Small Scale Structure and Cold Dark Matter

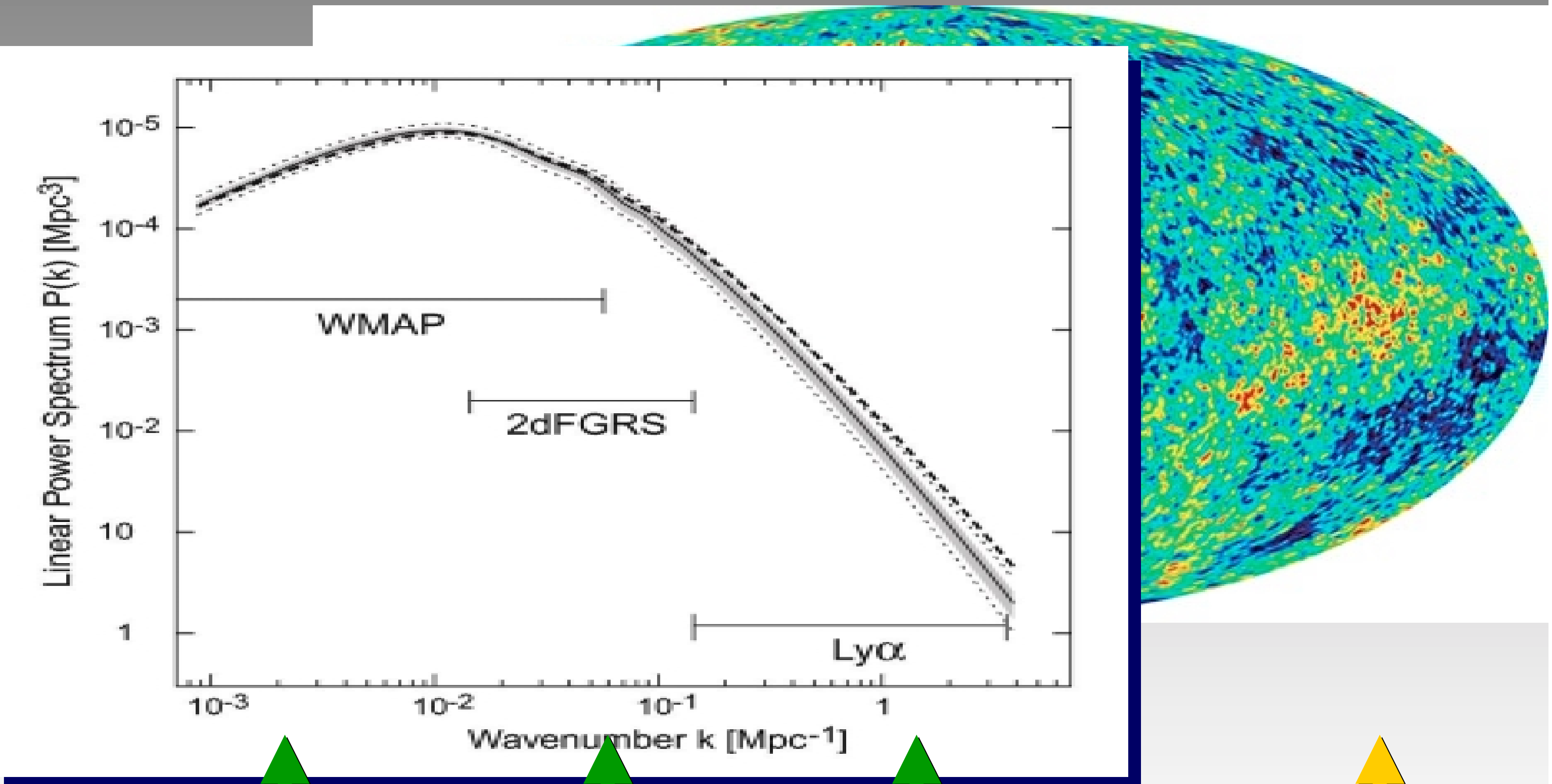
Matthias Steinmetz (AIP)

AIP

Outline

- Small scale structures as a test of cosmological models
- Density profiles of dark matter halos
- Shapes of dark matter halos
- Substructure of dark matter halos
  - abundance
  - accretion rates
- Summary and conclusion

Cosmology after WMAP



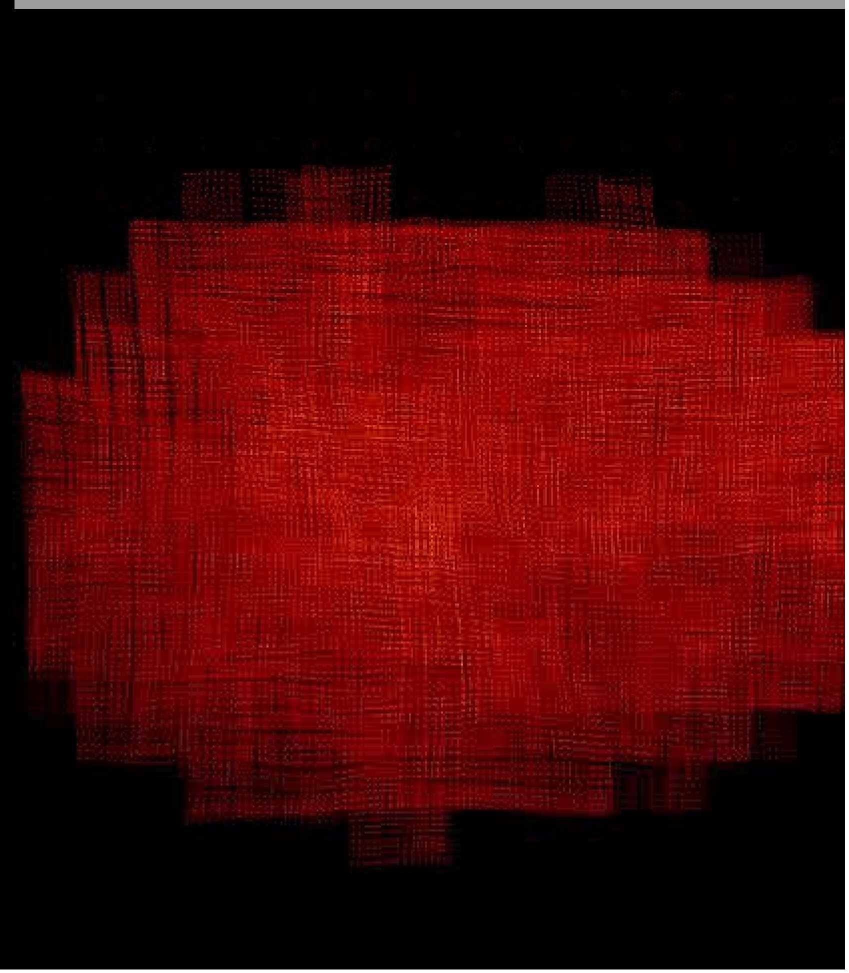
Cosmic Microwave background

Large-Scale Structure

Quasar Absorption Lines

Substructure in the Galaxy

Structure formation by gravitational instability



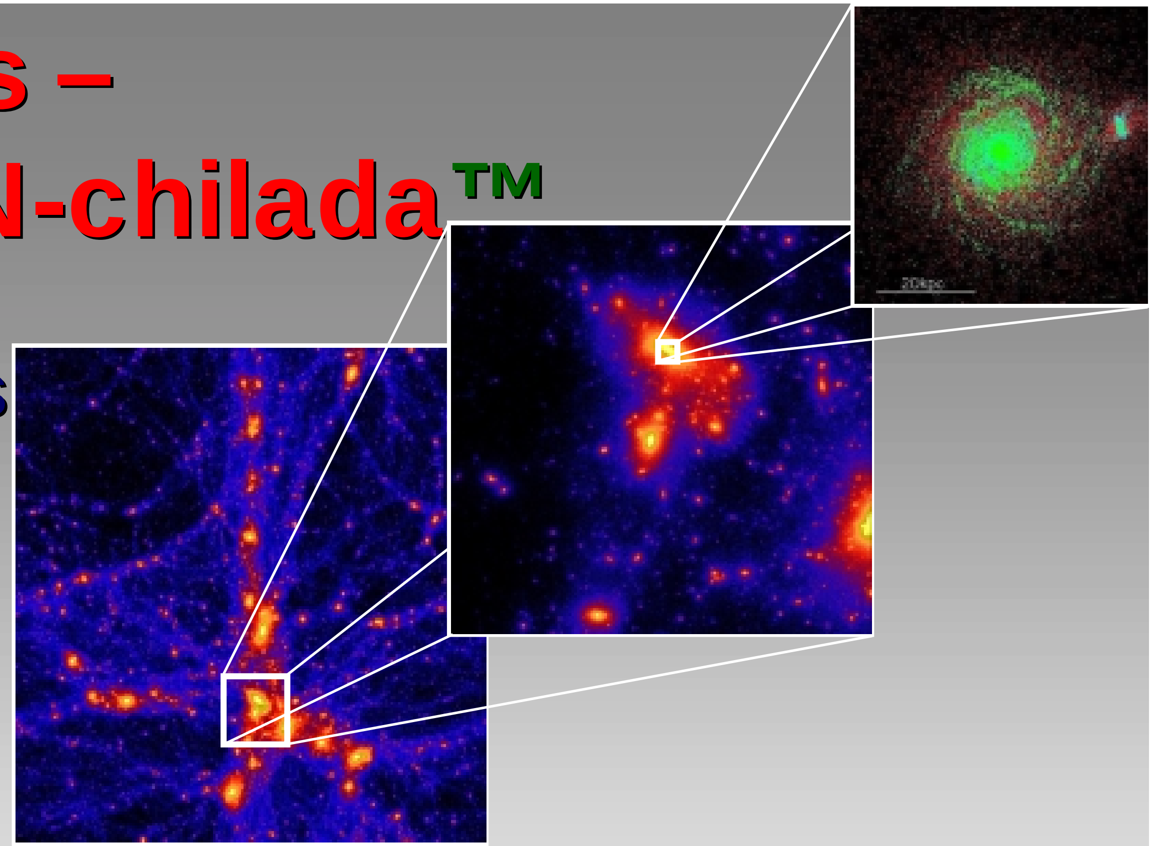
DESY Theory Workshop 2004
Particle Cosmology

September 29th 2004

Formation of the Milky Way: what do the textbooks say …

- The Milky Way formed 10 billion years ago
  - the disk is thin ↯ substantial accretion
  - the oldest thin disk stars >10 billion years old
  - rotational support, ordered motion ↯ mixed up by mergers
- however
  - many disks are warped and/or lopsided (>50%?)
  - difficult to create long-living features

Simulations – the whole N-chilada™

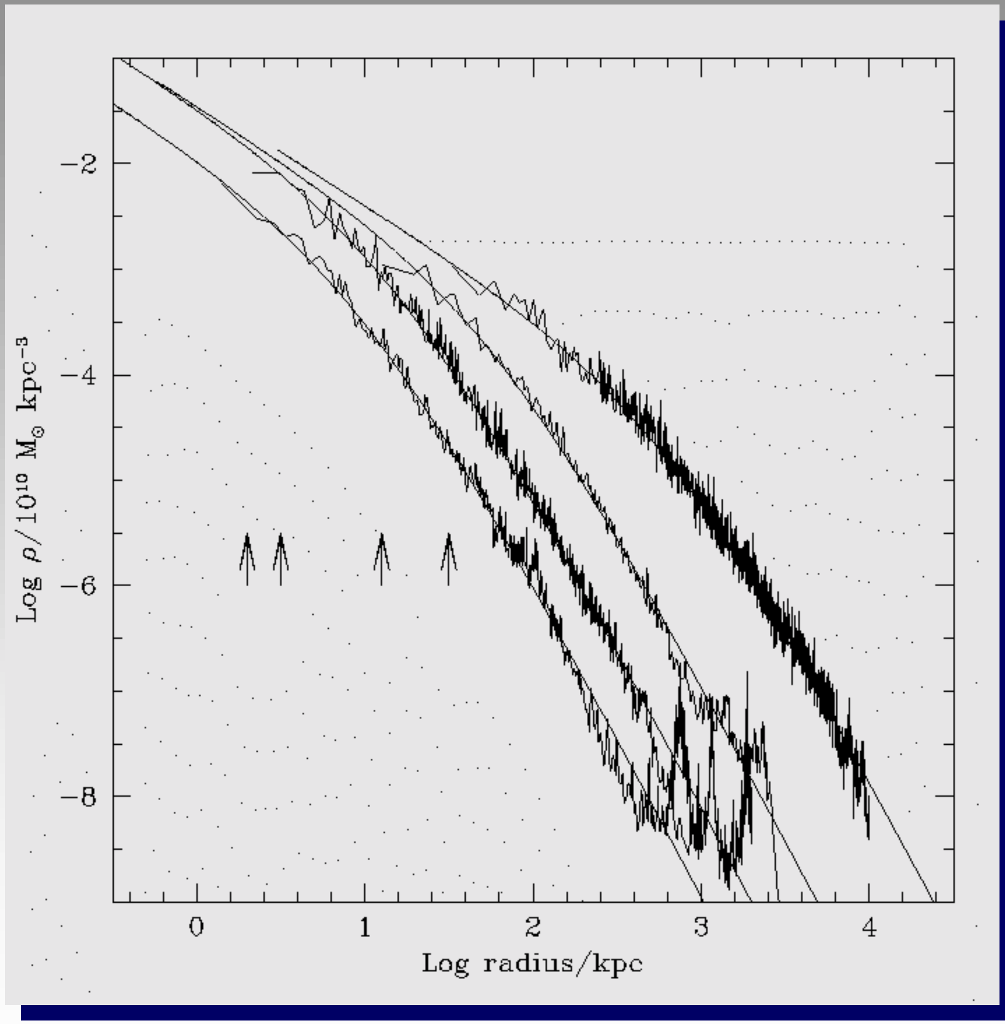


- re-simulate individual halos at much higher resolution
  - dark matter, stars: N-body
  - gas: SPH
  - including gas physics
    - radiative cooling processes
    - heating due to photoionizing UV background
    - star formation: phenomenological recipes
    - feedback due to supernovae, stellar winds etc.
    - metal enrichment
  - tidal forces of the environment

™: George Lake

The Density Profile of Cold Dark Matter Halos

Density



Radius

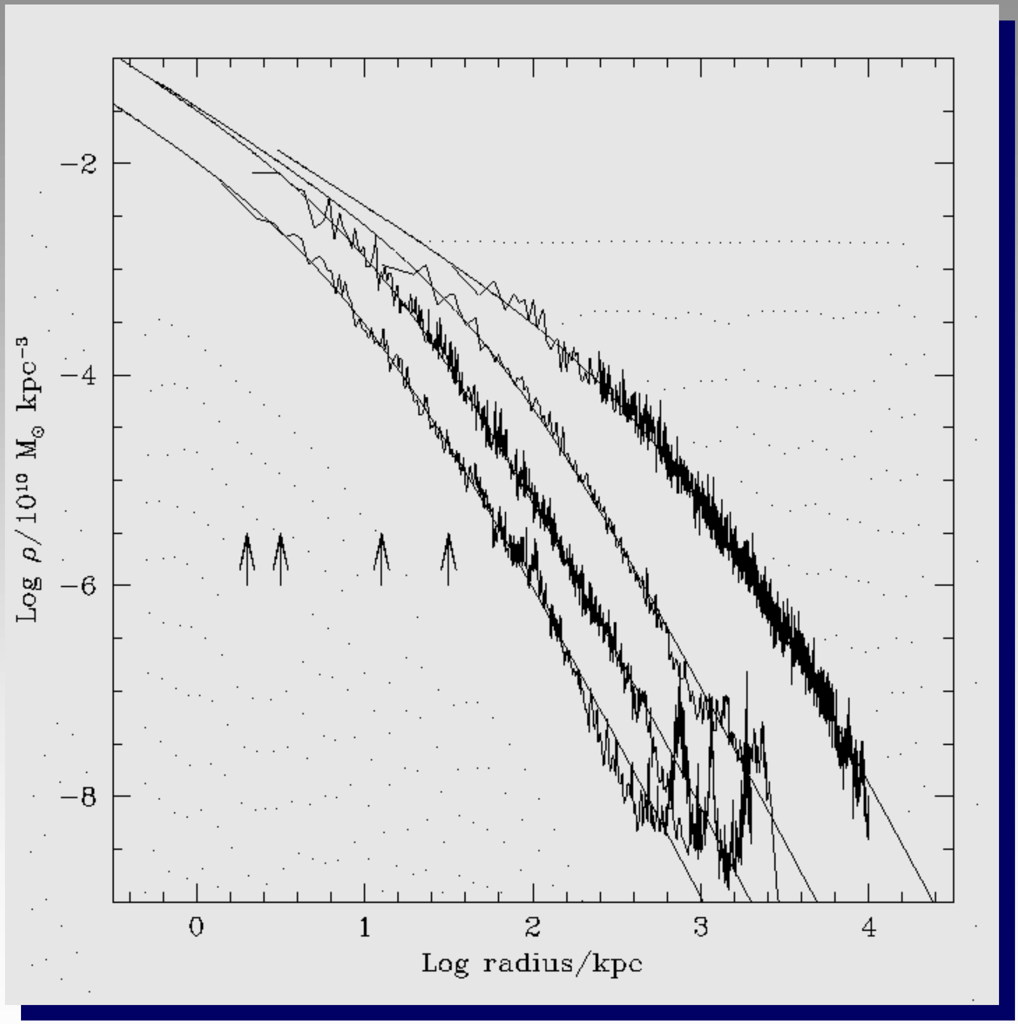
- Mass profiles of dark halos are independent of halo mass and cosmological parameters

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

Navarro, Frenk & White 1997

The Density Profile of Cold Dark Matter Halos

Density



Radius

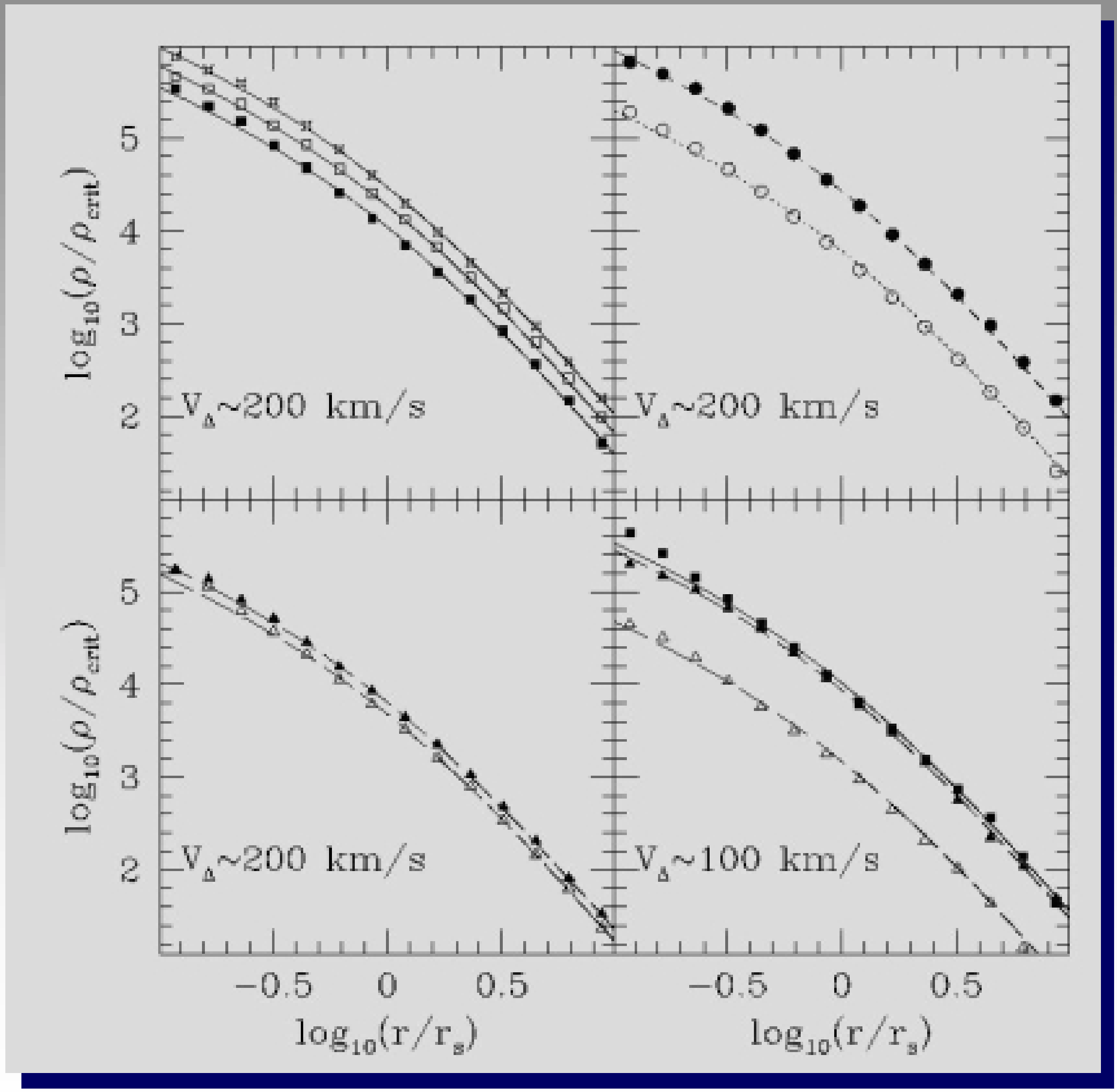
- There is no obvious density 'plateau' or 'core' near the center
- The profile is shallower than isothermal near the center
- How much shallower?
  - NFW: -1
  - Moore: -1.5

Navarro, Frenk & White 1997

Halo profiles for different CDM and WDM cosmologies

σ_8

WDM

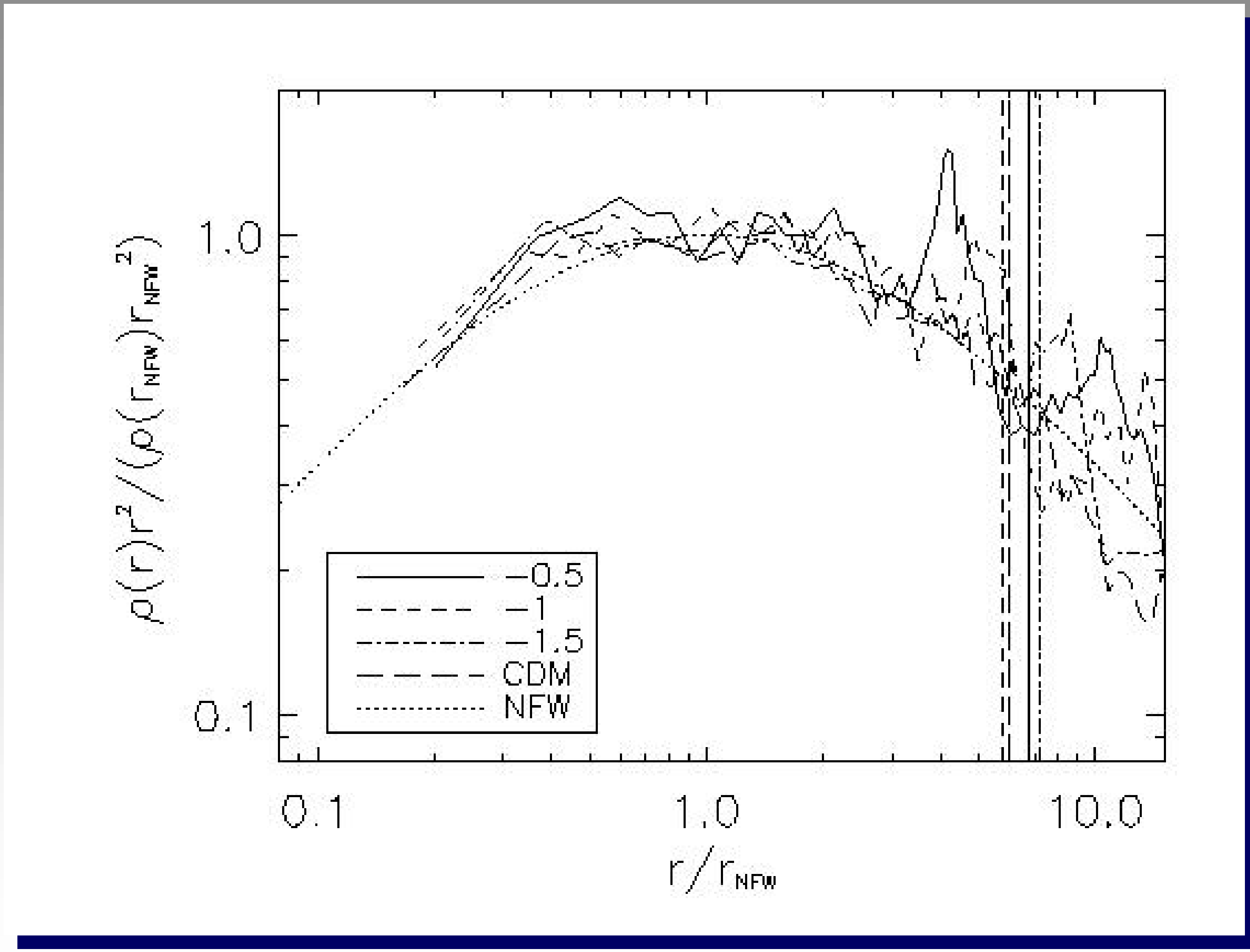


Γ

v_c

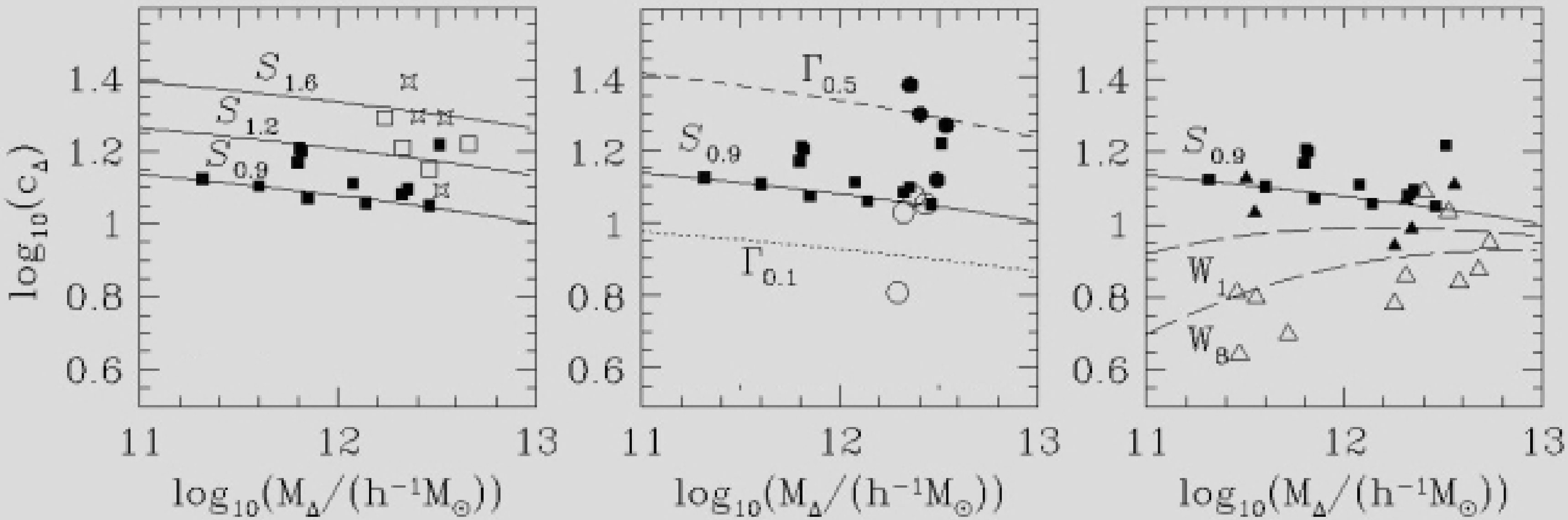
Eke, Navarro & Steinmetz 2001

Halo profiles for non-hierarchical models



Huss, Jain & Steinmetz 1999

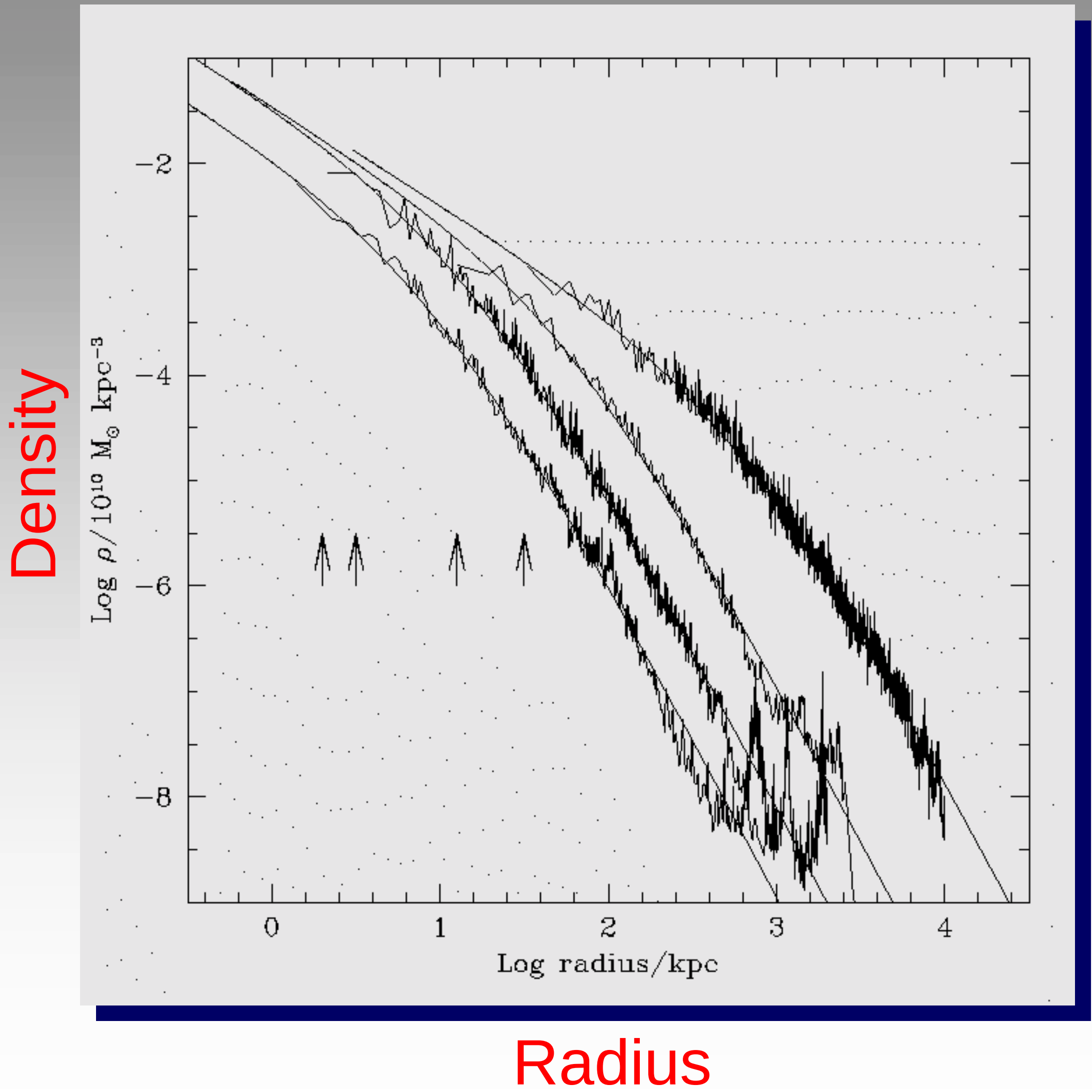
Halo concentration vs cosmological parameters



$\Rightarrow$ for CDM-type models: $c = R_{vir}/R_s \approx 10$ for galaxy halos

Eke, Navarro & Steinmetz 1999

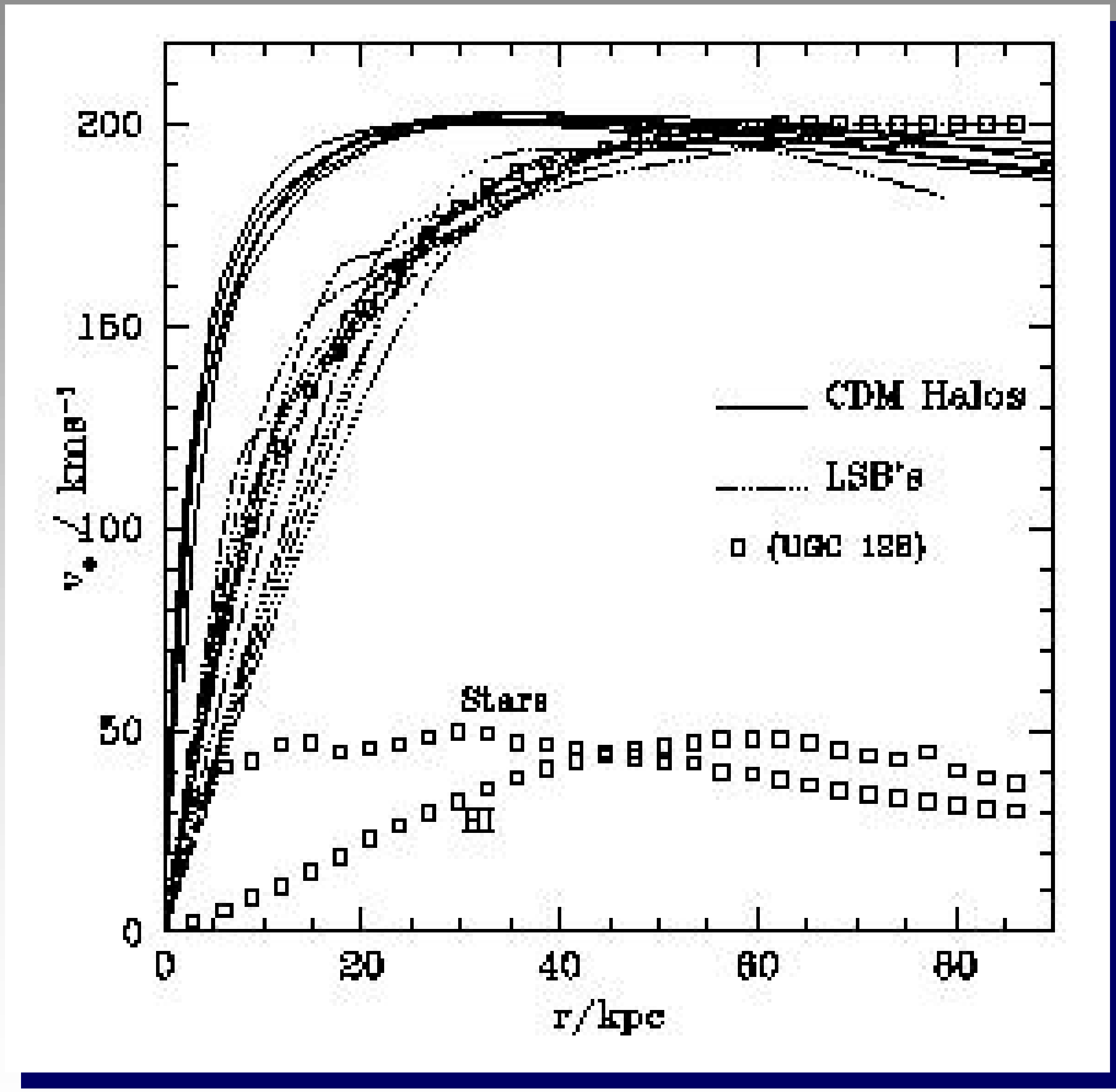
The Density Profile of Cold Dark Matter Halos



Halo fitting → two parameters:

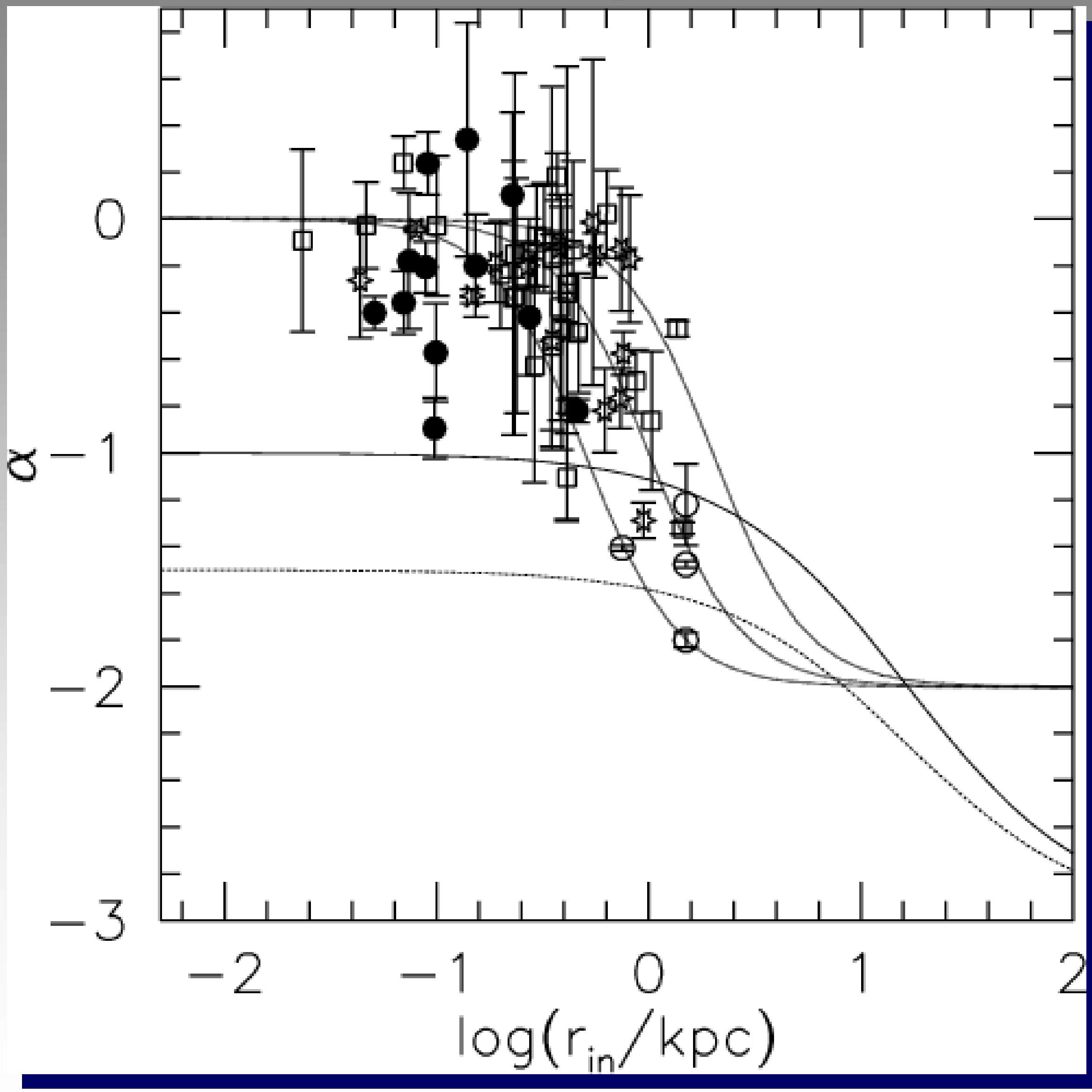
- Circular velocity v_c
- Concentration $c = R_{vir}/R_s$
- Cosmology (Ω, Λ, σ_8 , power spectrum) determines c

Constraint: Rotation Curves of low surface brightness galaxies (LSBs)



Moore et al. 1999

Dark matter profiles of LSBs



LSBs seem to have cores

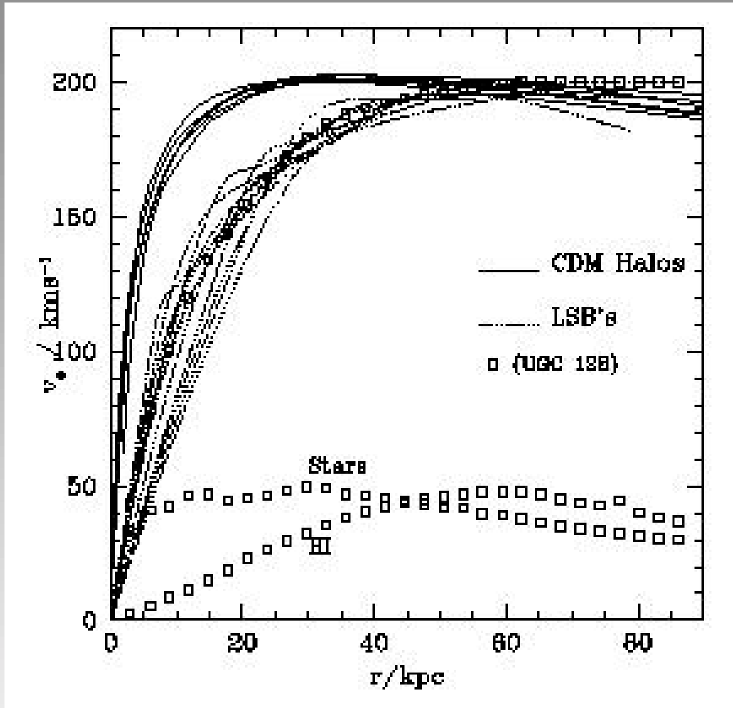
⚡

CDM halos

McGaugh et al. 2002

LSB rotation curves vs cusps

- Some caveats:
  - Strictly, the disagreement is between gas rotation speeds and halo circular velocities.
  - The two may differ if:
    - halo is not spherical
    - velocity dispersion of the gas or disk thickness is important
    - there are departures from equilibrium.
  - The disagreement reported so far is with fitting formulae, not with the actual structure of simulated CDM halos: simulating dwarf halos at high resolution is hard.



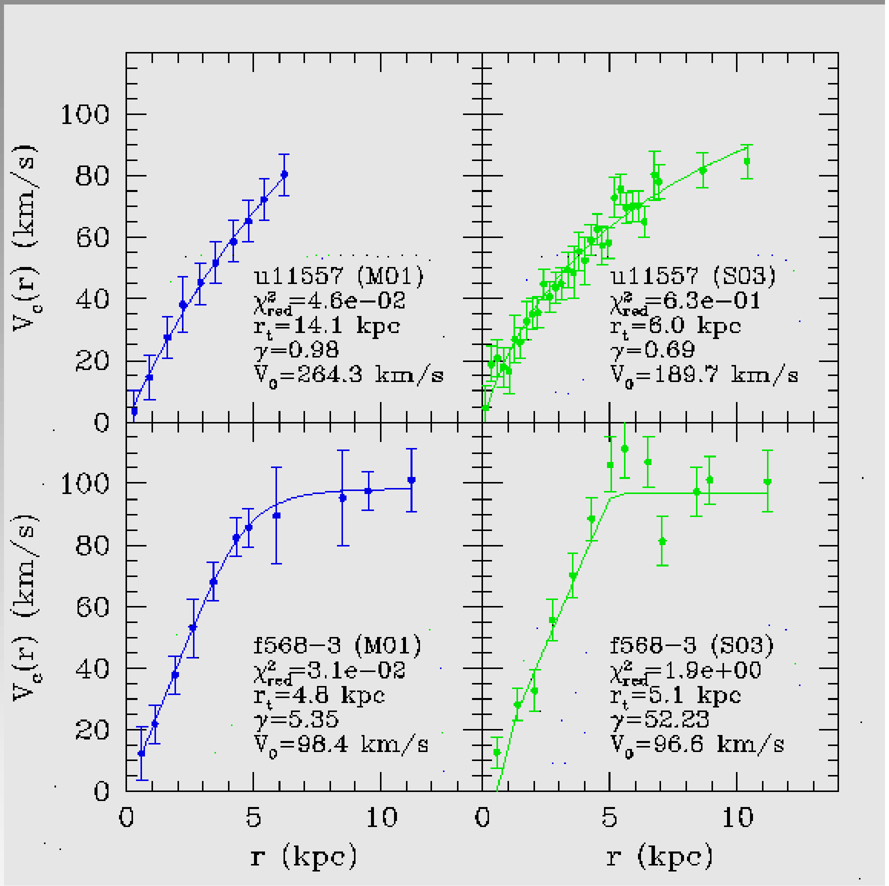
AIP

DESY Theory Workshop 2004
Particle Cosmology

September
29th 2004

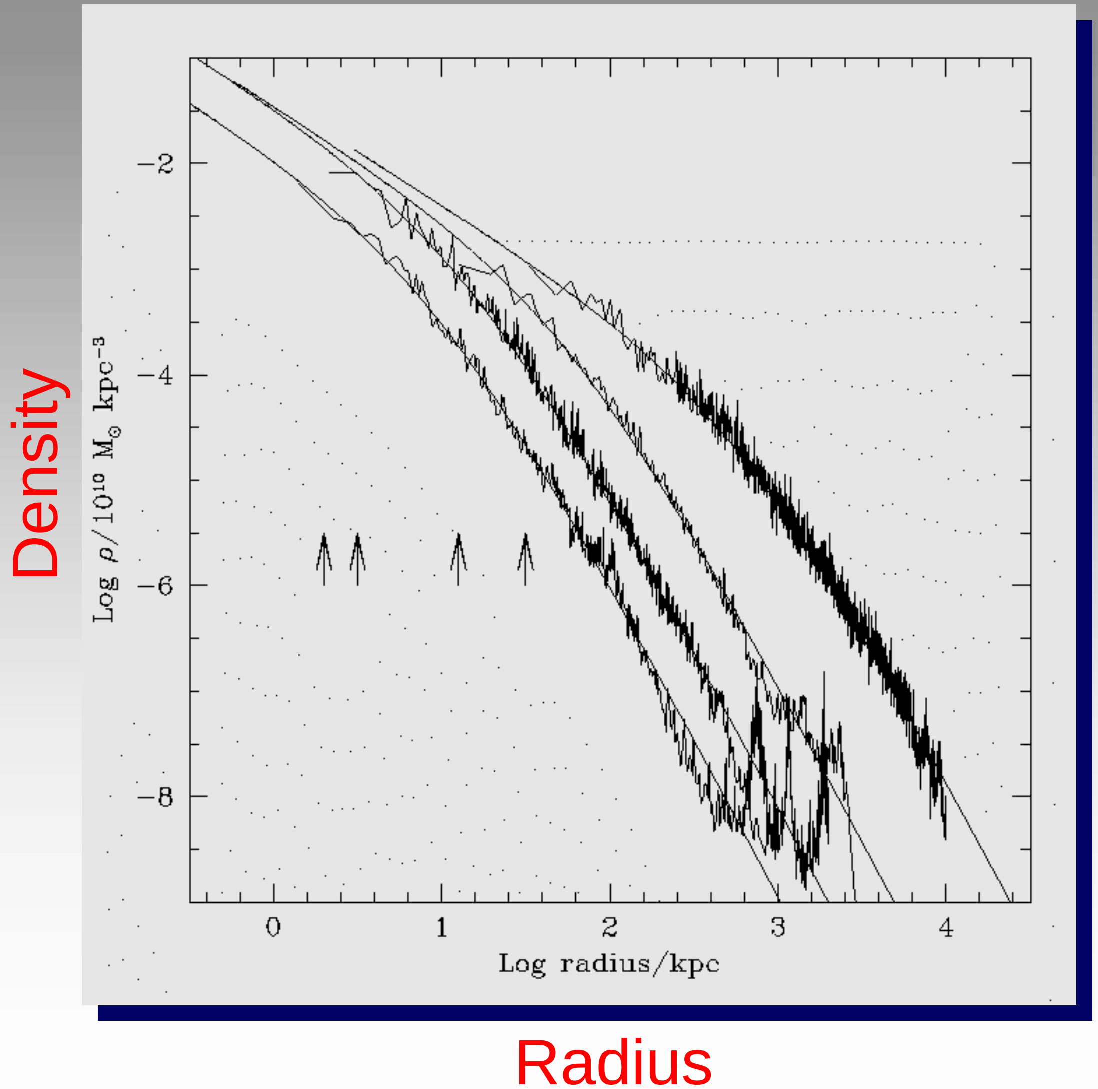
LSB rotation curves vs cusps

- More caveats:
  - Early HI rotation curve datasets were spuriously affected by beam smearing. The situation has improved with the H-alpha observations
  - Some disagreements between observers remain, as does some ambiguity in the interpretation of published data.



McGaugh et al Swaters et al

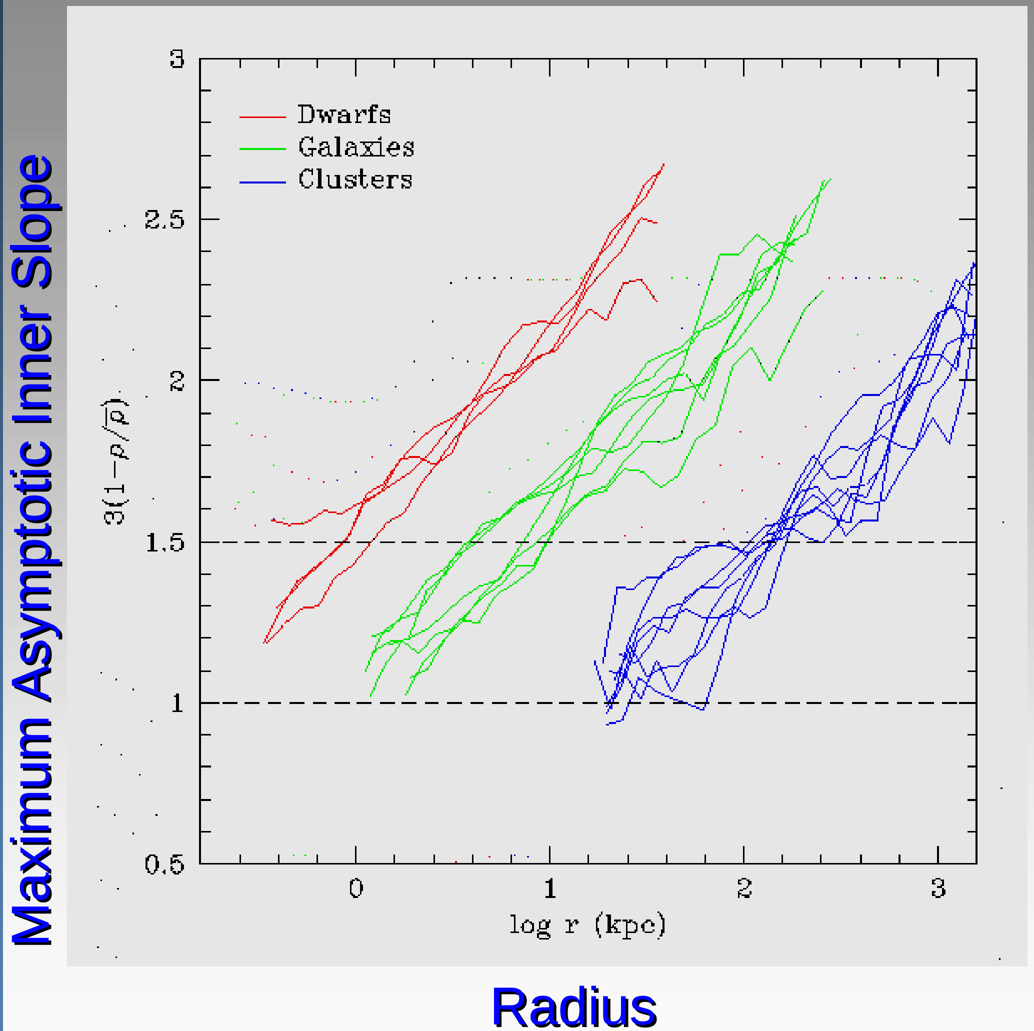
The Density Profile of Cold Dark Matter Halos



Halo fitting → two parameters:

- Circular velocity v_c
- Concentration $c = R_{vir}/R_s$
- Cosmology (Ω, Λ, σ_8 , power spectrum) determines c

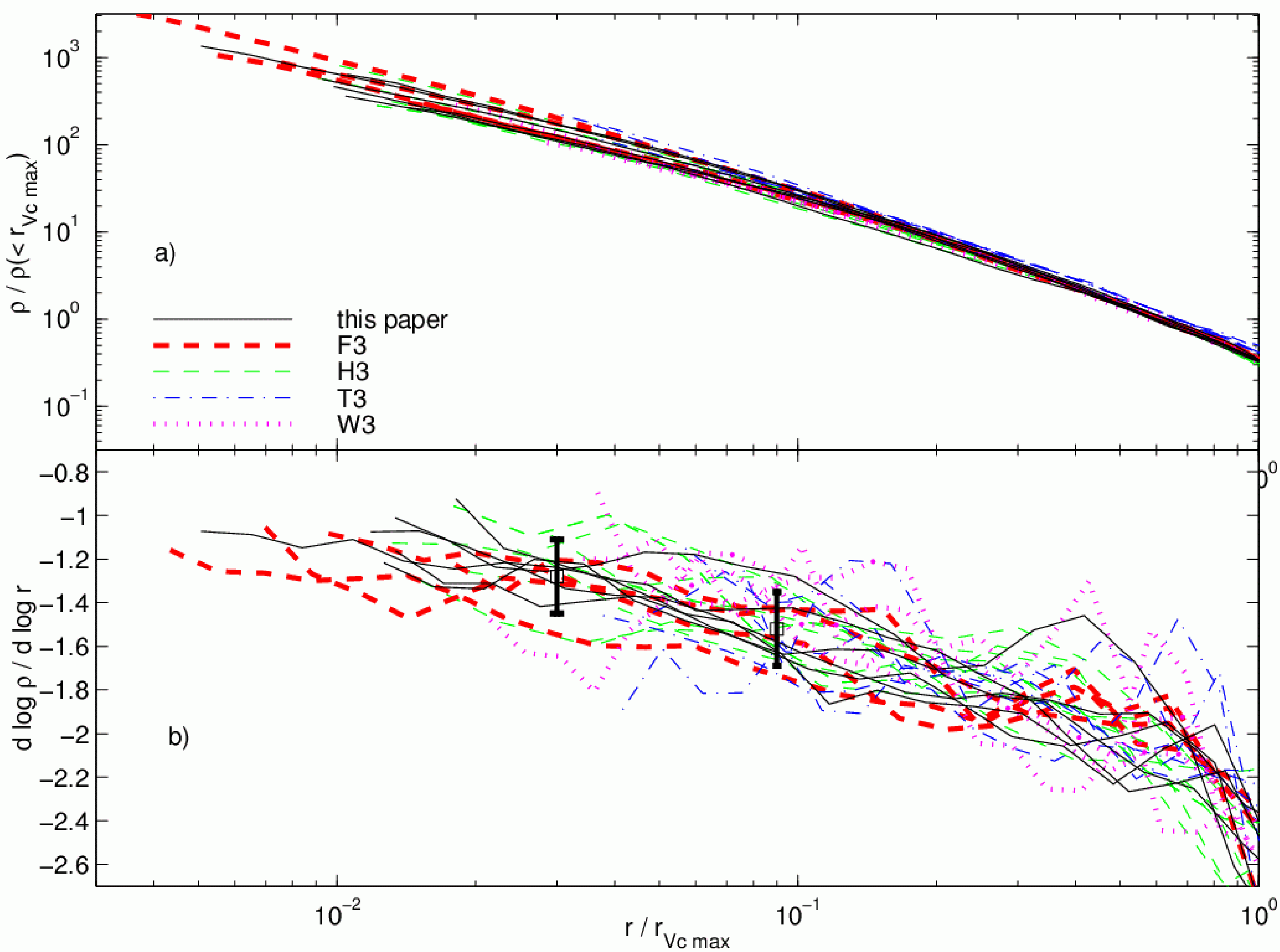
Recent results for ΛCDM halos



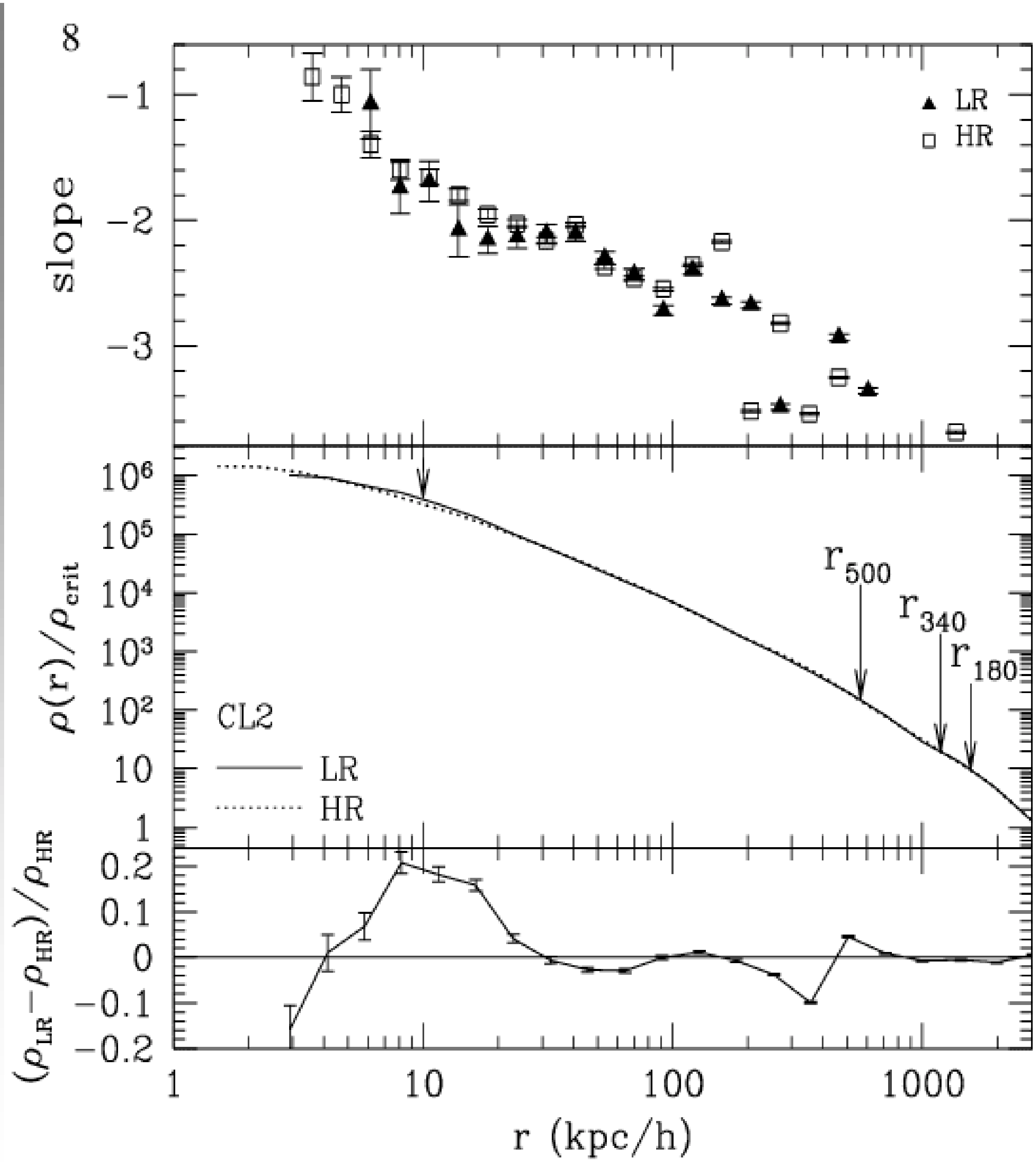
- The total mass enclosed within a given radius is robustly measured in the simulations.
- Combined with the local density, it may be used to derive an upper limit to the inner asymptotic logarithmic slope
- No obvious convergence to a power law

Hayashi, et al 2003

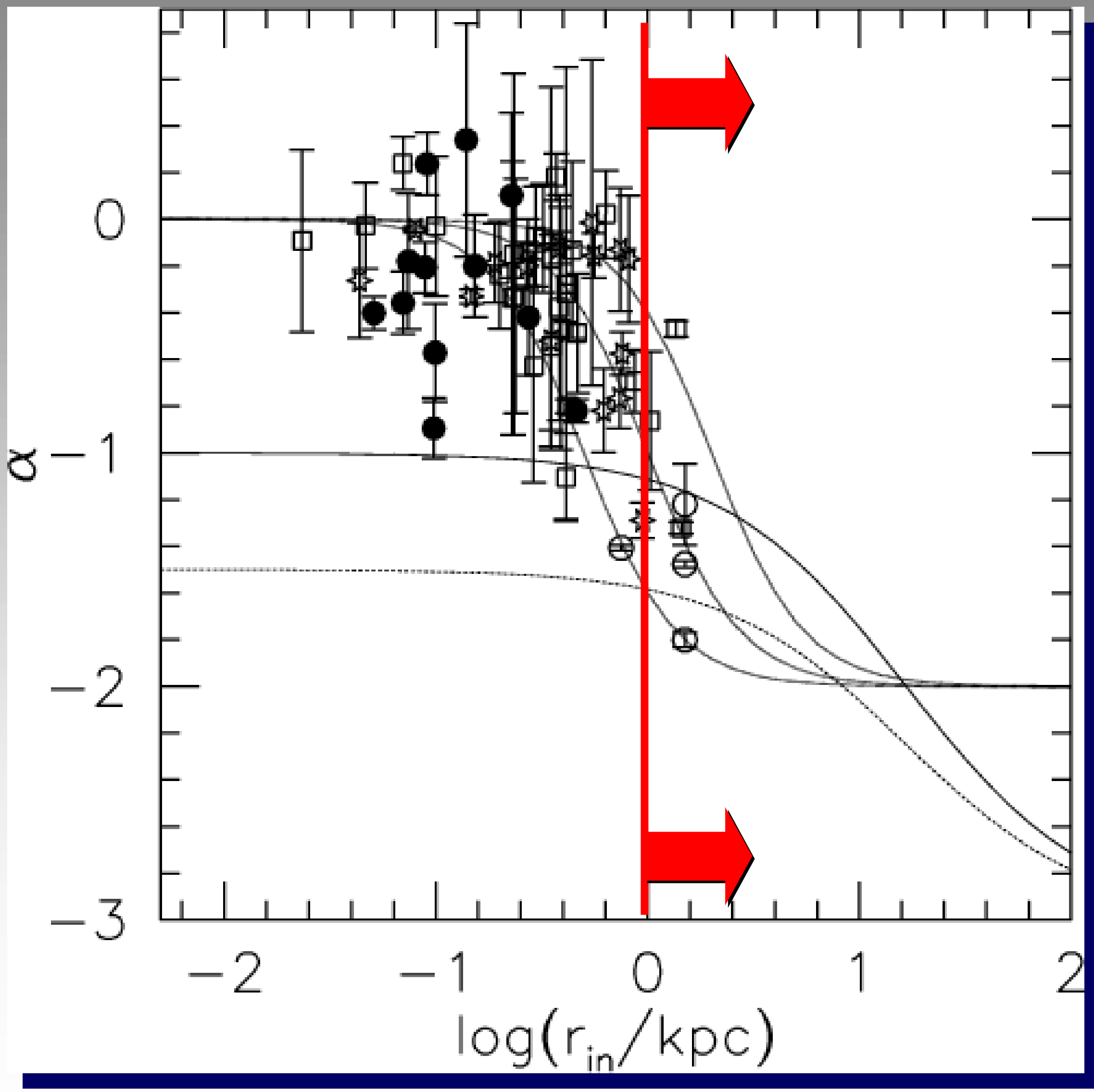
Diemand et al



Gottloeber et al



Dark matter profiles of LSBs



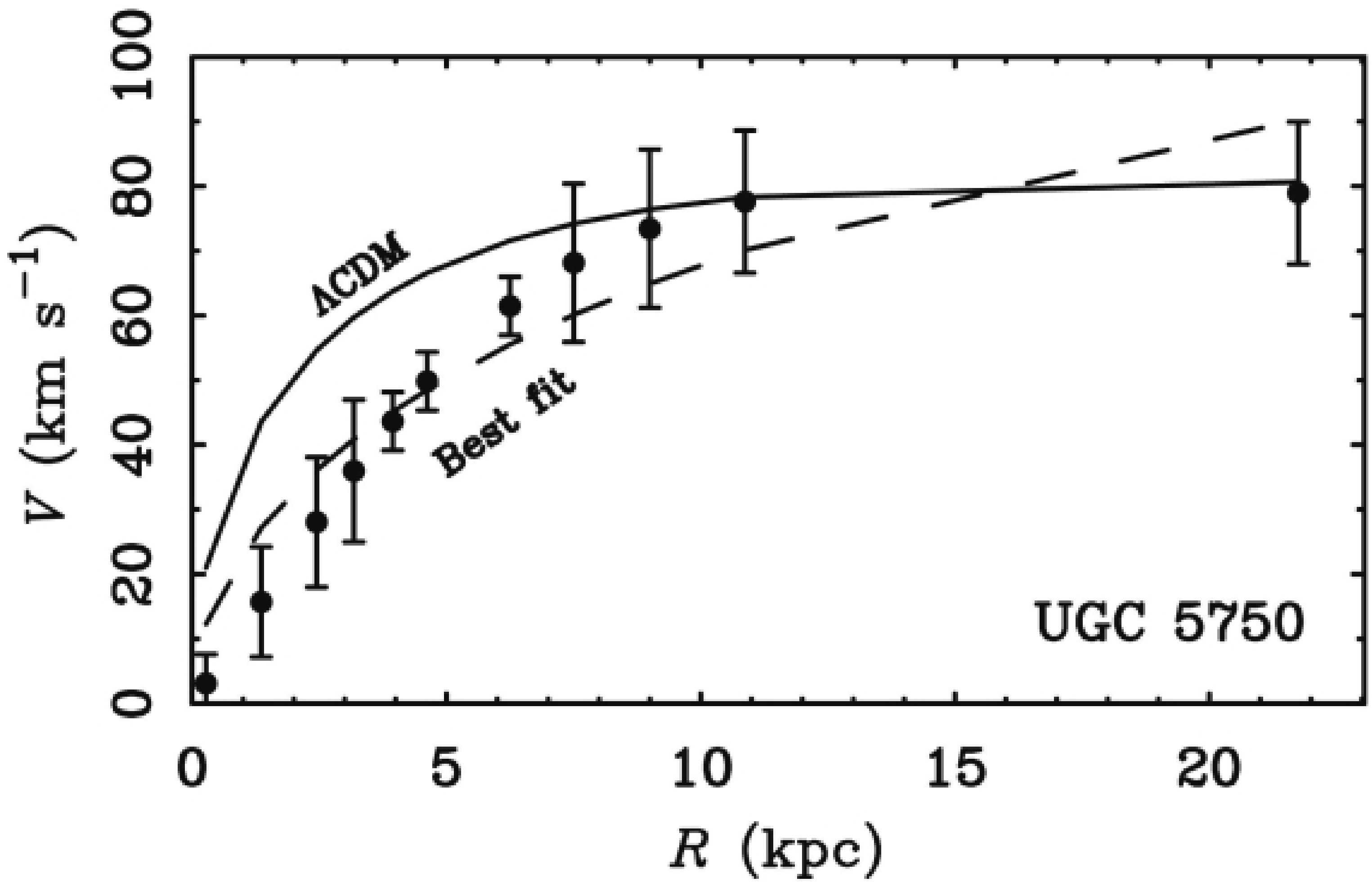
LSBs seem to have cores

↯

CDM halos ???

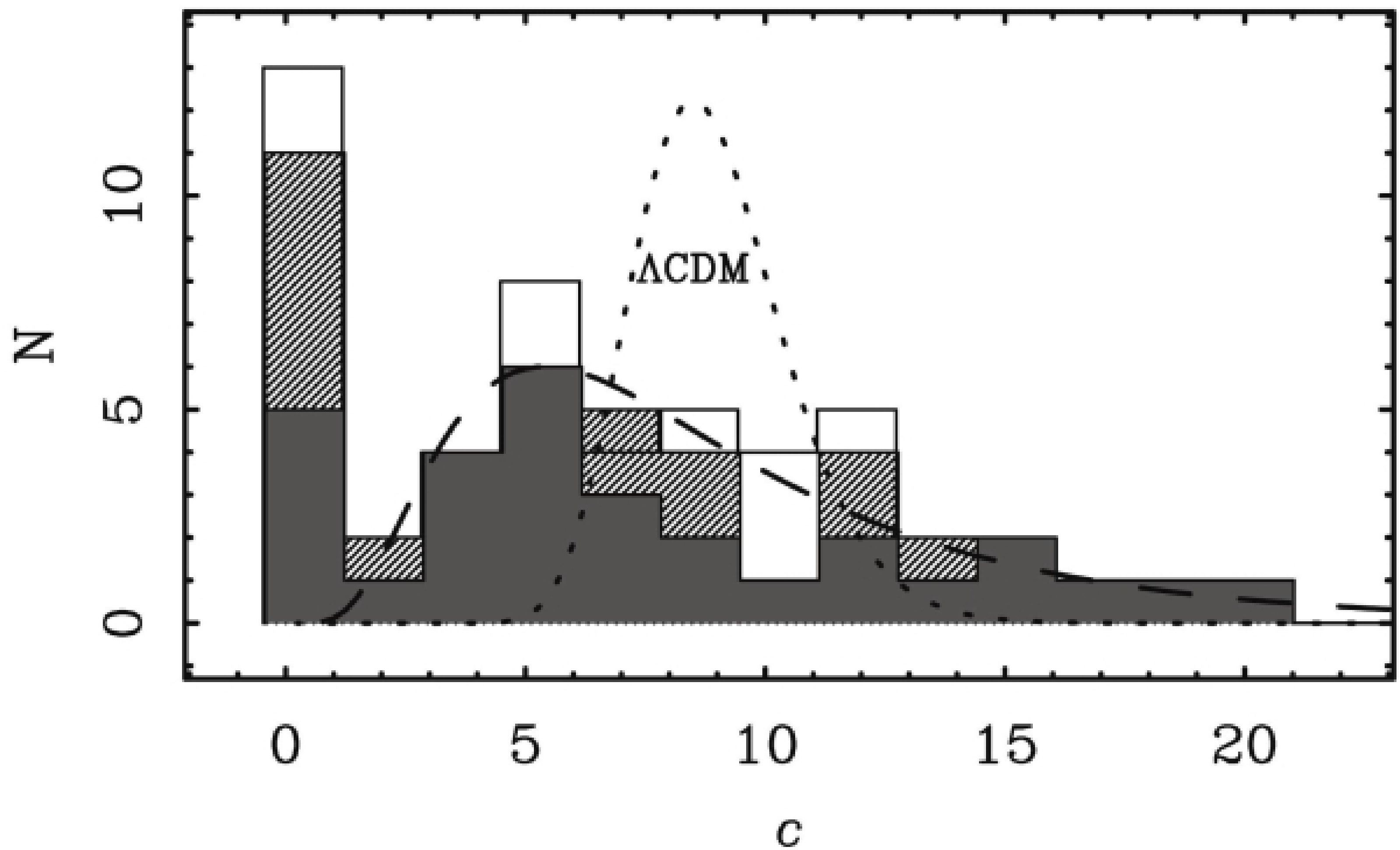
McGaugh et al. 2002

Concentration as inferred from LSBs



⇒ **best fit: c≈2 ↯ c≈10 (CDM)** McGaugh et al. 2002

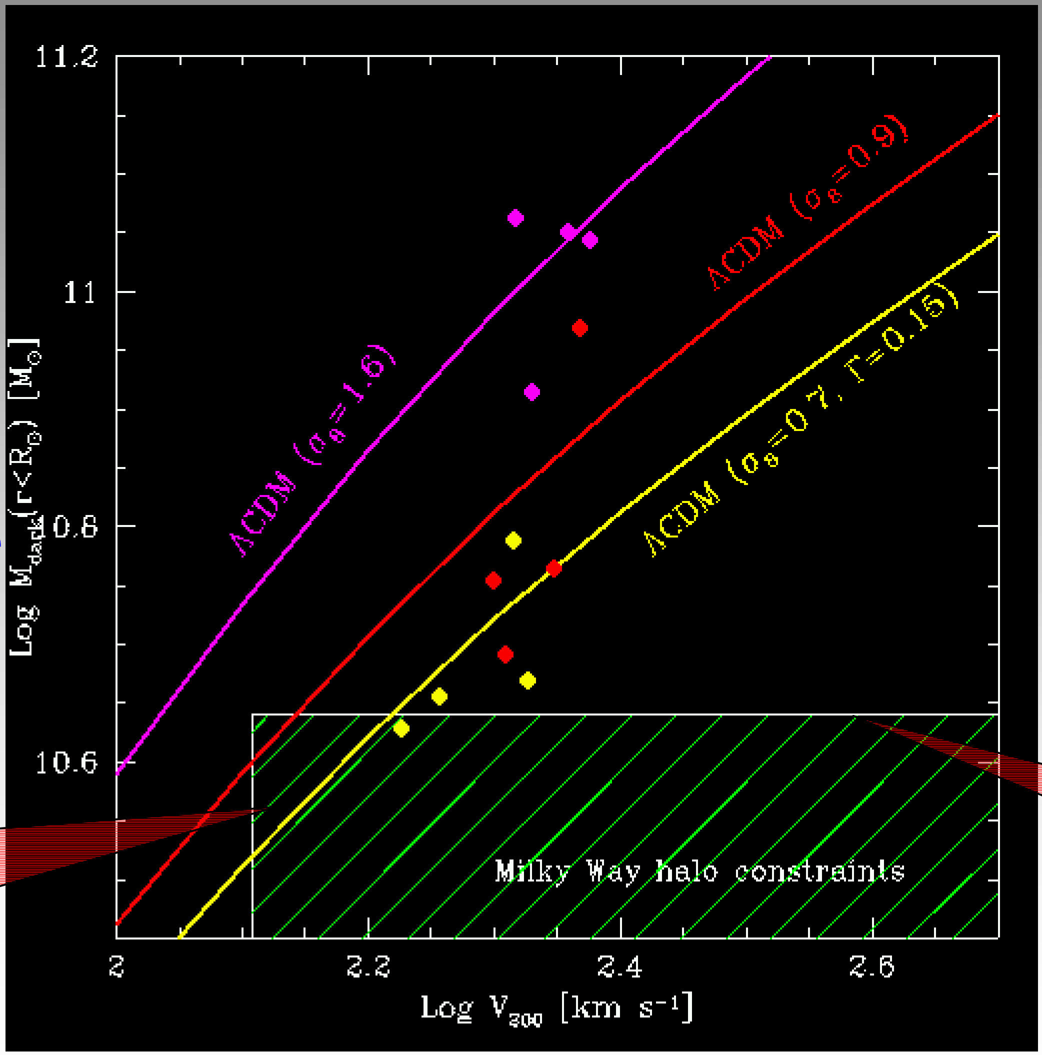
Concentration as inferred from LSBs



McGaugh et al. 2002

Dark Matter in the Milky Way

Dark Mass within the Solar Circle



Constraint from universal baryon fraction

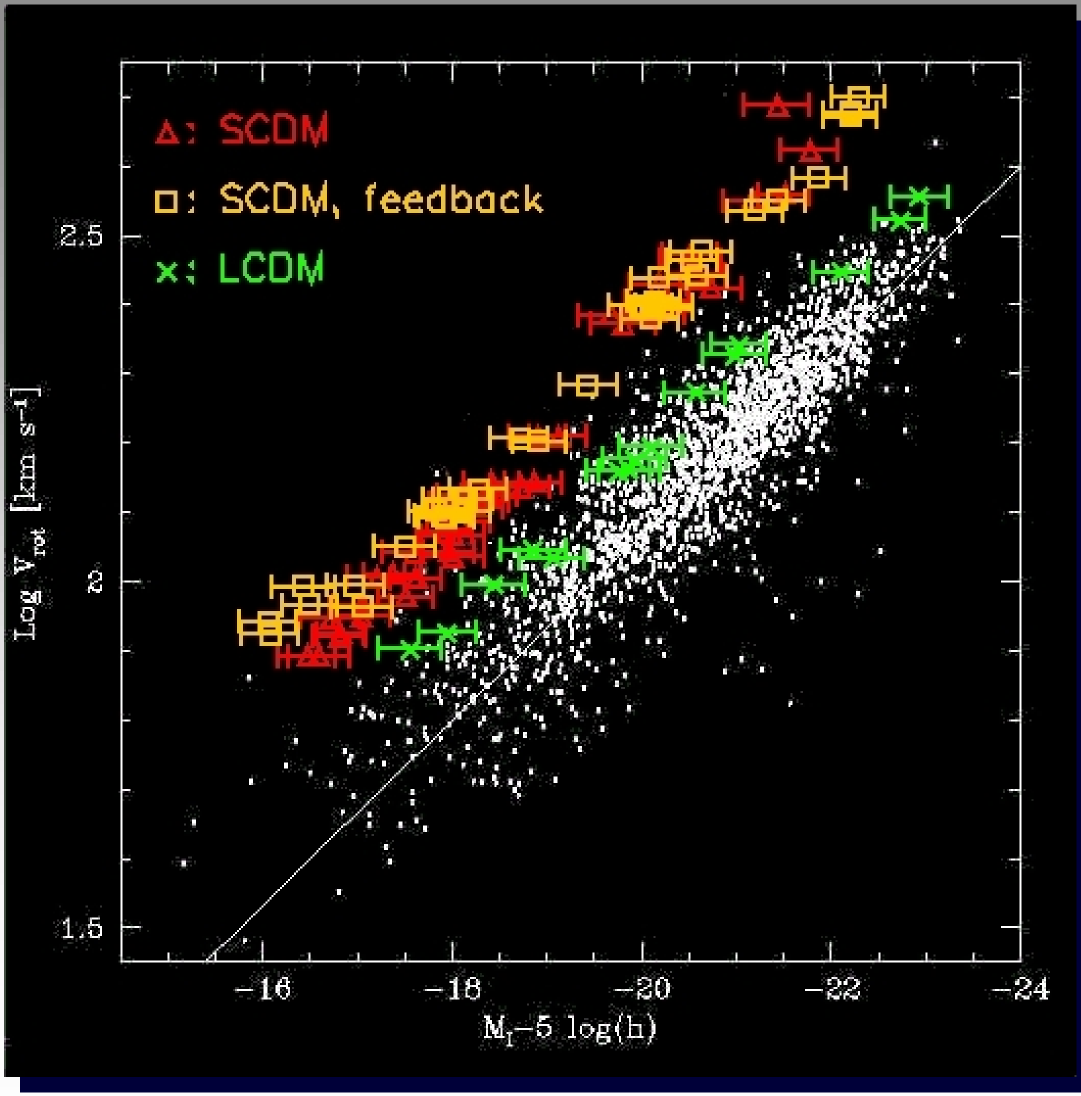
Dark mass constraint from Oort limit

MW dynamics $\Rightarrow$ c≤10

Eke, Navarro & Steinmetz 2000

Halo Mass (Circular Velocity)

The Tully-Fisher Relation

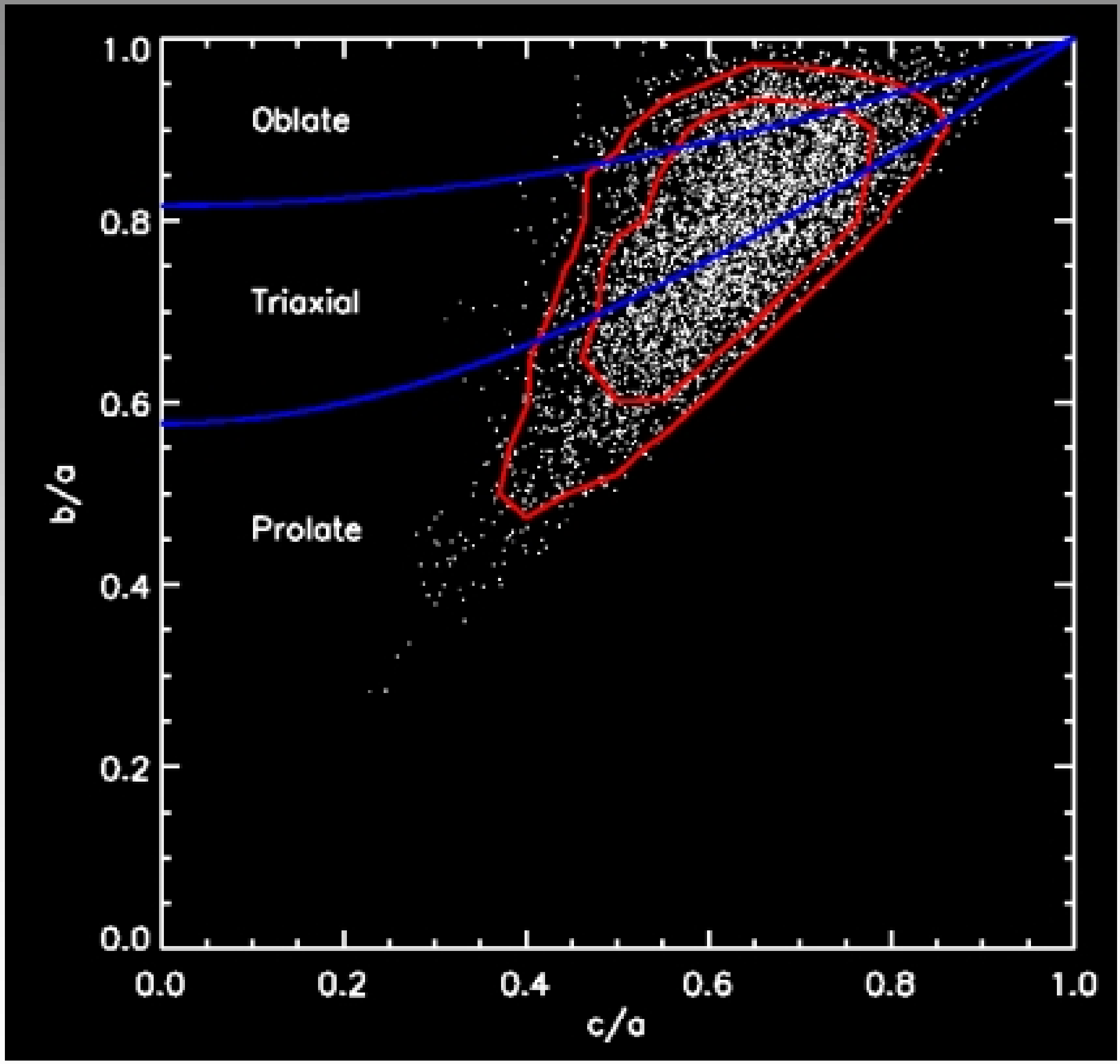


Zero-point of Tully-Fisher relation

⇒ c≤10

Eke, Navarro & Steinmetz 2001

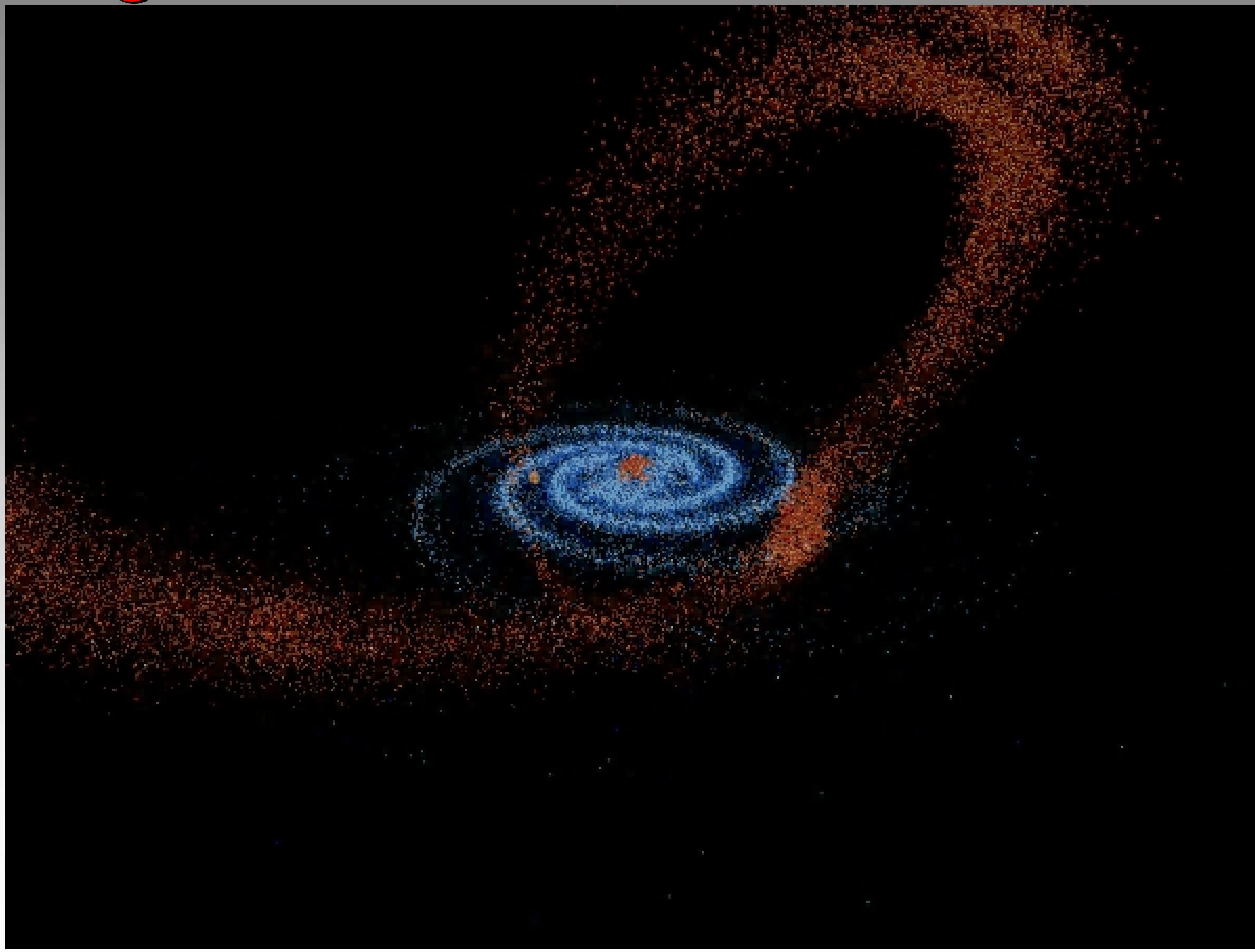
Shapes of Dark Matter Halos



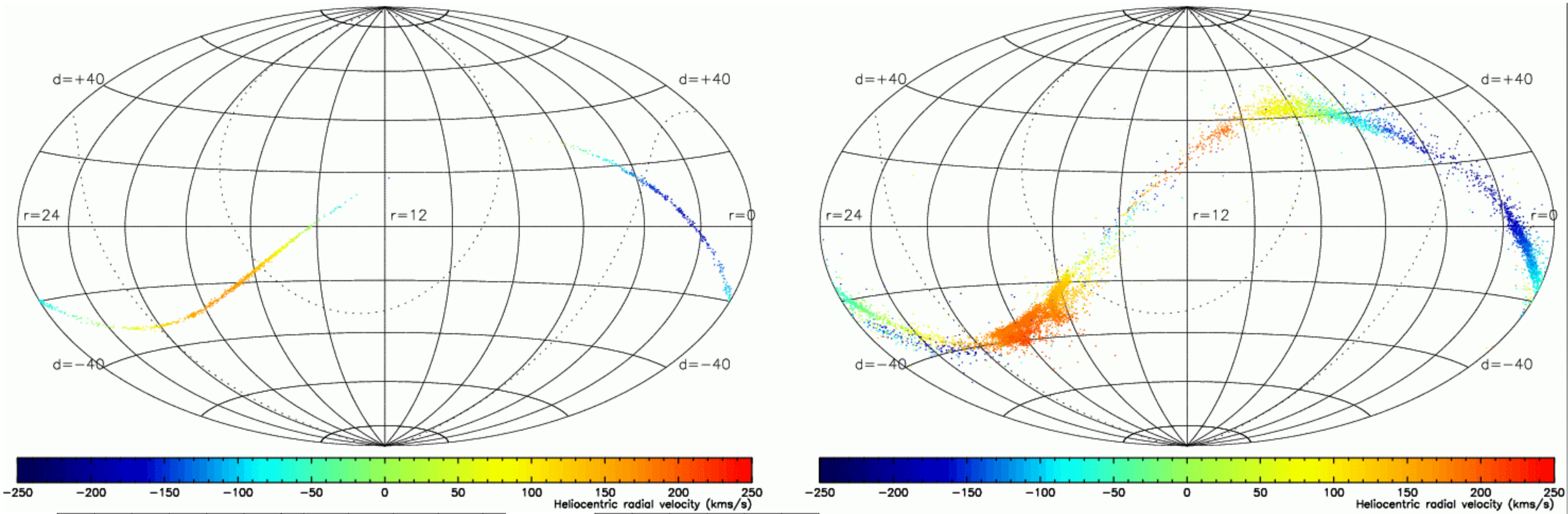
- Mostly prolate or triaxial

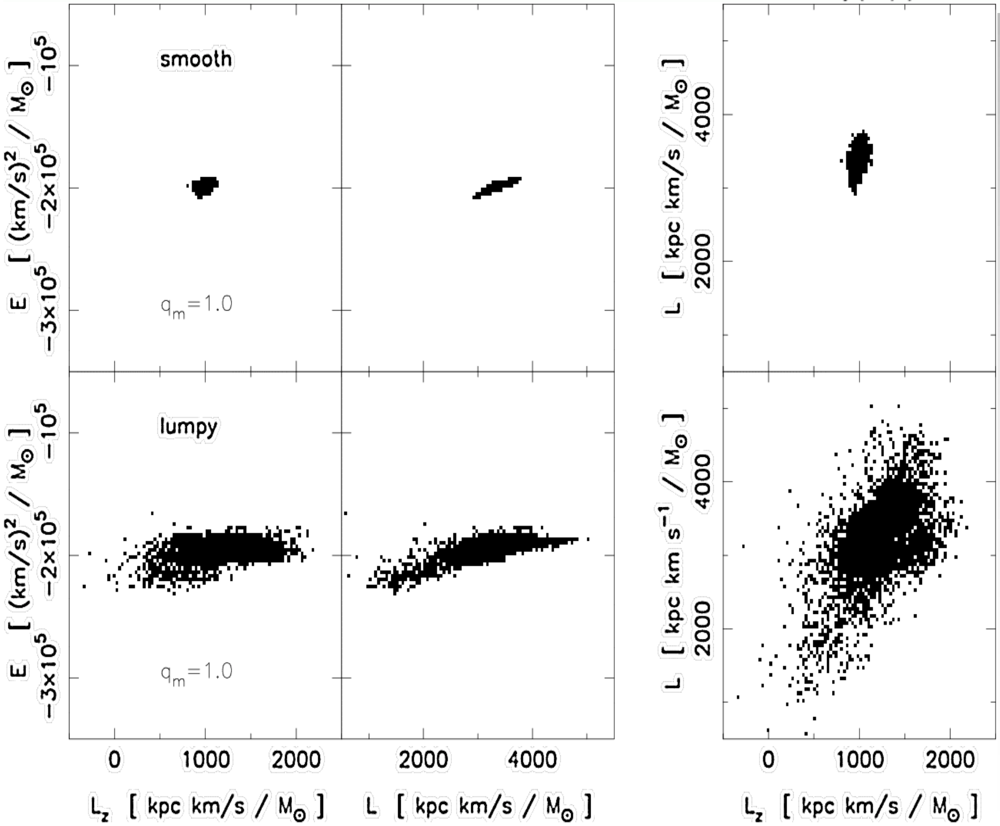
Bailin & Steinmetz 2004

Sagittarius Dwarf



Majewski et al. 2003





Sag Dwarf stream puts tight limits on the clumpiness of the Galaxy halo

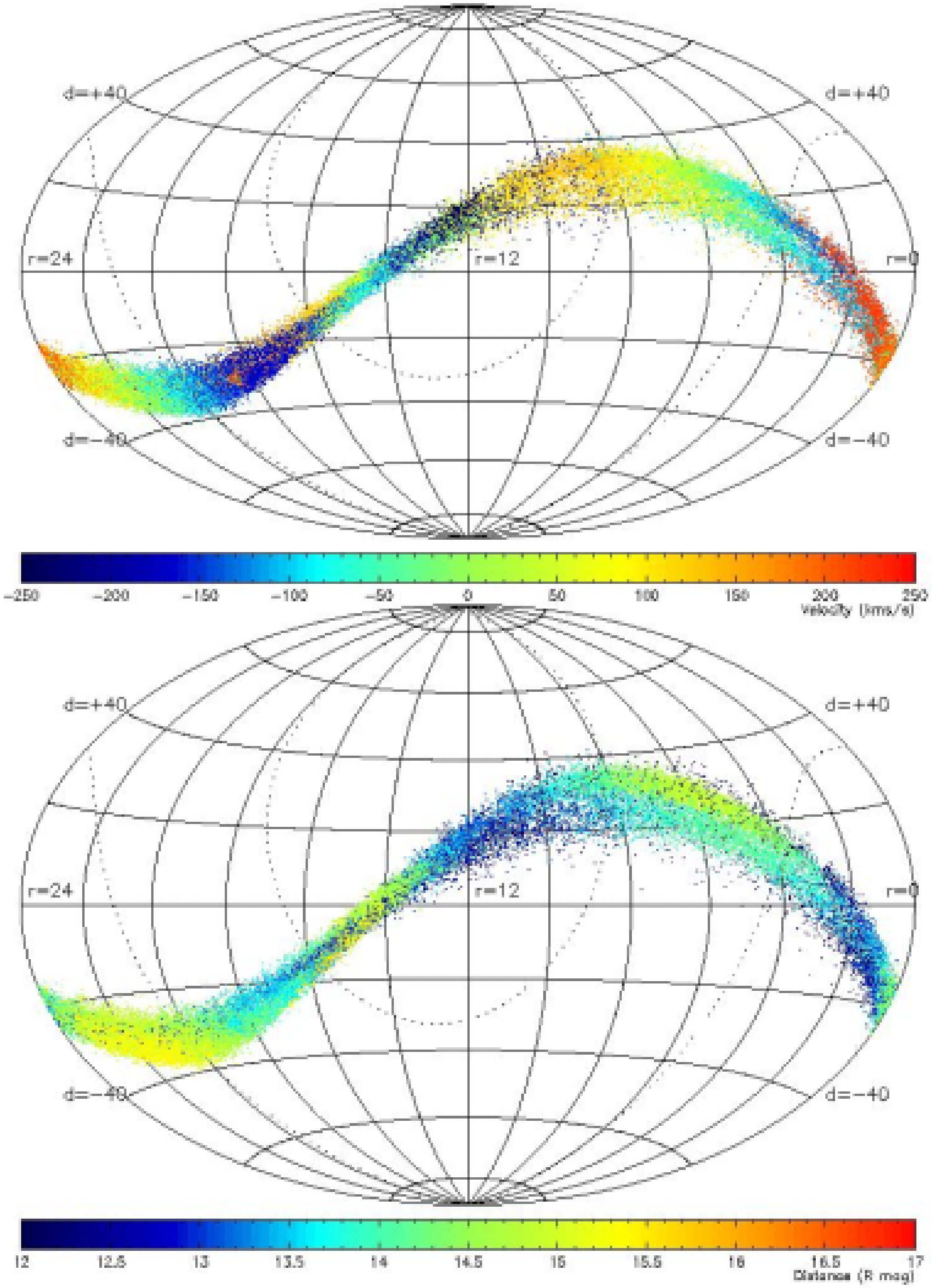
Ibata et al 2002

DESY Theory Workshop 2004
Particle Cosmology

September
29th 2004

VELOCITIES

DISTANCES



$q_m = 1.0$

$v_c = 220$ km/s

Sag Dwarf stream puts tight limits on the flattening of the Galaxy halo

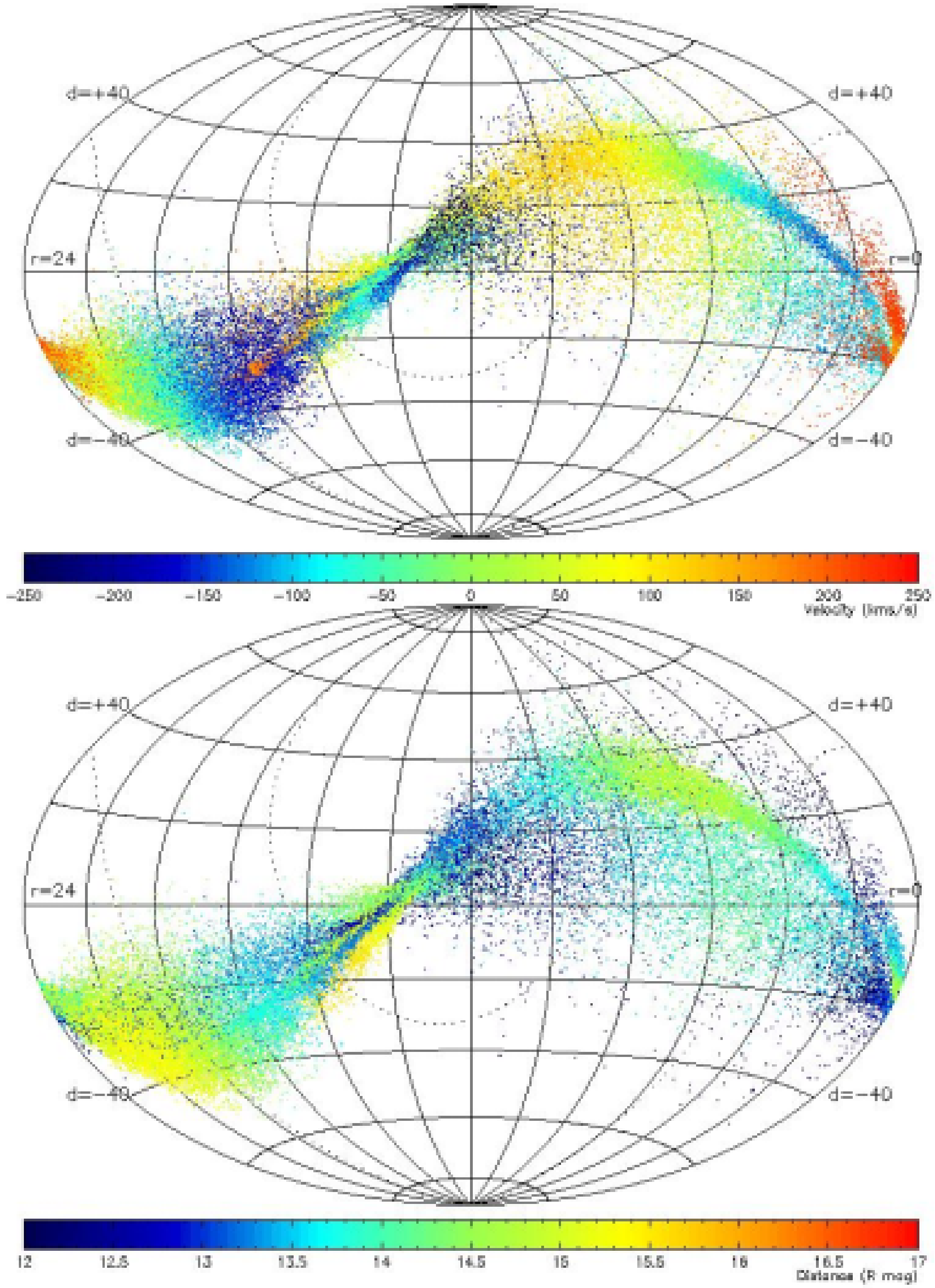
AIP

DESY Theory Workshop 2004
Particle Cosmology

September
29th 2004

VELOCITIES

DISTANCES



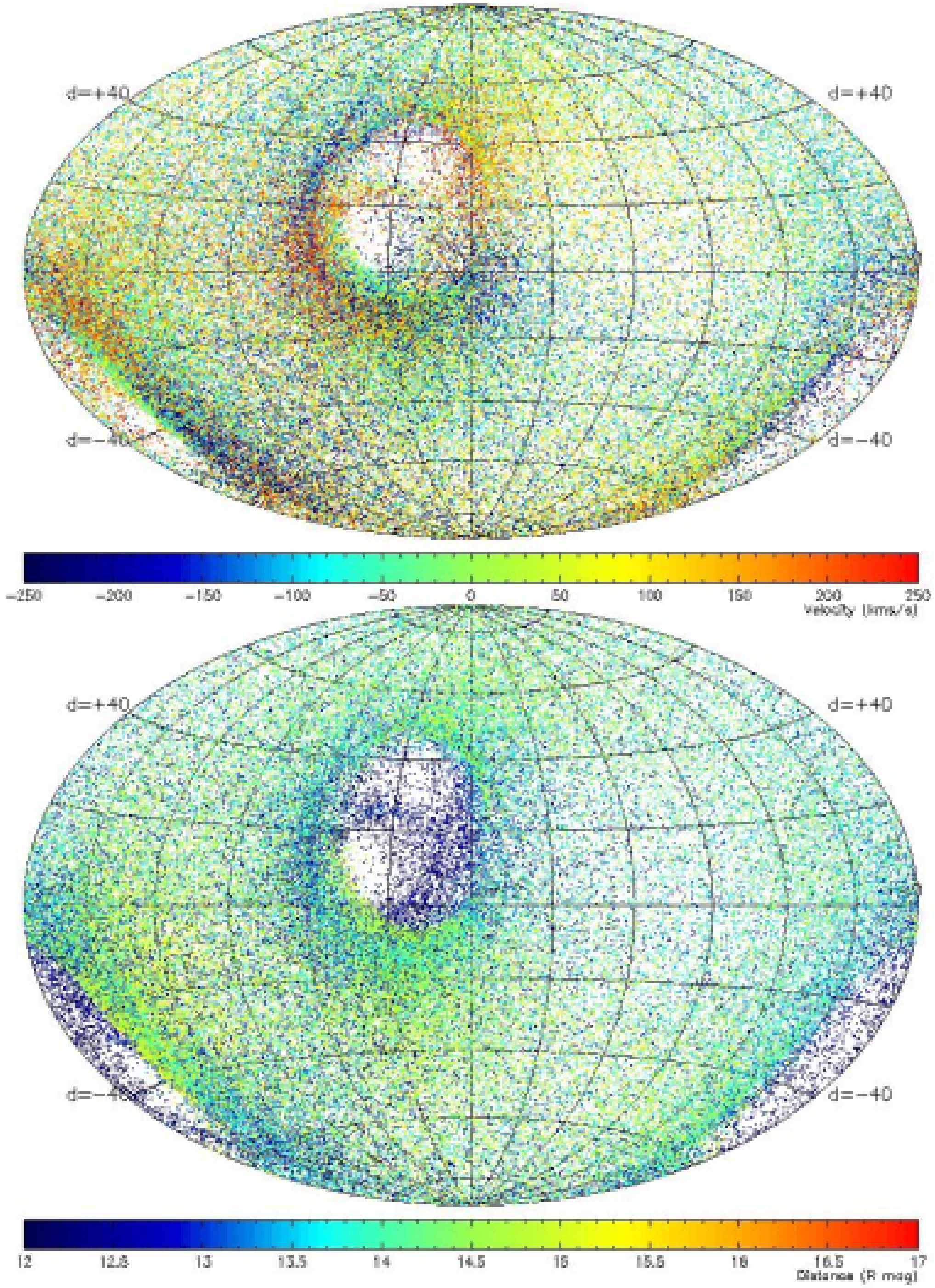
$q_m = 0.9$

$v_c = 220$ km/s

Sag Dwarf stream puts tight limits on the flattening of the Galaxy halo

VELOCITIES

DISTANCES

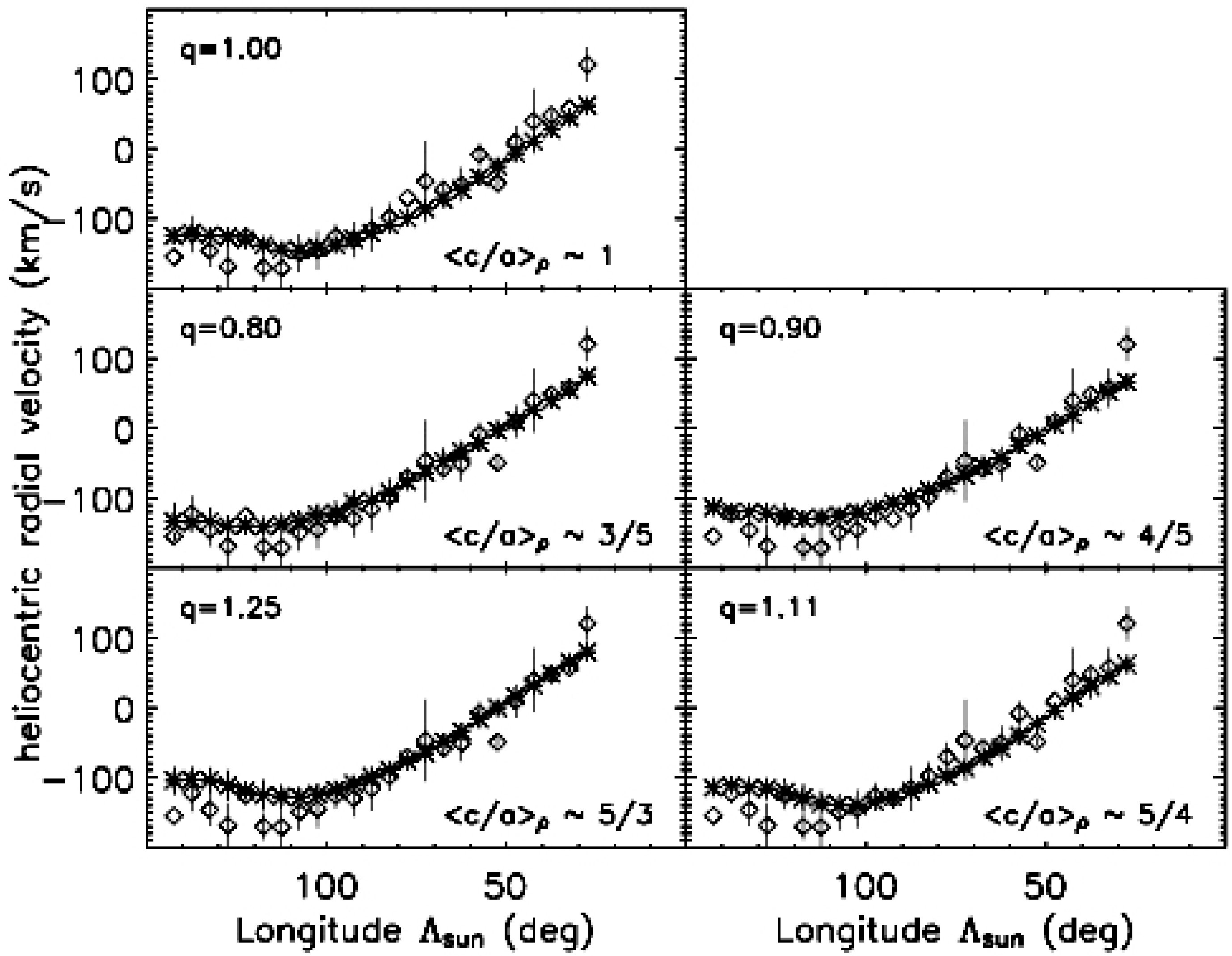


$q_m = 0.7$

$v_c = 220$ km/s

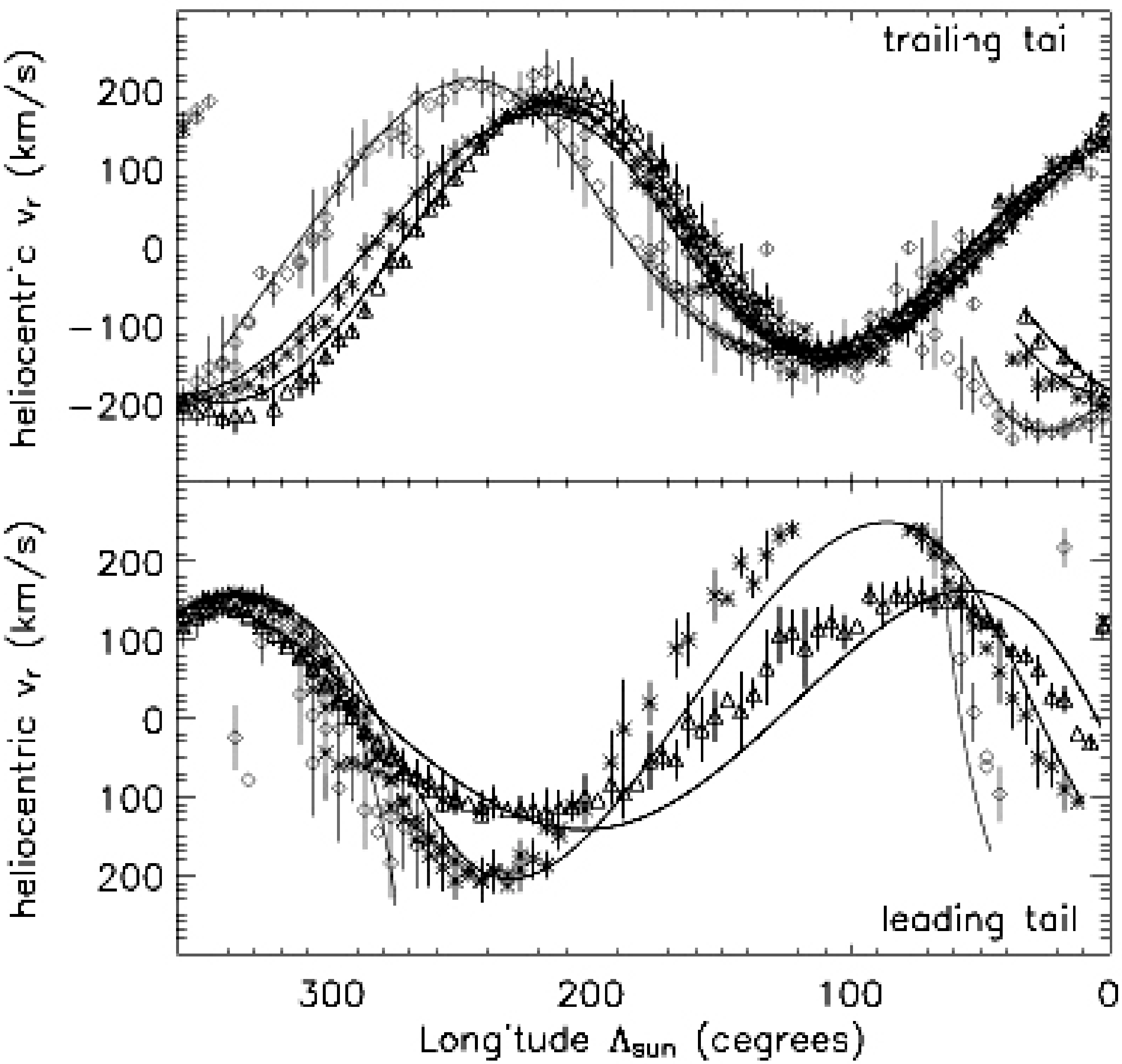
Sag Dwarf stream puts tight limits on the flattening of the Galaxy halo

Stars stripped within last 2 Gyr



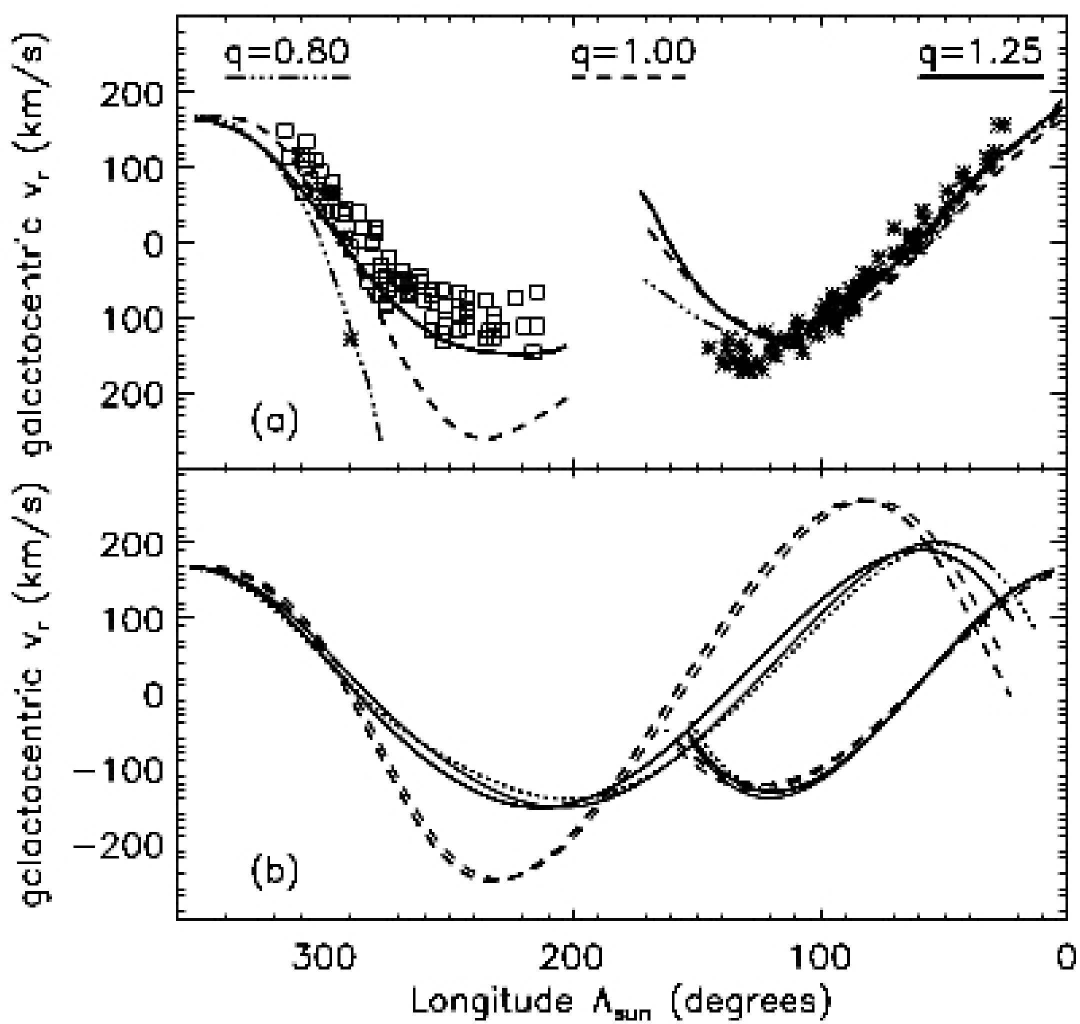
Helmi 2004

Stars stripped within last ~4 Gyr

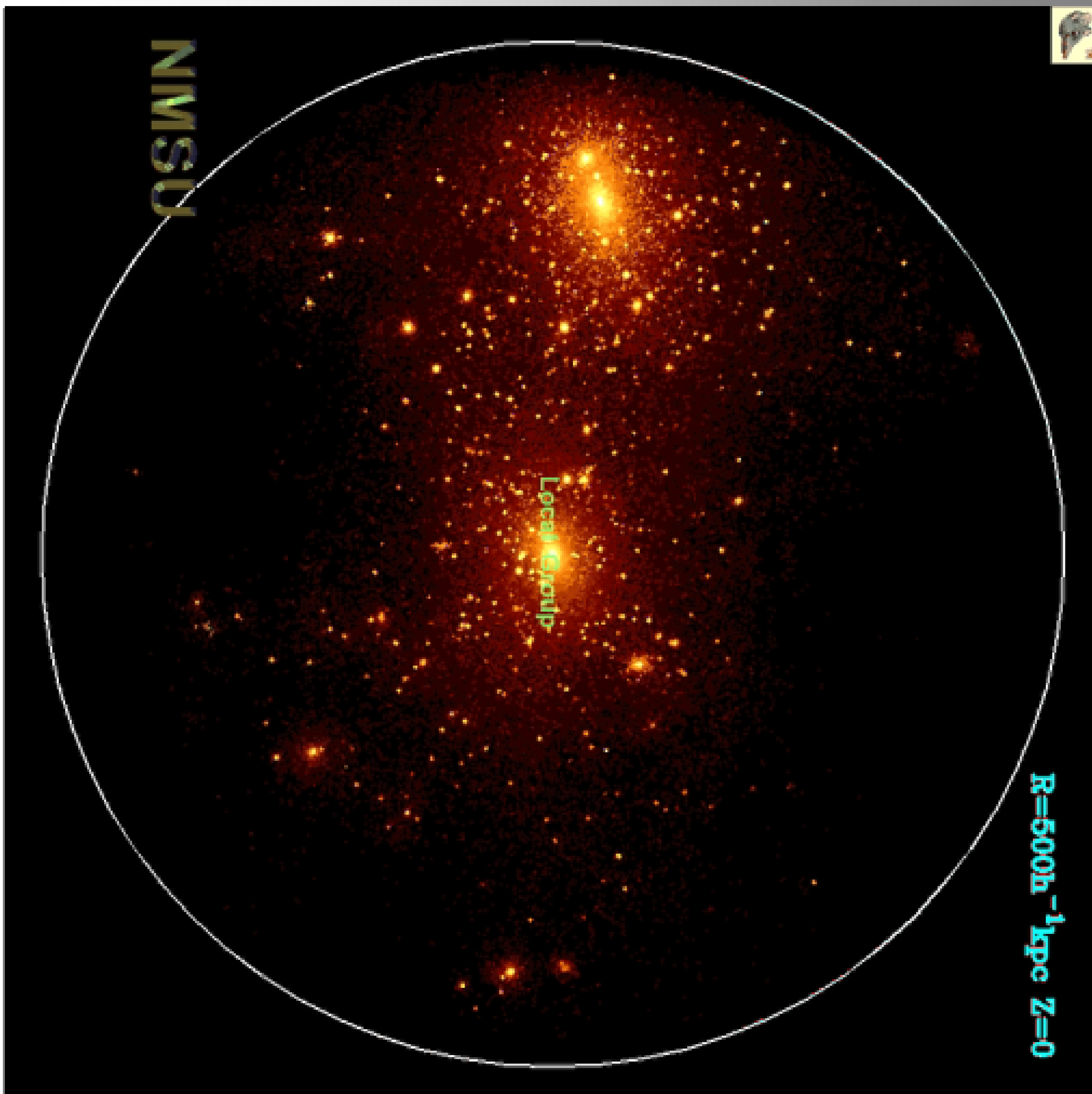


Helmi 2004

Stars stripped within last ~4 Gyr

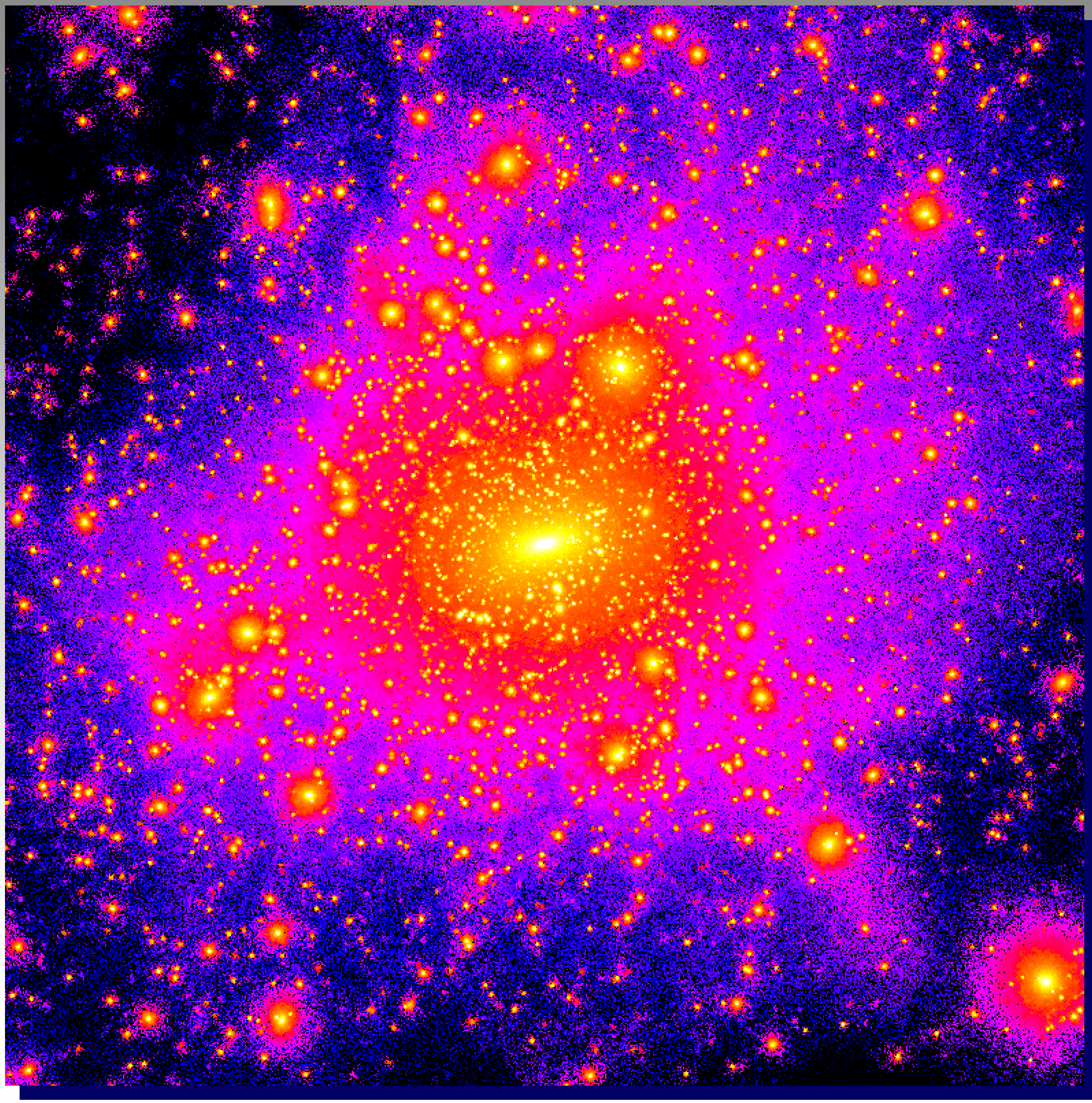


Helmi 2004



Klypin et al
2001

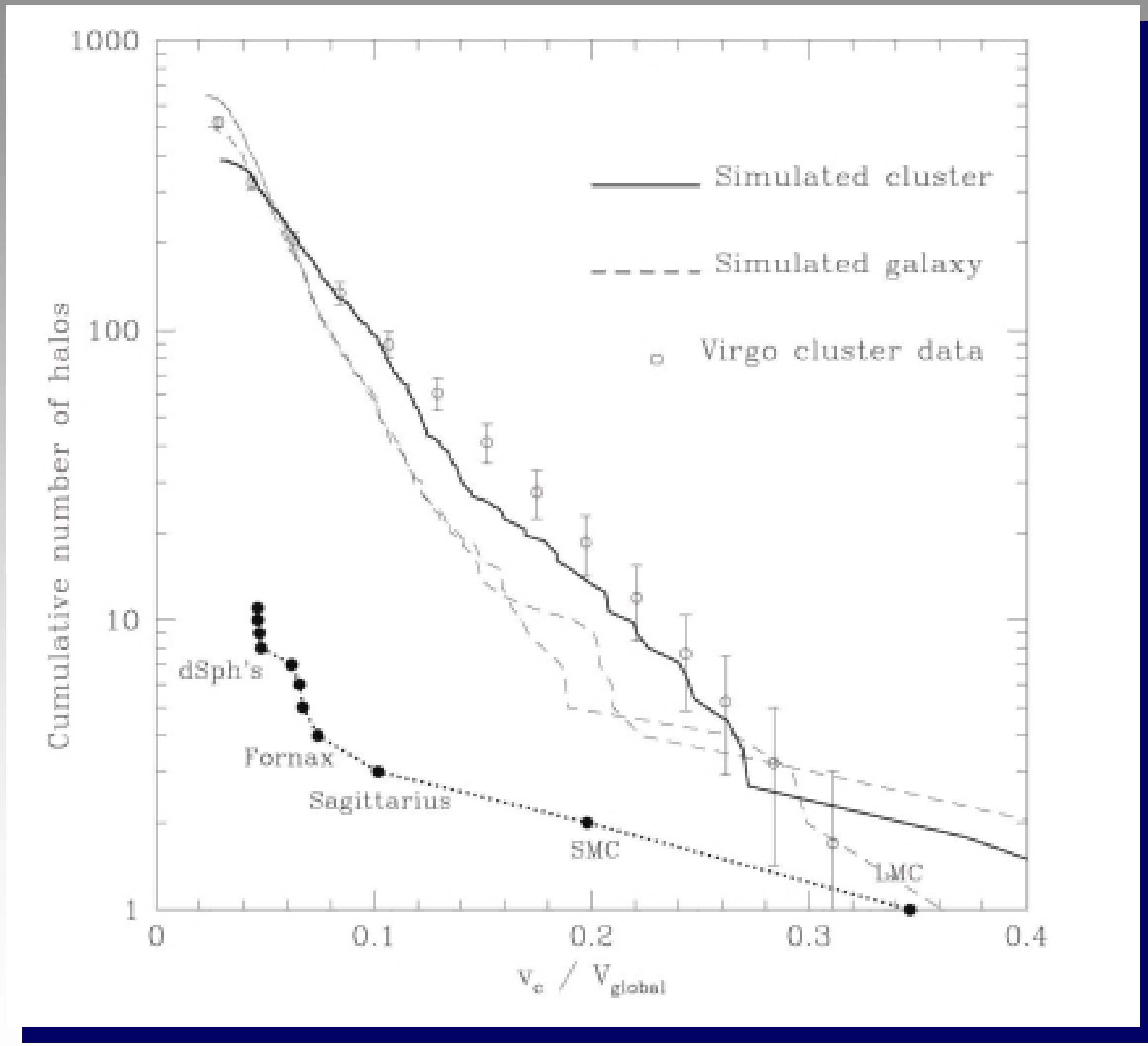
The halo of a ΛCDM galaxy halo



Navarro et al 2001

Substructure and the abundance of Milky Way satellites

cumulative number



circular velocity

Moore et al 1999
Klypin et al 1999

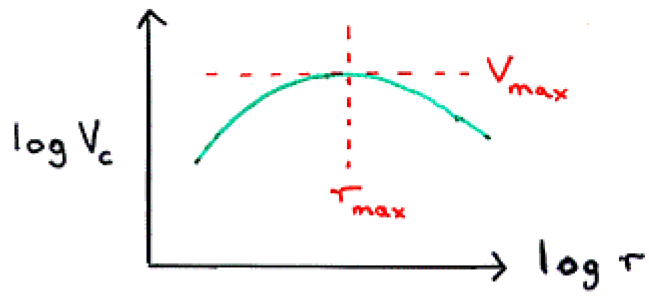
AIP

DESY Theory Workshop 2004
Particle Cosmology

September
29th 2004

Dwarf Spheroidal Halos

	σ (km/s)	r_h (pc)
Sculptor	6.6	150
Carina	6.8	290
Sextans	6.6	470
Leo II	6.7	225



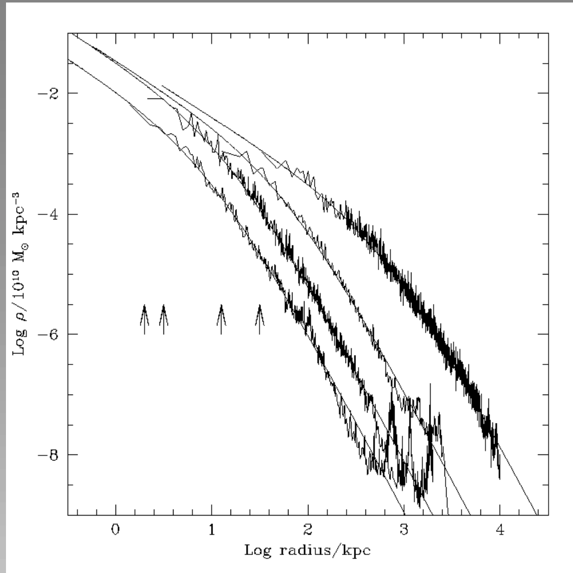
$$V_c^2 = \frac{G M(r)}{r}$$

$$\sigma^2 = \frac{1}{3}\frac{1}{M_*}\int V_c^2(r)\frac{dM_*}{dr}dr \approx \frac{1}{3}V_c^2(r_h)$$

$$\rightarrow \quad \sigma = \frac{1}{\sqrt{3}} f\left(\frac{r_h}{r_{max}}\right) V_{max}$$

For ΛCDM simulations $r_{max} \simeq 5\,\mathrm{kpc}\,\frac{V_{max}}{20\,\mathrm{km/s}}$

For NFW shape: $\sigma = 6.5$ · $r_h = 300 \rightarrow V_{max} = 22$ km/s

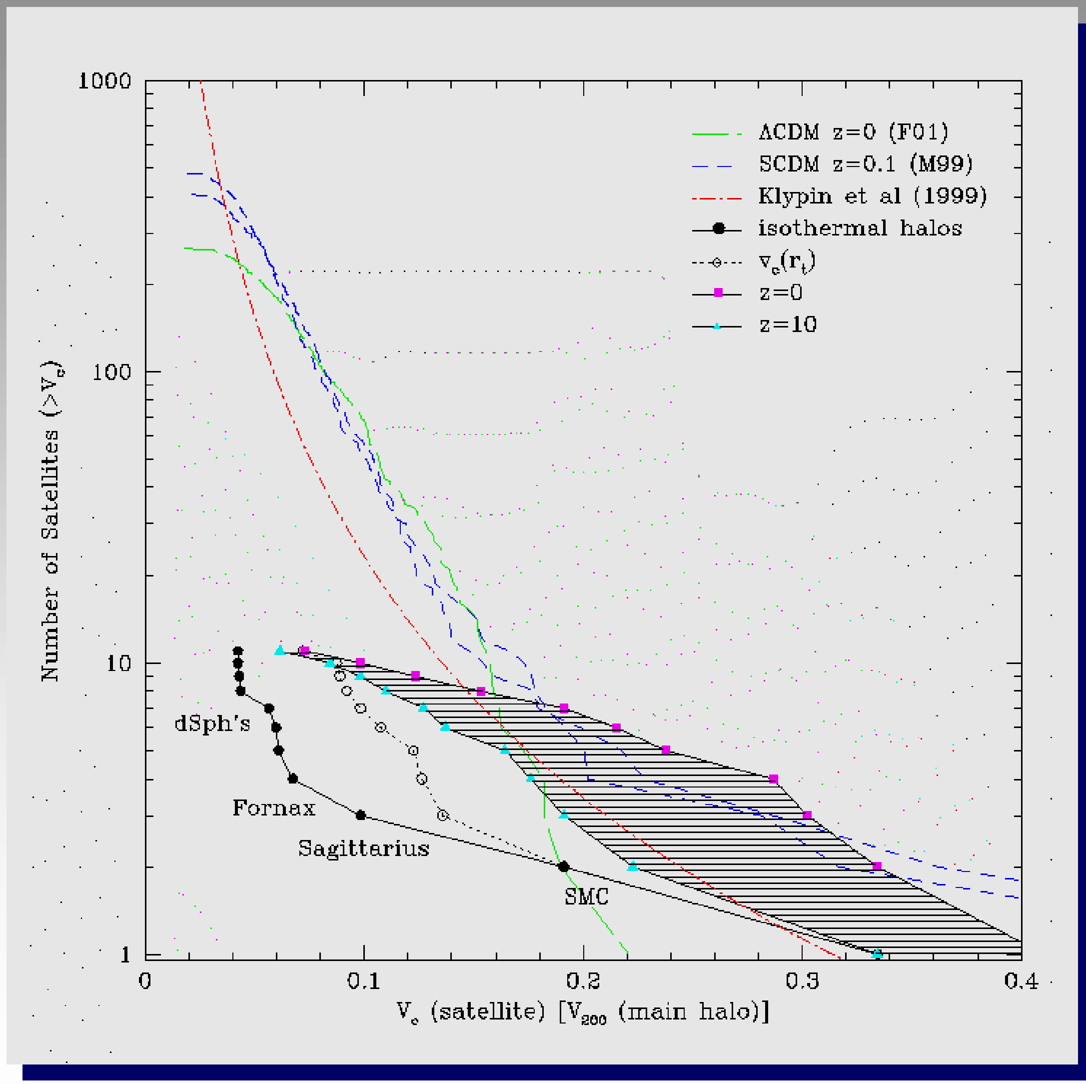


Dark Halos are shallower than isothermal (logarithmic slope >-2) near the center.

S.D.M. White 2000

Substructure and the abundance of Milky Way satellites

cumulative number



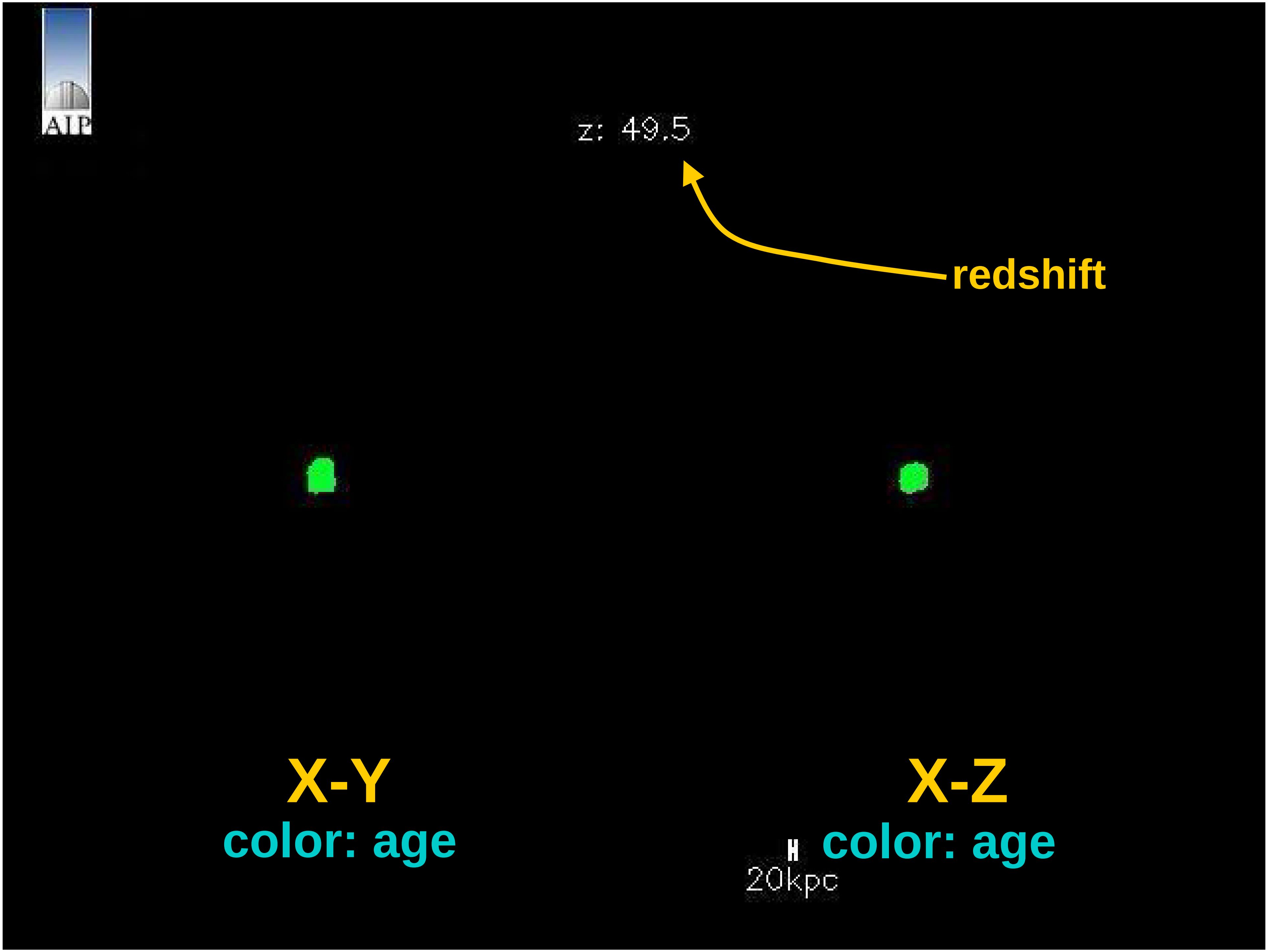
circular velocity

Once the structure of the halos is taken into account, there is good agreement between the number of massive substructure halos and the number of Milky Way satellites.

Hayashi et al 2002

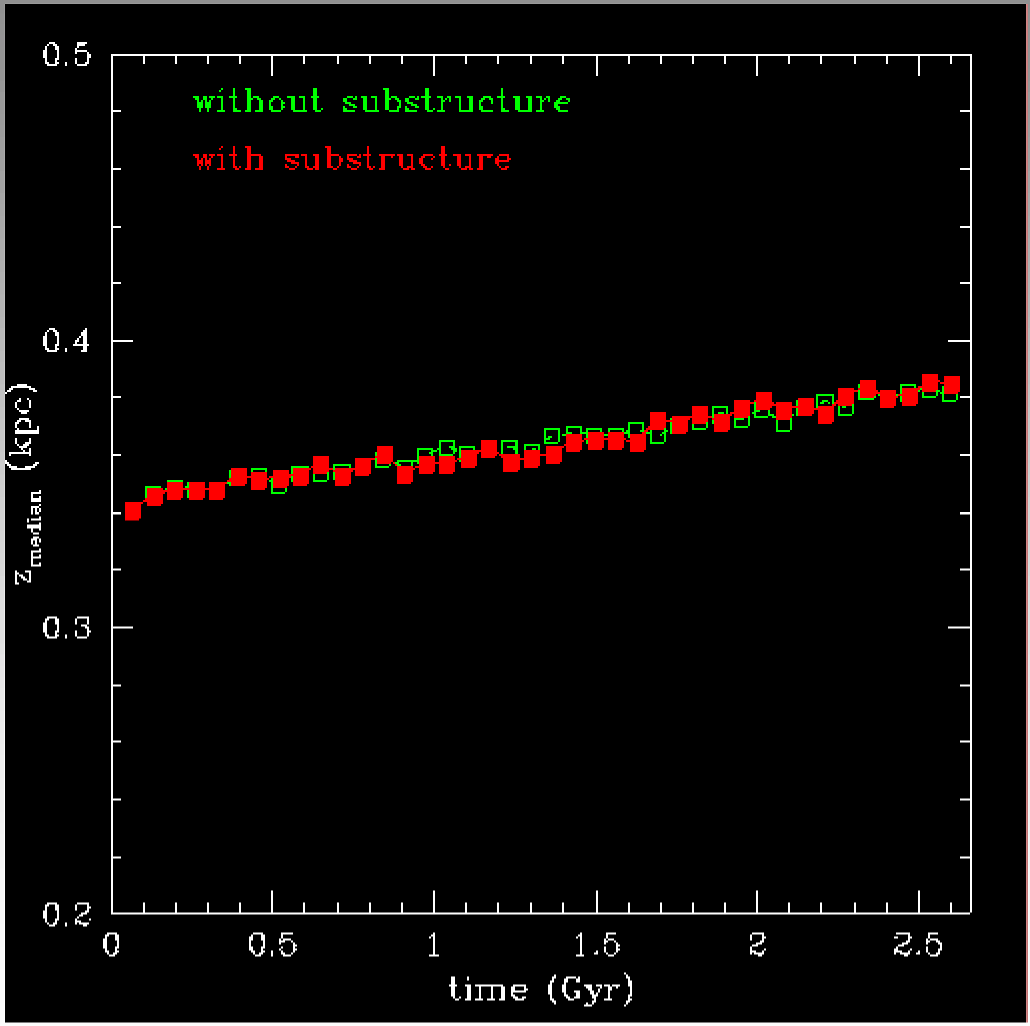
DESY Theory Workshop 2004
Particle Cosmology

September 29th 2004


z: 49.5
redshift
X-Y
color: age
X-Z
color: age
20kpc

Heating of a Milky Way-like stellar disk by substructure

Stellar disk thickness



Time in Gyrs

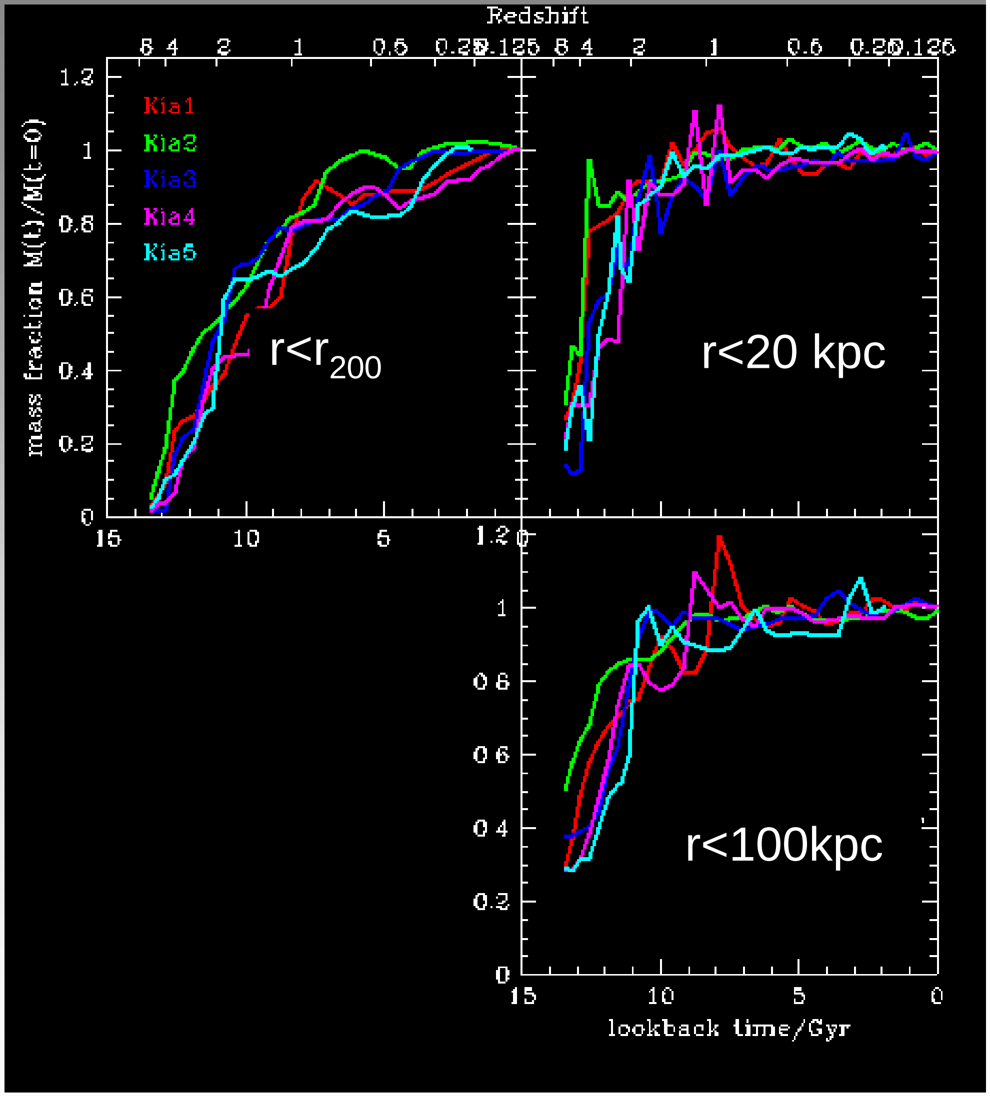
Green curve: without substructure
Red curve: with substructure

Substructure halos seem to contribute little to the thickening of the disk!

Font & Navarro 2001

Dark mass accretion history

- Similar temporal evolution of the dark matter component
- ~50% of the mass inside r_{200} assembled by z~2
- Mass inside 20 and 100 kpc ~ constant in the last 10 Gyrs



DESY Theory Workshop 2004
Particle Cosmology

September 29th 2004

Conclusions

- Small scale structures can be used to further test cosmological models
- Test on scales that have not been used to design and calibrate the cosmological model
  - density profiles of dark matter halos
  - shapes of dark matter halos
  - substructure
  - …
- SSS provides serious challenges for the concordance model that merit further investigations
- Solution: Astronomy or Astrophysics or Particle Physics ?