University of Durham

The small-scale “problems“ of CDM

Carlos Frenk, ICC Durham

The Ogden Centre
at Durham

Take home message: two pleas

1. To experimentalists. Please keep looking for CDM – it is very likely that it is out there!

2. To theorists. Please do not invent new particles to solve the "small-scale crisis" of CDM - there is no such crisis!

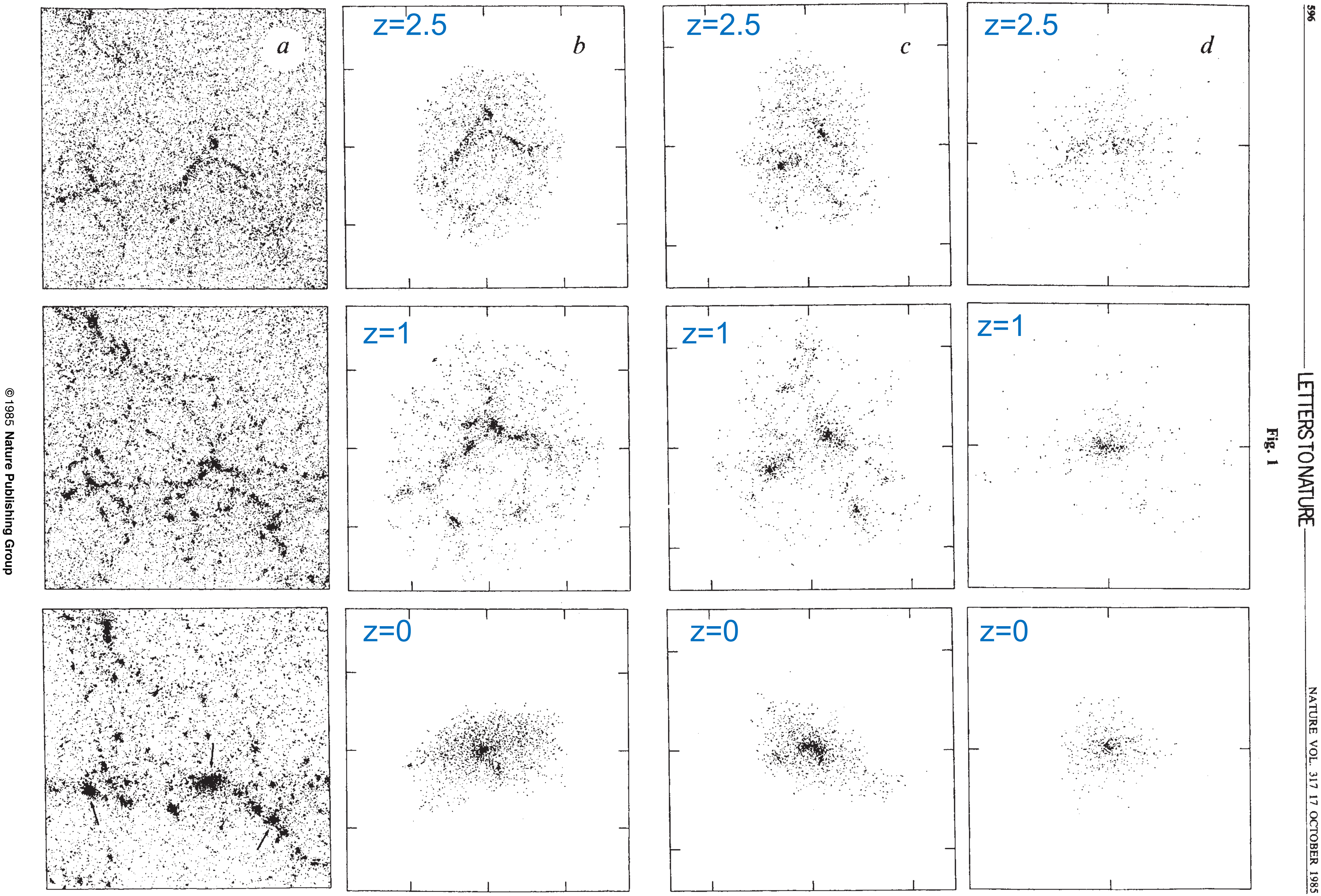
University of Durham

The four small-scale “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

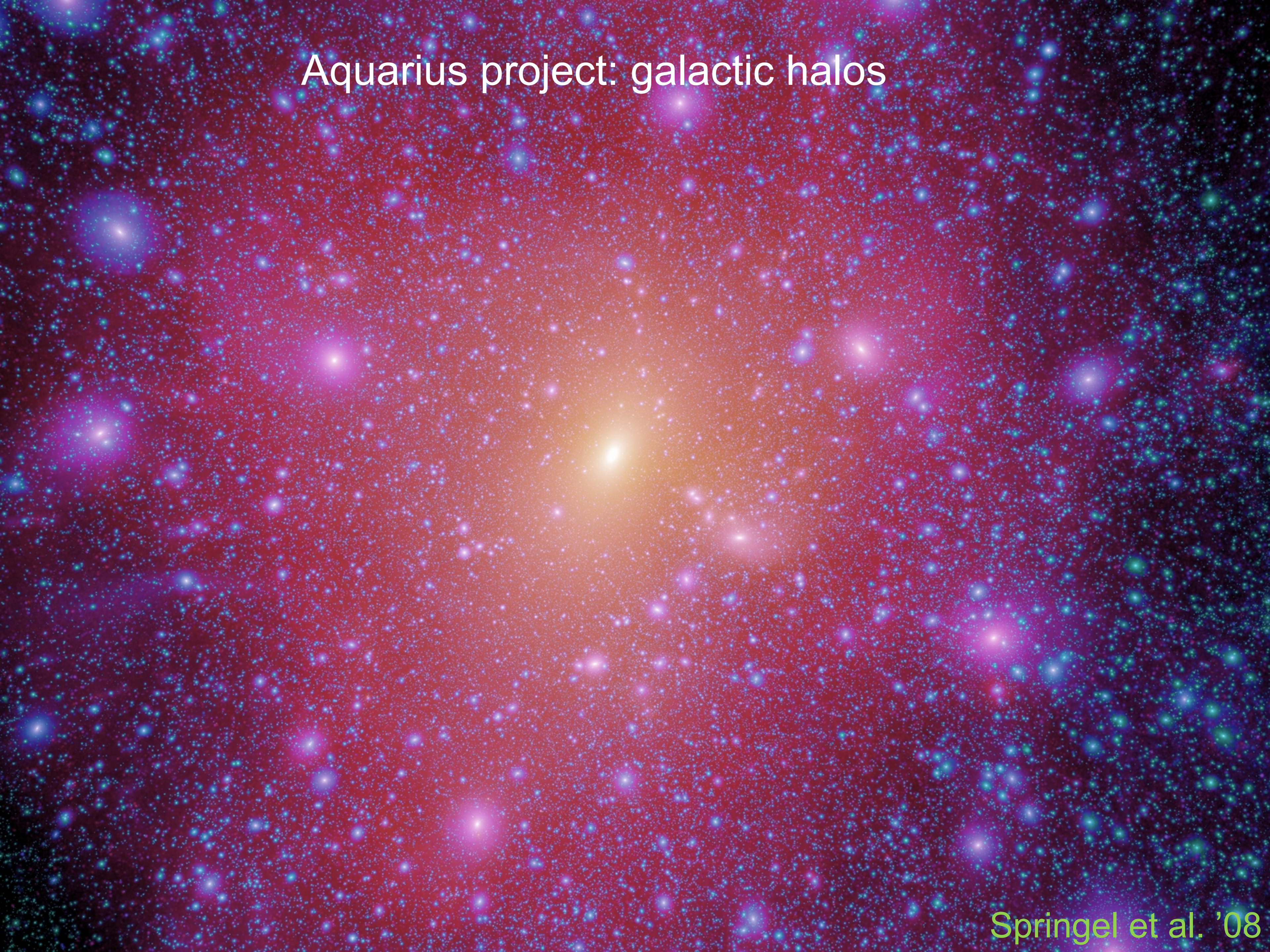
Solved before they became a “problem” for CDM

Formation of CDM halos



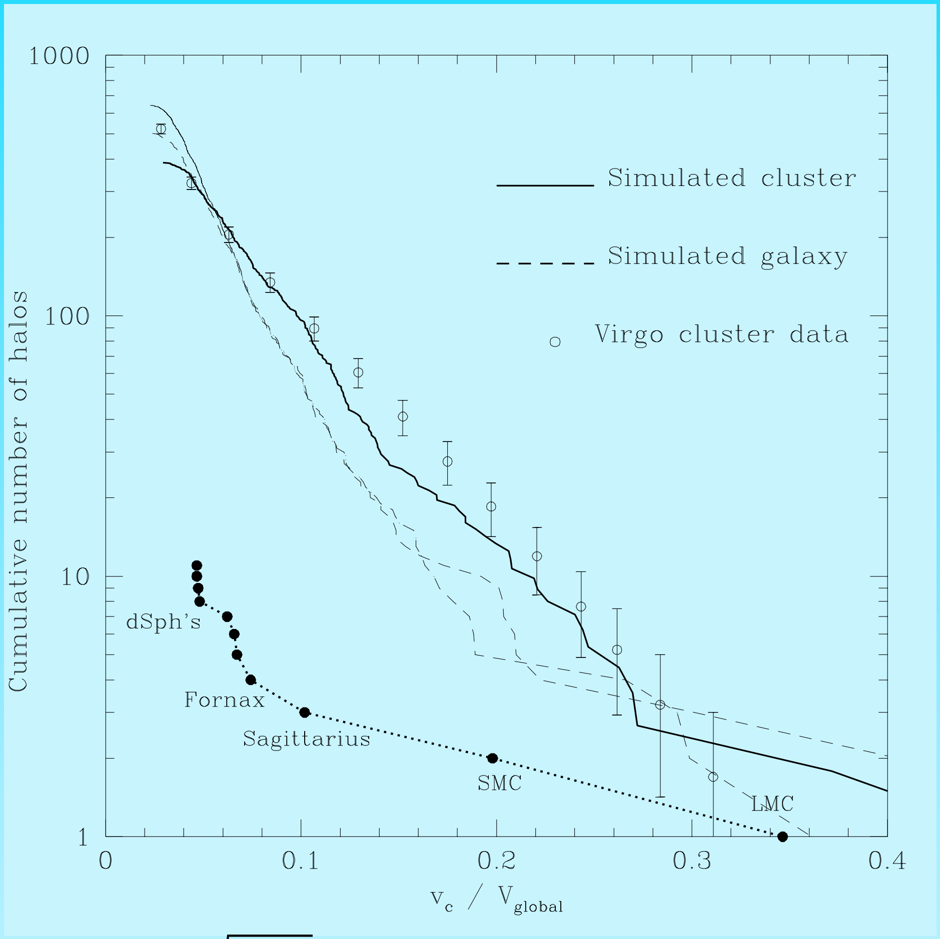
Frenk et al 1985

Aquarius project: galactic halos



Springel et al. '08

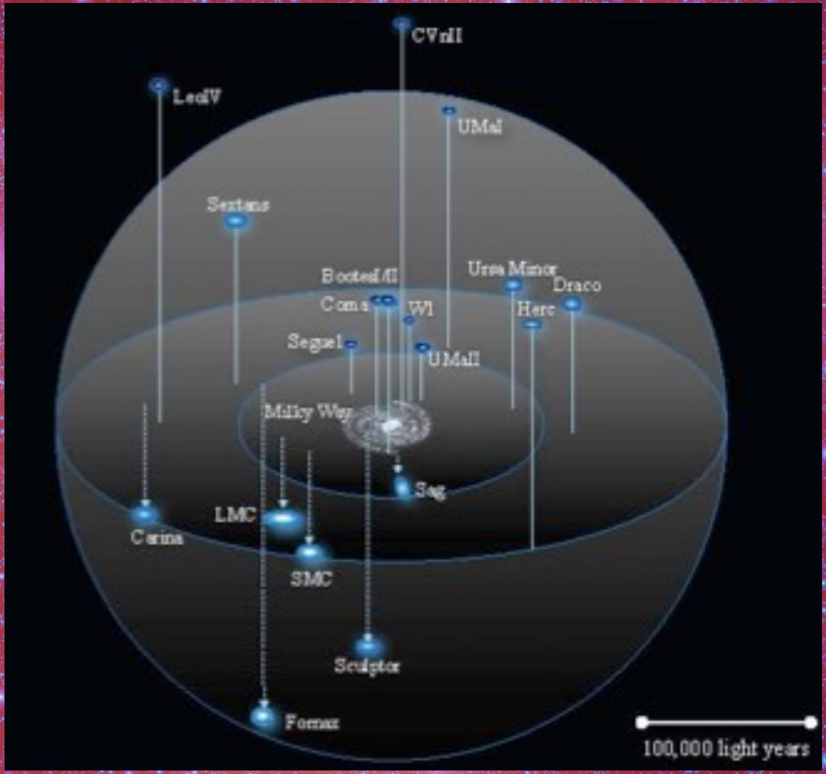
Moore et al ‘99 Klypin et al ’99



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

Institute for Computational Cosmology

In the MW: ~55 satellites discovered so far



“Missing satellites” problem:

CDM predicts many more subhalos in the Milky Way than there are observed satellites

Springel et al. ’08

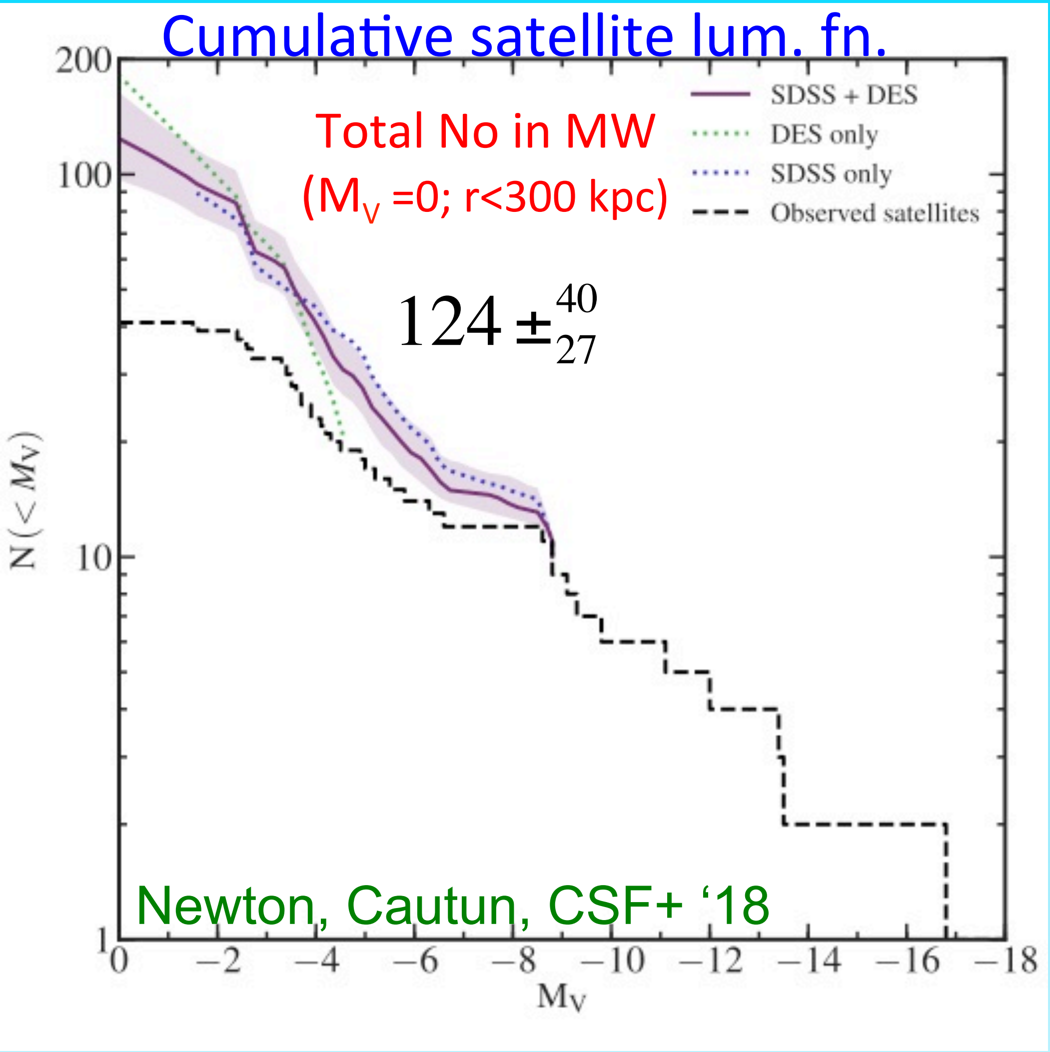
University of Durham

The MW satellite luminosity function

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)

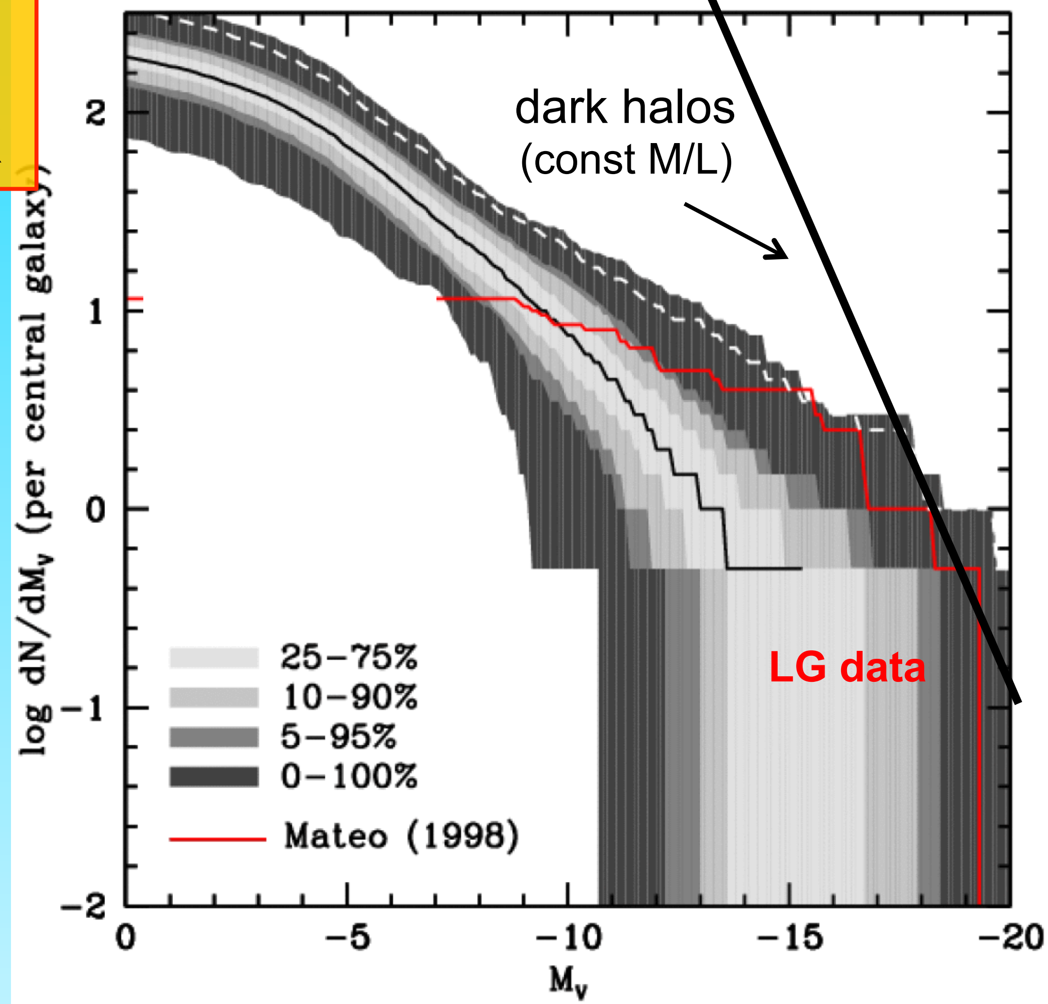



Most subhalos never make a galaxy!

Luminosity Function of Local Group Satellites

Semi-analytic model of galaxy formation including effects of reionization and SN feedback

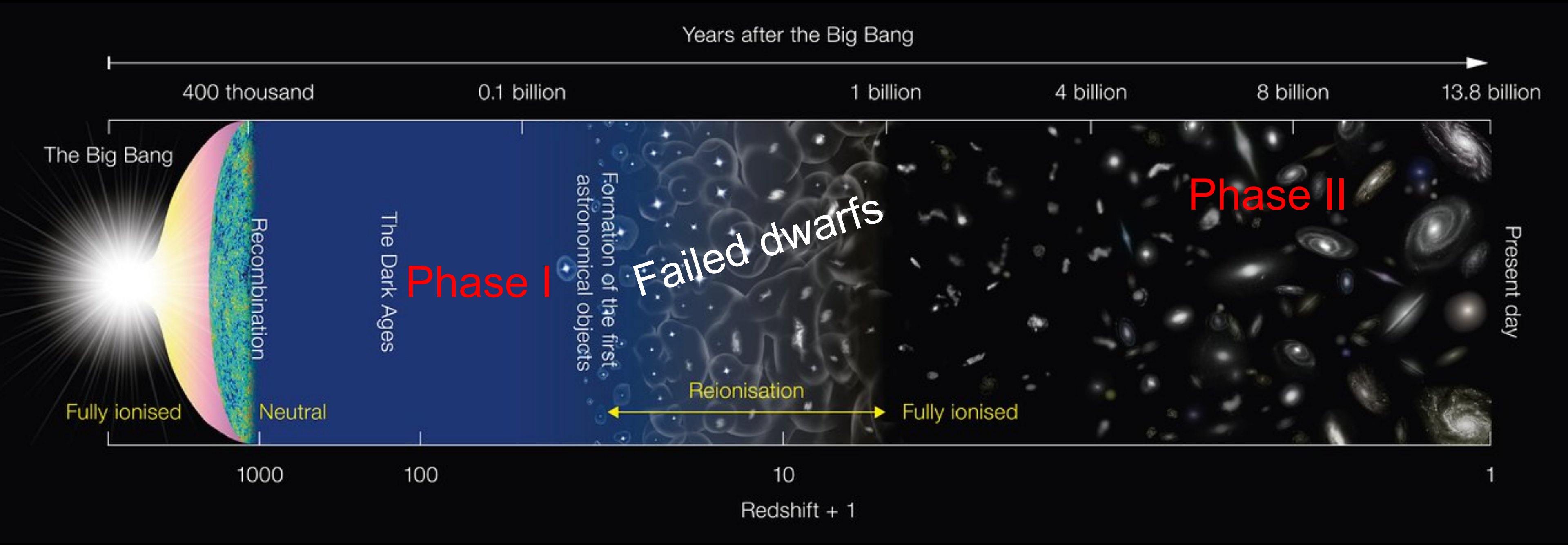
- Median model → correct abundance of sats brighter than M_V=-9 (V_{cir} > 12 km/s)
- Model predicts many, as yet undiscovered, faint satellites



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

University of Durham
Institute for Computational Cosmology

The two phases of galaxy formation



Phase I: During the "dark ages" H gas is neutral

First stars reionize H and heat it up to 10^4K

Phase II: H Gas is ionized ("T_{vir}" > 10^4K form)

A galaxy formation primer

1. Before reionization, stars can only form if gas can cool for which

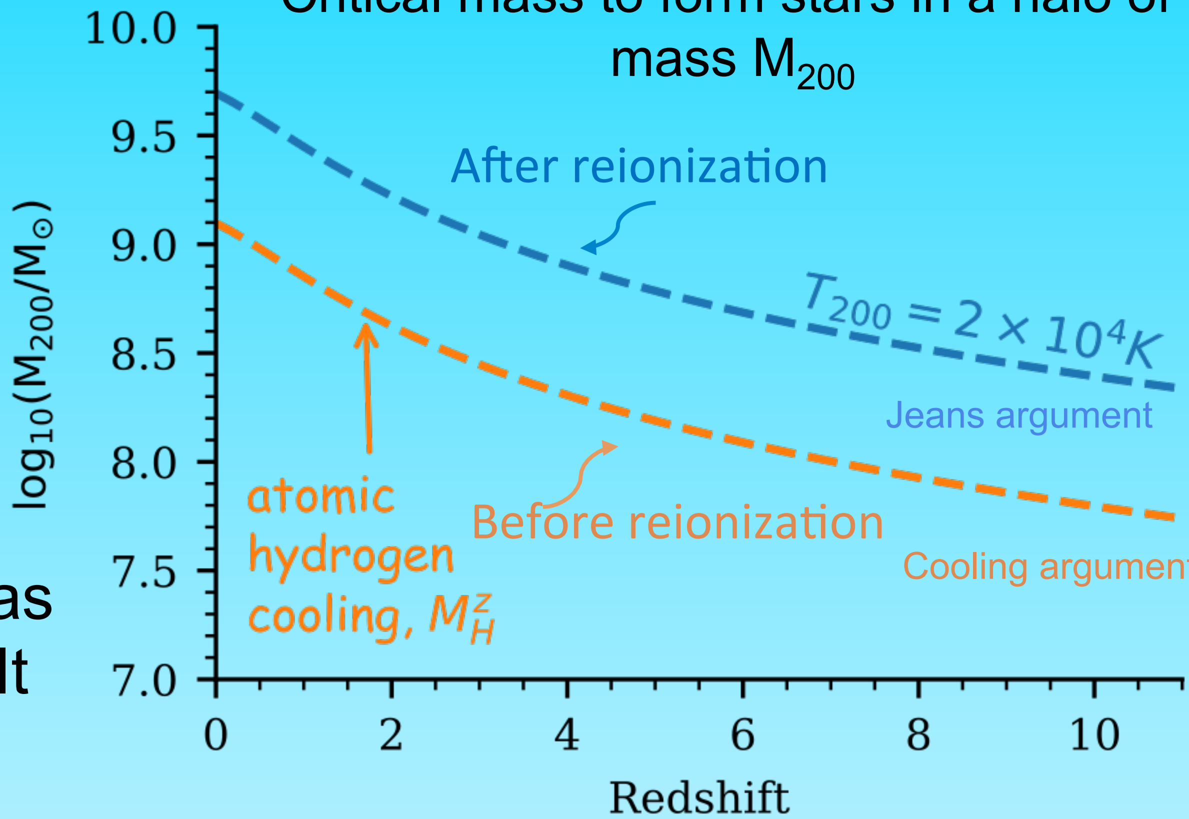
→ T>7000 K

$$M_H^z \sim (4\times10^7\ M_\odot)\left(\frac{1+z}{11}\right)^{-3/2}$$

2. After H reionization, gas is heated to T=2x10^4 K. It can only cool and form stars in halos with:

$T_{vir} > T_{IGM} = 2\text{x}10^4$ K

Critical mass to form stars in a halo of mass M_{200}



Benitez-Llambay & CSF '20

University of Durham
Institute for Computational Cosmology

A galaxy formation primer

University of Durham

1. Before reionization, stars can only form if gas can cool for which

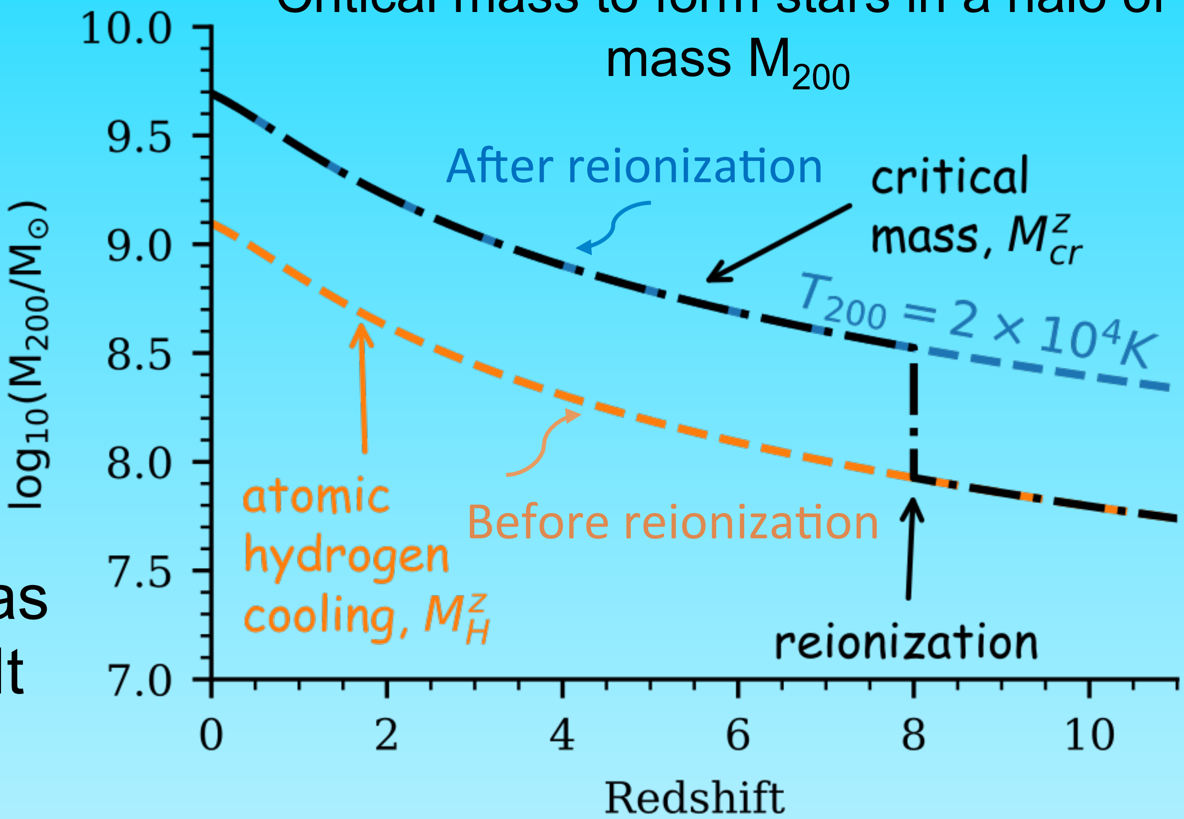
→ T>7000 K

$$M_H^z \sim (4 \times 10^7\ M_\odot)\left(\frac{1+z}{11}\right)^{-3/2}$$

2. After H reionization, gas is heated to $T=2\text{x}10^4$ K. It can only cool and form stars in halos with:

$T_{vir} > T_{IGM} = 2\text{x}10^4$ K

Critical mass to form stars in a halo of mass M_{200}



Benitez-Llambay & CSF '20

Institute for Computational Cosmology

A galaxy formation primer

University of Durham

1. Before reionization, stars can only form if gas can cool for which

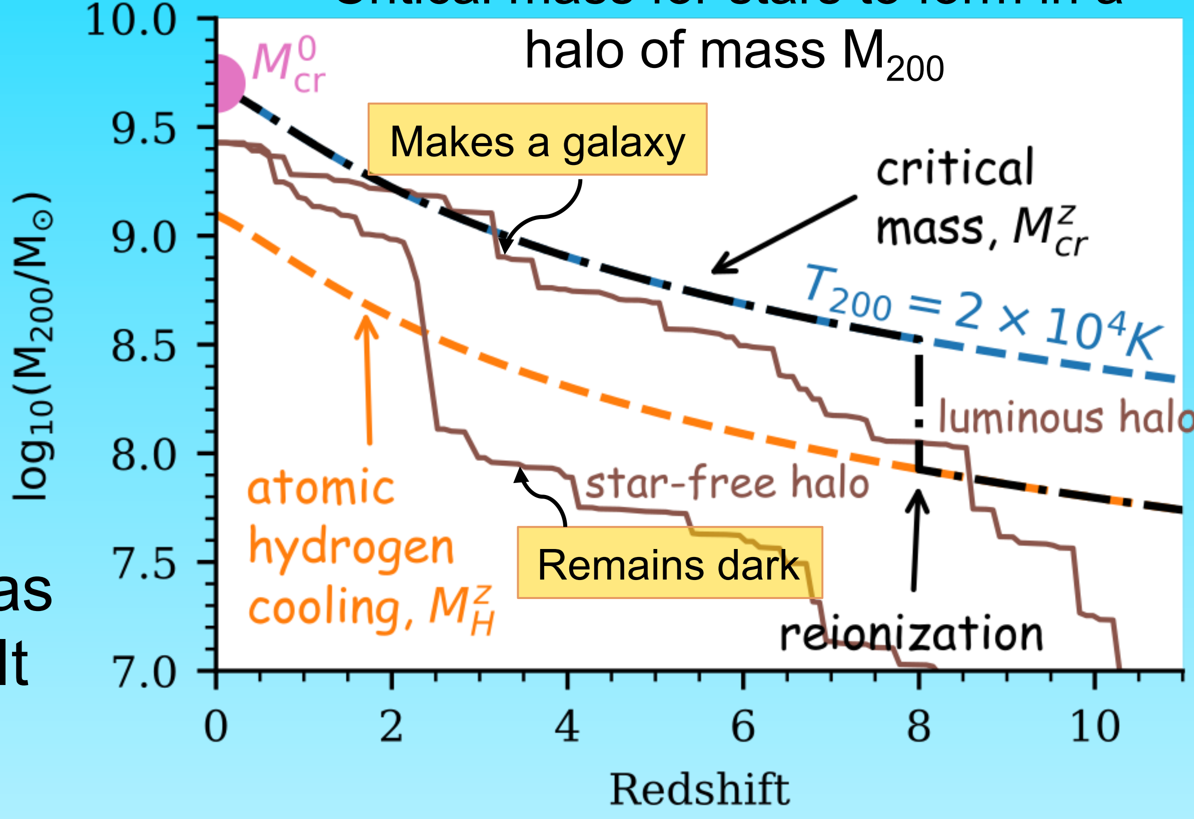
→ T>7000 K

$$M_H^z \sim (4\times 10^7\ M_\odot)\left(\frac{1+z}{11}\right)^{-3/2}$$

2. After H reionization, gas is heated to T=2x10^4 K. It can only cool and form stars in halos with:

$T_{vir} > T_{IGM} = 2\times10^4$ K

Critical mass for stars to form in a halo of mass M_{200}



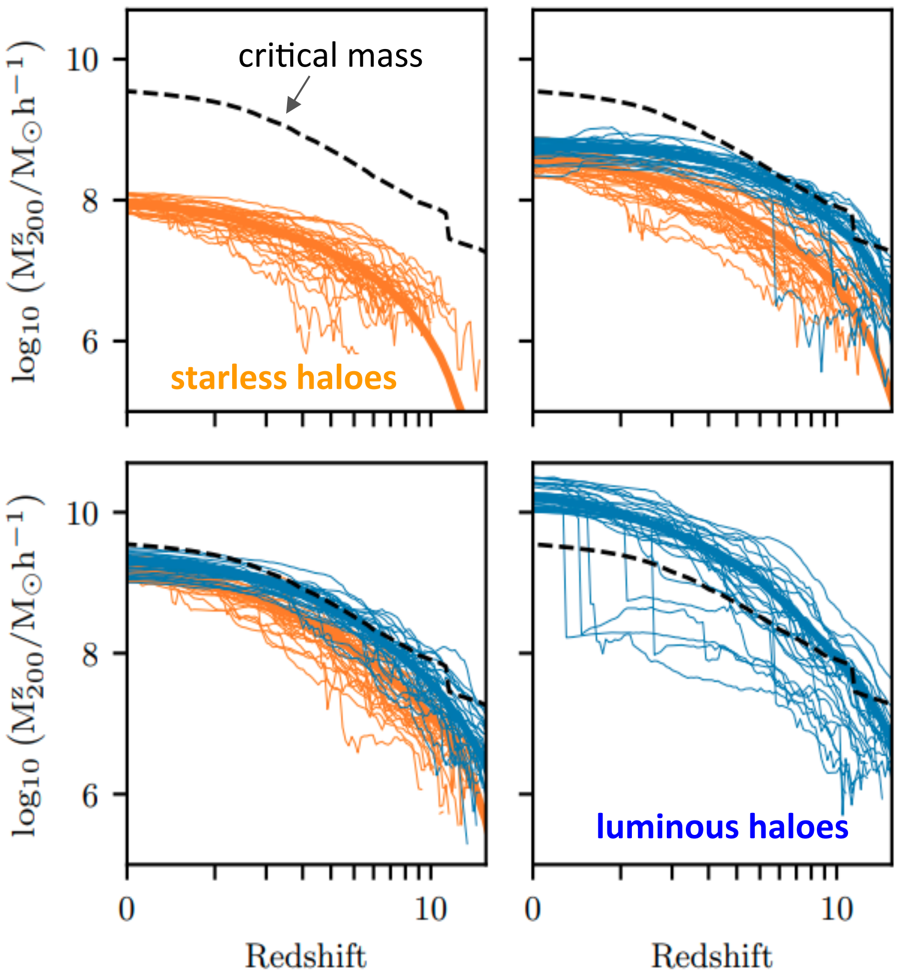
Benitez-Llambay & CSF '20

Institute for Computational Cosmology

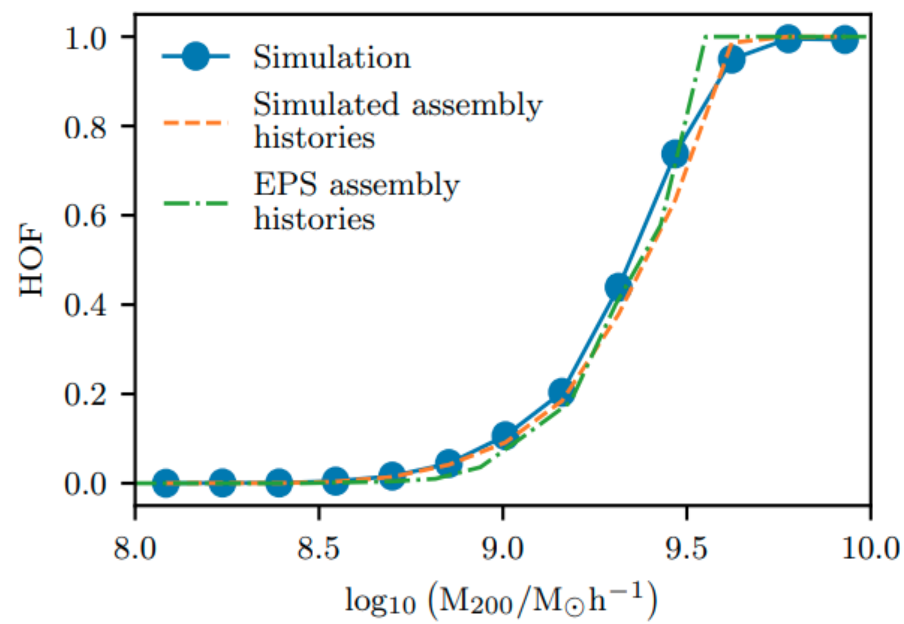
University of Durham

A galaxy formation primer

Mass assembly histories for different final masses

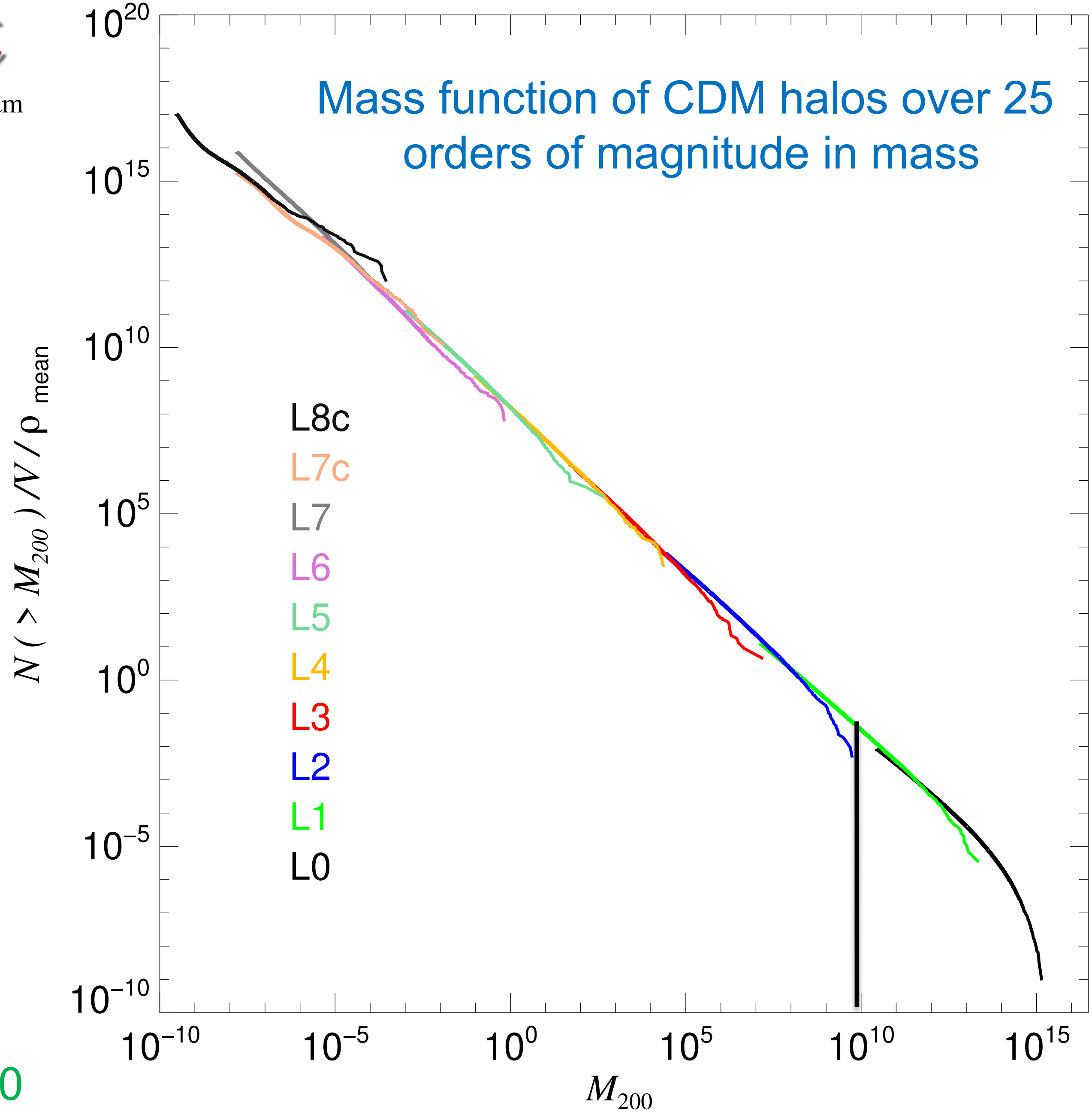


Halo Occupation Fraction (HOF): fraction of halos of a given mass that host a galaxy



Benitez-Llambay & CSF '20

Institute for Computational Cosmology



Wang et al '20

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

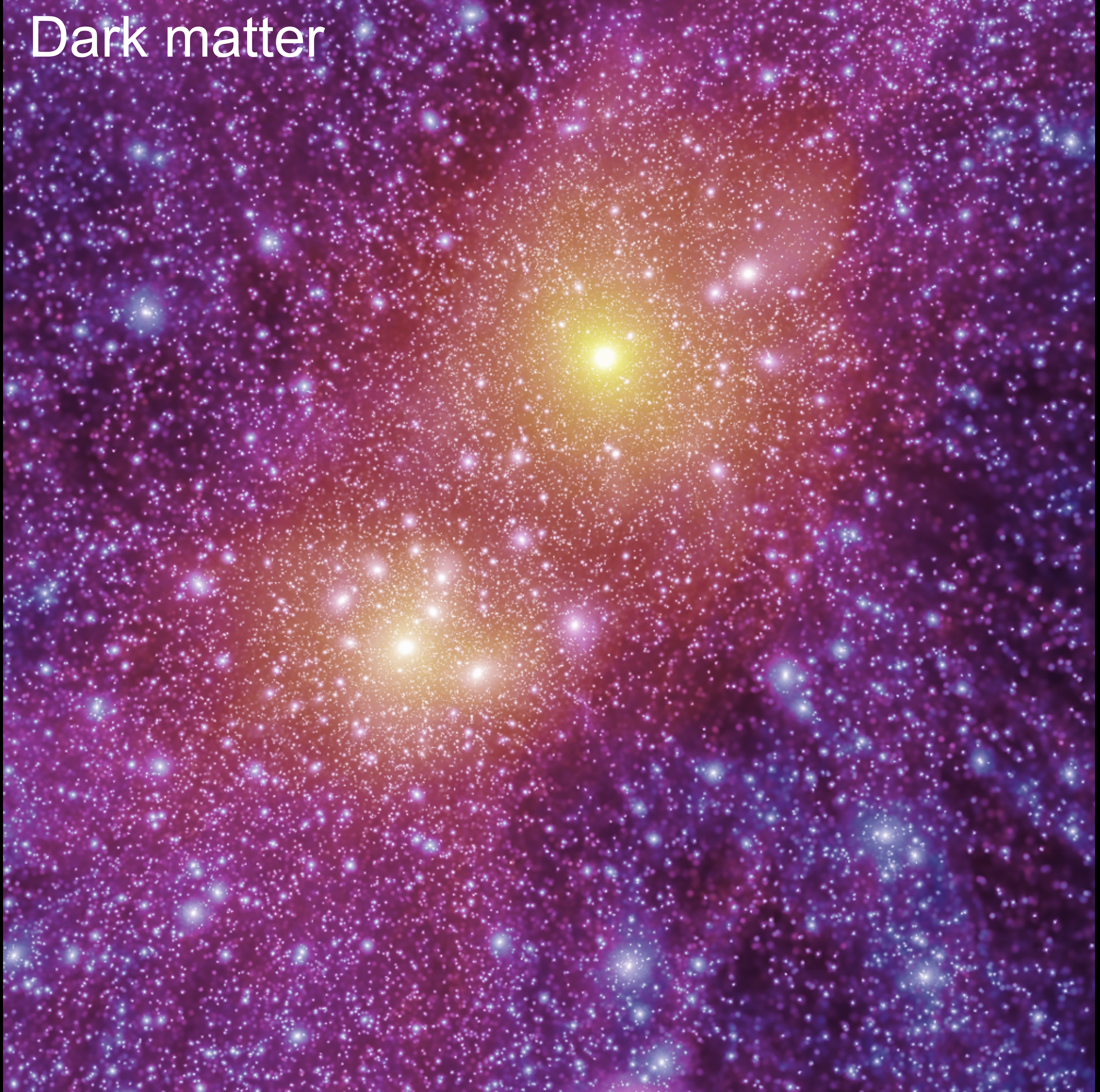
The EAGLE simulation is a project by the Virgo Consortium.
Images courtesy of Richard Bower.

VIRGO

APOSTLE
EAGLE full
hydro
simulations

Local Group

CDM



Sawala, CSF
et al '16

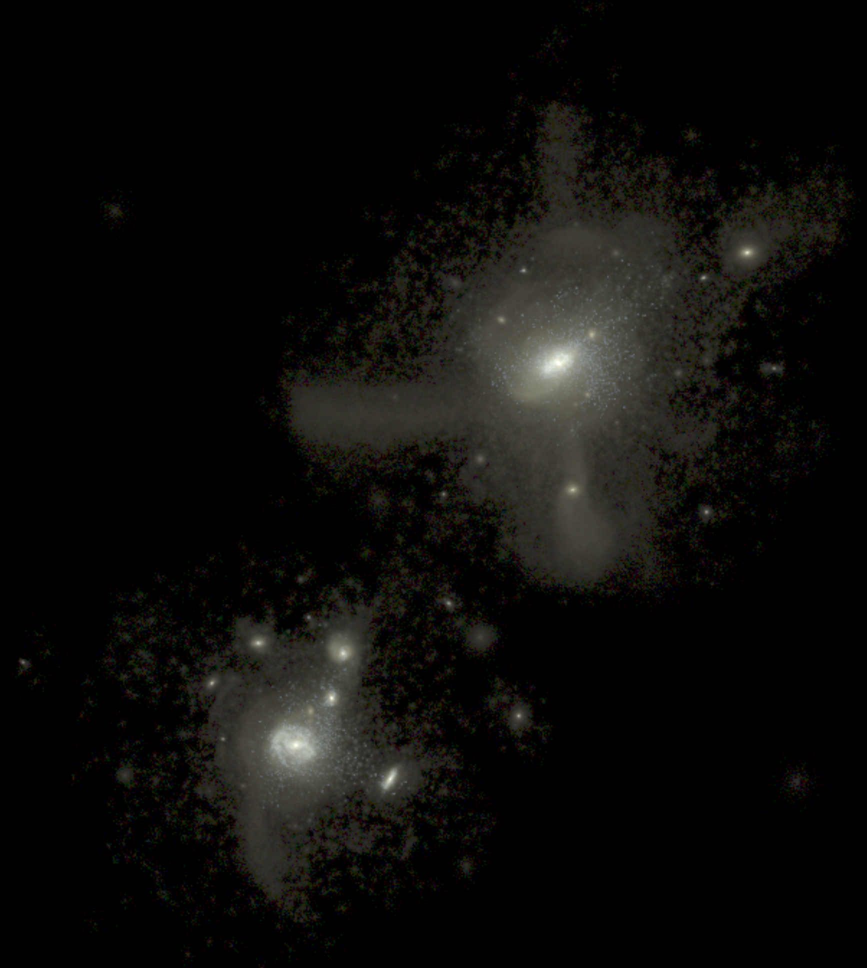
VIRGO

Stars

APOSTLE
EAGLE full
hydro
simulations

Local Group

Stars

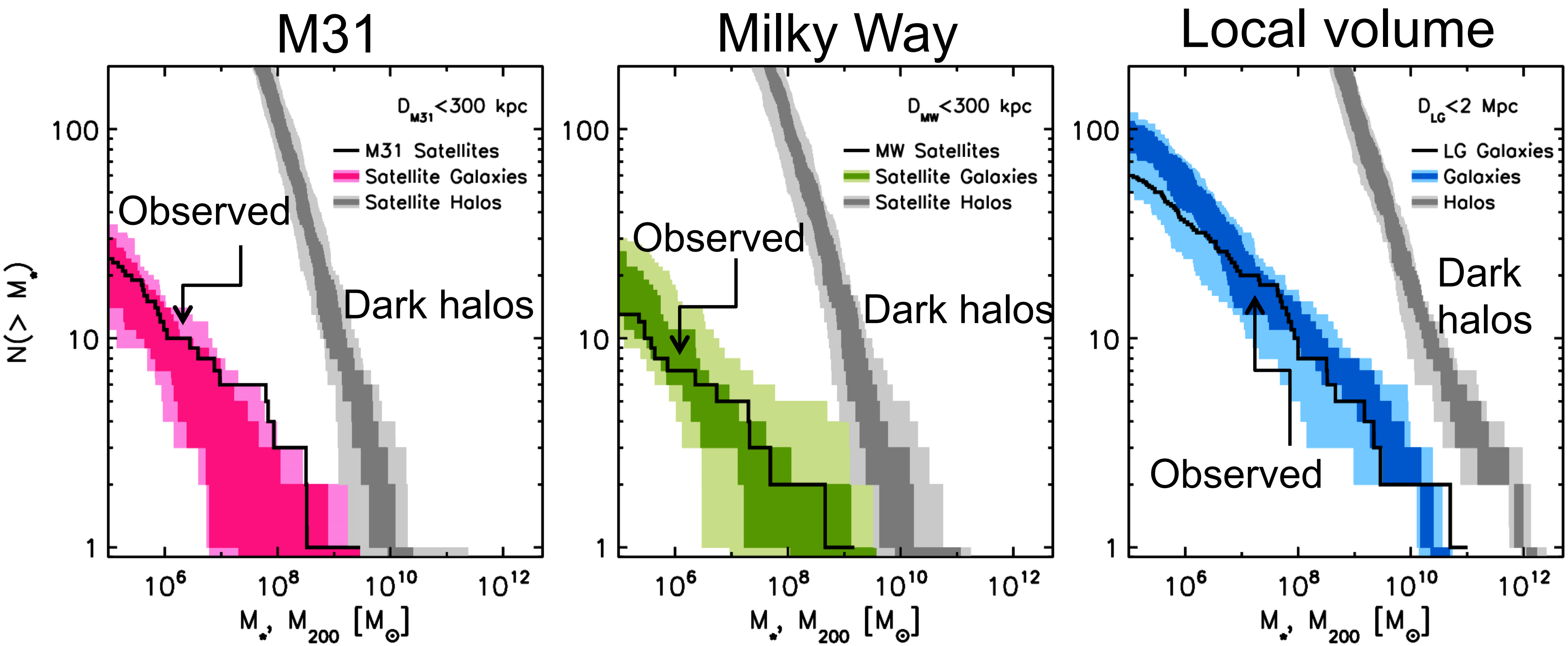


Far fewer satellite galaxies than CDM halos

Sawala, CSF
et al ‘16

EAGLE Local Group simulation

University of Durham



Sawala, CSF et al '16

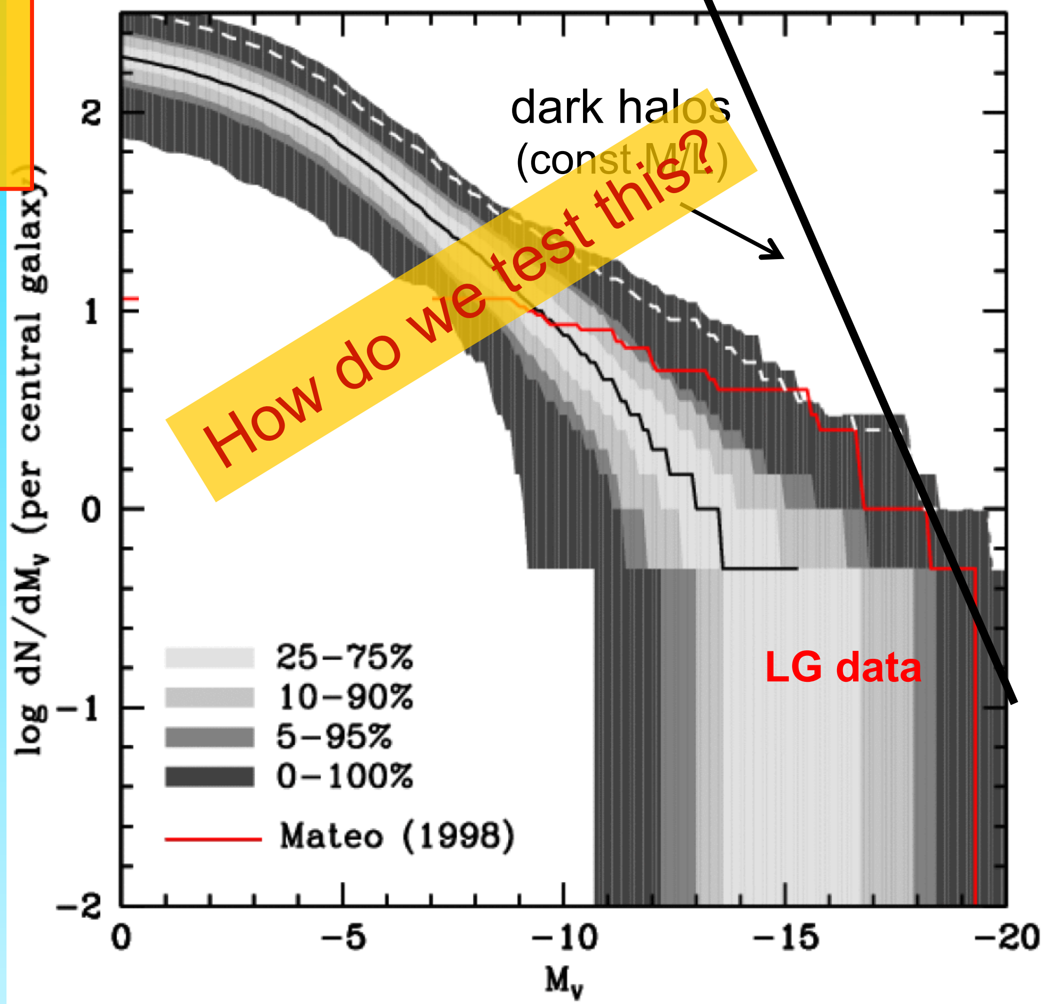
Institute for Computational Cosmology

Luminosity Function of Local Group Satellites

University of Durham

Semi-analytic model of galaxy formation ncluding effects of reionization and SN feedback

- Median model → correct abundance of sats brighter than M_V=-9 (V_{cir} > 12 km/s)
- Model predicts many, as yet undiscovered, faint satellites

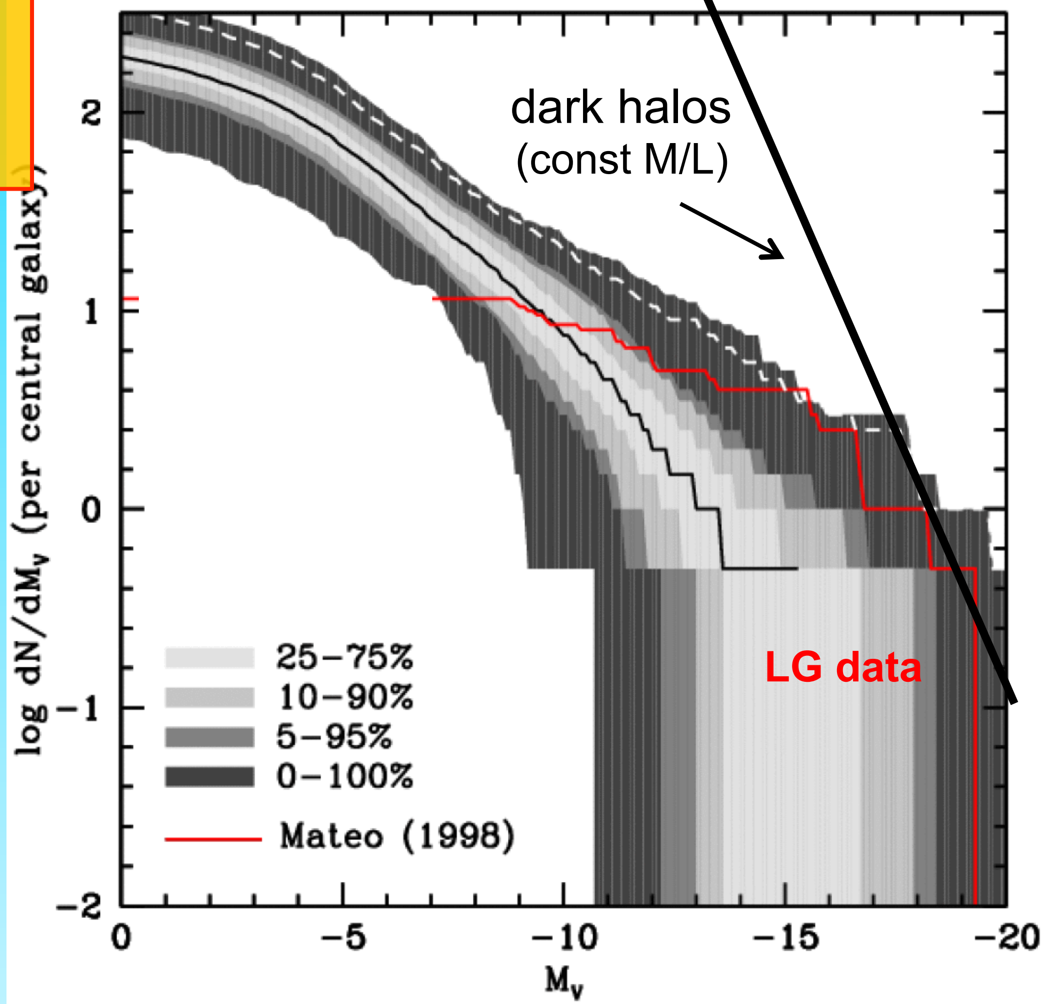


Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman+ ’93, Bullock+ ’00, Somerville ‘02)

Luminosity Function of Local Group Satellites

Semi-analytic model of galaxy formation ncluding effects of reionization and SN feedback

- Median model → correct abundance of sats brighter than M_V=-9 (V_{cir} > 12 km/s)
- Model predicts many, as yet undiscovered, faint satellites



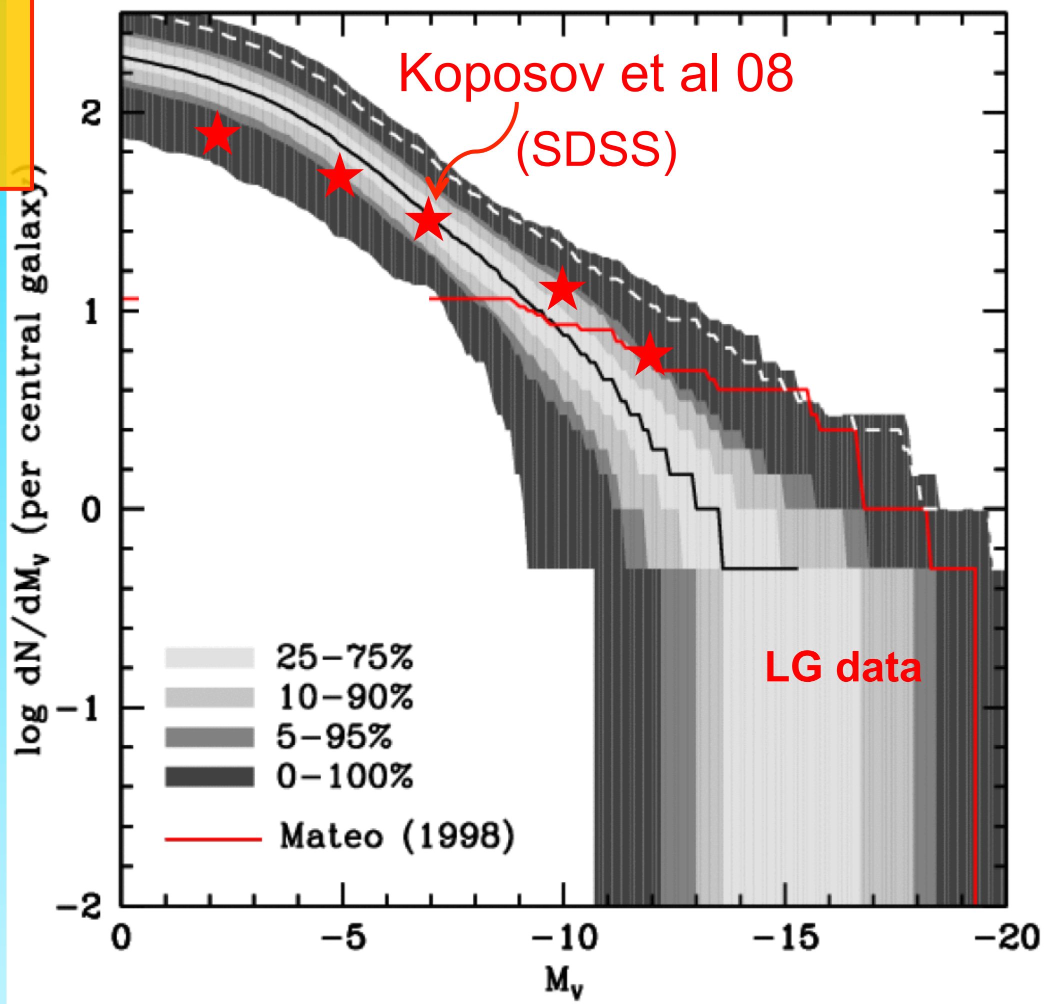
Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman+ ’93, Bullock+ ’00, Somerville ‘02)

Luminosity Function of Local Group Satellites

Semi-analytic model of galaxy formation ncluding effects of reionization and SN feedback

- Median model → correct abundance of sats brighter than M_V=-9 (V_{cir} > 12 km/s)

- Model predicts many, as yet undiscovered, faint satellites



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

When galaxy formation is taken into account

→

CDM predicts the observed abundance of satellites

→

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

University of Durham

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

University of Durham

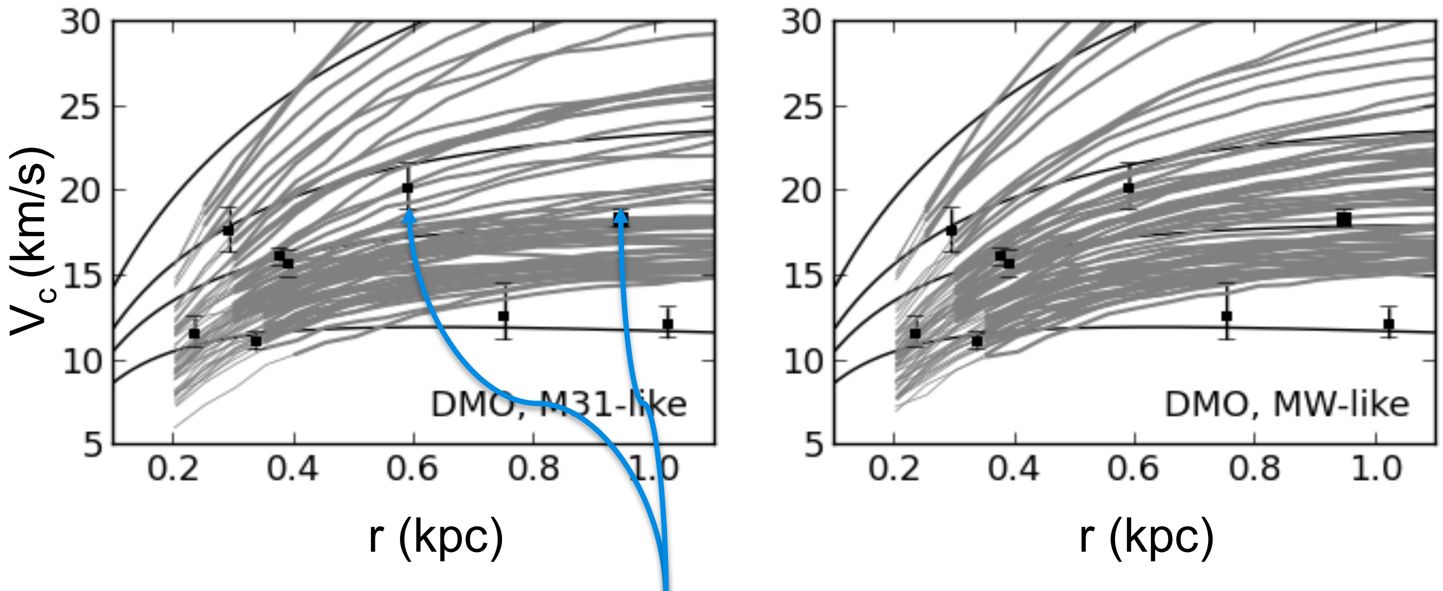
Boylan-Kolchin et al. '11

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

$V_{max} = \max V_c$

TBTF: DM simulations make ~10 subhalos with V_{max} > 30 km/s but MW has only 3

DM-only simulation



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

(excluding LMC, SMC, Sag)

Institute for Computational Cosmology

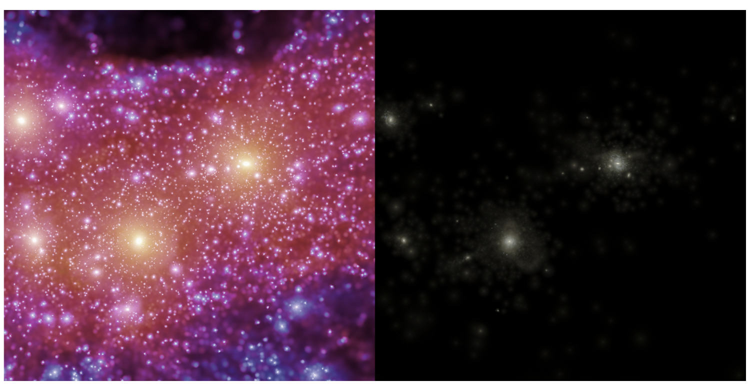
To-big-to-fail in CDM: baryon effects

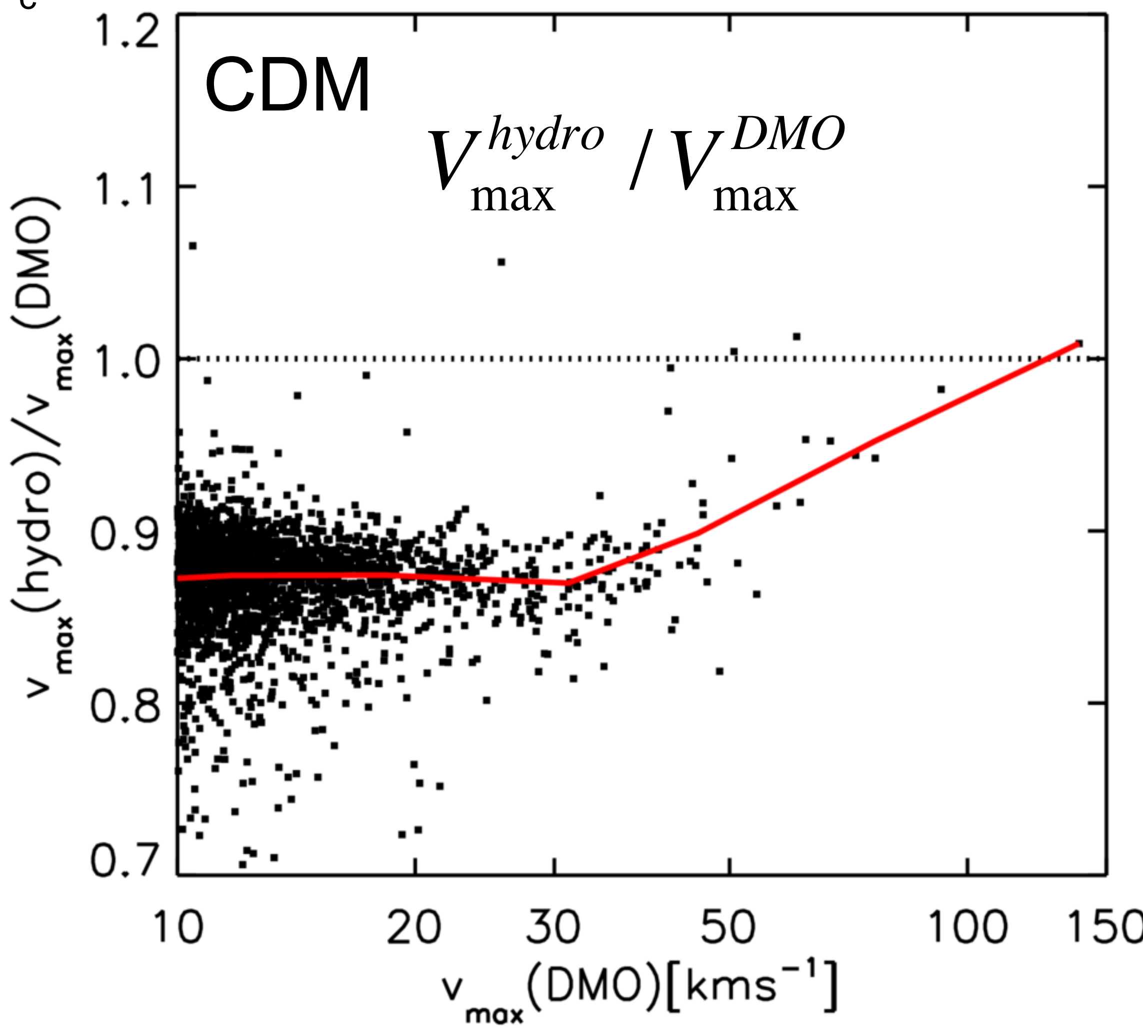
University of Durham

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

Reduction in V_{max} due to gas loss (reionization + SN feedback) at early times

→ Lowers halo mass & thus halo growth rate





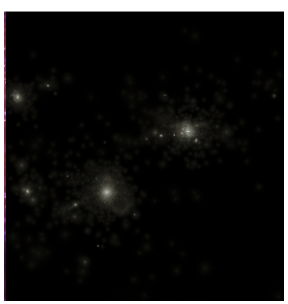
Sawala, CSF et al. ‘13, ‘14

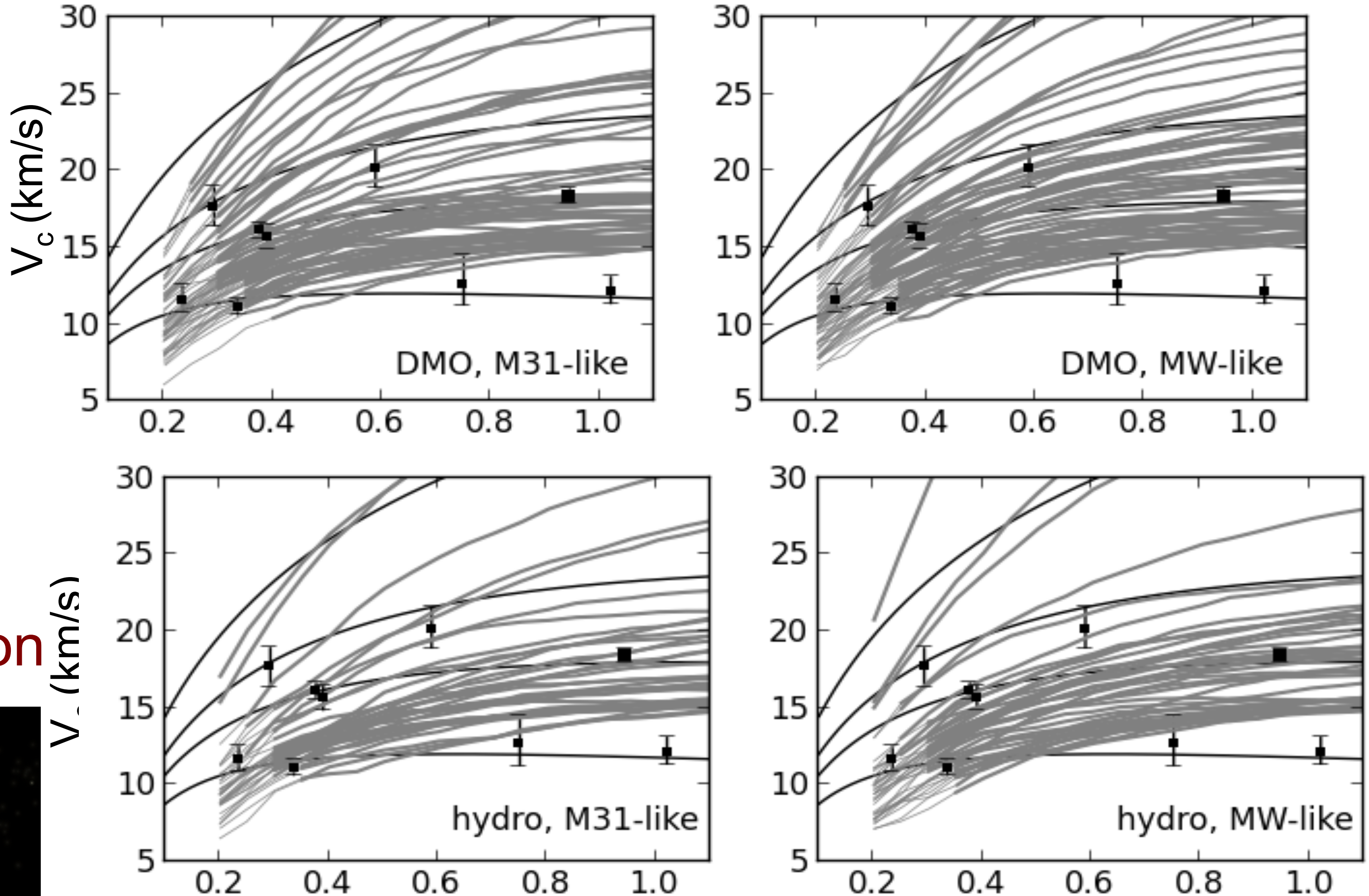
Too-big-to-fail: the baryon bailout

University of Durham

DM-only simulation

Gas simulation





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

Sawala, CSF et al. '14, '16

When galaxy formation is taken into account

→

Rotation curve amplitude slightly reduced

→

There is NO too-big-to-fail problem

University of Durham

The “small-scale crisis” of CDM

The four “problems” of CDM

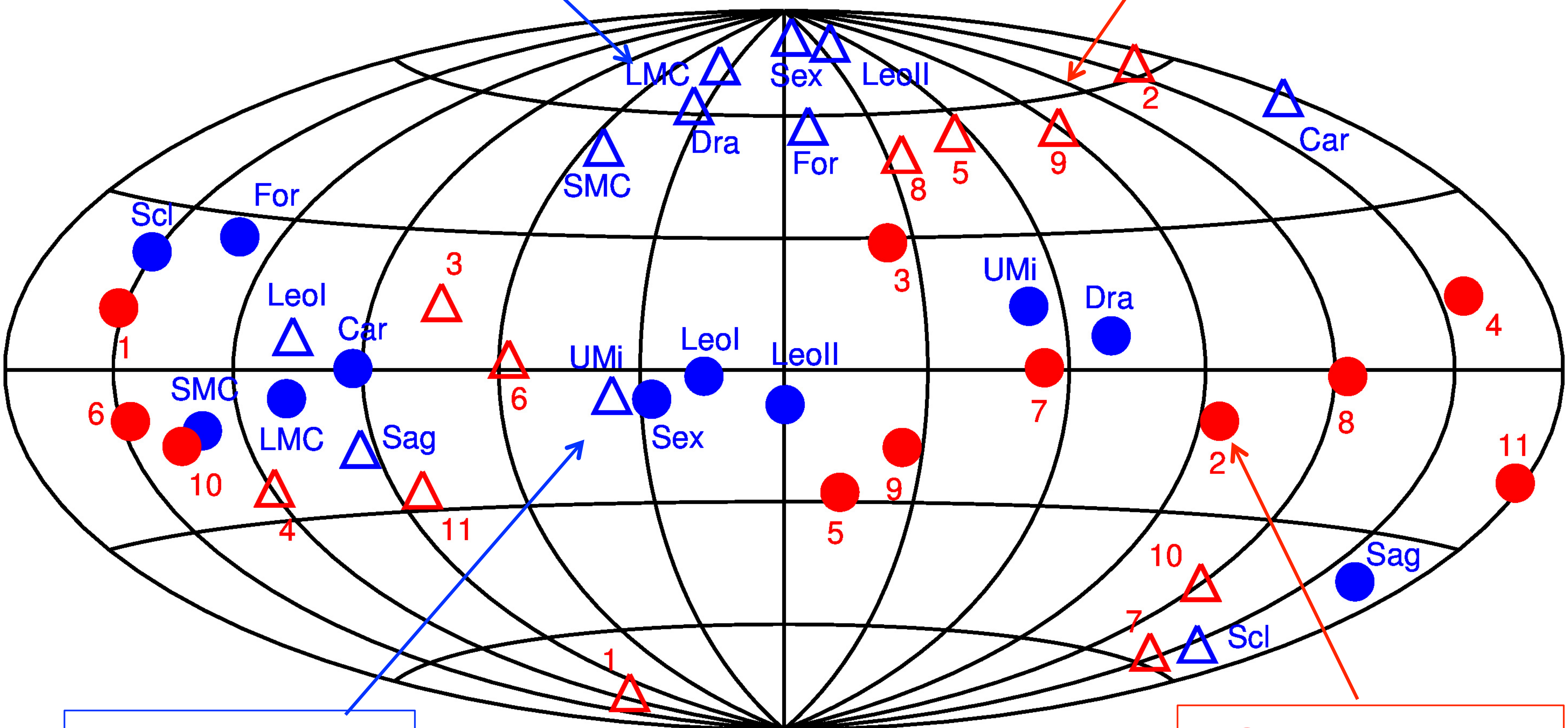
1. The “missing satellites” problem
2. The “too-big-to-fail” problem
3. The “plane of satellites” problem
4. The “core-cusp” problem

University of Durham

The “satellite disk” problem

Direction of ang. mom.

Direction of ang. mom



MW satellites

LG simulations

Lynden-Bell ’76
Shao ‘19 ‘20

Institute for Computational Cosmology

A satellite plane in Andromeda

(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

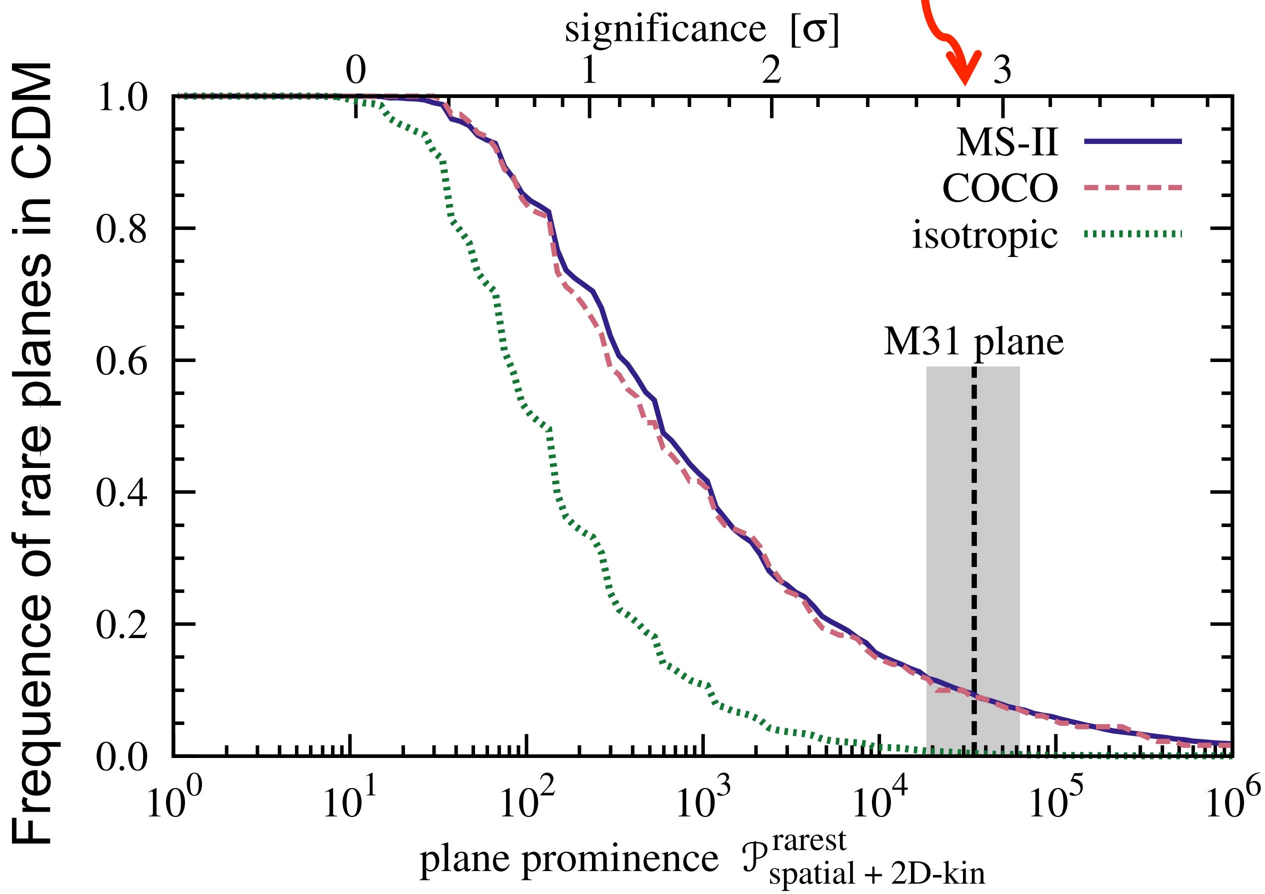
Abstract

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

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 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

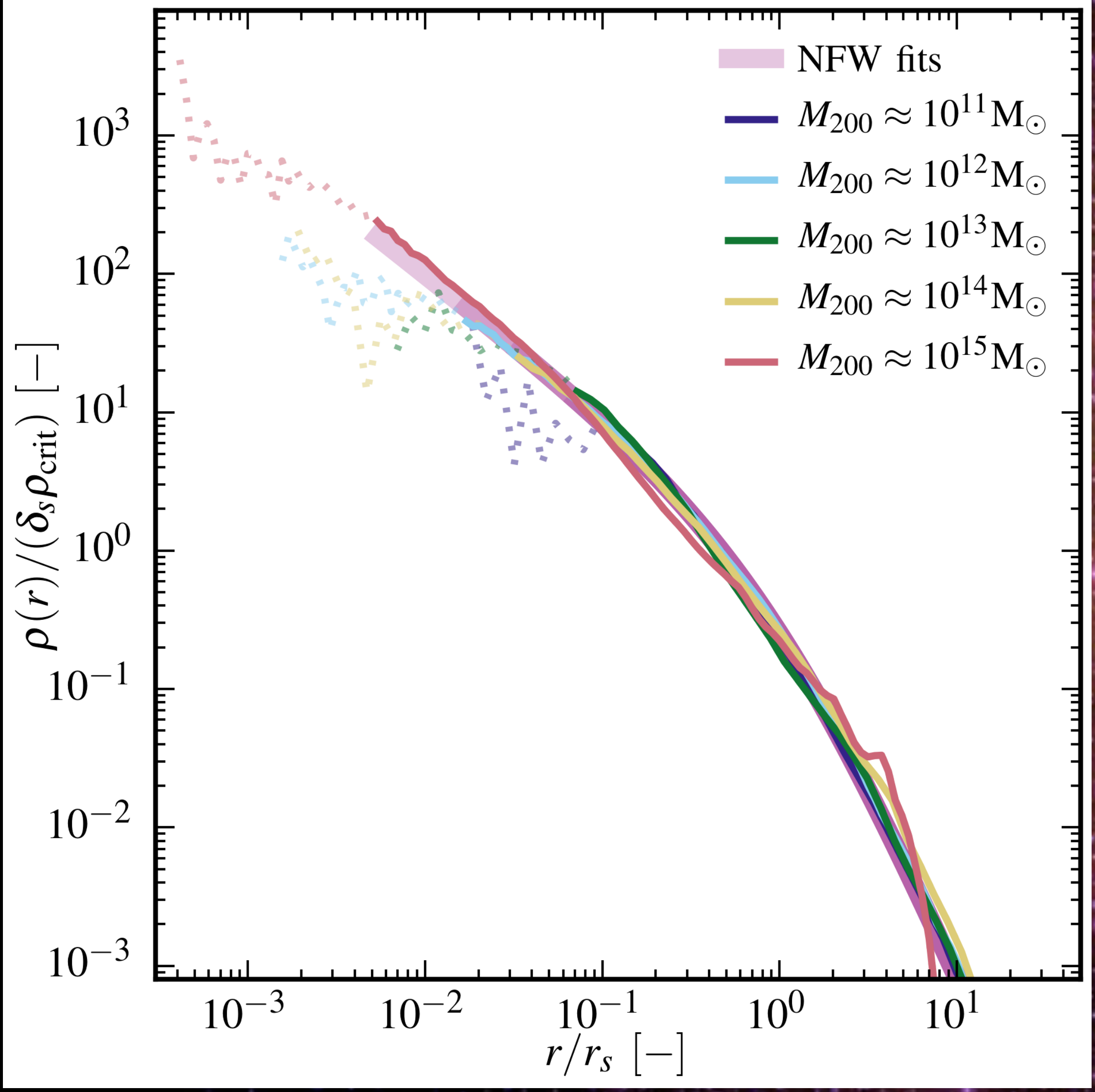
Cautun, CSF, et al '15

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

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

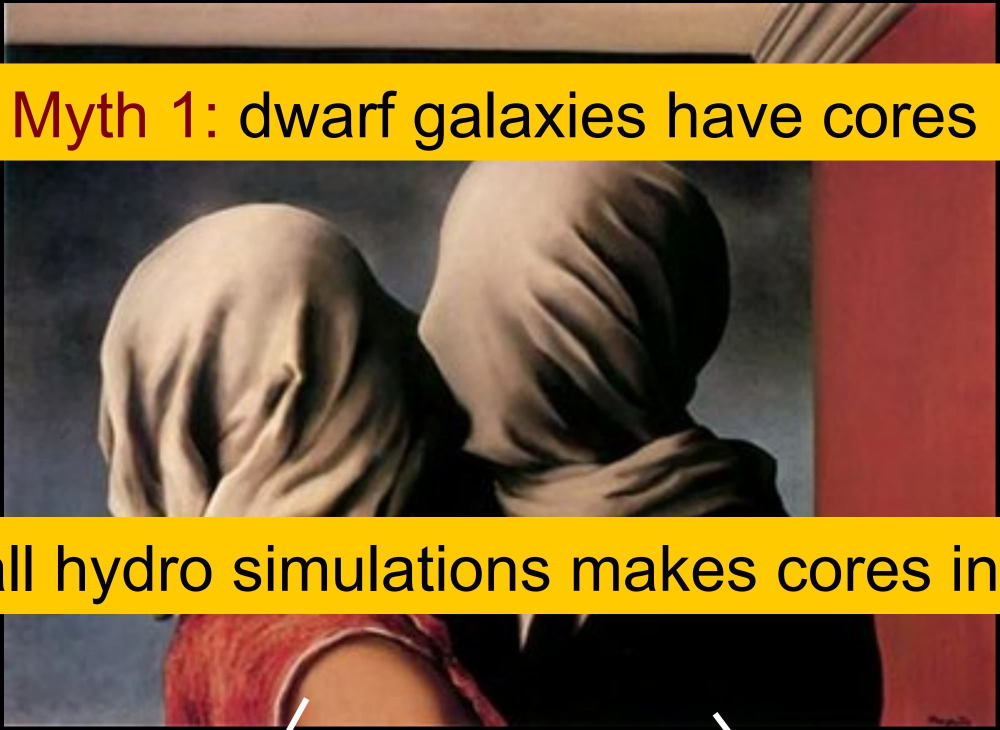
Fitted by simple formula:

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

(Navarro, Frenk & White '97)

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

Cores or cusps?



Myth 1: dwarf galaxies have cores

Myth 2: all hydro simulations makes cores in dwarfs

Cores

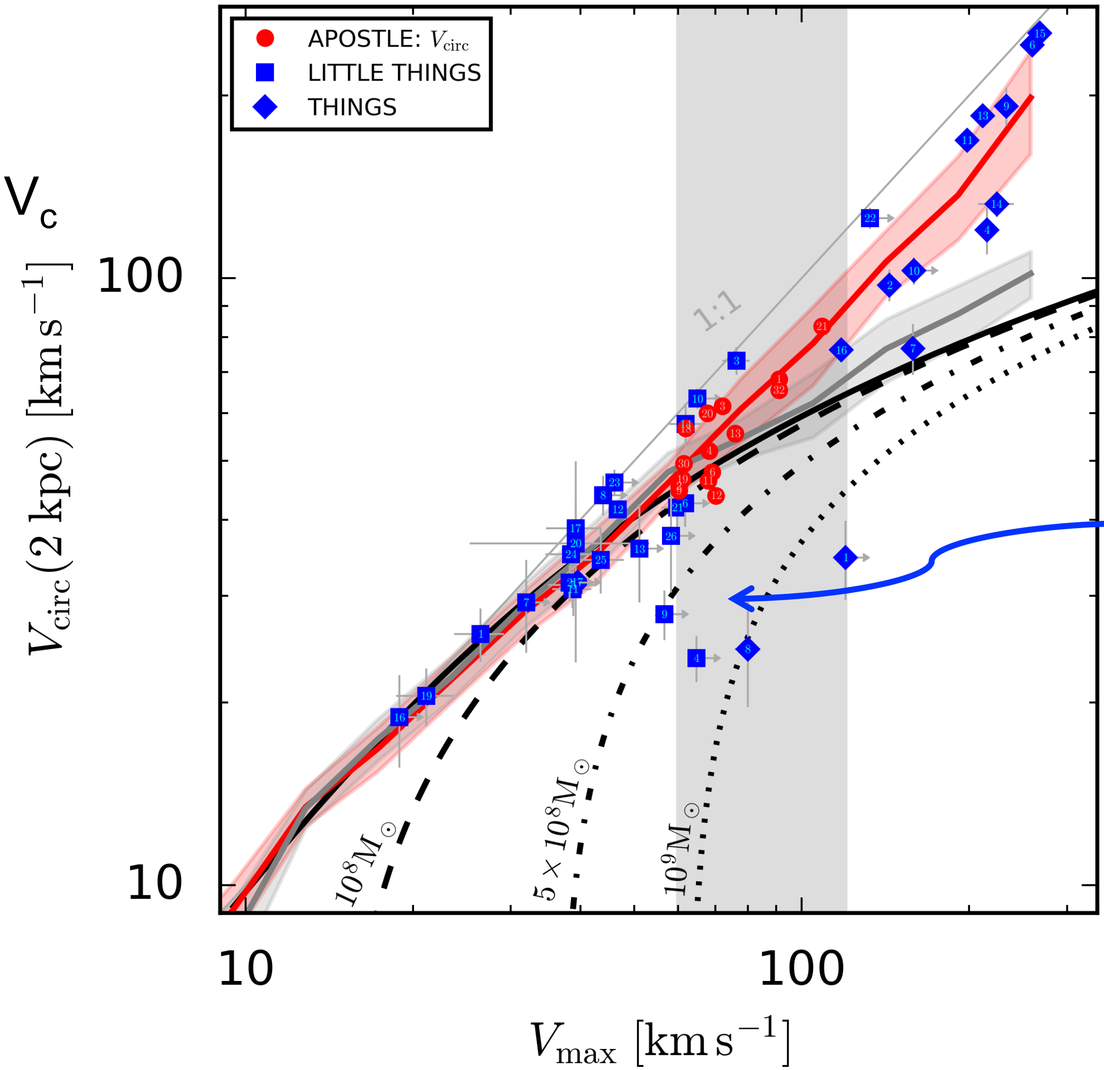
Cusps

The diversity of rotation curves

University of Durham

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

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



THINGS & LITTLE THINGS (cores)

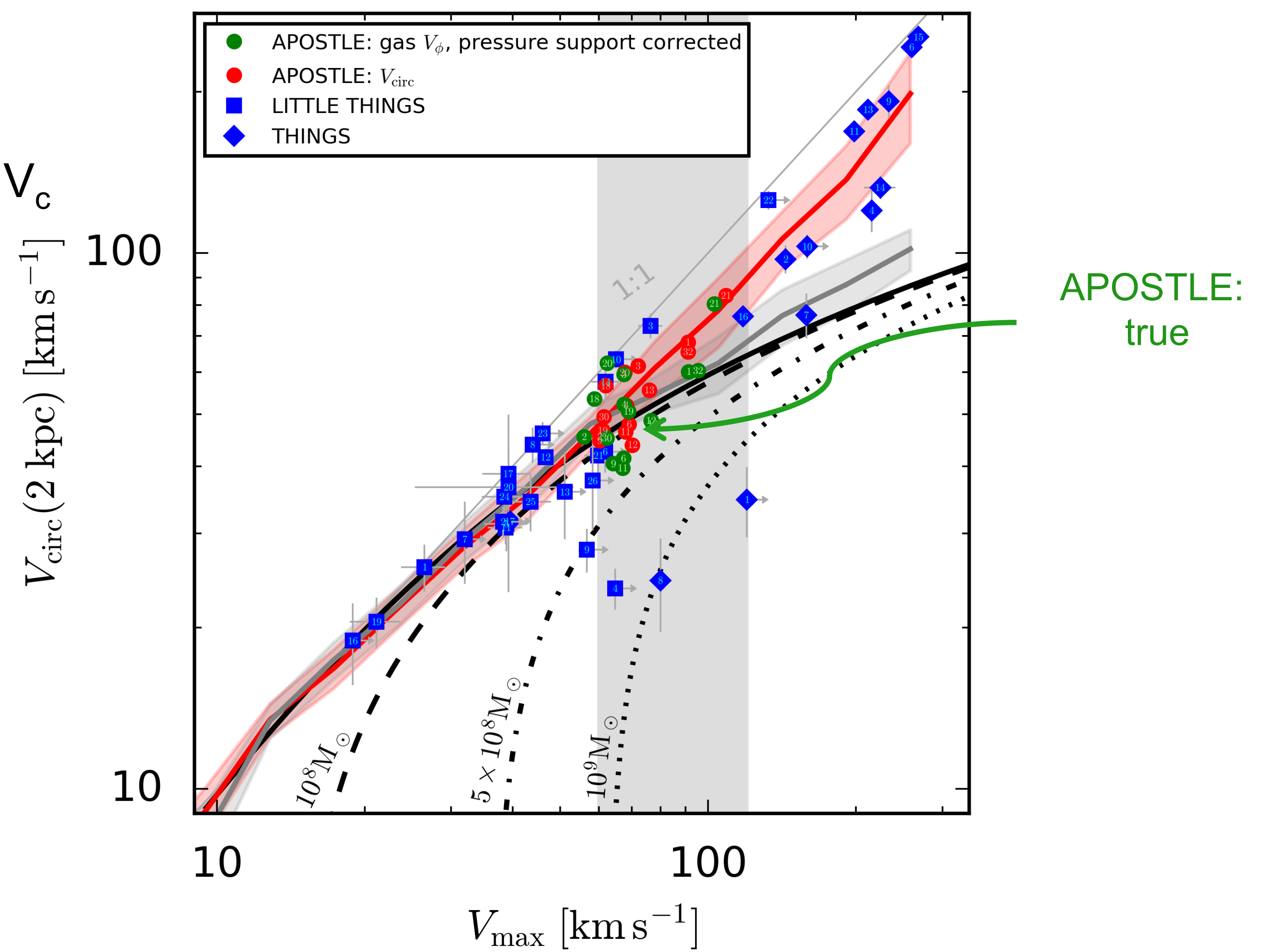
Oman+ '19

The diversity of rotation curves

University of Durham

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

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



Oman+ '19

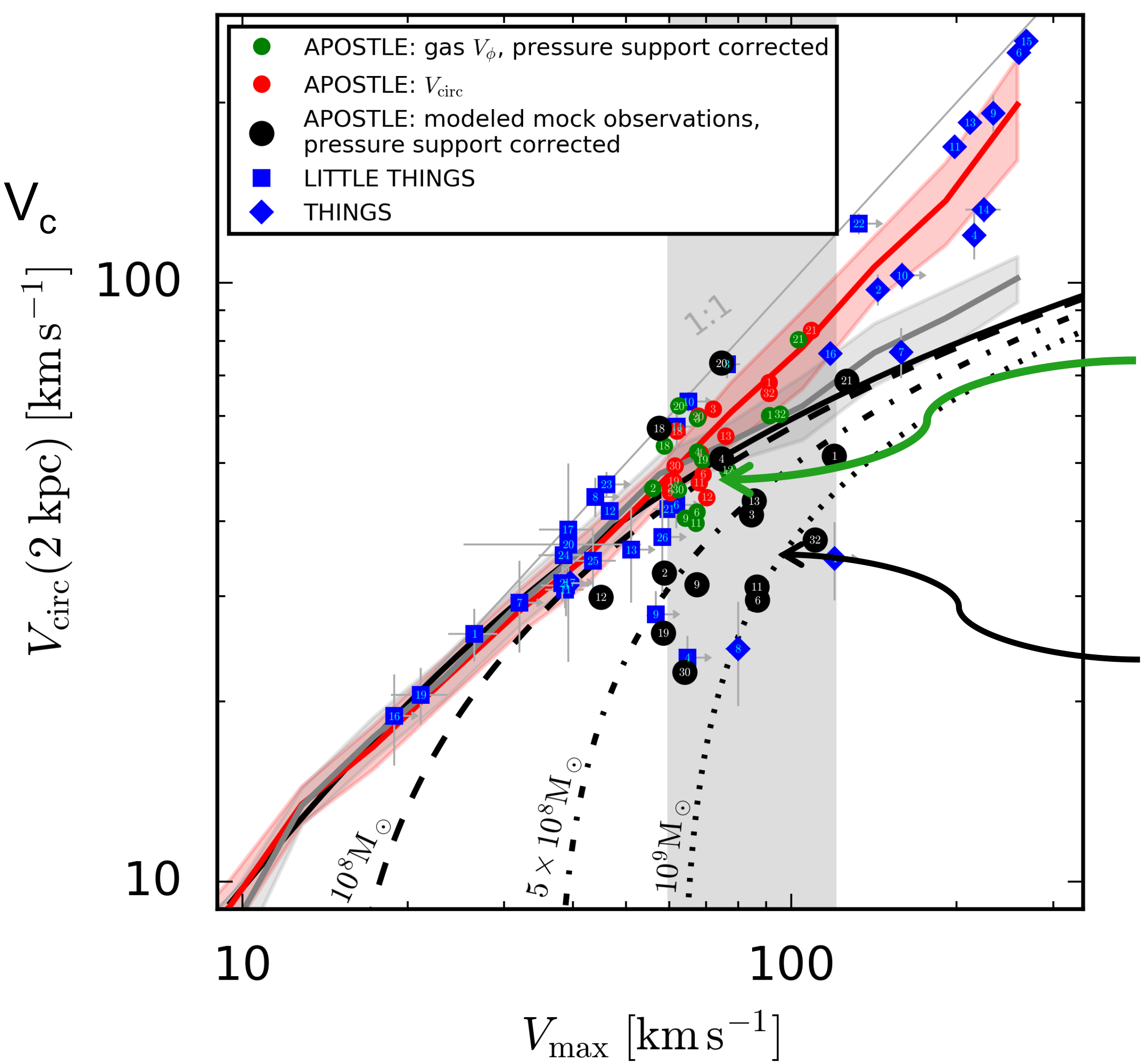
Institute for Computational Cosmology

The diversity of rotation curves

University of Durham

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

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



Oman+ '19

Institute for Computational Cosmology

ICC

But if cores were found in halos, would this rule out CDM?

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)

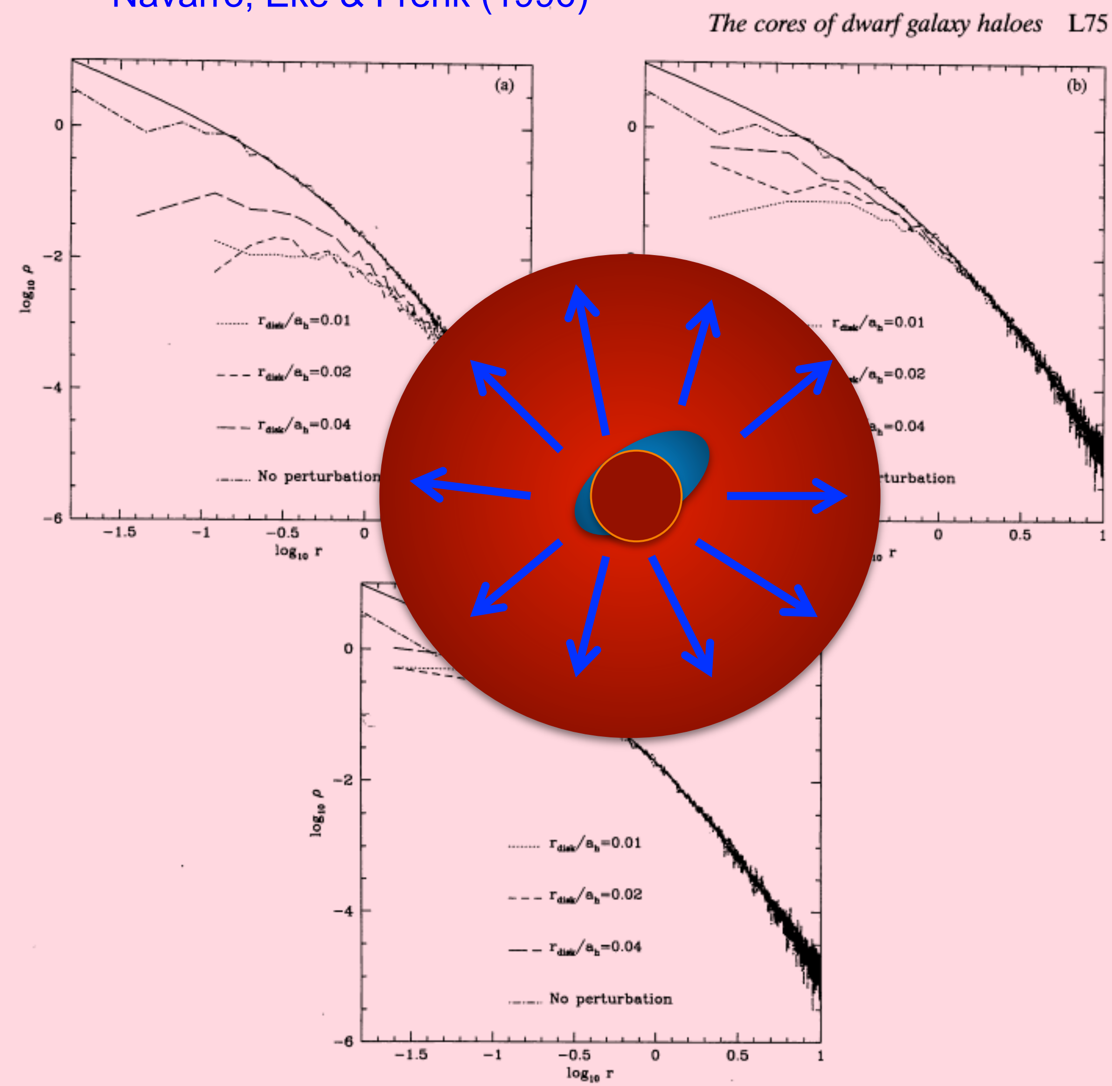
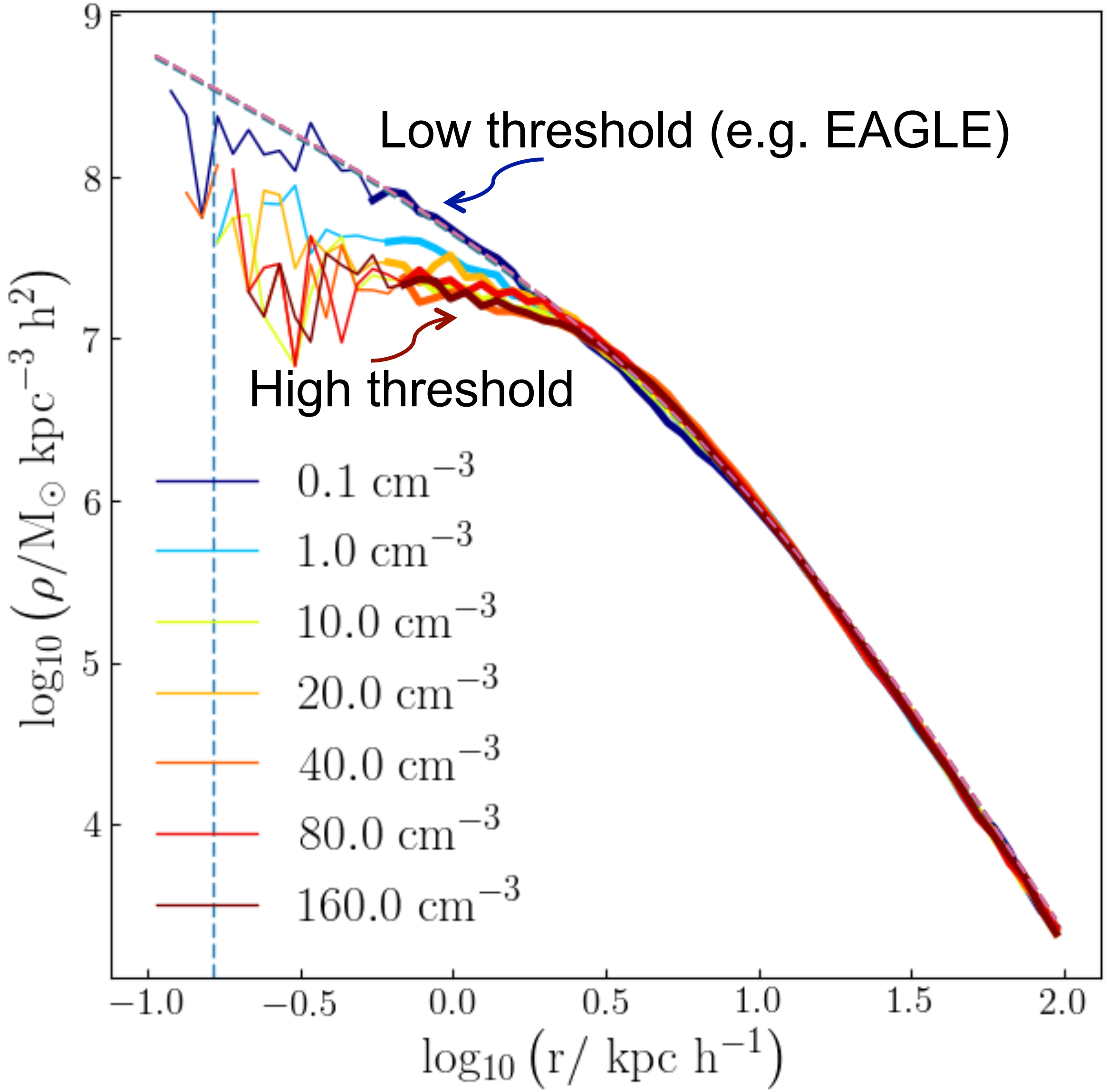


Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot–dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{disc}=0.2$.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

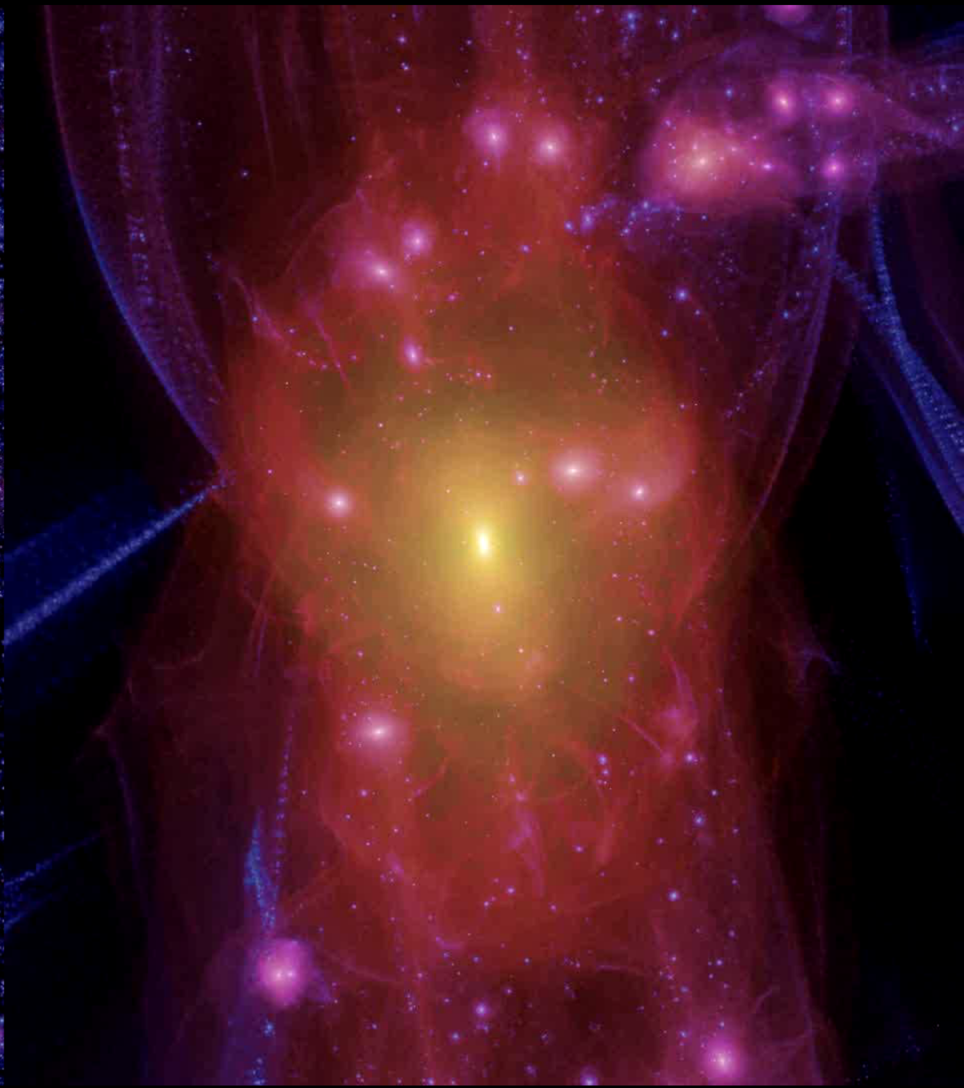
Cores or cusps in simulations?



Benitez-Llambay, CSF et al '17

cold dark matter

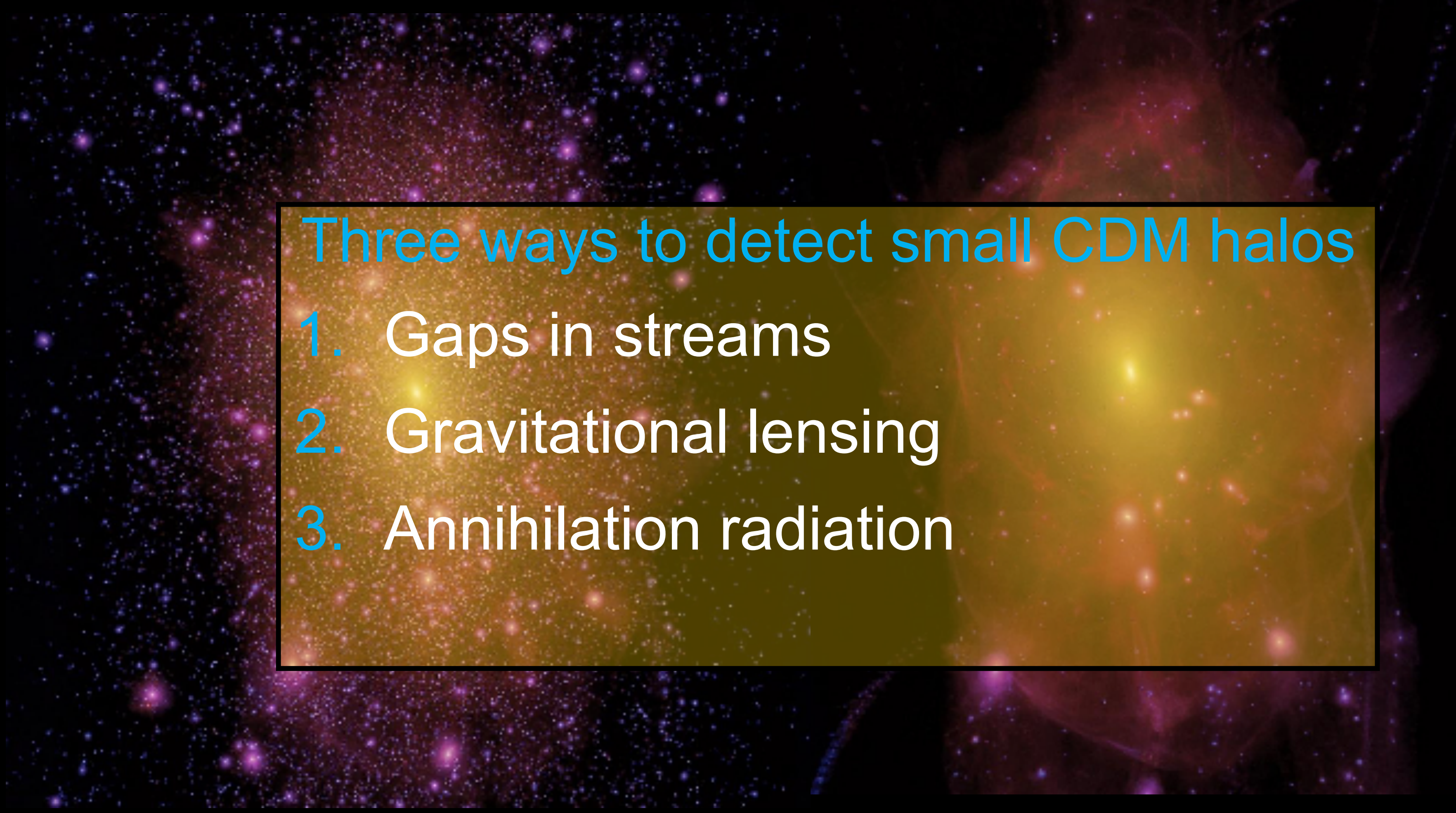
warm dark matter



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

Can we count dark haloes?

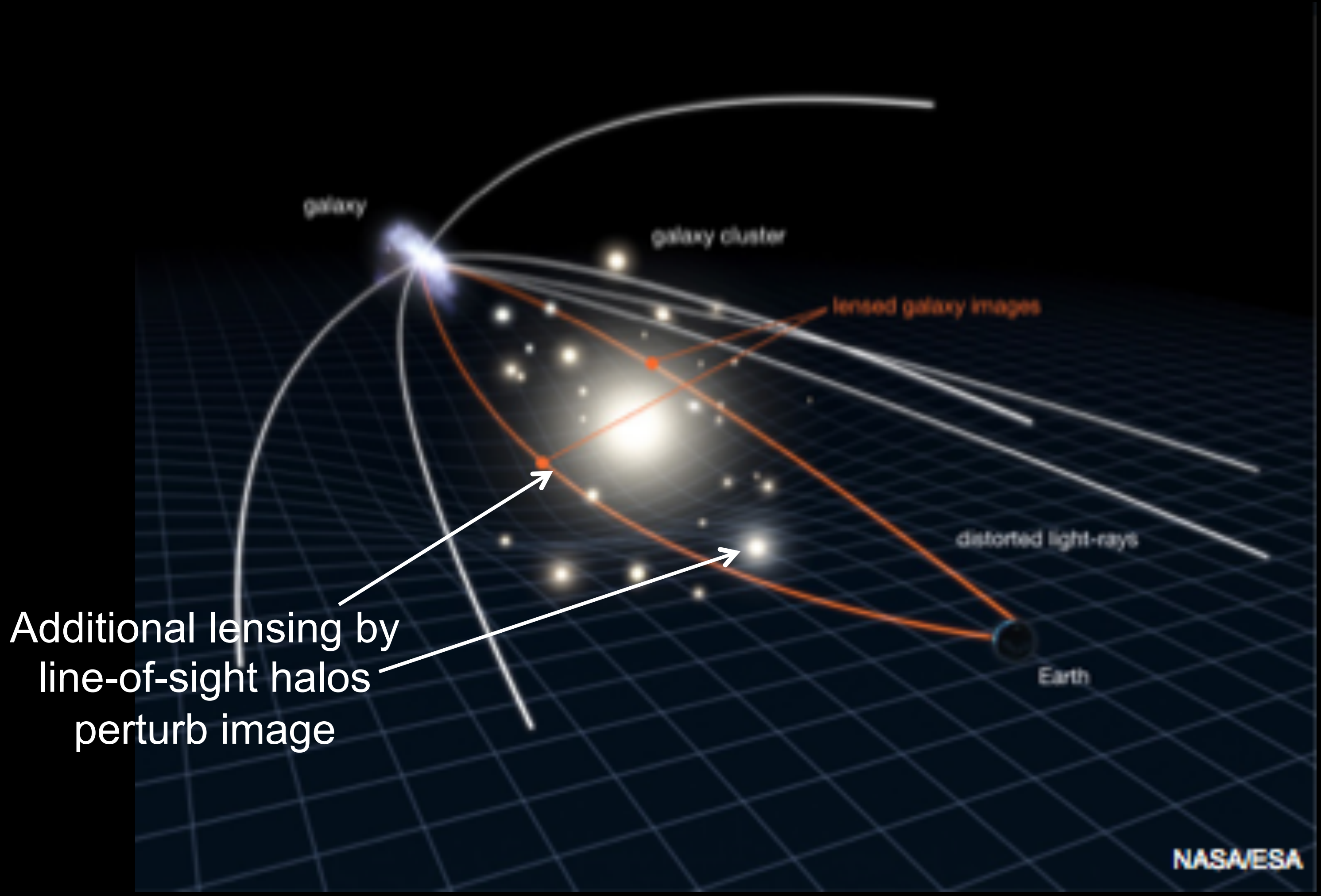
cold dark matter | warm dark matter



Three ways to detect small CDM halos

1. Gaps in streams
2. Gravitational lensing
3. Annihilation radiation

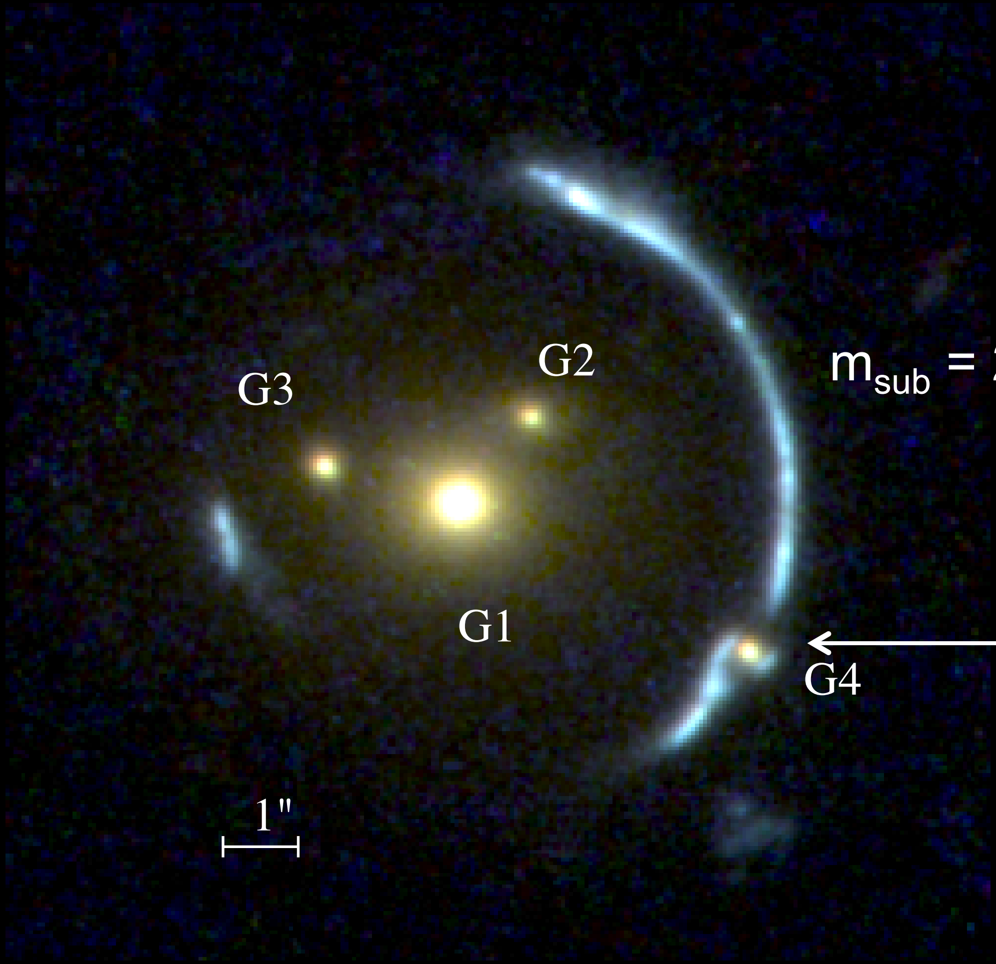
Gravitational lensing: Einstein rings



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



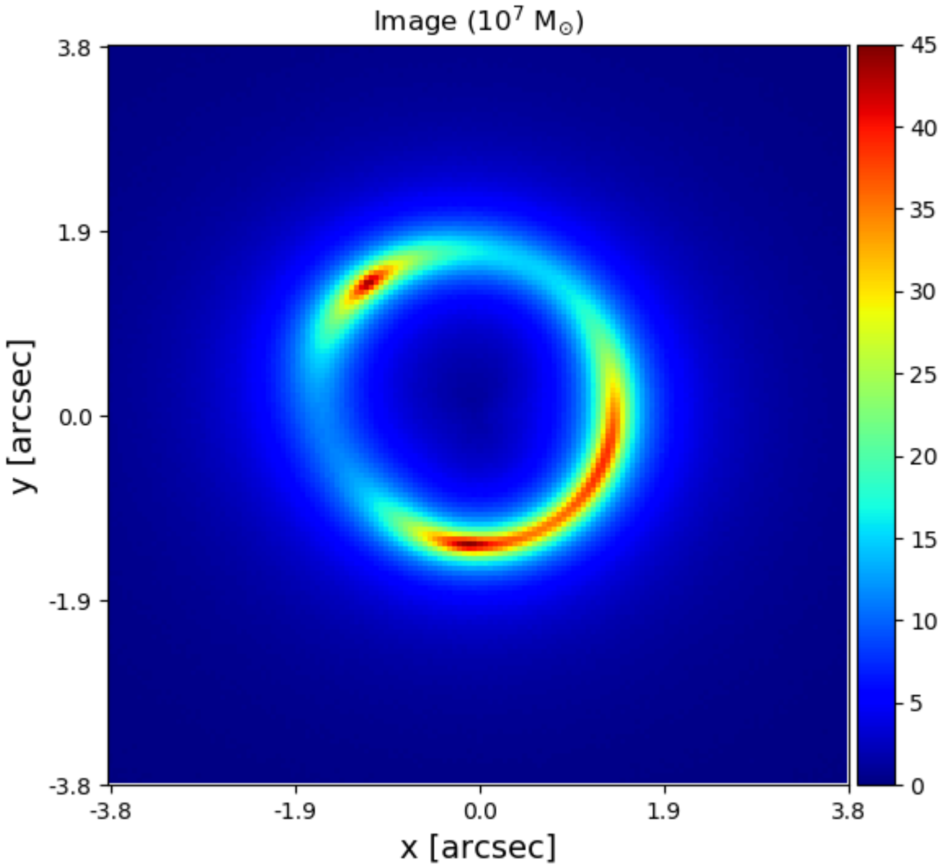
$m_{sub} = 2.8 \times 10^{10} M_o$

Vegetti et al ‘10

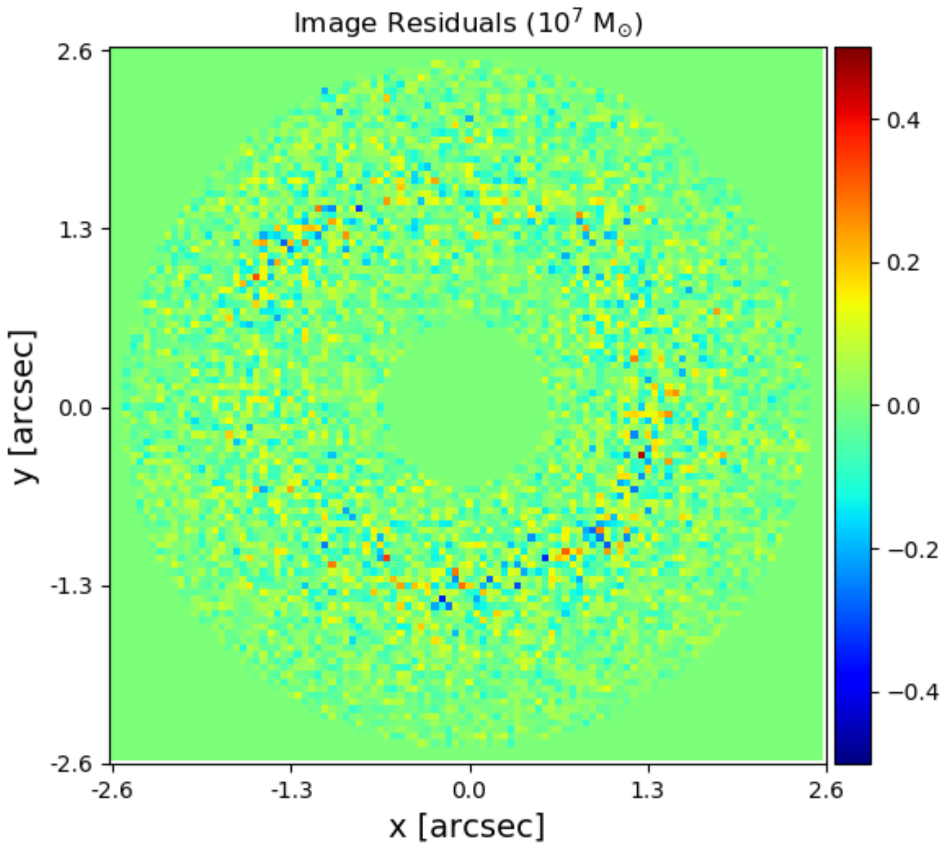
Gravitational lensing: Einstein rings

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

Institute for Computational Cosmology

University of Durham

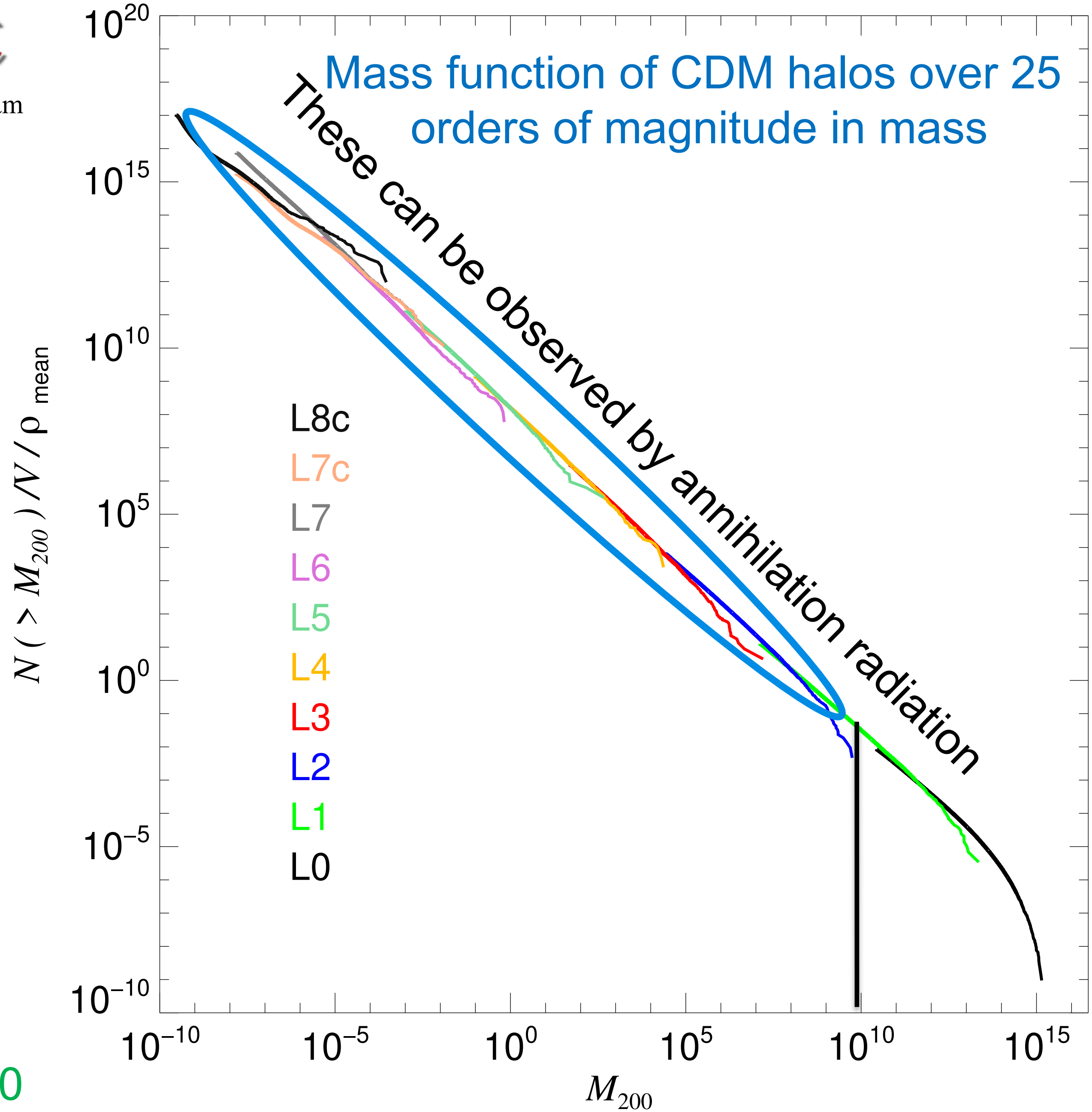
Detecting substructures with strong lensing

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

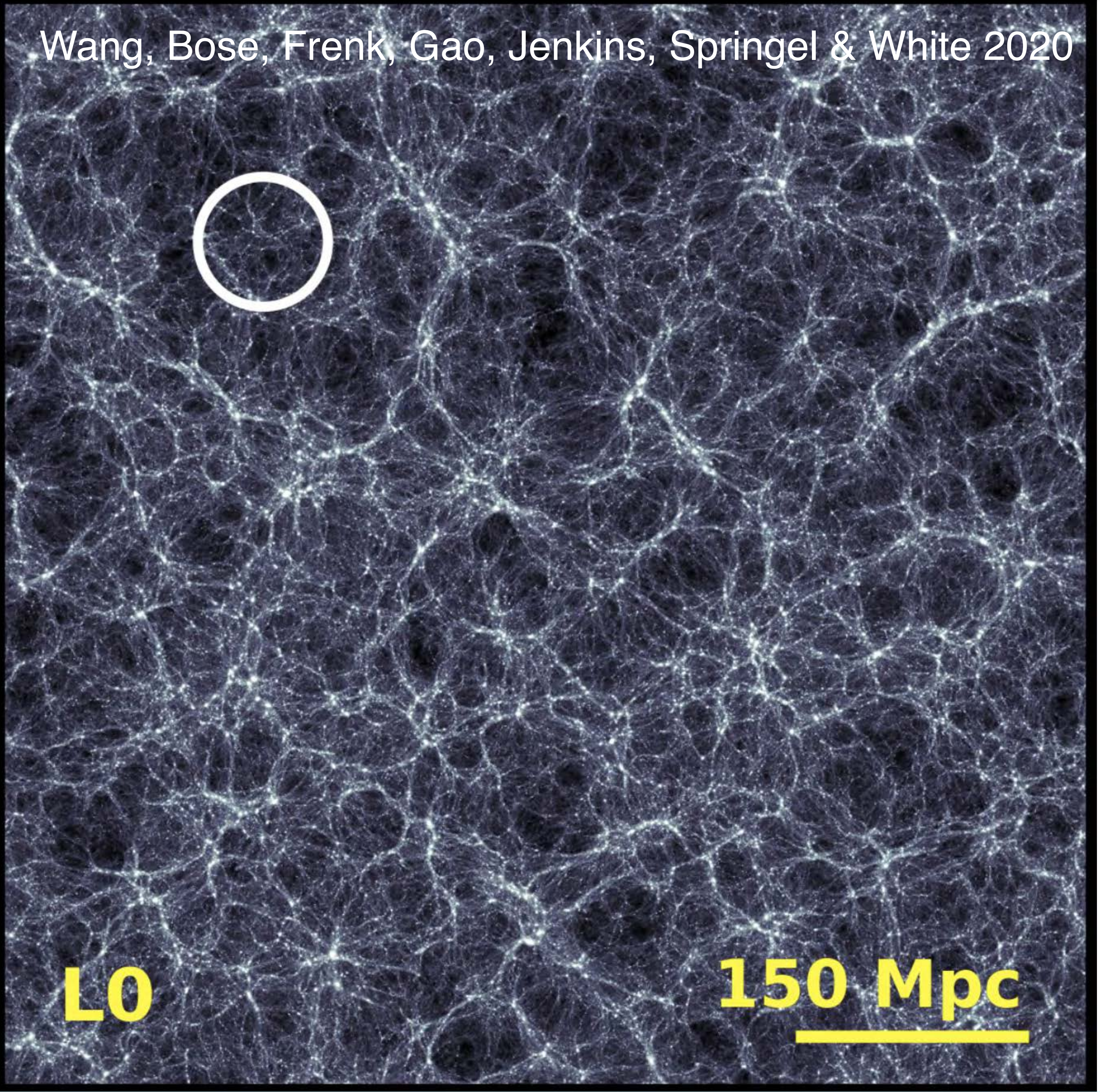
~100 Einstein ring systems with detection limit of 10^7 $h^{-1}M_o$ is enough to either rule out a 7 keV sterile ν or CDM itseilf

Li, CSF et al '16

ICC
University of Durham



Wang et al '20



The VVV simulation

Planck cosmology

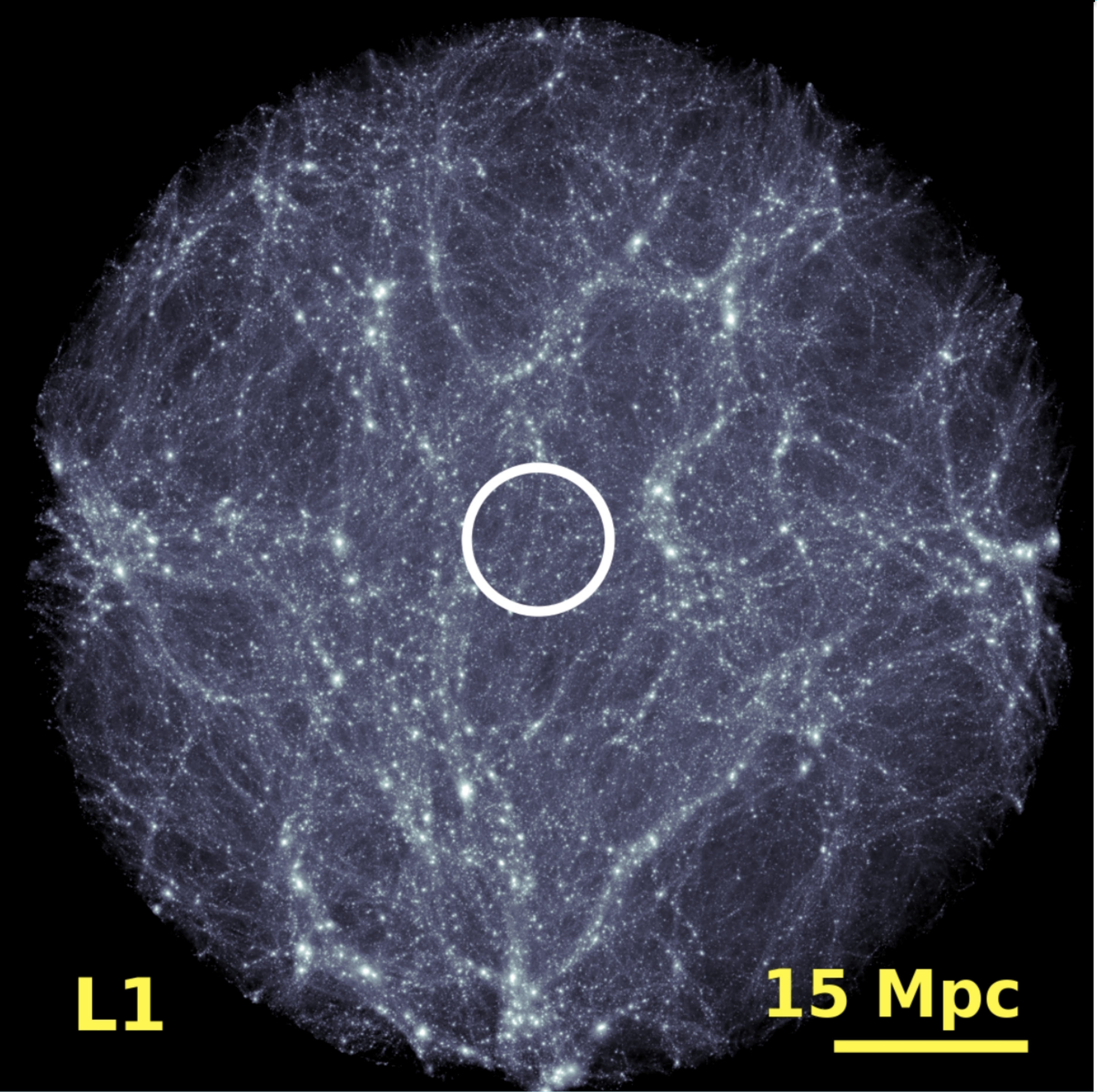
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{14}\ M_{\odot}$

Base Level

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

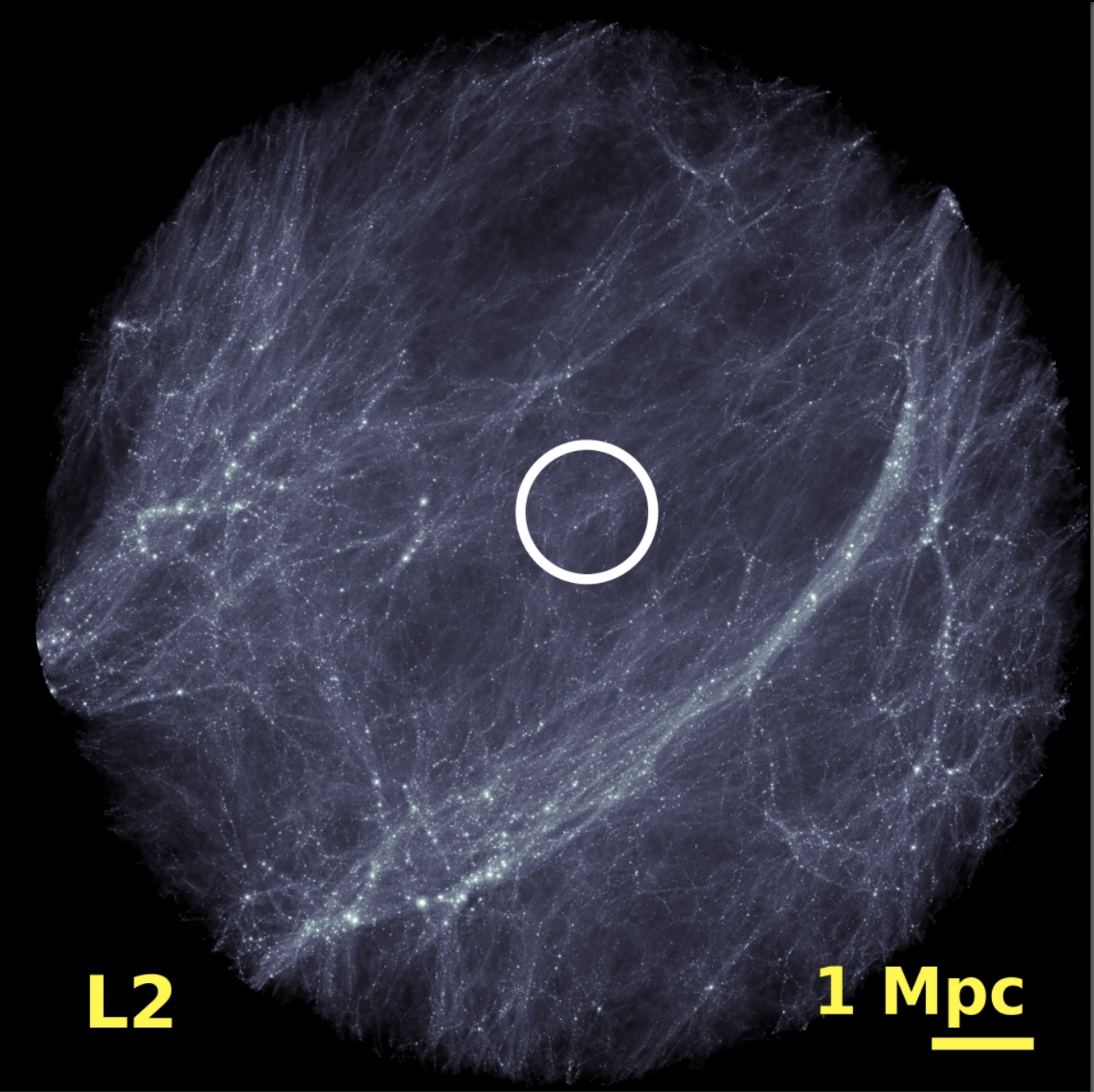
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{12} M_\odot$

Zoom Level 1

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

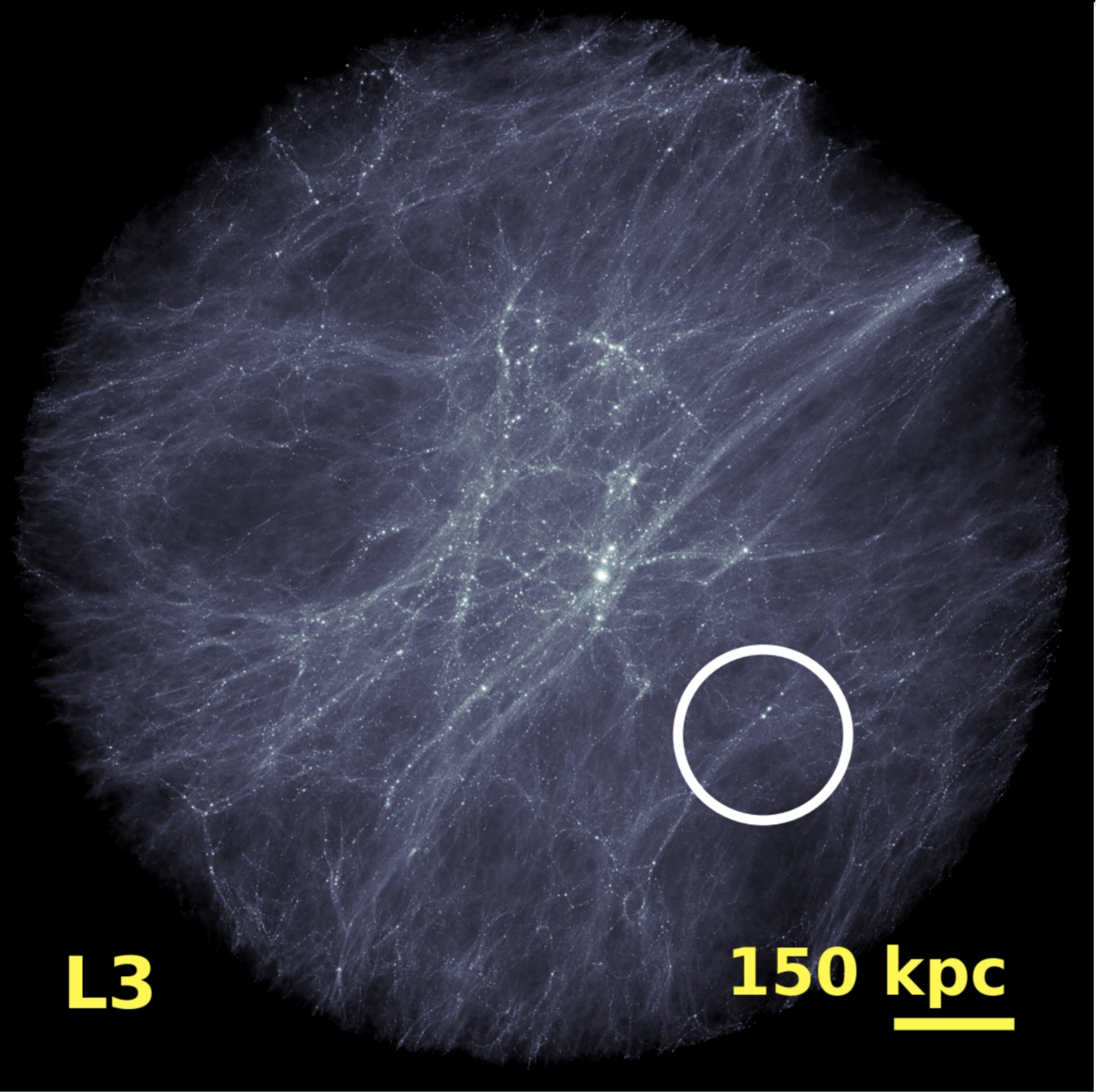
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^9 M_\odot$

Zoom Level 2

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

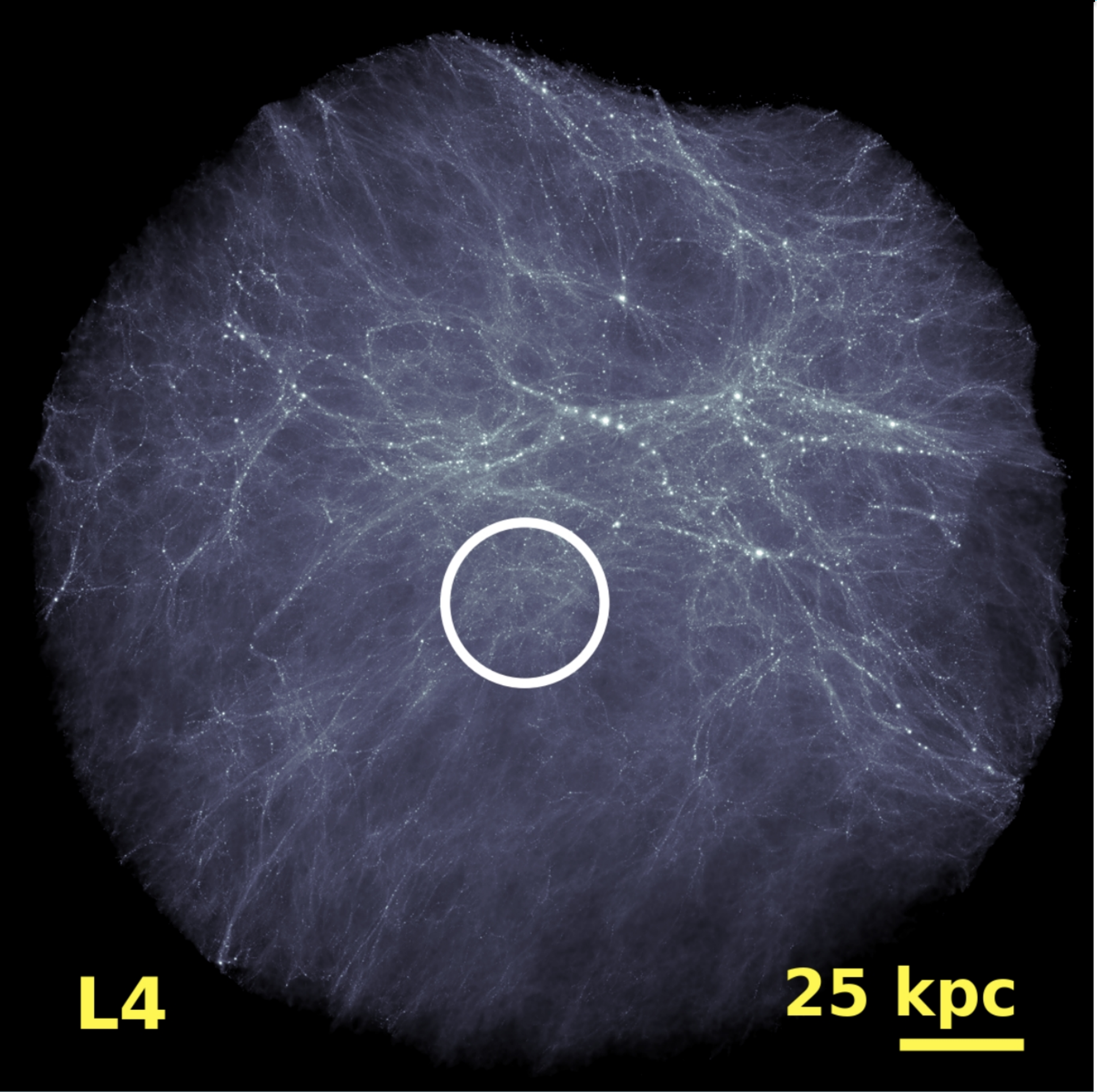
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^6 M_\odot$

Zoom Level 3

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

Dark matter only

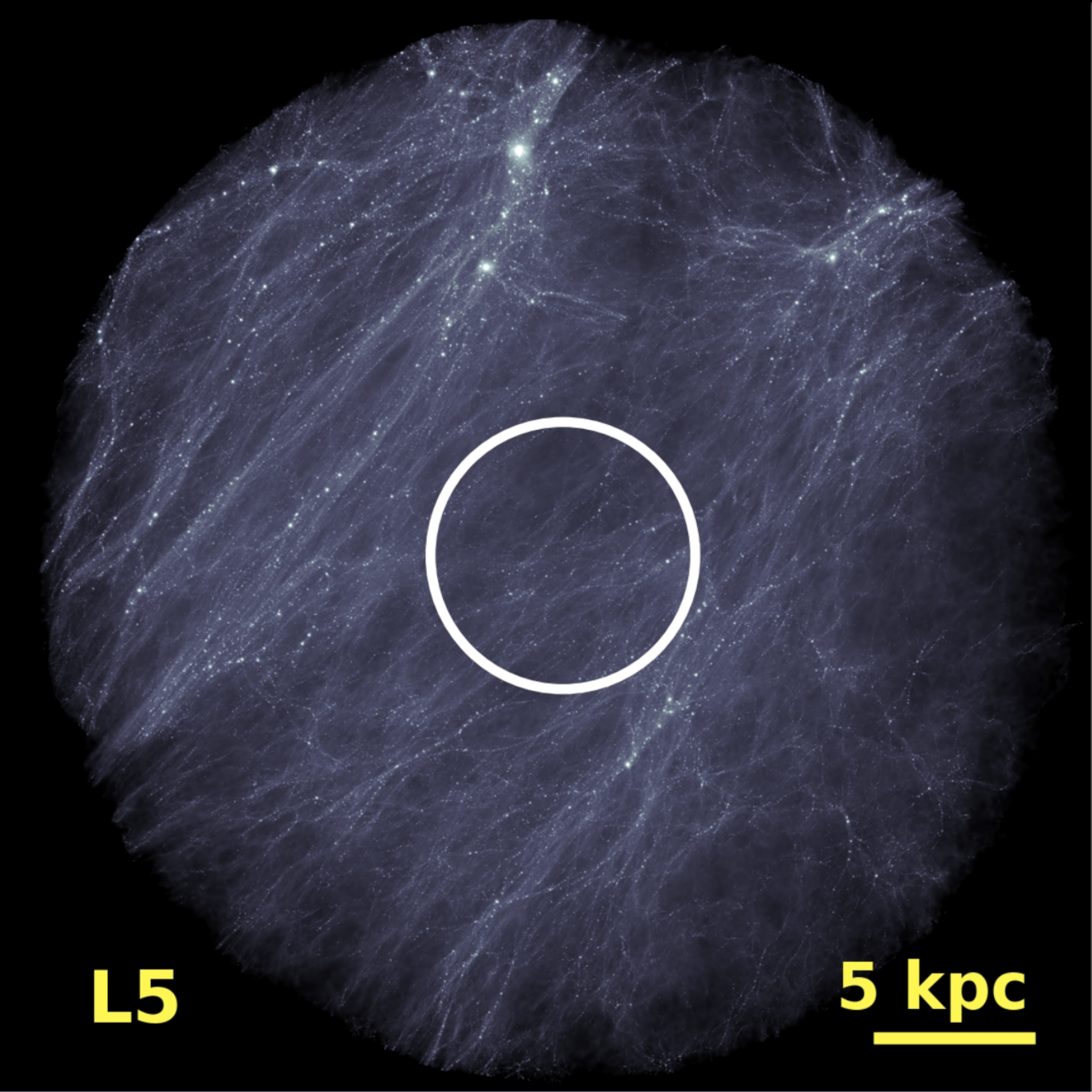
Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^3 M_\odot$

Zoom Level 4

Wang, Bose et al 2020

The VVV simulation



Planck cosmology

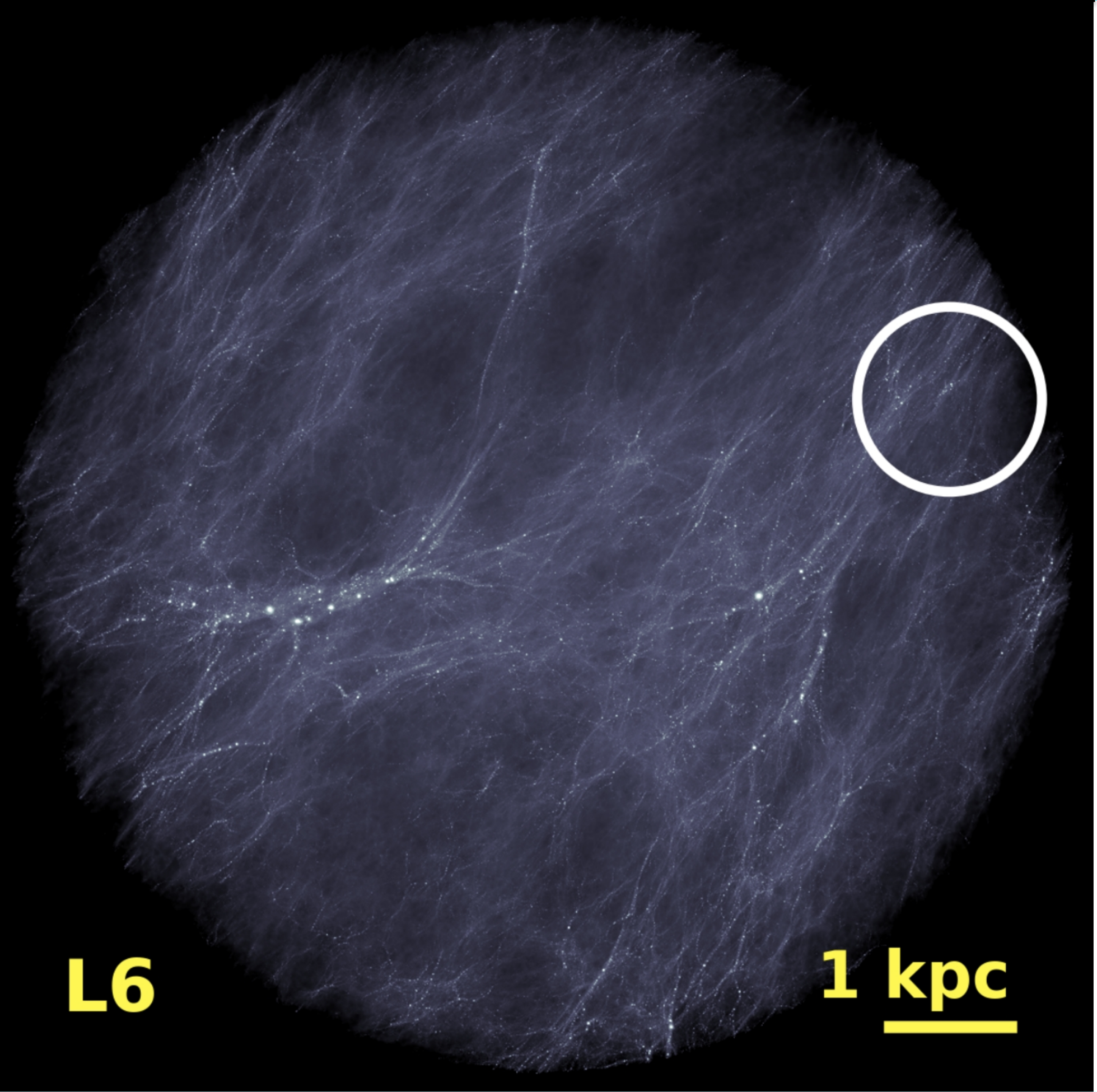
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10\ M_{\odot}$

Zoom Level 5

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

Dark matter only

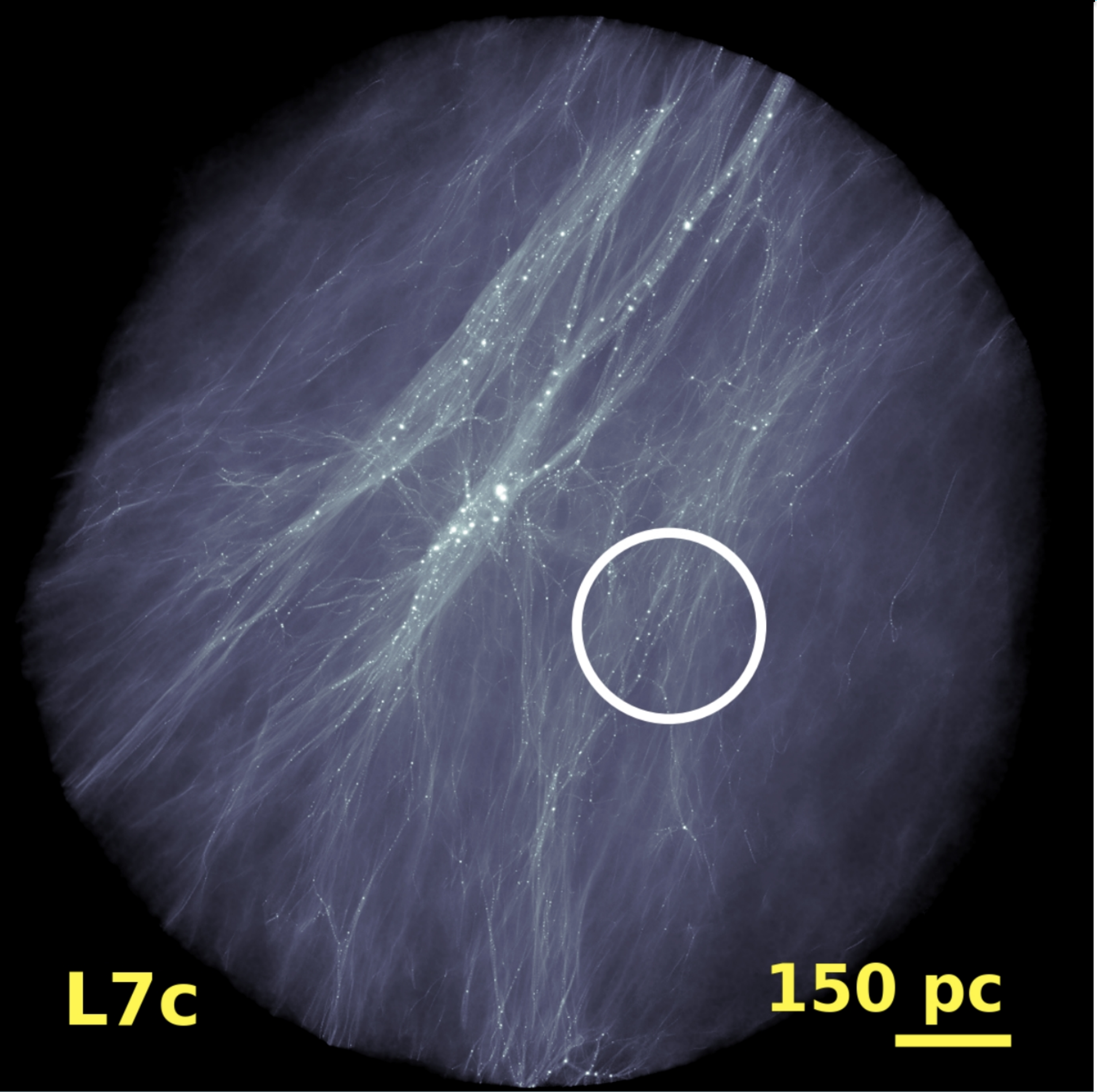
Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{-1}\ M_{\odot}$

Zoom Level 6

Wang, Bose et al 2020

The VVV simulation



Planck cosmology

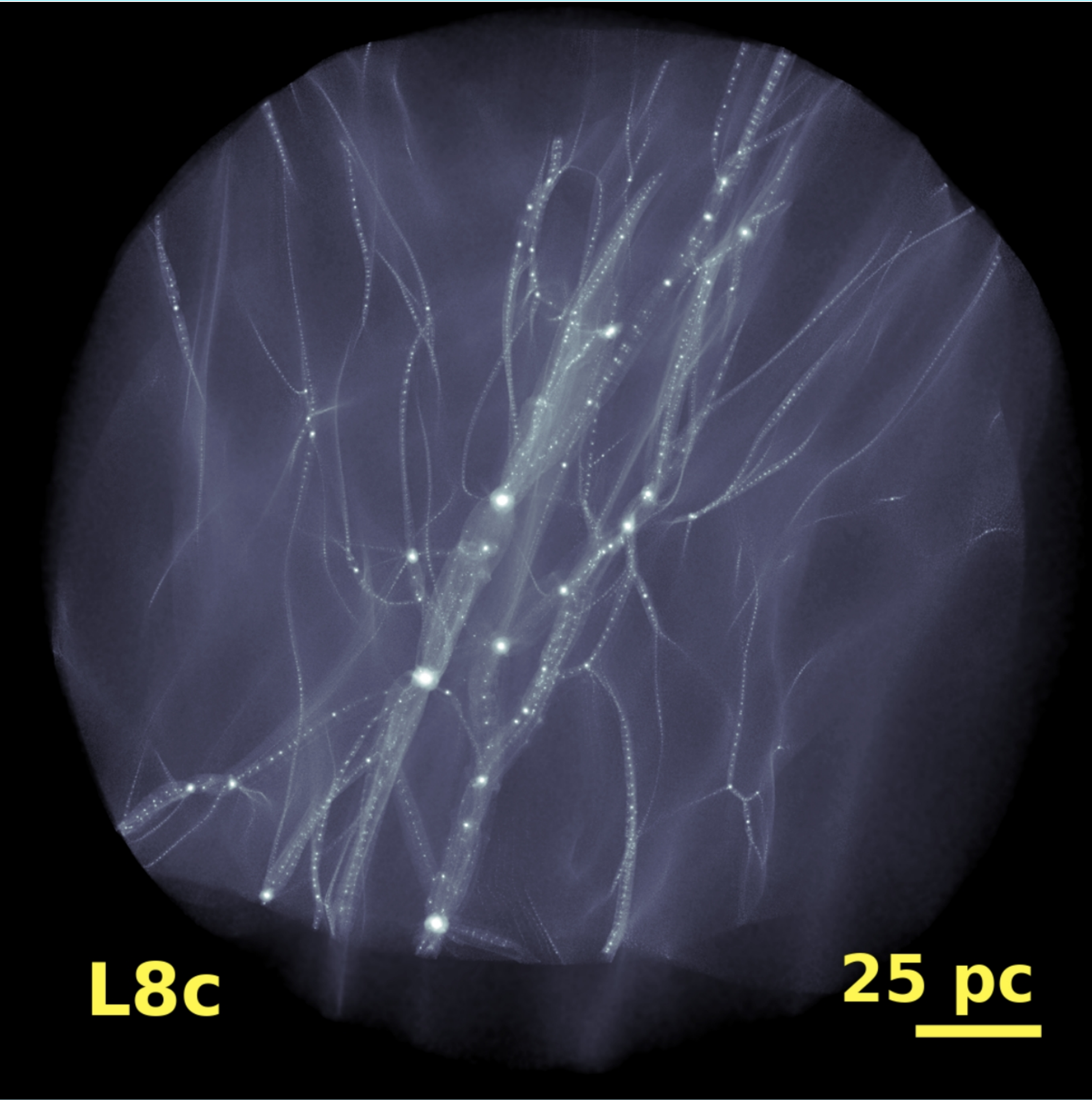
Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{-4}\ M_{\odot}$

Zoom Level 7

Wang, Bose et al 2020



The VVV simulation

Planck cosmology

Dark matter only

Dynamic range of 30 orders of magnitude in mass

$M_{char} = 10^{-6}\ M_{\odot}$

Zoom Level 8

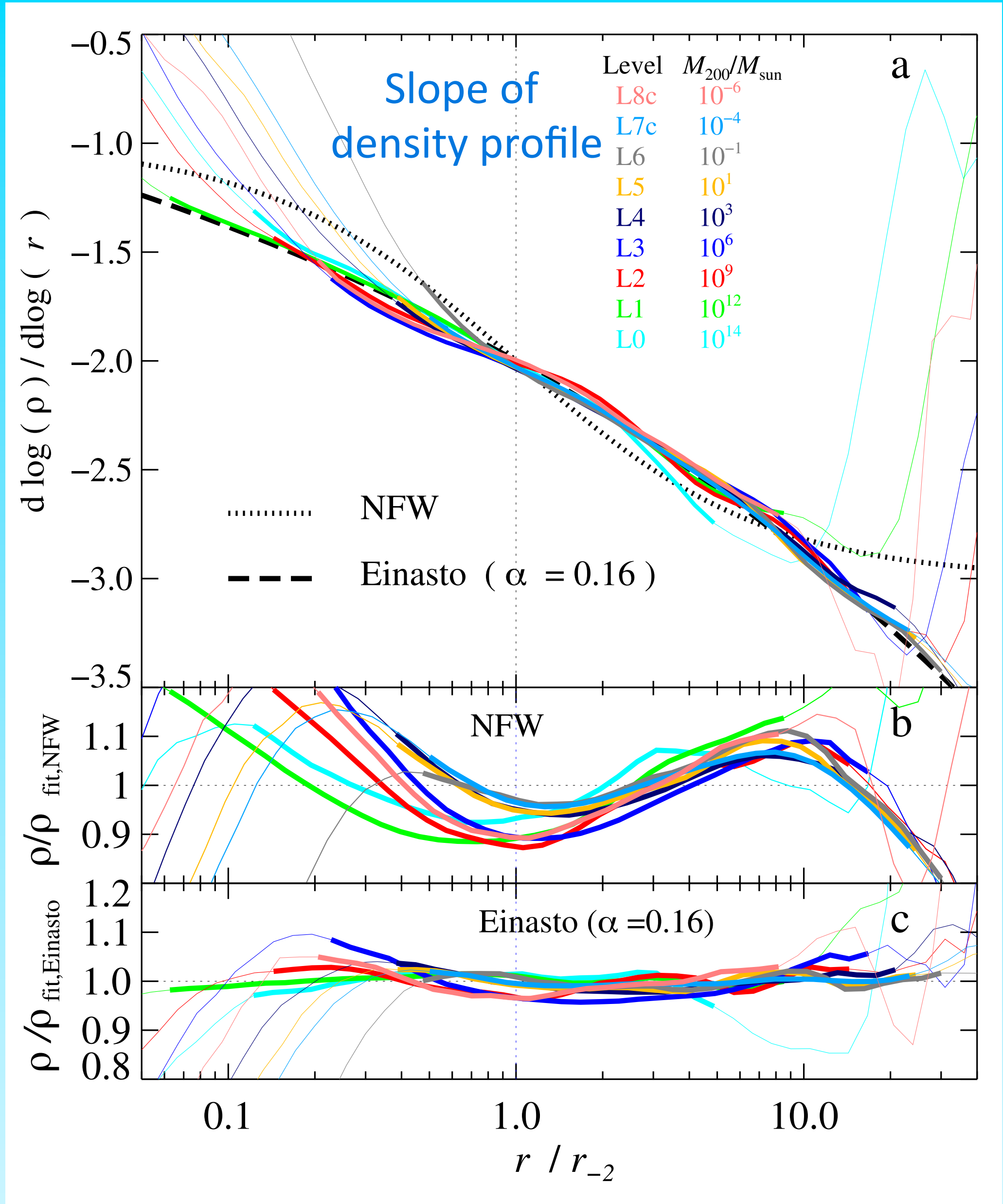
The density of this region is only ~3% of the cosmic mean

Wang, Bose et al 2020

Density profile shapes

University of Durham

Over 19 orders of magnitude in halo mass and 4 orders of magnitude in density, the mean density profiles of halos are **universal** and fit by NFW to within 20% and by Einasto (α =0.16) to within 7%



Wang, Bose, CSF + '20

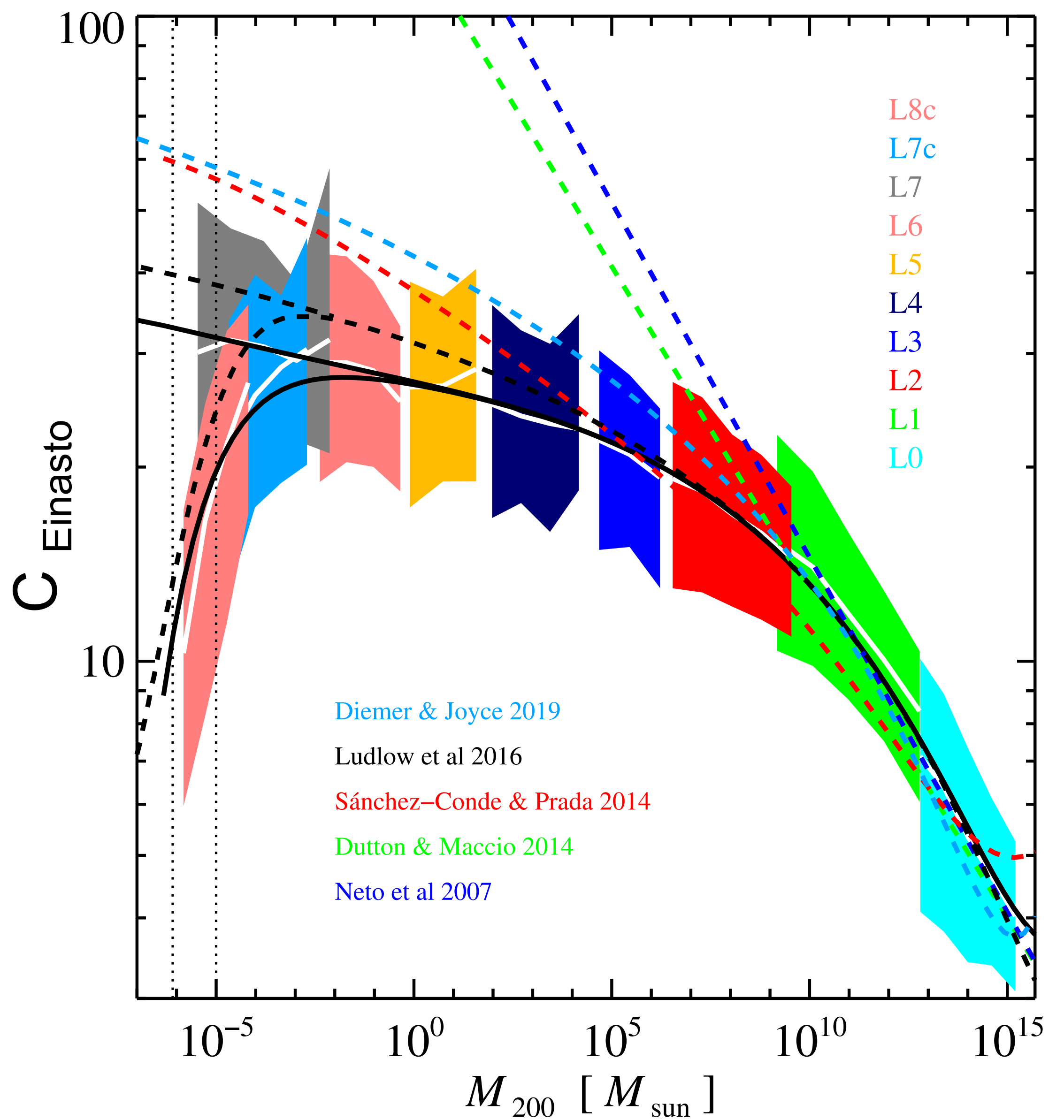
Concentration-mass relation

University of Durham

Concentrations at small mass are lower than all previous extrapolations by up to factors of tens.

A turndown at 10^3 Earth masses is due to the free-streaming limit.

The scatter depends only weakly on halo mass

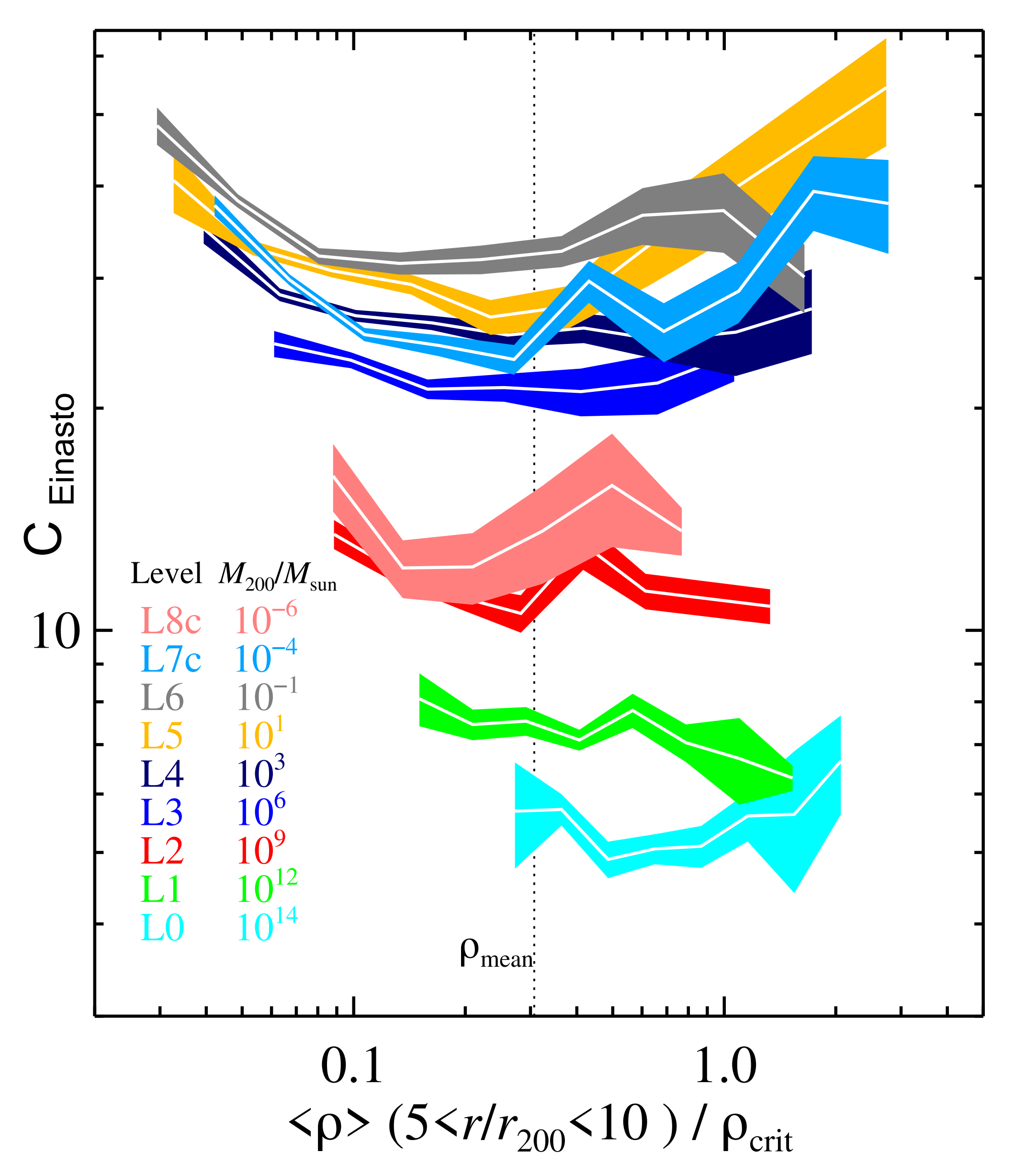


Wang, Bose, CSF + '20

Concentration-density relation

At given halo mass, concentration does not depend on local environment density

The range of local environment density does not depend strongly on halo mass



Wang, Bose, CSF + '20

Annihilation luminosity

University of Durham

The contribution of halos to the mean z = 0 luminosity density of the Universe is almost independent of their mass over the mass range

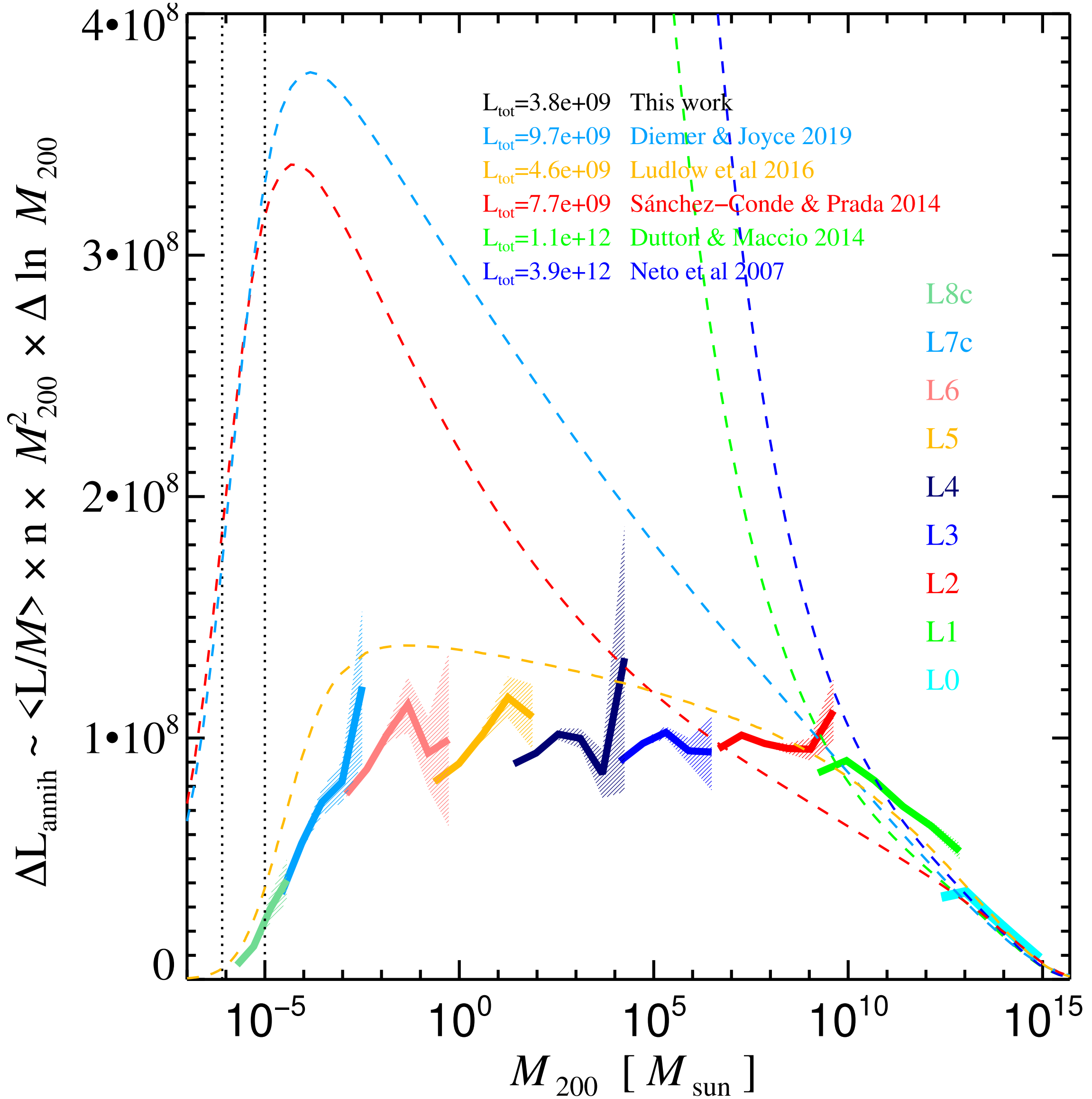
$10^{-4}\,M_\odot < M_{halo} < 10^{12}\,M_\odot$

It is lower than previously estimated by factors between 3 and 1000

This still neglects the substructure contribution to halo luminosity

Wang, Bose, CSF + '20

Annihilation luminosity per unit cosmological volume



Conclusions I

The small-scale "crisis" of CDM

"Solved" by:

1. "Missing satellites"	1. Galaxy formation
2. "Too-big-to-fail"	2. Galaxy formation
3. "Plane of satellites"	3. Statistics
4. "Core-cusp"	4. Baryon effects

Conclusions II

- The abundance and structure of small halos is sensitive to the nature of dark matter
- Smallest halos: in CDM → Earth mass. In WDM → dwarf gal.
- Halos of collisionless dark matter have universal NFW density profiles at low redshift on all mass scales
- Near the cutoff, free-streaming reduces halo concentration
- Mass-concentration relation independent of local environment
- Very small (sub)halos can dominate the annihilation luminosity

Conclusions

- The abundance and structure of small halos is sensitive to the nature of dark matter
- Free streaming of collisionless dark matter induces a small scale cut-off in the halo mass function. This can be on dwarf galaxy scales for WDM but is much smaller for CDM
- Halos of collisionless dark matter have universal density profiles at low redshift on all mass scales.
- Near the cutoff, free-streaming reduces halo concentration
- Low-mass halos identified at z=0 do not form from typical regions of the early Universe, but rather from the rare regions that are not incorporated into a higher mass halo
- Very small (sub)halos can dominate the annihilation luminosity