Outline

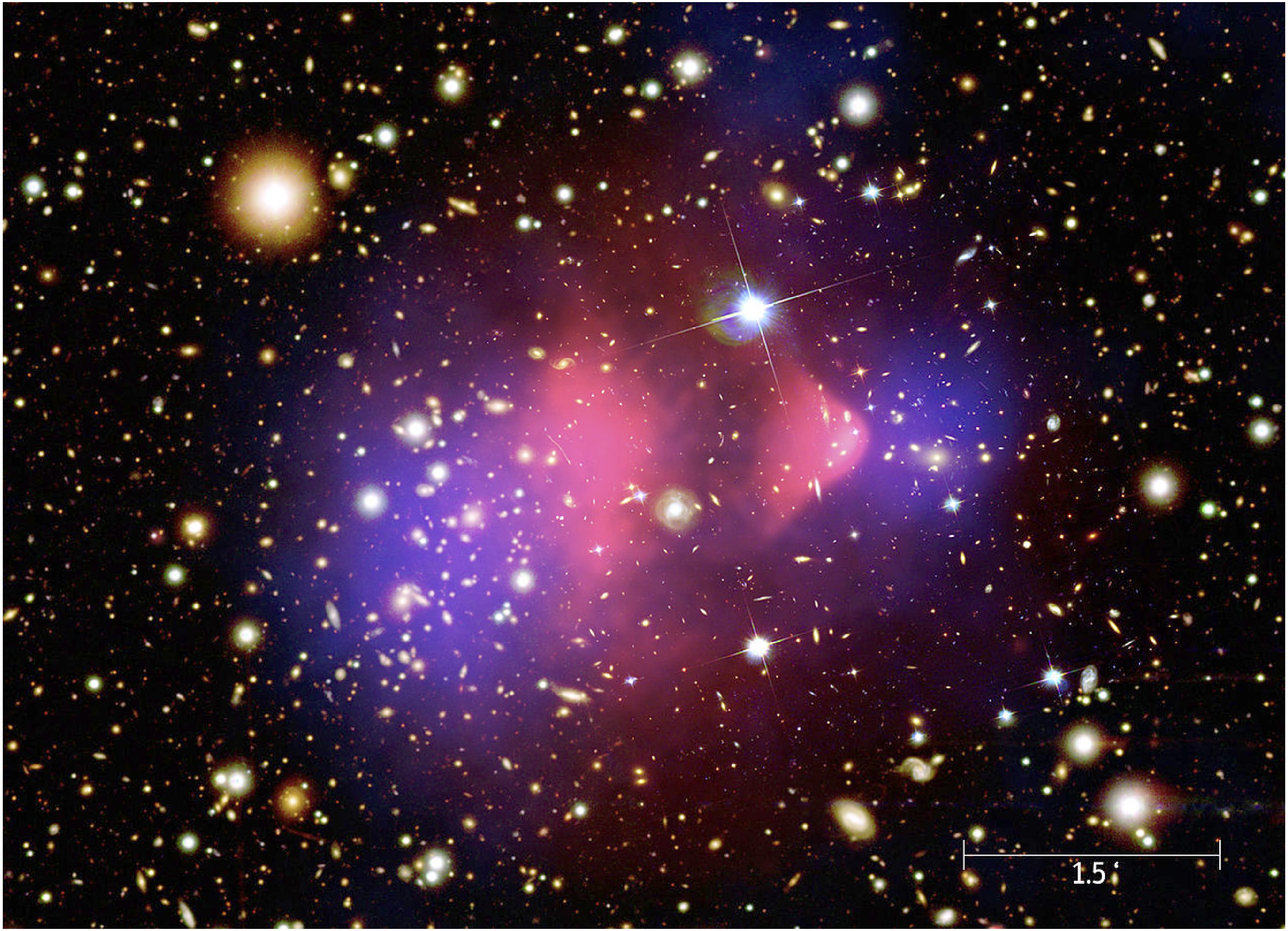
- Finish up dark matter
  - Elementary particles
  - Modified gravity
- Galaxies
  - Types
  - Luminosity function
  - Collisions

Dark Matter

- Elementary particles
  - Neutrinos – can calculate number of expected neutrinos from cosmology, analogous to cosmic microwave background. Neutrinos do not contribute sufficient mass unless the individual particles are massive. Recent suggestions of 3.5 keV X-ray line from clusters of galaxies suggesting 7 keV neutrino.
  - Weakly interacting massive particles (WIMPs) – WIMPs of in GeV to TeV mass range solve both dark matter problem and explain mass of Higgs boson. Searching for at LHC and in direct detection experiments (LUX, Xenon1T).
  - Axions – predicted to solve problem in QCD. Convert to photons with sufficient strong magnetic field. Searching for at Axion Dark Matter Experiment.

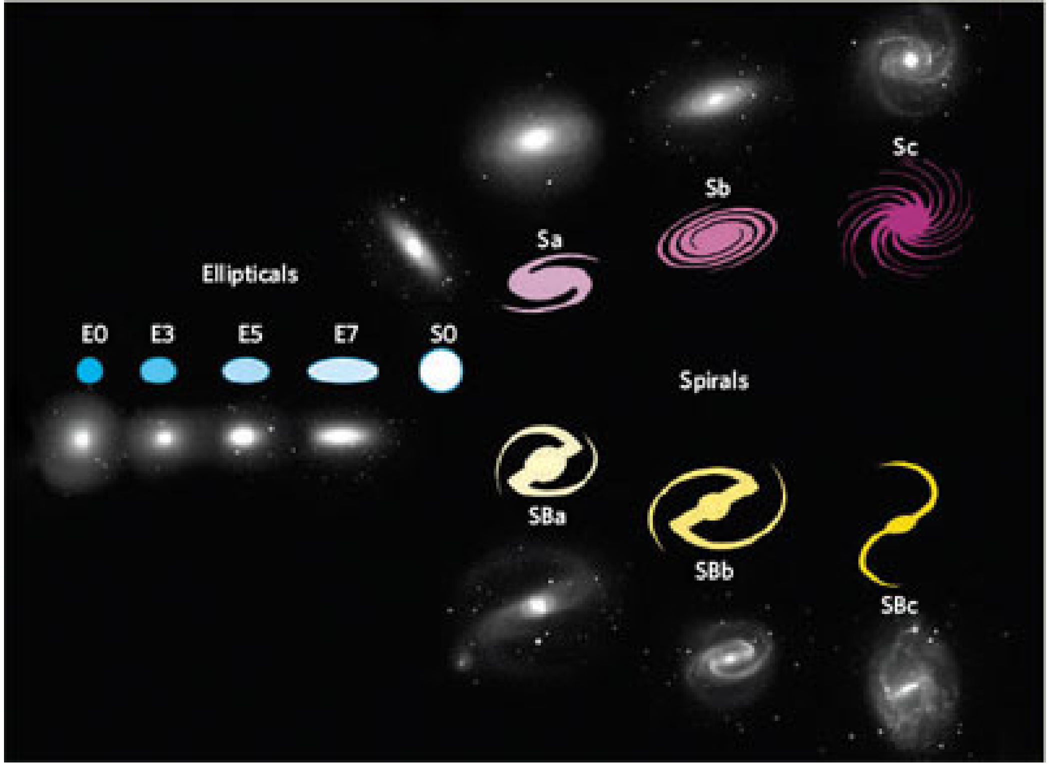
Modified Gravity

- Modified gravity – maybe Newton's laws are incorrect at large distances or very low accelerations.
- Milgrom suggested "Modified Newtonian Dynamics" (MOND) in which $F = ma$ is replaced by $F = ma^2/a_0$ for $a < a_0 = 10^{-8}$ cm/s^2.
- MOND "predicts" flat rotation curves (problem 6-7a) and does remarkably well in explaining the properties of many galaxies.
- Could we modify Newton's gravitational force law instead of Newton's second law ($F = ma$)? Do on board (problem 6-7b).
- Thought to be ruled out by Bullet cluster – a collision between two galaxies in which X-rays show baryons are concentrated at center, while gravitational lensing shows most of the mass is on the outer edges.



Total mass is in blue, X-ray emitting baryonic matter is in red.

Classification of galaxies

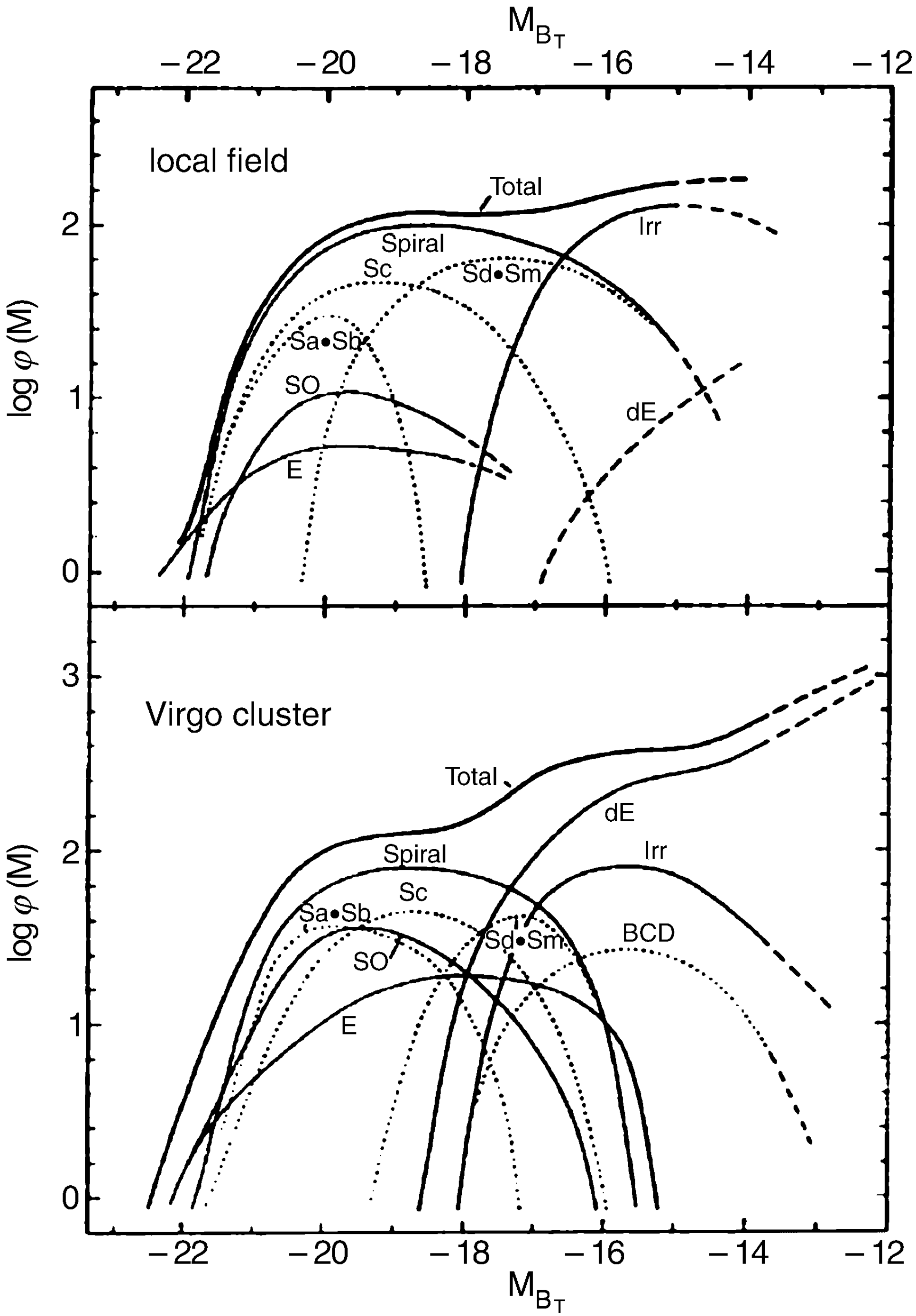


- Ellipticals: En, where n=0 for round, n=7 for oblong.
- Spirals: Sx, where x = indicates brightness of bulge relative to arms, how tightly the arms are wrapped, and the definition of the arms: a (bright, tight, fuzzy), b, c (dim, loose, sharp). Later "d" and ab, bc, cd were added. If the arms have a central bar, then SBx.
- Elliptical galaxies are "early-type"; spiral galaxies are "late-type".
- Later additions to classification scheme:
- Lenticulars: S0 and SB0, mostly bulge with a little bit of disk typically with poorly defined arms.
- Use of SA, SAB, SB for spirals, where SA = S, SAB = intermediate.
- Sub-classification of irregulars: Irr I (weak structure), Irr II (no structure). Addition of Magellanic cloud types, LMC is an irregular, but is sometimes classified as SBm.

Luminosity functions

- Luminosity function, how does the number of galaxies vary as a function of galaxy luminosity
- $\Phi(L)\mathrm{d}L$ = number of galaxies in luminosity interval $[L, L+\mathrm{d}L]$. Can be a density (i.e. divide number by volume) or simply a number (say for all galaxies in the Virgo cluster). Often Φ is specified in terms of absolute magnitude, M, instead of L.
- Sometimes, the integral luminosity function is presented – number of galaxies more luminous than L.

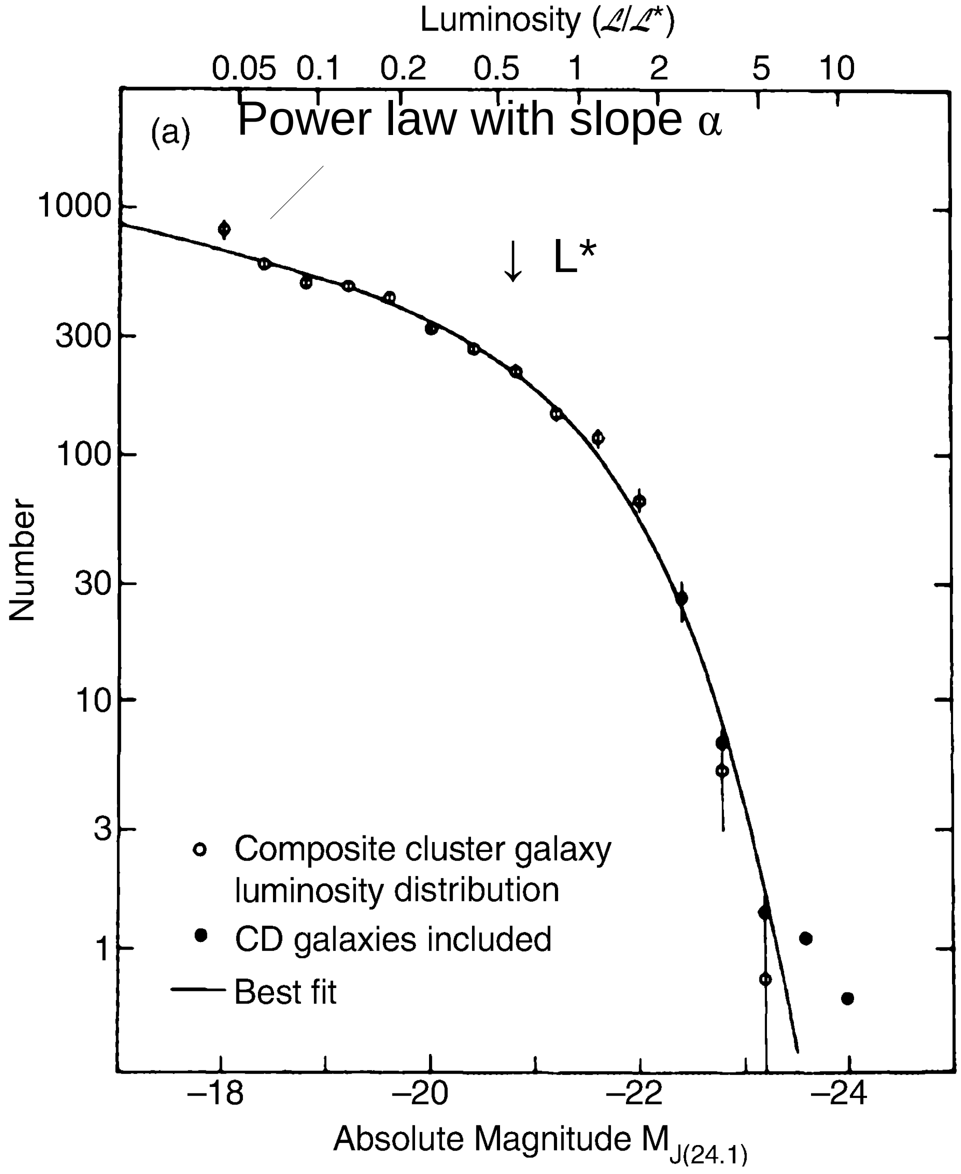
  Measuring Φ is straight forward for a cluster, all galaxies are at the same distance. Need to be careful about removing foreground/background objects, but these can be identified by redshift. Also, Φ may be incomplete at low L.
- Measuring Φ in the field is more difficult. Need to either construct a volume limited sample or correct for fact that more luminous galaxies can be detected at larger distances (Malmquist bias).



Luminosity functions

- Different types of galaxies have different luminosity functions. Luminosity function gives quantitative information about distribution of luminosities and relative number of galaxies of different types as a function of luminosity.
- Luminosity function is different in different environments. E.g. compared to the field, clusters have fewer spirals and more ellipticals particularly at very high and very low luminosities.

Luminosity functions



- If one looks at a very large number of galaxies, the luminosity function appears to follow the Schechter function:
  - Power law (slope α) at low luminosity
  - Exponential cutoff above $L*$
  - $L* = 2\times10^{10}\ L_{Sun}$.
- Milky Way and M31 are ~ L*

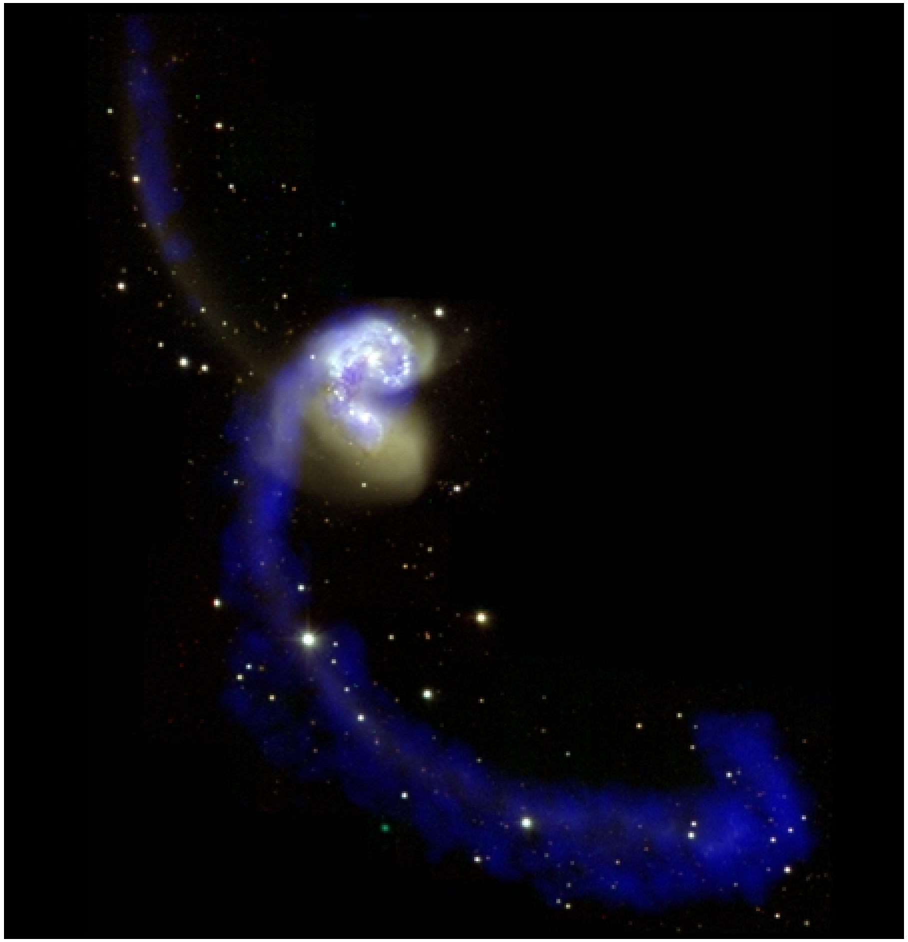
$$\varphi(L)=\varphi(L*)\left(\frac{L}{L*}\right)^{-1}\exp\left(-\frac{L}{L*}\right)$$

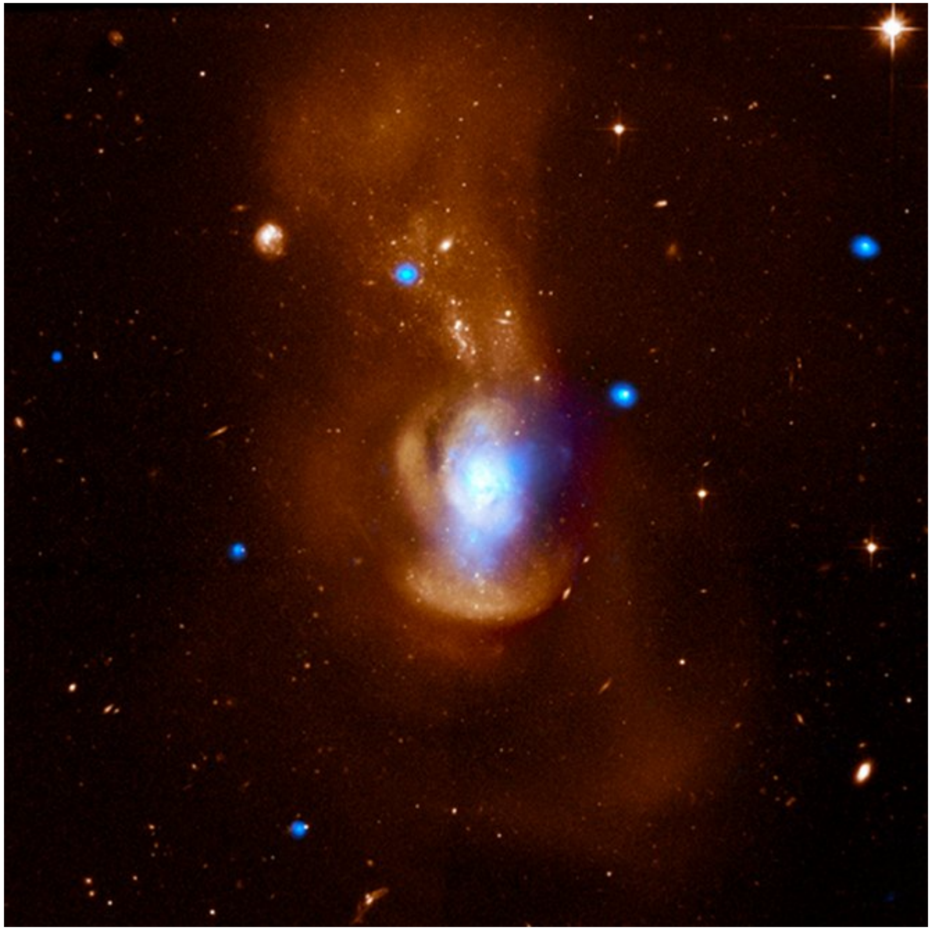
Density of Galaxies

- There is about one L* galaxy per 100 Mpc^3.
- Hence $\varphi(L^*) \sim 0.01\ \mathrm{Mpc}^{-3}$.
- Random velocity between nearby galaxies ~ 500 km/s.
- Cross-section $\sigma \sim \pi(50\ \mathrm{kpc})^2$.
- Time between collisions = $1/n\sigma v \sim 3\times10^{12}$ years.
  - Compare to age of universe

- Collision rate was higher in early universe because galaxies were closer together.
- Also, galaxies are not uniformly distributed. Clustering greatly increases probability of collision.

Galaxy Collisions





- Collisions cause tidal interactions, can lead to galaxy mergers.

Homework

- For next class:
  - Problem 6-4 (gravitational lensing)