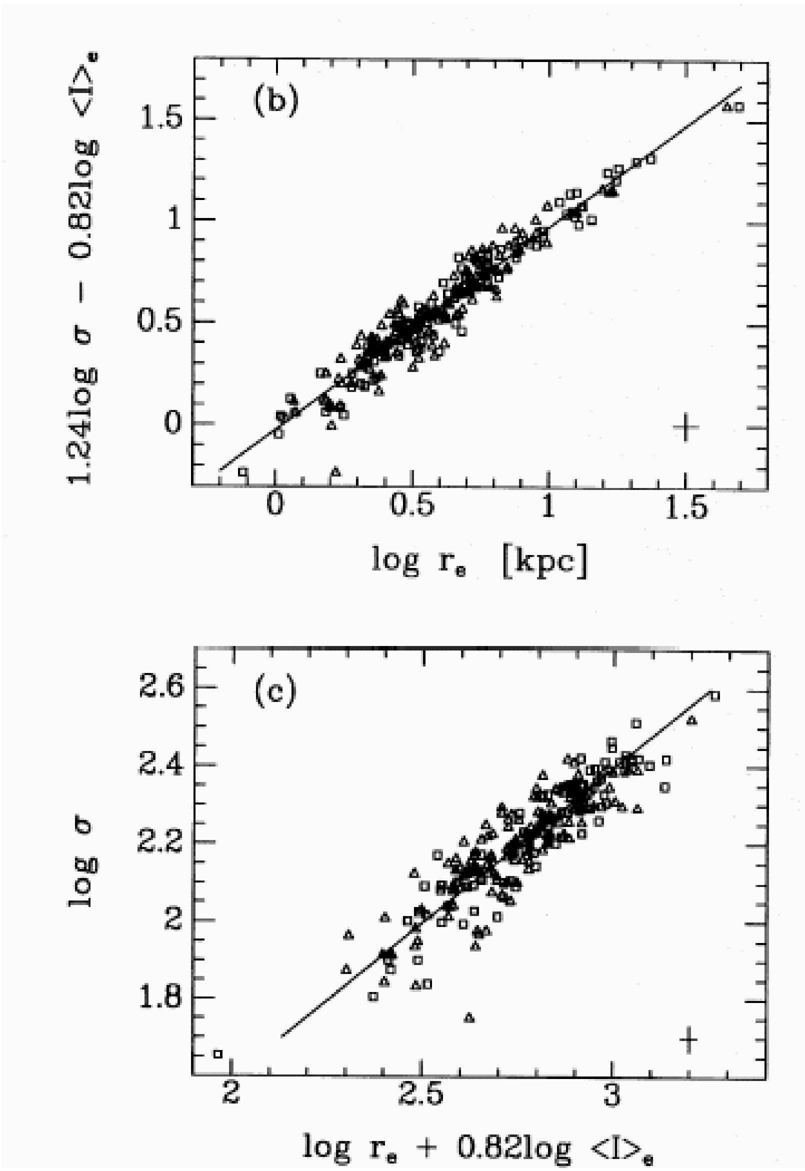
GALAXIES 626

Lecture 19:

Clusters and Dark Matter

Fundamental plane



Plots show edge-on views of the fundamental plane for observed elliptical galaxies in a galaxy cluster.

Approximately:

$$R_e \mu s^{1.24} I_e^{-0.82}$$

Measure the quantities on the right hand side, then compare apparent size with R_e to get distance

Origin of the fundamental plane unknown…

Jorgensen et al. 1996 MNRAS 280 167

What do we want to know about Dark Matter?

Observations

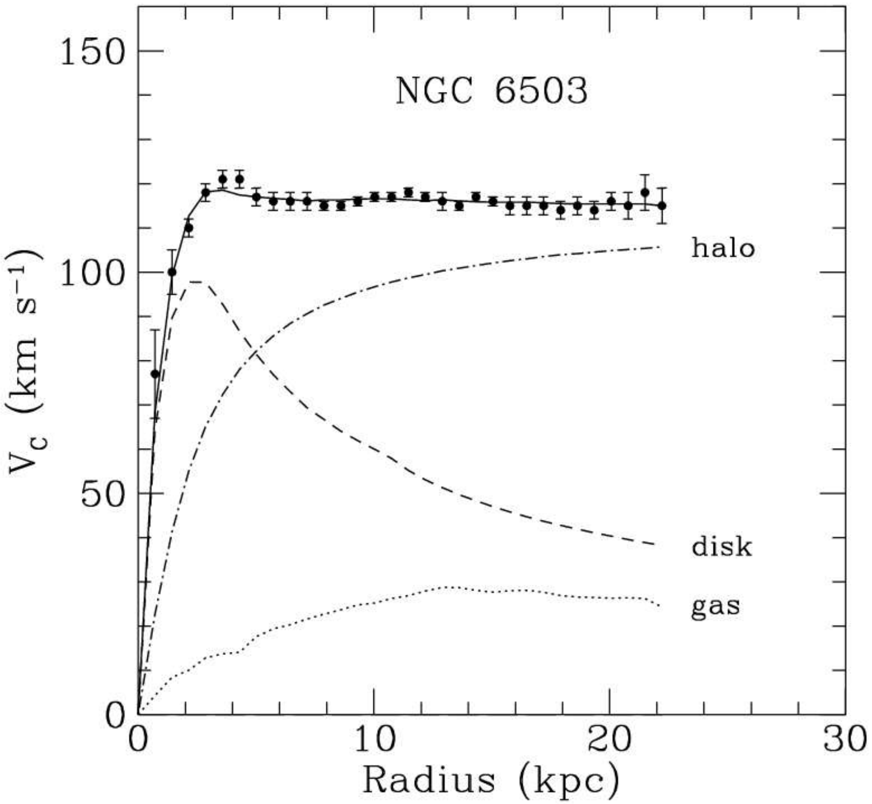
evidence of DM
abundance of DM
distribution of DM

Interpretation:

Nature of DM
properties of DM (mass, interaction, ...)
role of DM in cosmic history
origin of DM, and relation with DE

Evidence of DM
galaxy rotation curve

$$\frac{GM(<r)}{r^2} = \frac{v^2}{r}$$



Spiral Galaxies

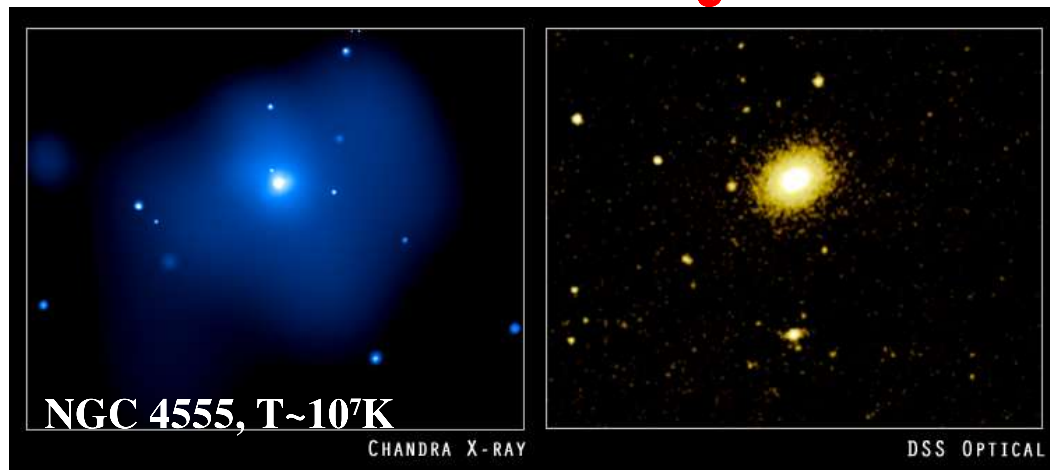
The inferred M/L of spiral galaxies is about M/L ≈ 10–30 $(M/L)_{\odot}$ and the fraction of dark matter increases outwards (i.e., the dark matter is less centrally concentrated than the luminous matter).

Ellipticals in the X-ray

- Hot gas

Gas heated by SN explosions trapped in galaxy potential well.

Hot electrons produce X-rays by bremsstrahlung



Elliptical Galaxies

Elliptical galaxies too contain dark matter (a somewhat higher proportion than spiral galaxies, in fact), with M/L ratios as high as 100 $(M/L)_{\odot}$

Clusters of galaxies

Most galaxies belong to some larger bound structure. Conventionally consider **groups** and **clusters**, with characteristic properties:

	Groups	**Clusters**
Core radius	250 h^{-1} kpc	250 h^{-1} kpc
Median radius	0.7 h^{-1} Mpc	3 h^{-1} Mpc
Velocity dispersion (line of sight)	150 km s^{-1}	800 km s^{-1}

(h is Hubble's constant in units of 100 km s^{-1} Mpc^{-1})

Roughly, consider a group to possess a handful to tens of bright galaxies, while a cluster may have several hundred galaxies.

Why are clusters interesting?

Observationally:

- Large number of galaxies at the same distance
- Most dramatic place to look for environmental effects on galaxy formation and evolution

Theoretically:

- `Largest bound structures in the Universe'. Time for a galaxy to cross a cluster is:

$$t_{cross} » 10^{10}\left(\frac{d}{10\ \mathrm{Mpc}}\right)\left(\frac{v}{1000\ \mathrm{km\ s^{-1}}}\right)^{-1}\ \mathrm{yr}$$

…galaxies on the outskirts of a cluster have only made ~ a few orbits of the cluster.

- `Fair sample of the Universe’. Deep potential well of a rich cluster retains gas at T ~ 10^8 K. Expect that the ratio:

$$f = \frac{M_{baryons}}{M_{total}}$$

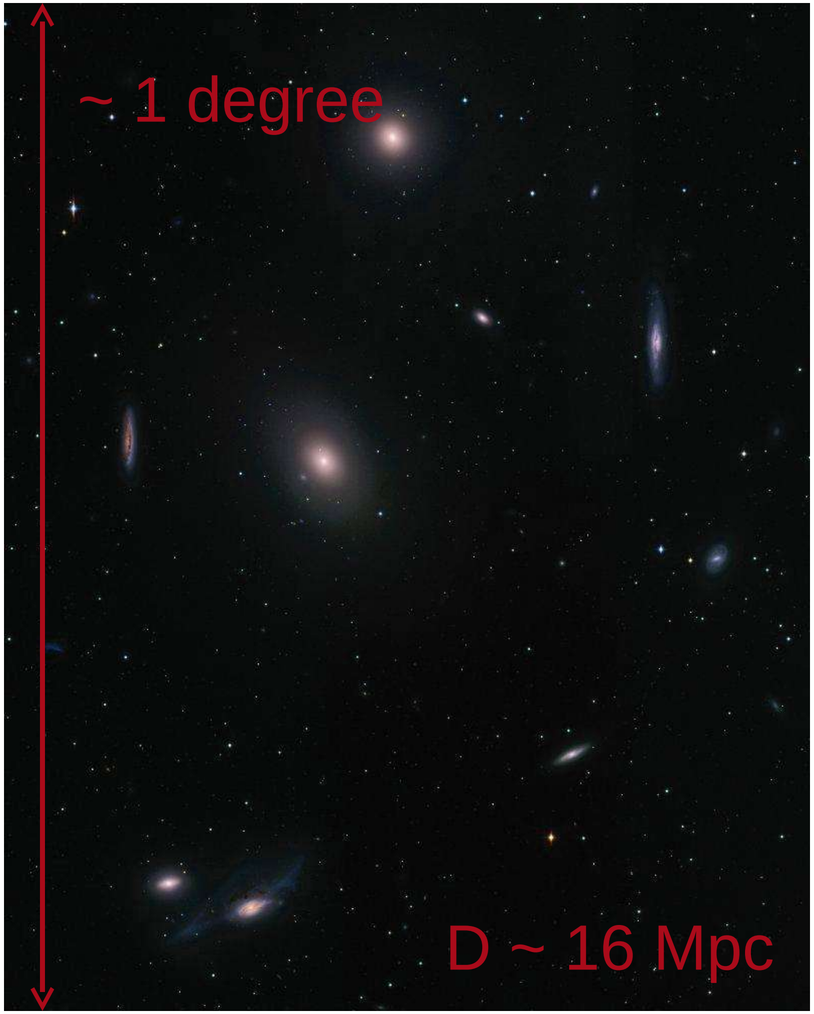
Stars + gas

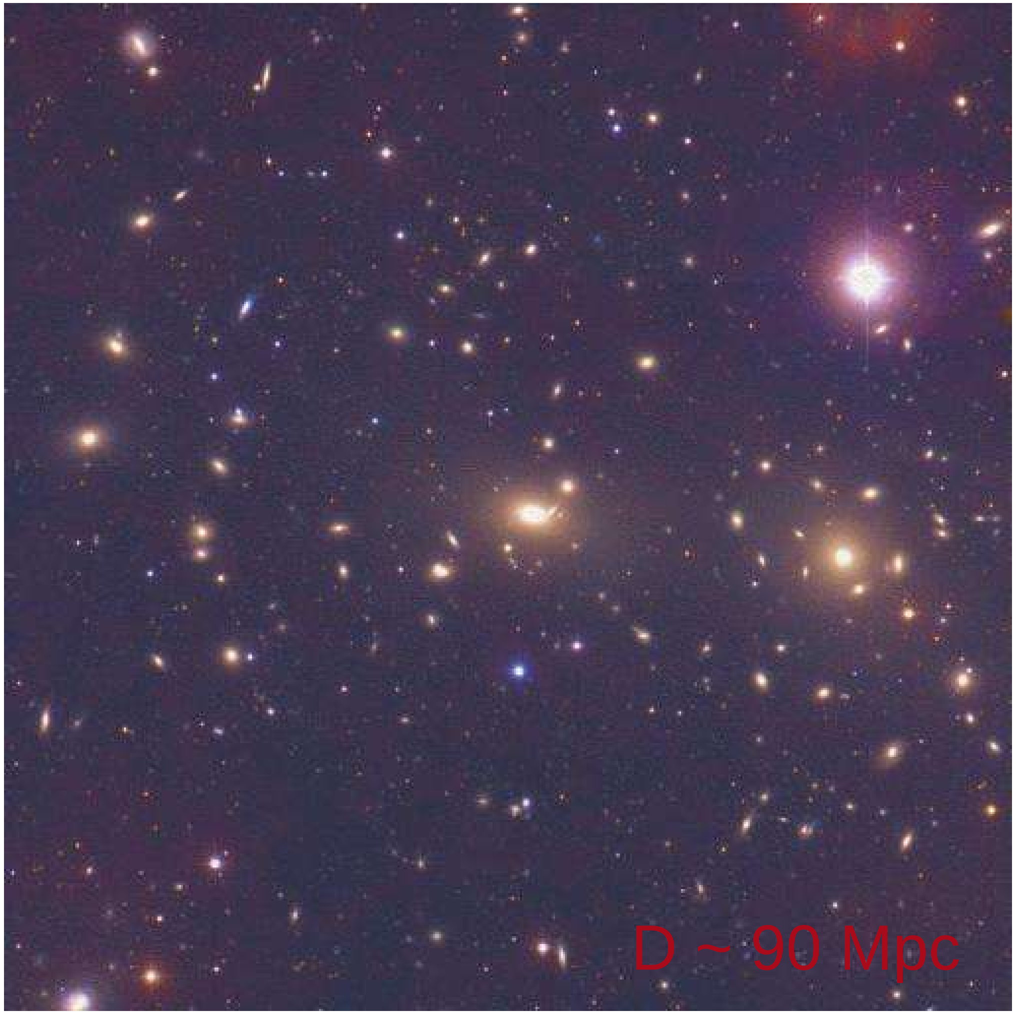
Stars, gas, dark matter

roughly represents the global value.

- Rare objects, formed from the most overdense peaks in the initial density field. Implies that their number density (number per Mpc^3) is a sensitive function of the **amplitude** of the initial fluctuations.

Cluster examples:





Surveys for galaxy clusters

Galaxy clusters contain galaxies, hot gas, and dark matter.
Can survey for each of these components using observations in different wavebands:

Optical

Look for an overdensity of galaxies in patches on the sky

Can use color information (clusters contain many elliptical galaxies, which are red) to help

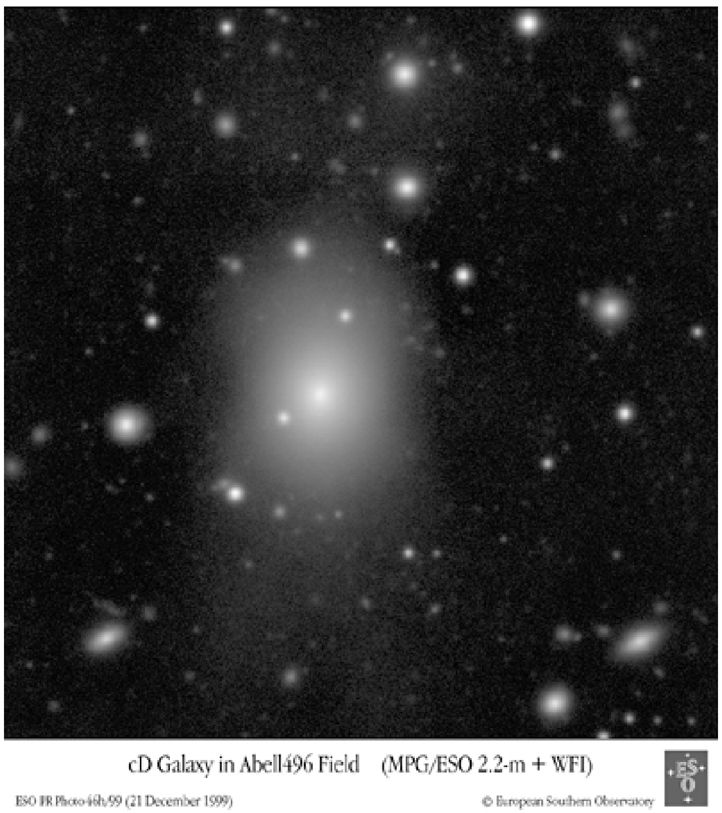
Disadvantages: vulnerable to projection effects, rich cluster in the optical may not have especially high mass

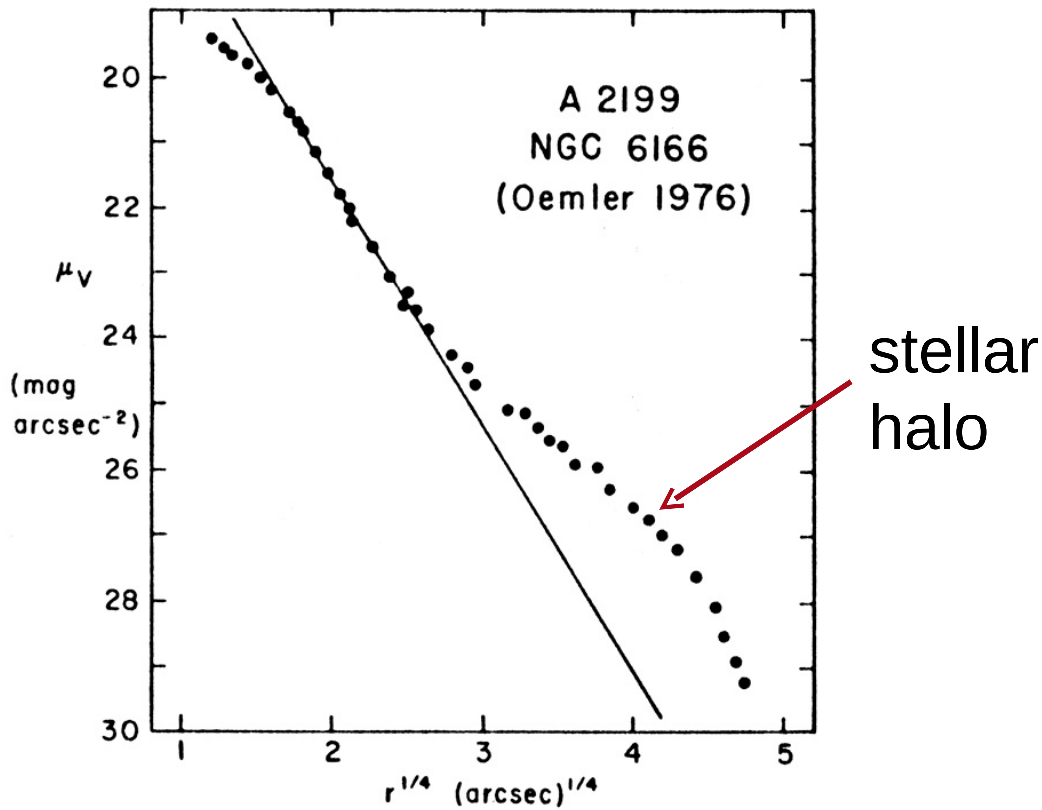
Properties of galaxies in galaxy clusters

Apart from the high density striking feature of the galaxy population in clusters:

<u>cD galaxies</u>

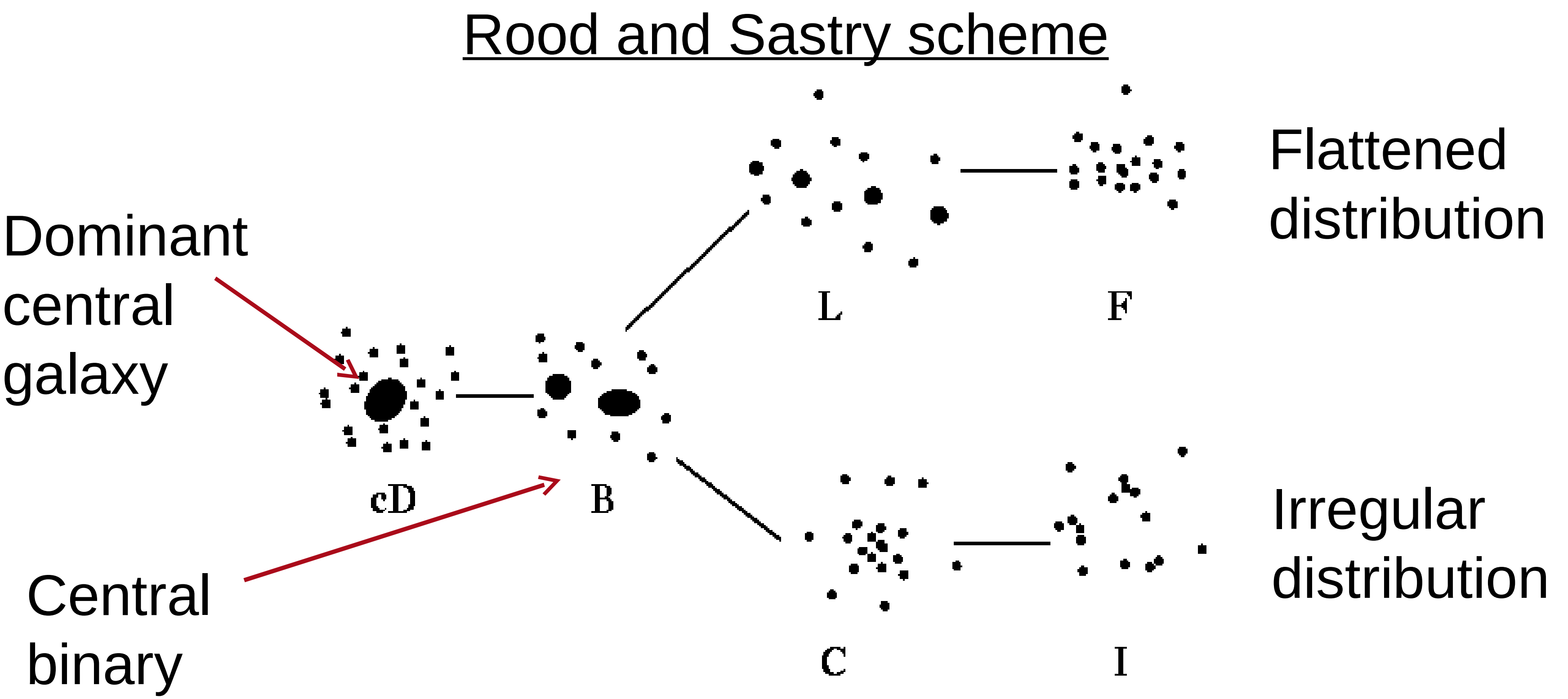
Many clusters have a single, dominant central galaxy





Classification of clusters

Can classify clusters of galaxies according to (i) **richness**, and (ii) **morphology**. No morphological scheme enjoys same support as Hubble's tuning fork diagram for galaxies. Example:



Importance: some clusters have cD galaxies. Expect a range of morphologies because clusters are young, merging systems…

Abell clusters

Catalog of galaxy clusters compiled by George Abell from visual inspection of sky survey plates.

Selection criteria:

- **Richness**. Let m_3 be the magnitude of the third brightest galaxy in a group or cluster. Require at least 50 galaxies with magnitudes between m_3 and $m_3 + 2$.
- **Compactness**. The > 50 members must be enclosed within a circle of radius 1.5 h^{-1} Mpc.

Original catalog contained ~ 2700 clusters.
Error rate was around 10%.

X-ray

Galaxy clusters contain hot gas, which radiates X-ray radiation due to bremsstrahlung.

Advantage: bremsstrahlung scales with density and temperature as $n^2T^{1/2}$ - i.e. *quadratically* in the density. **Much less** vulnerable to accidental line-of-sight projection effects.

Disadvantage: still not detecting clusters based on mass.

Sunyaev-Zeldovich effect

Distortion of the microwave background due to photons scattering off electrons in the cluster. Measures:

$$\int n_e \, dl$$

Mass weighted measure, though of gas not dark matter.

Gravitational lensing

Detect clusters from the distortion of background galaxy images as light passes through the cluster.
Measures the total mass
But very difficult - not yet used as a survey technique

Mass estimates

Simplest mass estimate for clusters uses the observed properties + the Virial Theorem. For a system in equilibrium with kinetic energy K and potential energy W:

$$2K + W = 0$$

$$\frac{1}{2}Mv^2 \qquad\qquad \frac{GM^2}{R}$$

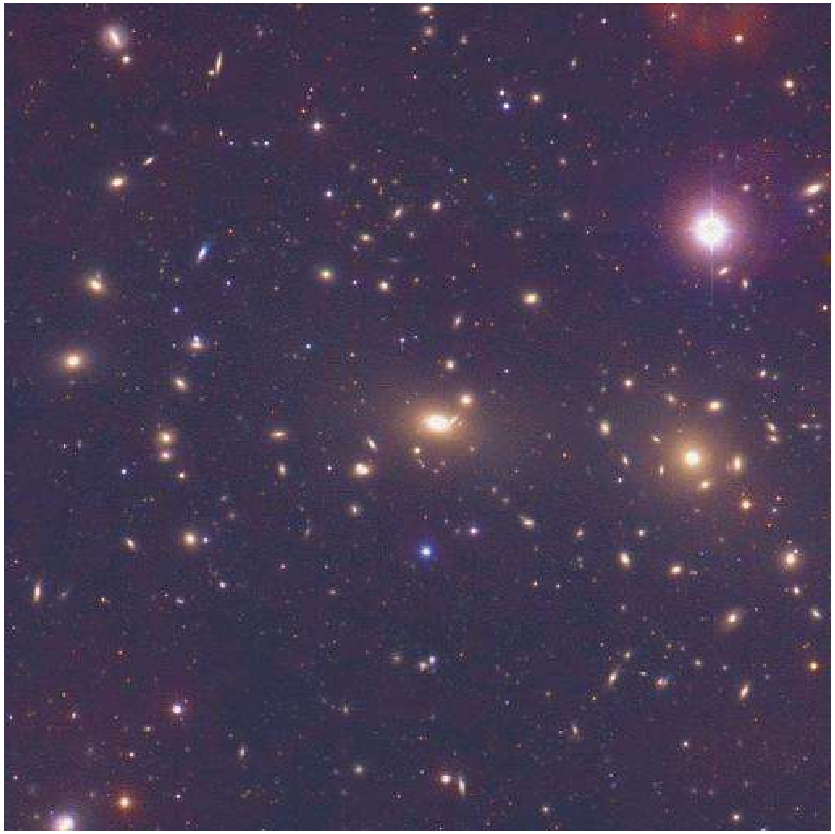
This gives: $$M \sim \frac{\sigma^2 R}{G} \sim 2 \times 10^{14} \left(\frac{\sigma}{10^3\ \mathrm{kms}^{-1}} \right)^2 \left(\frac{R}{1\ \mathrm{Mpc}} \right) \mathrm{M}_{\mathrm{sun}}$$

Very approximate - but right order of magnitude.
Rich cluster has a mass of ~10^{15} Solar masses

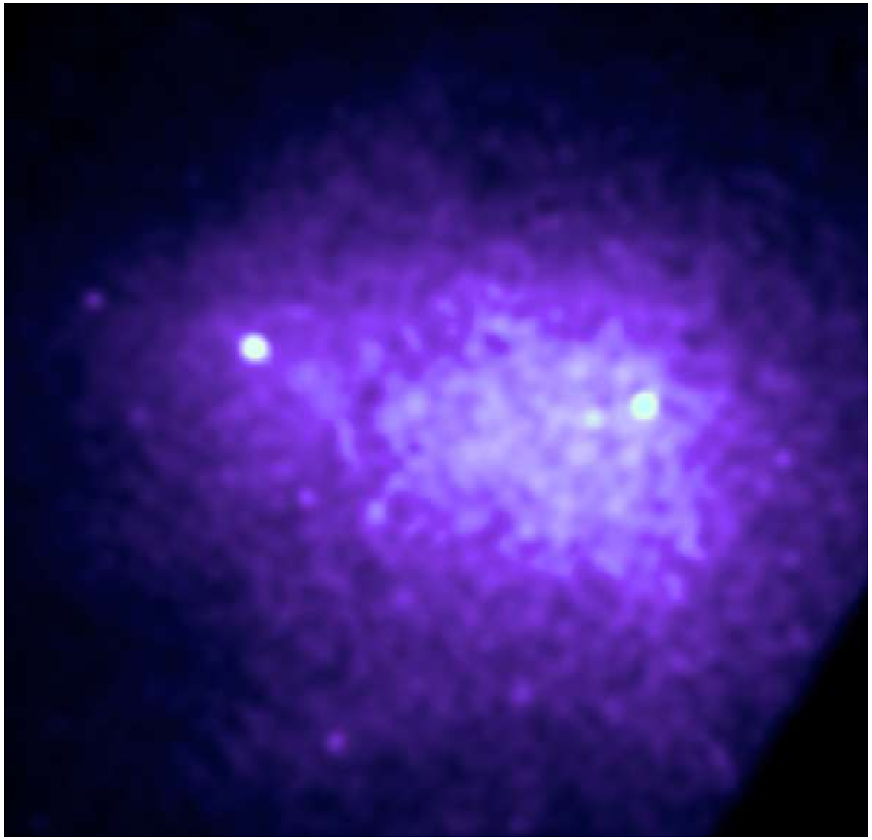
Can also measure mass using X-ray observations and gravitational lensing.

Gas in galaxy clusters

Observe extended emission in X-ray observations of clusters of galaxies - indicates presence of hot gas distributed throughout the cluster volume:



Coma in the optical



Coma in X-rays

If the gas is in virial equilibrium within the cluster, expect:

$$kT \sim \frac{1}{2} m_p v^2$$

Guess thermal velocity ~ σ = 1000 km s^{-}

⇨ T ~ 6 x 10^7 K - radiation via bremsstrahlung

Formula for the bremsstrahlung emission from a thermal plasma at temperature T is:

$$\varepsilon_\nu^{ff} = 6.8 \times 10^{-38} Z^2 n_e n_i T^{-1/2} e^{-h\nu/kT} \text{ erg s}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1}$$

Ion charge is Ze

Number density of electrons, ions

Cooling cores

Is the gas in galaxy clusters radiating enough to cool significantly? Integrated over frequency, bremsstrahlung emission is:

$$e^{ff} = 1.4 \times 10^{-27} T^{1/2} n_e n_i Z^2 \text{ erg s}^{-1} \text{ cm}^{-3}$$

Roughly, estimate:

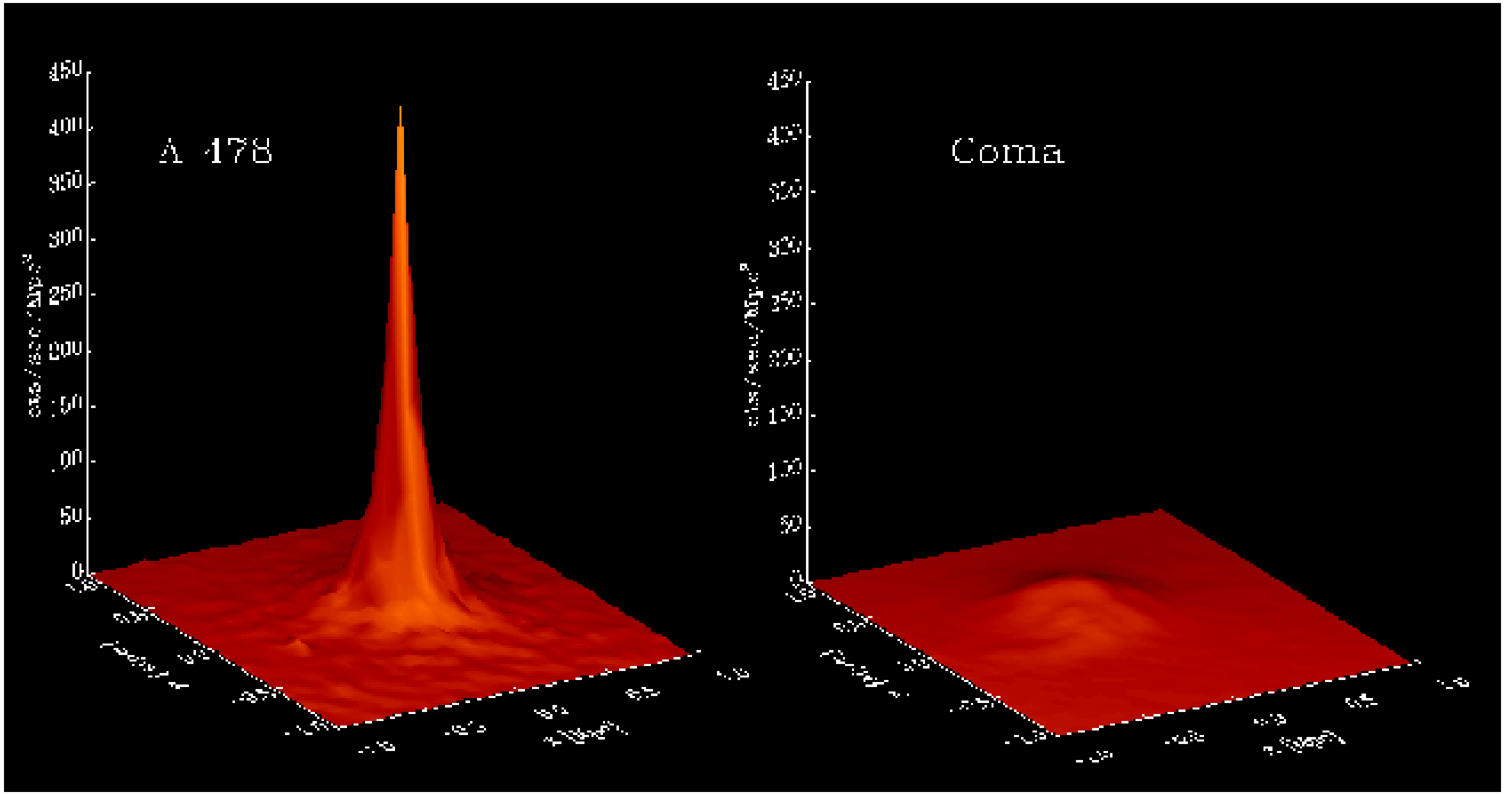
$$t_{cool} \sim \frac{n_e kT}{1.4 \times 10^{-27} T^{1/2} n_e^2}$$

$$\approx 3 \left(\frac{T}{10^8 \text{ K}} \right)^{1/2} \left(\frac{n_e}{0.01 \text{ cm}^{-3}} \right)^{-1} \text{ Gyr}$$

Gas in most of the cluster will not cool - $n_e < 10^{-2}$ cm^{-3}. But dense gas in the core is expected to cool significantly.

Cooling time scales as n^{-1}, hence might expect that:

- Cooling starts
- Pressure drops
- Gas flows in: increased density
- Increased cooling: runaway



Some clusters show very bright cores, suggesting that this process is going on…

But what happens to the cool gas? Do **not** observe:

- Very high rates of star formation
- Lines in the soft X-ray spectrum from the cool material

Suggests that some source of **heating** balances the cooling at a lower temperature, possibly:

- Conduction from the hotter regions at larger radius
- Heating due to AGN outflows

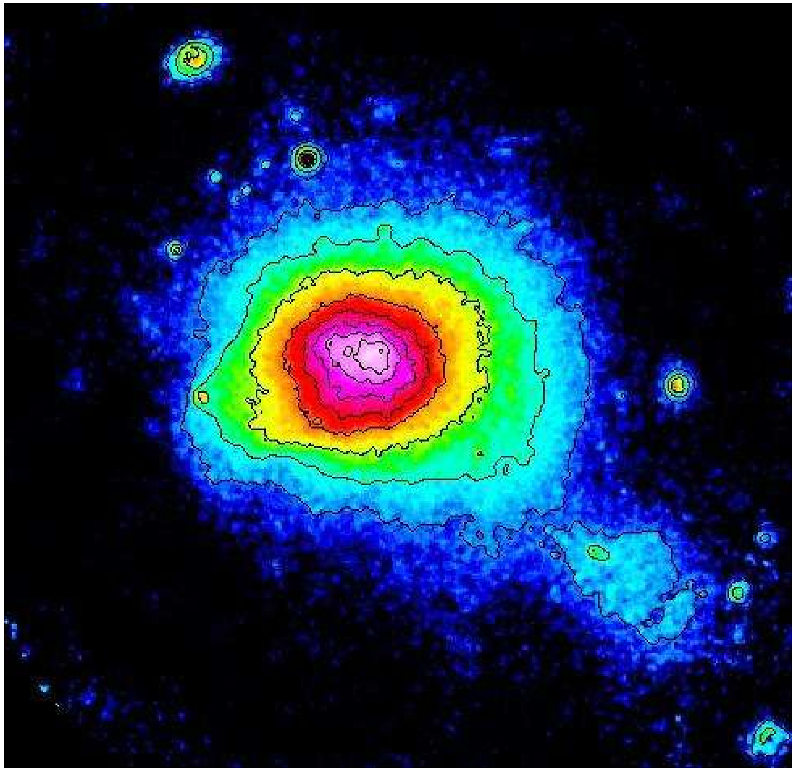
X-ray observations of clusters

hydrostatic equilibrium

$$\frac{GM(r)}{r^2} = -\frac{k_B T}{\mu m_H}\left[\frac{d\log\rho}{dr} + \frac{d\log T}{dr}\right]$$

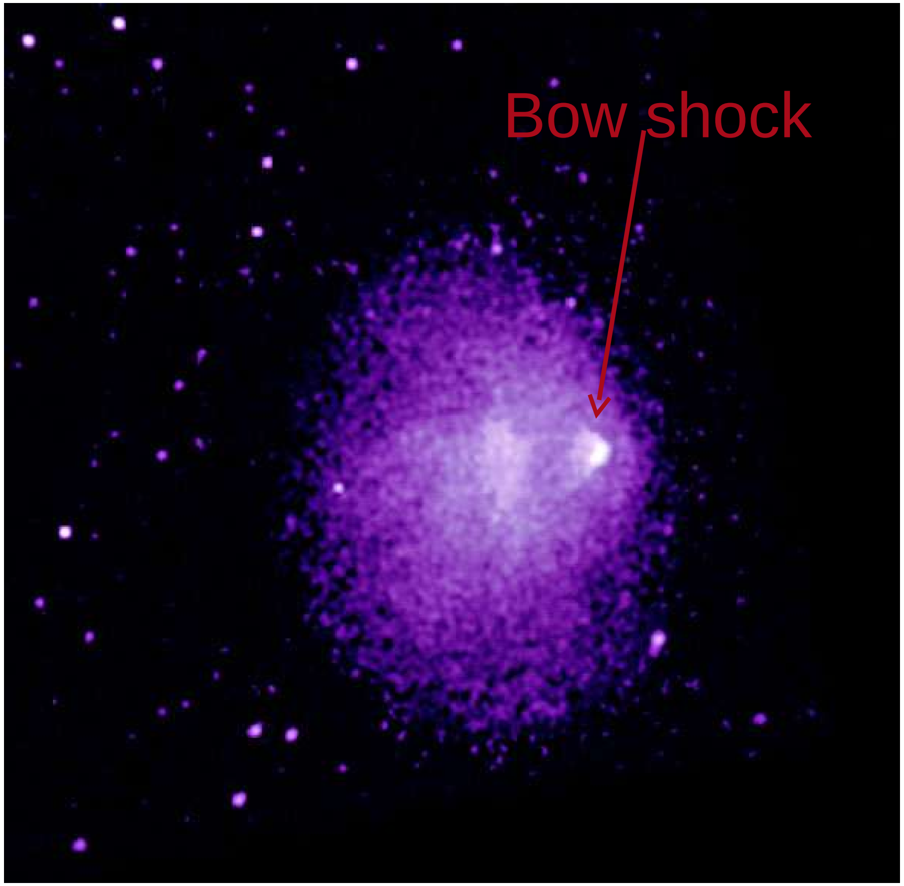
beta model:

$$\rho = \rho(0)(1 + r^2/r_c^2)^{-3\beta/2}$$

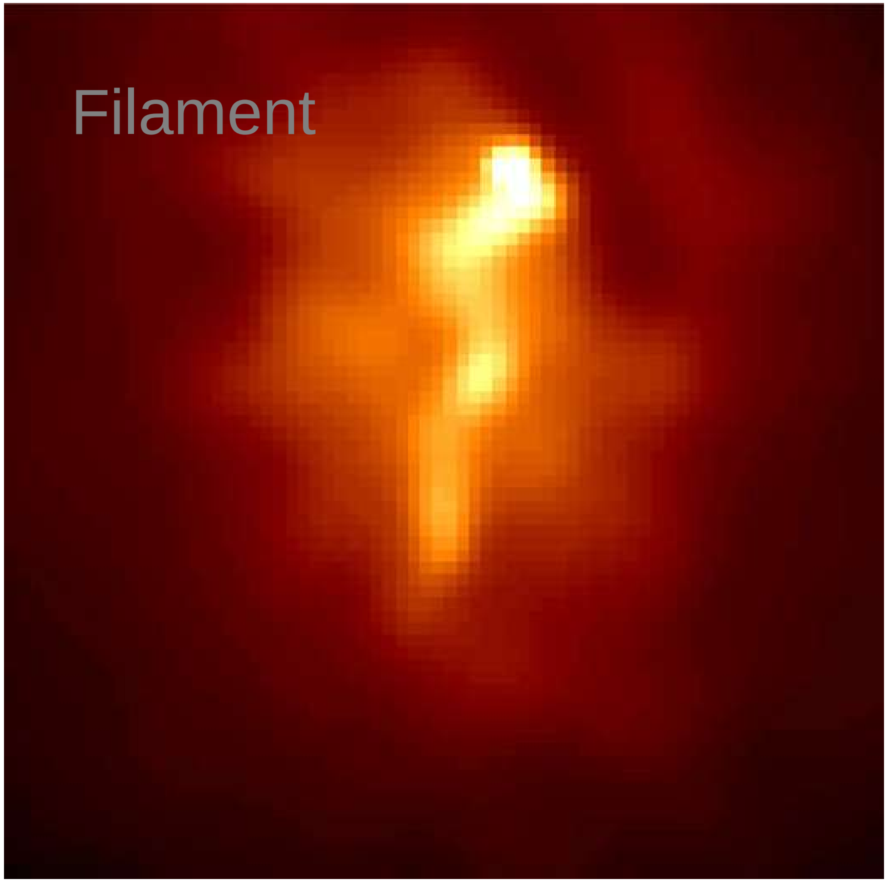


Some complications

High resolution observations with *Chandra* show that many clusters have substructure in the X-ray surface brightness



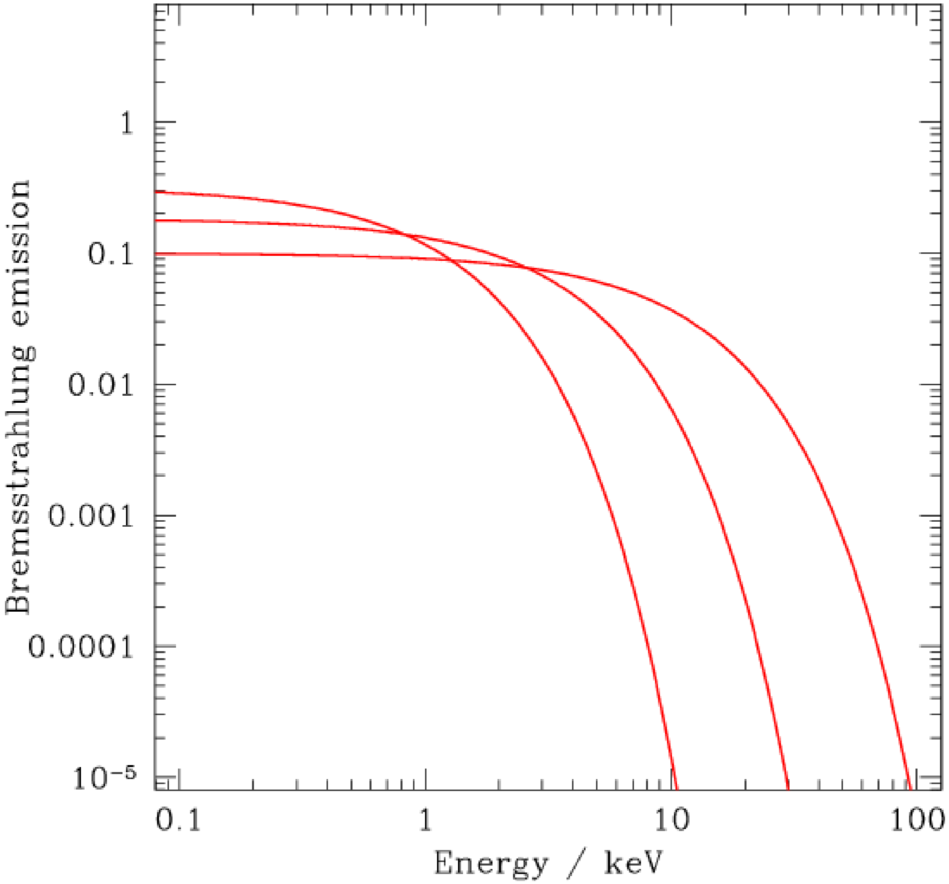
1E 0657-56



A 1795

From X-ray observations, easiest quantities to measure are:

- **Luminosity L_X - depends on density, temperature and volume of the cluster**
- **X-ray surface brightness as f(radius)**
- **Mean temperature from the spectrum**



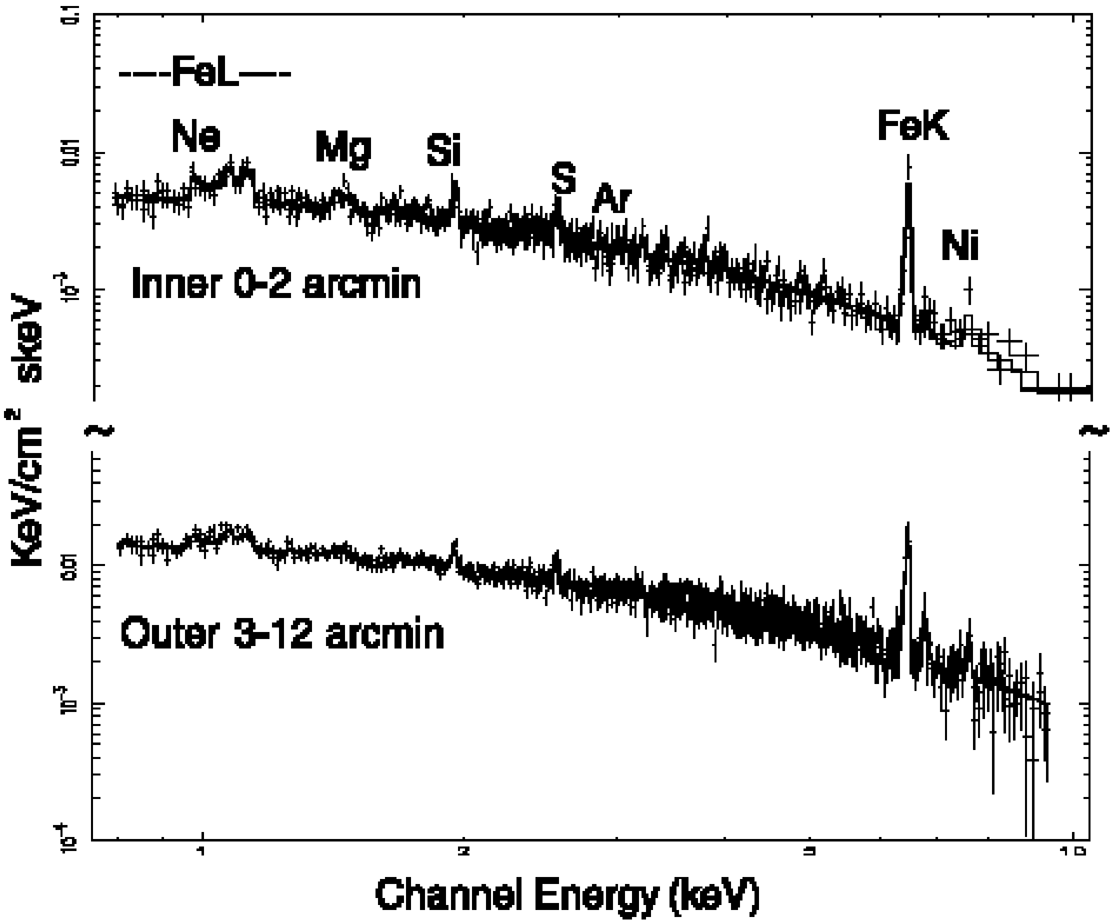
Bremsstrahlung has a flat spectrum up to $h\nu = kT$ followed by an exponential cutoff

Plot shows temperatures of 10^7, 3×10^7 K, 10^8 K

Most clusters have T between 2×10^7 K and 10^8 K

Harder to measure…

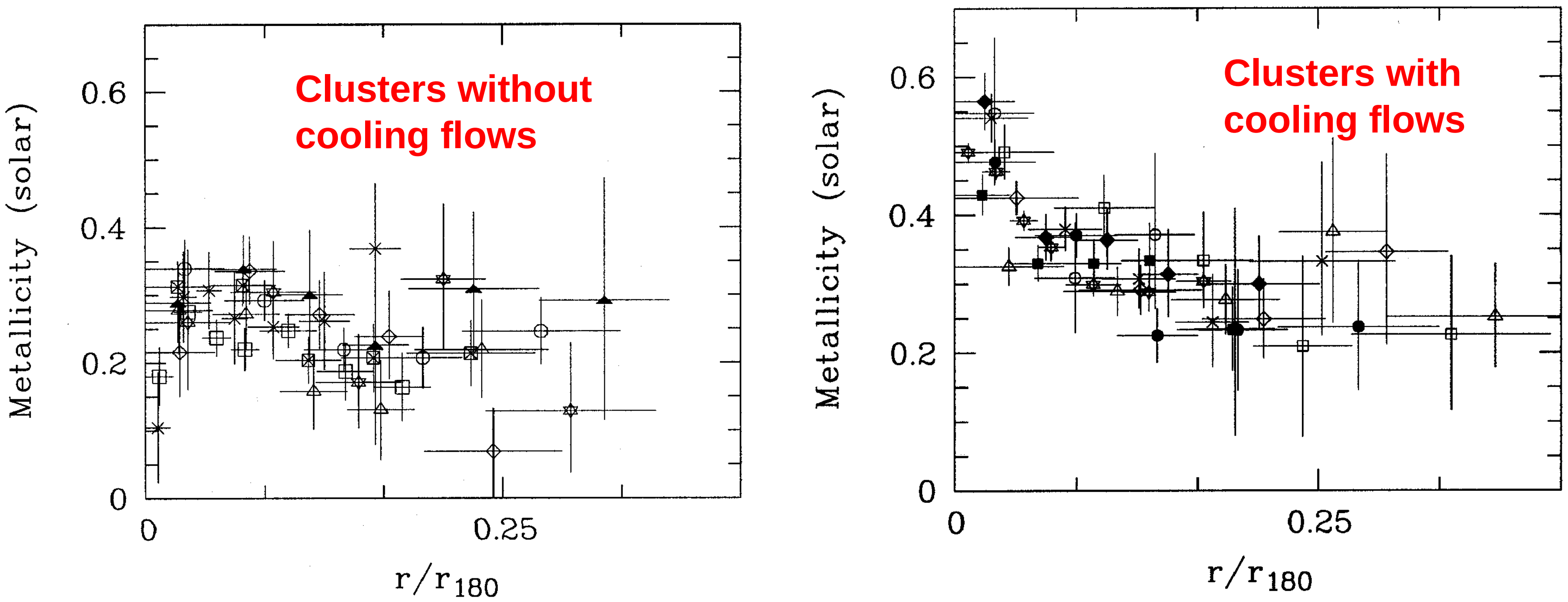
- **Temperature gradient**
- **Metallicity of the cluster gas**



Example of an ASCA spectrum of a cluster showing line emission

Metals in clusters

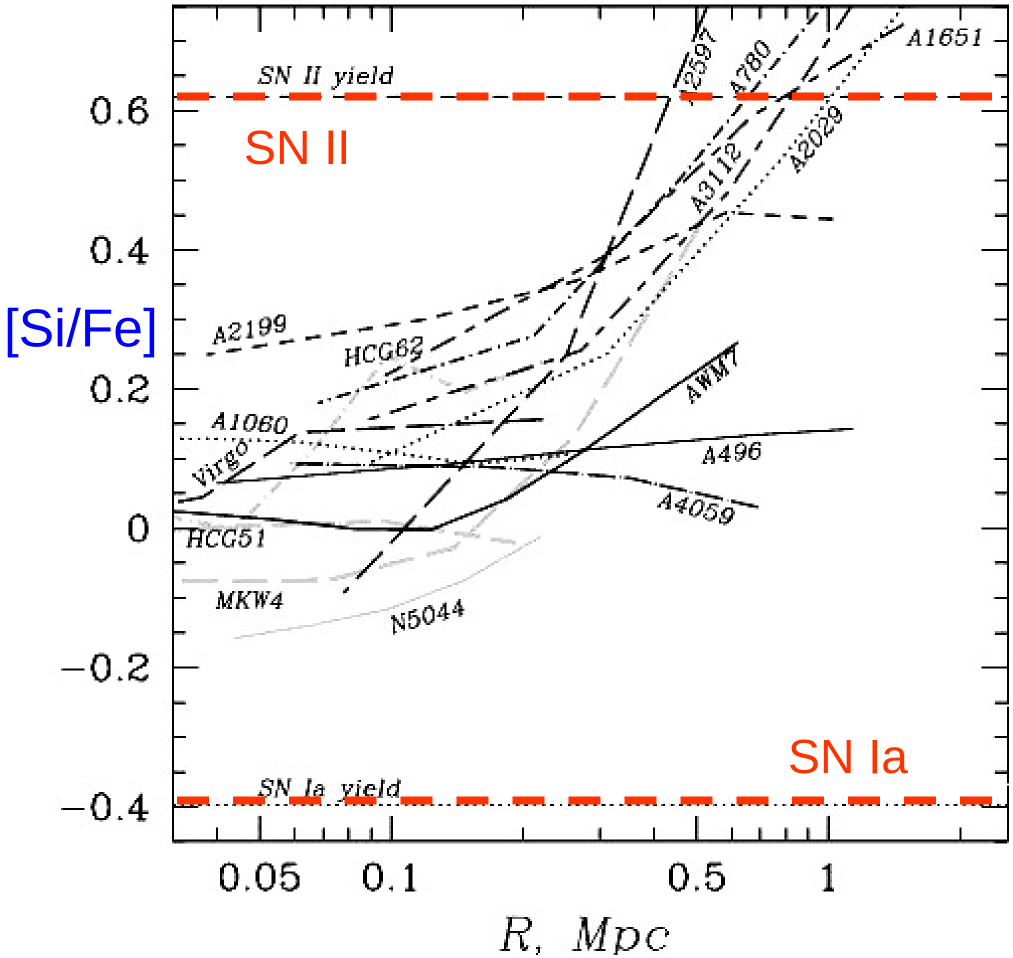
Abundance Gradients (Beppo-SAX)



Metallicity Gradients in non-cooling flow clusters and cooling flow clusters

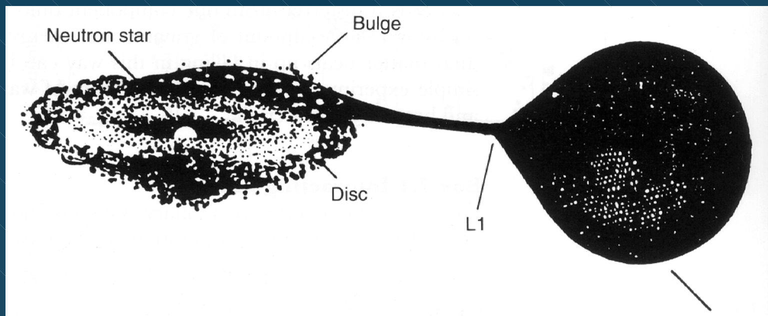
- these metallicity measurements refer essentially to the Fe abundance

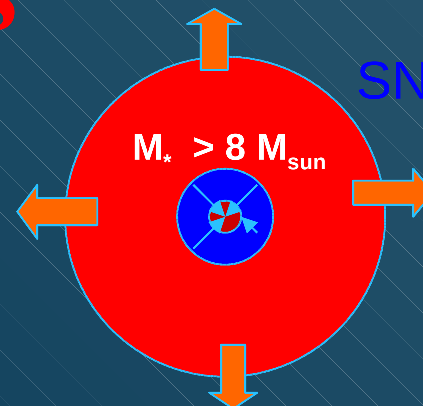
Radial Abundance Variations of Fe and Si in Various Clusters and Groups



- The central enhancement is more enriched by SN Ia than the outer parts of the ICM
- In the outer regions the metals in the ICM are dominated by the contribution from SN II !

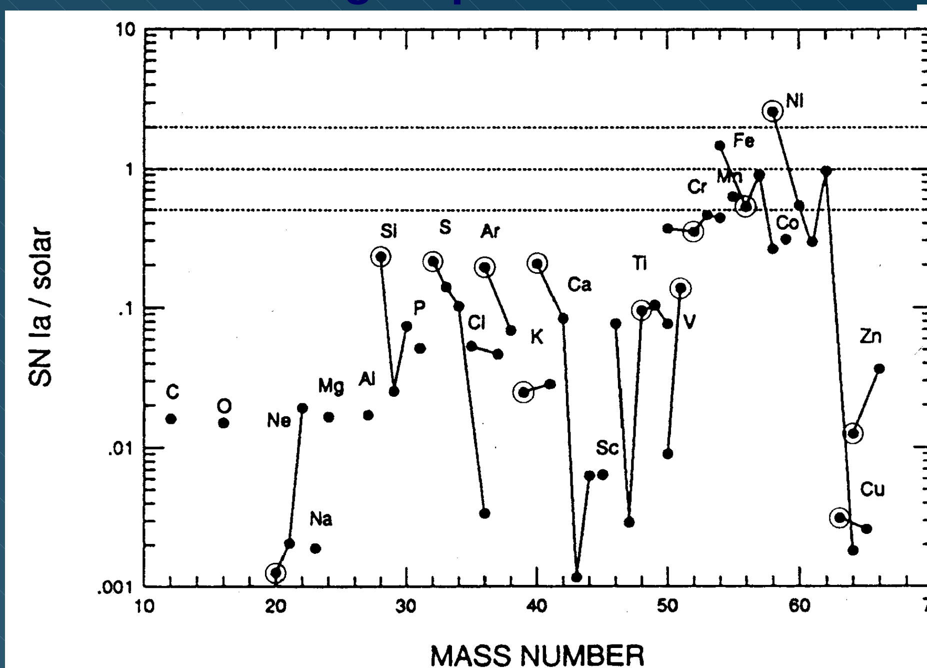
Two types of SN as ICM Poluters



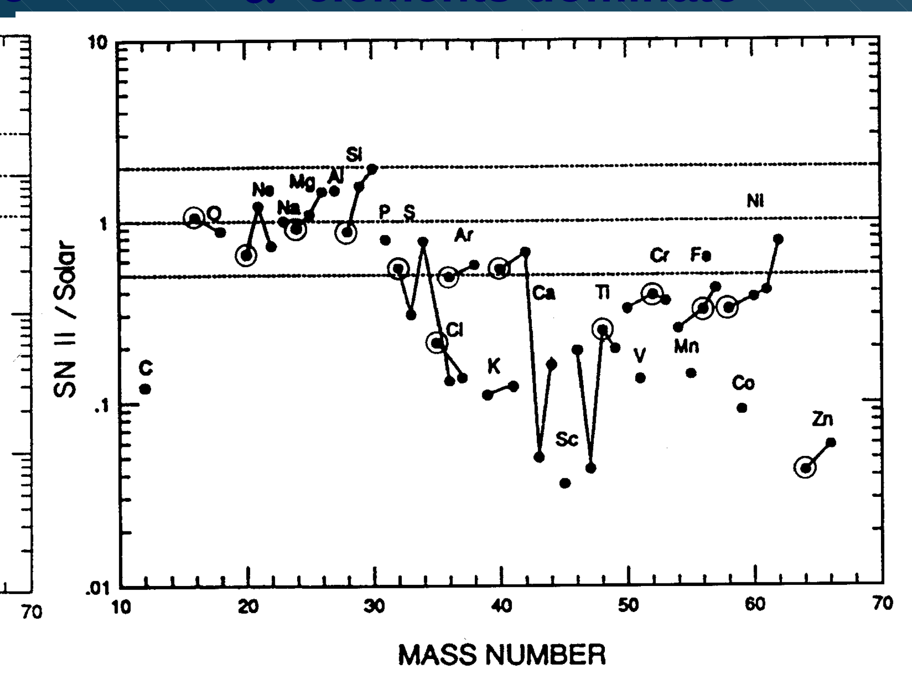


SN Type II

Fe- group elements dominate



α- elements dominate

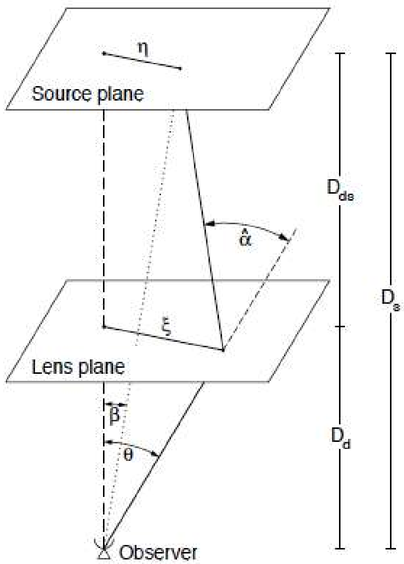


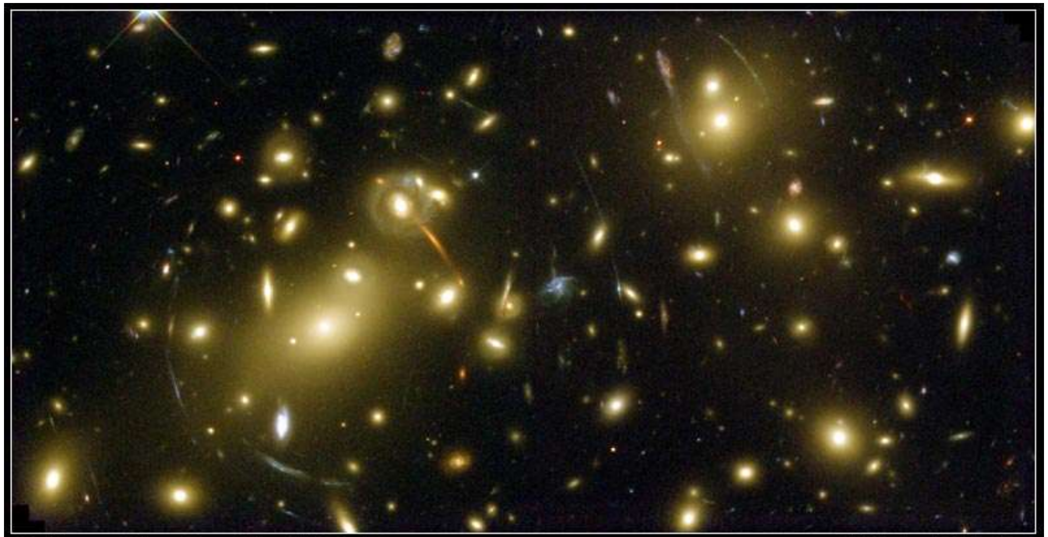
Conclusion from the Abundance Pattern

- Most of the Fe in the center comes from SN Ia
- The abundance pattern clearly favor slow deflagration/detonation models – with incomplete burning of the α-elements

→ The total Fe contribution by SN II falls about a factor of 1.5-2 short in explaining the wide-spread Fe abundance with classical IMF models

Strong Gravitational Lensing





$$\alpha = \frac{4GM}{c^2 \xi} = \frac{4\pi \langle v_{\parallel}^2 \rangle}{c^2}$$

$$\theta_E = \alpha \frac{D_{ds}}{D_s}$$

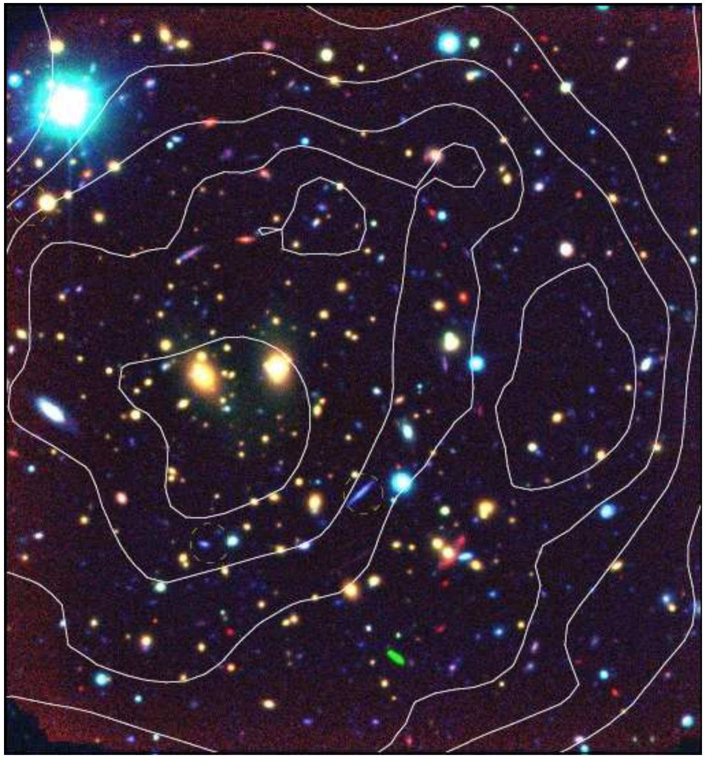
Weak Lensing mass reconstruction

Image ellipticity -> shear->

$$\alpha = \nabla\psi, \qquad \kappa = \frac{1}{2}\nabla^2\psi = \frac{\Sigma}{\Sigma_{cr}}$$

invert the equation

$$\boldsymbol{\alpha}(\boldsymbol{\theta}) = \frac{1}{\pi}\int_{\mathbb{R}^2} \mathrm{d}^2\theta' \, \kappa(\boldsymbol{\theta}') \, \frac{\boldsymbol{\theta}-\boldsymbol{\theta}'}{|\boldsymbol{\theta}-\boldsymbol{\theta}'|^2}$$



RXJ1347.5-1145

Universal DM Abundance inferred from clusters

- mass to light ratio x light density
- cluster baryon fraction/BBN baryon abundance
- cluster mass function
- evolution of cluster mass function

Bahcall: Ω_m=0.2
Blanchard: Ω_m=1.0

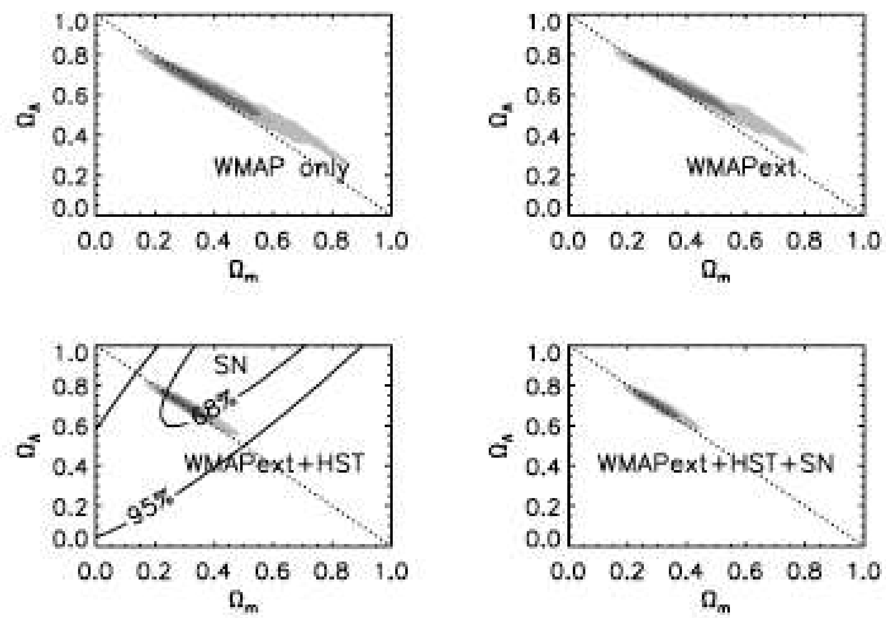
WMAP result

WMAP Combined fit:

$\Omega_m h^2$=0.135+-0.009

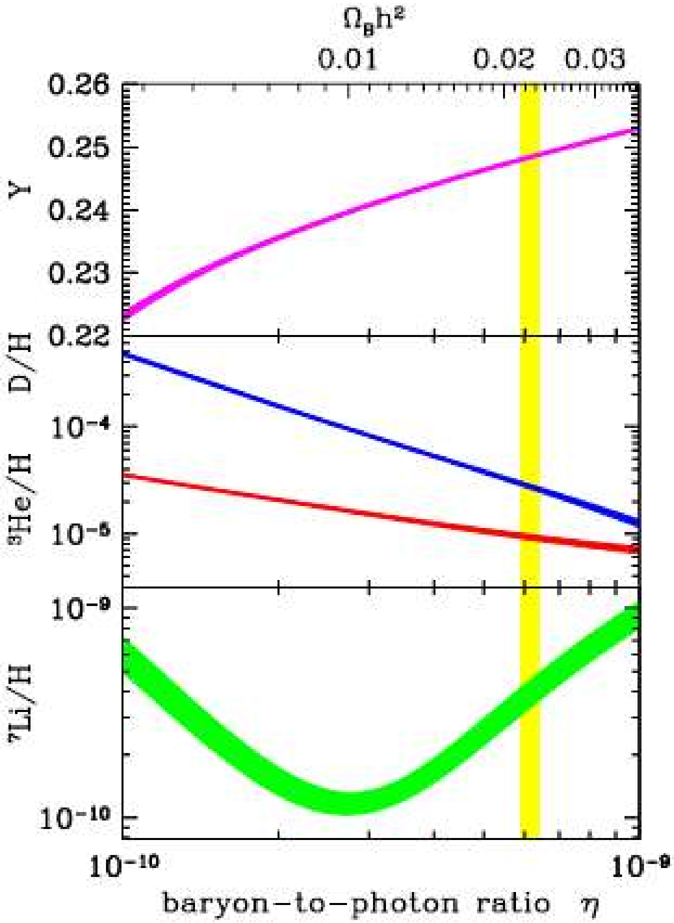
Ω_m=0.27+-0.04

Results depend on Supernovae and Hubble constant data.

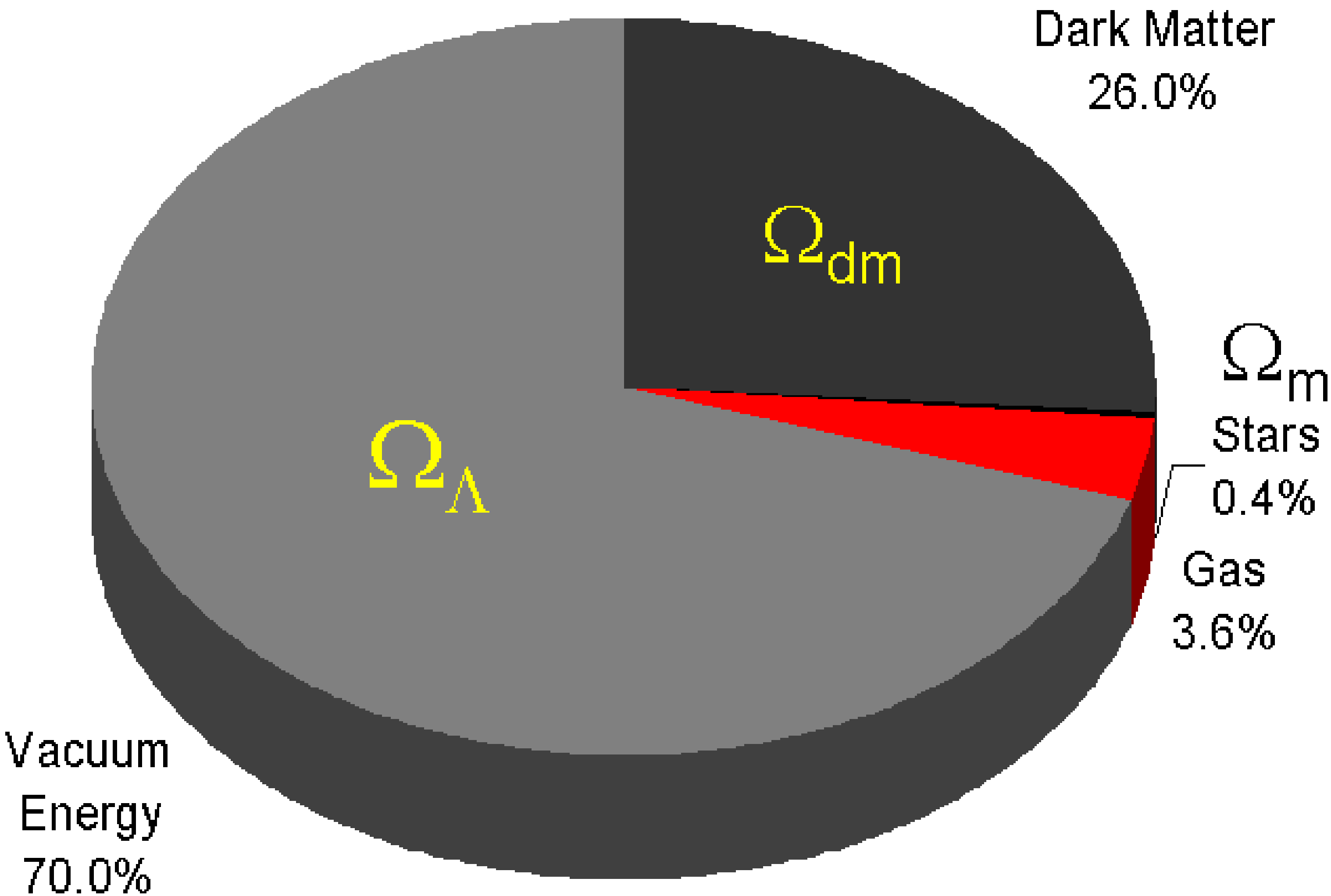


Can DM be baryons?

If all DM is baryonic, it is in conflict with Big Bang Nucleonsynthesis and Cosmic Microwave Background anisotropy.



Matter & Energy Content of the Universe



Possible Dark Matter Candidates

MACHOs

Massive Compact Halo Objects

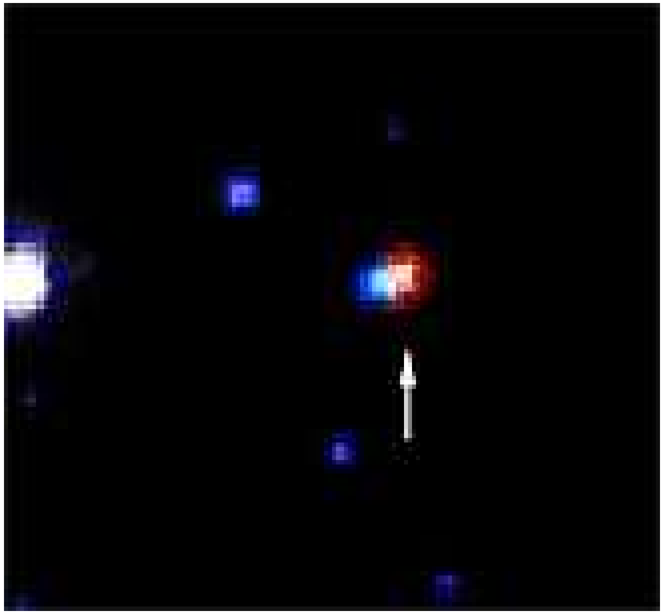
WIMPs

Weakly Interacting Massive Particles

MACHOs

Possible Candidates

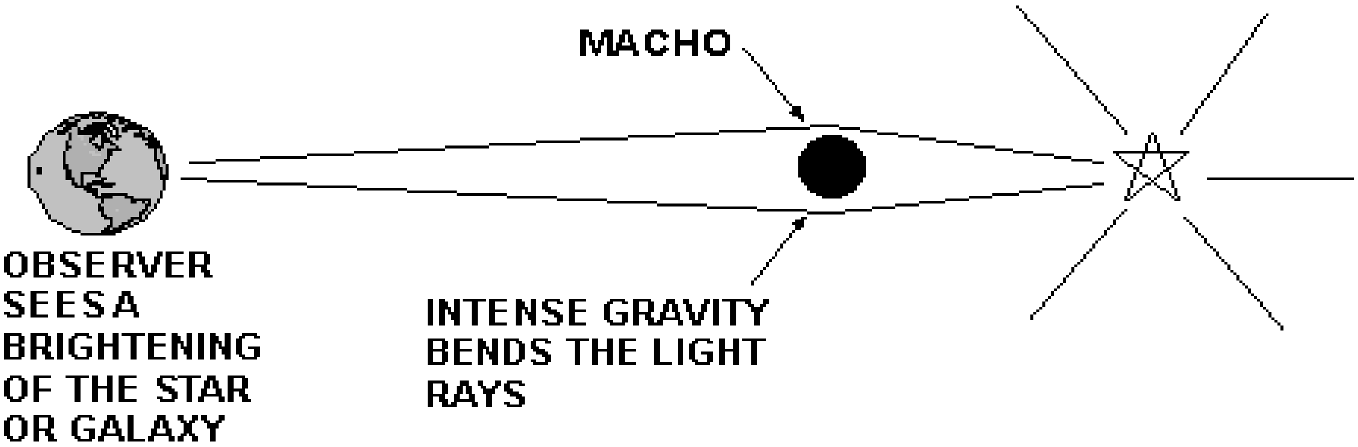
- Brown Dwarfs
- Low Mass,
  Faint Red Stars
- White Dwarfs
- Neutron Stars
- Black Holes



MACHOs

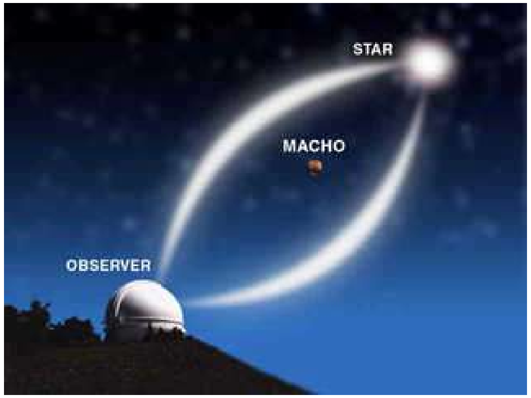
Detection Method

- Gravitational Lensing

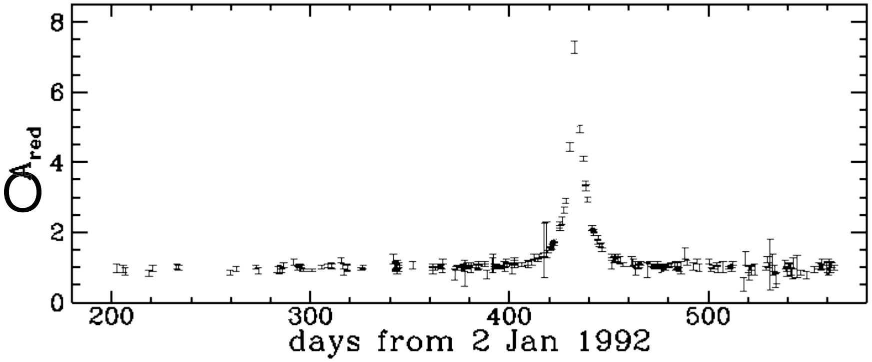


Gravitational Lensing--how MACHOs focus light

MAssive COmpact Halo Objects (MACHO)



The result of MACHO experiment (Alcock et al 1996):
20% of halo can be due to MACHO



WIMPs

- neutral particles formed during the Big Bang
- pass through massive particles without interacting
- exert and experience only gravitational (and possibly weak) forces
- ie, photinos, neutrinos, gravitinos, axions
- only neutrinos have been detected

WIMPs

Detection Methods and Projects

- The AMANDA Project

  (Antarctica Muon and Neutrino Detector Array)

- The Cryogenic Dark Matter Search

- The DAMA Experiment

  (Particle Dark Matter Searches with Highly Radiopure Scintillators at Gran Sasso)

HDM and CDM

Hot Dark Matter

- particles with masses of zero or near-zero
- travel at/near speed of light
- masses between 1 million and 1 thousandth the mass of an electron
- primary candidate → Neutrino
- HDM may comprise 20% of matter in the Universe

Cold Dark Matter

- sufficiently massive particles that travel at subrelativistic velocities
- ie, WIMPs
- masses 10-100 times a proton's mass
- CDM may comprise 70% of matter in the Universe

Does Dark Matter Really Exist?

Basis of Newton's Universal Law of Gravitation →

the gravitational force between 2 objects is directly proportional to the product of their mass, and is inversely proportional to the sequence of the distance between them

Current DM evidence assumes this theory applies to the large scale of galaxies but perhaps this is not true on large scales?

→ MOND (Modified Newtonian Dynamics)

F=ma does not hold → fits to observed rotation curves for galaxies

Alternatives to CDM

WDM: reduce the small scale power
Self-Interacting Dark Matter (Spergel & Steinhardt 2000)
Strongly Interacting Massive Particle
Annihilating DM
Decaying DM
Fuzzy DM

Candidates of decaying DM

active neutrino, sterile neutrino, unstable susy particle, crypton, super heavy dark matter, R-violating gravitino, moduli, axino, SWIMP, quintessino, Q-ball, topological defect, primodial black hole ...

Dark matter summary

Observations are in general agreement with LCDM, most data consistent with low DM density (0.2-0.3),.

DM is not baryonic
DM is not hot
WIMPs are the classic CDM

End