# II. Observing Galaxy Clusters

# Summary

- Density contributions of mass and dark energy expressed in terms of $\rho_c$
- Several distance measures in expanding Universe
  - observable distances $d_A$, $d_L$ related to z via E(z)
  - derive E(z) and constrain $\Omega_M$, $\Omega_\Lambda$ by measuring d
- Volume also sensitive to E(z) – constraints from known number densities
- Dark Energy thought of as fluid with $p_\Lambda = w\rho_\Lambda$
  - can constrain w by measuring E(z)
- Growth of structure depends on cosmological parameters
  - through competition between collapse and expansion (E(z))
  - clusters sensitive to $\sigma_8$ - variance of initial density distribution

# Growth of Structure

In addition to geometrical tests (distances and volumes), can constrain cosmology by growth of structure

Tiny density perturbations in early Universe grow to form observed large scale structure

★ growth sensitive to cosmology

Model density variation in terms of density contrast δ

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

where $\rho$ is density in a region and $\bar{\rho}$ is mean matter density

★ N.B. δ depends on size of region considered

# Growth of Structure

- Regions with δ>0 are overdense and tend to collapse
- Regions with δ<0 are underdense and tend to grow less dense

In non-expanding Universe, overdense regions collapse exponentially

In expanding Universe, collapse must compete with expansion

- regions denser than a critical value will collapse
- analogous to Universe as a whole

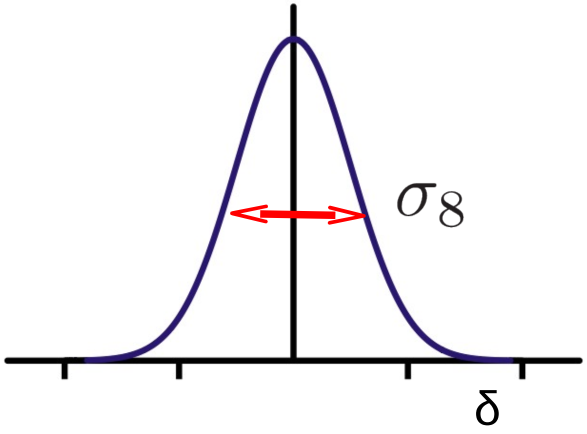
# Growth of Structure

Growth of structure thus sensitive to

- ★ initial density distribution
- ★ expansion history of Universe – i.e. E(z)

Galaxy clusters sensitive to amplitude of δ distribution

- ★ measured via $\sigma_8$
- ★ sd of δ values measured in spheres of radius 8 Mpc

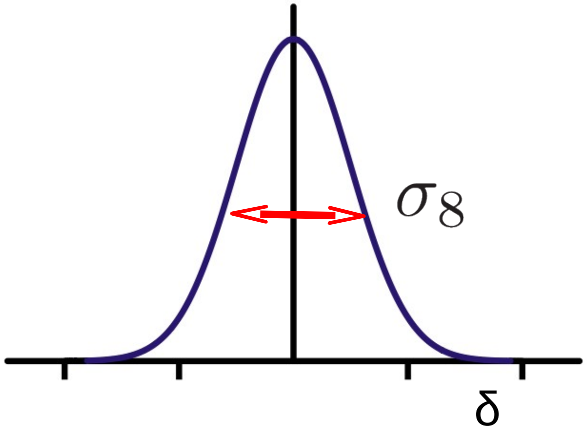


# Growth of Structure

Larger values of $\sigma_8$ correspond to less uniform initial density distribution

★ more structure in Universe

Clusters grow from high δ tail of distribution so number of clusters very sensitive to $\sigma_8$

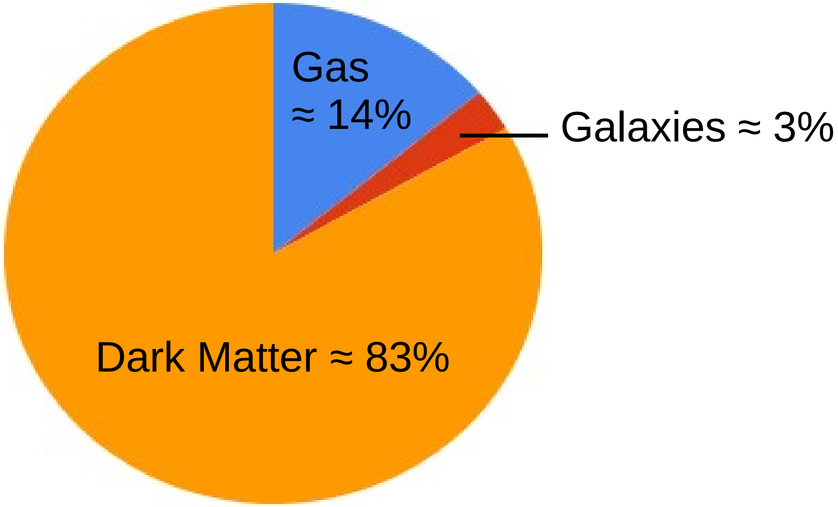


# Observing Galaxy Clusters

- Growth of structure
- 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

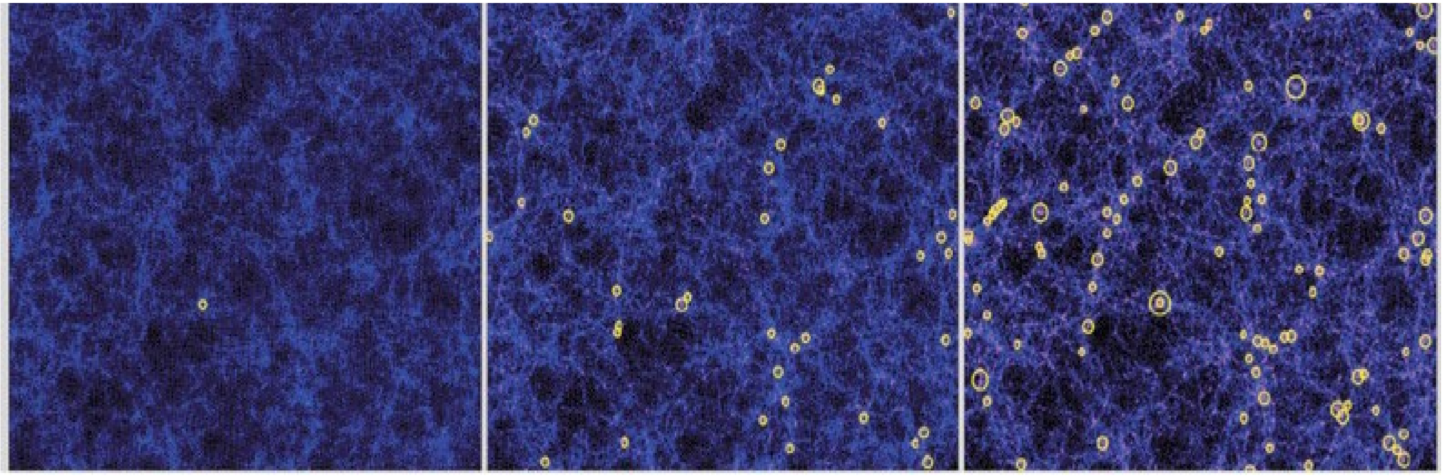
- Take approx $10^{15}M_\odot$ dark matter
- Marinade in approx $10^{14}M_\odot$ hot ($10^7$K) ionised gas
- Sprinkle with 100's of galaxies of various shapes and sizes ($\sim10^{13}M_\odot$)
- Finished product approx 2Mpc in radius



# 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

S. Borgani, and L. Guzzo, 2001, Nature, 409, 39-45

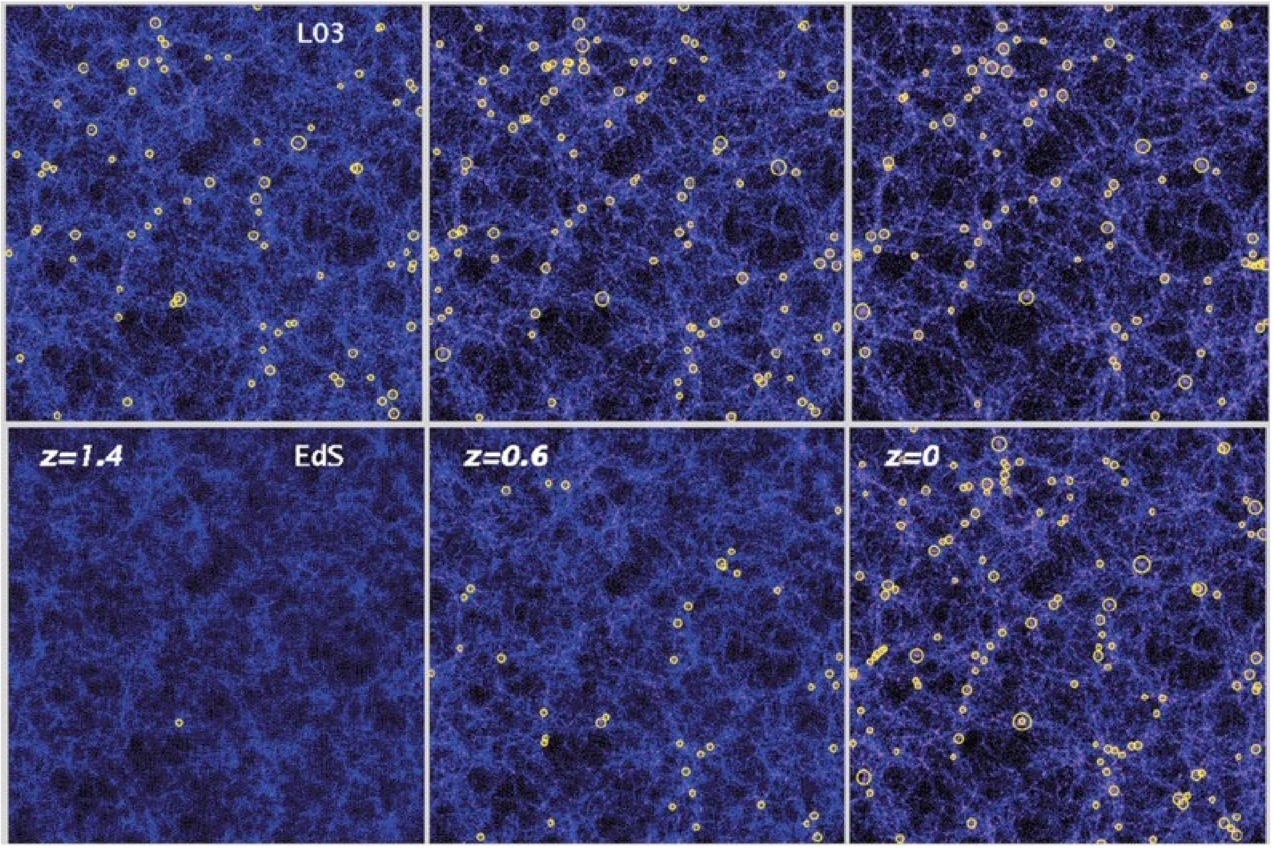
# Clusters & Cosmology

Growth of large scale structure traced by clusters

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

Flat Universe
Λ=0.7

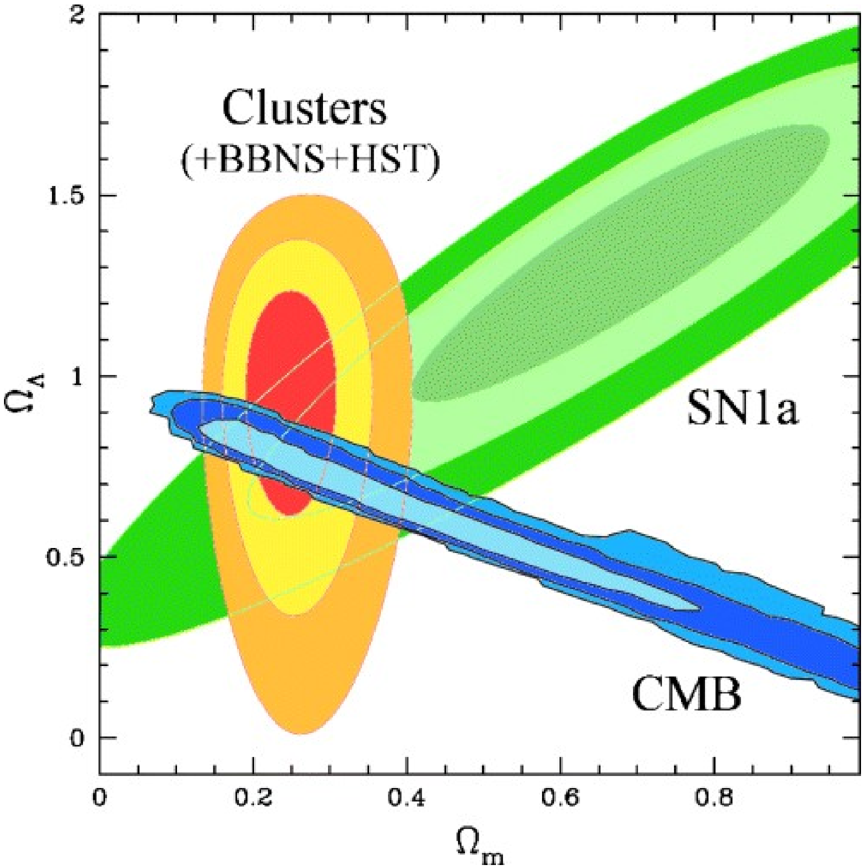
Flat Universe
Λ=0



# 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**

Allen et al, 2008, MNRAS, 383, 879-896

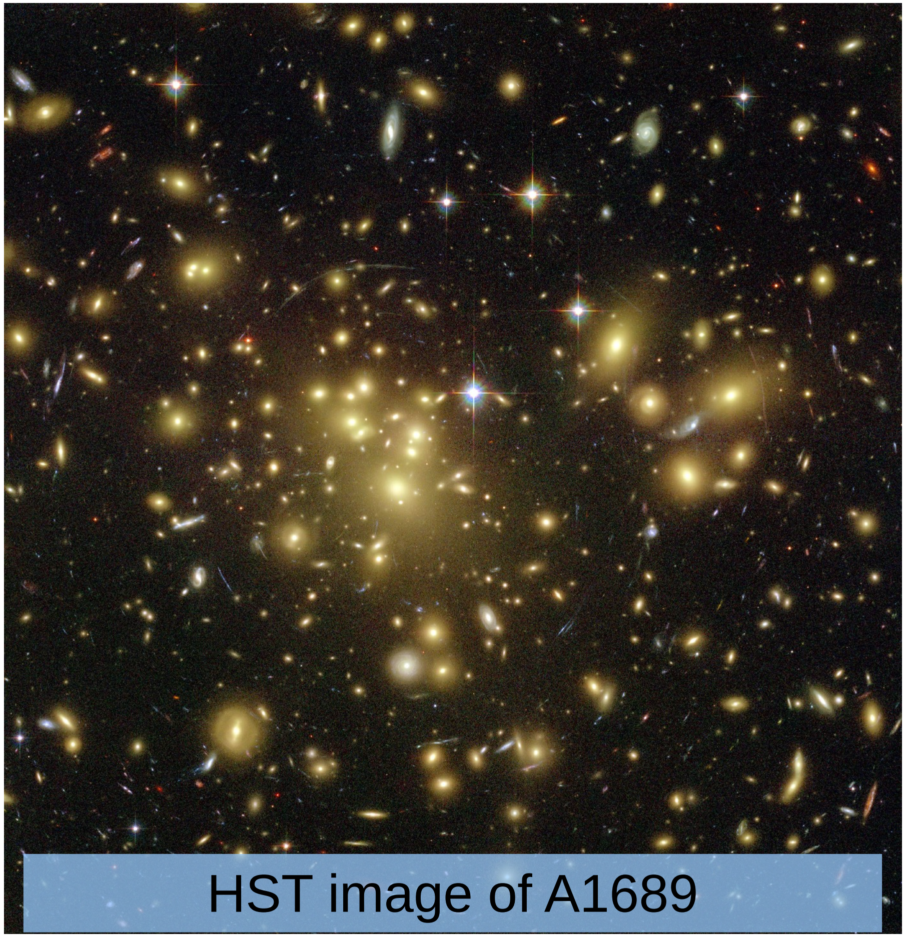
# Optical Properties

First studied in optical

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

Abell (1958) catalogue

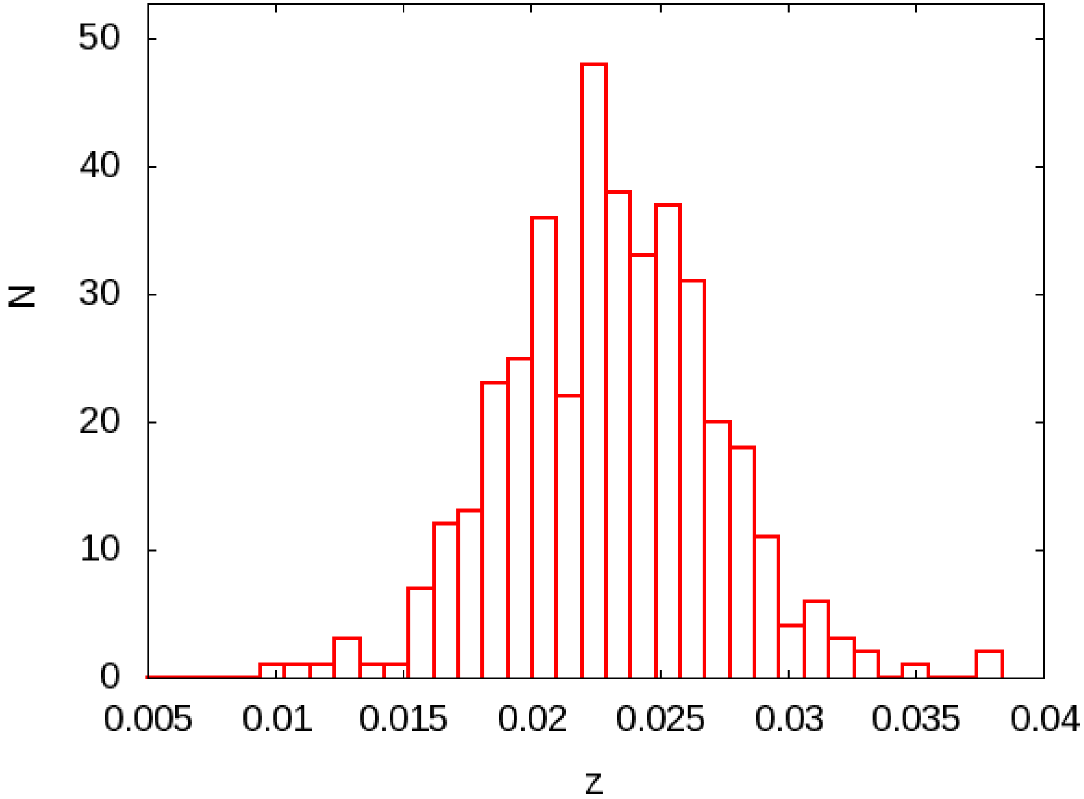
- ★ Detect clusters based on overdensities of galaxies
- ★ Suffers projection effects
- ★ Study richness and morphology of clusters


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?



Redshift histogram for the coma cluster

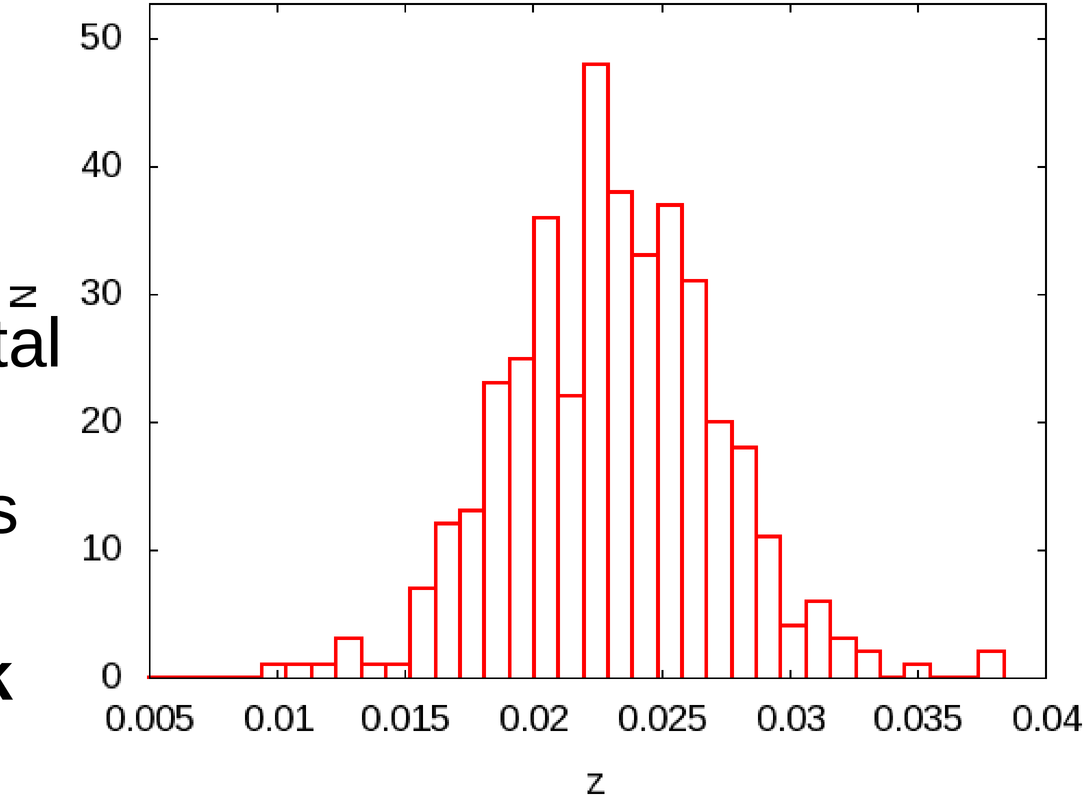
# Optical Properties

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

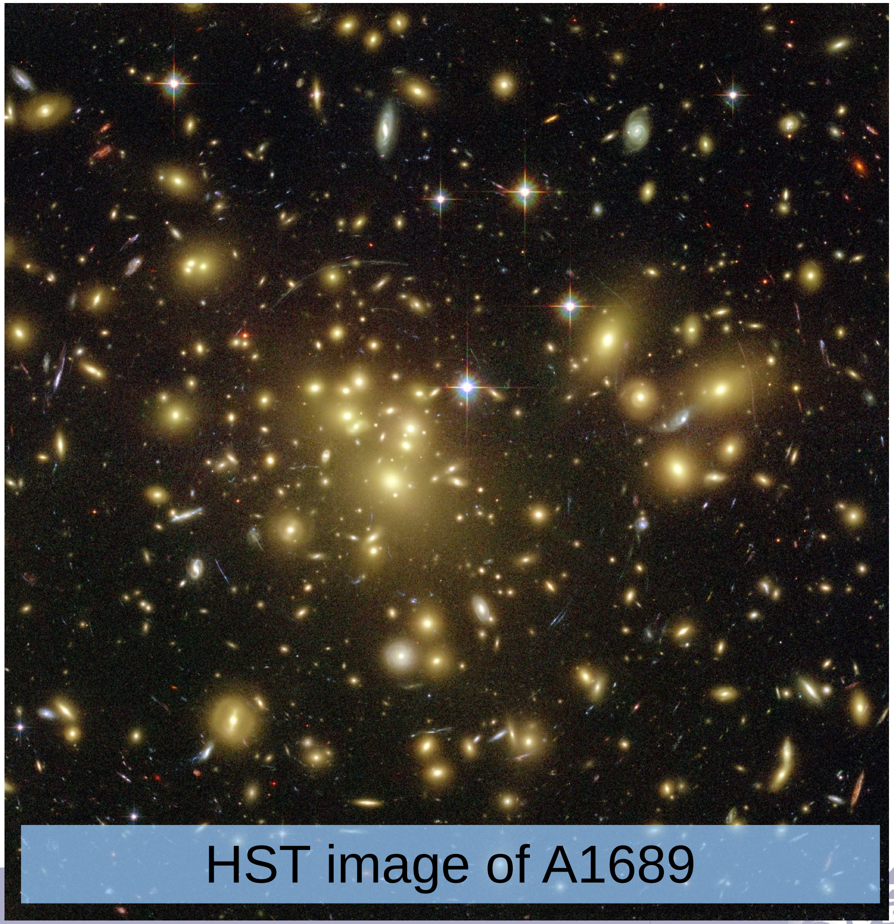
- **Virial theorem** gives total cluster mass
- Zwicky found <1% mass in galaxies
- **First evidence for dark matter**



Redshift histogram for the coma cluster

# Gravitational Lensing

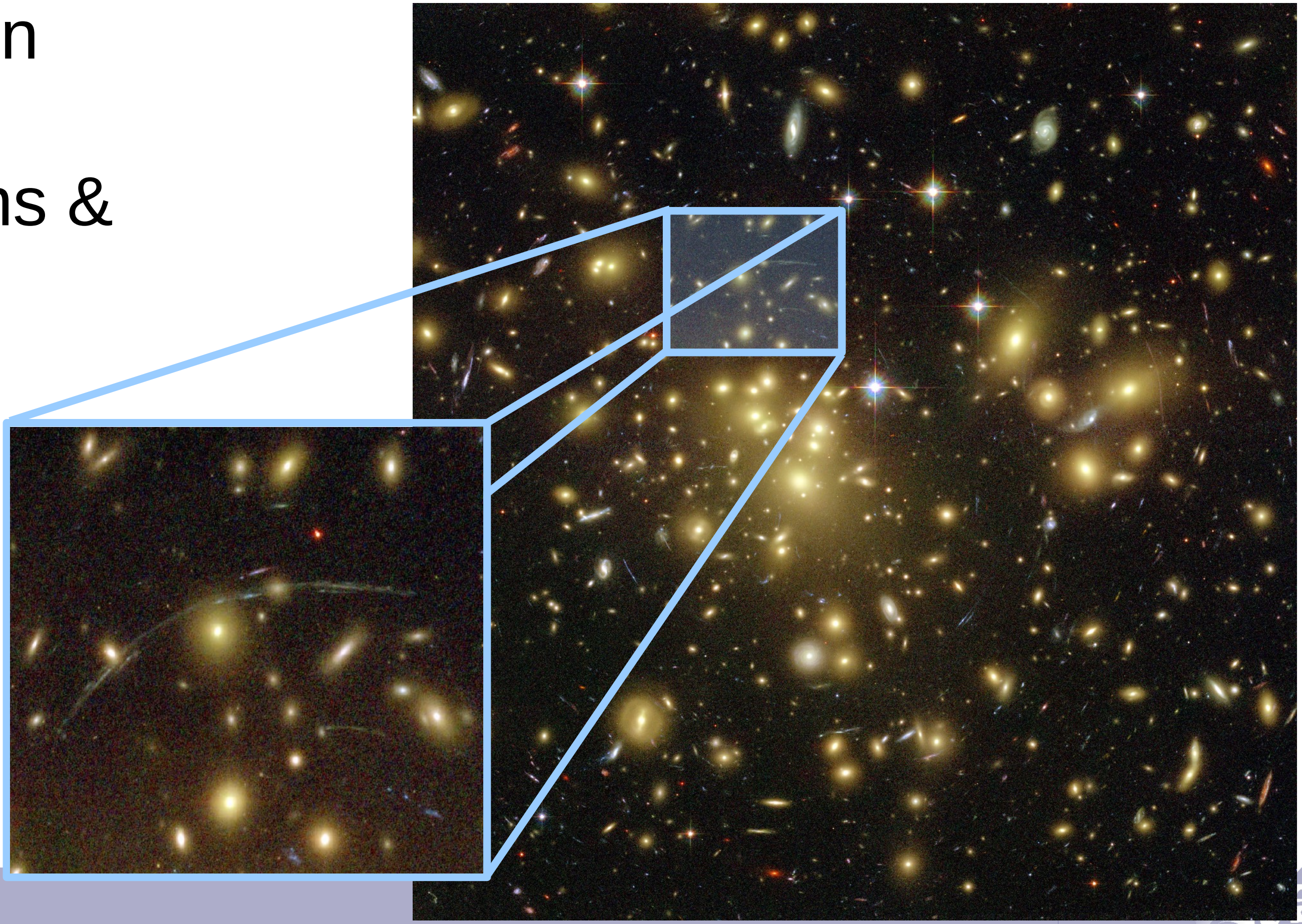
- Deep gravitational potential in clusters acts as gravitational lens
- Distorts shapes of background galaxies
- Effect strongest in cores
- Arc like distortions & multiple images
  - “**Strong lensing**”



HST image of A1689

# Gravitational Lensing

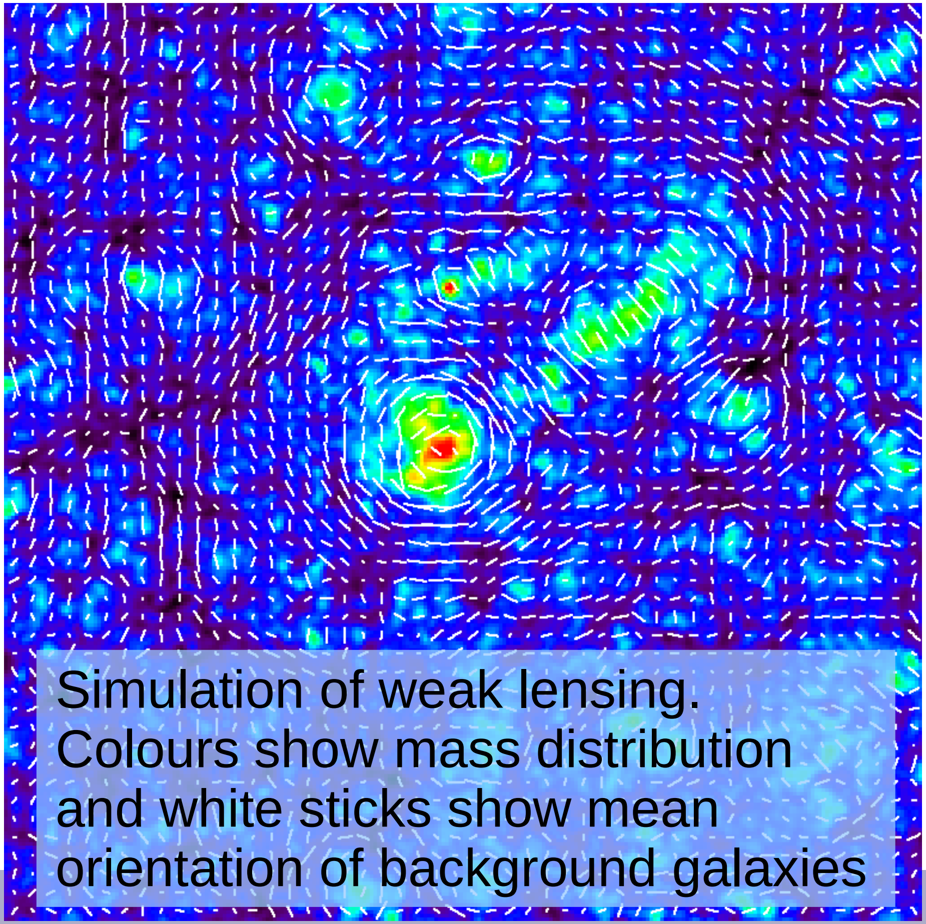
- Deep gravitational potential in clusters acts as gravitational lens
- Distorts shapes of background galaxies
- Effect strongest in cores
- Arc like distortions & multiple images
  - “**Strong lensing**”
- Determine mass structure in cluster cores



# 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

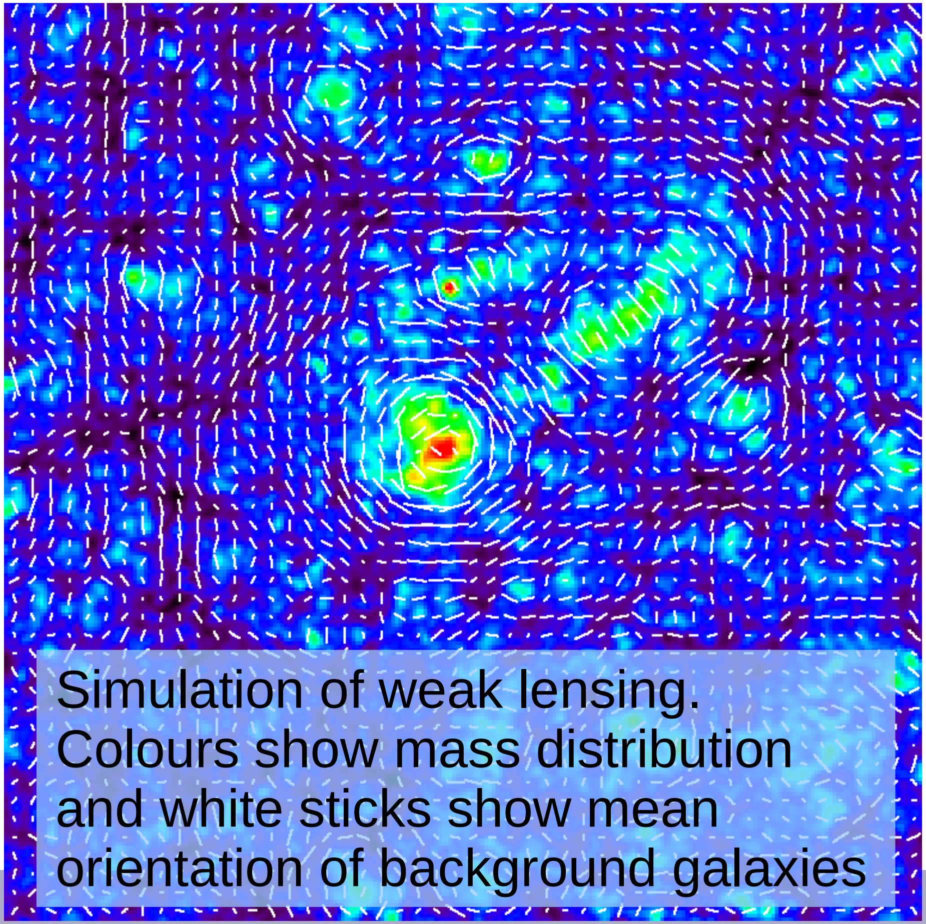
- ★ will be random if no lensing signal

Mellier, araa, 37:127-189, 1999
Hoekstra mnras, 339:1155-1162, 2003

# 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

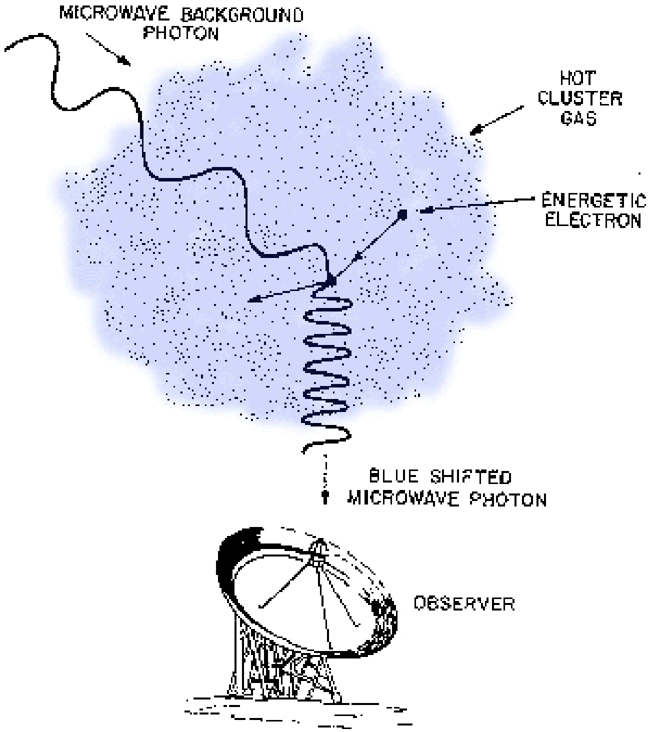
- Introduces uncertainties

Weak lensing gives cluster masses to large radii

- all lensing requires z of bg galaxies
- many for WL

# Sunyaev-Zel'dovich effect

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



e.g. Birkinshaw, physrep , 310:97-195, March 1999

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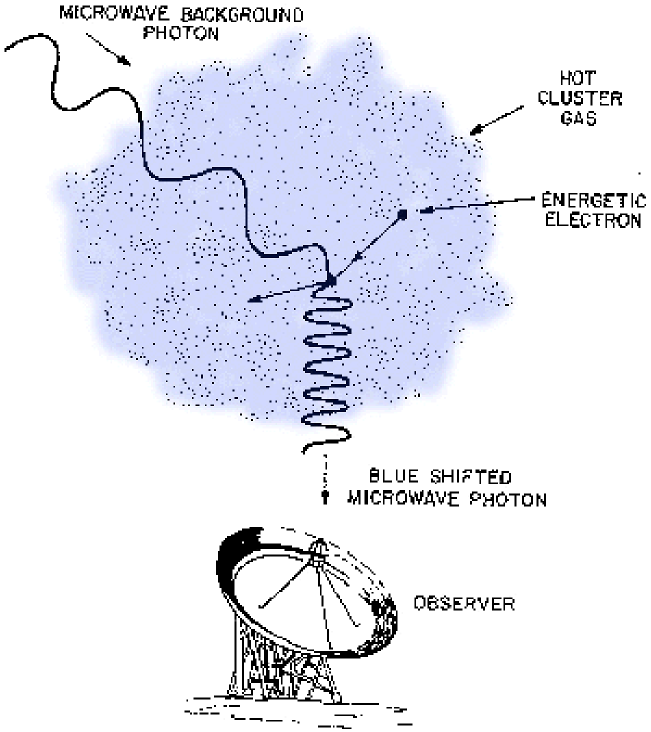
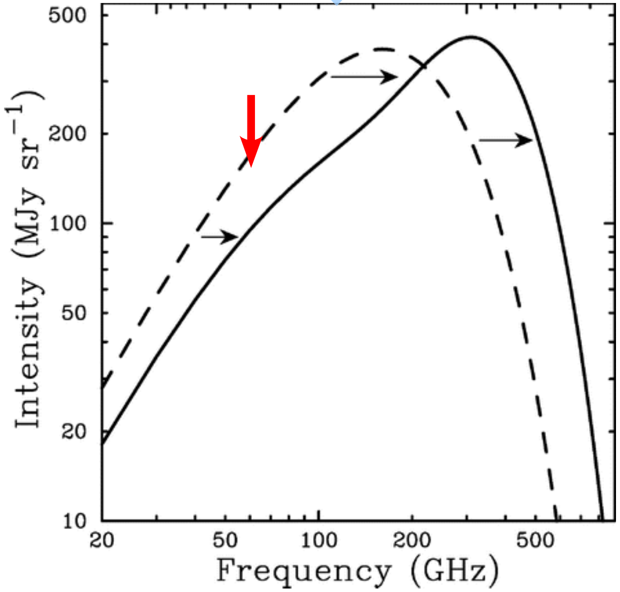
Distorts shape of CMB spectrum – intensity drops at lower frequencies





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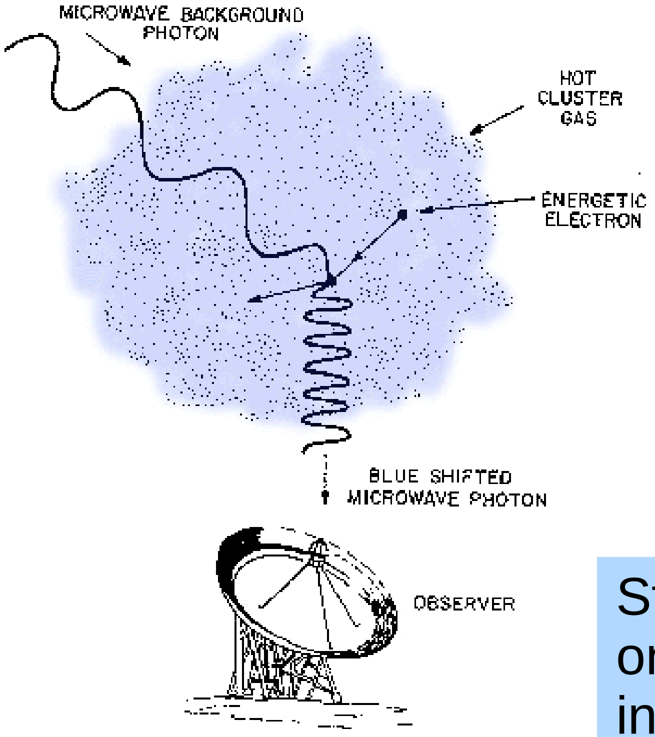
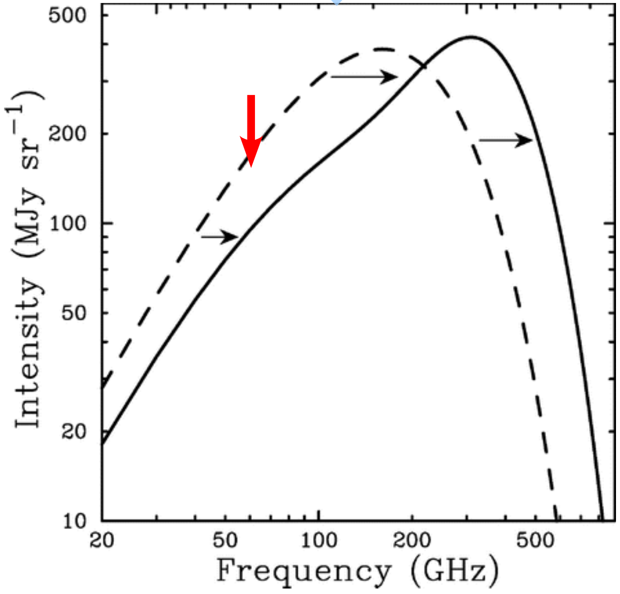
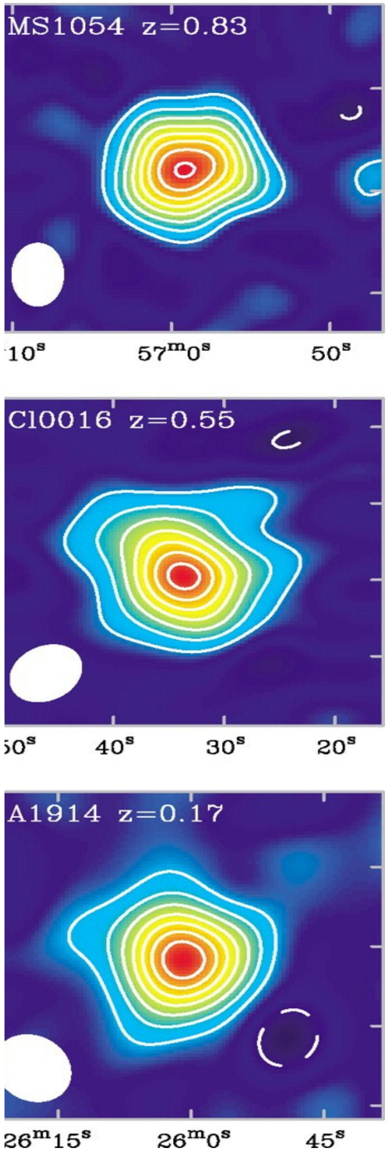




Strength of effect depends on T and ρ of ICM, but is independent of redshift!



e.g. Birkinshaw, physrep , 310:97-195, March 1999

# Sunyaev-Zel'dovich effect

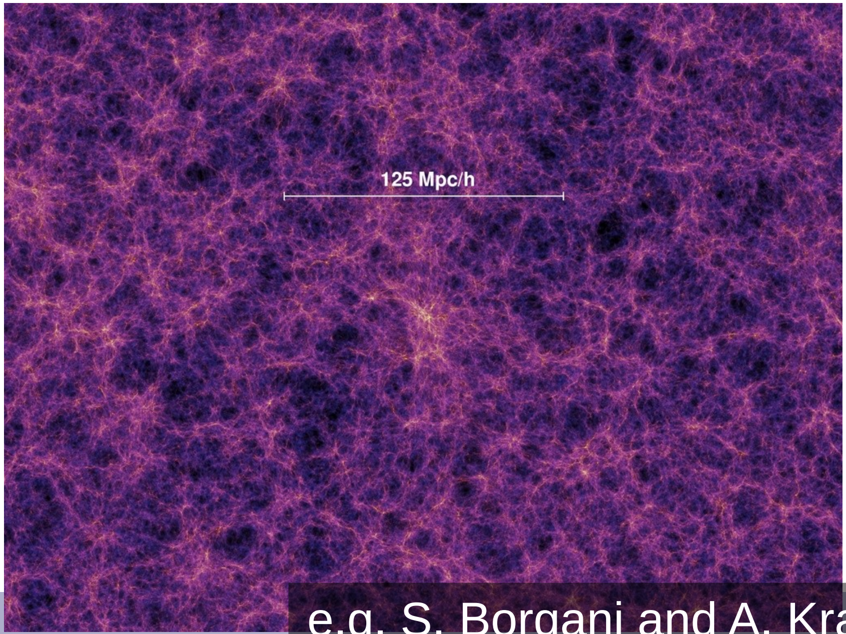
SZ observations give properties of ICM

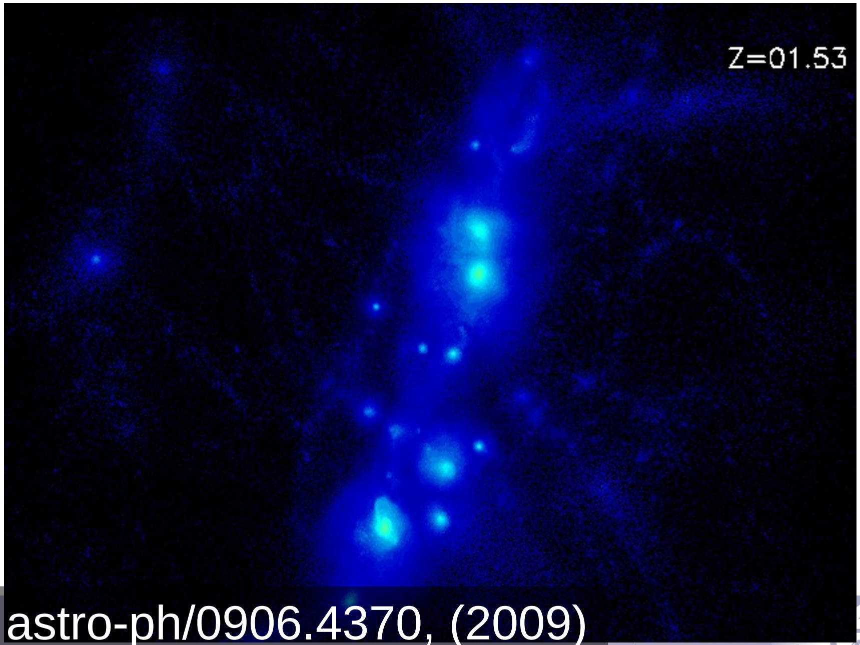
- Can determine cluster masses subject to some assumptions (see X-ray)
- Simulations suggest SZ masses accurate and precise
- Not tested by observations

# 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

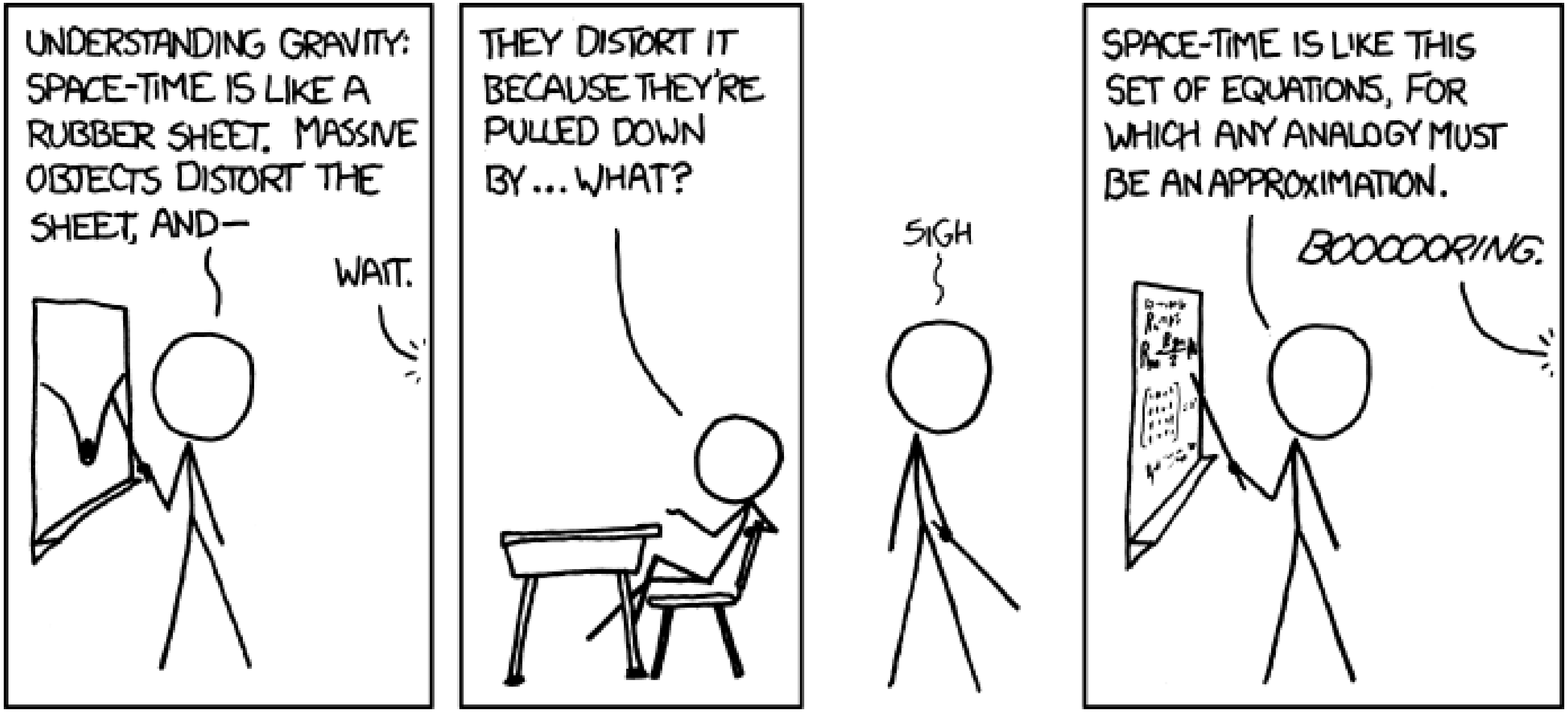




e.g. S. Borgani and A. Kravtsov astro-ph/0906.4370, (2009)

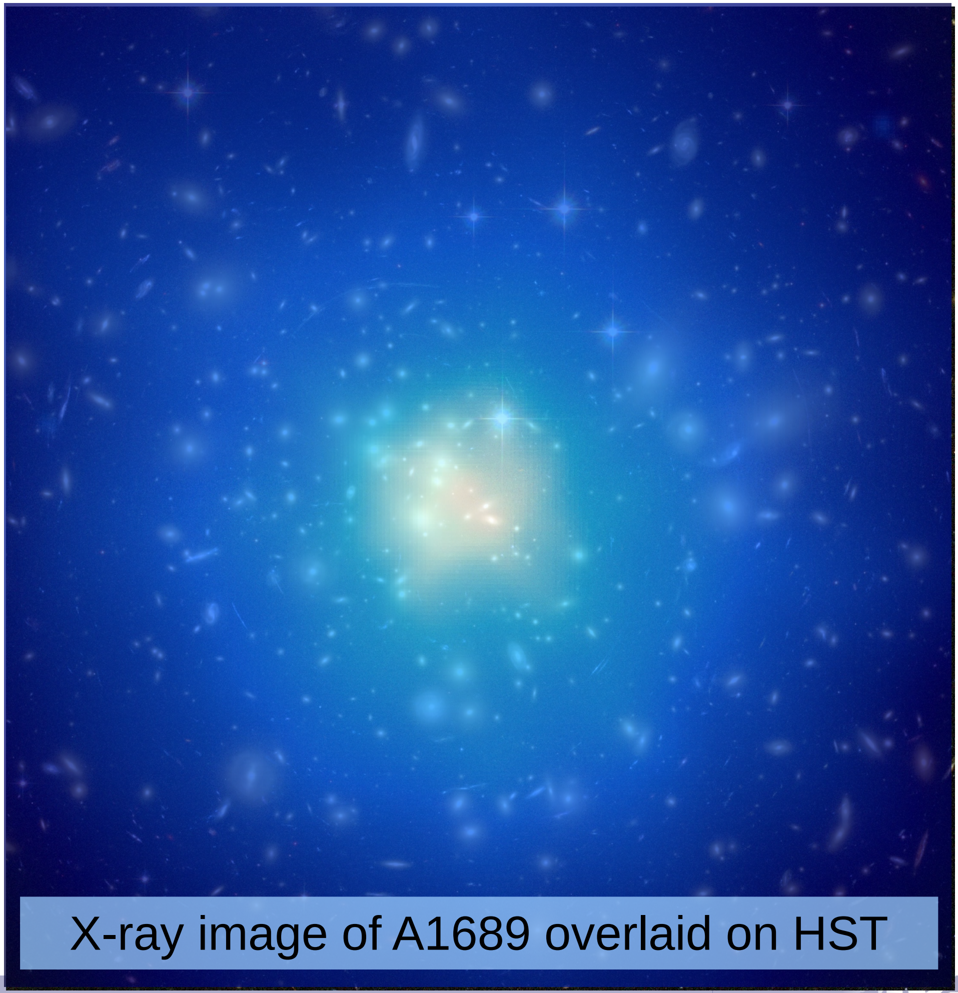
# xkcd break

“Teaching Physics”



# X-ray Properties

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



X-ray image of A1689 overlaid on HST

- ★ 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 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

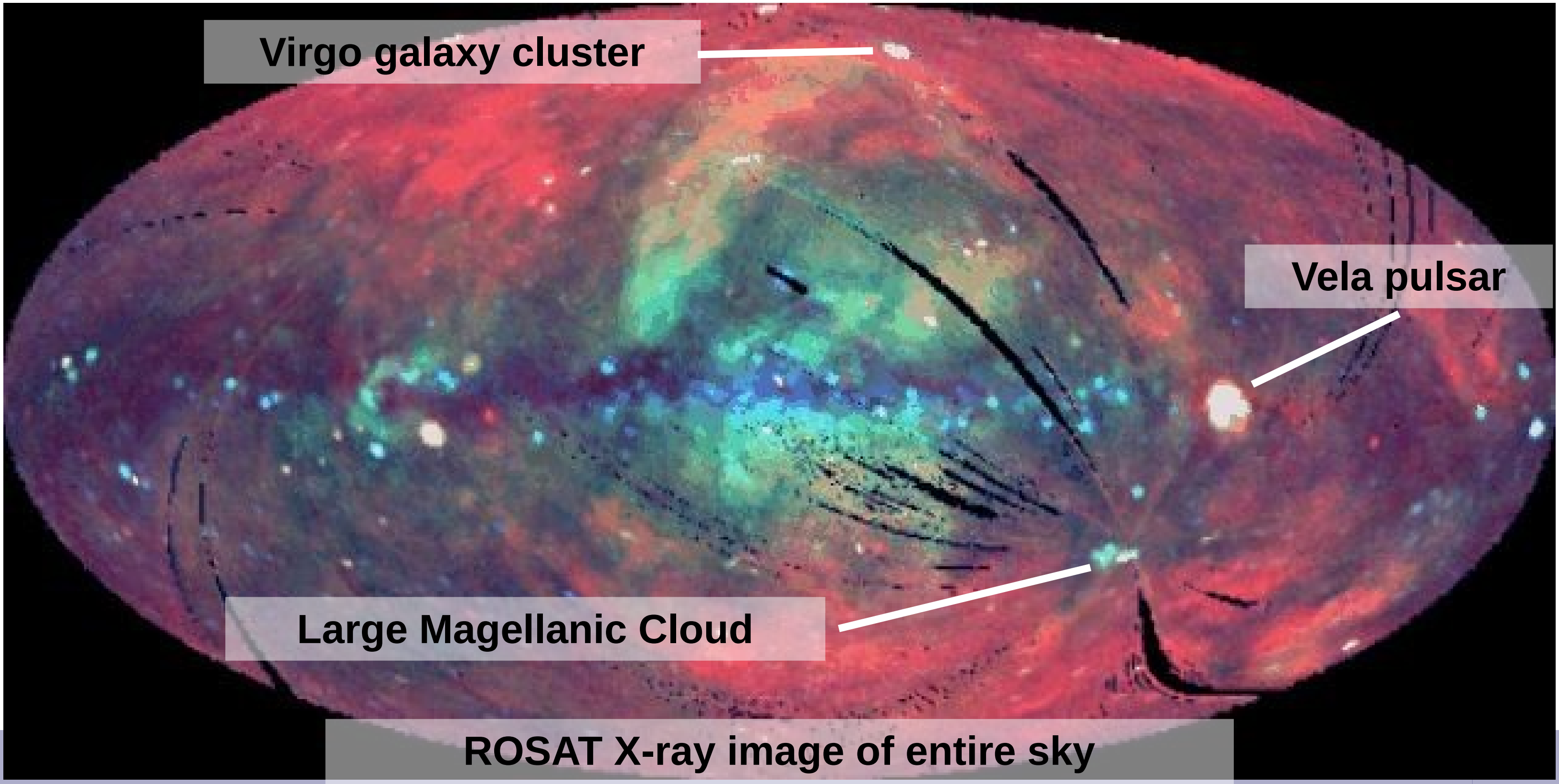
$$L_X \propto \int n_e n_i T^{1/2} dV \qquad (1.1)$$

★ Depends strongly on ρ, more weakly on T

e.g. Sarazin, Reviews of Modern Physics, 58:1-115, 1986.

# X-ray Properties

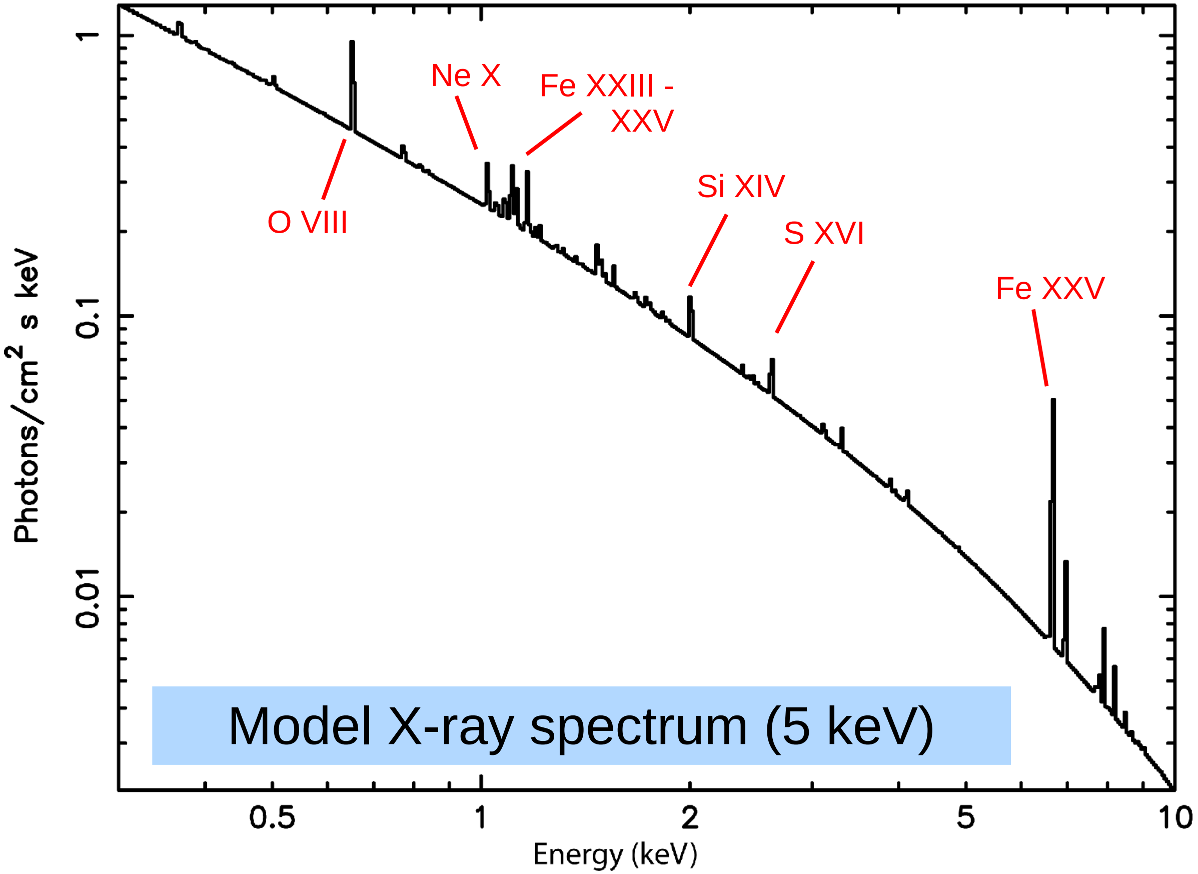
- **Intensity of X-ray emission $\propto \rho^2$**
- High X-ray luminosity (**Lx**) means clusters detectable to high z
- Large samples of clusters detected in X-ray surveys



ROSAT X-ray image of entire sky

# 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

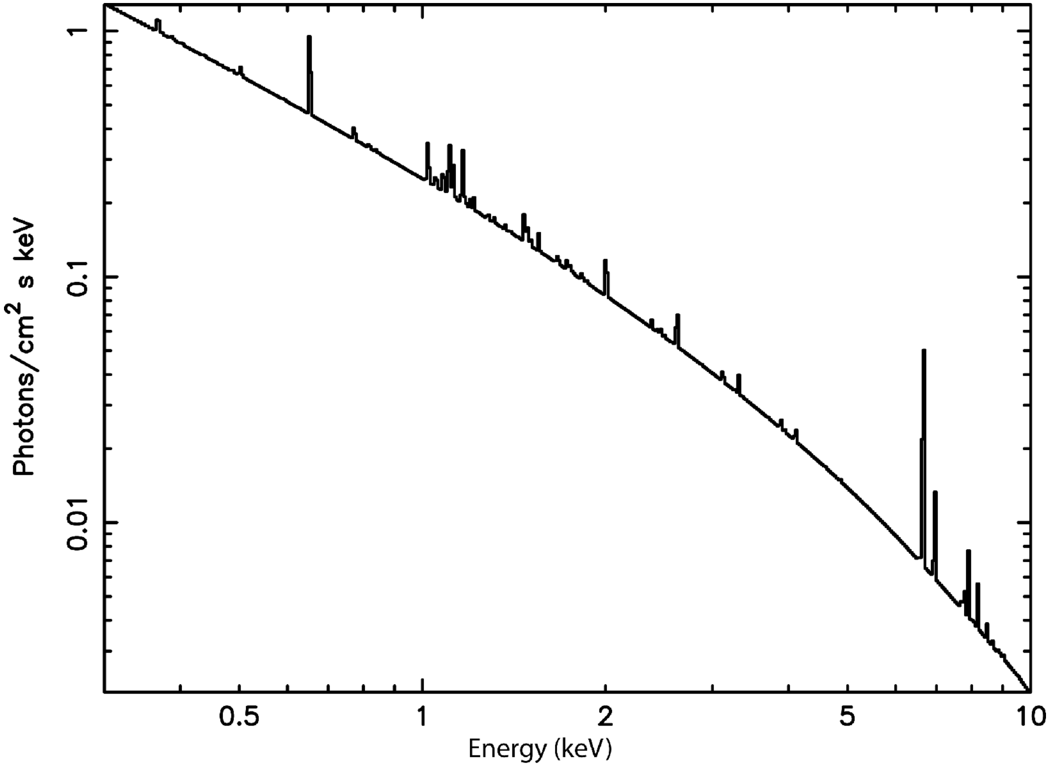


n.b. Fe XXV means $Fe^{25+}$

e.g. H. Böhringer and N. Werner, aapr , 18:127-196, feb 2010

# X-ray Spectra

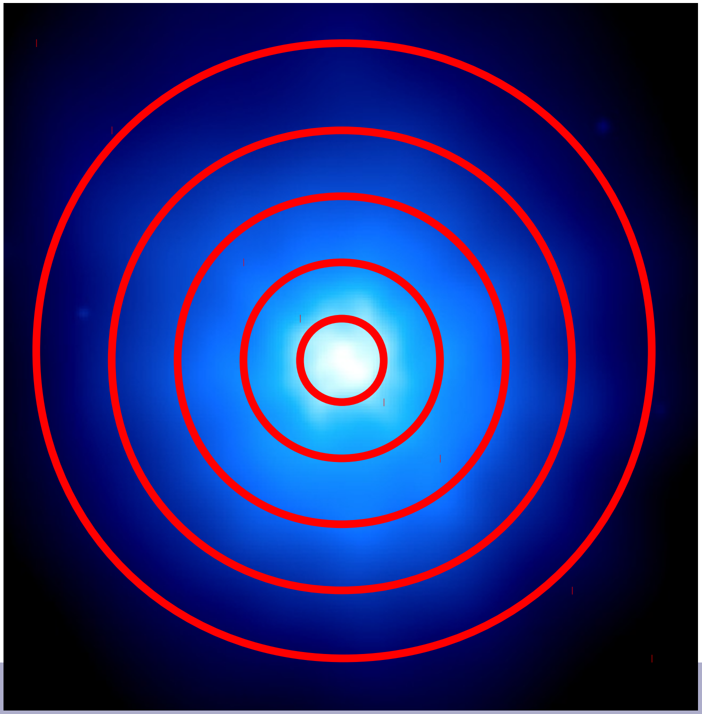
- ★ Models fit to observed X-ray spectra give temperature (**kT**) of the ICM
- ★ kT in range ~1 to ~15 keV

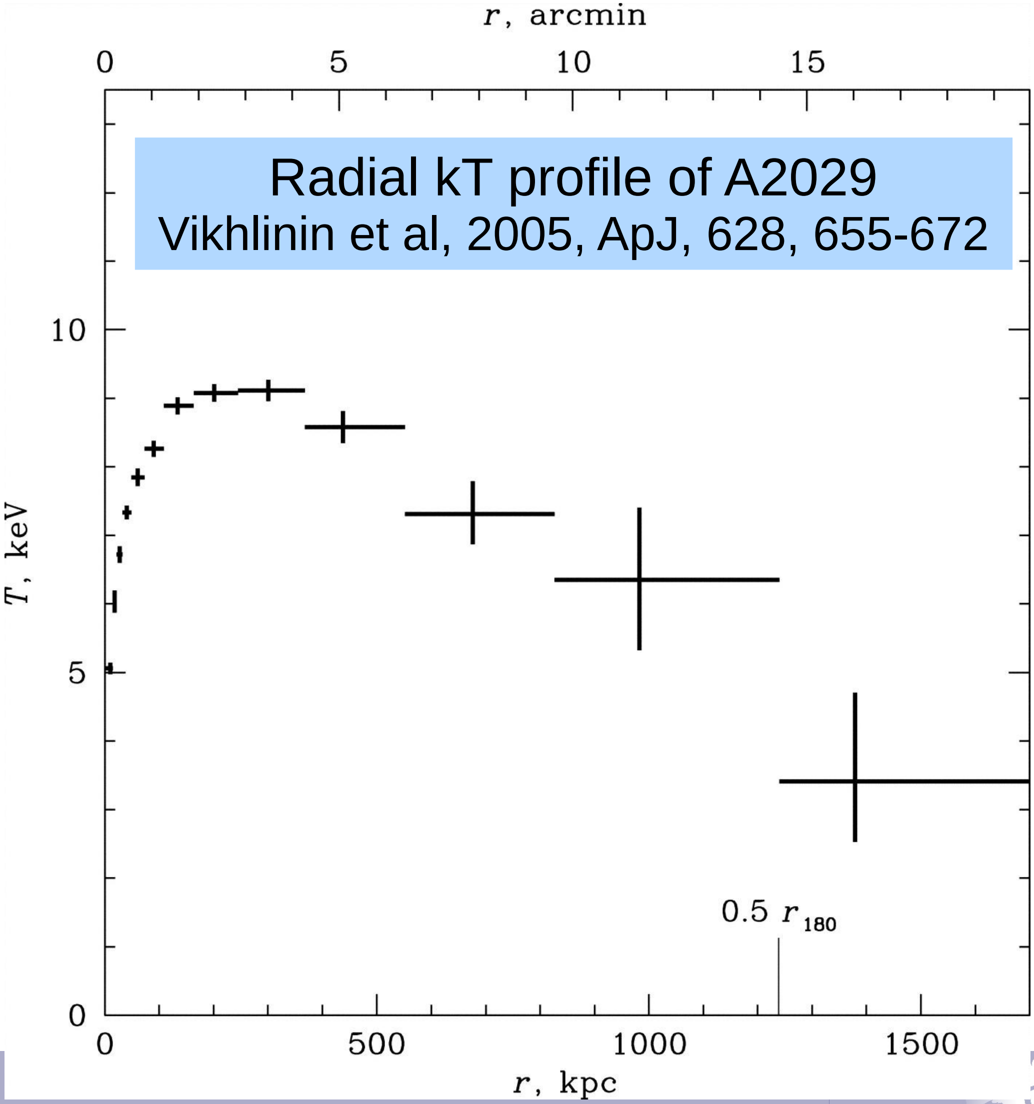


- ★ Gas heated to these temperatures during cluster formation
- ★ kT gives mean KE of gas particles
- ★ Apply virial theorem to give cluster mass
- ★ Again, dark matter is required

# X-ray Temperature Profiles

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

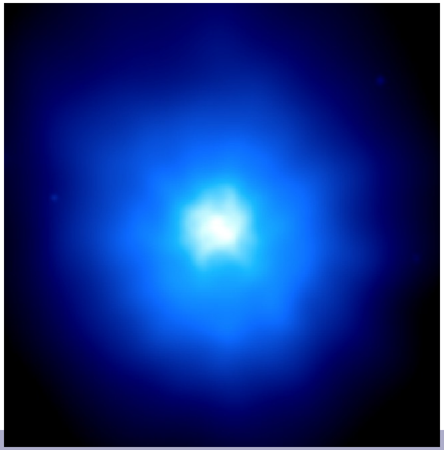


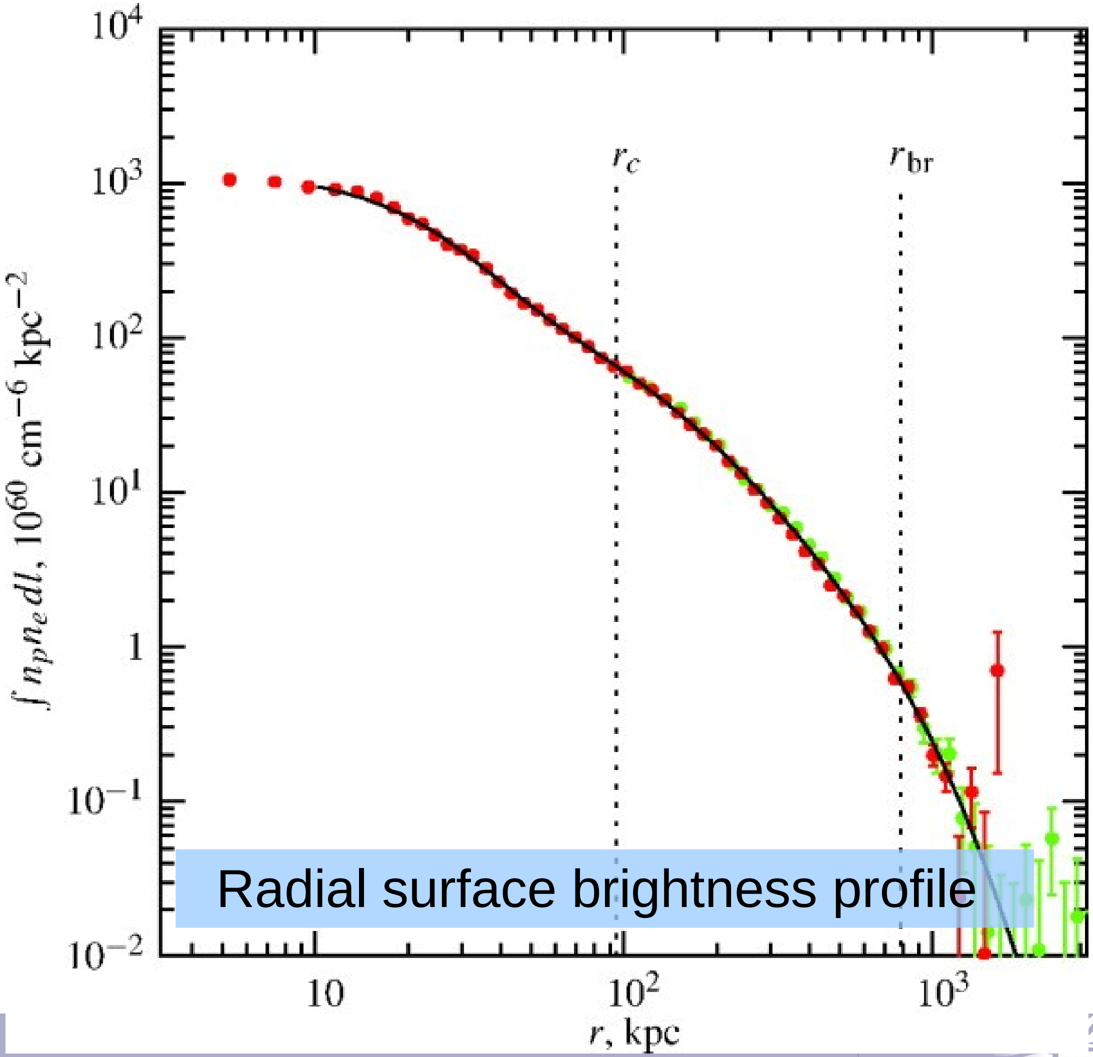


Radial kT profile of A2029
Vikhlinin et al, 2005, ApJ, 628, 655-672

# 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

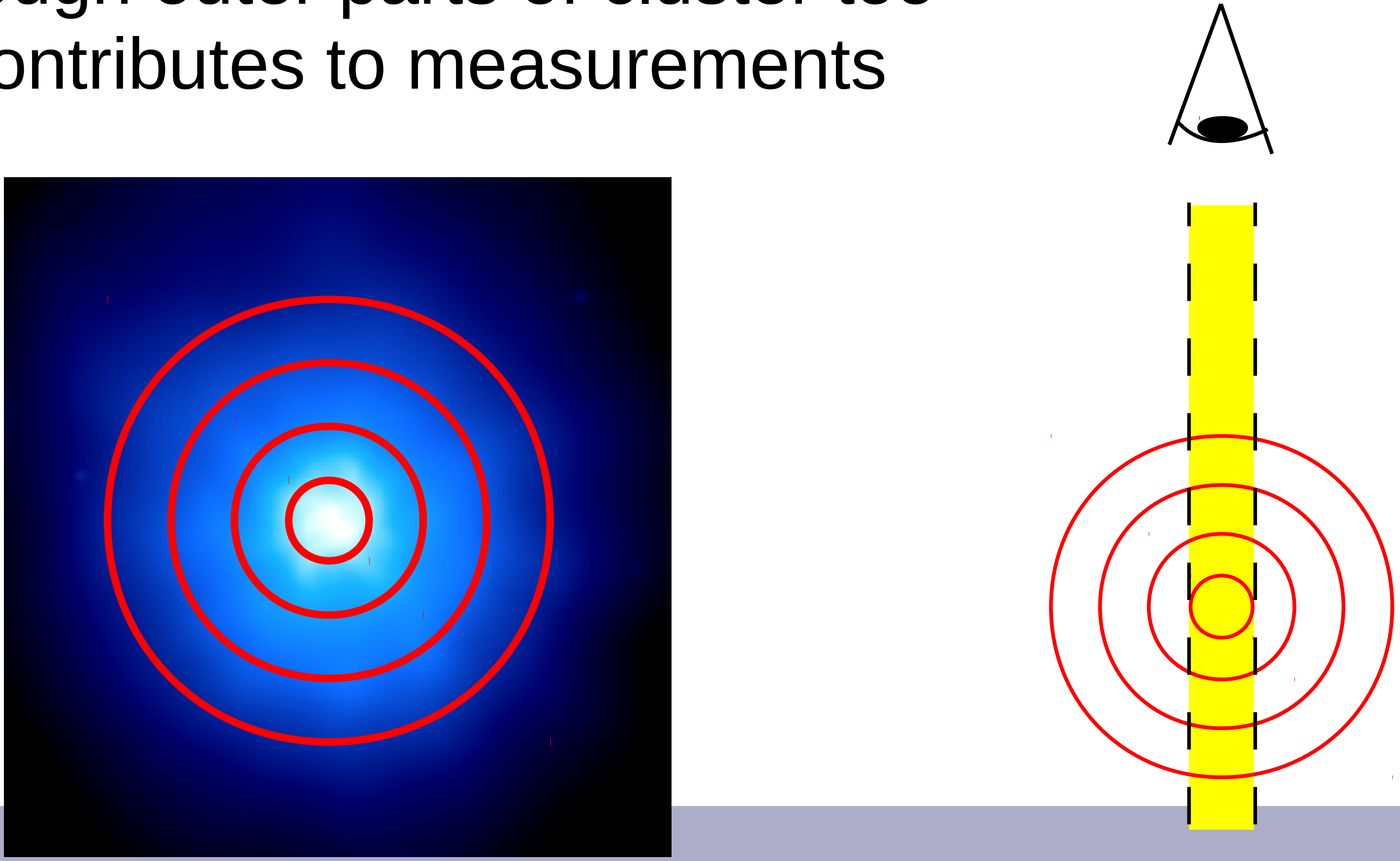




Radial surface brightness profile

# 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) (and gradients) of gas allows us to derive M(r) for total mass **including dark matter**

e.g. Evrard, et al, 1996, ApJ, 469, 494

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

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

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

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

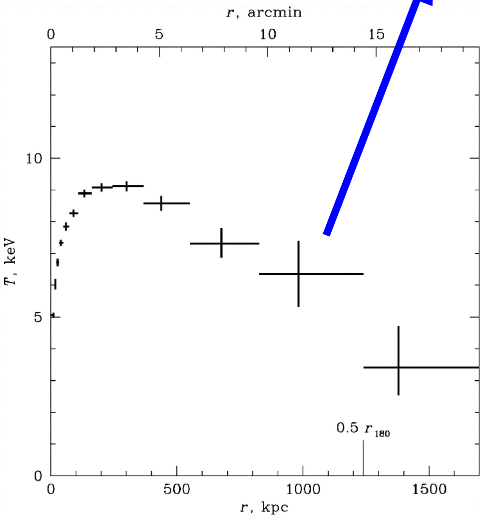
$$\frac{dP}{dr} = \frac{k}{\mu m_p} \frac{d}{dr}(\rho T) = \frac{k}{\mu m_p}\left[\rho \frac{dT}{dr} + T \frac{d\rho}{dr}\right]$$

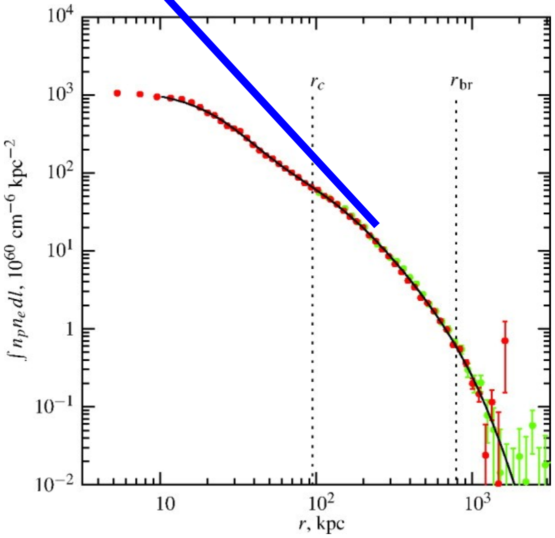
substitute into (a):

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

# Hydrostatic Masses

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





Measure kT and density and gradients at R

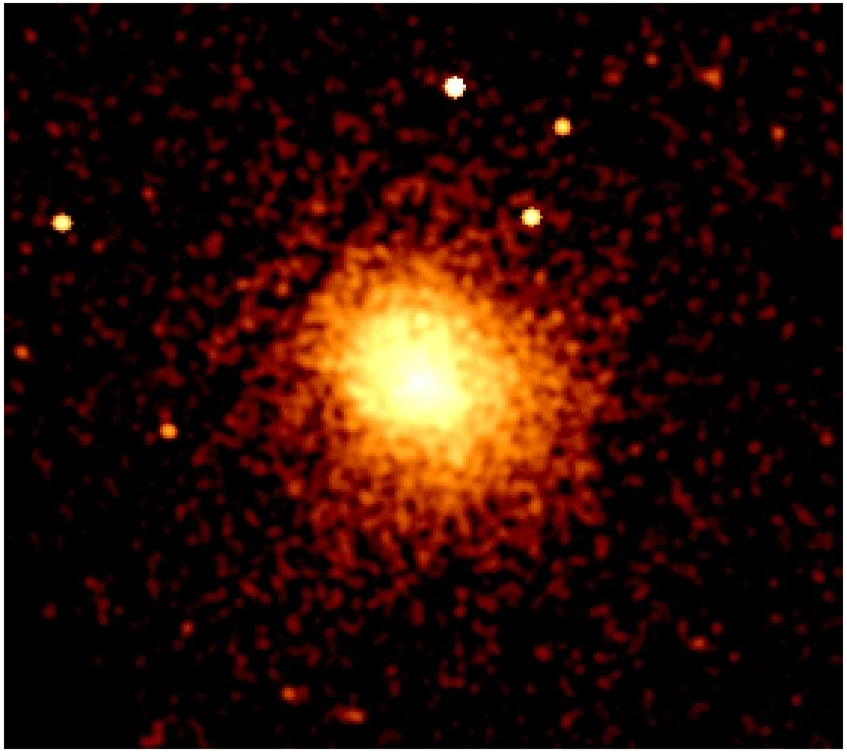
★ gives **total** mass internal to R

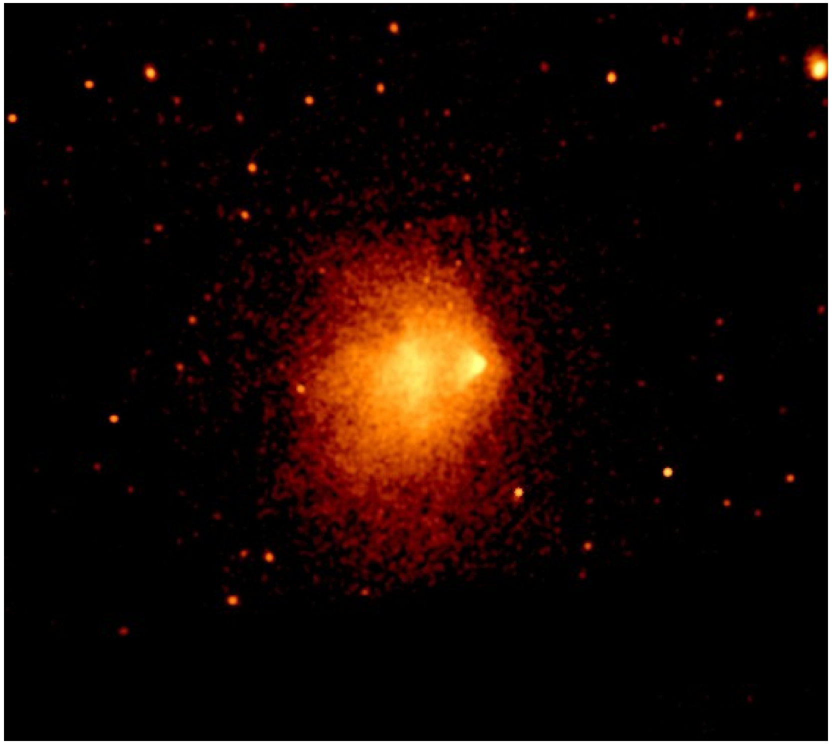
★ **providing** cluster is in hydrostatic equilibrium

★ **need high quality data**

# Hydrostatic Masses

- Which of these clusters are in hydrostatic equilibrium?





- Hydrostatic masses are reliable but need relaxed clusters and high quality data

# 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