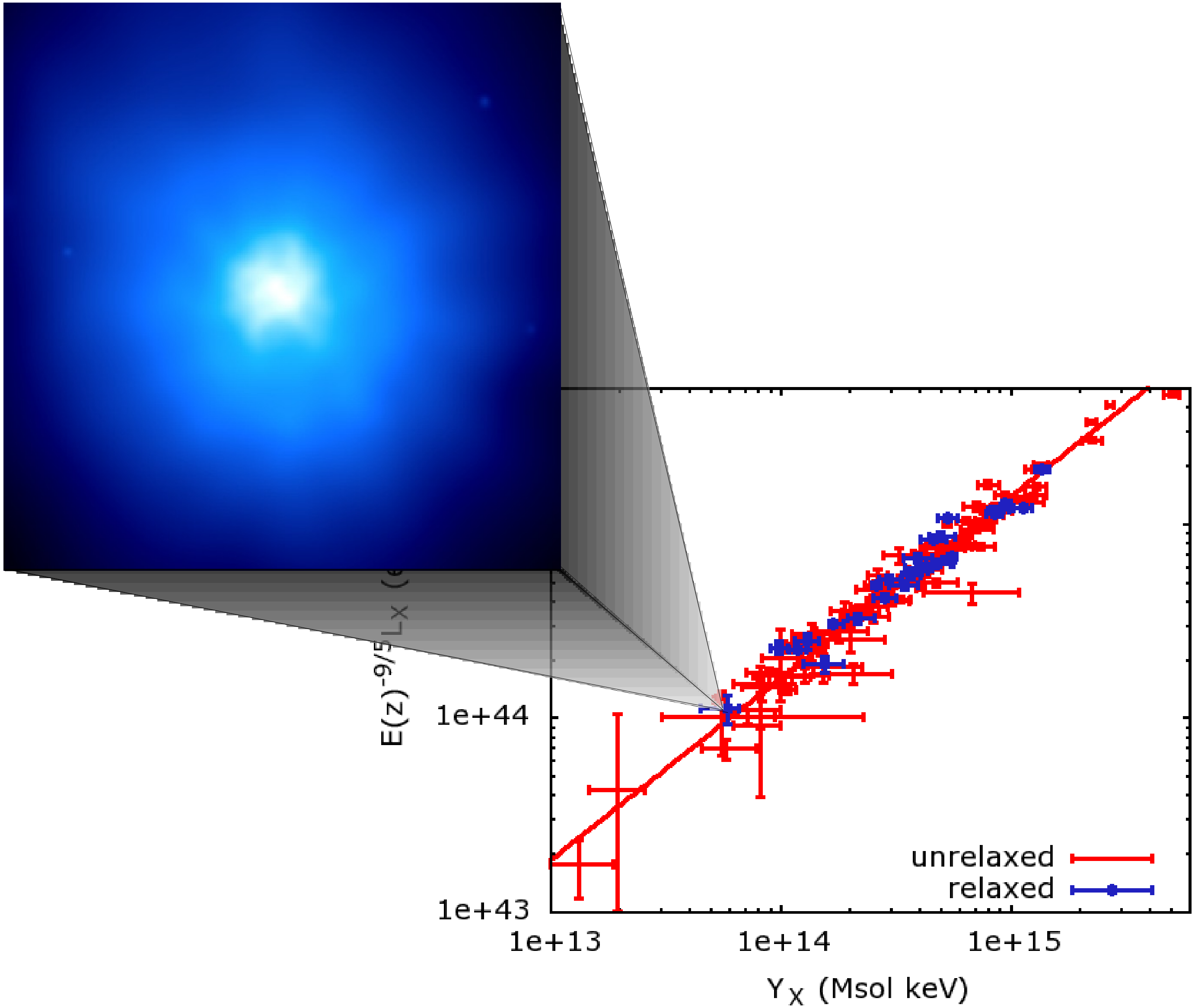
Galaxy Clusters and Self Similarity I



About Me

- Dr Ben Maughan
  - Degree: Cardiff
  - Ph.D: Birmingham
  - Chandra Fellow: Harvard-Smithsonian Centre for Astrophysics
- Research:
  - X-ray properties of galaxy clusters
  - Cosmology
- Room 4.19
- ben.maughan@bristol.ac.uk

Lectures

Tuesday 9.00	Wednesday 11.10	Thursday 12.10am
BJM	BJM	BJM

- Lecture material online:

  http://www.star.bris.ac.uk/bjm/lectures/topics

Course Outline

- Introduction to galaxy clusters and properties at different wavelengths
- Self similarity in galaxy clusters – theoretical background and comparison with observations
- Observational results on similarity breaking and causes

Reading List & Exam

Read at least one of the following papers:

- Branchesi et al. (2007), A&A, 472, 739-748
- Kotov & Vikhlinin (2005), ApJ, 633, 781-790
- Lumb et al. (2004), A&A, 420, 853-872
- Magliocchetti & Bruggen (2007), MNRAS, 379, 260-274

Exam consists of short and long answer question on each topic

- answer all short and 2 long questions
- full marks on my long question requires correctly referencing one paper above e.g.

  "Maughan et al. (2007) showed that the scatter in the X-ray luminosity – mass relation is significantly lower than previously thought."

Today

Introduction to galaxy clusters

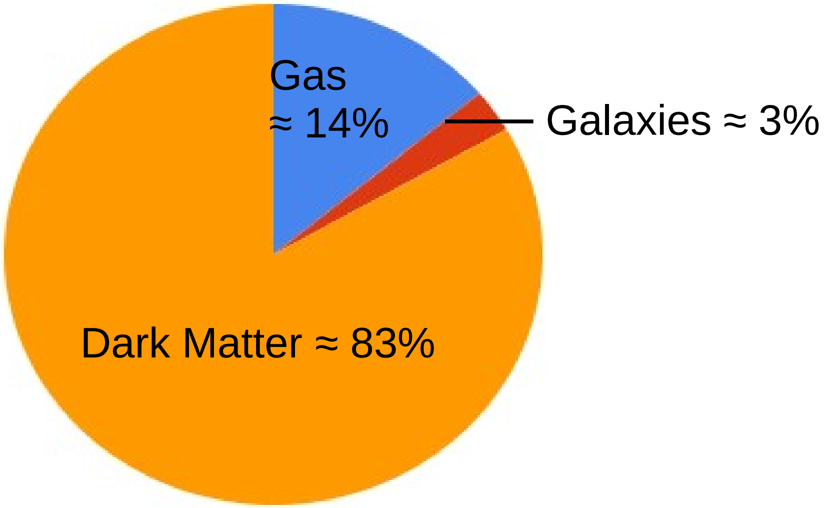
- Why so interesting?

Properties at different wavelengths

- Optical
- Gravitational Lensing
- Sunyaev Zel'dovich effect
- Numerical simulations
- X-ray

Galaxy Cluster Recipe

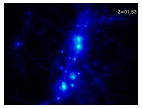
- Take approx $10^{15}M_\odot$ dark matter
- Marinade in approx $10^{14}M_\odot$ hot (10^7K) ionised gas
- Sprinkle with 100's of galaxies of various shapes and sizes ($\sim10^{13}M_\odot$)
- Finished product approx 2Mpc in radius



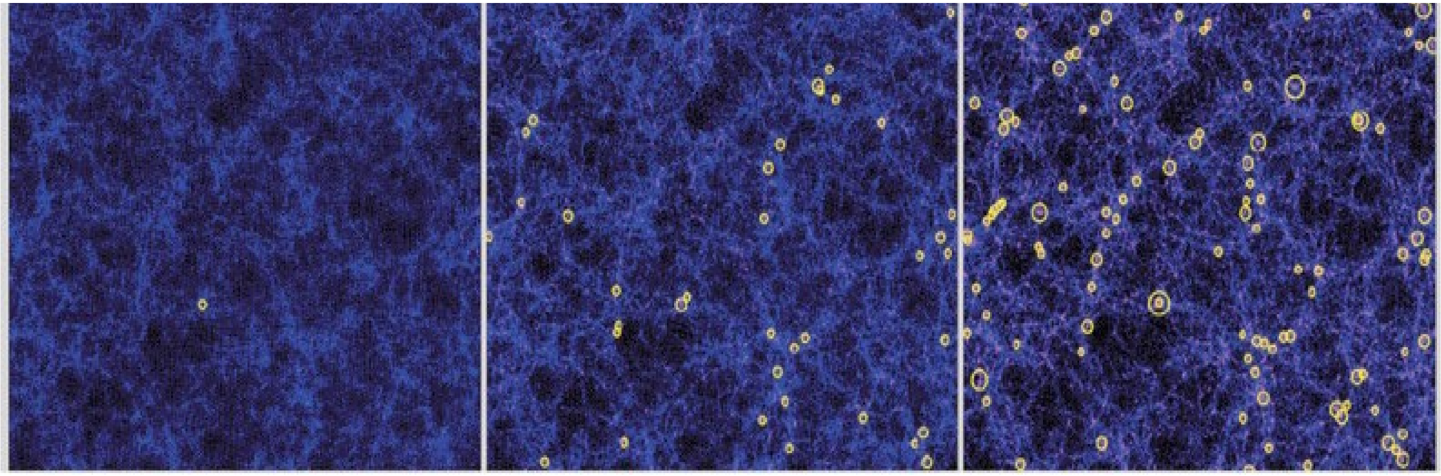
Clusters & Cosmology

Early Universe was smooth with tiny density perturbations after Big Bang

- Density peaks amplified by gravity
- Galaxy clusters form via series of mergers of smaller systems – **hierarchical formation**



- Largest gravitationally bound objects in Universe



Simulation of development of structure in Universe.
Circles show locations of galaxy clusters

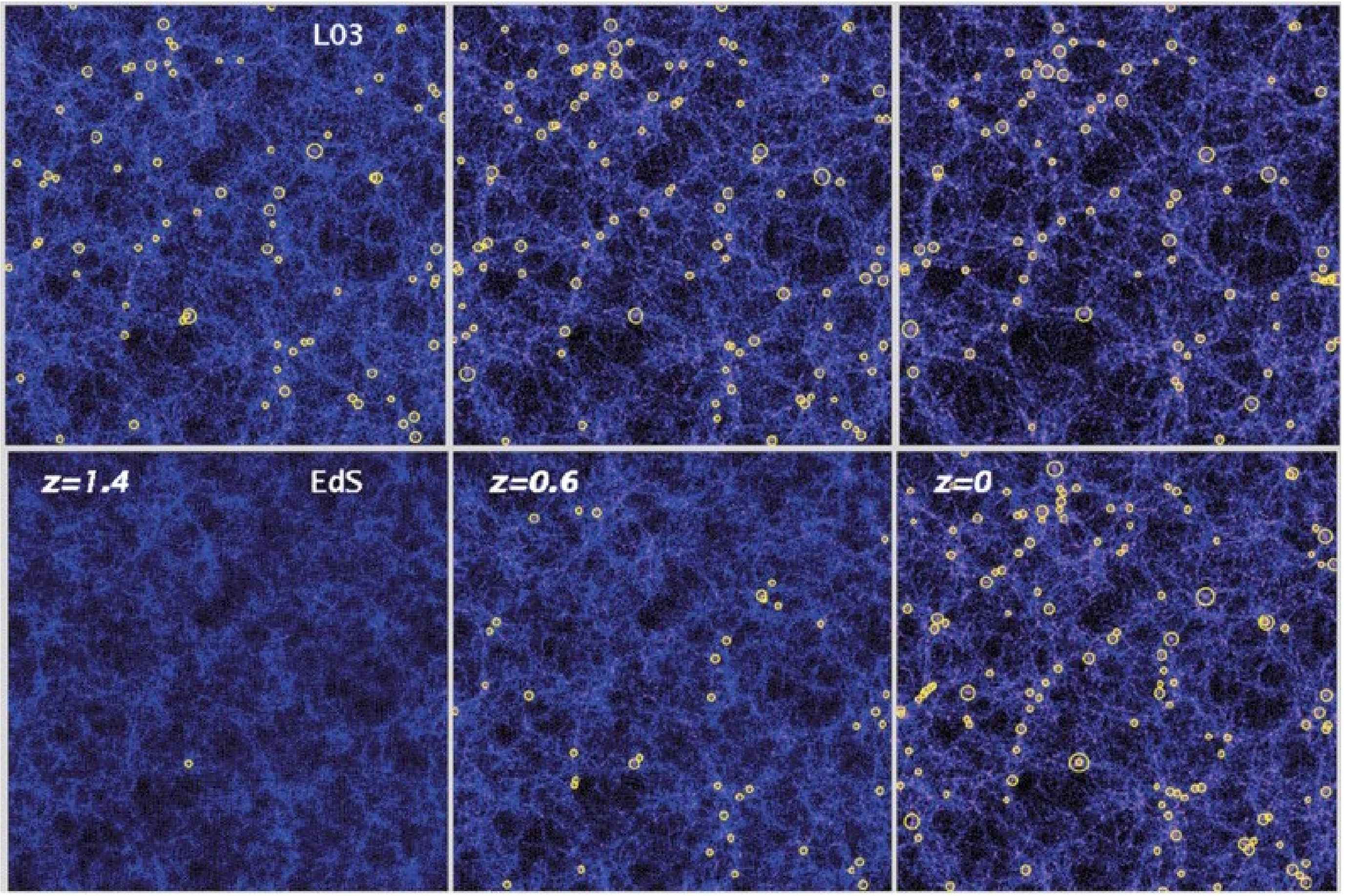
Clusters & Cosmology

Growth of large scale structure traced by clusters

- Sensitive to cosmological parameters
- **Clusters provide powerful tests of cosmological models**

Flat Universe
Λ=0.7

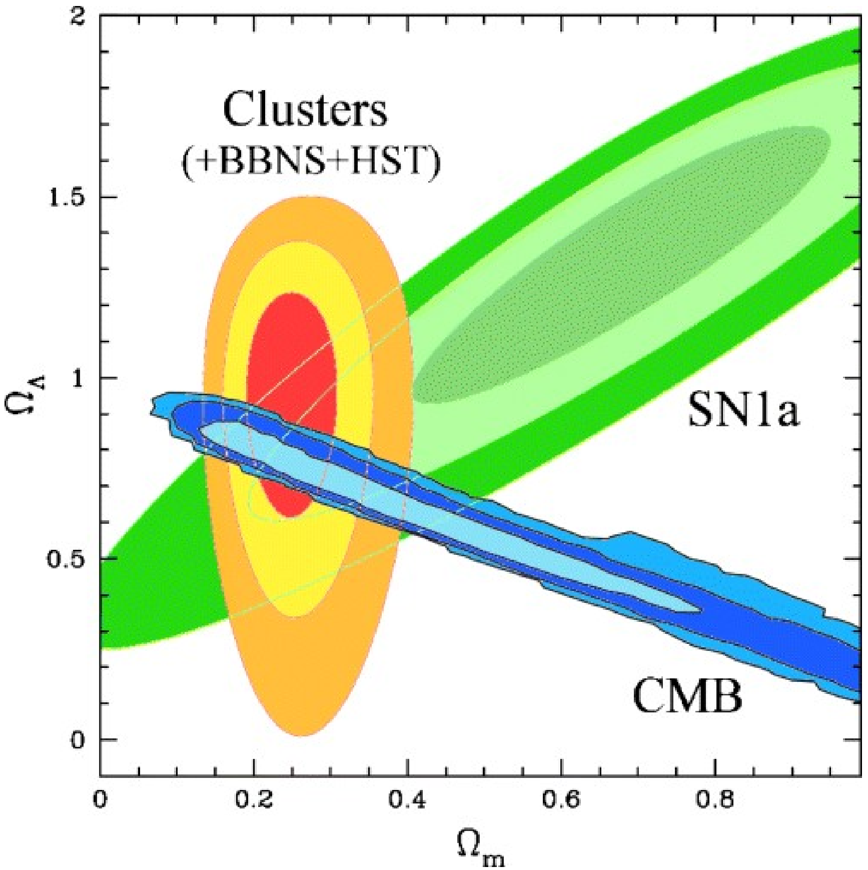
Flat Universe
Λ=0



Clusters & Cosmology

Constraints competitive, independent and different degeneracies to other methods

- **Cosmological tests require cluster masses**



Two principal reasons to study galaxy clusters:

- Measuring masses for cosmology
- Unique laboratories for interesting physical processes

Best cosmological constraints need **large samples** out to **high redshift**

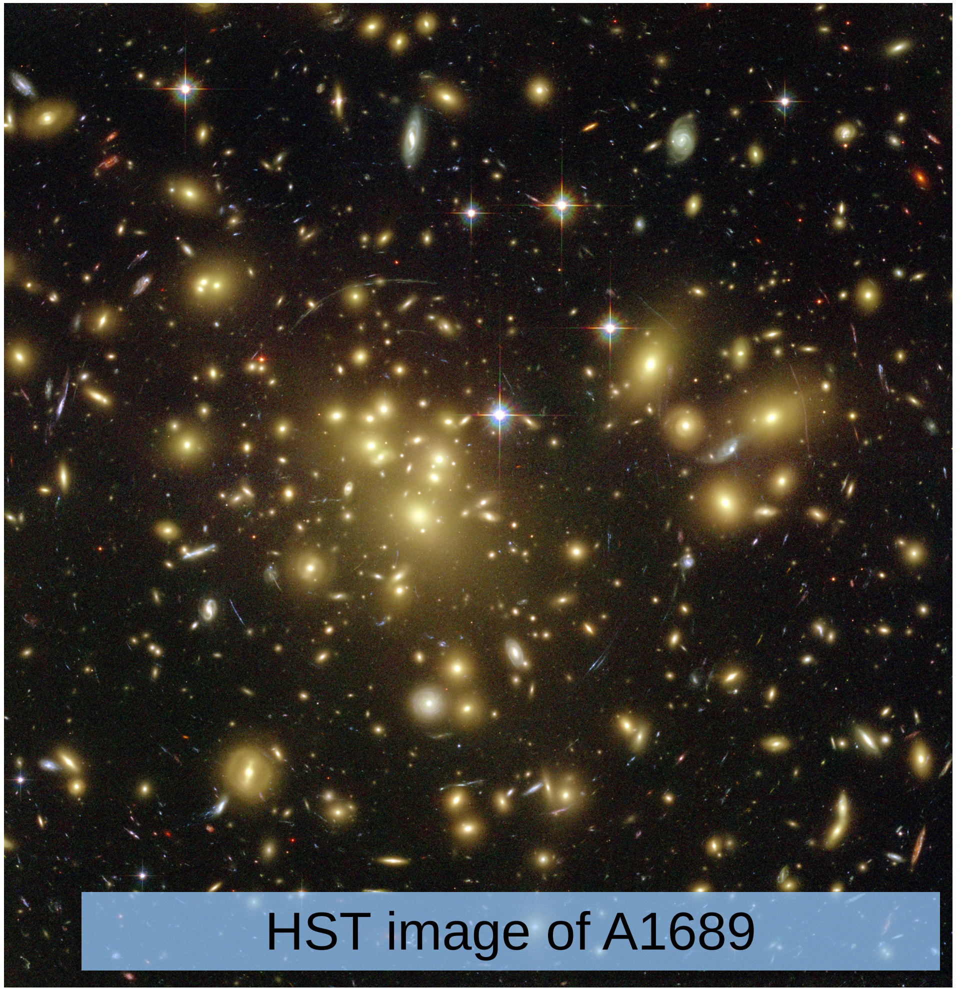
Optical Properties

First studied in optical

- **100s or 1000s of member galaxies**

Abell (1958) catalogue

- Detect clusters based on overdensities of galaxies
- Suffers projection effects
- Study richness and morphology of clusters



HST image of A1689

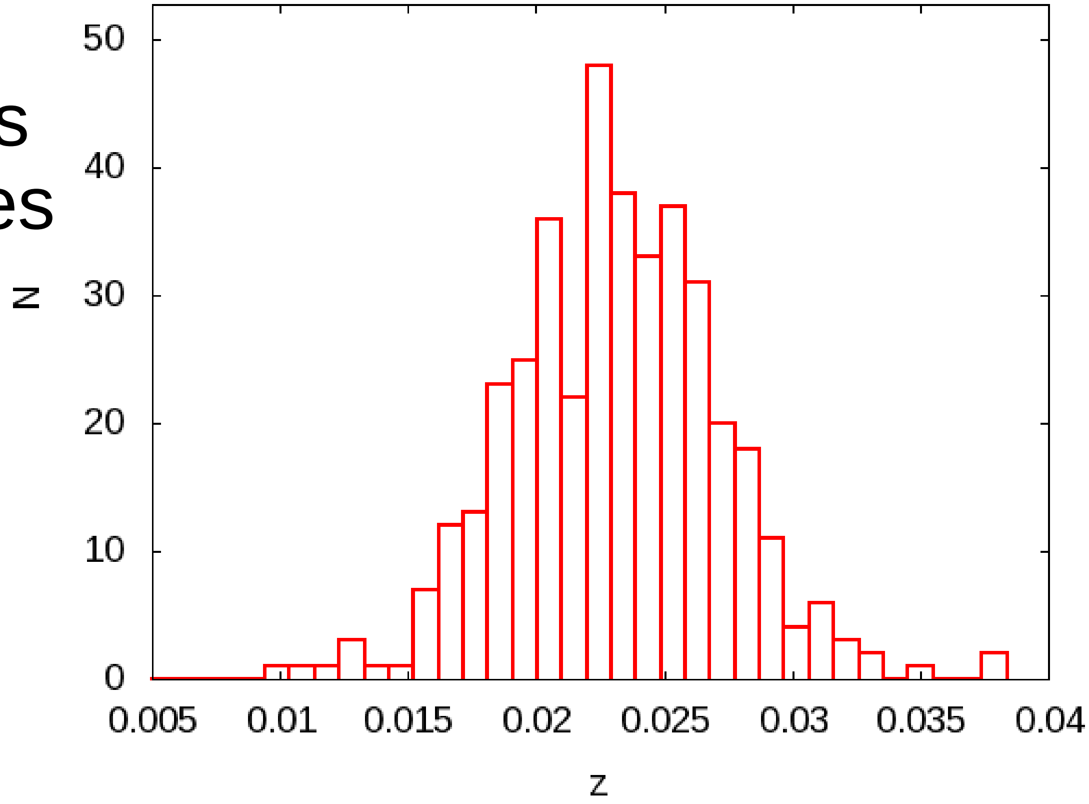
Optical Properties

Zwicky (1933) measured redshifts of galaxies in coma

- What is z of Coma? Why don't galaxies have same z?
- Velocity dispersion

Velocity dispersion gives kinetic energy of galaxies

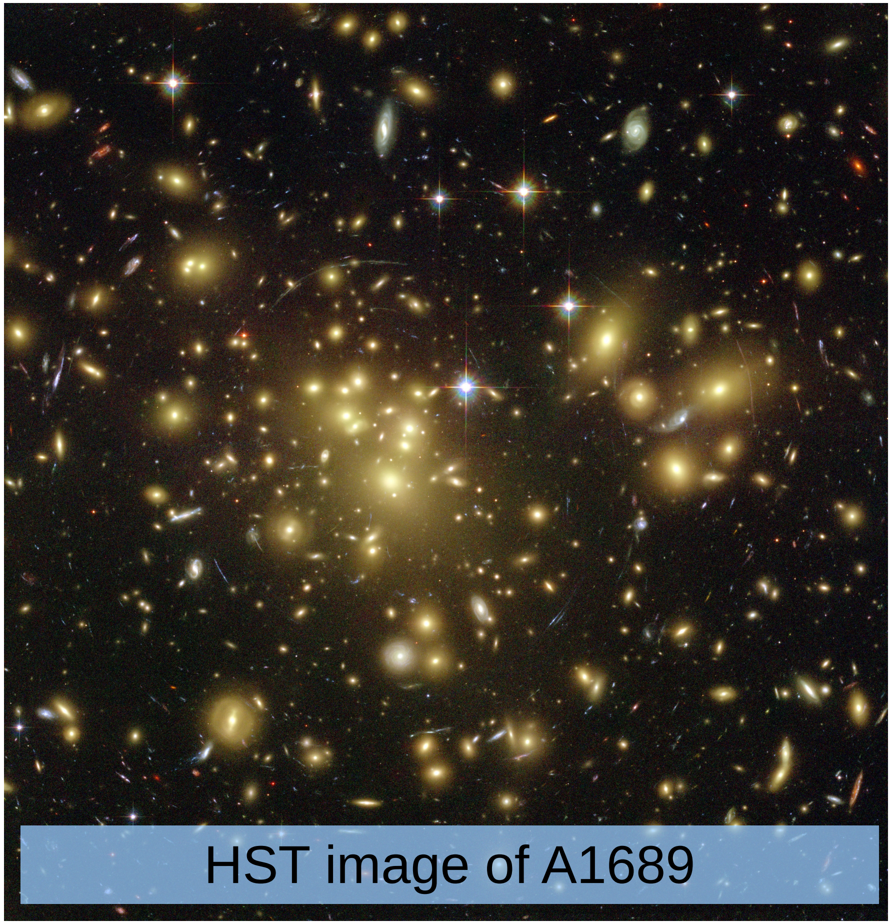
- **Virial theorem** gives total cluster mass
- Zwicky found <1% mass in galaxies
- **First evidence for dark matter**



Redshift histogram for the coma cluster

Gravitational Lensing

- Deep gravitational potential in clusters acts as gravitational lens
- Distorts shapes of background galaxies
- Effect strongest in cores
- Arc like distortions & multiple images
  - “Strong lensing”


HST image of A1689

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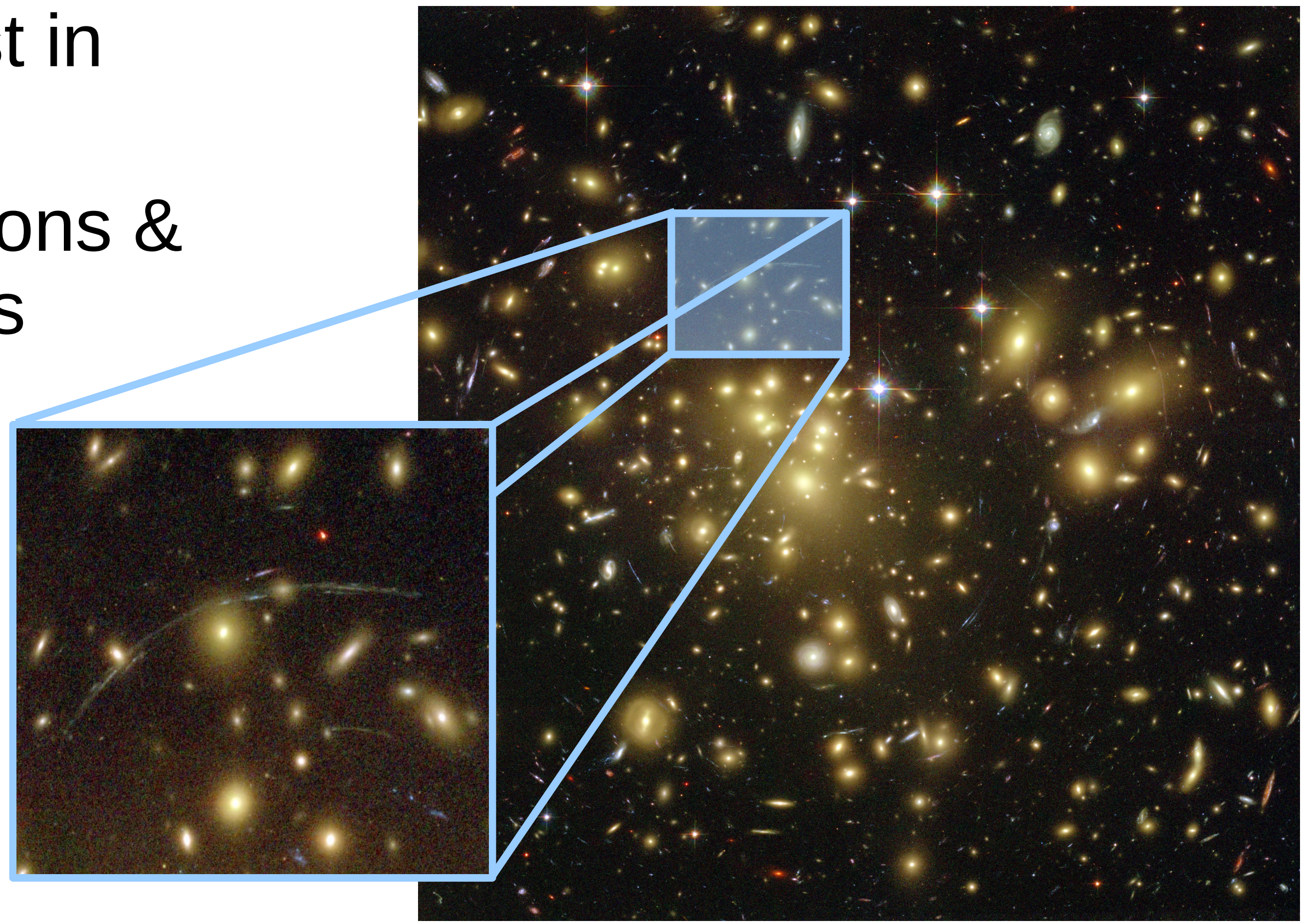
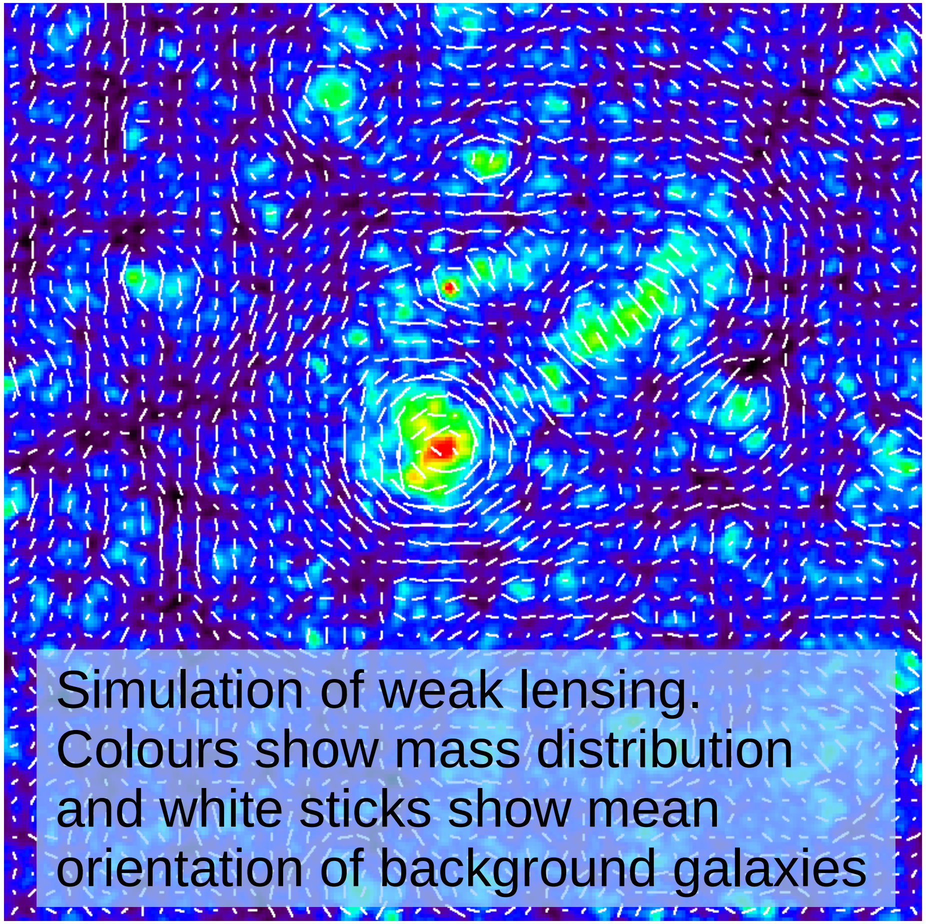


Gravitational Lensing

Outside cluster cores, effect is weaker

- Subtle elliptical distortions to background galaxy shapes - “weak lensing”



Simulation of weak lensing. Colours show mass distribution and white sticks show mean orientation of background galaxies

Can't measure distortion for a particular galaxy

- Don't know what shape it was originally

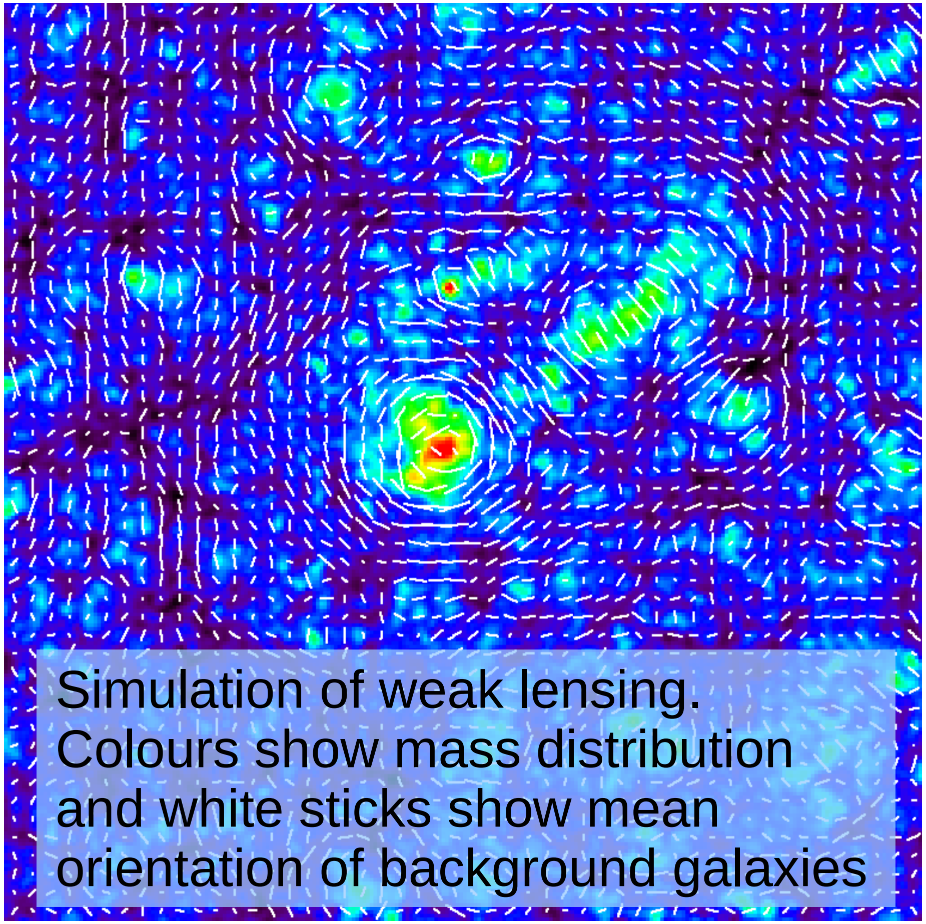
Measure statistical distortions of many galaxies

- Will be random if no lensing signal

Gravitational Lensing

Both strong and weak lensing can be used to determine cluster masses

- Sensitive to **all mass** along line of sight



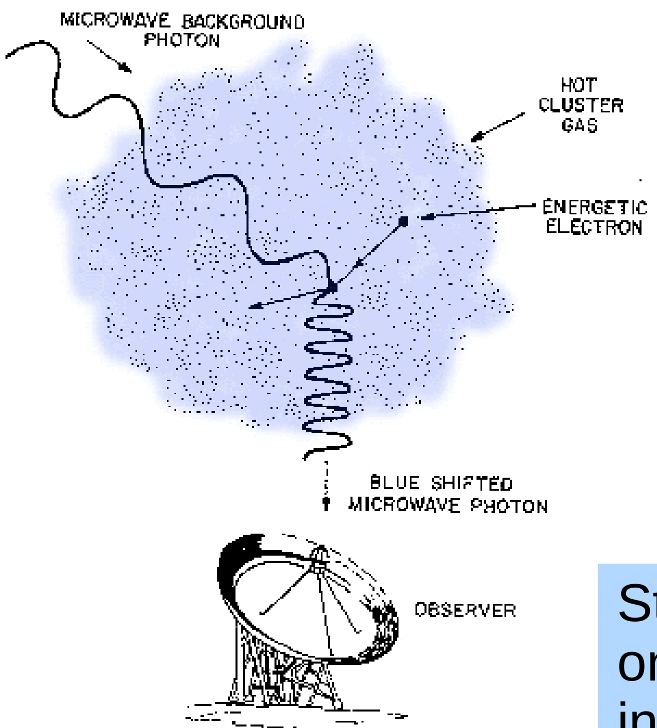
Simulation of weak lensing. Colours show mass distribution and white sticks show mean orientation of background galaxies

Affected by mass in large scale structure around clusters

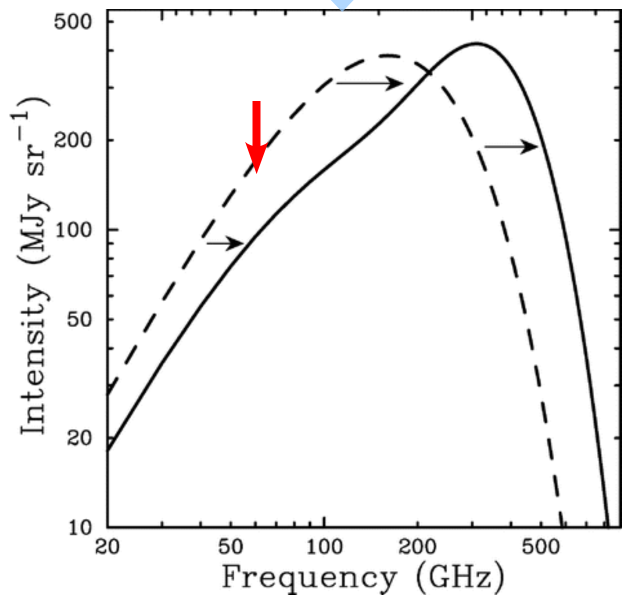
- Introduces uncertainties

Sunyaev-Zel'dovich effect

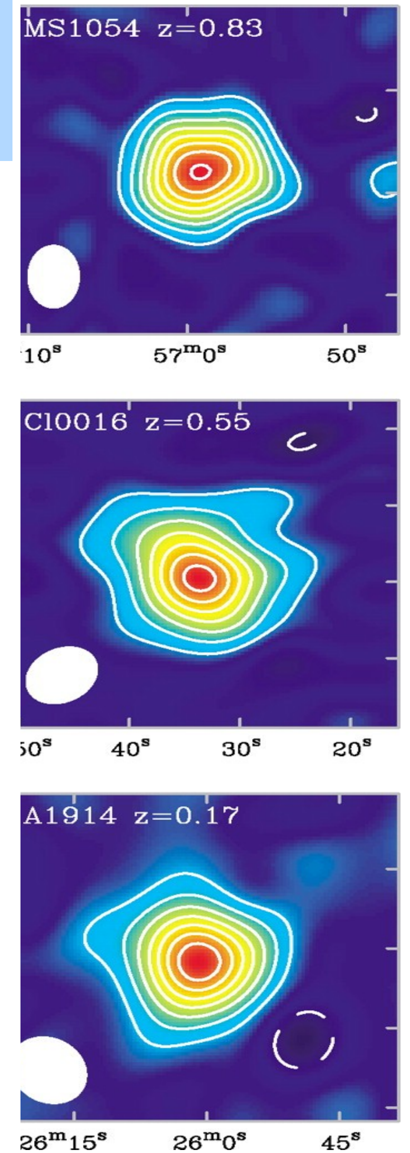
Microwave background photons are inverse Compton scattered to higher energies by electrons in ICM



Distorts shape of CMB spectrum – intensity drops at lower frequencies



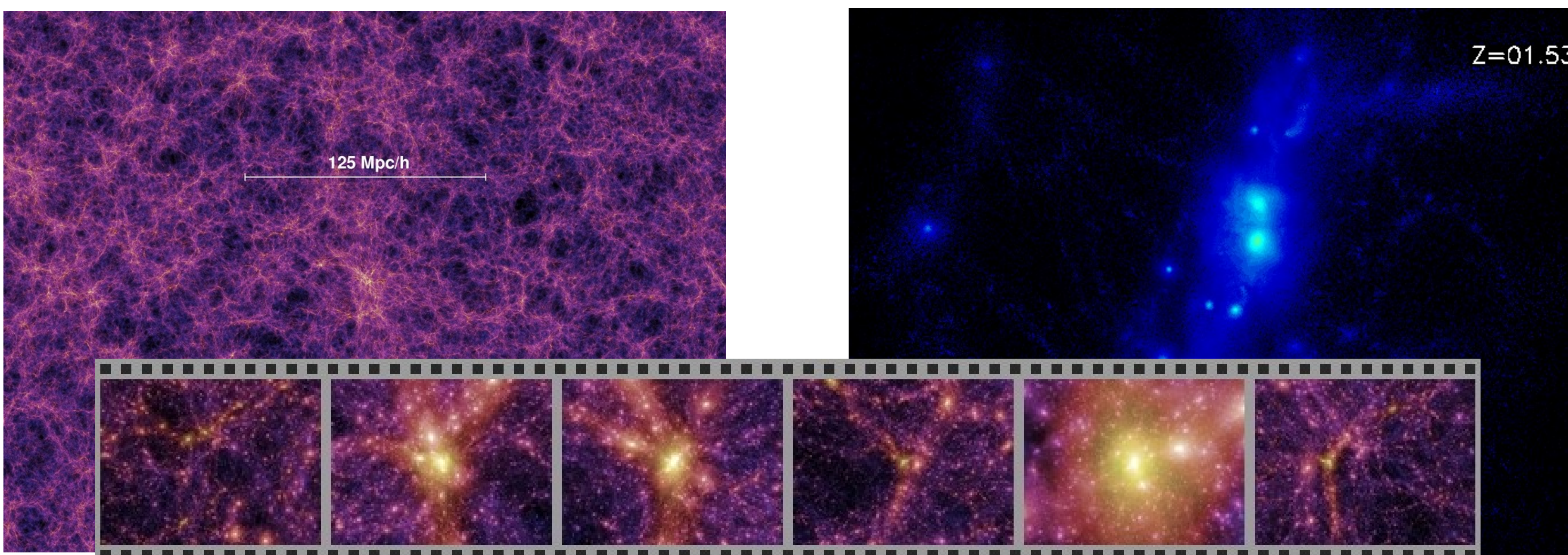
Strength of effect depends on T and ρ of ICM, but is independent of redshift!



Numerical Simulations of Clusters

Computer simulations allow testing of cluster models, include dark matter

- What physical processes must be included in simulations to match observations of real clusters?
- Simulations also allow study of dynamics of clusters on timescales too long for direct observation



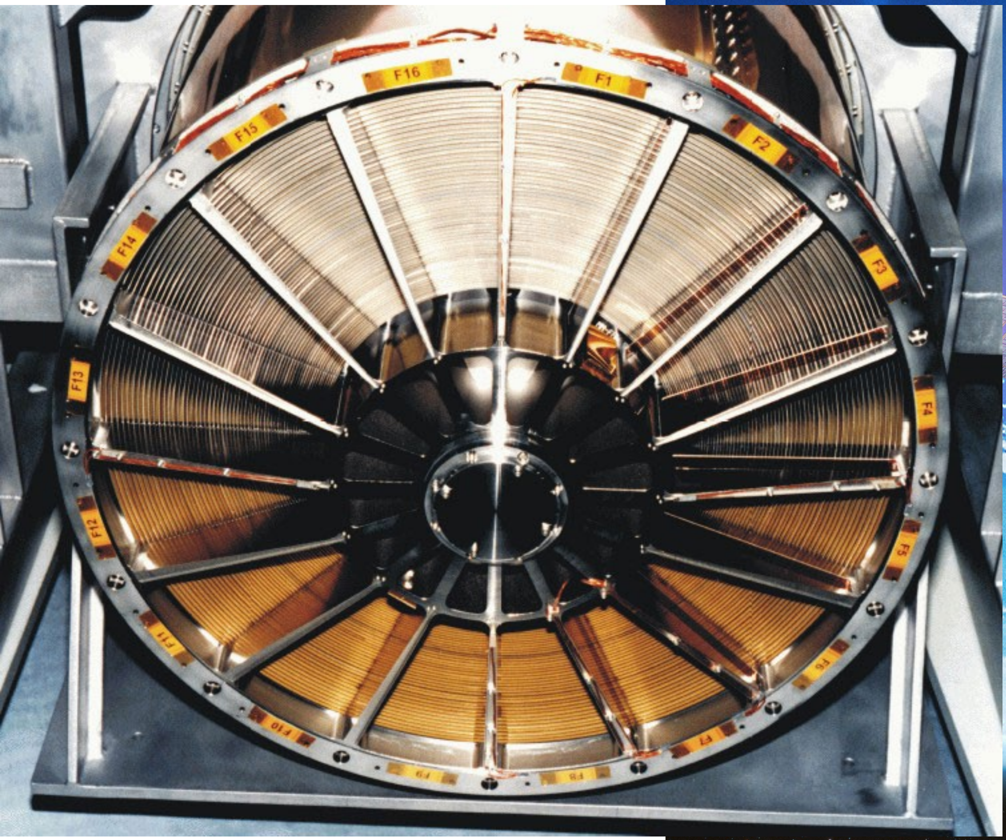
Summary

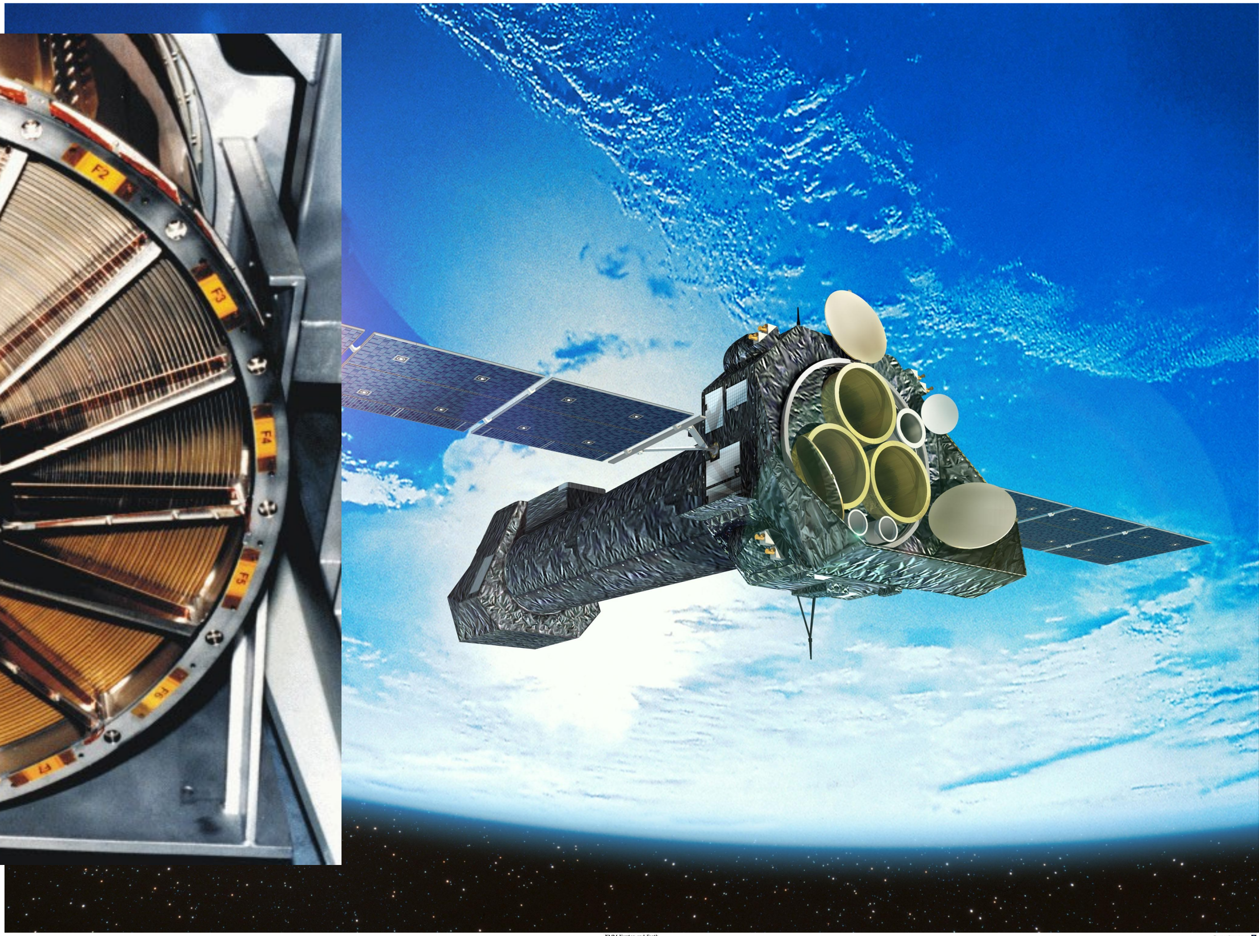
- Galaxy clusters studied at different wavelengths:
- Optical
  - Galaxy velocity dispersions, richness, morphology
- Gravitational lensing
  - Strong and weak lensing can give cluster masses
- SZ effect
  - Sensitive to ICM properties, independent of z
- Simulations
  - Formation & which physical processes important
- X-ray...

XMM-Newton 1999-

3 X-ray telescopes each with 58 nested Wolter mirrors

- Effective area approx 0.4 m^2





XMM-Newton 1999-

3 X-ray telescopes each with 58 nested Wolter mirrors

- Effective area approx 0.4 m^2

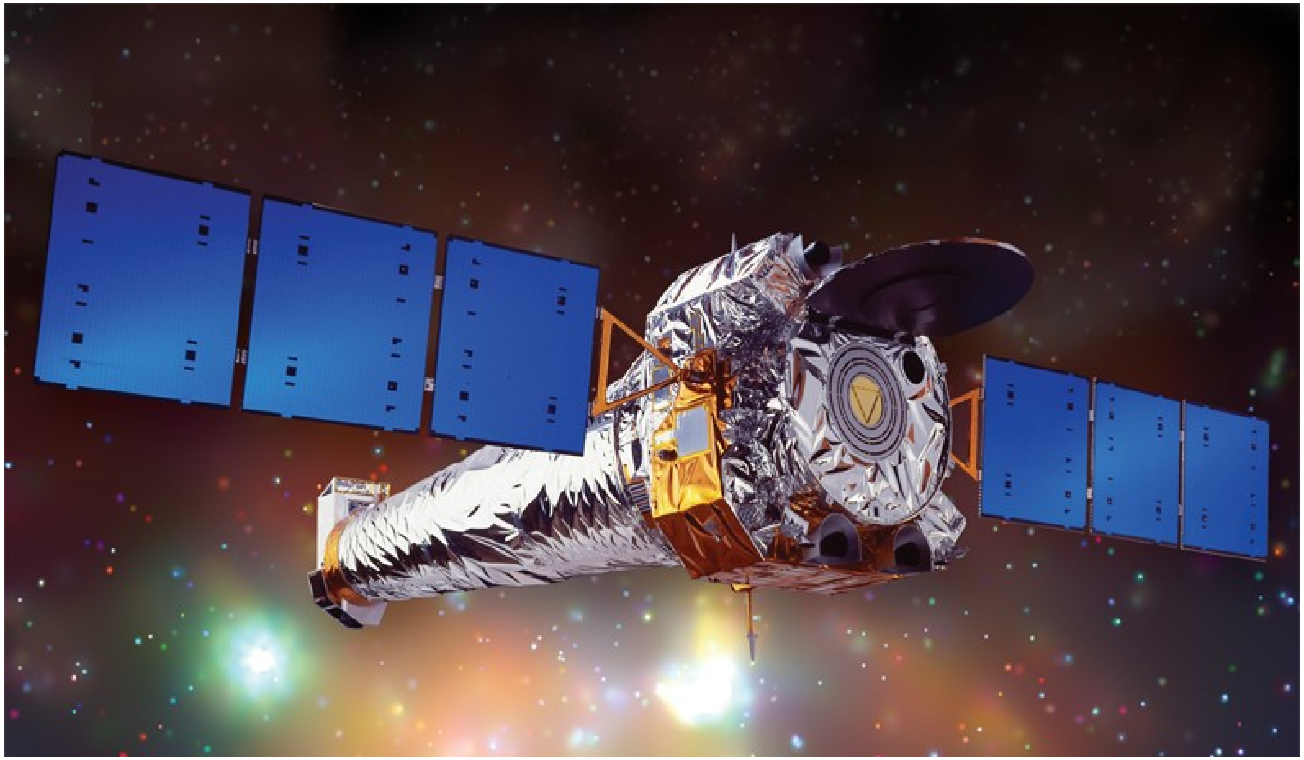
- 3 CCD cameras
- 2 diffraction gratings for improved spectroscopy
- ESA mission


XMM-Newton and Earth

Chandra X-ray Observatory 1999-

Single X-ray telescope with 4 nested Wolter mirrors

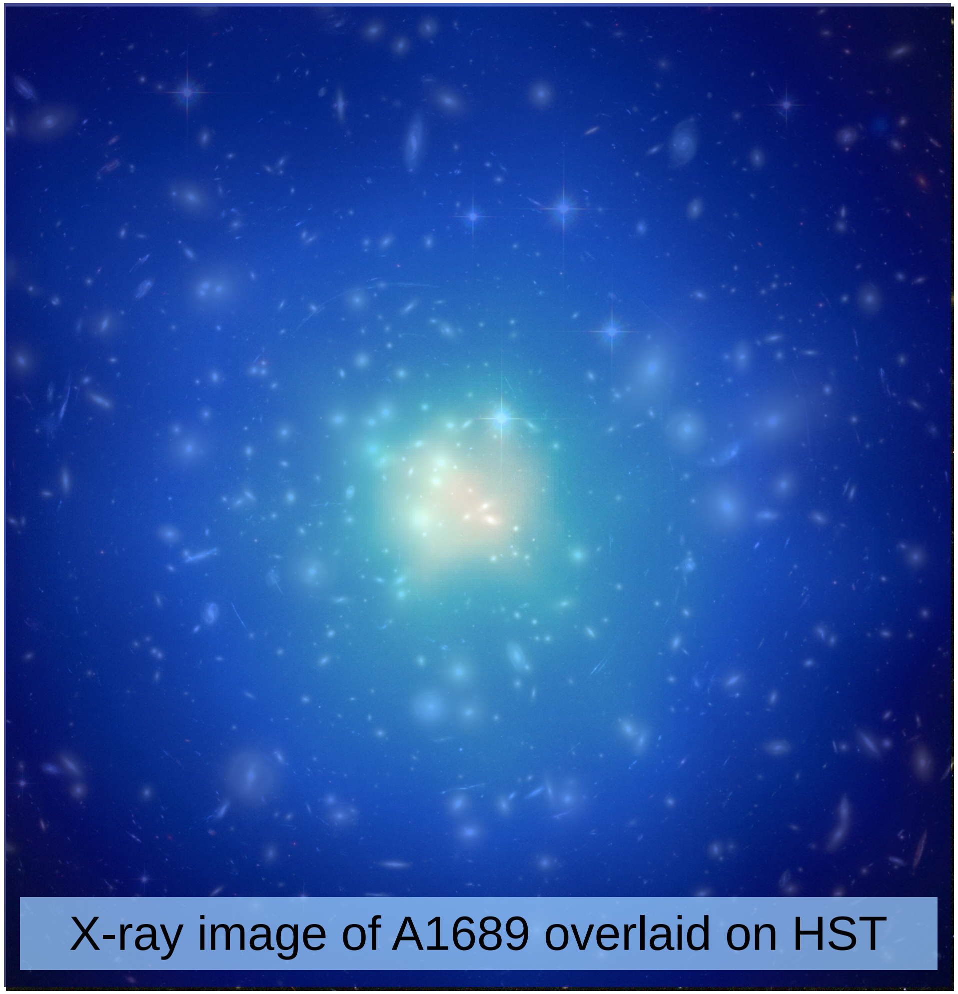
- Effective area approx 0.1 m^2
- Lower sensitivity than XMM-Newton
- PSF of 0.5 arcsec compared to 15 arcsec for XMM
- CCD camera and diffraction grating



X-ray Properties

Galaxy clusters first detected as X-ray sources in 1966 using rocket-based detectors

- Source of emission initially debated
- Better data showed **bremsstrahlung** emission from hot, ionized gas
- Free-free emission from electrons accelerating around ions
- Highly luminous X-ray sources


X-ray image of A1689 overlaid on HST

X-ray Properties

Emissivity of a bremsstrahlung-emitting plasma is:

$$\epsilon_\nu \propto \frac{Z^2 n_e n_i}{T^{1/2}} e^{-\left(\frac{h\nu}{kT}\right)}$$

ε = energy emitted per unit frequency, time and volume

n_e, n_i = number densities of electrons and ions

Z = charge on ion, T = temperature, ν = frequency

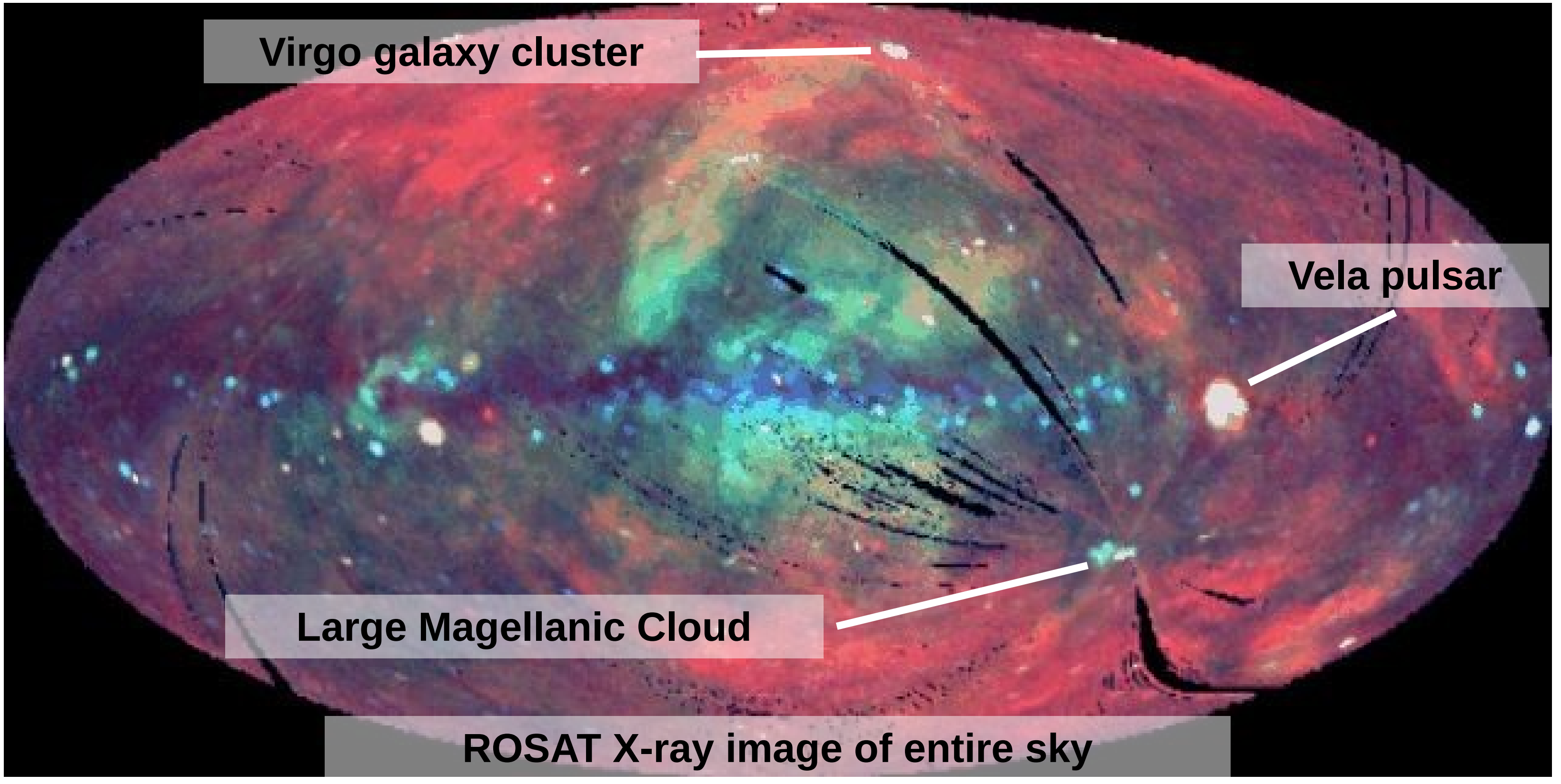
The luminosity of the **intra-cluster medium (ICM)** is given by integral of ε over all frequencies and then over volume of cluster

$$L_X \propto \int n_e n_i T^{1/2} dV \qquad (1.1)$$

- Depends strongly on ρ, more weakly on T

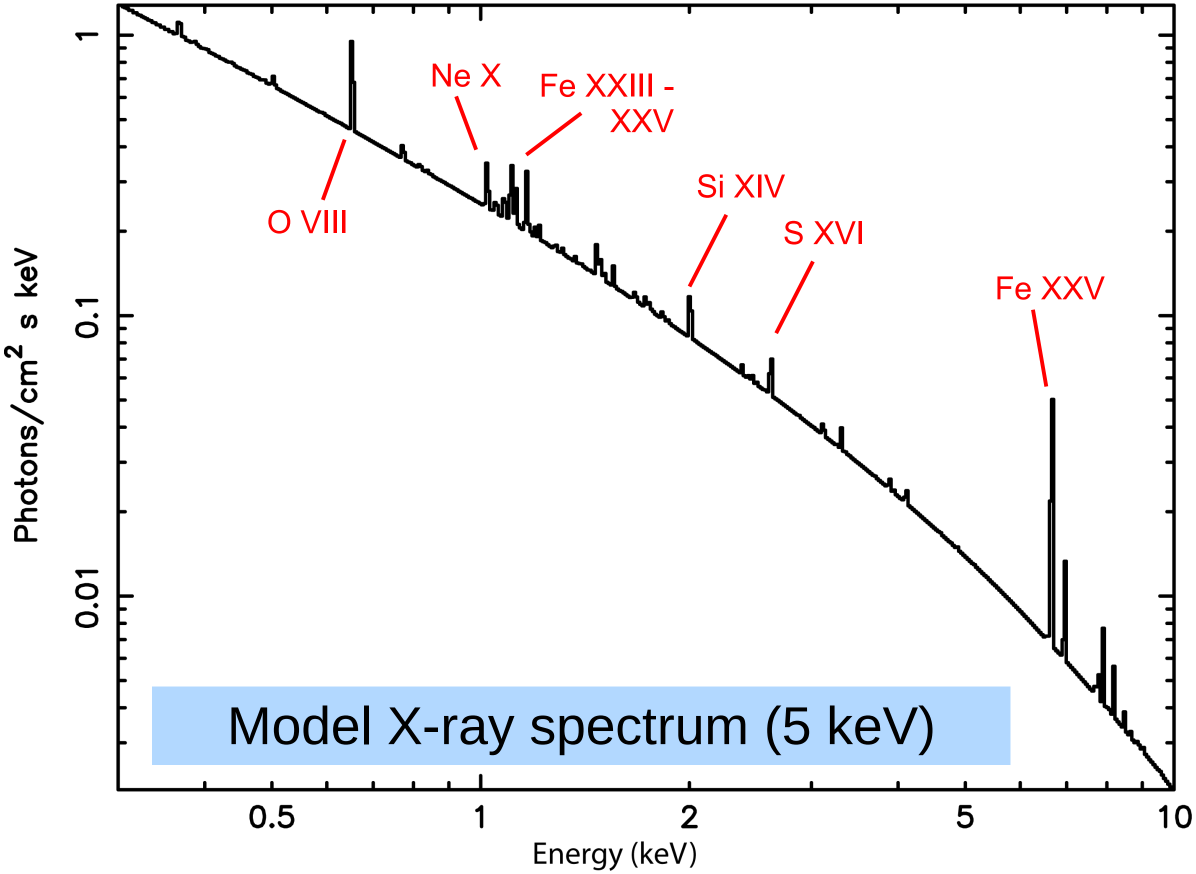
X-ray Properties

- **Intensity of X-ray emission $\propto \rho^2$**
- High X-ray luminosity (**Lx**) means clusters detectable to high z
- Large samples of clusters detected in X-ray surveys



X-ray Spectra

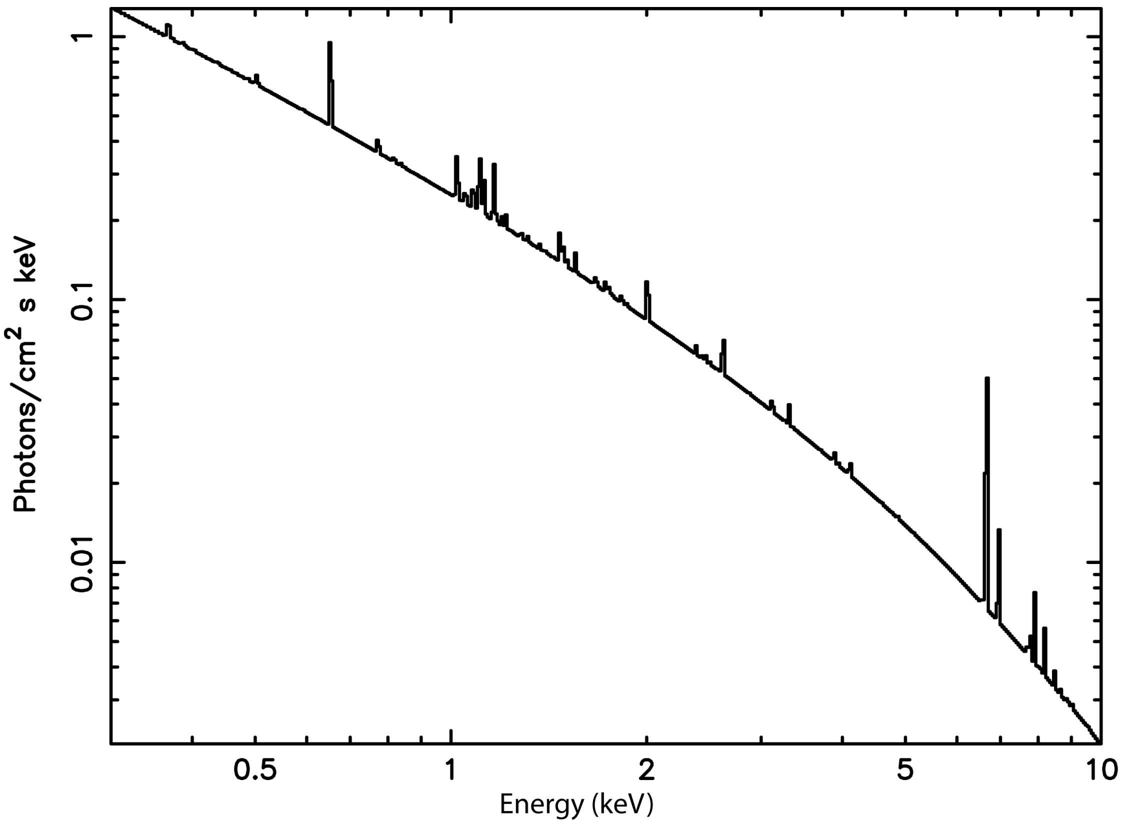
- X-ray emitting gas (ICM) composed of H, He, and trace heavier elements
- X-ray spectra of ICM show continuum from bremsstrahlung and line emission from e.g. Fe, Si
- Metal abundances indicate ICM been processed through stars



n.b. Fe XXV means Fe^{25+}

X-ray Spectra

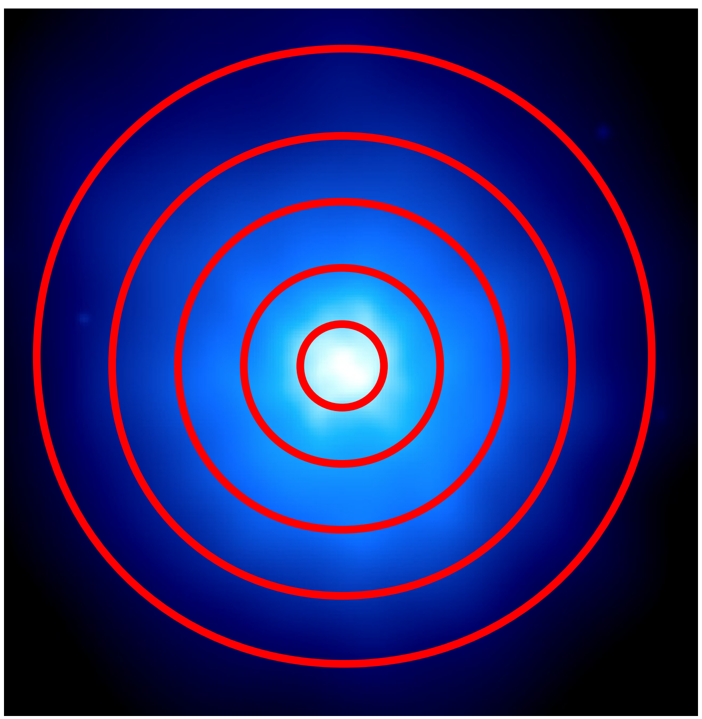
- Models fit to observed X-ray spectra give temperature (**kT**) of the ICM
- kT in range 1 to 15 keV

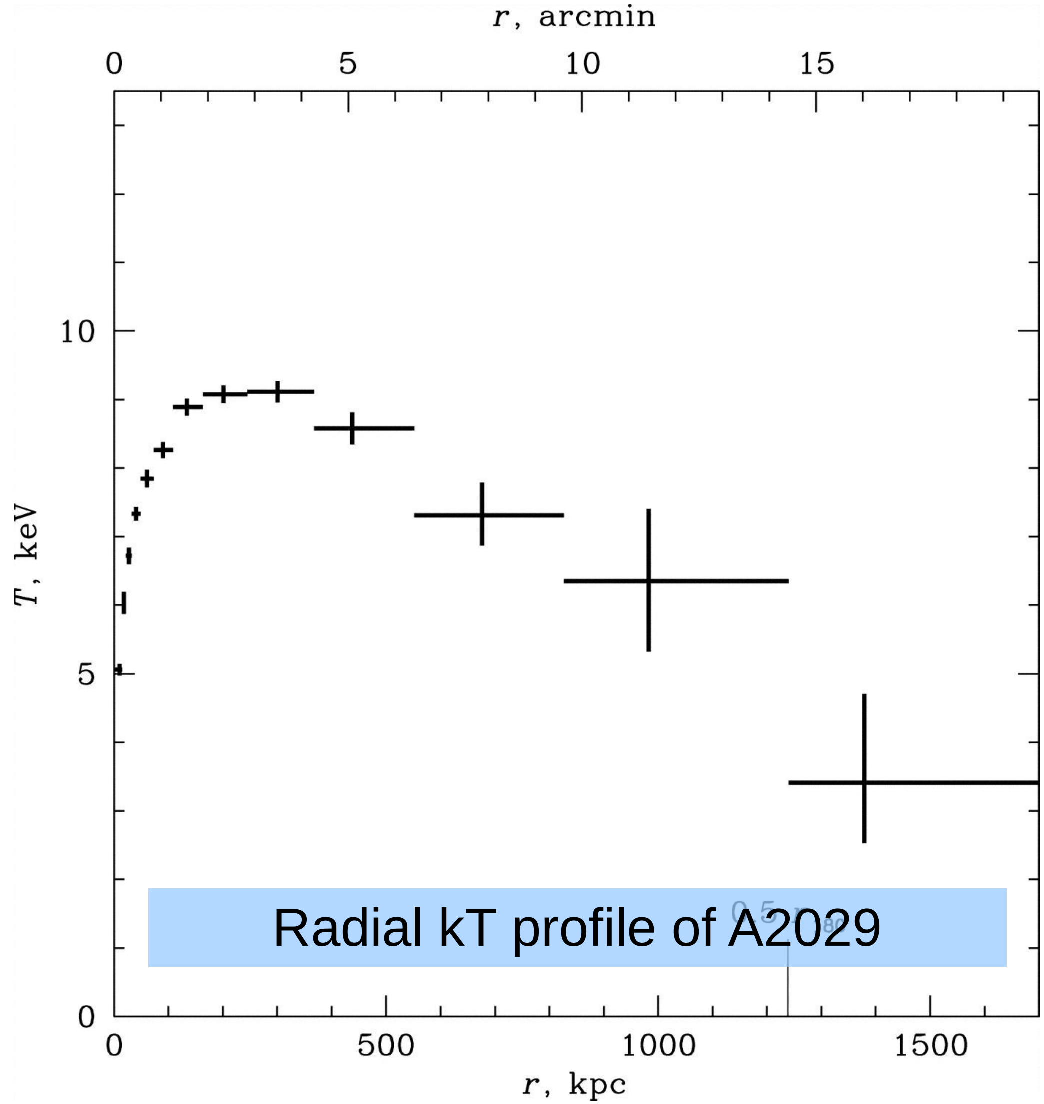


- Gas heated to these temperatures during cluster formation
- kT gives mean KE of gas particles
- Apply virial theorem to give cluster mass
- Again, dark matter is required

X-ray kT Profiles

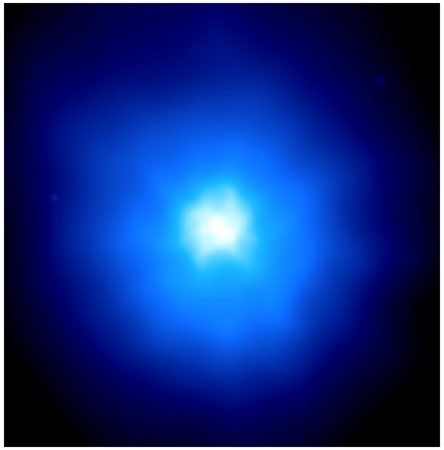
- Measure kT in several annular regions if data is good enough
- Gives kT and its gradient as a function of radius

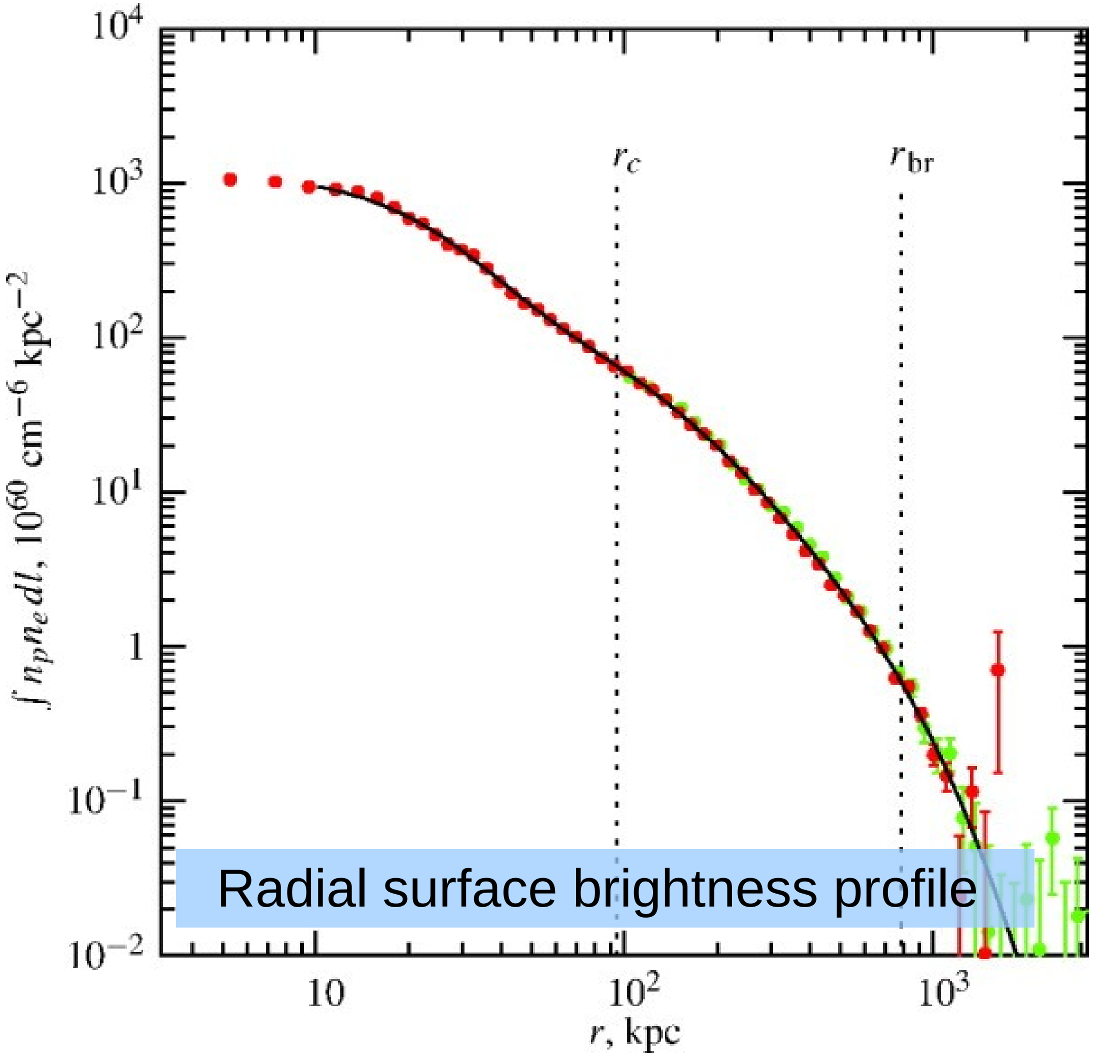




X-ray Surface Brightness Profiles

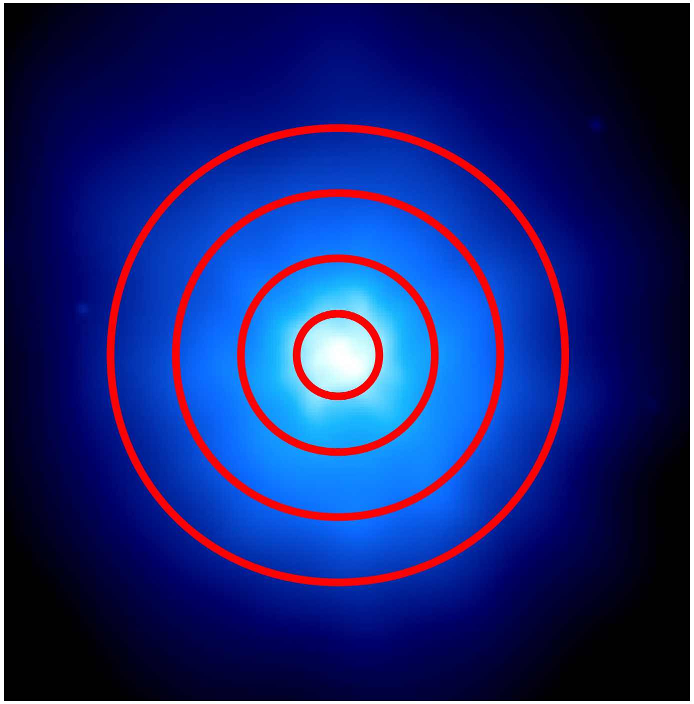
- Surface brightness profiles show the distribution of the ICM density
- Fit model to observed SB profiles to recover ICM density and its gradient as function of radius

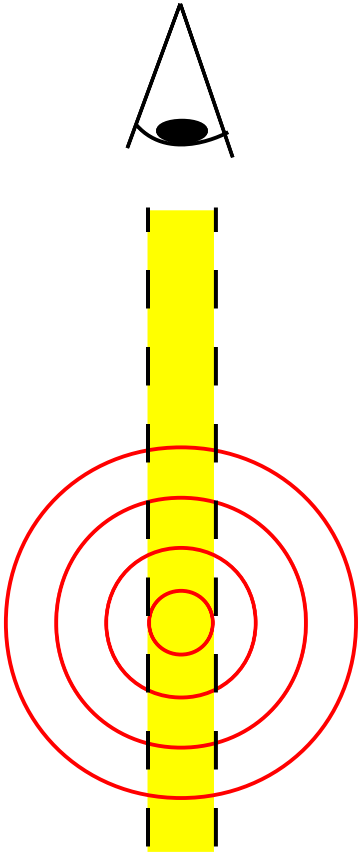




CAUTION! Projection Effects

- Observed surface brightness and kT profiles are a projection along line of sight of the true 3D emission
- When we look at centre of cluster we are looking through outer parts of cluster too
  - – contributes to measurements





Hydrostatic Equilibrium

- If the ICM is in hydrostatic equilibrium with total gravitational potential (pressure balances gravitation):

$$M(r) = \frac{-r^2}{G\rho(r)} \frac{dP}{dr}$$

- Which, for an ideal gas gives:

$$M(r) = \frac{-r^2 k}{G \mu m_p \rho(r)} \left[\rho(r) \frac{dT}{dr} + T(r) \frac{d\rho}{dr} \right]$$

- So measuring T(r) and ρ(r) of gas allows us to derive M(r) for total mass **including dark matter**

Example: Hydrostatic Equilibrium

Starting with eqn hydro eqm, and using ideal gas law (PV = nRT = NkT) show that

$$M(r) = \frac{-r^2 k}{G\mu m_p \rho(r)} \left[\rho \frac{dT}{dr} + T \frac{d\rho}{dr} \right]$$

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$$M(r) = \frac{-r^2}{G \rho(r)} \frac{dP}{dr} \quad \text{(a)}$$

$$PV = NkT = \frac{M_{gas}}{\mu m_p} kT$$

Where μ is mean atomic mass per particle & m_p is proton mass

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Where μ is mean atomic mass per particle & m_p is proton mass

$$P = \frac{\rho k T}{\mu m_p}$$

$$\frac{dP}{dr} = \frac{k}{\mu m_p} \frac{d}{dr}(\rho T) = \frac{k}{\mu m_p} \left[\rho \frac{dT}{dr} + T \frac{d\rho}{dr} \right]$$

substitute into (a):

$$M(r) = \frac{-r^2 k}{G \mu m_p \rho(r)} \left[\rho \frac{dT}{dr} + T \frac{d\rho}{dr} \right]$$

Summary of X-ray Properties

- X-ray observations of galaxy clusters allow us to measure these key properties:
  - X-ray luminosity (from images or spectra)
  - kT of the ICM (from spectra)
  - Metal abundances in ICM (from spectra)
  - Density of ICM (from surface brightness profile)
- Combining radial profiles of kT and ρ of ICM we can infer total mass assuming hydrostatic equilibrium

Summary

Galaxy clusters consists of

- Dark matter (~80%), hot gas (~15%), galaxies (~5%)

Galaxy cluster studies important for

- Measuring cluster masses for cosmology
- Investigating physical processes in clusters

Observations at different λ and simulations used

X-ray observations particularly powerful

- Detect clusters to high-z
- Measure ICM properties
- Infer total cluster mass