X-ray and radio observations of the radio relic galaxy clusters 1RXS J0603.3+4214 and RXC J1053.7+5453

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Itahana, Takizawa, Akamatsu et al. (2015), PASJ, 67, 113
Itahana, Takizawa, Akamatsu et al. (2017), PASJ, 69, 88

THE POWER OF FARADAY TOMOGRAPHY
--- TOWARDS 3D MAPPING OF COSMIC MAGNETIC FIELDS ---
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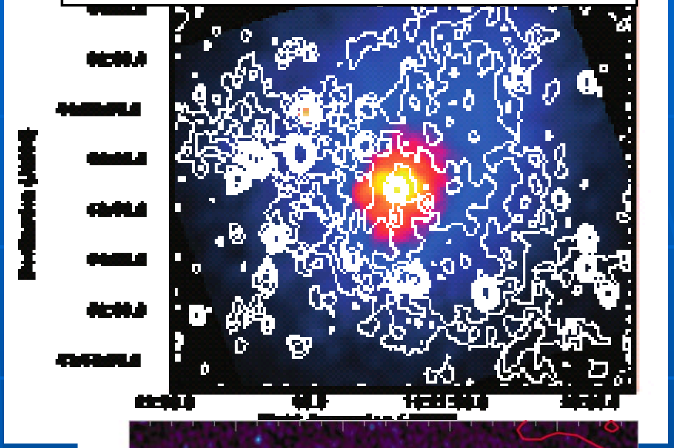
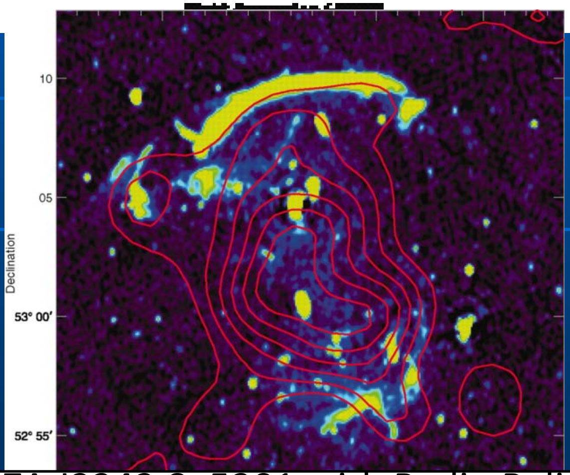
Radio Halos / Relics

- Some merging galaxy clusters have diffuse non-thermal radio emitting regions.
  (E_e~GeV, B~μG)
- Radio halos and (mini halos)
  - Located near the center, similar to X-ray morphology
  - Associated with ICM turbulence???
- Radio relics
  - Located in the outskirts, arc-like shape,
  - Likely associated with ICM shocks?

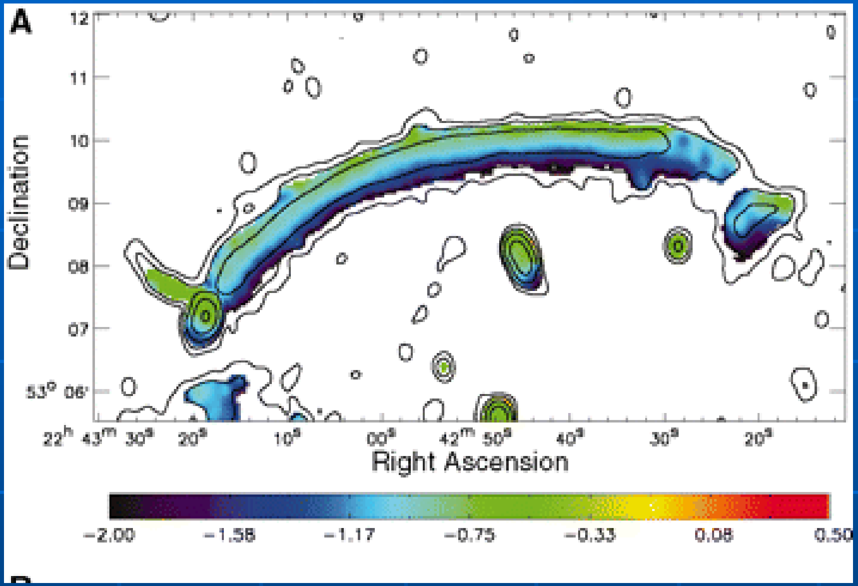
Abell 2319 with Radio Halo
Rosat X-ray image (colors)
Radio image (contours)
Feretti et al. 1997

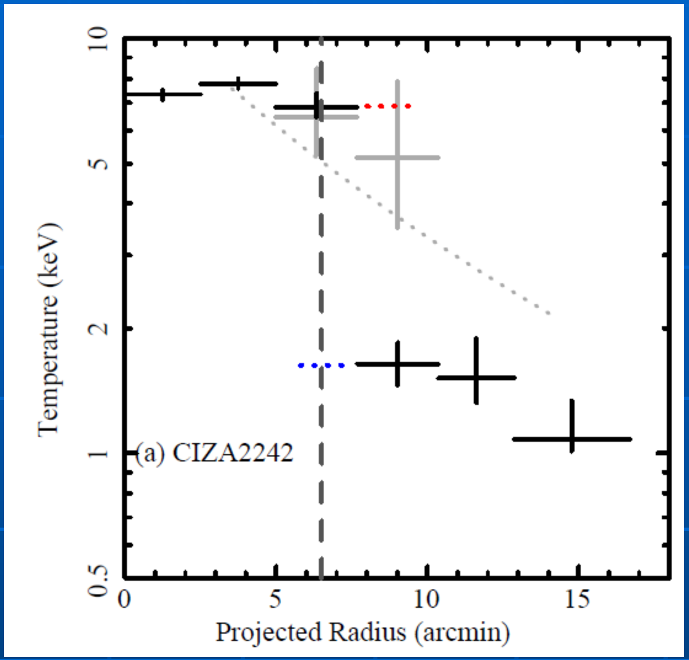




CIZA J2242.8+5301 with Radio Relic
Rosat X-ray image (contours)
Radio image (colors)
Van Weeren et al. 2010

Mach Number Estimation of Shocks at Radio Relics : Two Methods





Radio Spectral index map of the relic in CIZA J2242.8+5301 (Van Weeren et al. 2010)

$F_{\nu} \propto \nu^{-\alpha}$ --> $N(E_e) \propto E_e^{-(2\alpha+1)}$

With a (simple) diffusive shock accerelation model,

--->

$M^2 = (2\alpha+2)/(2\alpha-2)$

Temperature Profile across the relic in CIZA J2242.8+5301 (Akamatsu & Kawahara 2013)

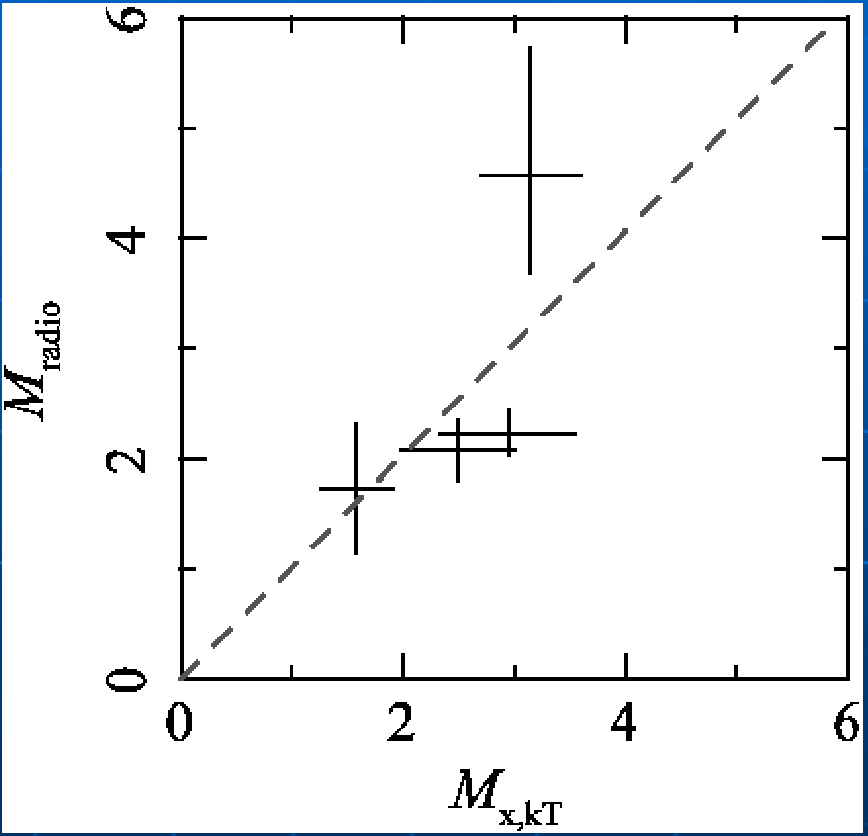
With the RH relation

---->

$T_{post}/T_{pre} = (5M^4 + 14M^2 - 3)/(16M^2)$

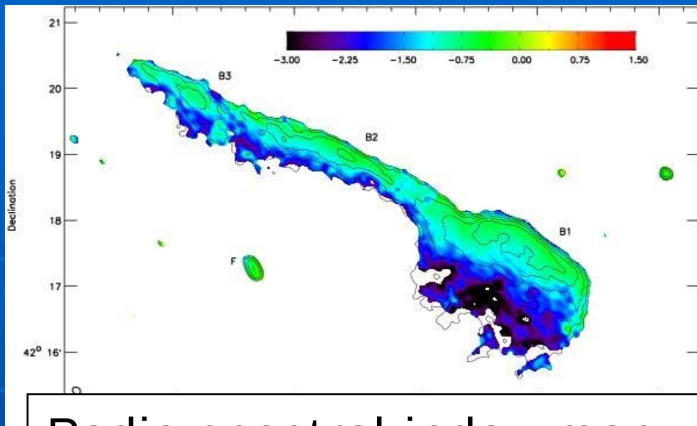
Radio Relics: Mach Number consistency???

- Akamatsu & Kawahara (2013) suggests that M_X and M_{radio} seem to be consistent with each other.
- A simple model of diffusive shock acceleration is correct?
- However, sample size is obviously too small to say something definite.

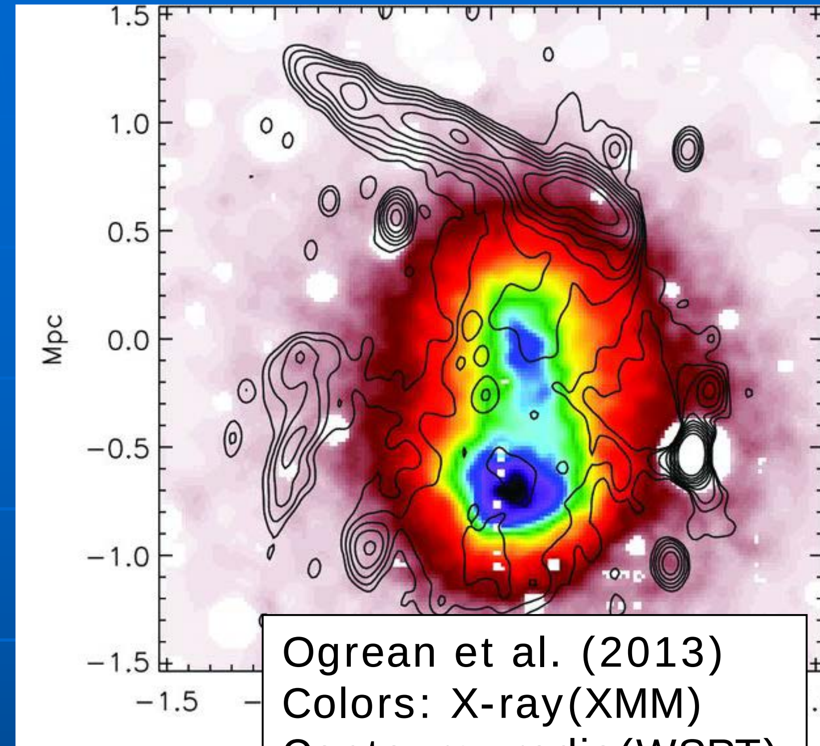


Akamatsu&Kawahara (2013)

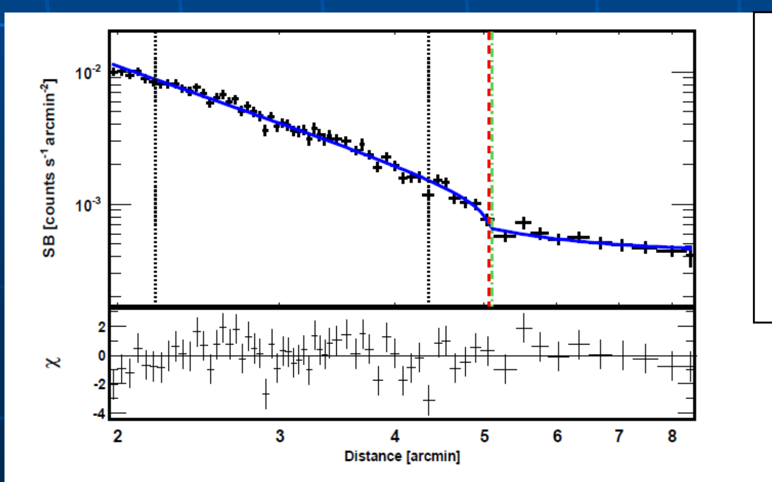
1RXS J0603.3+4214 with “toothbrush-relic”



Radio spectral index map
(van Weeren et al. 2012)
α_{inj}=0.6−0.7 ---> M_{radio}=3.3−4.6



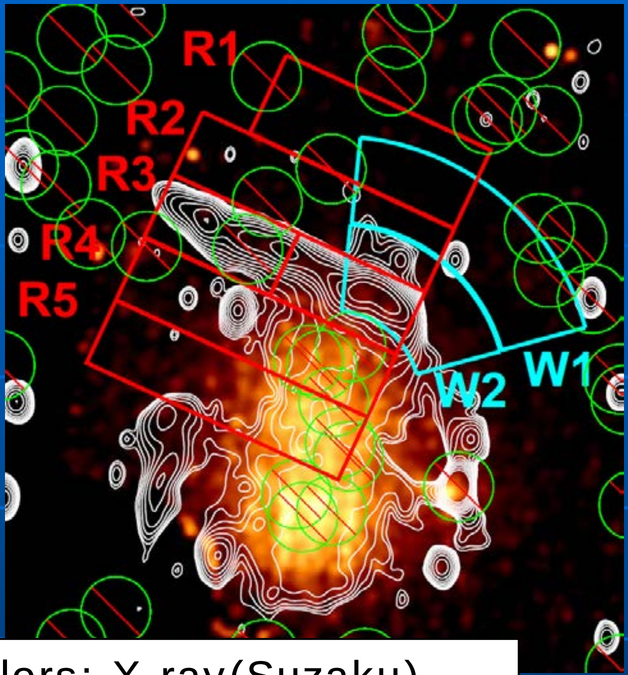
Ogrean et al. (2013)
Colors: X-ray(XMM)
Contours: radio(WSRT)



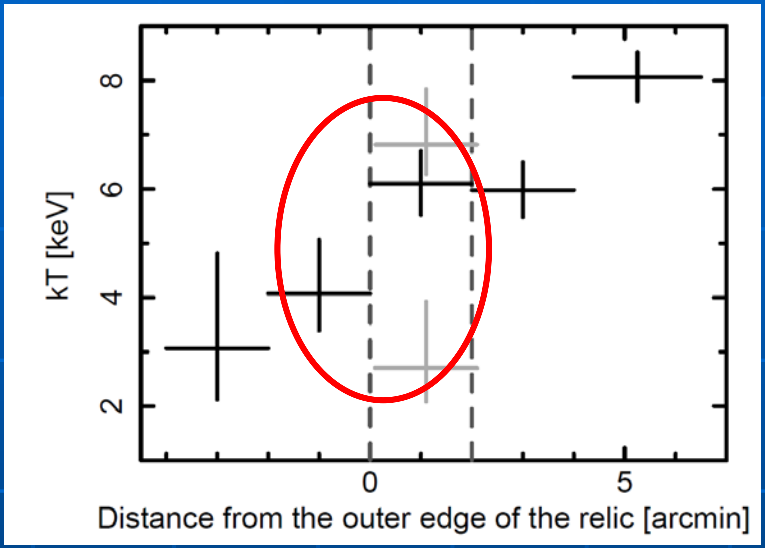
X-ray surface brightness profile across the relic (Ogrean et al. 2013)
$M_X=1.7^{+0.41}_{-0.42}$
Shock is shifted outward from the relic outer edge????

$$\frac{\rho_2}{\rho_1} = \frac{4M_X^2}{M_X^2+3}$$

toothbrush-relic: temperature profile across the relic (Itahana et al. 2015)



Colors: X-ray(Suzaku)
Contours: radio(WSRT)



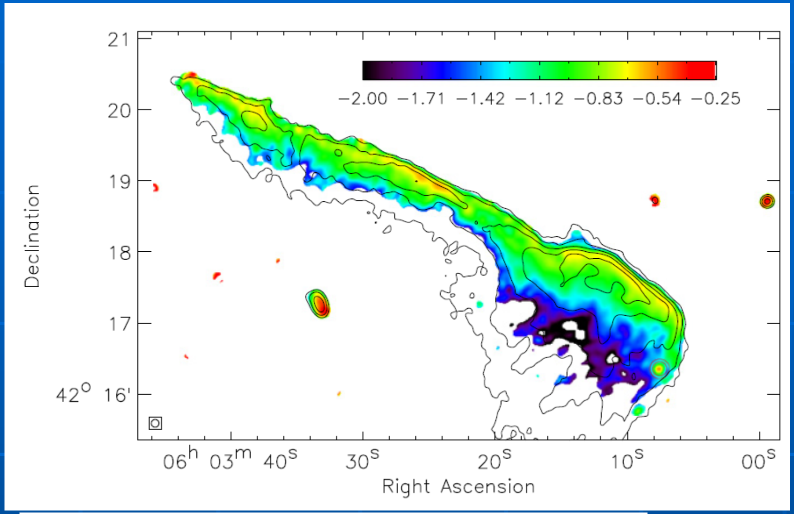
$$\frac{T_2}{T_1} = \frac{5{M_X}^4 + 14{M_X}^2 - 3}{16{M_X}^2}$$

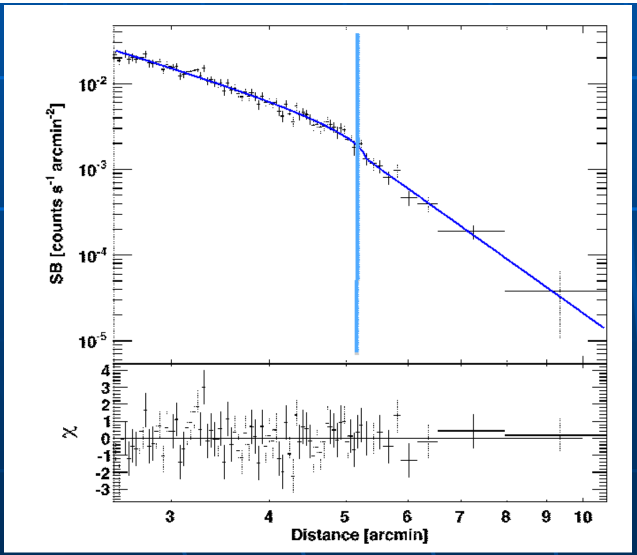
- Obtained Mach number

$$1.50^{+0.37+0.25+0.14}_{-0.27-0.24-0.15}$$

- Similar to the XMM results(Ogrean et al. 2013, surface brightness analysis), but more robust for uncertanities of line-of-sight structures.
- Inconsistent with radio results.

After our work,,,(van Weeren et al. 2016)





- New radio data (LOFAR+VLA) show steeper spectra.

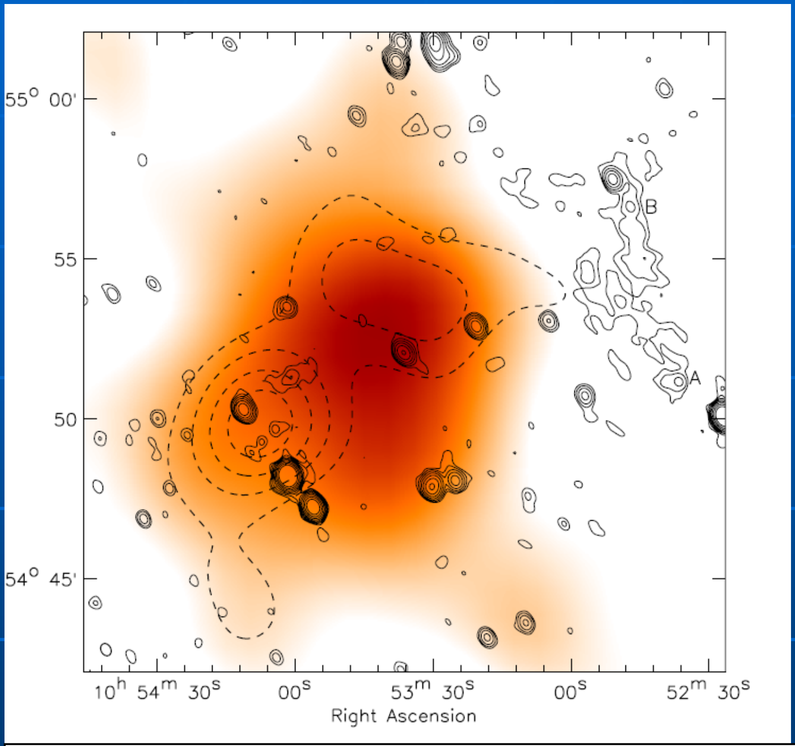
$$\alpha = -0.8 \pm 0.1$$

$$\mathcal{M} = 2.8^{+0.5}_{-0.3},$$

- Chandra X-ray data indicate shock is just at the outer edge of the relic, maybe XMM result is incorrect.

$\mathcal{M} \approx 1.2$, with an upper limit of $\mathcal{M} \approx 1.5$

RXC J1053.7+5453

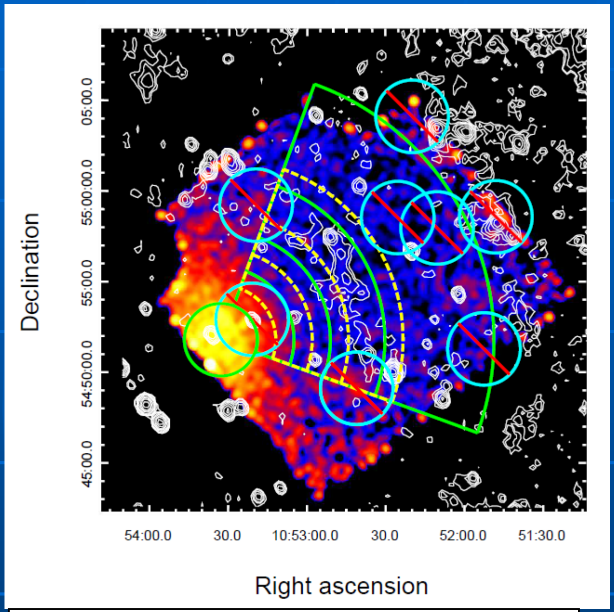


van Weeren (2011)

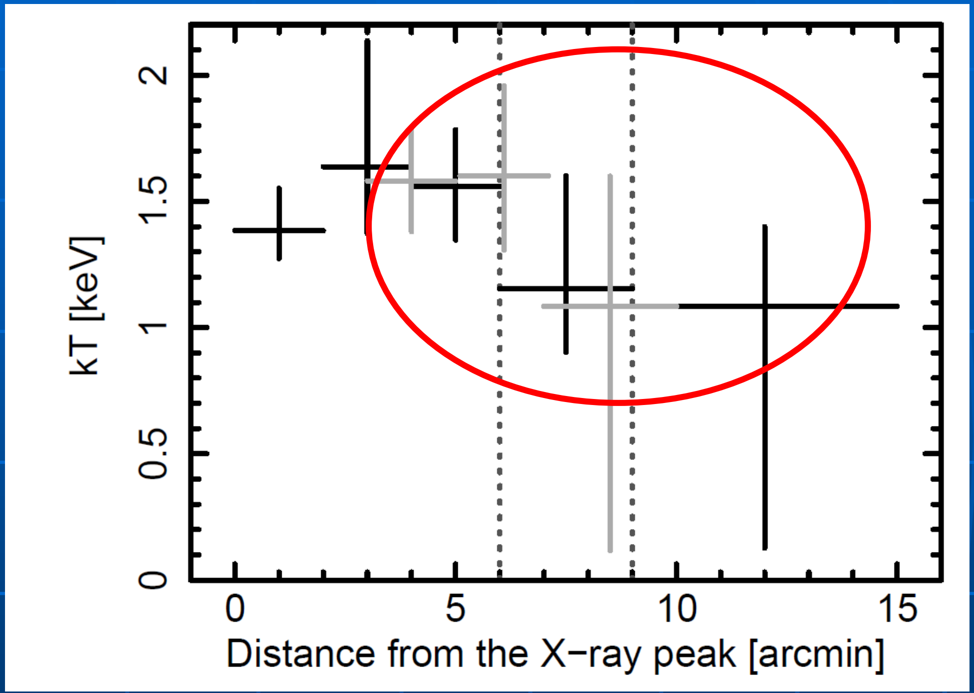
Colors: X-ray(ROSAT)
Solid contours: radio(WSRT)
Dotted contours: galaxy distribution

- Elongated X-ray morphology, with radio relic (van Weeren et al. 2011)
- Two subgroups in galaxy distribution.
- No direct temperature measurements (kT ~3keV is expected from L_x-kT relation)
- No radio spectral information

RXC J1053: temperature profile across the relic (Itahana et al. 2017)



Colors: X-ray(Suzaku)
contours: radio(WSRT)

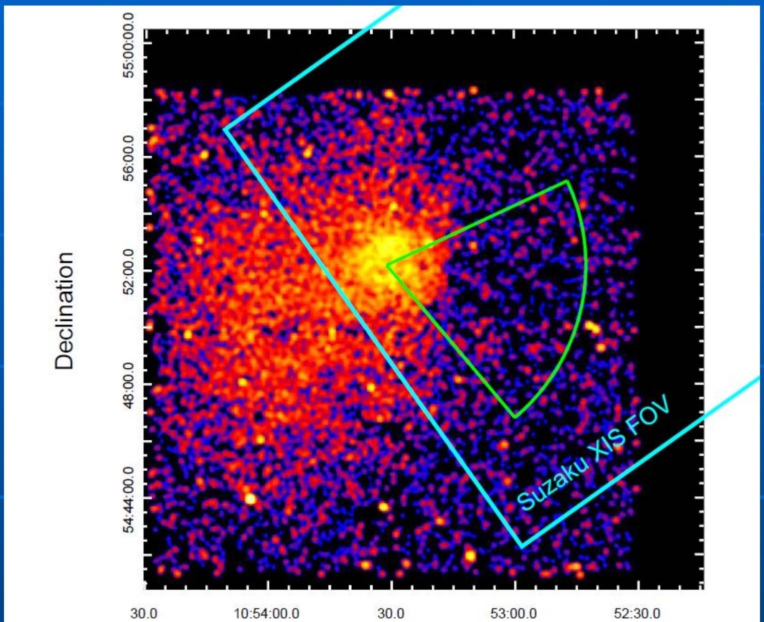


$$\frac{T_2}{T_1} = \frac{5{M_X}^4 + 14{M_X}^2 - 3}{16{M_X}^2}$$

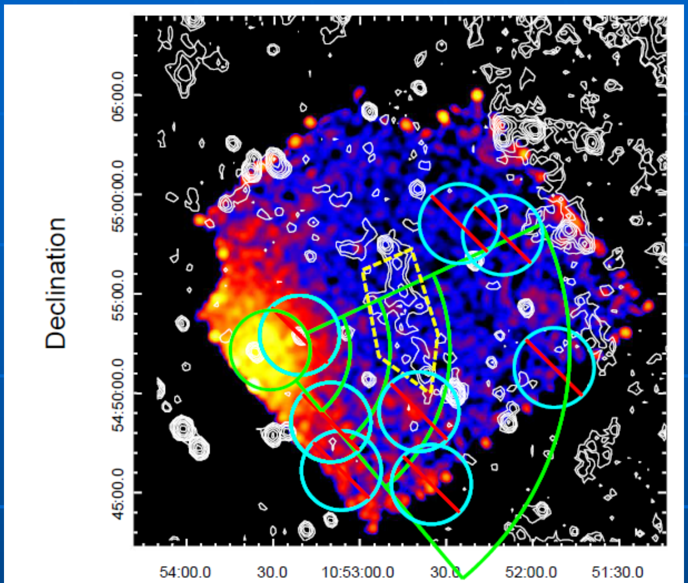
$$M_X = 1.44^{+0.48+0.14+0.03}_{-0.91-1.34-0.04}$$

- Unfortunately, we do not have any radio spectral inormation.

RXC J1053: Surface britness edge (Itahana et al. 2017)



Colors: X-ray(Chanda)

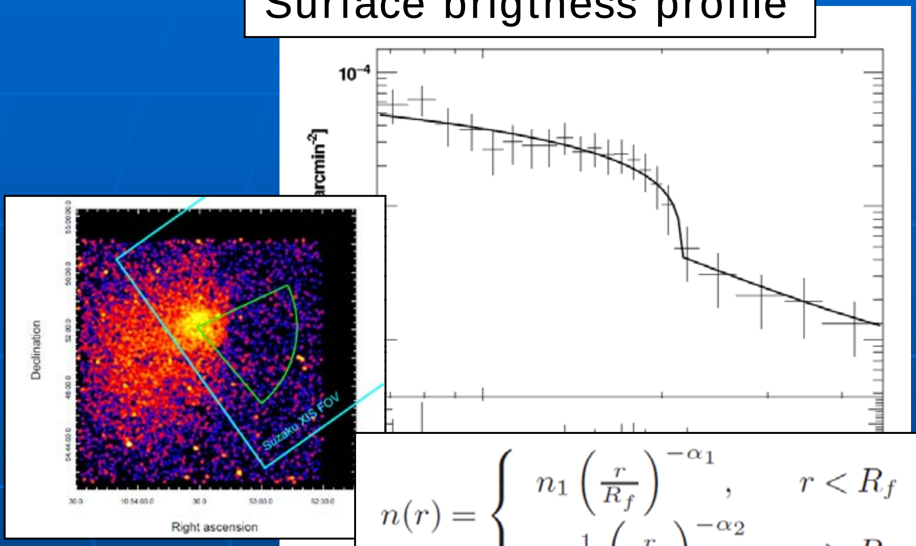


Colors: X-ray(Suzaku)
contours: radio(WSRT)

- We found surface brightness edge, between the cluster X-ray peak and relic.
- This indicates the discontinuity in the density structure.
- Shock?, contact discontinuity?, others?

RXC J1053: Surface britness edge (2) (Itahana et al. 2017)

Surface brigtness profile



$$n(r) = \begin{cases} n_1 \left(\frac{r}{R_f}\right)^{-\alpha_1}, & r < R_f \\ n_1 \frac{1}{C} \left(\frac{r}{R_f}\right)^{-\alpha_2}, & r > R_f \end{cases}$$

Temperature profile

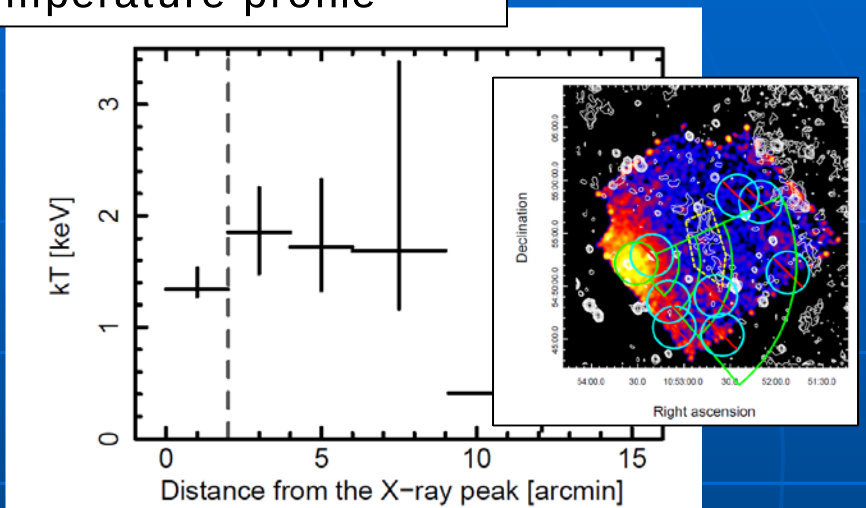


Fig. 8. The temperature profile across the surface brightness edge. The position of the surface brightness edge is displayed by dark gray dotted line.

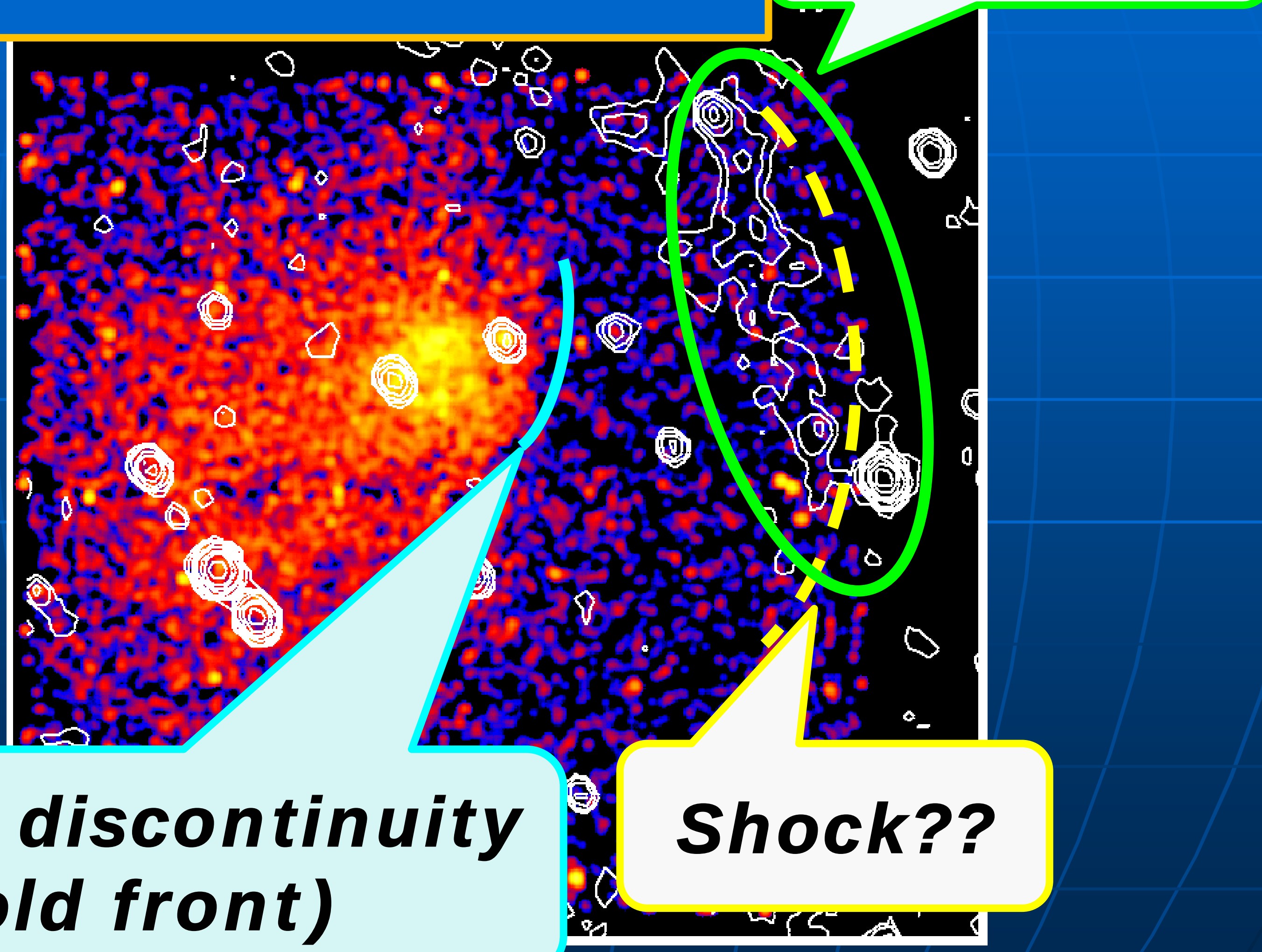
$$n_1/n_2 = 2.44^{+2.50}_{-1.22}$$

$$T_1/T_2 = 0.72^{+0.24}_{-0.15}$$

$$P_1/P_2 = 1.76^{+1.89}_{-0.95}$$

- This is not a shock, may be a contact discontinuity.

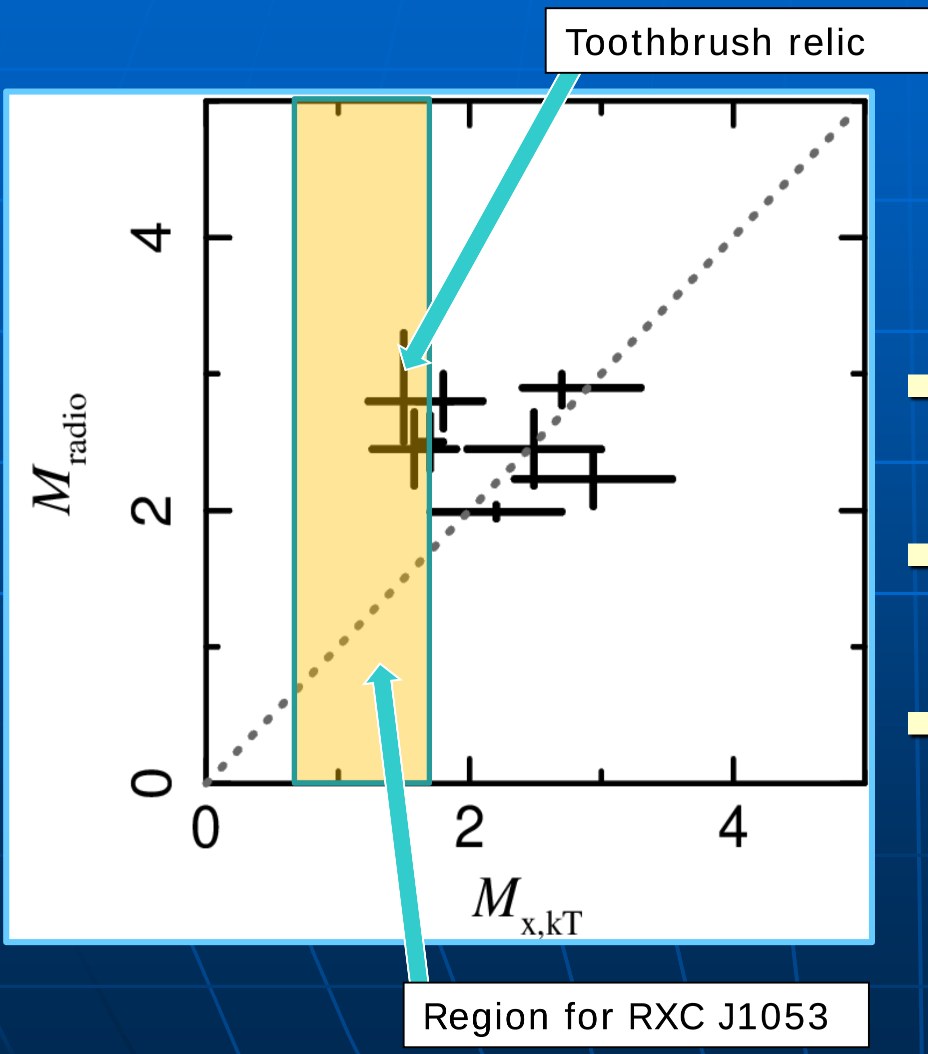
East – West merger event ??

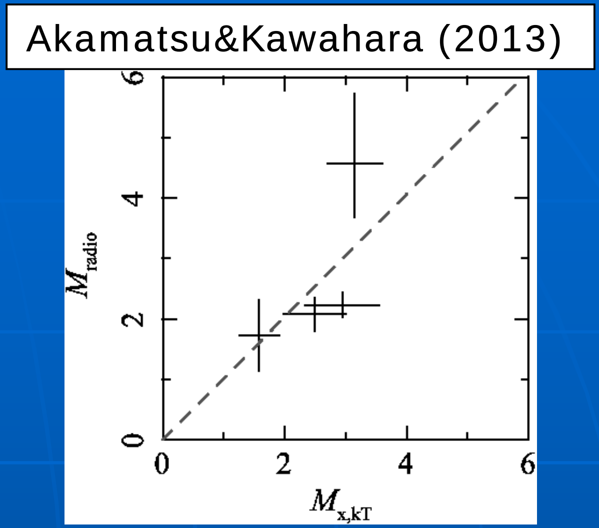


Summary

- Diffuse non-thermal radio emssions are found in some clusters of galaxies (radio halos, relics). Radio relics are likely associated with shocks in the ICM.
- Comparison with X-ray and radio observation results provide us with implications of diffusive shock acceleration model.
- In toothbrush relic, there is a hint of inconsistency between X-ray and radio Mach number estimates.
- In RXC J1053, we measure ICM temperature for the first time and estimate Mach number of shock candidate at the relic and found a feature like a contact discontinuity.

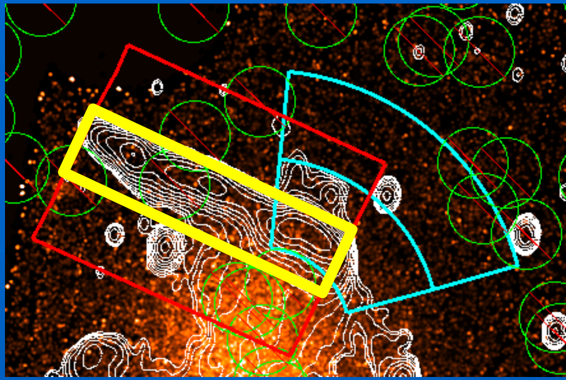
Radio relic Mach number problem: updated version





- Sample size becomes slightly larger.
- Some radio results has been changed.
- Basically, M_X and M_{radio} seems to be consisitent with each other, but some outliers like “toothbrush” may exist.

Magnetic field strength (Toothbrush relic)



- Non-thermal X-ray（0.3-10 keV） upper limit

$$F_{IC[0.3\text{–}10\mathrm{keV}]} < 2.24\times10^{-13}\quad \mathrm{erg/cm^2/s}(90\%信頼度)$$

- Radio flux corresponding to X-ray (0.3–10 keV)

$$F_{sync[0.3\text{–}10\mathrm{keV}]} = 6.8\times10^{-15}\left(\frac{B}{\mathrm{G}}\right)^{-0.1}$$

(van Weeren et al. 2012)

$$S_{1382\mathrm{MHz}} = 319.5 \pm 20.8\ mJy$$

$$\frac{F_{sync}}{F_{IC}} = \frac{B^2/8\pi}{U_{CMB}}$$

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

Energy density(toothbrush relic)

- Magnetic field

$$U_B = \frac{B^2}{8\pi} > 1.0\times10^{-13}\ \mathrm{erg/cm^3}$$

- Thermal ICM

$$U_{th} = \frac{3}{2}\frac{n_e kT}{\mu} = 8.6\times10^{-12}\ \mathrm{erg/cm^3}$$

- Non-thermal electrons

$$U_e = \int C\left(\frac{E}{m_e c^2}\right)^{1-p} dE < 3.6\times10^{-14}\ \mathrm{erg/cm^3}$$

$$\frac{U_B}{U_{th}} > 1.2\times10^{-2}$$

$$\frac{U_e}{U_{th}} < 4.3\times10^{-3}$$

Magnetic Field Strength (RXC J1053 relic)

$$\frac{S_{Synch}}{S_{IC}} \propto \frac{B^{(p+1)/2}\nu_{Synch}^{-(p-1)/2}}{(kT_{CMB})^{(p+5)/2}\nu_{IC}^{-(p-1)/2}}$$

$$S_{1382\,\mathrm{MHz}} = 15 \pm 2\ \mathrm{mJy}$$

(van Weeren et al. 2011)

- $\Gamma = 2.0$

$S_{\mathrm{IC}} < 2.22 \times 10^{-10}$ Jy at 10 keV ($\nu_{\mathrm{IC}} = 2.4 \times 10^{18}$ Hz)

→ $B > 0.73\mu\mathrm{G}$

- $\Gamma = 3.8$

$S_{\mathrm{IC}} < 1.11 \times 10^{-8}$ Jy → $B > 2.00\ \mu\mathrm{G}$

Energy Density (RXC J1053 relic)

$$U_{th} = 1.52^{+1.10}_{-0.45} \times 10^{-13}\ \mathrm{erg/cm^3}$$

$$n_e = 3.12^{+0.78}_{-1.08} \times 10^{-5}\ \mathrm{cm^{-3}}$$

In case of $\Gamma = 2.0$

$$U_{\rm mag} > 2.1 \times 10^{-14}\ \mathrm{erg/cm^3}.$$

$$U_{\rm mag}/U_{\rm th} > 0.14.$$

$$U_e < 7.8 \times 10^{-16} \mathrm{erg/cm^3}.$$

$$U_{\rm e}/U_{\rm th} < 5.1 \times 10^{-3}$$

In case of $\Gamma = 3.8$

$$U_{\rm mag} > 1.6 \times 10^{-13}\ \mathrm{erg/cm^3}$$

$$U_{\rm mag}/U_{\rm th} > 1.00$$

$$U_e < 5.6 \times 10^{-12}\ \mathrm{erg/cm^3}$$

$$U_{\rm e}/U_{\rm th} < 36.7.$$

- Unlikely???

A Simple DSA is not correct?

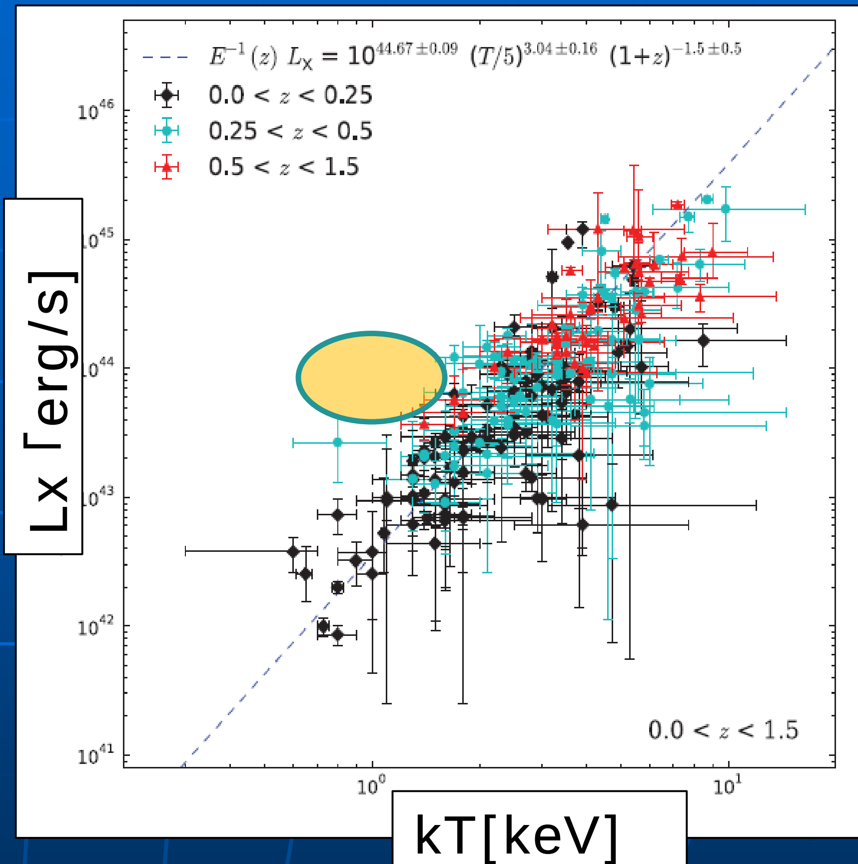
The spectrum is not a single power−law??

Temperature in the central region of RXC J1053

$$kT = 1.38^{+0.17+0.04+0.01}_{-0.11-0.04-0.01}\ \mathrm{keV}$$

- Lx – kT relation (Hilton et al. 2012)

$$\log\left(\frac{L_X}{E(z)\,\mathrm{erg/s}}\right) = (44.67 \pm 0.09) + (3.04 \pm 0.16)\log\left(\frac{kT}{5\,\mathrm{keV}}\right) - (1.5 \pm 0.5)\log(1+z)$$



$$L_{X[0.1-2.4keV]} = 0.96 \times 10^{44}\ \mathrm{erg/s}$$

$$z = 0.0704$$

$$\sigma = 665^{+51}_{-45}\ \mathrm{km/s}$$

$$kT = 3.04 \pm 1.08\ \mathrm{keV}$$