X-ray observations of cluster shocks

Hiroki Akamatsu (SRON/NWO Veni)
Hajime Kawahara, Reinout van Weeren,
Fabio Zandanel, Huub Röttgering
and *Suzaku* key project team

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~~X-ray observations of cluster shocks~~

X-ray investigations on radio emissive region, radio relic, in galaxy clusters

Introduction
Open issues related to X-ray observations
X-ray view of radio relic clusters
- **CIZA J2242.8+5301 ("*Sausage*" relic)**
- **Other relics**

Discussion
- **Shock properties at radio relics**

What's next? Phase separated study of merging phenomena
Summary
(if interested) short summary of X-ray obs of Sausage relic (P49-52)

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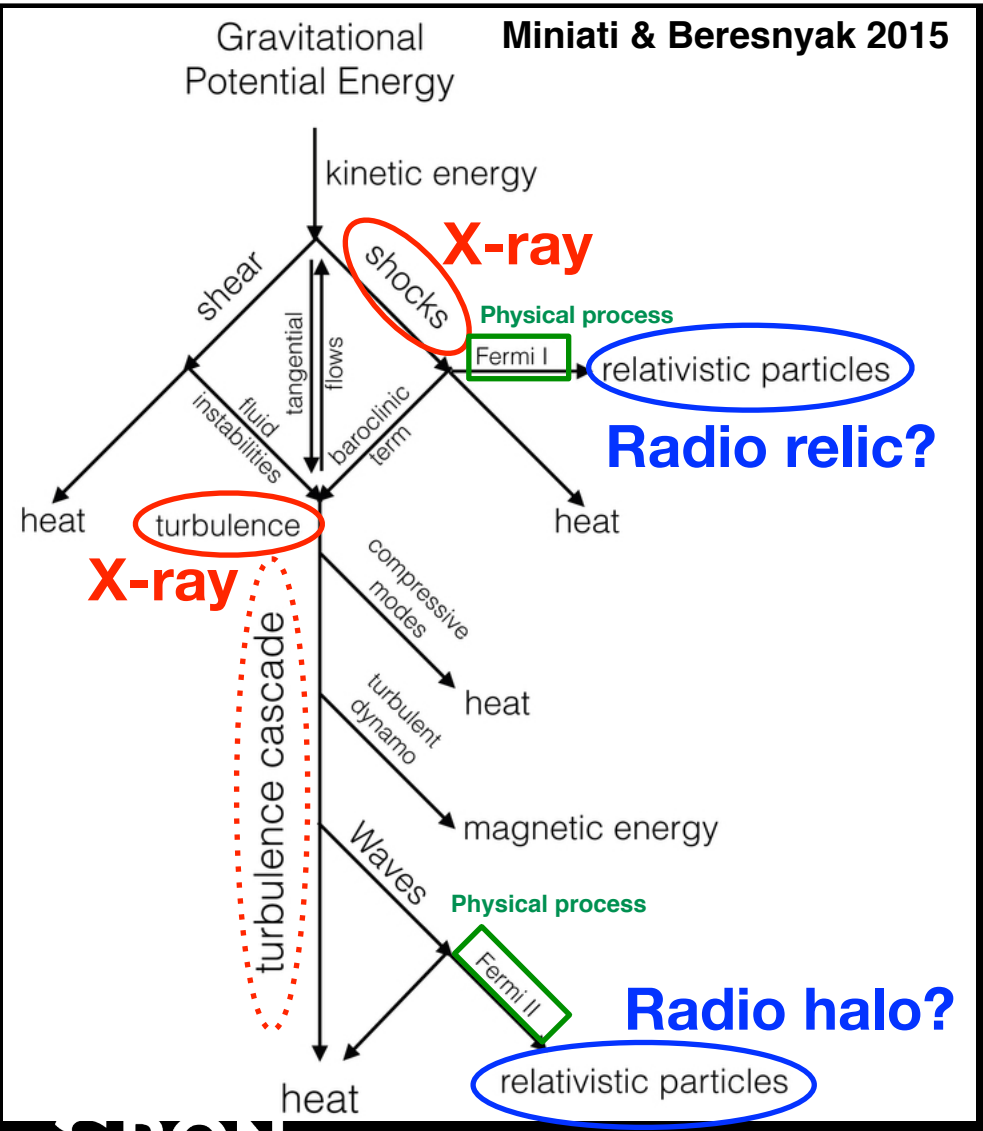
Introduction: Power of multi-wavelength approach on ICM physics



X-ray and radio are complementary to explore physical processes in the ICM

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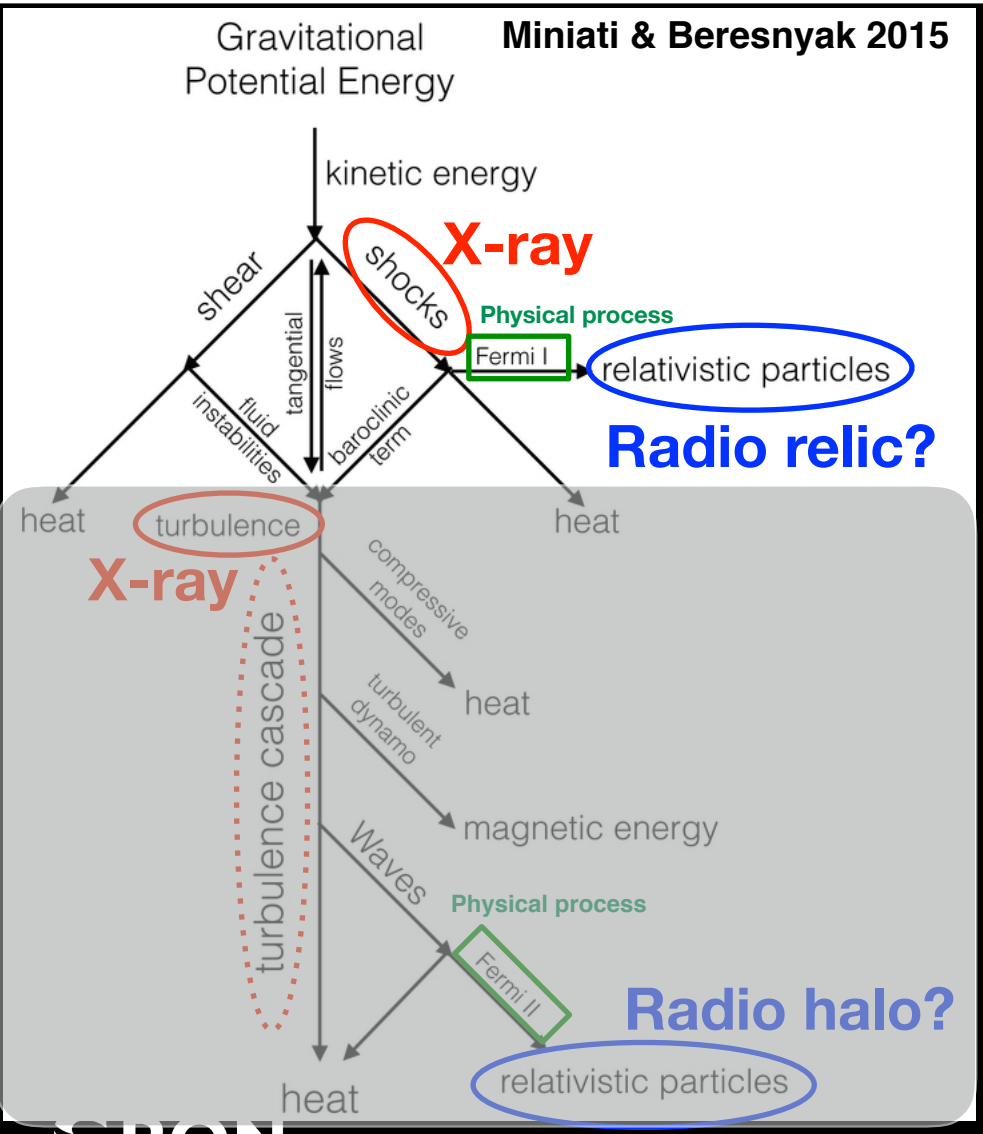


X-ray and radio are complementary to explore physical processes in the ICM

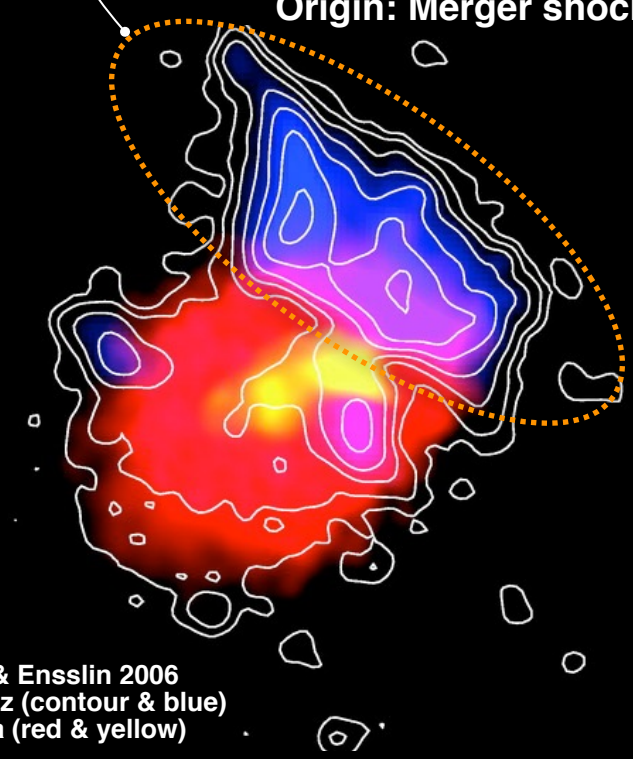
Radio Relic

Main target of the talk

Located at cluster outskirts

Shallow X-ray emission

Origin: Merger shocks?



Clarke & Ensslin 2006
VLA 1.4 GHz (contour & blue)
Chandra (red & yellow)

Short review: Open (observational) issues related to radio relics

1.) No radio emission in some shock structures
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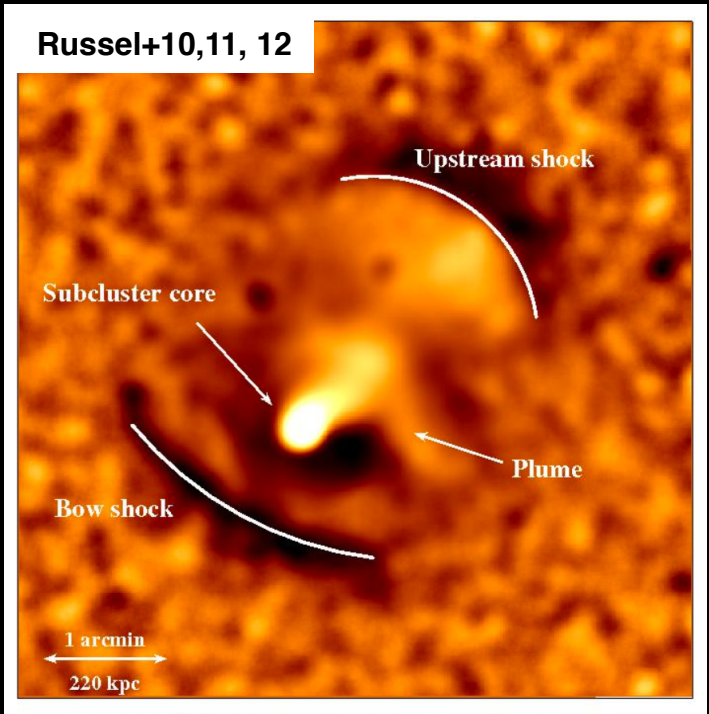
A merger mystery: no extended radio emission in the merging cluster Abell 2146



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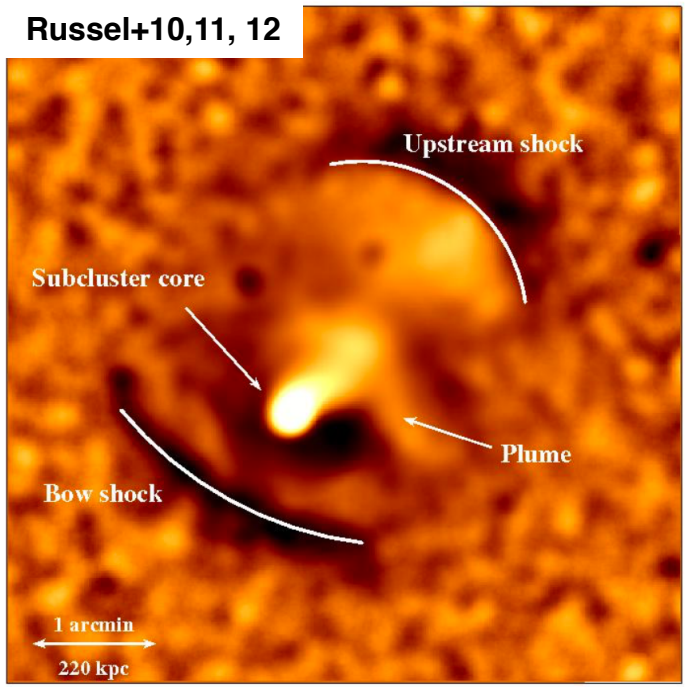
A merger mystery: no extended radio emission in the merging cluster Abell 2146

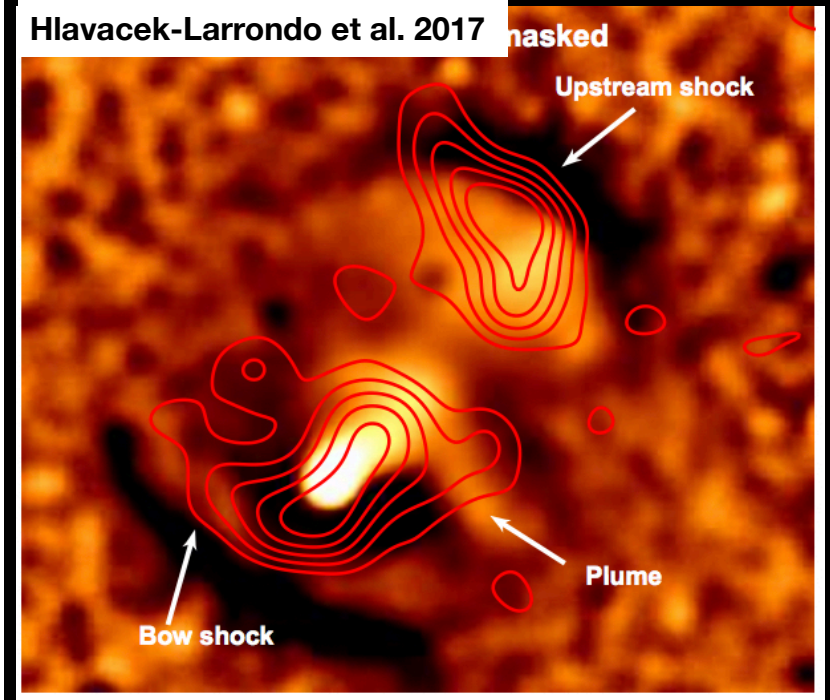
Mystery solved: discovery of extended radio emission in the merging galaxy cluster Abell 2146

Hlavacek-Larrondo-san's talk at tomorrow

Russel+10,11, 12



Hlavacek-Larrondo et al. 2017



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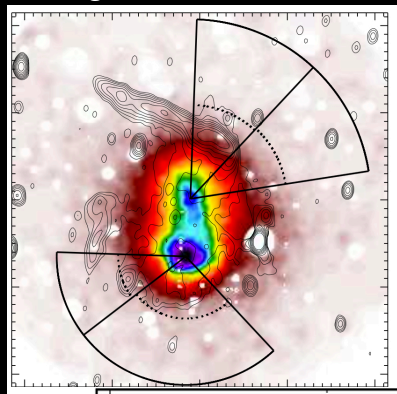
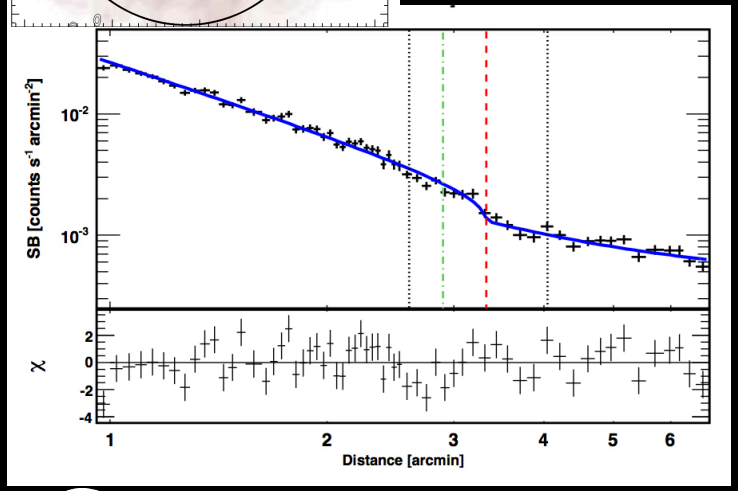


Challenges to our understanding of radio relics:
X-ray observations of the Toothbrush cluster

(ii) at the Toothbrush, the shock front is, in part, spatially offset from the radio emission



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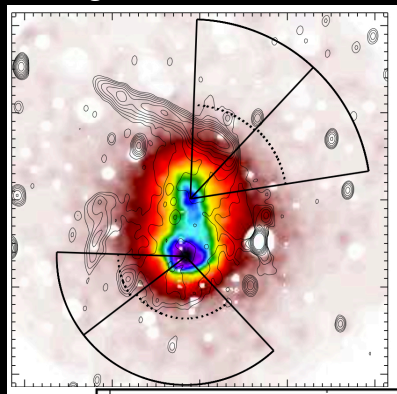

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van Were et al. 2016 with deep Chandra data

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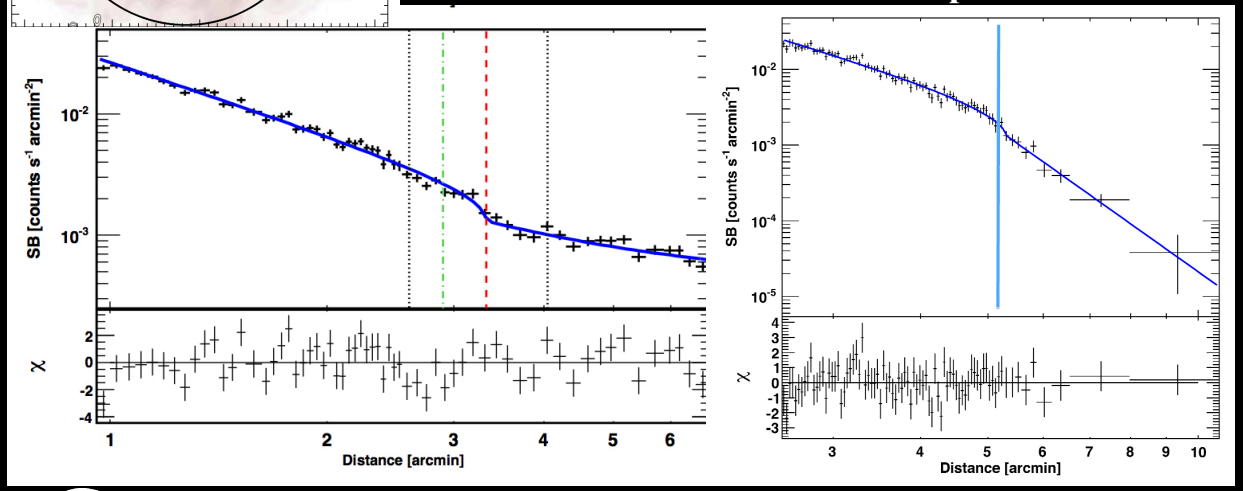

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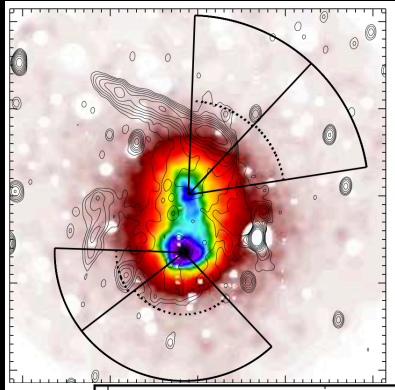

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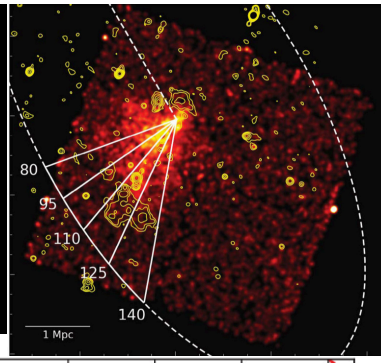
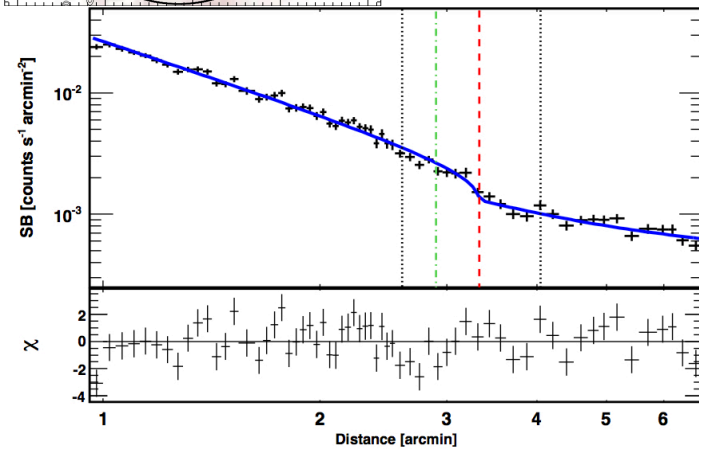
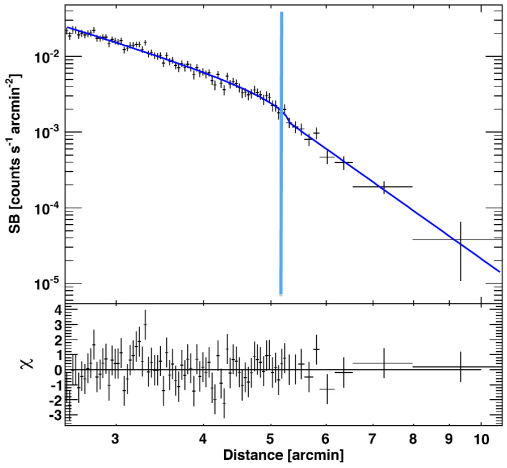
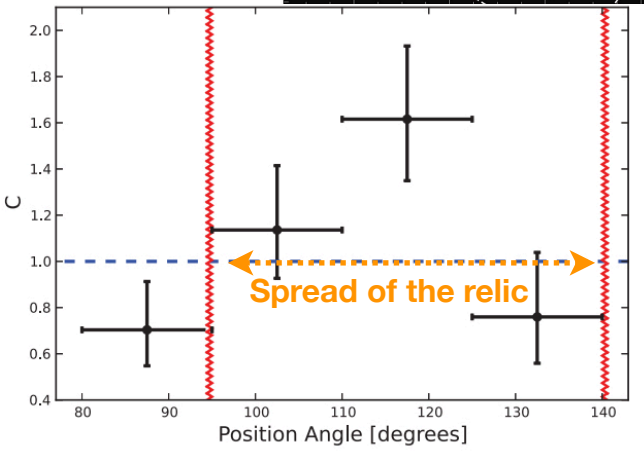
No shock across part of a radio relic in the merging galaxy cluster ZwCl 2341.1+0000?

Ogrean et al. 2014









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D. Hoang al. 2017 and his talk on Monday: LOFAR observation of ``Sausage'' cluster

Inconsistent?

Source	$\alpha_{\rm inj}$	$\alpha_{\rm int}$	$\mathcal{M}_{\rm inj}$	$\mathcal{M}^{e}_{\rm int}$	$\mathcal{M}^{X}$
RN	-0.81 ± 0.11	-1.11 ± 0.02	$2.7^{+0.6}_{-0.3}$	$4.4^{+0.4}_{-0.3}$	$2.7^{+0.7}_{-0.4}{}^{a}$
RS	-1.19 ± 0.22	-1.41 ± 0.05	$2.0^{+0.3}_{-0.2}$	$2.4^{+0.1}_{-0.1}$	$1.7^{+0.4}_{-0.3}{}^{a}$
R1	-0.90 ± 0.11	-1.18 ± 0.10	$2.4^{+0.4}_{-0.2}$	$3.5^{+1.6}_{-0.6}$	$2.5^{+0.6}_{-0.2}$

X-ray and radio: Consistent?

Suzaku: Fifth Japanese X-ray Satellite (2005~2015)

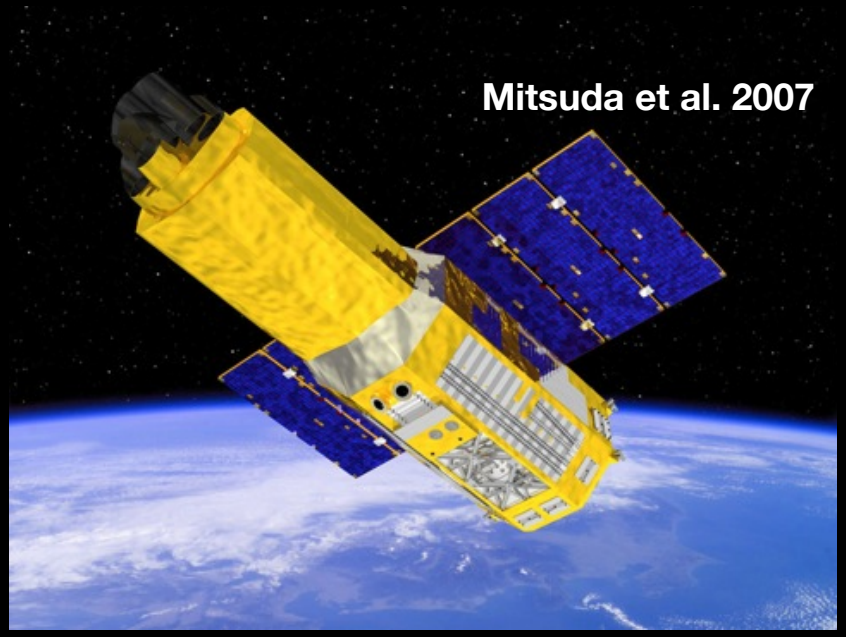
Low and stable background, *Suzaku* could explore outskirts of clusters (see Reiprich+13)

Nice instrument to investigate ICM properties at outskirts via spectroscopy

Drawbacks: limited angular resolution (PSF~2 arcmin)

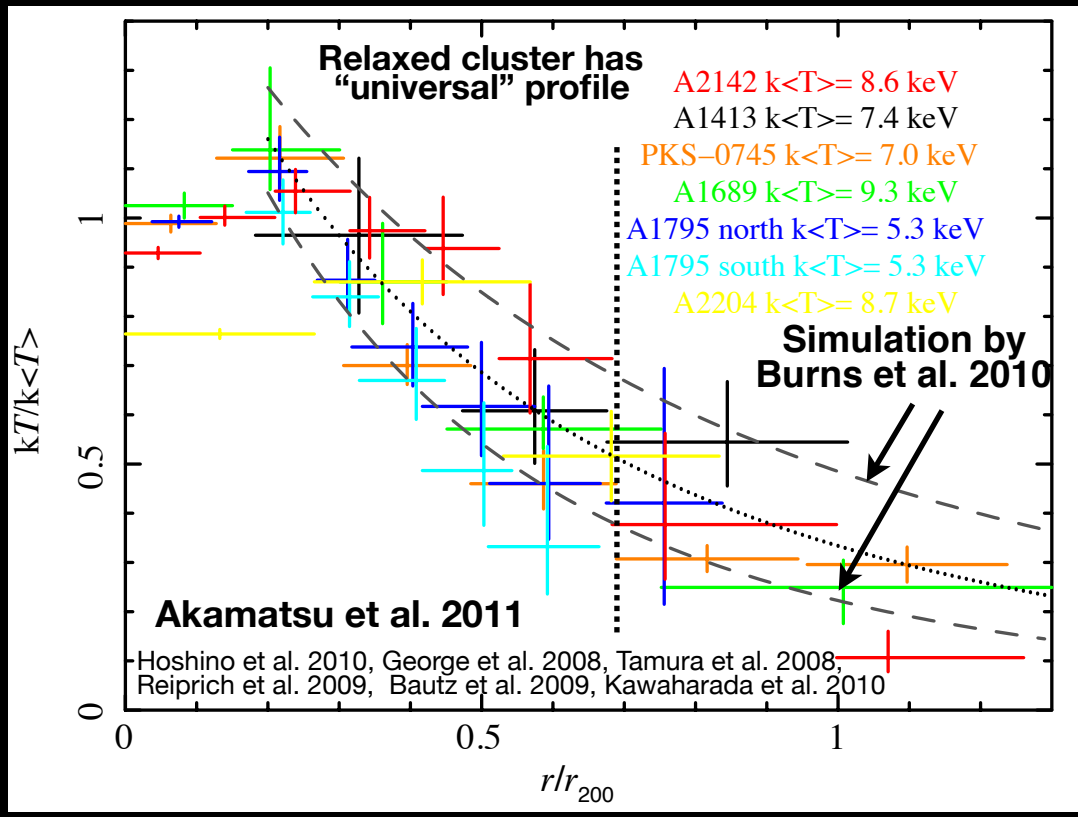
=> Careful data analysis is needed (although common at outskirts)

=> Combination of other satellites (XMM, Chandra)



Mitsuda et al. 2007

For results from Hitomi, please see Markevitch-san's, Zhuravlera-san's talk



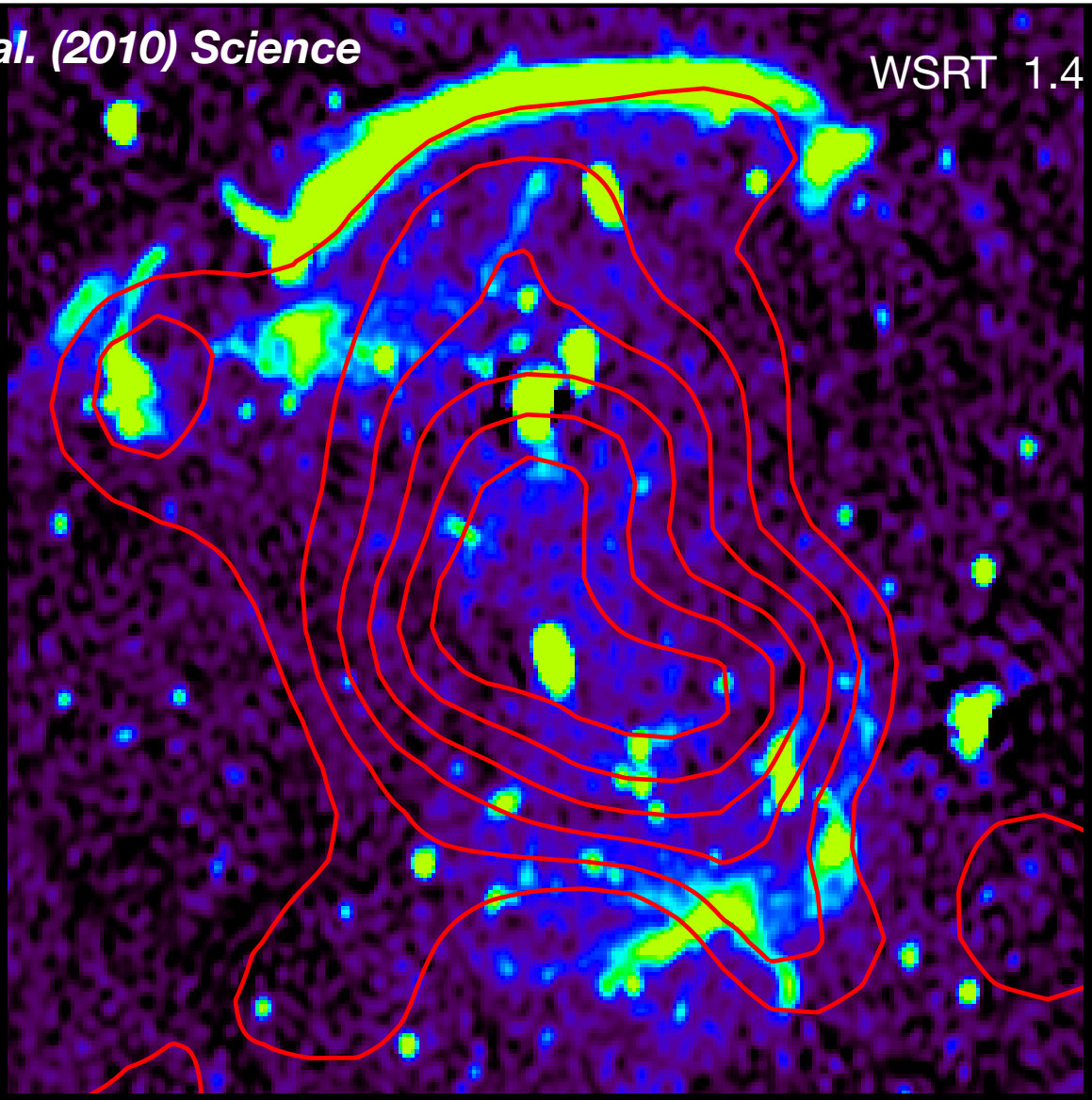
Suzaku view of radio relic clusters

CIZA J2242.8+5301

and etc.,

CIZA J2242.8+5301 (a.k.a Sausage relic)

van Weeren et al. (2010) Science



WSRT 1.4 GHz radio image

z = 0.192
Lx ~ 6 x 10^{44} erg/s
kT ~ 9 keV

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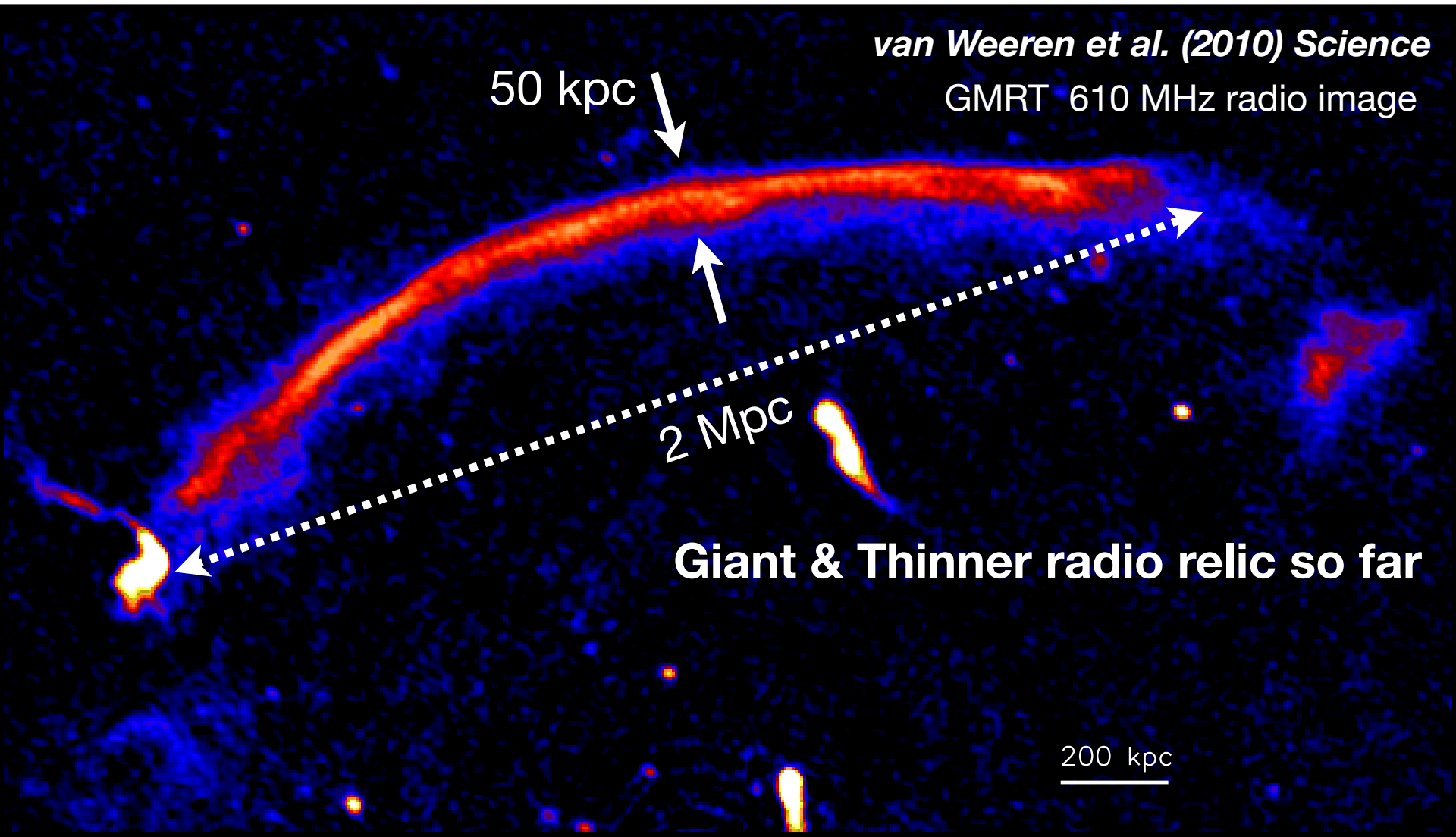
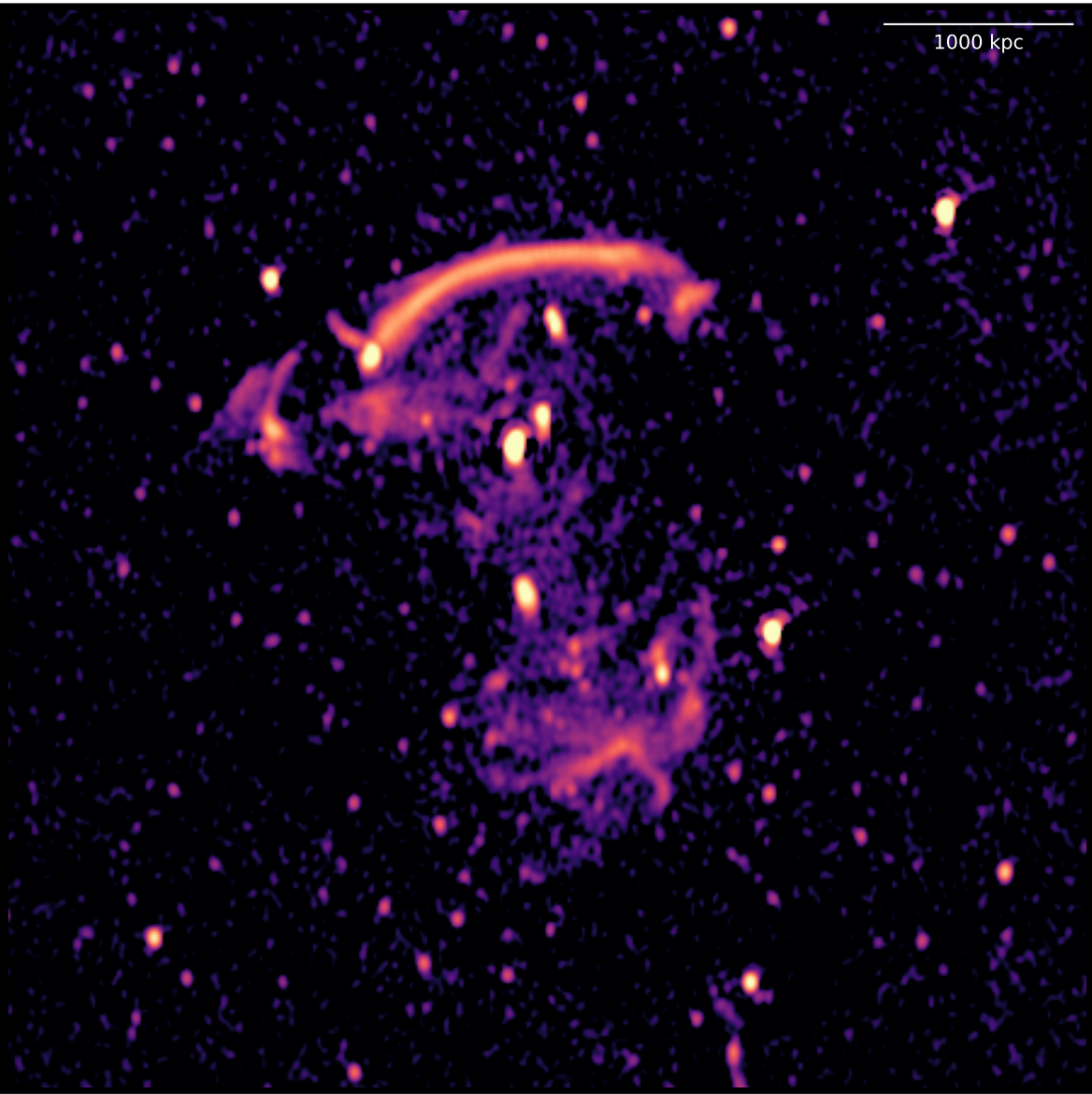
CIZA J2242.8+5301 (a.k.a Sausage relic)



CIZA J2242.8+5301: Suzaku observations



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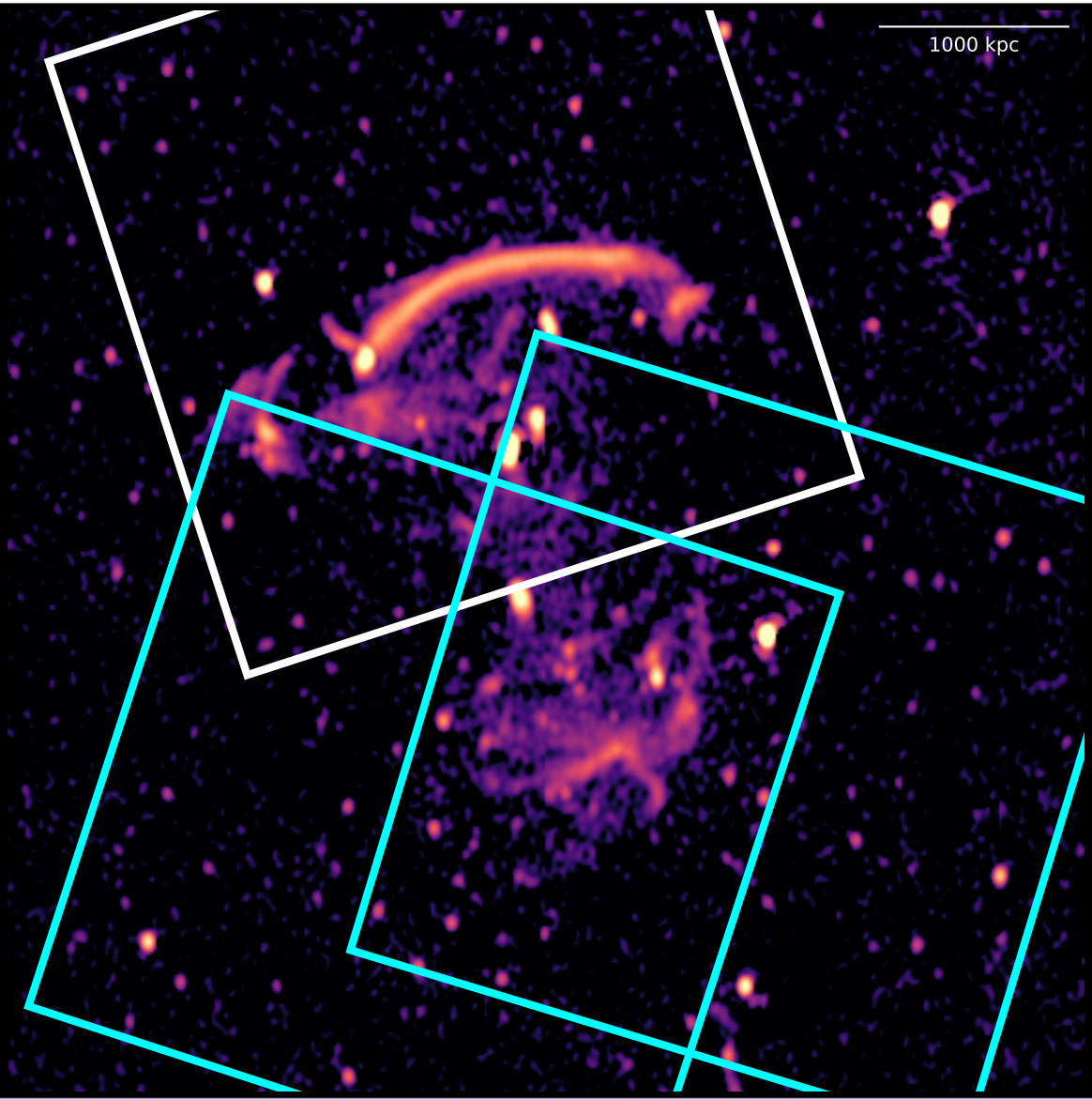

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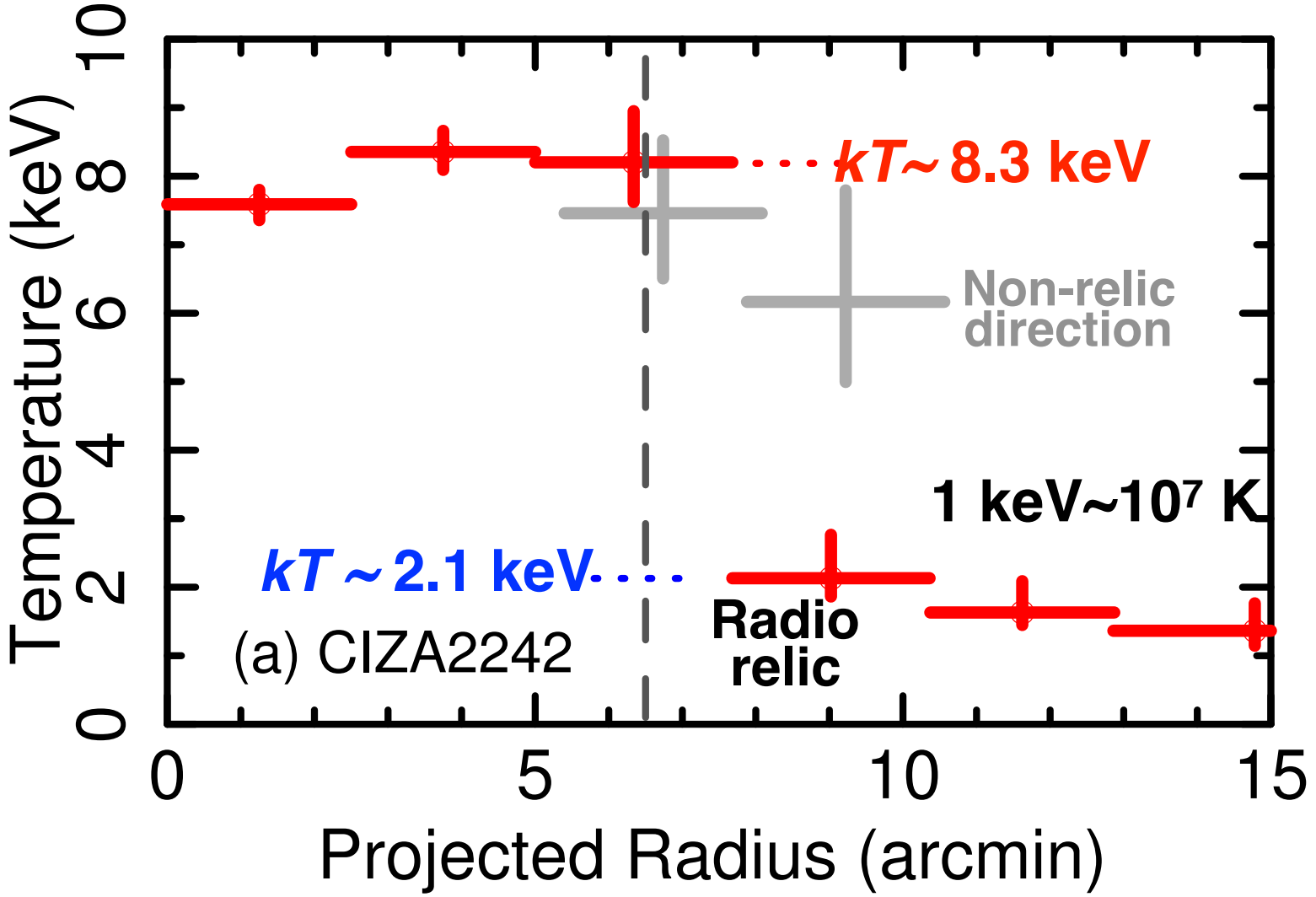
CIZA J2242.8+5301 *(Akamatsu & Kawahara 2013, HA et al. 2015)*



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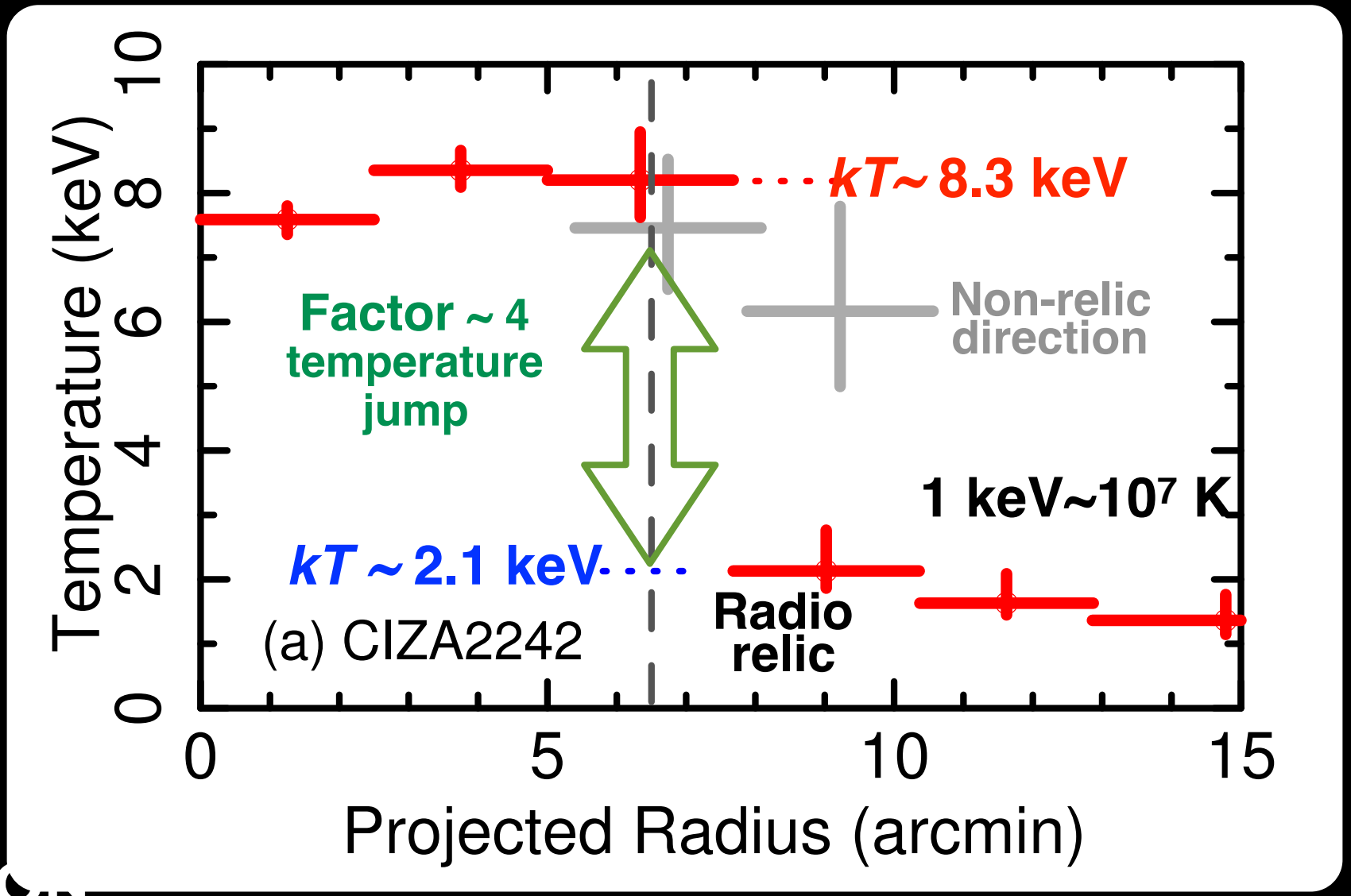

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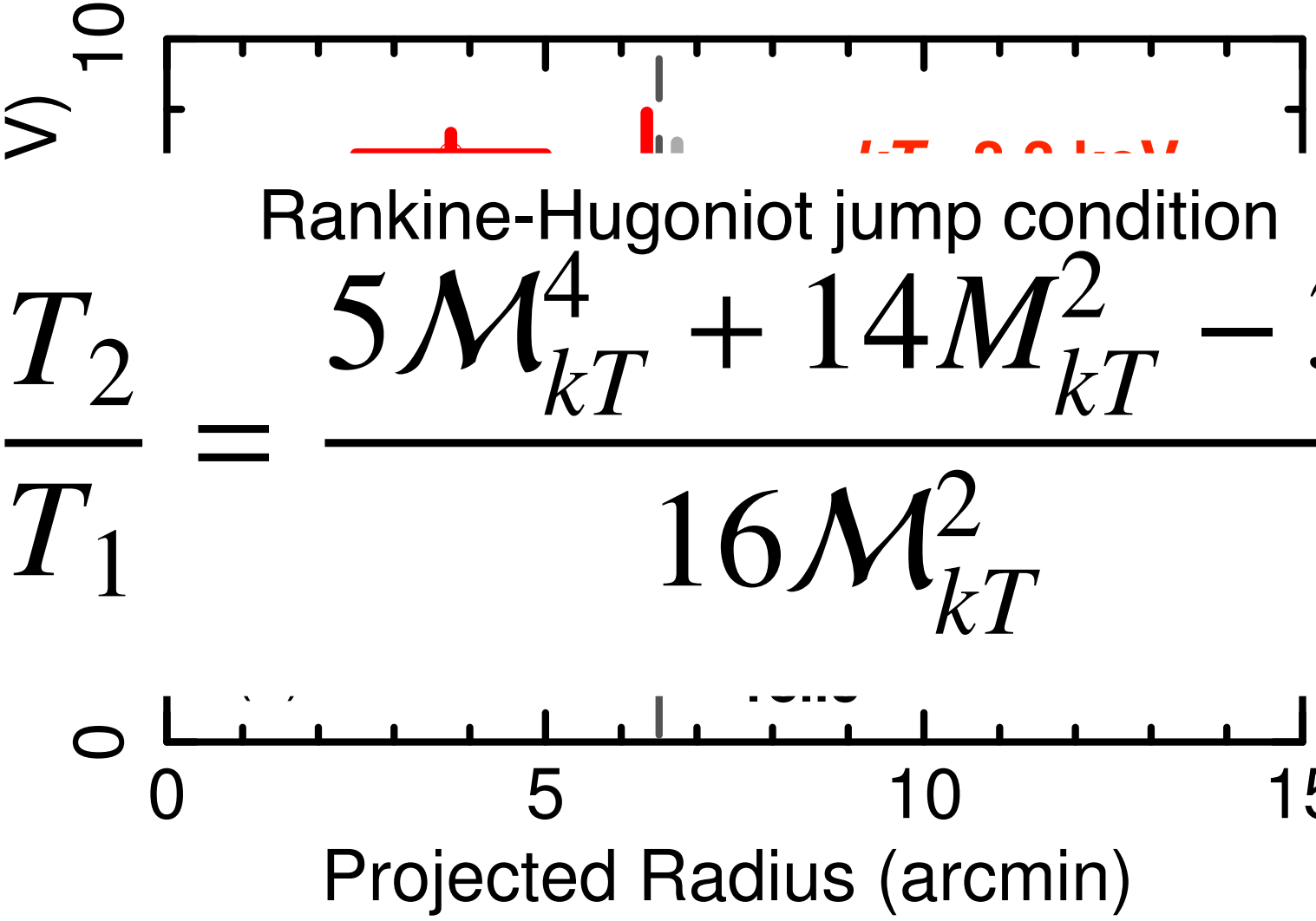

Rankine-Hugoniot jump condition

$$\frac{T_2}{T_1} = \frac{5\mathcal{M}_{kT}^4 + 14\mathcal{M}_{kT}^2 - 3}{16\mathcal{M}_{kT}^2}$$

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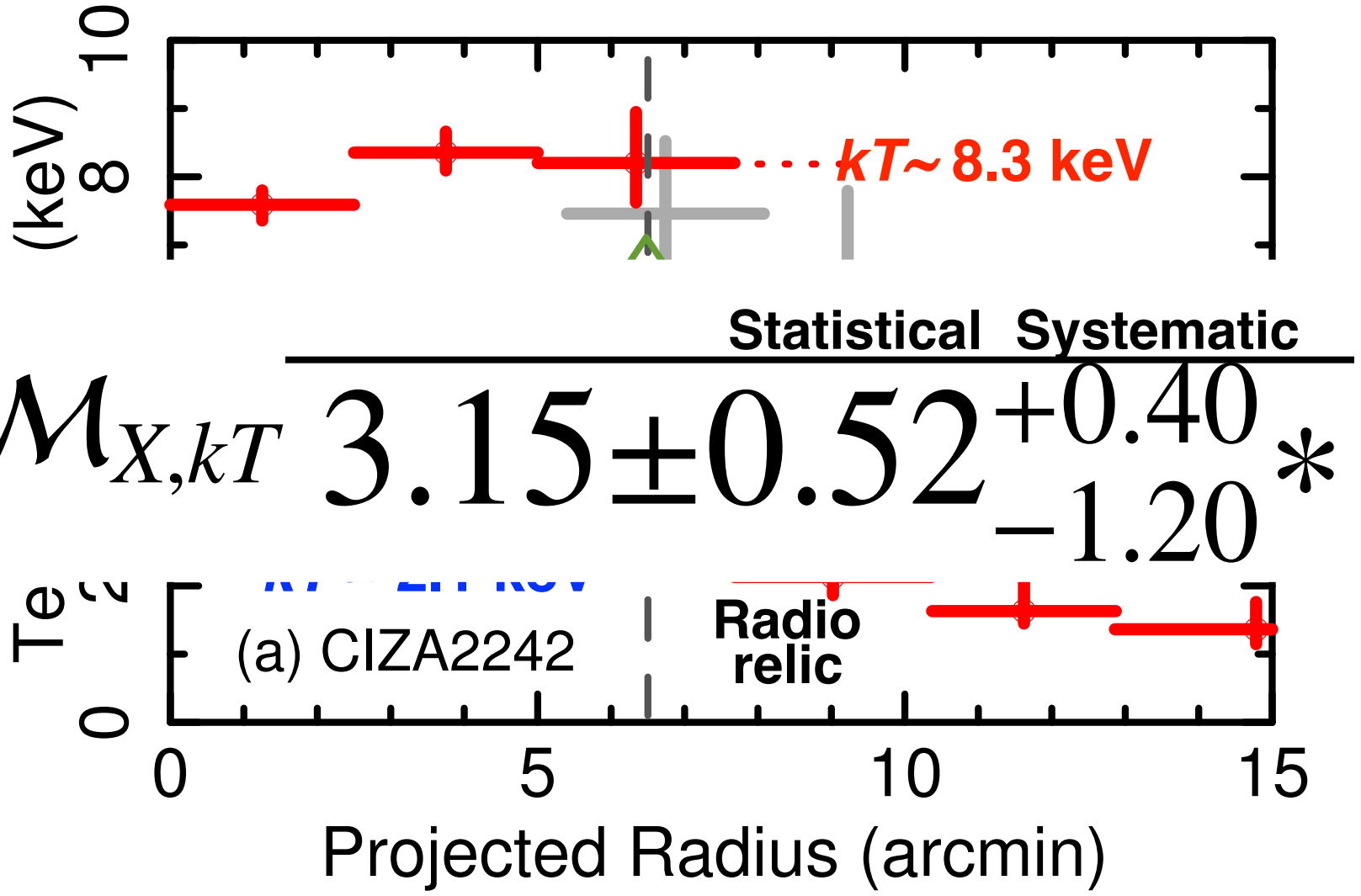

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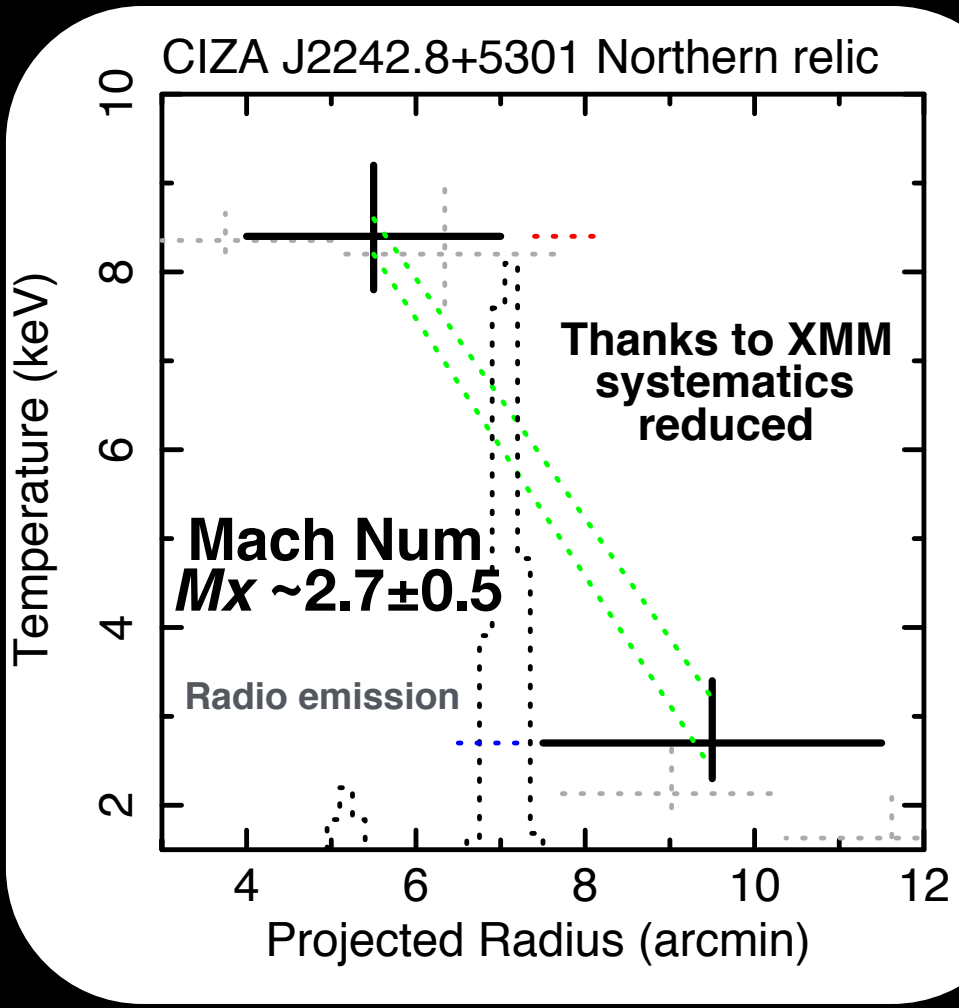

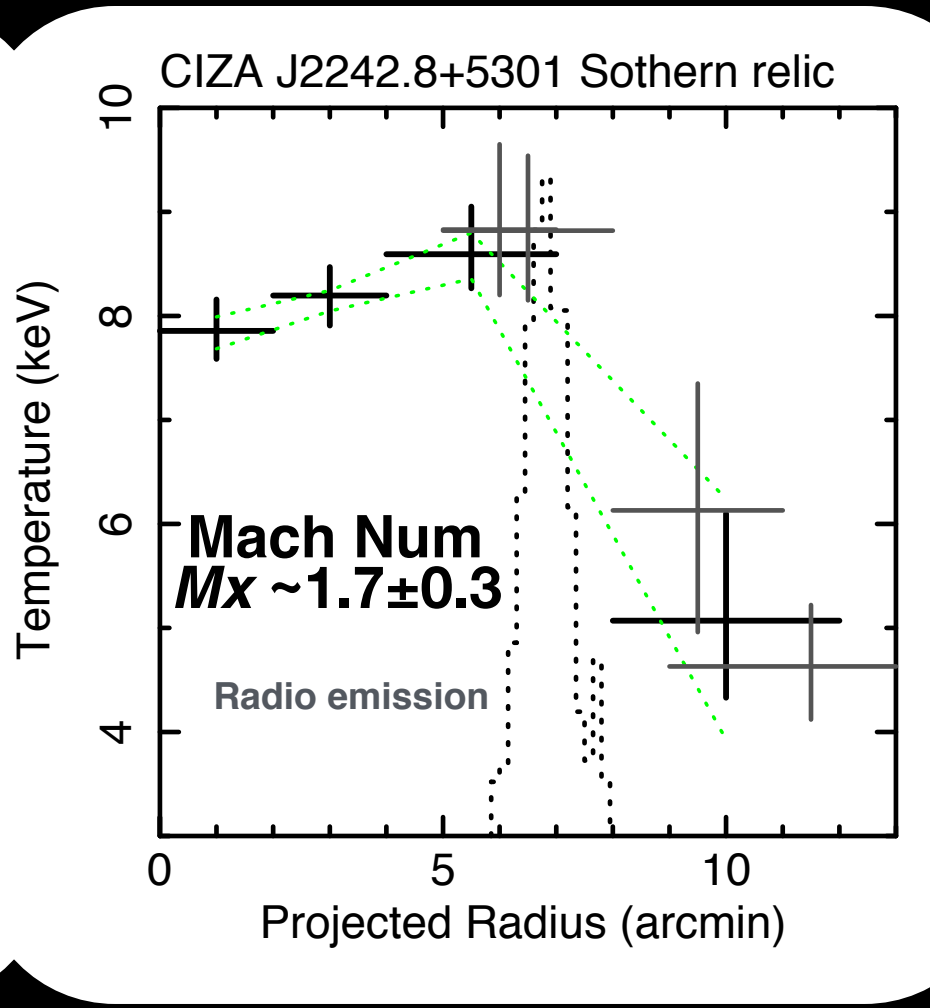

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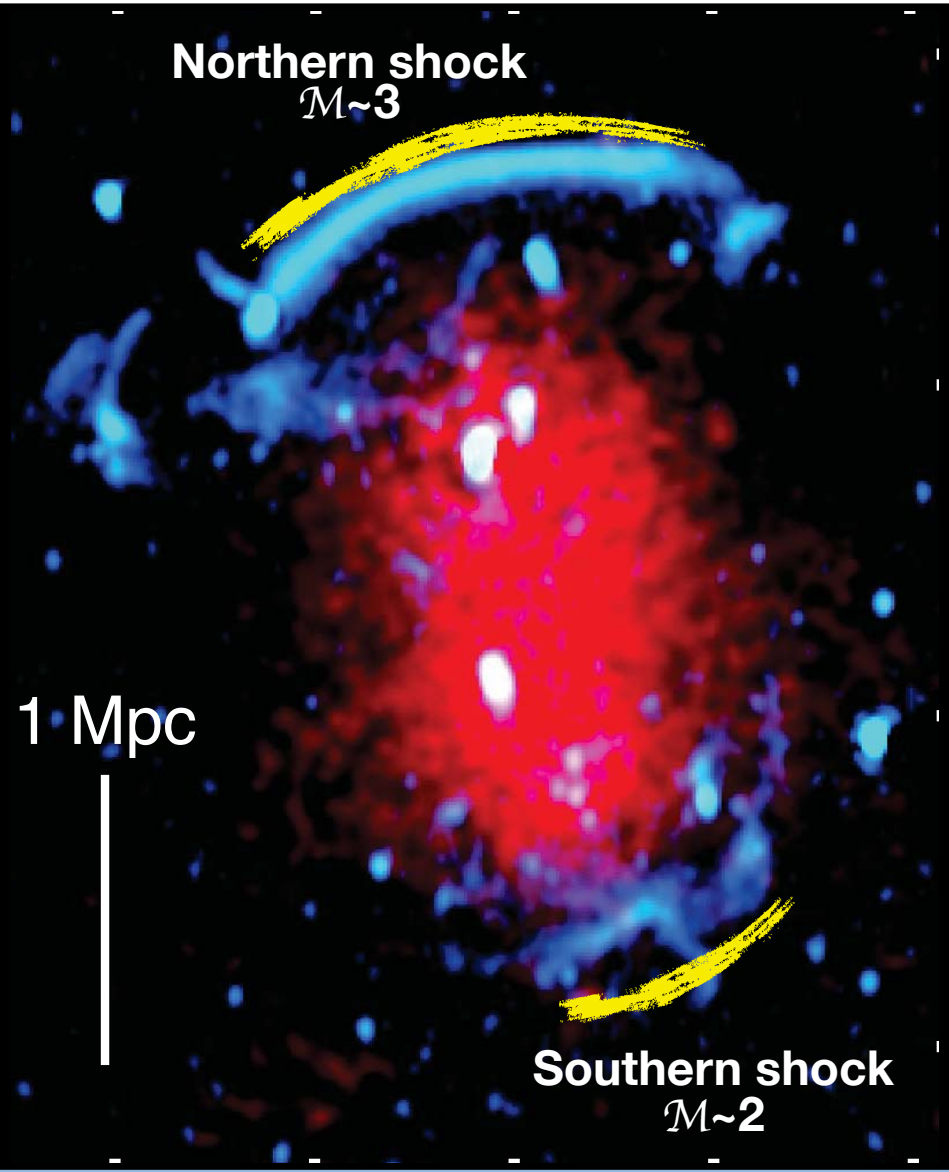

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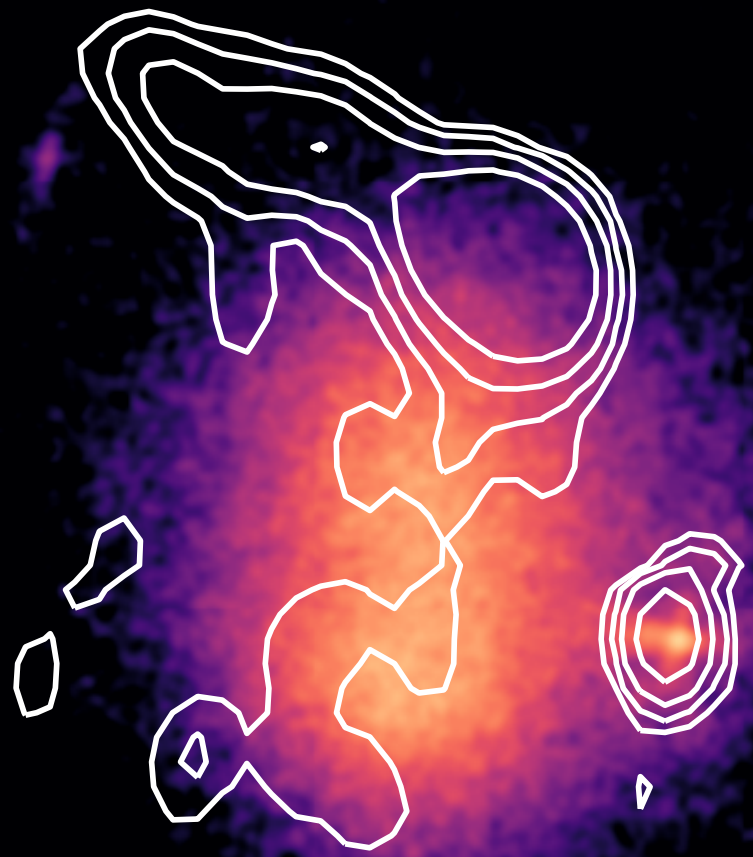
Other relics: Toothbrush relic (Itahana et al. 2015)



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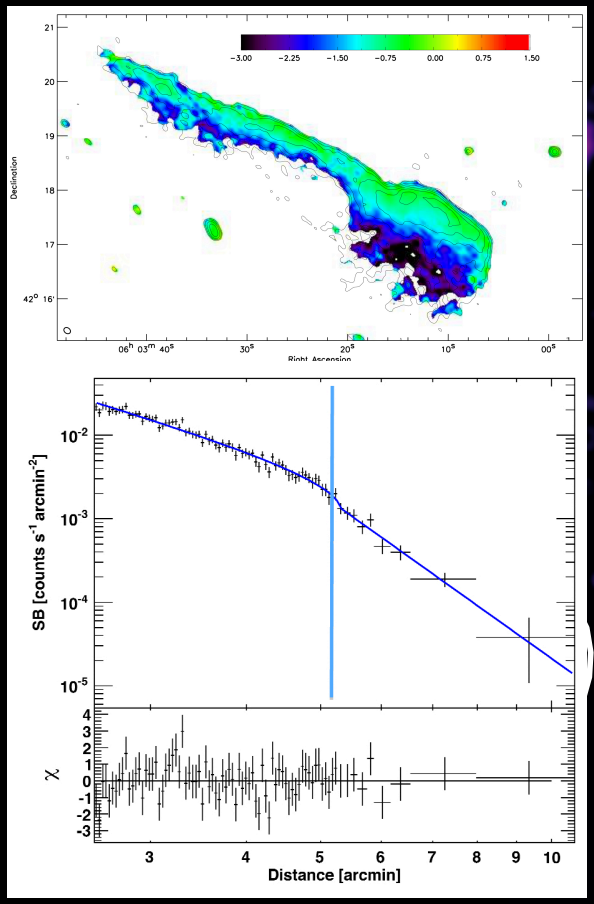
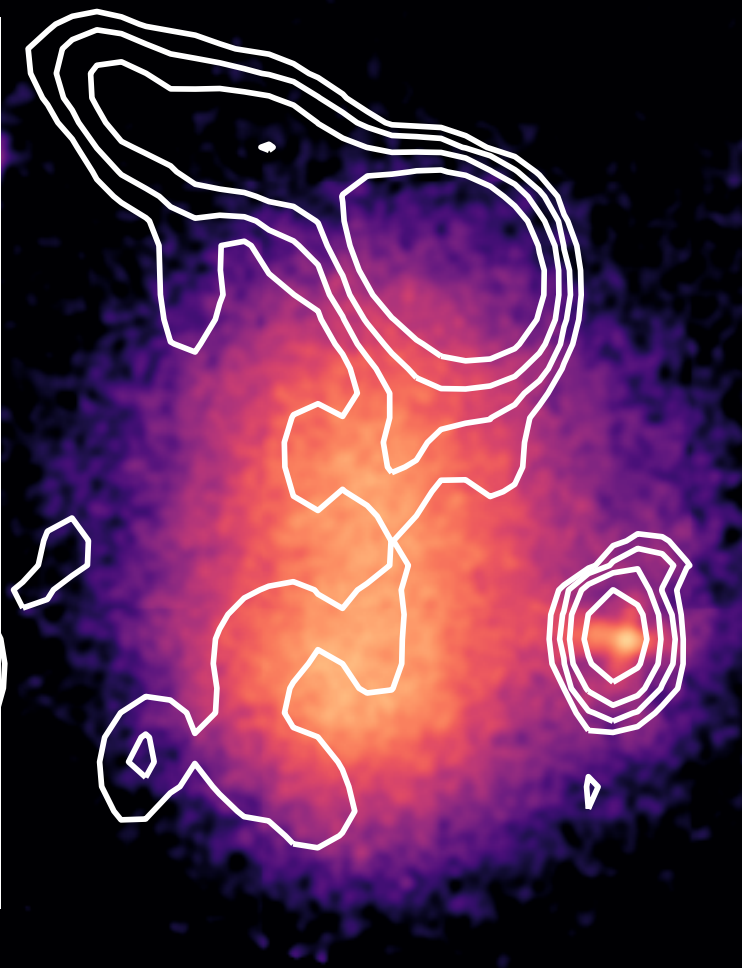


van Weeren et al. (2016)



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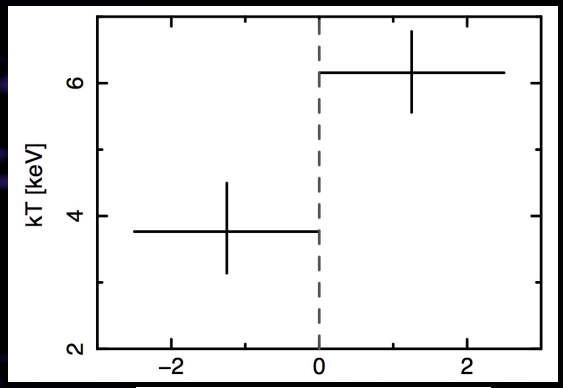
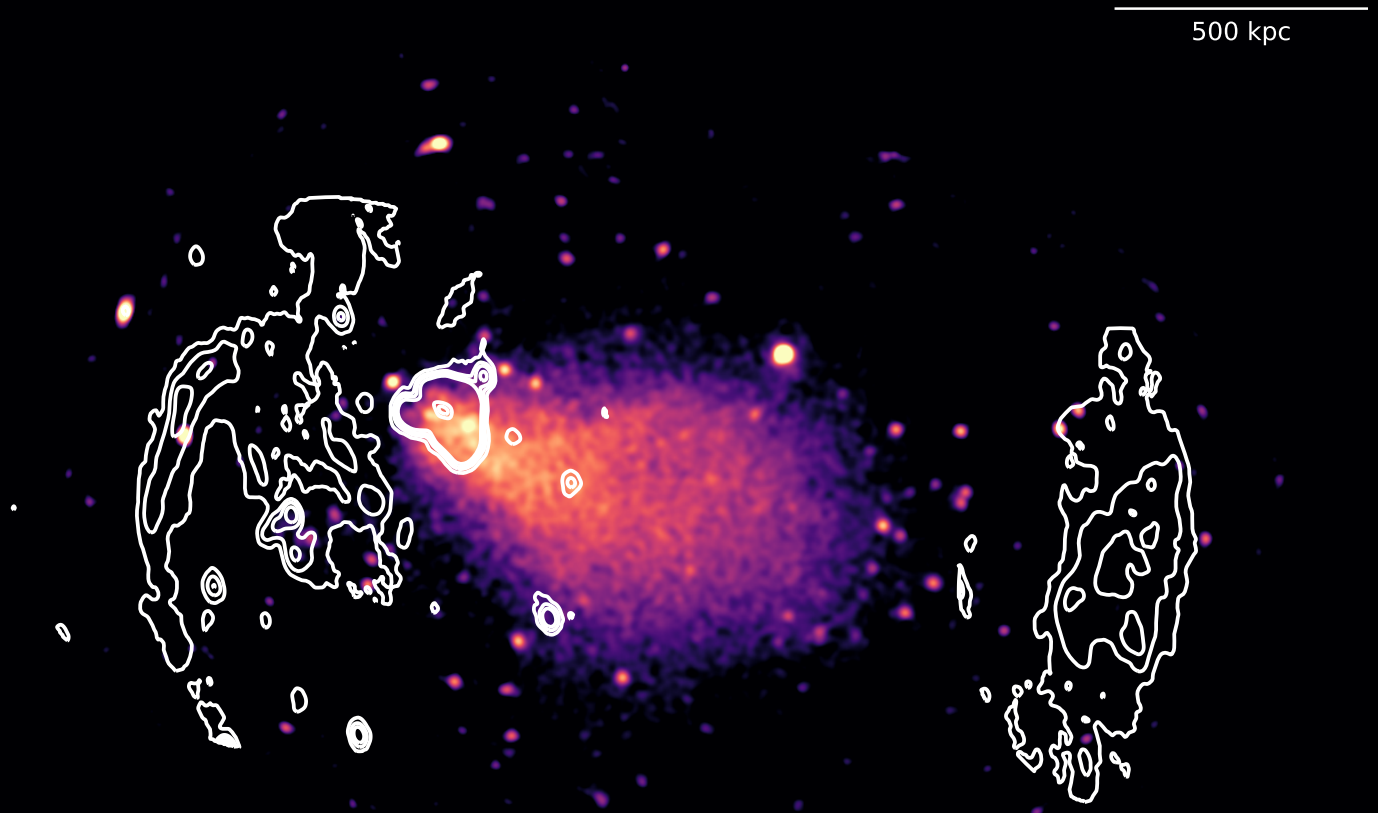


$$M_X = 1.50^{+0.28}_{-0.24}$$

Other relics: A3376 *(HA+12b, I. Urdampilleta's talk at tomorrow)*



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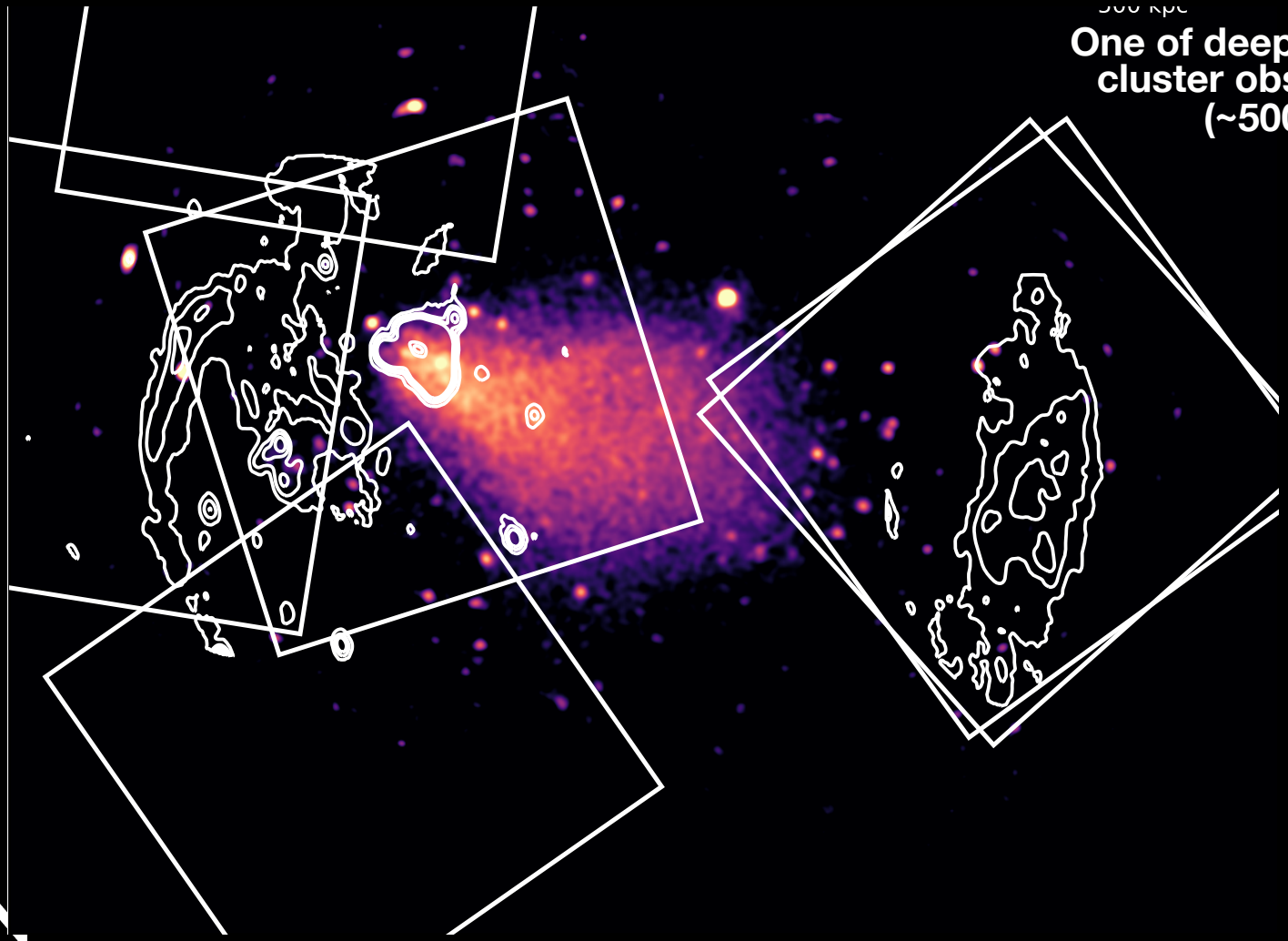
Is there spatial discrepancy between thermal and non-thermal components



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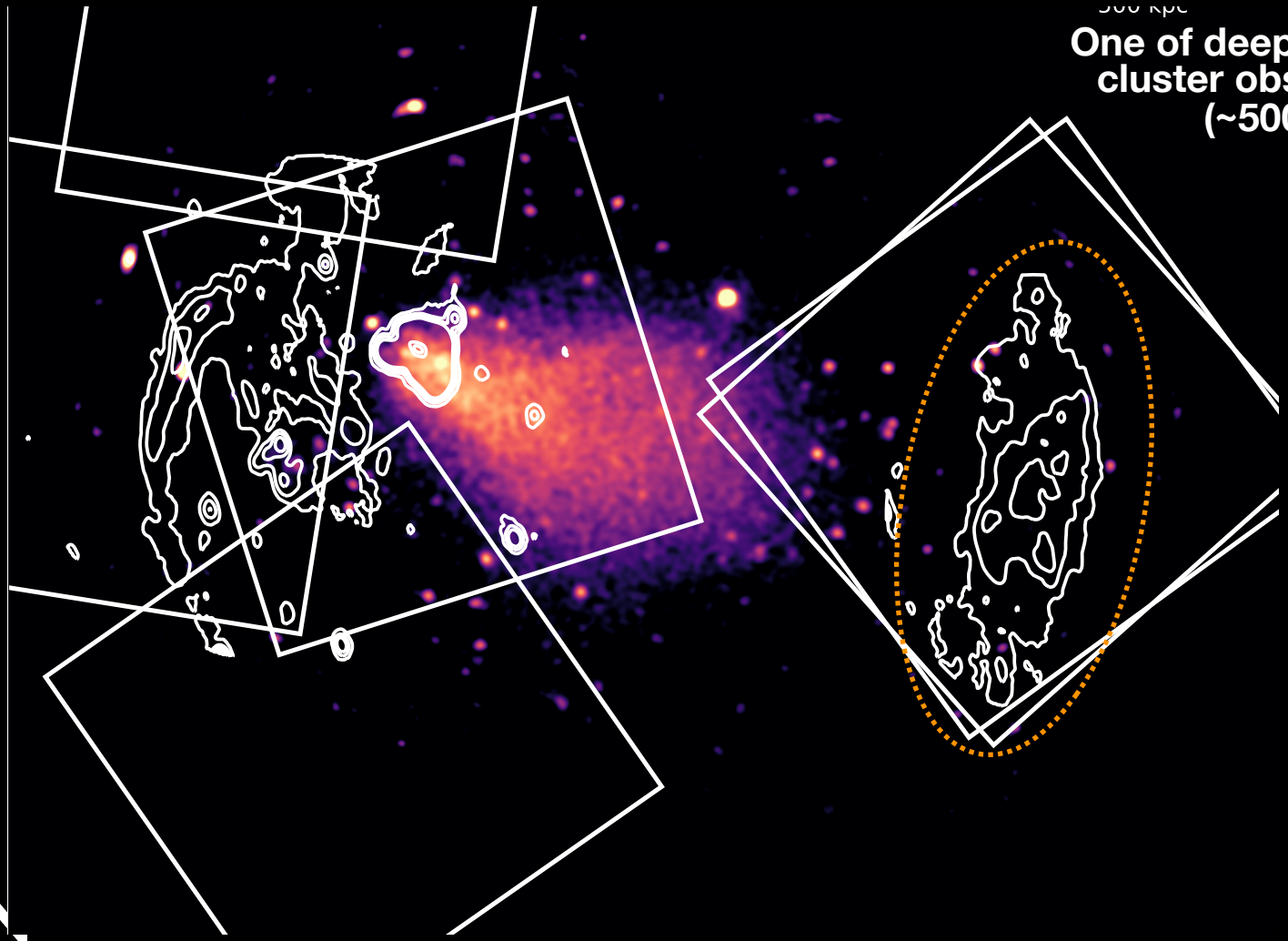

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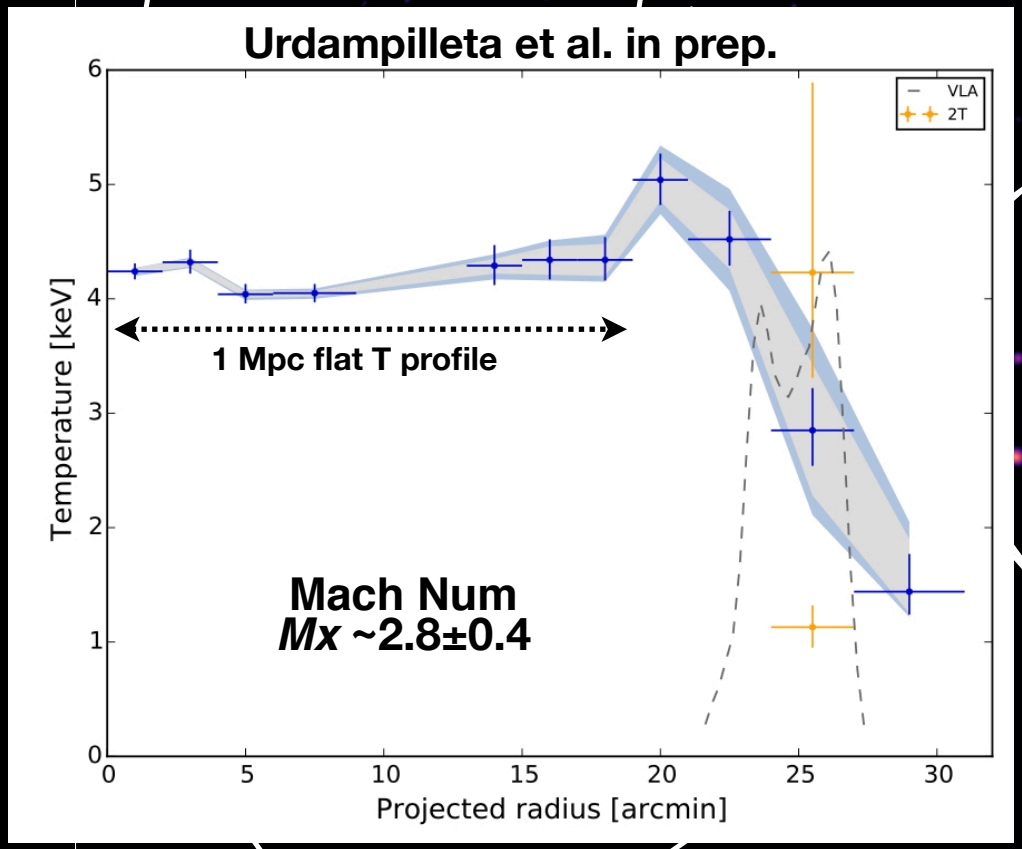
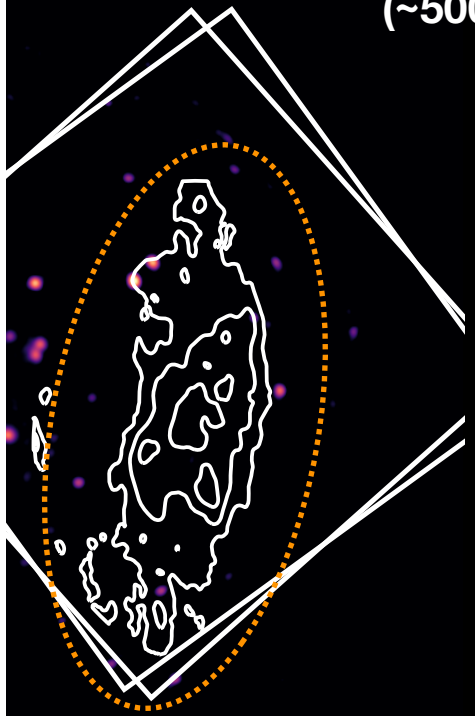
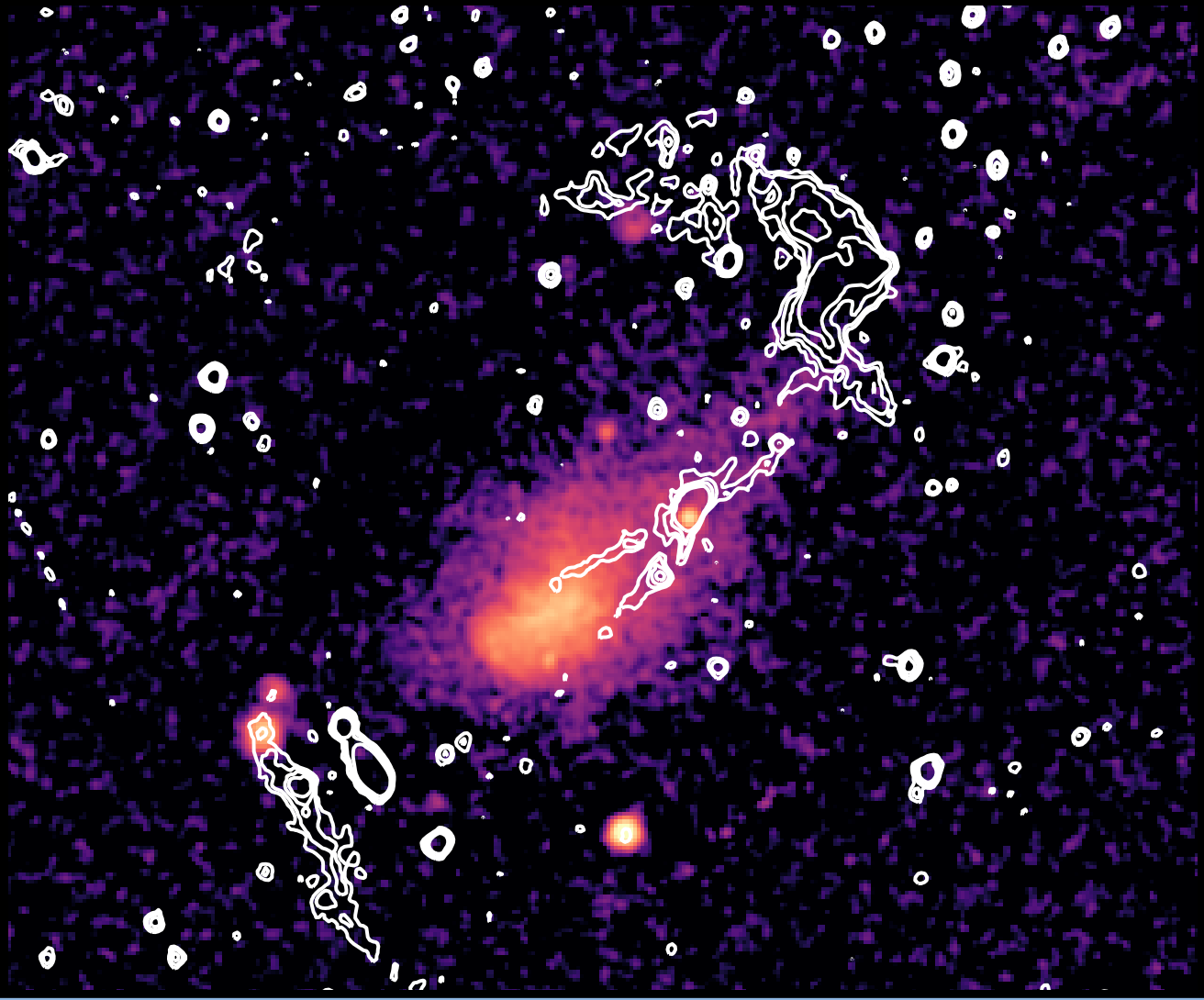
One of deepest *Suzaku* cluster observations (~500 ks)





Other relics: A3667 *(HA+12a, E. Storm et al. in prep.)*



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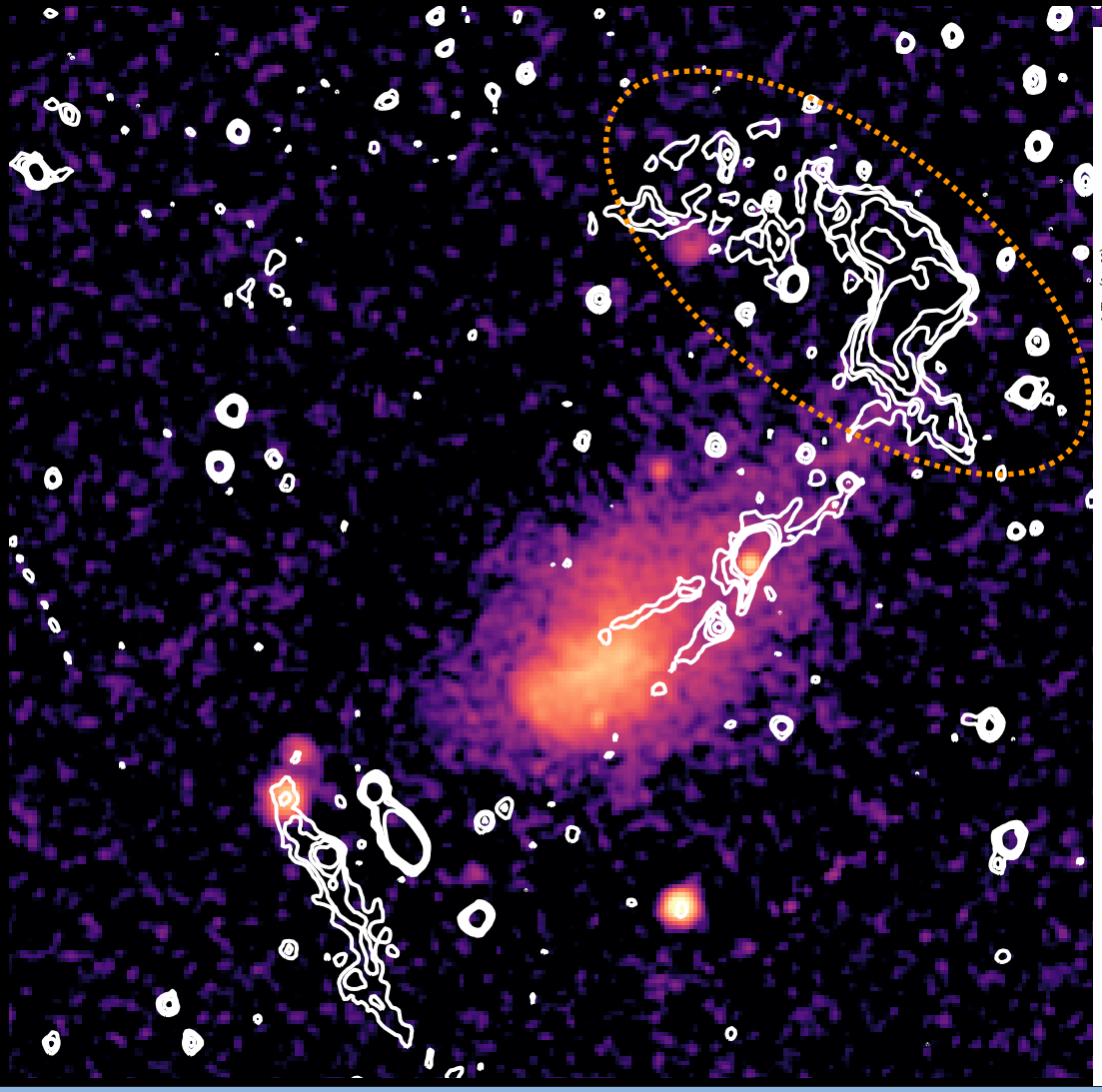

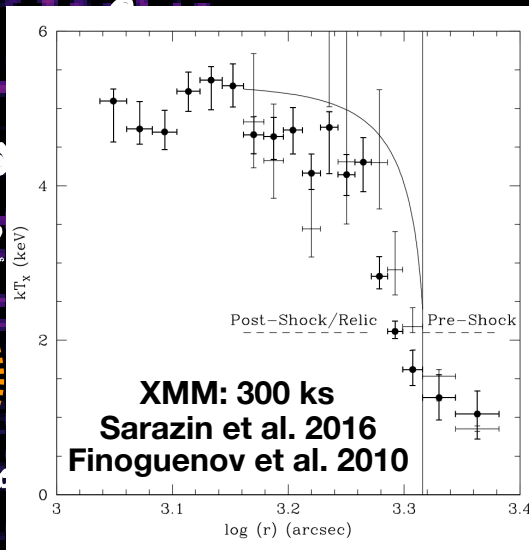

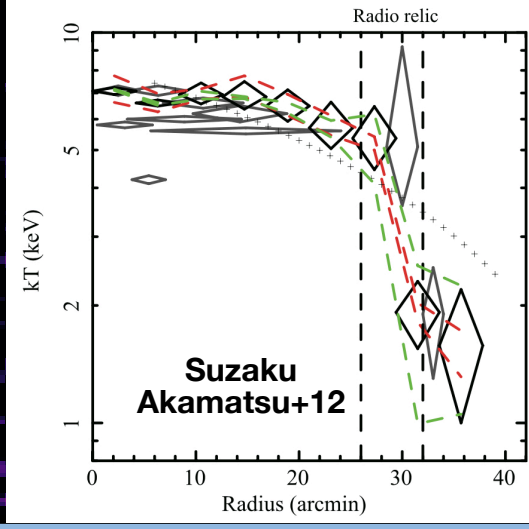

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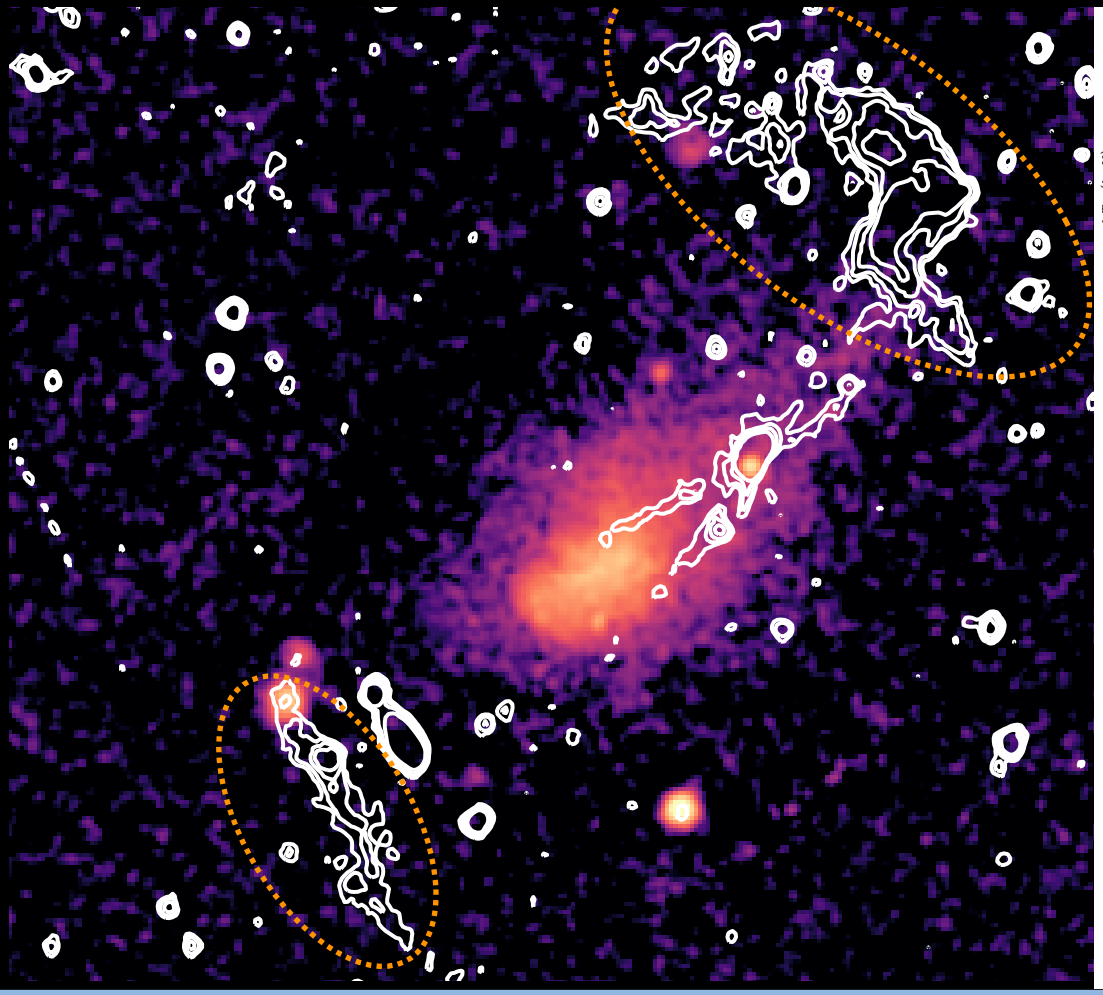
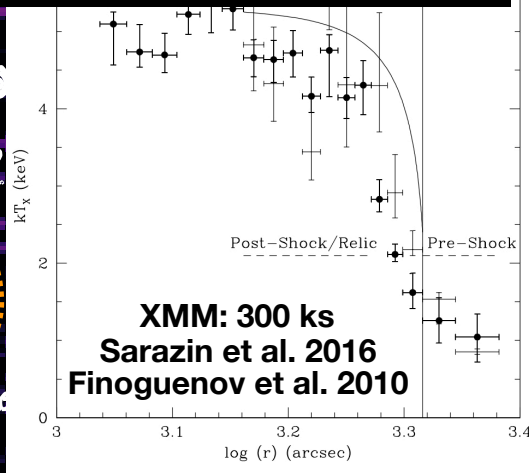
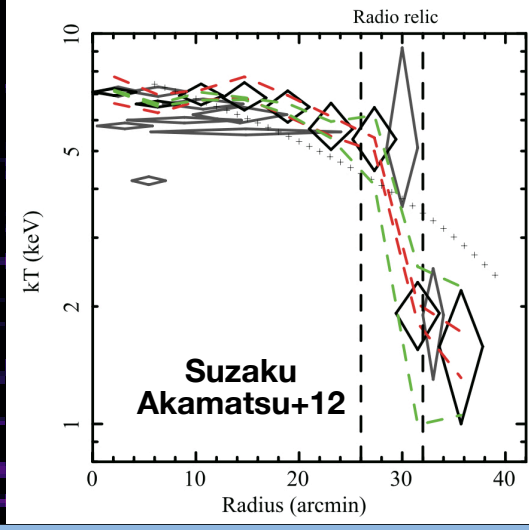
If it's true, how electrons are accelerated?







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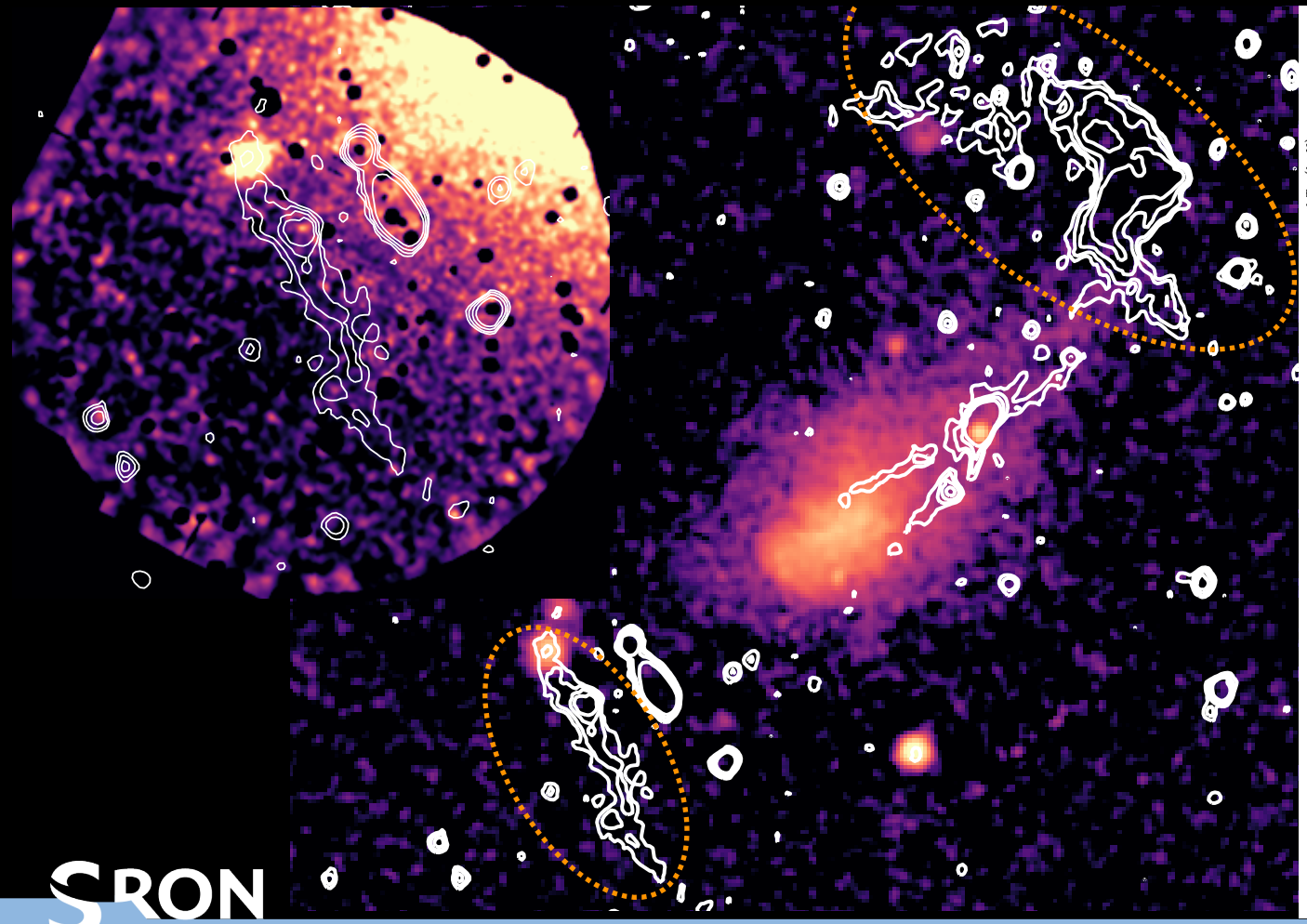
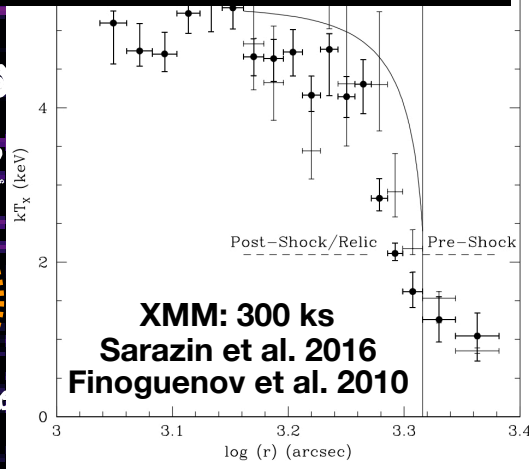
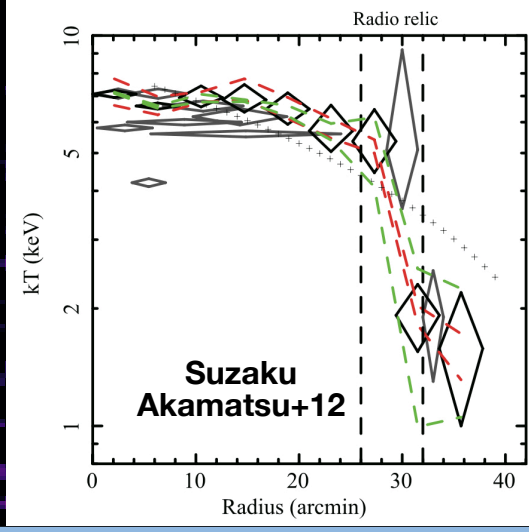


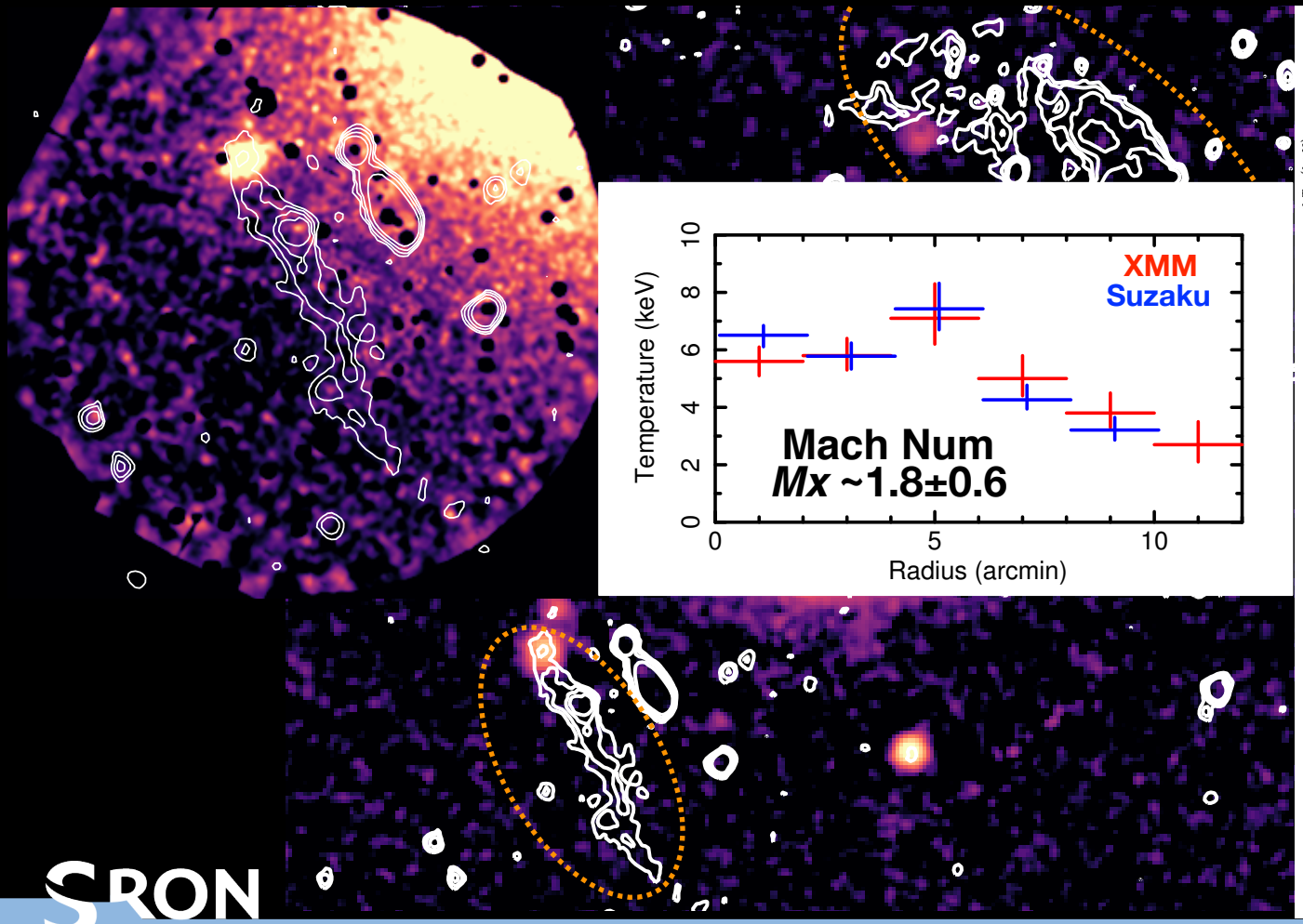


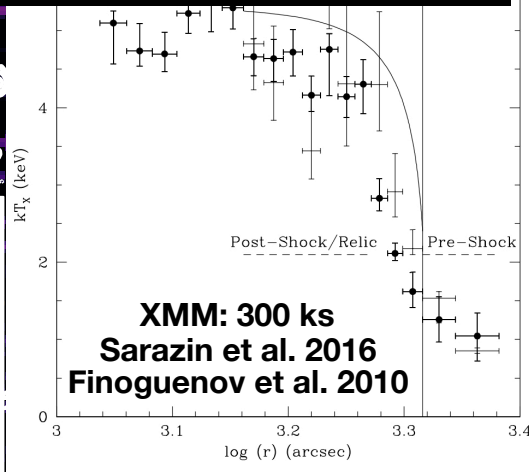


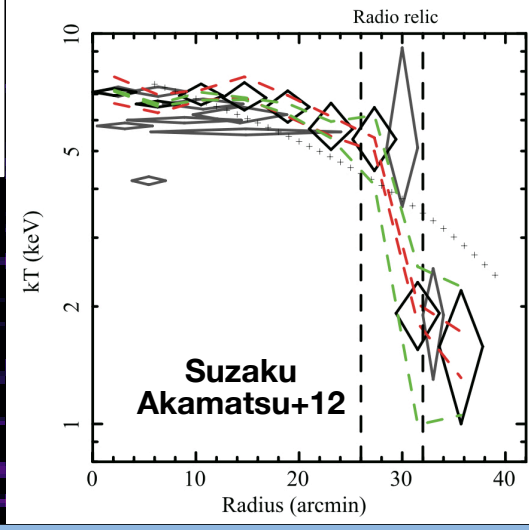
Other relics: A3667 *(HA+12a, E. Storm et al. in prep.)*

Question:

Is it true that Suzaku detected weak shock across the SE relic (M~1.7)?
If it's true, how electrons are accelerated?







Summary of X-ray observations of radio relics

- Systematic X-ray observations of radio relics revealed a relationship between radio relics and shock fronts
- Mach numbers from X-ray observation span $M \sim 2$-3

Radio relics are an excellent tracer of shock structures

-Related our works:

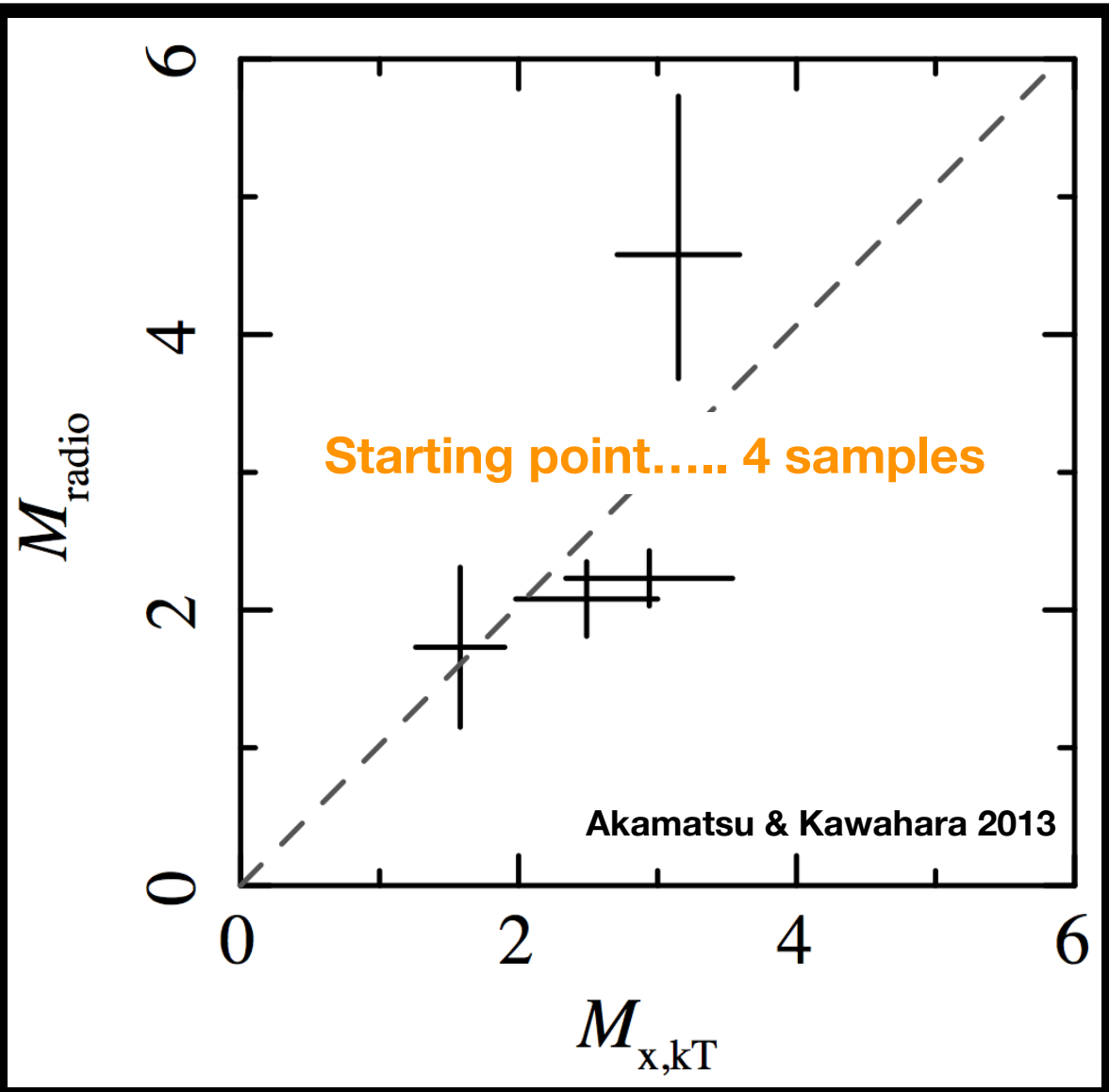
Akamatsu et al. 2012a: Properties of the Intracluster Medium of Abell 3667 Observed with Suzaku XIS
Akamastu et al. 2012b: X-Ray View of the Shock Front in the Merging Cluster Abell 3376 with Suzaku
Akamatsu & Kawahara 2013: Systematic X-ray Analysis of Radio Relic Clusters with SUZAKU
Akamatsu et al. 2013: Suzaku X-Ray Observations of the Accreting NGC 4839 Group of Galaxies and the Radio Relic in the Coma Cluster
Akamatsu et al. 2015: Suzaku X-ray view of the Sausage cluster CIZA J2242.8+5301
Akamatsu et al. 2017: Suzaku observations of the merging galaxy cluster Abell 2255: The northeast radio relic
Ibaraki, Akamatsu et al. 2014: Suzaku study of gas properties along filaments of A2744
Itahana, Akamatsu et al. 2015: Suzaku observations of the galaxy cluster 1RXS J0603.3+4214: Implications of particle acceleration processes in the "Toothbrush" radio relic
Trasatti, Akamatsu et al. 2015.: The radio relic in Abell 2256: overall spectrum and implications for electron acceleration
Hattori, Akamatsu et al.: Search for WHIM around A2744 using Suzaku
Hoang, Akamatsu et al. 2017
Uldanpiletta, Akamatsu et al. in prep.
Storm, Akamatsu et al. in prep.

SRON

Discussion:

Shock properties at radio relics

Shock property: Mach number from X-ray and Radio

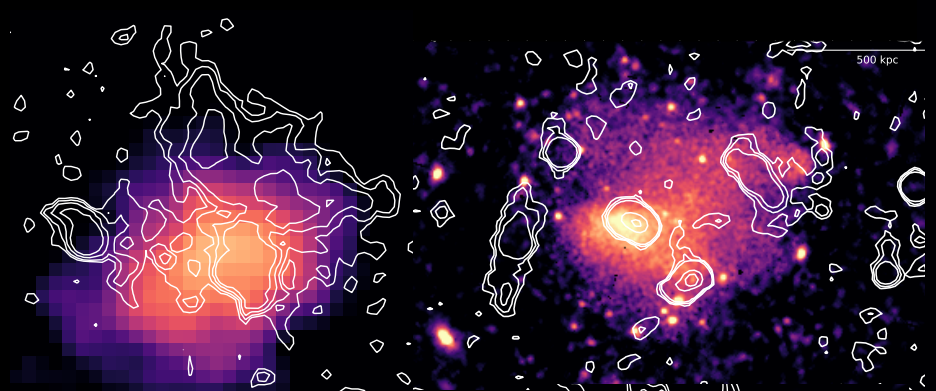


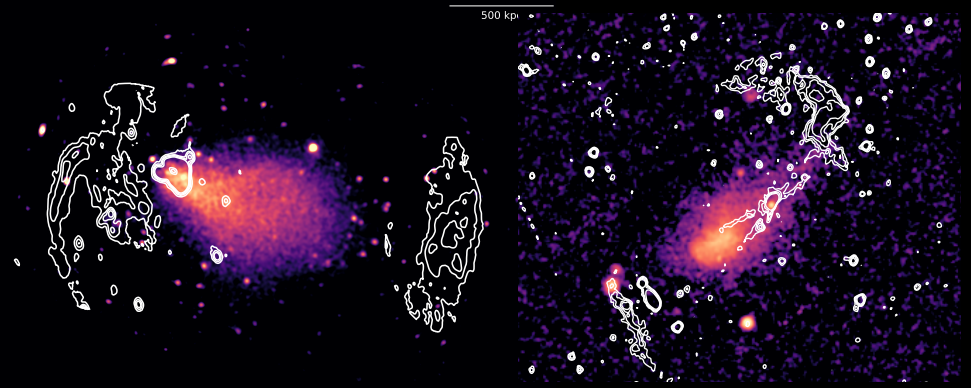
Keep in mind: assumptions

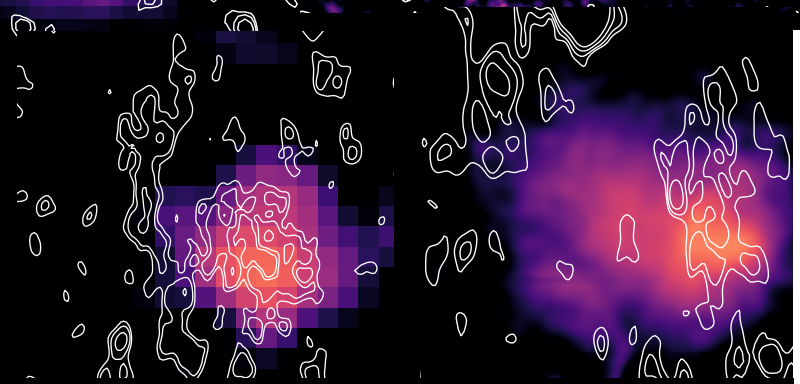
Samples

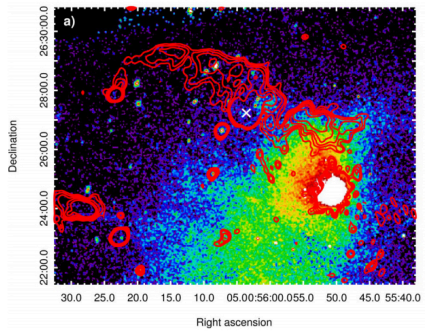
Let's increase samples

(Even though data size is much smaller than LOFAR, proper analysis takes time…..)

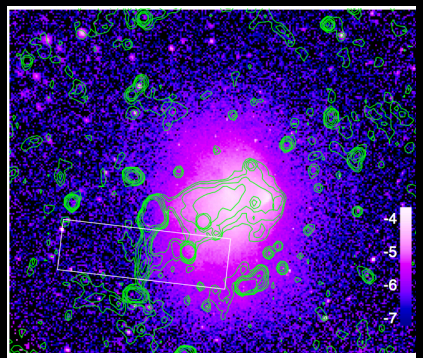








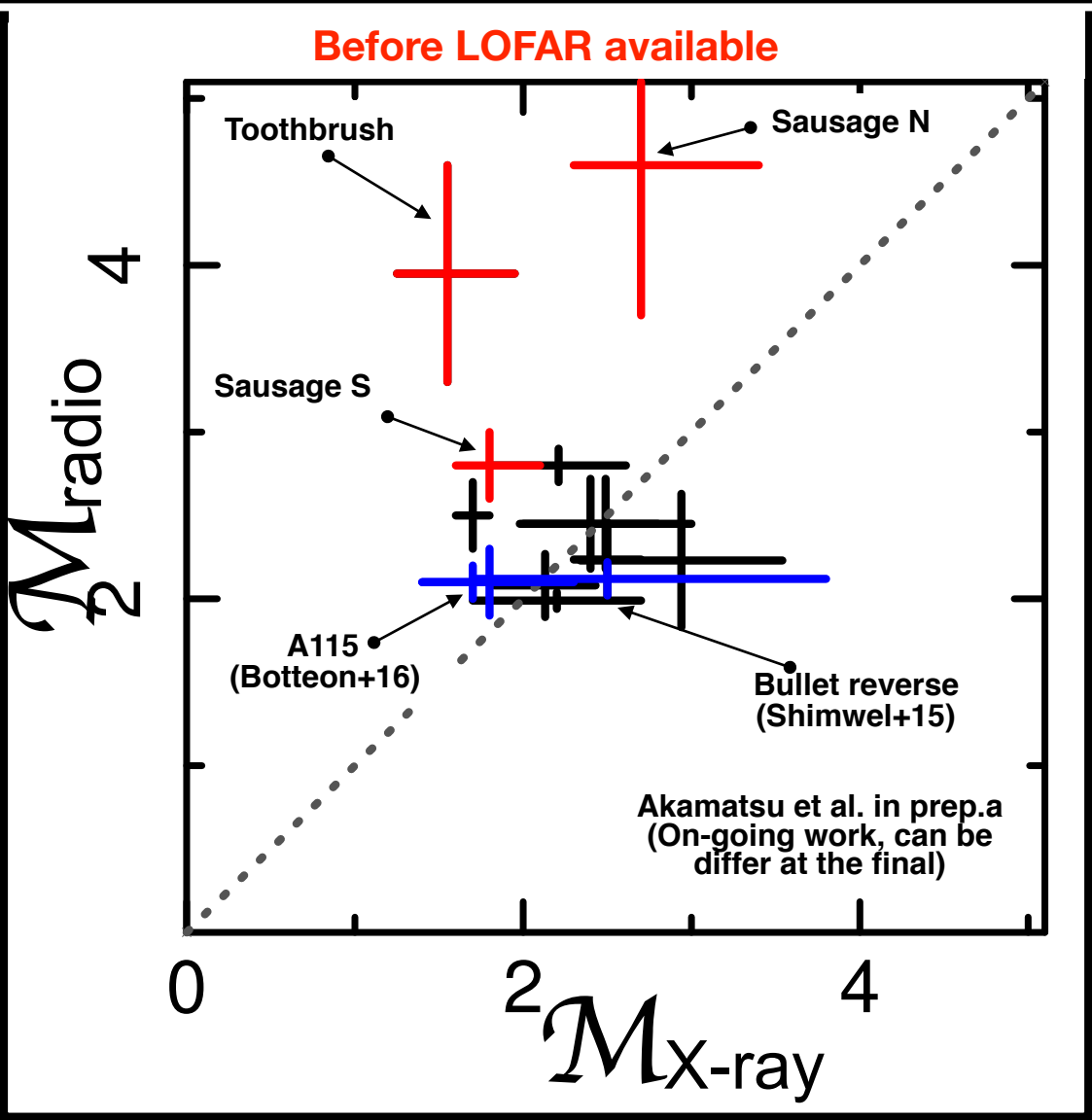
A115: Botteon+16



Bullet: Shimwell+15

and three more relics

Shock property: Mach number from X-ray and Radio



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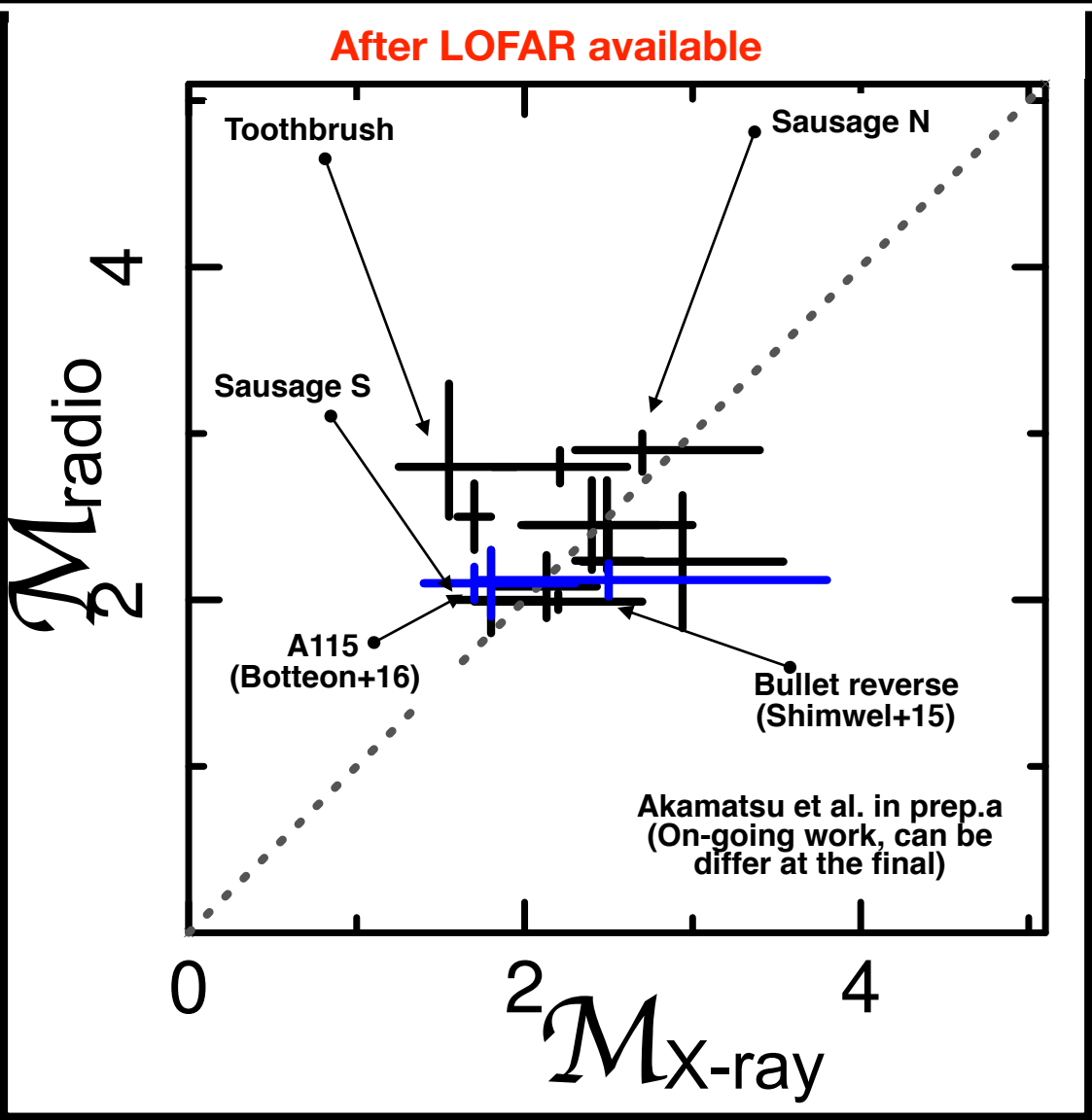
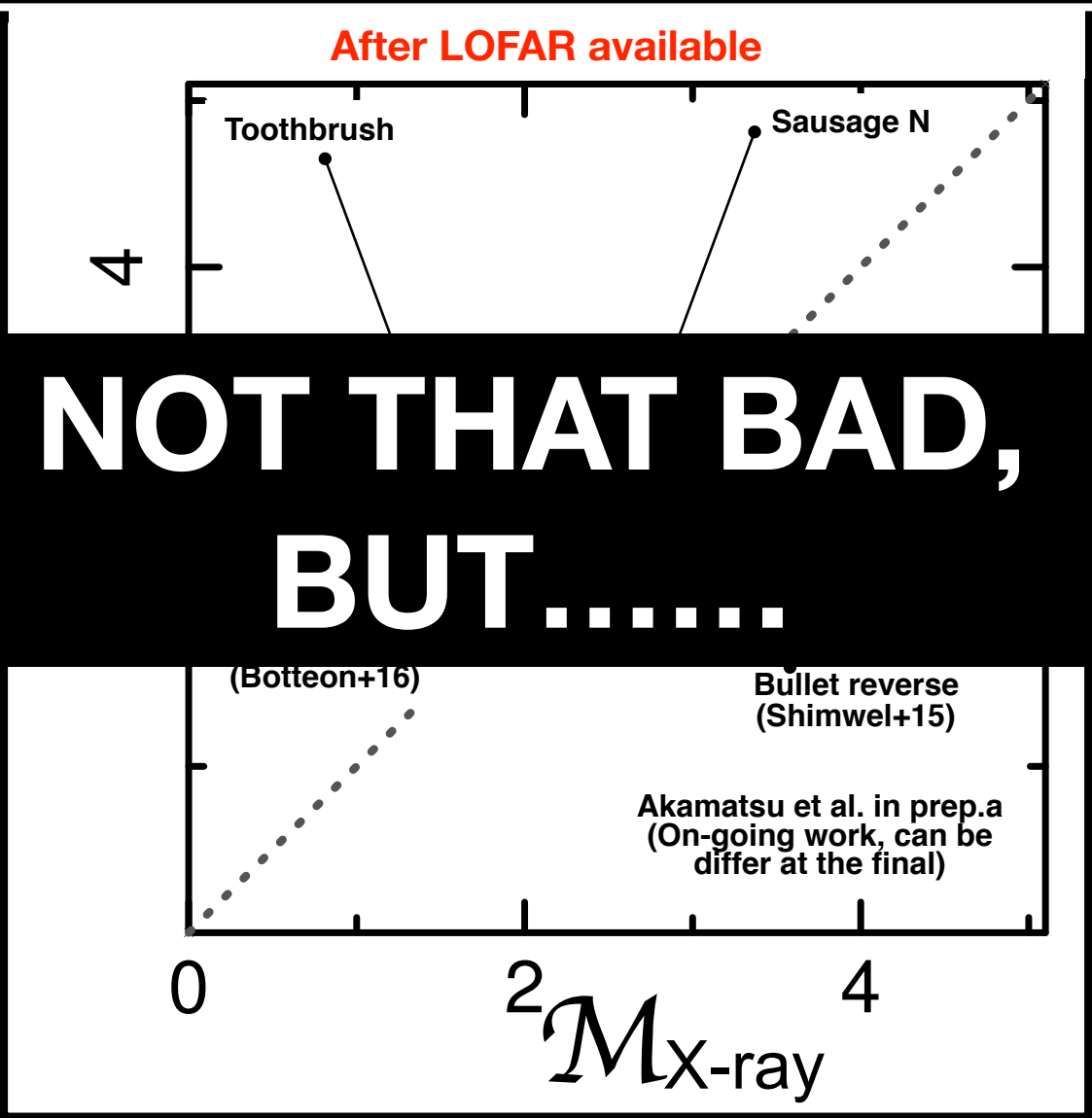


Shock property: Mach number from X-ray and Radio



Shock property: Mach number from X-ray and Radio

Several cautions/scenarios…. (took from Akamatsu+17a)

$\mathcal{M}_{\rm radio}$

- projection effects that can lead to the underestimation of the Mach numbers from X-ray observations (Skillman et al. 2013; Hong et al. 2015);
- an underestimation of the post-shock temperature with electrons not reaching thermal equilibrium. Such a phenomenon is observed in SNRs (van Adelsberg et al. 2008; Yamaguchi et al. 2014; Vink et al. 2015);
- Clumpiness and inhomogeneities in the ICM (Nagai & Lau 2011; Simionescu et al. 2011), which will lead to nonlinearity of the shock-acceleration efficiency (Hoeft & Brüggen 2007);
- pre-existing low-energy relativistic electrons and/or re-accelerated electrons, resulting in a flat radio spectrum with a rather small temperature jump (Markevitch et al. 2005; Kang et al. 2012; Pinzke et al. 2013; Kang & Ryu 2015; Stroe et al. 2016);
- a nonuniform Mach number as a results of inhomogeneities in the ICM, which is expected in the periphery of the cluster (Nagai & Lau 2011; Simionescu et al. 2011; Mazzotta et al. 2011);
- shock-drift accelerations, suggested from particle-in-cell simulations (Guo et al. 2014a,b);
- other mechanisms, for instance turbulence accelerations (e.g., Fujita et al. 2015, 2016).

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Shock property: Mach number from X-ray and Radio

Several cautions/scenarios…. (took from Akamatsu+17a)

$\mathcal{M}_{\rm radio}$:

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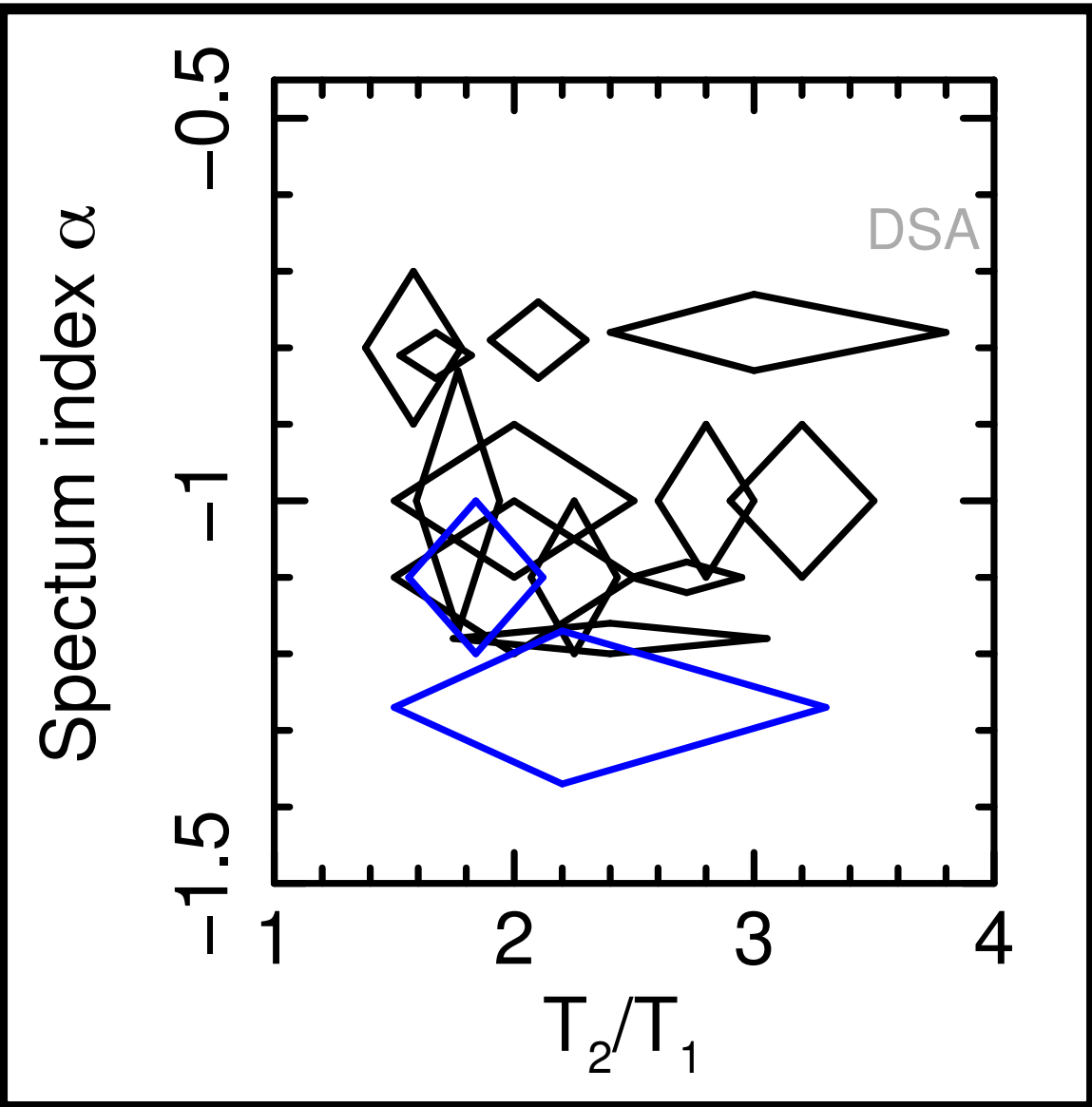
- other mechanisms, for instance turbulence accelerations (e.g., Fujita et al. 2015, 2016).

Potential systematics in X-ray

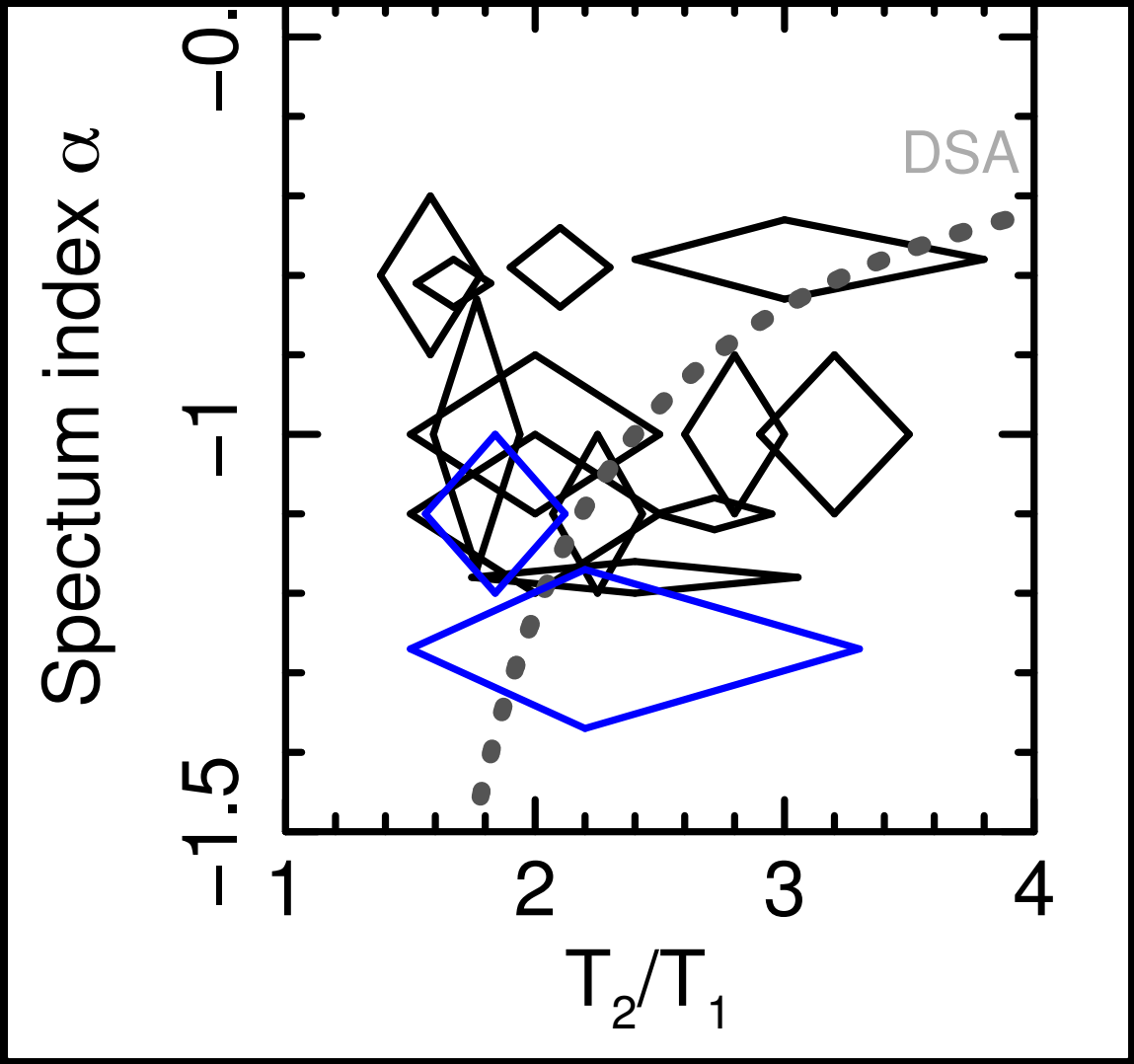
Potential systematics in Radio: see:
Stroe+14b,
Hoang+17
Di Gennaro-san's talk

Comparison in observables



Comparison in observables

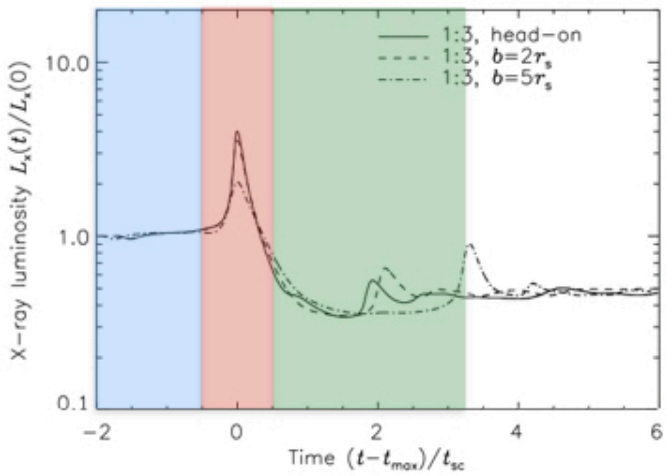
Please draw your curve/indicate new observables

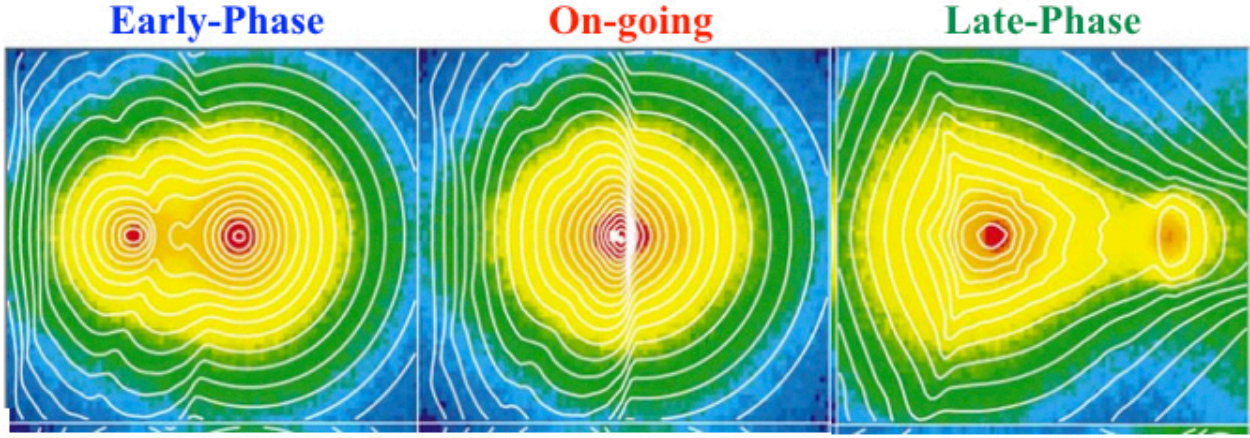


What's next? Phase separated study of merging phenomena

Our understanding of merging clusters, acquired by lots of X-ray observations,
is limited in the context of the whole process of cluster mergers
=> Biased to 'On-going phase' due to merger boost
=> Limited samples of other phases (Early-/Late-phase)

Merger boost

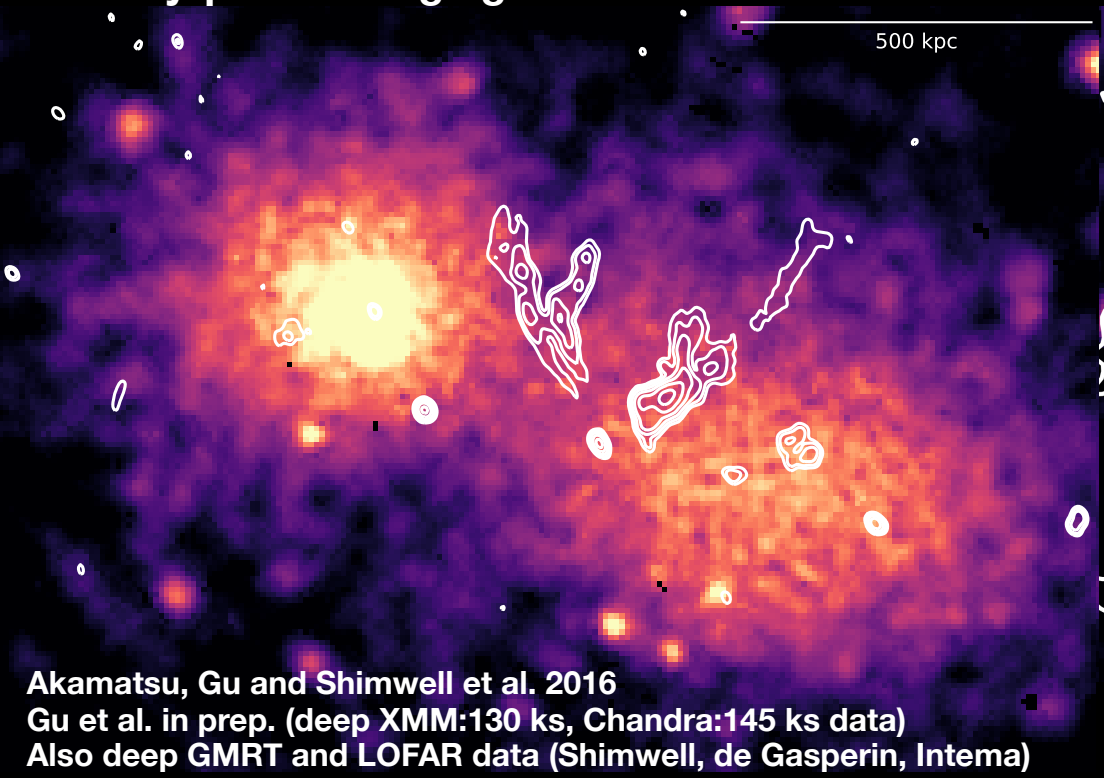




Ricker & Sarazin 2001

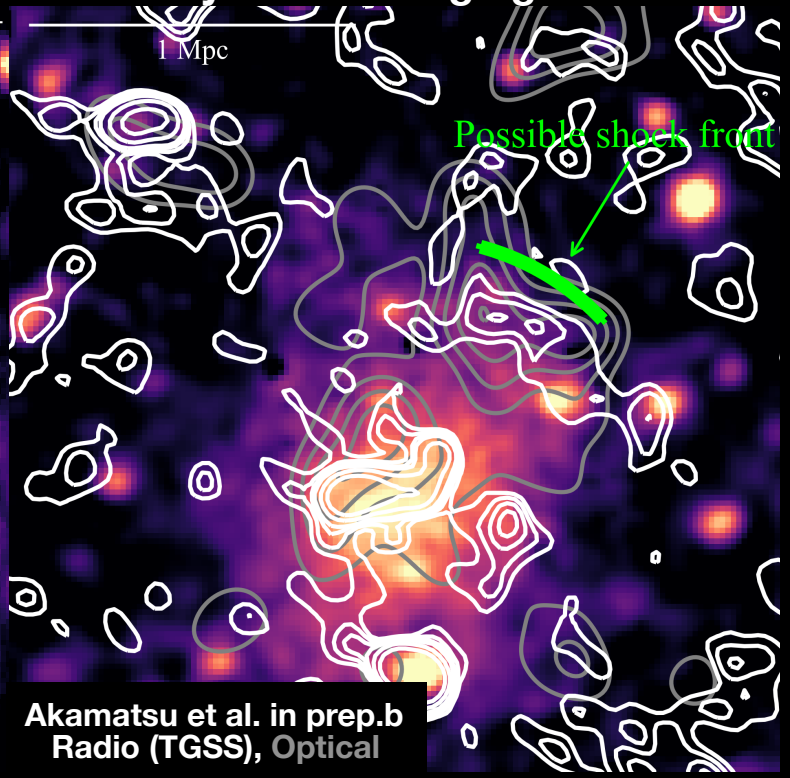
What's next? Phase separated study of merging phenomena

Early-phase merging cluster with radio emission



Akamatsu, Gu and Shimwell et al. 2016
Gu et al. in prep. (deep XMM:130 ks, Chandra:145 ks data)
Also deep GMRT and LOFAR data (Shimwell, de Gasperin, Intema)

Newly-found merging cluster



Akamatsu et al. in prep.b
Radio (TGSS), Optical

Summary

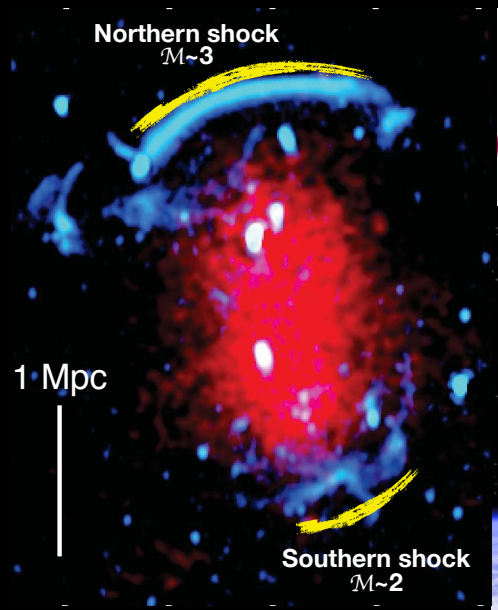
Systematic X-ray observations of the radio relic revealed
relationship between radio relics and shock fronts

Radio relics are an excellent tracer of the shock structures

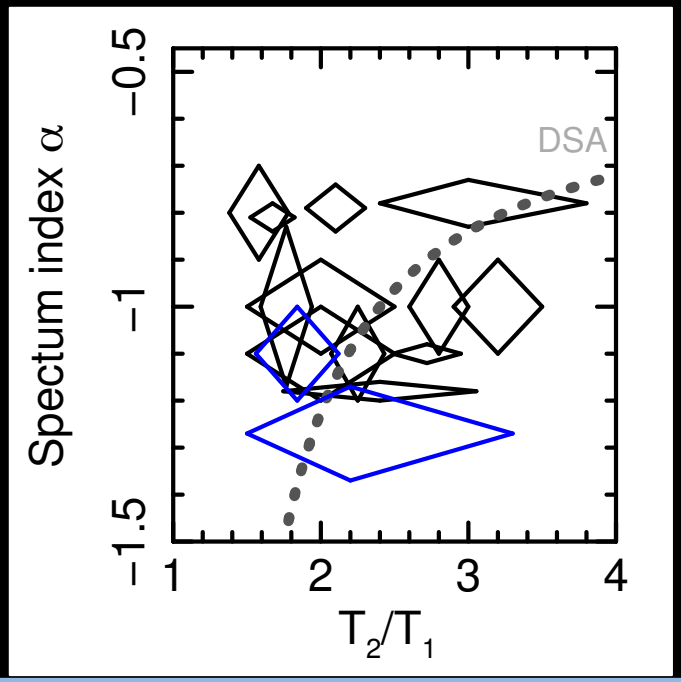
It is really helpful having close collaborations
between X-ray, radio and theory (& simulation)

=> please tell us your thought on observables

A new try is also on-going



LOFAR



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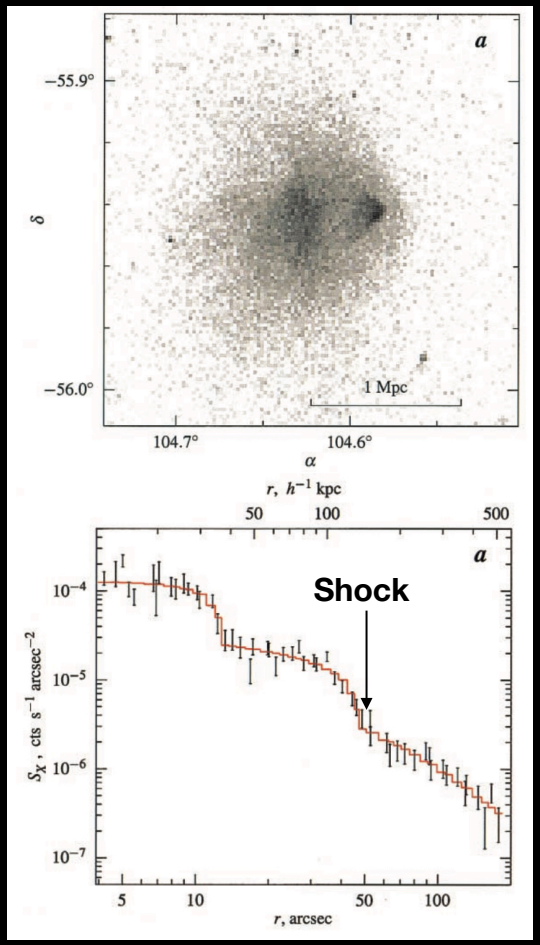
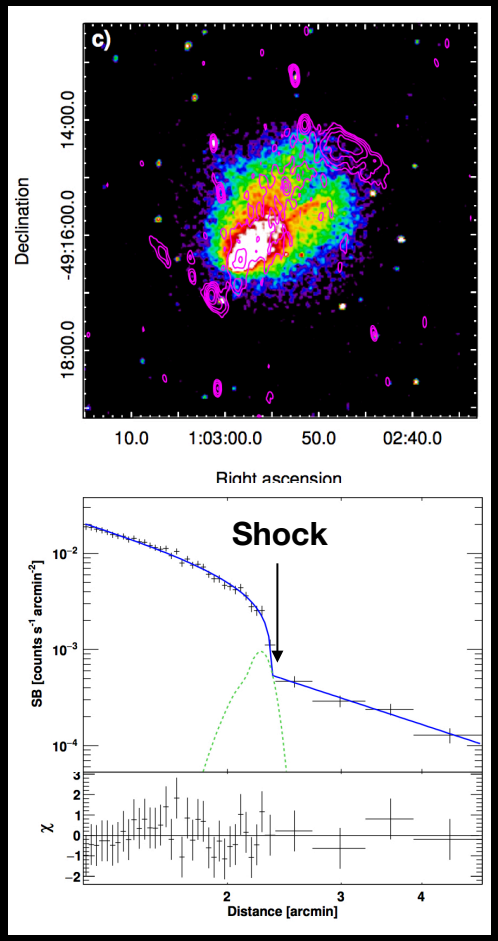
X-ray observations of M~3 shock in surface brightness

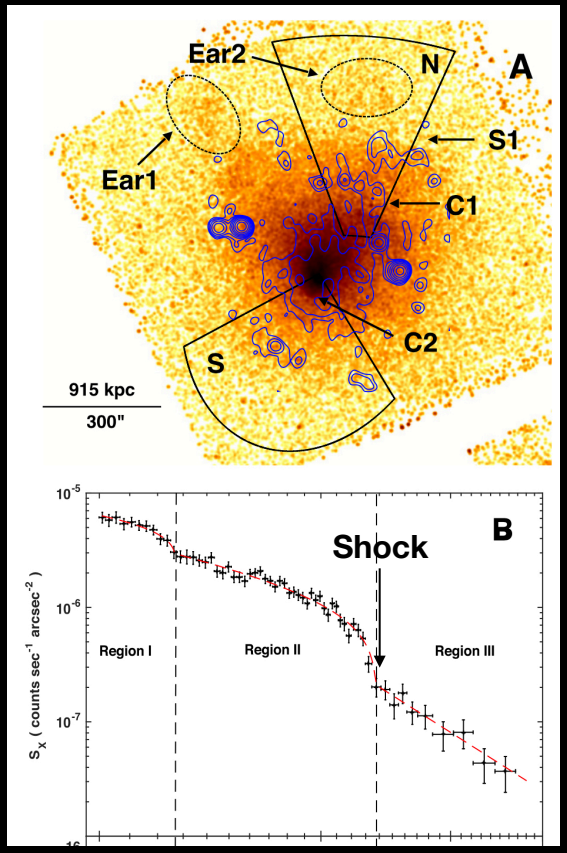
Markevitch+02



Botteon+16



Dasaida+16



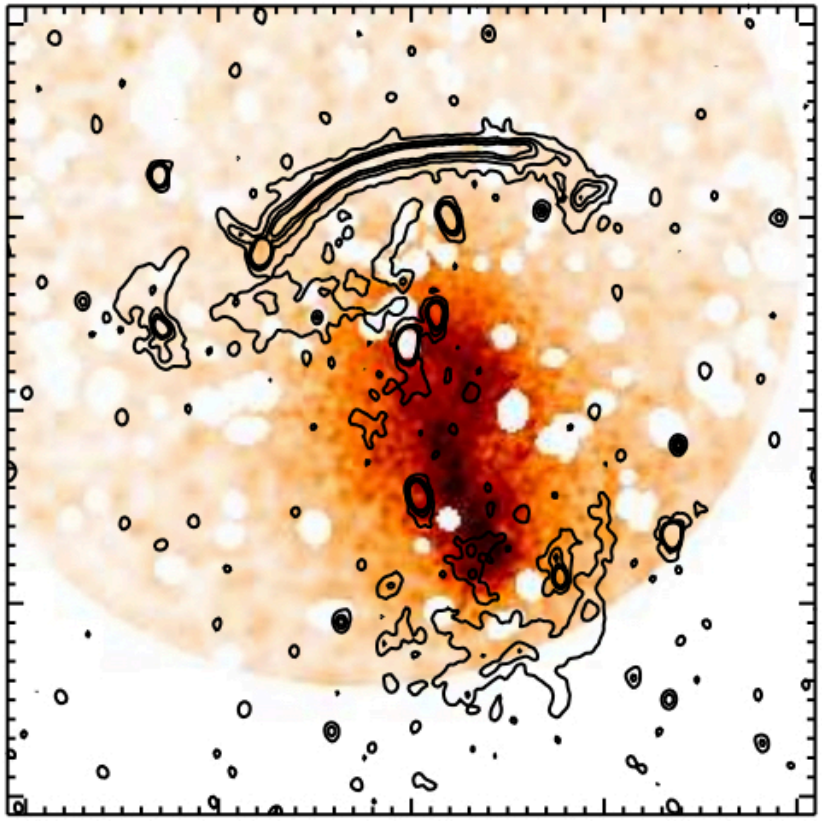
XMM-Newton X-ray observations of Sausage relic

Currently 3 major X-ray observational data on Sausage relic:

XMM-Newton: 130 ks, suffering flare => effectively 65 ks

Chandra: 200 ks with Faint mode (suboptimal setting for dim source)

Suzaku: 120 ks with 60 ks for the background estimation, limited PSF~1.7'

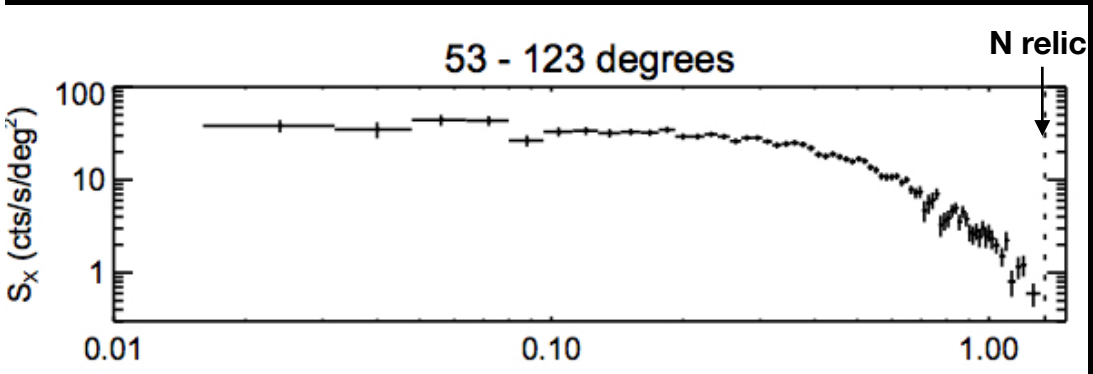


***XMM-Newton* observations of the merging galaxy cluster CIZA J2242.8+5301**

G. A. Ogrean[1⋆], M. Brüggen[1], H. Röttgering[2], A. Simionescu[3], J. H. Croston[4], R. van Weeren[2], M. Hoeft[5]

In the text

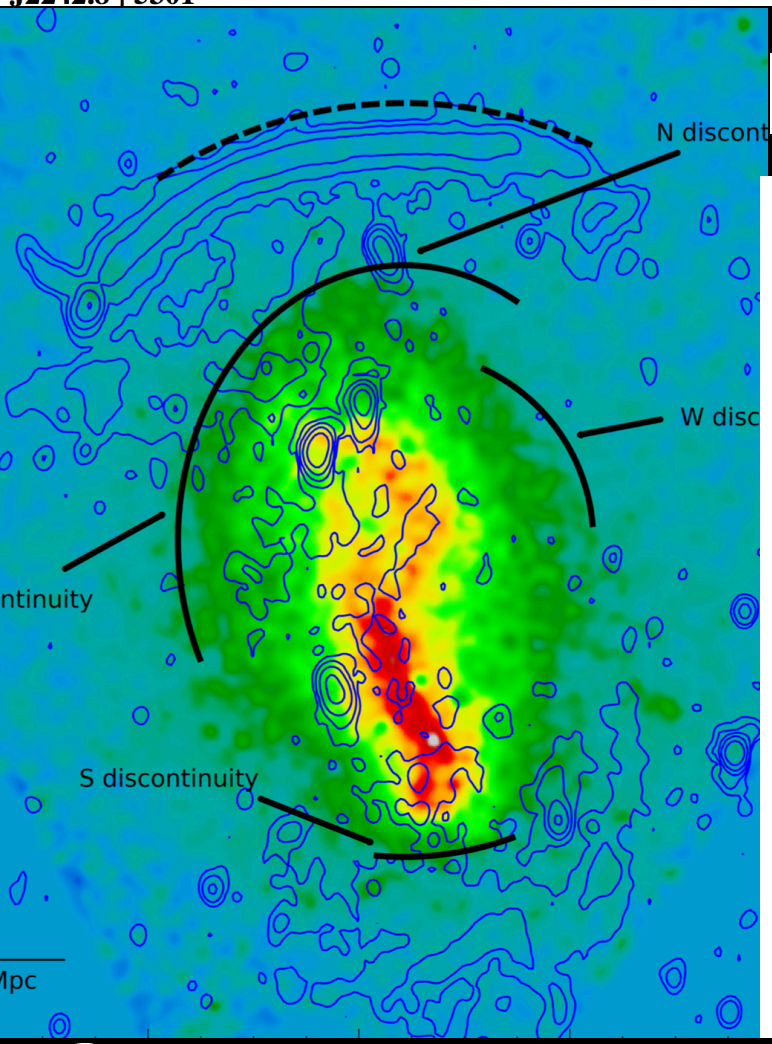
Beyond the northern relic, there is a single bin of SNR ≈ 1.8 (not shown in Figure 4) and surface brightness 0.08 ± 0.05, so a factor of ~ 7 lower than the surface brightness in the (putative) post-shock region. Unfortunately, the ICM signal beyond the relic is too low to allow us to model……



Chandra X-ray observations of Sausage relic

Multiple density discontinuities in the merging galaxy cluster CIZA J2242.8+5301

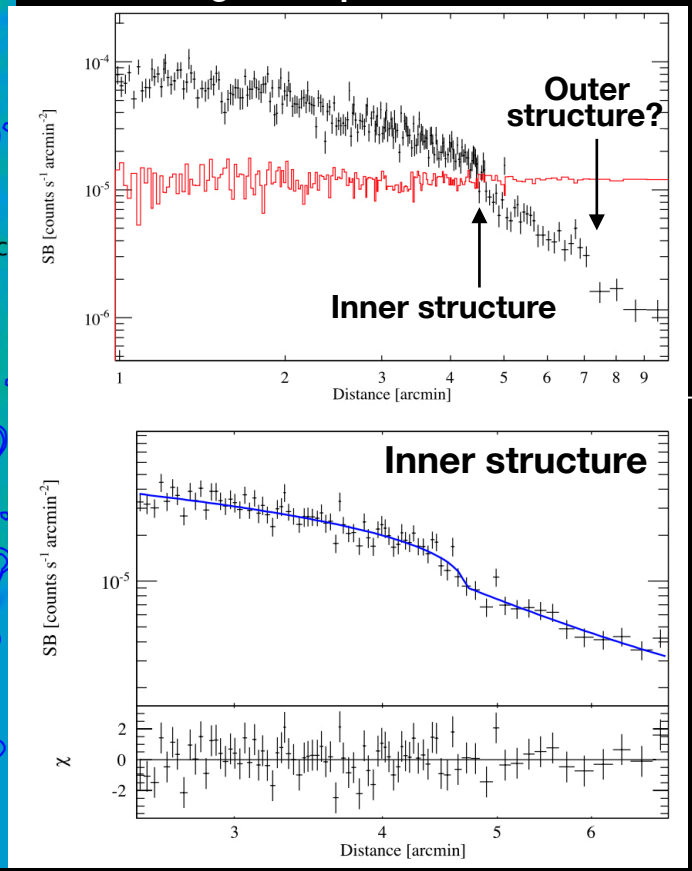
G. A. Ogrean,[1★] M. Brüggen,[1] R. van Weeren,[2] H. Röttgering,[3] A. Simionescu,[4] M. Hoeft[5] and J. H. Croston[6]



In the abstract

observations of the cluster. The *Chandra* surface brightness profile across the northern relic only hints to a surface brightness discontinuity (<2σ detection). Nevertheless, our reanalysis

Surface brightness profile for the N relic



In the main text

Unfortunately, the net count statistics beyond the outer N discontinuity are very poor, and we were only able to detect a shock at slightly more than 1σ confidence level. Therefore, the fit to the outer part of the profile is not presented here.

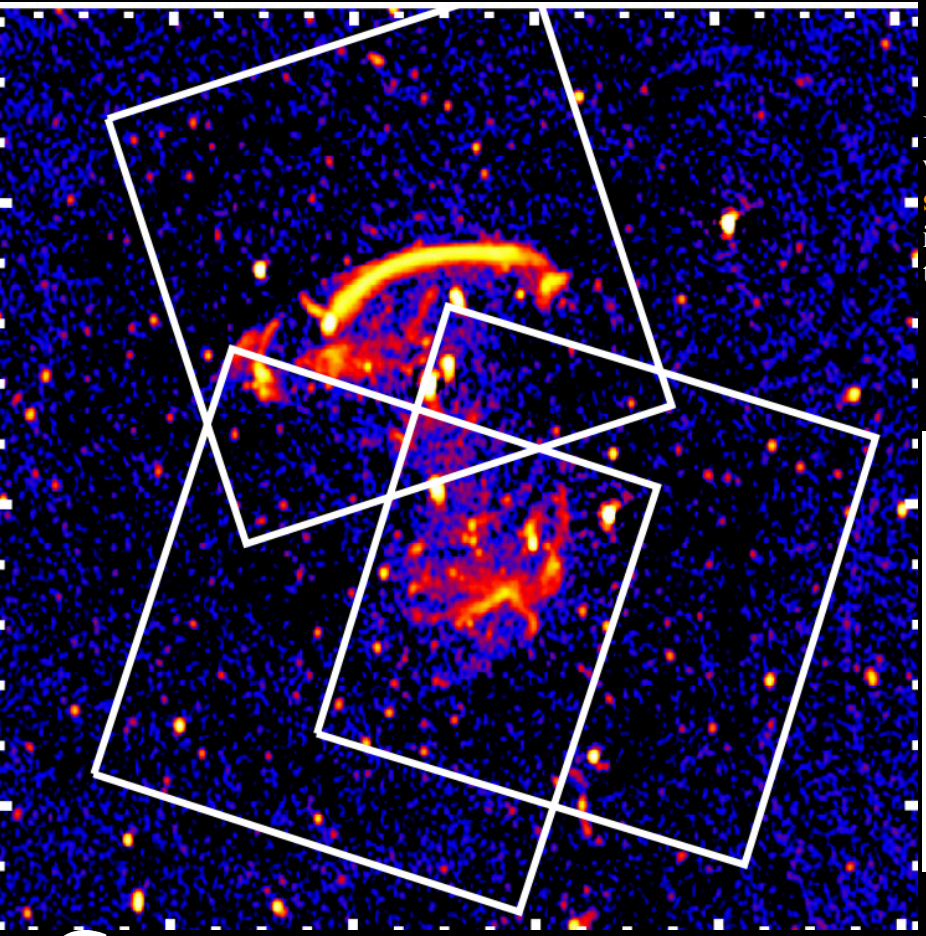
Good news

Chandra SAC approves deep observation (350 ks) (PI: M. Markevitch)

Suzaku X-ray observations of Sausage relic

Systematic X-ray Analysis of Radio Relic Clusters with *SUZAKU*

Hiroki Akamatsu[1] and Hajime Kawahara[2]



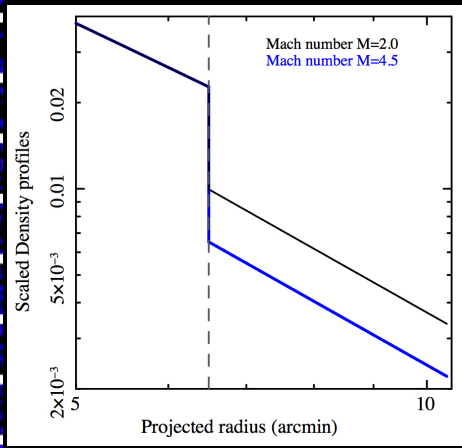
Suzaku X-ray study of the double radio relic galaxy cluster CIZA J2242.8+5301

H. Akamatsu[1], R. J. van Weeren[2], G. A. Ogrean[2], H. Kawahara[3], A. Stroe[4], D. Sobral[4,7,8], M. Hoeft[6], H. Röttgering[4], M. Brüggen[5], and J. S. Kaastra[1,4]

In the text (A&K 2013)

For the CIZA2242 case, the PSF of Suzaku corresponds to 380 kpc, which is probably much larger than the length of shock. Hence the surface brightness jump should be significantly diluted by other area in the bin. We need more observations with a higher angular resolution to confirm the shock structure in the surface brightness profile

Model density profile



Expected surface brightness convolved with PSF