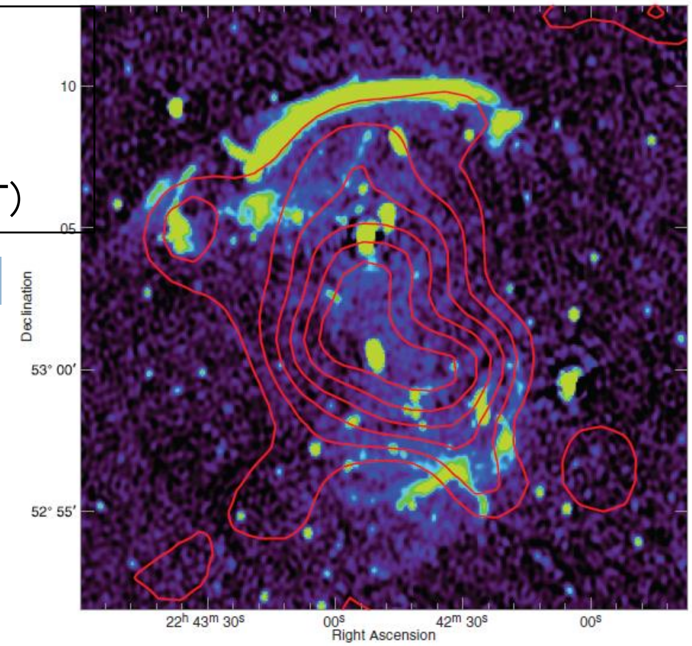
Suzaku Observations of the Galaxy Cluster 1RXS J0603.3+4214

Madoka Itahana (Yamagata Univ.),
M. Takizawa (Yamagata Univ.), H. Akamastu (SRON),
T. Ohashi ,Y. Ishisaki (Tokyo Metropolitan Univ.),
H. Kawahara (Tokyo Univ.), R. J. van Weeren (CfA)

Itahana et al. (2015) PASJ, 67, 113

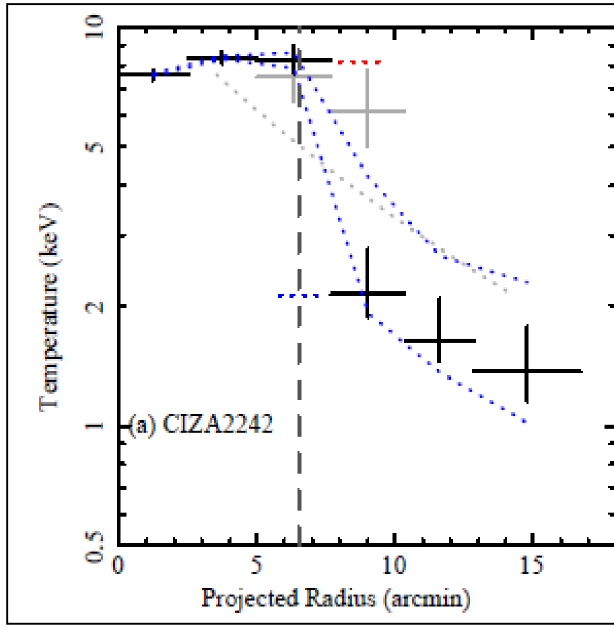
Introduction

CIZA J2242.8+5301
(van Weeren et al. 2010)
colors: radio
contours : X-ray (ROSAT)



- Radio relics
  - Non-thermal radio emission region
  - Cosmic-ray (~Gev) + magnetic field (~μG) => Synchrotron radiation
  - Arc-like shape
  - It is located in the periphery of the cluster.
  - X-ray observations show a temperature jump at the outer edge of the relic.

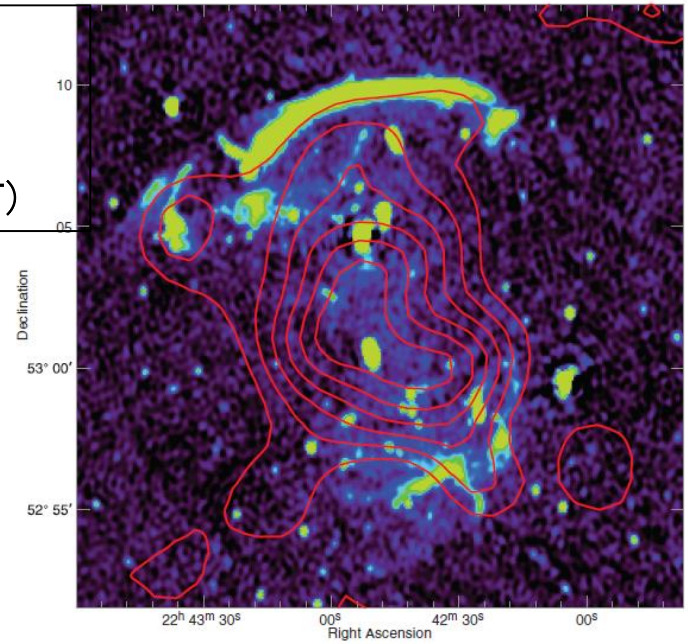
=>direct evidence of the association of relics with shocks



Akamatsu & Kawahara (2013)

Introduction

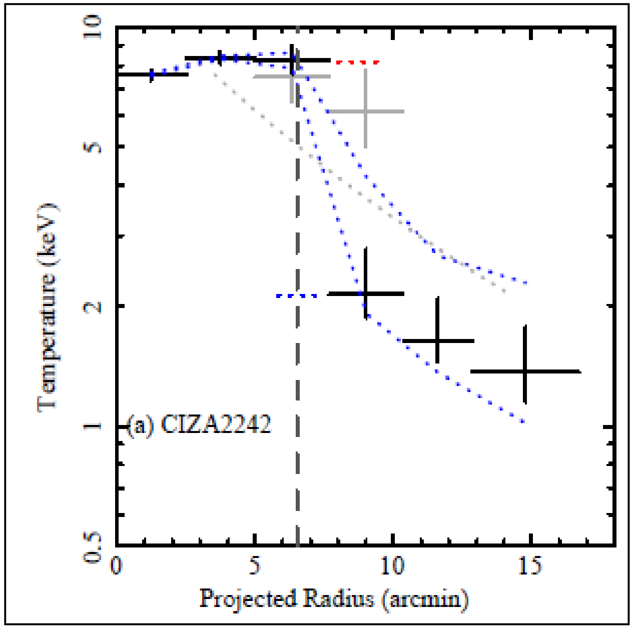
CIZA J2242.8+5301
(van Weeren et al. 2010)
colors: radio
contours : X-ray (ROSAT)



- Radio relics
  - Non-thermal radio emission region
  - Cosmic-ray (~Gev) + magnetic field (~μG) => Synchrotron radiation
  - A c-lik
  - It is loc e cluster
  - X-ray (temperature jump at the outer edge of the relic.

Non-thermal X-ray will be emitted through inverse Compton processes with CMB

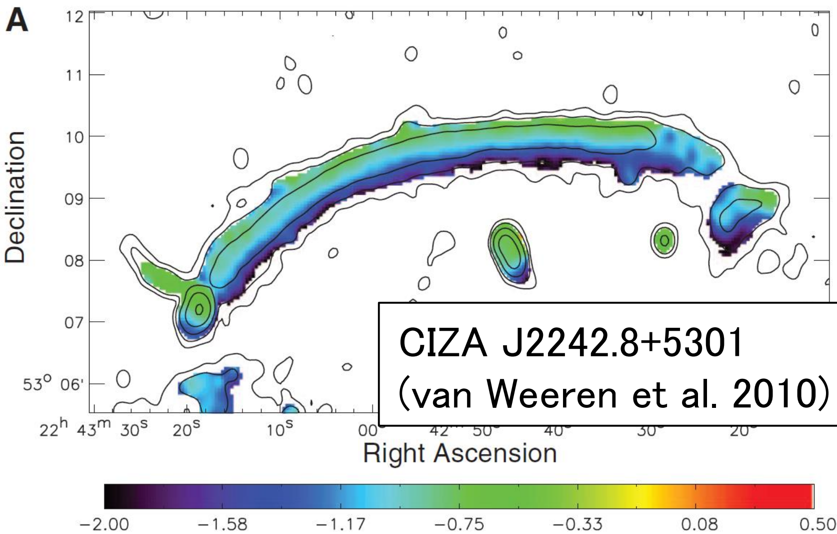
=>direct evidence of the association of relics with shocks



Akamatsu & Kawahara (2013)

Mach number estimation

Radio observations

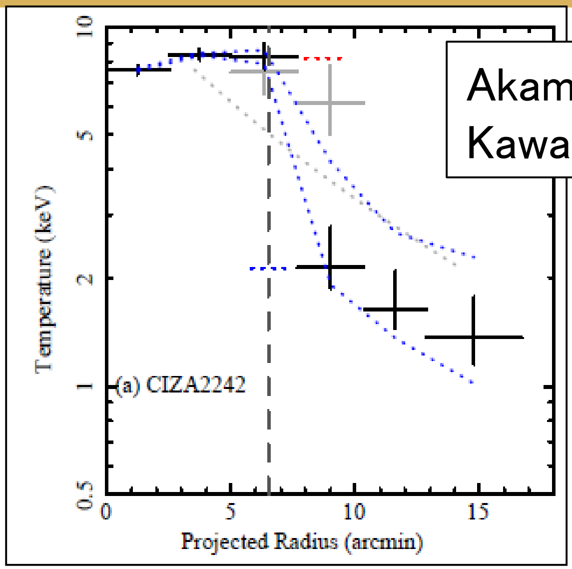


CIZA J2242.8+5301
(van Weeren et al. 2010)

- Spectral index map
- Simple Diffusive shock acceleration (DSA) theory

$$\alpha = \frac{M_{radio}^{2}+1}{M_{radio}^{2}-1} - \frac{1}{2}$$

X-ray observations



Akamatsu & Kawahara (2013)

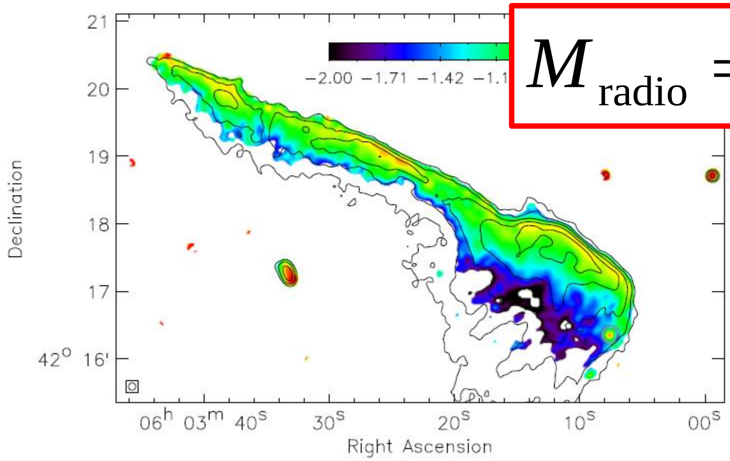
- Temperature (or surface brightness) profile
- Rankine – Hugoniot relation

$$\frac{T_{\rm post}}{T_{\rm pre}} = \frac{5M_x^{4}+14M_x^{2}-3}{16M_x^{2}}$$

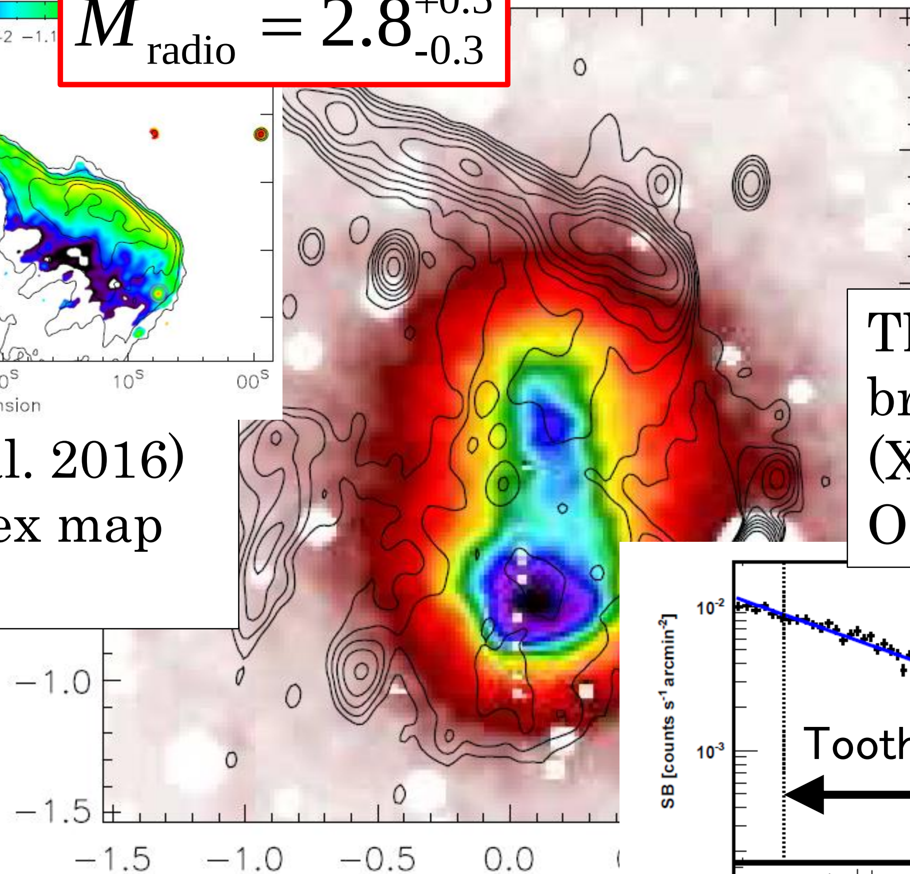
1RXS J0603.3+4214 (Toothbrush Cluster)

(RA, Dec)=(90.7885, +42.2628) z=0.225

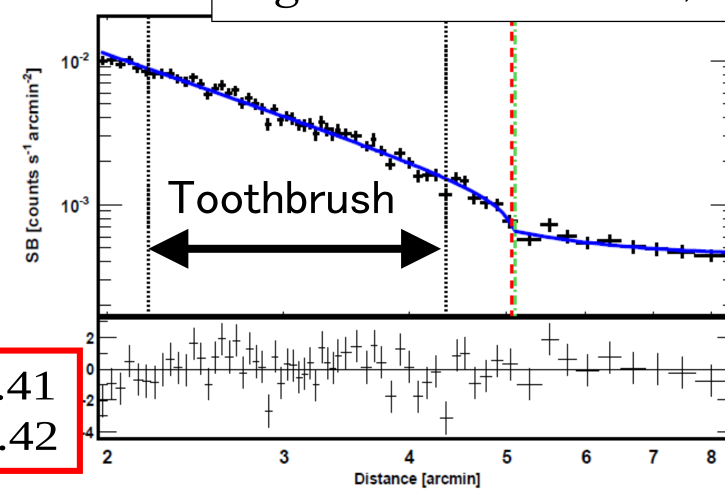
$M_{radio} = 2.8^{+0.5}_{-0.3}$



(van Weeren et al. 2016)
The spectral index map
(115 - 610 MHz)



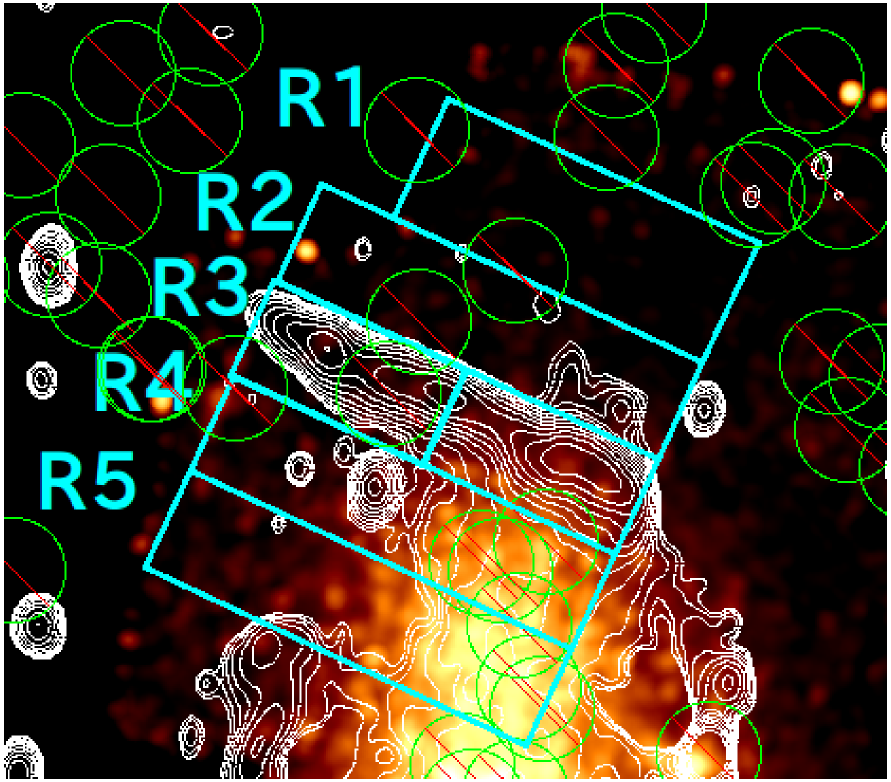
The X-ray surface brightness distribution
(XMM-Newton : Ogrean et al. 2013)



$M_X = 1.7^{+0.41}_{-0.42}$

Suzaku Observation

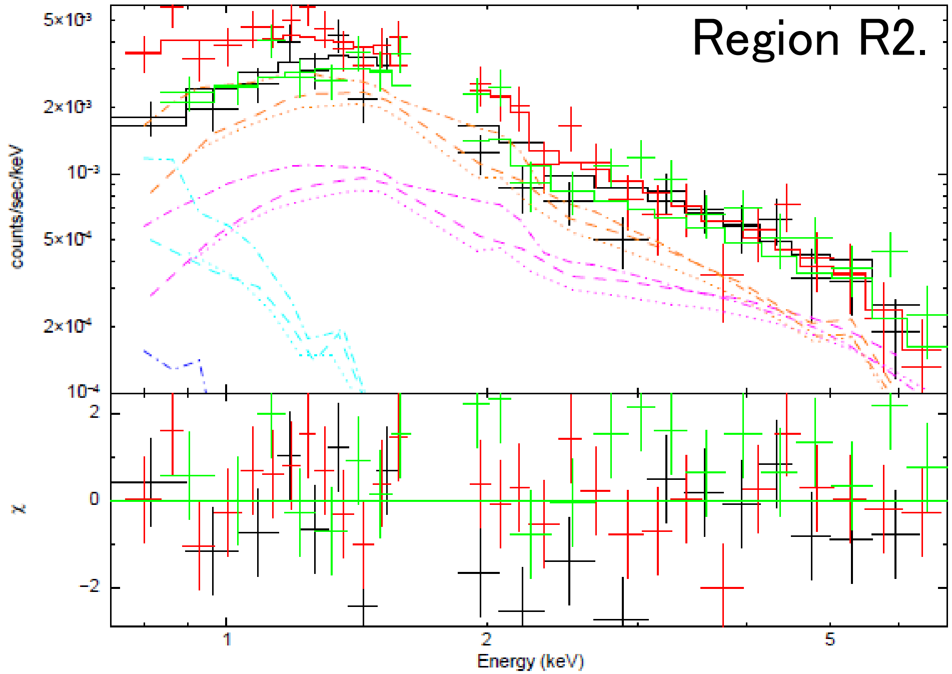
- Observation data :
  2012 10/7-10/10
- Exposure time :
  124 ksec
- Assuming that the shock is located at the relic outer edge.

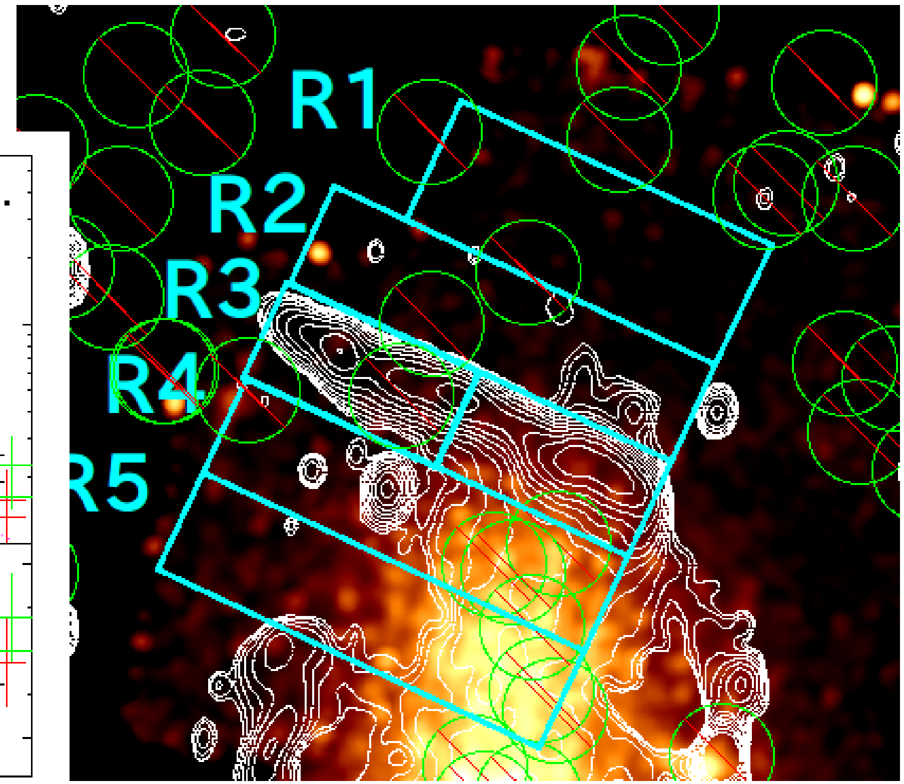


Suzaku xis image with the 1.16-1.78 GHz radio contours (van Weeren et al. 2012)

Suzaku Observation

- Observation data :

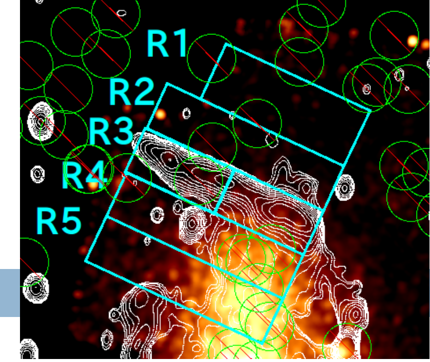


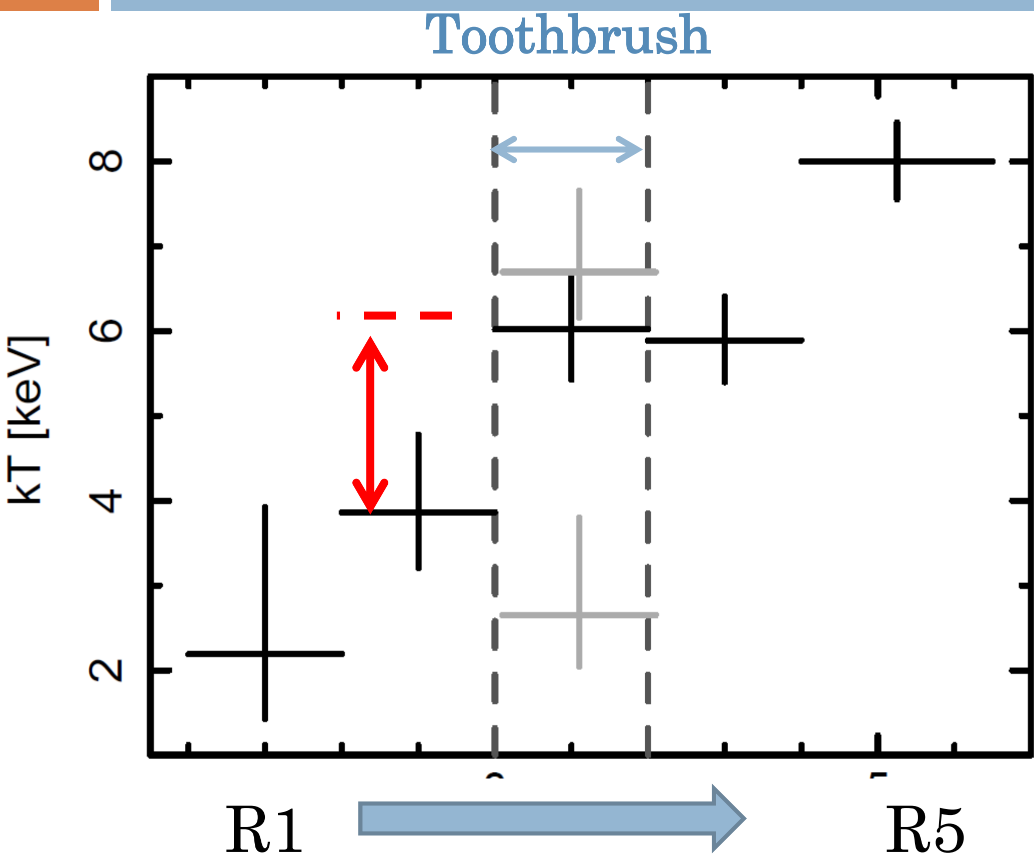


Blue: LHB Light Blue: MWH
Magenta:CXB Orange: ICM

Suzaku xis image with the 1.16–1.78 GHz radio contours (van Weeren et al. 2012)

Temperature Profile





$$M_{radio} = 2.8^{+0.5}_{-0.3}$$

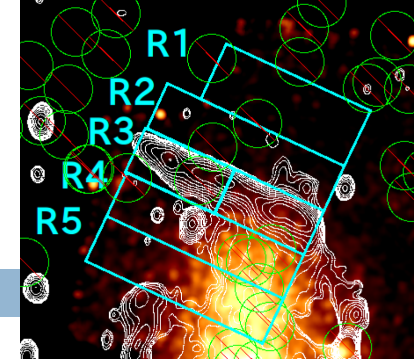
(van Weeren et al. 2016)

$$M_X = 1.55^{+0.38+0.27+0.10}_{-0.28-0.27-0.15}$$

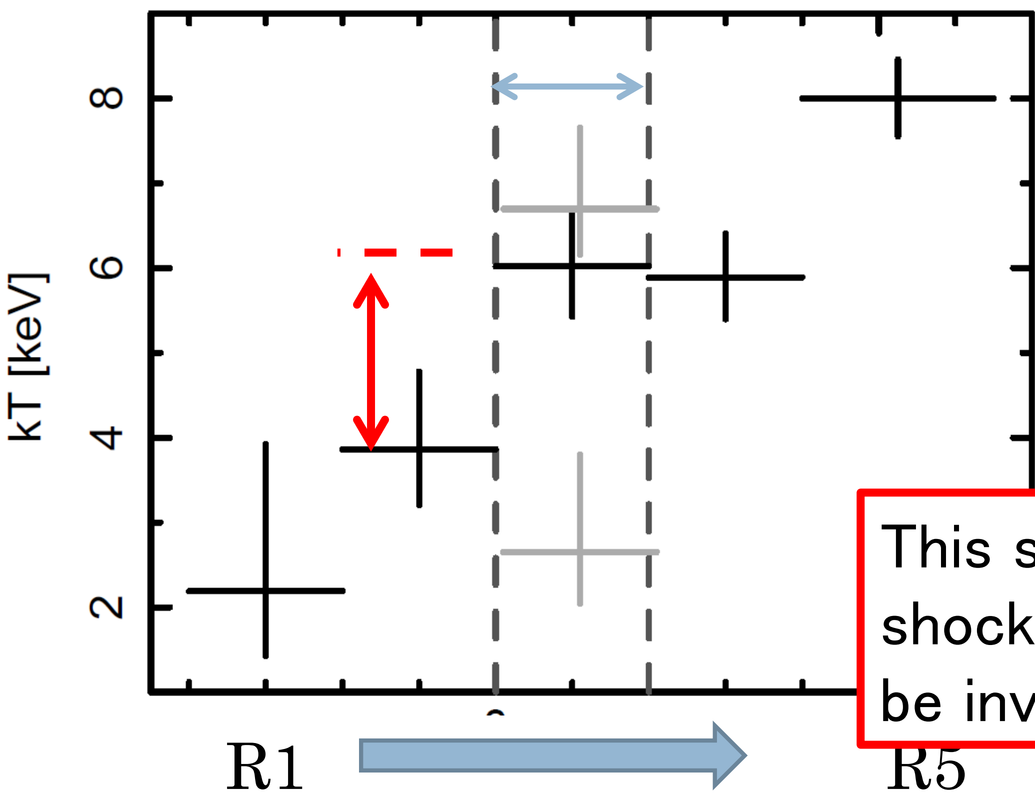
$$\frac{T_{post}}{T_{pre}} = \frac{5M_X^{\ 4} + 14M_X^{\ 2} - 3}{16M_X^{\ 2}}$$

This Mach number is significantly lower than the value estimated from radio data even considering both statistical and systematic errors.

Temperature Profile



Toothbrush



$$M_{\text{radio}} = 2.8^{+0.5}_{-0.3}$$

(van Weeren et al. 2016)

$$M_X = 1.55^{+0.38+0.27+0.10}_{-0.28-0.27-0.15}$$

This suggests that a simple diffusive shock acceleration theory seems to be invalid for this relic.

value estimated from radio data even considering both statistical and systematic errors.

$$\frac{T_{post}}{T_{pre}} = \frac{5M_X^{\ 4} + 14M_X^{\ 2} - 3}{16M_X^{\ 2}}$$

Mach number of the shocks around relics

- Radio Observations
  - Spectral index map with Simple DSA theory

$$\alpha = \frac{M_{radio}^{2} + 1}{M_{radio}^{2} - 1} - \frac{1}{2}$$

- X-ray Observations
  - Temperature profile with Rankine-Hugoniot relation

$$\frac{T_{\rm post}}{T_{\rm pre}} = \frac{5M_{x}^{4} + 14M_{x}^{2} - 3}{16M_{x}^{2}}$$

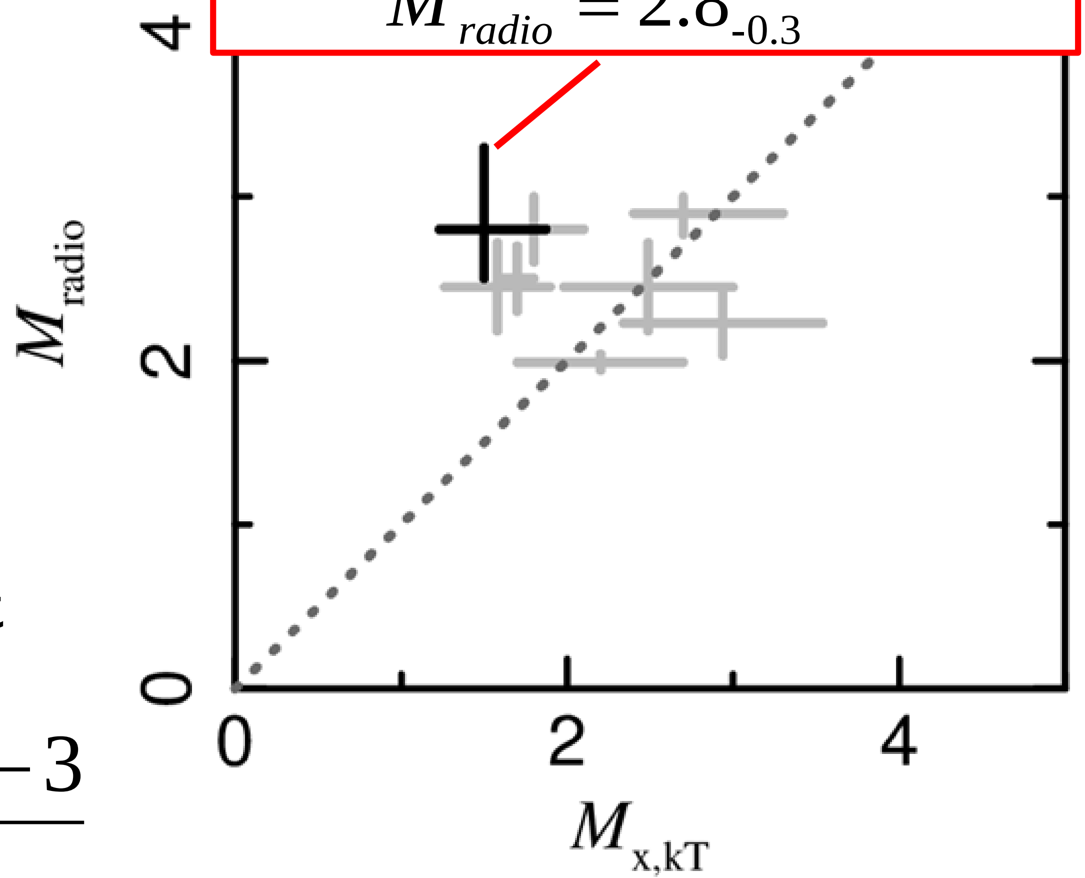
Toothbrush

(Itahana et al. 2015)

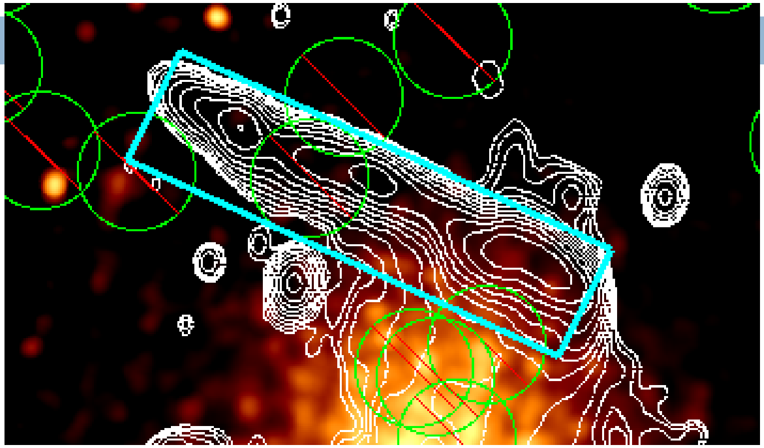
$$M_{X} = 1.55^{+0.29}_{-0.25}$$

(van Weeren et al. 2016)

$$M_{radio} = 2.8^{+0.5}_{-0.3}$$



Magnetic field strength at the Toothbrush relic



- Search for the non-thermal X-ray components
  - Upper limit

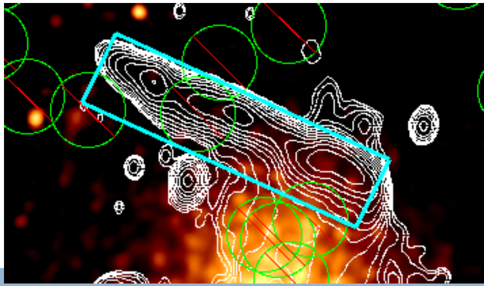
$$F_{\mathrm{IC[0.3\text{-}10keV]}} < 2.2\times10^{-13}\ \mathrm{erg/s/cm^2}$$

- Lower limit of magnetic field strength

$$B > 1.6\,\mu\mathrm{G}$$

- Even considering uncertainties of the thermal ICM temperature and the radio spectral index, lower limit on the magnetic field strength still remains μG level.

Energy density in the relic



- The energy density of the magnetic field

$$U_B = \frac{B^2}{8\pi}$$

$$> 1.0 \times 10^{-13}\ \mathrm{erg/cm^3}$$

- The energy density of the thermal ICM

$$U_{th} = \frac{3}{2}\frac{n_e kT}{\mu}$$

$$= 8.6 \times 10^{-12}\ \mathrm{erg/cm^3}$$

Our results

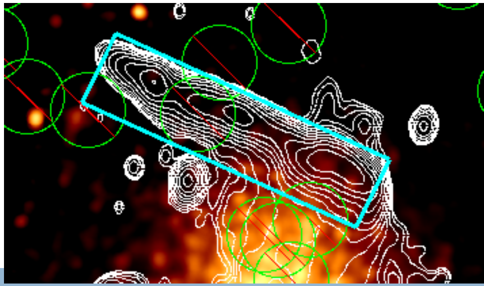
$$B > 1.6\ \mu\mathrm{G}$$

$$kT = 6.10\ \mathrm{keV}$$

$$n_e = 3.54 \times 10^{-4}\ \mathrm{cm^{-3}}$$

$$\frac{U_{\mathrm{mag}}}{U_{\mathrm{th}}} > 1.2 \times 10^{-2}$$

Energy density in the relic



- The energy density of the magnetic field

$$U_B = \frac{B^2}{8\pi}$$

$$> 1.0\times 10$$

- The energy dens

$$U_{th} = \frac{3}{2}\frac{n_e k}{\mu}$$

$$= 8.6\times 10^{-12}\ \mathrm{erg/cm^3}$$

Our results

$$B > 1.6\,\mu\mathrm{G}$$

$$kT = 6.10\ \mathrm{keV}$$

$$\mathrm{m}^{-3}$$

- The magnetic energy could be more than a few % of the thermal one and the ICM evolution and structures could be somewhat affected by the magnetic field.

$$\frac{U_{\mathrm{mag}}}{U_{\mathrm{th}}} > 1.2\times 10^{-2}$$

Summary

- We observed the field around the "Toothbrush" radio relic in the galaxy cluster 1RXJ0603 with SUZAKU.
- The mach number estimated from the temperature difference is ~1.6, which is significantly lower than the value estimated from the radio data even considering both statistical and systematic errors.
- This suggests a simple DSA theory, which is assumed in the mach number estimation from the radio data, seems to be invalid for this relic.
- The upper limit of the inverse compton component flux and lower limit of the magnetic field strength become ~2.2 erg/cm^2/s and ~1.7 μG, respectively.
- We estimated the energy densities of the thermal ICM and magnetic field in the radio relic from our results.
- The magnetic energy could be more than a few % of the thermal one and the ICM evolution and structures could be somewhat affected by the magnetic field.
- Itahana et al. (2015) PASJ, 67, 113