The Structure and Substructure of Cold Dark Matter Halos

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The Big Question

CDM halos: Main results

- CDM mass profiles are nearly **universal**
  – shape is independent of mass
- CDM density profiles are **cuspy**
  – no evidence for a constant-density central “core”
- CDM halos are **clumpy**
  – Abundant but non-dominant substructure
- CDM halos are **triaxial**
  – Preference for prolate configuration, asphericity increasing toward the center.

CDM halos: Outstanding issues

- **The Structure of the Central Cusp**
  - Power-law divergent slope ($\rho \propto r^{-1}$ or $\rho \propto r^{-1.2}$ or $\rho \propto r^{-1.5}$?)
    - Annihilation signal
  - Disk galaxy rotation curves (cusp vs core vs triaxiality)
- **The Structure of Substructure**
  - Mass profile and abundance of Local Group satellites
  - Annihilation signal from substructures and "boost factors"
  - Abundance, spatial distribution and kinematics
    - lensing flux ratio anomaly, satellite distribution + orbits
- **The Phase-Space Distribution of Dark Matter**
  - Implications for direct dark matter detection experiments
- **The Origin of a Universal Density Profile**
  - Theoretical interest
  - Important to understand baryon-induced transformations of dark halo structure

The Aquarius programme

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

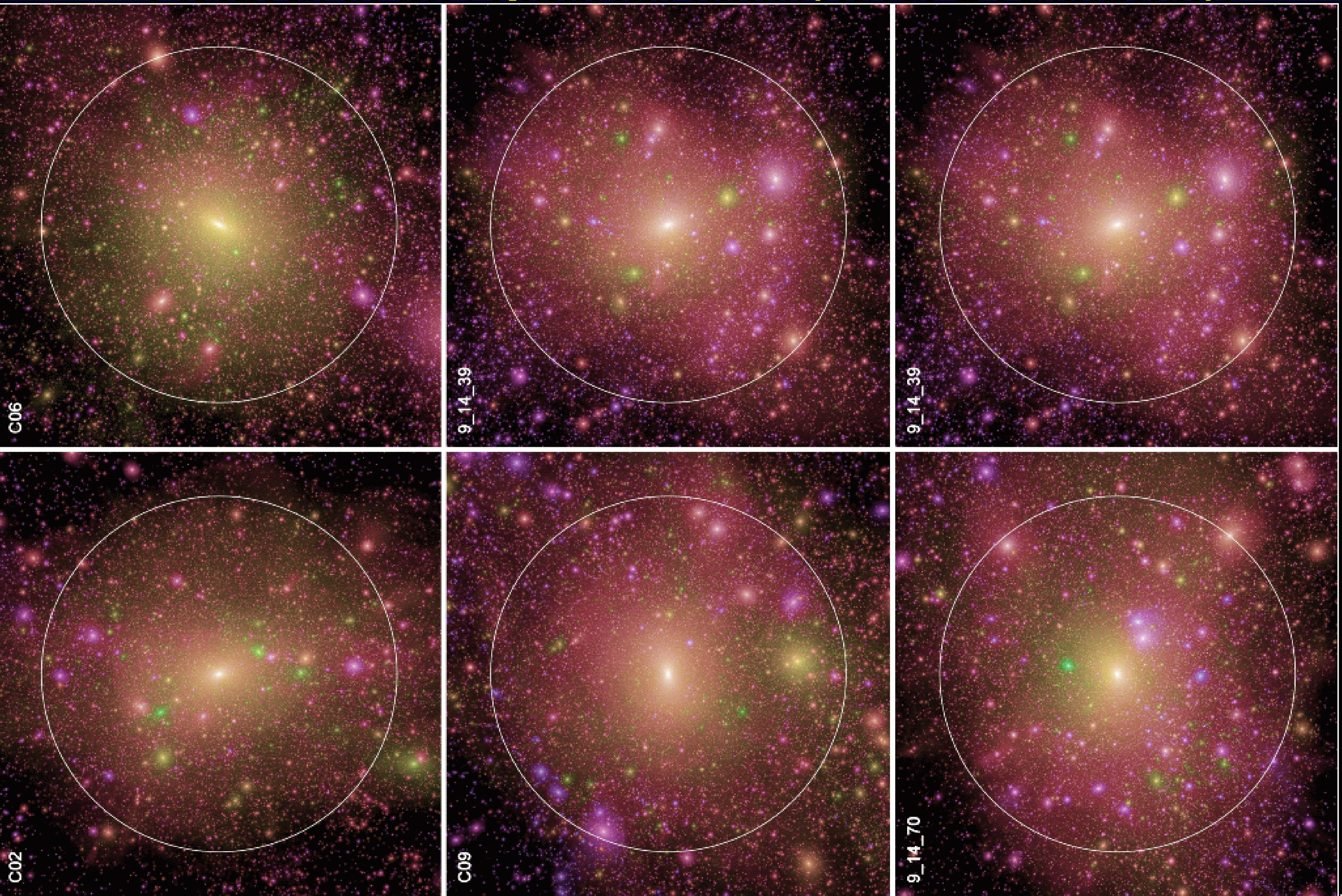
Numerical resolution	Particle number in halo (N_{50})	# of substructures	mass resolution
Aq-A-5	808,479	299	3.14×10^6 M_0
Aq-A-4	6,424,399	1,960	3.92×10^5 M_0
Aq-A-3	51,391,468	13,854	4.91×10^4 M_0
Aq-A-2	184,243,536	45,024	1.37×10^4 M_0
Aq-A-1	1,473,568,512	297,791	1.71×10^3 M_0 (15 pc/h softening)

Springel et al ‘08

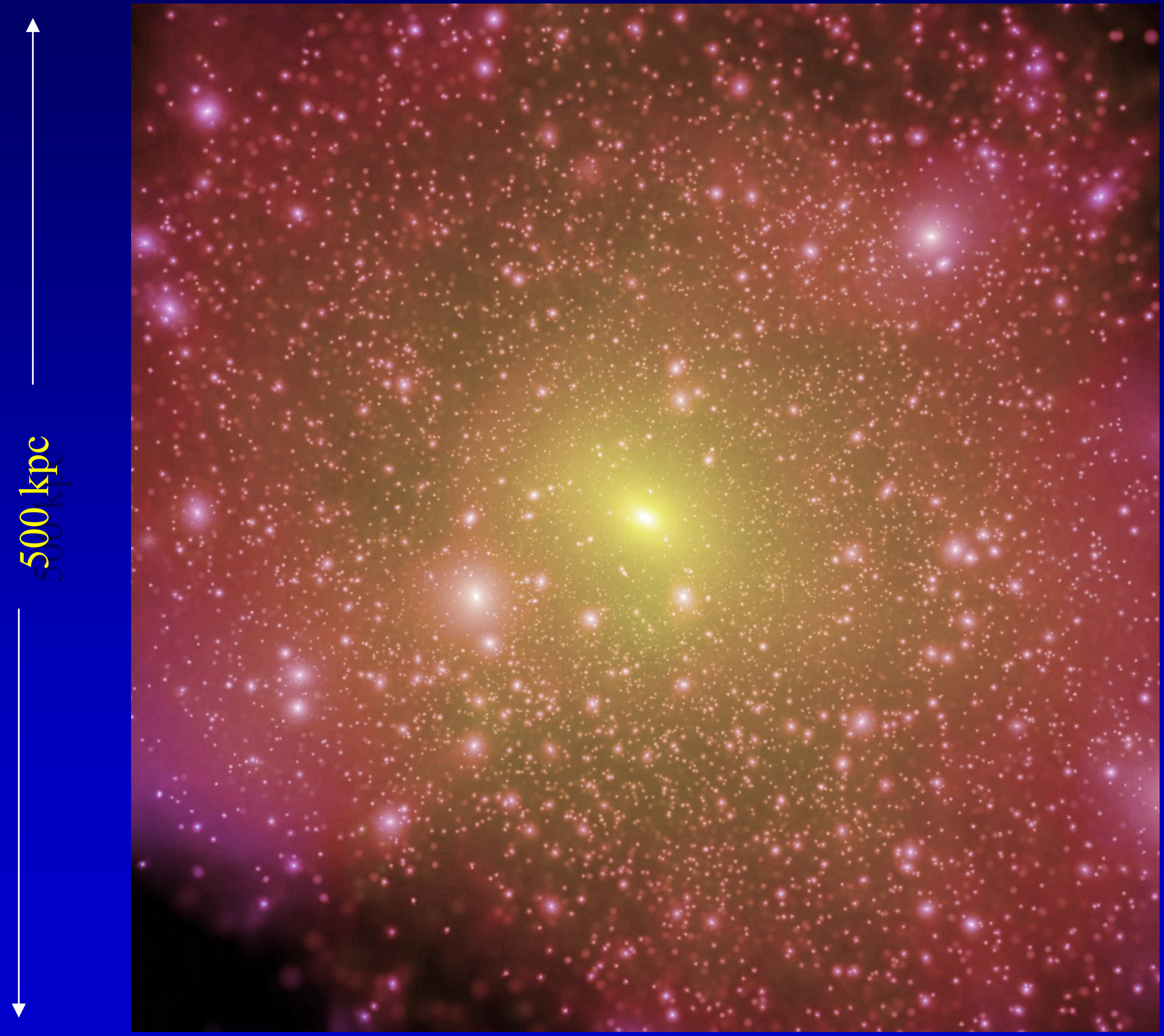
“Via Lactea I simulation”	84,700,000	~10,000	2.18×10^4 M_0
“Via Lactea II simulation”	470,000,000	~100,000	3.92×10^3 M_0

Diemand et al ‘07, 08

Pictures of all Aquarius halos (level-2 resolution)



Aquarius: the Billennium simulation



The Aquarius "Billennium" halo simulation. A dark matter halo with 1 billion particles within the virial radius.

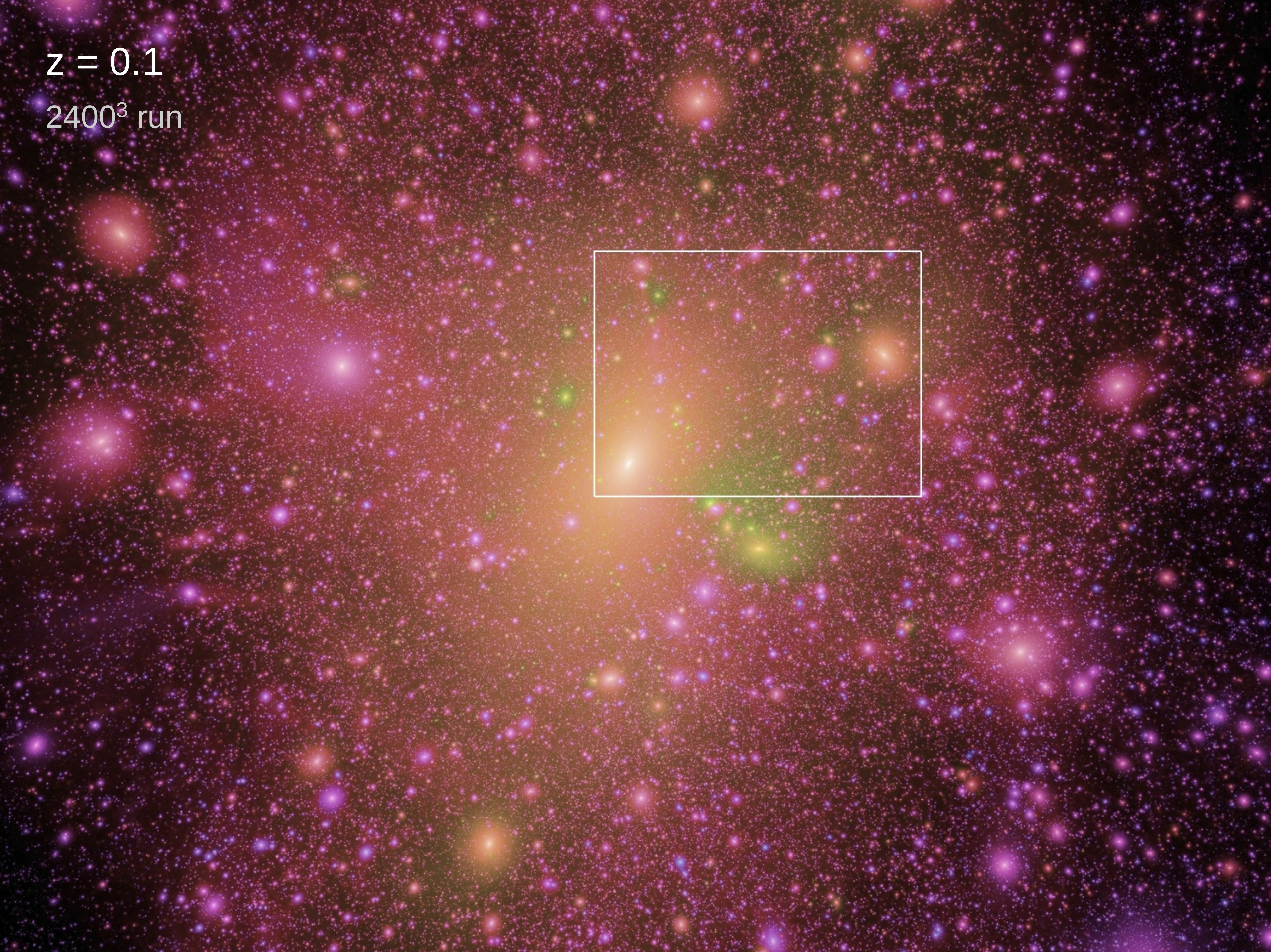
Play Movie


z = 1.5
400³ run


z = 1.5
1200^3 run

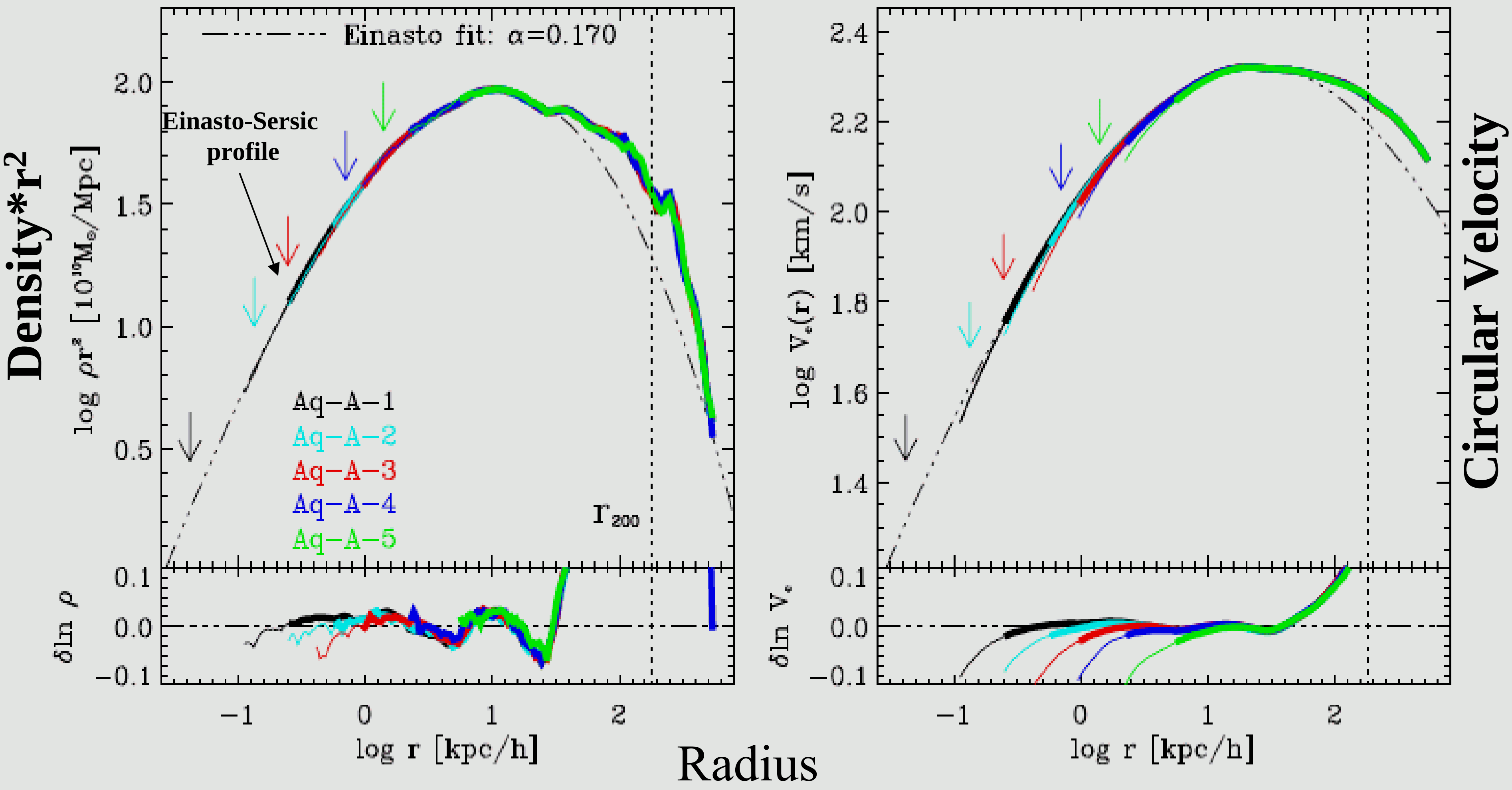
z = 1.5
2400^3 run


z = 0.1
2400³ run


z = 0.1
2400³ run

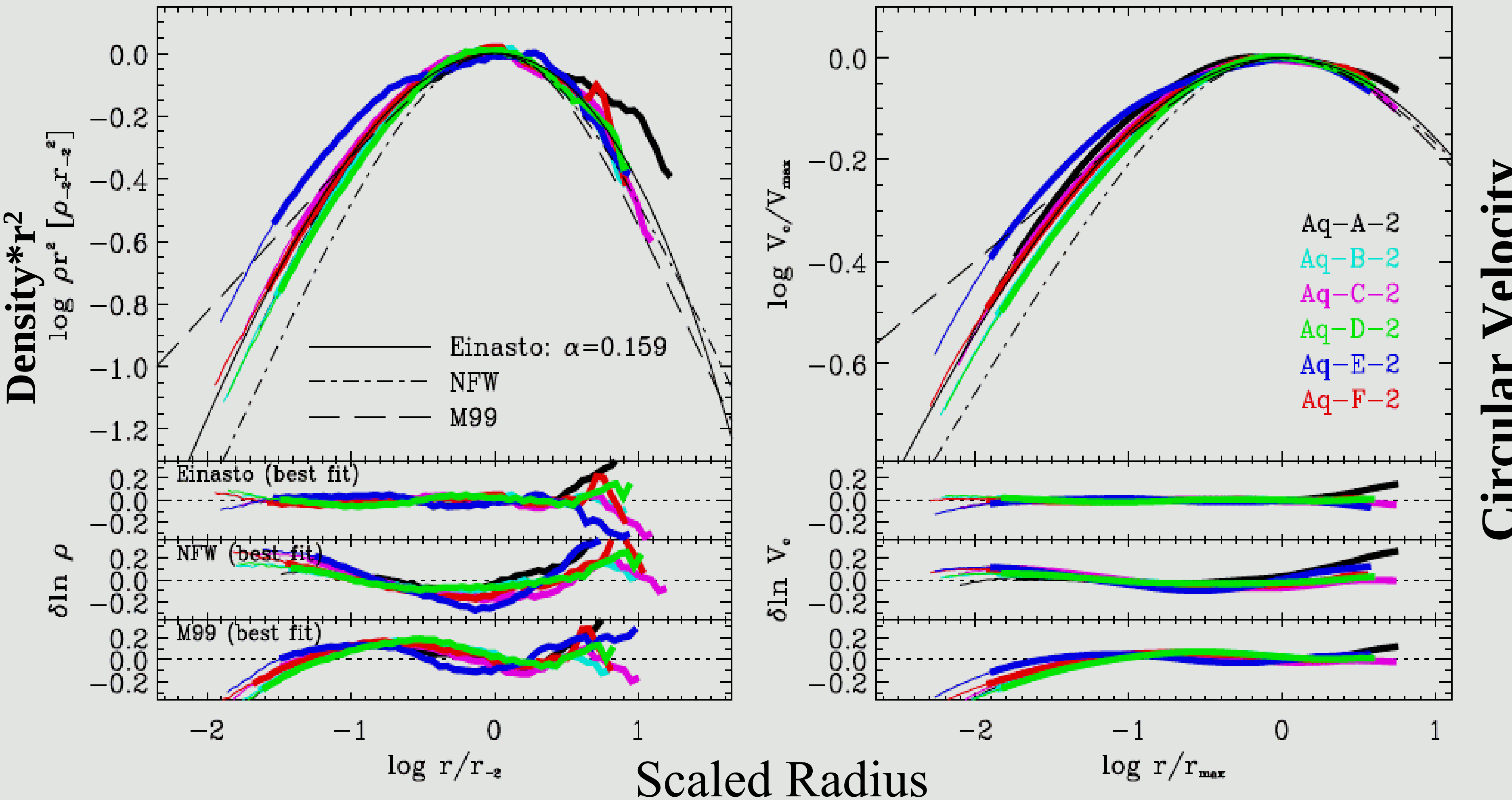
z = 0.1
2400³ run

The Mass Profile: numerical convergence



•Excellent numerical convergence down to radius where the collisional relaxation time approaches the age of the universe

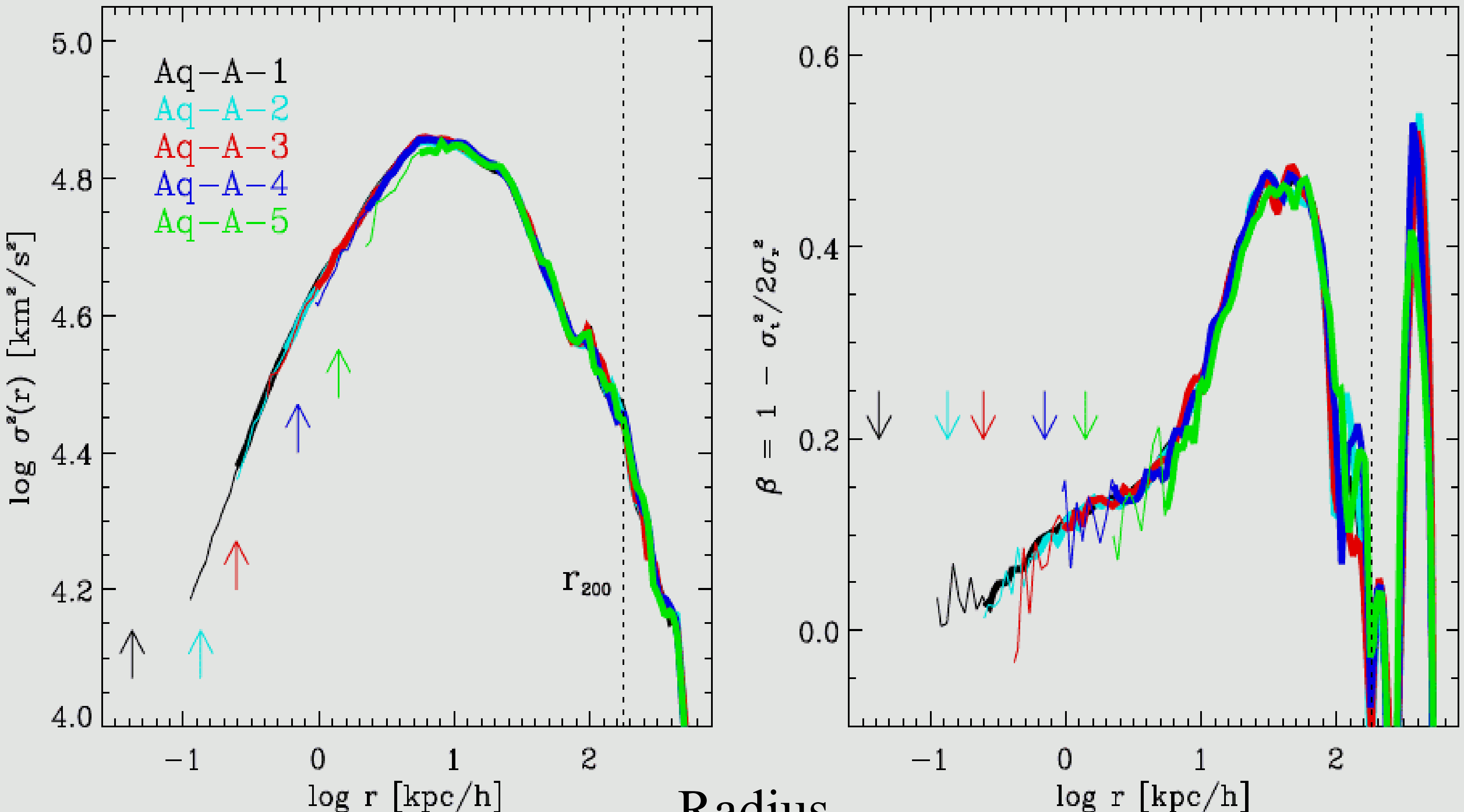
Self-similarity in the mass profile?



•Slight but significant deviations from similarity.

•A “third parameter” is needed in order to describe accurately the mass profiles of CDM halos.

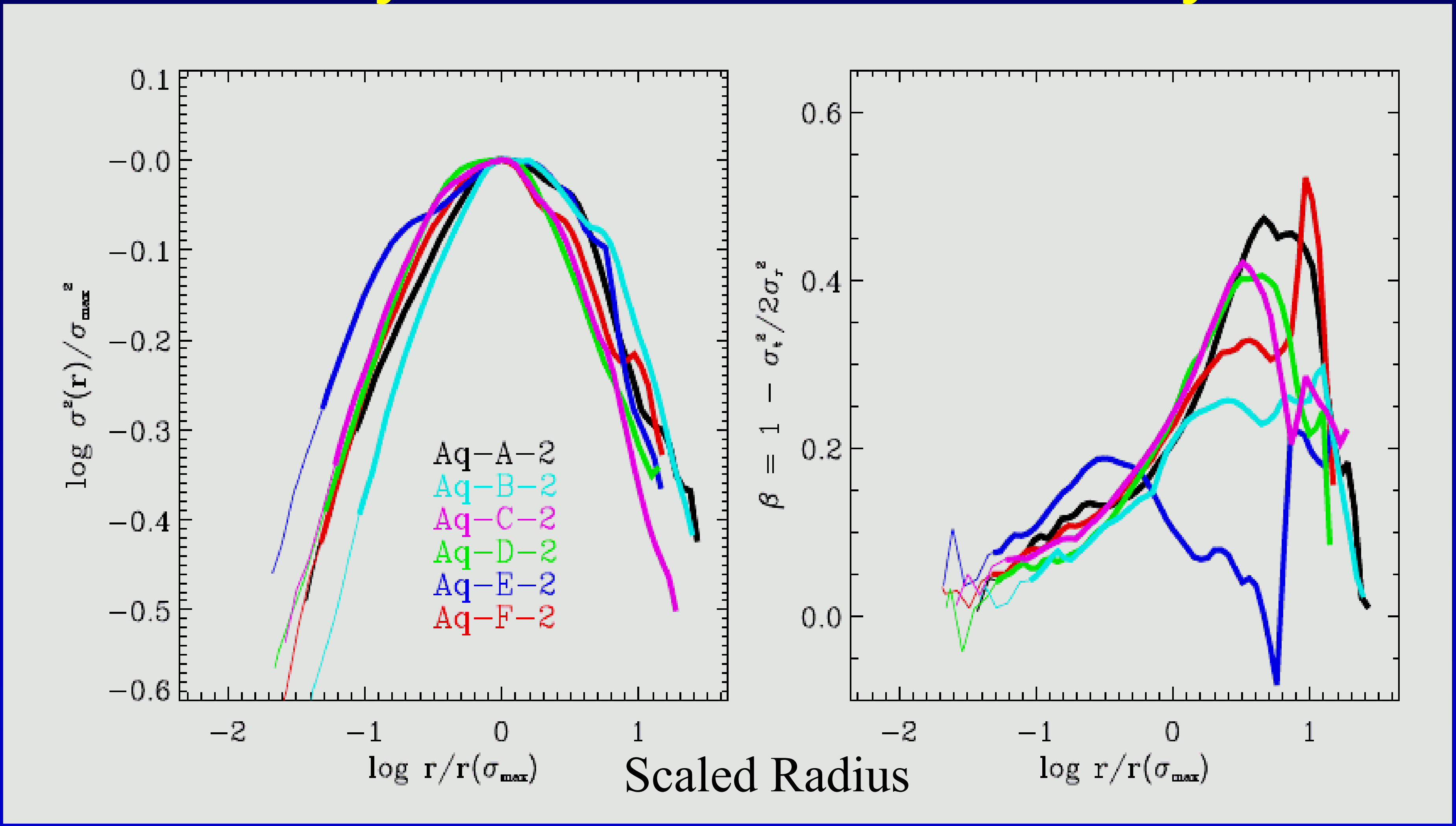
Velocity structure: convergence



Radius

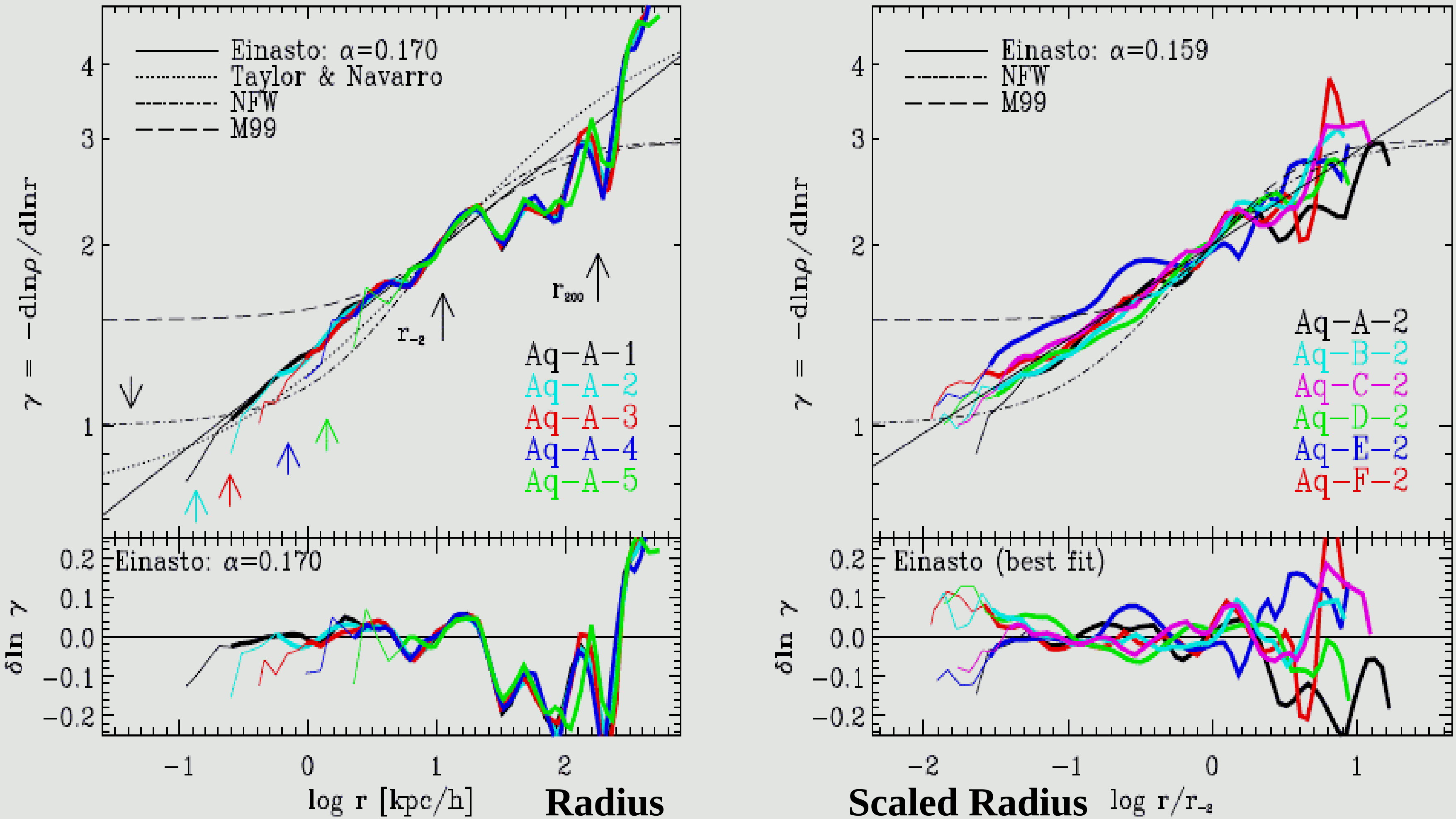
•Excellent numerical convergence down to radius where the collisional relaxation time approaches the age of the universe

Velocity structure: self-similarity?



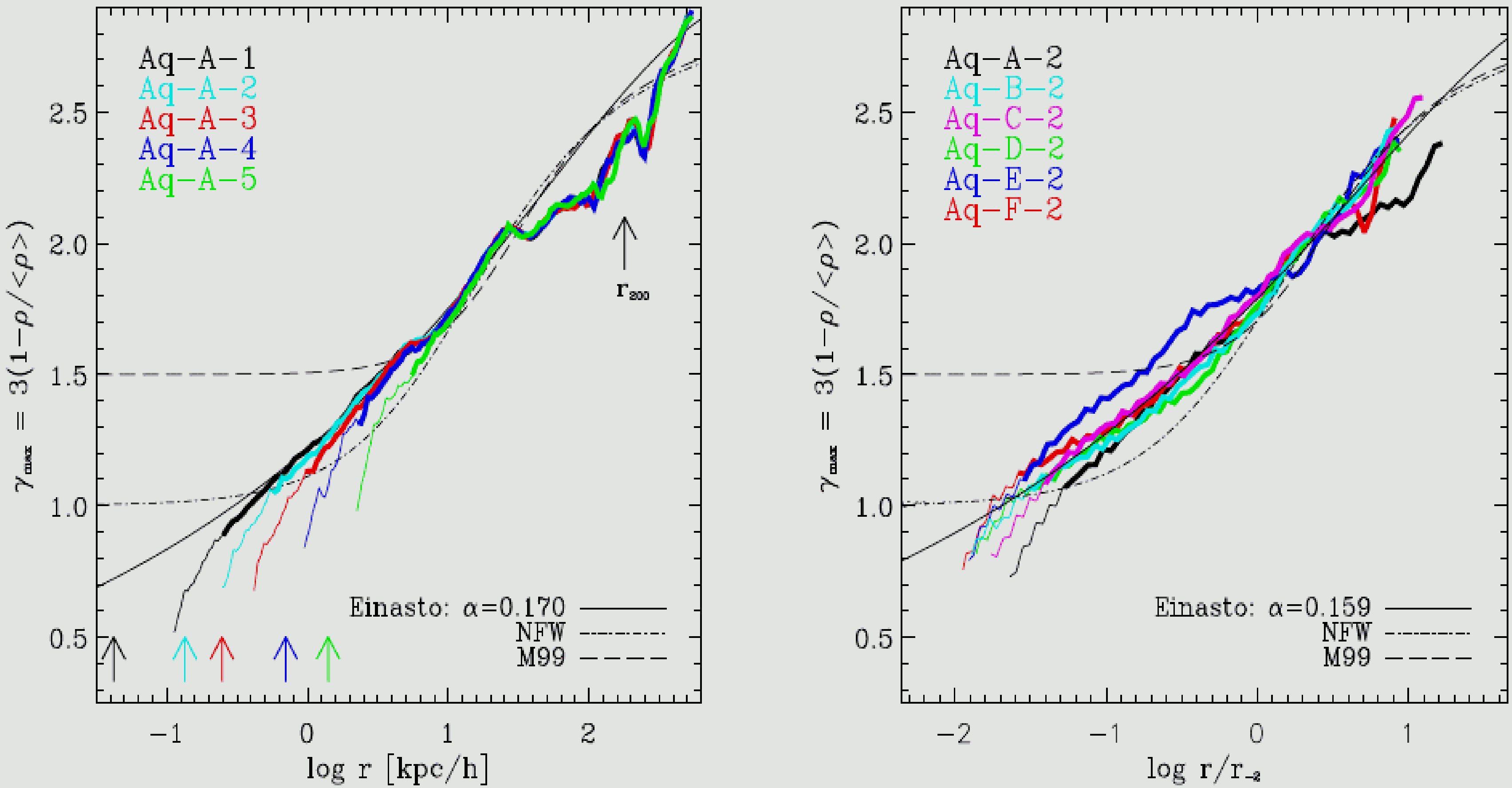
- Slight but significant deviations from similarity.
- Note that deviant systems in mass are also deviant in velocity
- Note similarity in shape between density and velocity dispersion

The Structure of the Cusp



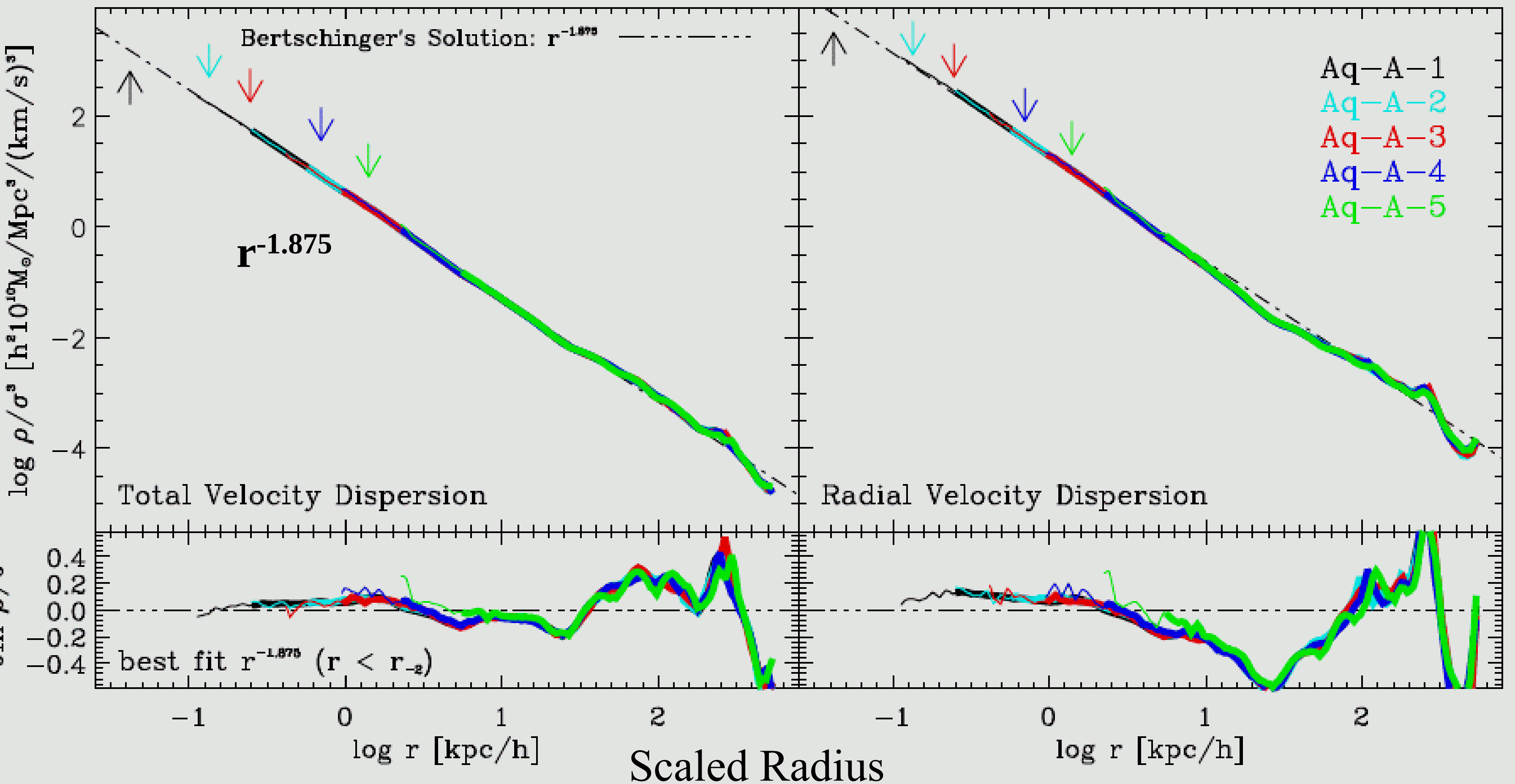
- Logarithmic slope scales like a power-law of radius: the Sersic/Einasto profile
- Innermost profile shallower than r^{-1}

The Cusp: Maximum Asymptotic Slope



•Maximum asymptotic slope of the cusp: shallower than r^{-1}

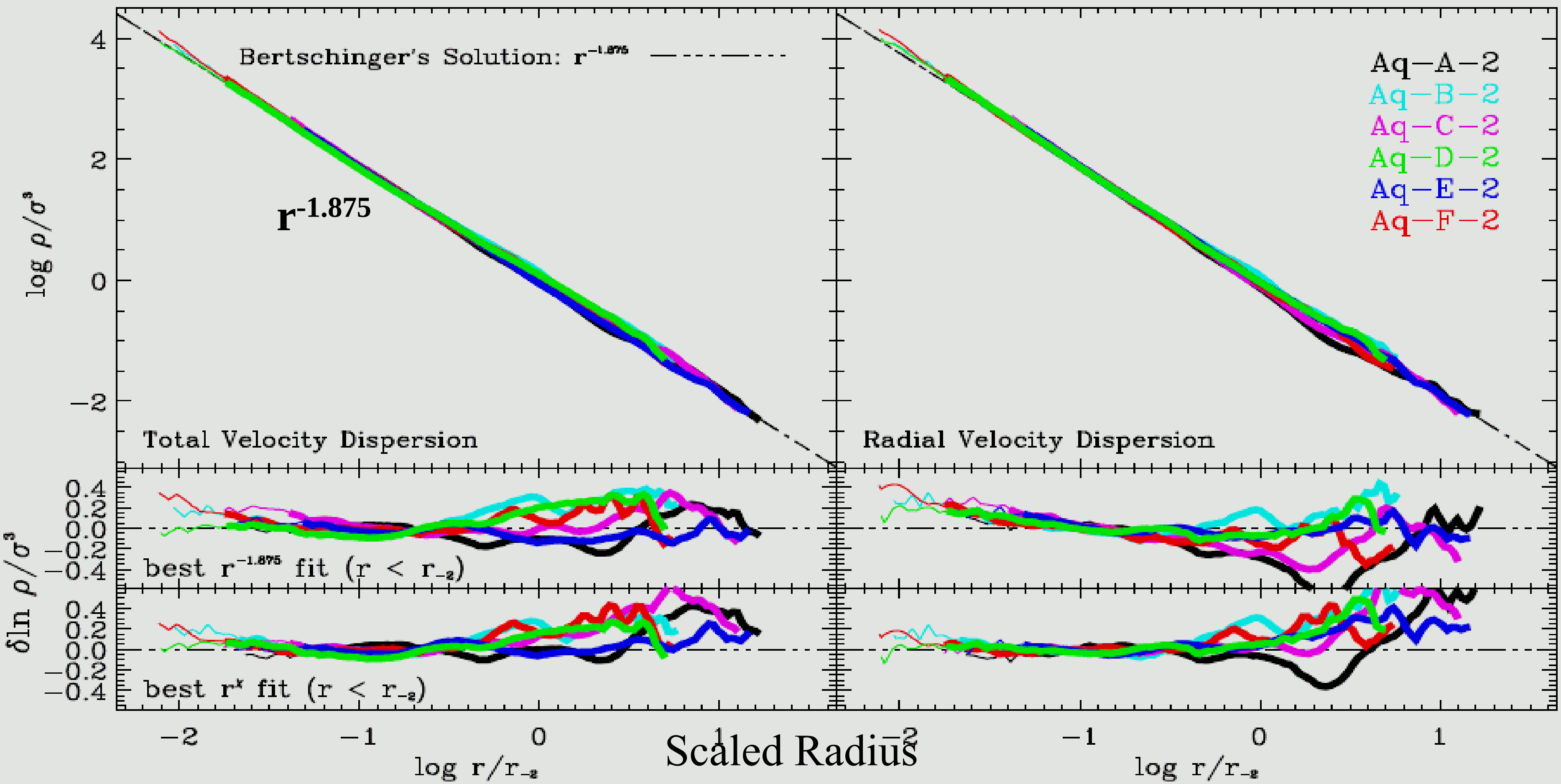
The “Phase-Space Density” Profile



- Remarkably, the “phase-space density”, ρ/σ^3, scales like a power law of radius
- This is the same dependence as in Bertschinger’s secondary infall similarity solution

Taylor & Navarro 2001

The “Phase-Space Density” Profile



- All halos seem to share the same “phase-space density”, ρ/σ^3, structure
- This seems to reflect a fundamental structural property of CDM halos

Summary

- The mass profile of CDM halos:
  - not strictly self-similar, and deviates slightly but significantly from the formula proposed by NFW.
  - It is well approximated by the Einasto profile

$$d\ln\rho/d\ln r \propto r^{\alpha}$$

- The Cusp:
  - $\rho \propto r^{-1.2}$ (or steeper) cusps ruled out,
  - cusp must be shallower than $\rho \propto r^{-1}$

- The "phase-space density":
  - seems to be a fundamental structural property of CDM halos.
  - A simple power law, with the same exponent as the self-similar secondary infall model, approximates well the profiles of all halos,

$$\rho/\sigma^{3} \propto r^{-1.875}$$

The End

"Great PowerPoint, Kevin, but the answer is no."