Galaxy Clusters

- Contain 10% of all galaxies
- Dark matter dominated (M/L > 100)
- Galaxy evolution different in clusters
- Tracers of growth and evolution of large scale structure
  - “Easily” identified at high z
Galaxy Clusters

- Early work of Abell (1958) → optical plates
- “Richness”
  - # of galaxies brighter than 2 magnitudes fainter than the 3rd brightest member → proportional to total # of galaxies in cluster
  - Compactness → within 1.5 Mpc (average separation between galaxies ~ 5 Mpc)
- \( N(R>1) = 10^{-5} \text{ Mpc}^{-3} \)
- Clusters correlated on scales ~26 Mpc
Basic Properties

- Mass $\sim 10^{15} \, M_\odot$
- Velocity dispersion $\sim 1000 \, \text{km s}^{-1}$
- Radius $\sim$ few Mpc
- Population $\sim$ few 100 galaxies
  - Schecter LF defined from galaxy clusters
Identifying clusters – spectroscopy
Identifying clusters – X-rays
Cluster Types

- **Spiral–rich**
  - E:S0:S → 1:2:3 → similar to field
  - Asymmetric structure

- **Spiral–poor**
  - E:S0:S → 1:2:1

- **Centrally dominant (cD)**
  - 1,2 dominant galaxies (ellipticals)
  - Few spirals (< 20%)
  - Spherical distribution of galaxies
Cluster Evolution

- Butcher–Oemler Effect
  - Moderate z clusters have large populations of blue galaxies
    - More AGN
    - More starbursting galaxies
    - “E+A” galaxies
Cluster Evolution

- Butcher–Oemler Effect
  - Moderate $z$ clusters have large populations of blue galaxies
    - More AGN
    - More starbursting galaxies
    - “E+A” galaxies
  - Higher velocity dispersions
  - Less centrally concentrated
Clusters as Isothermal Spheres

- Hydrostatic equilibrium
  - \( \frac{dp}{dr} = - \frac{GM\rho}{r^2} \)
  - \( M = \int 4\pi r^2 \rho(r) dr \Rightarrow dM = 4\pi r^2 \rho(r) dr \)
  - \( \frac{d}{dr}(r^2/\rho \ dp/dr) + 4\pi Gr^2 \rho = 0 \)

  - Assume:
    - Ideal gas law \( p = \rho k_B T/\mu \) (\( \mu = \text{mean mass} \))
    - \( 3/2 \ k_B T = \frac{1}{2} \mu v^2 \)
Isothermal Spheres

- Density profile $\rho(r) = \Sigma A_n r^{-n}$
- Central density $\rho_0 = (9v^2)/(4\pi GR^2 \sqrt{1/2})$

Ideal gas $p = \rho k_B T/\mu m_H$, so...

$$(\rho k_B T/\mu m_H)[(1/\rho)(d\rho/dr)+(1/T)(dT/dr)] = -(GM(<r)\rho)/r^2$$

thus, mass goes as $T$, $\rho$ and X-ray luminosity depends on density and temperature
Some numbers

- Cluster masses
  - Galaxies $\rightarrow 10^{12} - 10^{14} \, M_\odot$
  - Gas $\rightarrow$ few times $10^{12} -$ few times $10^{14}$
  - Gravitational $\rightarrow 10^{13} - 10^{15} \, M_\odot$
  - More mass in gas than stars, dark matter dominated !!!!!
Compton scattering optical depth
- \[ y = \int \left( \frac{k_B T}{m_e c^2} \right) \sigma_T N_e dl \]

Decrement in Rayleigh–Jeans region of spectrum
- \[ \frac{\Delta I}{I} = -2y \rightarrow \sim 10^{-4} \]

Hot gas from clusters affects microwave background \( \rightarrow \) best measured in radio part of the spectrum \( \rightarrow \) search tool for distant clusters
S–Z Effect

- CMB + hot plasma $\rightarrow$ Compton scattering $\rightarrow$ distortions in the CMB
- Source of hot plasma? Galaxy clusters
- Distortion of the BB spectrum dominated by:
  - $y = \sigma_T \int n_e (kT_e / m_e c^2) dl$
    - $\sigma_T$ is the Thompson cross section
  - Integral is along line of sight
  - Recall $T_e$ is a function of cluster mass
- Map large scale structure, find clusters, measure cluster masses
- Detection via radio continuum observations
Superclusters

- The Peculiar Velocity Field and the Great Attractor
  - Motions: Earth, Sun, Milky Way, Local Group, Virgo!!!!
    - The observed motion of the Virgo Cluster implies something extremely massive in the direction of the southern Milky Way → The Great Attractor

- Observed Superclusters
  - There are collections of clusters in the nearby Universe (Perseus–Pisces ridge); usually not spherical (like individual clusters)

- Finding the Great Attractor