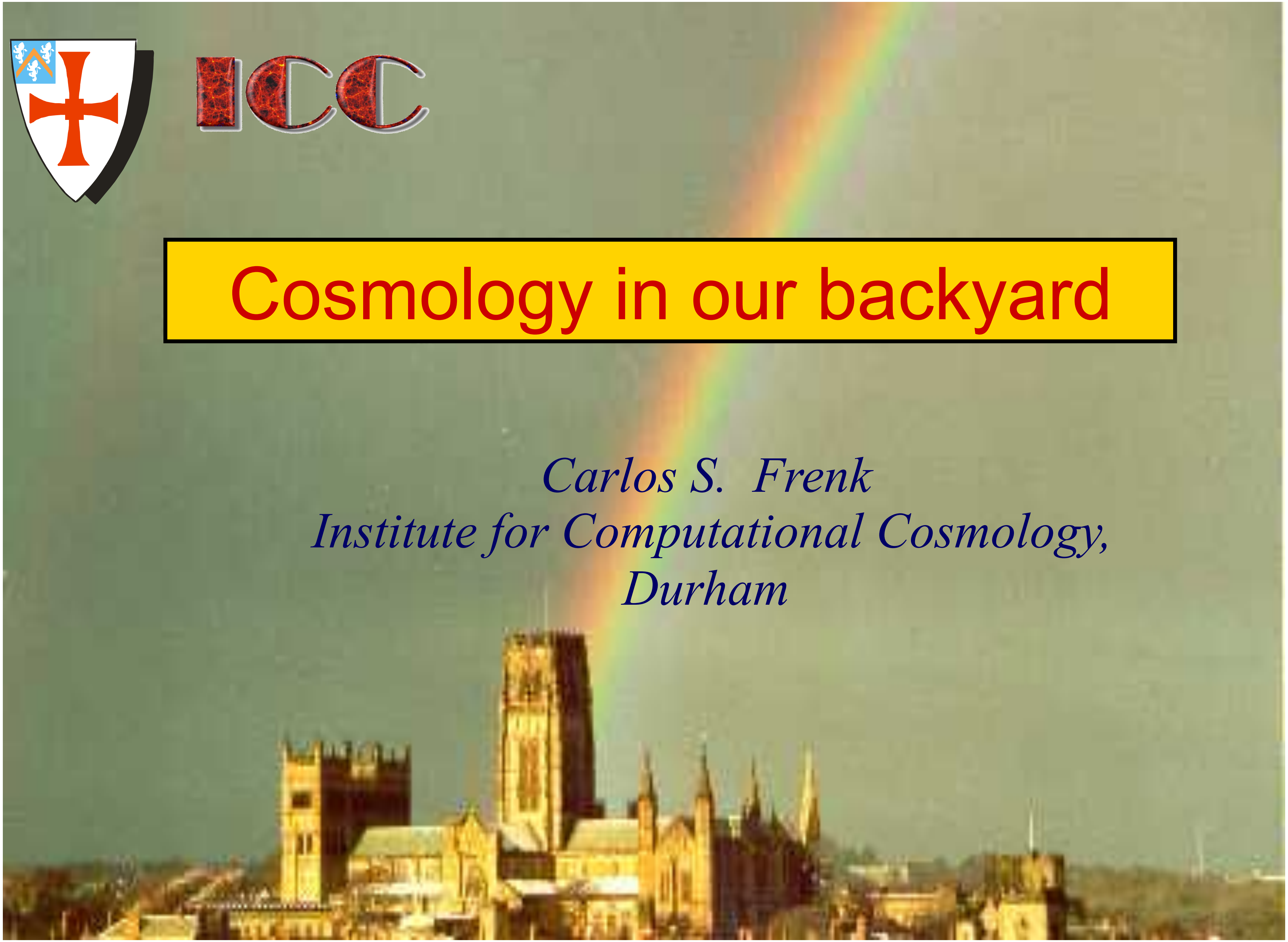


Cosmology in our backyard

Carlos S. Frenk
Institute for Computational Cosmology,
Durham

The cold dark matter model

Detecting cold dark matter

If CDM is a supersymmetric particle, 3 possibilities

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

If CDM is an axion:

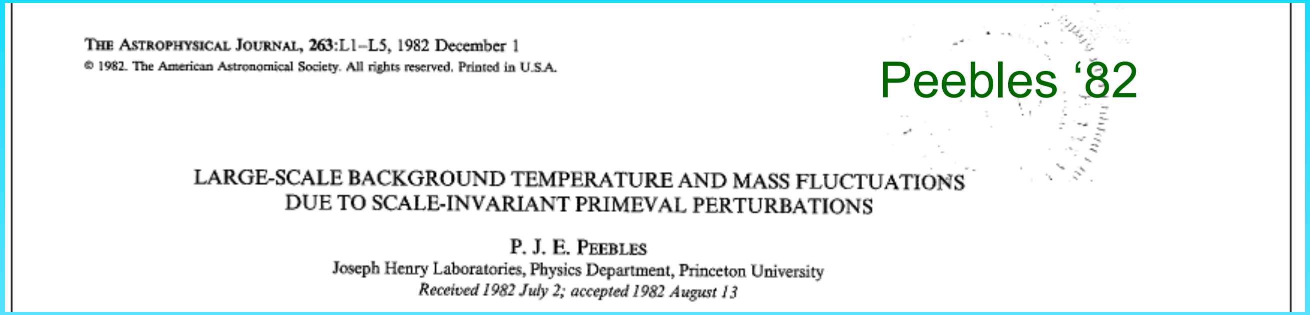
- Direct detection in resonant magnetic cavity

The cold dark matter model

How likely is it that the CDM hypothesis is correct?

(from an astrophysical point of view)

The cold dark matter cosmogony



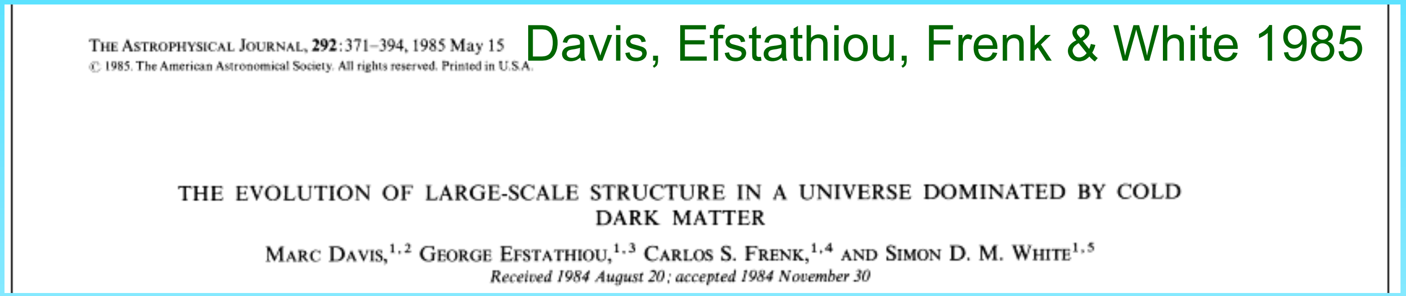
Peebles ‘82

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

Received 1982 July 2; accepted 1982 August 13



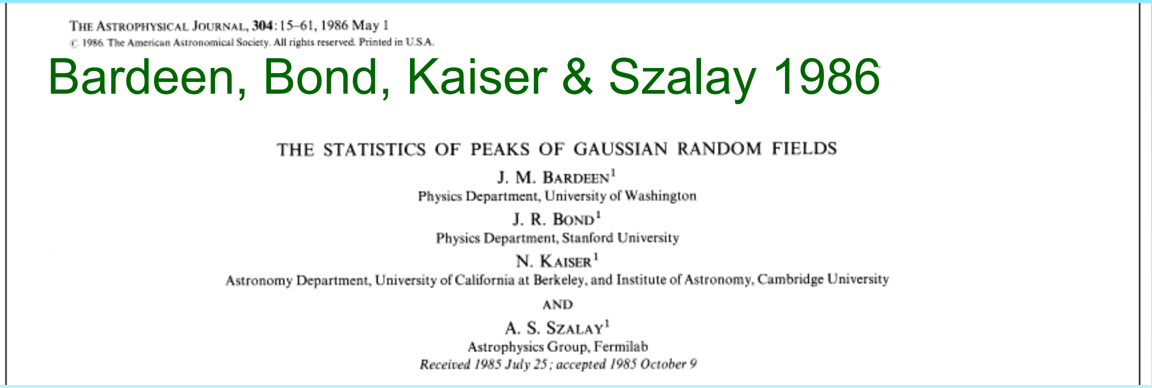
Davis, Efstathiou, Frenk & White 1985

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

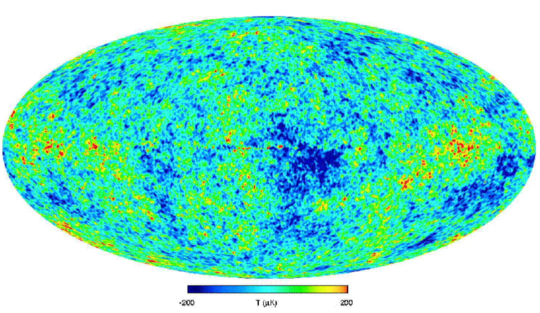
THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

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

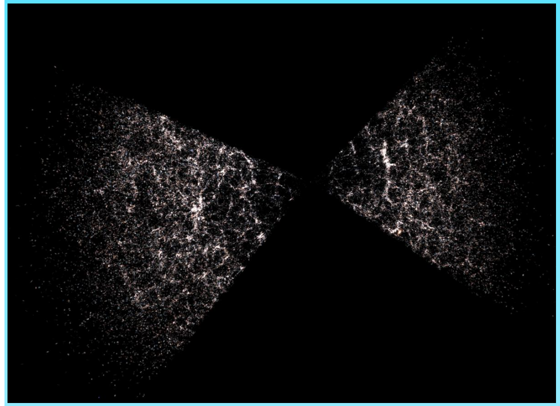
Received 1985 July 25; accepted 1985 October 9

University of Durham

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

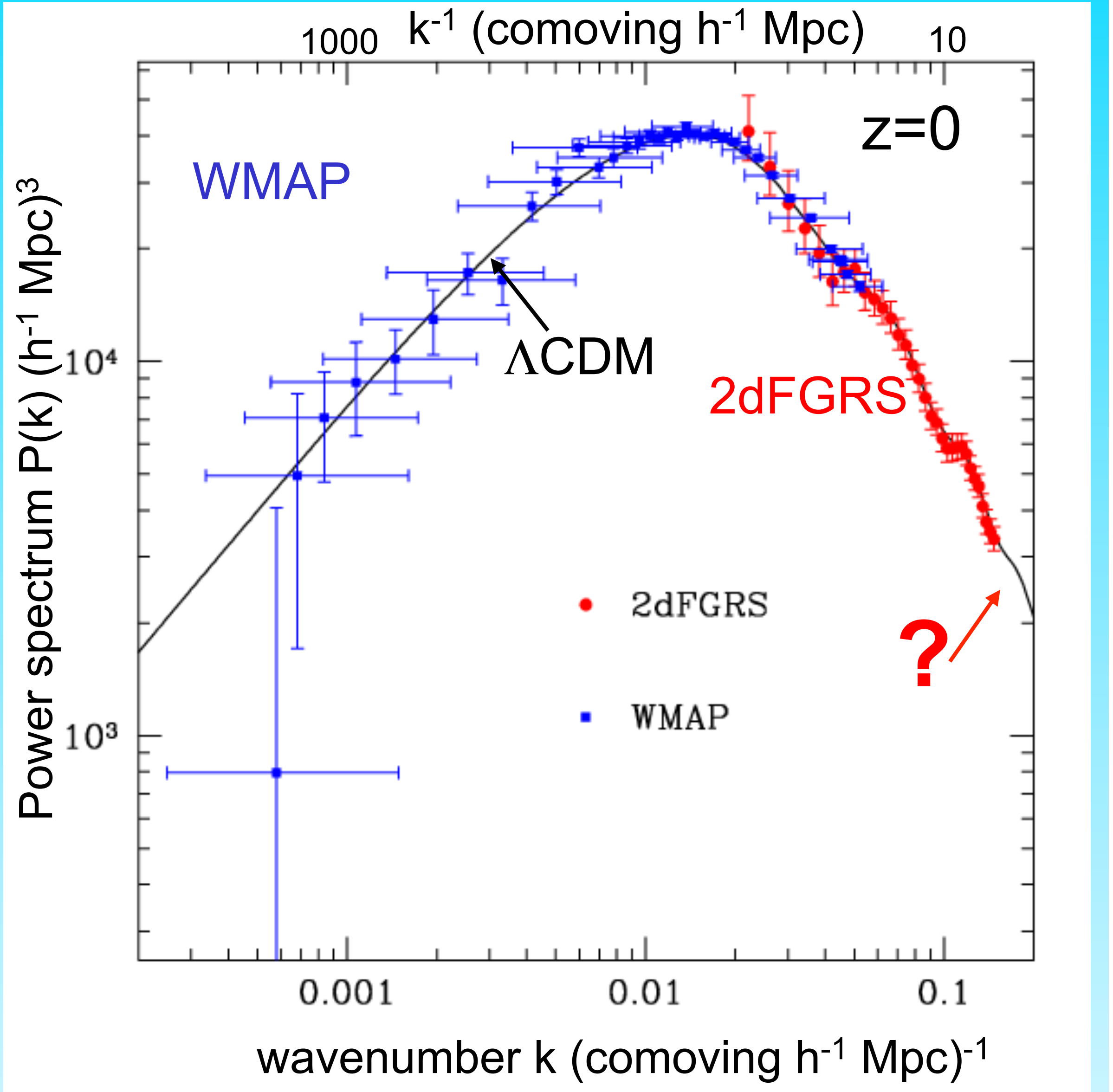


z~1000



z~0

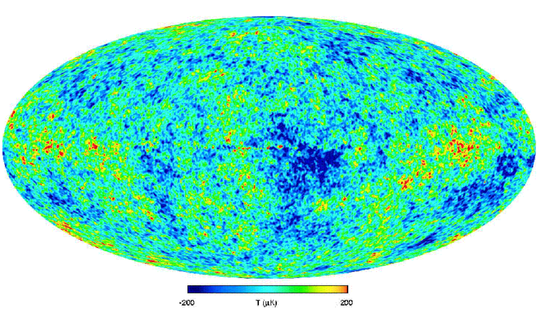
⇒ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc



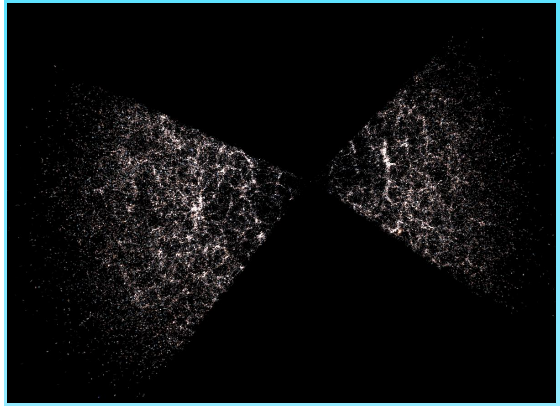
Sanchez et al 06

ICC
University of Durham

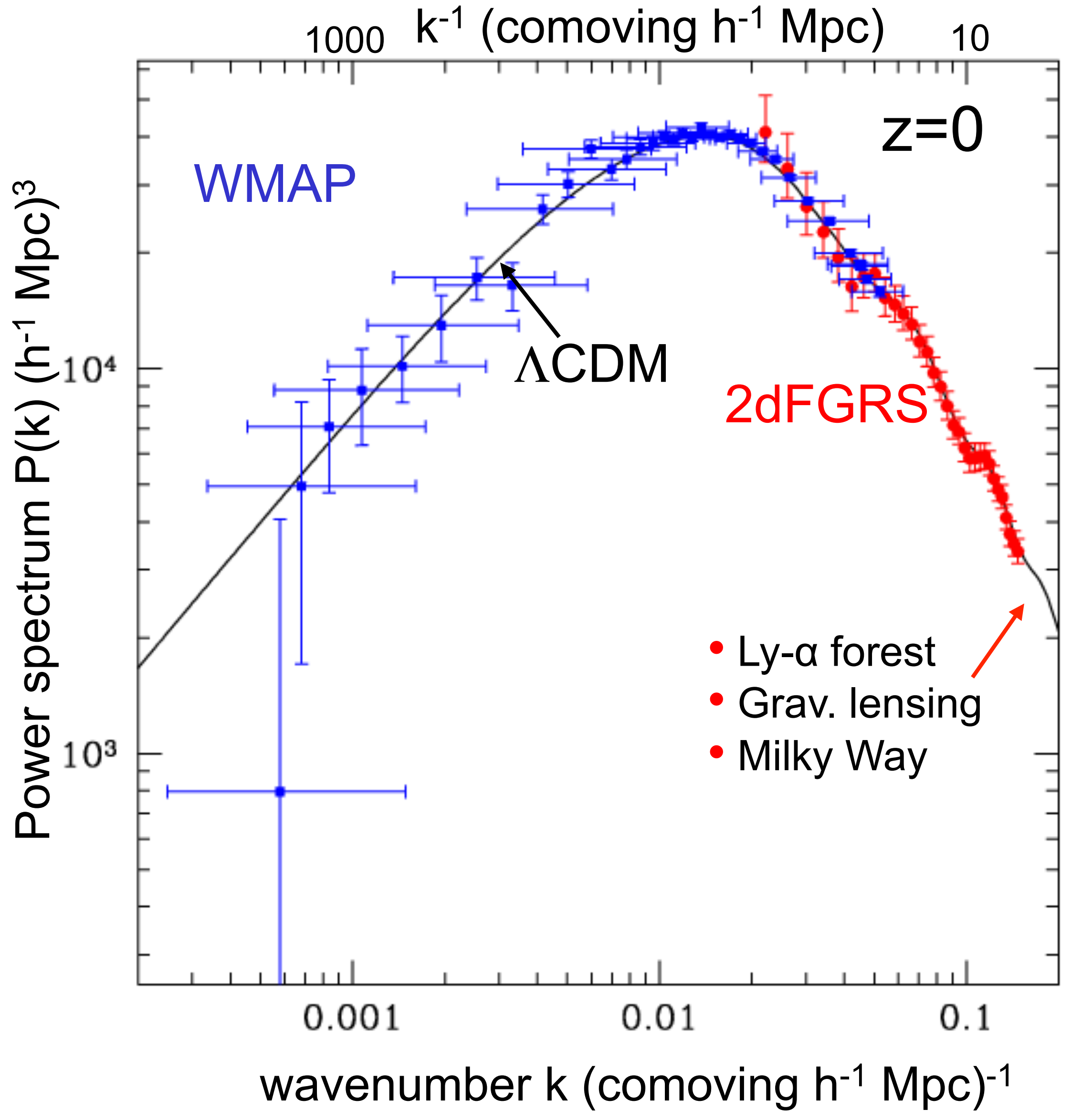
The cosmic power spectrum: from the CMB to the 2dFGRS



z~1000



z~0



- Ly-α forest
- Grav. lensing
- Milky Way

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

Sanchez et al 06

The small-scale structure depends sensitively on the nature of the dark matter

University of Durham

Non-baryonic dark matter candidates

Type	example	mass
hot	neutrino	a few eV
warm	sterile ν majoron	keV-MeV
cold	axion neutralino	10^{-5}eV- >100 GeV

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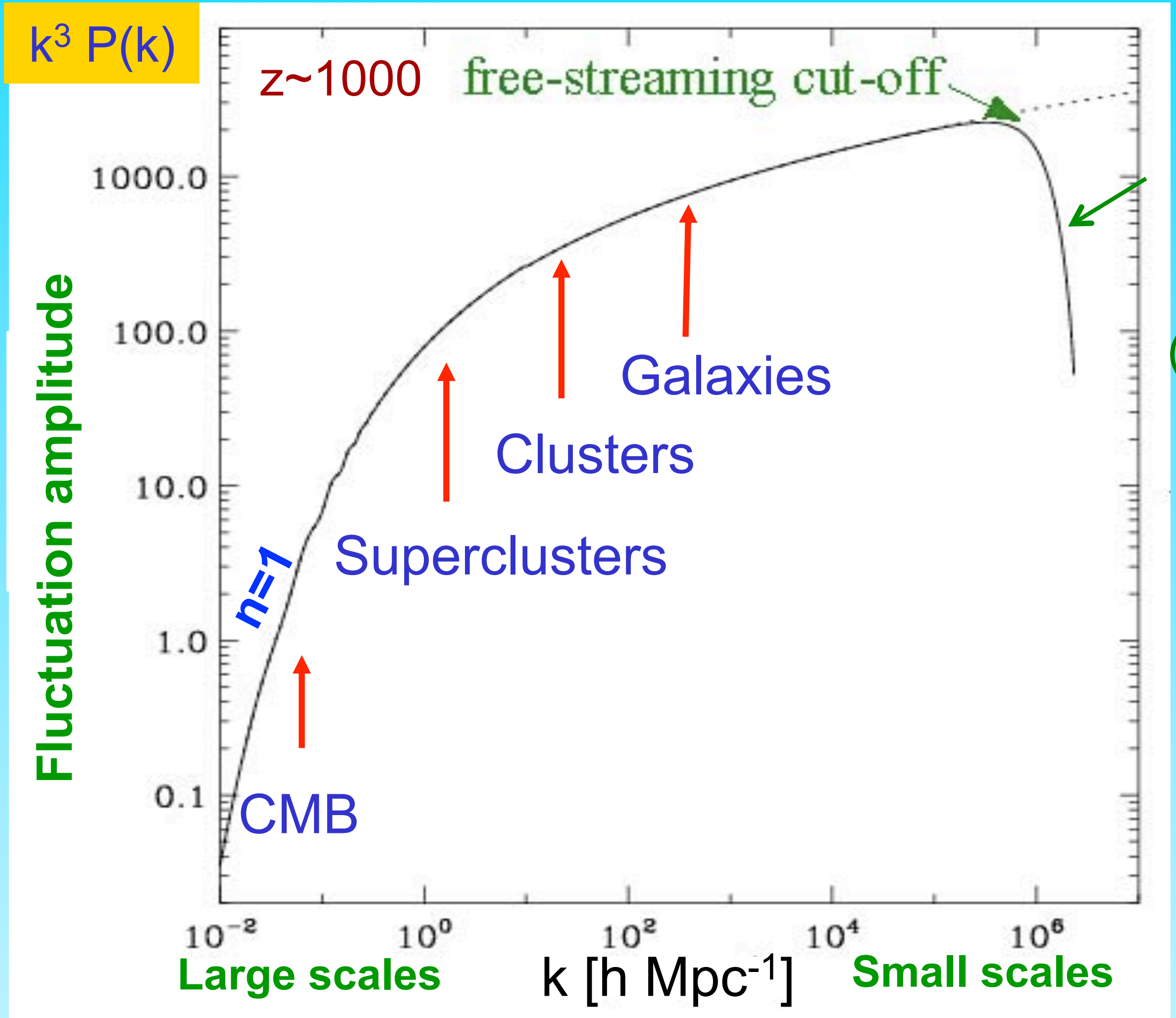
The cold dark matter linear power spectrum

“Power per octave”



10^{-6} M_o for 100 GeV wimp (Green etal 04)

University of Durham

The cold dark matter power spectrum

$\lambda_{cut} \propto m_x^{-1}$

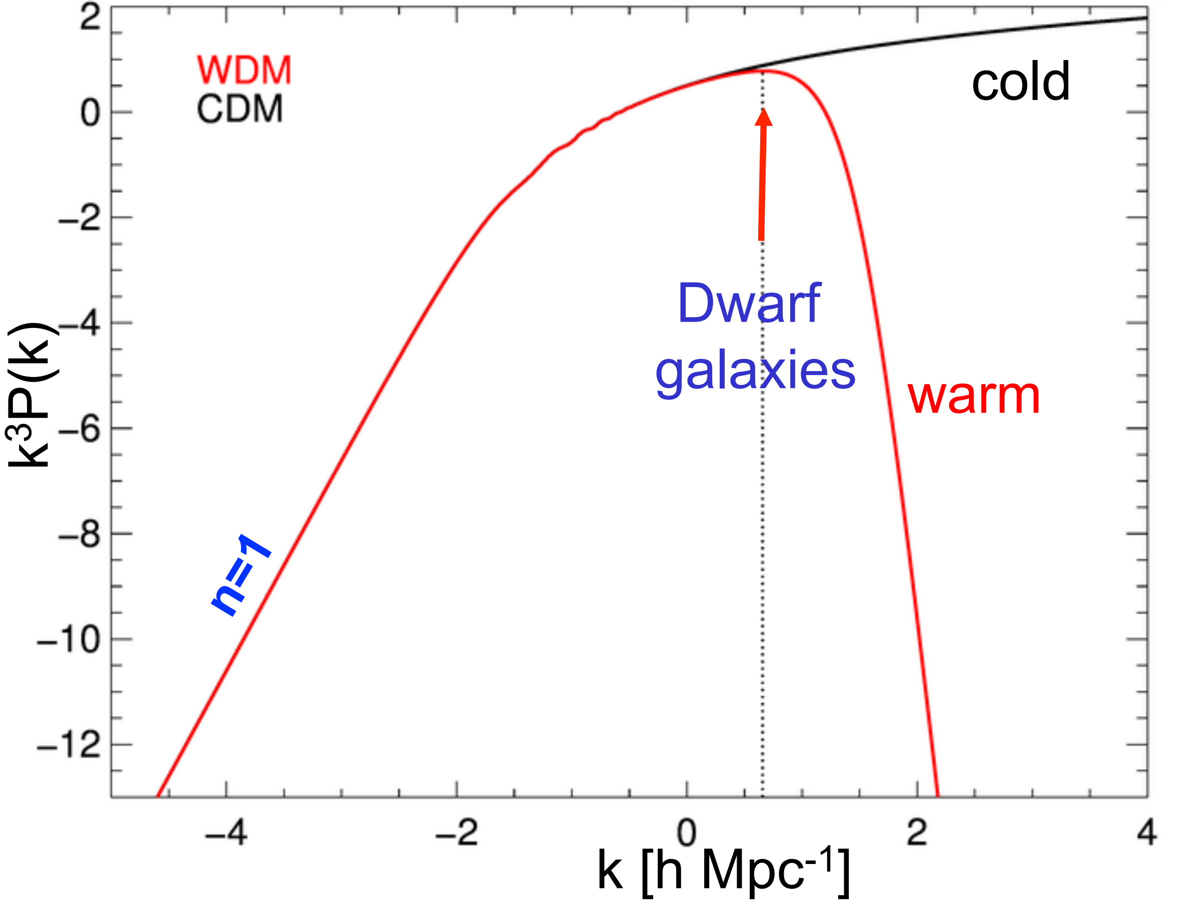
Ly-α forest (z~2-3) ➔

$m_{WDM} \gtrsim$ 4keV (2σ) for thermal relic

$m_{WDM} \gtrsim$ 2 keV (2σ) for sterile neutrinos

(Viel etal '08; Boyarsky etal '09)

The linear power spectrum ("power per octave")



$M_{cut} \sim 10^{10} (\Omega/0.3)^{1.45} (h/0.65)^{3.9} (keV/m_{wdm})^{3.45} h^{-1} M_o$

Institute for Computational Cosmology

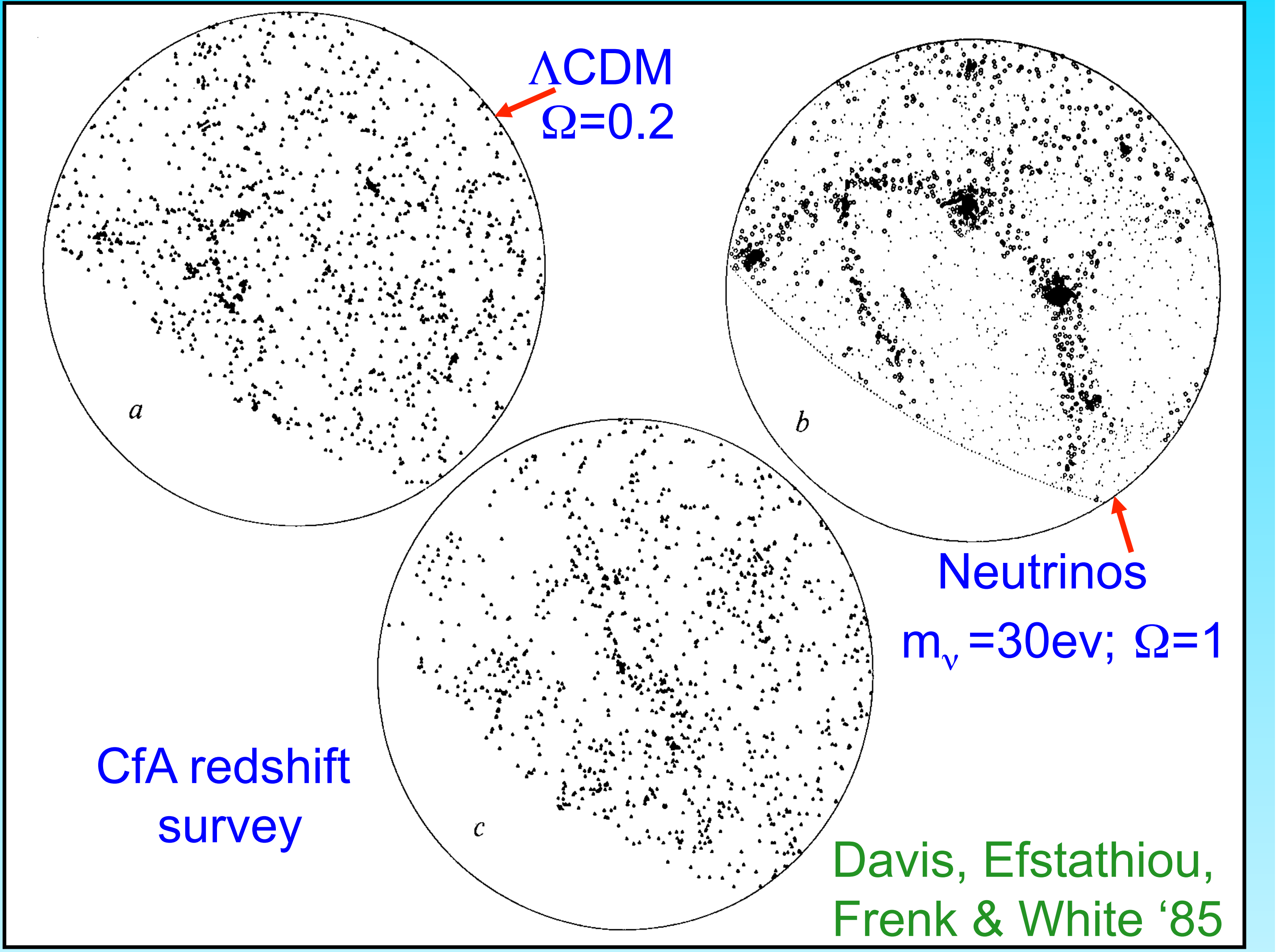
University of Durham

Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

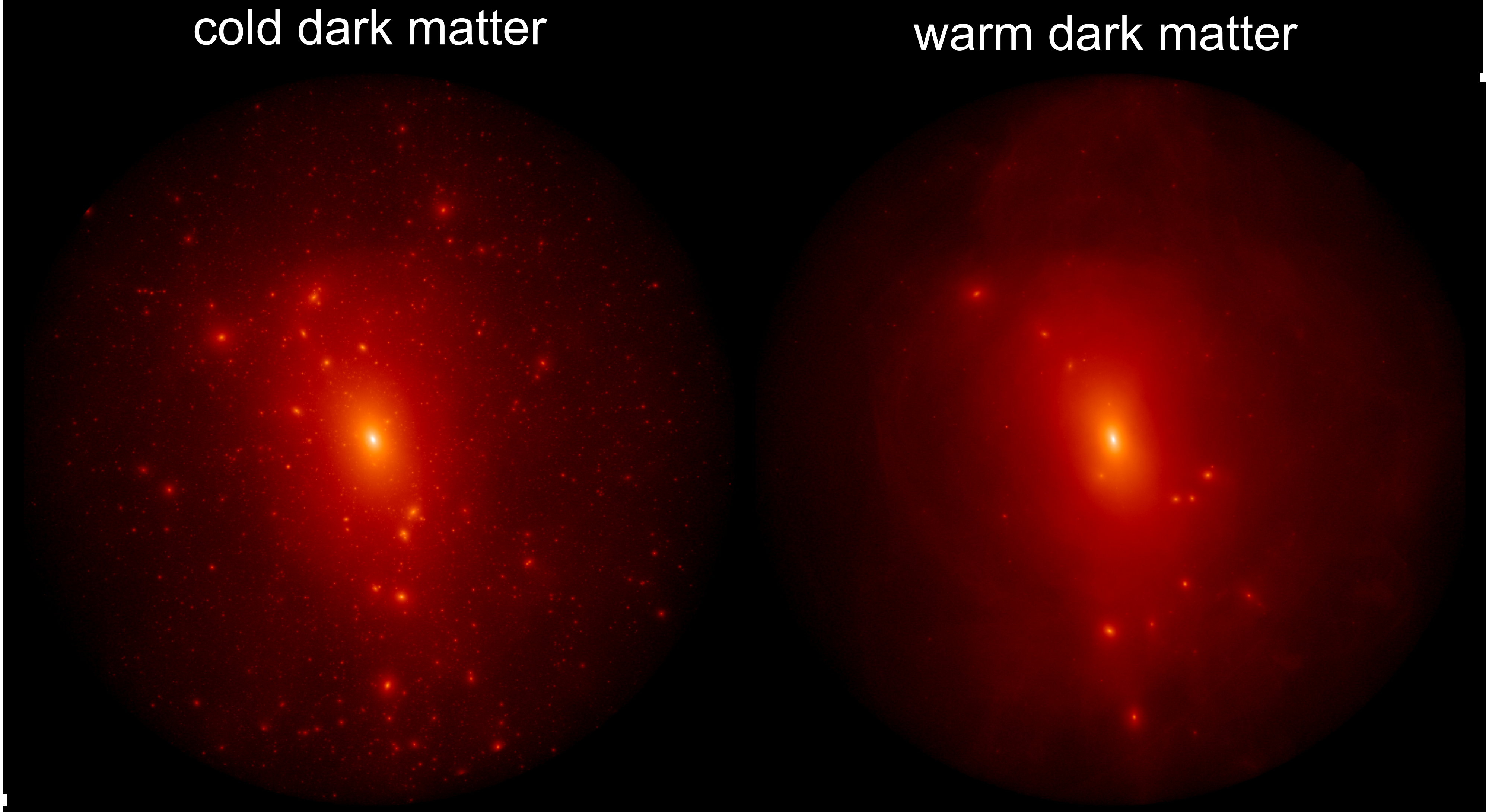
In CDM structure forms hierarchically



Davis, Efstathiou, Frenk & White '85

Non-baryonic dark matter candidates

Type	example	mass
~~hot~~	~~neutrino~~	~~a few eV~~
warm	sterile ν majoron	keV-MeV
cold	axion neutralino	10^{-5}eV- >100 GeV



cold dark matter

warm dark matter

Gao, Lovell et al 2011

University of Durham

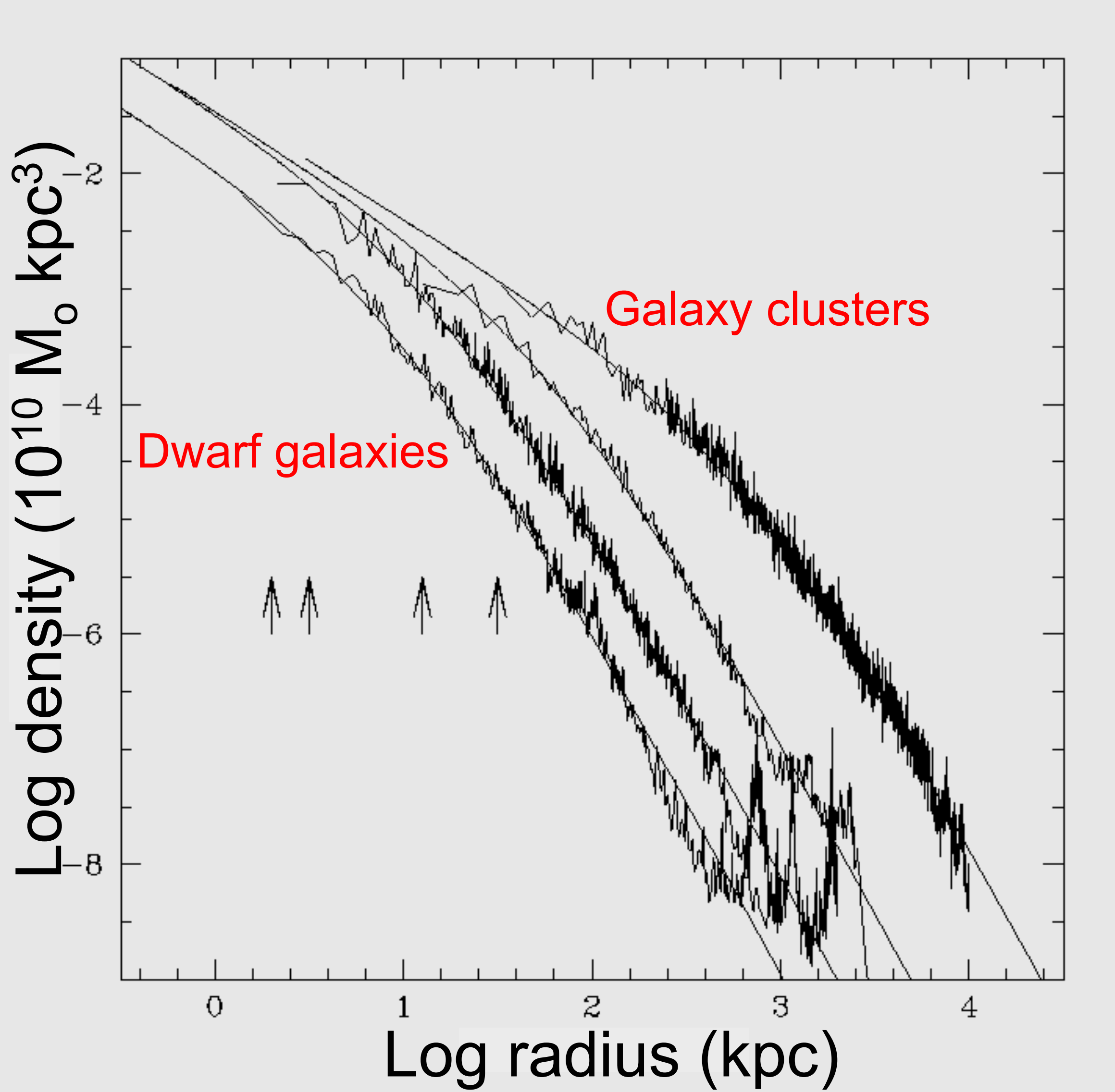
The Milky Way and the nature of the dark matter

- Test CDM predictions on galaxy scales
  - Structure of dark matter halos
  - Number of satellite galaxies
  - Remnants of hierarchical formation (streams)


z = 48.4
T = 0.05 Gyr
500 kpc

The structure of cold dark matter halos

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.

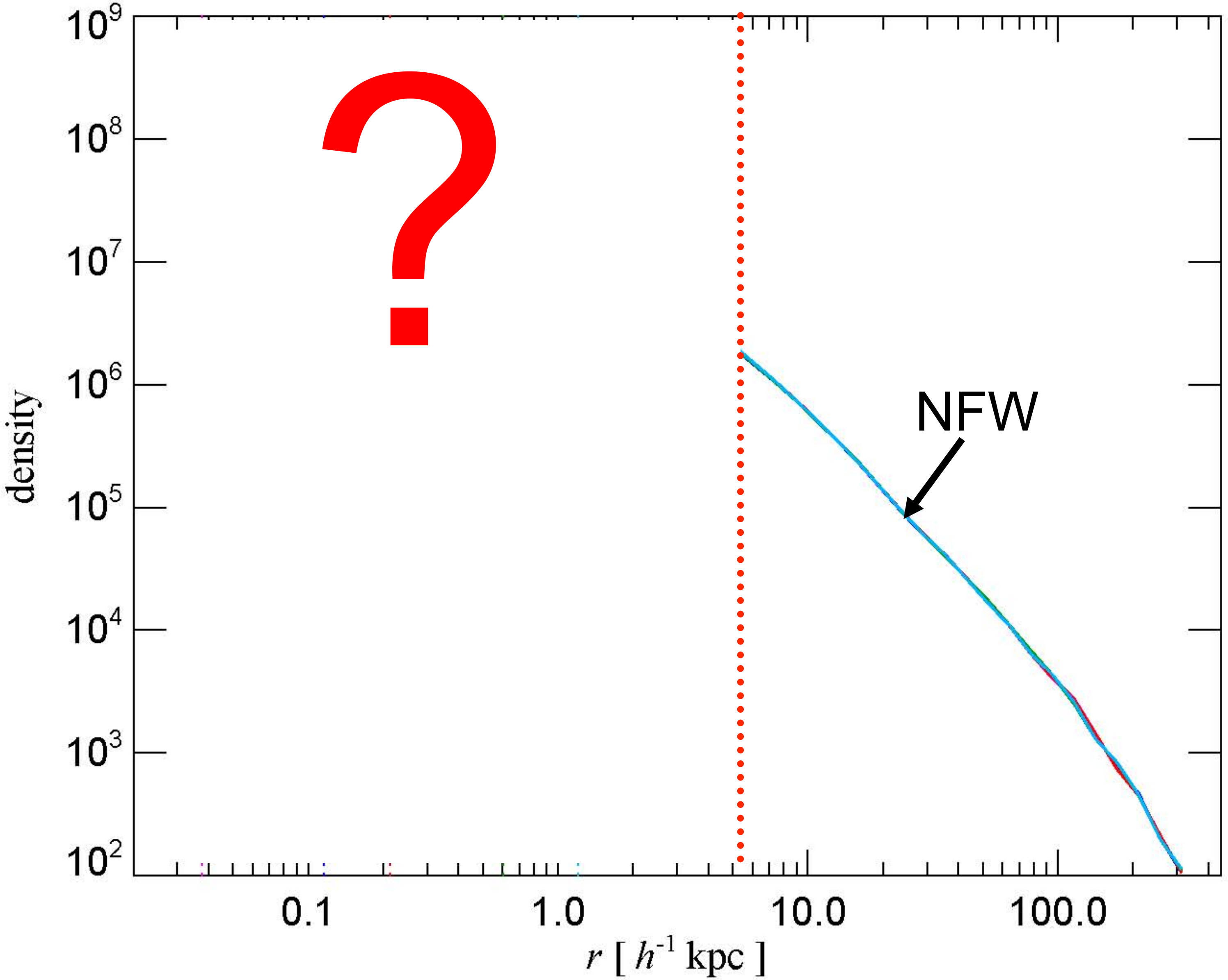
(Navarro, Frenk & White '97)

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

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

Density profile $\rho(r)$

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



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

UK, Germany, Netherlands, Canada, Japan, China 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	$3.14 \times 10^6\ M_0$
Aq-A-4	6,424,399	1,960	$3.92 \times 10^5\ M_0$
Aq-A-3	51,391,468	13,854	$4.91 \times 10^4\ M_0$
Aq-A-2	184,243,536	45,024	$1.37 \times 10^4\ M_0$
Aq-A-1	1,473,568,512	297,791	$1.71 \times 10^3\ M_0$ (15 pc/h softening)

VIRGO

Simulation data, movies, pictures available at:

www.mpa-garching.mpg.de/Virgo

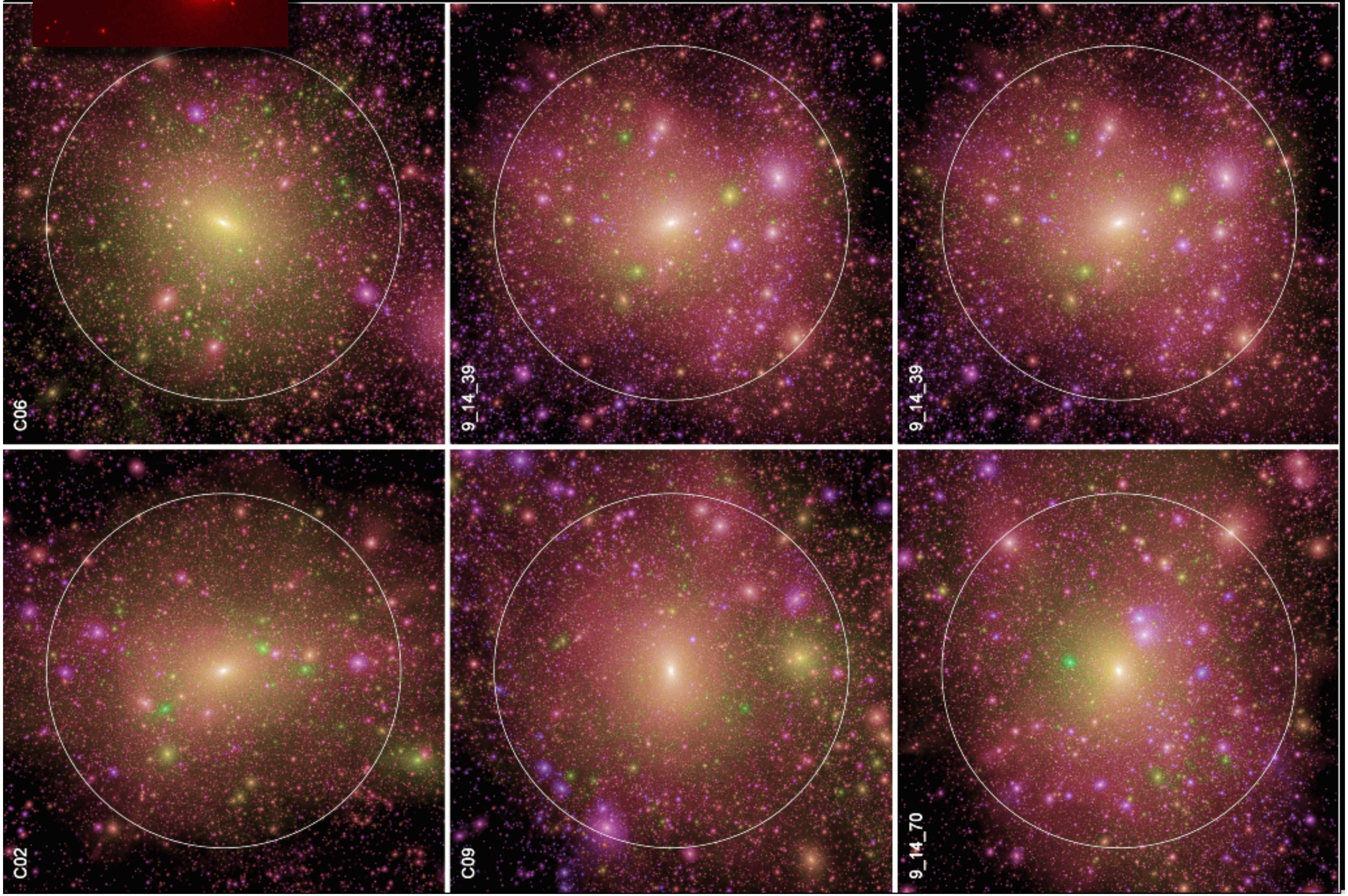
www.durham.ac.uk/virgo

UK, Germany, Netherlands,
Canada, Japan, China

Springel et al ‘08

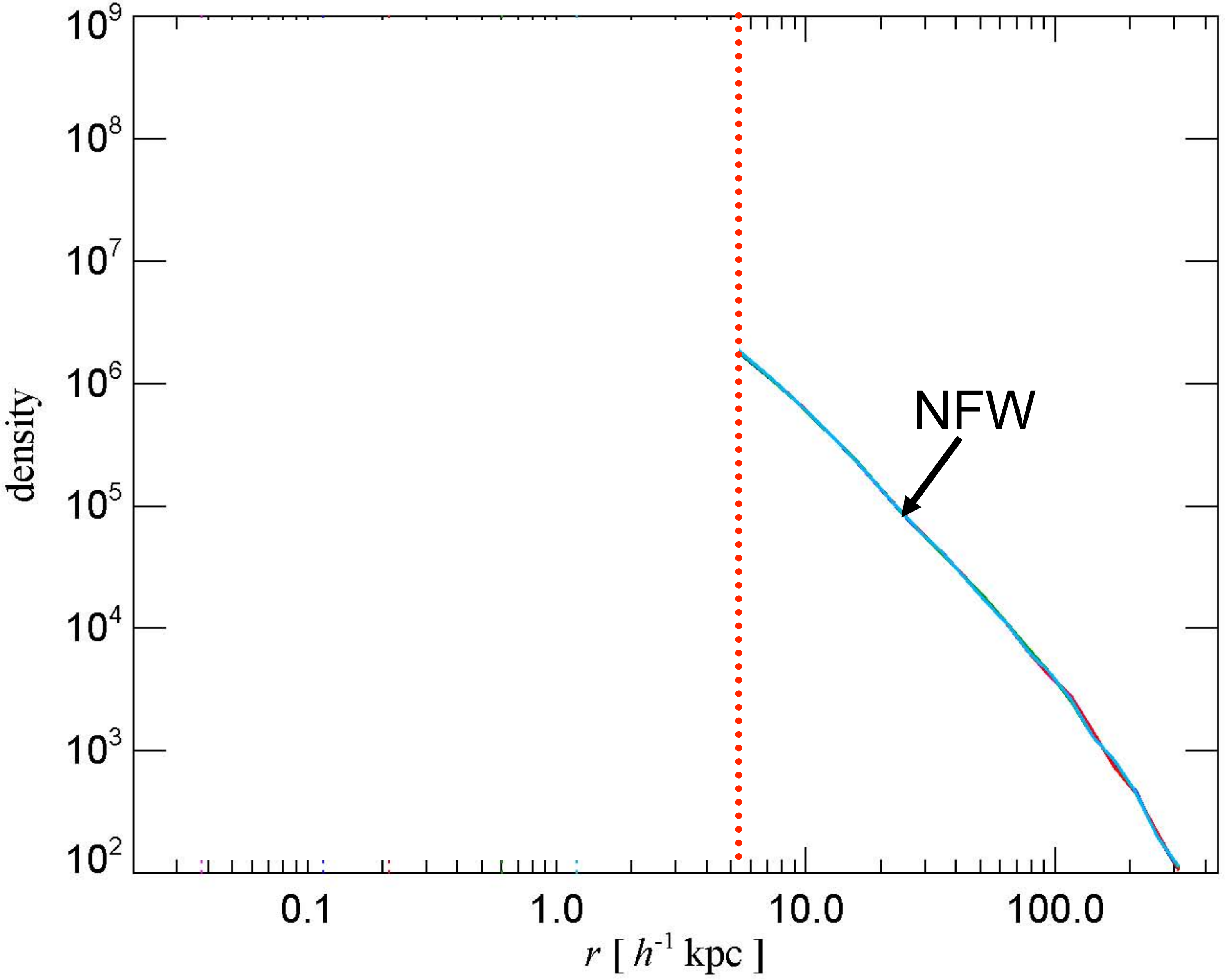
VIRGO

Images of all Aquarius halos (level-2)



Density profile $\rho(r)$

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



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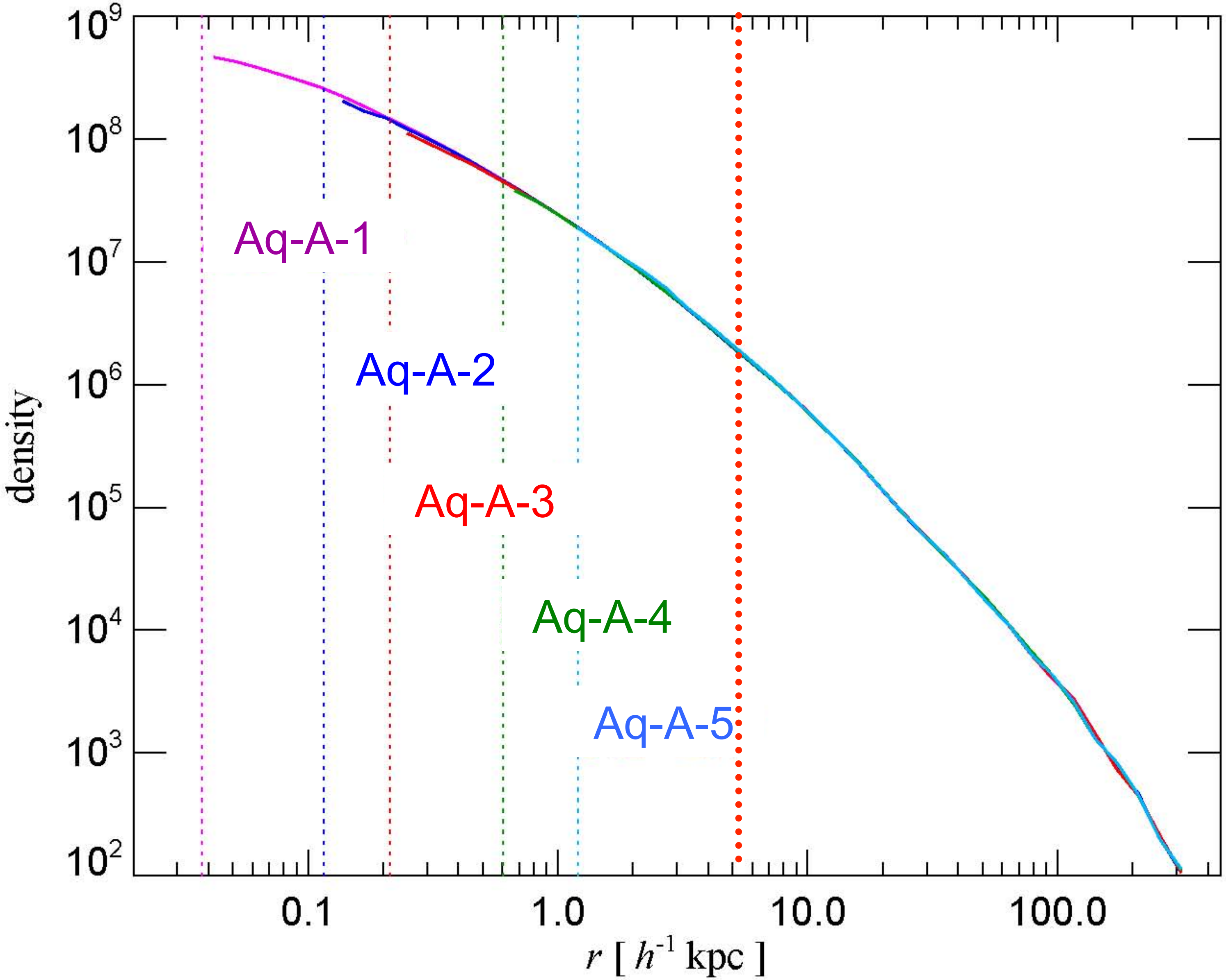
Density profile ρ(r)



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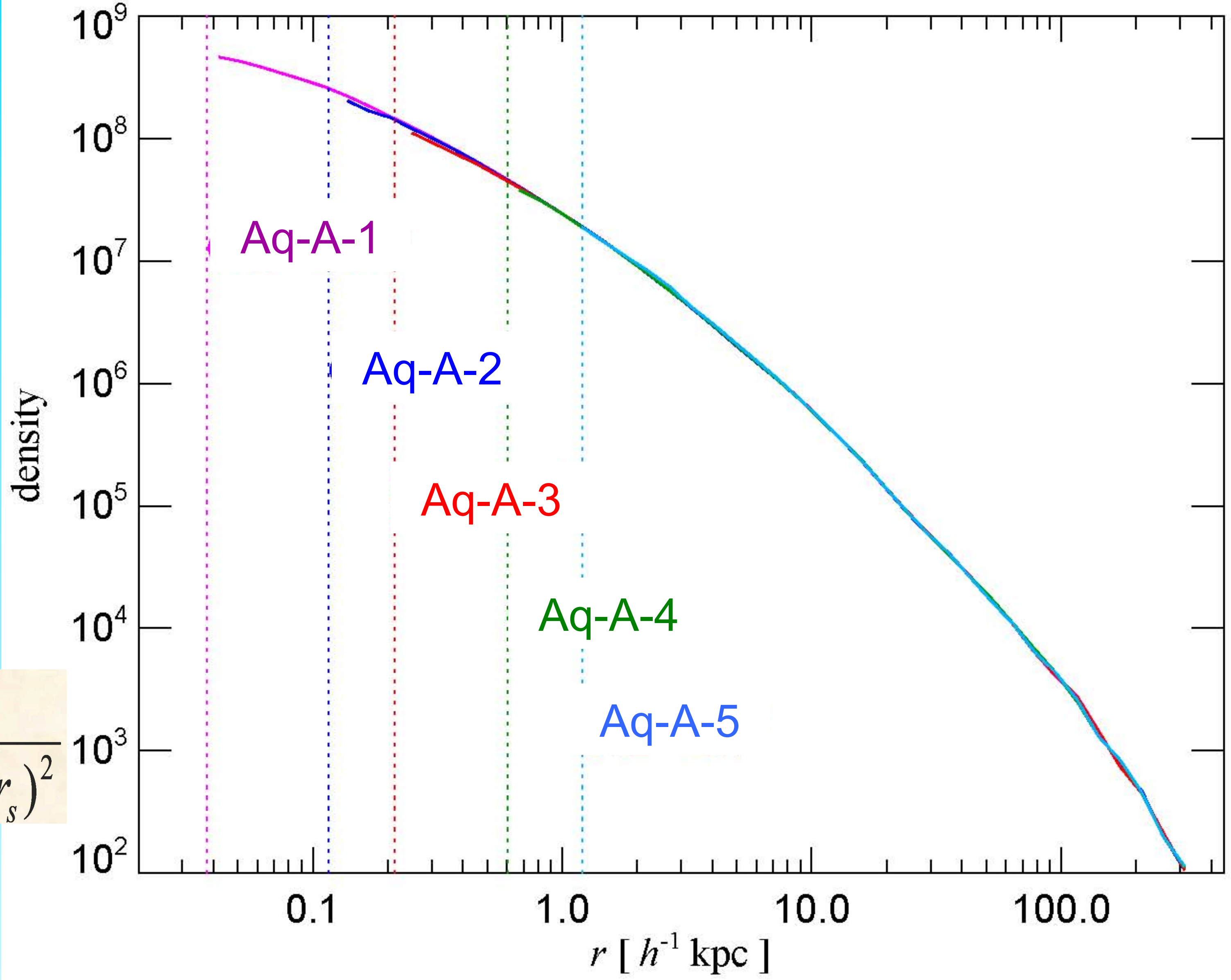
Density profile ρ(r): convergence test

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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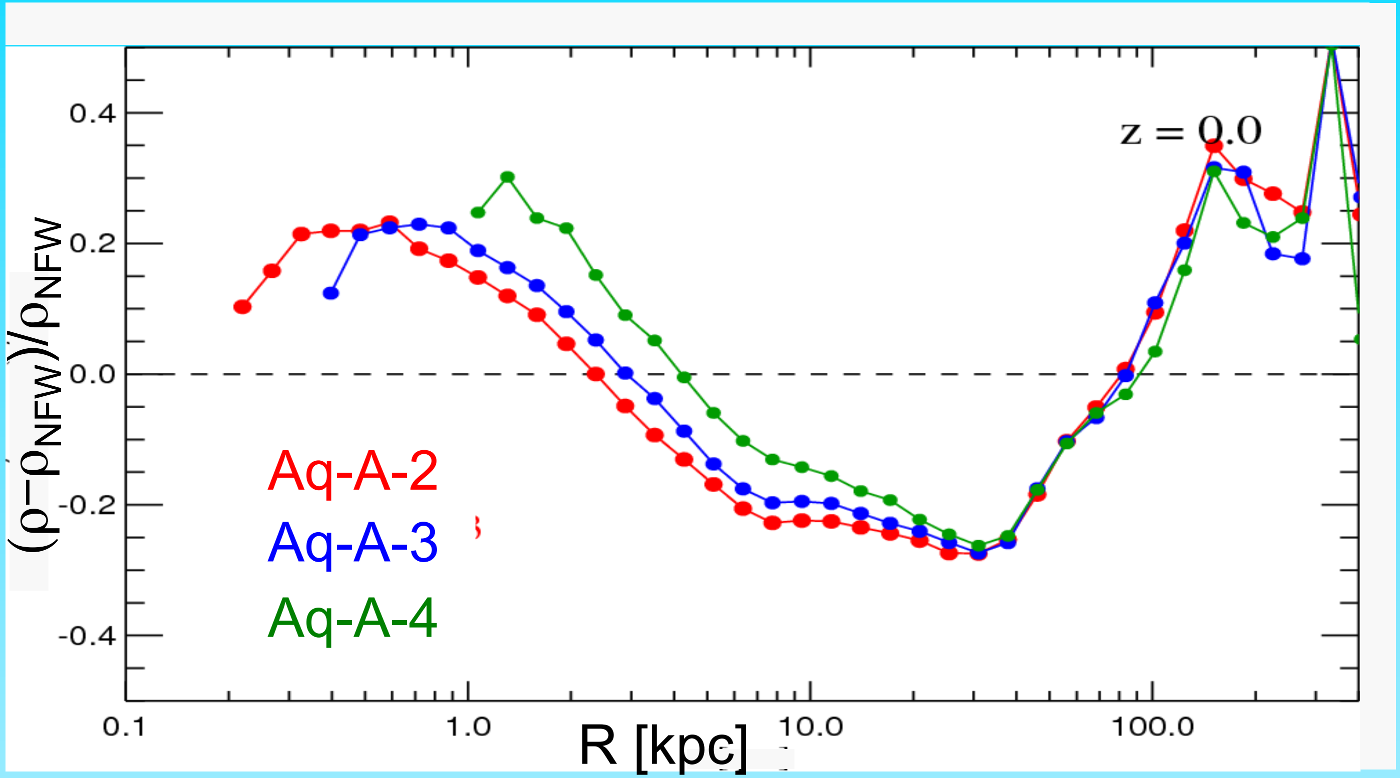
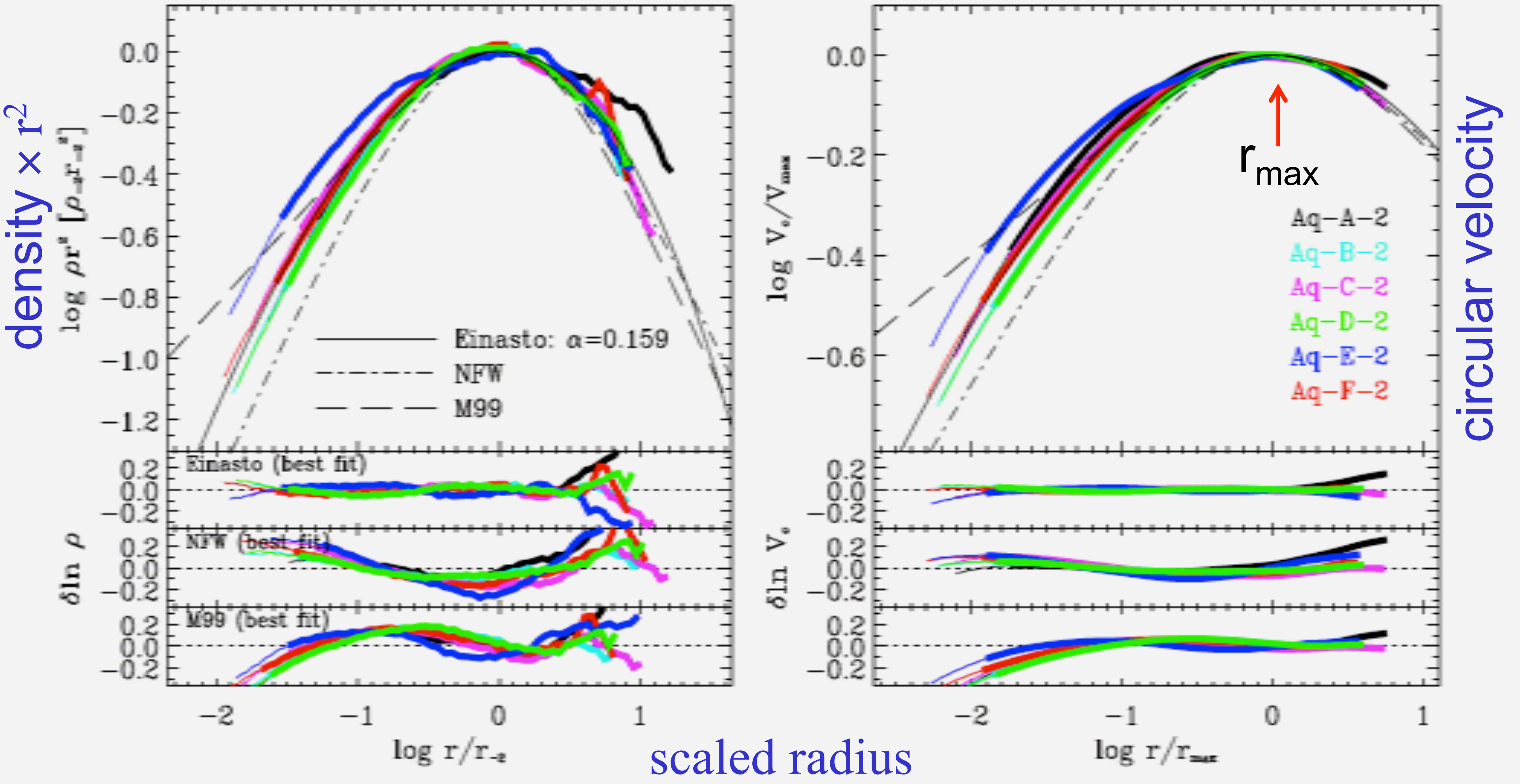
Deviations from NFW



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

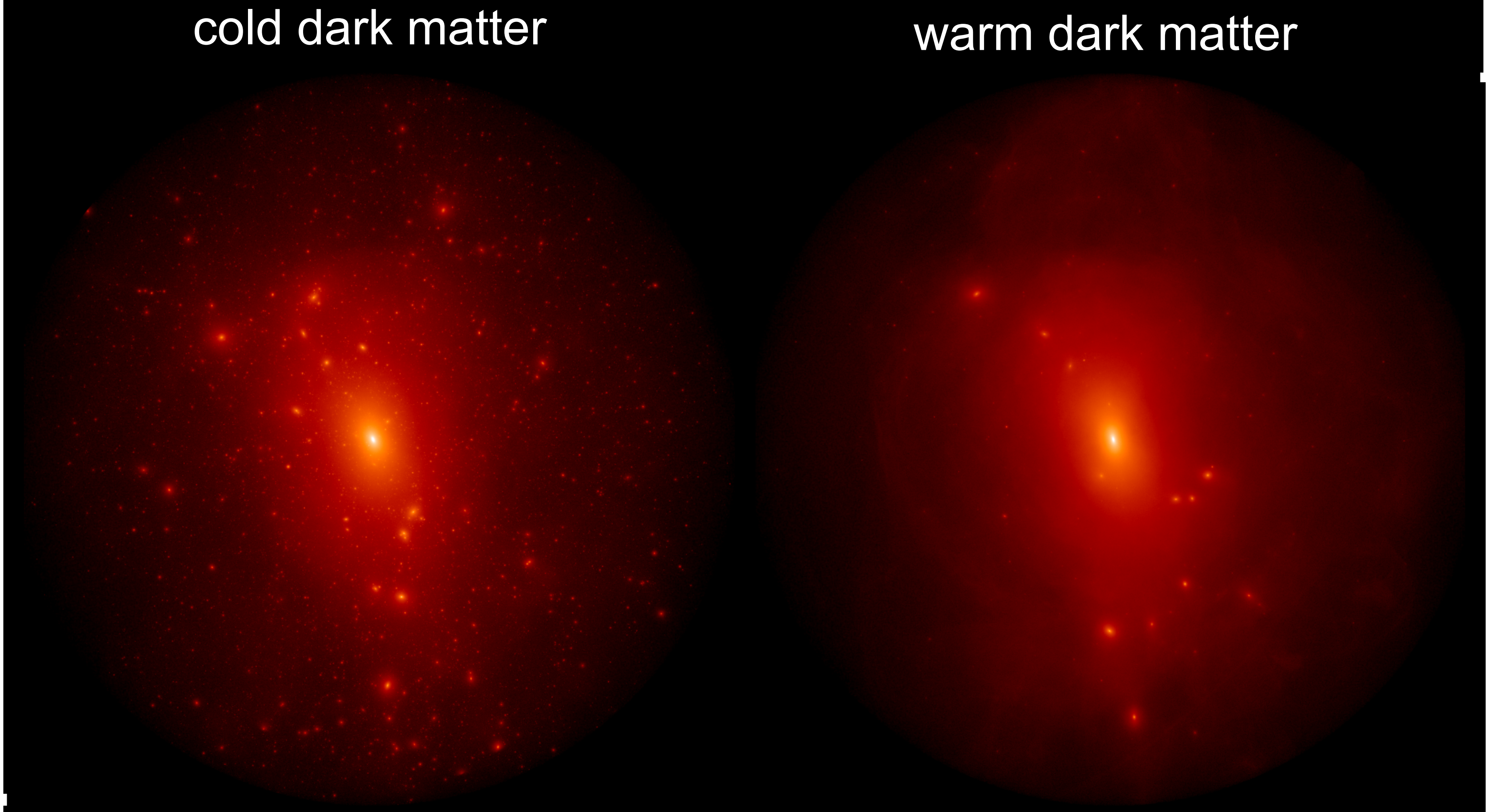
6 HALOS: LEVEL 2 RESOLUTION



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



cold dark matter

warm dark matter

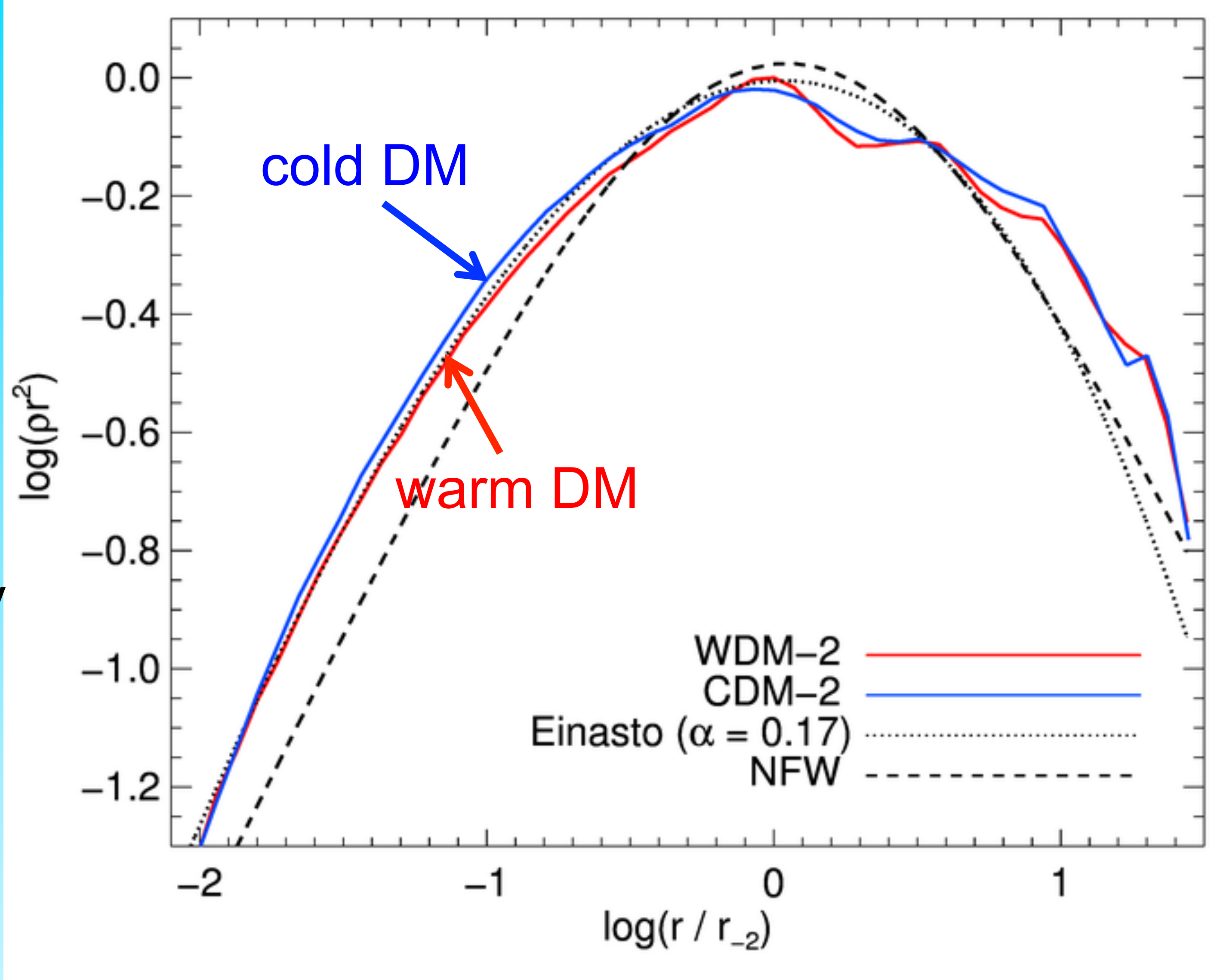
Gao, Lovell et al 2011

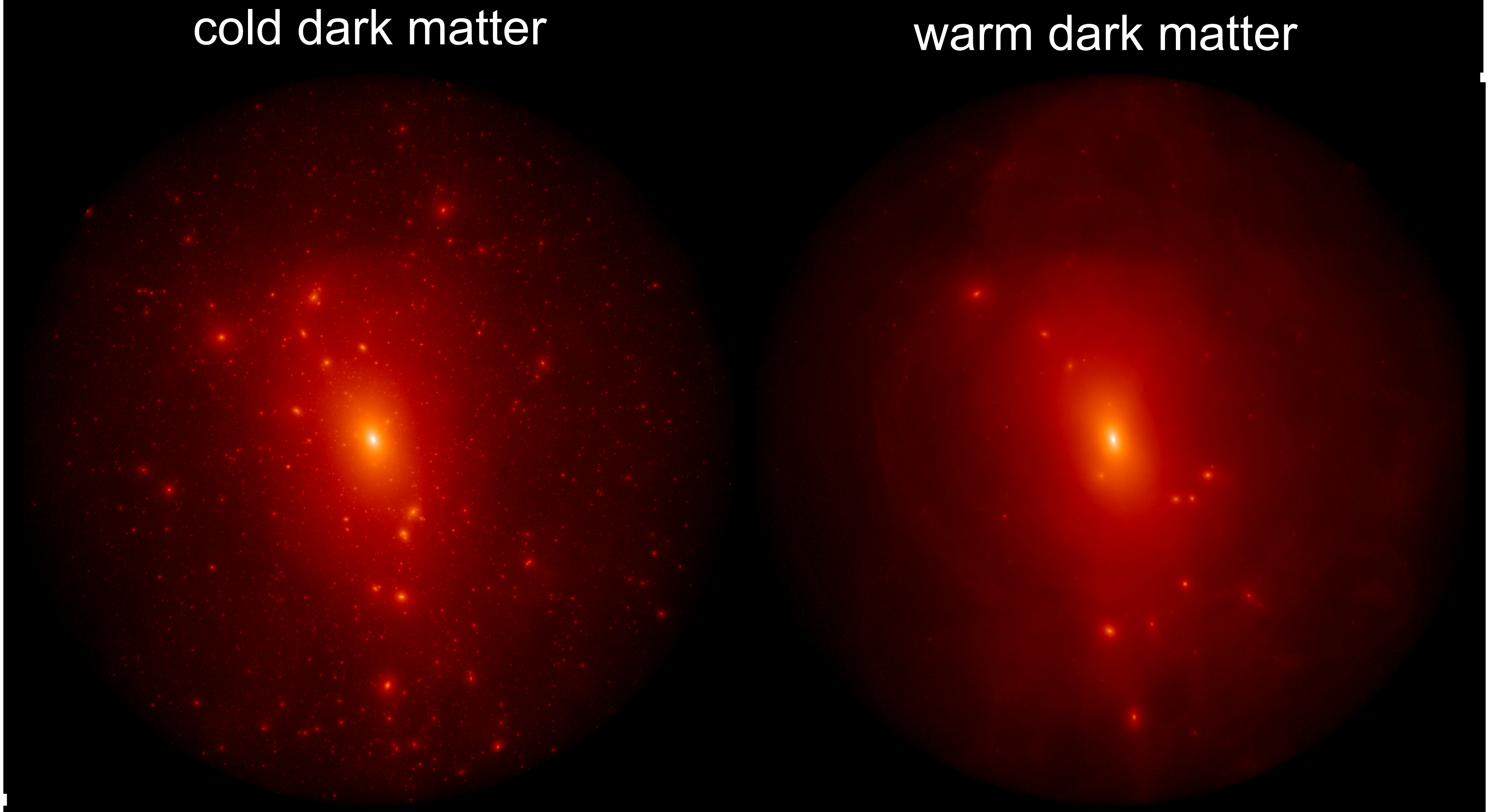
University of Durham

Density profile ρ(r)

Central cusp also exists in WDM…

but, depending on the particle mass, substructures may have cores, not cusps



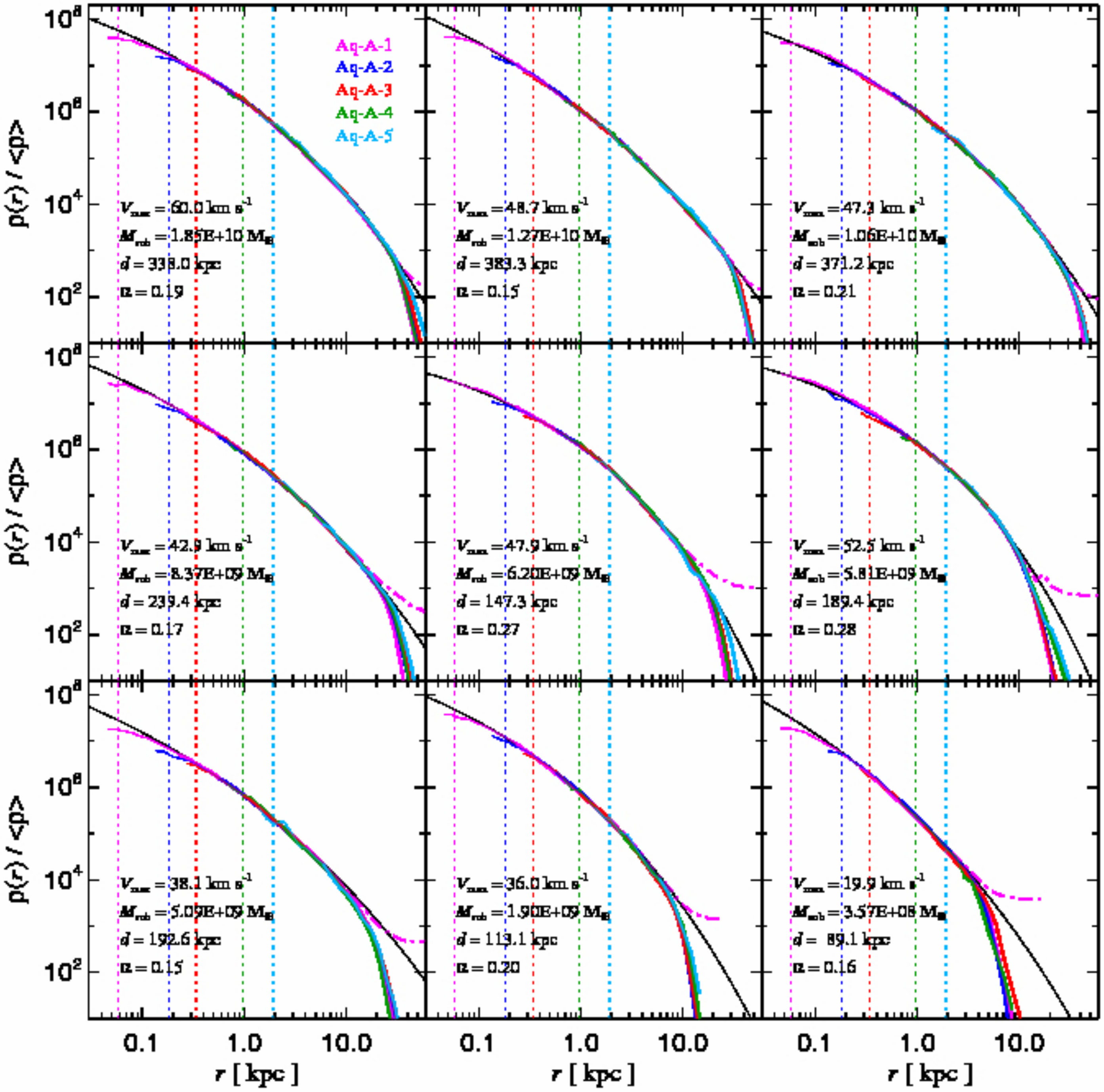


cold dark matter

warm dark matter

Gao, Lovell et al 2011

Subhalo density profiles



Well fit by Einasto

converged to
r=100pc

Springel et al'08

A cold dark matter universe

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

"Cuspy" density profiles

Does nature have them?

Look in galaxies and clusters

Halo likely to be modified by the galaxy forming in it ?

Baryons relatively less important in clusters than in halos

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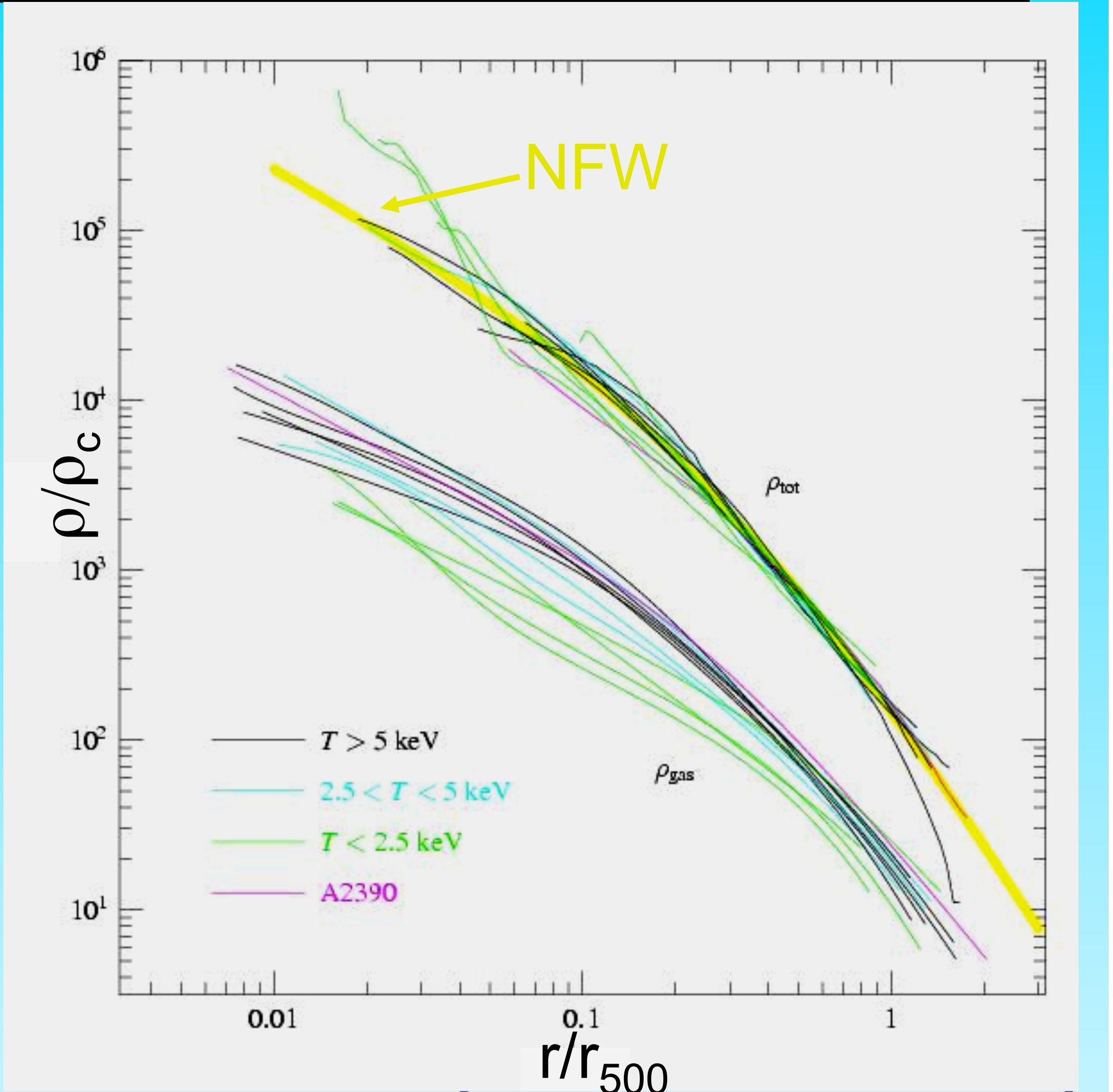
The central density profile of galaxy cluster dark halos

X-ray data

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

Excellent agreement with CDM halo predictions

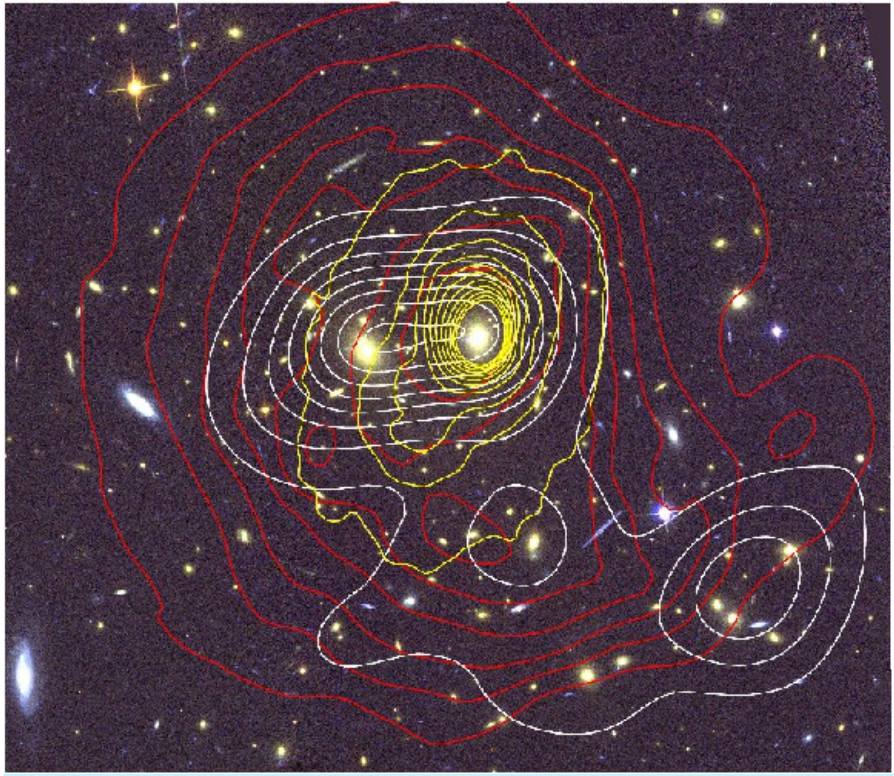


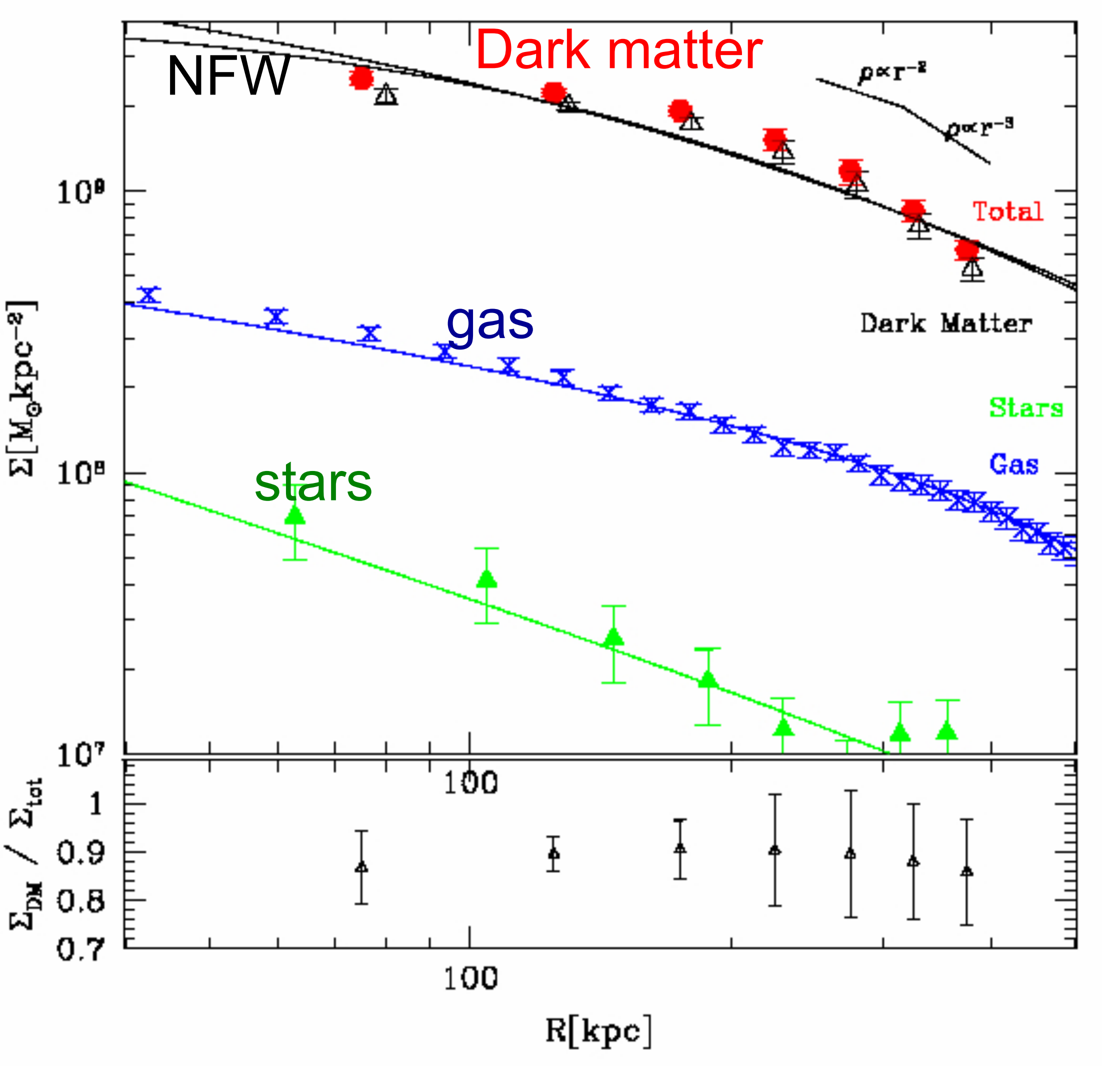
Vikhlinin et al ‘06

Dark matter profile in clusters

Rx –J1347.5

X-rays, strong and weak lensing data





Bradac et al '08

A cold dark matter universe

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

“Cuspy” density profiles ← fundamental prediction of CDM

Does nature have them?

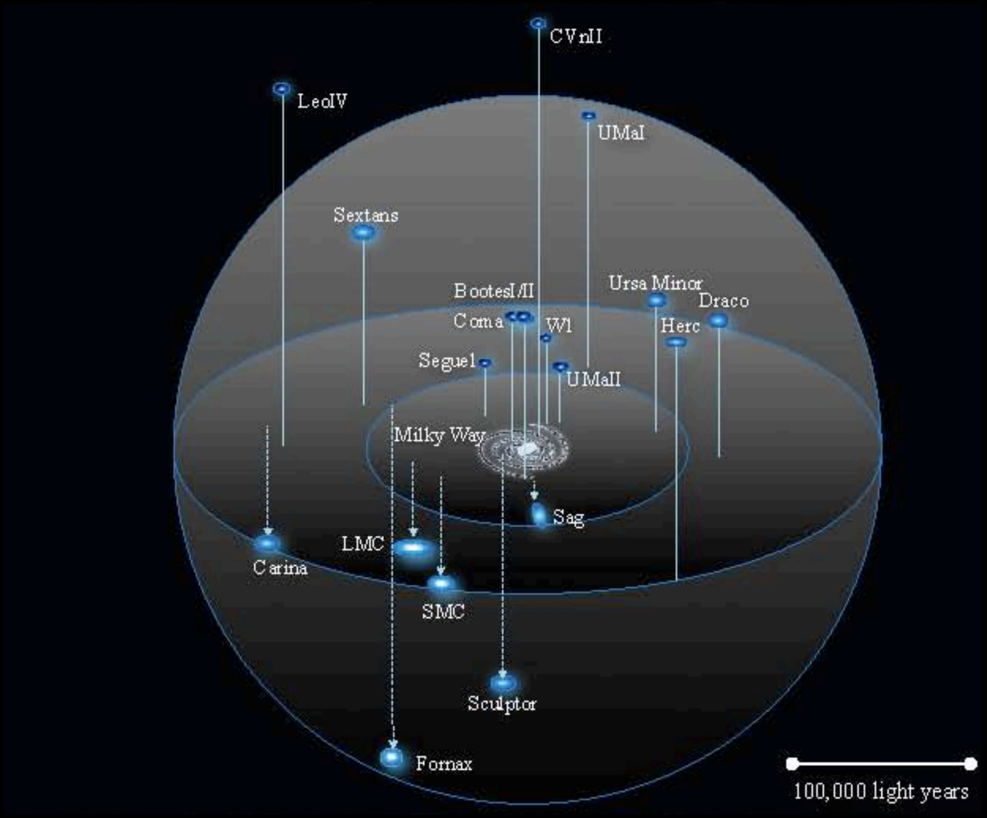
Look in galaxies and clusters

Halo could be modified by the galaxy forming in it ?

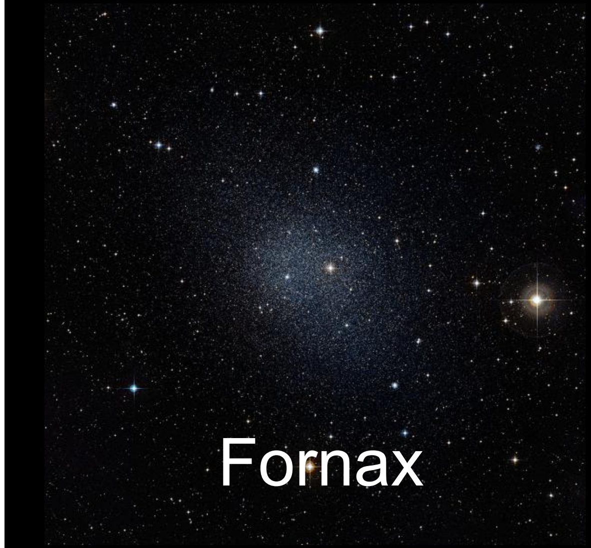
Best place to look: dwarf satellites of the MW

Dwarfs have (M/L)~1000 → baryon effects not important ?

The satellites of the Milky Way”



Dwarf galaxies around the Milky Way


Fornax


Sculptor


Leo I

© Anglo-Australian Observatory


Sextans


Carina


Sagittarius

The structure of dark matter halos

Dwarf sphs: cores or cusps?

Jeans eqn:

stellar density profile

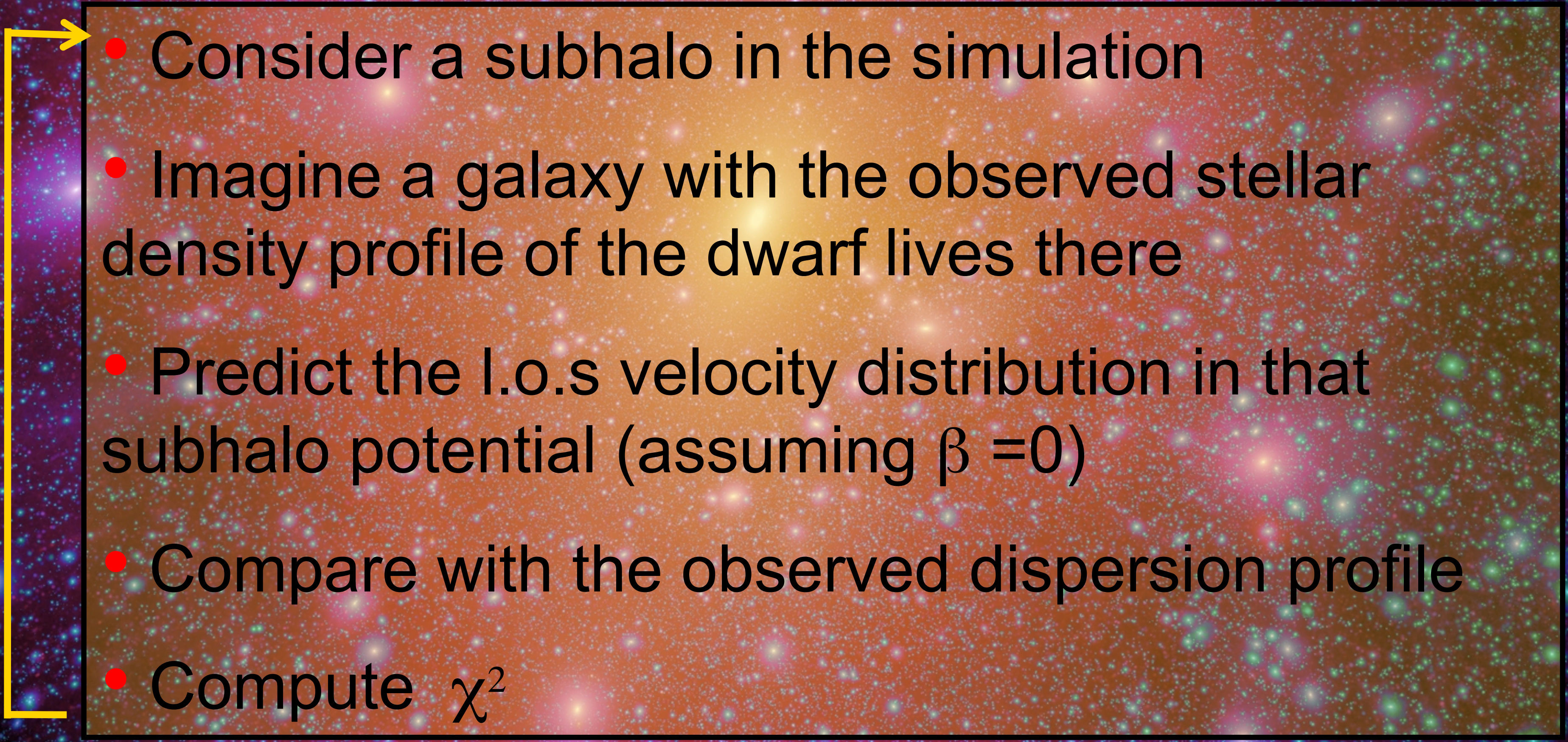
radial velocity dispersion

$$\frac{GM(r)}{r} = -\sigma_r^2 \left[\frac{d \ln \rho_*}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

from Aquarius sim

vel. anisotropy

For each dwarf spheroidal with good kinematic data



- Consider a subhalo in the simulation
- Imagine a galaxy with the observed stellar density profile of the dwarf lives there
- Predict the l.o.s velocity distribution in that subhalo potential (assuming $\beta = 0$)
- Compare with the observed dispersion profile
- Compute χ^2

Strigari, Frenk & White 2010

University of Durham

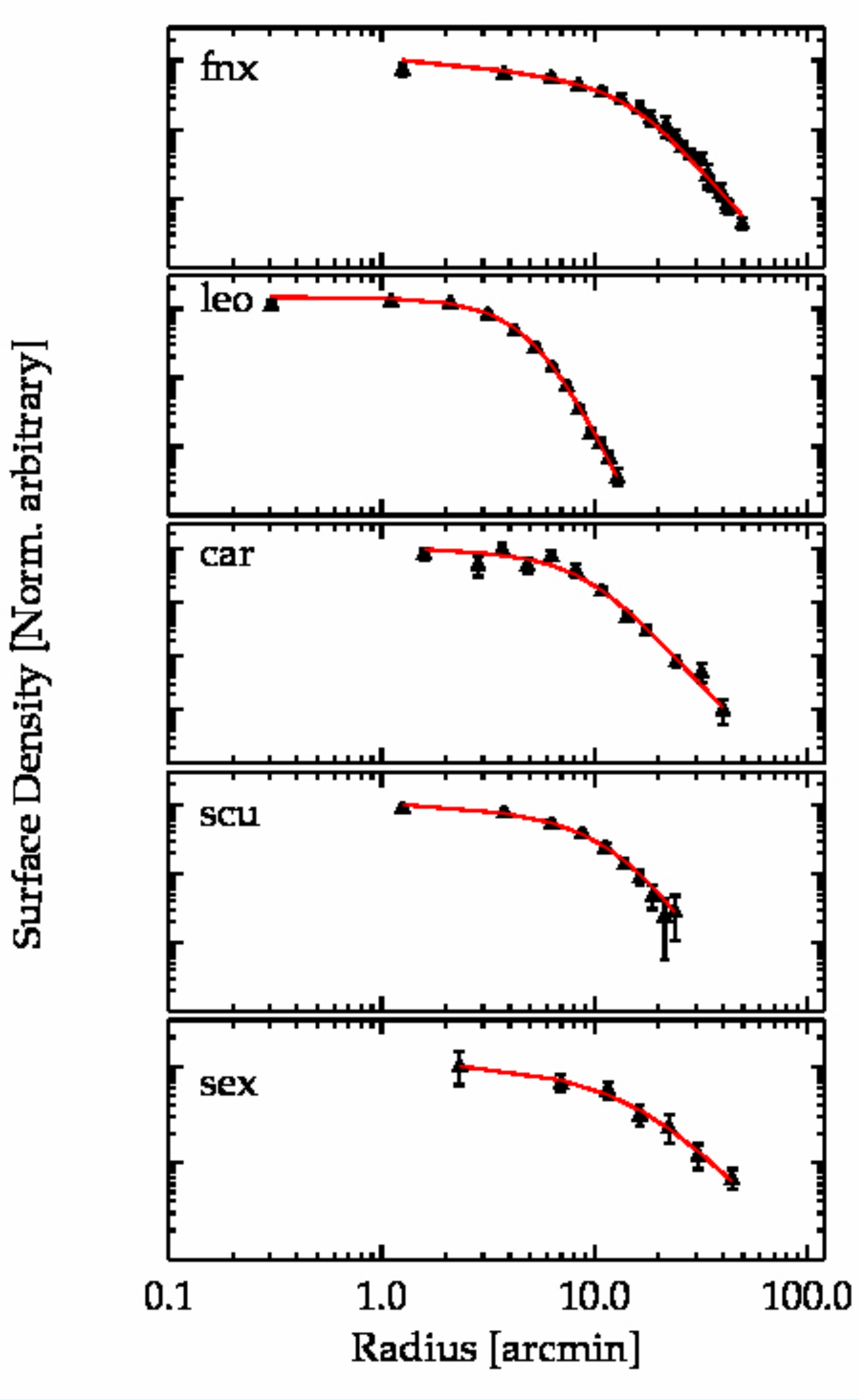
Milky Way Dwarfs

Fit stellar surface density profile with a 3D profile of the form:

$$\rho_*(r) \propto \frac{1}{x^a(1+x^b)^{(c-a)/b}}$$

Satellite	a	χ^2 /d.o.f.
Fornax	1	1.0
Leo I	0	1.6
Carina	0.5	1.1
Sculptor	0.5	0.4
Sextans	0.5	01

Strigari, Frenk & White 2010



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Dwarf sphs: cores or cusps?

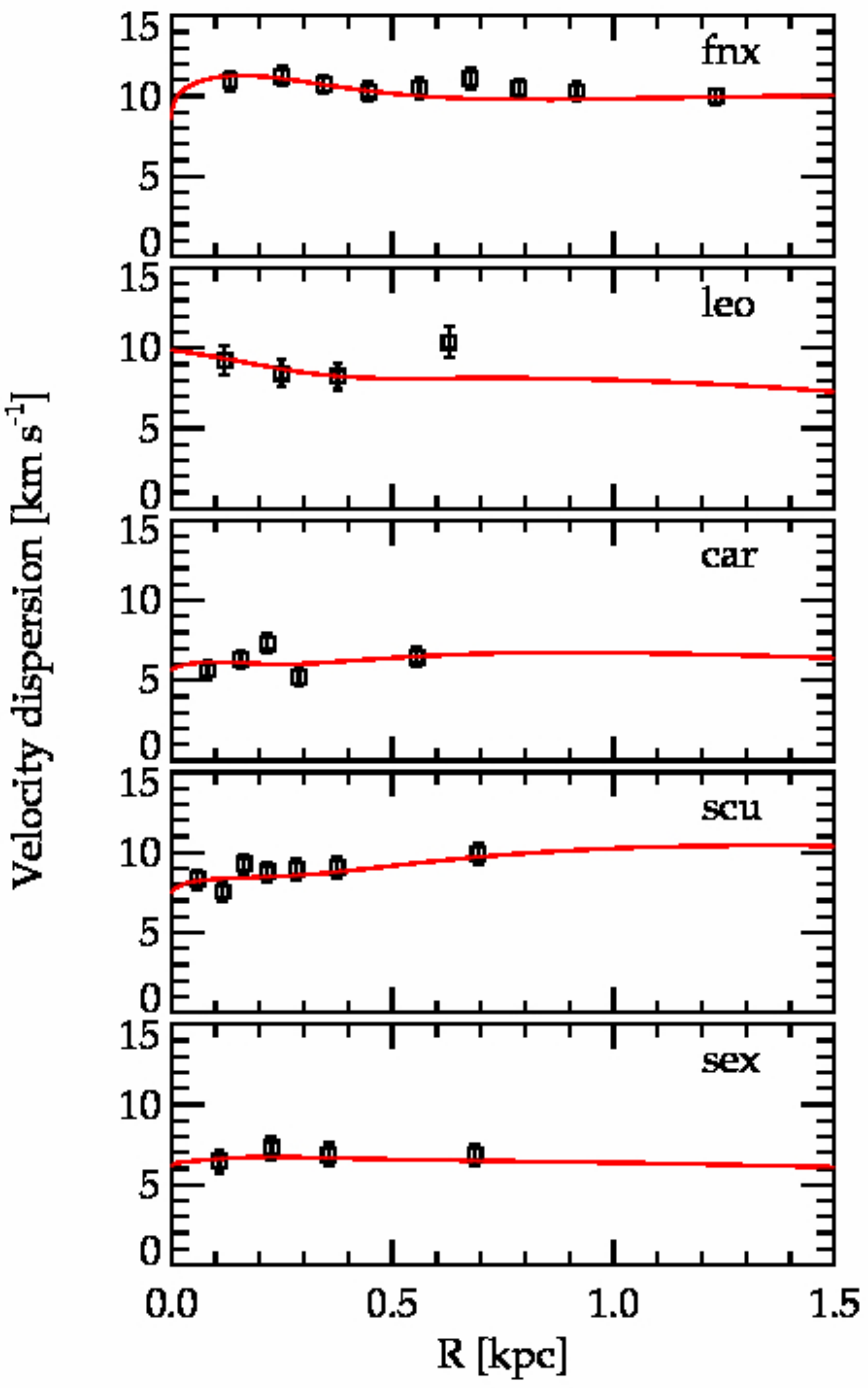
Jeans eqn:

$$\frac{GM(r)}{r} = -\sigma_r^2\left[\frac{d\ln\rho_*}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

from Aquarius sim

vel. anisotropy

- Assume isotropic orbits
- Solve for σ_r (r)
- Compare with observed σ_r (r)
- Find "best fit" subhalo



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Dwarf sphs: cores or cusps?

Jeans eqn:

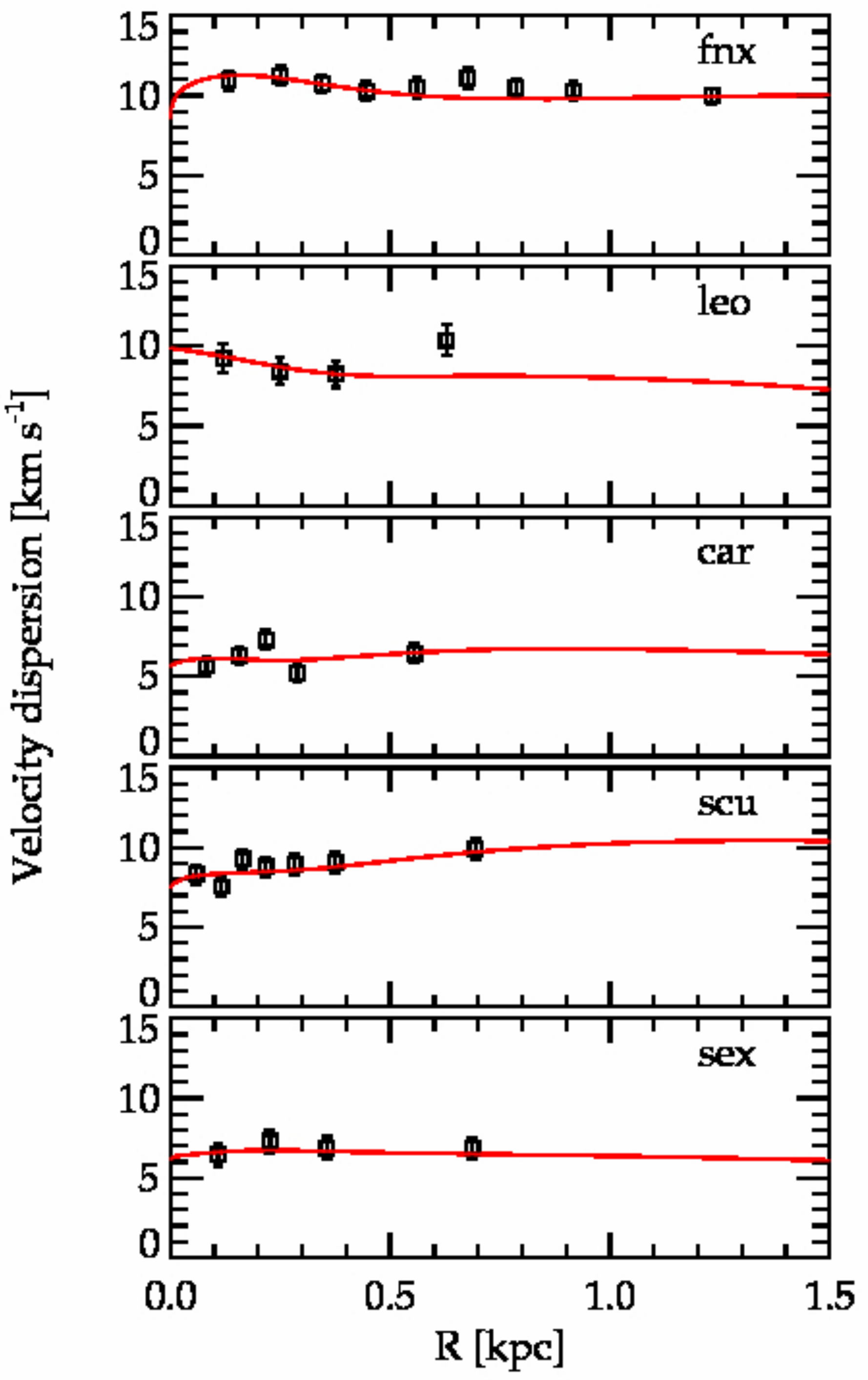
$$\frac{GM(r)}{r} = -\sigma_r^2\left[\frac{d\ln\rho_*}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right]$$

from Aquarius sim

vel. anisotropy

1-p= prob. that “best fit” can be rejected

Satellite	**1-p**
Fornax	0.4
Leo I	0.5
Carina	0.4
Sculptor	0.8
Sextans	0.2



Strigari, Frenk & White 2010

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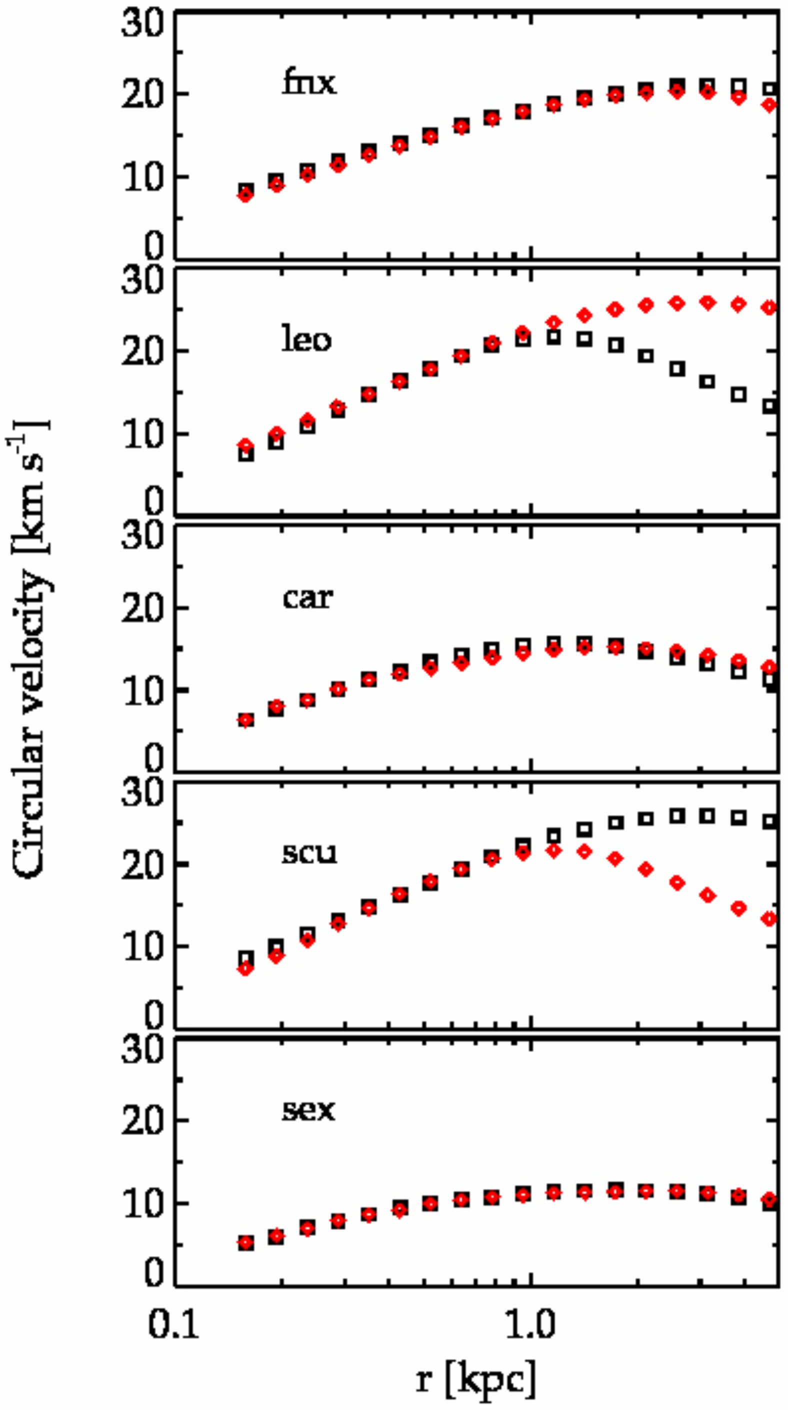

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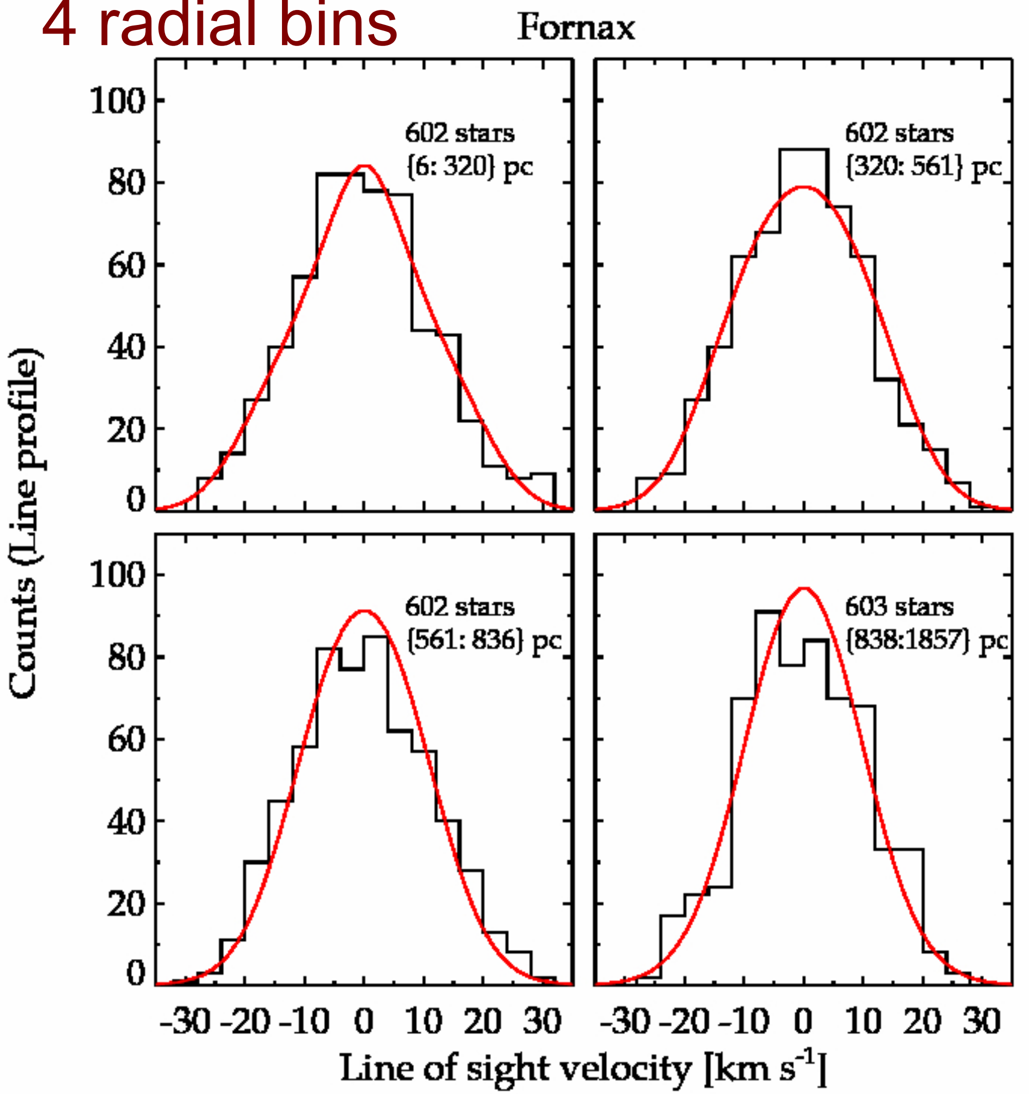
Velocity distribution function

$$f(\varepsilon) = \frac{1}{\sqrt{8}\pi^2} \int_{\varepsilon}^{0} \frac{d^2\rho_*}{d\Psi^2} \frac{d\Psi}{\sqrt{\Psi - \varepsilon}}$$

$$\varepsilon = \Psi(r) + v^2/2$$

4 radial bins



KS rejection probability

Satellite	b1	b2	b3	b4
Fornax	0.95	0.85	.997	0.98
Leo I	0.54	0.48	0.69	.997
Carina	0.49	0.56	0.71	0.66
Sculptor	0.68	0.32	0.38	0.33
Sextans	0.59	0.19	0.97	0.03

Strigari, Frenk & White 2010

Velocity distribution function

$$f(\varepsilon) = \frac{1}{\sqrt{8}\pi^2} \int_{\varepsilon}^{0} \frac{d^2\rho_*}{d\Psi^2} \frac{d\Psi}{\sqrt{\Psi - \varepsilon}}$$

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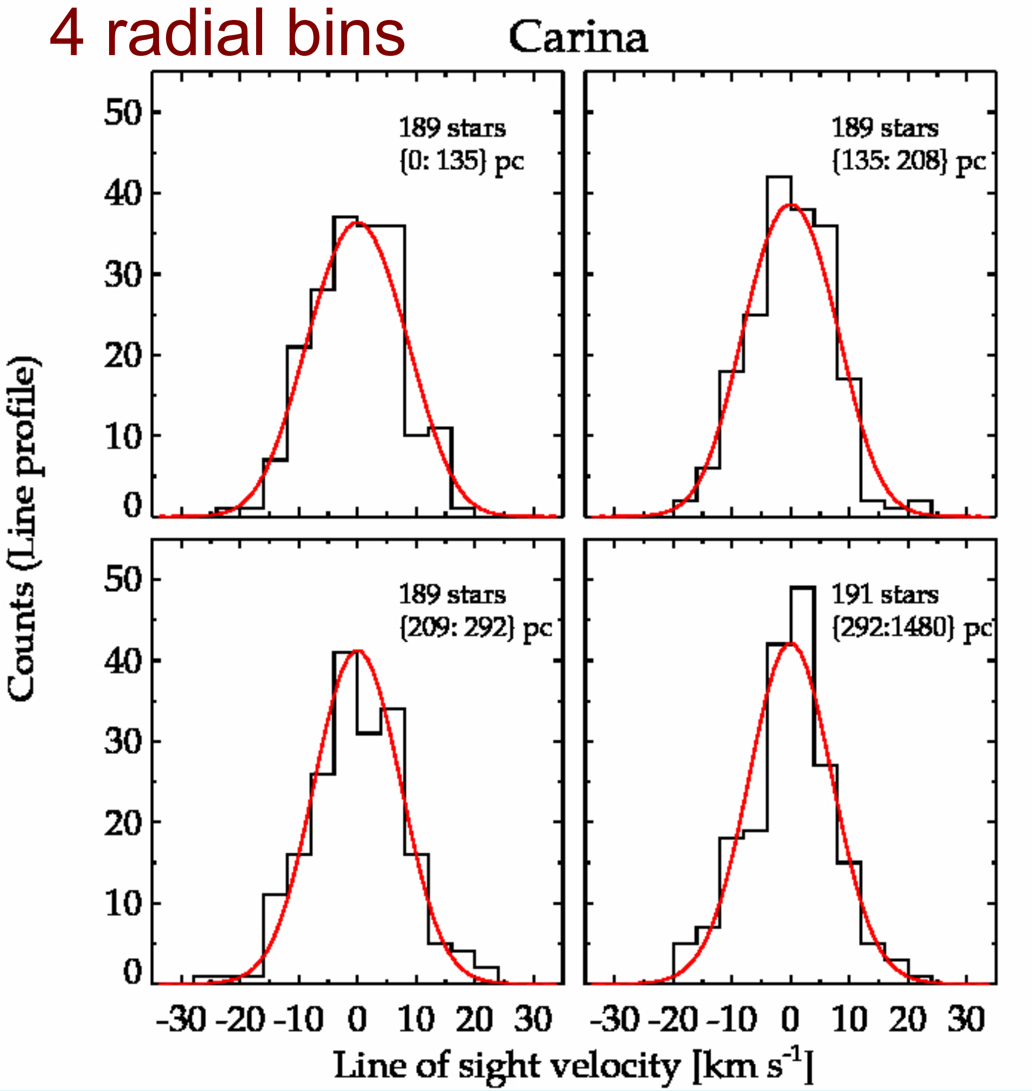

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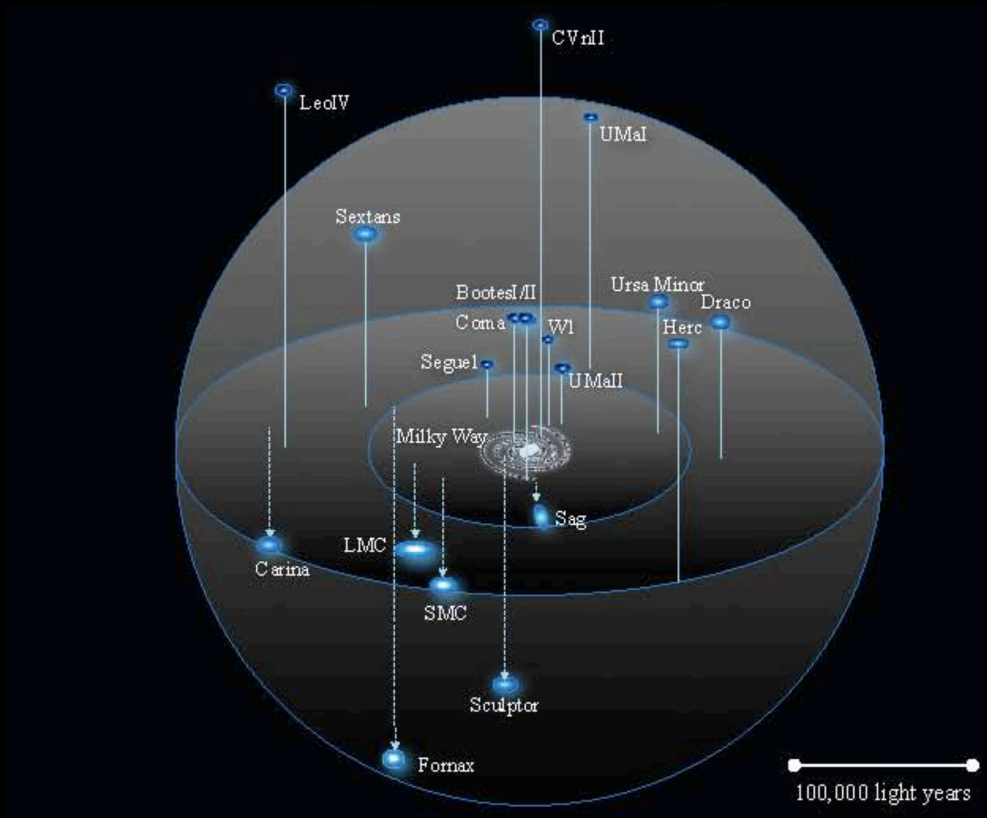
Sextans	0.59	0.19	0.97	0.03

Strigari, Frenk & White 2010

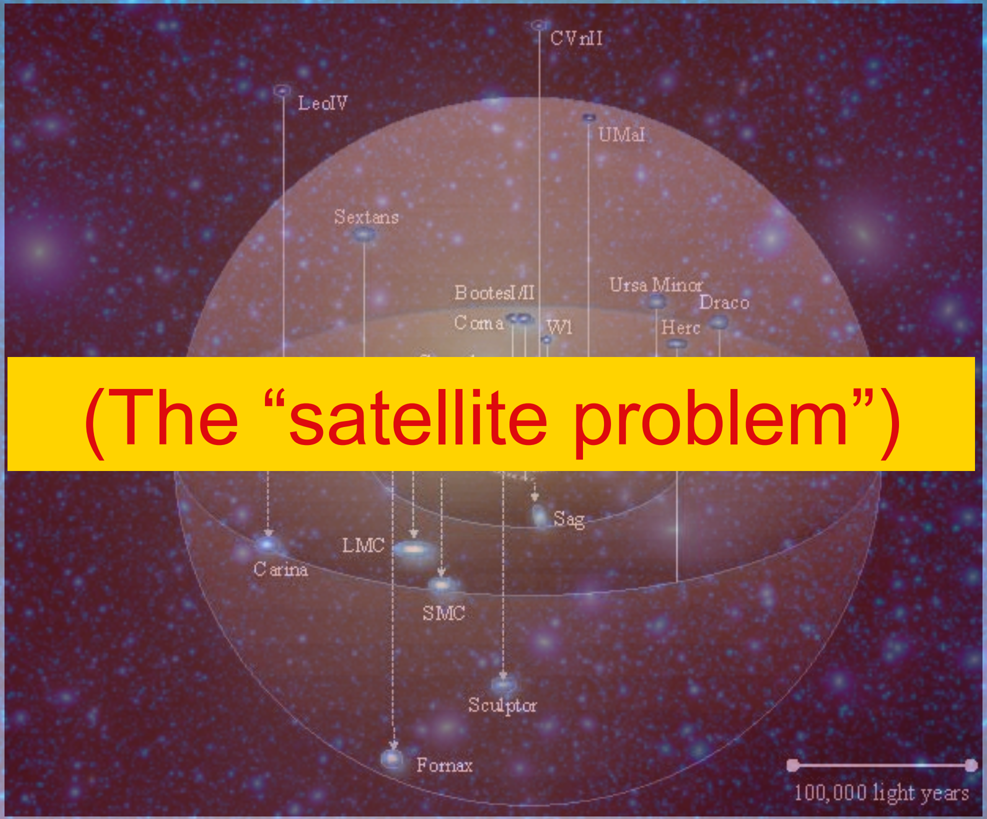
Cluster and satellite data consistent with cuspy dark halos

Does CDM predict the right number of satellites?



Simulations produce >10^5 subhalos

Simulations produce >10^5 subhalos

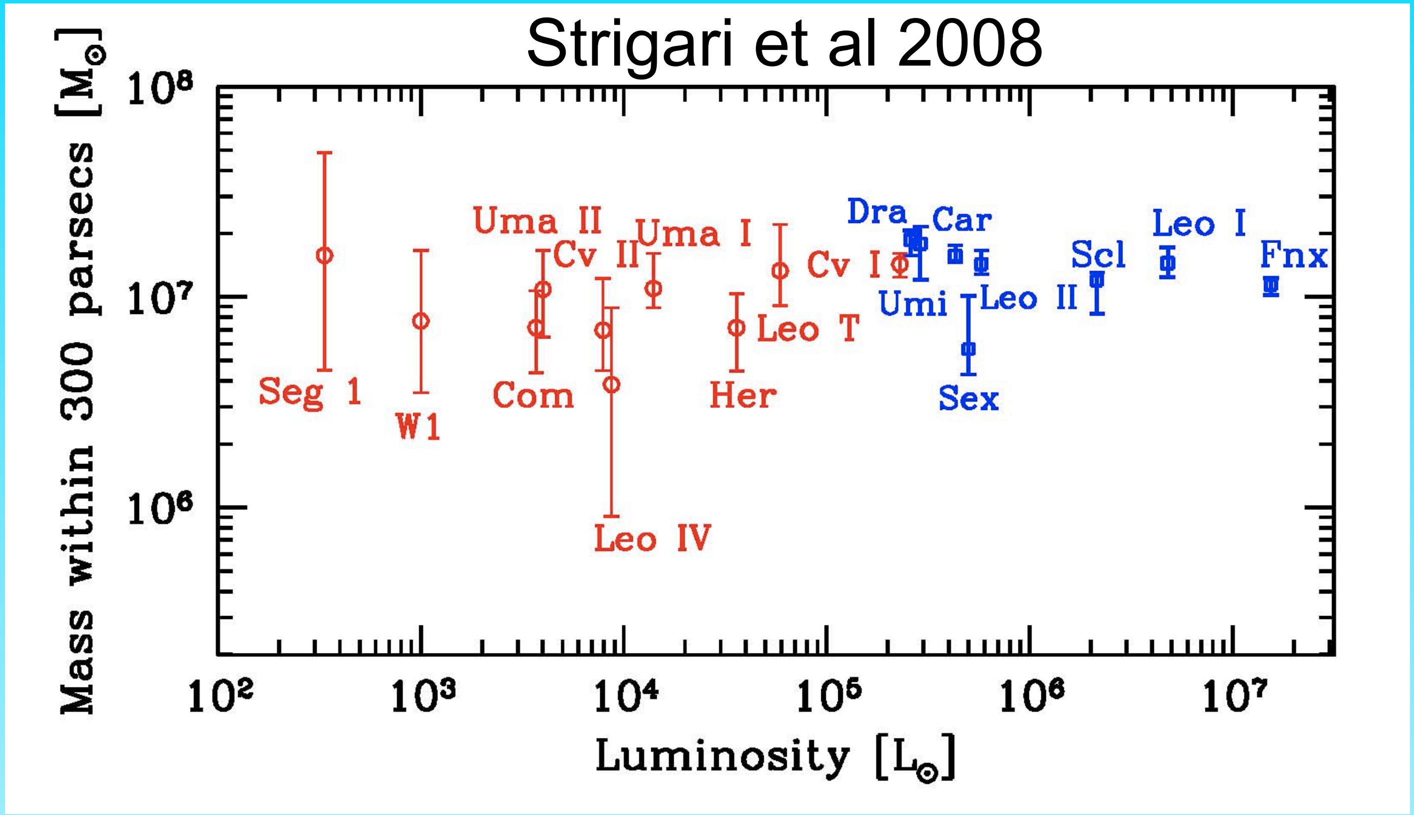


(The “satellite problem”)

But only a few tens of satellites have been discovered in the Milky Way

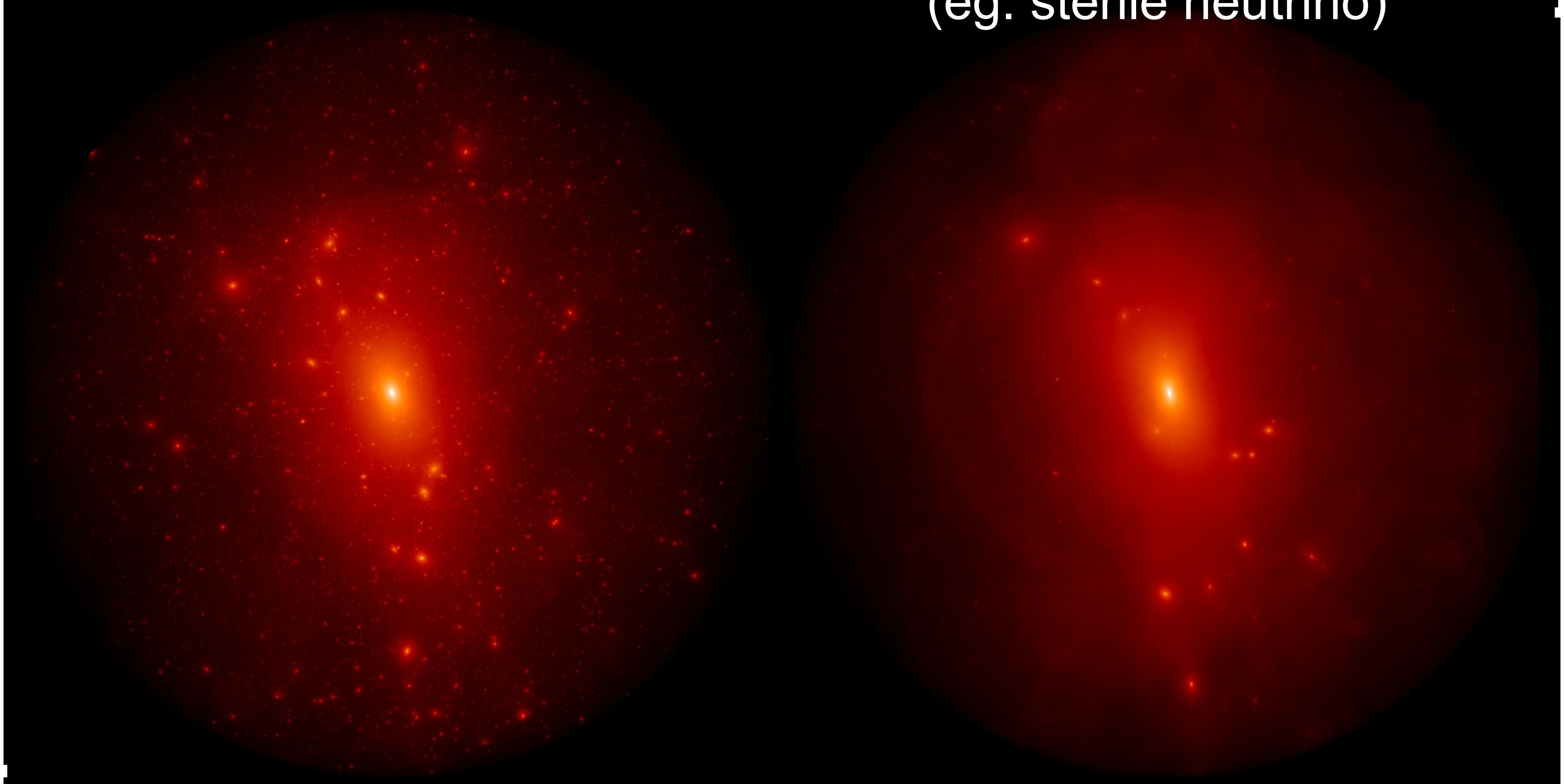
University of Durham

A special scale in cosmology?



Is this special scale due to:

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



cold dark matter

warm dark matter
(eg. sterile neutrino)

Gao, Lovell et al 2011

Halo substructures

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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)

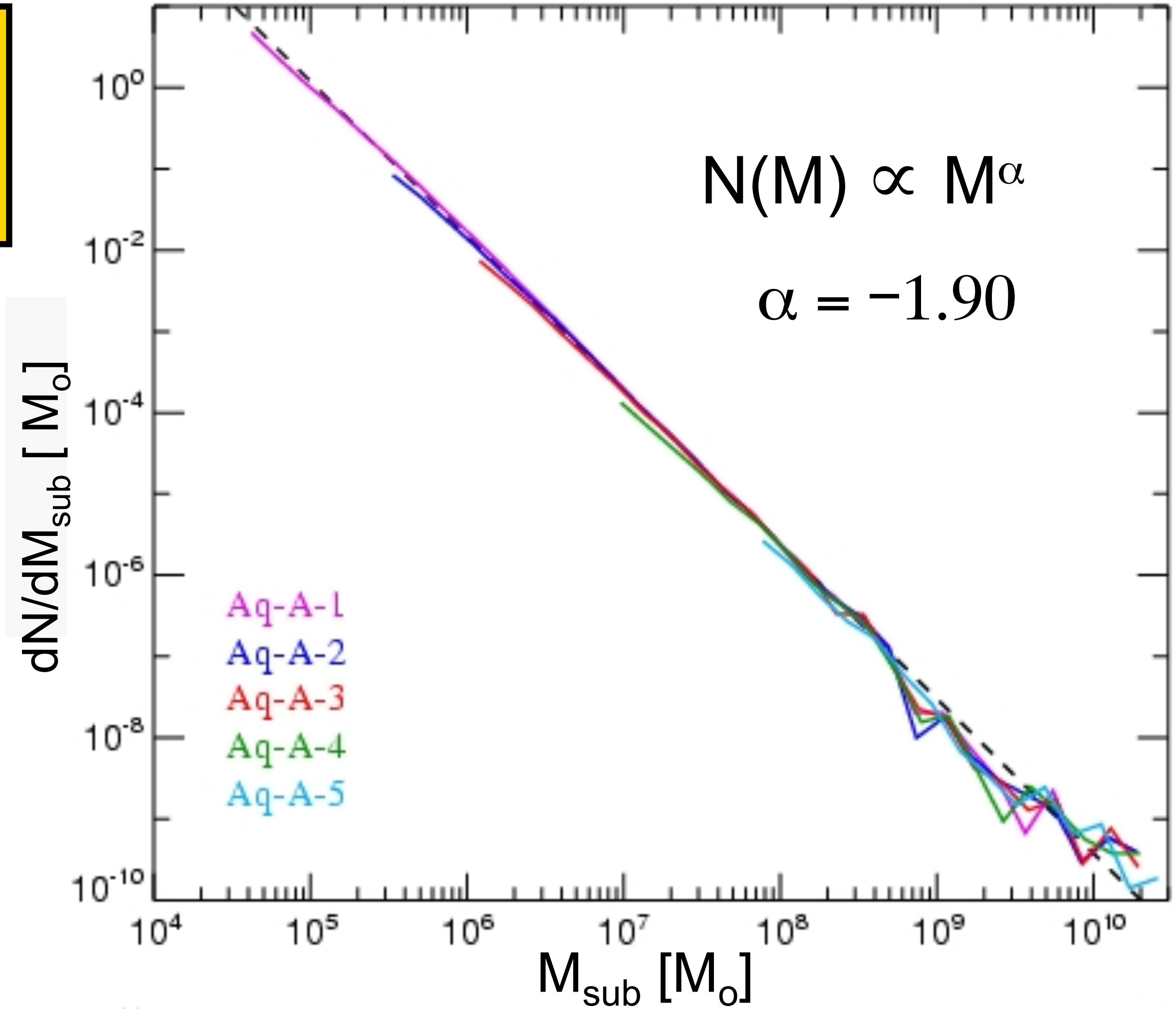
Springel et al ‘08

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

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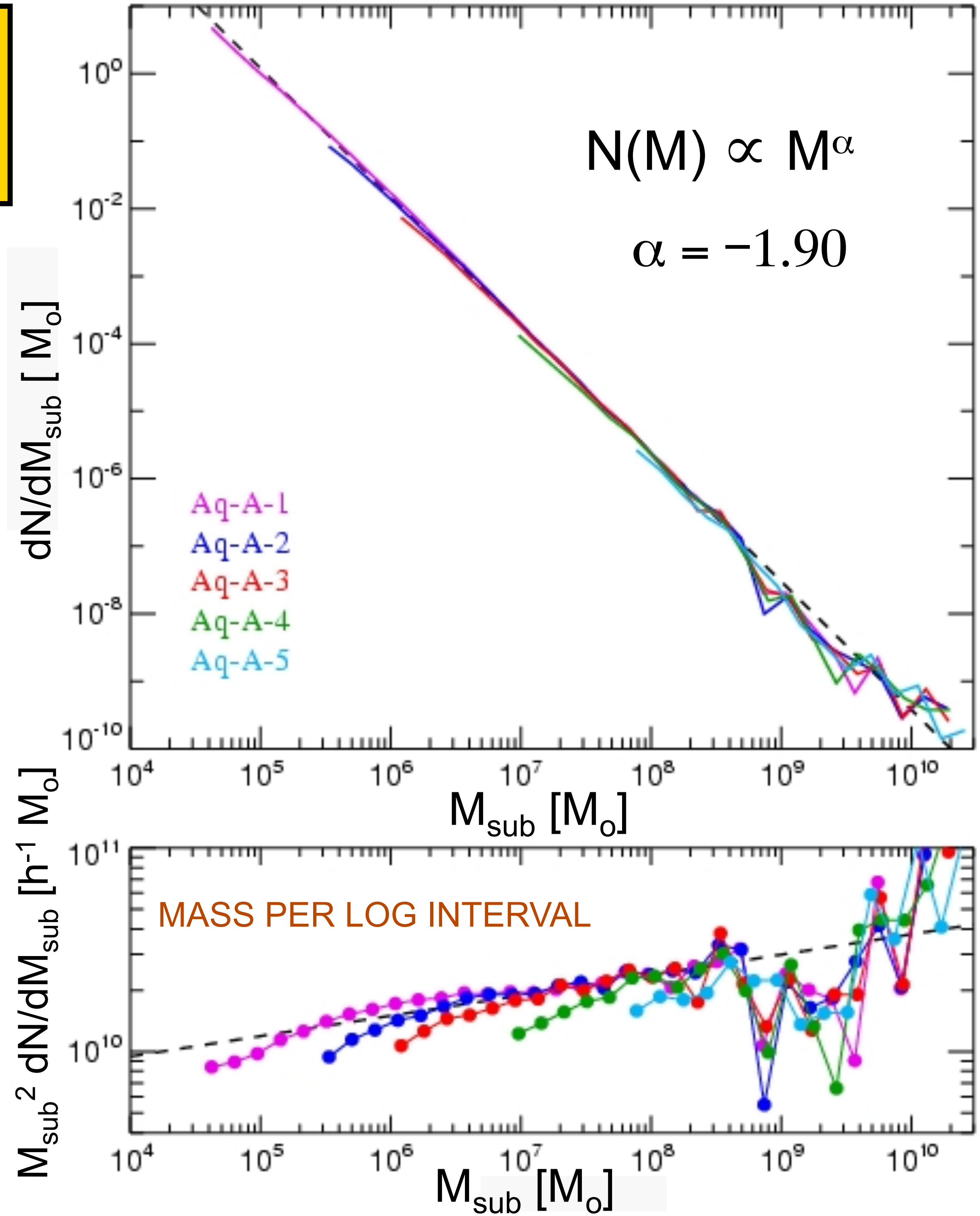
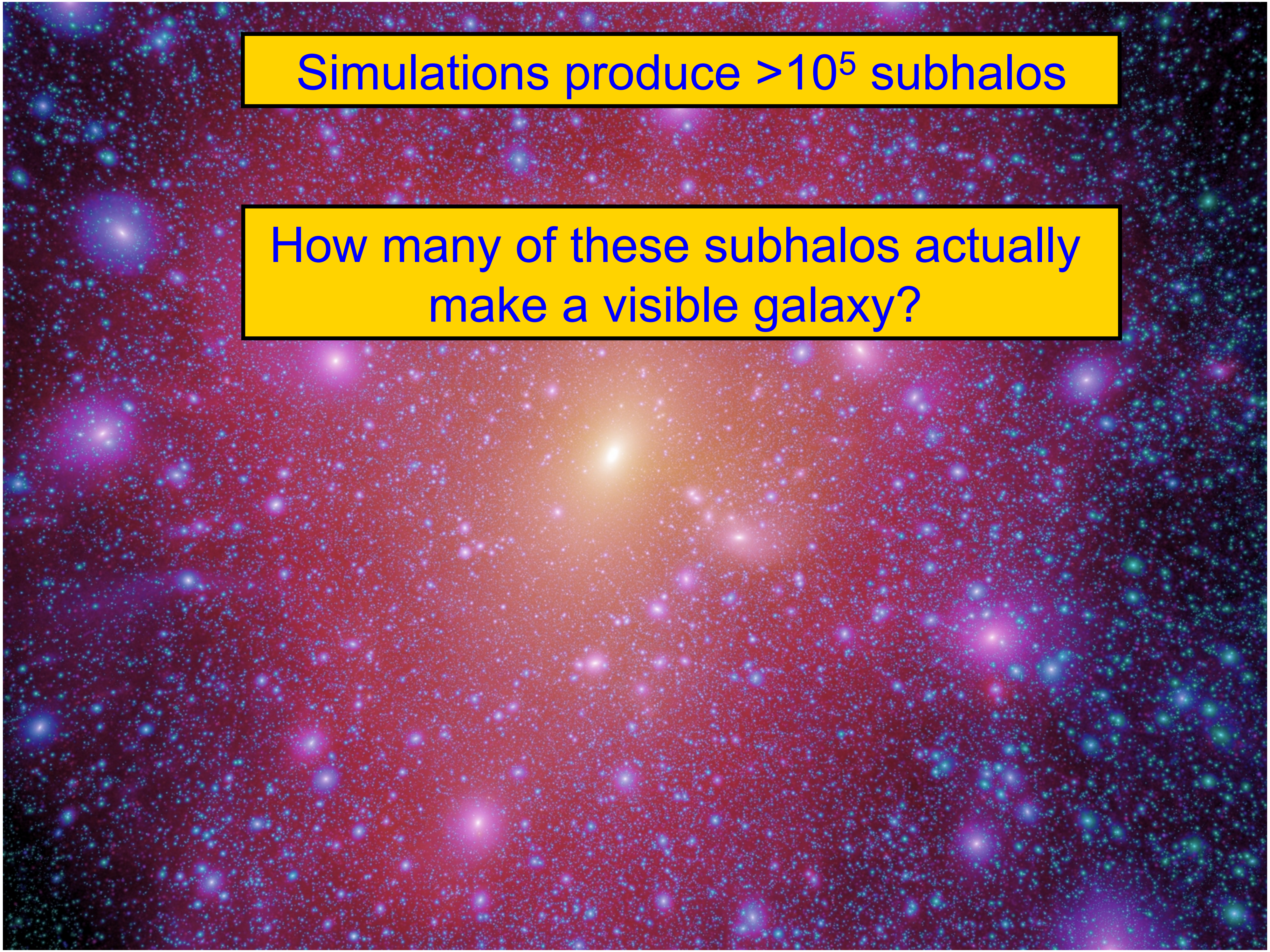
Virgo consortium
Springel et al 08

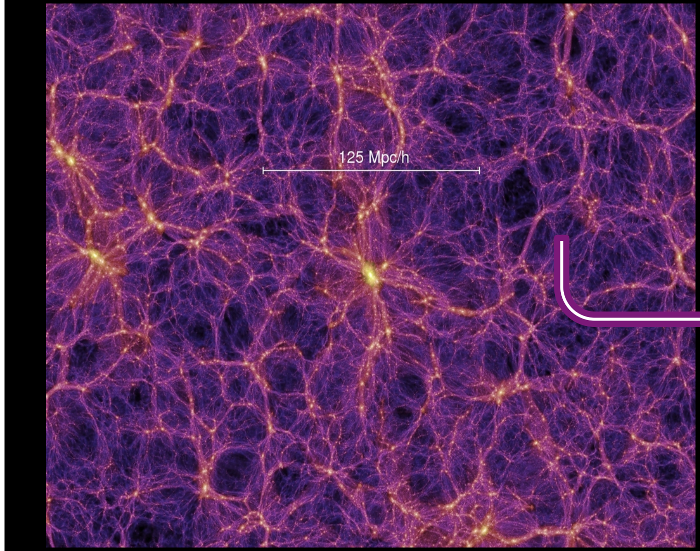


Simulations produce $>10^5$ subhalos

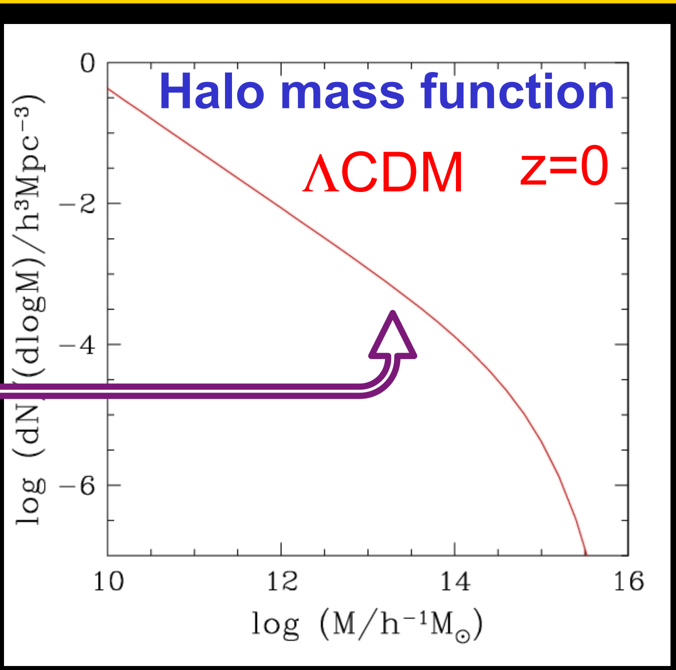


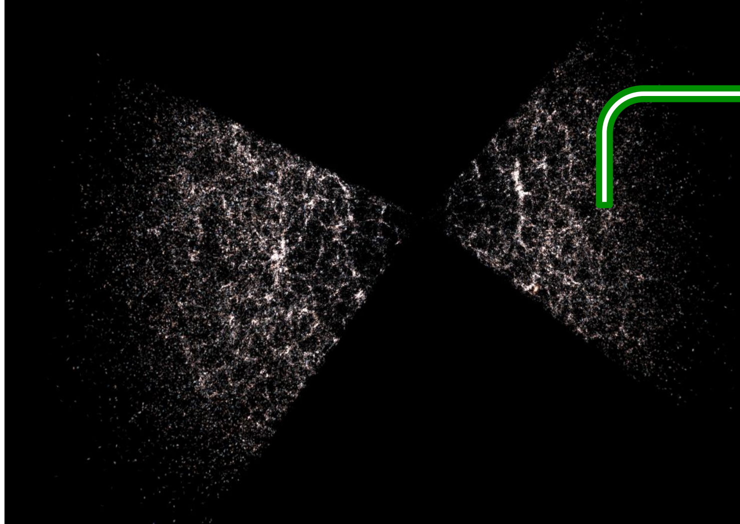
How many of these subhalos actually make a visible galaxy?

The abundance of dark halos

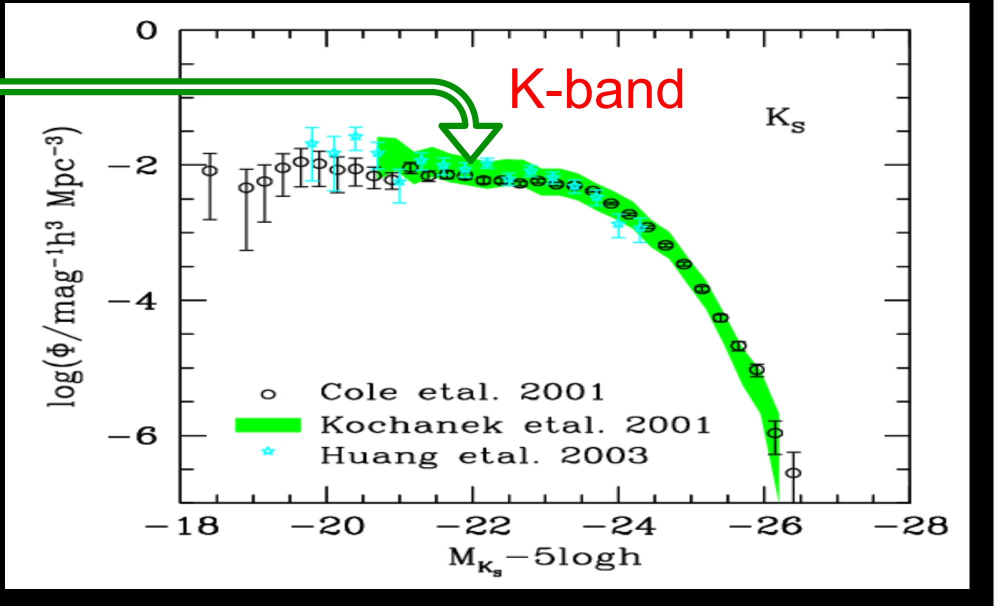


Millennium run





2dFGRS



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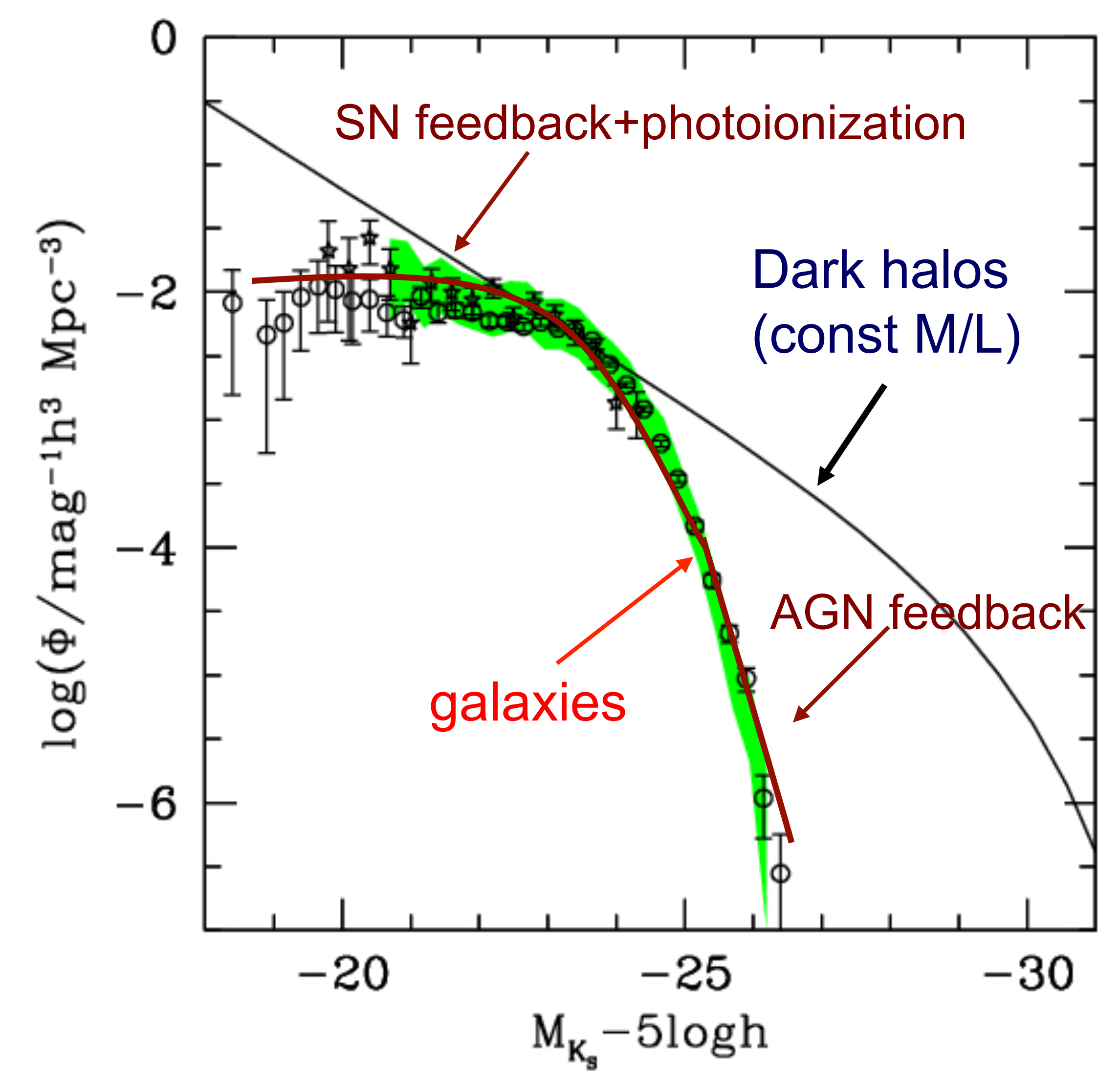
The galaxy luminosity function

The halo mass function and the galaxy luminosity function have different shapes

⇨

Complicated variation of M/L with halo mass



Benson, Bower, Frenk, Lacey, Baugh & Cole ‘03

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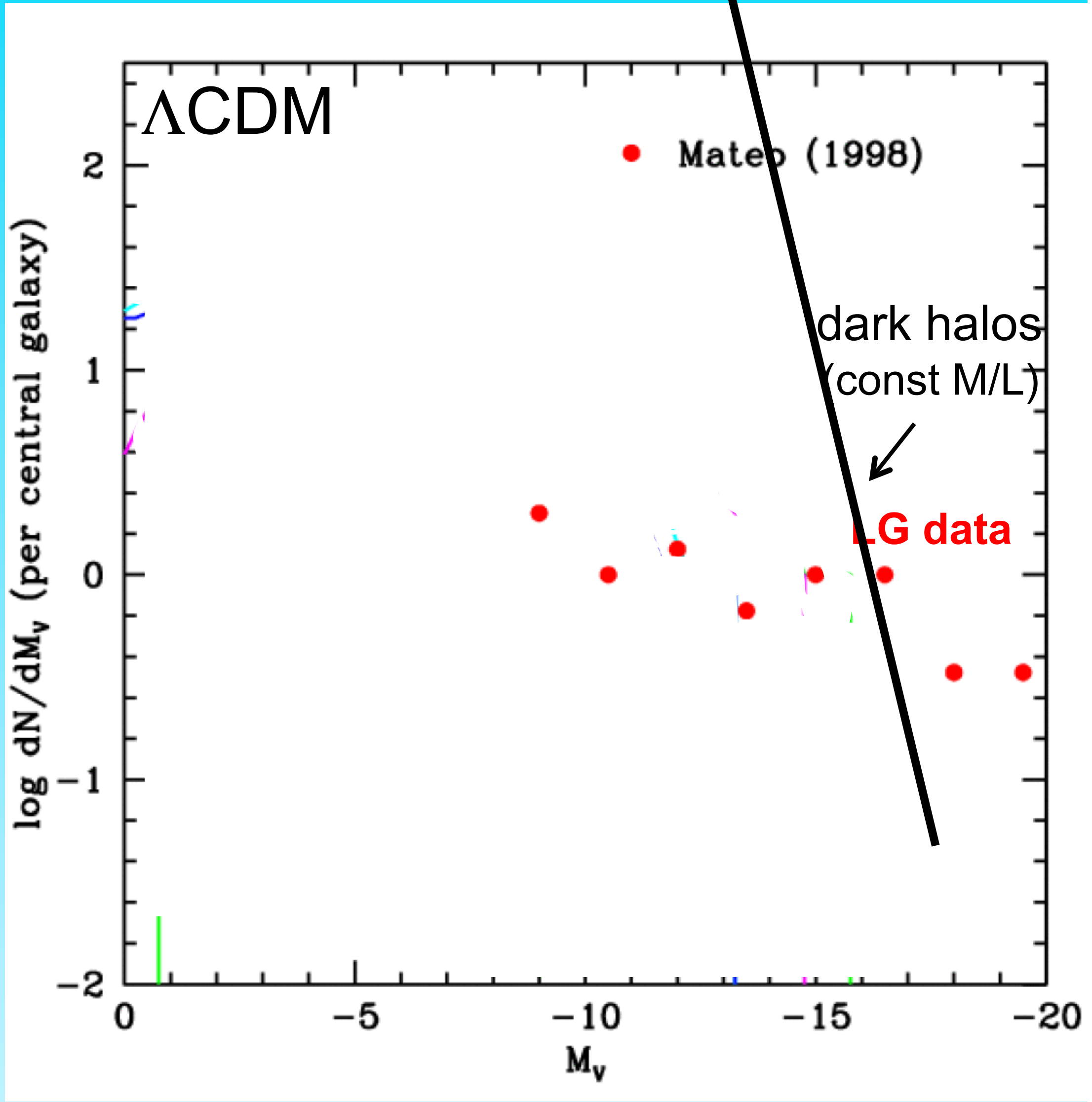
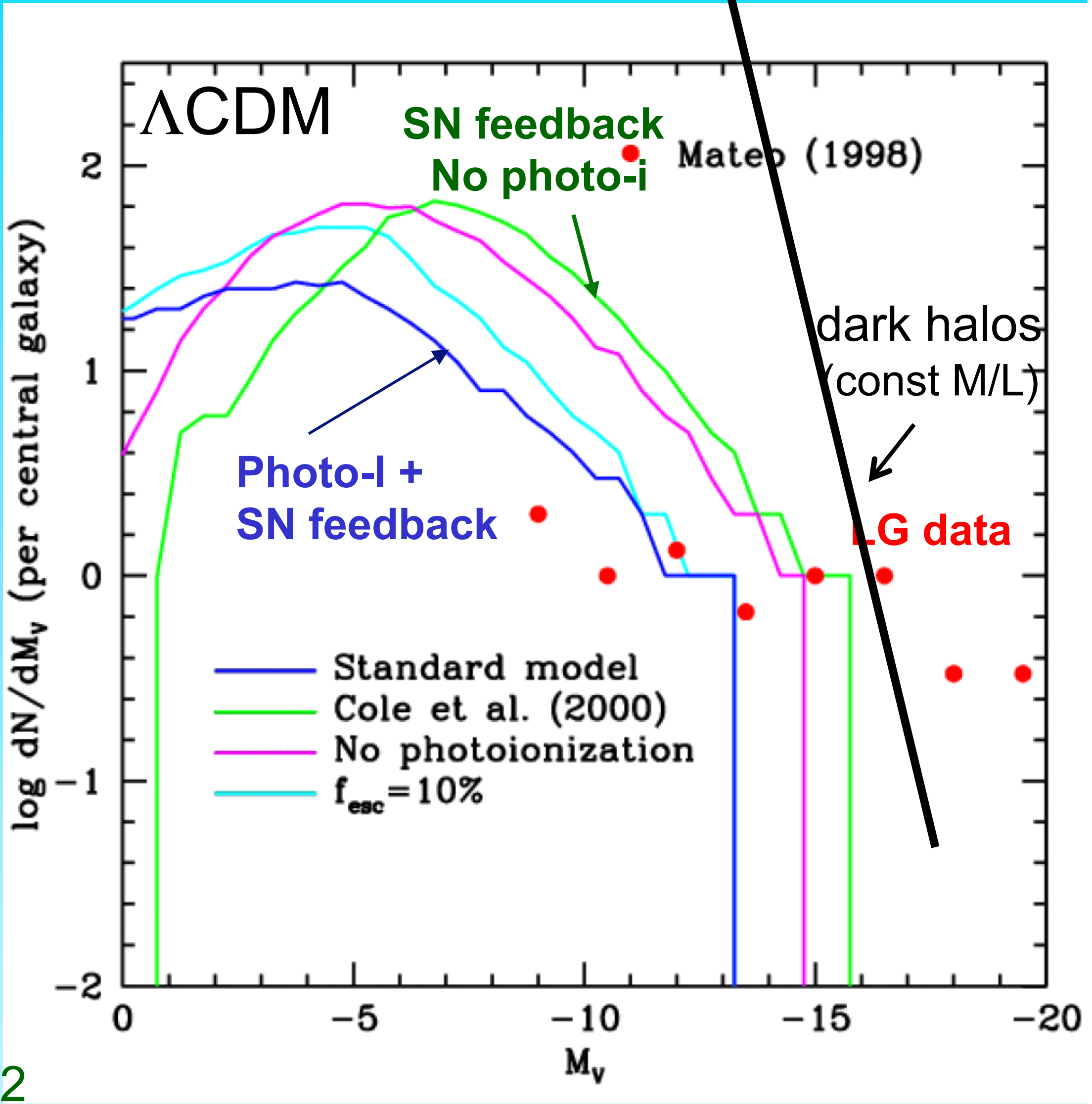
Luminosity Function of Local Group Satellites



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)

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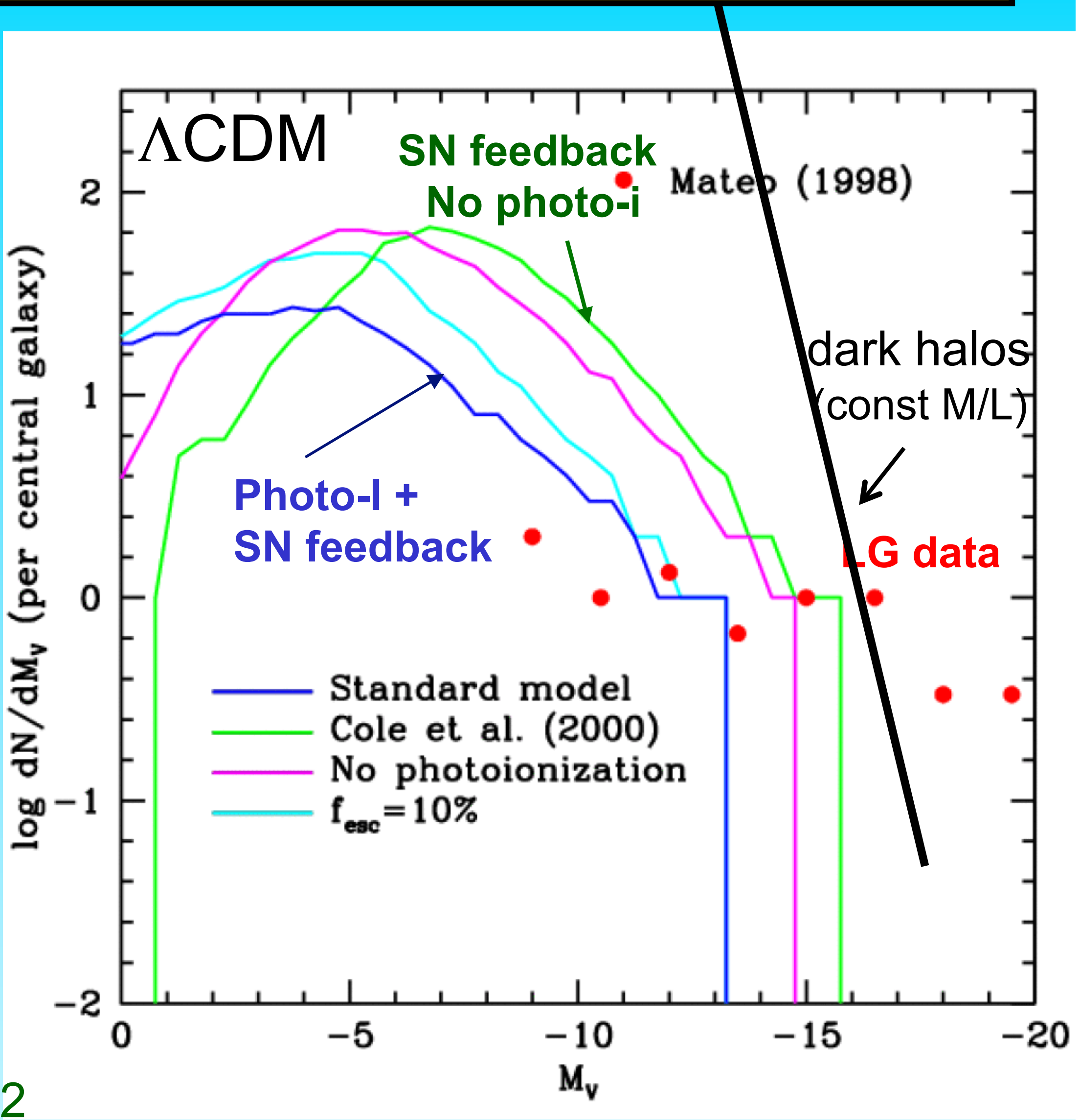

Benson, Frenk, Lacey, Baugh & Cole ’02
(see also Kauffman etal ’93, Bullock etal ’01)

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The satellites of the Milky Way

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

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

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Luminosity Function of Local Group Satellites

- Photoionization inhibits the formation of satellites
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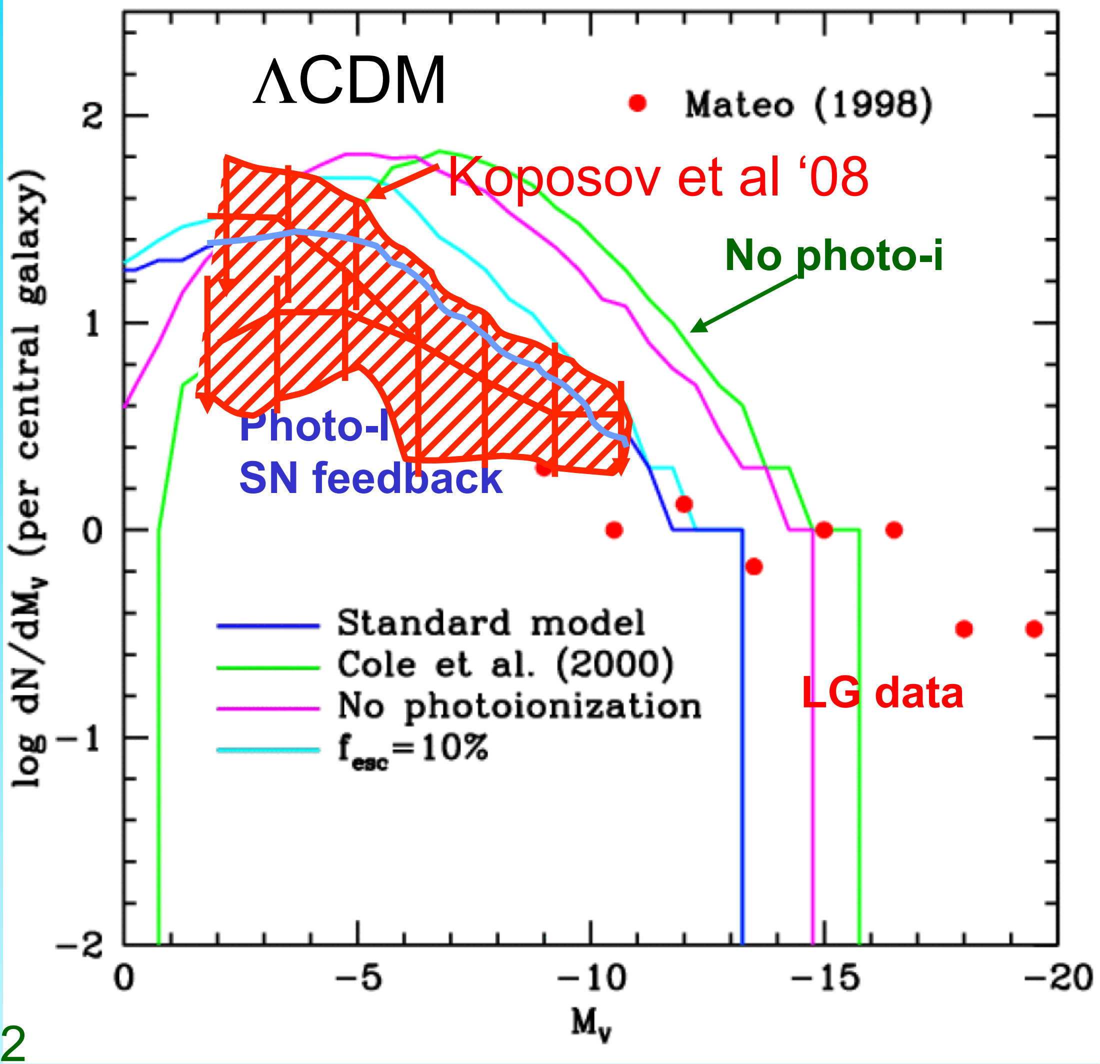
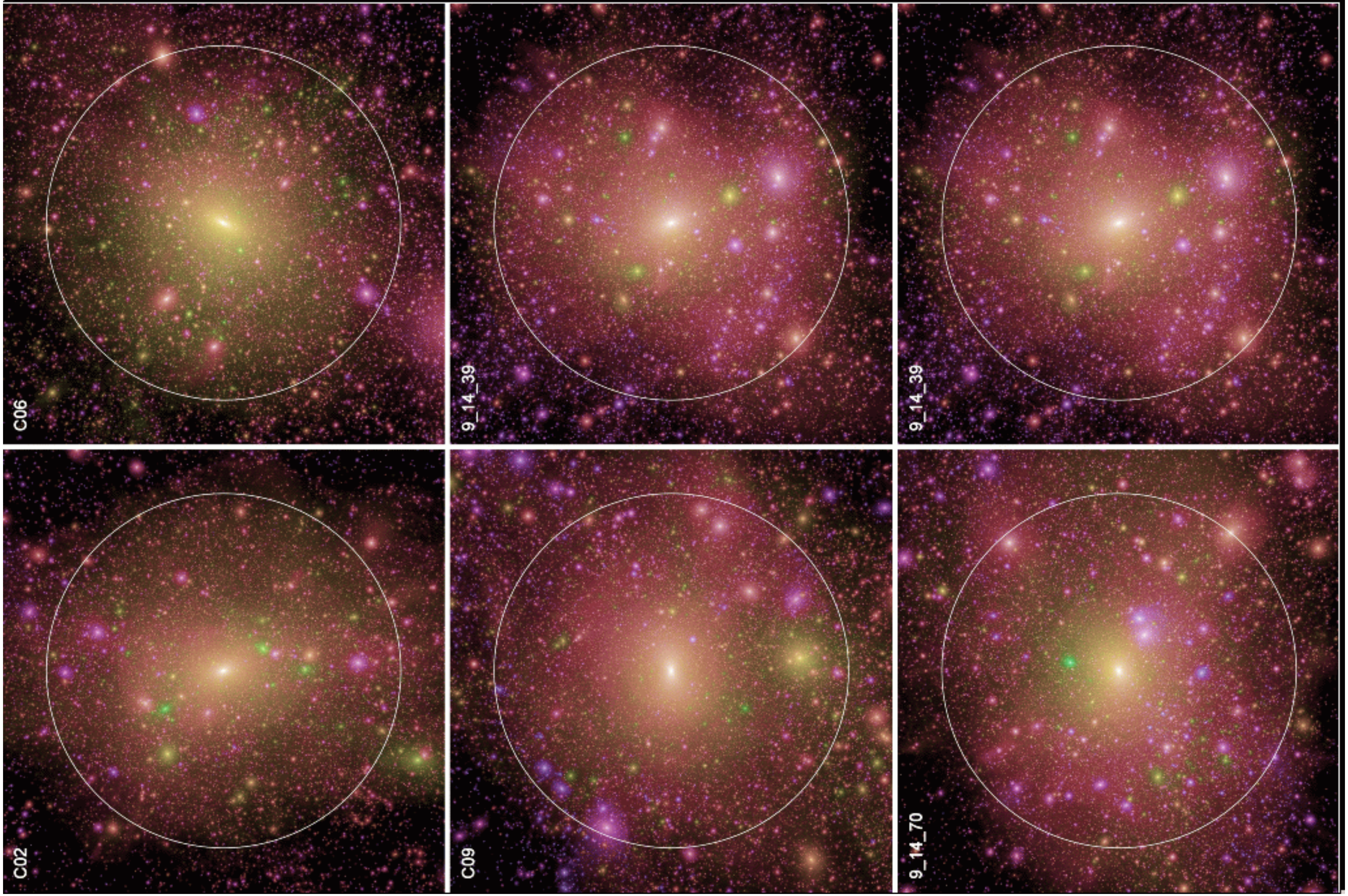


Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman etal '93, Bullock etal '01)

Modelling baryonic physics in Aquarius halos



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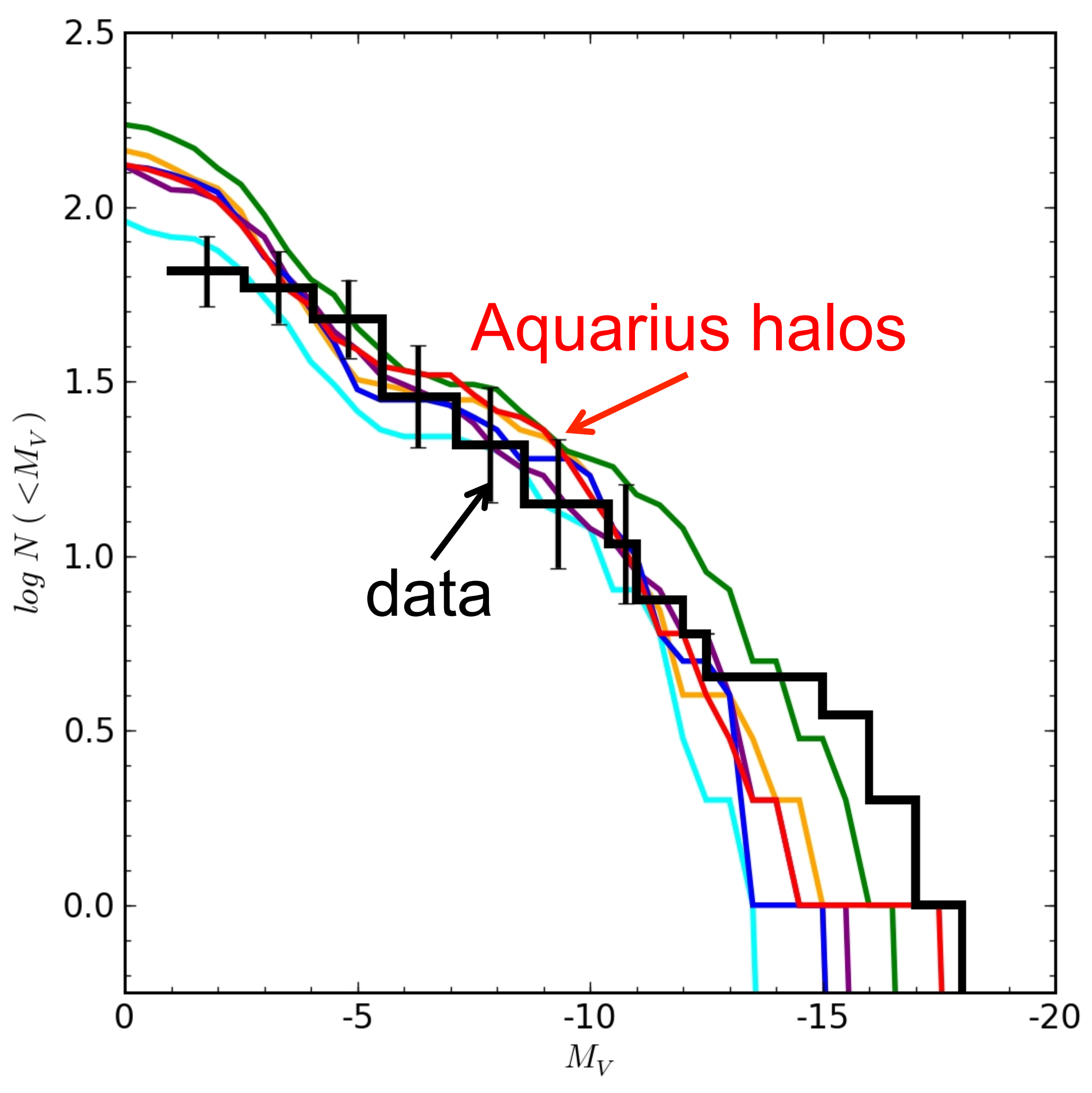
Luminosity function of Milky Way satellites

Semi-analytic modelling

Reionization as in the Okamoto et al simulations

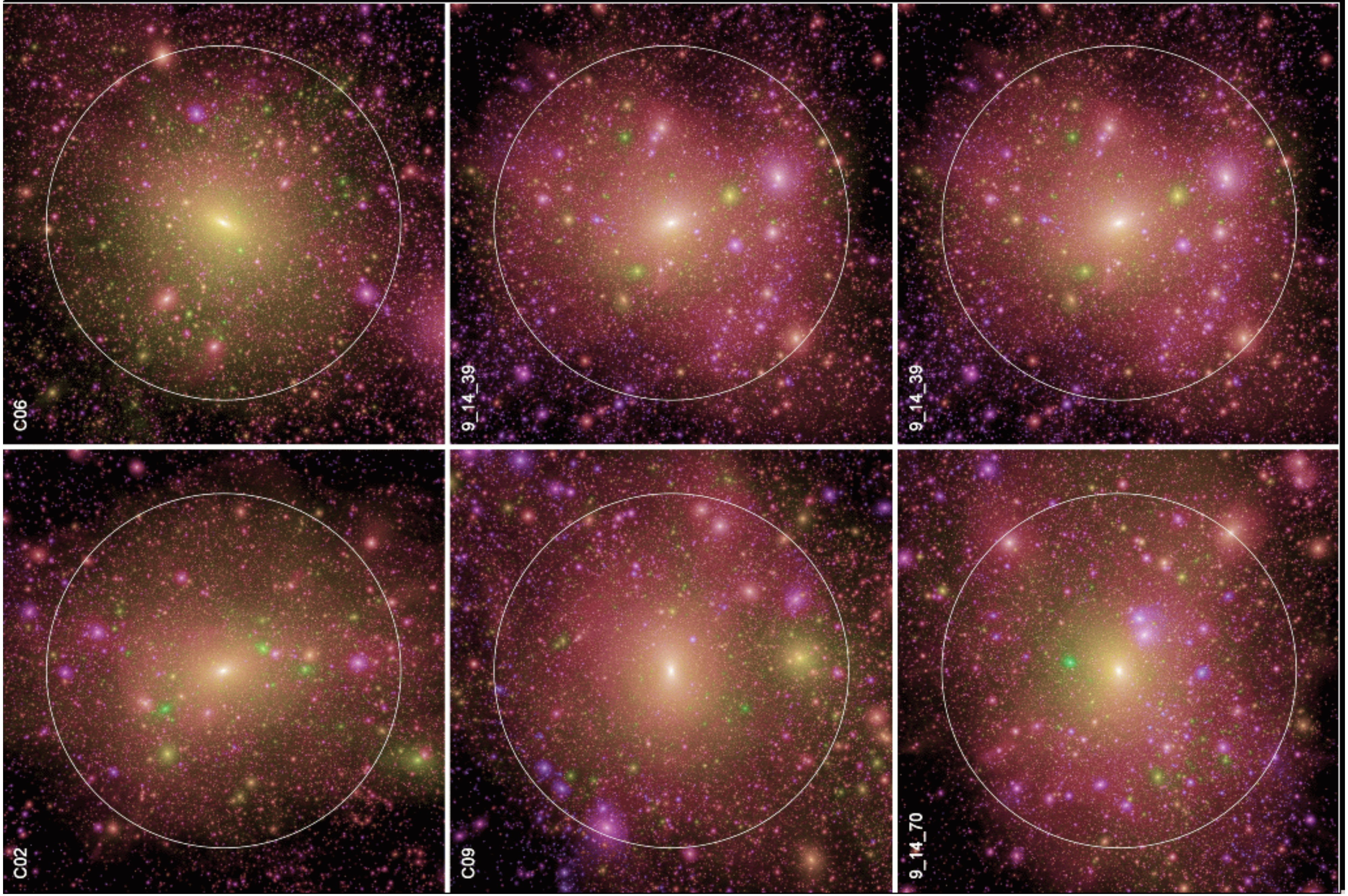


Cooper, Cole, Frenk, Benson et al '09

Institute for Computational Cosmology

Hydrodynamic simulations of Aquarius halos

Modelling baryonic physics in Aquarius halos



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Modelling the baryons in Aquarius using SPH simulations

Okamoto & Frenk '09

- $M_{sph} \sim 4\times10^5\ M_\odot$
- 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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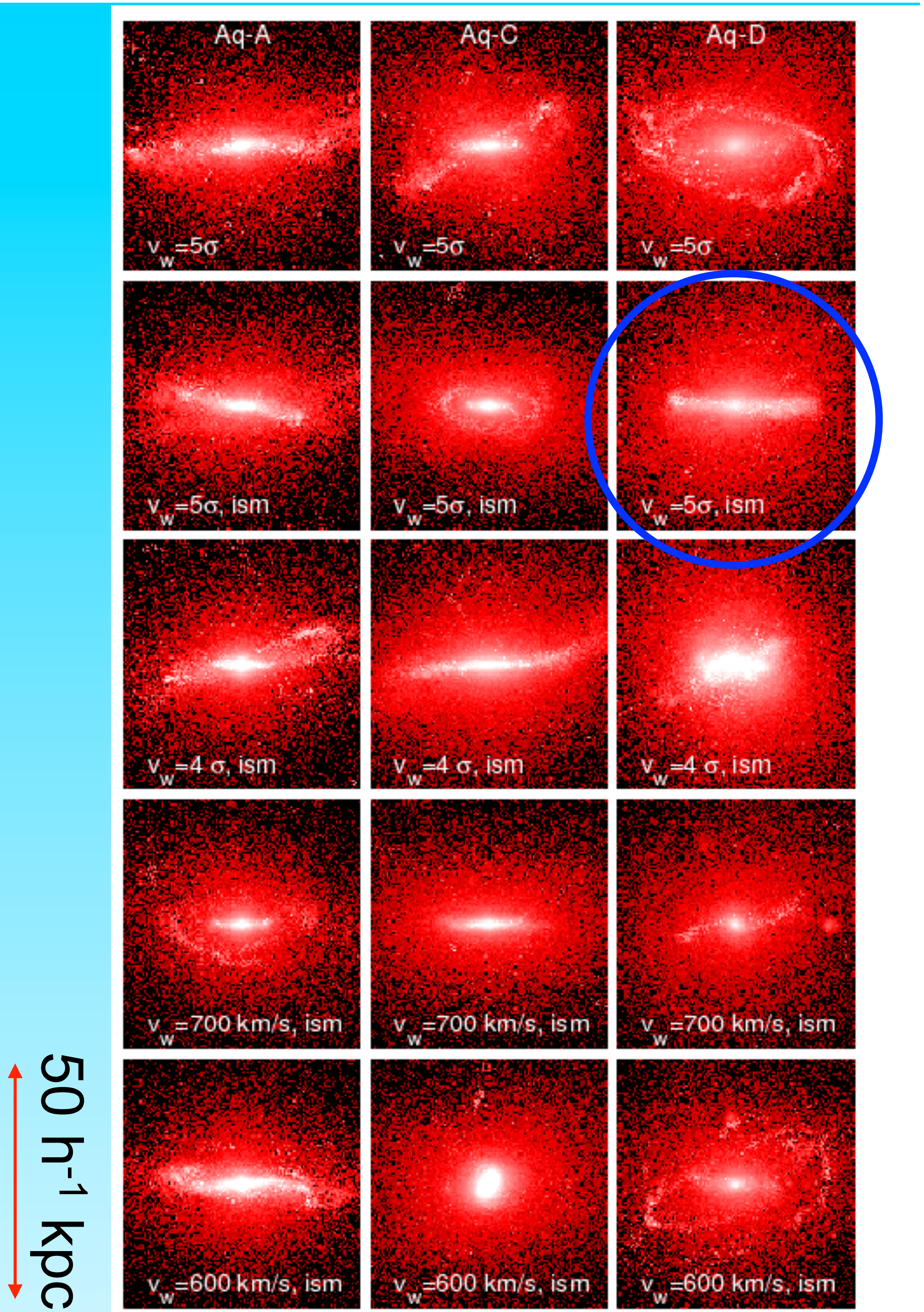
Central galaxies

- 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



Okamoto, Frenk, Jenkins, Theuns ‘09

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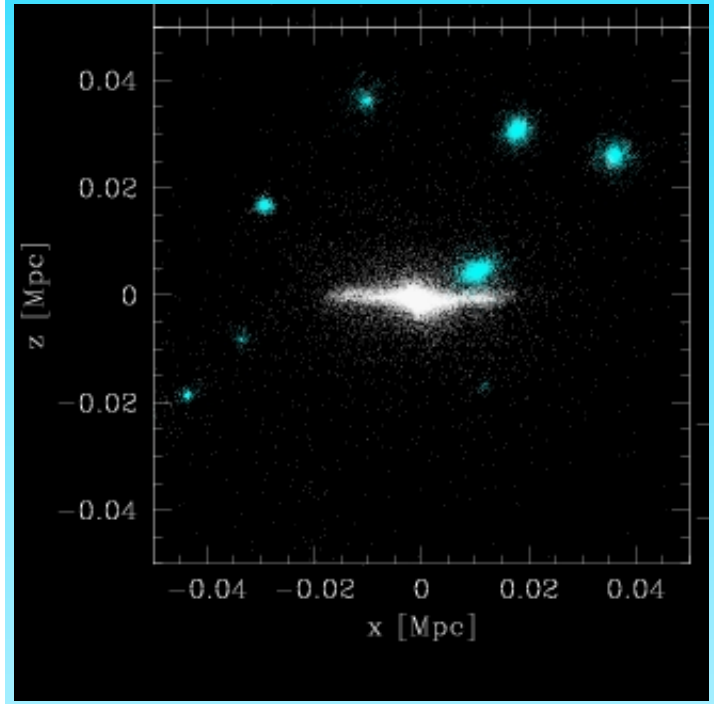
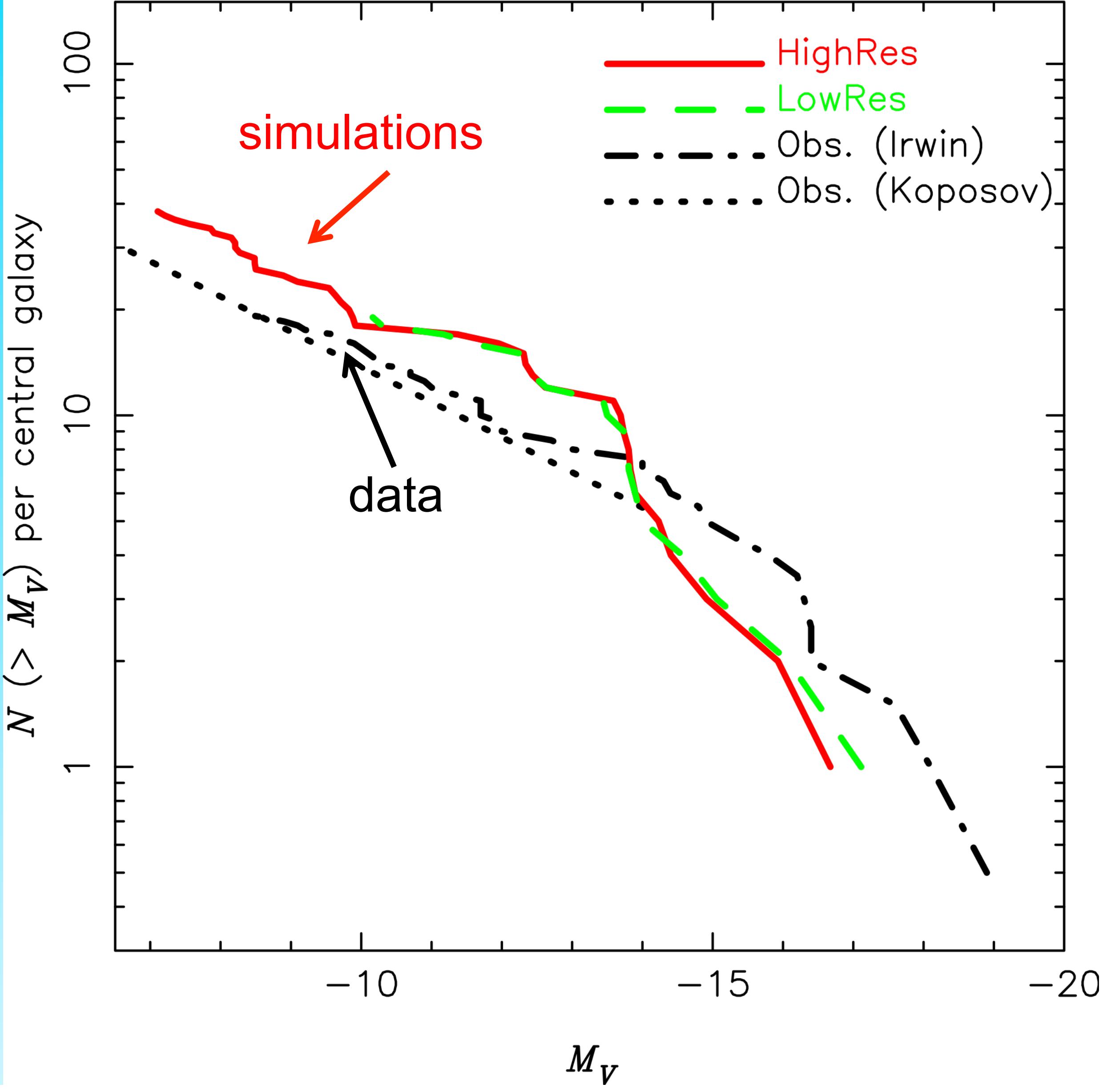
Luminosity function of Milky Way satellites

Hydrodynamic sims in Aquarius halos





Note: ultra-faint satellites not resolved in simulation

Okamoto & Frenk ‘09

Circular velocity functions

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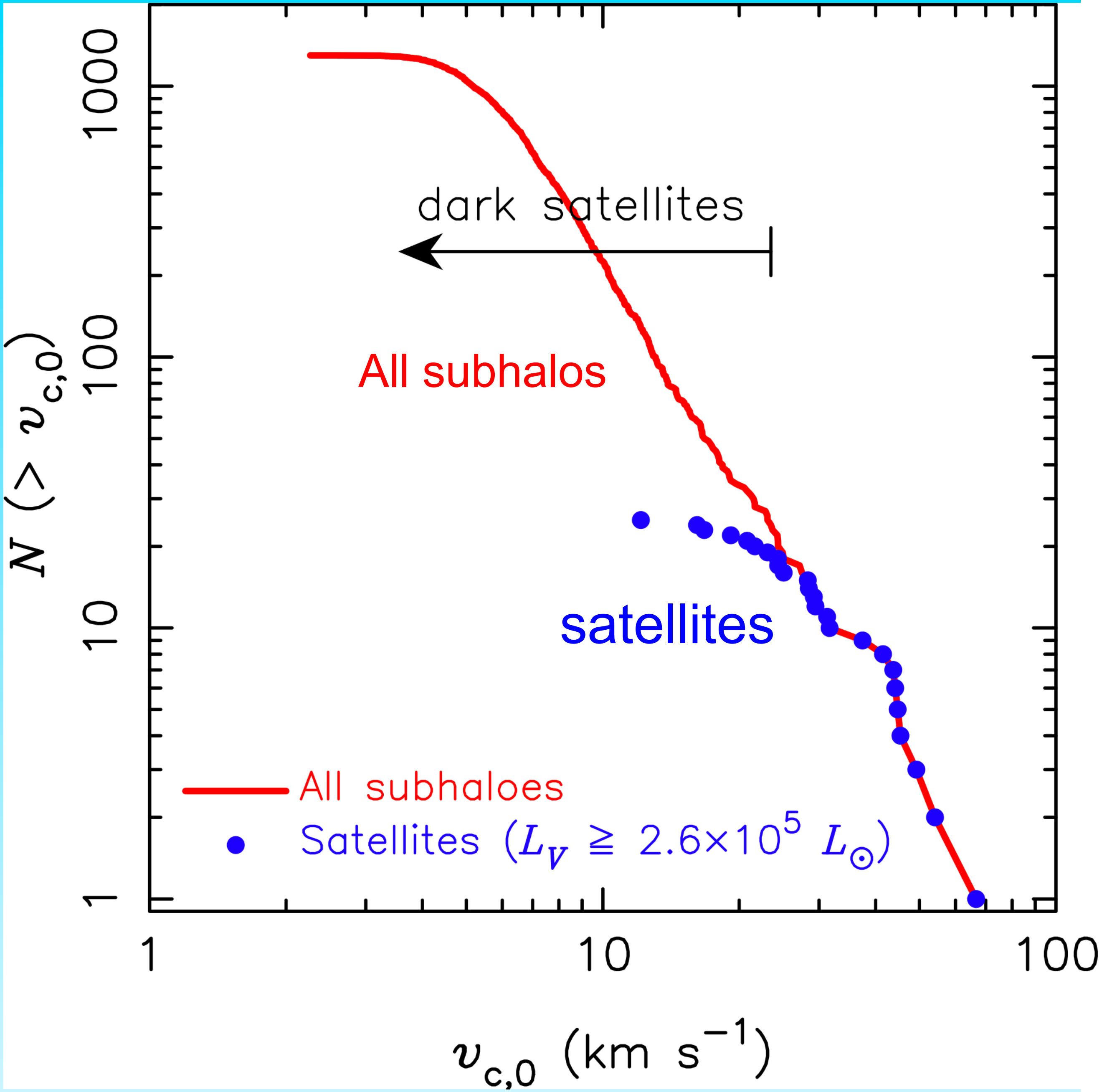
- All subhalos with $v_c > 20$ km/s make a satellite of $L > 2.6\times10^5 L_o$

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



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Formation history of luminous & dark sats

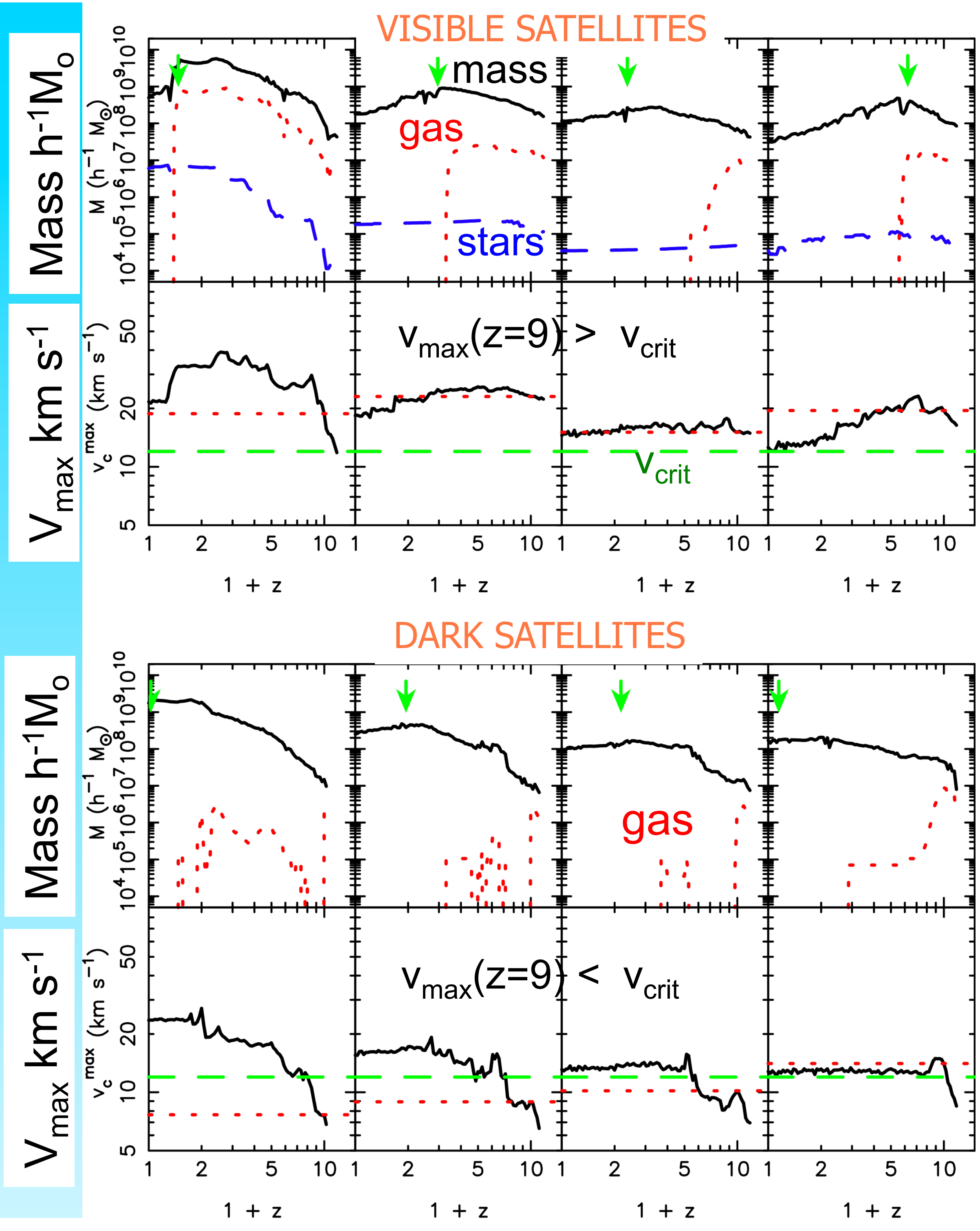
Note:

Reionization is at z=9

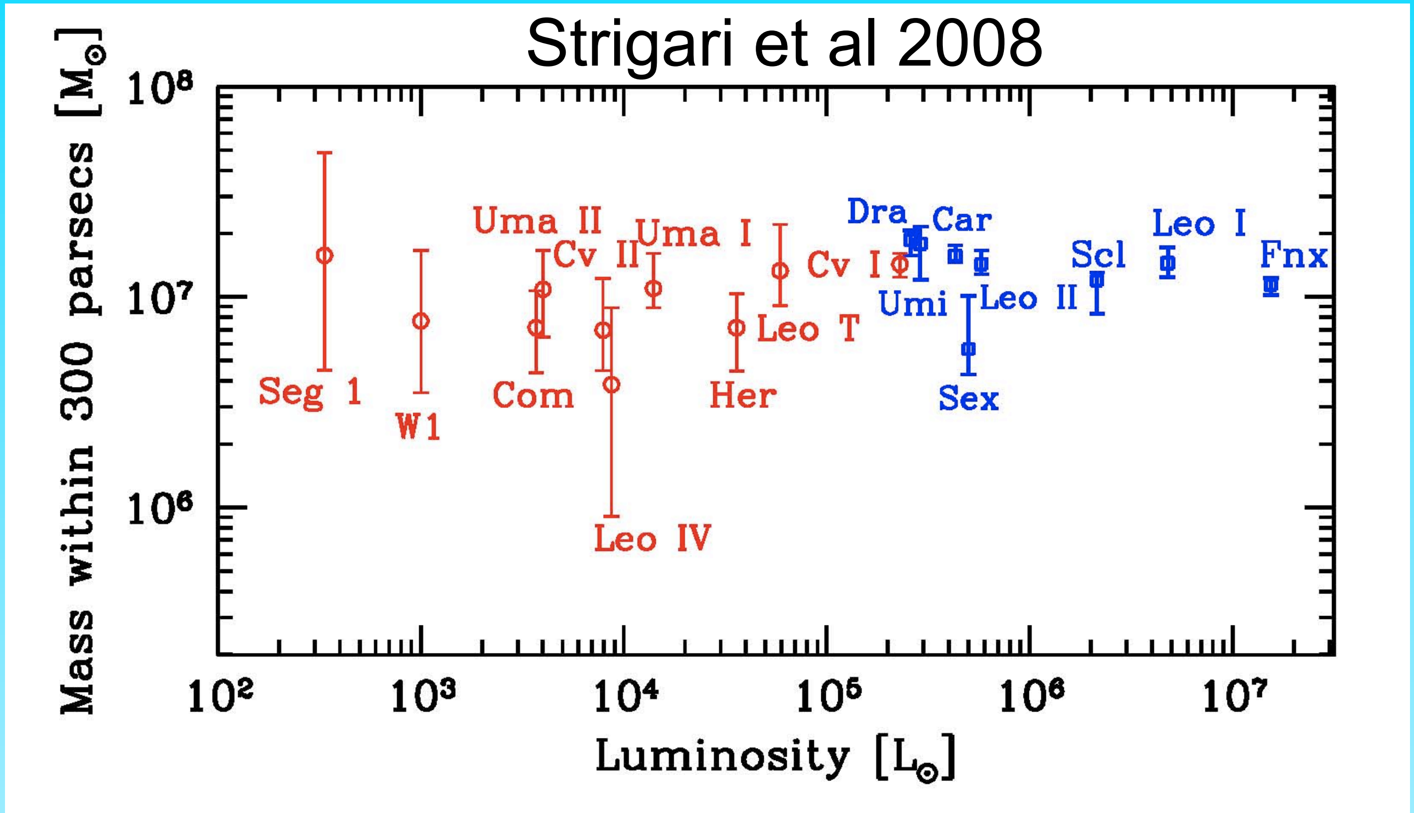
↓ Sat accreted onto halo

- 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

Okamoto & Frenk '09



A special scale in cosmology?



Is this special scale due to:

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

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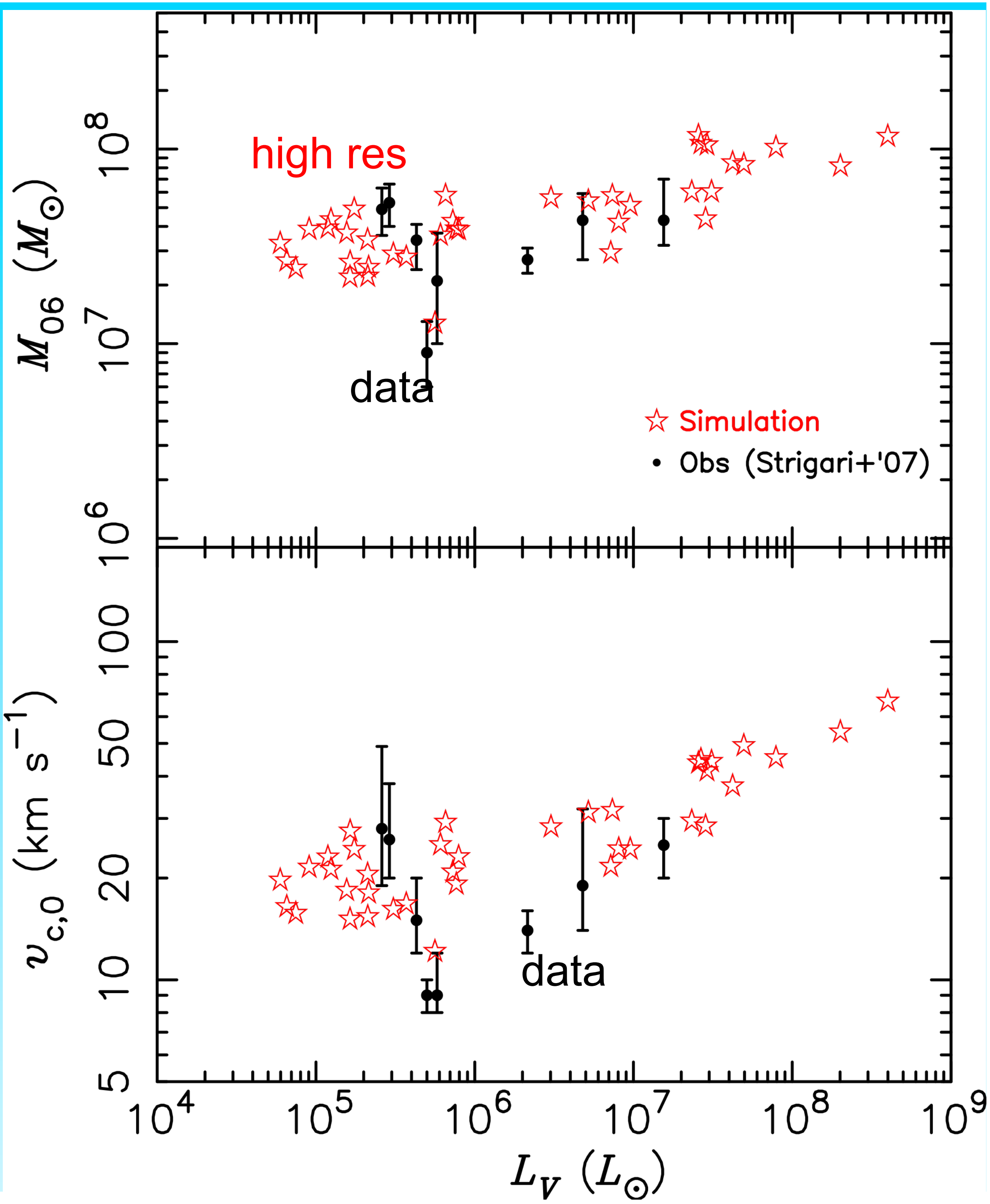
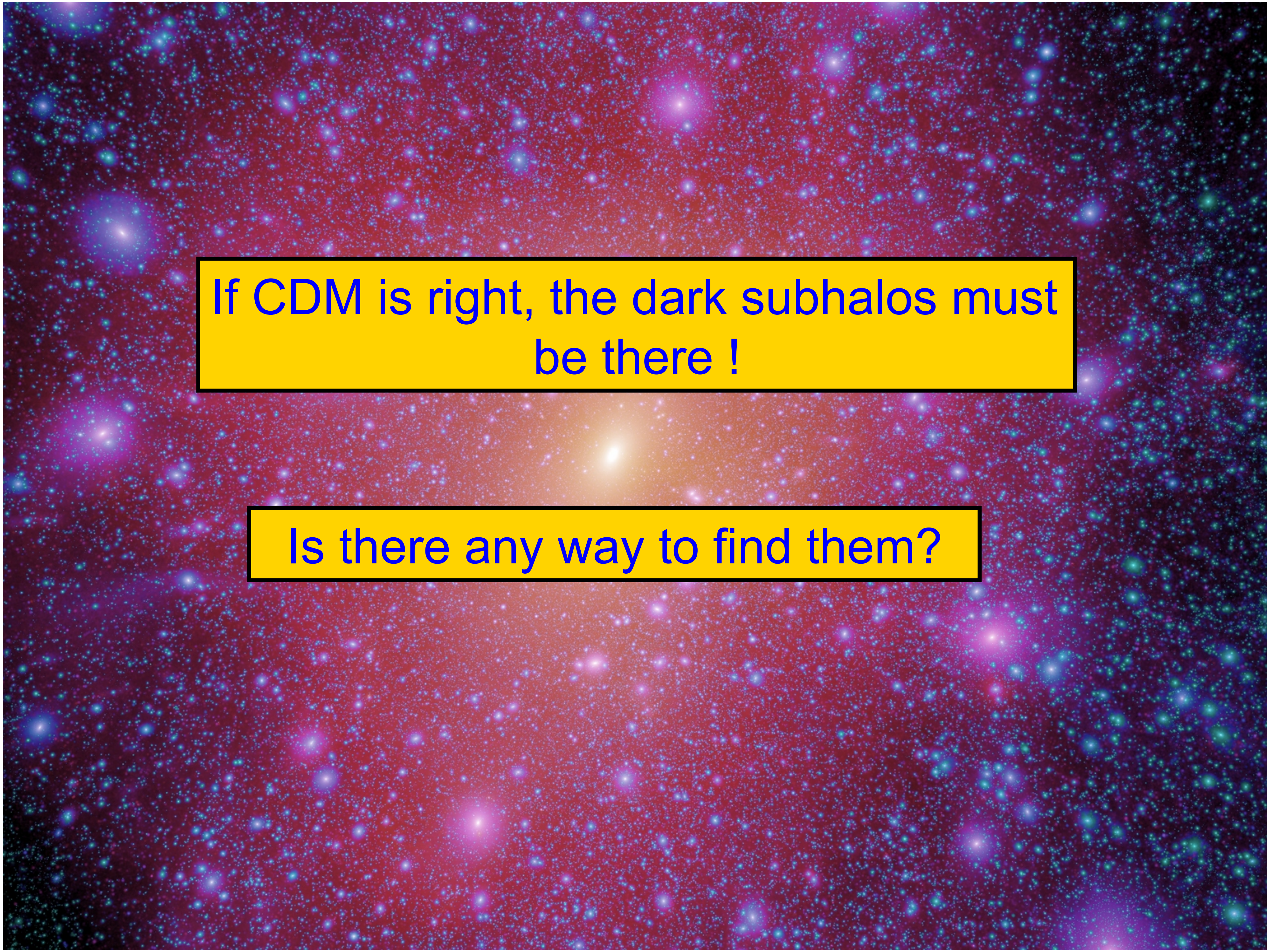
Mass within 600 pc

Models reproduce the M_{600} – L relation

$V_{circ,max}$ within 600 pc

Okamoto & Frenk '09

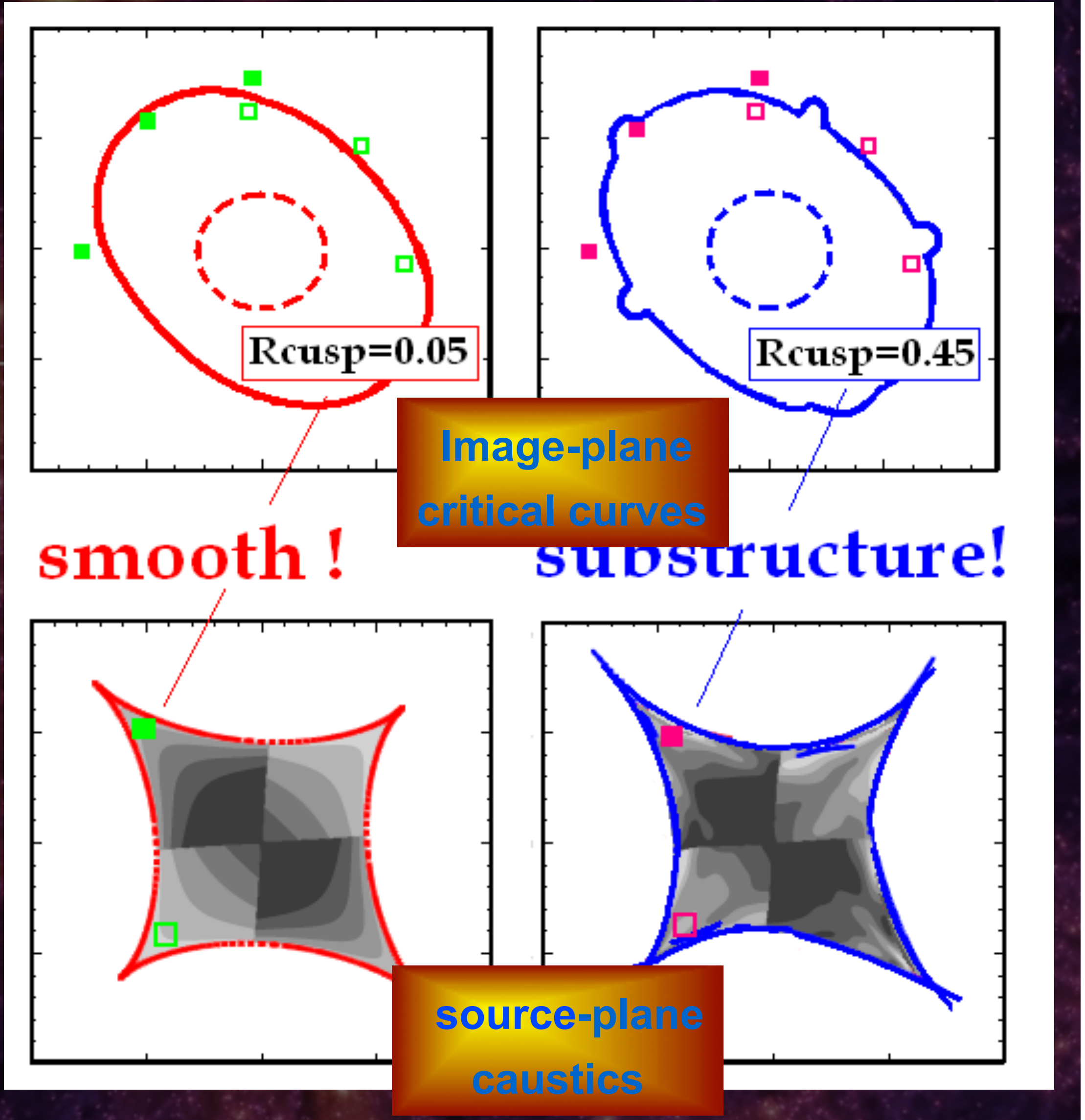




If CDM is right, the dark subhalos must be there !

Is there any way to find them?

- Background QSO aligned with lens → caustic
- Sources near cusp obey flux cusp-caustic relation if lens is smooth
- If lens is lumpy → flux-anomaly
- Cusp-caustic relation violation seen in 3 multiply-imaged quasars



$R_{cusp} = (|\mu_A+\mu_B+\mu_C|) / (|\mu_A|+|\mu_B|+|\mu_C|)$

R_{cusp} --> 0, when total μ --> infinity

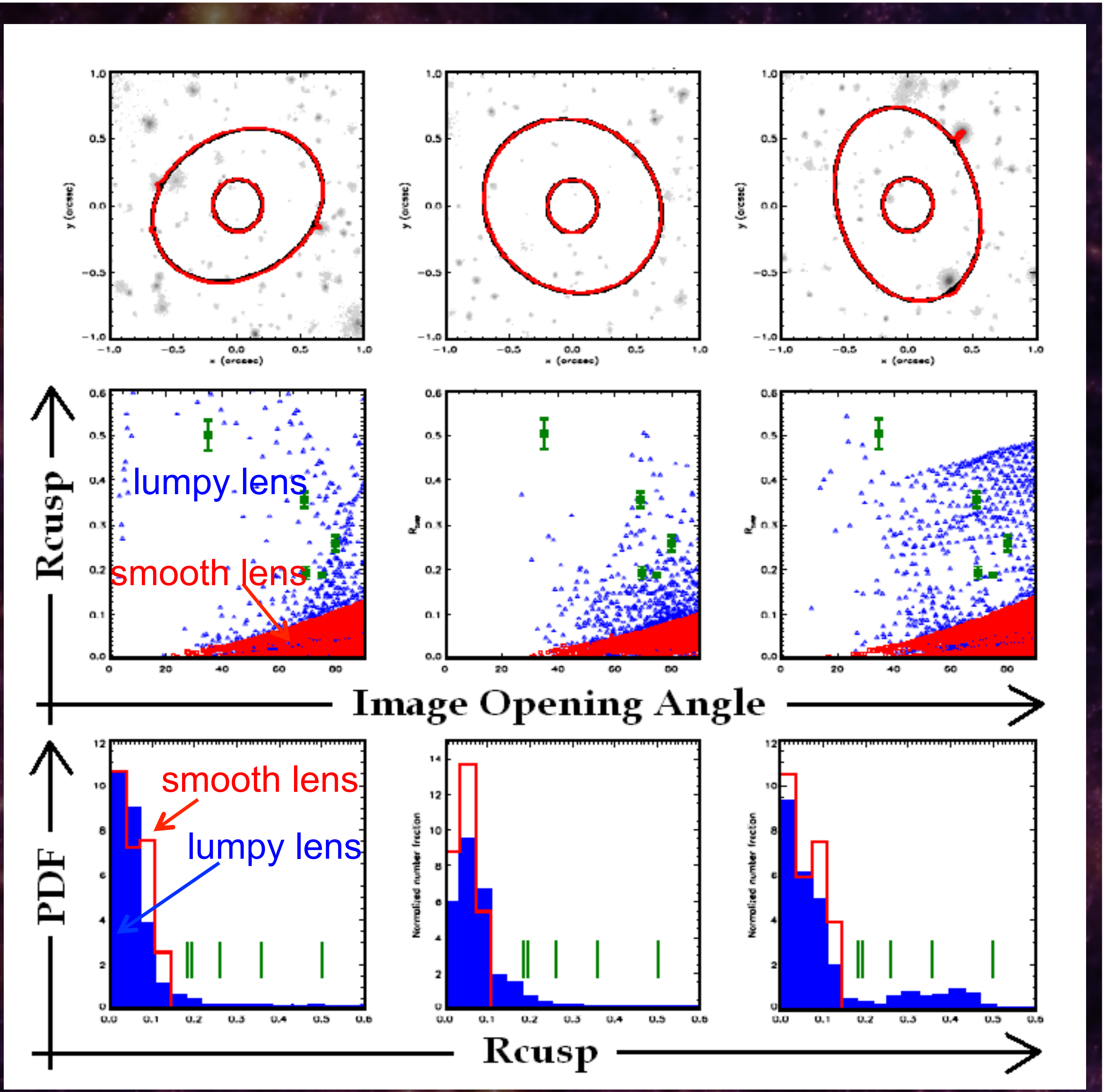
Dandan Hu + Aquarius '09 '10

- 3/5 QSOs caustic lenses ($\Delta\theta \lesssim 90^\circ$) show violation due to substructures.

- Observed violation is too strong ($P_{obs} < 0.01$) !

- CDM halos DO NOT have enough substructure in inner parts

Dandan Hu + Aq ’09, ‘10



The Milky Way and the nature of the dark matter

- Test CDM predictions on galaxy scales
  - Structure of dark matter halos
  - Number of satellite galaxies
  - Remnants of hierarchical formation (streams)

The Milky Way and the nature of the dark matter

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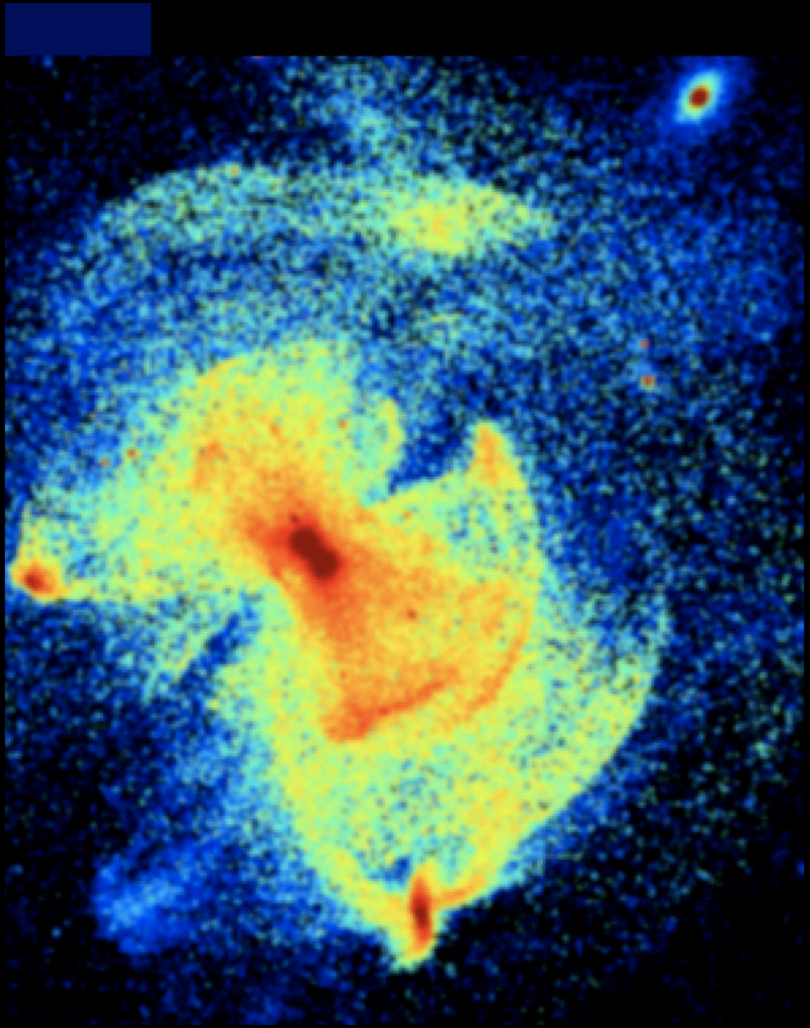
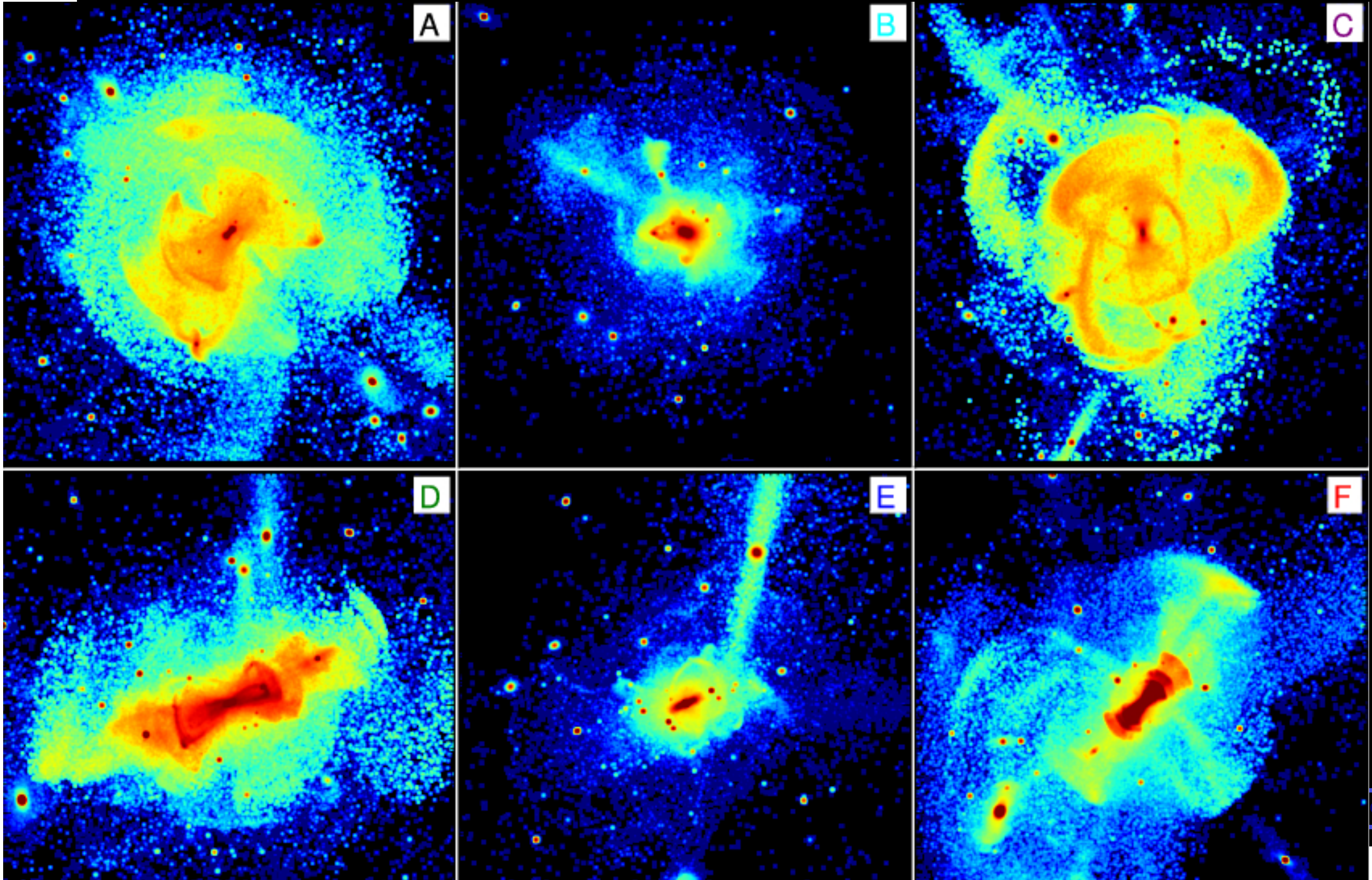
The stellar halo of the Milky Way

The stellar halo of the Milky Way



Aquarius dark matter simulation + stars

Cooper et al ‘10



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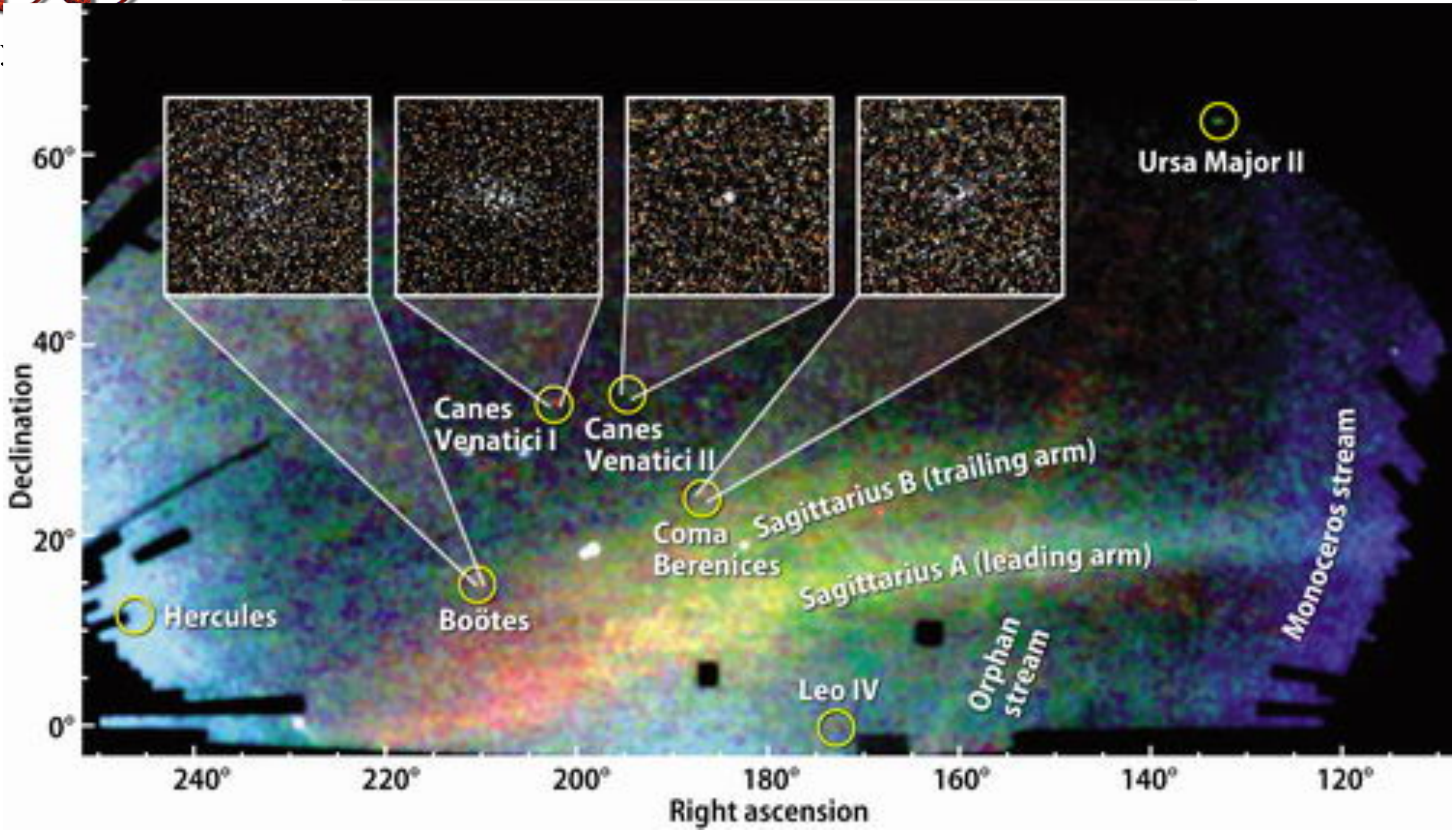
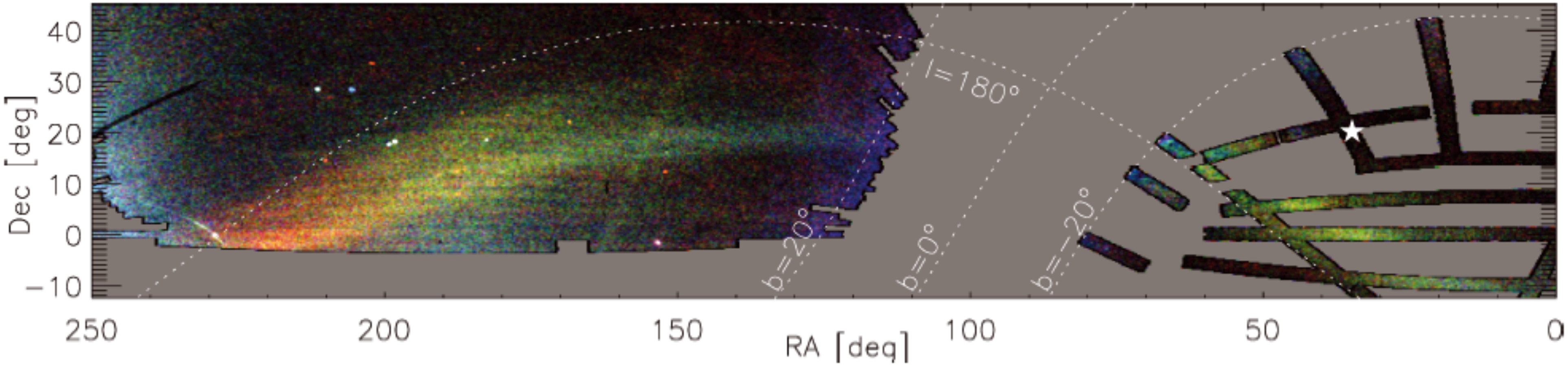
Tidal streams

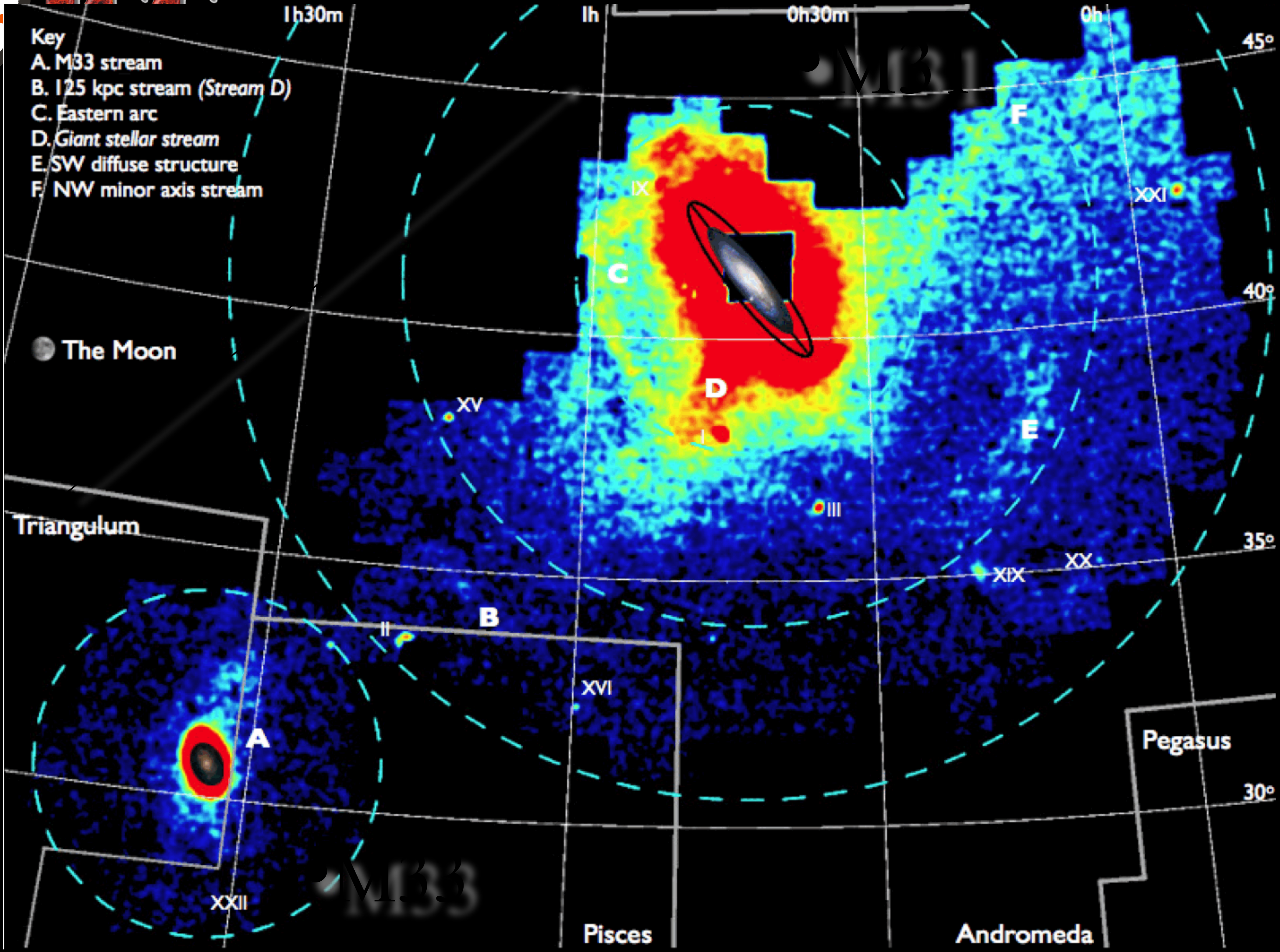
The field of streams



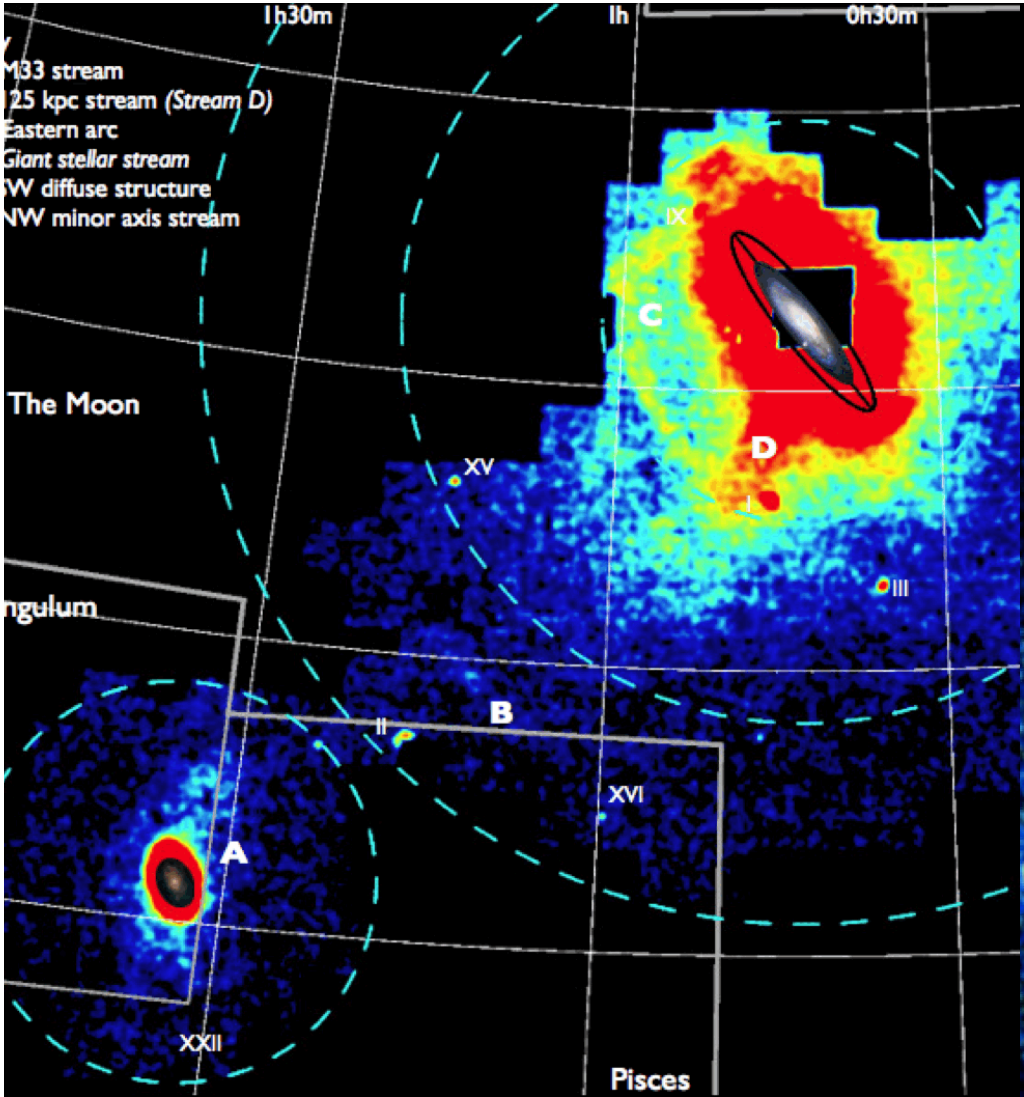


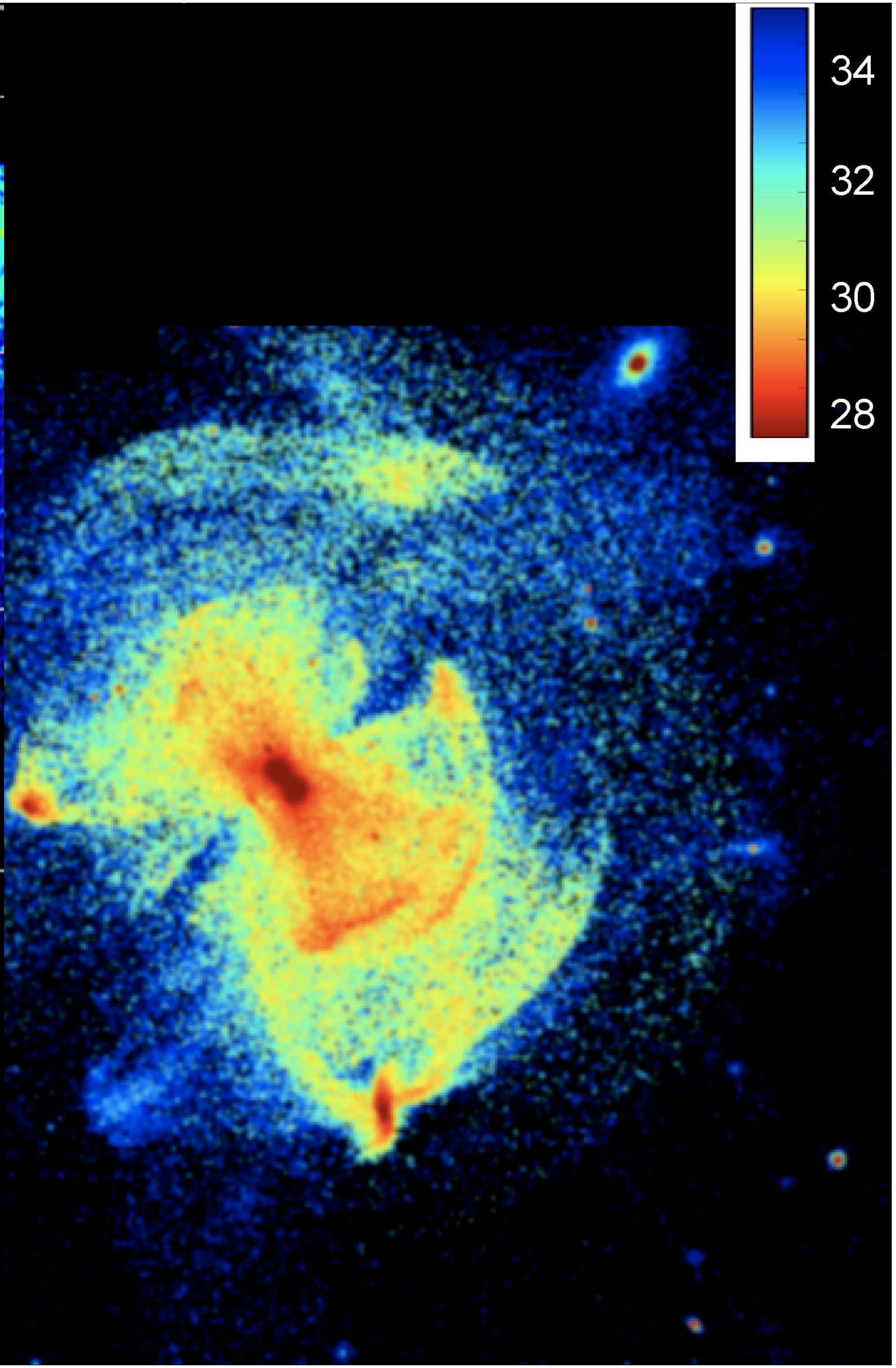
Belokurov et al '07

The PANDA survey of M31

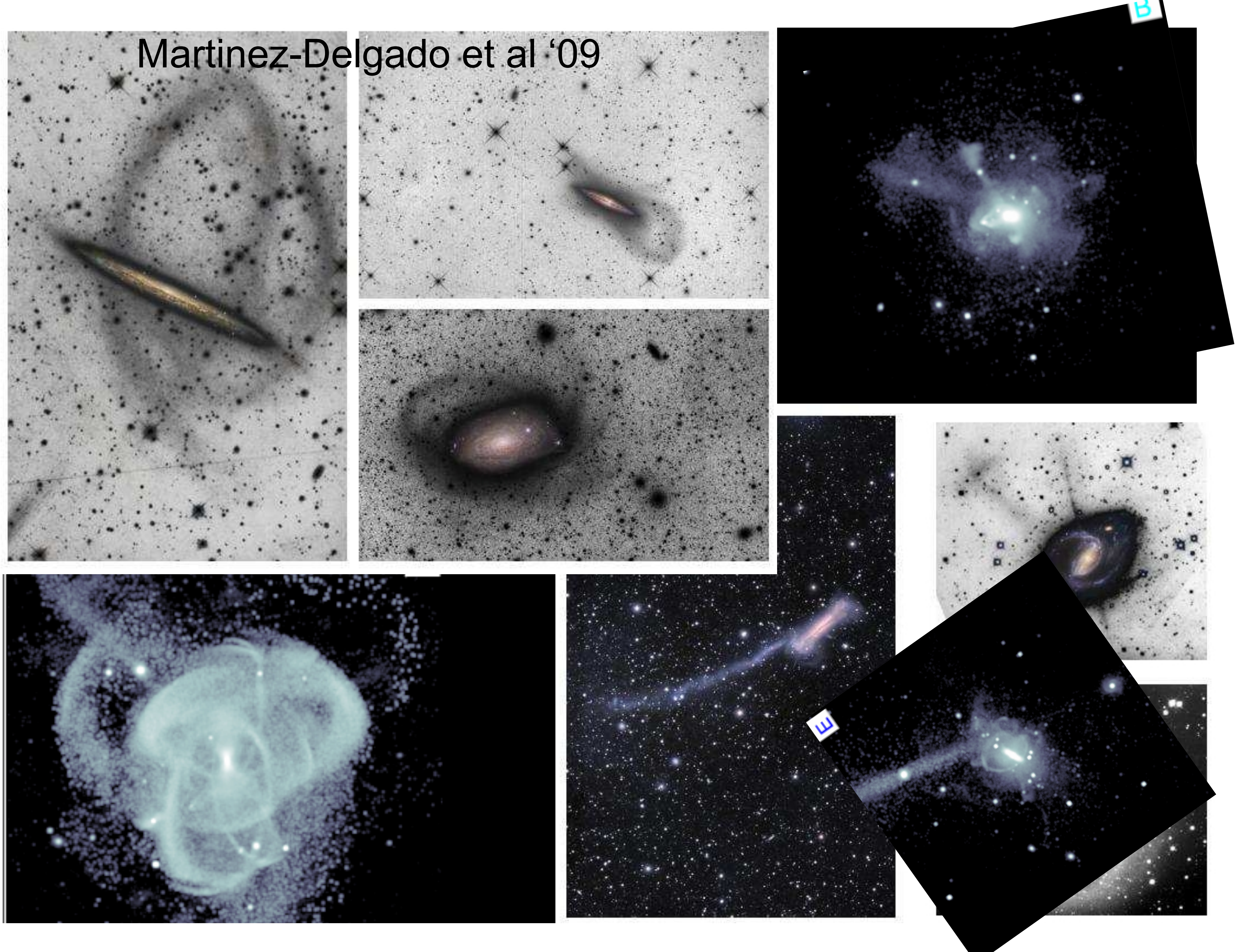


McConnachie, Ibata Navarro, Widrow, Babul … '09


1h30m
1h
0h30m
M33 stream
125 kpc stream (Stream D)
Eastern arc
Giant stellar stream
W diffuse structure
NW minor axis stream
The Moon
ngulum
IX
C
D
I
XV
III
B
II
XVI
A
XXII
Pisces


34
32
30
28

Martinez-Delgado et al ‘09



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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

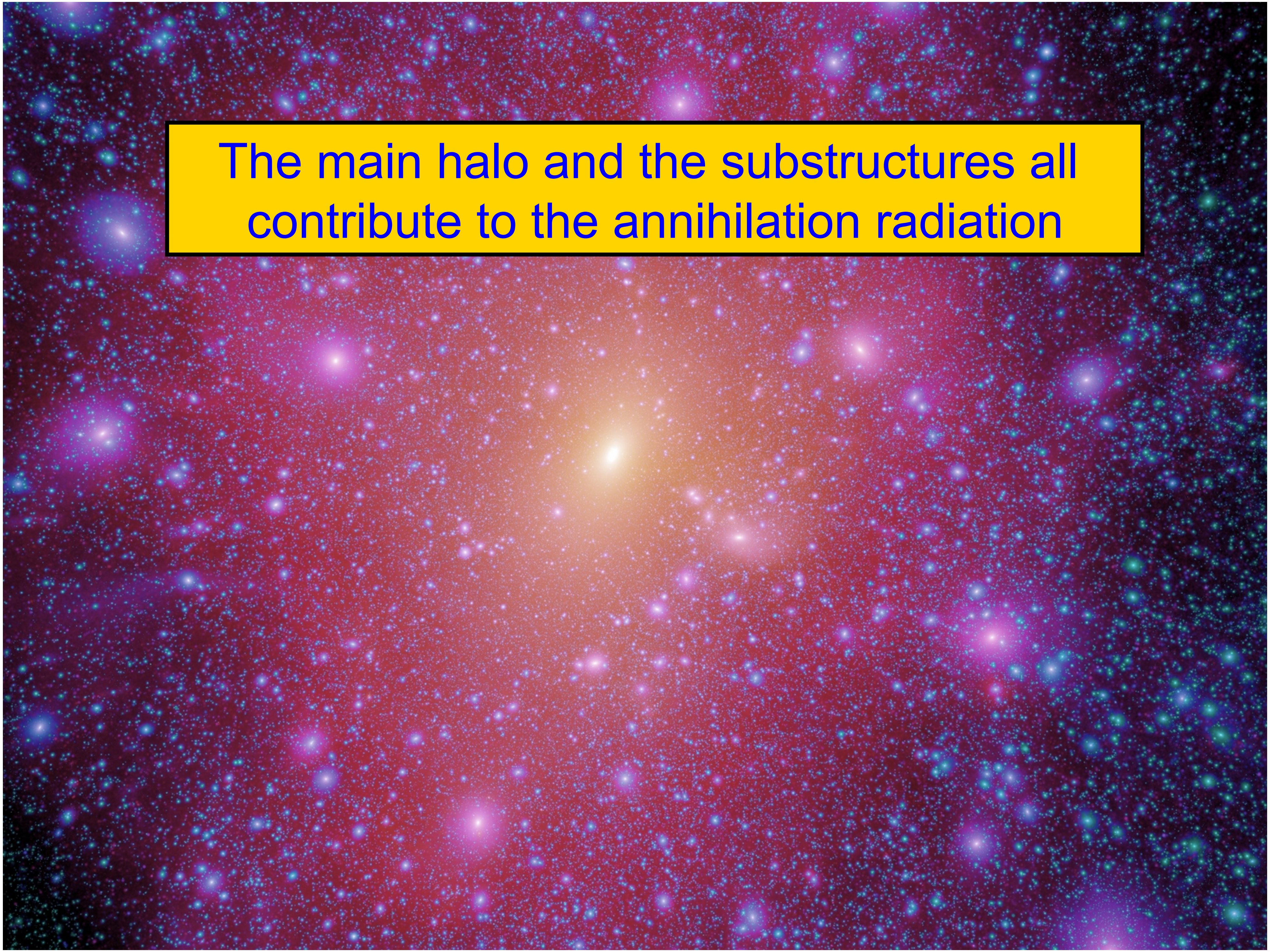
Intensity of annihilation radiation at ***x*** depends on:

$$I(\mathbf{x}) = \int \underset{\uparrow}{\rho^2(\boldsymbol{x})} \, \underset{\uparrow}{\langle \sigma v \rangle} \, dV$$

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

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

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



The main halo and the substructures all contribute to the annihilation radiation

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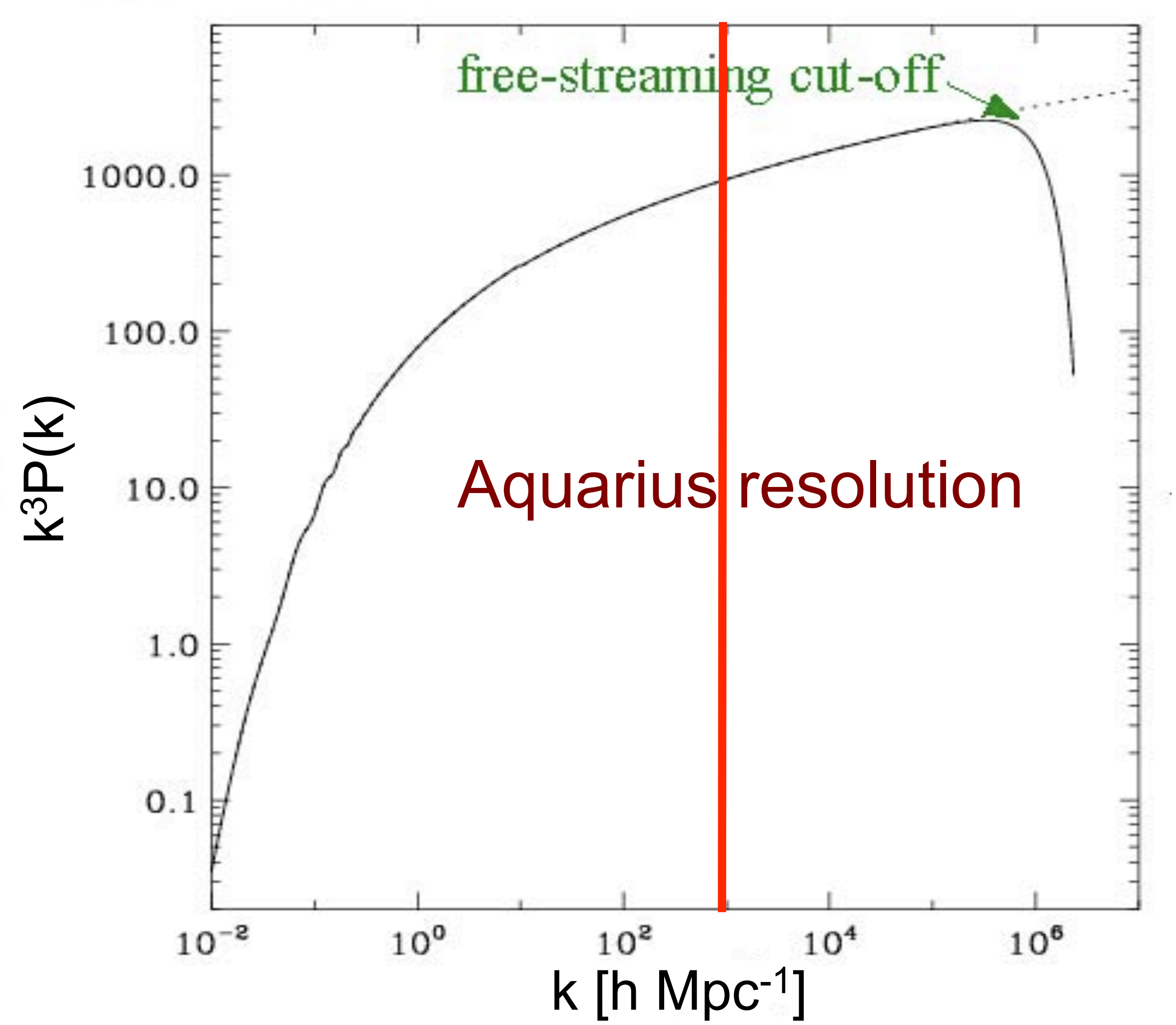
The cold dark matter power spectrum

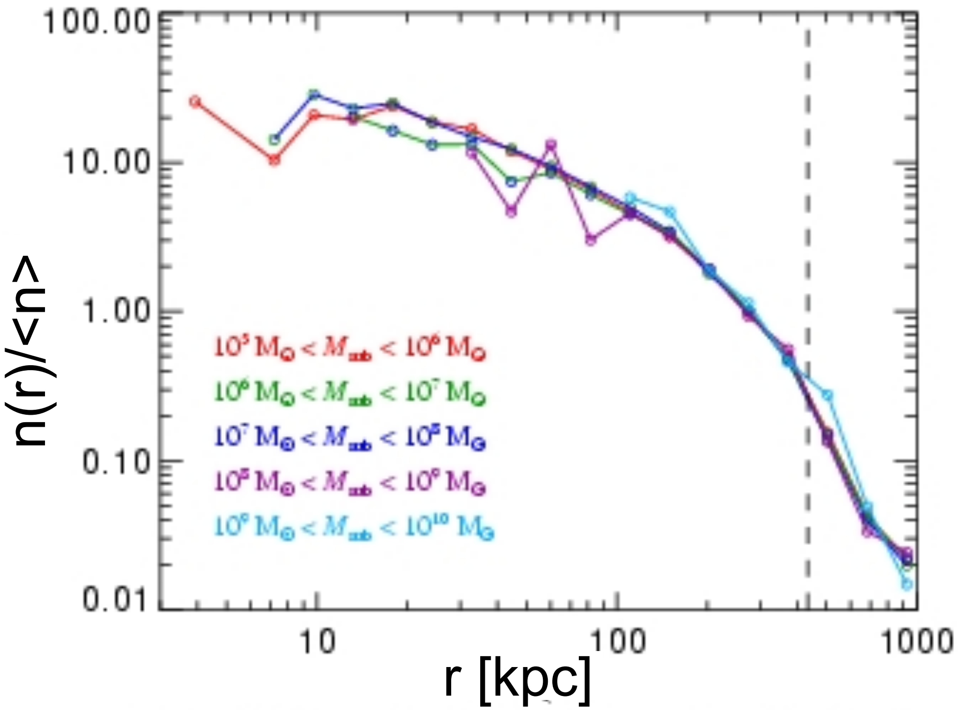
The linear power spectrum
(“power per octave”)

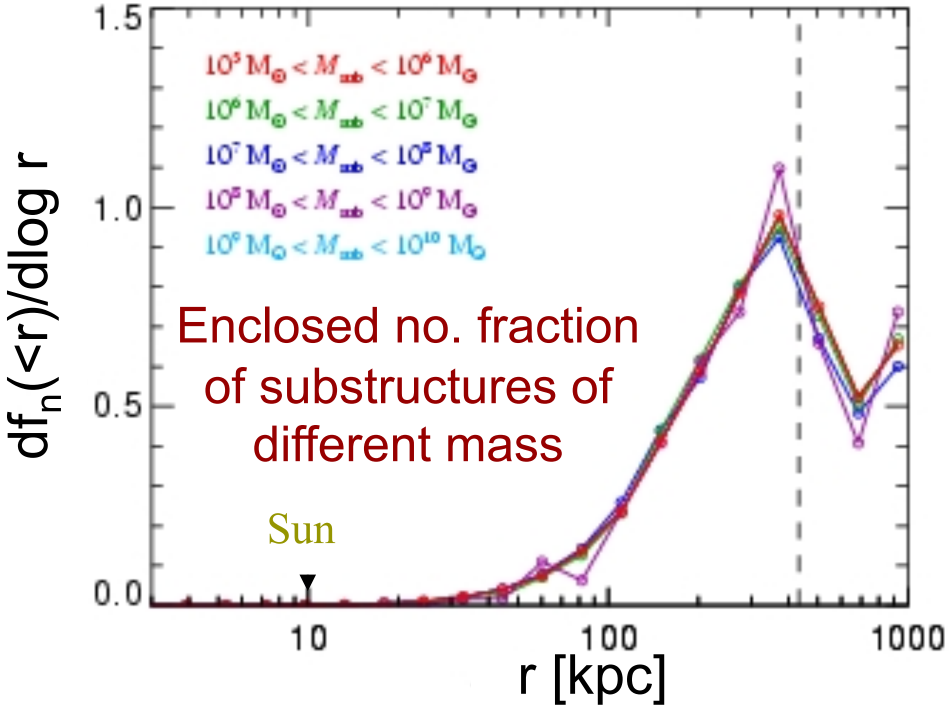
Assumes a 100GeV wimp
Green et al ‘04



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





Enclosed no. fraction of substructures of different mass

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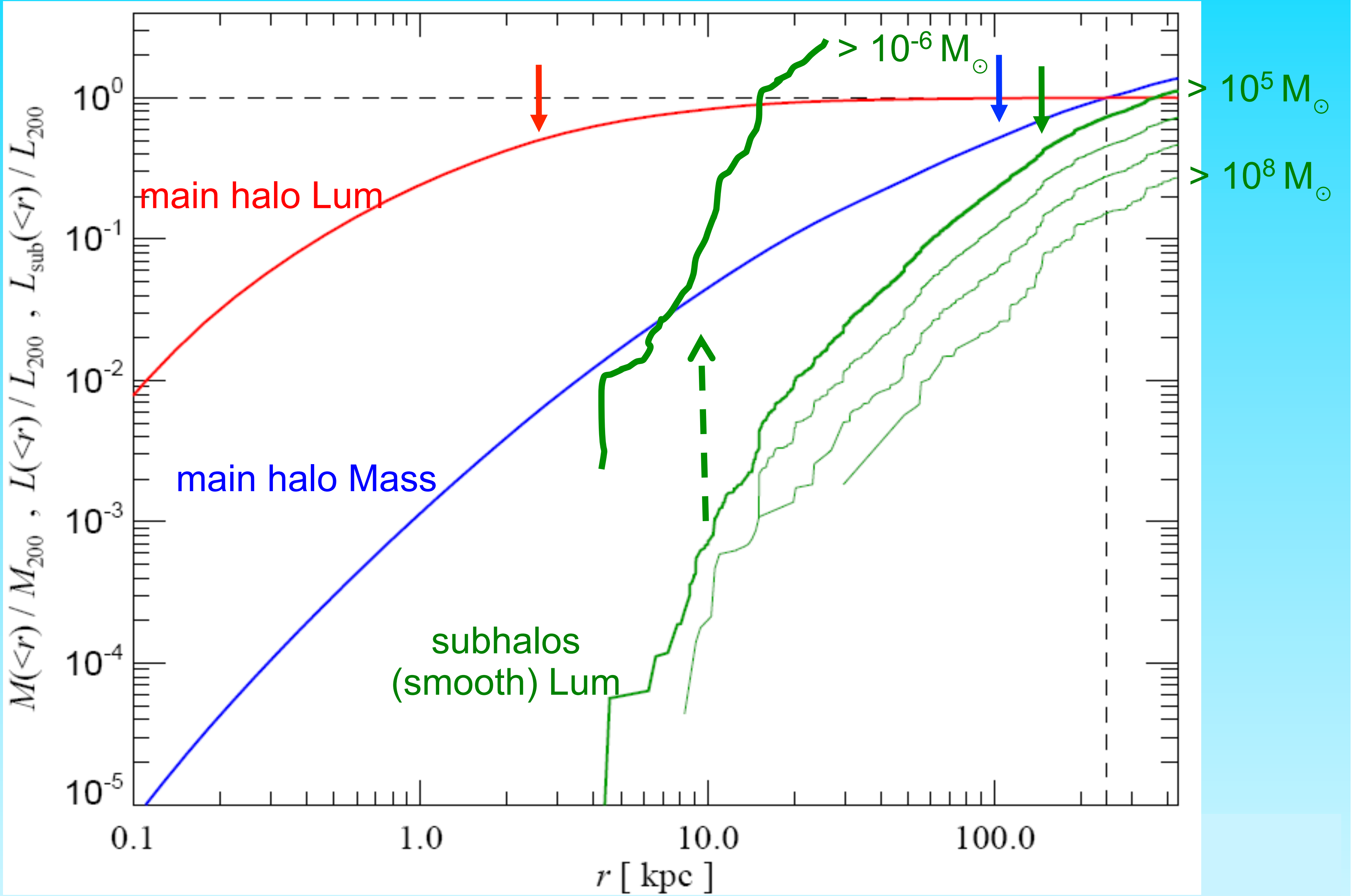
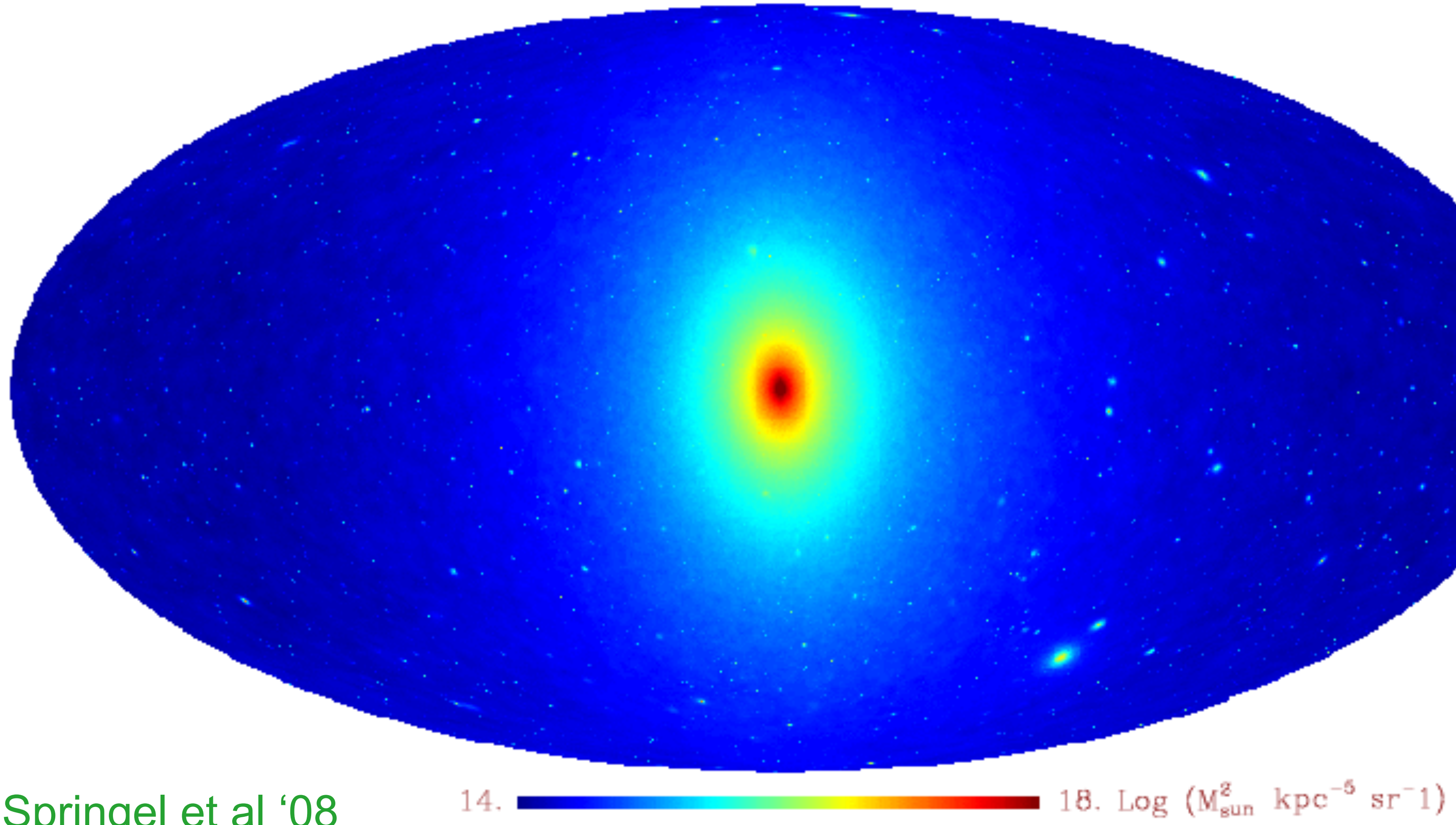
Mass and annihilation radiation profiles of a MW halo



The Milky Way seen in annihilation radiation

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



Springel et al ‘08

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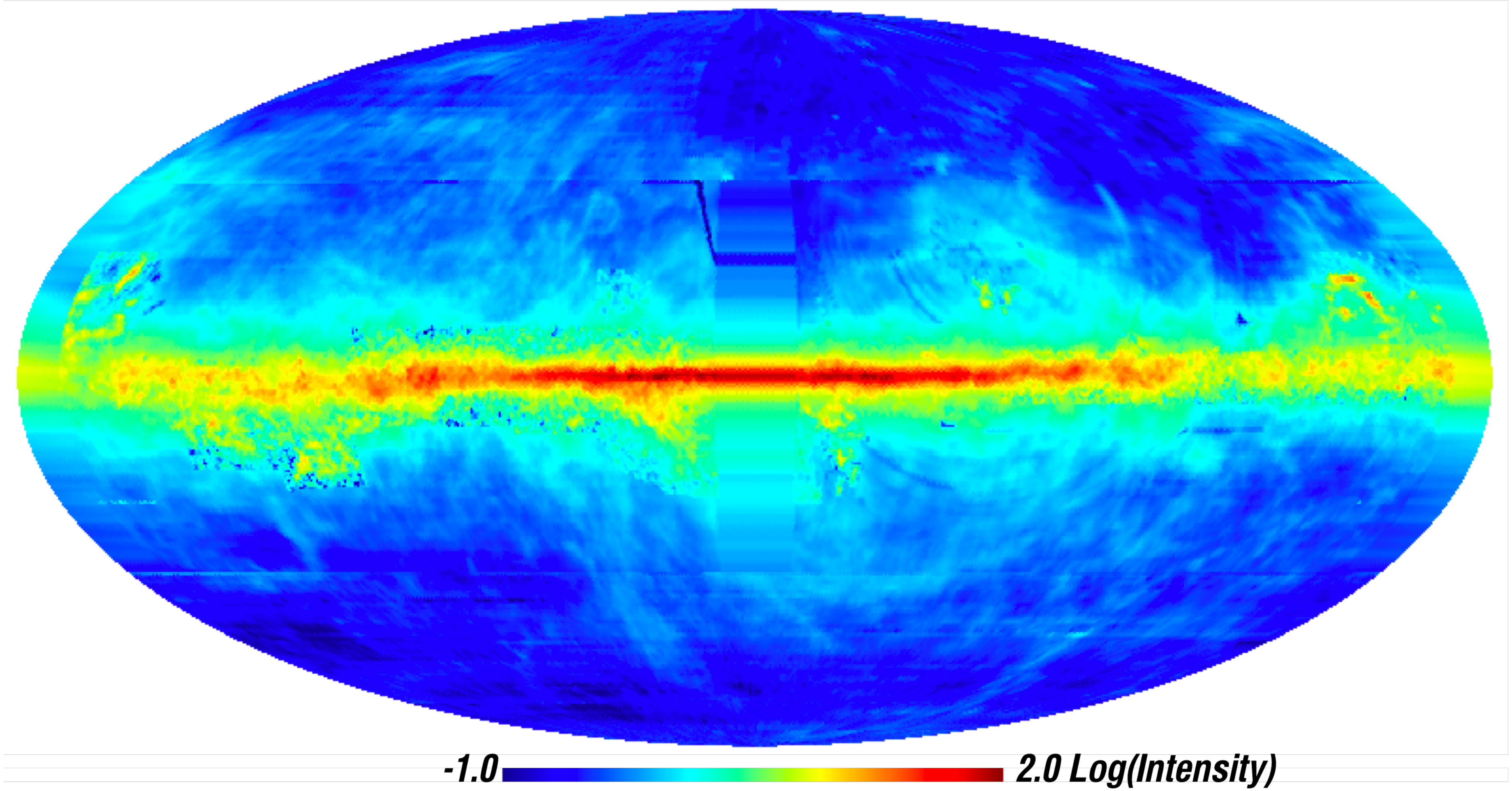
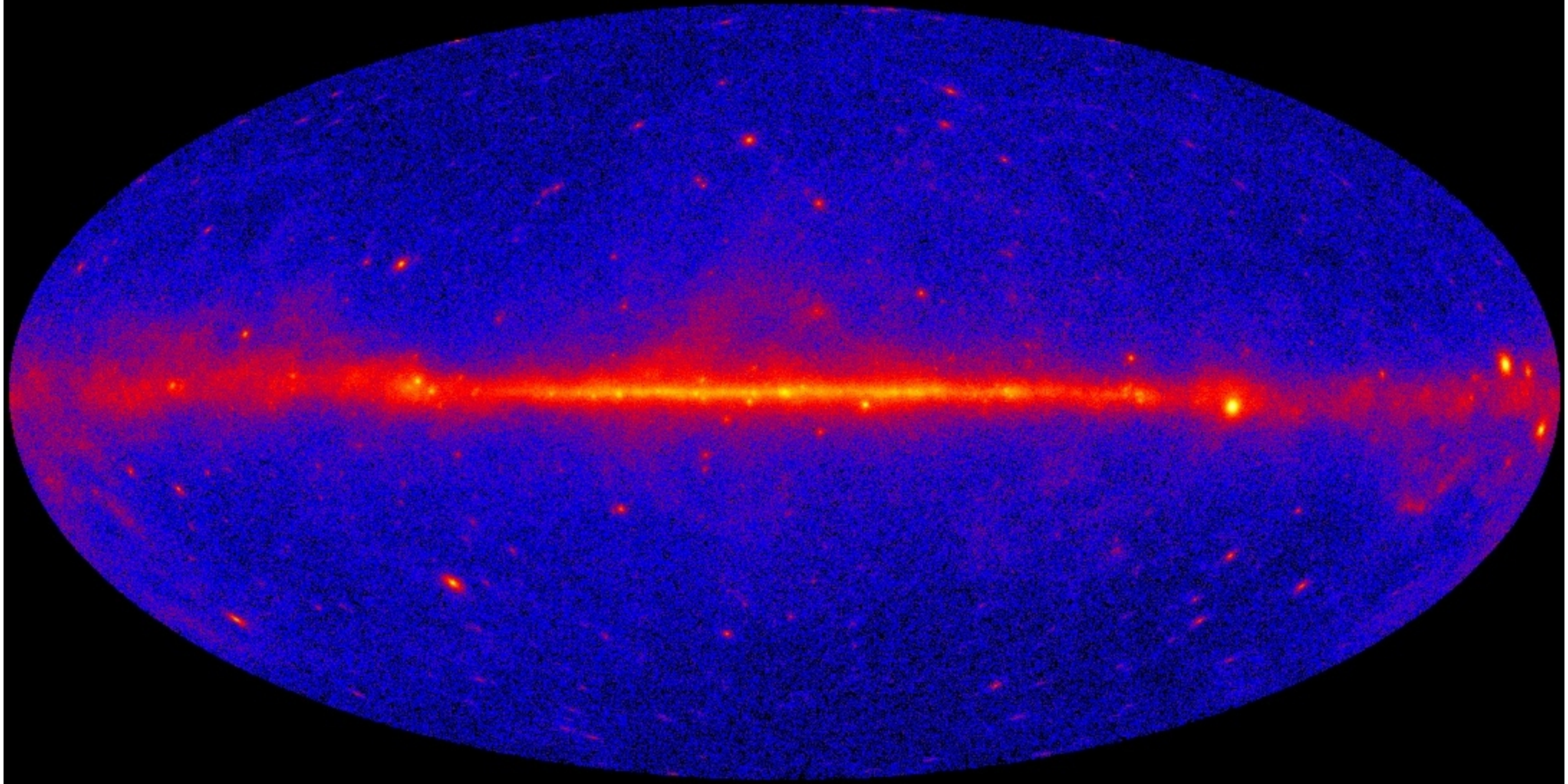
The Milky Way seen in annihilation radiation

GALPROP, optimized



The first-year all-sky image from Fermi



Cold dark matter ?

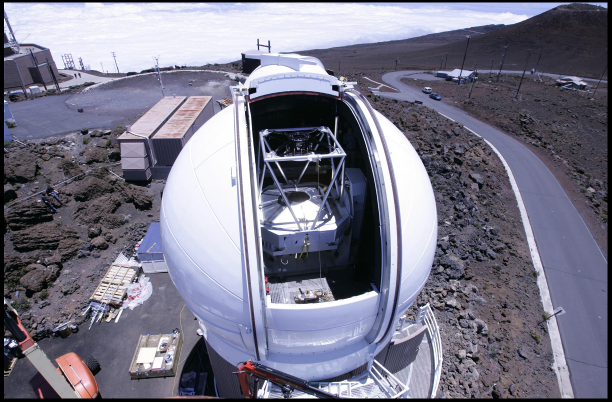
In CDM:

- Dark halos of all masses have “cuspy” density profiles, described by NFW form (to ~10 - 20%) or “Einasto” (to 5%)

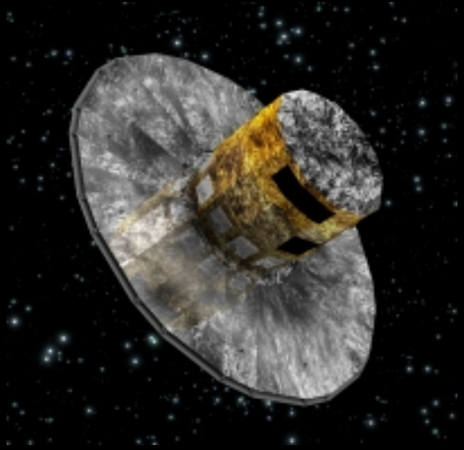
In the Milky Way

- Satellite data (photo/kinematics) consistent with predicted cusps
- No. of satellites (“satellite problem”) explained by gal formation
- Stellar streams (e.g Sag.) consistent with hierarchical formation

Milky Way



Pan-starrs: will discover (many?) new satellites



Gaia will make a 3D map of the Milky Way

Conclusions: CDM detection

- Many small substructures, with convergent mass fraction
  - DM distribution not fractal nor dominated by Earth-mass objects
- γ-ray annihilation may be detectable by FERMI which should:
  - First detect smooth halo (unless $\sigma v \neq$ const.)
  - Then (perhaps) detect dark subhalos with no stars
  - Sub-substructure boost irrelevant for detection

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