Physical Status of the Intracluster Medium Investigated through Radio and X-ray Observations

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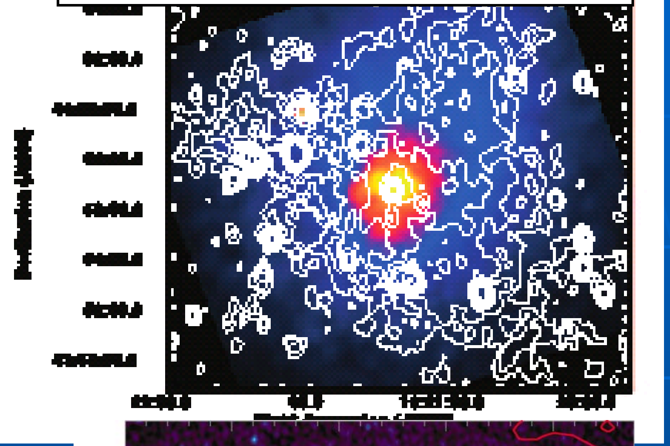
Itahana, Takizawa et al. (2015), PASJ, 67, 113
Itahana, Takizawa et al. PASJ accepted, arXiv:170807004
Sugawara, Takizawa et al. PASJ accepted, arXiv:1708.09074

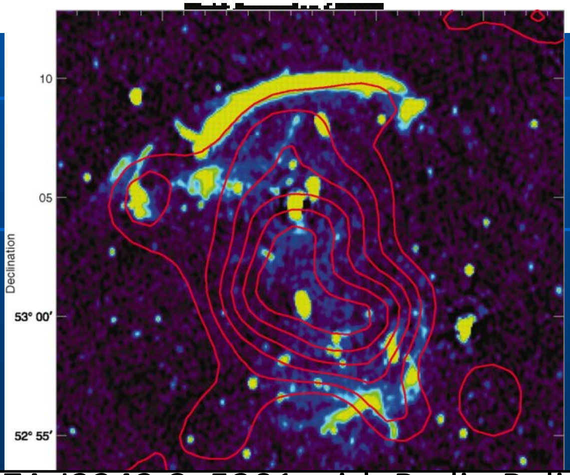
DTA workshop 2017
8 November 2017@NAOJ Mizusawa

Radio Halos / Relics

- Some merging 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?

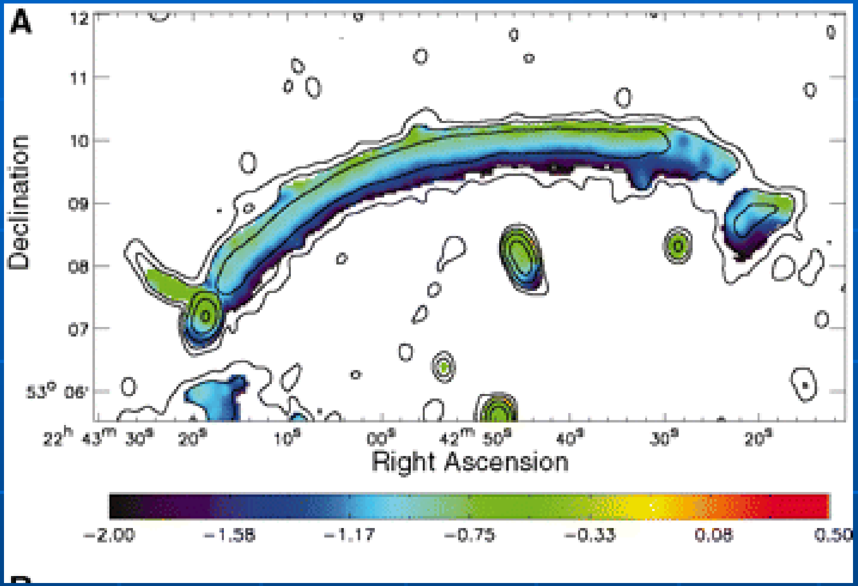


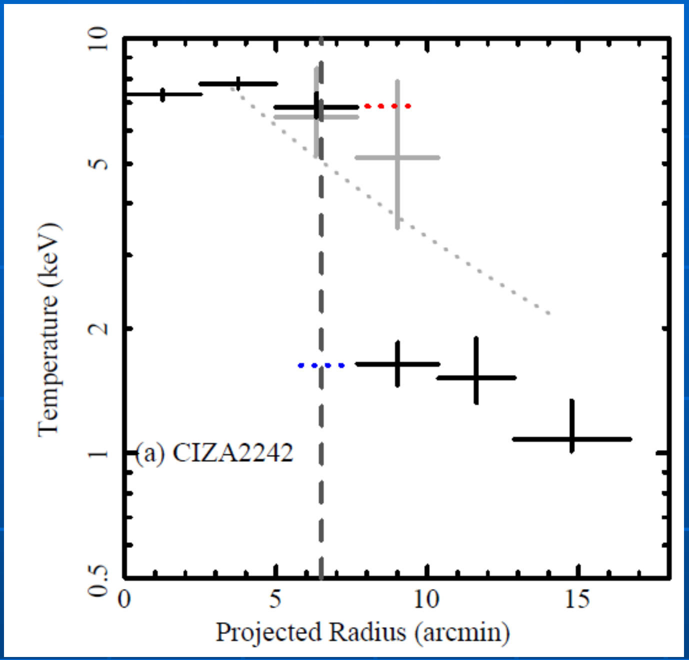
Abell 2319 with Radio Halo
Rosat X-ray image (colors)
Radio image (contours)
Feretti et al. 1997



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)

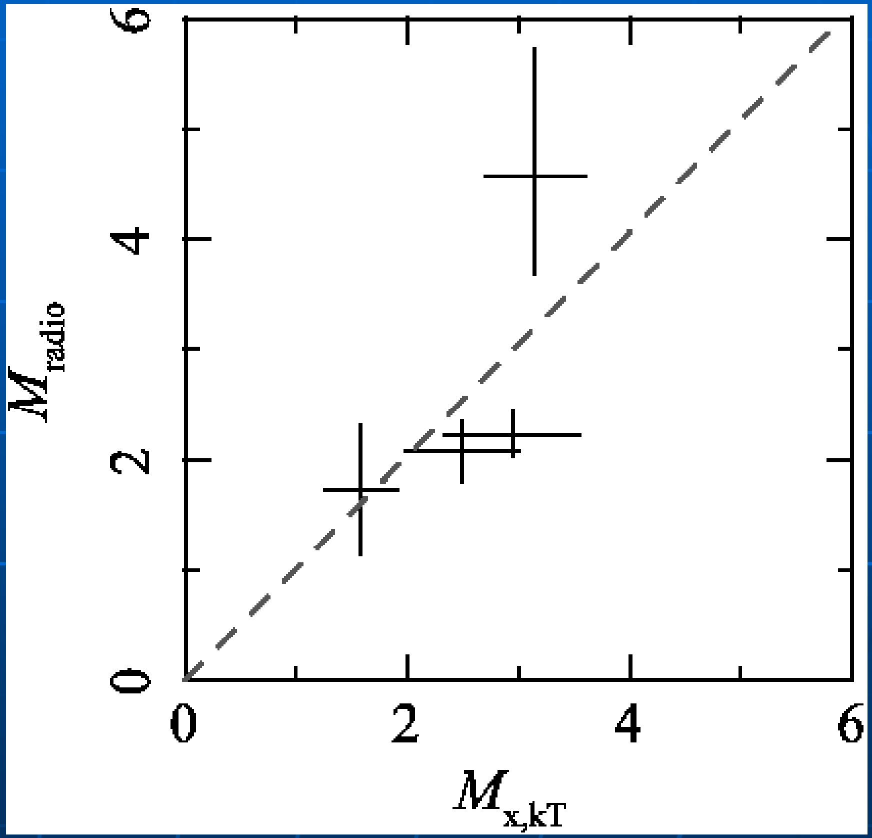
With the RH relation

---->

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

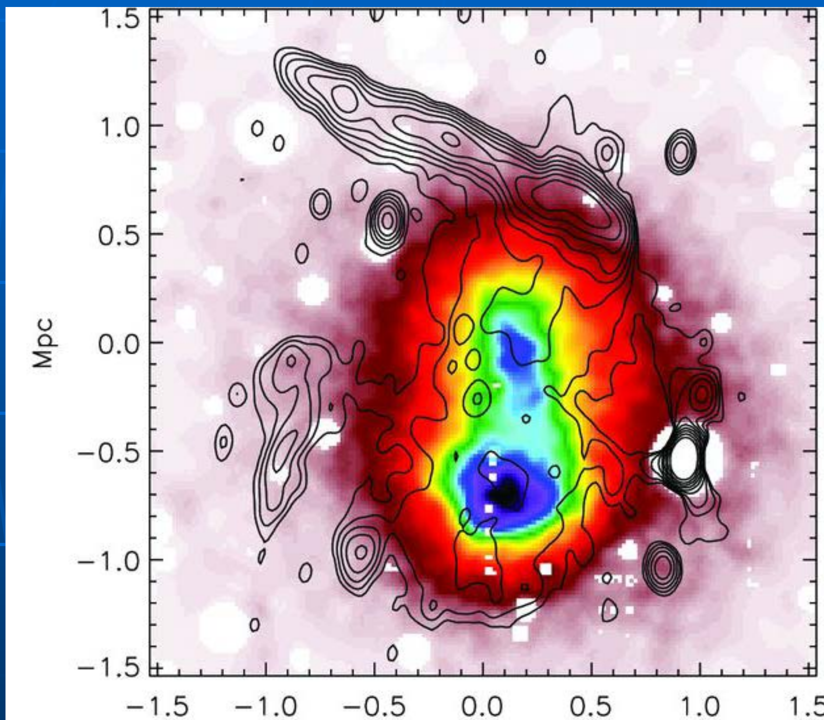
Radio Relics:
Mach Number consistency???

- 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.



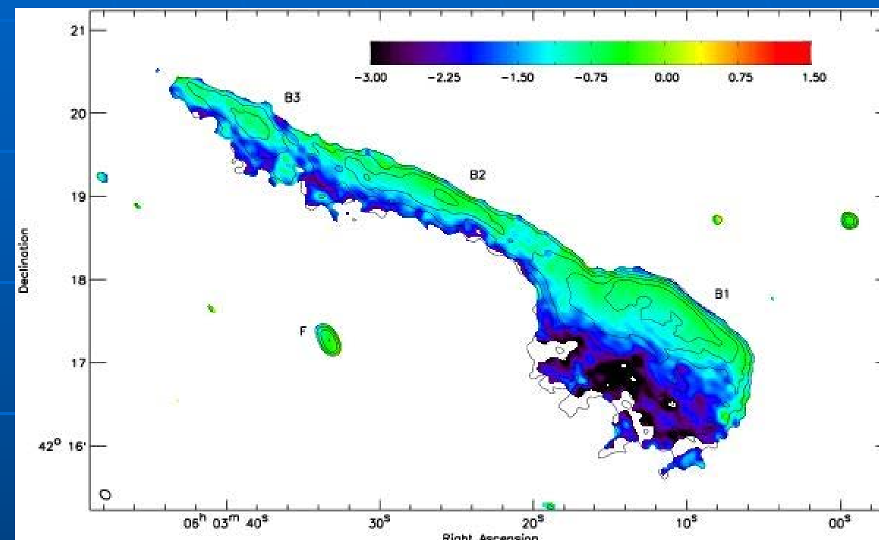
Akamatsu&Kawahara (2013)

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



Ogrean et al. (2013)

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



Radio spectral index map
(van Weeren et al. 2012)

α_{inj}=0.6−0.7
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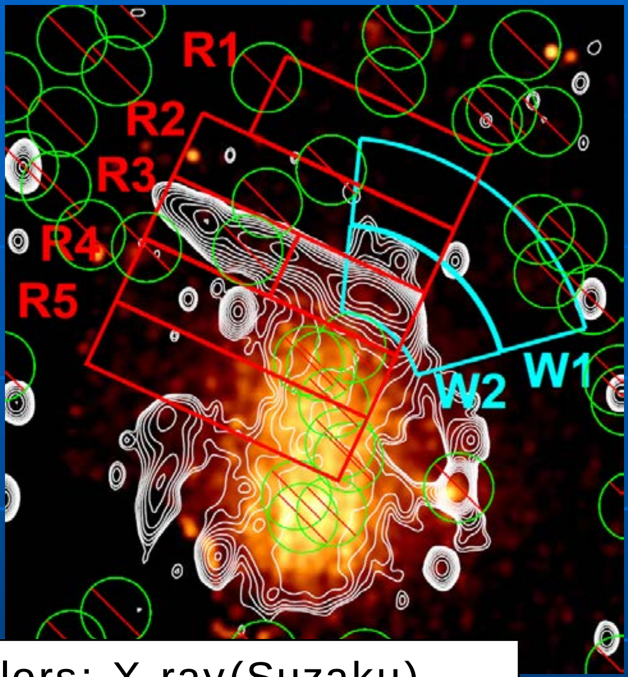
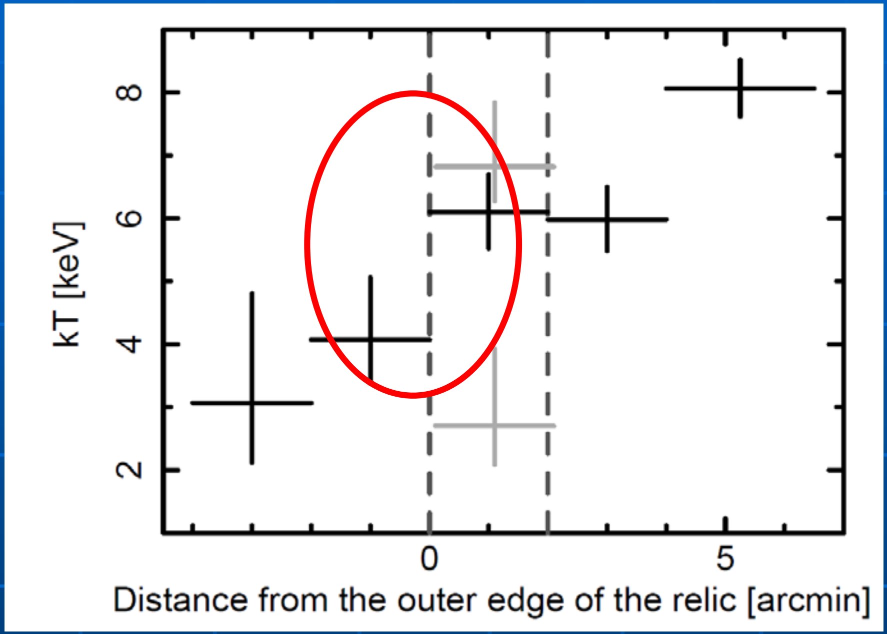
M_{radio}=3.3−4.6

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



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



- Obtained Mach number

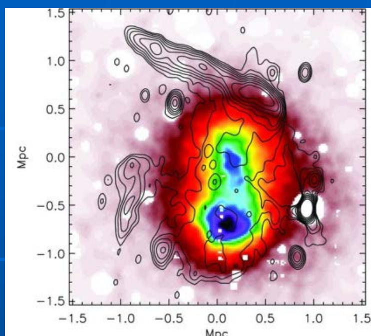
$$1.50^{+0.37+0.25+0.14}_{-0.27-0.24-0.15}$$

- Cf. updated radio results infer ～3

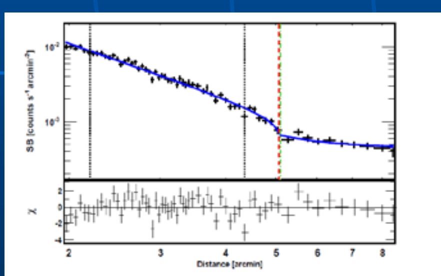
$$\frac{T_2}{T_1} = \frac{5{M_X}^4 + 14{M_X}^2 - 3}{16{M_X}^2}$$

Comparison with XMM results

- Ogrean et al. (2013) obtained a similar Mach number for the toothbrush relic with XMM data.



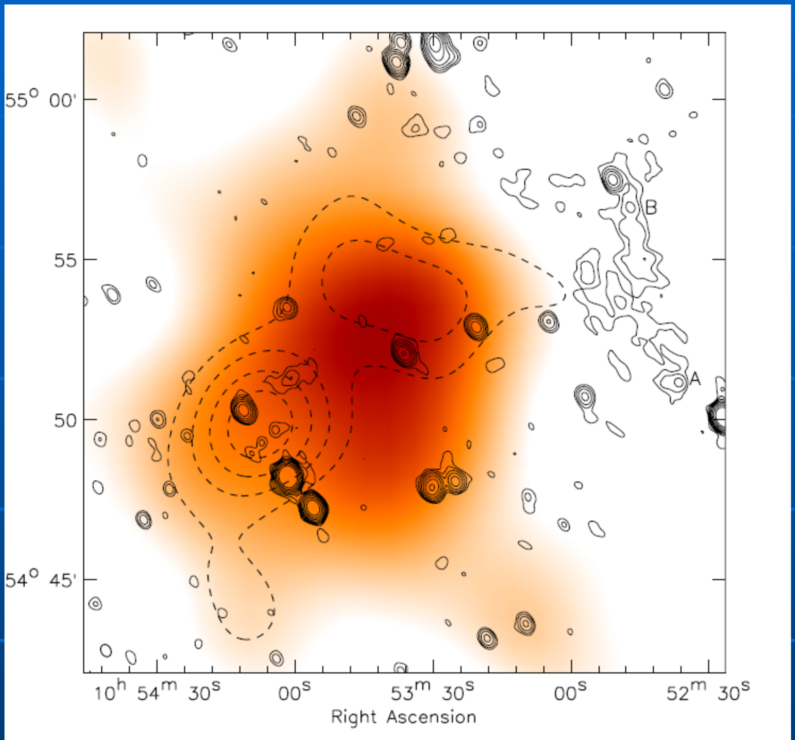
- Their results are based on X-ray surface brightness distribution analysis, which is much more severely affected by line-of-sight projection effects and, in principle, some assumptions are necessary for 3D density distribution.



$$\frac{\rho_2}{\rho_1} = \frac{4M_{\mathrm{X}}^2}{M_{\mathrm{X}}^2 + 3}$$

- Our results are more robust and model-independent.

RXC J1053.7+5453

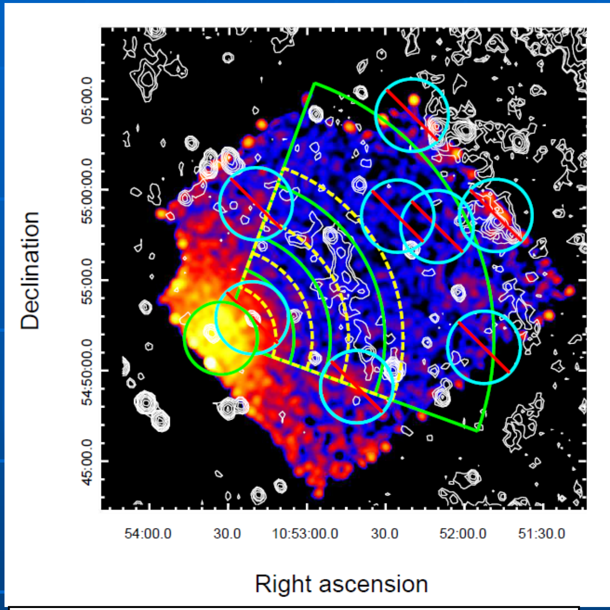


van Weeren (2011)

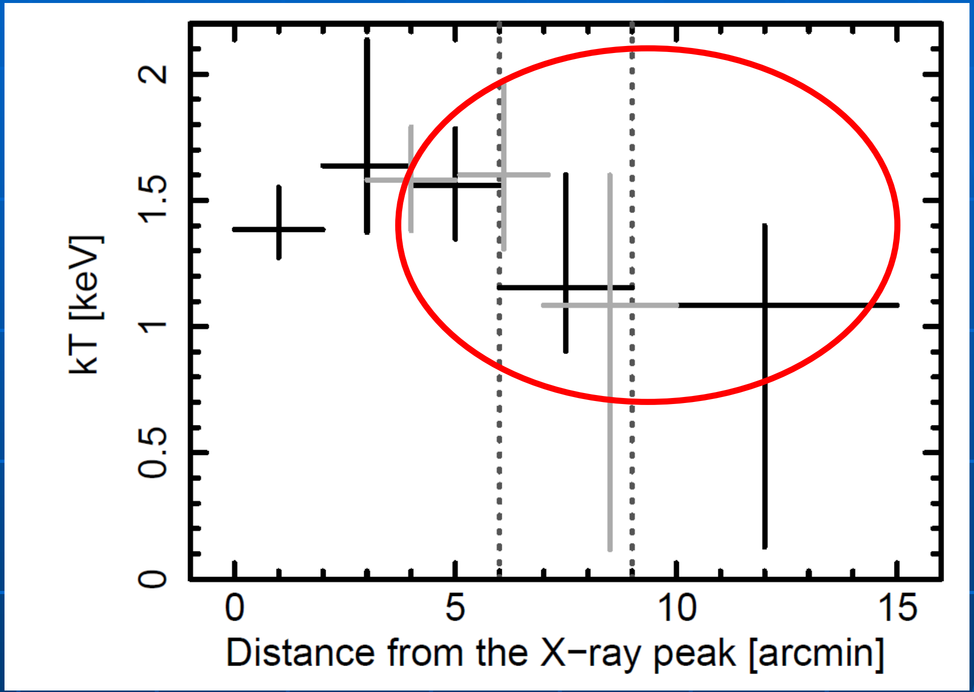
Colors: X-ray(ROSAT)
Solid contours: radio(WSRT)
Dotted contours: galaxy distribution

- 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 spectrum information

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



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

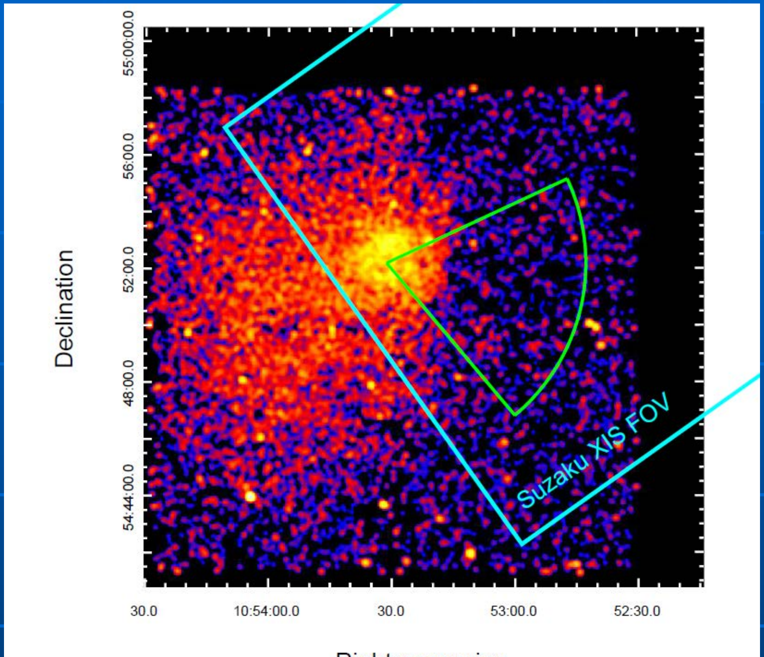


$$\frac{T_2}{T_1} = \frac{5{M_X}^4 + 14{M_X}^2 - 3}{16{M_X}^2}$$

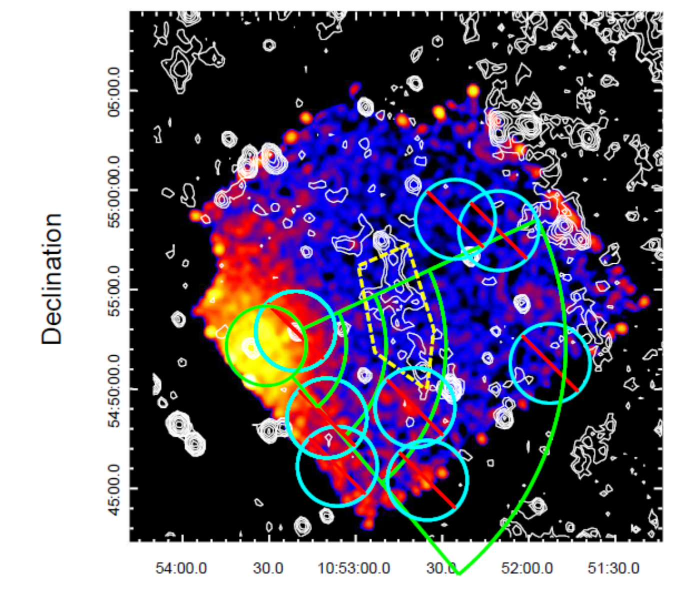
$$M_X = 1.44^{+0.48+0.14+0.03}_{-0.91-1.34-0.04}$$

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

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



Colors: X-ray(Chanda)

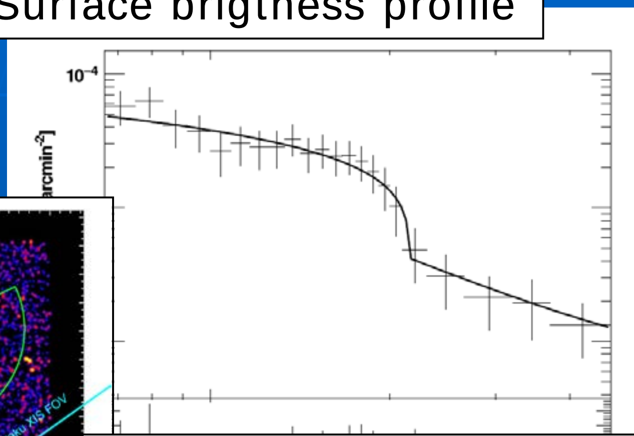


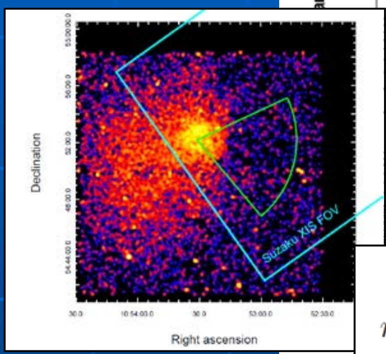
Colors: X-ray(Suzaku)
contours: radio(WSRT)

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

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

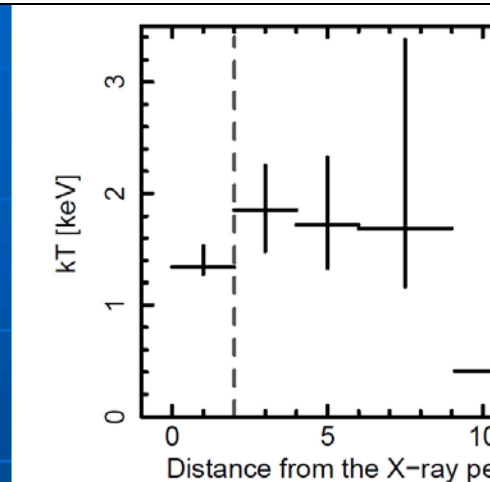
Surface brigtness profile





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

Temperature profile



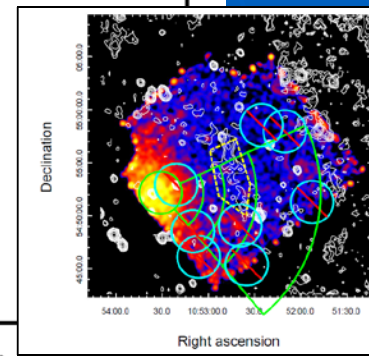


Fig. 8. The temperature profile across the surface brightness edge. The position of the surface brightness edge is displayed by dark gray dotted line.

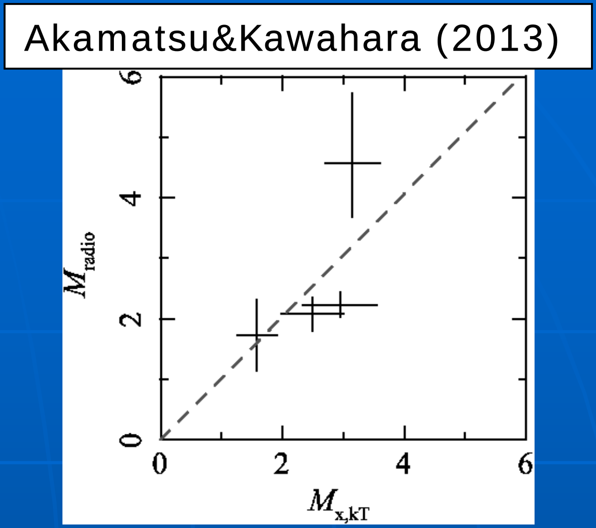
$$n_1/n_2 = 2.44^{+2.50}_{-1.22}$$

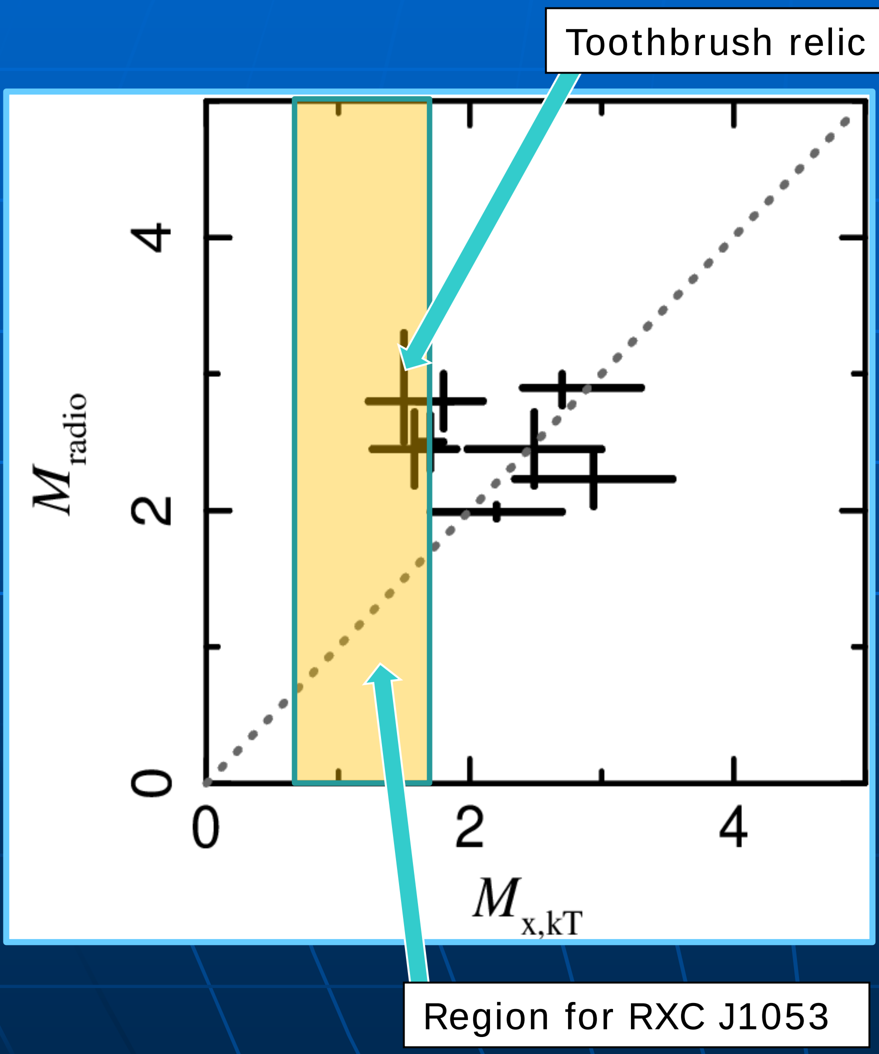
$$T_1/T_2 = 0.72^{+0.24}_{-0.15}$$

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

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

Radio relic Mach number problem: updated version



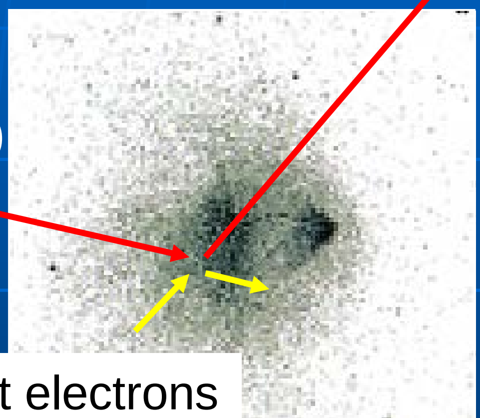


- Sample size becomes slightly larger.
- Some radio results has been changed.
- Basically, M_X and M_{radio} seems to be consisitent with each other, but some outliers like “toothbrush” may exist.

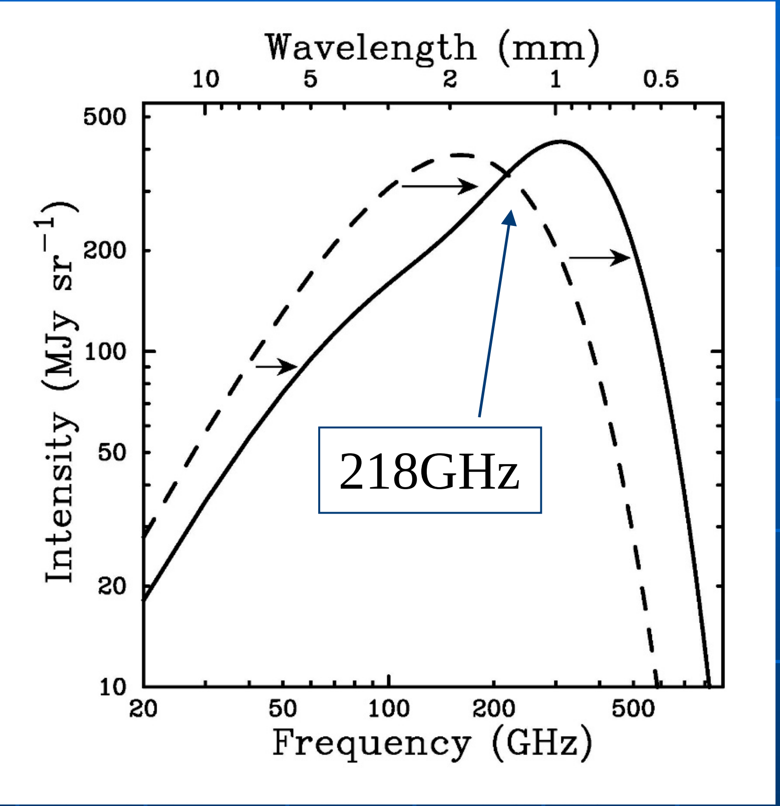
Sunyaev-Zel'dovich effect

Inverse Compton Scatterings

CMB photons
(2.7K black body)



Hot electrons
($10^{7\text{-}8}$K)



Cosmic Microwave Background (CMB) spectrum is modified because of inverse Compton scattering with hot gas such as ICM

- Decrement in mm band (R-J side)
- Increment in sub-mm band (Wein side)

SZ vs X-ray

$I_X \propto \int n_e^2\, T_e^{1/2}\, dl$

$I_{SZ} \propto \int n_e\, T_e\, dl$

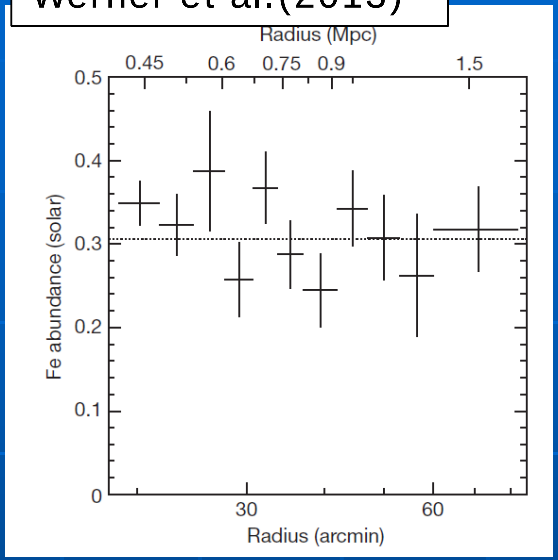
X-ray is more sensitive to density structures, while SZ is relatively sensitive to temperature structures.

$I_X \propto (1+z)^{-4}$

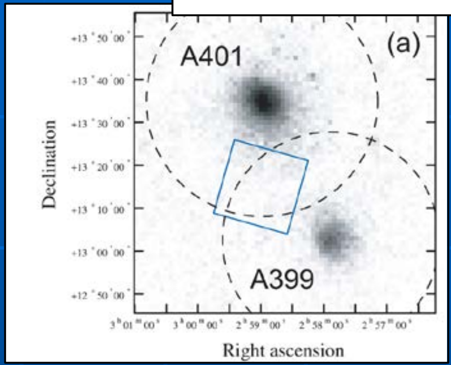
$I_{SZ} \propto (1+z)^0$, because $U_{CMB} \propto (1+z)^4$

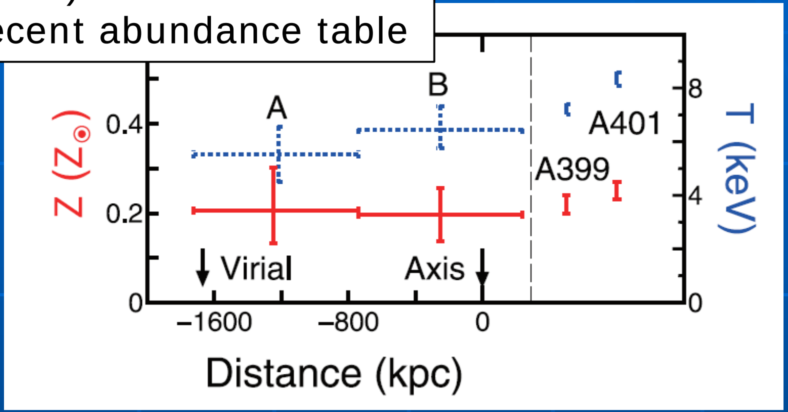
Metal Abundance in the outskirts of galaxy clusters

Fe abundance of
Perceus cluster
Werner et al.(2013)

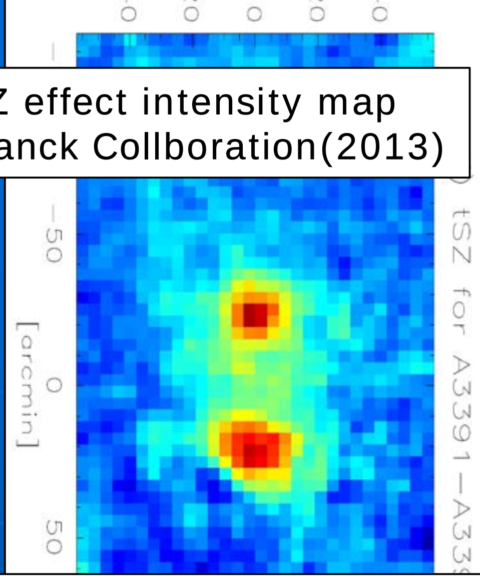


A399&A401
Fujita et al.(2008)
Z〜0.3 with recent abundance table

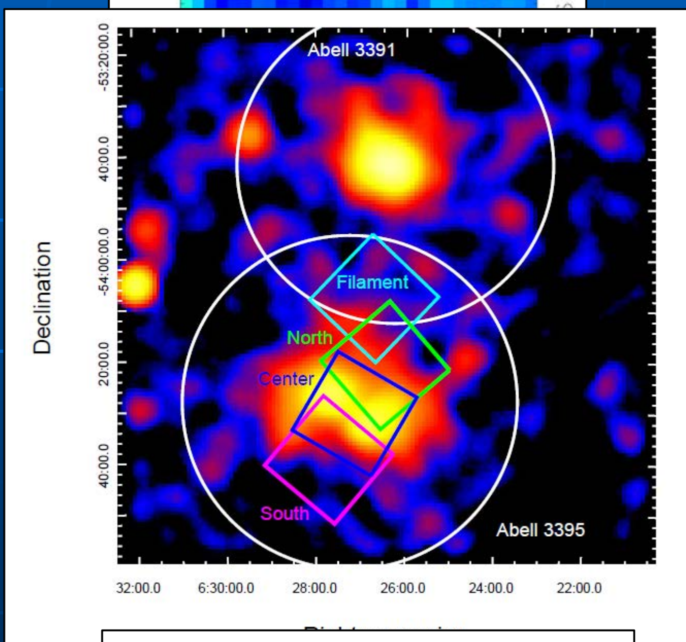




- Metal abundance in the cluster outskirs contains crucial information about transport processes of heavy elements from galaxies to the intergalactic space.
- There are only a few limited examples of the abundance measurements at the virial radius of clusters (A401&A399、Perseus, Virgo), because they are faint.
- Z〜 0.3 solar, relatively high, which suggest an eraly enrichment scenario owing to outflows powered by SNs and/or AGNs.
- We need more samples.



SZ effect intensity map
Planck Collboration(2013)

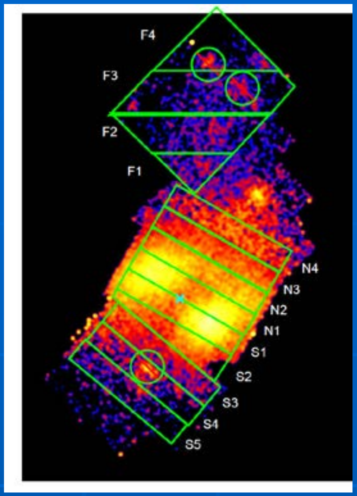


A3395&3391
ROSAT image
White circles: virial radi
Squares: Suzaku XIS FOV

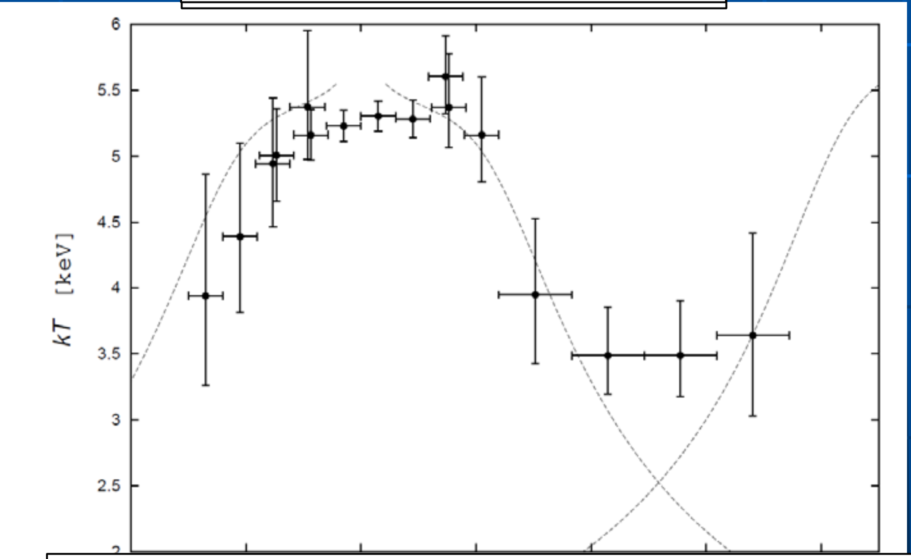
Abell 3395 & Abell 3391

- Virial radi are overlapped with each other. pre-merger?
- Hot ICM in the linked region
  - Diffuse X-ray emissions are detected with ROSAT and ASCA (Tittley & Henriksen 2001).
  - SZ effect detection (Planck Collaboration 2013)
- Because of the interaction of two clusters, the linked region is relatively bright, and suitable for the measurements of the abundance (similar to A399&A401).

A3395&3391: kT distribution (Sugawara et al. 2017)



kT distrubution
Dotted line: universal kT profile proposed by Okabe et al.(2014)



south<---------------------------->north

- kT distribution from the north of A3395 to rhe south(region connecting to A3391)
- The results are compared with the universal kT profile proposed by Okabe et al.(2014)
- Linked region have relatively high kT

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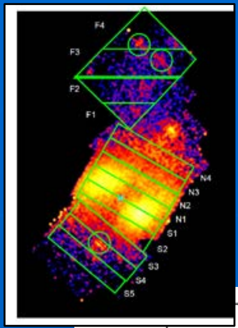
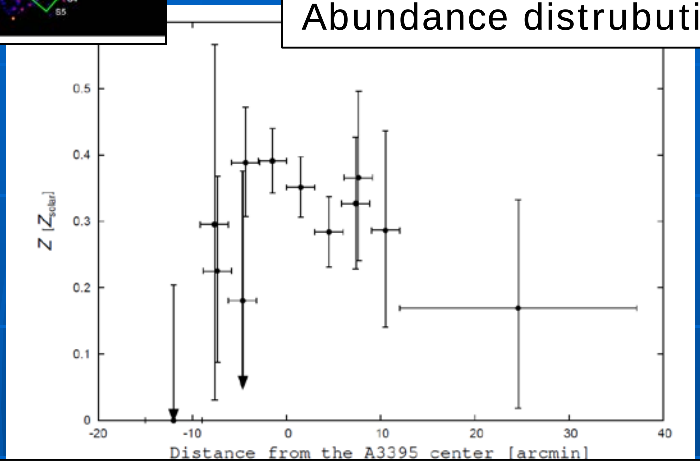
  A hint of ICM heating because of merger??

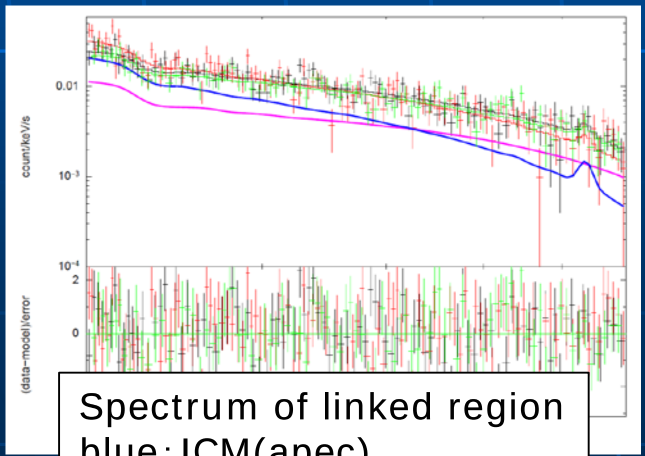


A3395&3391: abundance distribution (Sugawara et al. 2017)

Abundance distrubution



south<------------------------->north



Spectrum of linked region
blue : ICM(apec)
mazenta : CXB

- Spetral fit in the energy range of 2-7 kev（to remove impacts of Fe-L lines ）
- In the linked region, we get

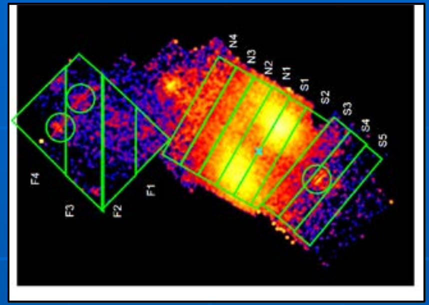
$$Z = 0.169^{+0.164+0.009+0.018}_{-0.150-0.004-0.015} \text{ solar,}$$

- Consisitent with the former results such as A399&A401, Perseus(Z～0.3).
- Suggest the early enrichiment scenario
- If we fit in the range of 0.7-7keV, Z<0.120 (Fe-L bias,Sasaki et al. 2015, Simionescu et al. 2015)

A3395&3391: Comparison with SZ results (Sugawara et al. 2017)

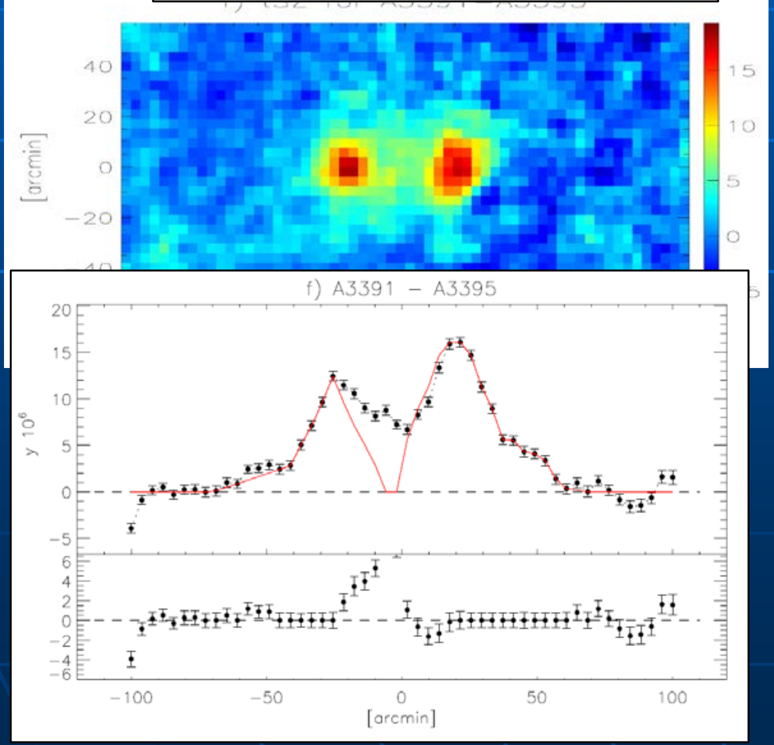
y-parameters in the linked region derived from the X-ray results

Region Number	$y\ (10^{-6})^{*}$
F1	$4.28^{+0.67+0.54+0.12}_{-0.60-0.68-0.13}$
F2	$2.90^{+0.31+0.41+0.13}_{-0.25-0.37-0.12}$
F3	$2.74^{+0.33+0.39+0.15}_{-0.25-0.36-0.13}$
F4	$2.95^{+0.64+0.54+0.19}_{-0.51-0.58-0.22}$



$$y = \int \left(\frac{kT_{\rm e}}{m_{\rm e}c^2} \right) n_{\rm e} \sigma_{\rm T} dl,$$

Planck Collaboration (2013)



- Assuming a simple geometry like cylinder, we obtained Compton y parameters only from the X-ray results (kT, n_e). --->～3×10^{-6}
- Our results are clearly smaller than the Planck results (～7×10^{-6}).
- Elongated structures along the line-of-sight？ (or inclined cylinder?)
- kT might be underestimated ?

About discrepancy of y parameters (geometrical factor etc)

- Assuming line-of-sight length L, normalization of apec model (ICM X-ray emission) is $N \propto n_e^2 L$
- Compton y parameter is $y \propto n_e L$
- Therfore, with fixed N, $y \sim L^{1/2}$
- If the assumed L is smaller than the actual L, y parameter will be underestimated.
- If the discrepancy is only owing to this geometrical effect, line-of-sight length should be ~5 times longer than the assumed value.
- A similar situation is realized if the filament is inclined to the line-of-sight derection only by ~ 10 degree.
- The difference seems too large to be explained by the geometrical effect.
- Other causes may be necessary (underestimation of X-ray kT measurements??).

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.
- SZ and X-ray observations give complemental information of ICM.
- In A3391 and 3395 filament, apparently inconsistent results are obtained from X-ray and SZ results, which give us information about geometrical structures and possible hidden heated gas.