Low frequency observations of diffuse radio emission in clusters of galaxies

Giulia Macario
Dipartimento di Astronomia, University of Bologna
INAF-IRA Bologna

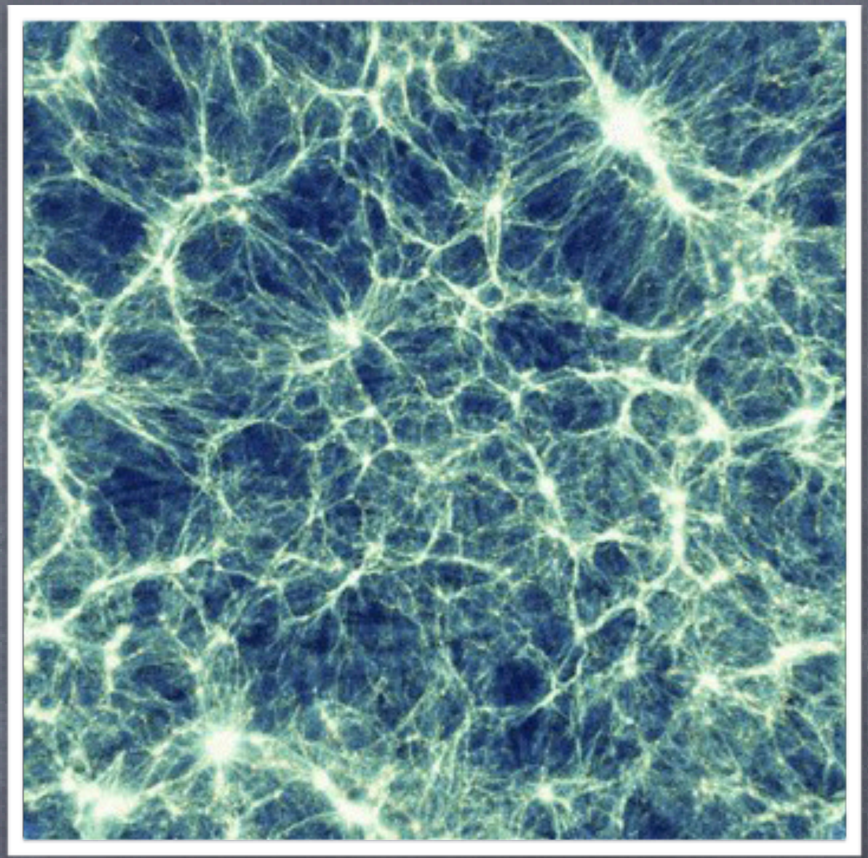
Ph.D. advisors: L. Gregorini (UniBo);
T. Venturi, G. Brunetti (IRA)
Main Collaborators: D. Dallacasa, R. Cassano (IRA);
S. Giacintucci, M. Markevitch (Harvard-CfA)

YERAC 2010 - Alcala' de Henares, July 8 2010

Galaxy clusters

Largest gravitationally bound systems in the Universe, Mpc scale

The "Bullet" cluster Credits: M. Markevitch

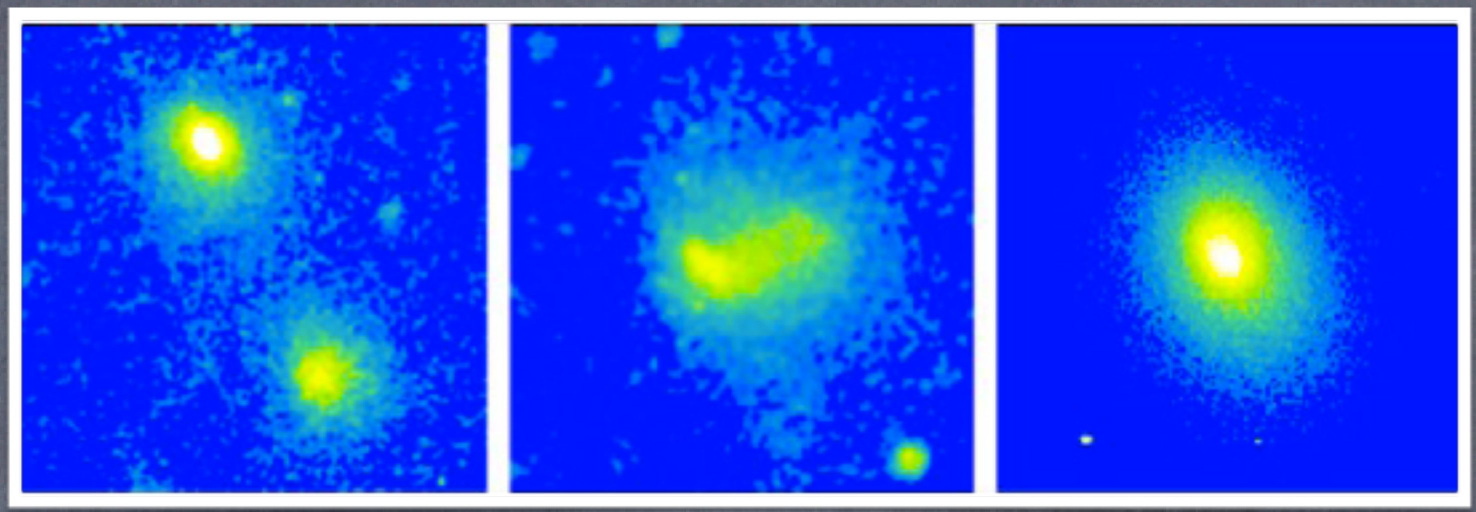


Borgani et al. 2004

- Galaxies: ~5% (optical)
- Dense and hot ICM: ~15% (X)
- Dark matter: ~80%

Clusters form by **accretion** of matter and **mergers** between sub-units at the intersection of filaments of the "cosmic web"

Cluster mergers



A399-A401-about to merge A754-major merger A2029-relaxed (few Gyrs)

Observational evidences of mergers from the **thermal** component:

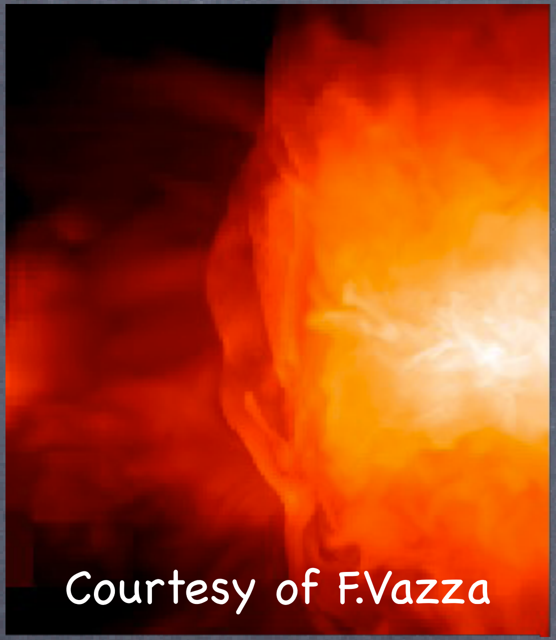
- **X-ray** : substructures in the ICM distribution, gradients in SB and T
- **Optical** : substructures in galaxy distributions

Cluster mergers

Cluster **mergers** are among the most energetic events in the Universe:

major merger energy release: > 10^64 ergs over 1 Gyr

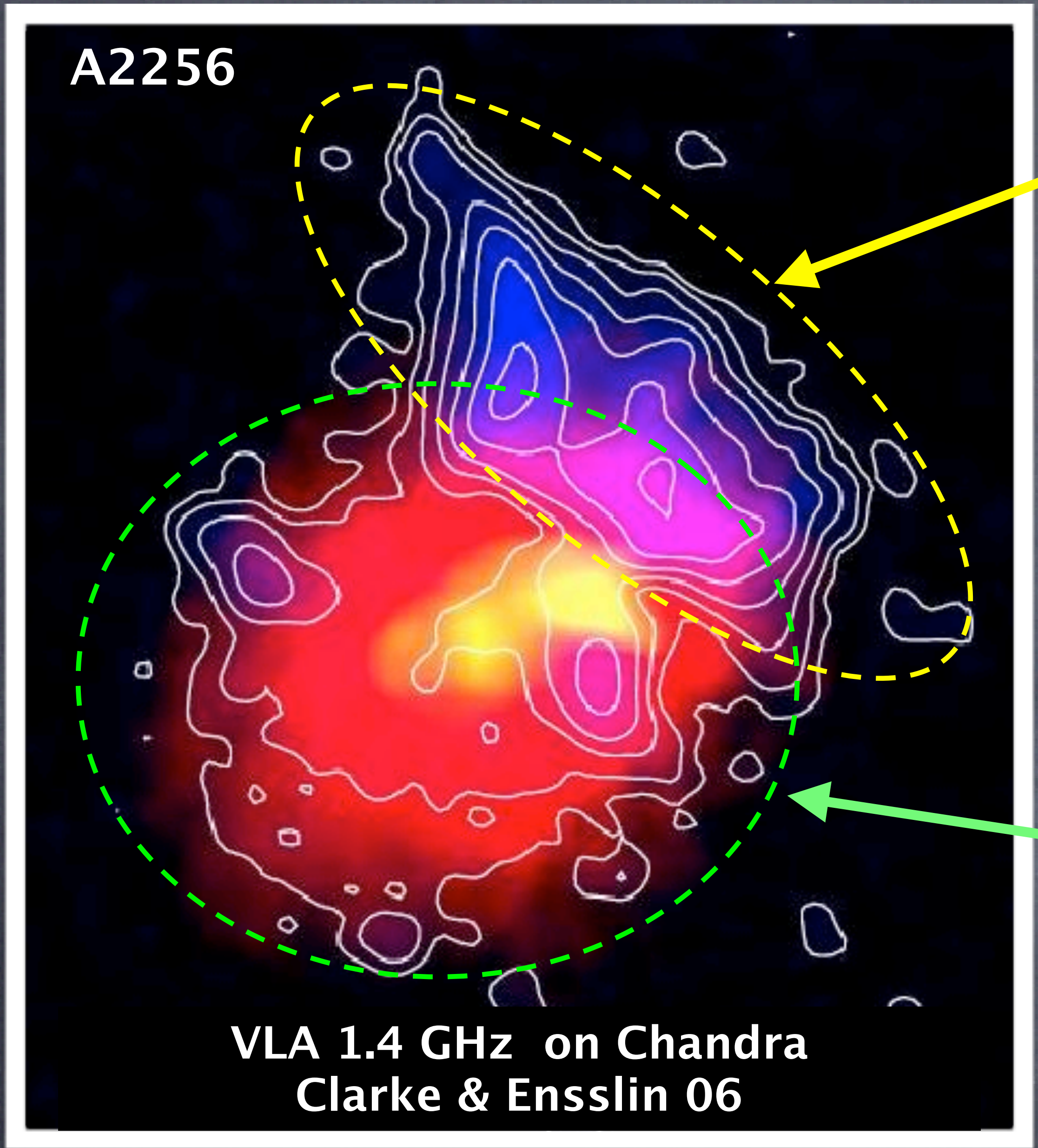
shocks and **turbulence**



amplify the cluster magnetic fields
accelerate particles from the thermal ICM
re-accelerate pre-existing relativistic particles

Mpc-scale non-thermal (synchrotron) radio emission,
observed in a fraction of **merging** cluster

Mergers and diffuse radio emission



Radio Relics: cluster outskirts, elongated, polarized up to ~30%

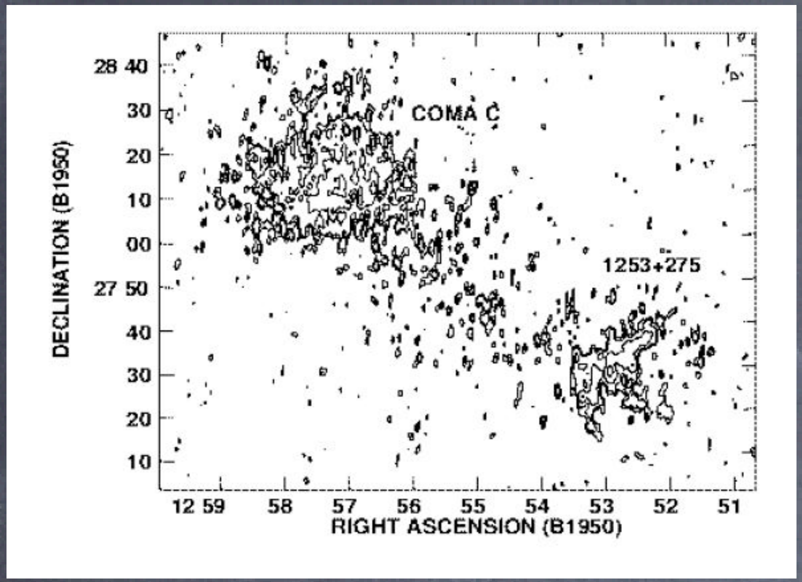
Radio Halos: centrally located, regular shape, usually unpolarized

Mpc scale sources, **NOT** associated with individual galaxies, but with the ICM

Probes the existence of GeV electron population and muG magnetic fields

Low SB, steep synchrotron spectra (**α~1.2-1.4**). Only ~50 known (poor statistic)

Origin of halos and relics

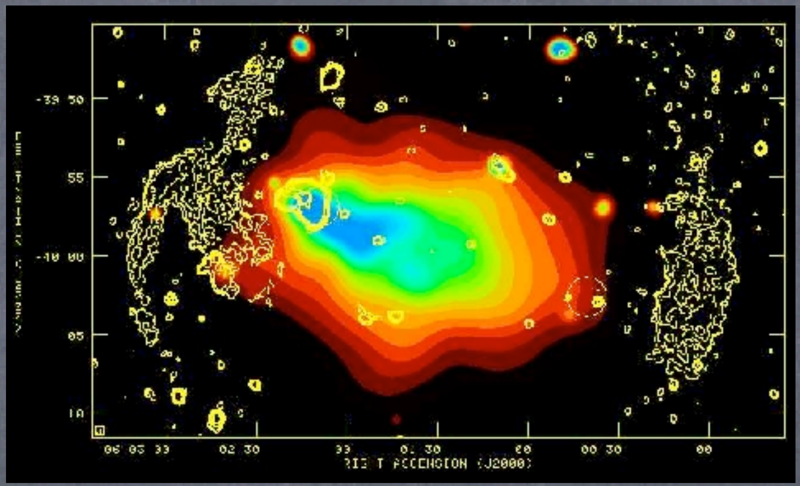


Coma cluster (Feretti et al. 1998)

Their Mpc size imply that

$$t_{diff} \gg t_{synchr}$$

i.e. 1 Mpc @ z=0.2:
9.5 Gyr >> 0.1 Gyr



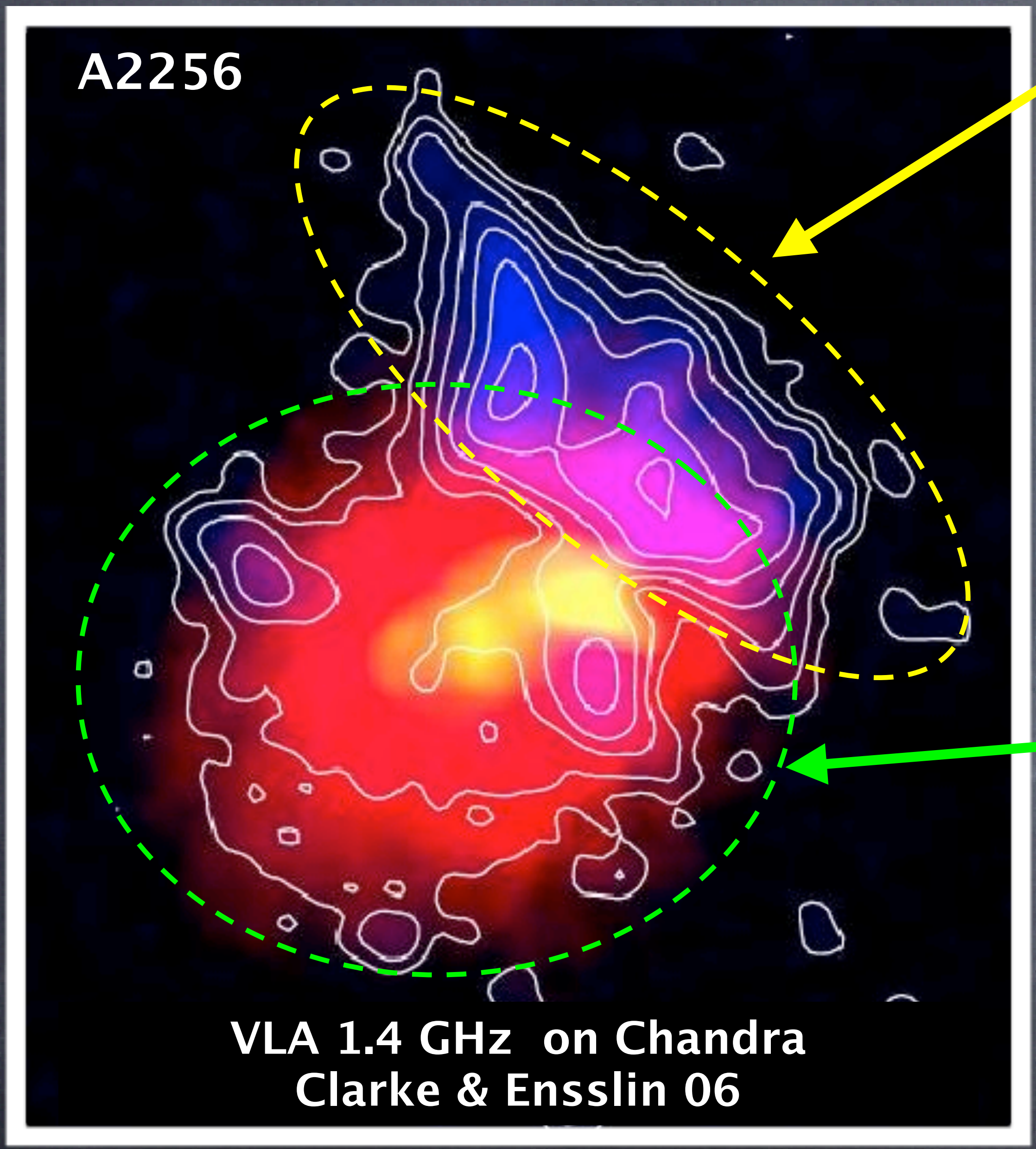
Abell 3376 (Bagchi et al. 2006)

Some form of (re-)acceleration is needed

Primary electron models: in situ re-acceleration of pre-existing electrons by merger shocks/ turbulence, first proposed by Jaffe (1977)

Secondary electron models: relativistic electrons injected in the cluster volume via p_{th}-p_{cr} collisions, first proposed by Dennison (1980)

Origin of halos and relics



Radio Relics

Origin: **merger** **shock**
(re-)acceleration of relativistic electrons or **shock** adiabatic compression of fossil radio plasma?

e.g. Ensslin et al. 1998; Rottgering et al. 1997; Ensslin & Gopal-Krishna 2001

Radio Halos

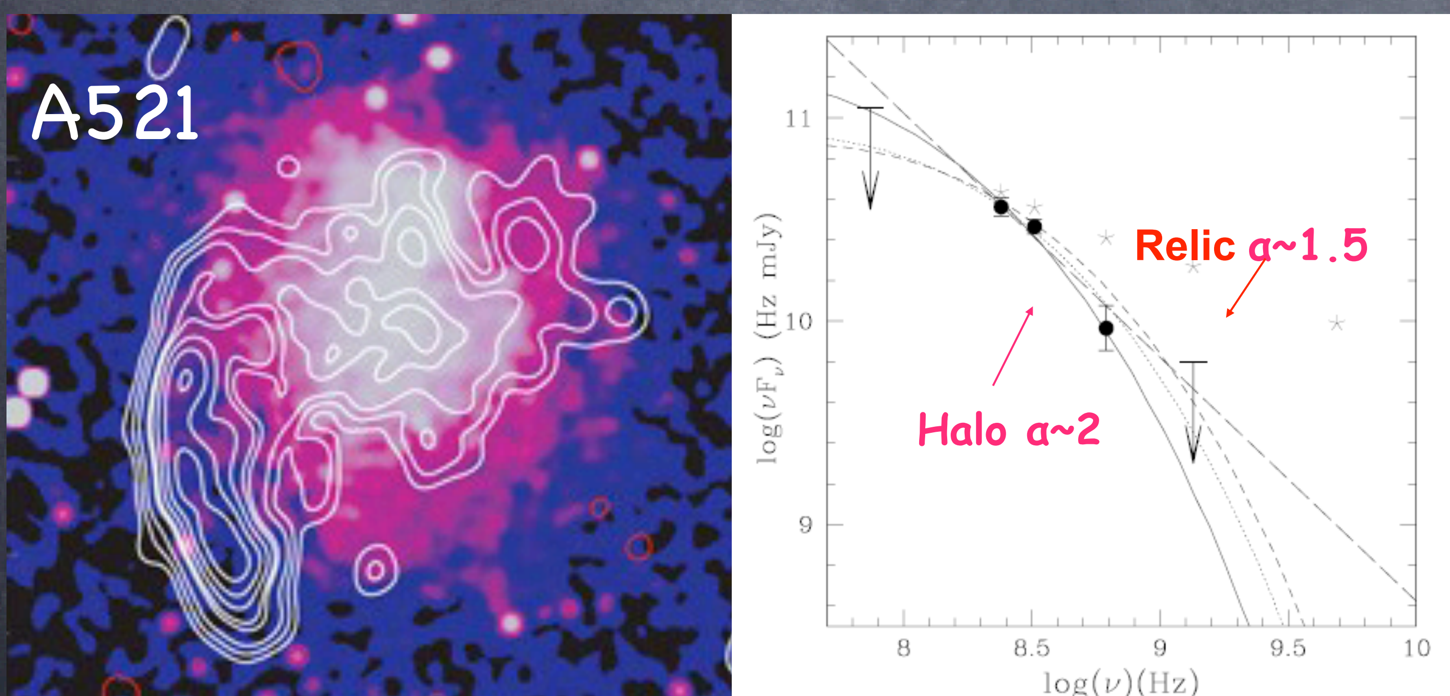
Origin: a promising possibility is in situ re-acceleration of preexisting relativistic electrons by **merger** driven **turbulence**

e.g., Brunetti et al. 2001, 2004; Petrosian 2001

The re-acceleration model and USSRHs

- A **unique** expectation of this model is the existence of Ultra-steep spectrum radio halos (**USSRHs**, α>1.6), due to less energetic mergers
- Low frequencies => easier to find, expected to be more numerous

(i.e. Cassano & Brunetti 2005; Cassano, Brunetti & Setti 2006, Cassano+ 2008)



GMRT 240 MHz on Chandra
Brunetti+ 2008, Nature

Relic:
shock acceleration?
(Giacintucci, Venturi, **Macario**+ 2008)

prototypical **USSRH** ->
turbulence re-acceleration
(Brunetti+ 2008, Nature)

8

Why low frequencies?

- Low frequency (<330 MHz) observations well suited to study such steep spectrum radio sources
- most observations of halos/relics @ 1.4 GHz (surveys, individual); only few object with spectral information
- to shed light on the scenarios proposed for their origin. In particular, discovery of new USSRHs would constrain the re-acceleration scenario.

Ph.D. project: GMRT low frequency (<327 MHz) follow up of RH/relics/candidates in clusters selected from GMRT RHSurvey (Venturi et al. 2007&2008; Venturi et al. 2009)

✓ GMRT (Giant Meterwave Radio Telescope) is well suited for RH/relic studies: low freq., good sensitivity both at compact and extended emission

I. Abell 697

II. Abell 754

I

"The very steep spectrum radio halo in Abell 697"

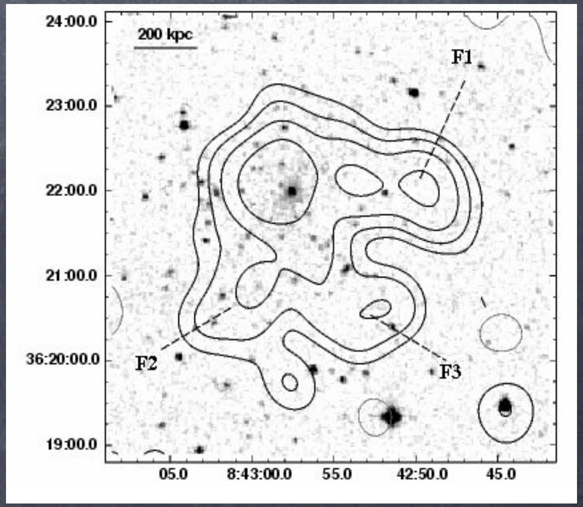
(Macario et al. 2010, in press A&A, arXiv:1004.1515)

Abell 697: a merging cluster with a giant RH

- **massive**, X-ray **luminous** cluster
- evidences of **merger** activity (optical/X-ray, Girardi+ 2006, Dhale+ 2002)

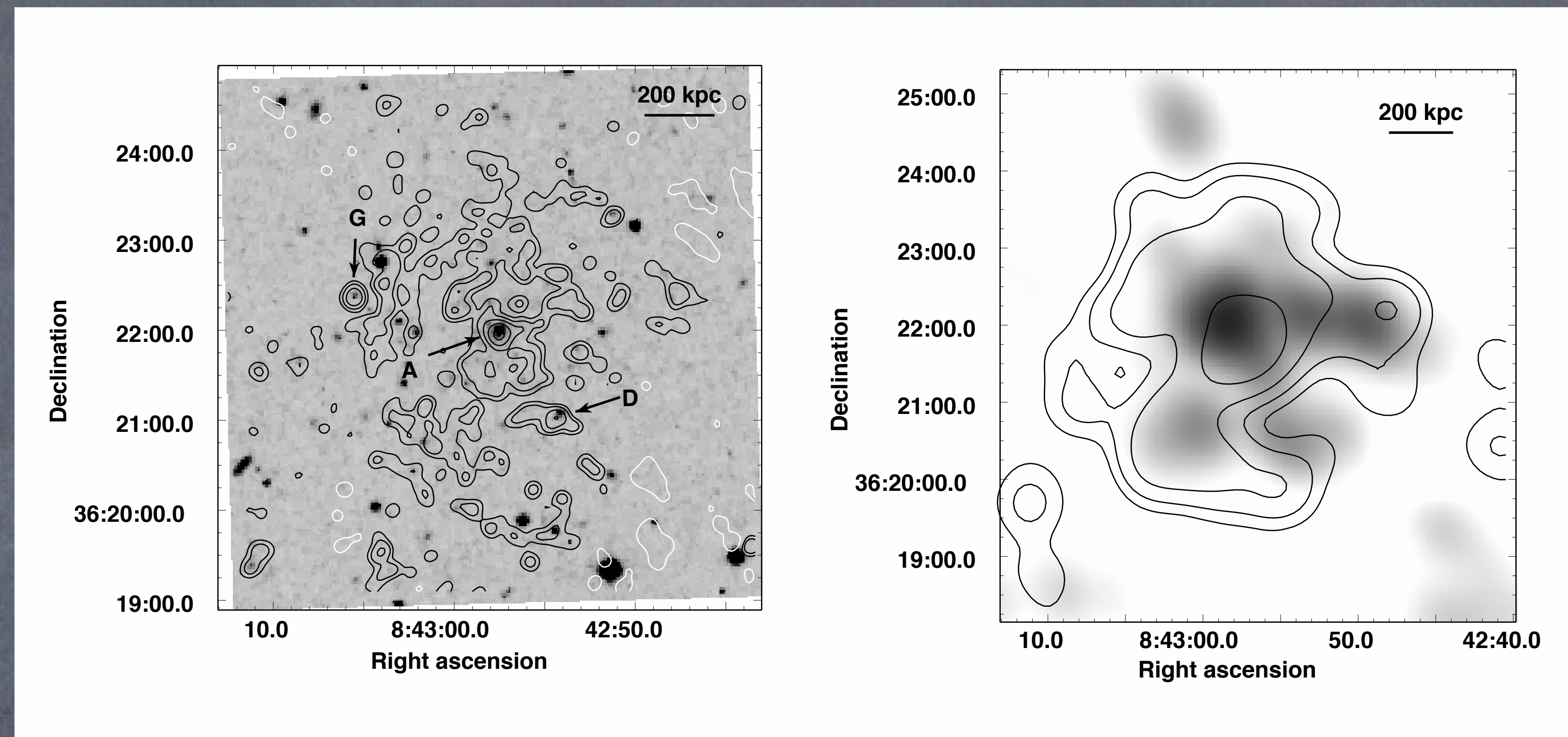
RA_{J2000}	08h 42m 53.3s
DEC_{J2000}	+36° 20′ 12″
Bautz–Morgan Class	II–III
Richness	1
z	0.282
σ_v	1334 km s^{-1} (a)
$L_{X[0.1-2.4keV]}$	10.57 × 10^{44} erg s^{-1}
M_V	2.25 × 10^{15} $M_\odot$ (b)
R_V	2.90 Mpc (b)

- Host a central **giant radio halo**:
  - hints from WENSS (Kempner&Sarazin2001), confirmed by GMRT observations @610 MHz (GMRT RHSurvey, Venturi+ 2007&2008)



Abell 697: observations

New high sensitivity **GMRT** follow up observations @ 327 MHz (8 h)



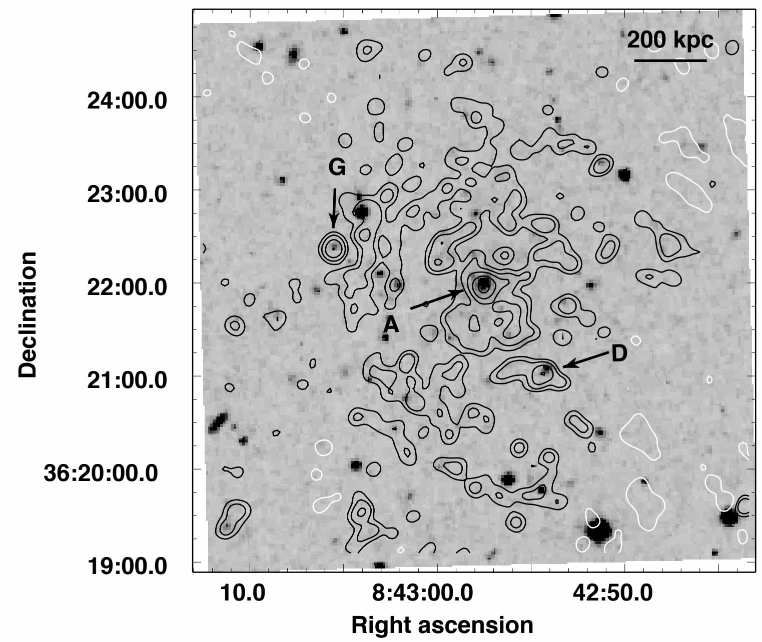
GMRT 327 MHz f.r. 10"x9" on DSS; rms ~45 μJy/b; 3σ f.c.

327 MHz cont., 47"x41" (rms ~150 μJy/b) on 610 MHz image (grey, rms ~50 μJy/b), point sources subtracted, 3σ f.c.

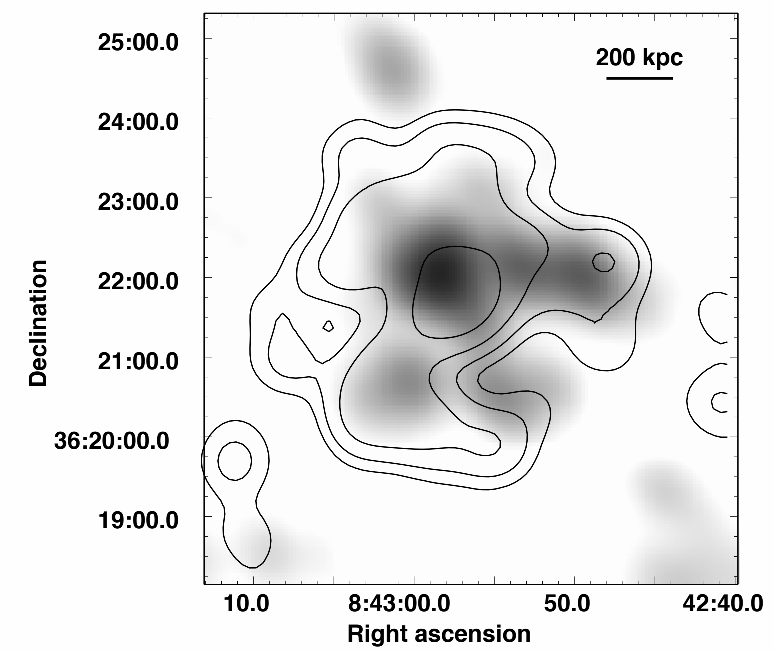
much brighter and larger @327 MHz

Abell 697: observations

New high sensitivity **GMRT** follow up observations @ 327 MHz (8 h)

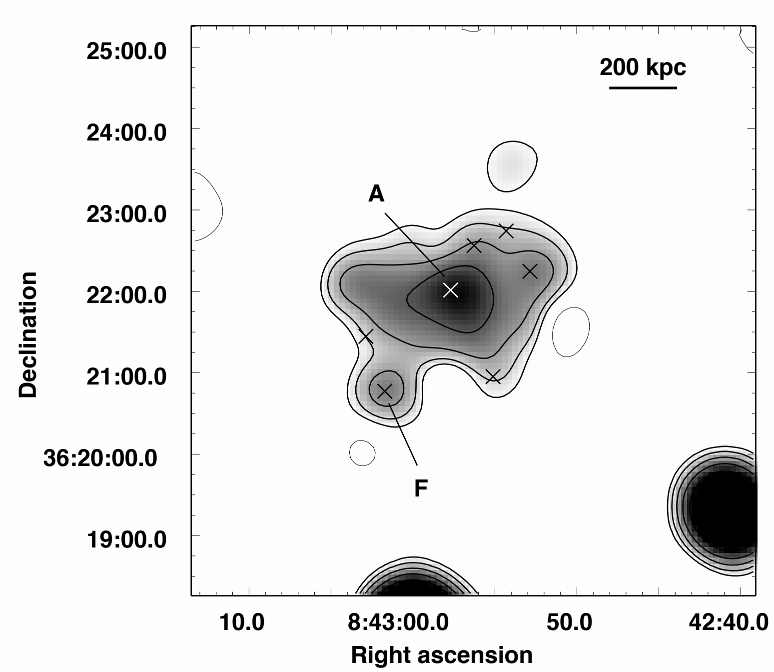


GMRT 327 MHz f.r. 10″x9″ on DSS; rms ~45 μJy/b; 3σ f.c.



327 MHz cont., 47″x41″ (rms ~150 μJy/b) on 610 MHz image (grey, rms ~50 μJy/b), point sources subtracted, 3σ f.c.

archive **VLA**-C obs. (50 min)



VLA 1350 MHz, 35″x35″, rms ~25 μJy/b, 3σ f.c.

much brighter and larger @327 MHz

Abell 697: spectral analysis

Abell 697: spectral analysis

- Flux density measurements @ 327, 610 and 1350 MHz

=> **observed integrated spectrum**

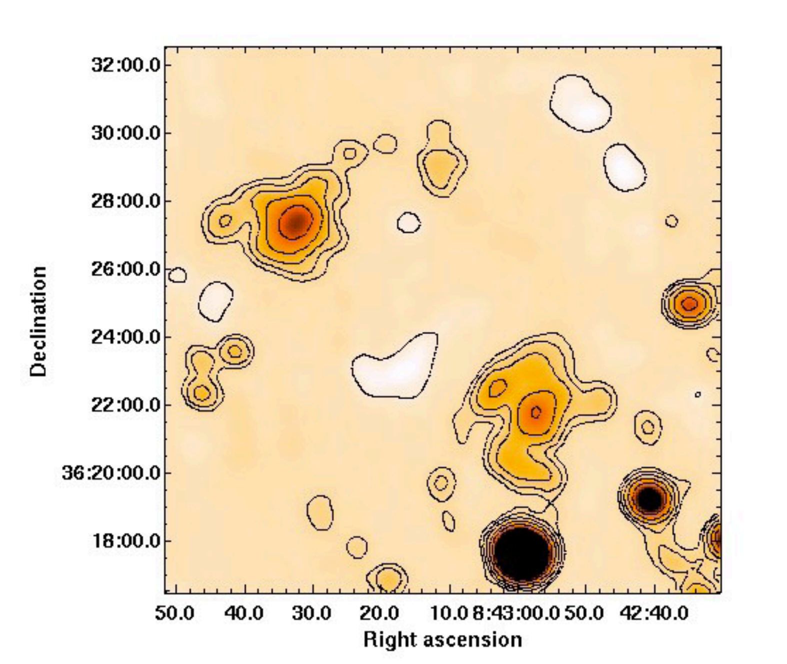
ν (MHz)	S_ν (mJy)	HPBW $'' \times ''$
325	47.3±2.5	46.8 × 41.4
610	14.6±1.7	46.4 × 35.9
1400	3.7±0.2	35.0 × 35.0

Abell 697: spectral analysis

- Flux density measurements @ 327, 610 and 1350 MHz

=> **observed integrated spectrum**

ν (MHz)	S_ν (mJy)	HPBW $'' \times ''$
325	47.3±2.5	46.8 × 41.4
610	14.6±1.7	46.4 × 35.9
1400	3.7±0.2	35.0 × 35.0



- Injection of "Fake radio halos" to estimate GMRT flux density losses and constrain the spectral steepness

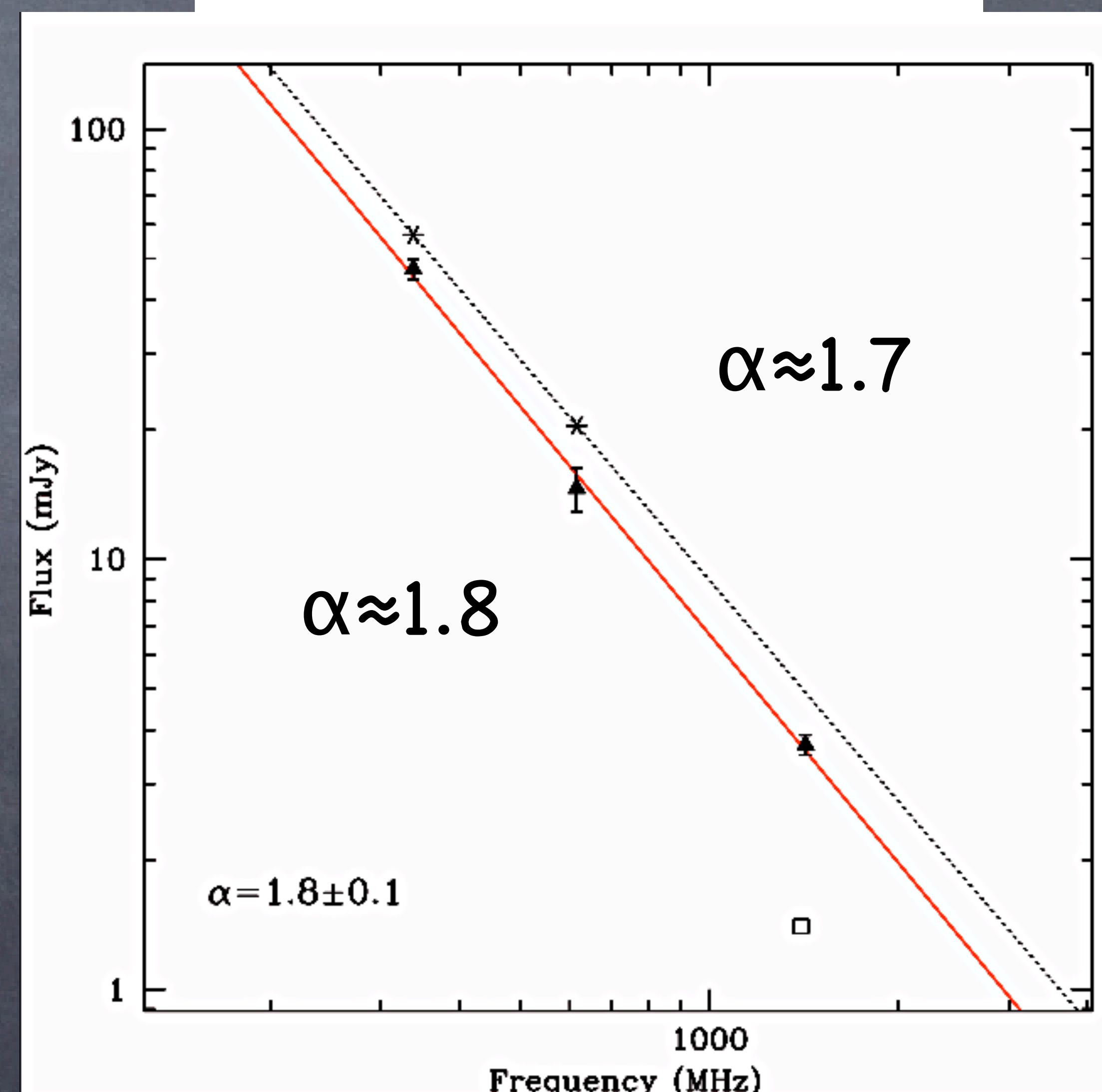
~20% losses => **"revised" spectrum**

Abell 697: spectral analysis

- Flux density measurements @ 327, 610 and 1350 MHz

=> **observed integrated spectrum**

ν (MHz)	S_ν (mJy)	HPBW $'' \times ''$
325	47.3±2.5	46.8 × 41.4
610	14.6±1.7	46.4 × 35.9
1400	3.7±0.2	35.0 × 35.0



- Injection of "Fake radio halos" to estimate GMRT flux density losses and constrain the spectral steepness

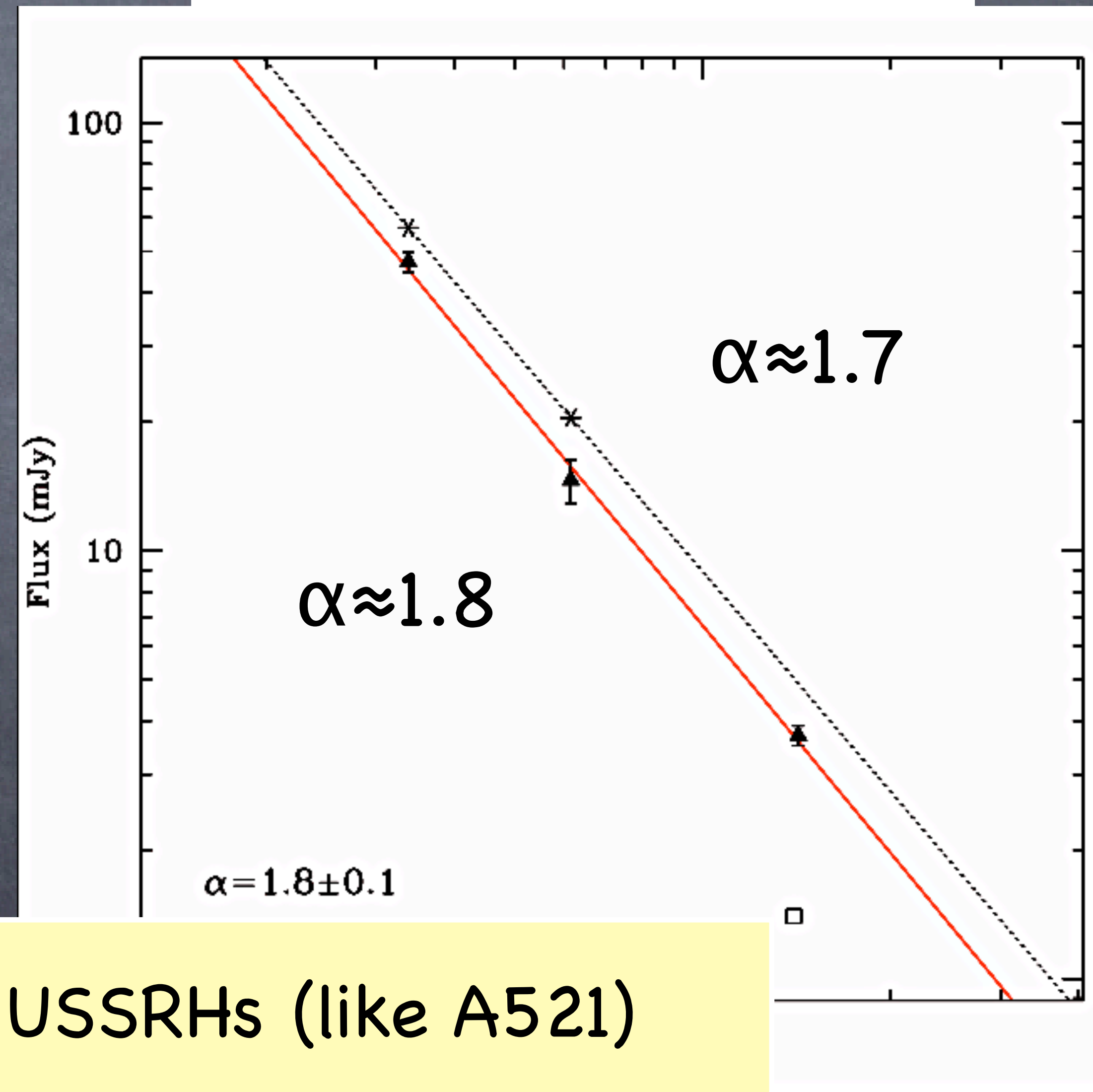
~20% losses => **"revised" spectrum**

Abell 697: spectral analysis

- Flux density measurements @ 327, 610 and 1350 MHz

=> **observed integrated spectrum**

ν (MHz)	S_ν (mJy)	HPBW ″×″
325	47.3±2.5	46.8 × 41.4
610	14.6±1.7	46.4 × 35.9
1400	3.7±0.2	35.0 × 35.0



- Injection of "Fake radio halos" to estimate GMRT flux density losses and constrain the spectral steepness

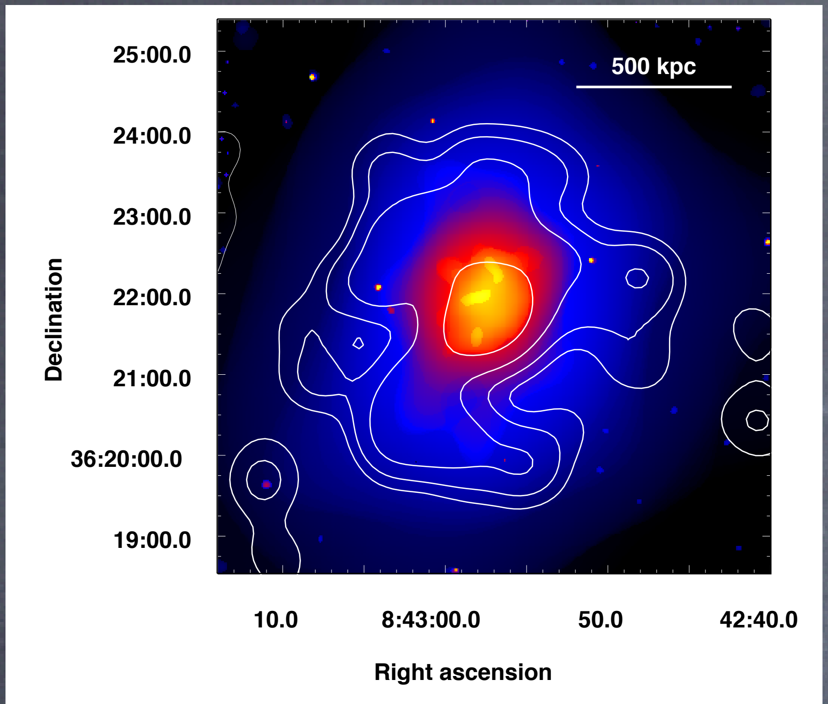
~20% losses => **"revised" spectrum**

A697 hosts another example of USSRHs (like A521)

Origin of the radio halo

14

Origin of the radio halo



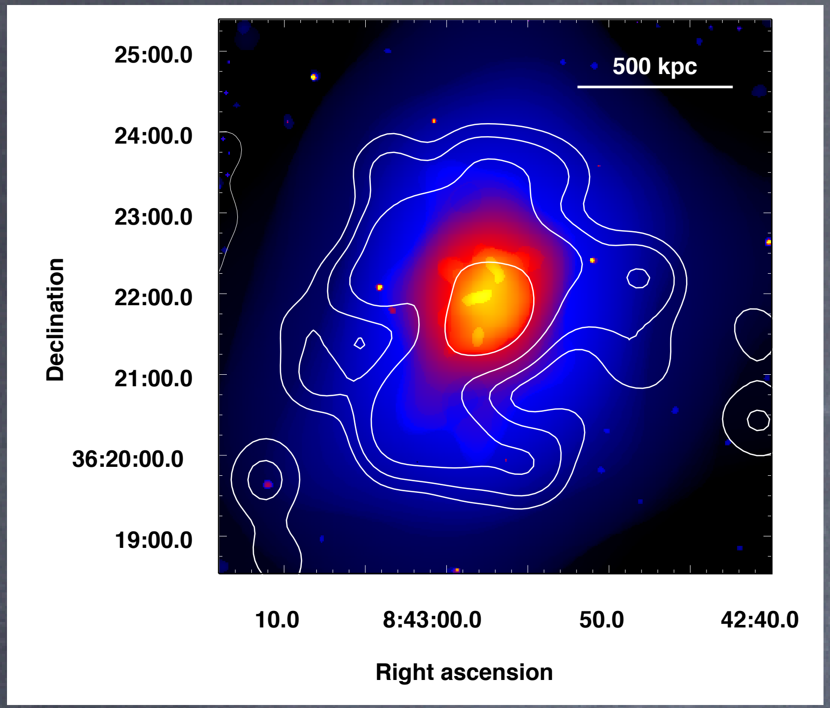
Giant RH LLS = 1.3 Mpc @327

Morphology similar to X-ray SB distribution

Chandra archive re-analysis favours a multiple merger scenario => **merger-halo connection**

327 MHz low res. contours on Chandra 0.5-9 keV (colours)

Origin of the radio halo

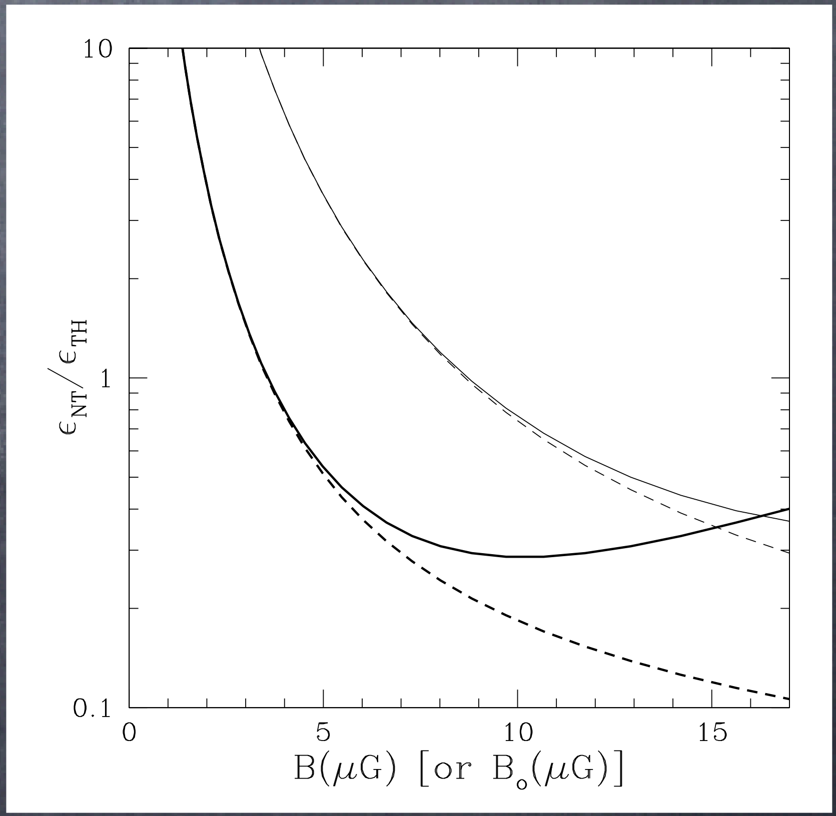


Giant RH LLS = 1.3 Mpc @327

Morphology similar to X-ray SB distribution

Chandra archive re-analysis favours a multiple merger scenario => **merger-halo connection**

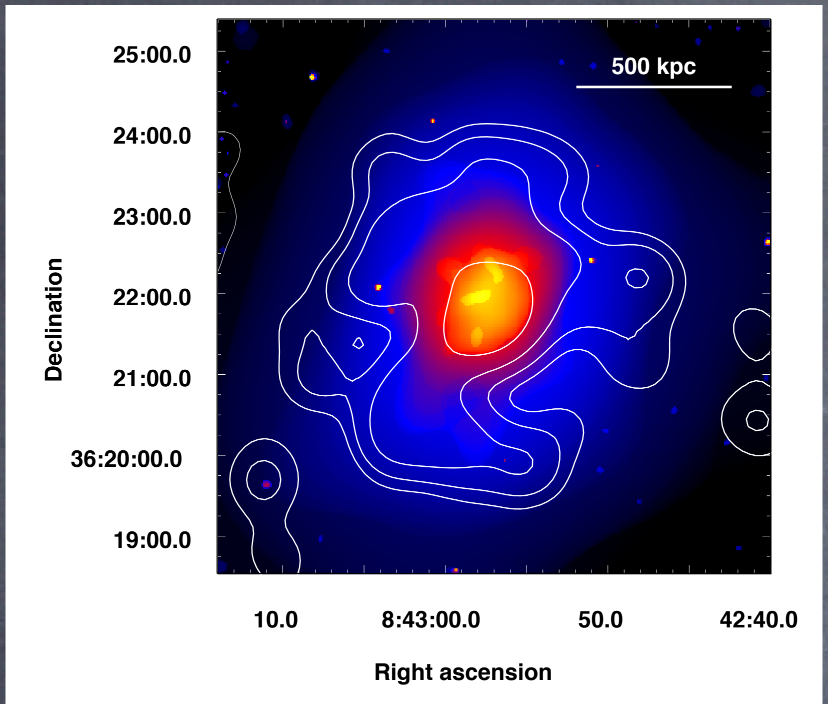
327 MHz low res. contours on Chandra 0.5-9 keV (colours)



theoretical implications of the very steep spectrum:

- unique expectation of the **re-acceleration** model
- hadronic (secondary) origin of the halo is **disfavored**! It would required an implausibly high p energy budget.

Origin of the radio halo



327 MHz low res. contours on Chandra 0.5-9 keV (colours)

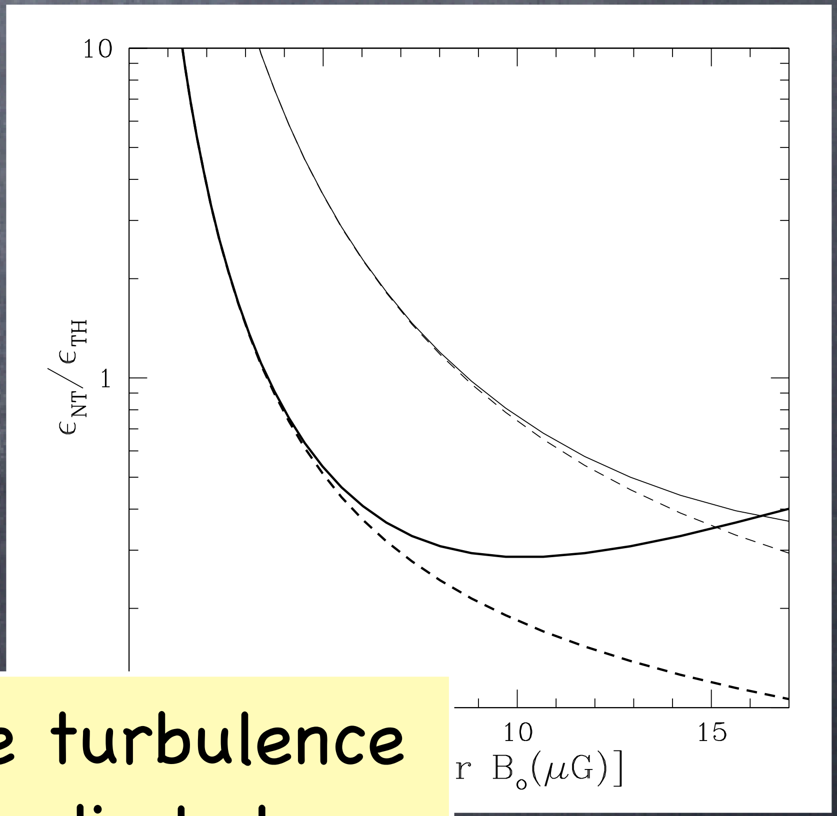
Giant RH LLS = 1.3 Mpc @327

Morphology similar to X-ray SB distribution

Chandra archive re-analysis favours a multiple merger scenario => **merger-halo connection**

theoretical implications of the very steep spectrum:

- unique expectation of the **re-acceleration** model
- hadronic (secondary) origin of the halo is **disfavored**! It would required an implausibly high p energy budget.



these results provide further support to the turbulence re-acceleration scenario for the origin of radio halos

II
"The shock front and the radio edge in the merging cluster Abell 754"

work in progress: **Macario et al., to be submitted to ApJ**

Abell 754: the prototype of a major merger

- nearby (z=0.05) hot, merging cluster

X -RAY (i.e. Henry & Briel 1995, Markevitch+ 2003, Henry+ 2004) and **optical** (Fabricant+ 1986, Zabludoff & Zaritzki 1995)

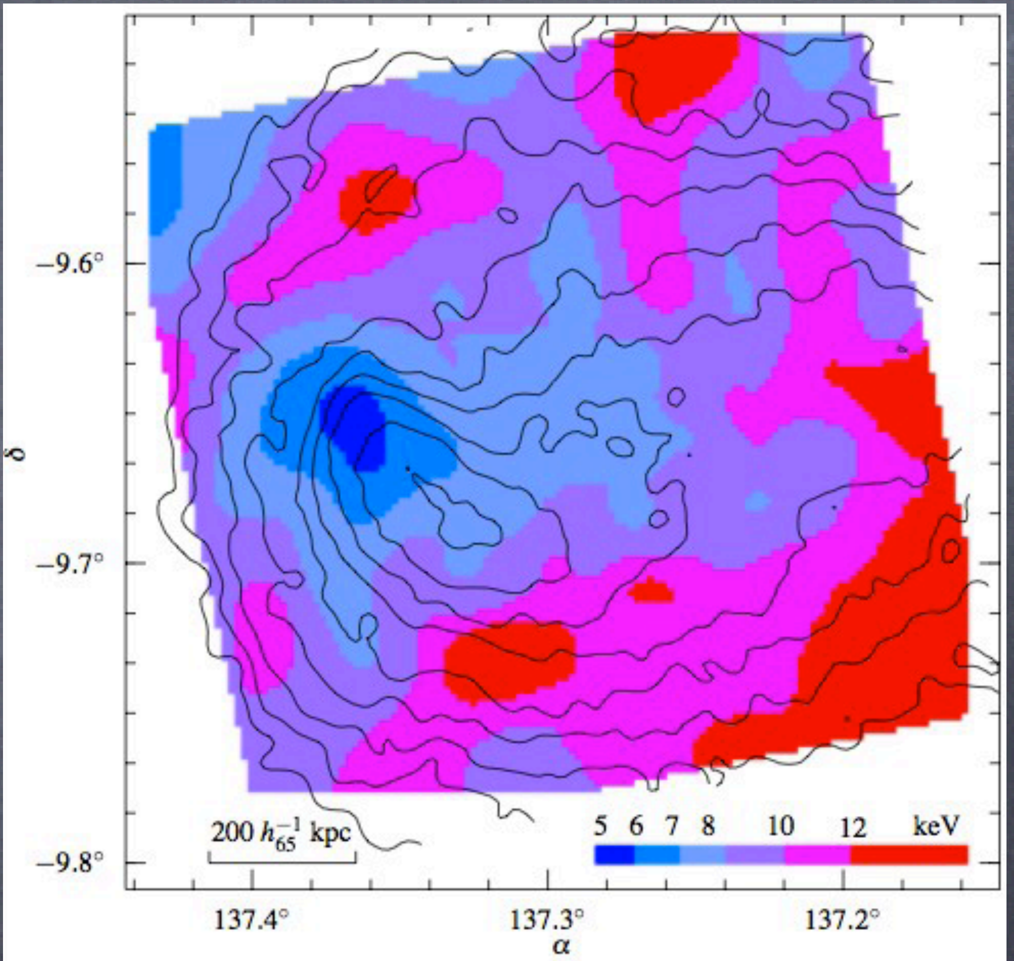
Abell 754: the prototype of a major merger

- nearby (z=0.05) hot, merging cluster

X -RAY (i.e. Henry & Briel 1995, Markevitch+ 2003, Henry+ 2004) and **optical** (Fabricant+ 1986, Zabludoff & Zaritzki 1995)

-2 (or more) sub-clusters **merging** along **W-E axis**

- **possible** presence of a **shock** front (Krivonos+ 2003, Henry+ 2004)



Chandra T map + ACIS 0.8-5 keV cont. (Markevitch+ 03)

Abell 754: the prototype of a major merger

- nearby (z=0.05) hot, merging cluster

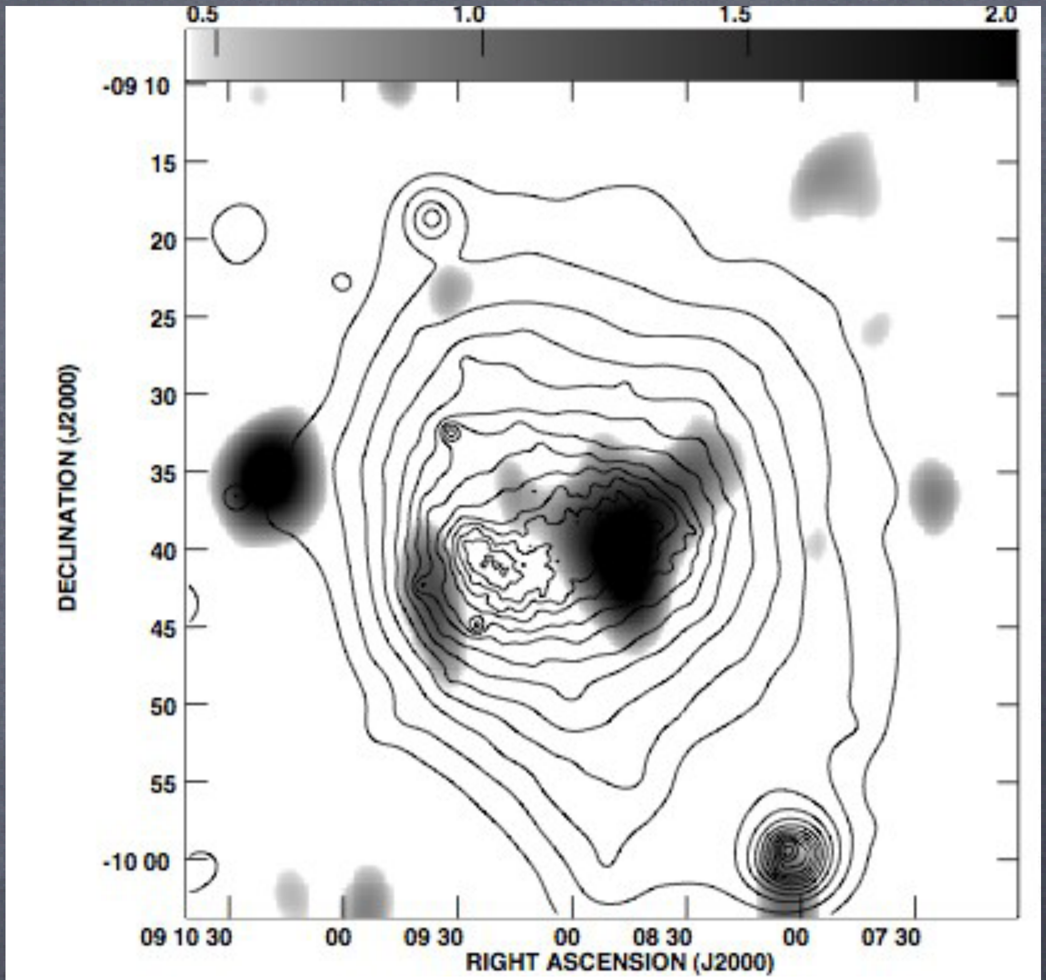
X -RAY (i.e. Henry & Briel 1995, Markevitch+ 2003, Henry+ 2004) and **optical** (Fabricant+ 1986, Zabludoff & Zaritzki 1995)

-2 (or more) sub-clusters **merging** along **W-E axis**

- **possible** presence of a **shock** front (Krivonos+ 2003, Henry+ 2004)

RADIO (Kassim+ 2001, Bacchi+ 2003, Kale+ 2009)

- **Radio halo** and **possible relic** detected at 74 and 1400 MHz

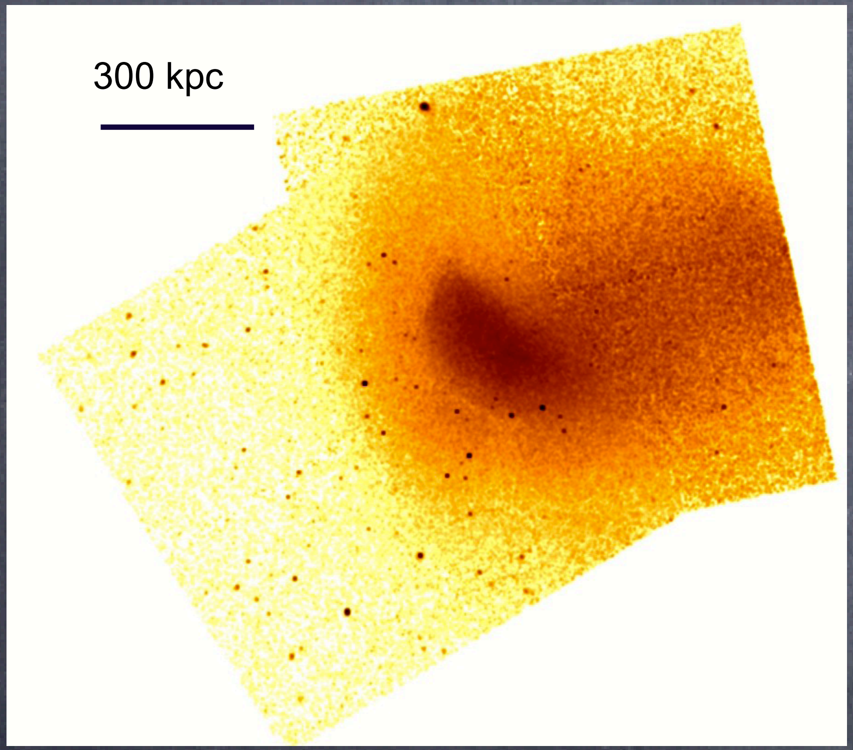


ROSAT **contours on VLA 74 MHz (Kassim+ 01)**

Abell 754: observations

X-ray Chandra

- Deep 95 ks (10743 obs)
- Arch. 39 ks (577 obs)

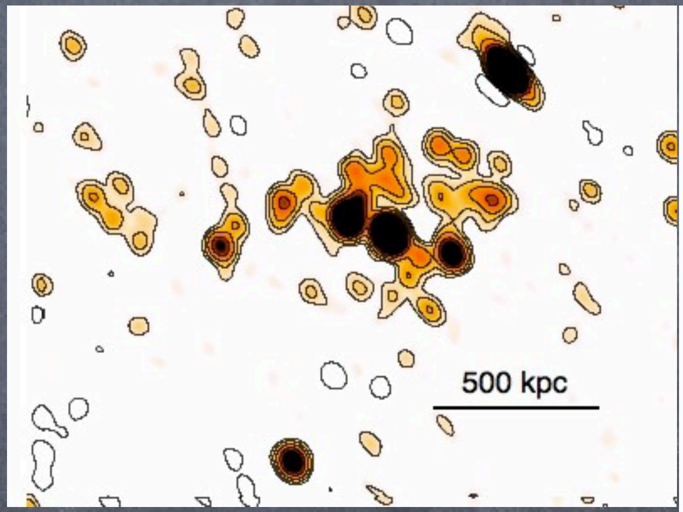


— Surface brightness profile
— Spectral analysis=>T

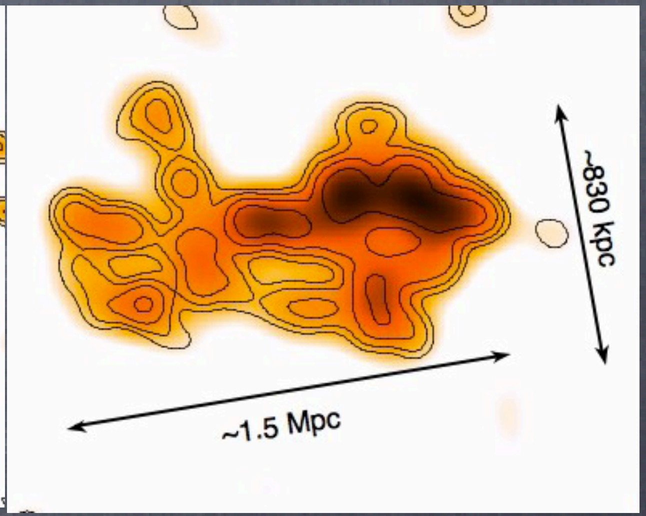
Radio

- GMRT 327 MHz, ~3 h
- Arch. VLA-D 1.4 GHz

+ 74 MHz image (Kassim+ 2001)



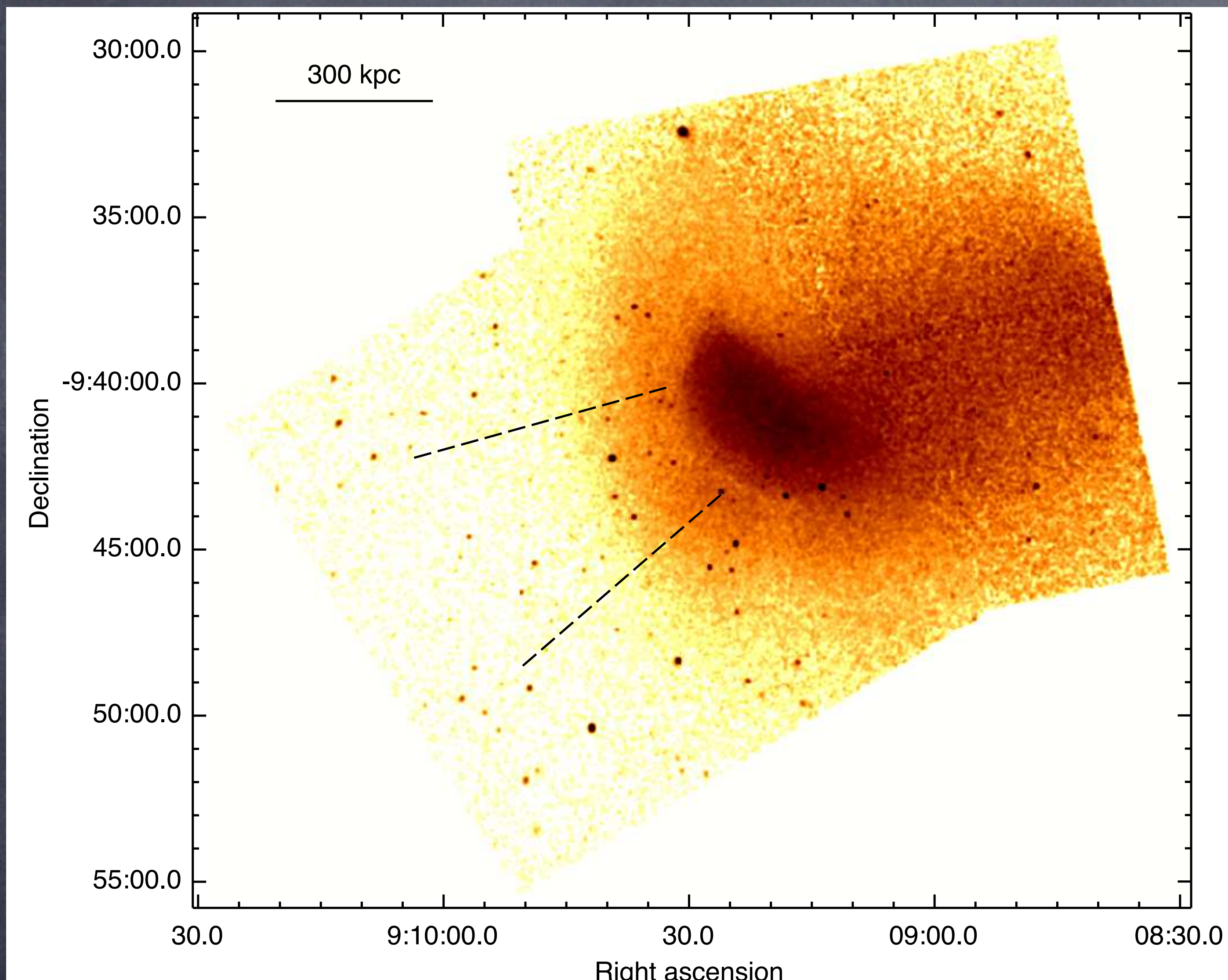
GMRT 327 MHz, Full res.



GMRT 327 MHz, ow res., sources subtracted

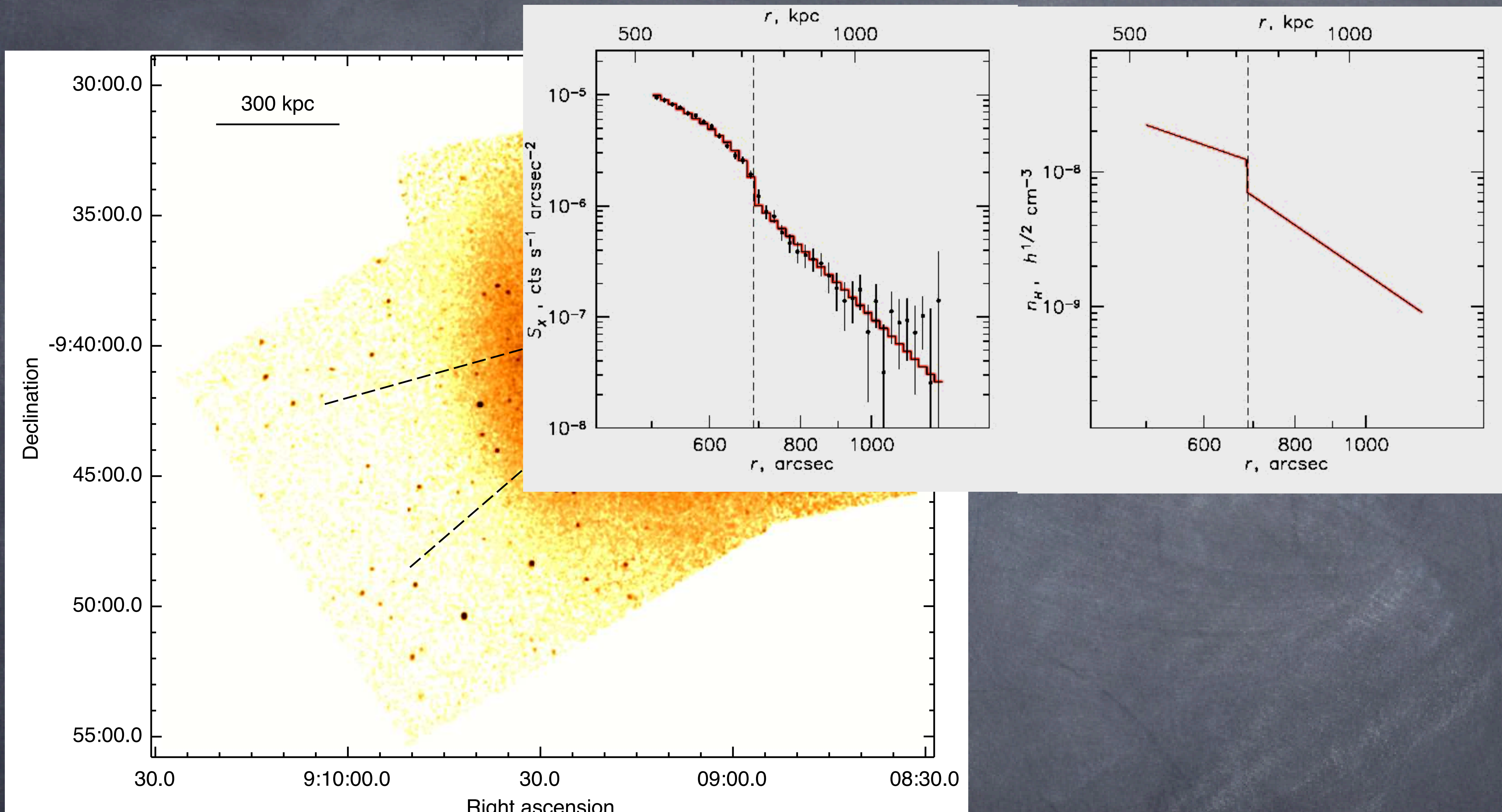
— Integrated radio spectrum of the diffuse emission

The shock front



Combined Chandra 95+39 ks, 0.5-4 keV

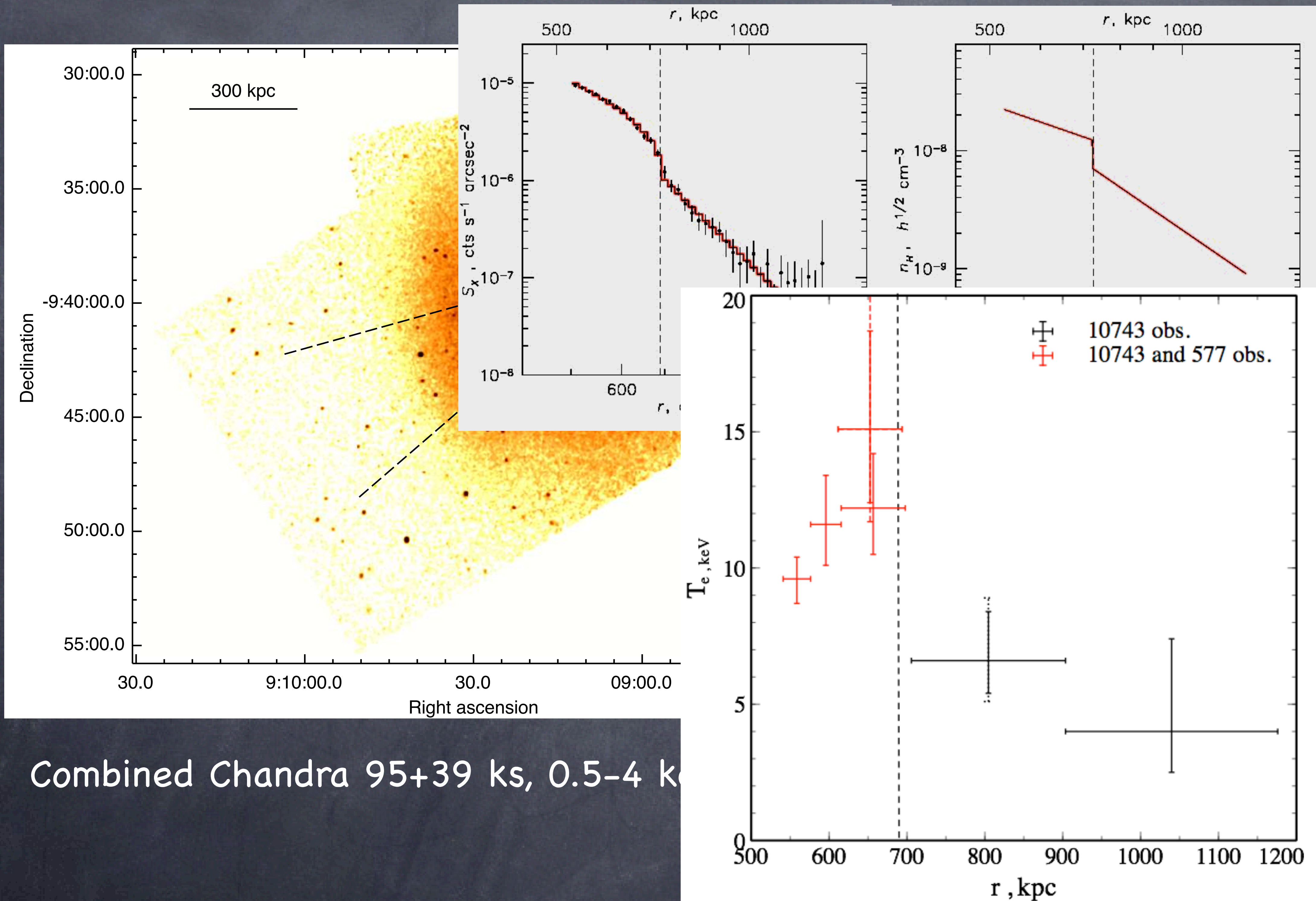
The shock front



$$\frac{\rho_2}{\rho_1} = 1.74^{+0.20}_{-0.14}$$

Combined Chandra 95+39 ks, 0.5-4 keV

The shock front

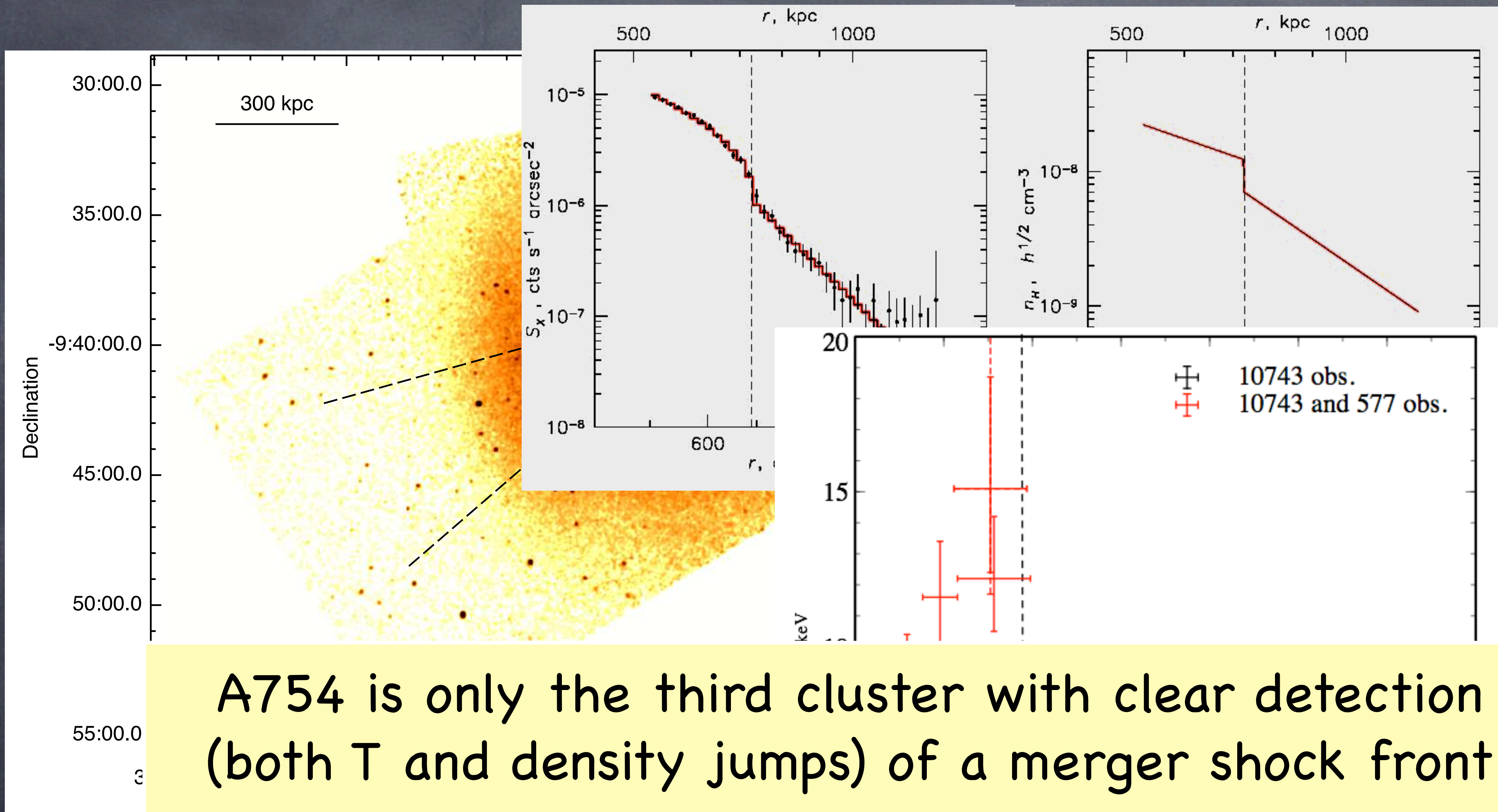


$$\frac{\rho_2}{\rho_1} = 1.74^{+0.20}_{-0.14}$$

$$\frac{T_2}{T_1} = 2.3 \pm 1.8$$

Combined Chandra 95+39 ks, 0.5-4 k

The shock front



$$\frac{\rho_2}{\rho_1} = 1.74^{+0.20}_{-0.14}$$

$$\frac{T_2}{T_1} = 2.3 \pm 1.8$$

Combi

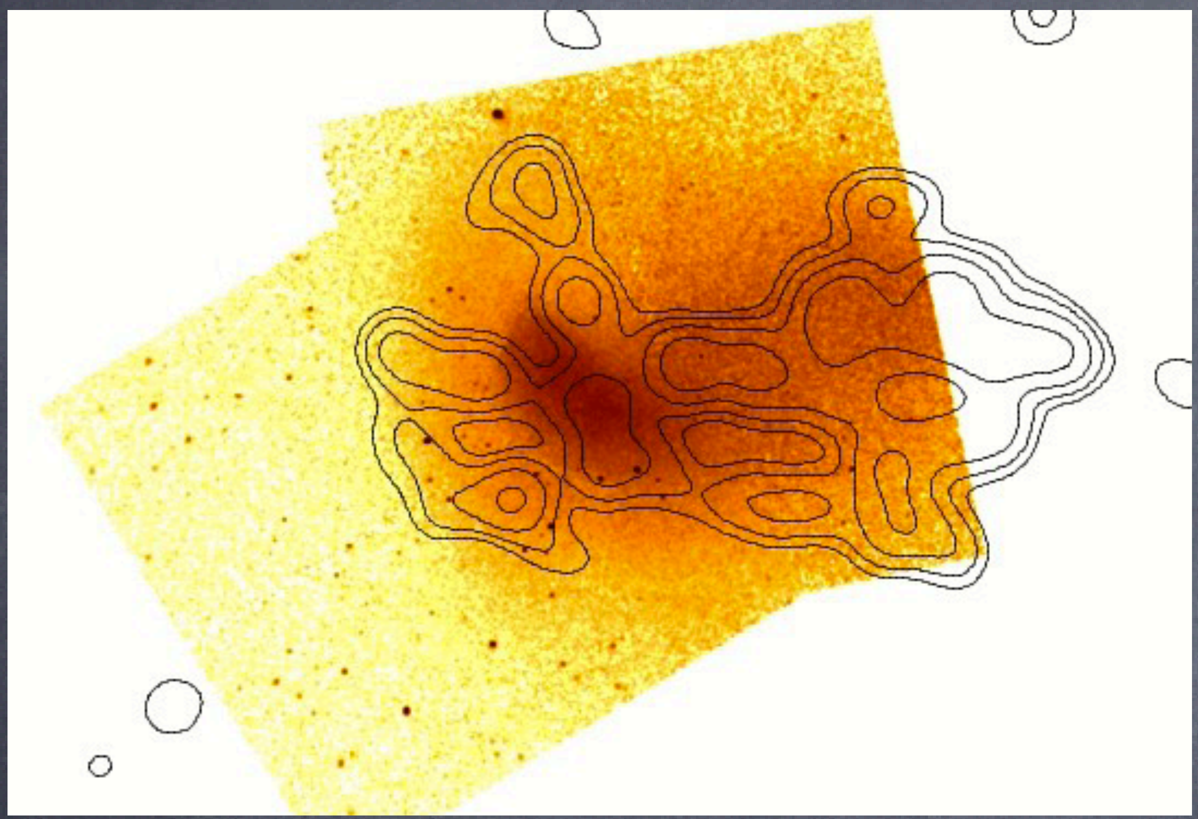
A754 is only the third cluster with clear detection (both T and density jumps) of a merger shock front

$$M = 1.52^{+0.14}_{-0.10}$$ Mach number

$$v_2 \simeq 1100 \text{ km/s}, \ v_1 \simeq 1900 \text{ km/s}$$ Velocities in the shock frame

Radio edge at the shock

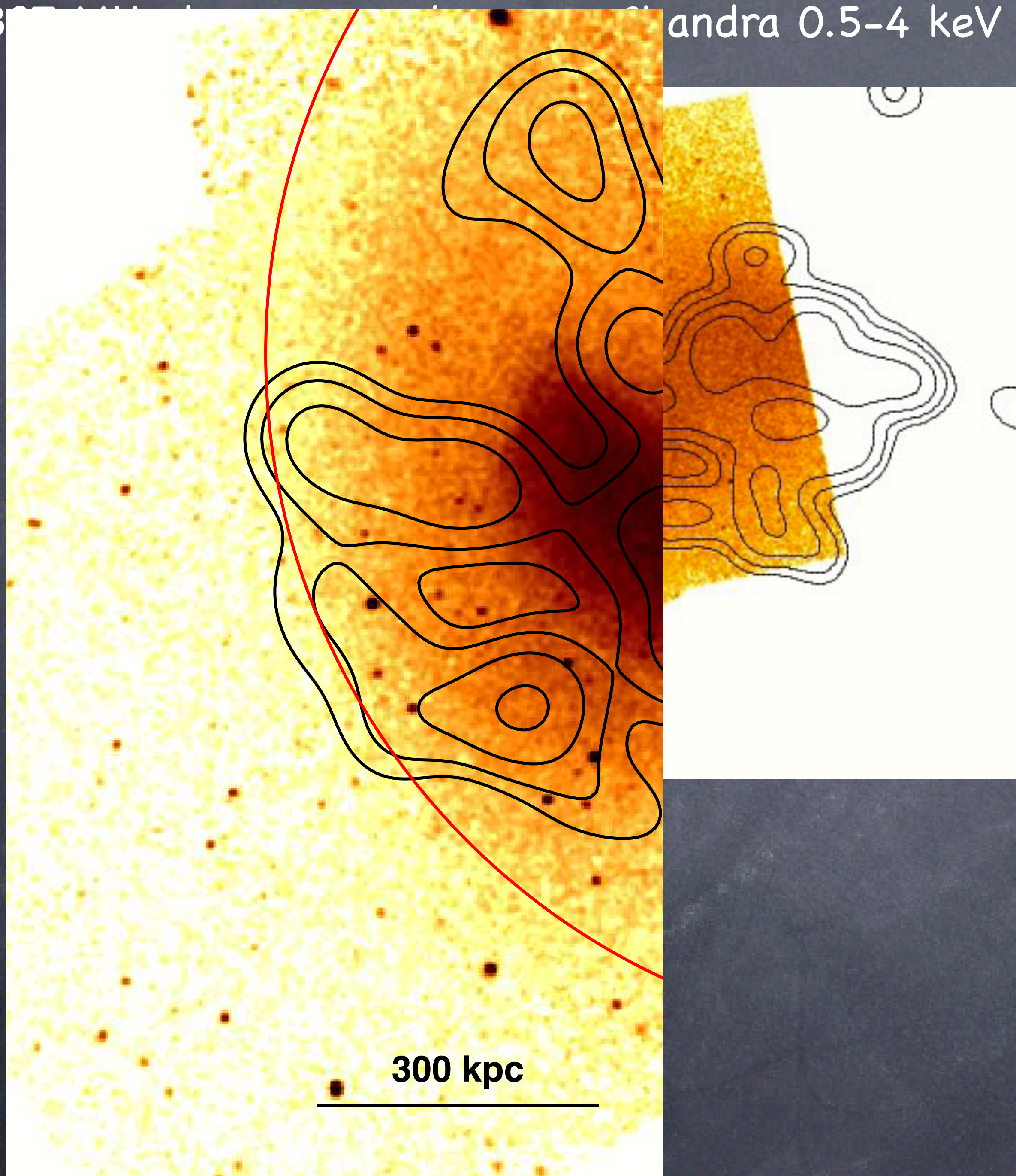
327 MHz low res. contours on Chandra 0.5-4 keV



19

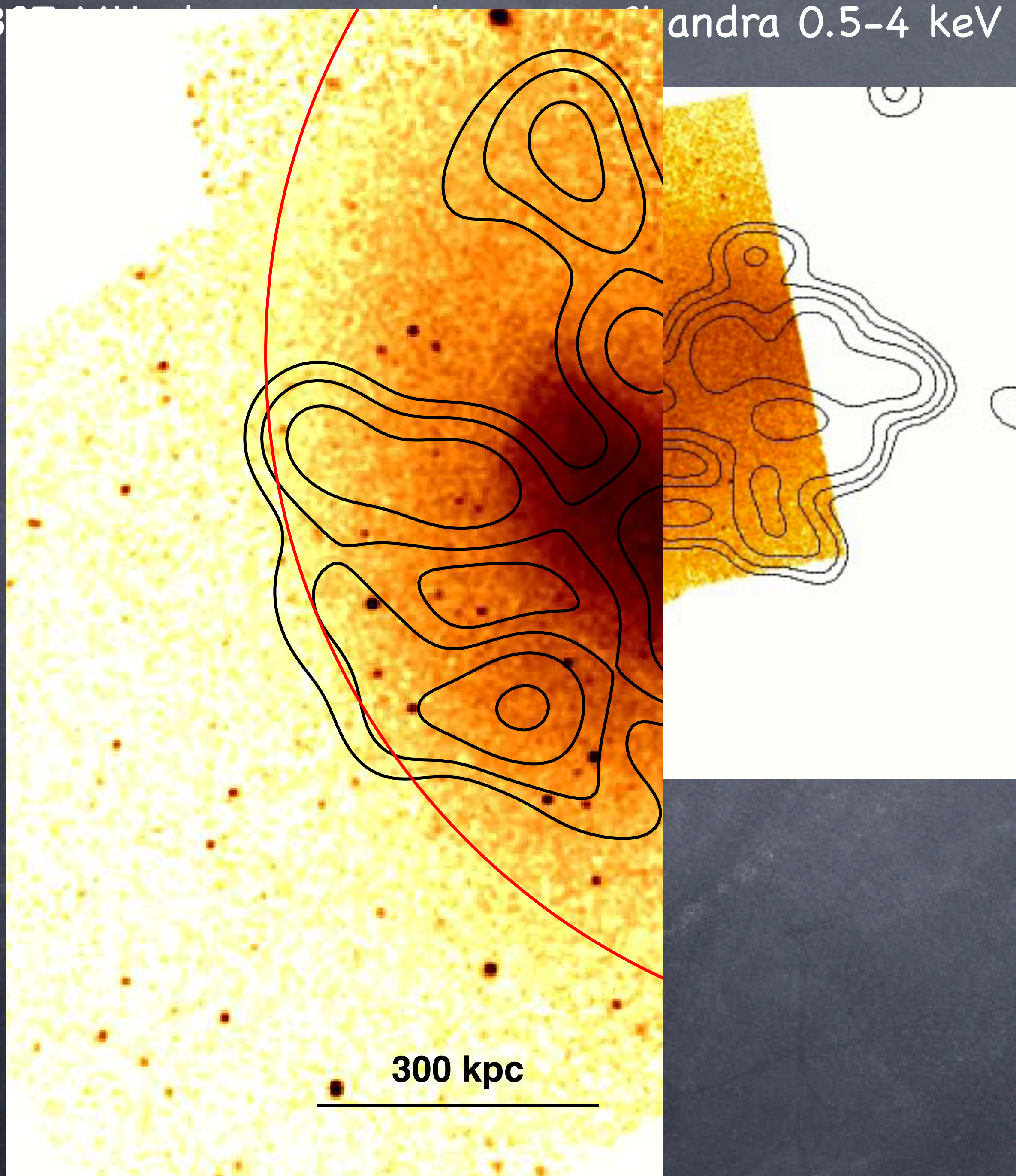
Radio edge at the shock

3 andra 0.5-4 keV

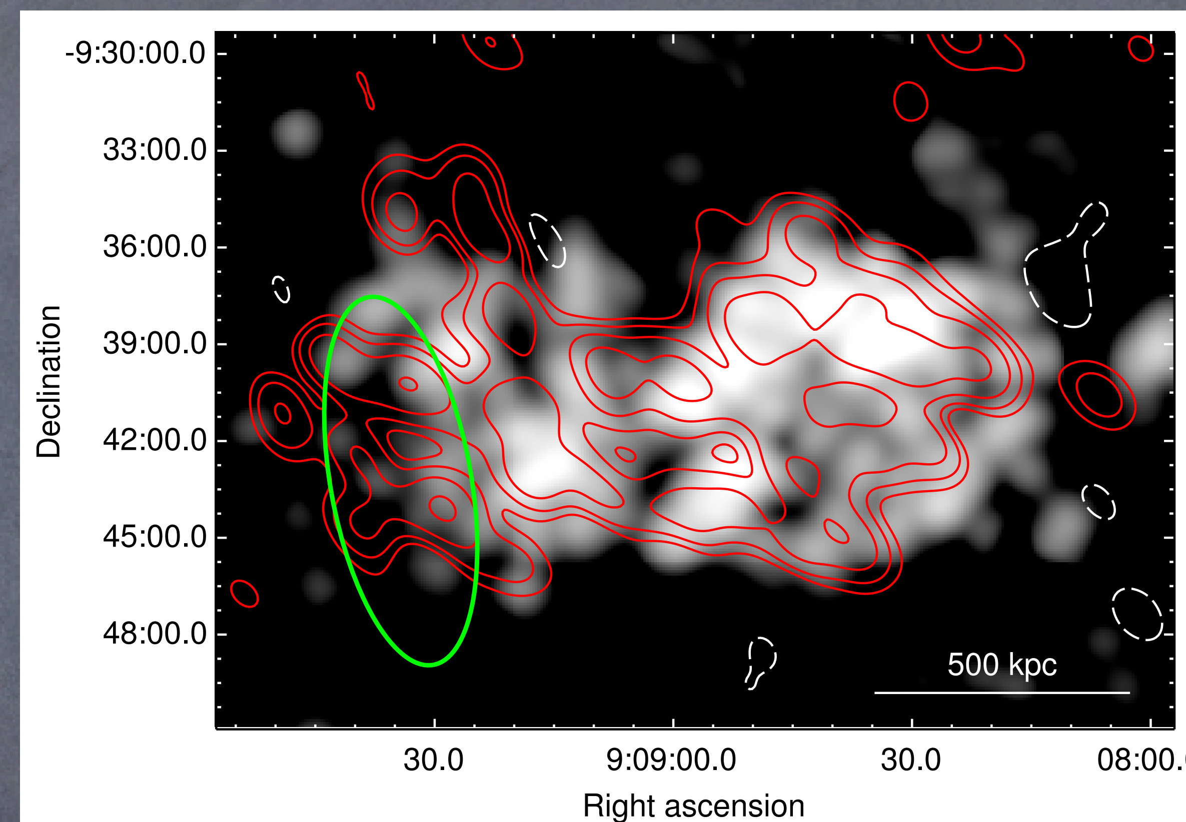


Radio edge at the shock

3 … andra 0.5-4 keV

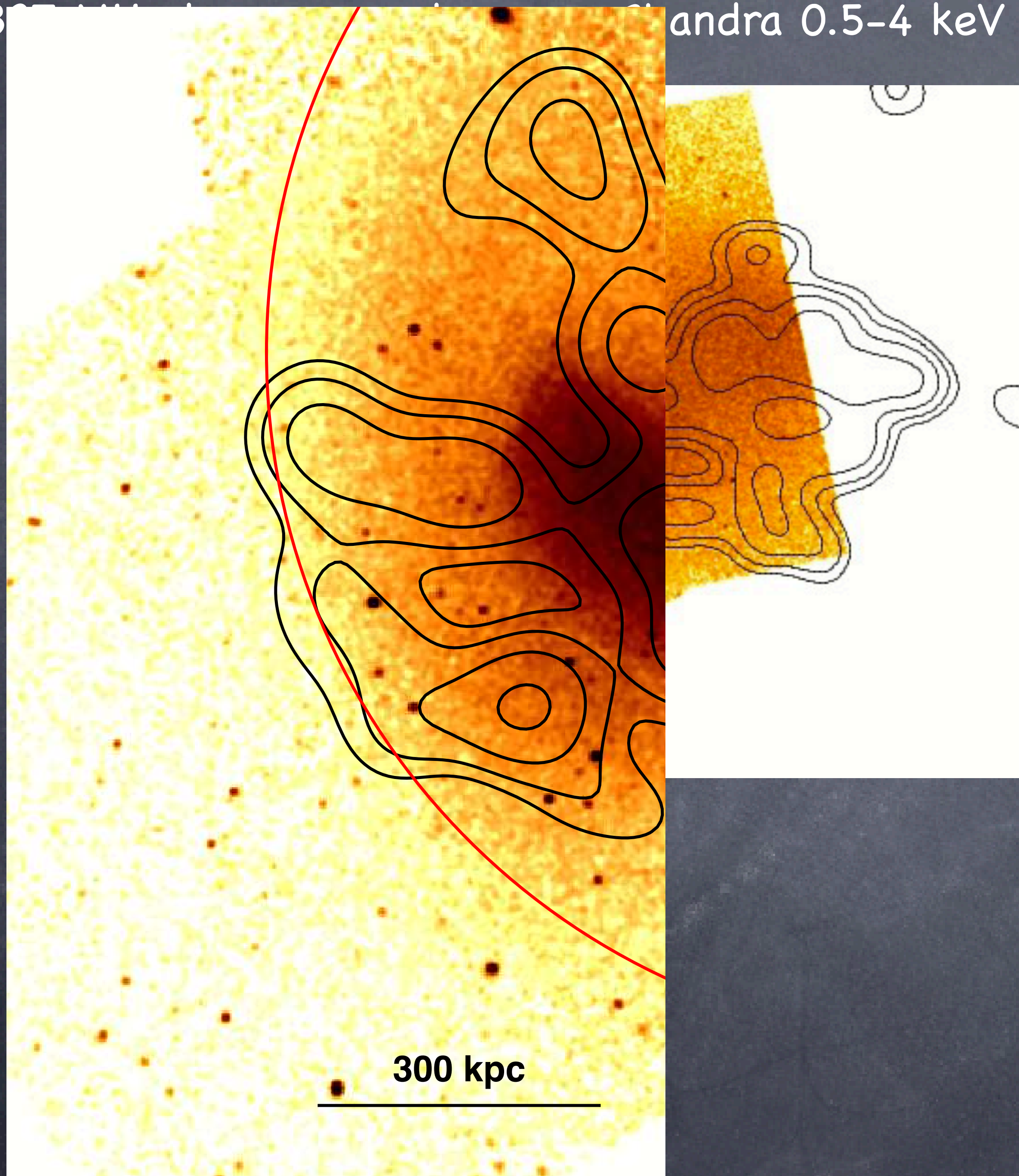


327 MHz cont. on 1.4 GHz image; green Kassim relic

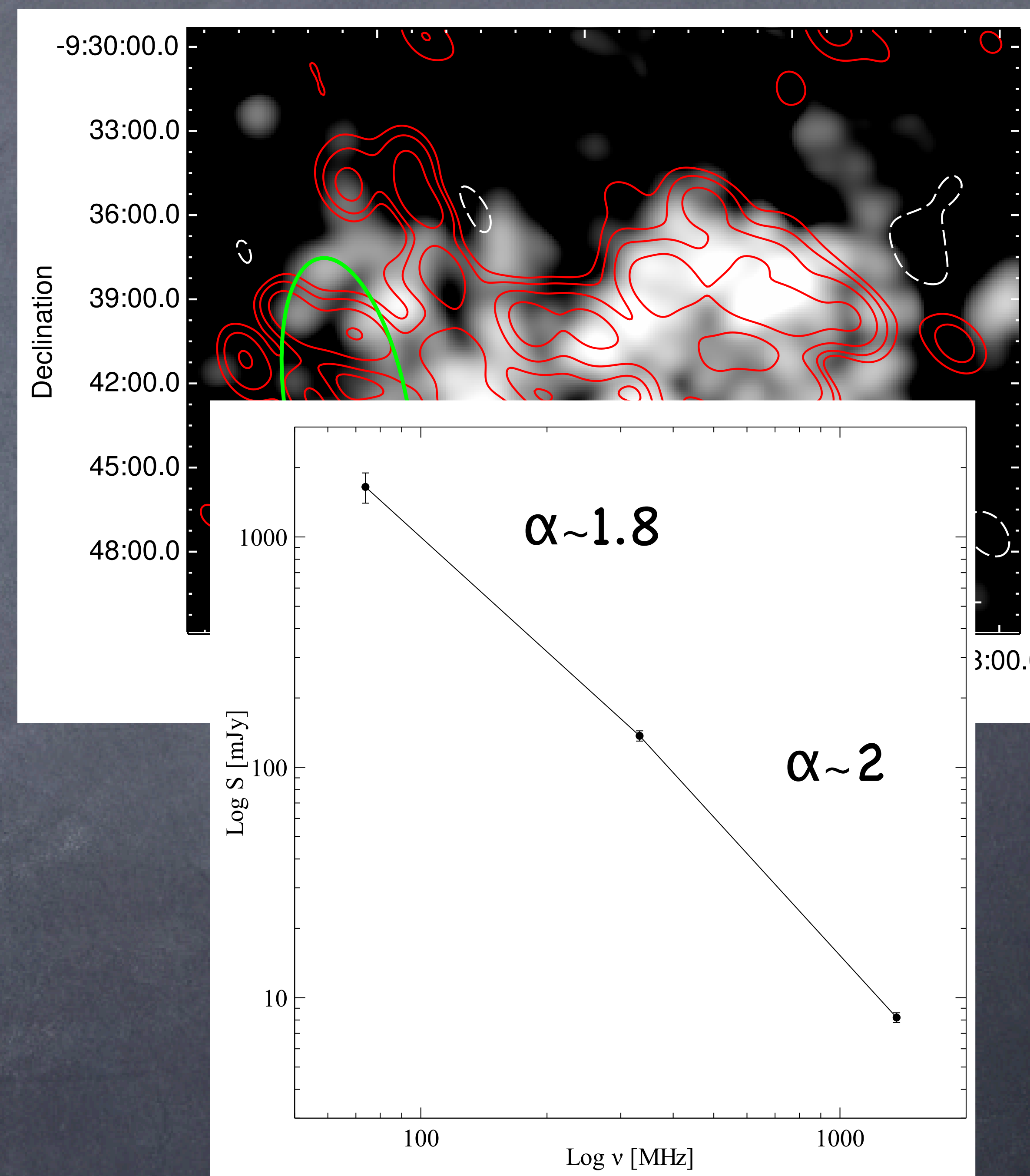


Radio edge at the shock

3 … andra 0.5-4 keV

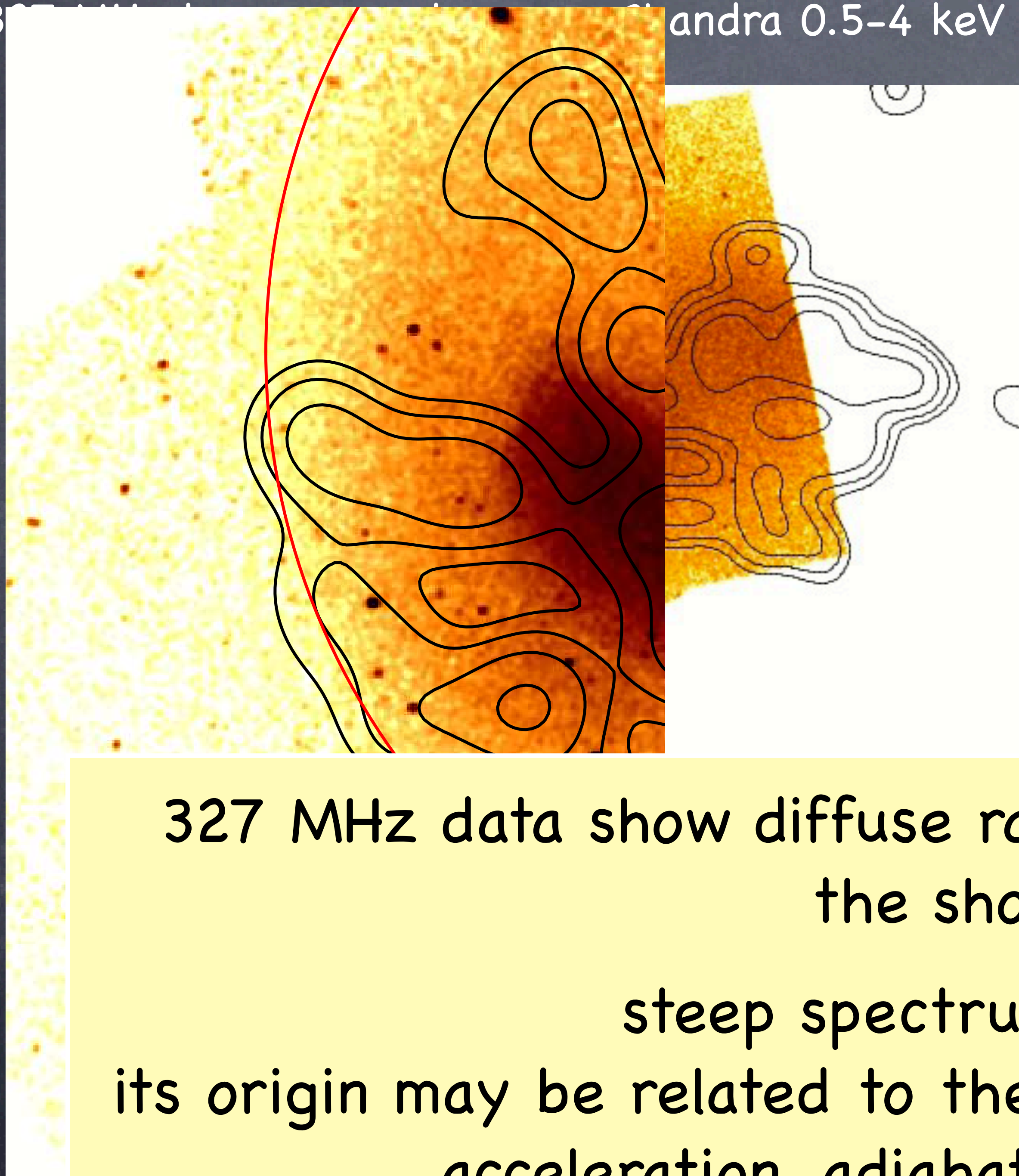


327 MHz cont. on 1.4 GHz image; green Kassim relic

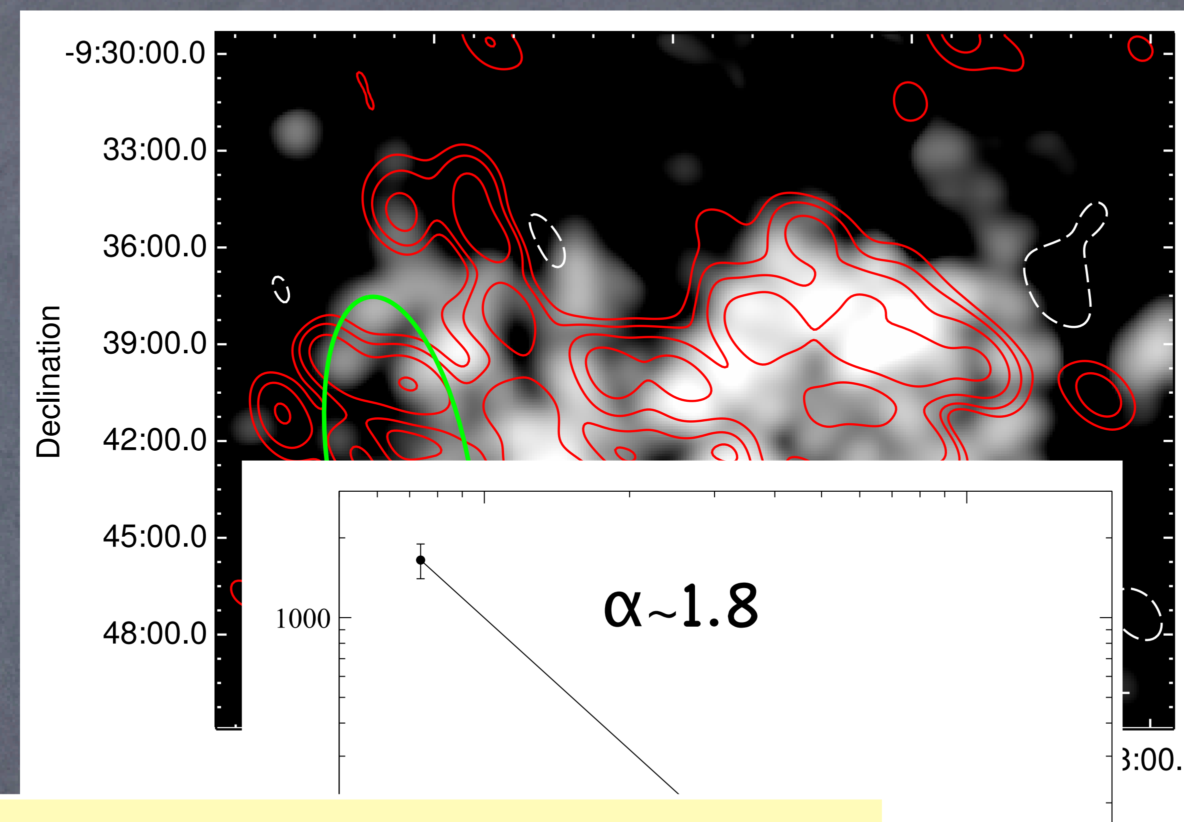


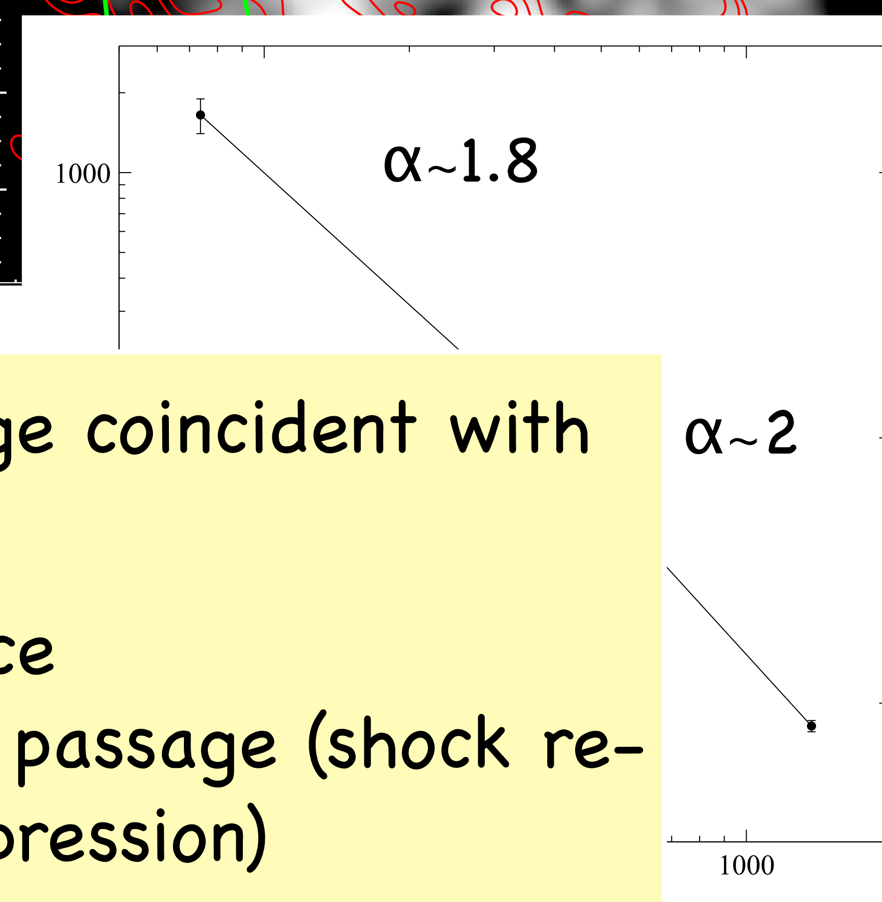
Radio edge at the shock

3 … andra 0.5-4 keV



327 MHz cont. on 1.4 GHz image; green Kassim relic





327 MHz data show diffuse radio edge coincident with the shock

steep spectrum source
its origin may be related to the shock passage (shock re-acceleration, adiabatic compression)

Summary and future work

1. Discovery of the very steep spectrum radio halo in **A697**. Strong support to the turbulence re-acceleration scenario for the origin of radio halos.

   - to constrain the spectrum: follow up study @ 150 MHz (GMRT) and 1.4-1.8 GHz (EVLA-D) in progress

2. Unambiguous detection of the merger shock front in **A754**; a radio edge with steep spectrum coincident with the front suggest that its origin is likely related to the shock passage.

   - new deep GMRT obs. at 150, 240, 327 MHz just required

Summary and future work

1. Discovery of the very steep spectrum radio halo in **A697**. Strong support to the turbulence re-acceleration scenario for the origin of radio halos.

   - to constrain the spectrum: follow up study @ 150 MHz (GMRT) and 1.4-1.8 GHz (EVLA-D) in progress

2. Unambiguous detection of the merger shock front in **A754**; a radio edge with steep spectrum coincident with the front suggest that its origin is likely related to the shock passage.

   - new deep GMRT obs. at 150, 240, 327 MHz just required

GMRT low frequency follow up of clusters with diffuse halo/relic (or candidate) emission from the GMRT RH survey is ongoing

Summary and future work

1. Discovery of the very steep spectrum radio halo in **A697**. Strong support to the turbulence re-acceleration scenario for the origin of radio halos.

   - to constrain the spectrum: follow up study @ 150 MHz (GMRT) and 1.4-1.8 GHz (EVLA-D) in progress

2. Unambiguous detection of the merger shock front in **A754**; a radio edge with steep spectrum coincident with the front suggest that its origin is likely related to the shock passage.

   - new deep GMRT obs. at 150, 240, 327 MHz just required

GMRT low frequency follow up of clusters with diffuse halo/relic (or candidate) emission from the GMRT RH survey is ongoing

Involved in the LOFAR survey key project (clusters WG)... **LOFAR is the future!**

Thanks...for being patient!

21