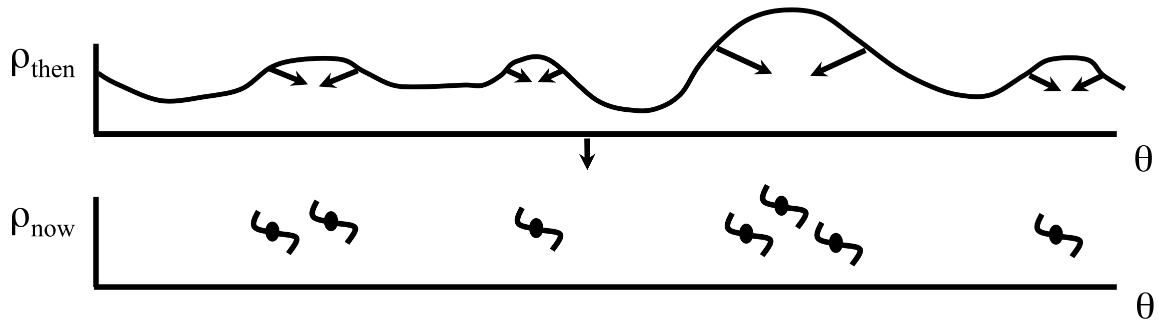
Lecture 5: Matter Dominated Universe: CMB Anisotropies and Large Scale Structure

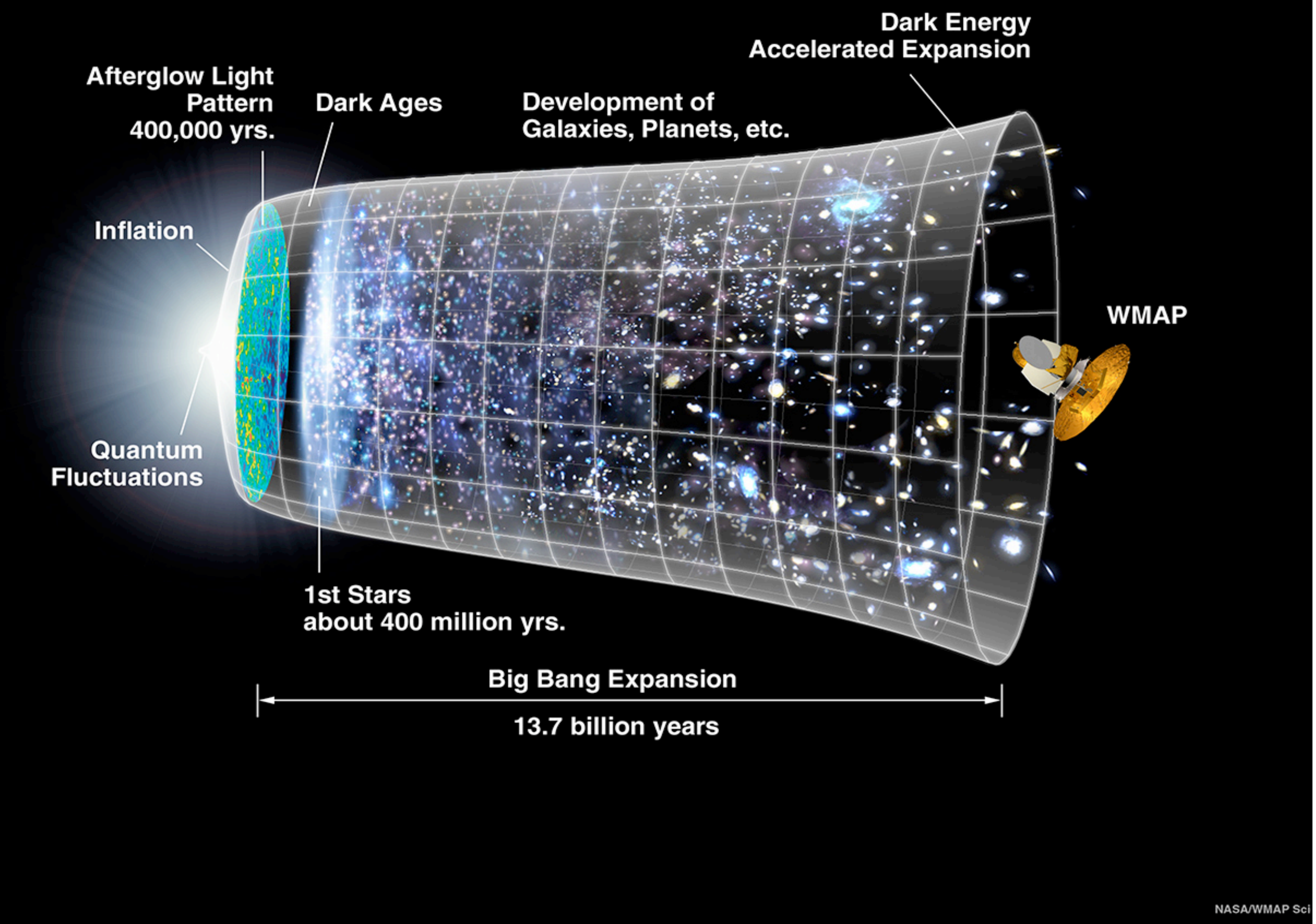
Today, matter is assembled into structures: filaments, clusters, galaxies, stars, etc.

Galaxy formation is not completely understood.

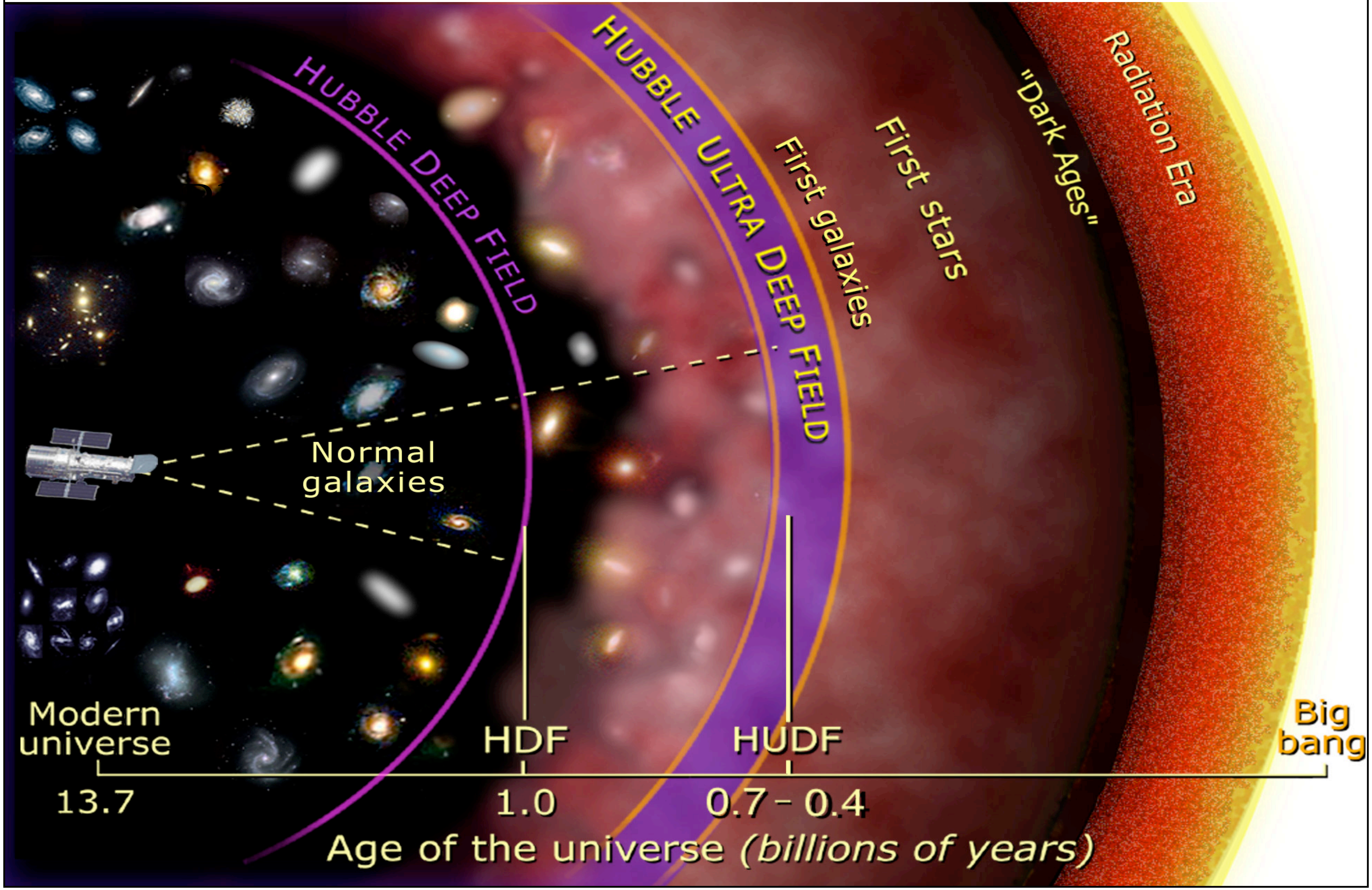
Main mechanism is gravitational instability:



Overview of Cosmic History



Looking Back in Time

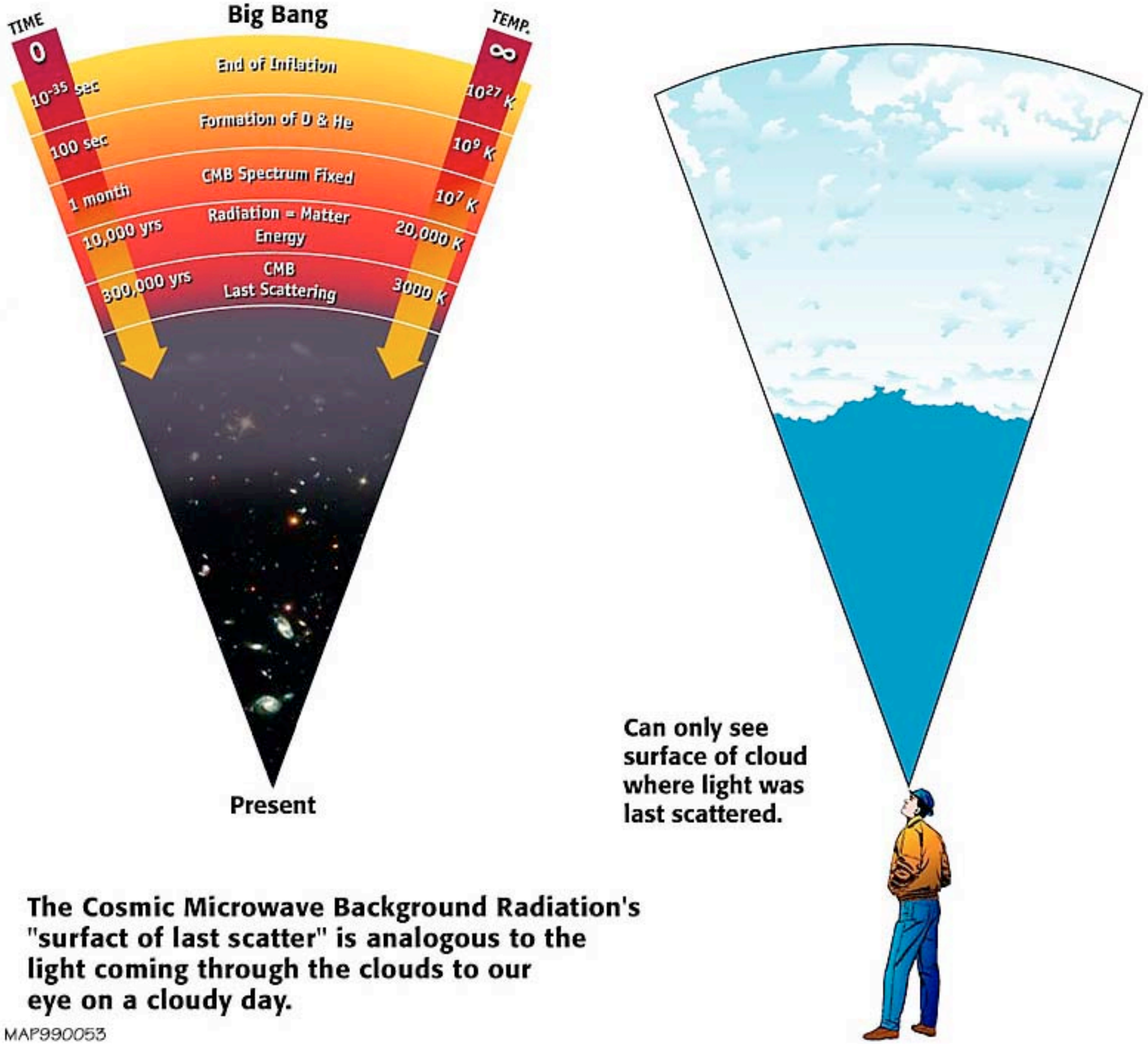


Surface of Last Scattering

Before decoupling:
matter and radiation tightly coupled.

After: radiation propagates freely.

The CMB retains an imprint of conditions on the *surface of last scattering*.



Almost perfect CMB isotropy --> almost uniform matter distribution at recombination

$z = 1100 \quad T \sim 3000\ \mathrm{K} \quad t \sim 3\mathrm{x}10^5\ \mathrm{yr}$

Tiny CMB <u>anisotropies</u>.

The "ripples" in T --> ripples in density.

$$\frac{\Delta T}{T} \approx 10^{-5} \approx \frac{\Delta \rho}{\rho}$$

After decoupling, gravity amplifies these initial density ripples.

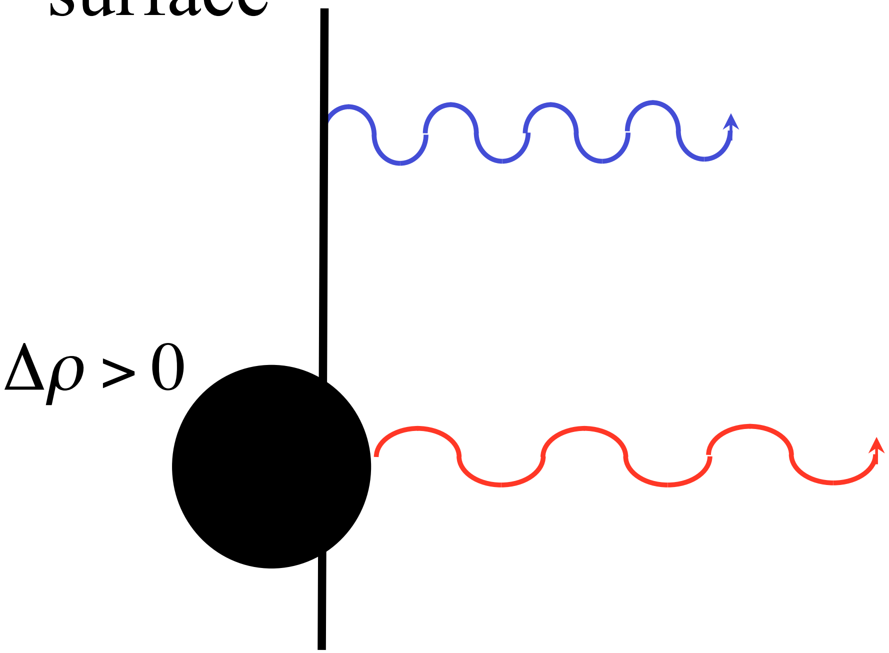
Three mechanisms give rise to anisotropies

- Sachs-Wolfe effect $\Delta\theta \sim 10^{\circ}$
- Doppler effect $\Delta\theta \sim 1^{\circ}$
- Re-ionization (Sunyaev-Zeldovich effect)

  $\Delta\theta \sim 0.1^{\circ}$

Sachs-Wolfe effect

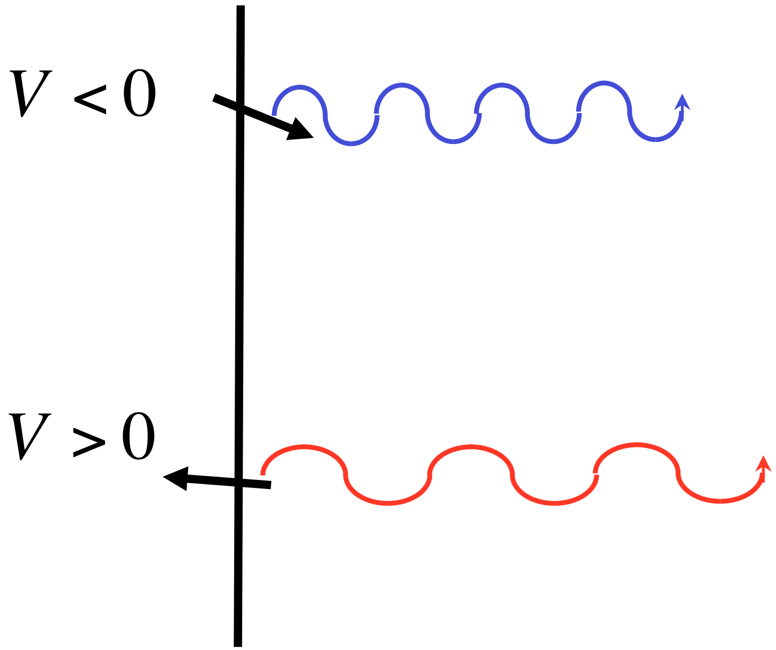
Photons from an over-dense region must climb out of the potential well, losing energy --> longer wavelength
--> lower T.



$$\boxed{-\frac{\Delta T}{T} \sim \frac{\Delta\rho}{\rho}}$$

Doppler effect

Gas velocity on the last-scattering surface produces Doppler shifts.



$$\boxed{-\frac{\Delta T}{T} = \frac{\Delta\lambda}{\lambda} = \frac{V}{c}}$$

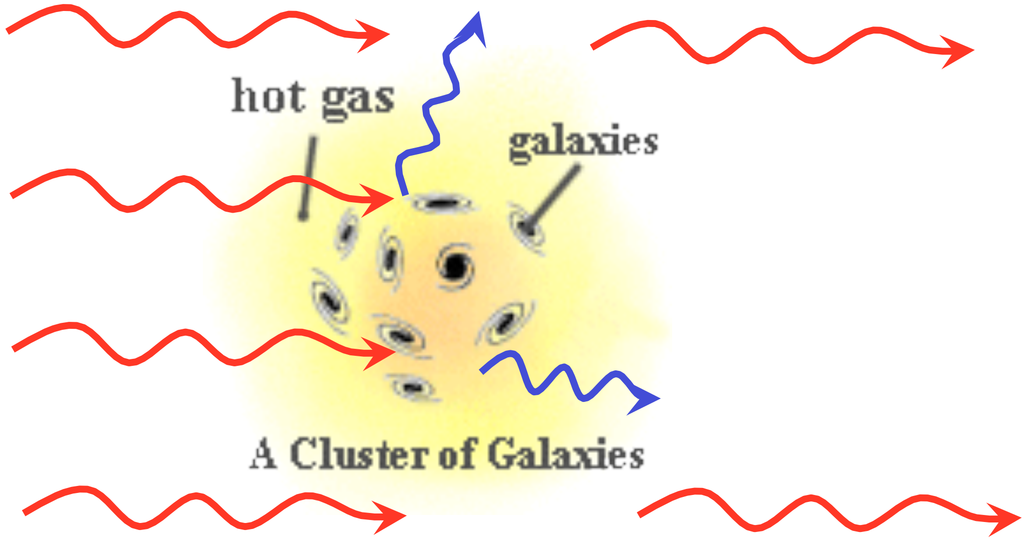
Re-ionisation
(Sunyaev-Zeldovich effect)

Once stars form, their UV radiation re-ionises nearby gas.

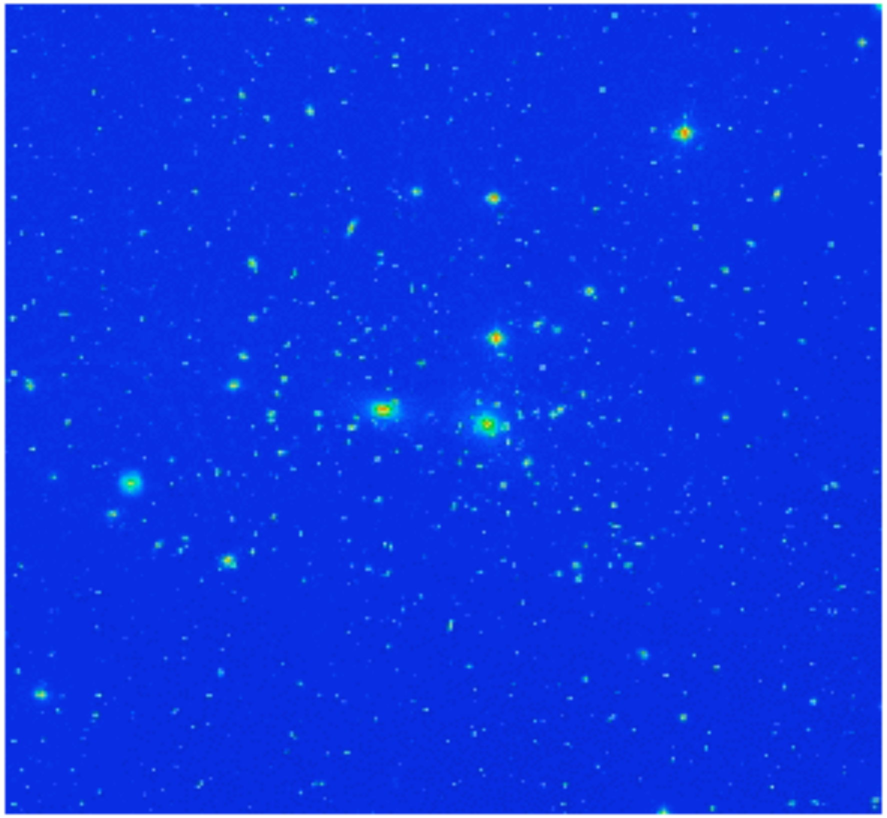
Once galaxy clusters form, gas falling in is shock-heated to X-ray temperatures (~$10^{6\text{-}8}$ K).

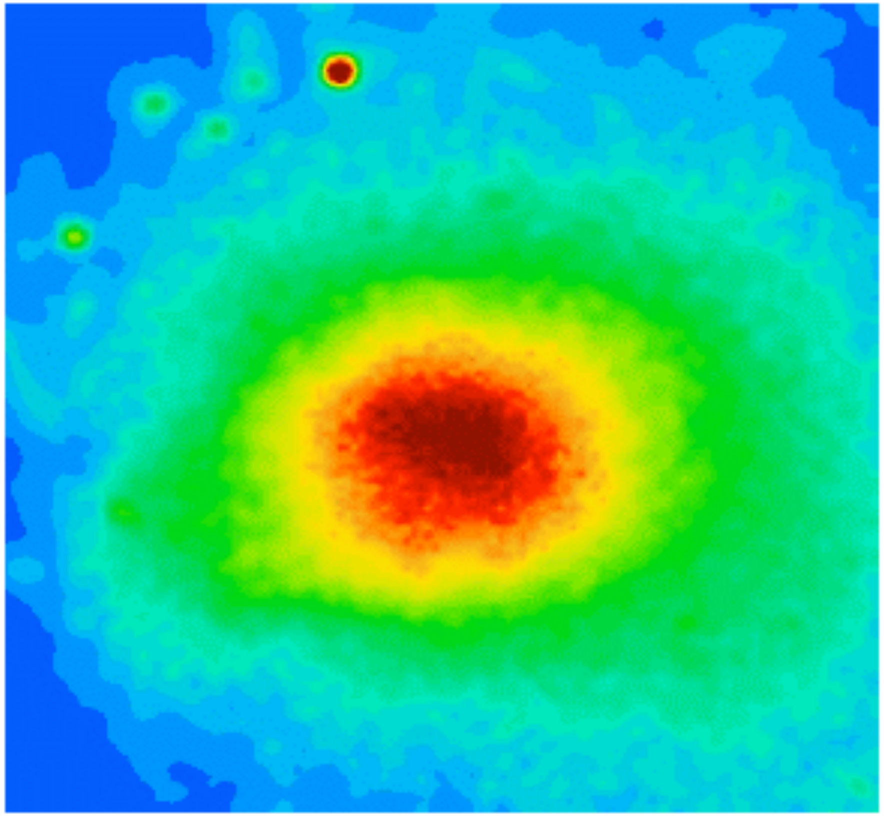
Free electrons liberated scatter CMB photons.

We see CMB silhouettes of the hot gas.



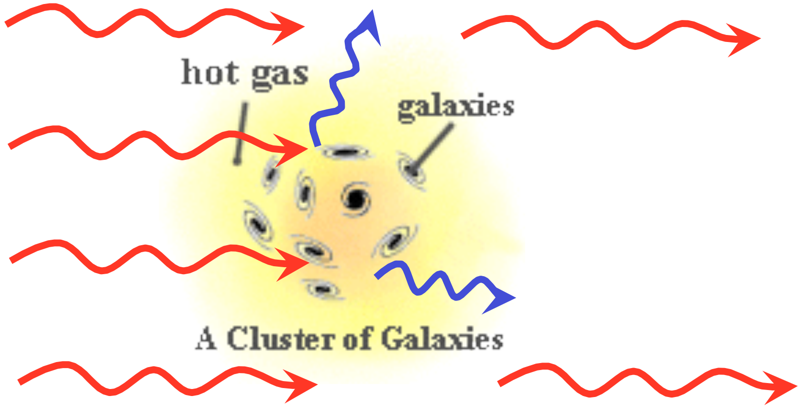
Galaxy Clusters are filled with hot X-ray gas

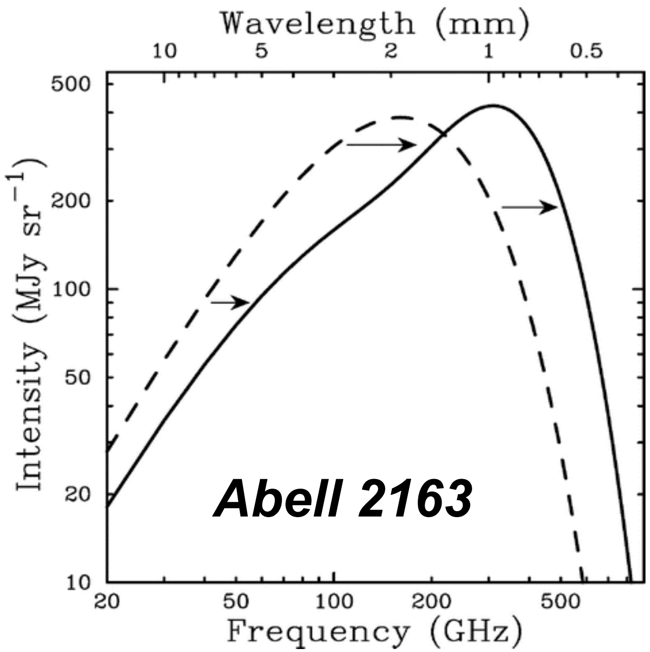


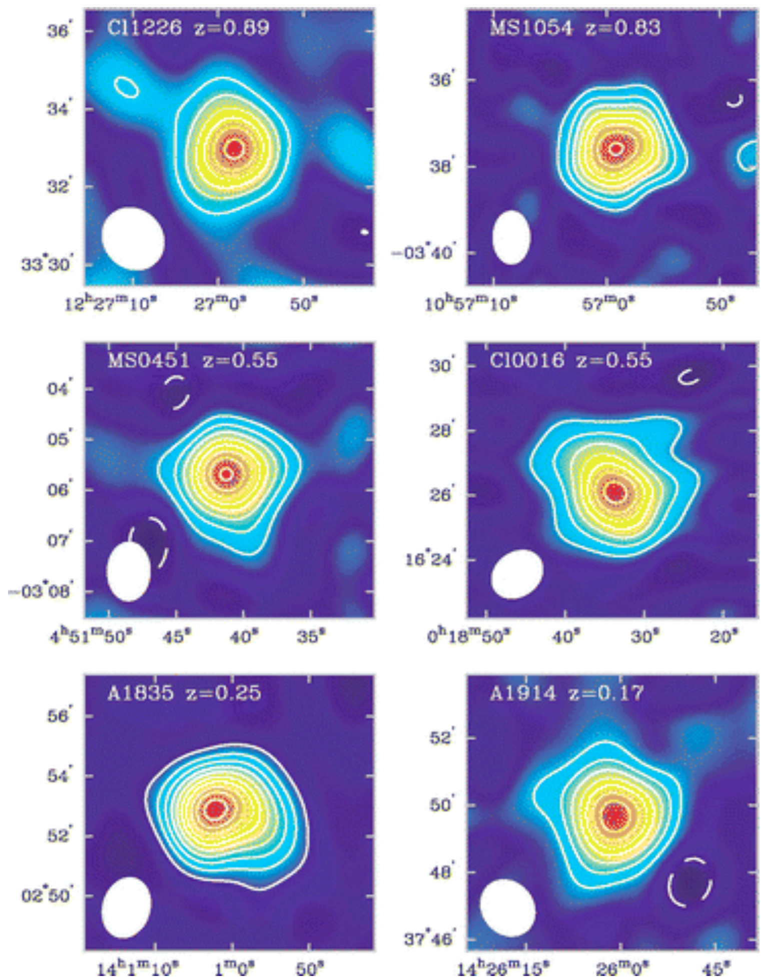


optical (galaxies) Coma cluster **X-ray (hot gas)**

SZ effect: CMB silhouettes of galaxy cluster x-ray gas

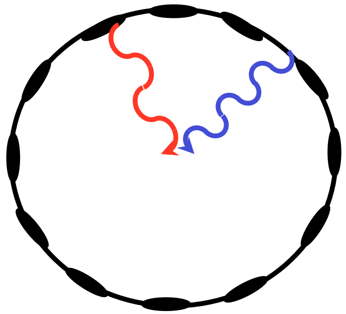






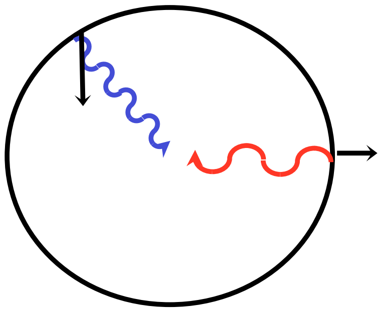
Carlstrom et al., 2002.

Sachs-Wolfe (SW) effect



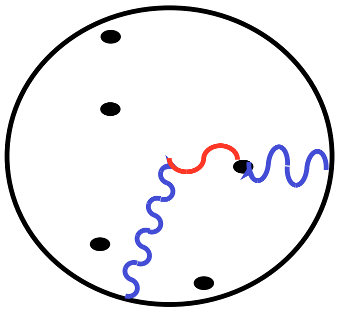
Mass distribution at recombination.

Doppler effect



Velocity distribution at recombination.

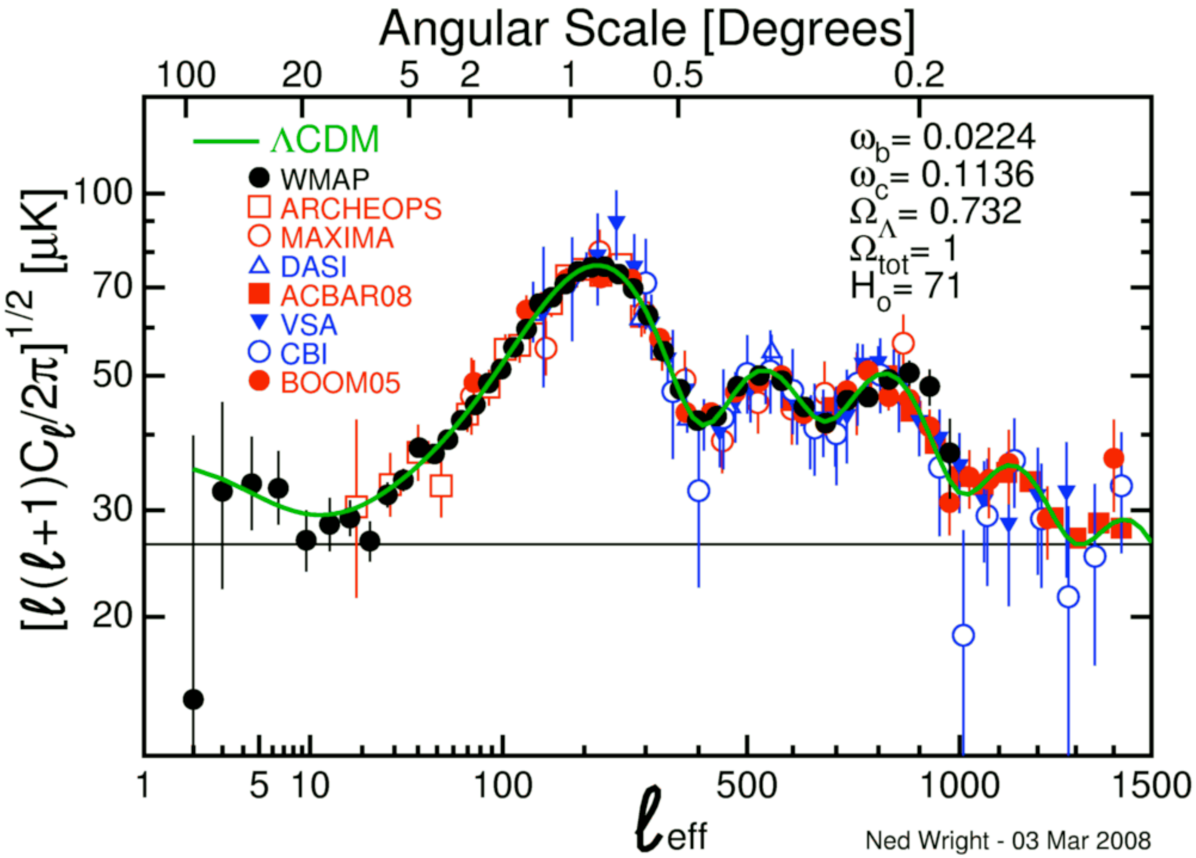
Sunyaev-Zeldovich (SZ) effect



Ionised gas in intervening galaxy clusters.

Power Spectrum of CMB anisotropies

Temperature ripple ΔT
vs angular scale
$\theta = 180^{o} / \ell$



Peak at 1^{o} scale
=> Flat geometry,
$\Omega_{tot}=1$

"Acoustic Peaks" arise from sound waves in the plasma era. Sound speed is $c/\sqrt{3}$. Peak when the duration of plasma era matches a multiple of half a sound wave oscillation period.

2004 Precision Cosmology

$h = 71 \pm 3$ expanding

$\Omega = 1.02 \pm 0.02$ flat

$\Omega_b = 0.044 \pm 0.004$ baryons

$\Omega_M = 0.27 \pm 0.04$ Dark Matter

$\Omega_\Lambda = 0.73 \pm 0.04$ Dark Energy

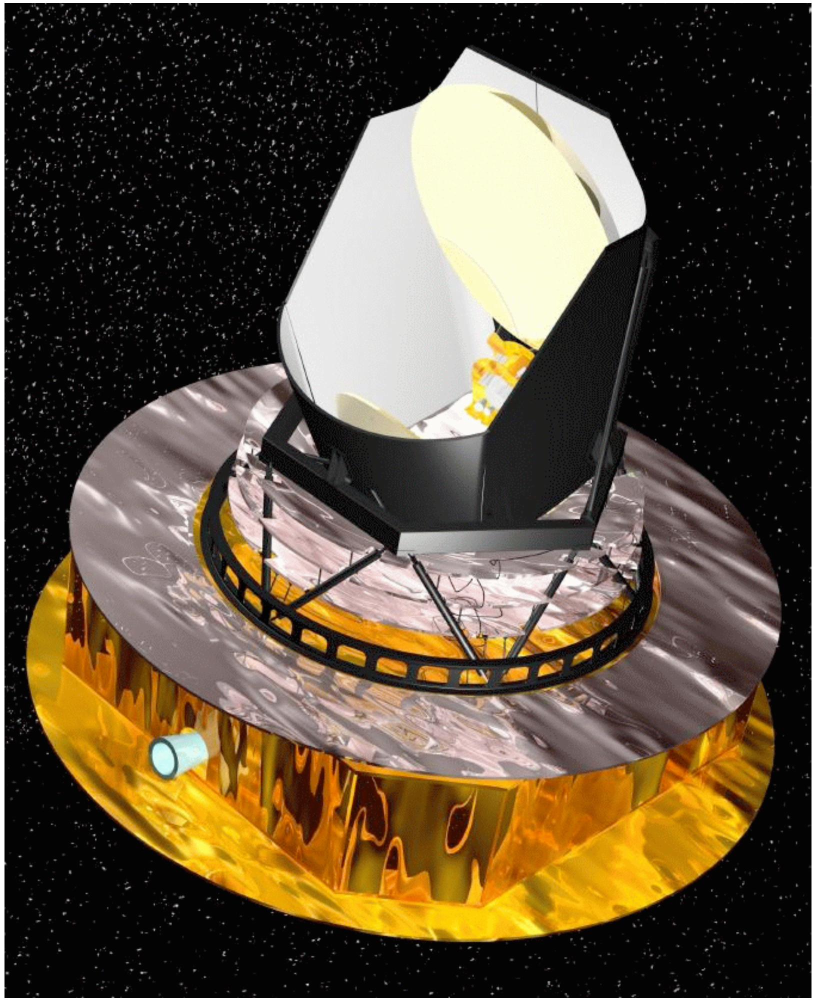
$t_0 = 13.7 \pm 0.2 \times 10^9$ yr now

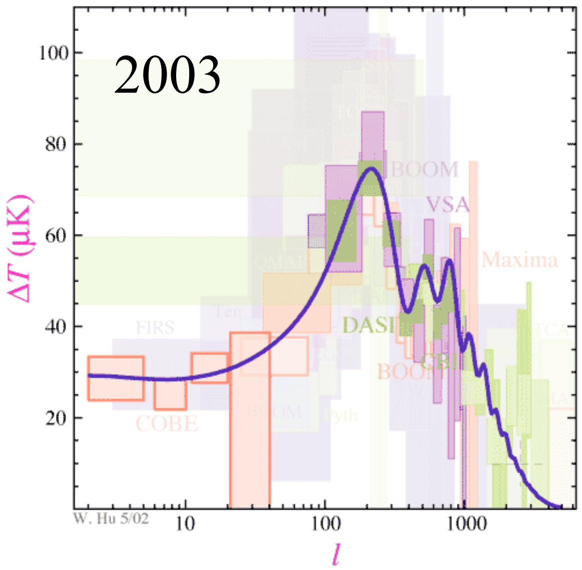
$t_* = 180^{+220}_{-80} \times 10^6$ yr $z_* = 20^{+10}_{-5}$ reionisation

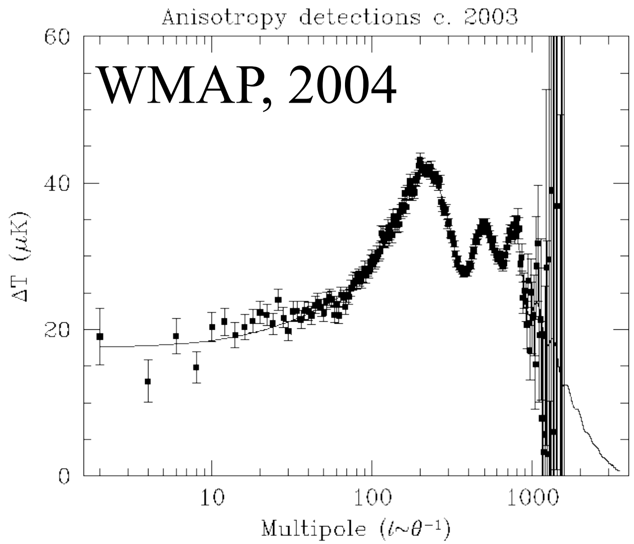
$t_R = 379 \pm 1 \times 10^3$ yr $z_R = 1090 \pm 1$ recombination

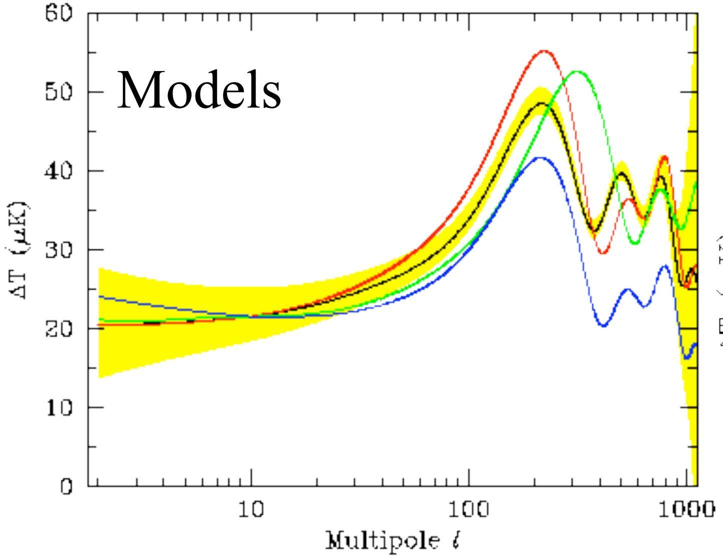
Planck

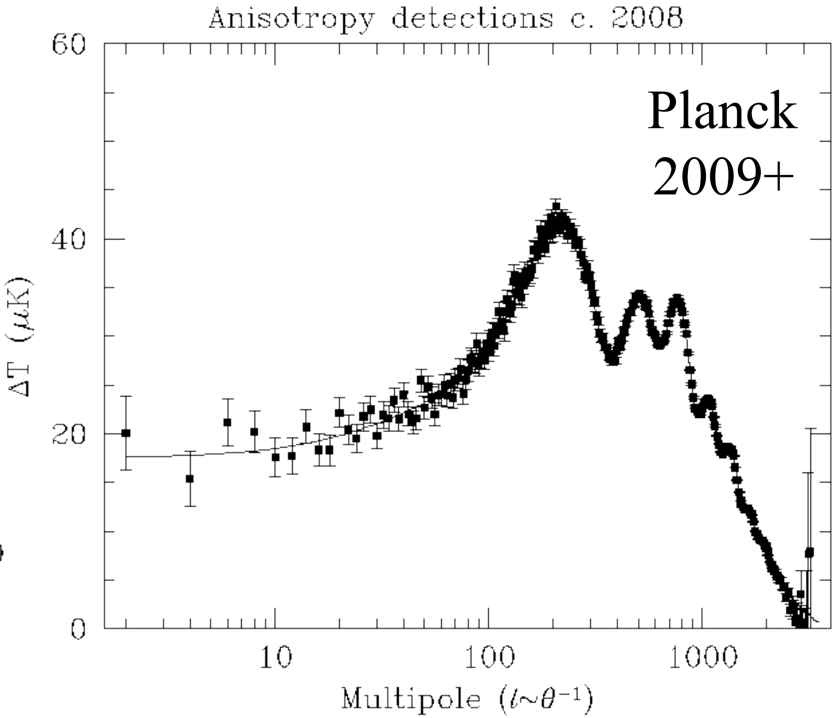
- Launched by ESA in 2009.




2003
ΔT (μK)
100
80
60
40
20
10
100
1000
l
W. Hu 5/02
BOOM
VSA
Maxima
DASI
FIRS
COBE

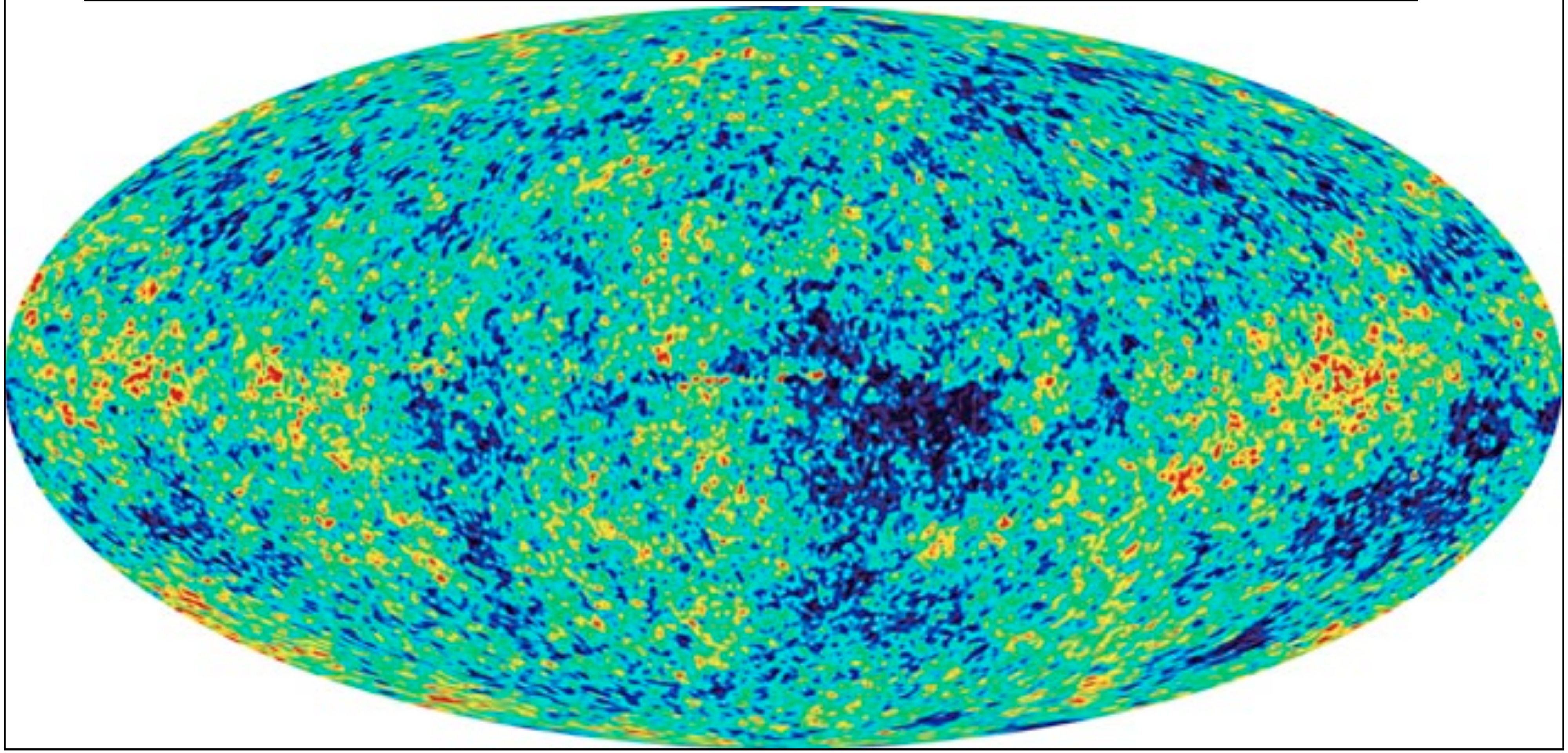

Anisotropy detections c. 2003
WMAP, 2004
60
40
20
0
ΔT (μK)
10
100
1000
Multipole (l~θ⁻¹)


Models
60
50
40
30
20
10
0
ΔT (μK)
10
100
1000
Multipole l


Anisotropy detections c. 2008
Planck
2009+
60
40
20
0
ΔT (μK)
10
100
1000
Multipole (l~θ⁻¹)

WMAP (and Planck) measure cosmological parameters to exquisite accuracy.

Anisotropies are the starting point for galaxy formation!



Large-Scale Structure formation

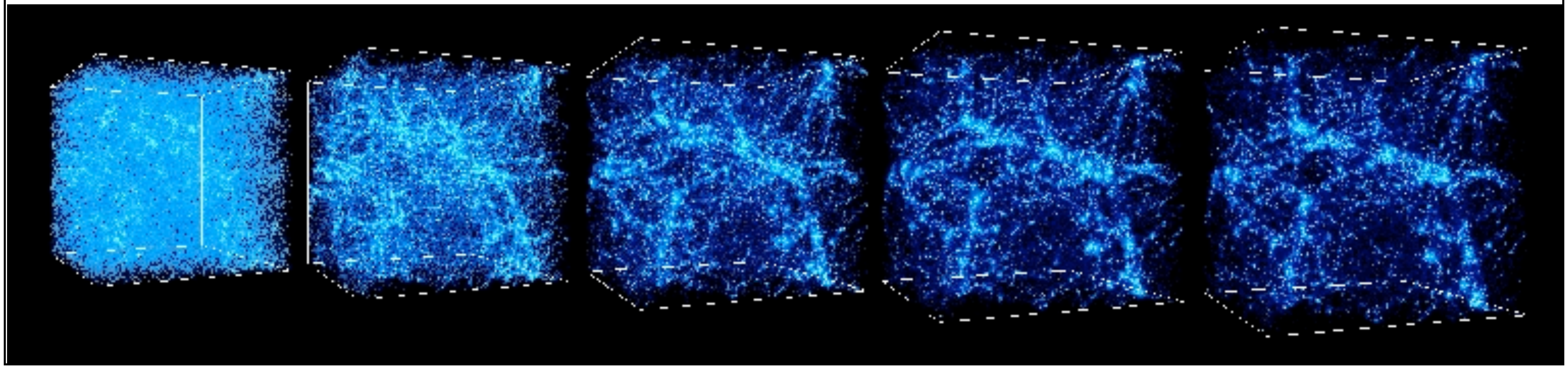
Simulations on supercomputers.

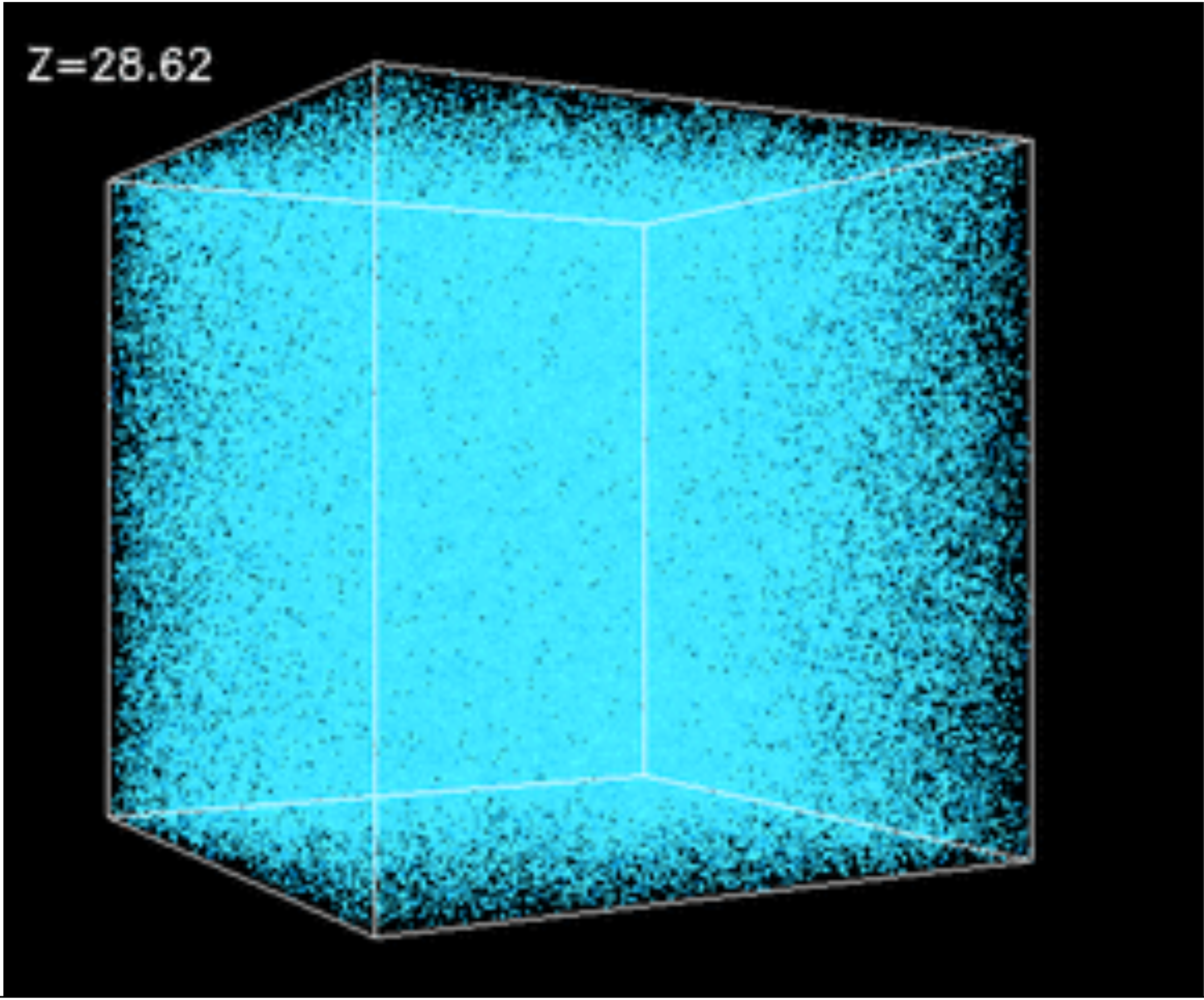
Up to ~10^{10} particles (Dark Matter) randomly placed then adjusted to match large scale anisotropies.

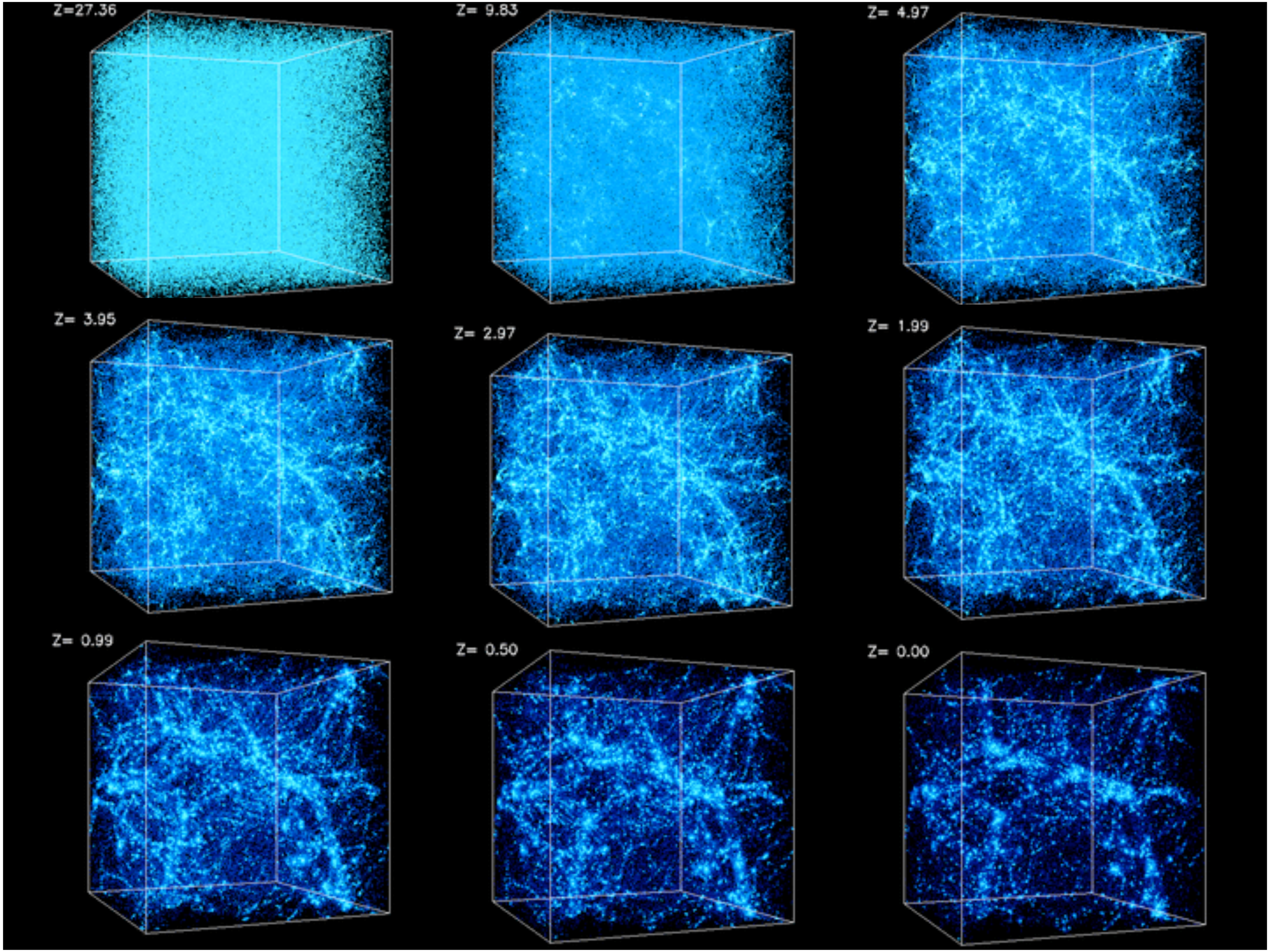
Gravitational accelerations computed.

Particle positions and velocities followed in time.

Box expands with *R(t)* appropriate for the assumed cosmological model.




Z=28.62


Z=27.36
Z= 9.83
Z= 4.97
Z= 3.95
Z= 2.97
Z= 1.99
Z= 0.99
Z= 0.50
Z= 0.00

The Cosmic Web

Large Scale Structure:

Like Soap Bubbles

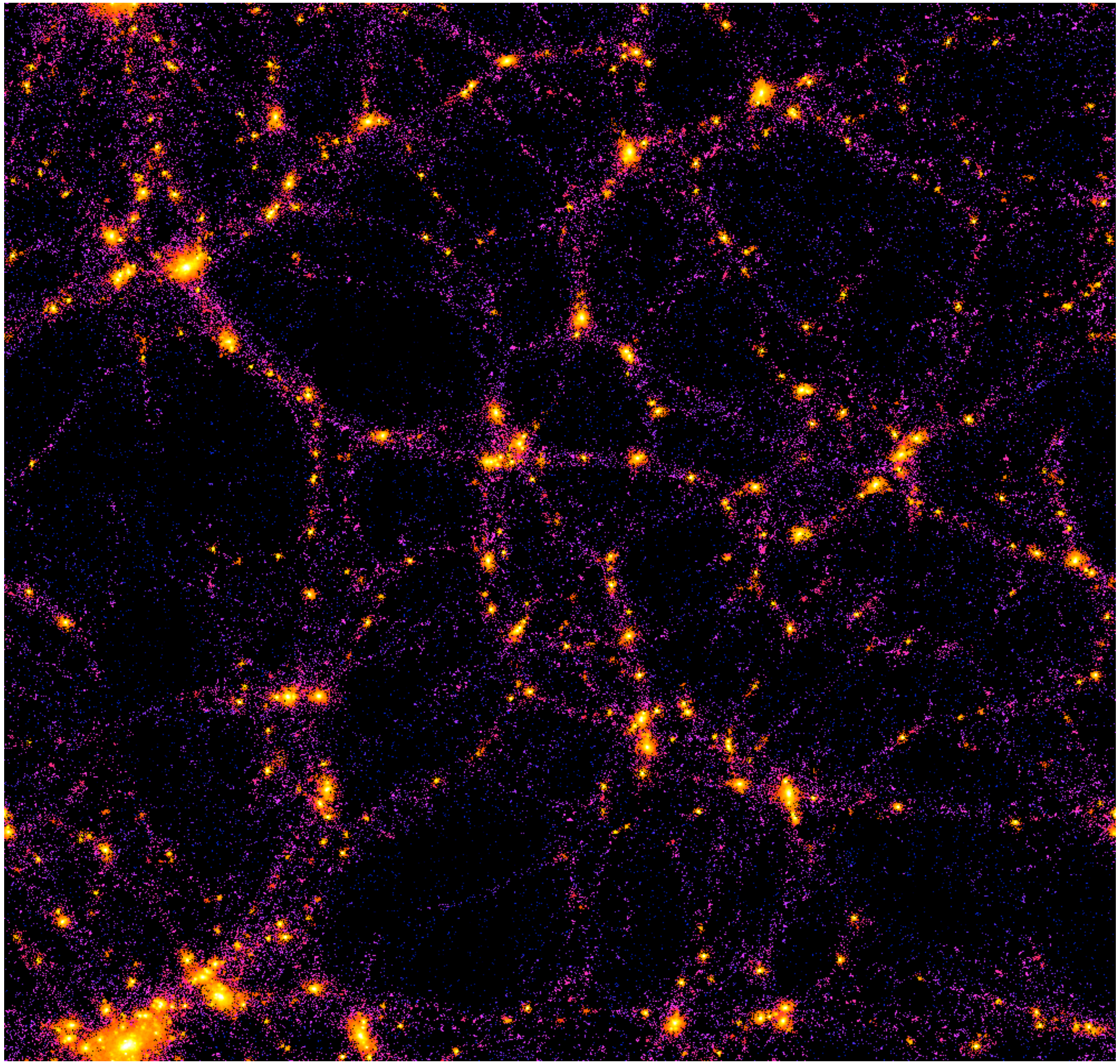
Empty **Voids**

~50Mpc.

Galaxies are in
1. **Walls** between voids.

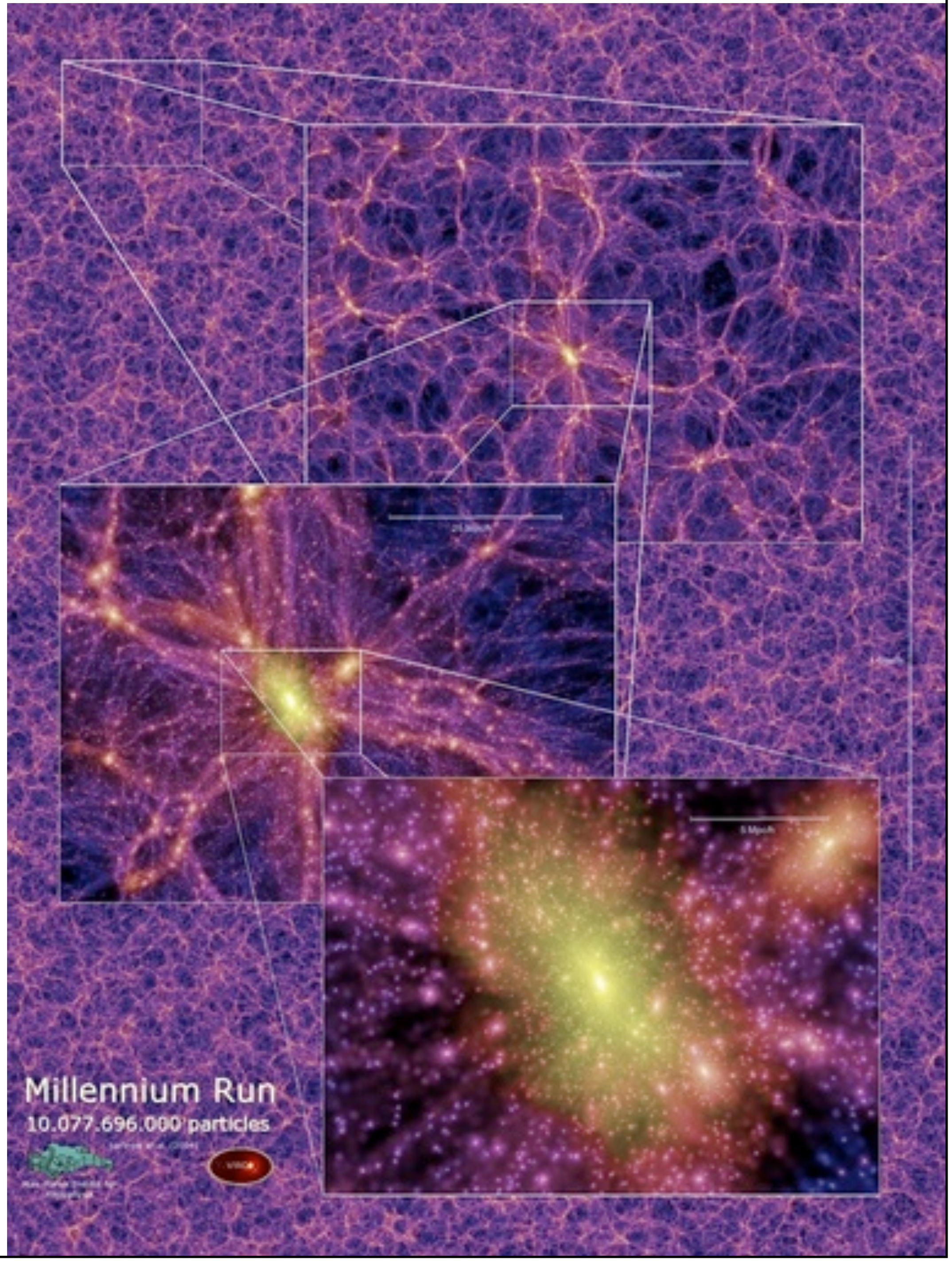
2. **Filaments** where walls intersect.

3. **Clusters** where filaments intersect.



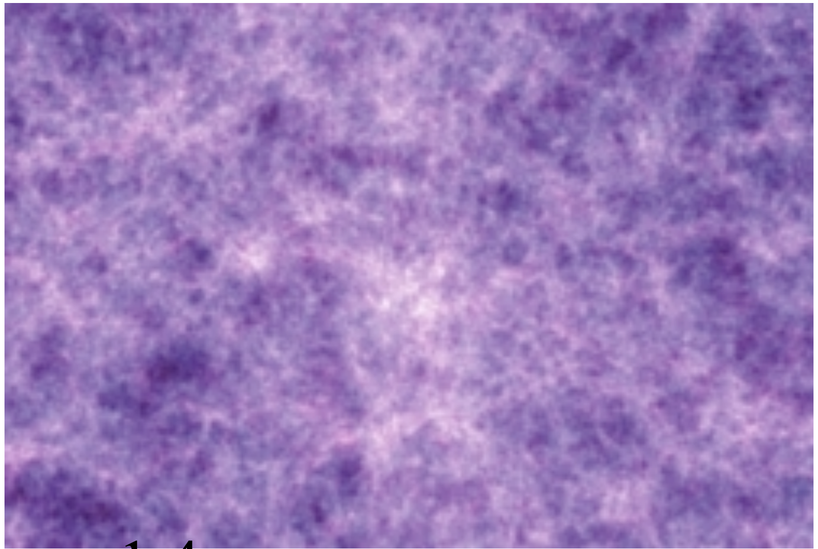
Consortium Millennium Simulation

- Hubble volume simulation.
- Close-ups of a galaxy cluster

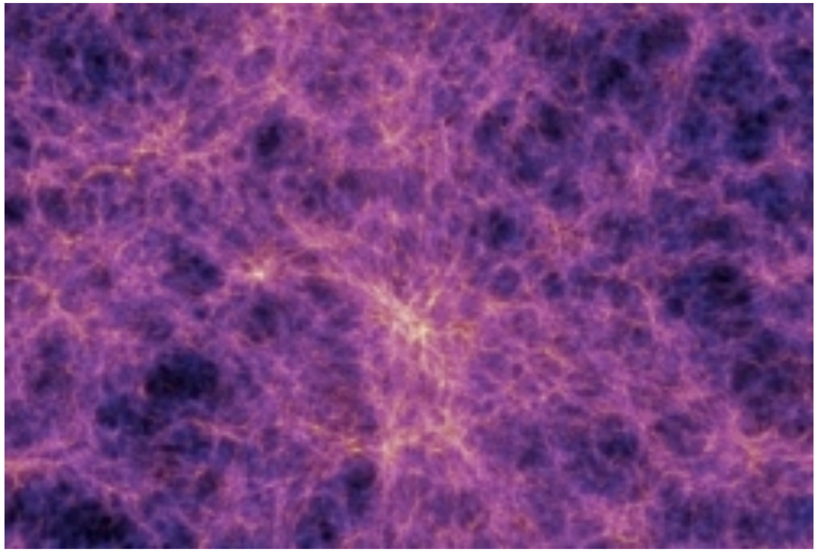


Millennium Simulation

$z = 18.3$



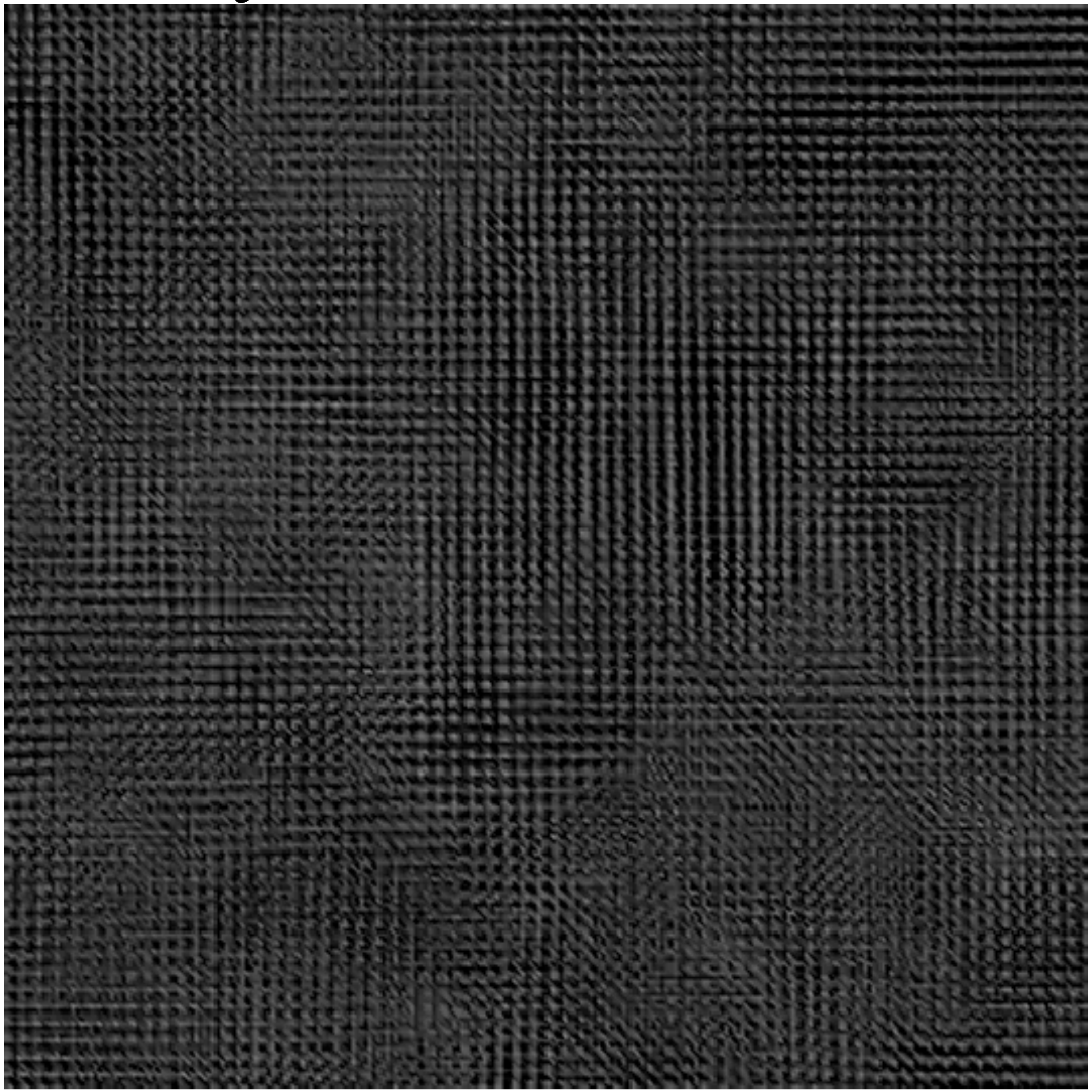
$z = 5.7$



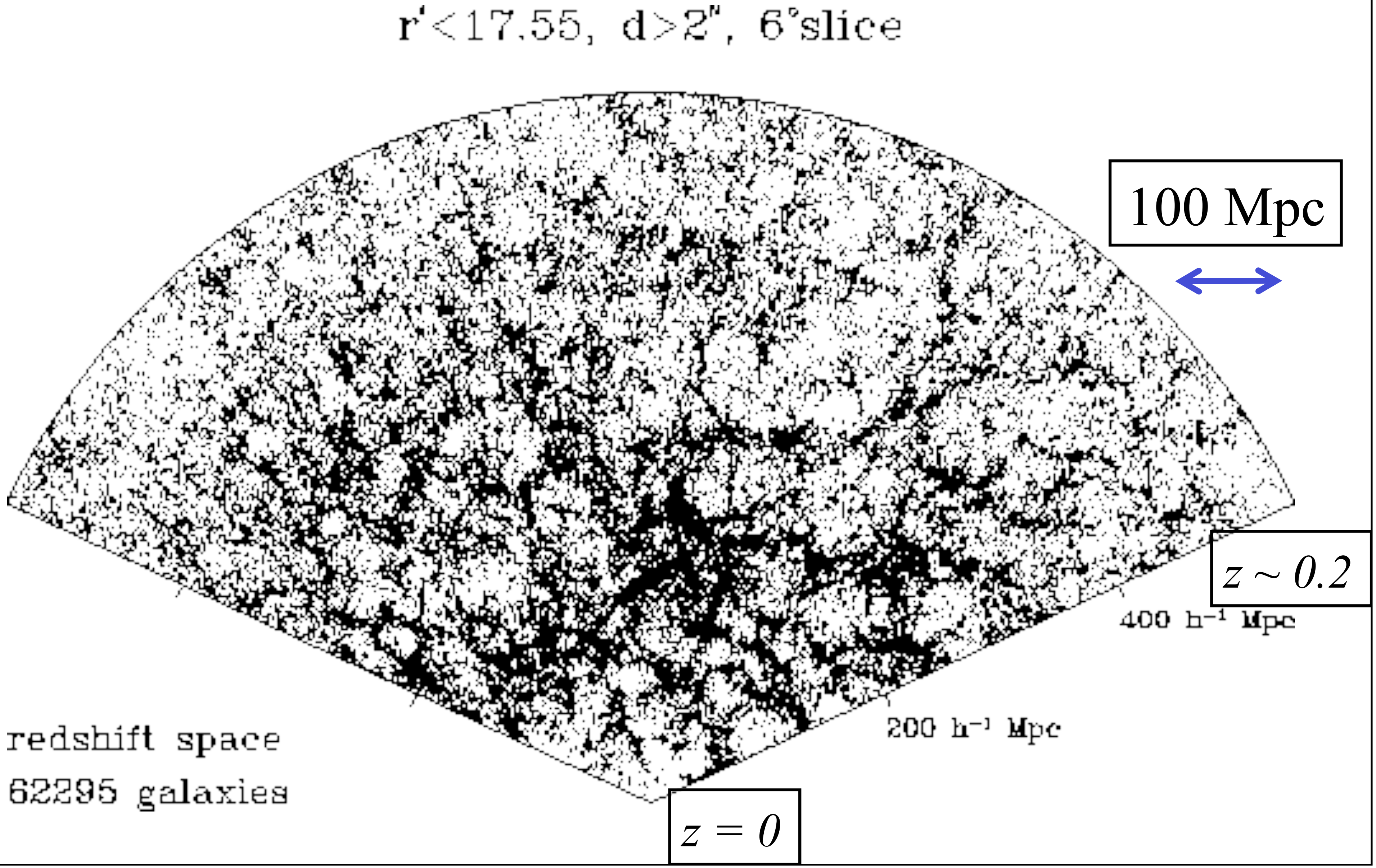
$z = 1.4$

$z = 0.0$

Galaxy Cluster Simulation



Galaxy Redshift Surveys



Galaxy Redshift Surveys

Large Scale Structure:

Empty **voids**

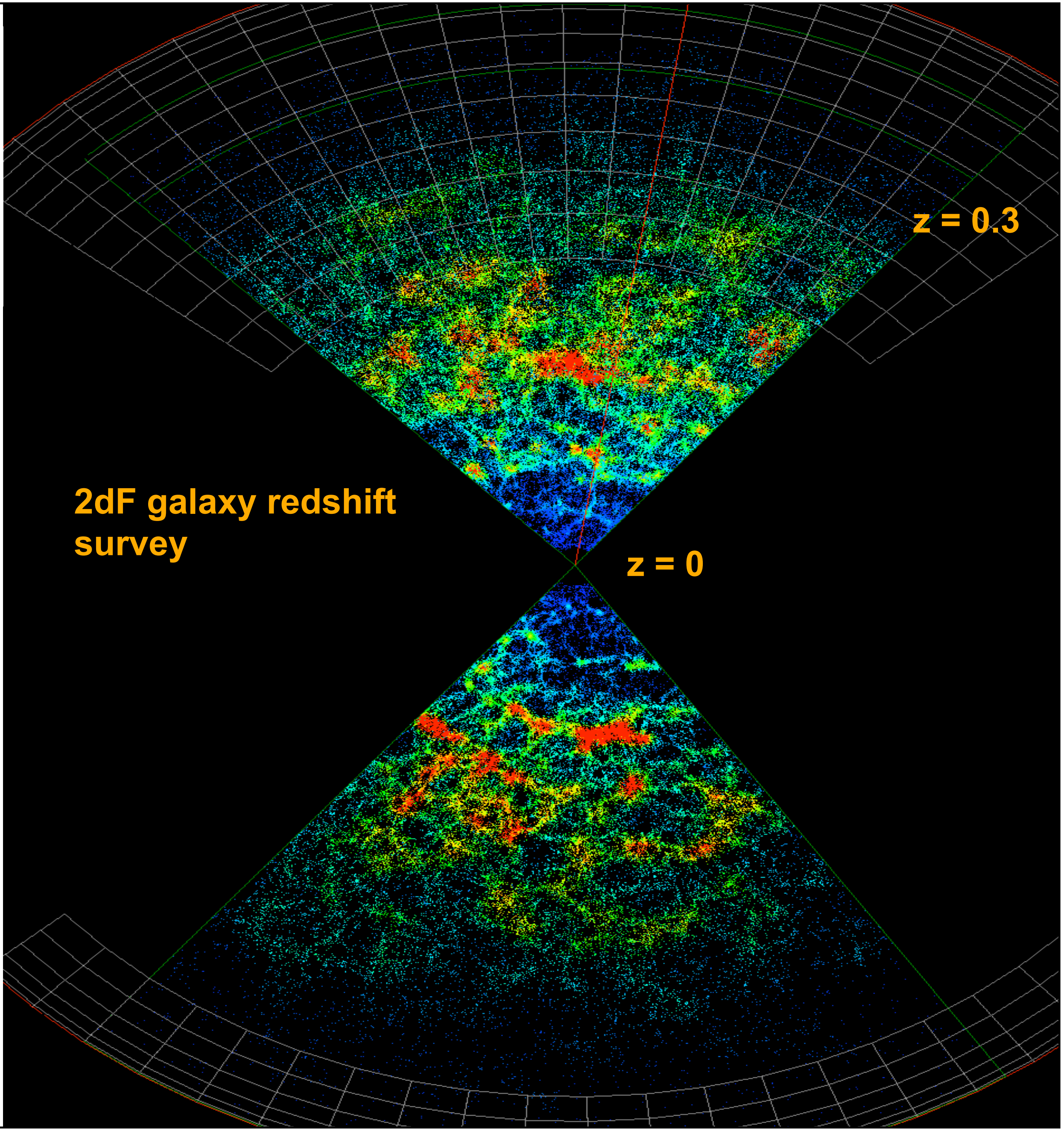
~50Mpc.

Galaxies are in
1. **Walls** between voids.

2. **Filaments** where walls intersect.

3. **Clusters** where filaments intersect.

Like Soap Bubbles !



Summary

- Observed CMB temperature anisotropies ($\Delta T/T \sim 10^{-5}$) give a snapshot of conditions on the surface of last scattering at $z=1100$.
- Three main effects give rise to $\Delta T/T$:
  Sachs-Wolfe ($\Delta T/T \sim -\Delta\rho/\rho$), Doppler ($\Delta T/T \sim V/c$)
  and Sunyaev-Zeldovich (Re-ionisation) effects.
- From the CMB Power Spectrum, most cosmological parameters are determined to a few percent. This determines the redshift-time relationship, $R(t) = 1 + z(t)$.
- Supercomputer simulations, with initial conditions from the CMB, tracking dark matter motions from low to high density regions, reveal the formation with redshift z of a bubble-like Large Scale Structure, a Cosmic Web, with voids, walls, filaments, and clusters.
- Similar structure is observed in the galaxy distribution derived from redshift surveys.