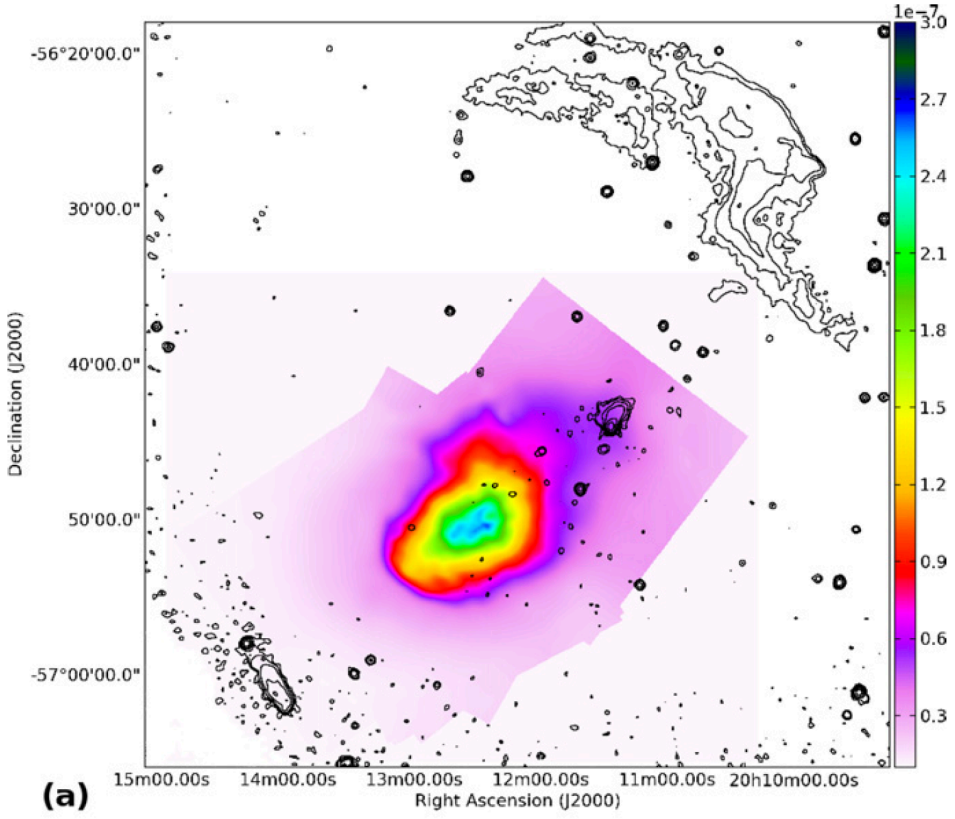
# Clusters of Galaxies – Recent X-ray/ Radio Results

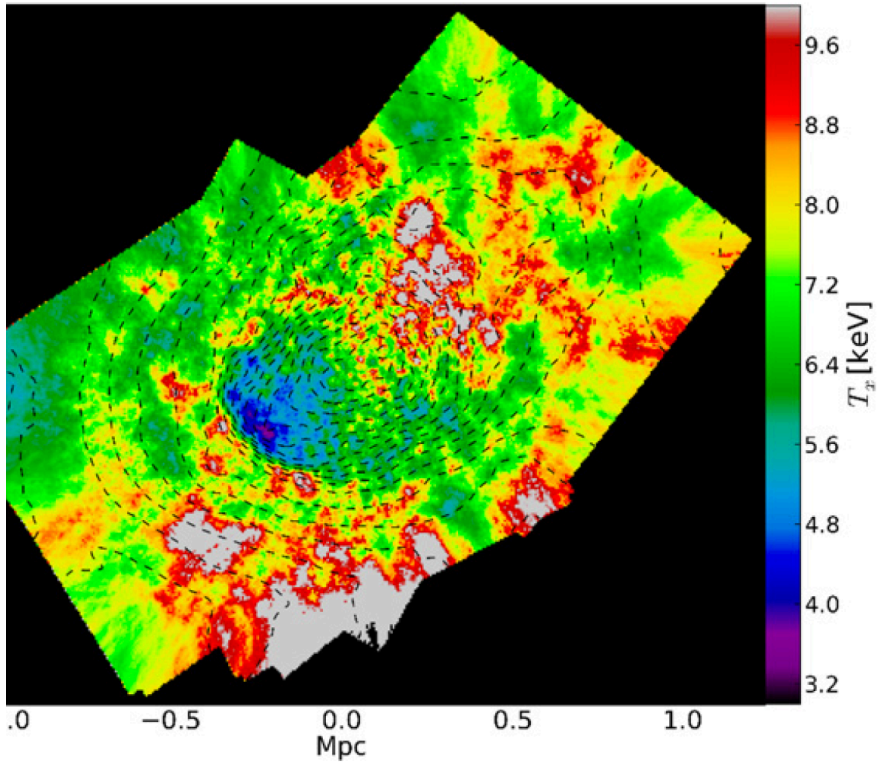
Ramij Raja, Majidul Rahman
and Abhirup Datta (IIT Indore)

**Collaborators:** Jack Burns, B. Alden (U. of Colorado),
Surajit Paul (SPPU), R. van Weeren (Leiden), H. Intema (Curtin), D. Rapetti (NASA, Ames), Pritpal Kaur (IIT, Kanpur), S. Malu (IIT Indore)

# Abell 3667 (z=0.055)

Datta et al. (2014)

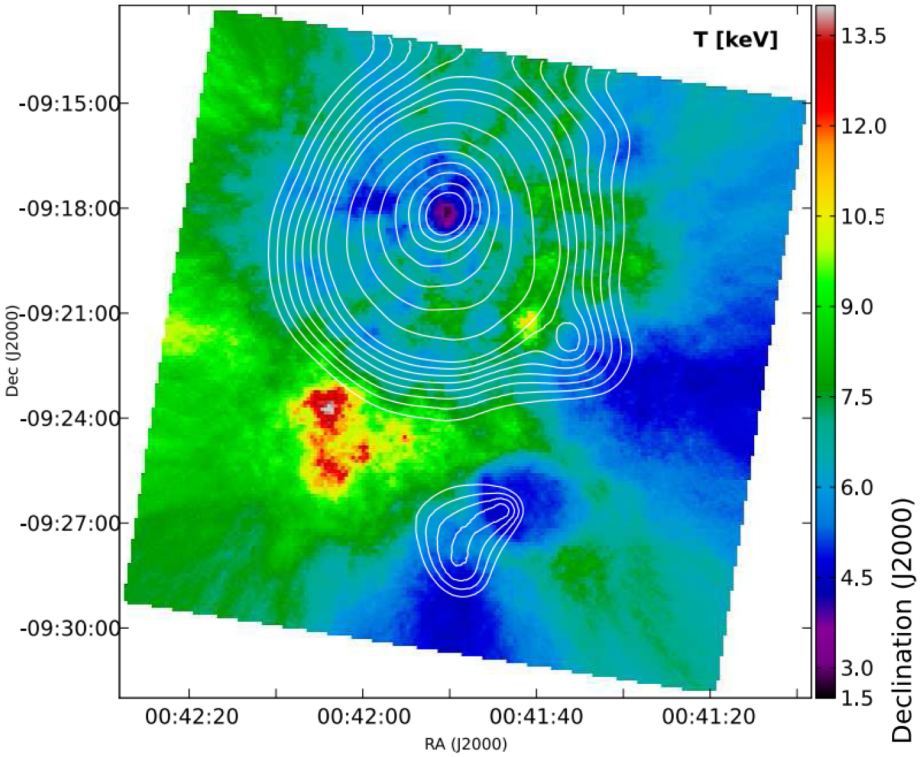


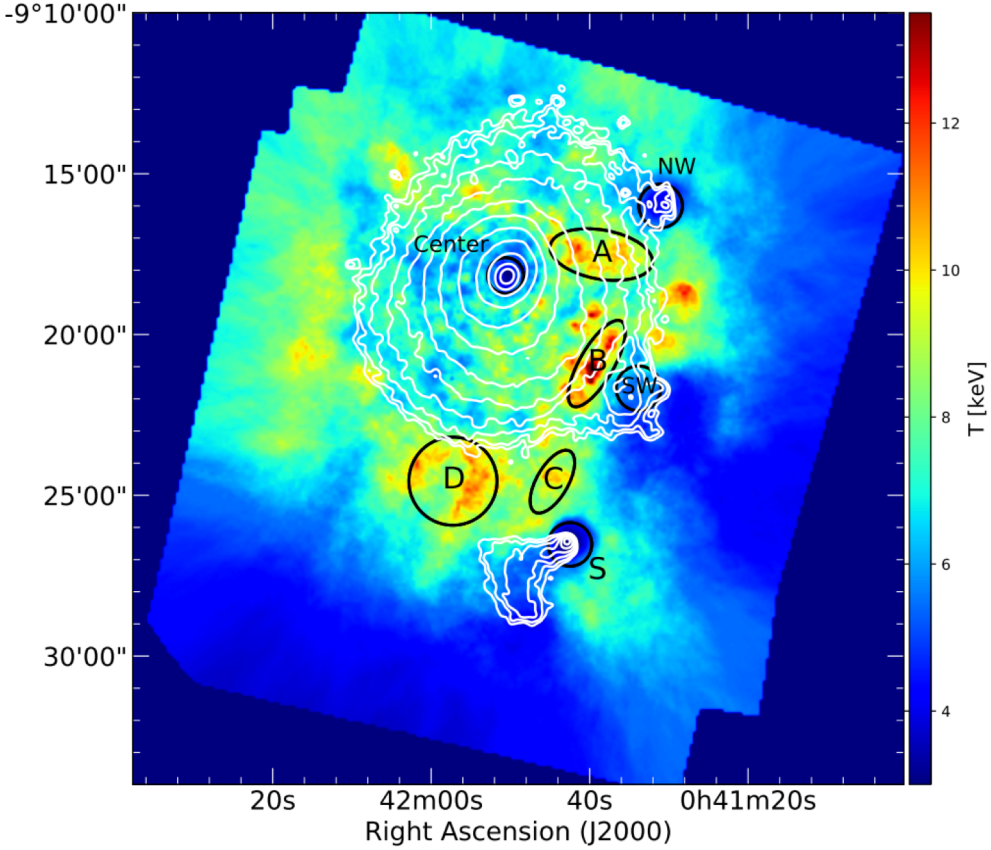

Radio results overlayed from Rottgering et al. (1997)
RMS noise ~ 0.3 – 0.7 mJy/bm at 18 and 20 cms

# Abell 85 (z=0.055)

MAJIDUL RAHAMAN
PhD scholar, IIT
Indore




Chandra temperature map by
**Schenck et al. 2014**



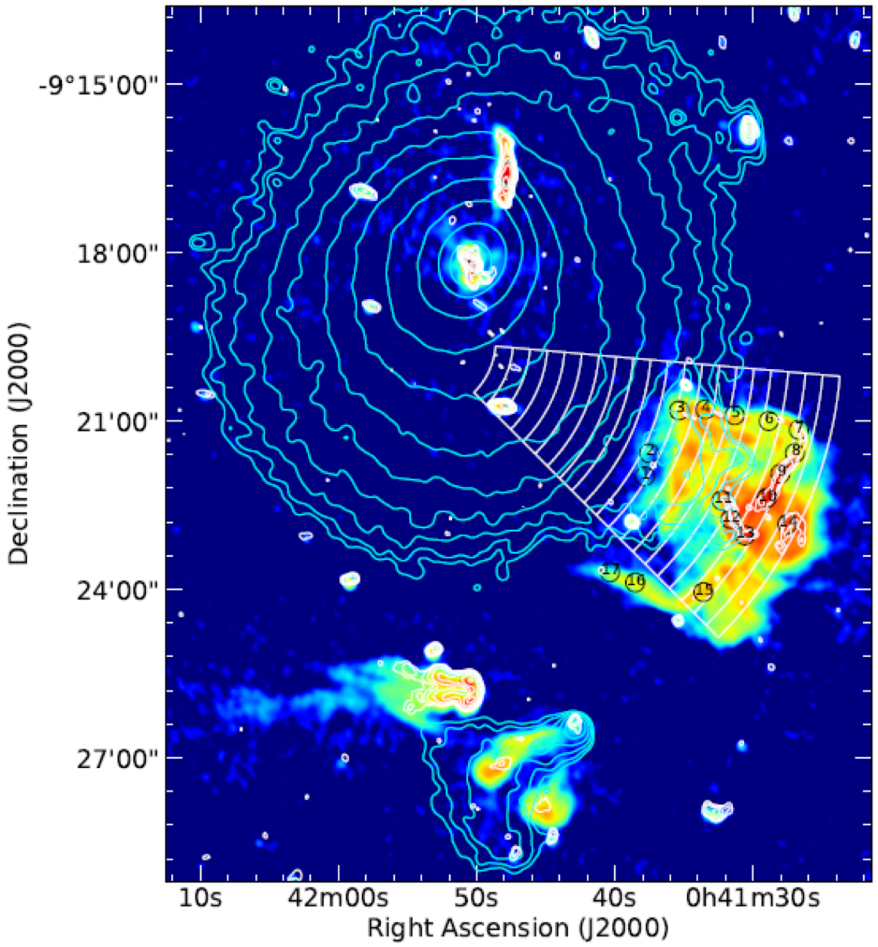

Chandra temperature map

Rahman et al. 2019b (in prep.)

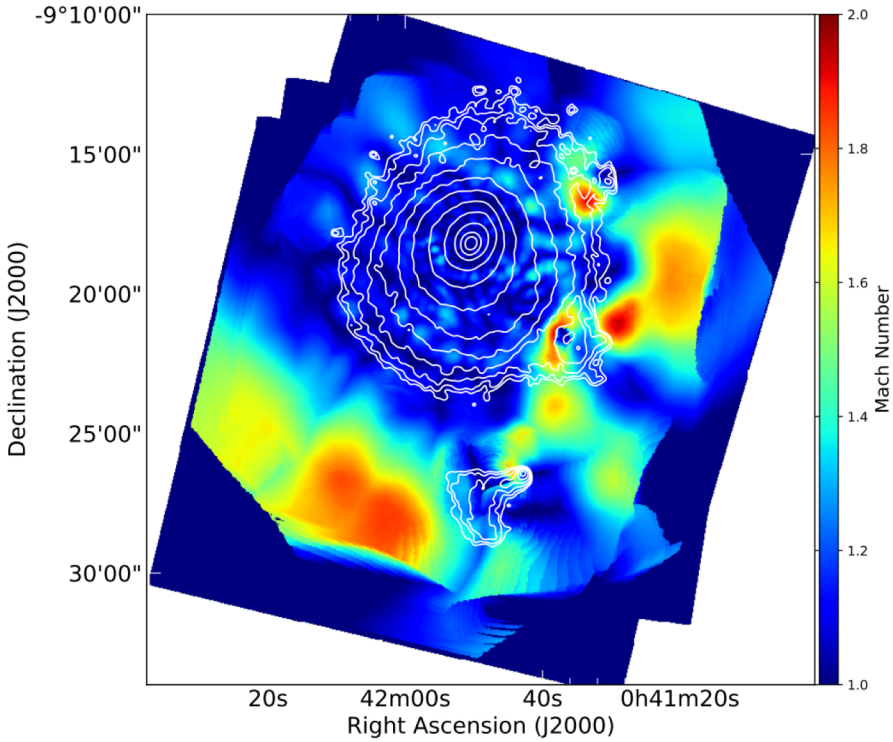
Better temperature map of the A85 cluster, showing disturbances in the ICM and prominent shock feature (region B)

# Abell 85

Rahman et al. 2019b (in prep.)




325 MHz GMRT observation of the A85 cluster shows the complex diffuse structure of the "presumed radio relic" shown with the 1.4 GHz white contours (Schenck et al. 2014).




Mach number map of the A85 cluster reveals the "bow shock" in front of the infalling south-west subcluster.

# SPT-CL cluster sample

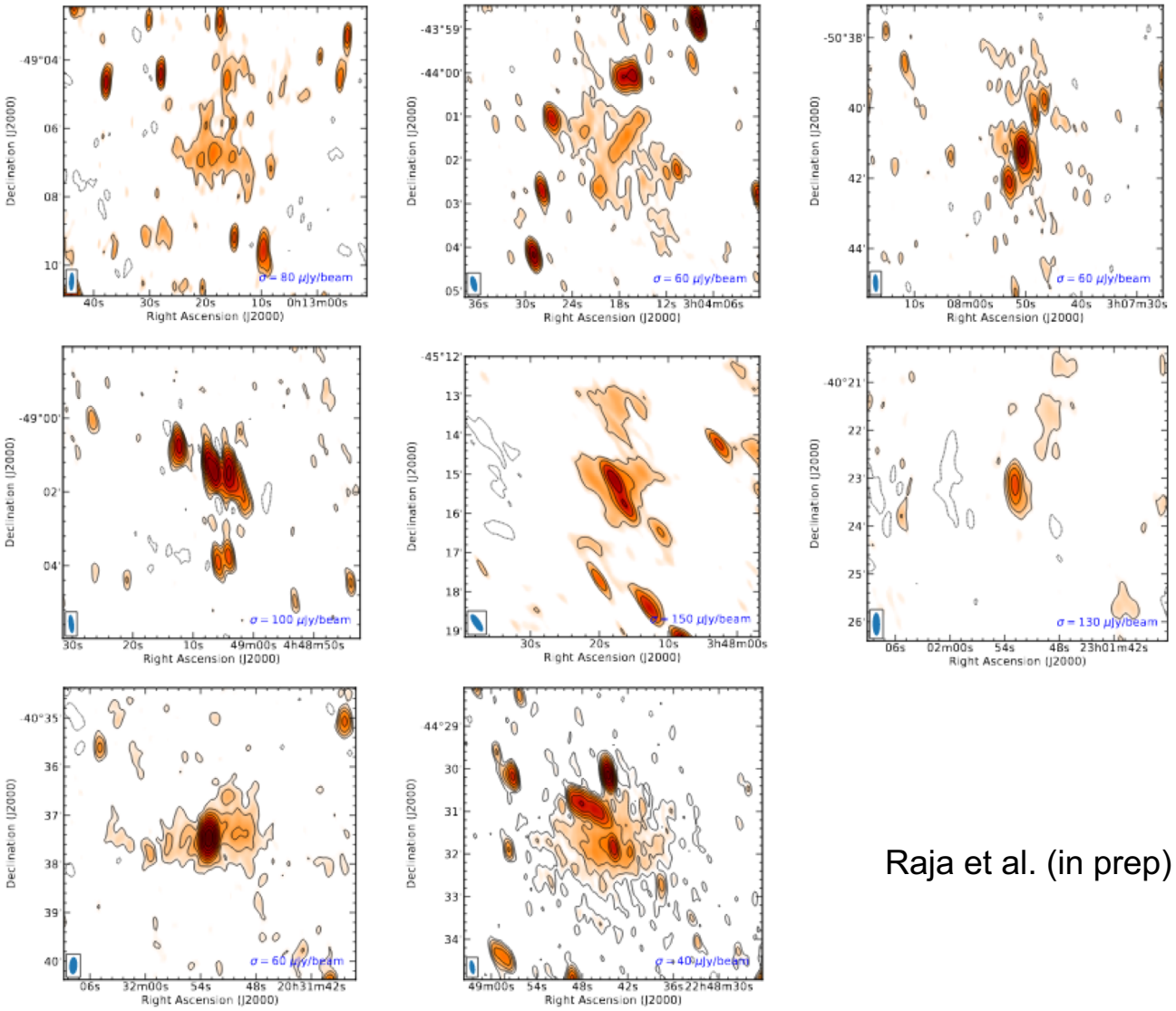


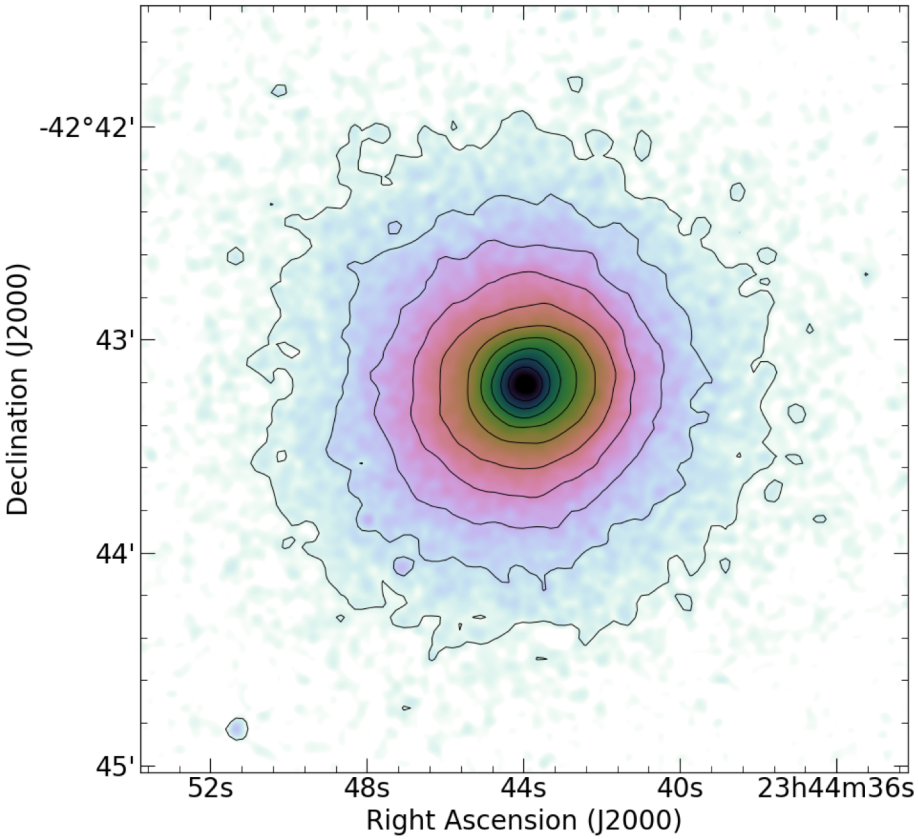

Figure 3: Detection of diffuse radio emission in the clusters observed during cycle 26 and 27. These are 8 clusters that host diffuse radio emission in a total of 18 observed clusters. (Raja+ in prep.)

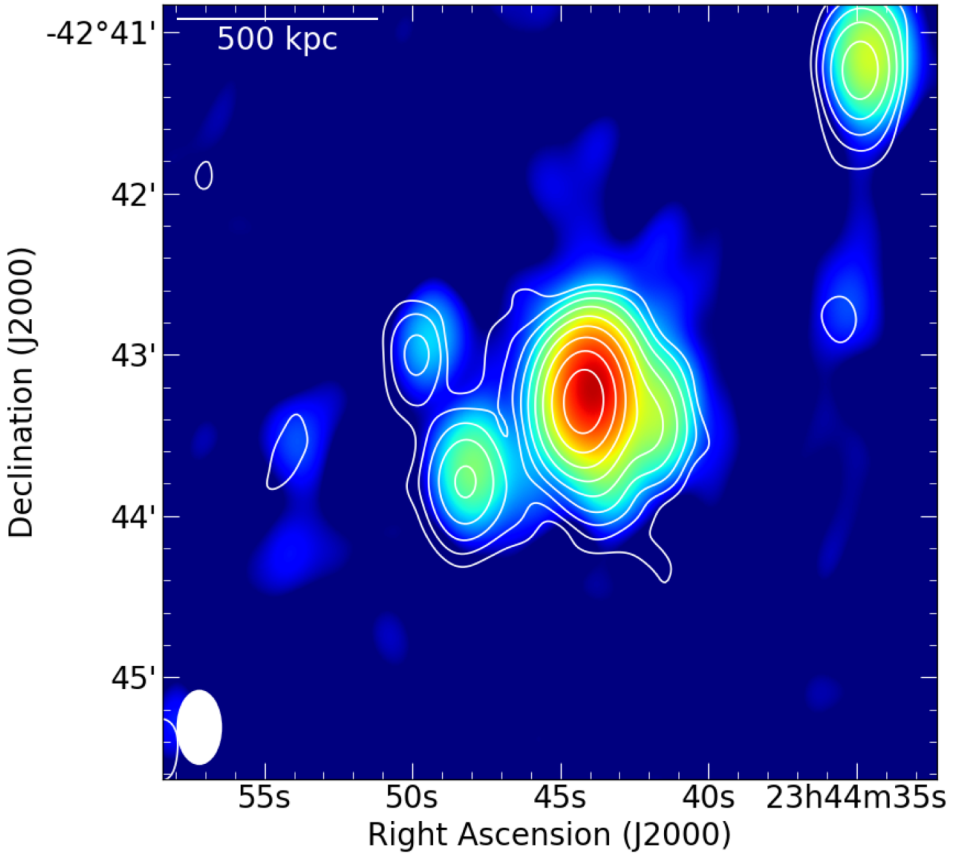
Raja et al. (in prep)

RAMIJ RAJA
PhD scholar, IIT Indore

1. GMRT 325 MHz observations of 18 SPT-CL clusters which resulted in the discovery of 8 new diffuse radio source.
2. A sub-sample of these was observed with the EVLA in L-band.
3. Multi-frequency analysis of two of the clusters are presented below.

# Phoenix Cluster




- Relaxed cool core cluster
- It's a massive cluster with $Mass = 12.6 \times 10^{14}\ M_{\odot}$
- Most X-ray luminous cluster in the Universe

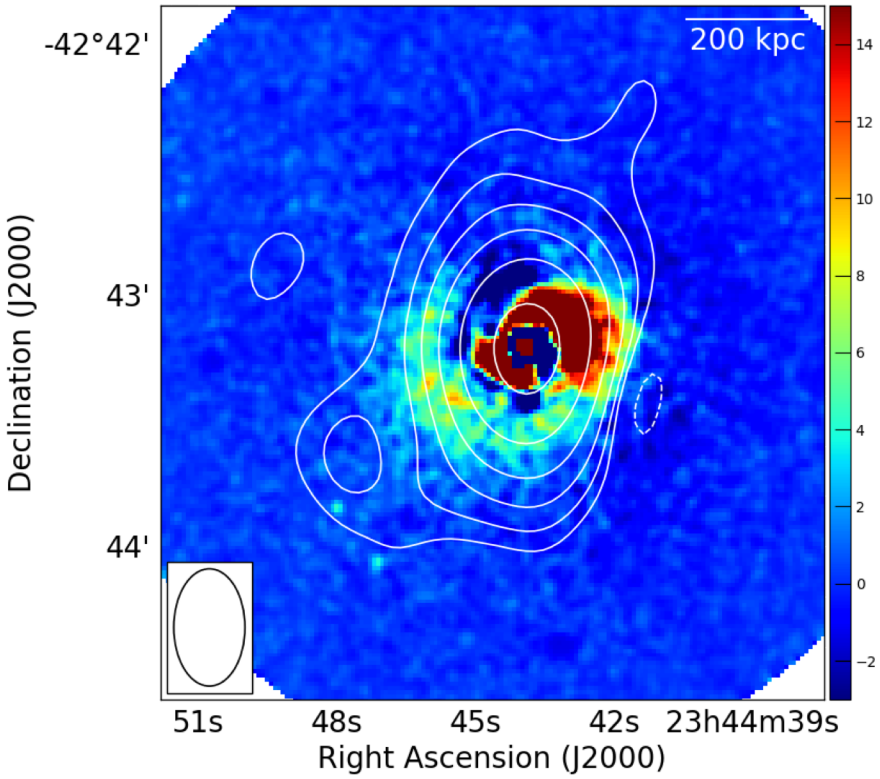
$L_{X_{2-10\,keV}} = 82^{+1}_{-2} \times 10^{44}$ erg/sec

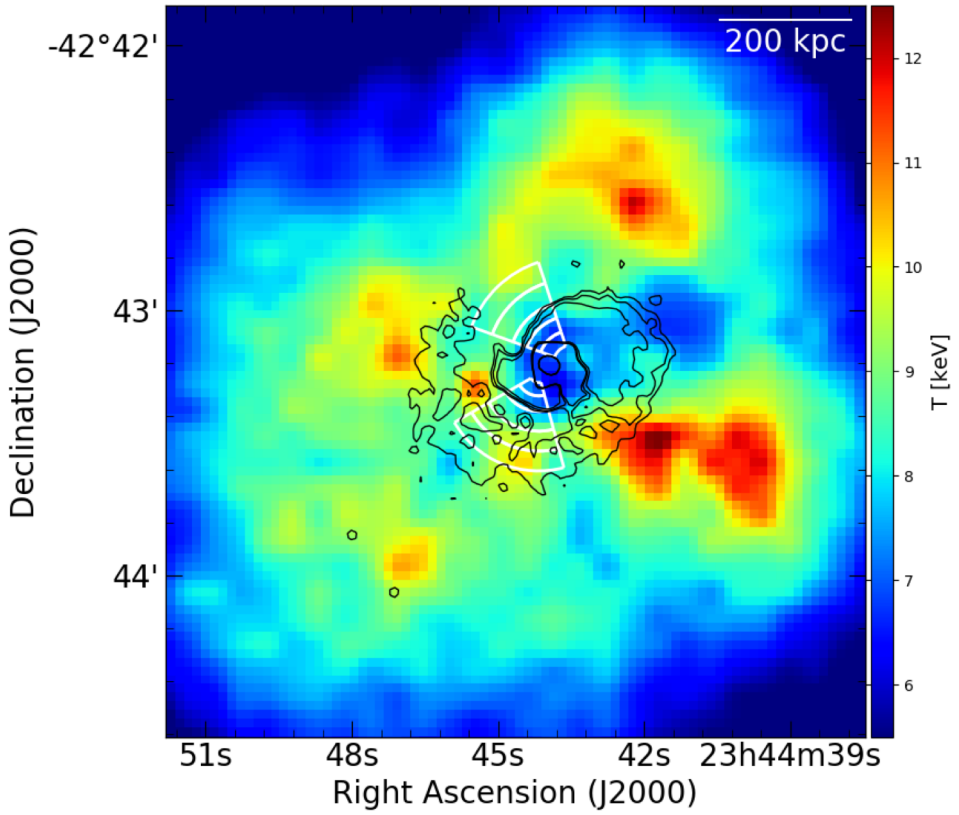
1.52 GHz image RMS noise = 25 μJy/beam
610 MHz image RMS noise = 50 μJy/beam
Beam = 28 x 17 arcsec

Raja et al. 2019a (ApJ under review)

Raja et al. 2019a (ApJ under review)

# Phoenix Cluster (z=0.596)



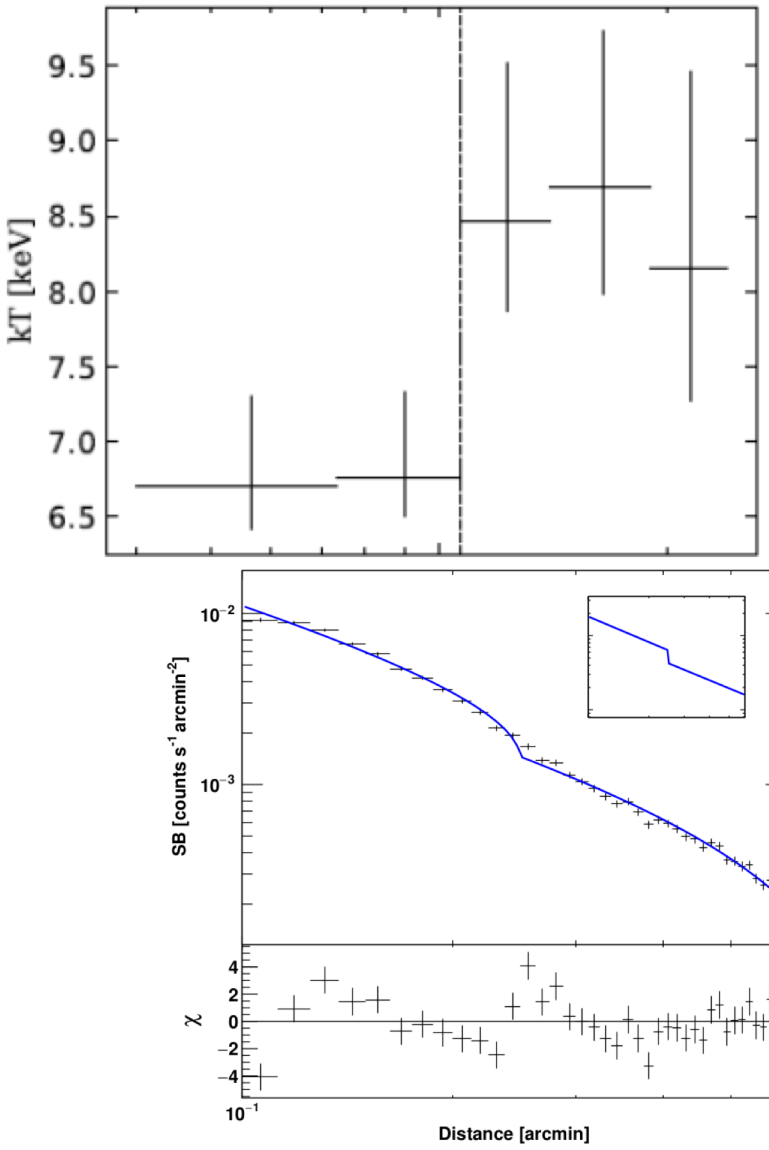




- *Chandra* X-ray unsharped-mask map showing the "brightness-excess" corresponding to the gas sloshing in the ICM.
- 1.7 GHz diffuse emission contours.

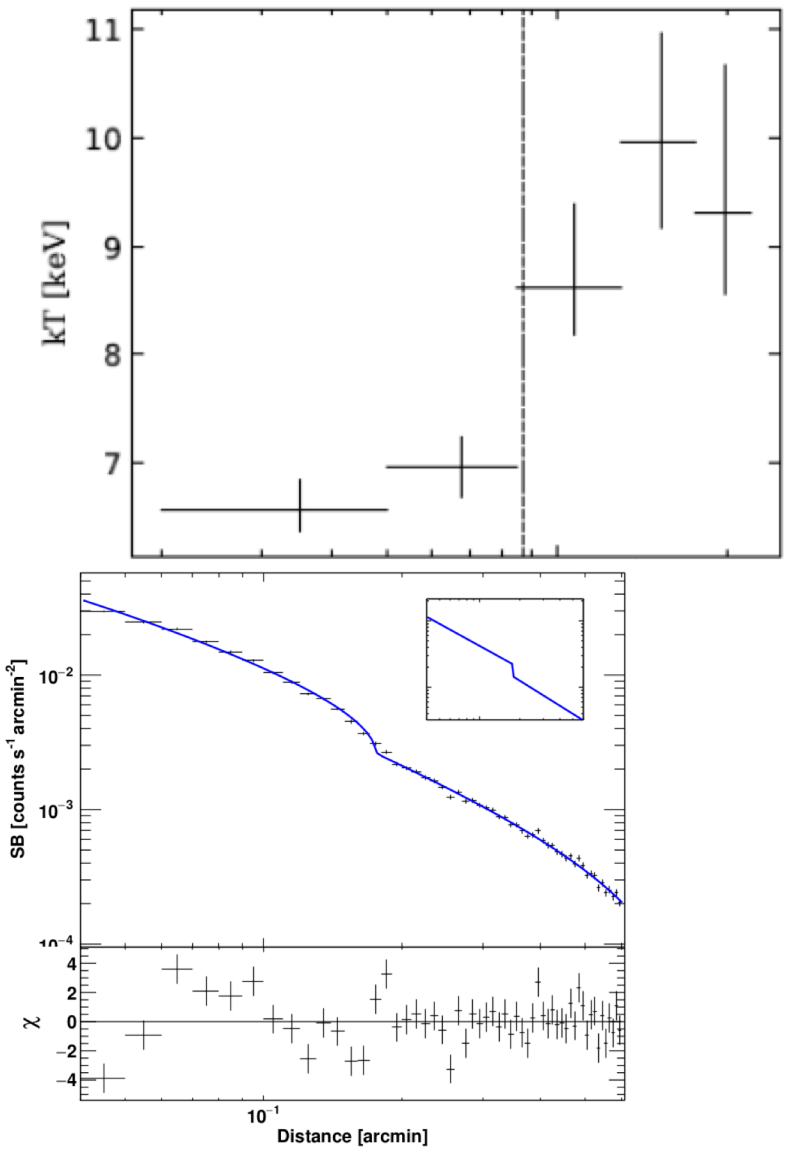
- *Chandra* X-ray temperature map overlaid with "brightness-excess" contours.
- Contact discontinuities along the white wedges.

# Phoenix Cluster (z=0.596)

Raja et al. 2019a (ApJ under review)

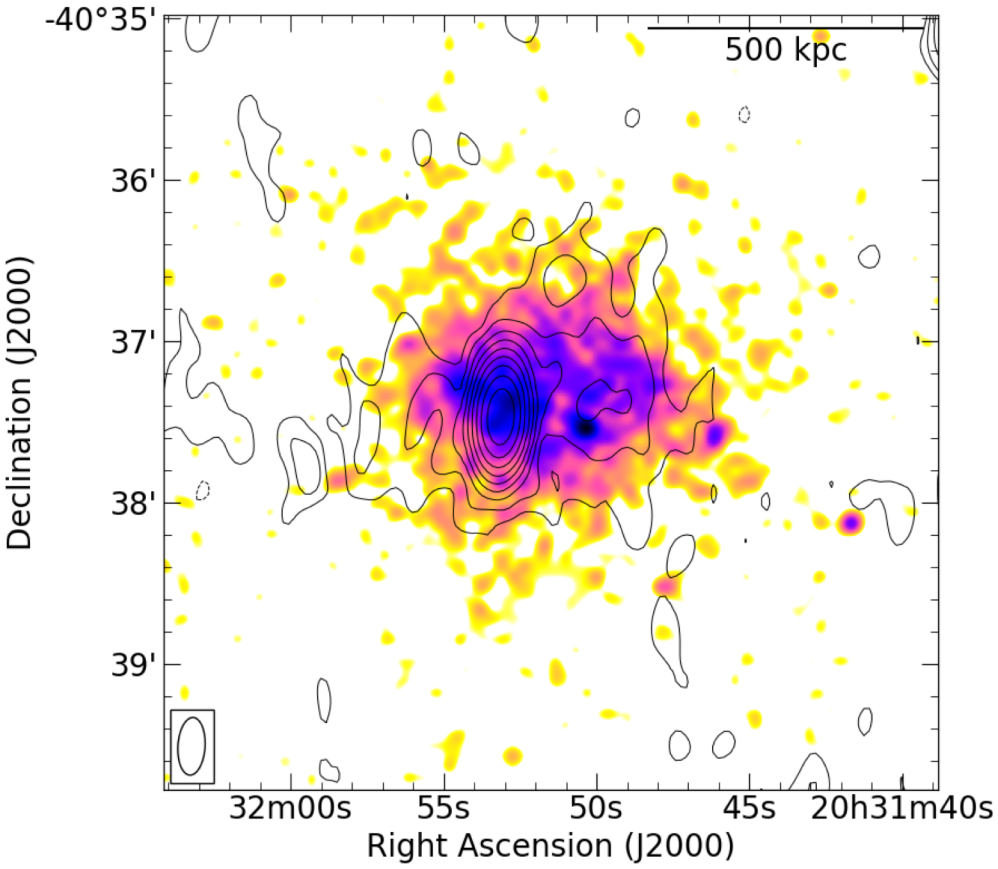



Pie 108-160 deg



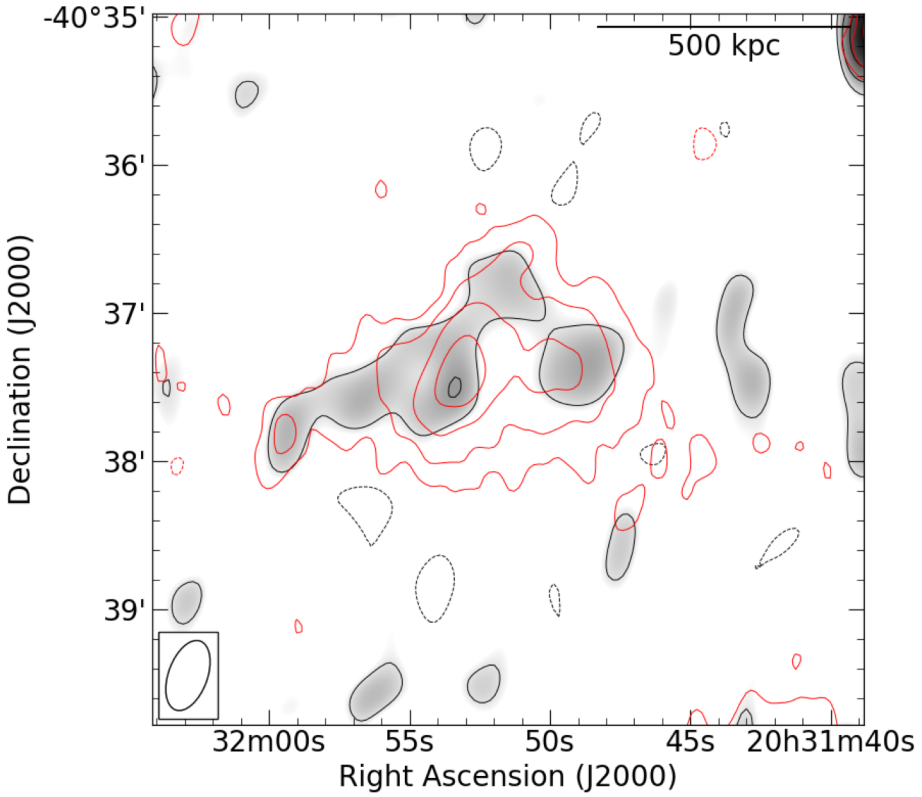

Pie 210-285 deg

# SPT-CL J2031-4037 (z=0.3416)




- Disturbed weak cool core cluster
- Mass = 9.83 x $10^{14}$ $M_{sun}$
- 325 MHz image with RMS noise = 60 μJy/beam and Beam = 21.5 x 10.1 arcsec

**Raja et al. 2019b (MNRAS under review)**




1.6 GHz image (RMS noise = 35 μJy/beam, Beam = 29.6 x 15.8 arcsec) with contours (black). The red contours are 325 MHz diffuse emission contours.

# SPT-CL J2031-4037

Raja et al. 2019b (MNRAS under review)

**Table 1.** Global cluster and Halo properties

| | |
|---|---|
| RA | 20h31m51.5s |
| DEC | -40d37m14s |
| $z$ | 0.3416 |
| $R_{500}$ [Mpc] | 1.342 |
| $M_{500}$ [$10^{14}$ $M_\odot$] | $9.83 \pm 1.5$ |
| $L_{[0.1-2.4\ keV]}$ [$10^{44}$ erg s$^{-1}$] | $4.389 \pm 0.28$ |
| $T_{central}$ [keV] | $12.2 \pm 2.4$ |
| $S_{Halo,325\ MHz}$ [mJy] | $16.73 \pm 1.72$ |
| $S_{Halo,1.6\ GHz}$ [mJy] | $1.26 \pm 0.17$ |
| $P_{Halo,1.4\ GHz}$ [$10^{24}$ W Hz$^{-1}$] | $1.11 \pm 0.11$ |
| $\alpha_{325}^{1679}$ [Halo] | $-1.27 \pm 0.19$ |

References: Bîrzan et al. (2017); Bleem, et al. (2015); McDonald, et al. (2013)

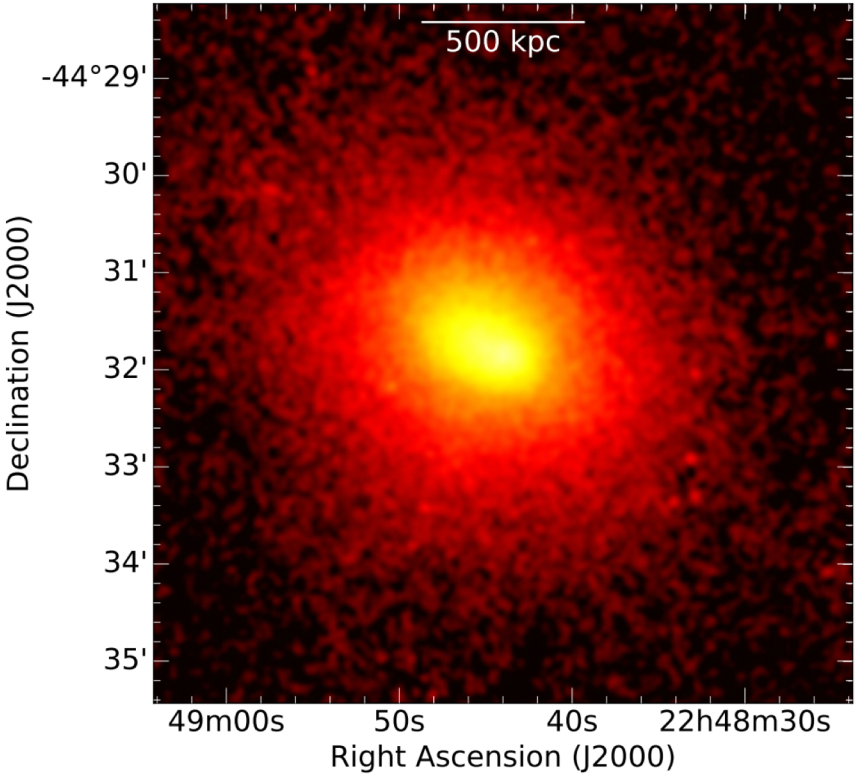
**Table 2.** Dynamical state

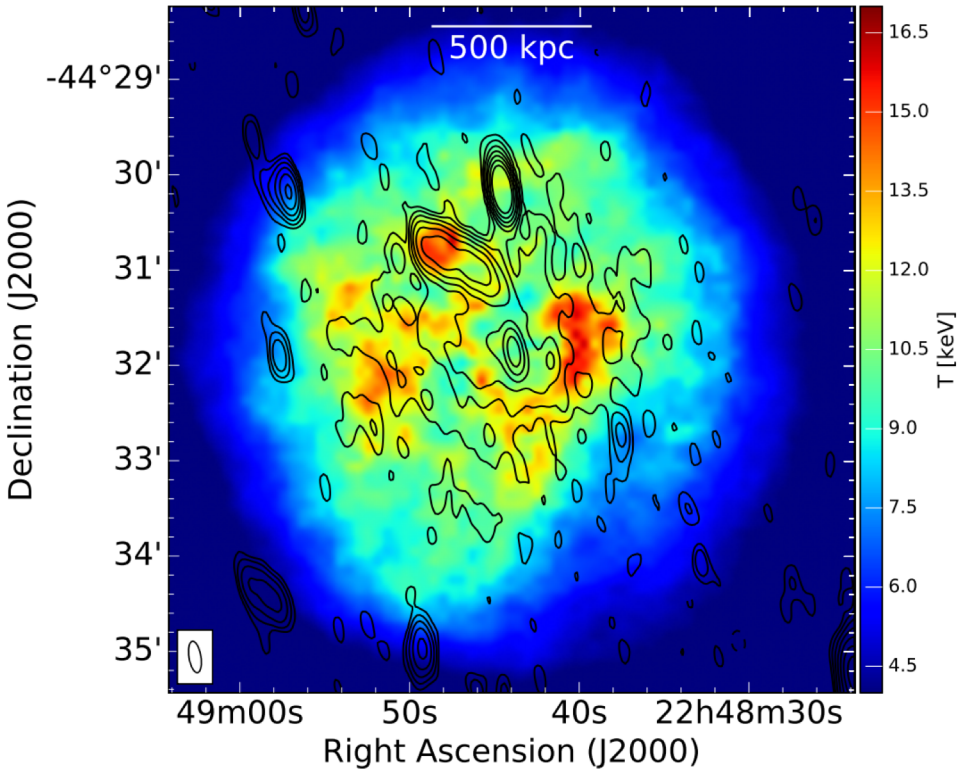
| Parameter | Value | Morphology | Ref. |
|---|---|---|---|
| $c_{SB}$ | $0.05^{+0.00}_{-0.02}$ | NCC | 1 |
| $t_{cool,0}$ [Gyr] | $3.43^{+0.75}_{-0.72}$ | WCC | 1 |
| $K_0$ [keV cm$^2$] | $189.8^{+39.9}_{-38.9}$ | NCC | 1 |
| $w$ | $0.017^{+0.001}_{-0.002}$ | NCC | 2 |
| $A_{phot}$ | $0.25 \pm 0.04$ | WCC | 2 |
| $E_z^{-2} n_{e,0}$ at $0.03 R_{500}$ | – | CC | 3 |

References: (1) McDonald, et al. (2013), (2) Nurgaliev, et al. (2017), (3) Morandi, Sun, Forman & Jones (2015).
NCC, WCC and CC represents Non Cool Core, Weak Cool Core and Cool Core respectively.

- Dynamically disturbed, weak cool core cluster
- Steep spectrum (-1.35 +/- 0.07) diffuse radio emission along the merger axis.
- Ultra-steep spectrum ( < -1.55 ) diffuse emission in the "off-axis" region.
- Minor merger event was unable to disrupt the cool core and injected less energy into the ICM.
- Both spectral and spatial steepening of the diffuse emission supports the turbulent re-acceleration model.

# SPT-CL J2248-4431 (z=0.351)




Mass = 15.5 x $10^{14}$ $M_{sun}$
$L_x$ = 3 x $10^{45}$ ergs/sec
Chandra = 120 ksec
Signature of merger with the existence of a cool core.

Diffuse radio emission at 325 MHz GMRT observation (black contours) overlaid on the *Chandra* temperature map.

Rahman et al. 2019a (in prep.)

# MACS J0417.5−1154 (z=0.44)

Kaur et al. (2018, 2019)

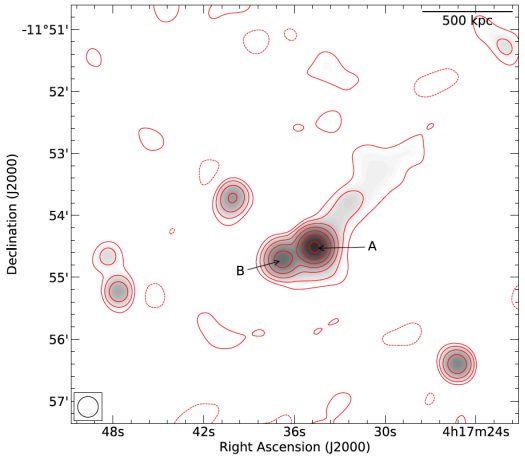



**Figure 1.** The GMRT radio image of the Galaxy cluster at 1387 MHz. The resolution of this image is 20″ with rms noise of 50$\mu$Jy/beam. The contours levels are drawn at [1, 2, 4, 8, ...] × 3$\sigma$. Dashed lines are negative contours at 3$\sigma$.

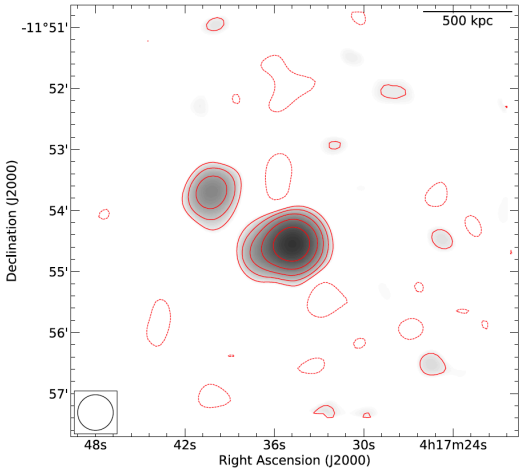
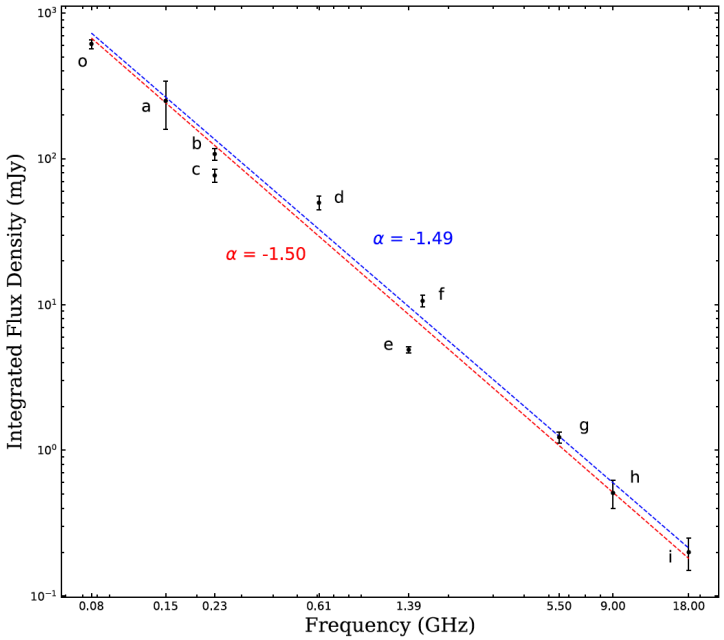



**Figure 2.** The ATCA radio image of the Galaxy cluster at 18 GHz. The resolution of this image is 35″ wit noise ($\sigma$) of 8$\mu$Jy/beam. The contours levels are dra [1, 2, 4, 8, ...] × 5$\sigma$. Dashed lines are negative conto 3$\sigma$.




GLEAMS data used in the SED of the Radio Halo