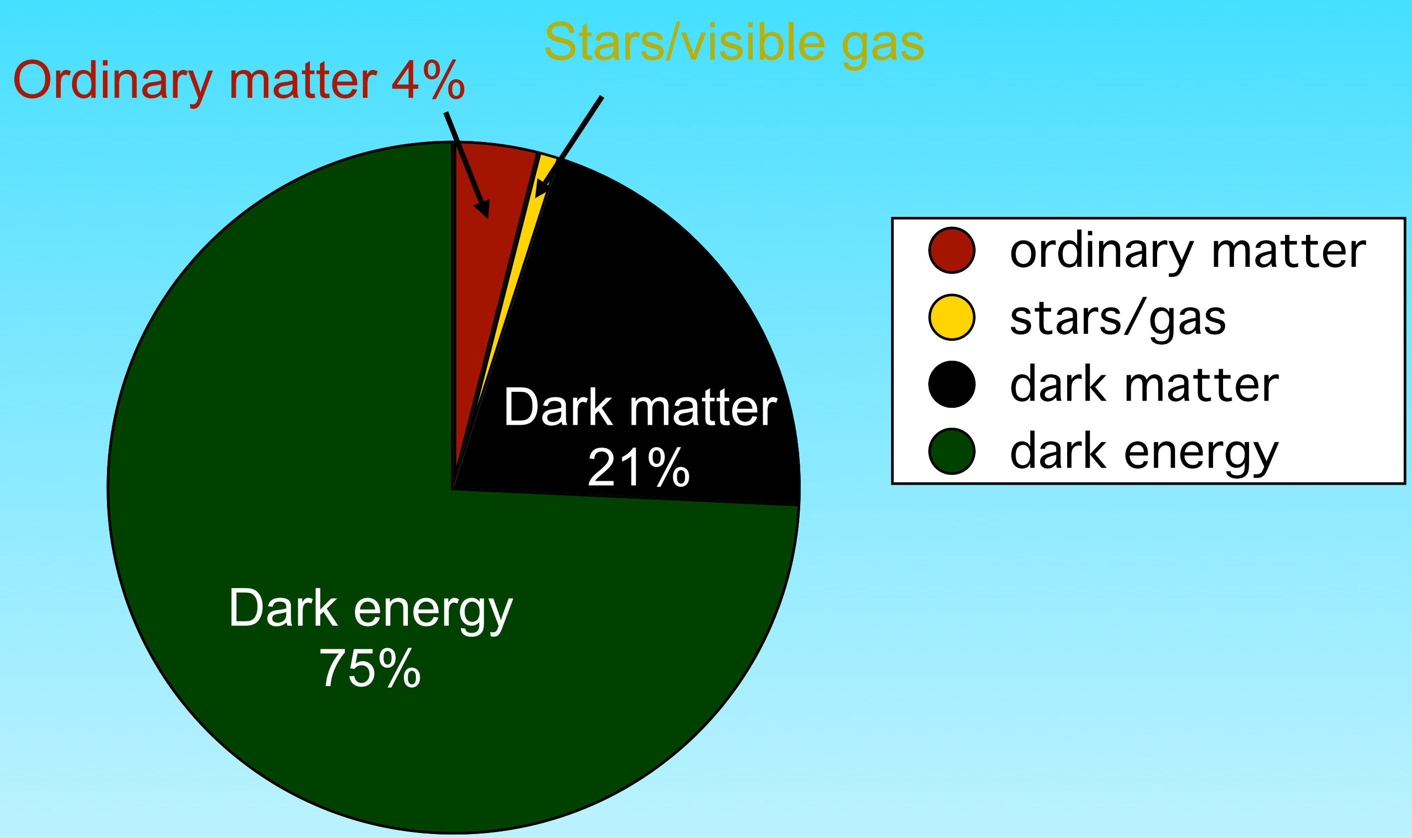
The small-scale structure of the Universe

Carlos S. Frenk
Institute for Computational Cosmology, Durham

The contents of the Universe

- The contents of our universe:



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Non-baryonic dark matter candidates

Type	candidate	mass
hot	neutrino	a few eV
warm	Sterile neutrino	keV-MeV
cold	axion neutralino	10^{-5}eV->100 GeV

The origin of cosmic structure

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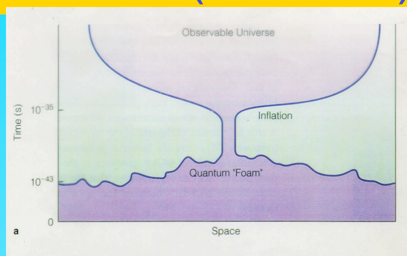
Inflation ($t \sim 10^{-35}$ s)



→ **QUANTUM FLUCTUATIONS:**

$\left|\delta_k\right|^2 \propto k^n \quad n \approx 1$

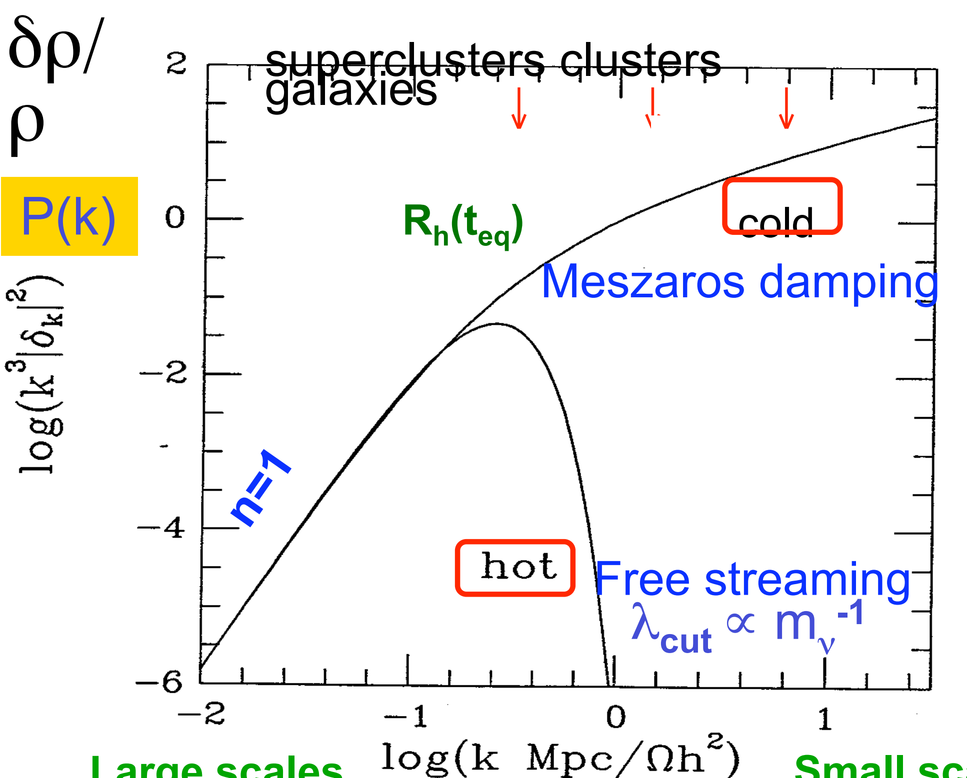
Gaussian amplitudes

→ **FLAT UNIVERSE**

\+ Damping (nature of dark matter)

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

→ Transfer function



- Hot DM (eg ~30 ev neutrino)
  - Top-down formation
- Cold DM (eg ~neutralino)
  - Bottom-up (hierachical)

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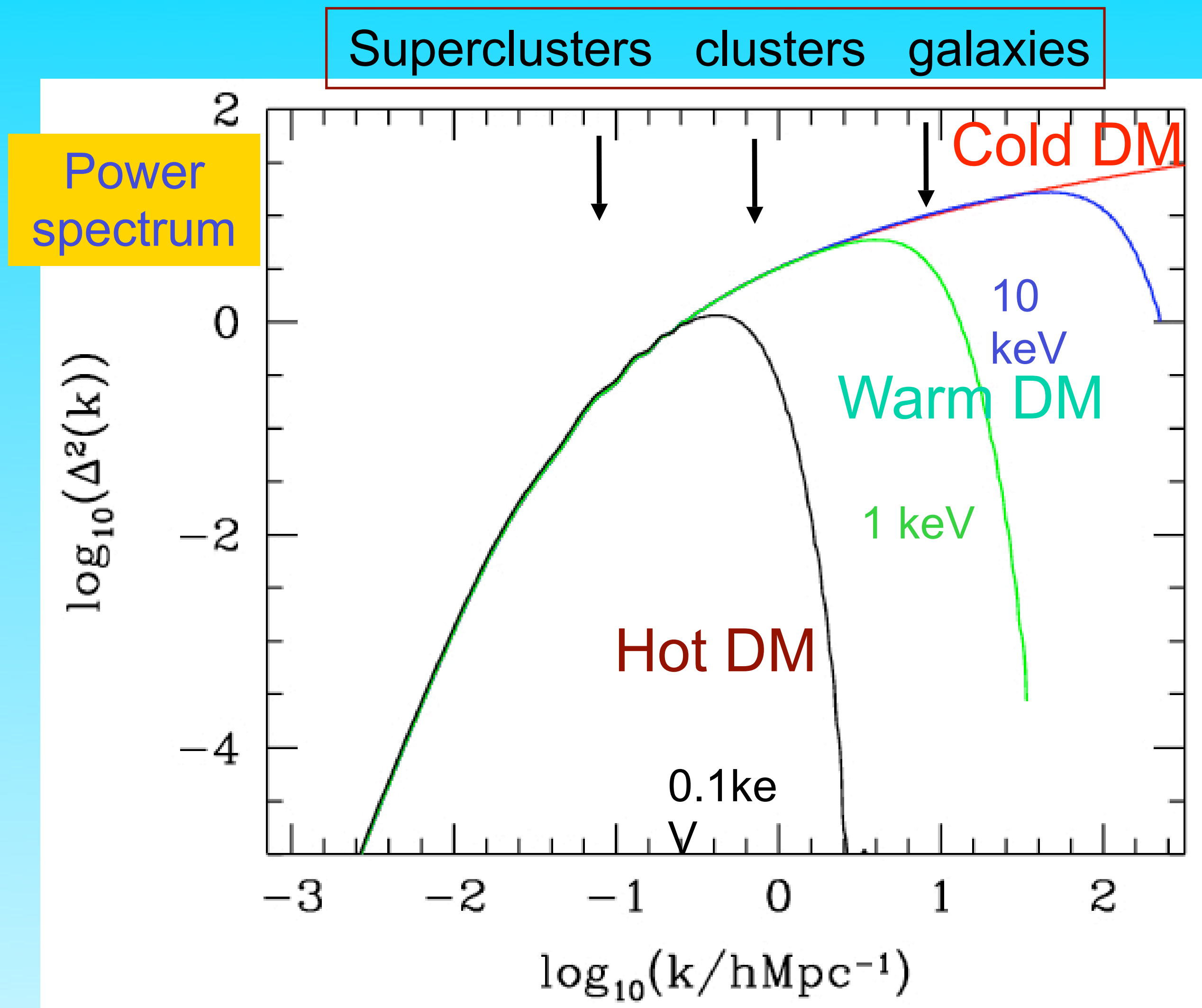
Non-baryonic dark matter



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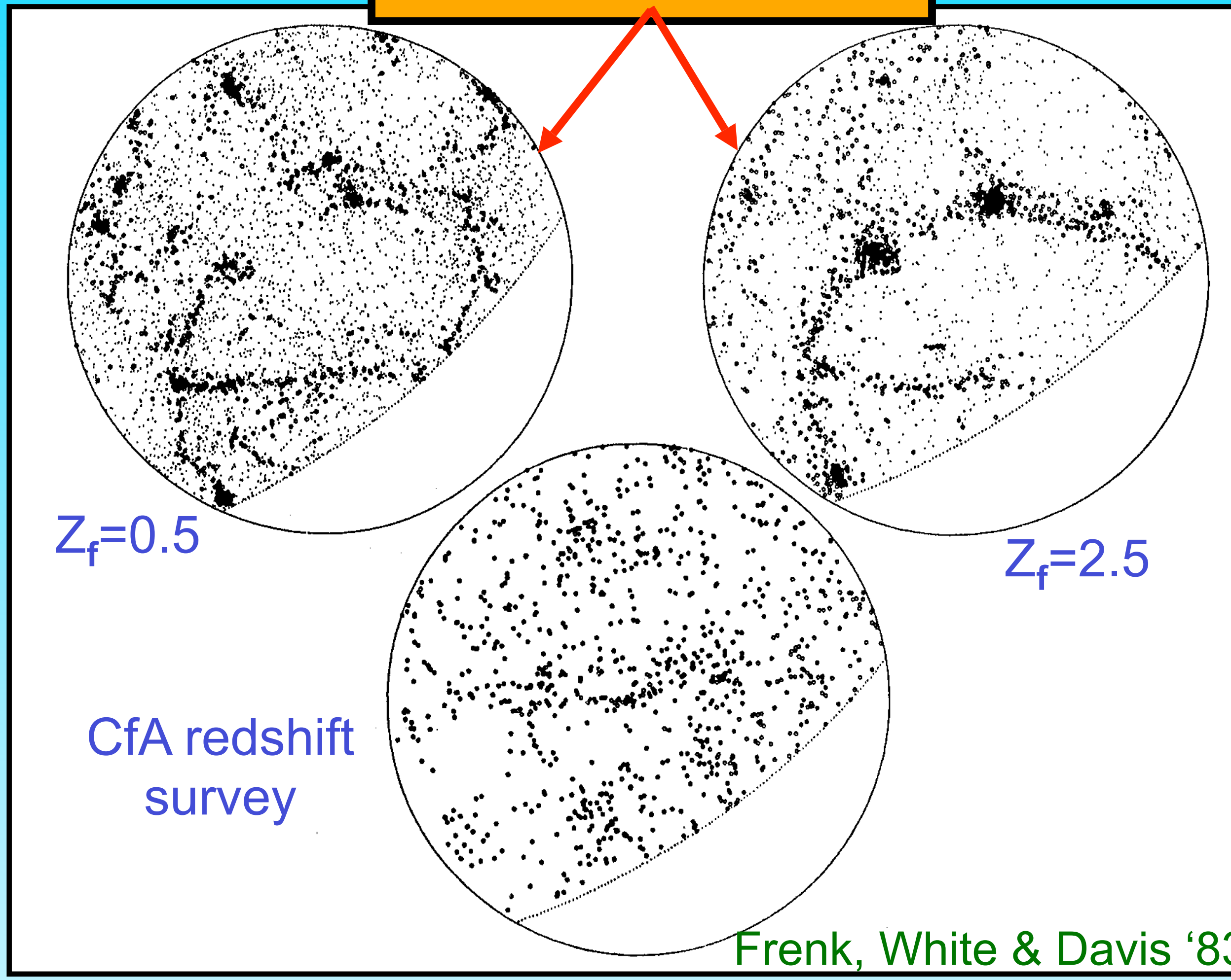
Neutrino (hot) dark matter

Ω_ν=1 (m_ν = 30 ev)

Free-streaming length so large that superclusters form first and galaxies are too young

⇨

Neutrinos cannot make an appreciable contribution to Ω and m_ν<< 10 ev



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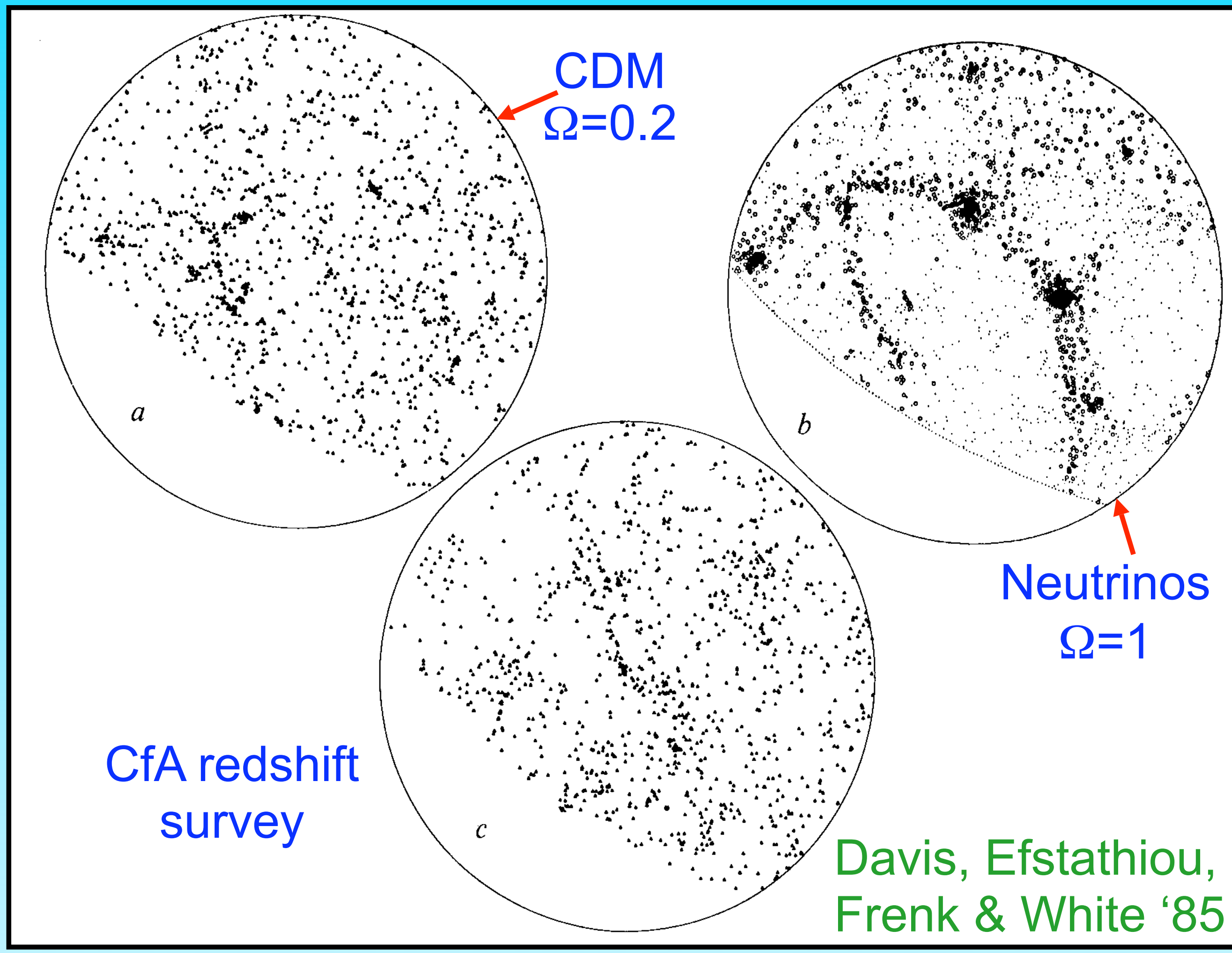
Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



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The cold dark matter cosmogony

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

Peebles '82

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

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

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

Davis, Efstathiou, Frenk & White 1985

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

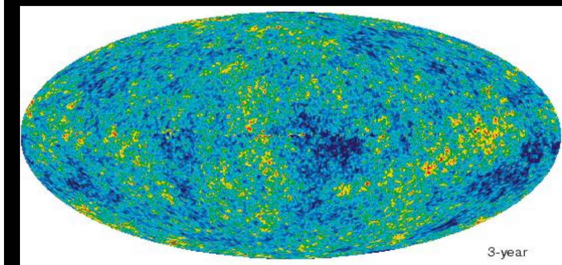
NATURE VOL. 311 11 OCTOBER 1984 REVIEW ARTICLE 517

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

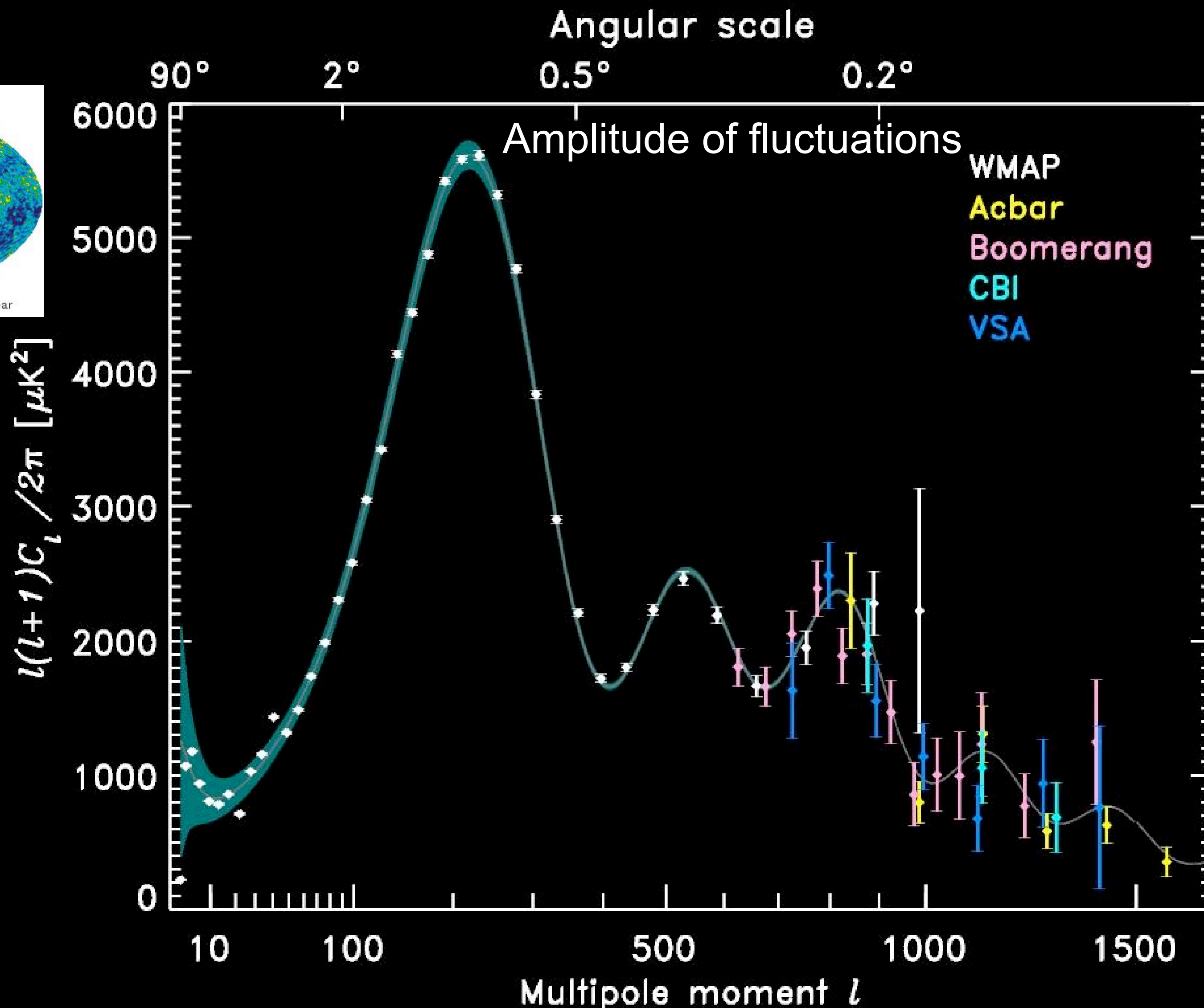
WMAP temp anisotropies in CMB



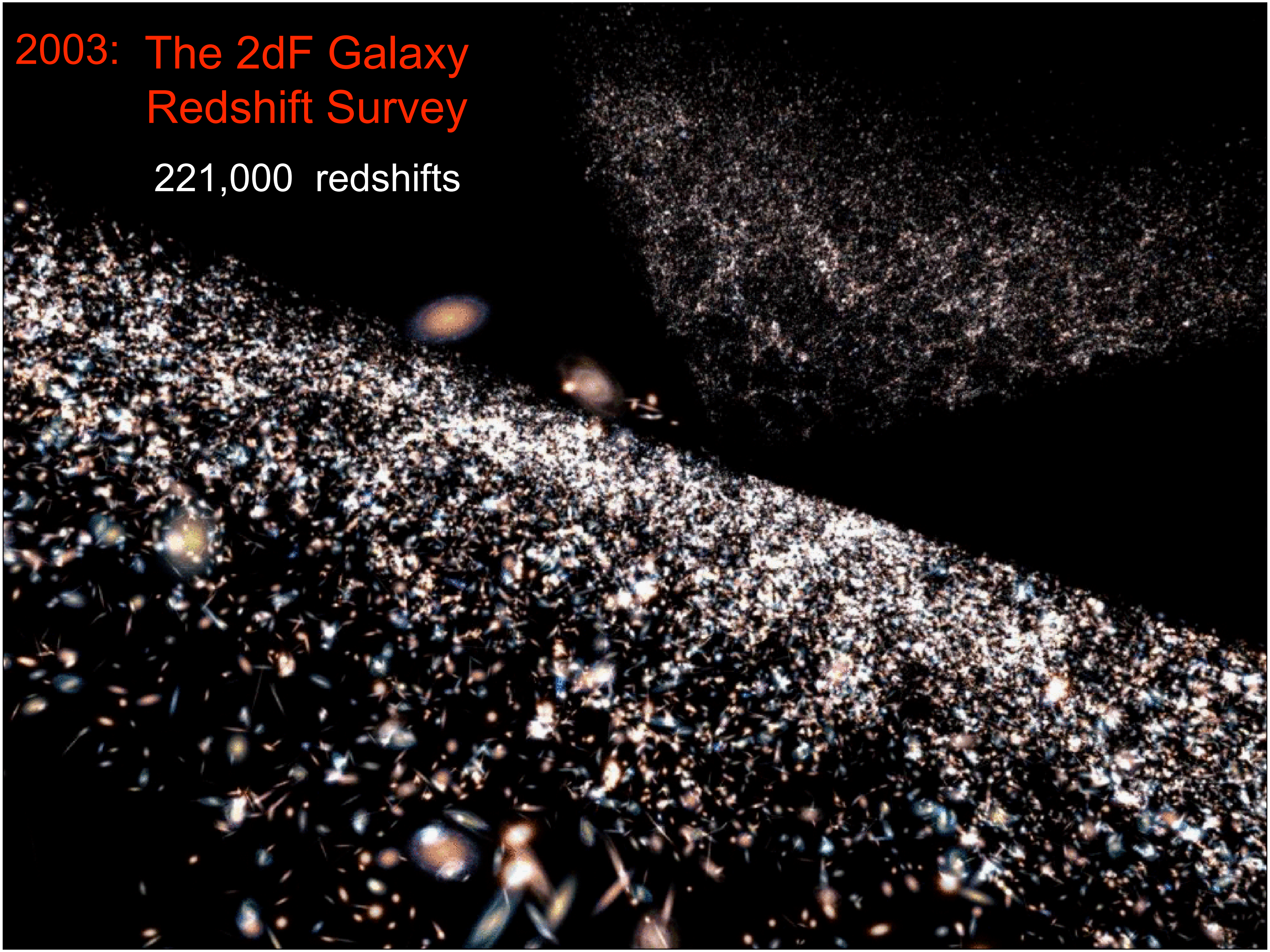
The amplitude of the CMB ripples is exactly as predicted by inflationary cold dark matter theory

The position of the first peak

→ FLAT UNIVERSE

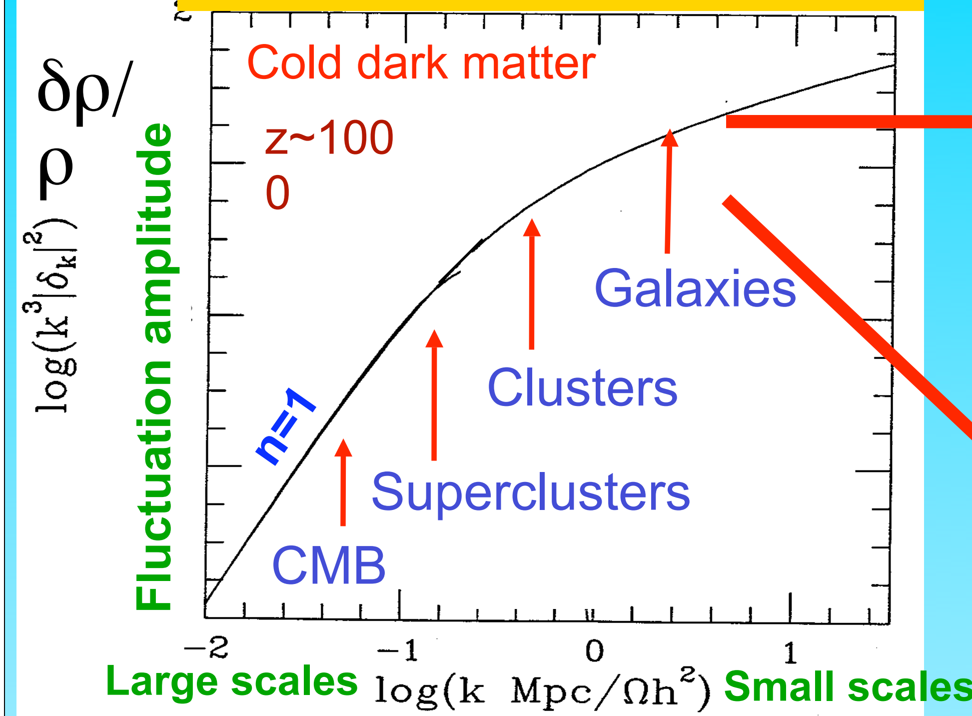


Hinshaw etal '06

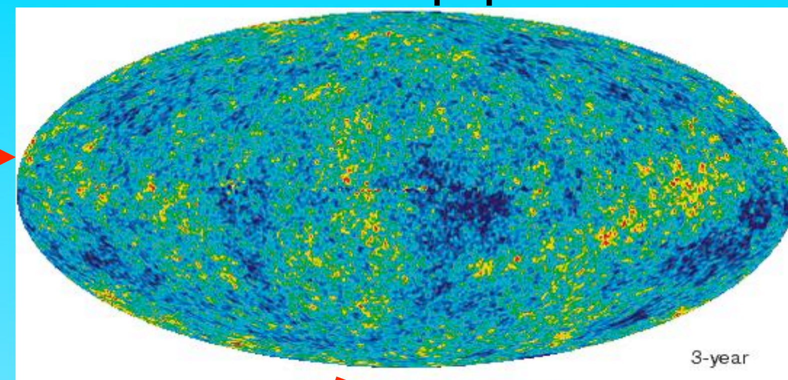

2003: The 2dF Galaxy Redshift Survey
221,000 redshifts

Testing the CDM paradigm

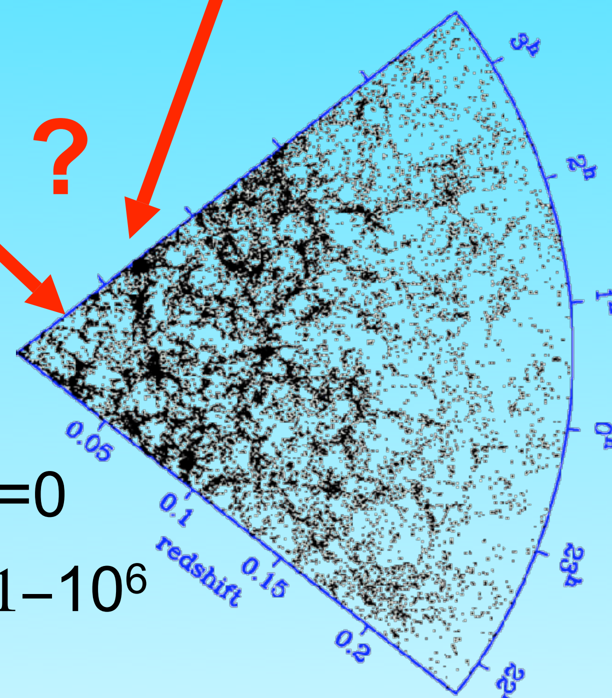
P(k) Initial conditions : ΛCDM



z=1000 $\delta\rho/\rho \sim 10^{-5}$



?



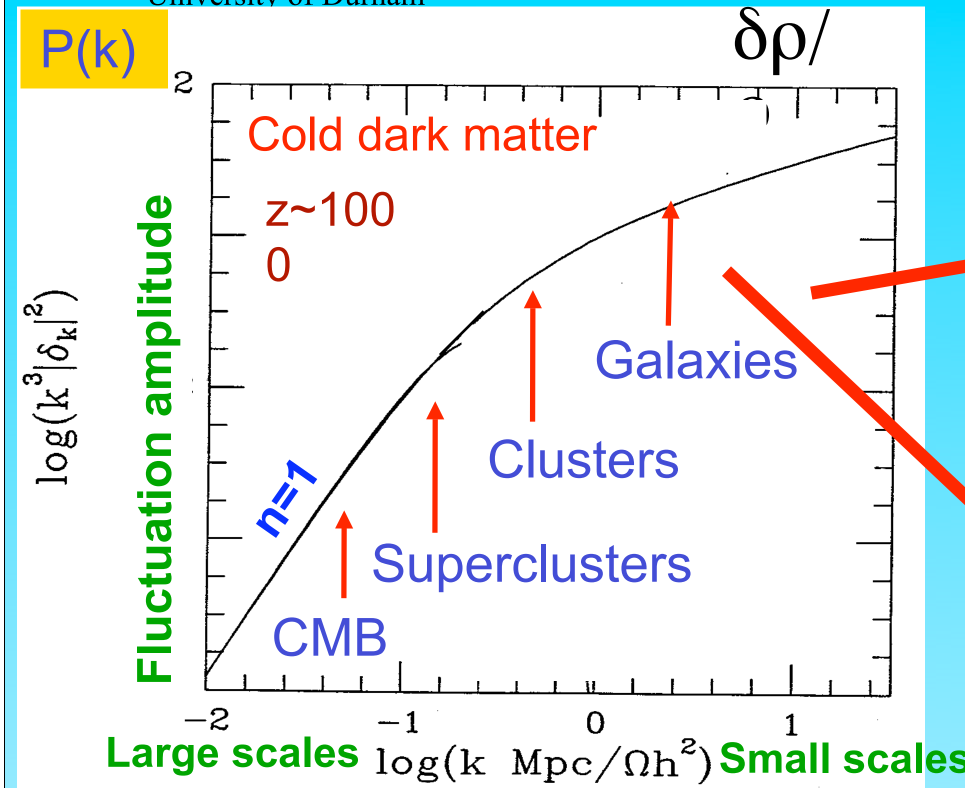
z=0

$\delta\rho/\rho \sim 1-10^6$

The galaxy distribution evolves from by fluctuationns seen in CMB by gravitational amplification.

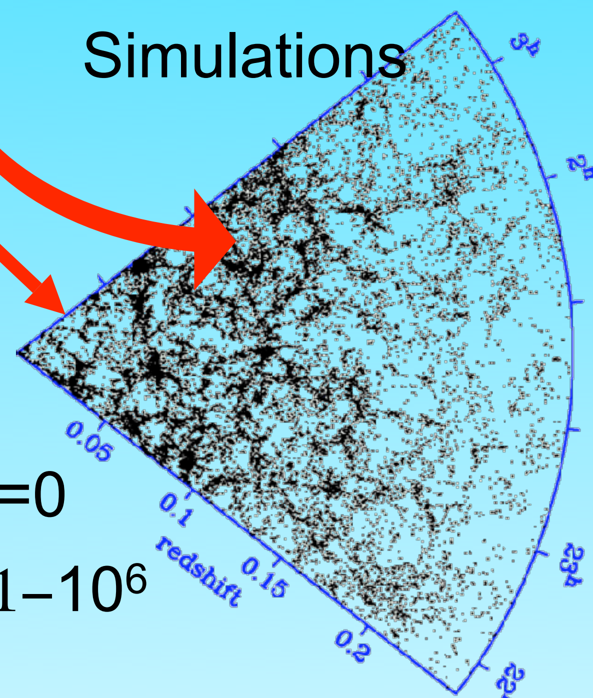
Testing the CDM paradigm

University of Durham



"Cosmology machine"

Simulations



Initial conditions : ΛCDM

Basic DM physics simple: structure grows primarily by gravity

z=0

$\delta\rho/\rho \sim 1\text{–}10^6$

→ N-body simulations

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University of Durham

The Millennium simulation

UK, Germany, Canada, US collaboration

Simulation data available at:

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

Pictures and movies available at:

www.durham.ac.uk/virgo

Nature, June/05

Cosmological N-body simulation

- 10 billion particles
- 500 h^{-1} Mpc box
- $m_p = 8\times10^8\, h^{-1}\, M_o$
- $\Omega = 1$; $\Omega_m = 0.25$; $\Omega_b = 0.045$; $h = 0.73$; $n = 1$; $\sigma_8 = 0.9$
- 20×10^6 gals brighter than LMC

Carried out at Garching using L-Gadget by V. Springel

(27 Tbytes of data)

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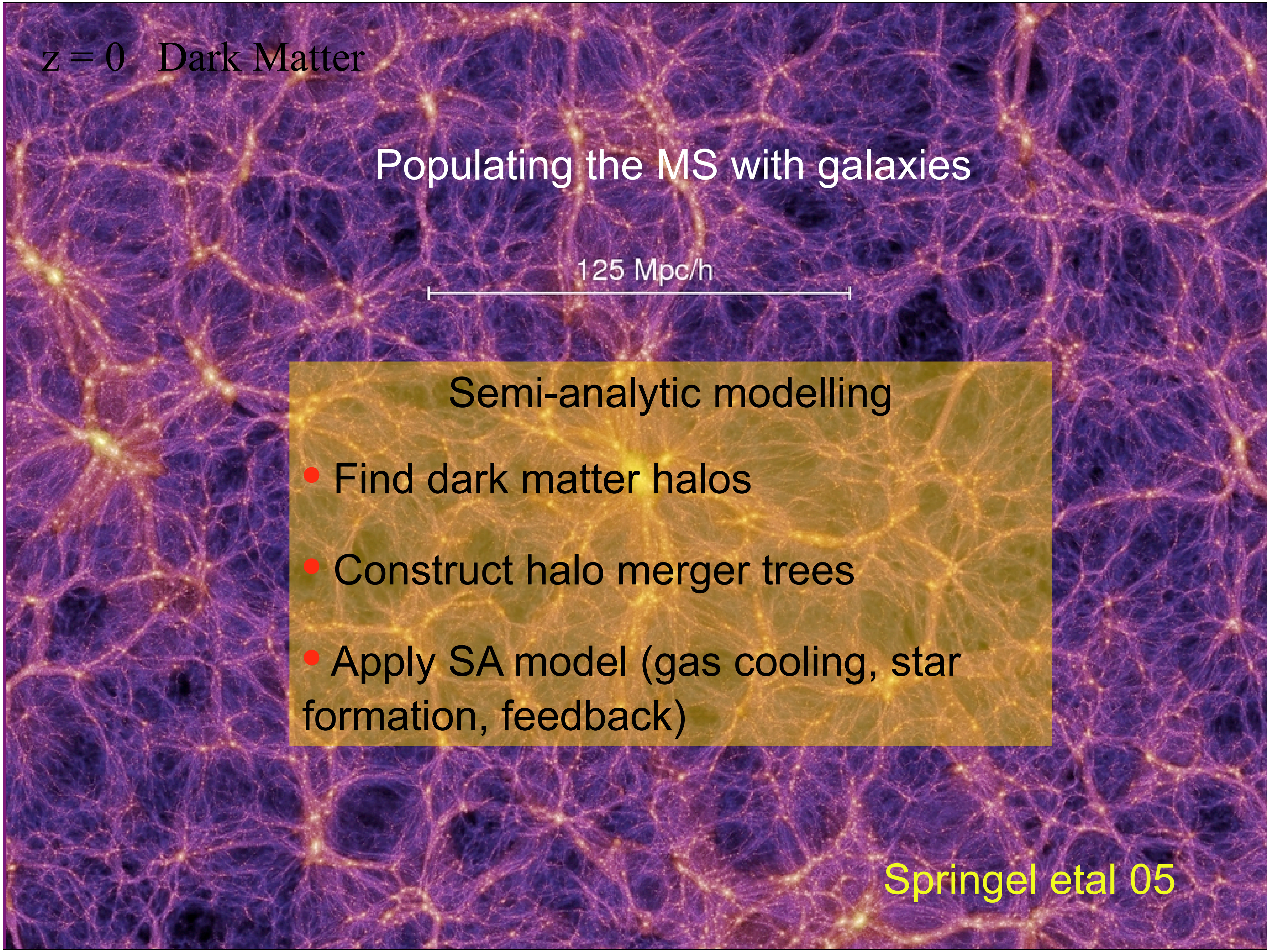
The Millennium simulation

QuickTime™ and a
3ivx D4 4.5.1 decompressor
are needed to see this picture.

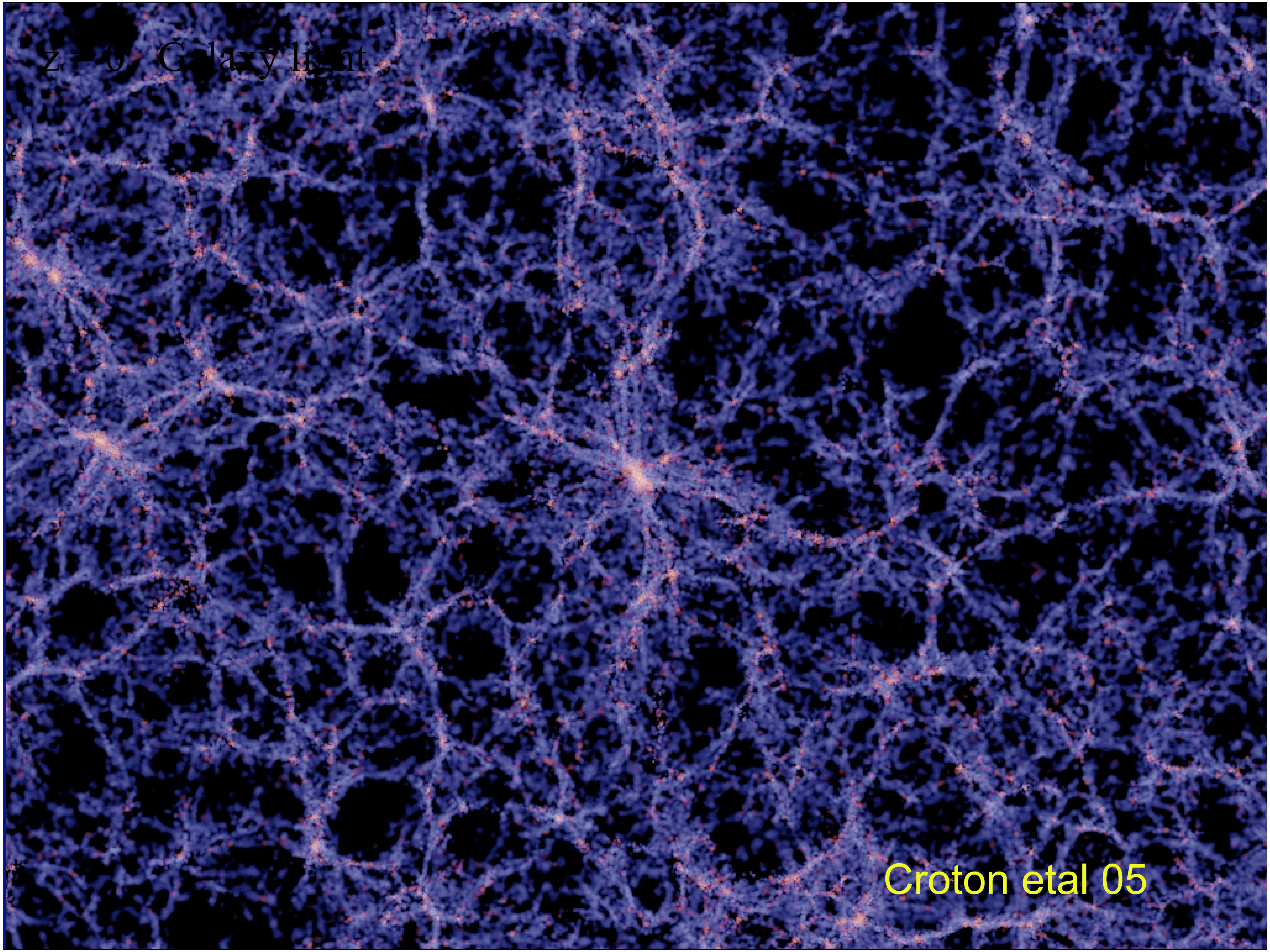
Springel et al Nature June/05

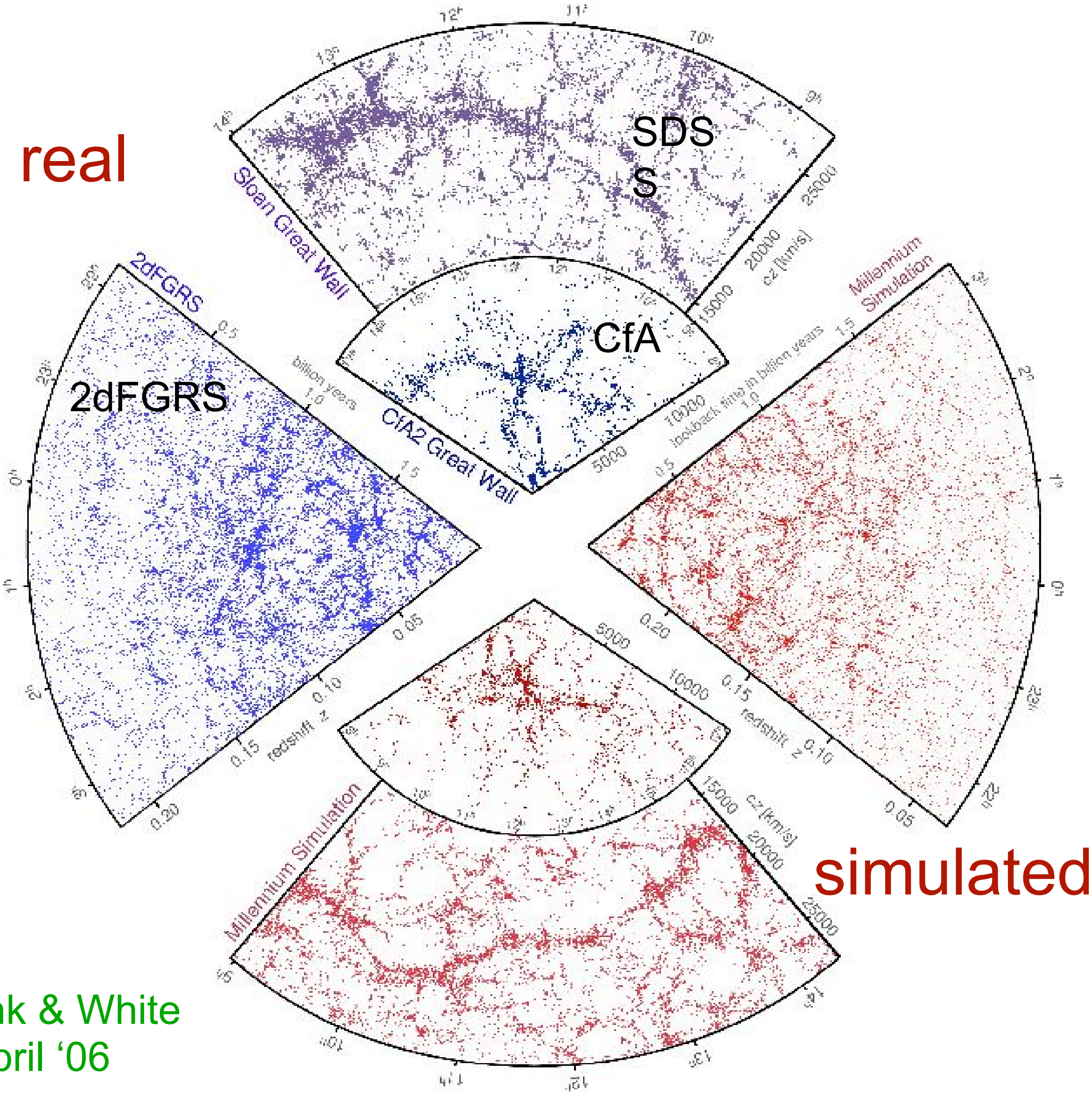


Populating the MS with galaxies

Semi-analytic modelling

- Find dark matter halos
- Construct halo merger trees
- Apply SA model (gas cooling, star formation, feedback)


z = 0   Galaxy light
Croton etal 05



Springel, Frenk & White
Nature, April '06

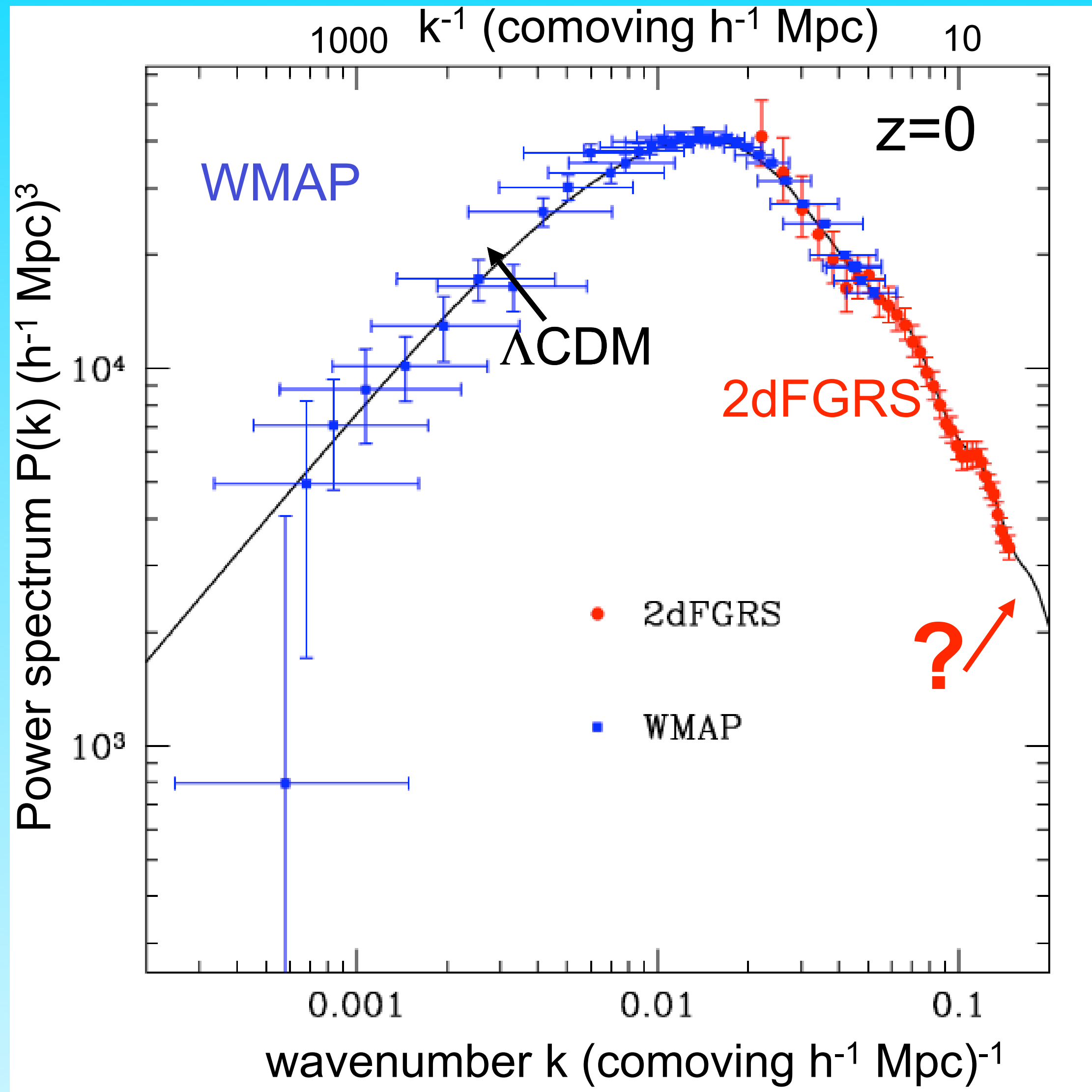
The cosmic power spectrum: from the CMB to the 2dFGRS

University of Durham

CMB:

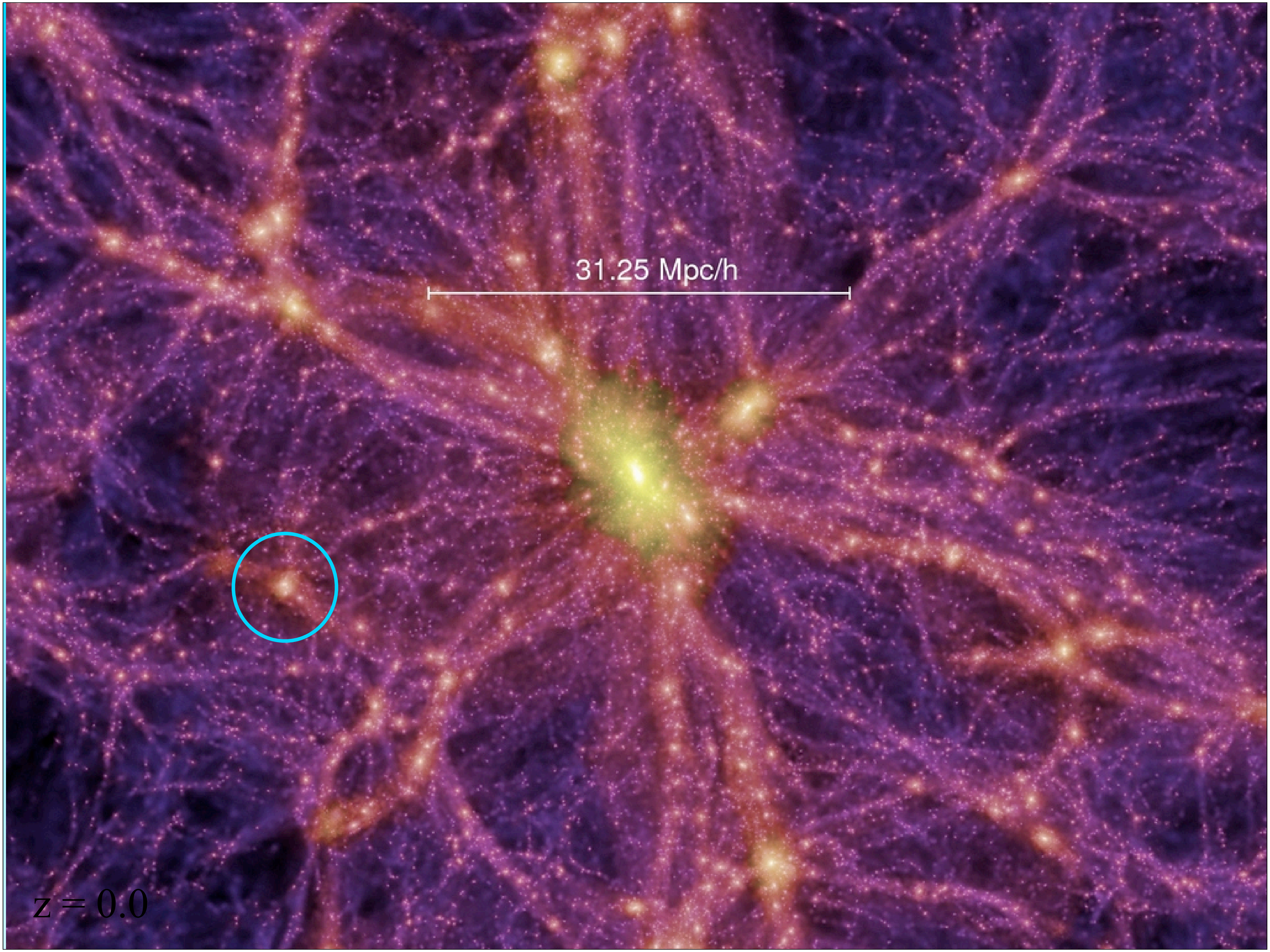
- Convert angular separation to distance (and k) assuming flat geometry
- Extrapolate to z=0 using linear theory

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

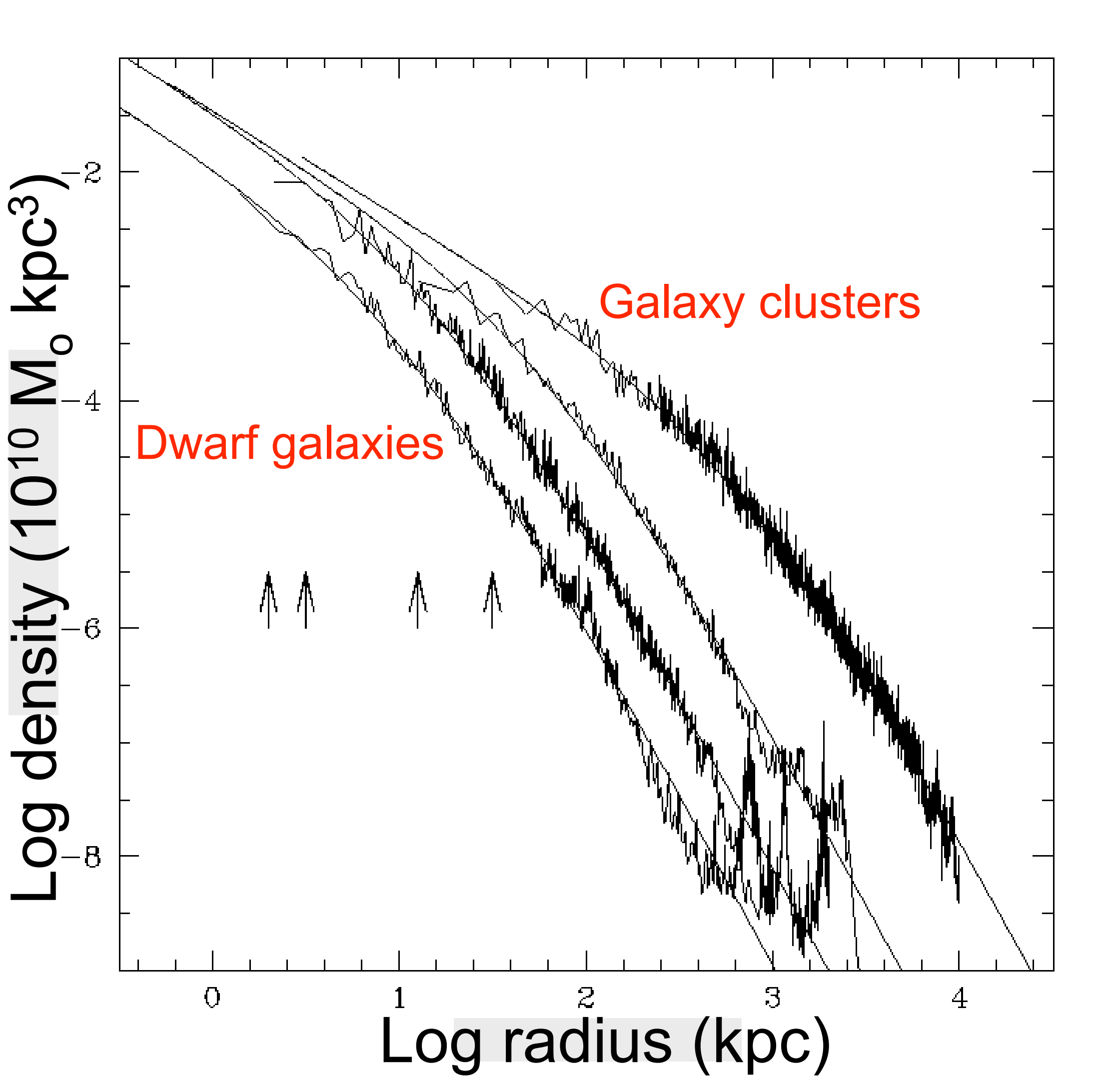


Sanchez et al 06

Is ΛCDM consistent with the data on small scales?


31.25 Mpc/h
z = 0.0

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 d)

ΛCDM halos (without the galaxies)

- Halos extend to ~10 times the 'visible' radius of galaxies and contain ~10 times the mass in the visible regions
- Halos are not spherical but approximate triaxial ellipsoids

more prolate than oblate
axial ratios greater than 2 are common
"Cuspy" density profiles with outwardly increasing slopes
d ln r / d ln r = g with g < -2.5 at large r g
g > -1.2 at small r
Substantial numbers of self-bound subhalos contain ~10% of the halo's mass

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A cold dark matter universe

N-body simulations show that cold dark matter halos (from galaxies to clusters) have:

- "Cuspy" density profiles
- Large number of self-bound substructures (10% of mass)

This has led to two well-publicized "problems":

- The "halo core" problem
- The "satellite" problem

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Explanations for the core/satellite "crises"

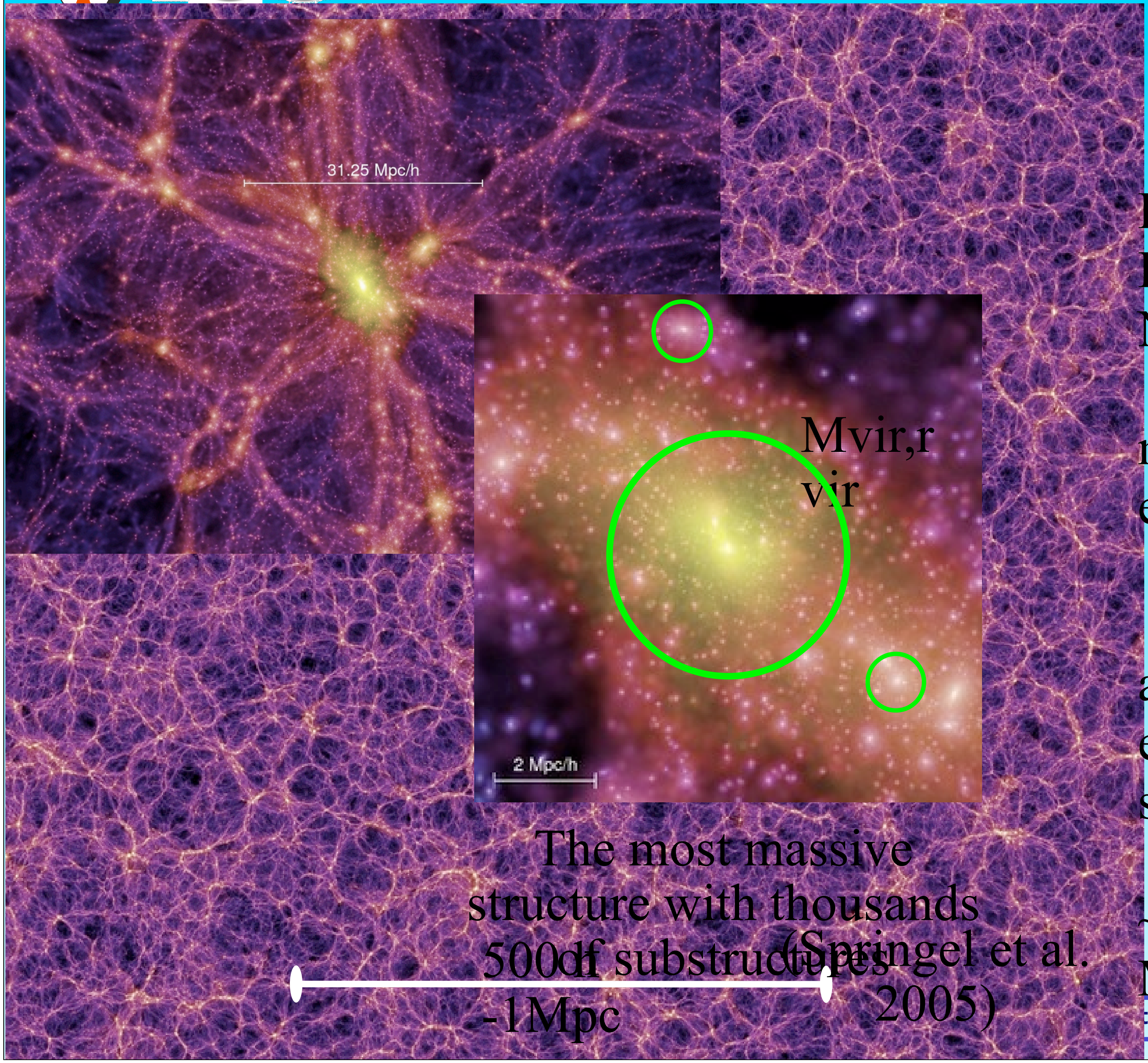
- The dark matter is warm
- The dark matter has a finite self-scattering cross-section
- The primordial density power spectrum has a break (or running spectral index)
- There is no dark matter -- gravity needs modifying
- Astrophysics: baryon effects, black holes, bars
- The comparison of models and data is incorrect

A cold dark matter universe

- The “halo core” problem
- The “satellite” problem
- A blueprint for the detection of CDM

The “cusp problem”

Density profile of dark datter halos



The most massive structure with thousands of substructures (Springel et al. 2005)

Millennium Simulation at z=0

LCDM cosmology
L = 500 Mpc/h
N = 1x1010

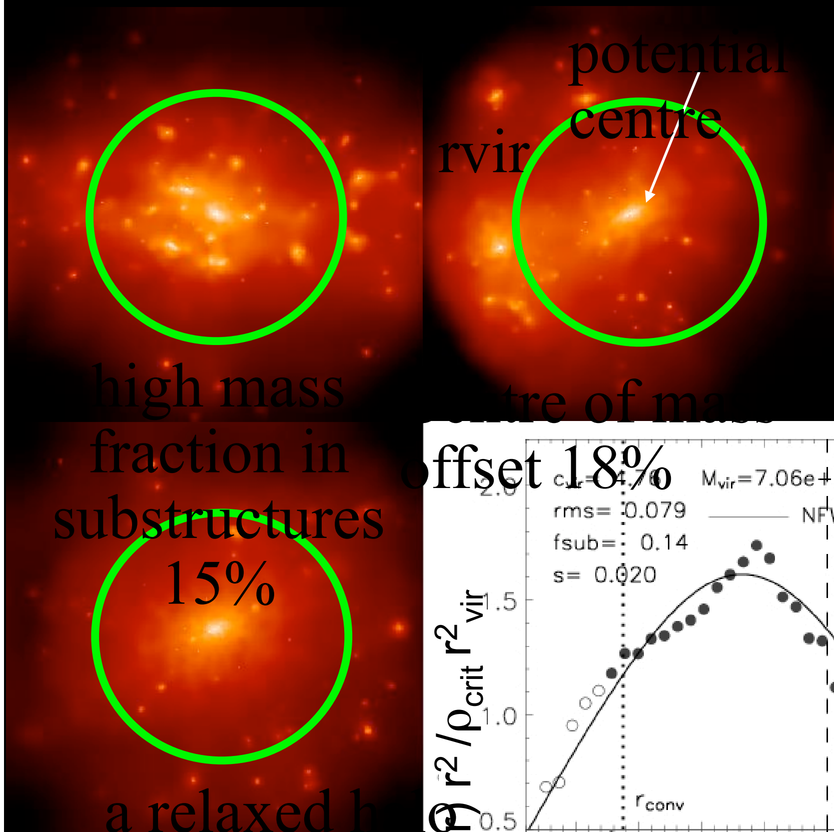
m = 8.6 x 108
e = 5kpc/h

1.7x106 groups and 1.8x107 embedded substructures

~106 halos
M>1011.5 h-1M0

Fausti, Cole, Navarro, Frenk, White, Springel '07

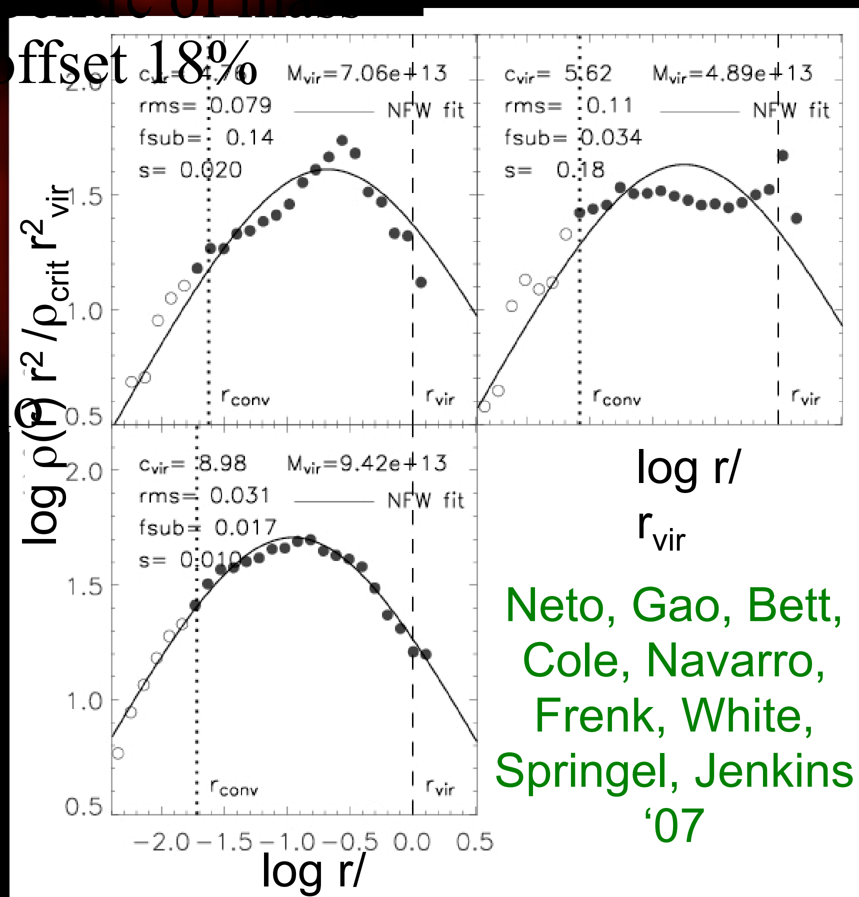
Density profile of dark matter halos



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

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

concentration



Neto, Gao, Bett, Cole, Navarro, Frenk, White, Springel, Jenkins '07

- Fitting unrelaxed halos results in low concentrations;

Unrelaxed halos have unstable density profiles;

…and for fixed mass, expect large scatter in c

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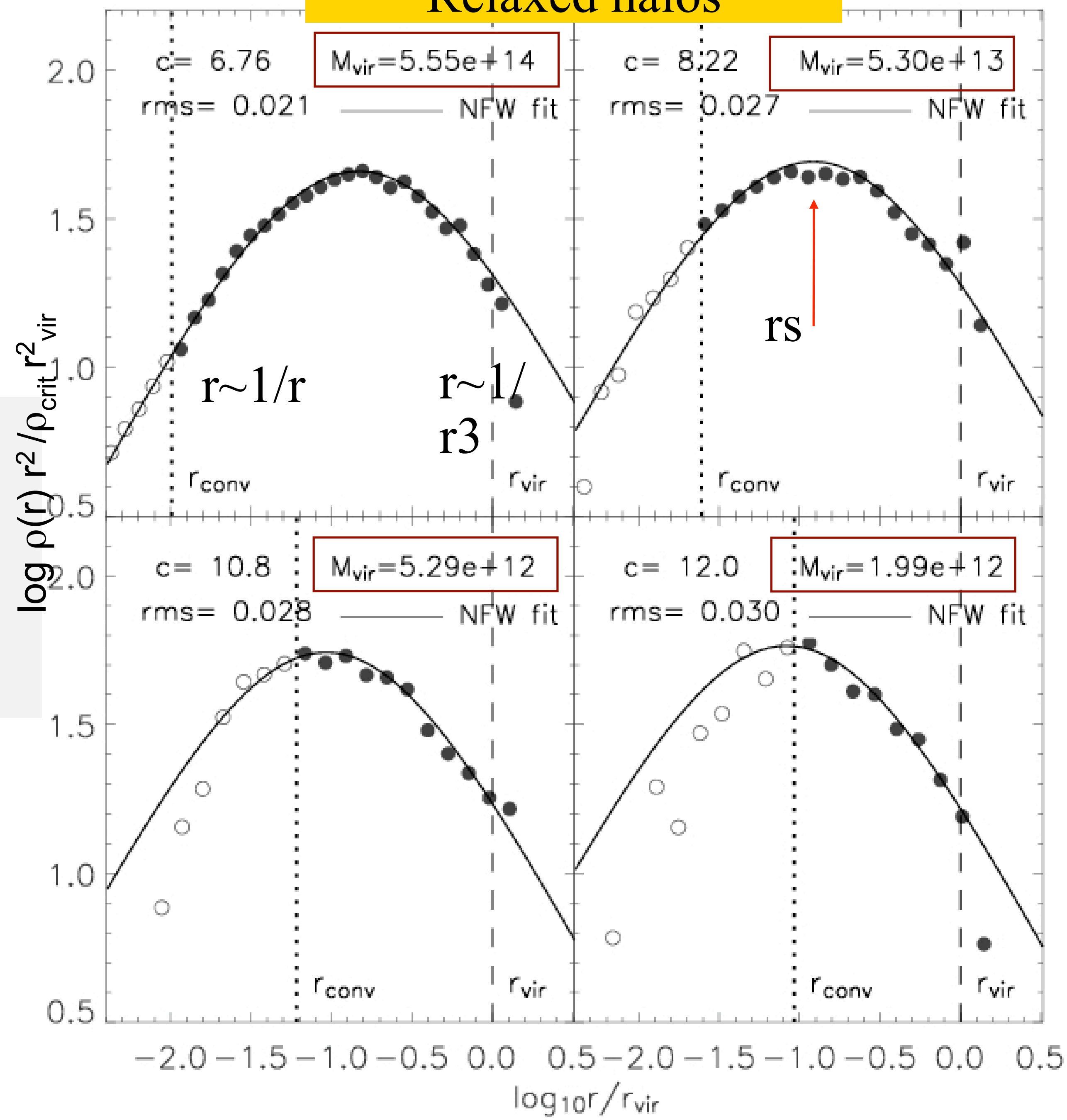
Relaxed halos

NFW profile provides a good fit to the density profile for halos of all masses



Neto, Gao, Bett, Cole, Navarro, Frenk, White, Springel, Jenkins ‘07

Deviations from NFW profile

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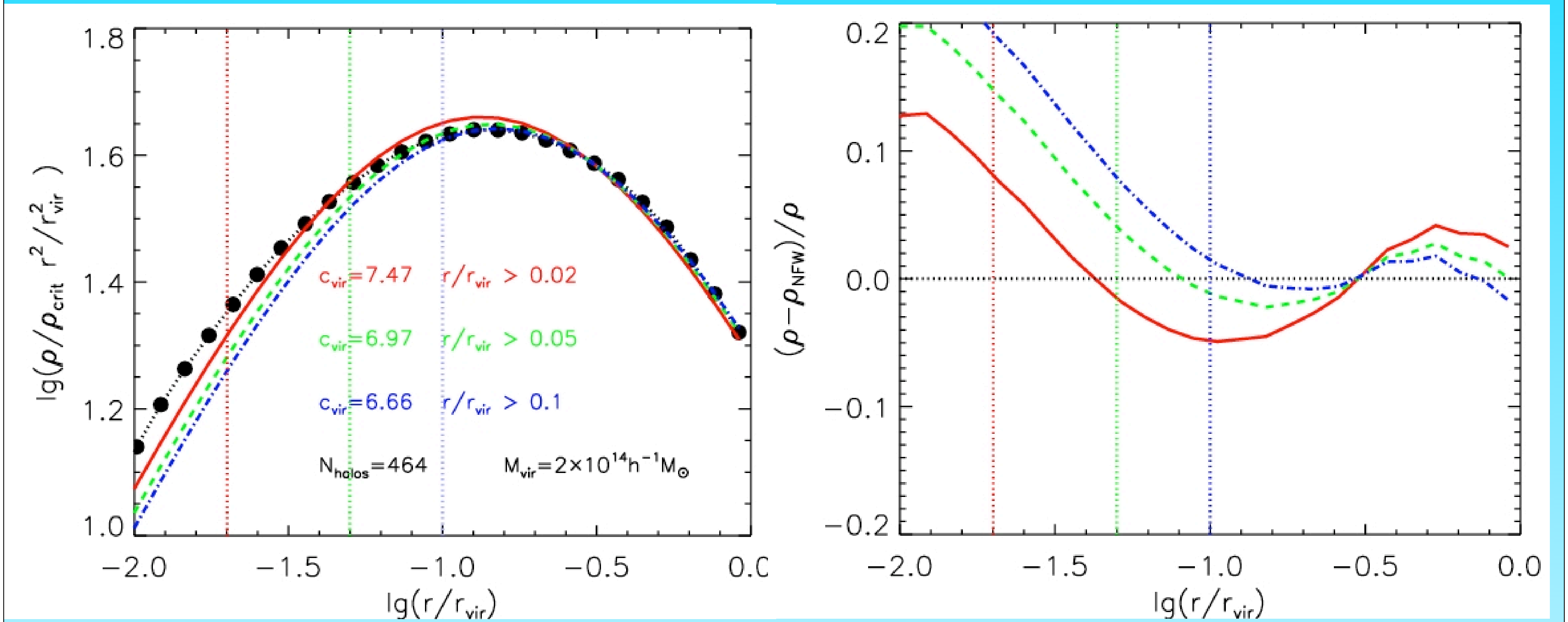
Stacked halos ($M \sim 2 \times 10^{14} h^{-1} M_o$) in Millennium



NFW gives good fits, with deviations of ≲ 10%

Gao, Navarro, Cole, Frenk, White, Springel, Jenkins, Neto ‘08

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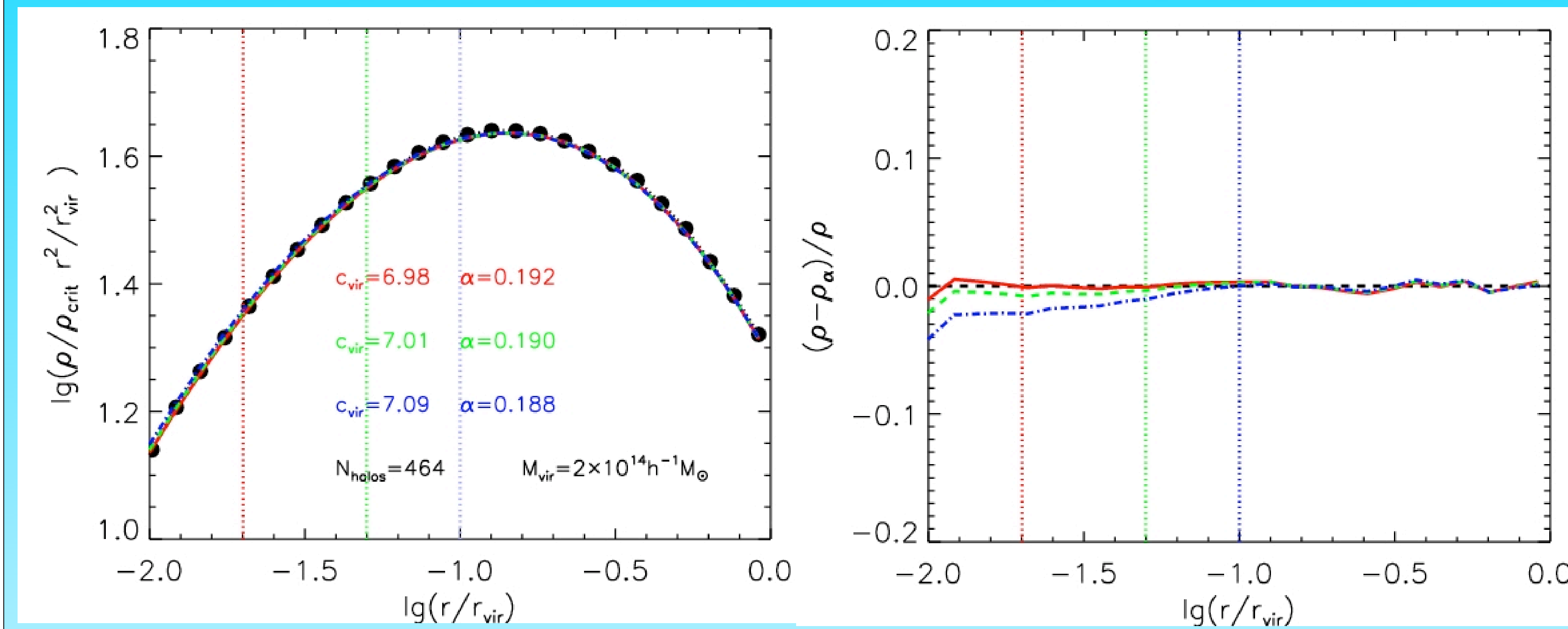
Deviations from NFW profile

Stacked halos ($M \sim 2 \times 10^{14} h^{-1} M_o$) in Millennium



Einasto profile (Navarro et al '04) [1 extra parameter]

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

Gao et al '08

Institute for Computational Cosmology

The very central cusp

The Aquarius programme

University of Durham

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	# of substructures	mass resolution
4003	5.546.052	1.412	2.49 x 105 M0/h
8003	44.049.741	9.490	1.67 x 105 M0/h
12003	157.239.052	30.178	1.00 x 104 M0/h
24003	1.258.000.000	~450.000	1.25 x 103 M0/h (15 pc/h softening)
NFW '96	10,000		1x 10^8 M_0/h
"Via Lactea I simulation"	~84.700.000	~10.000	1.53 x 104 M⊙/h

Diemand, Kuhlen & Madau (2007)

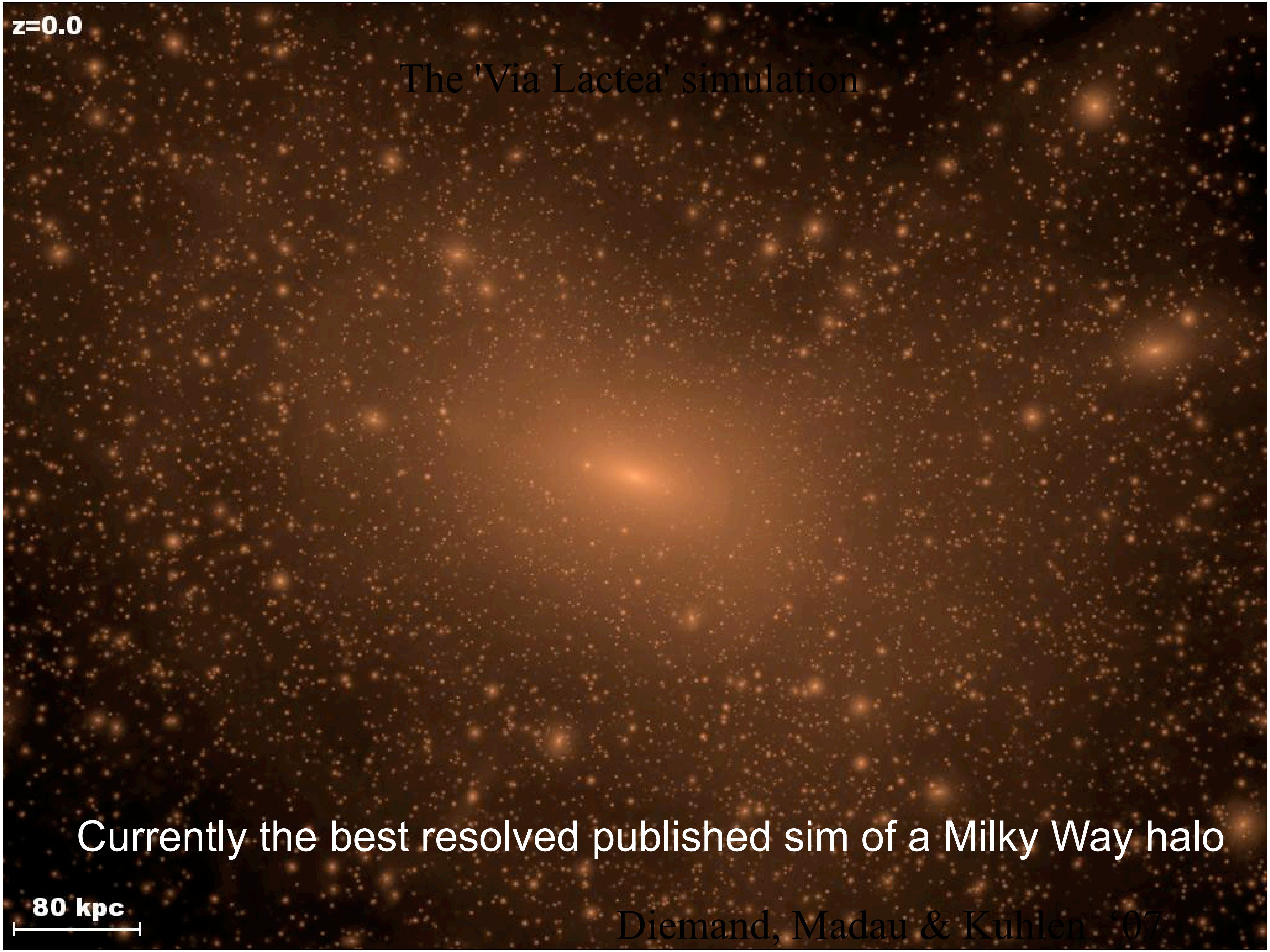
University of Durham

Aquarius - the movie

Institute for Computational Cosmology

z = 0.1
24003
run
A galactic dark matter halo
1.25 billion particles inside r_{vir}
Springel, Jenkins, Volgensberger, Wang,
Helmi, Navarro, Frenk & White '08

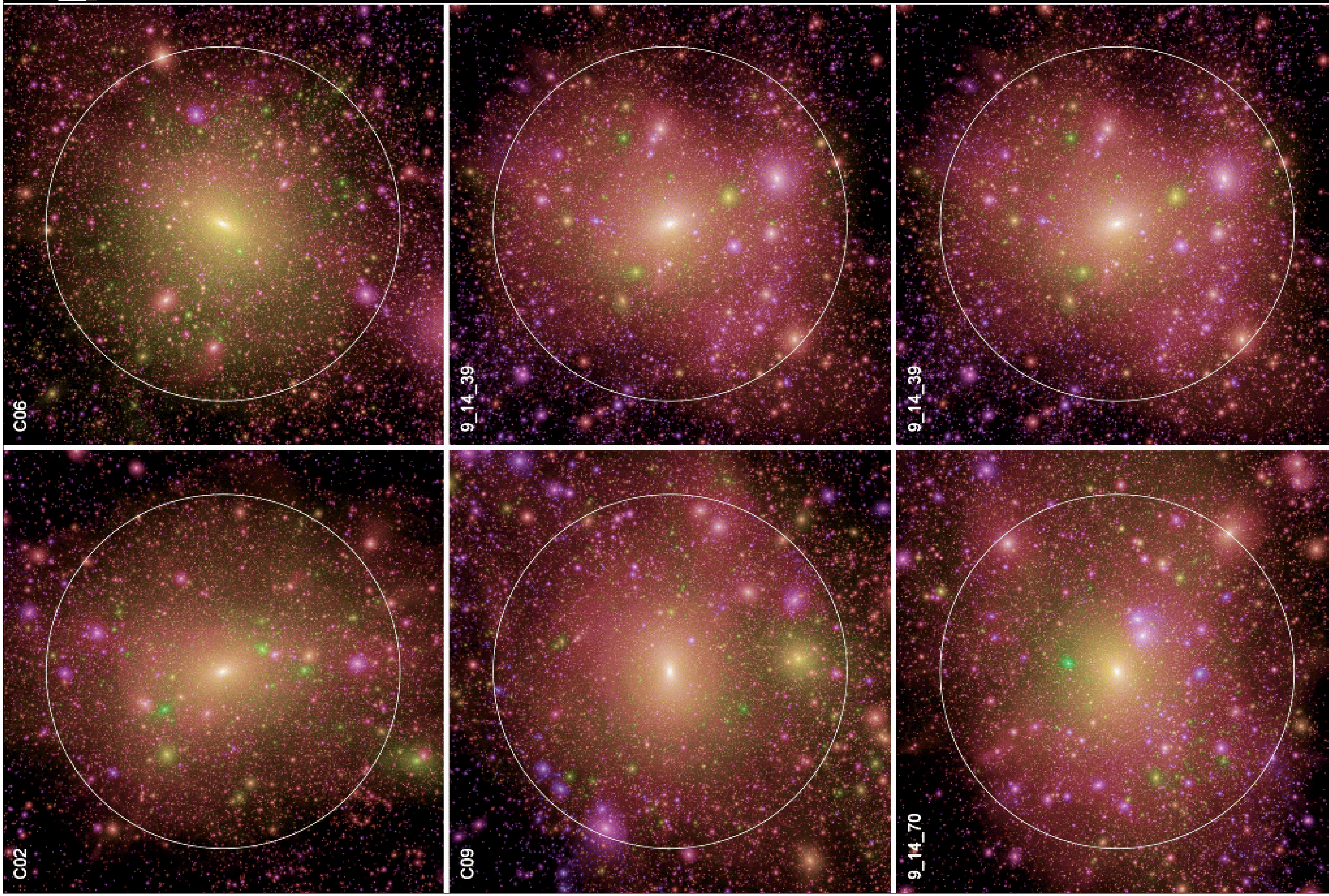
The 'Via Lactea' simulation



Currently the best resolved published sim of a Milky Way halo

Diemand, Madau & Kuhlen '07

Images of all Aquarius halos (1200^3)



Density profile ρ(r)

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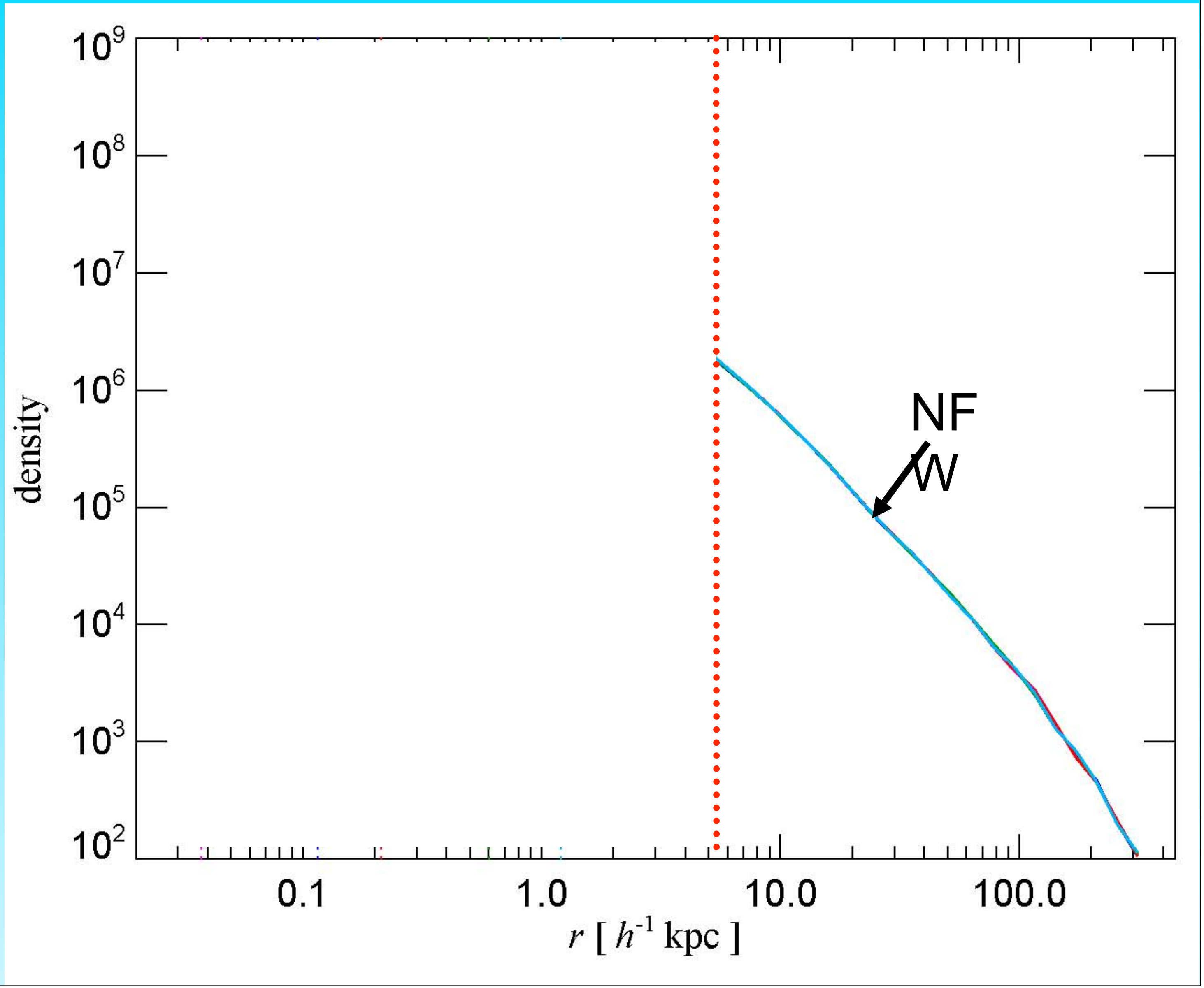
Orignal NFW simulations resolved down to 5% of rvir



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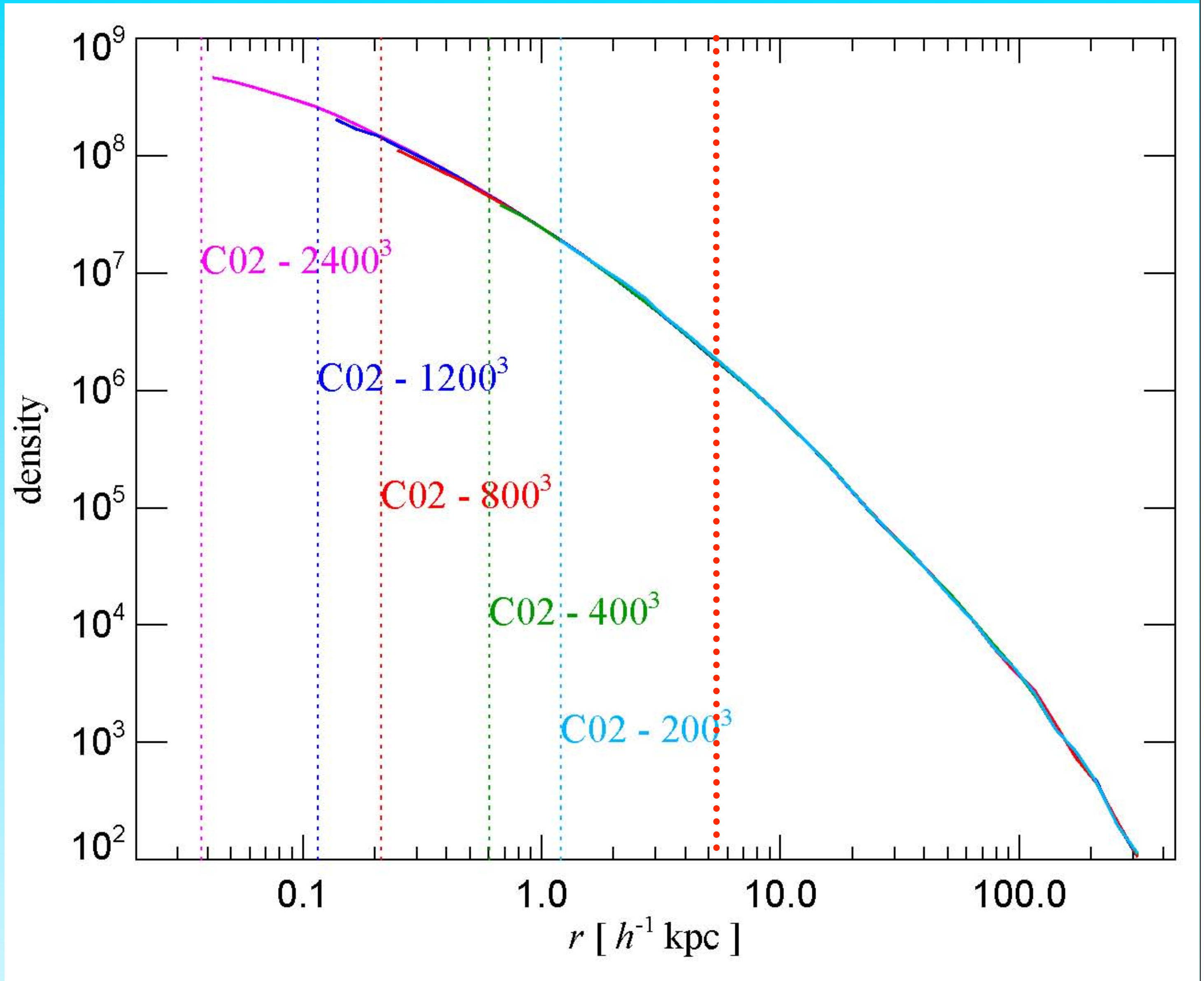
Density profile ρ(r)



Density profile ρ(r): convergence test

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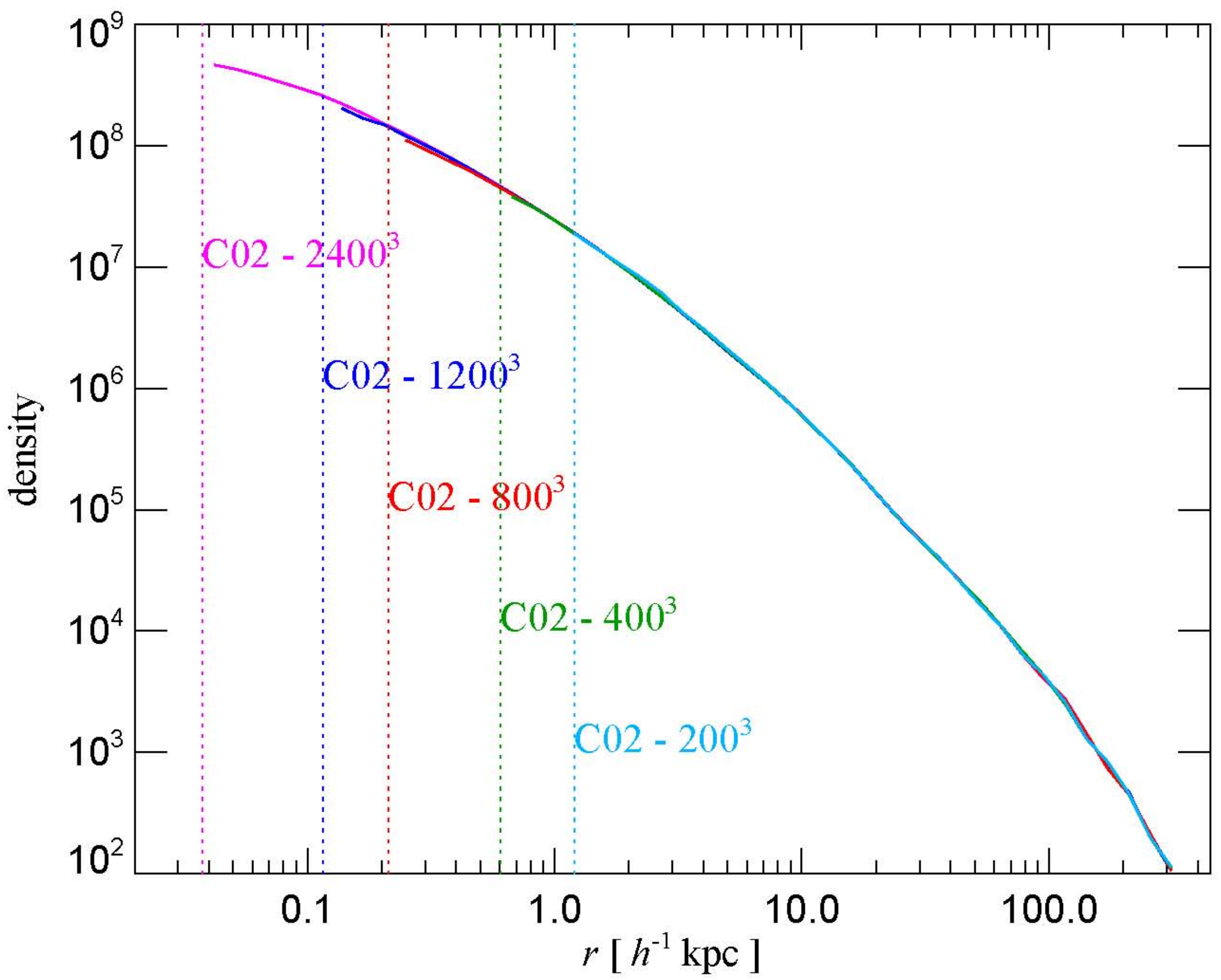
The spherically averaged density profiles show very good convergence, and are approximately fit by a NFW profile



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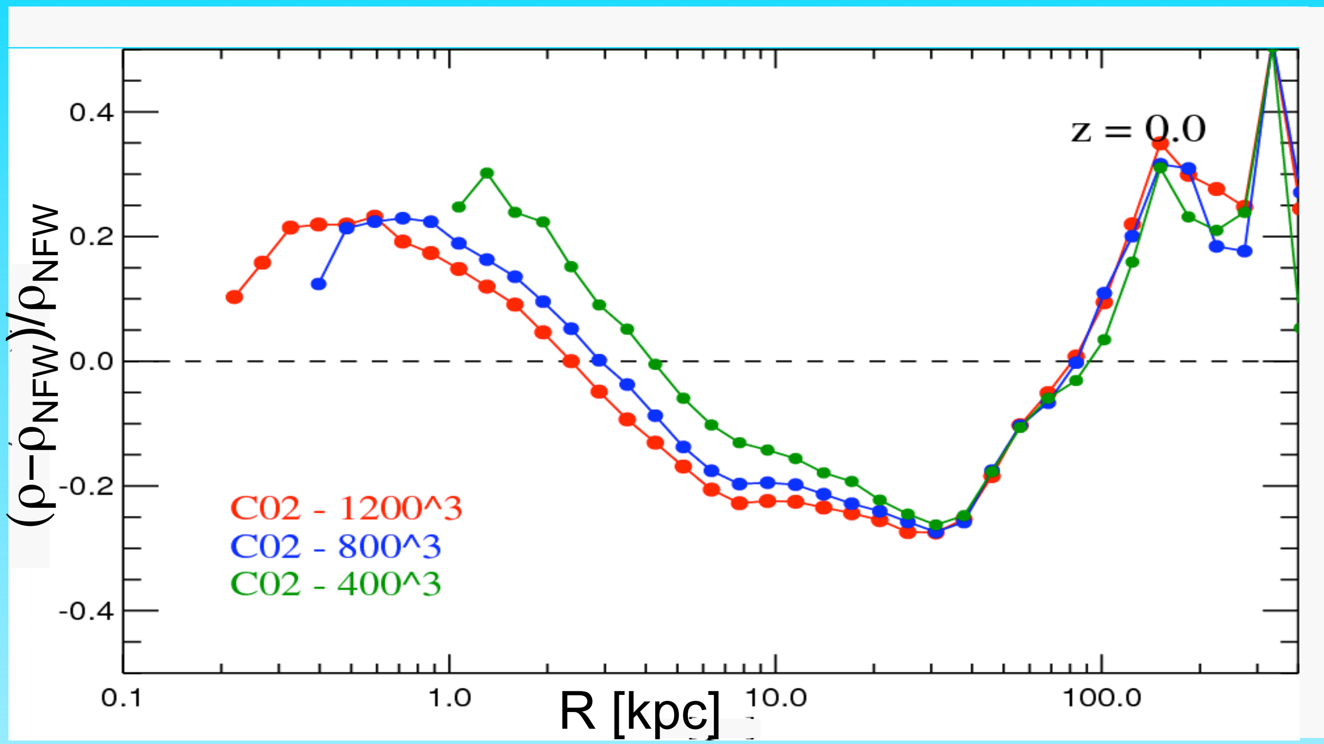
Deviations from NFW

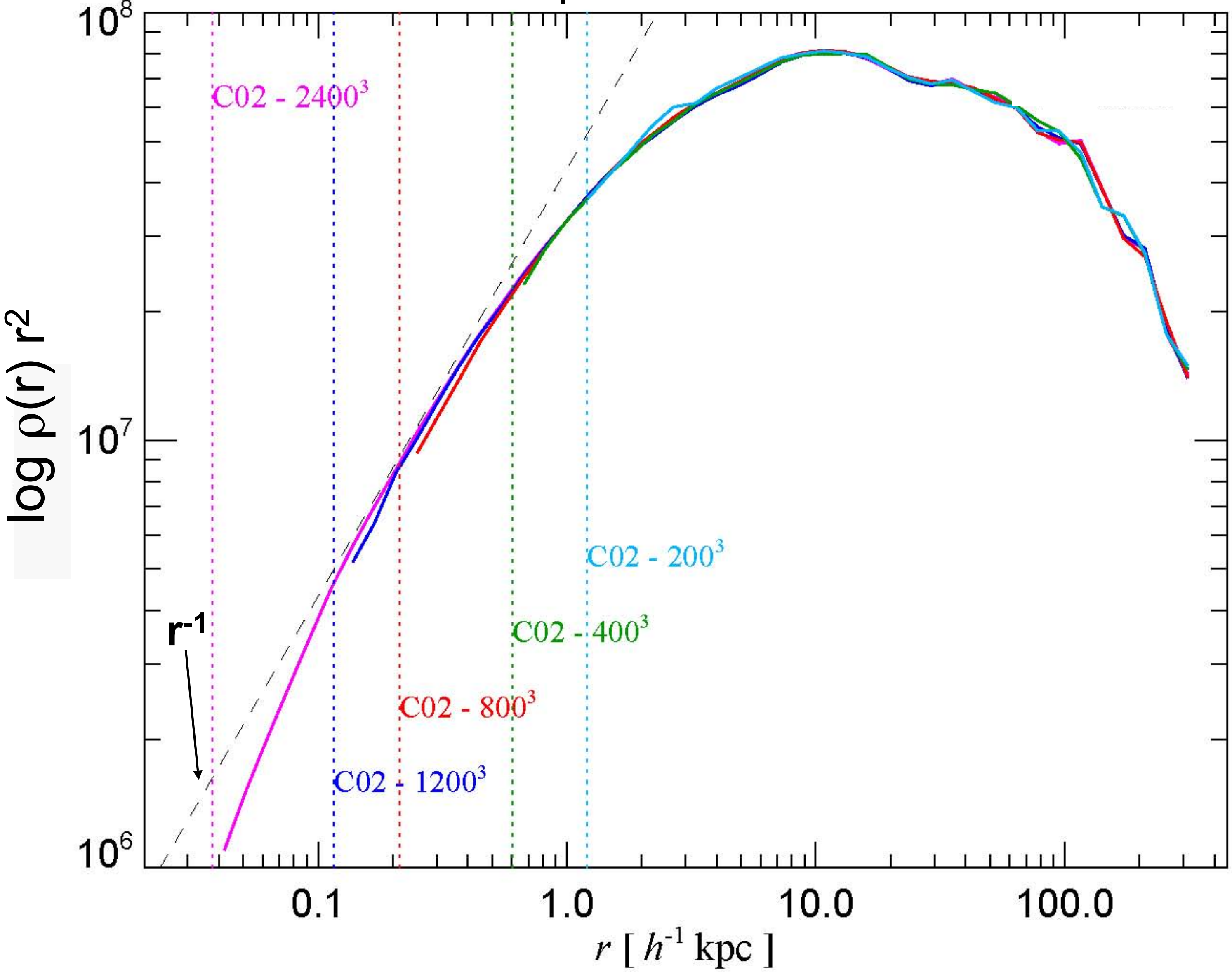


The density profile is fit by the NFW form to ~10-20%. In detail, the shape of the profile is slightly different.

Density profile ρ(r)

University of

Inner Cusp is shallower than r^{-1}



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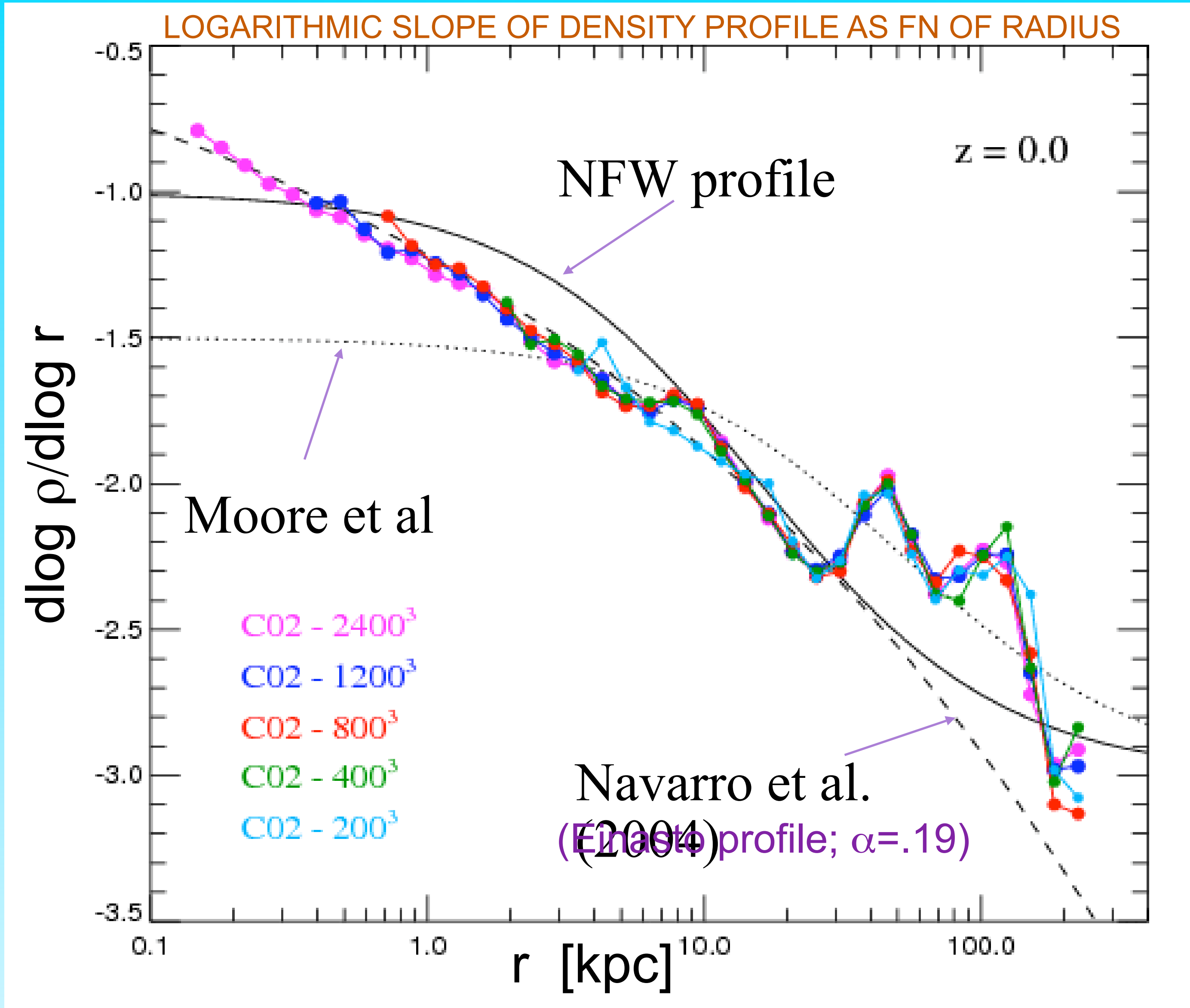
Slope of the density profile

Density profile becomes shallower towards the centre

No obvious convergence to a power law profile
Innermost slope is shallower than -1



A Cold dark matter universe

University of Durham

N-body simulations show that cold dark matter halos (from galaxies to clusters) have:

- "Cuspy" density profiles

Does nature have them?

This has led to the well-publicized

- The "halo core" problem

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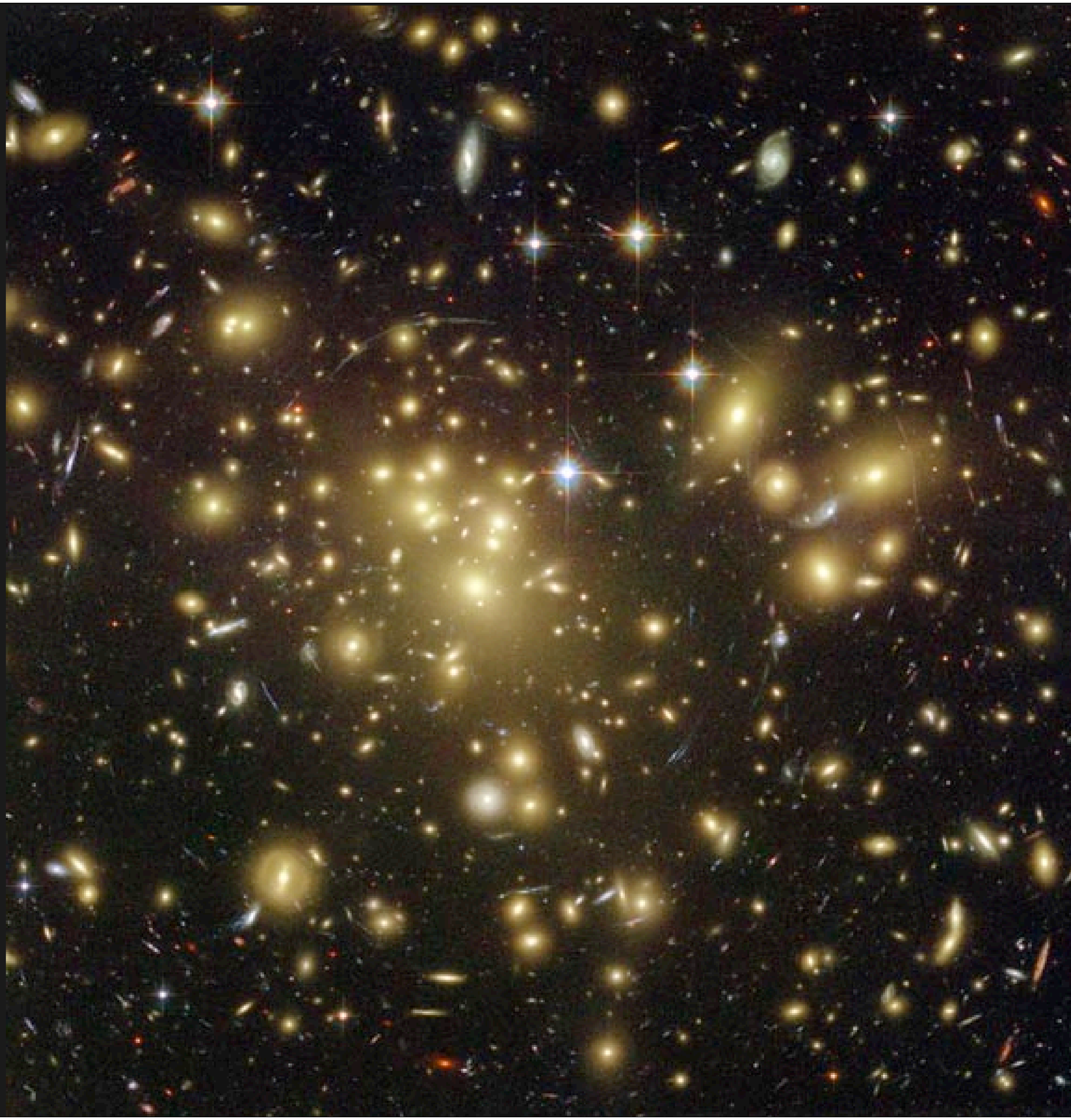
The density profile of galaxy cluster dark halos

Do real dark halos have the profiles found in the simulations?

Profiles can be probed by:

- Gravitational lensing and/or X-ray emission in clusters
- Galaxy rotation curves → messy { Galaxy changes $\rho(r)$; Halos are triaxial }



The central density profile of galaxy cluster dark halos

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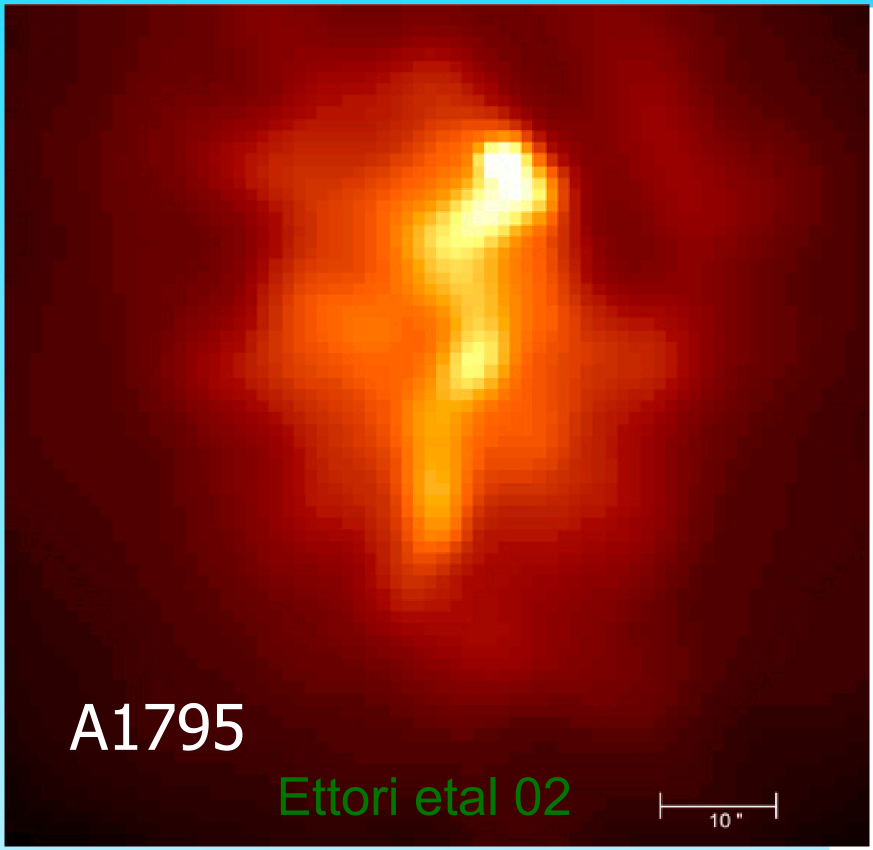
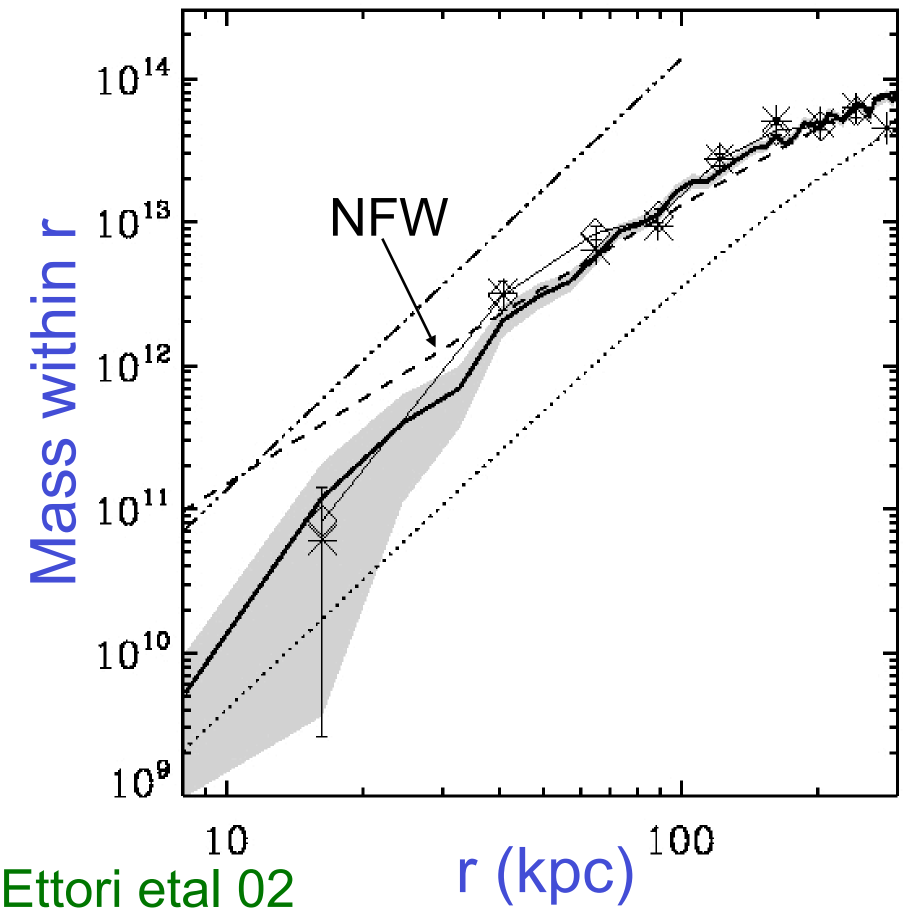
Inner DM density profile inferred from X-ray data (Chandra)



A1795 (z=0.0632)



Ettori etal 02

Profile shallower than NFW (β = 0.59 ±0.15)

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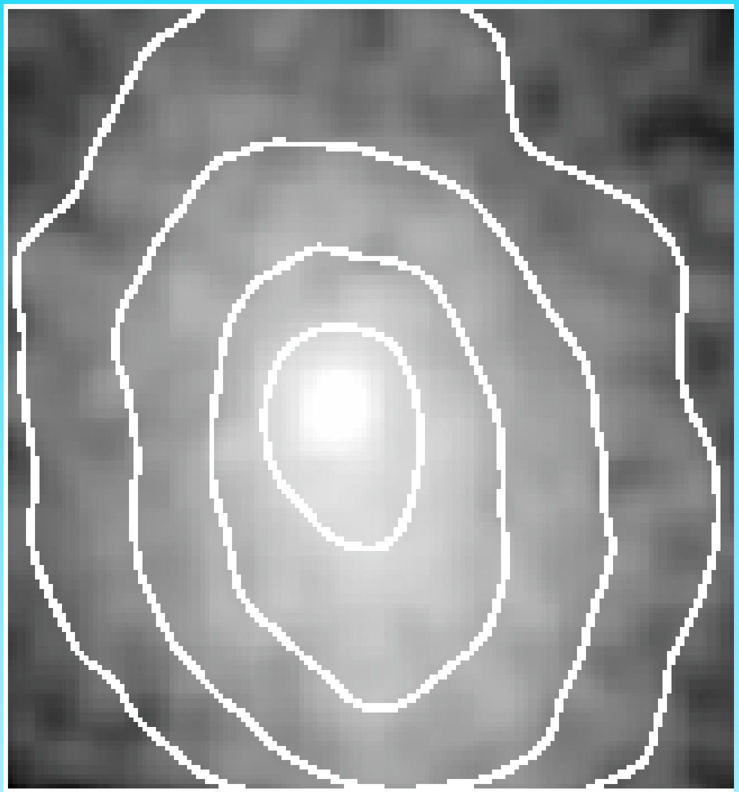
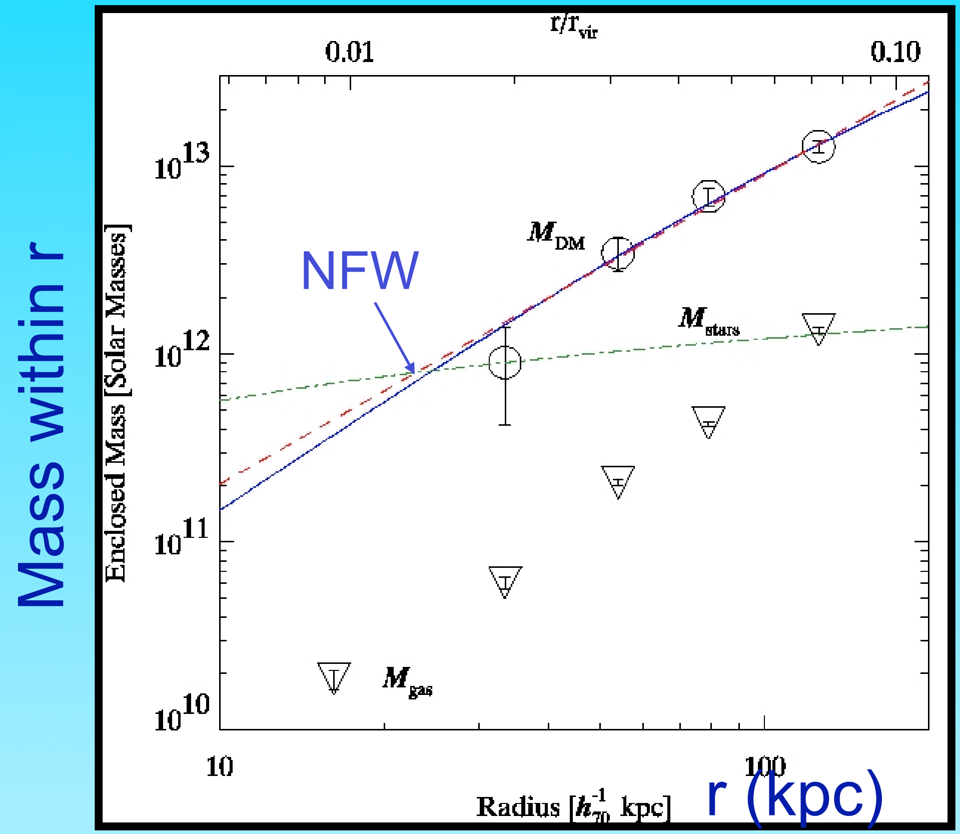
A2589: another relaxed cluster

(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

The central density profile of galaxy cluster dark halos

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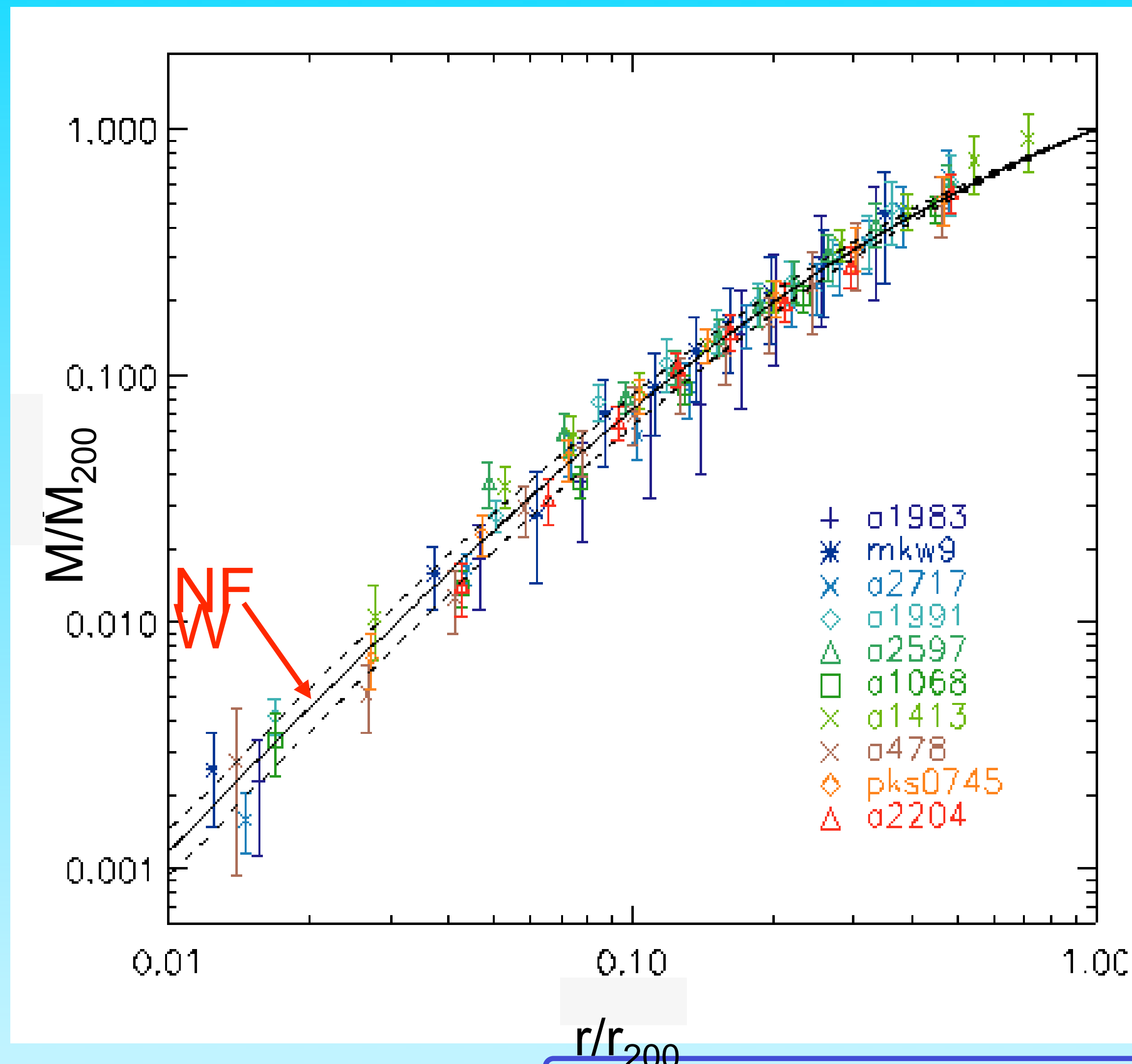
X-ray data

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

Excellent agreement with CDM halo predictions



Pointecouteau et al '05

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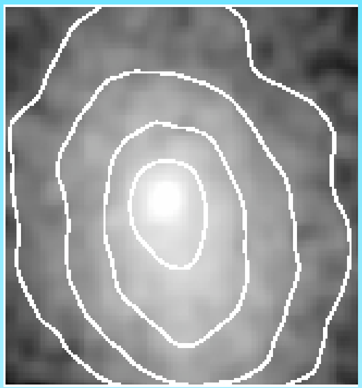
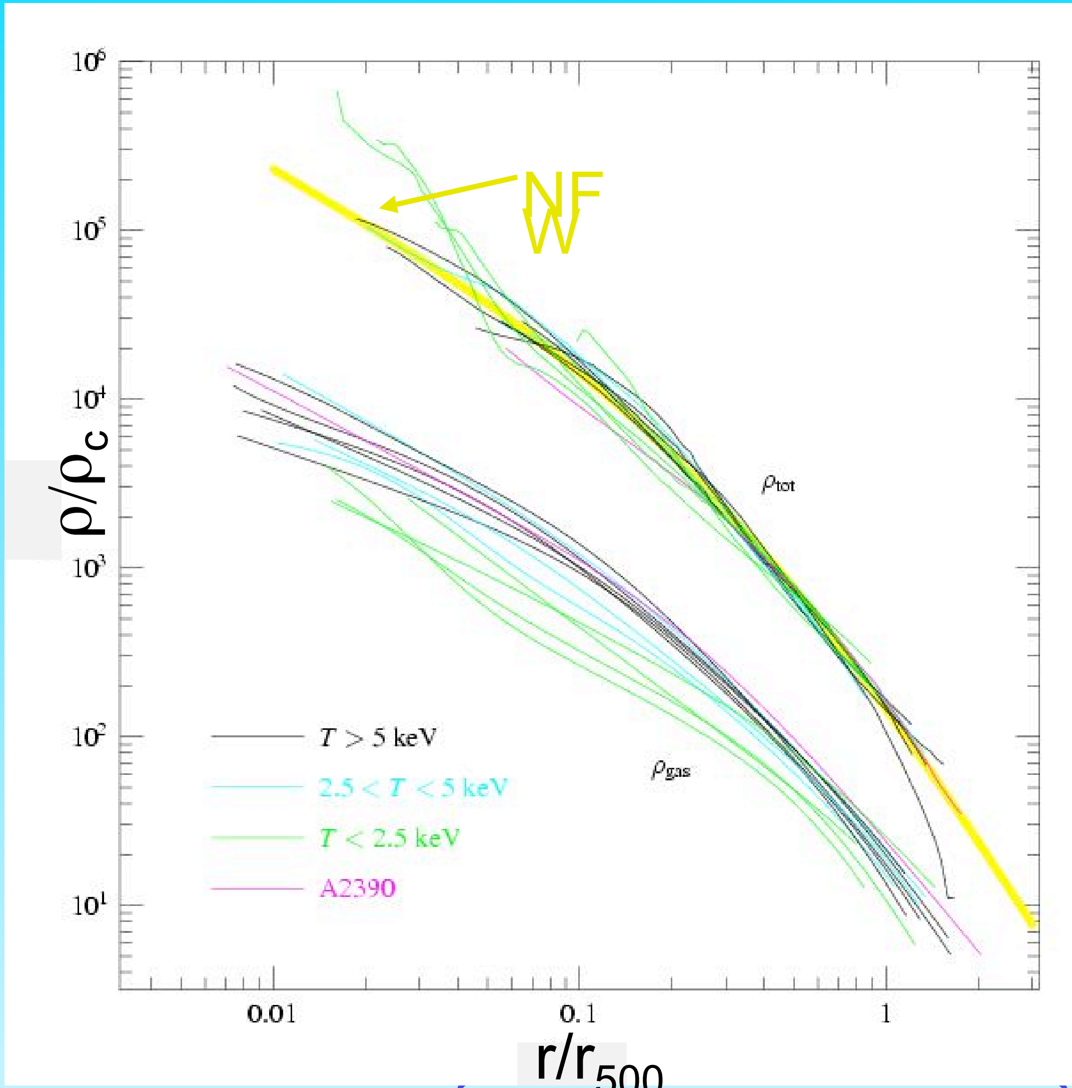
The central density profile of galaxy cluster dark halos

X-ray data

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



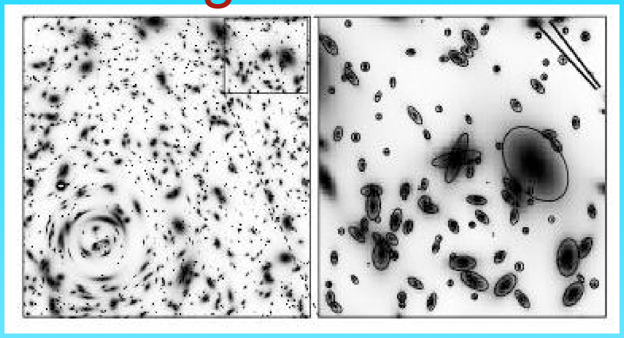
Excellent agreement with CDM halo predictions



Vikhlinin et al '06

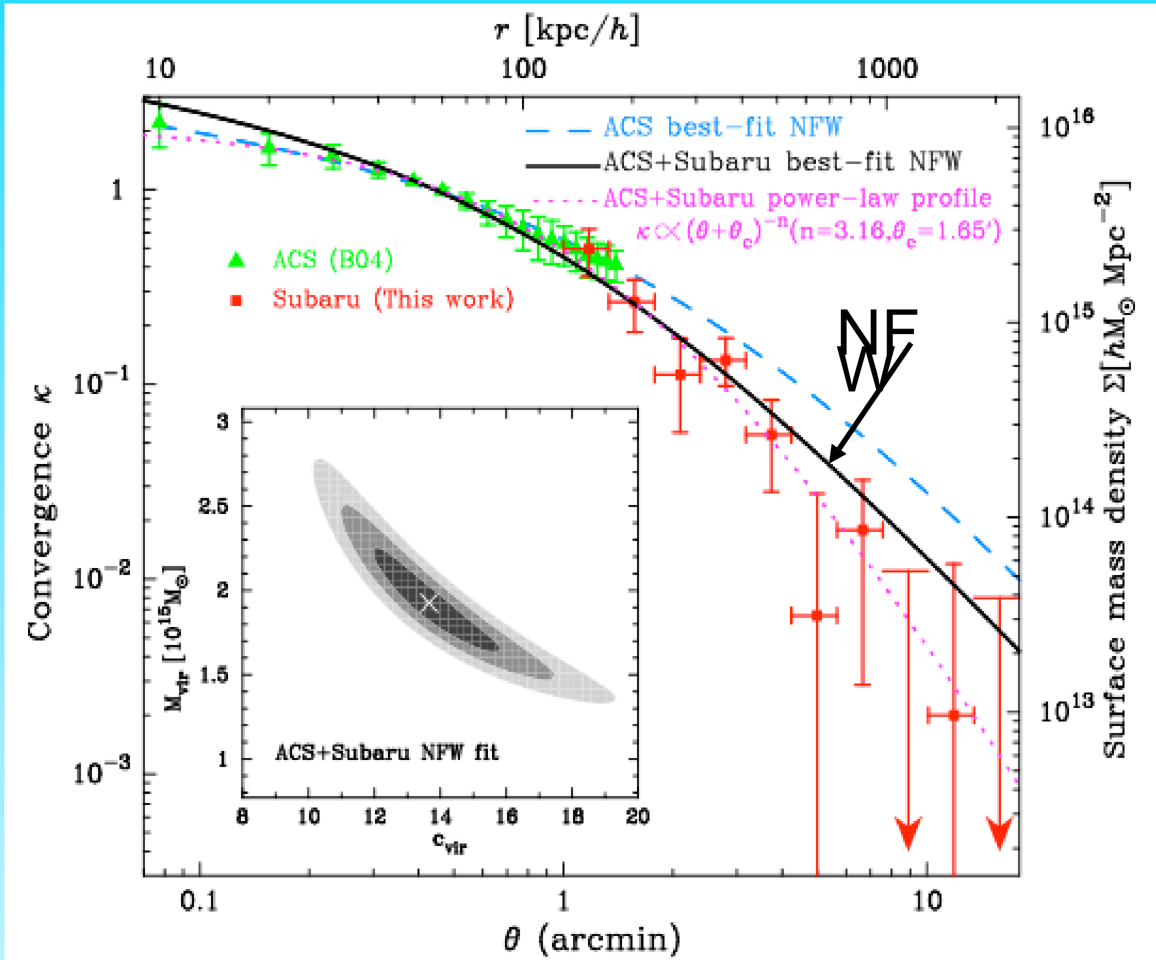
The central density profile of galaxy cluster dark halos

Lensing data



Mass distribution inferred from weak & strong lensing

Excellent agreement with CDM halo predictions



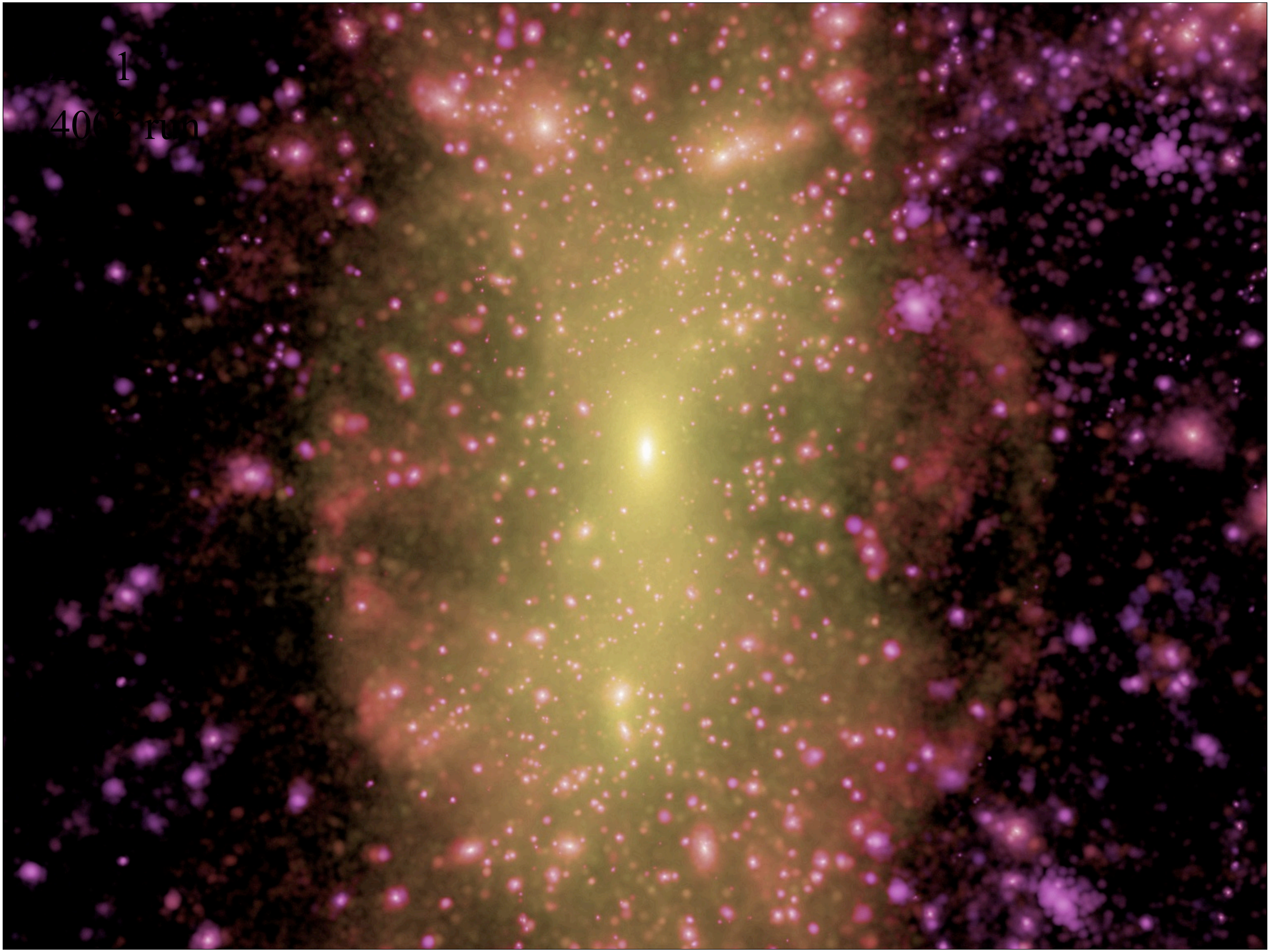
Abell cluster 1689 - Oguri et al 05

The “halo-core problem” ?

The inner profiles of cluster halos seen consistent with the cusps predicted in ΛCDM

The “satellites problem”

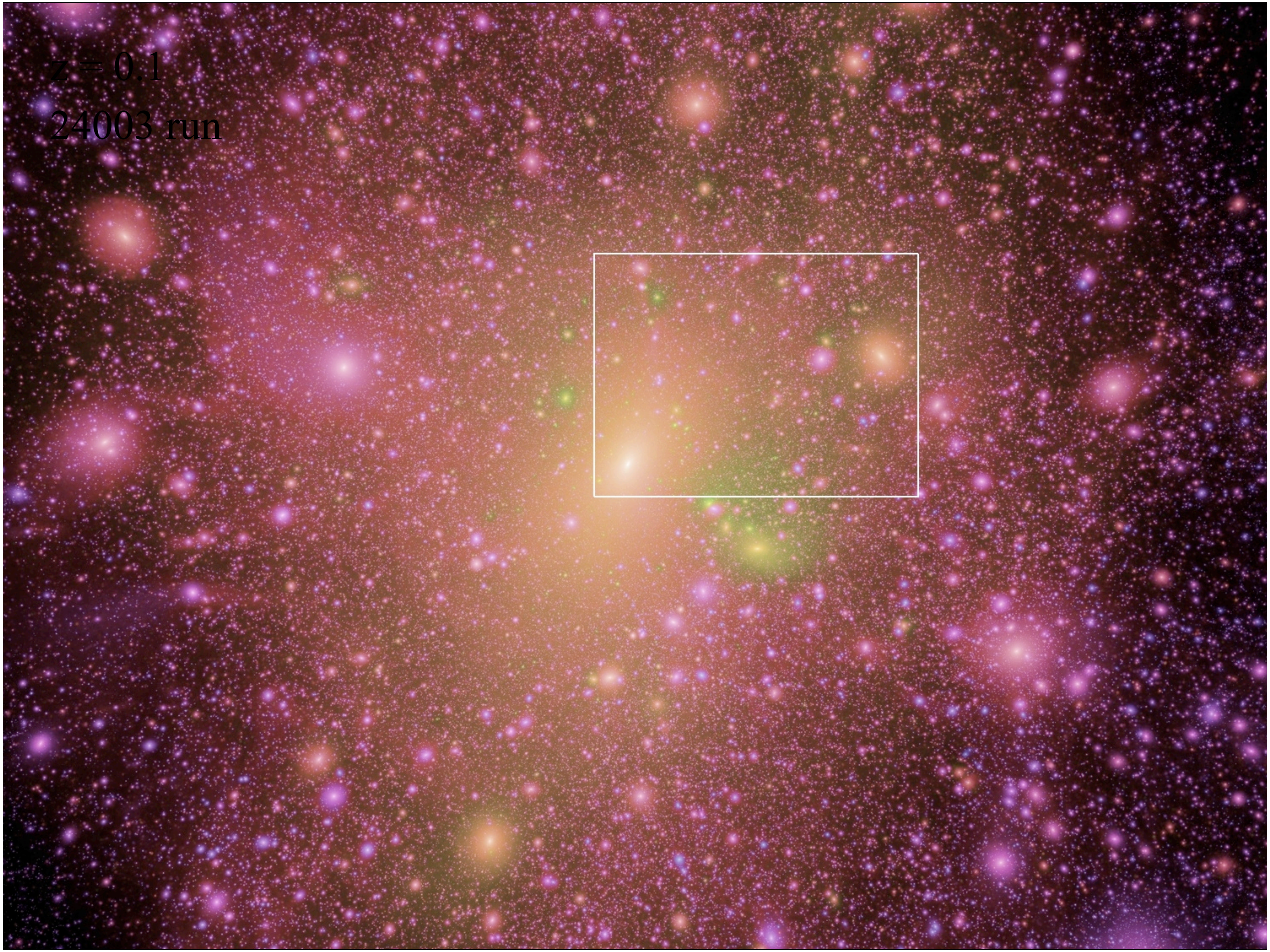

z = 0.1
24003 run




z = 1.
12003 run

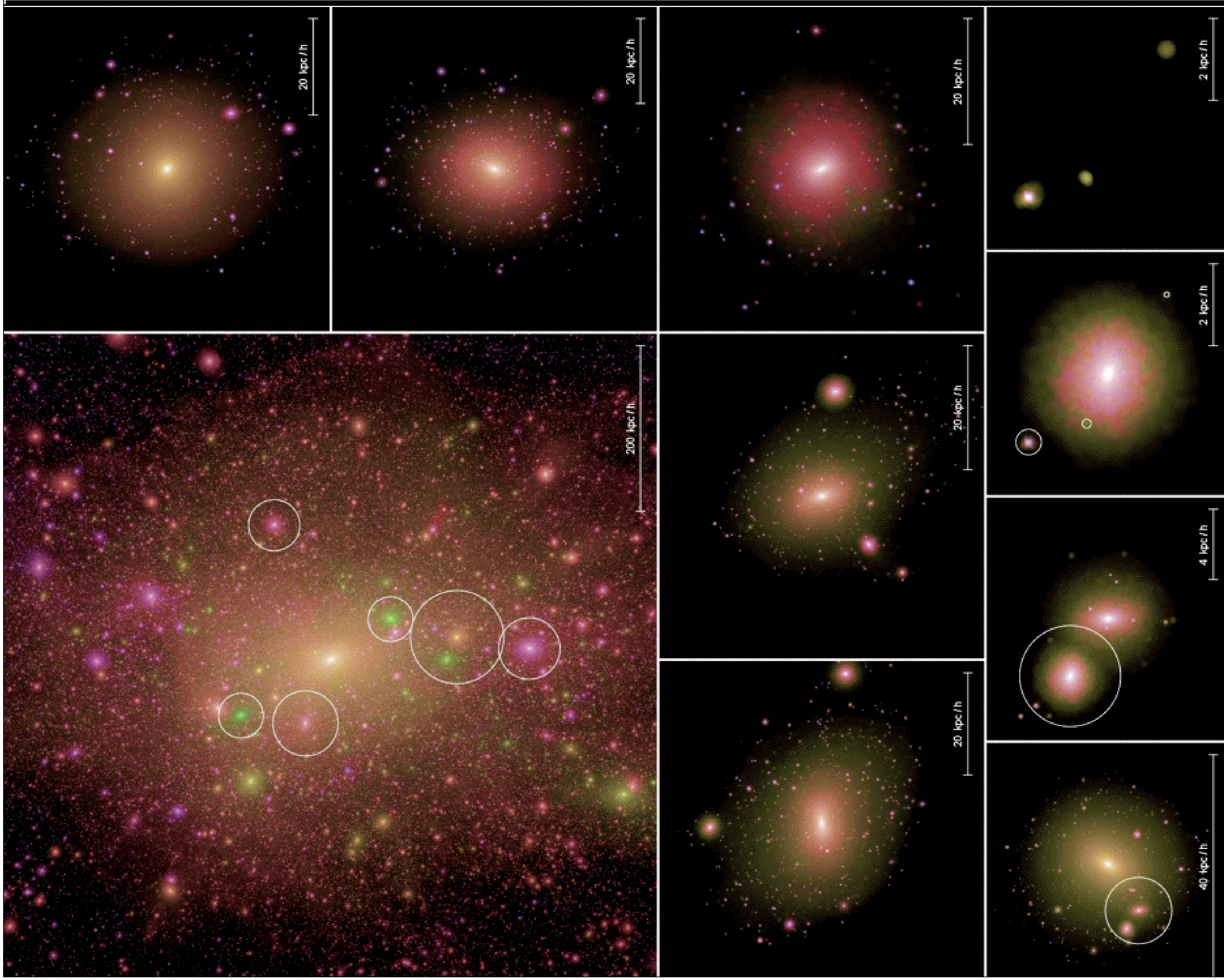

z = 1.5
24003 run


z = 0.1
24003 run


z = 0.1
24003 run


z = 0.1
24003 run

Substructures within substructures



There are substructures embedded within other structures

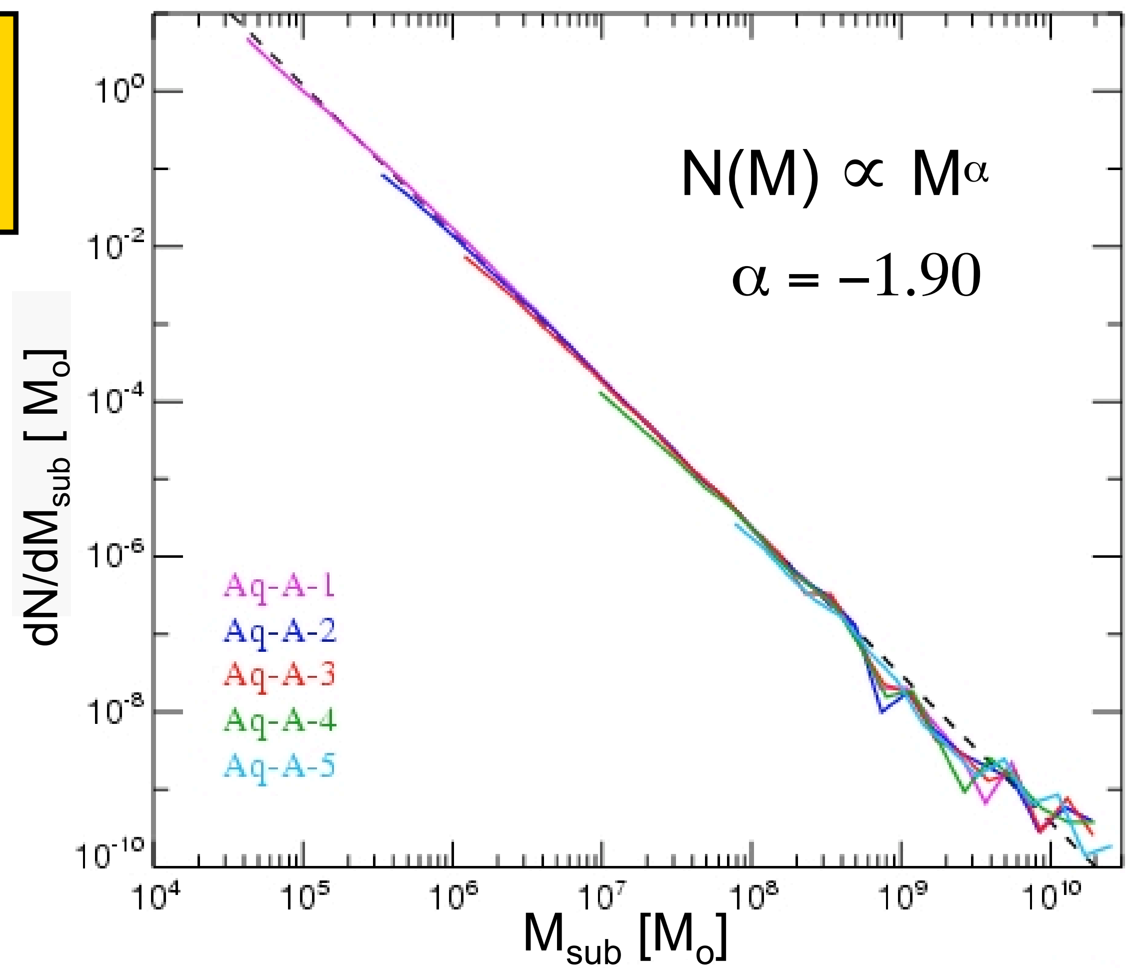
The hierarchy is cleary NOT self-similar and is heavily dependent on the degree of tidal stripping of the subhalo

The mass function of substructures

The subhalo mass function is shallower than M2

- 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 '08



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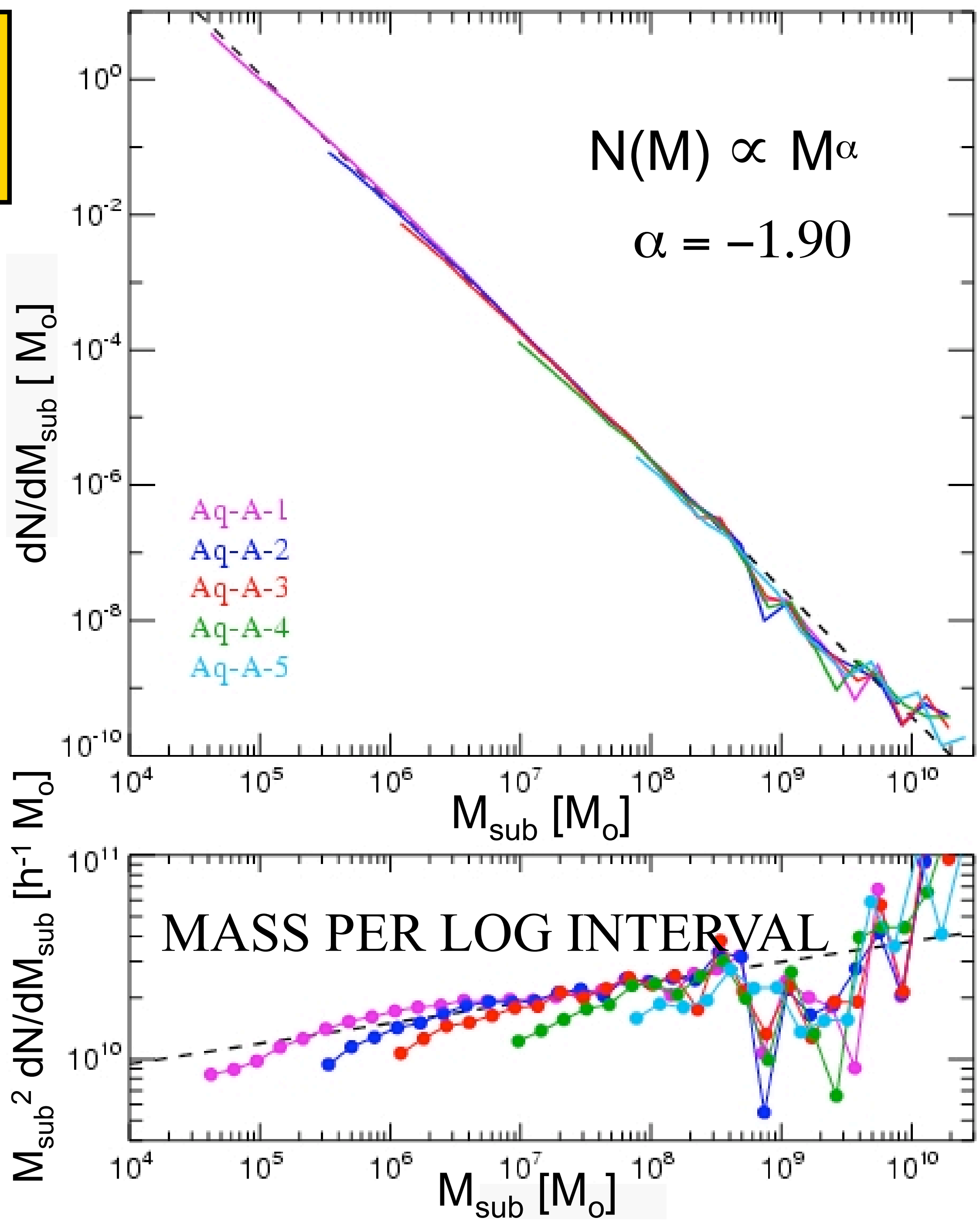


The substructure circ velocity function

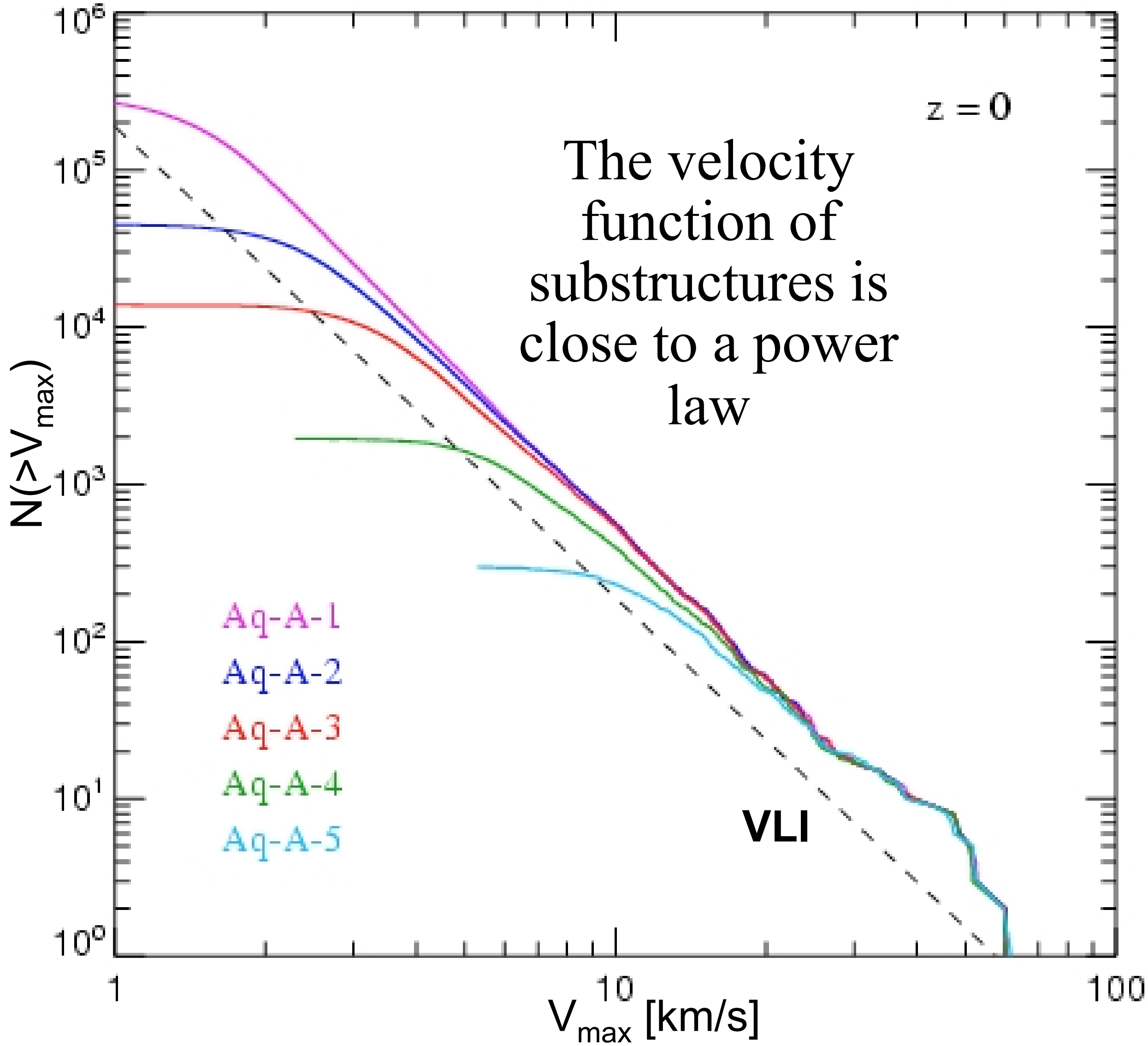
University of Durham

We find *3 times* as many subhalos as Diemand et al find for Via Lactea I

- Cosmic variance? - No
- Substructure finding algorithm? - No
- Different cosmological parameters? - No

Crucial for interpretation of abundance of Milky Way satellites and annihilation signal from substructures

CUMULATIVE NUMBER OF SUBSTRUCTURES AS A FUNCTION OF VMAX,



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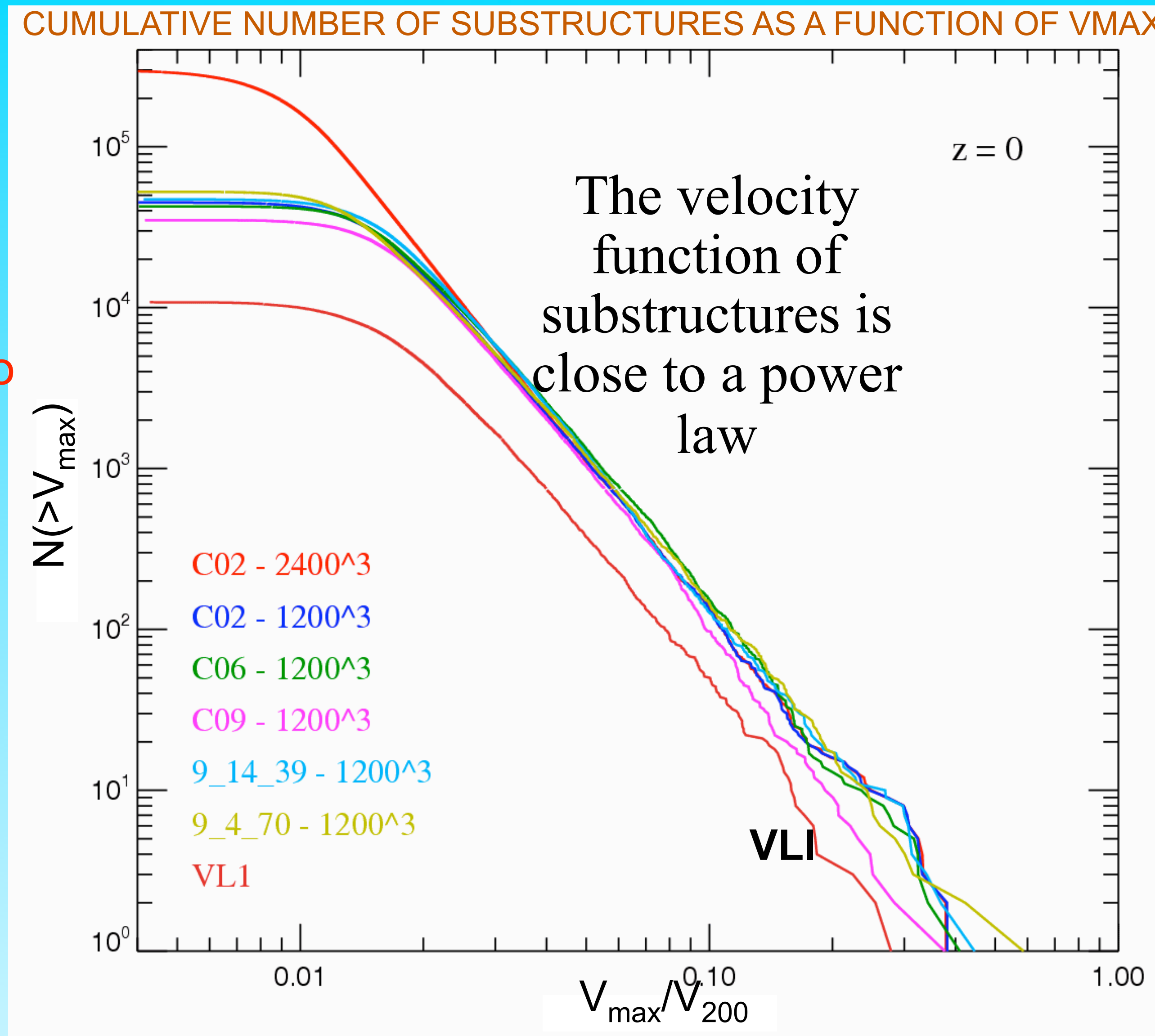
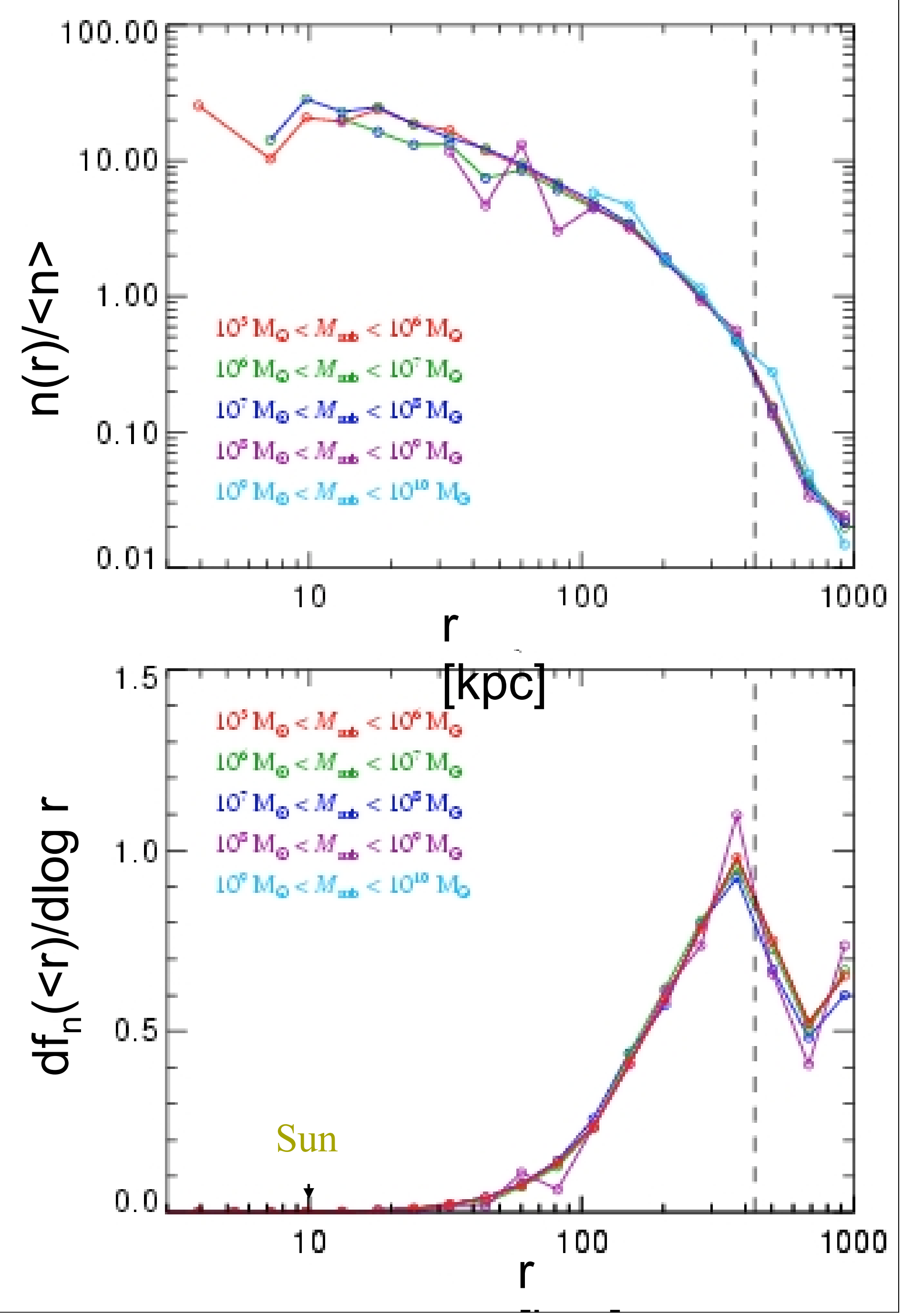


The subhalo number density profile

- 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



ICC
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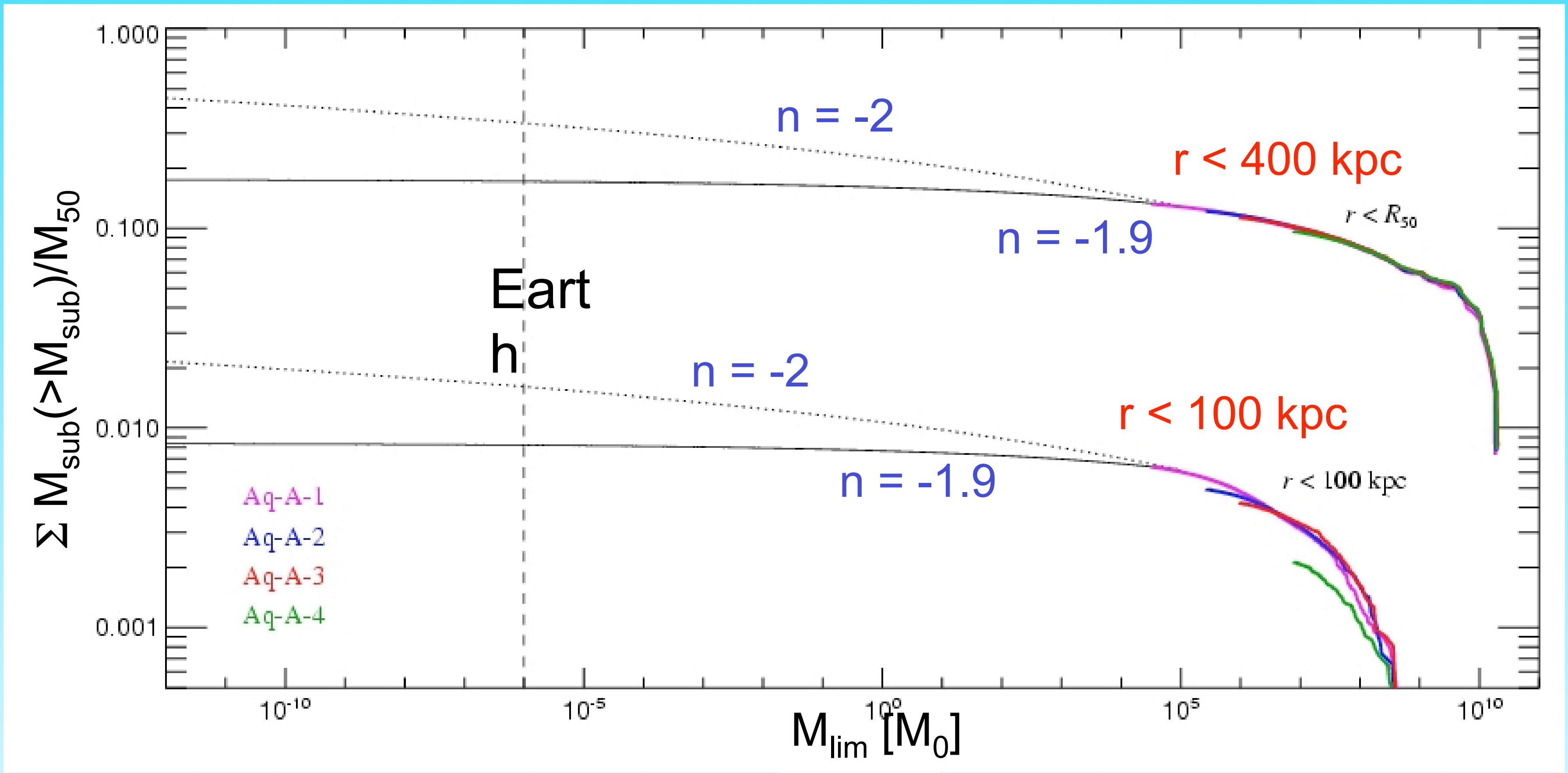
How lumpy is the MW halo?

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

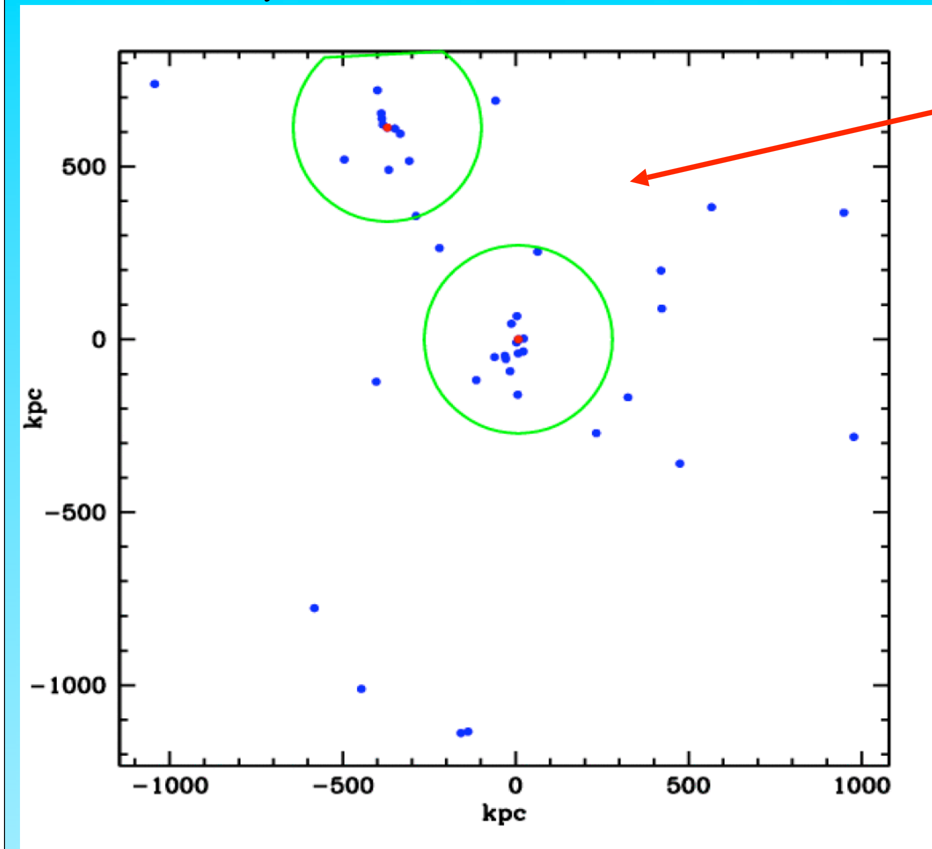
The Milky Way halo is expected to be quite smooth!



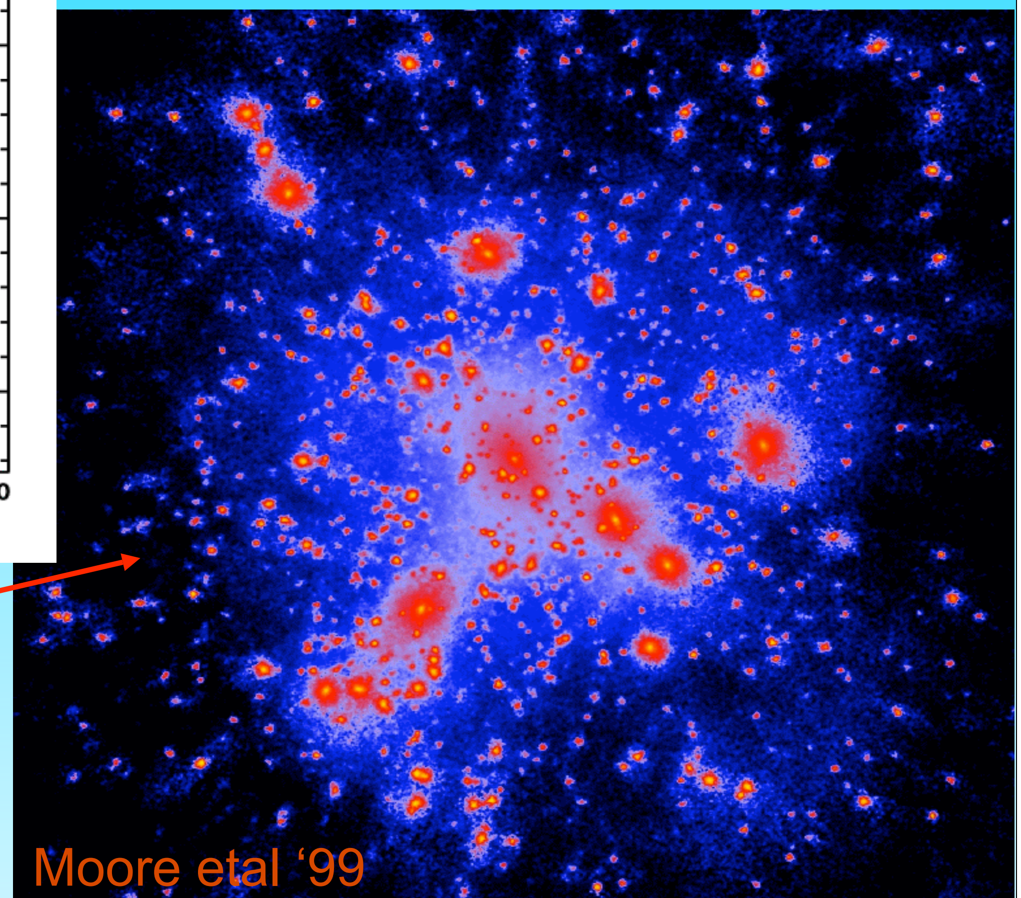
The “satellite problem”

University of Durham

The satellites of the Local Group



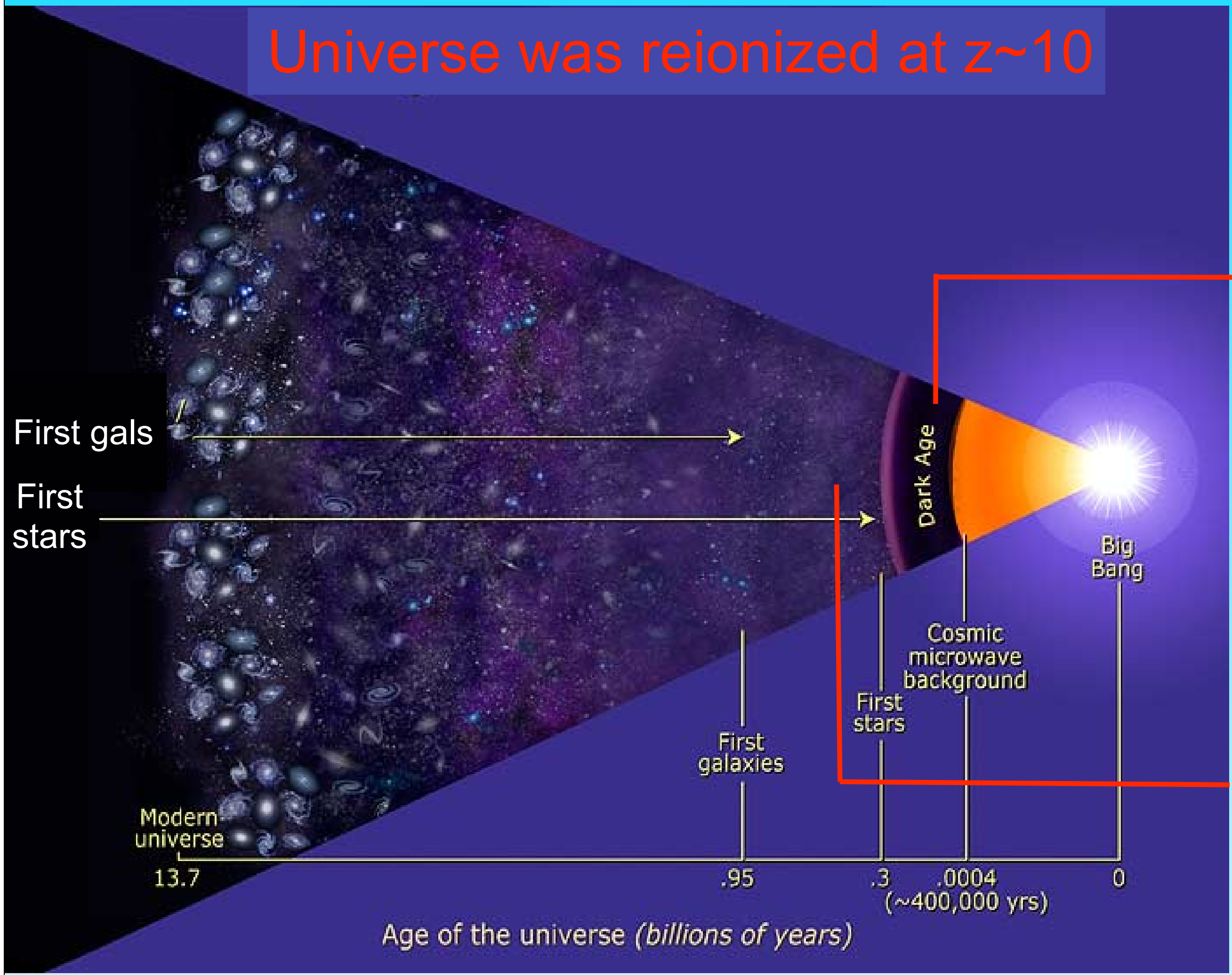
The Local Group contains only about 40 bright satellites



N-body simulations produce 1000s of small subhalos


z = 0.1
24003 run

Feedback in galaxy formation



From STSci picture gallery

Effects of reionization

Gas is neutral → cools in small halos

H is reionized at z~(10-6)

Gas heated ~10^4K → cannot cool in halos with V<40 km/s


z = 0.1
24003 run
Substructure in cold dark matter halos
Only the few small subhalos that formed before reionization can cool gas and make a visible galaxy
Springel, Jenkins, Vogelsbergerer, Wang,Helmi, Navarro, Frenk & White '07

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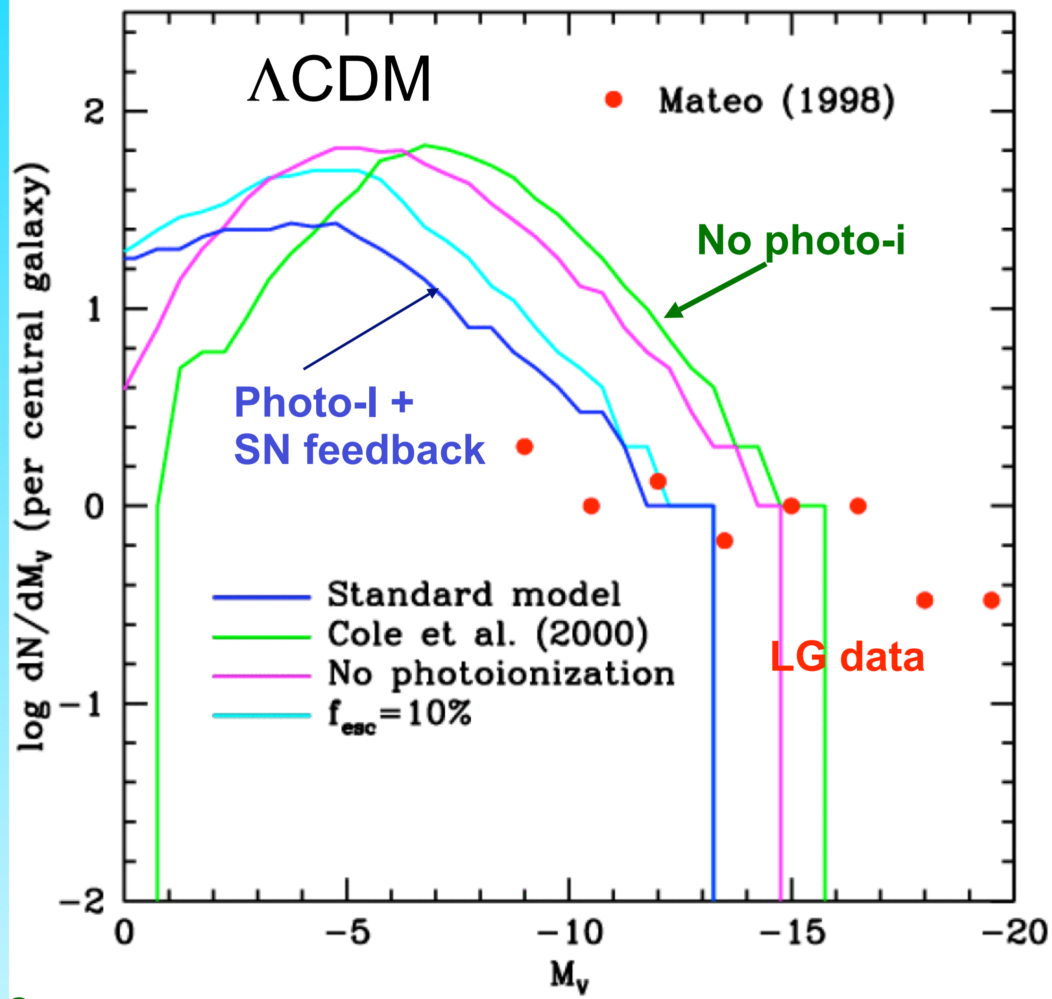
Luminosity Function of Local Group Satellites

- Photoionization inhibits the formation of satellites
- Abundance of satellites 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)

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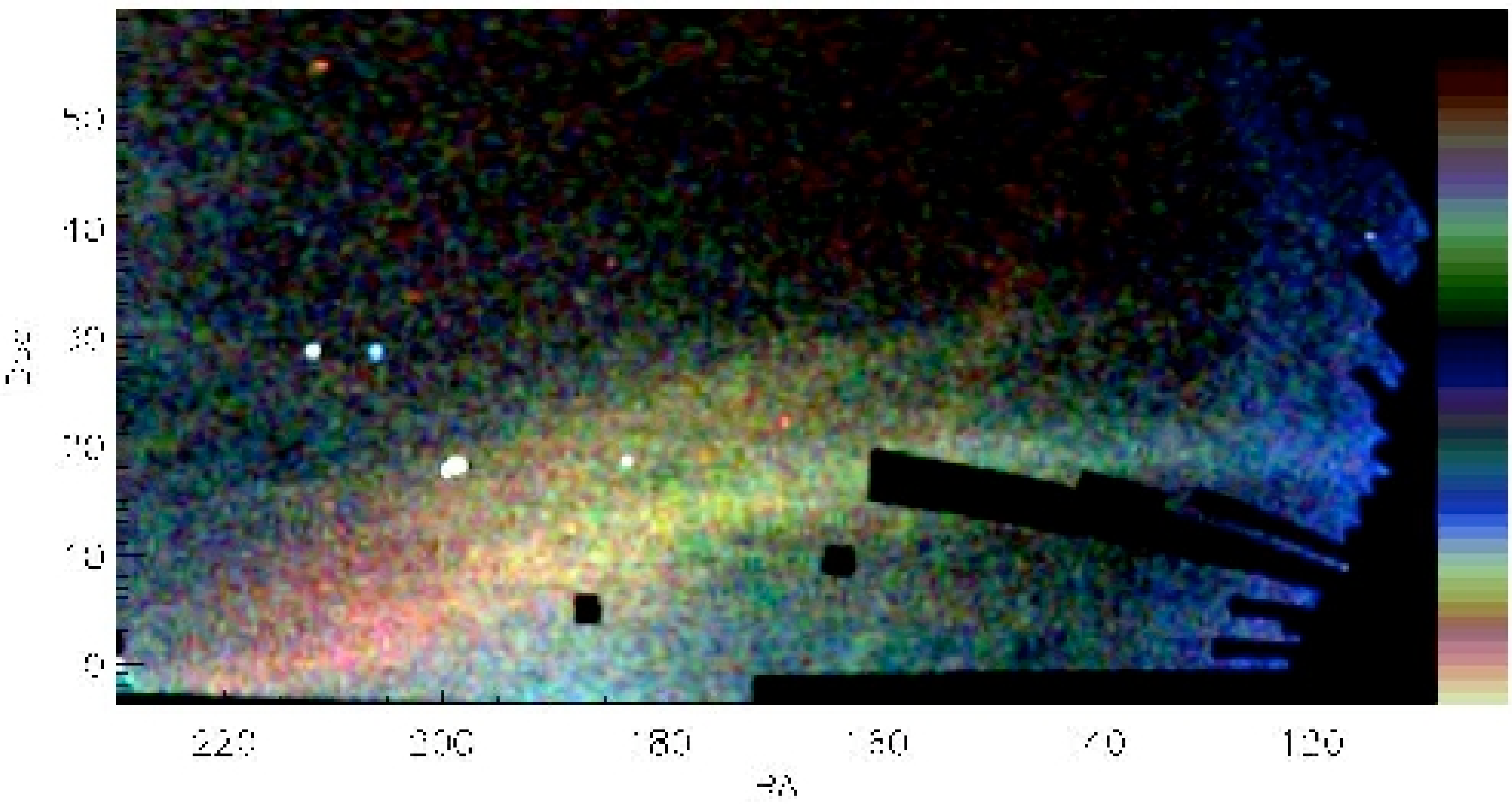
The field of streams

Belokurov et al '07



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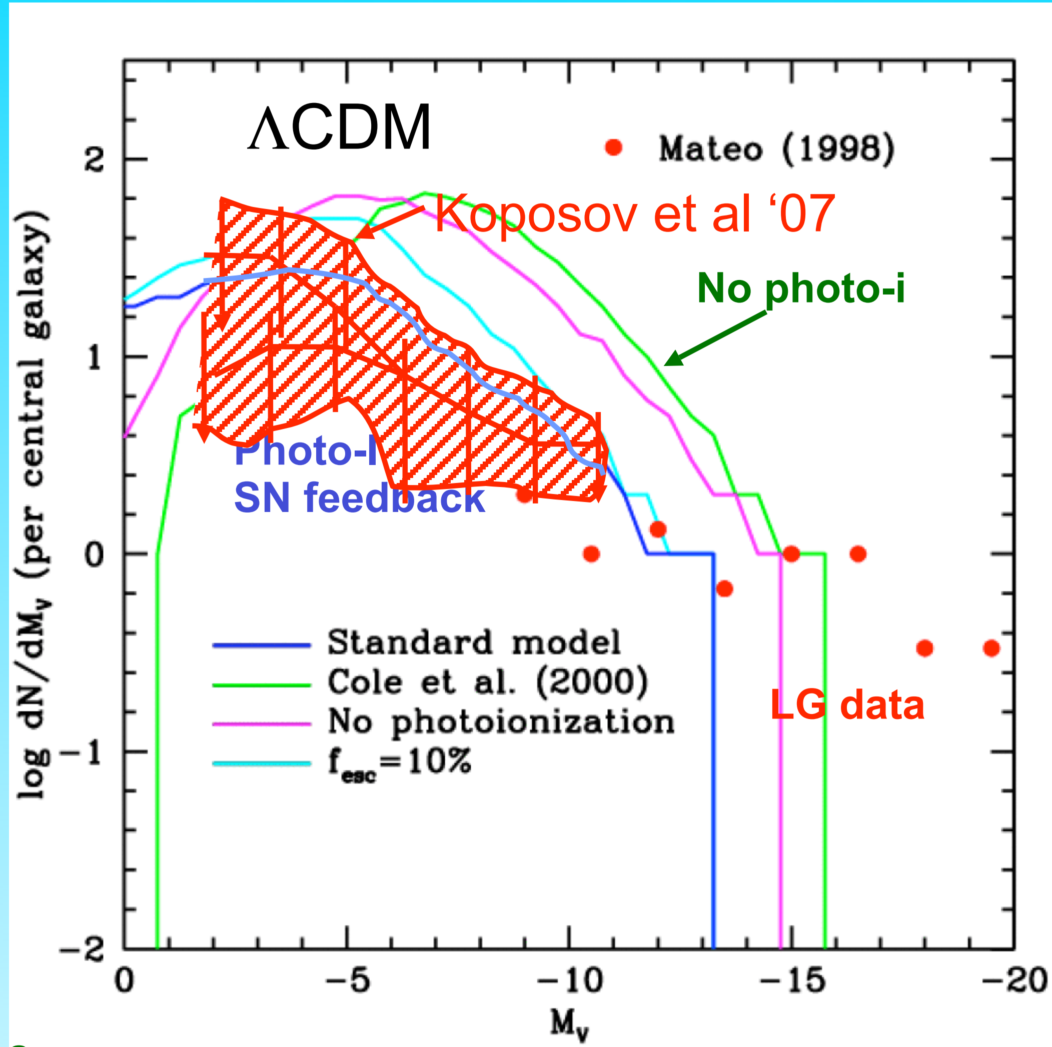

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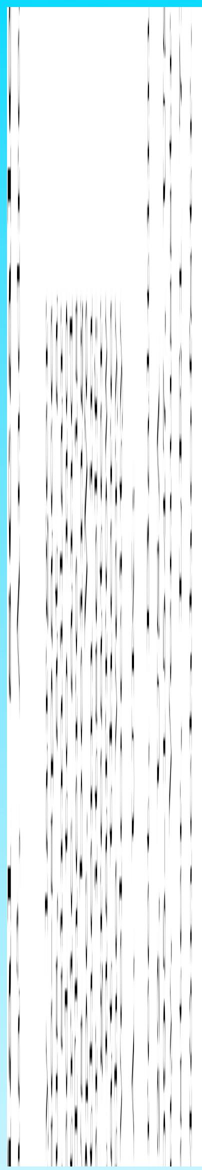

ABSTRACT

There has long been evidence that low-mass galaxies are systematically larger in radius, of lower central stellar mass density, and of lower central phase-space density, than are star clusters of the same luminosity. The larger radius, at a comparable value of central velocity dispersion, implies a larger mass at similar luminosity, and hence significant dark matter, in dwarf galaxies, compared to no dark matter in star clusters. We present a synthesis of recent photometric and kinematic data for several of the most dark-matter dominated galaxies. There is a bimodal distribution in half-light radii, with stable star clusters always being smaller than ~ 30pc, while stable galaxies are always larger than ~ 120pc. We extend the previously known observational relationships and interpret them in terms of a more fundamental pair of intrinsic properties of dark matter itself: dark matter forms cored mass distributions, with a core scale length of greater than about 100pc, and always has a maximum central mass density with a narrow range. The dark matter in dSph galaxies appears to be clustered such that there is a mean volume mass density within the stellar distribution which has the very low value of about $0.1\,M_{\odot}$ pc^{-3} (about 5GeV/c^2 cm^{-3}). All dSphs have velocity dispersions equivalent to circular velocities at the edge of their light distributions of ~ 15km s^{-1}. In two dSphs there is evidence that the density profile is shallow (cored) in the inner regions, and so far none of the dSphs display kinematics which require the presence of an inner cusp. The maximum central dark matter density derived is model dependent, but is likely to have a mean value (averaged over a volume of radius 10pc) of $\sim 0.1\,M_{\odot}$ pc^{-3} (about 5GeV/c^2 cm^{-3}) for our proposed cored dark mass distributions (where it is similar to the mean value), or $\sim 60\,M_{\odot}$ pc^{-3} (about 2TeV/c^2 cm^{-3}) if the dark matter density distribution is cusped. Galaxies are embedded in dark matter halos with these properties; smaller systems containing dark matter are not observed. These values provide new information into the nature of the dominant form of dark matter.

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Mass function of MW satellites

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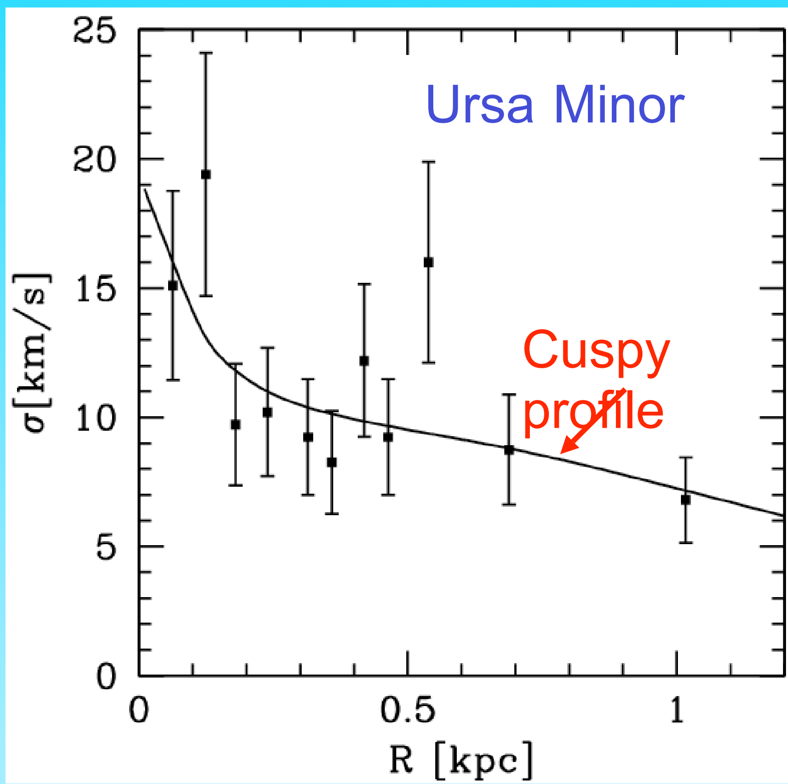
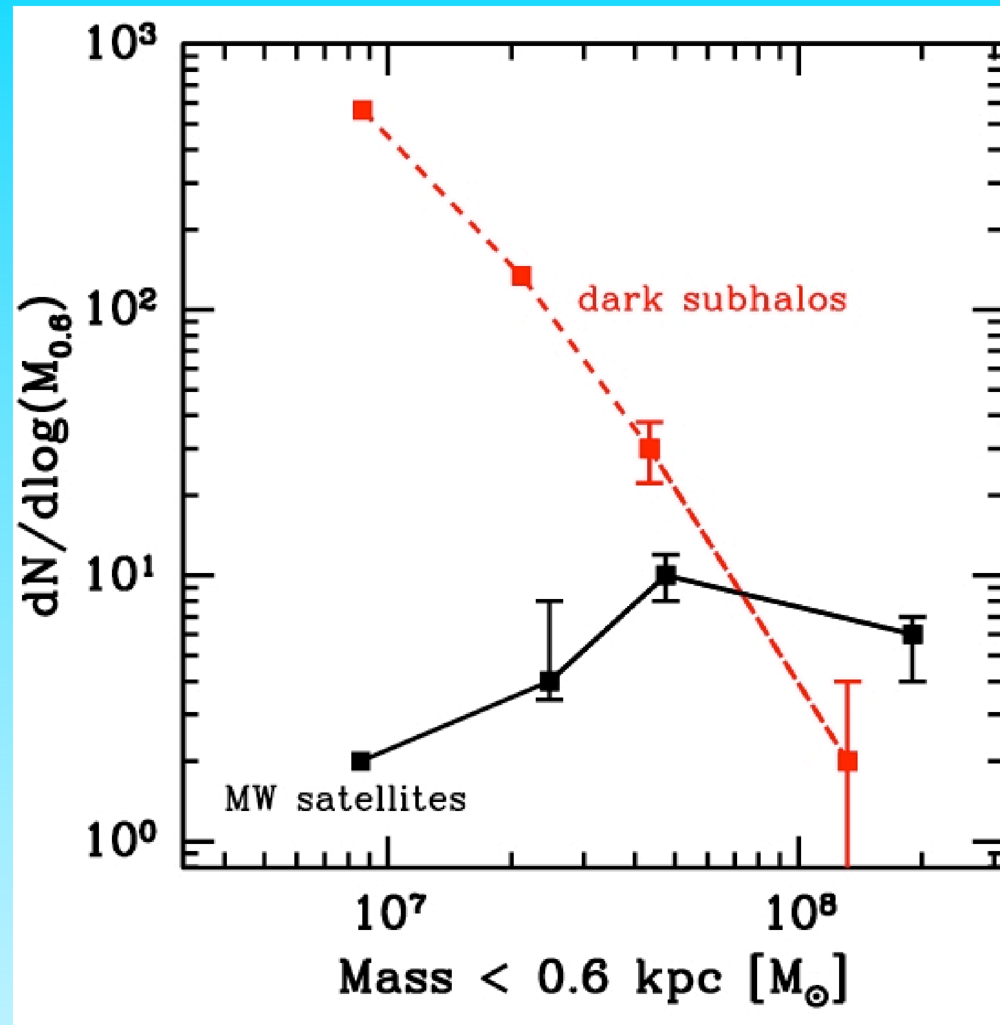
Strigari et al '07

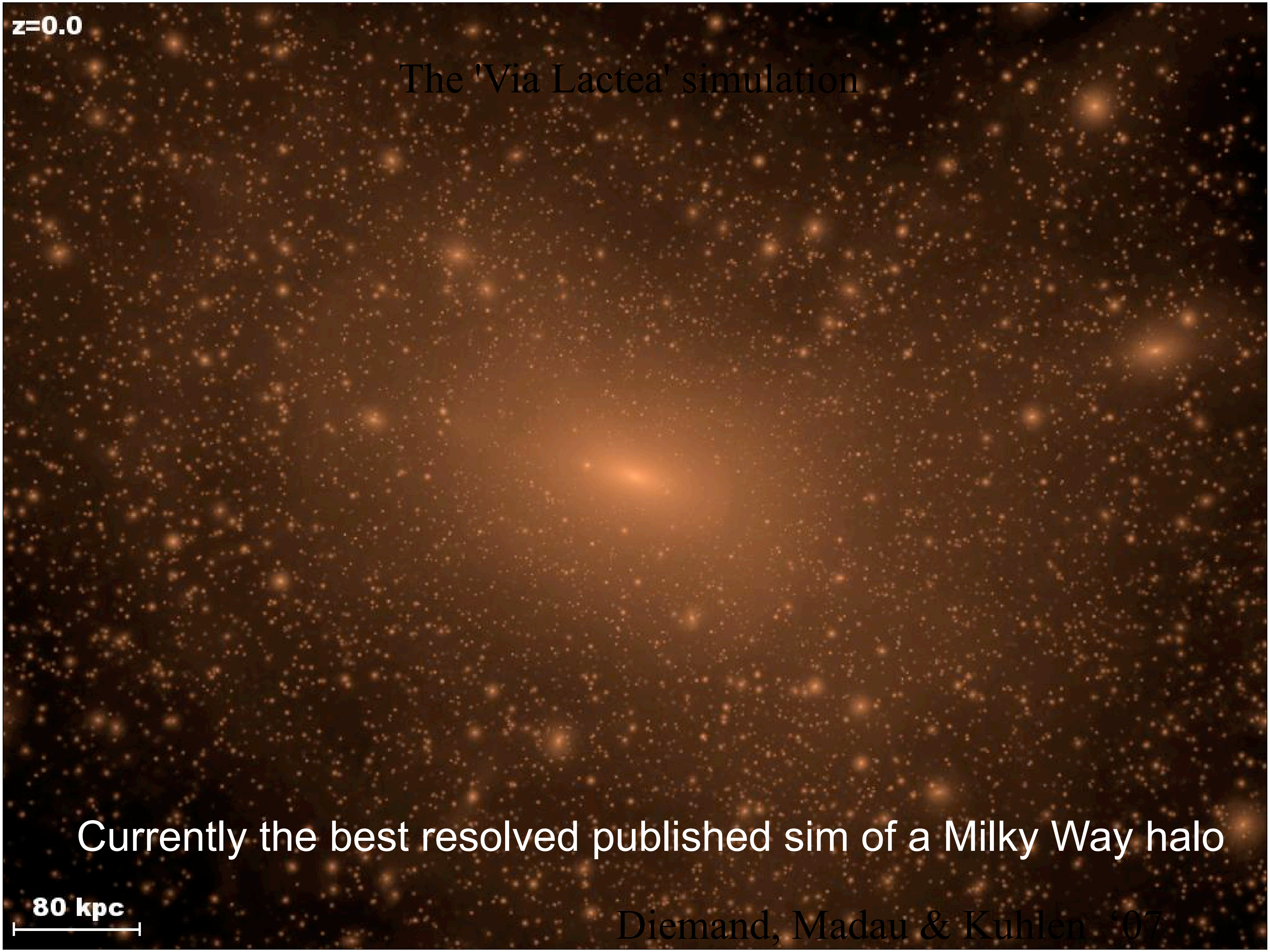


Estimate mass within 0.6 kpc from velocity dispersion data



Institute for Computational Cosmology

The 'Via Lactea' simulation



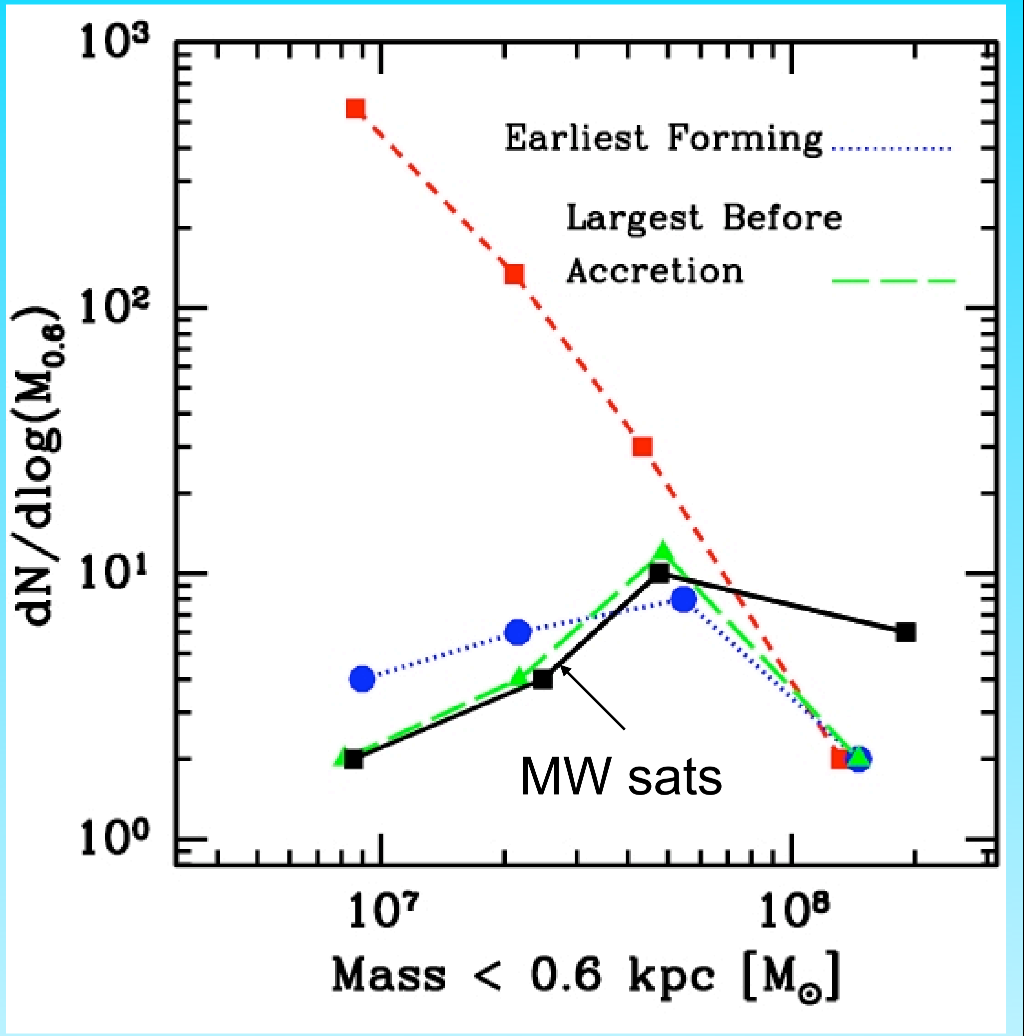
Currently the best resolved published sim of a Milky Way halo

Diemand, Madau & Kuhlen '07

Mass function of MW satellites

University of Durham

MW satellite mass function consistent with ΛCDM provided most massive satellites are identified with largest halos before accretion (c.f. Benson et al '02, Libeskind et al '07)



Strigari et al '07

Institute for Computational Cosmology

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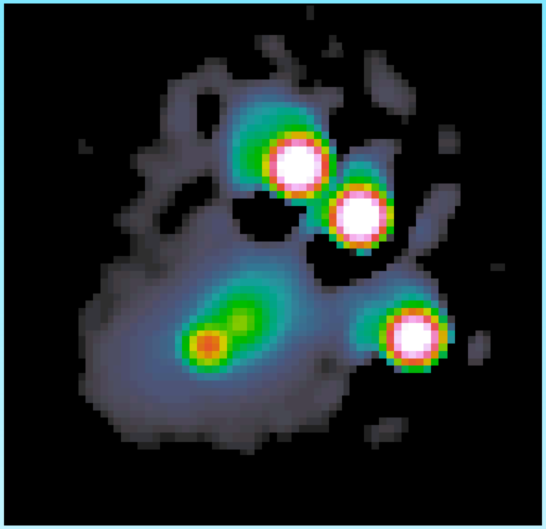
Substructure in CDM halos

Halos have large number of self-bound substructures containing ~10% of the masss and with $dN/dM \sim M^{-1.9}$

→ Substructures may be observable {

- Gravitational lensing effects
- γ -ray annihilation emission



Anomalous flux ratios in multiply-imaged quasars ⇒ Substructure

Dalal & Kochanek ‘02, Metcalfe & Zhao ‘02

A blueprint for detecting halo CDM

Supersymmetric particles annihilate and if x-section is right, the annihilation radiation may be observable

Intensity of annihilation radiation depends on:

$$\int r2(x) \langle sv \rangle dV$$

More on substructure convergence

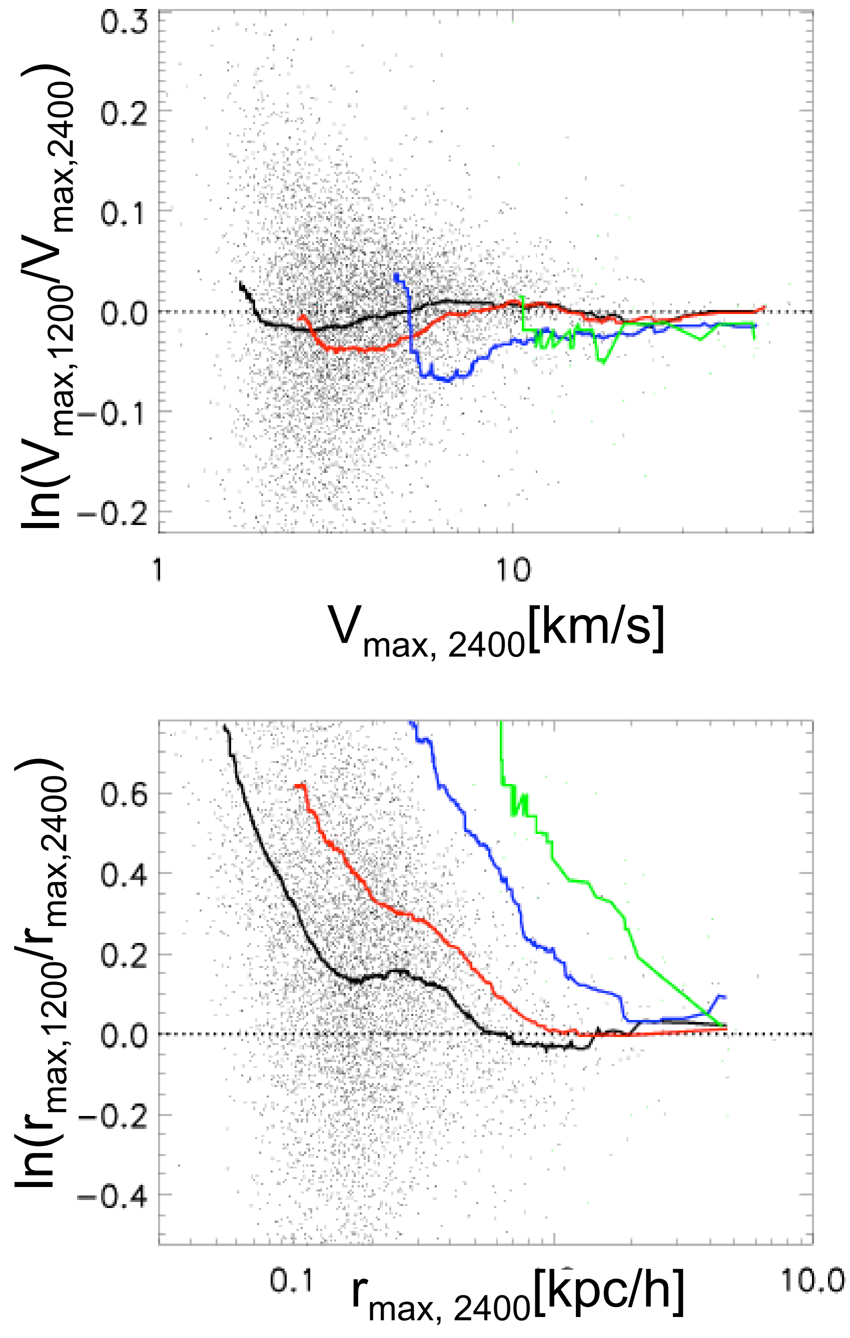
Convergence in the size and maximum circular velocity for individual subhalos cross-matched between simulation pairs.

Biggest simulation gives convergent results for

Vmax > 1.5 km/s
rmax > 165 pc

Much smaller than the halos inferred for even the faintest dwarf galaxies

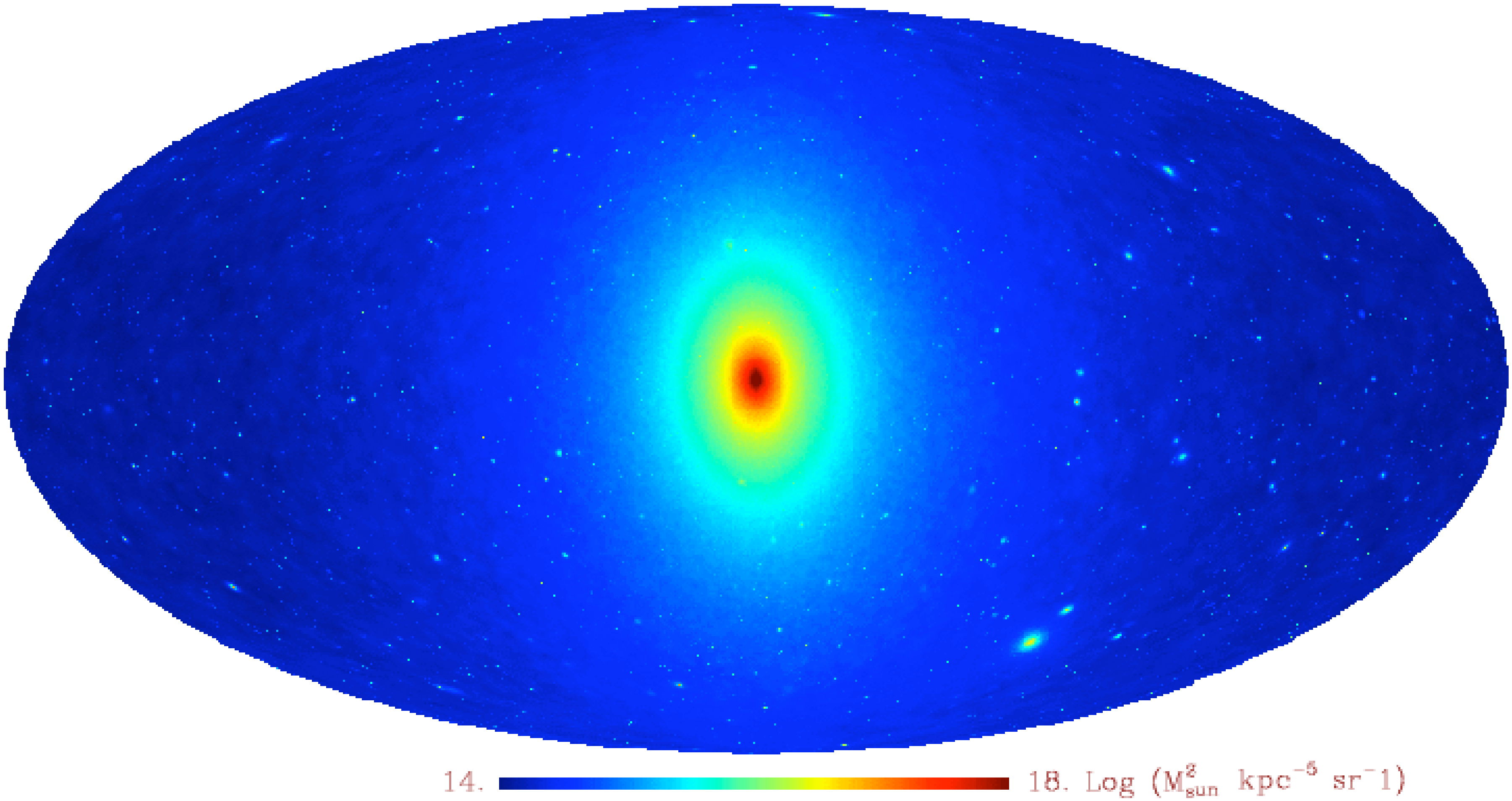
Virgo Consortium



Milky Way halo seen in DM annihilation radiation

University of Durham

Aquarius simulation: N200 = 1.1 x 109



Mass and annihilation radiation profiles of a MW halo

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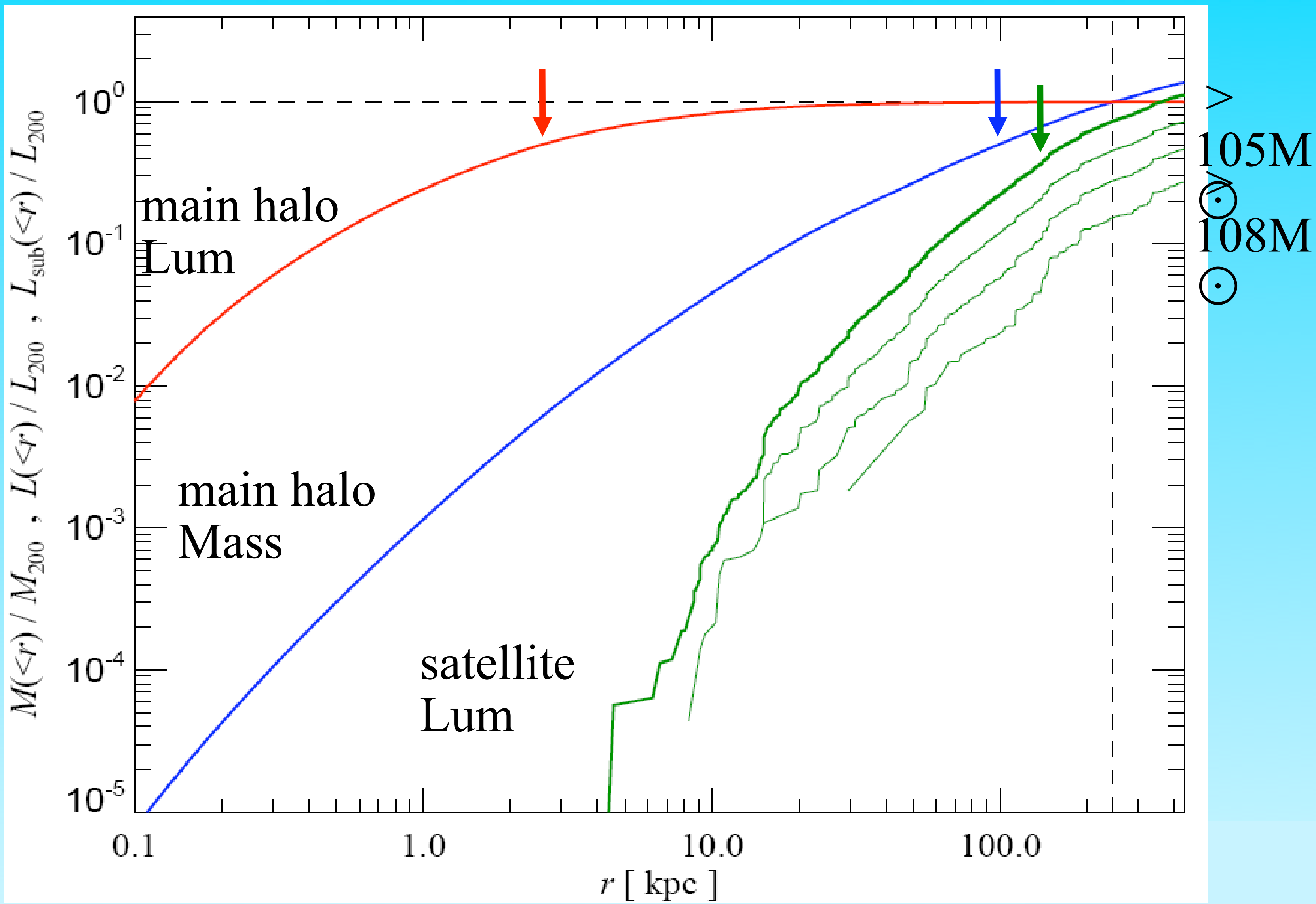

A blueprint for detecting halo CDM

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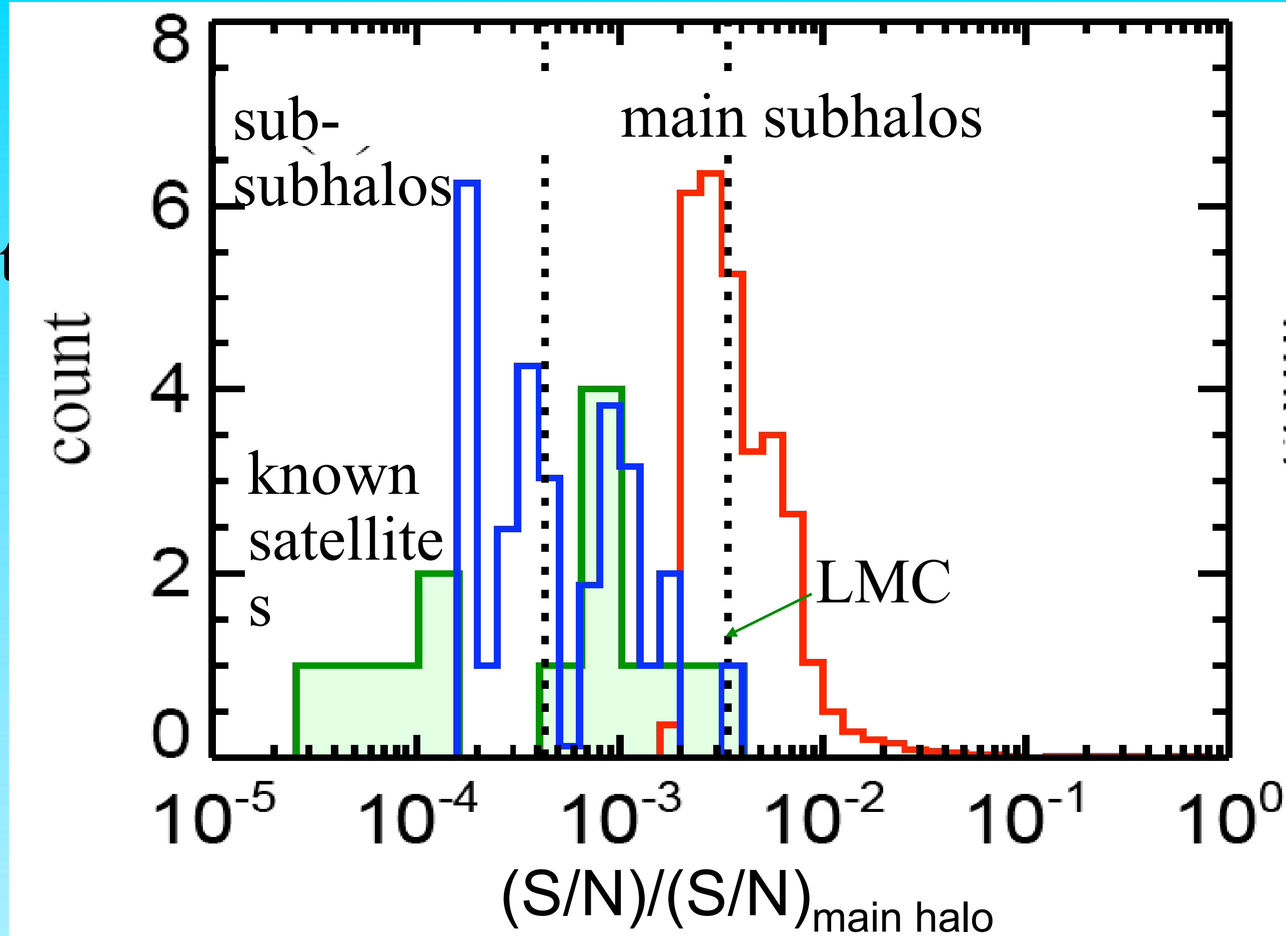
S/N for detecting subhalos in units of that for detecting the main halo 30 highest S/N objects, assuming use of optimal filters



- 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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Conclusions: ΛCDM on small scales

- Predictions from ΛCDM for dark matter are well established
- On large-scales, ΛCDM agrees with staggering amount of data, from CMB to gals
- On small-scales, N-body simulations of ΛCDM predict:

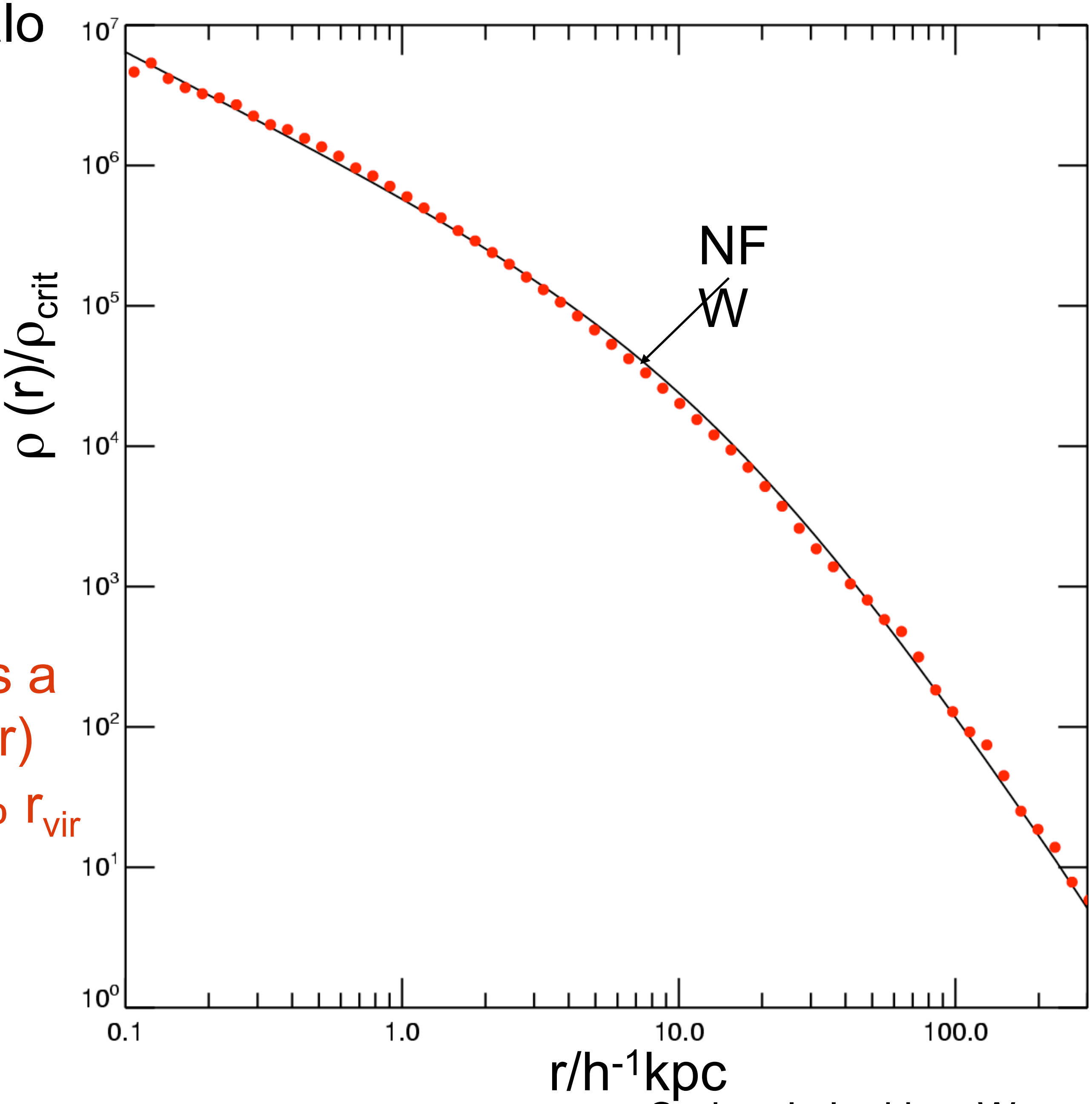
– cuspy halo profiles, with inner log slope $\leq$ -1

– many small substructures, with convergent mass fraction

- Evidence for cusps in galaxy cluster halos
- Dwarf galaxy (e.g. sats) and LF “problems” solved by astrophysics
- TEST: substructures should be observable (lensing, γ-rays)
- GLAST may discover DM - near centre of the galaxy

A galactic halo

N=800^3



NFW profile is a good fit to $\rho(r)$ down to ~0.1% r_{vir}

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