Radio observations of cluster mergers

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OUTLINE

- Diffuse cluster radio emission: radio halos and relics
  ➔ non-thermal components of the ICM

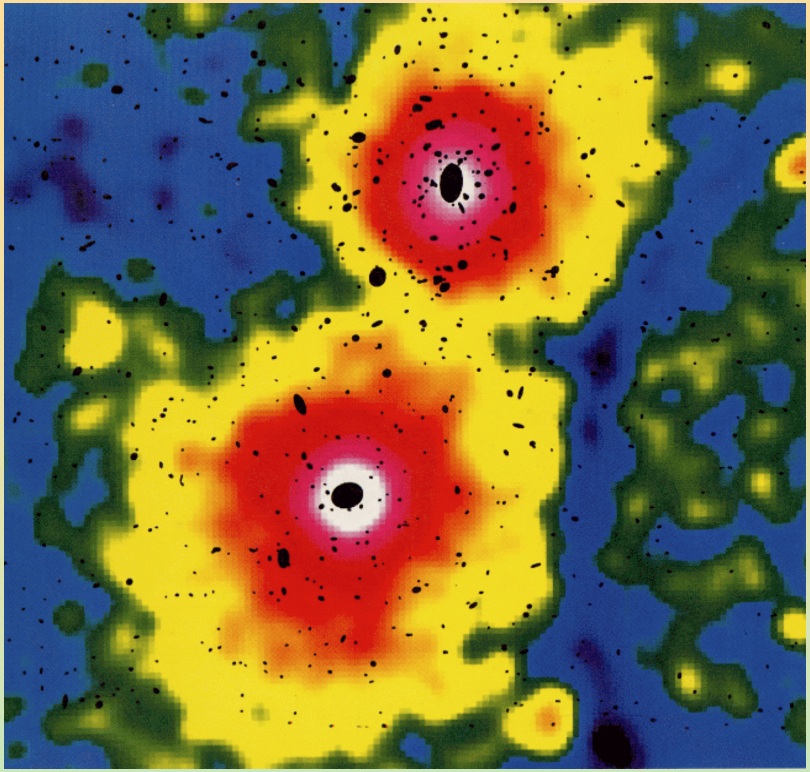
- Radio - X ray comparison

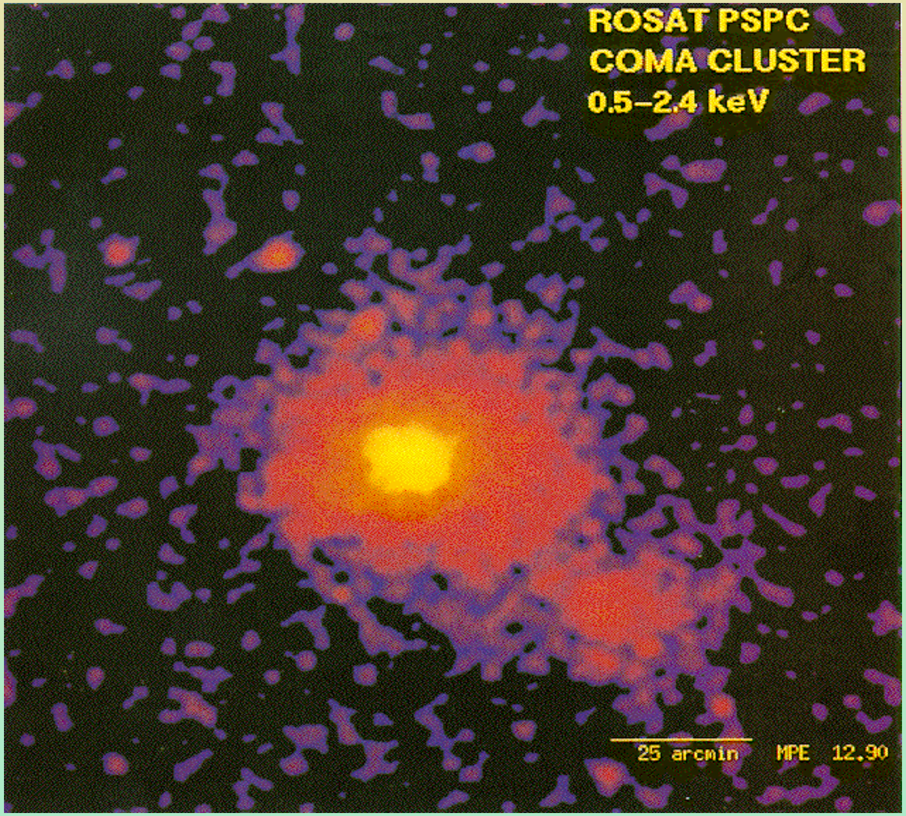
- Connection between the existence of halos and relics and the presence of cluster merging processes
  ➔ reacceleration of radiating particles

H_0= 50 km s^{-1} Mpc^{-1} q_0 = 0.5

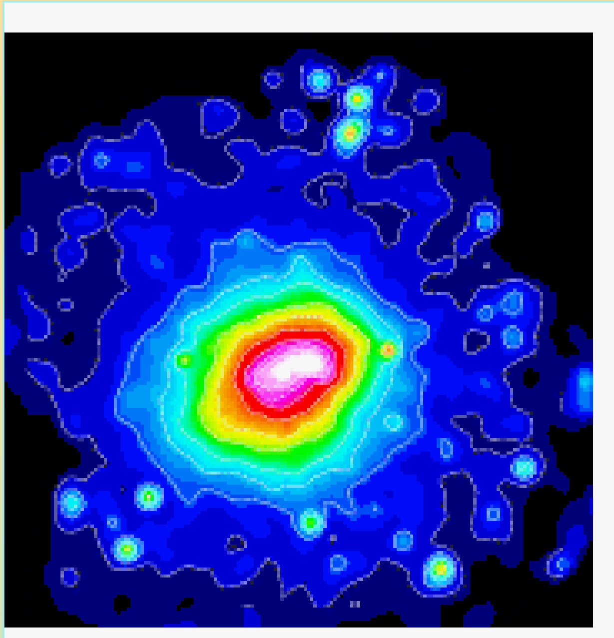
ROSAT PSPC
A3528

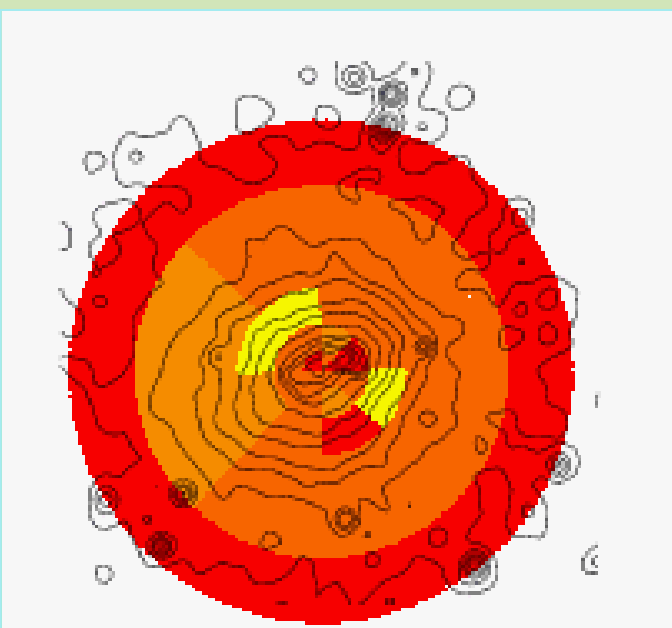
MERGING CLUSTERS

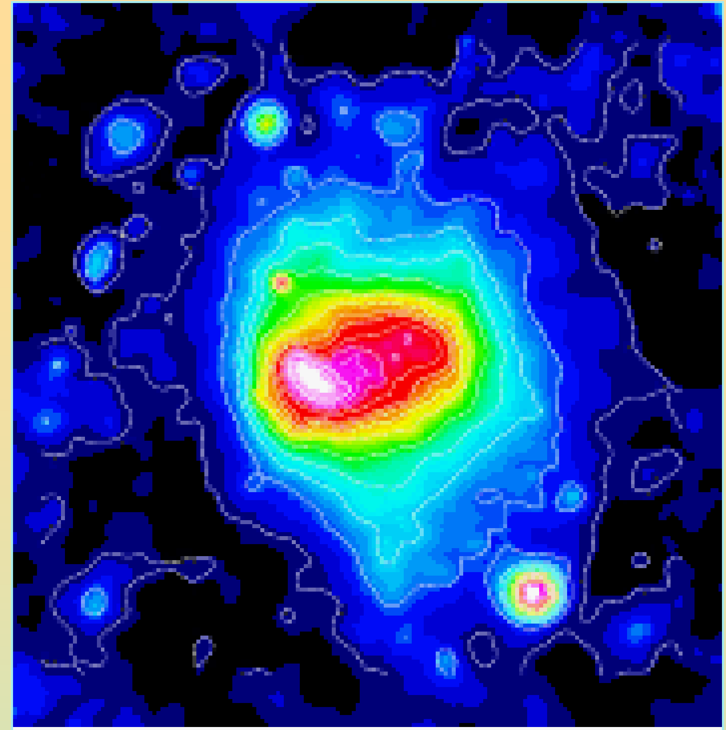


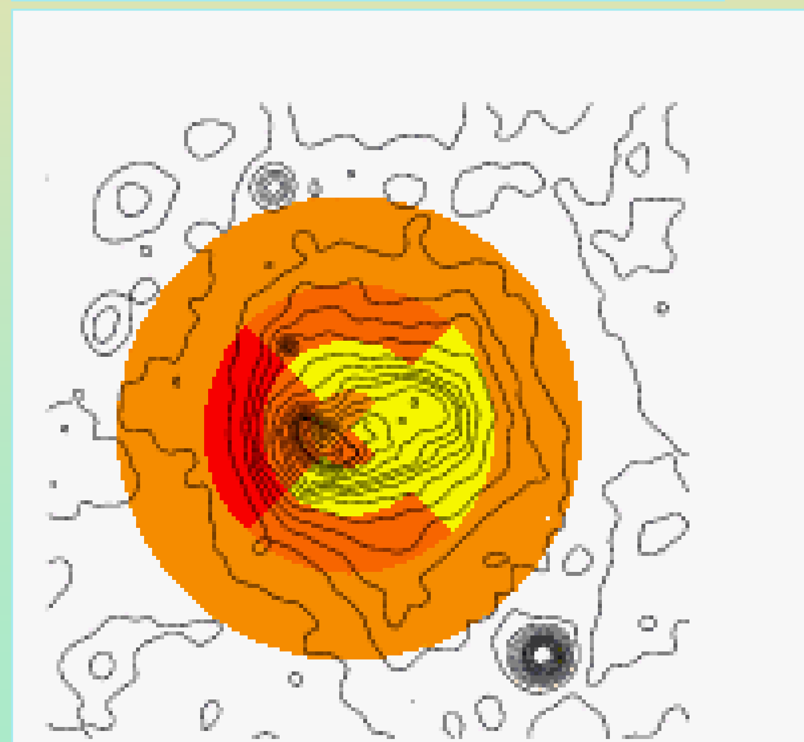


A2256
ROSAT PSPC - ASCA









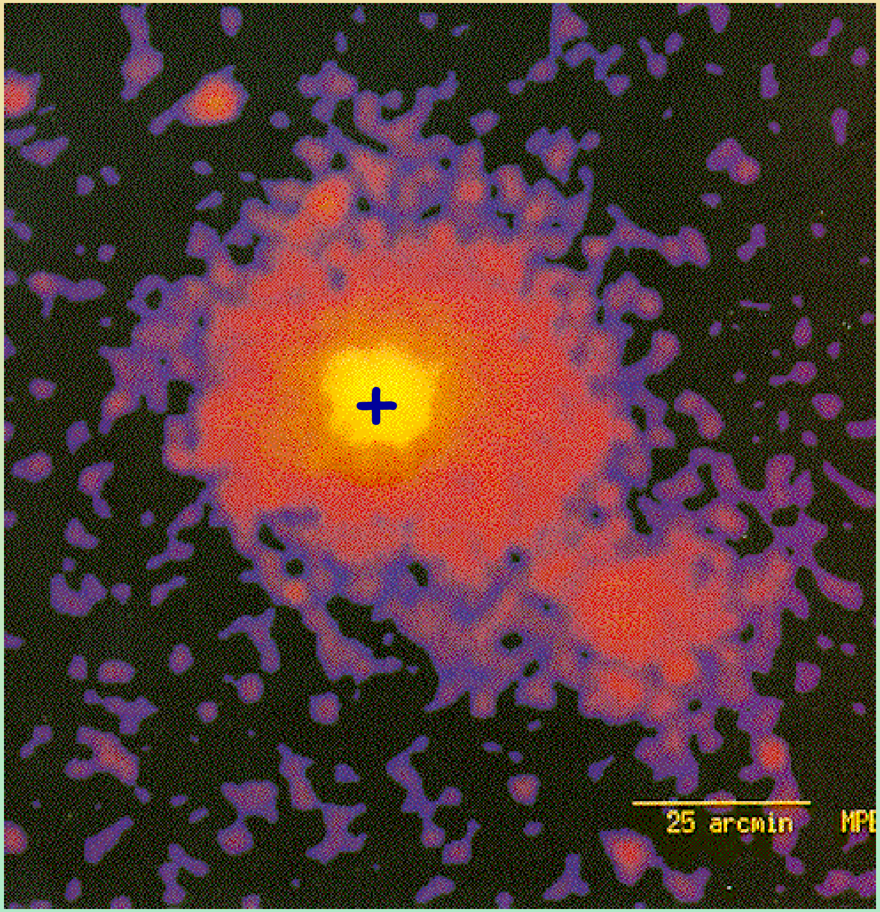
ROSAT PSPC

A754

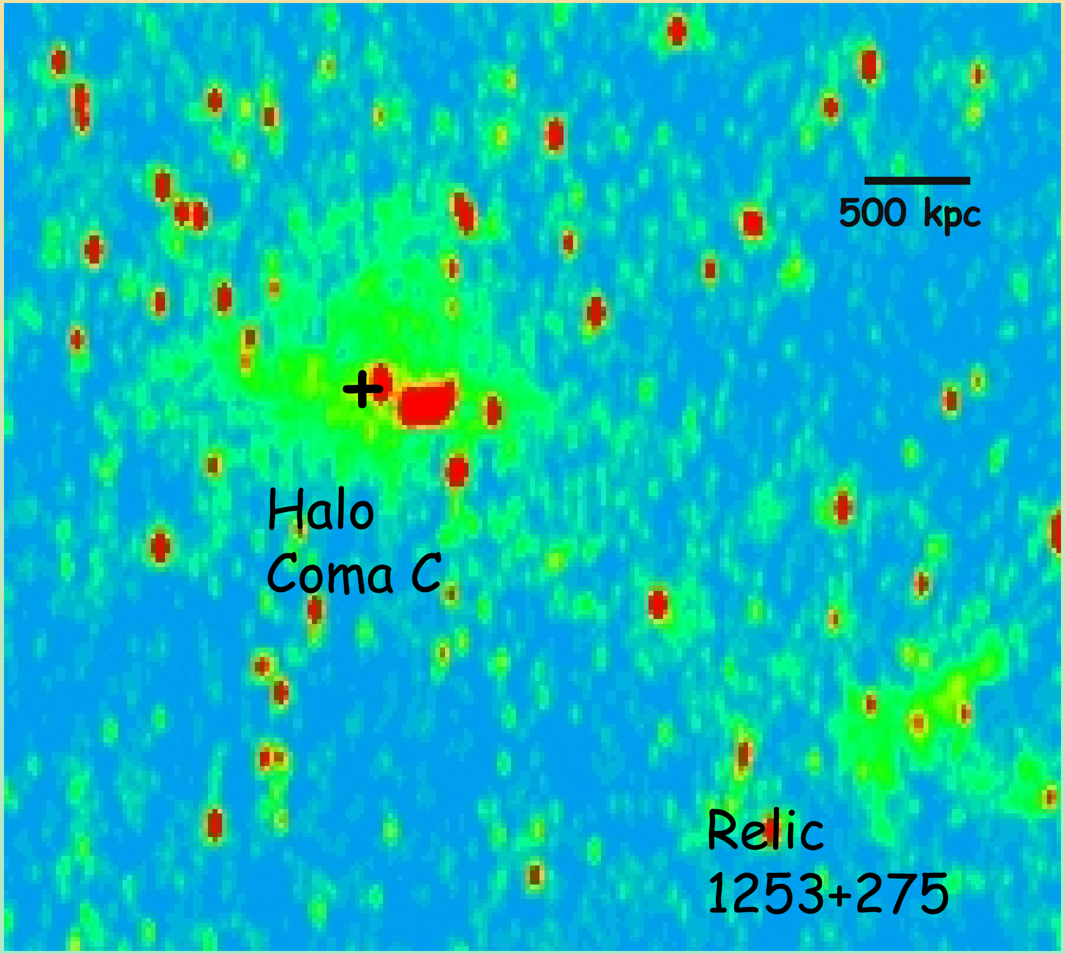
ASCA

Coma Cluster

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



X-ray: ROSAT (White et al. 1993)



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

Diffuse radio sources are classified in two groups according to their location

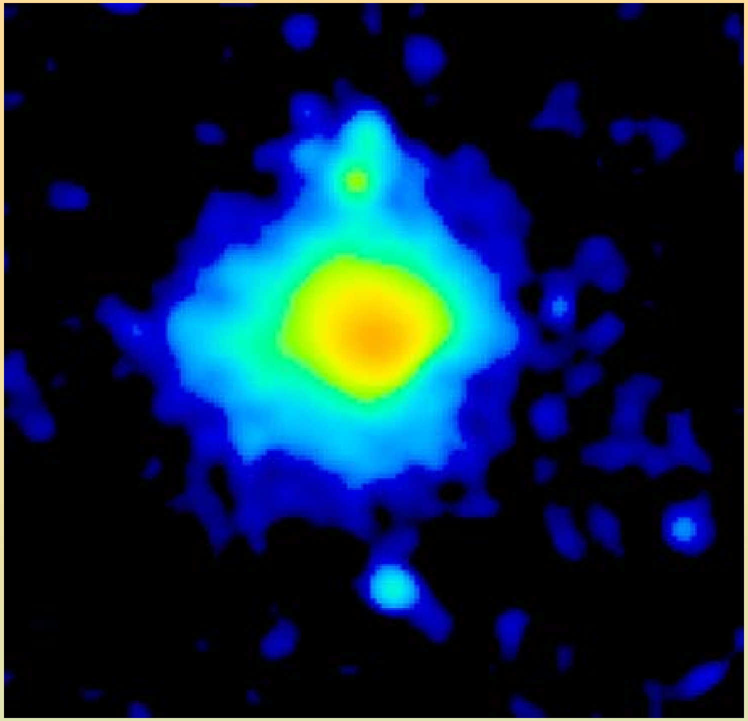
Halos : cluster center

Relics : cluster peripheries

A 2163

z = 0.2

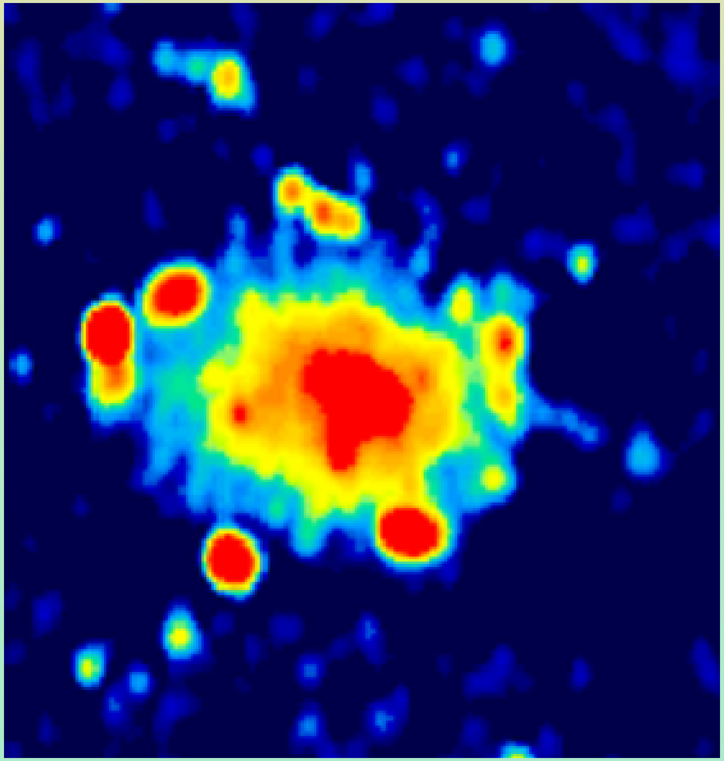
Optical: Galaxies



X-ray :
Thermal gas

(Arnaud et al.)

~ 3 Mpc

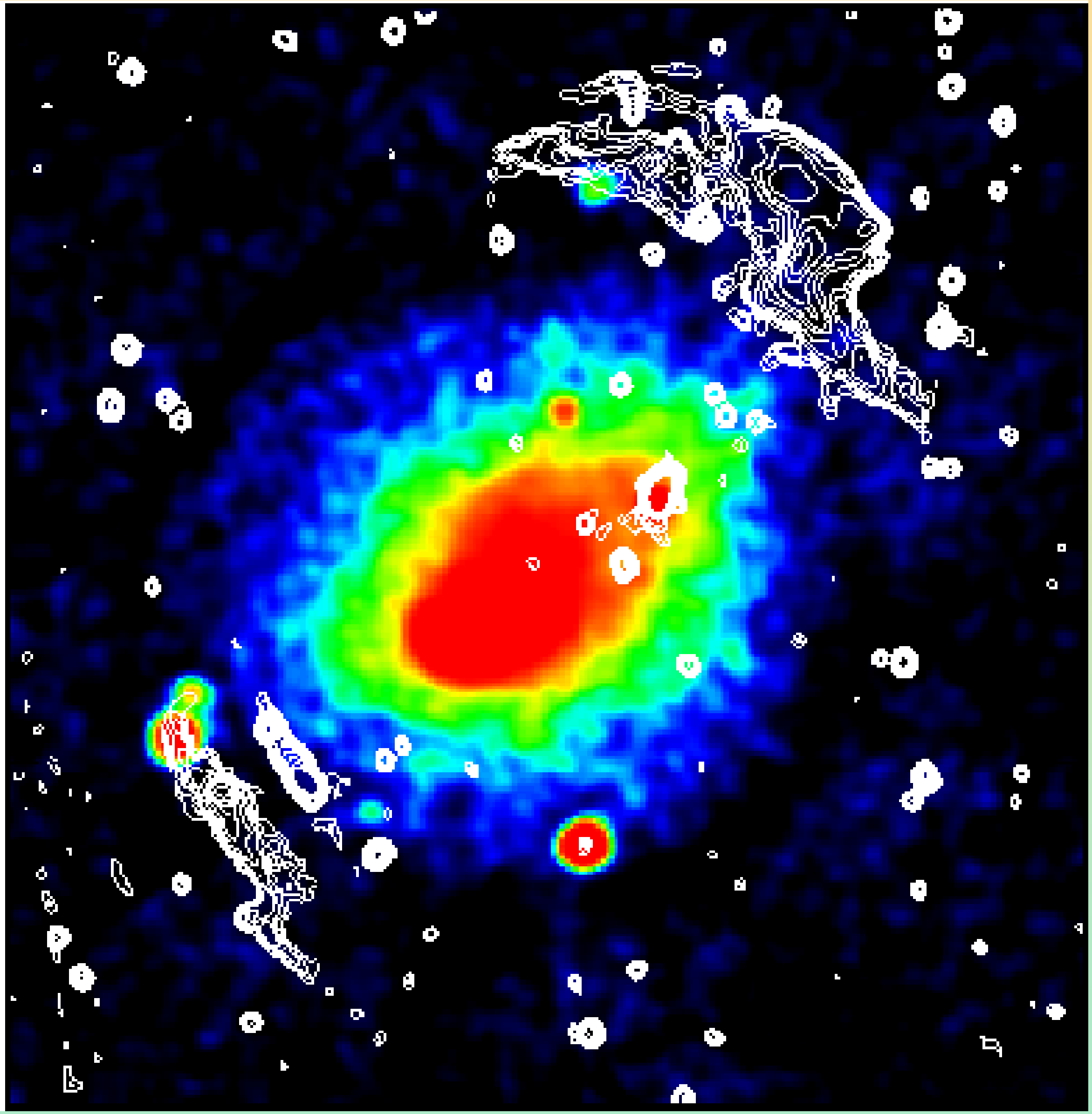


RADIO:
Radio Galaxies
+ Diffuse

(Feretti et al.)

A 3667

z = 0.055



Contours: Radio
Color: X-ray
(Rottgering et al. 1997
Johnston-Hollitt et al.
2001, 2003)

Main components of Clusters

Dark matter : 82-85 %
Galaxies : 2-3 % - optical
Gas (ICM) : 13-15 % - X-ray

HALOS and RELICS tell us that there are
additional non-thermal components - radio

- MAGNETIC FIELDS of intensity ~ μG
- RELATIVISTIC ELECTRONS of energy ~ GeV

Origin of radiating electrons :

- primary
- secondary

WHAT DO WE KNOW FROM RADIO DATA

Equipartition :

Minimum non-thermal energy density :

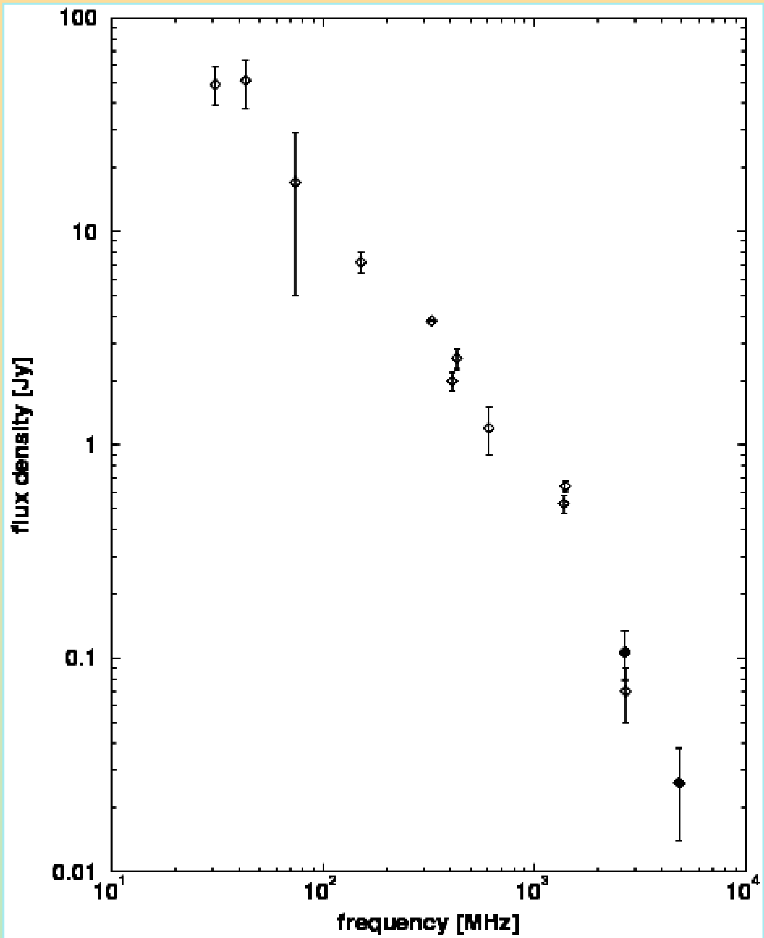
$\sim 10^{-14} - 10^{-13}$ erg cm^{-3}

(1000 times lower than thermal one!)

Equipartition magnetic field ~ 0.1 – 0.5 μG

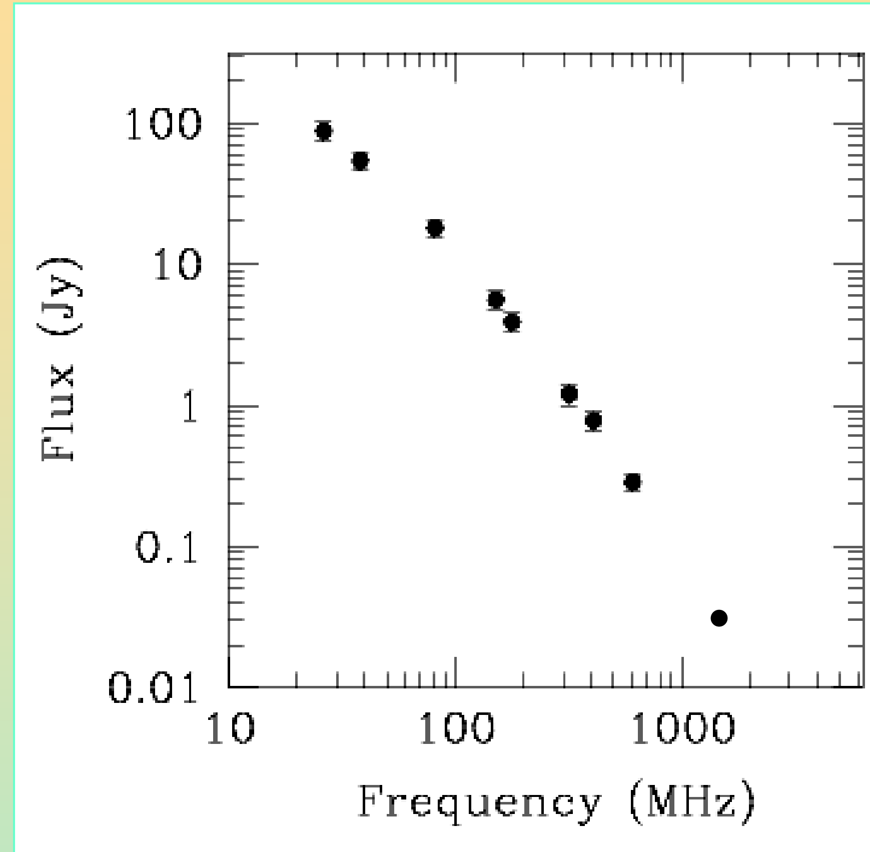
Spectra : energy distribution, reacceleration, age of the radiating electrons

Coma C



(Thierbach et al. 2002)

A1914



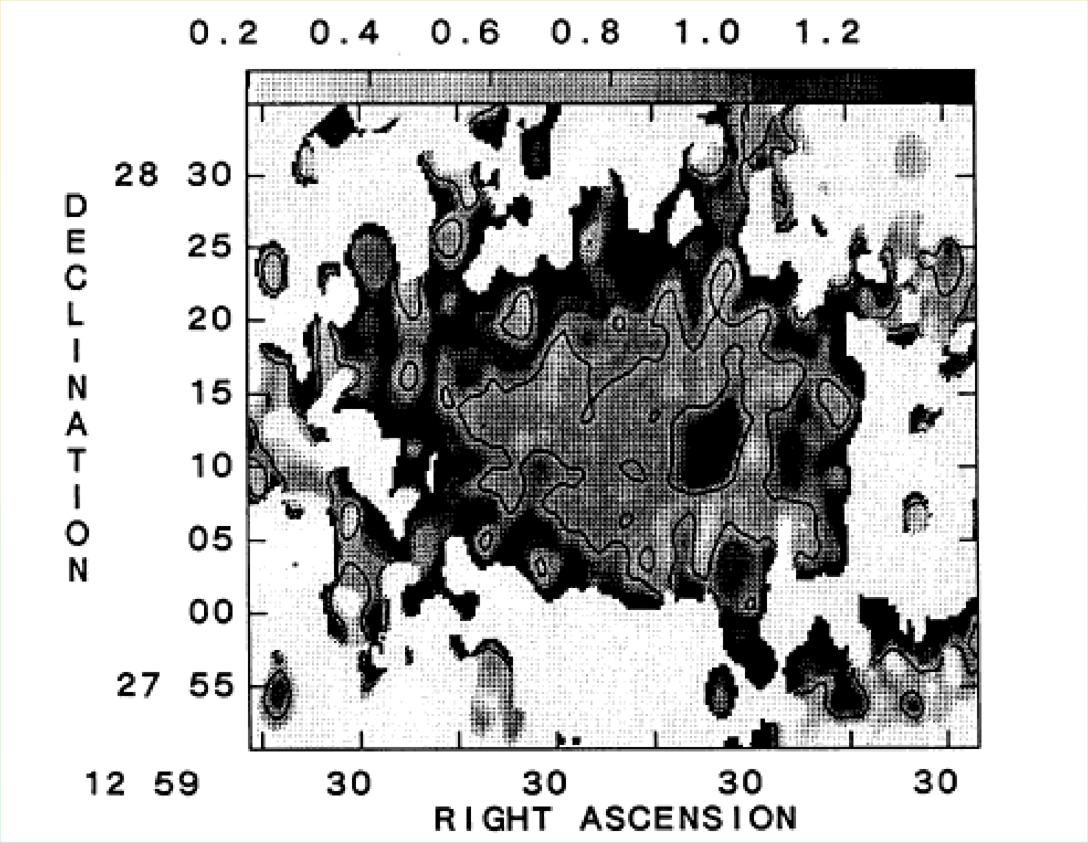
(Komissarov & Gubanov 1994,)

Spectral cutoff

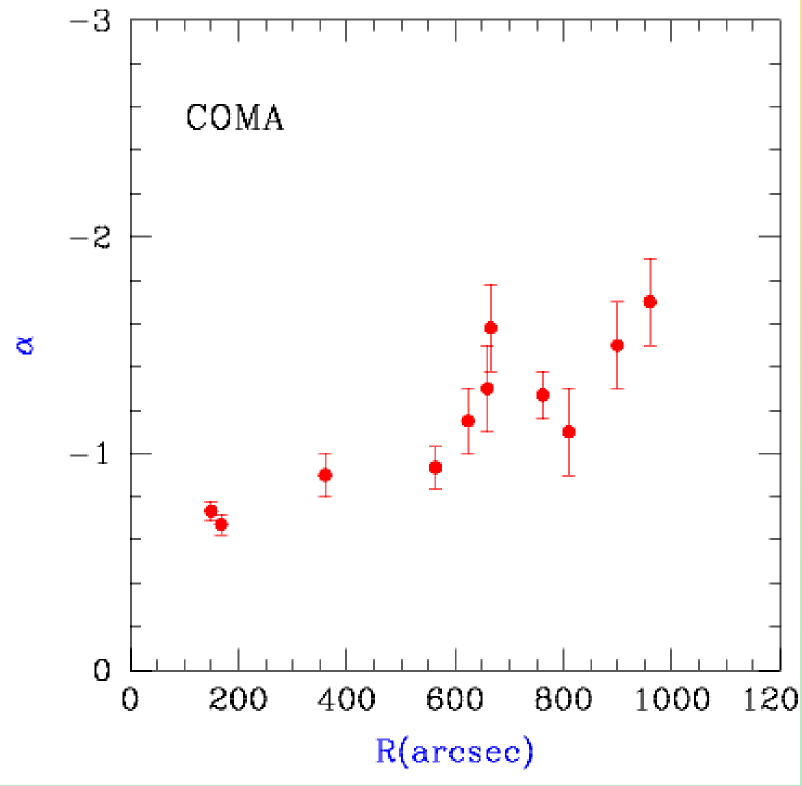
A 754 : $\alpha_{0.07}^{0.3} \sim 1.1$ $\alpha_{0.3}^{1.4} \sim 1.5$ **(Kassim etal.01,Bacchi etal03)**

A 2319 : $\alpha_{0.4}^{0.6} \sim 0.9$ $\alpha_{0.6}^{1.4} \sim 2.2$ **(Feretti et al. 1997)**

COMA C : Map of spectral index between 0.3 GHz and 1.4 GHz
(WSRT) (VLA + DRAO)

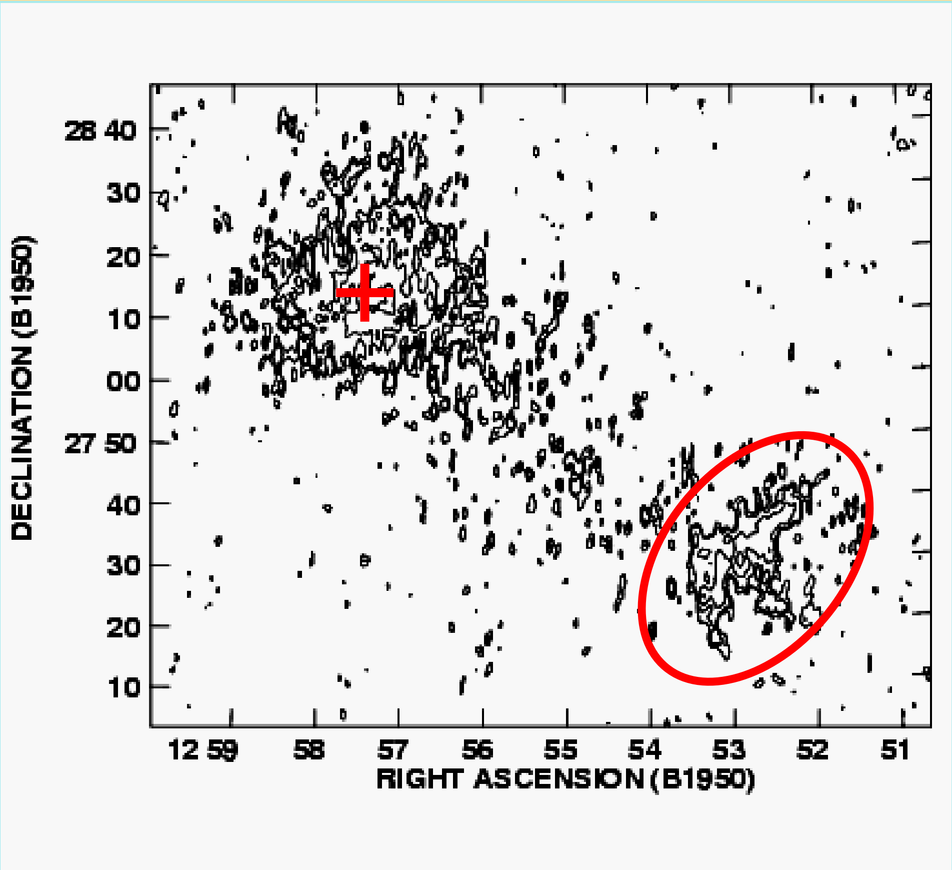


(Giovannini et al., 1993, ApJ 406, 399)

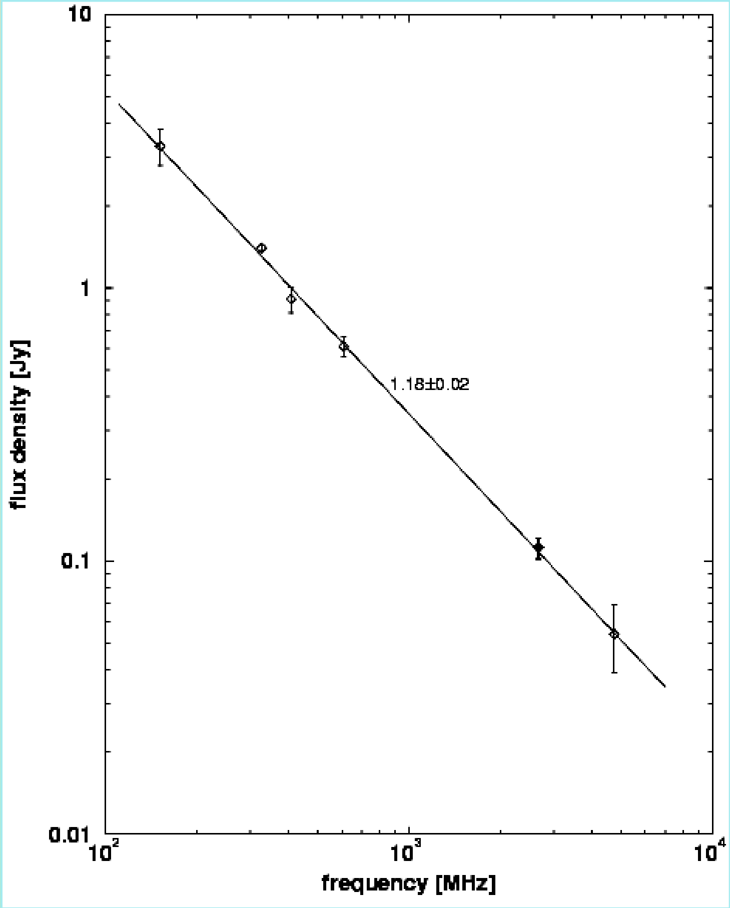


(Brunetti et al., 2001, MNRAS 320, 365)

Coma Relic : 1253+275



(Cluster center)



Integrated spectrum

(Thierbach et al. 2002)

Radiative electron lifetime: ~ 10^8 yr

➔ particles cannot travel cluster distances

NEED FOR REACCELERATION

➔ <u>MERGER</u>

The connection to merger would explain - at least in part - why the diffuse radio emission is <u>not</u> detected in all clusters of galaxies

Detection rate:

~ 10% of a complete X-ray flux limited sample of clusters

~ 35% of clusters with X-ray luminosity > 10^{45} erg s^{-1}

(At the NVSS surface brightness limit - Giovannini & Feretti 2002)

Several arguments have been presented in the past years to support the connection between cluster mergers and halos and relics:

- Substructures X-ray (Schuecher et al. 2001)
- Substructures optical (Boschin et al. 2003)
- Absence of a strong cooling flow (Edge, Stewart, Fabian 1992, Feretti 1999)
- Temperature gradients (Markevitch et al. 1998) (Govoni et al. 2004)
- Large distance from neighbours (Schuecker 1999, 2002)
- Values of $\beta_{spec} > 1$ (Feretti 2000)
- Large core radii (Feretti 2000)
- Relation between radio power and the dipole power ratio (Buote 2001)
- Similarity between radio and X-ray structures (Govoni et al 2001)
- Shocks and cold fronts (Markevitch et al. 2002)

RADIO – X RAY COMPARISON

Link between relativistic and thermal plasma in clusters

X ray emission brings the signature of cluster mergers

Radio – X ray connection :

- structures
- gas temperature
- spectra
- correlations

Comparison of

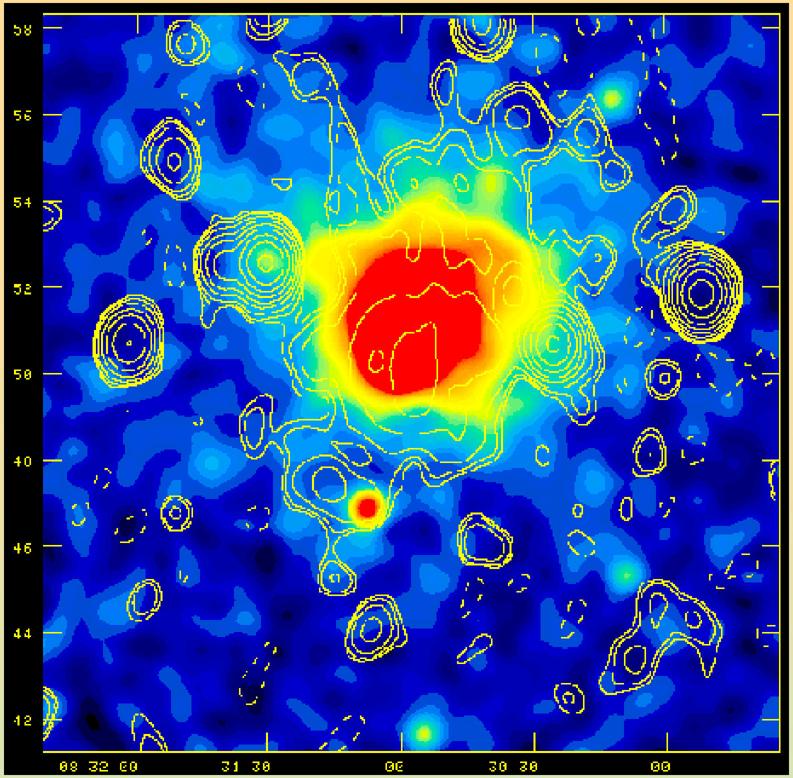
radio structure

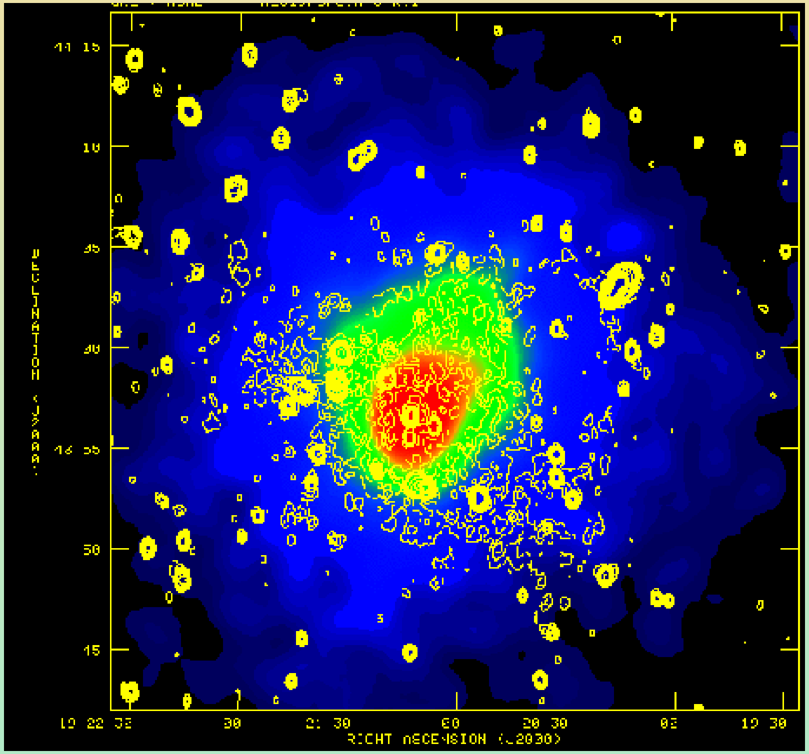
X-ray structure

gas temperature

Large scale （ROSAT)

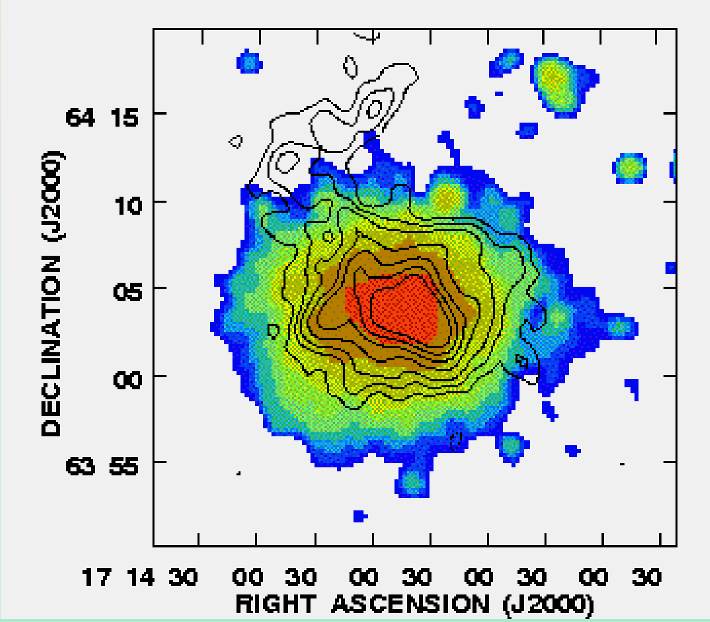
A665





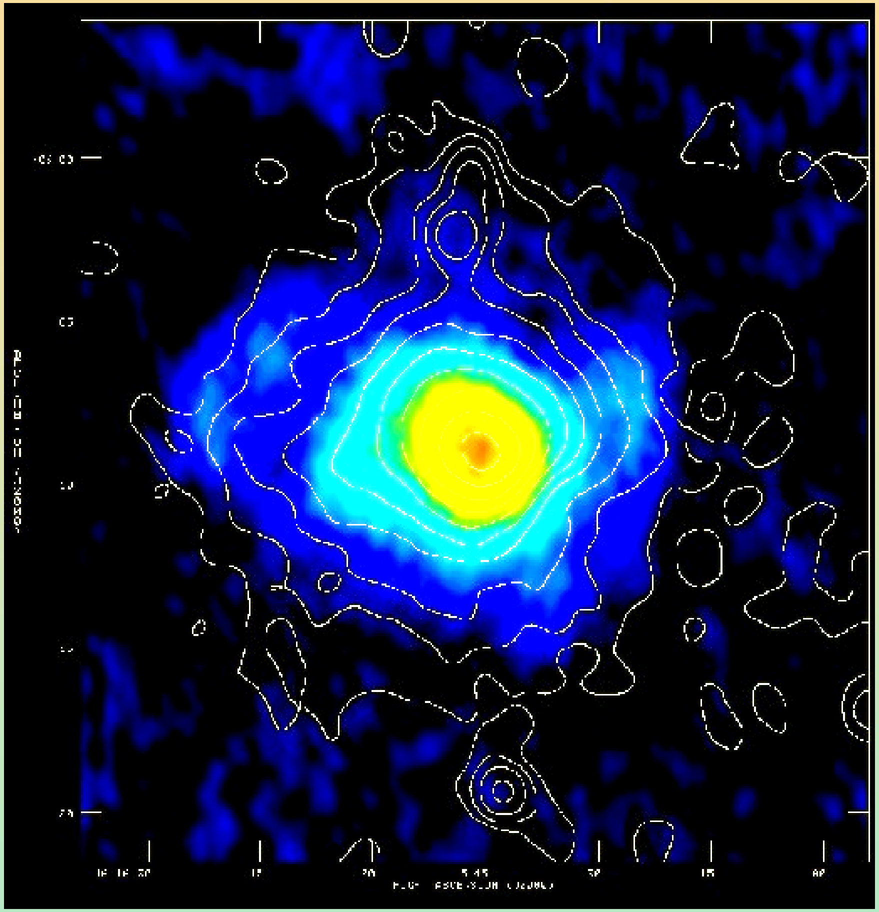
A2319

A2255



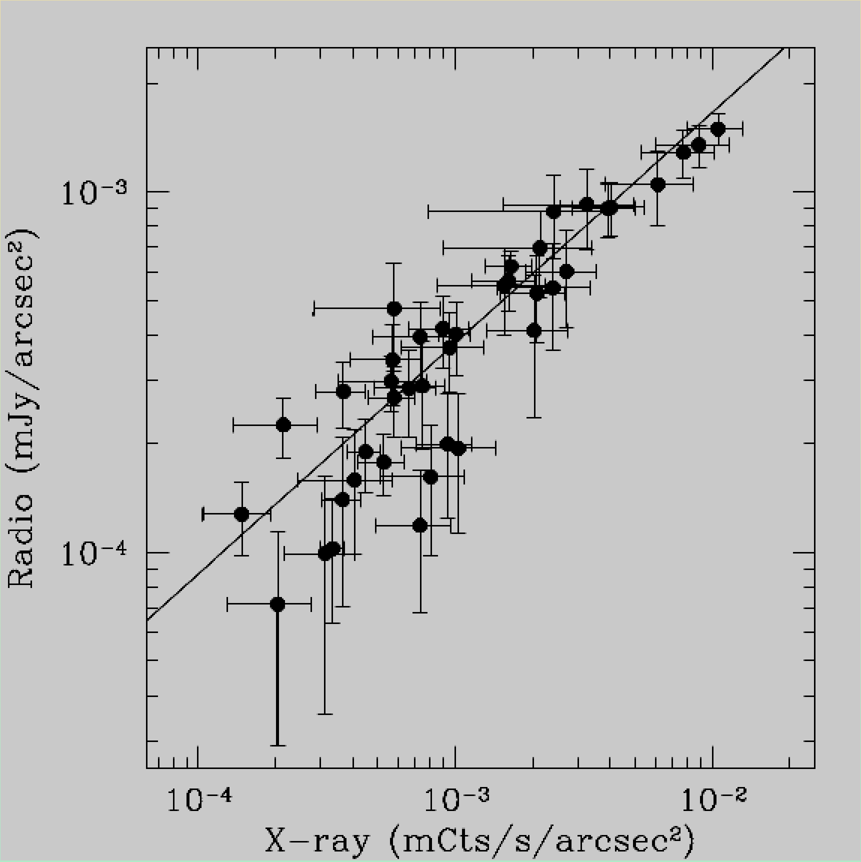
Govoni et al. 2001

Similarity of radio and X-ray emission on the large scale: correlation between radio and X-ray brightness



Color: radio, contours = X-ray

$$S_{radio} \propto S_X^{\ 0.64}$$

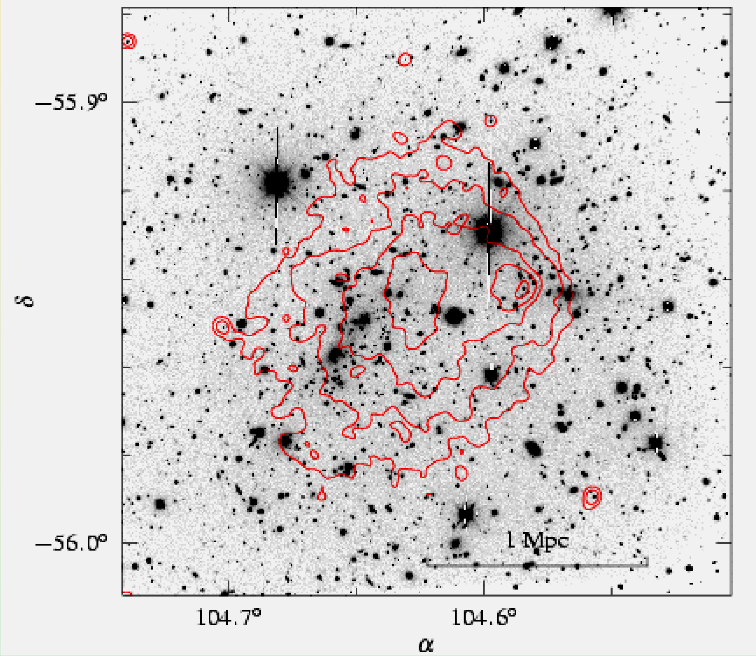


(Feretti et al. 2001)

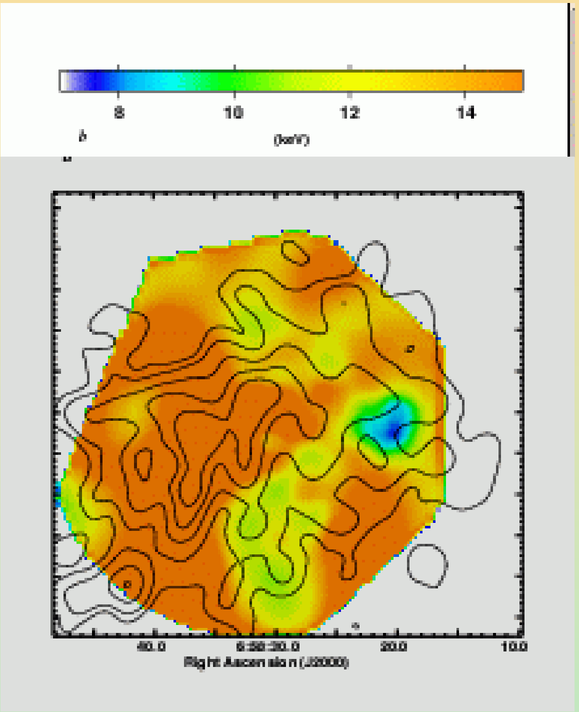
A 2163 z =0.203

1E 0657-56 CHANDRA

$z = 0.296$, $L_x = 1.4\ 10^{46}$, Radio Halo Size = 1.9 Mpc



X-ray brightness

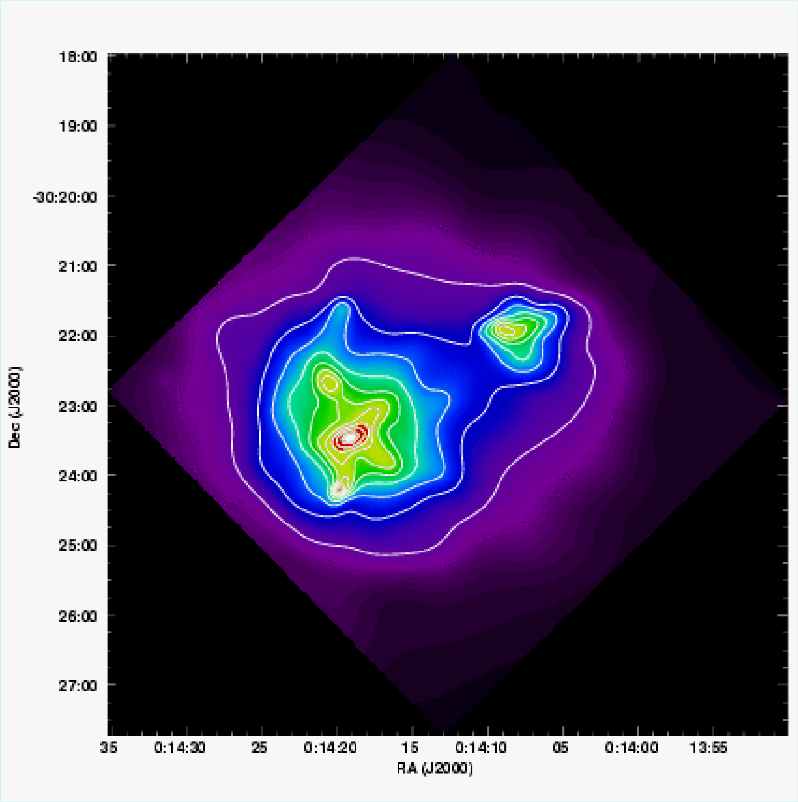


Radio (contours)
Temperature (color)

(Liang et al. 2000, Markevitch et al. 2002, Govoni et al.astro-ph/0401421)
Markevitch THIS CONFERENCE

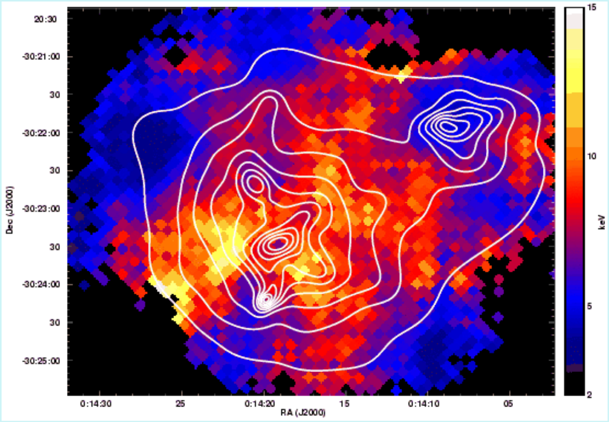
A 2744 CHANDRA

(Kempner & David astroph/0310185)

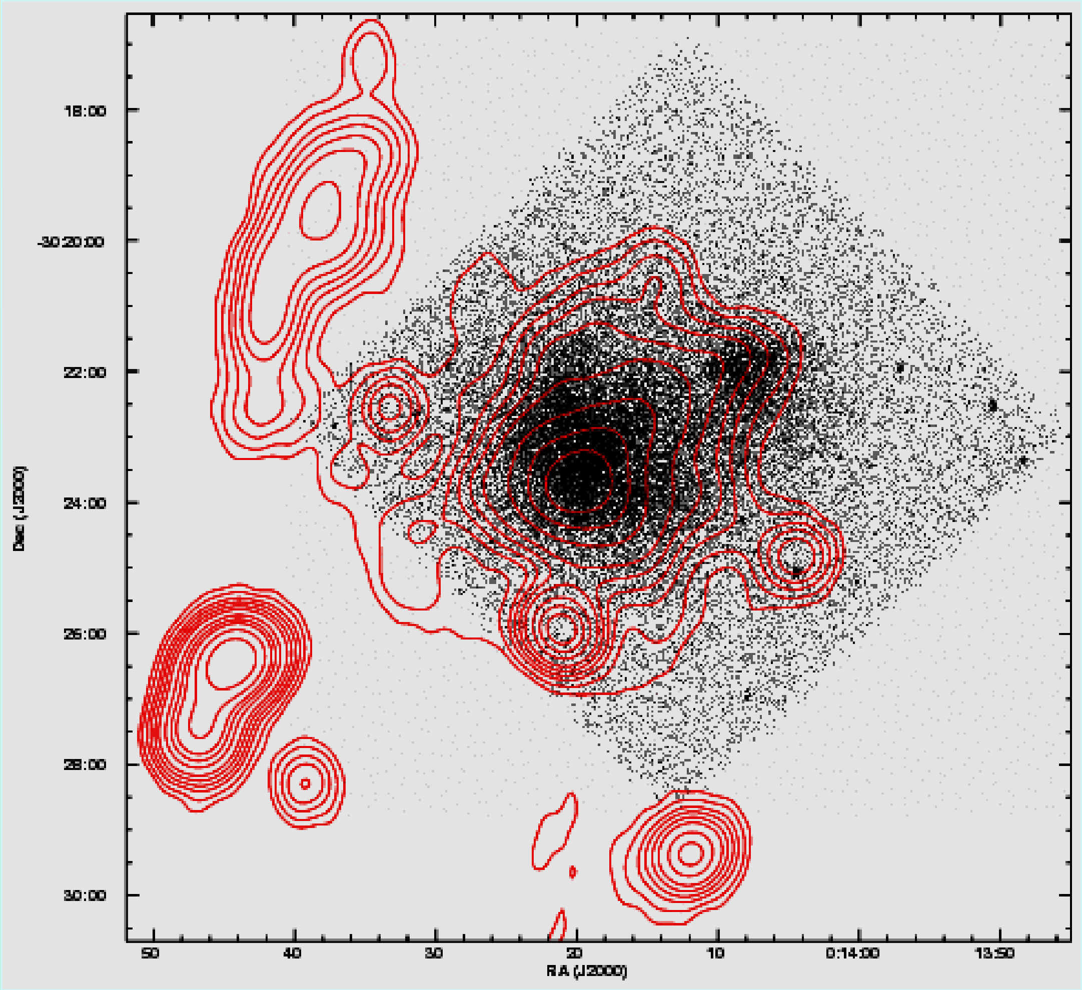


X-Ray brightness

Temperature

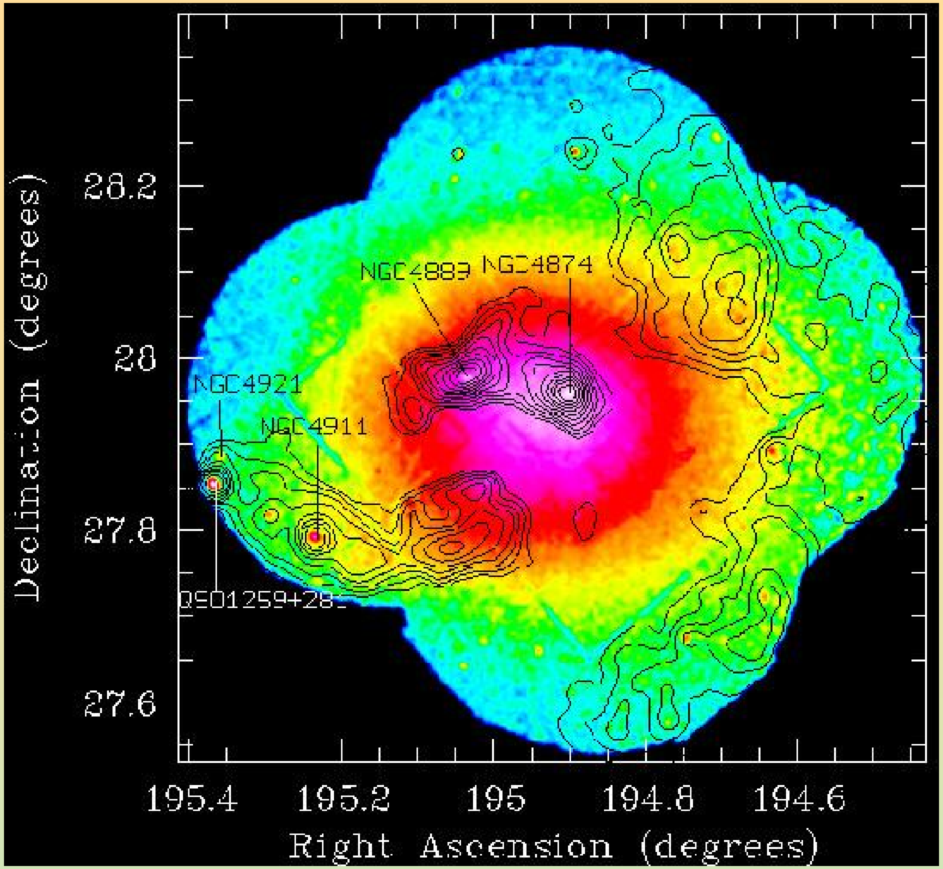


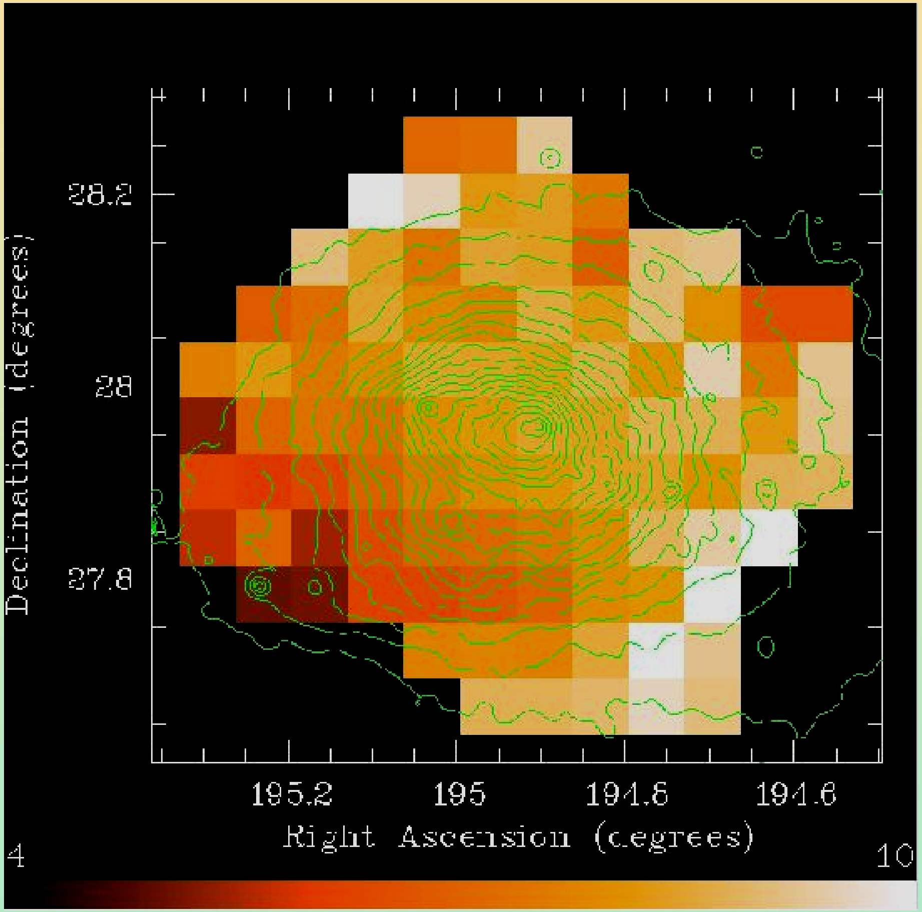
Radio - Xray

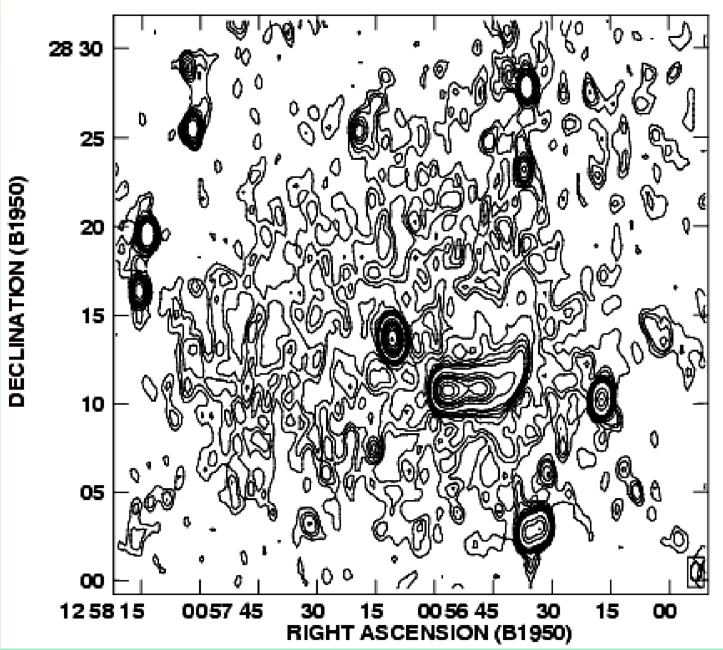


Coma - XMM

Arnaud et al. 2001



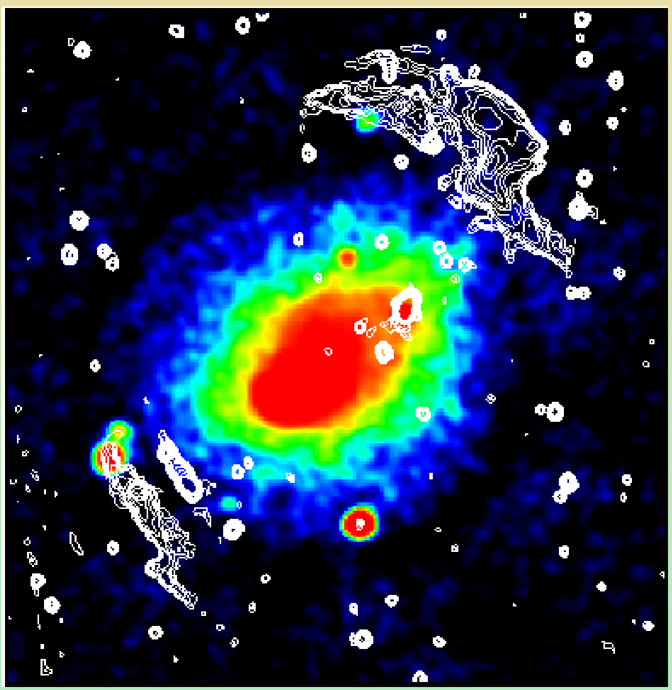




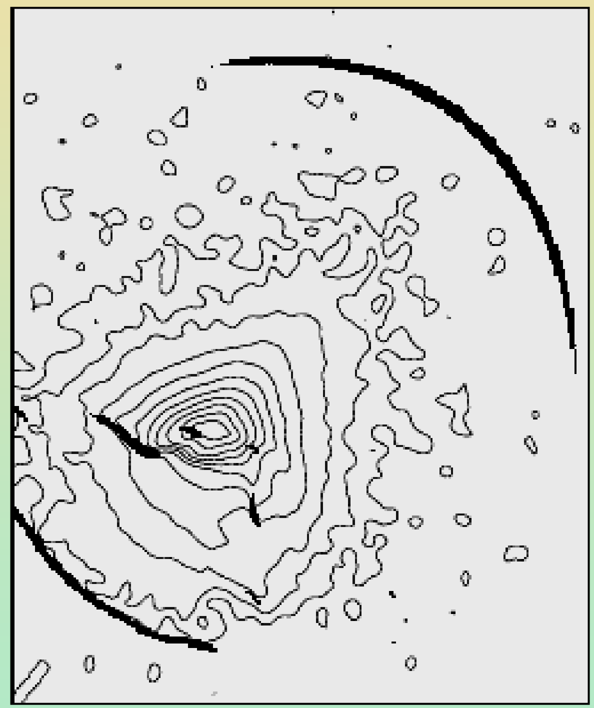
RADIO RELICS

Relics have been suggested to be tracers of shock waves in merger events

(Ensslin et al. 1998, Ensslin & Gopal-Krishna 2001, Roettiger et al.1996))



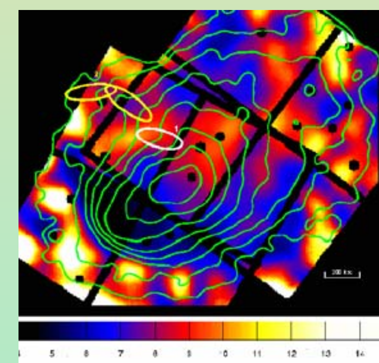
Observed
Radio – X-ray
Rottgering et al. (1997)
Johnston-Hollitt et al. 2001



Simulated
(Roettiger et al. 1999)

A 3667

z = 0.055



X-Ray Chandra
(Mazzotta et al. 2001)

Comparison between

radio spectral maps

X-ray features

Maps of the radio spectral index are a powerful tool to understand the connection between thermal and relativistic plasma

Synchrotron spectrum reflects two important parameters affected by the merger

strength of magnetic field

efficiency of e^- reacceleration

➔ Spectral index variations versus X–ray clumps

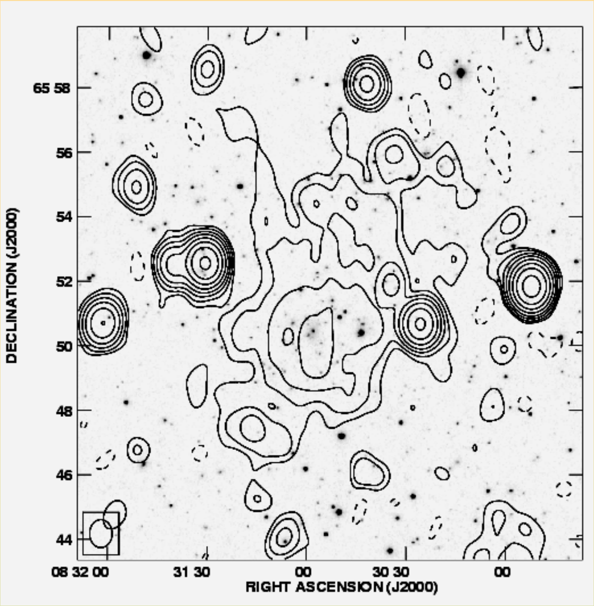
➔ Radial spectral trends

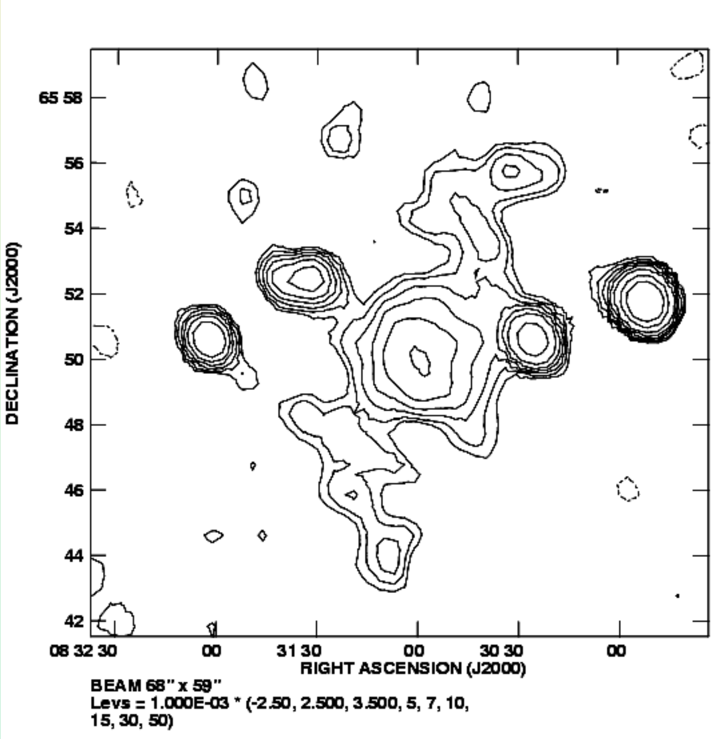
Abell 665

z = 0.1818,

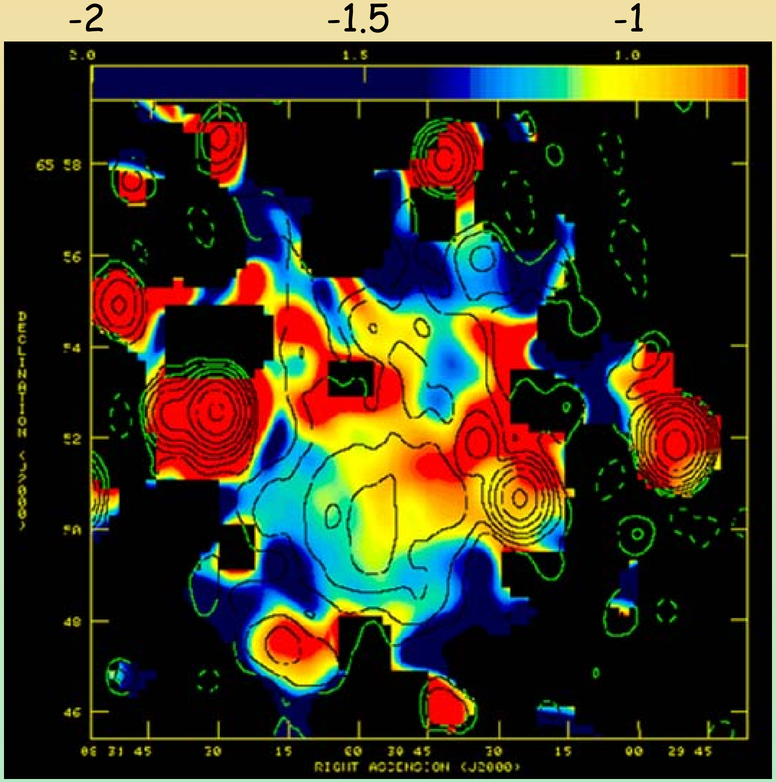
kT = 8.8 keV

VLA - 1.4 GHz (Giovannini & Feretti 2000)





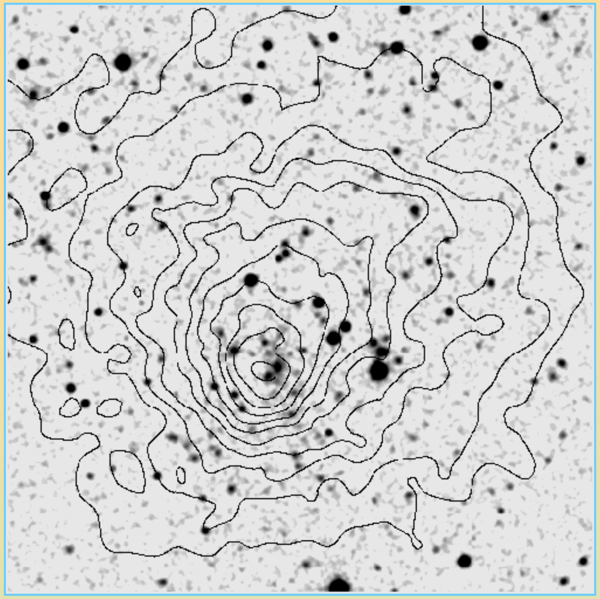
VLA 0.3 GHz (9 h, B + C)



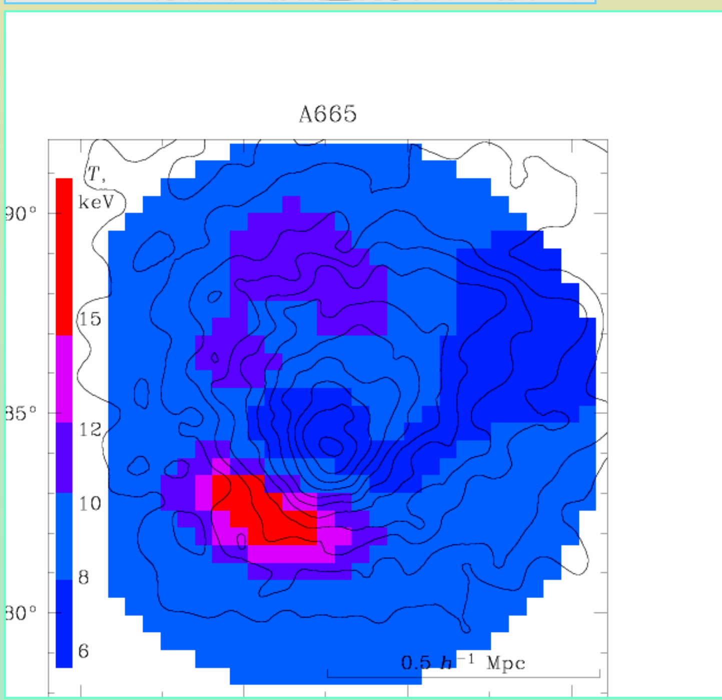
Feretti et al. To be submitted

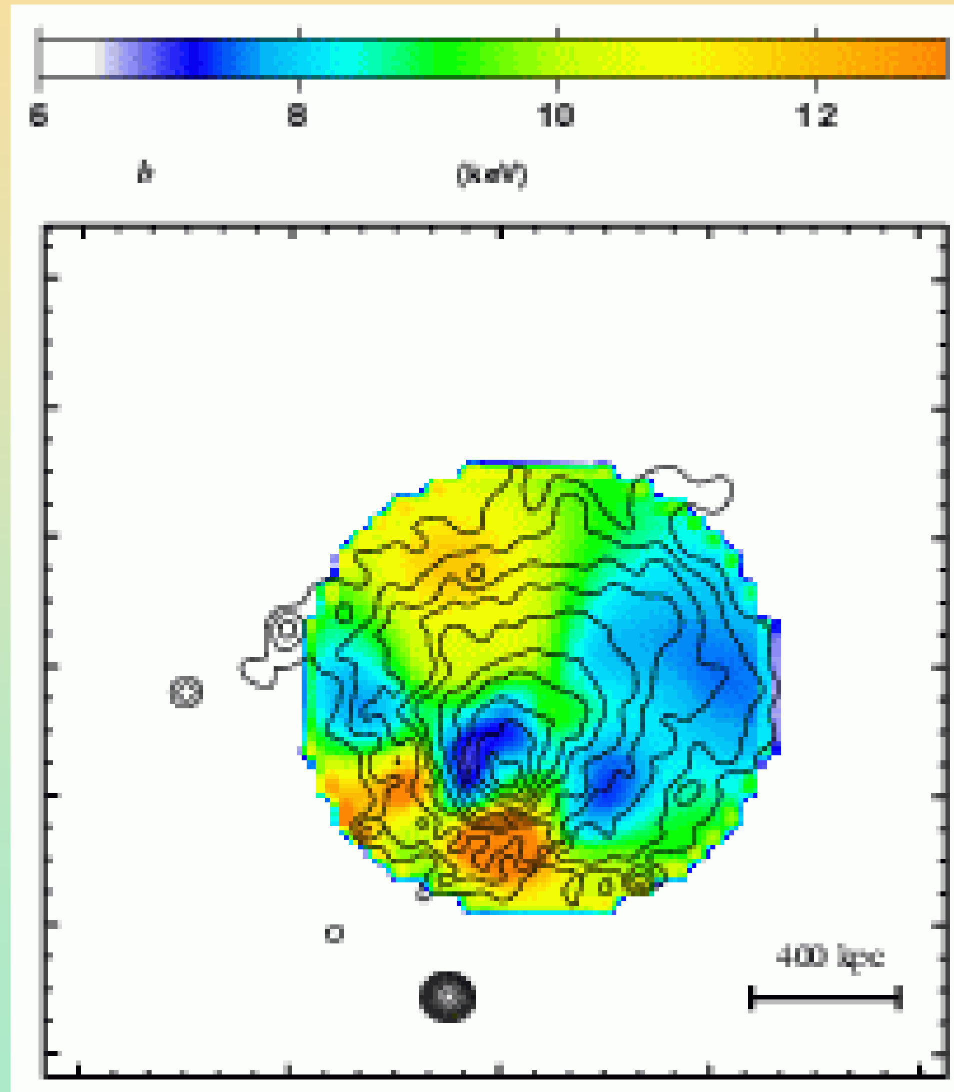
Clumpiness
Flattening to the NE
Steepening to the SW

X-ray brightness (Chandra)



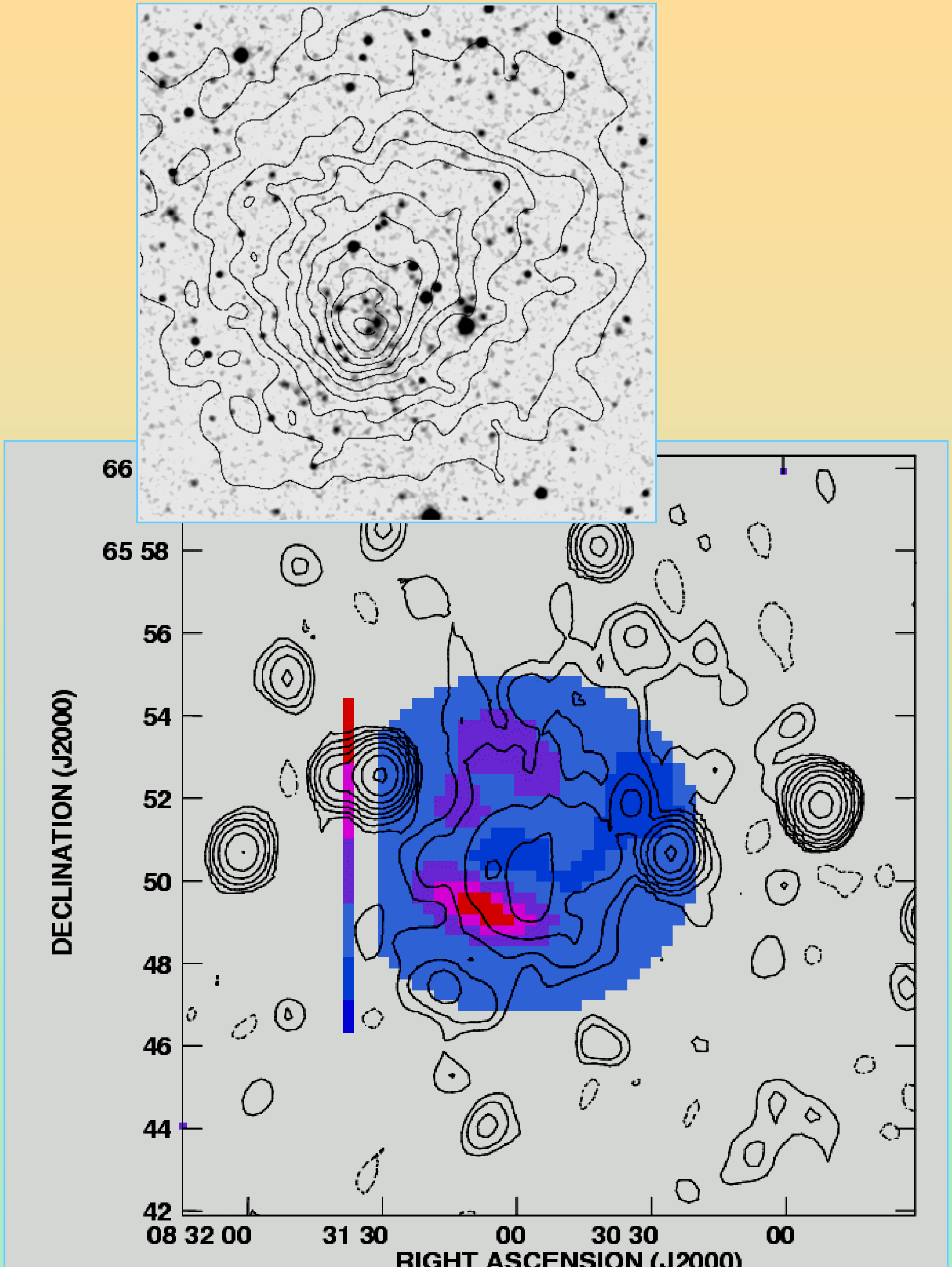
Markevitch & Vikhlinin 2001, 8.5 ksec

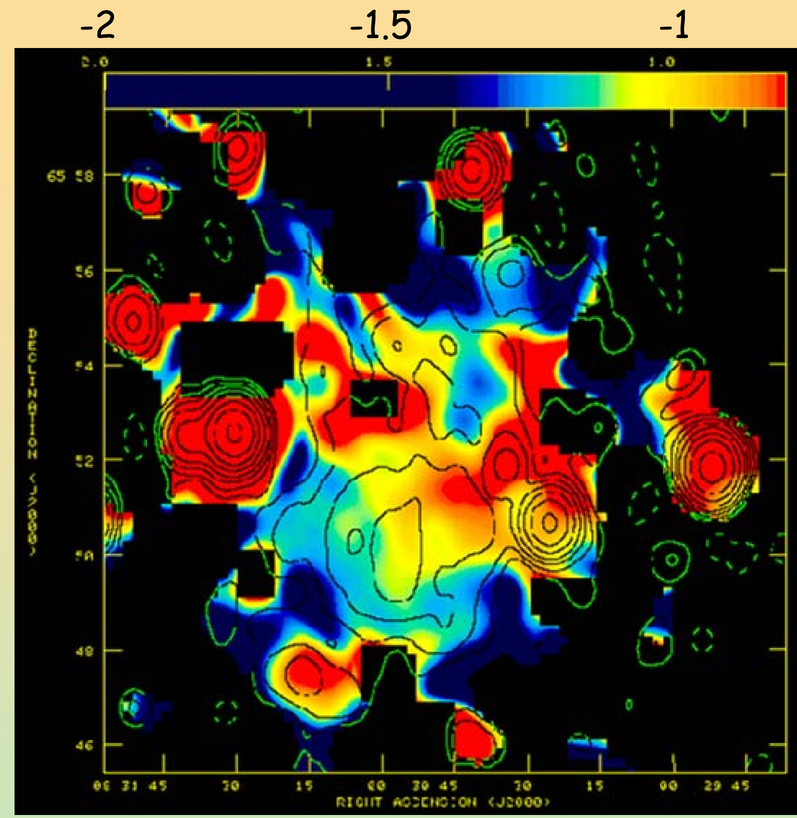




Govoni et al. 2004, astro-ph/0401421, 8.5 + 23.8 ksec

Temperature (Chandra)





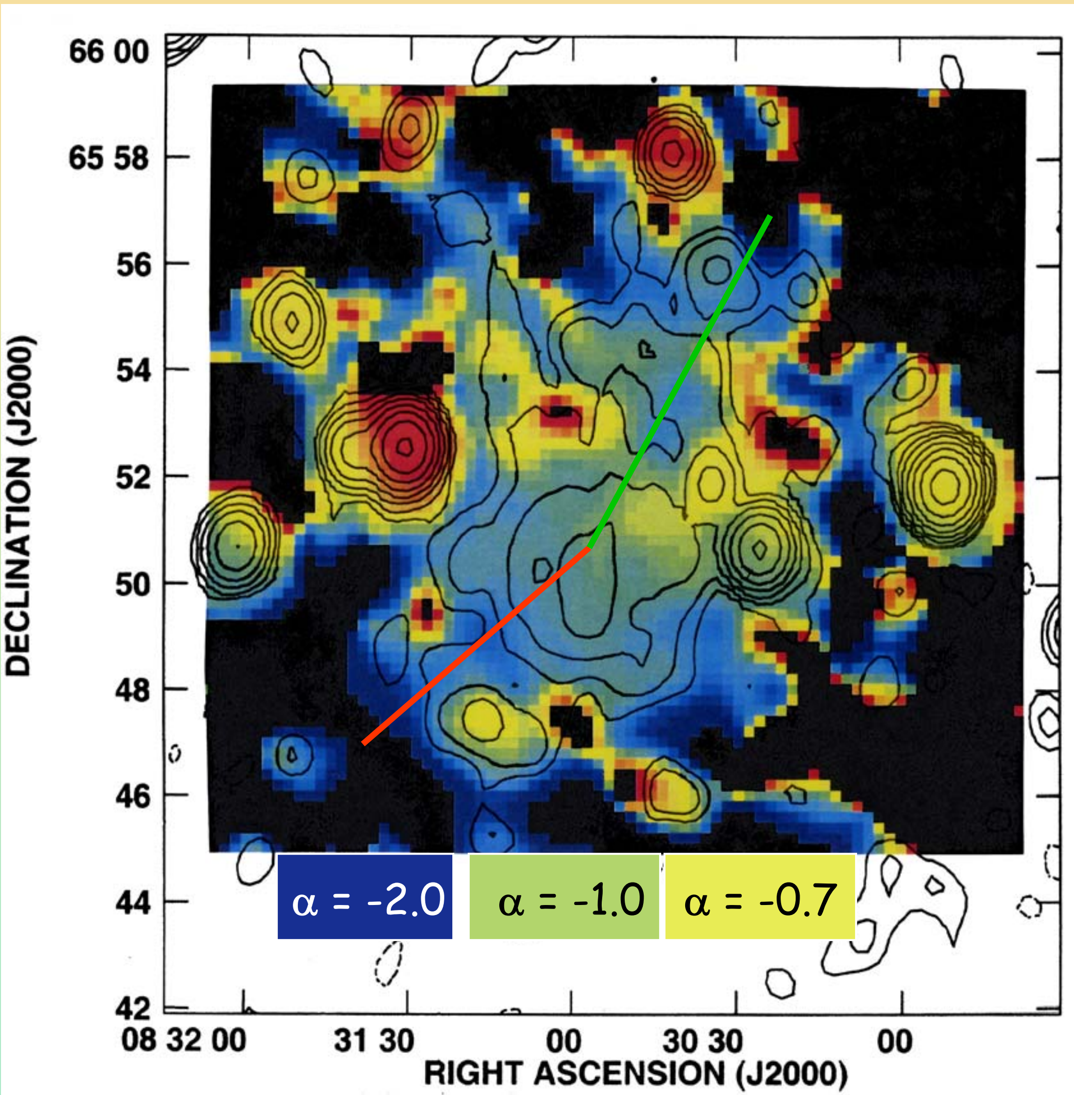
Clumpiness

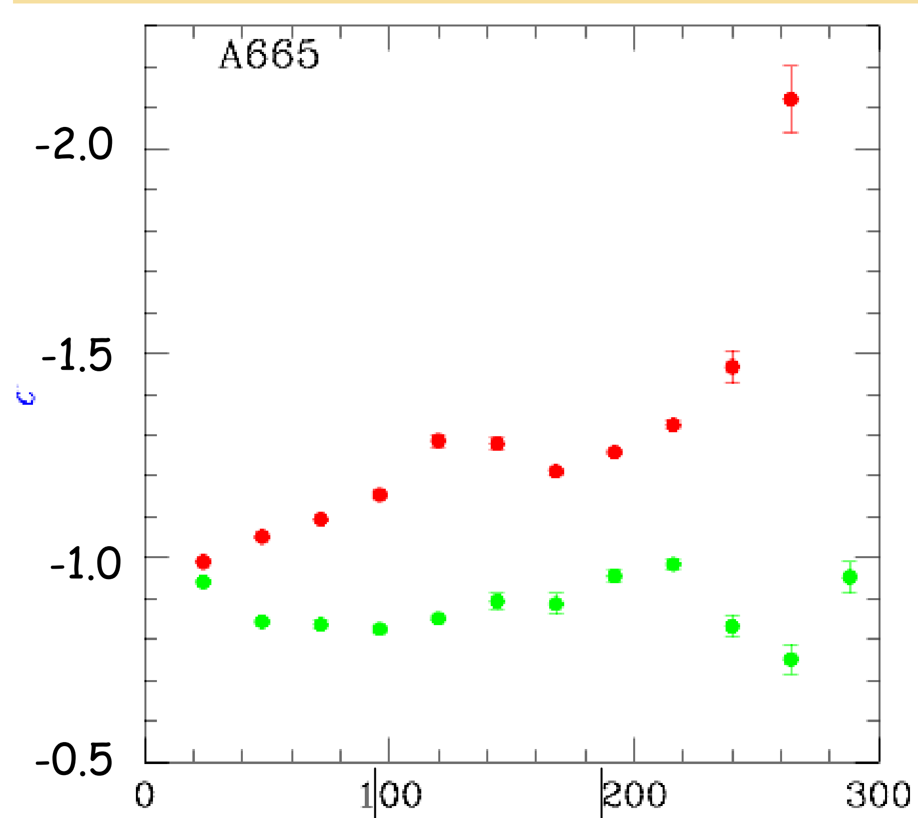
Flattening in the region of the extended emission

Steepening to the SW

No connection to the shock

Spectral index profiles (0.3 GHz – 1.4 GHz)



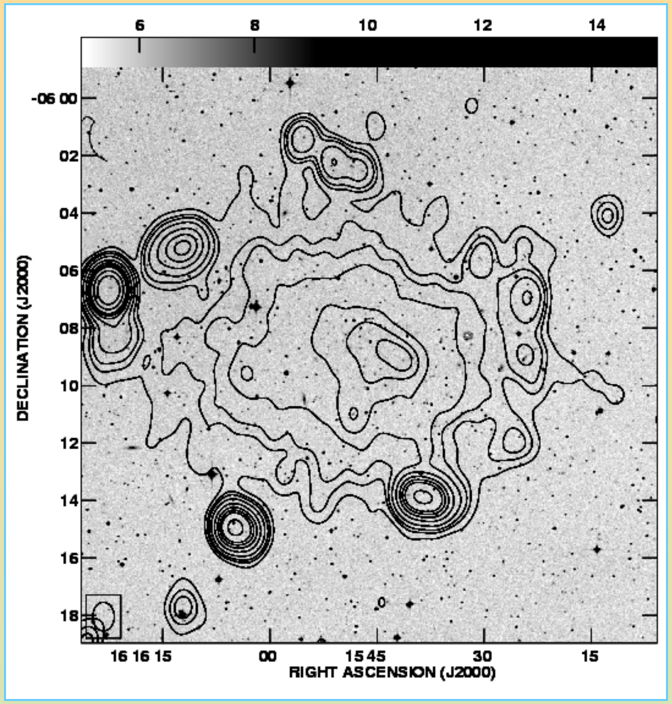


380 kpc
$1\ r_c$

760 kpc
$2\ r_c$

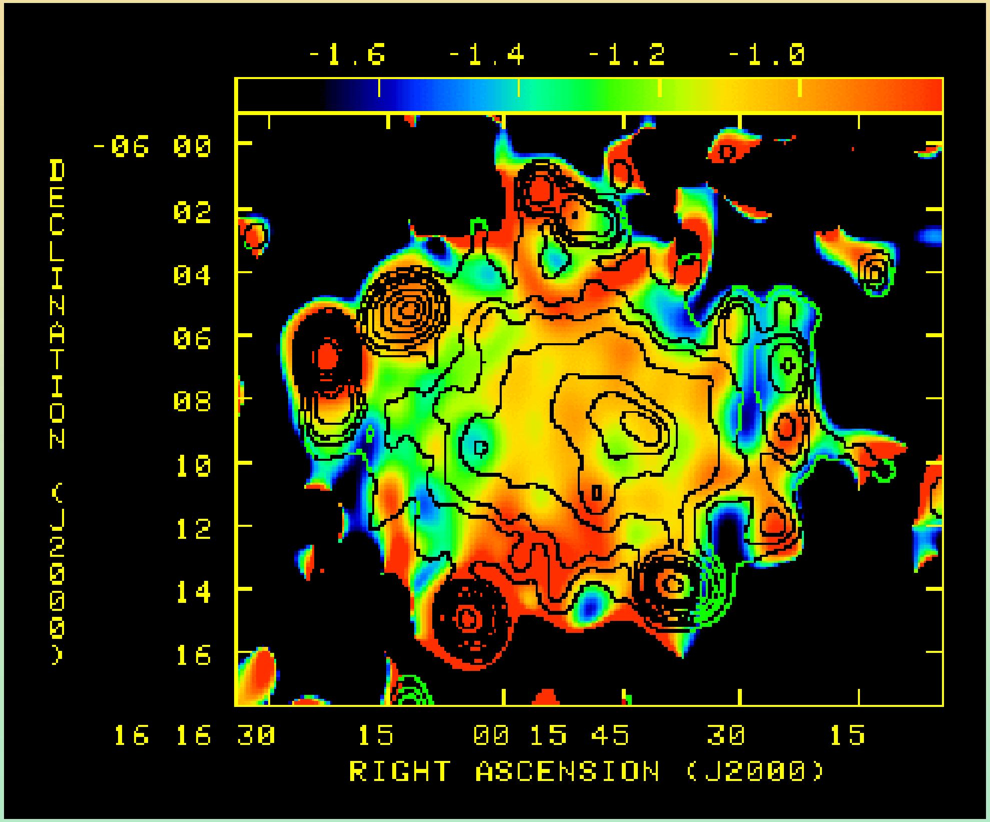
R

VLA - 1.4 GHz (Feretti et al. 2001)

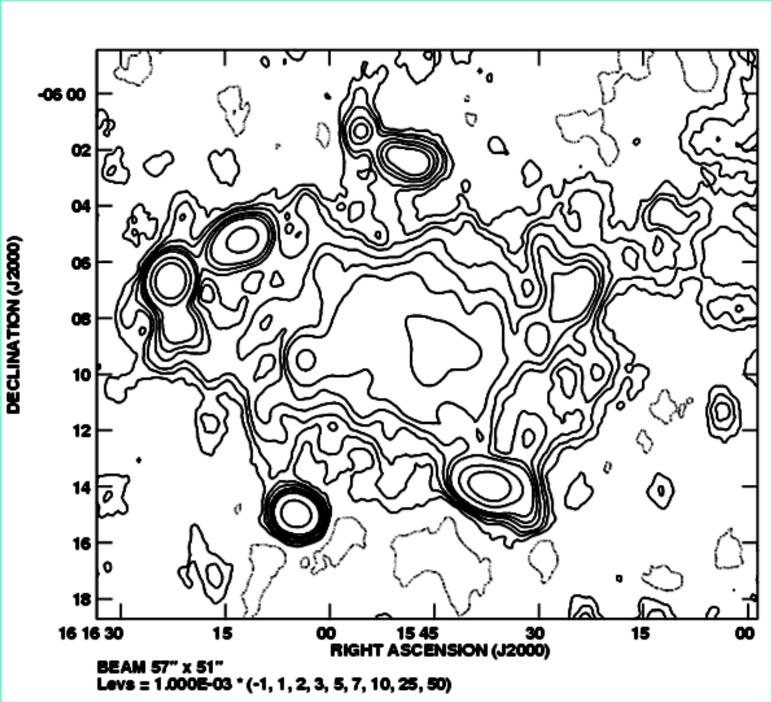


Abell 2163

z = 0.203
kT = 12.3 keV



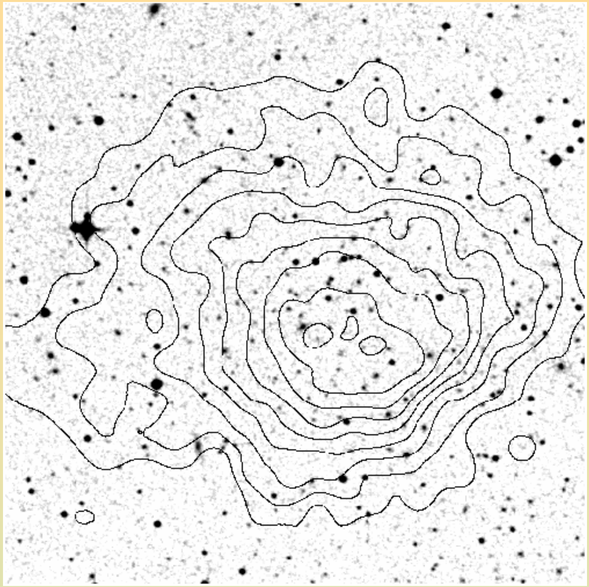
Feretti et al. To be submitted



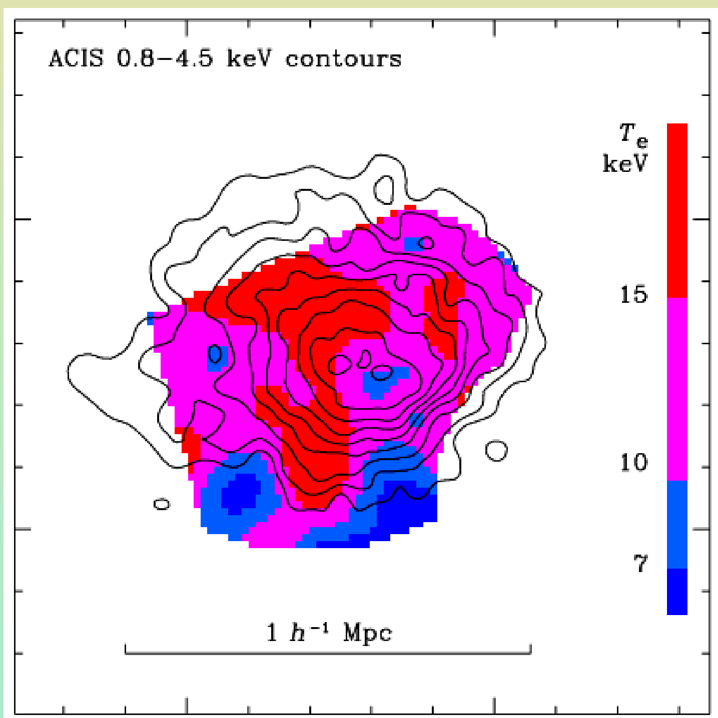
VLA - 0.3 GHz (9.5 h, B + C)

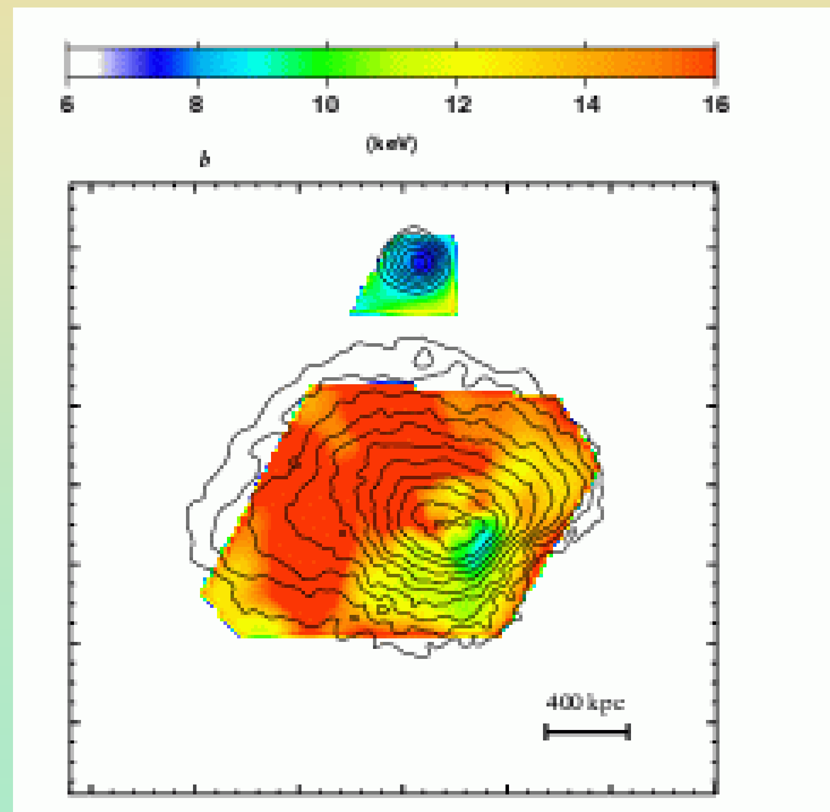
Clumpiness
Flattening in the NS direction
Steepening to the E and to the W

X-ray brightness (Chandra)



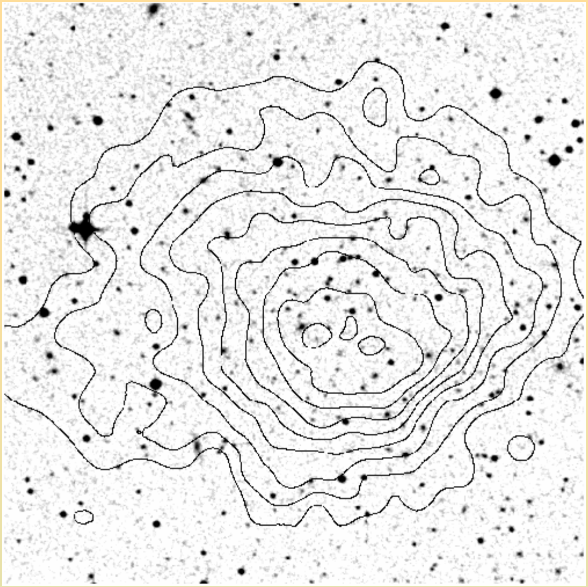
Markevitch & Vikhlinin 2001 9.5 ksec

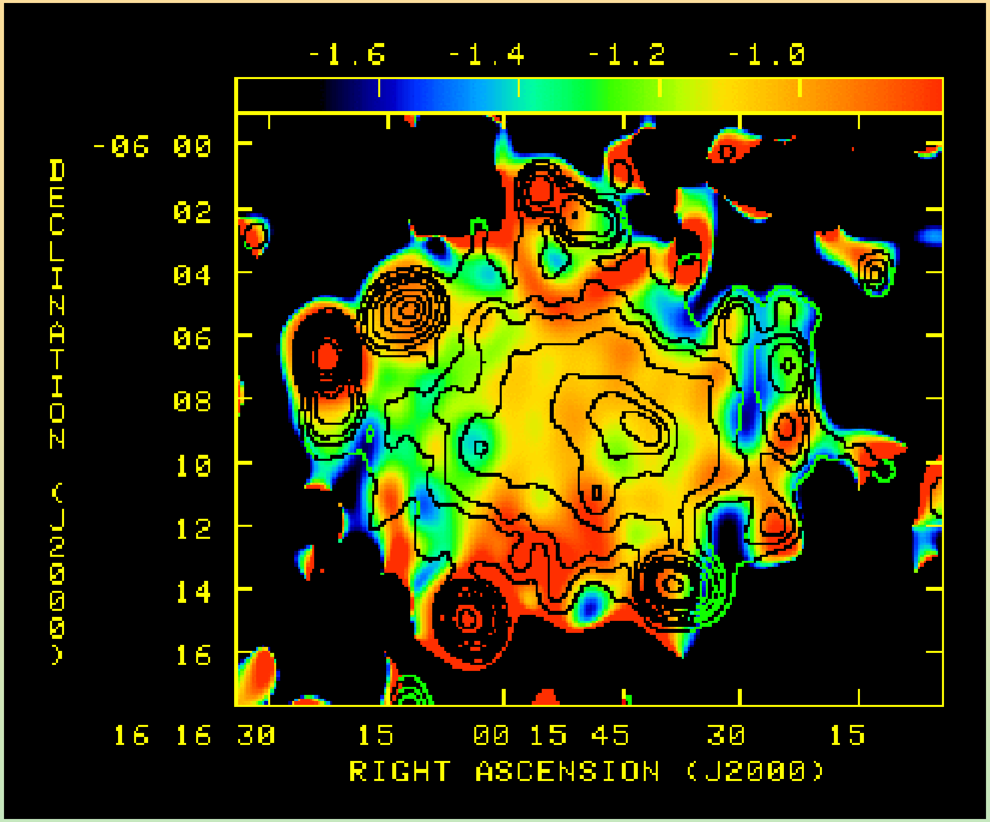


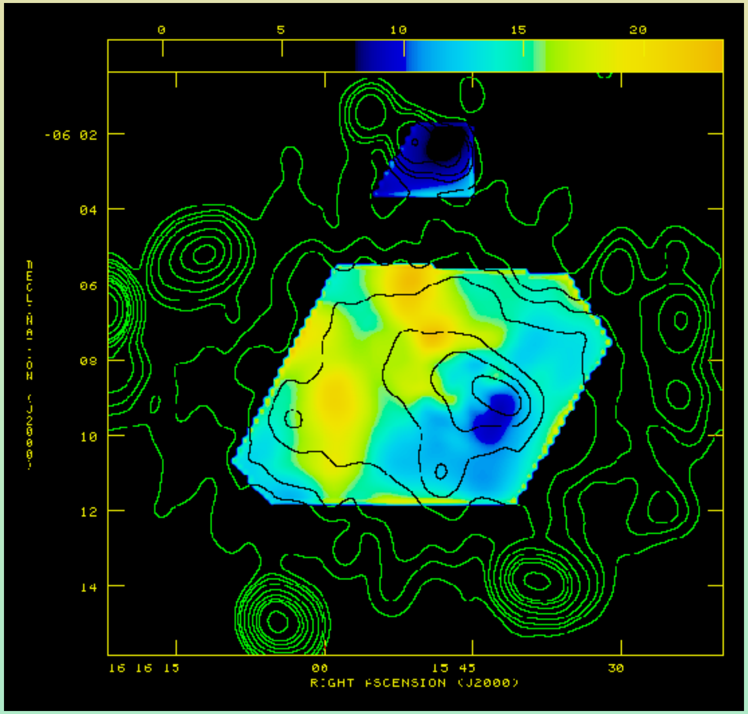


Govoni et al. 2004, astro-ph/0401421, 70 ksec

Temperature (Chandra)







Clumpiness

Flattening in region influenced by the merger

Steepening to the E and W

RESULTS:

Regions influenced by the merger show flatter spectra, indicating

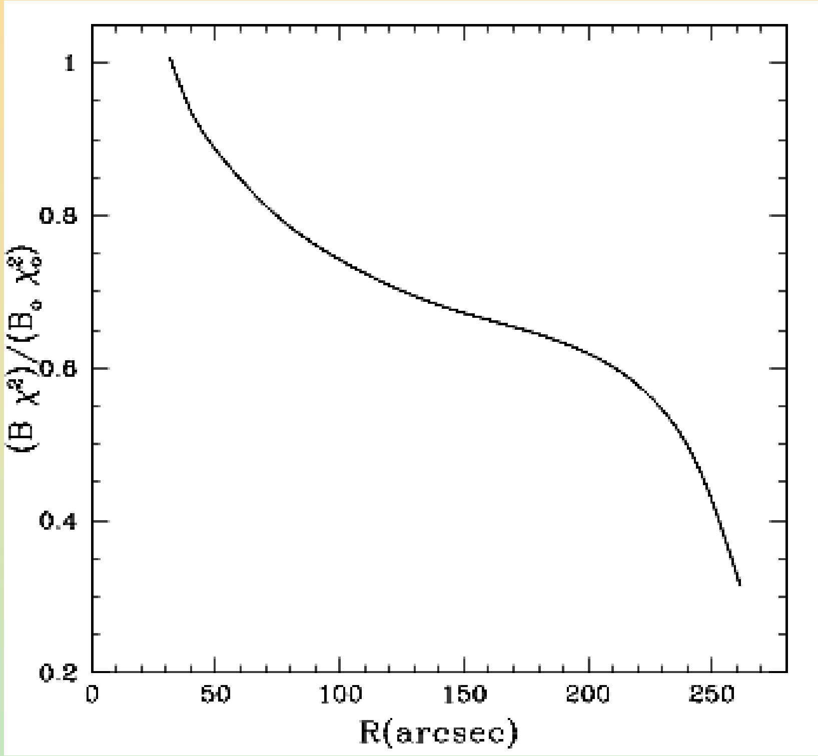
- higher energy density (~ 15%)
- more energetic electrons
- electrons reaccelerated more recently

$t \sim 4\ 10^7$ yr

Radial steepening is detected in regions not influenced by the merger, as due to combined effect of

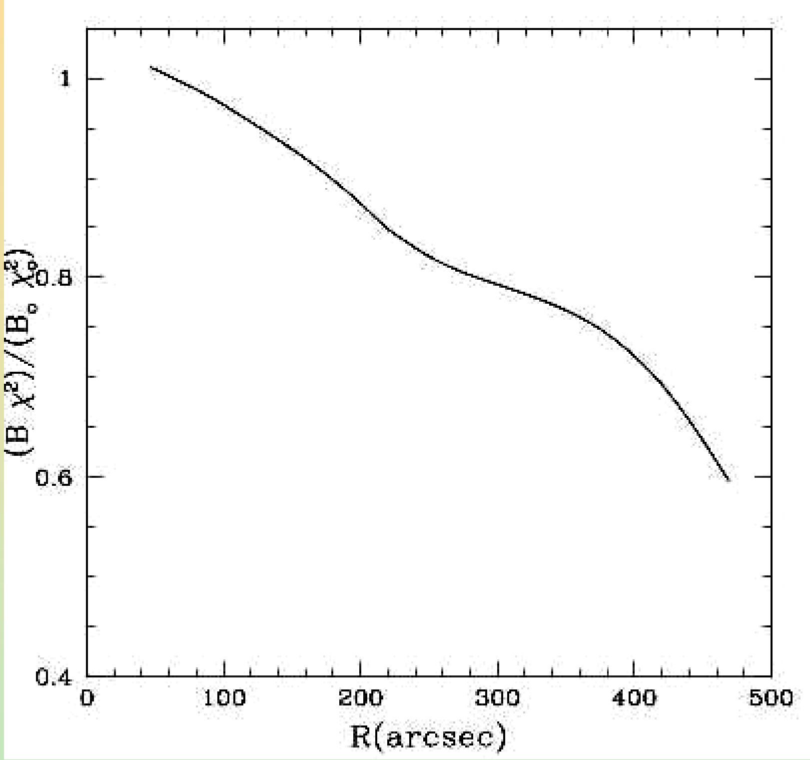
a radial decrease of the cluster magnetic field strength and
a cutoff in the electron energy distribution

➔ profile of magnetic field



1
0.8
0.6
0.4
0.2
0
50
100
150
200
250
R(arcsec)

A665



1
0.8
0.6
0.4
0
100
200
300
400
500
R(arcsec)

A2163

Halo and relic clusters are characterized by recent / ongoing cluster mergers

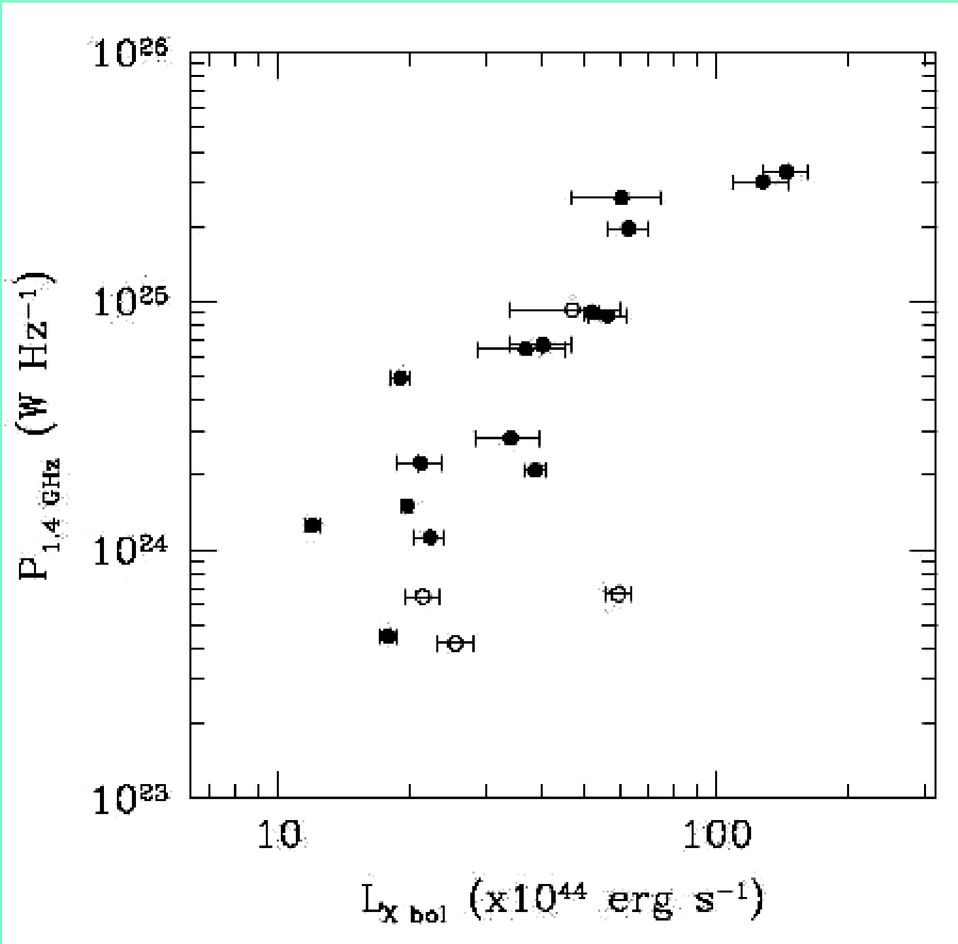
BUT : NOT ALL MERGING CLUSTERS HAVE HALOS OR RELICS AT THE PRESENT DETECTION LIMITS

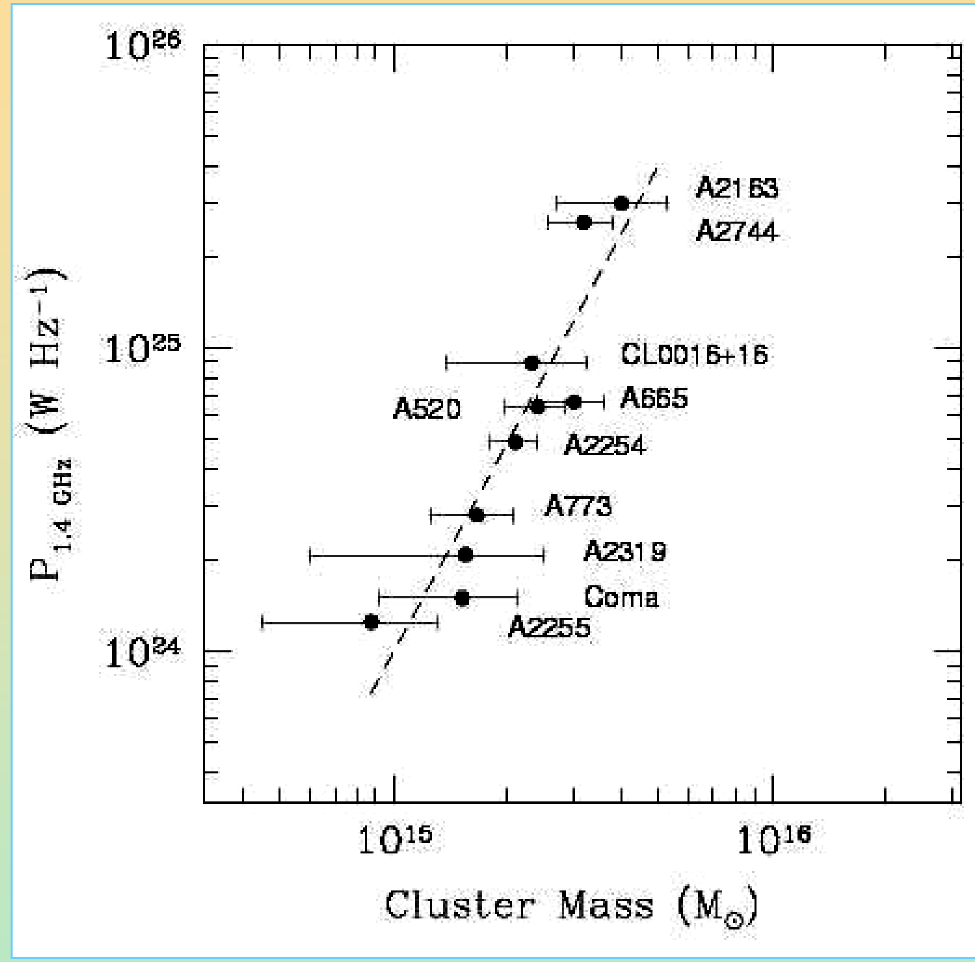
Correlations between halo

radio parameters

X ray parameters

Halo radio power vs cluster L_x and Mass



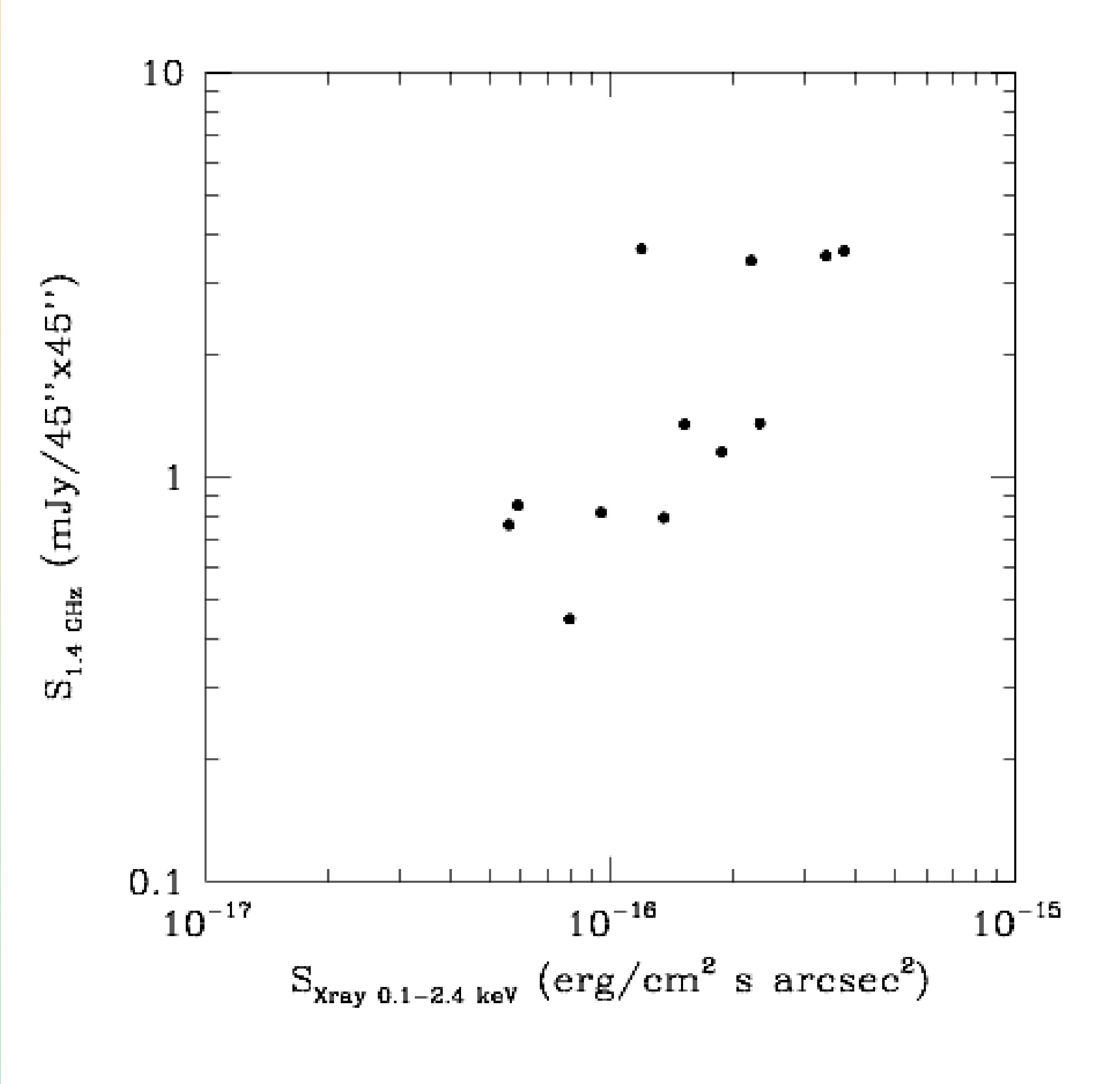


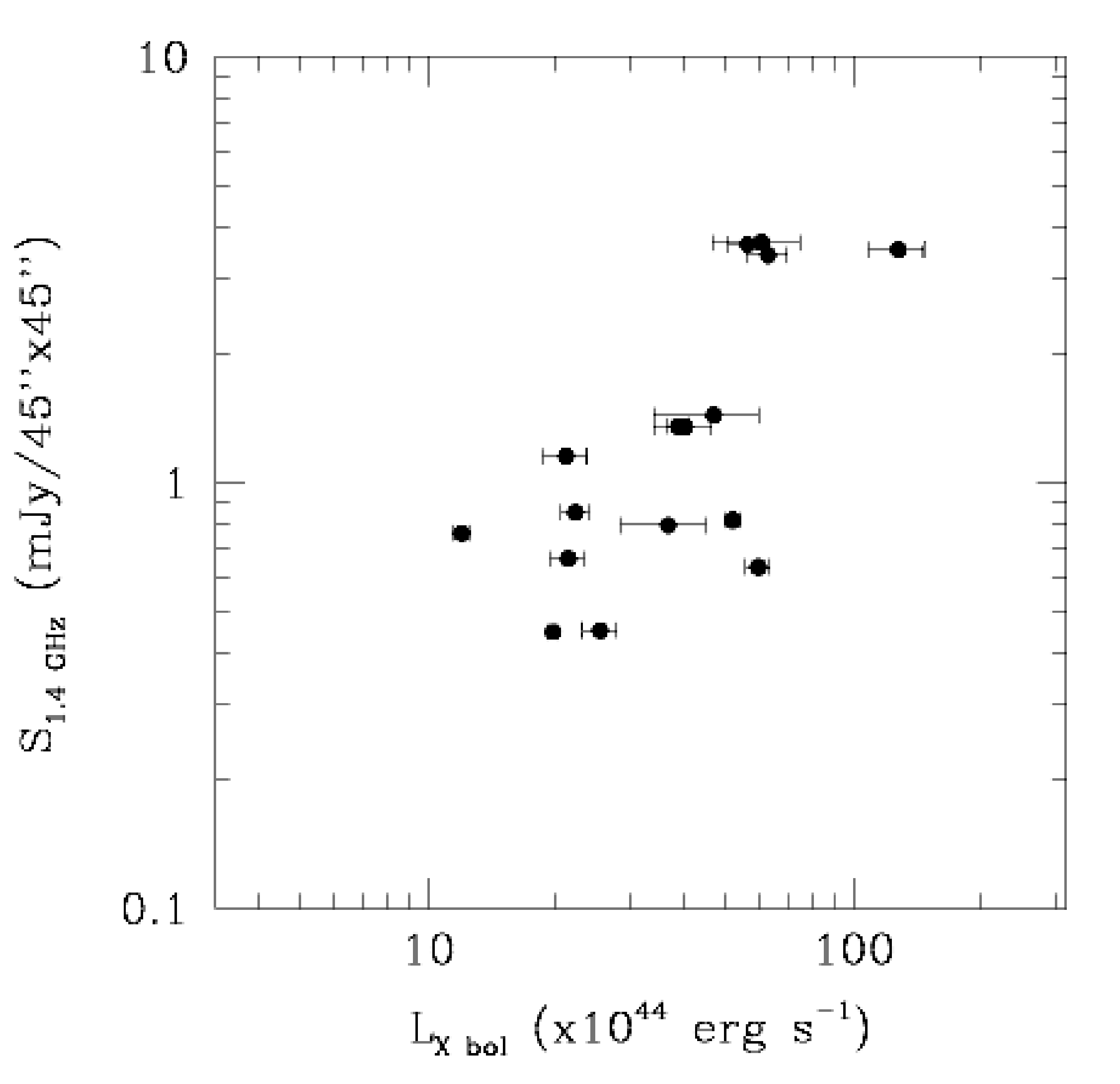
Halos > 1 Mpc (•) and < 1 Mpc (o)

$$P_{radio} \propto M^{2.3}_{cluster}$$

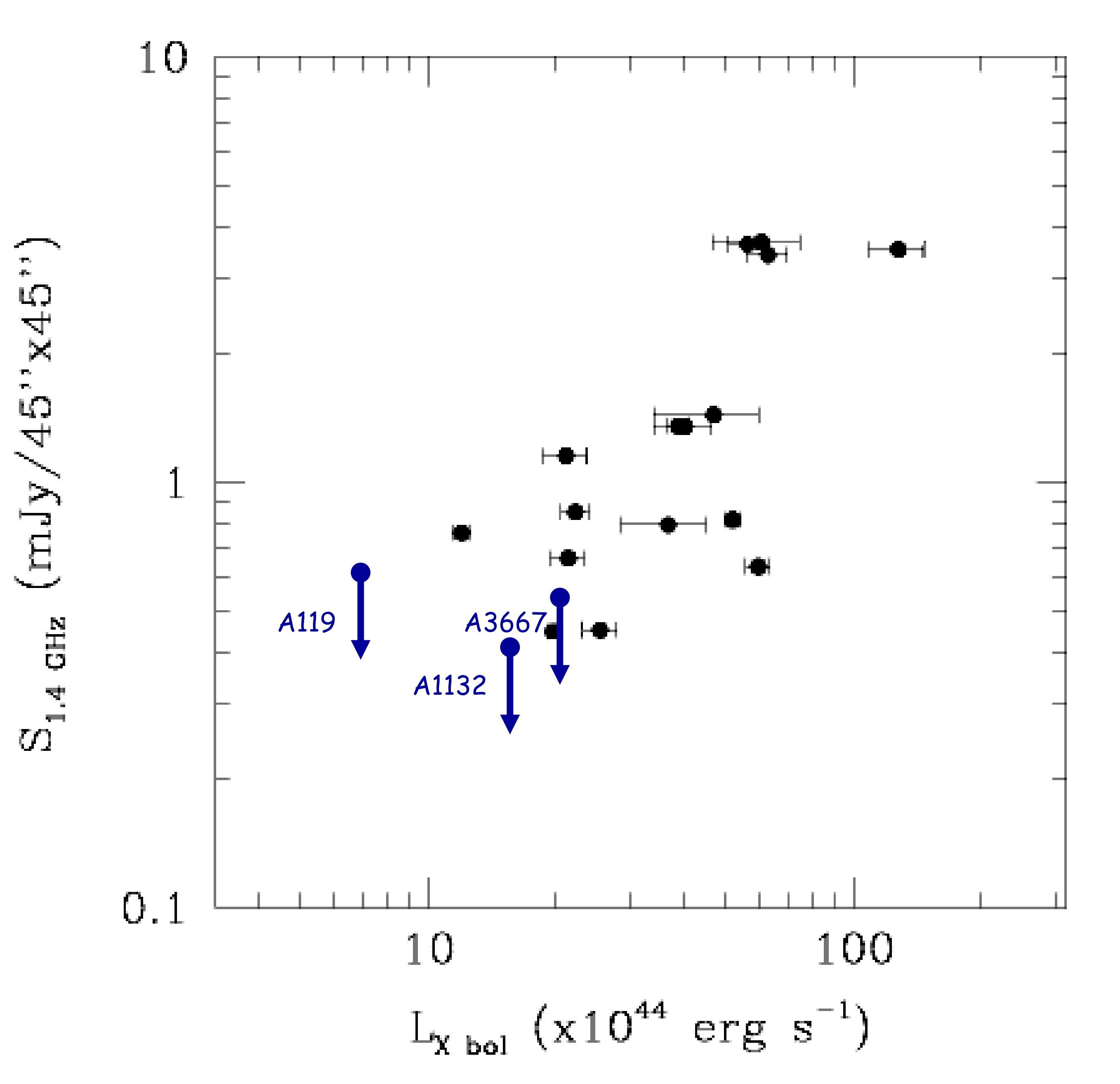
(Feretti 2002
Bacchi et al 2003)

Halo radio brightness vs X ray brightness





10
1
0.1
10
100
$S_{1.4\ GHz}$ (mJy/45''x45'')
$L_{X\ bol}$ ($x10^{44}$ erg s^{-1})



10
1
0.1
10
100
$S_{1.4\ GHz}$ (mJy/45''x45'')
$L_{X\ bol}$ (x10^{44} erg s^{-1})
A119
A3667
A1132

RADIO – X RAY COMPARISON

Hard X-ray : NON - THERMAL

Relativistic electrons of $\gamma \sim 10^4$

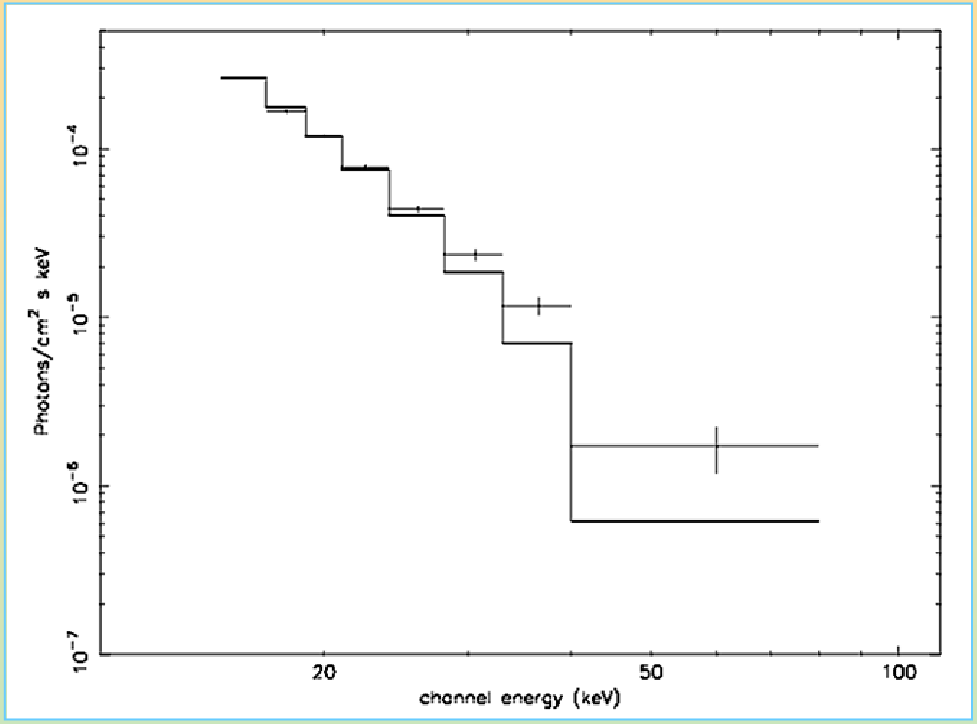
➔ synchrotron emission in radio
➔ inverse Compton emission in hard X ray

Comparison between Radio and X-ray emissions gives estimates of magnetic field and relativistic particle energy density

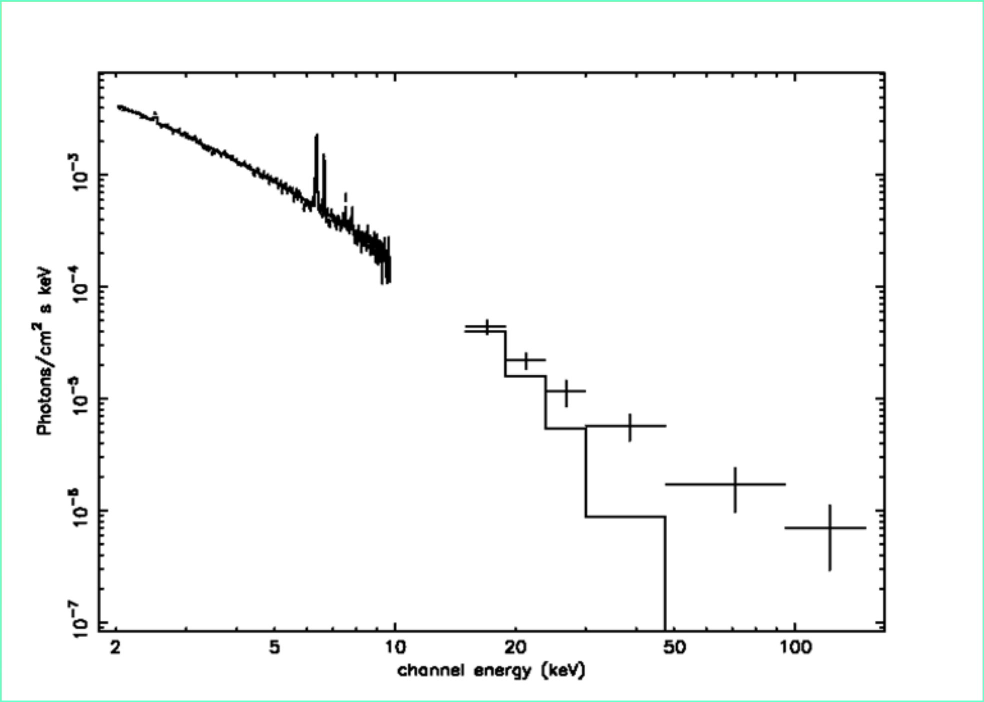
$$\frac{L_{syn}}{L_{IC}} \propto \frac{U_B}{U_{ph}}$$

Coma

Abell 2256



Fusco-Femiano et al. 2004, astro-ph/031262



Fusco-Femiano et al. 2000

Thermal: T = 8.2 keV

Non Thermal flux = 1.5 10^{-11} erg cm^{2} s^{-1} in the 20–80 keV range

B = 0.16 μG

Thermal: T = 7.5 kev

NT Flux = 1.2 10-11 erg cm-2 s-1 between 20-80 keV

B_{center} = 0.5 μG
B_{periph} = 0.05 μG

Hard X-ray emission

Detection in:
- Coma (BeppoSAX: Fusco-Femiano et al. 2004)
  (RXTE: Rephaeli et al. 1999, Rephaeli & Gruber 2002)
- A 2256 (BeppoSAX: Fusco-Femiano 2000)

Marginal detection in :
- A 2199 (Kaastra et al. 1999)
- A 754 (Fusco-Femiano et al. 2002)

Upper limits:
- A 119 (Fusco-Femiano et al. 2002)
- A 3667 (")
- A 2163 (Feretti et al. 2001)

IC emission in soft X ray band possibly detected from ROSAT in A85 (Bagchi et al. 1998)

CONCLUSIONS

- The presence of diffuse radio emission in clusters (halos and relics) is linked to cluster merger processes

- Recent cluster mergers provide the energy to the formation and maintenance of the radio halos and relics

- The connection between halos and mergers favours halo models where the radiating particles are reaccelerated in situ

- The images of the radio spectral index indicate flatter spectra in the regions influenced by the merger, supporting the electron reacceleration models

QUESTION : DO ALL MERGING CLUSTERS HAVE HALOS ?

THANK YOU