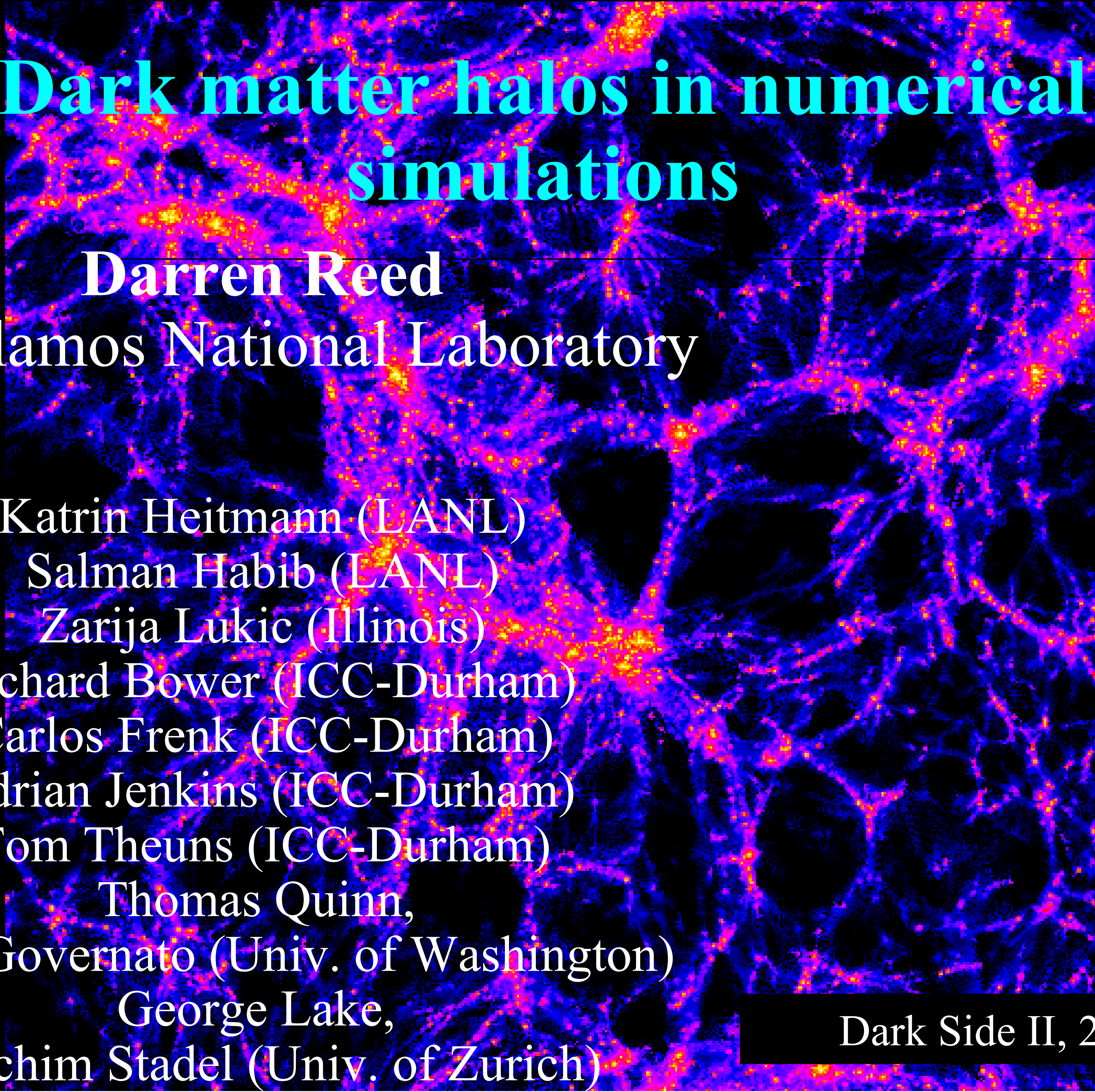

Dark matter halos in numerical simulations

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Richard Bower (ICC-Durham)
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Adrian Jenkins (ICC-Durham)
Tom Theuns (ICC-Durham)
Thomas Quinn,
Fabio Governato (Univ. of Washington)
George Lake,
Joachim Stadel (Univ. of Zurich)

Dark Side II, 2008

Overview

- What is a dark matter halo?
- Why simulate dark matter? Link P(k) (@ high redshift) to:
    - Halo numbers (how many?)
    - Halo distribution (where?)
    - Halo internal structure
- Problems
    - Simulation difficulties
    - CDM difficulties
- Conclusions

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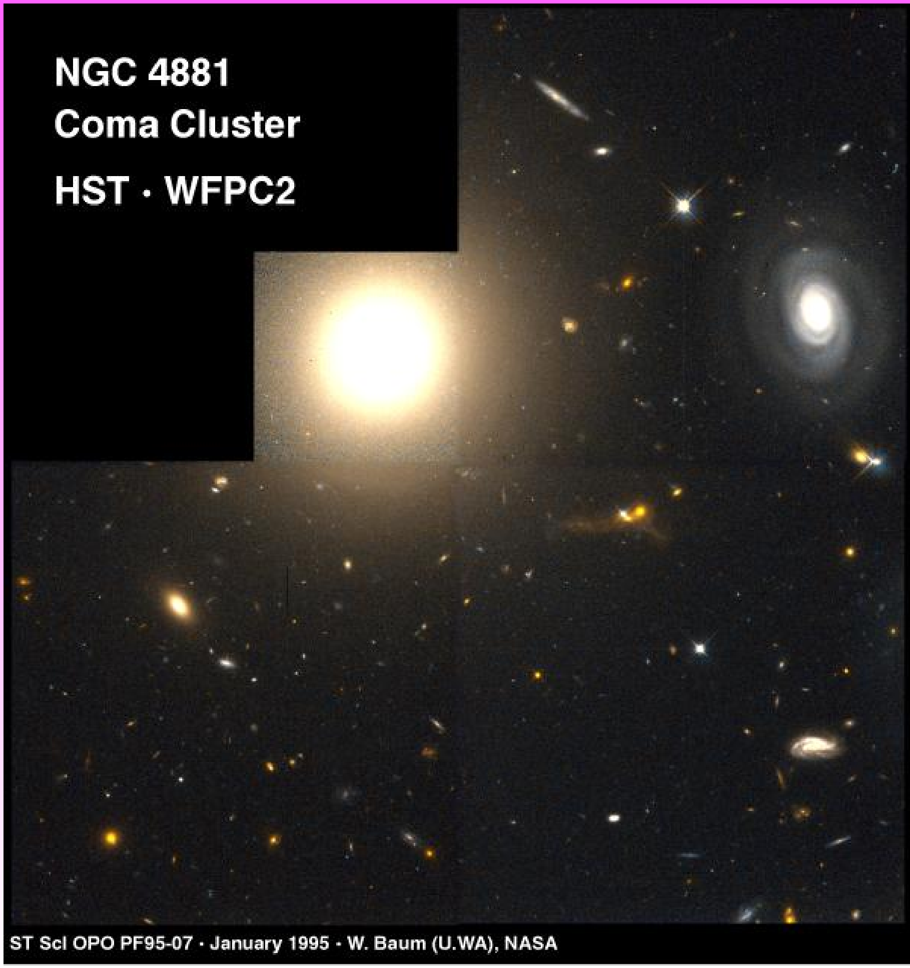
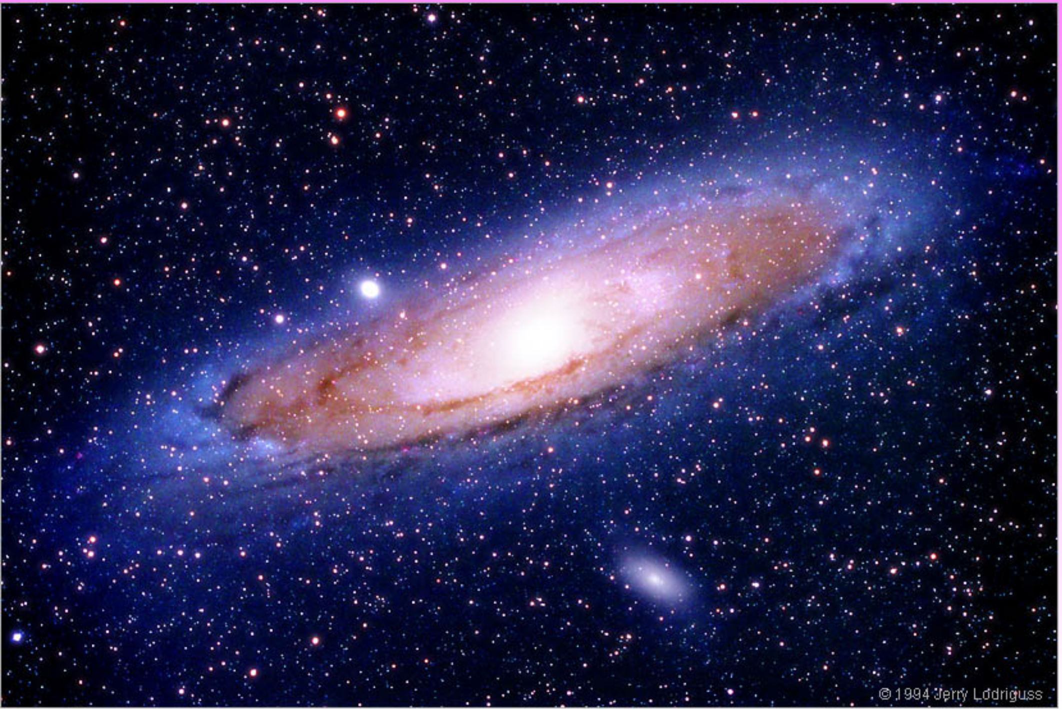
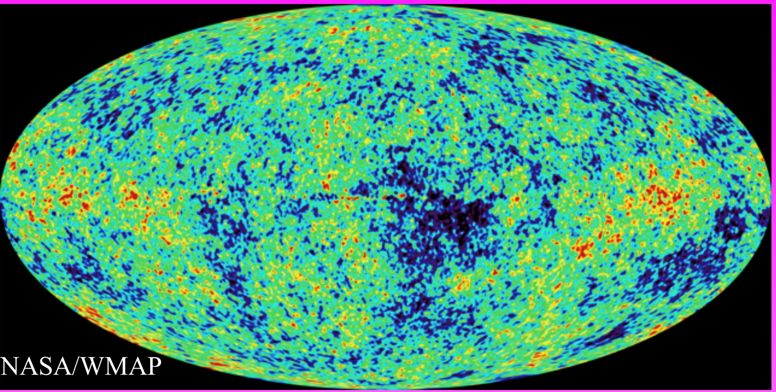
What are dark matter halos?

- Bound, collapsed, virialized, ellipsoids
- Hosts to galaxies, groups, and clusters
- Rotation curves, lensing, x-rays $\longrightarrow$ Dark matter
- Overdensity $\Delta \sim 200$





Simulation Techniques

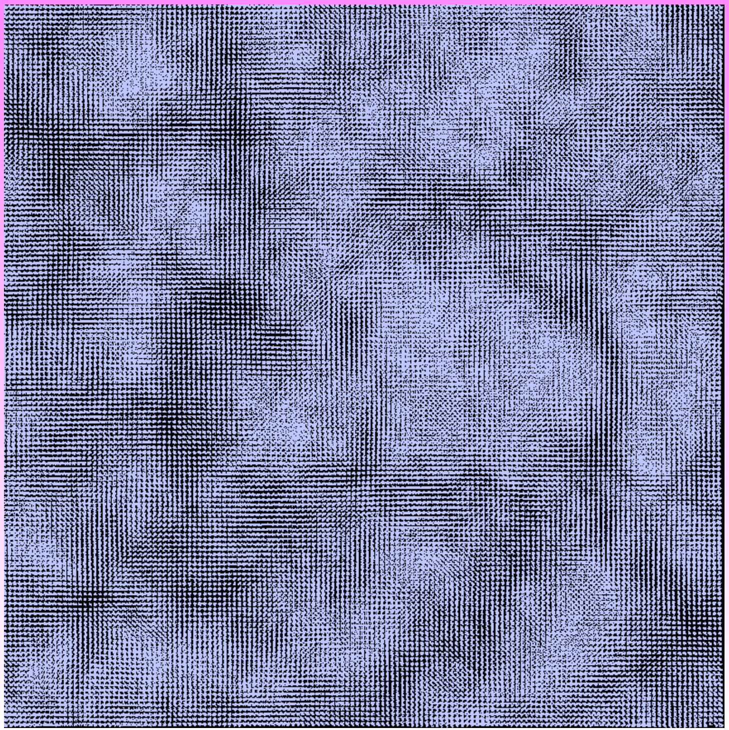


+ Hi-z SNe, 2df, etc. →

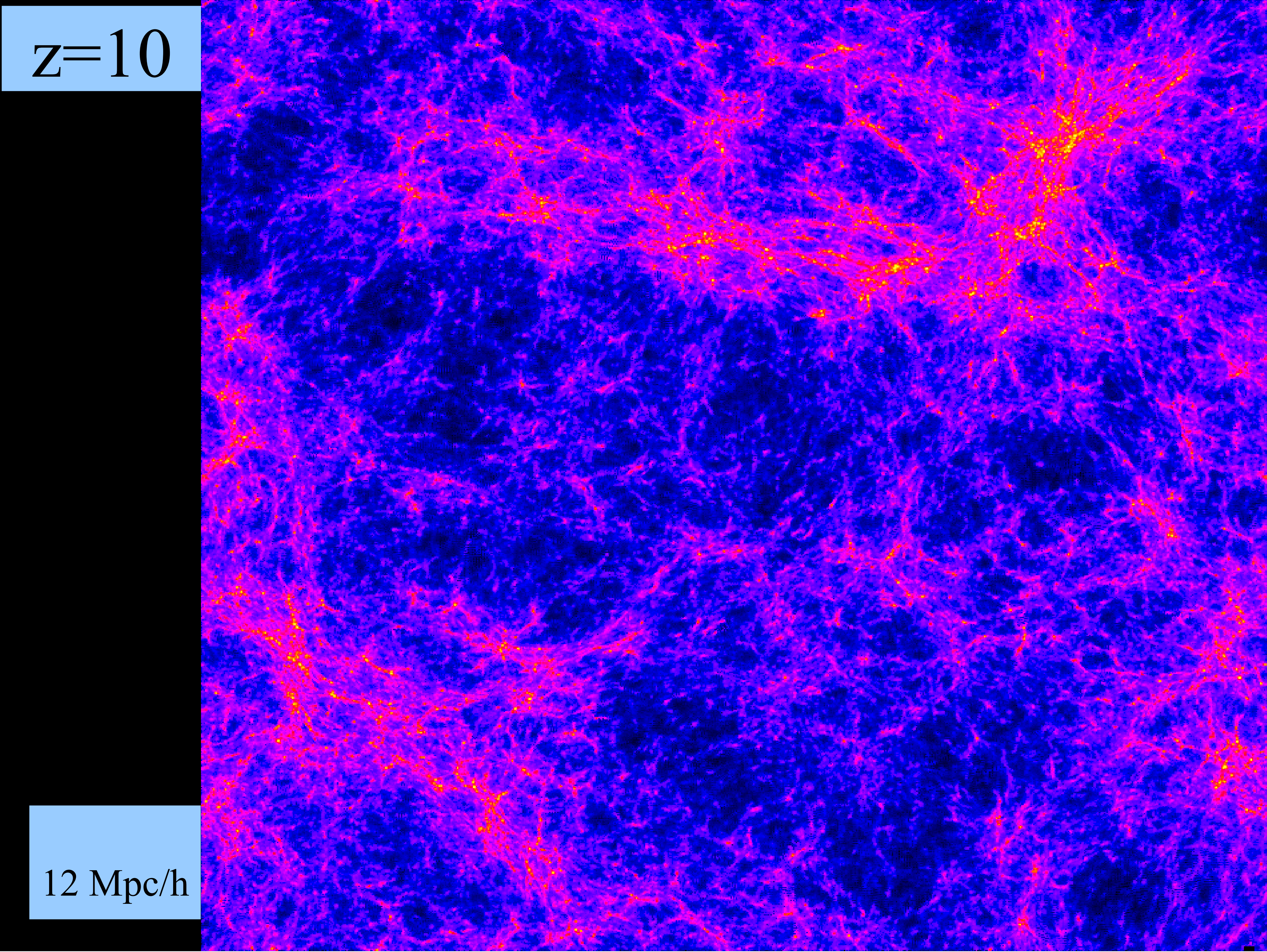
Cosmological parameters:
(Ω=0.25, Λ=0.75, σ_8=0.9, H_0=73, n_s=1)

σ_8: amplitude of power spectrum, (rms mass fluctuation of 8 Mpc/h spheres)

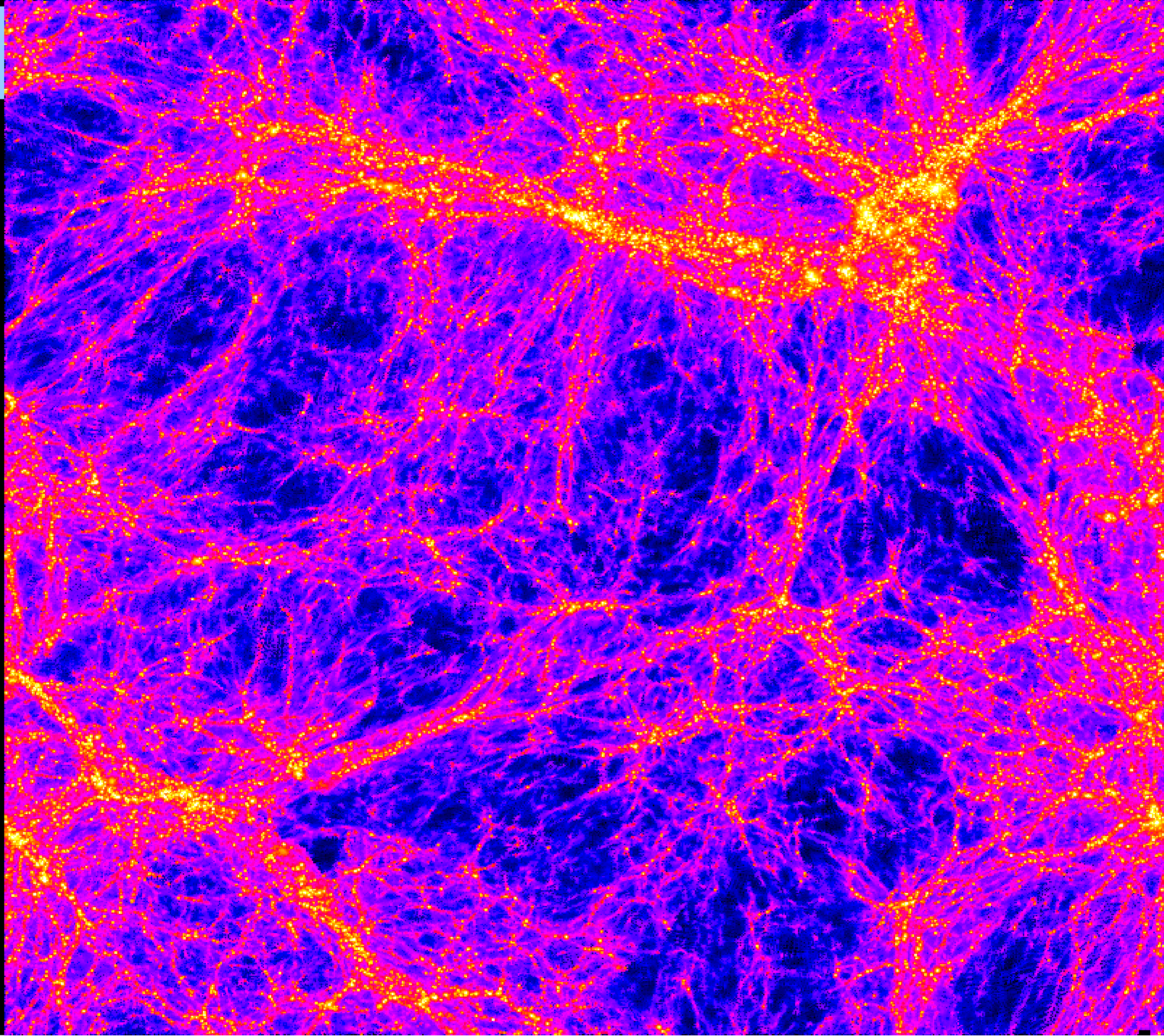
→ High-z (linear) gaussian random realization →



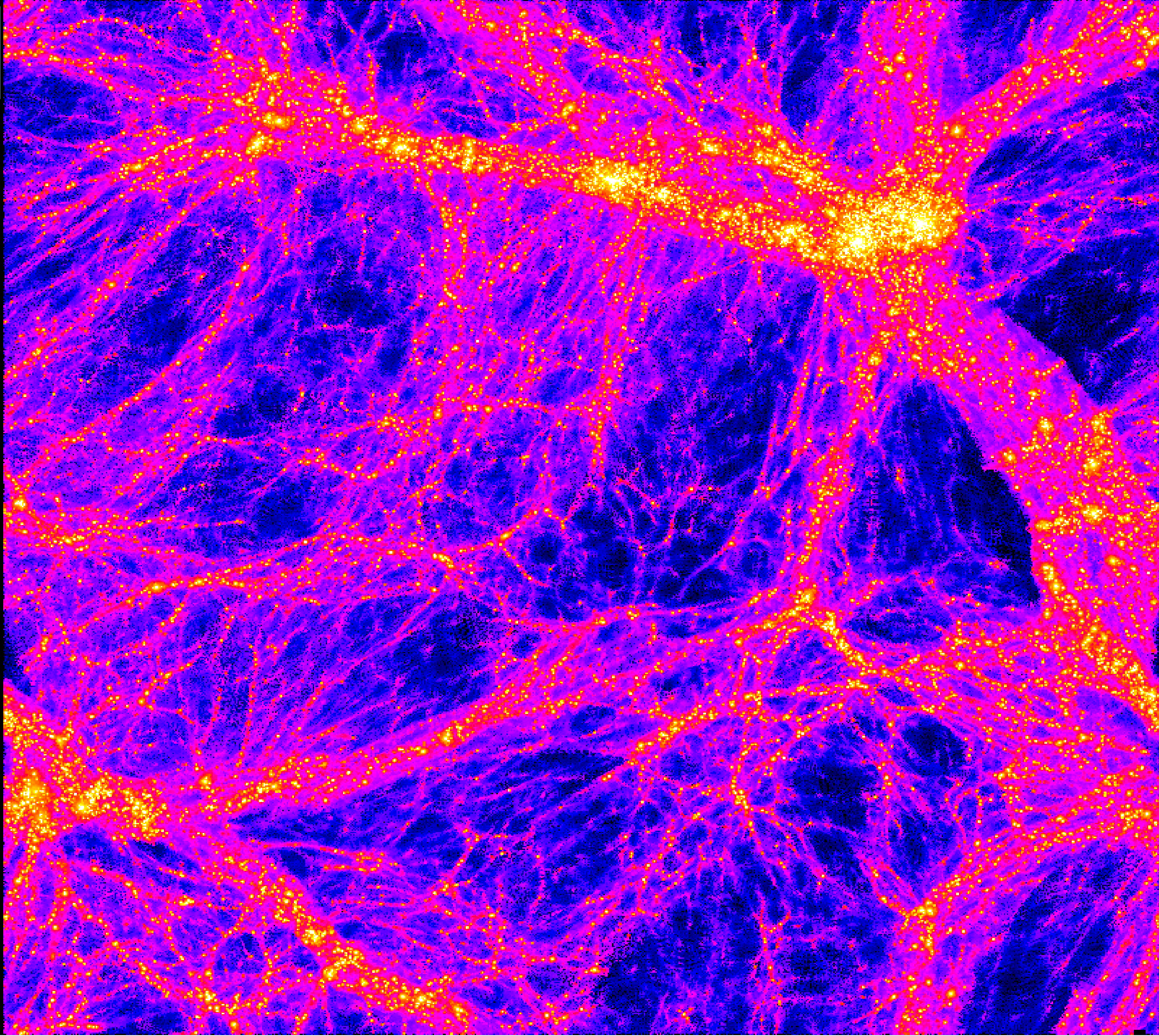
→ Evolve particles (gravity)
L-GADGET2 (PM-tree code V. Springel)
GASOLINE (Stadel, Wadsley, Quinn)


z=10
12 Mpc/h

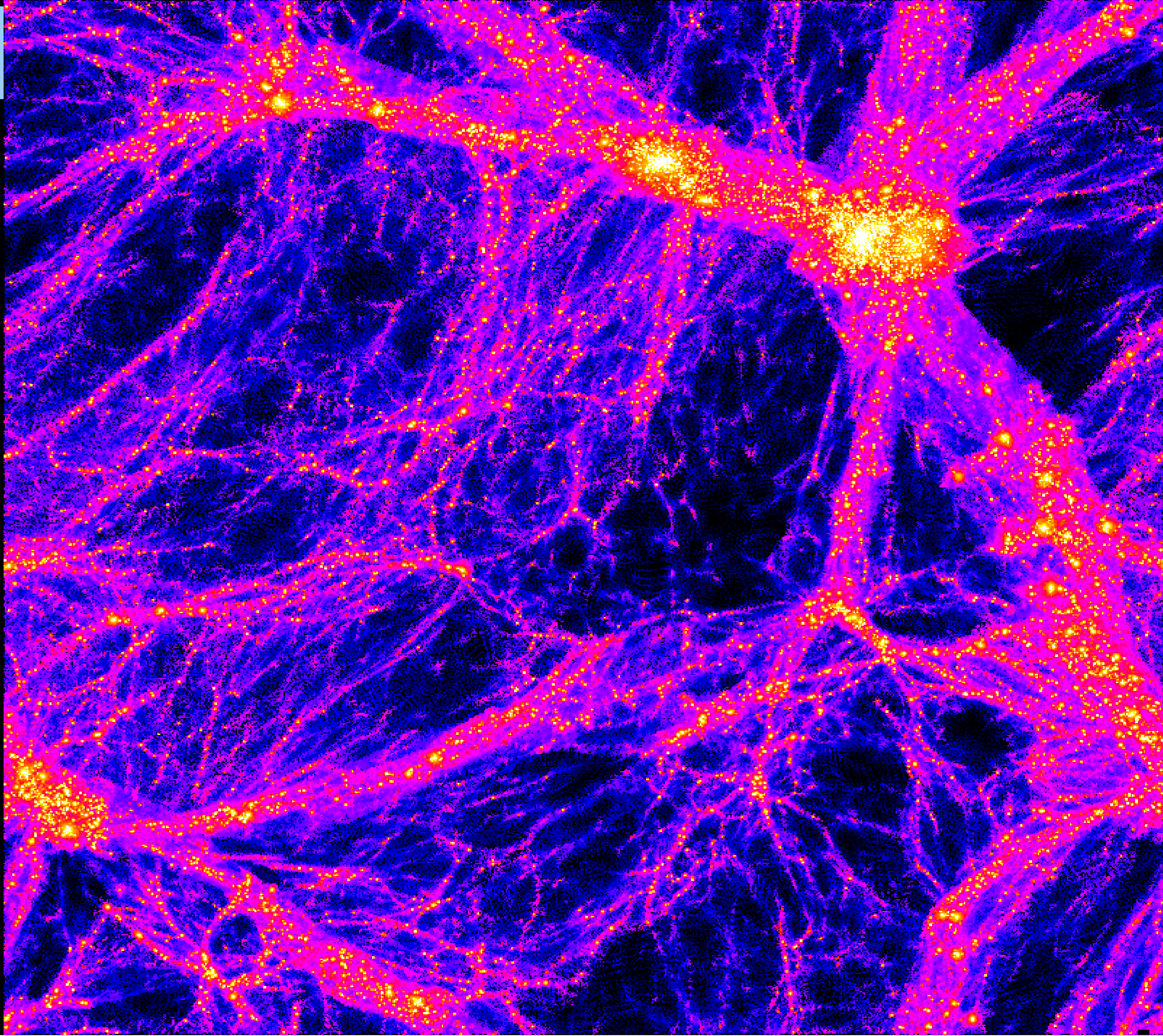
z=3



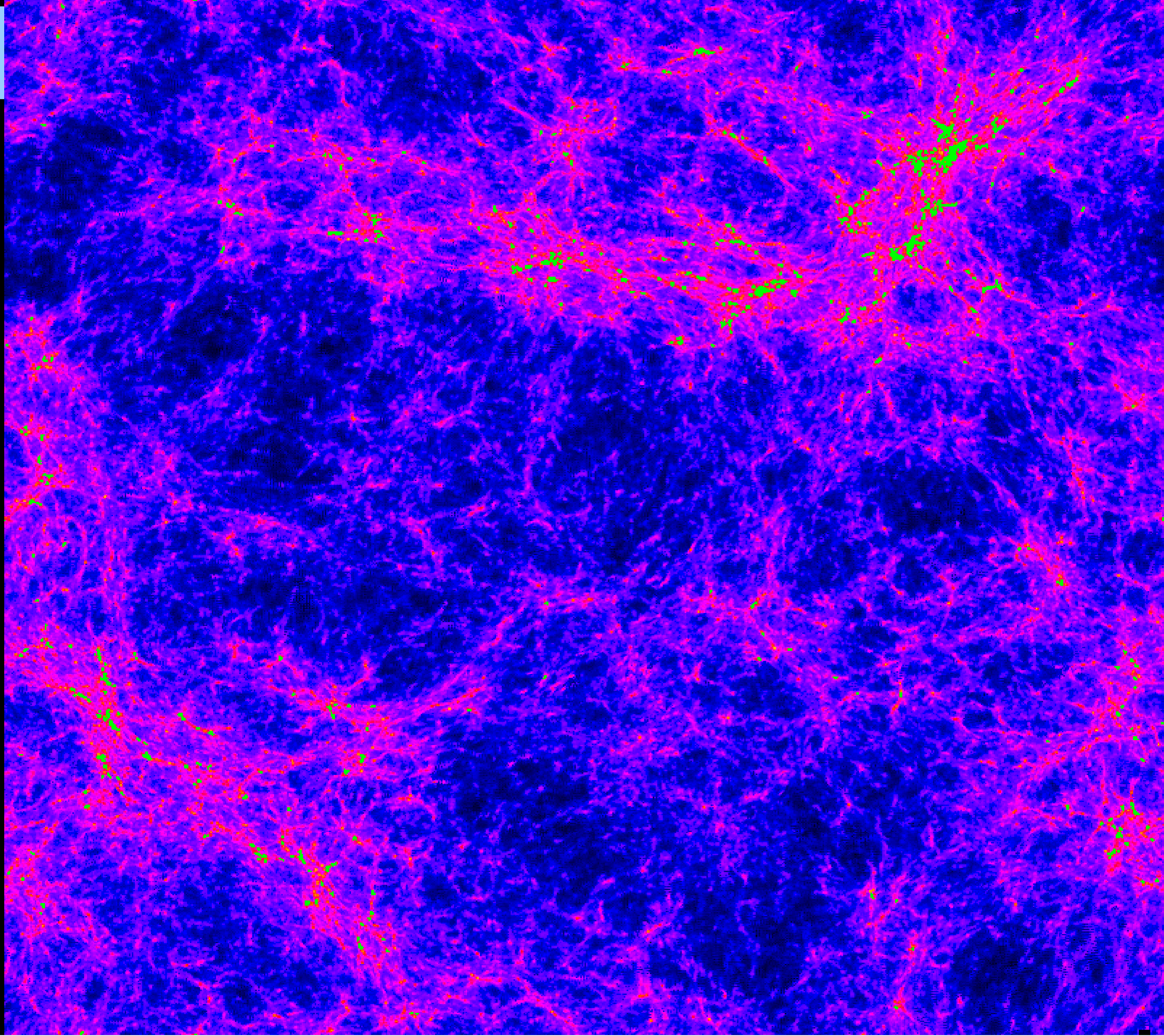
z=1

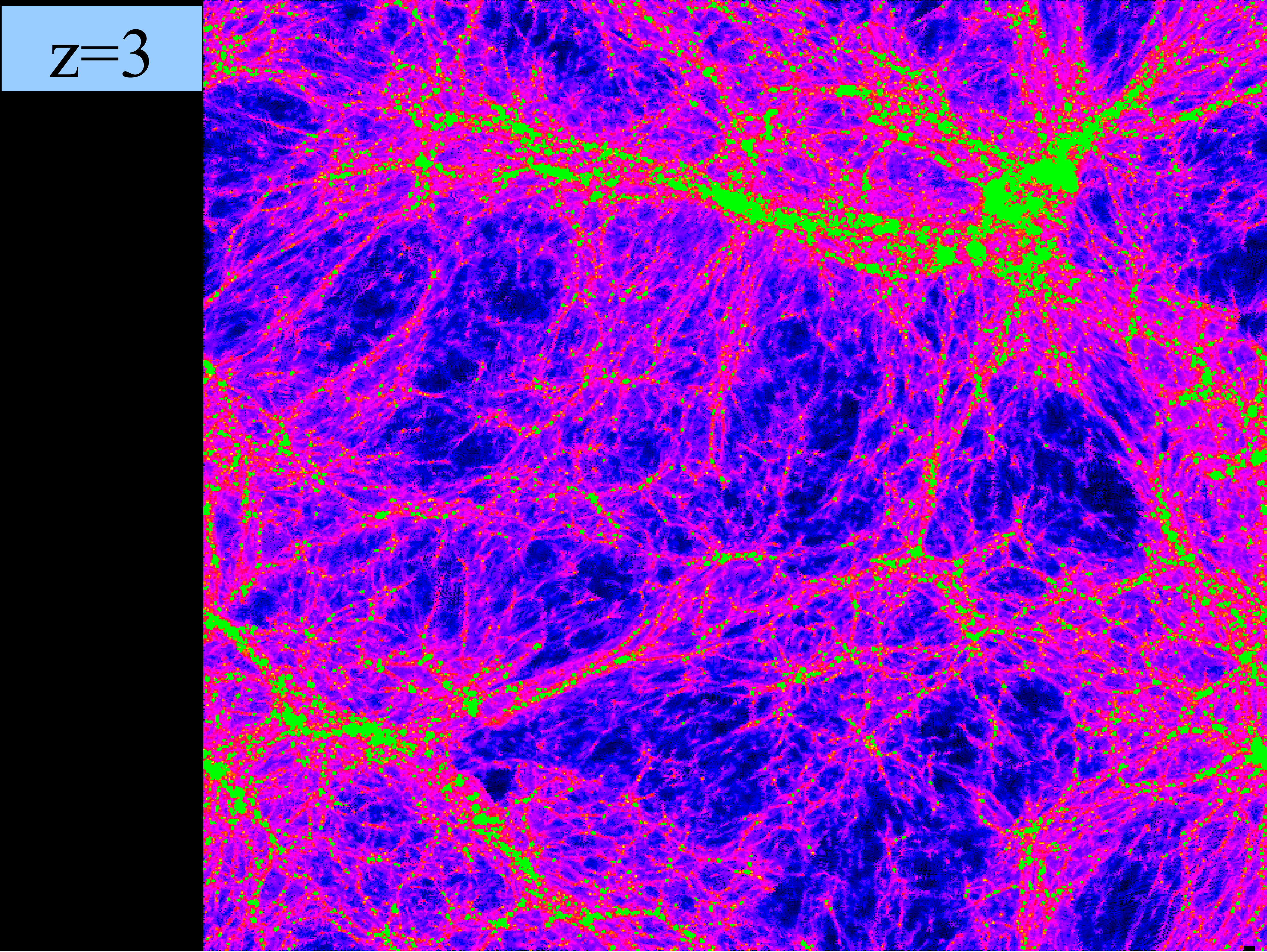


z=0

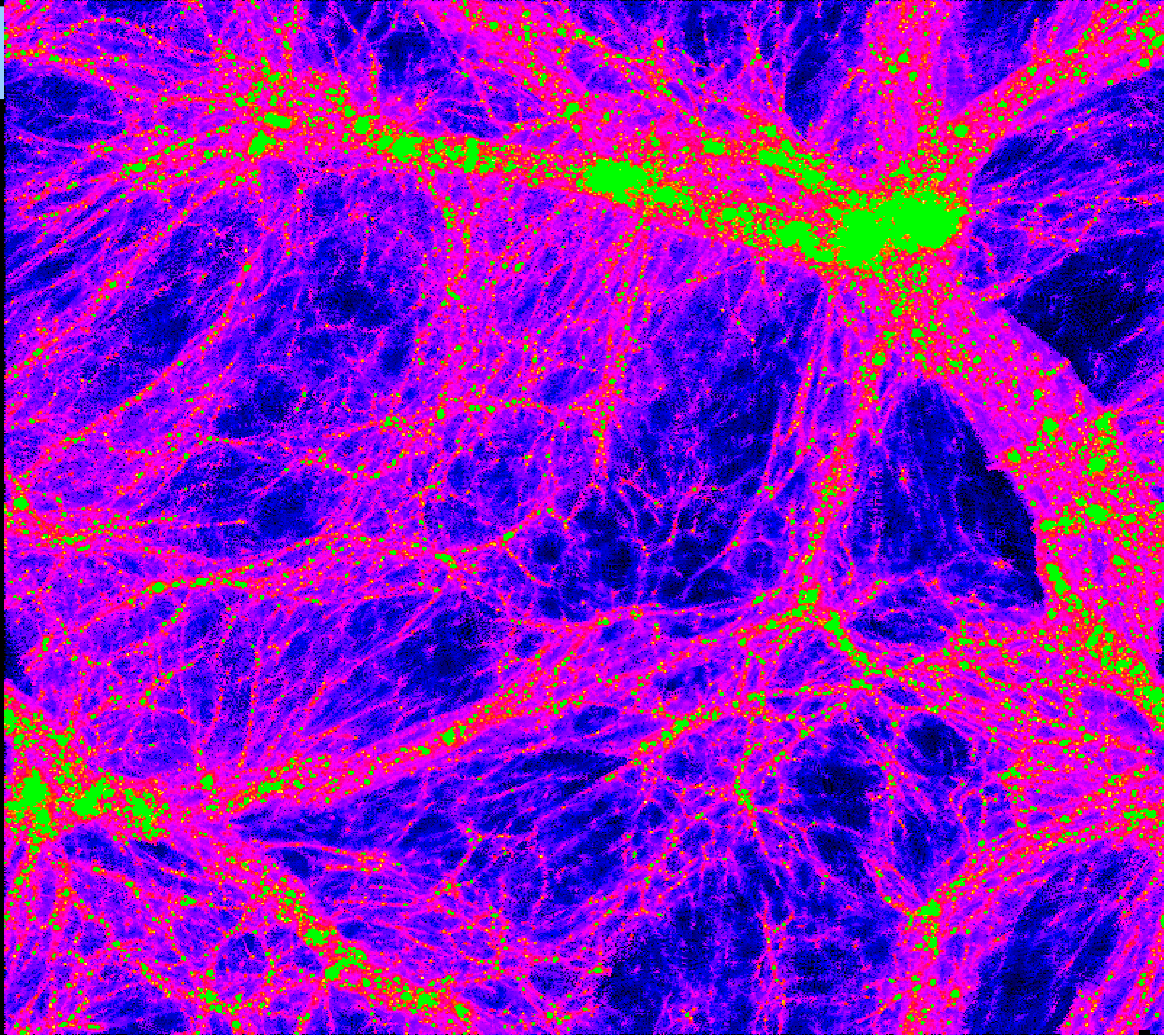


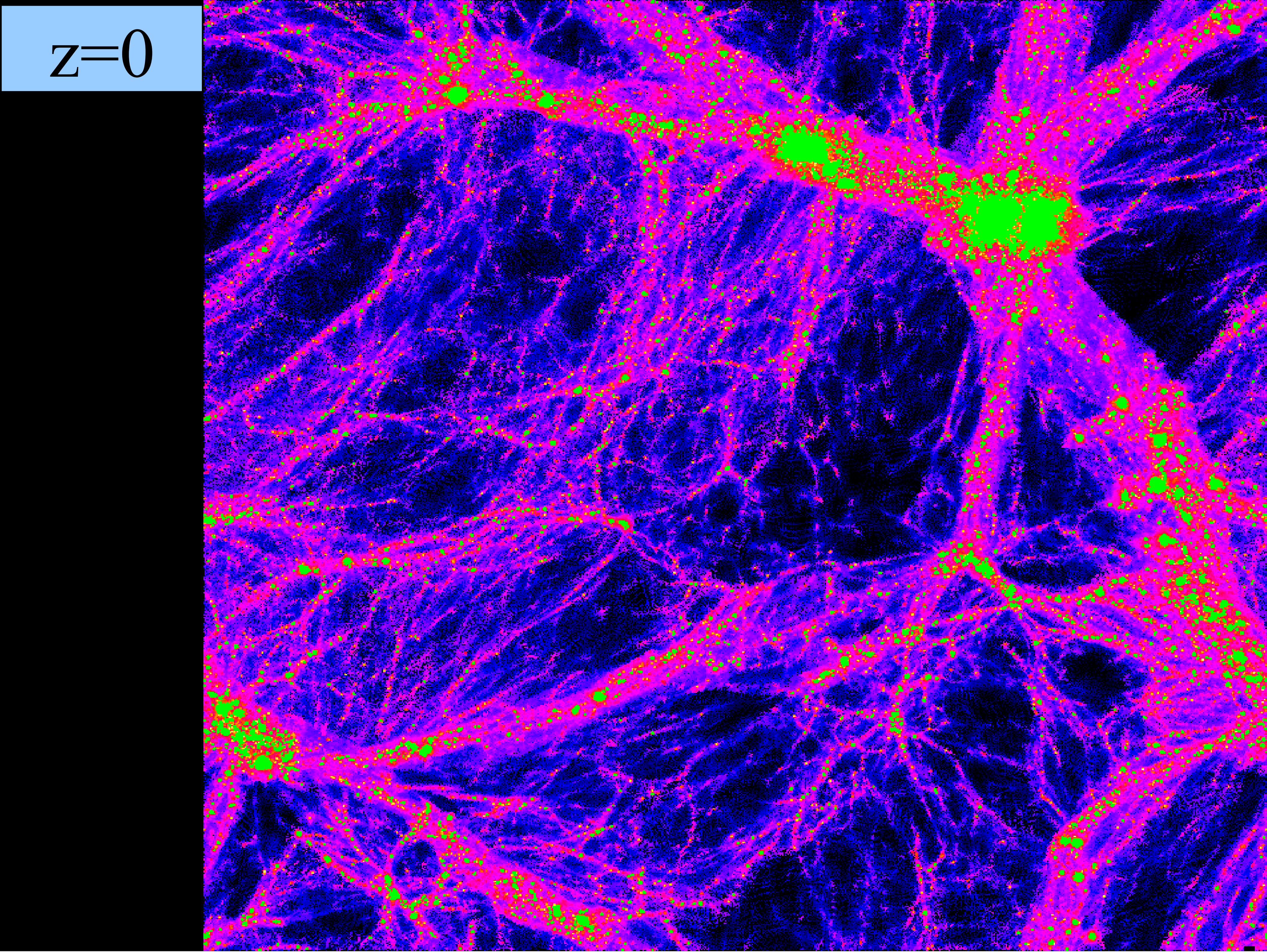
z=10




z=3

z=1




z=0

What is a halo?

friends-of-friends

~iso-density

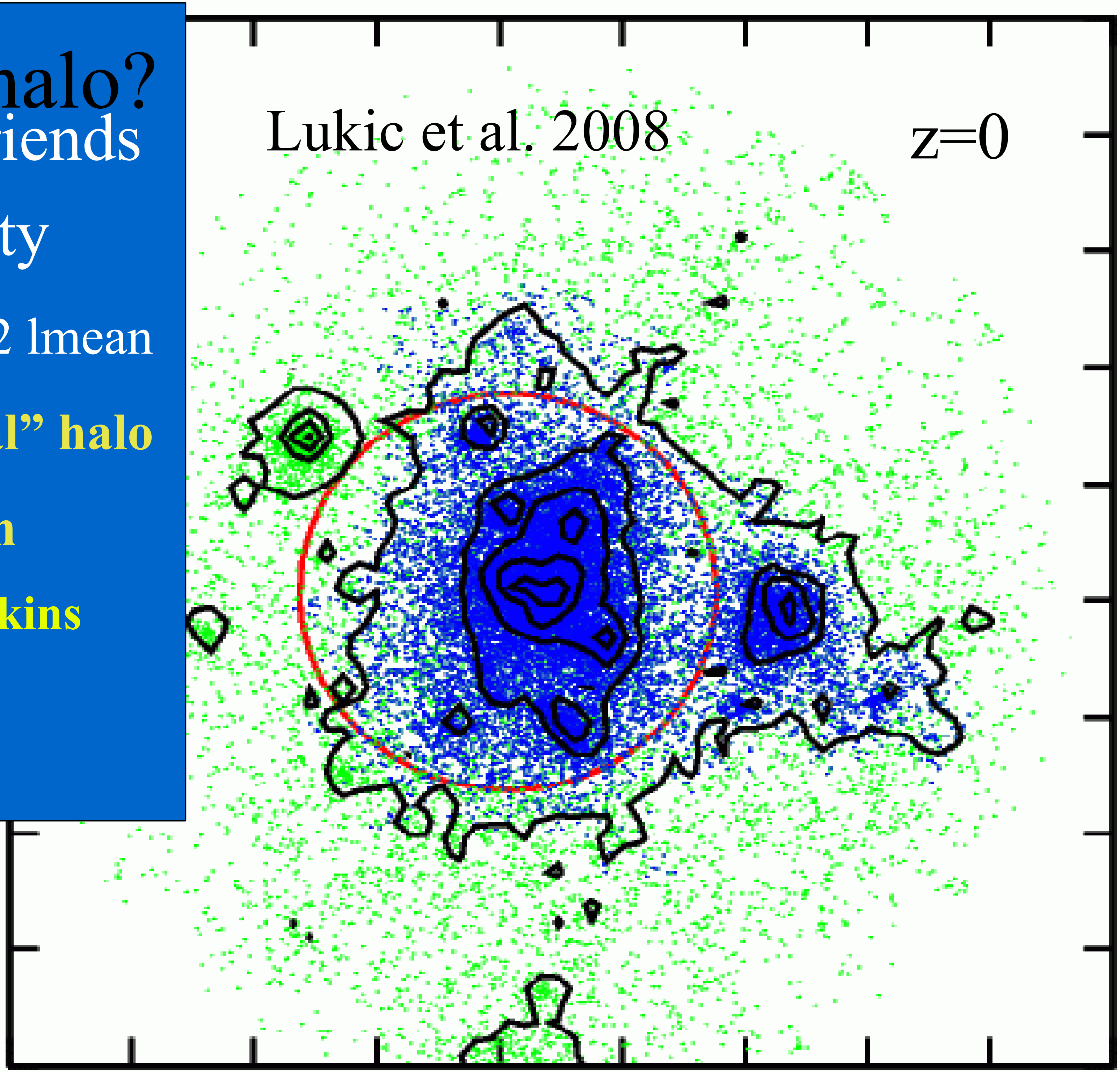
link length ~ 0.2 lmean

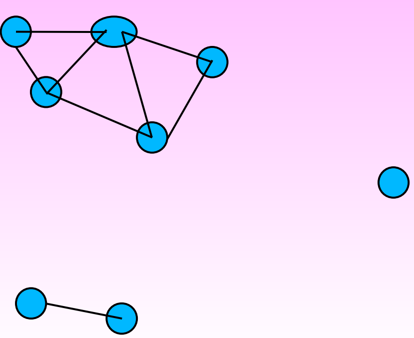
→ **~“universal” halo**

mass function

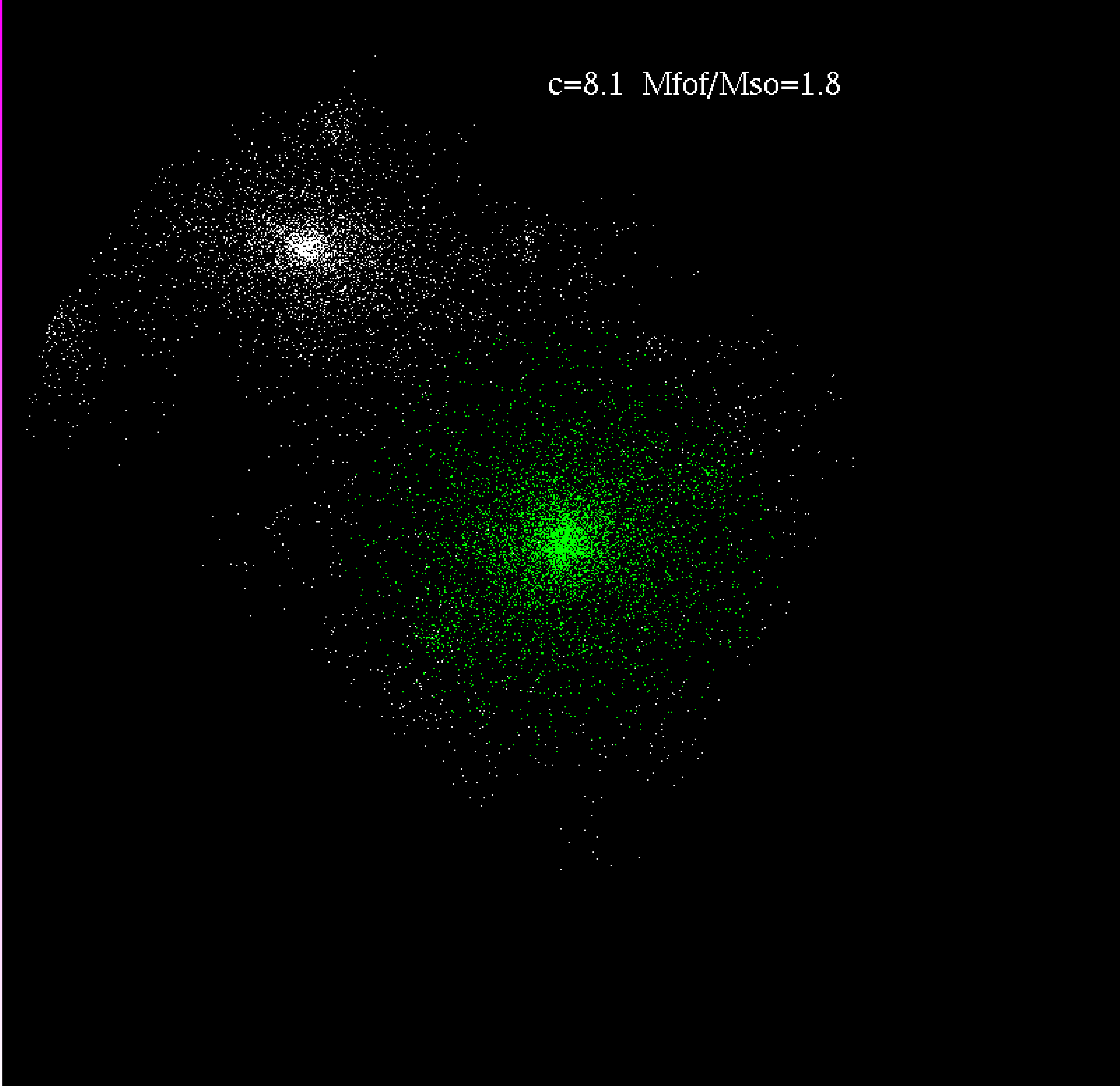
f(σ_{mass}(m)) (Jenkins

et al 2001)

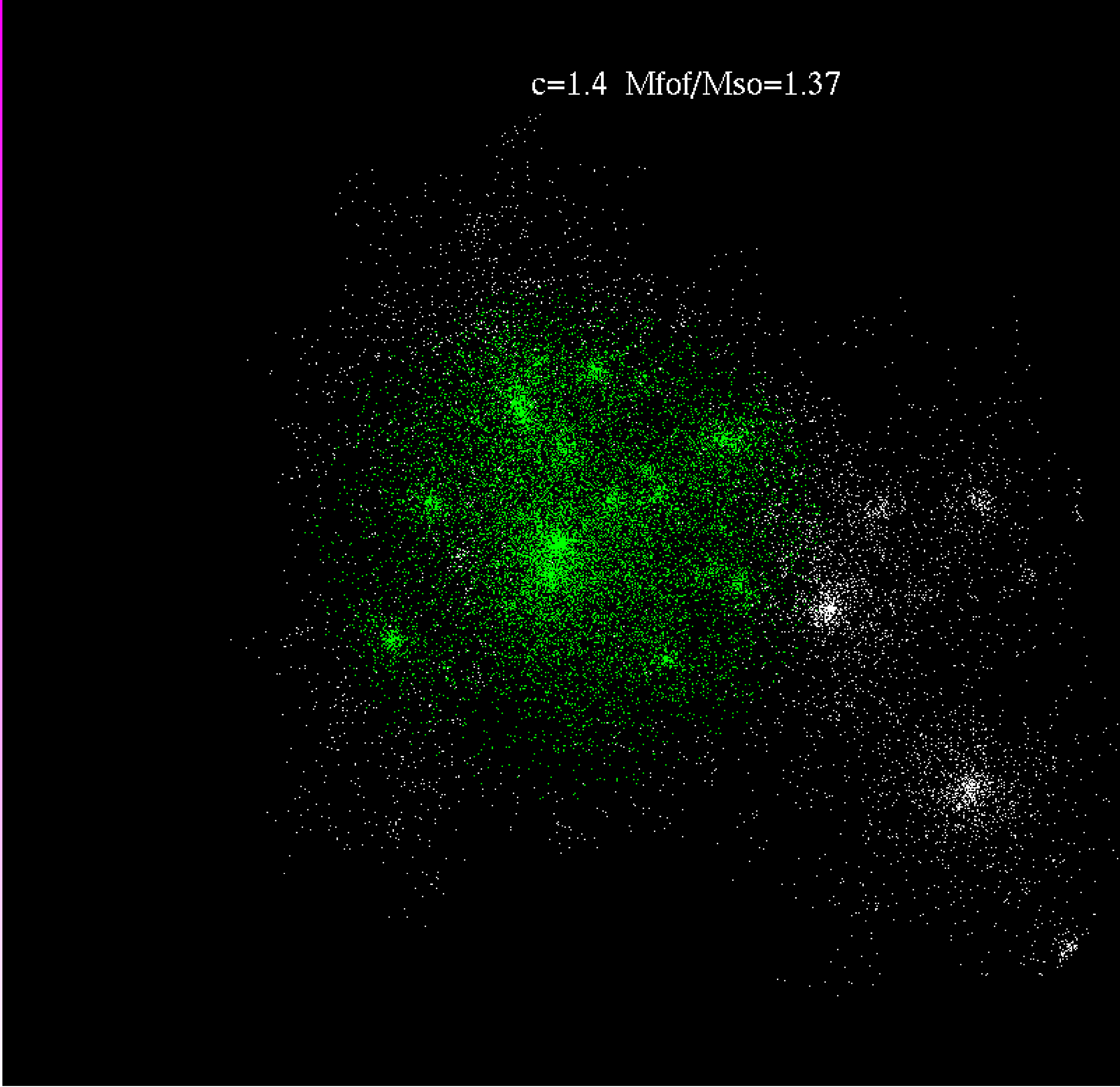




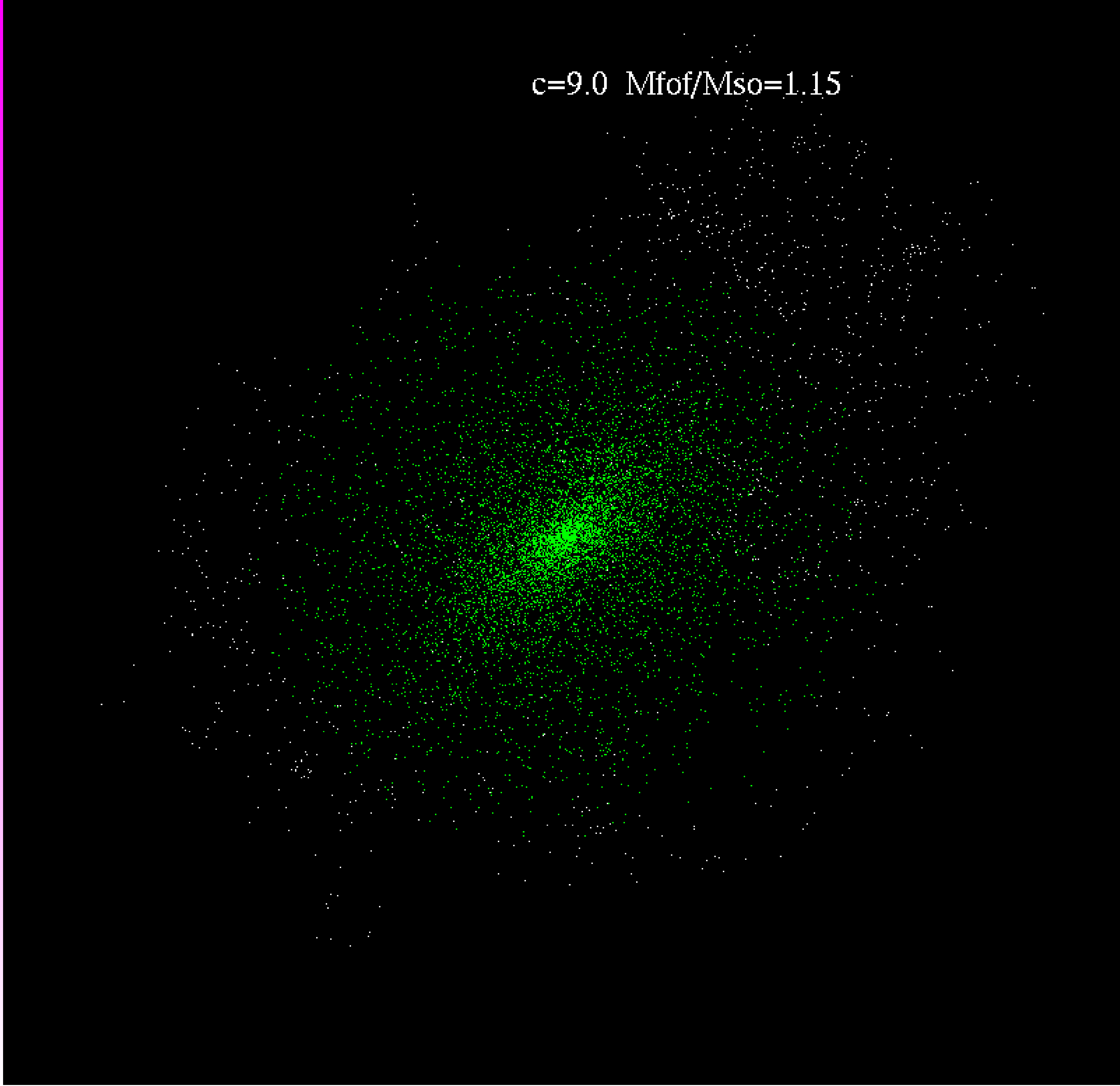
What is a halo?



What is a halo?



What is a halo?



Overview

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why simulate halos?

Cosmological probe:

numbers: e.g. halo numbers vs. cluster numbers

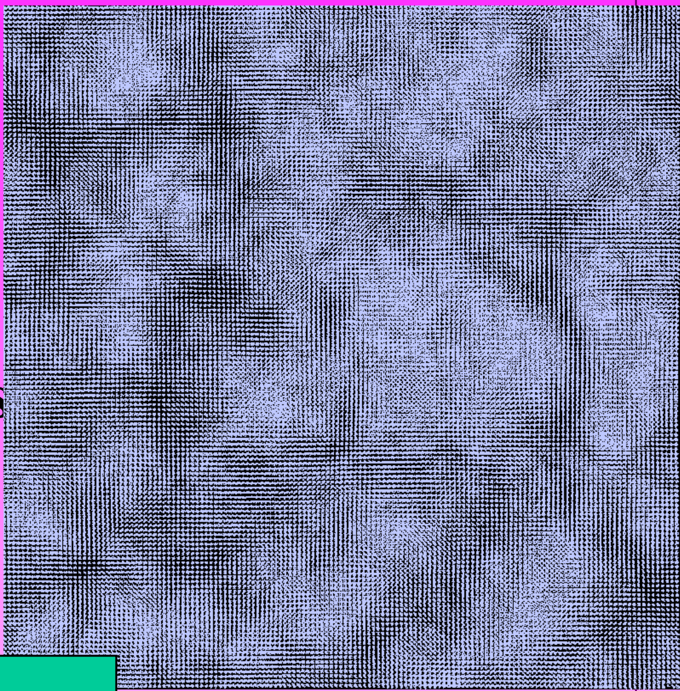
clustering: halo bias relates observable galaxies to underlying mass distribution (p(k))

internal structure: satellite numbers, density profiles

Astrophysics: e.g. galaxy formation

Halos: Press & Schechter approach

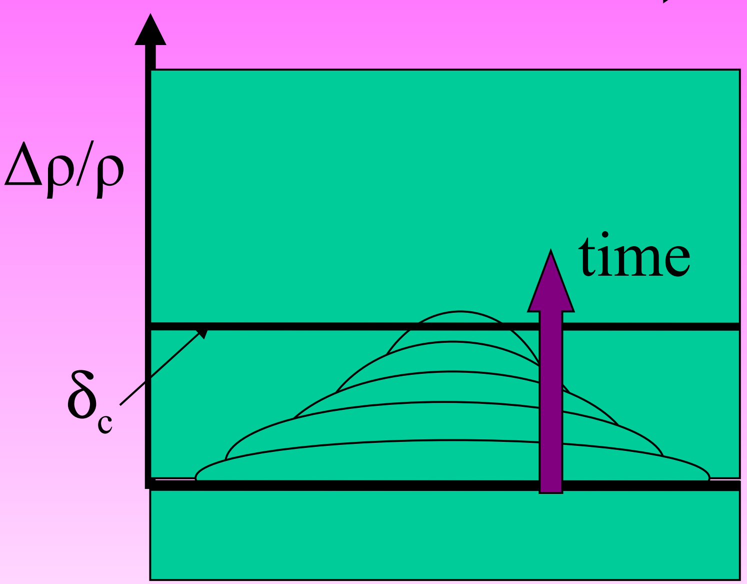
- P(k), initial gaussian random field of linear fluctuations



  – Spherical fluctuations grow (linear, Δρ/ρ) until critical overdensity, **δ_c=1.686**

→ **enclosed mass collapses**

halo forms



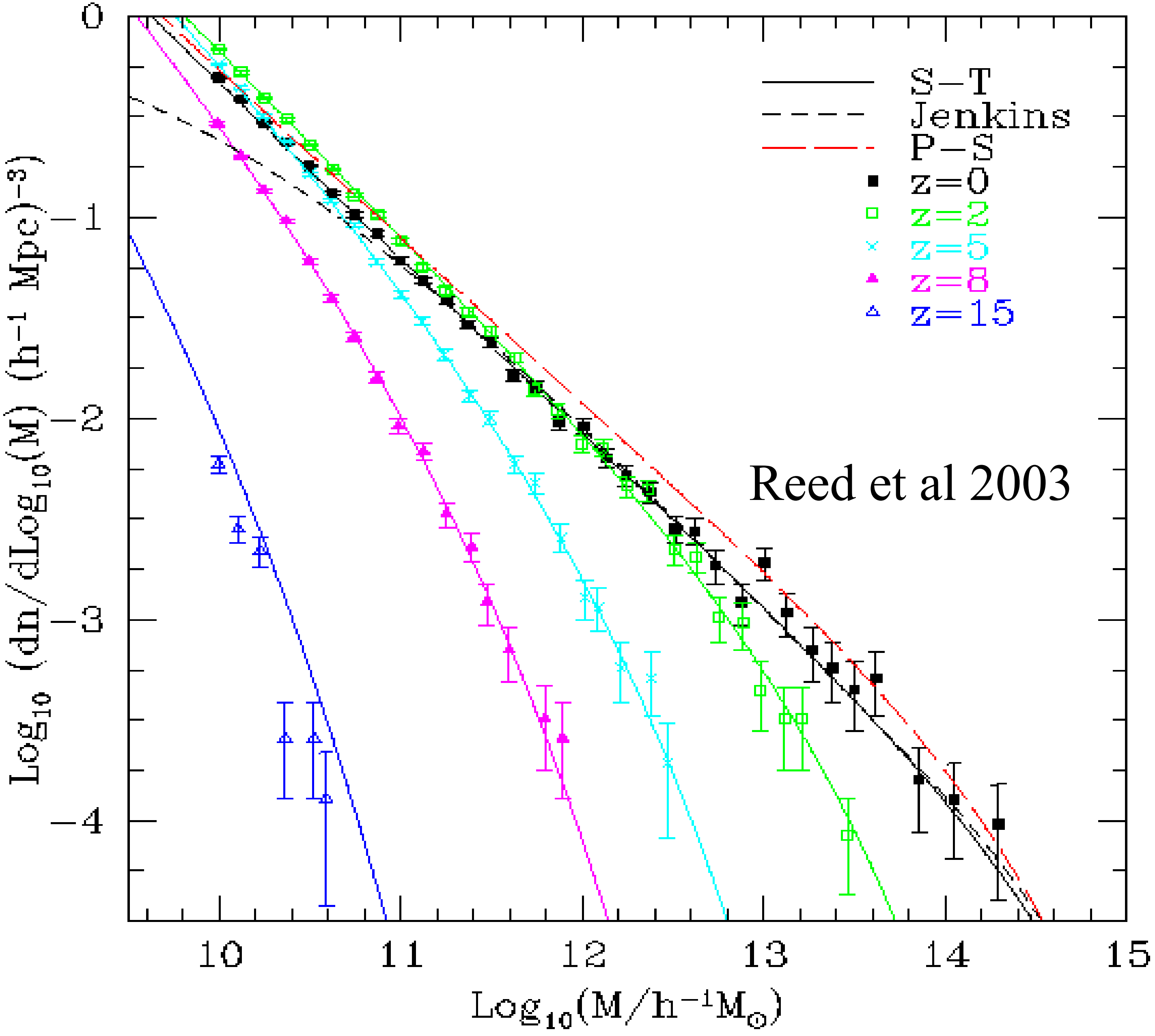
statistics (universality)

→

n(m,z) clustering

- P(k) → **σ^2(M)** (cosmology dependent)

Solid: Sheth & Tormen fit/“prediction”: ellipsoidal collapse



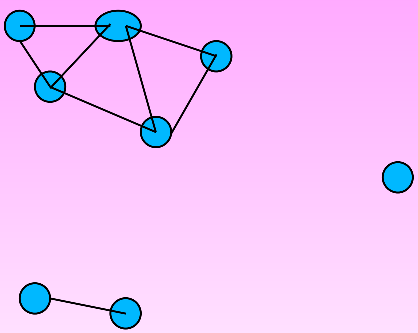
Halo selection:

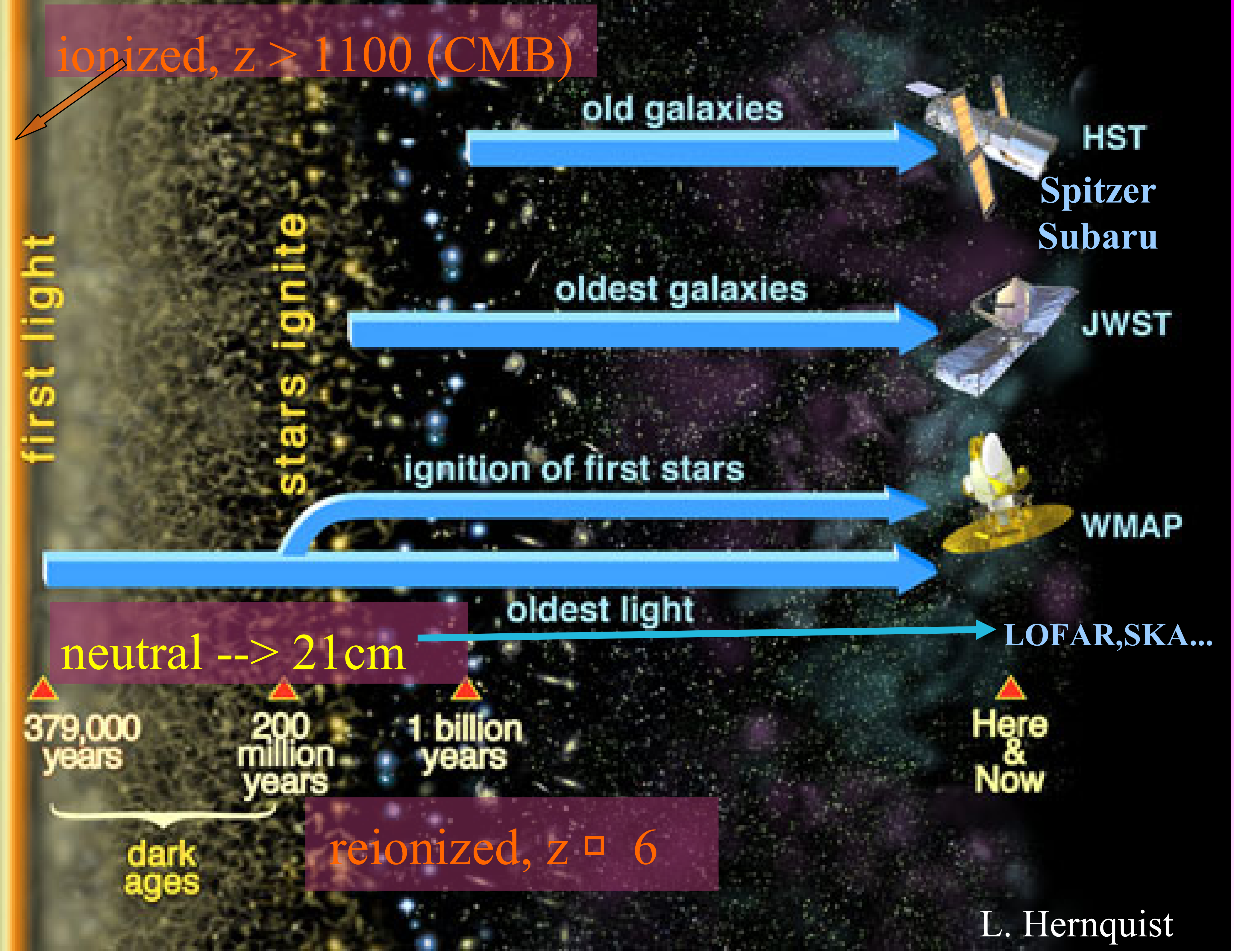
1-friends-of-friends

links together particles

separated by < `l.l.'

l.l.=0.2 mean part. sep.




ionized, z > 1100 (CMB)
first light
stars ignite
old galaxies
HST
Spitzer
Subaru
oldest galaxies
JWST
ignition of first stars
WMAP
oldest light
LOFAR,SKA...
neutral --> 21cm
379,000 years
200 million years
1 billion years
Here & Now
dark ages
reionized, z □ 6
L. Hernquist

star formation in metal free gas

mini-halo

T_{vir} >~ 2000K:

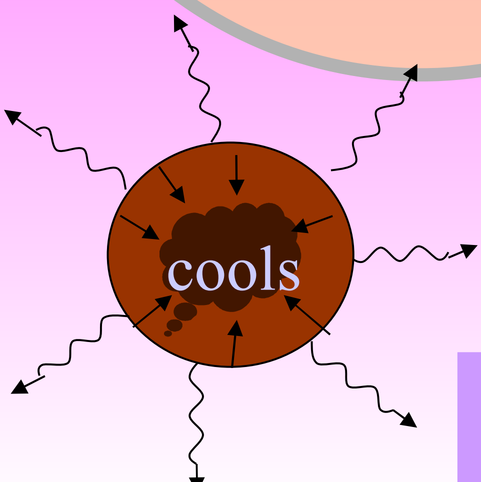
Mhalo ≥ ~**$10^{5.5}$ Msun**

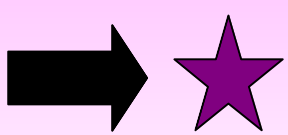
$H + e^- \rightarrow H^- + h\upsilon$

$H^- + H \rightarrow H_2 + e^-$

H_2 line cooling

Inefficient





~10-1000 M_{sun}?

T_{vir}>10^4K:

Mhalo ≥ **~10^8 Msun**

Atomic cooling

Efficient

lots of stars?

1st galaxies?

high z (reionizing era) halos

-z>~ 8 galaxy luminosity functions

-JWST (or sooner) to measure z >~ 6 clustering

--galaxies form within halos

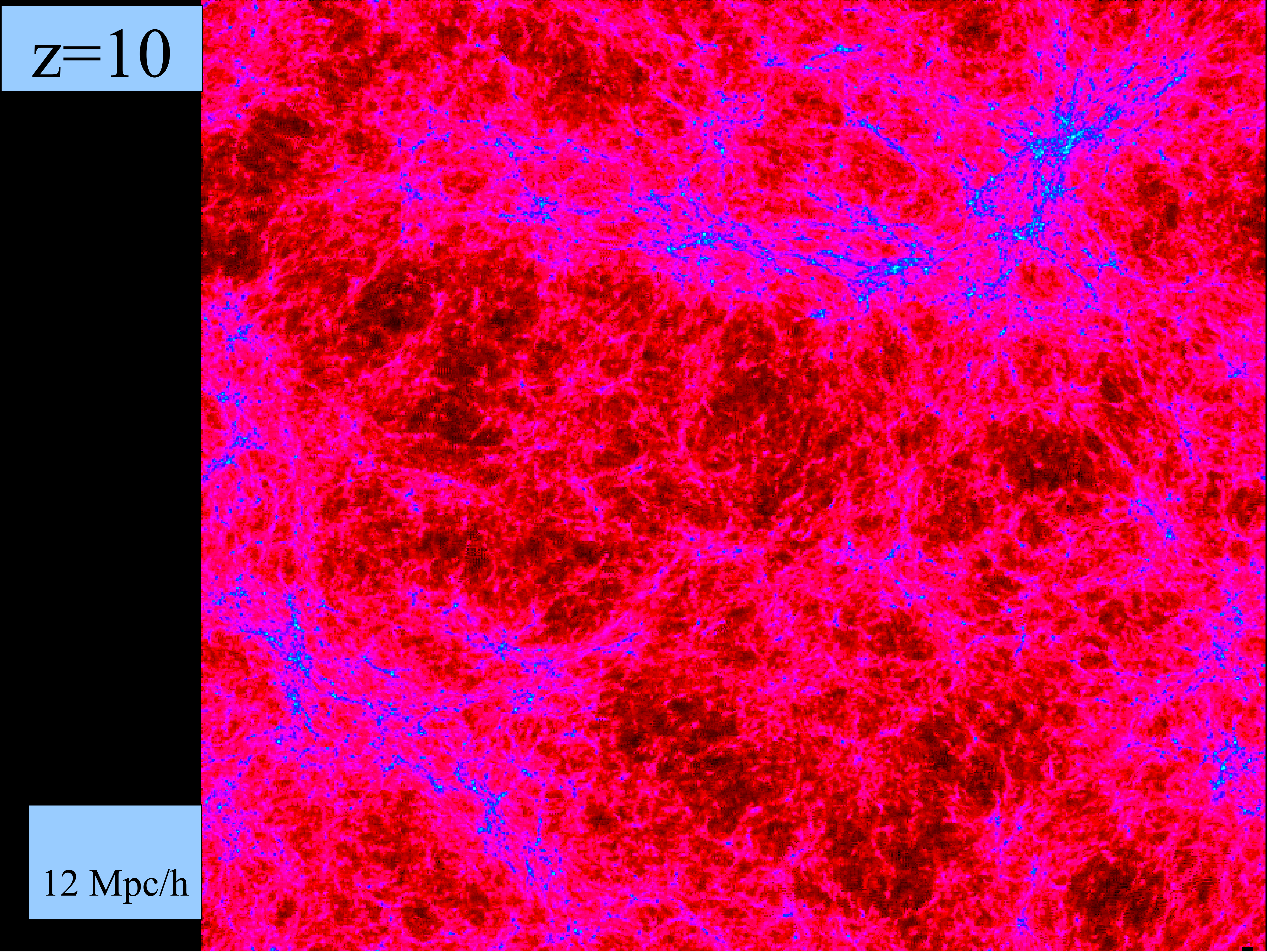
-galaxies + clustering at high redshift

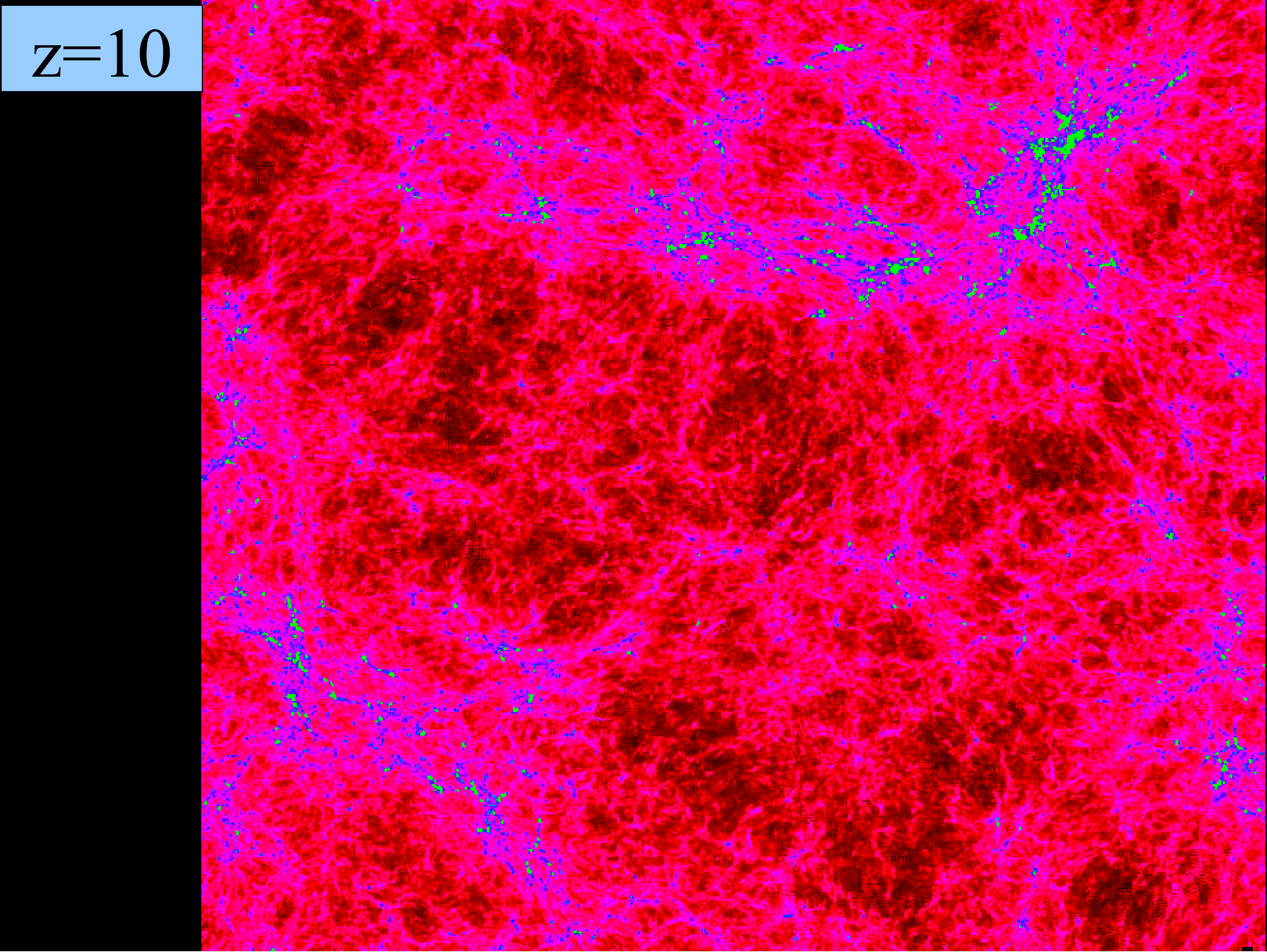
--sensitive to cosmology (e.g. σ_8 , D.M. type)

--sensitive to galaxy formation physics (e.g. SNe)

→ ***probe cosmology and galaxy form. physics***

& robust test of analytics


z=10
12 Mpc/h


z=10

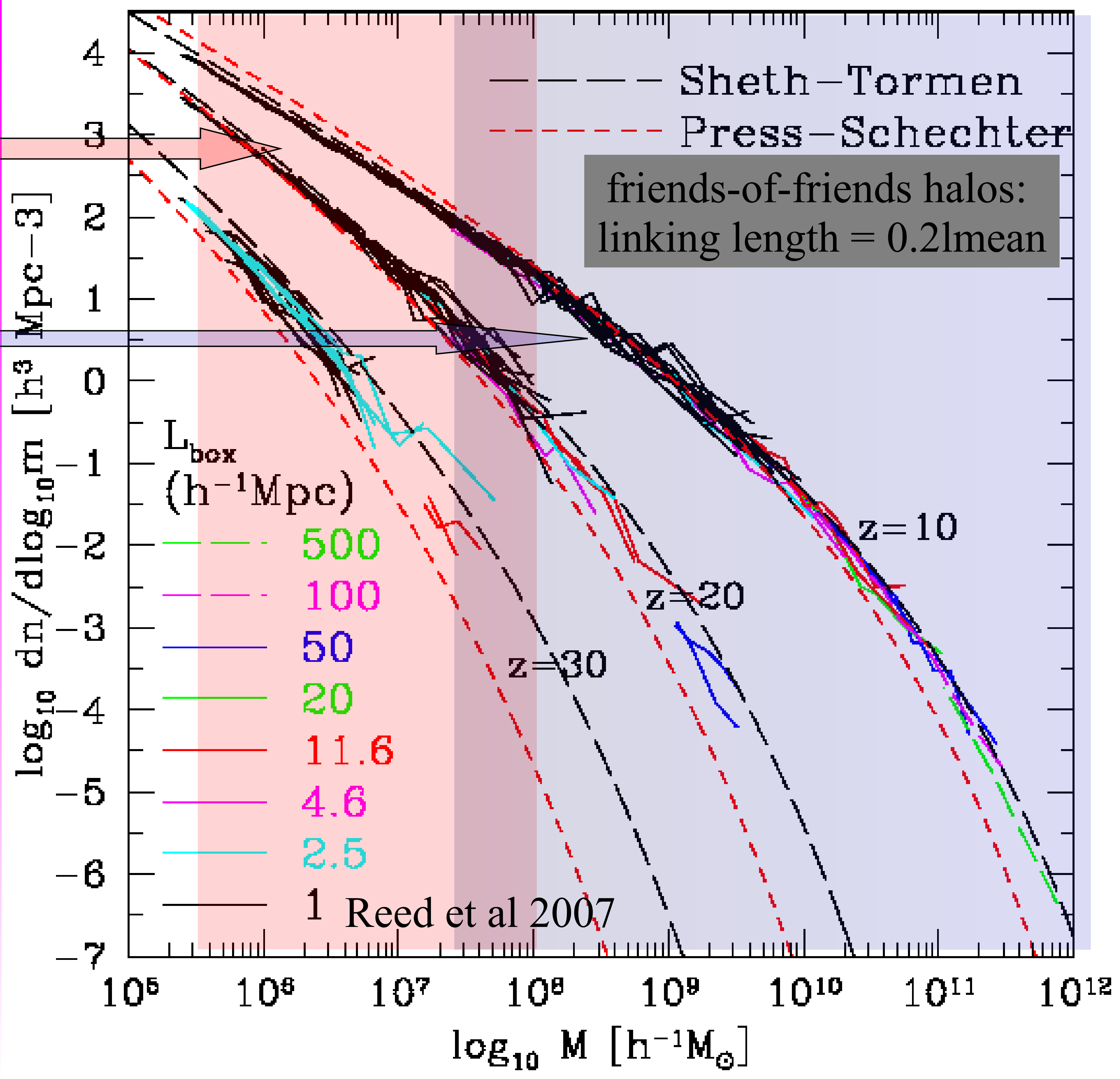
1st stars

H_2-cooled halos

1st galaxies

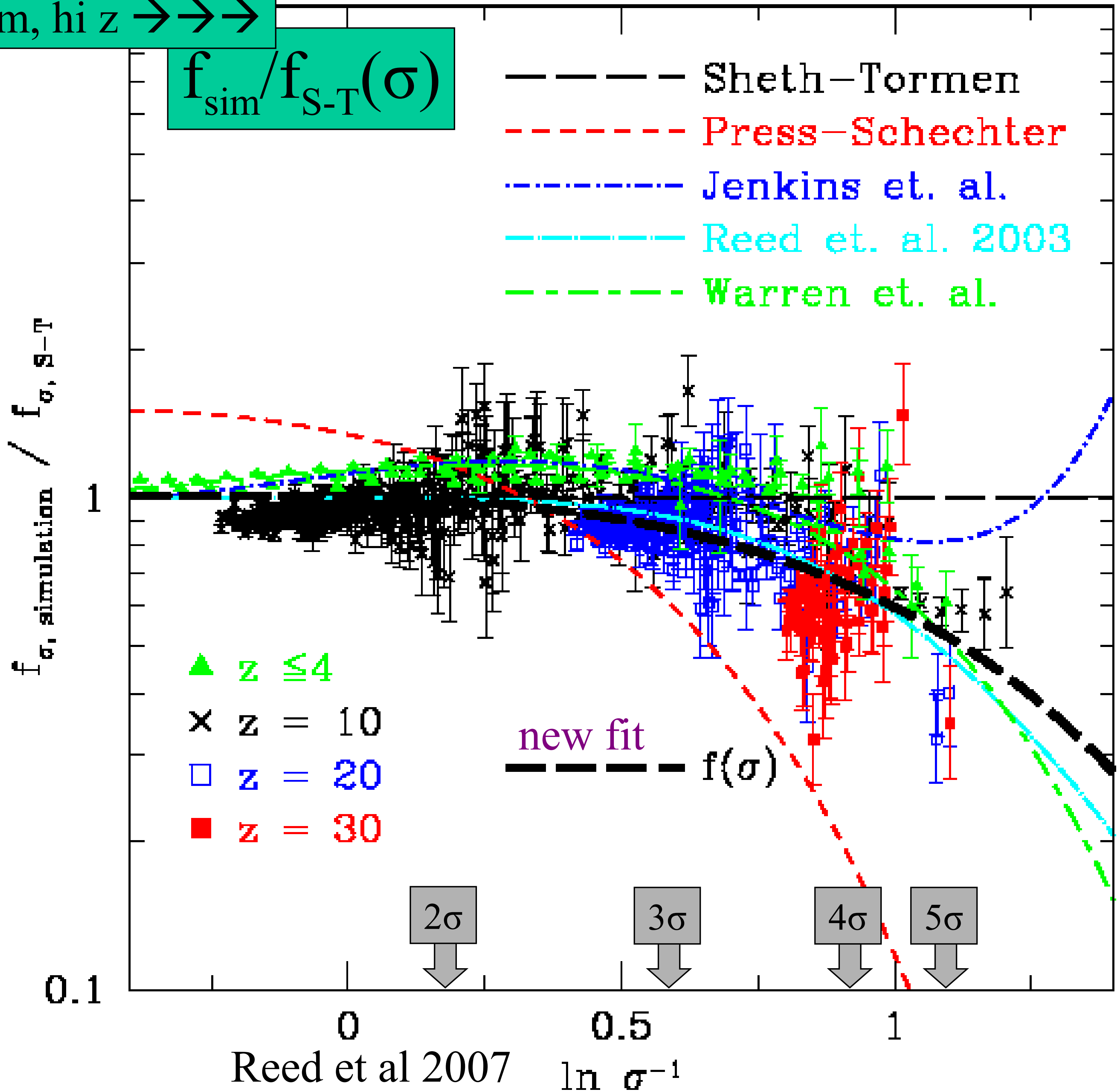
atomic-cooled halos

comoving abundance



fraction collapsed mass versus analytic fits

hi m, hi z →→→



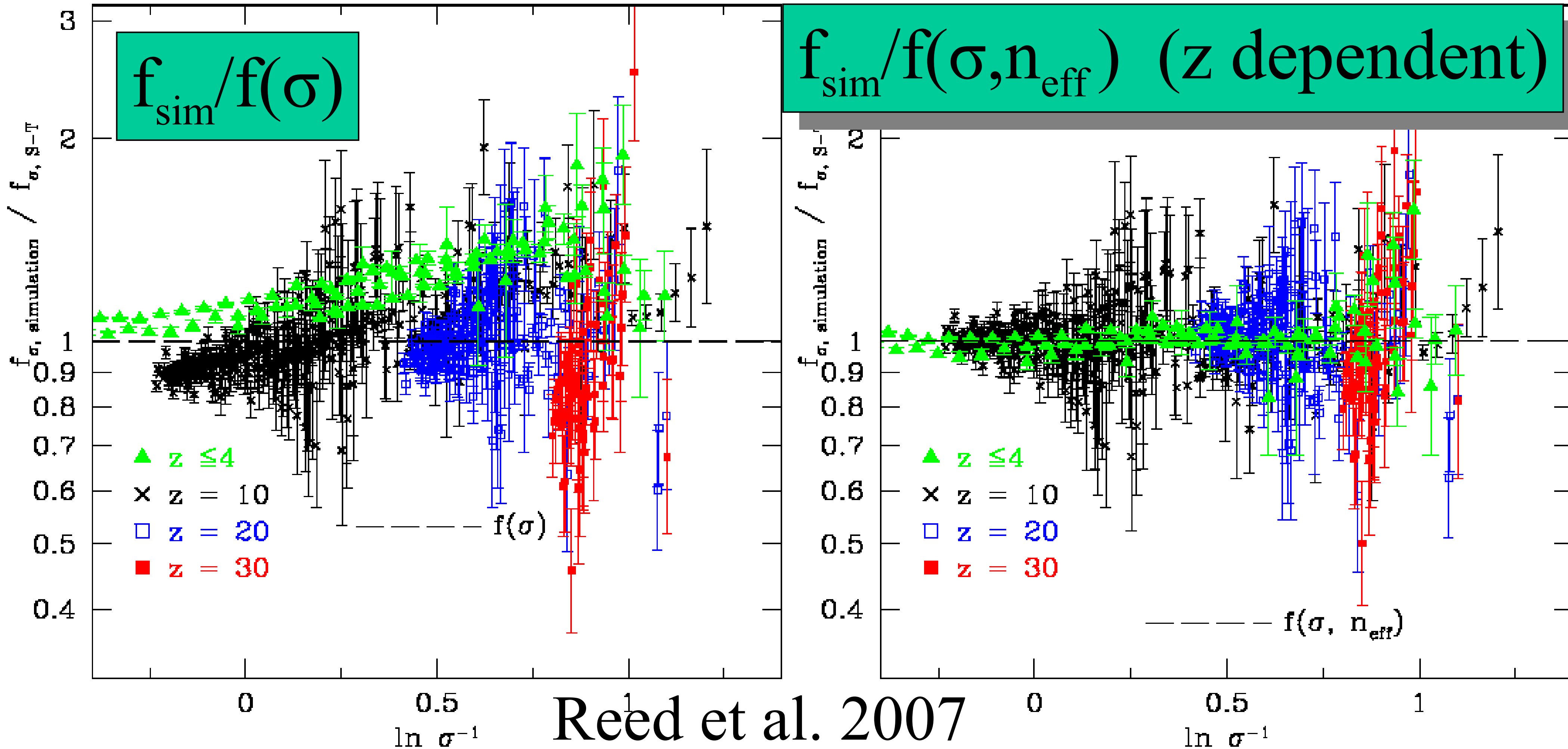
Reed et al 2007

Is f(σ) redshift invariant?

Is f(σ) redshift invariant?
“almost”

$\mathbf{n_{eff}}$≡slope of P(k) at scale of halo

P(k) α k^{neff}



Reed et al. 2007

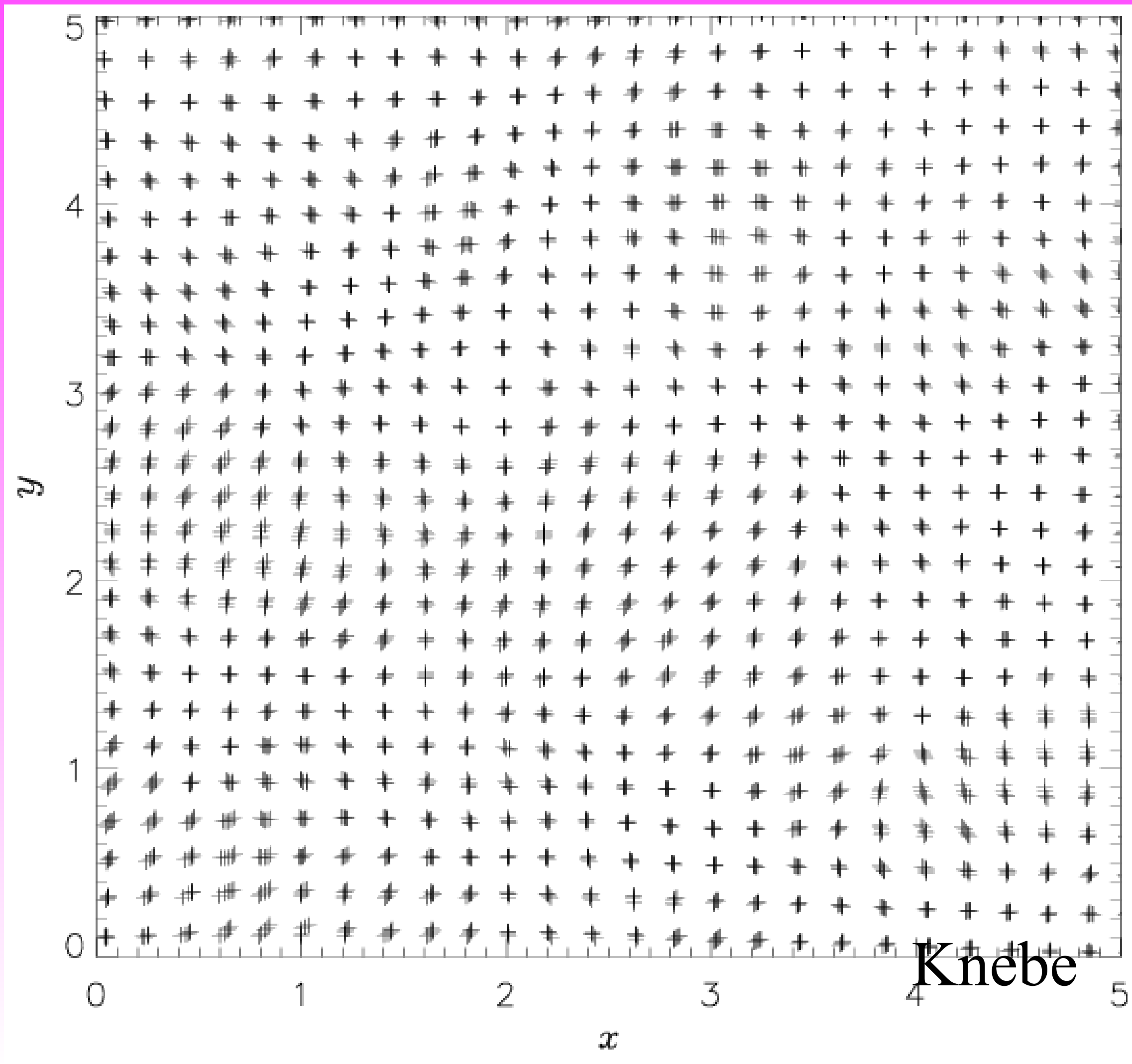
Problem: Starting redshift

Random realization of
ΛCDM density fluctuation spectrum.

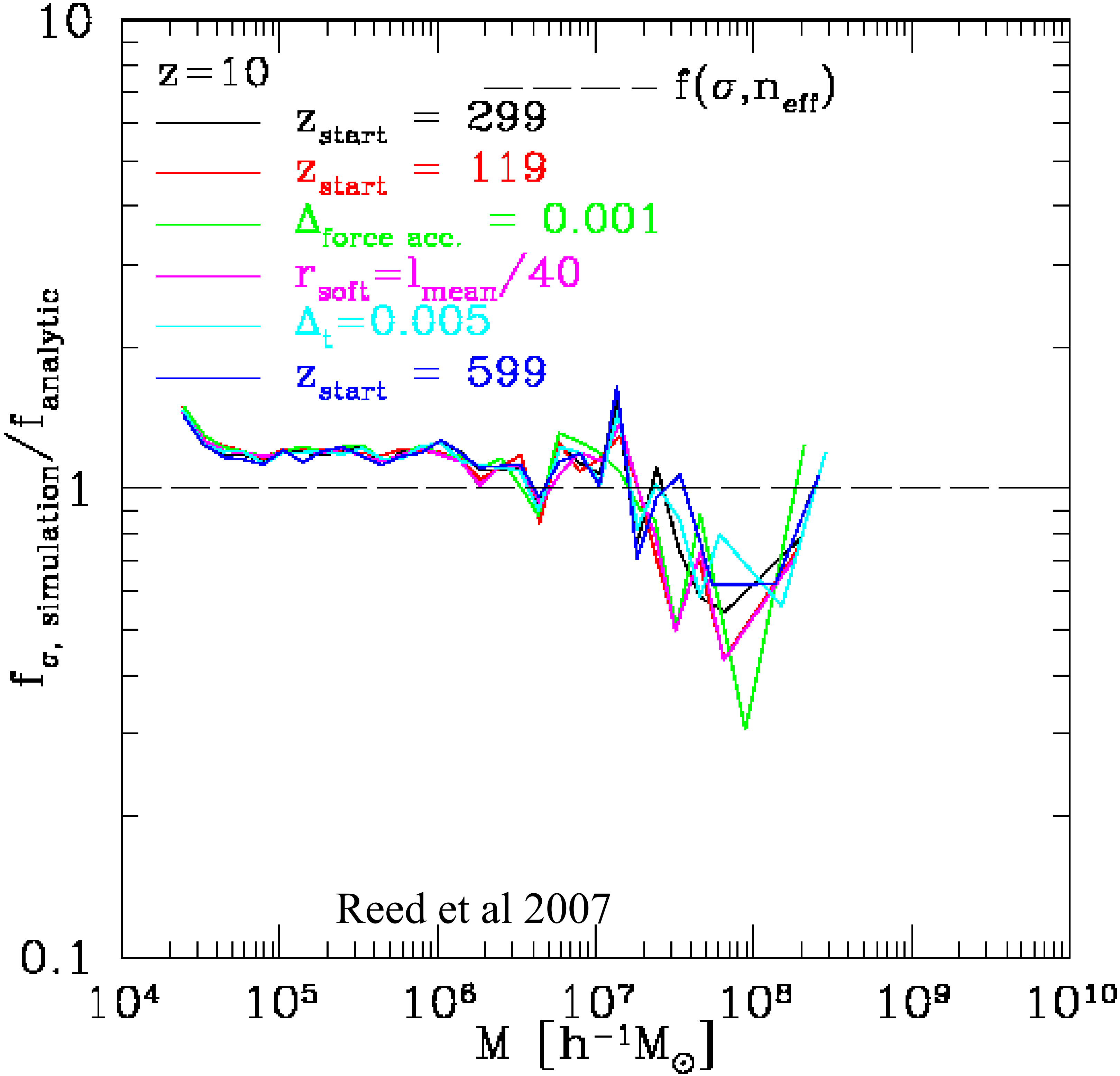
- Linearly extrapolate to z_{start} ($\delta \propto (1+z)^{-1}$)
  - High z_{start}: avoid non-linear structures
- Map particle positions to density field – Zeldovich approx.

$$\vec{x} = \vec{q} - D(t)\vec{S}(\vec{q})$$

- Evolve with gravity, gas physics

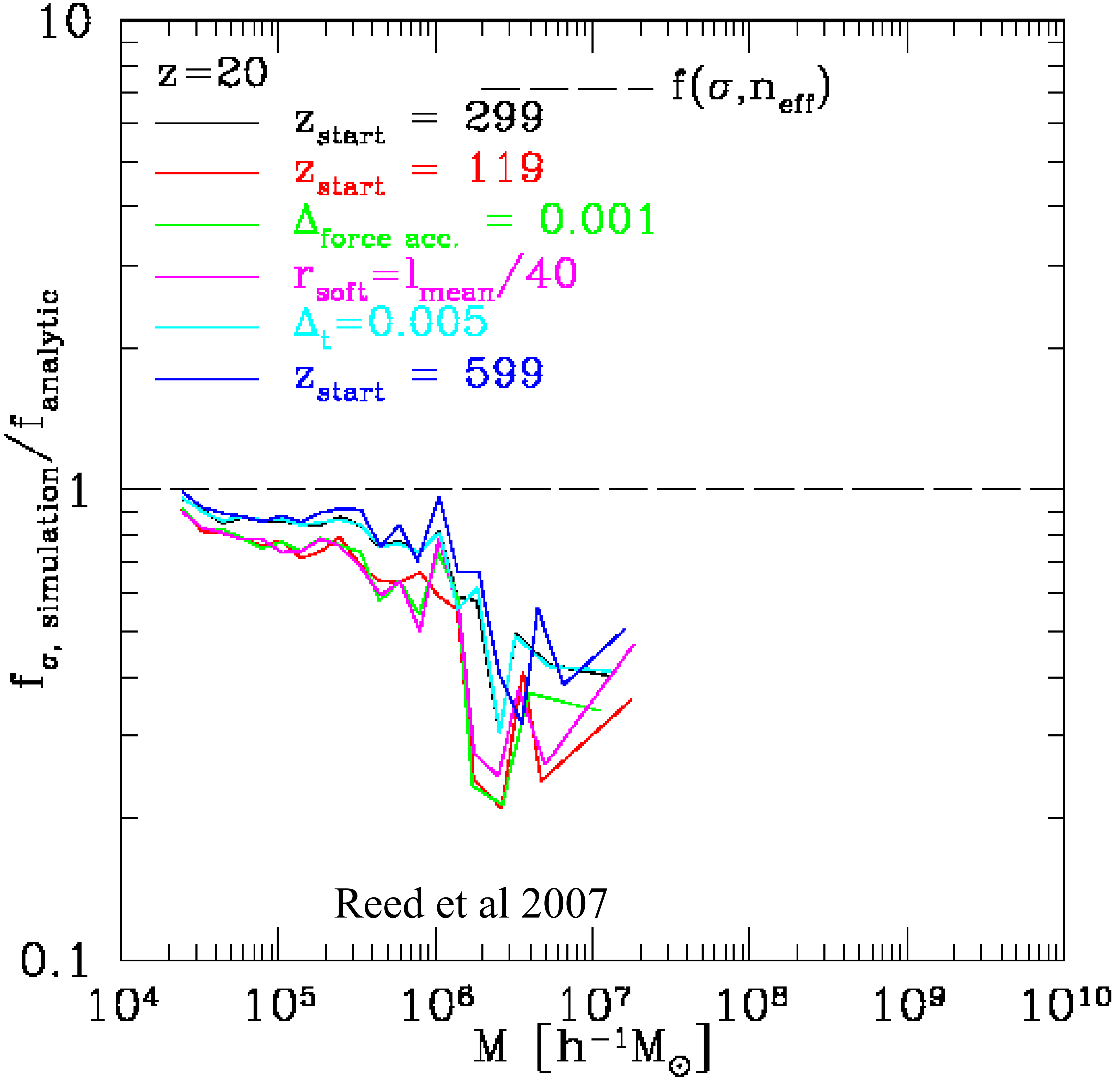


z=10



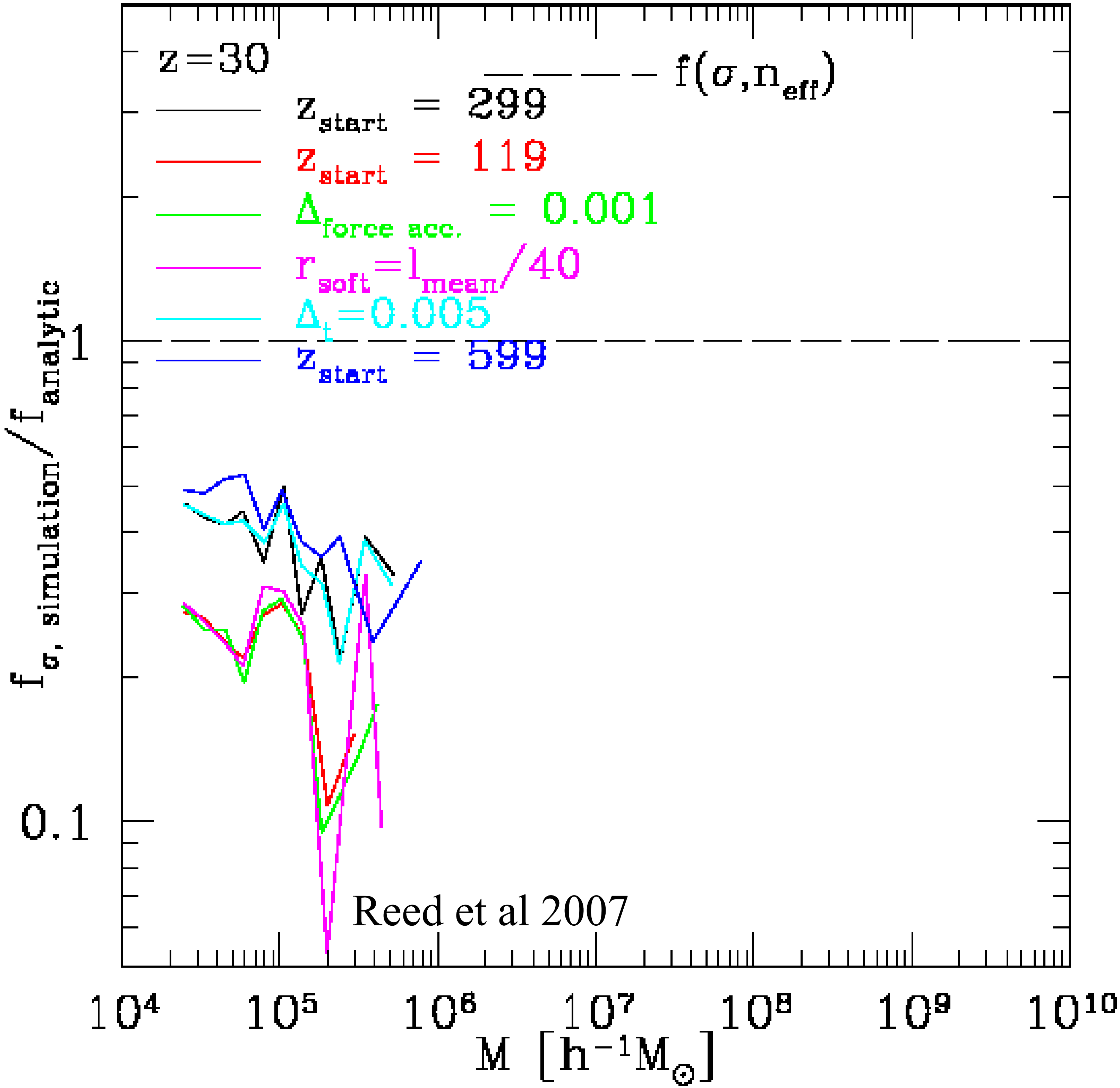
z=10
f(σ,n_eff)
z_start = 299
z_start = 119
Δ_force acc. = 0.001
r_soft=l_mean/40
Δ_t=0.005
z_start = 599
f_σ, simulation/f_analytic
10
1
0.1
10^4
10^5
10^6
10^7
10^8
10^9
10^10
M [h^-1 M_⊙]
Reed et al 2007

z=20



z=20
f(σ,n_eff)
z_start = 299
z_start = 119
Δ_force acc. = 0.001
r_soft=l_mean/40
Δ_t=0.005
z_start = 599
f_σ, simulation/f_analytic
M [h^-1M_⊙]
10
1
0.1
10^4
10^5
10^6
10^7
10^8
10^9
10^10
Reed et al 2007

z=30



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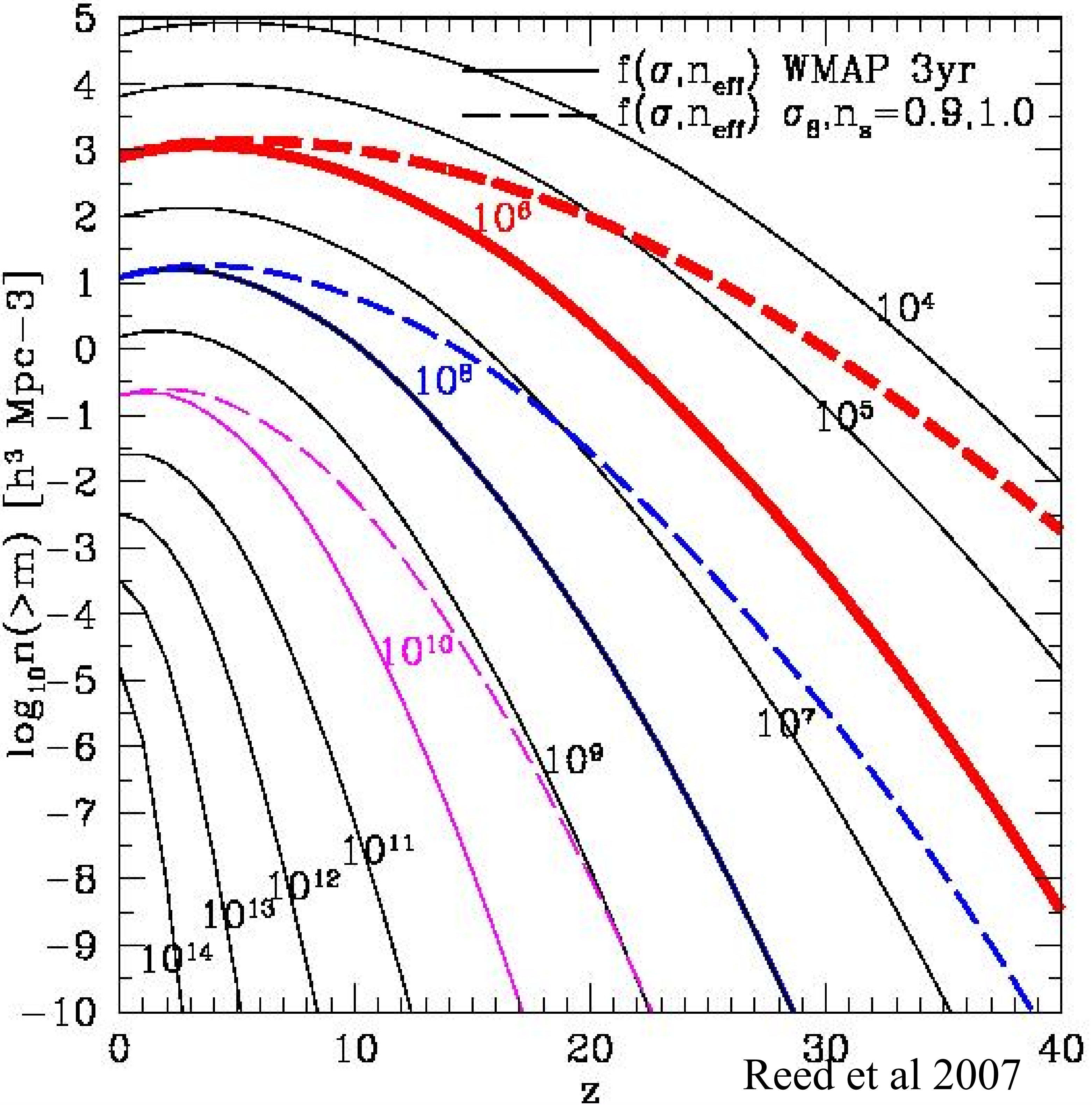
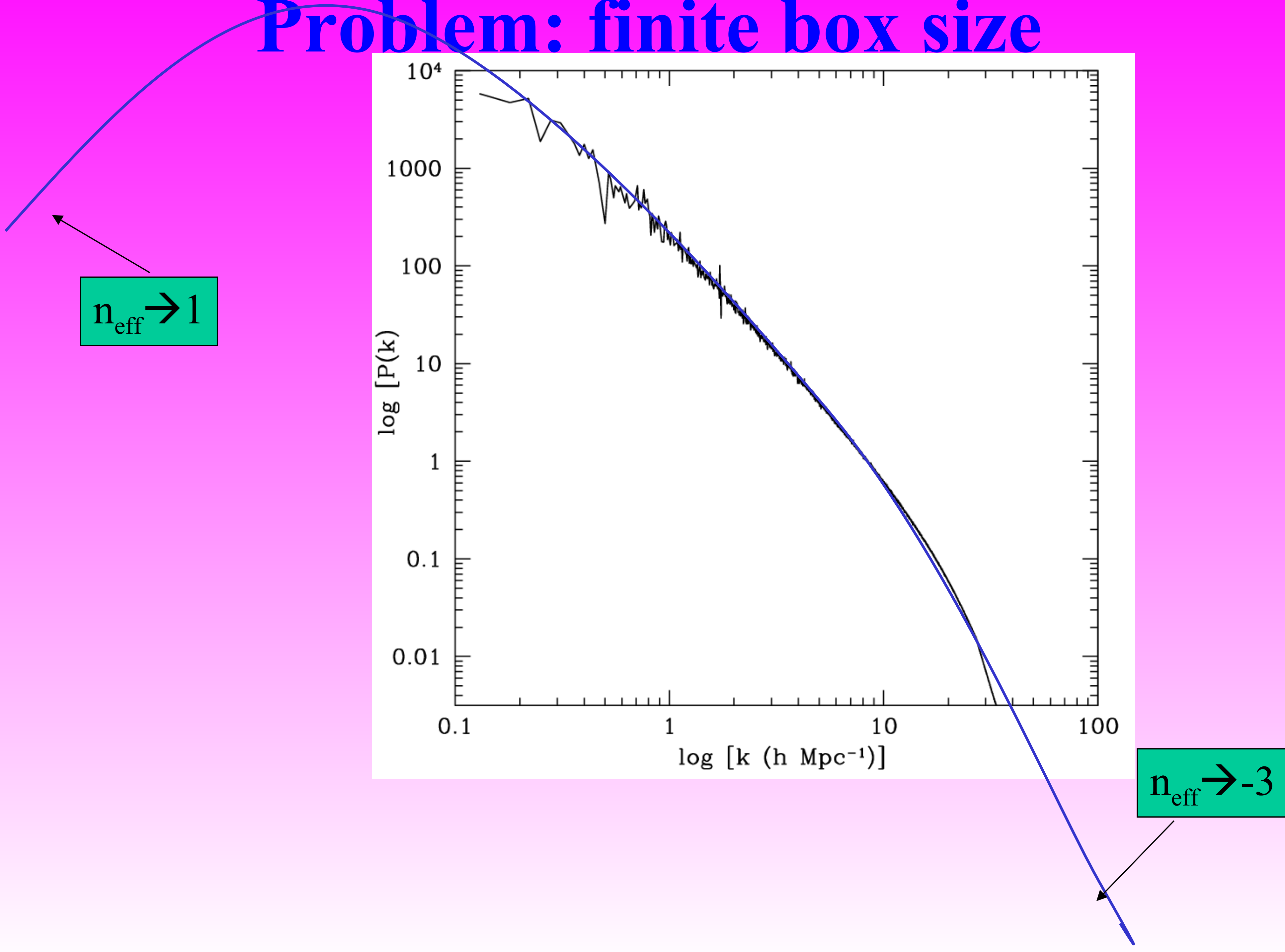
Reed et al 2007
10^4
10^5
10^6
10^7
10^8
10^9
10^10
M [h^-1 M_⊙]
f_σ, simulation/f_analytic

cosmological probe at high z?



Reed et al 2007

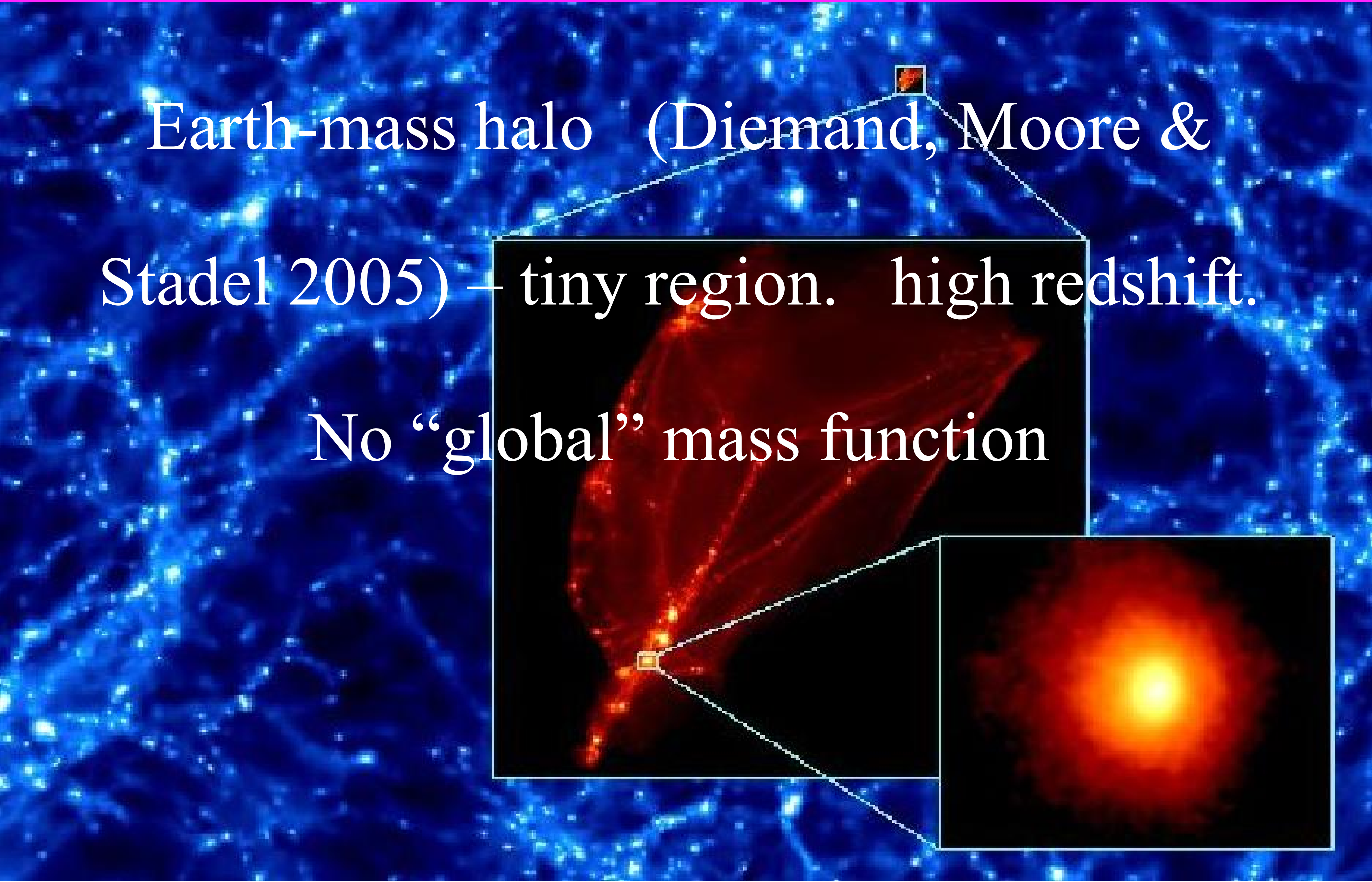
Problem: finite box size

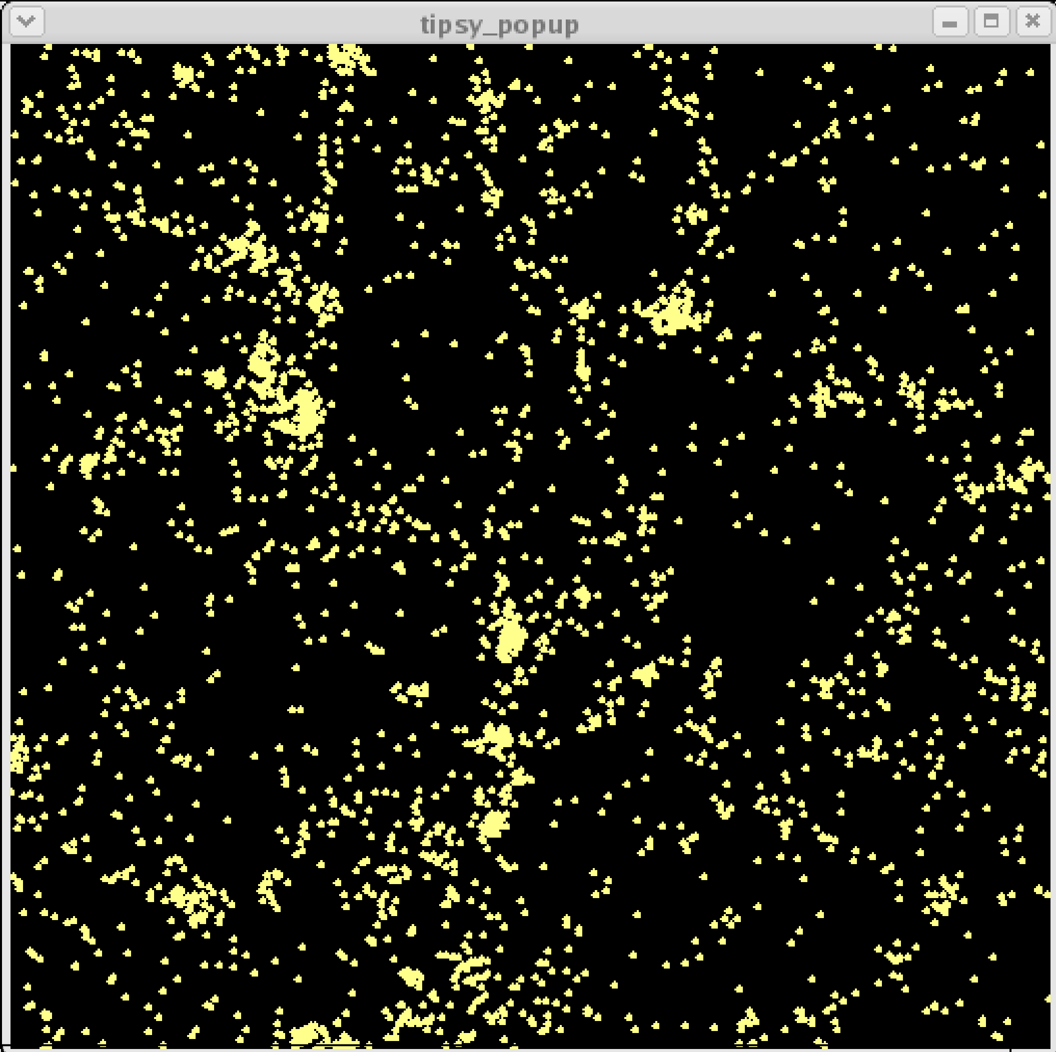


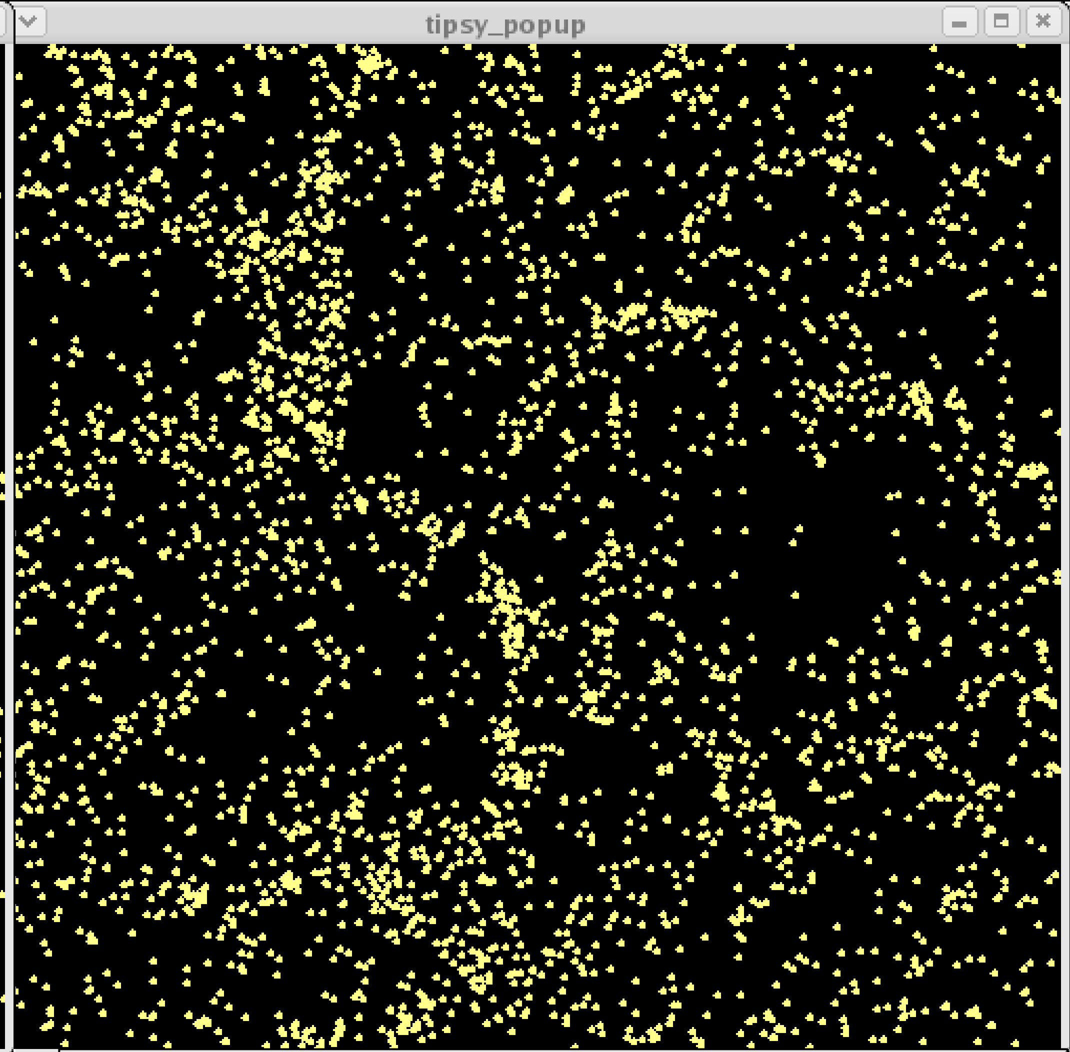
Want micro-halo mass function.......

Earth-mass halo (Diemand, Moore & Stadel 2005) – tiny region. high redshift.

No “global” mass function







highly clustered, “biased”

weakly clustered

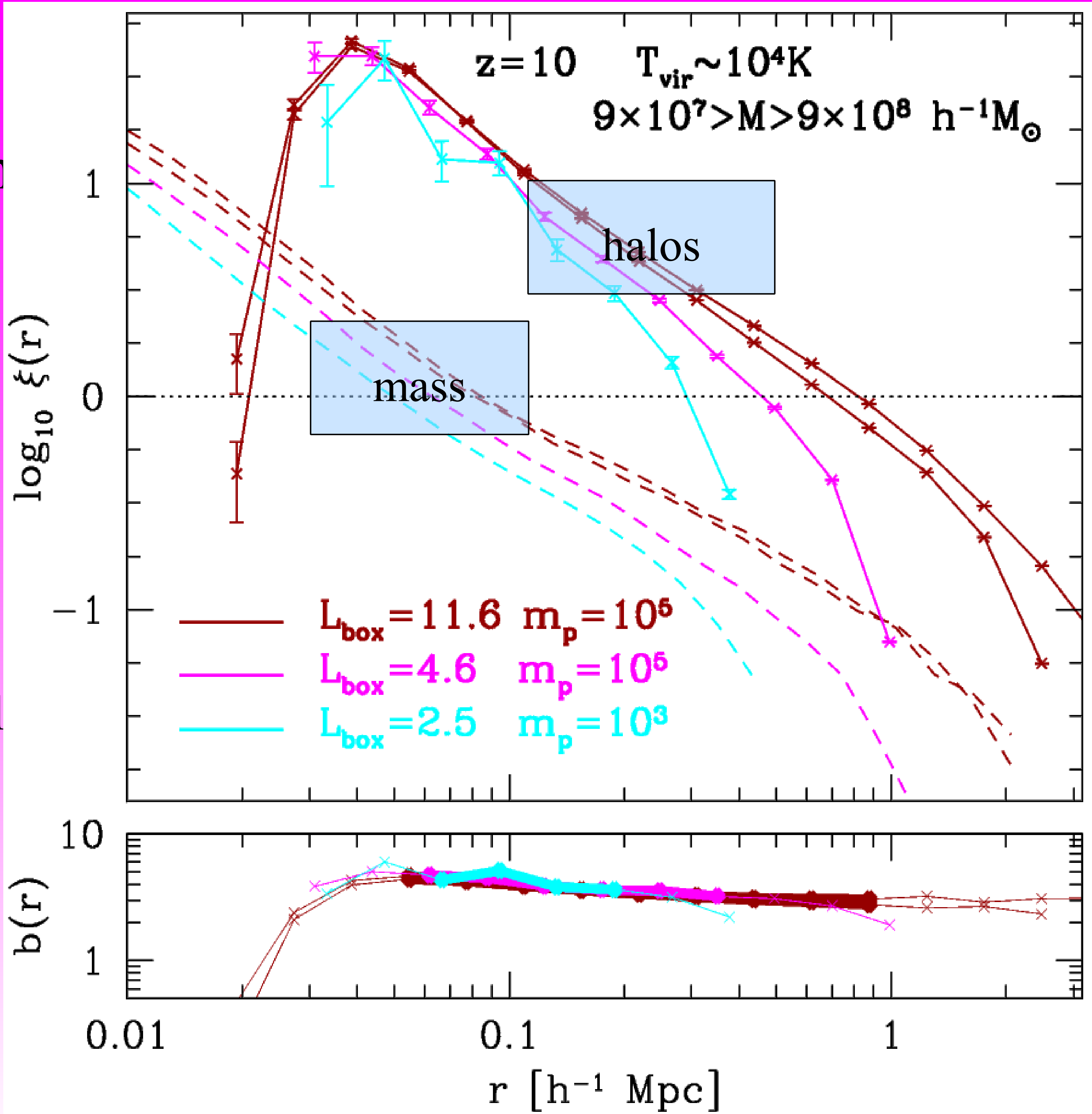
$\xi(r) = N_{pair}/N_{pair\_random} - 1$

$bias(r) = (\xi_{halos}(r)/\xi_{mass}(r))^{1/2}$

- halo bias
- auto-correlation function of "galaxy" halos

$\xi(r) = N_{pair}/N_{pair\_random} - 1$

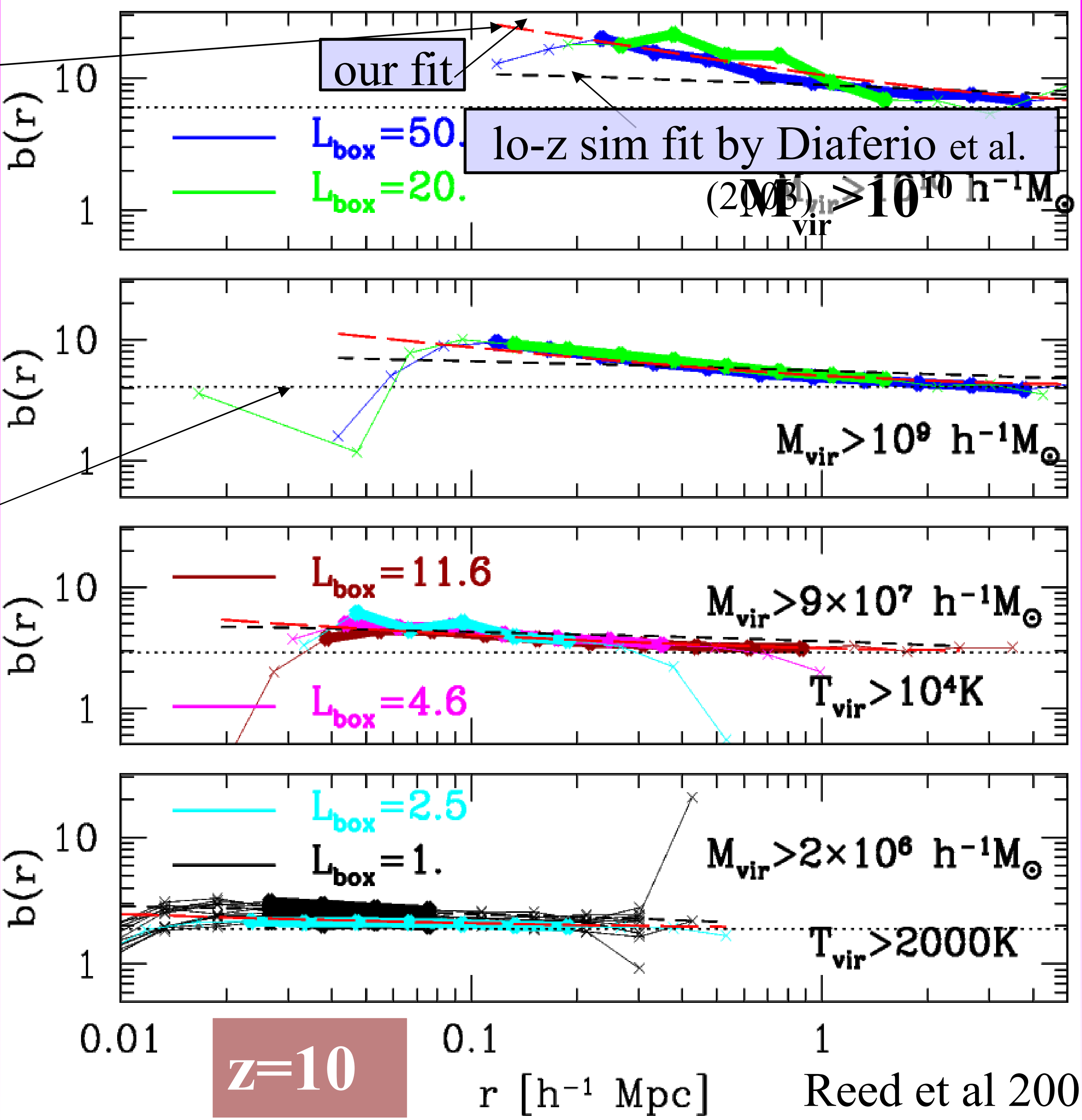
$b = (\xi_{halos}/\xi_{mass})^{1/2}$



Reed et al 2008

Scale-dependence of halo bias

Small scales strongly biased "non-universal" vs lo-z sims



Sheth, Mo & Tormen large scale prediction (b_{SMT})

z=10

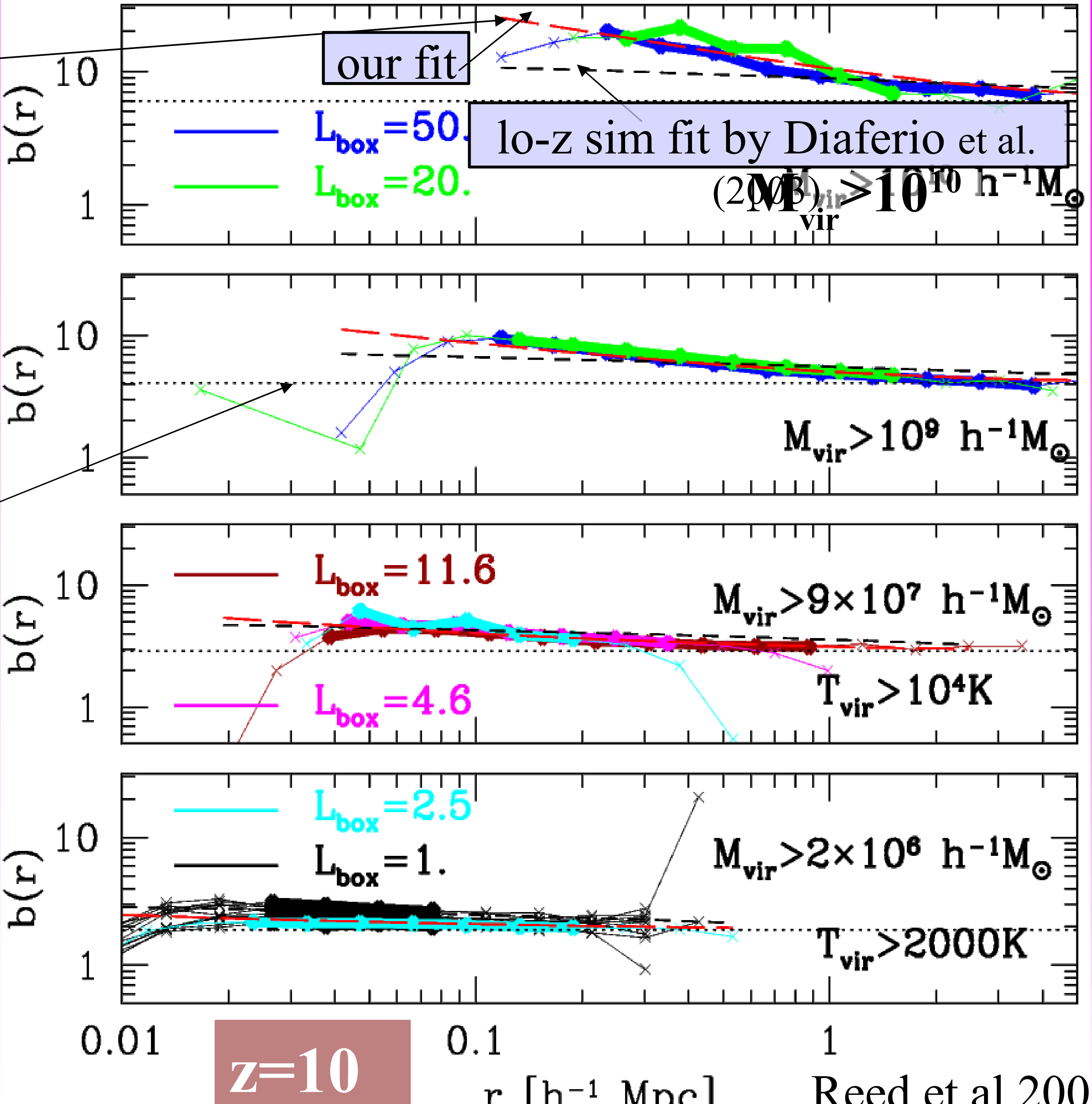
Reed et al 2008

$$b(m,r,z) = b_{SMT}(m,z)[1 + 0.03 b_{SMT}(m,z)^3 \sigma(r,z)^2]$$

Small scales strongly biased "non-universal" vs lo-z sims

b(r) =f(σ$_{mass}$(r))

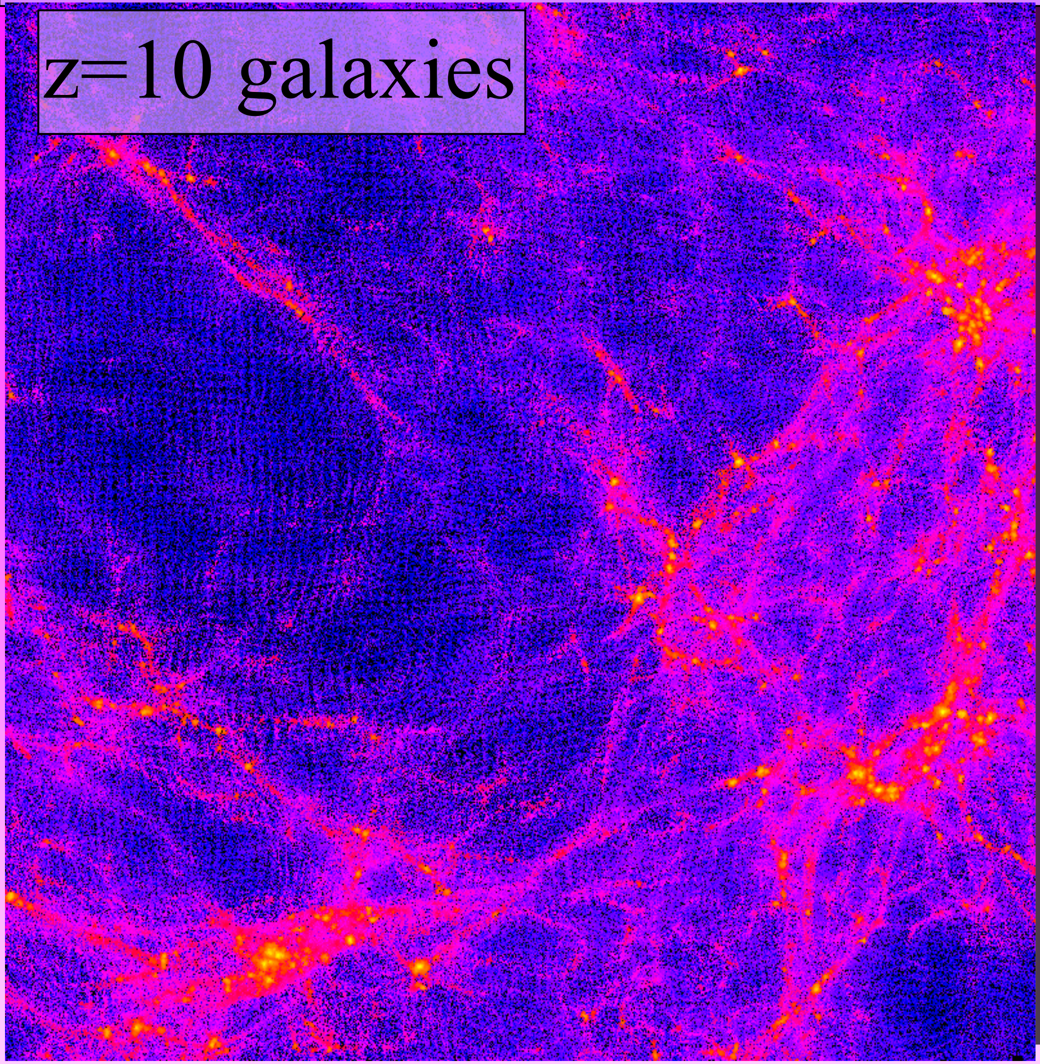
Sheth, Mo & Tormen large scale prediction (b_{SMT})

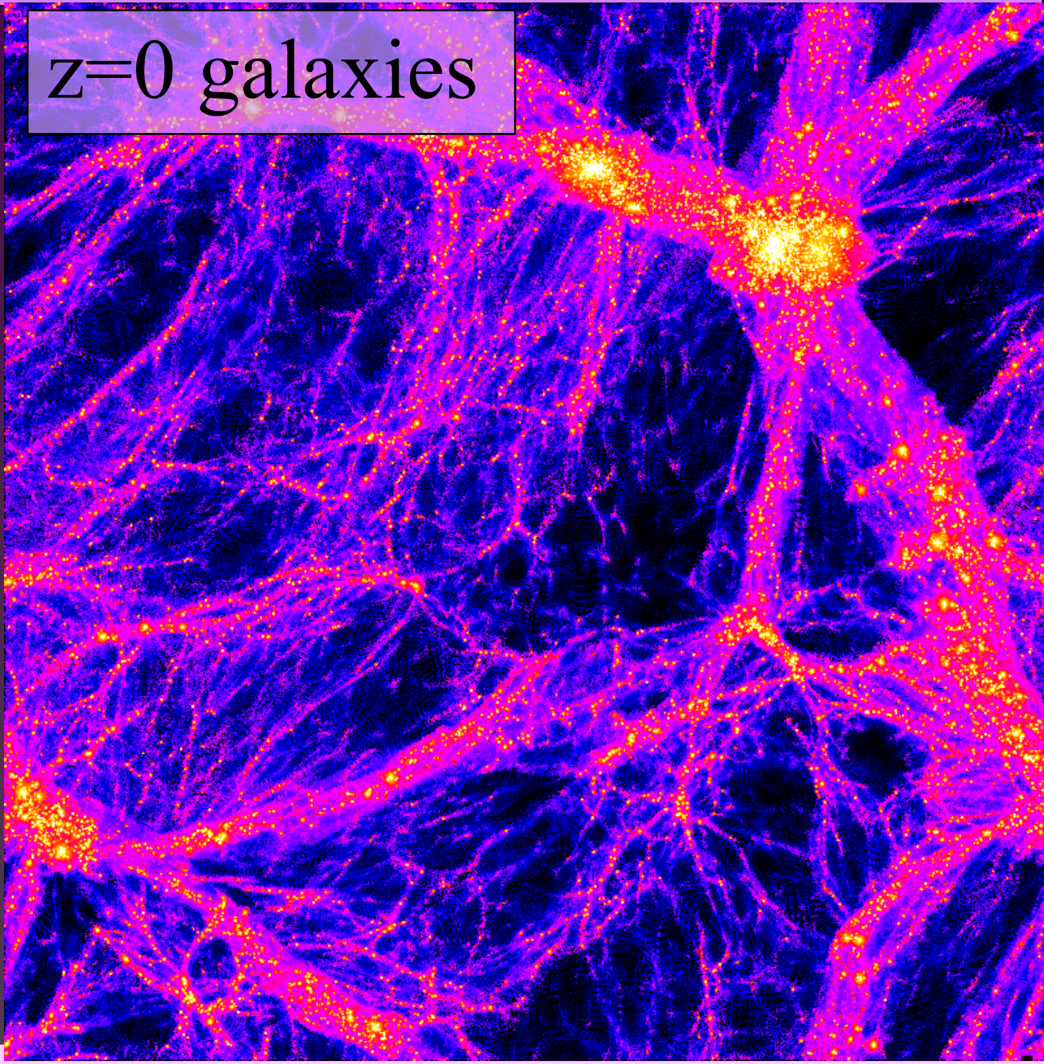


z=10

Reed et al 2008

Why is the scale dependence of halo bias so steep during the dark ages?



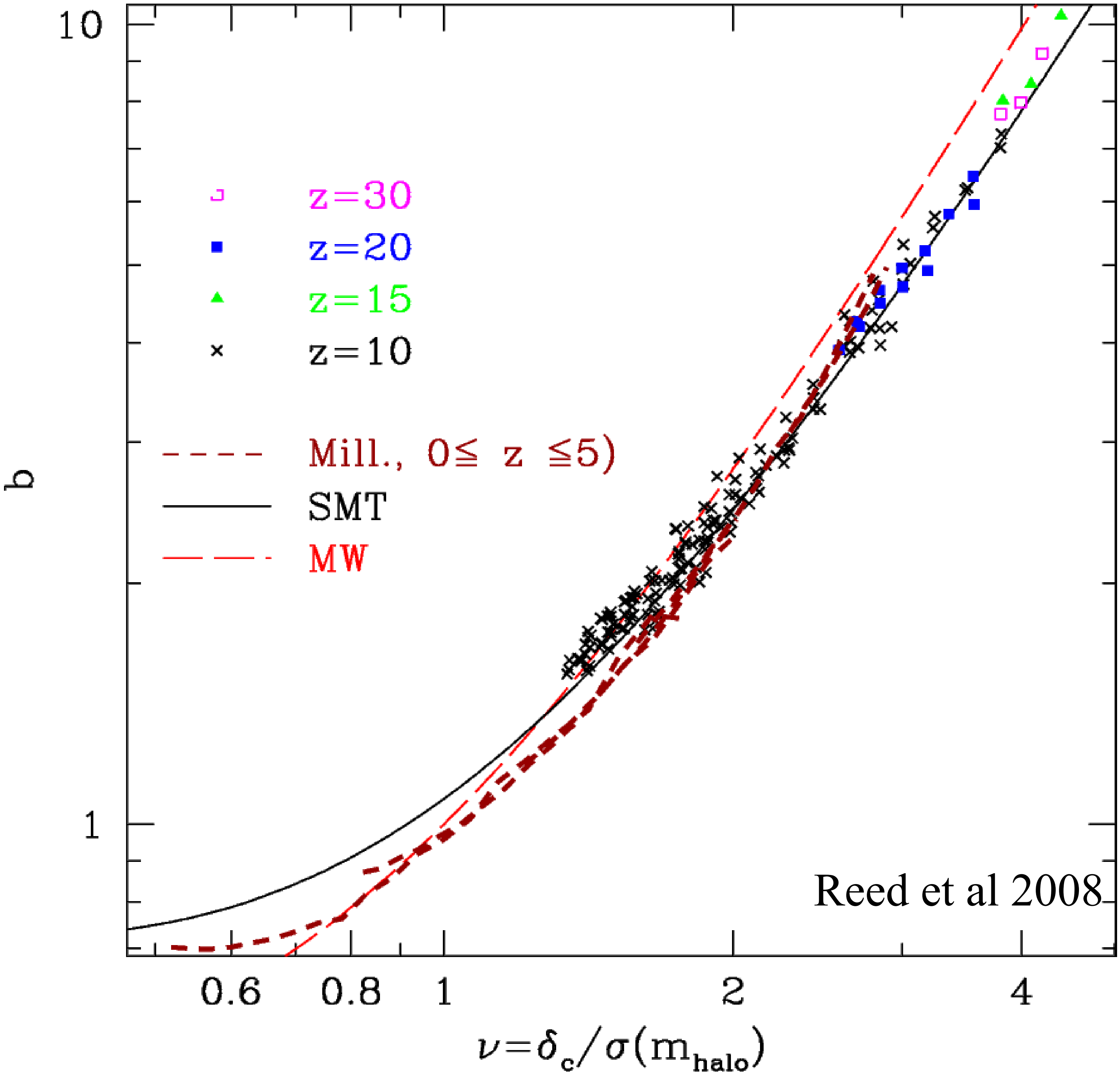


"universal" mass variable, ν,

MW=predictions of Mo & White (1996)

SMT=Sheth, Mo & Tormen (2001)

Millennium run data from Gao et al. (2005).



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  - Halo internal structure
- ***Problems***
  - ***Simulation difficulties***
  - ***CDM difficulties***
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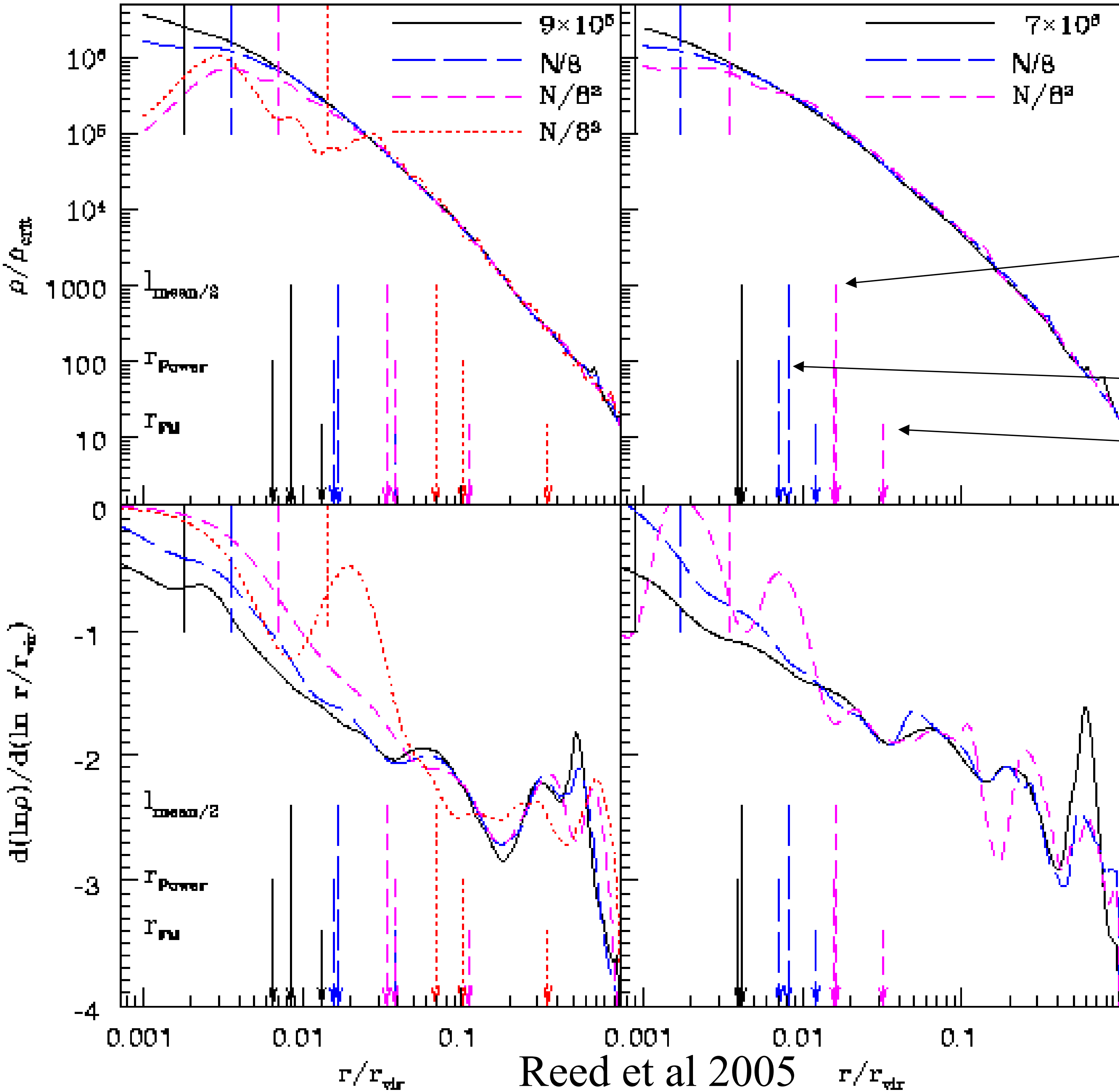
Motivations for studying halo structure

- -Probe fluctuation spectrum & dark matter type
- -Observational comparisons
  - Subhalos- satellites, lensing, D.M. Annihilation (e.g. Koushiappas)
  - Density profiles-- rotation curvies, lensing, X-ray
  - r^{-1} or $r^{-1.5}$ cusp?
  - asymptotic central slope down to what radius?
- Universal? How does profile shape or subhalo distribution depend on mass, redshift?
- Baryons ignored

Density profile convergence tests



Lmean/2

Power et al.

FM

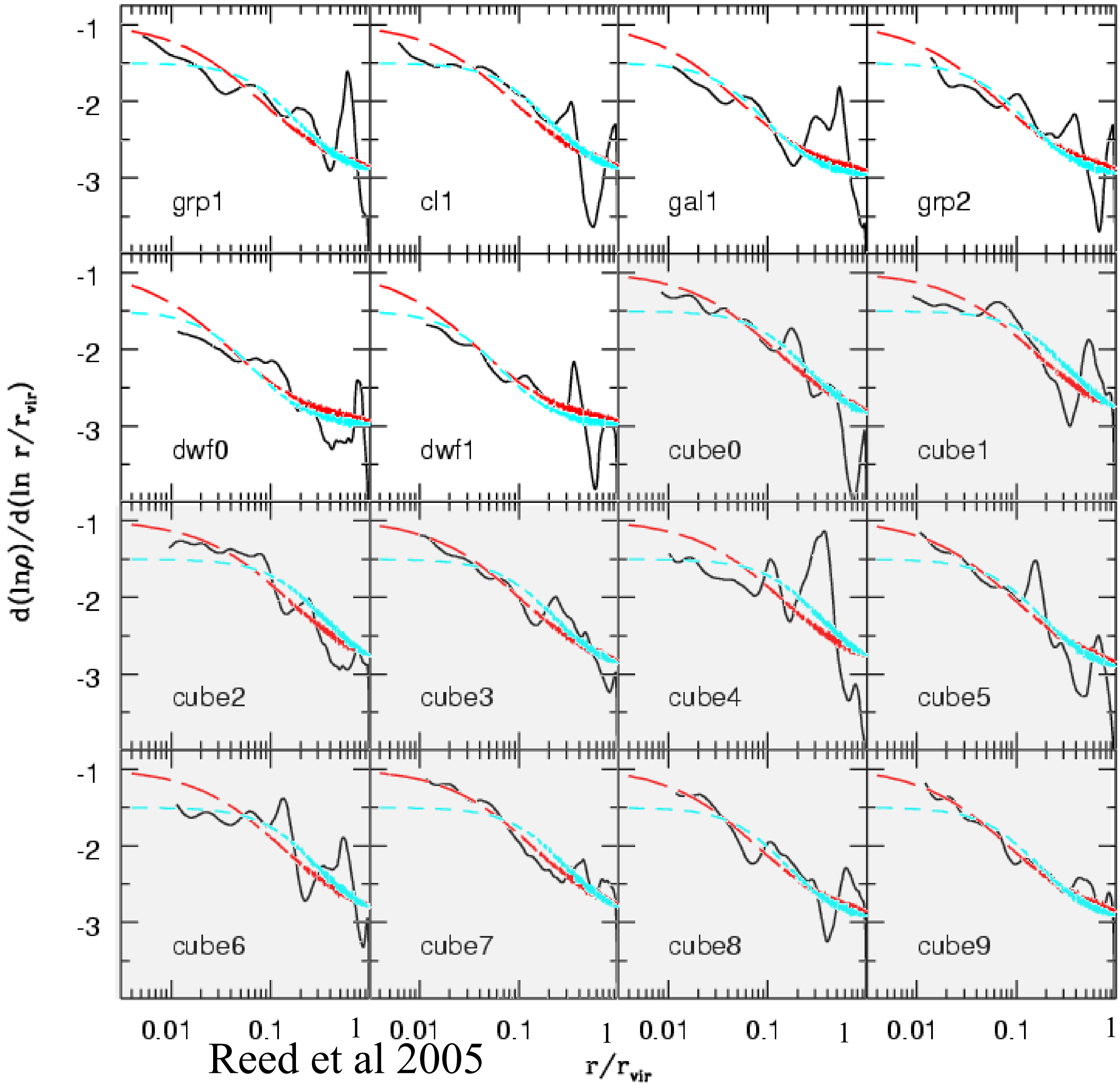
$R_{min} \approx Np^{-1/3}$

Moore et al 1998

Np= # particles

within virial radius

Reed et al 2005



Reed et al 2005

Not "universal"

Asymptotic Cusps?

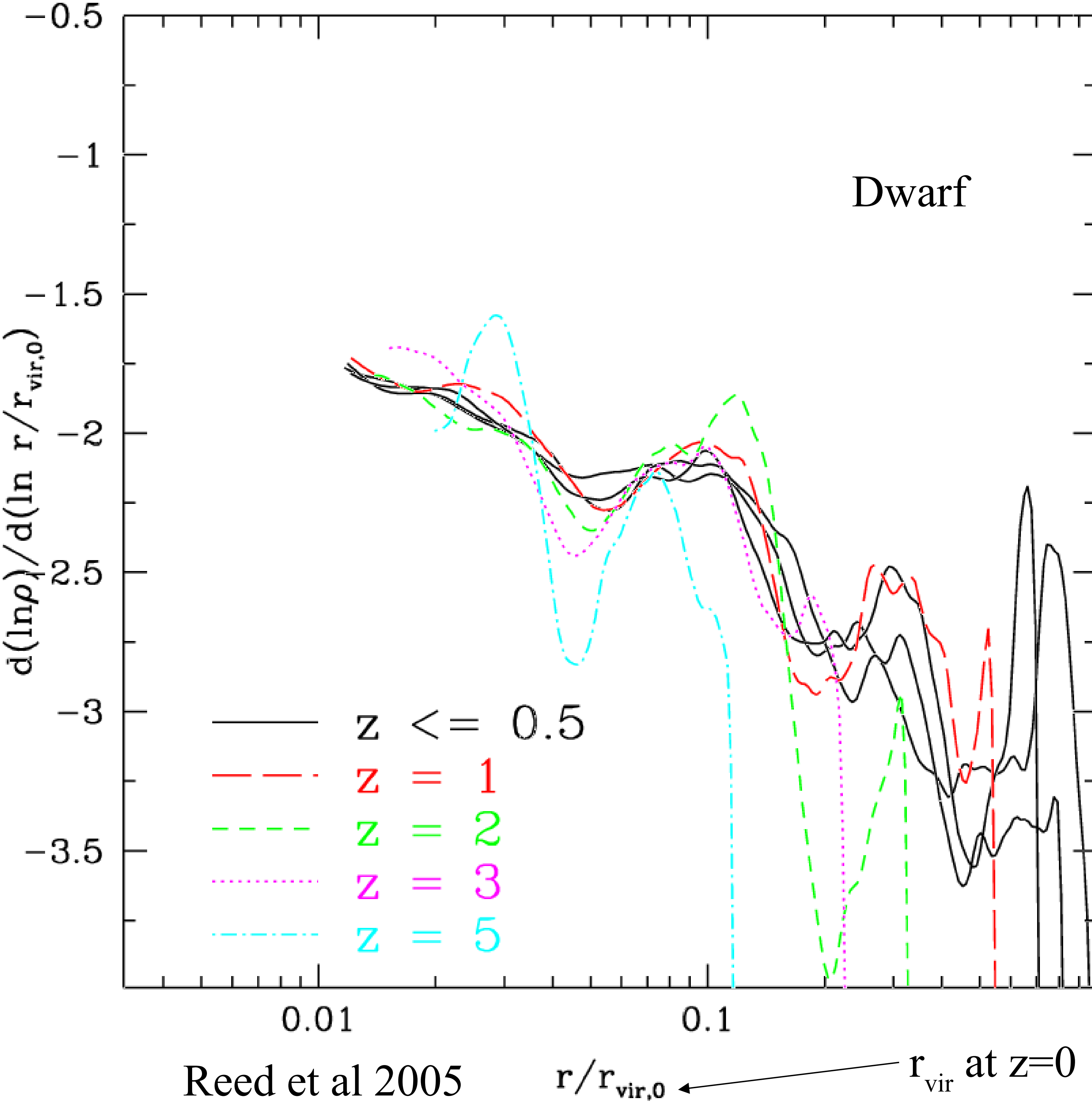
Logarithmic profile slope:

Sims ———

best fit :

NFW ———

Moore - - - - - -



Reed et al 2005

r_{vir} at z=0

Physical (non-comoving) slope:

no evolution $\rho'(r/r_{vir}(z=0))$ instead of $\rho'(r/r_{vir}(z))$

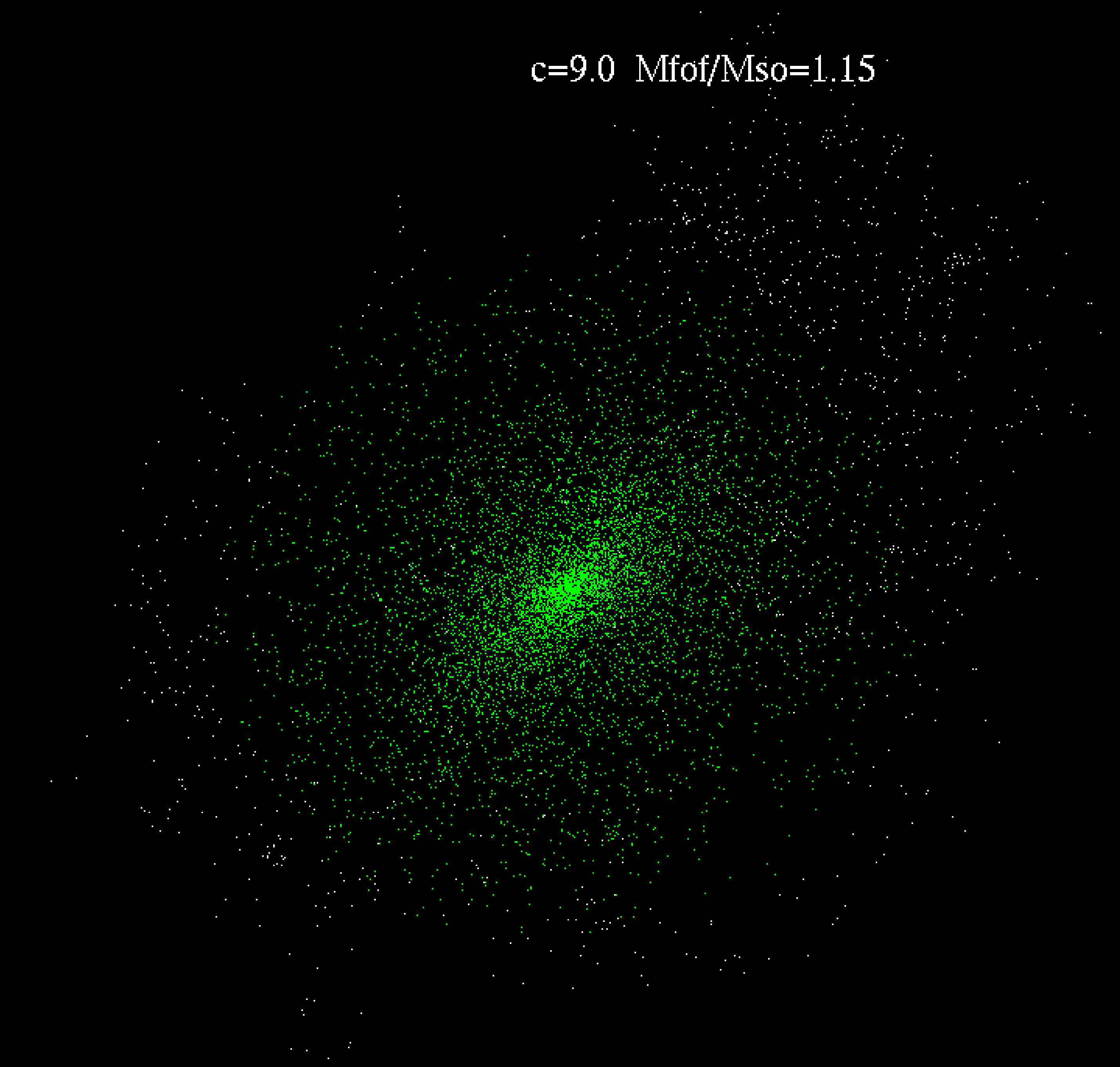
Hi-z: r_{vir} small

Halo cusp is frozen in at high z.

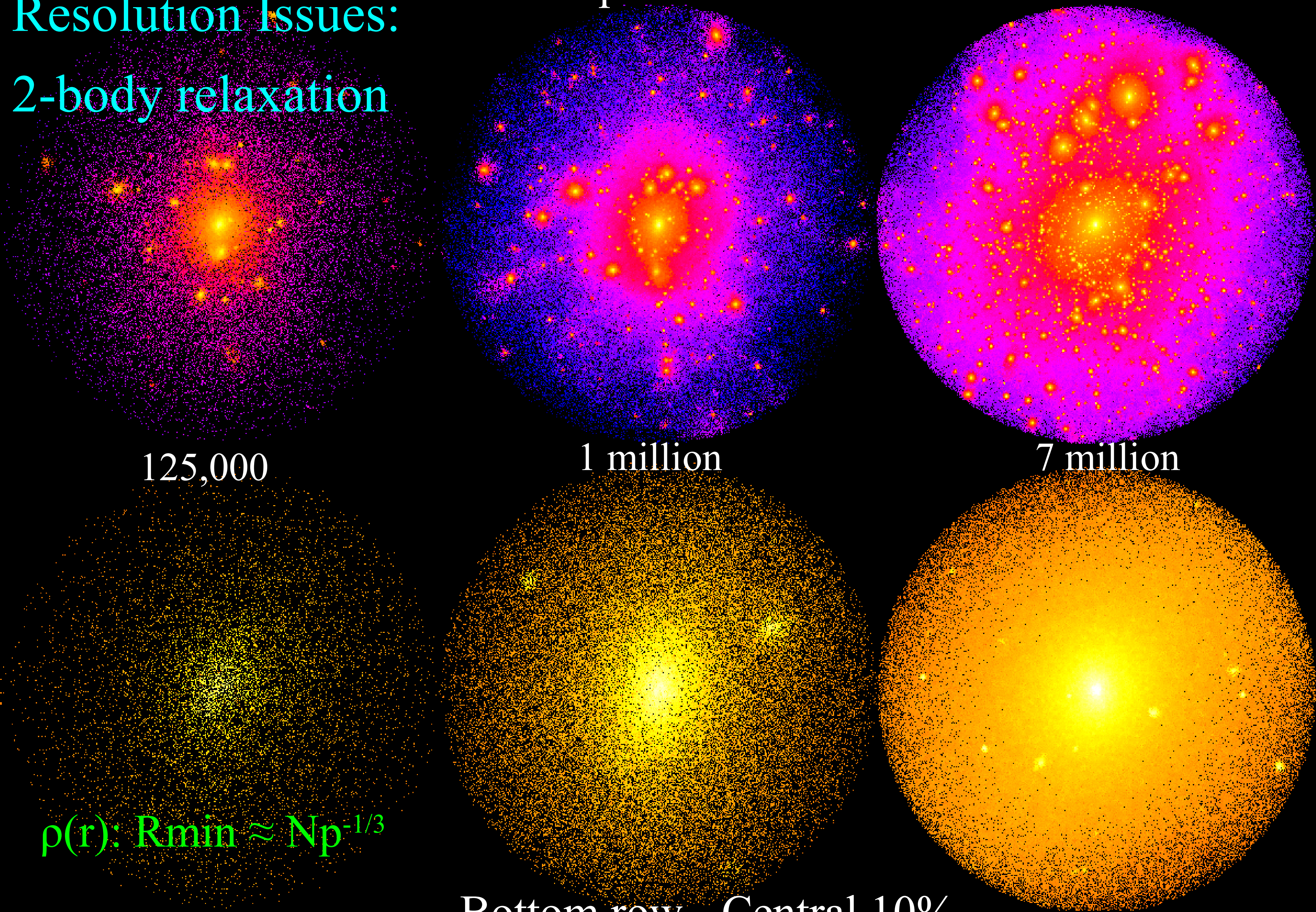
Low z merging halos don't affect cusp.

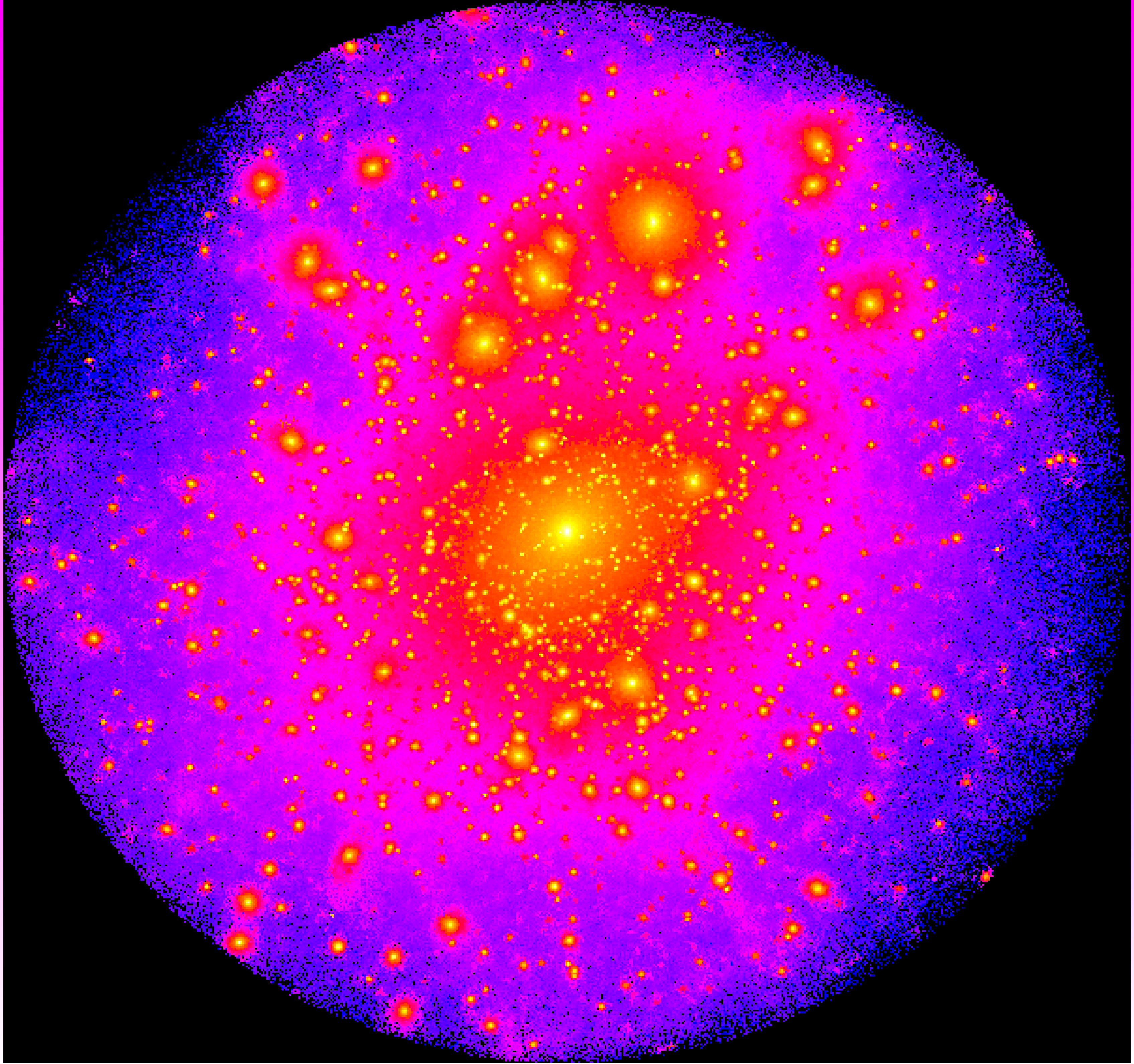
Subhalos:

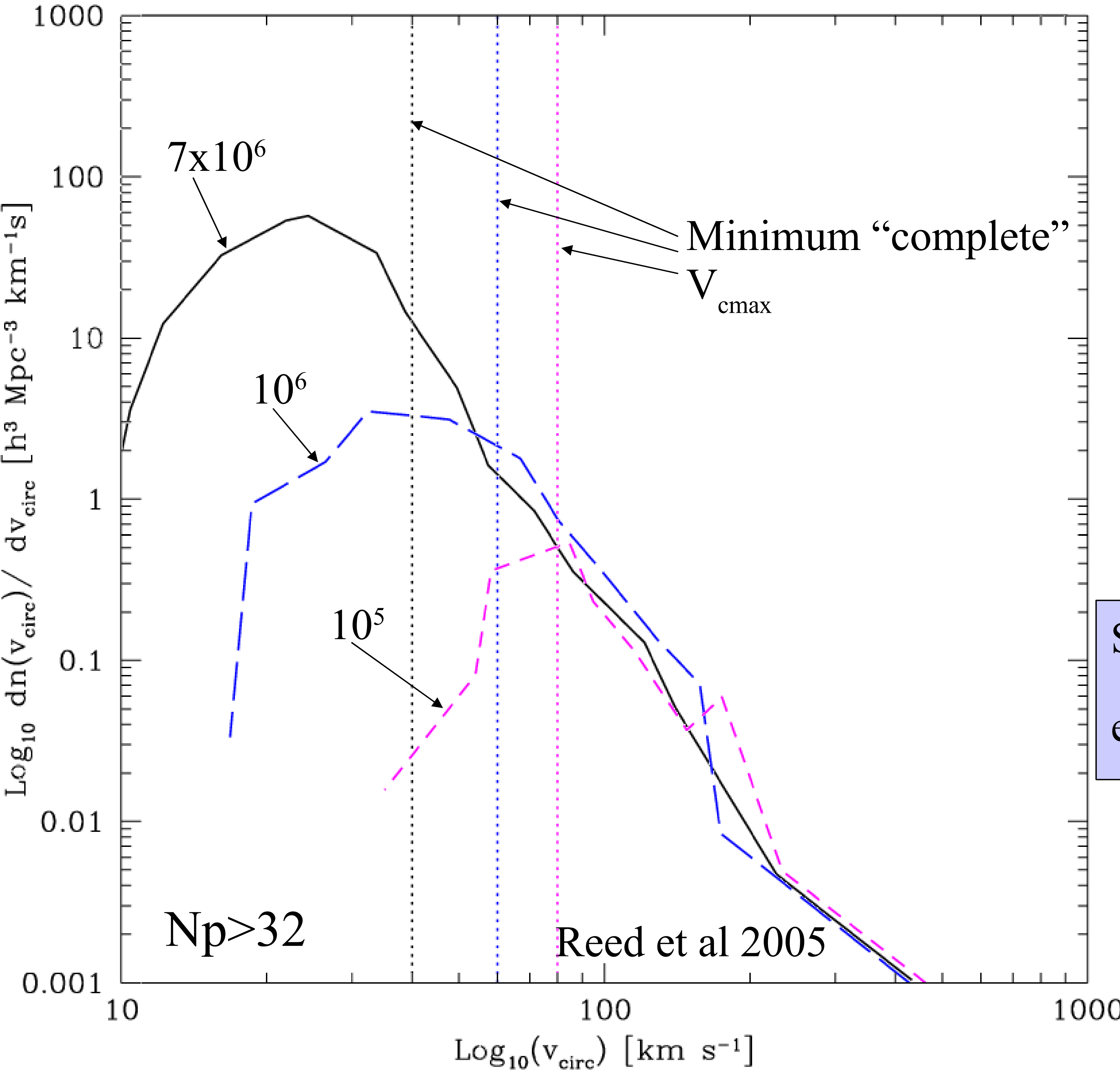
Too few satellites?---overmerging



Resolution Issues:
2-body relaxation

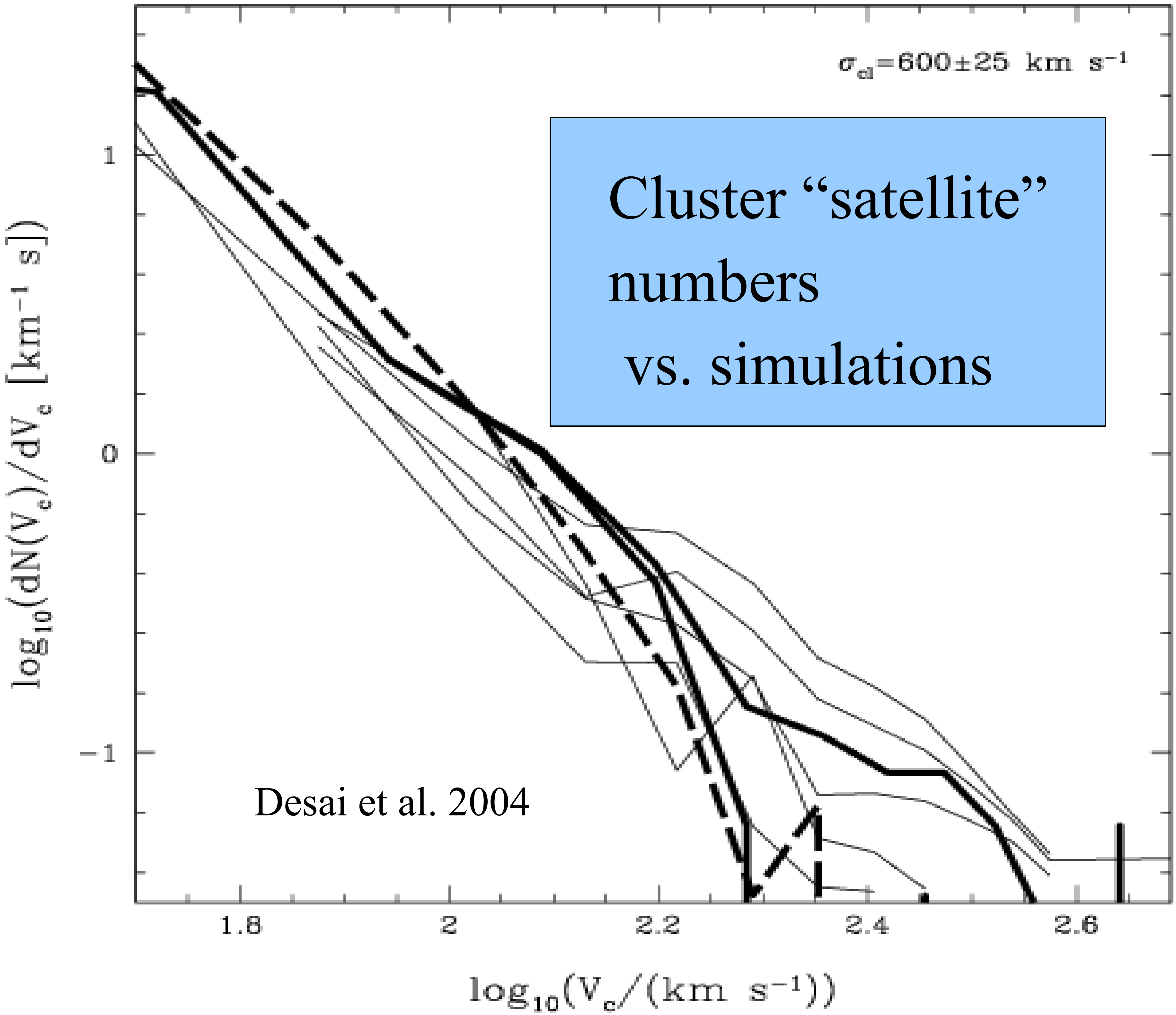






subhalo convergence tests:

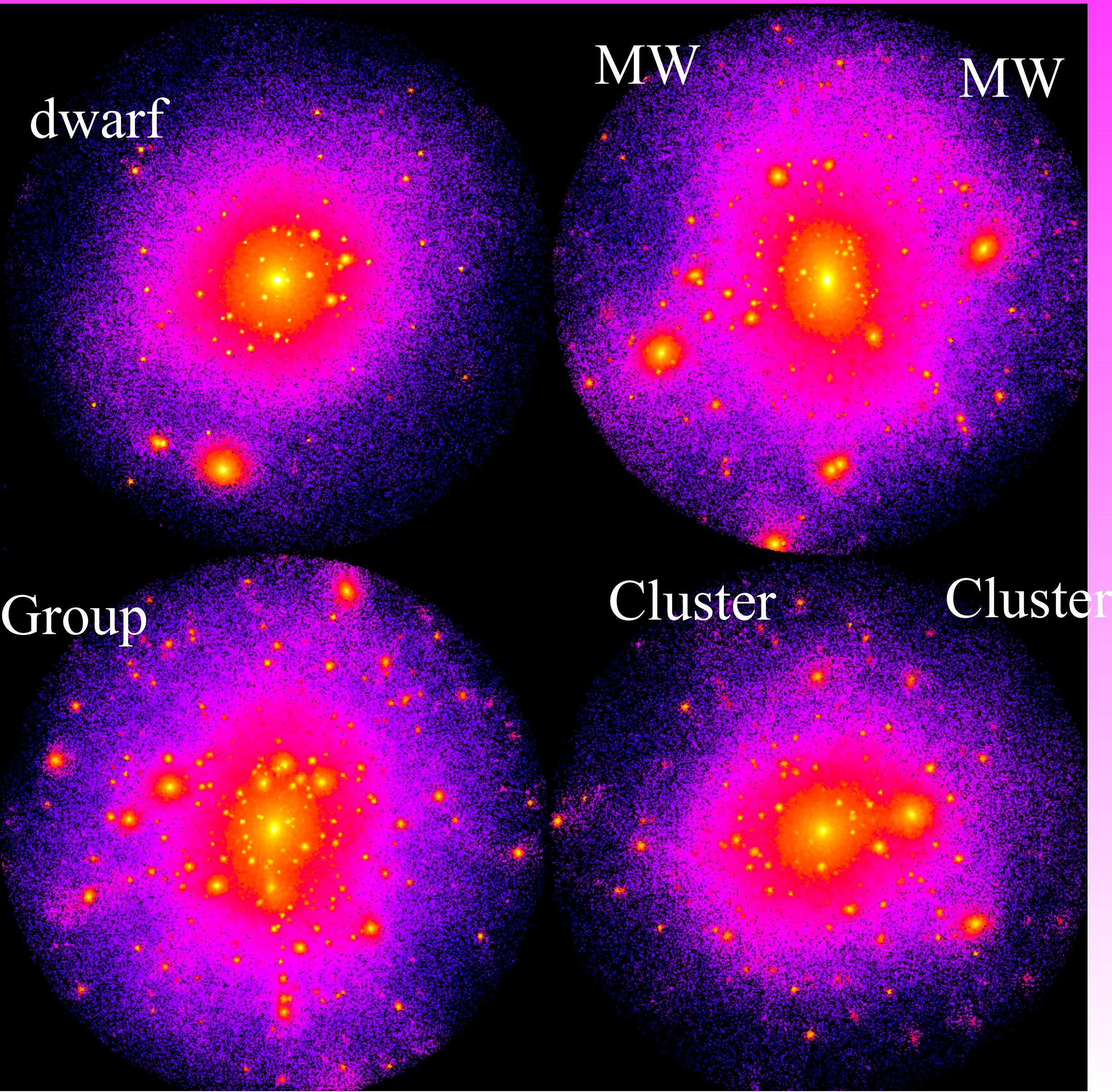
Small halos too easily destroyed



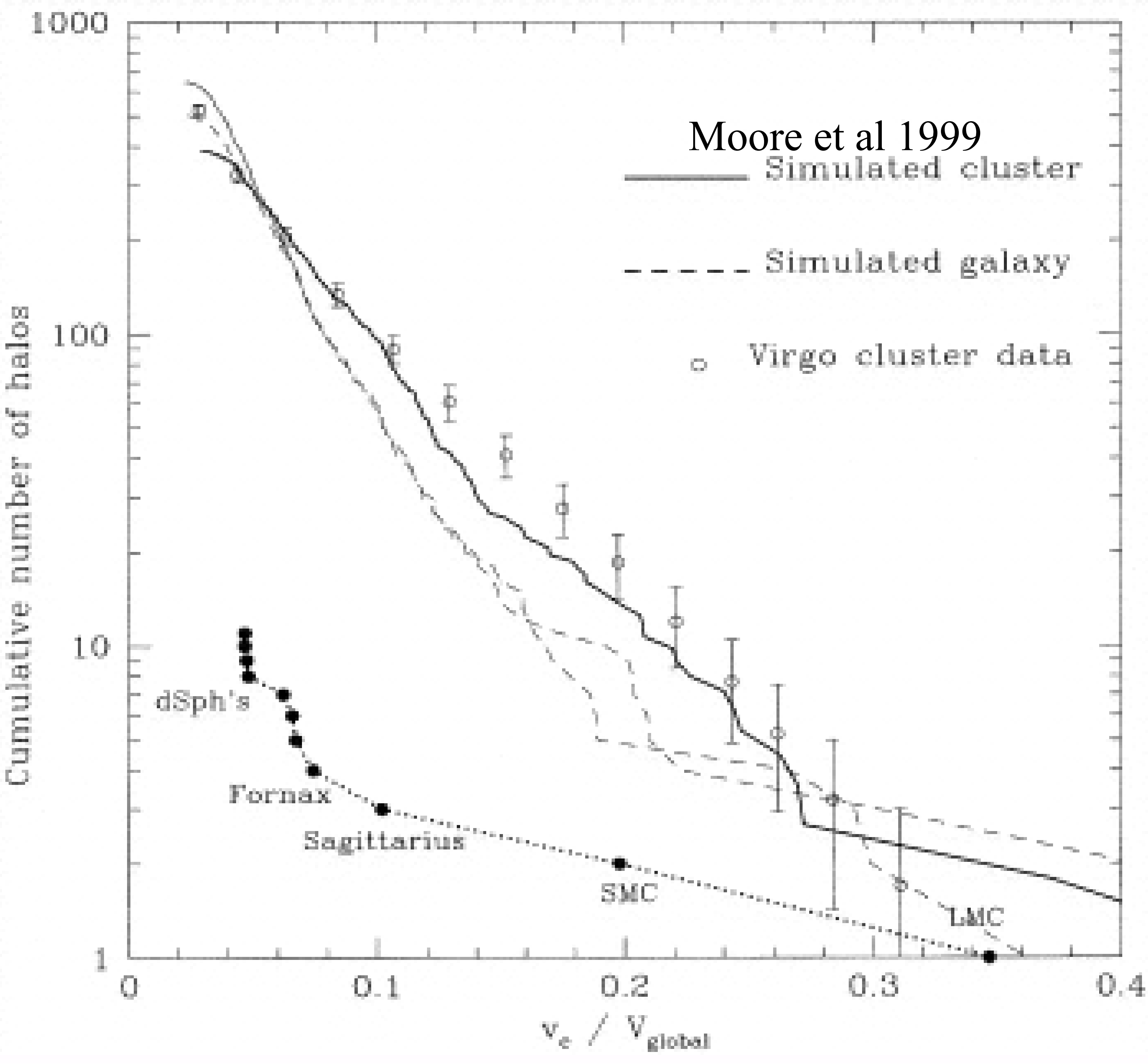
σ_{cl}=600±25 km s^{-1}
Cluster "satellite" numbers vs. simulations
Desai et al. 2004
1
0
−1
1.8
2
2.2
2.4
2.6
$\log_{10}(dN(V_c)/dV_c\ [km^{-1}\ s])$
$\log_{10}(V_c/(km\ s^{-1}))$

CDM crisis
“missing” local group satellite galaxies

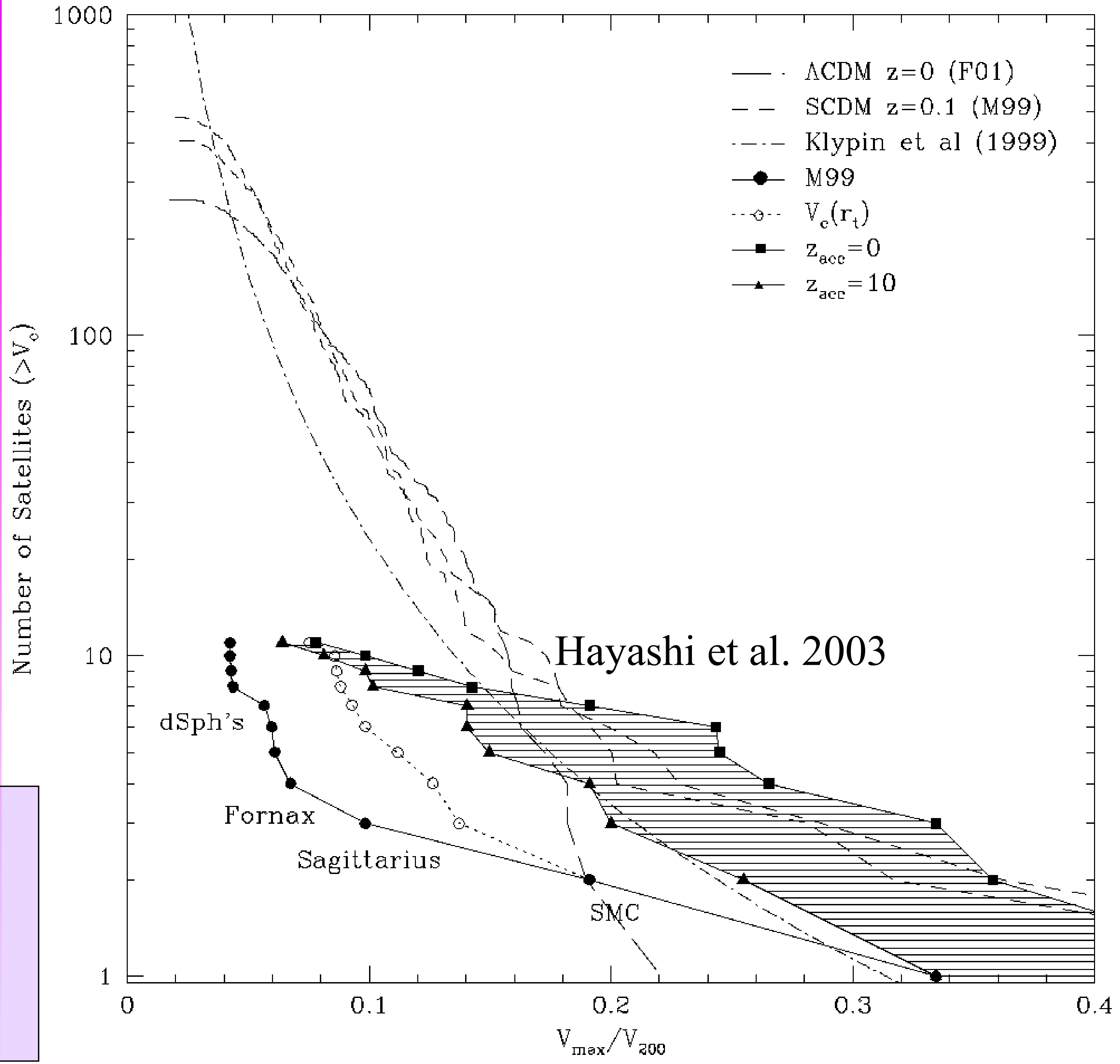
Simulated Halos



Real Halos



Moore et al 1999
Simulated cluster
Simulated galaxy
Virgo cluster data
Cumulative number of halos
1000
100
10
1
0
0.1
0.2
0.3
0.4
v_c / V_{global}
dSph's
Fornax
Sagittarius
SMC
LMC

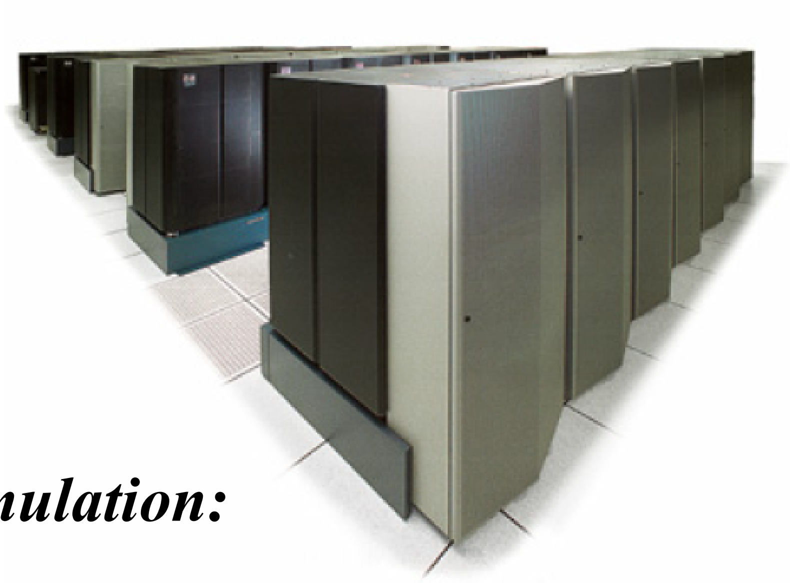


works well
if subhalos
not cuspy

Solutions to missing satellite problem

- Warm dark matter
- Supernovae
- Reionization/ UV background
- We see only inner parts of large satellites
- We only see most massive satellites
- We only see oldest satellites
- Decaying dark matter
- faulty intelligence

Cosmological Simulations
some problems



•***Simulation:***

An imitation; a sham.

Assumption of a false appearance.

(American Heritage Dictionay)

Kolb & Turner(?)

Cosmological Simulations some problems

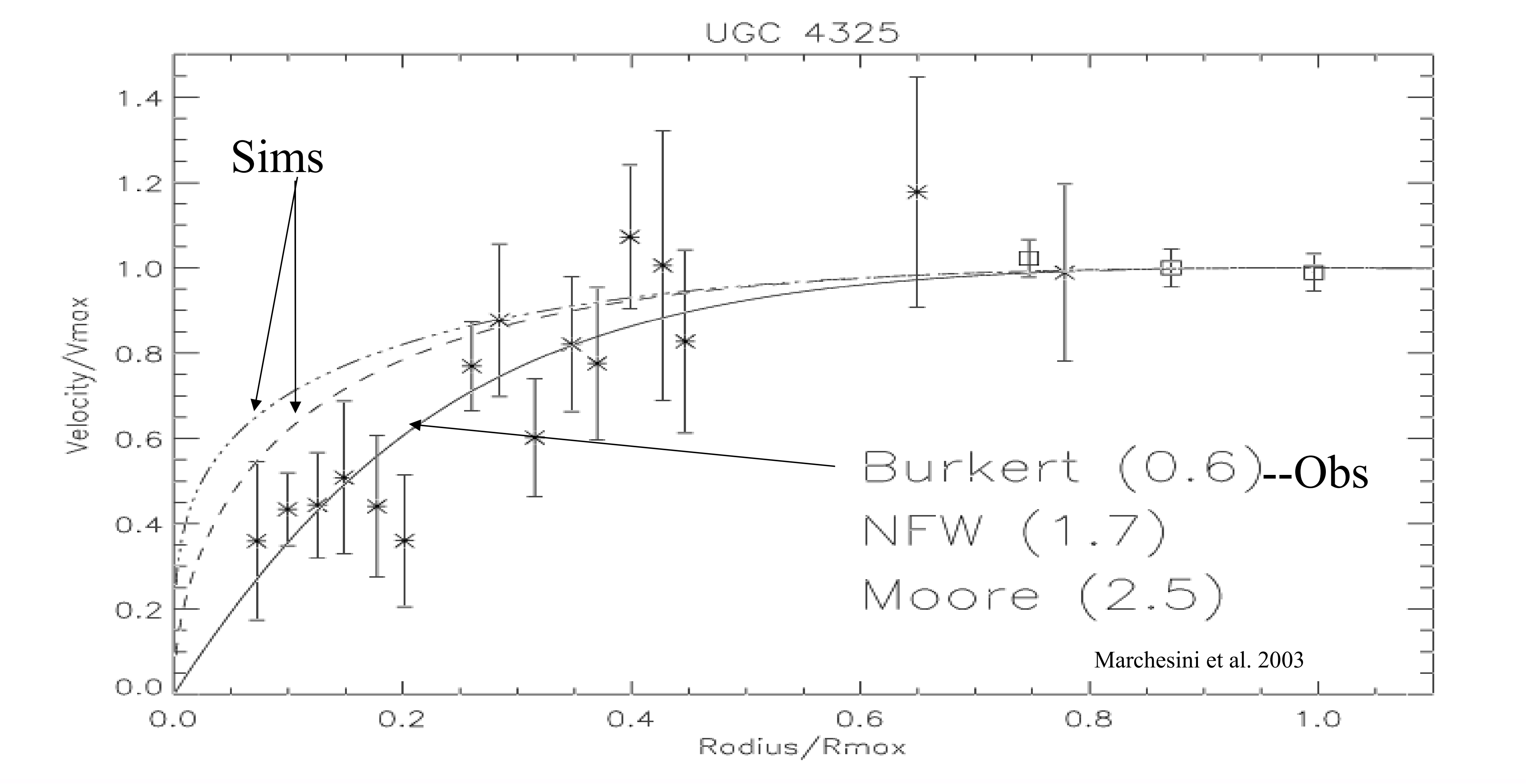
Answers.com:

- ***Simulation:***
- ***1. Something false or empty that is purported to be genuine;***
- ***a spurious imitation.***
- ***2. The quality of deceitfulness;***
- ***empty pretense.***

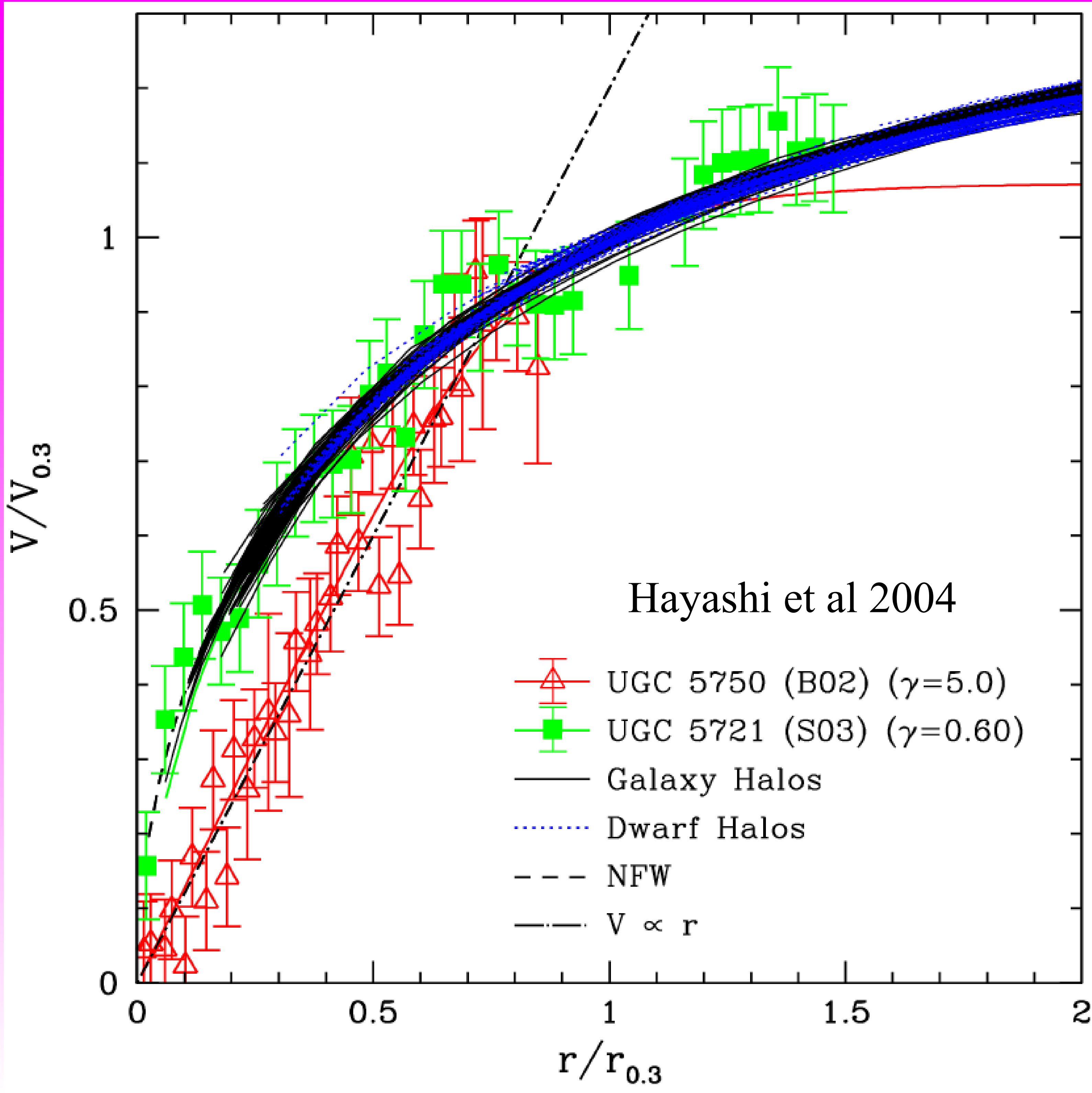
- ***3. One who assumes a false character;***
- ***an impostor: "He a man! Hell! He was***
- ***a hollow sham!" (Joseph Conrad).***
- ***4. A decorative cover made to simulate***
- ***an article of household linen and***
- ***Used over or in place of it:***
- ***A pillow sham***

Another CDM crisis
Flat cores in LSBs
(low surface brightness galaxies)

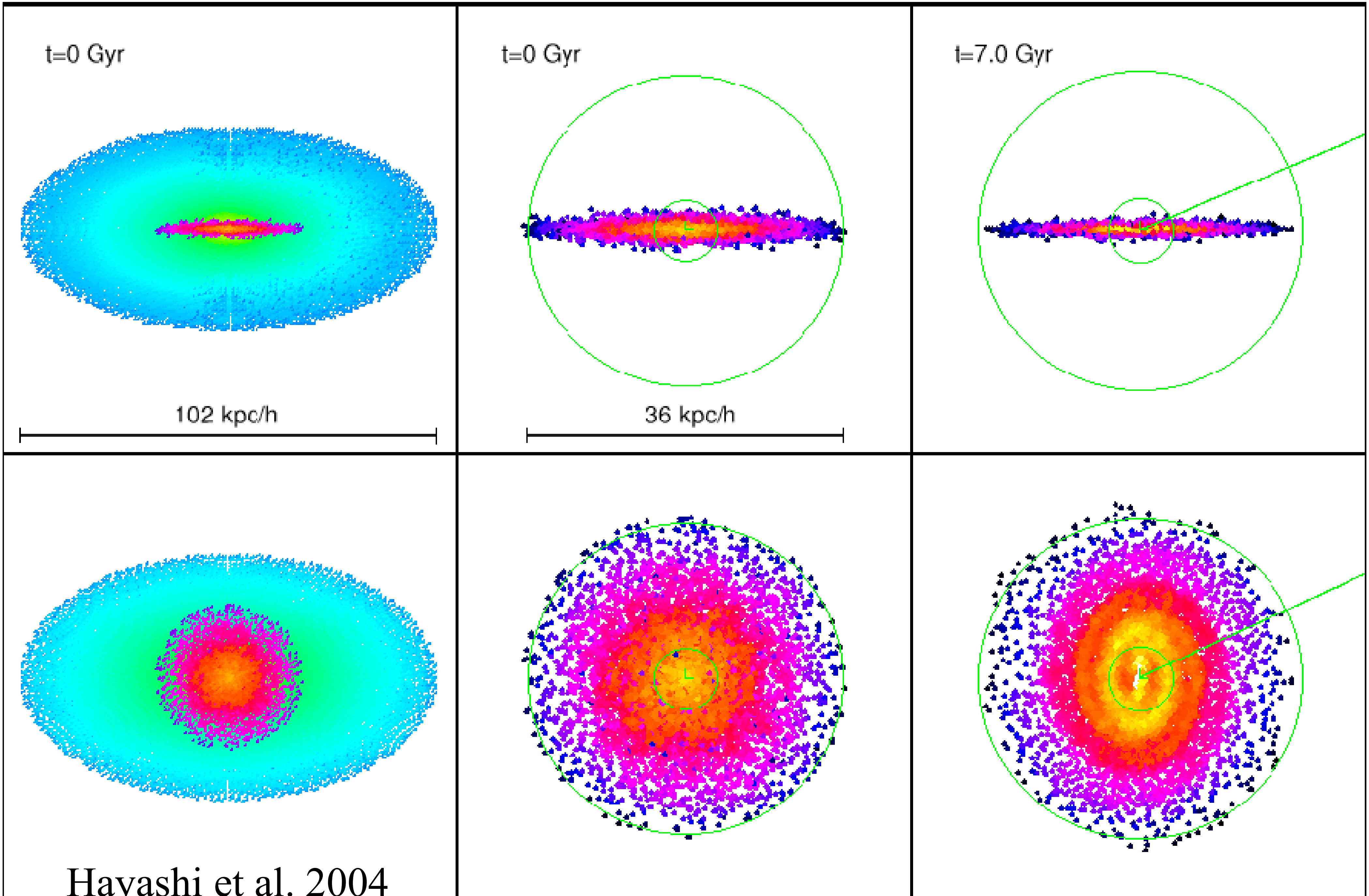
Observed “cores” vs CDM simulation cusps



Rotation curves

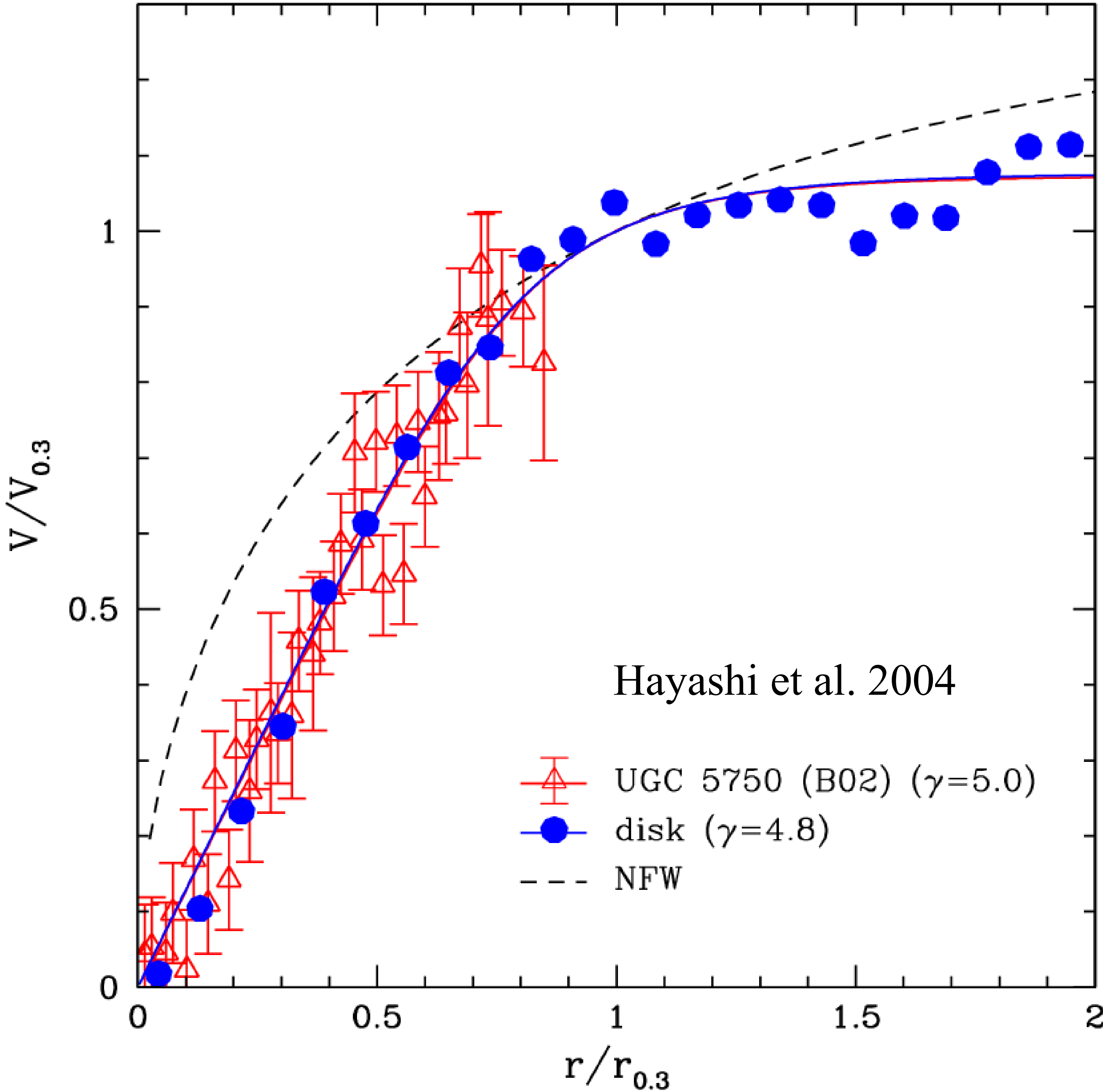


Disk placed in triaxial halo: $V_c \neq (GM/R)^{1/2}$



Hayashi et al. 2004

Rotation curve problem solved(?)

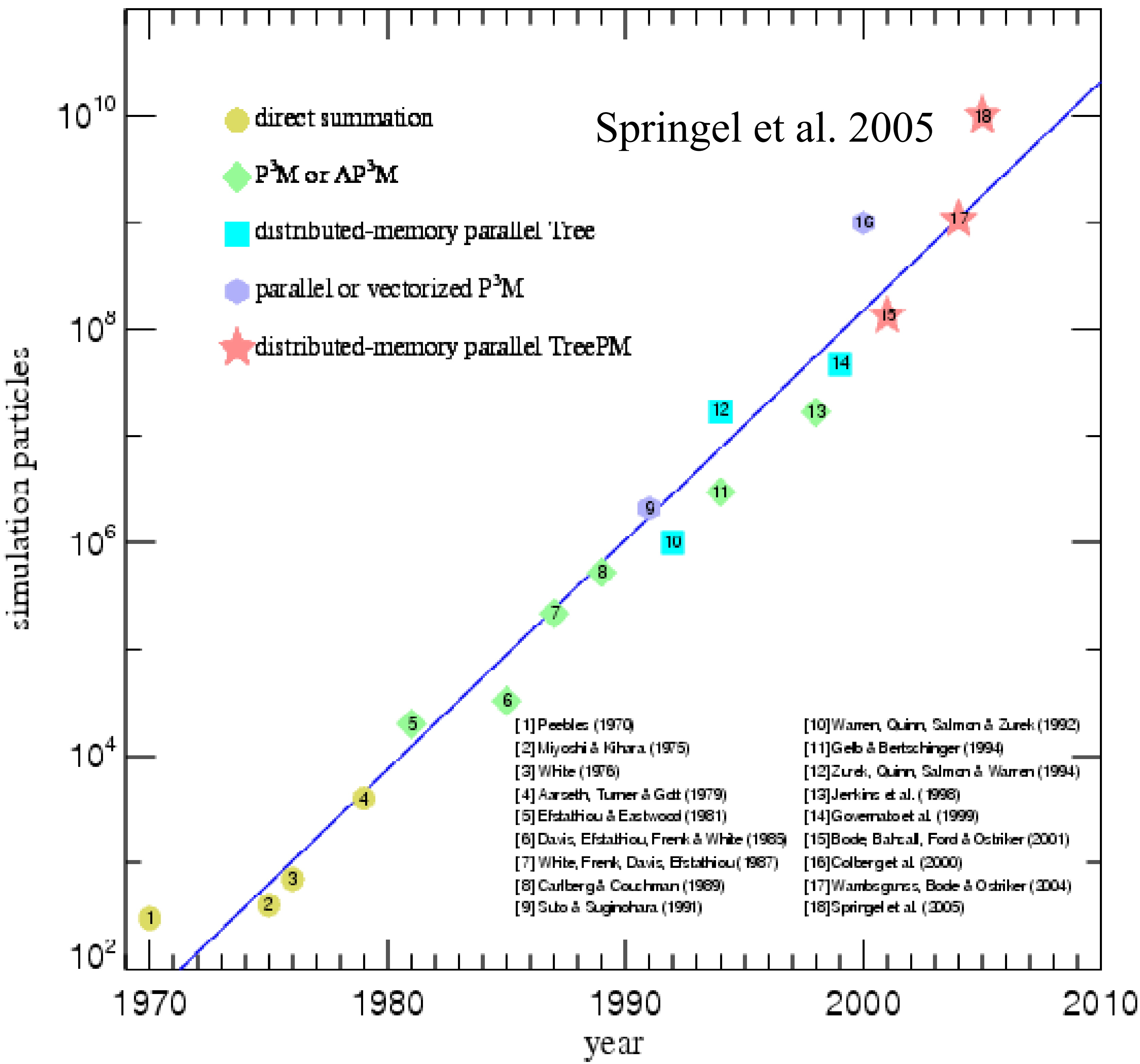


When to trust simulations?

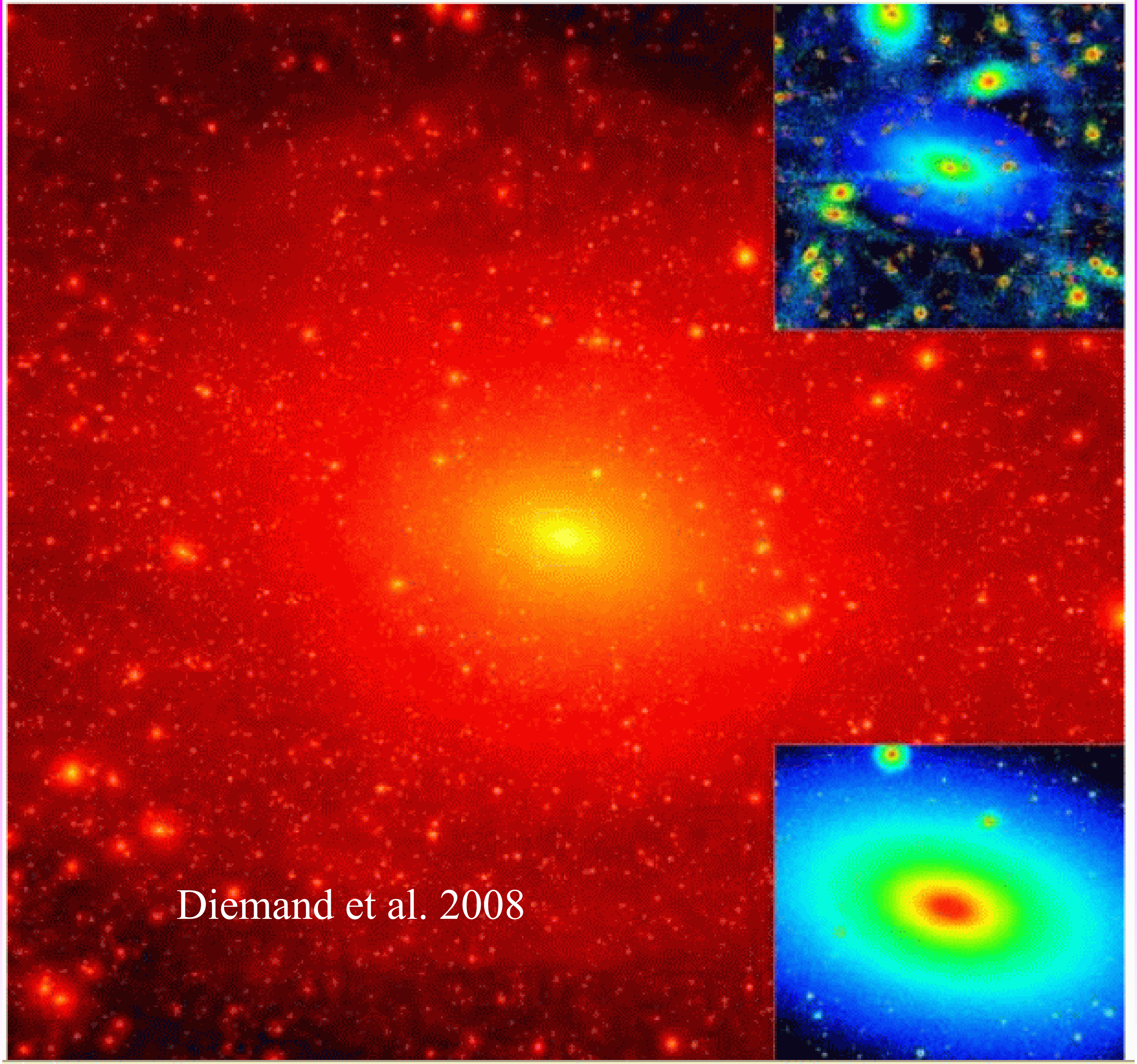
- Convergence tests:
  - Particle number, **starting redshift**, force resolution, timestep, boxsize
  - gravity only simulations OK
  - Simple, adiabatic hydrodynamics, OK?
- Simulations break when:
  - galaxies, star formation, feedback, other “unresolved” physics
  - Resolution issues not tested/understood

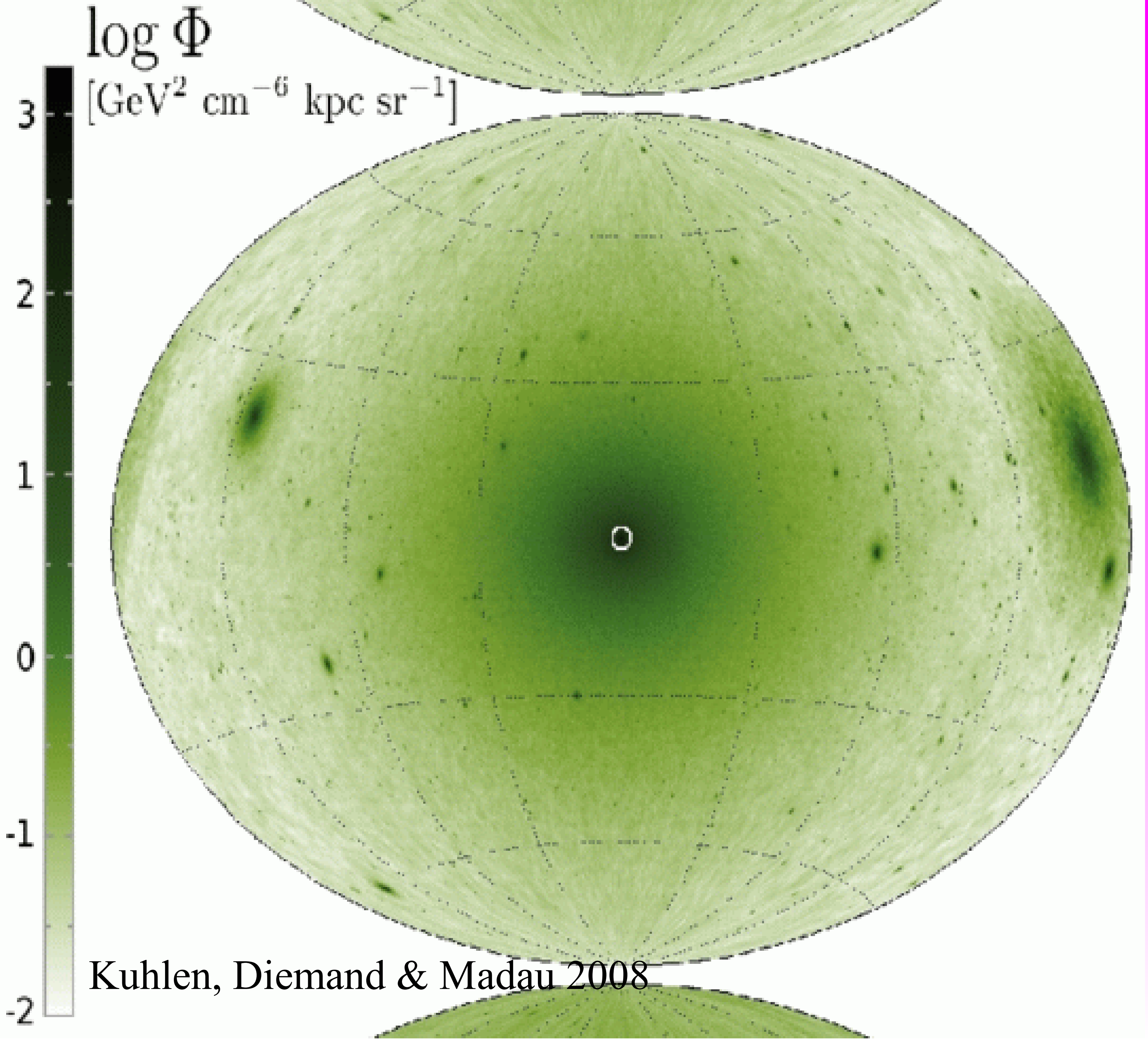
“successes” -simulating nonlinear problems

- Cuspy profile – but assumes dark matter only universe
  - Not predicted
- “painting” galaxies onto halos for observational comp.
  - semi-analytics (e.g. starburst during halo merger)
  - HOD (Halo Occupation Distribution)
    - Prob. Ngal within Mhalo, to match galaxy correlation function
- Basis for “precision” cosmology:
  - Cluster mass function
  - p(k) for weak lensing



Springel et al. 2005
direct summation
P³M or AP³M
distributed-memory parallel Tree
parallel or vectorized P³M
distributed-memory parallel TreePM
simulation particles
year
1970
1980
1990
2000
2010
10^10
10^8
10^6
10^4
10^2
[1] Peebles (1970)
[2] Miyoshi & Kihara (1975)
[3] White (1976)
[4] Aarseth, Turner & Gott (1979)
[5] Efstathiou & Eastwood (1981)
[6] Davis, Efstathiou, Frenk & White (1985)
[7] White, Frenk, Davis, Efstathiou (1987)
[8] Carlberg & Couchman (1989)
[9] Suto & Suginohara (1991)
[10] Warren, Quinn, Salmon & Zurek (1992)
[11] Gelb & Bertschinger (1994)
[12] Zurek, Quinn, Salmon & Warren (1994)
[13] Jenkins et al. (1998)
[14] Governato et al. (1999)
[15] Bode, Bahcall, Ford & Ostriker (2001)
[16] Colberg et al. (2000)
[17] Wambsganss, Bode & Ostriker (2004)
[18] Springel et al. (2005)


Diemand et al. 2008

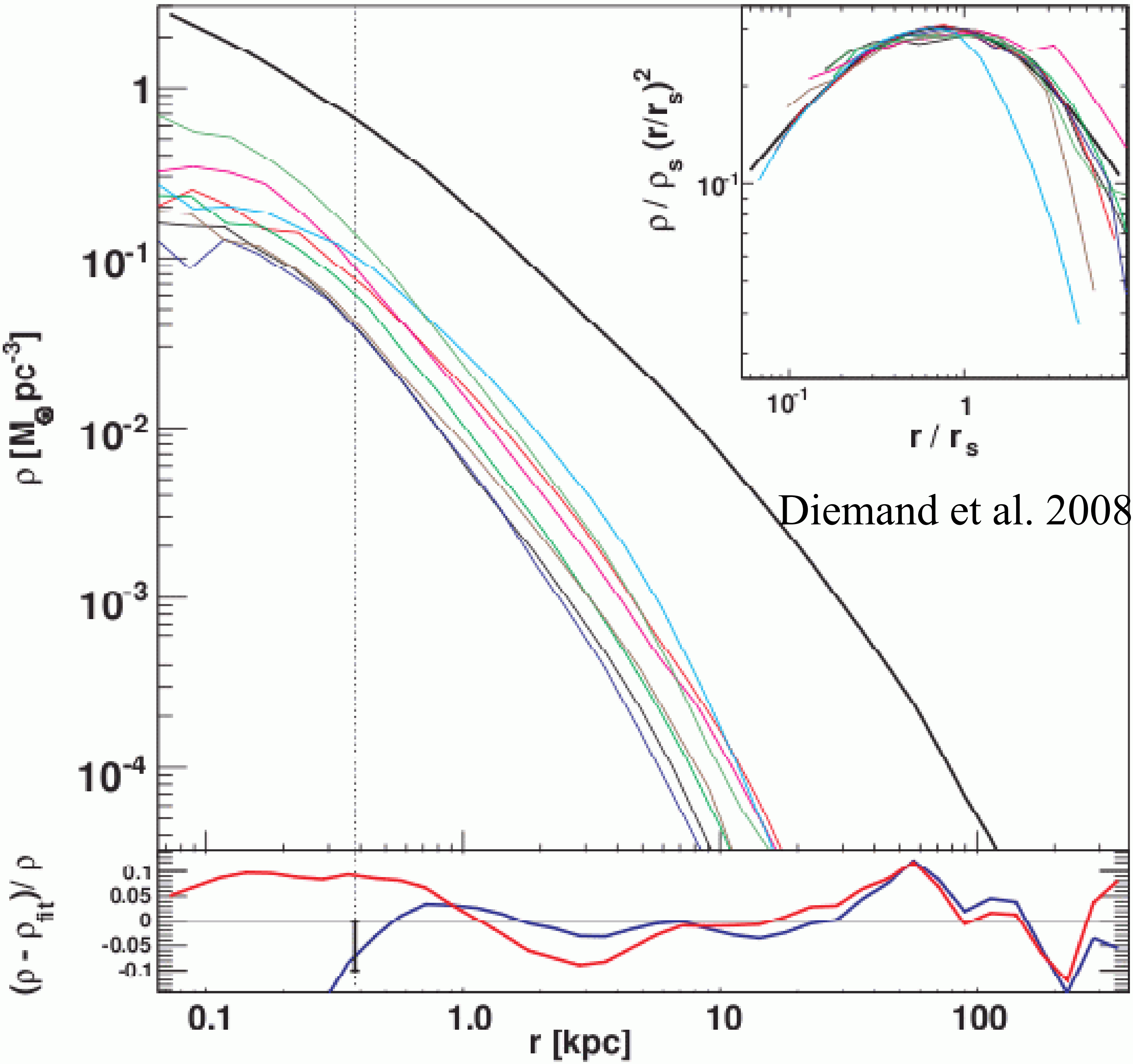


Kuhlen, Diemand & Madau 2008

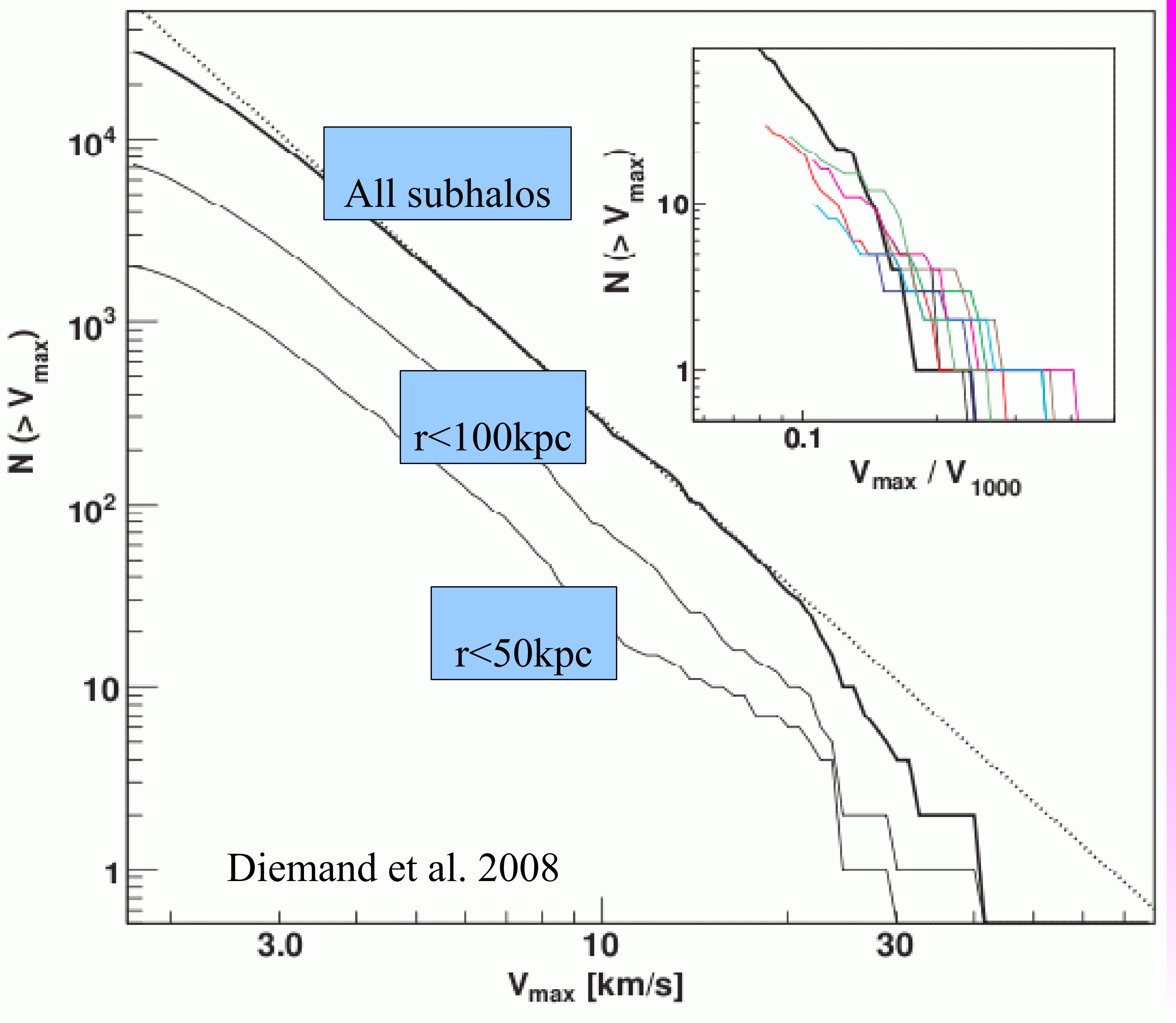
$R_{min} \sim N_p^{-1/3}$

10^6 vs. 10^9 particles.

10 x better (spatial) res. for 10^6 x more work.



Diemand et al. 2008



All subhalos
r<100kpc
r<50kpc
Diemand et al. 2008
N (> V_max)
10^4
10^3
10^2
10
1
3.0
10
30
V_max [km/s]
N (> V_max)
10
1
0.1
V_max / V_1000

Big Simulations

- Now: >billion particles in a halo
  - "Via Lactea 2" (Stadel, Madau, Kuhlen et al.)
  - "billennium" (Springel, Navarro et al)
- To model Milky Way halo, including micro-(sub)halos
  - get D.M. Annilihation signal (e.g. Koushiappas)
  - Earth mass: need ~ 10^{-8} Msun particle -------- ~10^{20} particles
  - 10^{11} times more particles -------- ~2060?

Conclusions

- Simulation successes:
  - Halo numbers
  - Halo distribution, clustering
  - Halo structure
- Problems
  - Simulations difficult to interpret
  - "trust" D.M.-only, w/convergence tests
  - Always need bigger sim., ***smaller scales***
  - CDM lives, so far
- Precision cosmology still needs simulations (e.g. evolution of cluster mass function, matter power spectrum)