Outline

- Go over AGN growth problem
- Groups and clusters
- How to measure the mass of clusters
- Large scale structure

Homework

- AGN growth problem

A supermassive black hole at the nucleus of a galaxy accretes at the Eddington luminosity with the efficiency of a maximally rotating black hole, $\eta = 0.42$. Find an expression for the mass of the black hole as a function of time – note that the Eddington luminosity changes as the black hole mass changes. How much time is needed to grow a 10^9 solar mass black if one starts with a 10 solar mass black hole?

Why would the black hole be (near) maximally rotating?

Groups and Clusters

- Galaxies are found in collections ranging from an individual, isolated galaxies to massive clusters with many thousands of members.
- Groups are usually defined as containing fewer than about 50 galaxies within a volume about 1 Mpc across, cluster are more than 50 galaxies typically spread across a larger volume.
- Many nearby galaxies that are members of the “Local Group” are very small and dim and would be impossible to detect even at distances of a few Mpc. Thus, strict counting of all the galaxies in a group/cluster is not feasible. Typically a “group” will have several galaxies with stellar luminosities similar to the Milky Way and a larger, but poorly determined number of smaller galaxies.

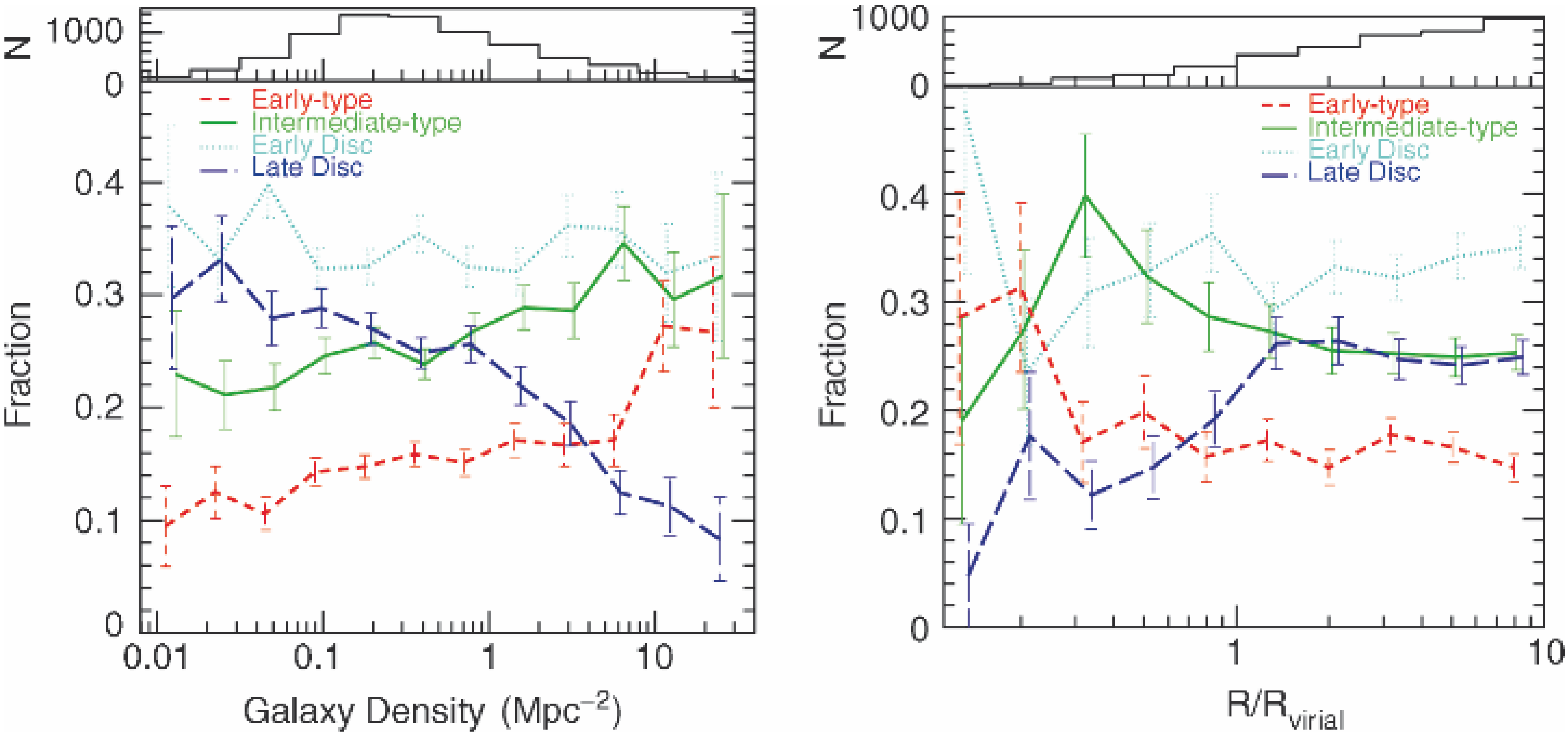
Nearby Groups and Clusters

- There are a number of other groups of galaxies that are neighbors to the local group, most have 2-4 large galaxies and are named for the largest galaxy.
- The M81 group contains M81, M82 (starburst), NGC 2403, and a number of smaller galaxies, currently 34 known. Several of these galaxies are interacting (notably M82 and M81) and have active star formation.
- Closest cluster is the Virgo cluster at 16 Mpc, with 250 large galaxies that cover a patch about 8 degrees across on the sky. Virgo is an irregular cluster and has 3 “sub clumps”.
- The closest massive cluster is Coma at ~100 Mpc, with ~1000 large galaxies. Coma is a “regular” cluster (smooth galaxy distribution with no sub-clumps) and is classified as a “rich” cluster.

A "Typical" Cluster

- There is a wide range in size and mass of clusters.
- We'll take as "typical" a cluster with 100 L* galaxies, size r = 1 Mpc, and velocity dispersion σ = 1000 km/s.
- "Cluster crossing time scale" = time it takes for a galaxy to cross the cluster
  - $\tau = r/\sigma = 3\times10^{24}$ cm/(10^{8} cm/s) = 3×10^{16} s = 10^{9} years.
- This is older than the typical ages of clusters (or galaxies), thus clusters are
  - gravitationally bound
  - relaxed – galaxies are gas are in thermal equilibrium
- Enhanced density of galaxies decreases time between interactions to a few Gyr. Thus, galaxies are likely to have interacted.

Morphology versus density



- Galaxy morphology is correlated with local density of galaxies and location in cluster (virial radius is a measure of the cluster size).
- This likely shows effect of interactions on galaxy evolution, but could be due to ram pressure striping removing gas from galaxies in dense regions.

Other cluster components

- Intergalactic or “rogue” stars – stars not associated with a particular galaxy. Thought to be stars ejected in galaxy-galaxy interactions.
- Gas clouds – HI clouds with masses up to 10^8 $M_{\rm Sun}$ and dynamical masses up to 10^9 $M_{\rm Sun}$ with nothing in the visible/UV/IR bands, i.e. no stars. May be primordial gas clouds similar to those from which galaxies formed.
- Hot, 10^7- 10^8 K, X-ray emitting plasma – the dominant form of baryonic matter in most rich, regular clusters.
- Dark matter

Cluster Mass

Three ways to determine cluster mass

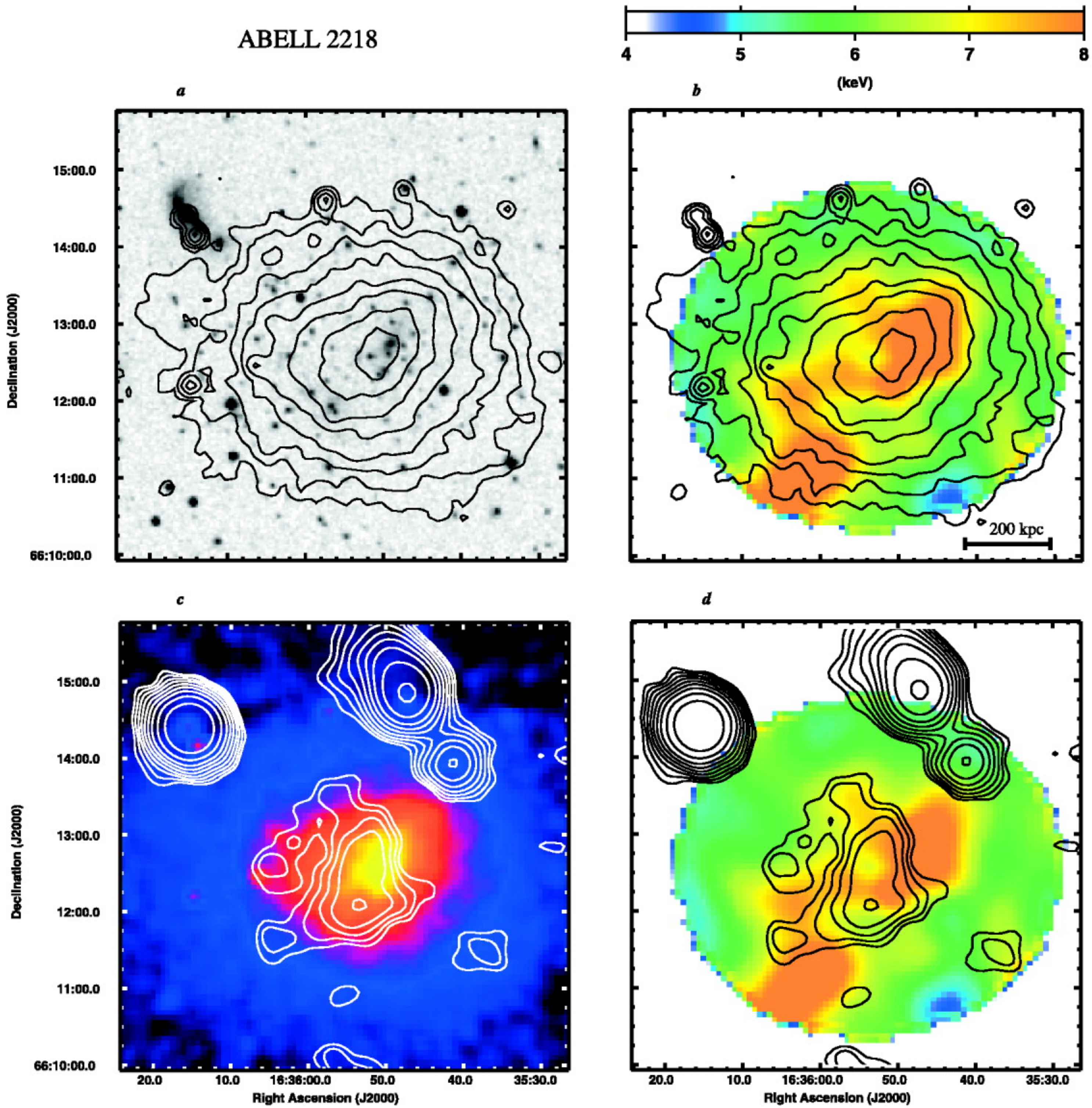
- Orbits of galaxies
- Gravitational lensing
- X-rays from hot gas

- Do orbits of galaxies on board

Gravitational Lensing

Optical image of Abell 2218

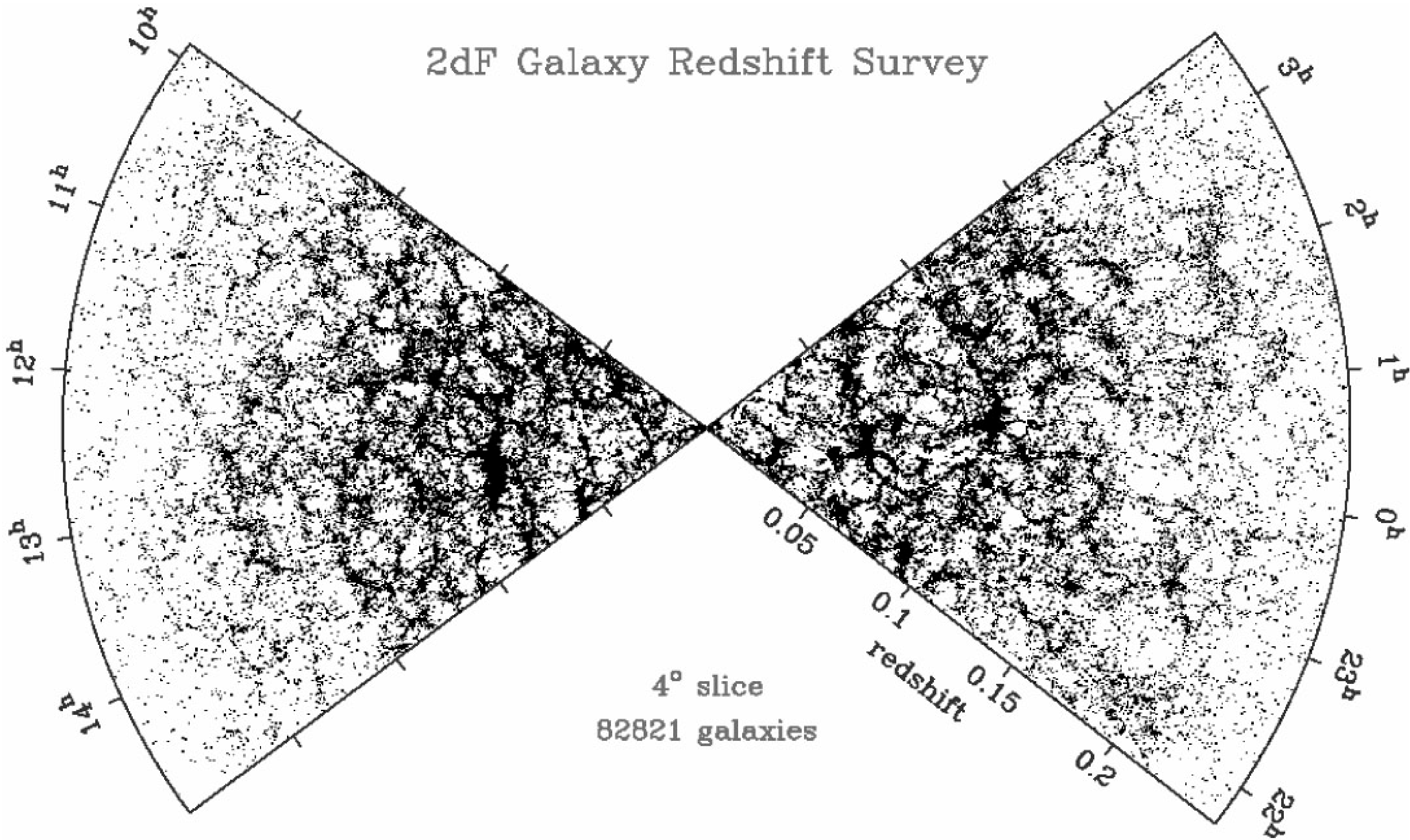
Hot Gas

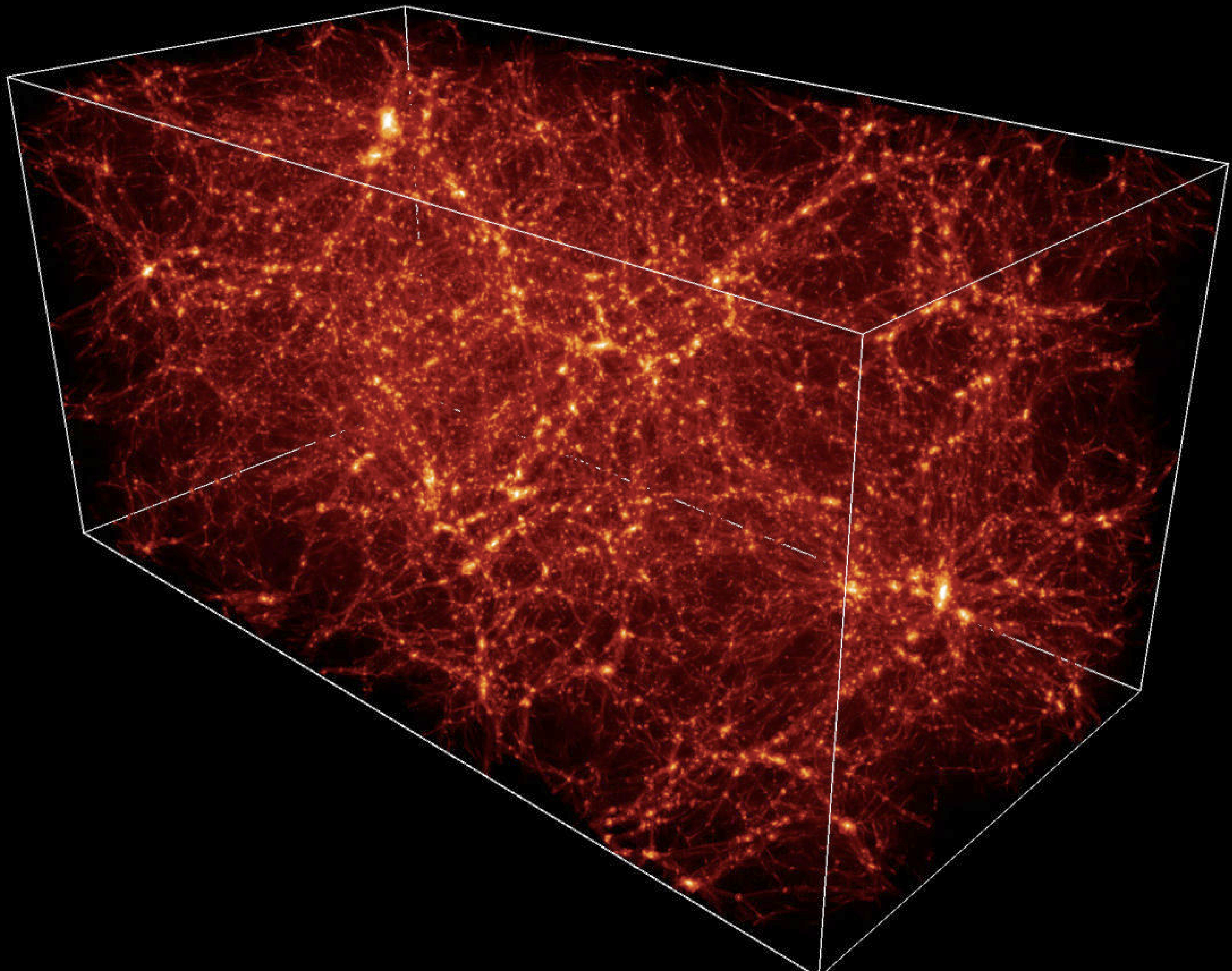


Mass:

- 1-2% stars
- 13% gas
- 85% dark

Large Scale Structure





Homework

- For next class: problem 6.6