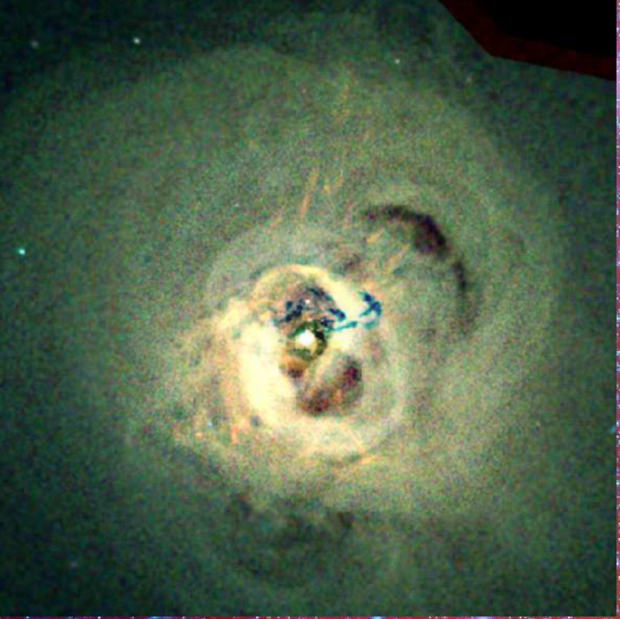
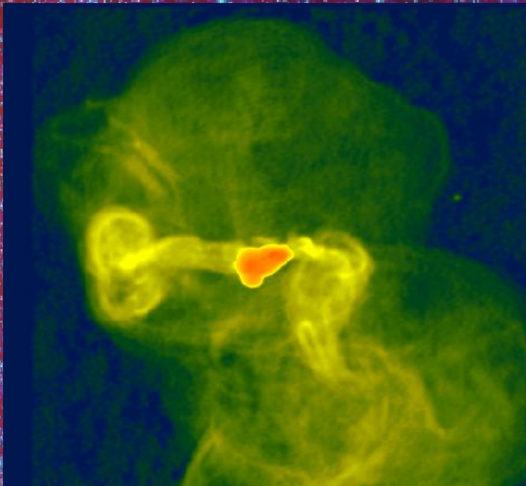


Galaxy Clusters
Garching, July 2010

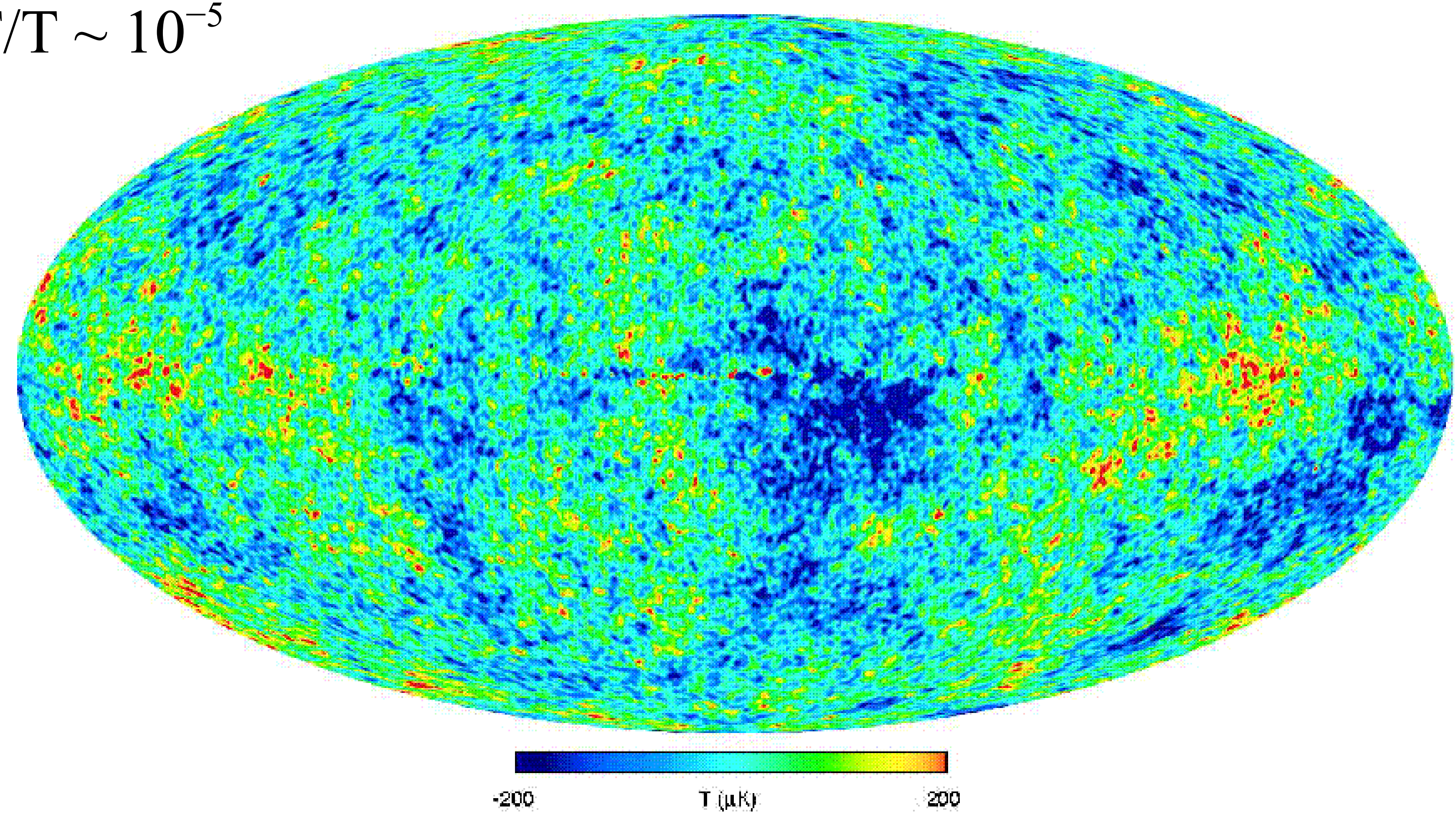
Galaxy clusters in an evolving universe

Simon White
Max Planck Institute for Astrophysics



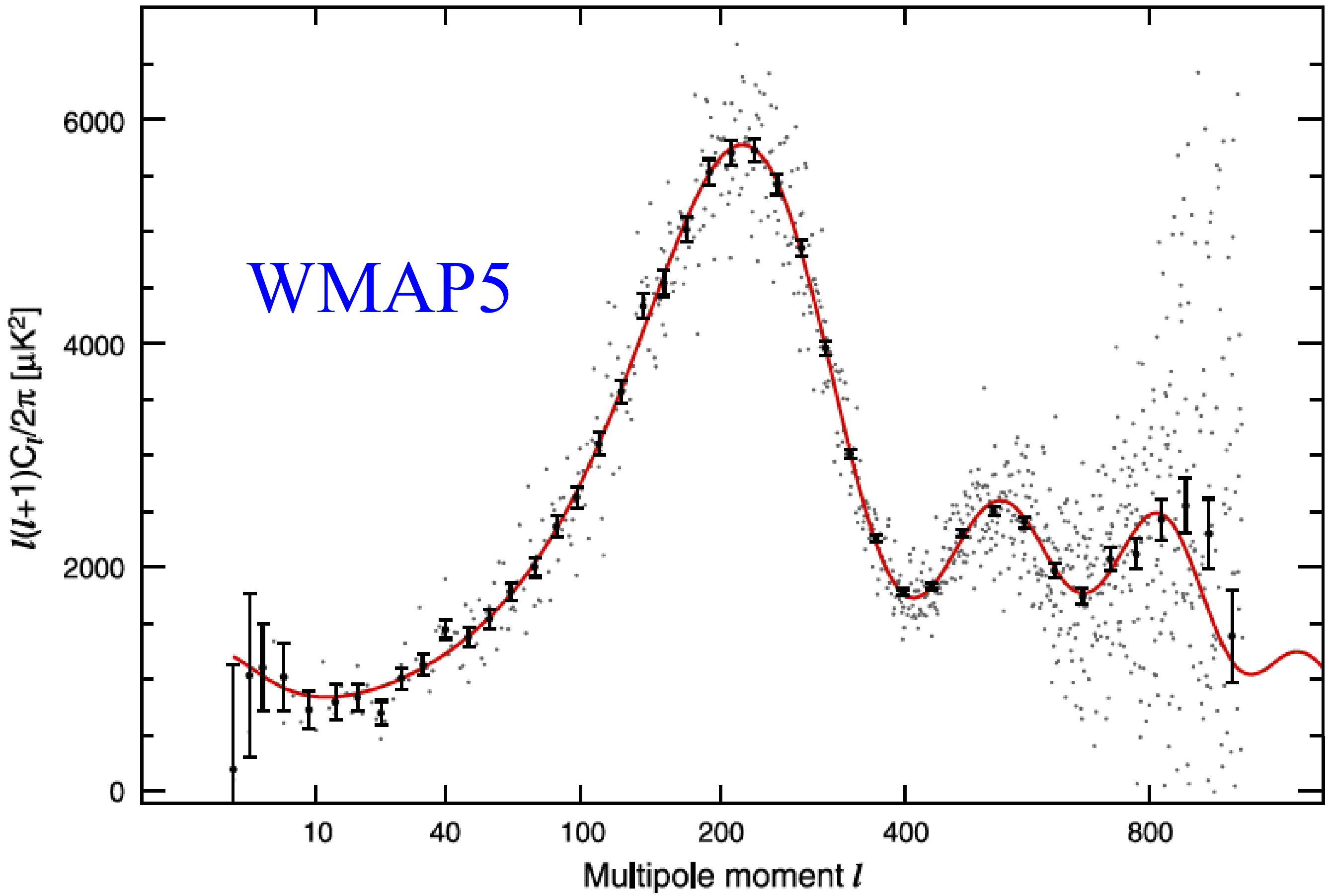
The *WMAP* of the whole CMB sky

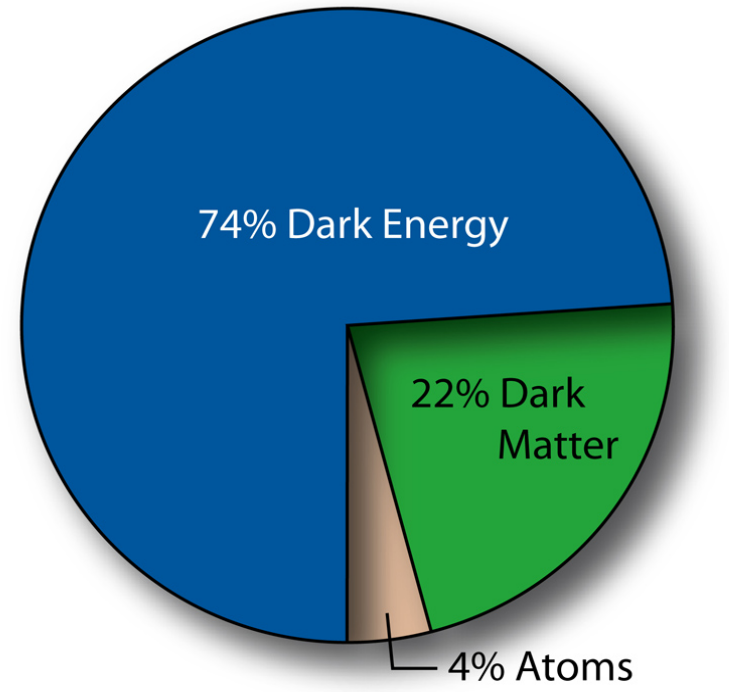
$\Delta T/T \sim 10^{-5}$



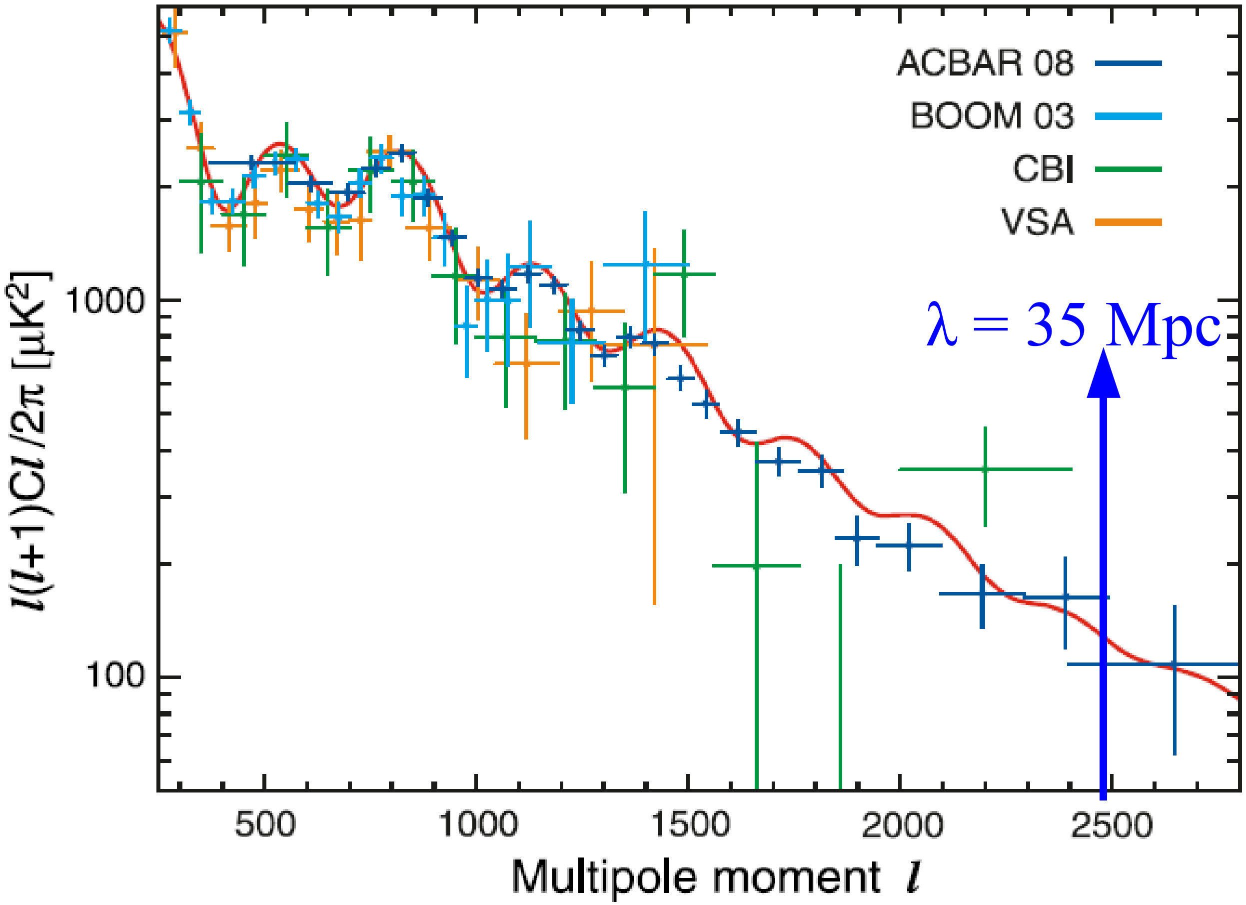
The initial conditions for all structure formation

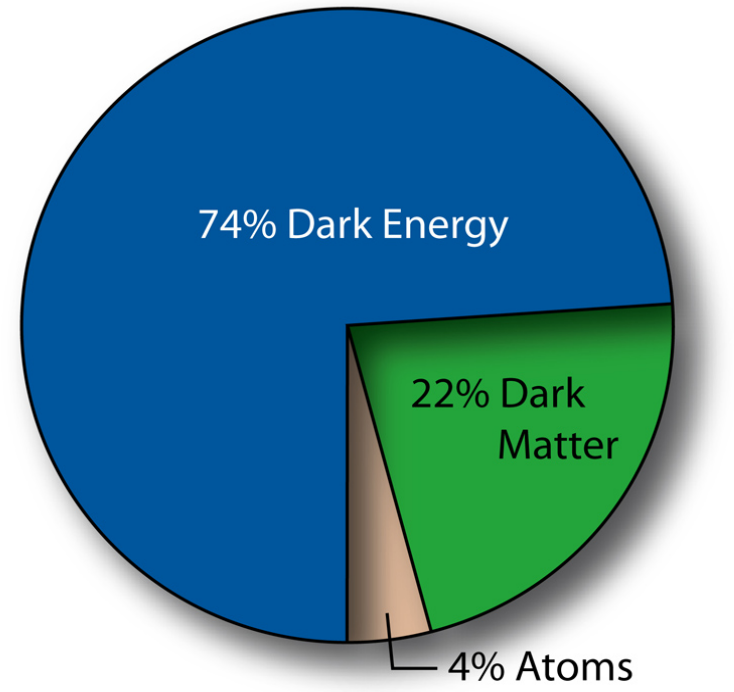
Bennett et al 2003





parameter	symbol	WMAP-5 alone	WMAP-5 + BAO + SNe	comment
CMB temperature	$T_{\rm CMB}$	2.728 ± 0.004 K	–	from (Fixsen *et al.* 1996)
total matter density	$\Omega_{\rm tot}$	$1.099^{+0.100}_{-0.085}$	1.0052 ± 0.0064	
matter density	$\Omega_{\rm m0}$	0.258 ± 0.03	0.279 ± 0.015	assuming spatial flatness
baryon density	$\Omega_{\rm b0}$	0.0441 ± 0.0030	0.0462 ± 0.0015	here and below
cosmological constant	$\Omega_{\Lambda 0}$	0.742 ± 0.03	0.721 ± 0.015	
Hubble constant	h	$0.719^{+0.026}_{-0.027}$	0.701 ± 0.013	
power-spectrum normalisation	σ_8	0.796 ± 0.036	0.817 ± 0.026	
age of the Universe in Gyr	t_0	13.69 ± 0.13	13.73 ± 0.12	
decoupling redshift	$z_{\rm dec}$	1087.9 ± 1.2	1088.2 ± 1.1	
reionisation optical depth	τ	0.087 ± 0.017	0.084 ± 0.016	
spectral index	$n_{\rm s}$	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$	





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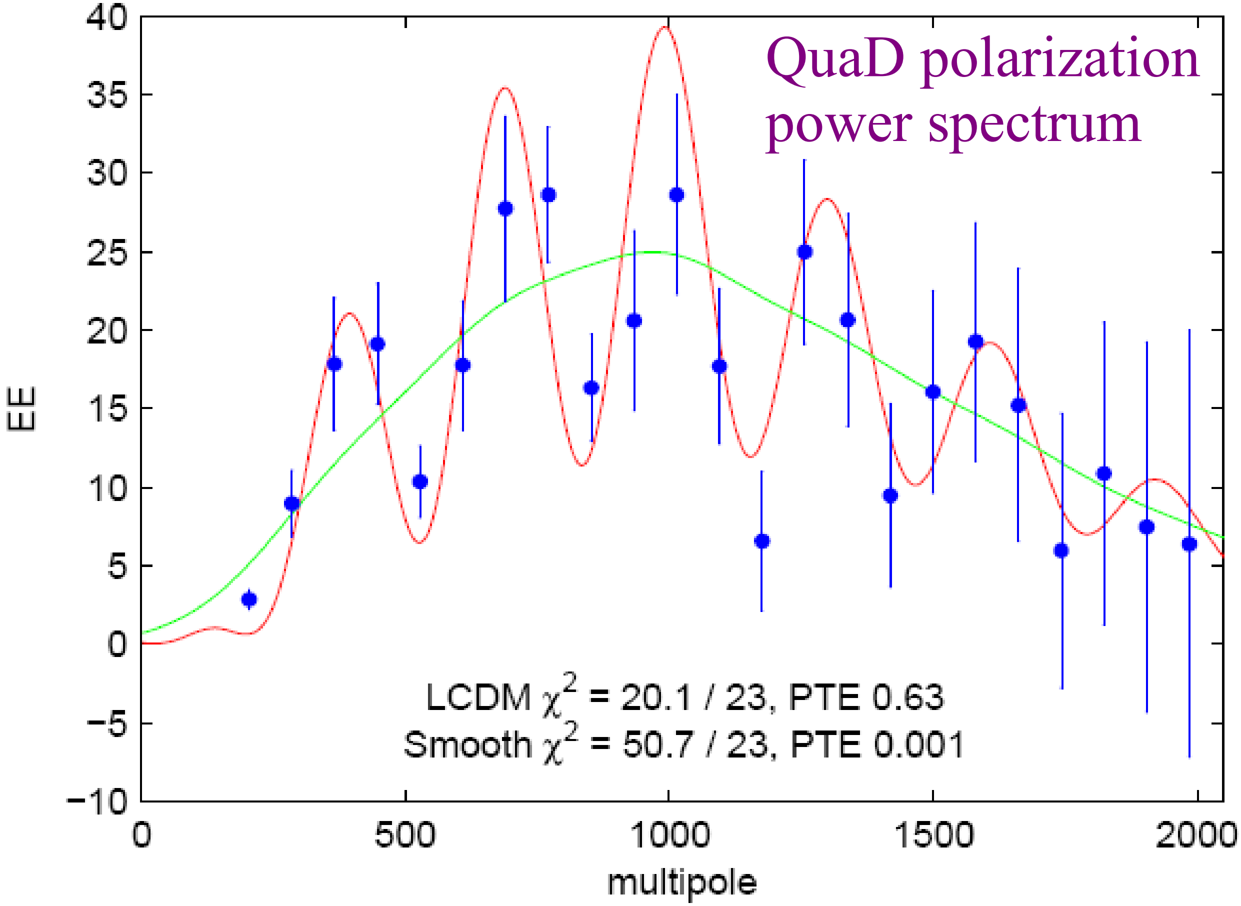

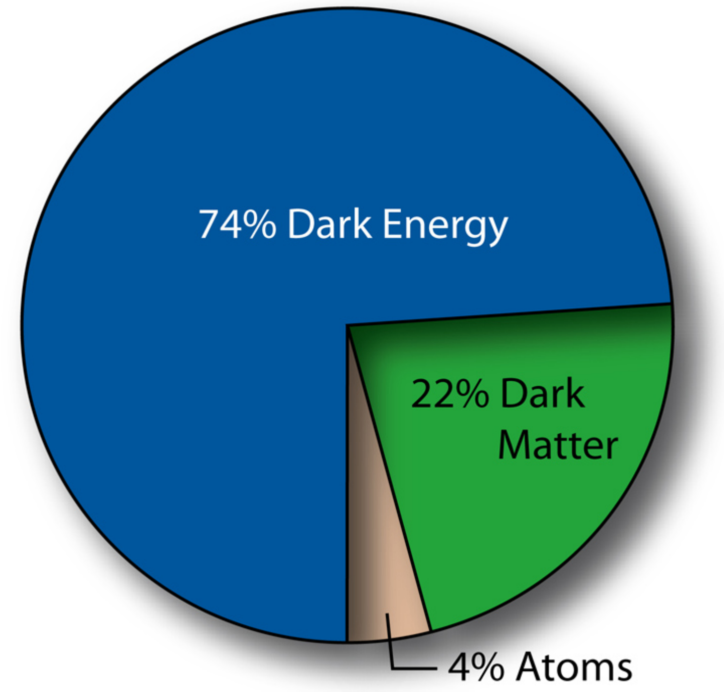

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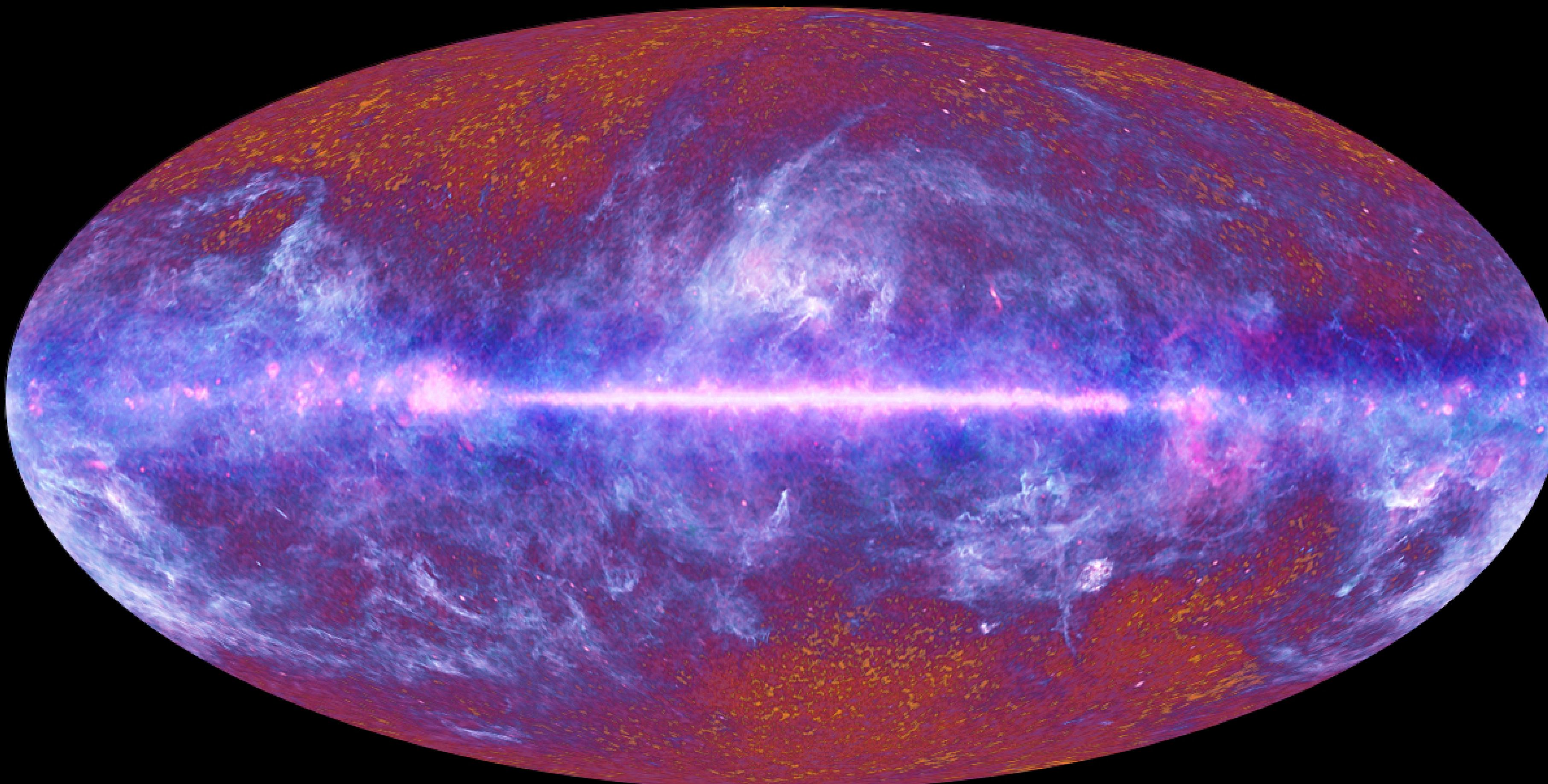


The Planck one-year all-sky survey

With the establishment of a standard structure formation paradigm, cluster studies split into three main threads

A: Tests of the paradigm / measurement of its parameters

- -- Statistics of matter distribution (Gaussian/non-Gaussian)
- -- Nature of dark matter (core structure, cluster galaxy halos)
- -- Nature of dark energy (N(M, z), baryon wiggles)
- -- Estimation of Ω_m, Ω_b / Ω_m, w, ...

B: Studies of the intergalactic medium

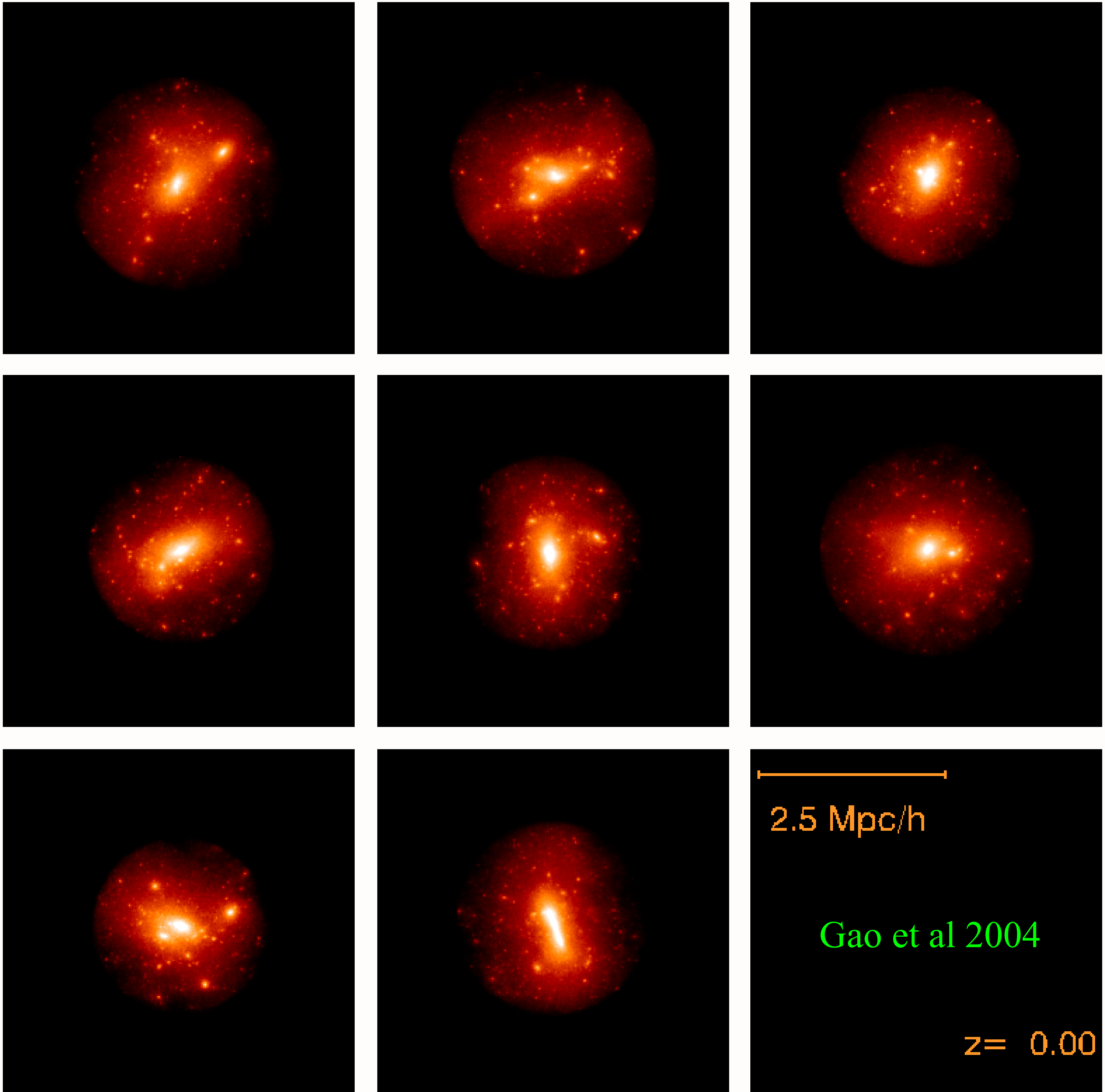
- -- thermodynamic history (heating/cooling, phases, conduction)
- -- dynamics (shocks, turbulence, stirring)
- -- enrichment history (Pop III, wind properties, mixing)
- -- nonthermal components (B-fields, CR's, radio bubbles)

C: Studies of galaxy evolution

- -- environment vs mass, structure, SFR... (<u>not</u> "morphology"!)
- -- early vs late imposition of trends (Nature vs Nurture)
- -- relation between galaxy and SMBH evolution

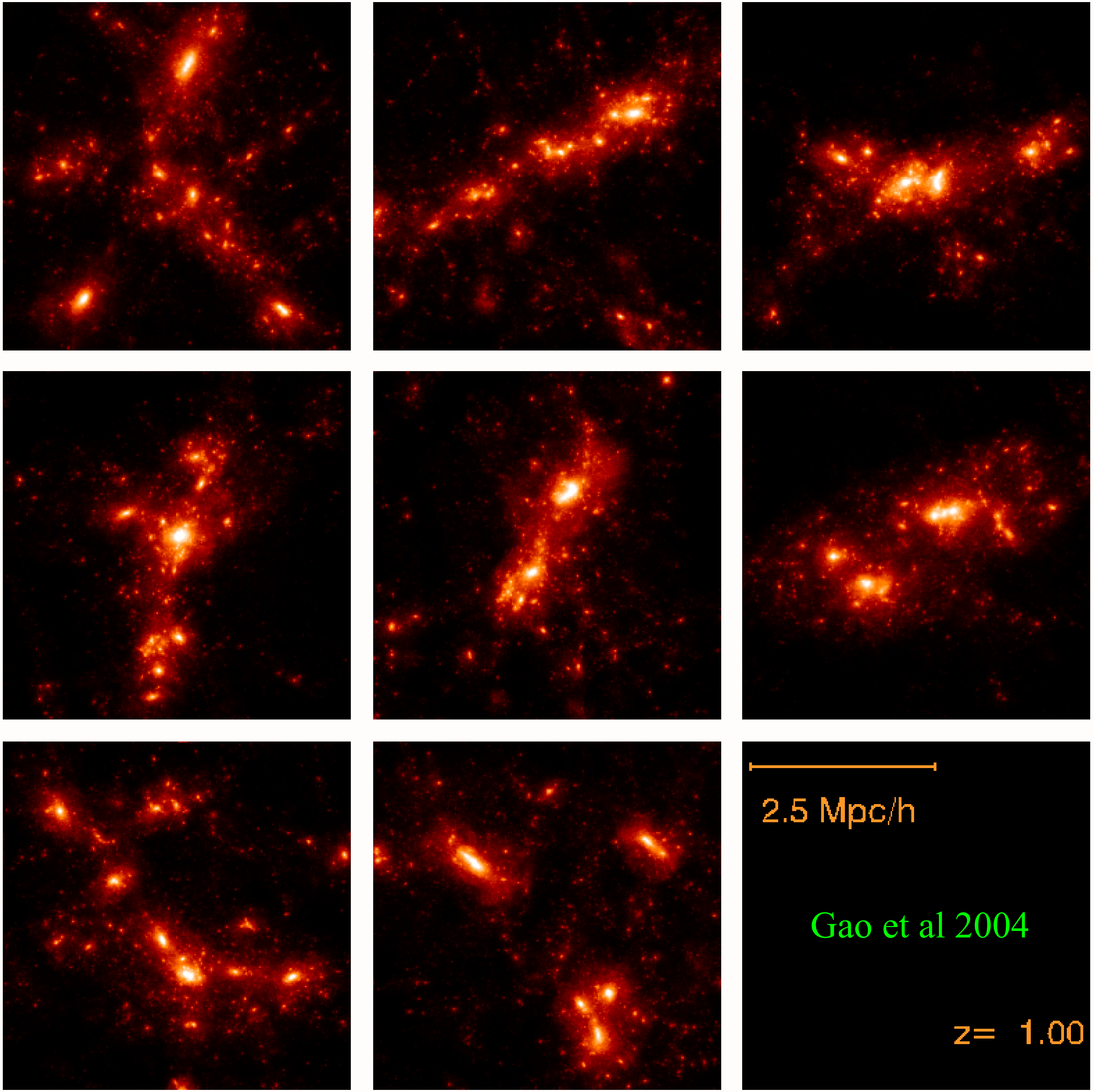
In the standard paradigm:

- clusters grow from inhomogeneous infall along filaments
- they have no edges – on large scales they become part of a globally homogeneous “cosmic web” -- on small scales their internal structure remembers their assembly history
- the 3-D structure around typical massive clusters is complex with many interacting sheets and filaments
- shock structures around clusters are extended and complex, punctuated by infalling cool clumps on the filaments $\longrightarrow$ cold fronts, abundance jumps, etc.



Cluster structure in ΛCDM

- Concordance cosmology
- Final cluster mass $\sim 10^{15}\,M_\odot$
- Only DM within R_{200} at $z = 0$ is shown



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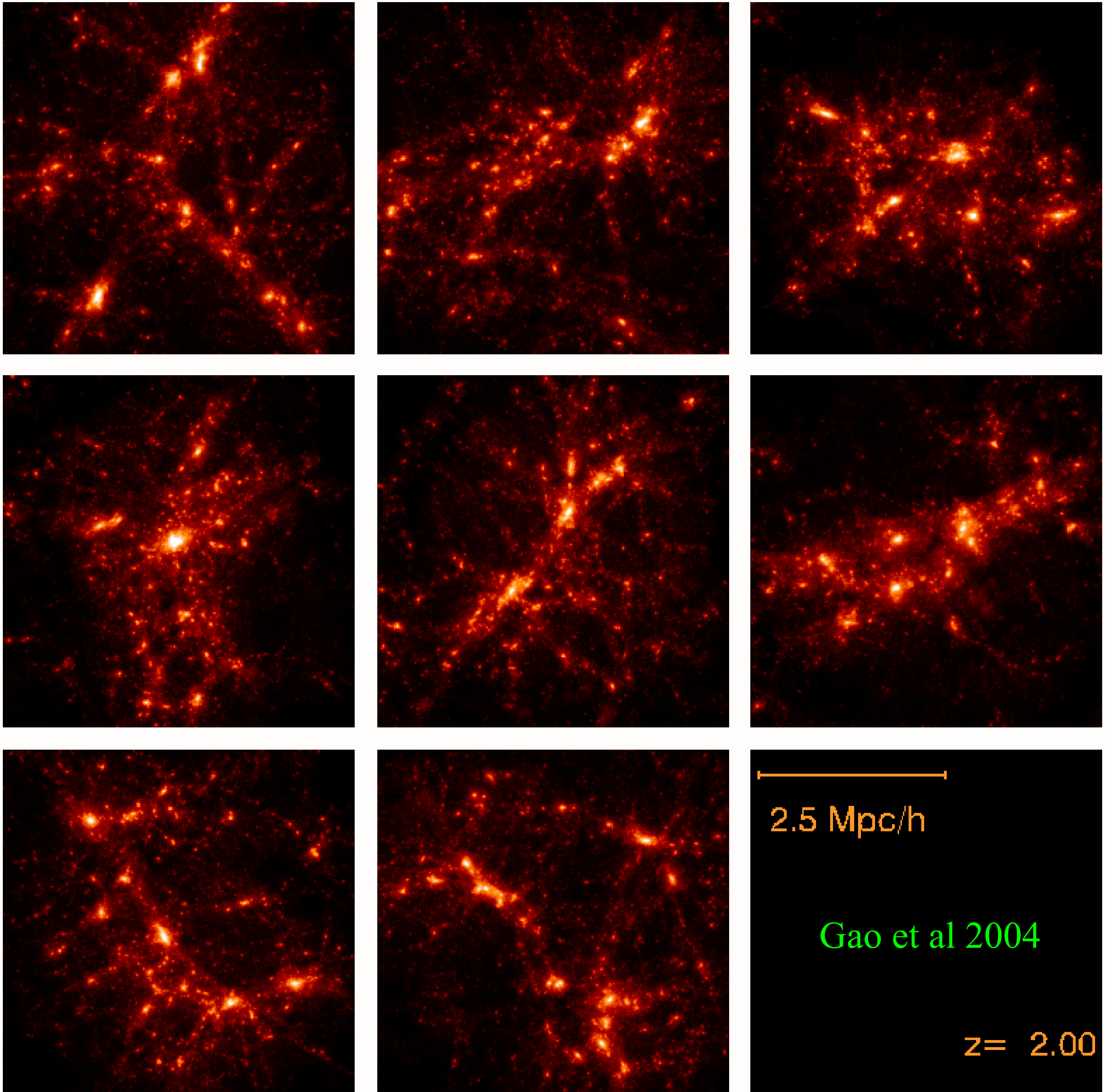

- Concordance cosmology
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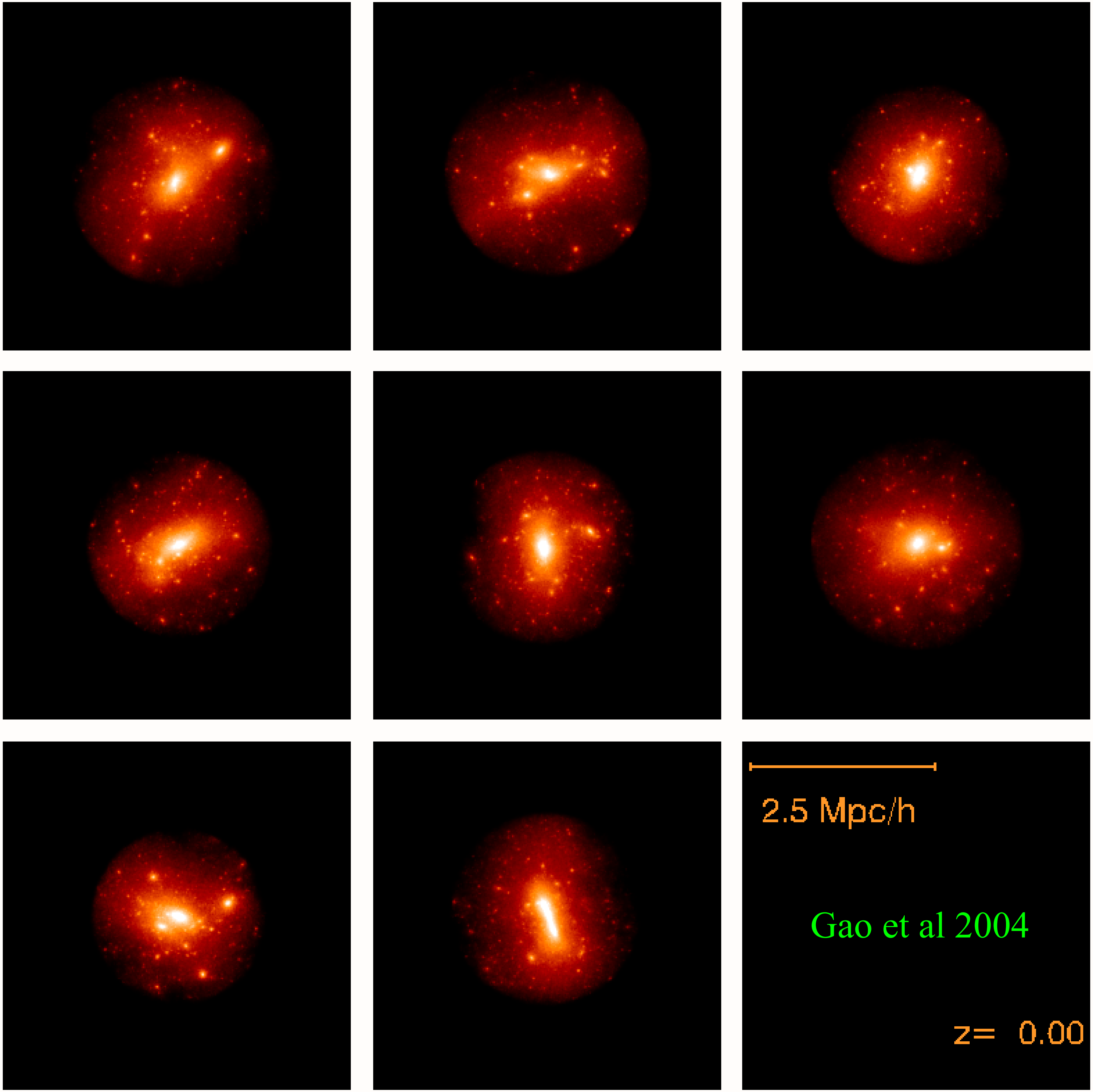

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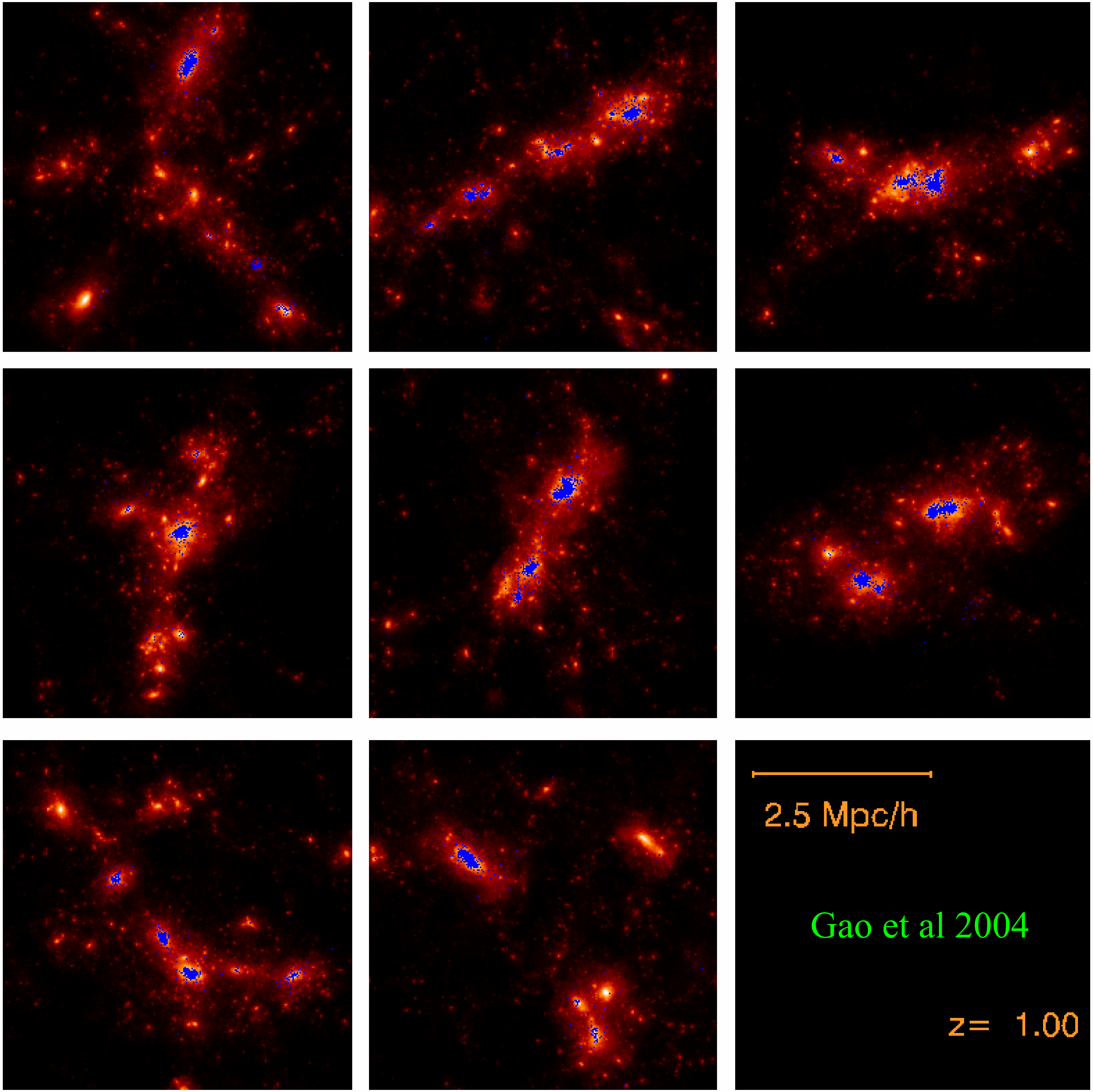
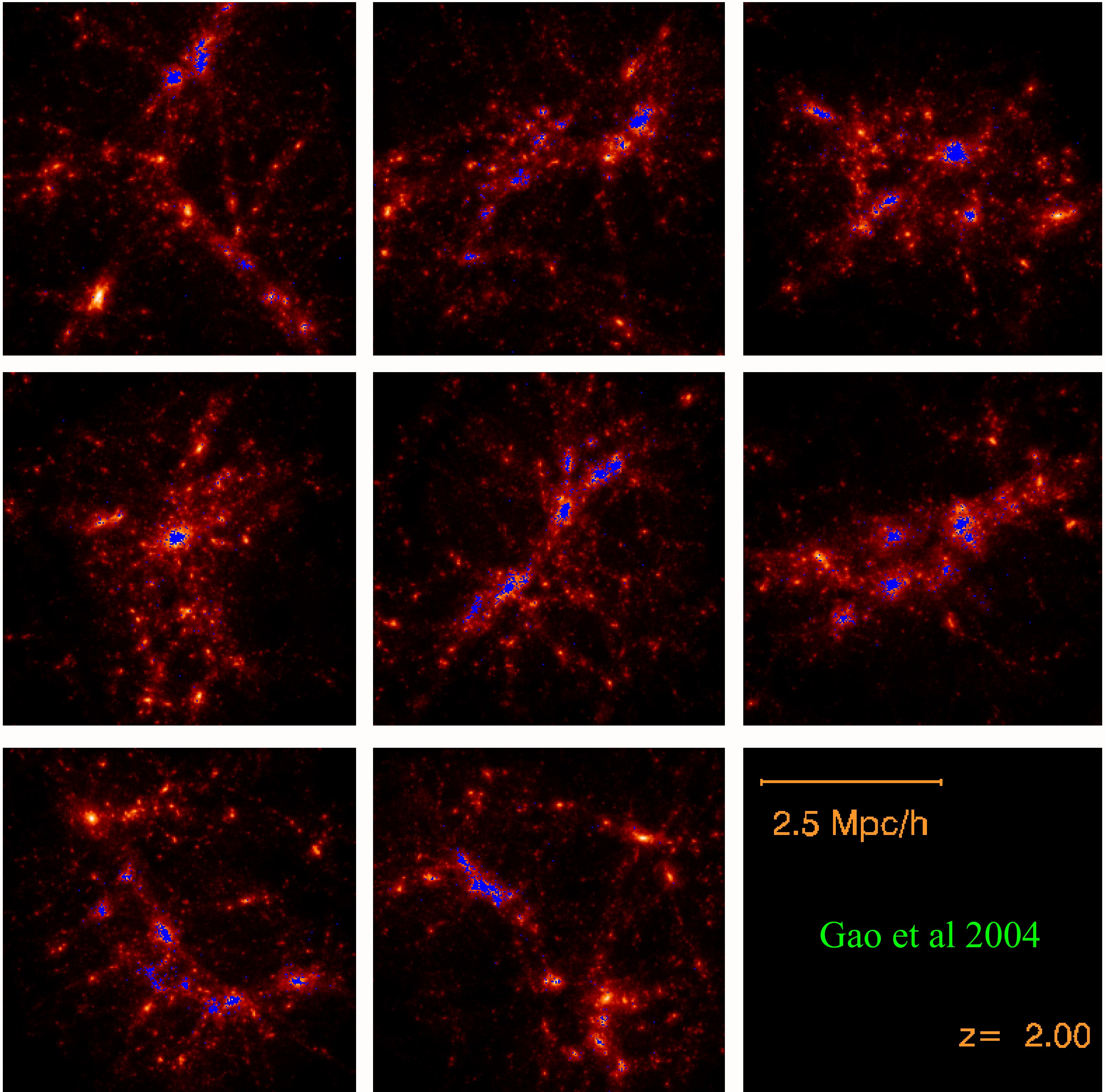


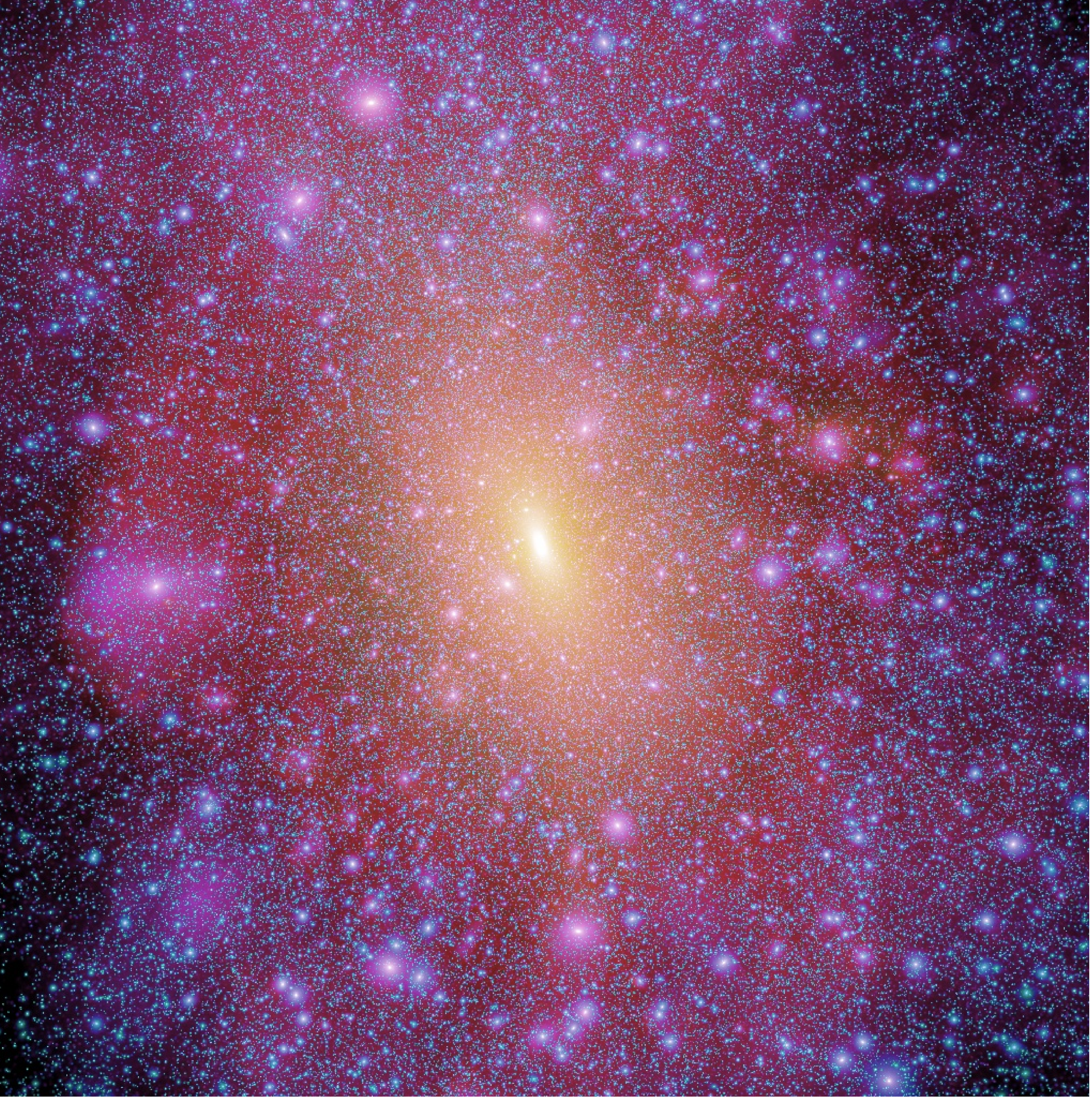
Cluster structure in ΛCDM

- Concordance cosmology
- Final cluster mass ~10^{15} $M_{\odot}$
- DM within 20kpc at z = 0 is shown blue



Cluster structure in ΛCDM

- Concordance cosmology
- Final cluster mass ~$10^{15}\,M_\odot$
- DM within 20kpc at $z = 0$ is shown blue



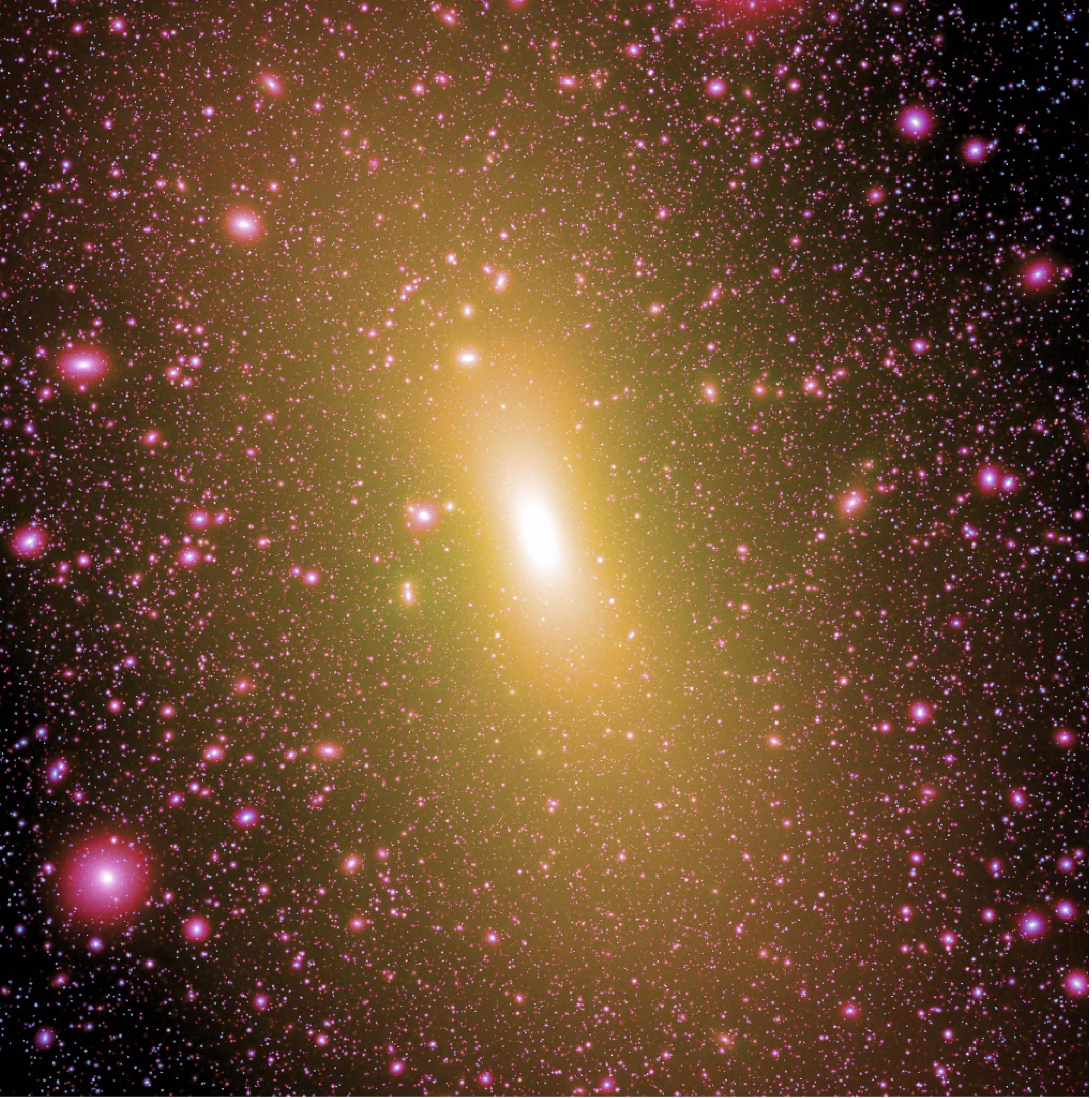
Phoenix-A-1

Gao et al 2010

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

$m_p = 5 \times 10^5 M_\odot$

Dark matter *only*!



Phoenix-A-1

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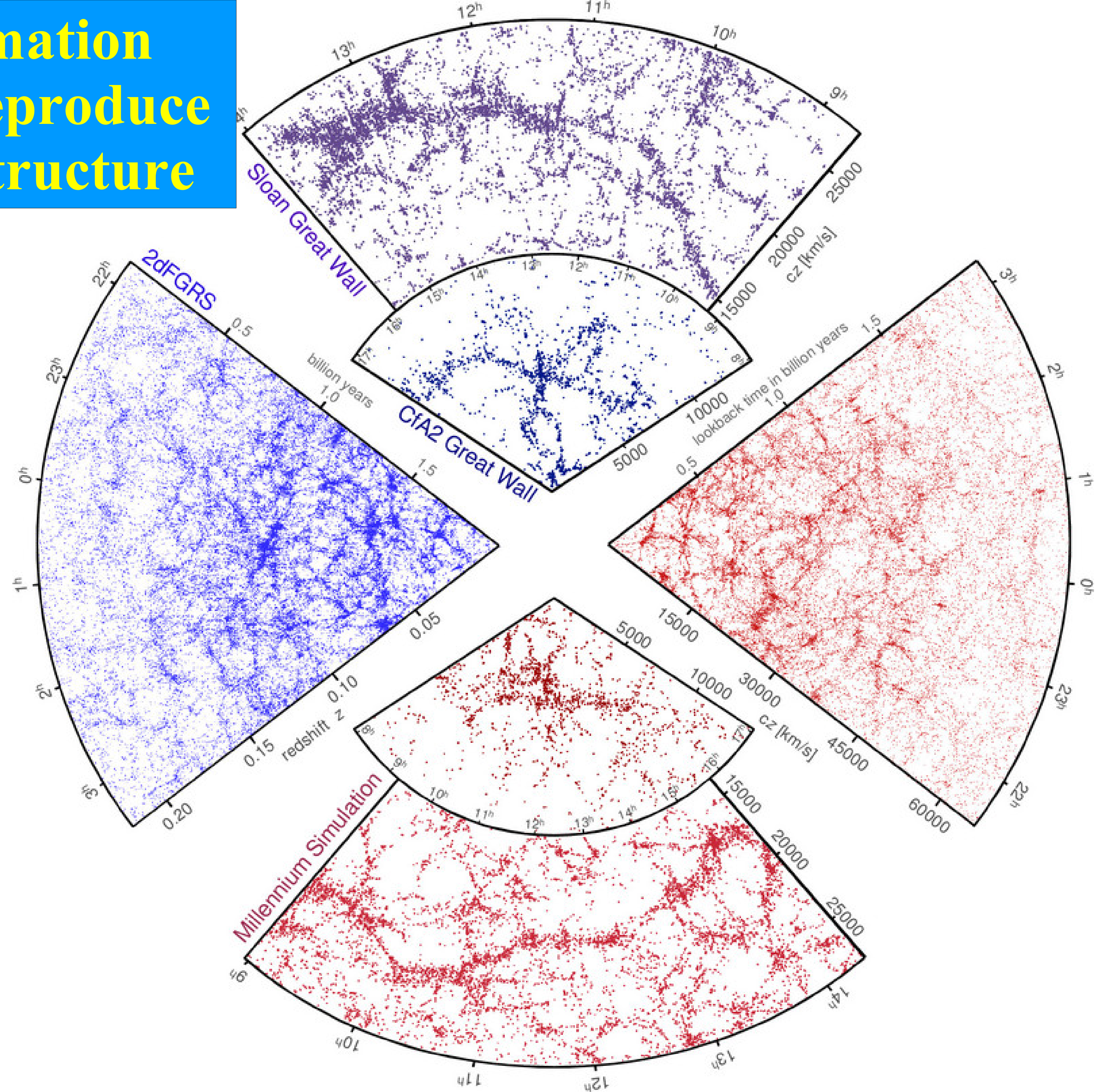
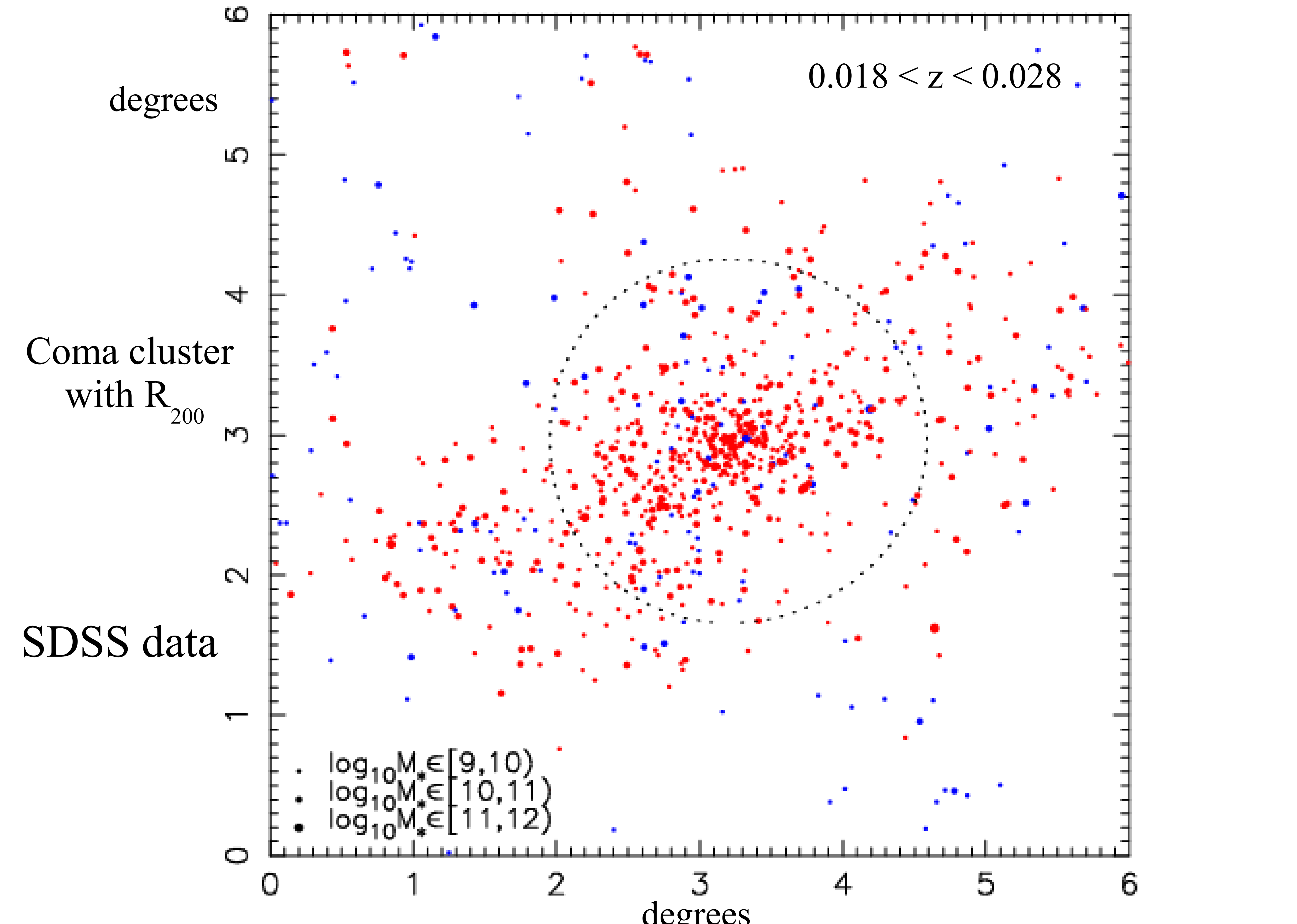
Dark matter *only*!

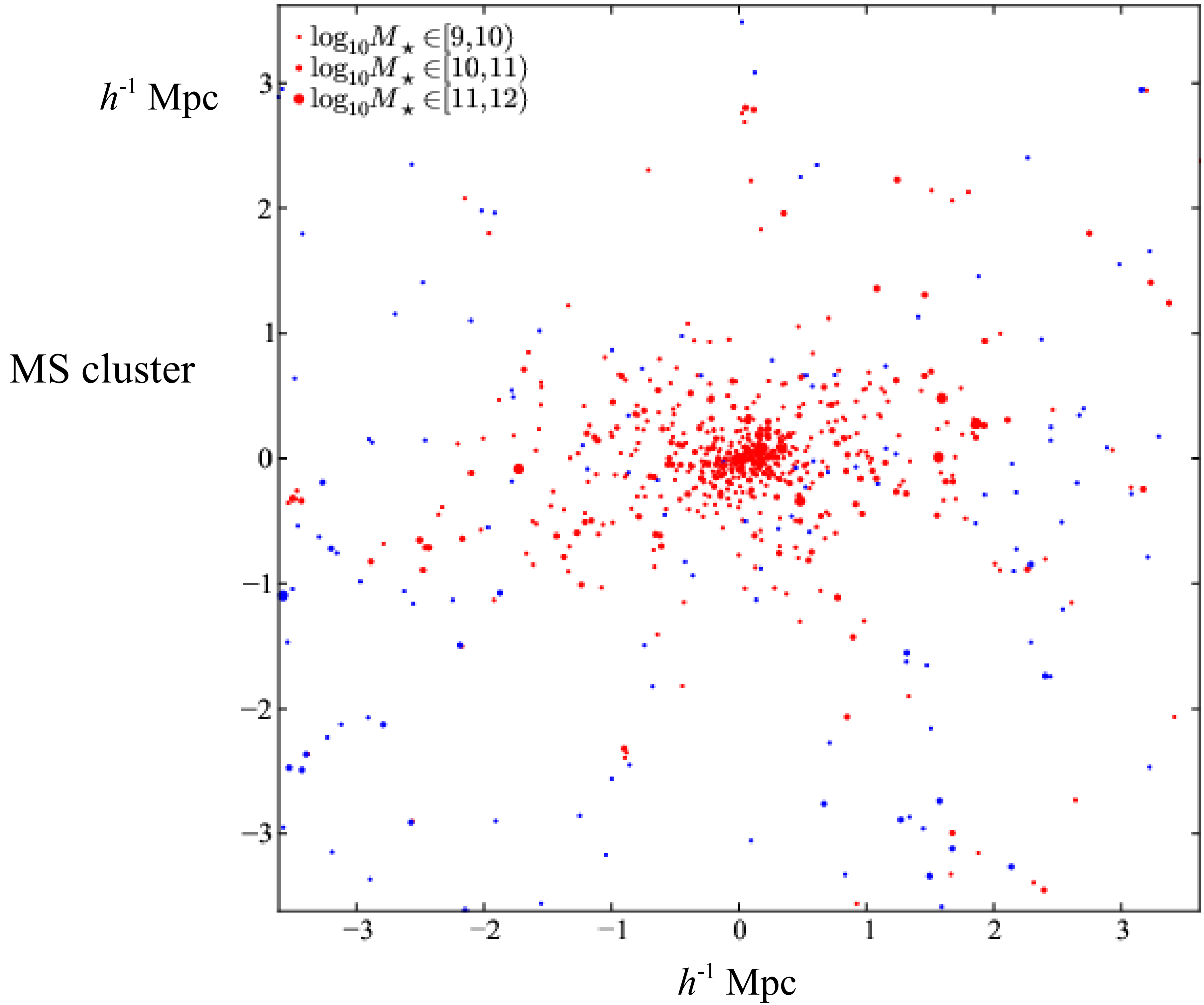
Galaxy formation simulations reproduce large-scale structure



Springel, Frenk & White 2006

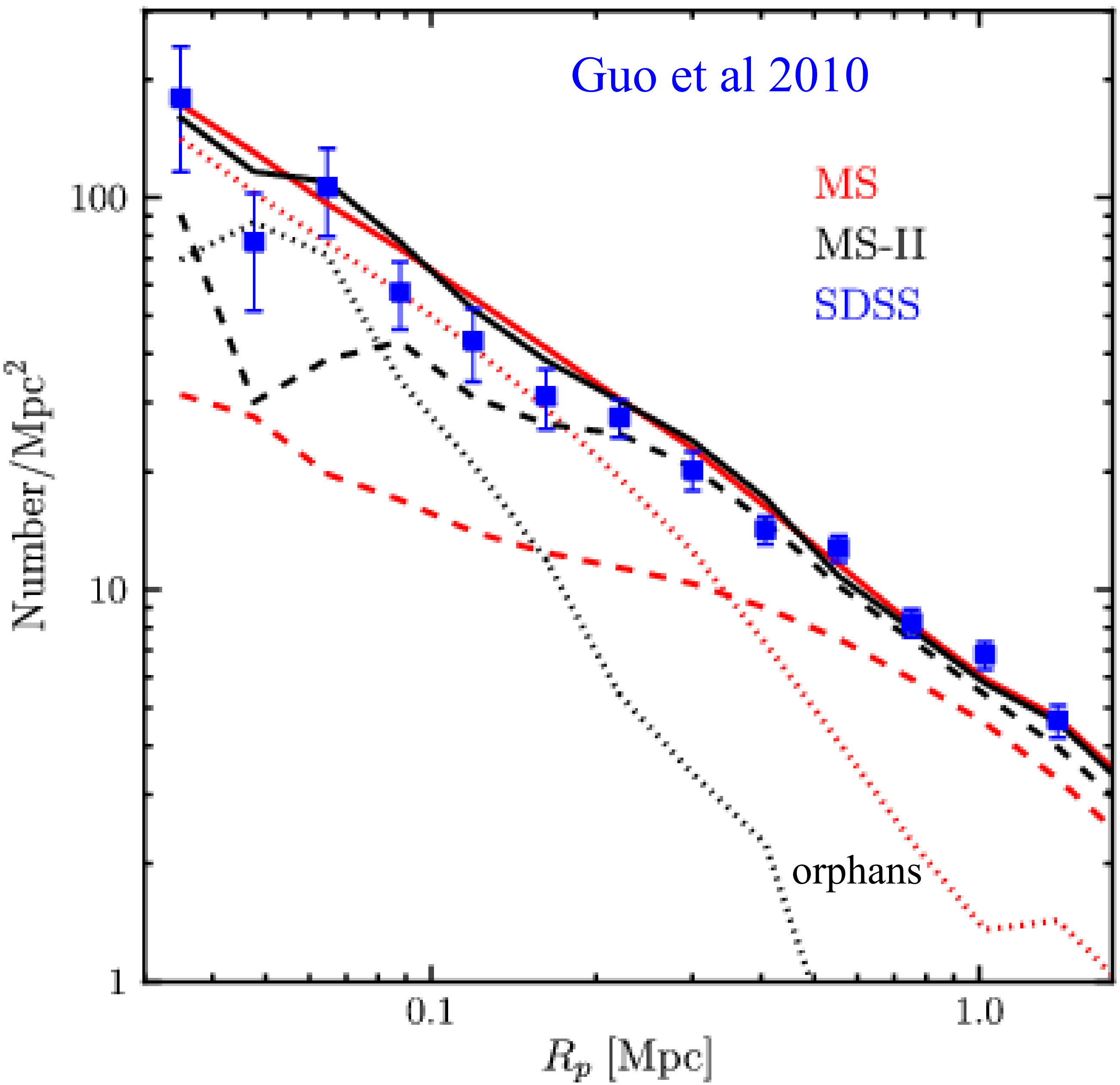


degrees
Coma cluster
with R_{200}
SDSS data
0.018 < z < 0.028
$\log_{10} M_* \in [9,10)$
$\log_{10} M_* \in [10,11)$
$\log_{10} M_* \in [11,12)$
degrees



h^{-1} Mpc
MS cluster
$\log_{10} M_\star \in [9,10)$
$\log_{10} M_\star \in [10,11)$
$\log_{10} M_\star \in [11,12)$
3
2
1
0
−1
−2
−3
h^{-1} Mpc

Galaxy formation simulations fit cluster galaxy count profiles



Stacks of clusters identified and matched in richness using an optimal filter in (R.A., Dec., z) space.

$\log M_{gal} > 10.0$

$14.0 < \log M_{clus} < 14.3$

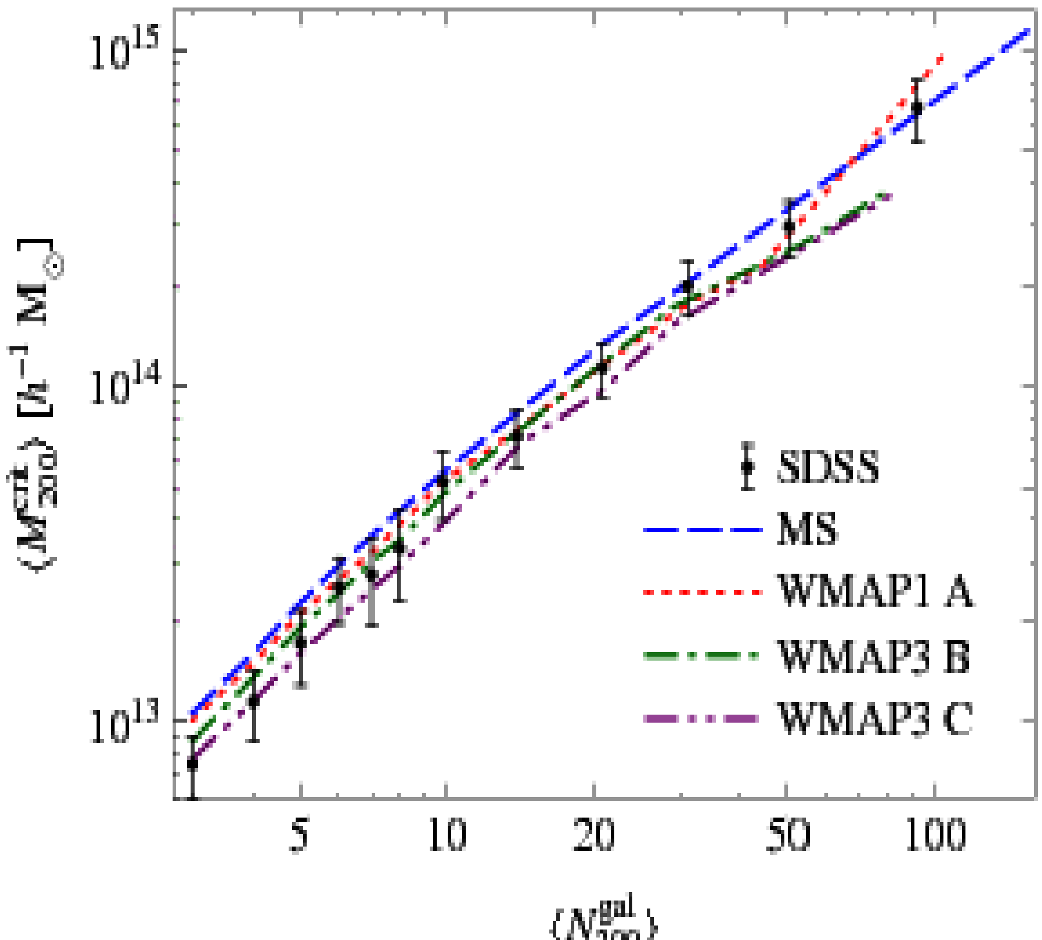
Note: good agreement of MS with MS-II despite mass resolution differing by 125 x

Galaxy formation simulations fit low-z groups and clusters

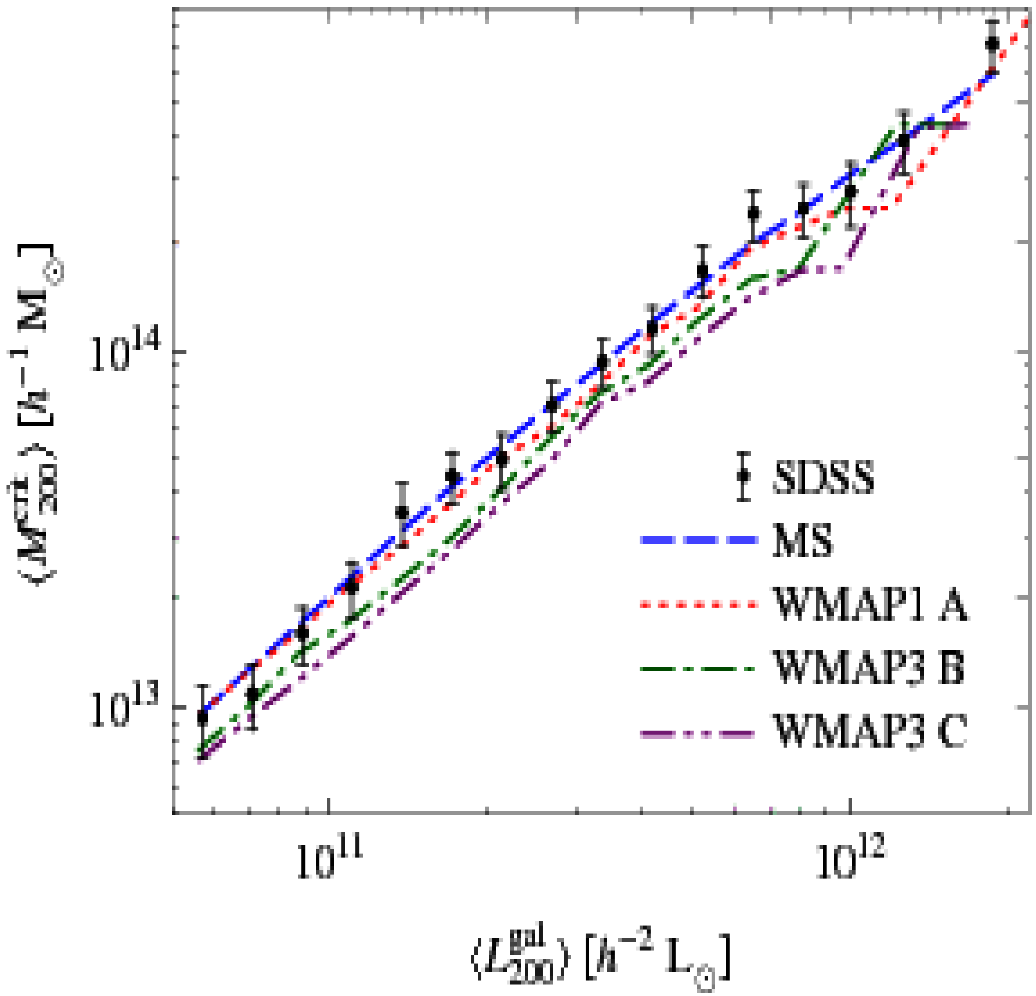
Hilbert & White (2009)

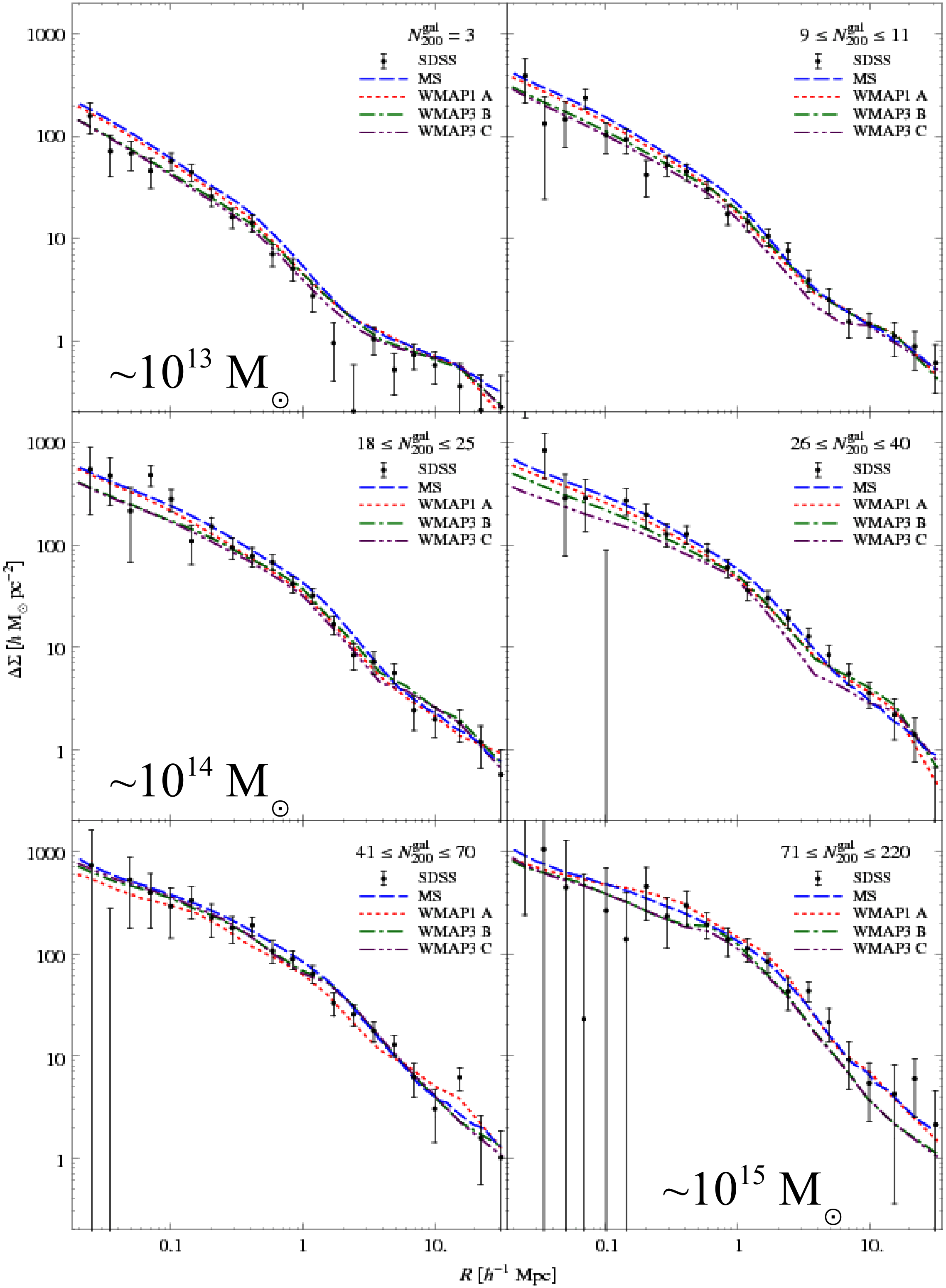
Observational data from the SDSS/maxBCG catalogue (Johnson et al 2007)

virial mass vs optical richness



virial mass vs red sequence luminosity





Galaxy formation simulations fit low-z groups and clusters

Hilbert & White (2009)

The simulated cluster population fits the detailed shape of the mean mass profile of groups and clusters as functions of N_{200} and L_{200}

This holds for masses

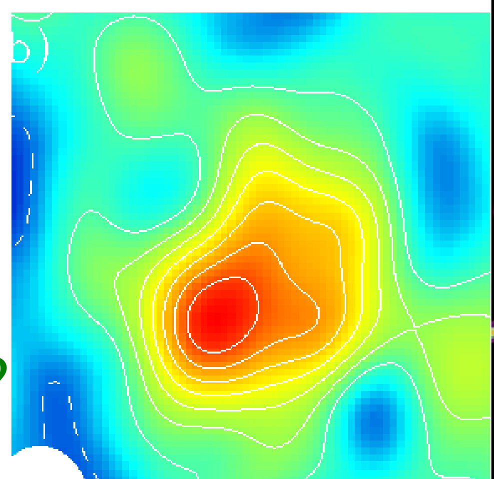
$$10^{13}\ M_\odot \le M_{200} \le 10^{15}\ M_\odot$$

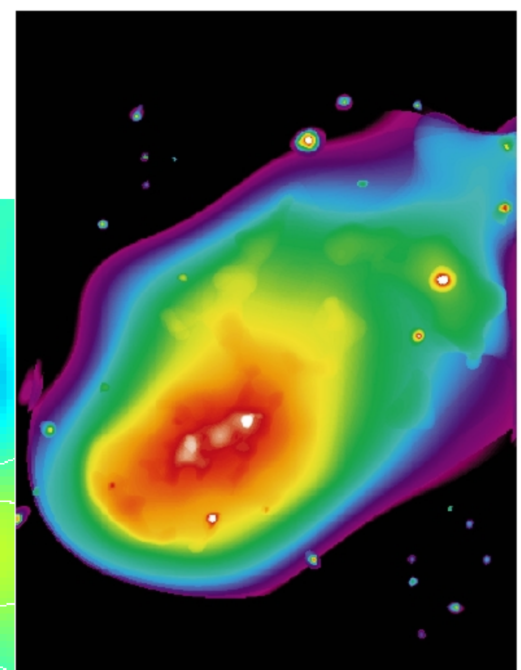
Note the strong central concentration of the observed and predicted mass profiles

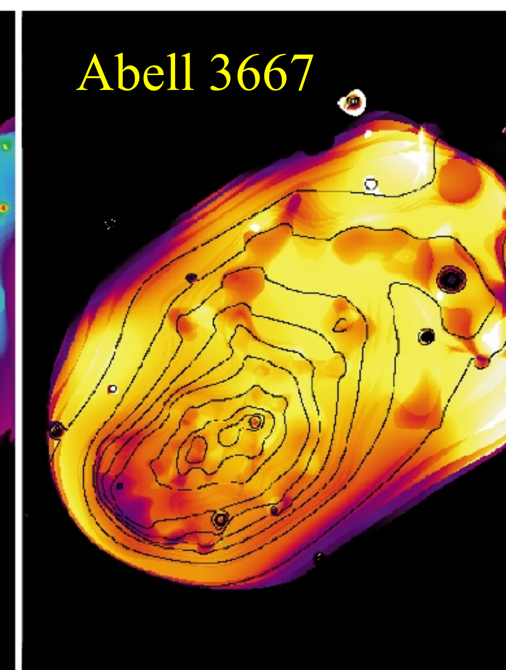
Lensing data from SDSS/maxBCG (Sheldon et al 2007)

Hydrodynamics and cluster formation

- Structure formation produces shocks which transform the K.E. of fluid motions into heat
- Bremsstrahlung and line emission from cluster gas is observable in X-rays: $S = \int dl \ \rho^2 \Lambda(T)$ $\longrightarrow$ Element abundances
- Cluster "shadows" are observable against the CMB through the Sunyaev-Zeldovich effect: $\Delta T \propto \int dl \, p$
- Hierarchical growth of structure produces the phenomenology observed in images of clusters
  - --asymmetries and sublumps
  - --shocks
  - --cold fronts
  - --cold cores
  - --B-fields?
  - --cosmic rays?
  - --radio sources?
  - --Z patterns?





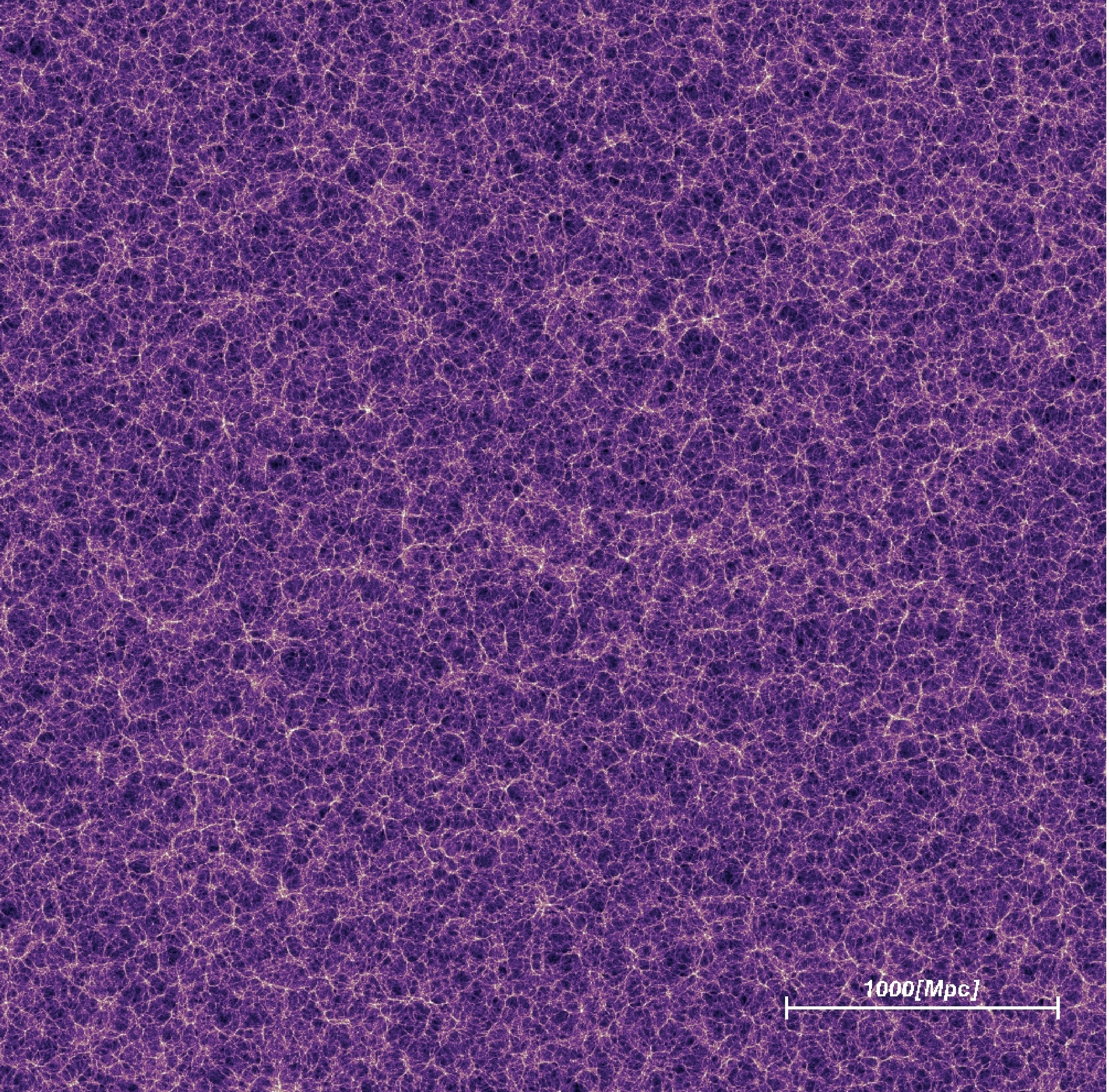


Simulation input to cluster studies

- Simulations of individual clusters can address
  - -- Evolution of internal density/temperature/metallicity fields
  - -- Origin/evolution of B-fields and relativistic components
  - -- Interactions with galaxies, AGN...
  - -- Constrain nature of DM, extra physics

    e.g. 1E0657-56 "The bullet cluster"

- Simulations of large cluster samples can address
  - -- Cluster abundances as functions of M, z, L_X, T_X, Z...
  - -- Cluster clustering as functions of M, z, L_X, T_X, Z...
  - -- Calibration of cluster Dark Energy projects



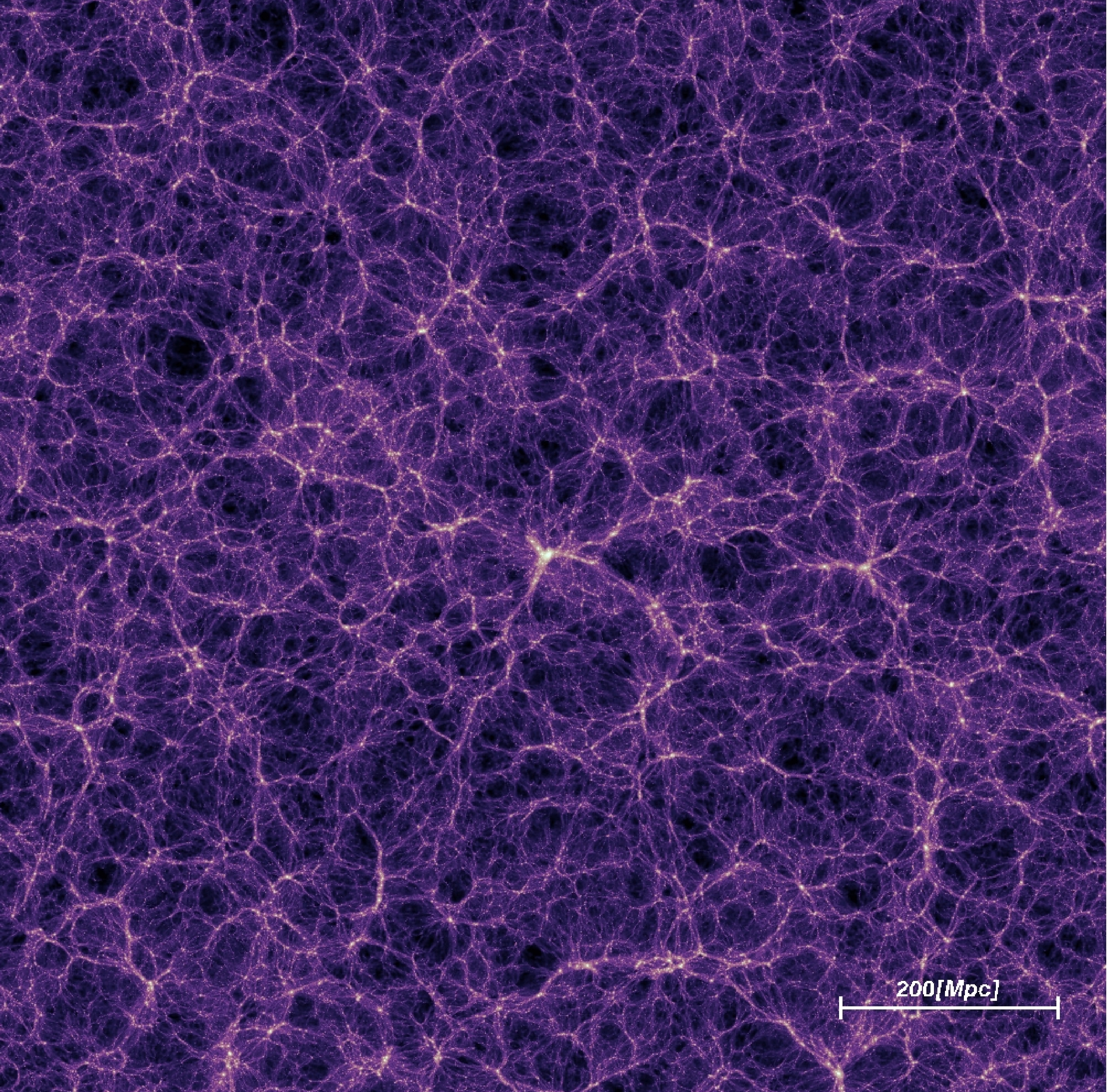
Millennium XXL

Angulo et al 2010

$N = 3 \times 10^{11}$

$m_p = 5 \times 10^9 M_\odot$

$L = 4.3$ Gpc



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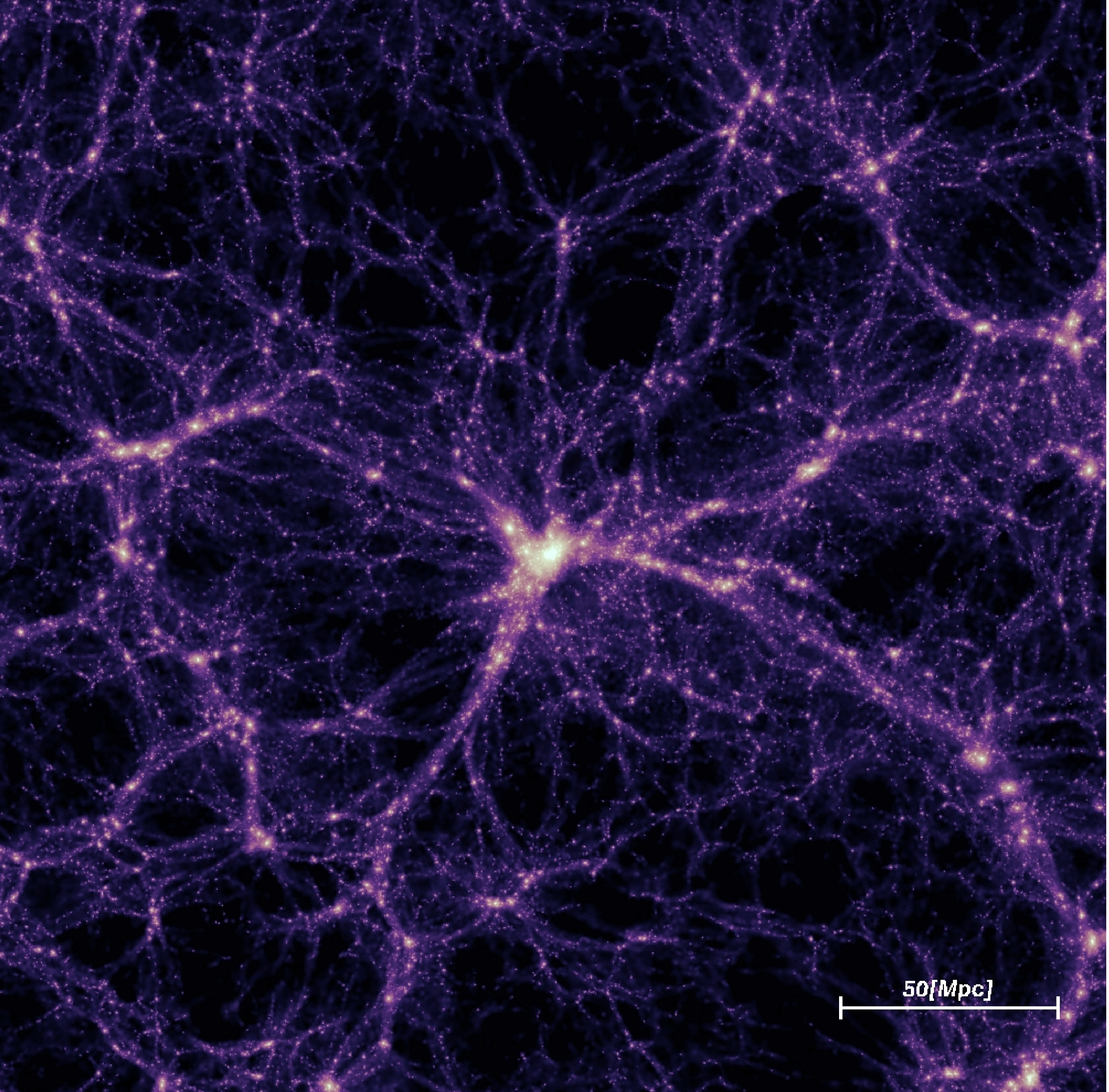

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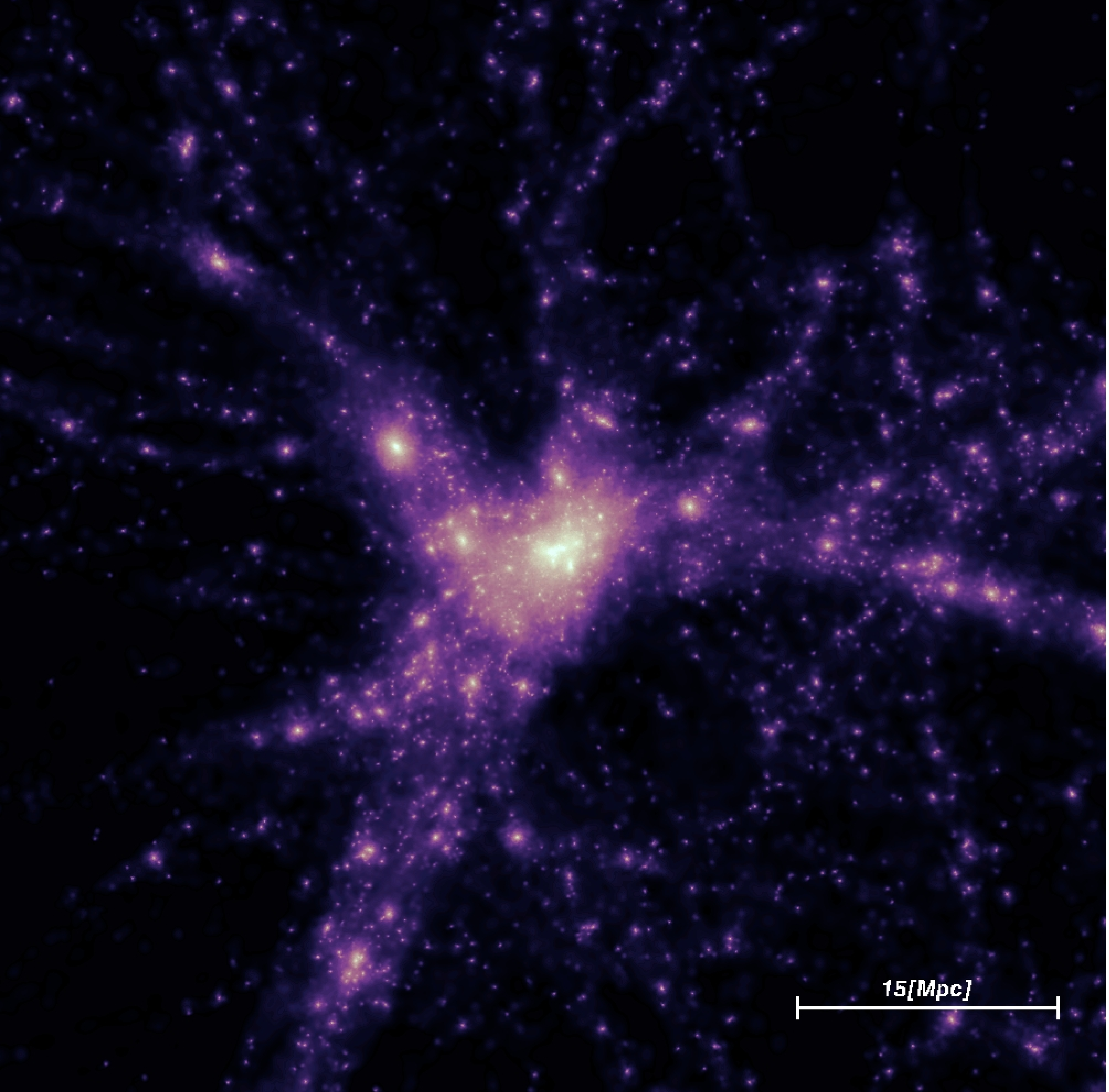

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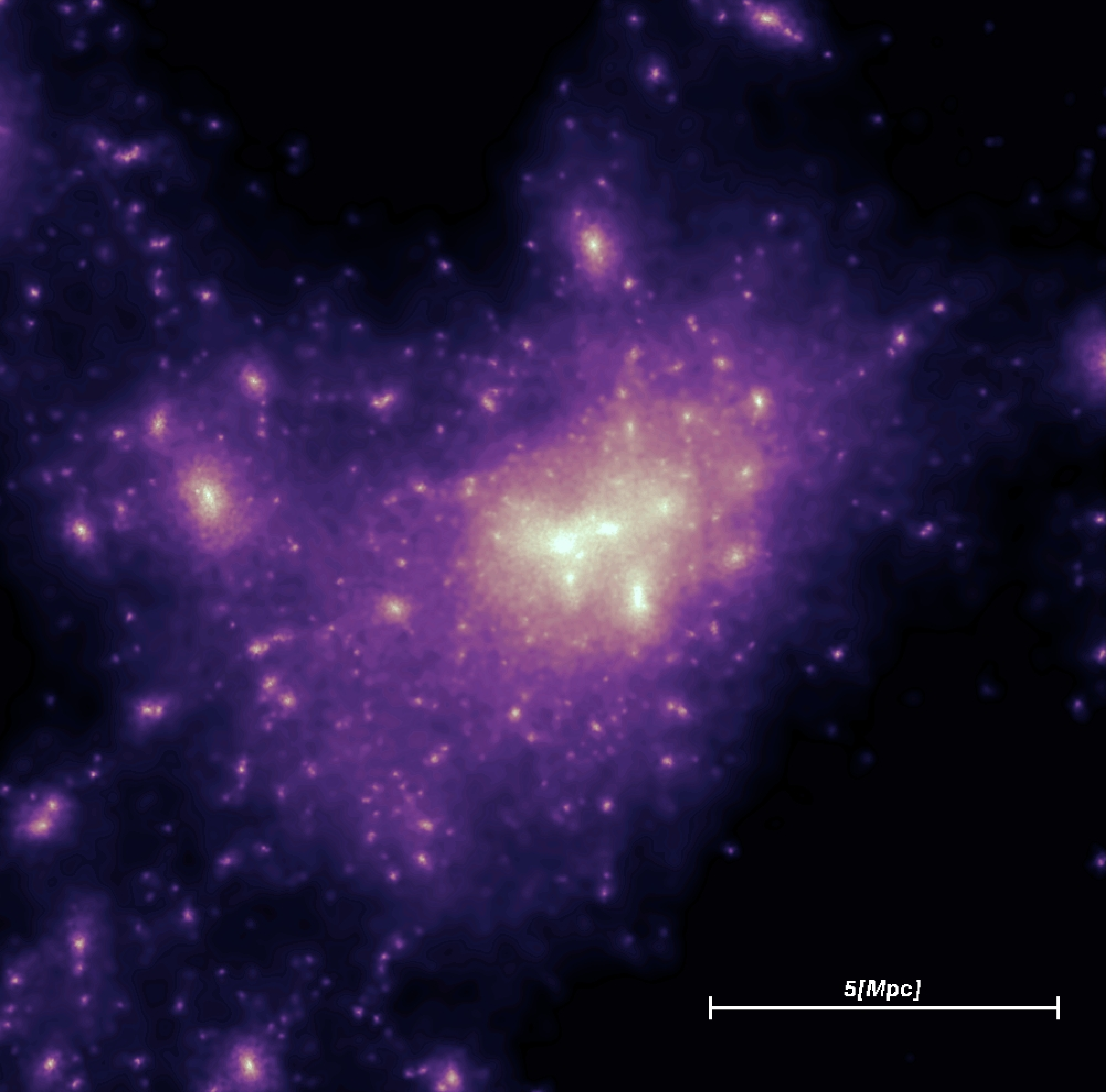

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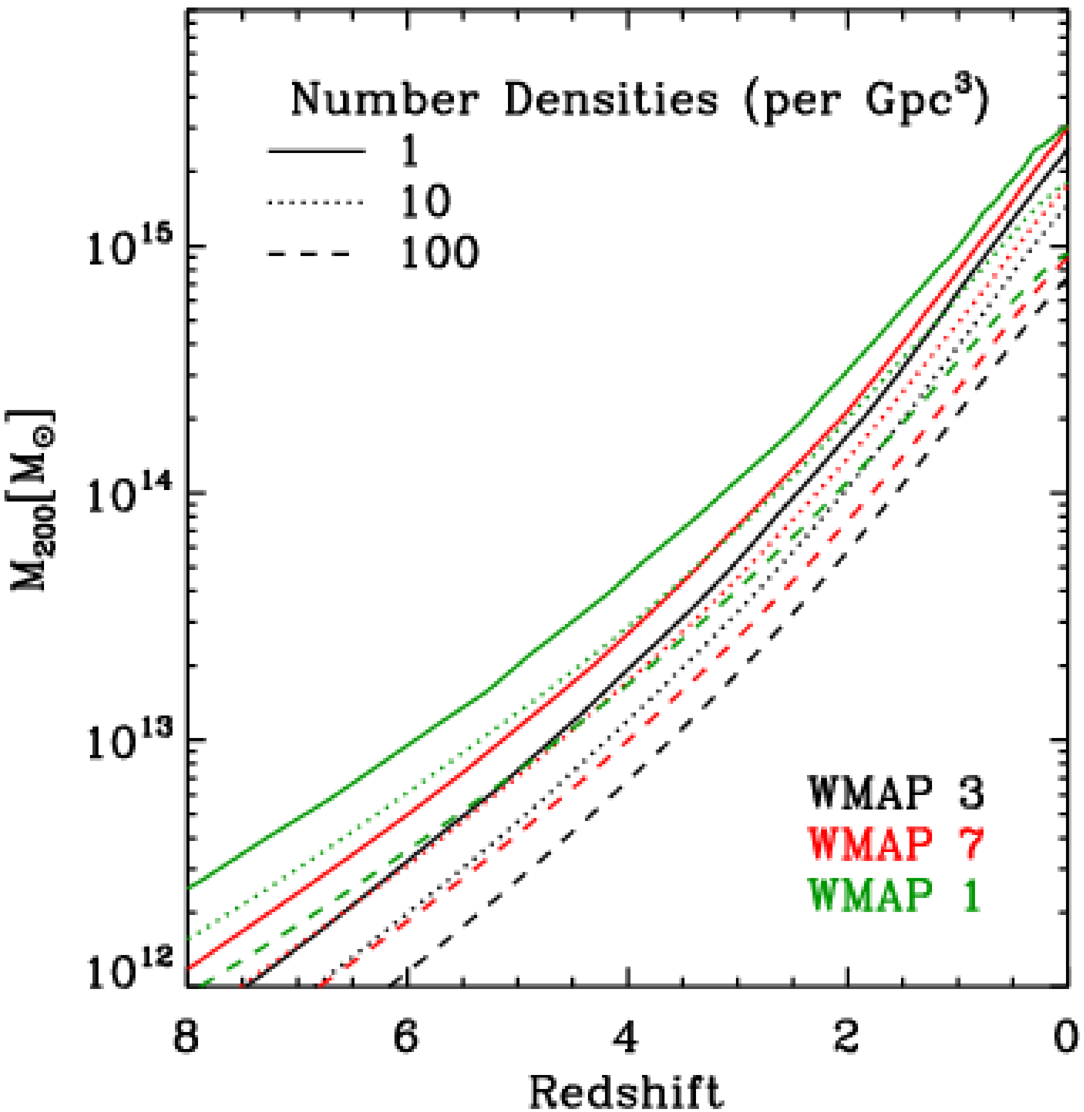
The abundance of the most massive halos

Angulo et al 2010



At z=0 the MXXL contains

687,764 halos: $M_{200} > 10^{14} M_\odot$

111,337 halos: $M_{200} > 3 \times 10^{14} M_\odot$

5,907 halos: $M_{200} > 10^{15} M_\odot$

At z=6 only 1 halo per Gpc^3 has mass $> 10^{13} M_\odot$ (WMAP1)

$> 5 \times 10^{12} M_\odot$ (WMAP7)

Abundances are lower than standard formulae imply

Uses of clusters in cosmology

- Cluster abundance to measure fluctuation amplitude σ_8
- Abundance evolution to measure σ_8(z) $\rightarrow$ w
- Baryon fraction to estimate $\Omega_\mathrm{b}/\Omega_\mathrm{m}$
- Baryon fraction evolution to estimate d_A(z) $\rightarrow$ w
- Clustering evolution to estimate $\Theta_{BAO}(z)$ $\rightarrow$ d_A(z) $\rightarrow$ w
- Core structure as a test of the nature of DM
- Clusters as laboratories for galaxy evolution

Uses of clusters in cosmology

- Cluster abundance to measure fluctuation amplitude σ_8
  Problem: converting cluster observables (L, T,...) to mass
- Abundance evolution to measure $\sigma_8(z) \rightarrow w$
  Problem: possible evolution of the L-M or T-M relations
- Baryon fraction to estimate Ω_b/Ω_m
  Problem: clumping, cosmic rays, extrapolation to R_{200}
- Baryon fraction evolution to estimate $d_A(z) \rightarrow w$
  Problem: evolution of clumping, cosmic rays, extrapolation...
- Clustering evolution to estimate $\Theta_{BAO}(z) \rightarrow d_A(z) \rightarrow w$
  Problem: sparse sampling
- Core structure as a test of the nature of DM
  Problem: How does cD assembly affect DM profile?
- Clusters as laboratories for galaxy evolution

Using cluster abundances to constrain cosmology

- Cluster abundance can be <u>measured</u> as a function of L_X, T_X, Y, L_{opt}, M_{lens}, σ_{gal}, Z.. to a level determined by observational precision and Poisson statistics

- Cluster abundances can be <u>predicted</u> as a function of M_{200}, σ_{dm}, c/a, conc., substr., spin... to a level determined by modelling uncertainties

- Typically each well observed quantity (e.g. L_X) depends on a number of well predicted quantities (e.g. M_{200}, σ_{dm}, c/a, conc., Z) <u>and</u> on z

- Cosmological information can be extracted *only* if these dependences and their redshift variation are sufficiently well understood.

Can clustering information help?

Using clustering to constrain cosmology

- Observationally one can measure clustering at z as a function of angular scale for clusters with specific properties (L_X, T_X, Y..)

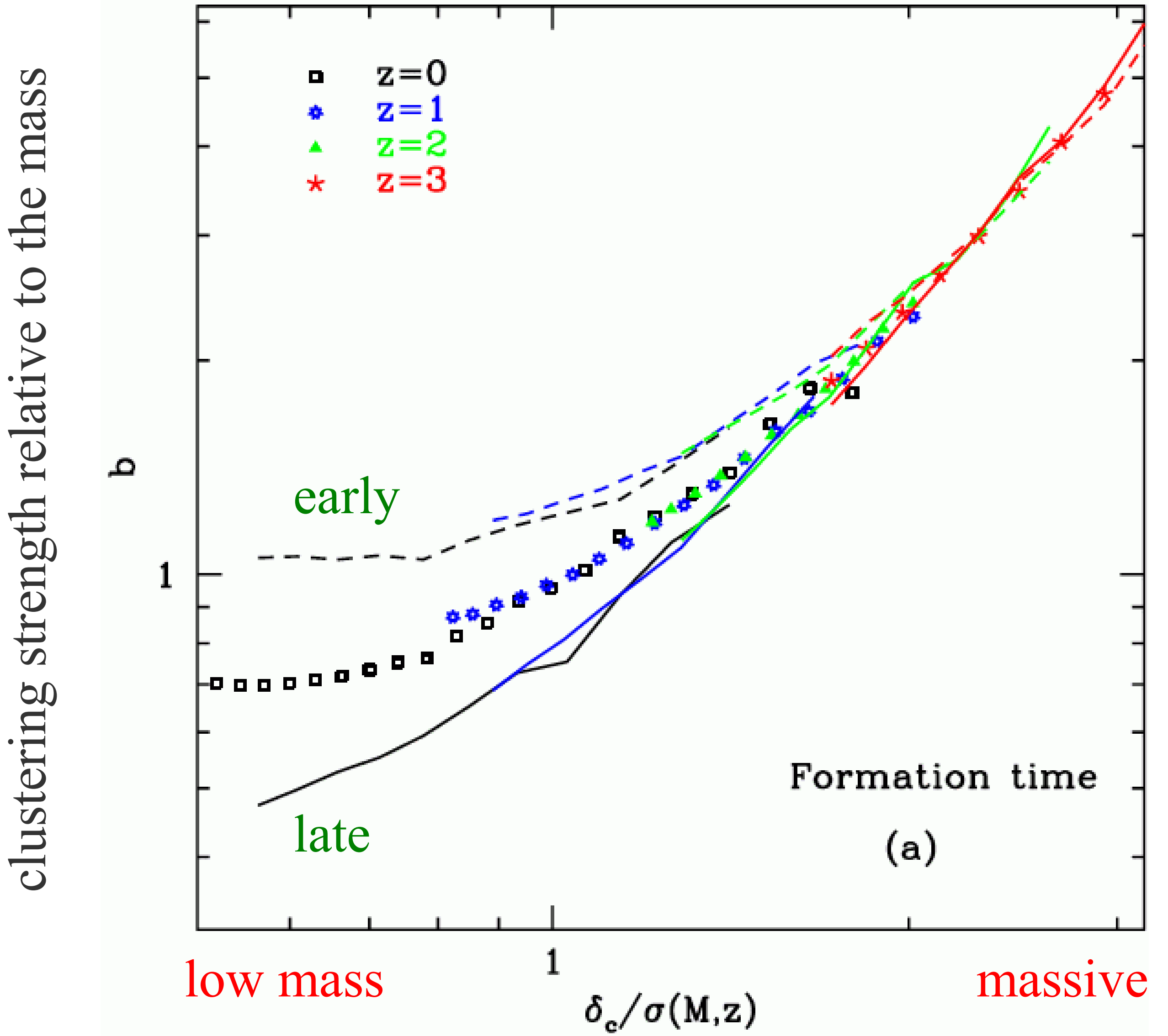
- Theoretically for given cosmology one can predict clustering both for the mass and for clusters with specific properties (M_{200}, c/a..)

- Thus one can compare the two provided the relation between observables and theoretical quantities is well enough known

- This comparison constrains cosmological parameters *provided* bias predictions are sufficient to get e.g. $\Theta_{BAO}(z)$ to better than 1%

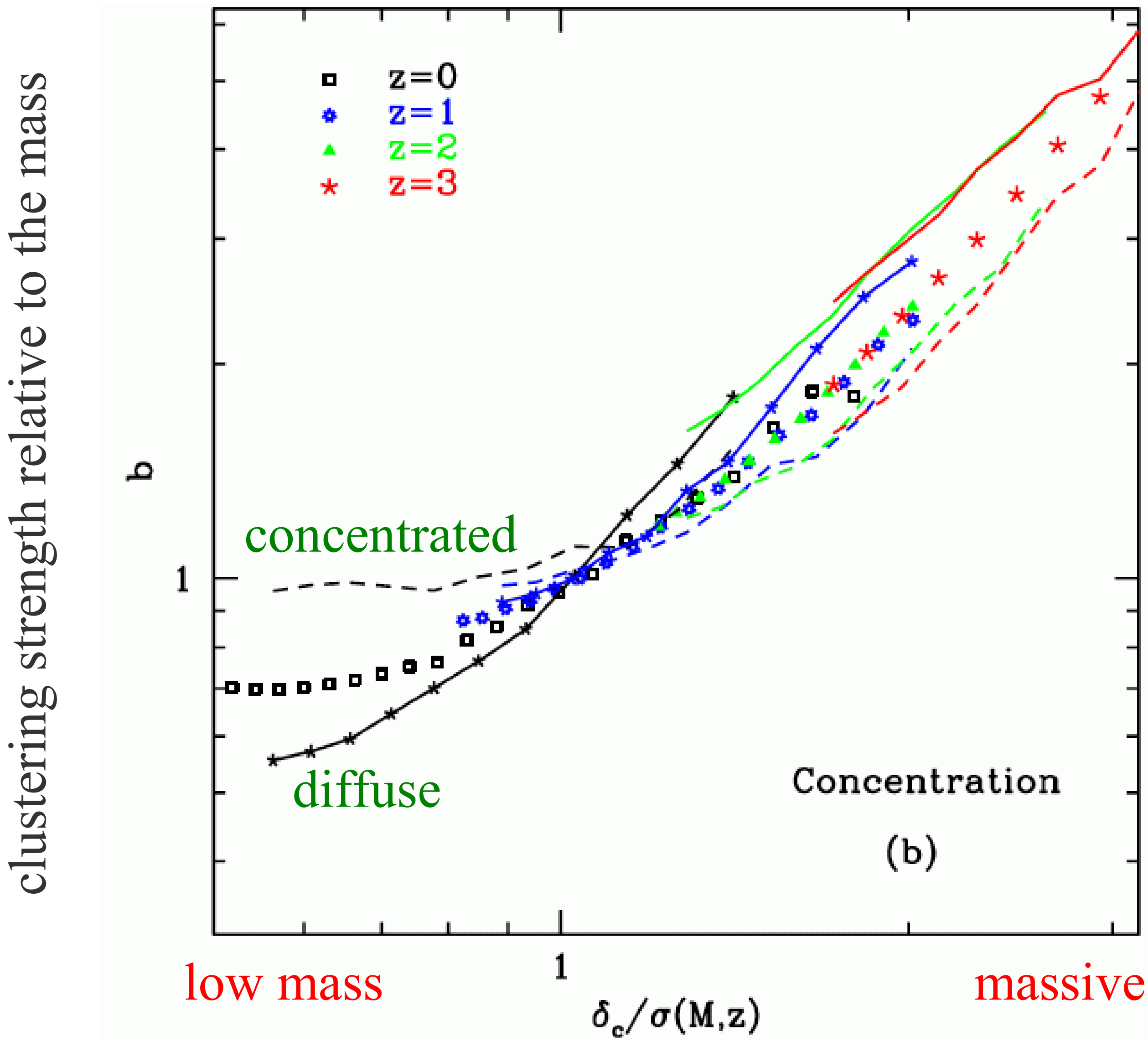
Halo bias as a function of mass and formation time

Gao & White 2007



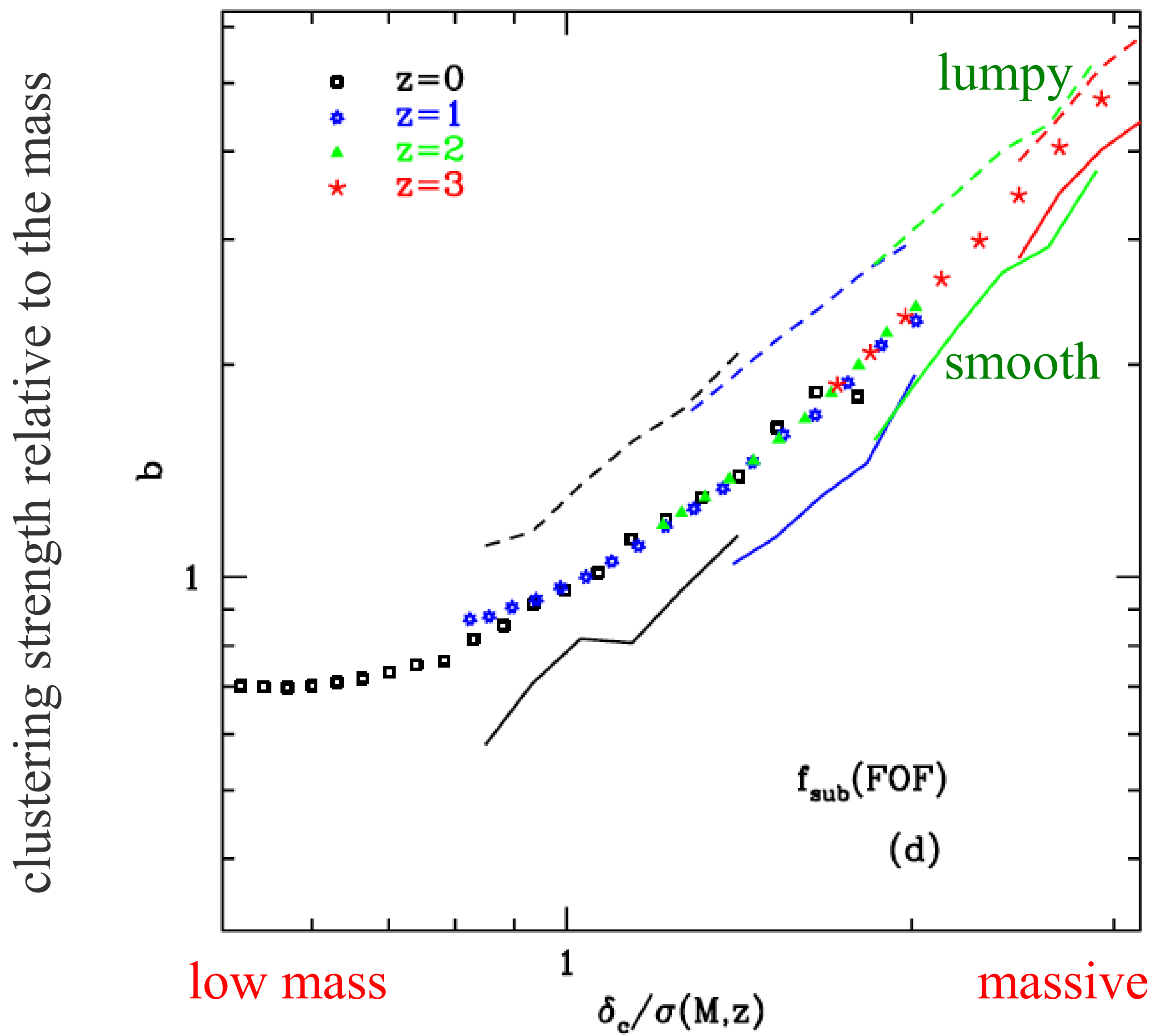
Halo bias as a function of mass and concentration

Gao & White 2007



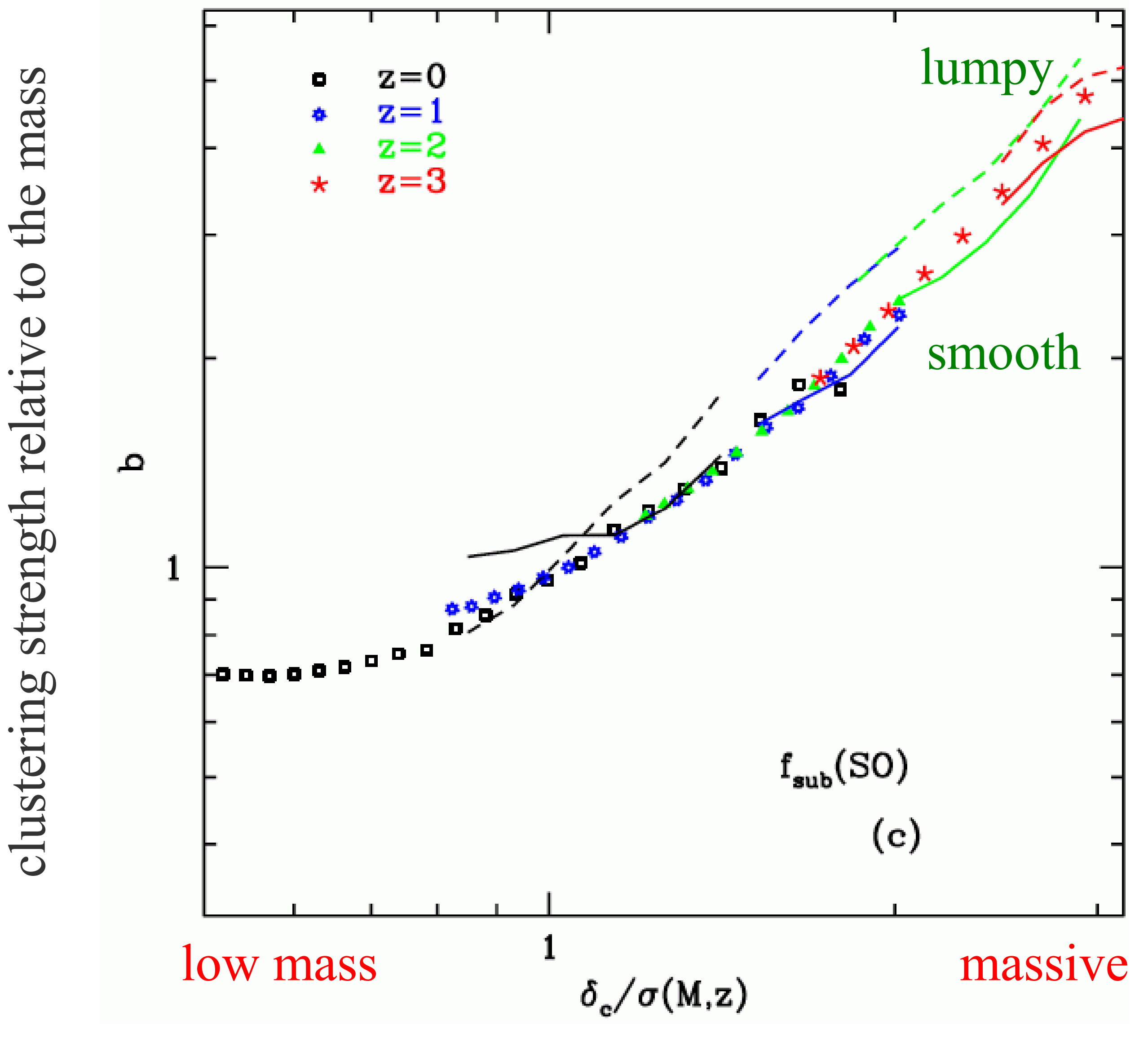
Halo bias as a function of mass and substructure

Gao & White 2007



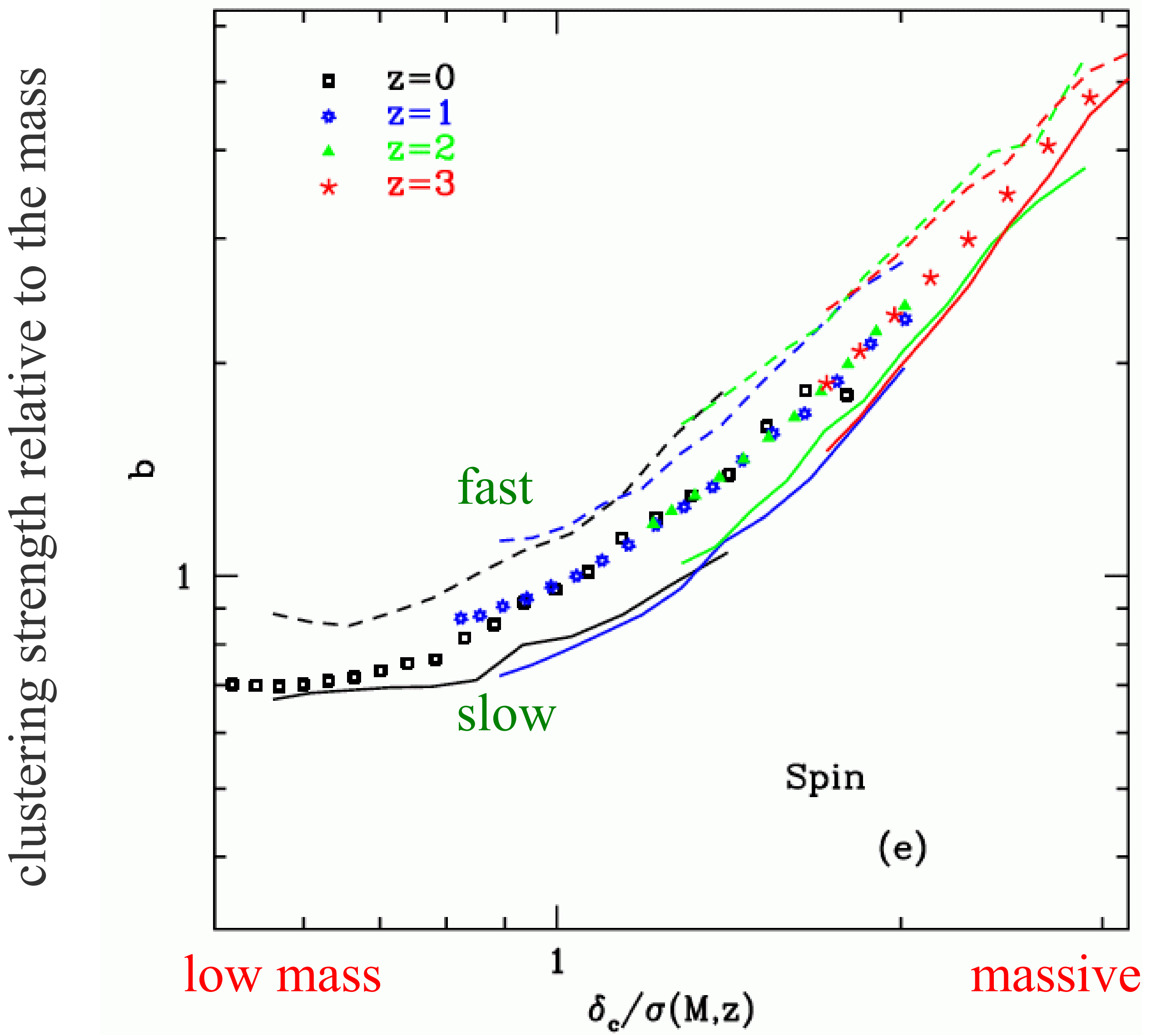
Halo bias as a function of mass and substructure

Gao & White 2007



Halo bias as a function of mass and spin

Gao & White 2007



Conclusions?

- Observable cluster properties depend on many cluster variables in addition to mass at the 10 to 20% level

- These dependences and their z-variation must be sufficiently well understood if cluster abundances are to constrain cosmology

- At the 10% level the large-scale bias of cluster populations is a complex function of cluster properties in addition to mass

- Substantial theoretical and numerical work is needed to make cluster abundances and clustering into precise enough tools to constrain Dark Energy. Observational confirmation through studies of cluster structure will be critical to getting a credible result.

  $\longrightarrow$ XEUS, detailed SZ-imaging, lensing...