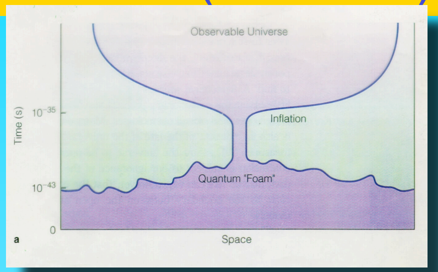
The structure of (mostly) dark matter halos

Carlos S. Frenk
Institute for Computational Cosmology, Durham

The origin of cosmic structure

University of Durham

Inflation ($t \sim 10^{-35}$ s)



→ QUANTUM FLUCTUATIONS:

$$\left\{ \begin{array}{l} |\delta_k|^2 \propto k^n \quad n \approx 1 \\ \text{Gaussian amplitudes} \end{array} \right.$$

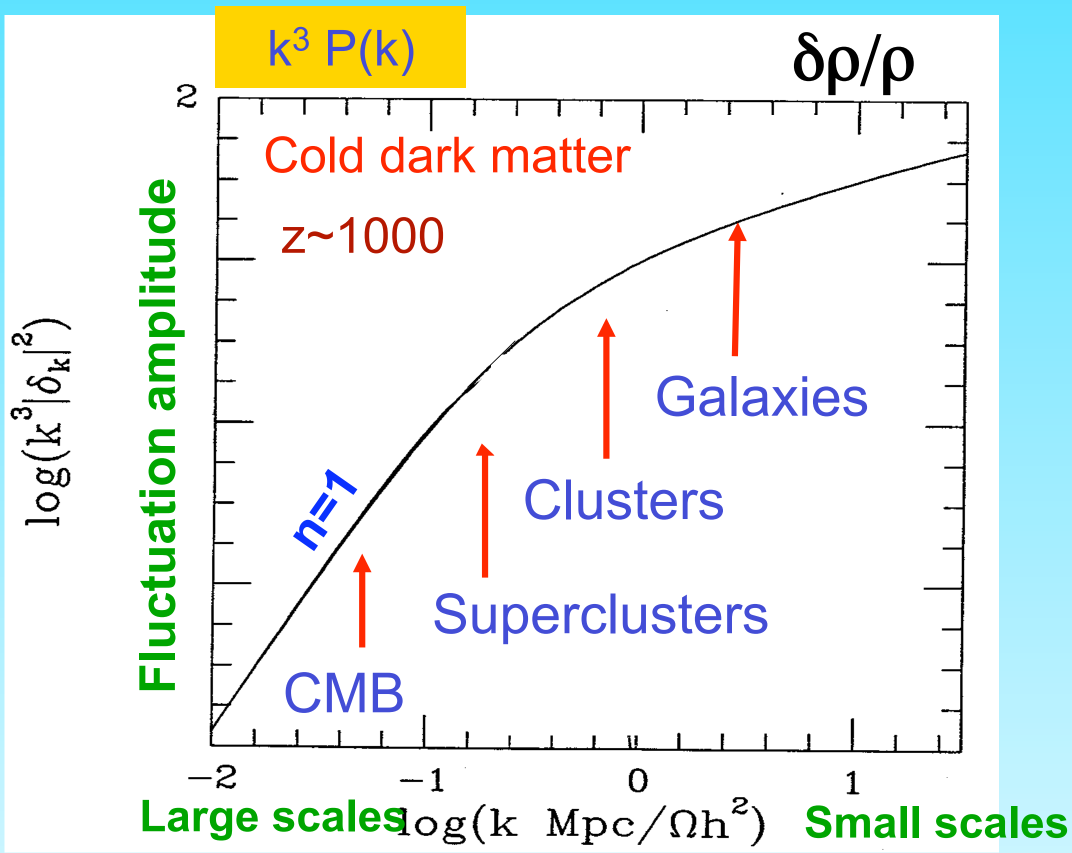
+

Damping (nature of dark matter)

→ FLAT UNIVERSE

$$P(k) = A k^n\, T^2(k,t)$$

Transfer function

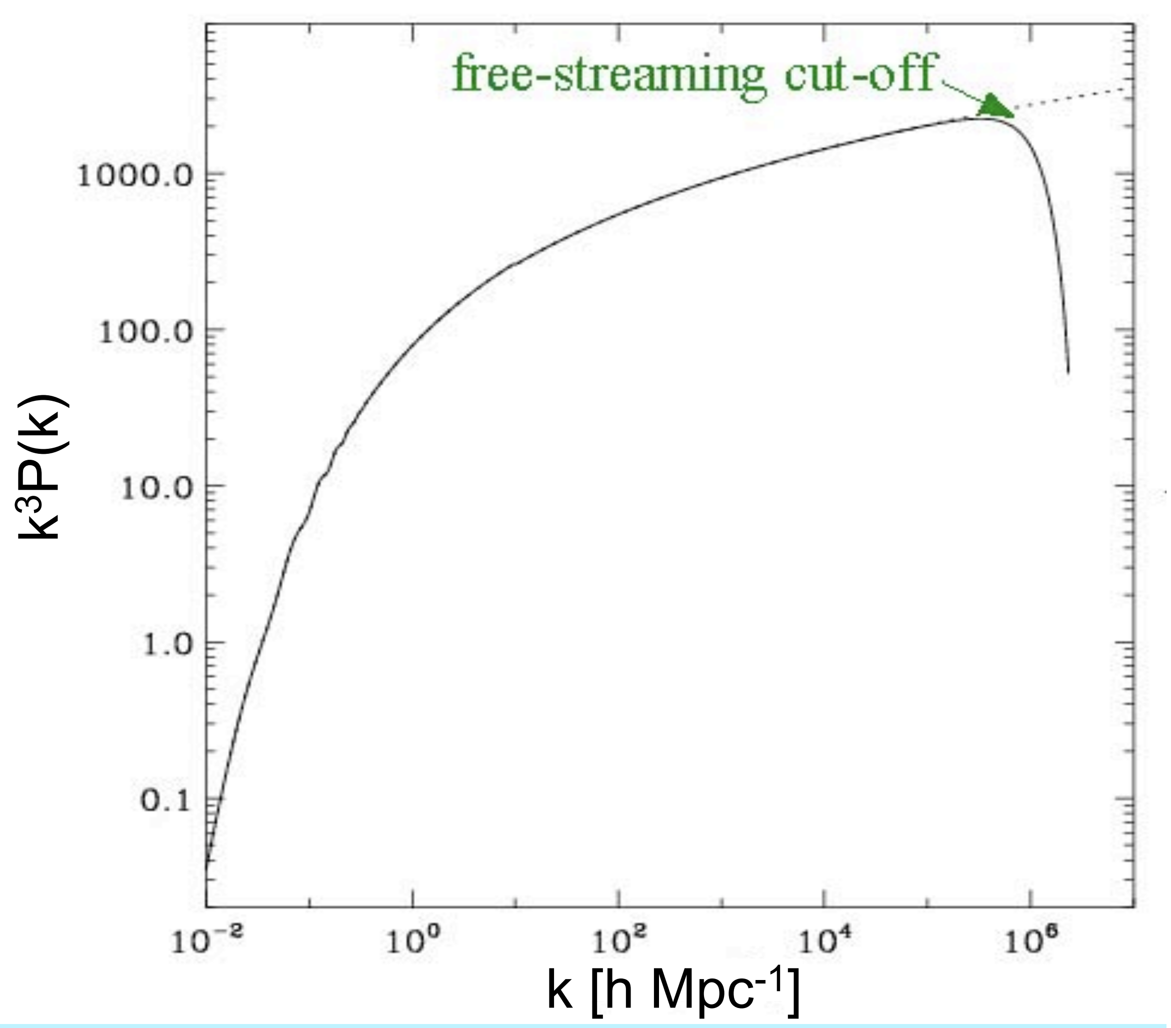


In the cold dark matter cosmogony structure forms hierarchically (i.e. small objects form first)

Institute for Computational Cosmology

The cold dark matter power spectrum

The linear power spectrum
("power per octave")



Assumes a 100GeV wimp
Green et al '04

University of Durham

The cold dark matter cosmogony

Peebles '82

THE ASTROPHYSICAL JOURNAL, 263:L1–L5, 1982 December 1

LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

P. J. E. PEEBLES
Joseph Henry Laboratories, Physics Department, Princeton University

Davis, Efstathiou, Frenk & White 1985

THE ASTROPHYSICAL JOURNAL, 292:371–394, 1985 May 15

THE EVOLUTION OF LARGE-SCALE STRUCTURE IN A UNIVERSE DOMINATED BY COLD DARK MATTER

MARC DAVIS,[1,2] GEORGE EFSTATHIOU,[1,3] CARLOS S. FRENK,[1,4] AND SIMON D. M. WHITE[1,5]
Received 1984 August 20; accepted 1984 November 30

THE ASTROPHYSICAL JOURNAL, 304:15–61, 1986 May 1

Bardeen, Bond, Kaiser & Szalay 1986

THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

J. M. BARDEEN[1]
Physics Department, University of Washington
J. R. BOND[1]
Physics Department, Stanford University
N. KAISER[1]
Astronomy Department, University of California at Berkeley, and Institute of Astronomy, Cambridge University
AND
A. S. SZALAY[1]
Astrophysics Group, Fermilab
Received 1985 July 25; accepted 1985 October 9

NATURE VOL. 311 11 OCTOBER 1984 — REVIEW ARTICLE — 517

Formation of galaxies and large-scale structure with cold dark matter

George R. Blumenthal* & S. M. Faber*
* Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, California 95064, USA
Joel R. Primack†§ & Martin J. Rees‡§
† Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA
‡ Institute of Theoretical Physics, University of California, Santa Barbara, California 93106, USA

Blumenthal, Faber, Primack & Rees 1984

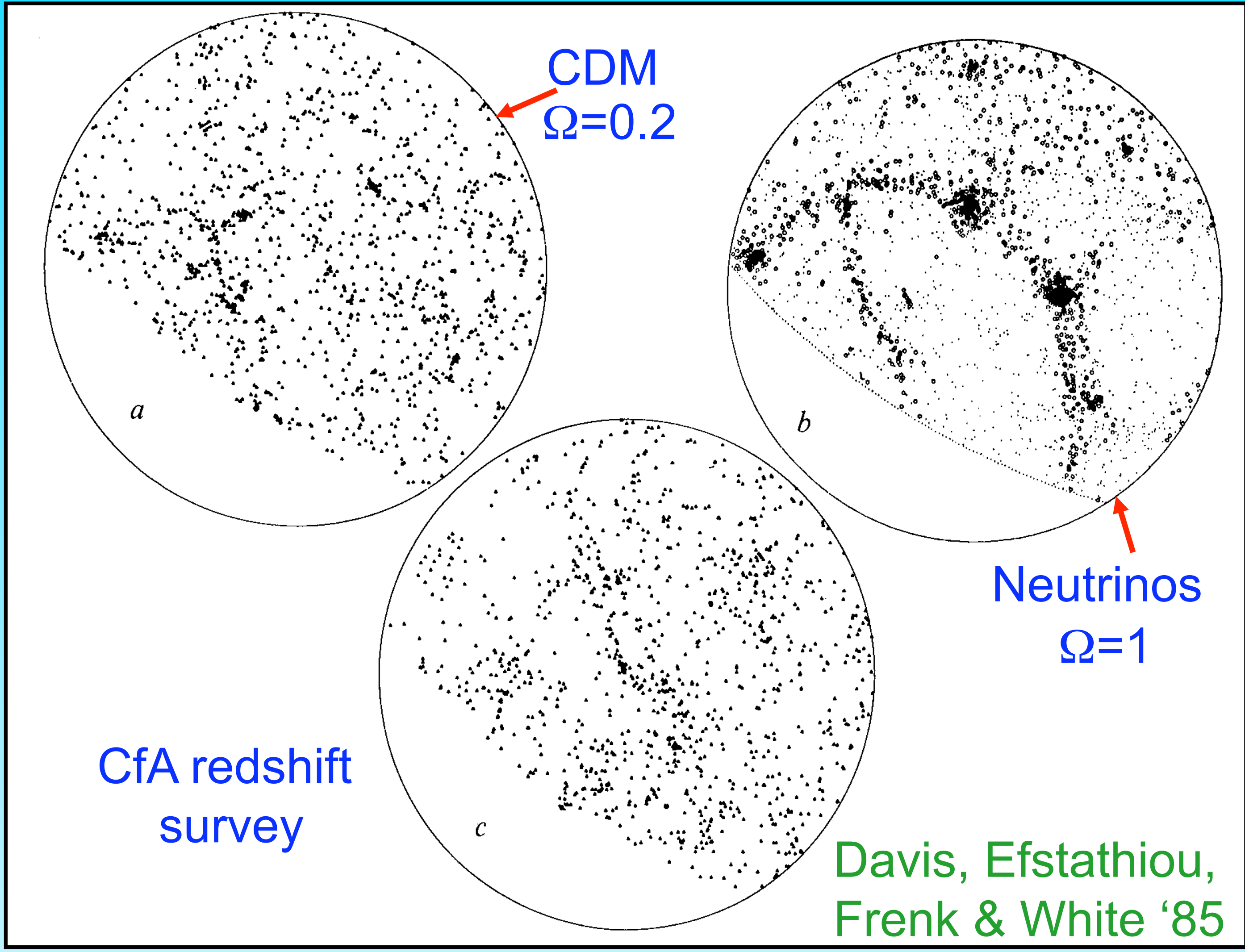
Non-baryonic dark matter cosmologies

University of Durham

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically

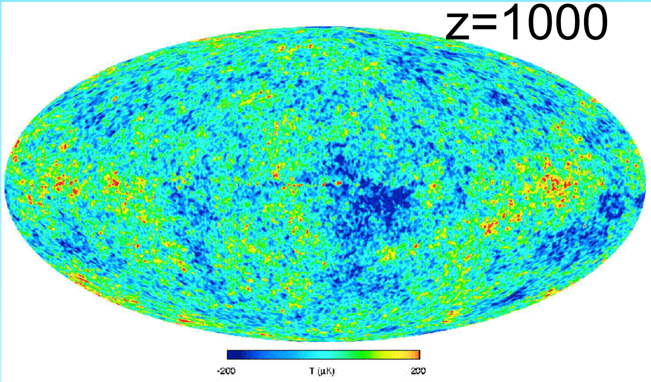


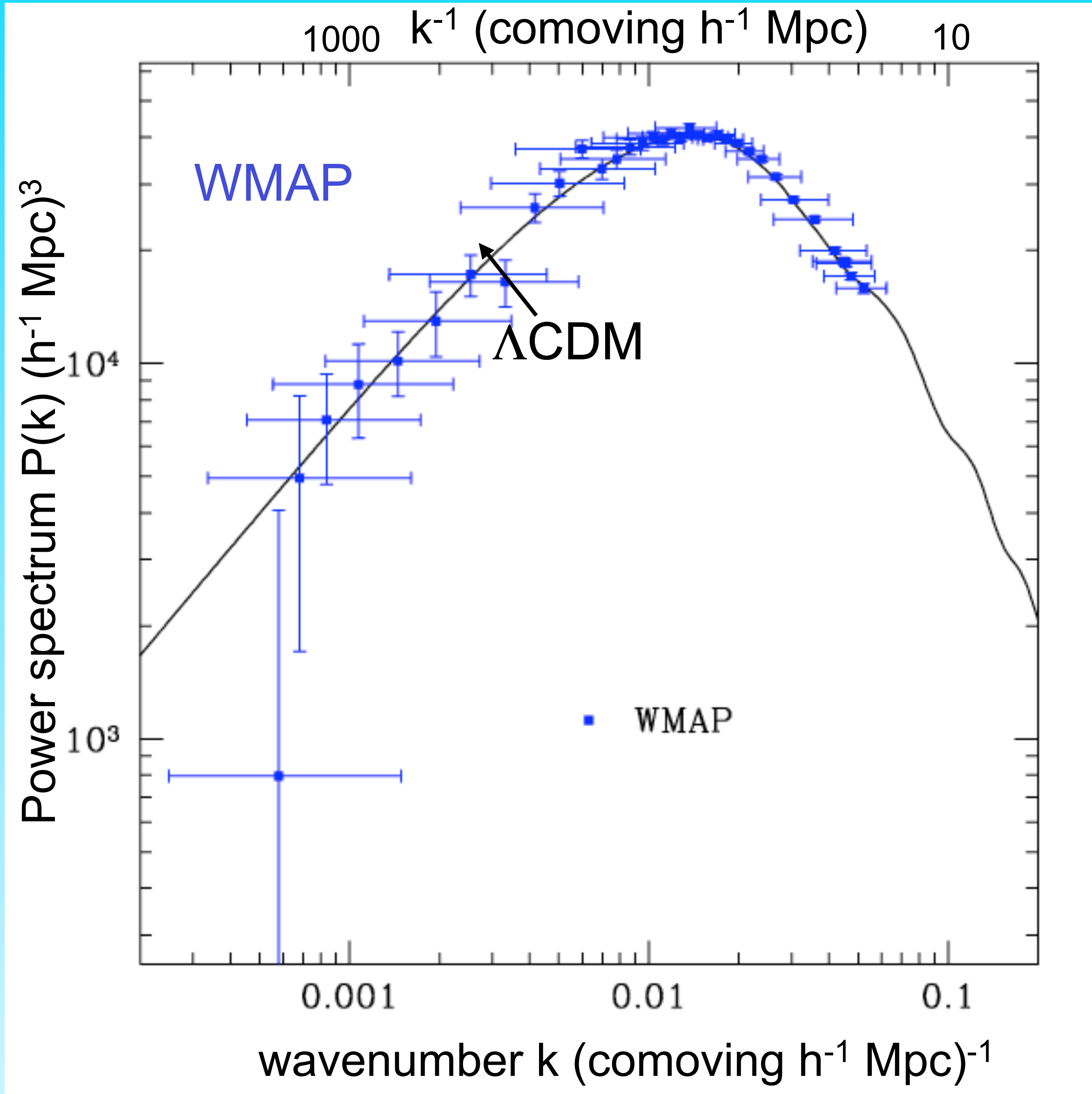
The cosmic power spectrum

University of Durham

CMB:

- Convert angular separation to distance (and k) assuming flat geometry
- Extrapolate to z=0 using linear theory





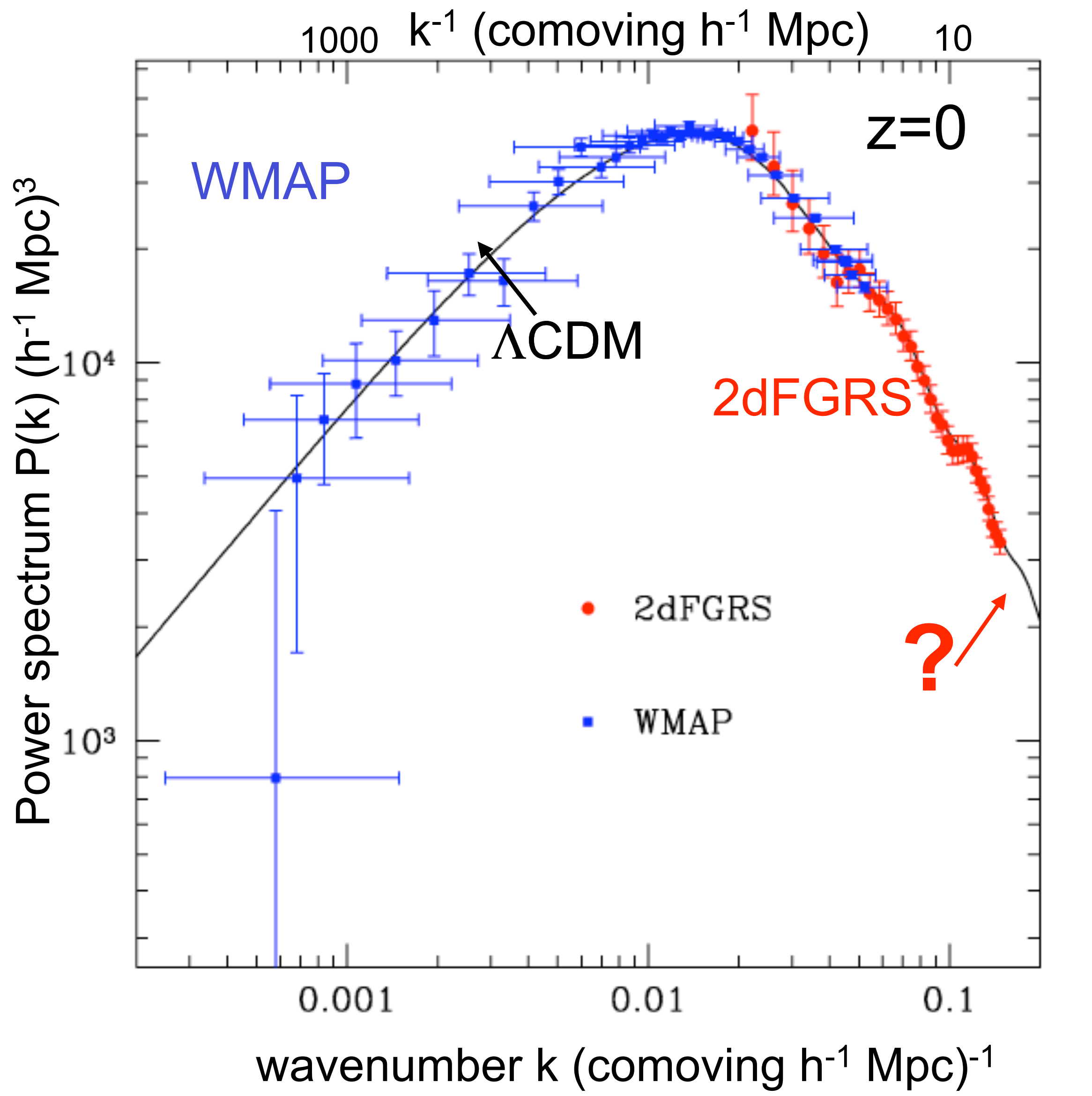
The cosmic power spectrum: from the CMB to the 2dFGRS

University of Durham

CMB:

- Convert angular separation to distance (and k) assuming flat geometry
- Extrapolate to z=0 using linear theory

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

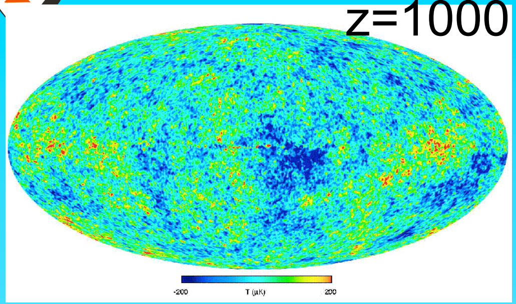


Sanchez et al 06

Galactic cold dark matter halos

3 topics:

- Halo cusp problem
- Satellite problem
- Possibility that CDM might soon be detected

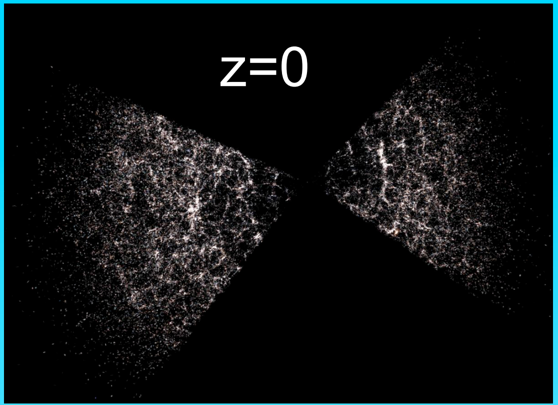


Cosmological model

$(\Omega_m, \Omega_\Lambda, h)$; dark matter

Primordial fluctuations

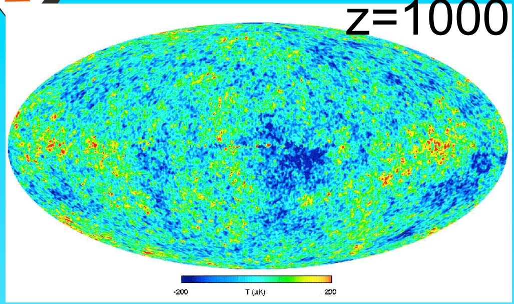
$\delta\rho/\rho(M, t)$



?

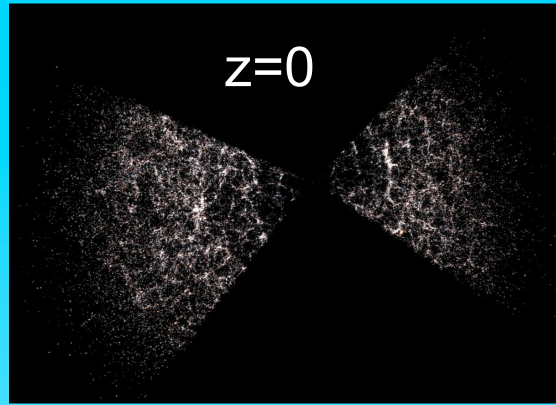
Formation and evolution of galaxies

z=1000



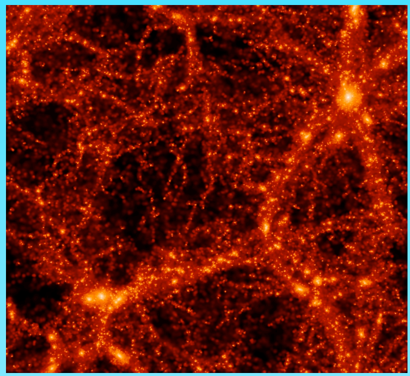
Cosmological model

$(\Omega_m, \Omega_\Lambda, h)$; dark matter



Primordial fluctuations

$\delta\rho/\rho(\mathbf{M}, \mathbf{t})$



Dark matter halos
(N-body simulations)

Well understood

Gas processes
(cooling, star formation, feedback)

Gasdynamic simulations

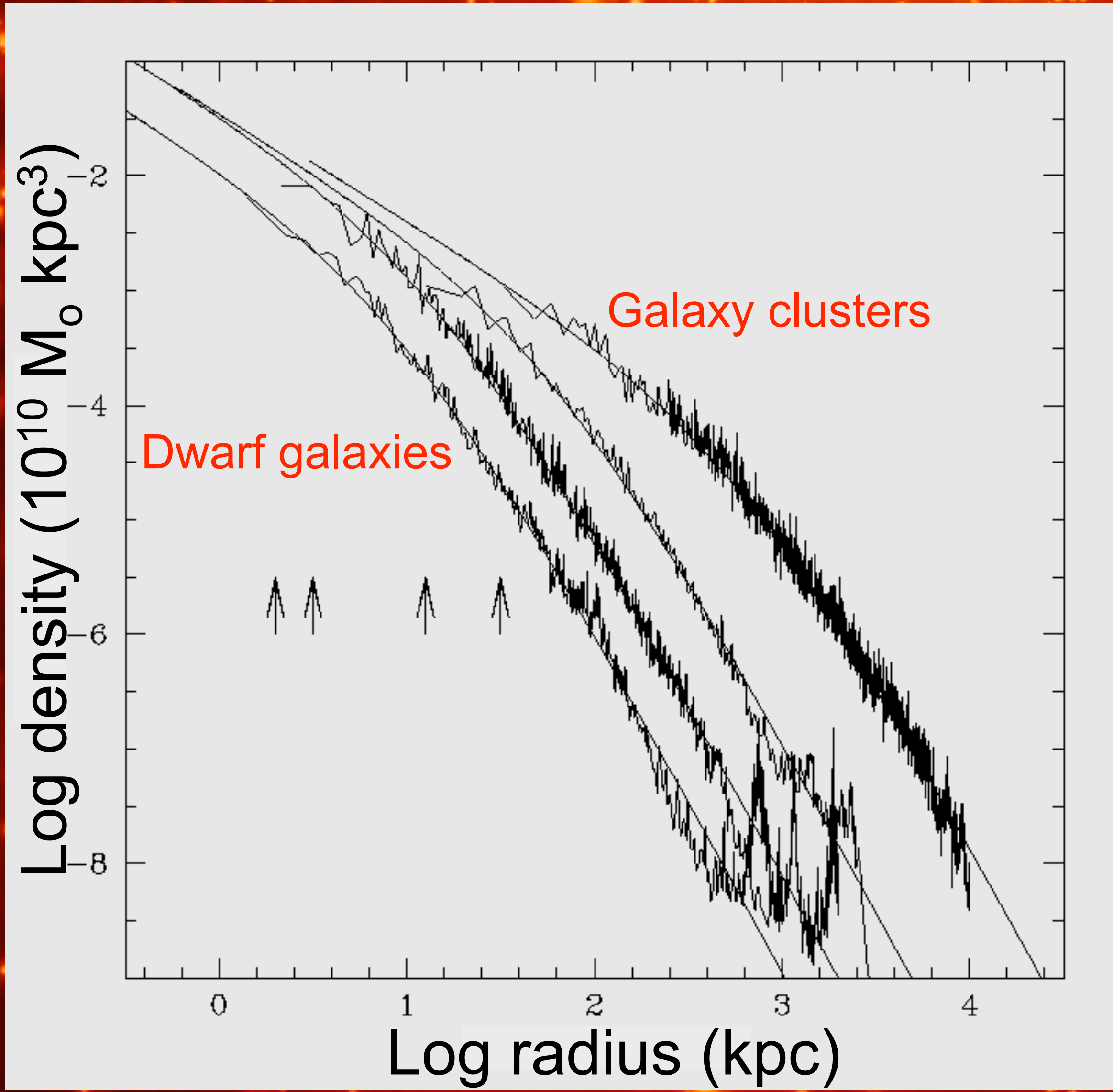
Semi-analytics

Formation and evolution of galaxies

The structure of cold dark matter halos

The halo cusp problem

The Density Profile of Cold Dark Matter Halos



Halo density profiles are independent of halo mass & cosmological parameters

There is no obvious density plateau or `core' near the centre.

(Navarro, Frenk & White '97)

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

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

The Aquarius programme

Carlos Frenk

Amina Helmi

Adrian Jenkins

Aaron Ludlow

Julio Navarro

Volker Springel,

Mark Vogelsberger

Jie Wang

Simon White

Aquarius ++

Shaun Cole

Andrew Cooper

Gabriella de Lucia

Takashi Okamoto

VIRGO

UK, Germany, Netherlands Canada collaboration

Pictures, movies and simulation data

available at:

http://www.mpa-garching.mpg.de/Virgo

www.durham.ac.uk/virgo

University of Durham

The Aquarius programme

6 different galaxy size halos simulated at varying resolution, allowing for a proper assessment of numerical convergence and cosmic variance

Numerical resolution	Particle number in halo (N_{50})	# of substructures	mass resolution
Aq-A-5	808,479	299	3.14×10^6 M_0
Aq-A-4	6,424,399	1,960	3.92×10^5 M_0
Aq-A-3	51,391,468	13,854	4.91×10^4 M_0
Aq-A-2	184,243,536	45,024	1.37×10^4 M_0
Aq-A-1	1,473,568,512	297,791	1.71×10^3 M_0 (15 pc/h softening)

VIRGO

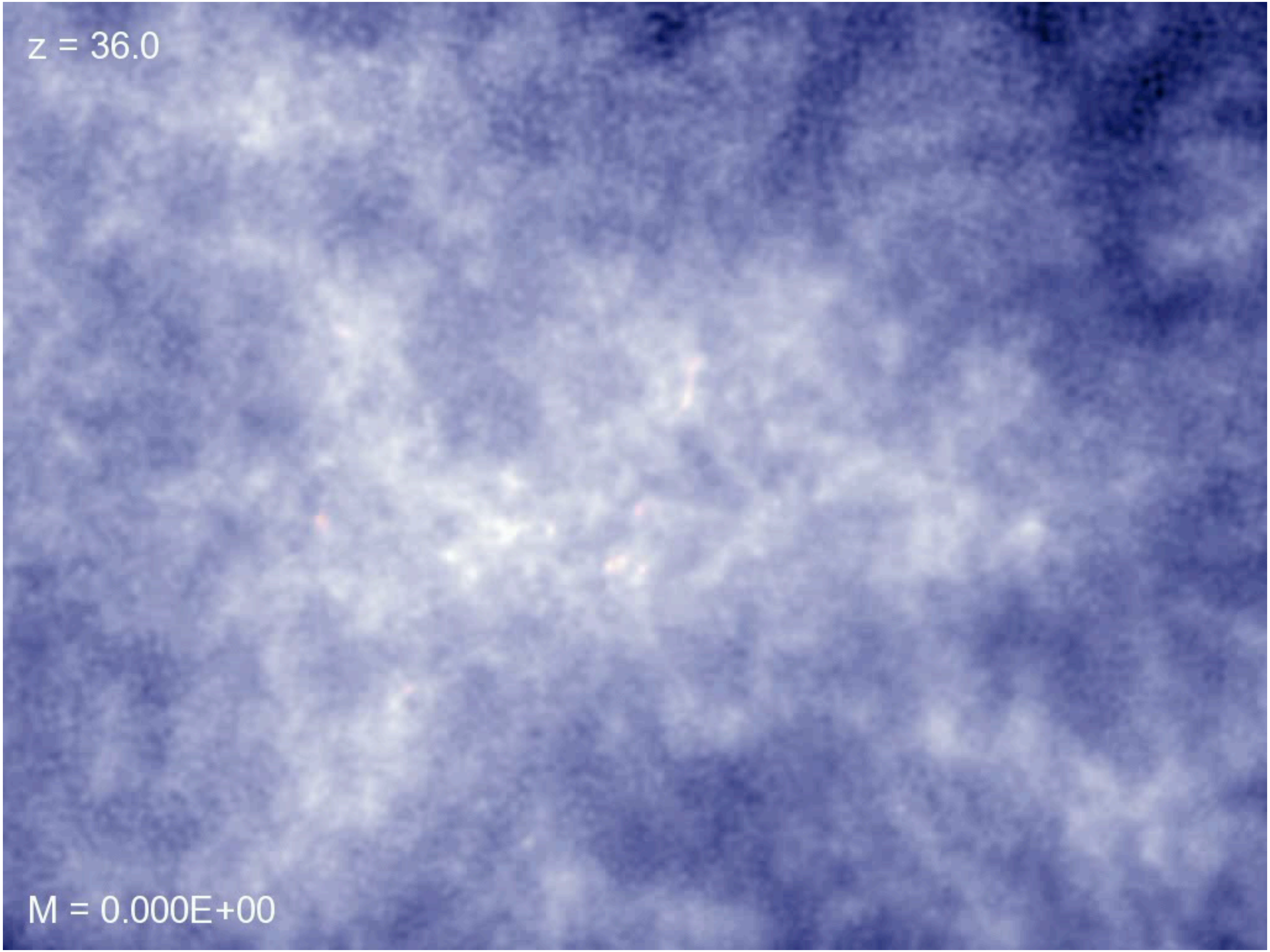
UK, Germany, Canada, Japan, US collaboration

Simulation data, movies, pictures available at:

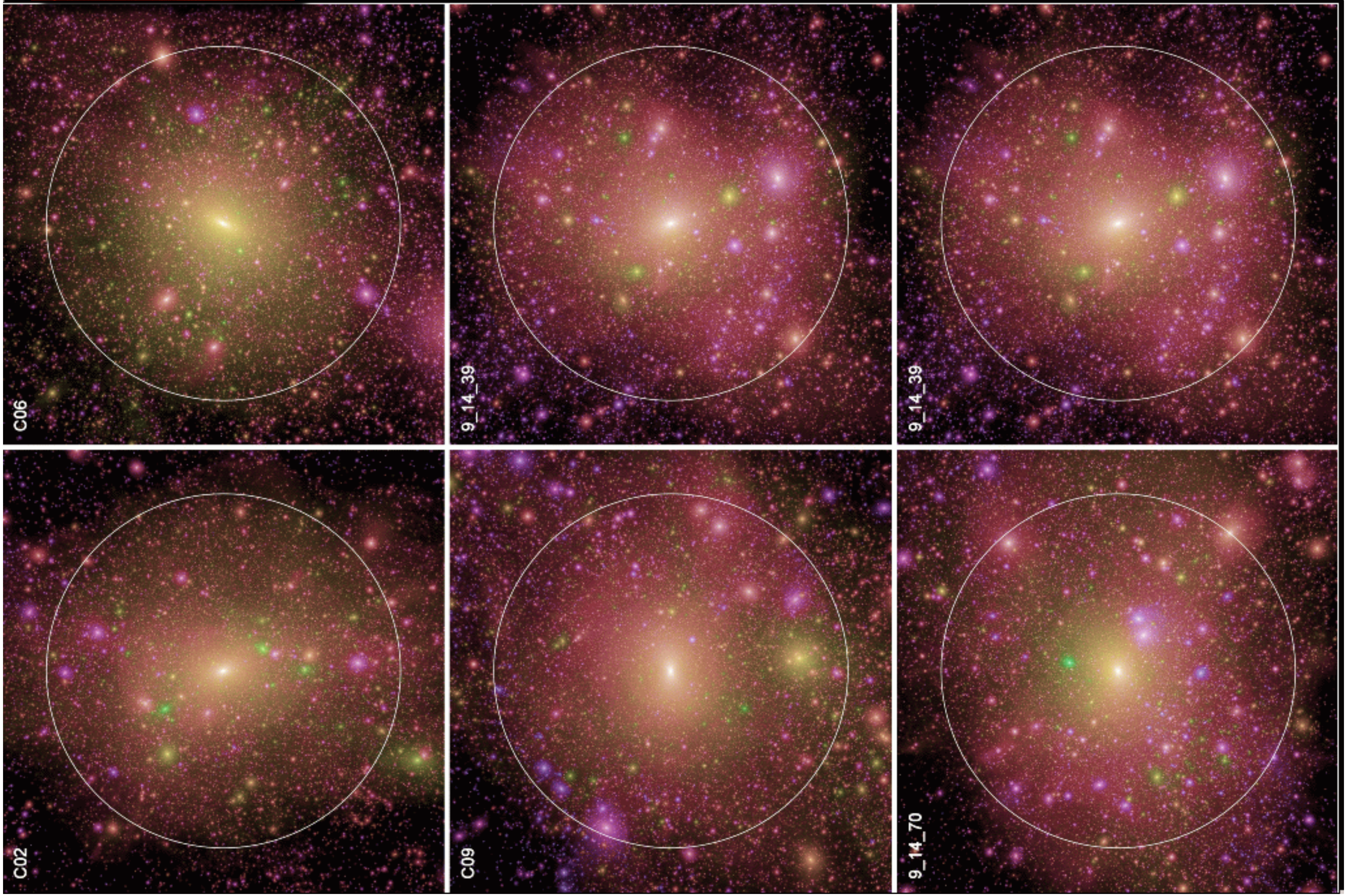
www.mpa-garching.mpg.de/Virgo

www.durham.ac.uk/virgo

Springel et al '08


z = 36.0
M = 0.000E+00

Images of all Aquarius halos (level-2)



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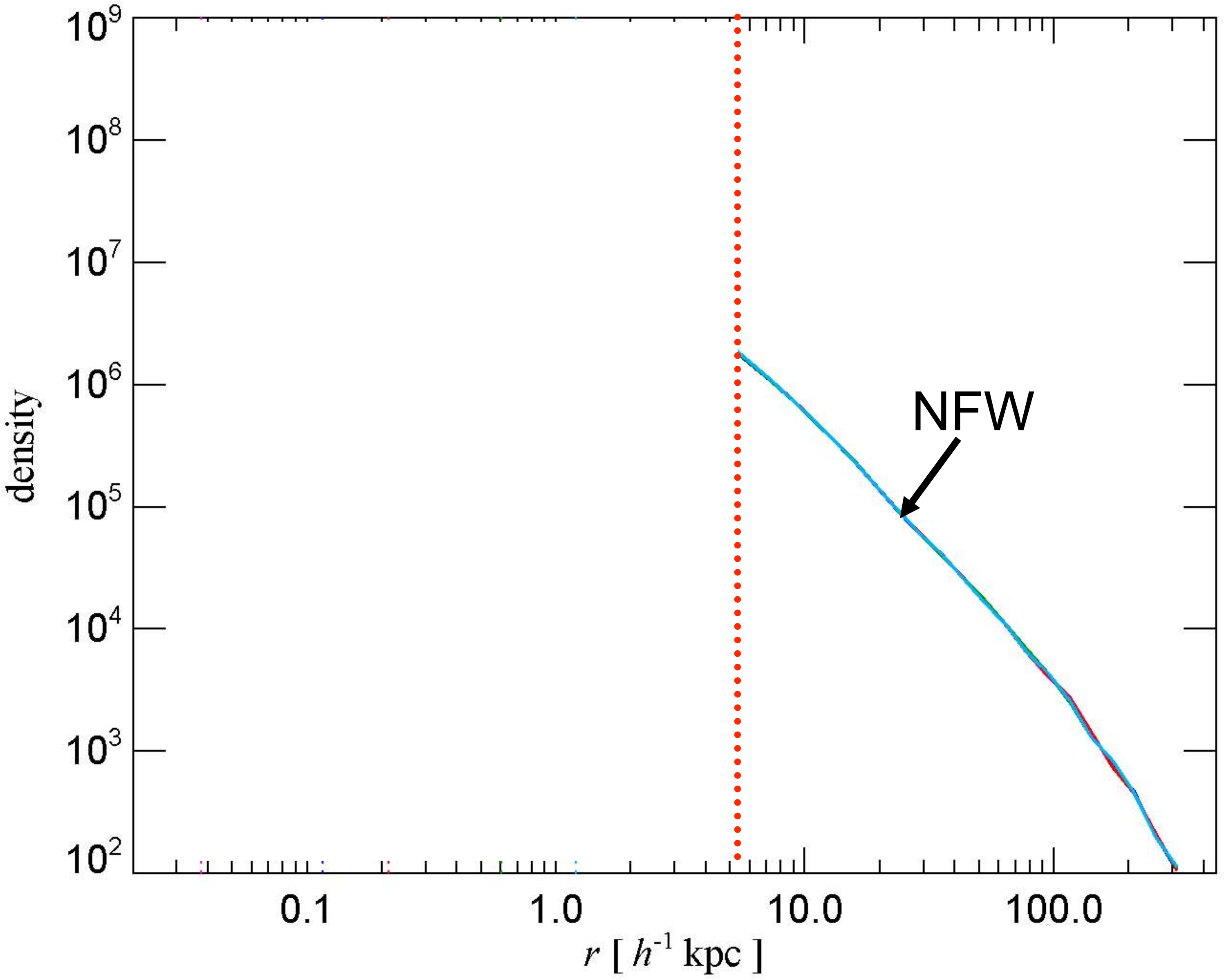
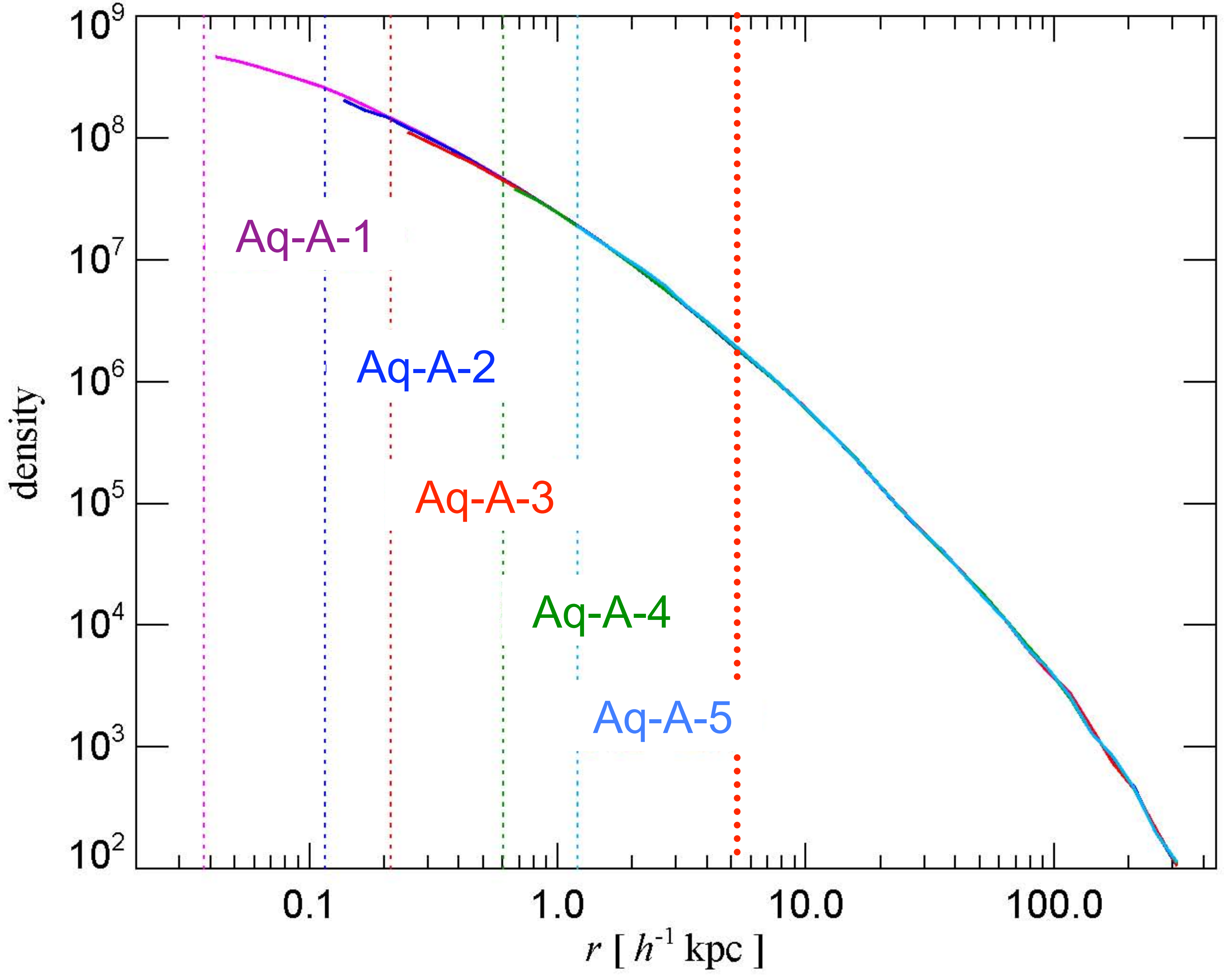
Density profile ρ(r)

Orignal NFW simulations resolved down to 5% of r_{vir}



University of Durham

Density profile ρ(r)

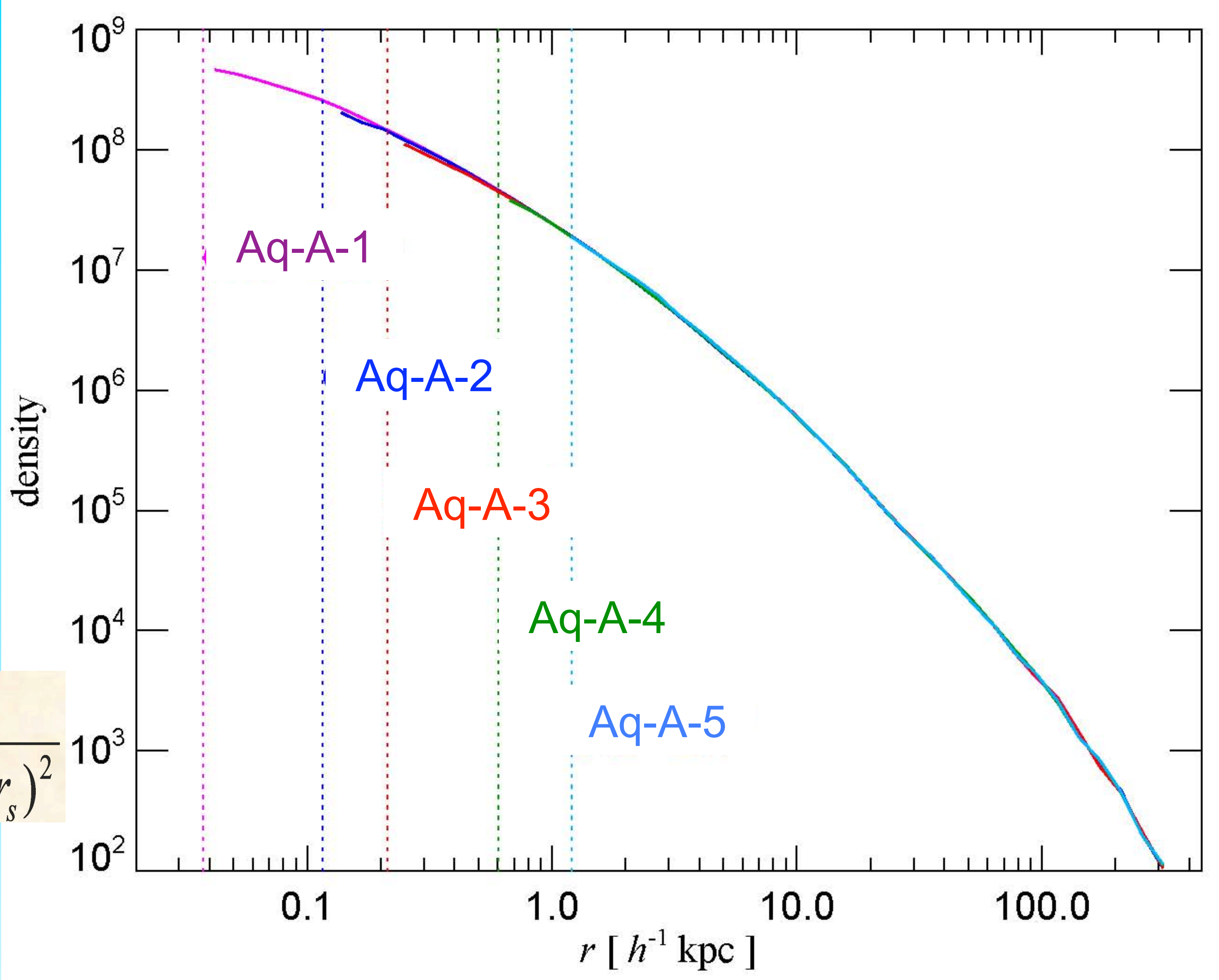


Density profile ρ(r): convergence test

University of Durham

The spherically averaged density profiles show very good convergence, and are approximately fit by a NFW profile

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



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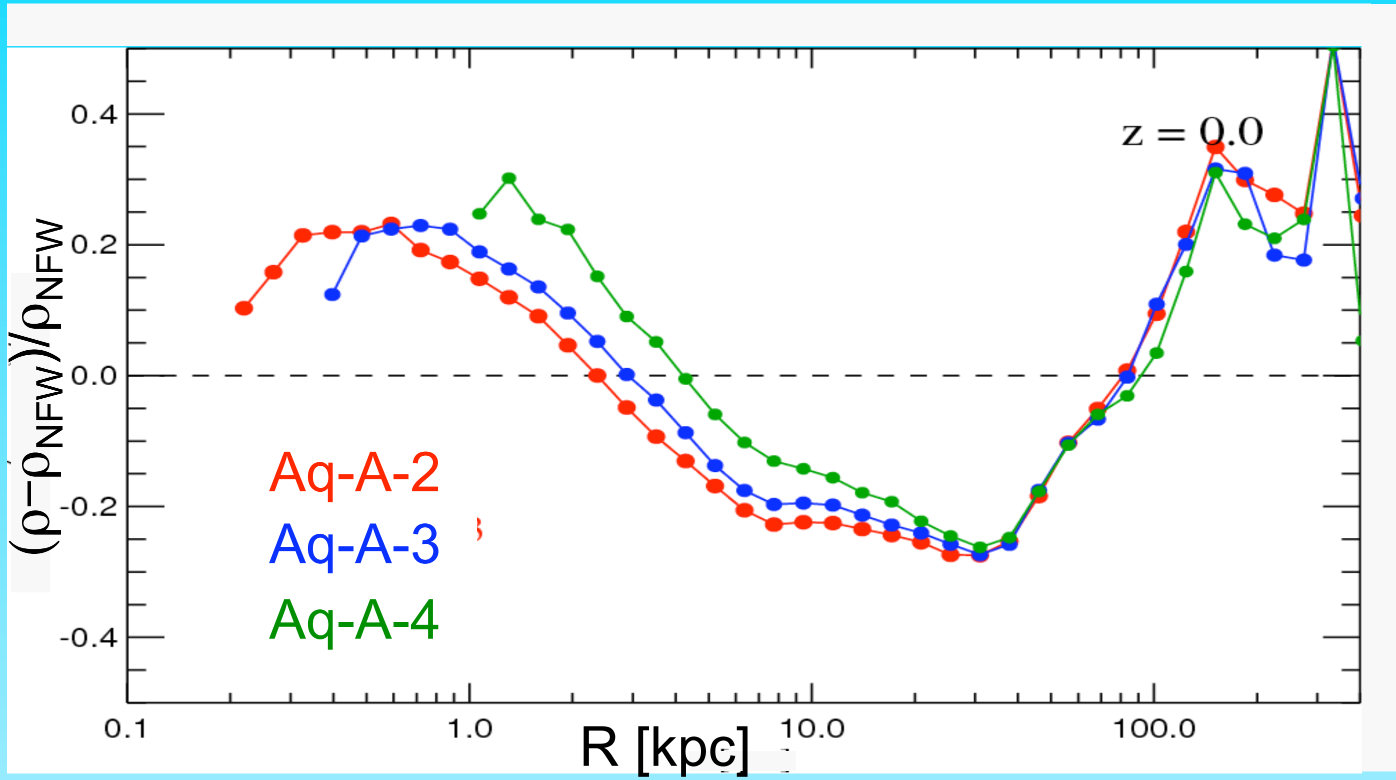
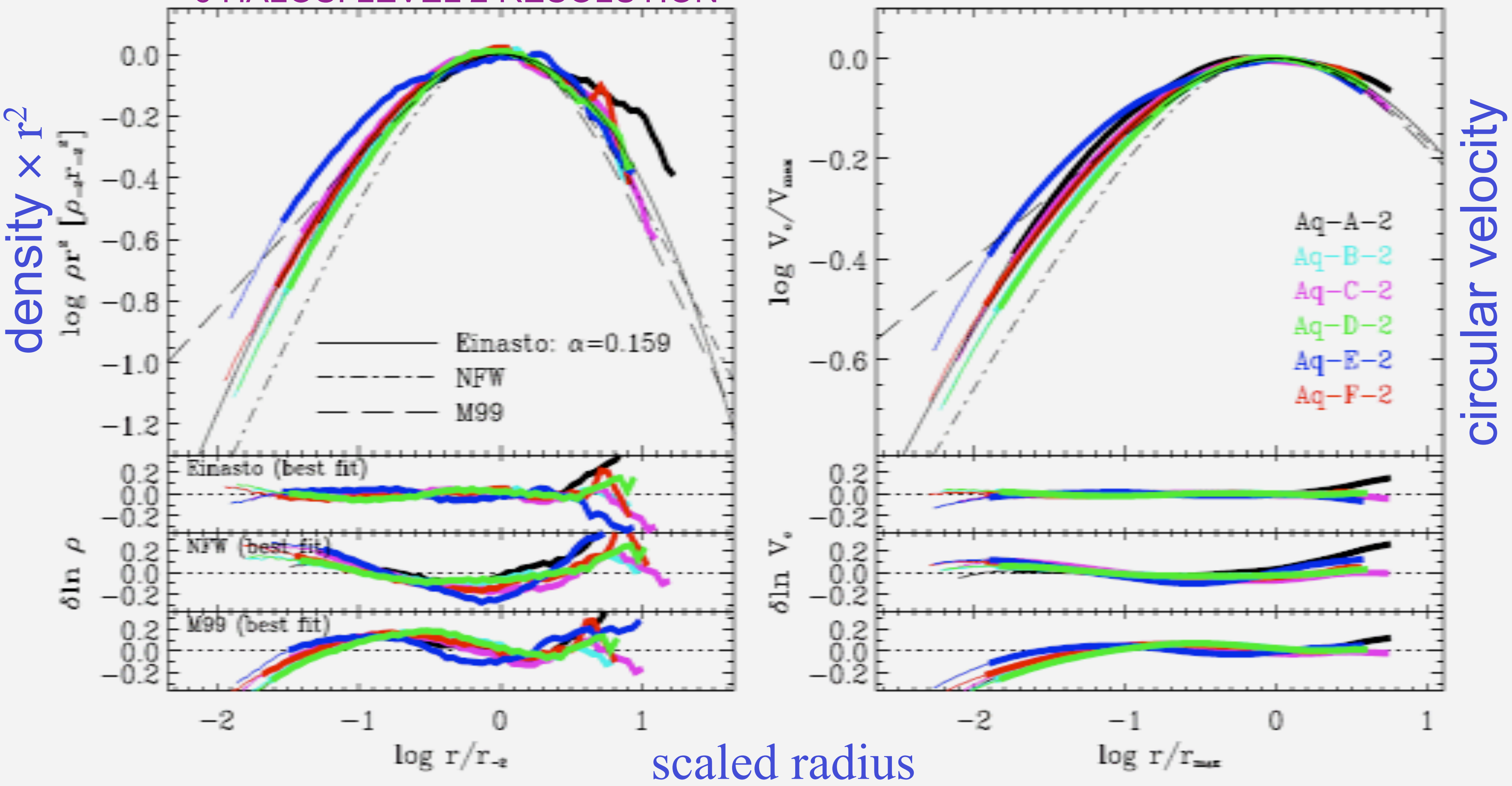
Deviations from NFW



The density profile is fit by the NFW form to ~10-20%.
In detail, the shape of the profile is slightly different.

Universality of the mass profile

6 HALOS: LEVEL 2 RESOLUTION

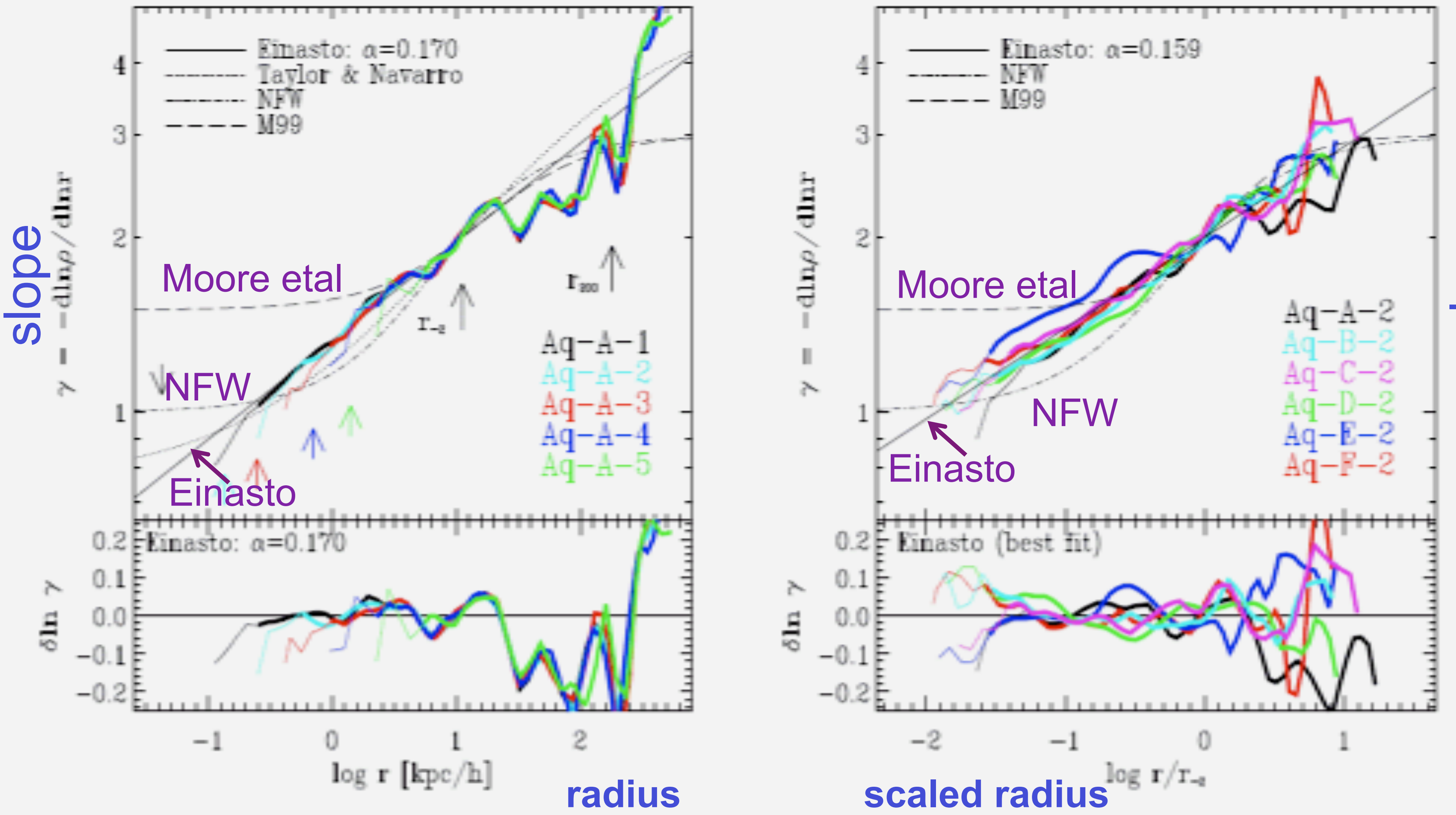


Slight but significant deviations from similarity.

A "third parameter" needed to describe accurately mass profiles of CDM halos.

Einasto: $\ln(\rho/\rho_{-2}) = -(2/\alpha)[(r/r_{-2})^{\alpha} - 1]$. Virgo Consortium 08

The structure of the cusp



Logarithmic slope scales like a power-law of radius: the Einasto profile
Innermost profile shallower than r^{-1}

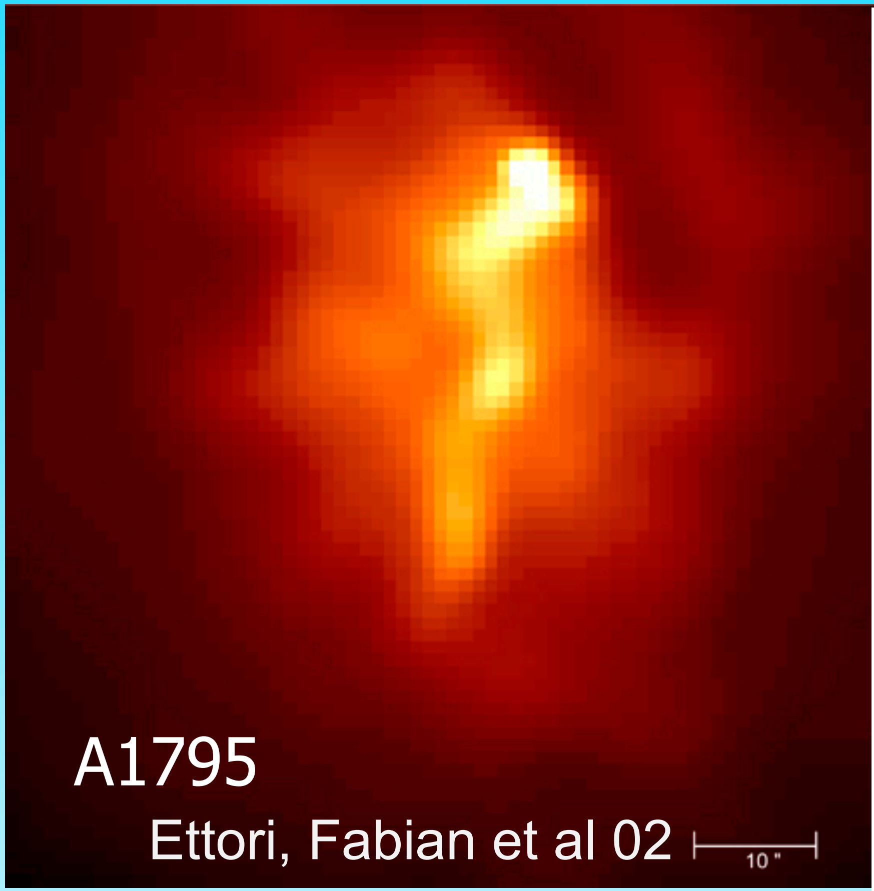
A cold dark matter universe

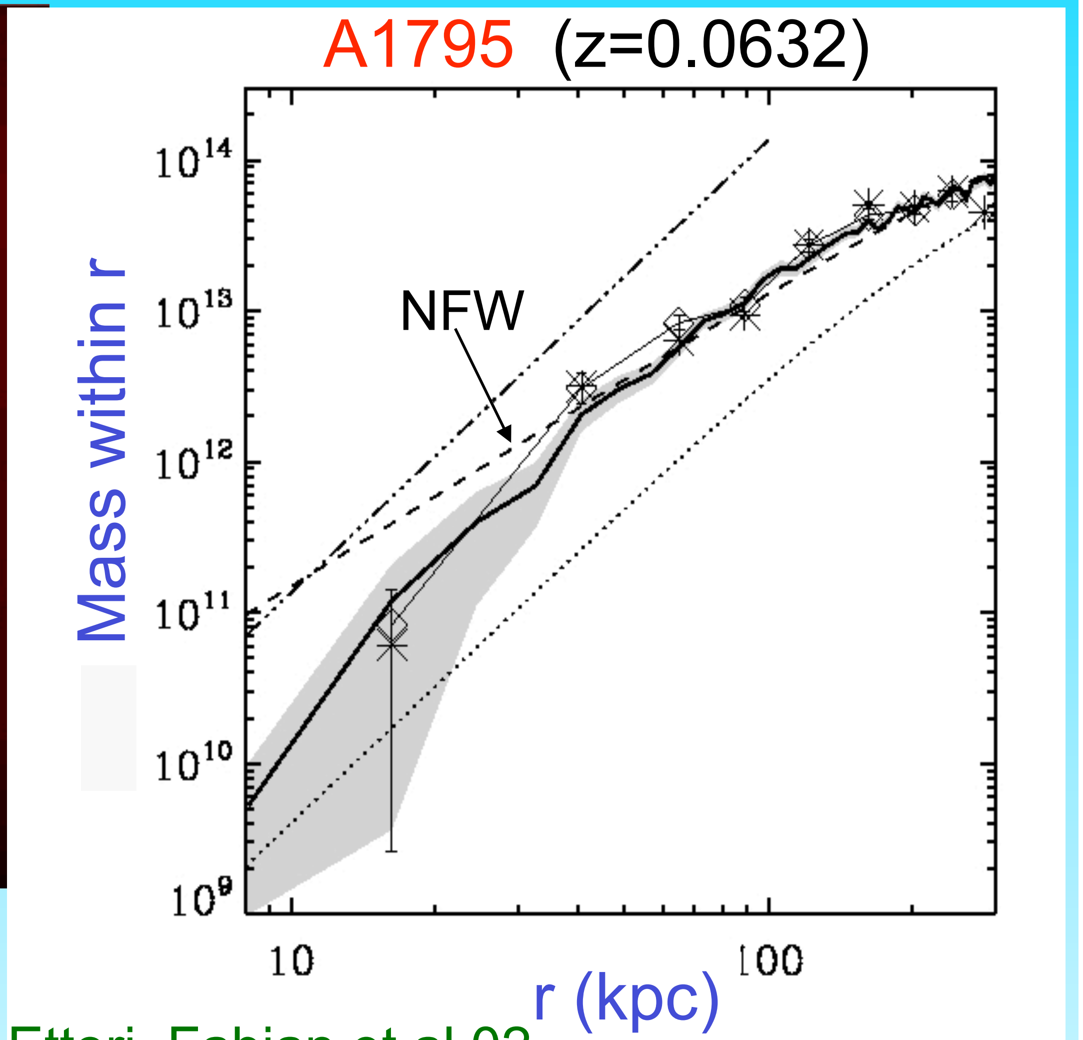
Probing the structure of cluster halos with X-rays

The central density profile of galaxy cluster dark halos

University of Durham

Inner DM density profile inferred from X-ray data (Chandra)





Ettori, Fabian et al 02

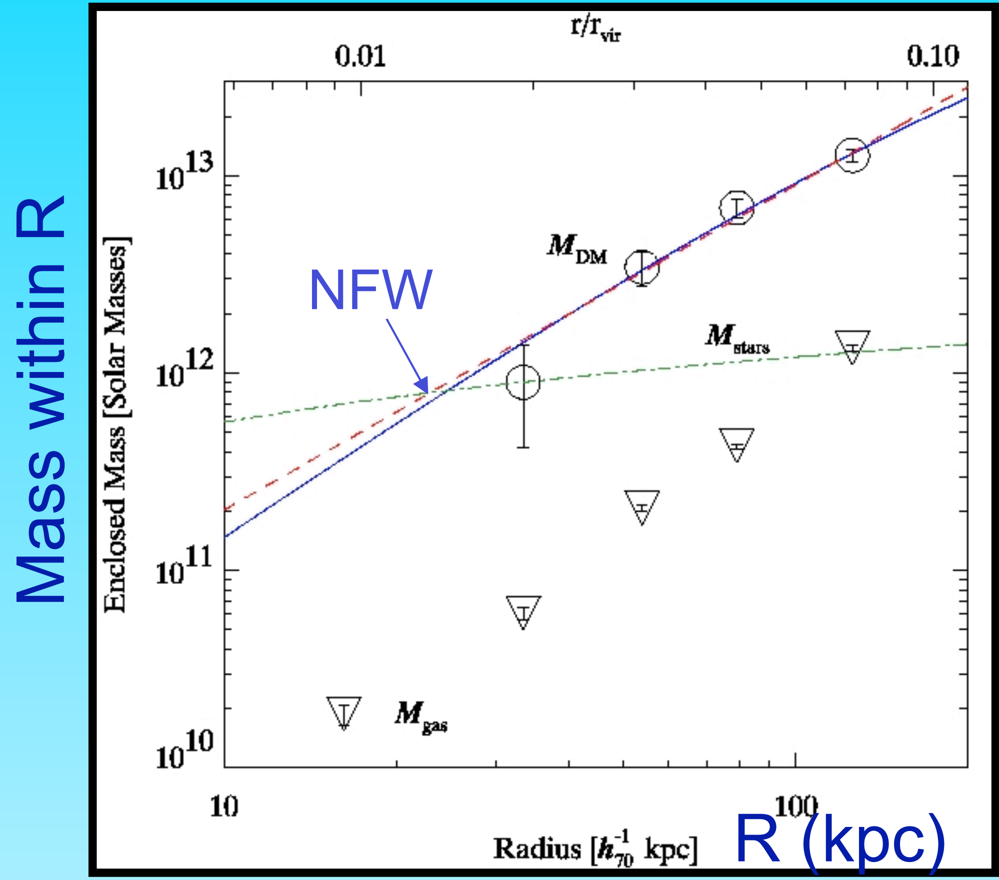
Profile shallower than NFW (β = 0.59 ±0.15)

A2589: another relaxed cluster

University of Durham

(Buote & Lewis 2004)

(z=0.0414: 1 arcsec = 0.83 kpc)



15 ks Chandra data show no asymmetries from 1 kpc to 1 Mpc

NFW (c=4.9 ±2.4) is good fit for $r>0.02\ R_{vir}$

From David Buote

Institute for Computational Cosmology

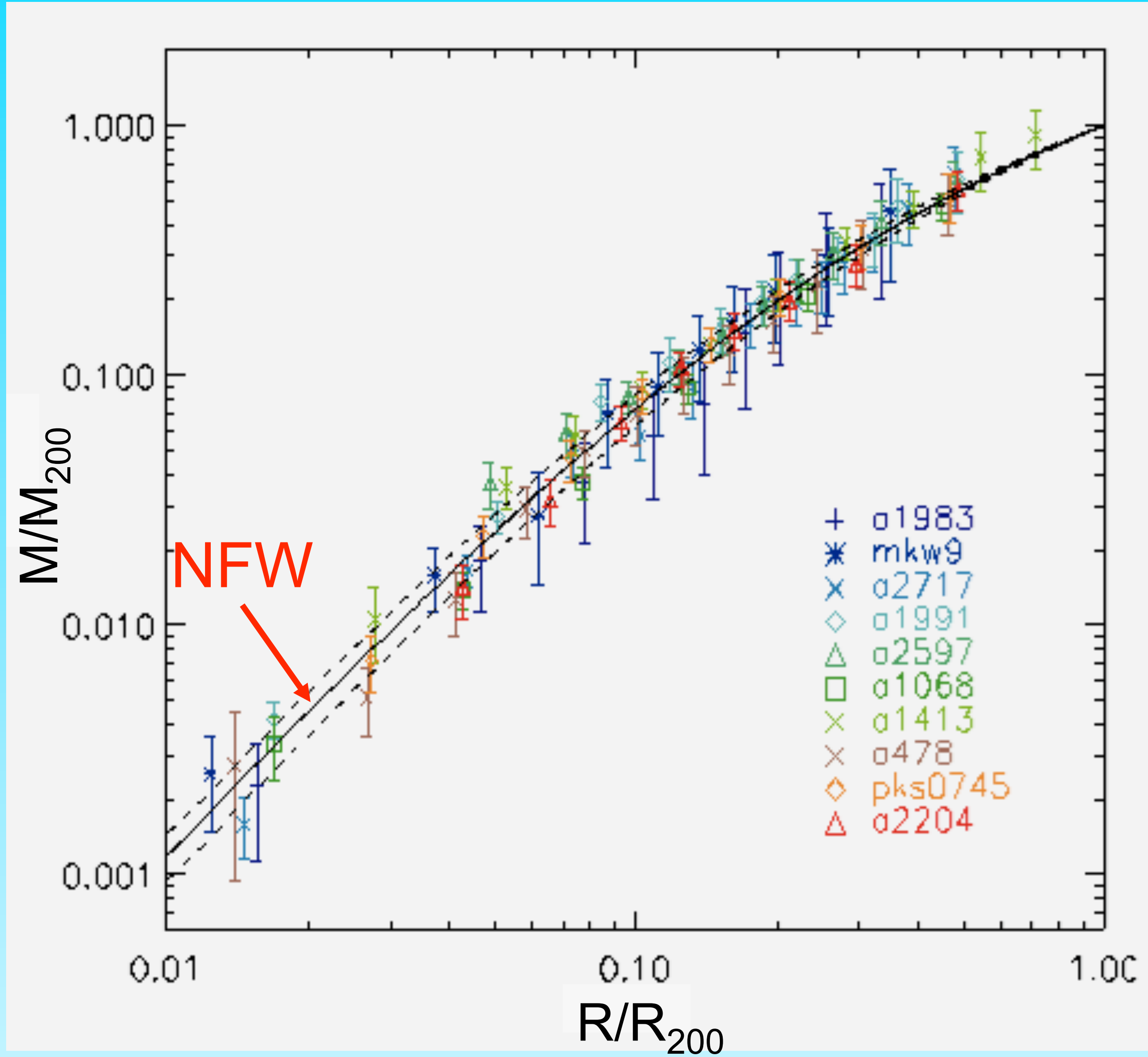
The central density profile of galaxy cluster dark halos

University of Durham

X-ray data

Mass profile of galaxy clusters, from X-ray data & assumption of hydrostatic equilibrium

Excellent agreement with CDM halo predictions



Pointecouteau et al '05

Institute for Computational Cosmology

The central density profile of galaxy cluster dark halos

X-ray data

Mass profile of galaxy clusters, from X-ray data & assumption of hydrostatic equilibrium

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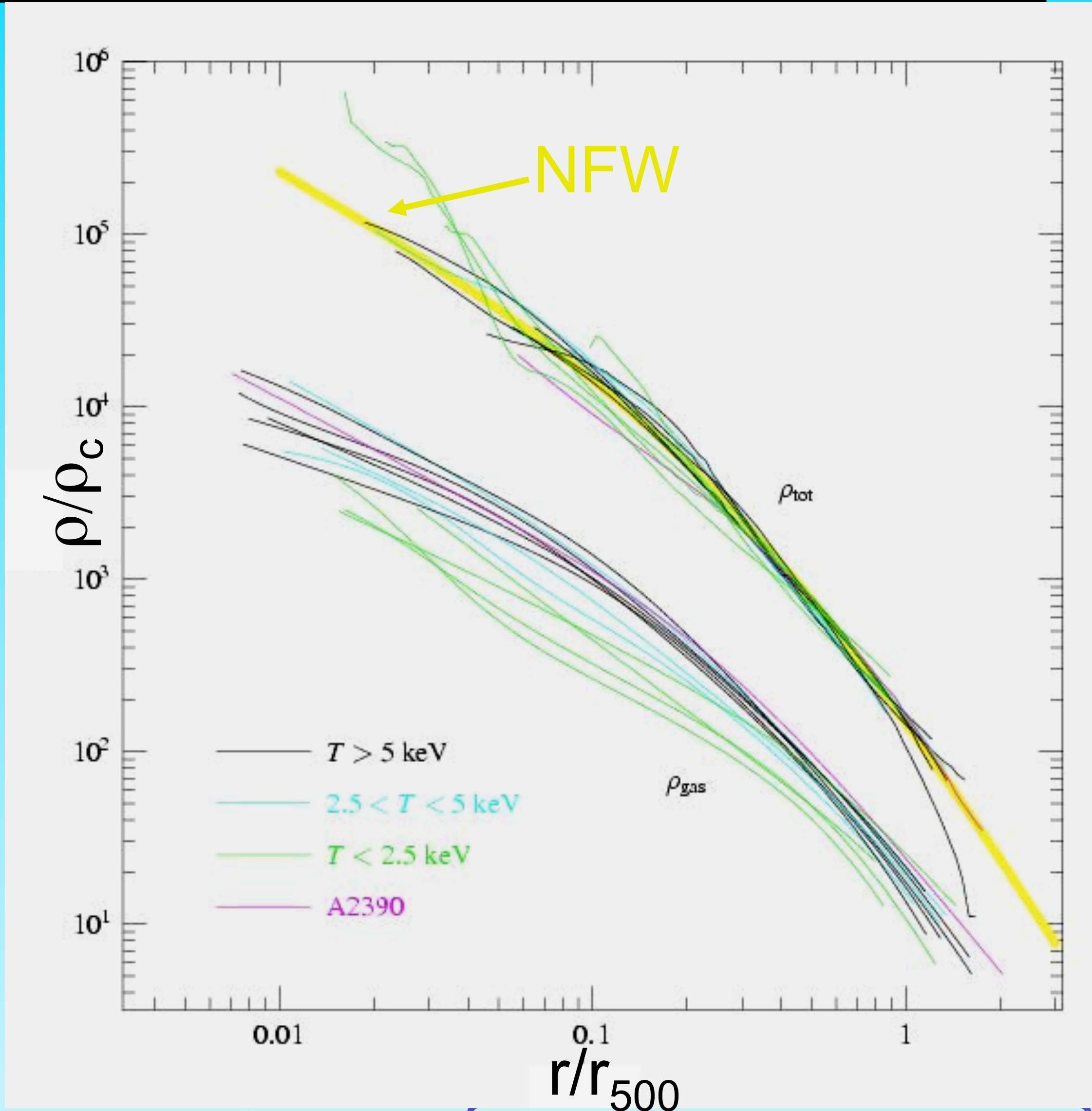


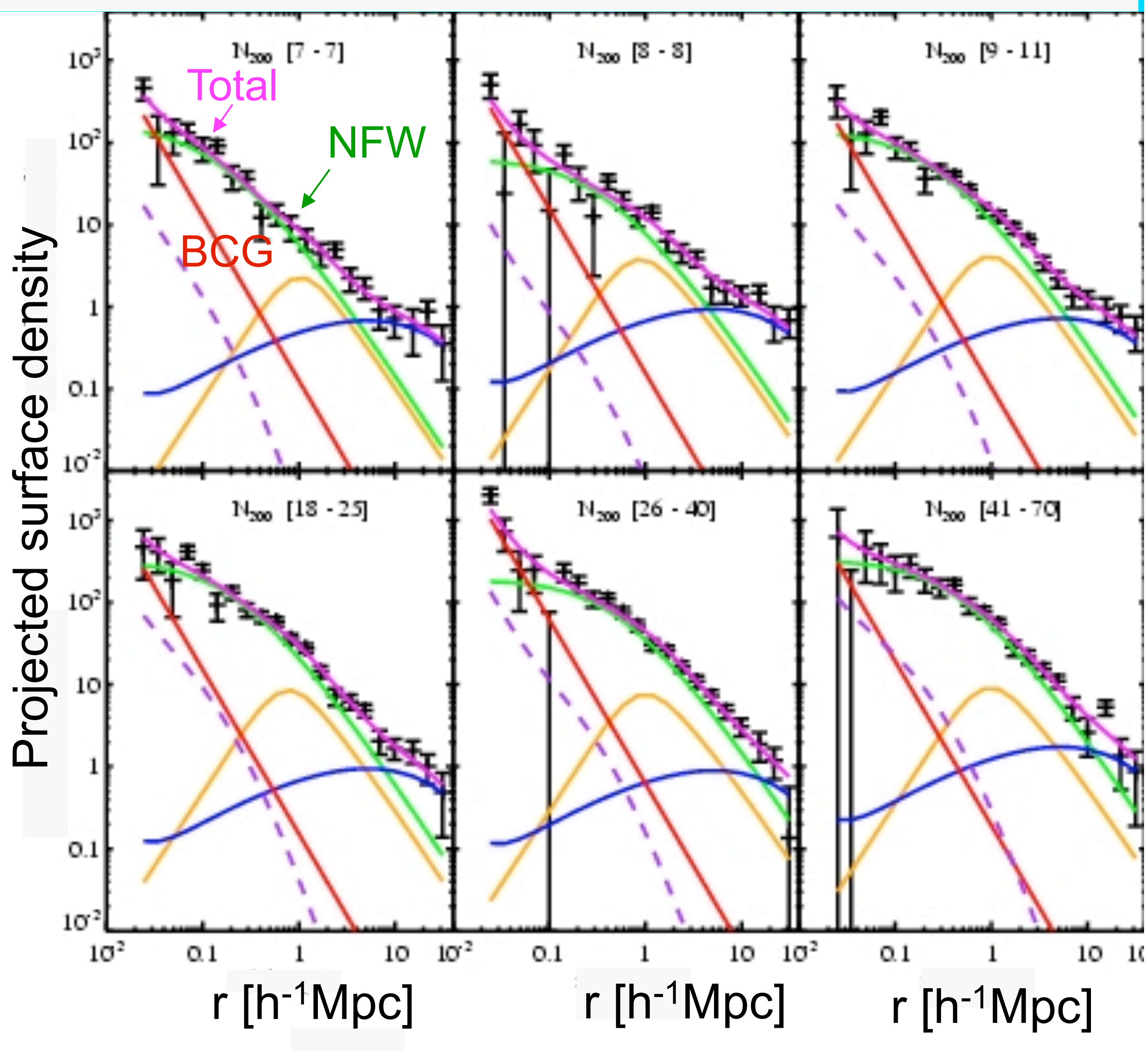
Vikhlinin et al '06

A cold dark matter universe

Probing the structure of cluster halos using gravitational lensing

The density profile of galaxy cluster dark halos

Johnston et al '07



Weak lensing for 130,000 groups and clusters from SDSS

Model contributions from brightest central galaxy, cluster dark halo and neigbouring dark halos

The density profile of galaxy cluster dark halos

University of Durham

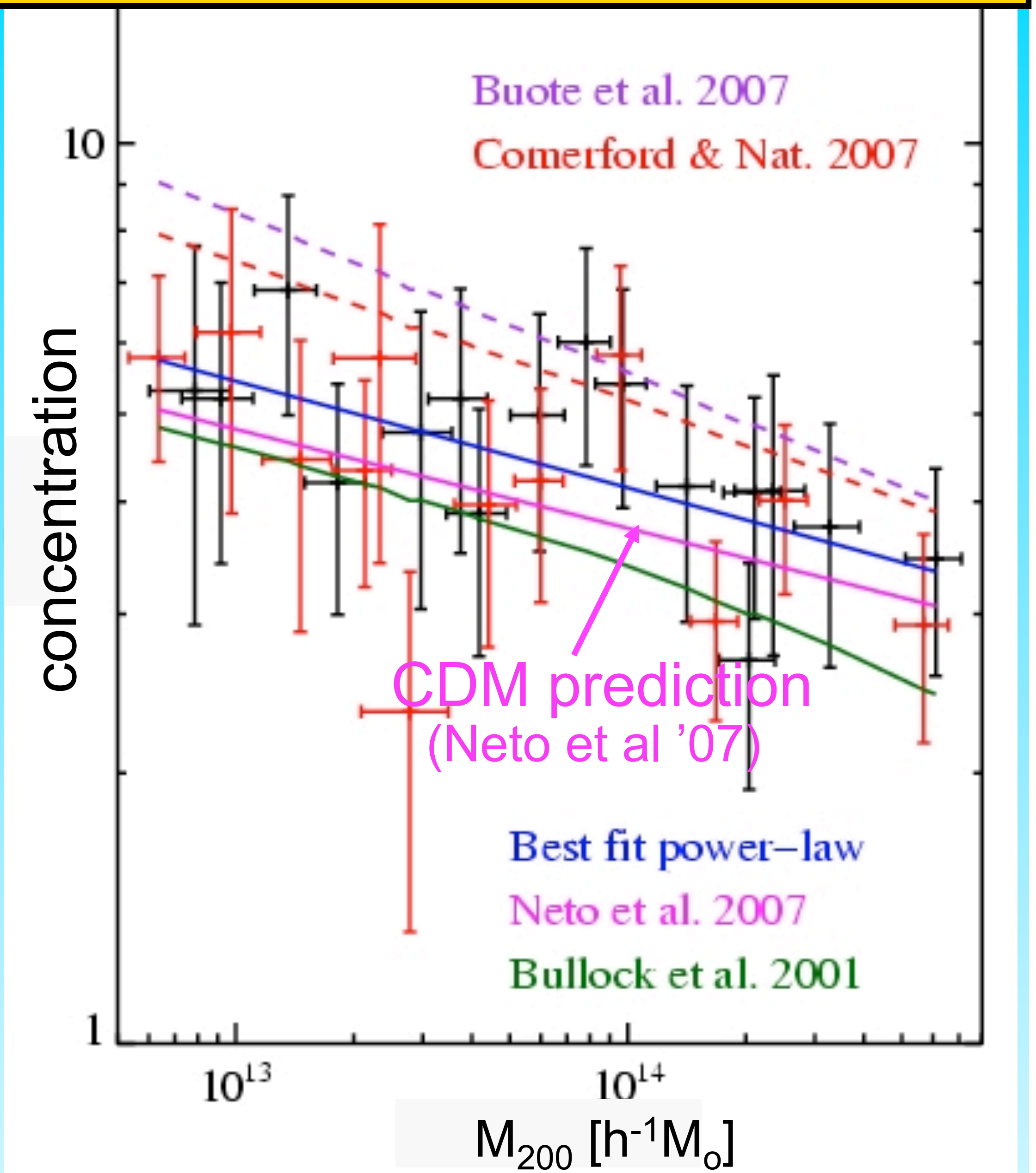
Concentration-mass relation

$$c = \frac{r_{200}}{r_s}$$

concentration

Weak lensing for 130,000 groups and clusters from SDSS

Johnston et al '07



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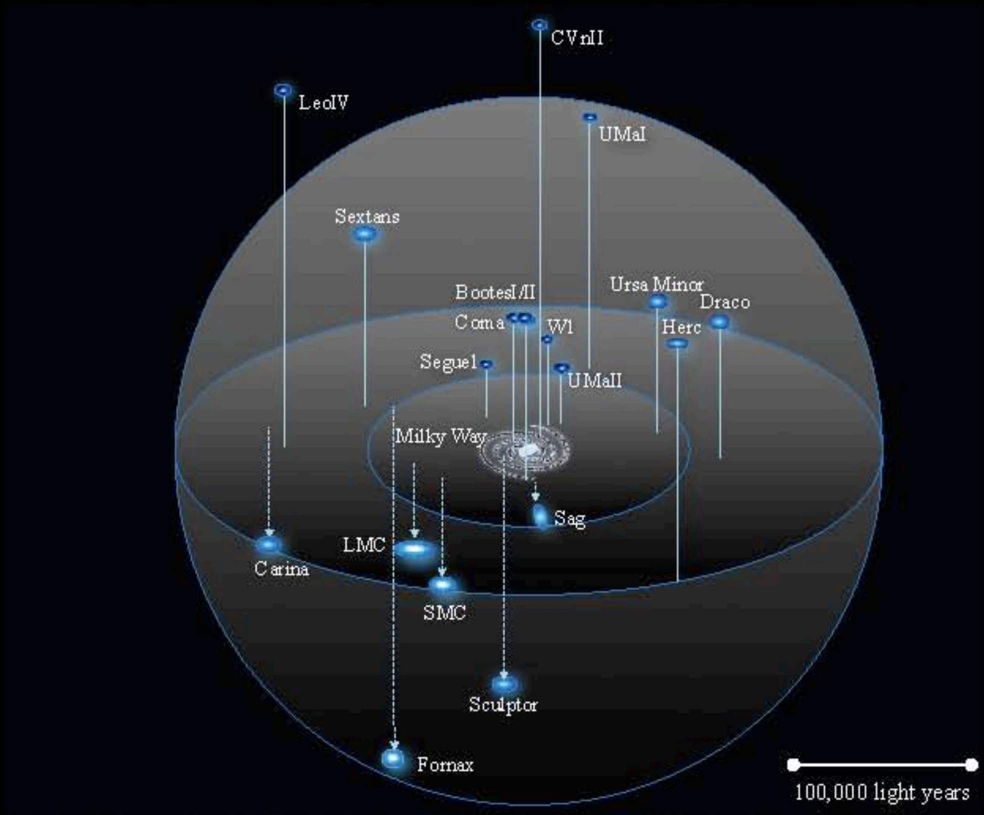
Halo structure: conclusions

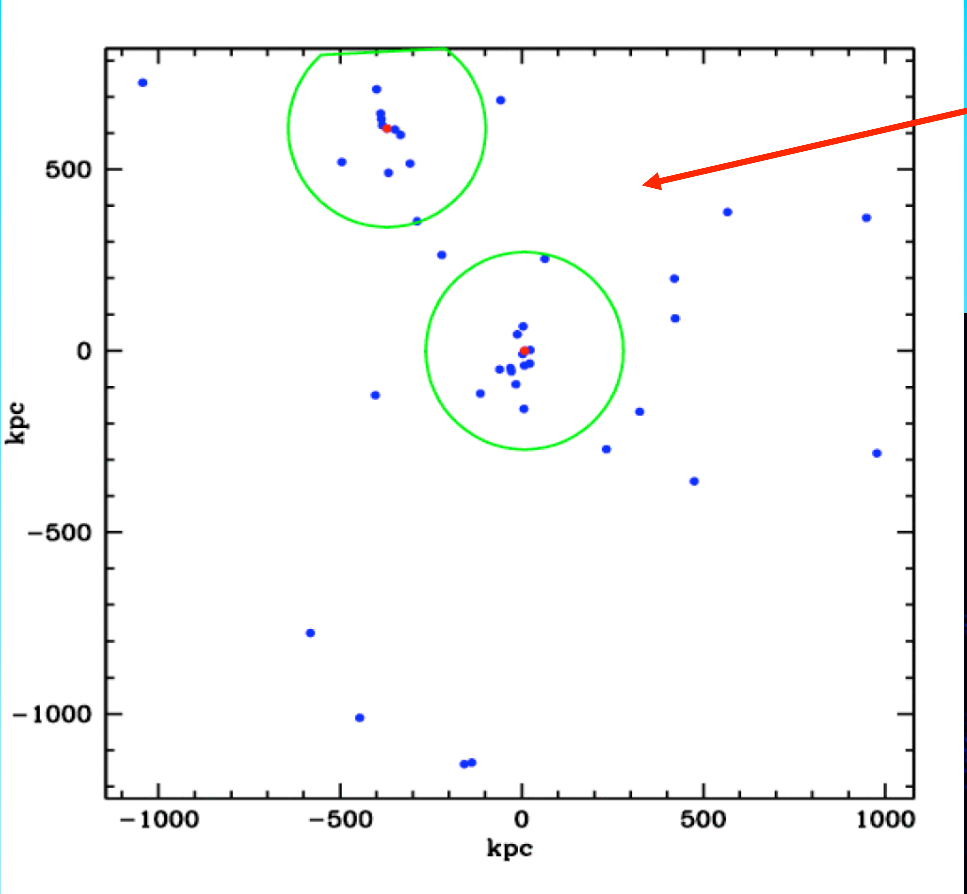
- Halos extend to ~10 times the 'visible' radius of galaxies and contain ~10 times the mass in the visible regions
- Halos are triaxial ellipsoids (not spherical)
- Halos have nearly universal “cuspy" density profiles
- Cusps are inferred in cluster halos

The “satellite problem(s)”



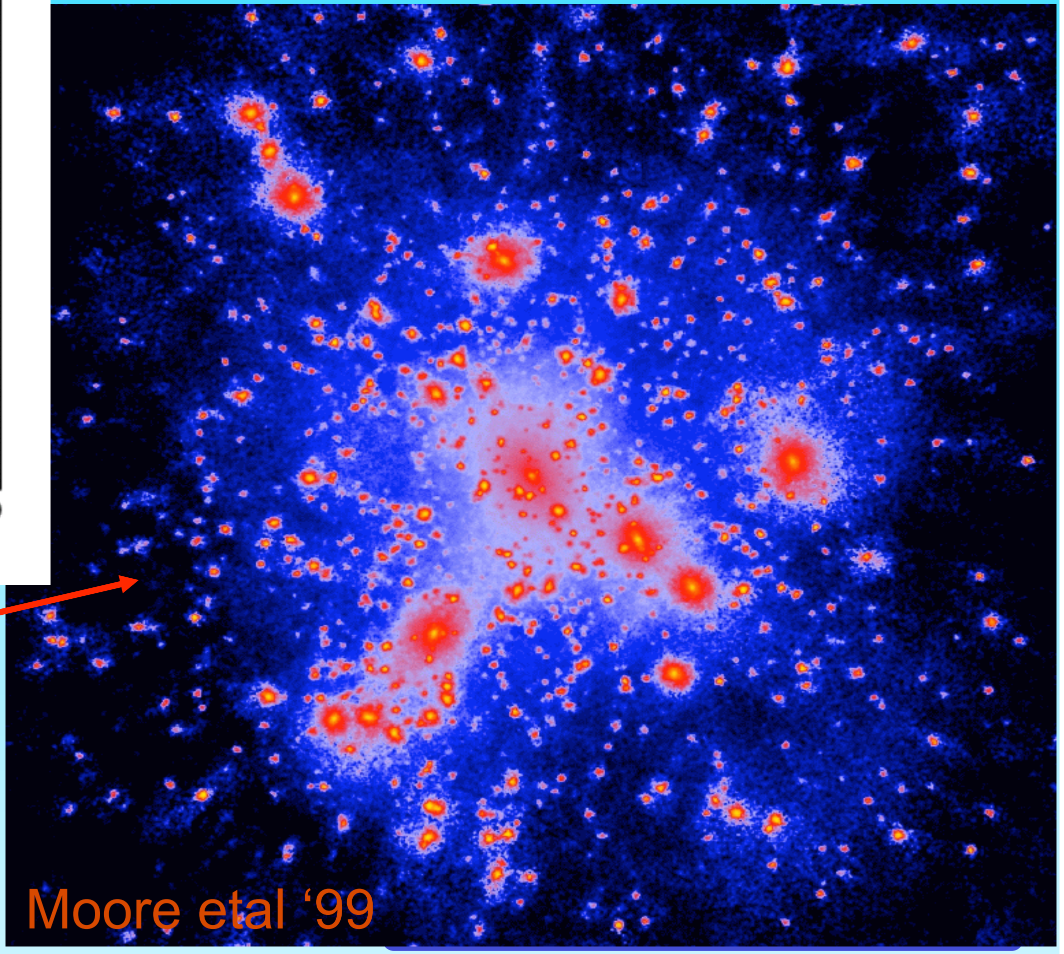
The satellites of the Local Group

University of Durham



The Local Group contains only about 35 bright satellites

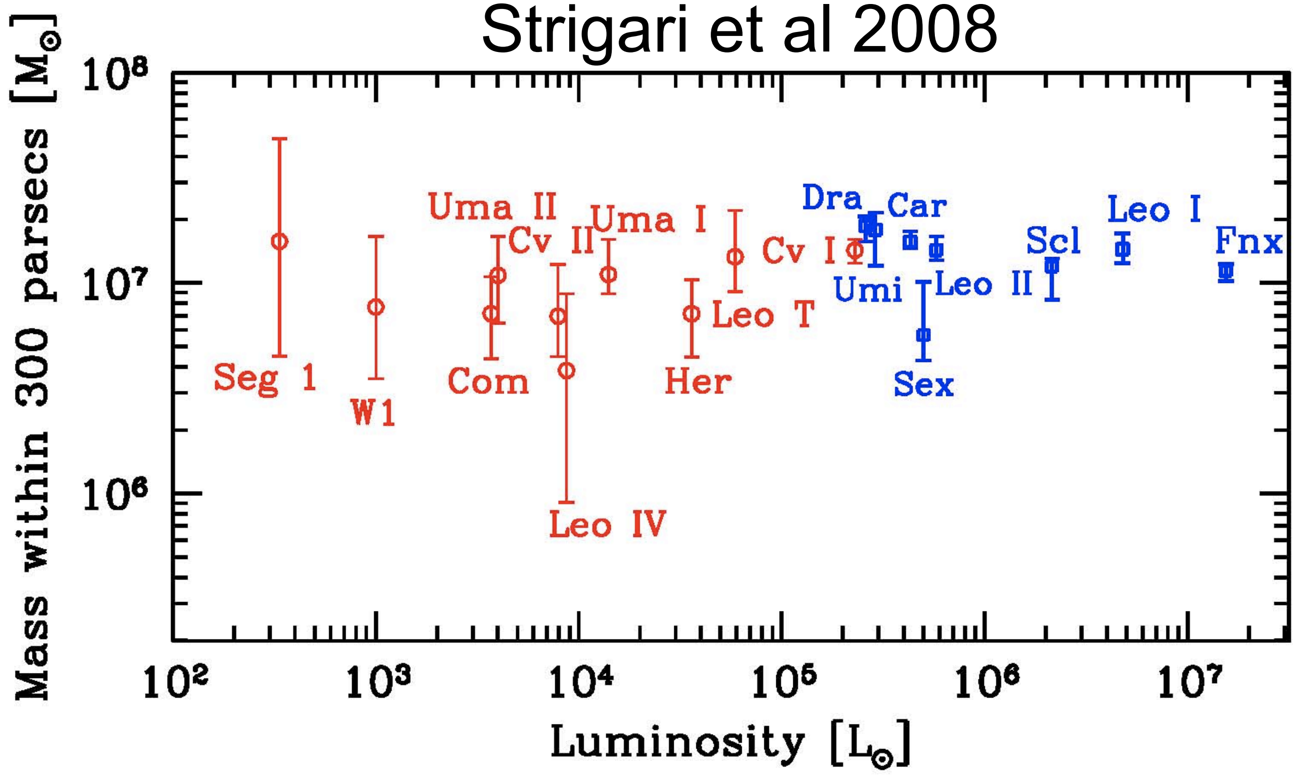
N-body simulations produce 1000s of small subhalos



A special scale in cosmology?

University of Durham

Strigari et al 2008



Is this special scale due to:

- Warm dark matter (e.g. sterile neutrino) ?
- Astrophysics in CDM halos?

Halo substructures

University of Durham

The Aquarius programme

6 different galaxy size halos simulated at varying resolution, allowing for a proper assessment of numerical convergence and cosmic variance

Numerical resolution	Particle number in halo (N_{50})	# of substructures	mass resolution
Aq-A-5	808,479	299	$3.14 \times 10^6\ M_0$
Aq-A-4	6,424,399	1,960	$3.92 \times 10^5\ M_0$
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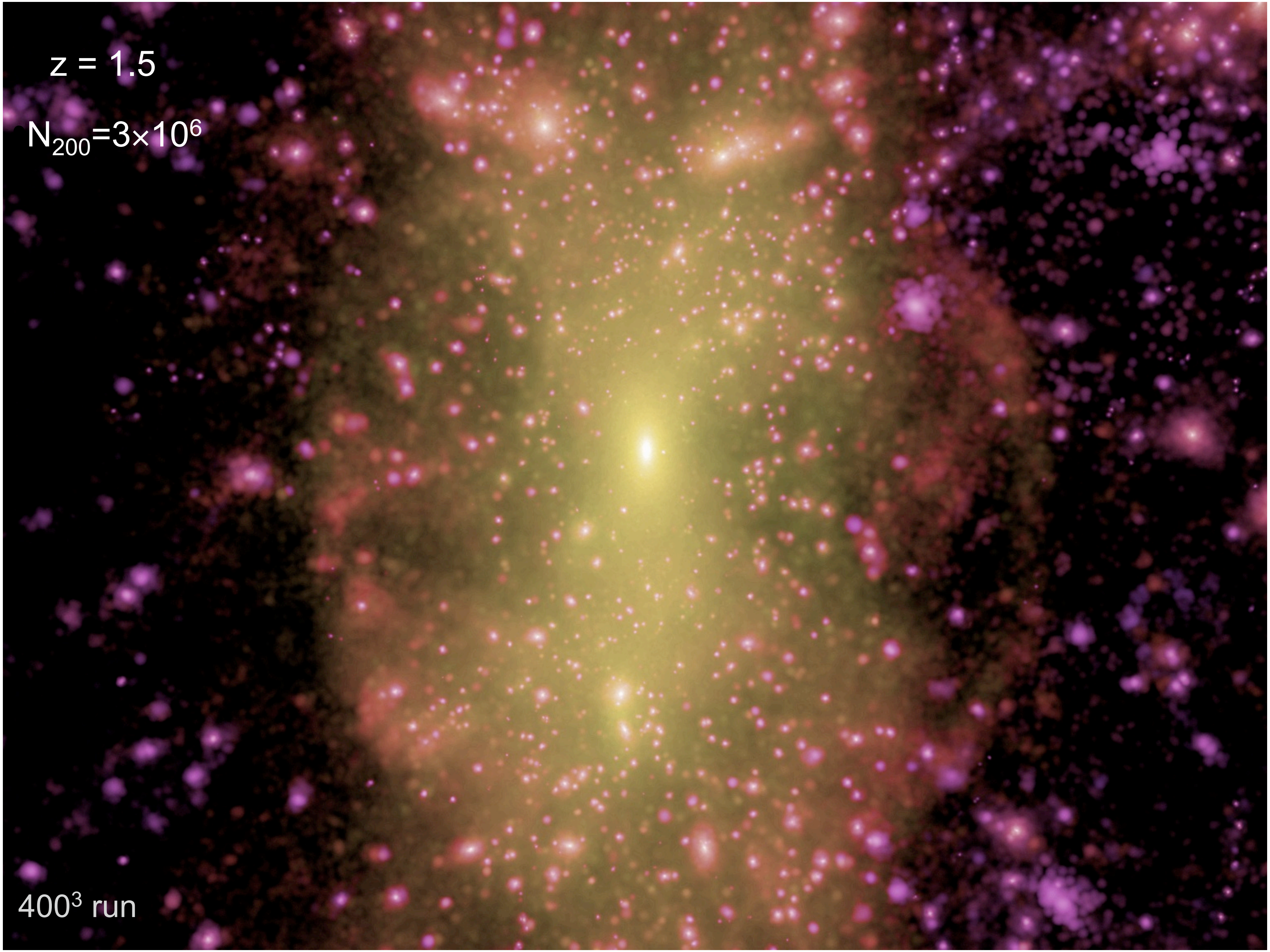
Springel et al ‘08


z = 1.5
N$_{200}$=3×10^6
400^3 run


z = 1.5
N_{200}=94×10^6
1200^3 run


$z = 1.5$
$N_{200}=750\times10^6$
2400^3 run

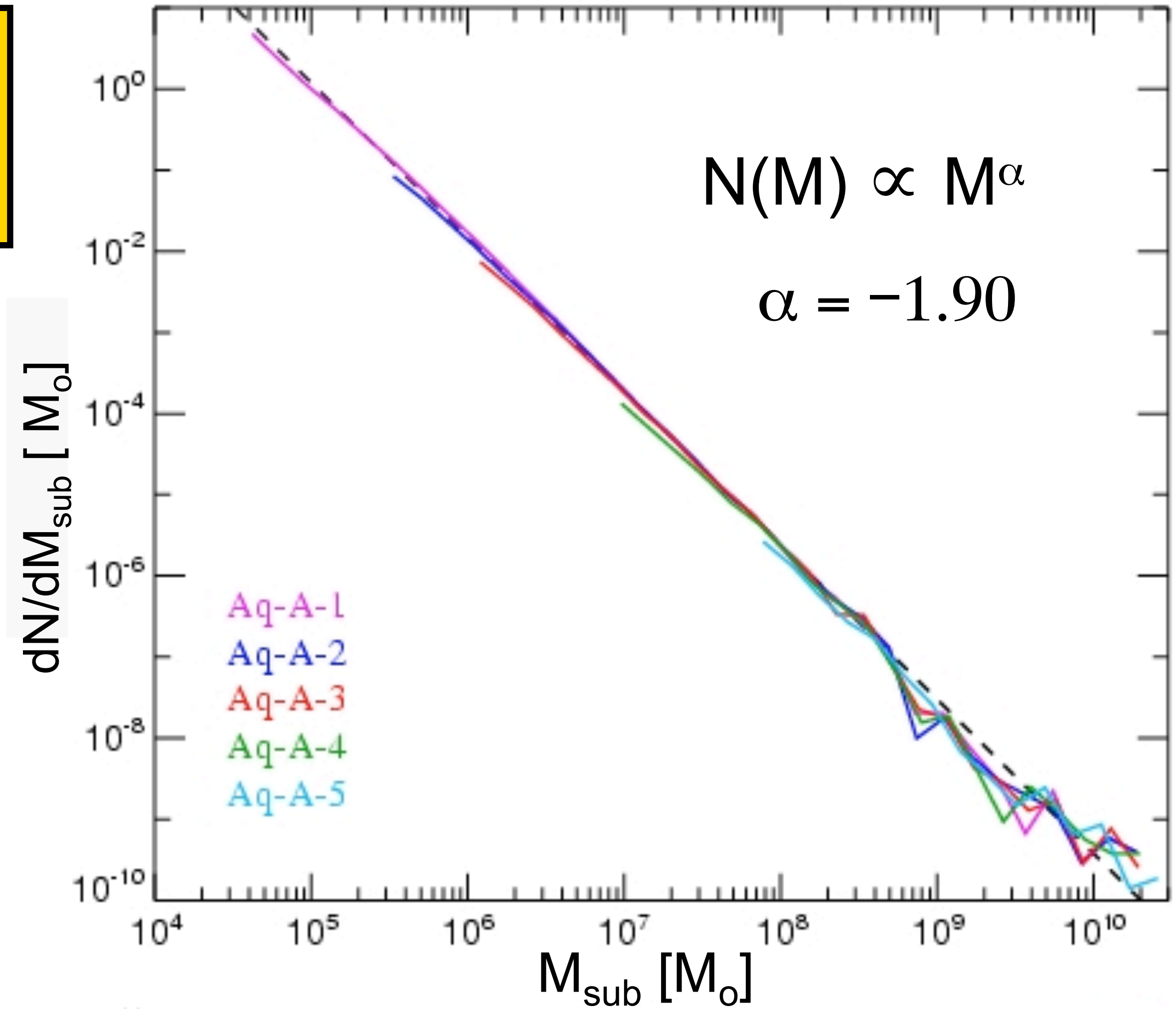
The mass function of substructures

The subhalo mass function is shallower than M^2

- Most of the substructure mass is in the few most massive halos

- The total mass in substructures converges well even for moderate resolution

Virgo consortium
Springel et al 08



300,000 subhalos within virialized region in Aq-A-1

Springel, Wang, Vogelsberger, Ludlow, Jenkins, Helmi, Navarro, Frenk & White '08

The mass function of substructures

The subhalo mass function is shallower than M^2

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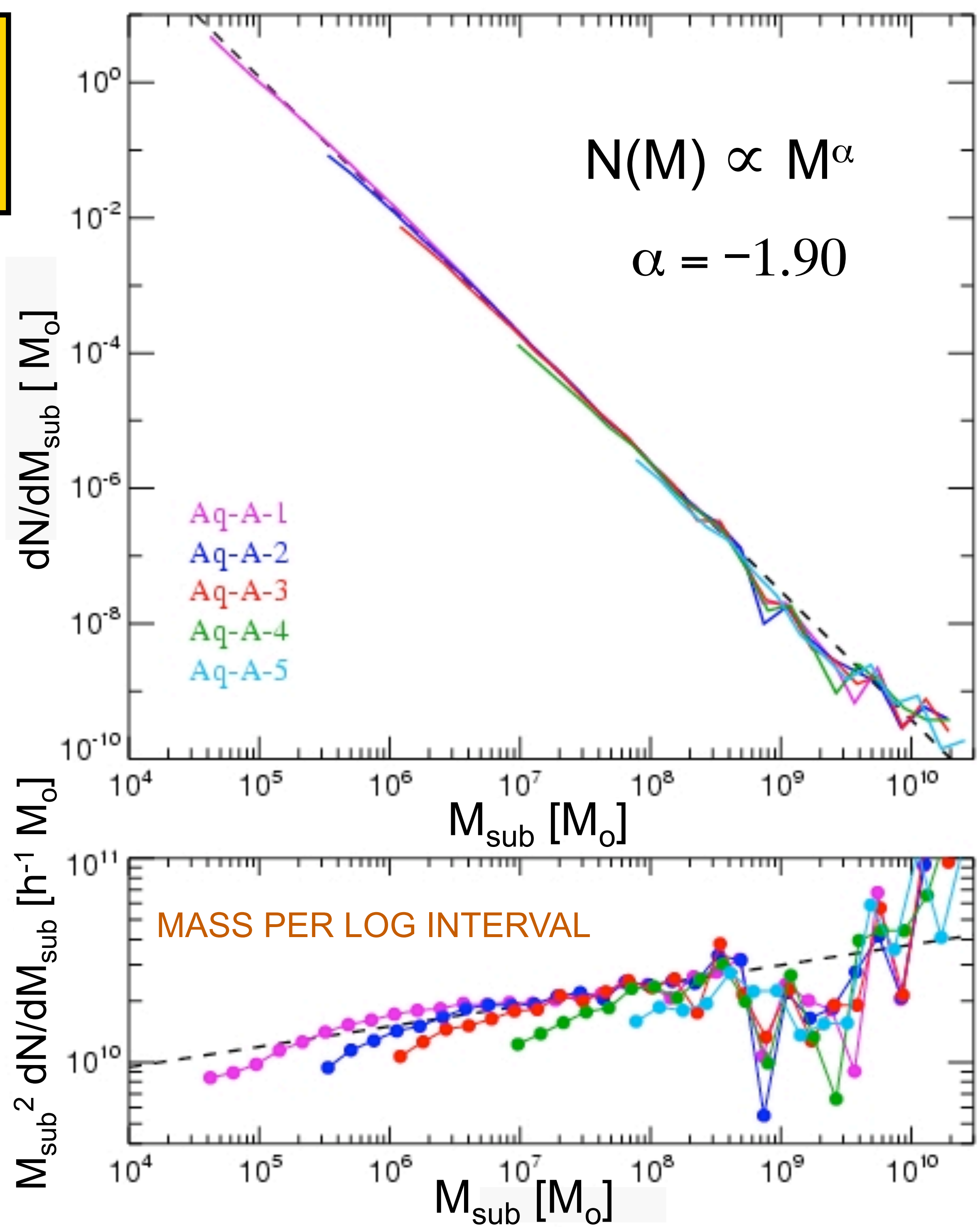
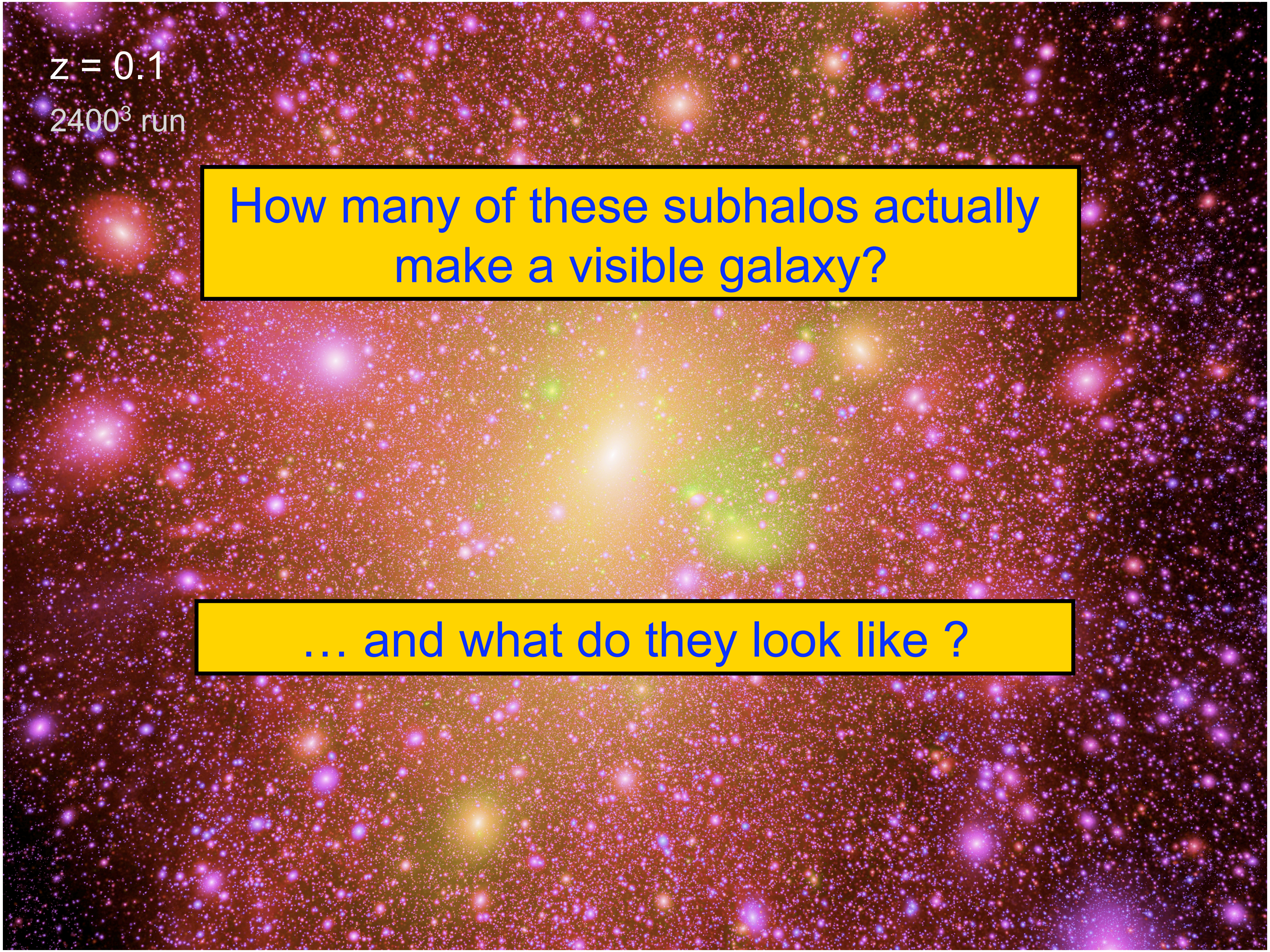
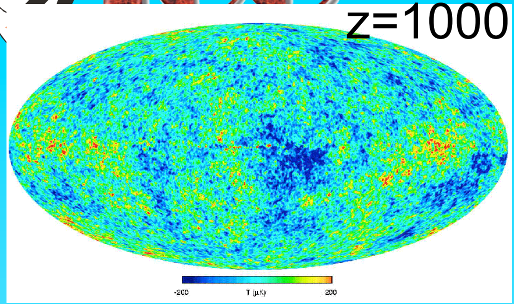
- The total mass in substructures converges well even for moderate resolution

Virgo consortium
Springel et al 08

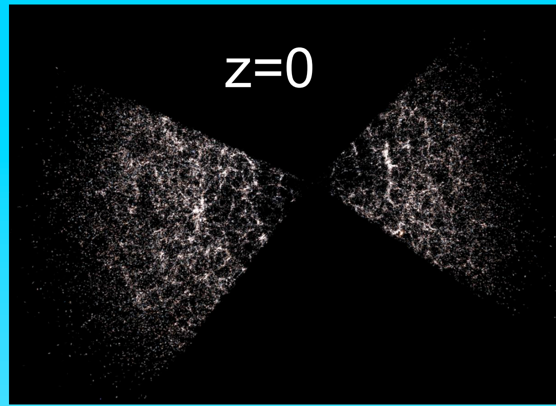



z = 0.1
2400^3 run
How many of these subhalos actually make a visible galaxy?
… and what do they look like ?



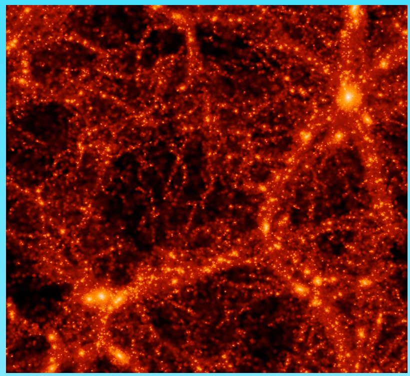
Cosmological model

(Ω_m, Ω_Λ, h); dark matter



Primordial fluctuations

$\delta\rho/\rho$(M, t)



Dark matter halos

(N-body simulations)

$\left.\right\}$ Well understood

Gas processes

(cooling, star formation, feedback)

Gasdynamic simulations

Semi-analytics

Formation and evolution of galaxies

Modelling galaxy formation

University of Durham

Aim: follow history of galaxy formation ***ab initio***, i.e starting from a cosmological model for structure formation so as to predict observables

Main baryonic processes:

- Shock-heating and radiative cooling of gas within halos

Sub-grid physics

- Star formation and SN feedback
- Reionization
- Production & mixing of metals
- Evolution of stellar populations
- Dust obscuration
- AGN feedback

Need to use phenomenological models

University of Durham

Modelling galaxy formation

Main baryonic processes:

Shock-heating and radiative cooling of gas within halos

Solve hydro equations numerically	Assume spherical symmetry & solve analytically
Hydrodynamical simulation	Semi-analytic model
+ Gas dynamics in full generality	- Approximate gas dynamics
- Limited dynamic range	+ Unlimited dynamic range
- Expensive: cannot explore range of sub-grid models	+ Can easily explore different sub-grid models

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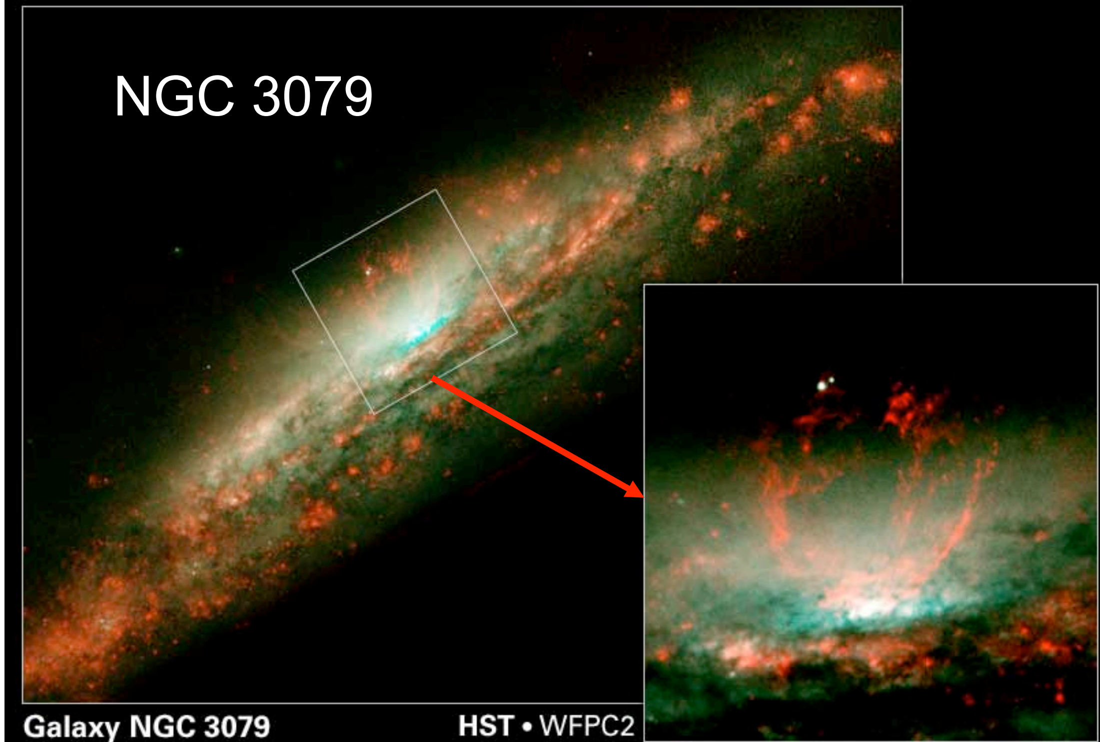
Feedback in galaxy formation

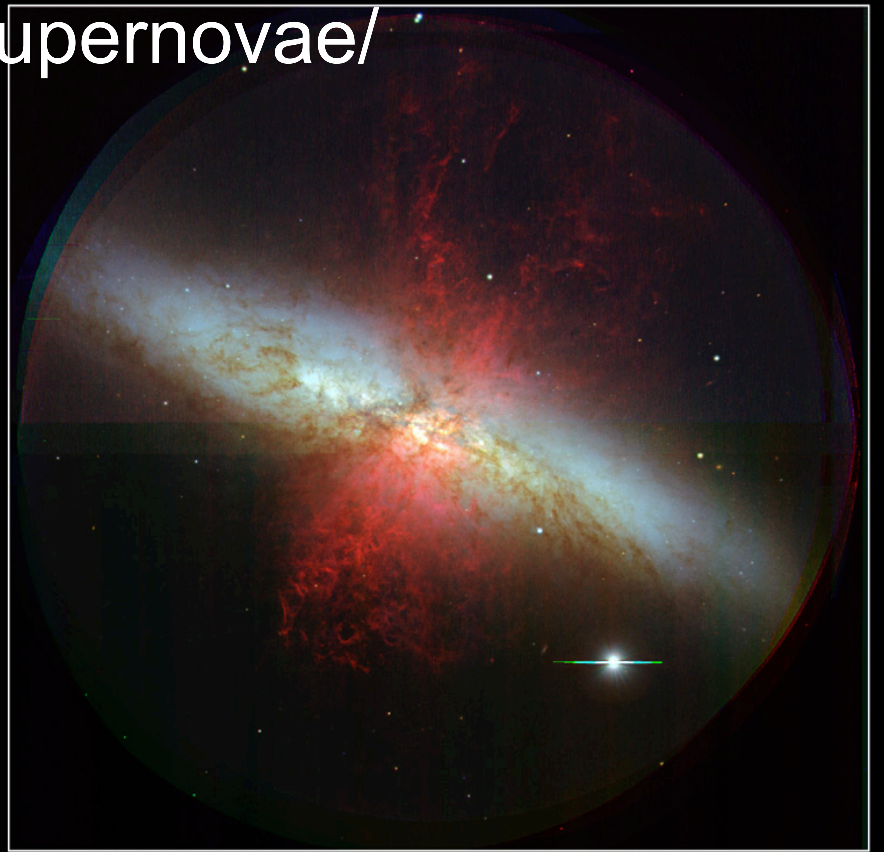
The faint end of luminosity function:

White & Rees '78 ⇒ Injection of supernovae/ stellar wind energy



Galaxy NGC 3079 **HST** • WFPC2

NASA and G. Cecil (University of North Carolina) • STScI-PRC01-28



M 82 (NGC 3034) FOCAS (B, V, Hα)

Subaru Telescope, National Astronomical Observatory of Japan March 24, 2000

Institute for Computational Cosmology

Photoionization

University of Durham

IGM is neutral

Halos accrete gas efficiently and form stars

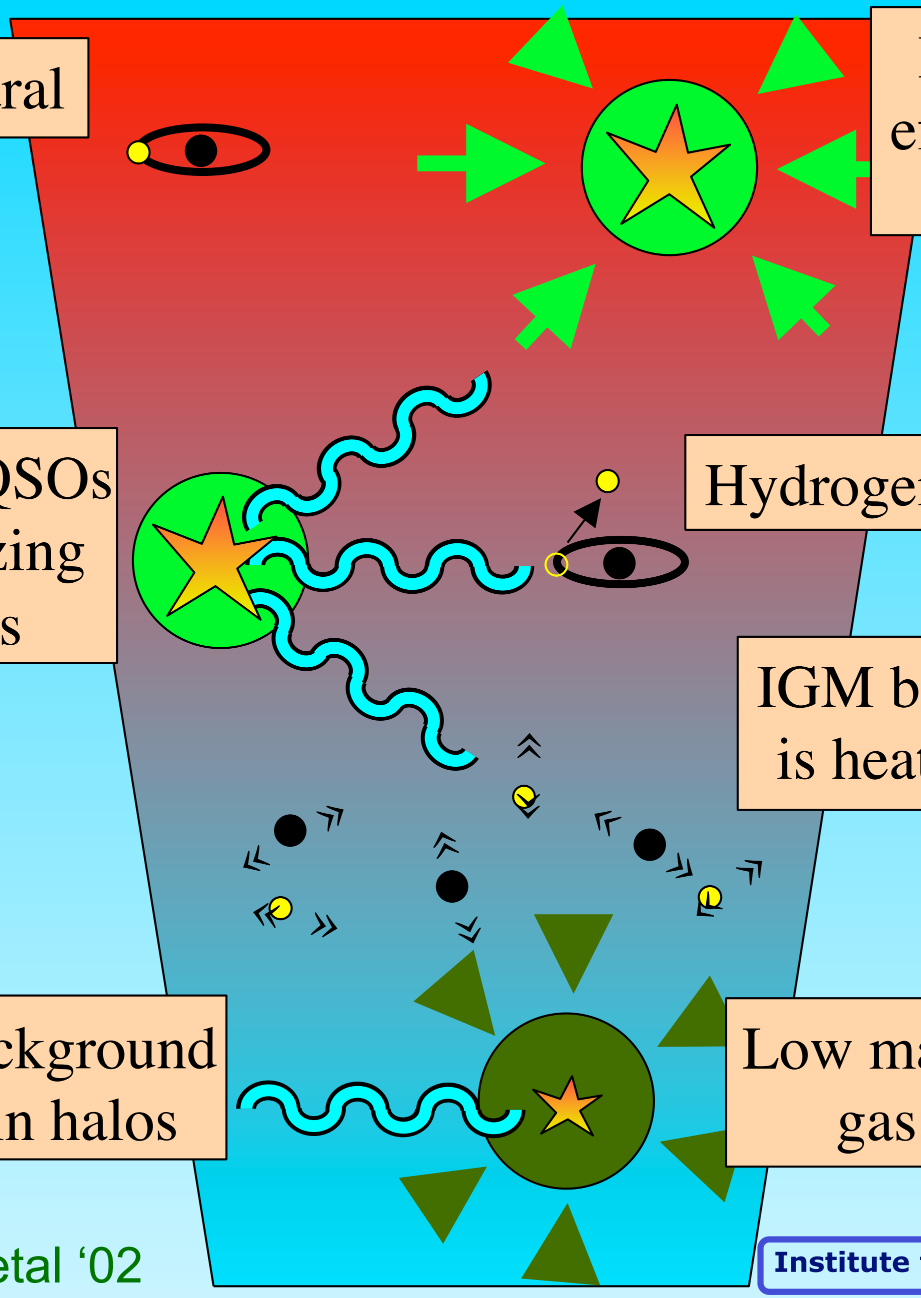
Z=10-20

Galaxies/QSOs emit ionizing photons

Hydrogen is photoionized

IGM becomes ionized and is heated to around 10^4K

Z~6



Ionizing background heats gas in halos

Low mass halos accrete gas inefficiently

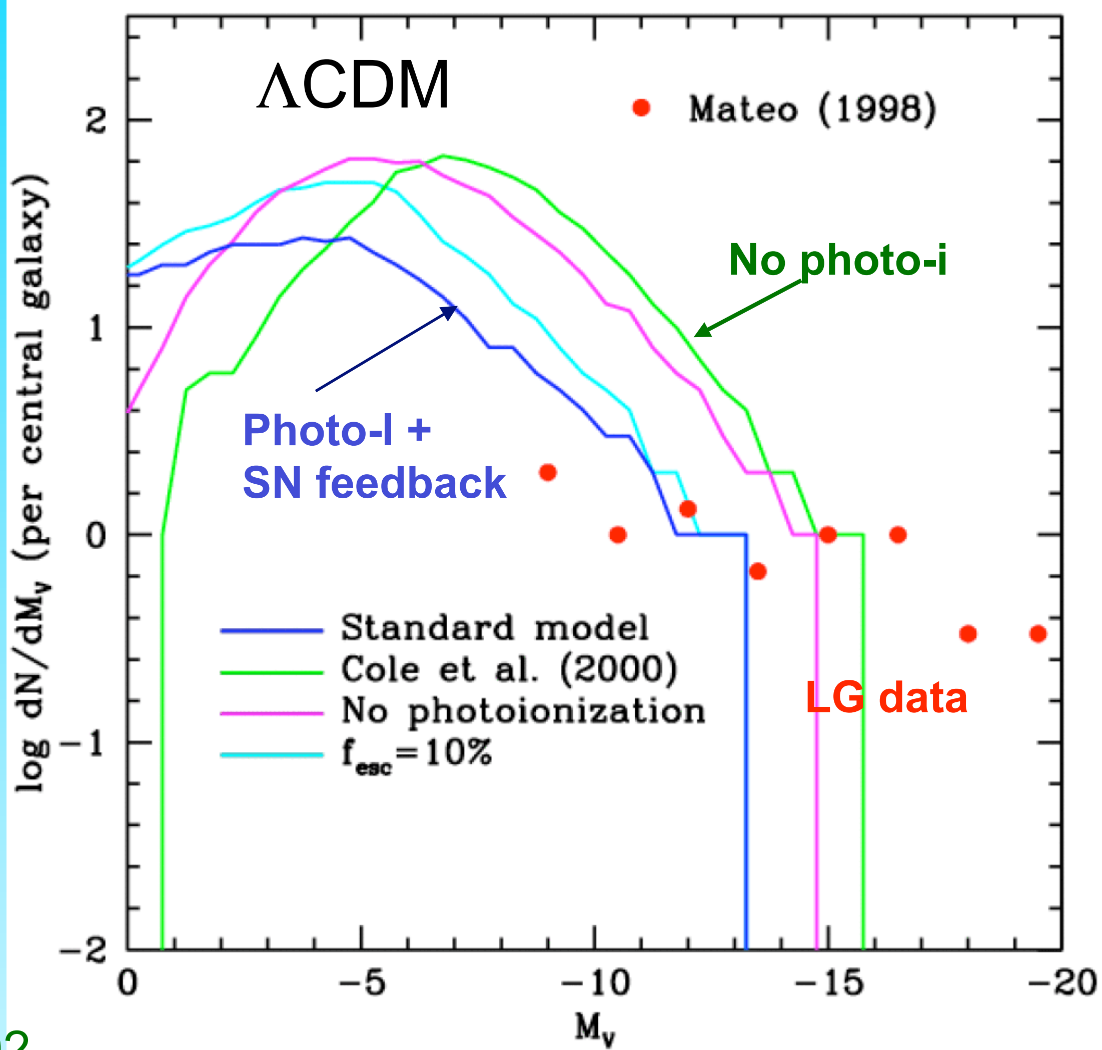
Z=0

Benson etal '02

Institute for Computational Cosmology

Luminosity Function of Local Group Satellites

- Photoionization inhibits the formation of satellites
- Abundance of satellies reduced by large factor!
- Median model gives 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 etal '93, Bullock etal '01)

The satellites of the Local Group

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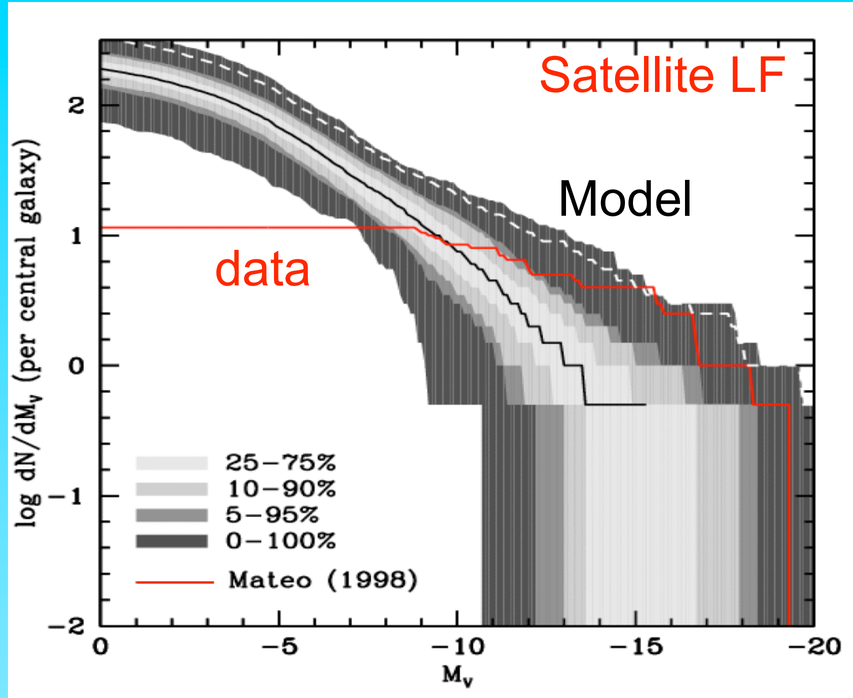
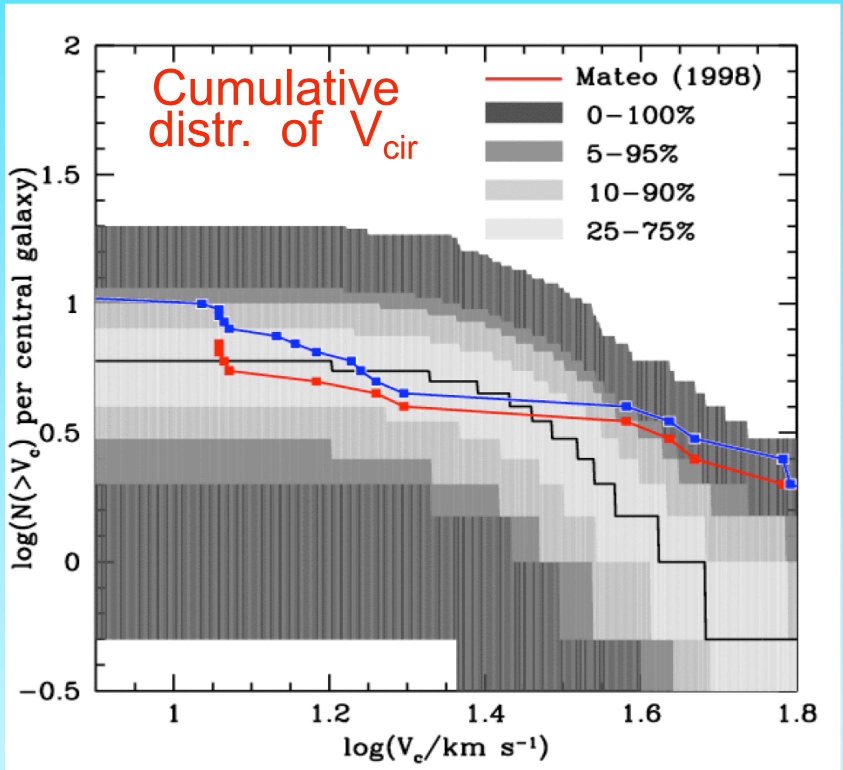
- LF of satellites within the virial radii of MW and M31

- Photoionization inhibits the formation of satellites





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The satellites of the Milky Way

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Name	Year discovered
LMC	1519
SMC	1519
Sculptor	1937
Fornax	1938
Leo II	1950
Leo I	1950
Ursa Minor	1954
Draco	1954
Carina	1977
Sextans	1990
Sagittarious	1994

The satellites of the Milky Way

ICC University of Durham

Several new satellites discovered in the past few years

Name	Year discovered
LMC	1519
SMC	1519
Sculptor	1937
Fornax	1938
Leo II	1950
Leo I	1950
Ursa Minor	1954
Draco	1954
Carina	1977
Sextans	1990
Sagittarious	1994

Name	Year discovered
Canis Major	2003
Ursa Major I	2005
Wilman I	2005
Ursa Major II	2006
Bootes	2006
Canes Venatici I	2006
Canes Venatici II	2006
Coma	2006
Leo IV	2006
Hercules	2006
Leo T	2007
Segue I	2007
Boo II	2007
Segue II	2009

Luminosity Function of Local Group Satellites

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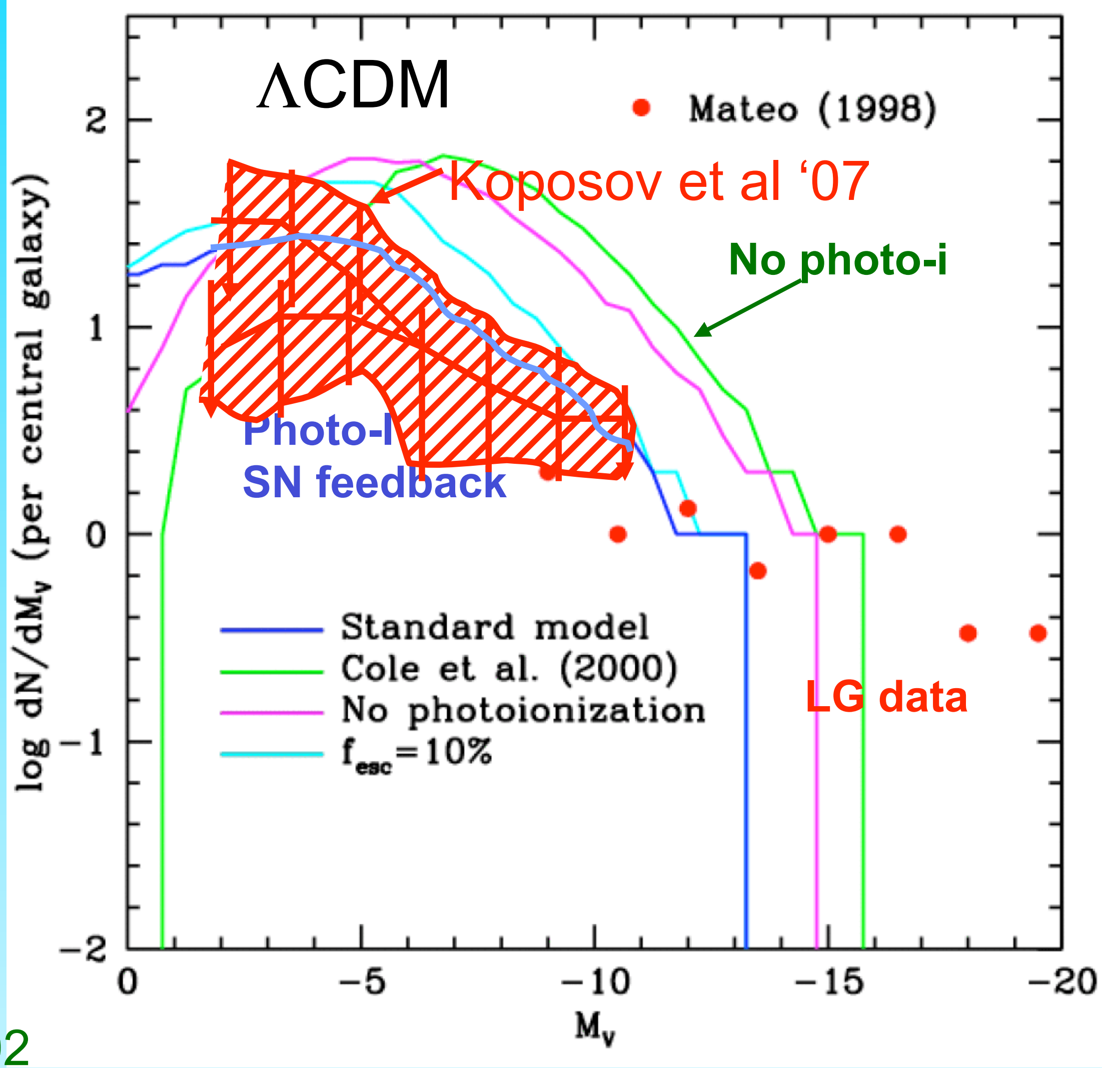

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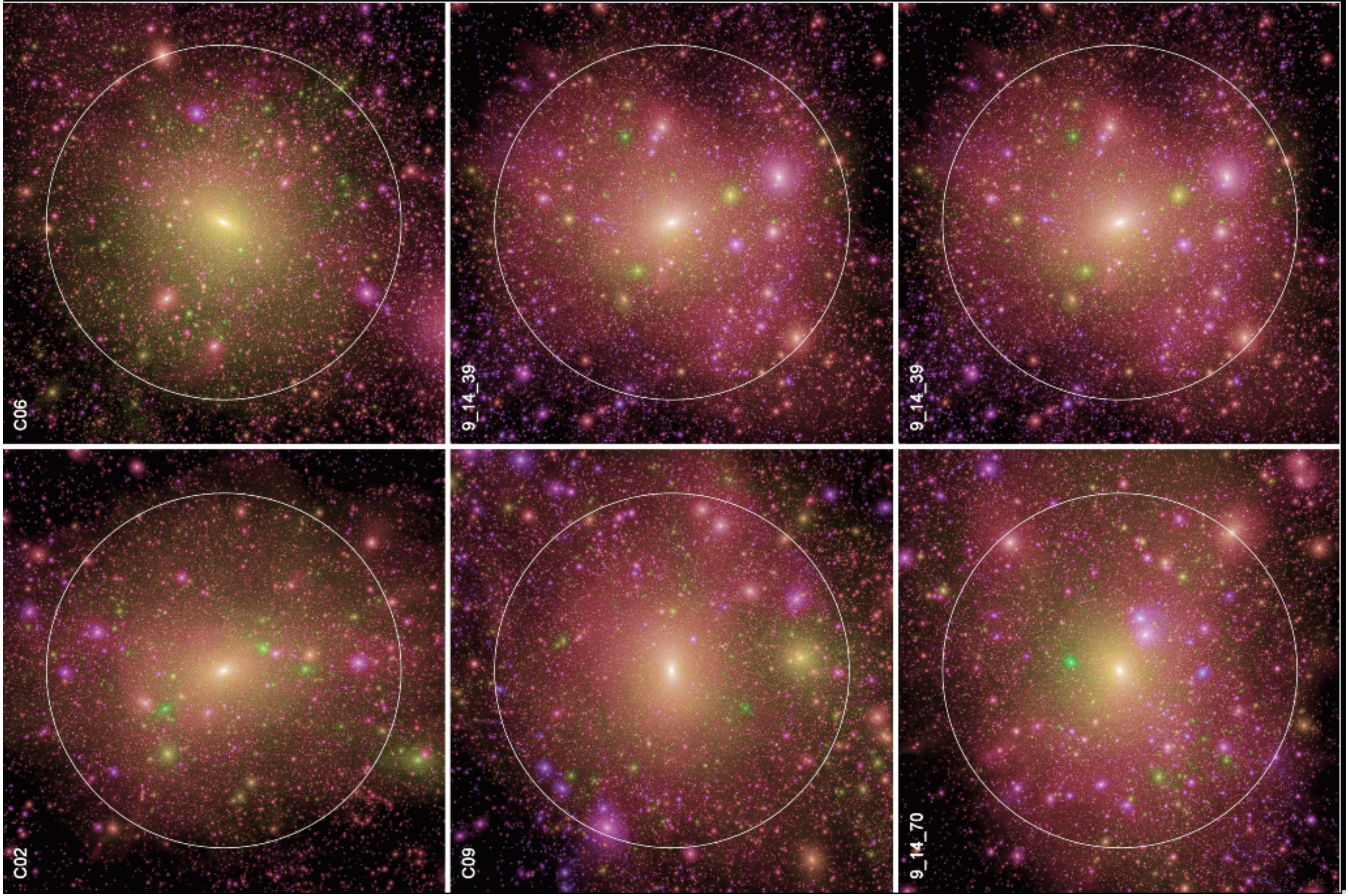
Modelling baryonic physics in Aquarius halos



Luminosity function of Milky Way satellites

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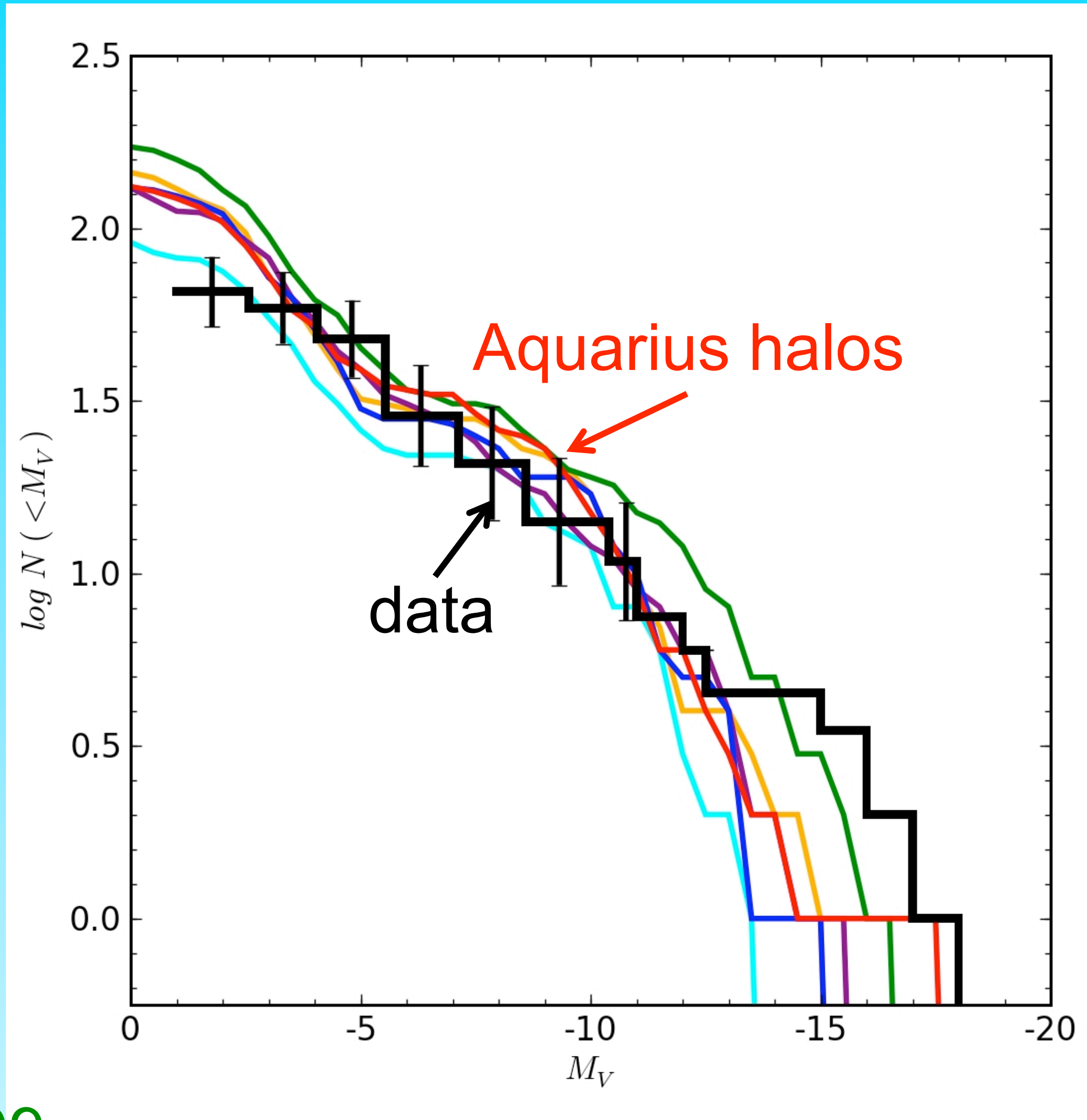
Semi-analytic modelling

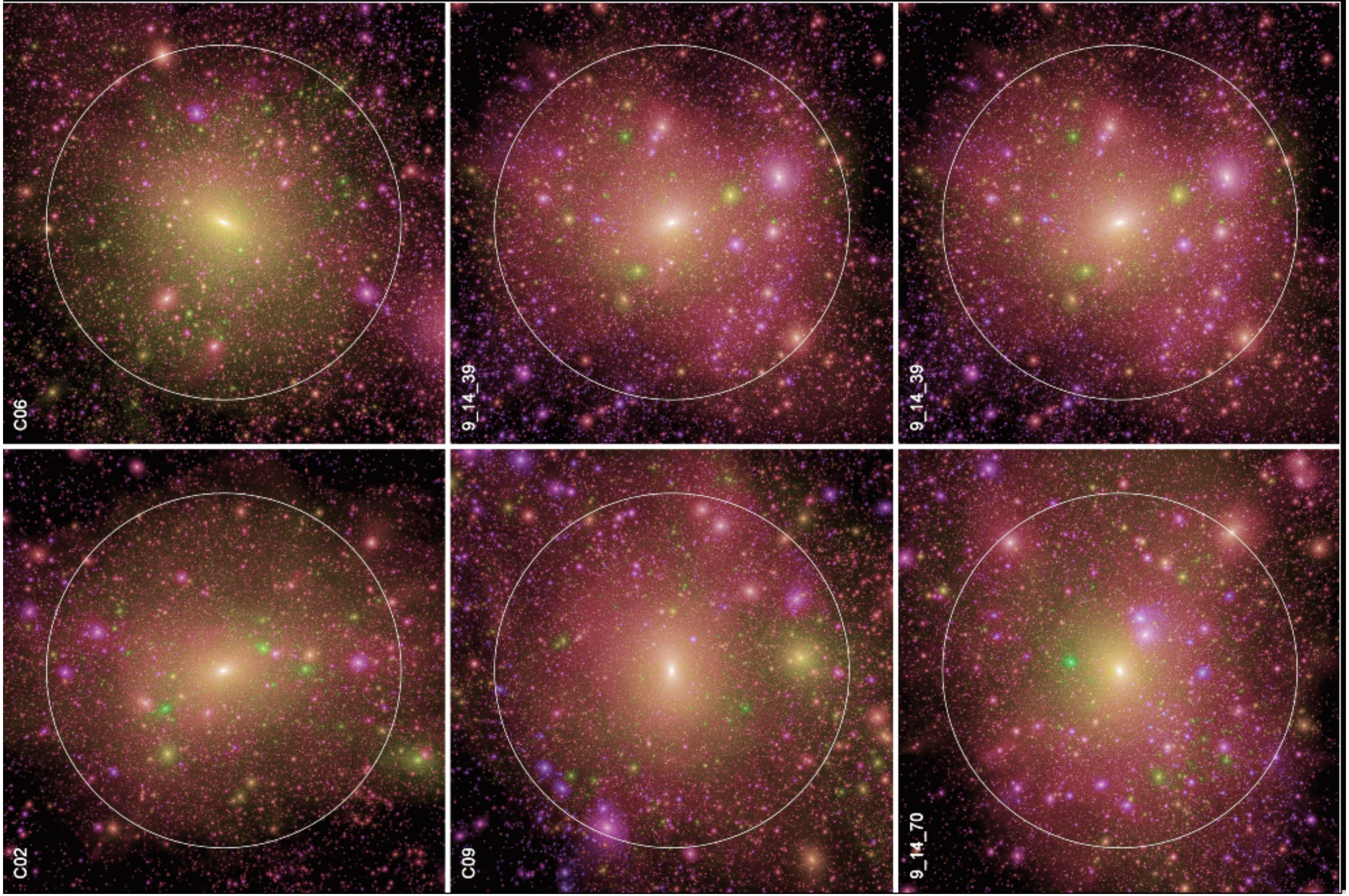
Reionization as in the Okamoto et al simulations



Cooper, Cole, Frenk et al '09

Hydrodynamic simulations of Aquarius halos

Modelling baryonic physics in Aquarius halos



Modelling the baryons in Aquarius using SPH simulations

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Okamoto & Frenk '09

- $M_{sph} \sim 4x10^5\ M_\odot$
- Model reionization due to external UV field
- Assume 100% of SN energy goes to kinetic energy of winds
- Two types of energy conserving winds
  – Wind models are characterised by the wind speed, v_w, and the mass loading factor, η, where

$$\dot{M}_w = \eta \dot{M}_*$$

$$\begin{cases} v_w \propto \sigma \text{ and } \dot{M}_w = \left(\dfrac{\sigma}{\sigma_0}\right)^{-2} \dot{M}_* \\ v_w = const. \text{ and } \dot{M}_w \propto \dot{M}_* \end{cases}$$

Winds are decoupled from hydrodynamic calculation for a while.

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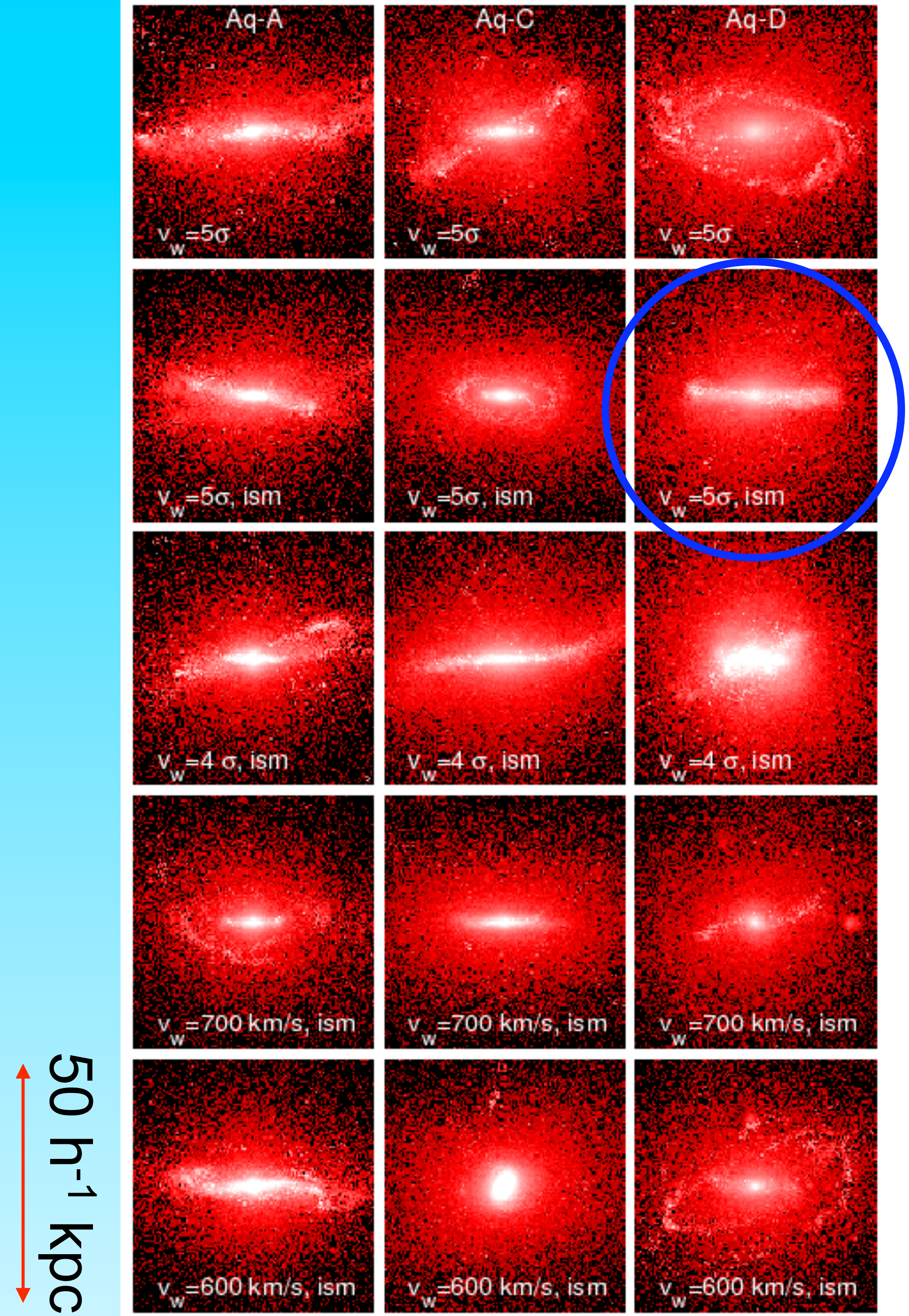
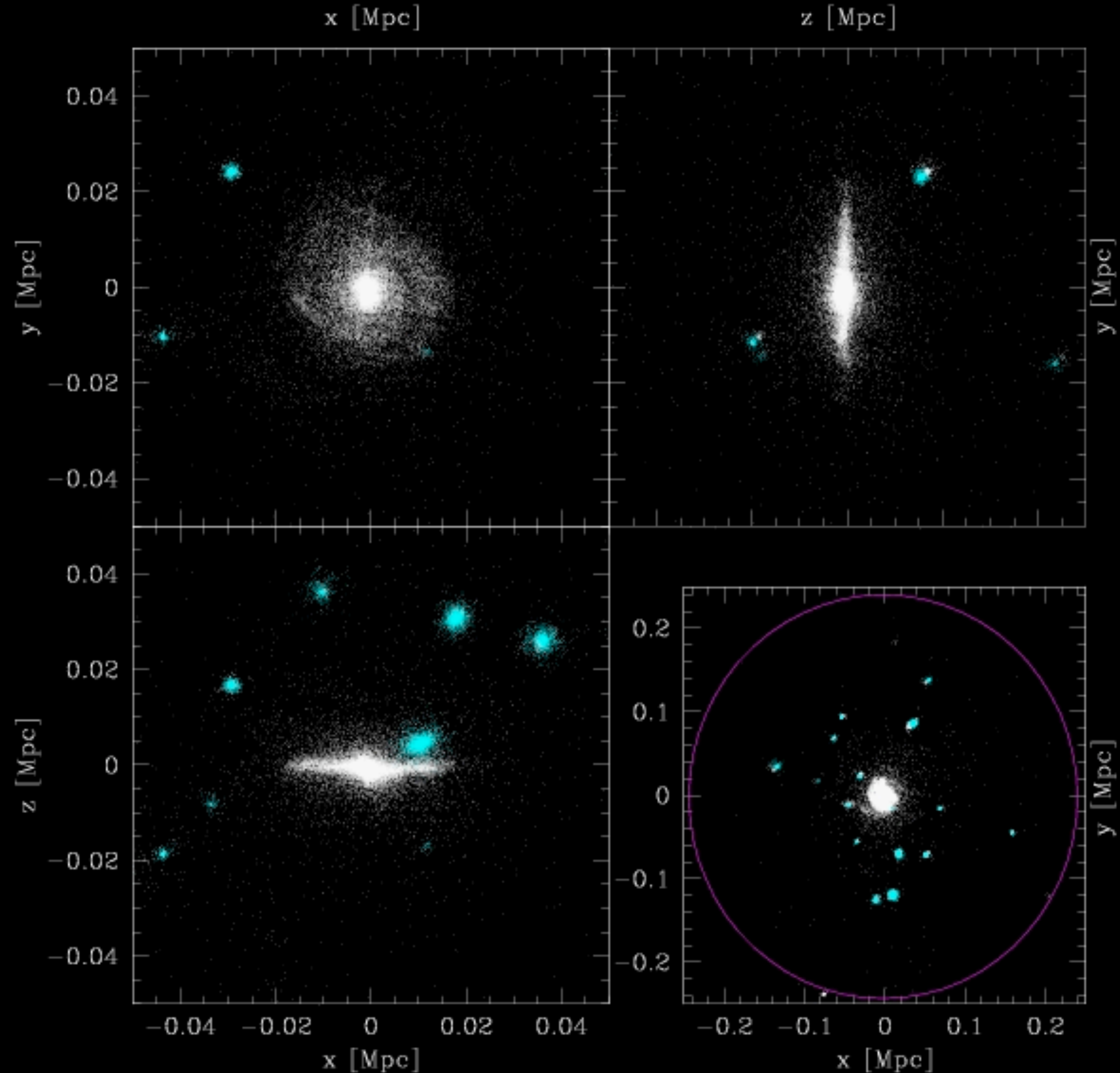
Central galaxies

- Edge-on views of B-band surface brightness
- z-axis defined by angular momentum of stars within 0.05 Rvir.
- Galaxy morphology sensitive to feedback treatment




x [Mpc]
z [Mpc]
y [Mpc]
z [Mpc]
y [Mpc]
y [Mpc]
0.04
0.02
0
−0.02
−0.04
0.2
0.1
0
−0.1
−0.2
x [Mpc]
x [Mpc]

Satellite luminosity function

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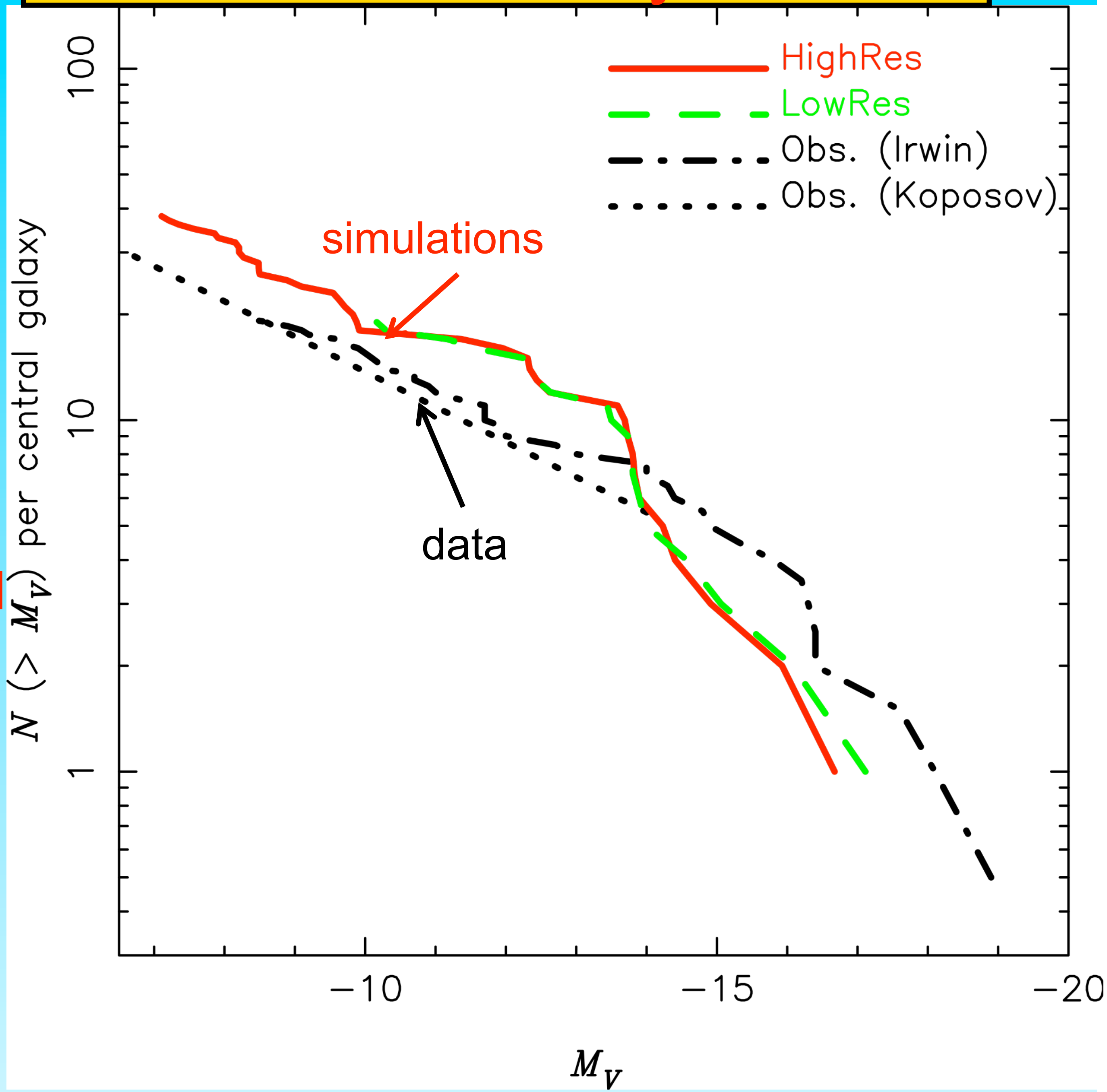
Good agreement with observations

Note: ultra-faint satellites not resolved in simulation



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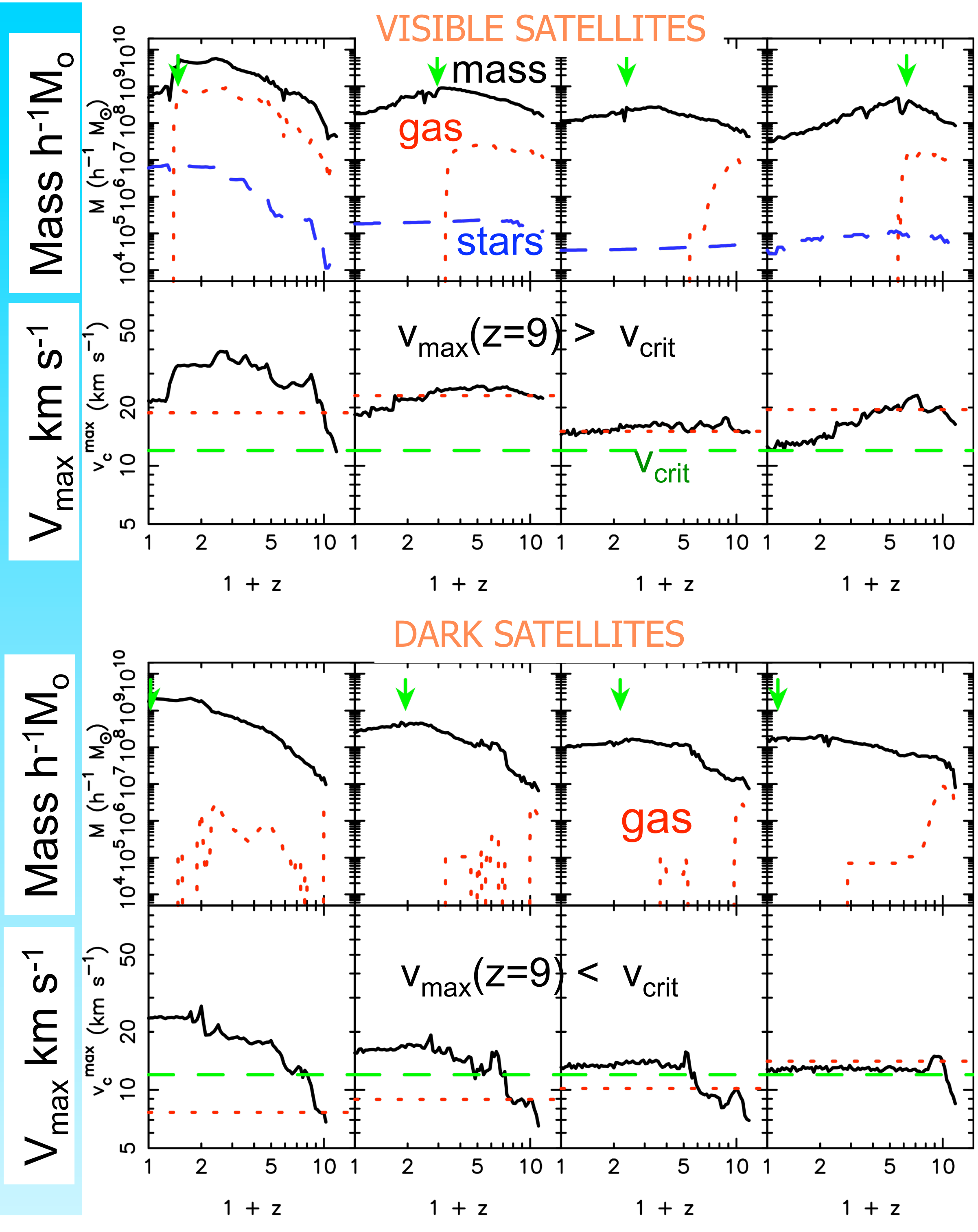
Formation history of luminous & dark sats

Note:

Reionization is at z=9

↓ Sat accreted onto halo

- For visible sats
  - $v_{max}(z=9) > v_{crit}$
  - Gas is stripped at infall
- For failed sats
  - $v_{max}(z=9) < v_{crit}$
  - gas evaporated by reion



Circular velocity functions

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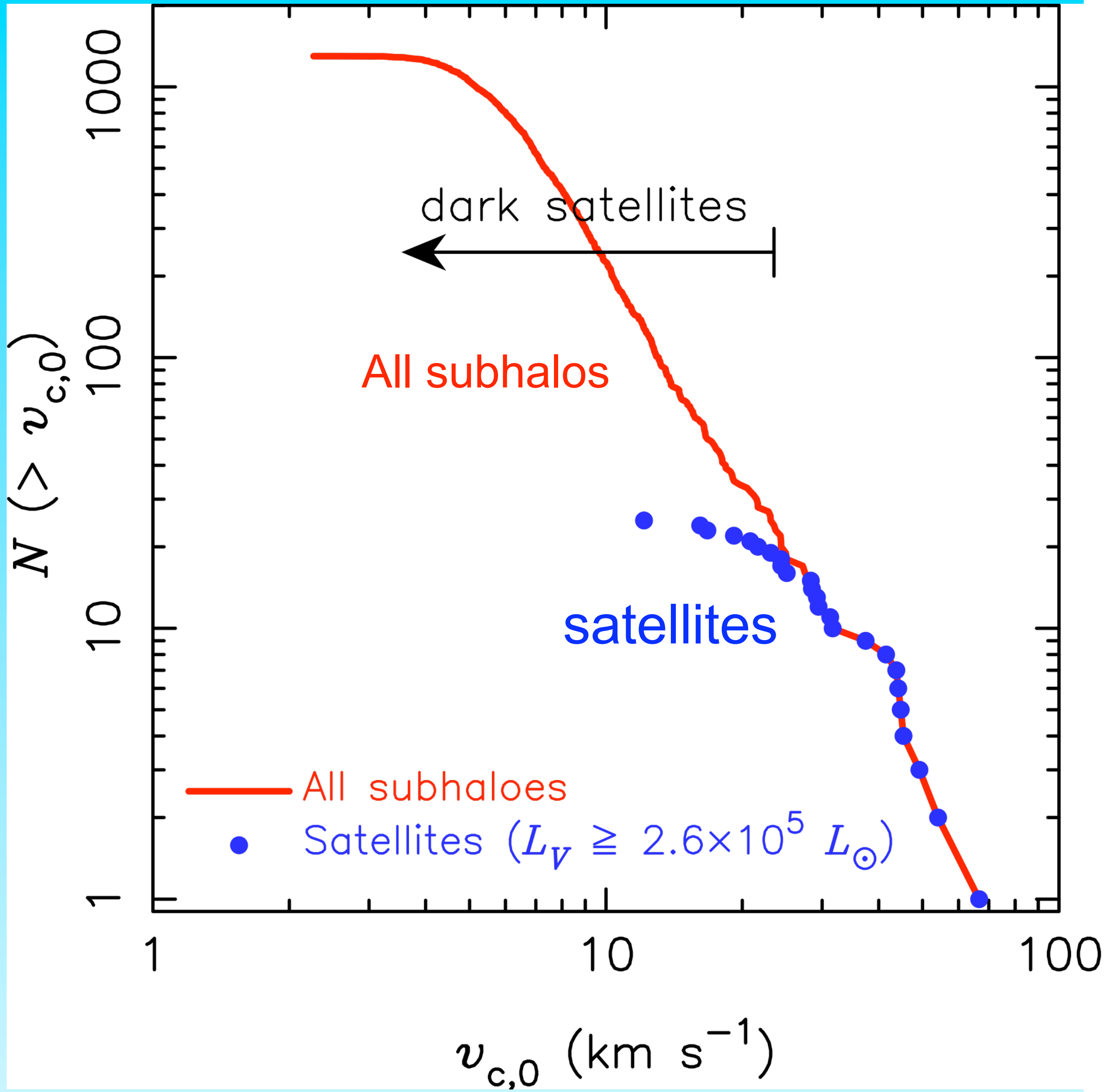
- All subhalos with v_c > 20 km/s make a satellite of $L > 2.6 \times 10^5 L_o$

- Satellite formation inhibited in subhalos of v_c < 20 km/s



A special scale in cosmology?

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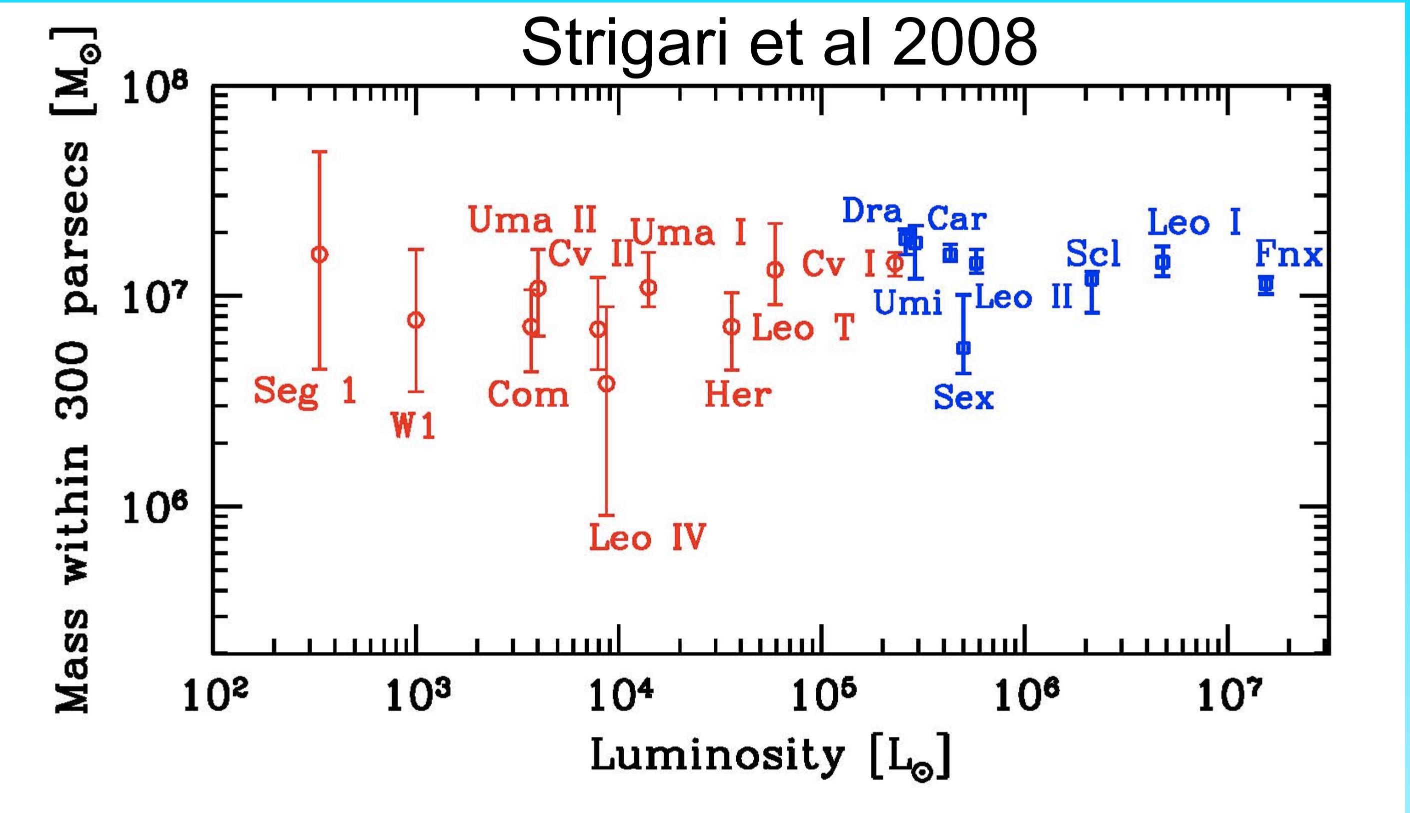

Is this special scale due to:

- Warm dark matter (e.g. sterile neutrino) ?
- Astrophysics in CDM halos?

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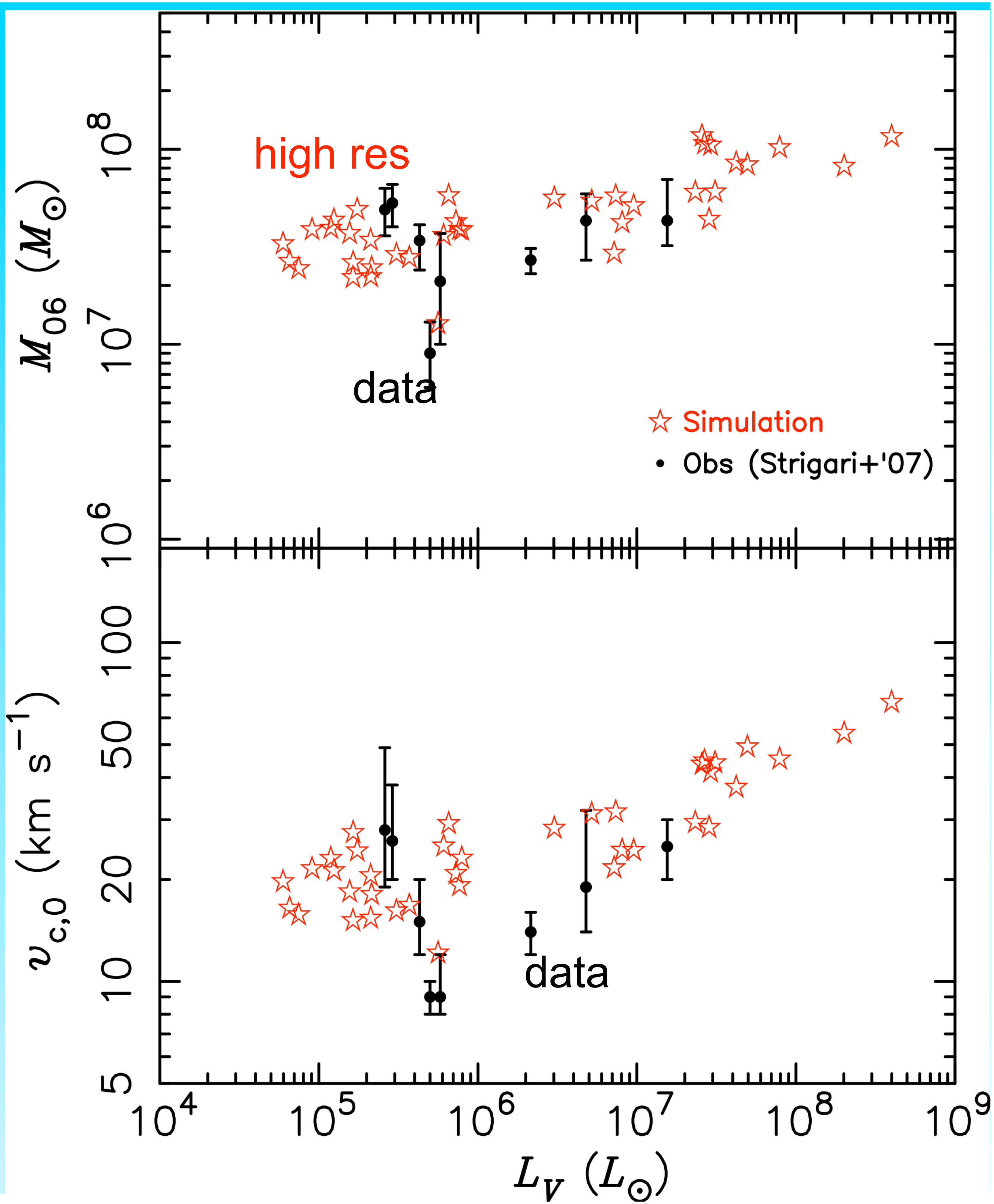
Mass within 600 pc

Models reproduce the M_{600} – L relation

$V_{circ,max}$ within 600 pc



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Conclusions: ΛCDM on small scales

- Many small substructures, with convergent mass fraction
  - the distribution of DM is not fractal nor is it dominated by Earth-mass objects
  - Large subhalo population is fundamental prediction of CDM
- Only the largest subhalos ($V_c(z=9)>12.5$ km/s) make a visible galaxy because of reionization and SN feedback
- Because of $V_{c,crit}$, the central density of satellites ends up being largely independent of satellite luminosity

The cold dark matter model

Detecting cold dark matter

If CDM is a supersymmetric particle, 3 possibilities

- Direct detection (underground labs)
- Indirect detection through annihilation radiation (e.g. γ rays)
- From evidence for SUSY at LHC

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The cold dark matter model

Detecting cold dark matter

If CDM is a supersymmetric particle, 3 possibilities

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A blueprint for detecting halo CDM

Supersymmetric particles annihilate and lead to production of γ-rays which may be observable by GLAST/FERMI

Intensity of annihilation radiation at ***x*** depends on:

$$\int \rho^2(\boldsymbol{x}) \, \langle \sigma v \rangle \, dV$$

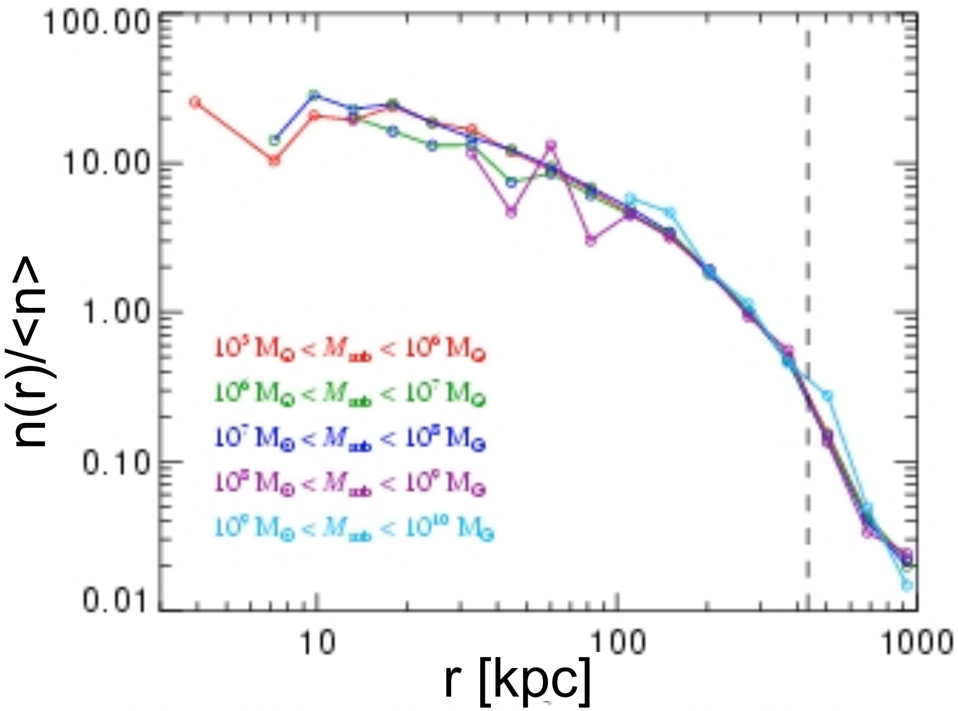
halo density at ***x***   cross-section

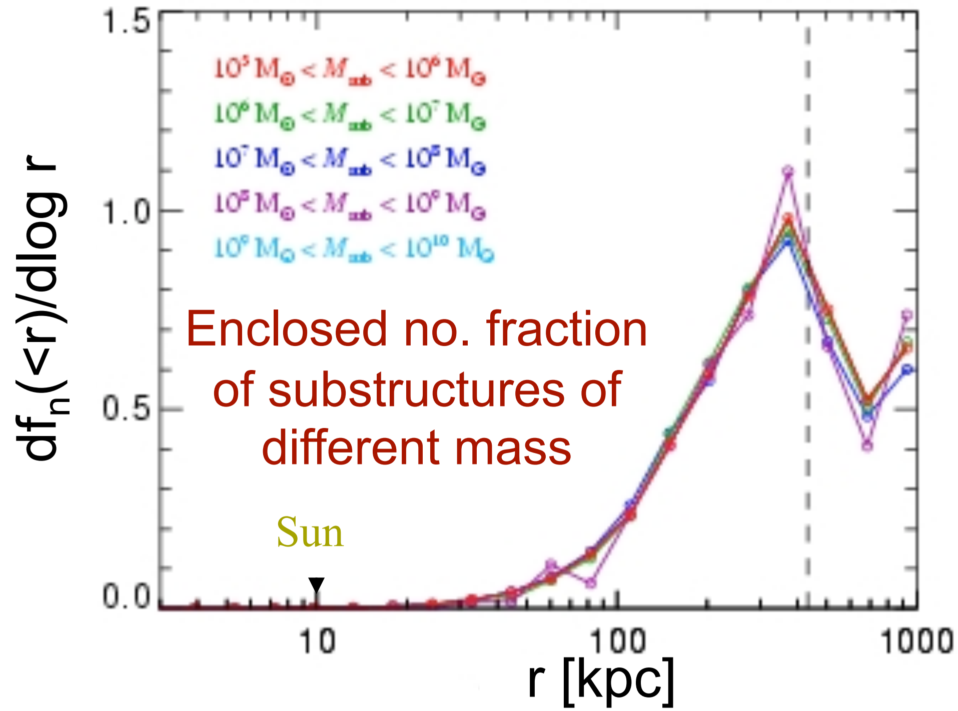
$\Longrightarrow$ Theoretical expectation requires knowing $\rho(\boldsymbol{x})$

$\Longrightarrow$ Accurate high resolution N-body simulations of halo formation from CDM initial conditions

The subhalo number density profile

- The spatial distribution of subhalos (except for the few most massive ones) is independent of mass
- Most subhalos are at large radii -- subhalos are more effectively destroyed near the centre
- Most subhalos have completed only a few orbits; dynamical friction unimportant below a subhalo mass threshold
- Subhalos are far from the Sun

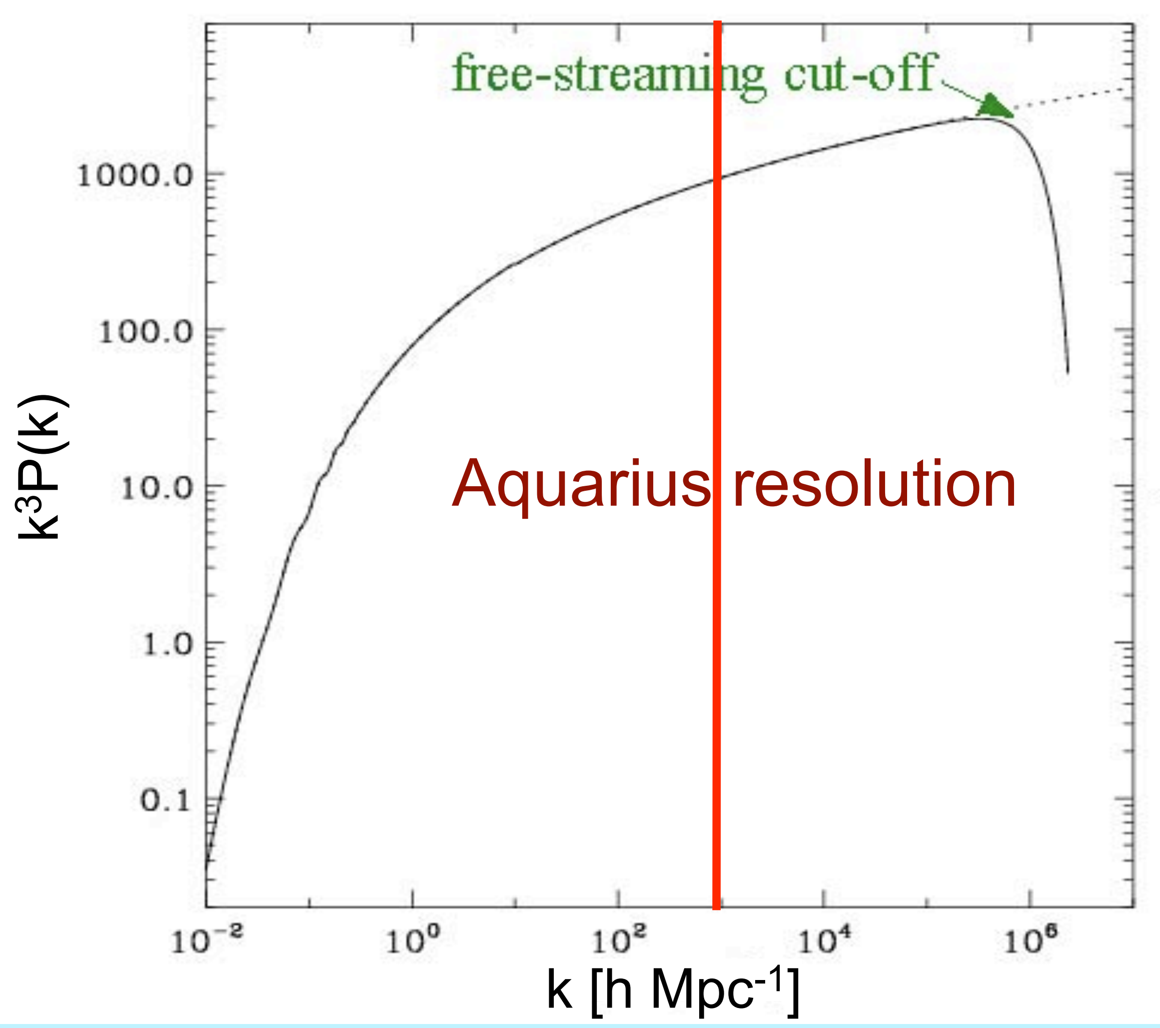




The cold dark matter power spectrum

The linear power spectrum
("power per octave")

Assumes a 100GeV wimp
Green et al '04



How lumpy is the MW halo?

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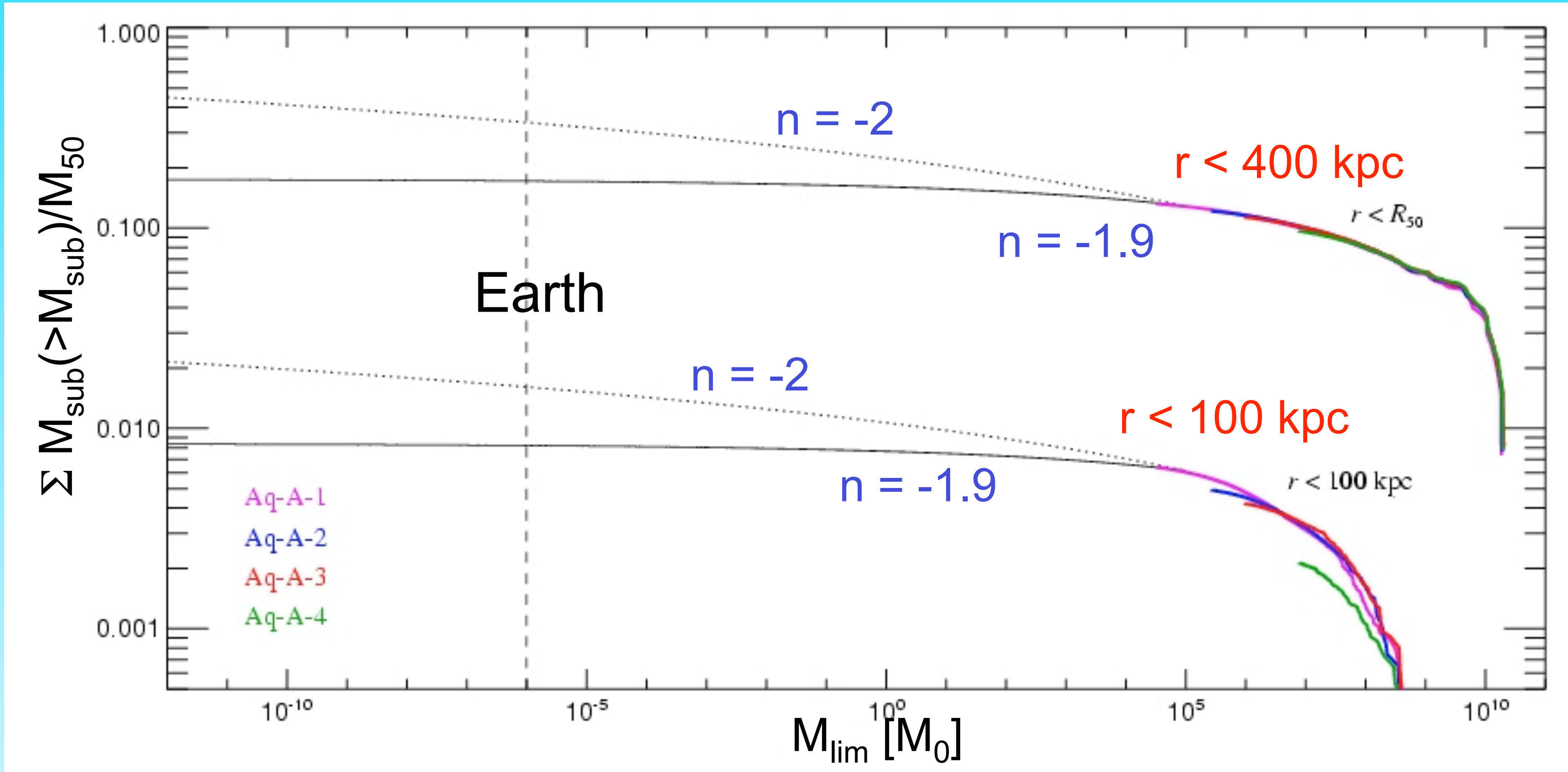
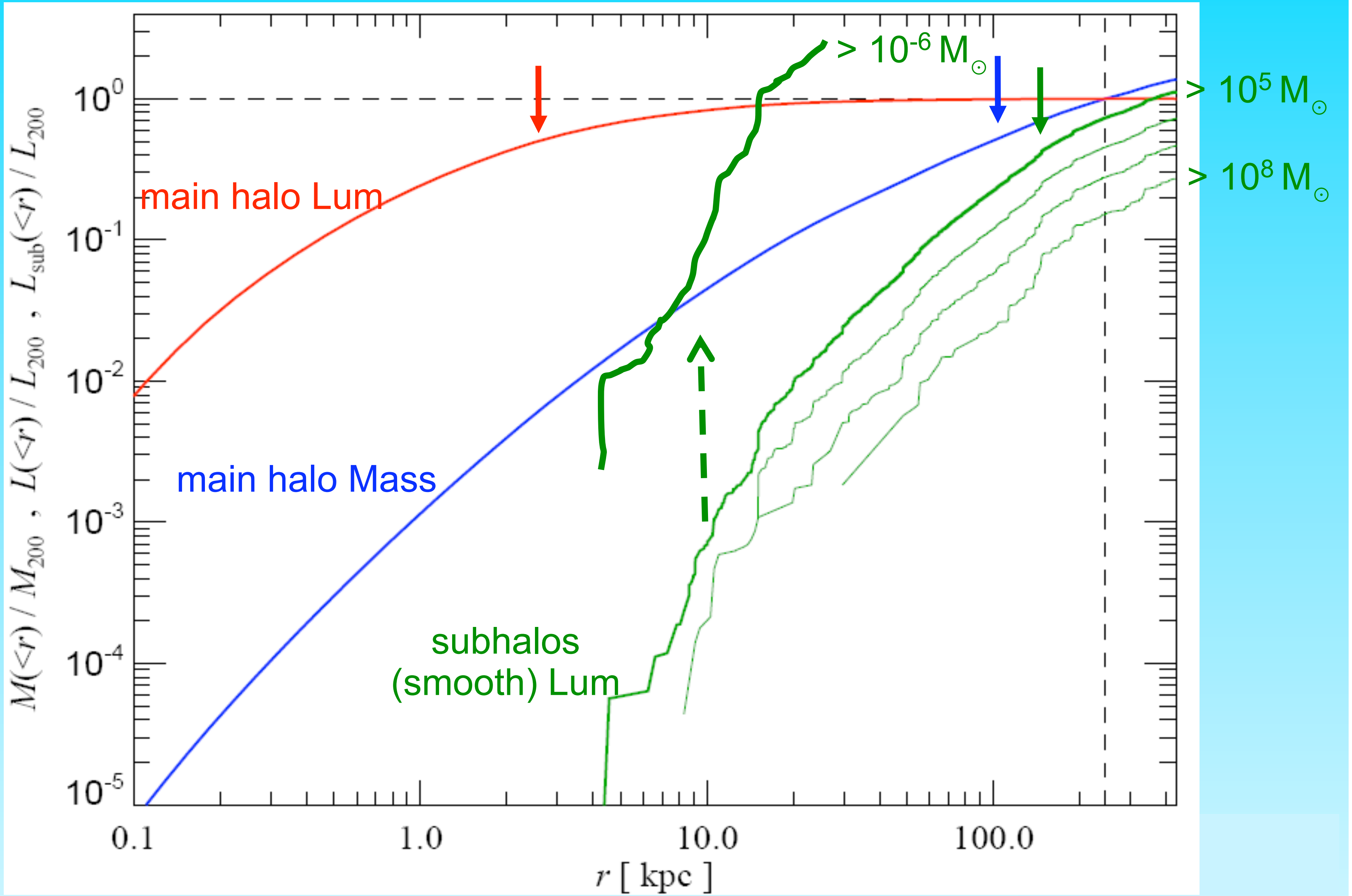
Mass fraction in subhalos as a fn of cutoff mass in CDM PS

The Milky Way halo is expected to be quite smooth!



Substructure mass fraction within R_{sun} < 0.1%

Mass and annihilation radiation profiles of a MW halo



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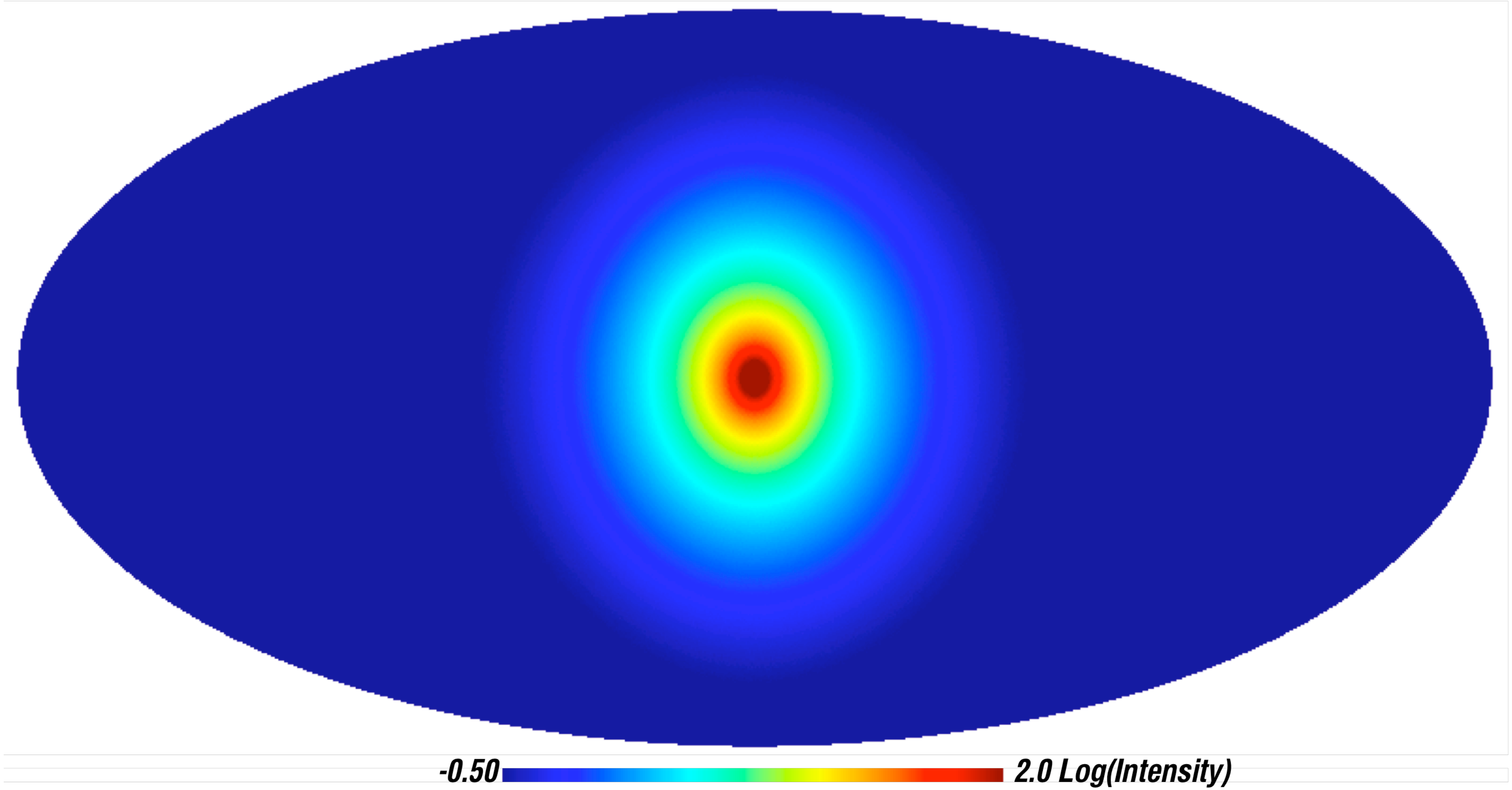
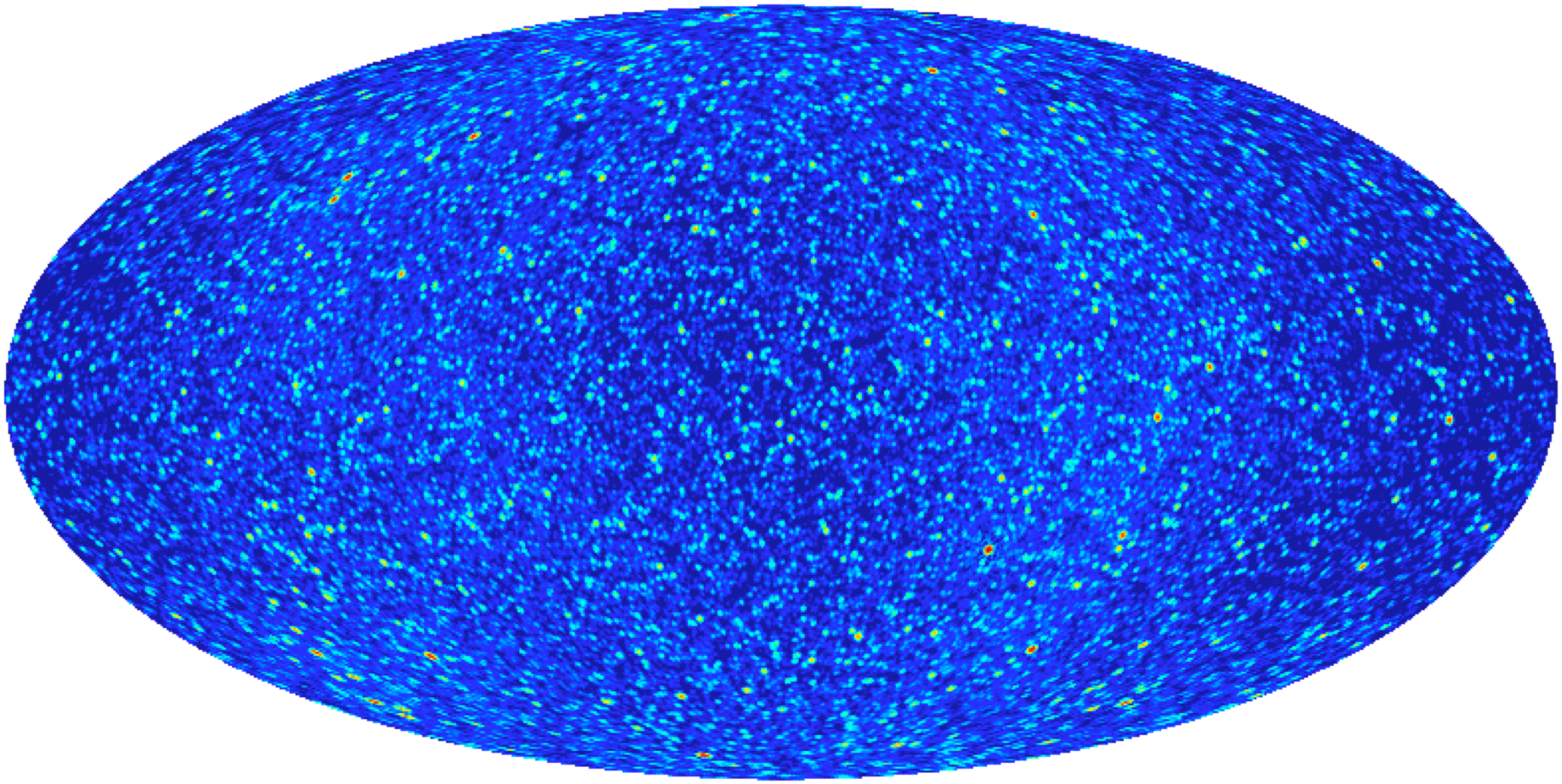
The Milky Way seen in annihilation radiation

smooth main halo emission (MainSm)



The Milky Way seen in annihilation radiation

emission from resolved subhalos (SubSm+SubSub)



-3.0 2.0 Log(Intensity)

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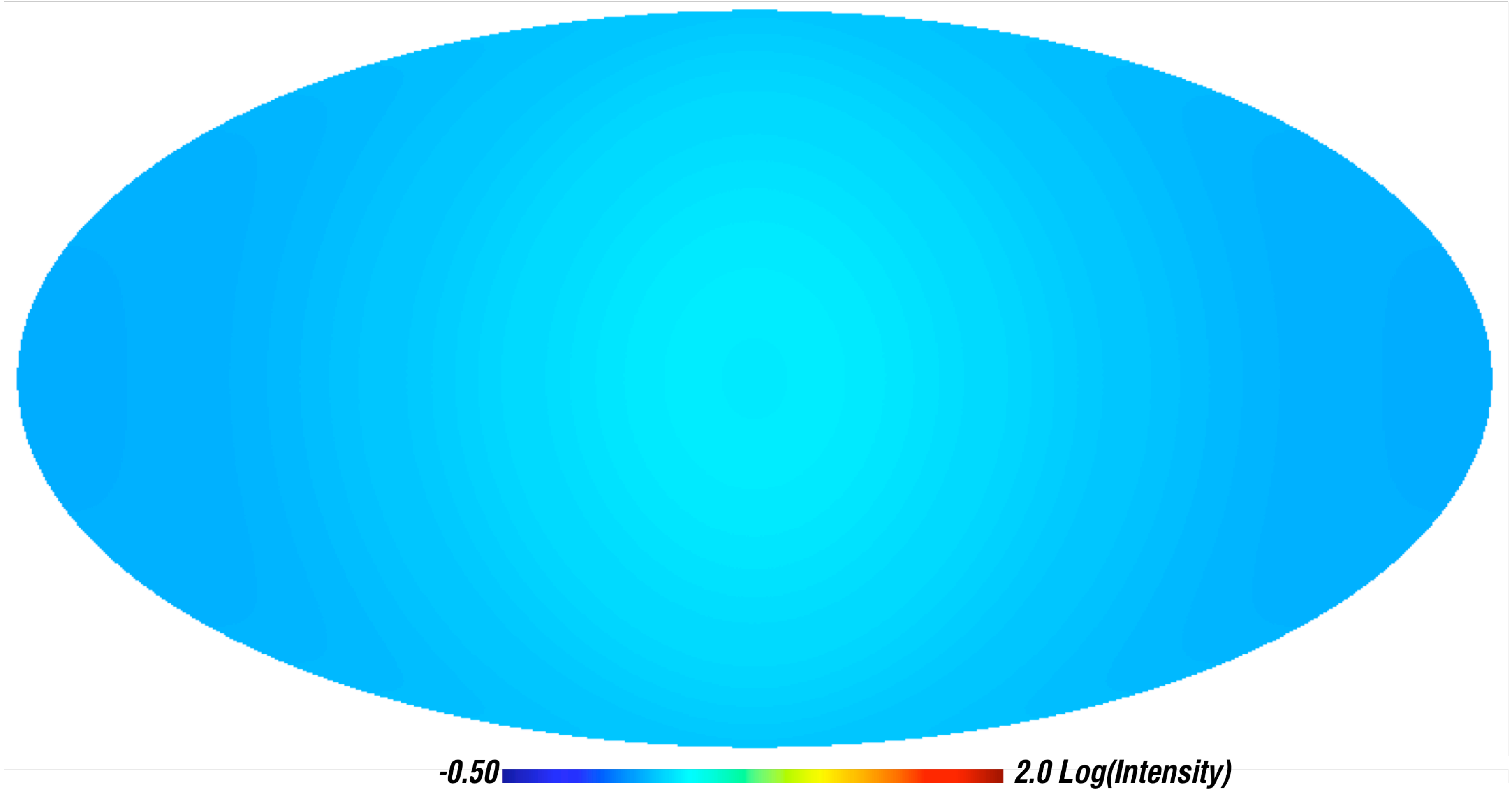
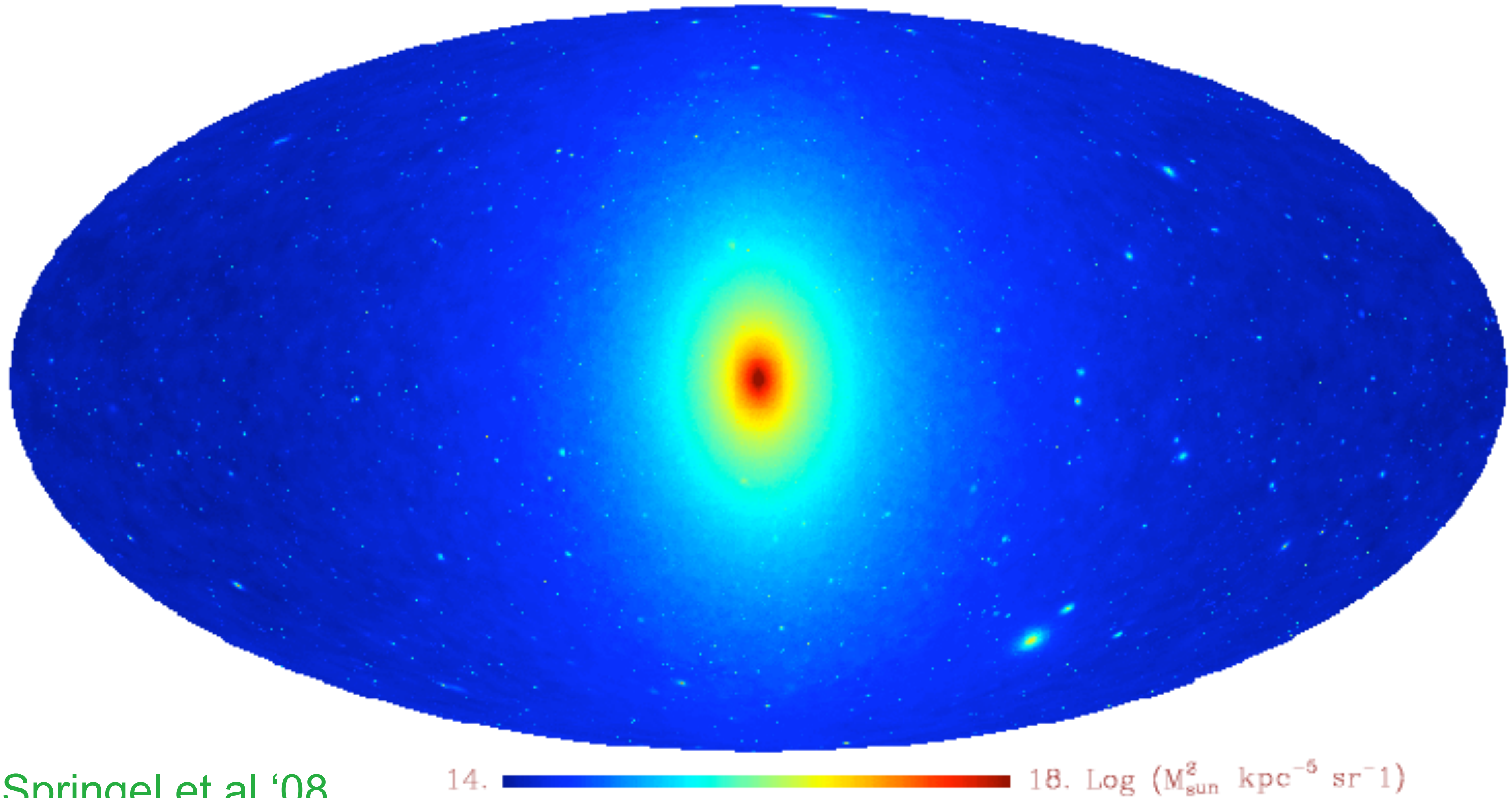
The Milky Way seen in annihilation radiation

unresolved subhalo emission (MainUn)



The Milky Way seen in annihilation radiation

Aquarius simulation: $N_{200} = 1.1 \times 10^9$



Springel et al ‘08

A blueprint for detecting halo CDM

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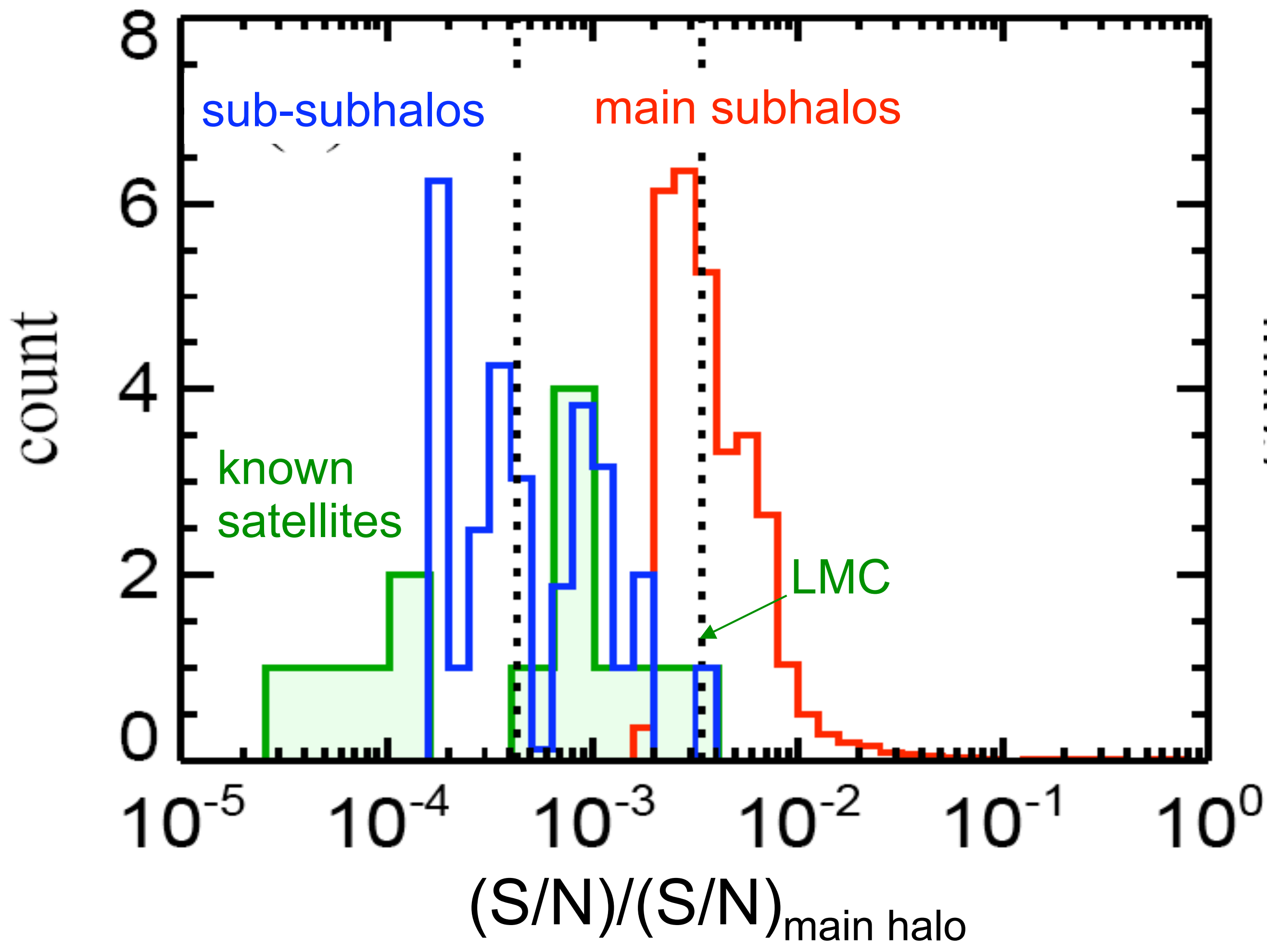
$S/N = F/(\theta^2_h + \theta^2_{psf})^{1/2}$

S/N for detecting subhalos in units of that for detecting the main halo.

30 highest S/N objects, assuming use of optimal filters



- Highest S/N subhalos have 1% of S/N of main halo
- Highest S/N subhalos have 10 times S/N of known satellites
- Substructure of subhalos has no influence on detectability

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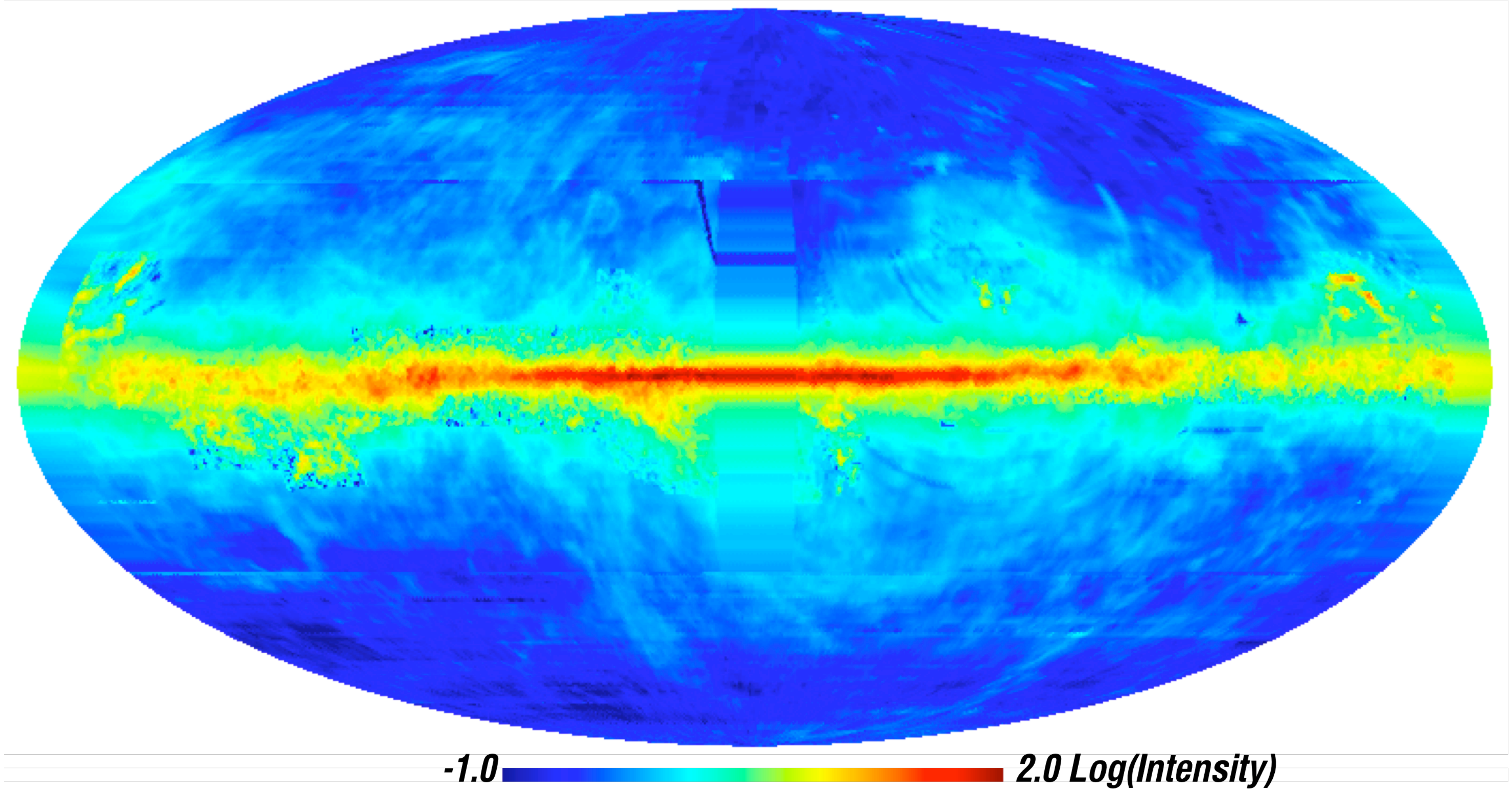
The Milky Way seen in annihilation radiation

GALPROP, optimized



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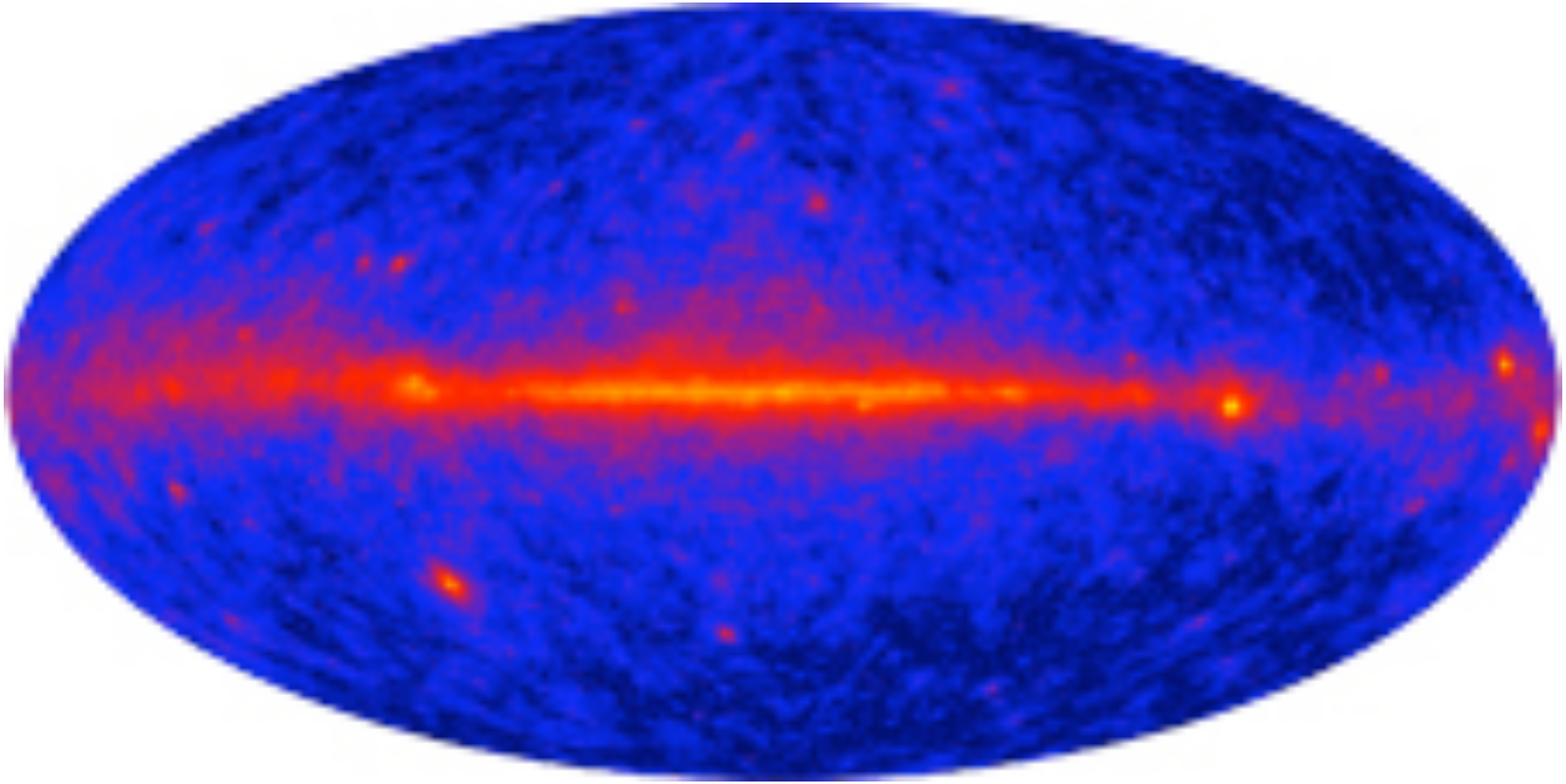
The first all-sky image from GLAST/Fermi



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Conclusions: ΛCDM on small scales

- Halos have "cuspy" profiles, with inner slope shallower than -1
- Profiles of relaxed halos described by NFW or Einasto form
- X-rays/lensing ⇒ Evidence for cusps in relaxed cluster halos
- Many small substructures, with (slowly) convergent mass fraction
  - DM distribution not fractal nor dominated by Earth-mass objects
- The "satellites problem(s)" probably explained by gal formation
- γ-ray annihilation may be detectable by FERMI which should:
  - First detect smooth halo (if background can be subtracted)
  - Then (perhaps) detect dark subhalos with no stars
  - Sub-substructure boost irrelevant for detection