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# Dwarfs: the giants of cosmology

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## Conference key questions

- Is ΛCDM correct? What can dwarf galaxies tell us about the identity of dark matter?
- Can we identify signatures of reionization in the dwarf population? What role did dwarfs play in reionization?
- What do the star formation histories and chemical properties of dwarfs tell us about galaxy formation?
- How will the next generation of surveys and simulations answer the above questions?

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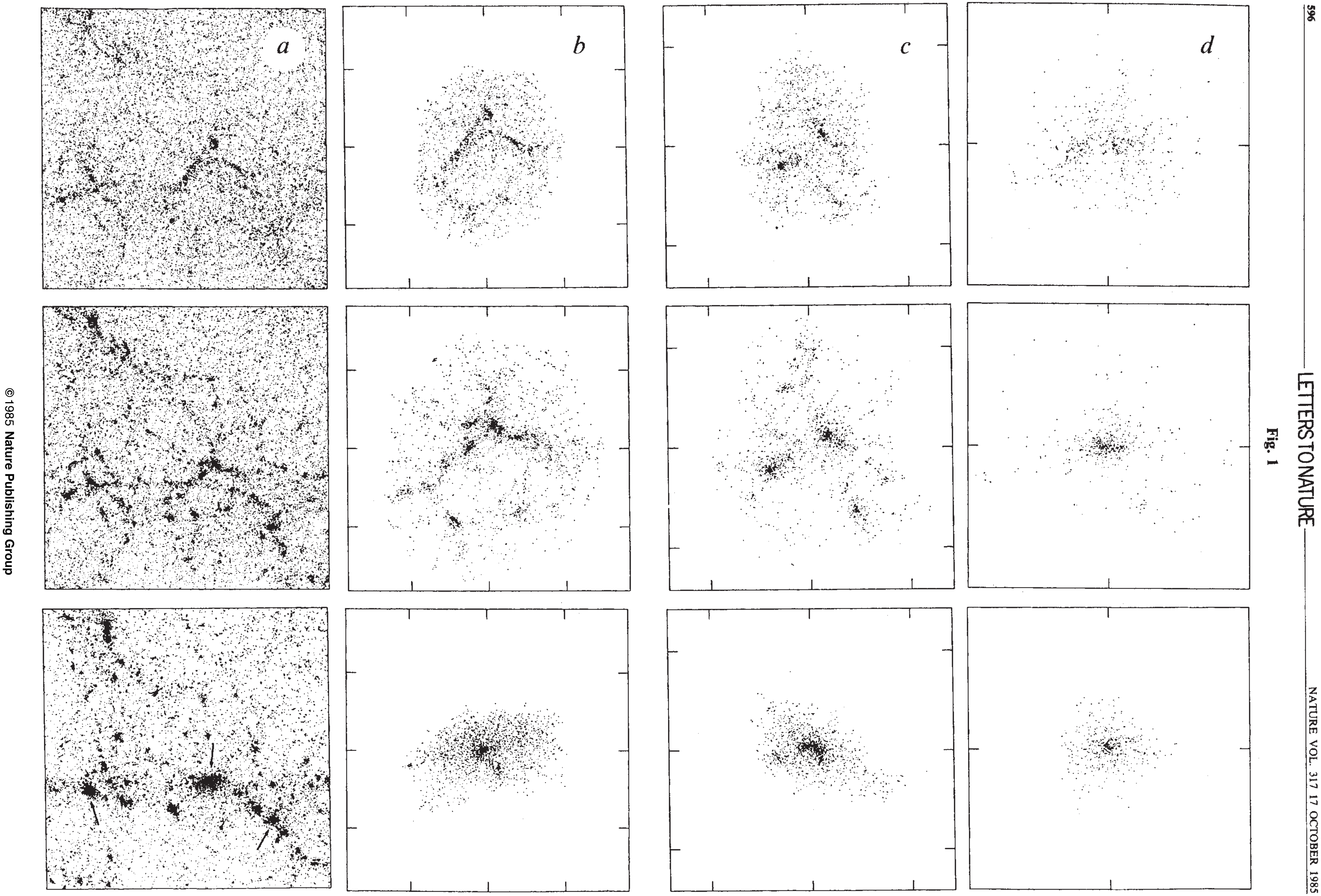
# Is ΛCDM incorrect?

## The four “problems” of CDM

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

Solved before they became a “problem” for CDM

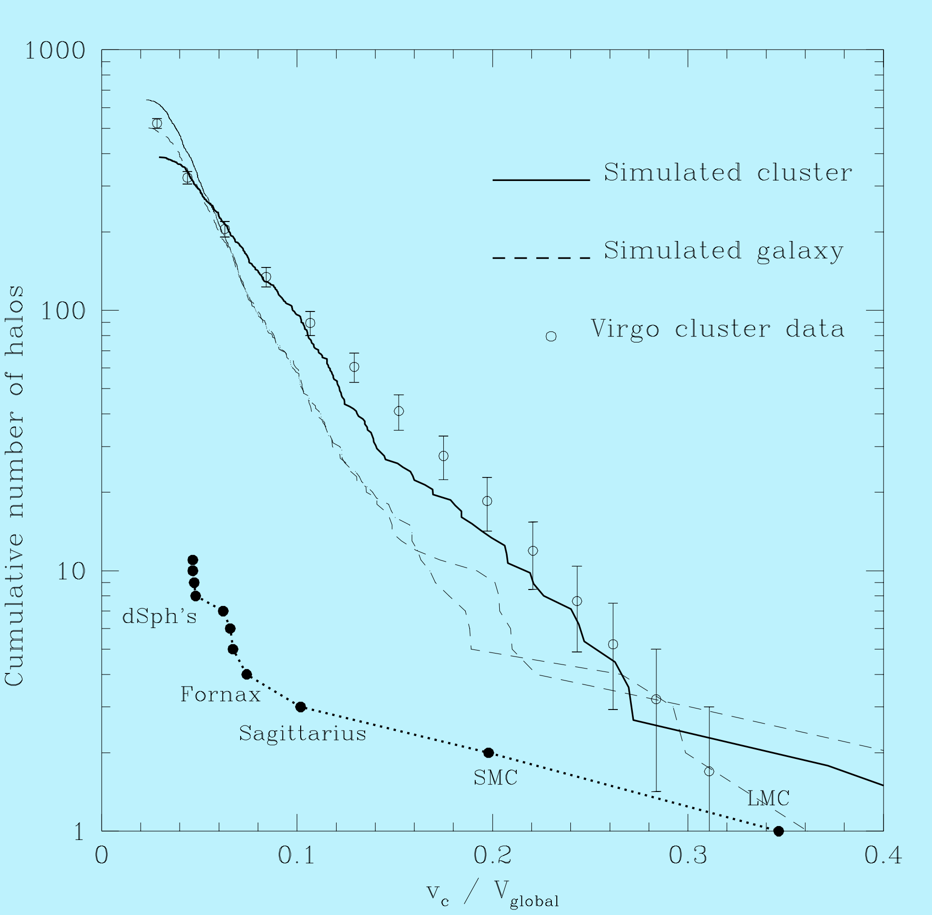
# Formation of CDM halos




Frenk et al 1985

# Moore et al ‘99

## See also Klypin et al ’99

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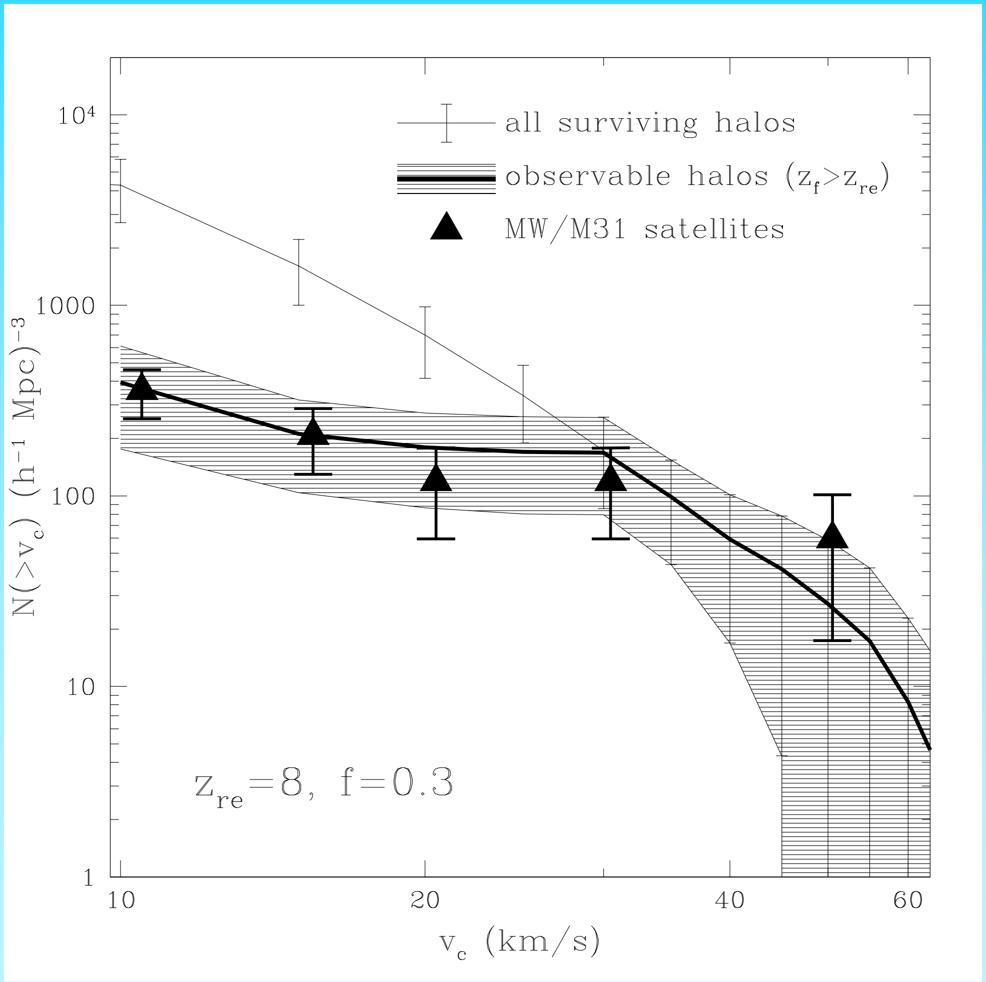
Bullock, Kravtsov, Weinberg '00

# Include simple model of reionization



# Luminosity Function of Local Group Satellites

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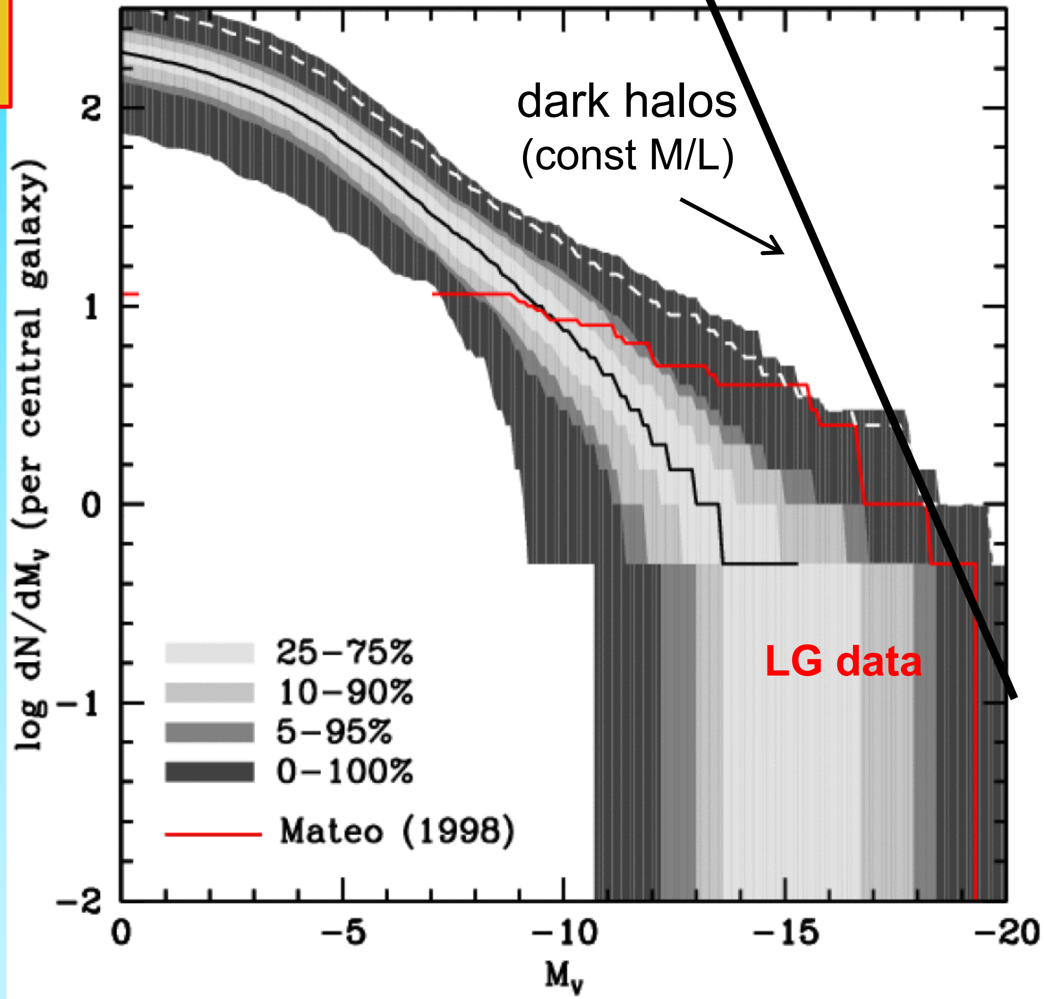
**Include effects of reionization and SN feedback**

- 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 (~10% of cases)




Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman+ ’93, Bullock+ ’00, Somerville ‘02)

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.

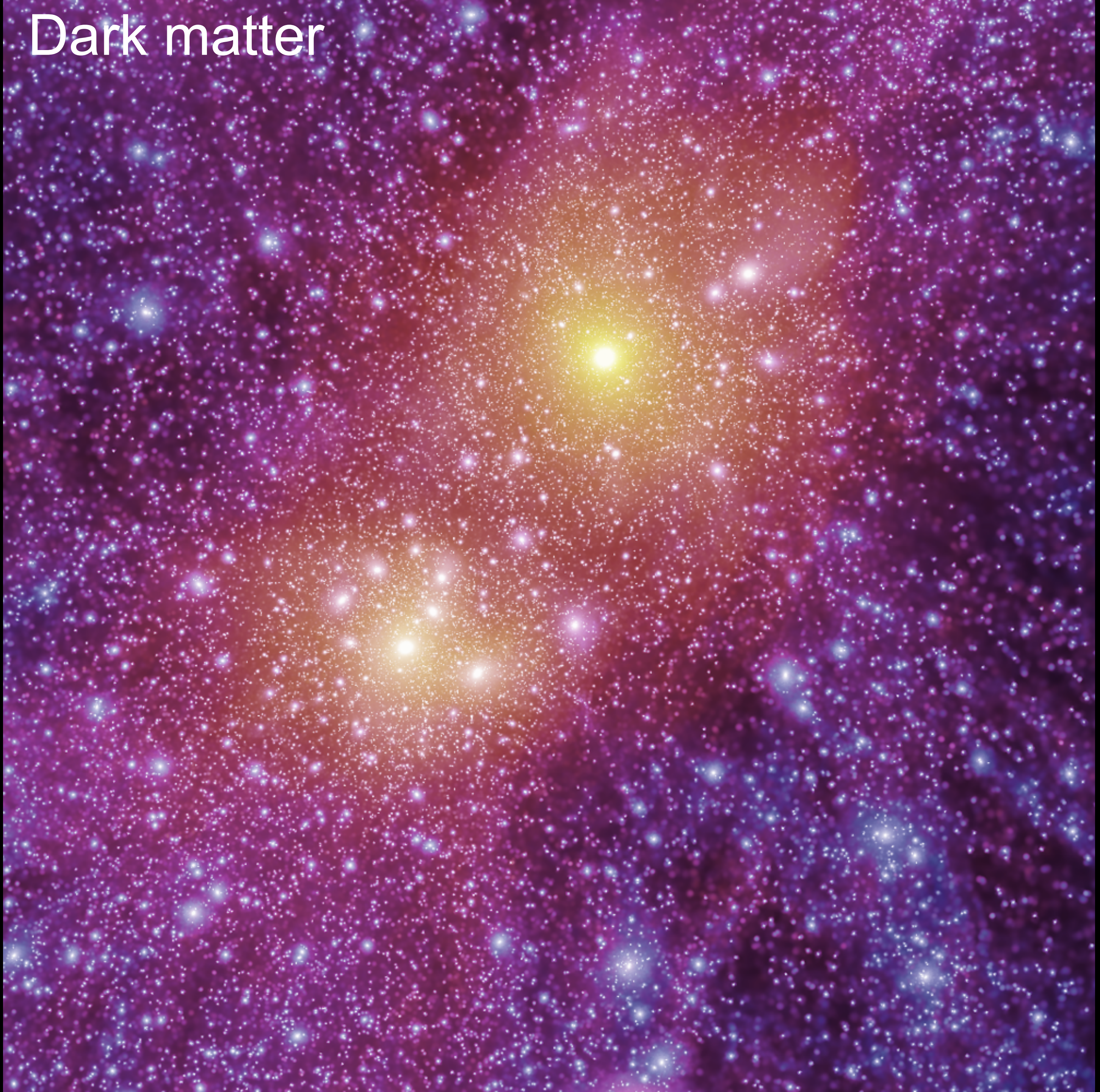
VIRGO

APOSTLE EAGLE full hydro simulations

Local Group

CDM

Sawala, CSF et al ‘16

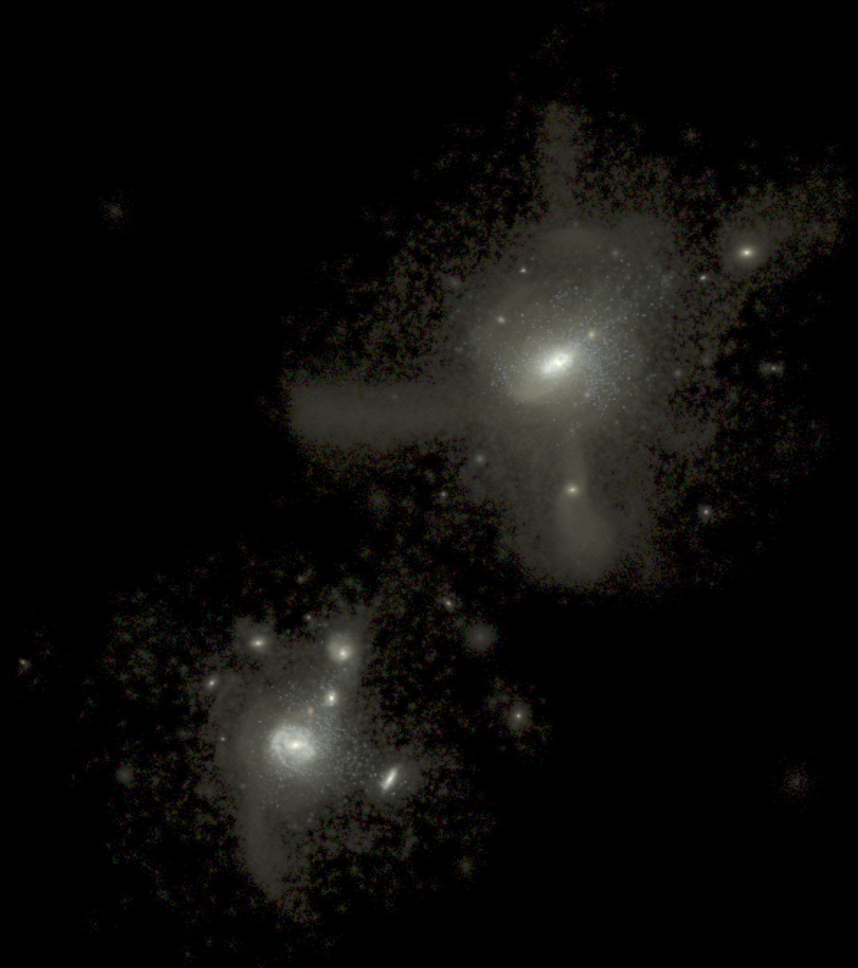


# Stars

APOSTLE EAGLE full hydro simulations

Local Group

Stars

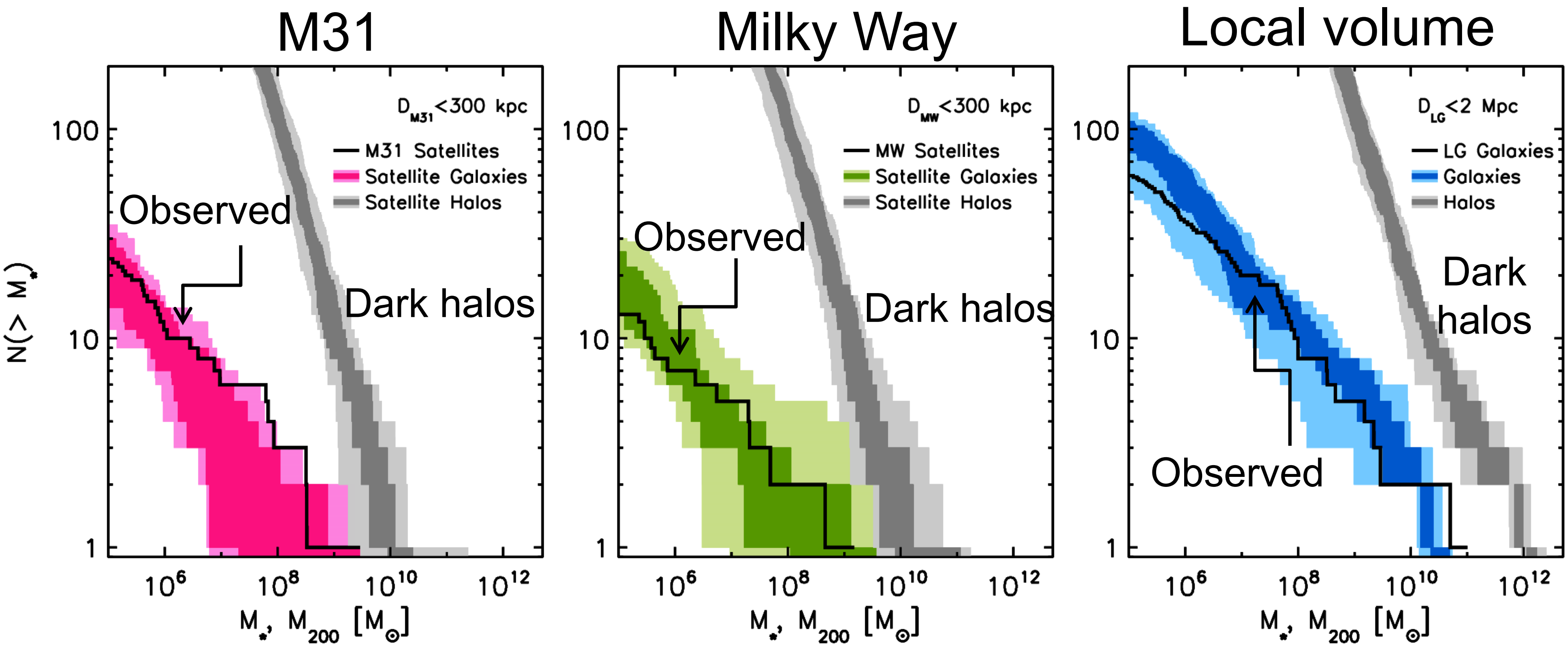


Far fewer satellite galaxies than CDM halos

Sawala, CSF et al '16

University of Durham

# EAGLE Local Group simulation




Sawala, CSF et al '16

# EAGLE Local Group simulation

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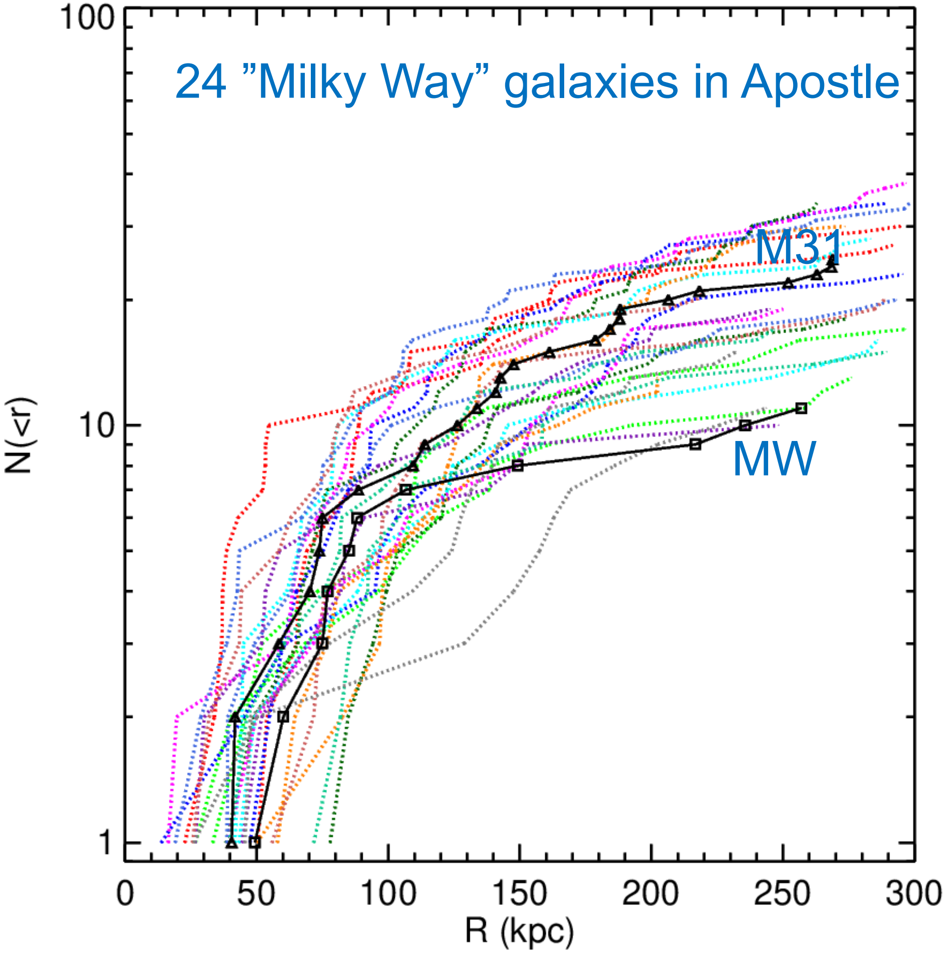
## … and the radial distribution

The radial distribution of the bright ($M>10^5 M_o$) is a ~10% outlier

(see A. Wetzler's talk)




Lovell et al '17, Fattahi et al '19

# Luminosity Function of Local Group Satellites

Include effects of reionization and SN feedback

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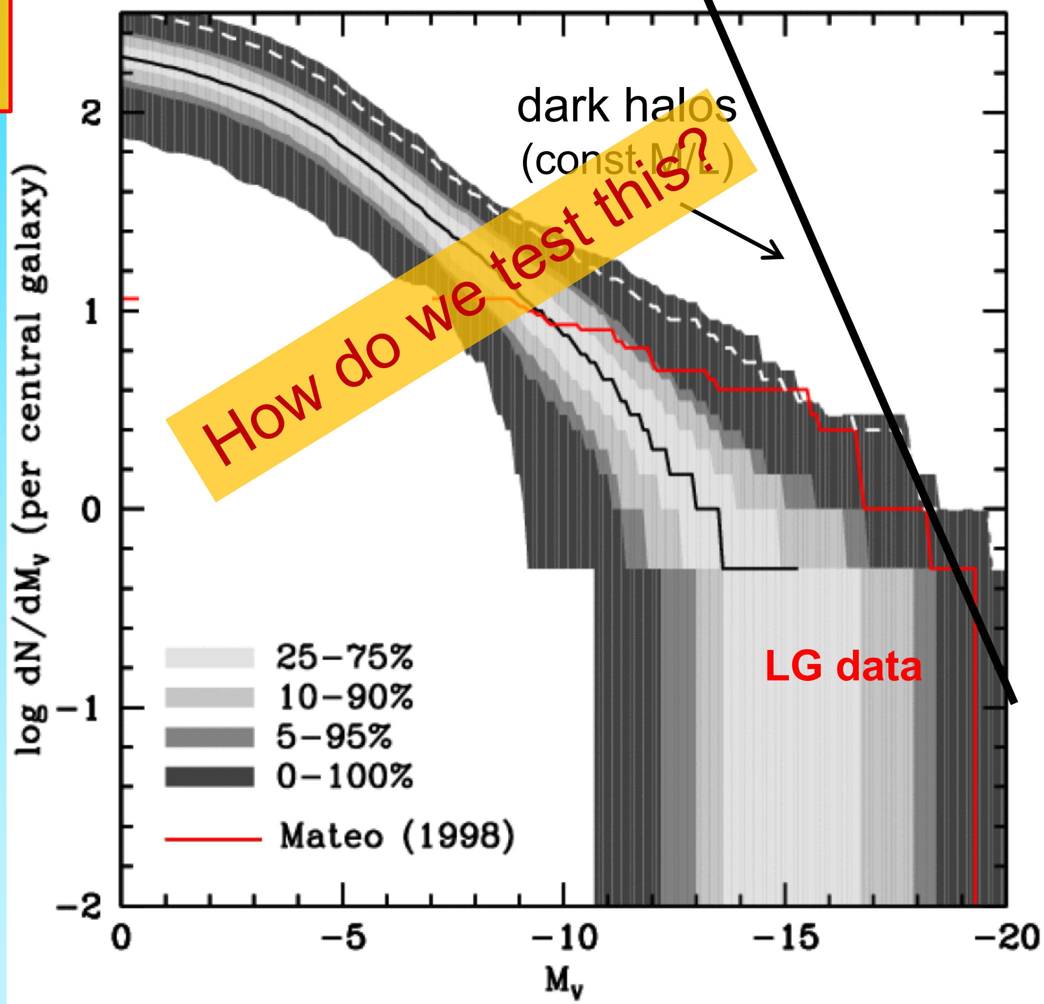


Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman+ ’93, Bullock+ ’00, Somerville ‘02)

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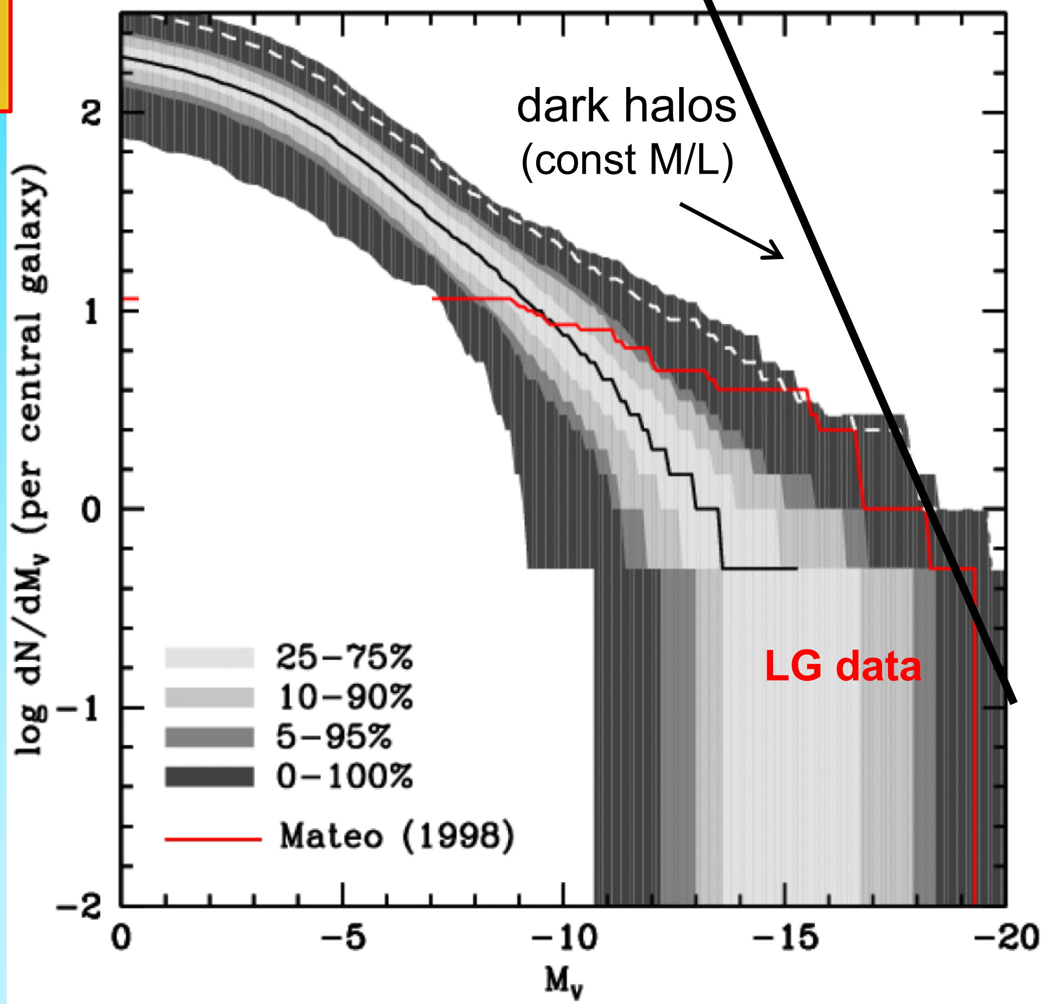


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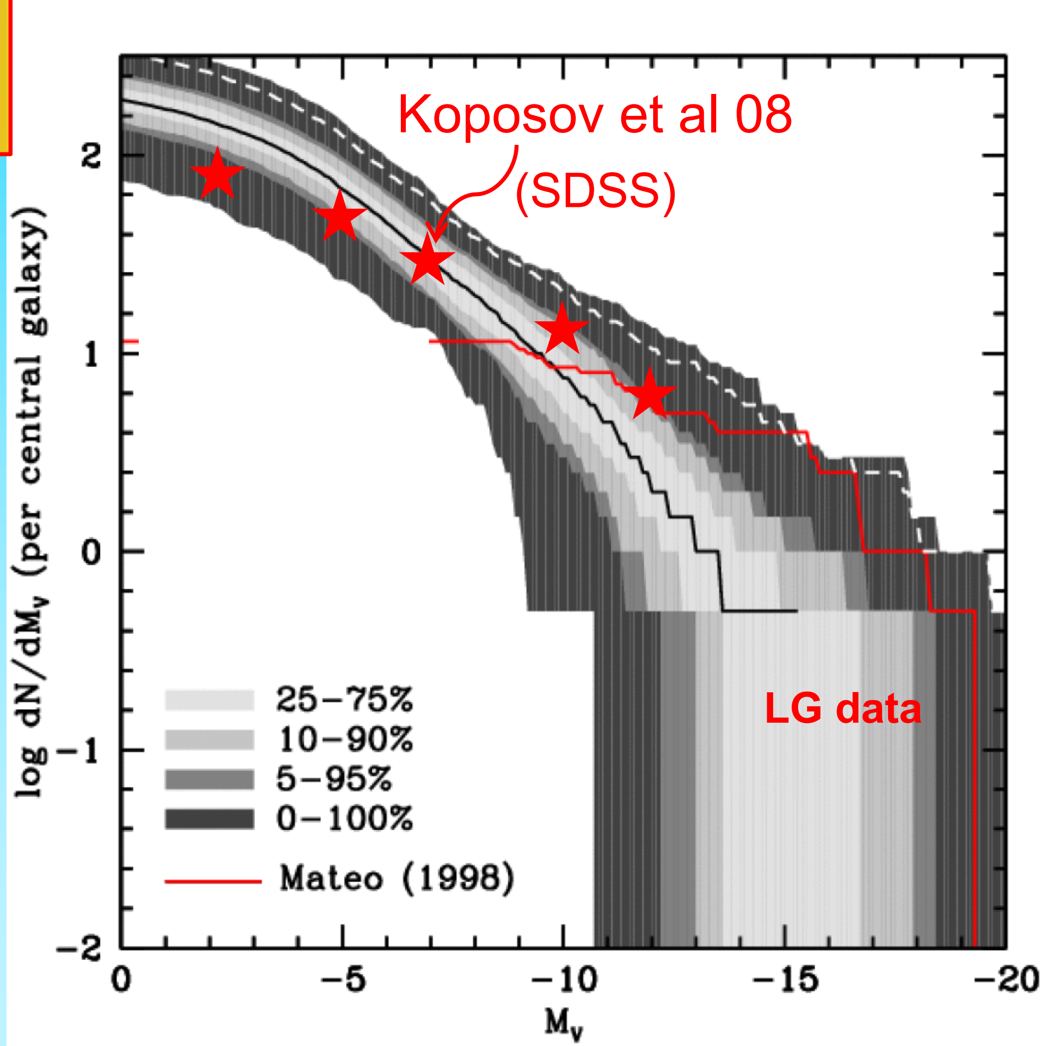


Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman+ ’93, Bullock+ ’00, Somerville ‘02)

# The MW satellite luminosity function

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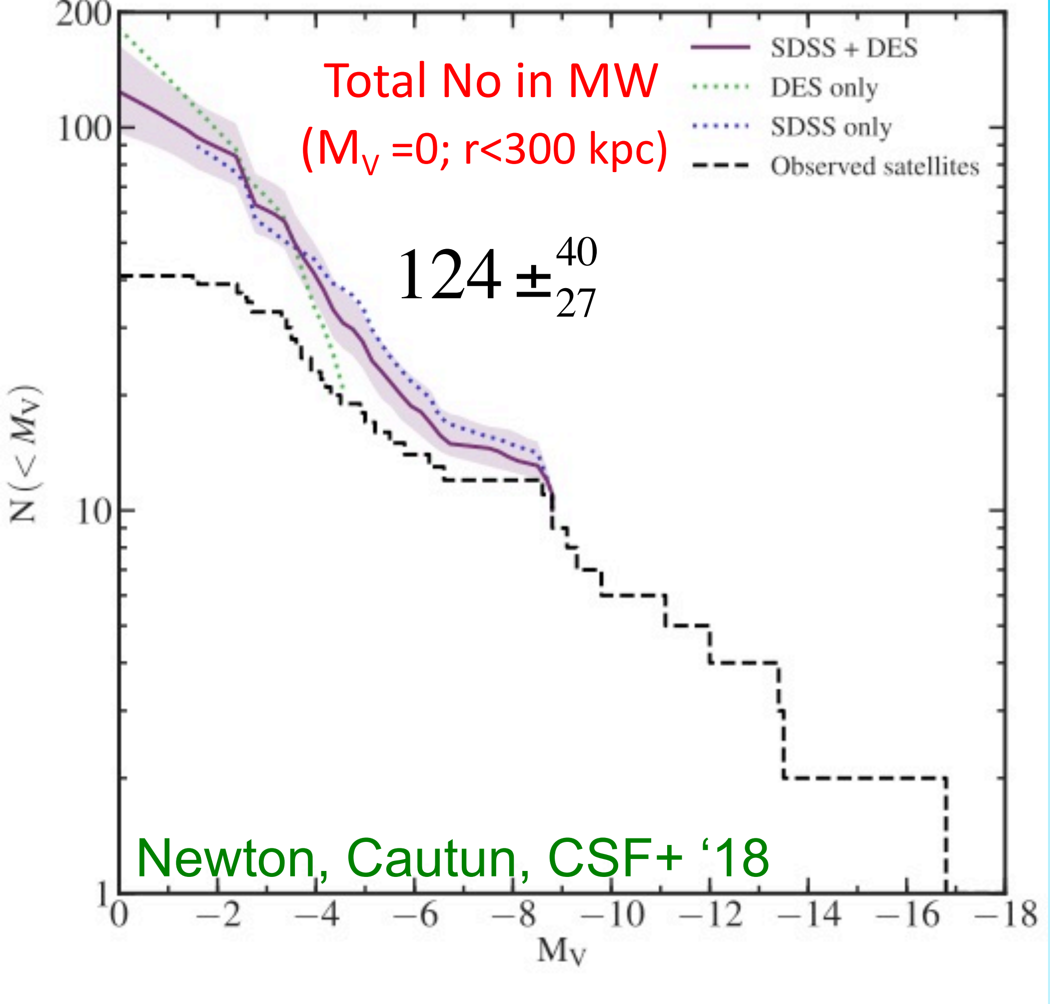
About 55 satellites known in the MW so far from partial surveys (e.g. SDSS, Pan-STARRS, DES)

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

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

Cumulative satellite lum. fn.



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# The MW satellite luminosity function

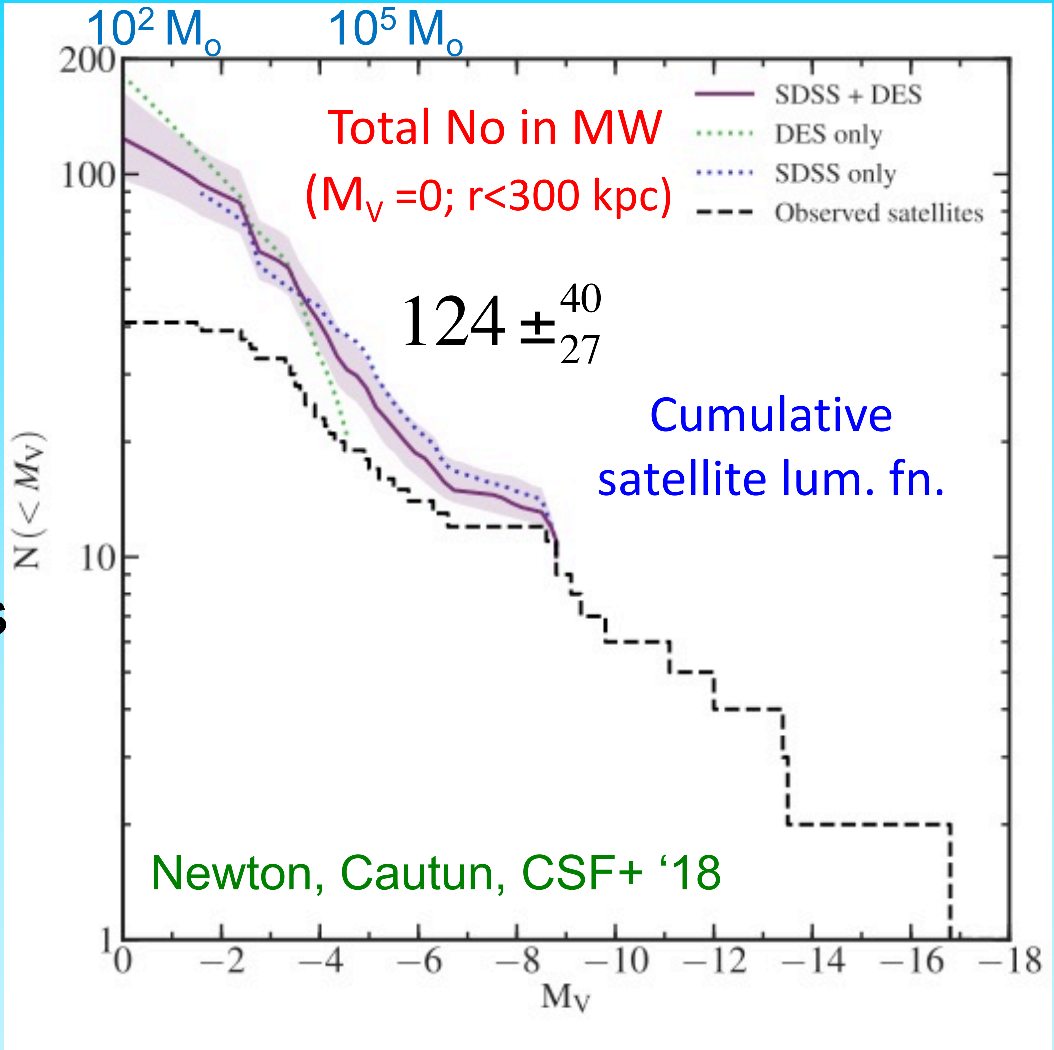
In the highest-resolution hydro galaxy simulations (Auriga, Apostle, Fire), the star particle mass is ~$10^4$ $M_o$

➡

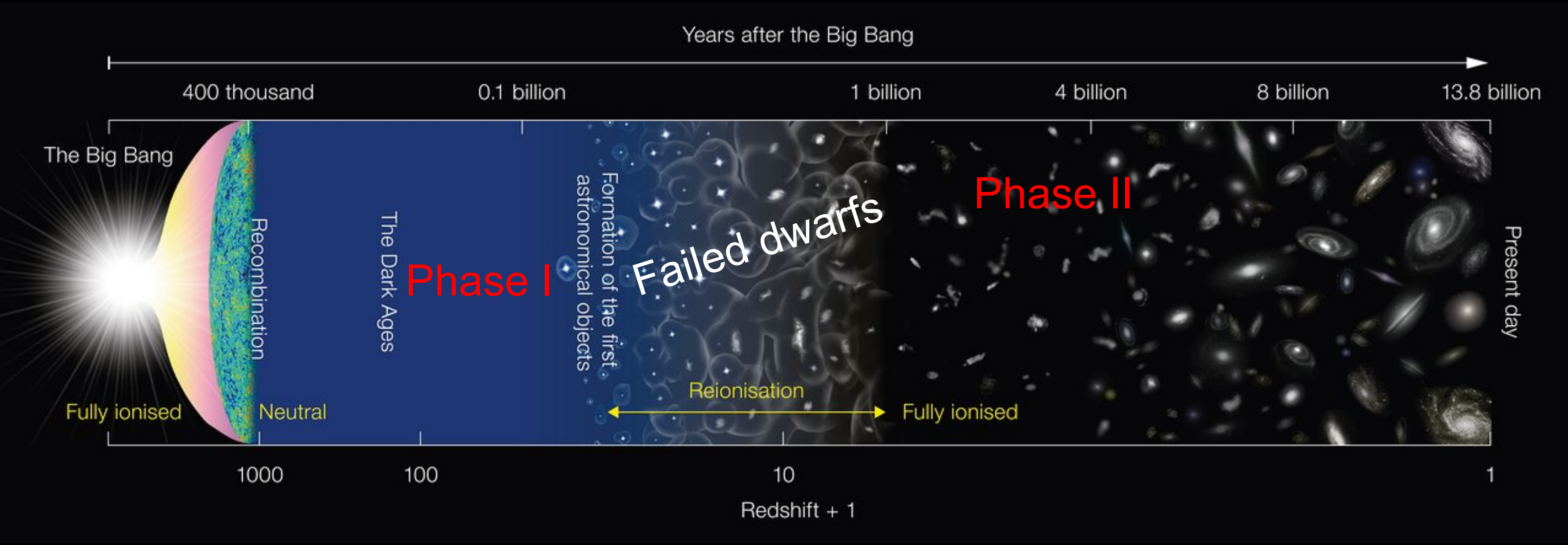
Can't study ultra-faint satellites with current hydro simulations

➡

But we can use semi-analytic modelling (GALFORM)



# The two phases of galaxy formation




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

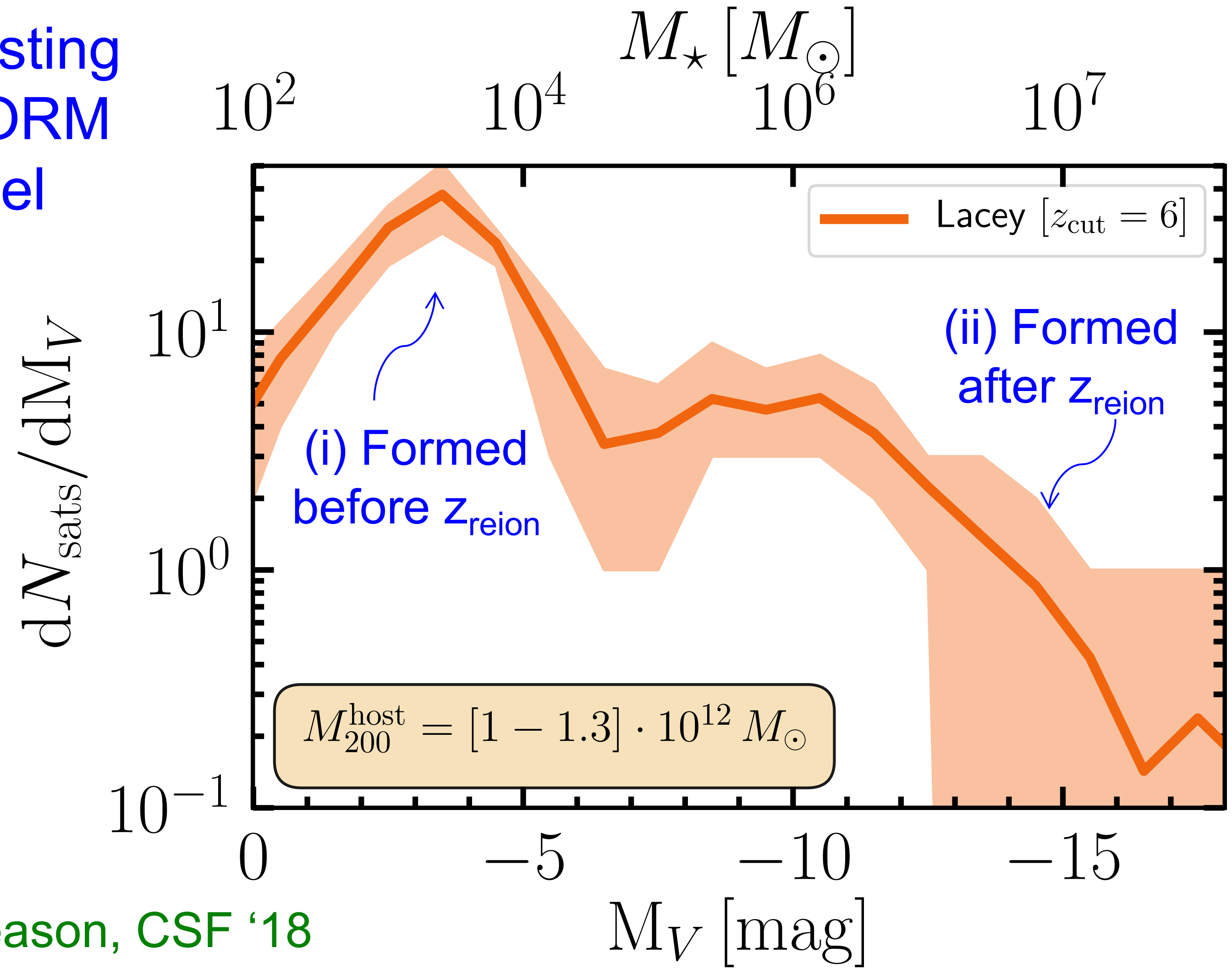
First stars reionize H and heat it up to $10^4$K → prevents gas from cooling in halos of "$T_{vir}$" < $10^4$K – galaxy formation is interrupted

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

# The satellite luminosity function

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

Pre-existing GALFORM model




Bose, Deason, CSF '18

# The MW satellite luminosity function

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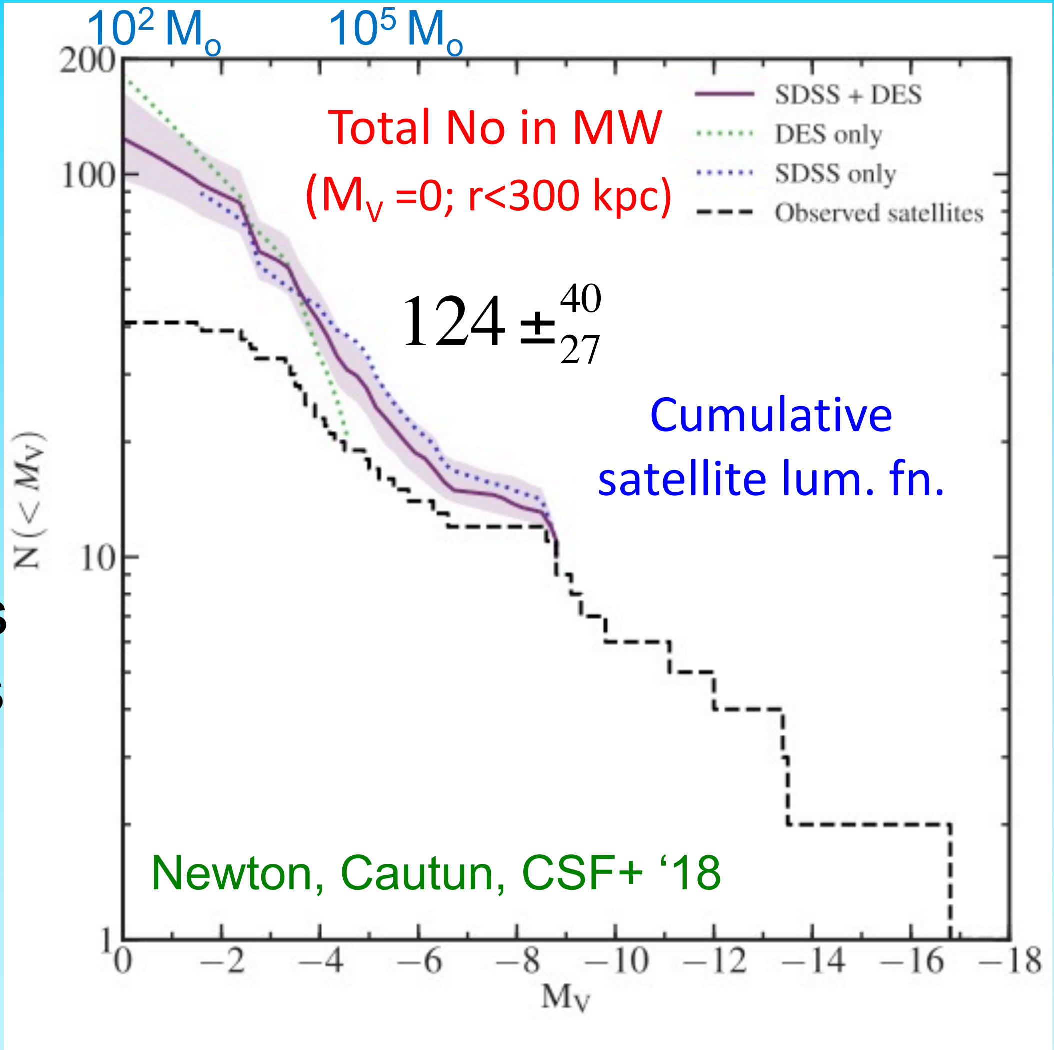

# The MW/M31 sat. luminosity function

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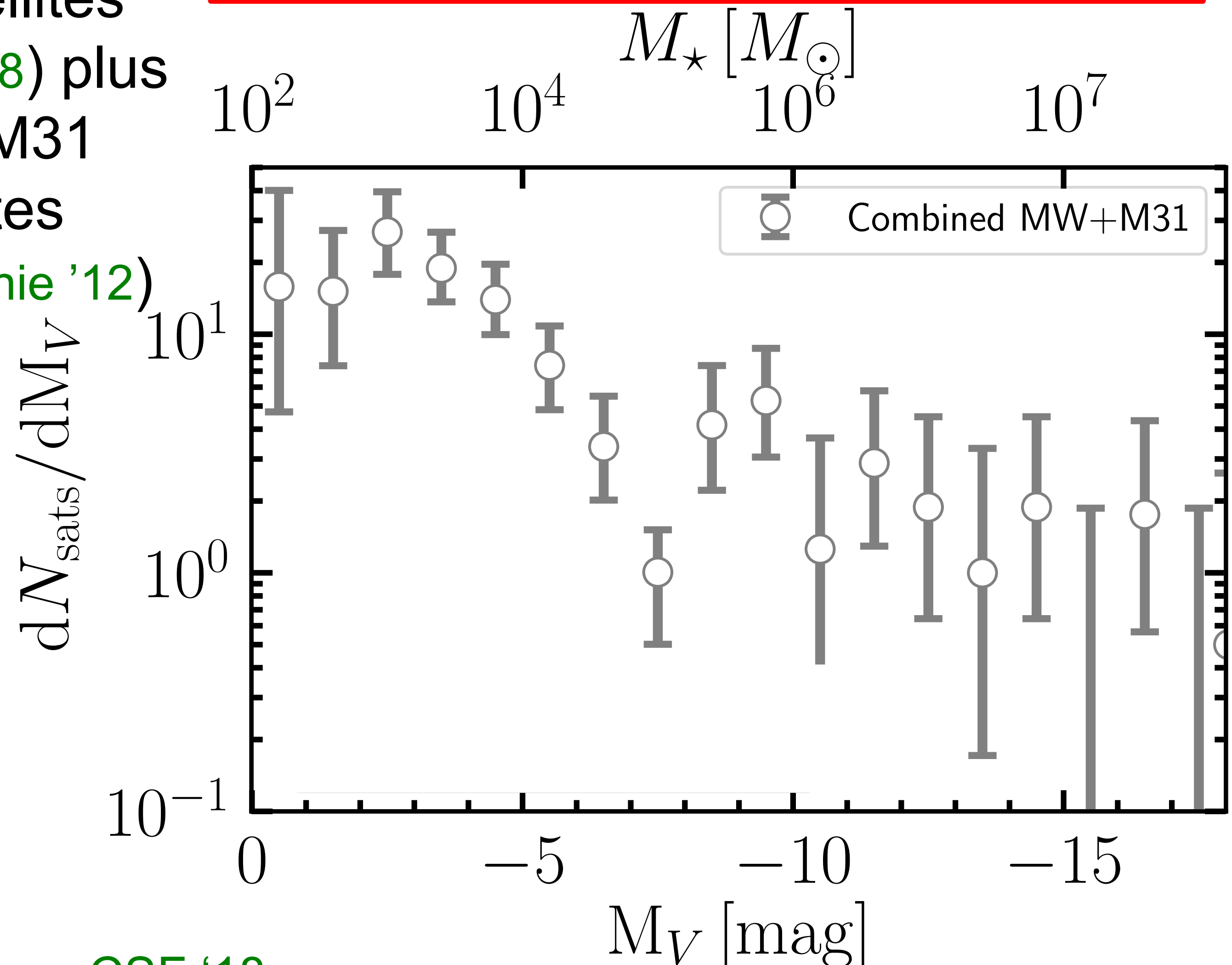
Differential satellite luminosity function

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




Bose, Deason, CSF '18

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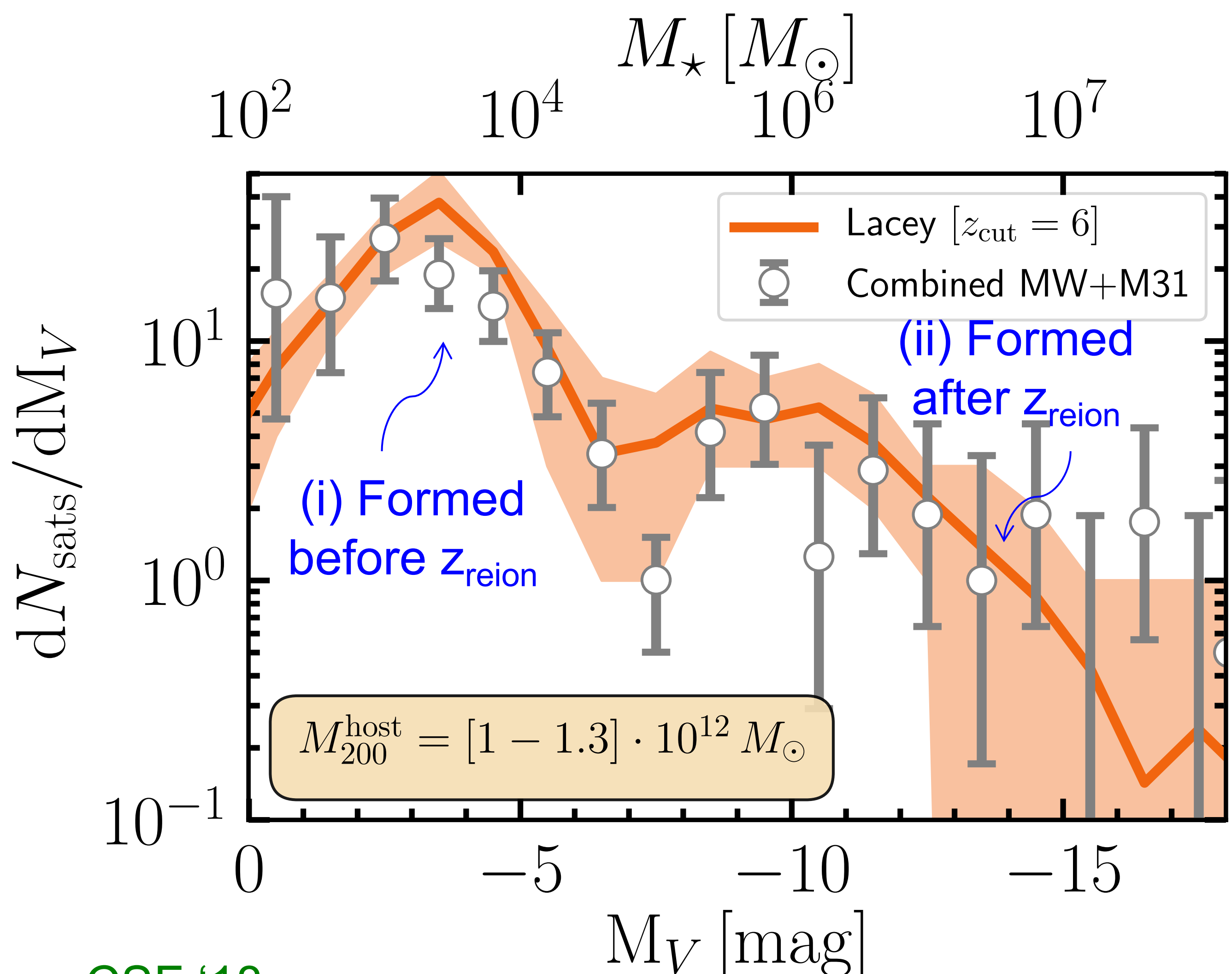
University of Durham

# Theory *vs* data: test of CDM prediction




Bose, Deason, CSF '18

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When galaxy formation is taken into account

→

CDM predicts the observed abundance of satellites

→

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

# The "small-scale crisis" of CDM

## The four "problems" of CDM

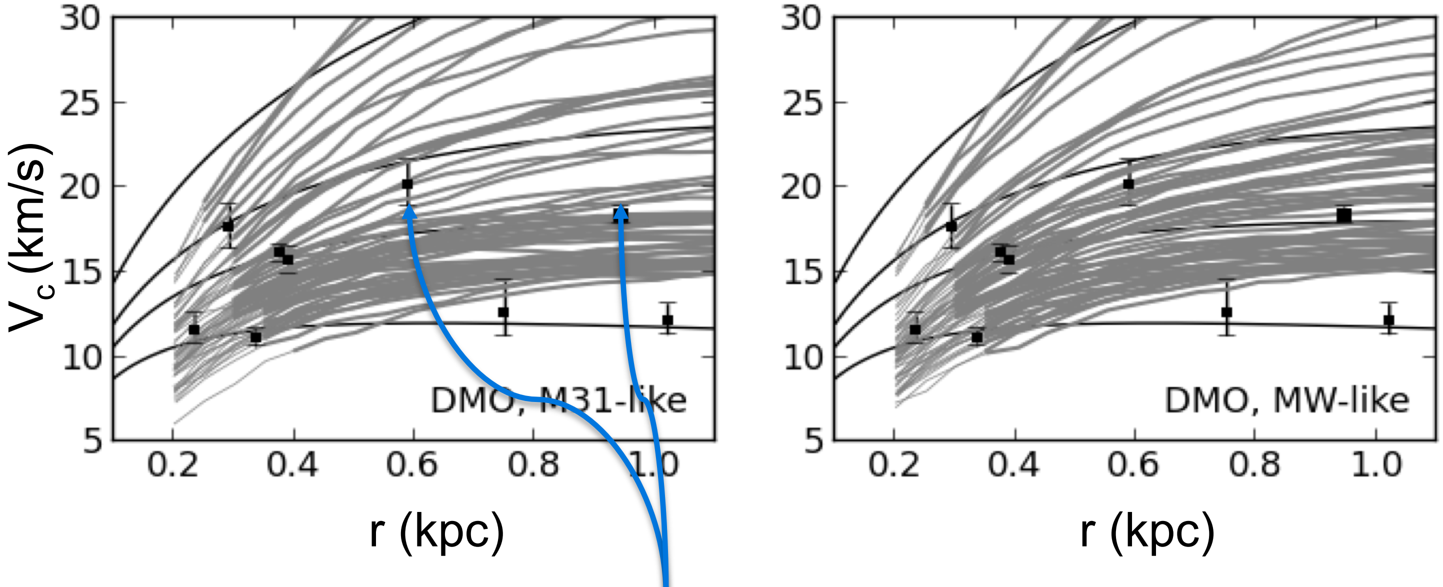
1. The "missing satellites" problem
2. The "too-big-to-fail" problem
3. The "plane of satellites" problem
4. The "core-cusp" problem

# Rotation curves of dark matter subhalos

Boylan-Kolchin et al. '11

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

DM-only simulation




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

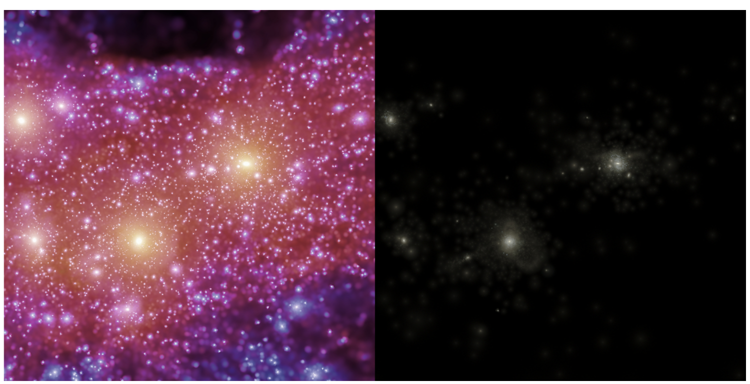
(excluding LMC, SMC, Sag)

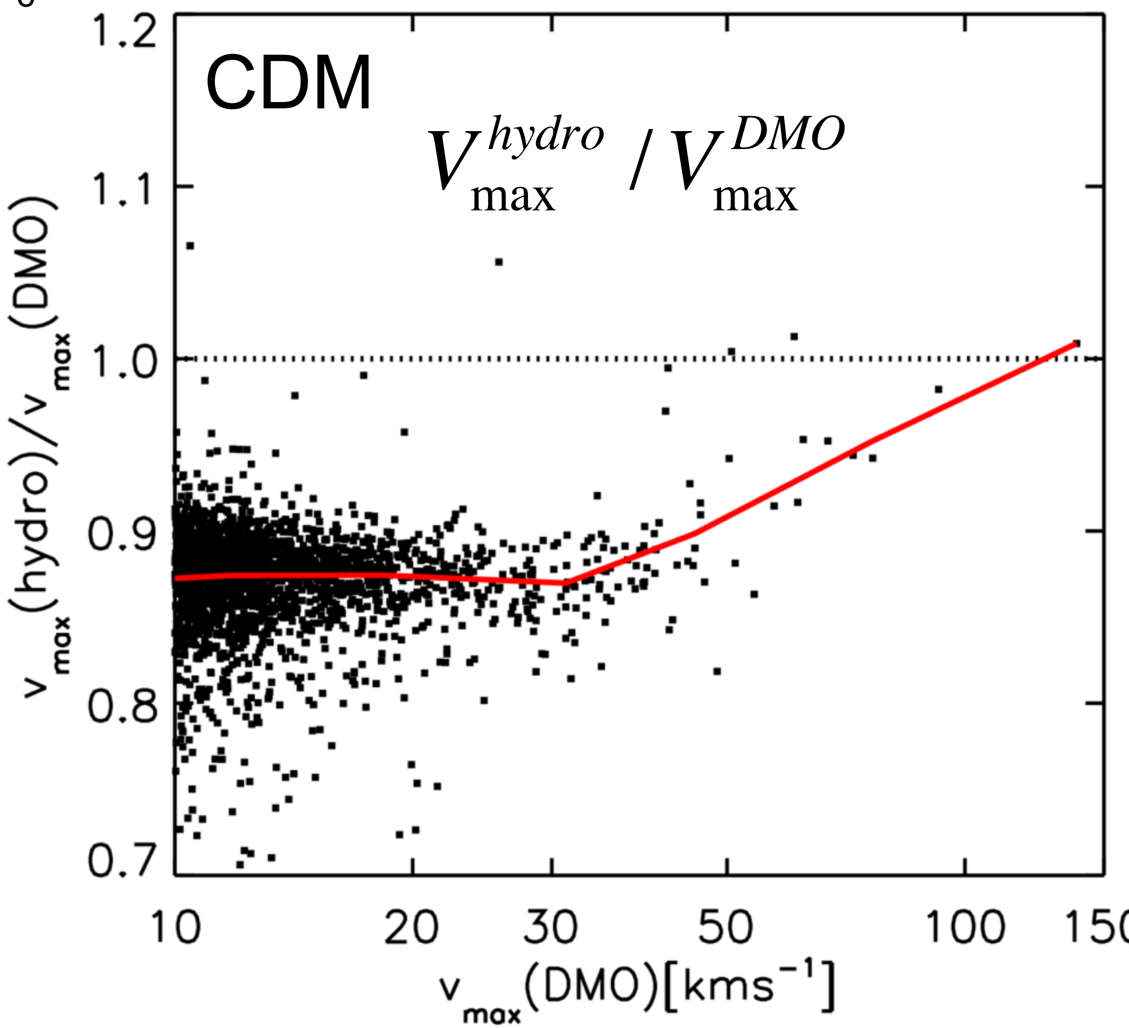
# To-big-to-fail in CDM: baryon effects

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

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

→ Lowers halo mass & thus halo growth rate






Sawala, CSF et al. '13, '14

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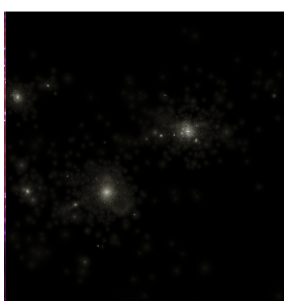
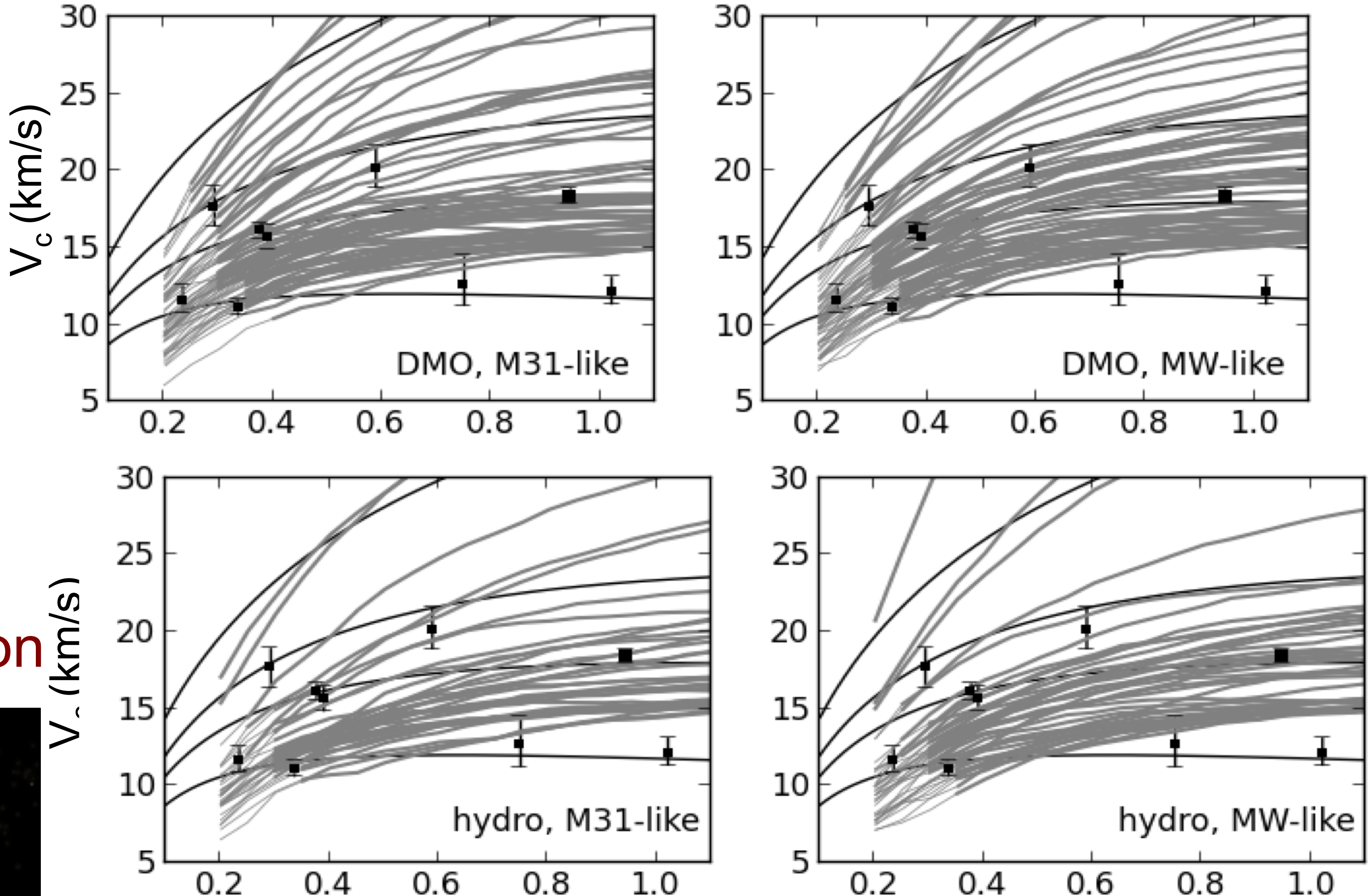
# Too-big-to-fail: the baryon bailout

DM-only simulation

Gas simulation






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

Sawala, CSF et al. '14

# The “small-scale crisis” of CDM

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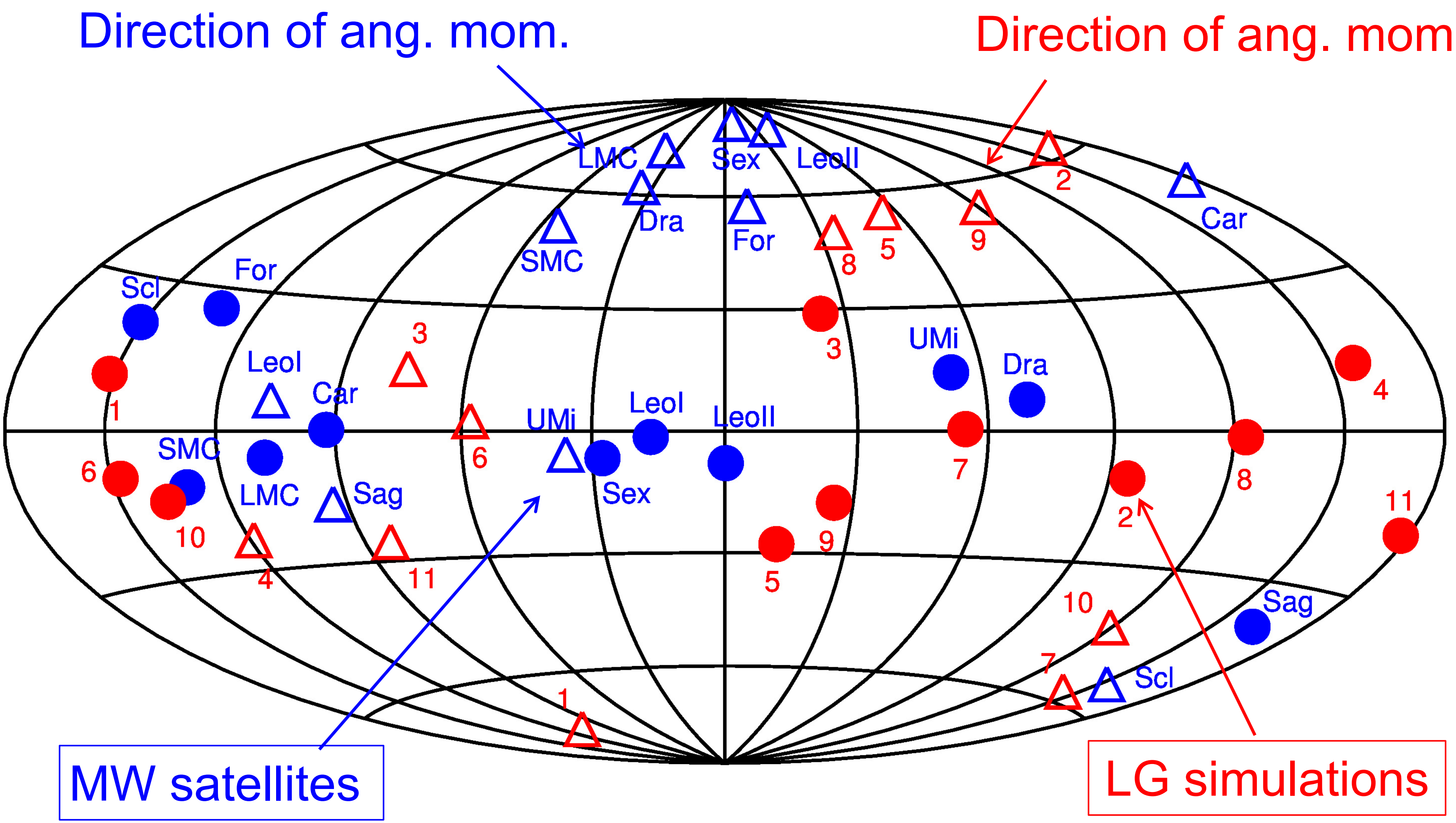
# The “satellite disk” problem




Lynden-Bell ‘76

# A satellite plane in Andromeda

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(From Millennium simulation) "0.04% of host galaxies 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 '14

MENU

nature
International journal of science

Letter | Published: 02 January 2013

## A vast, thin plane of corotating dwarf galaxies orbiting the Andromeda galaxy

Rodrigo A. Ibata, Geraint F. Lewis, Anthony R. Conn, Michael J. Irwin, Alan W. McConnachie, Scott C. Chapman, Michelle L. Collins, Mark Fardal, Annette M. N. Ferguson, Neil G. Ibata, A. Dougal Mackey, Nicolas F. Martin, Julio Navarro, R. Michael Rich, David Valls-Gabaud & Lawrence M. Widrow

*Nature* **493**, 62–65 (03 January 2013) | Download Citation

### Abstract

Dwarf satellite galaxies are thought to be the remnants of the population of primordial structures that coalesced to form giant galaxies like the Milky Way[1]. It has previously been suspected[2] that dwarf galaxies may not be isotropically distributed around our Galaxy, because several are correlated with streams of H I emission, and may

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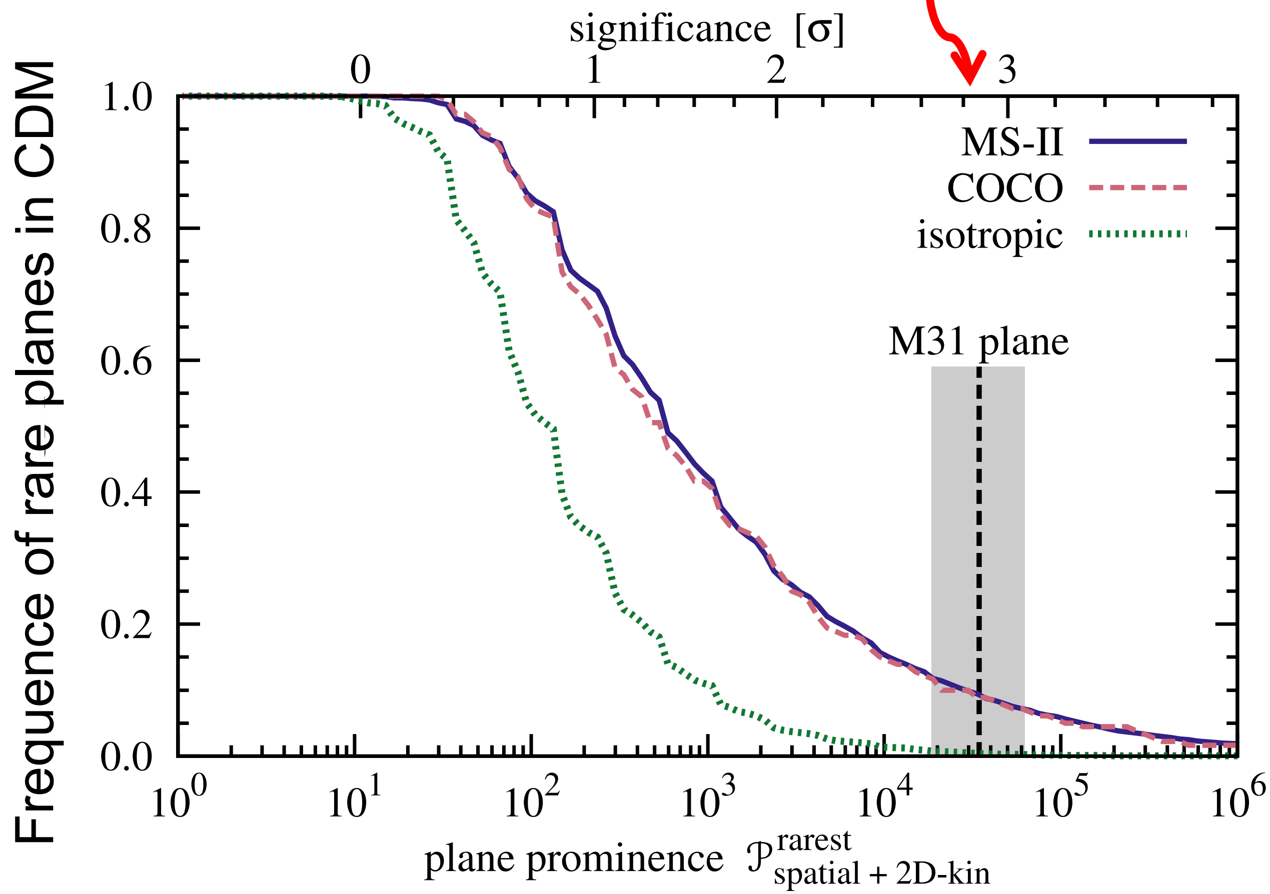
# The significance of Ibata's plane

Including "trials factor"




- 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

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, CSF, et al '15

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# The "small-scale crisis" of CDM

## The four "problems" of CDM

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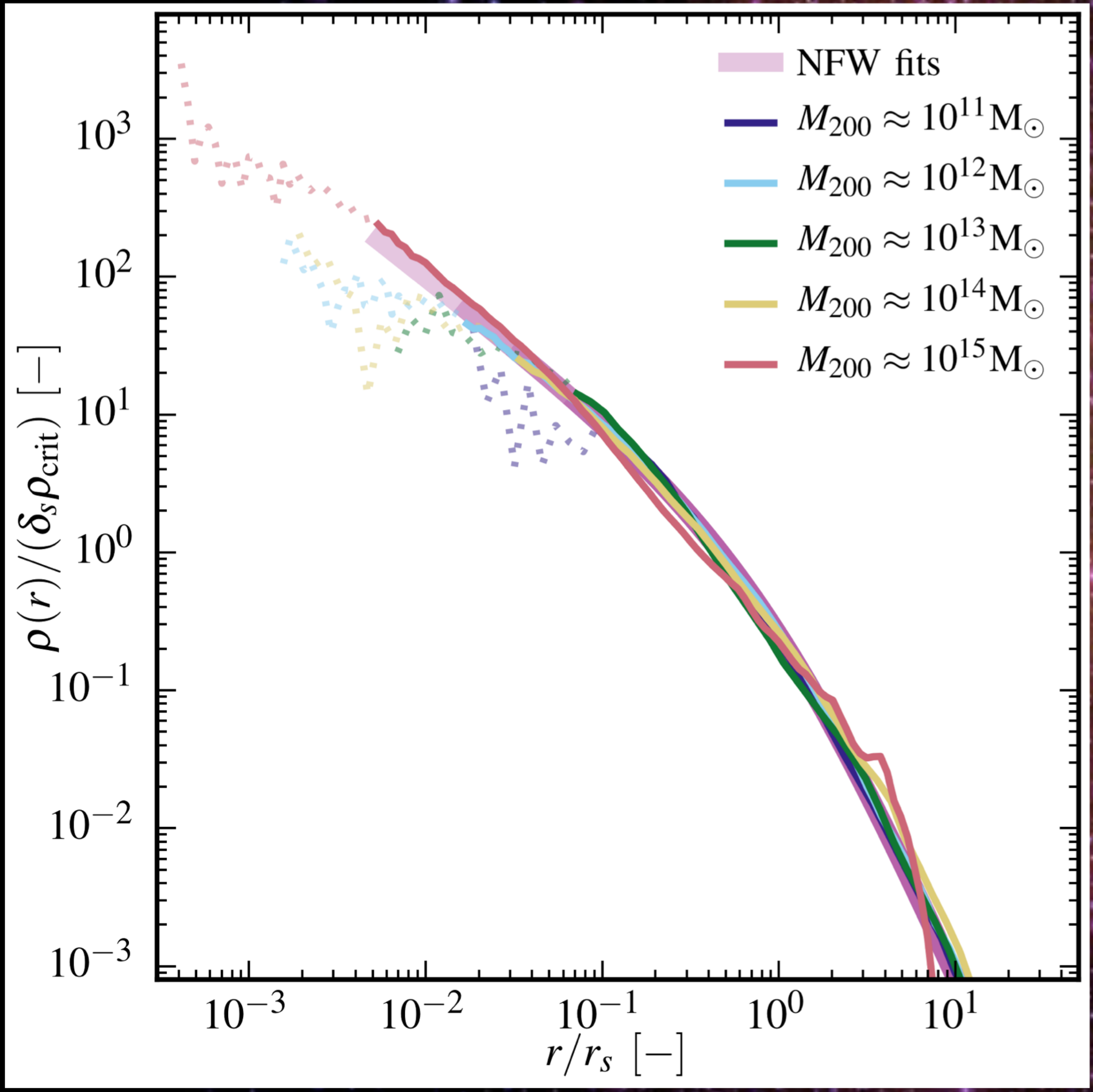
# The Density Profile of Cold Dark Matter Halos




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

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

Fitted by simple formula:

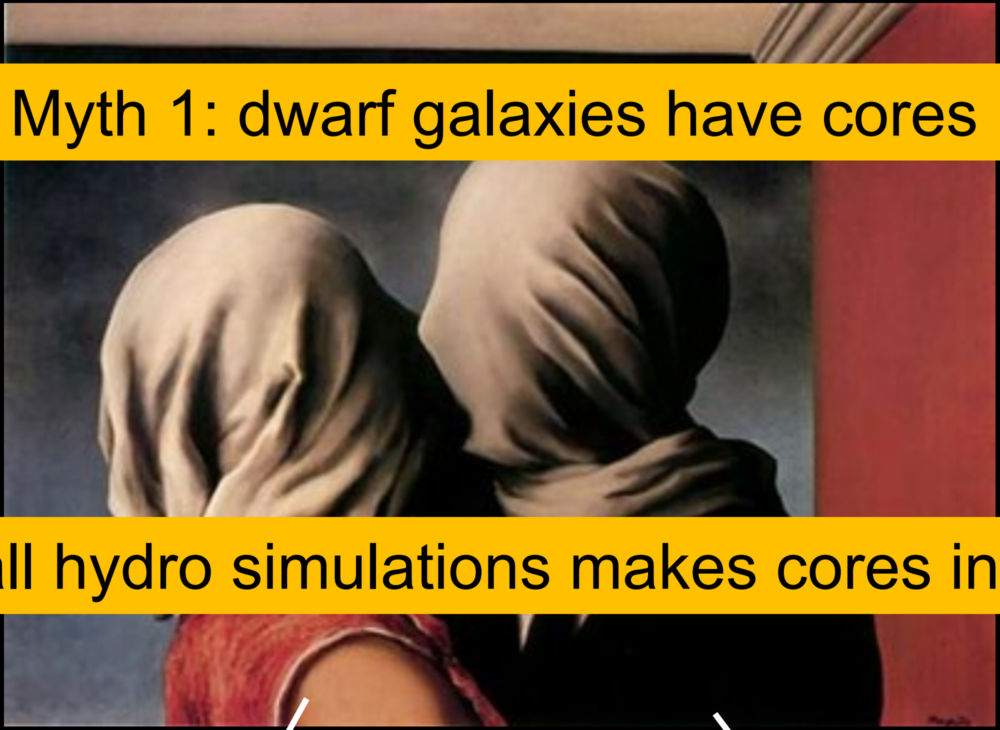
$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

(Navarro, Frenk & White '97)

More massive halos and halos that form earlier have higher densities (bigger $\delta$)

ICC

# Cores or cusps?



Myth 1: dwarf galaxies have cores

Myth 2: all hydro simulations makes cores in dwarfs

Cores

Cusps

# The physics of core formation

Cusps → cores

Perturb central halo region by growing a galaxy adiabatically and removing it suddenly (Navarro, Eke & Frenk '96)

Cores may also form by repeated fluctuations in central potential (e.g. by SN explosions) (Read & Gilmore '05; Pontzen & Governato '12,'14; Bullock & Boylan-Kolchin '17)

Navarro, Eke & Frenk (1996)

*The cores of dwarf galaxy haloes* L75

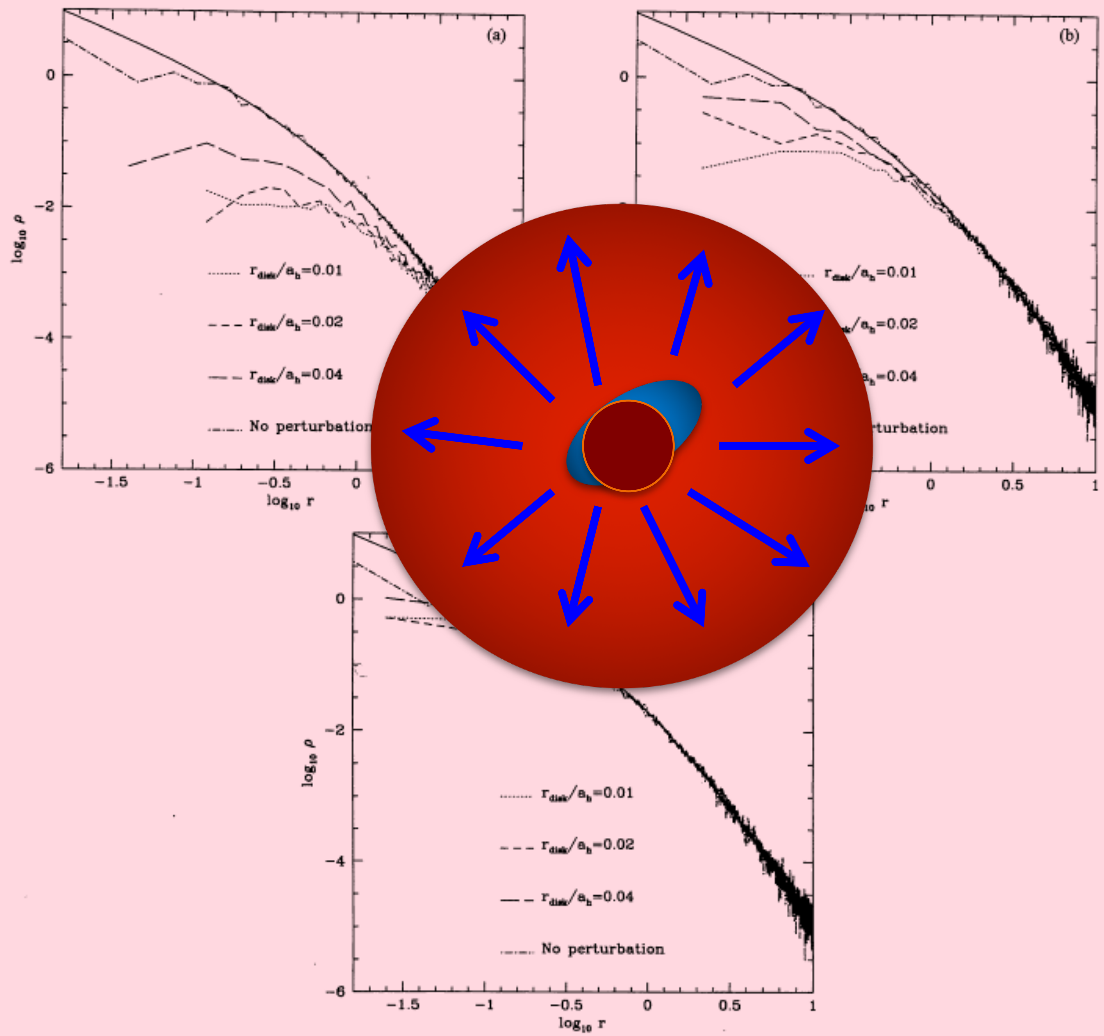
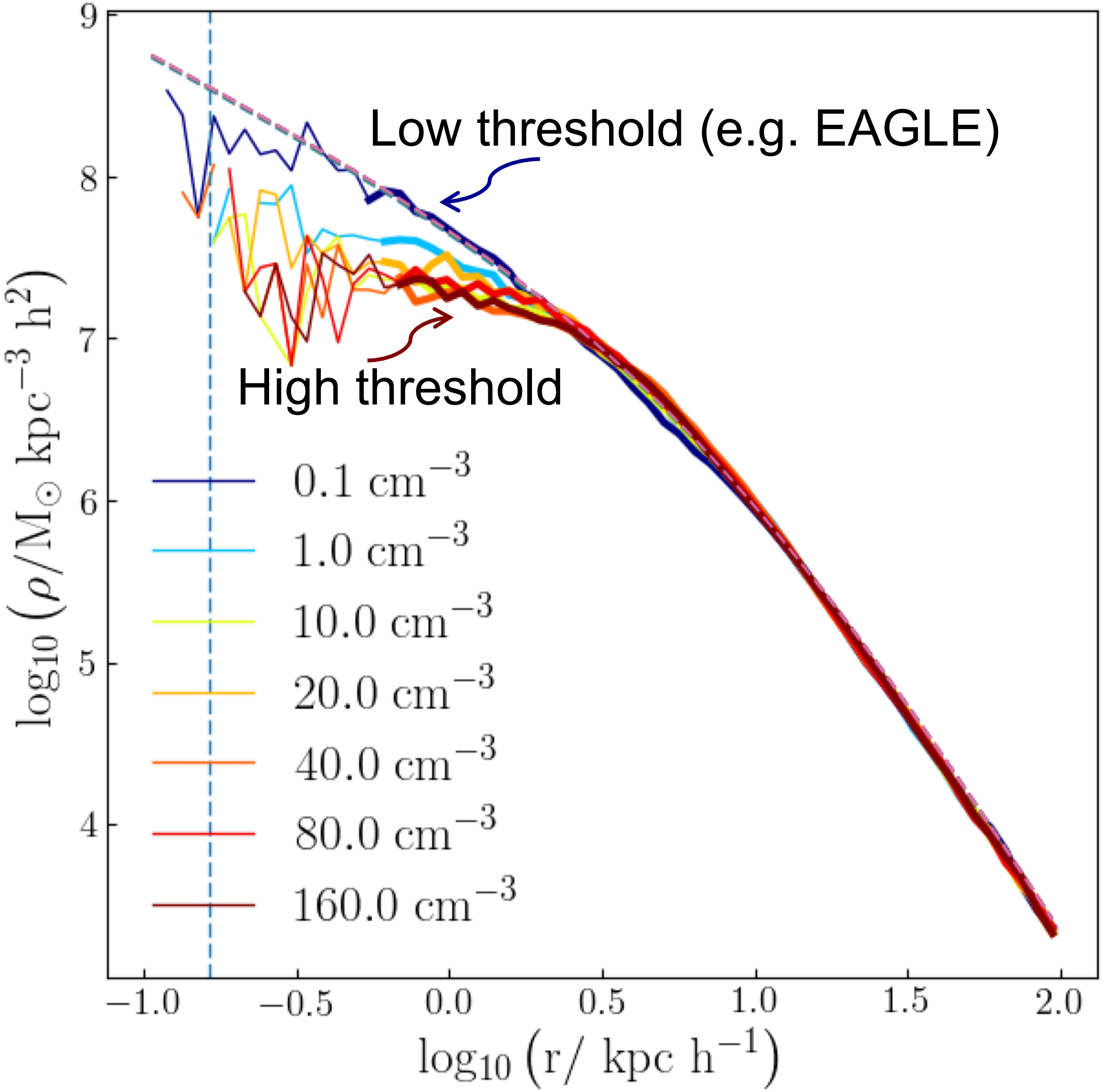



**Figure 3.** Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

# Cores or cusps in simulations?




Benitez-Llambay, CSF et al '17

University of Durham

# The "small-scale crisis" of CDM

## The four "problems" of CDM

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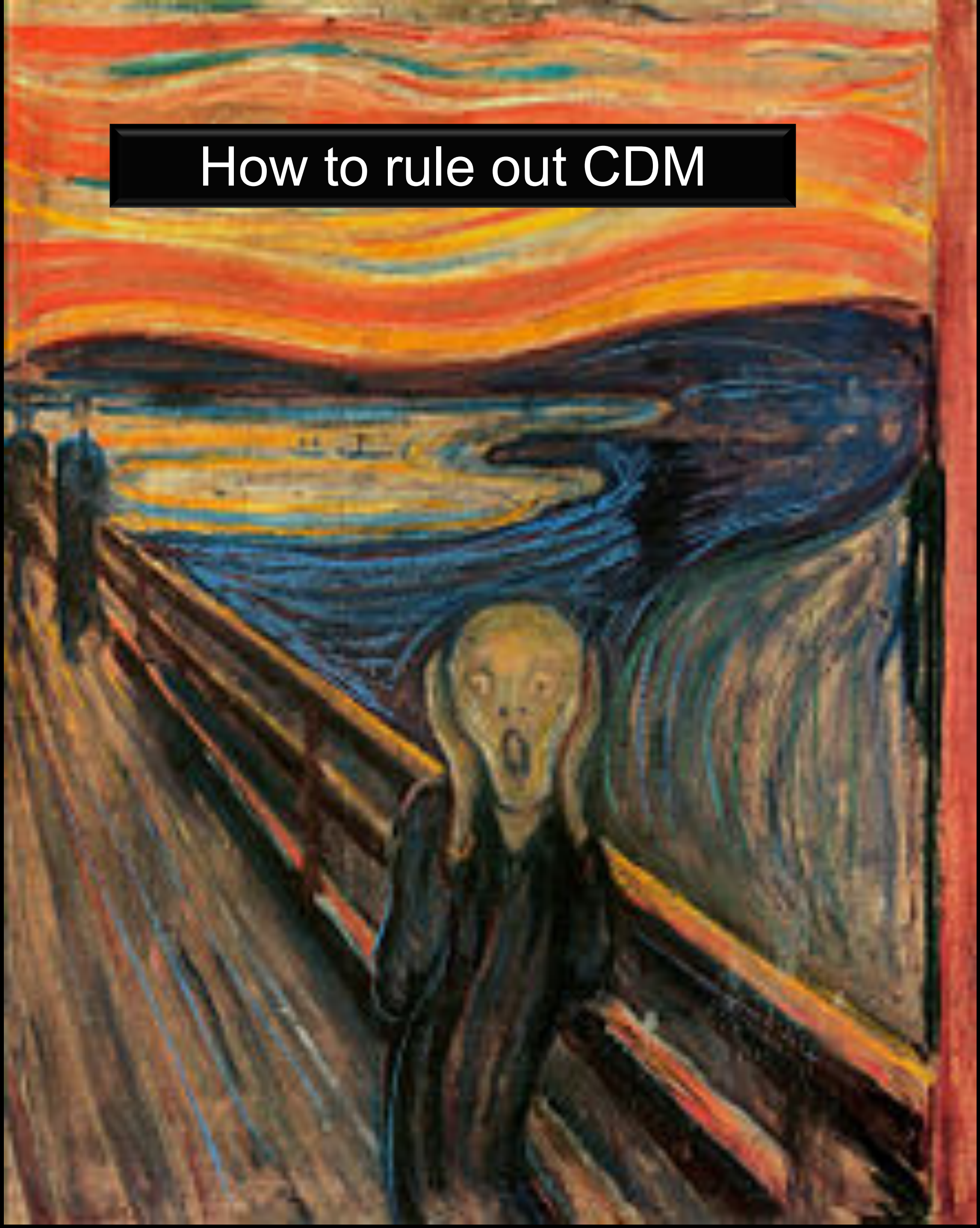
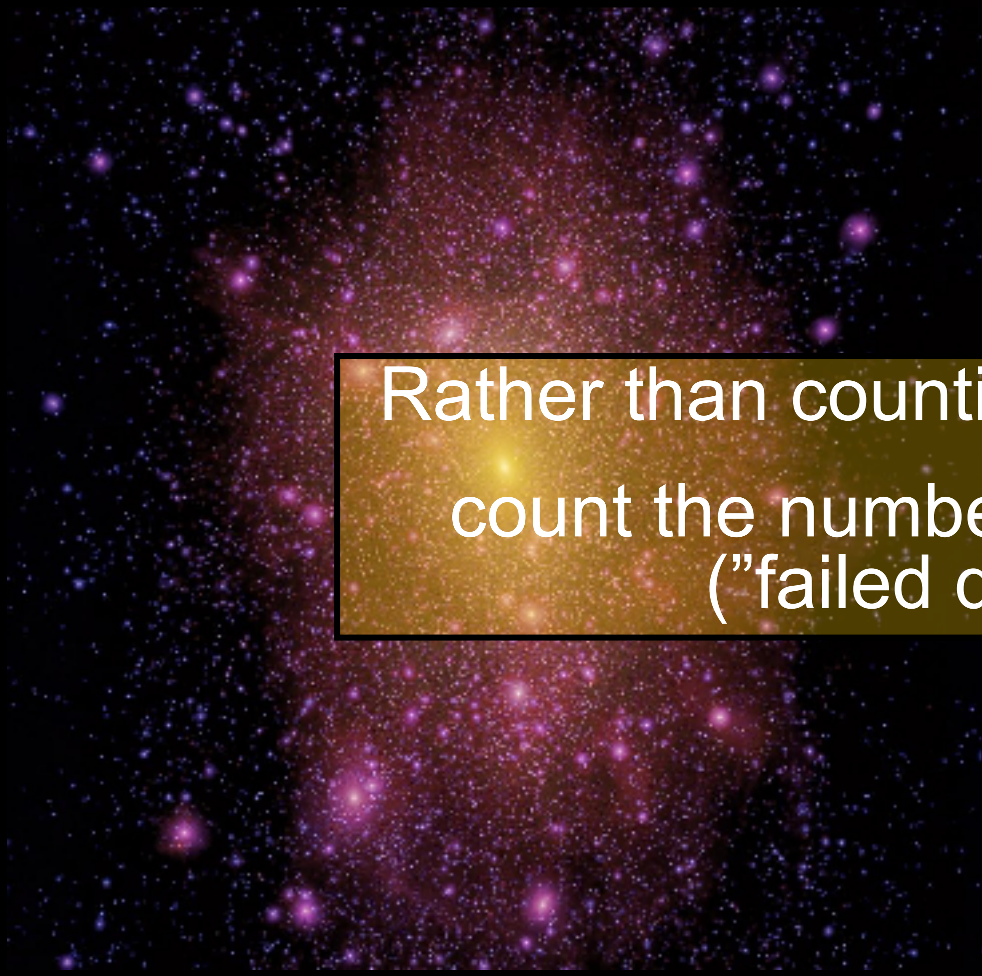
1, 2, 4 → problems only if you ignore galaxy formation!

# How to rule out CDM

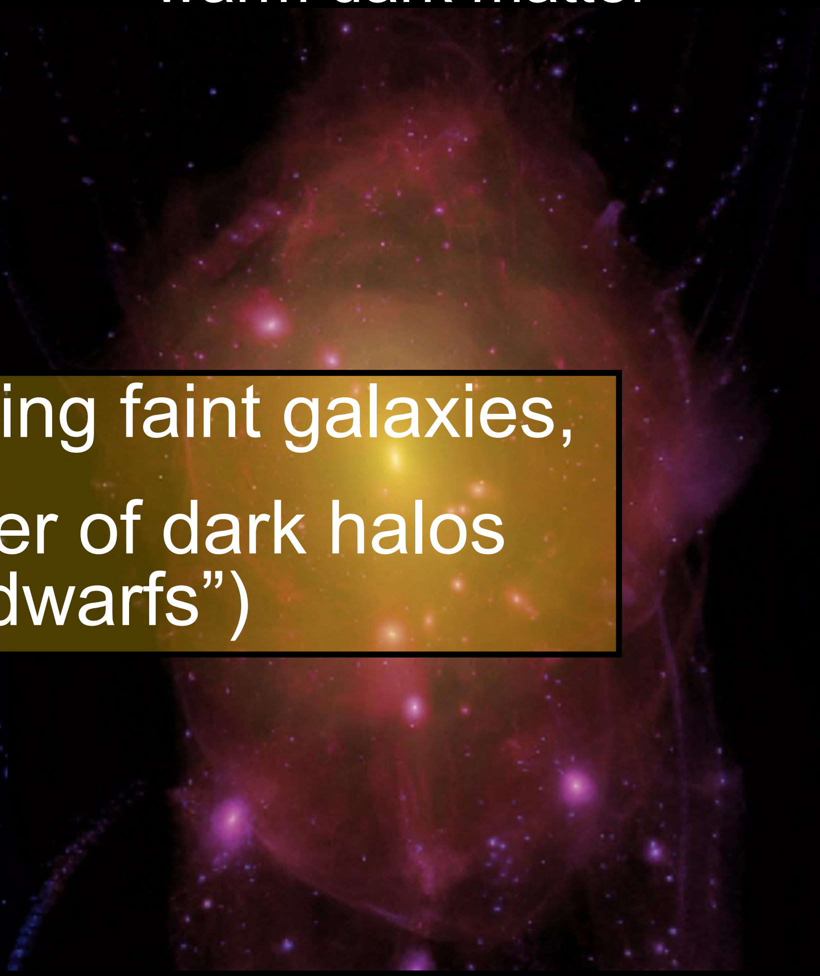


# Can we distinguish CDM/WDM?

cold dark matter



warm dark matter



Rather than counting faint galaxies,

count the number of dark halos ("failed dwarfs")

# Can we distinguish CDM/WDM?

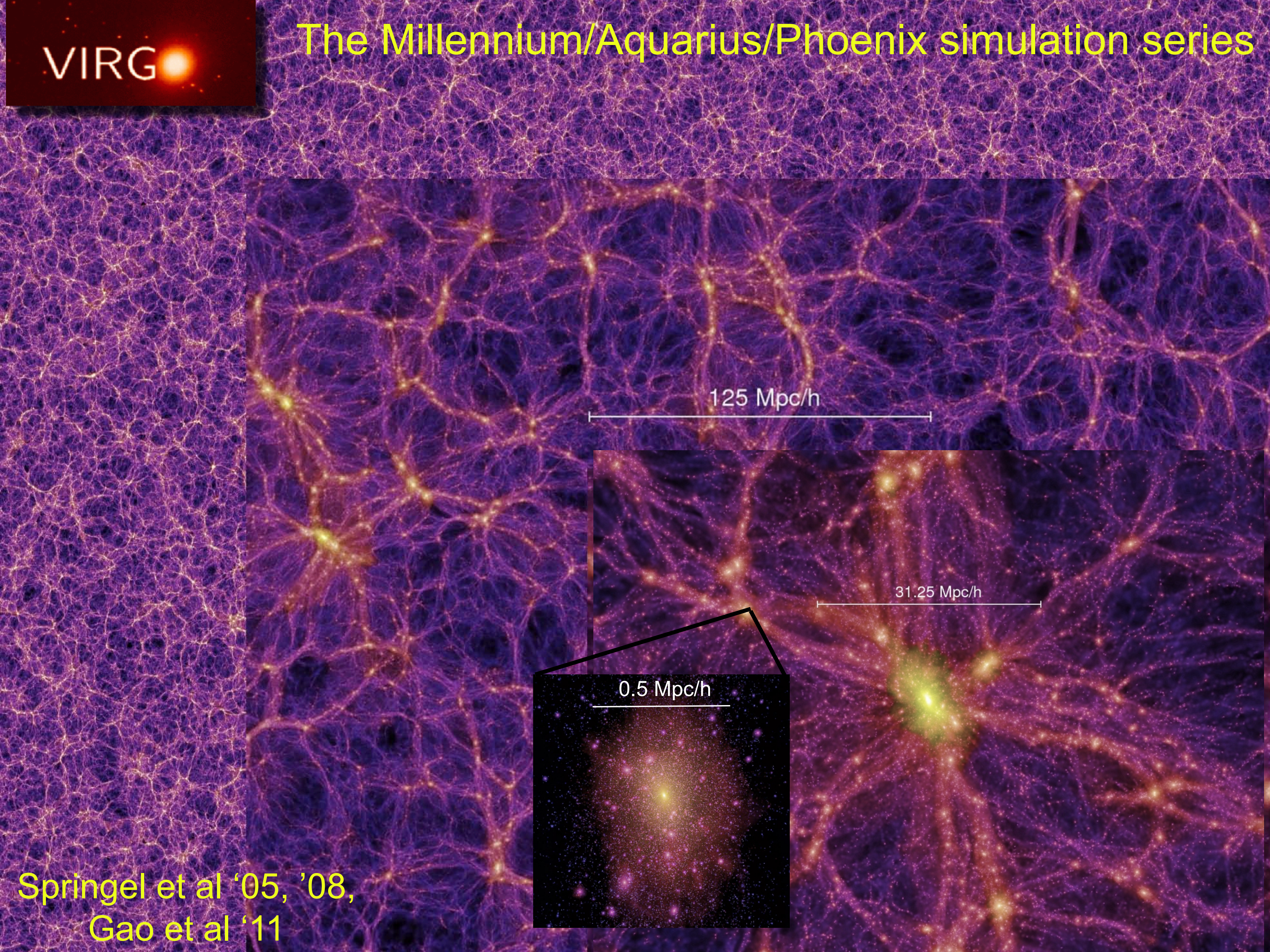
cold dark matter

warm dark matter

Three ways to count dark halos

1. ReLHICS (Benitez-Llambay)
2. Gaps in streams (Erkal)
3. Gravitational lensing (Nirenberg)

# The Millennium/Aquarius/Phoenix simulation series

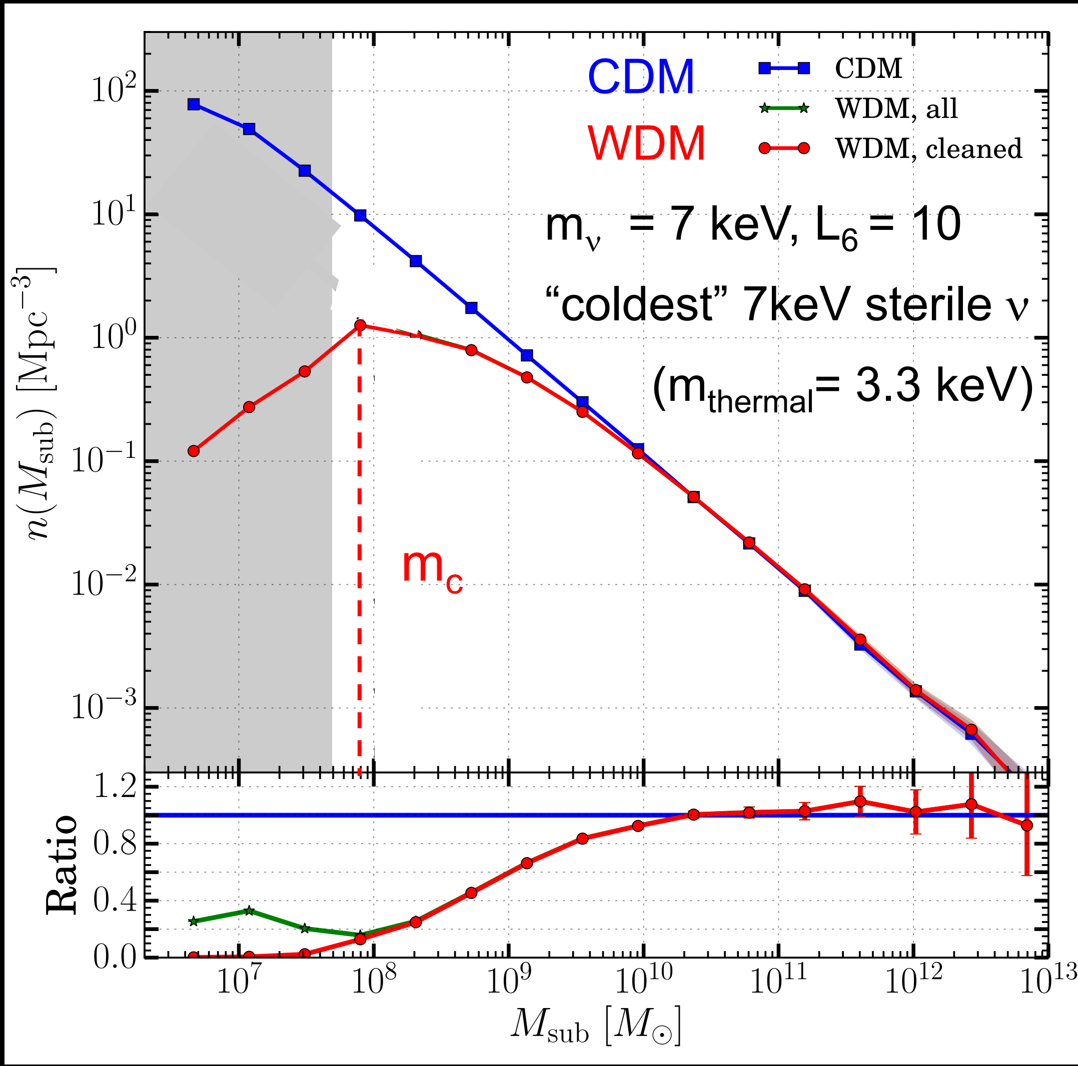



Springel et al ‘05, ’08,
Gao et al ‘11

# The subhalo mass function

CDM

WDM




3 x fewer WDM subhalos at $3 \times 10^9$ $M_o$

10 x fewer at $10^8$ $M_o$

Bose, CSF et al '16

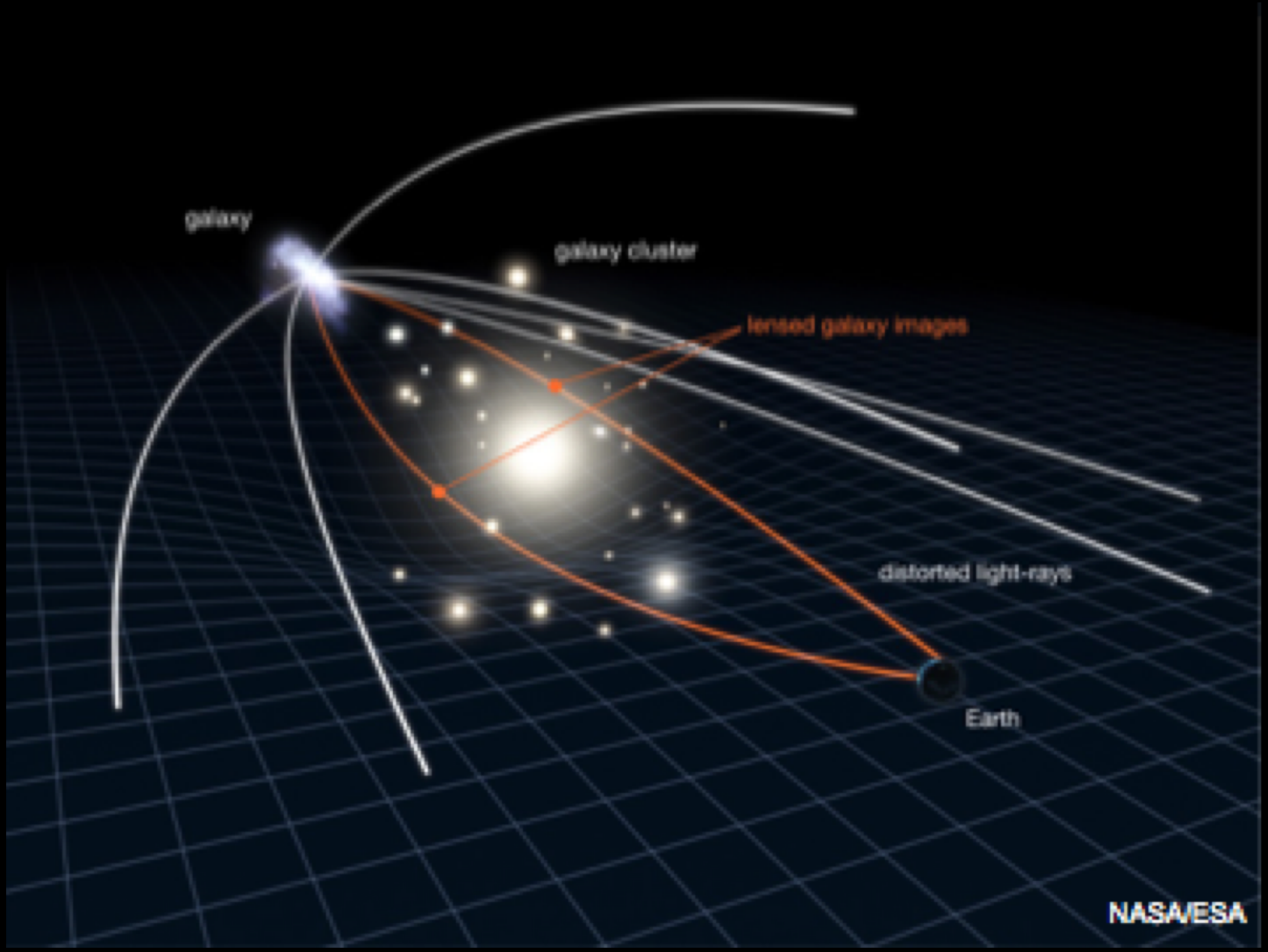
# Can we distinguish CDM/WDM?

cold dark matter

warm dark matter

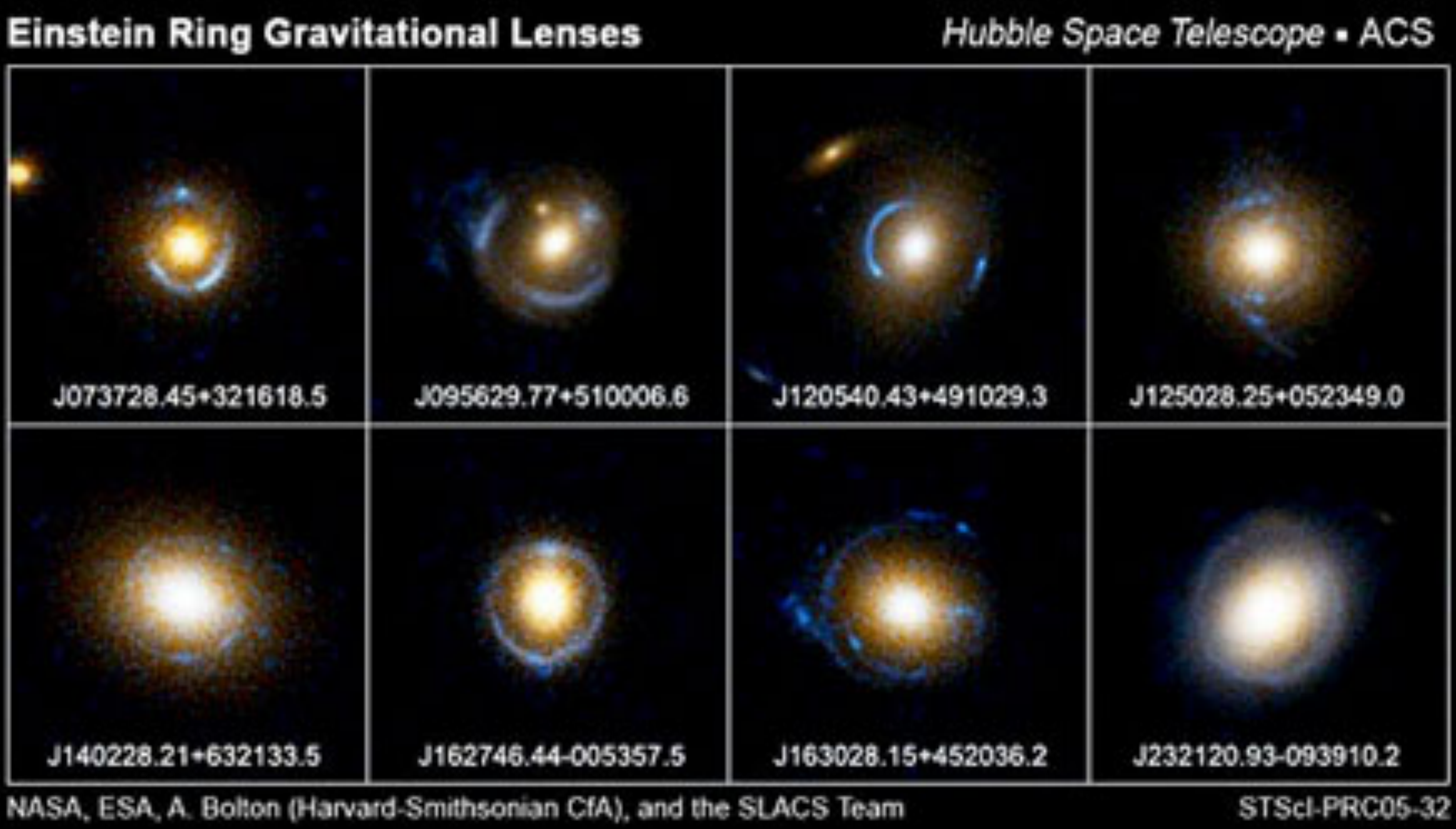
Dark halos can be detected through gravitational lensing

# Gravitational lensing: Einstein rings

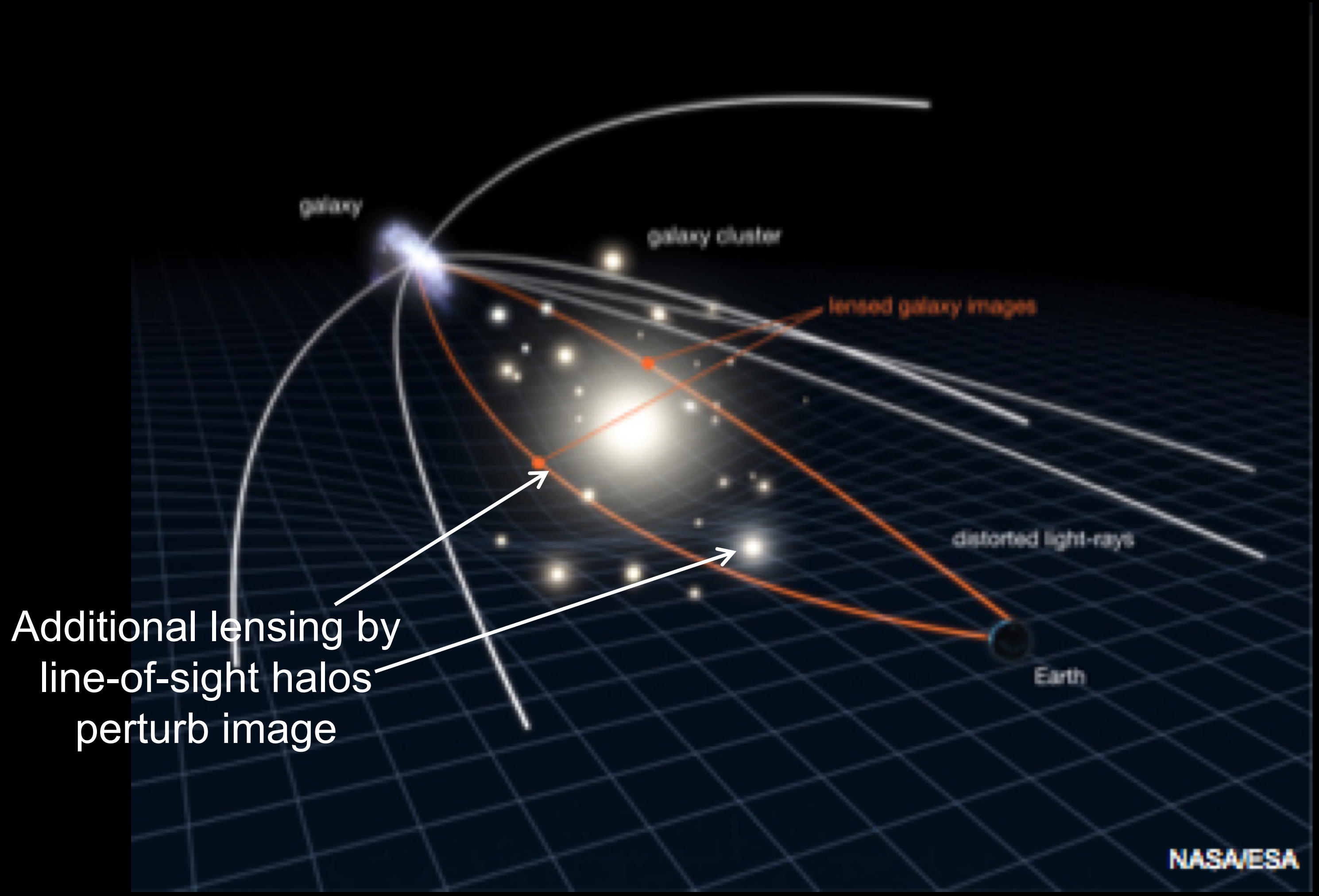



When the source and the lens are well aligned → strong arc or an Einstein ring

# SLAC sample of strong lenses



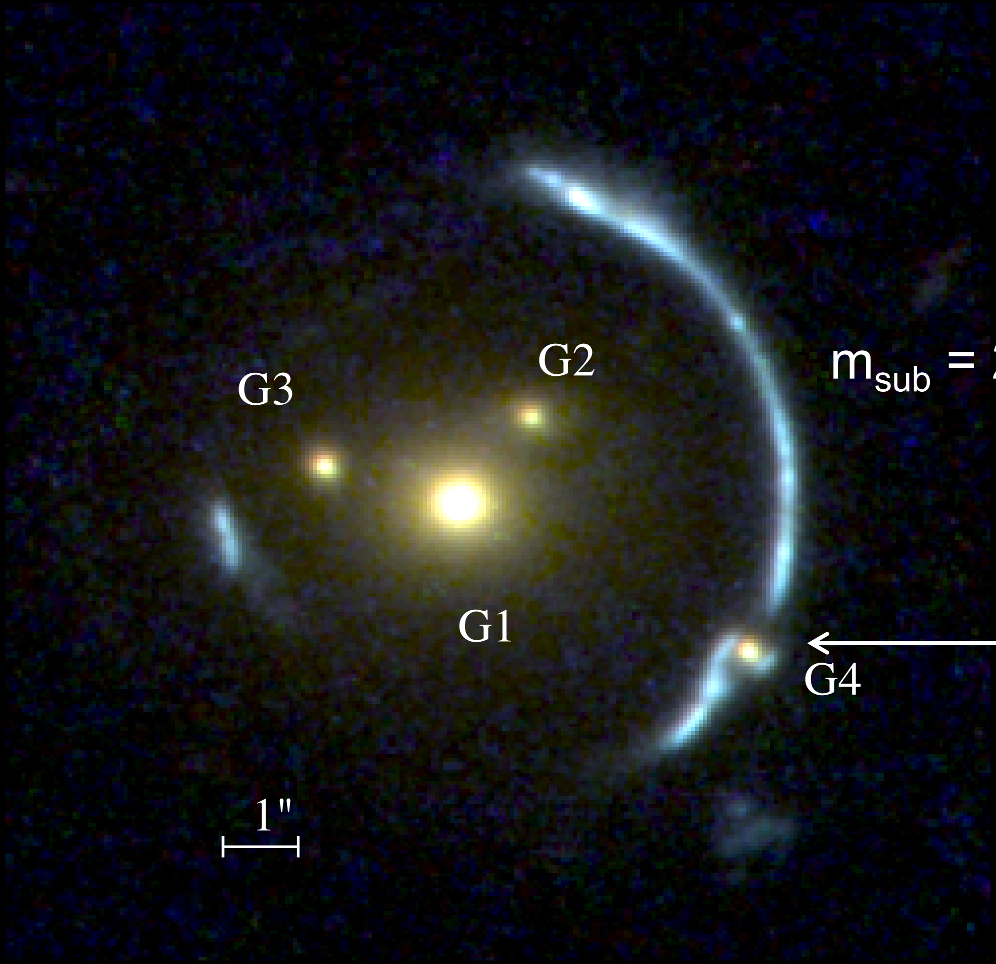
# Gravitational lensing: Einstein rings




When the source and the lens are well aligned → strong arc or an Einstein ring

# Gravitational lensing: Einstein rings

Halos projected onto an Einstein ring distort the image



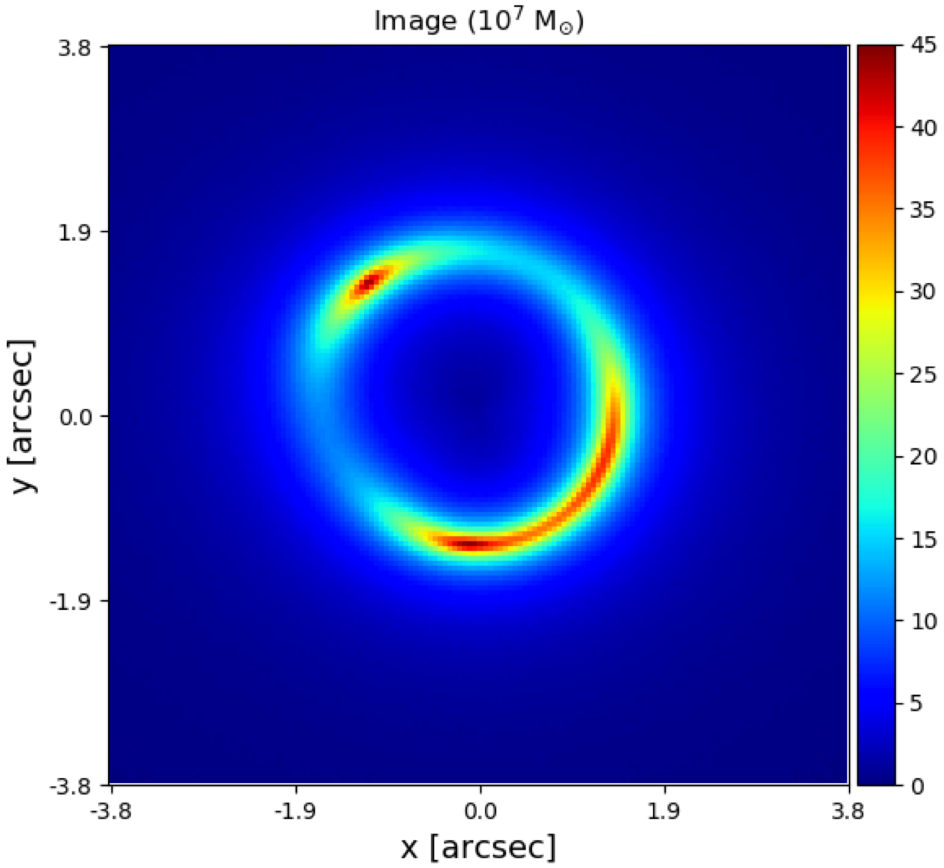

$m_{sub} = 2.8 \times 10^{10}\, M_o$

Vegetti et al '10

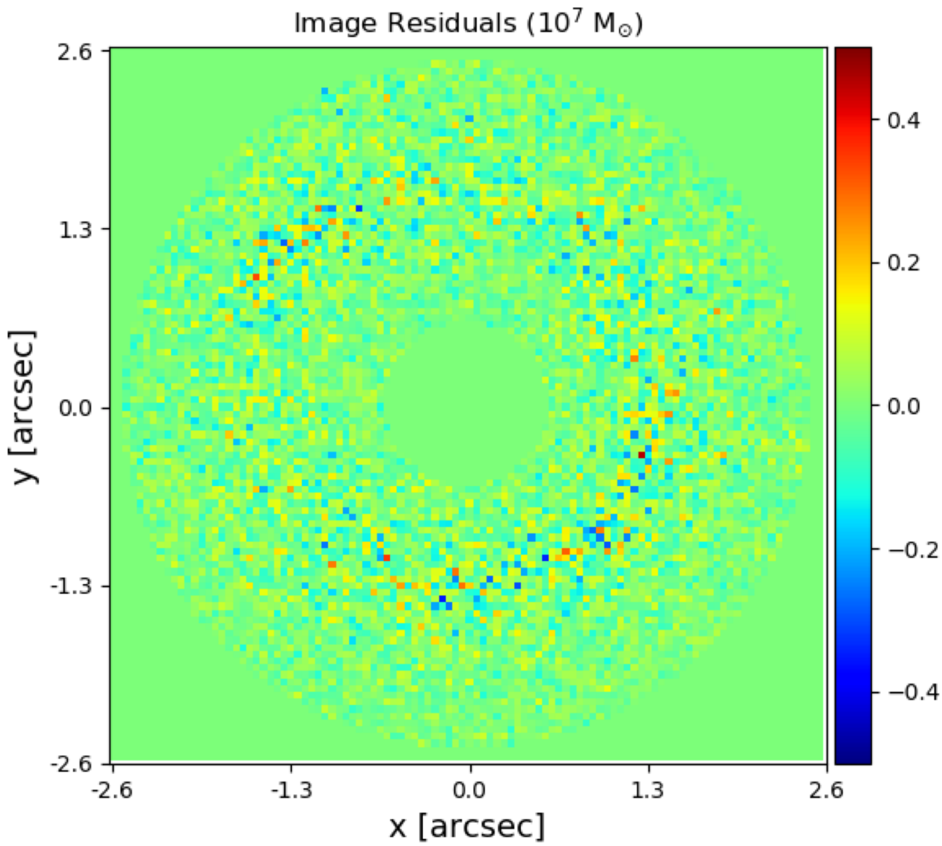
# Gravitational lensing: Einstein rings

HST "data": $z_{source}$=1; $z_{lens}$=0.2   $10^7$ $M_o$ halo – NOT so easy to spot

Image




Residuals




He, Li, CSF et al '19

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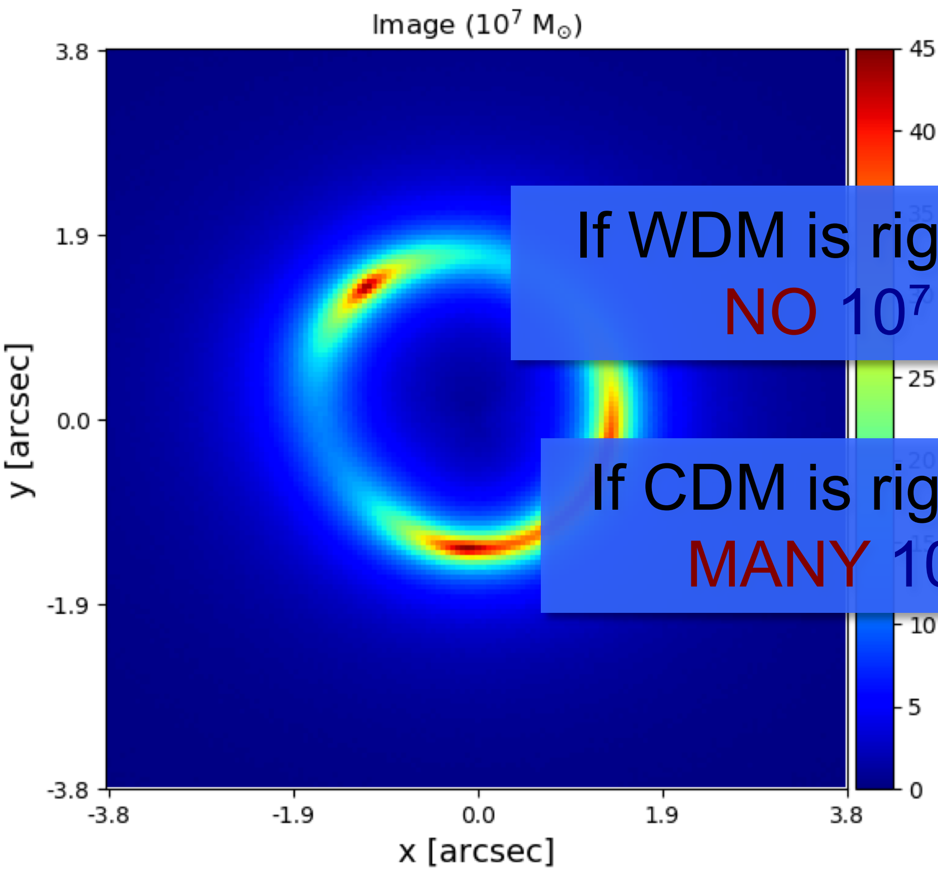
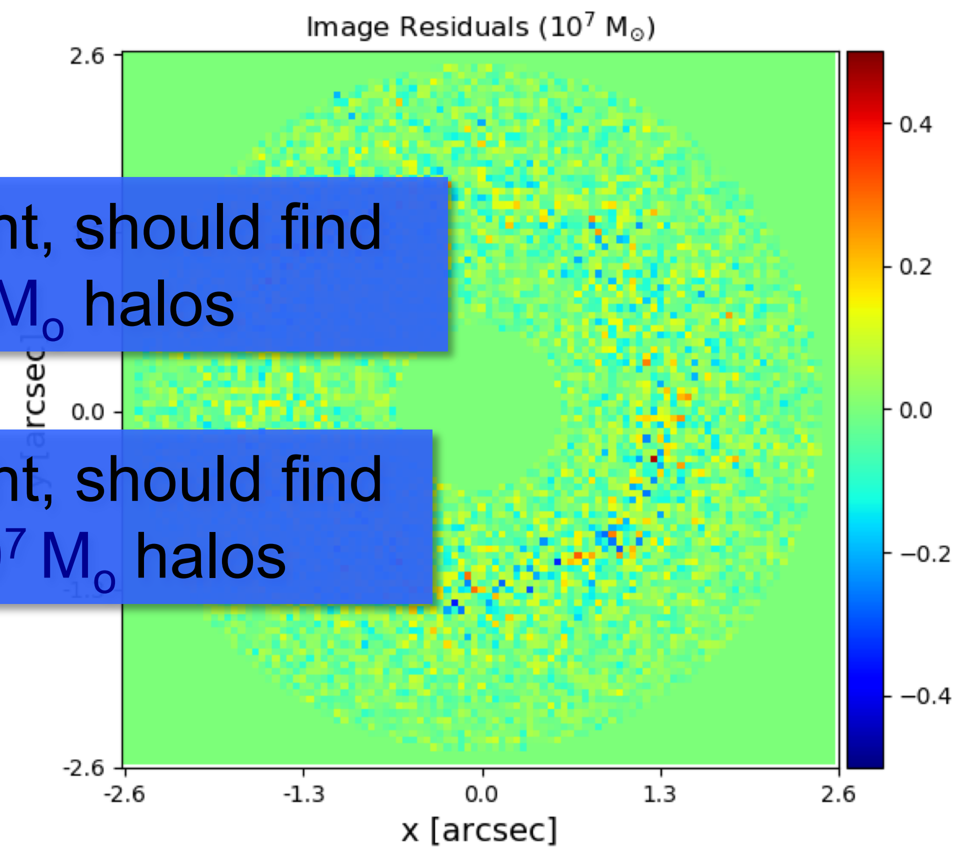
# Detecting substructures with strong lensing

Can detect subhalos as small as $10^7 - 10^8 M_o$




If WDM is right, should find NO $10^7 M_o$ halos

If CDM is right, should find MANY $10^7 M_o$ halos

He, Li, CSF et al '19

Institute for Computational Cosmology

University of Durham

# Detecting substructures with strong lensing

Detection limit = $10^7\ h^{-1}M_o$ is achievable with current data and techniques

~100 Einstein ring systems with detection limit of $10^7\ h^{-1}M_o$ is enough to either rule out a 7 keV sterile $\nu$ or CDM itseilf

Li, CSF et al '16

# Conclusions

- Is ΛCDM correct? What can dwarf galaxies tell us about the identity of dark matter?

- Can we identify signatures of reionization in the dwarf population? What role did dwarfs play in reionization?

- How will the next generation of surveys and simulations answer the above questions?

# Conclusions

- Is $\Lambda$CDM correct? What can dwarf galaxies tell us about the identity of dark matter?

No evidence that $\Lambda$CDM is incorrect; dwarfs rule out part of WDM parameter space

- Can we identify signatures of reionization in the dwarf population? What role did dwarfs play in reionization?

The ultra-faints ($M_* < 10^5 M_o$) made most of their stars $z > z_{reion}$

- How will the next generation of surveys and simulations answer the above questions?

Distortions of strong gravitational lenses offer a clean test of CDM *vs* WDM and can potentially rule out CDM