Arrow of time

10^{-43} sec. Planck time. Inflation begins

10^{-32} sec End of Inflation: origin of fluctuations. Flat and hot Universe

1 sec. T=1Mev. Neutrino decouple from the rest of matter. Composition: relativistic particles dominate: gamma, neutrino, electrons, positrons. Nonrelativistic particles: protons, neutrons, DM

100 sec. T=0.1Mev. BBN: all neutrons are in He. Composition after BBN: γ and ν dominate. Nonrelativistic particles: p, He, e, DM: subdominant.

z=3000 Moment of equality: density of relativistic particles (γ and ν) is equal to the density of nonrelativistic particles. Fluctuations in DM on all scales grow with the same rate.

z=1100. T=3000K=0.3eV. Recombination and decoupling. Photons start to travel freely. Gas is mostly neutral.

z=10. First massive galaxies and supermassive black holes.

z=7. Universe is fully re-ionized.

z=2. Last major-merger for our Galaxy. Last stars formed in E galaxies in clusters.

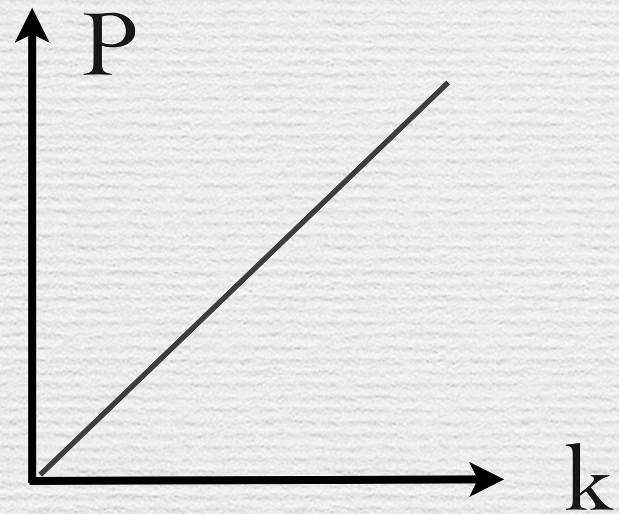
z=0.5 Sun is formed.

Evolution of perturbations at early times:

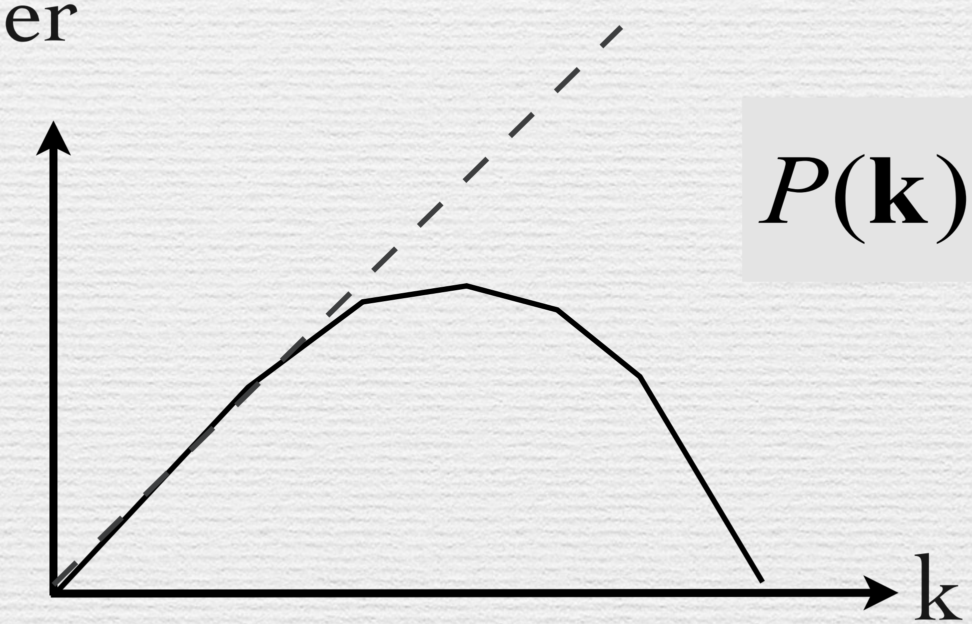
linear growth

Inflation provides very a simple spectrum of fluctuations: gaussian fluctuations in metrics (=gravitational potential):
$(\Delta\phi)^2 \propto$ constant when averaged over spheres of radius R.

This gives the power spectrum of fluctuations in the density
$P(k) \propto k$, where k is a wavenumber



After Inflation



$$P(\mathbf{k}) = \left|\delta(\mathbf{k})\right|^2$$

After moment of equality

Nonlinear effects

- Zeldovich approximation: collapsing waves in a cold (=low random velocities) fluid produce a web of filaments: $r(t) = r_0 + v(r_0)t$
- Virialization tends to produce spherical objects
- Dynamical friction produces merging of halos
- On scales larger than 20kpc the only thing which dynamically matters is the dark matter

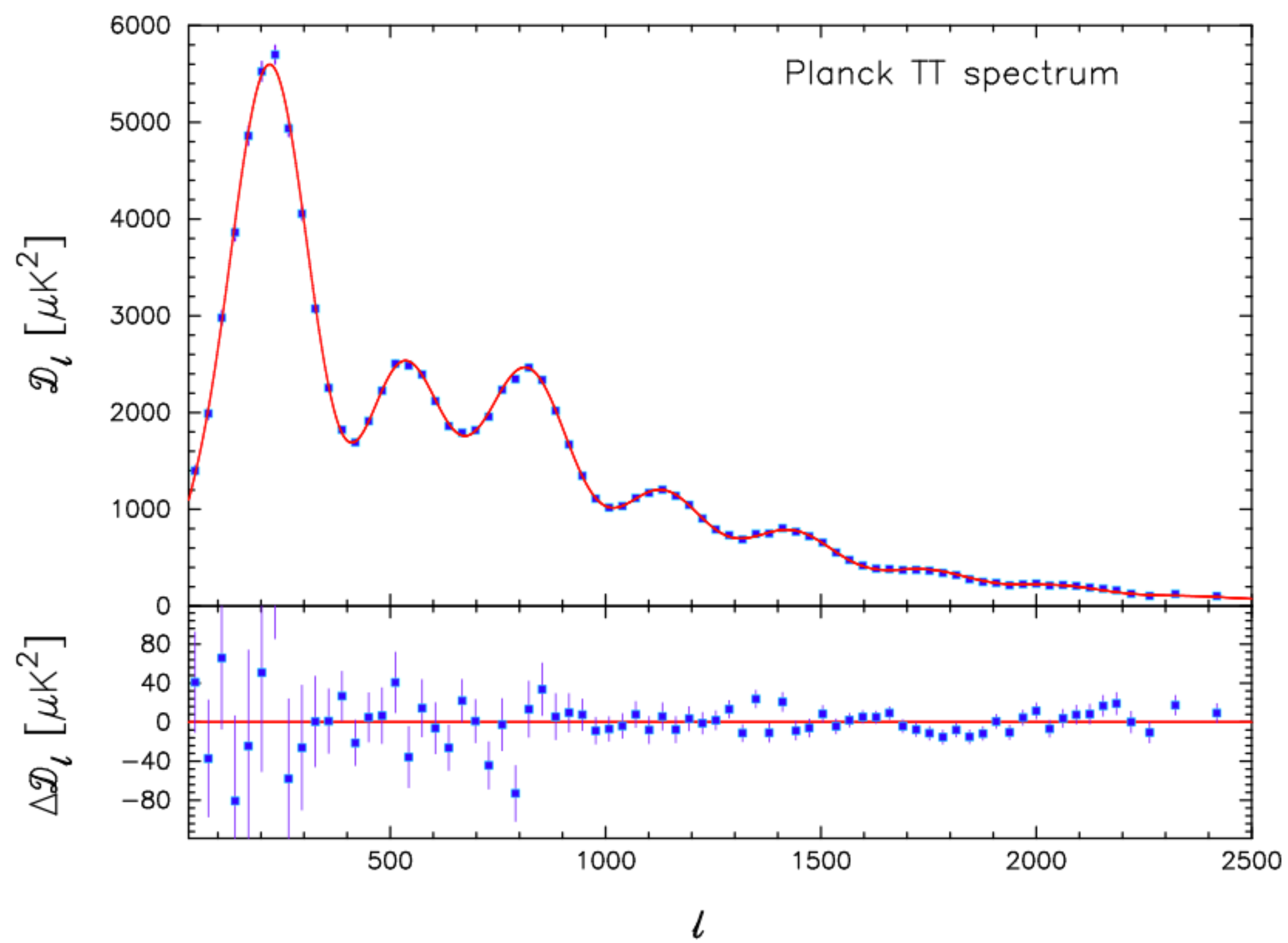
Probing different epochs with observations

Epoch	Phenomenon	Test
Inflation	Spectrum of perturbation on very long scales	•Large-scale CMB anisotropies •Large-scale spectrum of perturbation in distribution of galaxies
Moment of equality	Position of maximum in the spectrum of perturbations	Distribution of galaxies: Spectrum, sizes of large voids, Superclusters.
BBN	abundance of light elements: He, D, Li	ISM, stellar atmospheres, spectra of high-z galaxies
Recombination	Small-scale structure of CMB	CMB anisotropies on armin -degree scales
Acceleration of the Universe	Distances depend on the rate of expansion	Distances to SNI
	Dark matter	•Rotation curves of galaxies •Possible annihilation signal from centers of galaxies •X-ray emission from clusters of galaxies •Lensing of galaxies

Isotropy and Homogeneity of the Universe

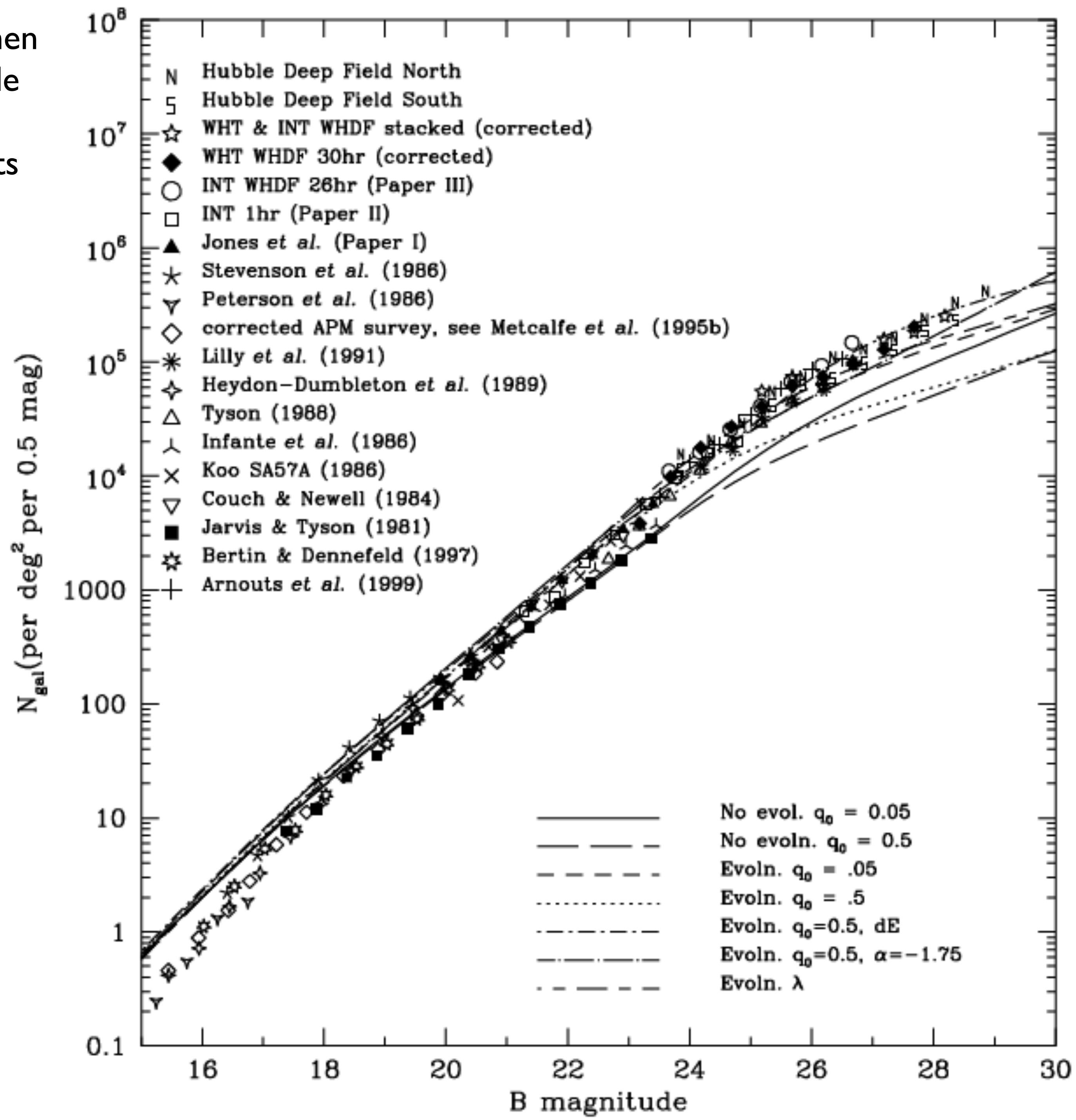
- – *galaxies:* Deep counts of galaxies $m_B > 18$ show only small variations of the number of galaxies in different directions in the sky. Note that there are large variations *along* the line-of-sight.
- – *radio sources:* Those are typically in galaxies. Counts are very deep and show high level of isotropy ($\Delta N/N < 10^{-3}$).
- – *X-ray background:* Typically unresolved AGNs. Background is isotropic at 1 percent level.
- – *Cosmic Microwave Background (CMB):* isotropic to the level $\Delta T/T \sim 10^{-5}$. Deviations from the isotropy are well studied. The largest deviation is the dipole, which is due to the motion of the Local Group relative to CMB: $V_{\rm dipole} \approx 650 \rm km\ s^{-1}$.

Planck Collaboration: Cosmological parameters



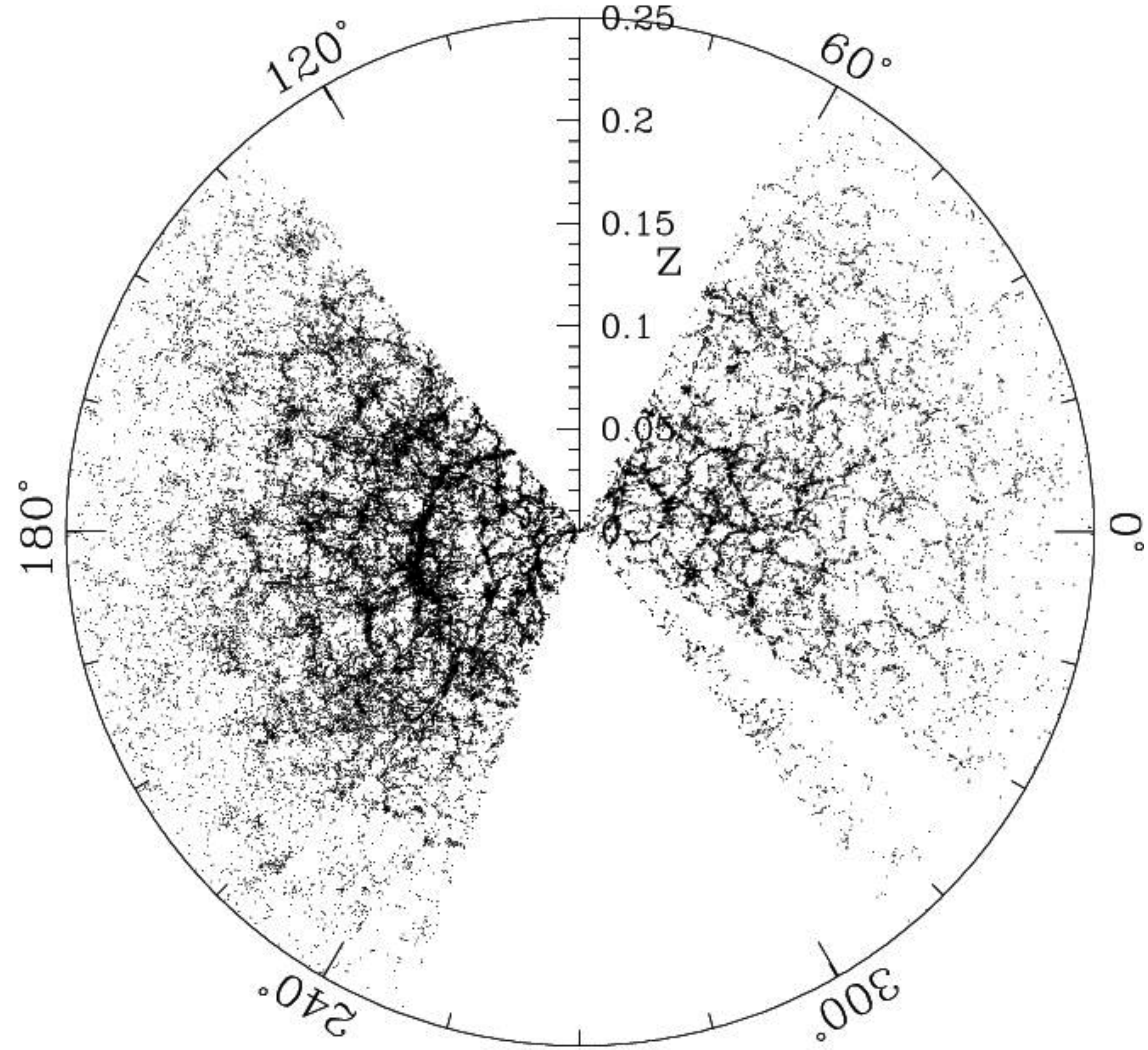
Homogeneity of the Universe

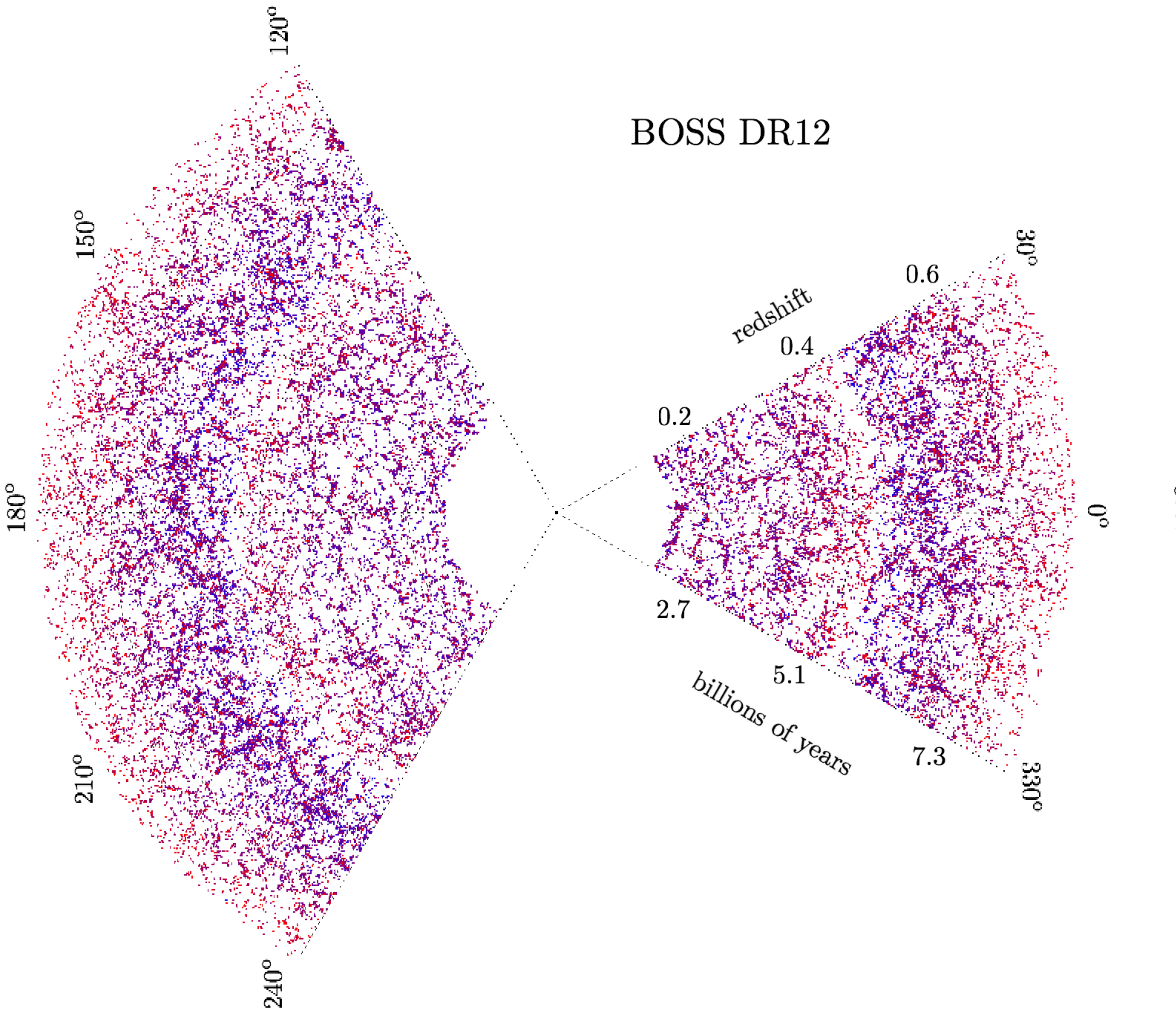
- Deep counts of galaxies provided the first observational arguments for homogeneity of the Universe. If the distribution of galaxies is homogeneous and galaxies are not evolving , then the number of galaxies with apparent magnitude m should scale $10^{0.6m}$. Indeed, this is what is observed up to some magnitude. When counts are too deep, galaxies are preferentially at very large redshifts where the evolution cannot be neglected.



Metcalfe et al 2000

- – SDSS: about 10,000 sq.deg on the sky; for galaxies the depth: $z < 0.4$
- – SDSS: about 10,000 sq.deg on the sky; 50,000 QSOs with $z < 5$
- – 2dF: two strips on the sky
- – anisotropy of CMB: WMAP and others.

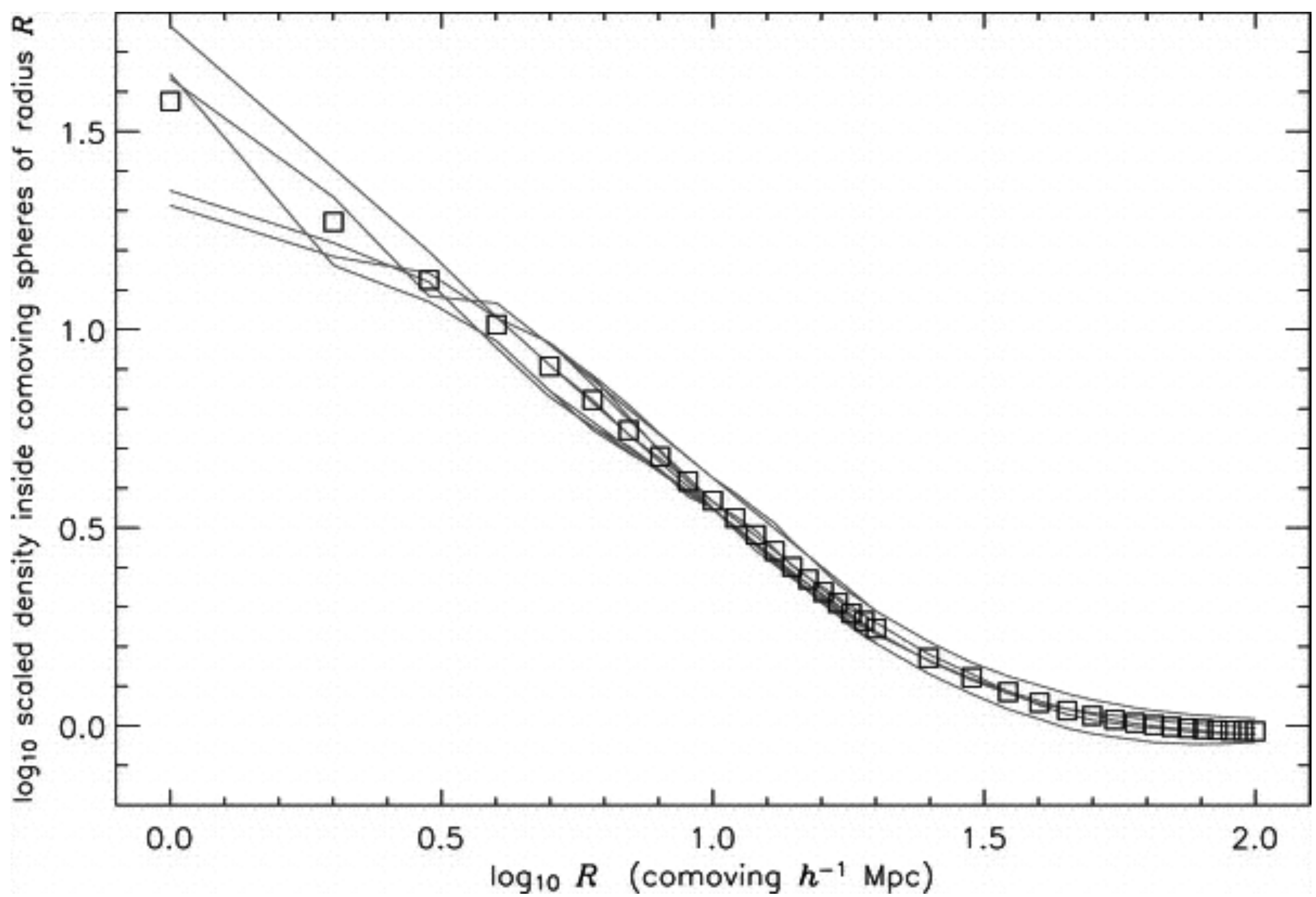



BOSS DR12
120°
150°
180°
210°
240°
30°
0°
330°
redshift
0.2
0.4
0.6
2.7
5.1
7.3
billions of years

- SDSS tested homogeneity of distribution of luminous red galaxies (LRG). Average number-density of LRGs inside a sphere of radius R approaches constant for $R > 30h^{-1}$ Mpc. There are very strong inhomogeneity at smaller scales. Disjoin regions on the sky of size $\sim 2 \times 10^7 h^{-1}\ \mathrm{Mpc}^3$ have variations of 7 percent around the mean density: clear sign of homogeneity on large $\approx 30 - 50h^{-1}$ Mpc scales.

- 2dF catalog and SDSS: measurements of the correlation function and the power spectrum of galaxies.

Hogg et al 2005



Average comoving number density (i.e., number counted divided by expected number from a homogeneous random catalog) of LRGs inside comoving spheres centered on the 3658 LRGs shown in Fig. 1, as a function of comoving sphere radius R. The average over all 3658 spheres is shown with squares, and the averages of each of the five R.A. quantiles are shown as separate lines. At small scales, the number density drops with radius, because the LRGs are clustered; at large scales, the number density approaches a constant, because the sample is homogeneous.

Global parameters of the Universe

- $H = 70$km/s/Mpc
- Age of the Universe 13.5Gyrs
- Slope of the spectrum of perturbations $n = 0.99 \pm 0.04$
- Normalization of the power spectrum of fluctuations $\sigma_8 = 0.9 \pm 1$
- Total baryons $\Omega_b h^2 = 0.024 \pm 0.001$
- Total matter $\Omega_m h^2 = 0.14 \pm 0.02$

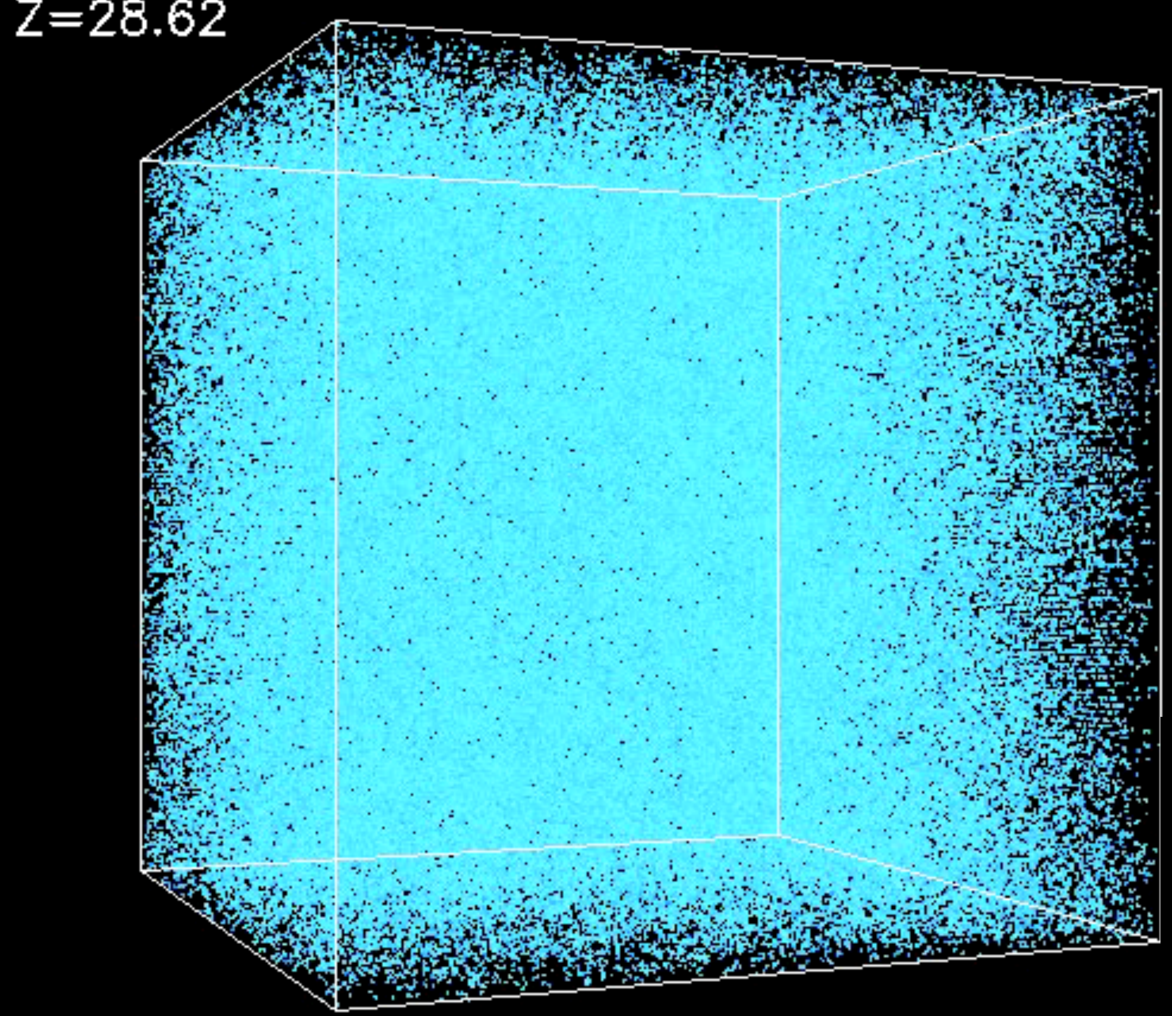
Cosmic Inventory

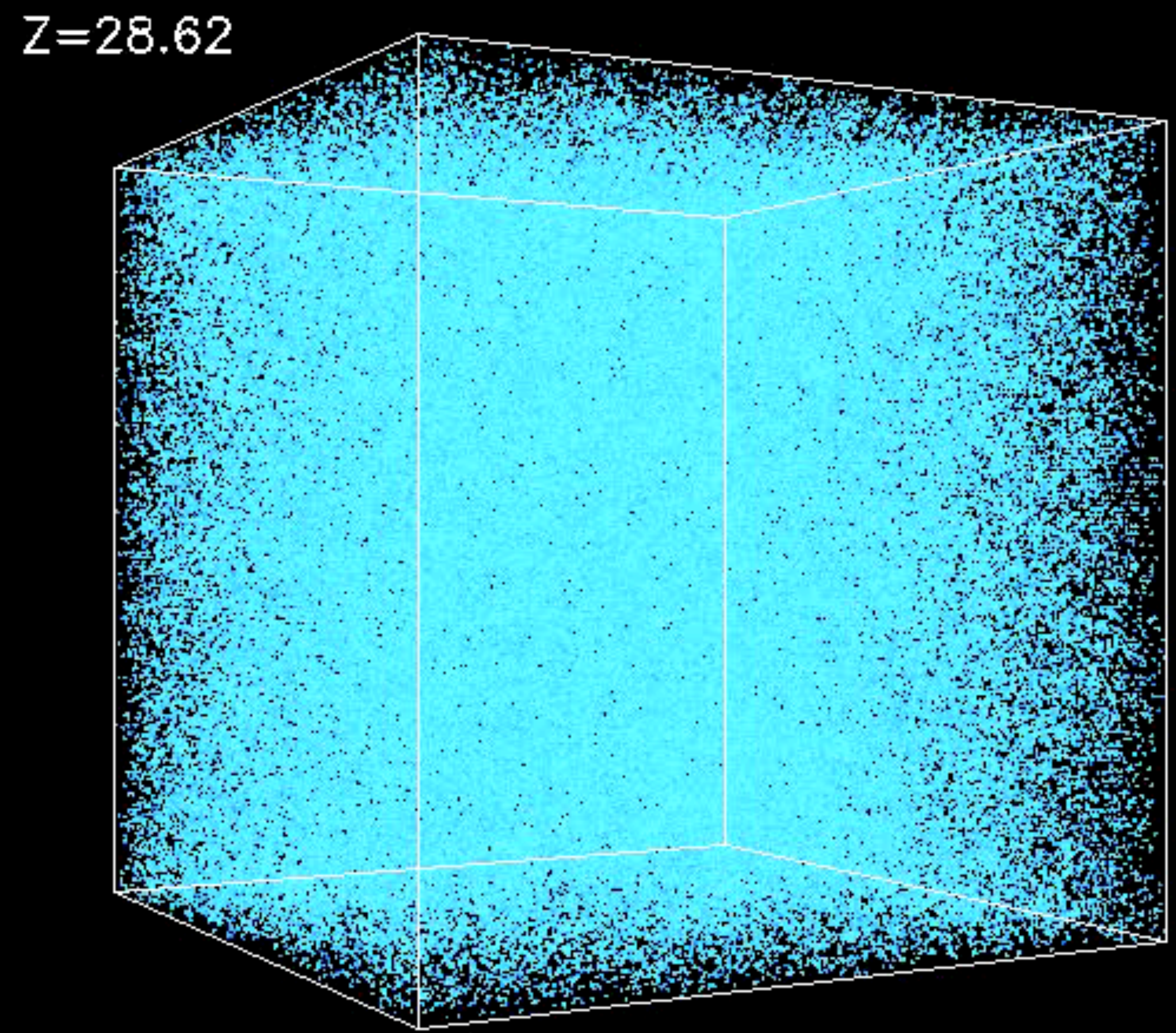
- Dark energy 0.72 ± 0.03
- Dark matter 0.23 ± 0.03
- primeval grav. waves $< 10^{-10}$
- Total dark sector 0.954
-
- Electromagnetic radiation $10^{-4.3\pm0.0}$
- Neutrinos $10^{-2.9\pm0.1}$

- Baryons 0.045 ± 0.003
- Warm intergalactic plasma 0.040 ± 0.003
- Virialized regions of galaxies 0.024 ± 0.005
- Stars $\Omega_{stars} = 0.0027 \pm 0.0005$ (SDSS, 2dF, 2MASS)
- Stars contain 6.0 ± 1.3 percent of all baryons
- Clusters of galaxies with mass $> 5 \times 10^{13} \mathrm{M}_\odot$: $\Omega_{cl} = 0.012 \pm 0.03$
-
- Luminosity density
- $L_B = (1.9 \pm 0.2) \times 10^8 h L_\odot Mpc^{-3}$
- $L_r = (2.3 \pm 0.2) \times 10^8 h L_\odot Mpc^{-3}$

Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10}A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

Non-linear evolution: from Zeldovich approximation to DM halos





Formation of a MW-size halo

0.5Mpc

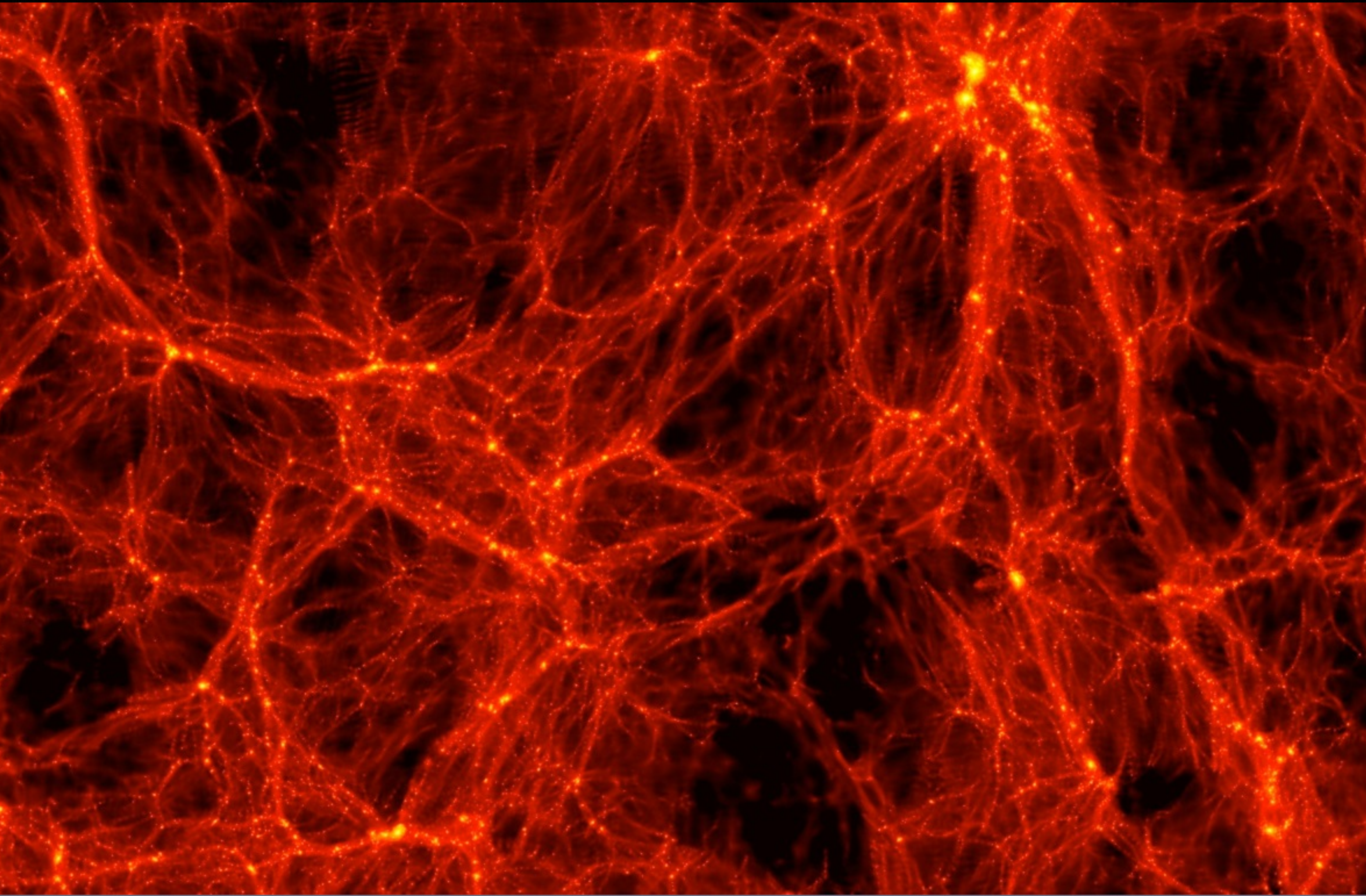
Z=40.52

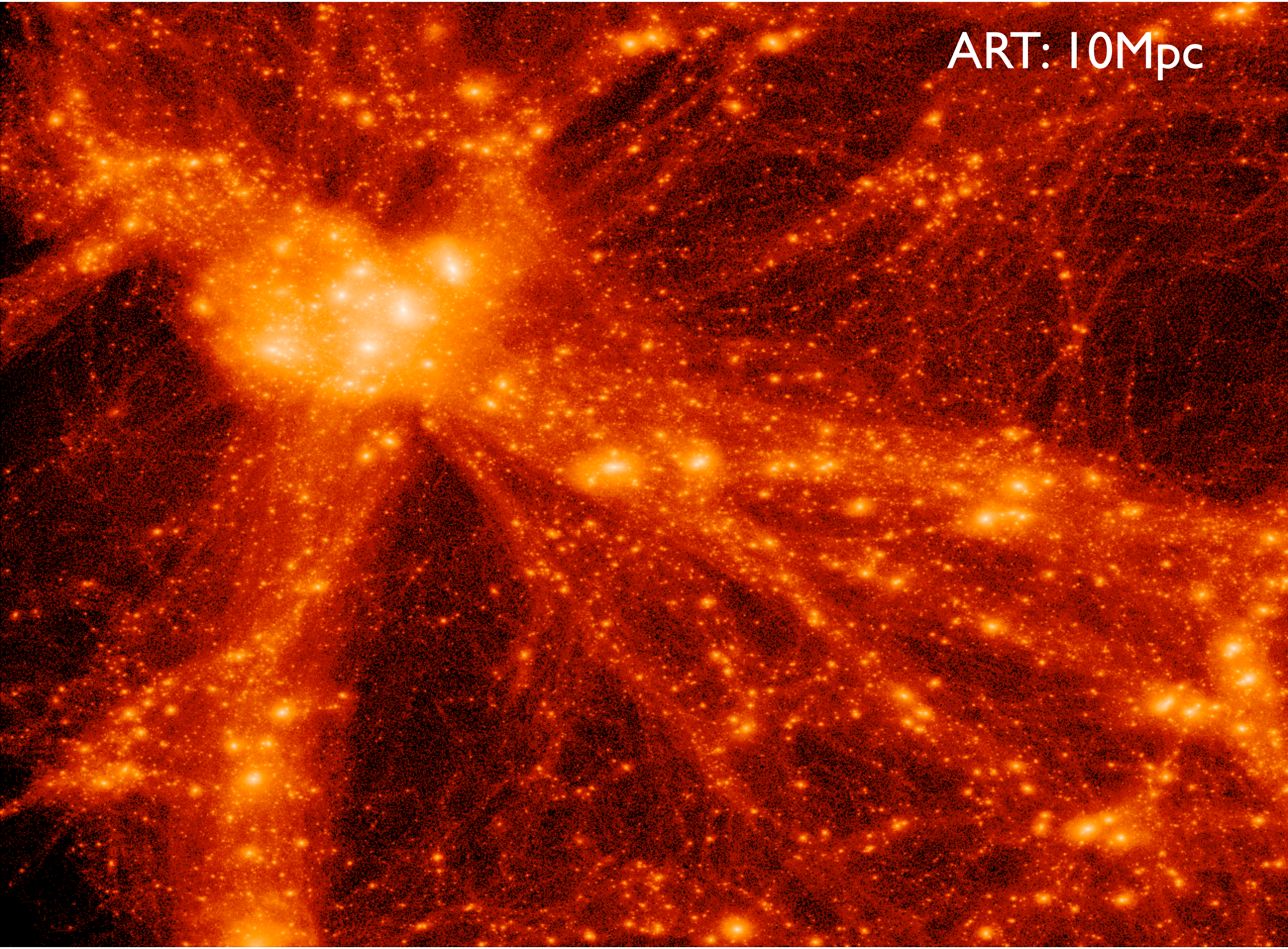
ART

Klypin, Kravtsov

LSS: 300Mpc

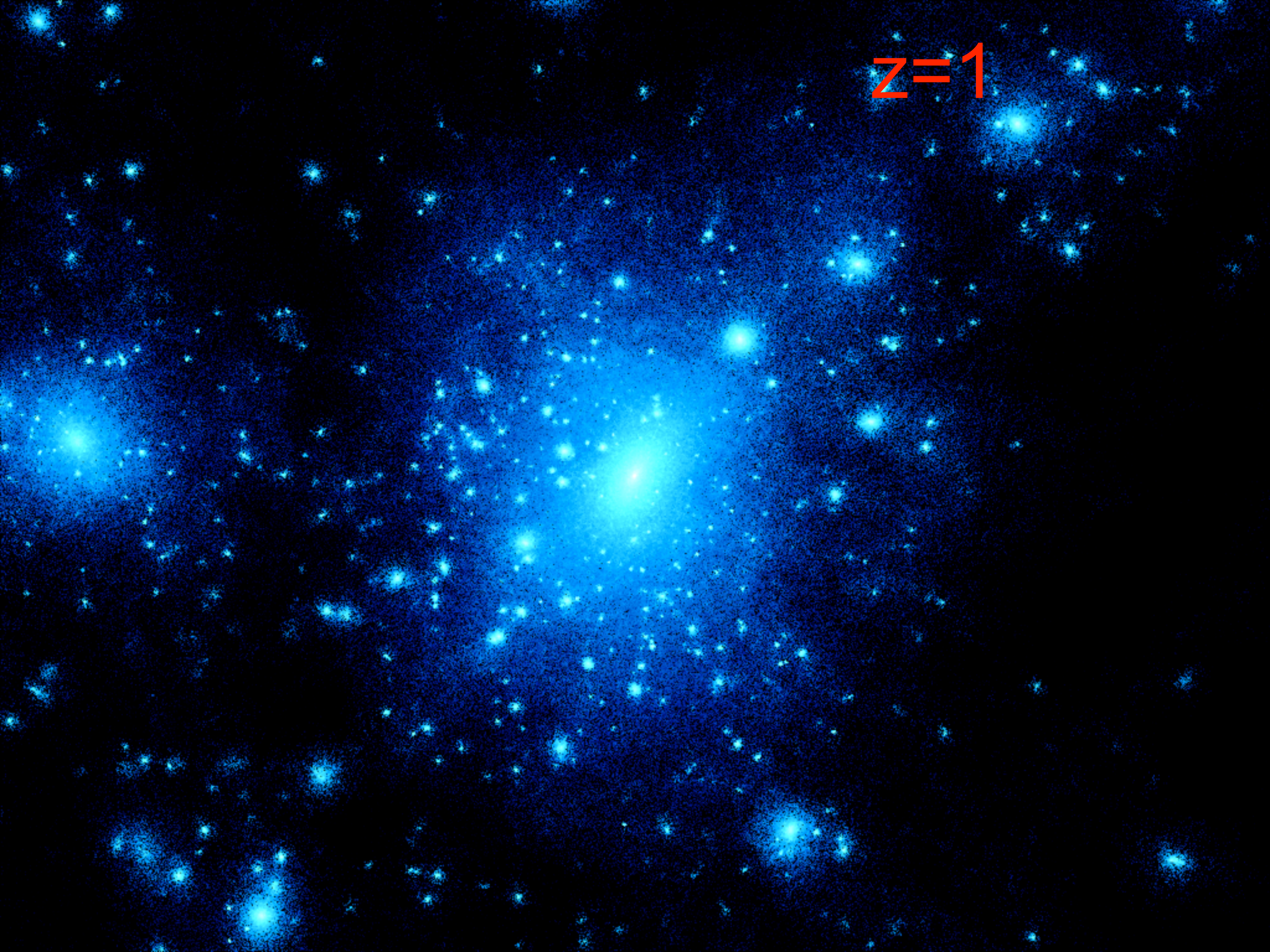
Ben Moore: PKDGRAV




ART: 10Mpc


0.8 Mpc/h


Local Group:z=0


z=1


Local Group:z=7