Too-big-to-fail: the baryon bailout

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

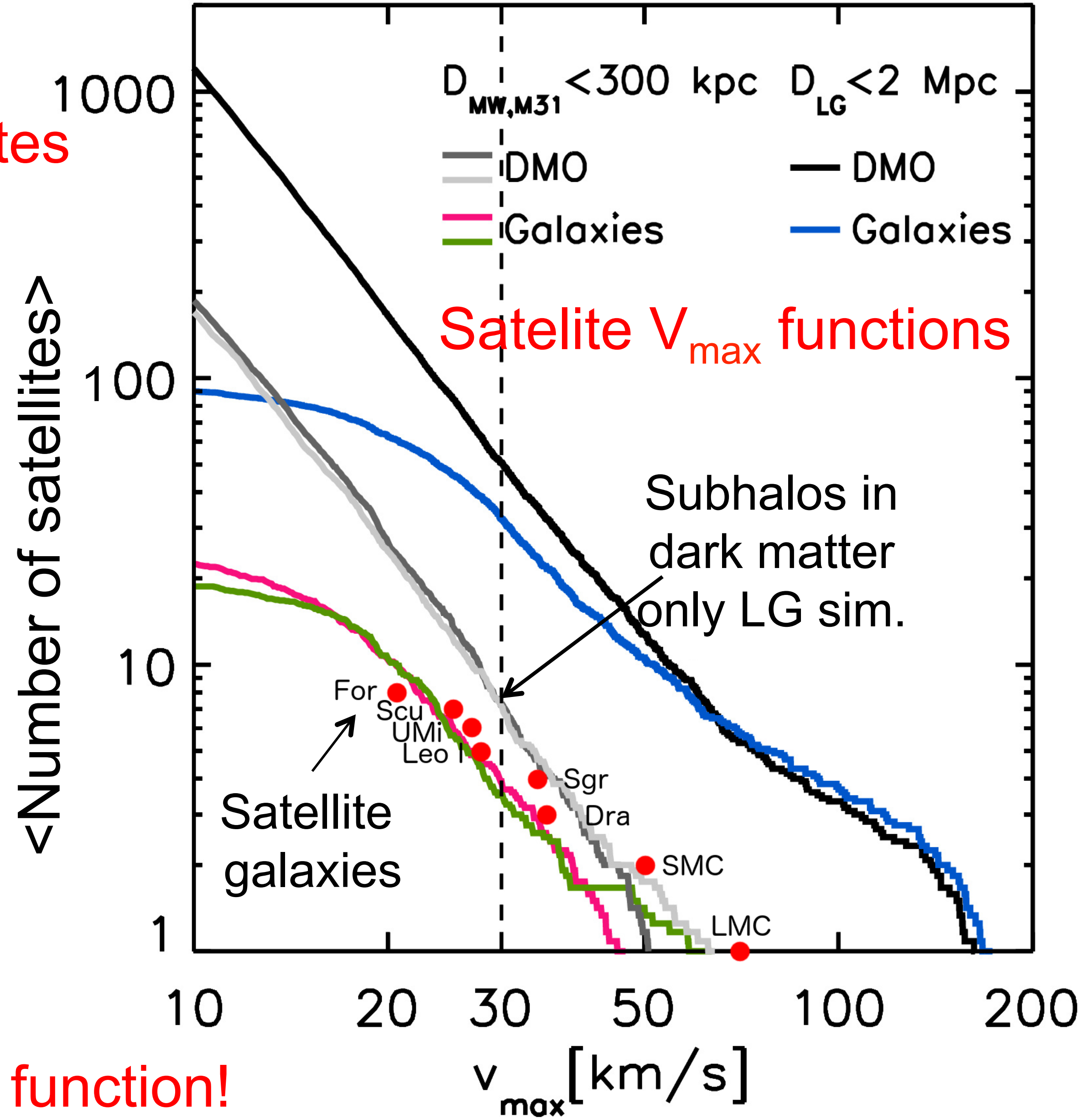


Sawala et al '15

University of Durham

Too-big-to-fail: the baryon bailout

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



… and with correct V_{max} function!

No too-big-to-fail problem in CDM

→

When “baryon effects” are included

Conclusions

1. The first galaxies

- Dwarf galaxies are important diagnostics for cosmology
- Have detected 2 populations of satellites in the Milky Way:

  (i) the "first galaxies" that formed before reionization ($M_* < 10^5\ M_0$)

  (ii) a brighter population that formed after reionization ($M_* > 10^5\ M_0$
- These populations were predicted by existing GALFORM model

2. The MW satellites in ΛCDM

When baryon effects are taken into account

- NO "satellite problem" in CDM (reionization + SN feedback)
- NO "too-big-to-fail problem in CDM (early ejection of gas)