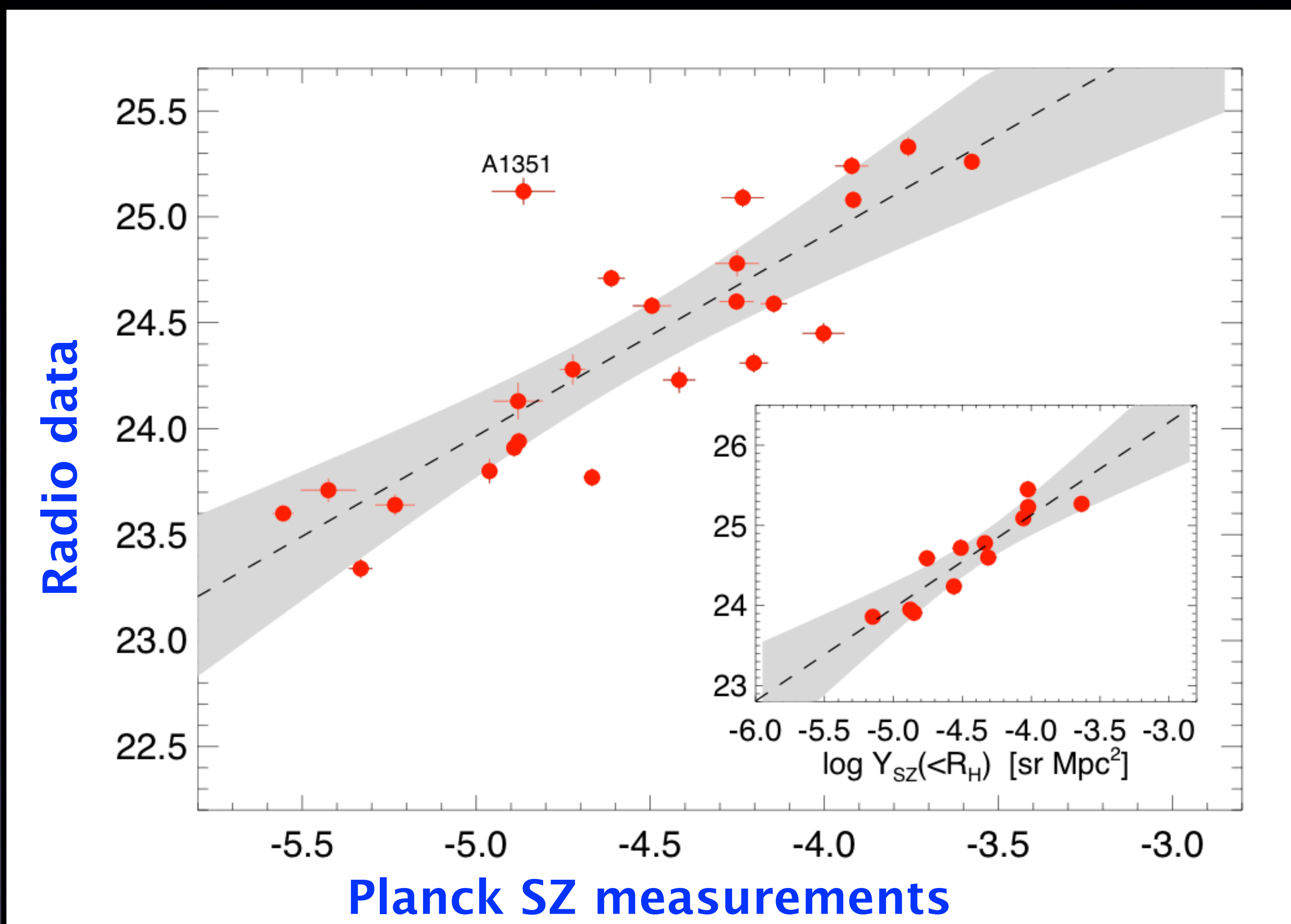
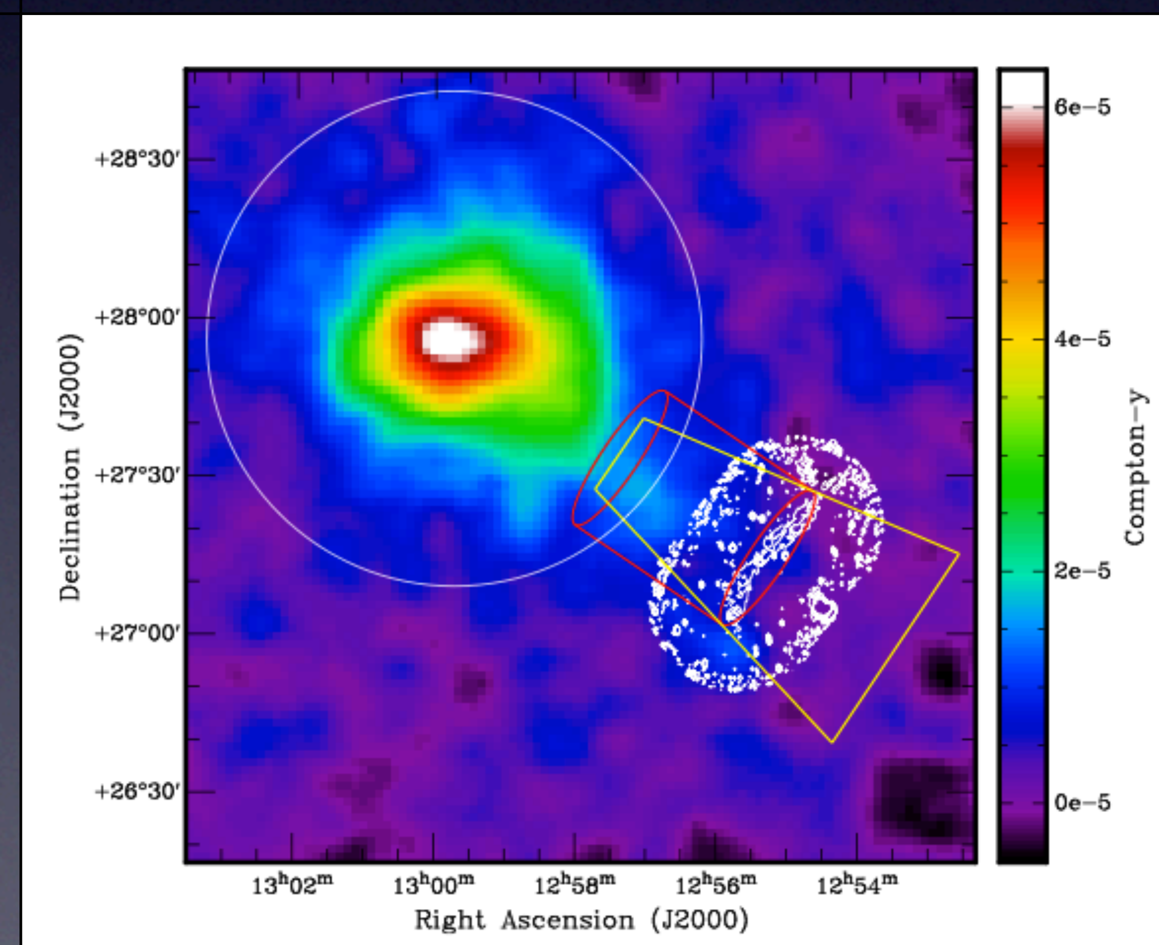
AN SZ TAKE ON

Cluster Diffuse Radio Emissions



Kaustuv Basu

Argelander Institute for Astronomy
University of Bonn



Radio–SZ correlation (for halos): **Basu 2012**
Radio halos in SZ selection: **Sommer & Basu 2014**
SZ shock in Coma radio relic: **Erler, Basu et al 2015**

An SZ tale of two phenomena

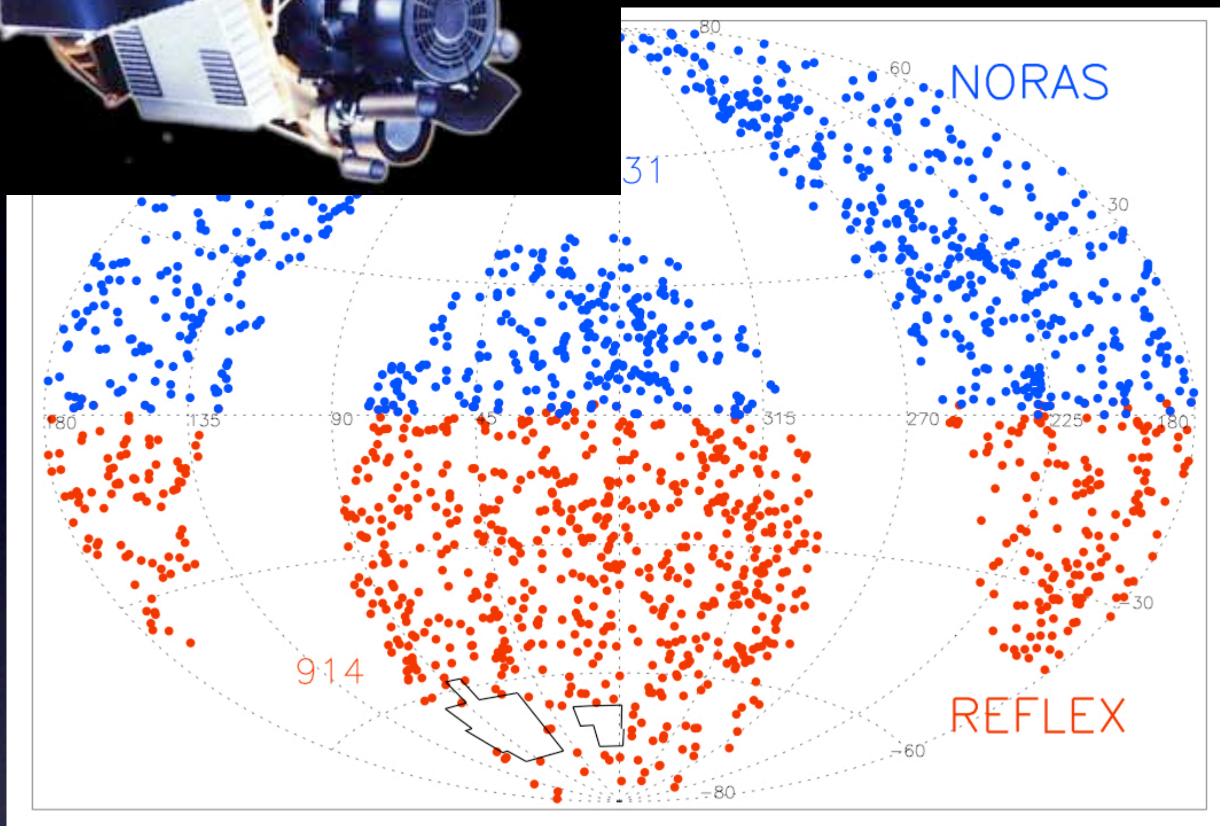
Radio Halos:

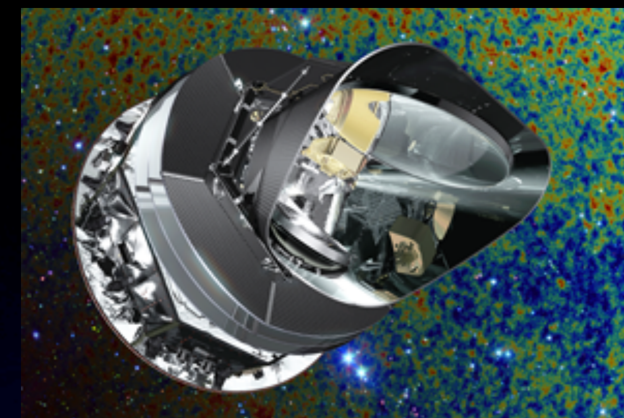
- Radio-SZ correlation for the giant radio halos in galaxy clusters
- A first attempt at measuring radio halo statistics from SZ selection
- Significant difference between SZ and X-ray selection: possible causes and implications for cosmology

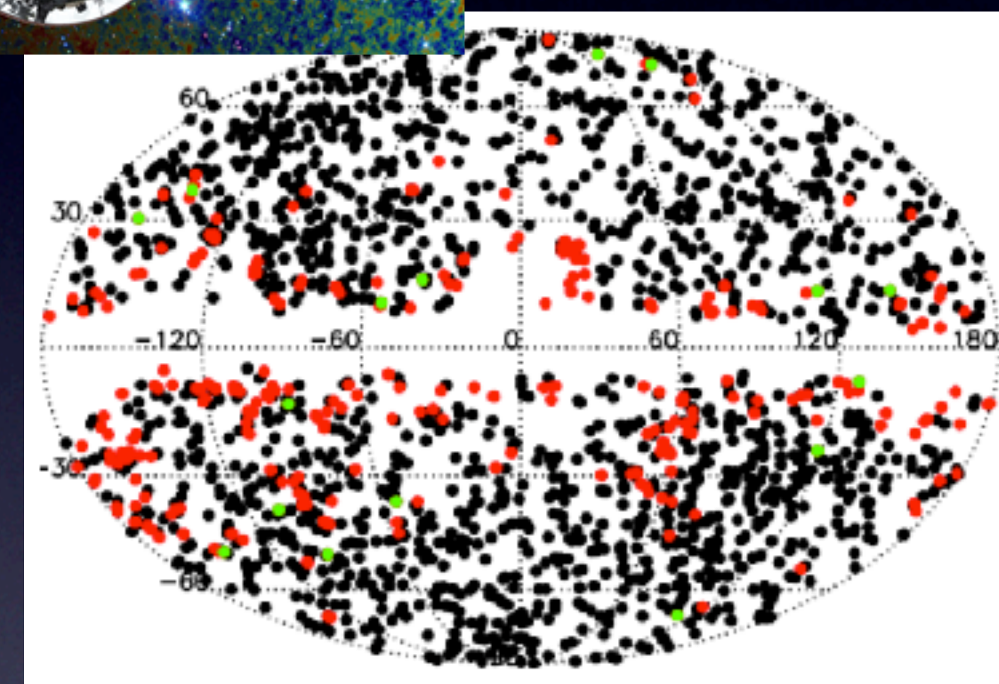
Radio Relics:

- Radio relics in the cluster outskirts: theoretical and observational connection to cluster merger shocks
- A first measurement of pressure discontinuity at a radio relic position from the SZ effect (also first SZ shock near cluster virial radius)
- SZ contamination in GHz-frequency observation of radio relics: caution for observers and challenge for theorists

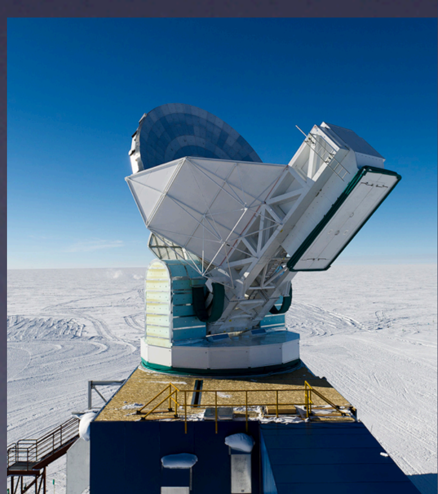
ICM-based cluster surveys



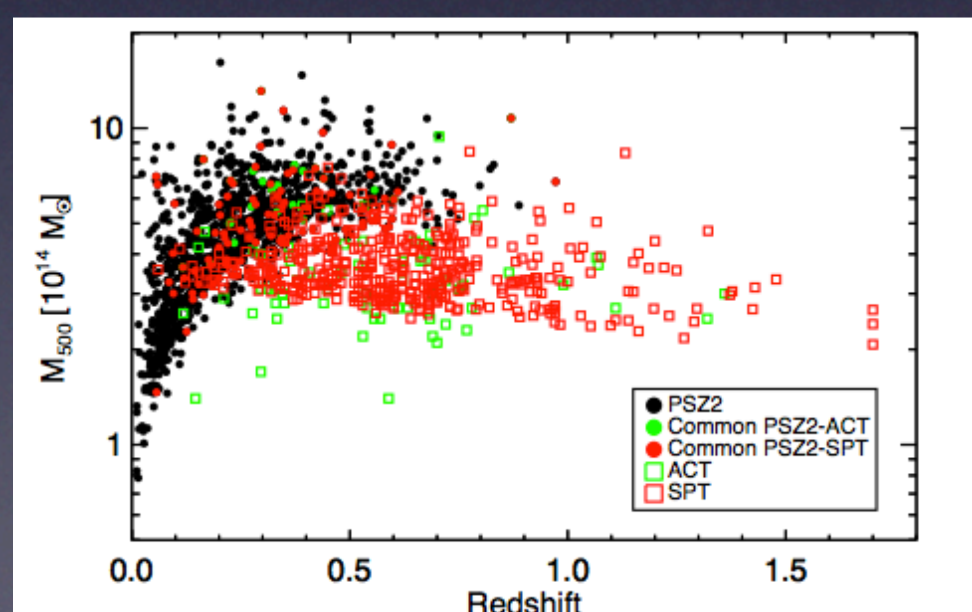




Planck cluster catalog 2015

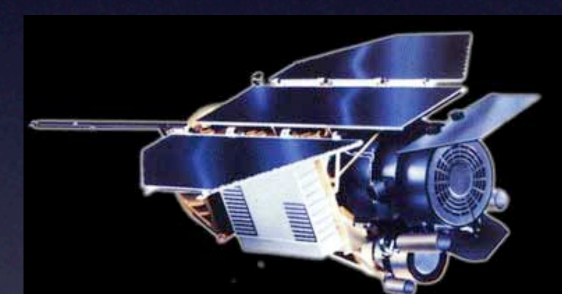


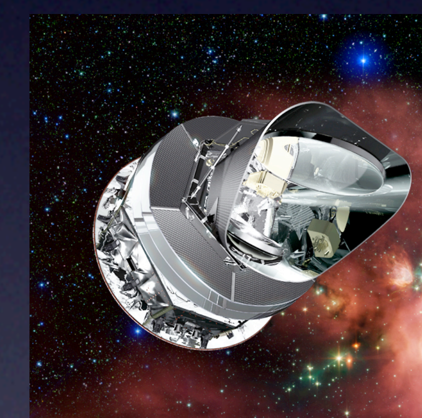
SPT



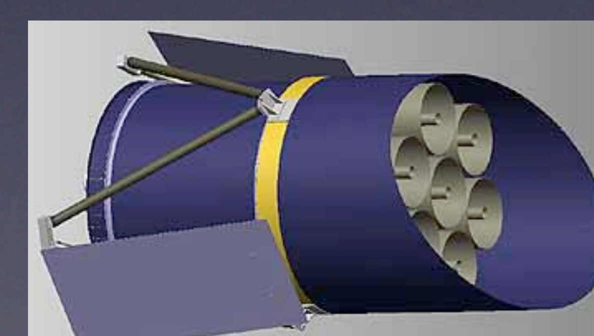
Planck collaboration 2015

“Where are they (in the radio)”?

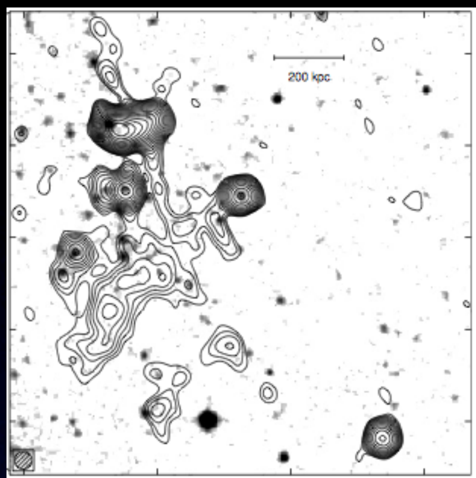

~1000 clusters

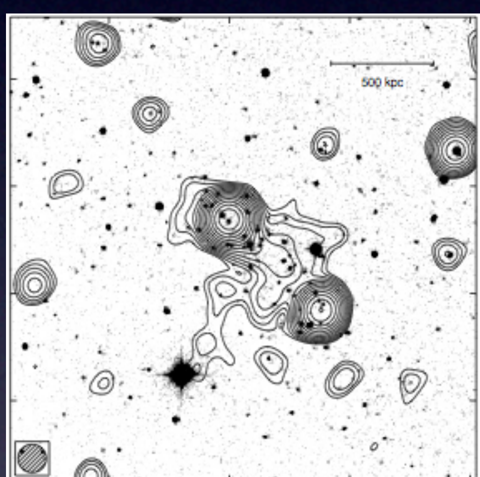

~1500 clusters

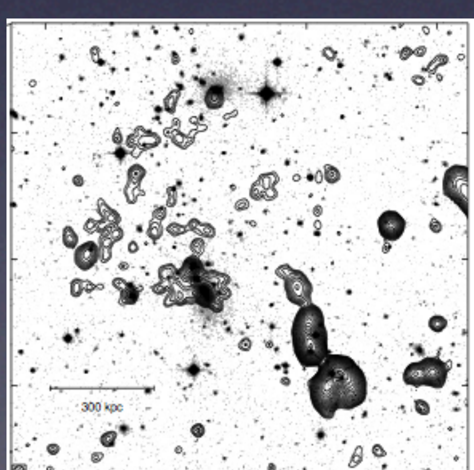

~2000 clusters

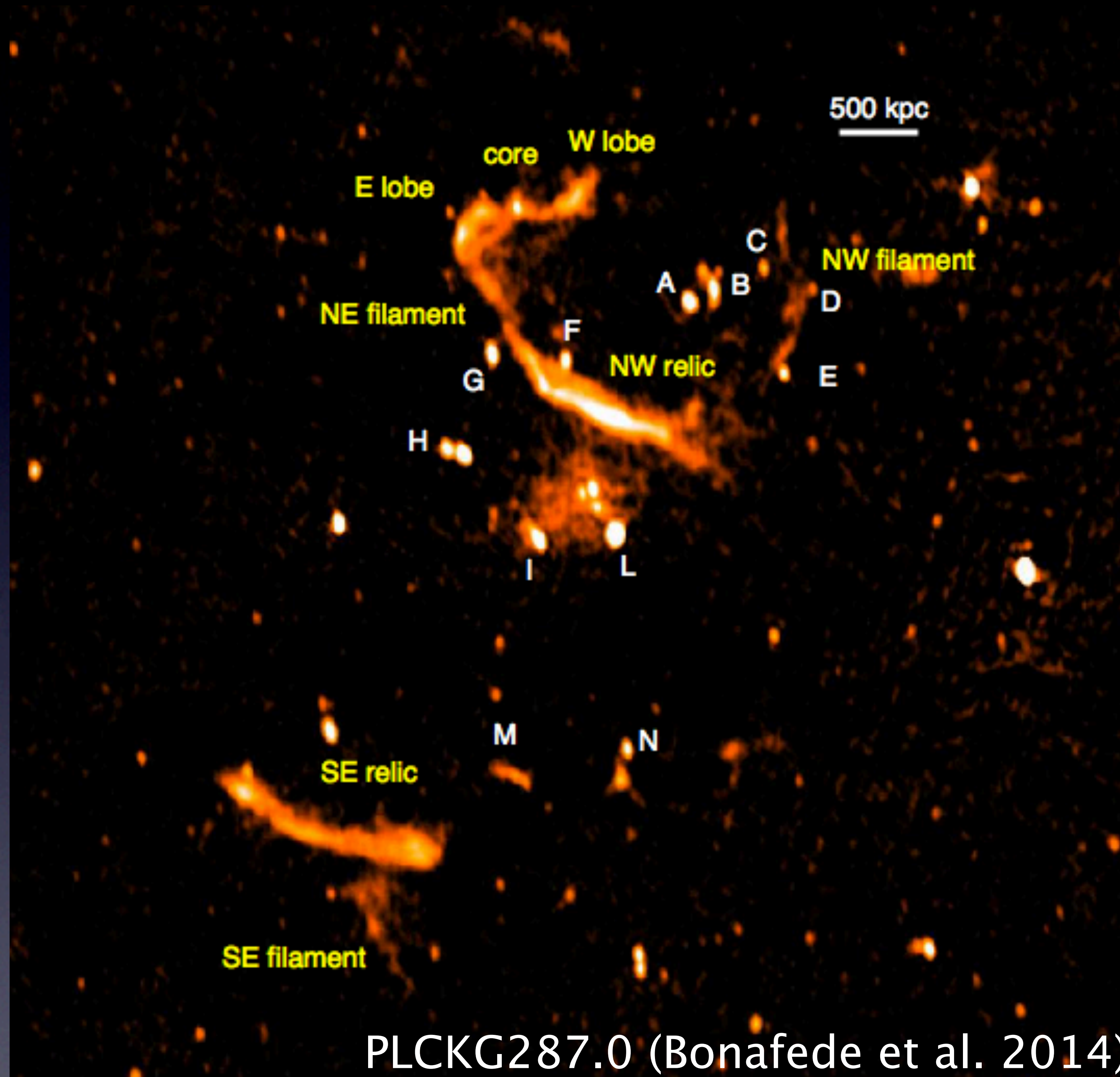

~100000 clusters

The complex radio cluster

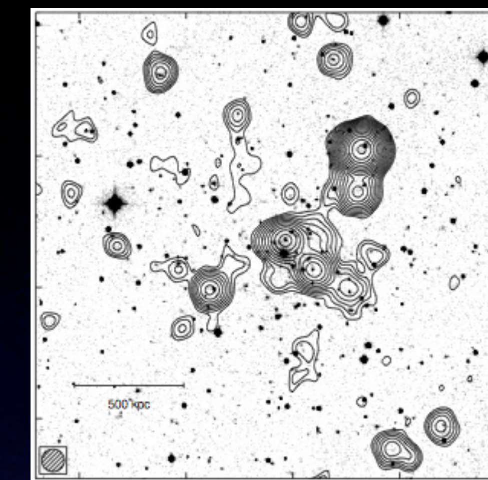


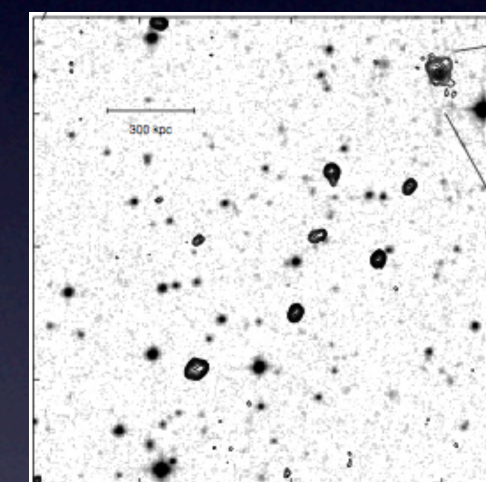


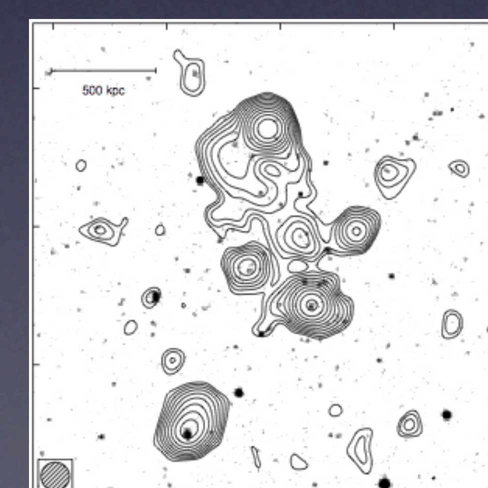




PLCKG287.0 (Bonafede et al. 2014)

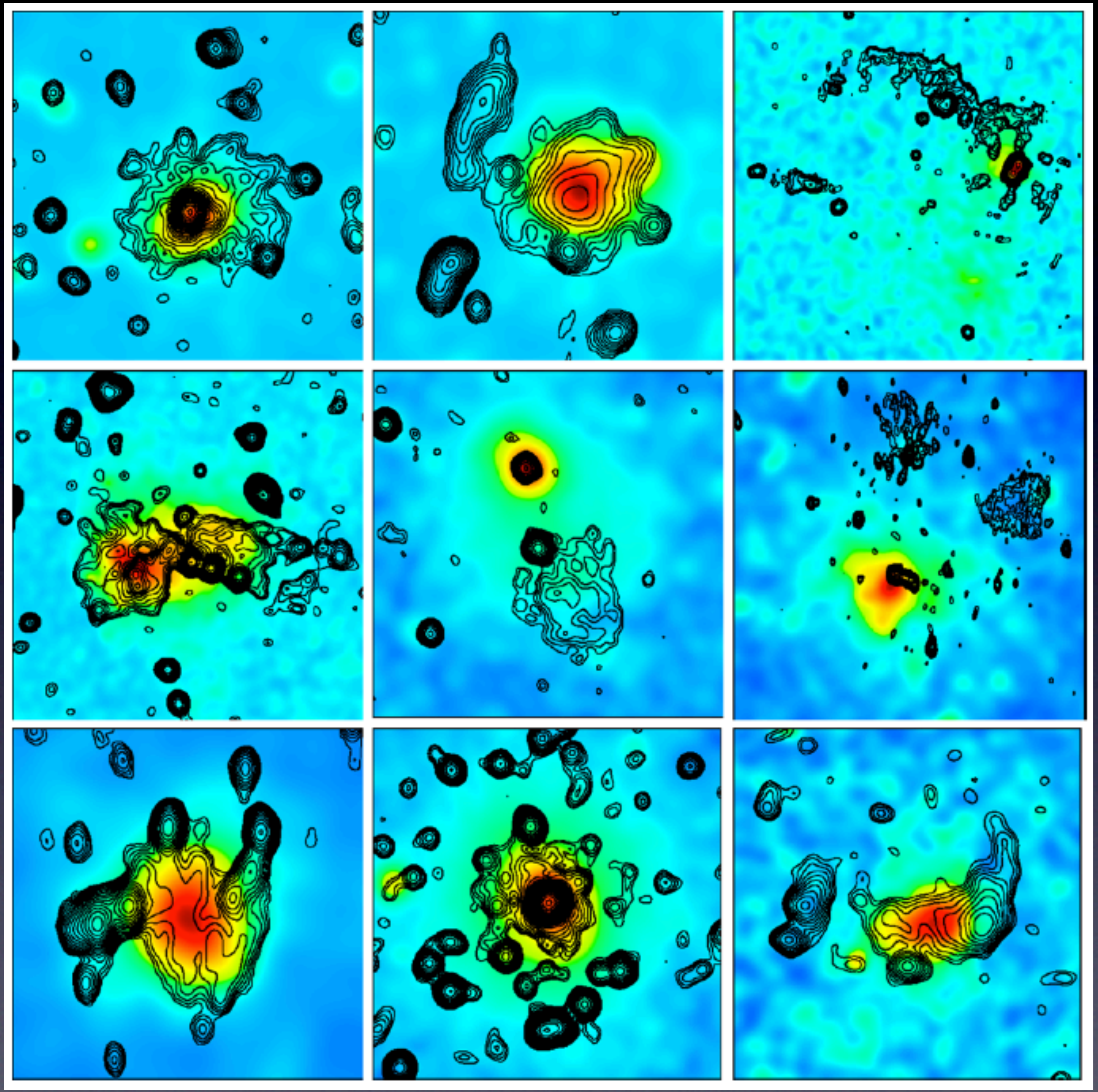






All contour plots from Giovannini et al. (2009)

Diffuse radio emission in clusters



Gallery taken from Feretti et al. (2012) *Color → X-ray*

Both terrible misnomers!

Radio halos: $L_{1.4\ GHz} \sim 10^{24-25}$ W/Hz

- Mpc scale diffuse sources near cluster centers
- Low surface brightness and generally not polarized
- Mostly steep spectrum (α ~ 1.2)
- Morphology roughly similar to X-ray or SZ emission, no severe projection bias

Radio relics: $L_{1.4\ GHz} \sim 10^{23-25}$ W/Hz

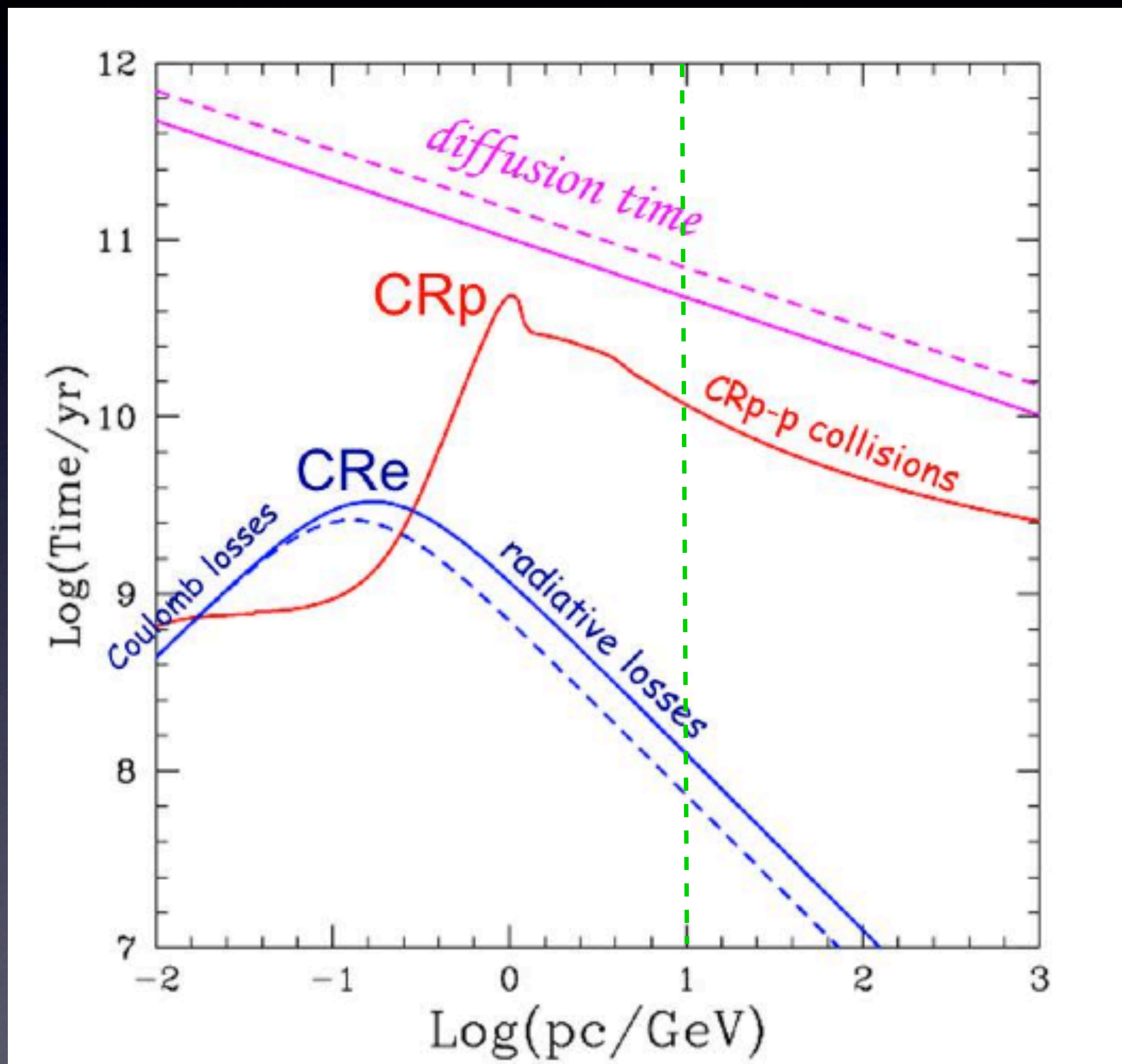
- Mpc scale elongated sources near cluster periphery
- Higher surface brightness and polarized
- Also steep spectrum (α ~ 1.2)
- Morphology resembles shock fronts, subject to projection bias

The radio halo "problem"

Radio halos imply GeV energy electrons filling up cluster volume (~ Mpc^3).
But CRe lifetimes are much shorter (~ 10^8 years) than cluster dynamic timescales.

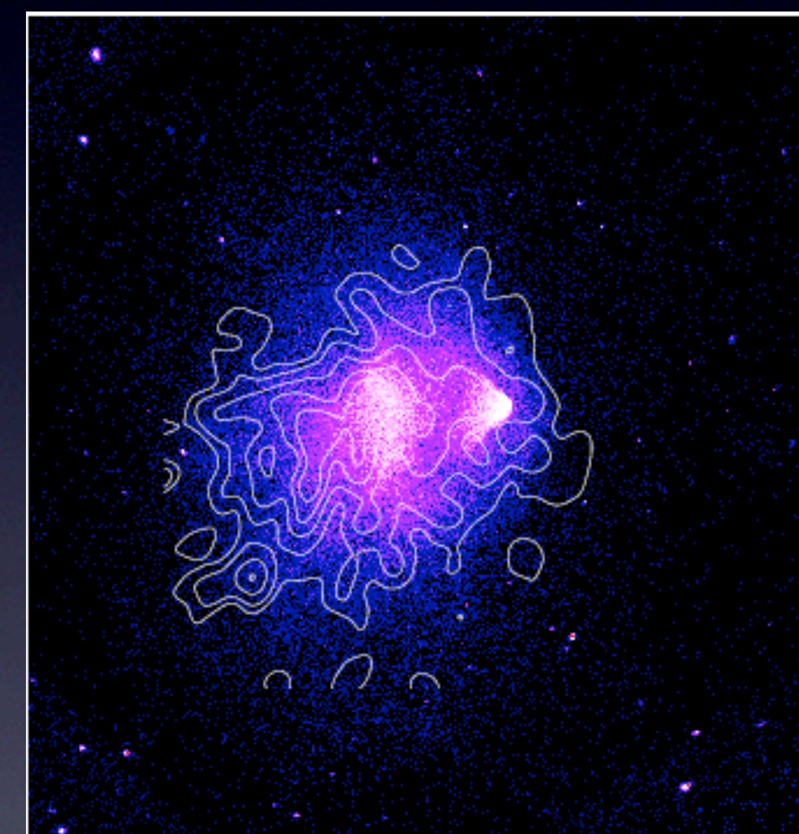
t_H →

$t_{merg.}$ →



(Fig. from Brunetti & Jones 2014)

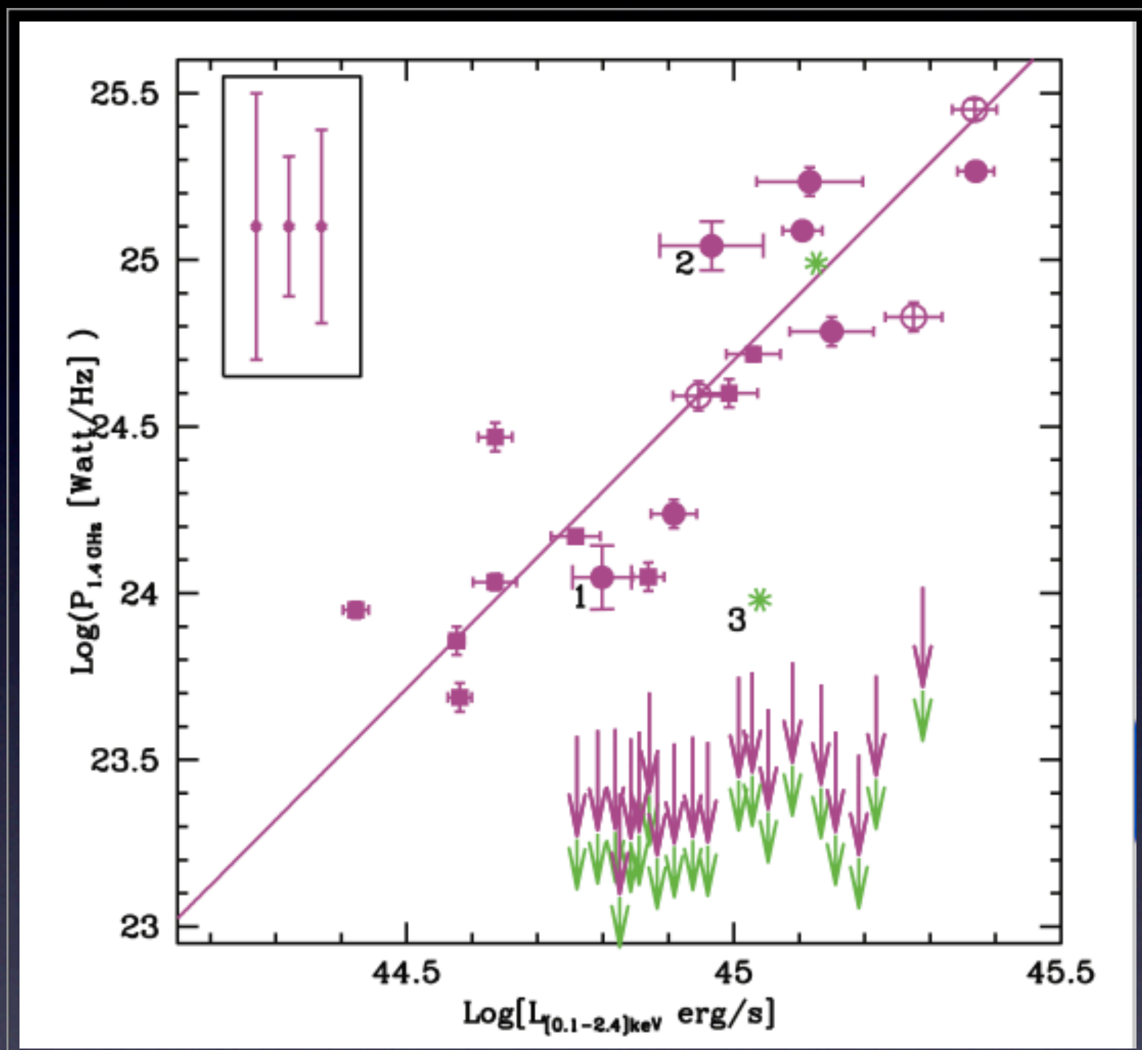
Some *in-situ* acceleration is necessary for the CRe



Radio halo in Bullet cluster (Liang et al. 2000)

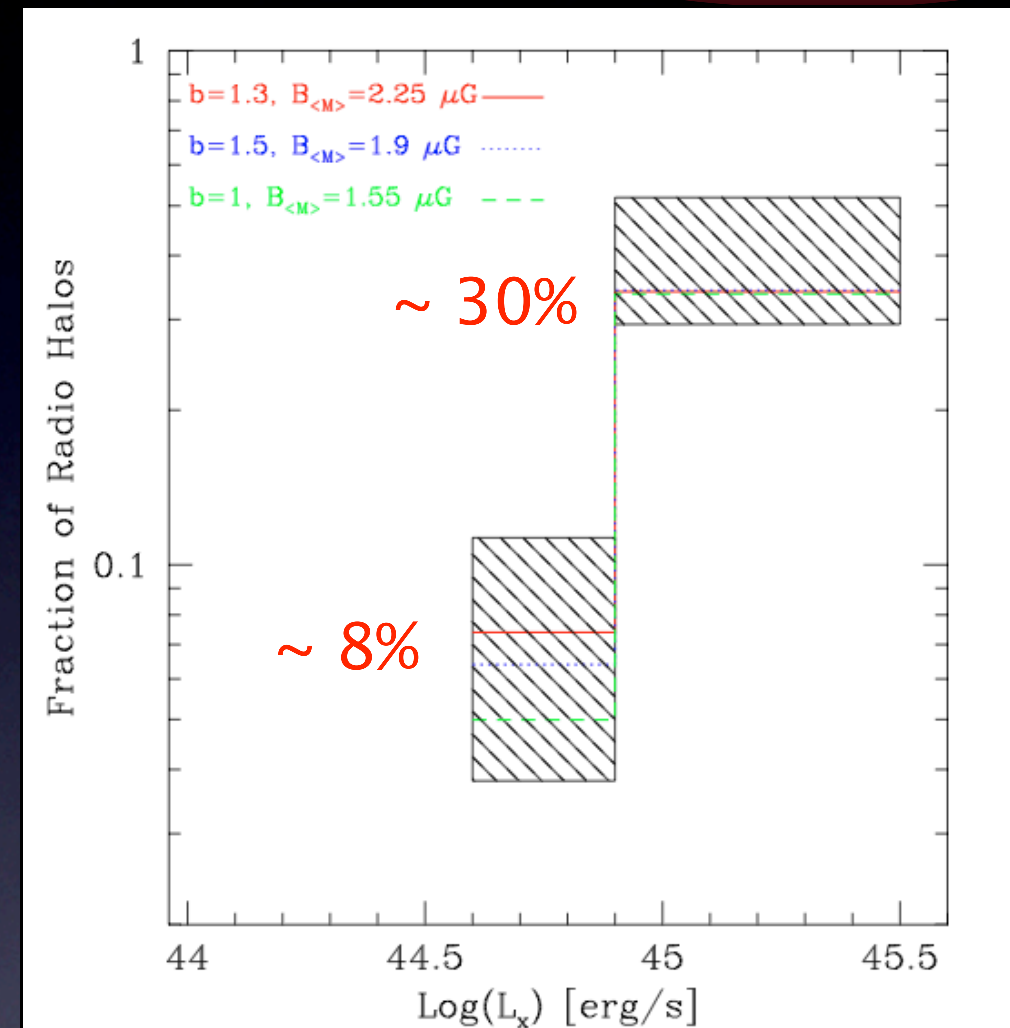
The "current wisdom" for radio halos

There is a strong bi-modality



Brunetti et al. (2007)

They are rare ***~40 known halos***



Cassano et al. (2010)

Primary models (or re-acceleration models):
electrons are accelerated in diffusive shocks via turbulence induced by cluster mergers, through inefficient Fermi-I process

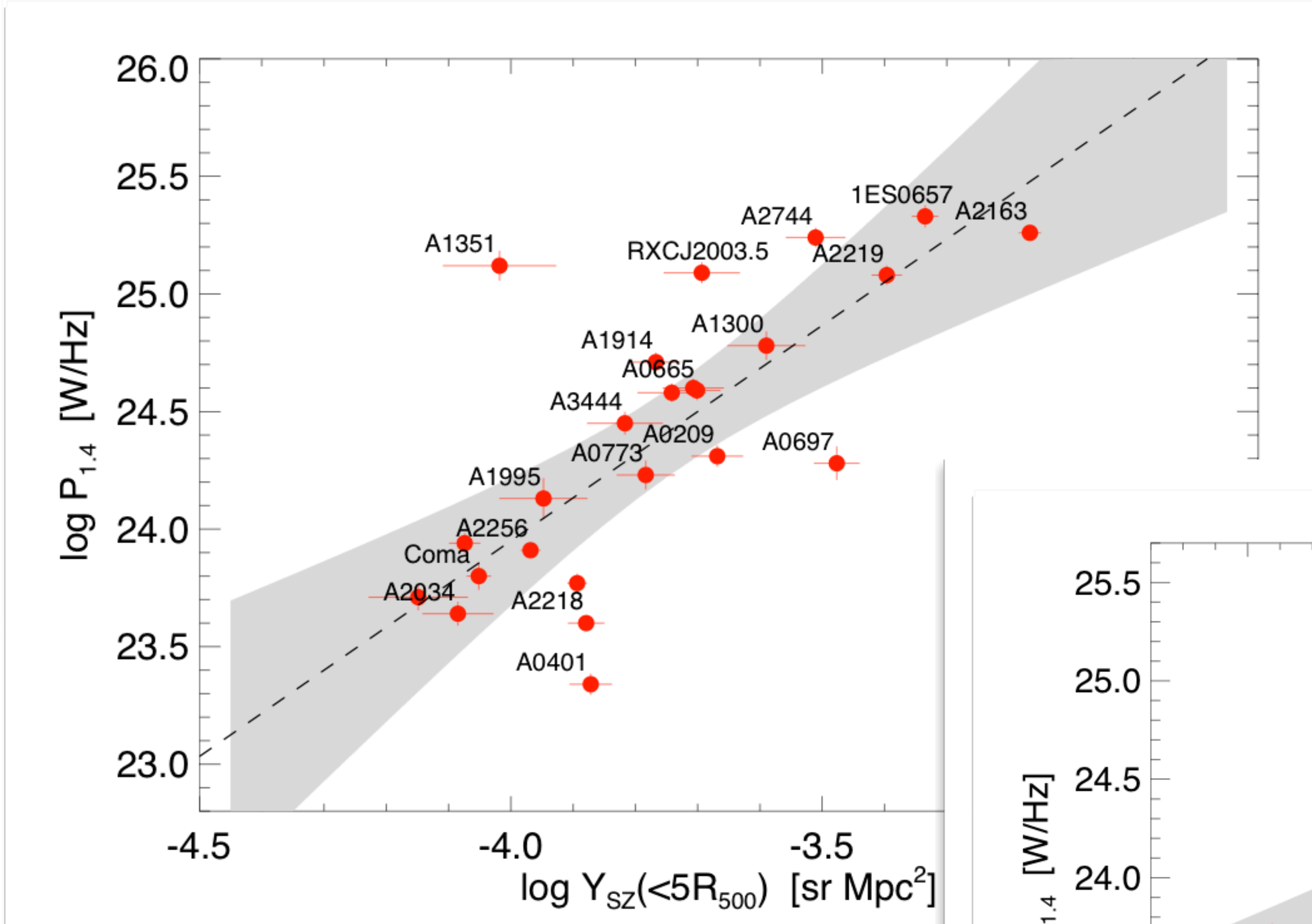
Secondary models (or hadronic models):
e^-/e^+ are produced from collision between thermal ions and cosmic ray protons, the latter having significantly longer lifetimes

Original competing models for radio halo origin

More complex hybrid models

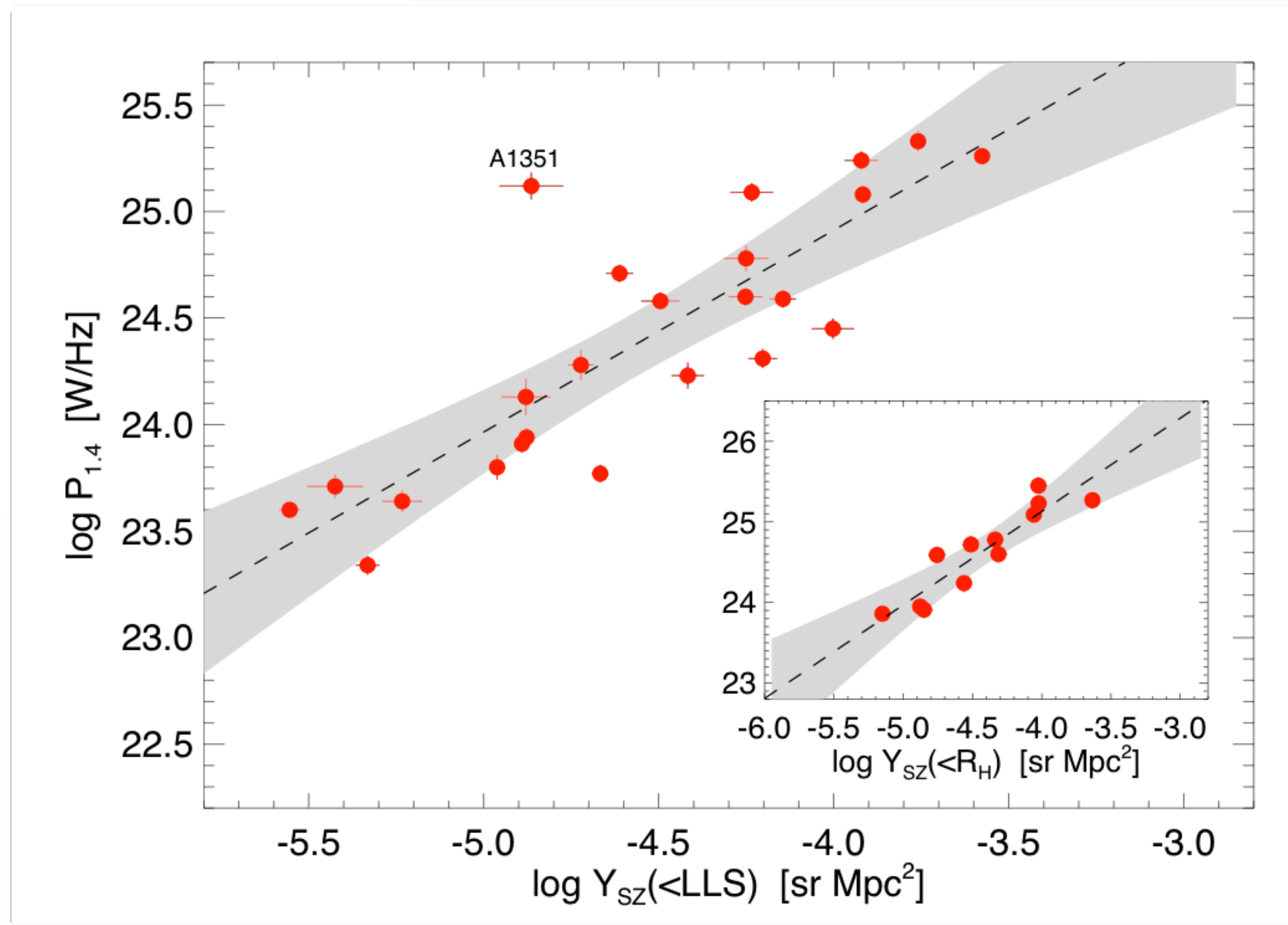
An “SZ take” on this issue

Radio - SZ Correlation



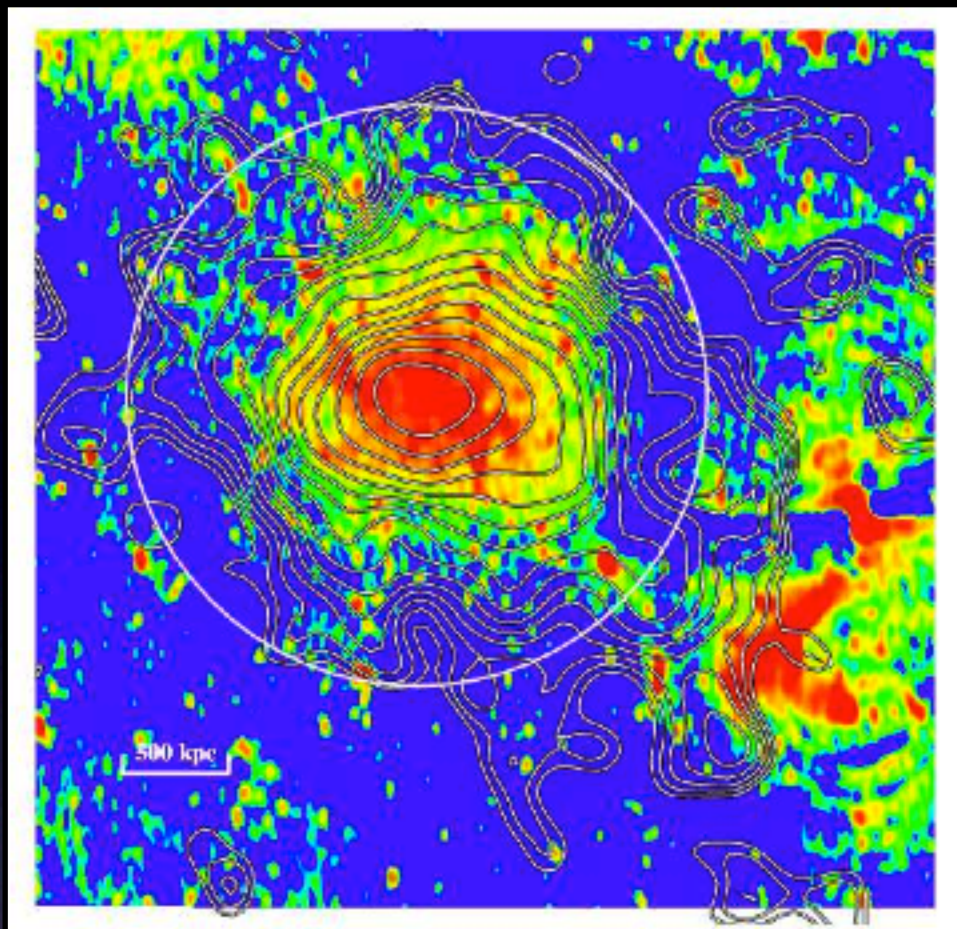
The cluster SZ signal and radio halo power are correlated (as expected from known X-ray correlation)

Basu (2012)

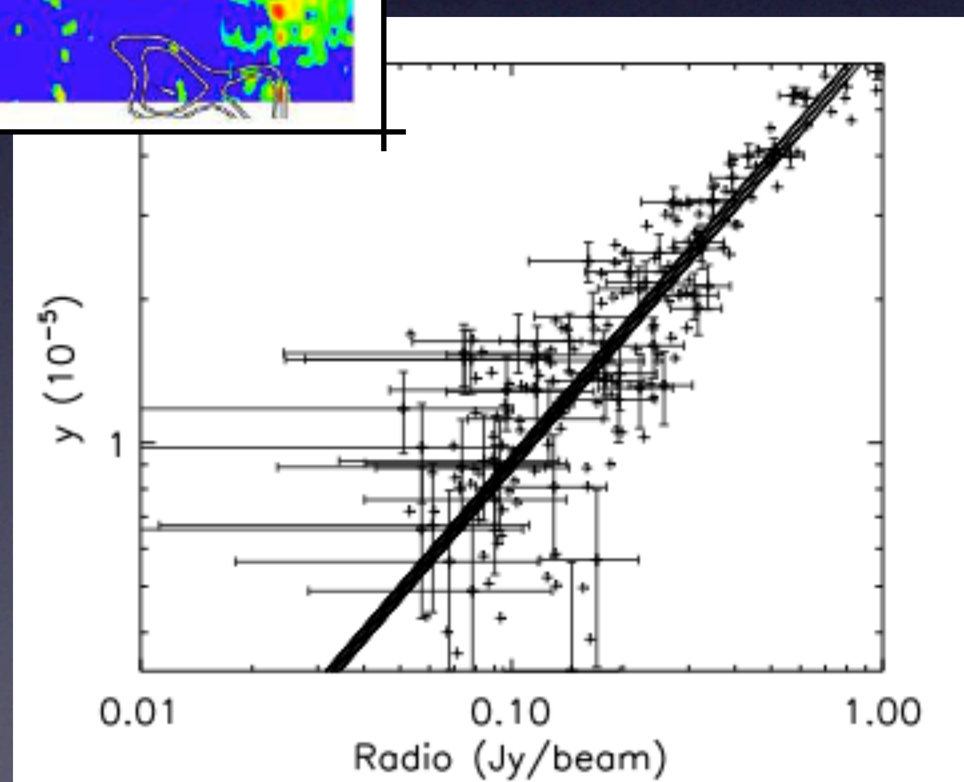


The correlation becomes tighter (and roughly linear) when the SZ signal is scaled to within the radio halo radius

Radio-SZ morphological connection



Planck collaboration result for Coma (2013)



Radio-SZ morphological comparison can provide crucial test for the theory of radio halo origin

From very simplified theoretical estimates

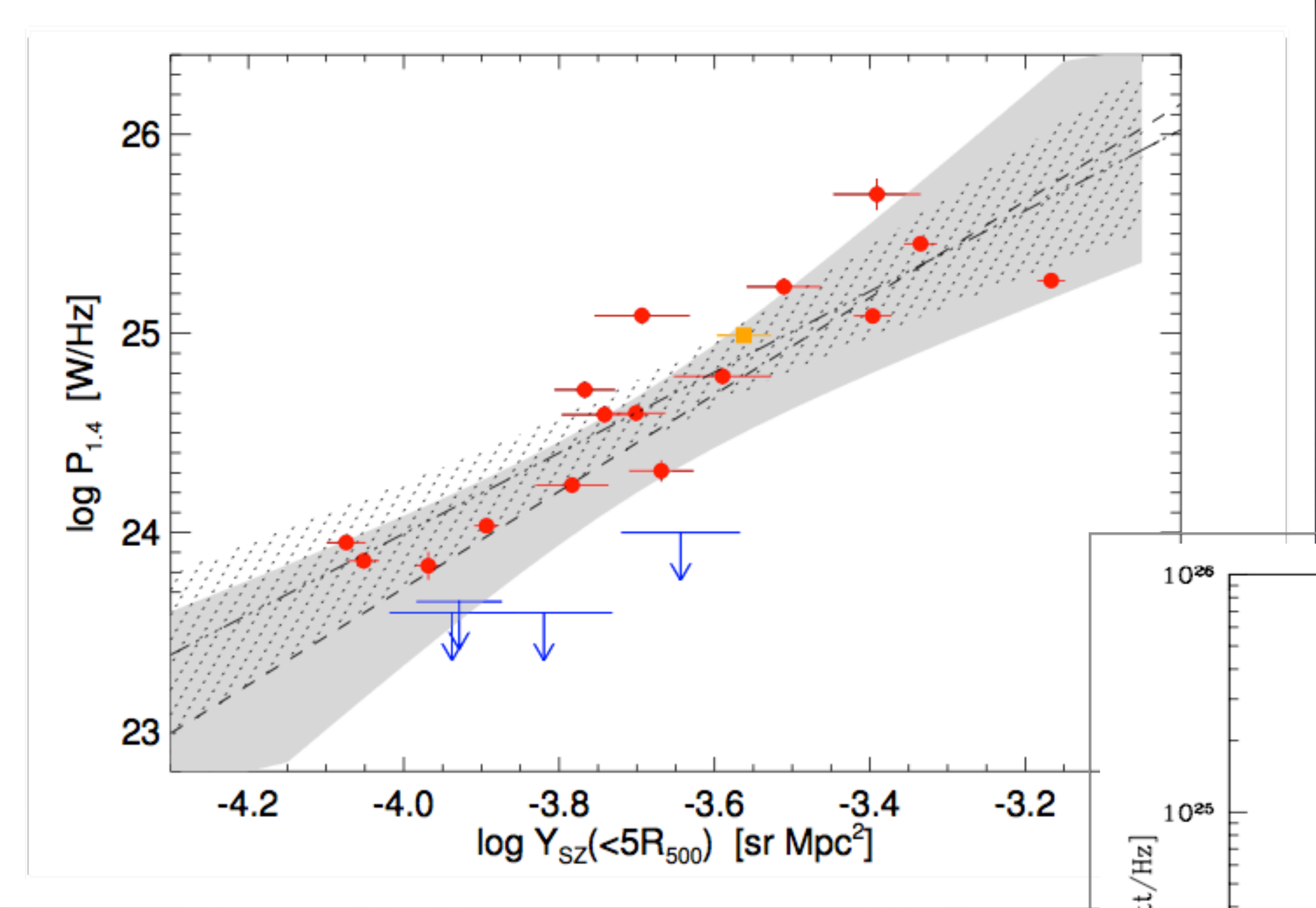
Hadronic model with secondary creation of CR electrons:

$$\epsilon_r \propto \mathrm{n_e} \propto y/T$$

Primary models with turbulent re-acceleration of CR electrons:

$$\epsilon_r \propto \mathrm{n_e}\, T^{1.5} \propto y\sqrt{T}$$

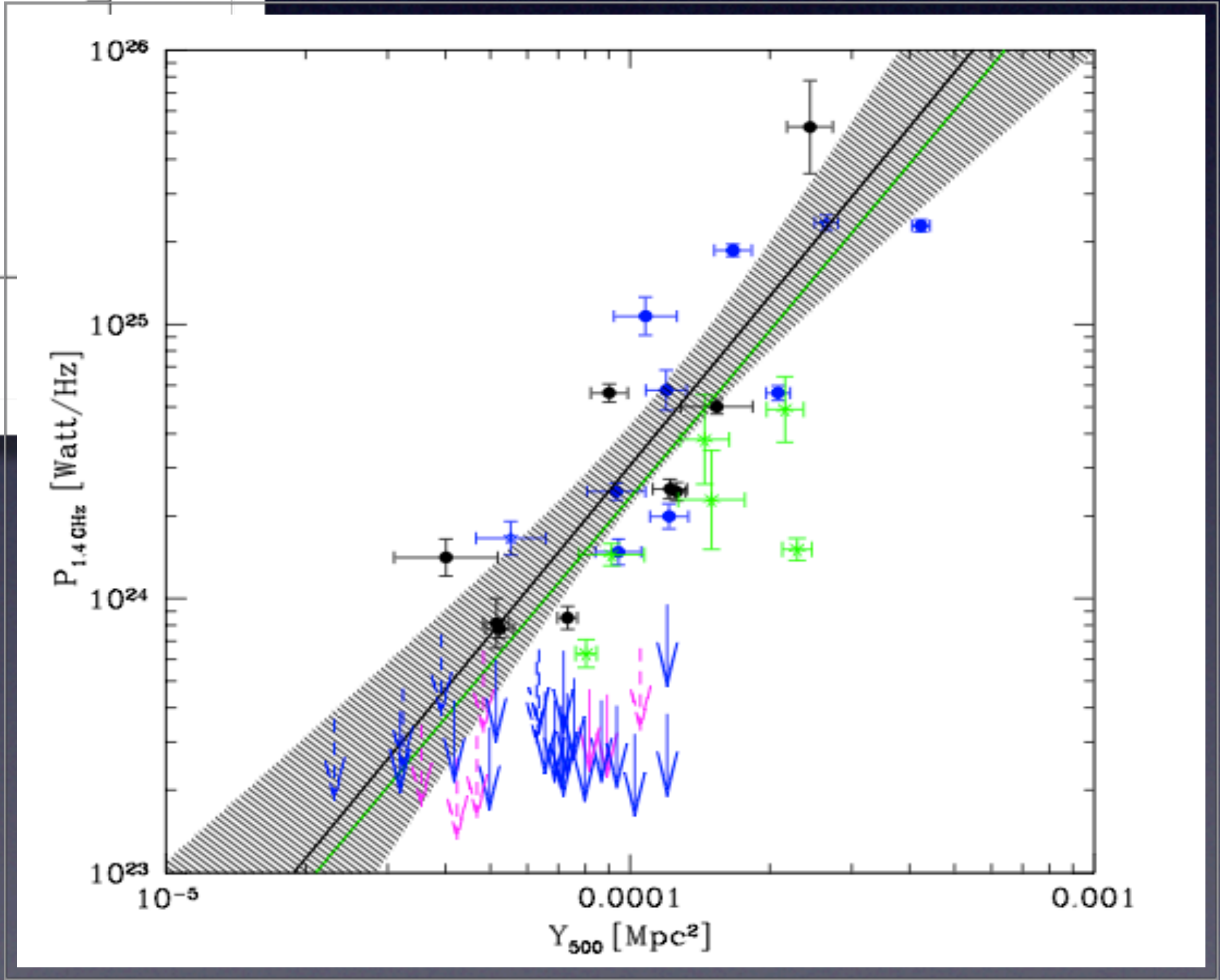
Reduced bi-modality in SZ



Basu (2012)

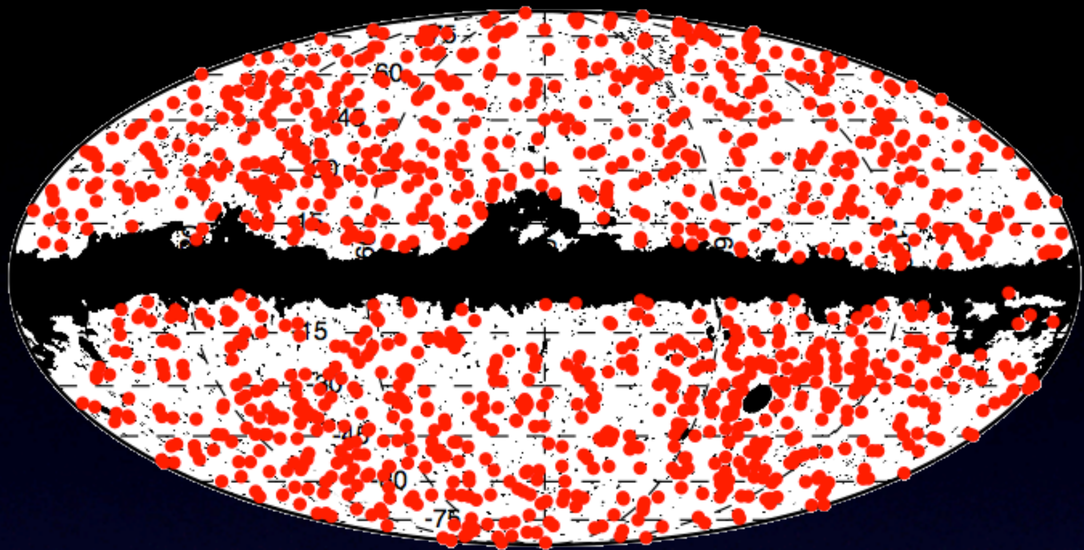
We found from *a posteriori* selection of radio halo clusters, taken from the Planck catalog, that the bi-modality is weak in the radio-SZ correlation.

But this is not enough: we need statistics from *a priori* SZ selection!



Cassano et al. (2013)
PSZ data and X-ray selection

Planck 2013 (PSZ) cluster catalog

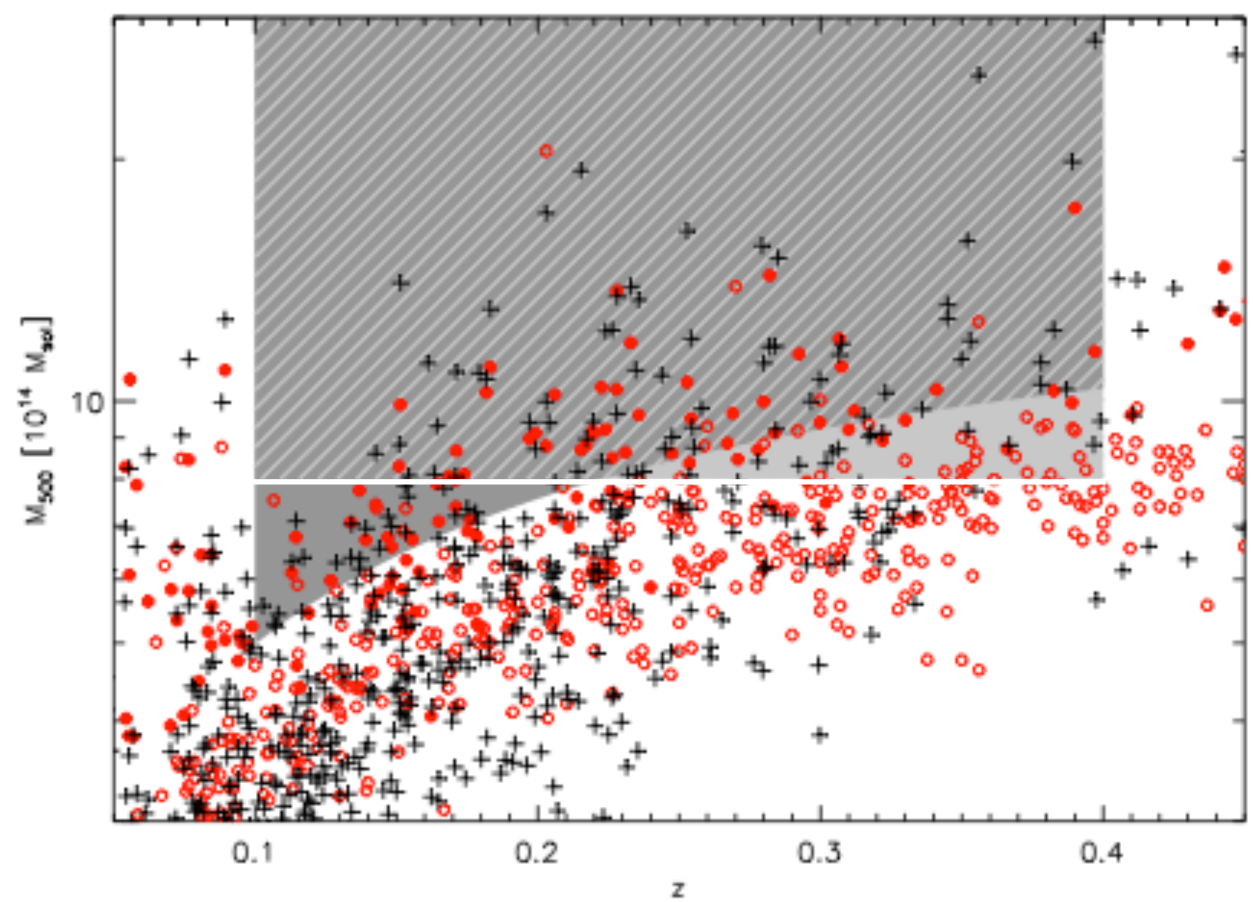


PSZ clusters (Planck coll. 2013)

- Two mass selections: 1) z-dependent mass-cut similar to the Planck *COSMO* sample, and 2) a constant mass-cut of $M_{500} > 8\times10^{14}\ M_\odot$
- Similar to the SZ, a complete X-ray selected sample is obtained based on the REFLEX+eBCS+MACS catalogs
- We then analyze 1.4 GHz radio survey data from the NVSS (Condon et al. 1998) to look for diffuse radio emission at cluster centers

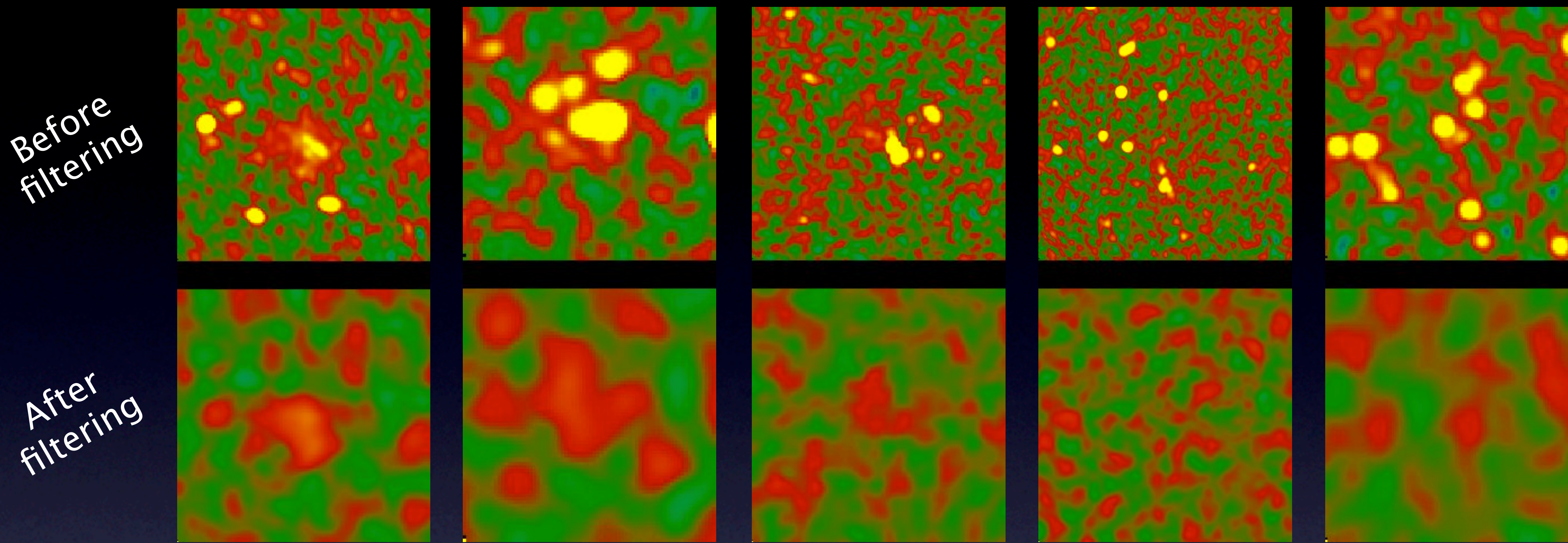
Sub-sample	Mass limit	Primary selection	Flagged due to bad data	Final sample
PSZ(V)	z-dependent	90	1	89
X(V)	z-dependent	86	1	85
PSZ(C)	$8\times10^{14} M_\odot$	79	0	79
X(C)	$8\times10^{14} M_\odot$	78	1	77

PSZ and REFLEX+eBCS+MACS



Sommer & Basu (2014)

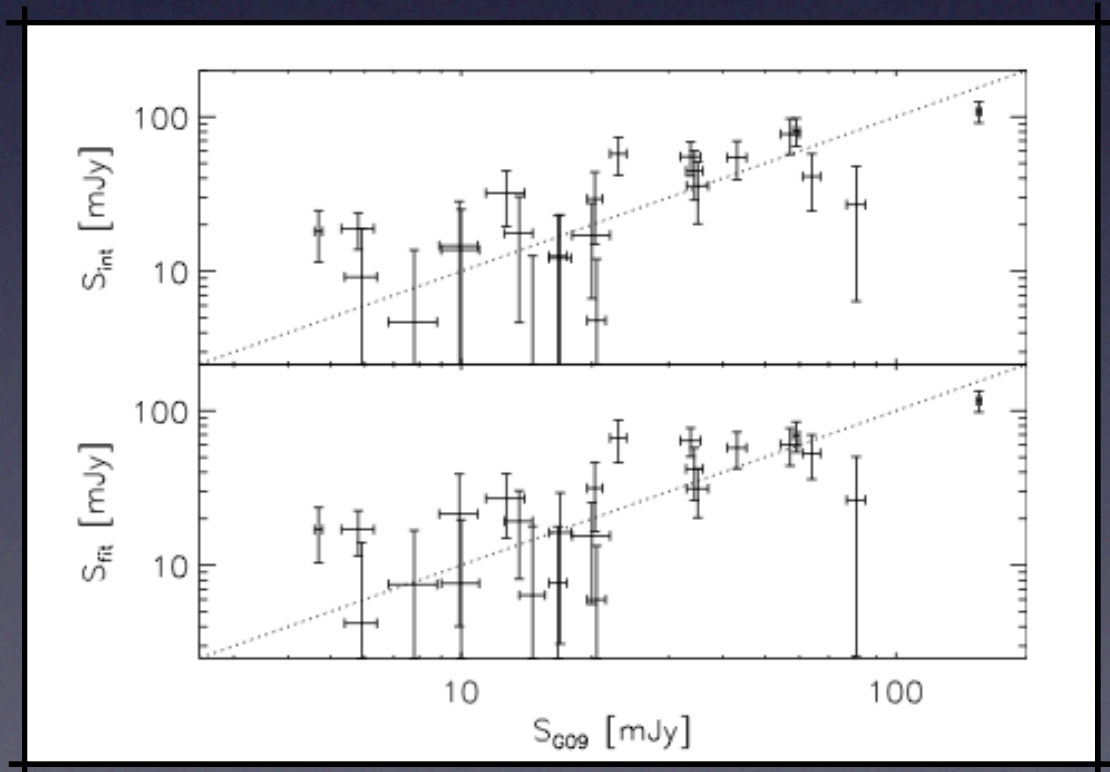
Filtering NVSS 1.4 GHz maps



- FIltering and modeling biases are controlled through <u>extensive set of simulations & null tests</u>

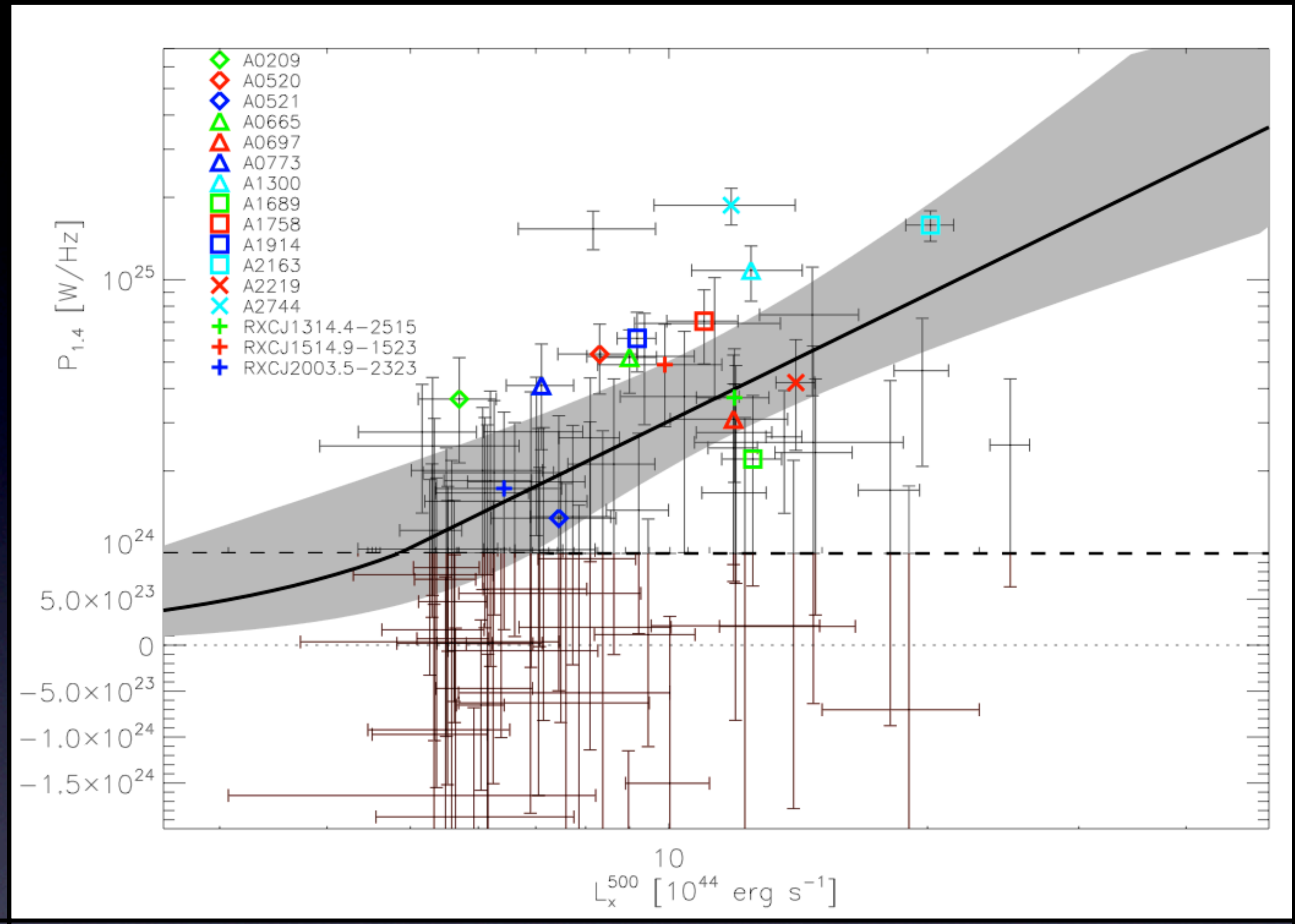
- Enhanced confusion due to the faint AGN and starburst population is modeled from their luminosity function and corrected

Flux comparison with Giovannini et al. (2009)



Noisy detections & regression analysis

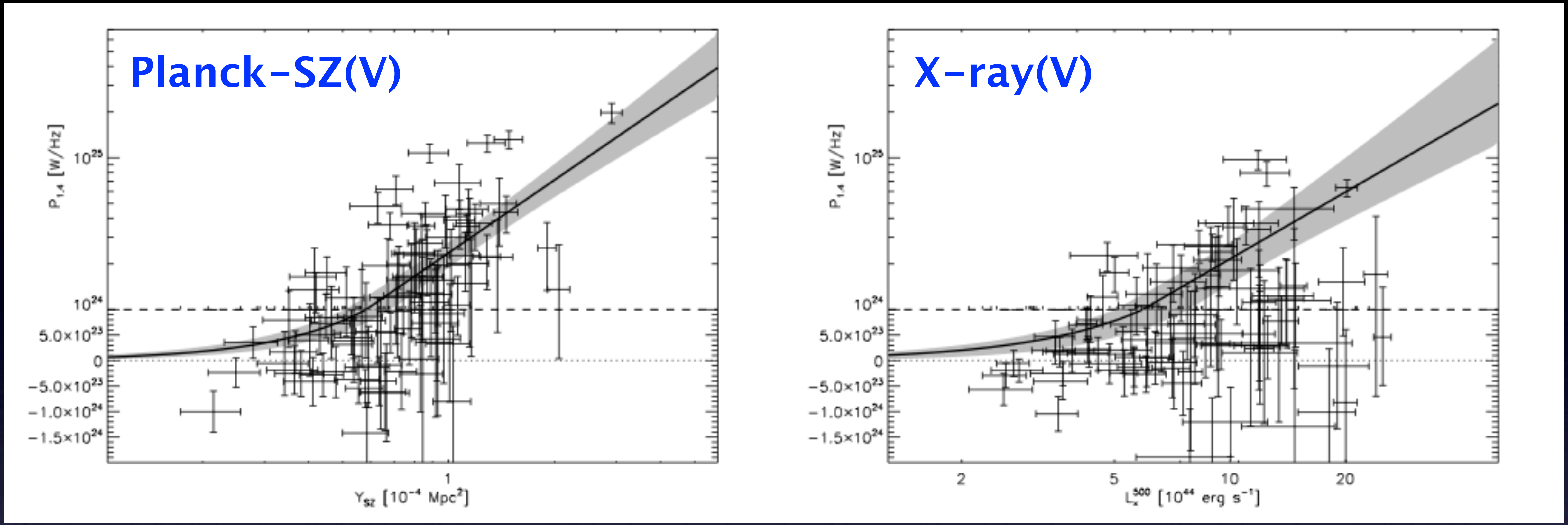
Most of our cluster radio halos from NVSS are non-detections. We do not stack maps, but rather assign individual radio power to each cluster.



We aimed to find the mass correlation of radio power, as traced by L_X or Y_{SZ}, and **determine the "radio off" fraction** that do not belong to this power-law scaling.

We developed a **regression method** that takes into account errors in both direction, intrinsic scatter, non-detections *and a dropout fraction* (i.e. zero population). Model parameters are found through a Markov Chain.

Results for the z-dependent mass-cut



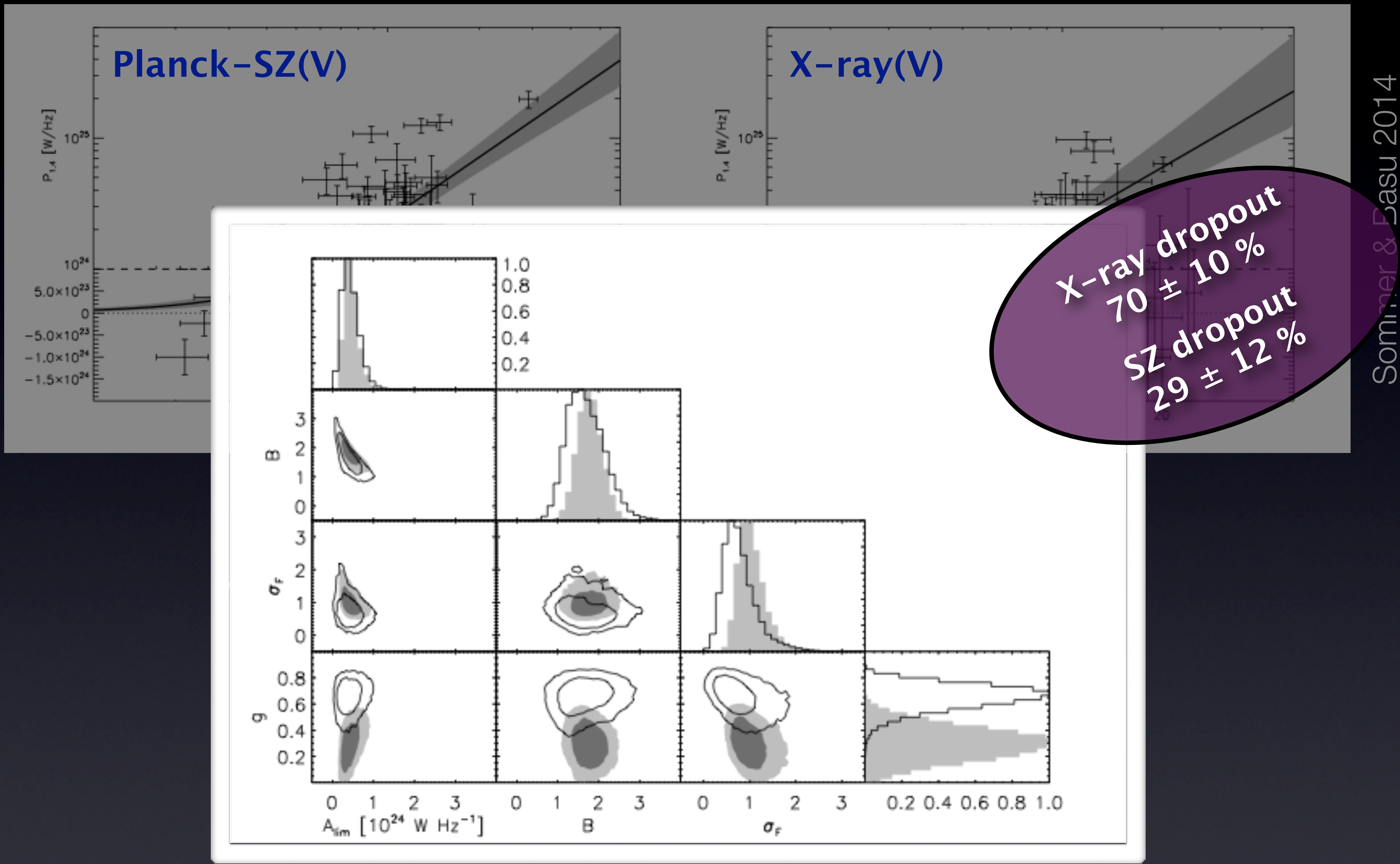
Sommer & Basu 2014

We fit simultaneously for an “on-correlation” population and a “zero” population for both SZ and X-ray sub-samples

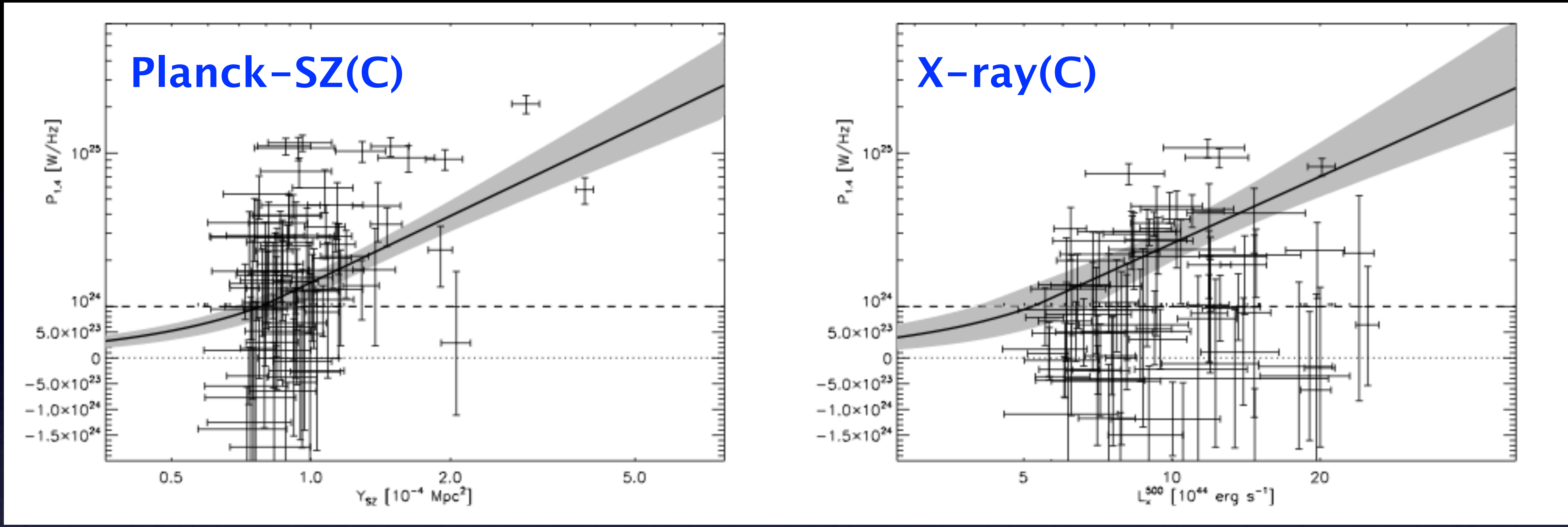
The “on-correlation” populations give consistent mass scaling, with large scatter

But the zero-populations are significantly different!

Results for the z-dependent mass-cut



Results for $M_{500} > 8\times10^{14}\ M_\odot$ mass-cut

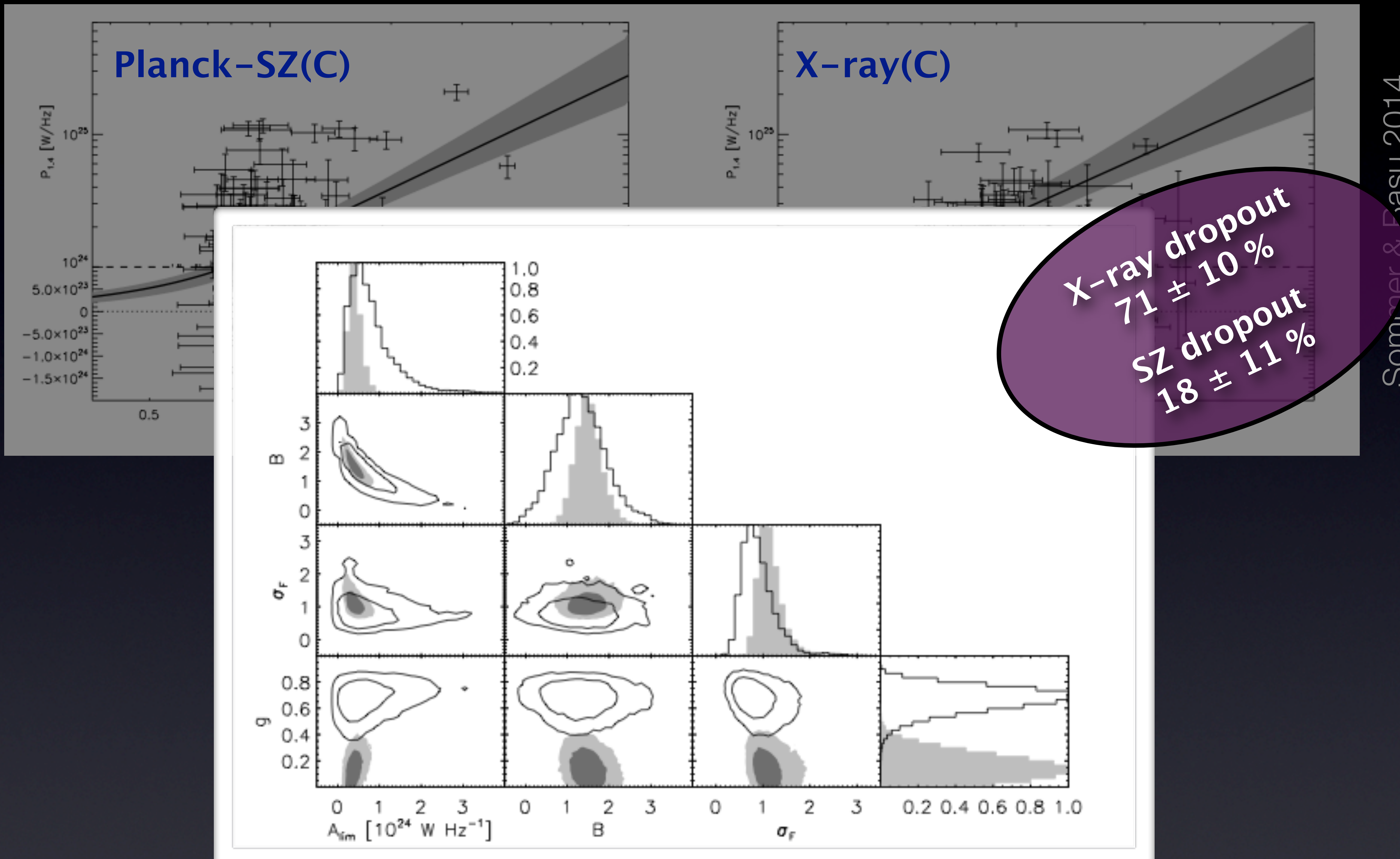


Sommer & Basu 2014

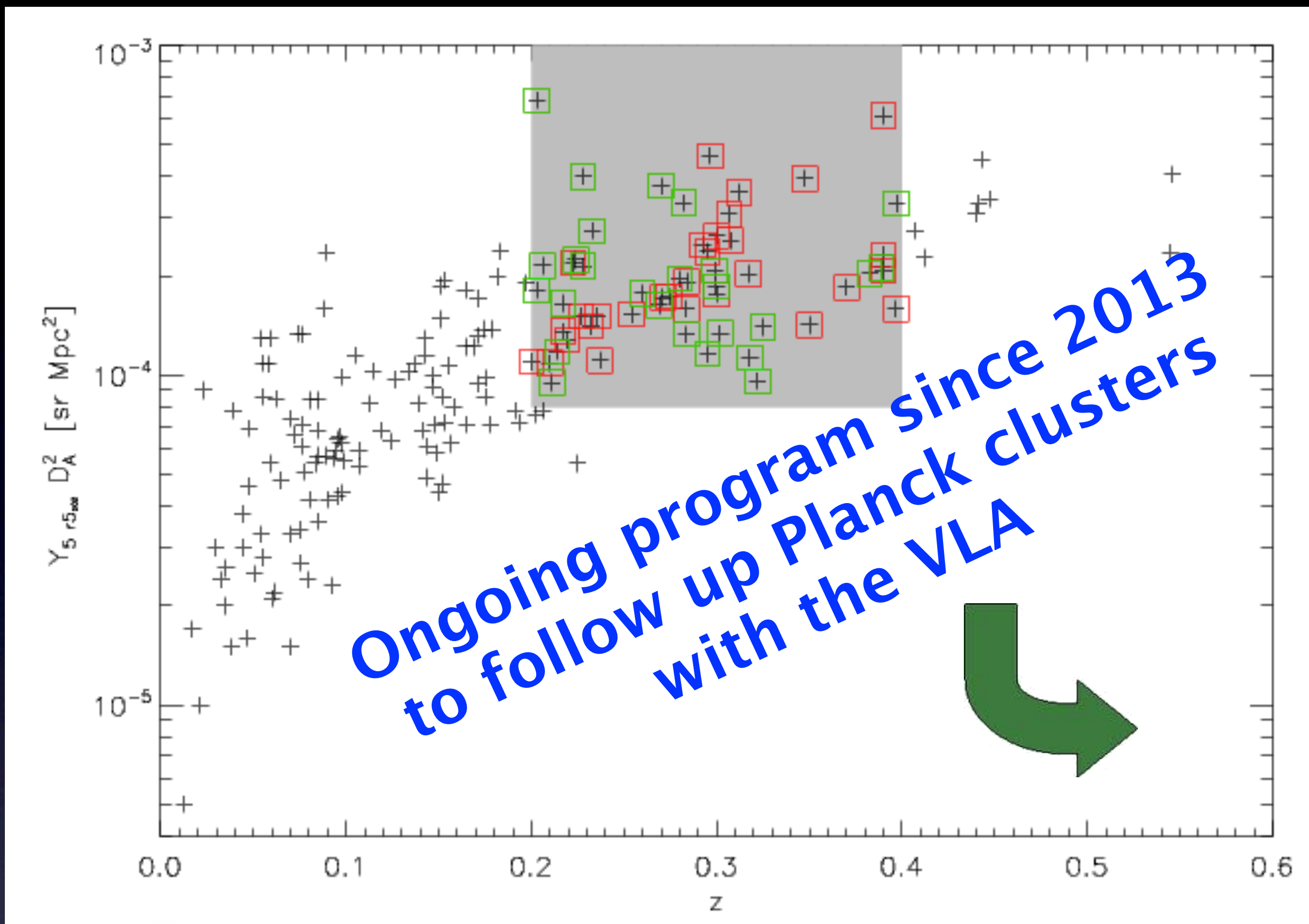
The difference in the radio "off-state" fraction between SZ and X-ray selection is ***marginally more prominent*** when constant mass-cuts are used.

The dropout fraction in X-ray sub-samples are all consistent with previous measurements (~70%), e.g. GMRT survey (Venturi et al. 2008), WENSS (Rudnick & Lemmerman 2009), etc.

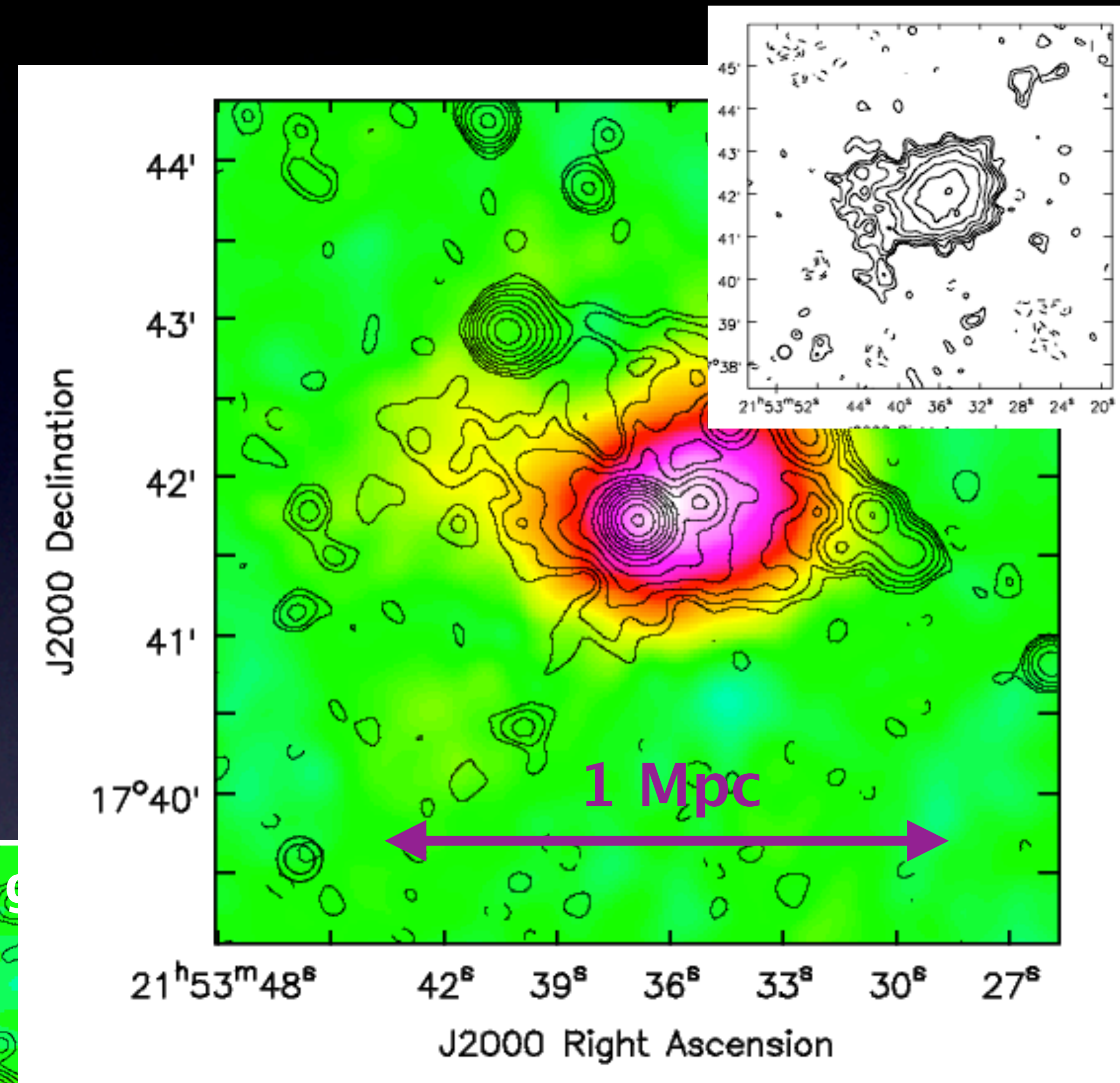
Results for $M_{500} > 8\times10^{14}\ M_\odot$ mass-cut

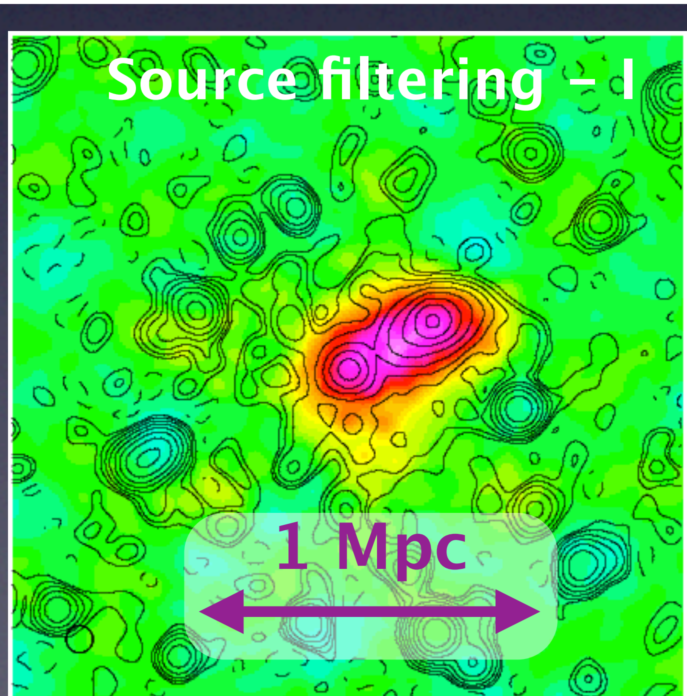


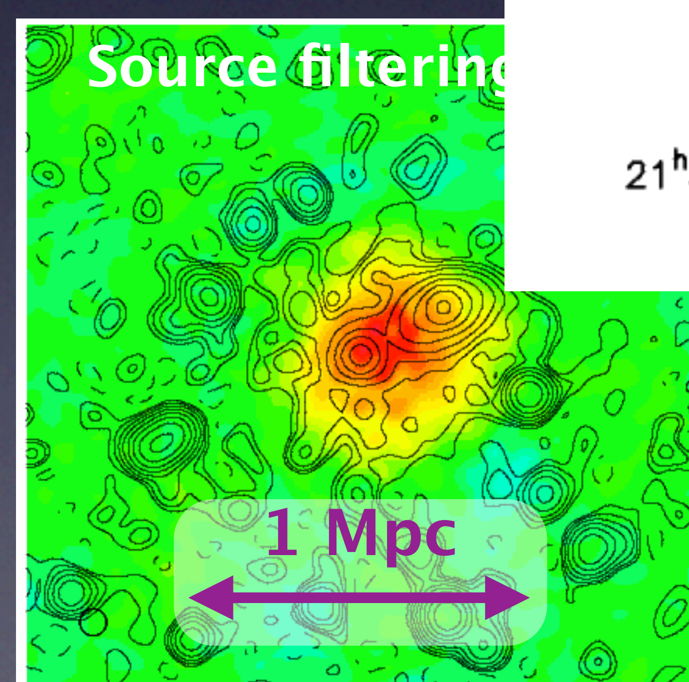
In progress: Radio follow-up of *Planck* clusters



Images: Martin Sommer (preliminary)





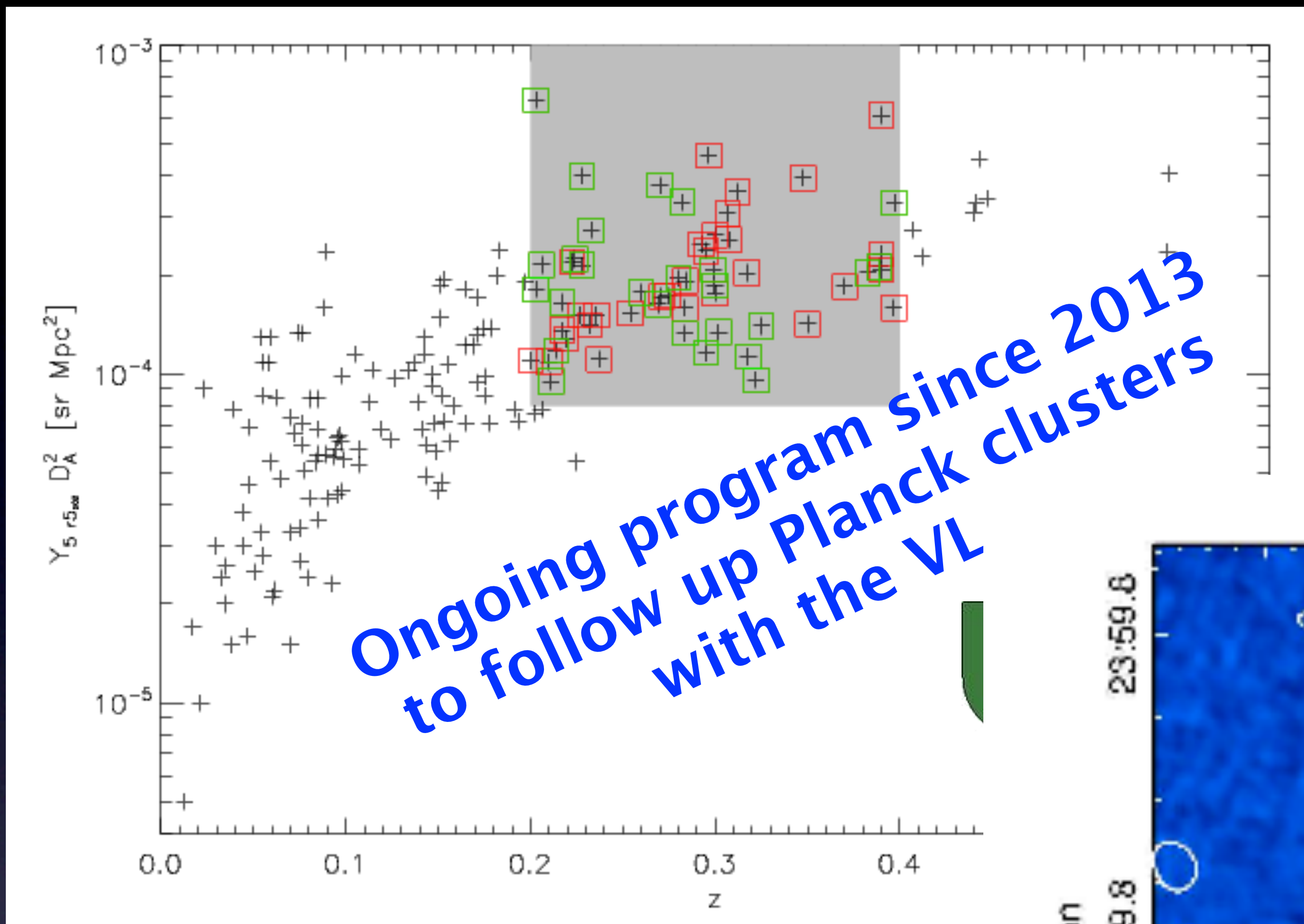


Sommer, Basu et al. in prep.

A 2390
Cool-core cluster at z=0.23

A 2261
Cool-core cluster at z=0.22

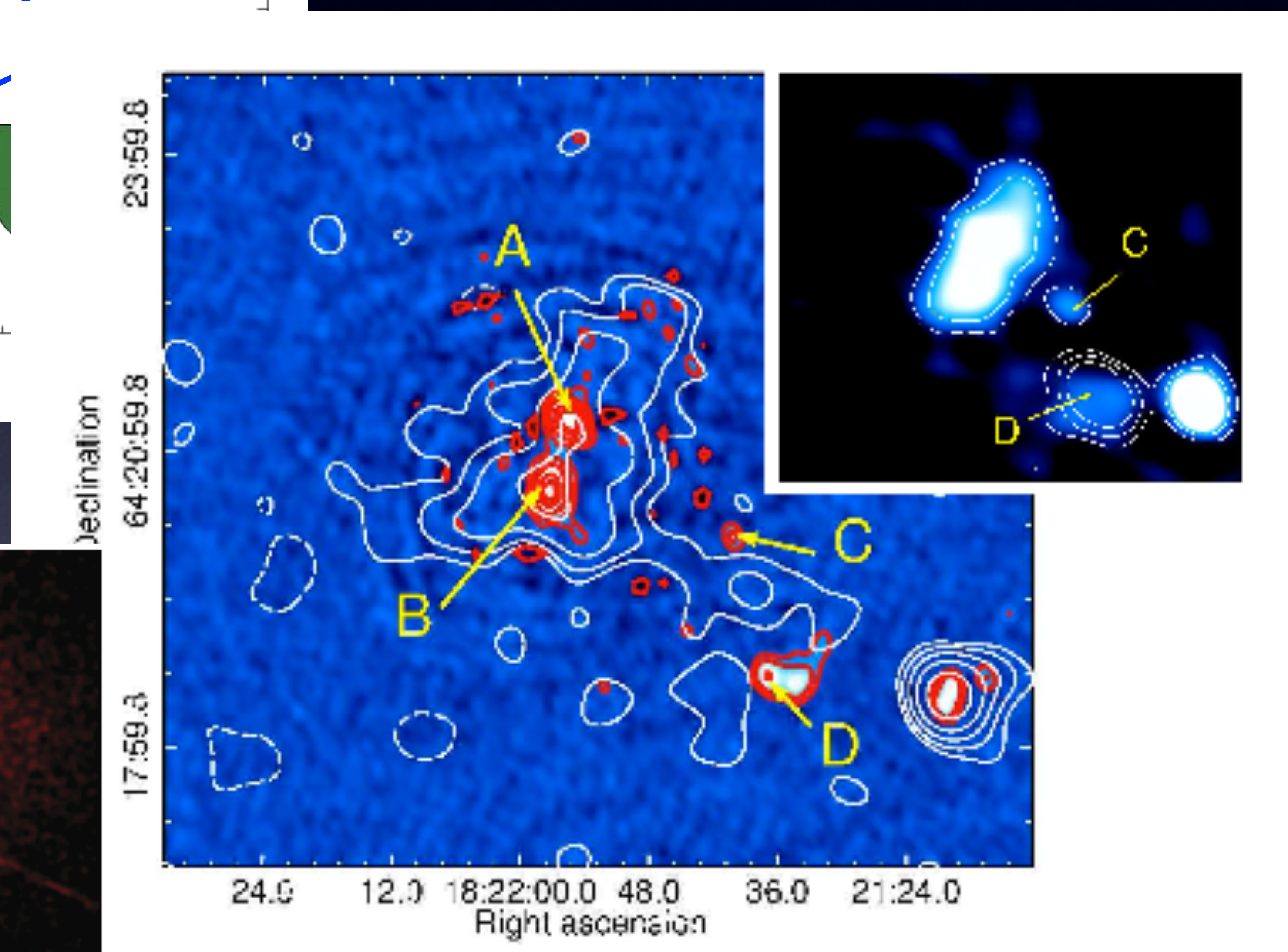
In progress: Radio follow-up of *Planck* clusters

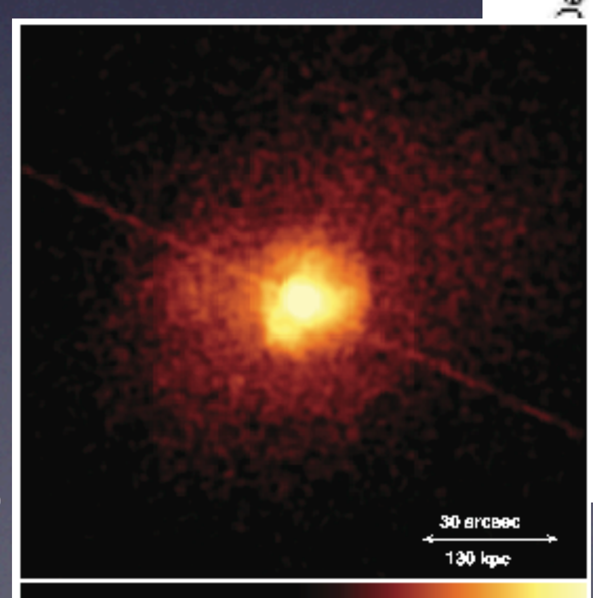


Ongoing program since 2013 to follow up Planck clusters with the VL

Radio halo in CL1821+643 (z=0.30)
Bonafede (+Basu) et al., 2014, MNRAS

GMRT radio data at 323 MHz

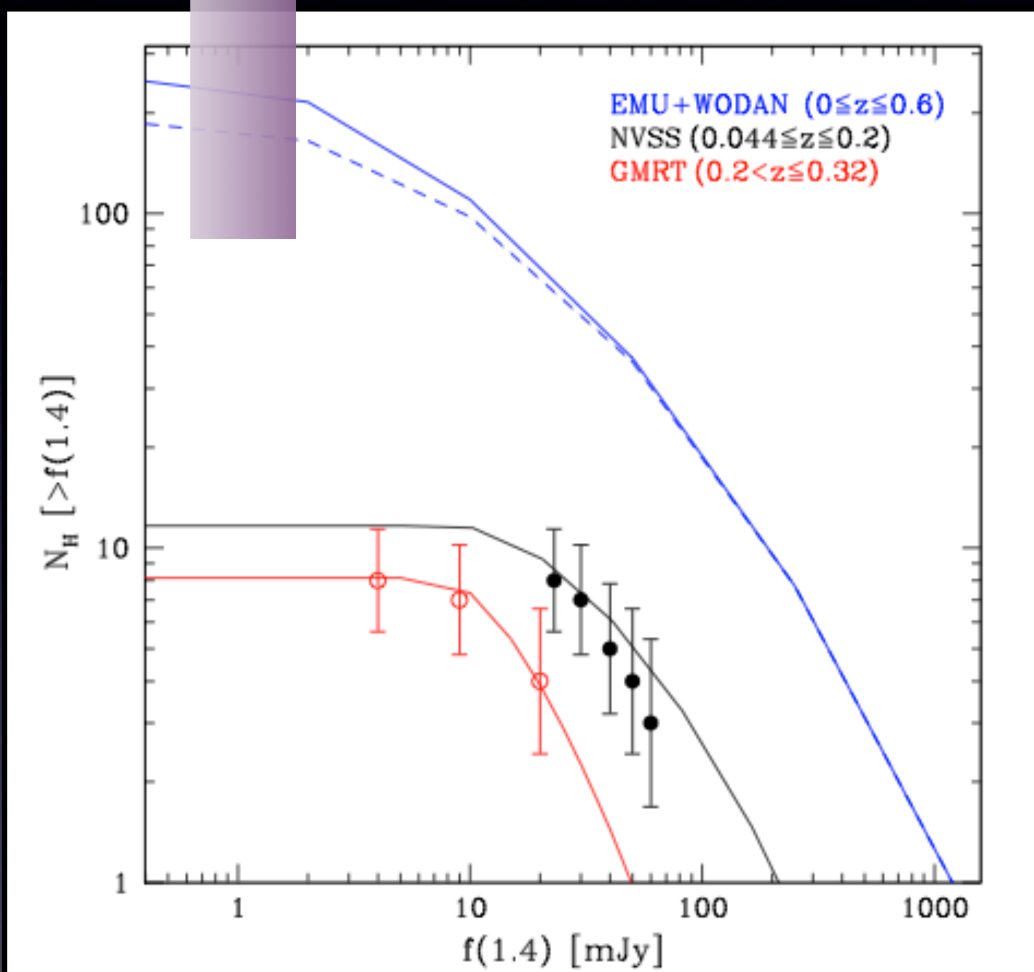




Chandra X-ray image
(Russell et al. 2008)

Number of radio halos in the sky

Factor ~5-10 up!

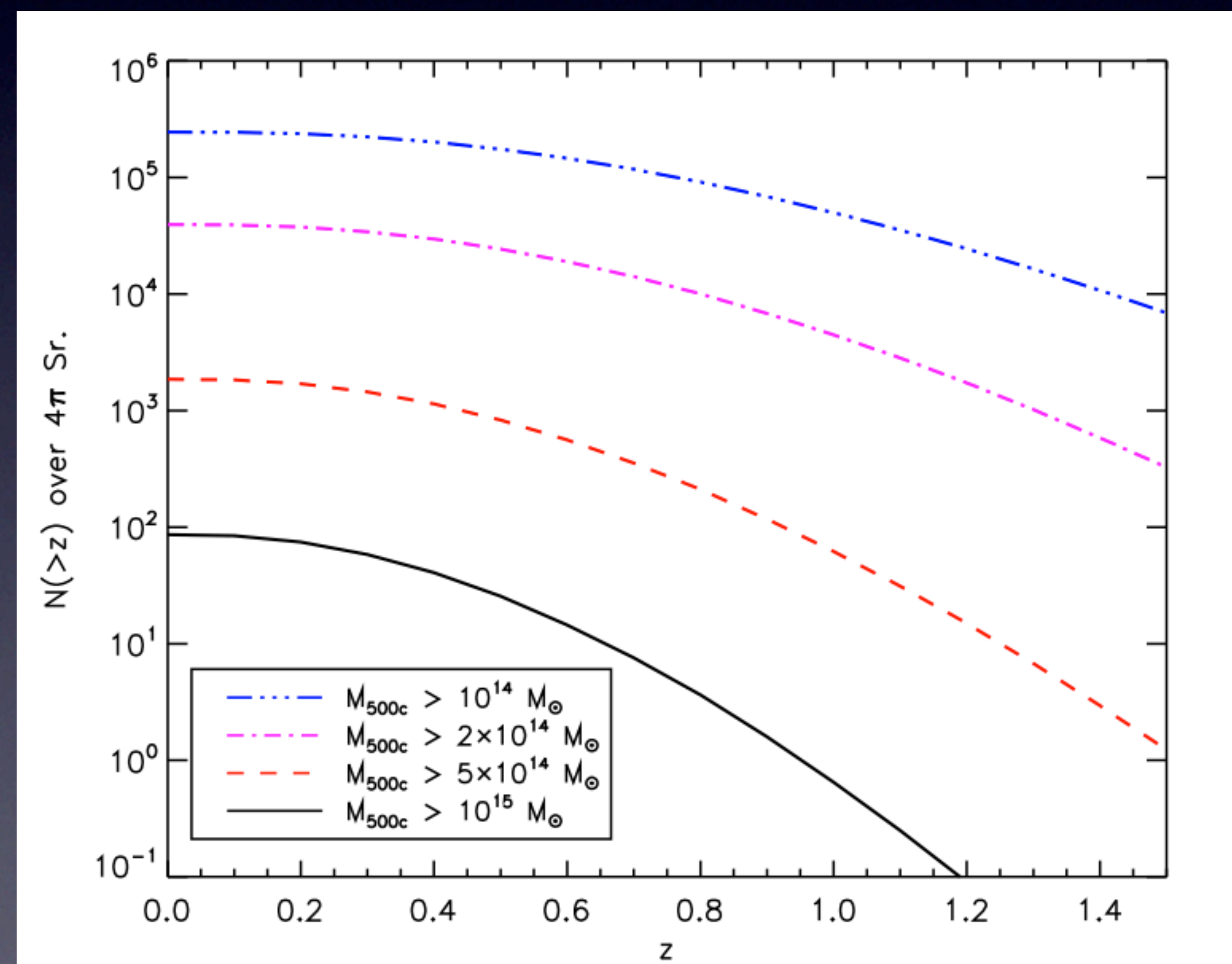


Current prediction for 1.4 GHz
All-sky, z<0.6

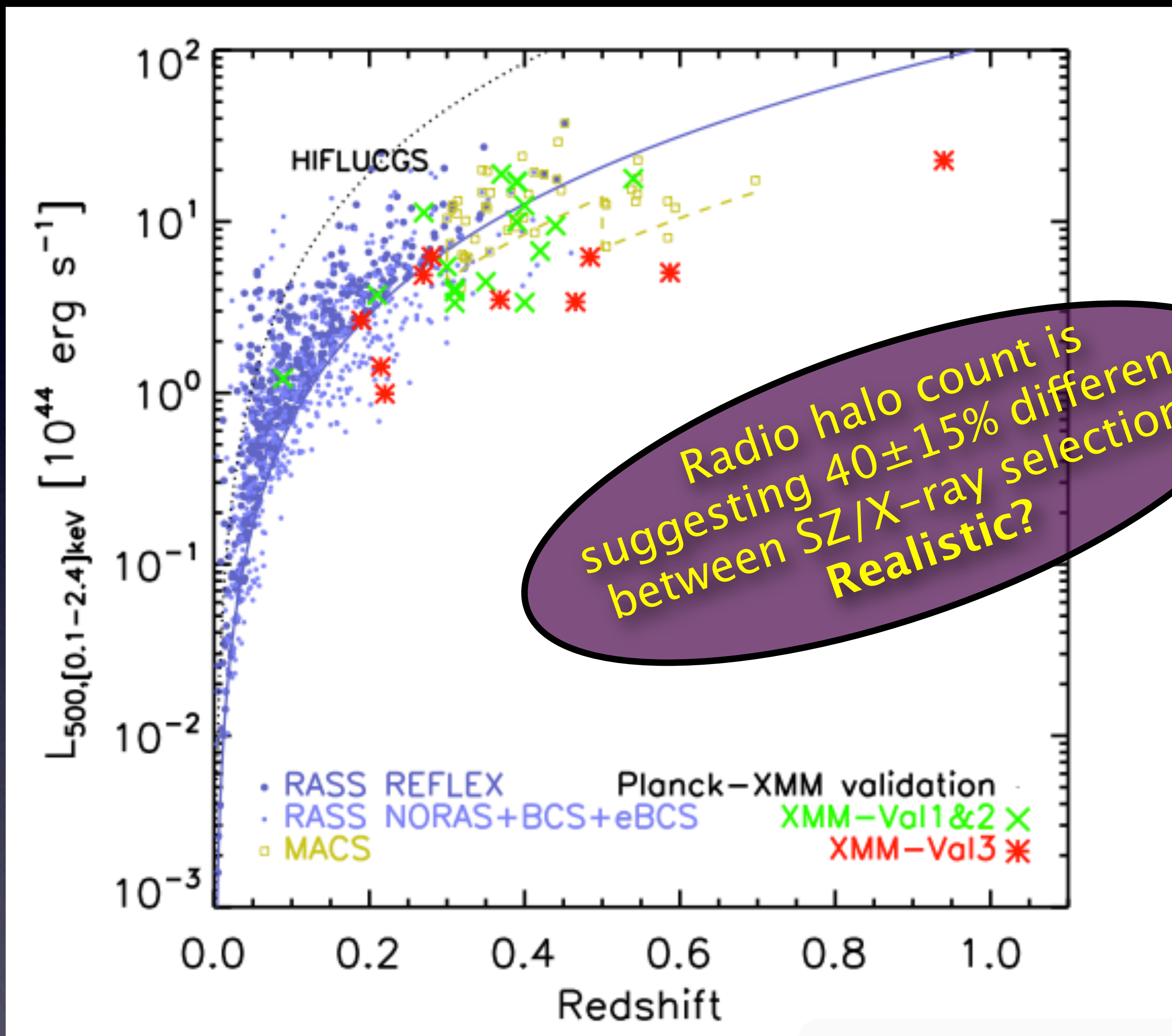
(Cassano et al. 2012)

There are over 1800 clusters with M_{500} > 5×10^{14} $M_\odot$ in the sky, ~1000 below redshift 0.5

750 ± 100 radio halos at z<0.5

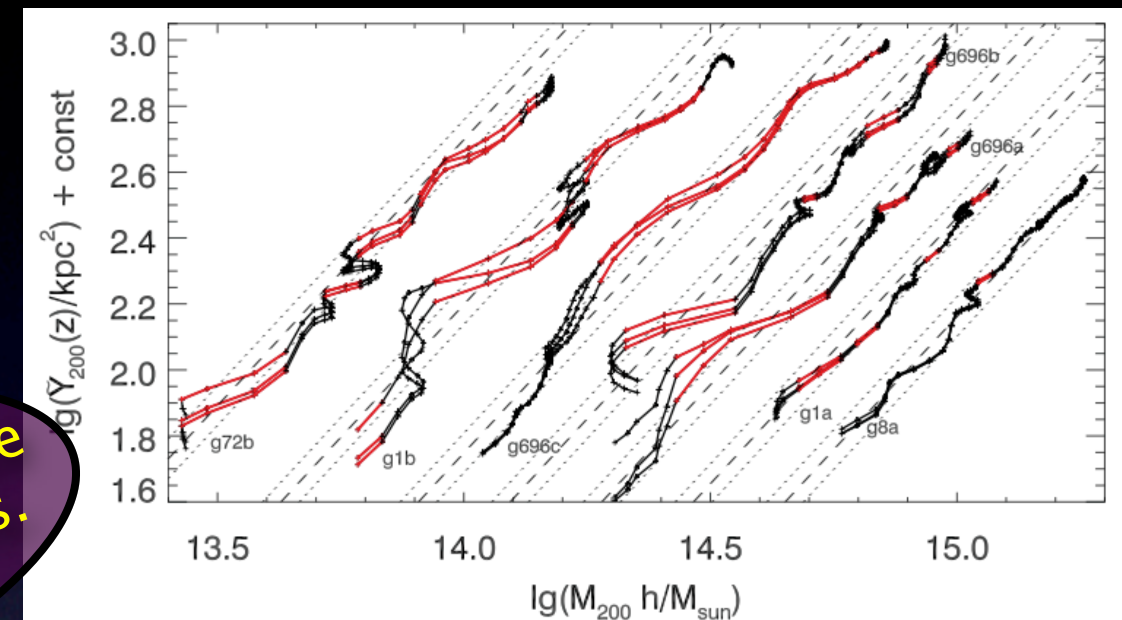


SZ/X-ray selection difference



Radio halo count is suggesting 40±15% difference between SZ/X-ray selections.
Realistic?

Planck XMM validation (intermediate results I, 2012)

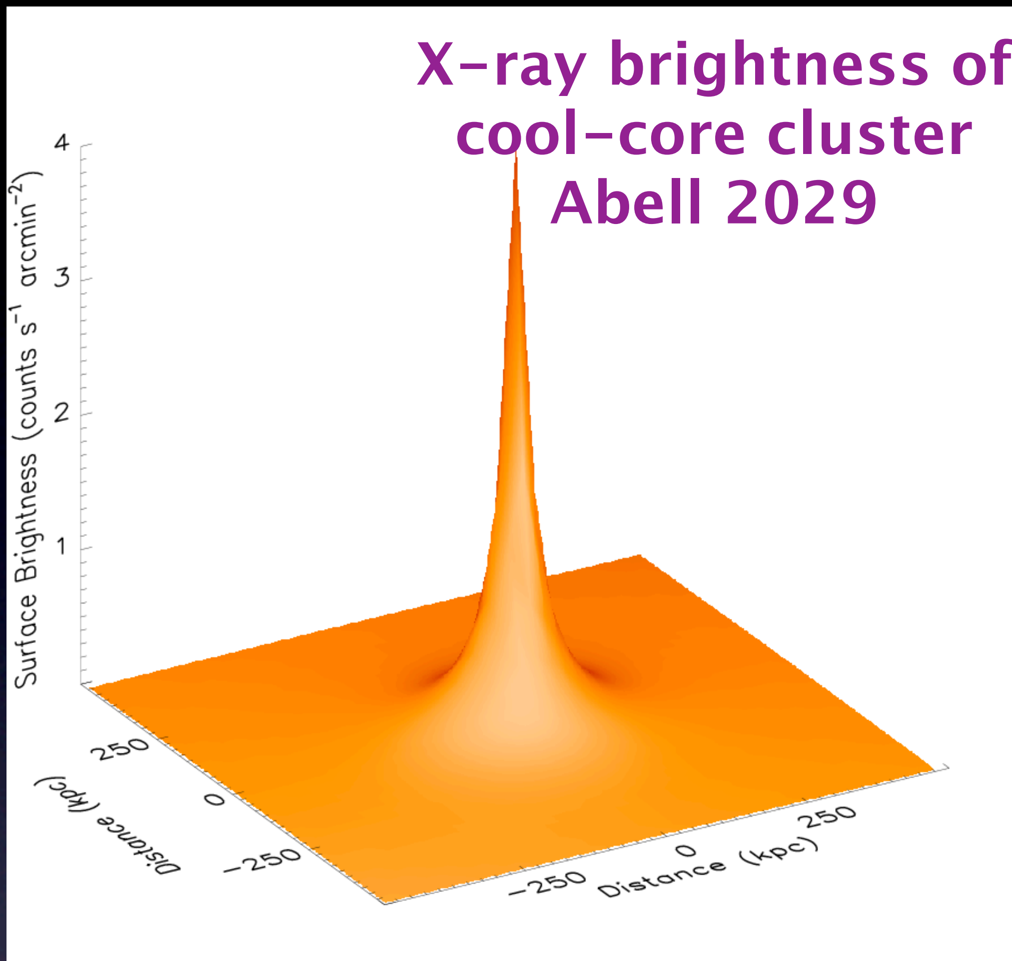


Change in the SZ signal during cluster merger process

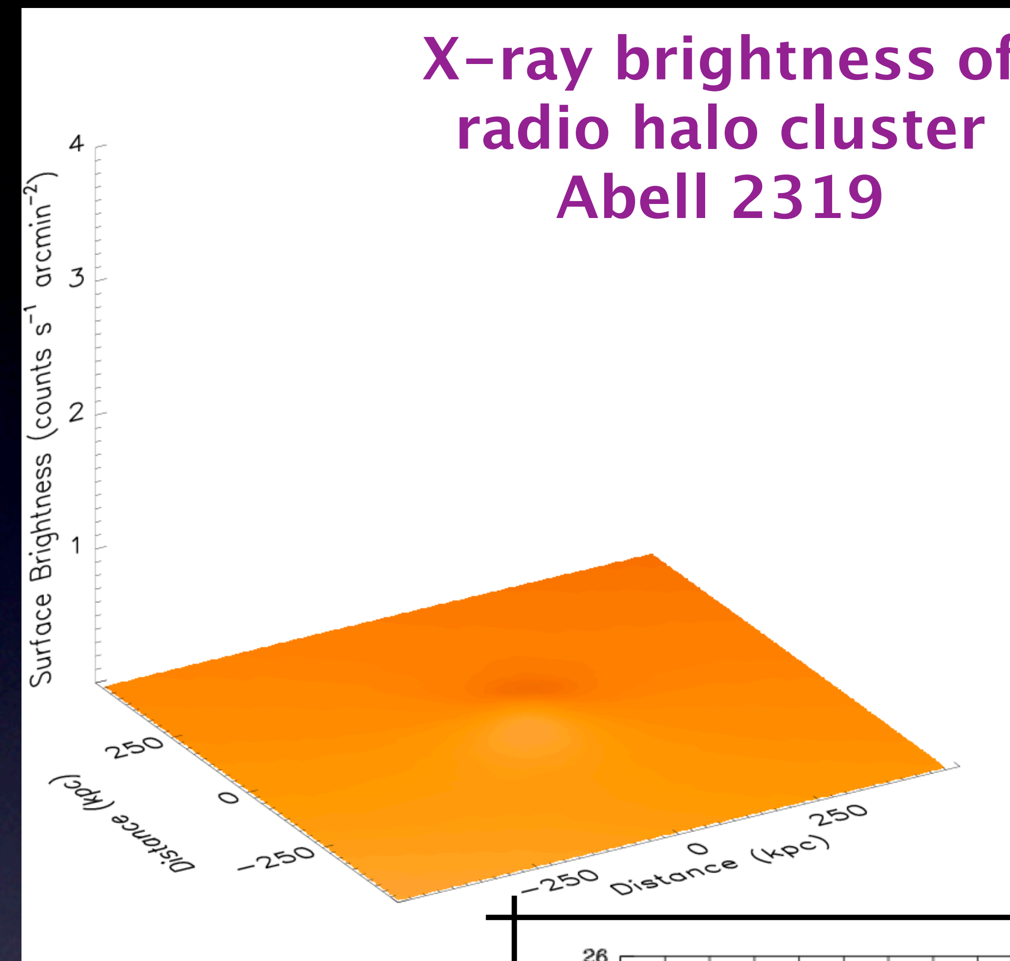
(Krause et al. 2012)

What is causing the difference between SZ and X-ray selection?

Selection difference: Cool-Core bias in X-rays



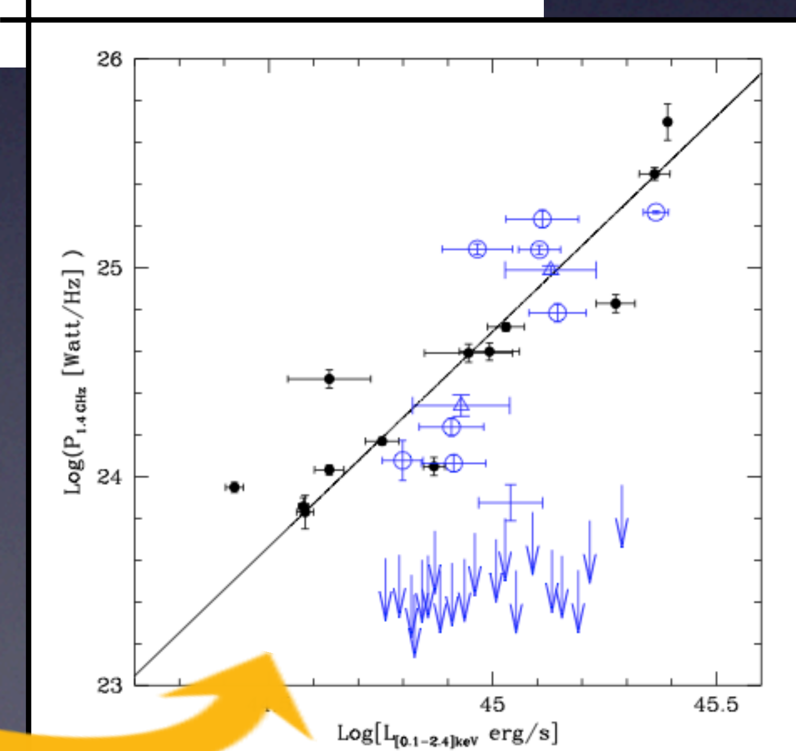
Million & Allen (2009)



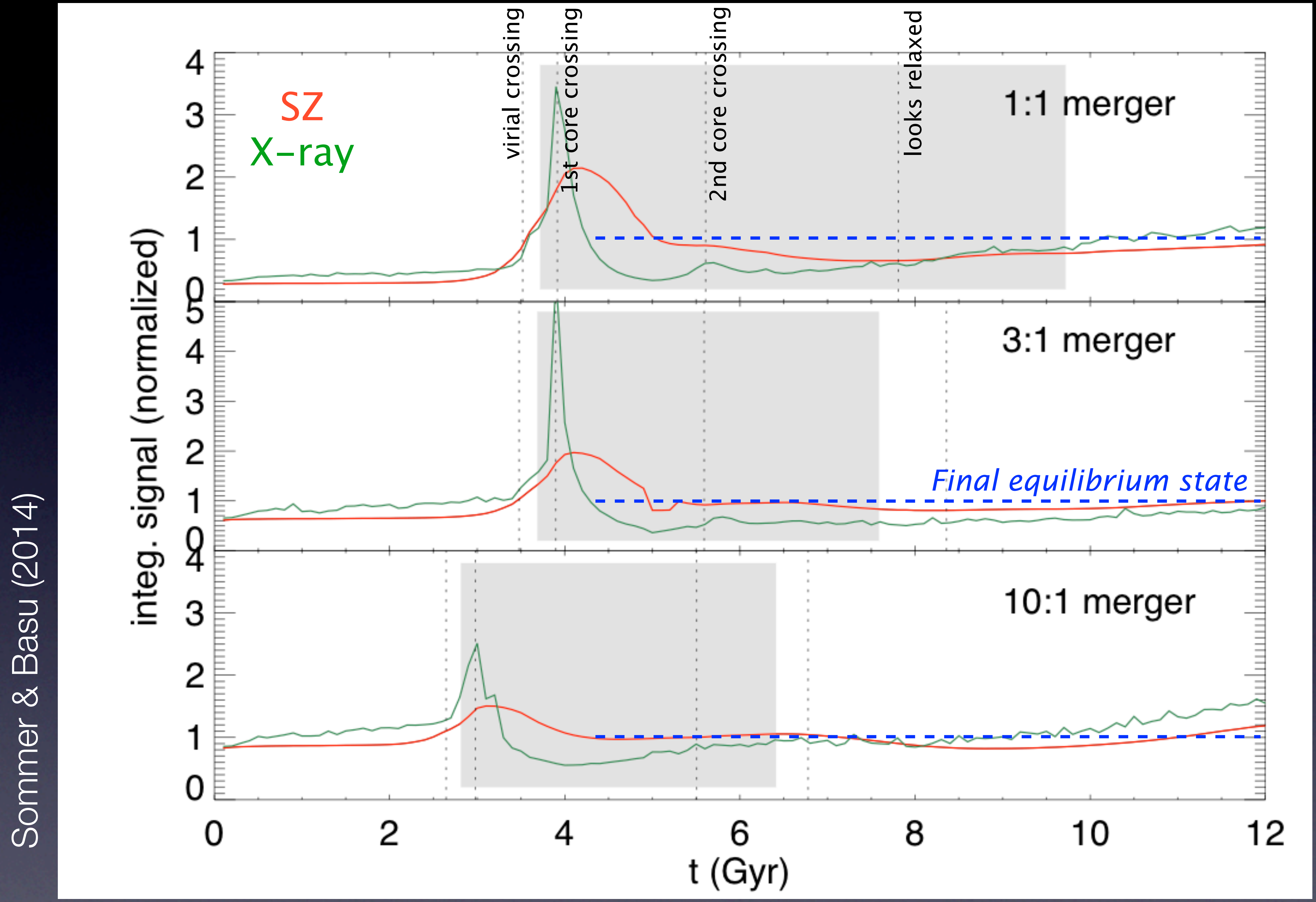
Relaxed, ***cool-core clusters*** are a minority, but they are over represented in X-ray flux limited samples

These systems generally do not host giant radio halos

➜ producing a **strong** bi-modal distribution in X-rays

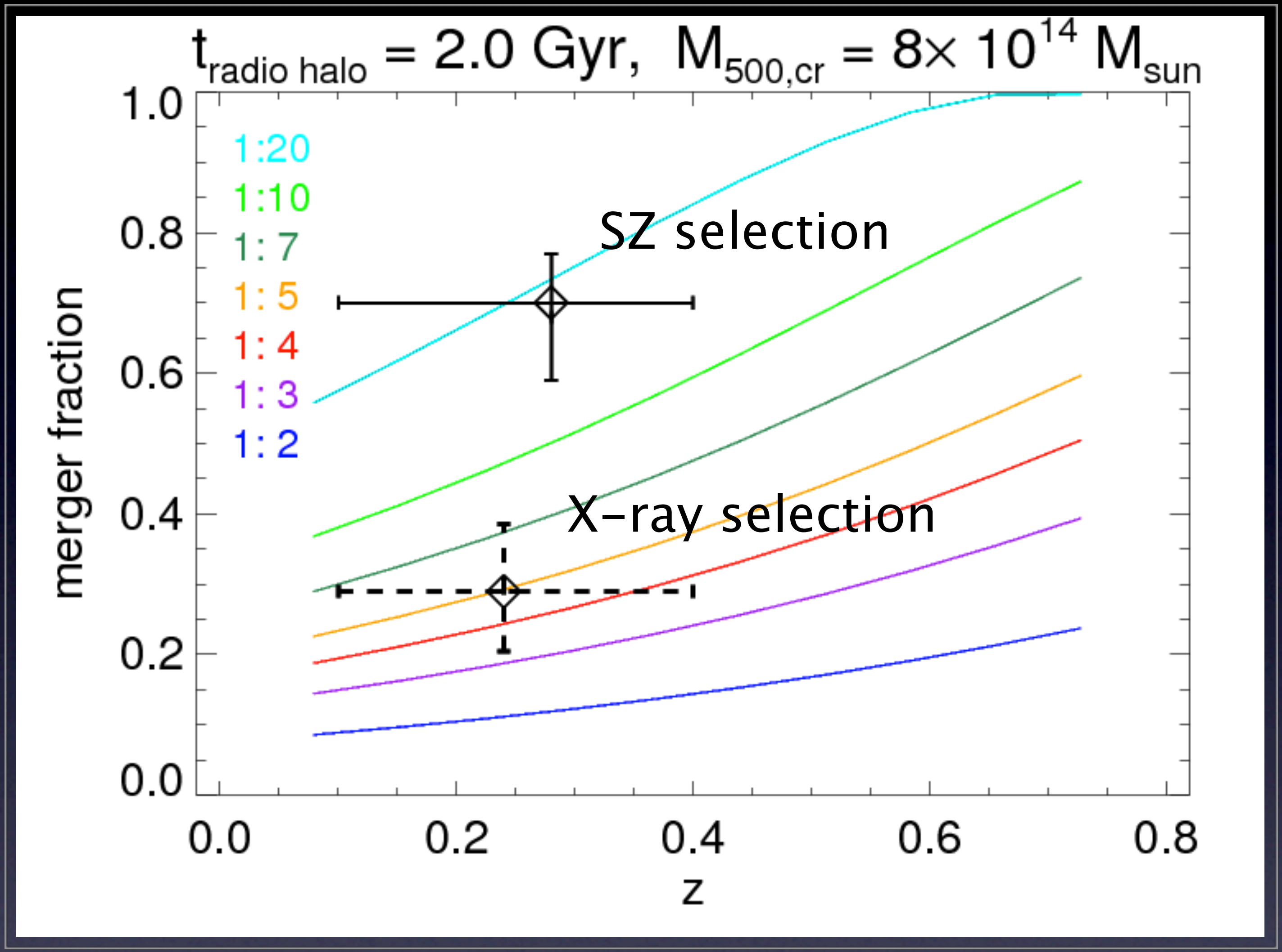


Selection difference: Merger Scenarios



N-body hydro simulation results from Poole et al. (2007)

Merger rate with radio halo counts

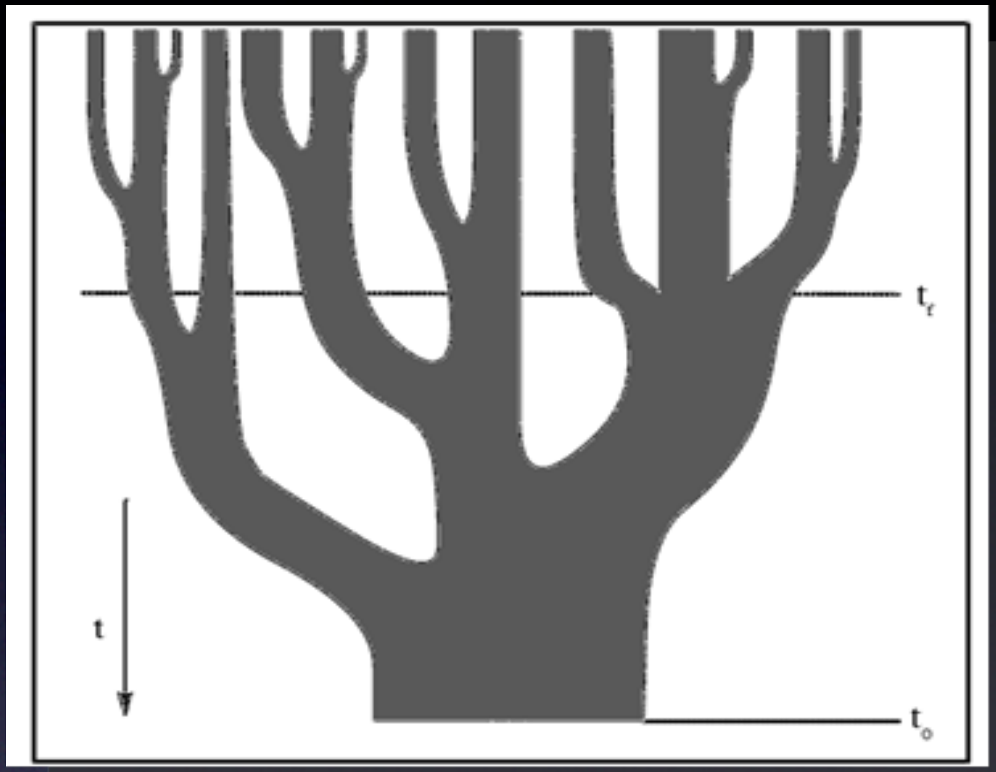


.. this will be extremely easy to check with the upcoming SKA pathfinders

Available radio survey data (NVSS) is not deep enough to test the mass- and redshift-dependence of the radio halo fraction, but..

Cosmology from the merger rate

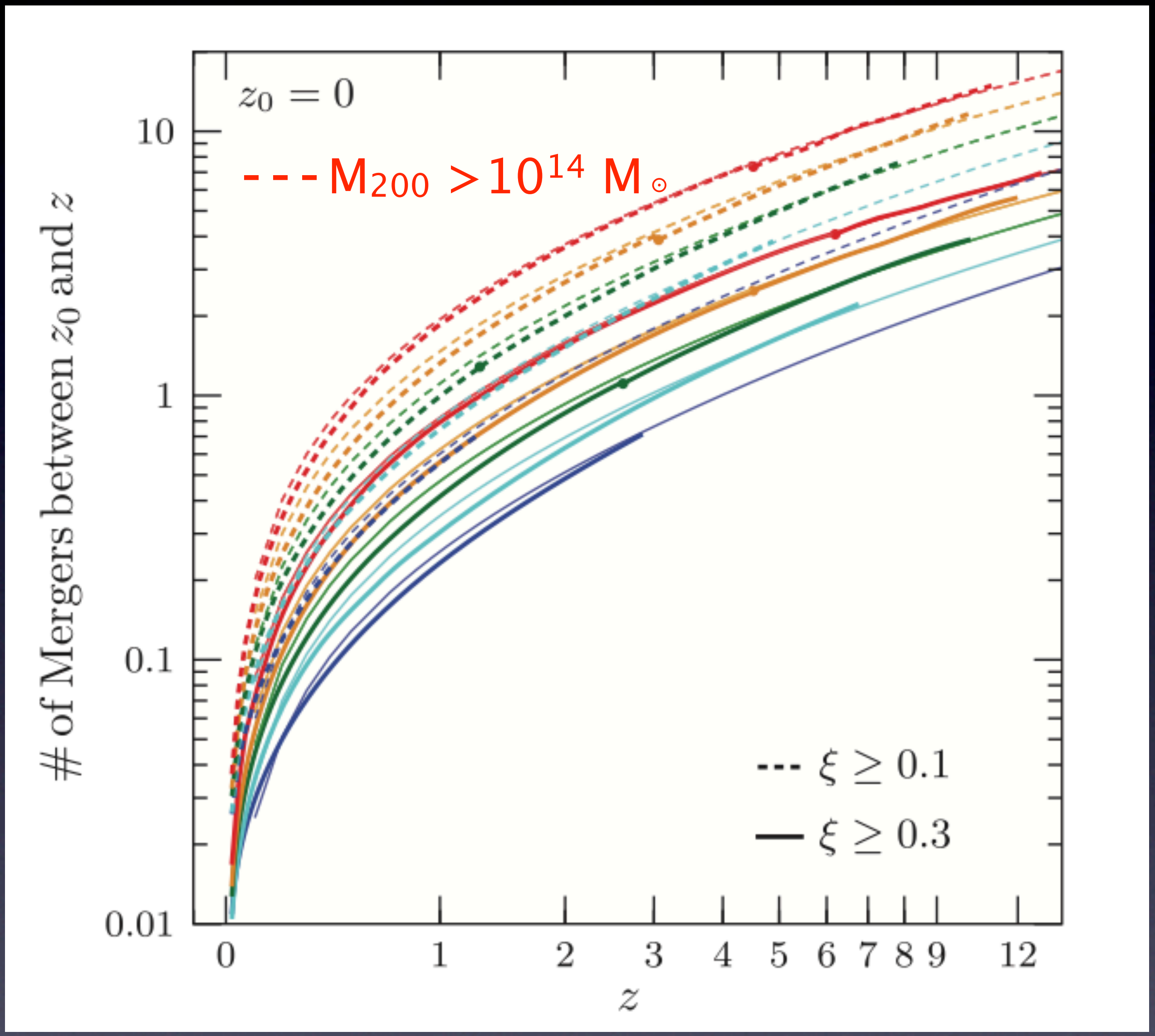
Merger rate brings extra cosmological information!



$$\dot{N}_{\rm PS}(M,t) = \frac{\partial N_{\rm PS}(M,t)}{\partial D}\frac{dD}{dt}$$
$$= -\frac{1}{D}\frac{dD}{dt}\left[1-\frac{\delta_c^{\,2}}{\sigma^2(M)D^2(t)}\right]N_{\rm PS}(M,t),$$

(Sasaki 1994)

Roughly 90% of the high mass halos experience **at least a 10:1 merger event** since z = 0.5



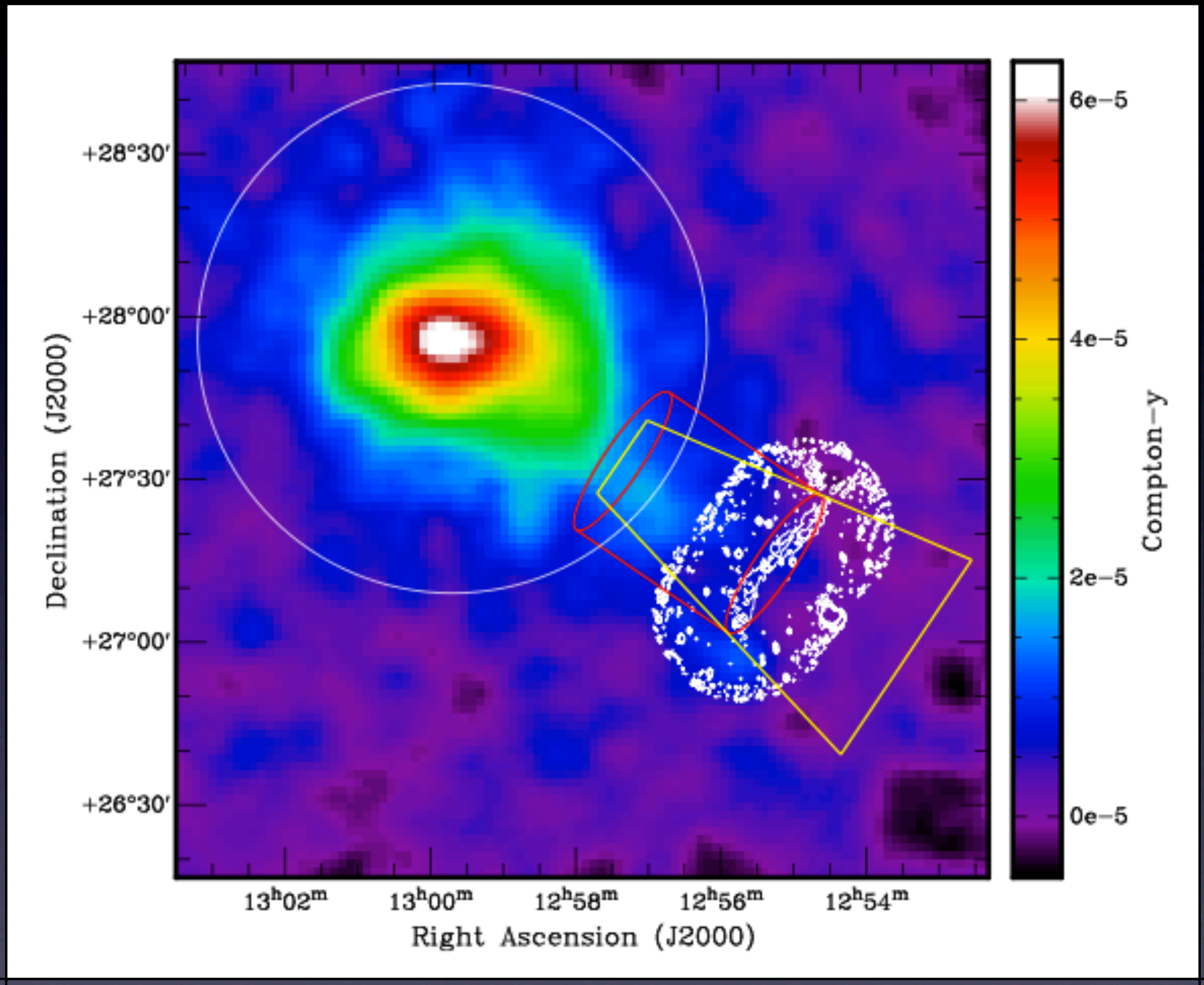
Fakhouri et al. (2010)

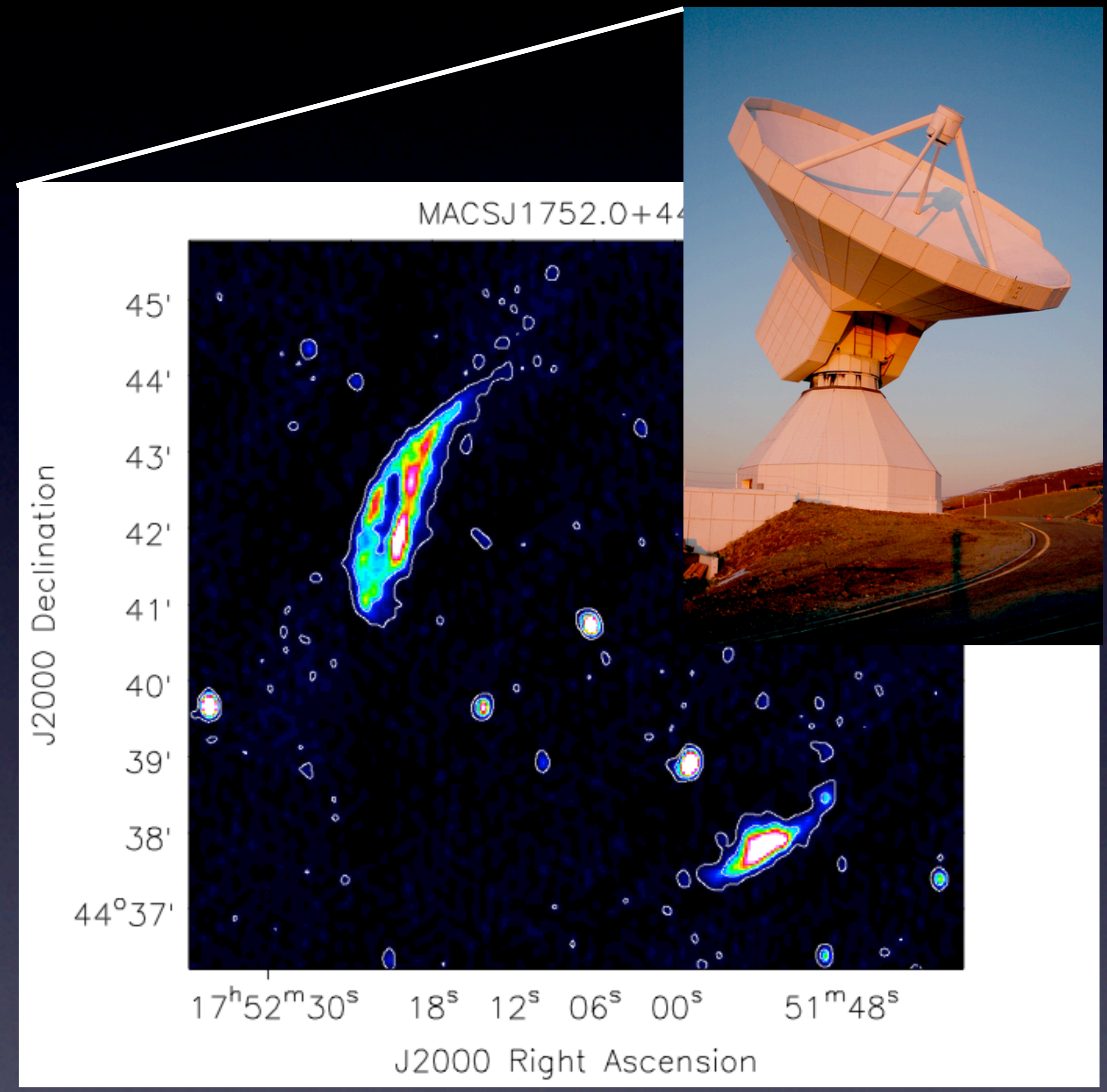
Millenium + Millenium II sims

(fixed σ_8=0.9 cosmology)

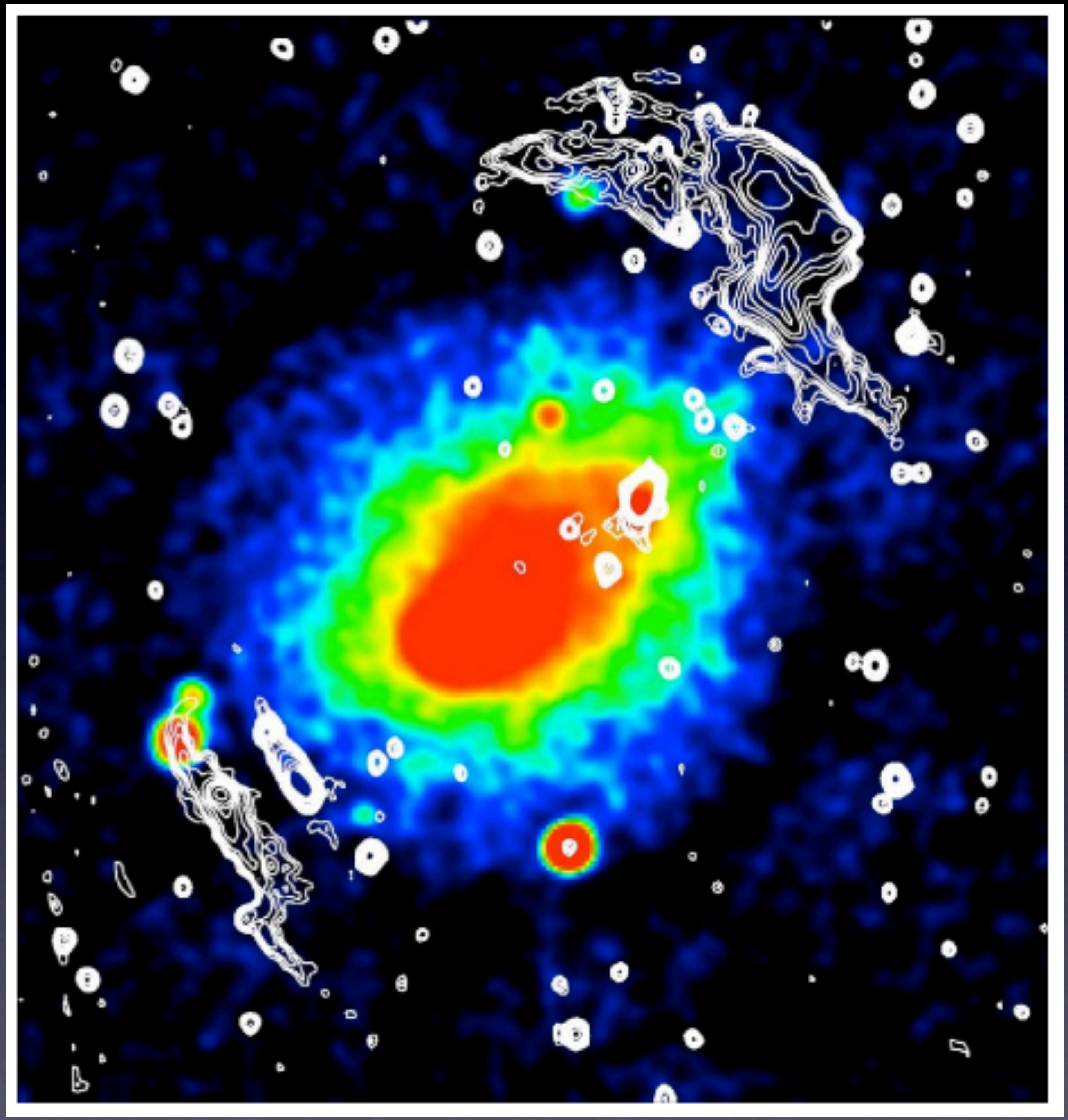
Now to cluster outskirts...

SZ take on radio relics:
Modeling shocks in the cluster outskirts





Radio relics



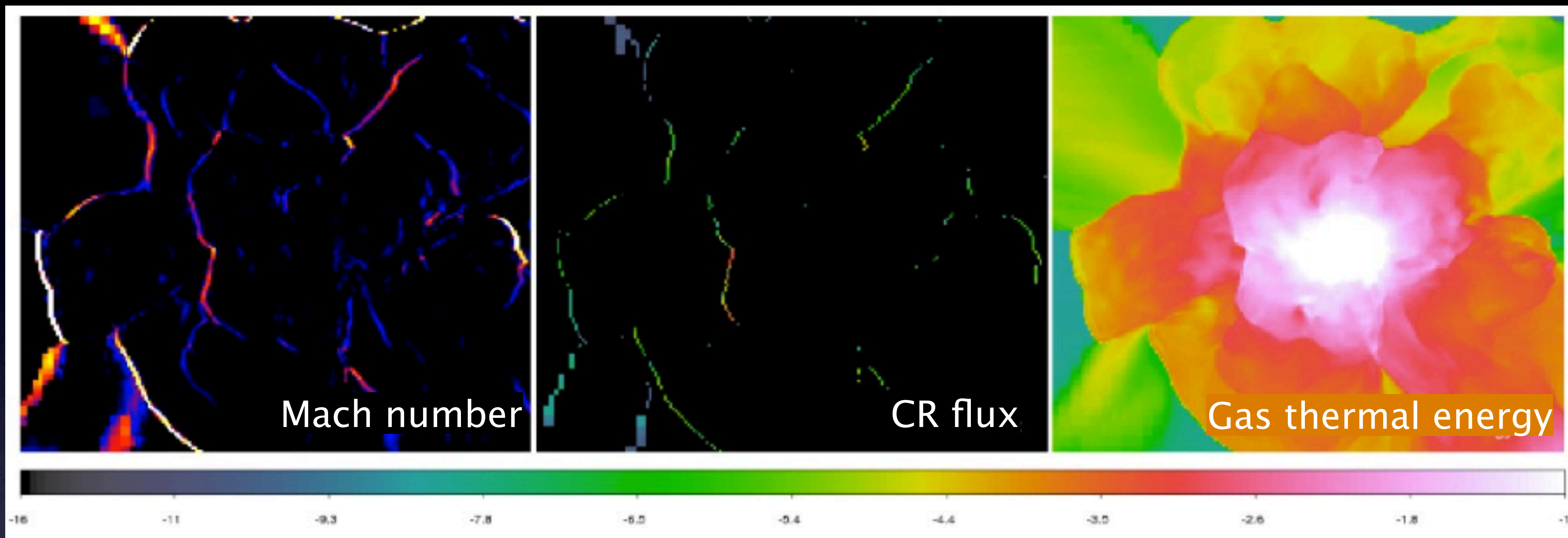
Radio relics: $L_{1.4\,GHz} \sim 10^{23-25}$ W/Hz

- Extended (up to ~ 1 Mpc) diffuse radio sources at the periphery of clusters
- Irregular morphology
- High degree of polarization
- Steep spectrum (α ~ 1.2)
- No optical counterpart
- Morphology resembles shock fronts, found only in disturbed clusters

Abell 3667 (Röttgering et al. 1997)
Color: X-ray, contours: radio

Connection to merger shocks

Vazza et al. (2012)

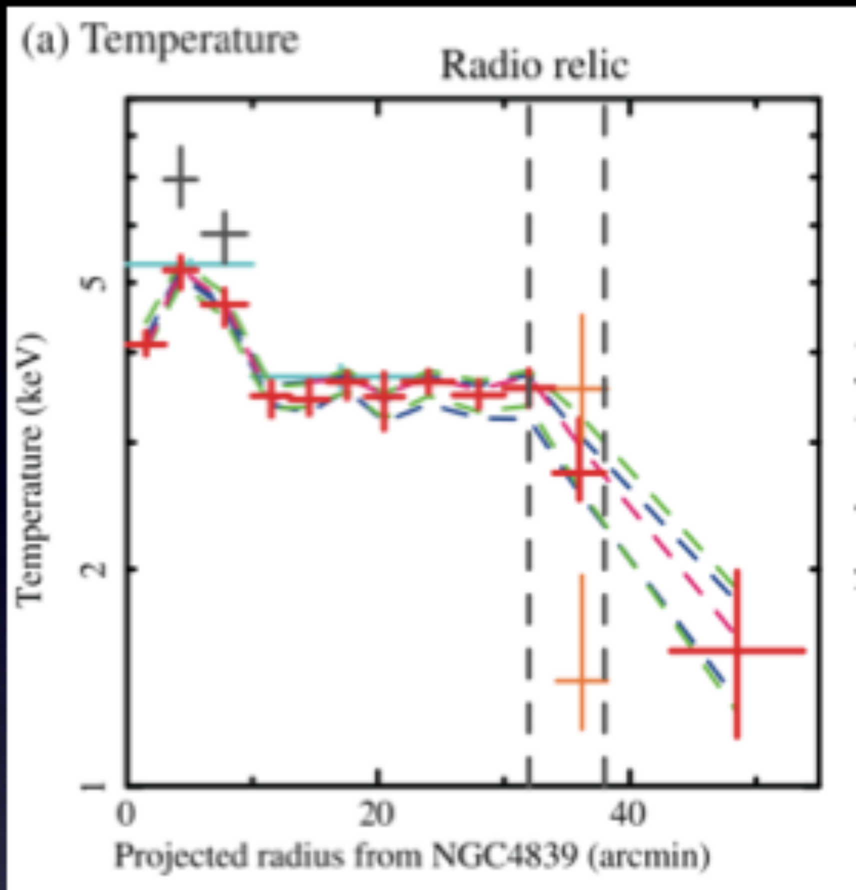


Radio relics are thought to be associated to cluster merger shocks. The shock fronts accelerate electrons (and also protons) with the Fermi-I mechanism, ans also compresses the magnetic fields. Those GeV electrons spiraling in the magnetic fields give rise to the synchrotron emission.

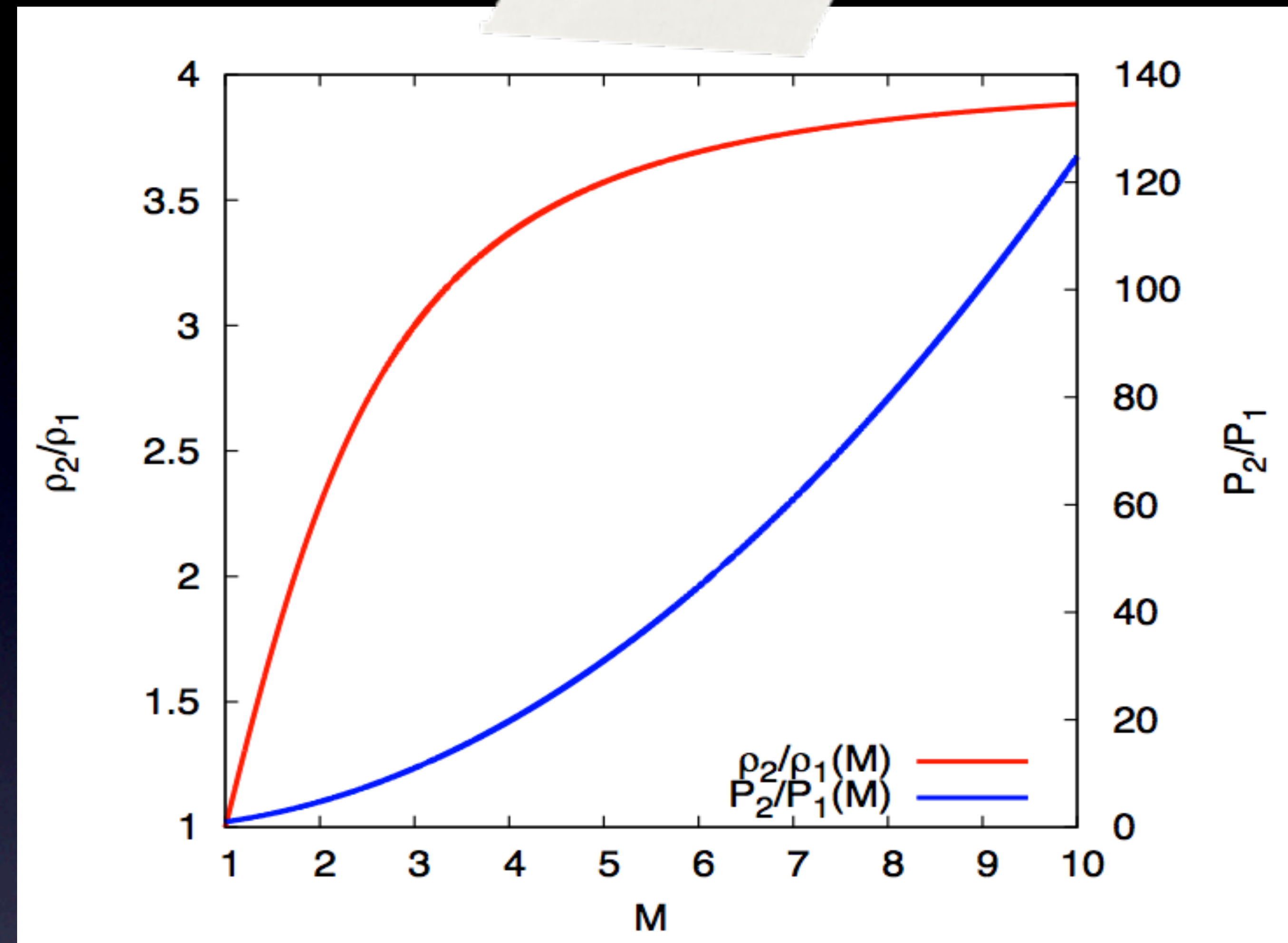
- Merger shocks have low Mach numbers (M ~2−4), so acceleration efficiency will be low

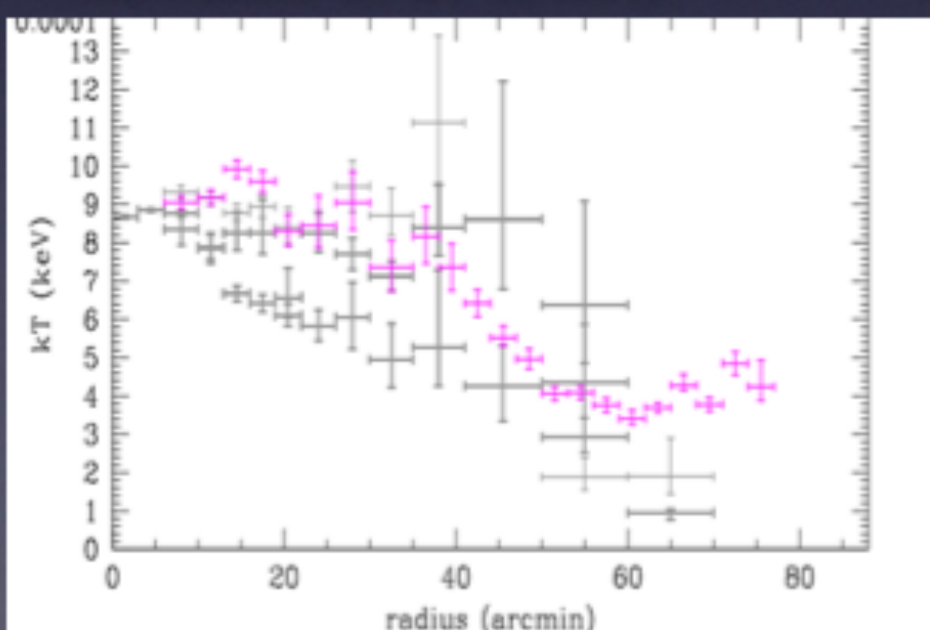
- Simulations predict many shock fronts, but only a few relics are known. Also, most of the relics do not have a detected shock feature.

Shocks with X-rays at relics



Akamatsu et al. (2013)

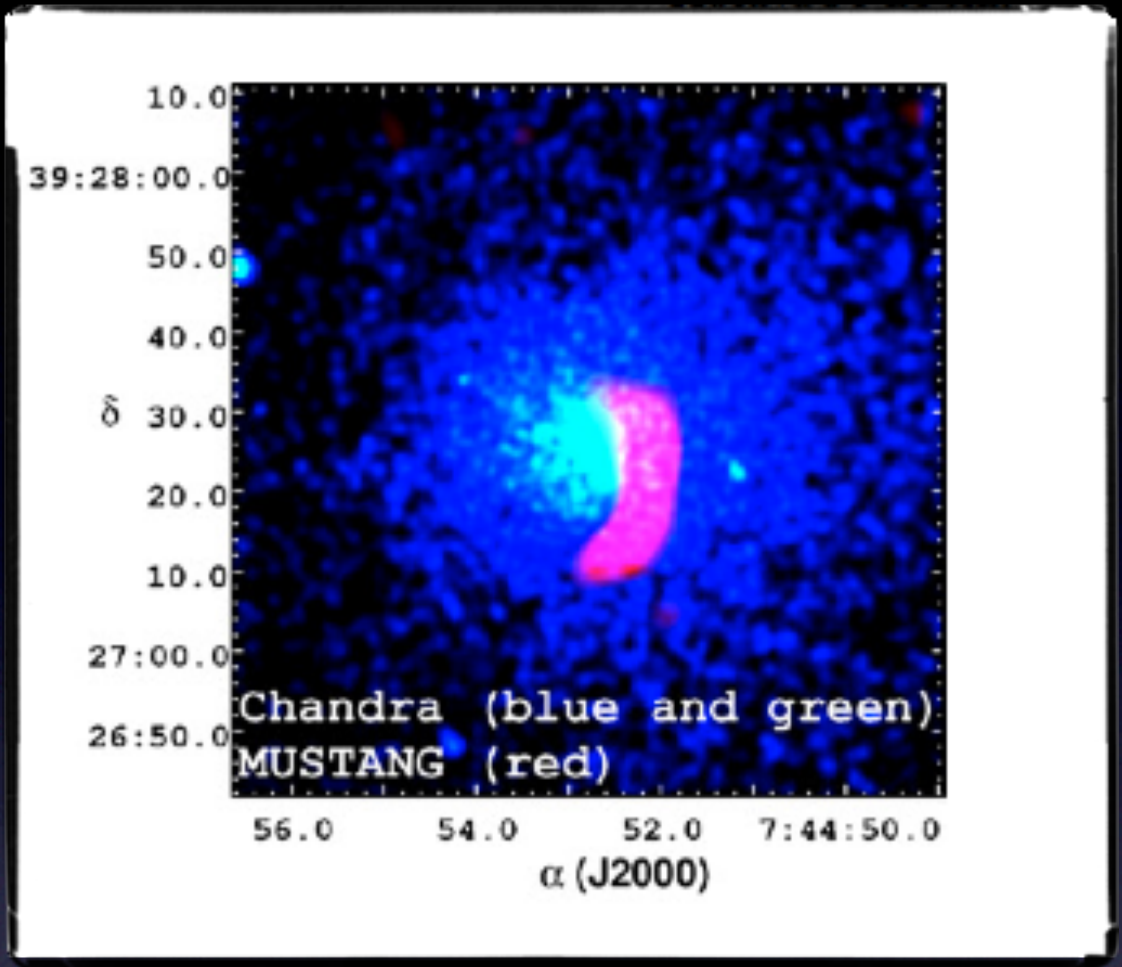




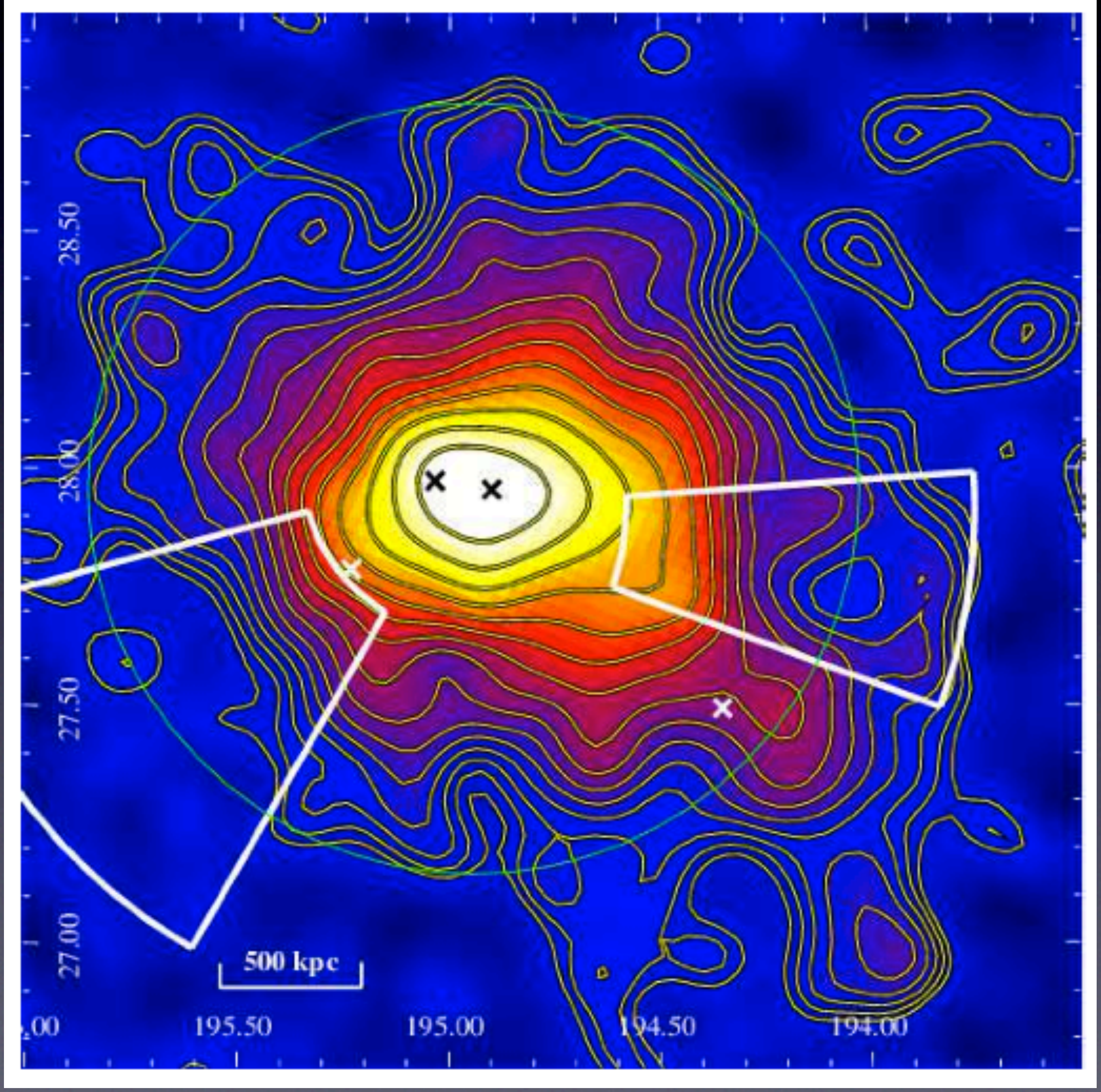
Simionescu et al. (2013)

- From X-ray one can determine shocks through density and pressure jumps
- Density jump is not very sensitive to Mach number change, and more affected by projection biases. It can also just show a contact discontinuity (cold front).
- Temperature at pre-shock regions difficult to determine, *not to mention for high redshift objects!*

Cluster shocks in SZ *(not at relics)*



SZ shock in MACS0744
(Korngut et al. 2011)

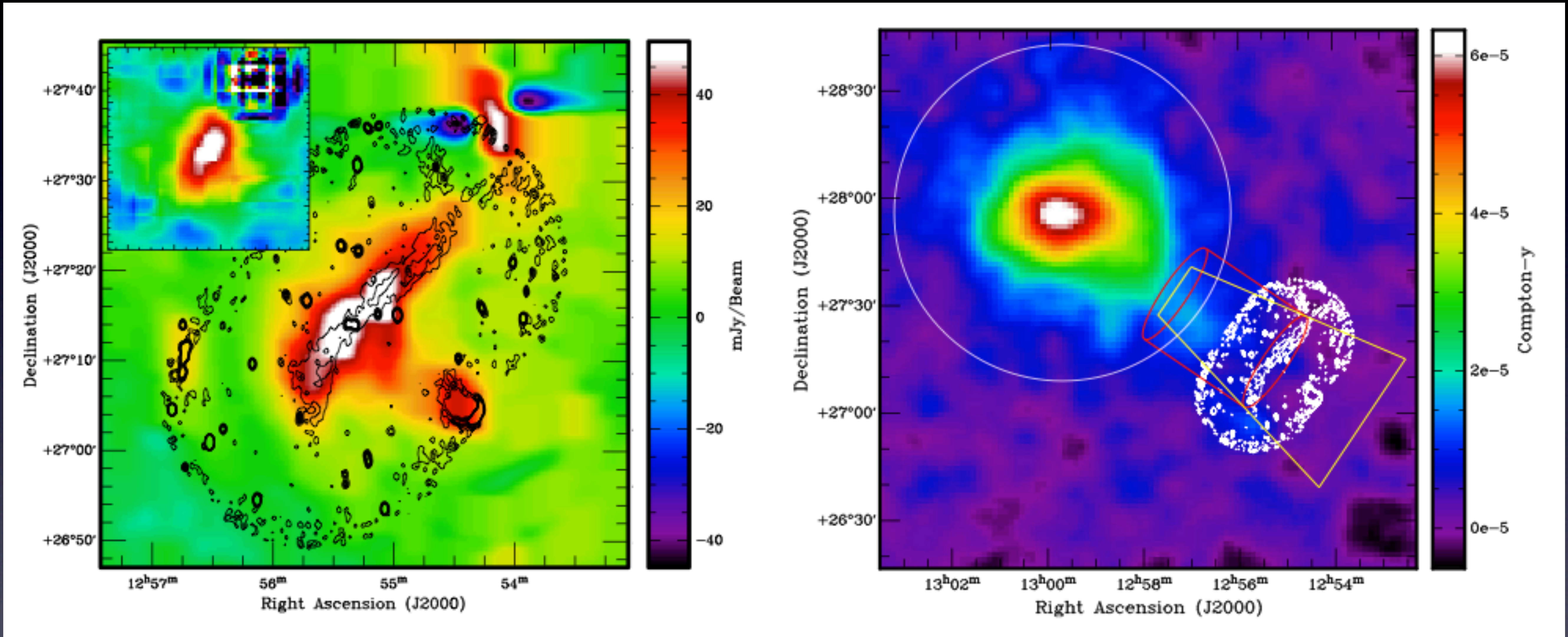


$R \leq R_{500}$ shocks in the Coma cluster
(Planck collaboration 2013)

Coma relic with the *Planck* SZ data

Coma relic has already been analyzed in X-rays:
Akamatsu et al. (2013), Ogrean & Brüggen (2013)

Erler, Basu et al. (2015), MNRAS, 447, 2497

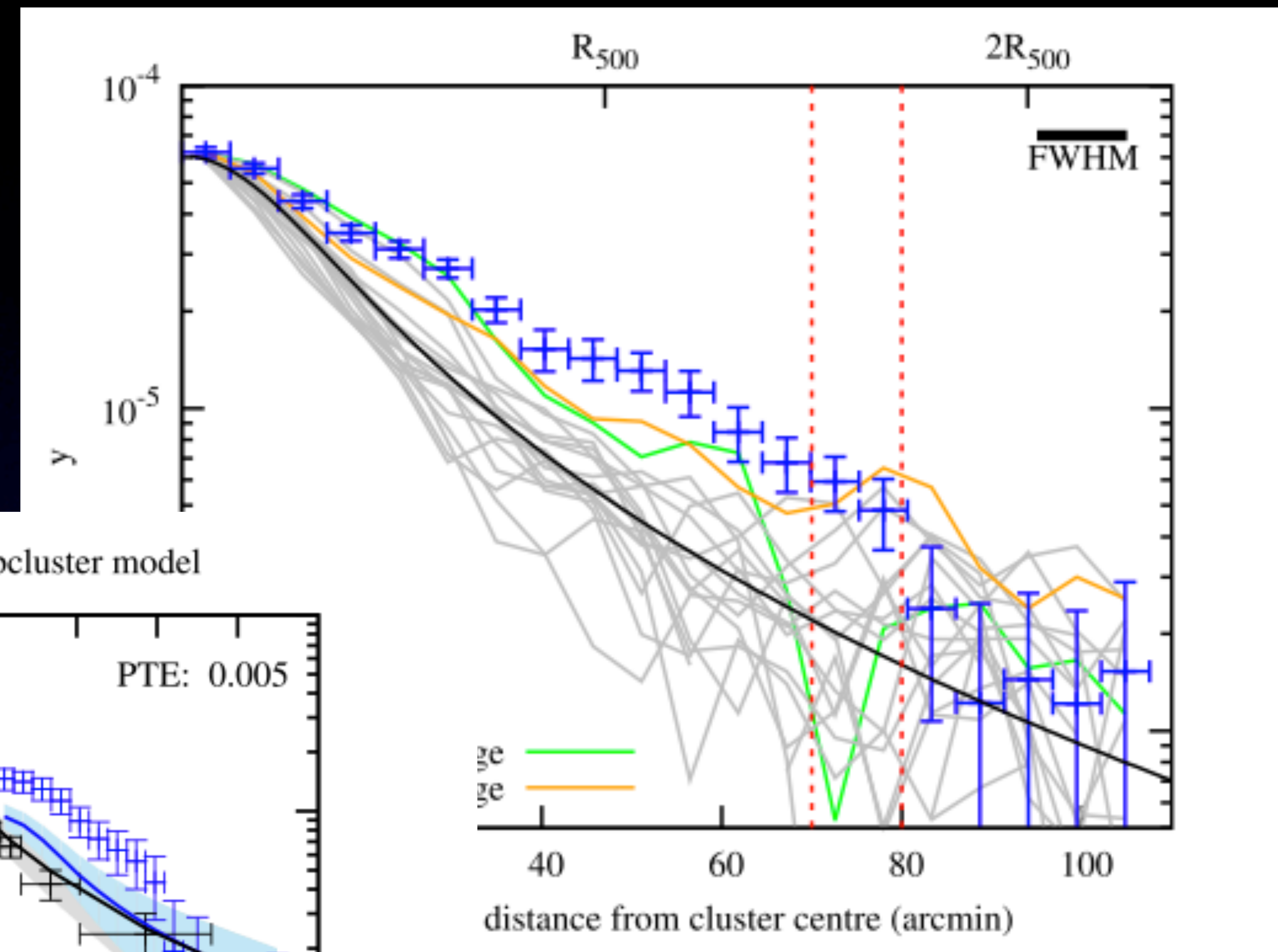


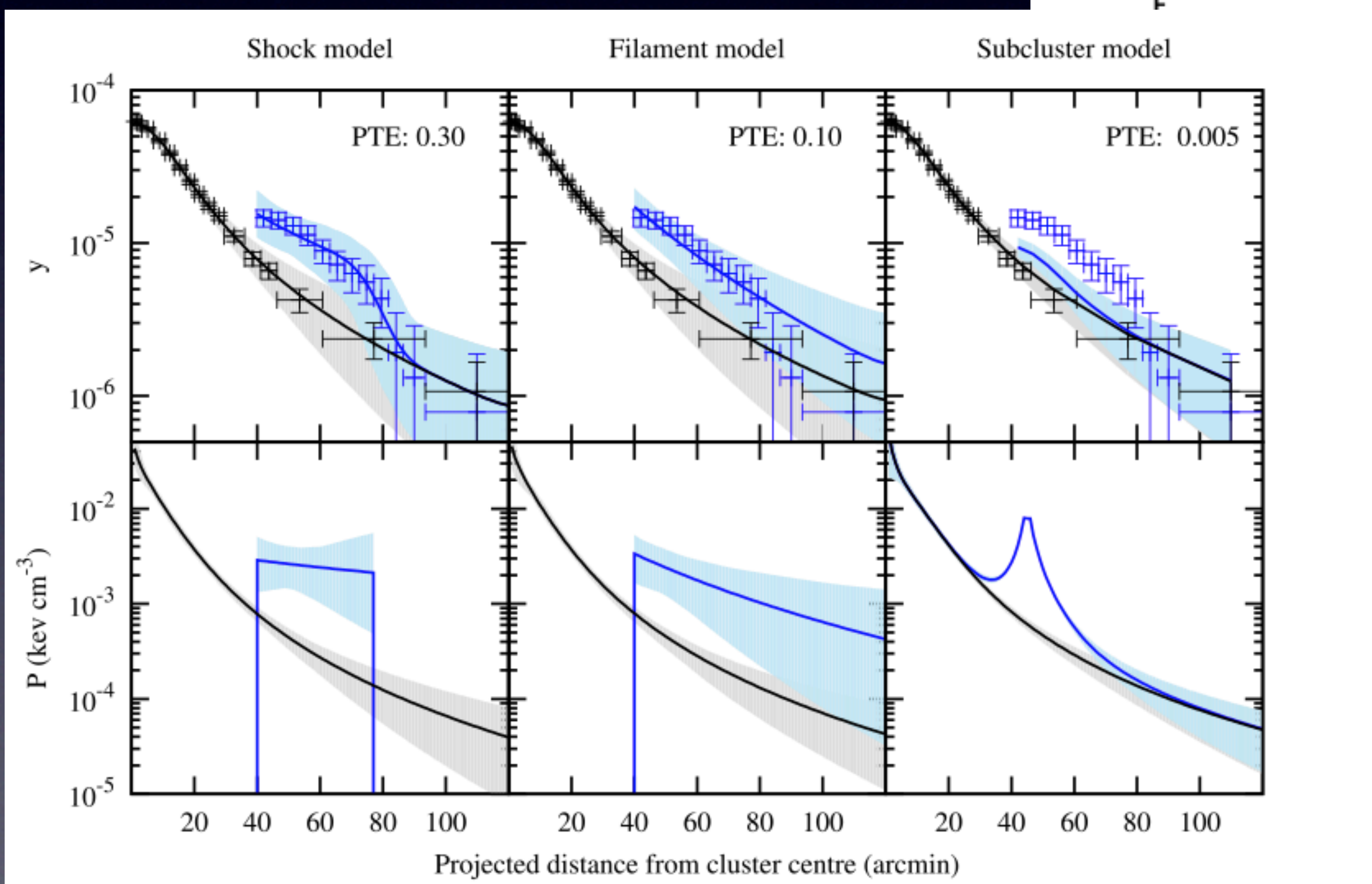
We used new 2.4 GHz radio data for the coma relic, and extracted our own y-map from the *Planck* 2013 public data release

Pressure jump at the Coma relic

y-maps extracted by a constrained ILC method, excellent agreement with the *Planck* profiles published for Coma.

Erler, Basu et al. (2015)



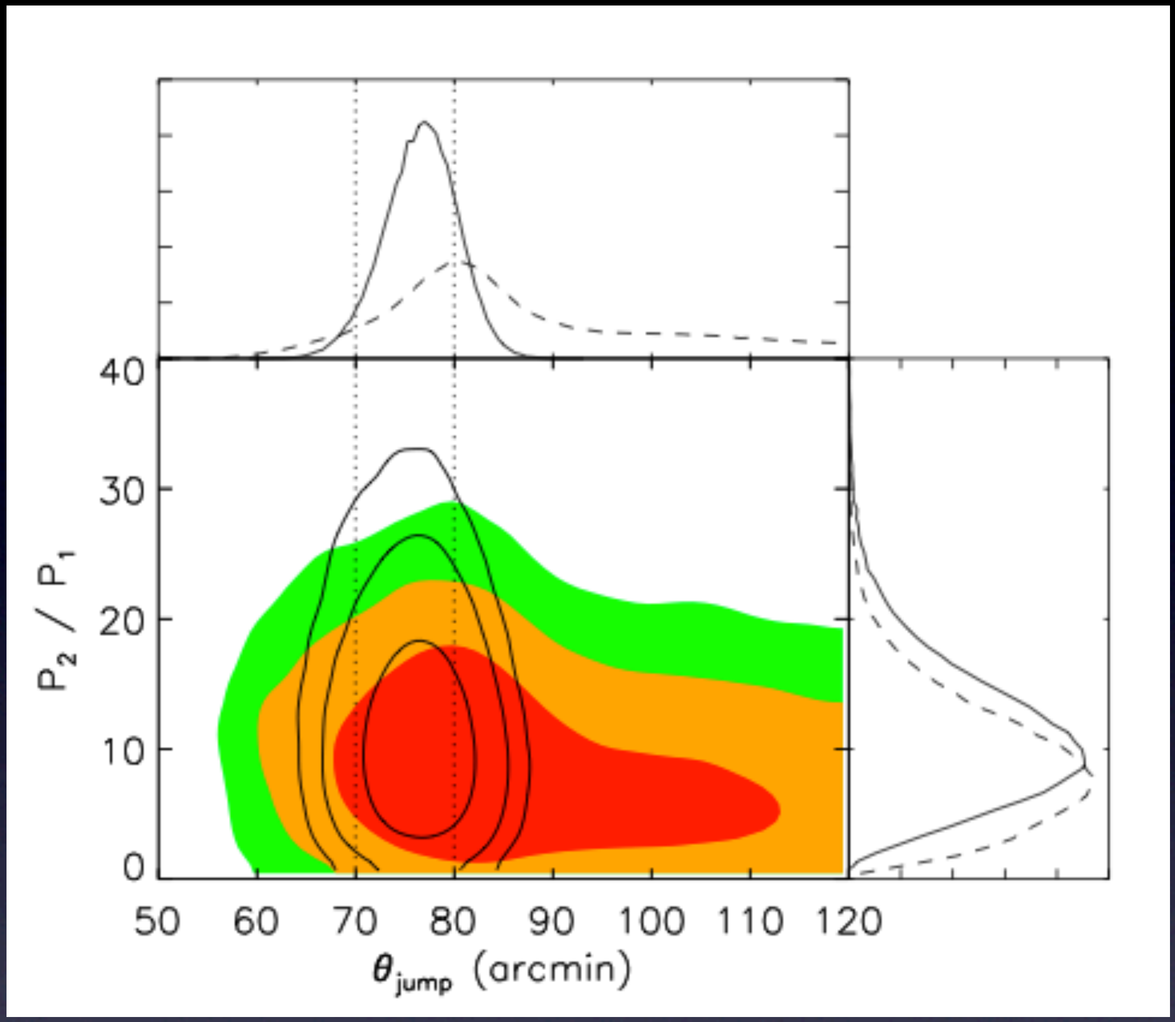


The low-significance shock observed at the relic position is attempted to fit with three alternative models.

A shock model, with pressure jump at the relic position, provides the best fit and compatibility with other data.

Results for Coma relic shock

Erler, Basu et al. (2015)



- SZ data favors a jump close the the relic without any radio prior, at 79^{+10}_{-9} arcmin (radio relic at 75 arcmin)
- Corresponding pressure ratio at the relic is $8.8^{+6.1}_{-3.4}$
- Pressure radio and jump location are uncorrelated

$$\frac{P_2}{P_1} = \frac{2\gamma \mathcal{M}^2 - \gamma + 1}{\gamma + 1}$$

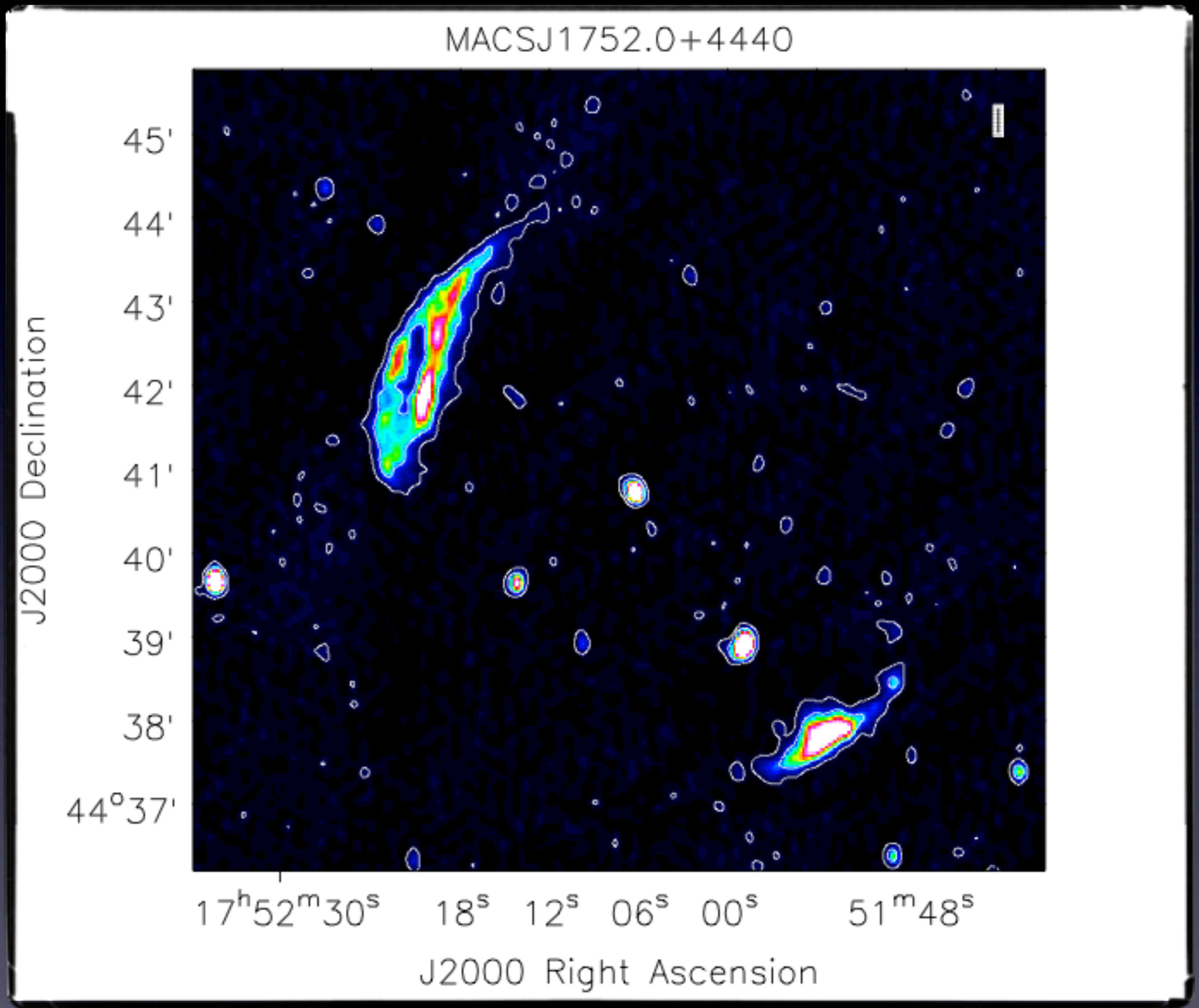
$$\mathcal{M} = 2.8^{+0.8}_{-0.6}$$

This is the first "detection" of a pressure discontinuity at a radio relic with the SZ effect. This also happens to be the first SZ shock feature detected near a cluster's virial radius.

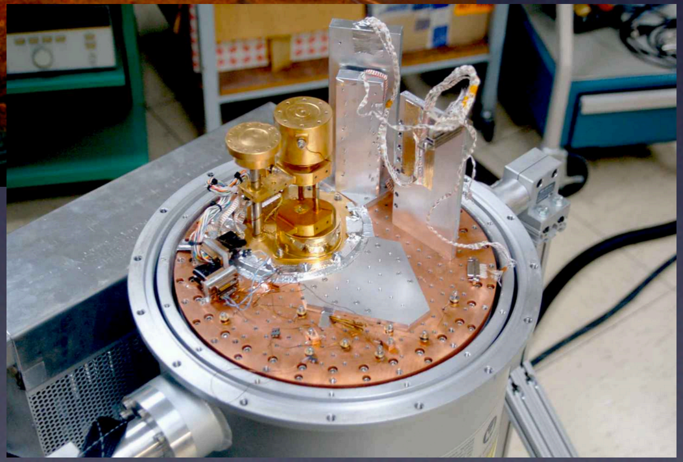
With the latest 2015 Planck data release, we have Mach number M = 3.4±0.5 (pressure ratio P_2/P_1 = 14.3±4.5)

Relics at high-z

Measuring cluster merger shocks through cosmic time!



Cluster MACS J1752.0+4440 at z = 0.37
(Bonafede et al. 2012)



Observed with IRAM GISMO bolometer array (analysis in progress)

Summary

Radio halo SZ connection:

- We made a first demonstration for the radio-SZ correlation for the giant radio halos in galaxy clusters, and also attempted to provide some statistics for radio halos in the SZ selection.
- The radio halo fraction in SZ (i.e. mass) selection is large (60%-80%), and the bi-modal division is weak.
- Counting radio halos can potentially provide new ways of constraining cosmology by measuring the cluster merger fraction.

Radio relic SZ connection:

- We obtained the first evidence for a cluster merger shock at a radio relic position from the SZ effect, analyzing Planck data for the Coma cluster.
- SZ method is particularly suitable for radio relics in the cluster outskirts, and for going to high redshifts.

The origin of diffuse cluster radio emission

- What we understood, need to understand, and need to investigate

  Acceleration, re-acceleration, seed CR populations, hadronic secondaries, old radio plasma, its stability and transport
- Are we on the right tracks?

  Are CR populations mobile or not? What is their transport regime (advection, diffusion, streaming)
- Are there discriminating predictions for the different scenarios?

  Radio flux, morphology, polarization, spectra, gamma-rays, IC limits & detection of CRe, what do the upper limits on CRp via hadronic channels really mean?
- Which observations do we need?

  Radio, X-ray, gamma? … surveys or targeted? … data fusion?