Radio Emission in Clusters of Galaxies

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Outline

- Cluster radio emission : halos, relics
  ICM non-thermal components
  (B fields + relativ. e^-)

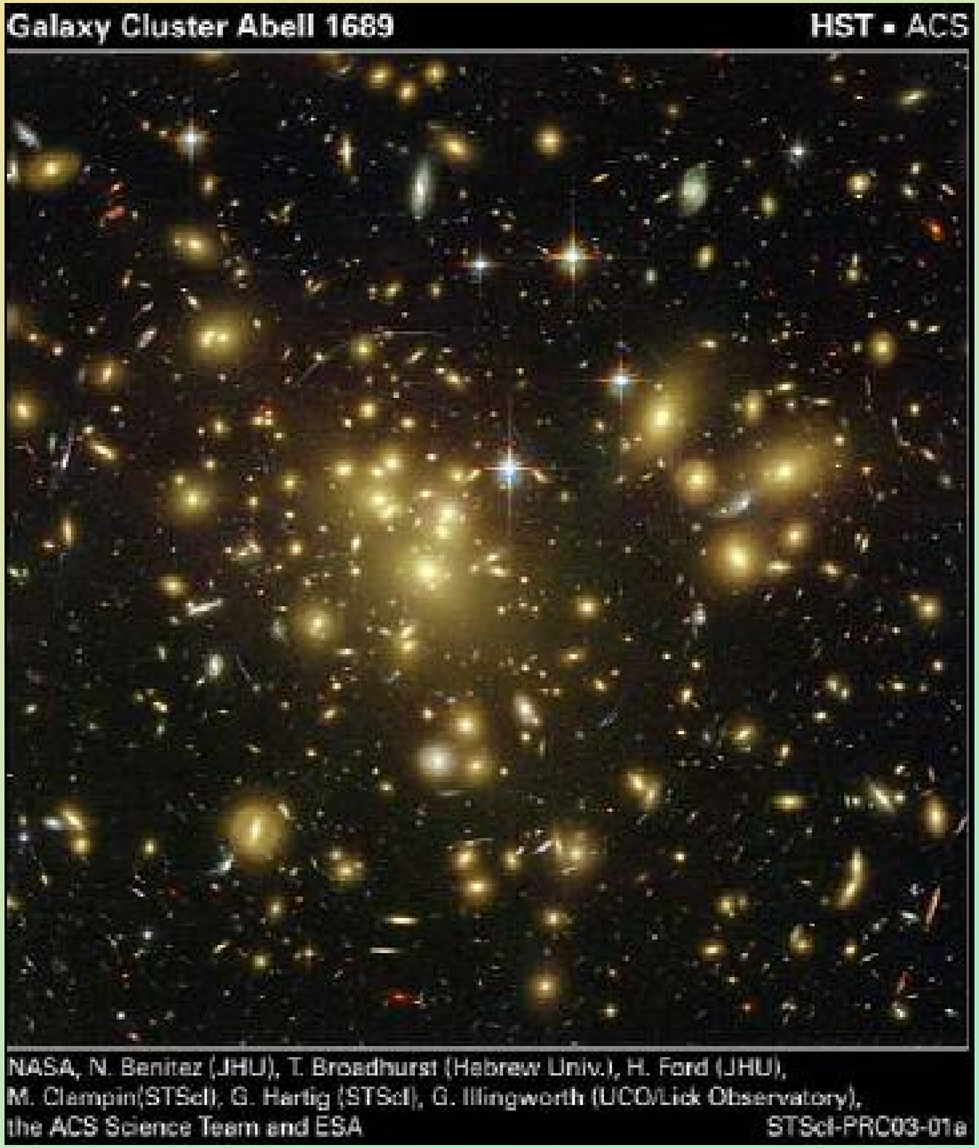
- Origin and evolution of B fields

- Origin and evolution of relativistic particles

- Connection to cluster merger processes
  MERGER-OMETER ?

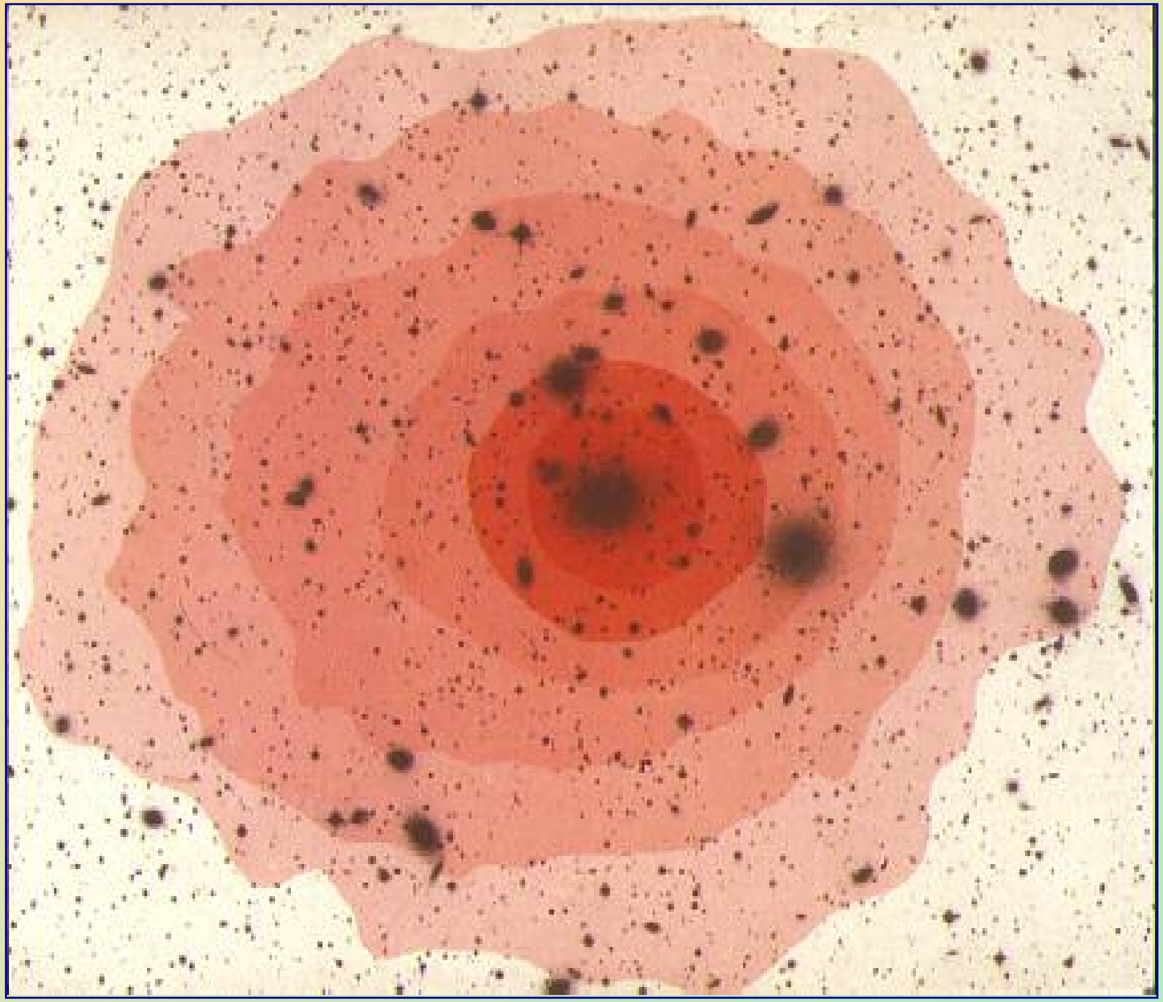
A cluster is a gravitationally bound system of galaxies

Coma cluster



A 1689

Hot Intracluster Medium (ICM)



X-ray emitting

Perseus Cluster

Cluster formation

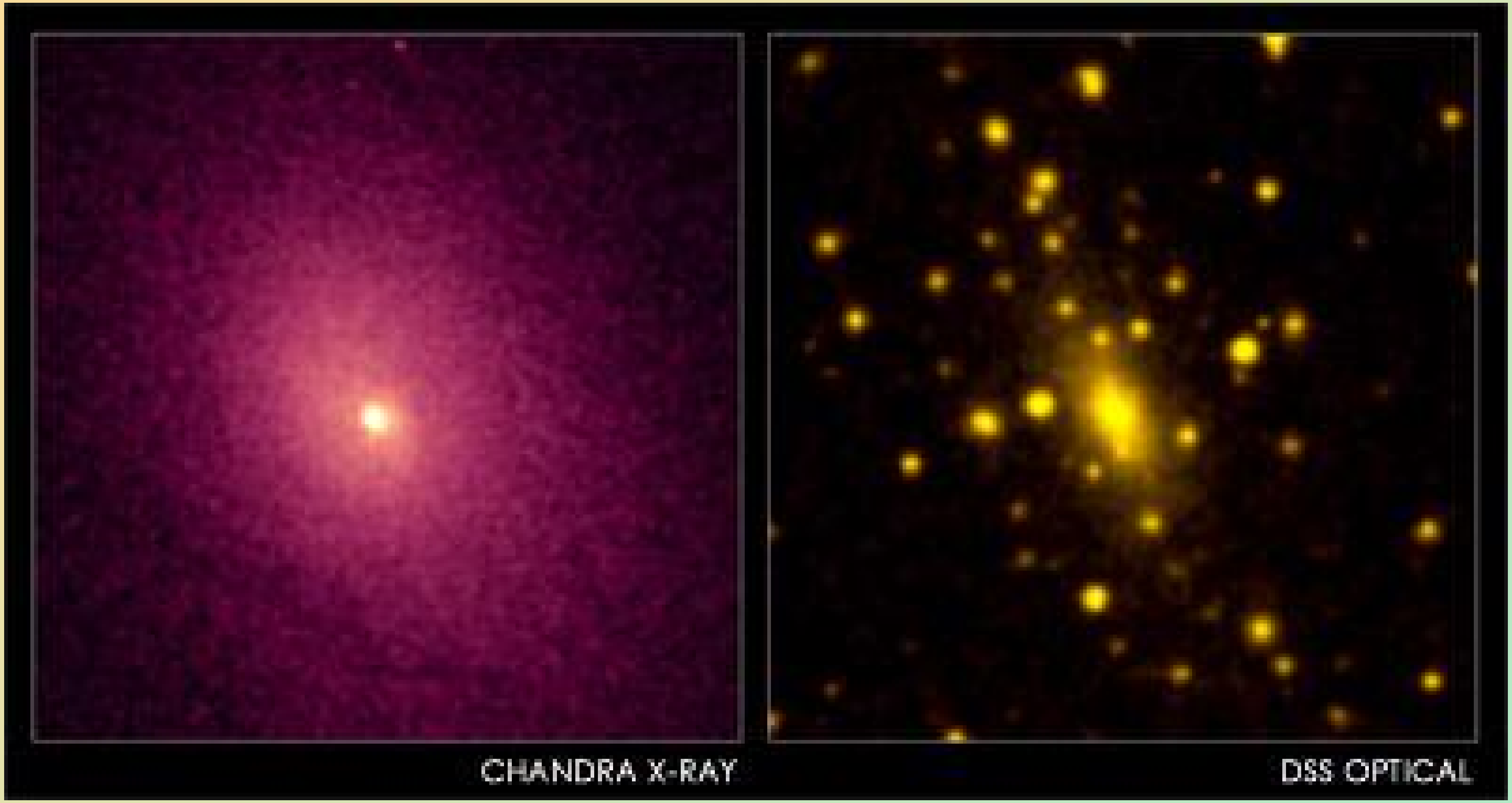
Clusters form from the gravitational collapse of primordial density fluctuations $\delta \equiv \delta\rho_m/\rho_m$

Hierarchical scenario (mergers) :

Galaxies ➔ Groups ➔ Clusters

Relaxed Clusters (cooling core)

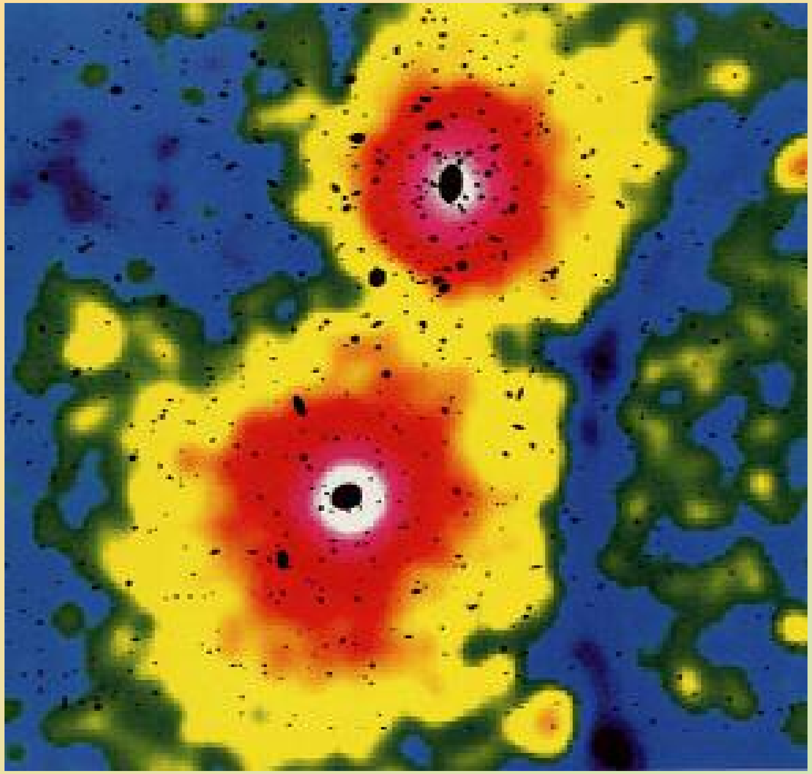
Less than 50 % of clusters that we observe now

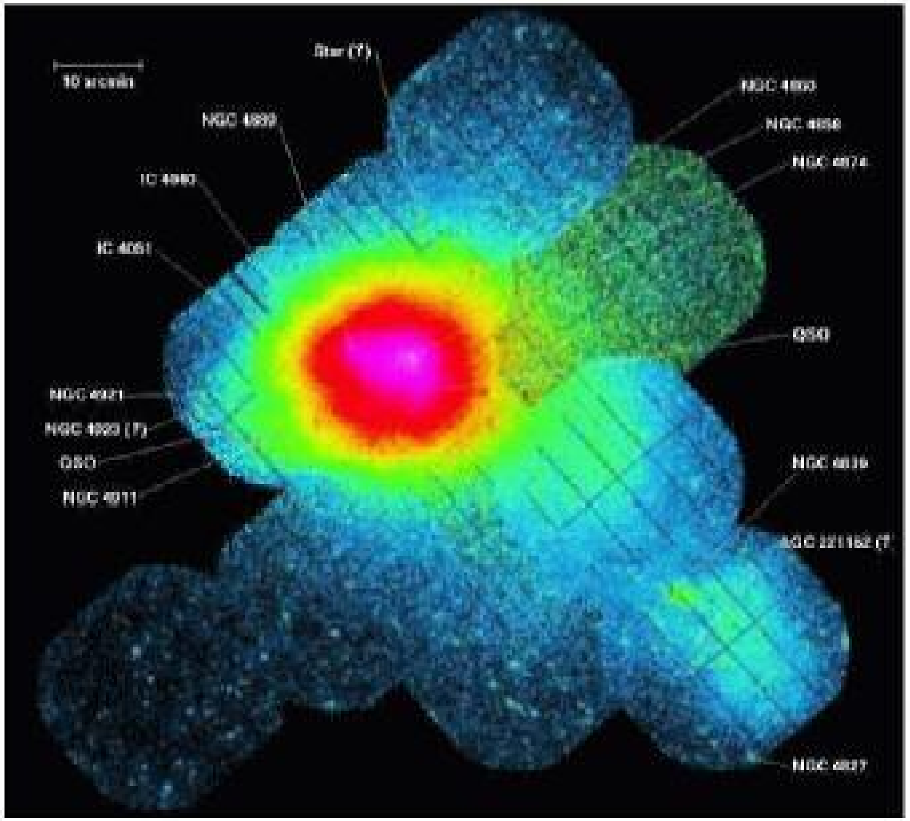


A 2029
(Lewis et al 2003)

Clusters during the formation process : merging

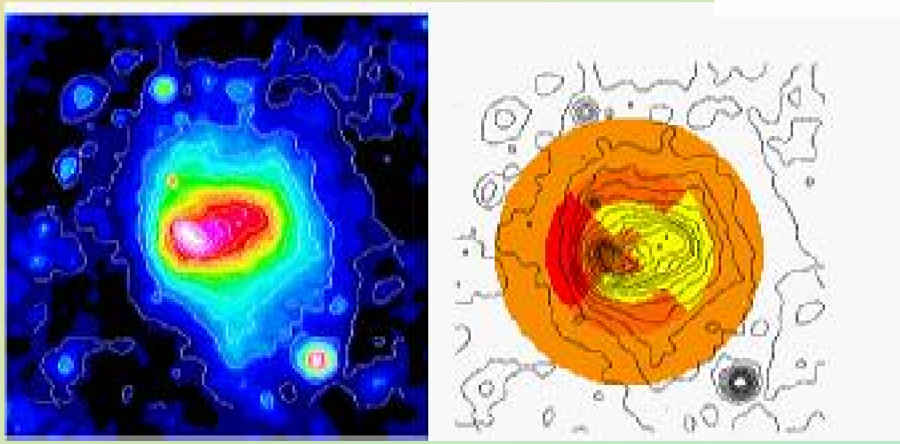
A3528 (Schindler 1998)





XMM-Newton Image of X-ray Emission from Coma Cluster, 0.3-2.0 keV

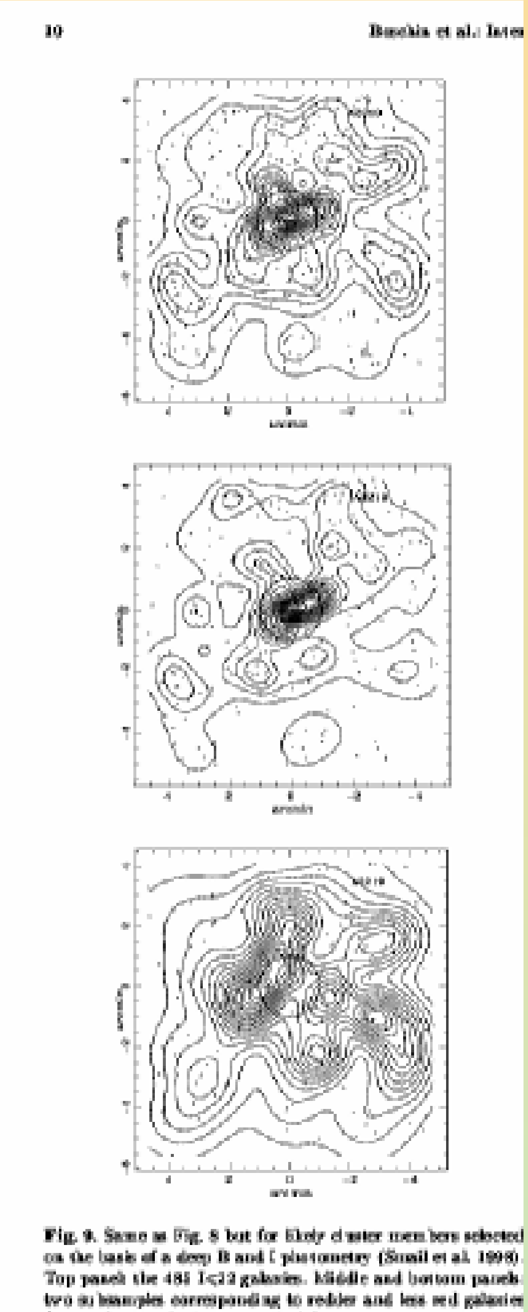
(Briel et al. 2001)

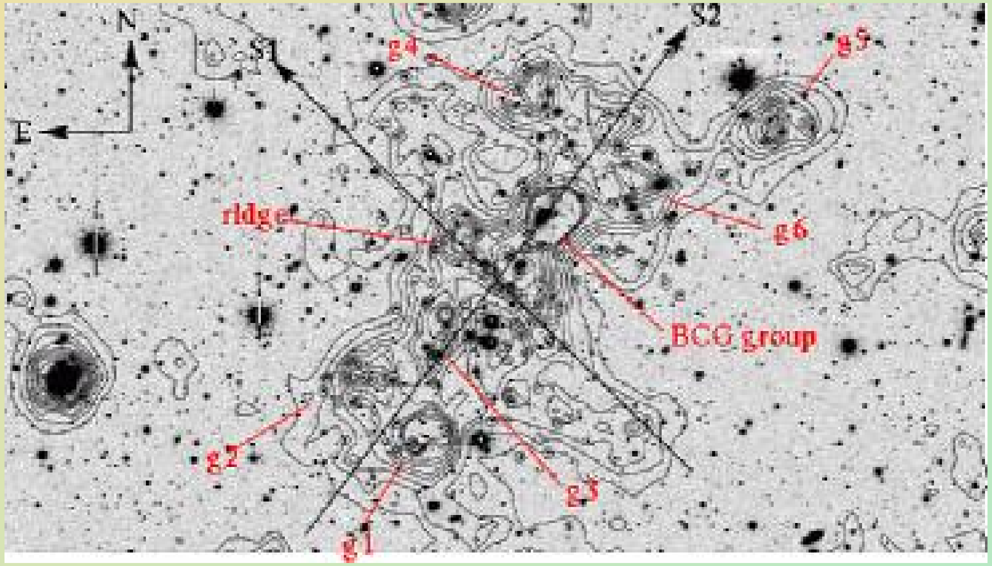


A 754

(Briel & Henry 1995)

Optical





A 521

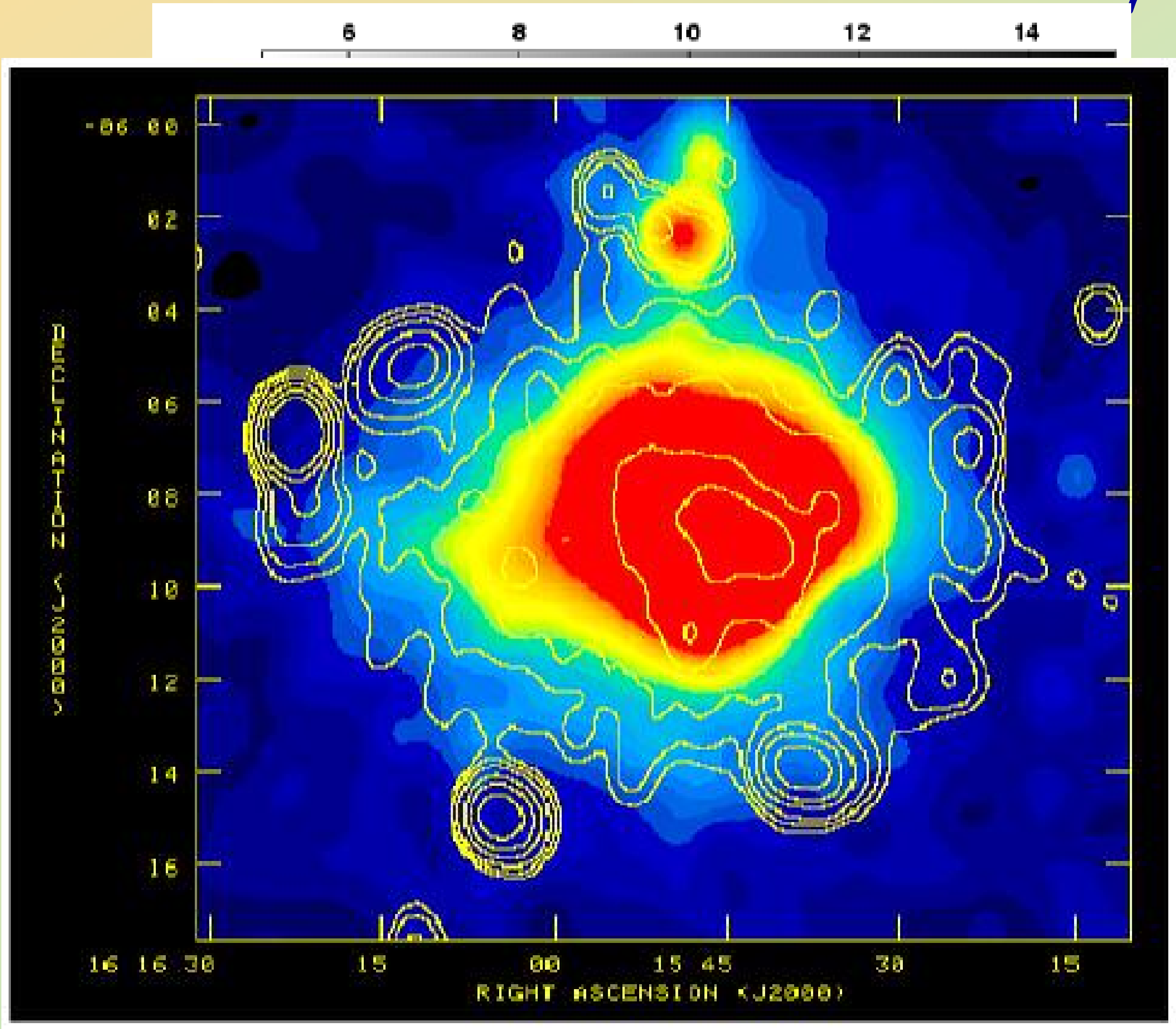
(Ferrari 2003)

A 2219

(Boschin et al 2004)

Diffuse Radio Sources in clusters :

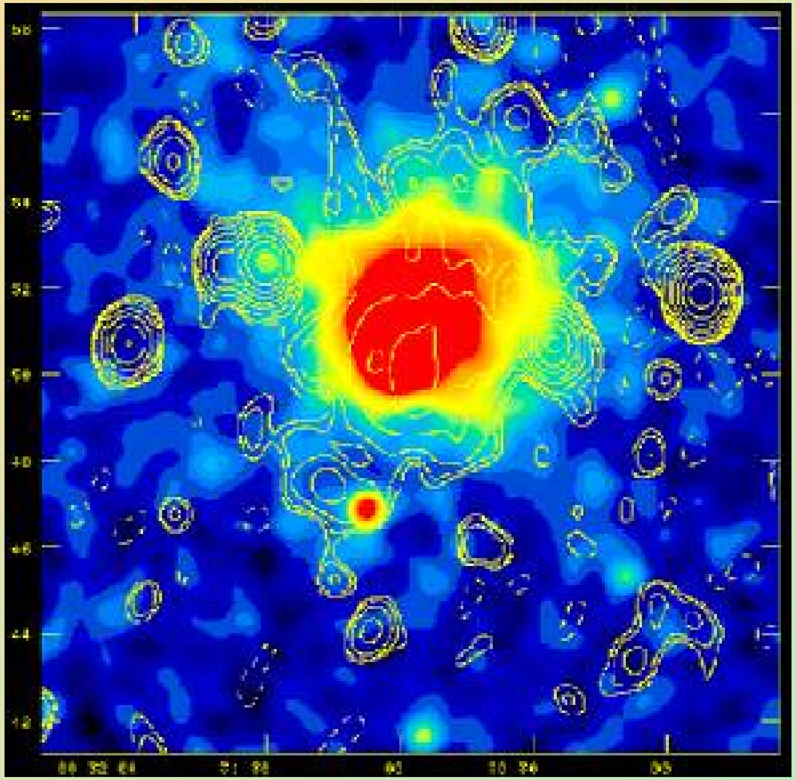
1 - radio halos : similar distribution as X-ray gas

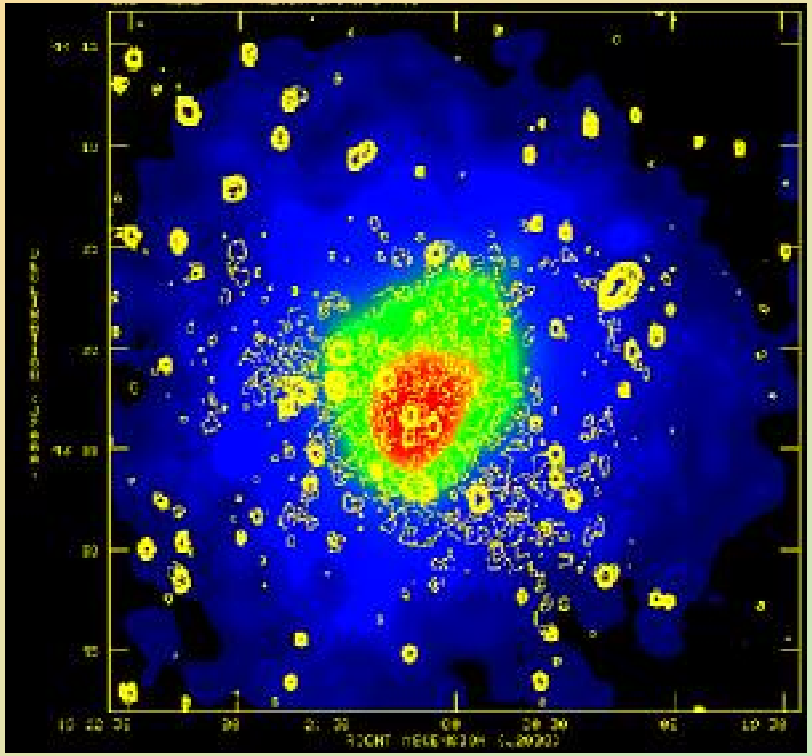


A2163

Halos

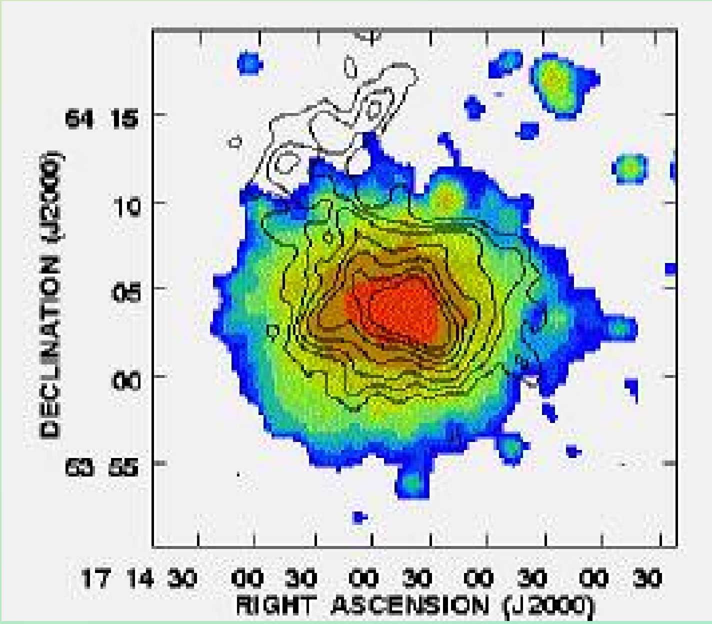
A665





A2319

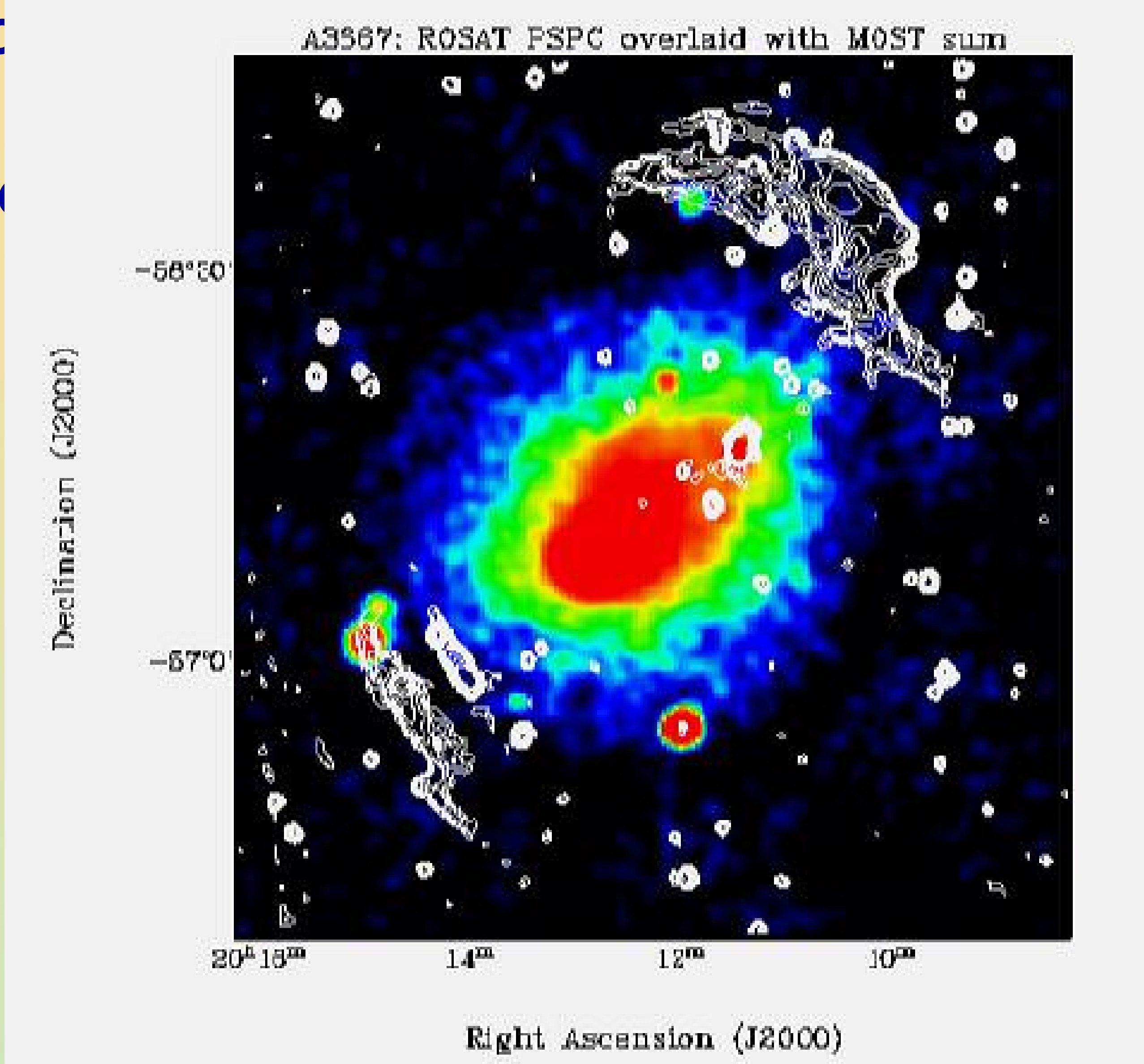
A2255



Diffuse Radio Sources in clusters :

1 - radi

2 - radi ...pheries

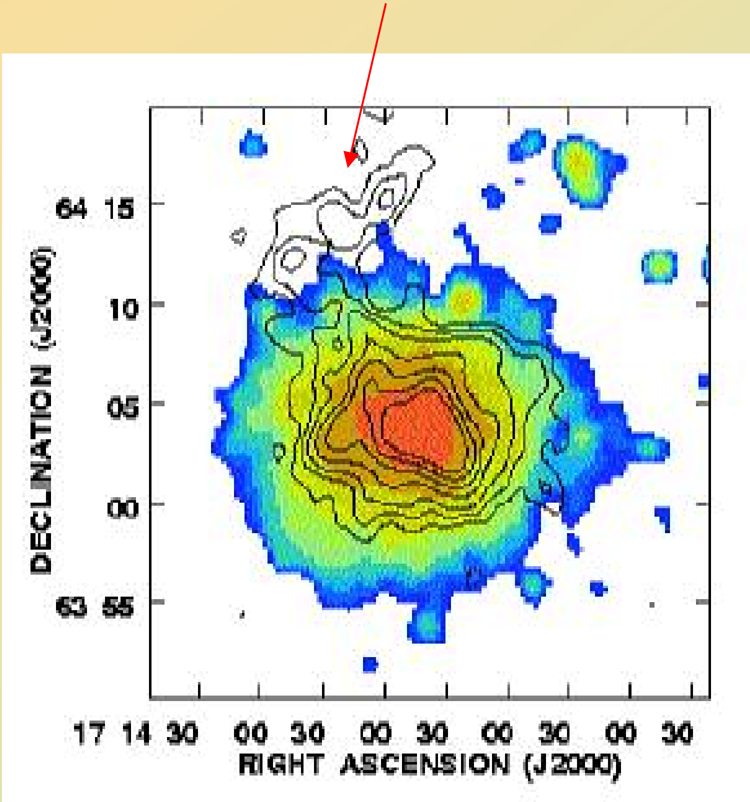


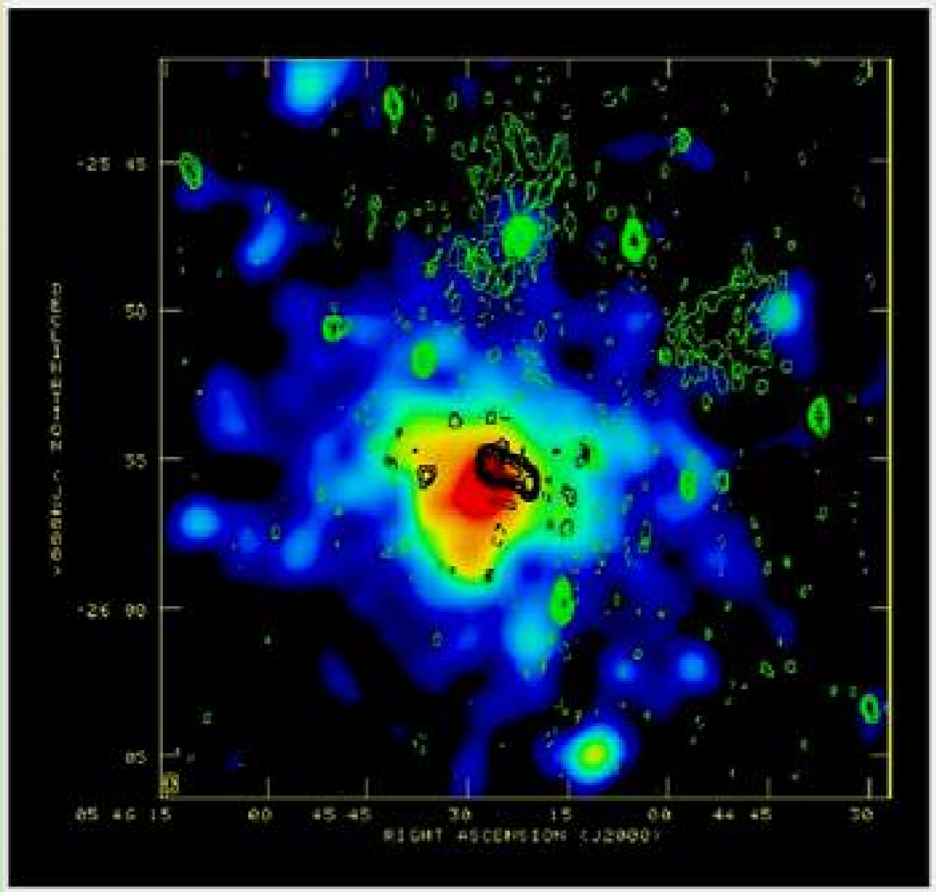
A3667

A2255

A548b

z= 0.0809 Relic size 730 kpc





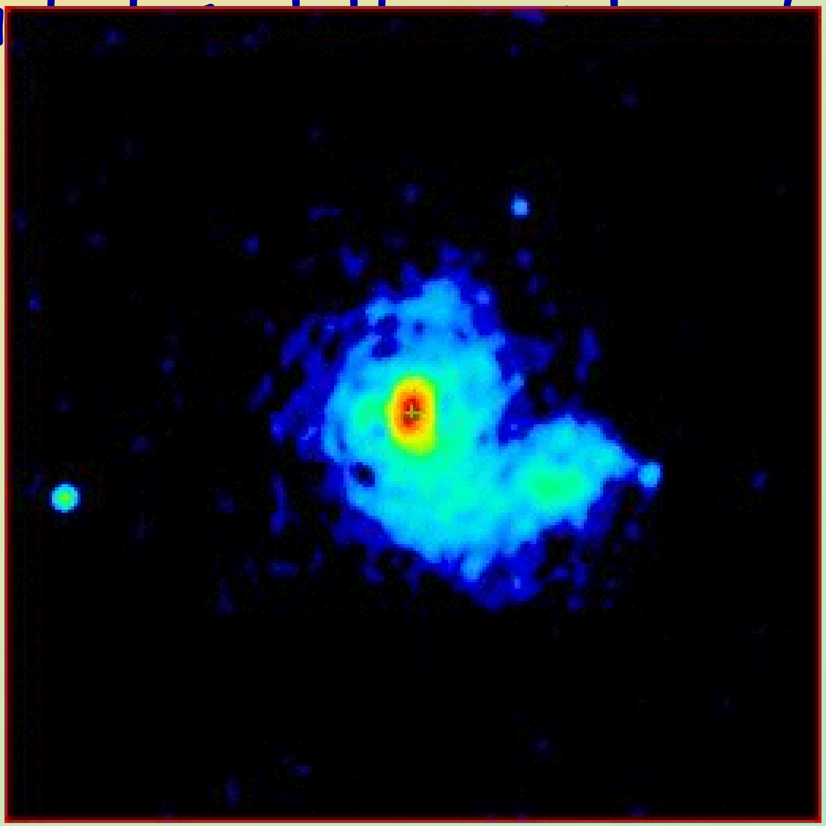
Feretti et al. 1997

Diffuse Radio Sources in clusters :

1 - radio halos

2 – radio relics

3 – mini[illegible] cooling core clusters



Perseus
Radio,   Size = 350 kpc
(Sijbring & De Bruyn 1993)

Diffuse R... rs :

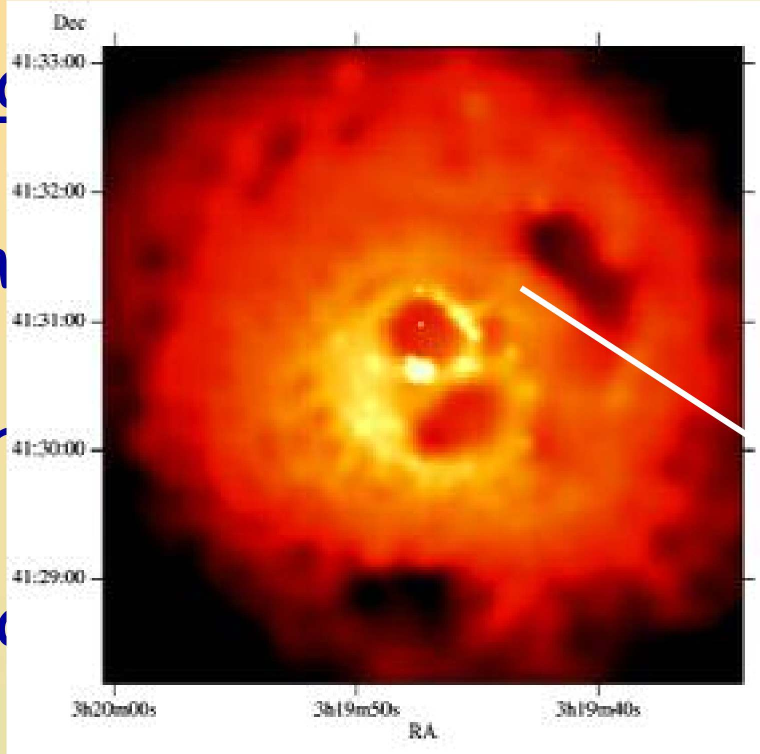
1 - radio h...

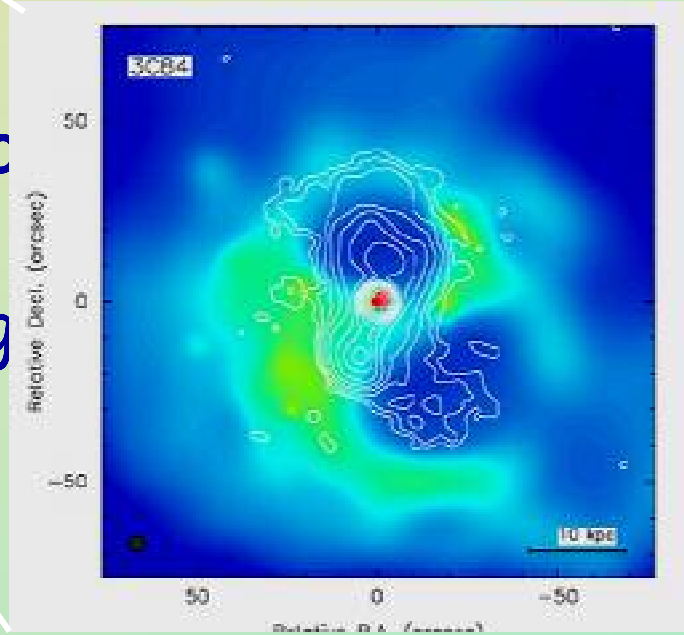
2 - radio r...

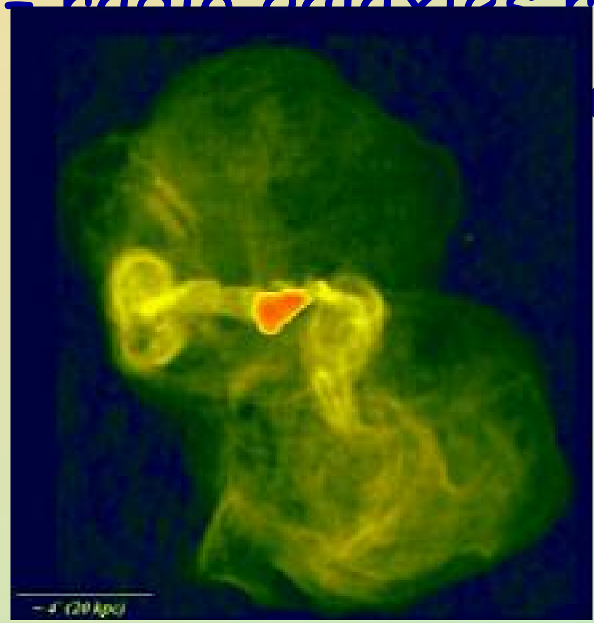
3 - mini-h... c...

4 - radio galaxies related to cD g...

...adio bubbles,







Diffuse Radio Sources in clusters :

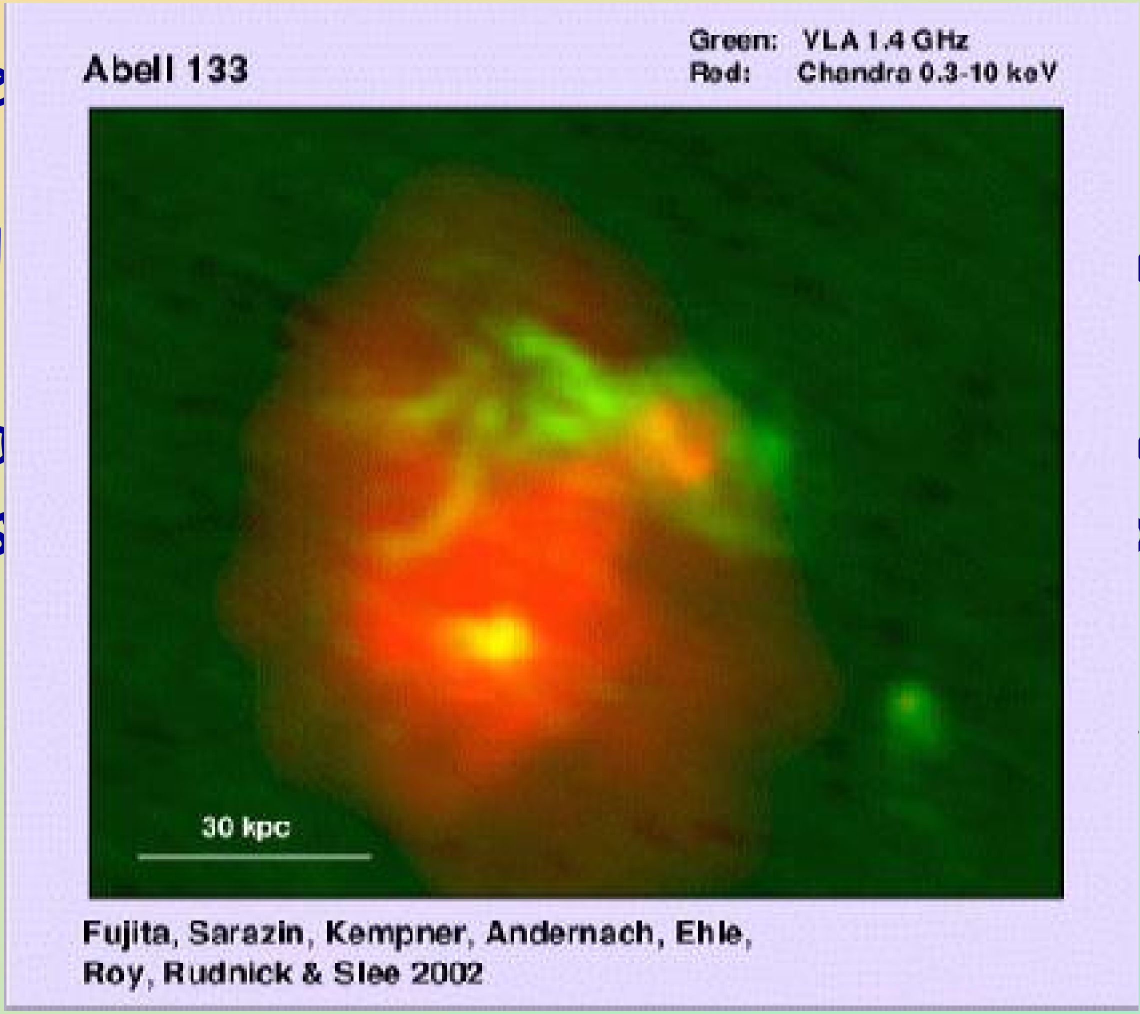
1 - radio halos

2 - radio re

3 - mini-hal clusters

4 - radio ga cool core
clus les

5 - central nd 4)



Diffuse Radio Sources in clusters :

1 - radio halos ⇐

2 – radio relics ⇐

3 – mini-halos at the center of cooling core clusters

4 – radio galaxies related to cD galaxies in cool core clusters, radio bubbles, ghost bubbles

5 - central relics (intermediate between 2 and 4)

→ all steep spectrum sources

Radio emission: synchrotron

Relativistic particles : ~ GeV, γ >> 1000

Mpc scales

HOW ?

Proved also by Hard X-ray emission of IC origin

Magnetic fields : ~ μG

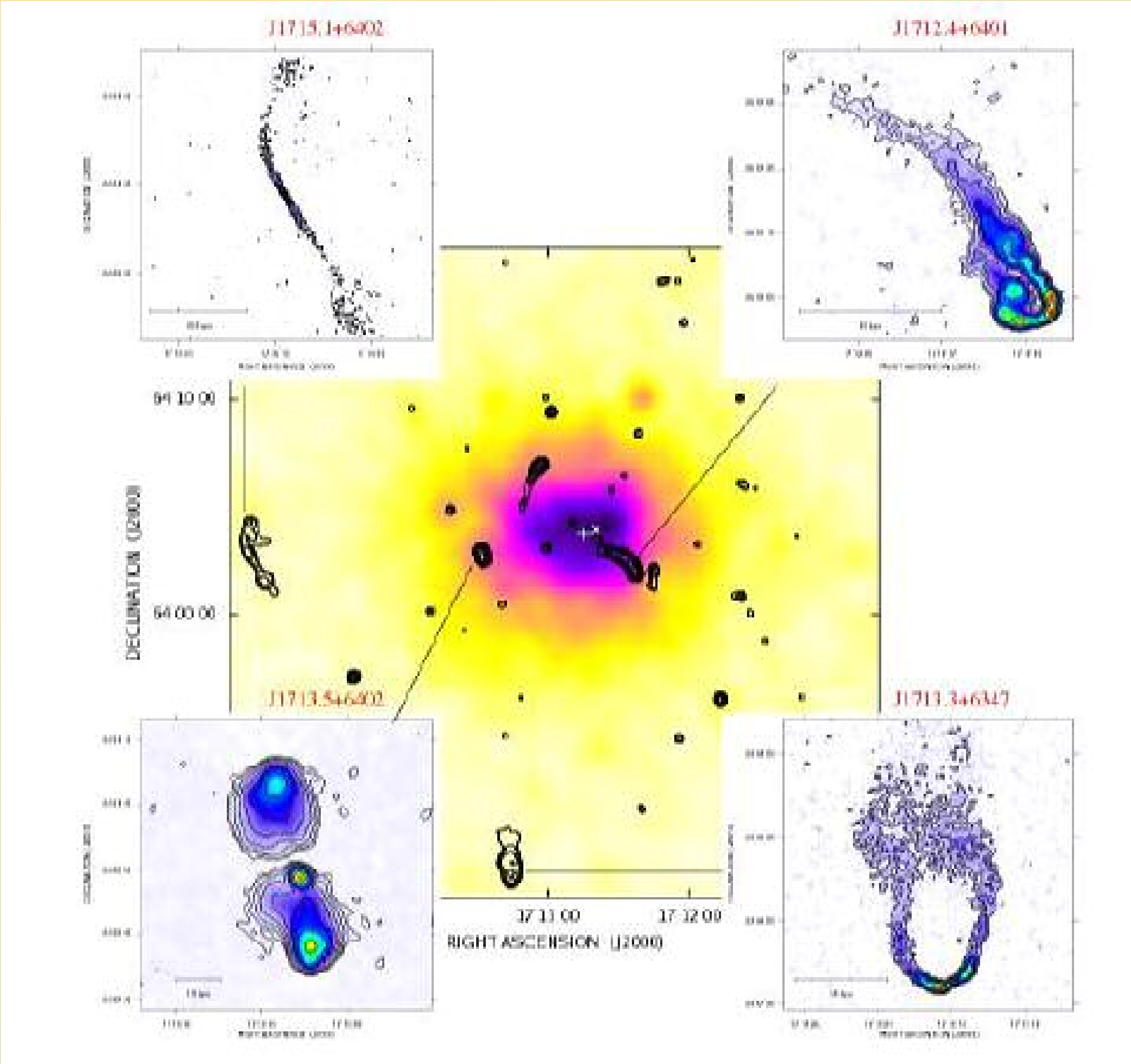
Mpc scales

➔ HOW ?

The presence of magnetic field can be indirectly probed by other studies, in particular:

Rotation Measure

Other techniques: IC emission
cold fronts
simulations

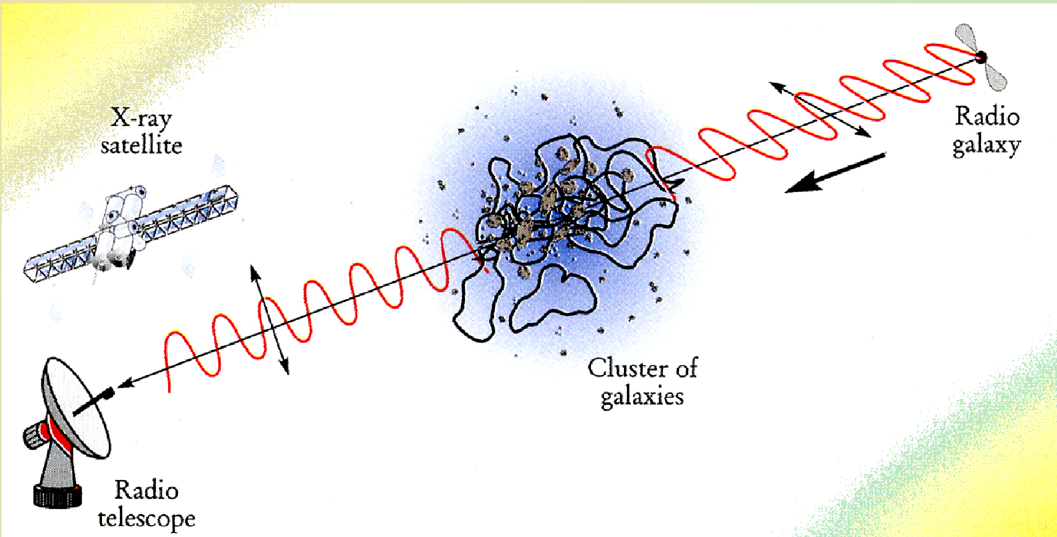


A2255 Govoni et al. 2006

Faraday Rotation

rotation of the plane of polarization of linearly polarized emission as it passes through a magneto-ionic plasma

-- due to the different phase velocities of the orthogonal circular modes



Kronberg 2002

Interpretation of Rotation Measure data :

$$RM = 811.9 \int_0^L n_e B_{||} d\ell \quad \mathrm{rad/m^2}$$

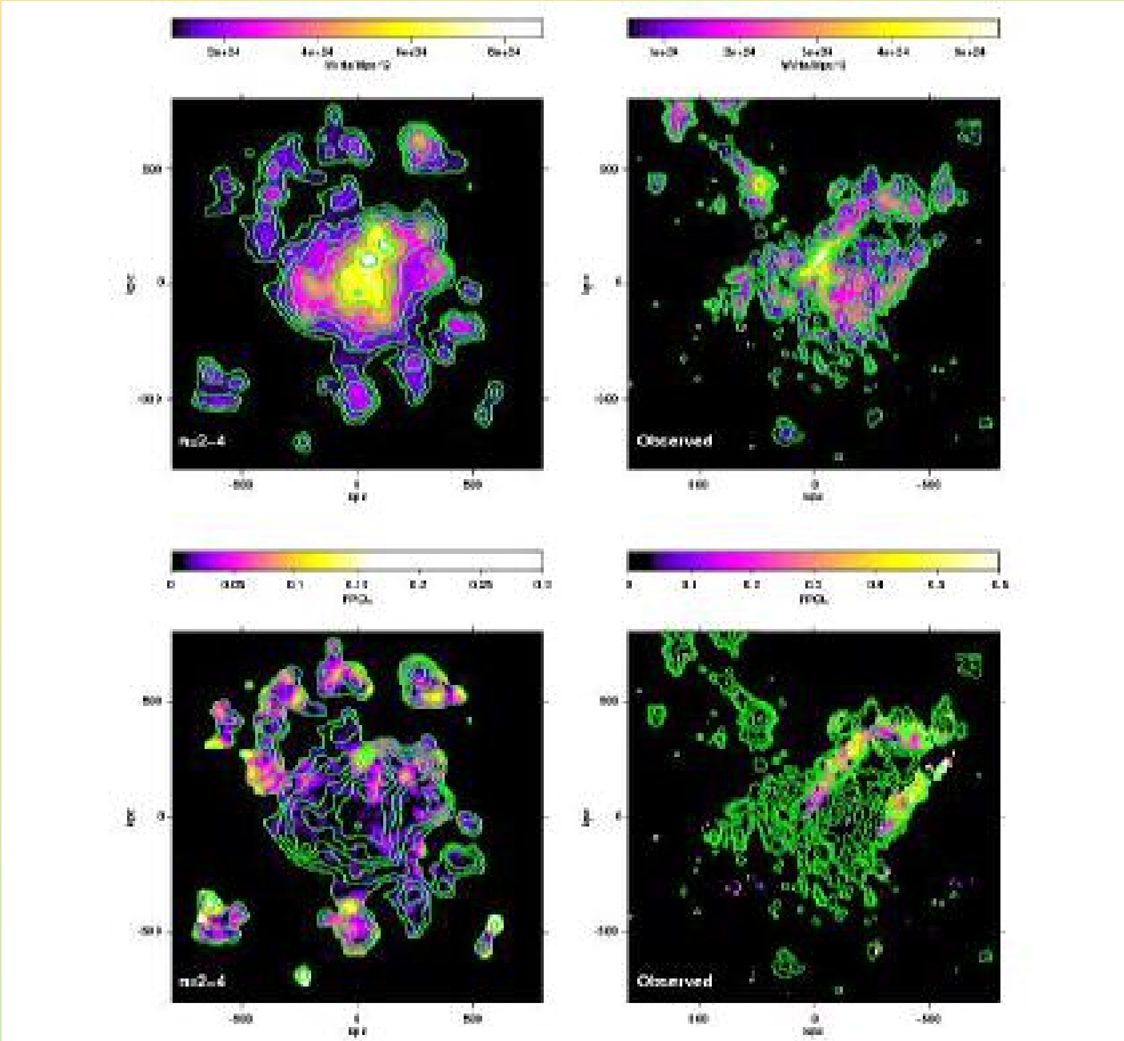
Values derived for B are model dependent
- analytical solution only for simplest cases

Otherwise:
- numerical techniques (Murgia, Govoni, 2004 - 2005)
- semianalitycal approach (Ensslin, Vogt)

Simulated Observed

Brightness

Frac polar



A2255 Govoni et al 2006

Magnetic fields

➔ Common in all clusters

(Carilli & Taylor 2002
Govoni & Feretti 2004)

also where there are no halos or relics

Questions to answer:

When and how were the first magnetic fields generated?

How are the presently observed cluster magnetic fields obtained ?

Relativistic particles

Clusters are good stores of relativistic particles:

Injected during the cluster formation from AGN activity (quasars, radio galaxies, etc.), or from star formation (supernovae, galactic winds, etc.) or from the thermal pool during violent processes

(Atoyan & Völk 1999, Brunetti et al. 2001, Blasi 2004)

➔ Production occurred in the past and therefore connected to the cluster dynamical history

However:

Electrons ➔ from CR ➔ γ up to ~ 10^4

need to be continuously reaccelerated to compensate for energy losses

(syn, IC, Coul losses)

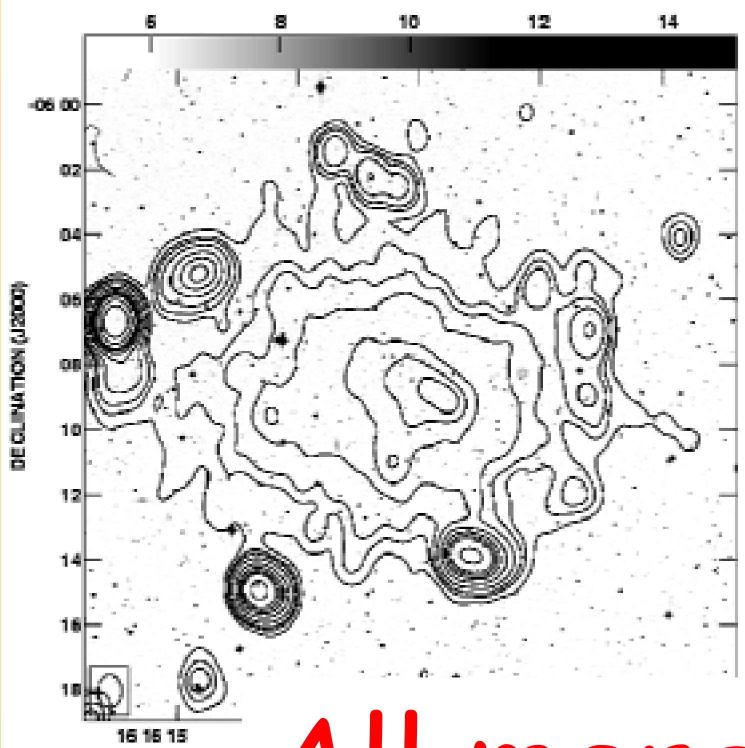
otherwise they are not energetic enough to emit detectable

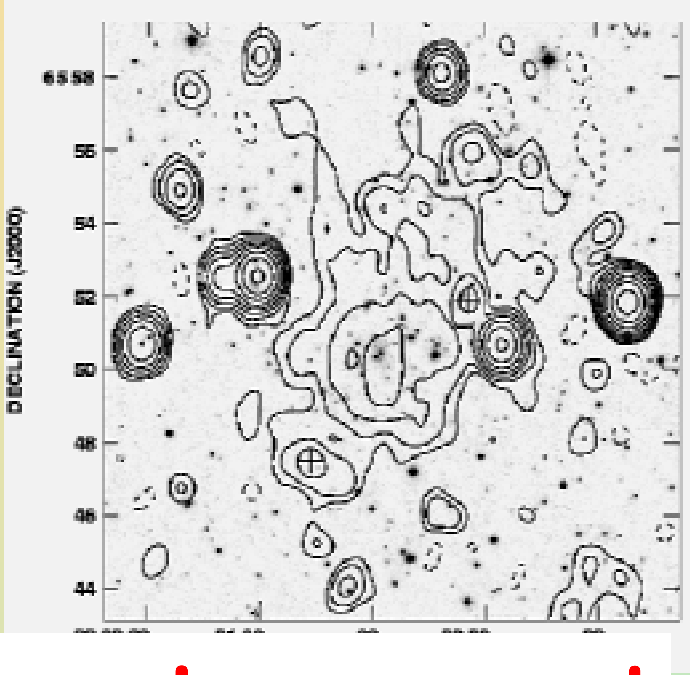
radio emission (Schlickeiser et al . 1987, Sarazin 1999)

AN IMPORTANT OBSERVATIONAL RESULT OBTAINED SO FAR IS THAT

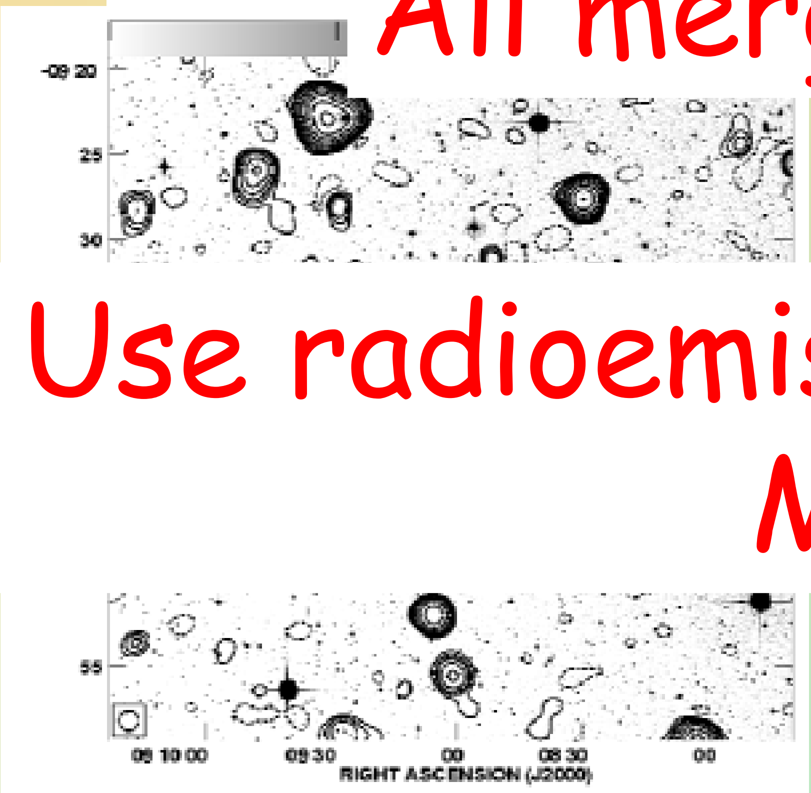
All halo and relic clusters contain evidence of dynamical evolution : recent / ongoing cluster mergers

- Substructures - X-ray
  - optical
- Absence of a strong cooling flow
- Temperature gradients
- Shocks and cold fronts





All merging clusters !



Use radioemission as

MERGER-OMETER !

Halo/merger connection

➔ energy supply to relativistic particles

Cluster mergers are the most energetic phenomena in the universe after the Big Bang

Collision v ~ 2000 km/s, $M \sim 10^{15}\ M_{\odot}$

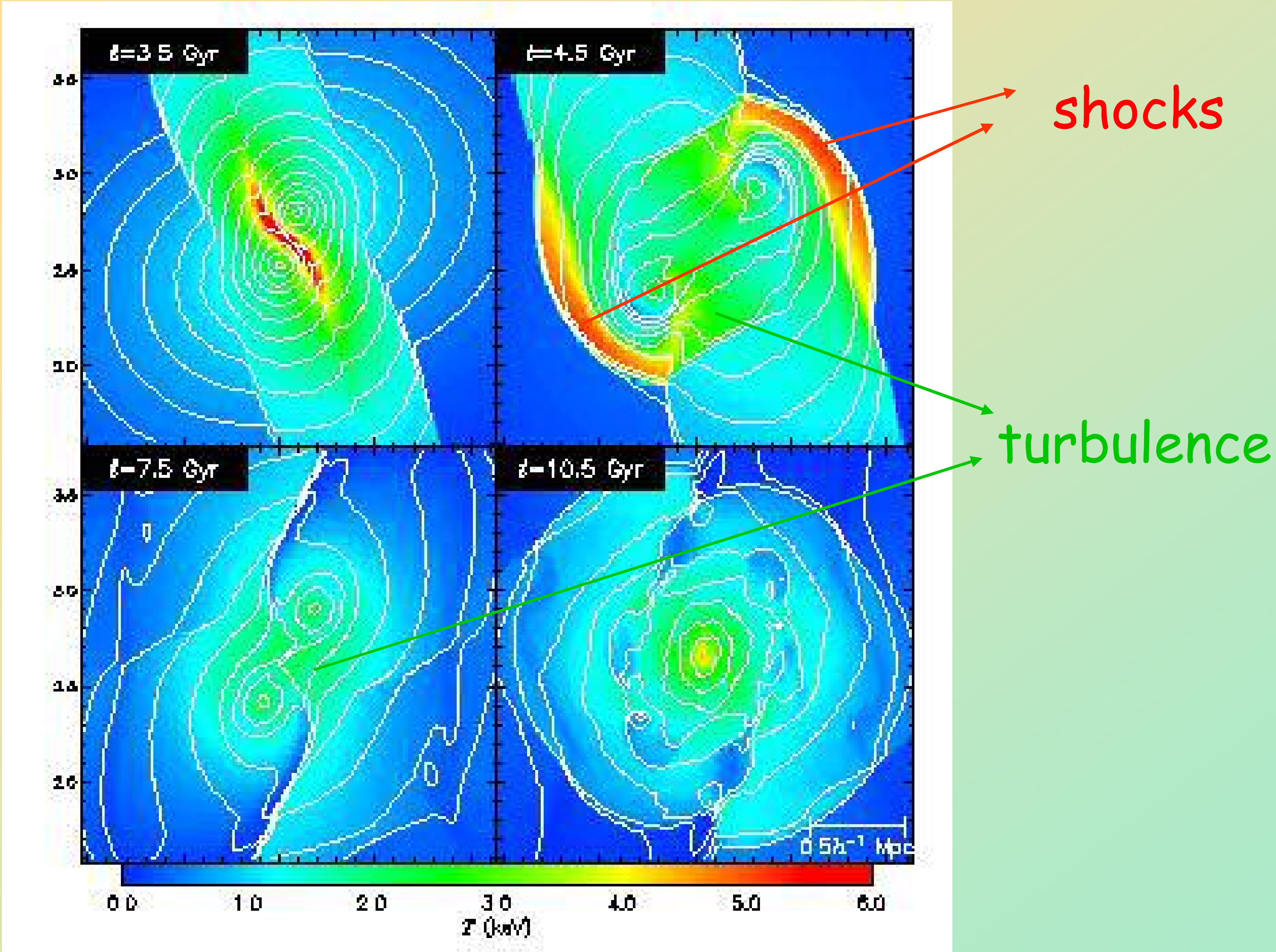
➔ $E \sim 10^{63\text{-}64}$ erg

Collision produces :

- merger shocks with velocity ~1000 km/s
- turbulence created after shock passage

Transfer of energy from merger to halos and relics

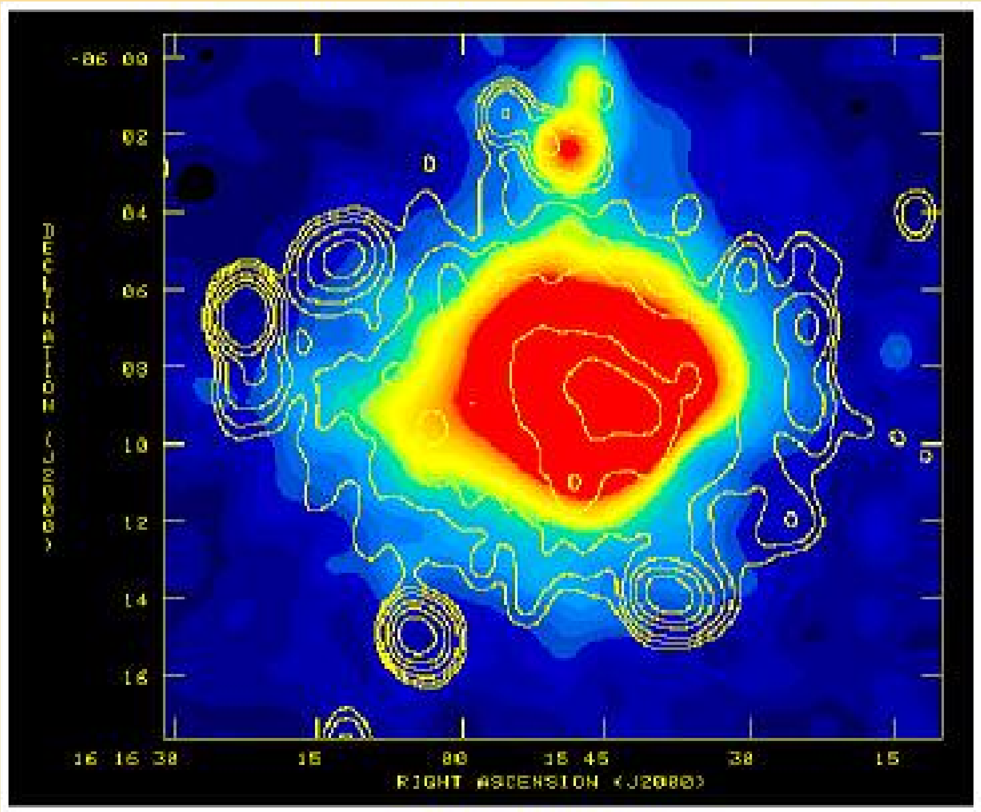
(Ricker & Sarazin 2001)



Color = temperature, Contours = X-ray brightness

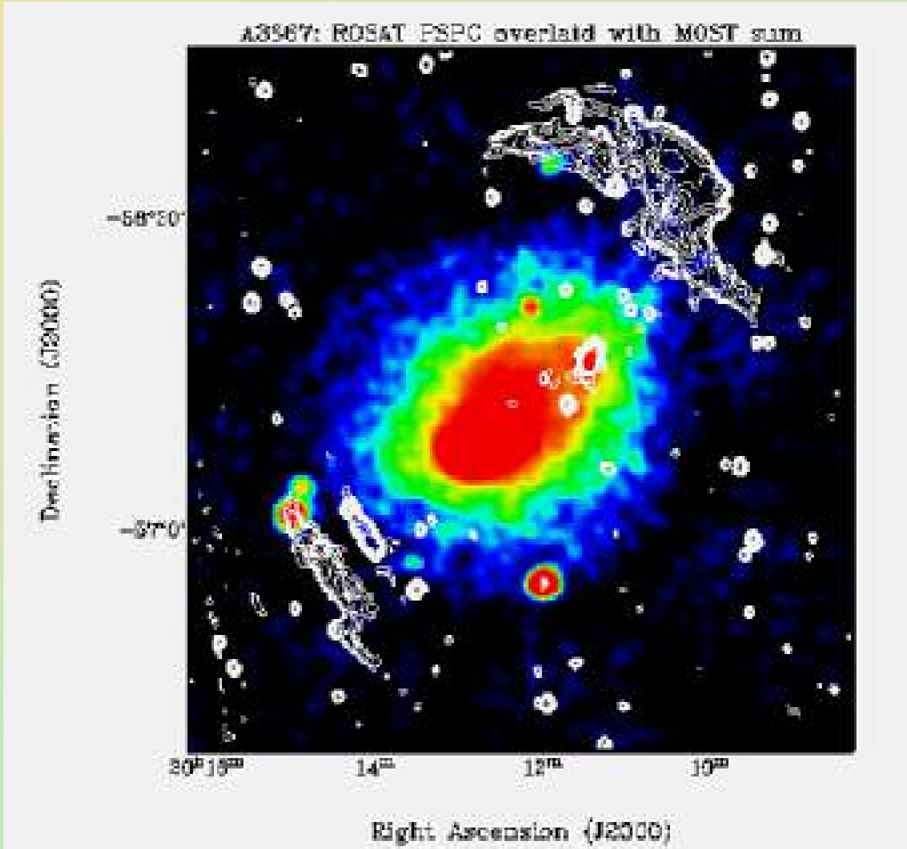
CURRENT VIEW

Halos



Turbulent reacceleration following shock passage ?

Relics



Shock reacceleration ?

Recent developments :

check DETAILS of the halo / merger connection

and of the relic / merger connection

HALOS : radio spectral index maps vs merger

radio spectrum reflects two important parameters affected by the merger

- strength of magnetic field
- efficiency of e^- reacceleration

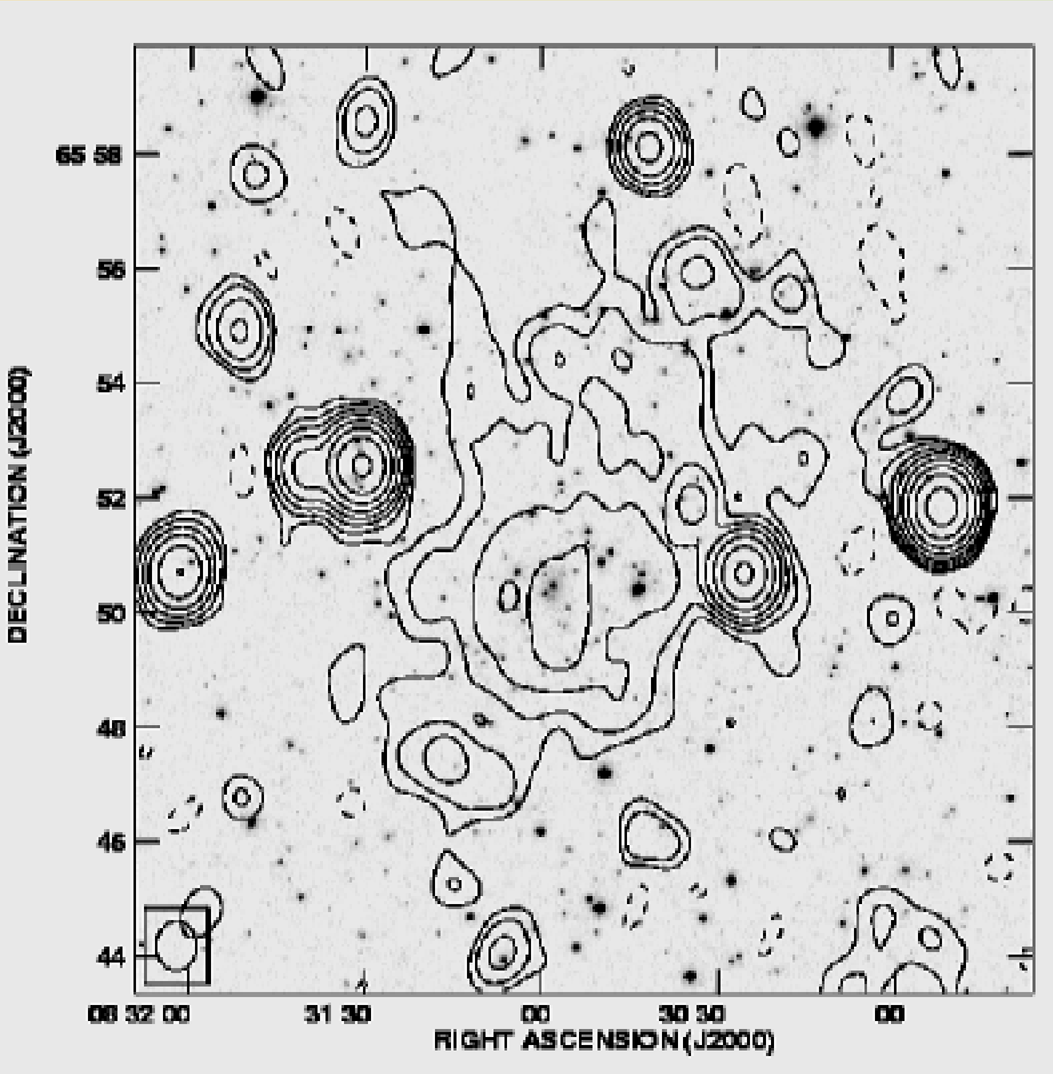
Flat spectrum → higher energy of radiating electrons

RESULTS : regions influenced by merger show flatter spectra

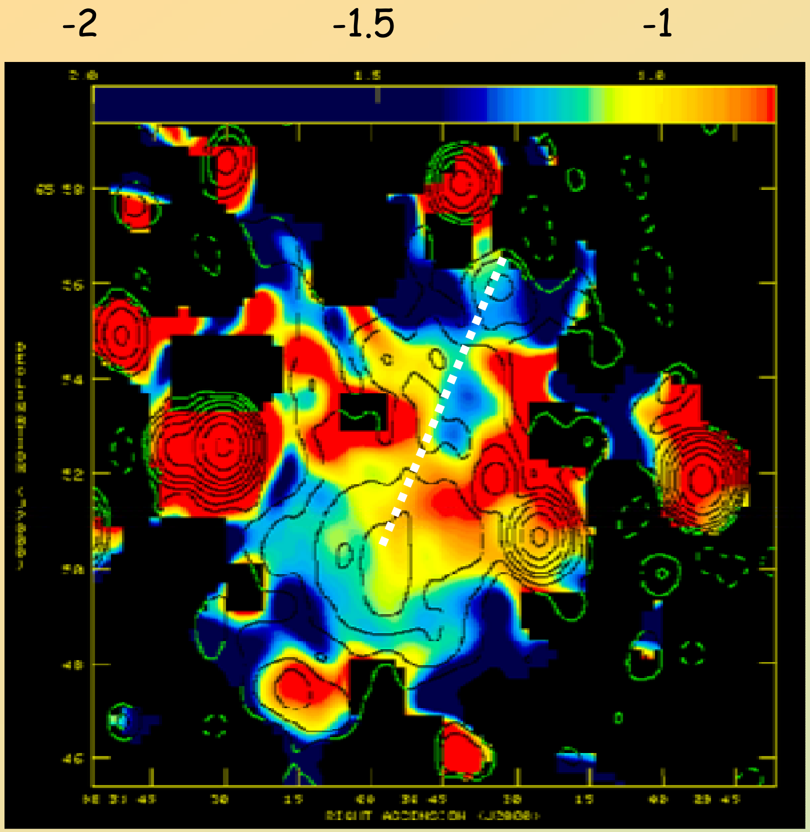
A 665

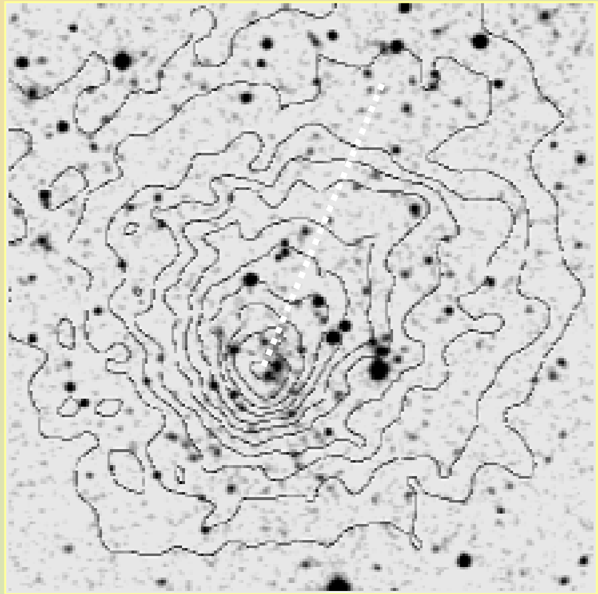
z = 0.1818,
kT = 8.3 keV

Radio image at 20 cm



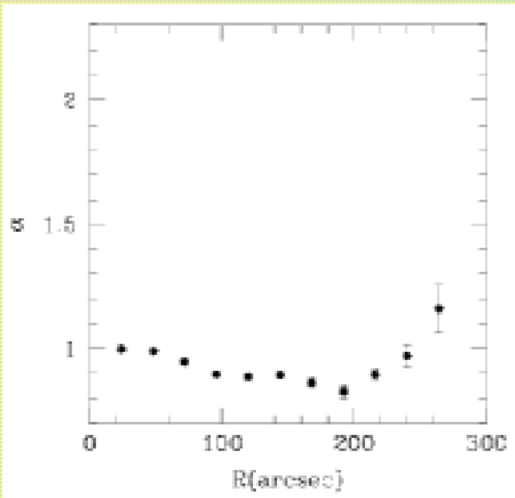
(Giovannini & Feretti, 2000)





Chandra - Markevitch & Vihklinin 2001

core radius = 95″
(380 kpc)



Spectrum is flatter in the region of the X-ray extended emission : X-ray subclump

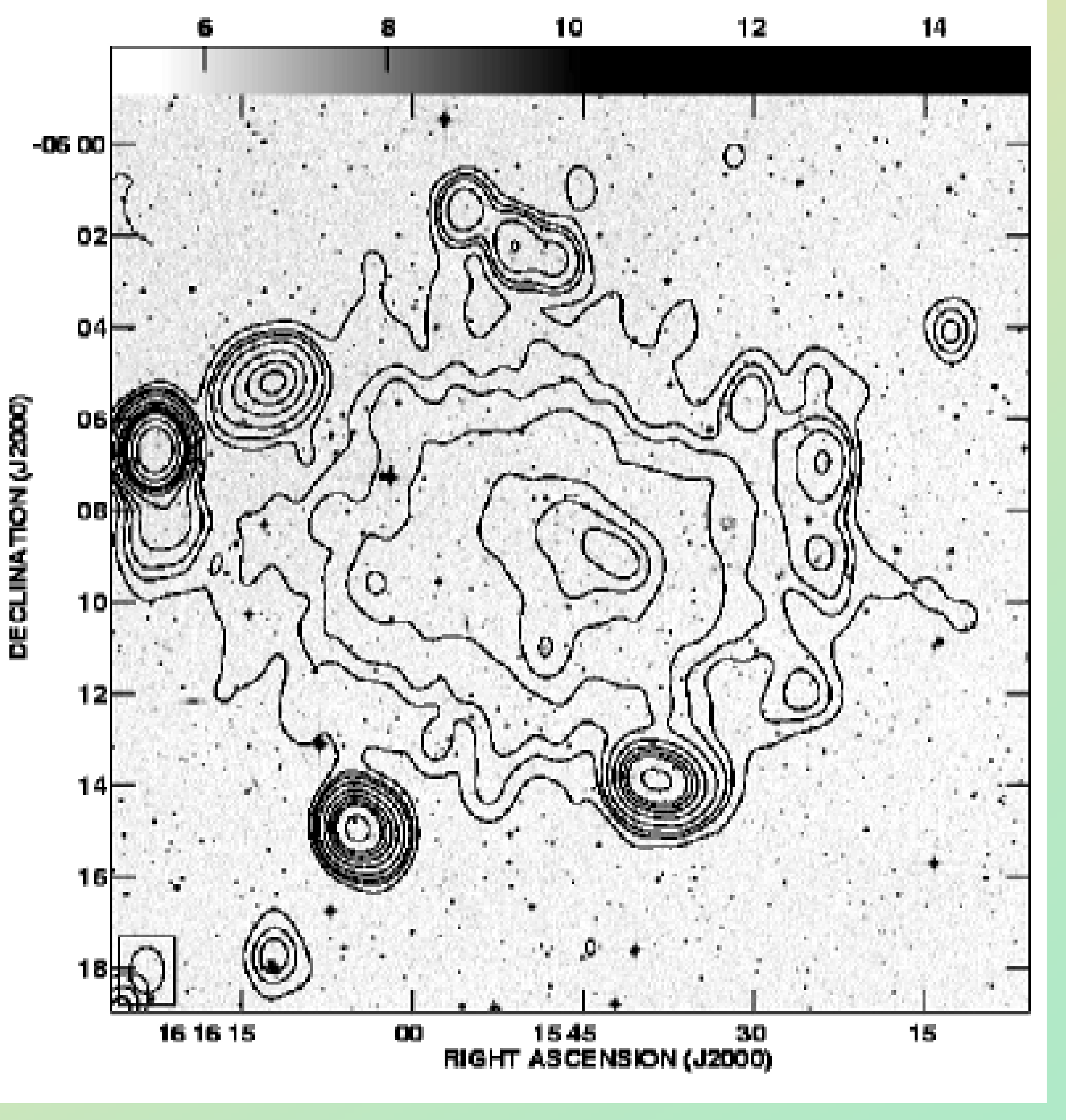
➔ merger

(Feretti et al. 2004)

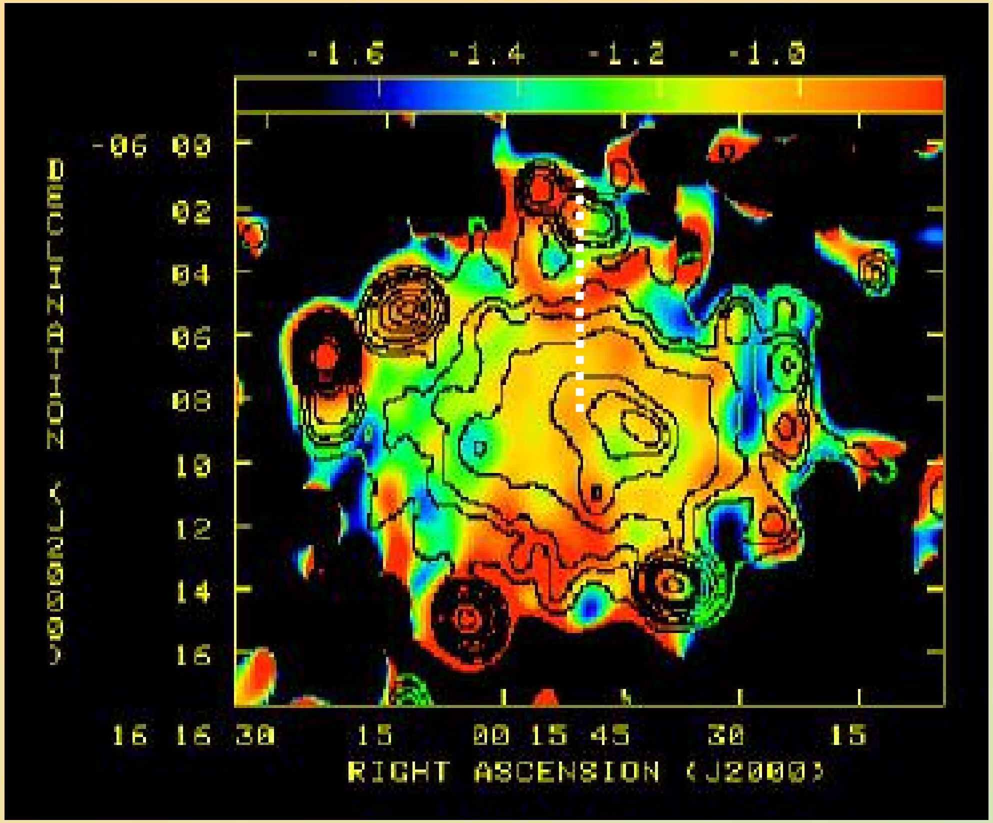
A 2163

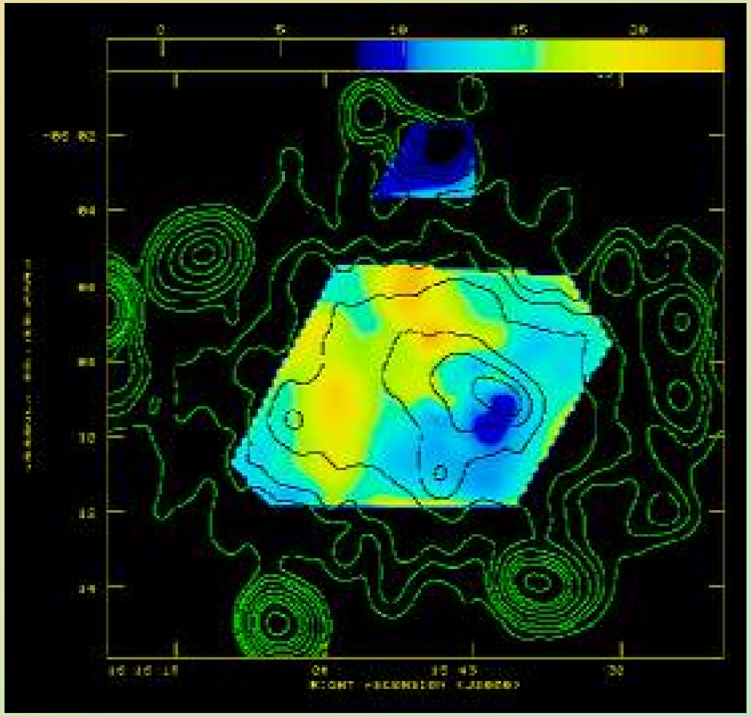
z = 0.203,
kT = 14.6 keV

Radio image at 20 cm



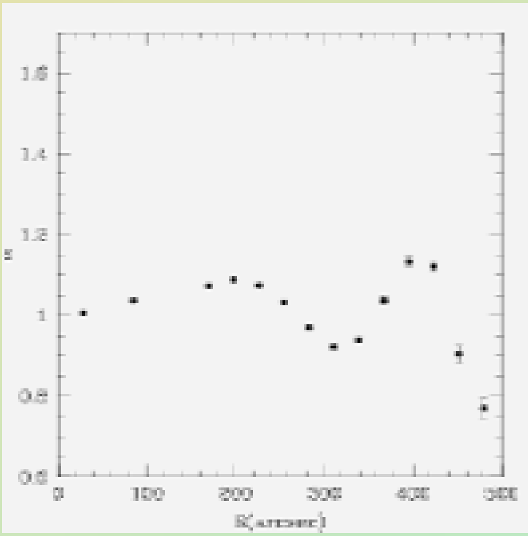
(Feretti et al., 2001)





Chandra – Govoni et al. 2004

core radius = 72"
(305 kpc)



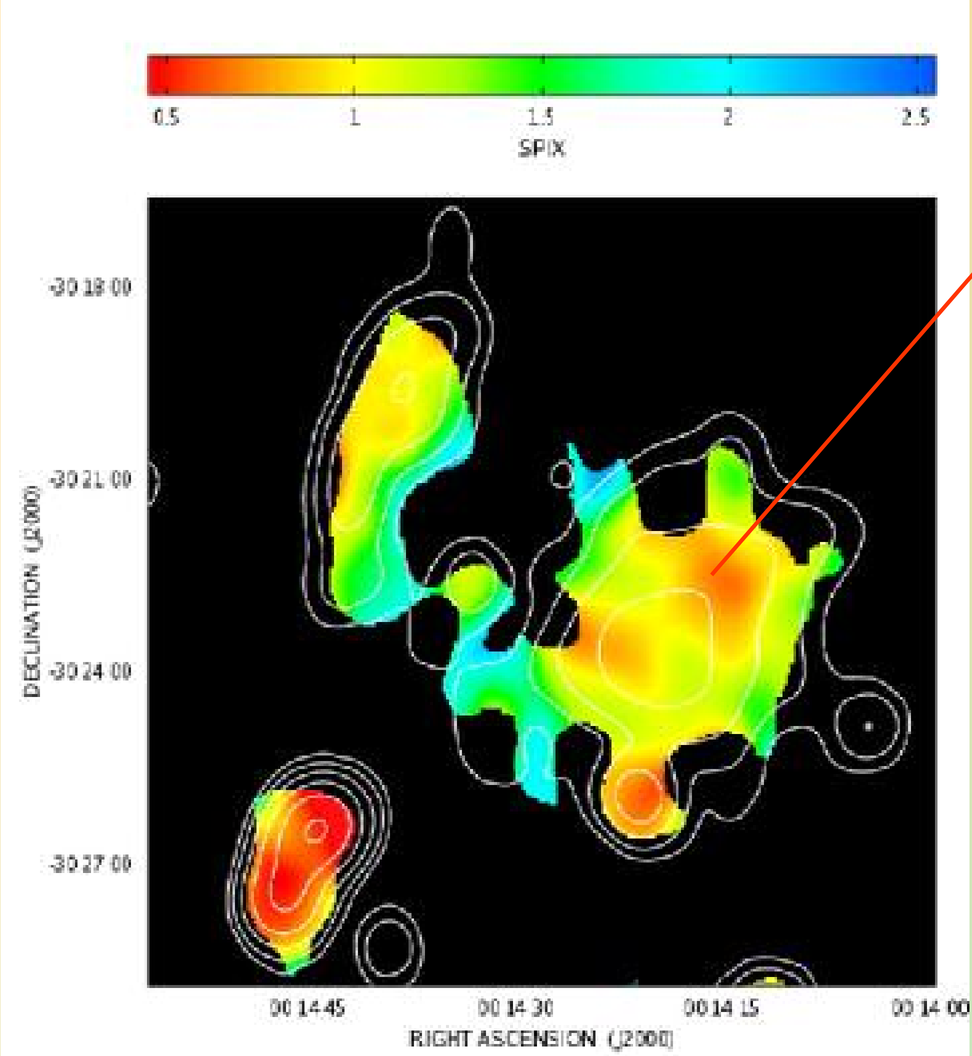
The spectrum is flatter in the western region and in the N-S stripe
➔ region of the
colliding/merging subclusters

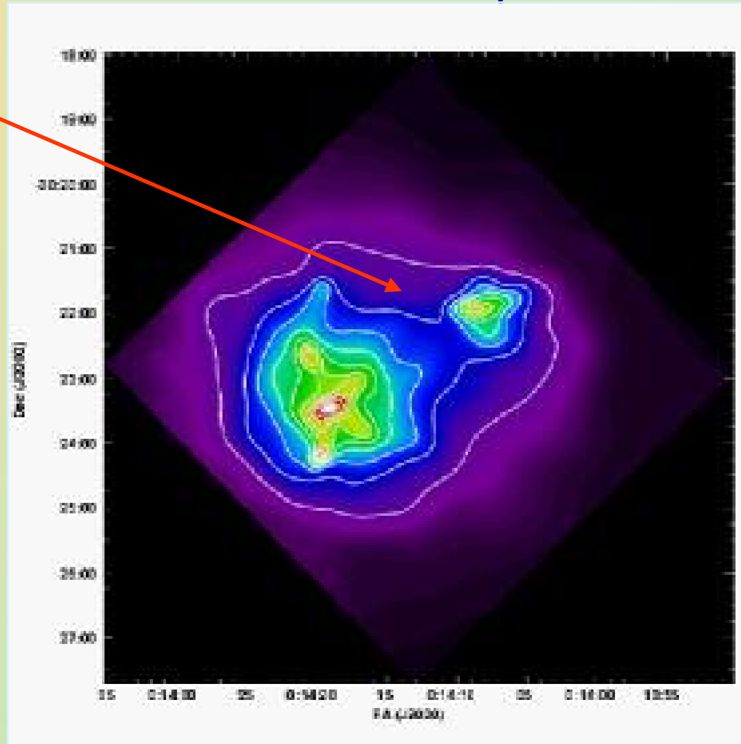
(Feretti et al. 2004)

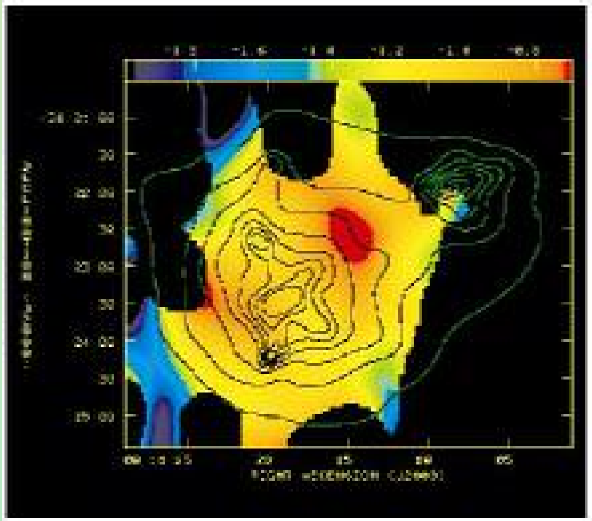
A 2744

Chandra X-ray emission

Kempner & David 2003



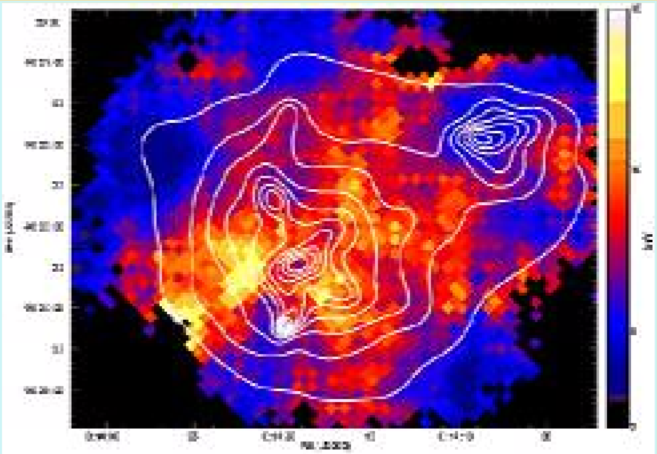




Color:
Spectral index
Contour:
X-ray emission

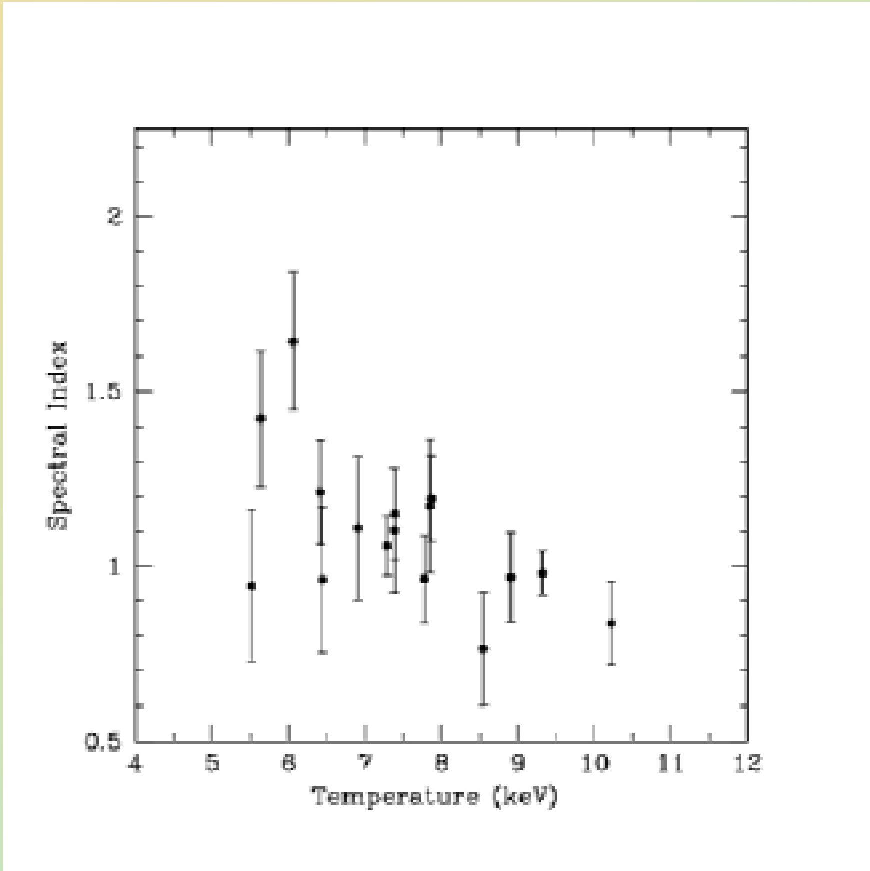
Spectral index map
between 90 and 20 cm

Orru' et al. 2006 AN and AA subm.



Color : temperature

(Kempner & David 2003)



Spectral index vs
Gas temperature

RESULTS:
Regions influenced by the merger show flatter spectra.

In regions of identical volume and same brightness at 0.3 GHz, α = 0.8 vs α = 1.3 implies

➔ energy density in the electron population

larger by a factor of ~ 2.5

Flatter spectrum could reflect a spectral (energy) cutoff at higher energies

ν_b = 1.4 GHz vs ν_b = 0.3 GHz

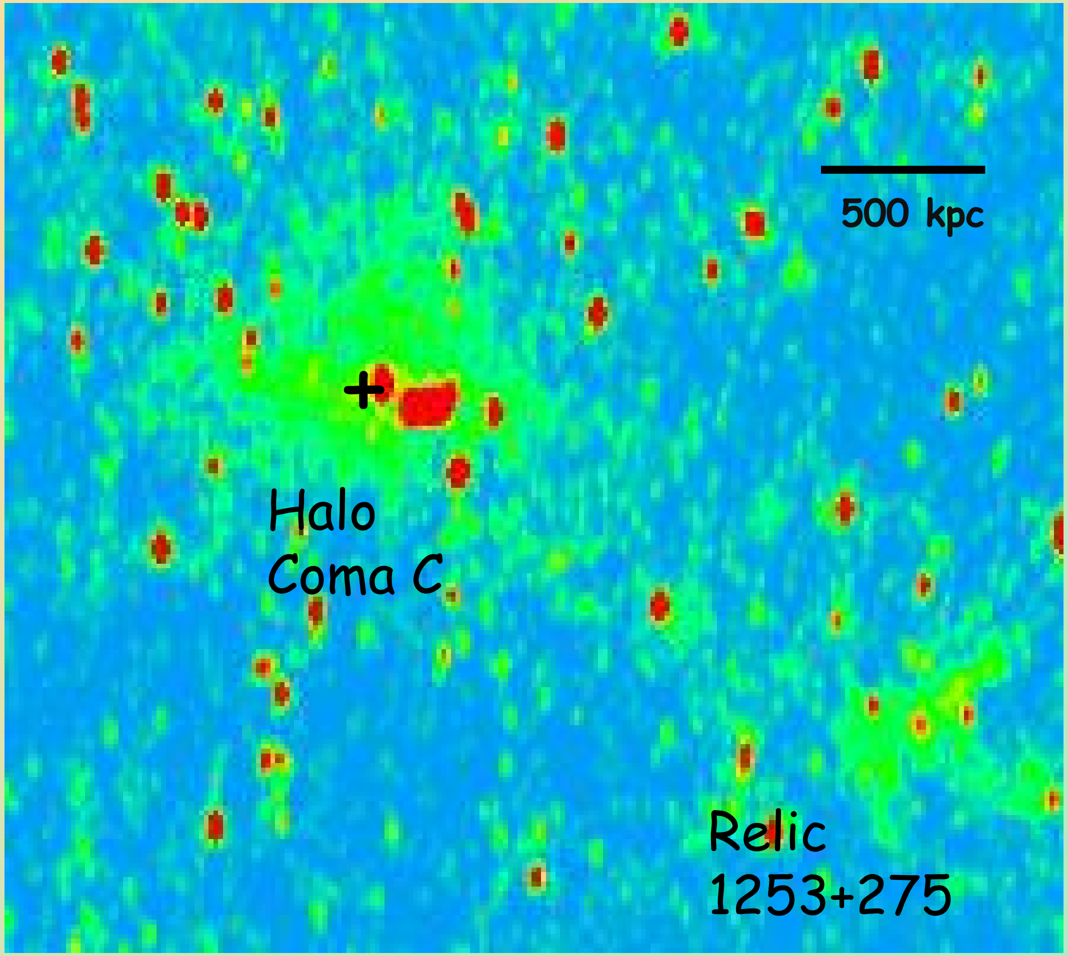
t ~ 4 10^7 yr vs t ~ 9 10^7 yr

➔ more recent injection event

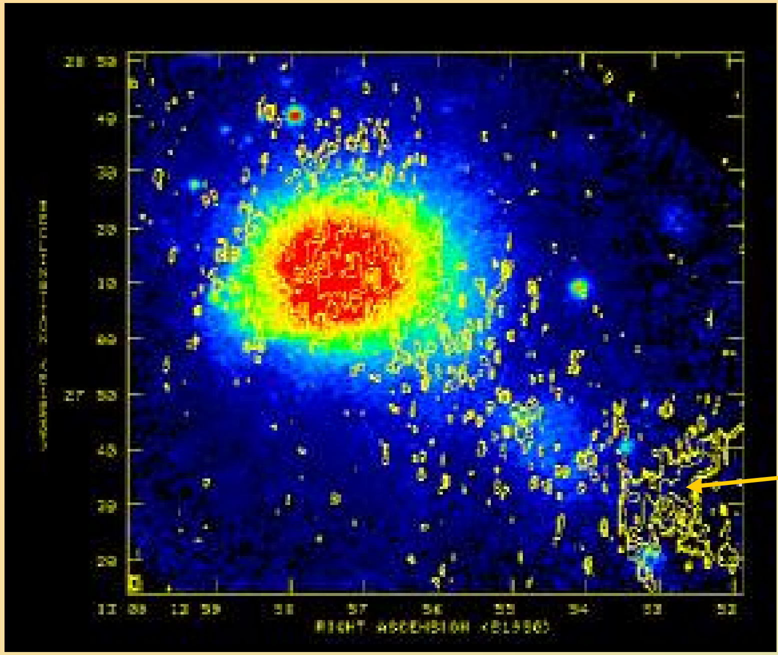
Next : analyse halo – merger link in detail,
possibly including merger evolution,
check models of reacceleration, confirm view
of turbulent reacceleration in halos

RELICS : Coma cluster

First cluster where a radio Halo and a Relic were detected
(Large 1959, Willson 1970, Ballarati et al. 1981)



RADIO: WSRT, 90 cm (Feretti et al.1998)



Color : X-ray ROSAT (Henry et al.)

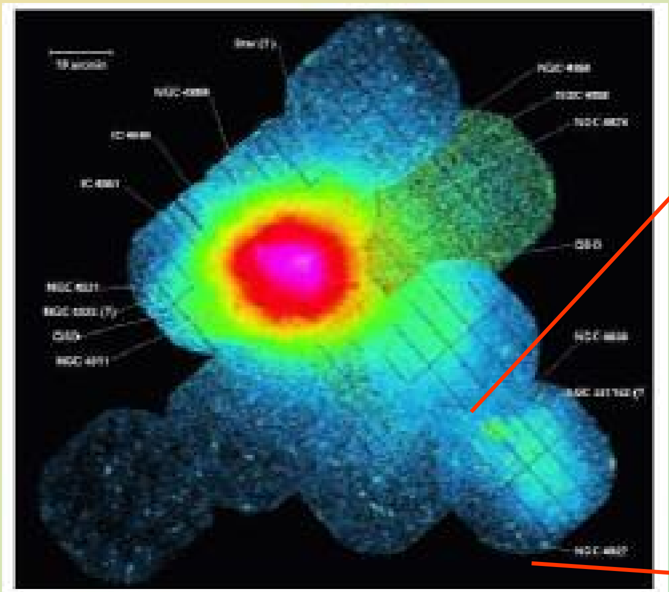
Contour : radio emission

relic

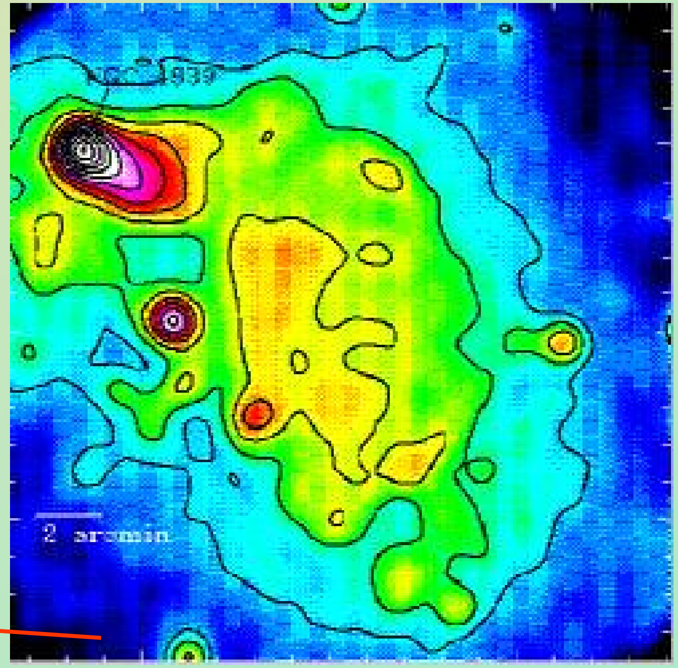
XMM

Neumann et al. 2001

Briel et al. 2001



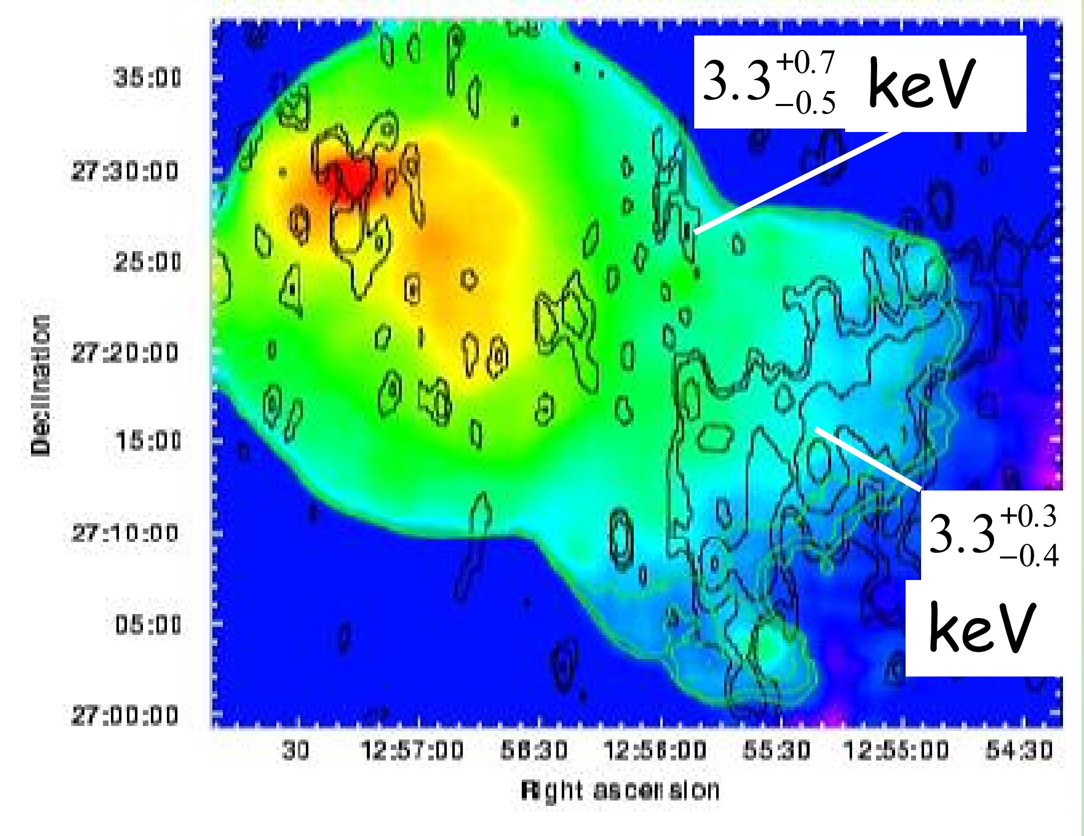
XMM-Newton image of X-ray Emission from Coma Cluster. 0.3-2.0 keV



T ~ 4.4 keV First infall

XMM

Feretti & Neumann 2006



XMM MOSAIC image – MOS – 0.3 – 2 kev
Gauss filter σ = 10″ + median filter

Color:
X-ray emission

Contours:
radio emission

Emission of the group extends to the radio relic

In the Coma cluster no shock is detected at the location of the relic

Next : check relic – shock connection in several clusters through observations and modeling

We can currently say that

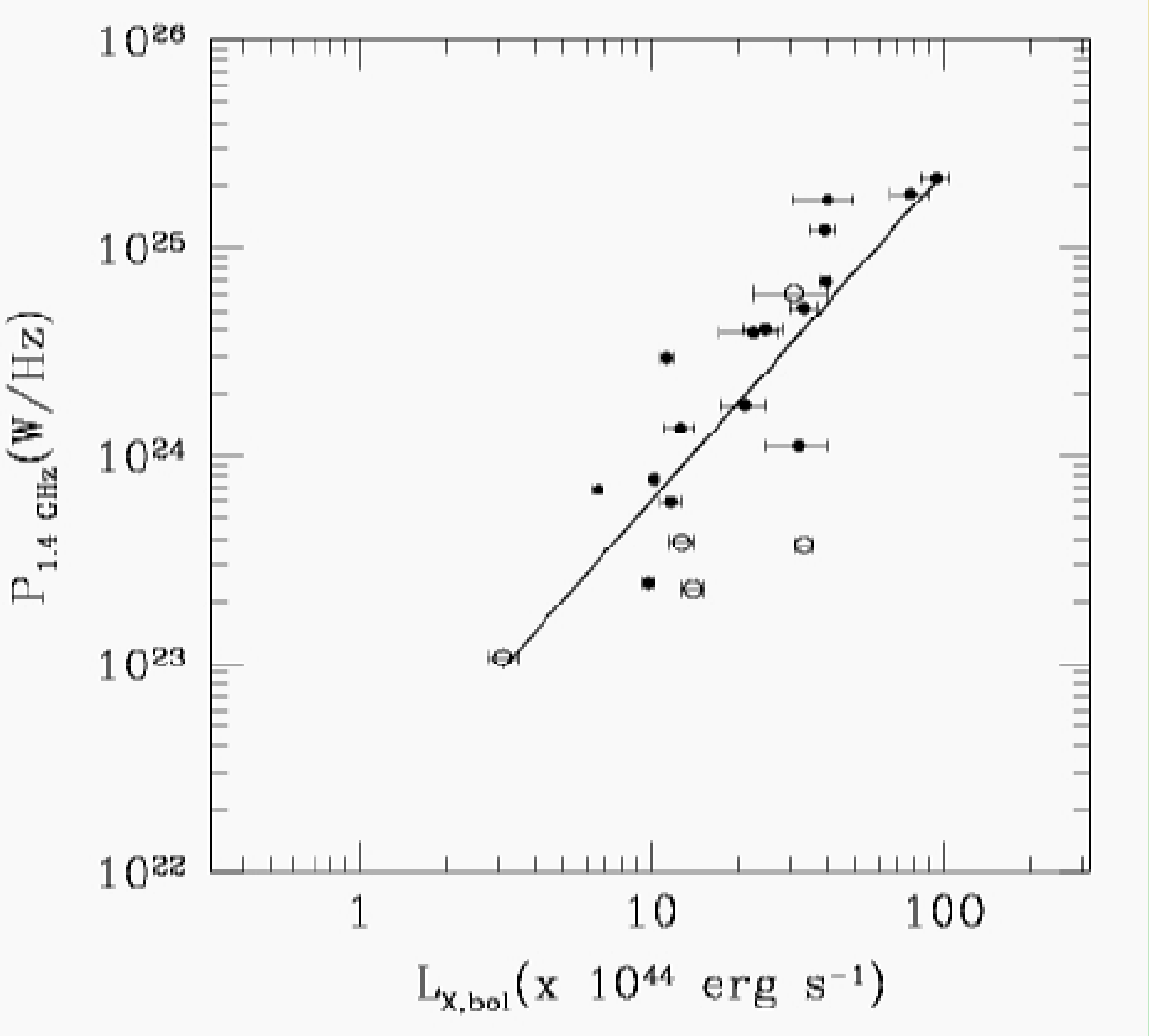
halo/relics ➔ merging clusters

We <u>cannot</u> say the reverse

merging clusters ~~➔~~ halo/relic

<u>Not all merging clusters show halos/relics</u>

-> 5 to 35 %



$$P_{1.4GHz} \propto L_{XBol}^{1.68\pm0.25}$$

See most recent in Cassano et al. 2006

MAJOR OPEN PROBLEMS

FOR OBSERVATIONISTS

- Details of the halo – merger link possibly including temporal evolution, consistency with models of turbulence reacceleration

- Shocks at relic locations

- Are radio halo common to all merging clusters, or only in the most massive ones?

FUTURE PROSPECTS

- define cluster dynamical state from X-ray and optical observations, give quantitative link between the cluster merger and the halo emission

- assess statistical properties of halos up to high z, investigate the evolutionary properties, and the implications for cosmology

- study magnetic field strength and structure from cluster polarimetric studies

THANK YOU