Cosmology and Large Scale Structure

Prof. Kevin Huffenberger
Dept. of Physics
Expanding universe & the Big Bang
In Fornax, $11.0 \text{ arcmin}^2$

$1 \text{ mm}^2 @ 1 \text{ m}$

13 million such patches to cover sky.
CMB fluctuations

\[ \sim \text{few hundred } \mu K \text{ around mean } T \]
Probing gravitational potential

Overdensity

Recombination

Potential

cold photon!
Cosmic Web

On the largest scales, single galaxies, groups, and clusters are most common along filamentary structures called the cosmic web.

Galaxies tend to avoid the voids.

Structure is natural consequence of gravitational collapse from Big Bang initial conditions, and can be simulated on a computer.
Cosmic web
Cosmological matter simulation

$z = 27.36$  Universe 120 million years old
$z = 9.83$  Universe 490 million years old
$z = 4.97$  Universe 1.2 billion years old

$z = 2.97$  Universe 2.2 billion years old
$z = 0.99$  Universe 6.0 billion years old
$z = 0.00$  Universe 13.7 billion years old

Figure 27-15
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Leo cluster

~ 100 Galaxies
330 Mly away
Coma cluster

~ 1000 galaxies
320 Mly away
$10^{14}-10^{15}$ solar masses
Virgo cluster

~ 1500 Galaxies
54 Mly away
10^{15} solar masses
The Dark-Matter Problem

- Visible mass in galaxy clusters too small for galaxy motions.

Need large amounts of dark matter.

Gravitational lensing by a cluster gives information about the distribution of matter in the foreground cluster.
Luminous matter insufficient to explain galactic motions in clusters
How gravitational lensing happens

Figure 24-30a
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Lensing

All of these blue arcs are images of the same distant galaxy.
Clusters with strong lensing arcs
Mass map

Coe et al 2010
Lensing mass map

Remember this one!
CMB lensing

observed

cosmic web

at

z \sim 2-3

background
CMB

(Hu & Okamoto 2001)
CMB lensed

(Hu & Okamoto 2001)

foreground mass

sky no longer isotropic
Cluster X-rays

The large accumulation of matter in a galaxy cluster makes a very deep gravitational potential well.

Gas falls in from outside, collides with cluster gas, heats to millions of degrees.

Glows in X-rays.
X-rays observed by satellite

Chandra

XMM-Newton
ROSAT
Integral...
Coma cluster

Virgo cluster
"Bullet cluster"

X-ray data
Chandra 0.5 Msec image

1E 0657–56

z=0.3

0.5 Mpc
Bullet cluster

Composite image of galaxy cluster 1E0657-56 showing visible galaxies, X-ray-emitting gas (red) and dark matter (blue)

Figure 24-32a
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Bullet cluster model

1. Two galaxy clusters approach each other

2. The two clusters begin to collide

3. Fluid resistance slows the gas down...

4. ...but the dark matter keeps on moving

Cluster 1
Cluster 2
Cluster 1 gas
Cluster 2 gas
Cluster 1 dark matter
Cluster 2 dark matter

A model of how the gas and dark matter in 1E0657-56 could have become separated

Figure 24-32b
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Sunyaev-Zeldovich effect

- ~ 3K photon
- 3K + δ photon

Galaxy cluster (100-1000 gal.)

Hot gas \( T \sim 10^8 \, \text{K} \)
SZ distorts CMB blackbody

Benson et al. (2003)

\( \tau = 0.01, \ T = 10 \ \text{keV} \)
Ground / balloon based telescopes

Atacama Cosmology Telescope

QUiet telescope

Boomerang

South Pole Telescope
Coma in SZ, by Planck

Planck early data:
~30 New cluster candidates,
~20 confirmed

ACT + SPT (to date): ~ 50-60 confirmed