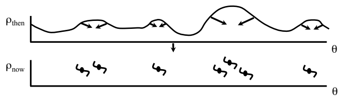
## *Lecture 5: Matter Dominated Universe: CMB Anisotropies and Large Scale Structure*

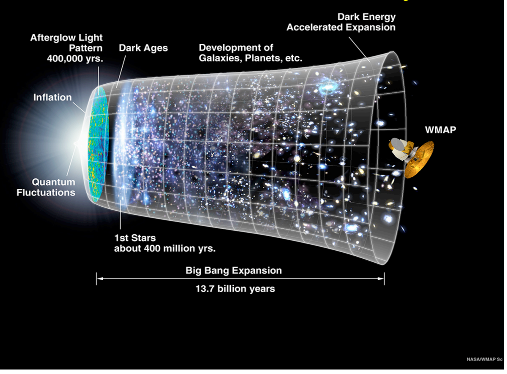
Today, matter is assembled into structures: filaments, clusters, galaxies, stars, etc.

*Galaxy formation is not completely understood.*

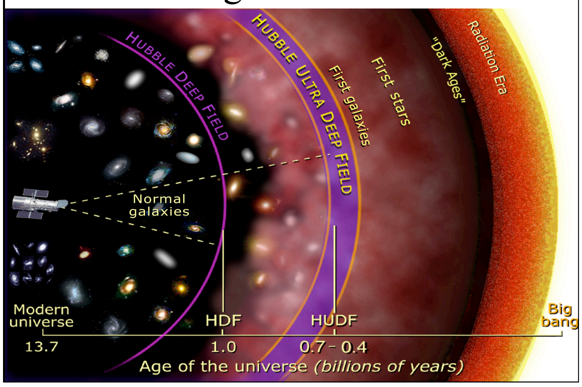
Main mechanism is gravitational instability:




## Overview of Cosmic History




## Looking Back in Time

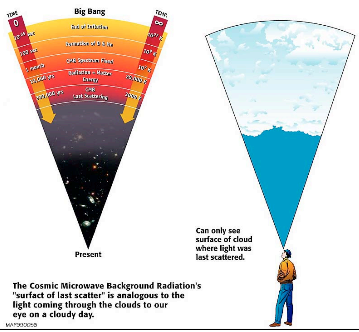



## ***Surface of Last Scattering***

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

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

Tiny CMB anisotropies.

The “ripples” in $T$ --> ripples in density.

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

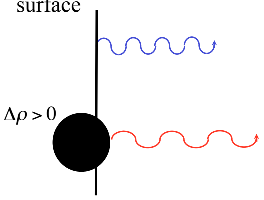
After decoupling, gravity amplifies these initial density ripples.

## *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

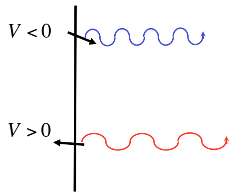
Photons from an over-dense region must climb out of the potential well, losing energy --> longer wavelength --> lower T.




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

## Doppler effect

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




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

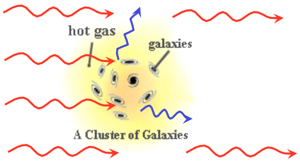
## Re-ionisation
### (Sunyaev-Zeldovich effect)

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

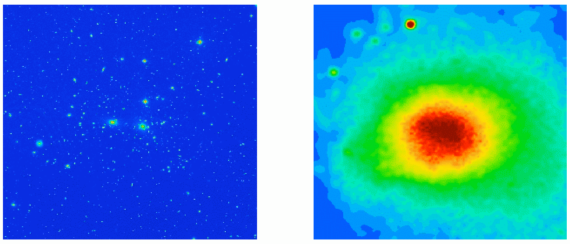
Once galaxy clusters form, gas falling in is shock-heated to X-ray temperatures (~$10^{6\text{-}8}$ K).

Free electrons liberated scatter CMB photons.

We see CMB silhouettes of the hot gas.

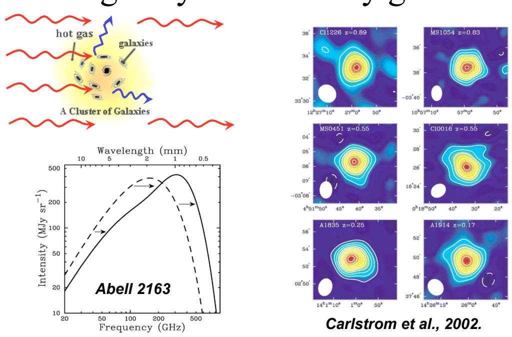



## Galaxy Clusters are filled with hot X-ray gas



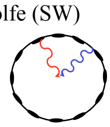
**optical (galaxies)** Coma cluster **X-ray (hot gas)**

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



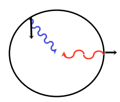

*Carlstrom et al., 2002.*

Sachs-Wolfe (SW) effect



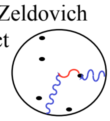
Mass distribution at recombination.

Doppler effect



Velocity distribution at recombination.

Sunyaev-Zeldovich (SZ) effect

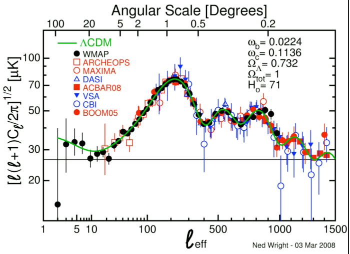


Ionised gas in intervening galaxy clusters.

## *Power Spectrum of CMB anisotropies*

Temperature ripple $\Delta T$ 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 |

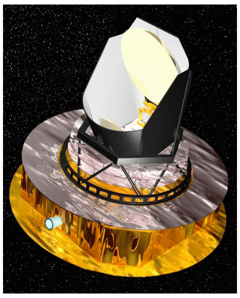
$t_0 = 13.7 \pm 0.2 \times 10^9$ yr — now

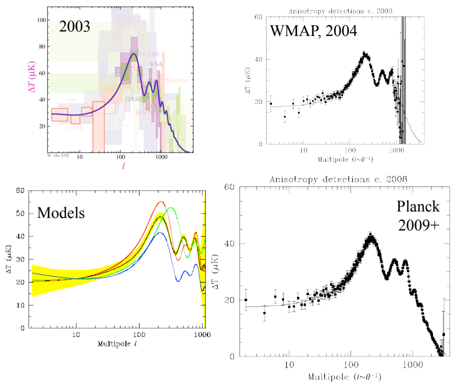
$t_* = 180^{+220}_{-80} \times 10^6$ yr $\quad z_* = 20^{+10}_{-5}$ — reionisation

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

## Planck

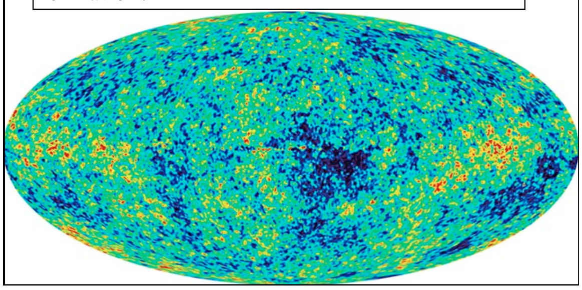
- Launched by ESA in 2009.






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

Anisotropies are the starting point for galaxy formation!



## *Large-Scale Structure formation*

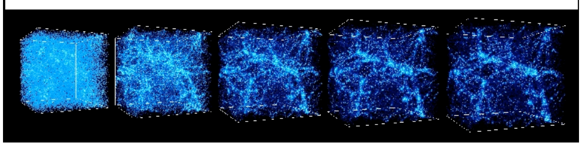
Simulations on supercomputers.

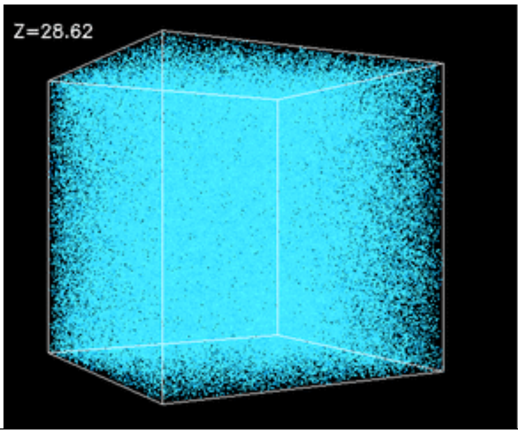
Up to $\sim 10^{10}$ particles (Dark Matter) randomly placed then adjusted to match large scale anisotropies.

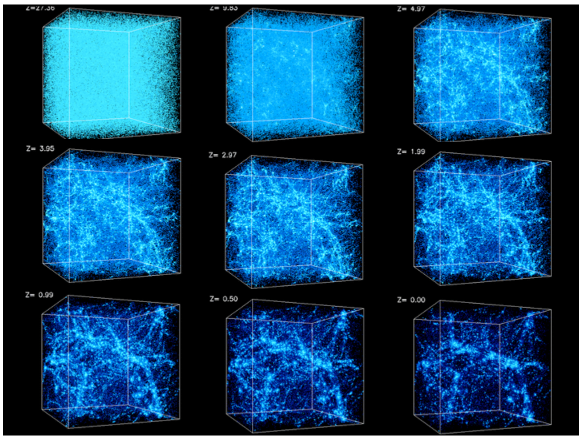
Gravitational accelerations computed.

Particle positions and velocities followed in time.

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






# The Cosmic Web

**Large Scale Structure**:

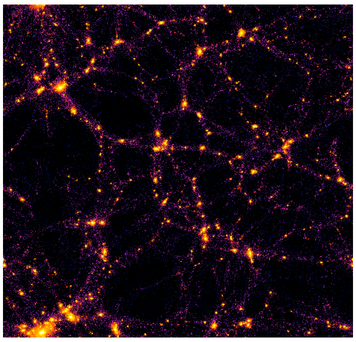
***Like Soap Bubbles***

Empty **Voids**

~50Mpc.

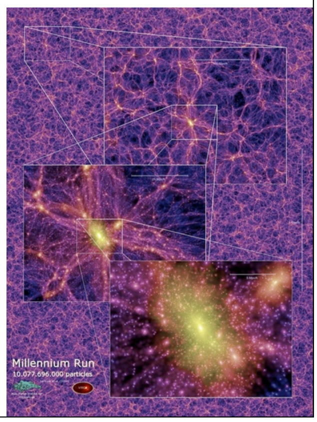
Galaxies are in

1. **Walls** between voids.
2. **Filaments** where walls intersect.
3. **Clusters** where filaments intersect.



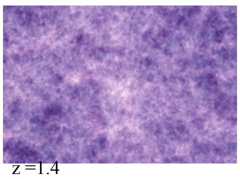
# VIRGO Consortium Millennium Simulation

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

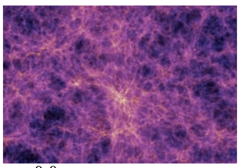



# Millennium Simulation

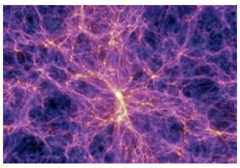
z = 18.3



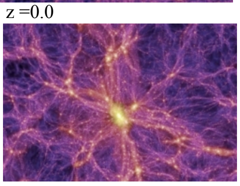
z = 5.7



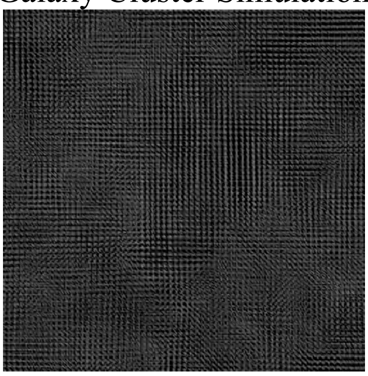
z =1.4



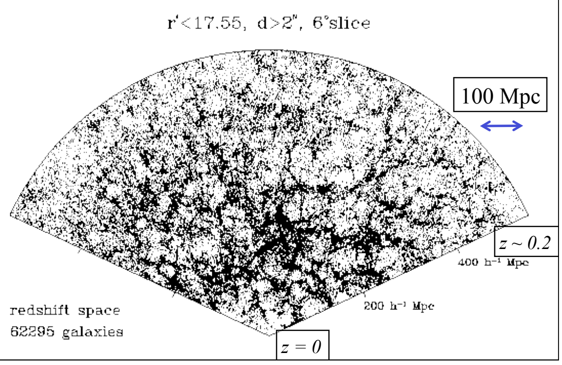
z =0.0



# Galaxy Cluster Simulation



## *Galaxy Redshift Surveys*




## Galaxy Redshift Surveys

**Large Scale Structure**:

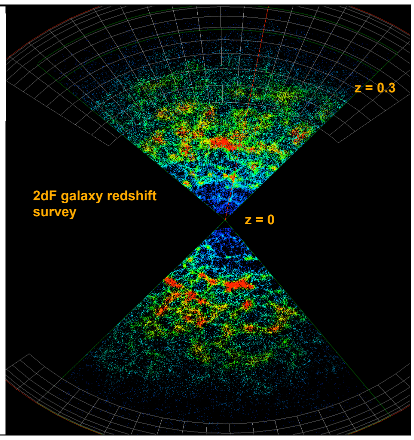
Empty **voids**

~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.