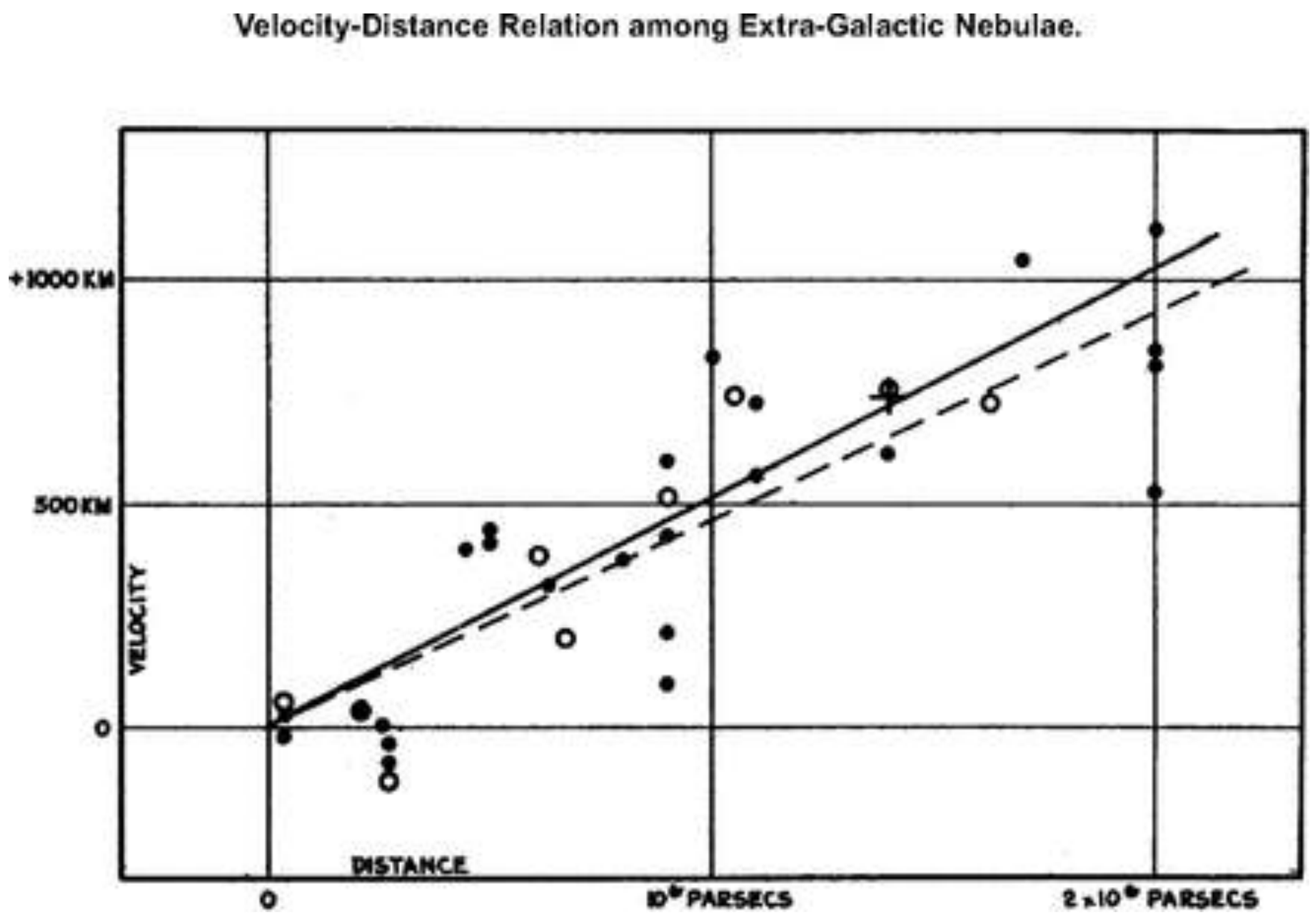
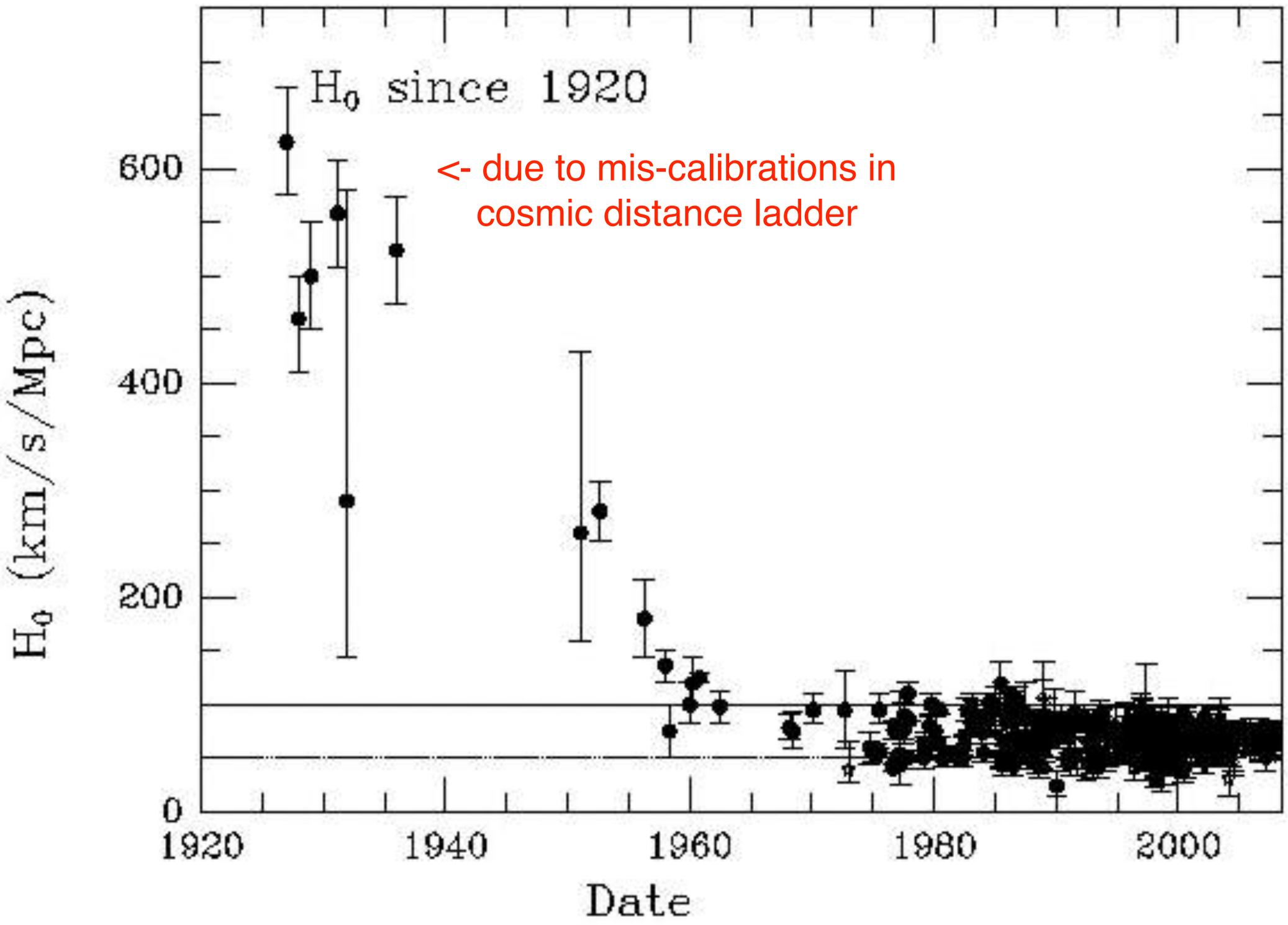
Hubble's original 1929 diagram



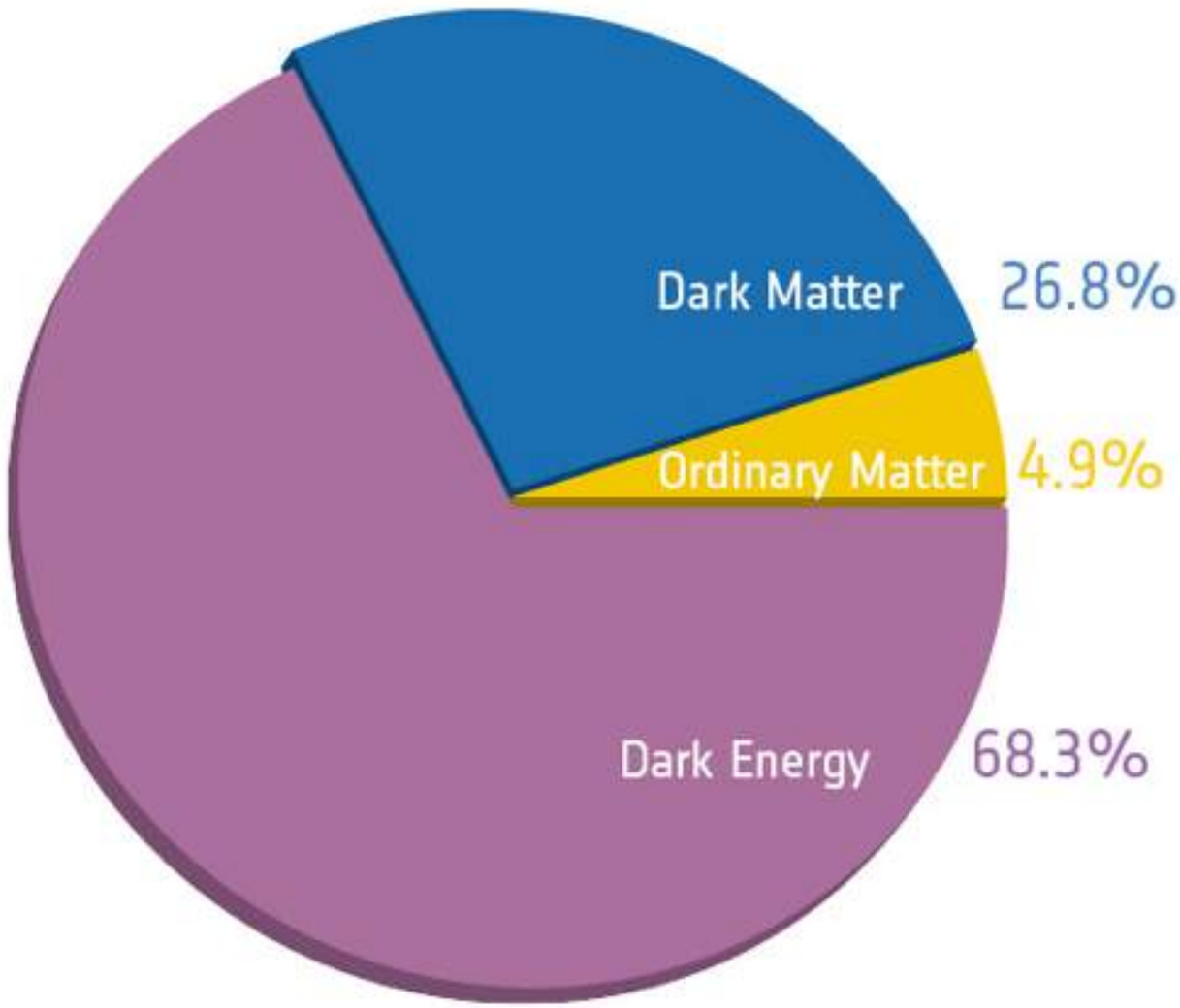
Distances determined using stars of known luminosity, including Cepheids

Note: velocity units should km/s

Measurements of the Hubble constant versus time



The standard ΛCDM cosmological model



Planck 2013

<u>In general:</u>

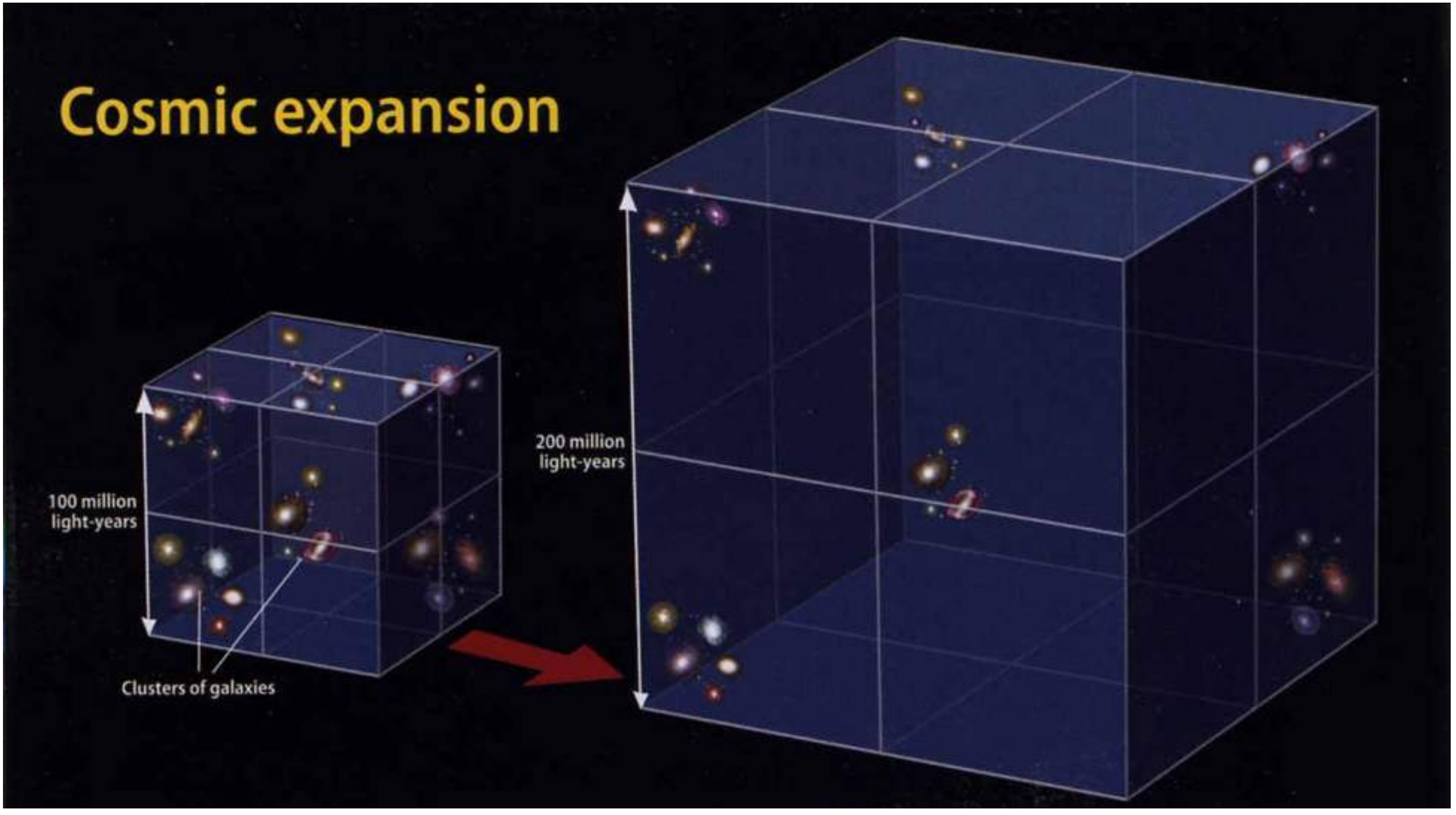
$$\Omega_x \equiv \frac{\rho_x}{\rho_{\rm crit}}$$

$\rho_{\rm crit}$ = critical density to close universe

<u>Our Universe:</u>

$$\Omega_{\rm tot} = 1$$
$$\Omega_{\rm DM} = 0.27$$
$$\Omega_{\rm b} = 0.05$$
$$\Omega_{\rm M} = \Omega_{\rm DM} + \Omega_{\rm b} = 0.32$$
$$\Omega_\Lambda = 0.68$$

Cosmic expansion



The Nobel Prize in Physics 2015

Ill. N. Elmehed. © Nobel Media AB 2015.

Takaaki Kajita

Prize share: 1/2

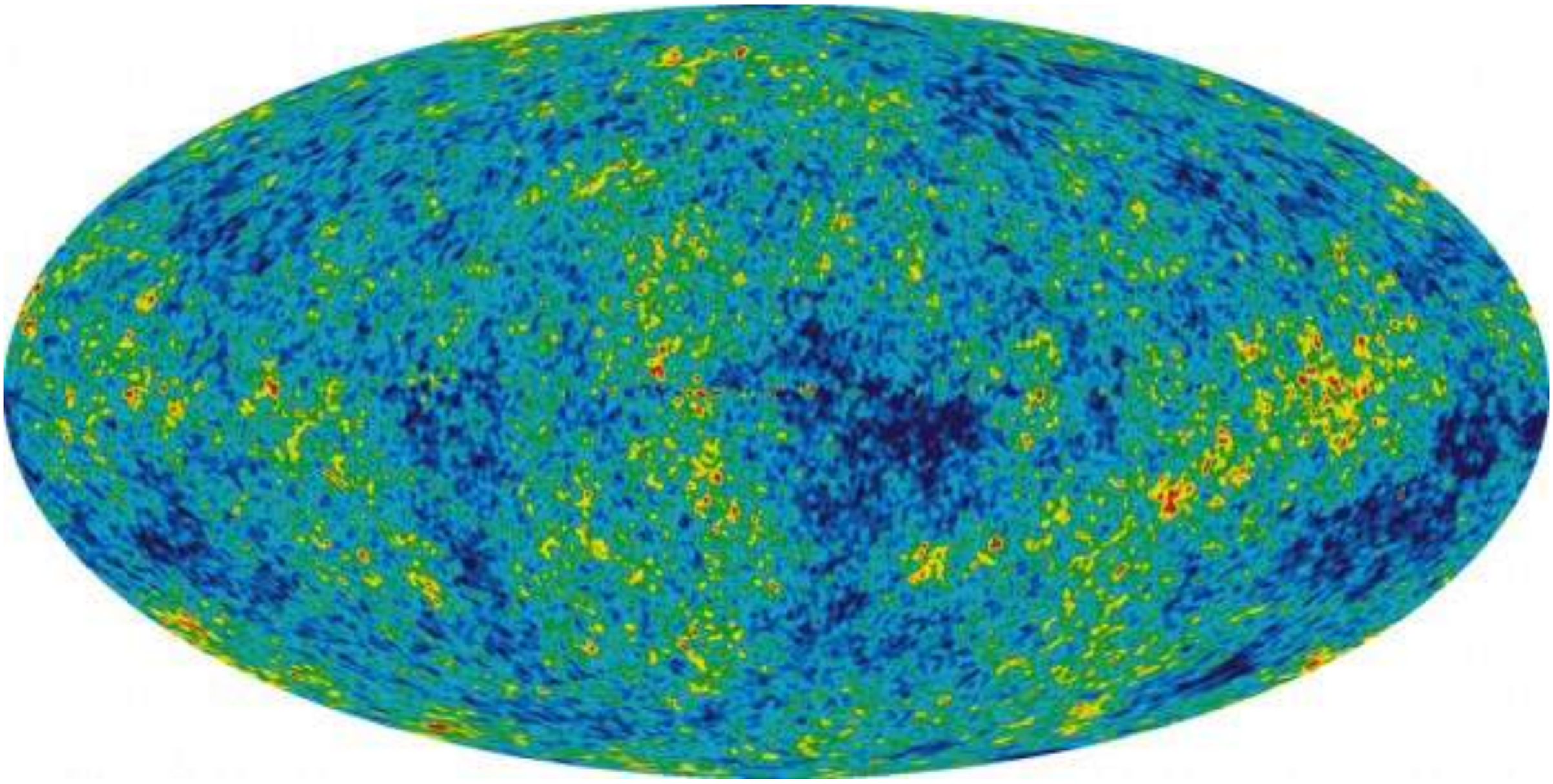
Ill. N. Elmehed. © Nobel Media AB 2015.

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

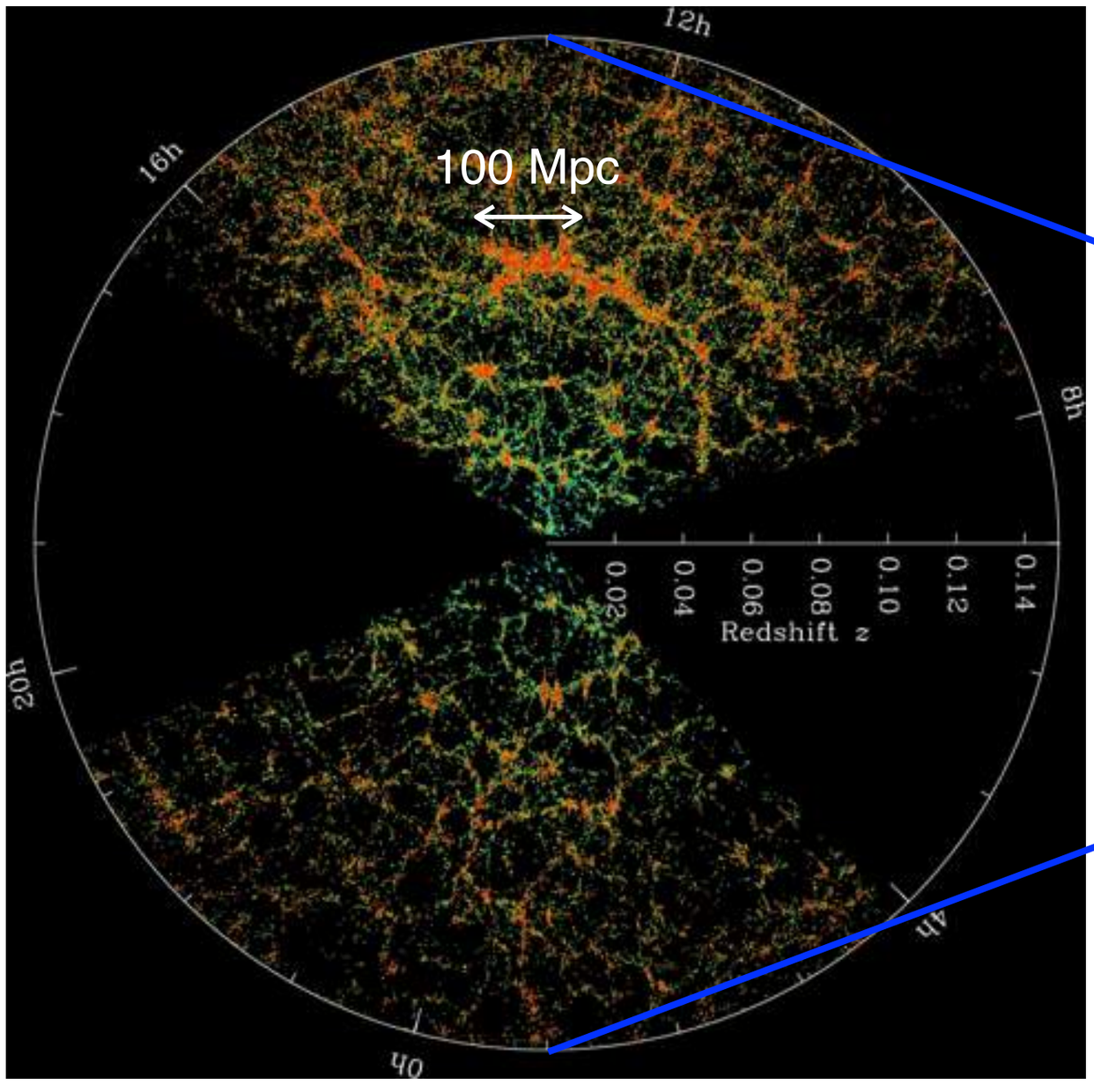
The CMB is uniform to 1 part in ~10^5



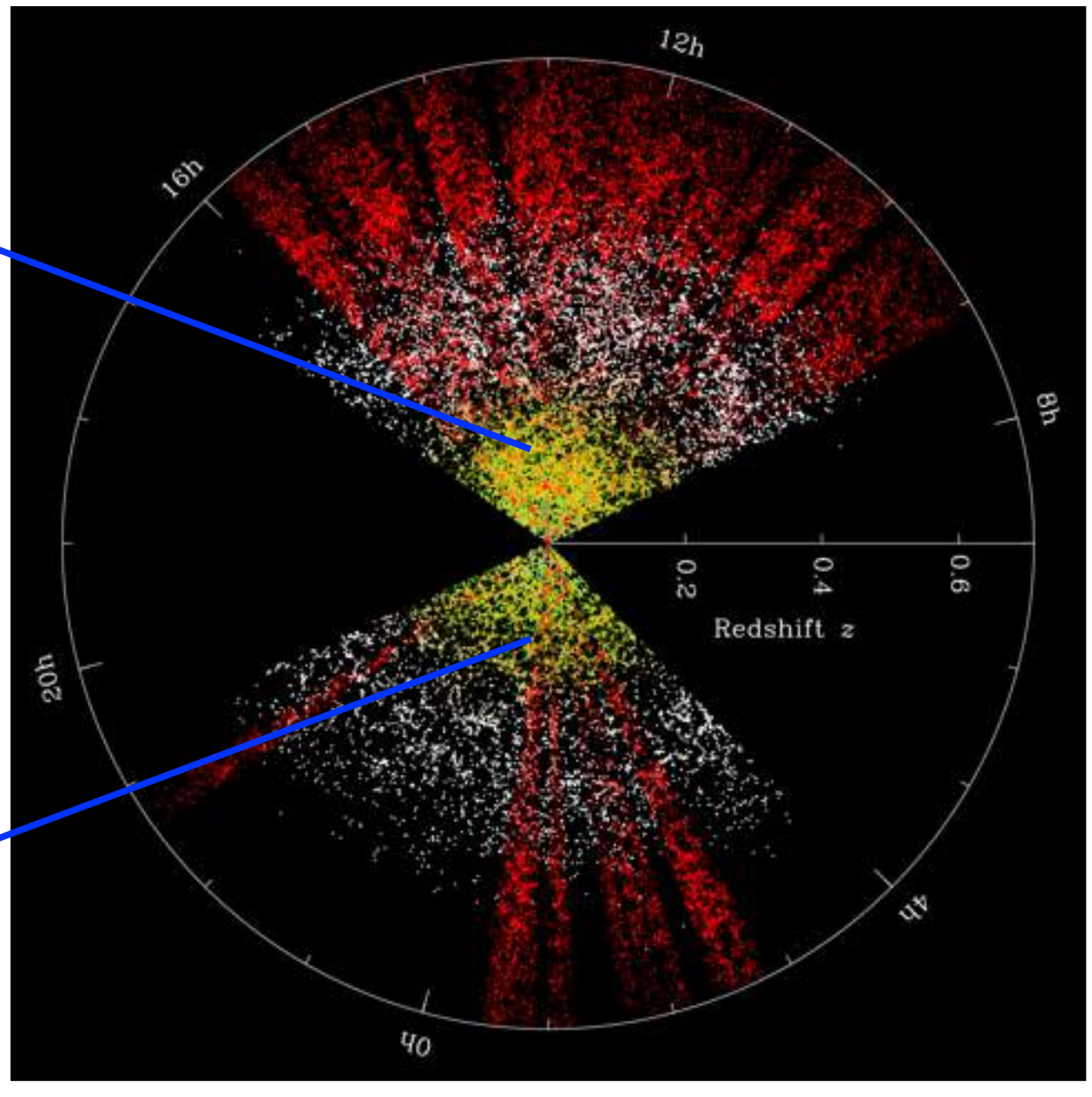
~density fluctuations at z~1,100

Galaxies map the late time distribution of matter

Sloan Digital Sky Survey galaxy distribution



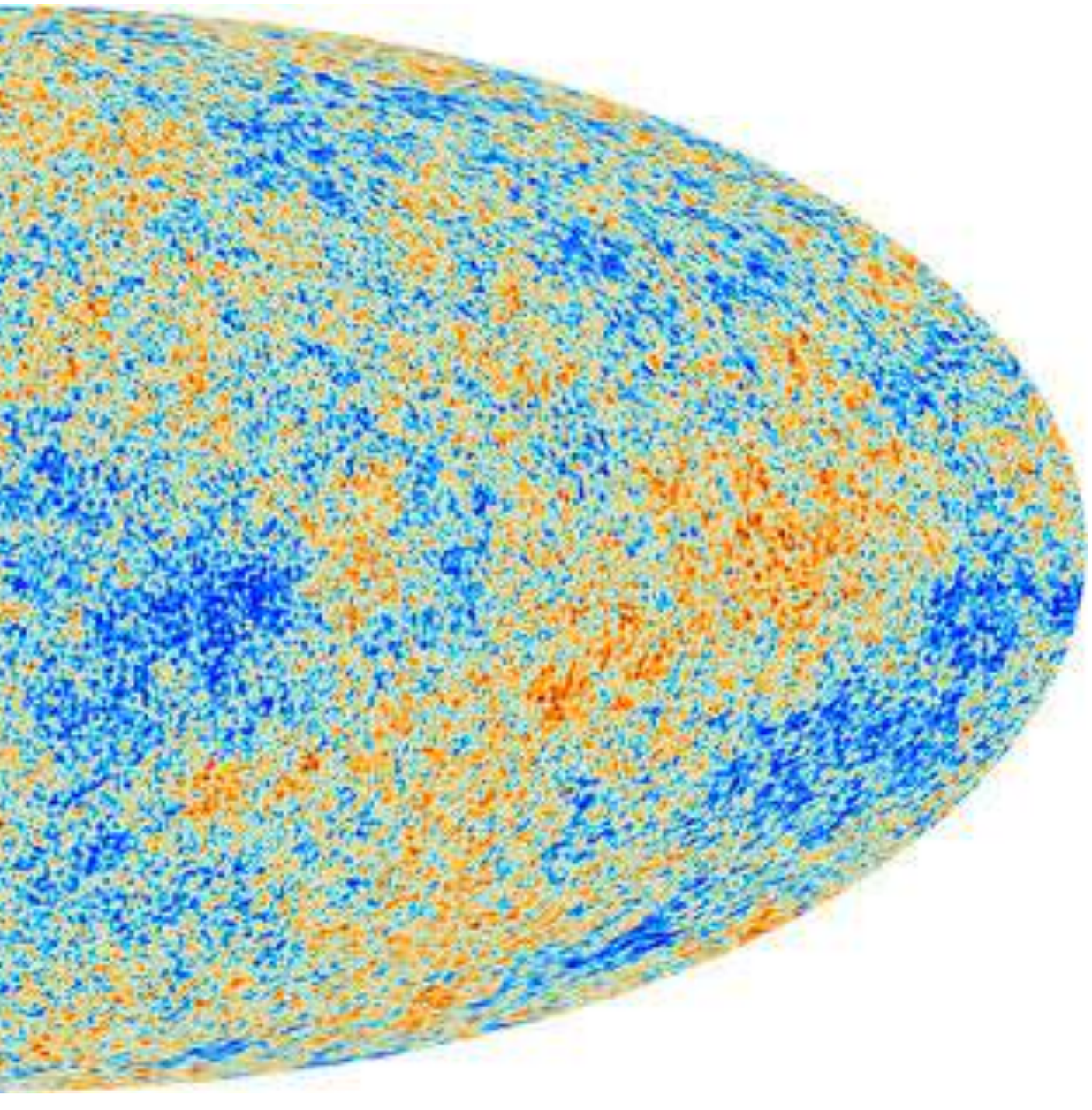
Update from Baryonic Oscillation Spectroscopy Survey



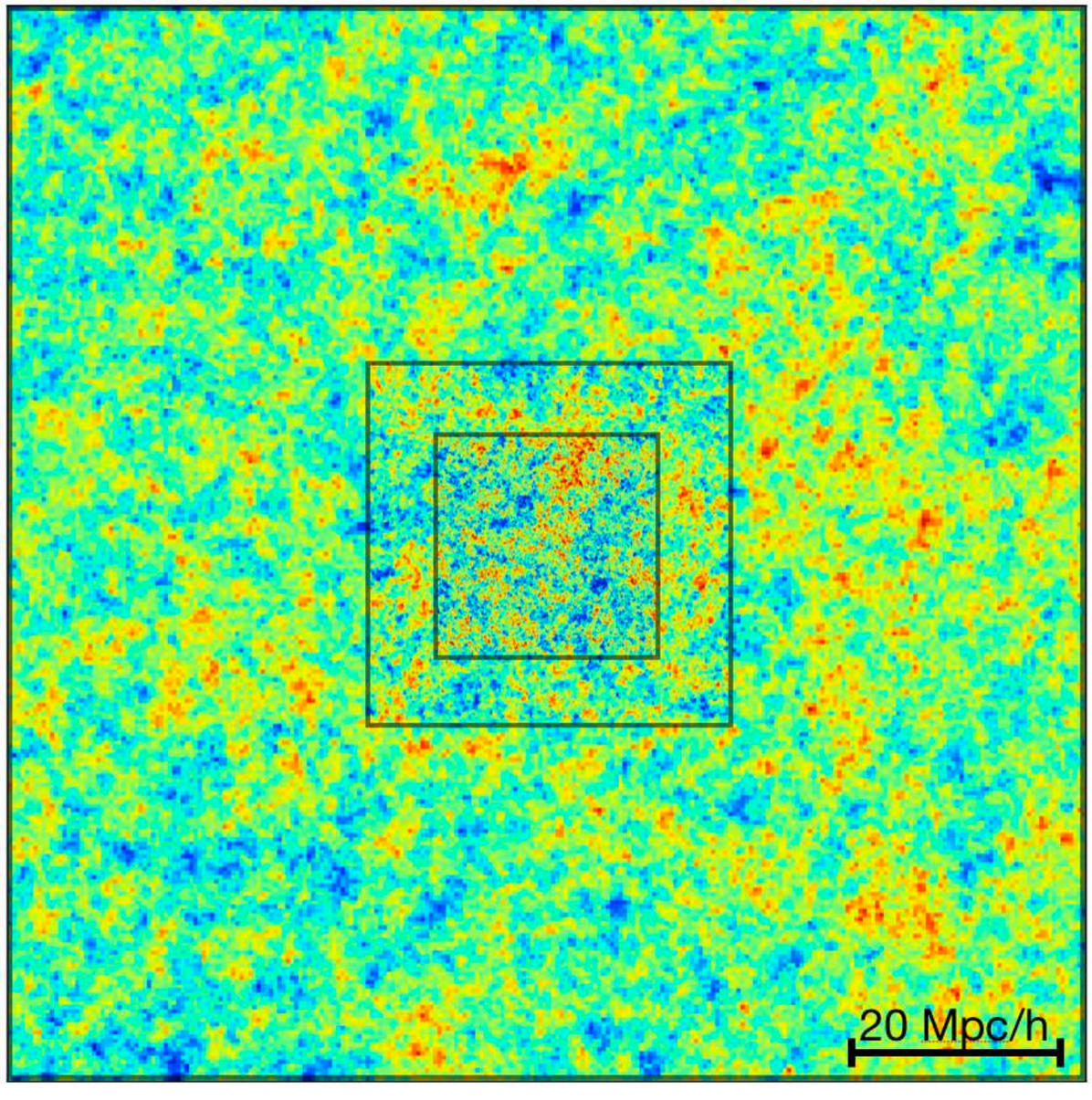
"Fingers" =
artifacts of sky coverage

CMB statistics provide initial conditions for structure formation (*N*-body) simulations

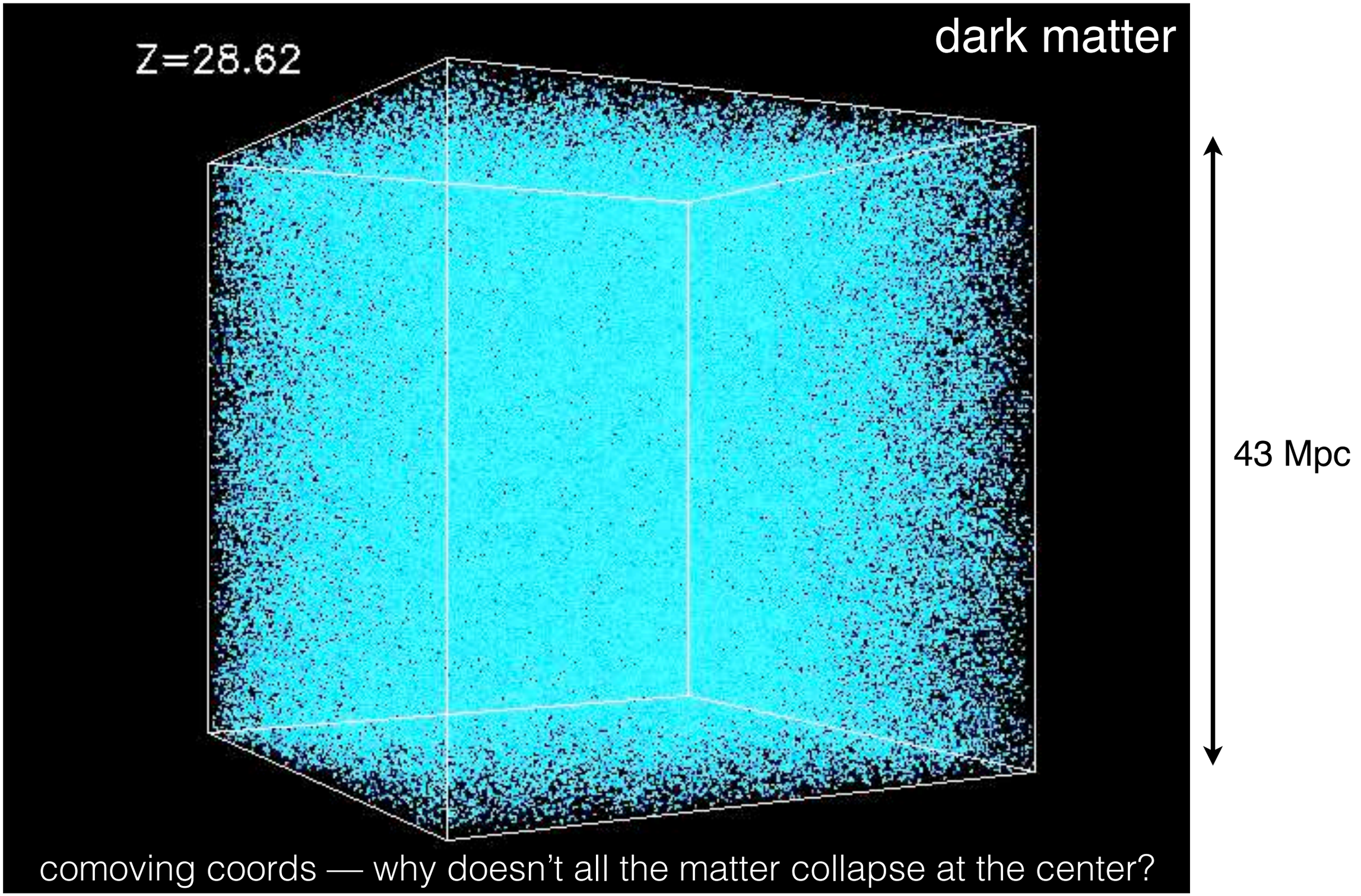
Microwave sky



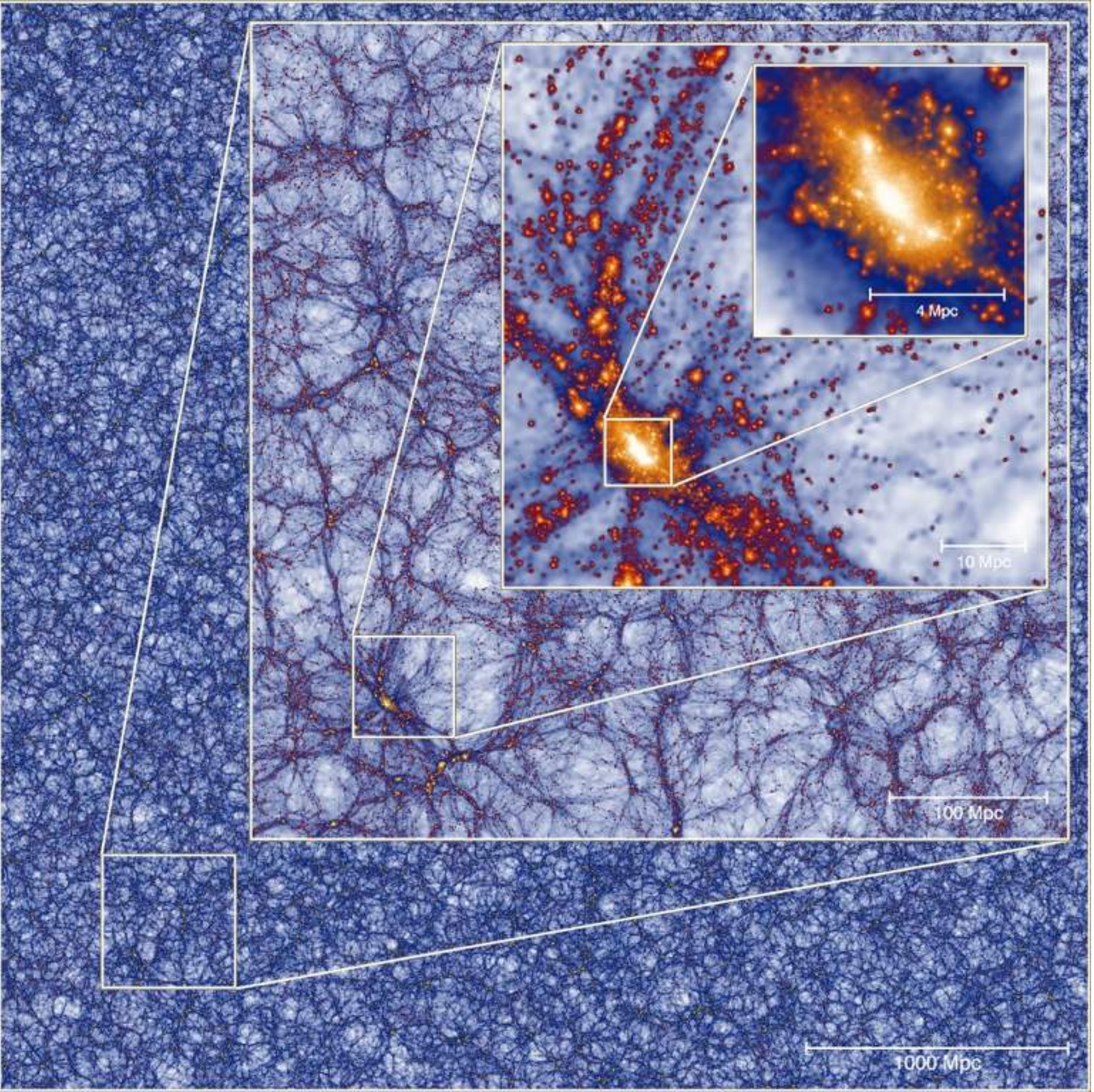
Simulation ICs



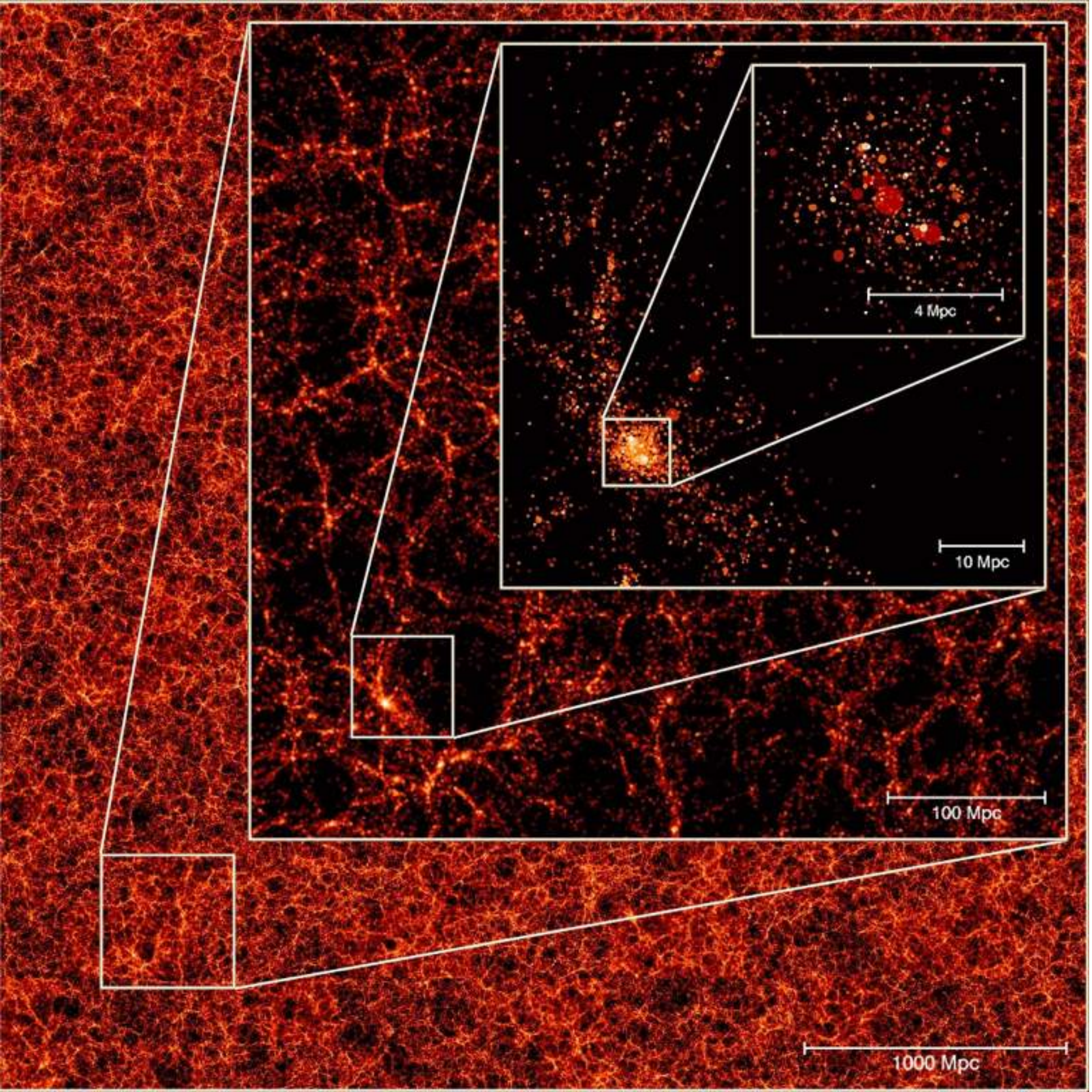
Large-scale structure formation in ΛCDM



Density peaks (dark matter halos) are the sites of galaxy



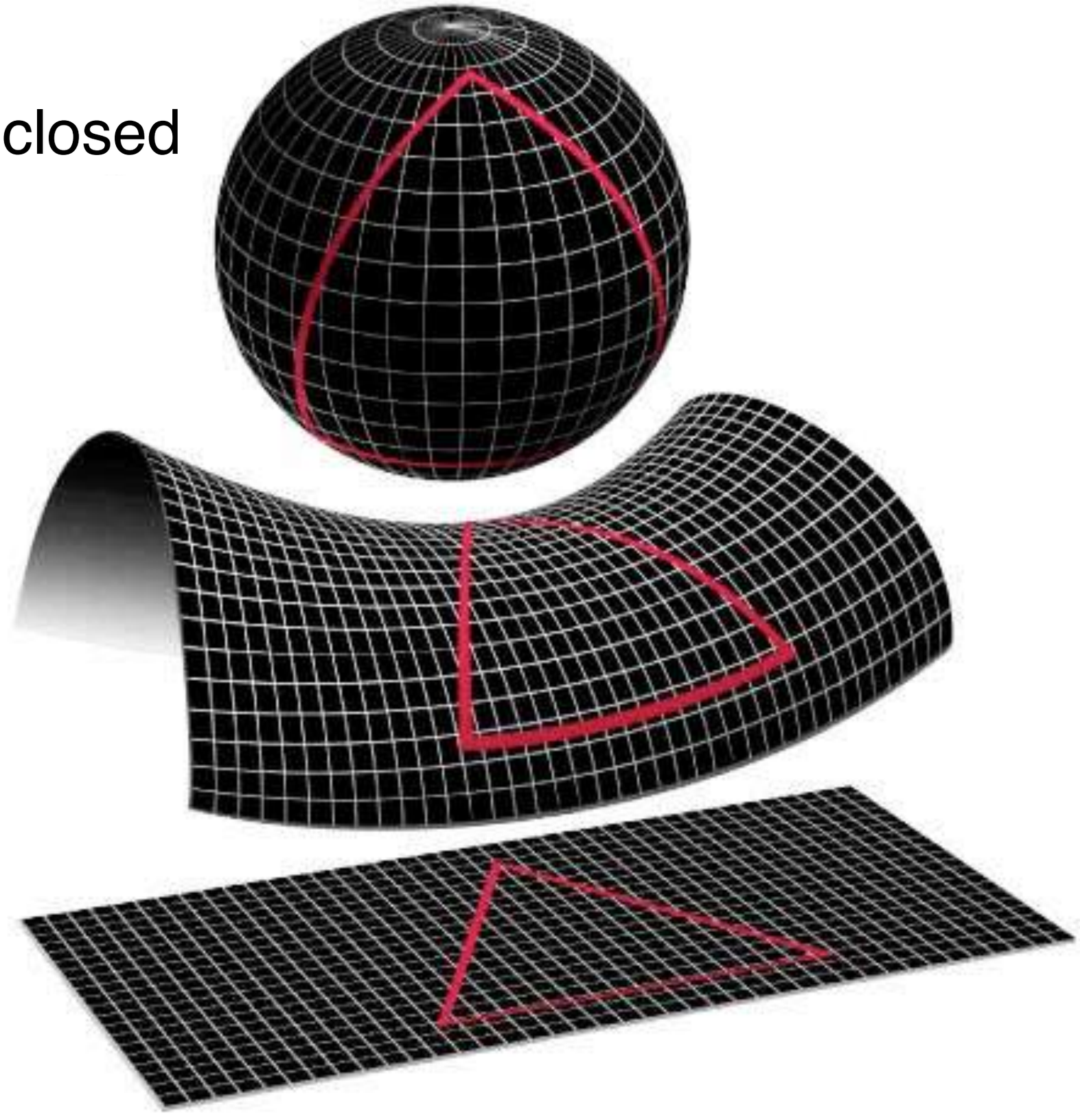
Dark matter
in Millennium-XXL
simulation
(Angulo+12)

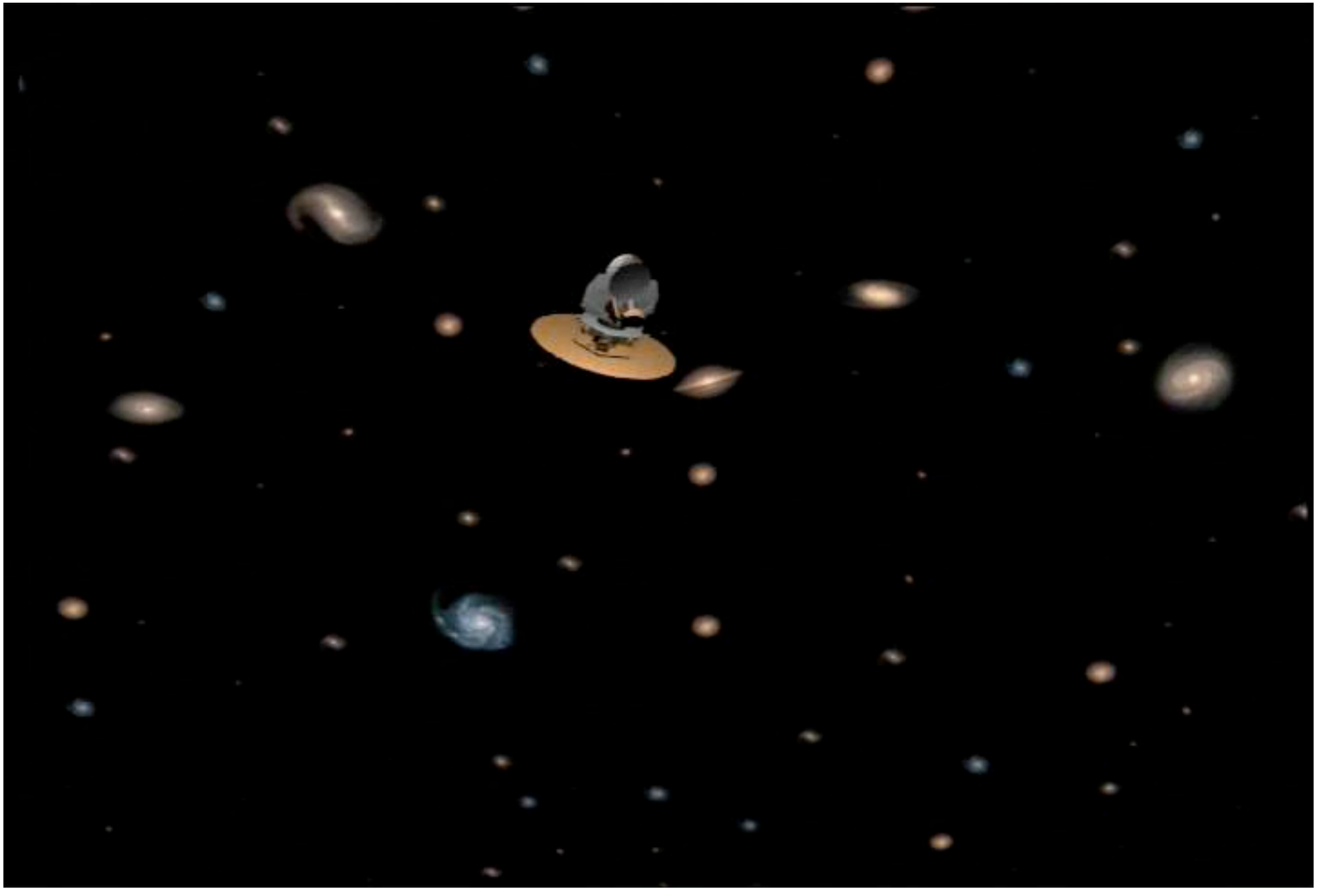


Galaxies
in Millennium-XXL
simulation
(Angulo+12)

closed

open



flat

Measuring the Universe's geometry using the CMB