Simulating the Universe in a computer

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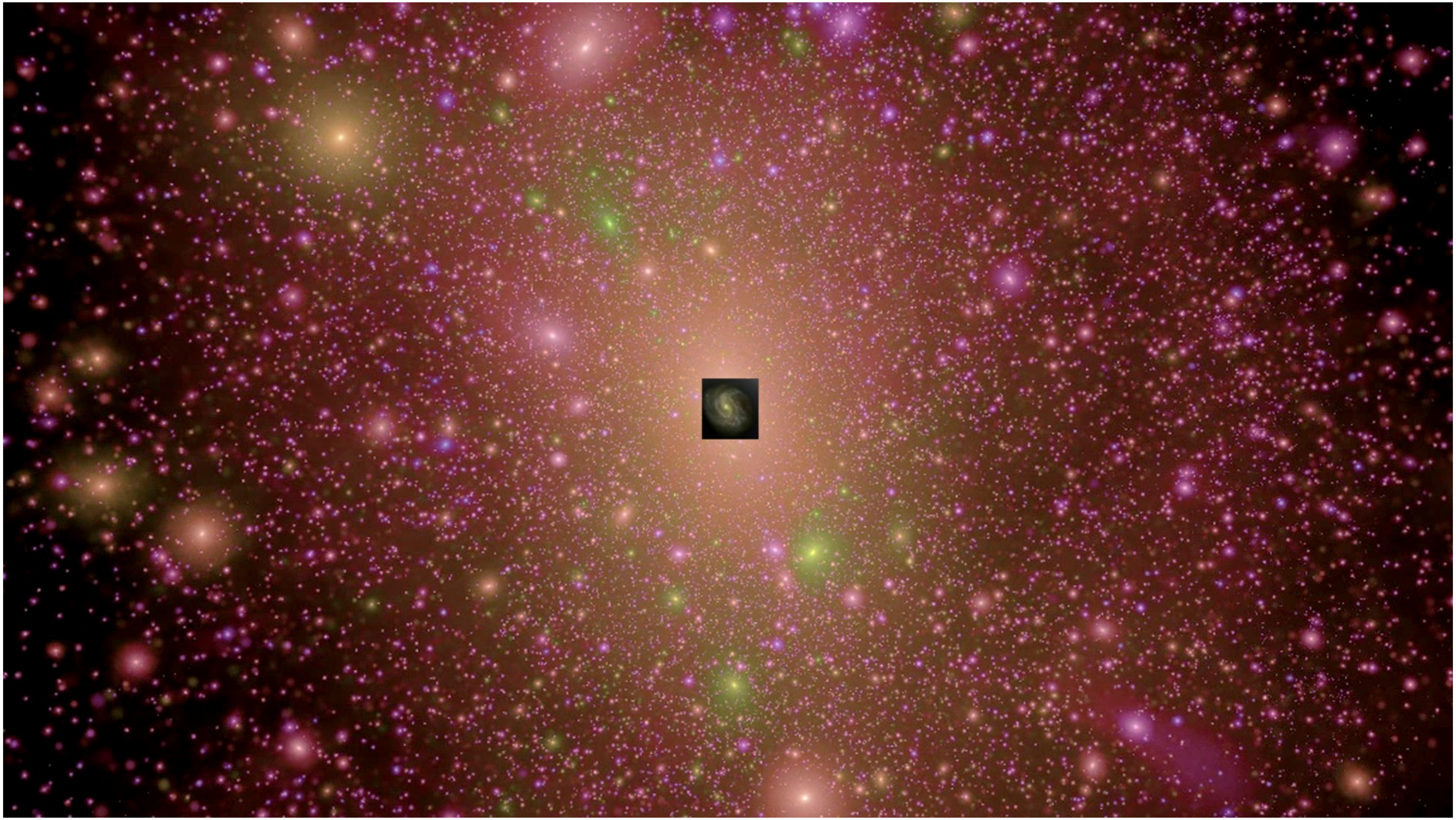
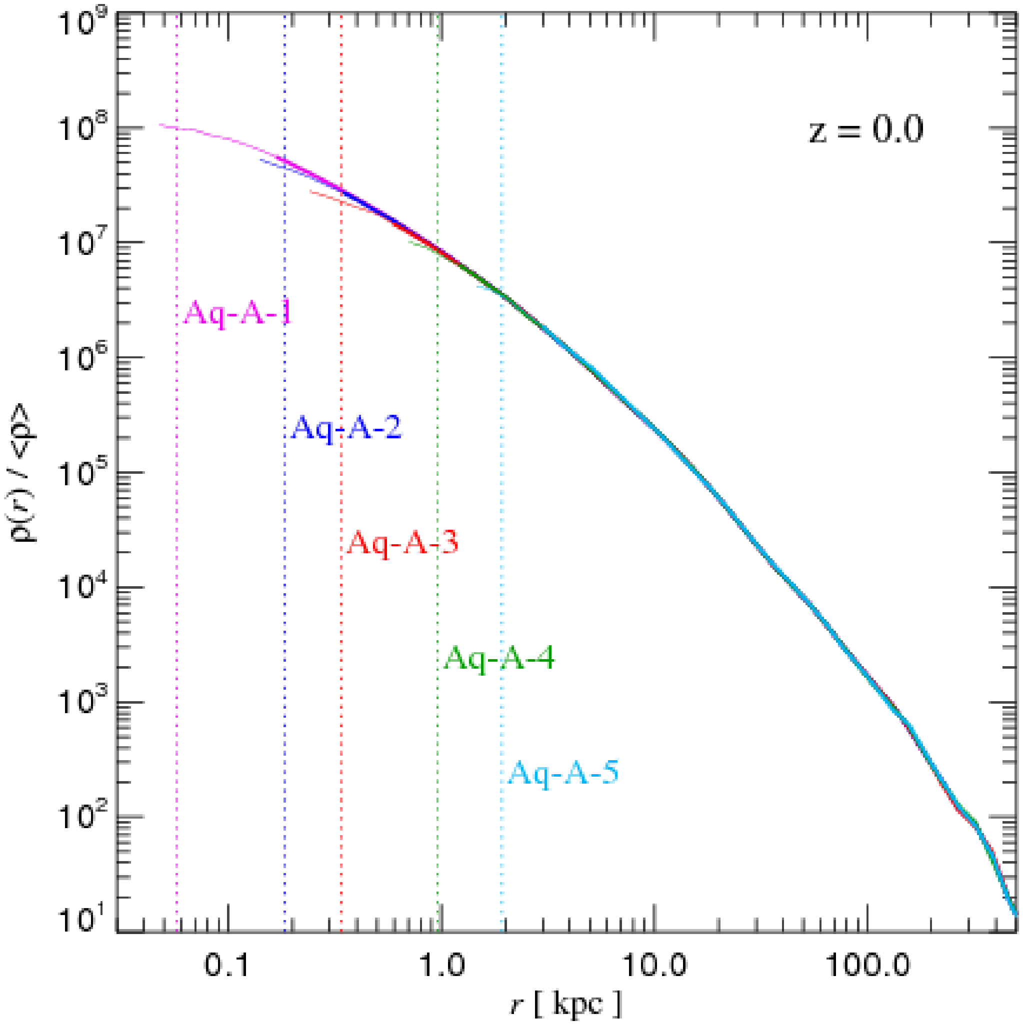
MAX-PLANCK-GESELLSCHAFT

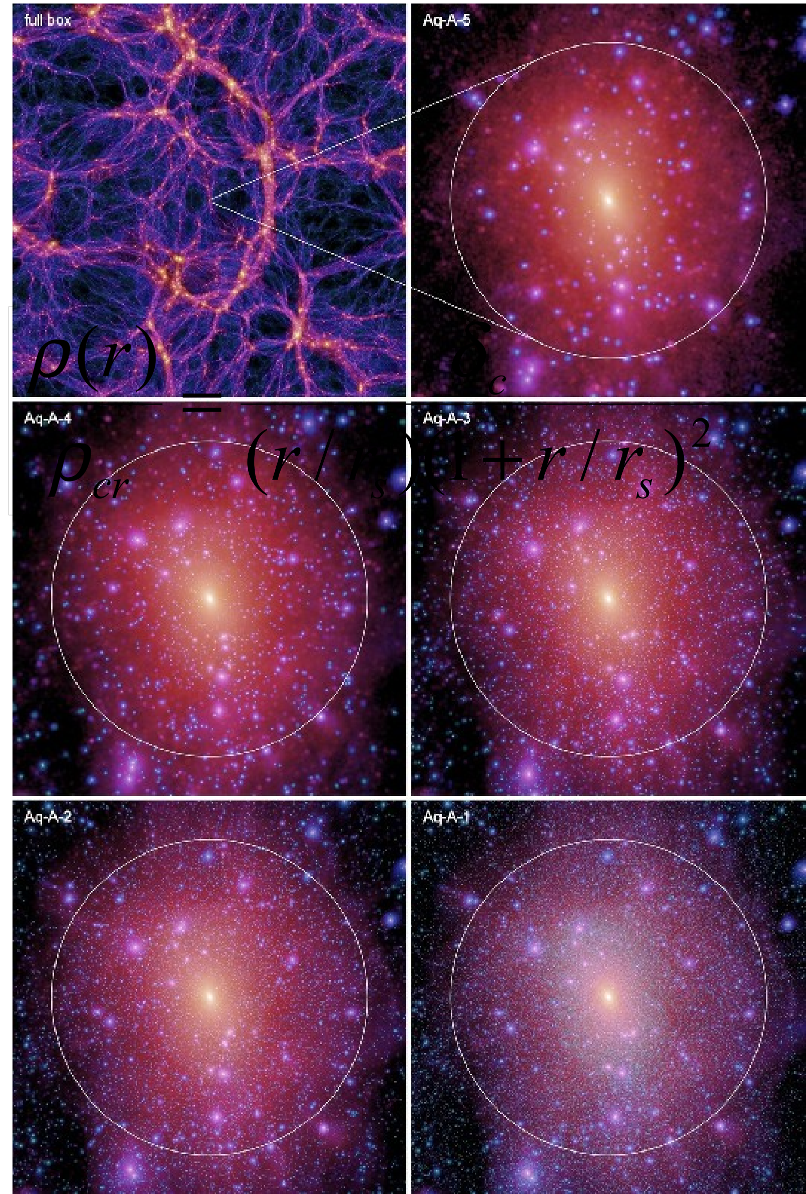
Halo structure at small scales

Halo structure at small scales



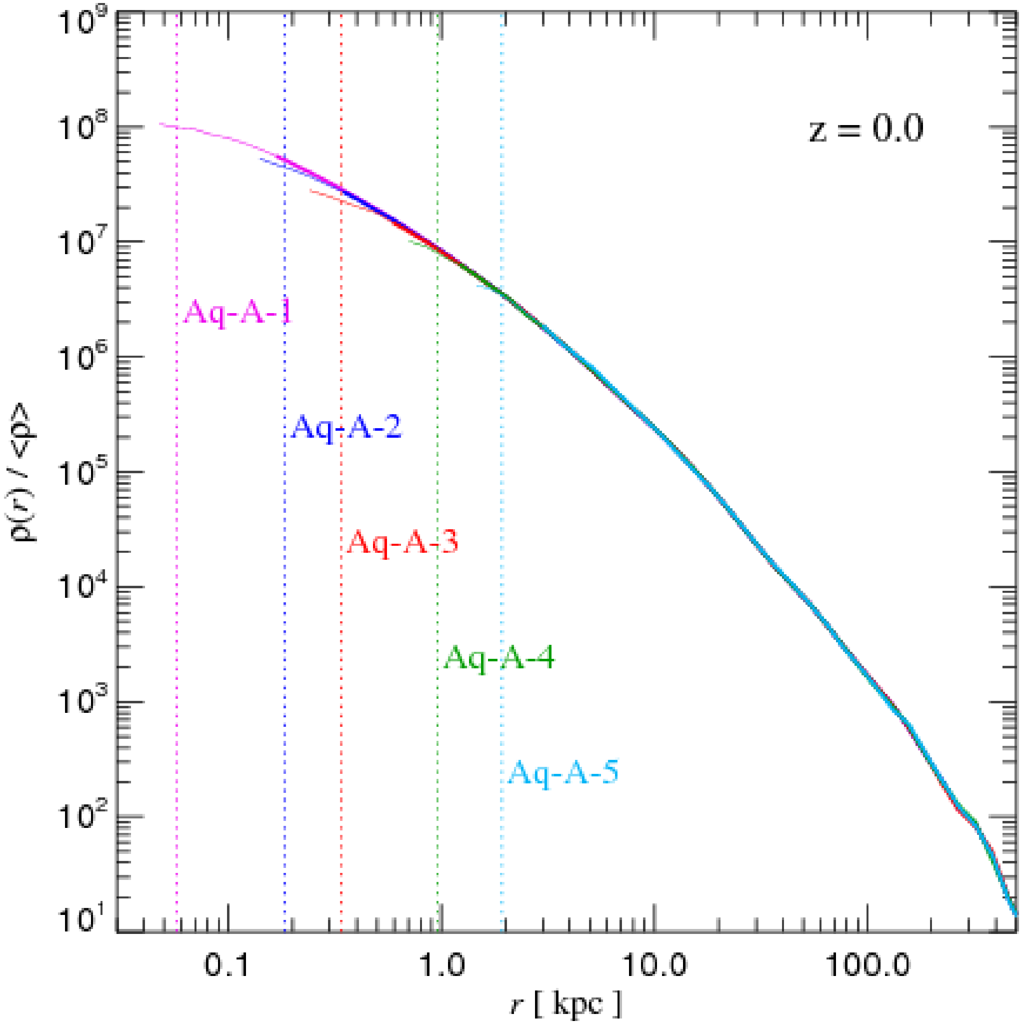
Halo density profile





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

Halo density profile



NFW profile

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

Two free parameters

δc normalization

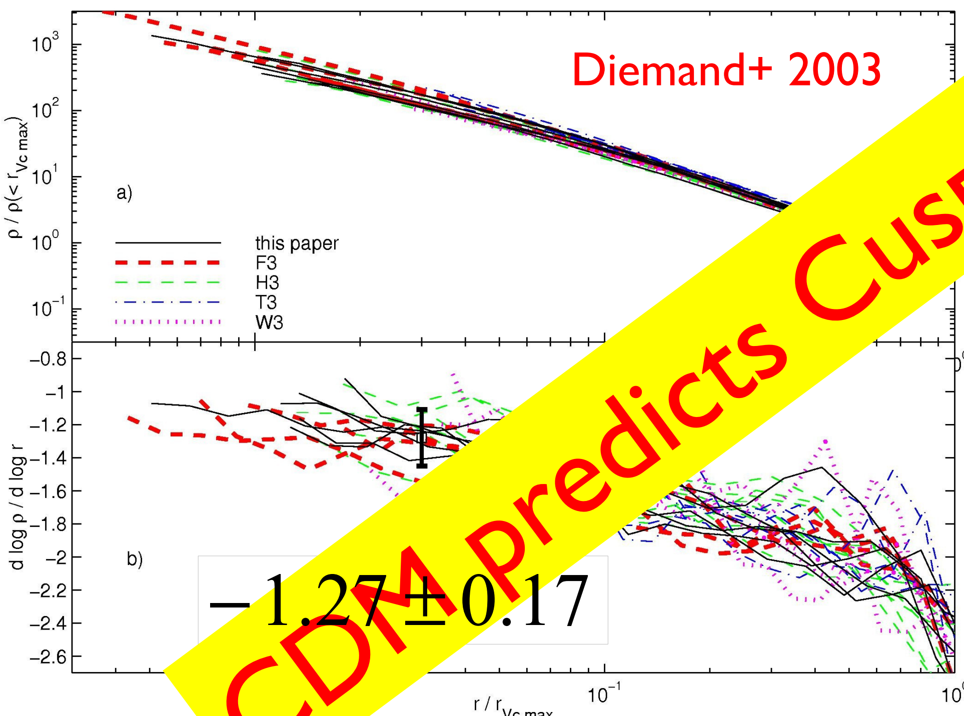
rs scale radius

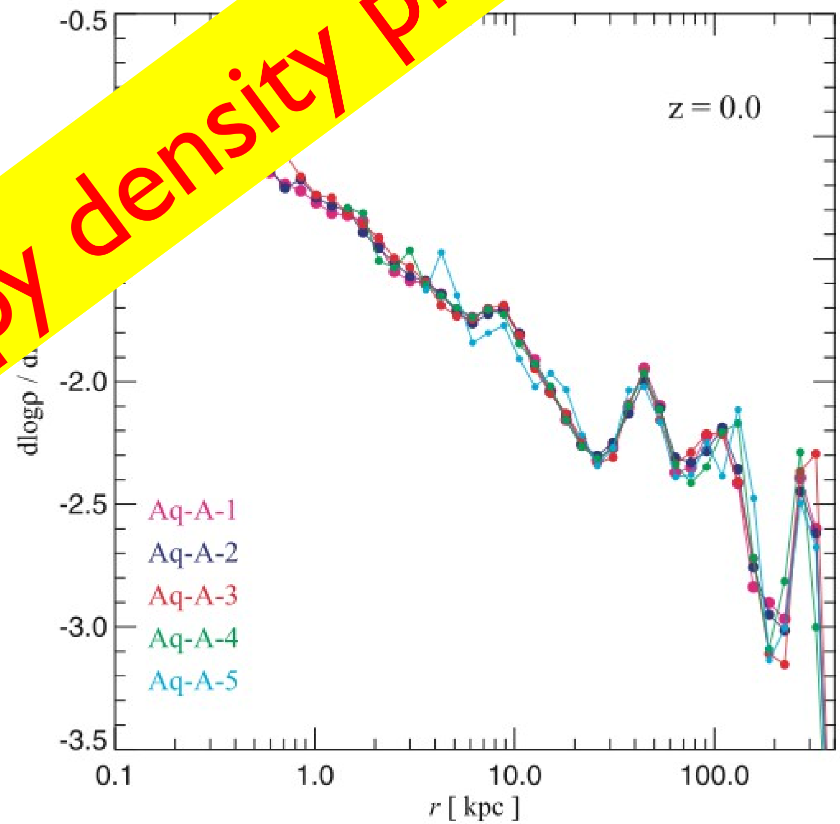
Inner density slope

Navarro, Frank & White (1997) : $\alpha = -1.0$

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

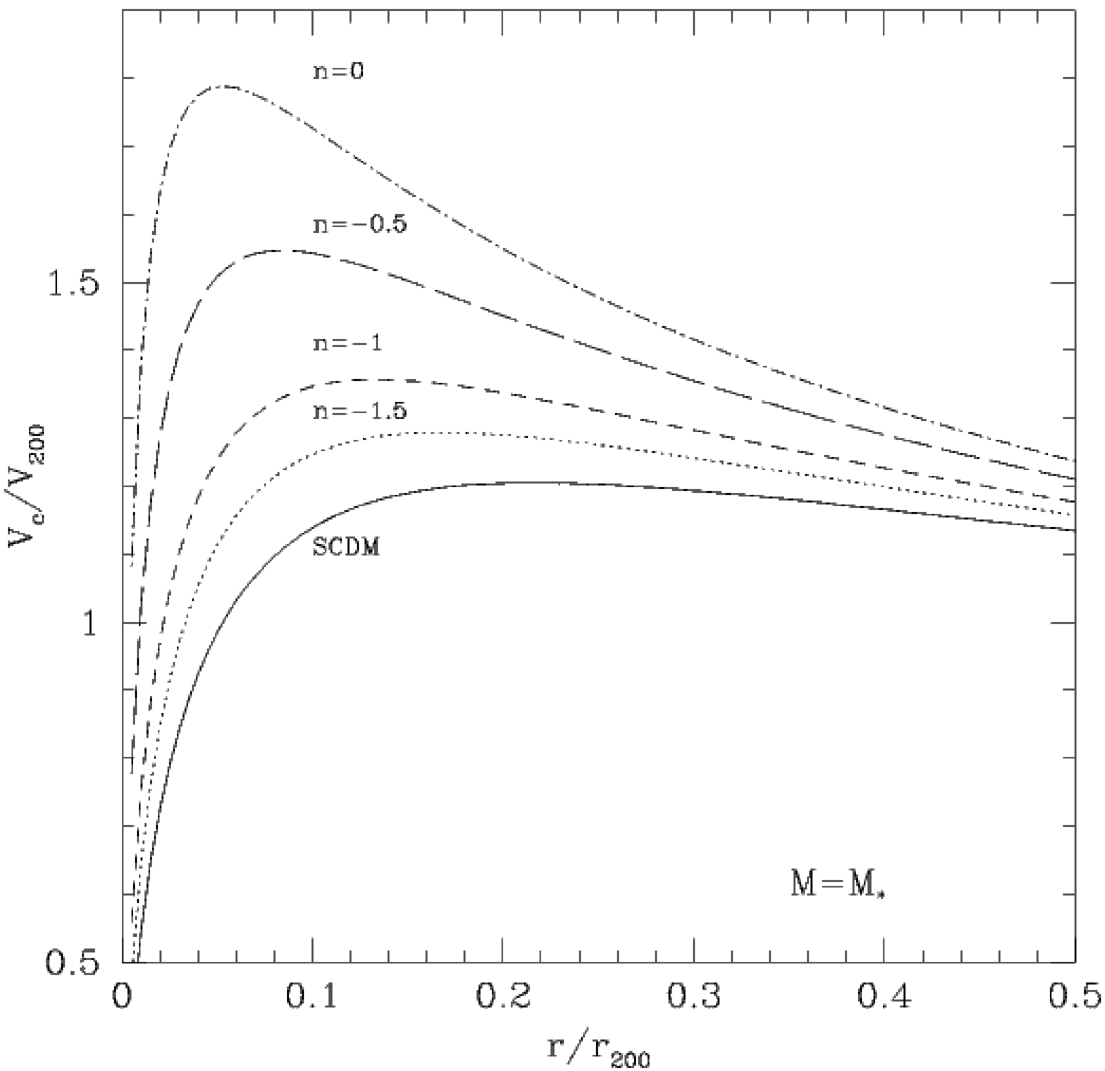
CDM predicts Cuspy density profiles





Springel+08

Halo density profile



NFW profile

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

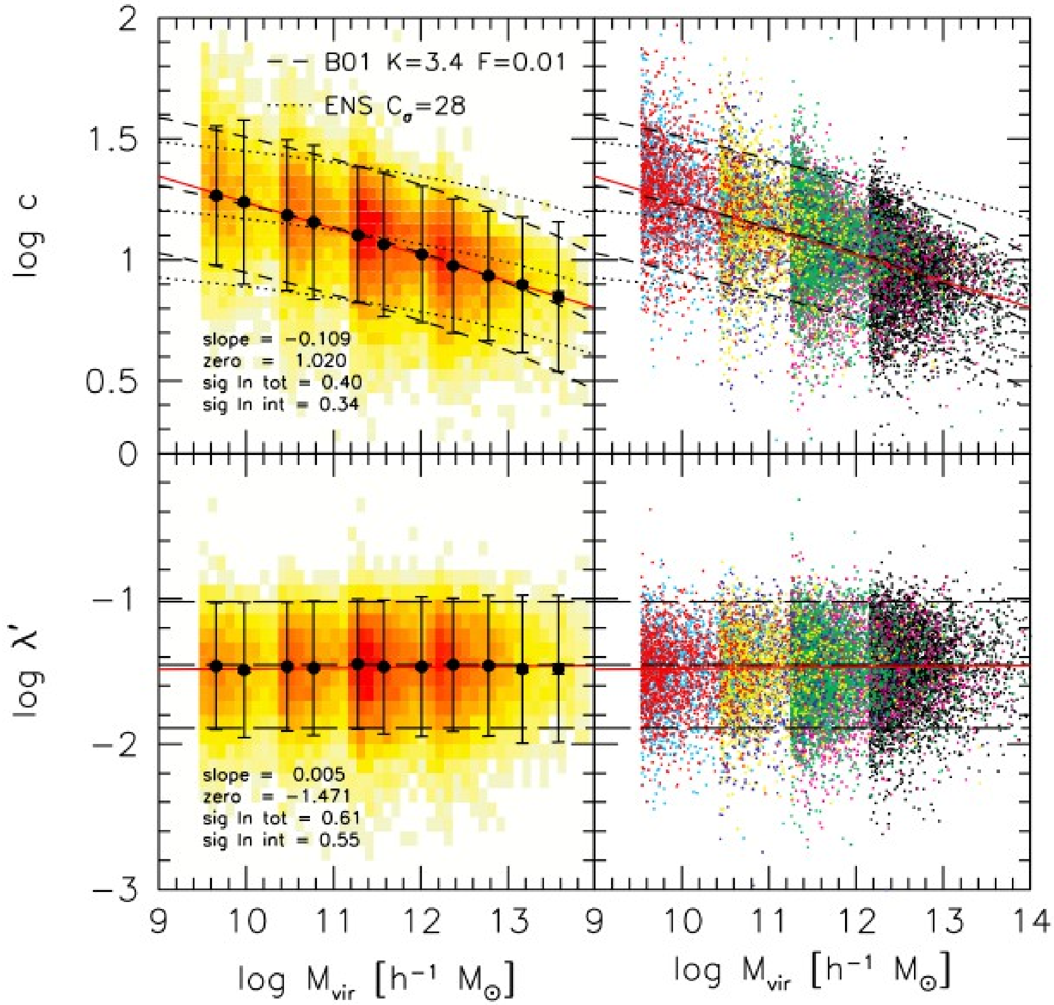
$$V(r) = \sqrt{\frac{GM(<r)}{r}}$$

Vmax

Rmax

Halo density profile

Macciò+07

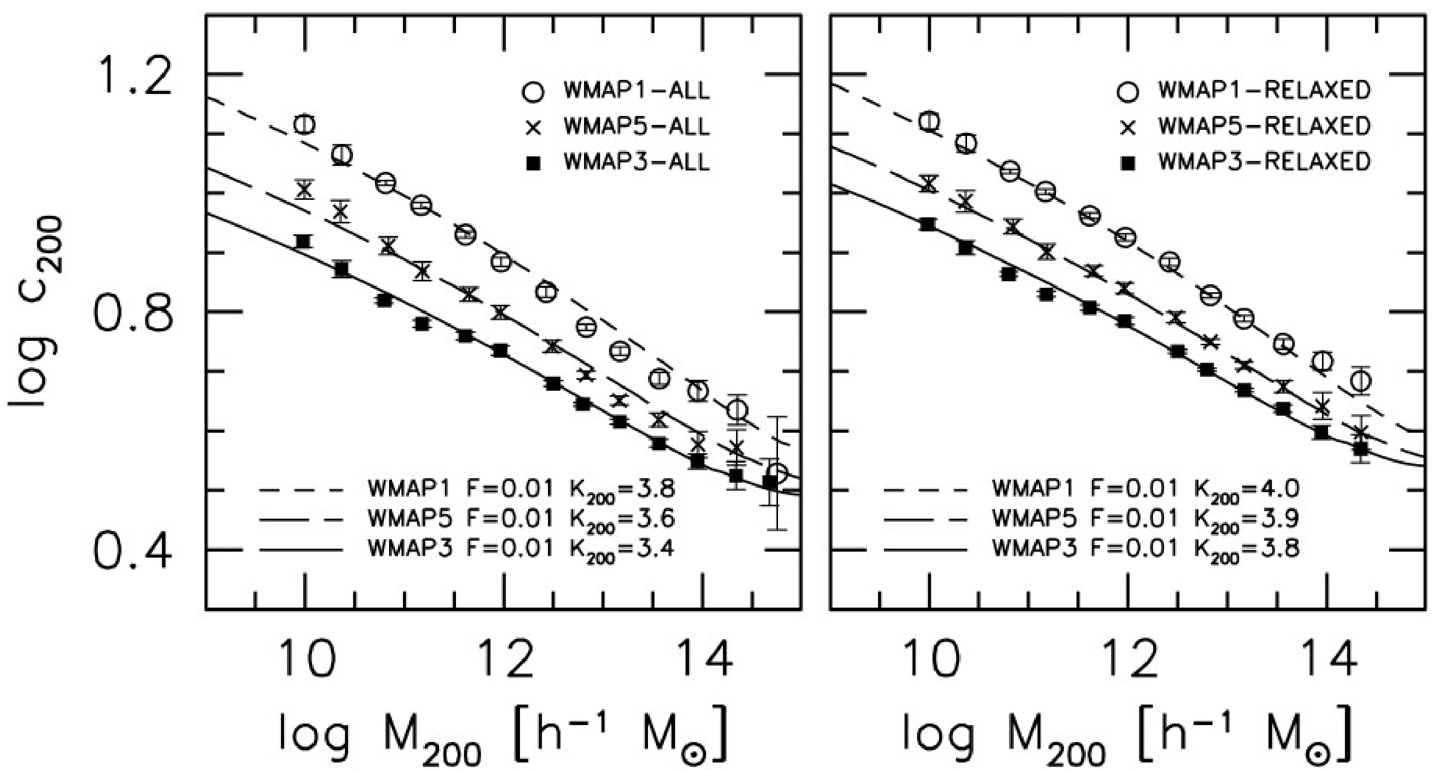


NFW profile

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

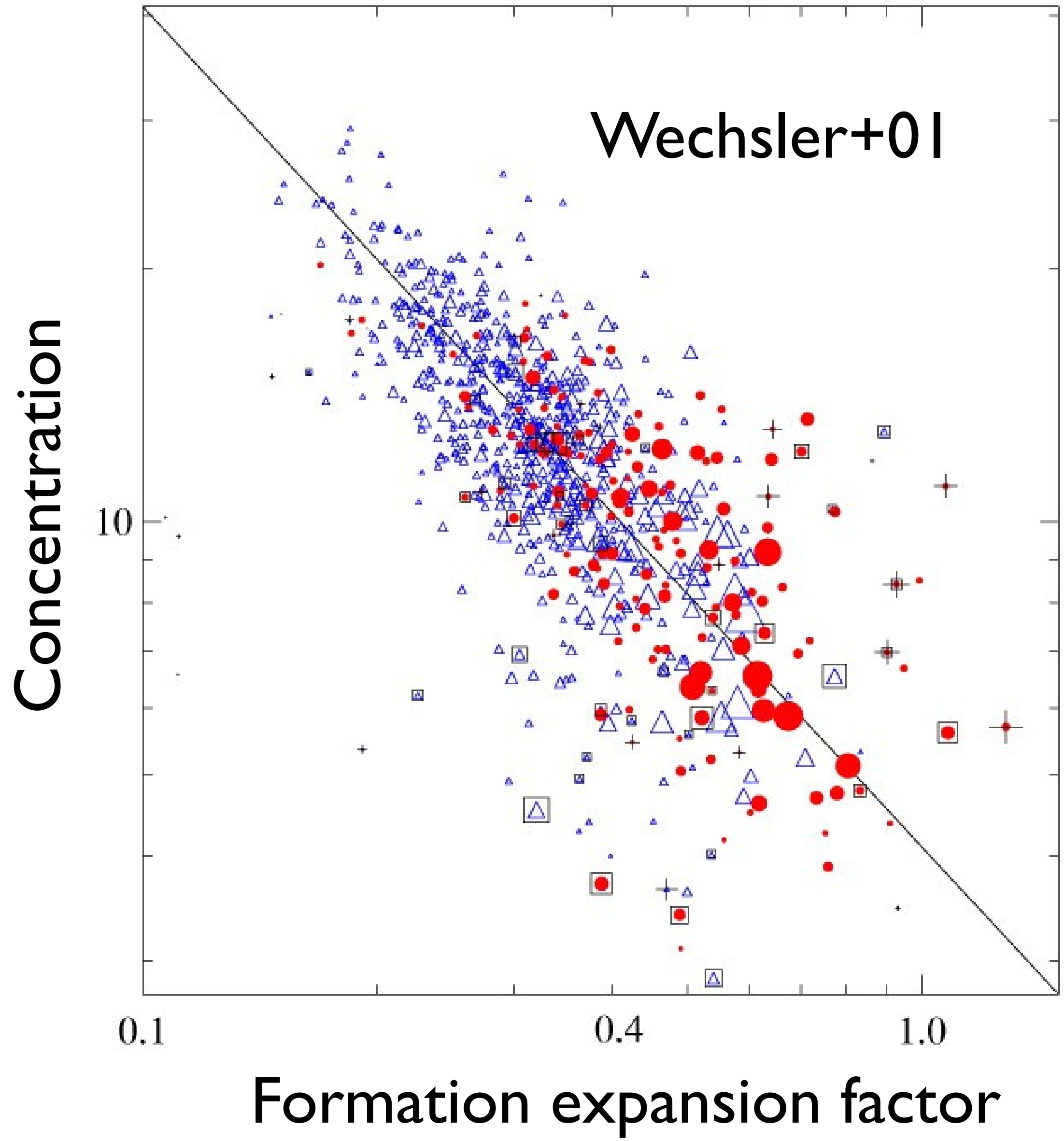
Rvir/rs = concentration

Name	$\Omega_\Lambda + \Omega_m$	Ω_m	h	σ_8	n	Ω_b
*WMAP*1	1.0	0.268	0.71	0.90	1.00	0.044
*WMAP*3	1.0	0.238	0.73	0.75	0.95	0.042
*WMAP*5	1.0	0.258	0.72	0.796	0.963	0.0438

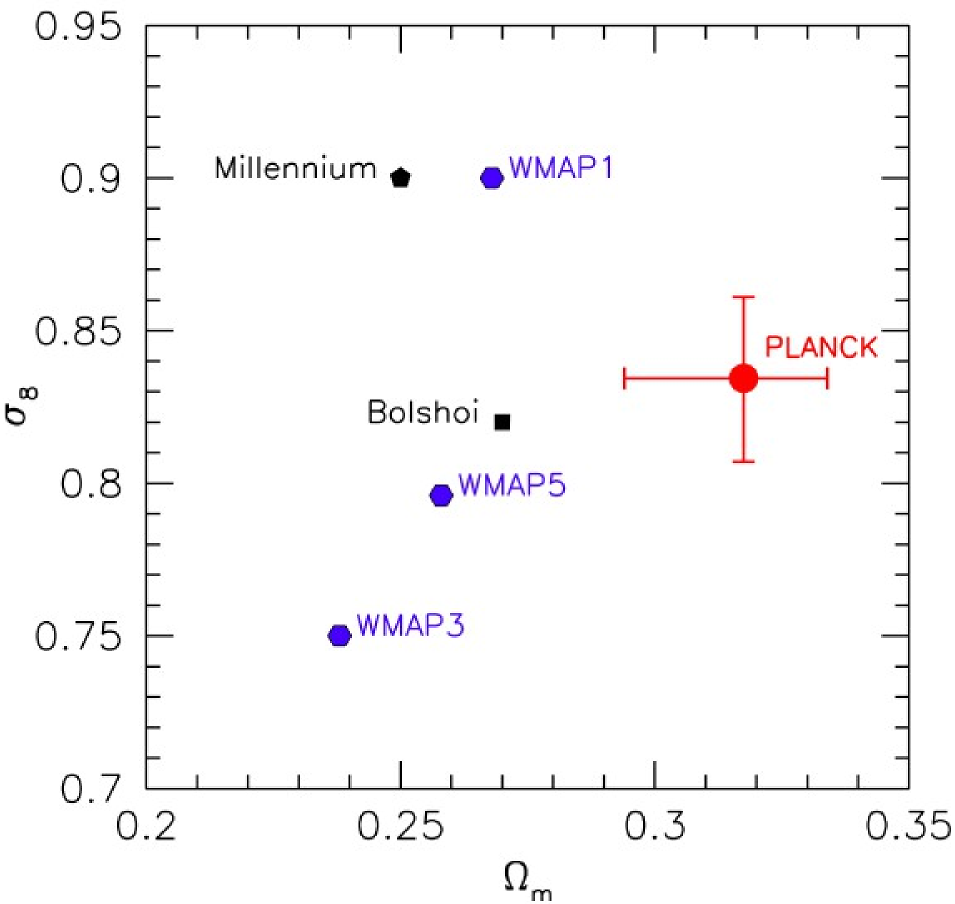


Macciò+08

Origin of concentration



Is NFW a good fit?

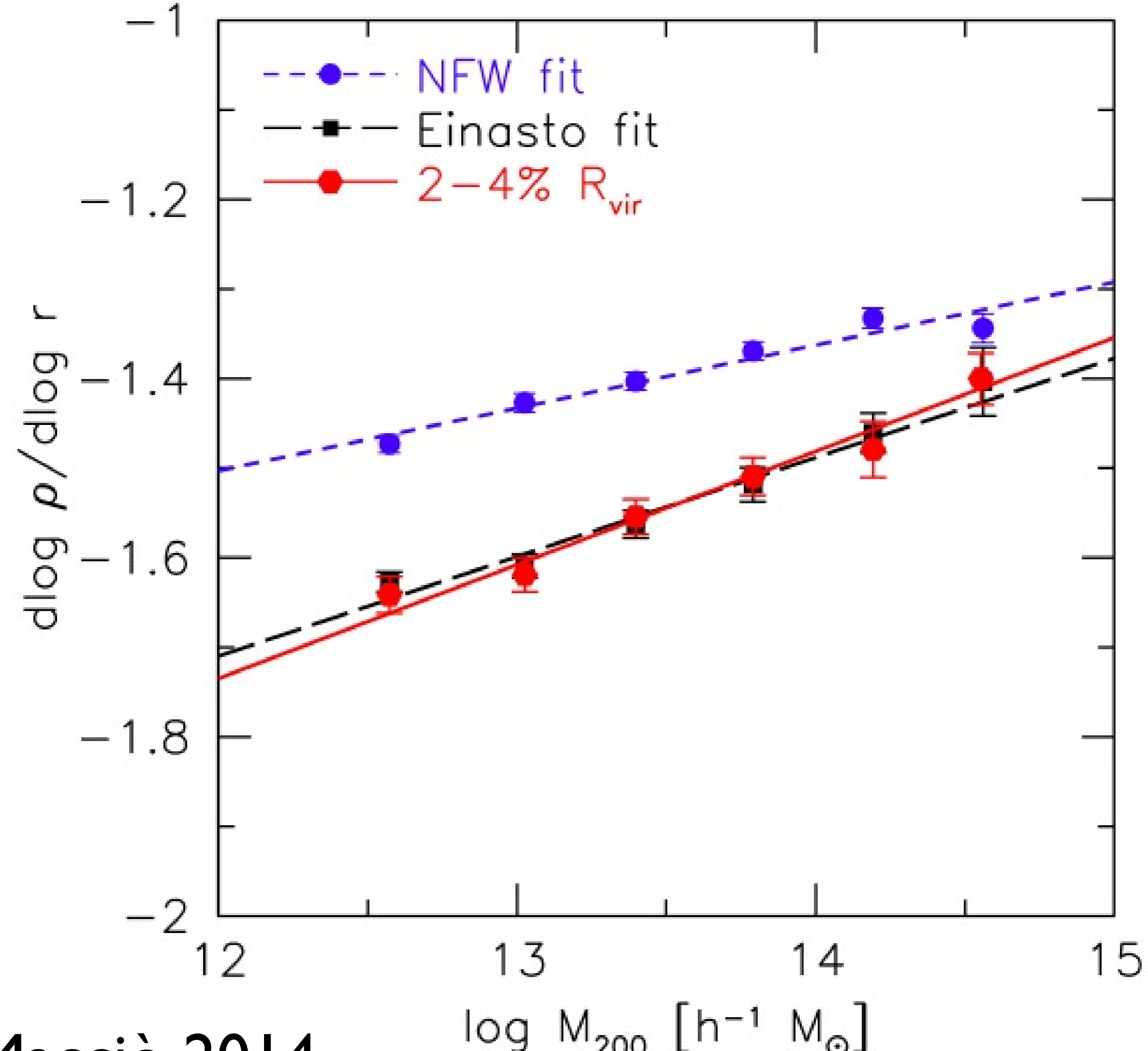


$$\frac{\rho_{\rm NFW}(r)}{\rho_{-2}} = \frac{4}{(r/r_{-2})(1+r/r_{-2})^2}$$

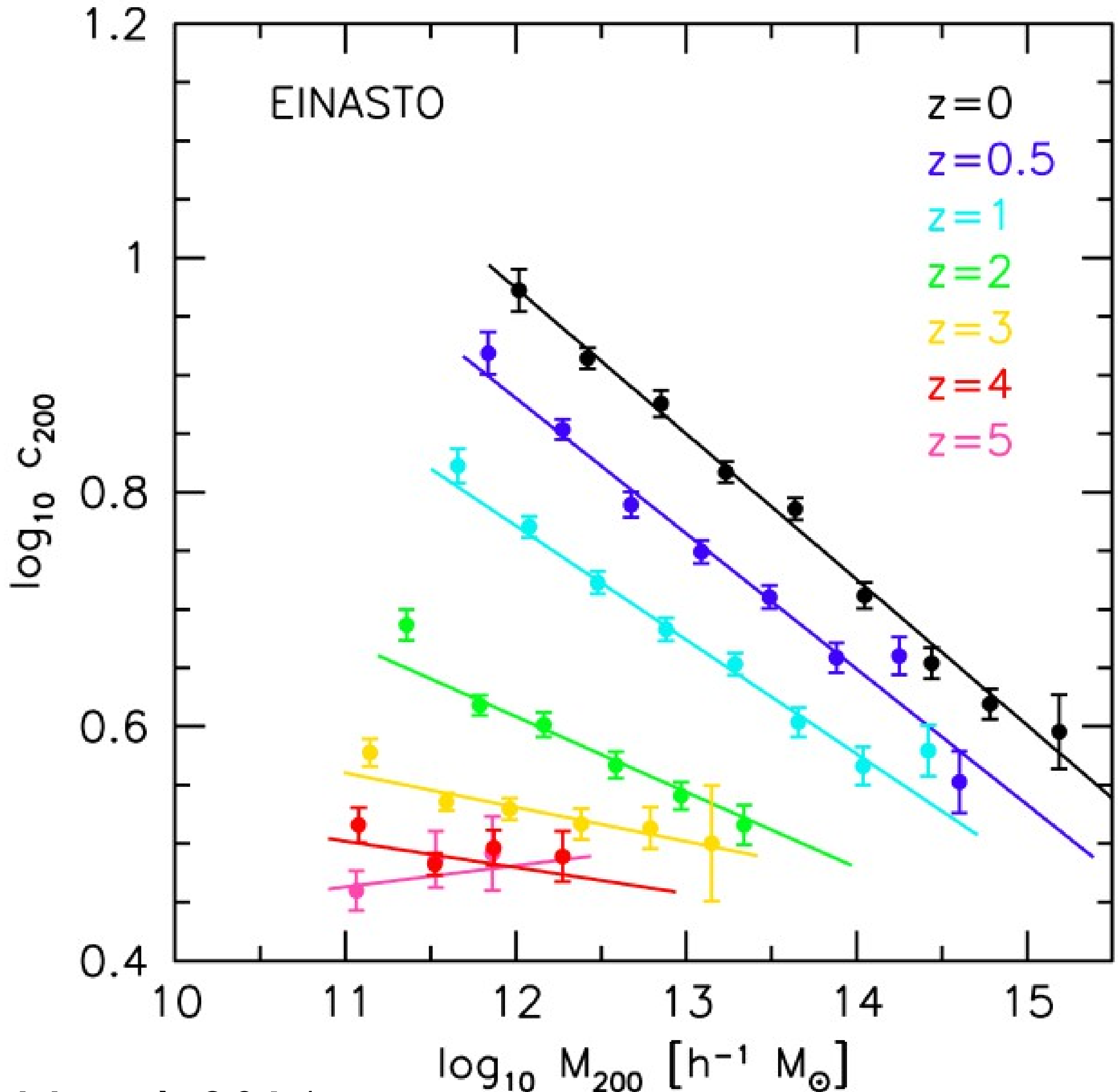
$$\frac{\rho_{\rm EIN}(r)}{\rho_{-2}} = \exp\left\{-\frac{2}{\alpha}\left[(r/r_{-2})^{\alpha}-1\right]\right\}$$

Dutton & Macciò 2014

Einasto vs. NFW

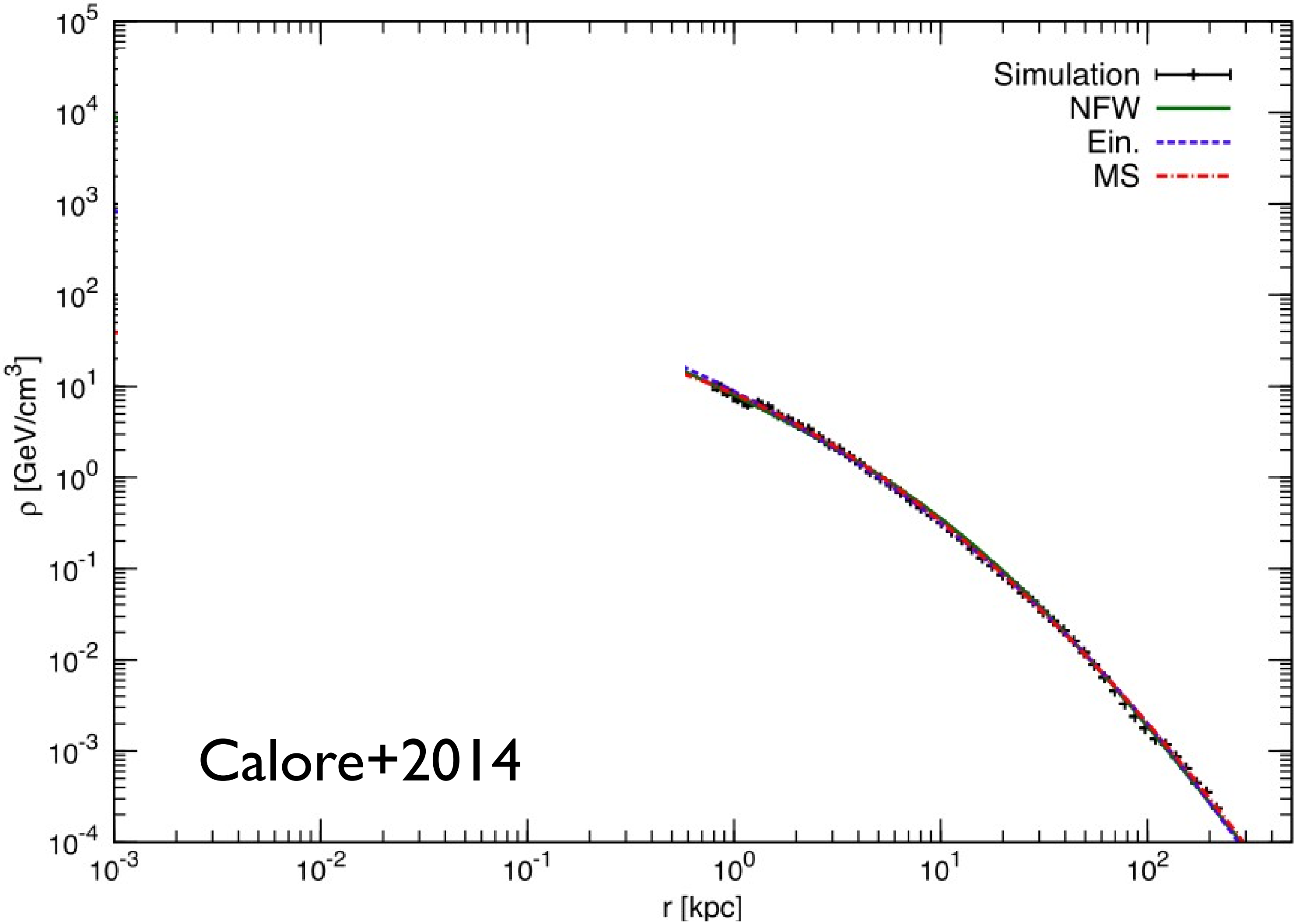


Dutton & Macciò 2014

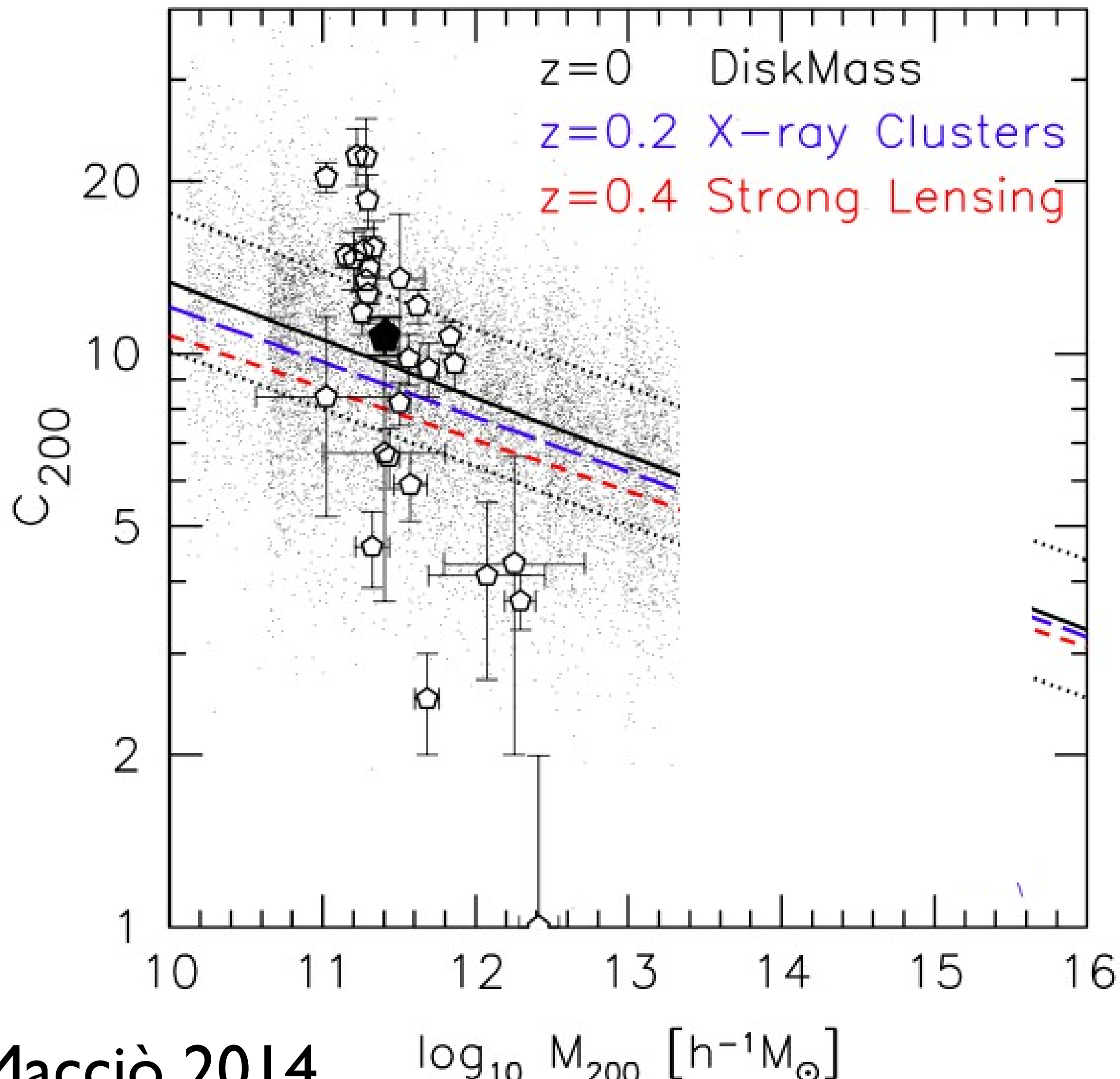


Dutton & Macciò 2014

Why should you care?



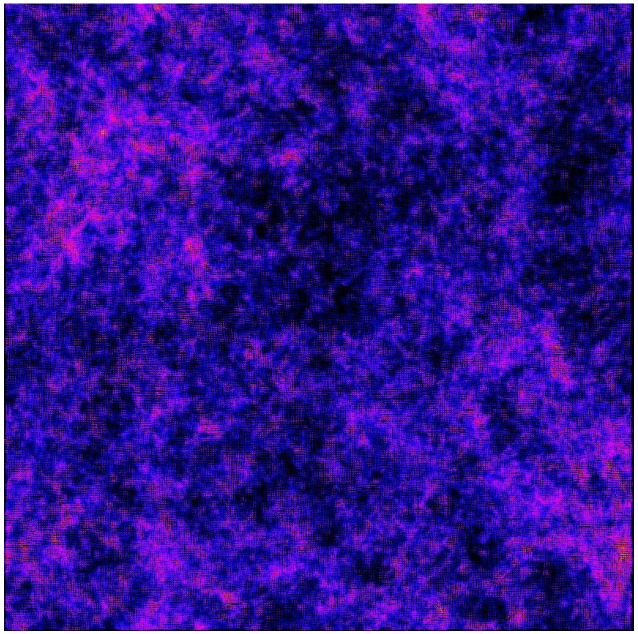
Concentrations vs. data



Dutton & Macciò 2014

Back to cosmology

Back to cosmology



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

$$\nabla^2 \Phi(x,t) = 4\pi G\, a(t)^2\, \rho(x,t)$$

$$\frac{dx}{da} = \frac{dx}{dt}\frac{dt}{da}$$

Expansion velocity

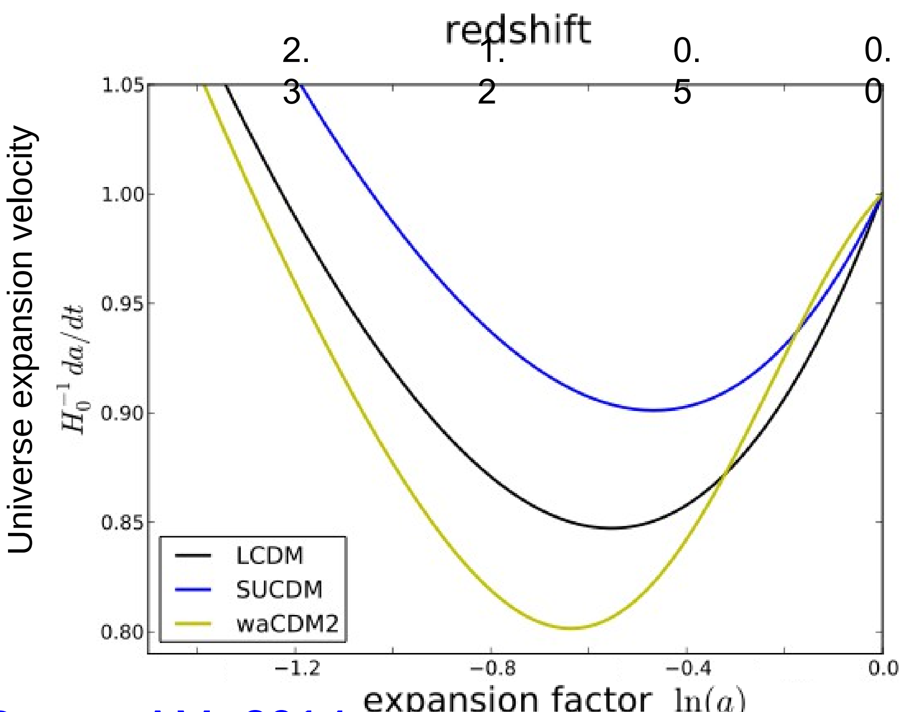
1) Initial conditions: Power Spectrum
2) Background evolution: a(t)

Dynamical Dark Energy

$w(z)$ ⇨ different background evolution

$$H(z) = H_0\sqrt{\Omega_{m_0}(1+z)^3 + \Omega_{r_0}(1+z)^4 + \Omega_{DE_0}}$$

matter   radiation



Penzo, AM+2014

same σ_8 at $z = 0$

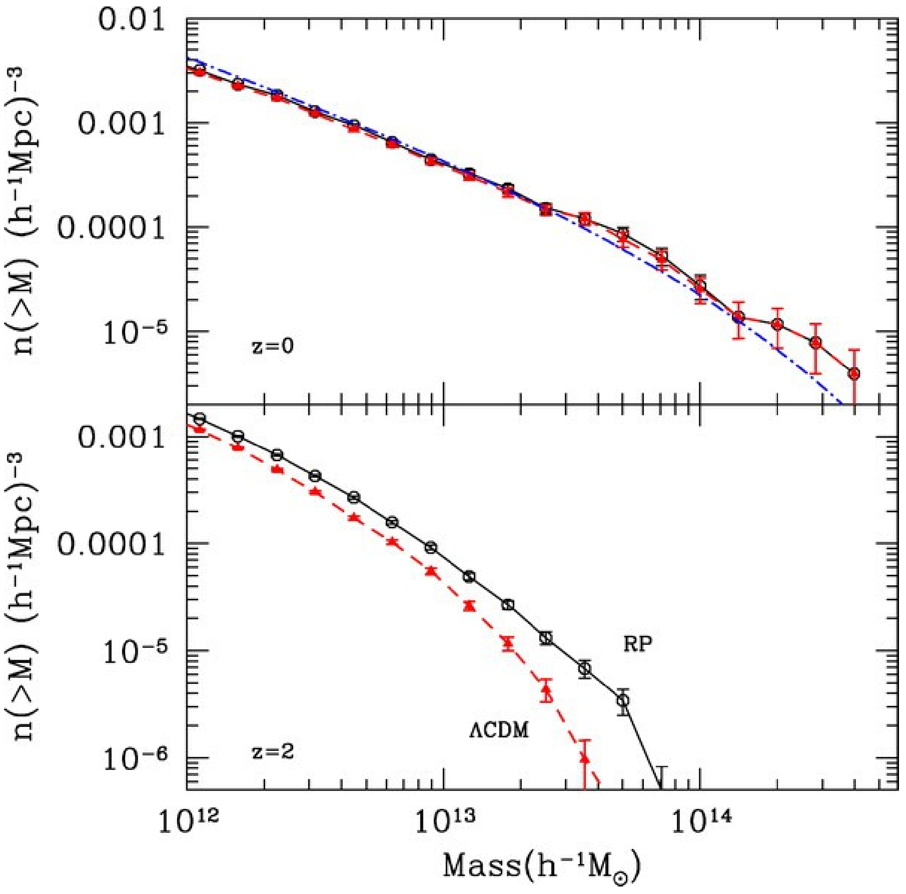
SUCDM has a faster expansion velocity

└─> structures start forming EARLIER

waCDM2 has a slower expansion velocity

└─> structures start forming LATER

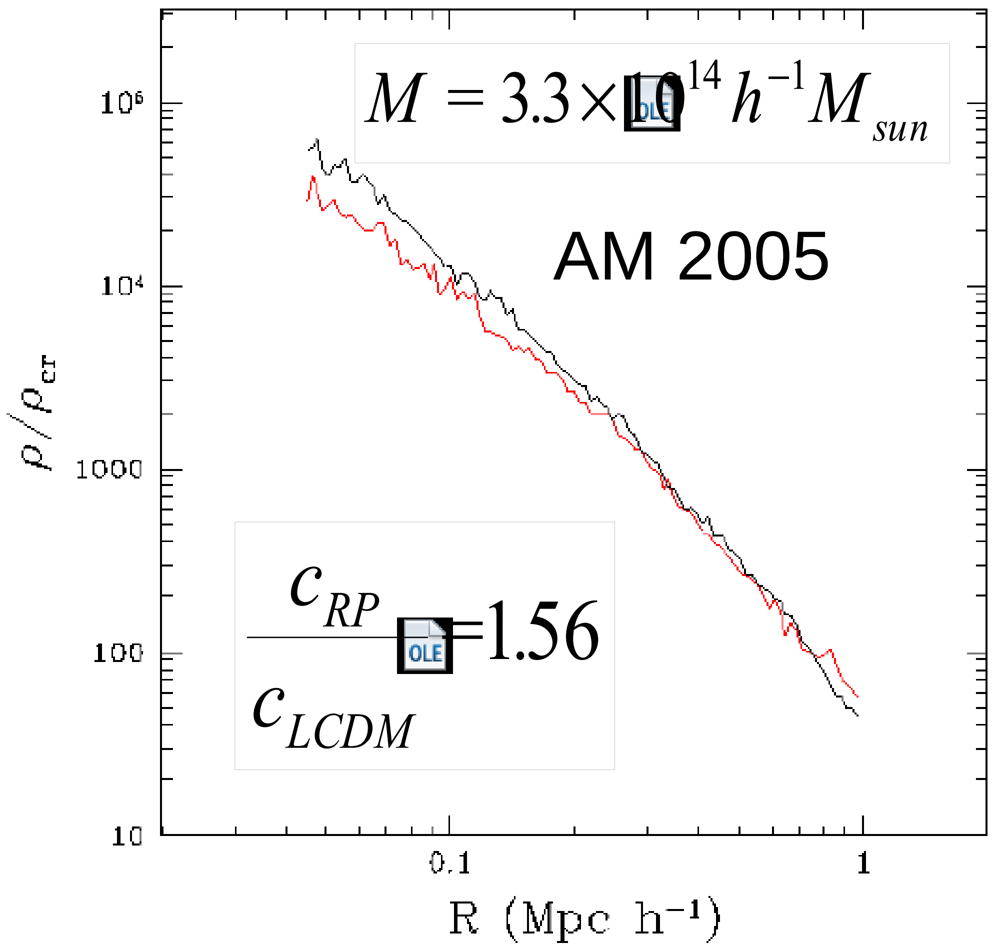
Faster than LCDM

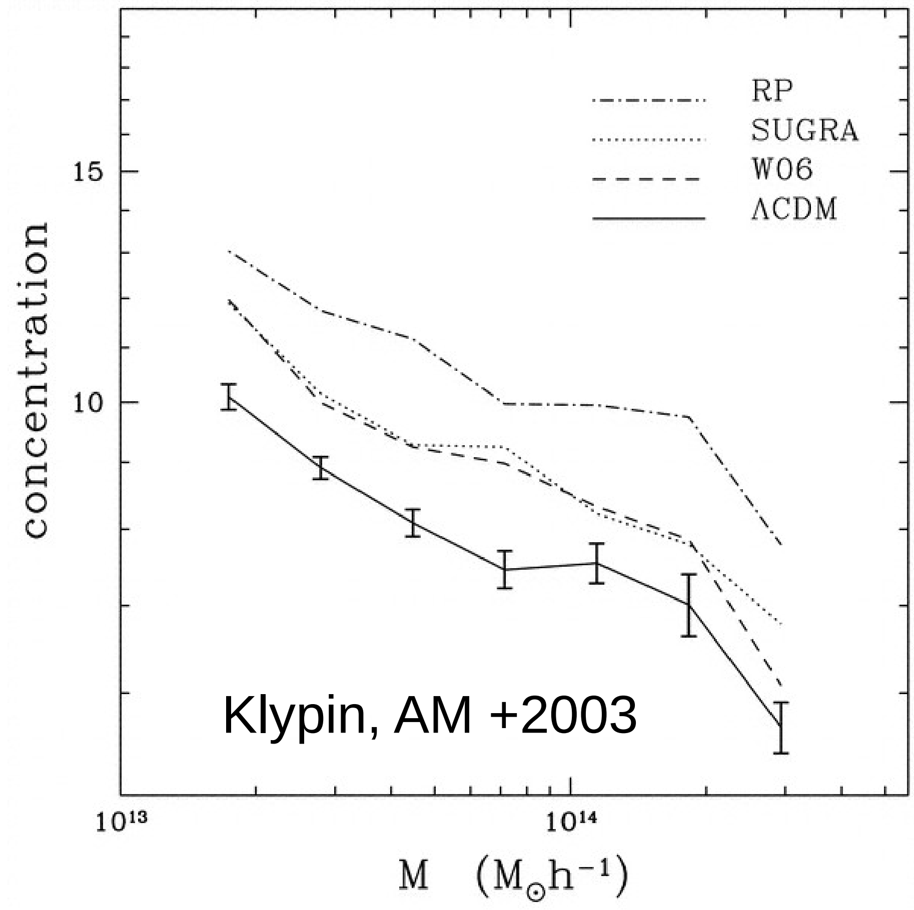


- DE suppresses structure formation
- More haloes at z>0
- Earlier formation time
- Larger concentration at fix Mass

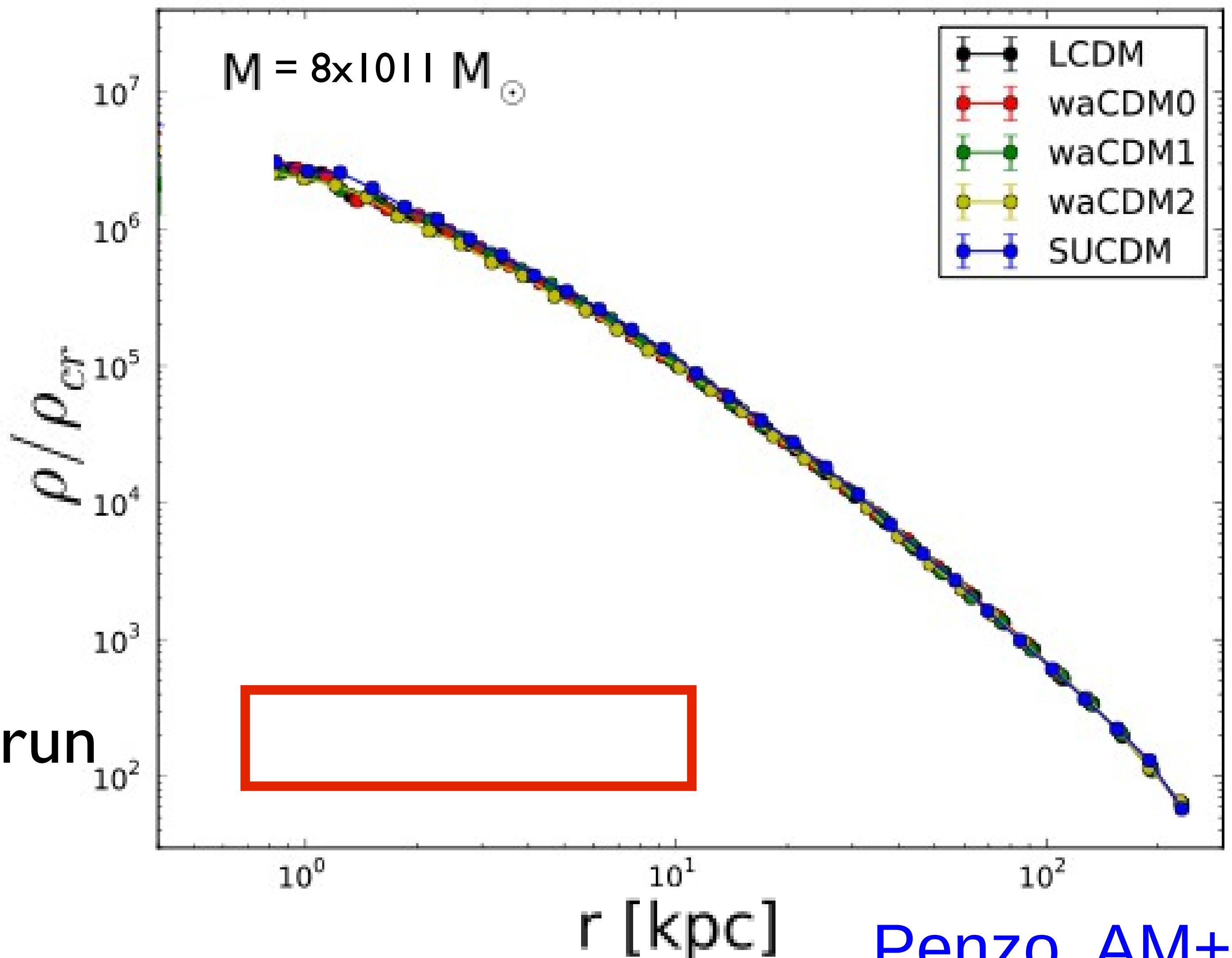
Klypin, AM +2003

Faster than LCDM





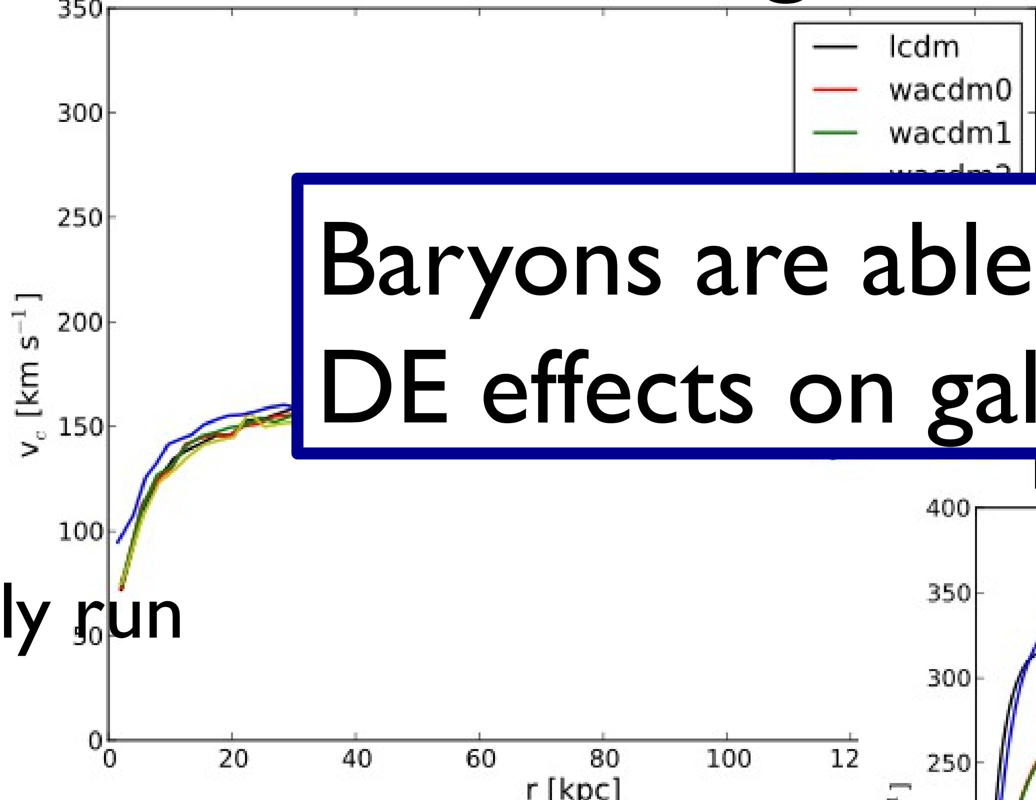
DE at galactic scales



M only run

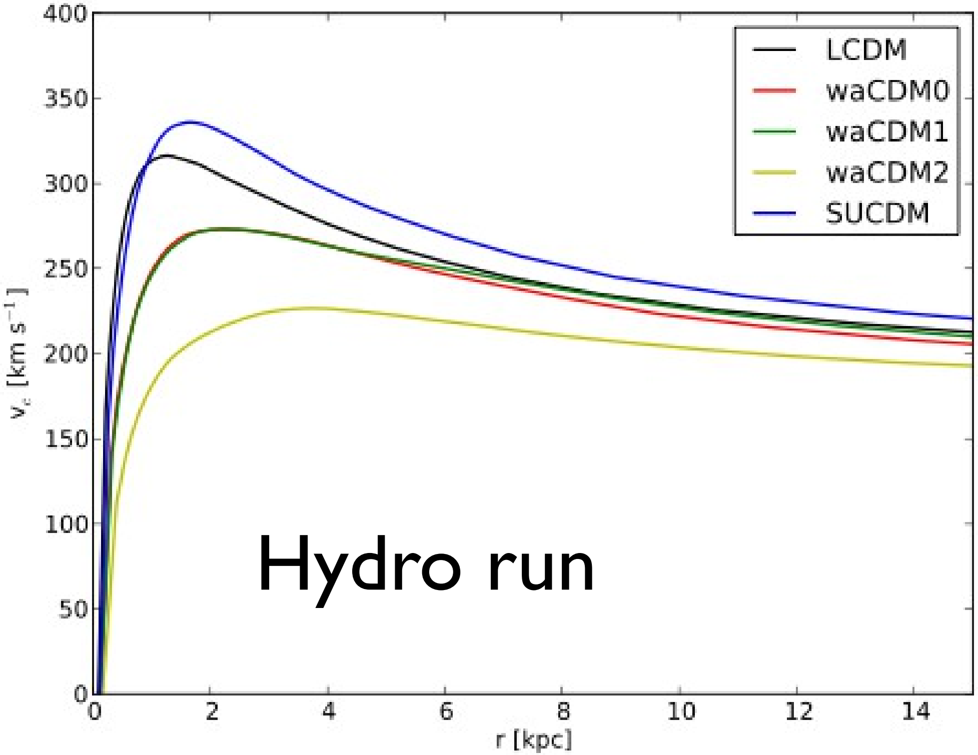
Penzo, AM+2014

DE on galactic scales



Baryons are able to amplify DE effects on galactic scales

nly run

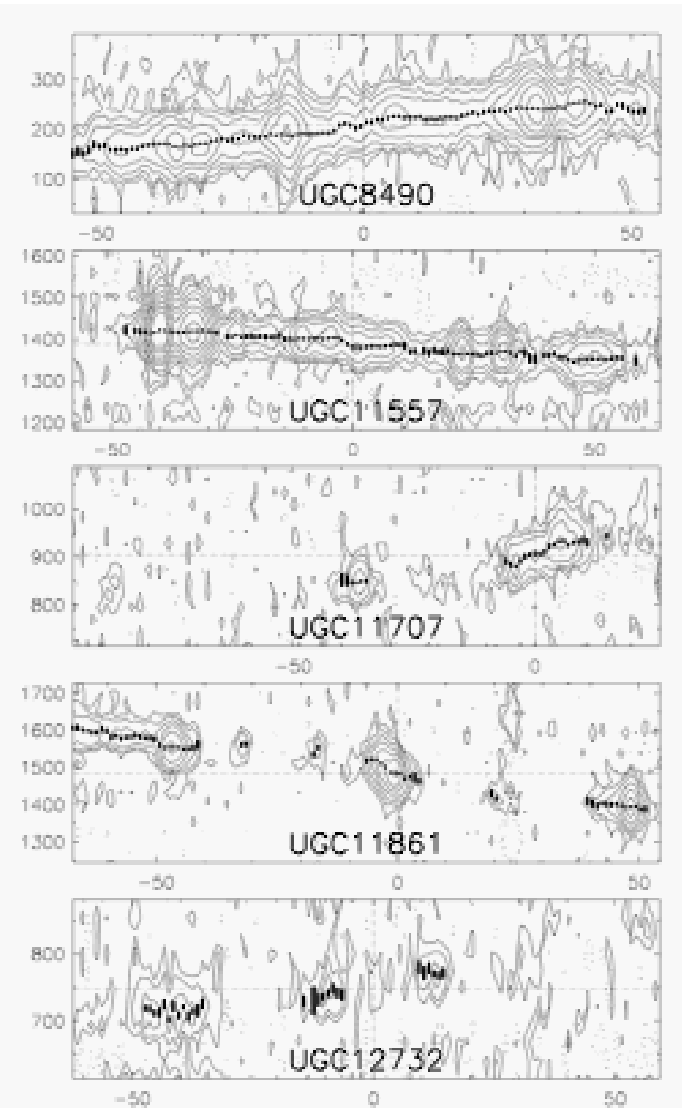


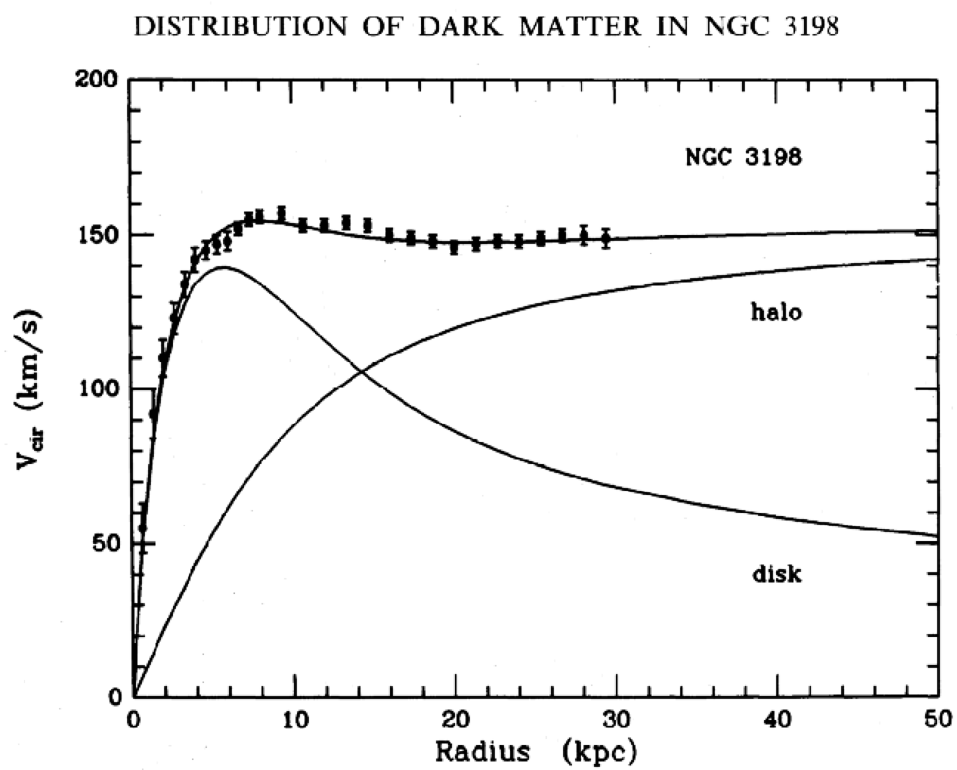
Penzo, AM+2014

Hydro run

Observed density profile

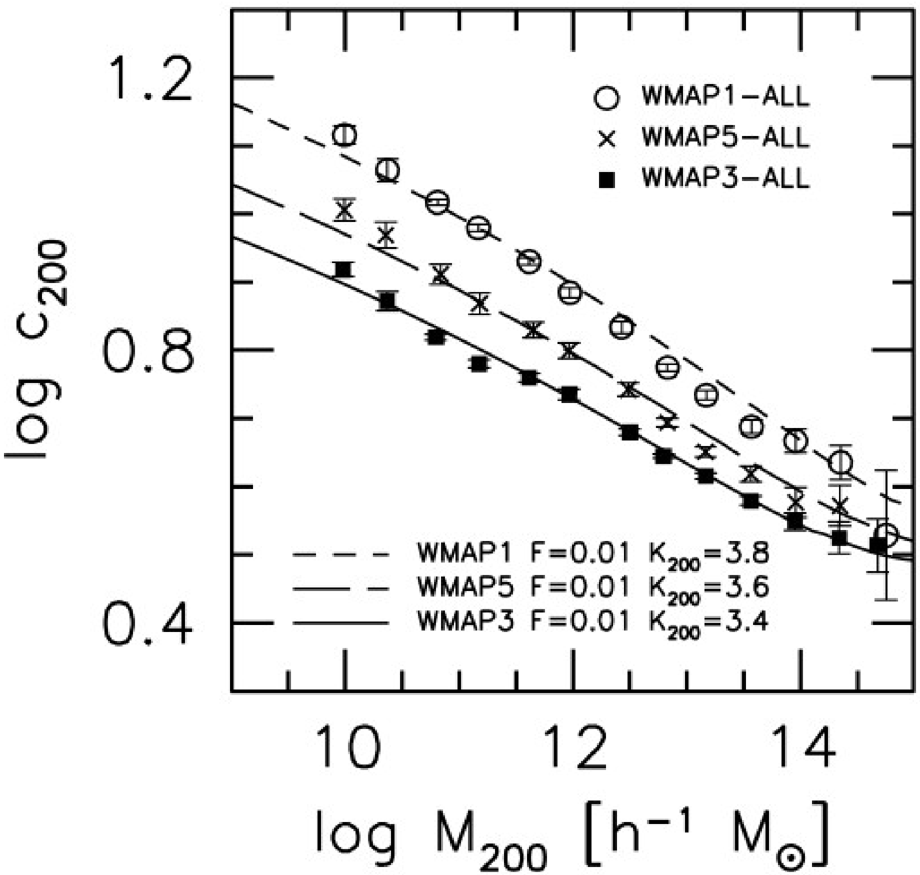
de Blok+02

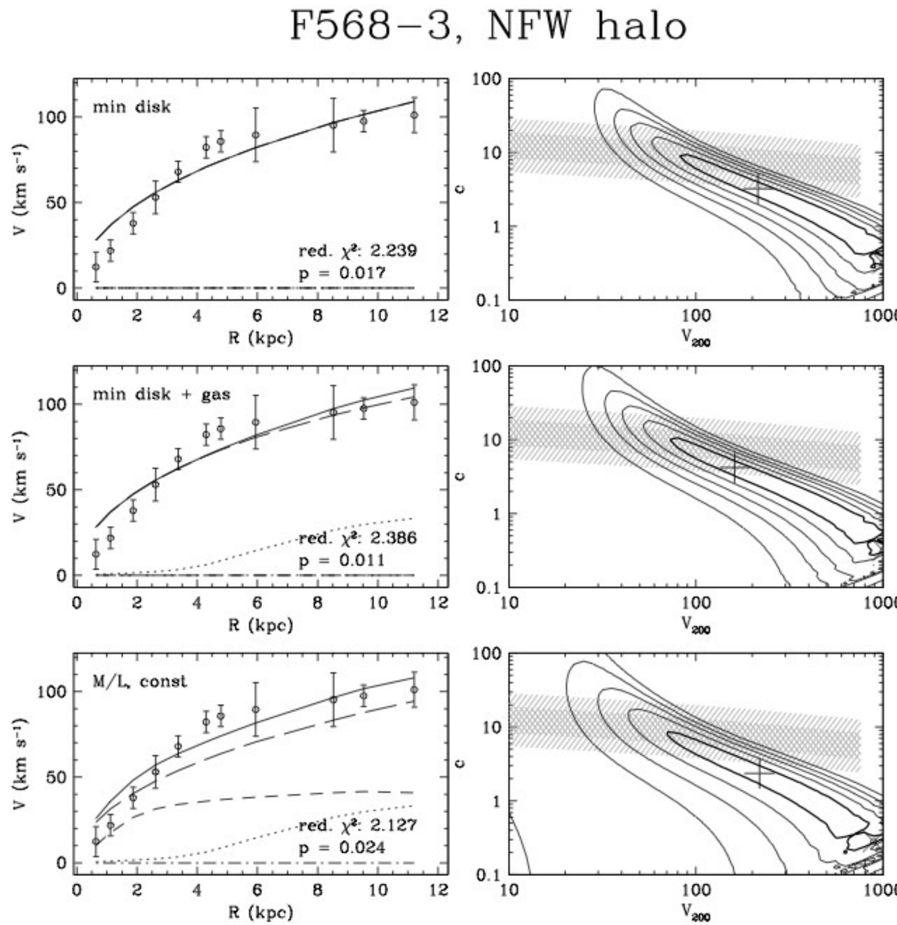




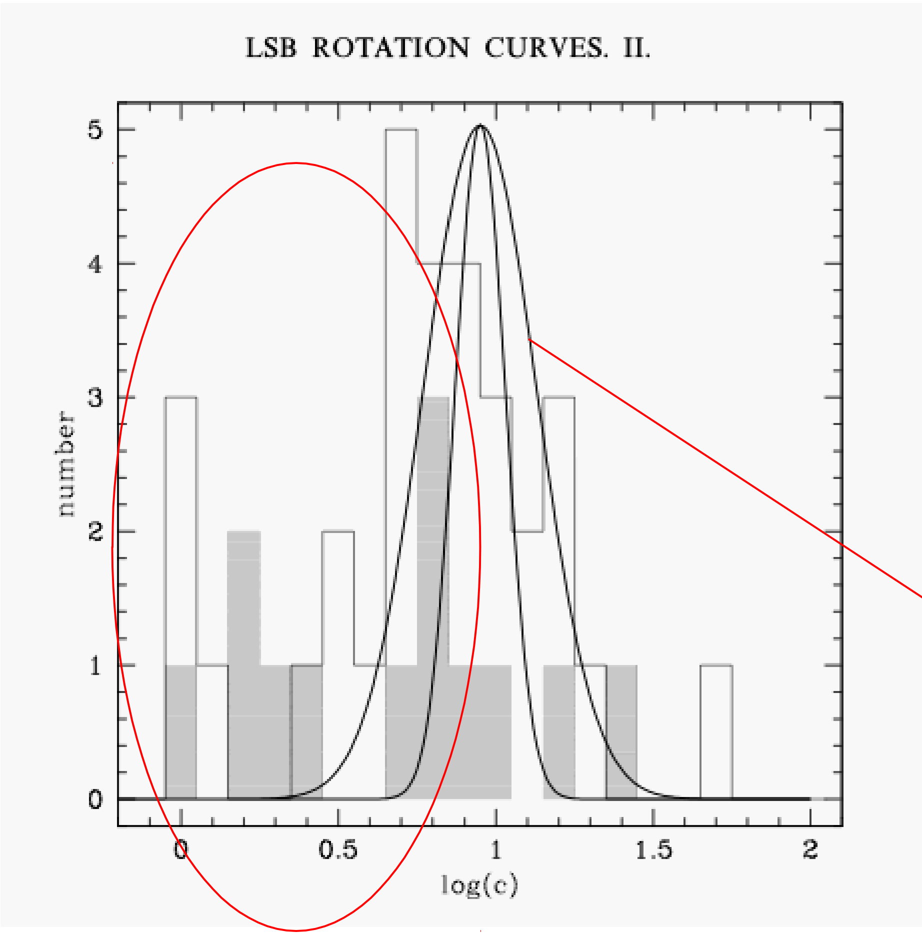
Observed density profile

de Blok+02





de Blok+ 2001a
30 LSB/Dwarf galaxies analyzed



Concentration distribution

NFW gives a poor fit

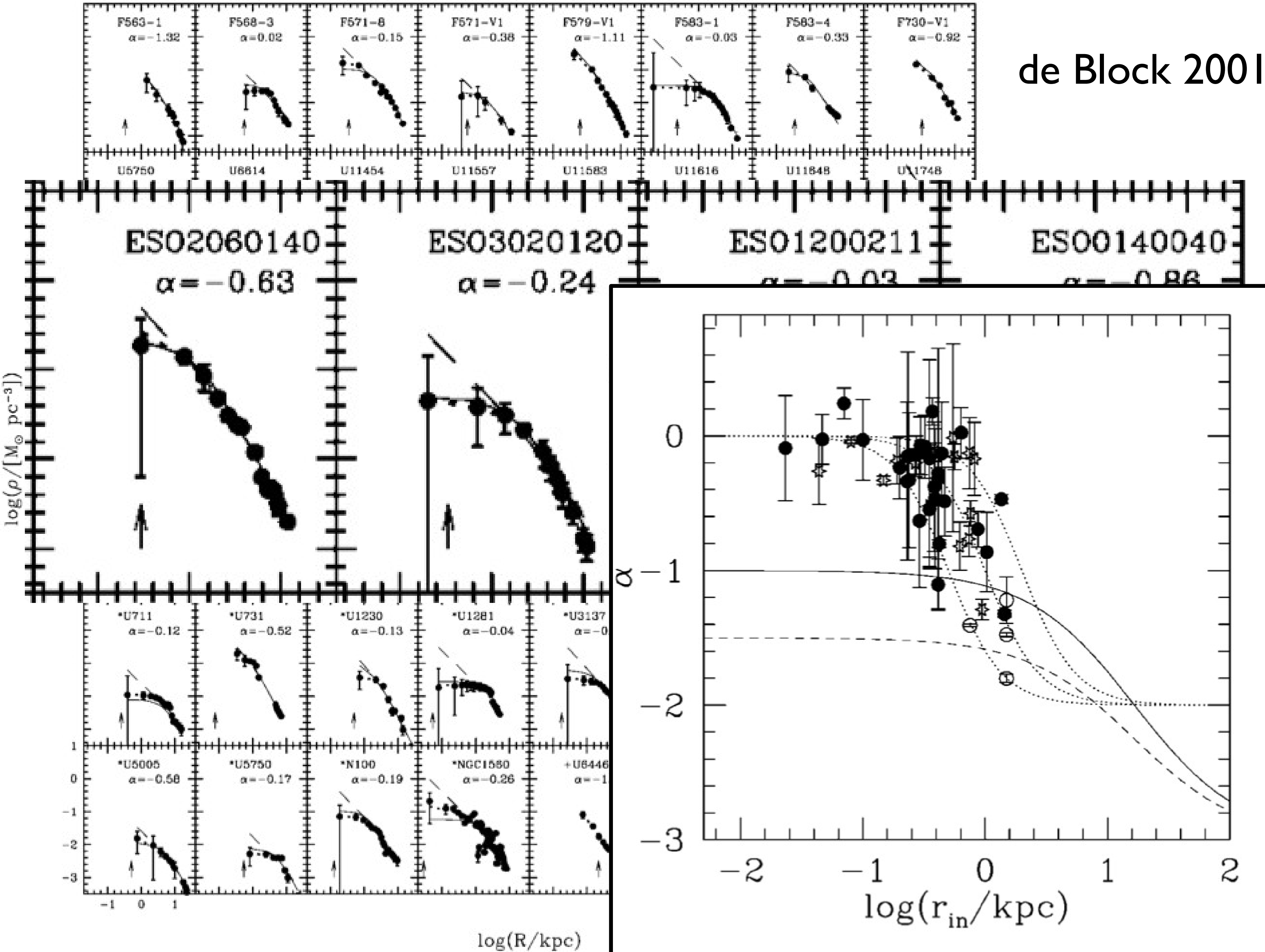
Concentrations too low

or too low mass-to-light ratio

Theoretical prediction
$\Omega m=0.3$
$\sigma 8=0.95$

Why is the concentration so low?

de Block 2001



CDM ruled out?

Swaters+ 01

Similar dataset of de Blok+ 2001

Different parameterization
of observational uncertainties

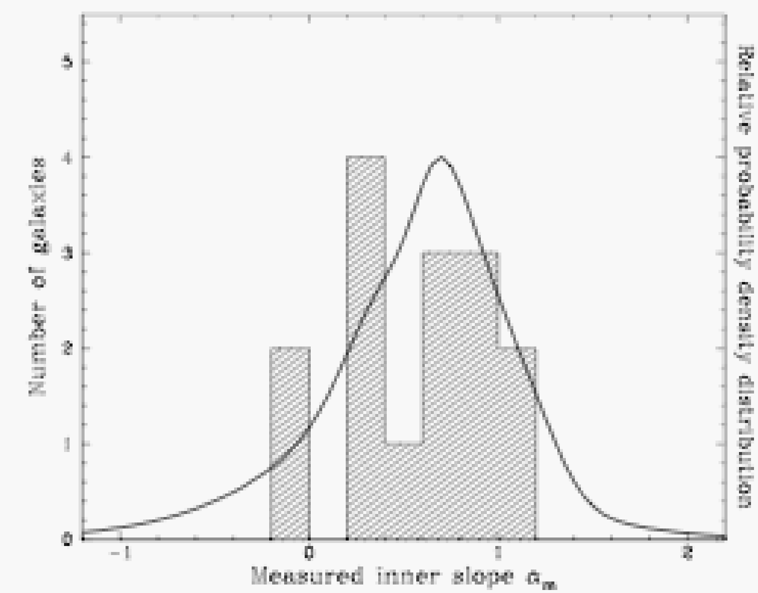
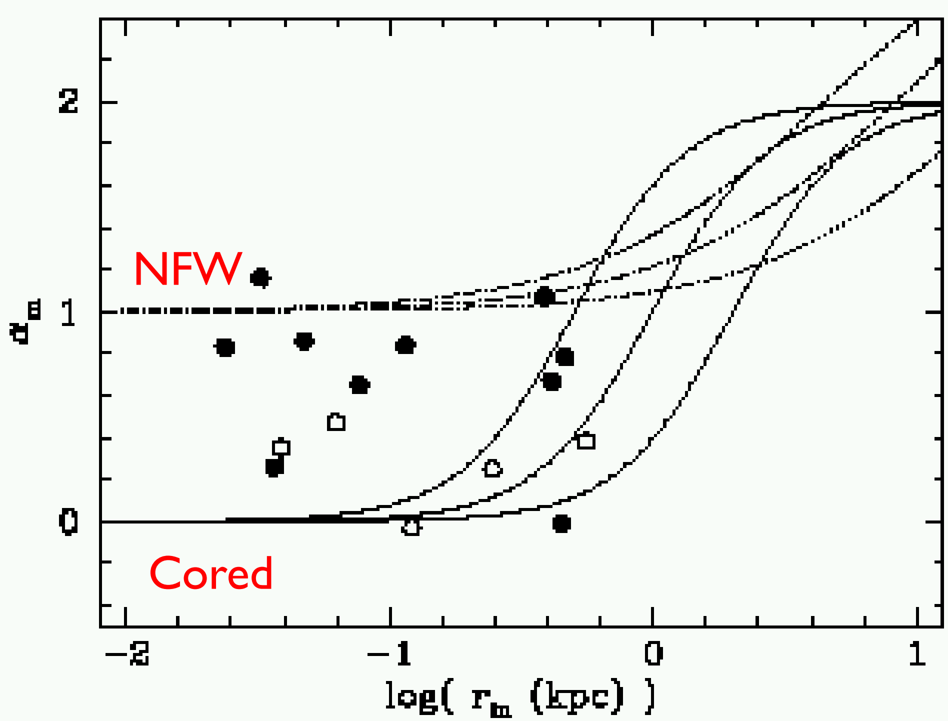


FIG. 6.—Histogram of measured inner slopes α_m. The solid line is the corresponding relative probability density distribution.



"… with the present data
it is not possible to rule out NFW…"

25% are inconsistent with NFW

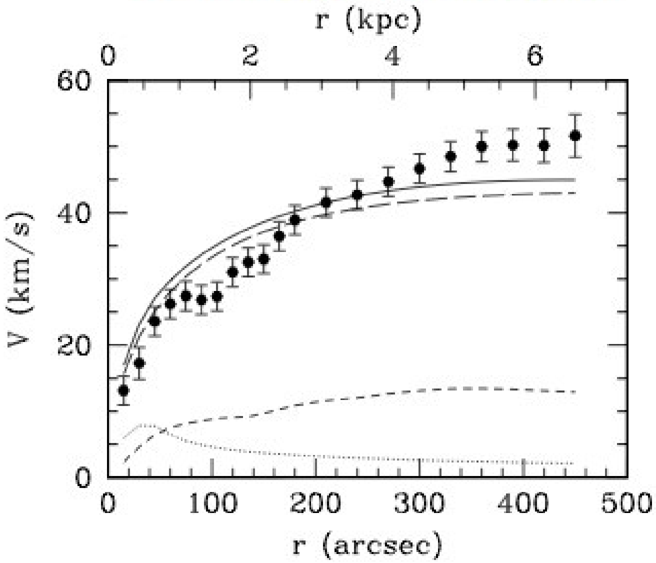
α>1 inconsistent with data

Is the question solved? Not at all

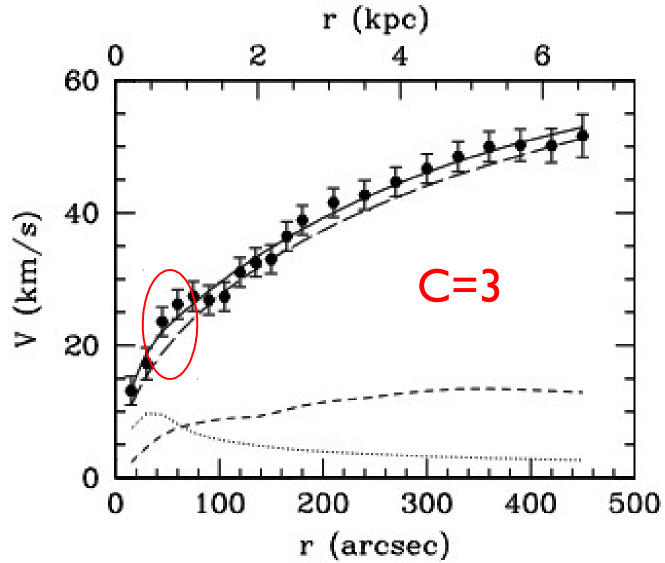
Gentile+05
Gentile+07

High resolution observations of single objects do show deviations from NFW

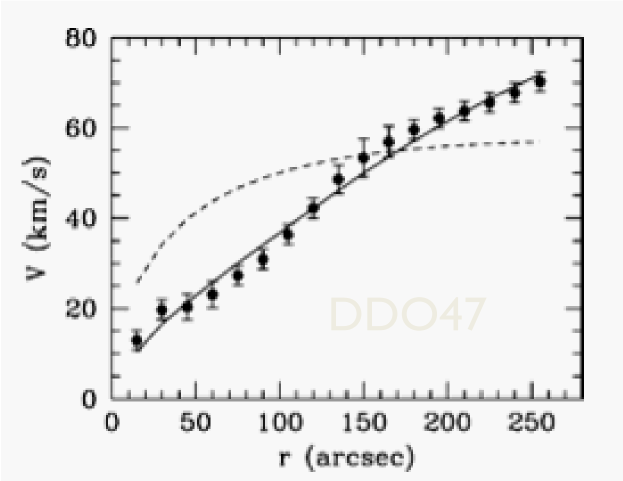
NFW and c_{vir}–M_{vir} relation



NFW and c_{vir} free

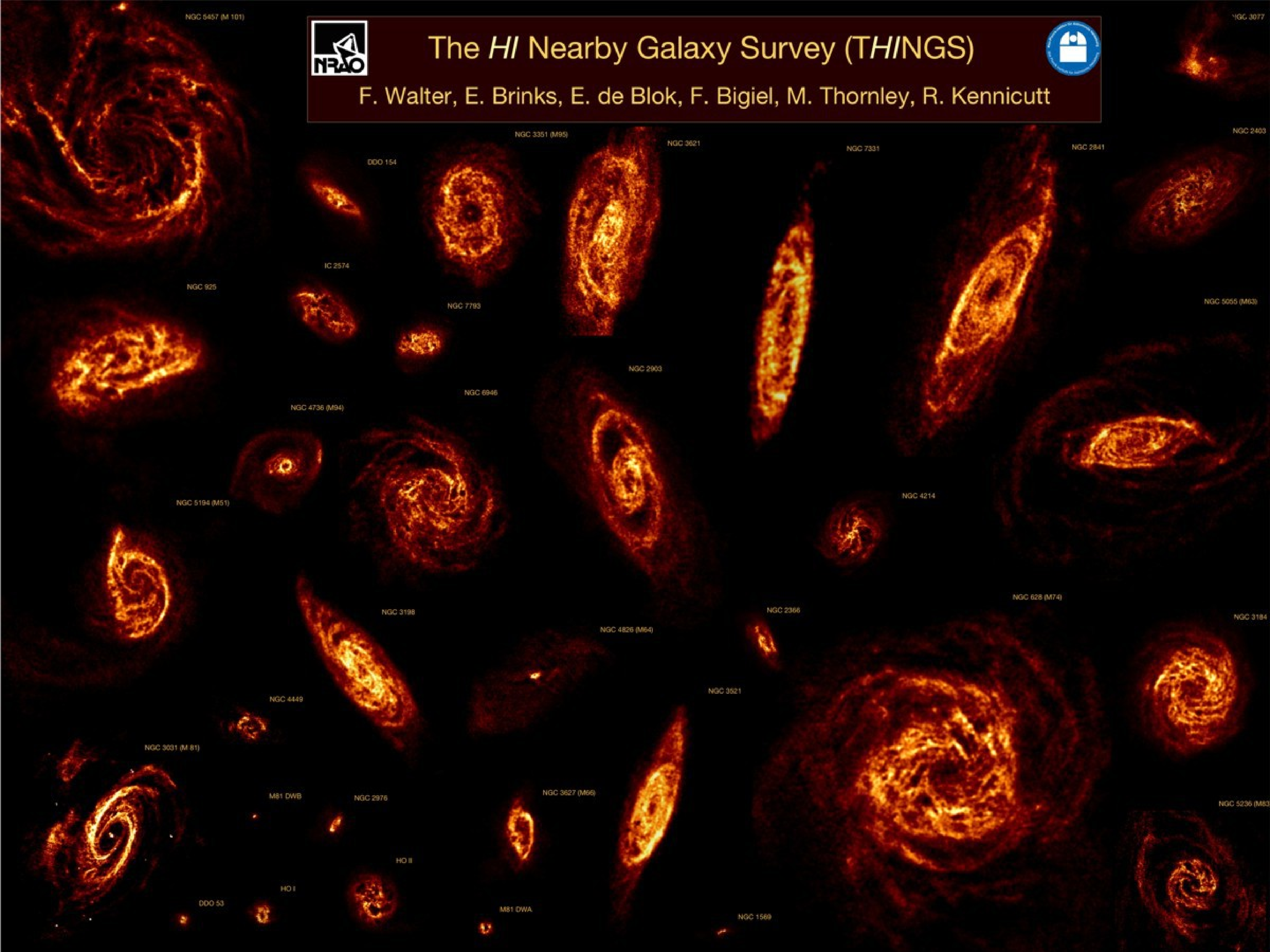


NGC3741

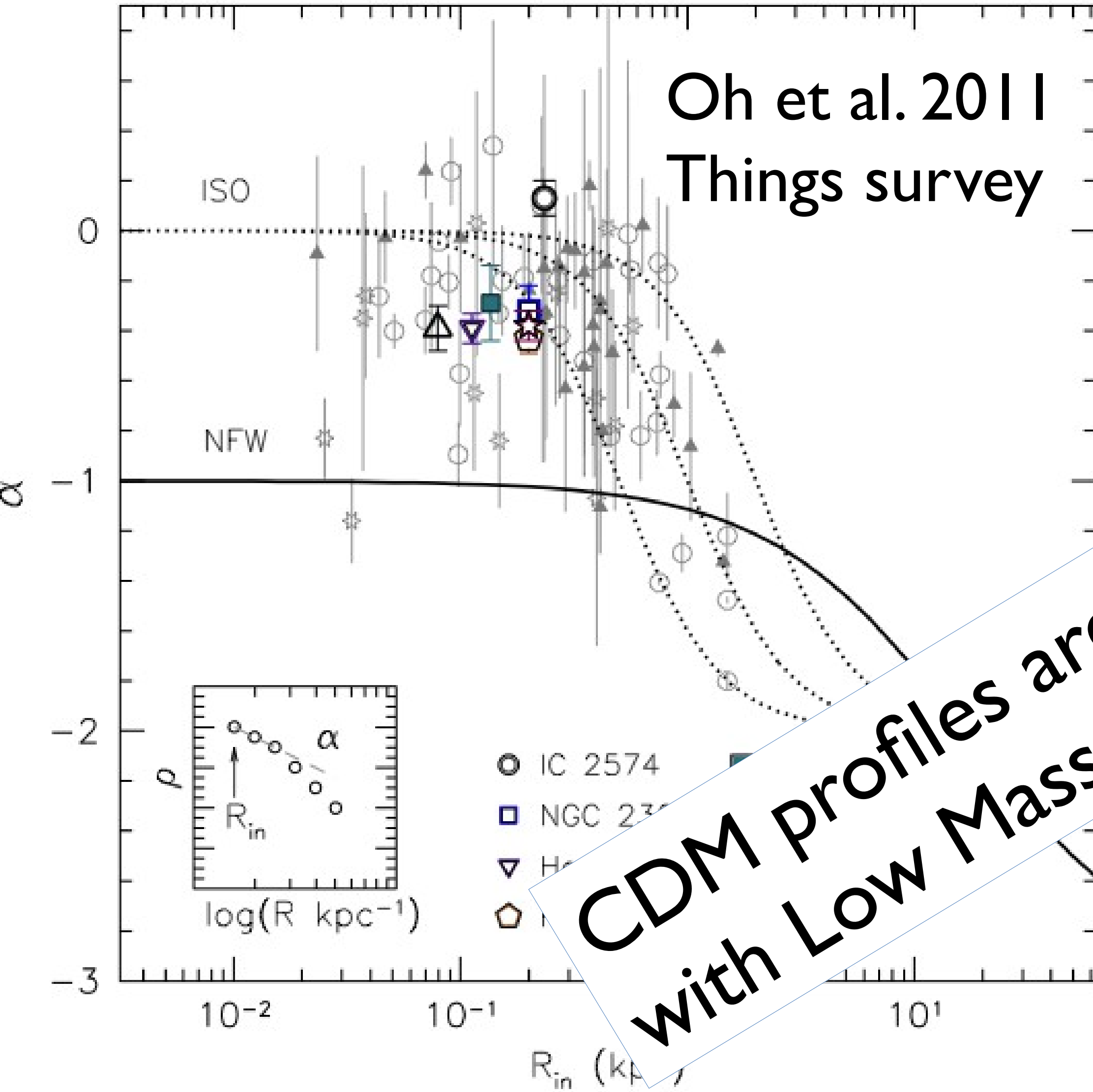


Observations do not like cuspy profiles

Bump?
non circular motion?


The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
NRAO
NGC 5457 (M 101)
NGC 3351 (M95)
NGC 3621
NGC 7331
NGC 2841
NGC 2403
DDO 154
IC 2574
NGC 925
NGC 7793
NGC 5055 (M63)
NGC 2903
NGC 6946
NGC 4736 (M94)
NGC 4214
NGC 5194 (M51)
NGC 628 (M74)
NGC 3198
NGC 2366
NGC 3184
NGC 4826 (M64)
NGC 3521
NGC 4449
NGC 3031 (M 81)
M81 DWB
NGC 2976
NGC 3627 (M66)
HO II
HO I
DDO 53
M81 DWA
NGC 1569

Galaxy density profile

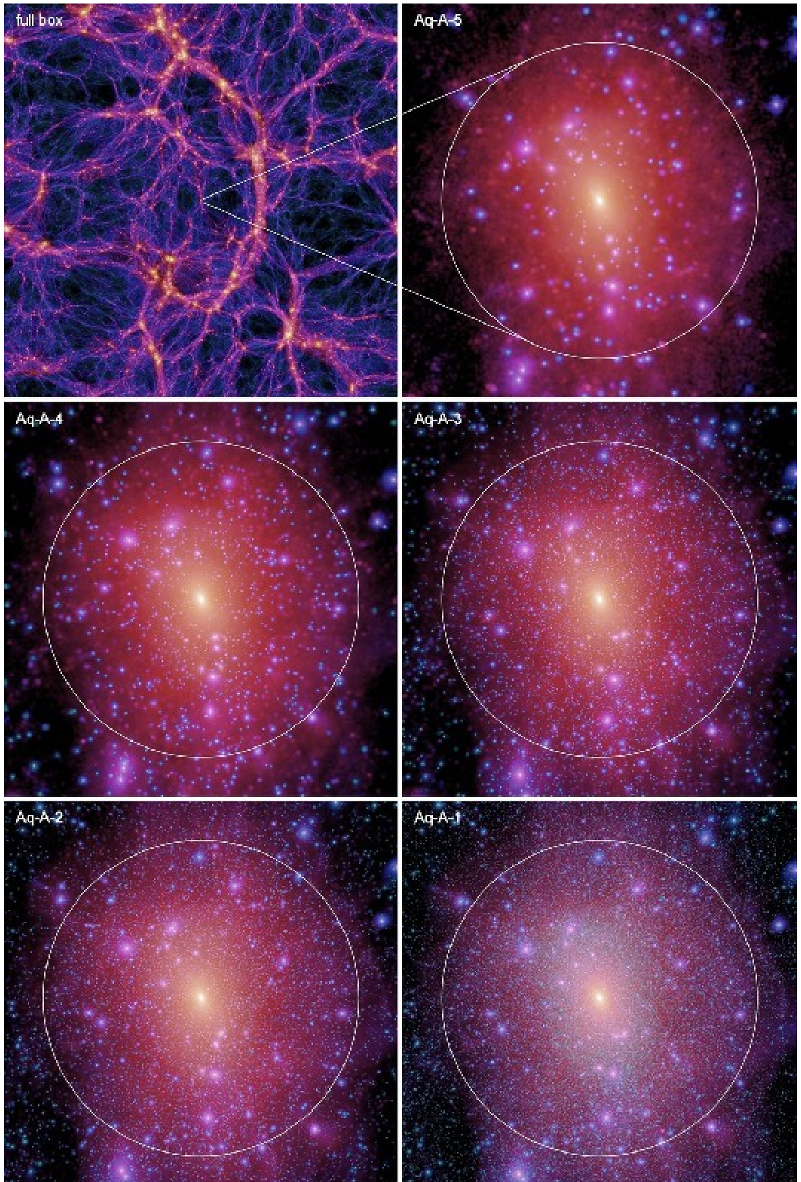


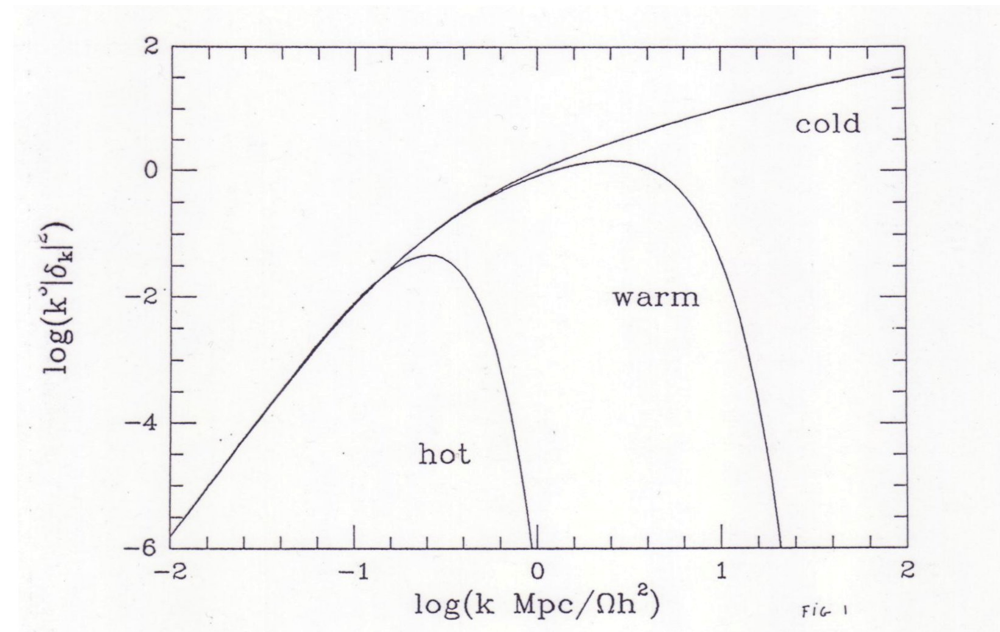
$$\frac{\rho(r)}{\rho_{cr}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

$$\rho(r \to 0) \propto r^{\alpha}$$

CDM profiles are inconsistent with Low Mass Galaxy Profiles

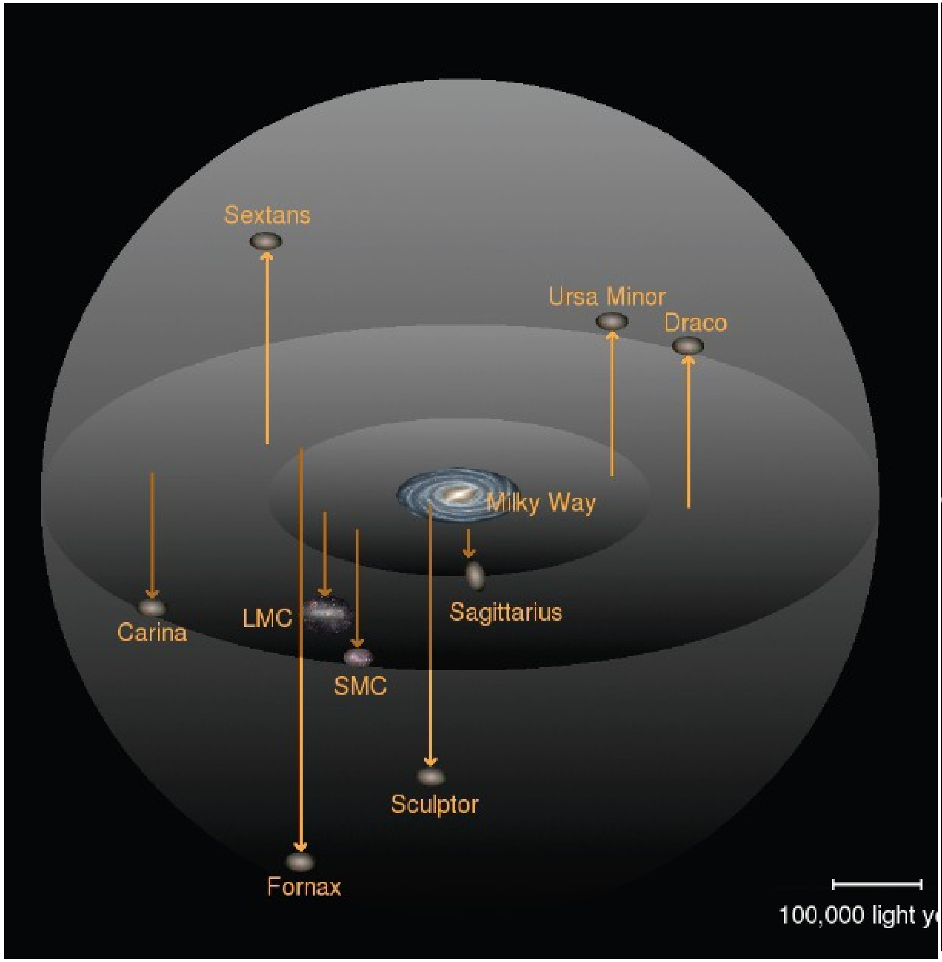
Substructure abundance

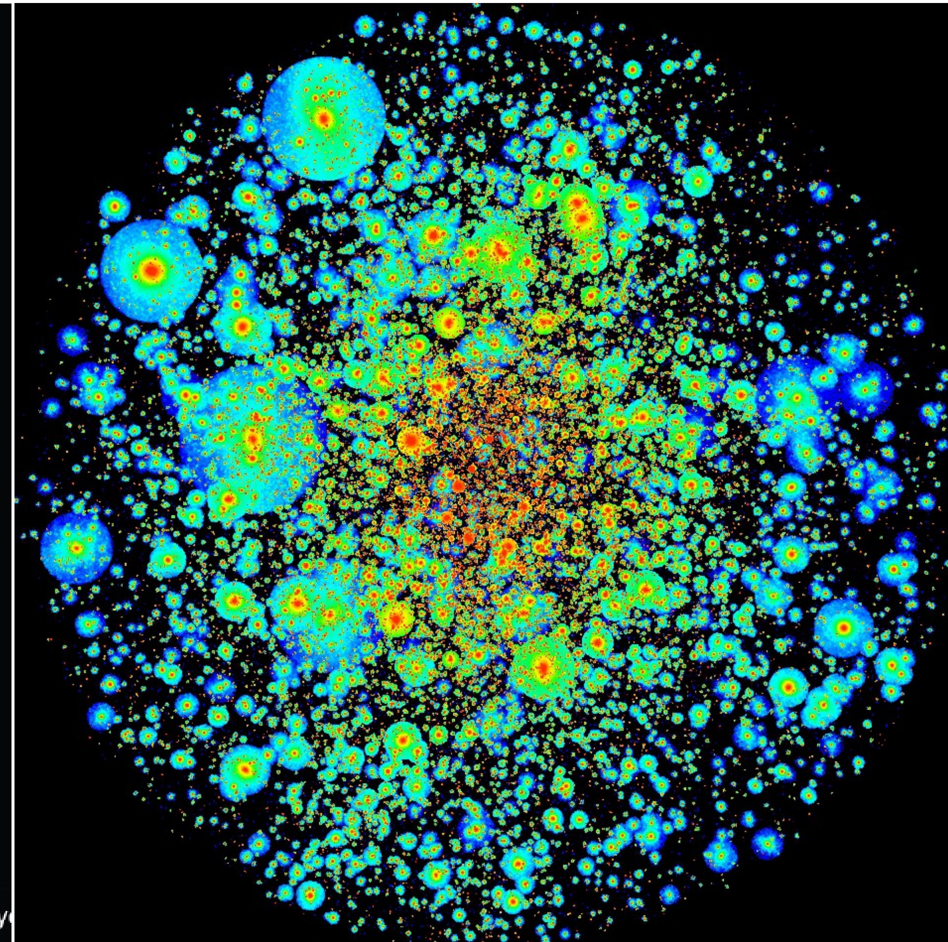




A lot of power on small scales

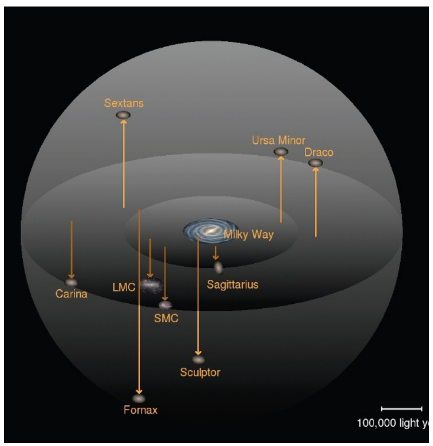
Substructure abundance

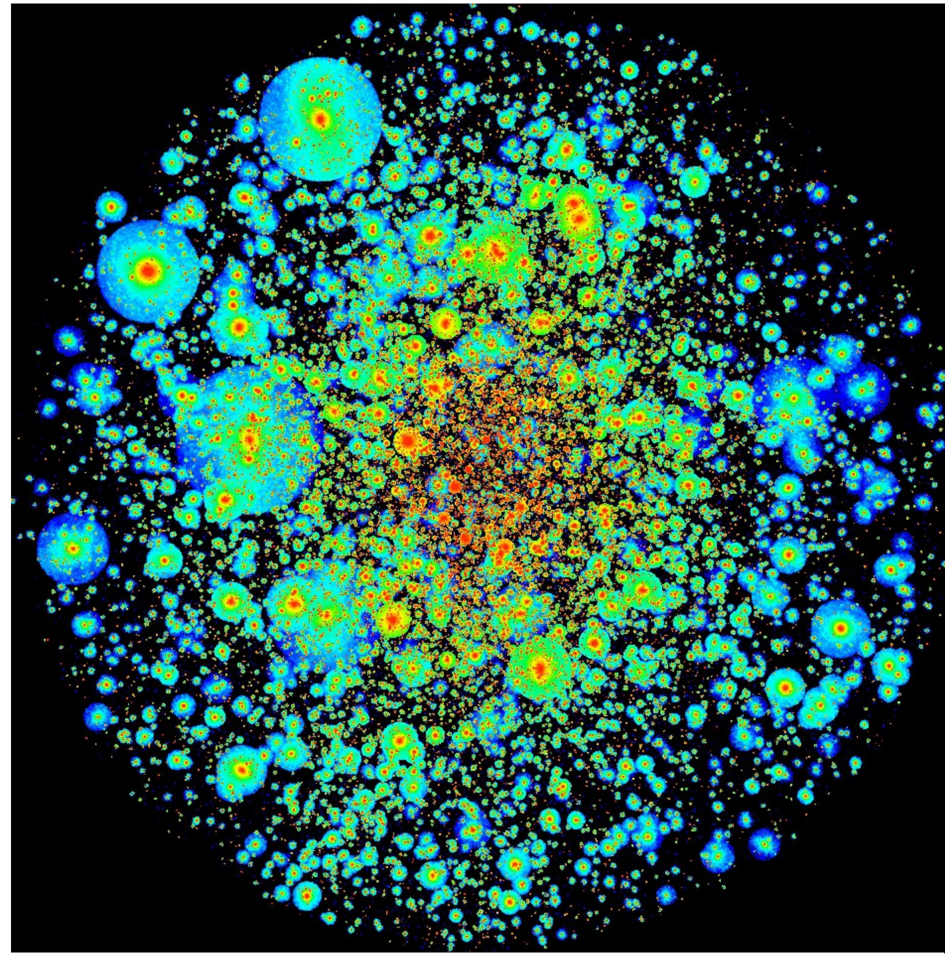




Not to scale

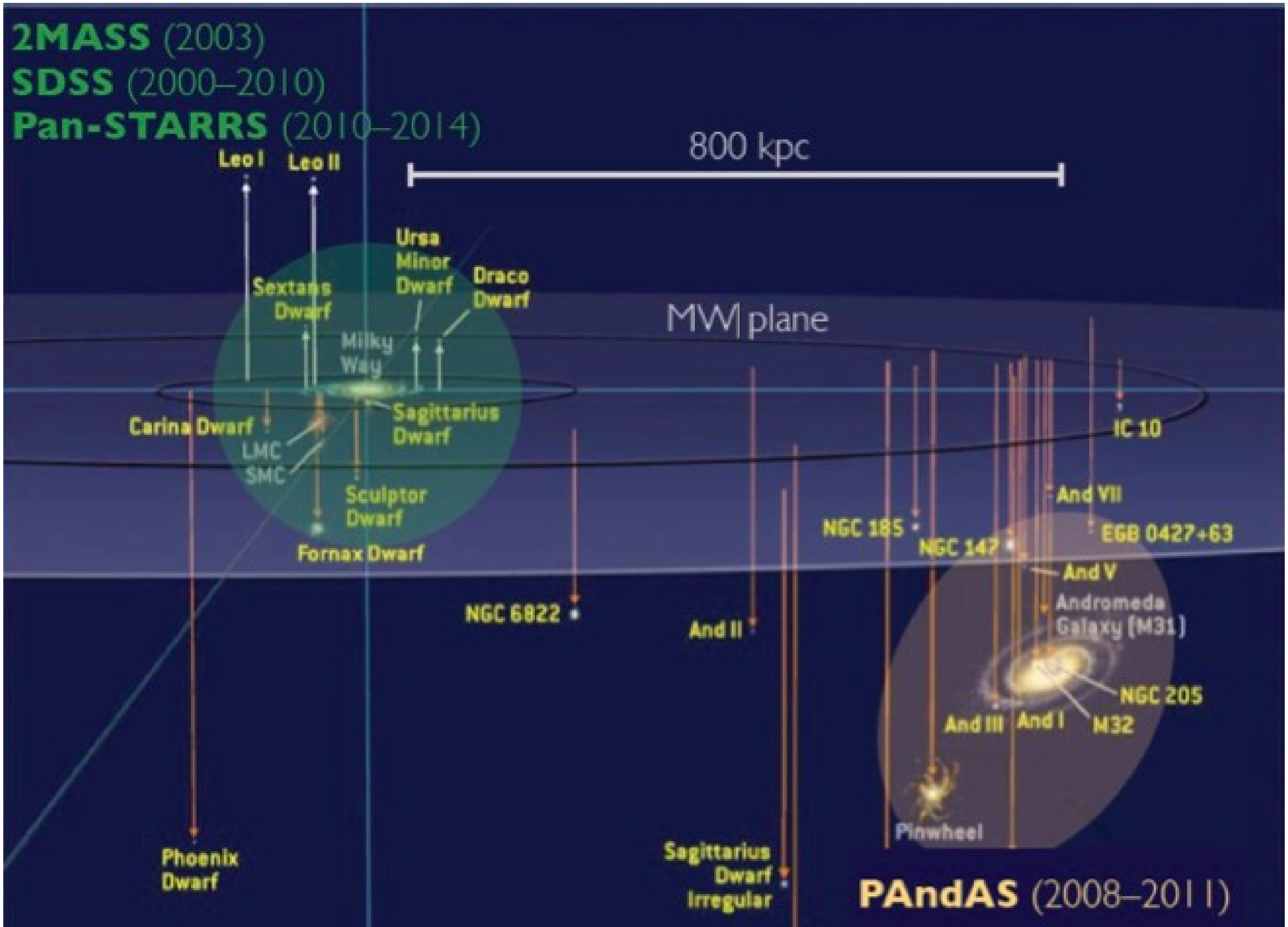
Substructure abundance

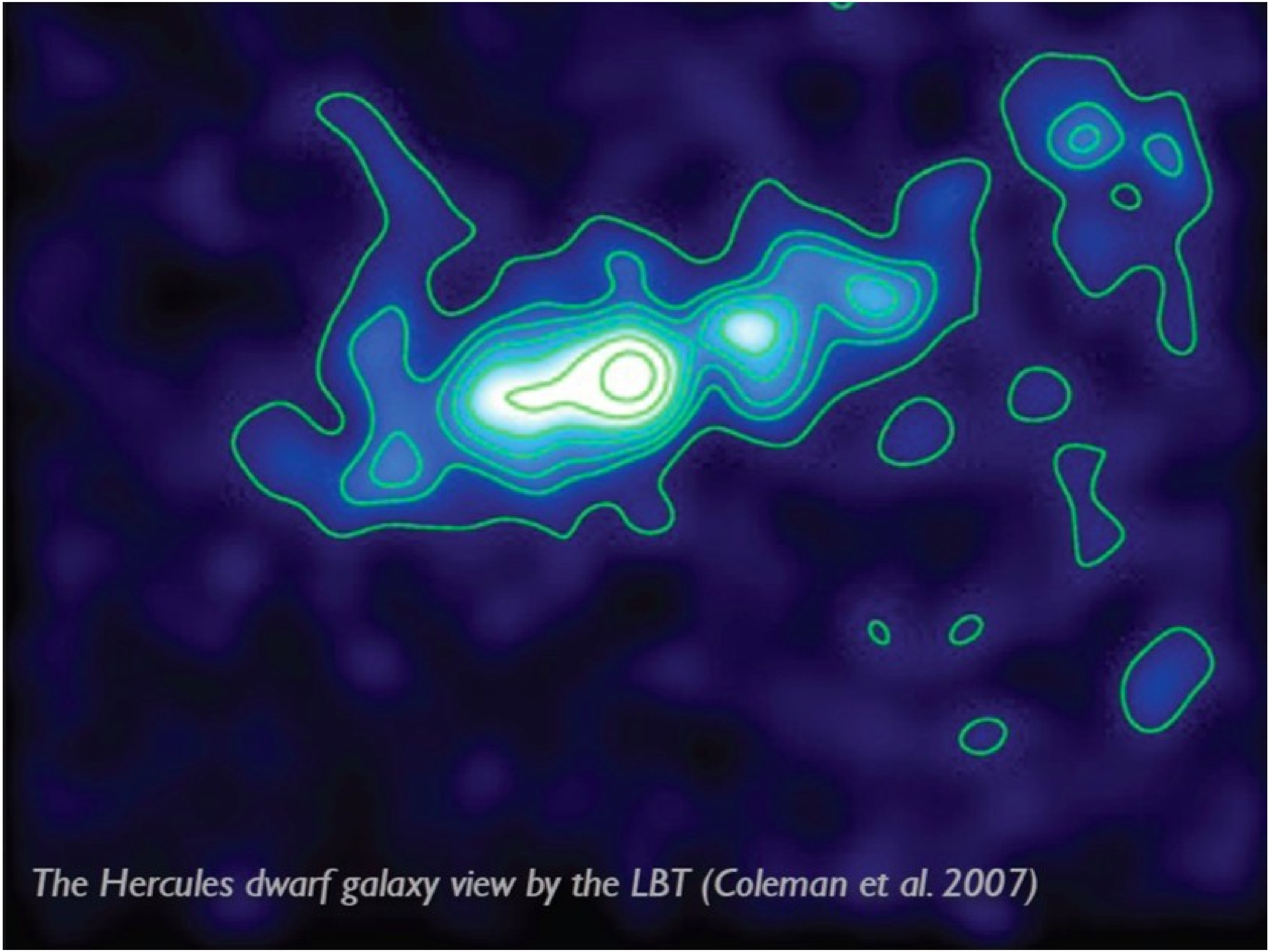




To scale

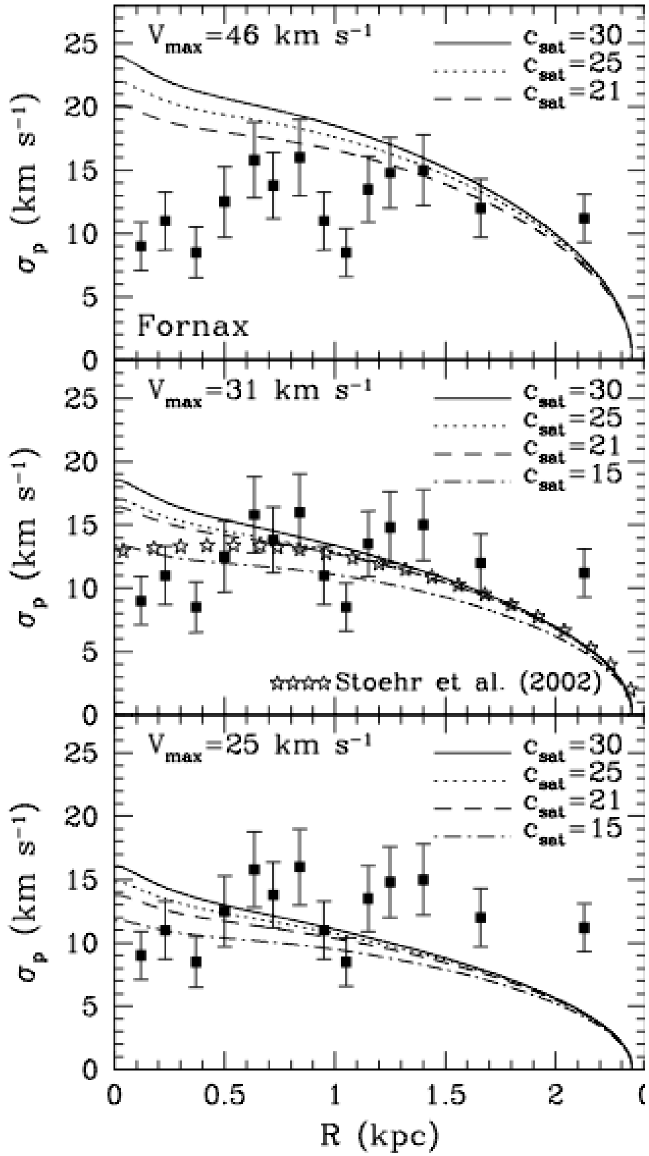
Dwarf Galaxies and the LG



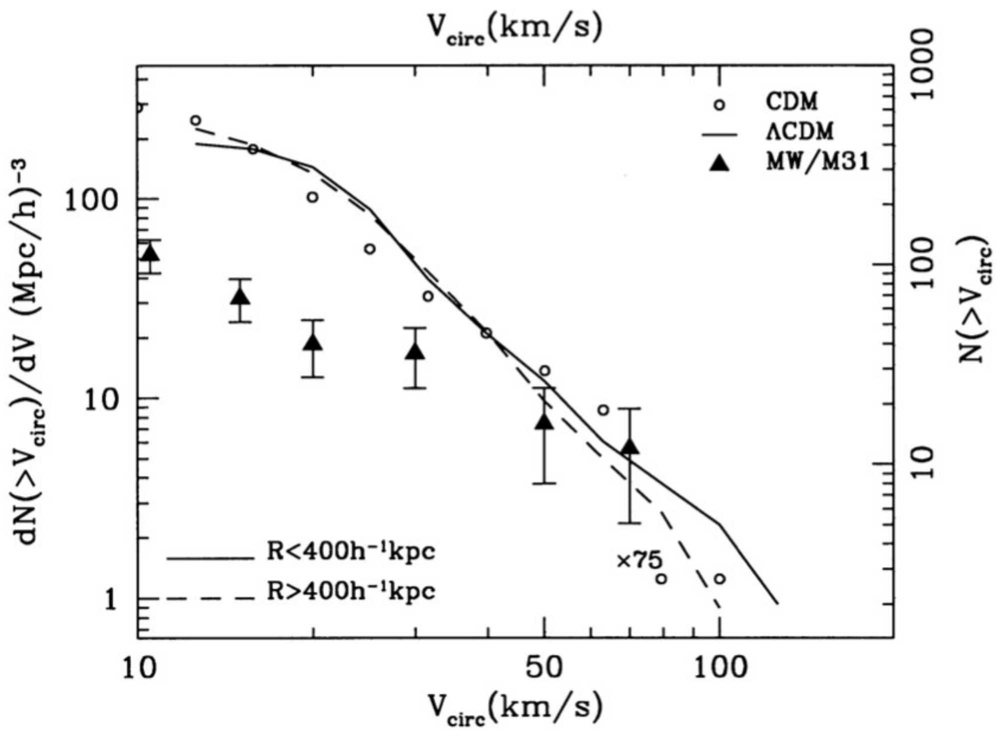


The Hercules dwarf galaxy view by the LBT (Coleman et al. 2007)

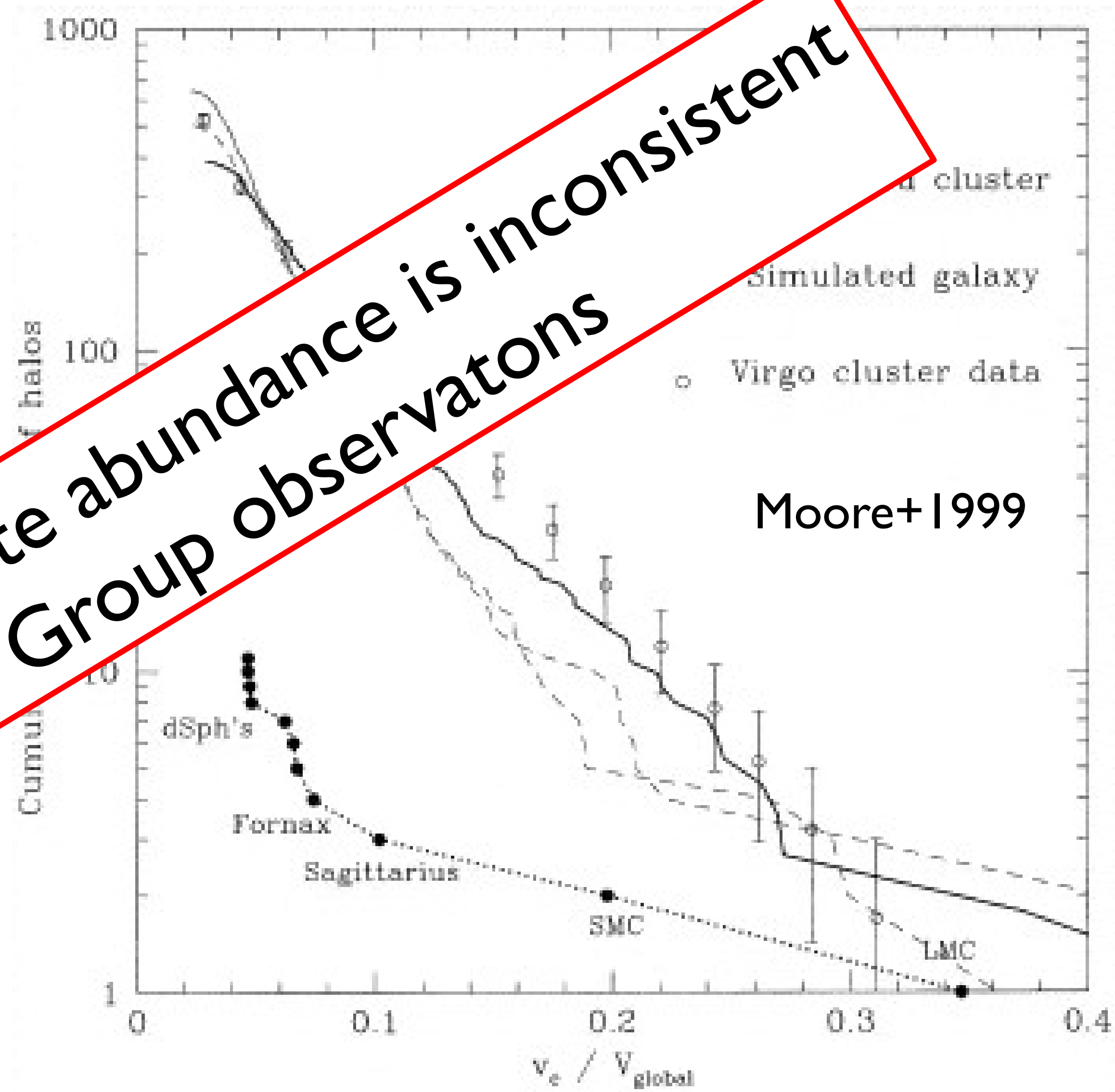
Quantitative approach



- Velocity dispersion from obs
- Fit with for a NFW model
- Compute Vmax (Vcirc)



DM haloes are (almost) self-similar



Moore+1999

CDM Satellite abundance is inconsistent with Local Group observatons

Dark Energy and satellites

Coupled Dark Energy

(Amendola 2000, AM+2004)

DE and DM can interact (e.g. exchange energy)

- Solution for the fine tuning problem (why is Λ so small)
- Solution for the coincidence problem (why ΩΛ≈Ωm)

$$DE \Rightarrow DE(t) + \beta \times DM(t)$$

Effects on Newtonian dynamics

What changes?

Macciò+2004
Baldi+2019

$$\dot{\vec{v}}_c = -H\vec{v}_c - \vec{\nabla}\frac{GM_c}{r}$$

test particle acceleration — Hubble drag — grav. potential

LCDM acceleration equation

What changes?

$$\dot{\vec{v}}_c = -H\left(1 - \frac{\beta_c(\phi)}{M}\frac{\dot{\phi}}{H}\right)\vec{v}_c - \vec{\nabla}\frac{\tilde{G}_c\tilde{M}_c}{r}$$

Macciò+2004

Baldi+2011

– additional contribution to proportional to coupling

What changes?

$$\dot{\vec{v}}_c = -H\left(1 - \frac{\beta_c(\phi)}{M}\frac{\dot{\phi}}{H}\right)\vec{v}_c - \vec{\nabla}\frac{\tilde{G}_c\tilde{M}_c}{r}$$

Macciò+2004
Baldi+2011

- additional contribution to proportional to coupling

- effective gravitational constant

$$\tilde{G}_c \equiv G_N\left[1 + 2\beta_c^2(\phi)\right]$$

What changes?

$$\dot{\vec{v}}_c = -H\left(1 - \frac{\beta_c(\phi)}{M}\frac{\dot{\phi}}{H}\right)\vec{v}_c - \vec{\nabla}\frac{\tilde{G}_c\tilde{M}_c}{r}$$

Macciò+2004
Baldi+2011

- additional contribution to proportional to coupling

- effective gravitational constant

$$\tilde{G}_c \equiv G_N\left[1 + 2\beta_c^2(\phi)\right]$$

- mass sourcing the grav. potential changes

$$\tilde{M}_c \equiv M_c e^{-\int \beta_c(\phi)\frac{\mathrm{d}\phi}{\mathrm{d}a}\mathrm{d}a}$$

What changes?

$$\dot{\vec{v}}_c = -H\left(1 - \frac{\beta_c(\phi)}{M}\frac{\dot{\phi}}{H}\right)\vec{v}_c - \vec{\nabla}\frac{\tilde{G}_c\tilde{M}_c}{r}$$

Macciò+2004
Baldi+2011

- additional contribution to proportional to coupling

- effective gravitational constant

$$\tilde{G}_c \equiv G_N\left[1 + 2\beta_c^2(\phi)\right]$$

- mass sourcing the grav. potential changes

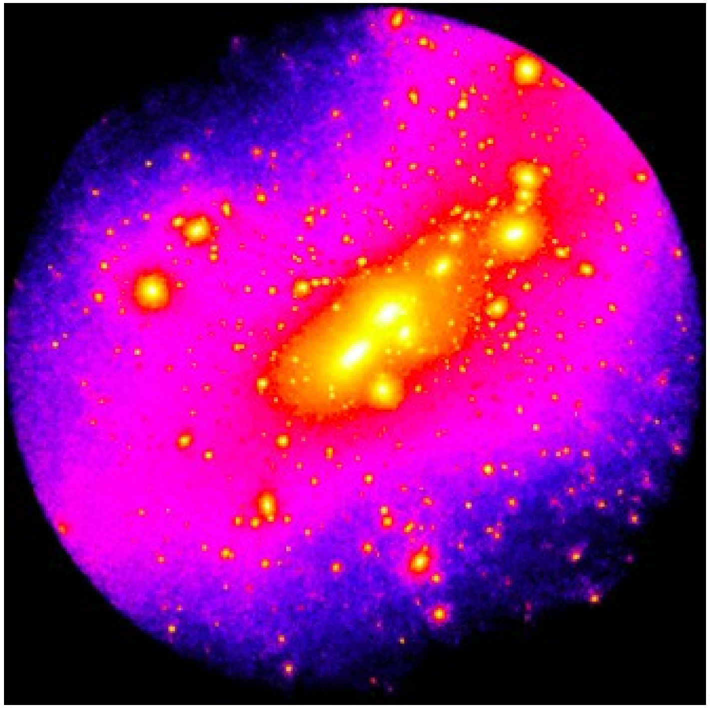
$$\tilde{M}_c \equiv M_c e^{-\int \beta_c(\phi)\frac{d\phi}{da}da}$$

ONLY DM PARTICLES ARE AFFECTED

(no coupling to baryons)

substructures:

LCDM

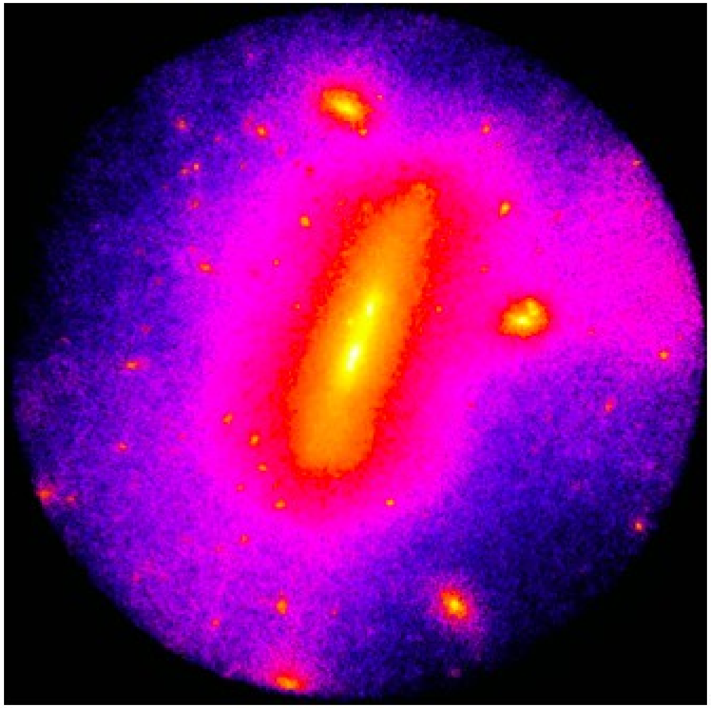


z = 1

M = 3.5e11 Msun/h

Rvir = 160 kpc/h

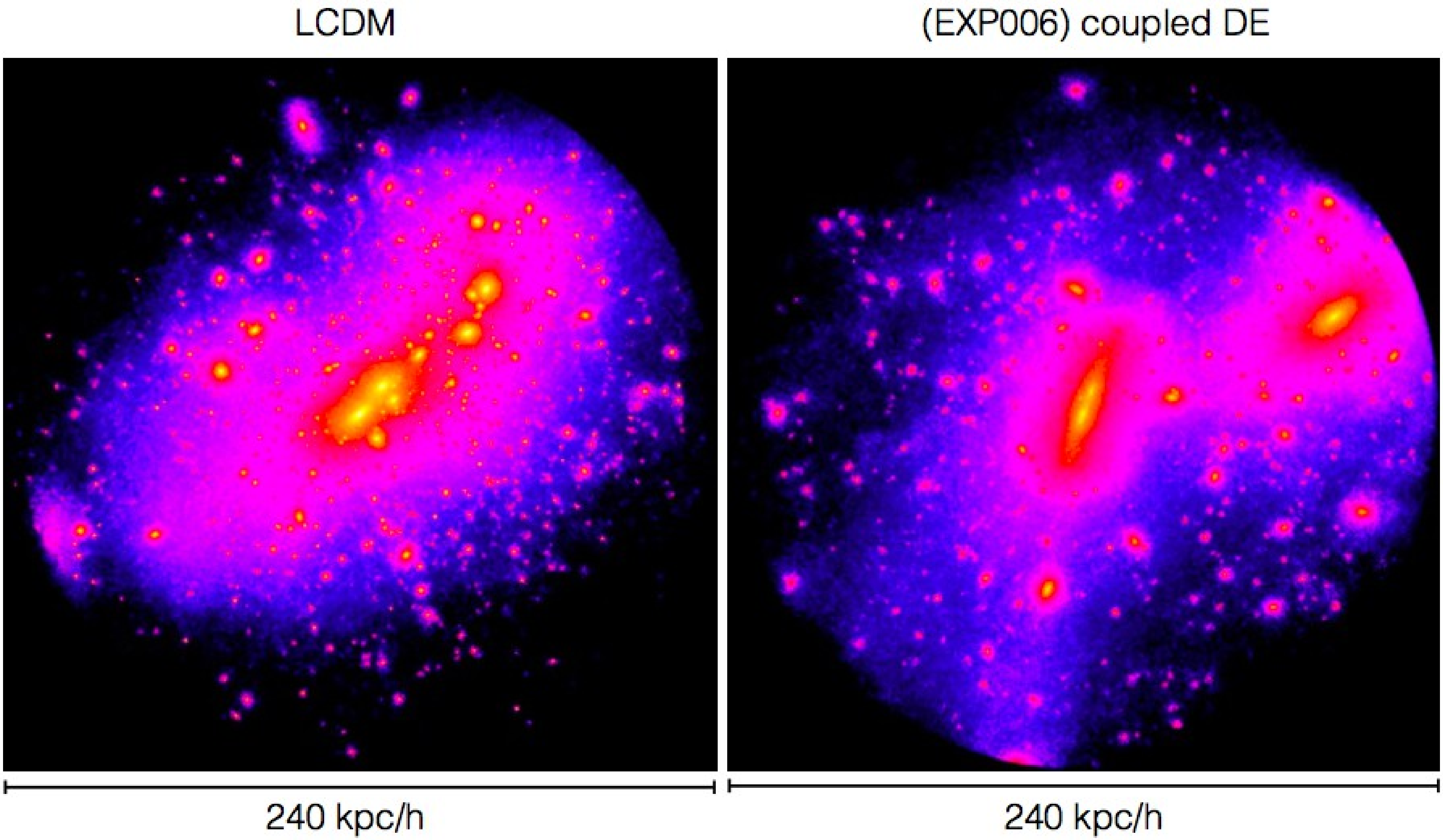
(extreme) coupled DE



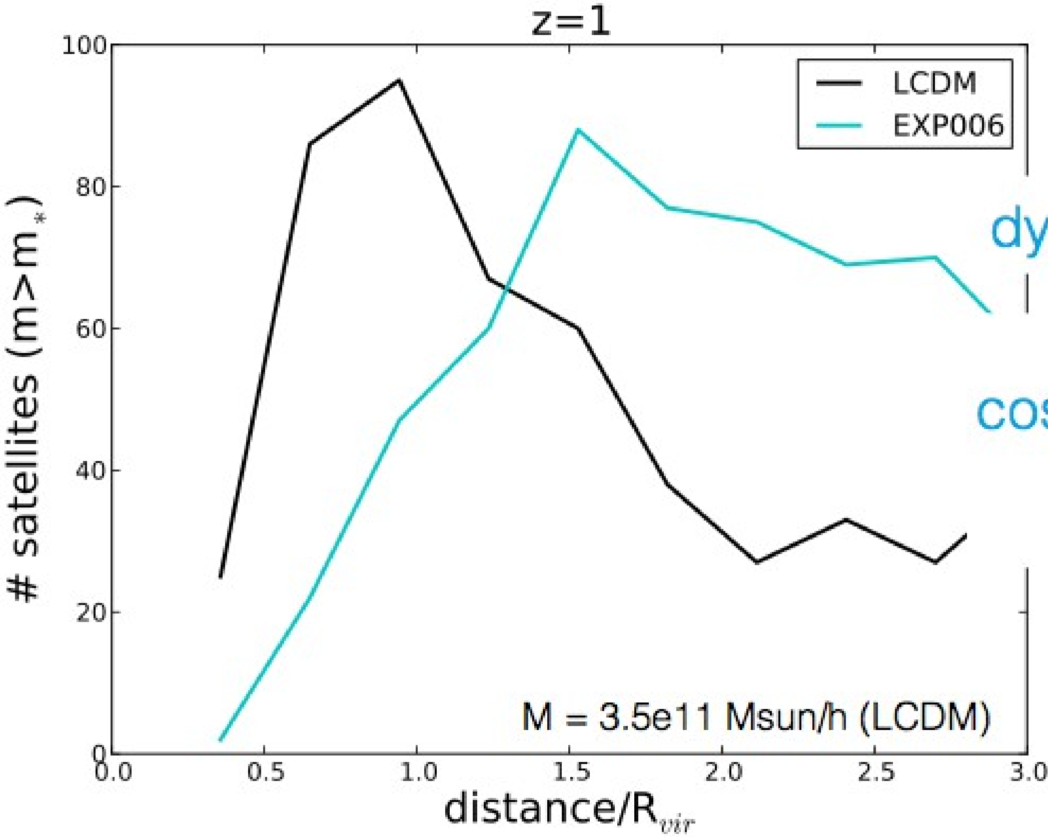
z = 1

M = 1.6e11 Msun/h

Rvir = 122 kpc/h


LCDM
(EXP006) coupled DE
240 kpc/h
240 kpc/h

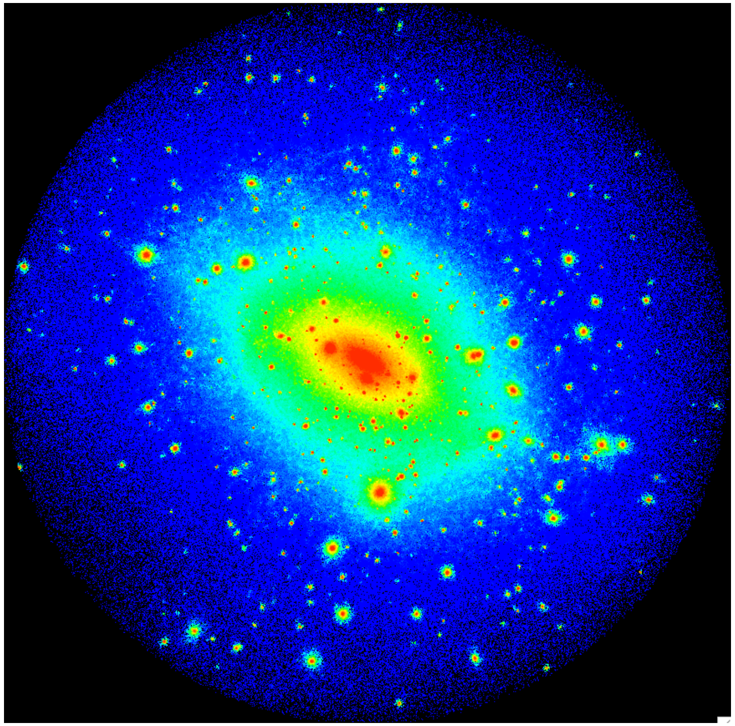
distribution of satellites:

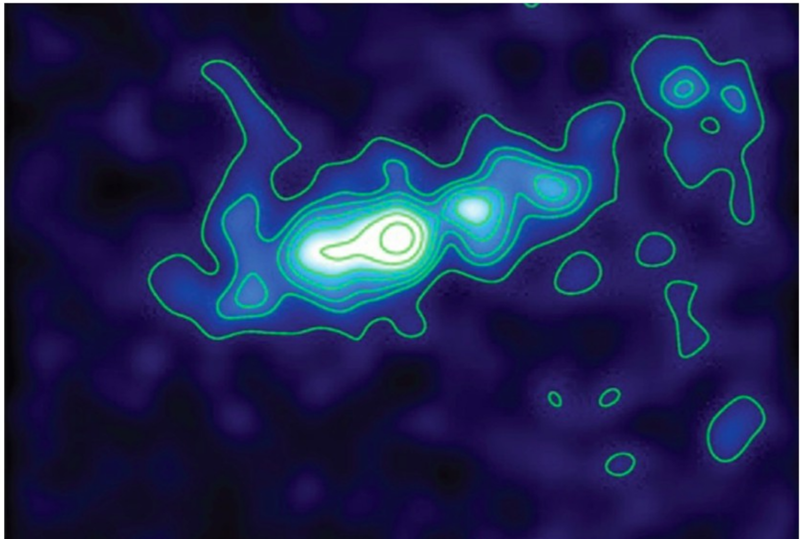


dynamical effects?

cosmological intrinsic differences?

Penzo et al. in prep



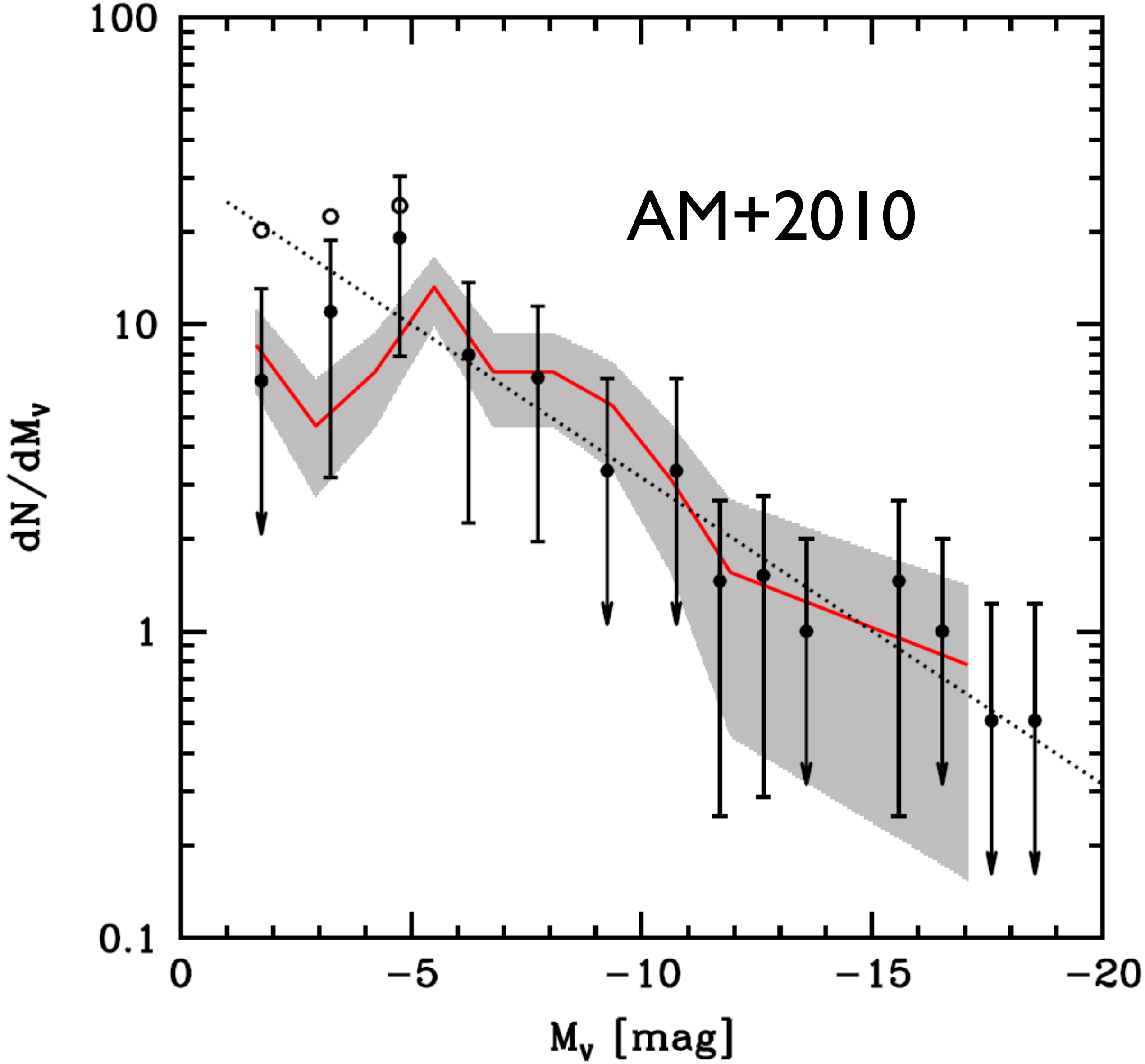


The Hercules dwarf galaxy view by the LBT (Coleman et al. 2007)

- Is CDM challenged by local observations? **YES**
- Is the Universe made by CDM alone? **NO**
- Are we comparing apples with apples? **NO**

If anything we are proving that there is more than CDM in our Universe

Easy to solve the MS problem with a bit of baryonic physics



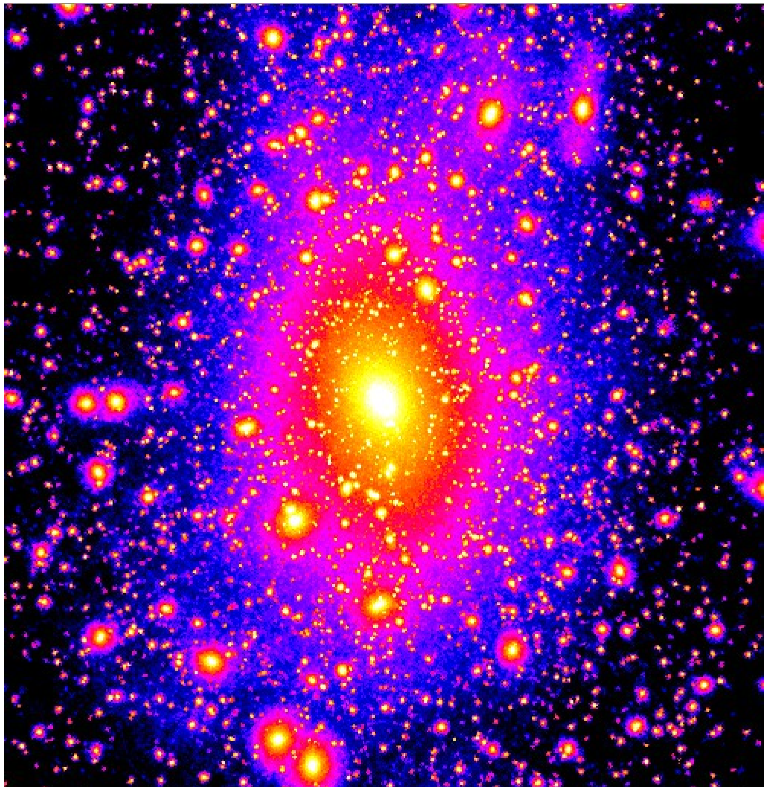
CDM model predictions

¾ of the satellites with MDM>107 Msun are dark
They do not host any observable galaxies

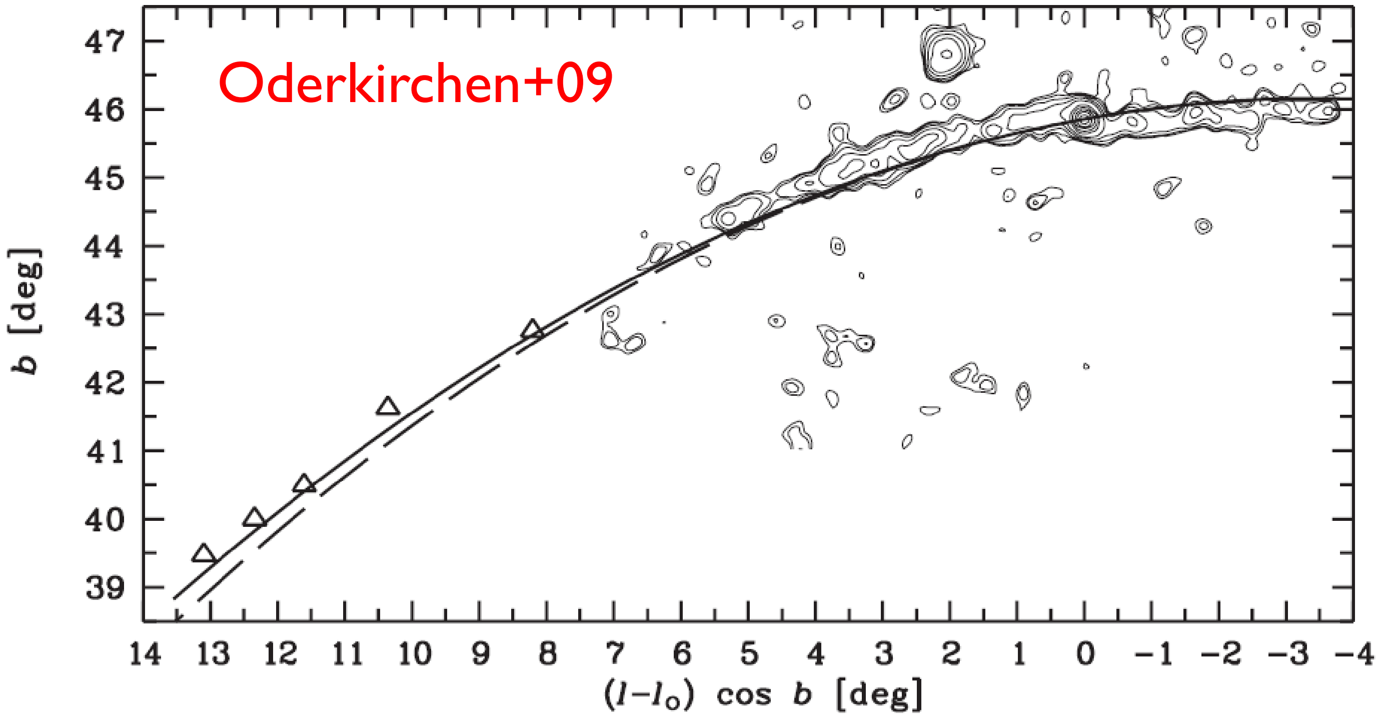
The presence of this large population of satellites
is a clear prediction of LCDM

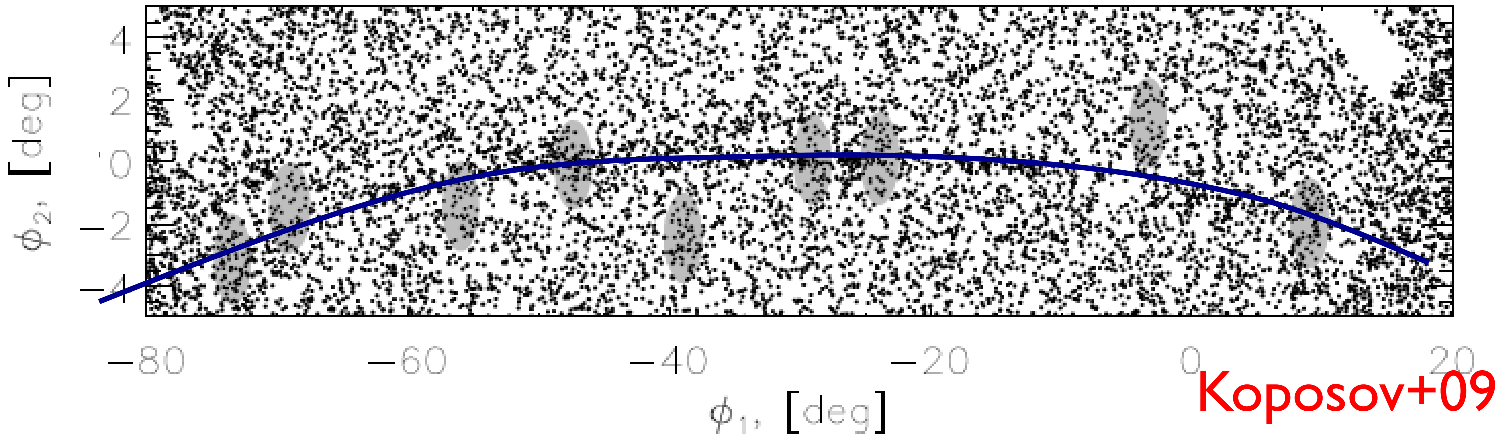
We need to "detect" them
to probe LCDM
to be correct

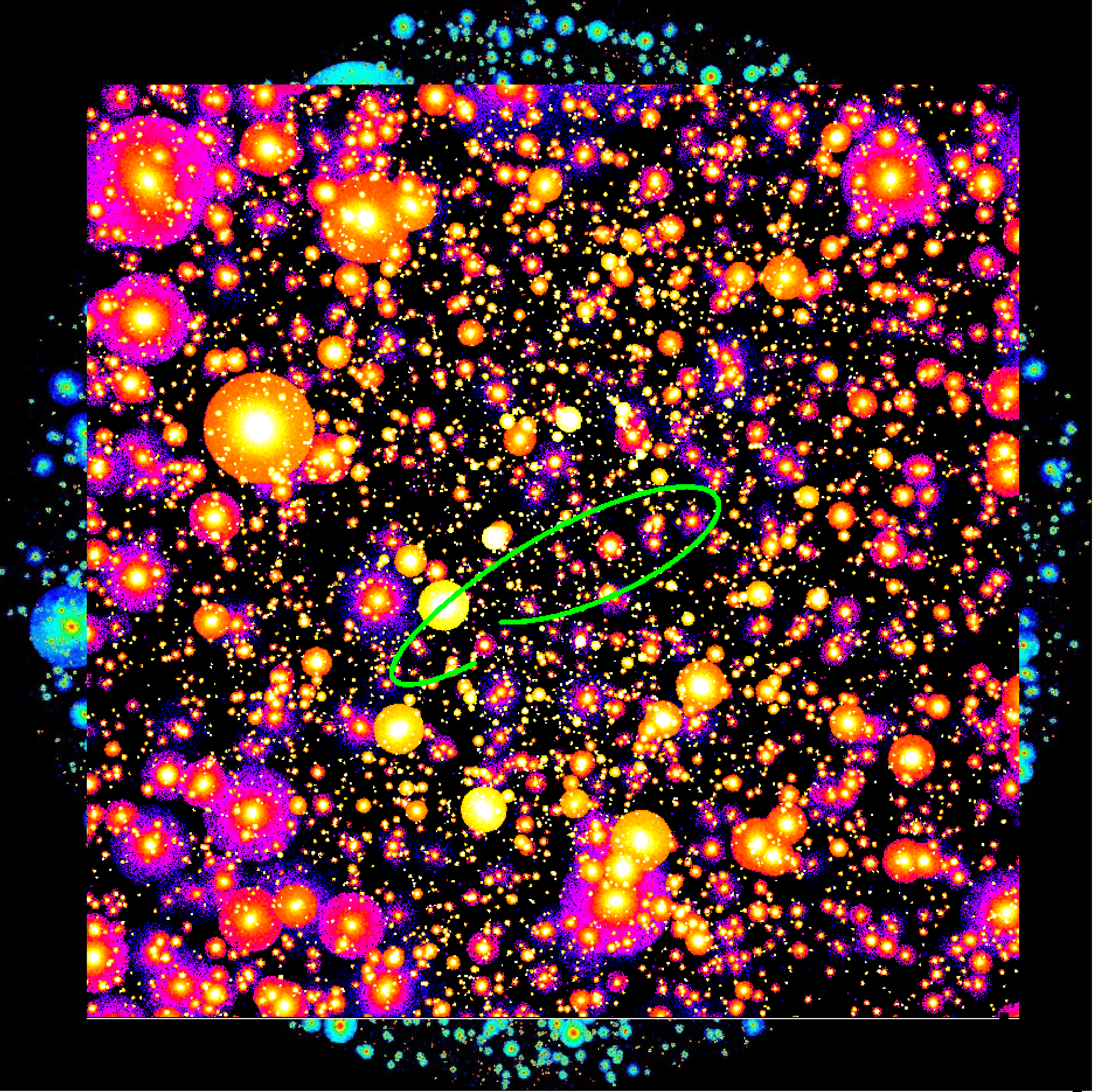
Lensing not really promising
Gamma Rays neither

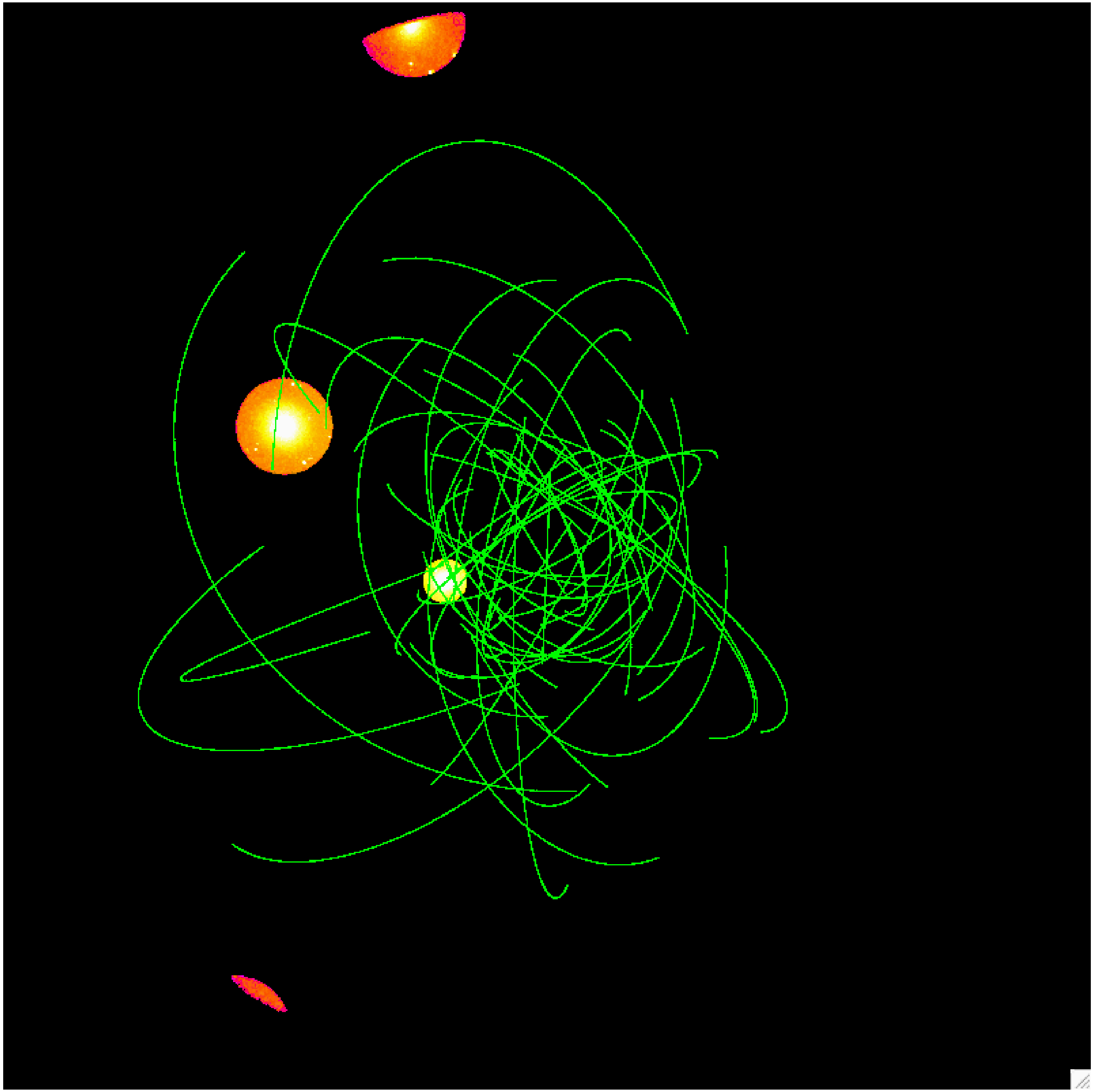


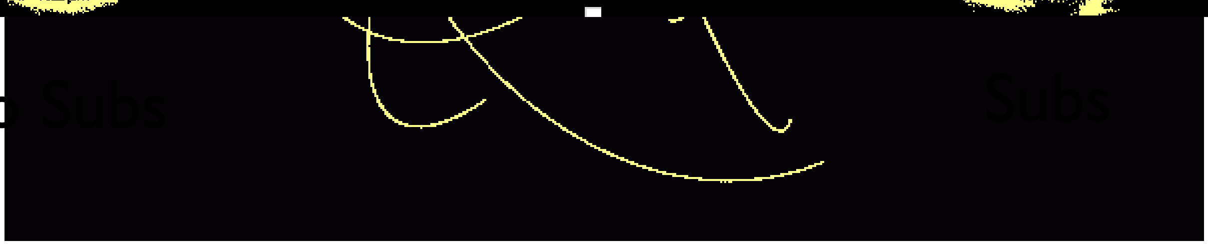
Heating of stellar streams











No Subs

Subs

Perturbations in stellar streams as a test for DM at small scales

Streams are in equilibrium with the NFW+Disk potential

No Subs

Subs

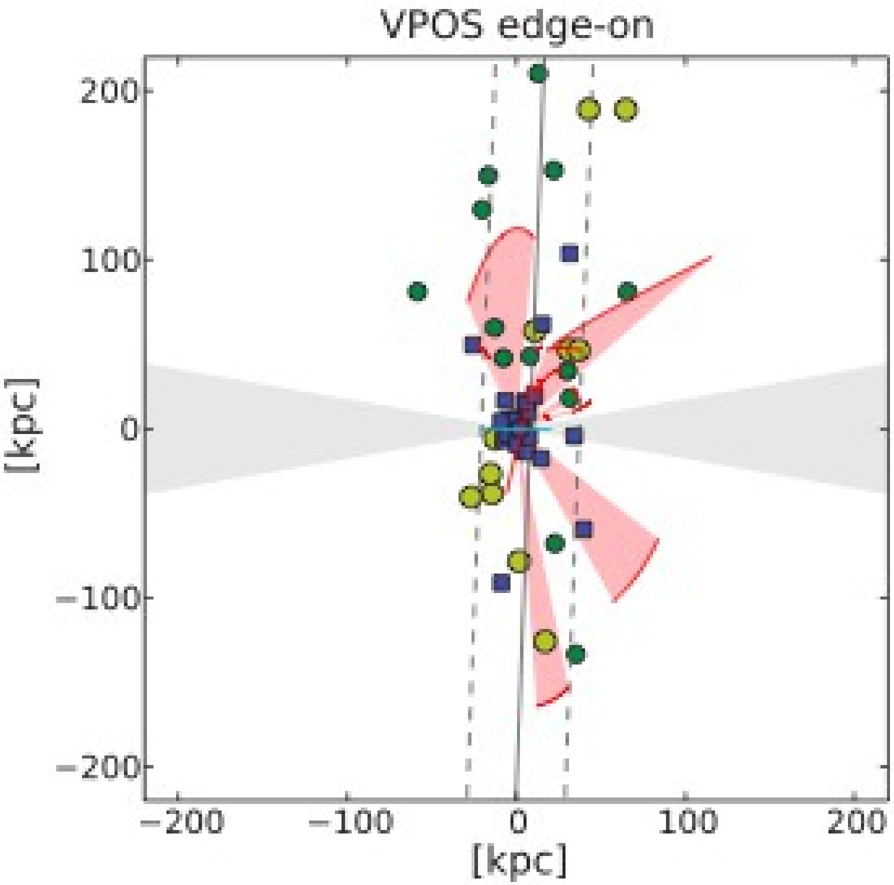
Unfortunately signal is very weak even for GAIA
Weinberger & Macciò 2014 (soon on astro-ph)

The Plane of satellites

The LG is keep challenging the CDM scenario

Satellite alignment

Pawlowski et al 2012



Satellites Plane?

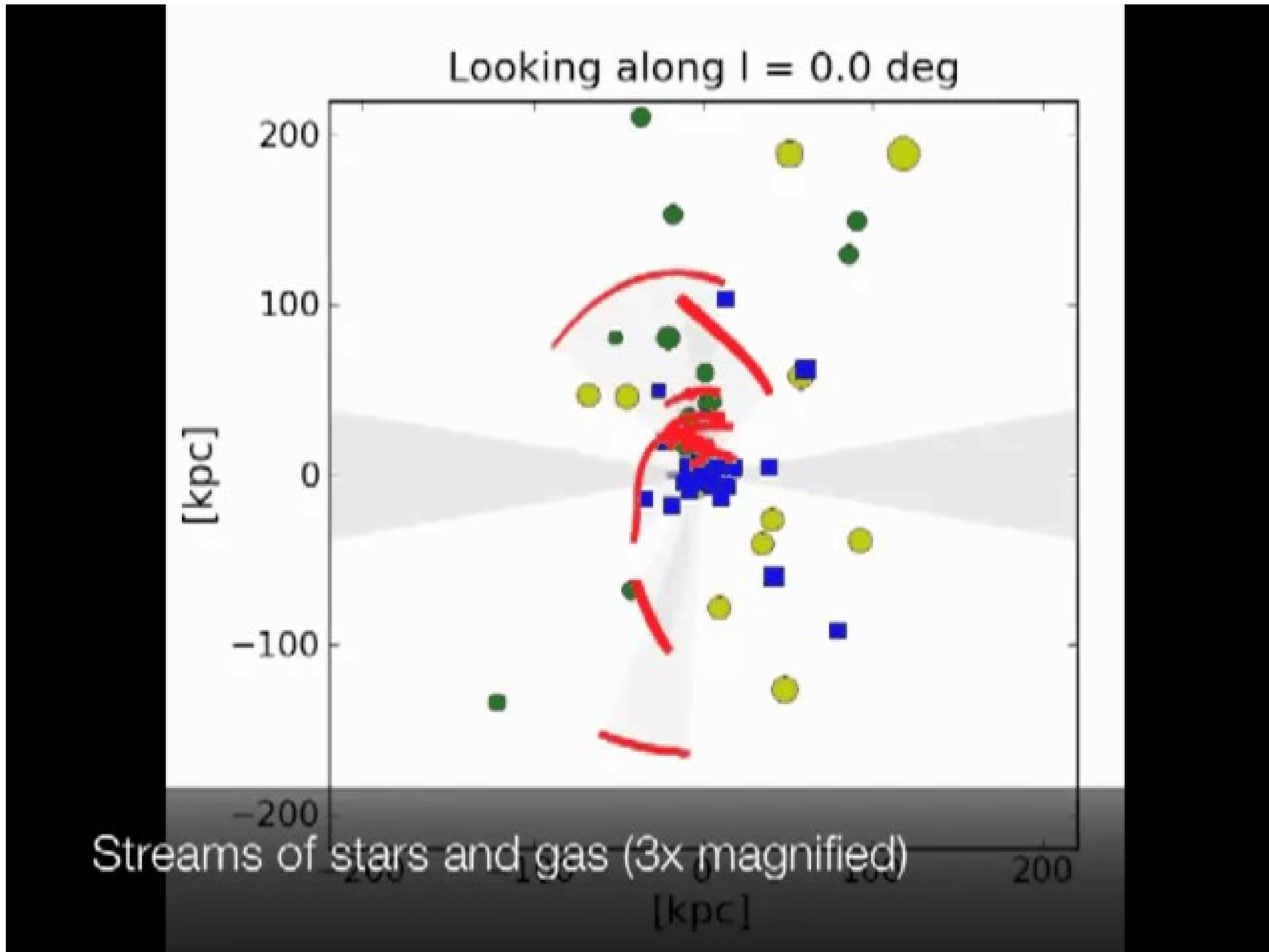
Bright Satellites

Faint Satellites

Globular Clusters

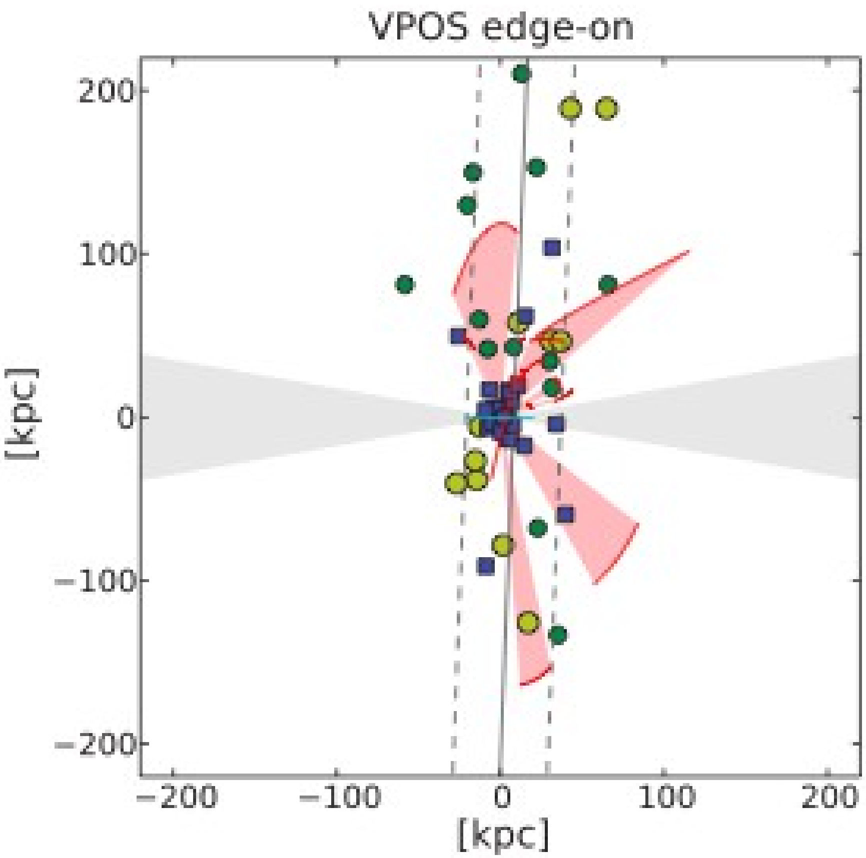
Streams

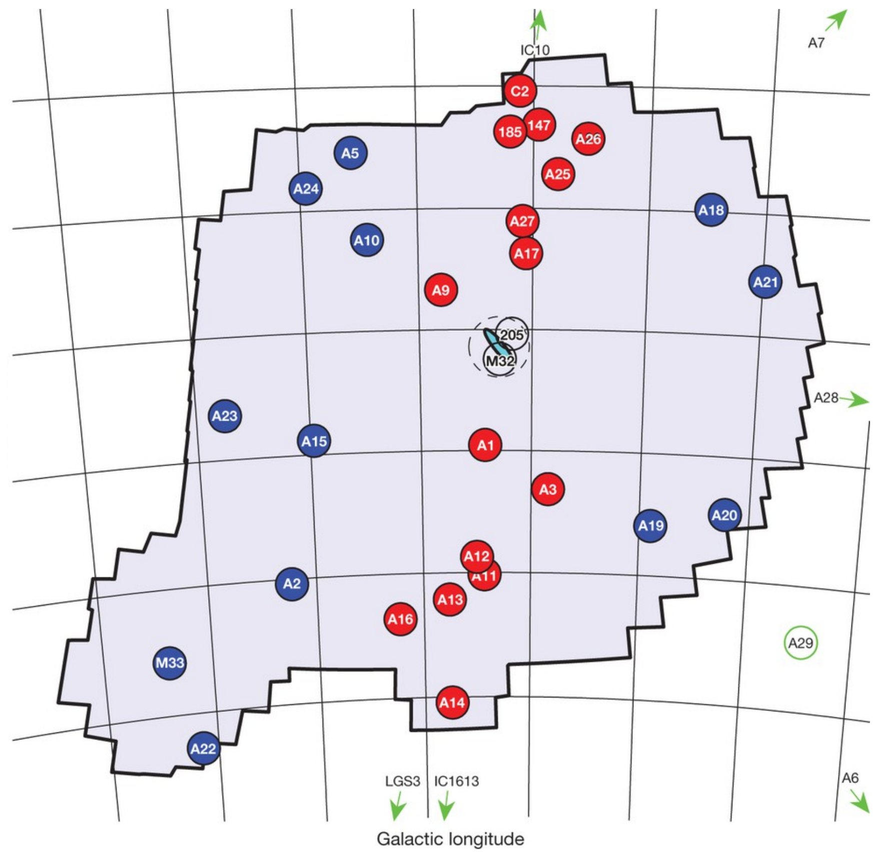
Pawlowski et al 2012



The Plane of satellites

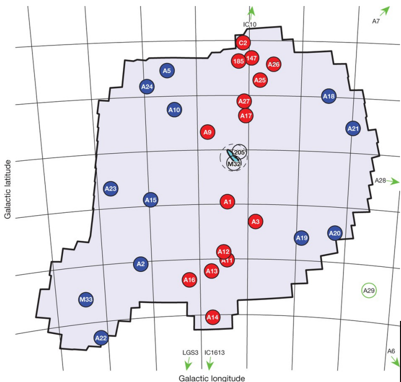
Ibata et al. 2013

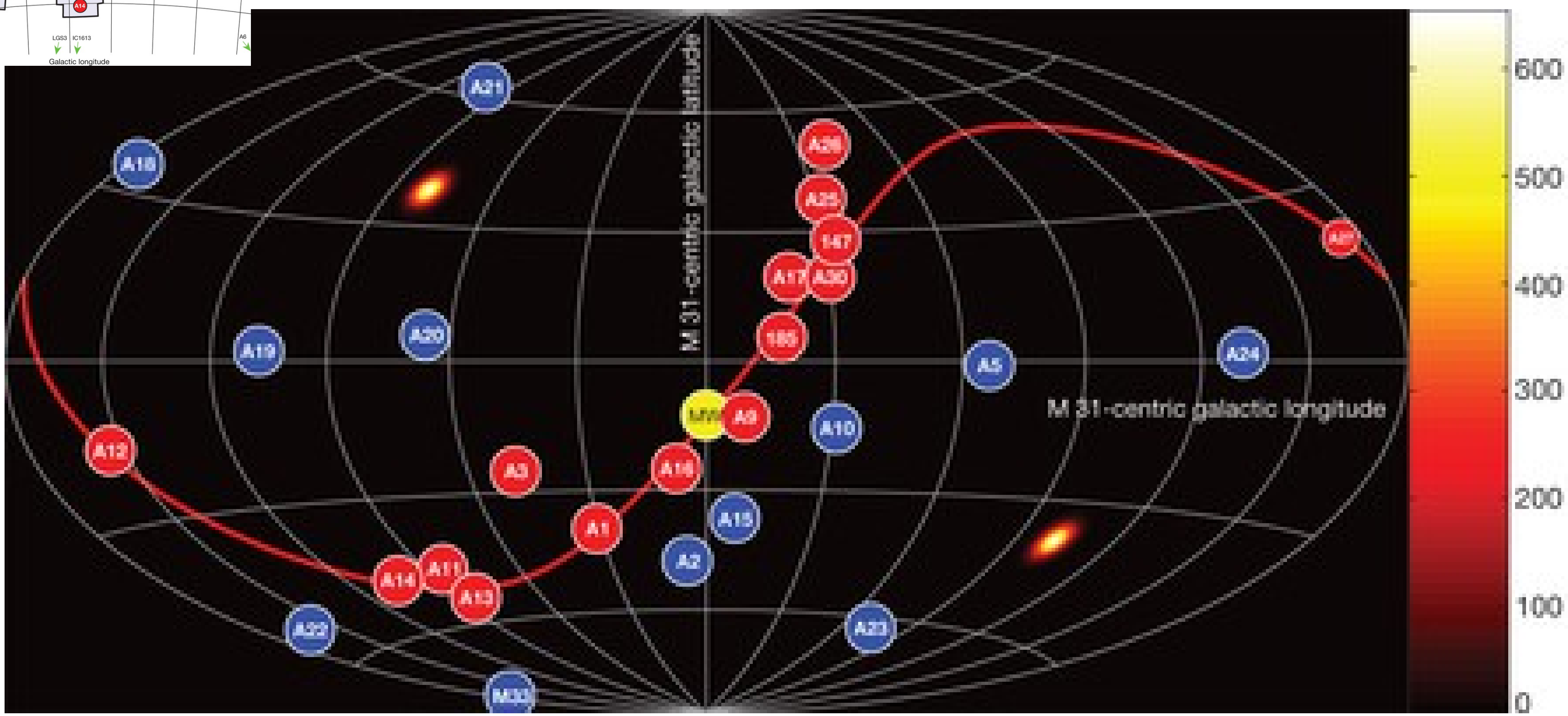




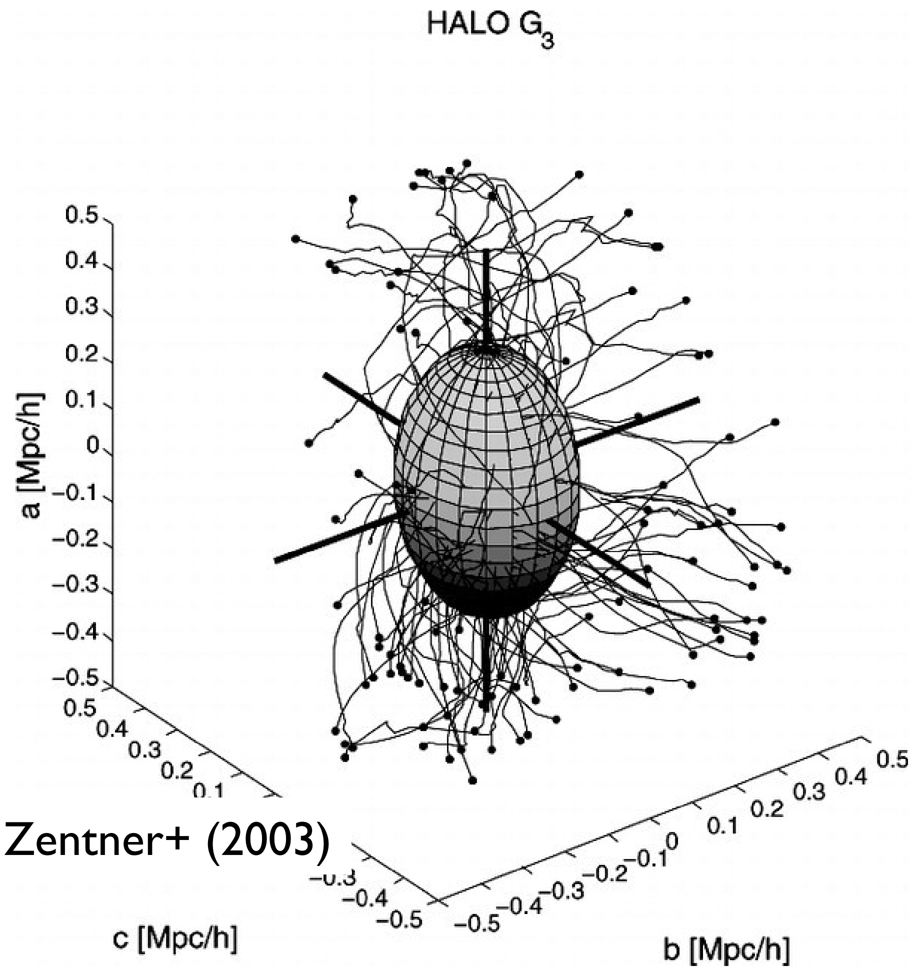
The Plane of satellites

Andromeda Plane of satellites is aligned with the MW disc ?????

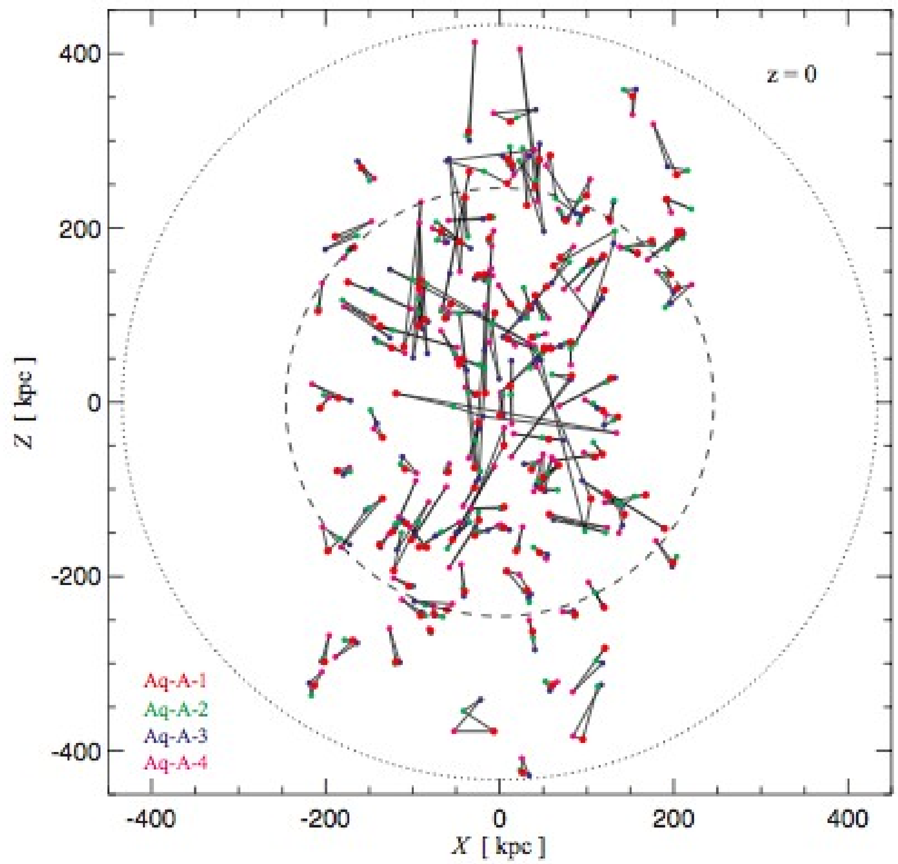




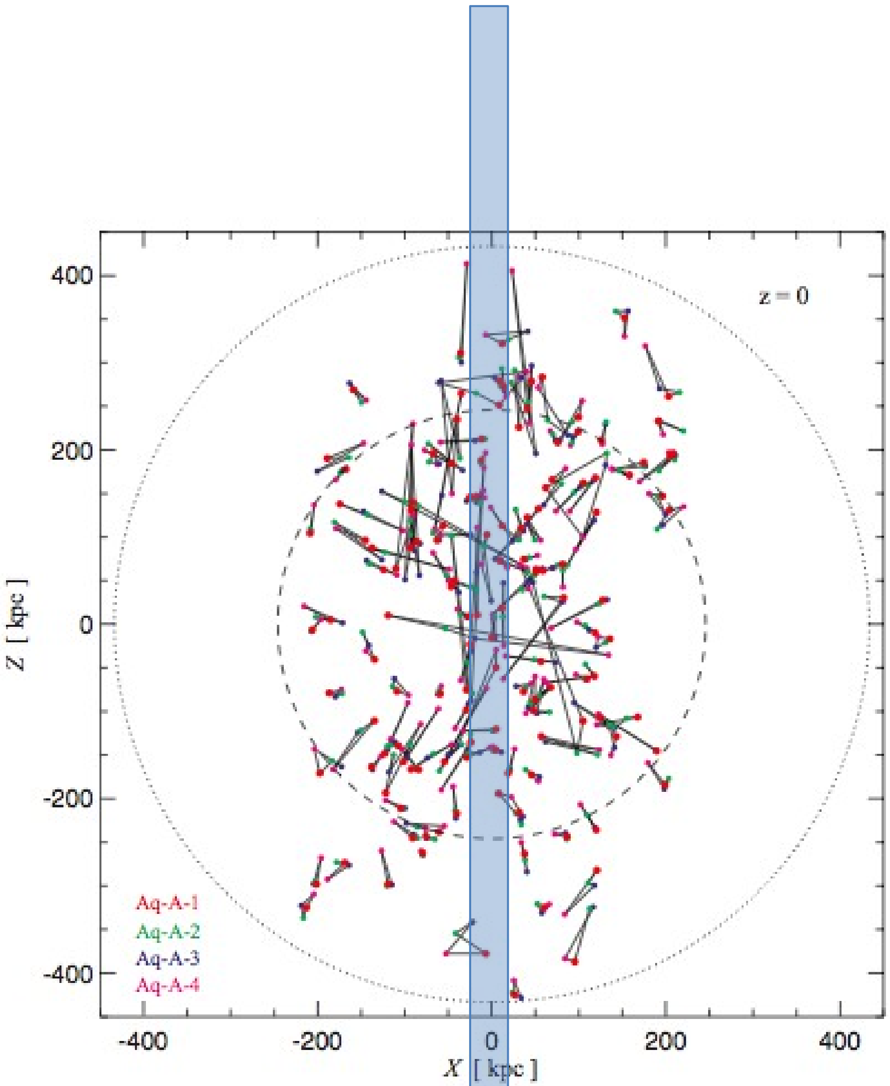
Simulations predictions

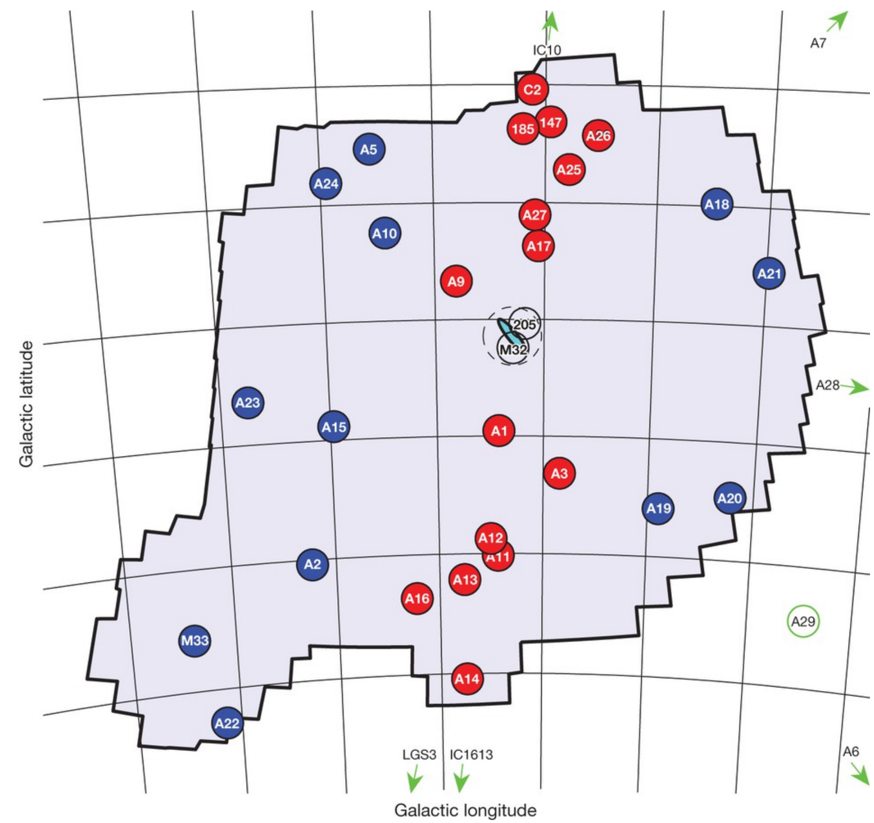


Zentner+ (2003)



Simulations predictions

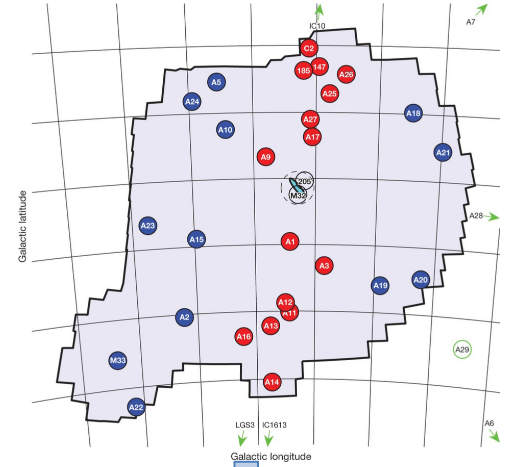


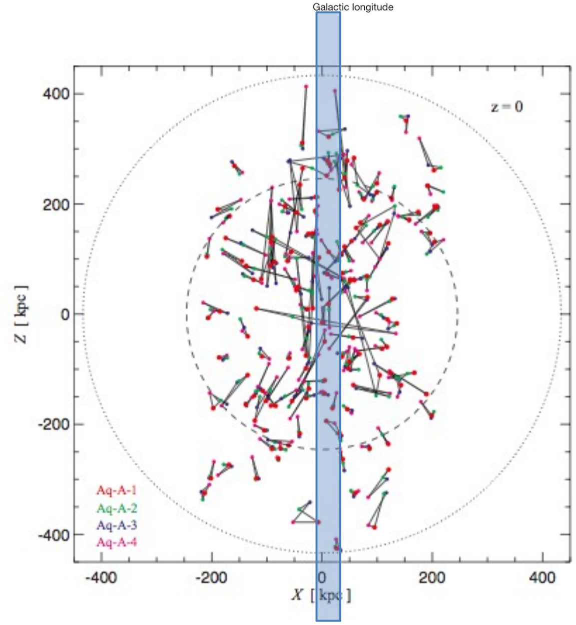


Simulations predictions

Open Problem

- Are we comparing apples with apples?
- Are luminous satellites special?
- Is the Local Group Special?





Summary

- Cold Dark Matter Theory very successful on Large scales
  - Power Spectrum
  - Topology and Spatial distribution

- Cold Dark Matter Theory inconsistent with galaxy properties on small scales
  - Profiles
  - Satellites
  - Plane of satellites

Solutions

- We need to modify the CDM paradigm

Tomorrow's talk on Warm Dark Matter

SIDM talk from Jesus

Solutions

- We need to modify the CDM paradigm
- We need to abandon the CDM paradigm
- Or have we forgotten something?

The Baryons !!!
Stars and Gas

Stay tuned for Greg's talk

Thank you