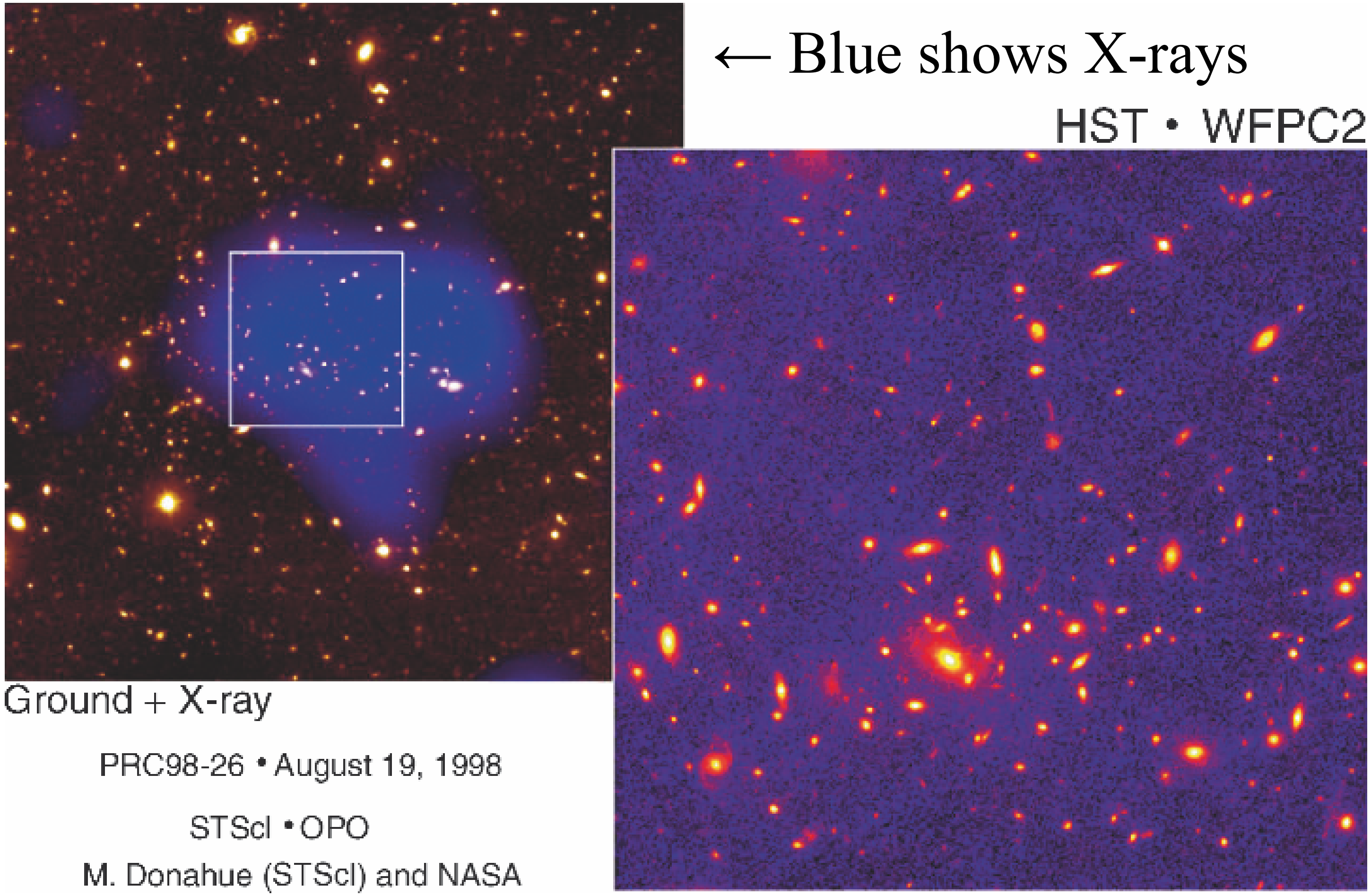
Clusters and Groups of Galaxies

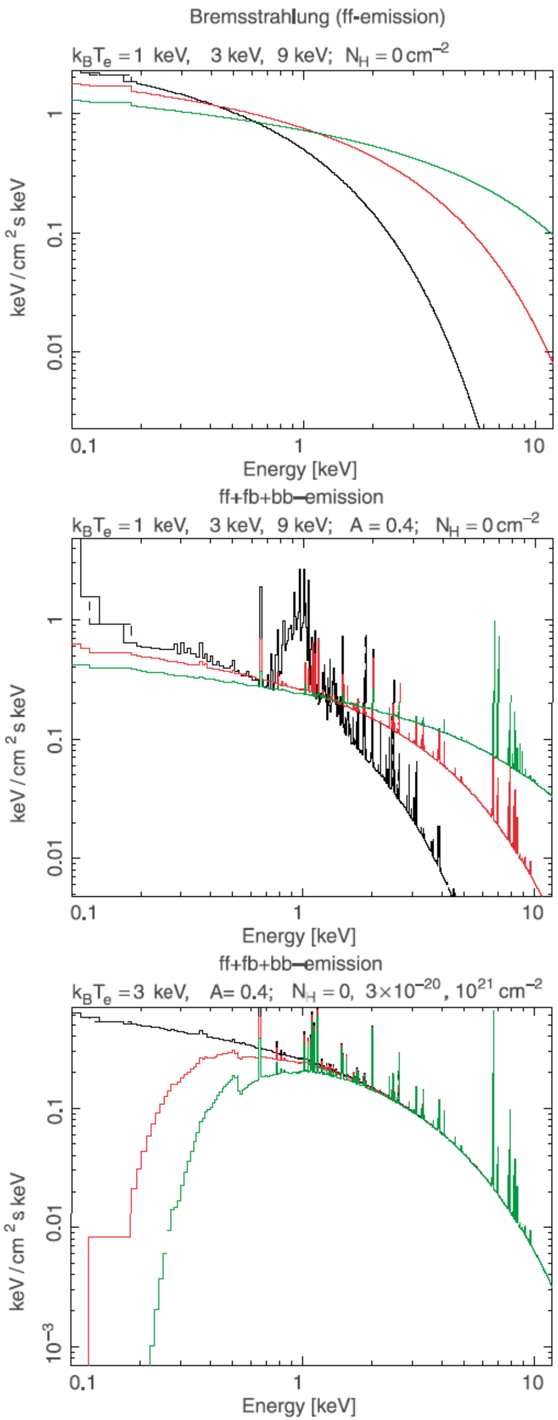
- X-ray emission from clusters
- Models of the hot gas
- Cooling flows
- Sunyaev-Zeldovich effect
- X-ray surveys and clusters
- Scaling relations
- Evolutionary effects

X-ray emitting gas in clusters



← Blue shows X-rays

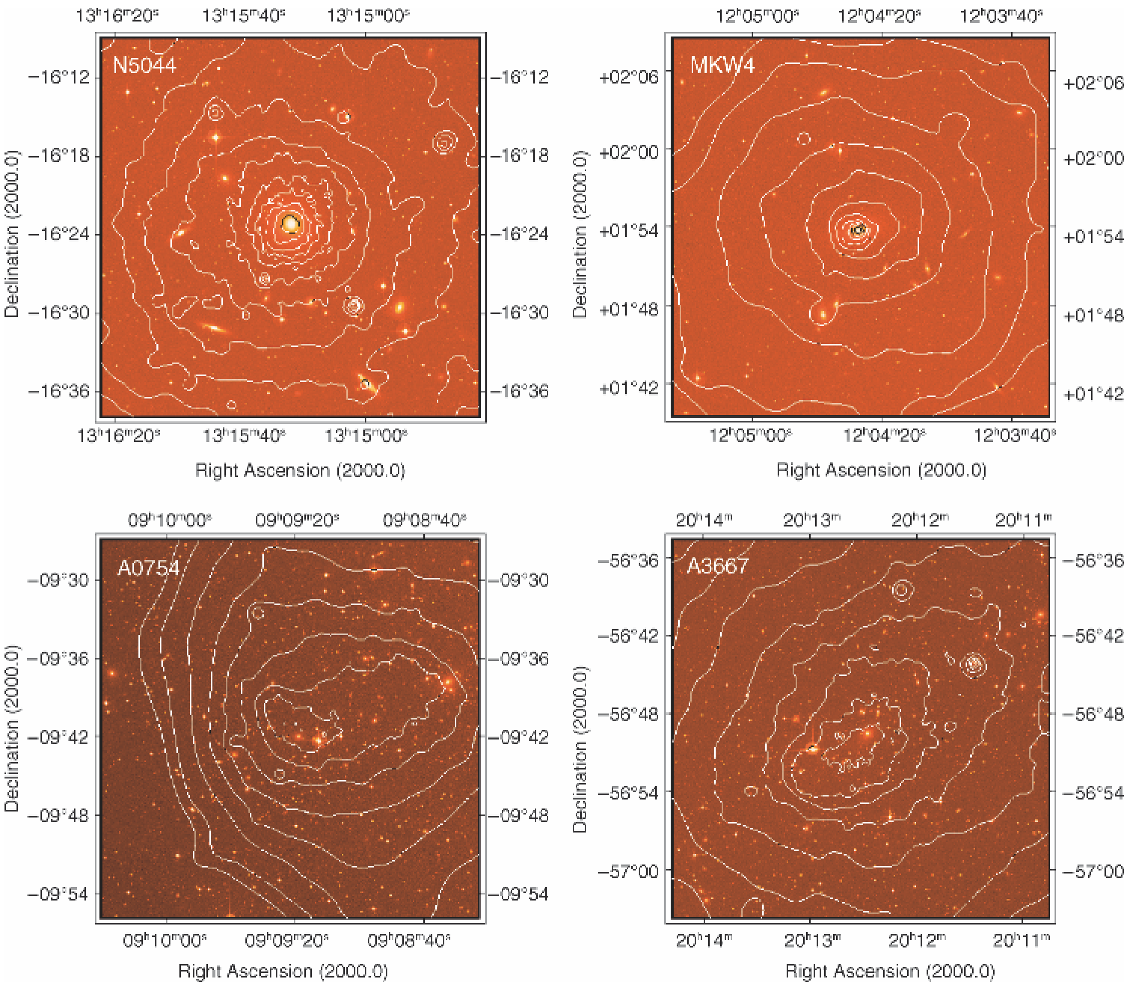
- X-ray emitting gas is at a temperatures of 10^7-10^8 K.
- X-ray luminosities are ~10^{43} to 10^{45} erg/s or ~10^9 to 10^{11} solar luminosities.
- X-rays emitted from a large fraction of the cluster volume.



X-ray emission

- Continuum spectrum from via free-free emission, electron is not bound ("free") in initial or final state of process, also called bremsstrahlung.
- Spectrum is flat for $E < kT$ and cuts off exponentially for $E > kT$.
- Free-free emissivity varies as n^2 and $T^{0.5}$.
- Lines from free-bound or bound-bound emission.
- At high temperatures there are only very highly ionized atoms, e.g. Fe XXV-XXVI produce K-shell lines of 6.4-7 keV and L-shell lines near 1 keV. At lower temperatures (< 2 keV), other lines are present (C, N, O, Ne, Mg, Si, S, Ar, Ca).
- Emissivity varies as n^2 and $T^{-0.6}$ so line emission dominates at low T.
- Absorption is important at low energies.

X-ray morphology



- X-ray emission can be regular or irregular (with multiple peaks).
- Regular clusters tend to be more luminous and hotter.
- If a cluster has a dominant, central galaxy (e.g. a cD), then the X-ray emission is usually strongest there.

Models of the X-ray emission

- Gas is in hydrostatic equilibrium.
- Sound speed $c_s = (kT/\mu m)^{1/2}$ where m = proton mass, μ = average molecular mass ~ 0.63.
- Sound crossing time = R/c_s ~ 1 Gyr << age of cluster → hydrostatic equilibrium.

- Hence pressure ($P = nkT = \rho_g\, kT/\mu m$) balances gravity: $\nabla P = -\rho_g \nabla\Phi$ were ρ_g is the gas density and Φ is the gravitational potential.
- For the spherically symmetric case:

$$\frac{1}{\rho_g}\frac{dP}{dr} = -\frac{d\Phi}{dr} = -\frac{GM(r)}{r^2}$$

- where M(r) is the total mass determining the gravitational potential.
- Substituting for *P*, one can then find M(r) if the gas temperature and gas density profiles are known:

$$M(r) = -\frac{kTr^2}{G\mu m}\left(\frac{d\ln\rho_g}{dr} + \frac{d\ln T}{dr}\right)$$

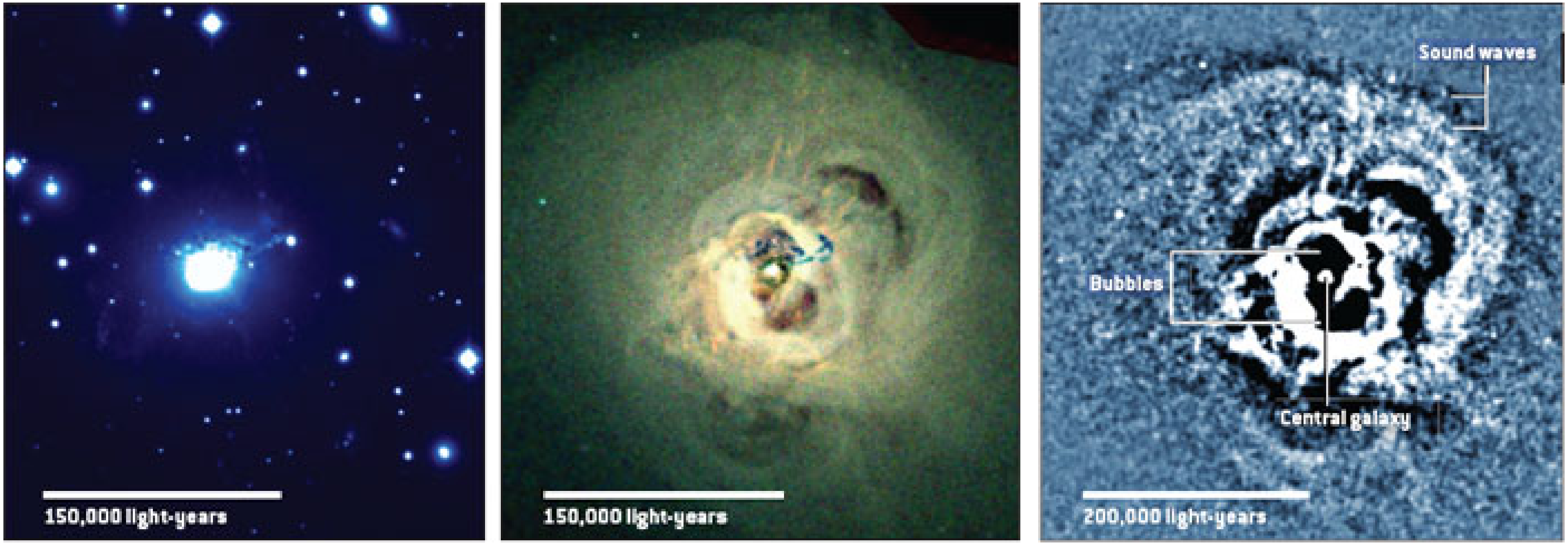
Models of the X-ray emission

- Thus, one can find the distribution of total mass for a cluster if one can measure properties of the gas alone: density, which can be determined from the brightness due to the n^2 dependence, and temperature.
- These 3-d quantities need to be related to the observed 2-d projections.
- In general, the data are not good enough to make detailed maps of density and temperature, so one needs simplifying assumptions. Typically, one assumes a King profile, $\rho(r) = \rho_0[1+(r/r_C)^2]^{-3/2}$, then $\rho_g(r) = \rho_{g0}[1+(r/r_C)^2]^{-3\beta/2}$ with $\beta = \mu m\sigma^2/kT$ and the projected brightness profile is $I(R) \sim [1+(R/r_C)^2]^{-3\beta+1/2}$.
- β and r_C can be determined by fitting to the observed $I(R)$.
- The fitted values (~ 0.65) for β tend to lie below the values (~ 1) calculated from σ and T. This likely indicates limitations in the data and/or the model assumptions (e.g. anisotropy).
- Results suggest typical rich clusters are by mass ~3% stars, ~15% hot gas, ~80% dark matter.
- Three methods for mass determinations, galaxy dynamics, X-ray gas, gravitational lensing, agree reasonable well.

Cooling flows

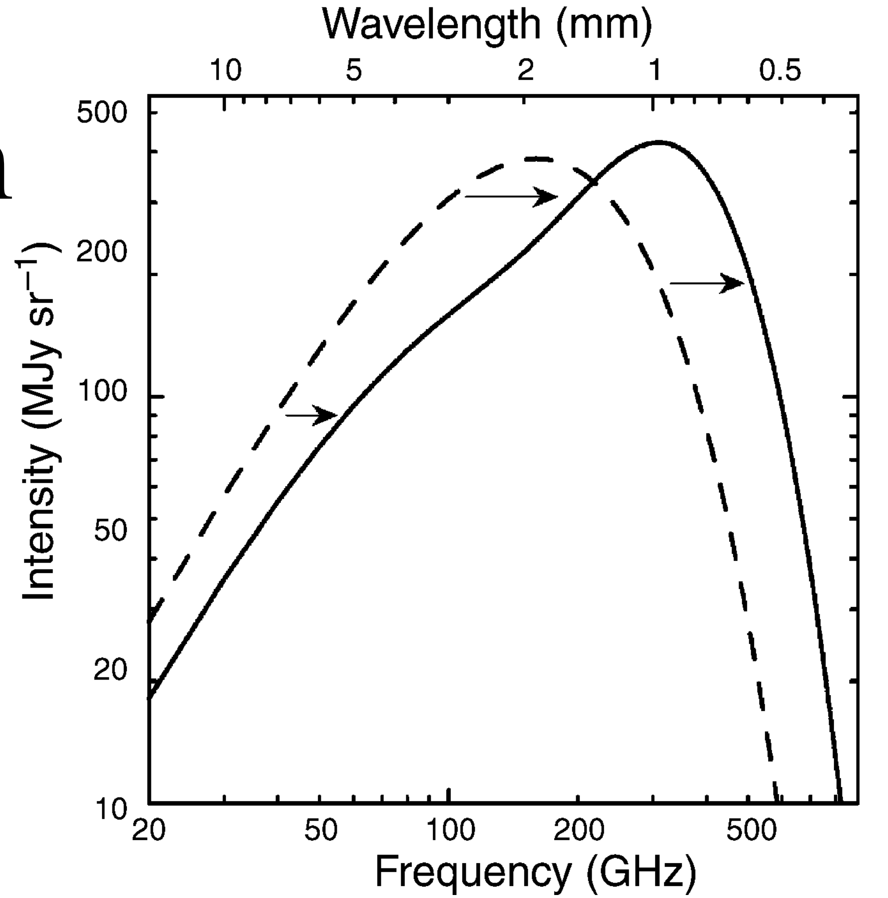
- X-ray emission releases energy, causing the gas to cool.
- Cooling time = 90 Gyr $(n/10^{-3}\ \mathrm{cm}^{-3})^{-1}\ (\mathrm{T}/10^{8}\ \mathrm{K})^{1/2}$
- Low density gas is OK, but high density gas near cluster cores should cool.
- As gas cools, its density increases leading to more rapid cooling in a runaway process – a cooling flow. The cool gas should then form stars, perhaps cD galaxies.
- The expected cooling flows are not observed, there is a minimum $kT \sim 1$ keV.

Cooling flows (not)



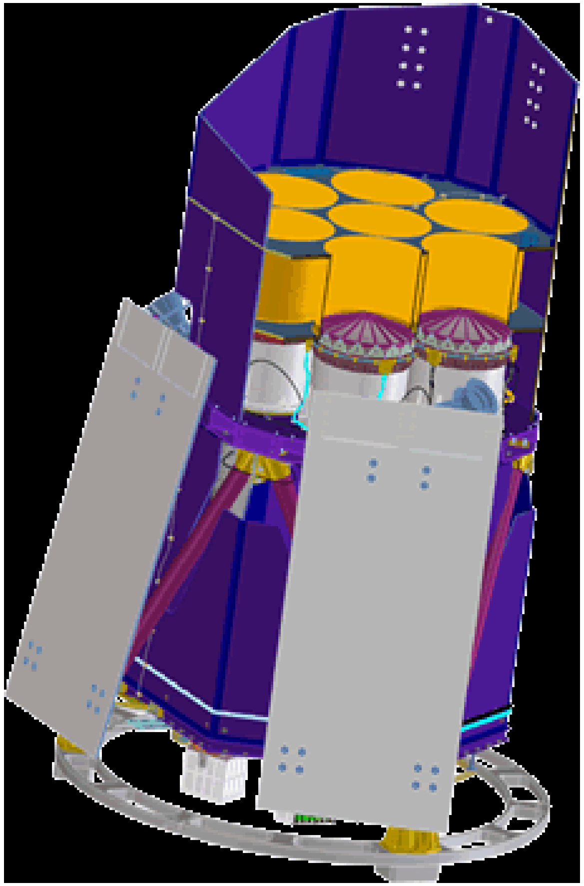
- Answer appears to be heating of intergalactic medium with energy deposited by jets from the central AGN.
- Chandra revealed bubbles, low X-ray emissivity regions containing high energy particles, created by the AGN jets. (Images are of the Perseus cluster with NGC 1275 at the core.)
- These bubbles cause sound waves in the gas that transport energy across the cluster.

Sunyaev-Zeldovich effect



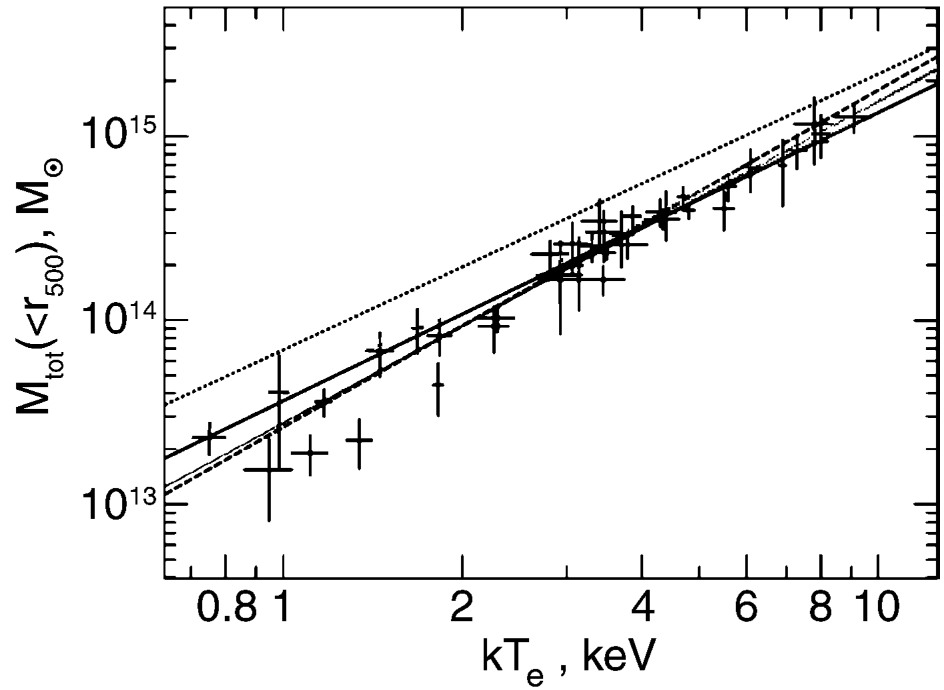
- Cosmic microwave background (CMB) photons scatter on electrons in cluster gas.
- On average, the photons gain energy in the scattering, thus the CMB spectrum measured in the direction of the cluster is shifted.
- For wavelengths > 1 mm, the intensity decrement $\sim \int P\, dl = \int nkT\, dl$
- One can map the SZ effect in the mm band and compare with X-ray maps.
- SZ can be used for distance measurement, $M \sim Ln$, $X \sim Ln^2 \rightarrow L \sim M^2/X$.

X-ray surveys and clusters



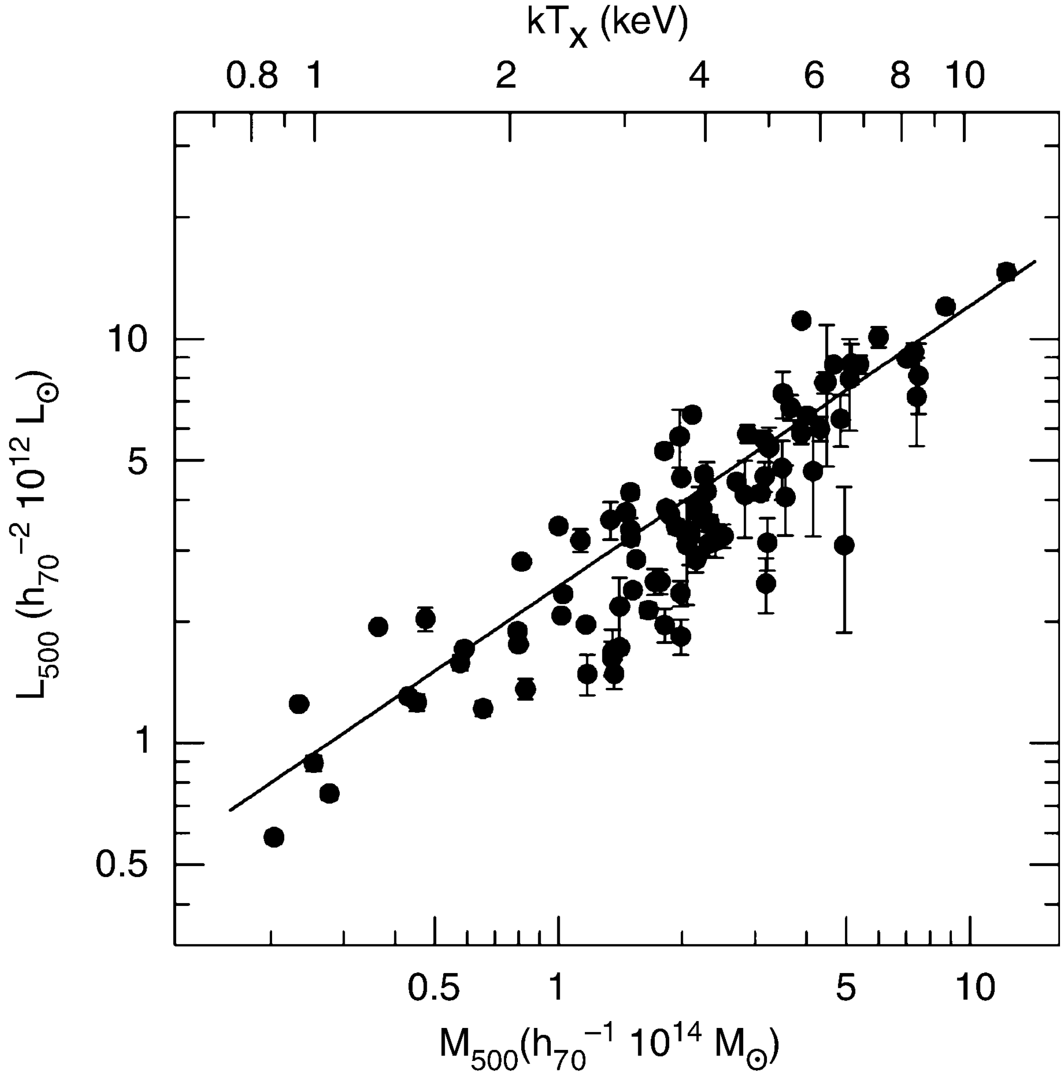
- ROSAT (Röntgensatellit) surveyed whole X-ray sky in 0.1-2.4 keV band and found ~100 clusters.
- Surveys with general purpose X-ray observatories, e.g. XMM observed the 2 sq. deg. COSMOS field and found 72 clusters.
- eROSITA (extended ROentgen Survey with an Imaging Telescope Array) is planned for the Russian Spectrum-Roentgen-Gamma (SRG) satellite and should survey the whole X-ray sky in the 0.5-10 keV band using 7 telescopes. They expect to find ~70,000 clusters.

Mass-Temperature relation



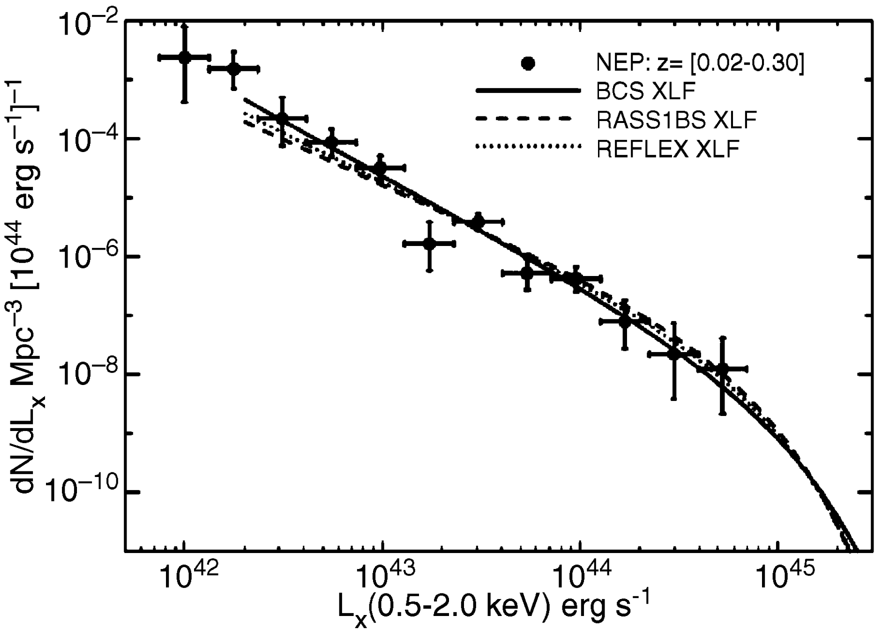
- Since $2E_k = -E_p$, $kT \sim mM/r$ where M = total mass. Define $M = (4\pi/3)\rho_V r^3$.
- Then $T \sim M/r \sim r^2 \sim M^{2/3}$, or $M \sim T^{3/2}$.
- Figure shows data. Best fit for clusters with $M > 5\times10^{13} M_{Sun}$ has $M \sim T^{1.58}$ (solid line).
- There are also relations $M \sim \sigma^3$ and $L_X \sim M^\alpha$.

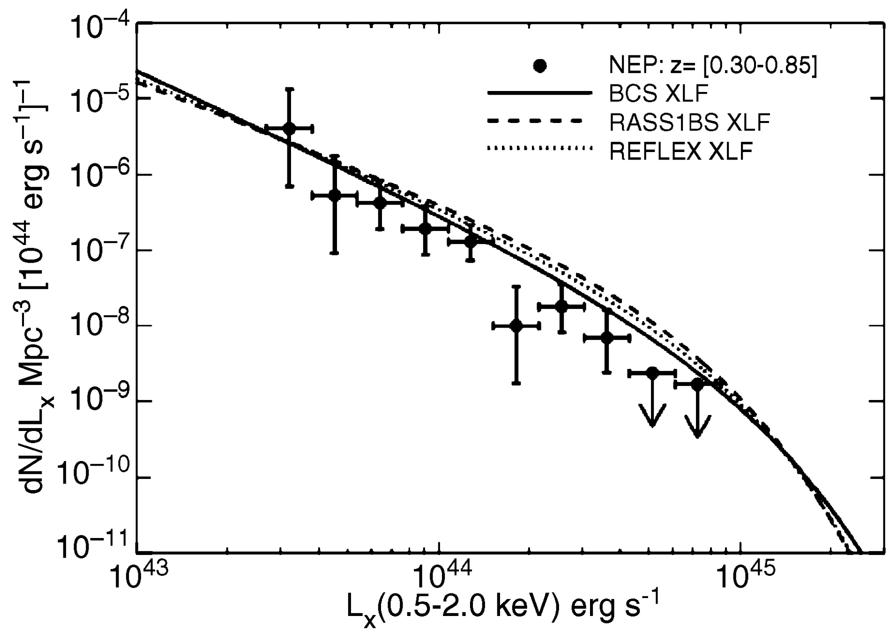
Mass-NIR luminosity



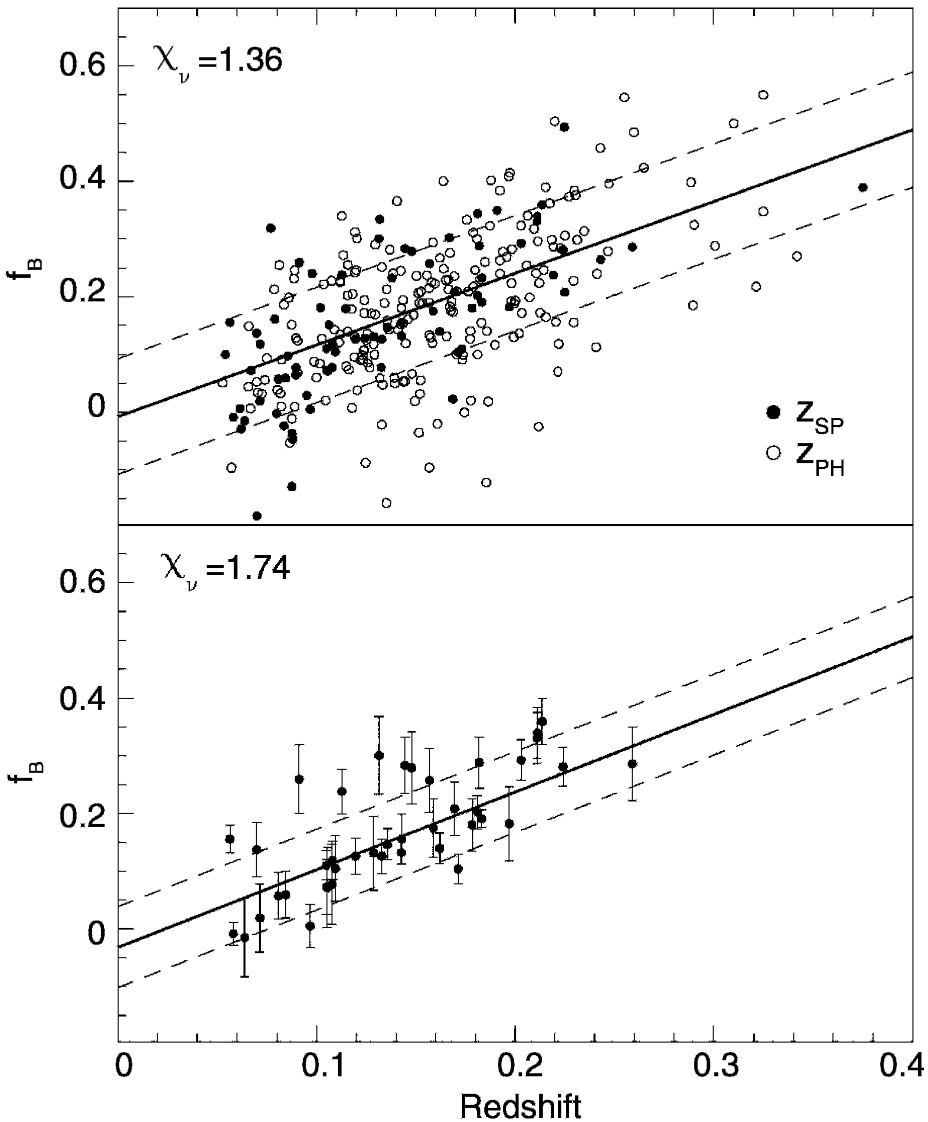
- Near infrared (NIR) luminosity is well correlated with total mass in stars.
- Figures show K-band (2.2 micron) luminosity versus mass, $L \sim M^{0.69}$.
- Good correlation suggests a close link between mass in luminous matter and mass in dark matter.

Luminosity variation with redshift?



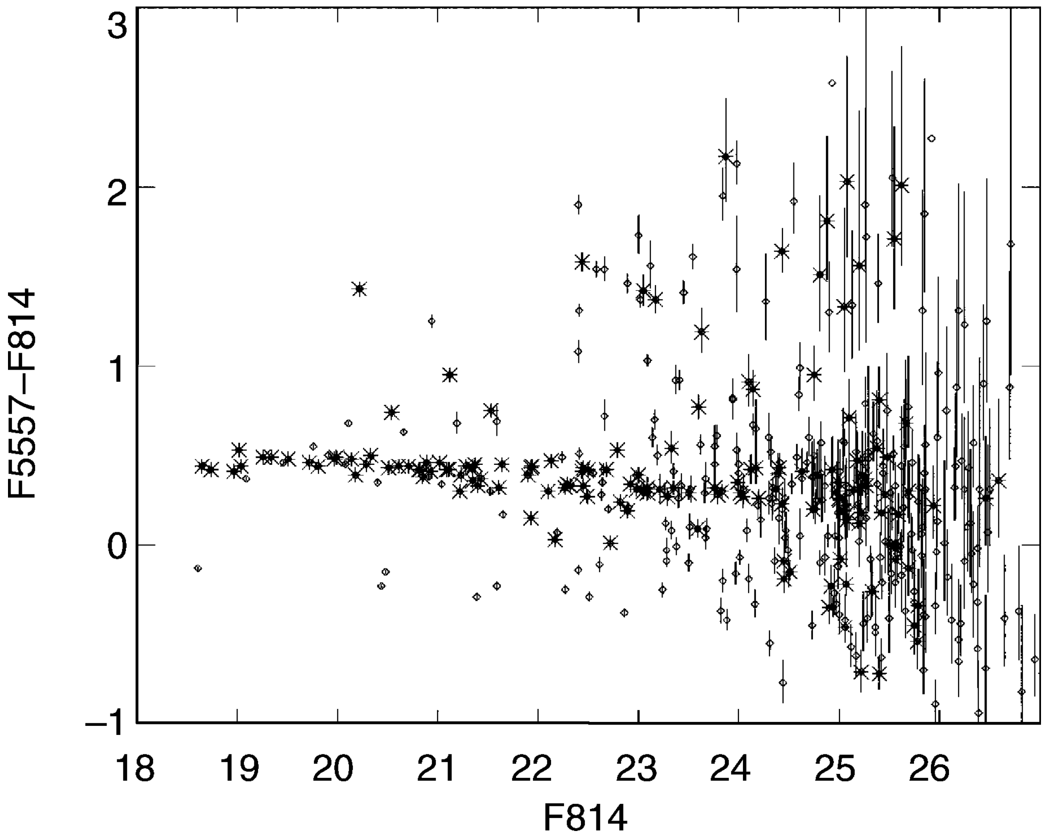


- Curves are for nearby, $z \sim 0$, clusters. Data points for indicated redshift range.
- Little or no evolution for low luminosities. Perhaps some evolution at high luminosities.



Butcher-Oemler effect

- Nearby clusters show a deficit of late-type (spiral, blue) galaxies.
- This effect is strongly redshift dependent (open circles show photometric redshifts, filled circles show spectroscopic redshifts).
- Late-type galaxies disappear or change into early-type galaxies over time.



Red cluster sequence

- Color-magnitude diagram for galaxies in Abell 2390. Stars are early-type galaxies.
- Red cluster sequence (RCS) is (slightly tilted) line of early-type galaxies.
- RCS is same for all clusters at given redshift – can use to estimate redshift.
- Suggests that stars in different clusters formed at about the same time.
- Tilt of line is due to metallicity dependence (bigger galaxies have higher metallicity).
- Galaxies evolve within clusters, but very little star formation occurs.

For next class

- Read 2.5.1 and 6.5.
- Homework for chapter 6 is now on the class web site and is due Monday, October 15.
- First draft of project papers will be due on October 29.