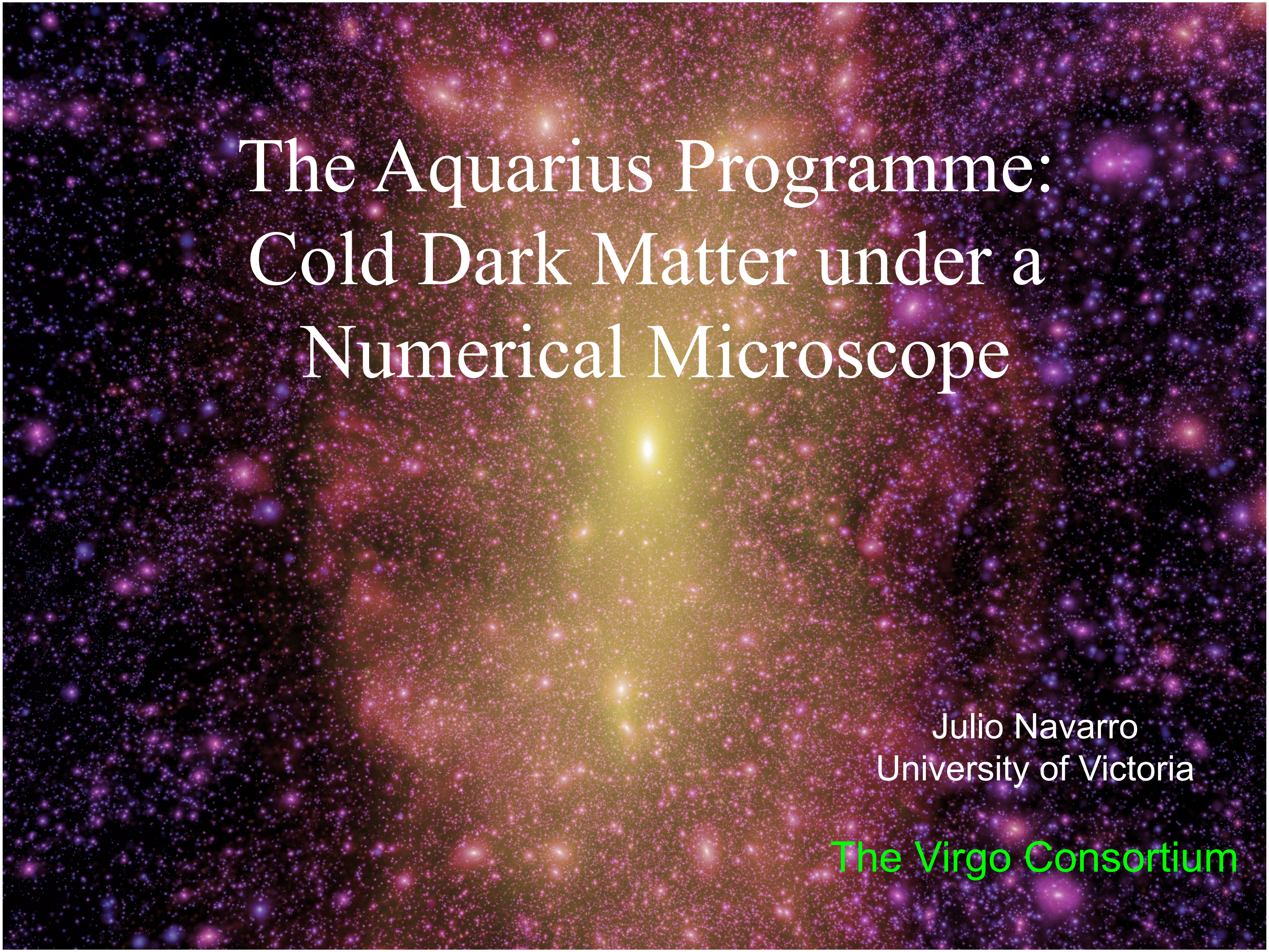
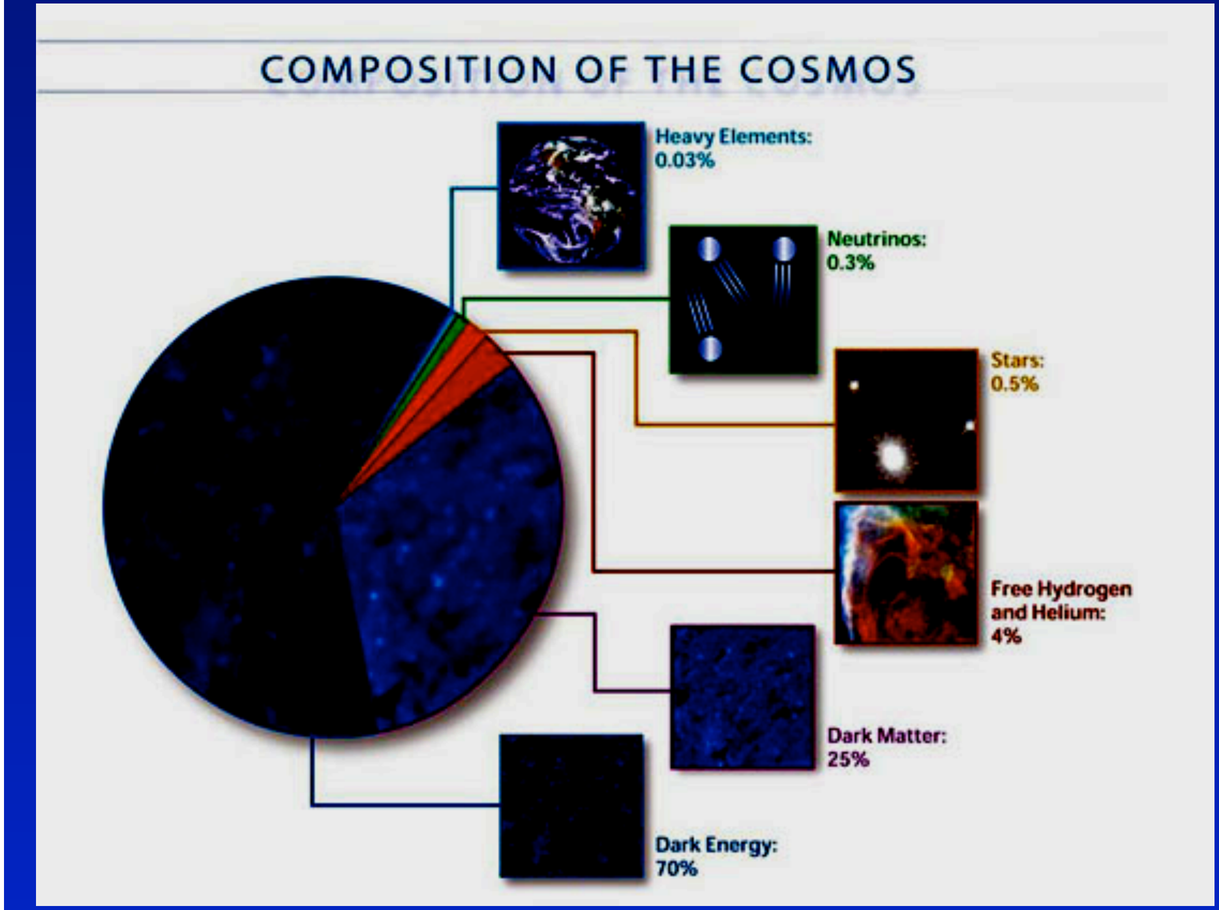


The Aquarius Programme: Cold Dark Matter under a Numerical Microscope

Julio Navarro
University of Victoria

The Virgo Consortium

The Current Paradigm



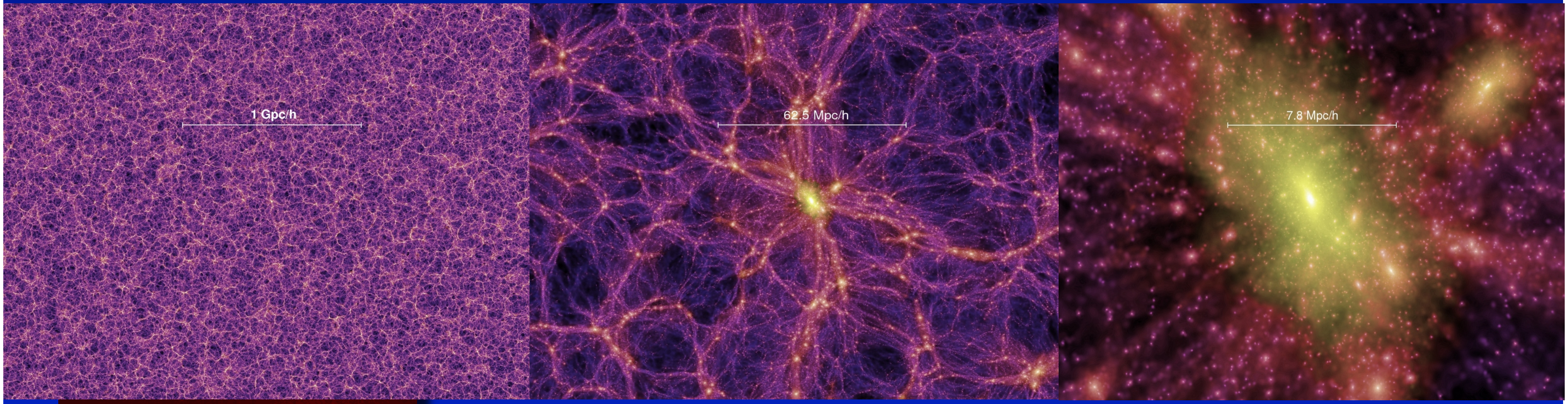
“The Pie of Ignorance”
our current inventory of the matter-energy content of the Universe

Cosmological measurements have challenged the very foundations of our physical understanding of Nature.

- What is the dark matter?
- What is the dark energy?
- What is the eventual fate of the Universe?
- How did galaxies like our own Milky Way form in such Universe?

N-body simulations track the clustering evolution of the dark matter from the Big Bang to the present

Millennium Simulation



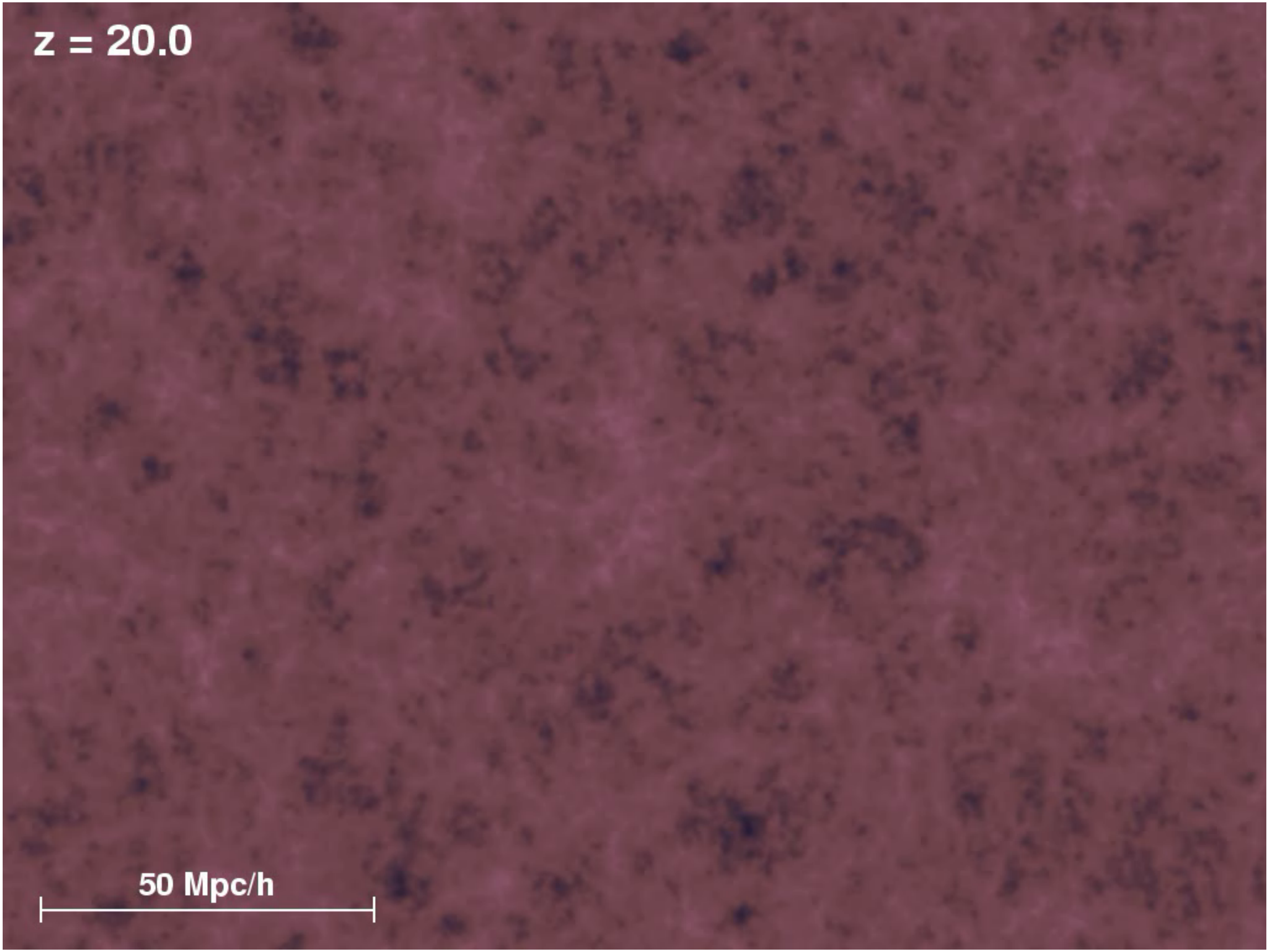
Springel et al ‘05

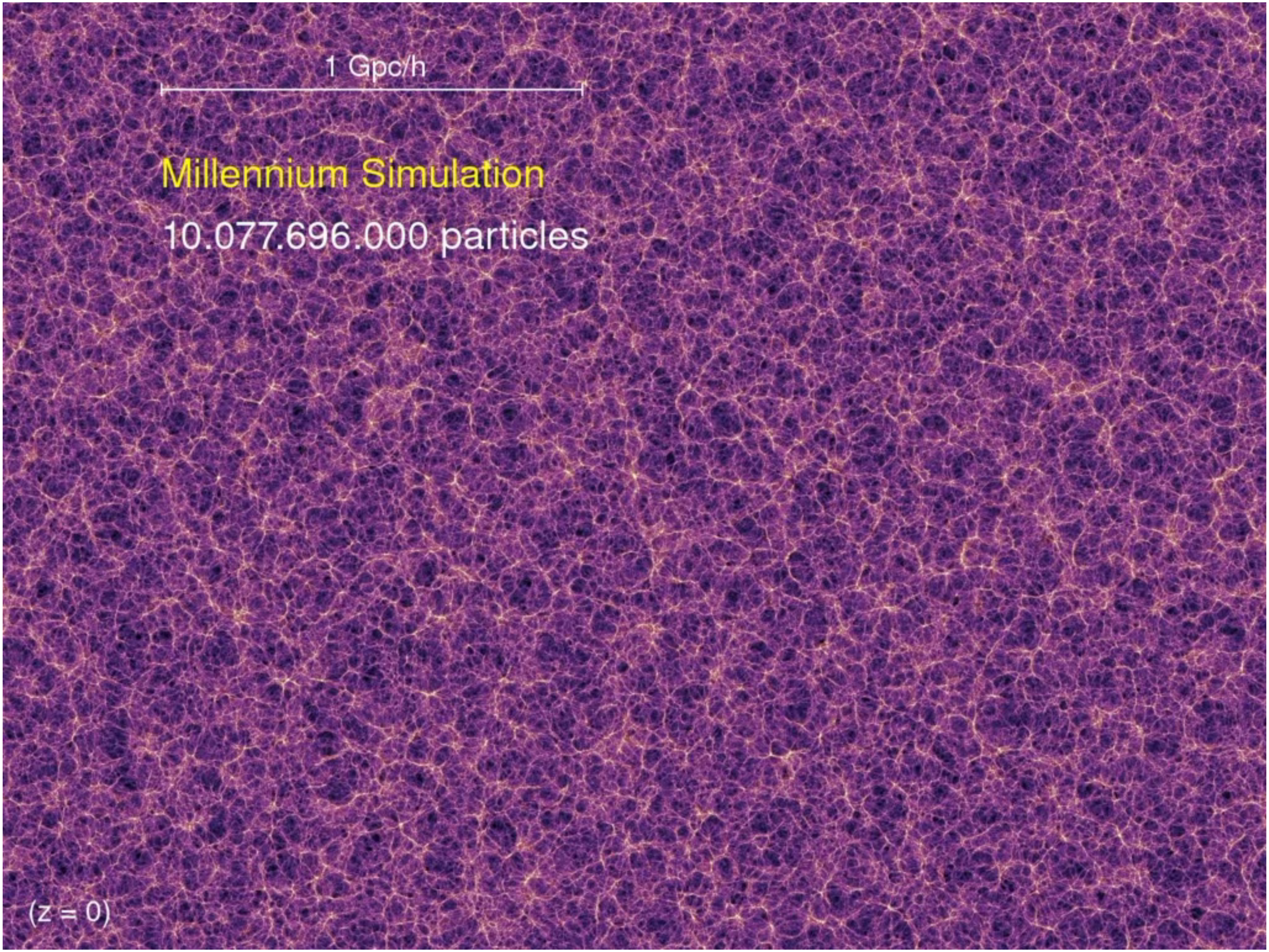
Simulation data, movies, pictures available at:

www.mpa-garching.mpg.de/Virgo

www.durham.ac.uk/virgo

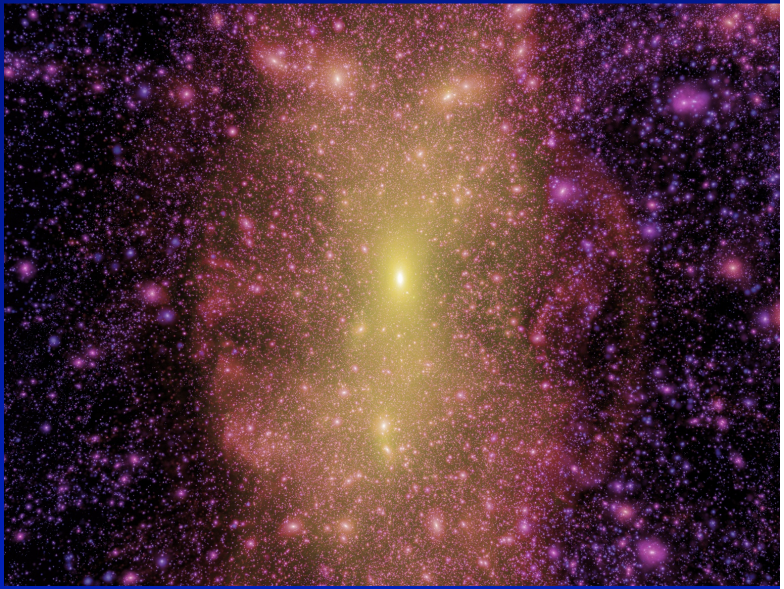
UK, Germany, Canada,
Japan, US collaboration


z = 20.0
50 Mpc/h


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

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

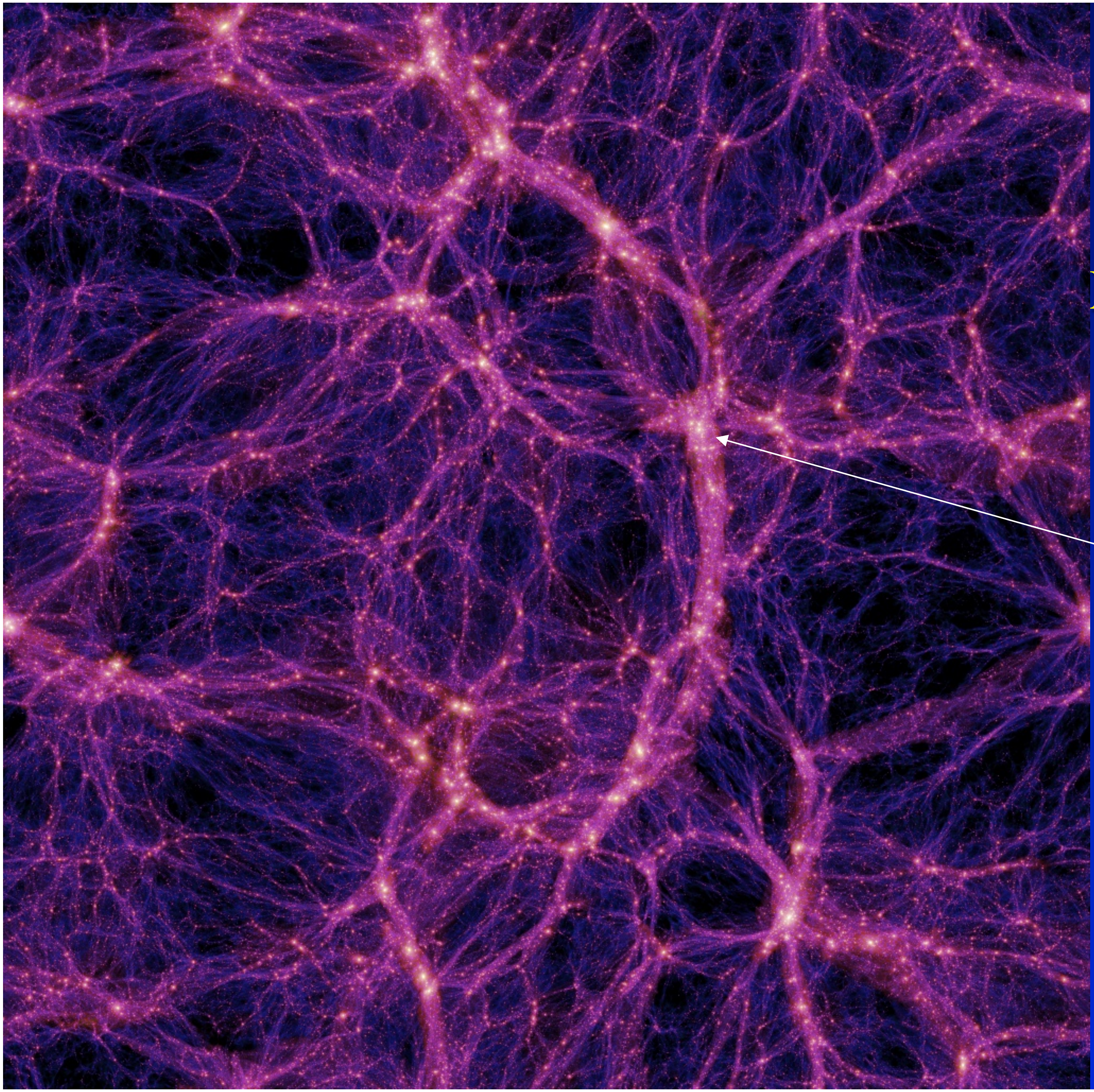
Numerical resolution	Particle number in halo (N_{50})	# of substructures	mass resolution
Aq-A-5	808,479	299	3.14×10^6 M_0
Aq-A-4	6,424,399	1,960	3.92×10^5 M_0
Aq-A-3	51,391,468	13,854	4.91×10^4 M_0
Aq-A-2	184,243,536	45,024	1.37×10^4 M_0
Aq-A-1	1,473,568,512	297,791	1.71×10^3 M_0 (15 pc/h softening)

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

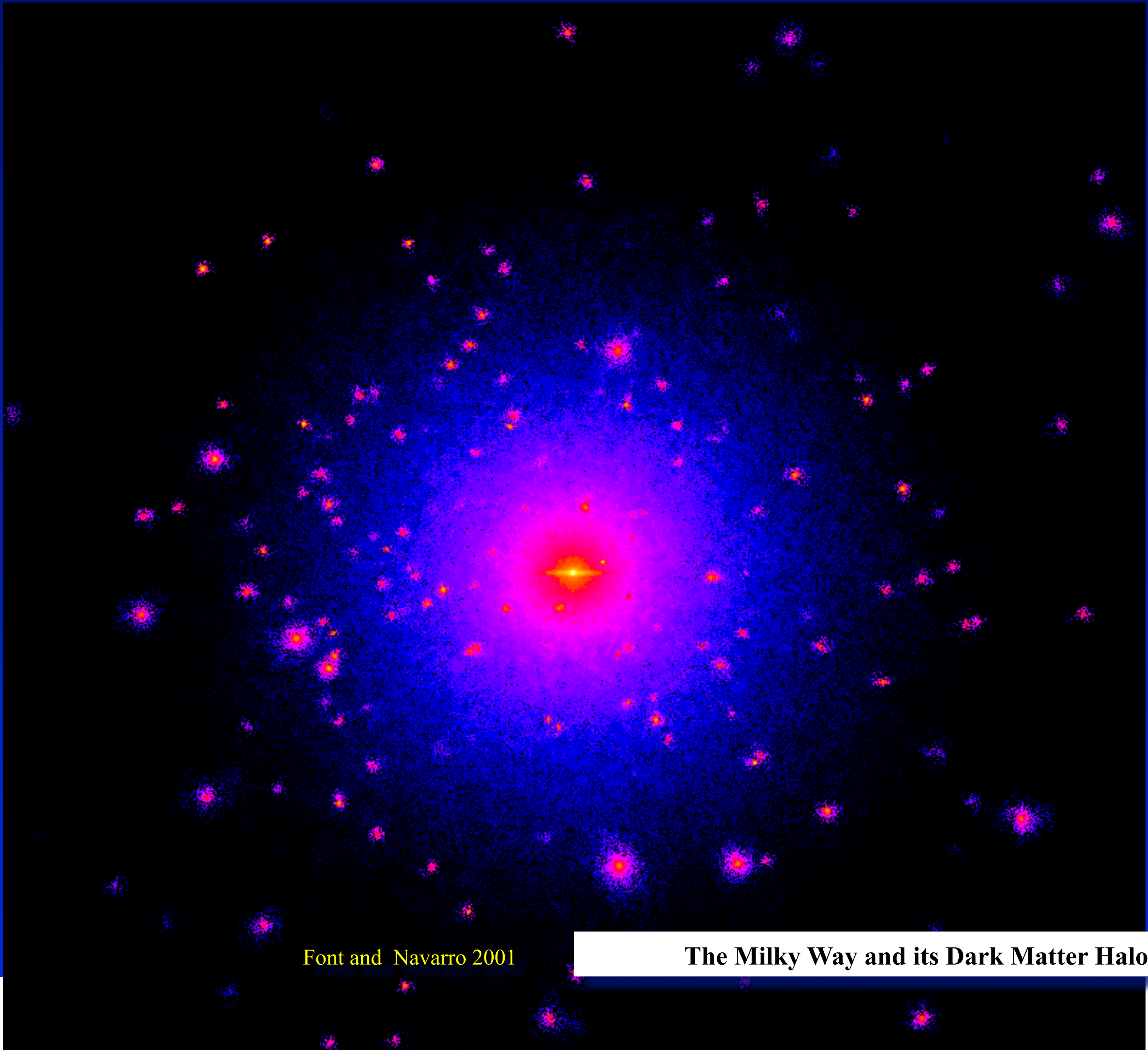
Diemand et al ‘07, 08

Aquarius halos in the Millennium-2 Run



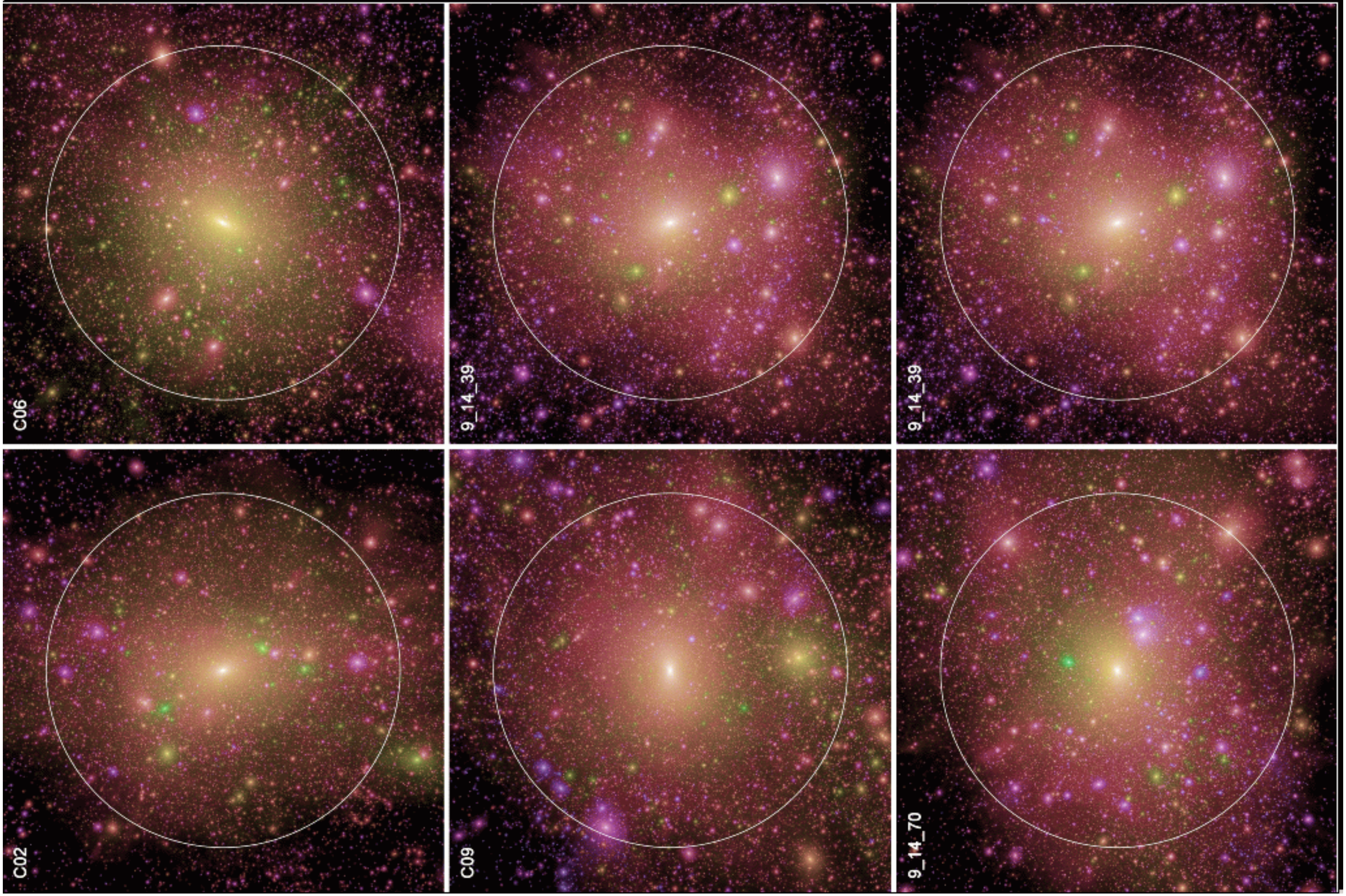
One of the Aquarius halos in the 100Mpc/h box parent simulation.

The Milky Way and its Dark Matter Halo

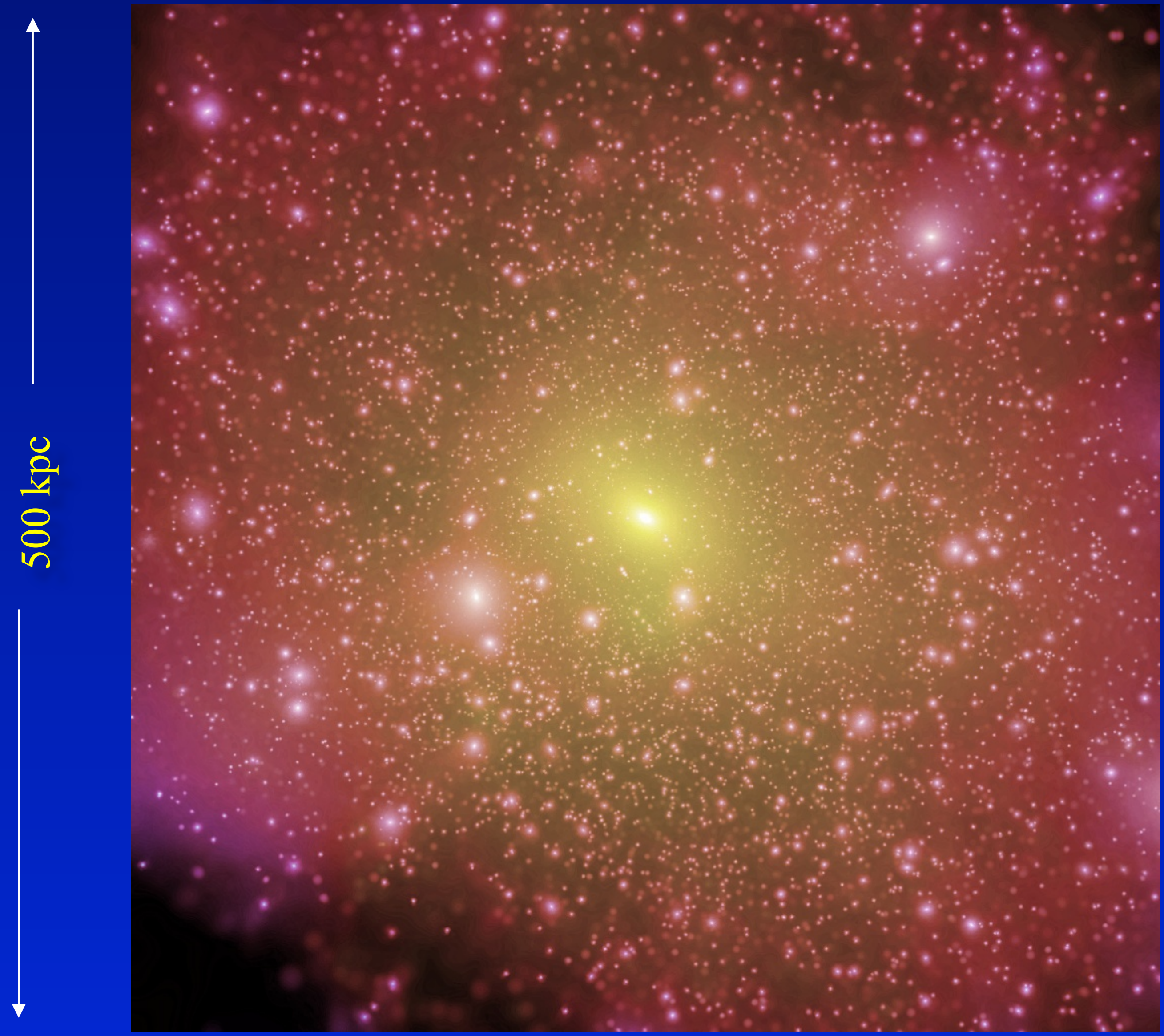


Font and Navarro 2001

Pictures of all Aquarius halos (level-2 resolution)

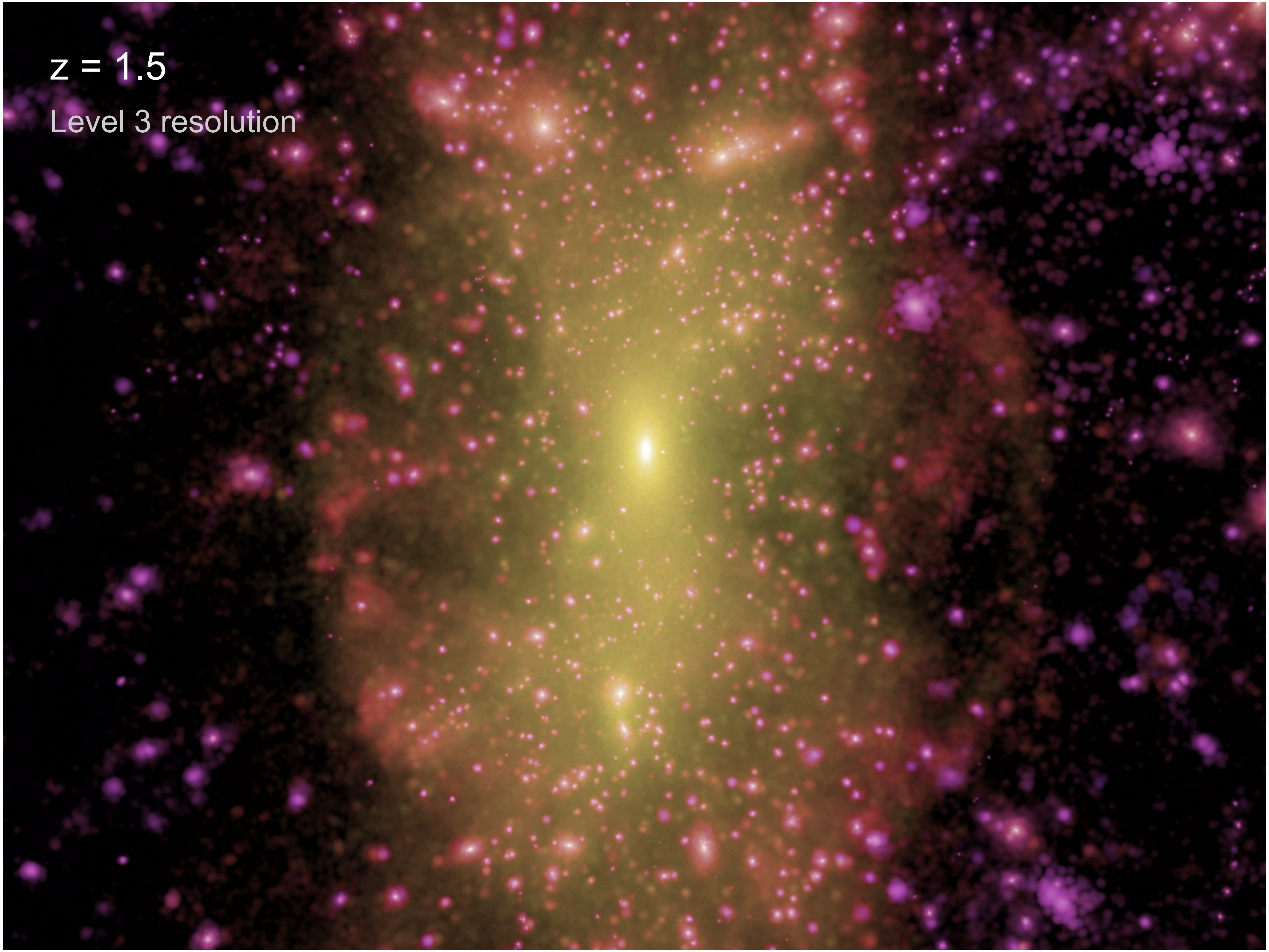


Aquarius: the Billennium simulation



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

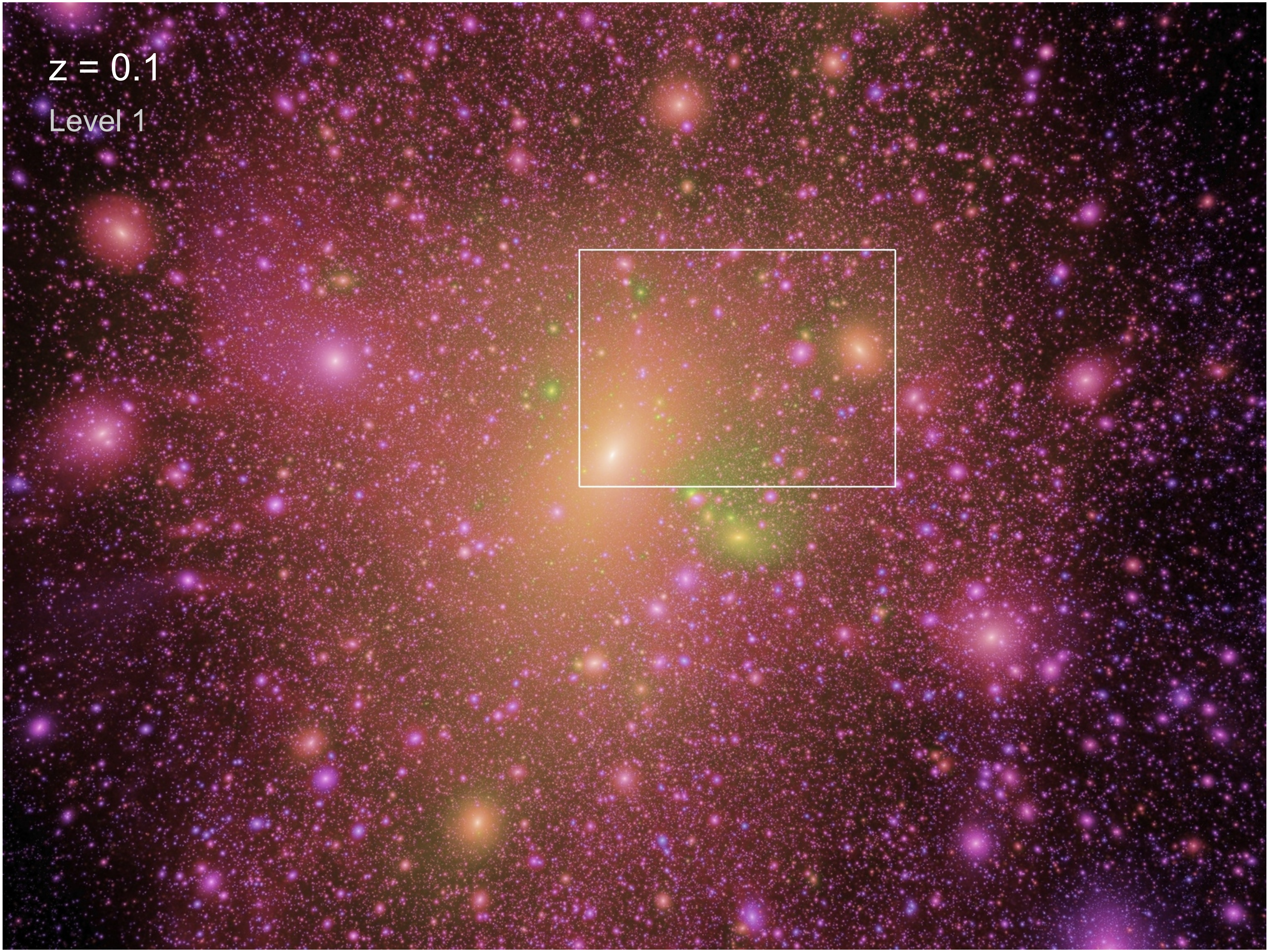

z = 48.4
T = 0.05 Gyr
500 kpc

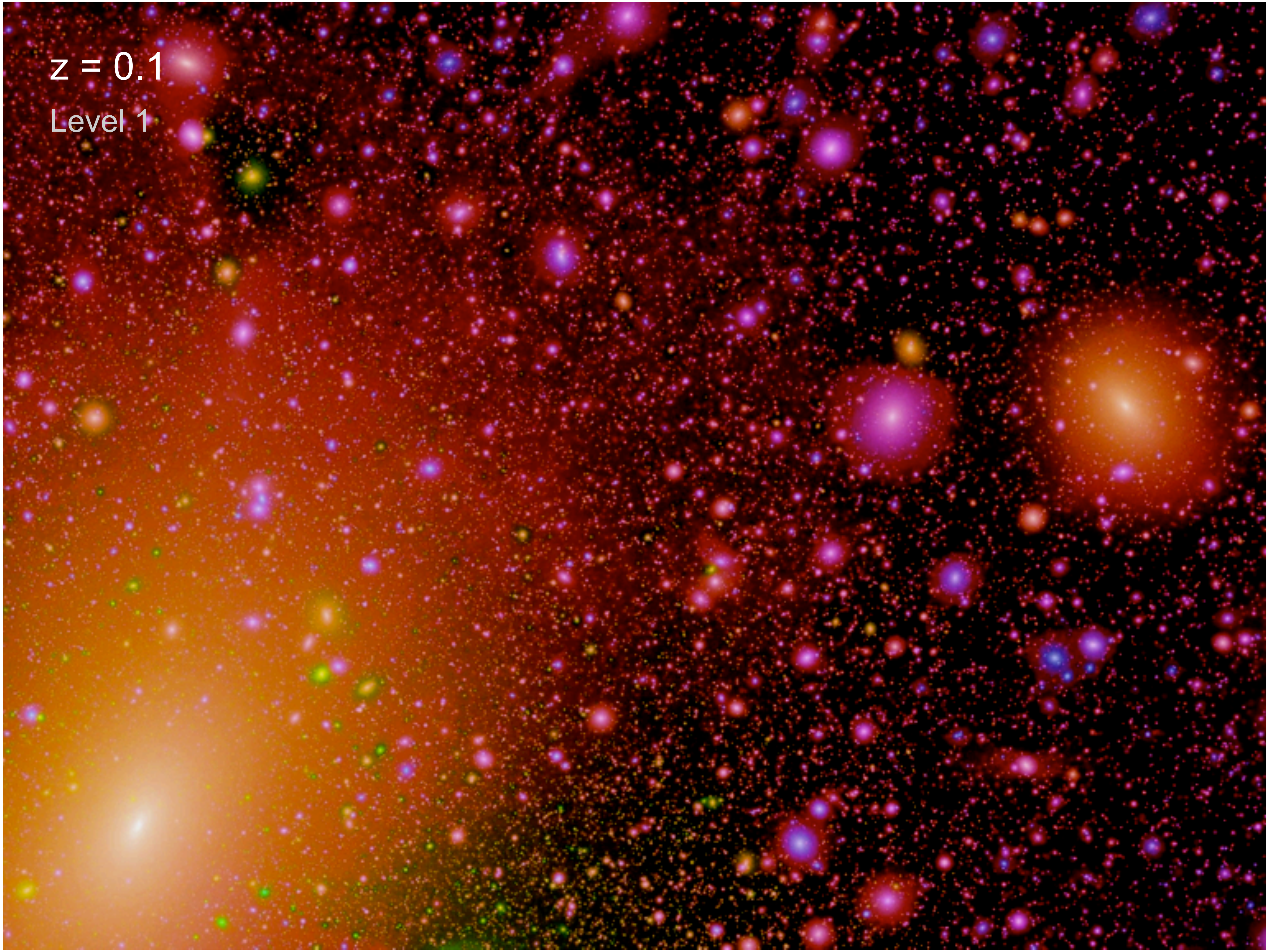

z = 1.5
Level 3 resolution


z = 1.5
Level 2 resolution

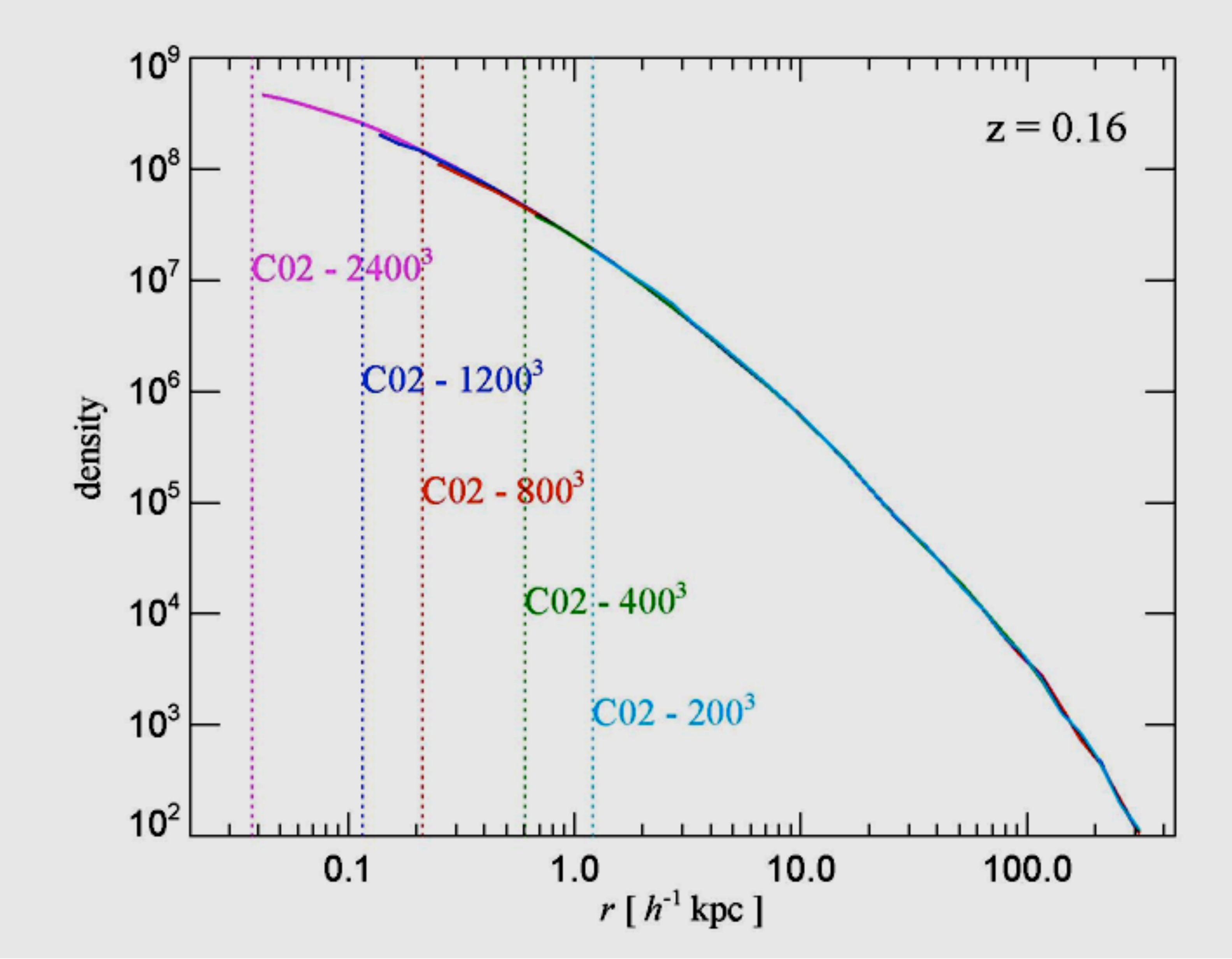

z = 1.5
Level 1 resolution


z = 0.1
Level 1

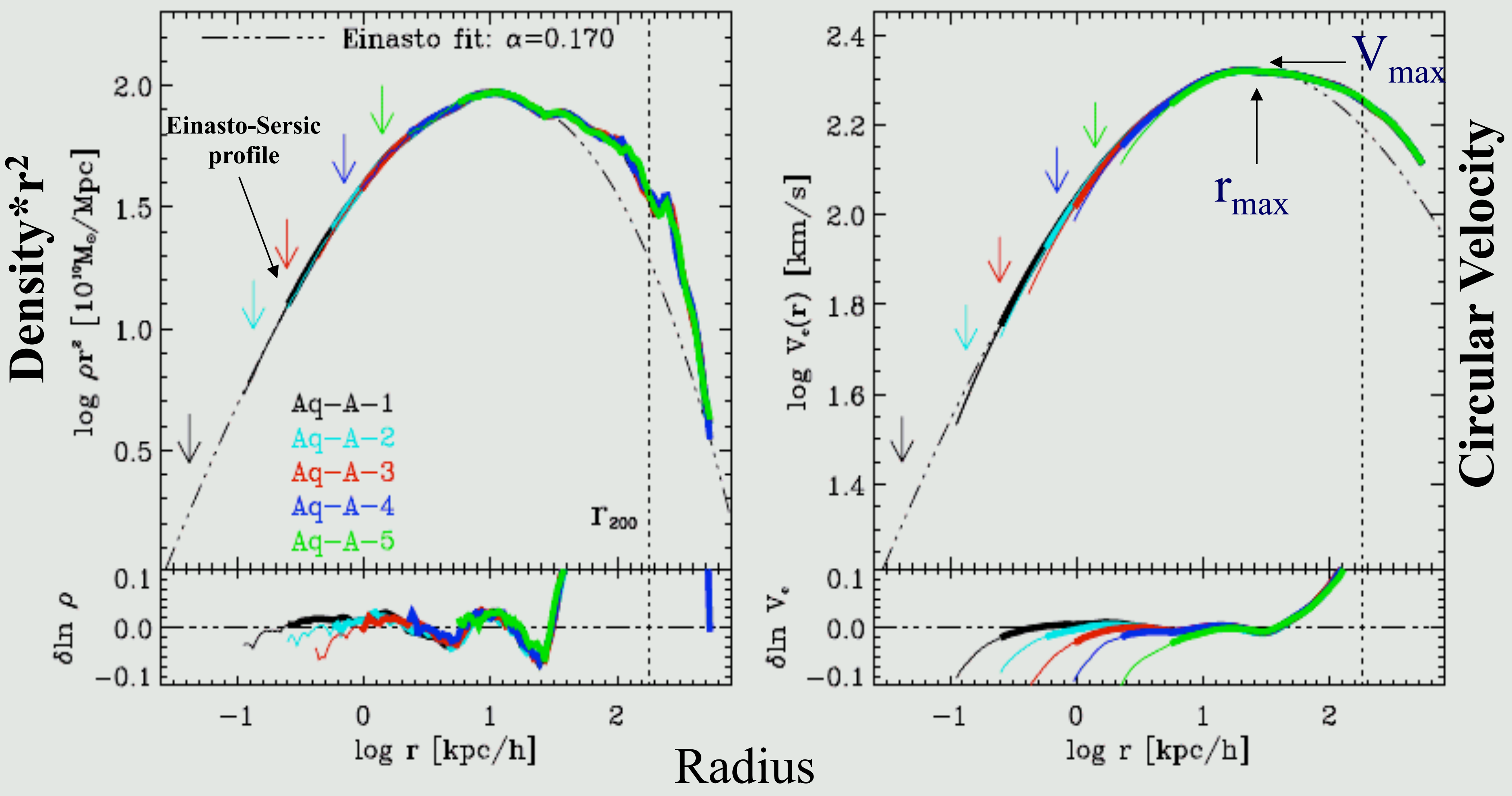

z = 0.1
Level 1


z = 0.1
Level 1

The Density Profile: numerical convergence

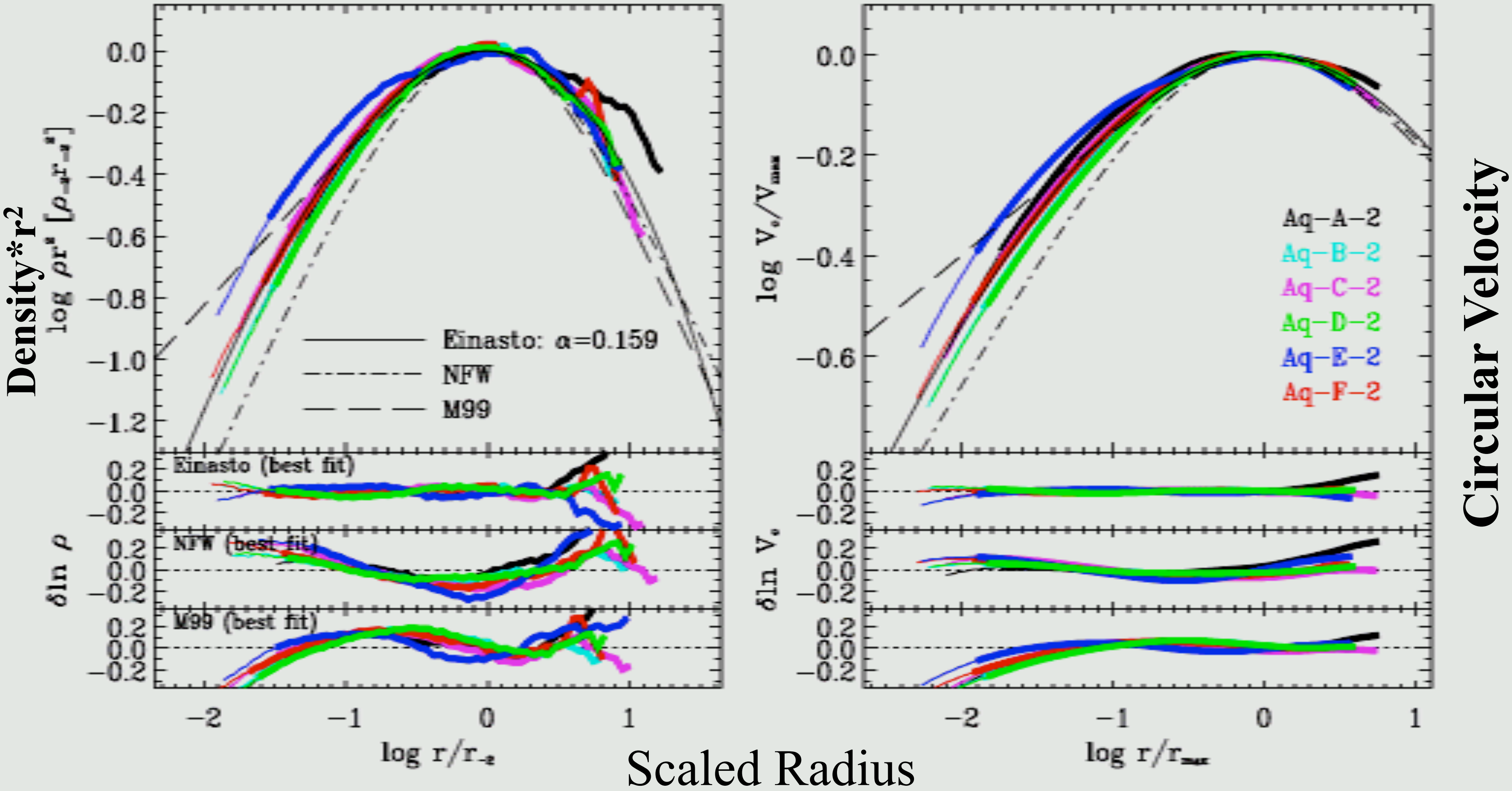


The Mass Profile: numerical convergence



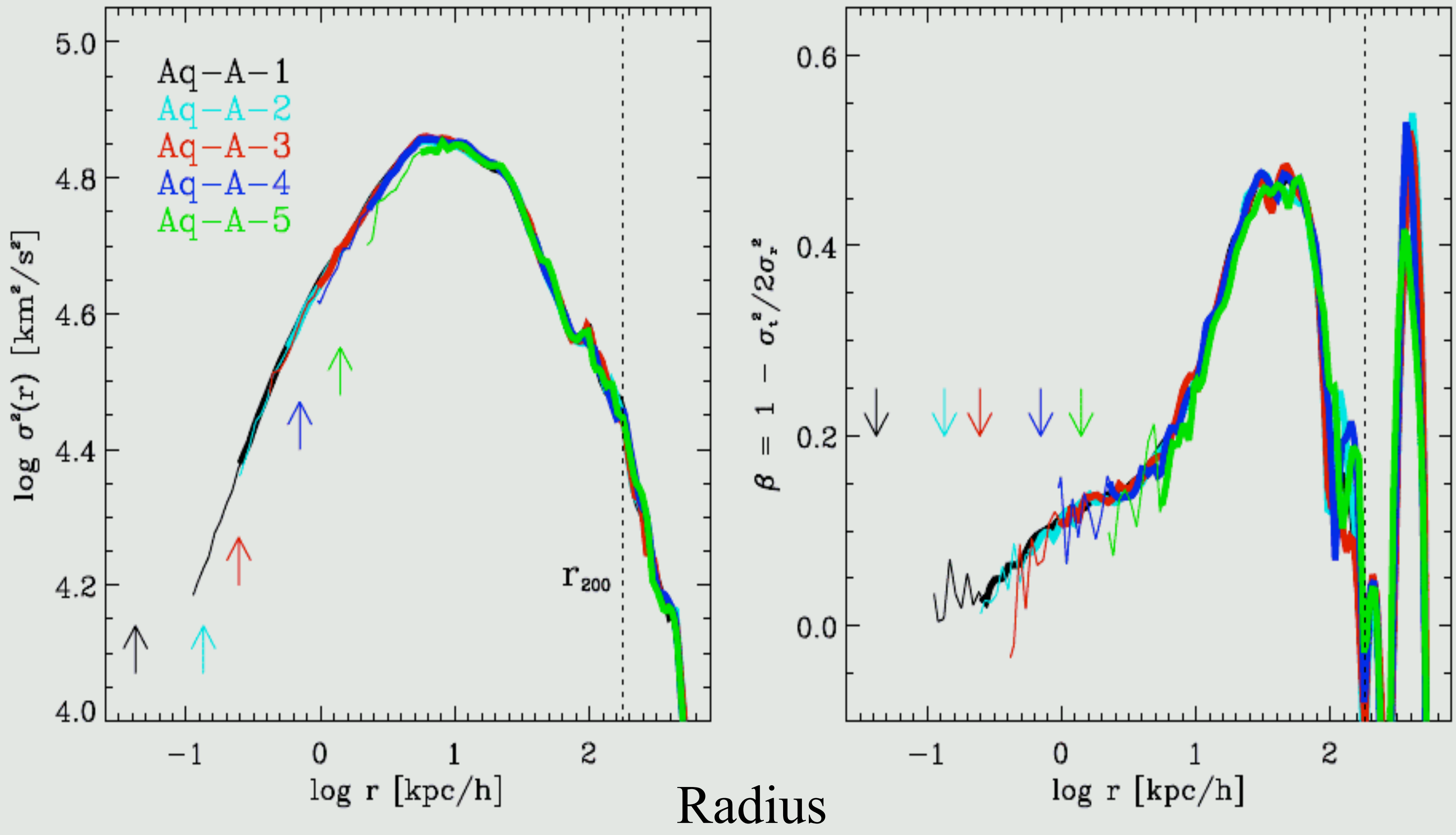
- Excellent numerical convergence down to radius where the collisional relaxation time approaches the age of the universe

Self-similarity in the mass profile?



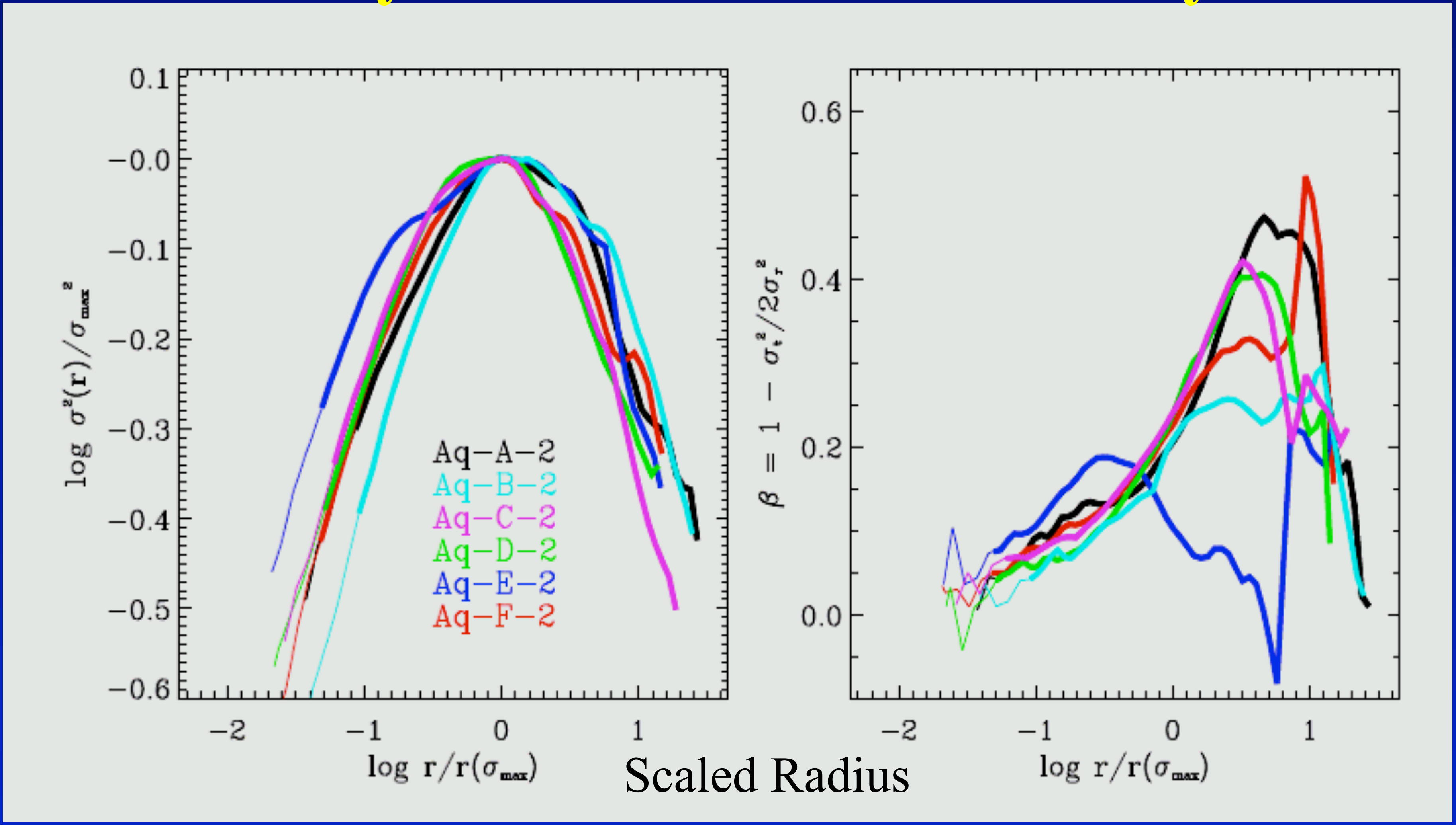
- Slight but significant deviations from similarity.
- A “third parameter” is needed in order to describe accurately the mass profiles of CDM halos.

Velocity structure: convergence



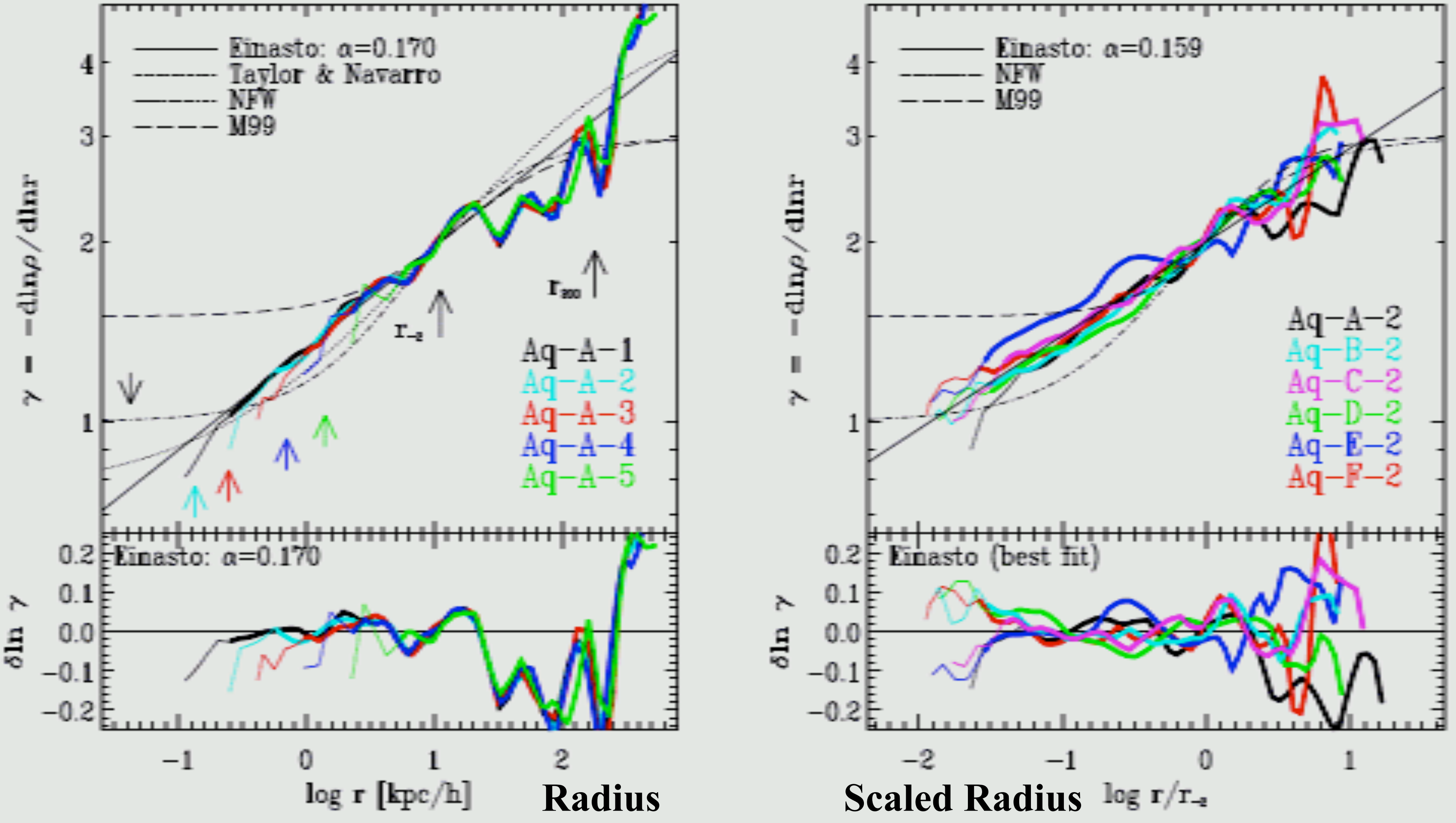
- Excellent numerical convergence down to radius where the collisional relaxation time approaches the age of the universe

Velocity structure: self-similarity?



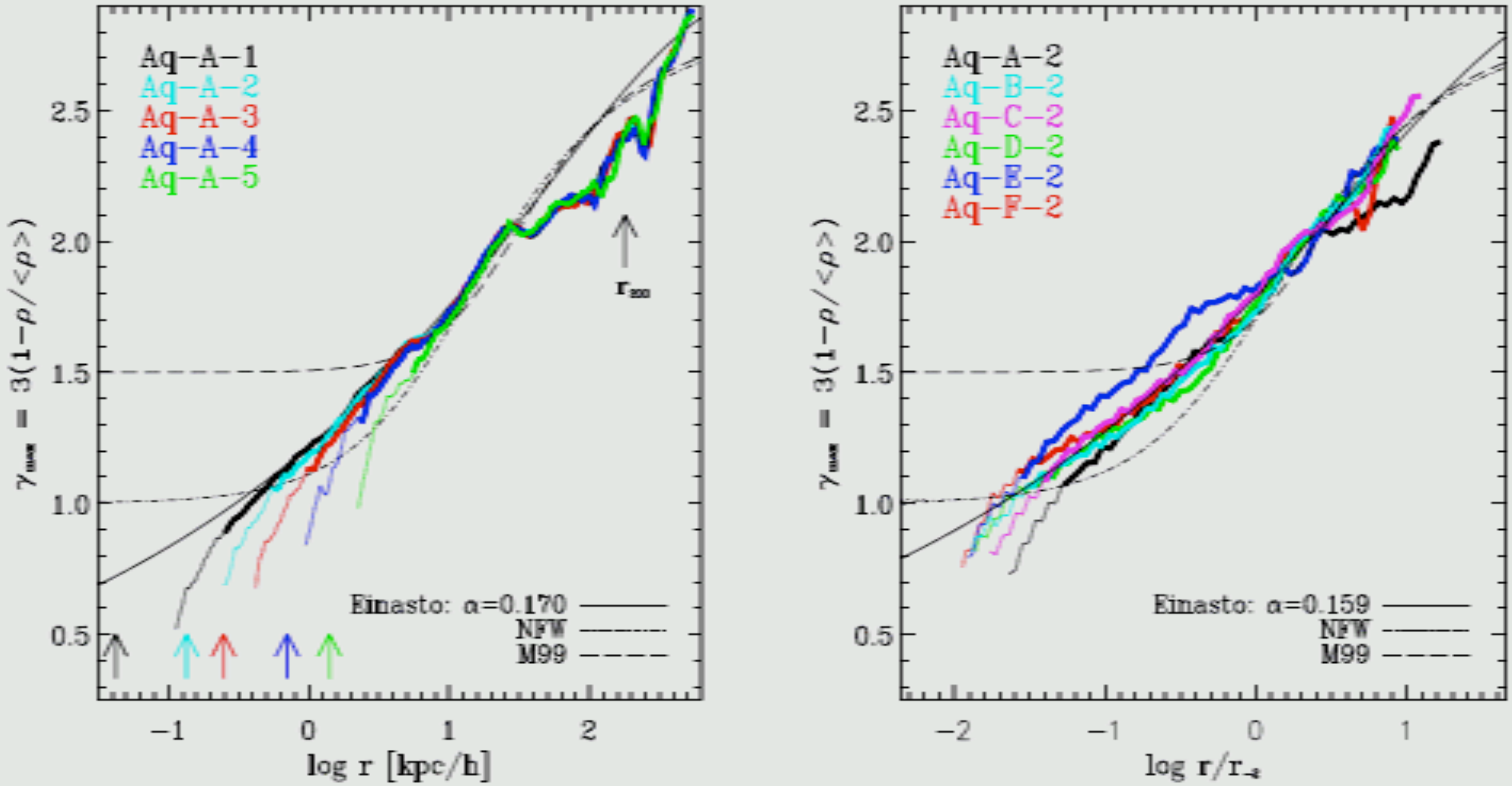
- •Slight but significant deviations from similarity.
- •Note that deviant systems in mass are also deviant in velocity
- •Note similarity in shape between density and velocity dispersion

The Structure of the Cusp



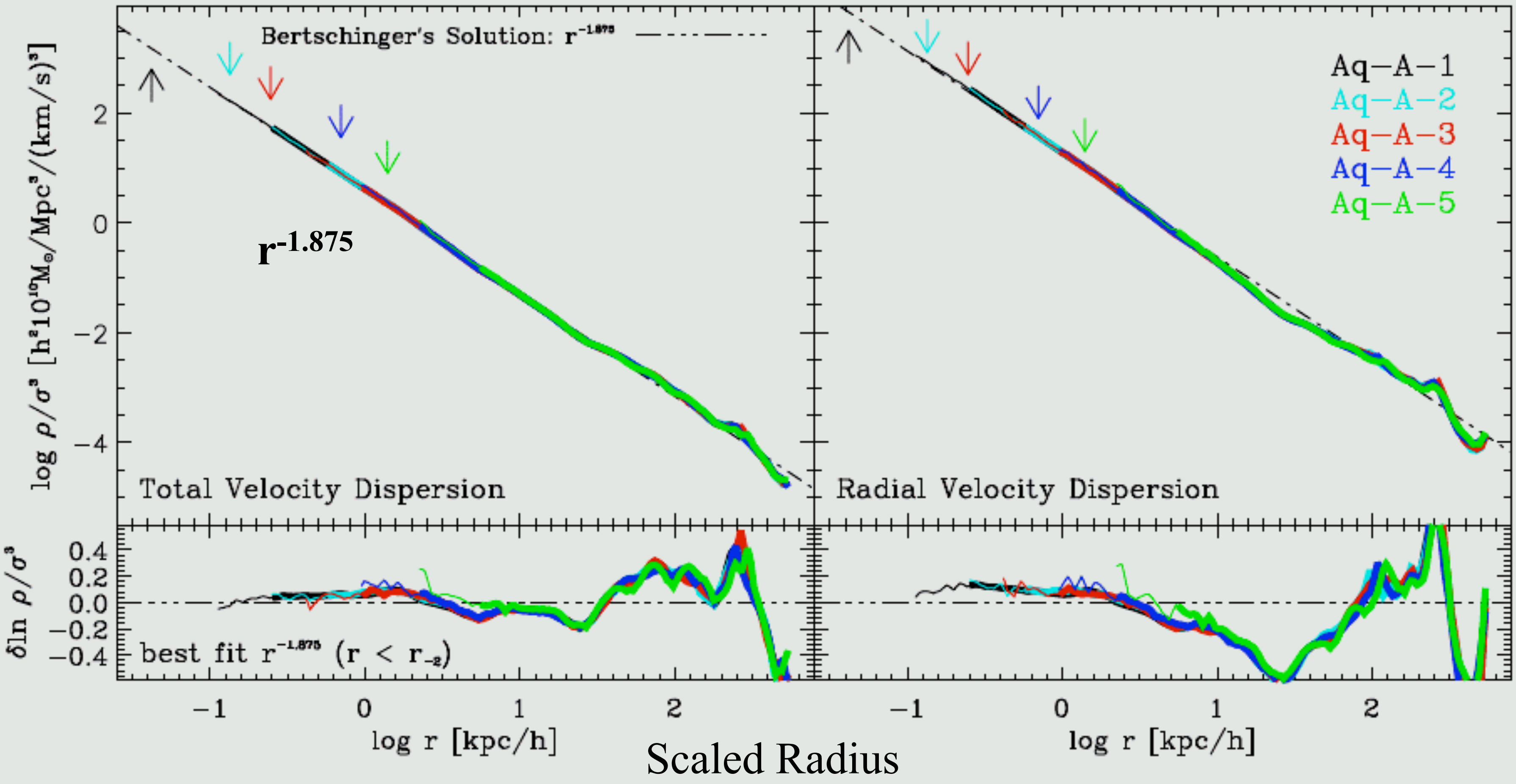
- Logarithmic slope scales like a power-law of radius: the Sersic/Einasto profile
- Innermost profile much shallower than $r^{-1.5}$and probably shallower than r^{-1}

The Cusp: Maximum Asymptotic Slope



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

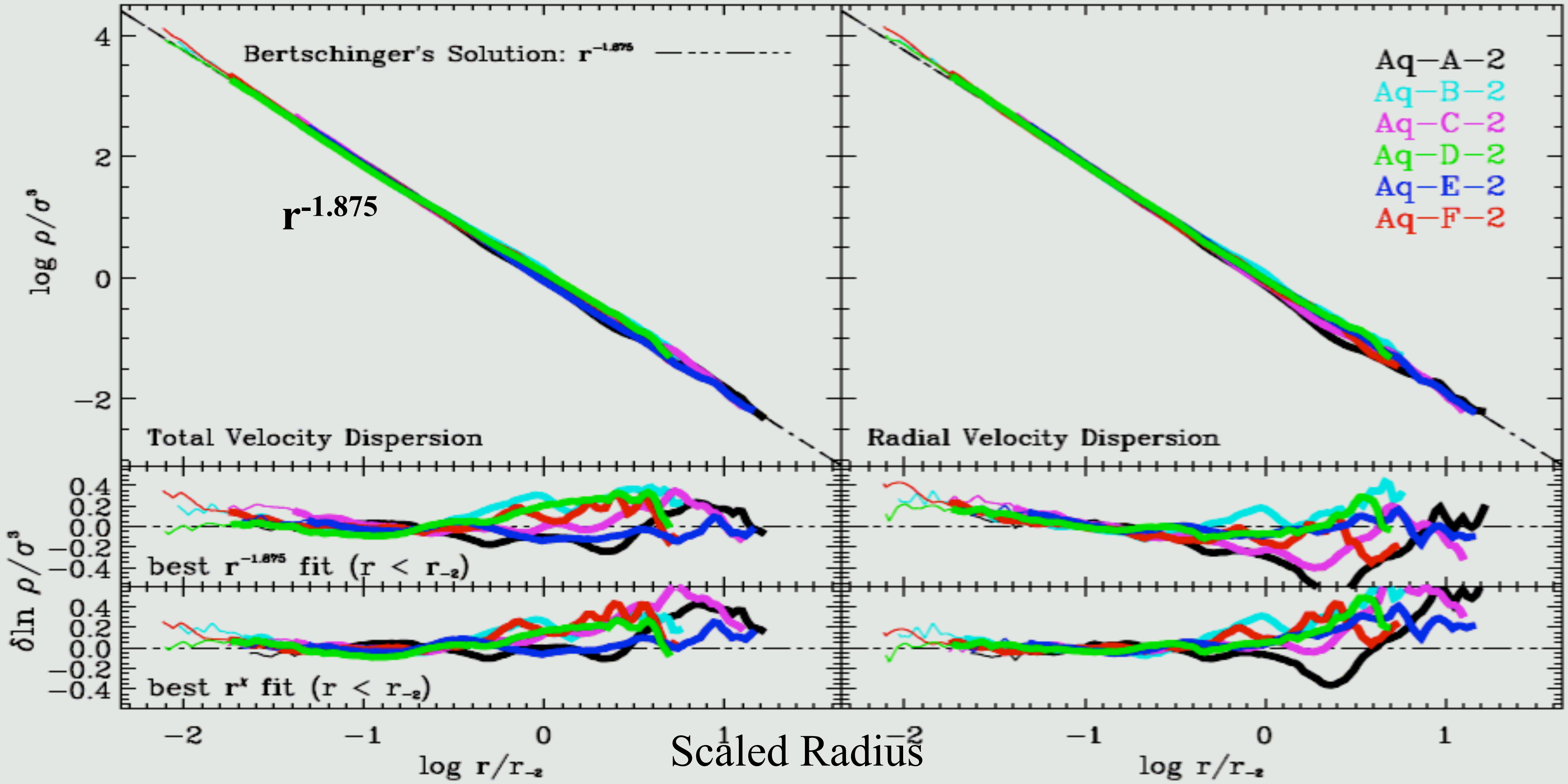
The “Phase-Space Density” Profile



- 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

A blueprint for detecting halo the CDM annihilation signal in the Galactic halo

Springel et al, 2008 Nature

CDM particles may annihilate and lead to production of γ-rays which could be observable by GLAST/FERMI

Emission of annihilation radiation depends on:

$$\int \underbrace{\rho^2(\boldsymbol{x})}_{\text{halo density at } \boldsymbol{x}} \underbrace{\langle \sigma v \rangle}_{\text{cross-section}} \, dV$$

⇒ Theoretical expectation requires knowing ρ(***x***)---may be very sensitive to substructure

⇒ Need accurate high resolution N-body simulations of halo formation from CDM initial conditions

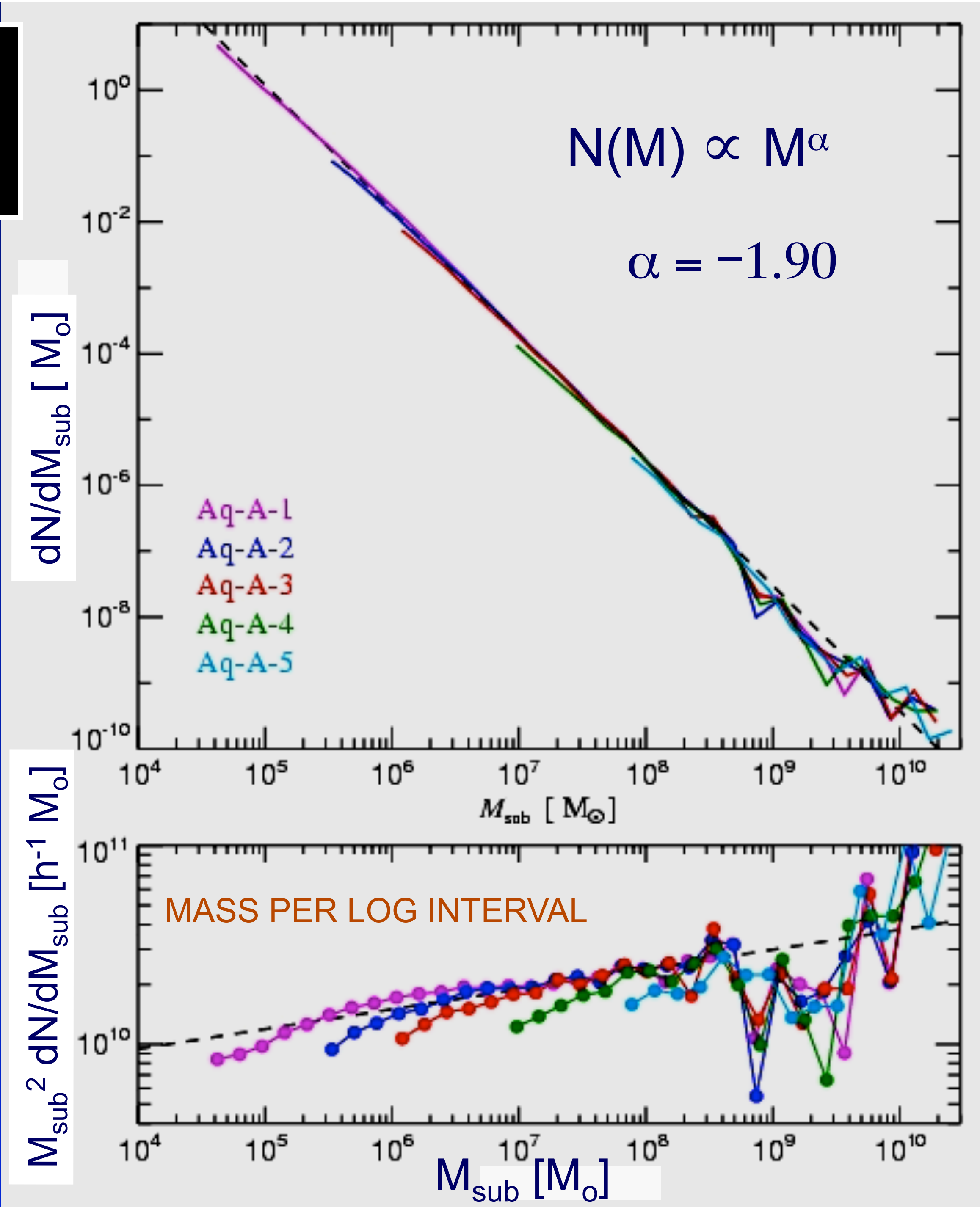
Substructure and annihilation signal in Cold Dark Matter halos

- Halo DM is mostly in small (e.g. Earth mass) clumps
- Small (Earth-mass) clumps should dominate DM annihilation signal observable from Earth
- Dwarf spheroidals/luminous satellites are the best targets for detecting DM annihilation signal
- Halo DM is in a self-similar (fractal) distribution of nested substructure halos (subhalos)
- Annihilation signal/detectability is significantly boosted by sub-substructure

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 (5 to 10% of the total) converges well even for moderate resolution

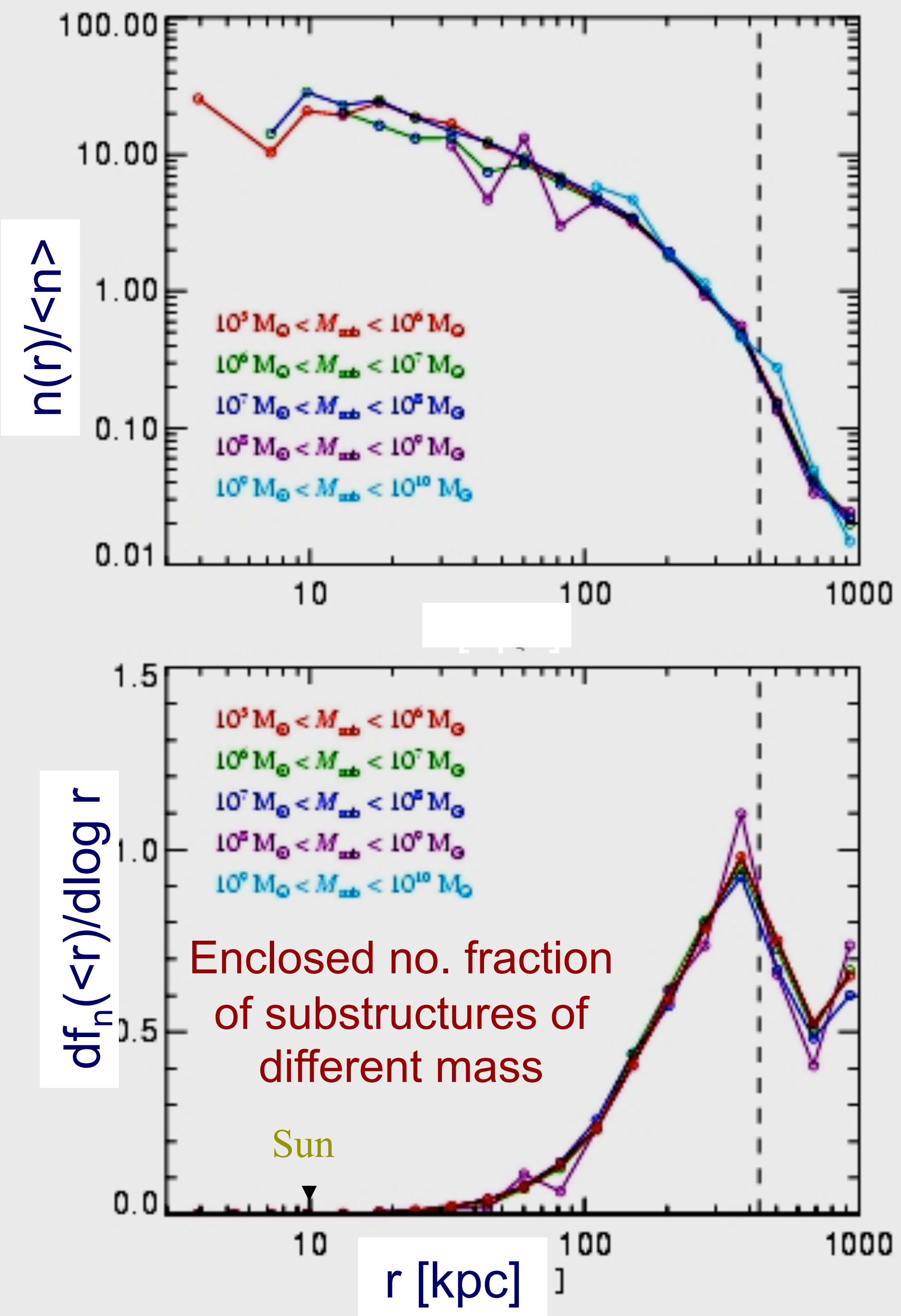

$N(M) \propto M^{\alpha}$

$\alpha = -1.90$

MASS PER LOG INTERVAL

The number density profile of substructure halos

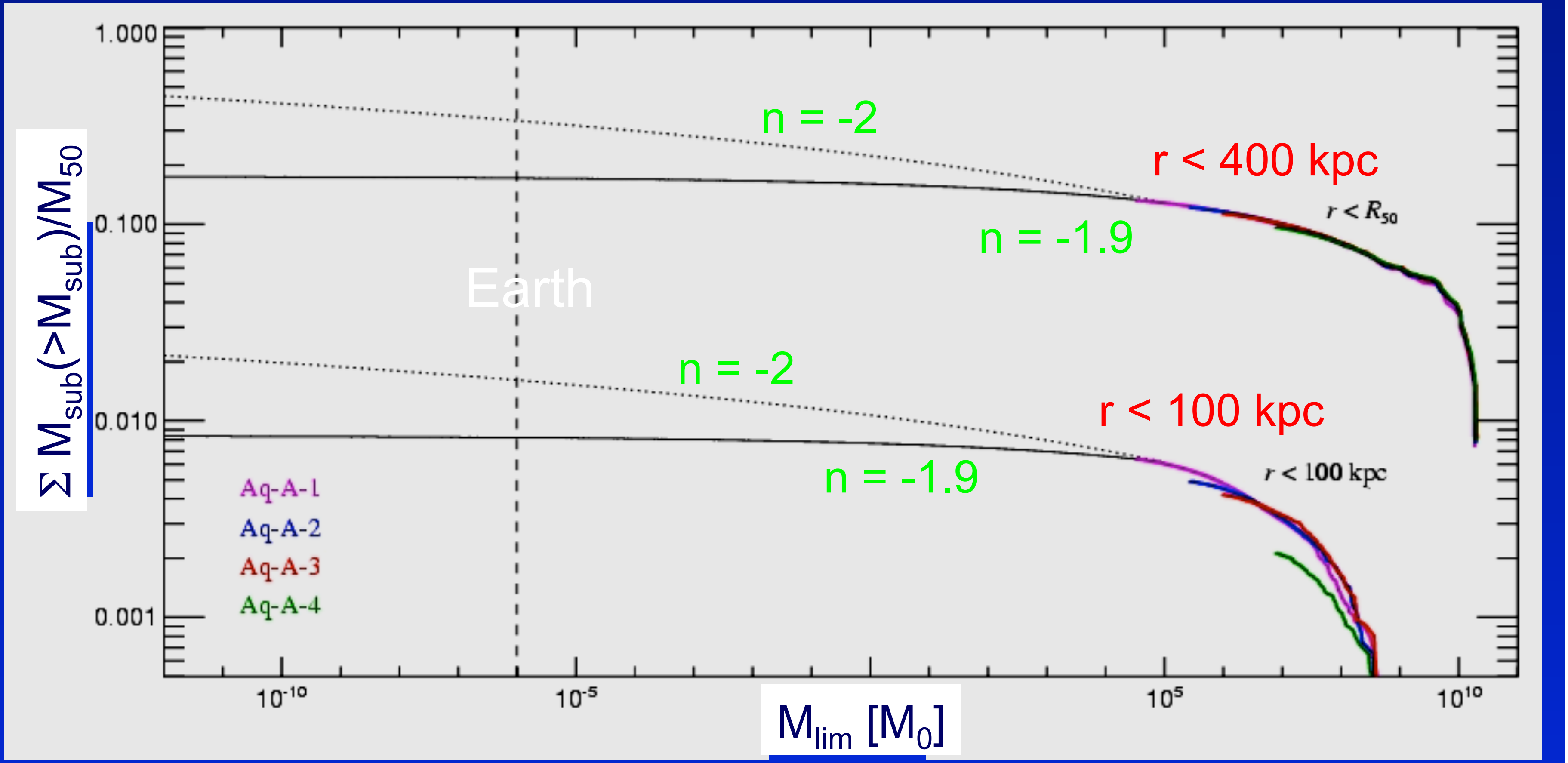
- The spatial distribution of subhalos (except for the few most massive ones) is independent of mass
- Most subhalos are at large radii -- subhalos are more effectively destroyed near the centre
- Most subhalos have completed only a few orbits; dynamical friction unimportant below a subhalo mass threshold
- Subhalos are far from the Sun



Enclosed no. fraction of substructures of different mass

How lumpy is the MW halo?

Mass fraction in subhalos as a function of the free-streaming cutoff mass in the CDM power spectrum



Substructure mass fraction within R_{sun} < 0.1%

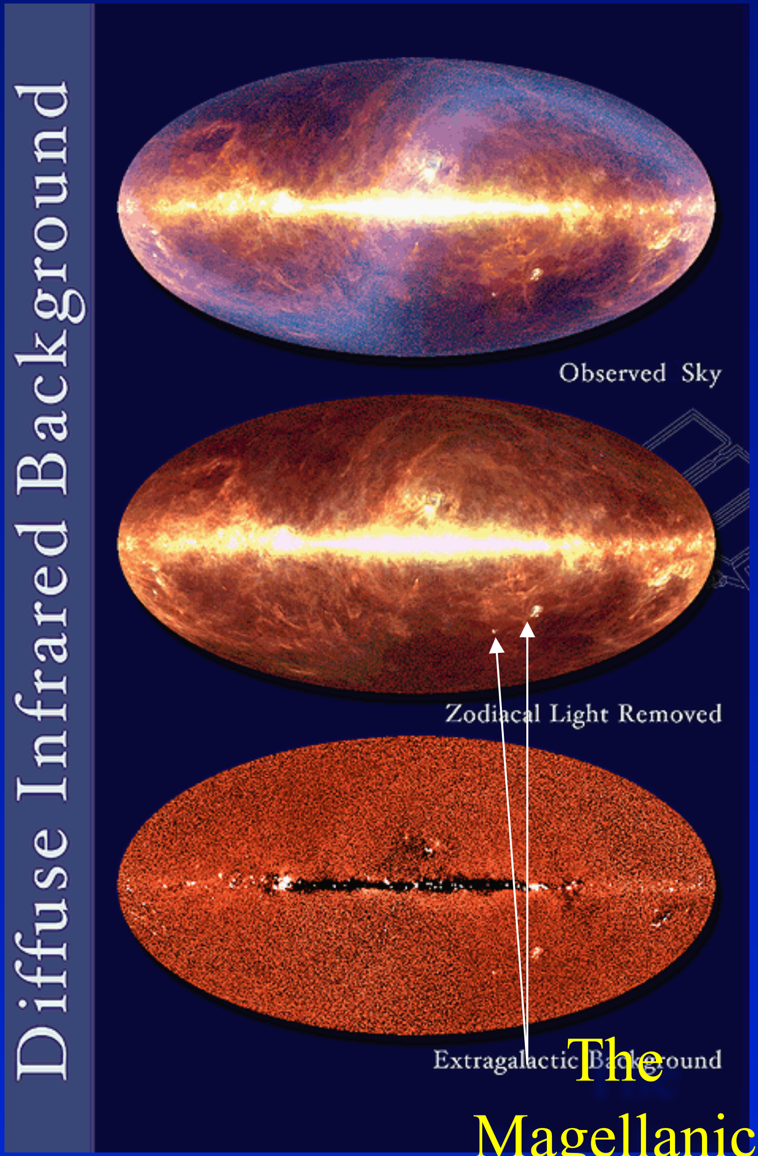
Annihilation radiation from the Milky Way halo and subhalos

- If small-scale clumping and angular variations in the background may be neglected, then for systems with self-similar density profiles:

1. Luminosity $\propto V_{max}{}^{4}/r_{max}$
2. Flux $\propto V_{max}{}^{4}/(r_{max}{}^{*}d^{2})$
3. Signal-to-noise $\propto V_{max}{}^{4}/(r_{max}{}^{2*}d)$

The Milky Way substructures

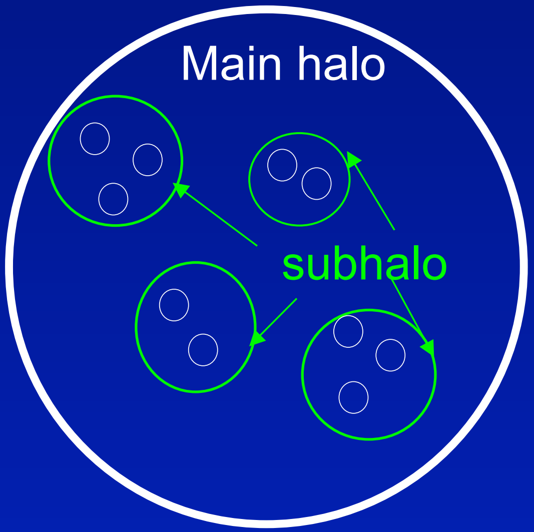
- The known substructure with largest signal-to-noise is the LMC, and it is easy to show that
  - $(S/N)_{MW}/(S/N)_{LMC} \sim 134!$
- Substructures are easier to detect than the main halo only if the "boost factor" from small-scale clumping overwhelms this simple scaling.



The Magellanic Clouds

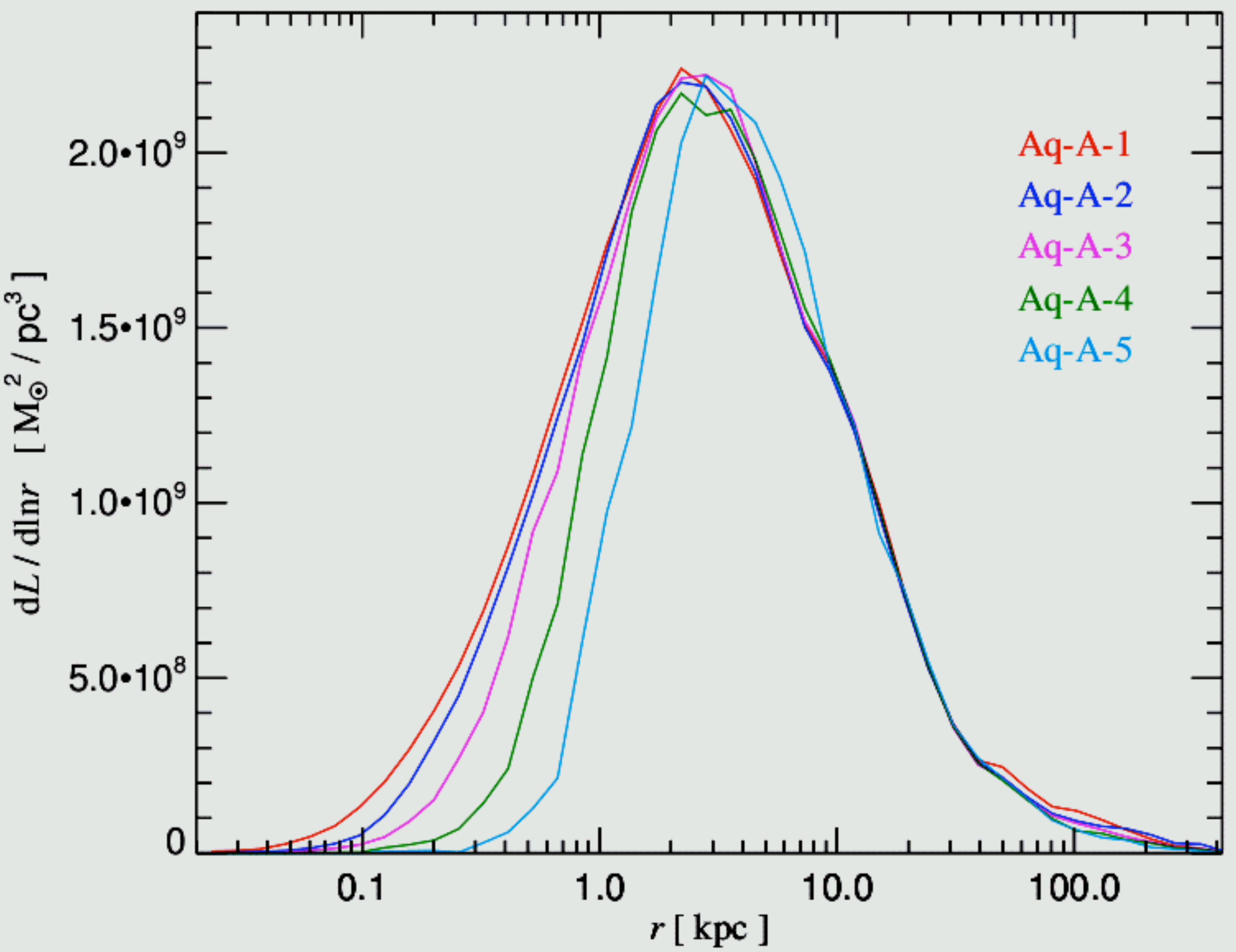
A blueprint for detecting halo CDM annihilation radiation

To calculate the annihilation luminosity from a dark matter halo (L) we need to consider the contribution from 4 components:



1. Smooth emission from main halo (MainSmooth)
2. Smooth emission from resolved subhalos (SubSmooth)
3. Emission from unresolved subhalos in main halo (MainUnres)
4. Emission from substructure of subhalos (SubSub)

The radiation from the main halo (MainSmooth)



- Lack of steep central cusp means that the radiation from the smooth main halo component is well defined and constrained.

- Half of the total luminosity comes from within ~3kpc, 95% from ~30kpc

- $L \sim V_{max}{}^4 / r_{max}$

The radiation from substructures (SubSmooth)

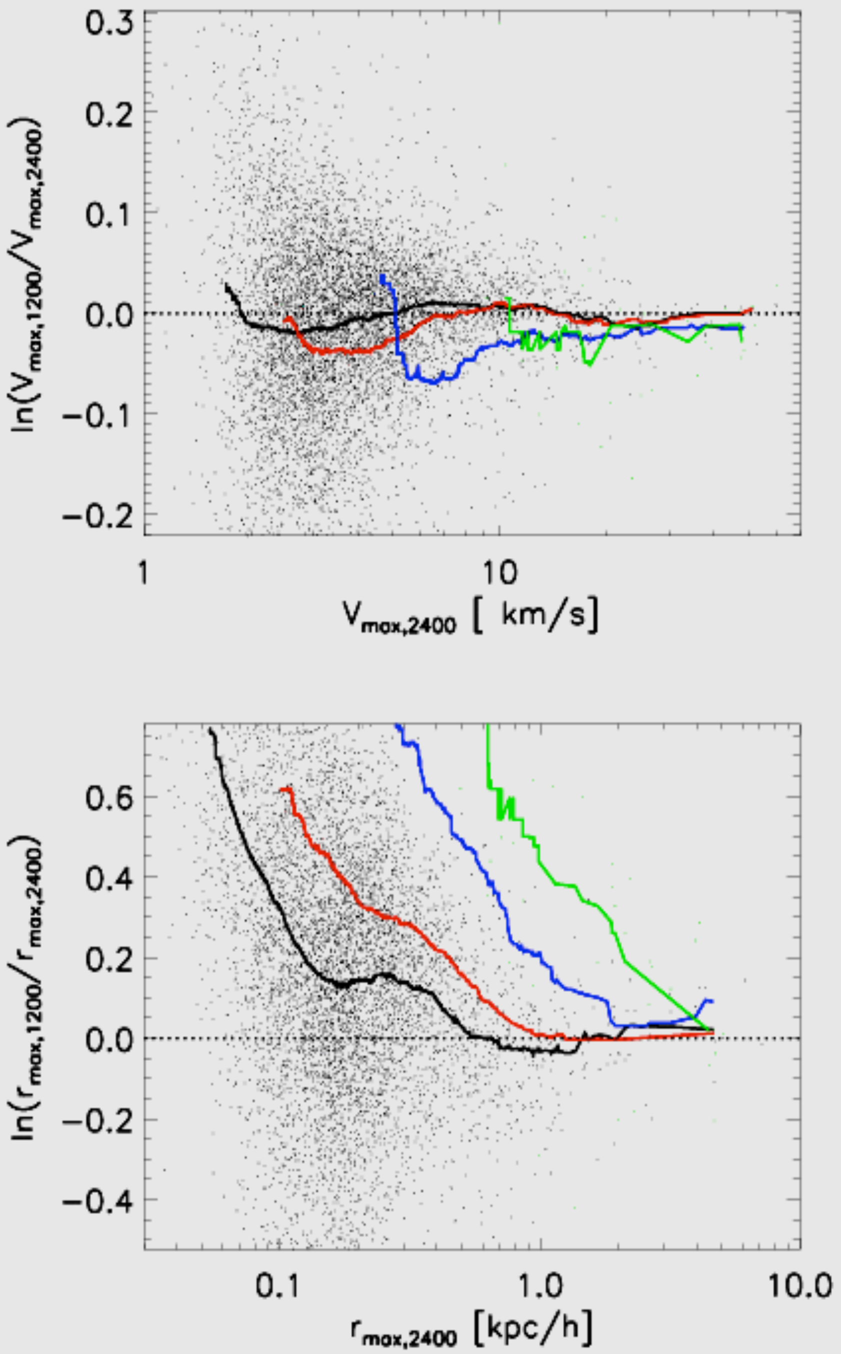
- This depends on being able to estimate accurately V_{max} and r_{max} for subhalos

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

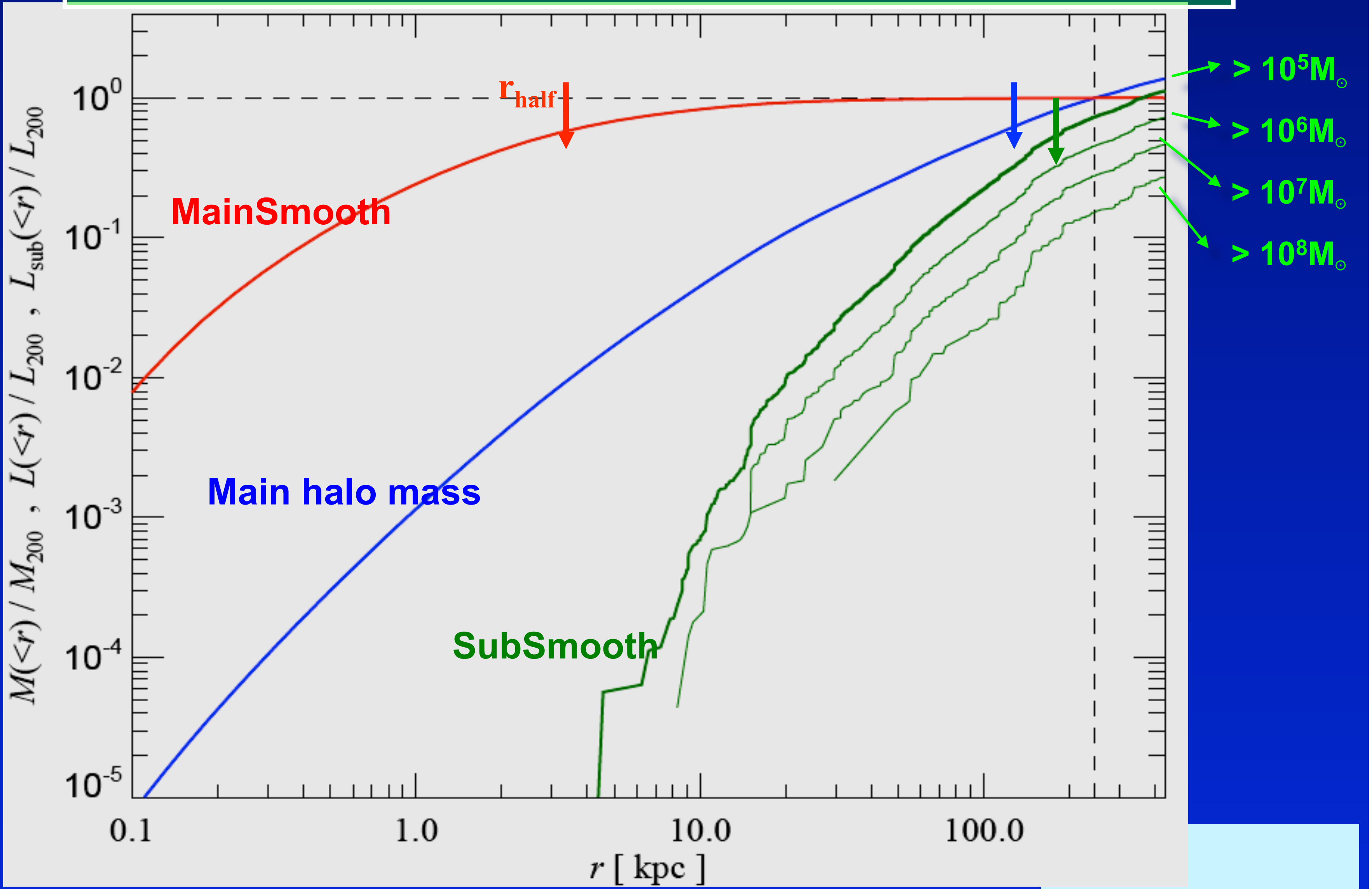
- Largest simulation gives convergent results for:

  $V_{max} > 1.5$ km/s
  $r_{max} > 165$ pc

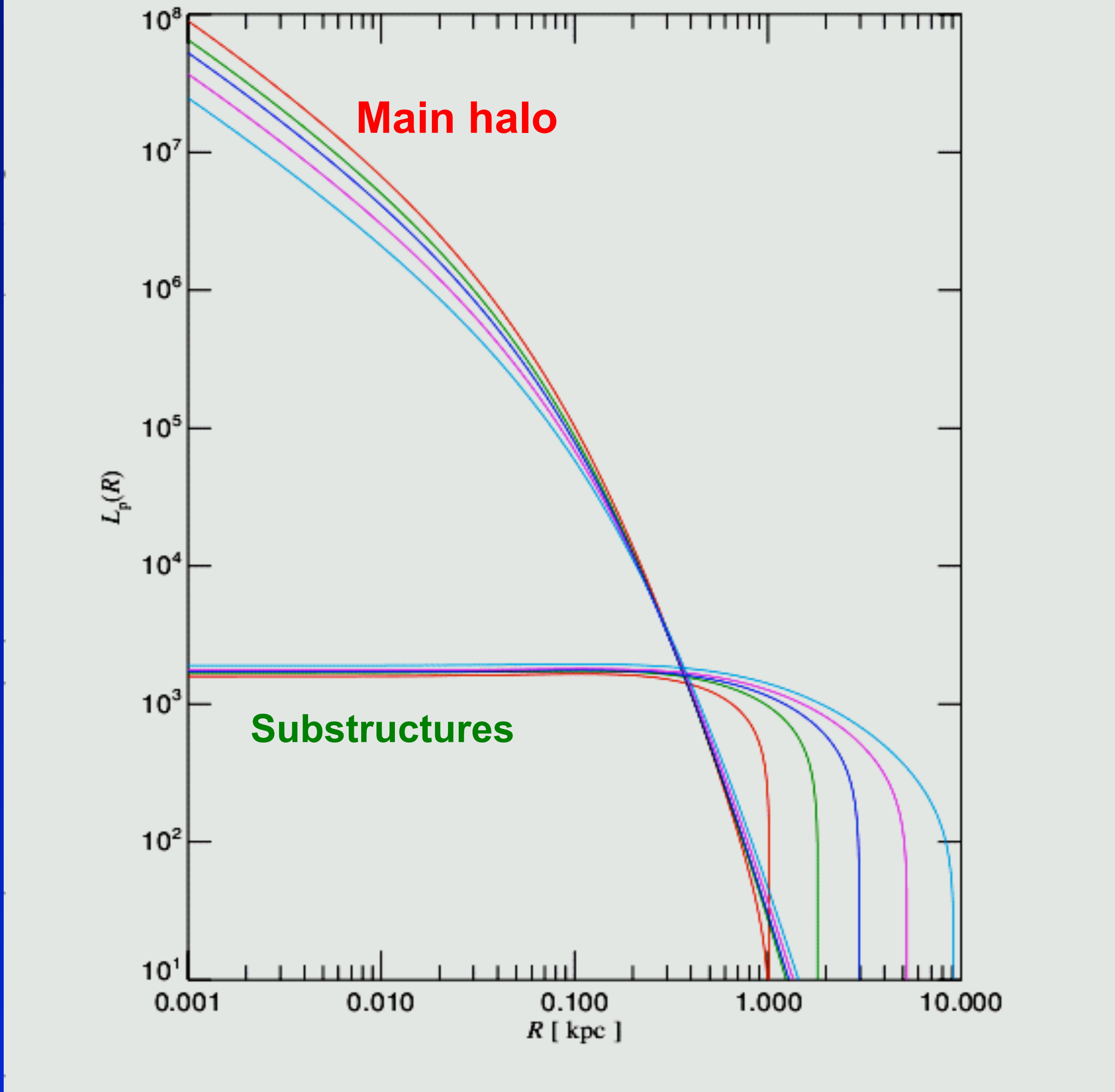
- These limits are much smaller than the halos inferred for even the faintest dwarf galaxies



Enclosed mass and annihilation radiation profiles



Projected annihilation radiation profile

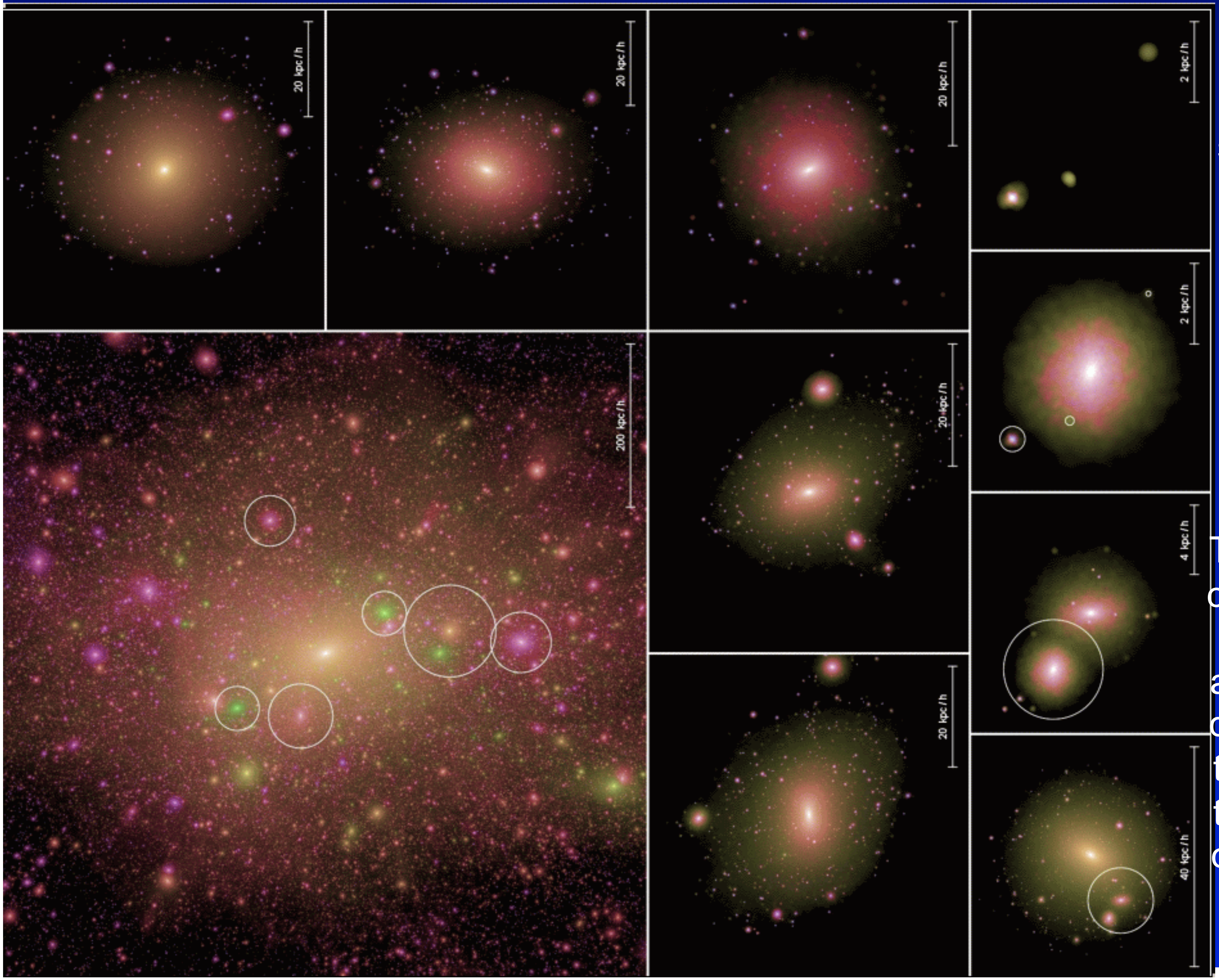


Extrapolating to $M_{sub}=10^{-6}$ M_{sun} yields $L_{SUBSMOOTH}$ ~ 200 $L_{MAINSMOOTH}$

- This is what would be seen by a distant observer

- The total flux from SUBSMOOTH and MAINSMOOTH are actually similar for an observer near the Sun.

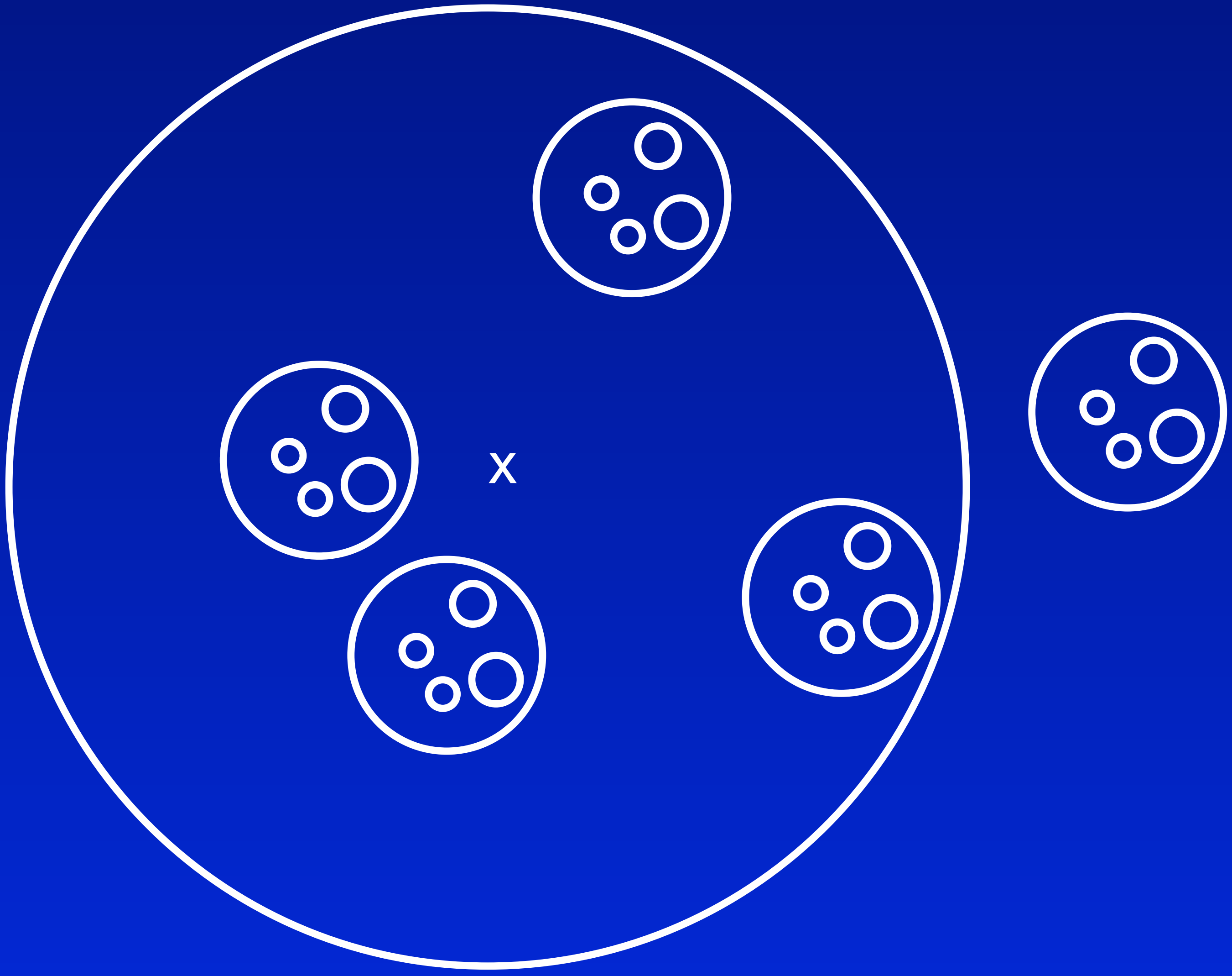
Substructures within substructures



There are substructures embedded within other structures. We detect 4 generations of nested subhalos.

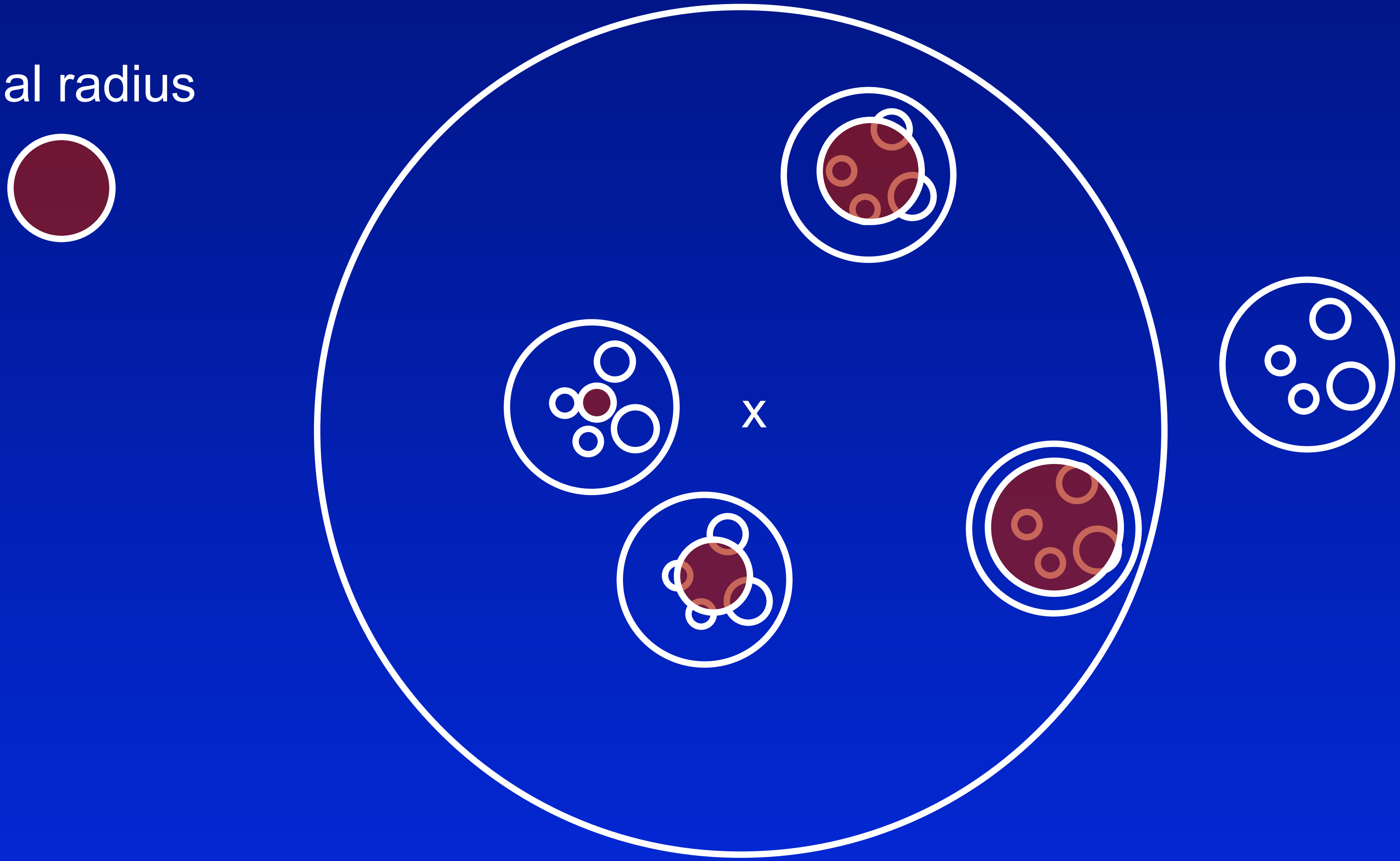
The hierarchy clearly is NOT self-similar and is heavily dependent on the degree of tidal stripping of the subhalo

A “fractal” distribution of nested substructures?



Tidal effects limit sub-substructures

Tidal radius

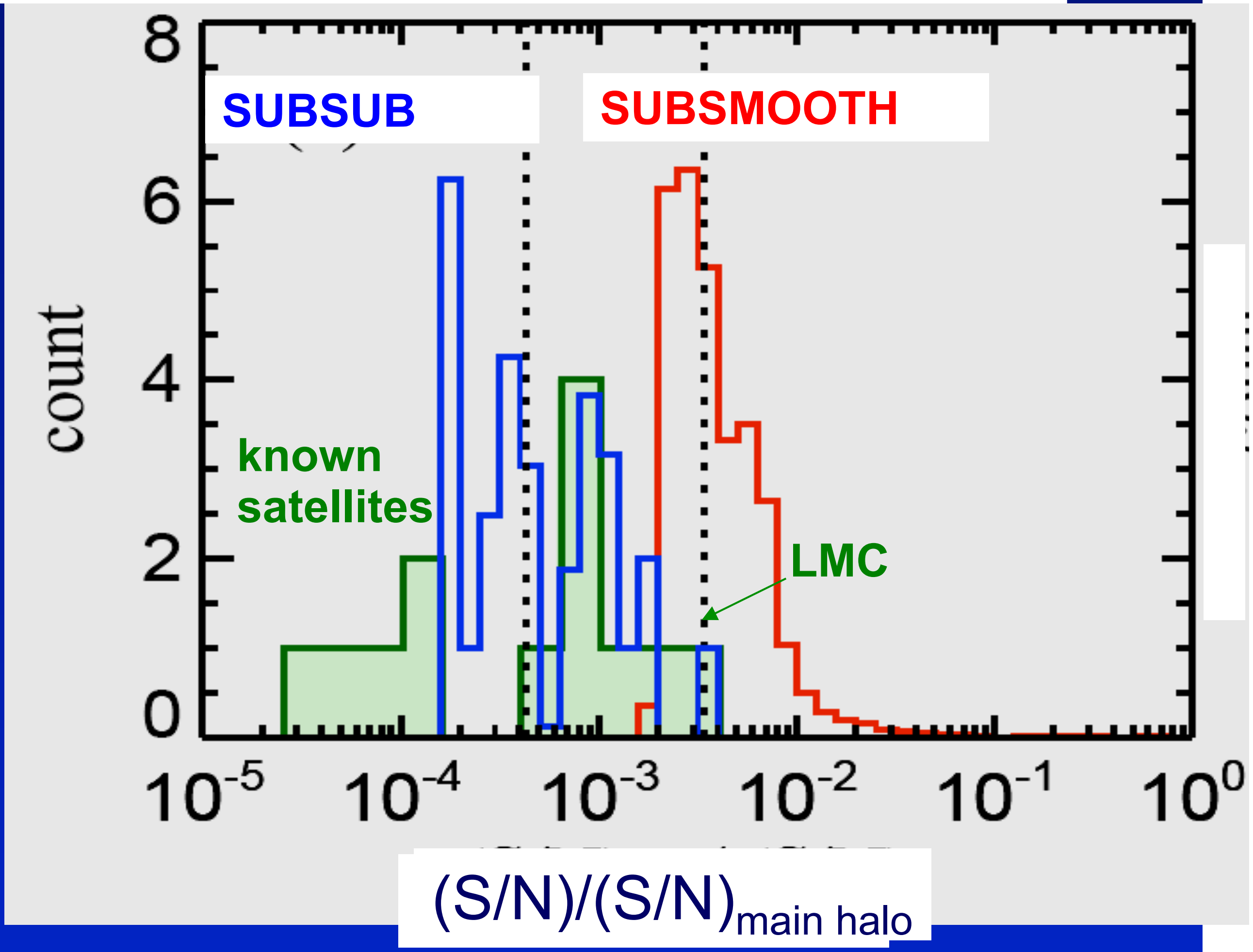


Detectability of substructure

- $S/N = F/(\theta^2_h + \theta^2_{psf})^{1/2}$

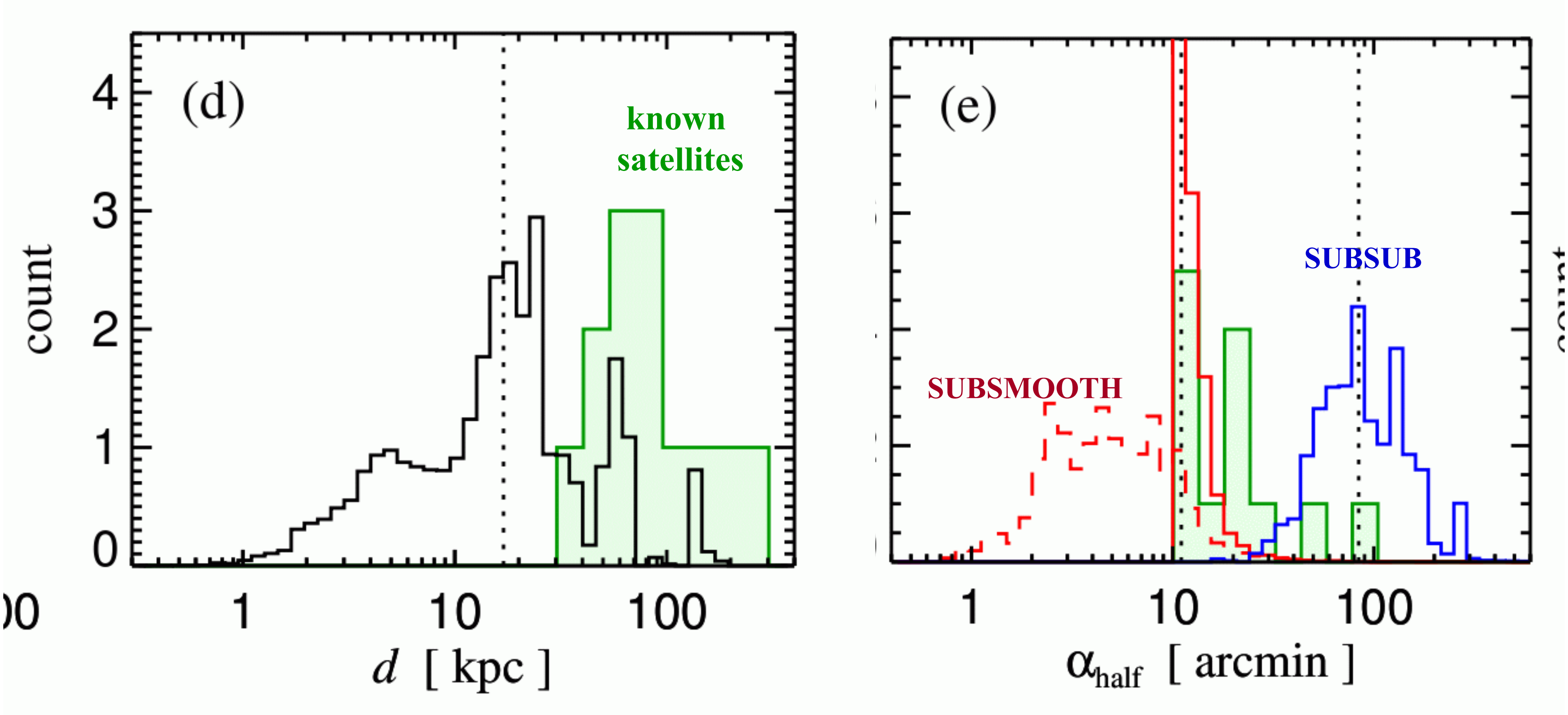
- S/N for detecting subhalos in units of that for detecting the main halo.

- 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 5-10 times S/N of known satellites
- Substructure of subhalos has no influence on detectability

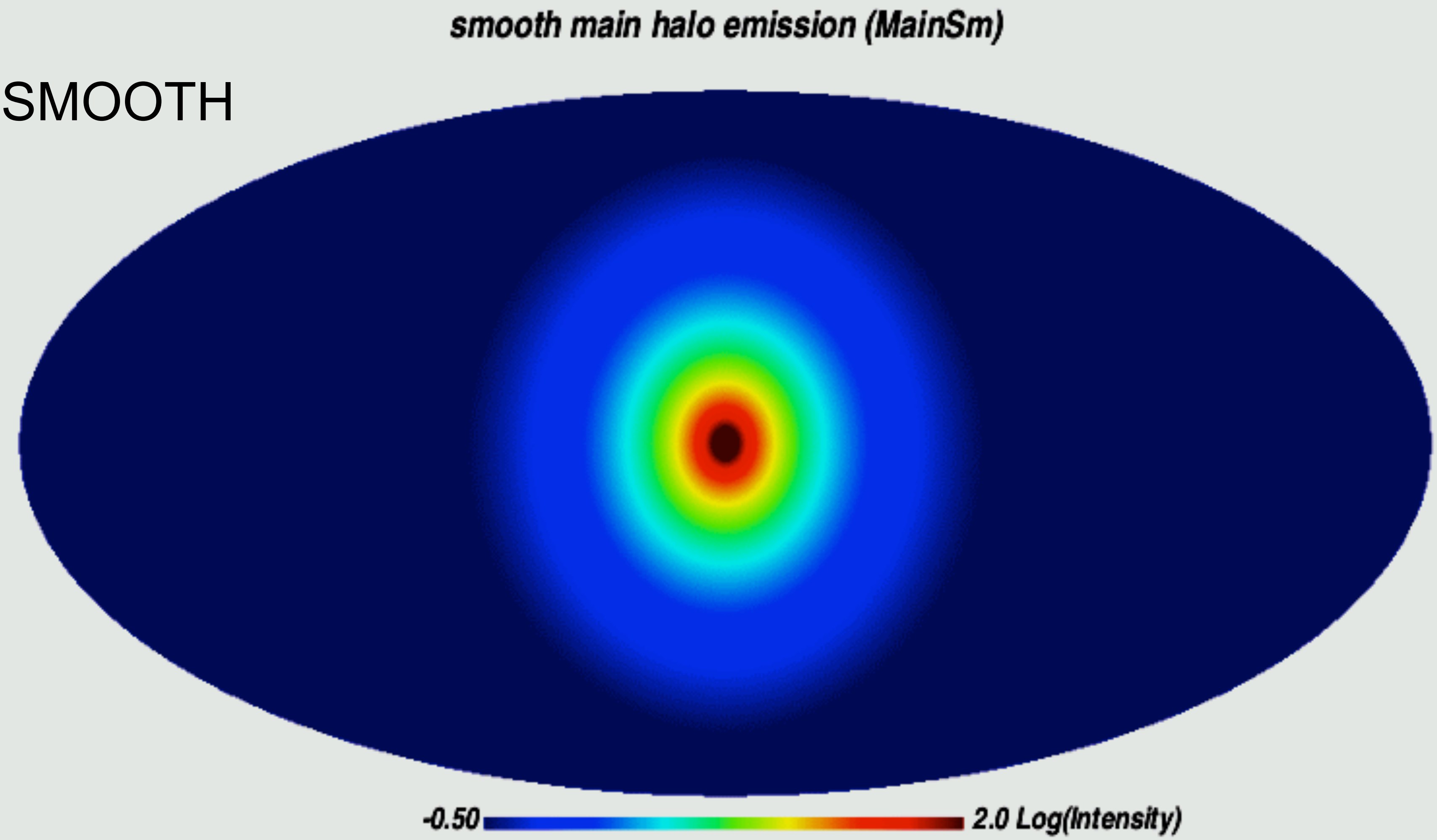
Distance and angular scale of most detectable substructures



- Highest S/N subhalos have half-light radii below 10 arcmin and will not be resolved by FERMI/GLAST

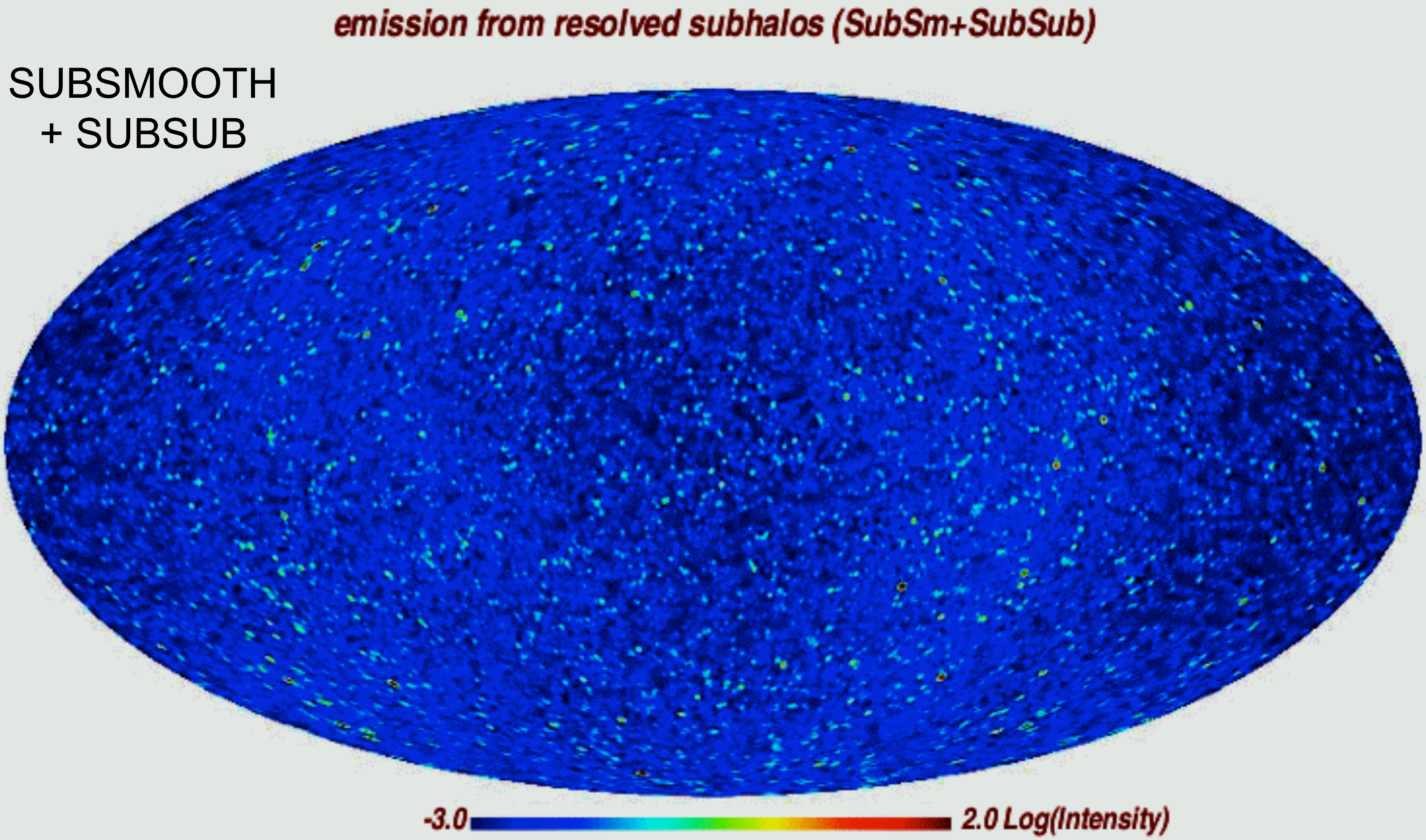
The gamma-ray sky lit by annihilation radiation

MAINSMOOTH



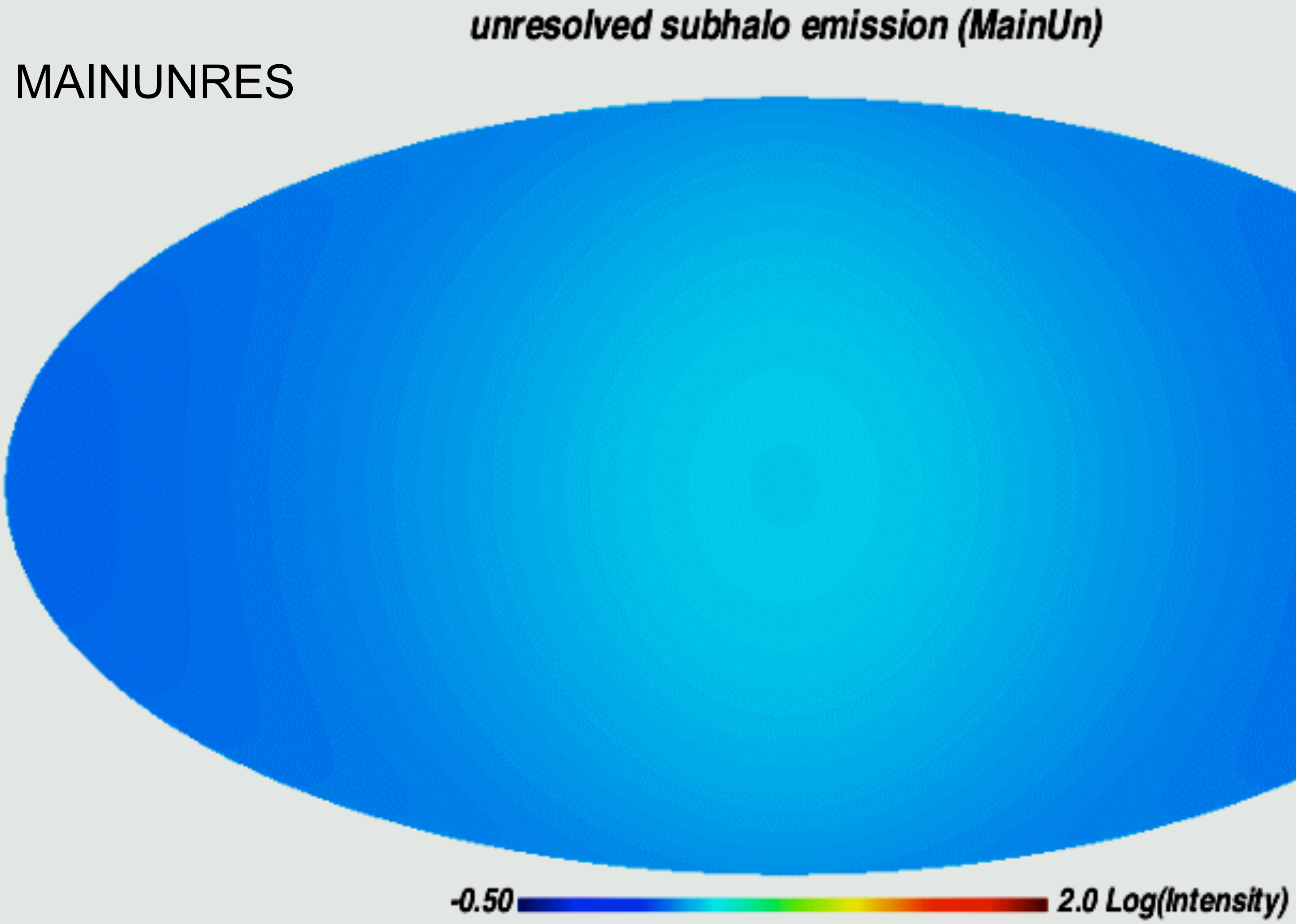
The gamma-ray sky lit by annihilation radiation

SUBSMOOTH
+ SUBSUB



The gamma-ray sky lit by annihilation radiation

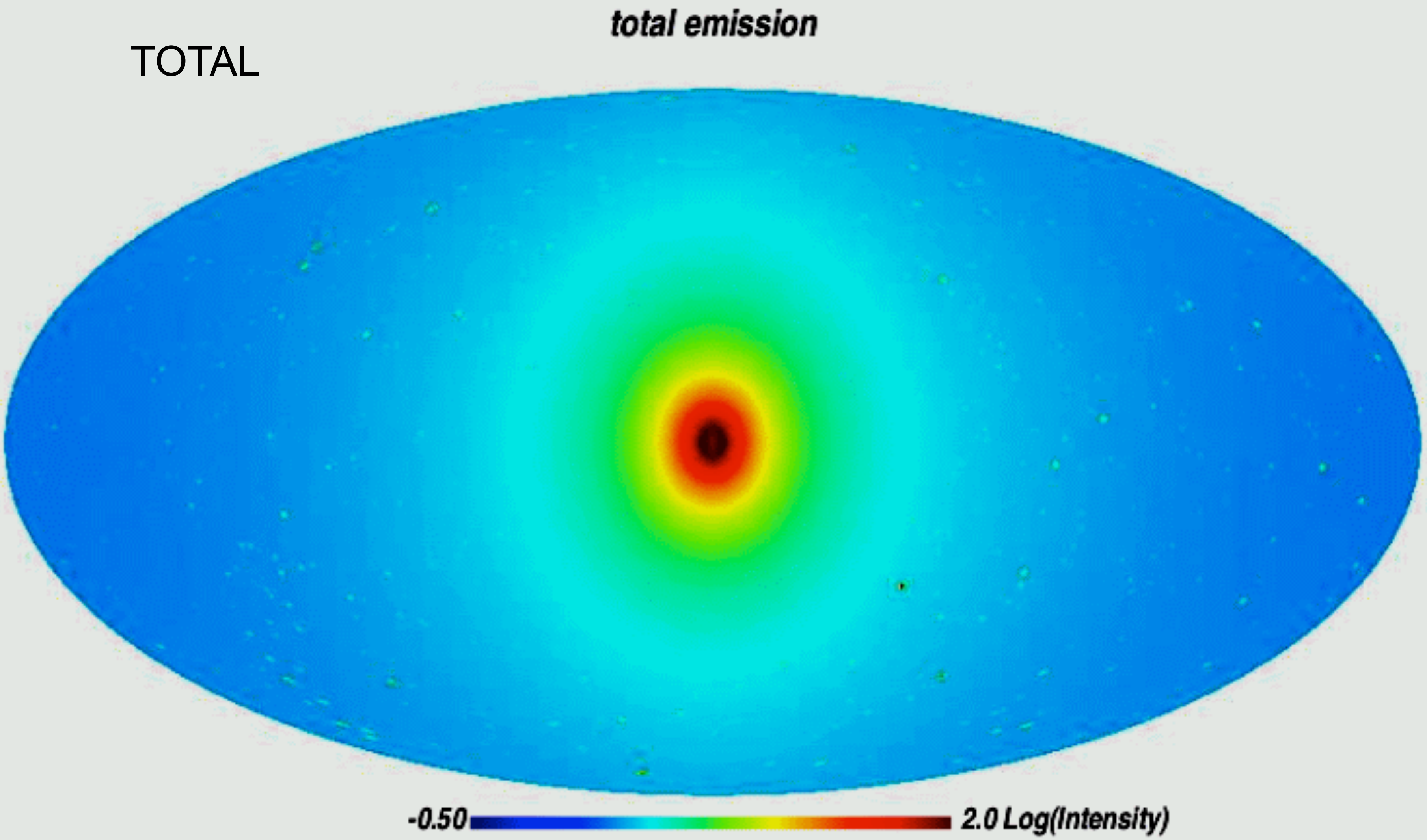
MAINUNRES



unresolved subhalo emission (MainUn)

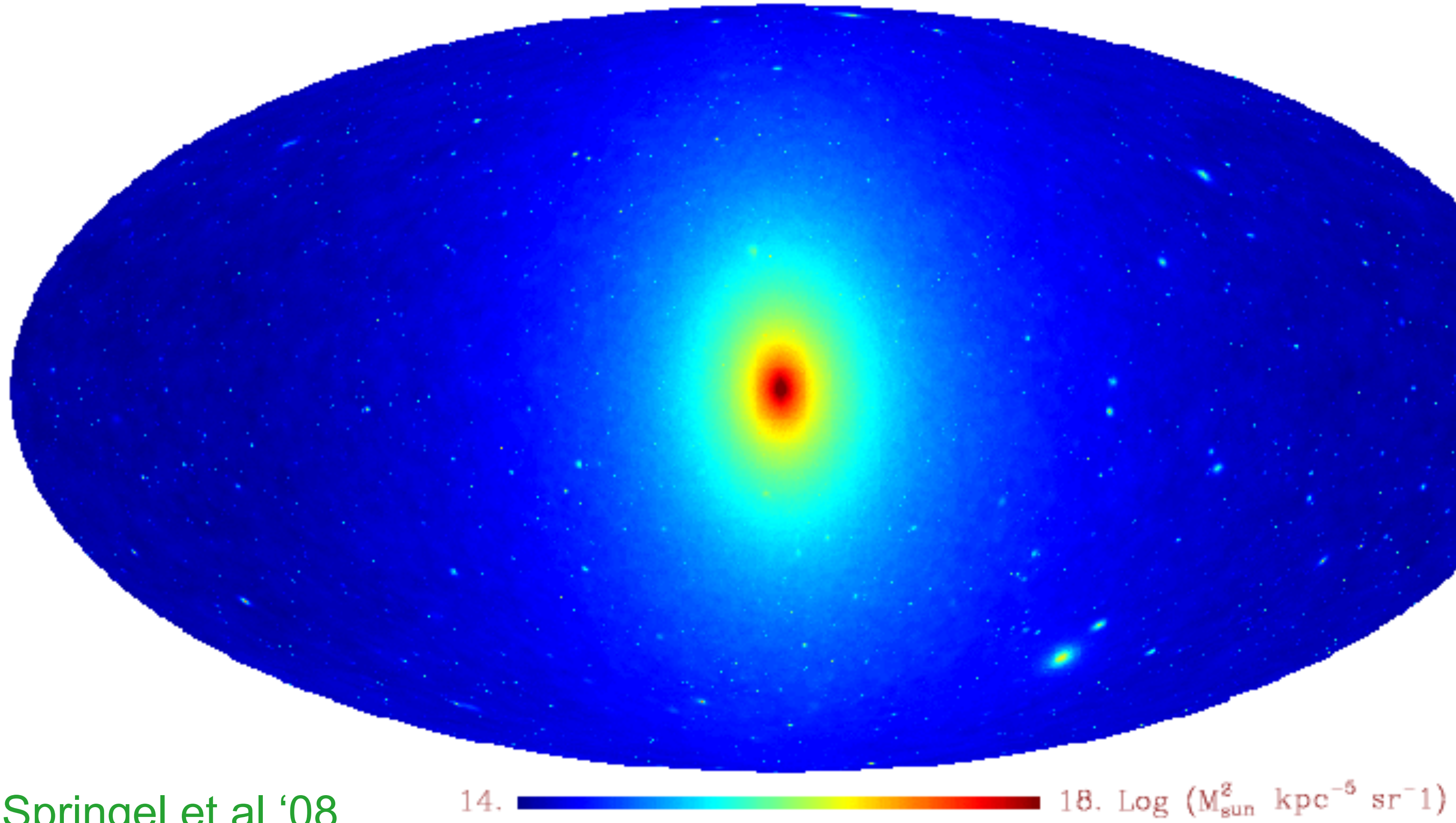
The gamma-ray sky lit by annihilation radiation

TOTAL



The gamma-ray sky lit by annihilation radiation

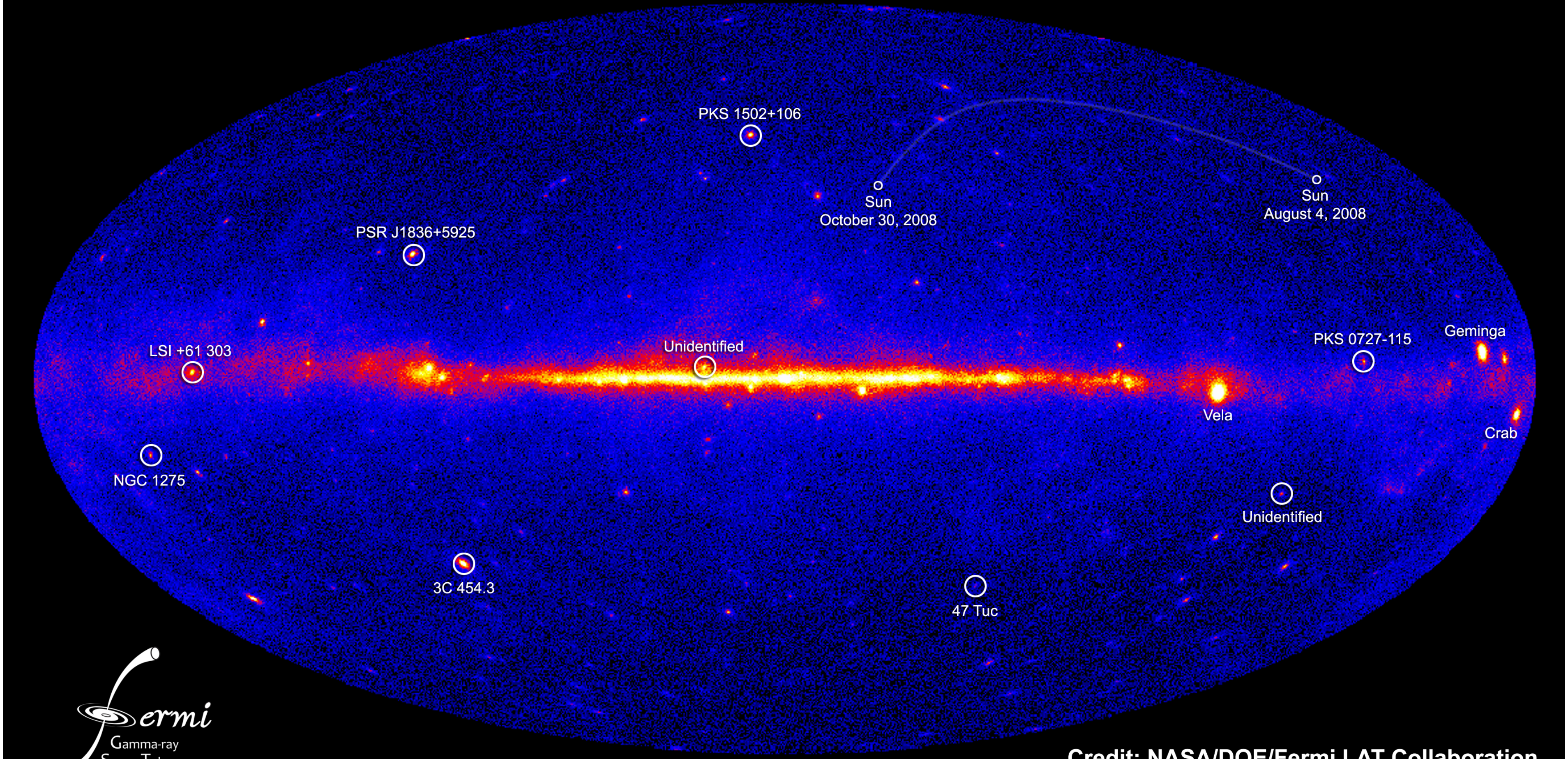
Aquarius simulation: $N_{200} = 1.1 \times 10^9$



Springel et al ‘08

The gamma-ray sky as seen by Fermi

NASA's Fermi telescope reveals best-ever view of the gamma-ray sky



Fermi
Gamma-ray
Space Telescope

Credit: NASA/DOE/Fermi LAT Collaboration

The End

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