

Title: Local group simulations of galaxy formation with blazar heating

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Abstract:

Feedback over 44 Orders of Magnitude  
Perimeter Institute, 16/03/2016

# Local Group Galaxies

Till Sawala

Carlos Frenk, Azadeh  
Fattahi, Julio Navarro,  
Christoph Pfrommer,  
Ewald Puchwein  
and EAGLE



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# Local Group Galaxies in a Blazar Heated Universe

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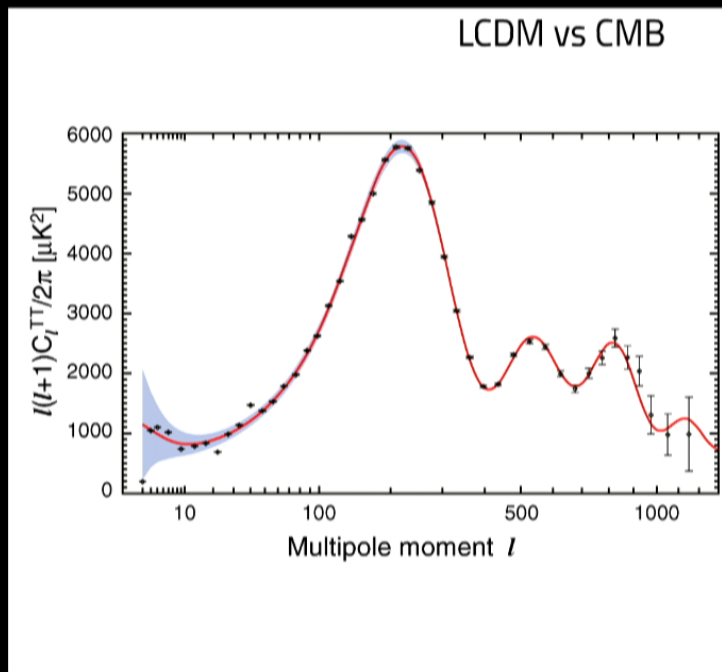
# Outline

Introduction

Reionization and dwarf galaxies in APOSTLE

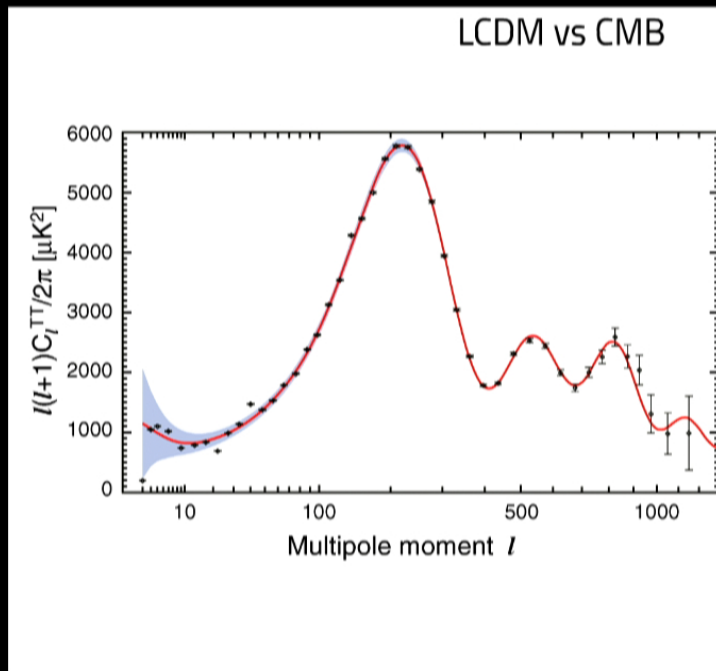
The Local Group in a Blazar heated Universe

# ΛCDM is *Largely* Successful

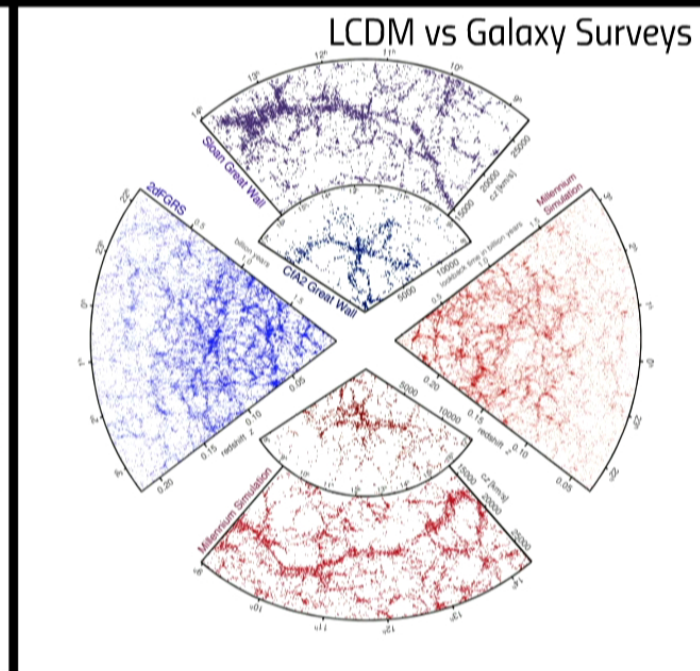


Larson et al. (2011)

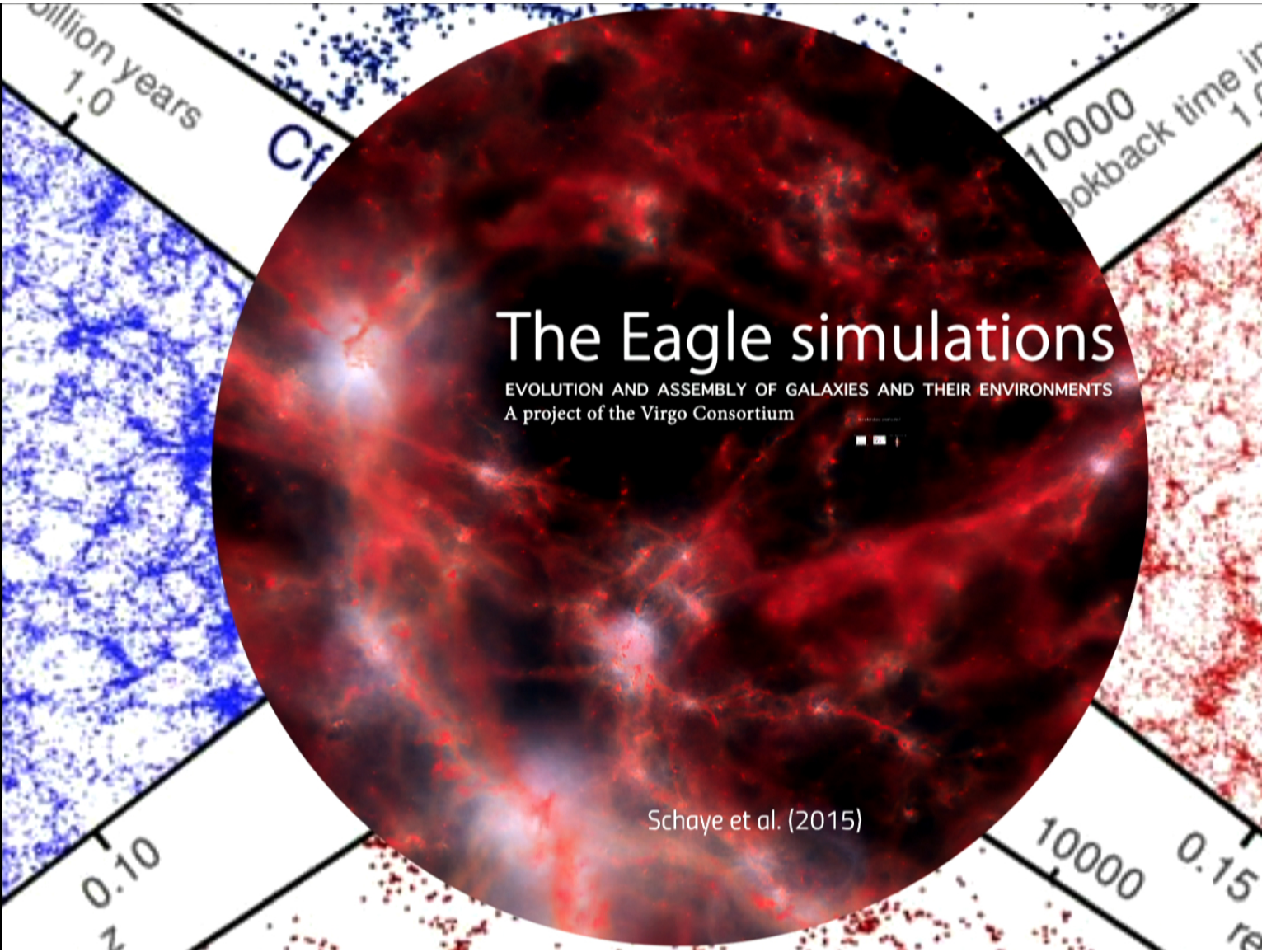
# ΛCDM is *Largely* Successful

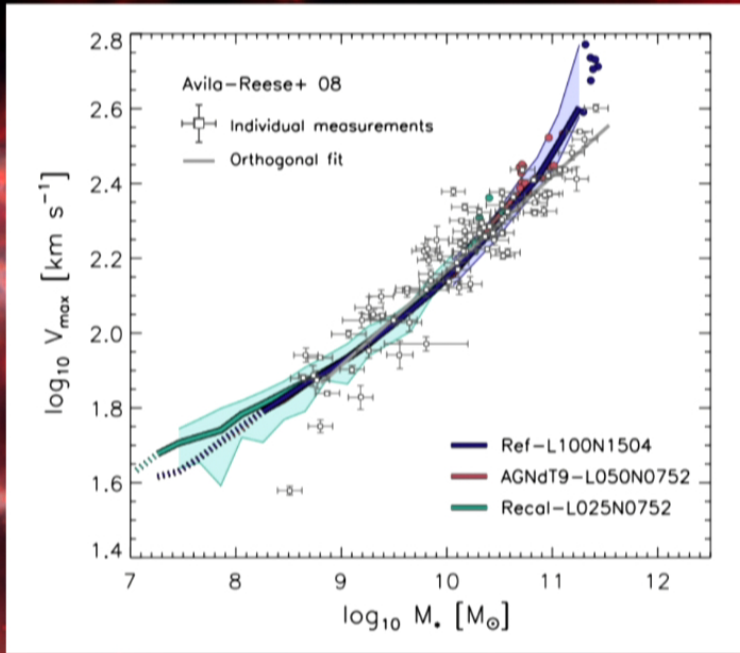
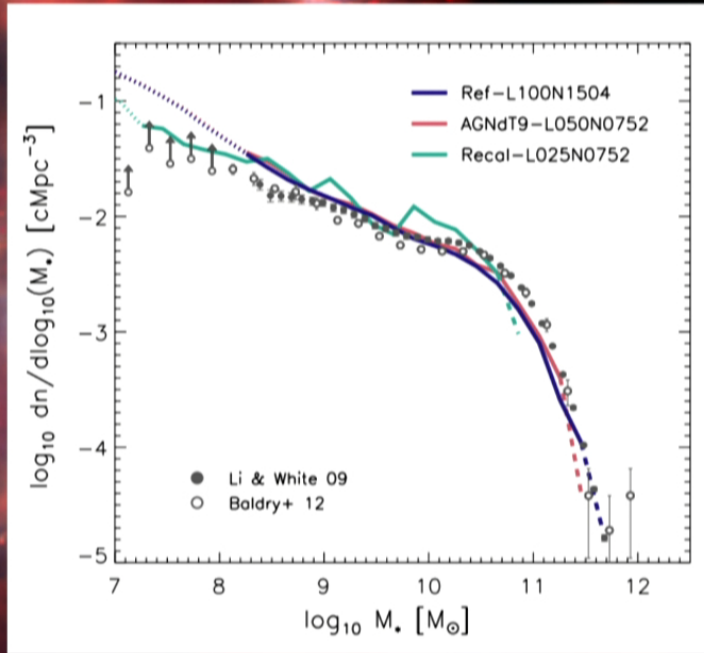


Larson et al. (2011)



Springel et al. (2005)



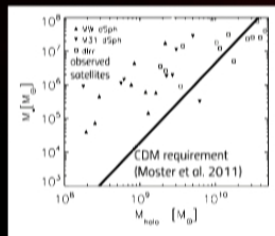


Schaye et al. (2015)



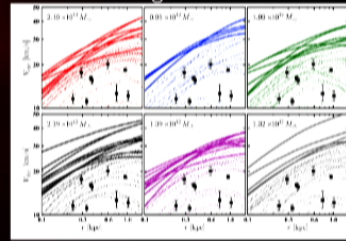
# But what about *small* scales?

Satellite galaxies don't fit their predicted CDM halos.



The stellar - halo mass ratios of satellite galaxies appear much higher than CDM requires to match the stellar mass and halo mass functions: the *missing satellite problem* ++

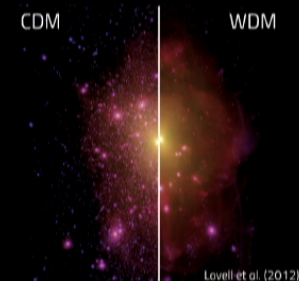
The "Too Big To Fail" Problem



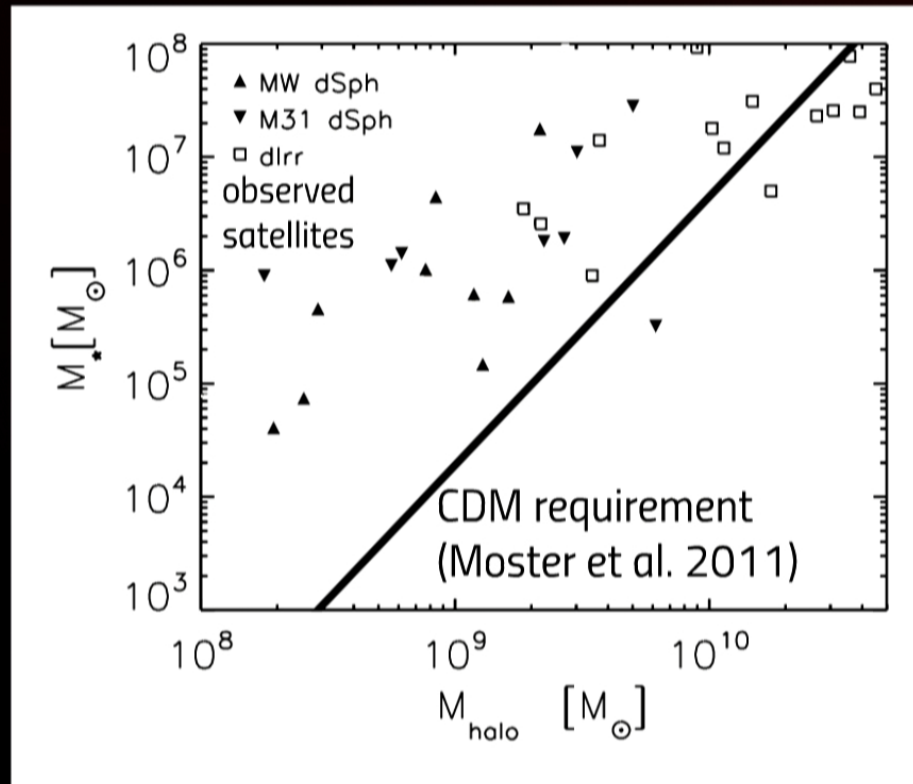
Boylan-Kolchin et al. (2011)

CDM appears to overpredict the number of large satellites that have no observed counterparts.

Alternatives to CDM become testable

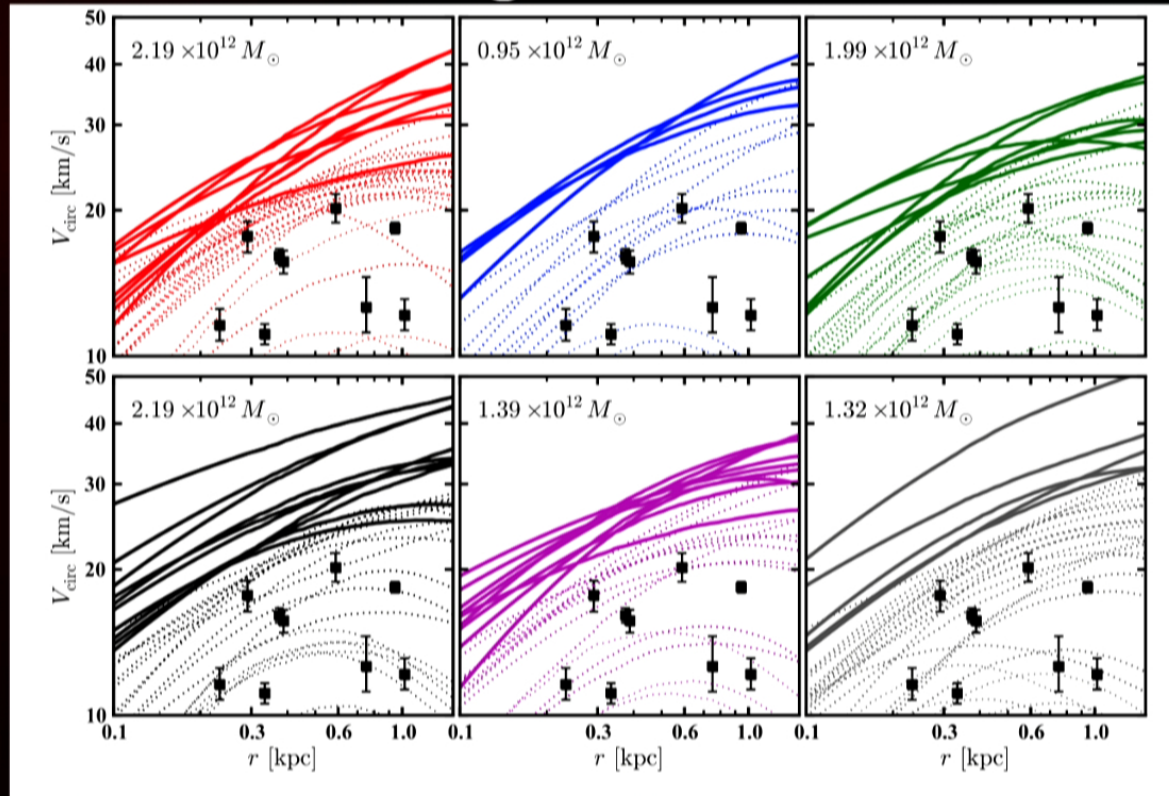


# Satellite galaxies don't fit their predicted CDM halos.



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# The "Too Big To Fail" Problem



Boylan-Kolchin et al. (2011)

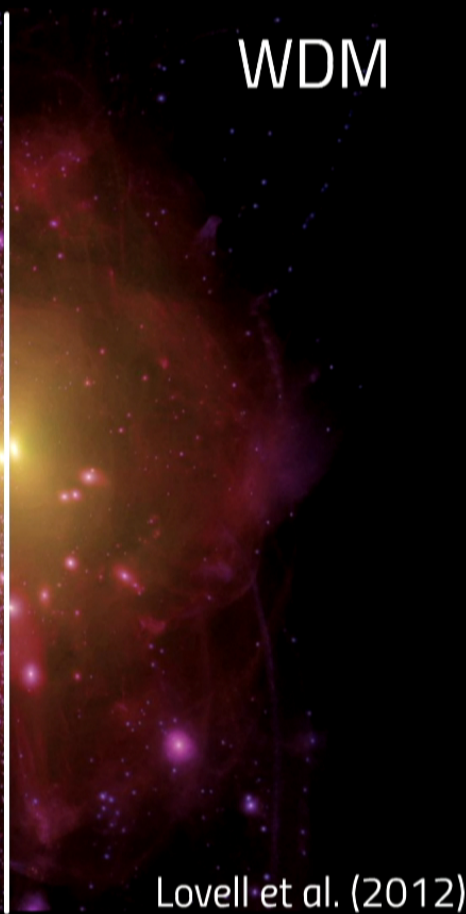
CDM appears to overpredict the number of large satellites that have no observed counterparts.

# Alternatives to CDM become testable

CDM



WDM

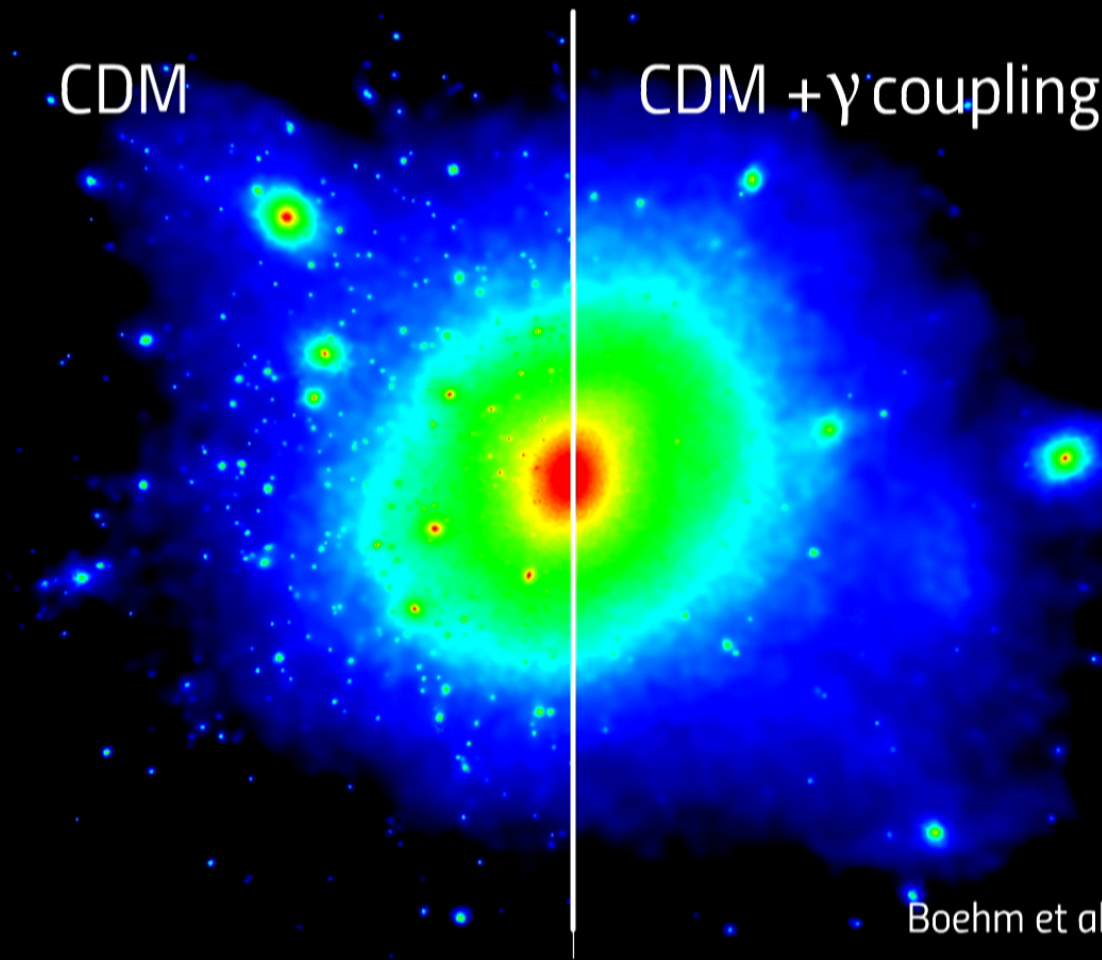


Lovell et al. (2012)

# Alternatives to CDM become testable

CDM

CDM +  $\gamma$  coupling



Boehm et al. (2014)

# CDM: Only nearly right?

- CDM is successful on large scales, but appears to fail on the small scales observed in the Local Group.
- On large scales, the formation of structures is determined by gravity, but on very small scales, baryonic effects are important.
- Is this a failure of CDM or merely of gravity-only simulations - can we extend the success of CDM to the Local Environment?

# AP O S T L E



# A Project Of Simulating The Local Environment

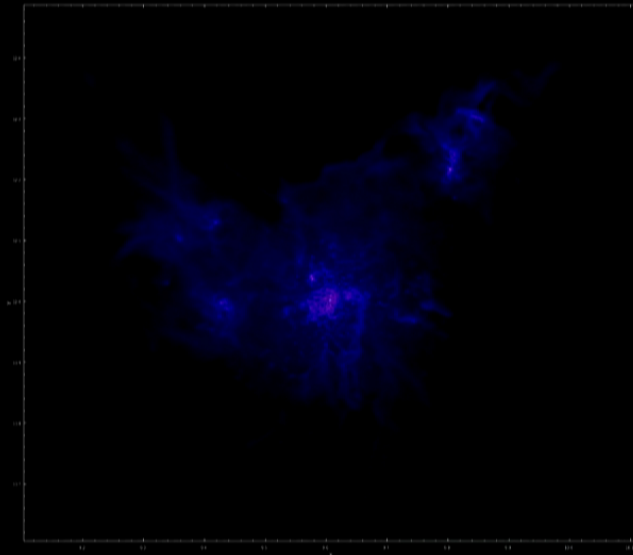
**12 Local Group analogue regions in CDM, kinematically selected from a large Dark Matter Only (DMO) simulation**

**Resimulated at up to 150 x higher resolution, as DMO and fully hydrodynamical, using the EAGLE code**



# Gas

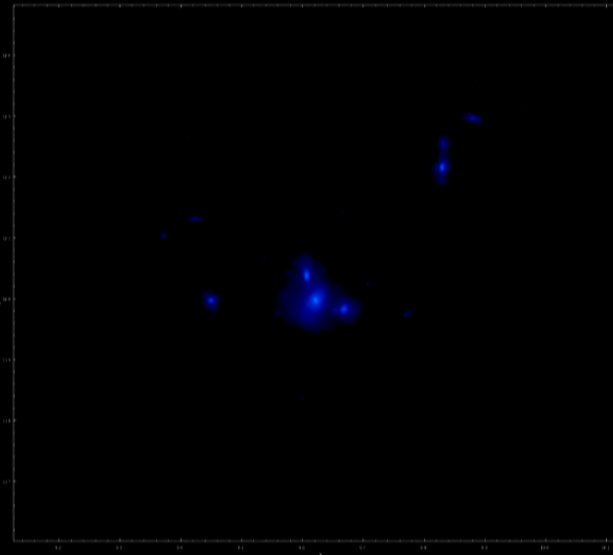
Example 1.101



Camera: 9 KAPL 12 000 10 000

# Stars

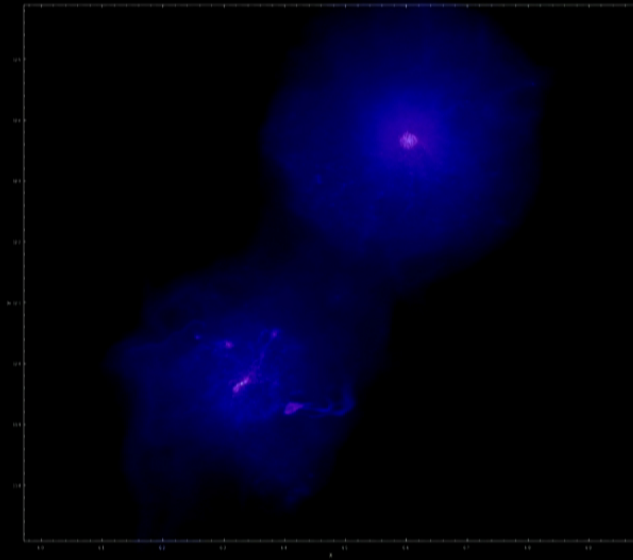
Example 1.117



Camera: 9 KAPL 12 000 10 000

# Gas

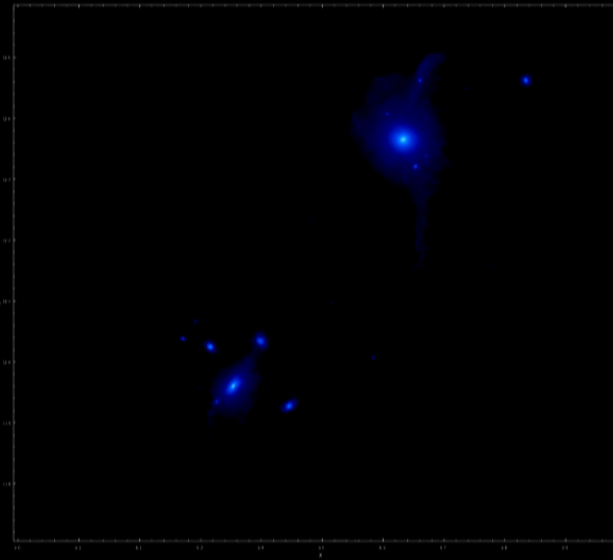
Example 1: 2015-10



Example 2: 2015-10-20

# Stars

Example 1: 2015-10



Example 2: 2015-10-20

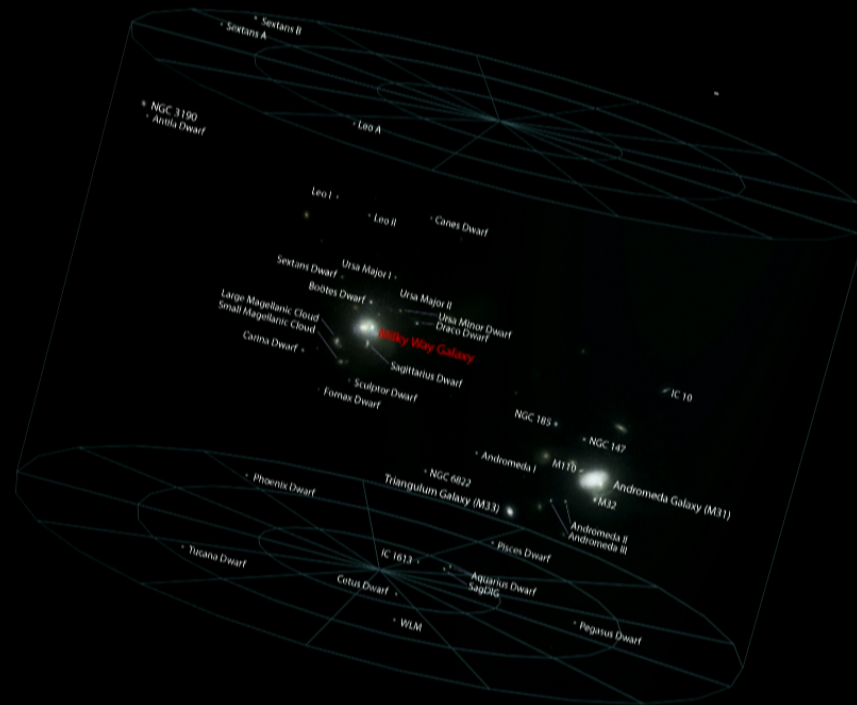
There are millions of CDM halos



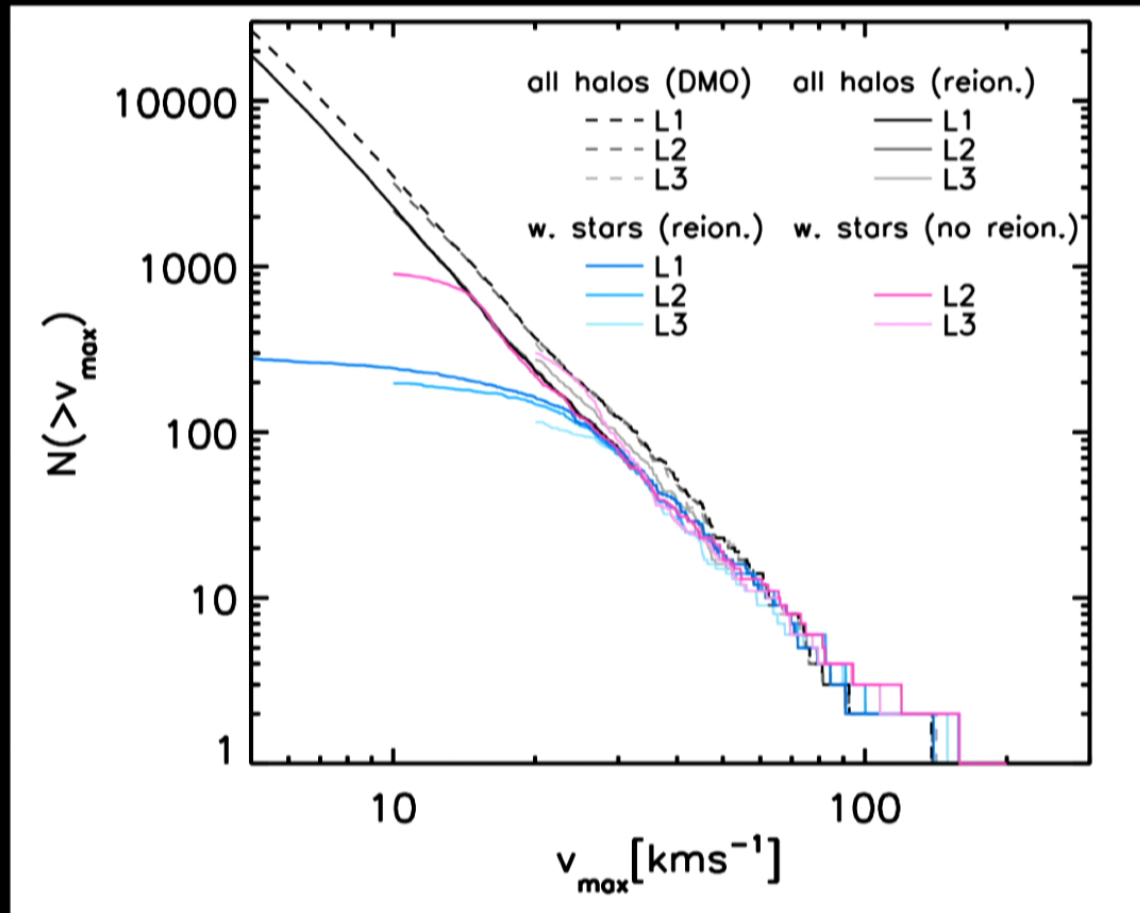
But only a few hundred galaxies



# But only a few hundred galaxies

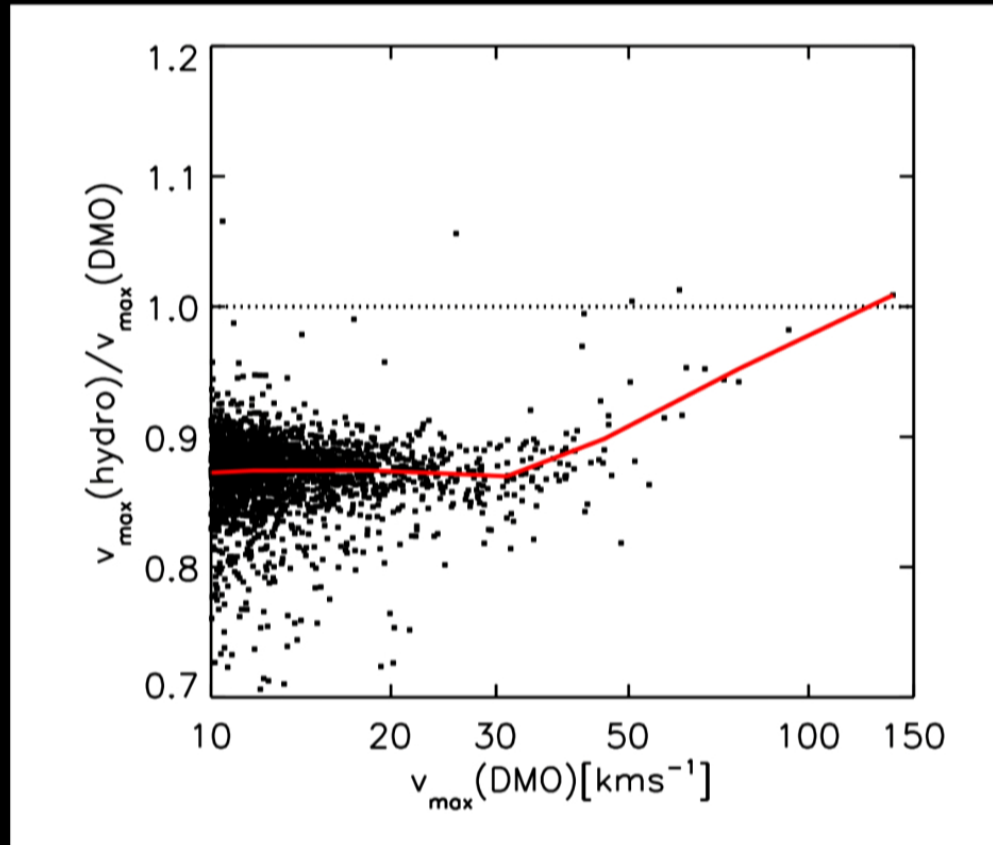


# Baryons change the number of both luminous and dark halos



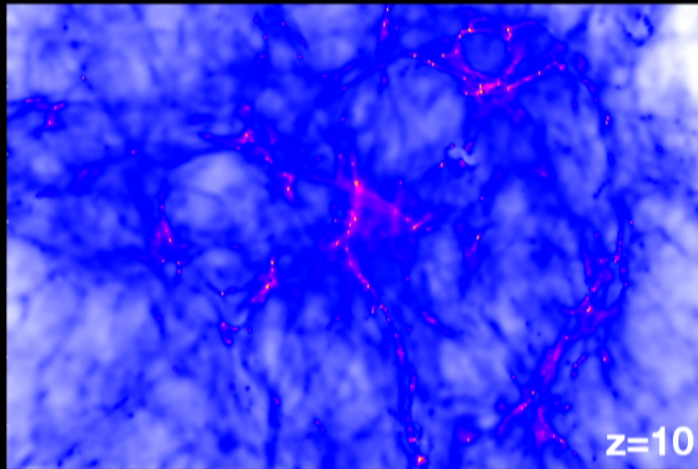
T.S.+ 2015

...because baryon loss means mass loss

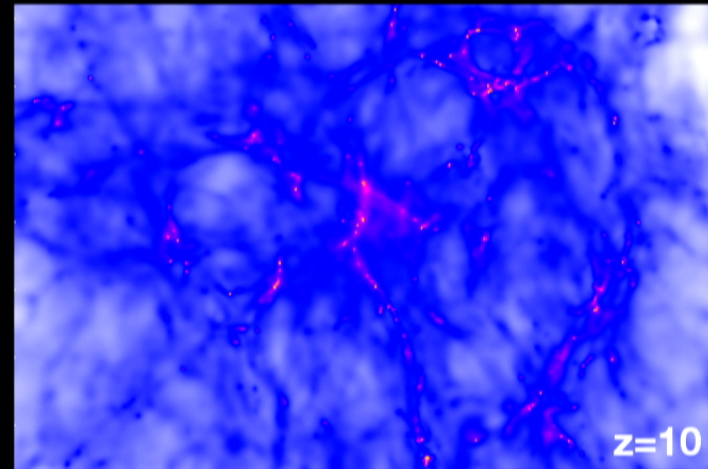


Note: reduction by more than universal baryon fraction, not just outflows, but reduced accretion of both gas and DM

...and reionization leaves halos dark



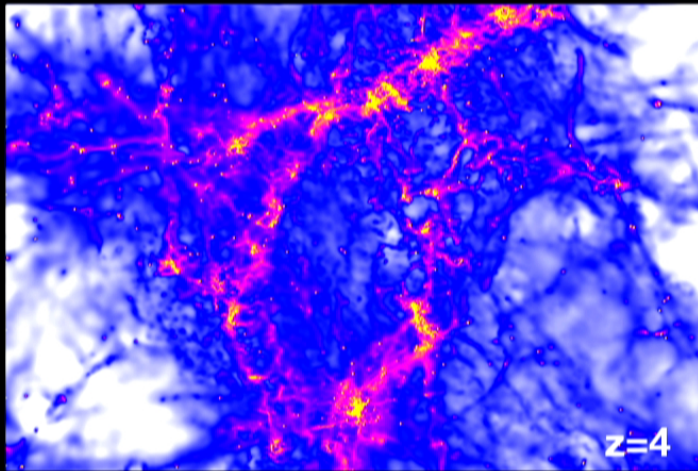
no reionization



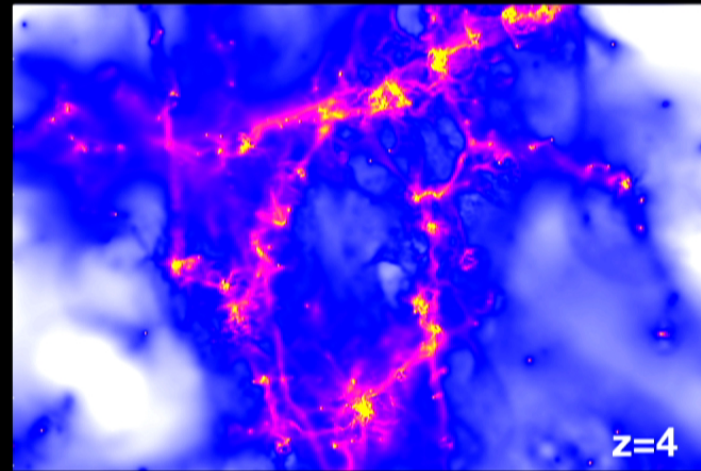
reionization included



...and reionization leaves halos dark

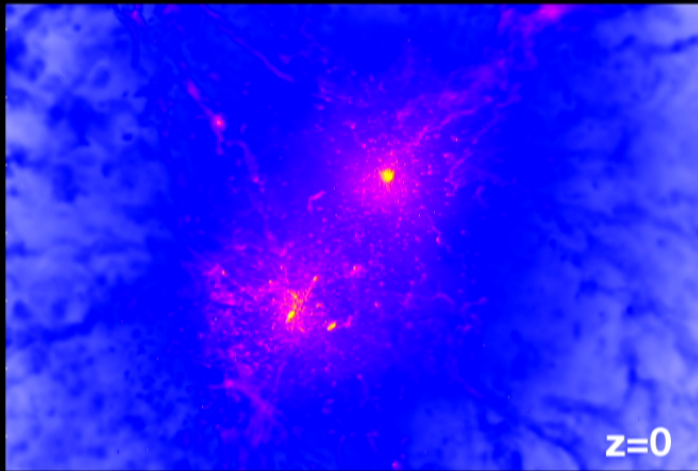


no reionization

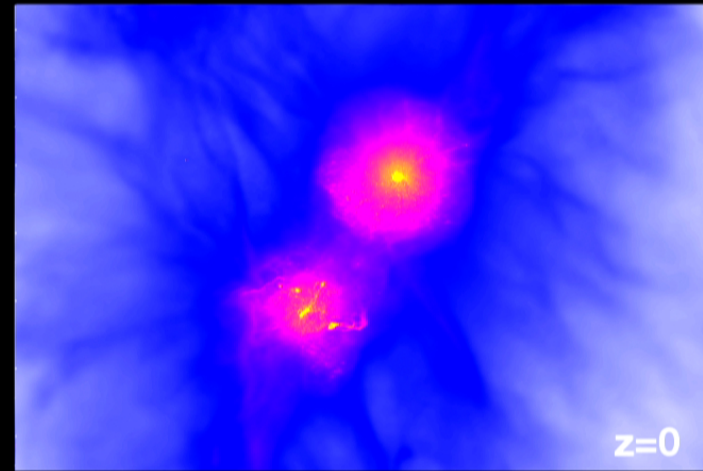


reionization included

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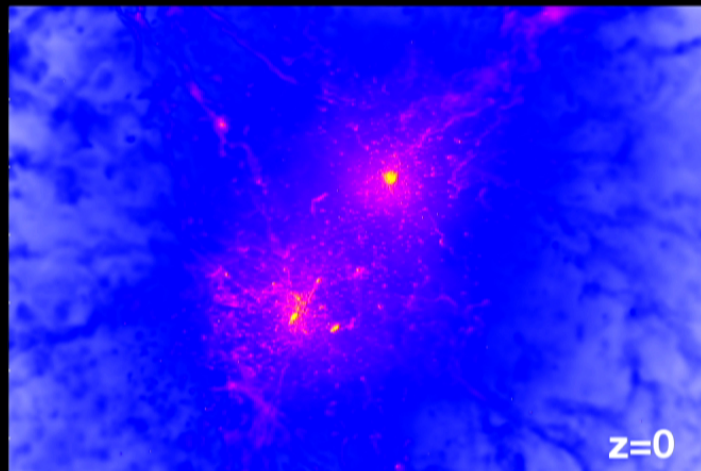


no reionization

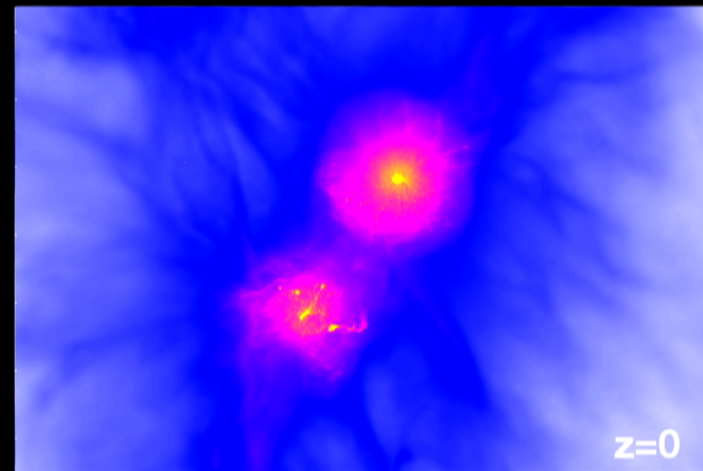


reionization included

...and reionization leaves halos dark

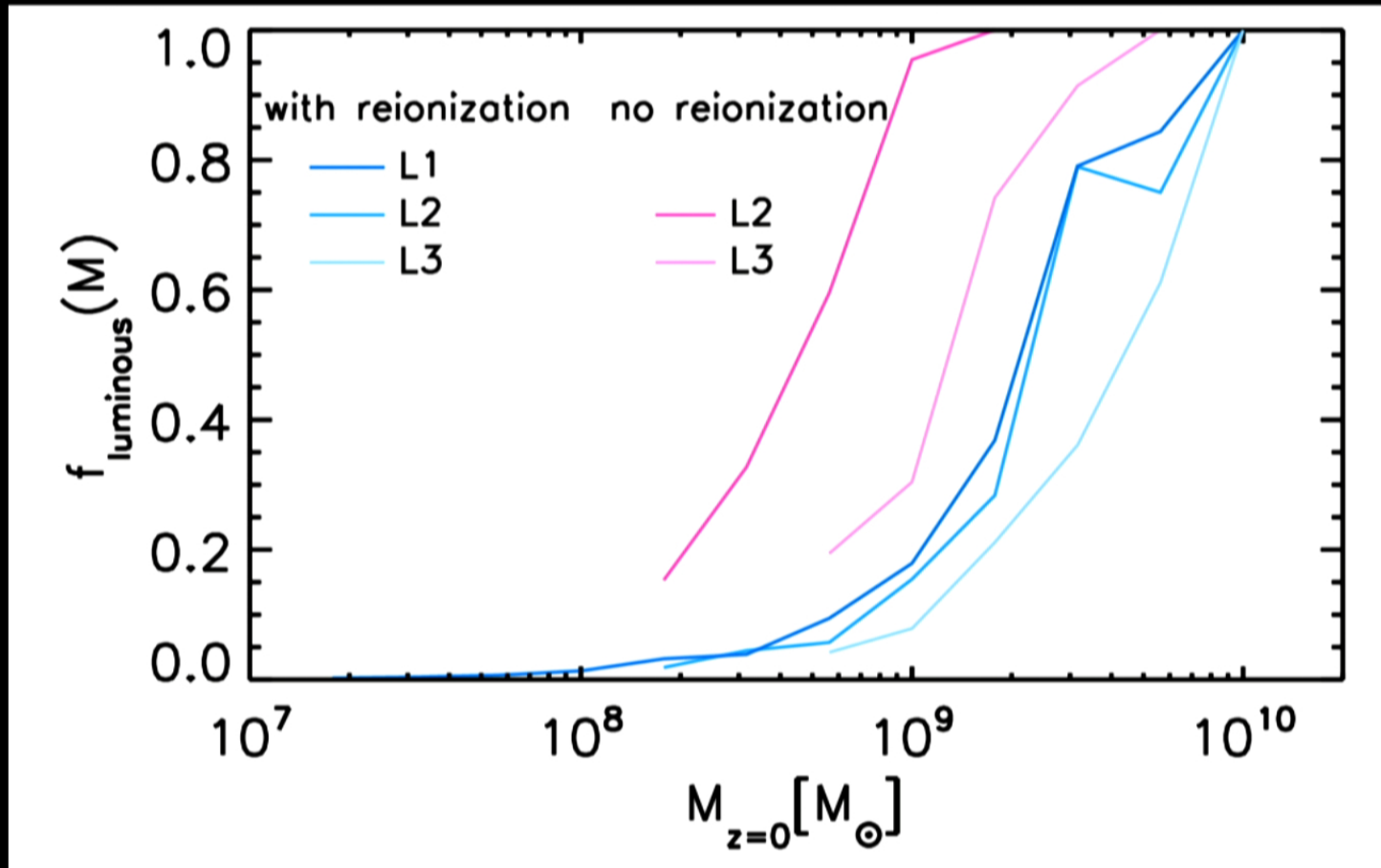


no reionization

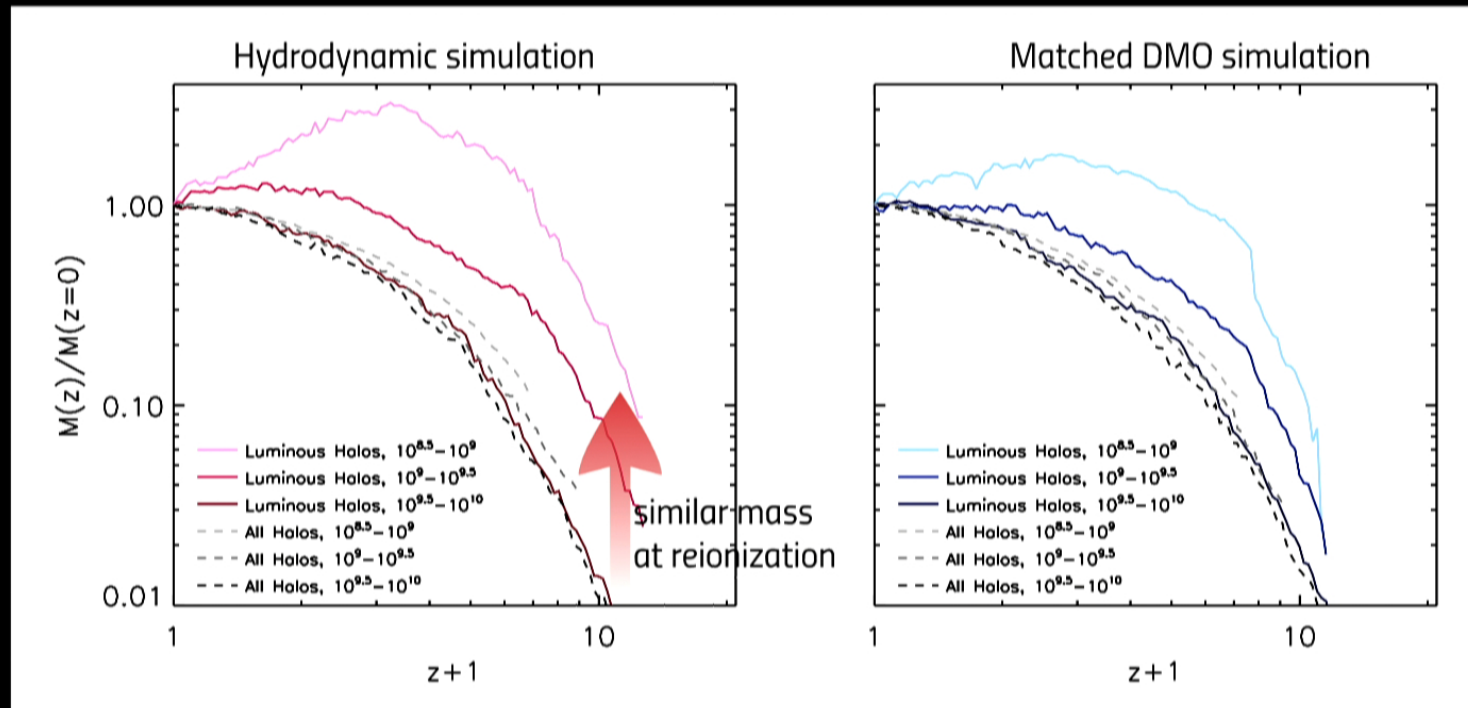


reionization included

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# Galaxy formation becomes a race.



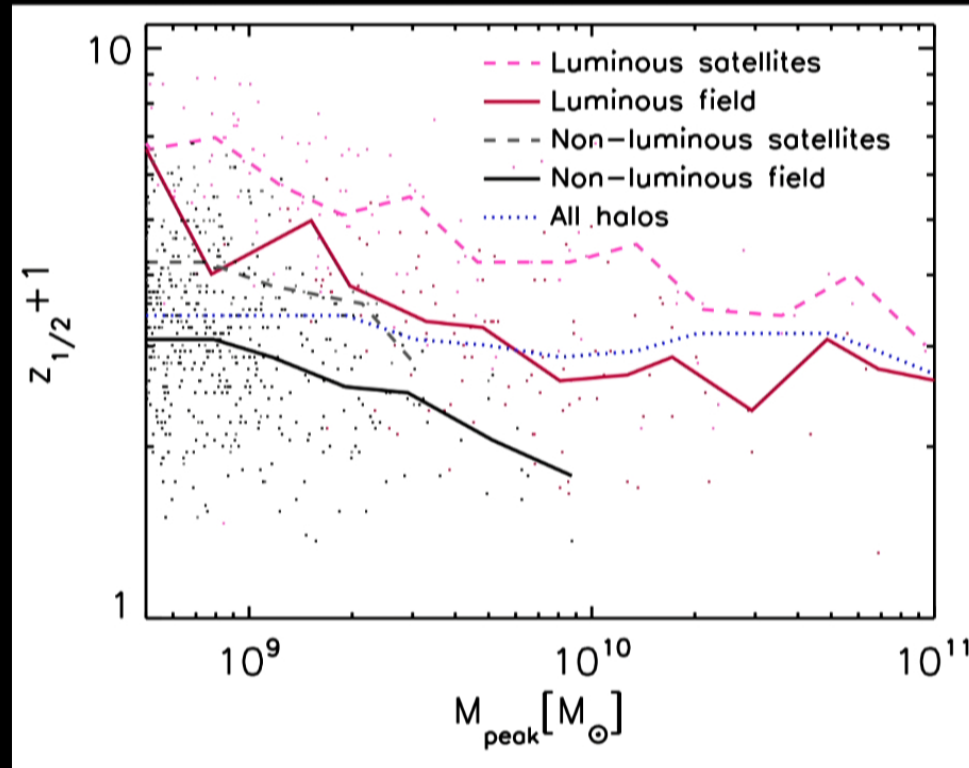
Lower mass halos formed slightly earlier (hierarchical formation).

Galaxies in low mass halos formed much earlier.

Field galaxies in the lowest mass halos likely to be "escaped" satellites.

T.S.+ 2016a

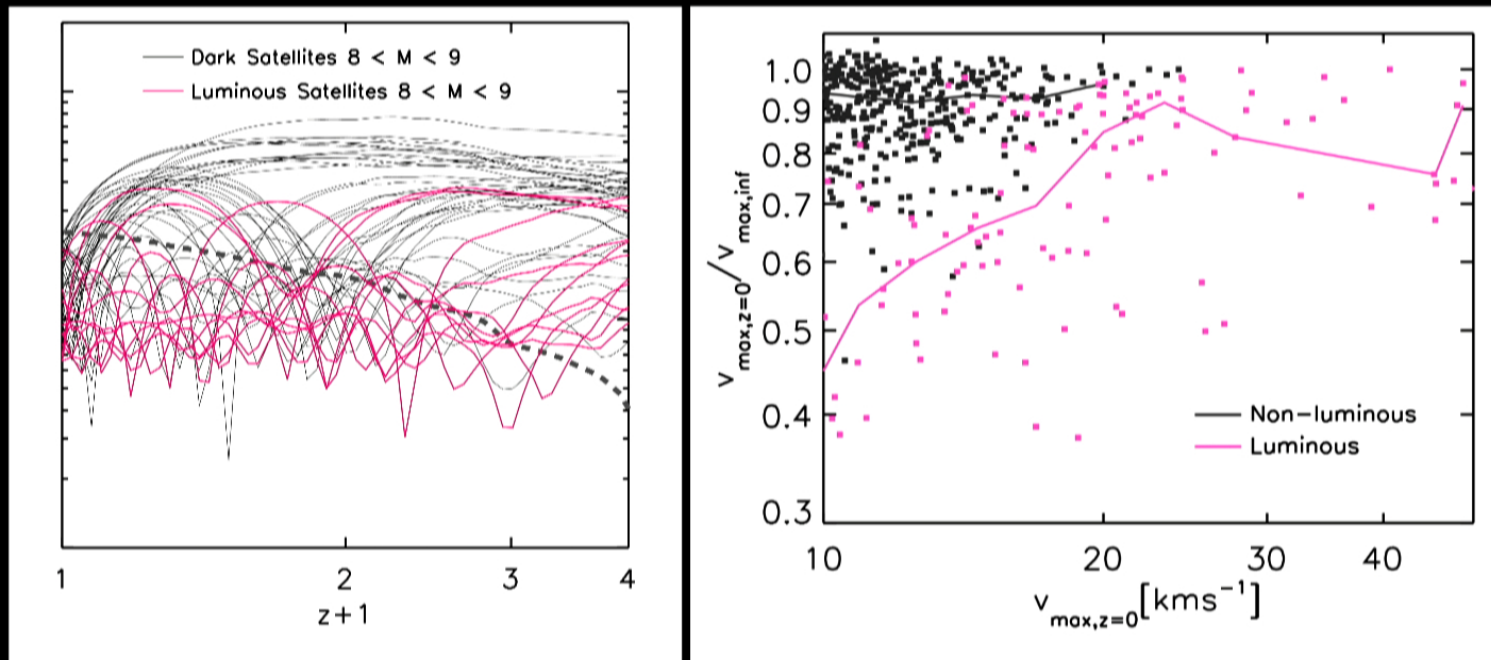
Formation times of low-mass galaxies are mass-dependent.



Unlike the total halo population, both sub-populations of luminous and non-luminous halos show strong mass dependence of formation times.

T.S.+ 2016a

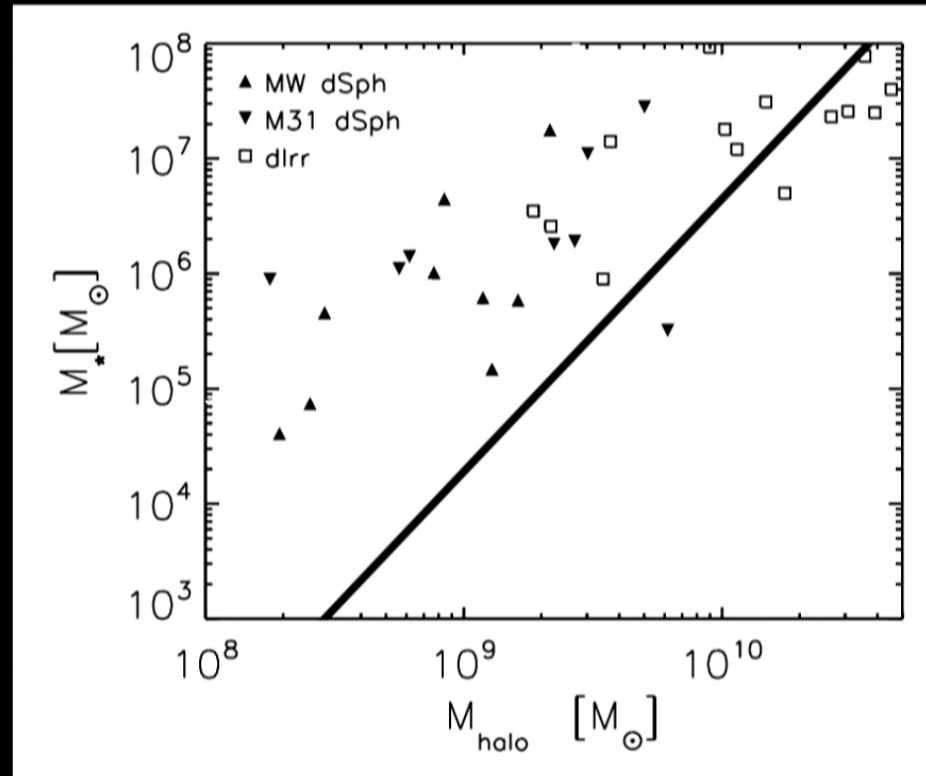
Where most halos are dark, those low mass halos that host satellite galaxies are strongly affected by tidal stripping.



In CDM, typical satellite galaxies do not live in typical halos.

T.S.+ 2016a

# Kinematics of satellites can be reproduced in CDM

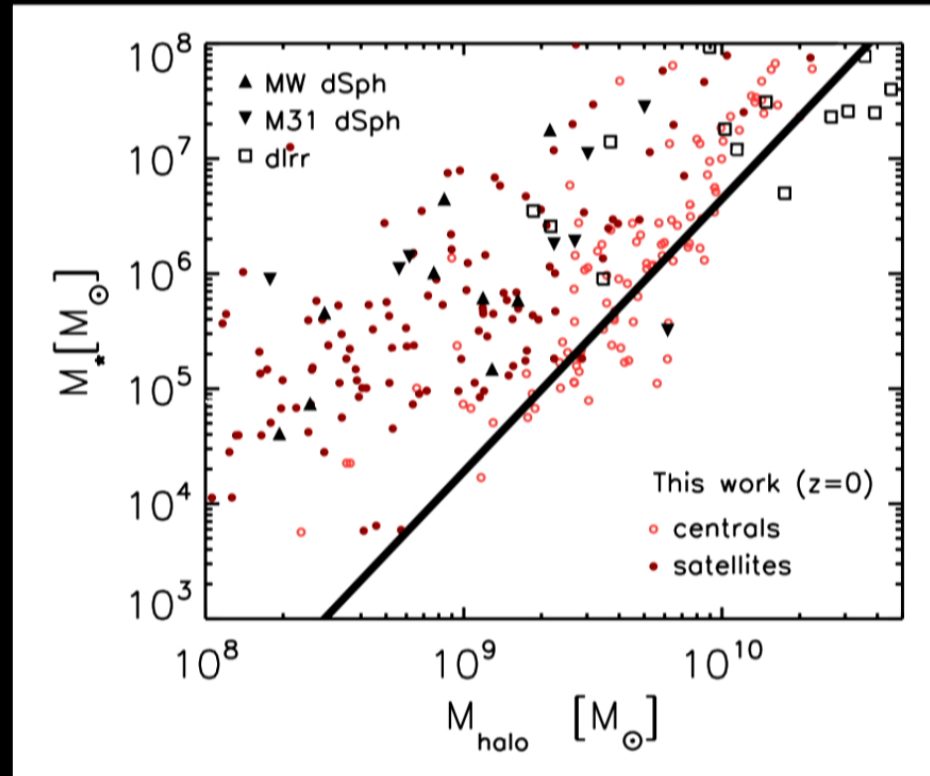


The partial occupation of halos and the strong stripping bends the stellar - halo mass relation of *galaxies* and can reconcile abundance matching with observations. There is no excess of galaxies, because typical *halos* are completely dark.

T.S.+ 2015



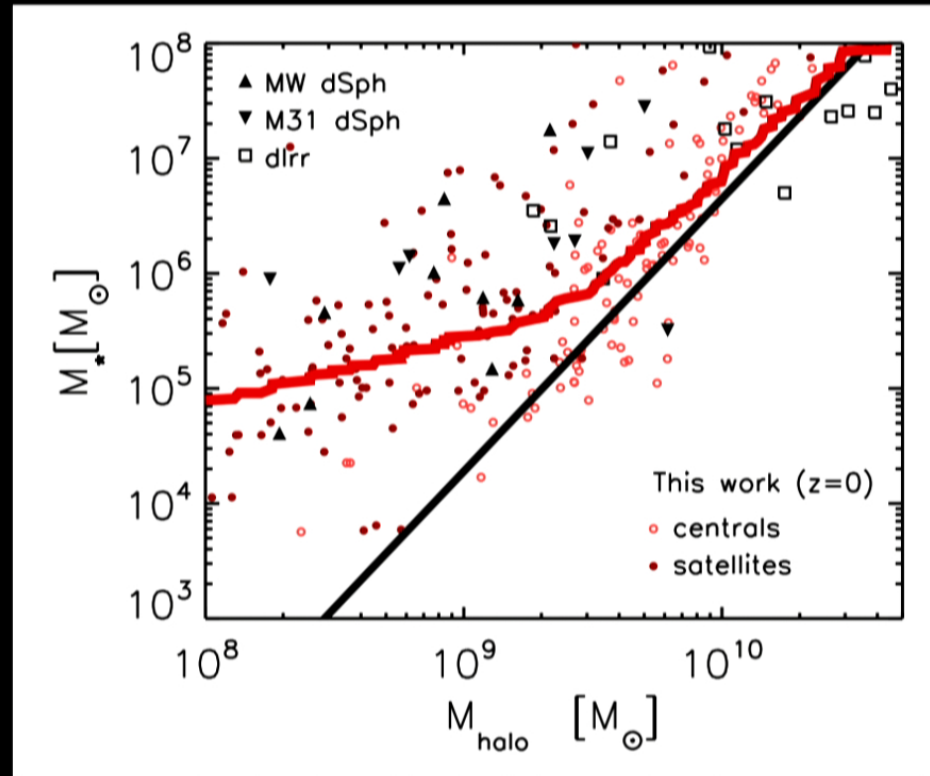
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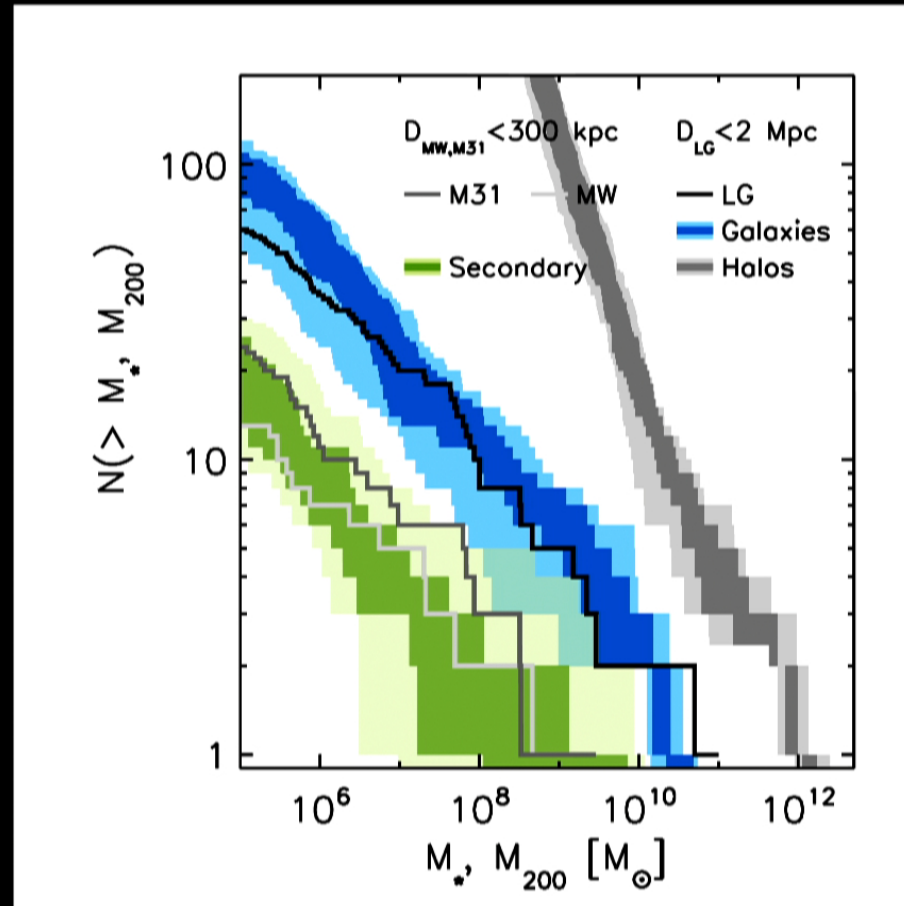
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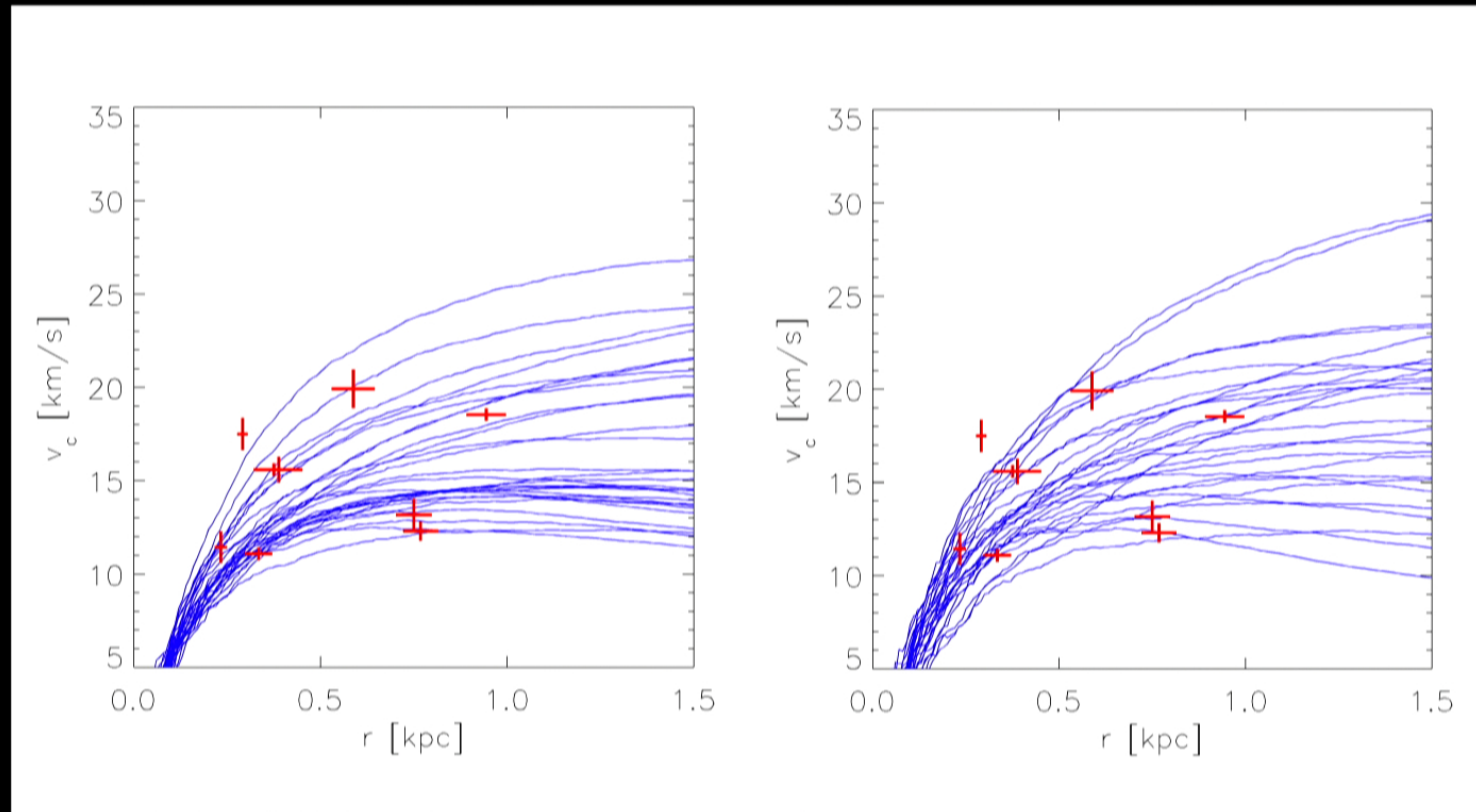
T.S.+ 2015

# No missing and no surplus satellites



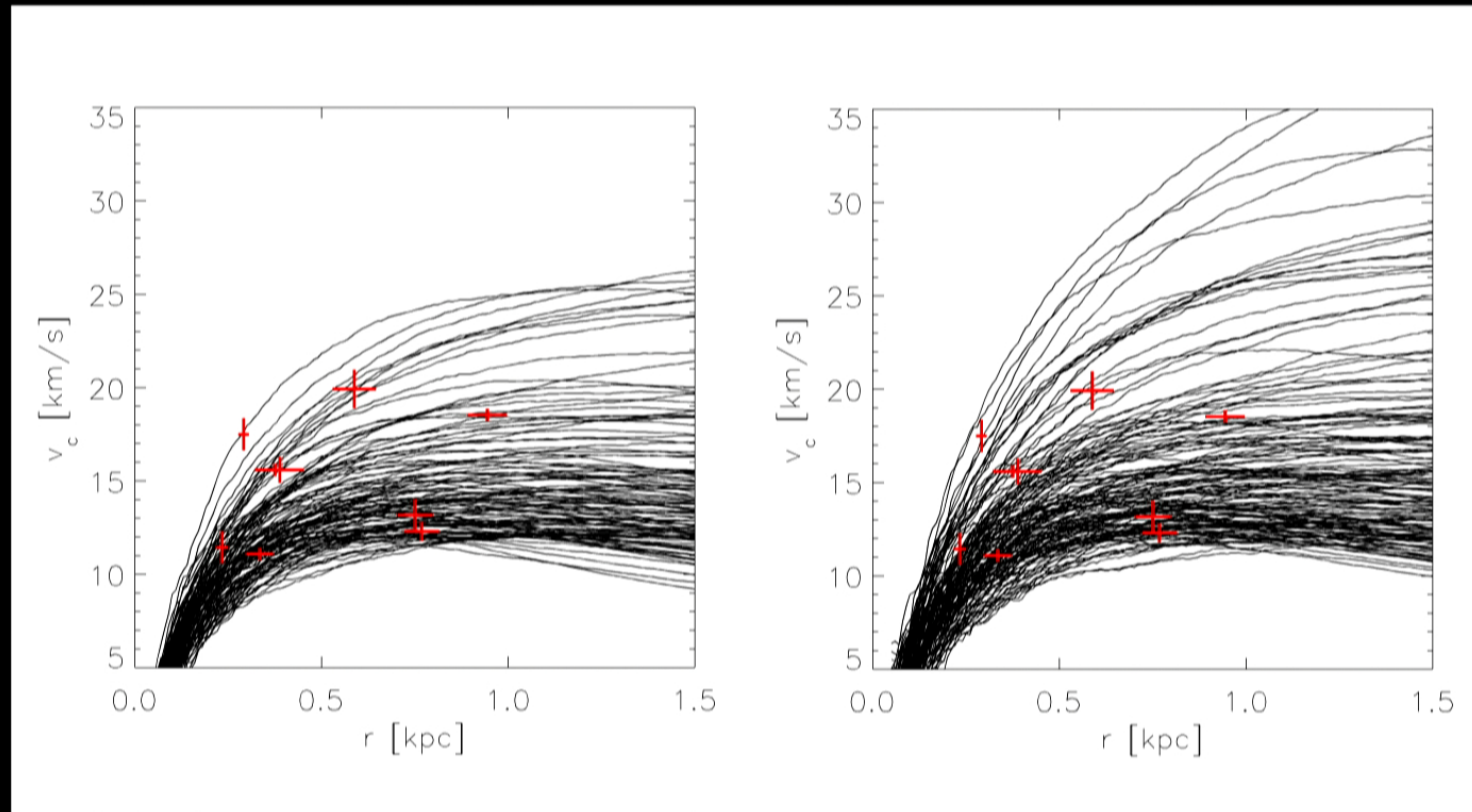
T.S.+ 2016b

# And no "too big to fail" problem



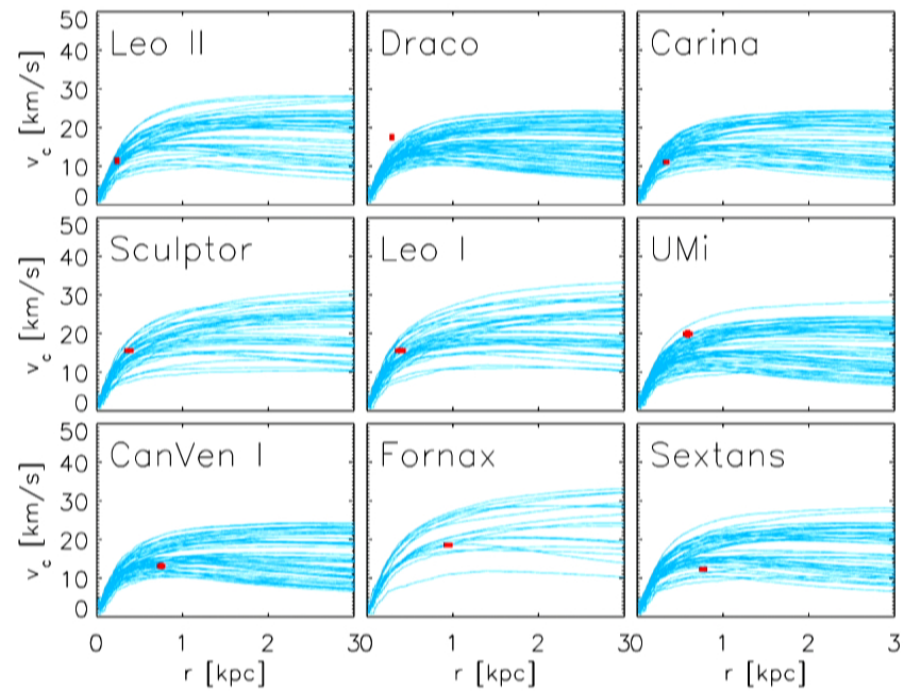
T.S.+ 2016b

# And no "too big to fail" problem



T.S.+ 2016b

# The right satellites in the right halos



Selecting purely by stellar mass

# The Local Group with Blazars



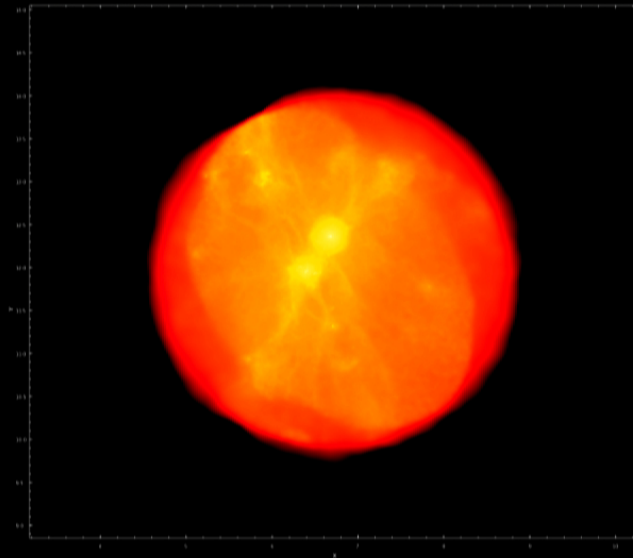
- 1 APOSTLE volume, low and intermediate resolution
- Simulated with the reference EAGLE model, and with the addition of "strong" Blazar heating, following Chang et al. (2011) & Puchwein et al. (2011): uniform Blazar heating rate per unit volume for  $z < 5$ .

simulation model	$\dot{Q}(z = 0)$ [eV Gyr <sup>-1</sup> cm <sup>-3</sup> ]
no blazar heating	0
weak blazar heating	$5.8 \times 10^{-8}$
intermediate blazar heating	$1.08 \times 10^{-7}$
strong blazar heating	$1.62 \times 10^{-7}$

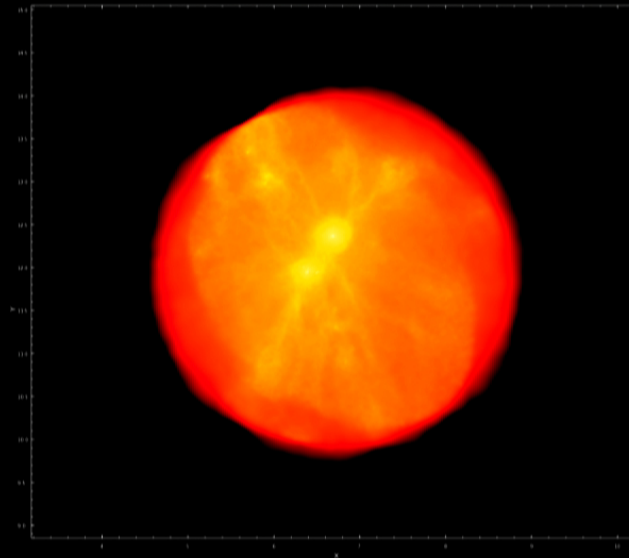
$$\log_{10} \left( \frac{\dot{Q}(z)}{\dot{Q}(z = 0)} \right) = 0.0315 \times [(1 + z)^3 - 1] - 0.512 \times [(1 + z)^2 - 1] + 2.27 \times [(1 + z) - 1]$$

from: Puchwein+ (2011),  
adopted from Chan+ (2011)

# The Local Group with Blazars



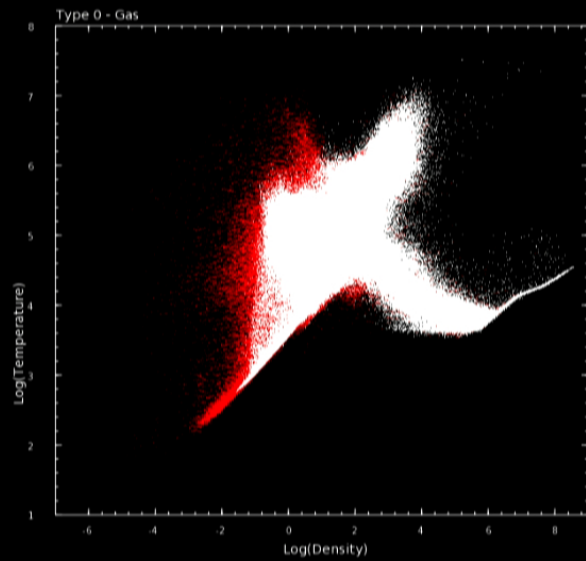
Contour: 0.718, 11.951, 59.105



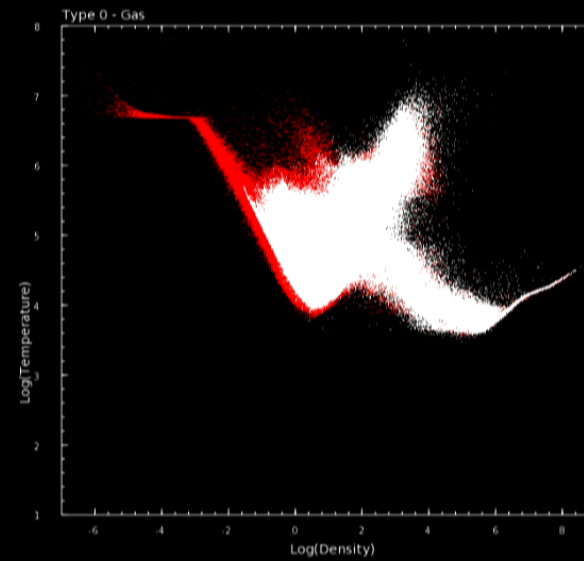
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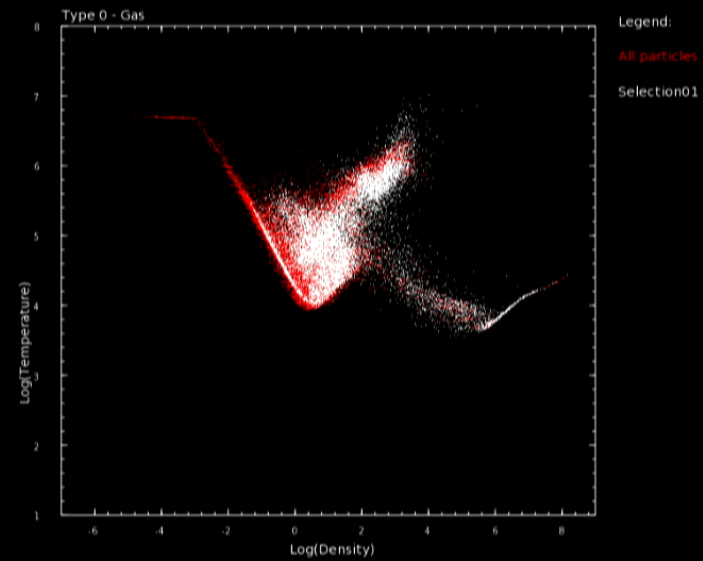
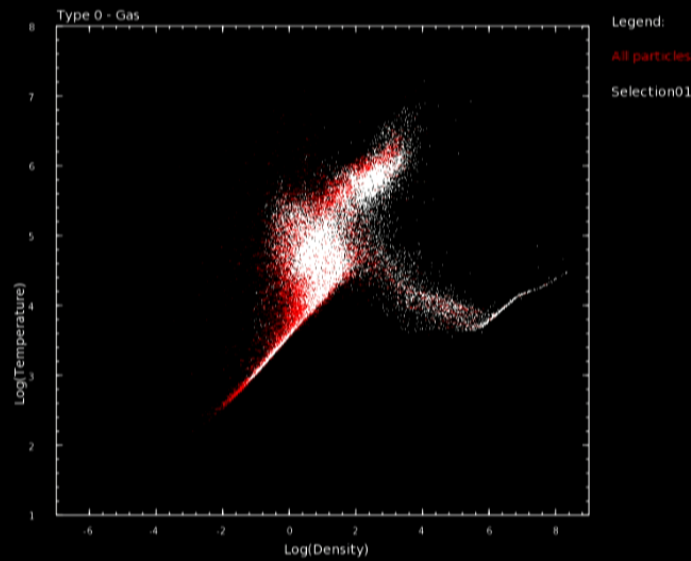


Legend:  
All particles  
Selection01

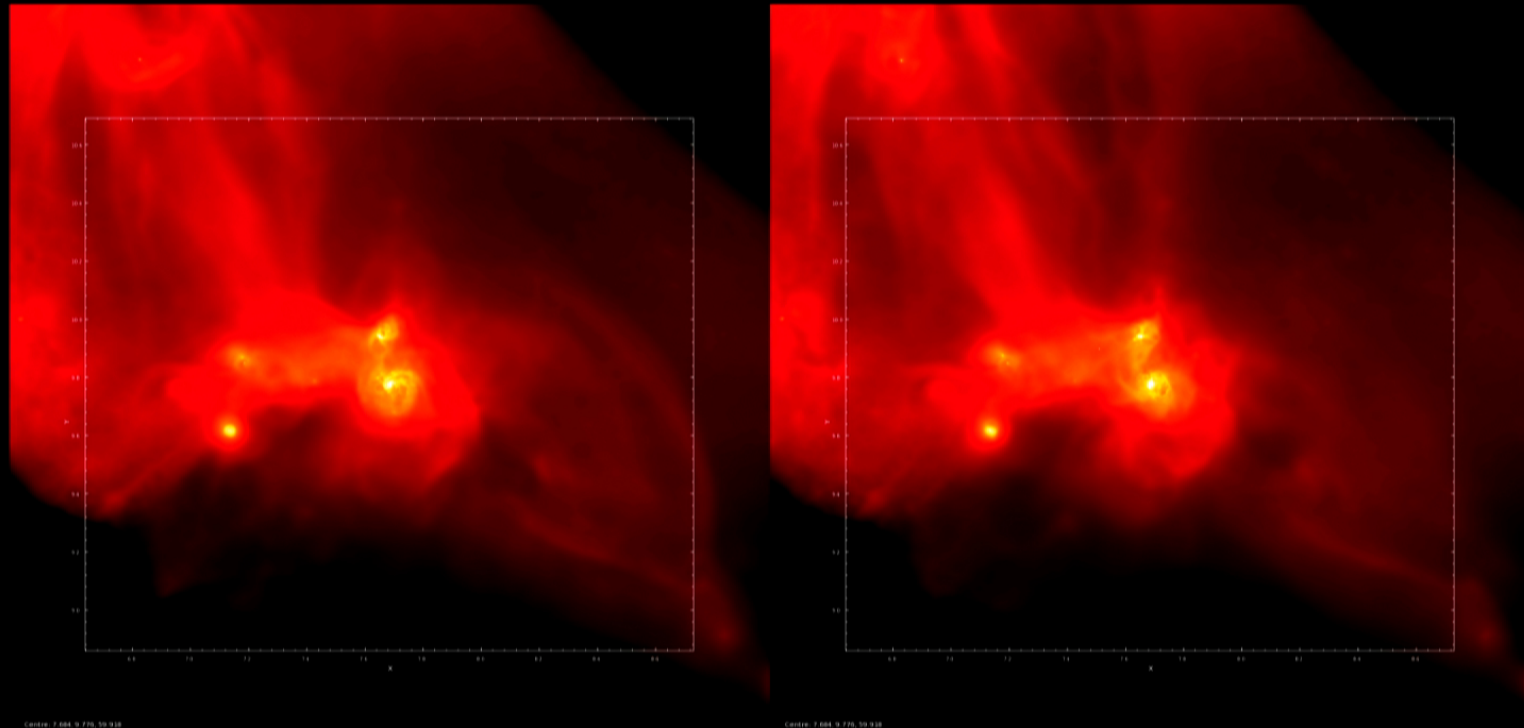


Legend:  
All particles  
Selection01

# The Local Group with Blazars



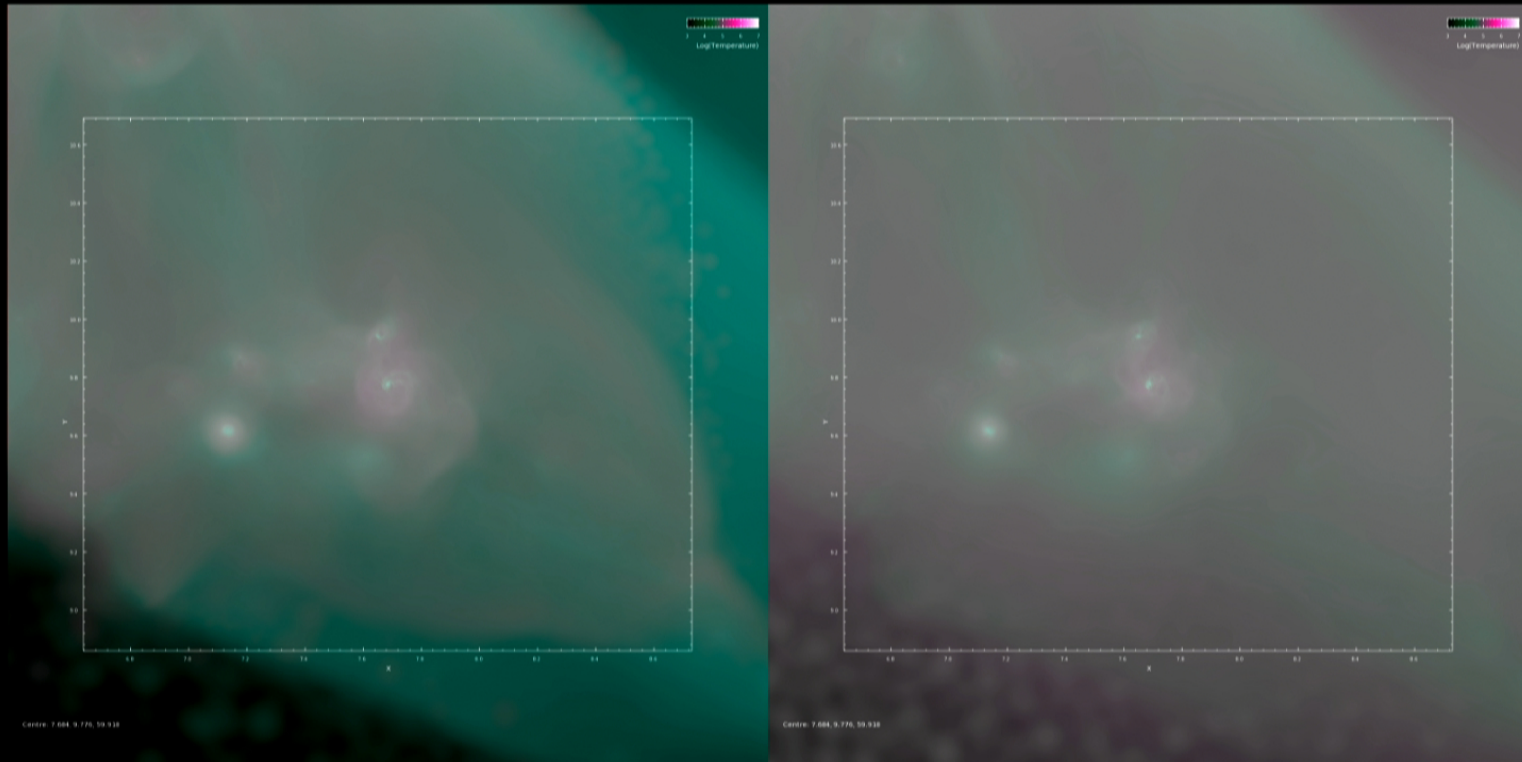
# The Local Group with Blazars



Centre: 1 684 x 770, 30 938

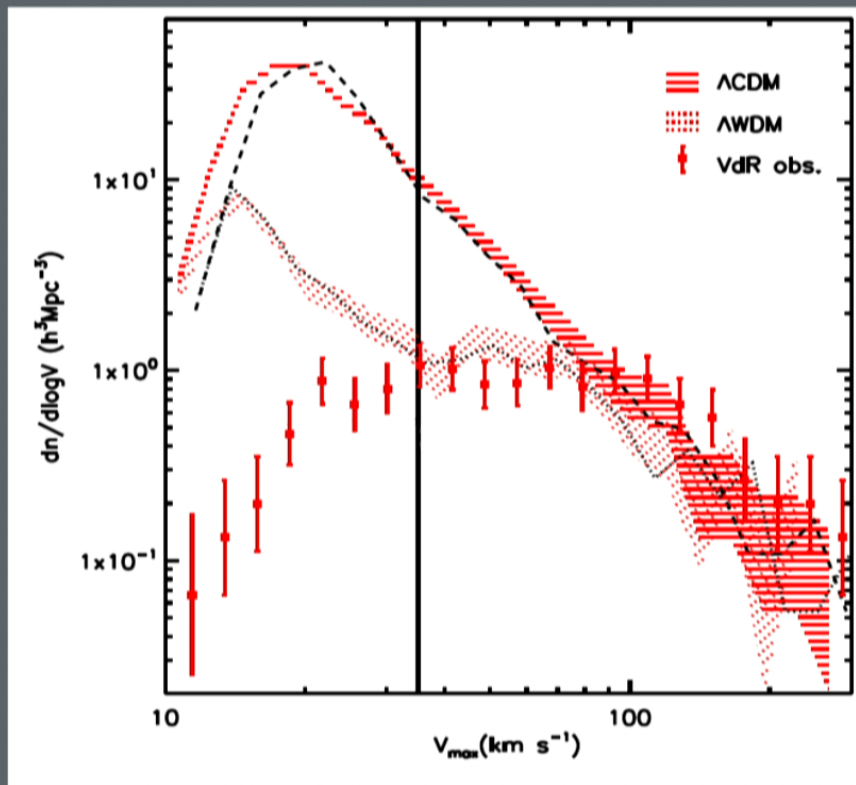
Centre: 1 684 x 770, 30 938

# The Local Group with Blazars



# Summary

- Including a "realistic" model for galaxy formation physics can reproduce the observed Local Group galaxy population in CDM, including the mass-to-light ratios of satellites.
- The success of CDM in explaining the observations extends to the scales testable in the Local Group. This is not a *verification*, but further progress from small scales requires to take baryon physics into account.
- Including even "strong" blazar feedback in the Local Group, leaving all else unchanged, heats the diffuse IGM, but has little effect on the LG galaxy population.

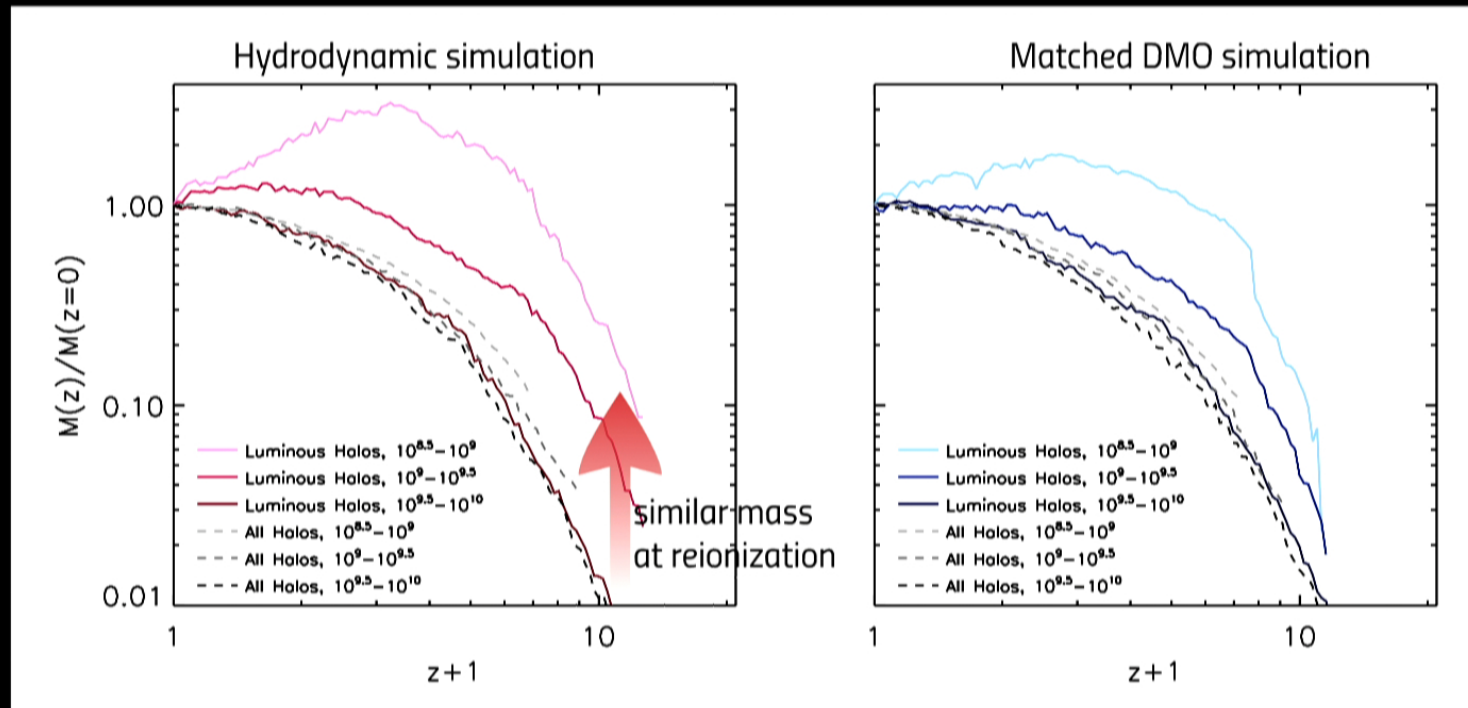


Zavala+ (2009)

# Simulations beyond the Local Universe (SIBELIUS)

- 2016-1017: Zoom + Constraint initial conditions, including the Local Voids
- Updates to the Eagle Code: Later reionization ( $z=11.5 \rightarrow z=8.8$ ), self-shielding, increased resolution.
- Perhaps a smoking gun for Blazar heating?

# Galaxy formation becomes a race.



Lower mass halos formed slightly earlier (hierarchical formation).

Galaxies in low mass halos formed much earlier.

Field galaxies in the lowest mass halos likely to be "escaped" satellites.

T.S.+ 2016a