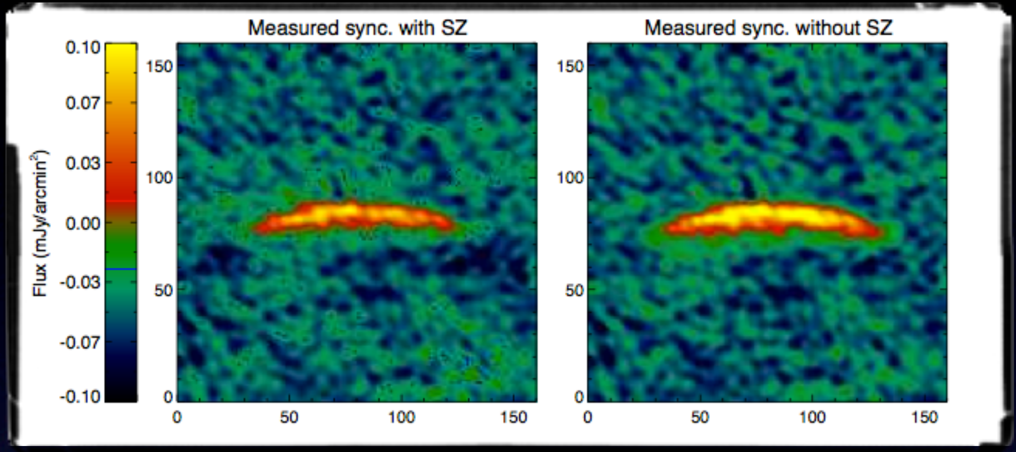
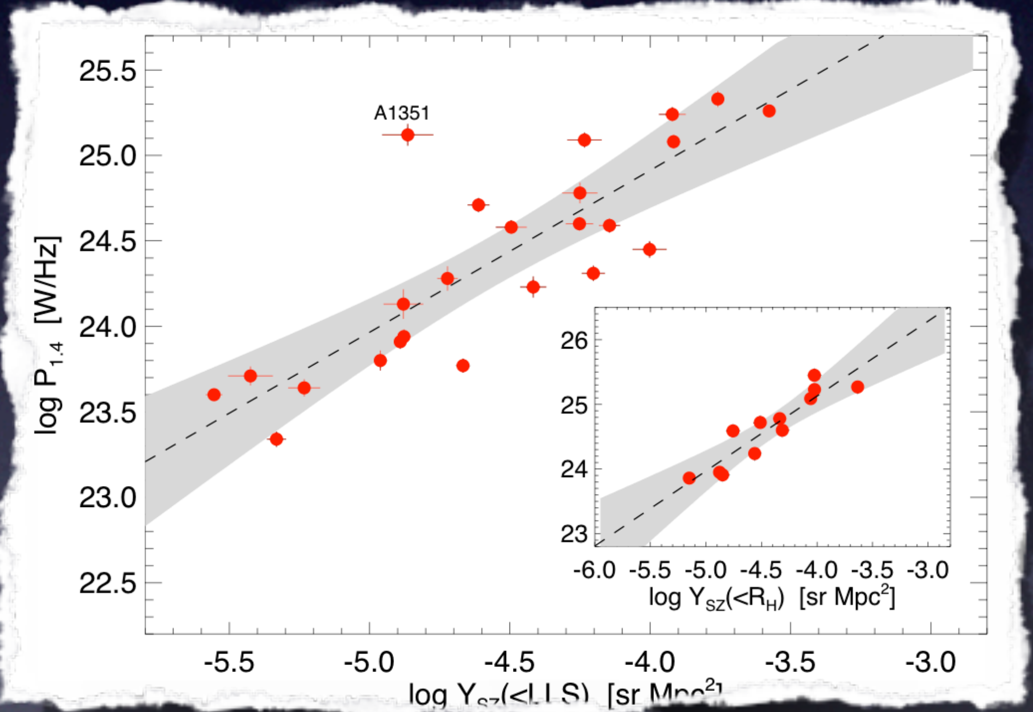
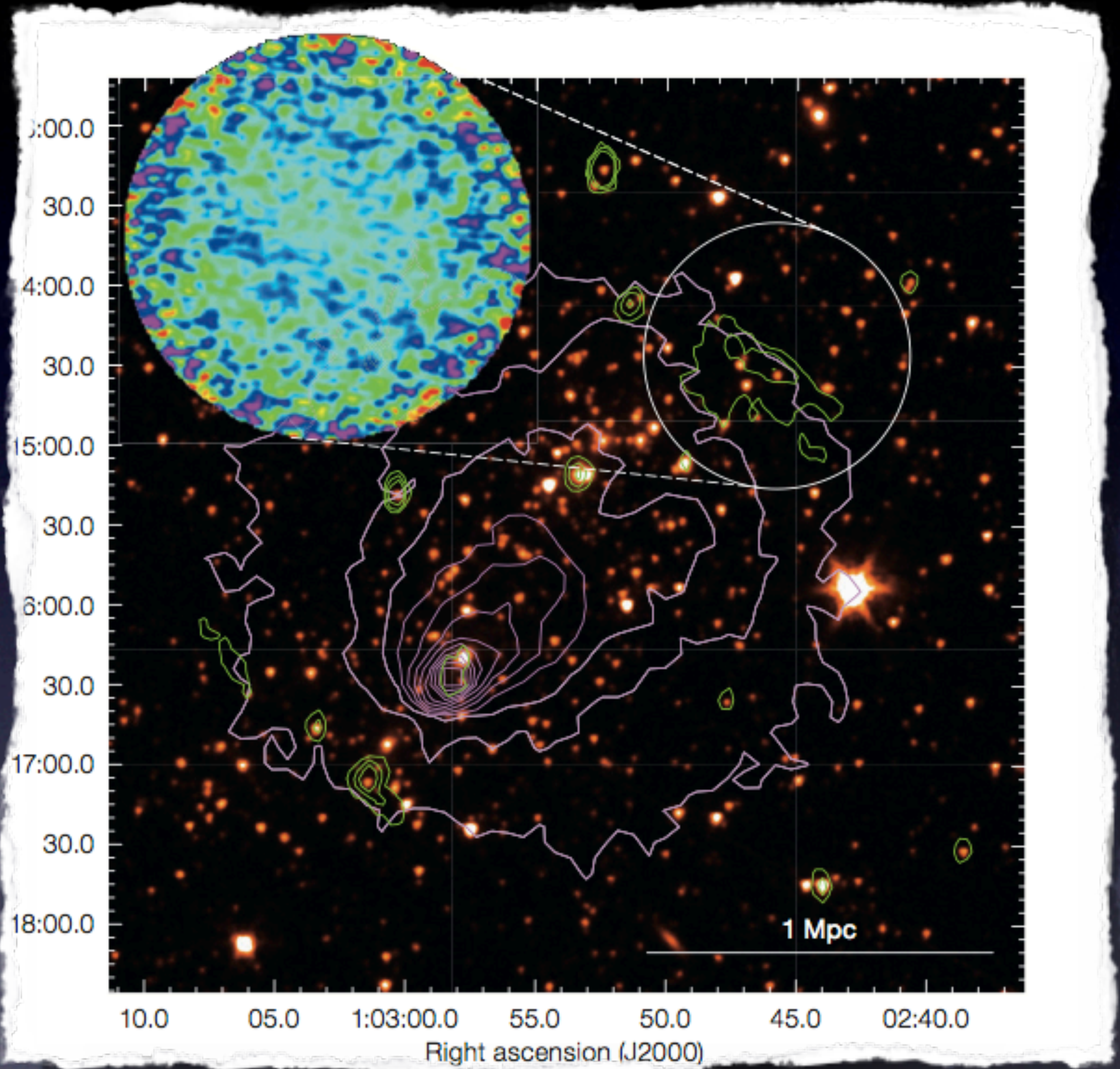
Galaxy cluster physics from the thermal / non-thermal connection



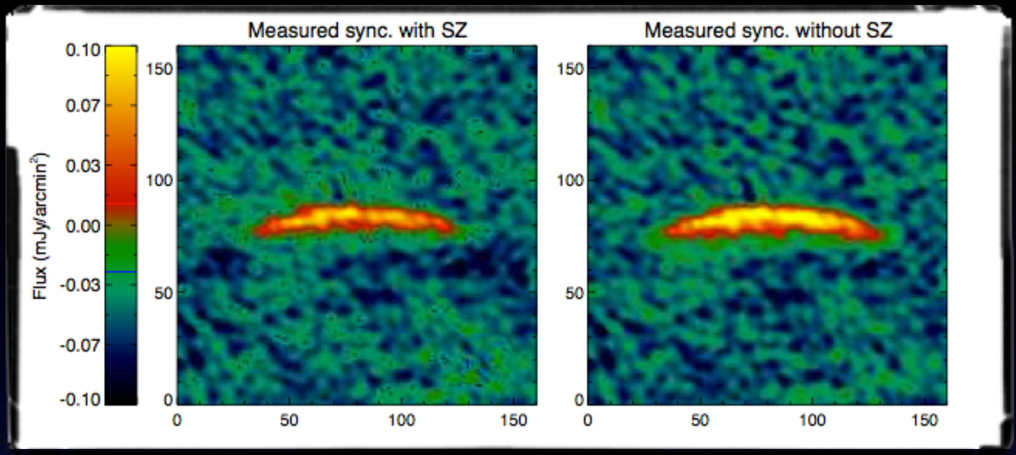


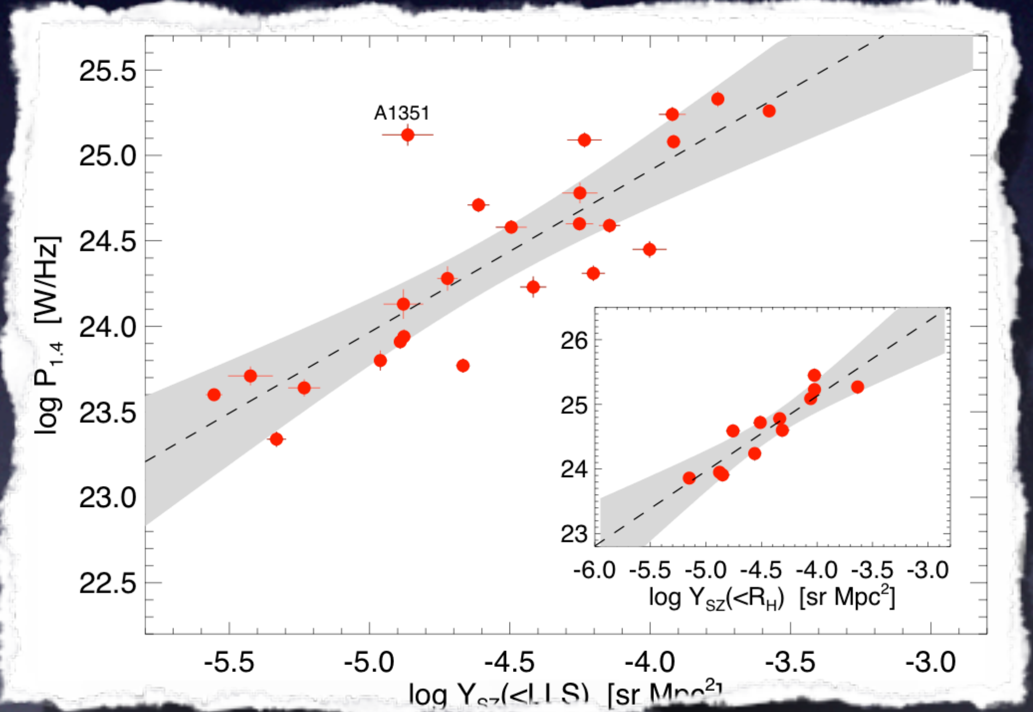


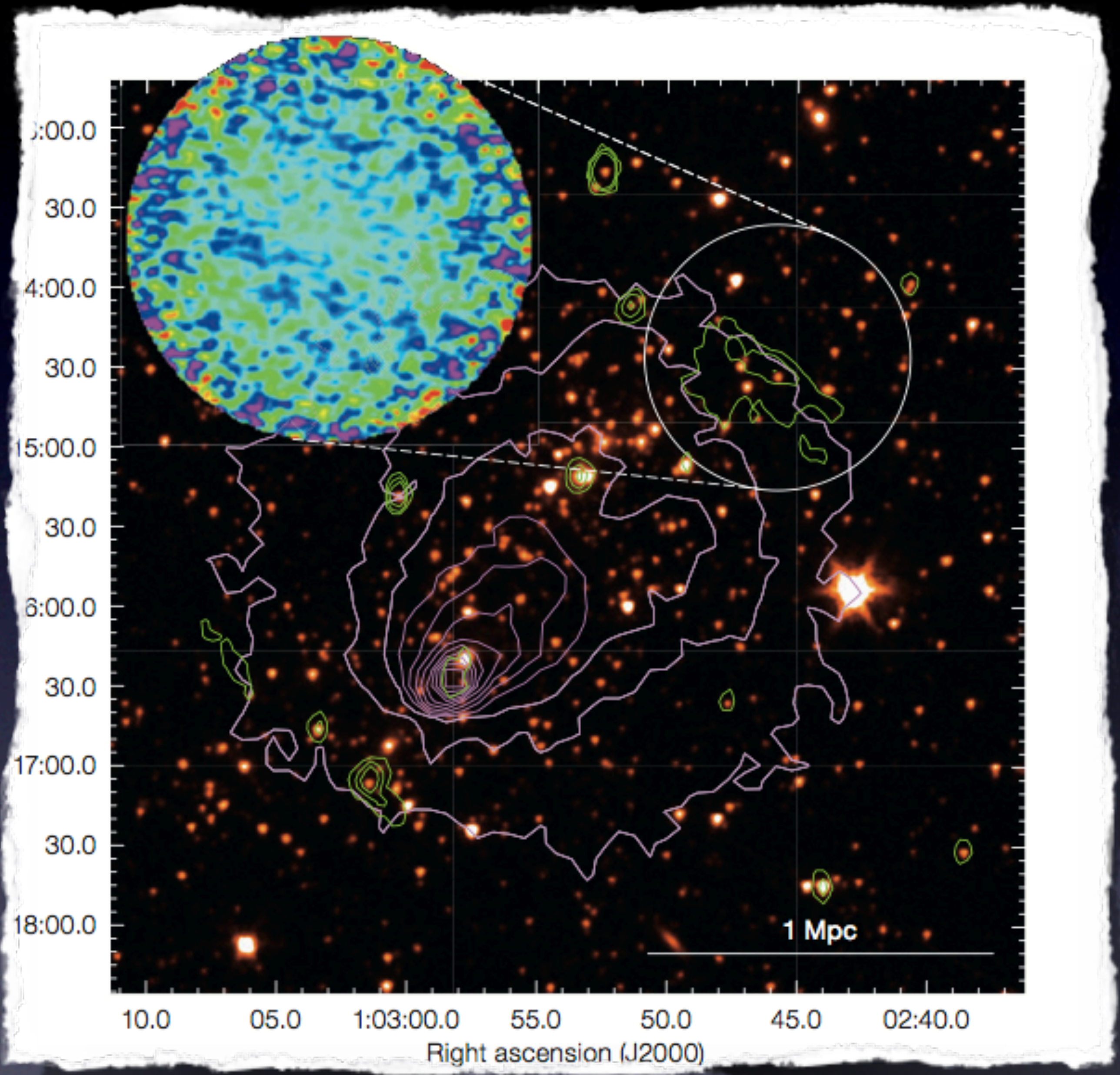
Kaustuv Basu (University of Bonn)

with Martin Sommer (Bonn), Jens Erler (Bonn), Franco Vazza (Hamburg), Dominique Eckert (Geneva), a.o.

Galaxy cluster physics *(+ cosmology)* from the thermal / non-thermal connection







Kaustuv Basu (University of Bonn)

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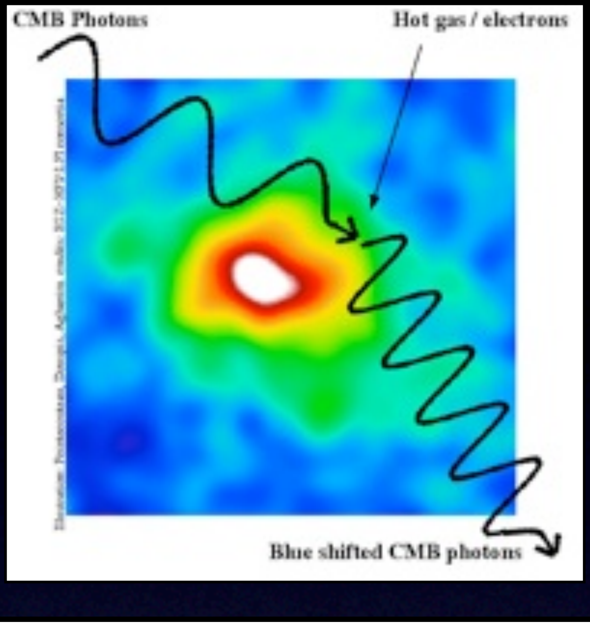
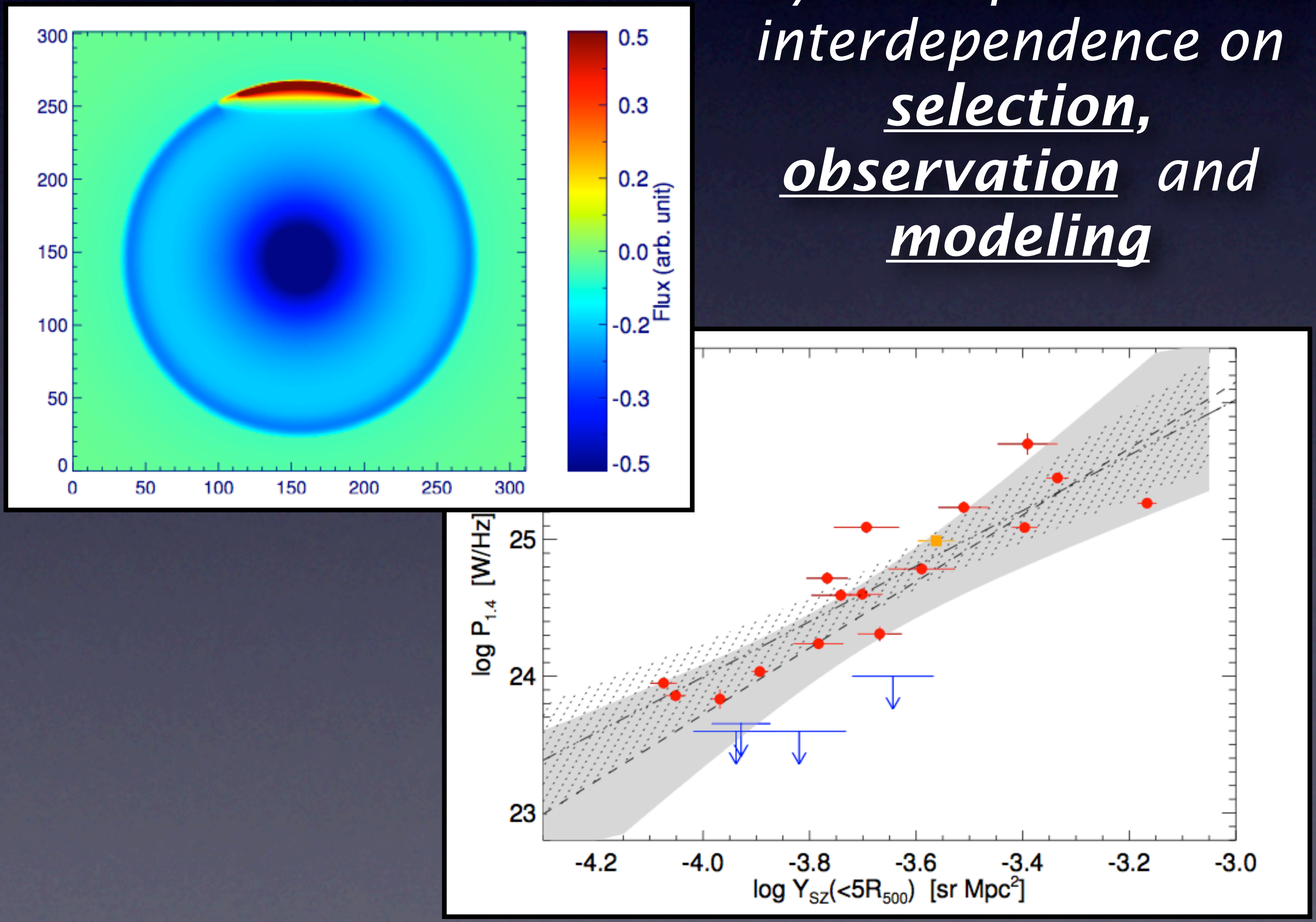
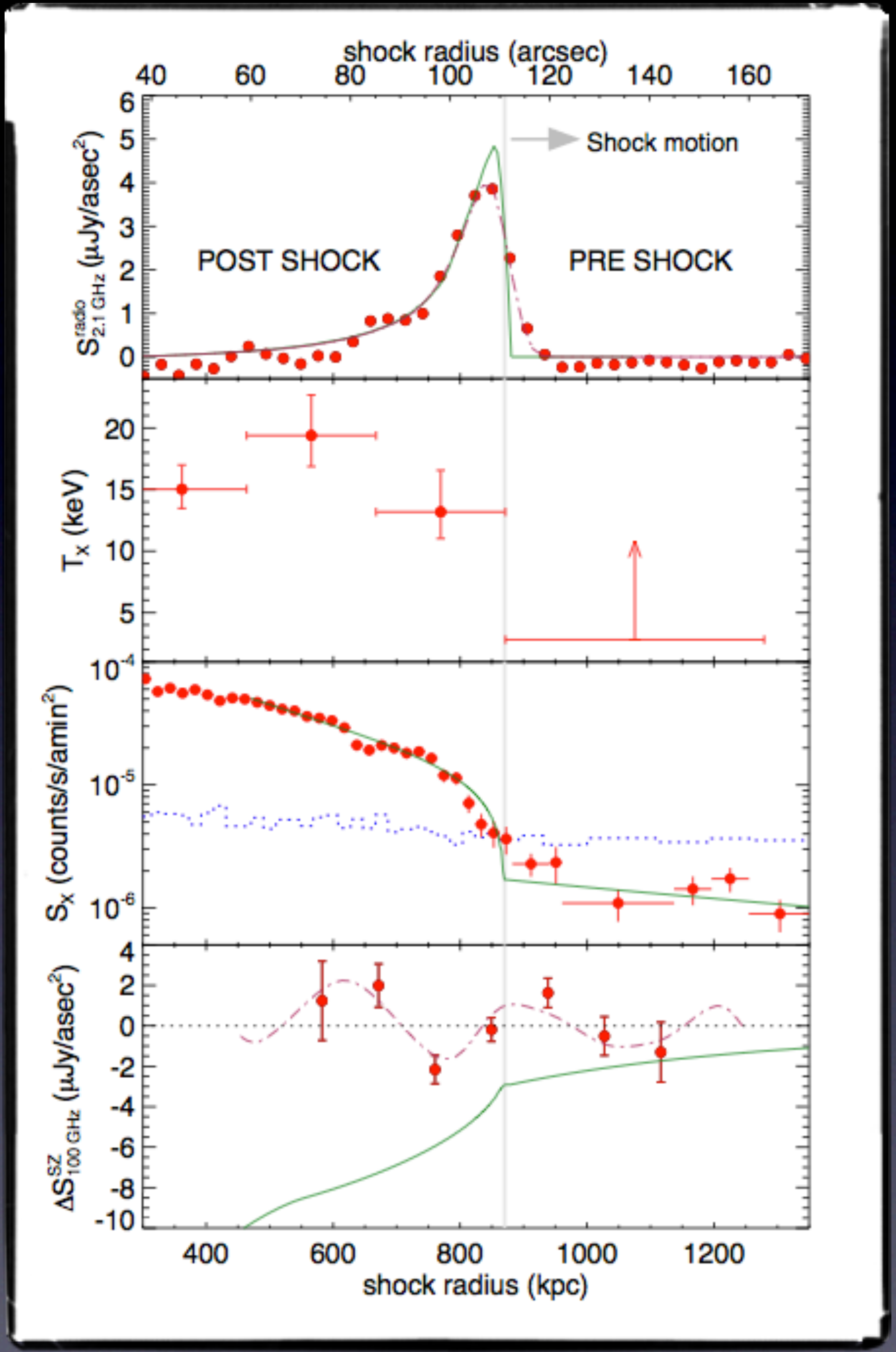
“Thermal / Non-thermal Connection”



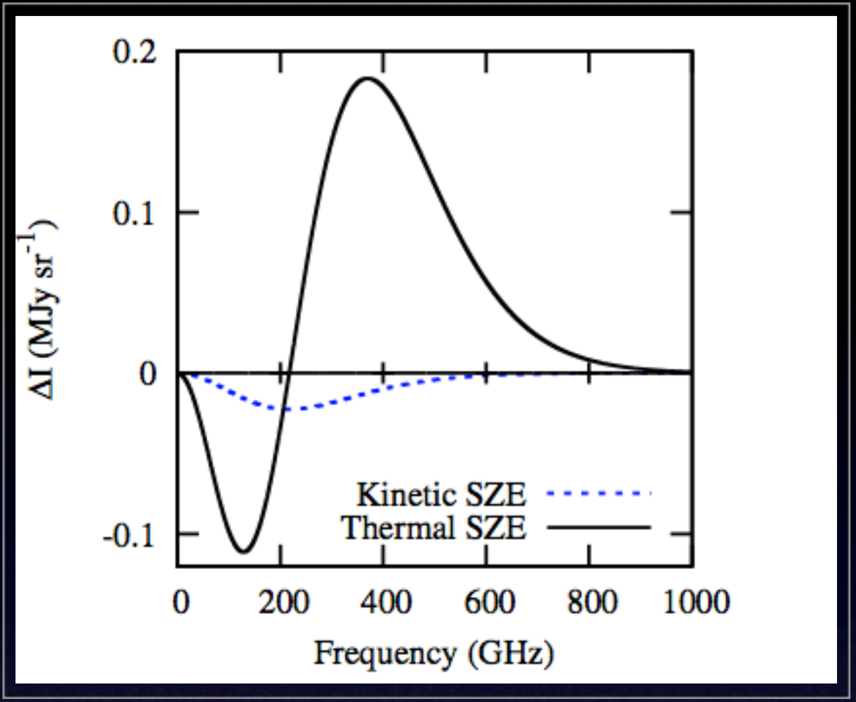
By “thermal” I will mostly talk about the Sunyaev-Zel’dovich (SZ) effect

By “connection” I will try to emphasize the interdependence on ***selection,*** ***observation*** *and* ***modeling***

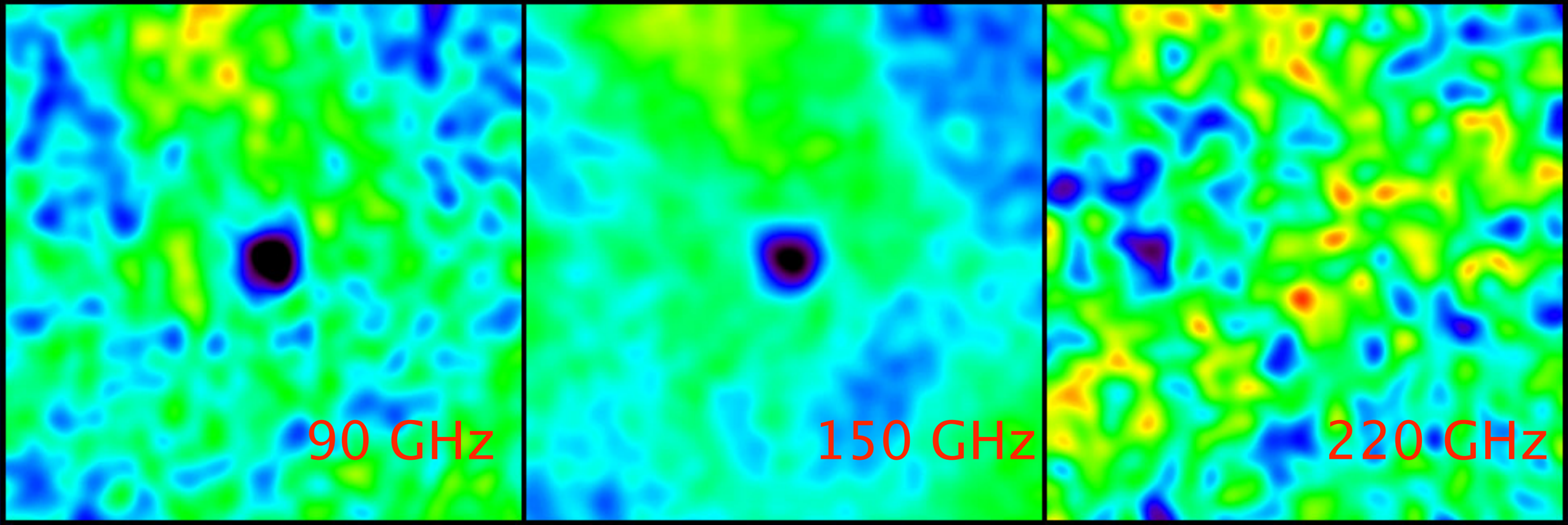




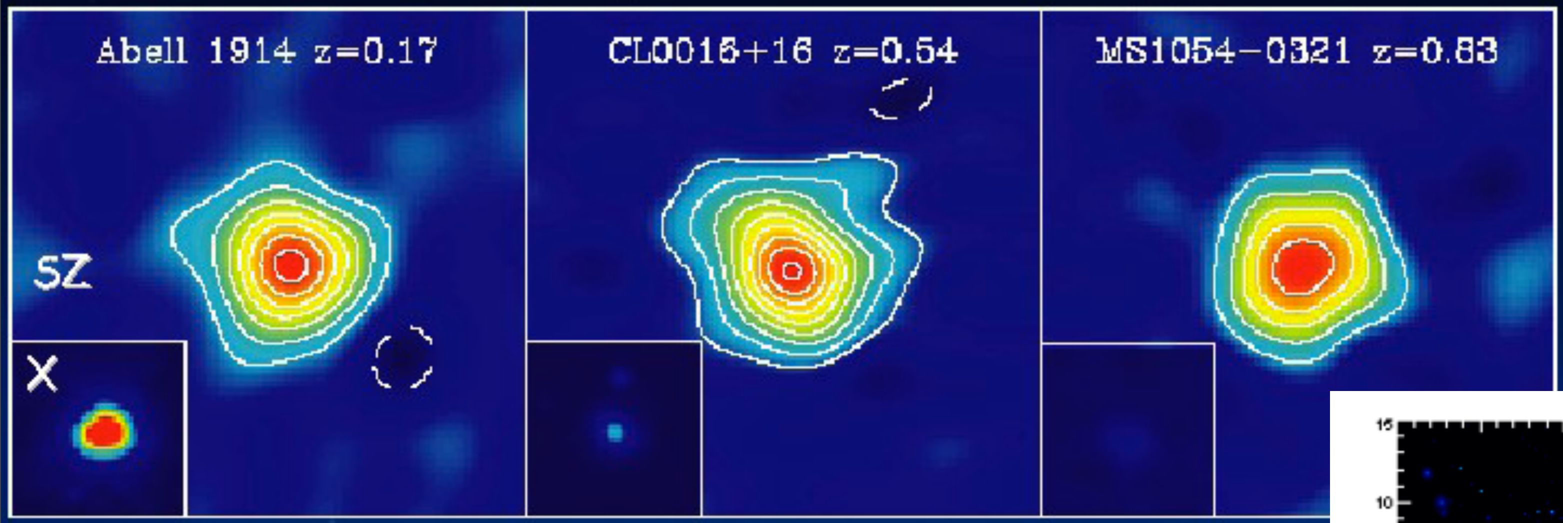
The Sunyaev-Zel'dovich (SZ) effect



SPT collaboration



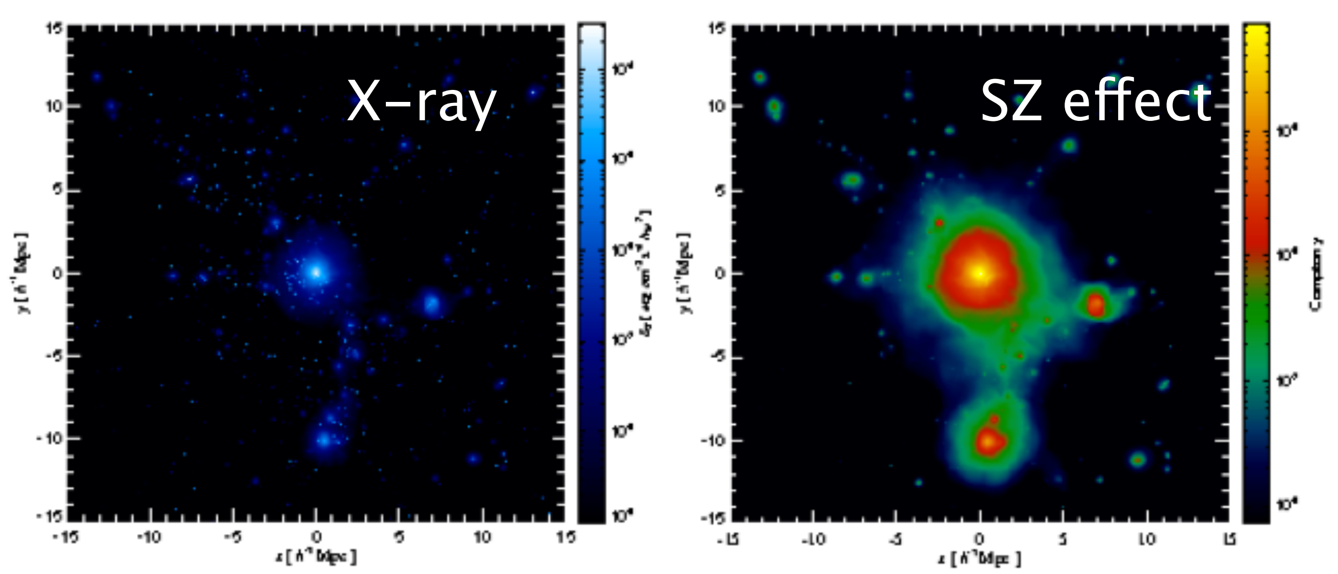
Carlstrom et al.



Line-of-sight signal:

$$\frac{\Delta T}{T_{\rm CMB}} = g(x) \int n_e(l)\, \frac{k_B T_e(l)}{m_e c^2}\, dl$$

Pfrommer et al. (sims)



Integrated signal:

$$\Delta S_\nu = \int \Delta I_\nu \, d\Omega \propto \frac{\int n_e T_e \, dV}{D_A^2} \propto \frac{f_{\rm gas} M_{\rm tot} T_e}{D_A^2}$$

An SZ tale of Two Phenomena

Radio Halos:

- Radio-SZ scaling relation for giant radio halos
- Radio halo statistics from SZ & X-ray selection in an unbiased way
- Follow-up observations of Planck clusters: high RH fraction confirmed
- Galaxy cluster merger rate — new tool for cosmology

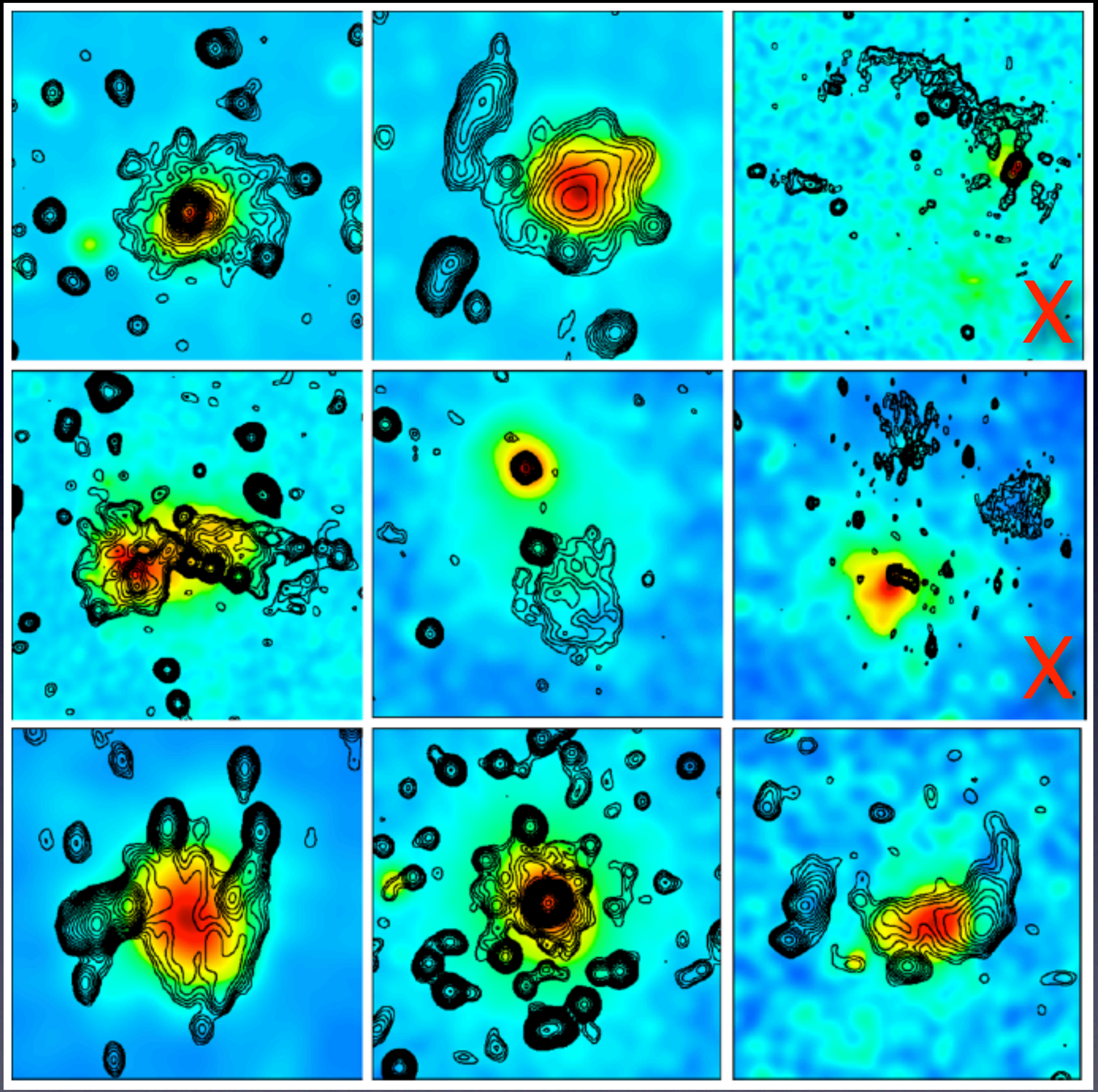
Basu (2012) ▪ Sommer & Basu (2014) ▪ Basu, Sommer et al. (2016) ▪ and others

Radio Relics:

- SZ contamination in GHz-frequency relic observations
- First measured SZ shocks in radio relics: Coma & El Gordo
- SZ/X-ray/synchrotron joint modeling — tool for cluster astrophysics

Erler, Basu et al. (2015) ▪ Basu, Vazza et al. (2016) ▪ Basu, Sommer et al. (2016)

Diffuse radio emission in clusters



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

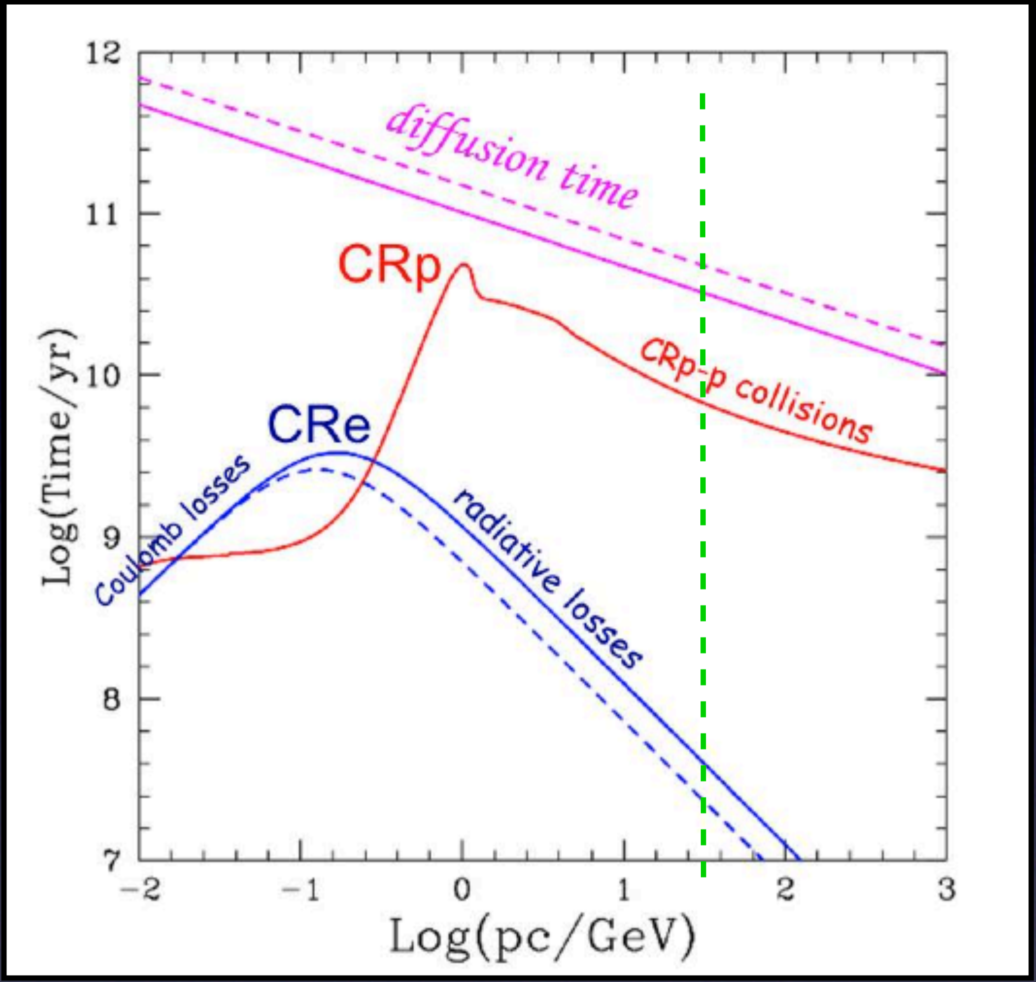
Radio halos: $L_{1.4\,\mathrm{GHz}} \sim 10^{24-25}$ W/Hz

- 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

Halos & relics — both terrible misnomers!

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.



(Brunetti & Jones 2014)

Some form of *in-situ* acceleration is necessary

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

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

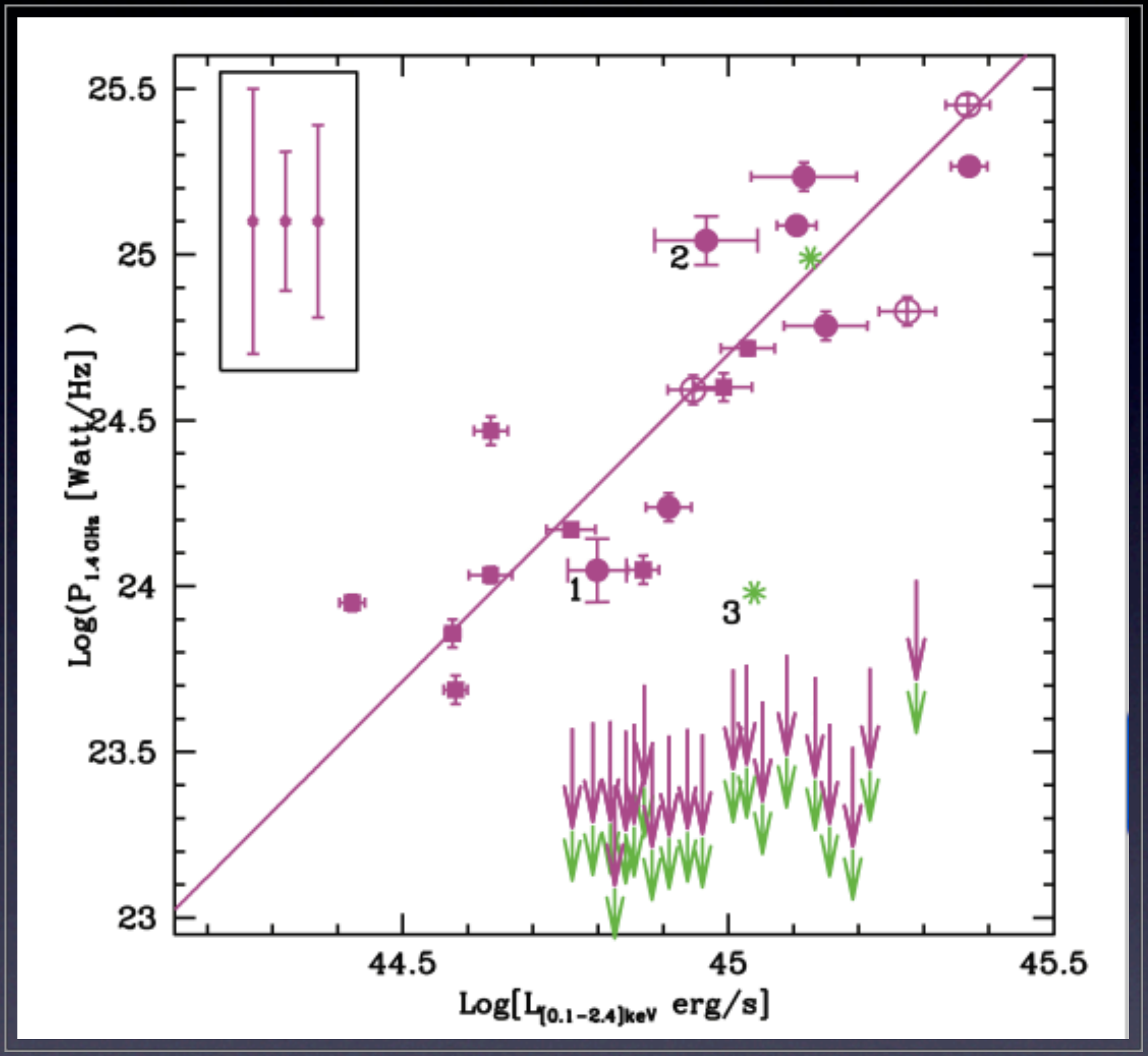
Original competing models for radio halo origin

More complex hybrid models

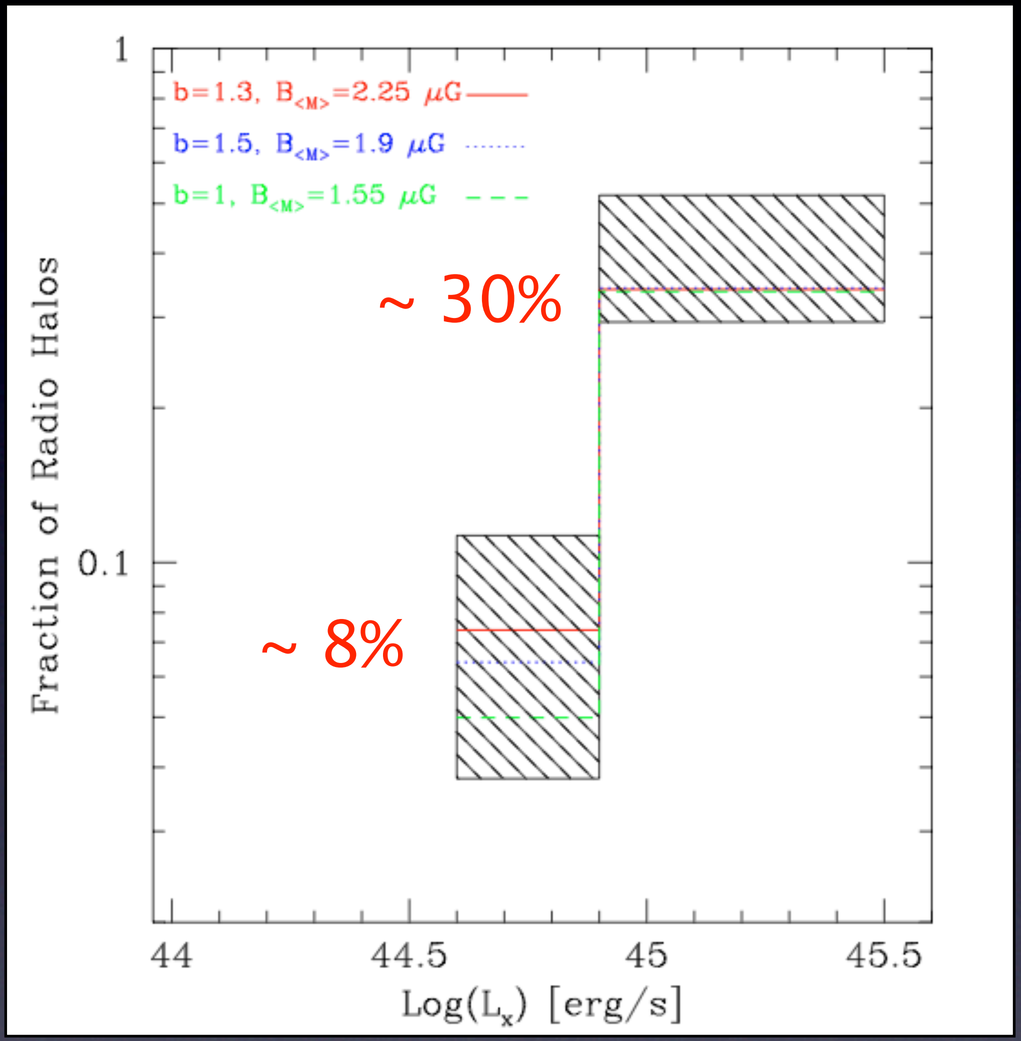
“Observational benchmarks” for radio halos

There is a <u>strong</u> bi-modality

They are <u>rare</u> **~40 known halos**



Brunetti et al. (2007)



Cassano et al. (2010)

“Observational benchmarks” for radio halos

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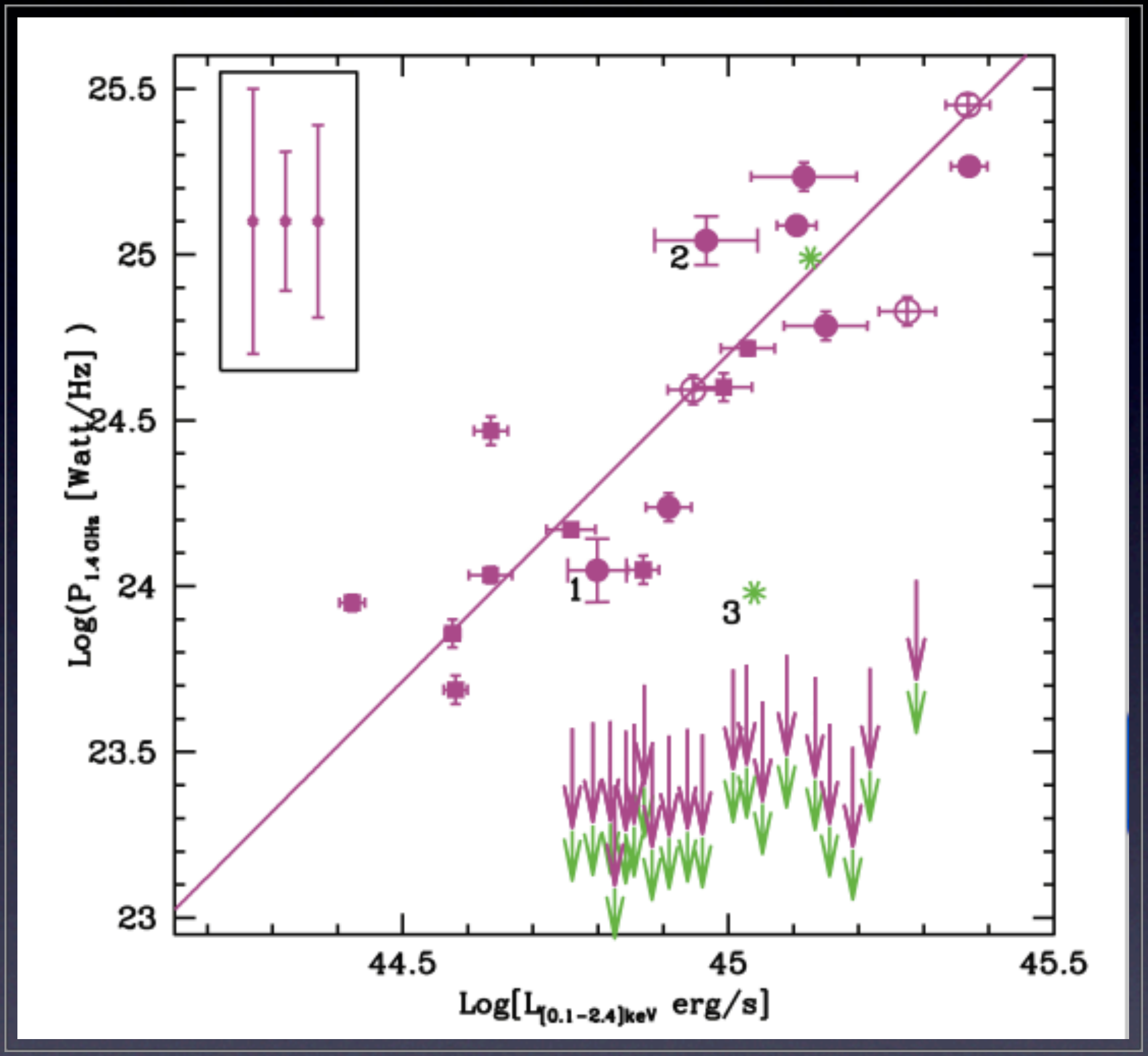
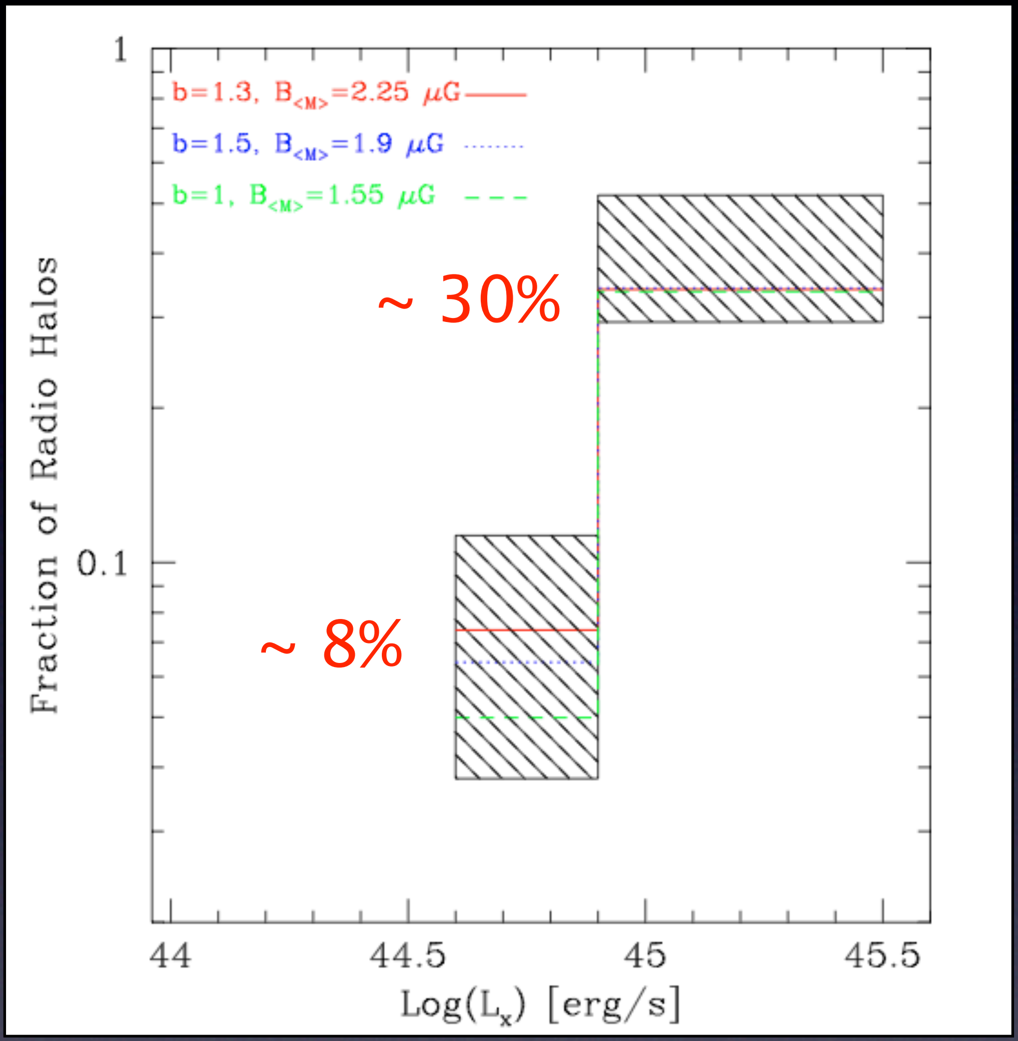
They are rare **~40 known halos**



Brunetti et al. (2007)



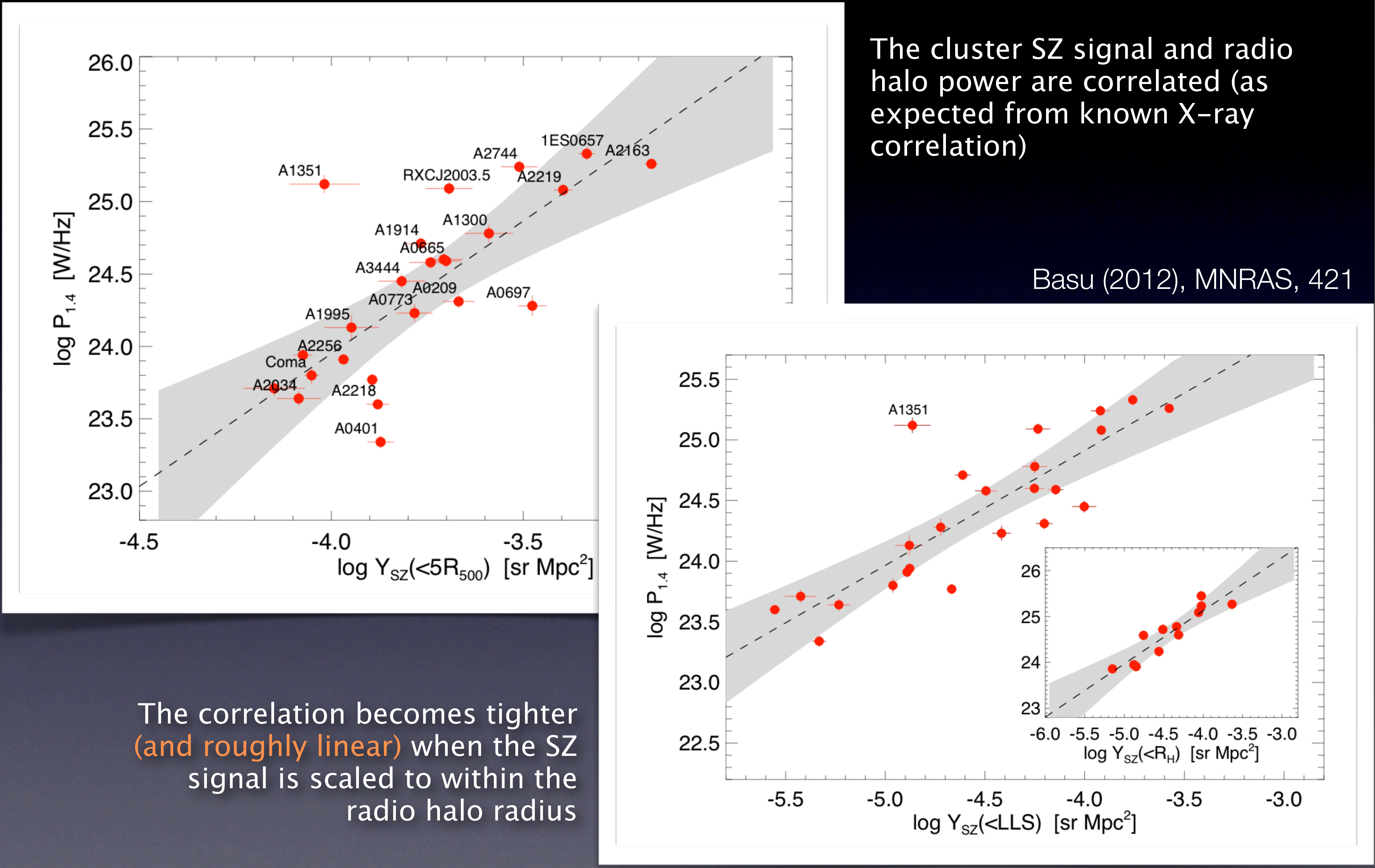
~ 30%

~ 8%

Cassano et al. (2010)

WHAT'S THE SZ TAKE ON THESE?

Radio - SZ Correlation

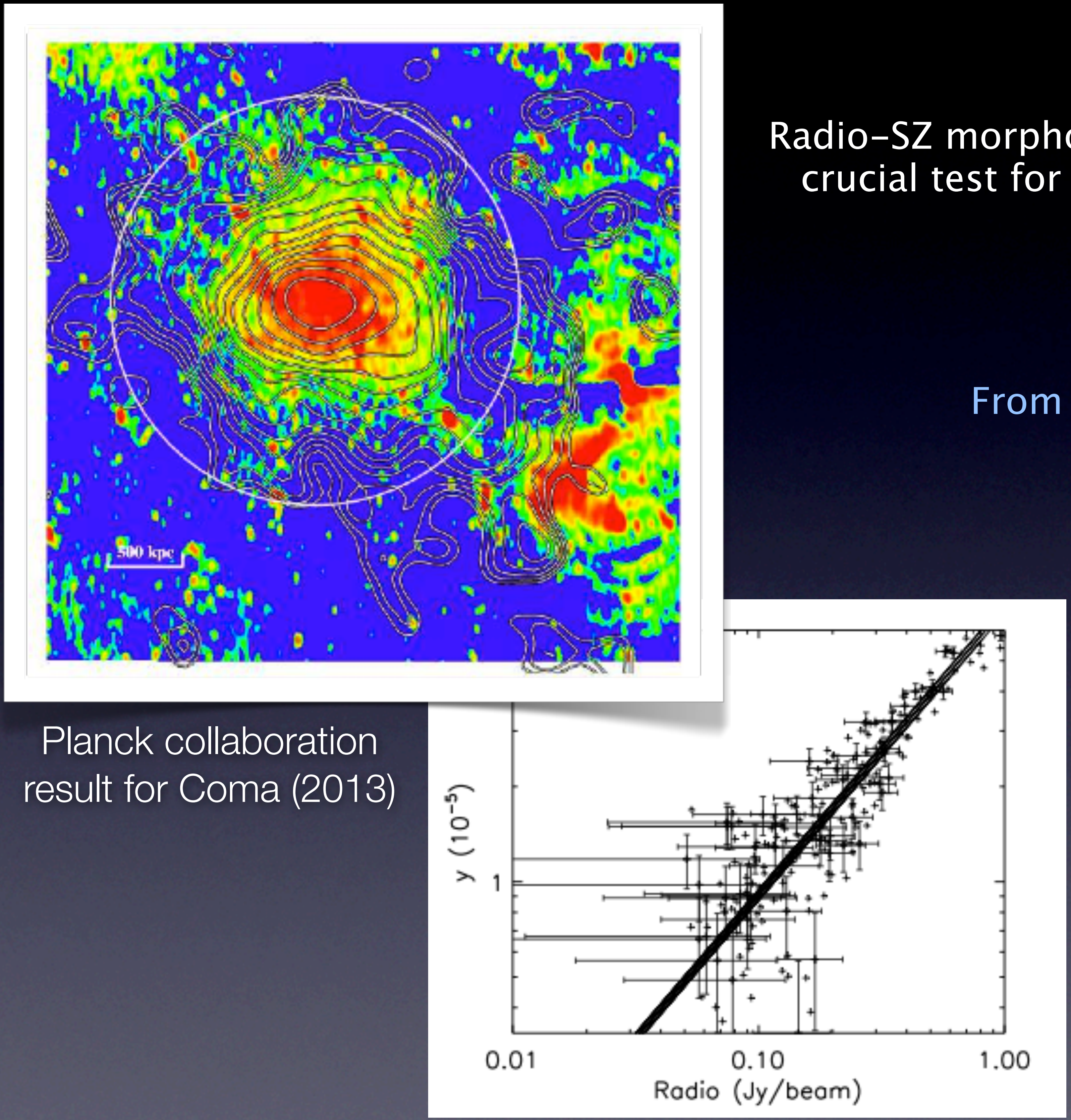


The cluster SZ signal and radio halo power are correlated (as expected from known X-ray correlation)

Basu (2012), MNRAS, 421

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

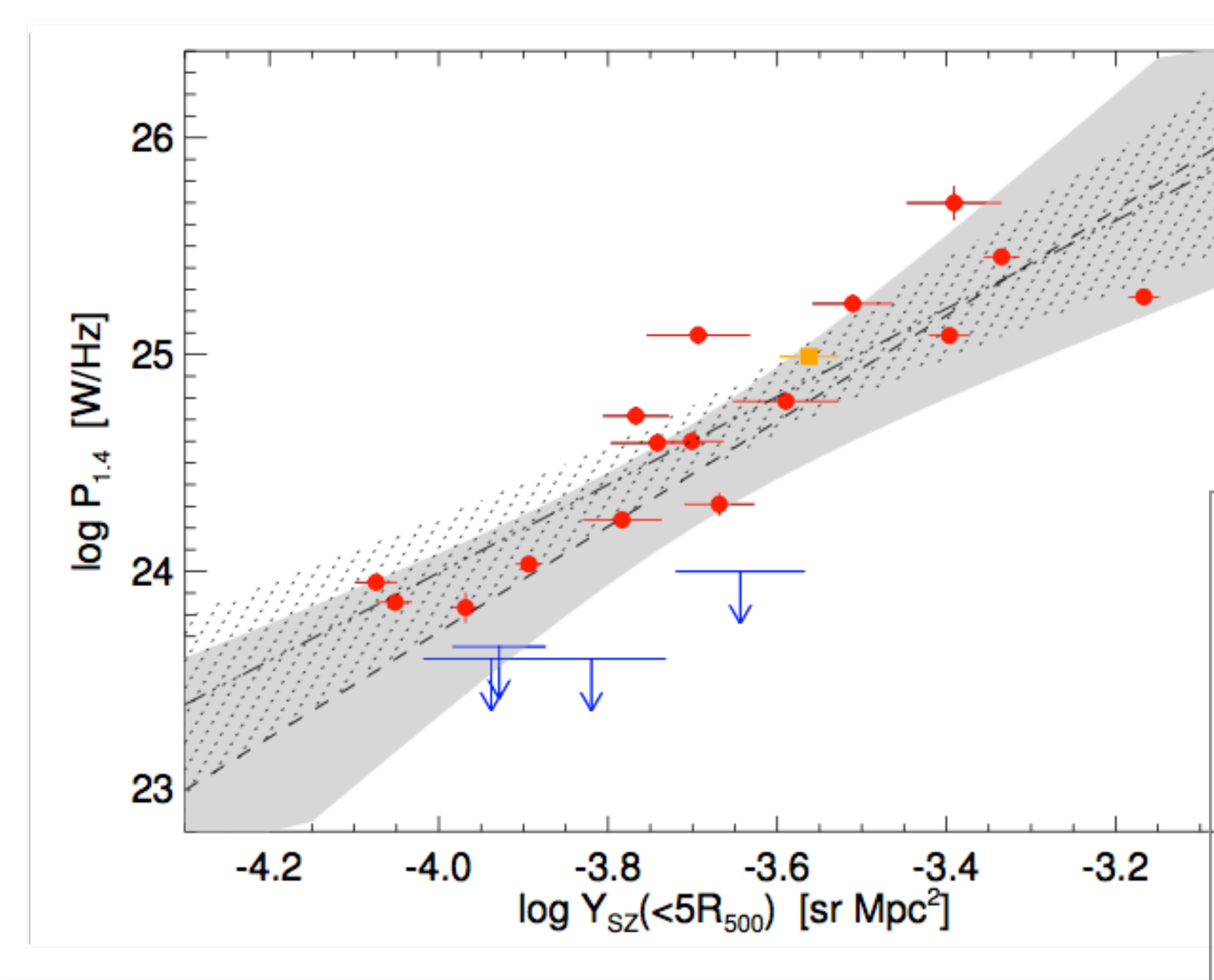
Hadronic model with secondary creation of CR electrons:

$$\epsilon_r \propto n_e \propto y/T$$

Primary models with turbulent re-acceleration of CR electrons:

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

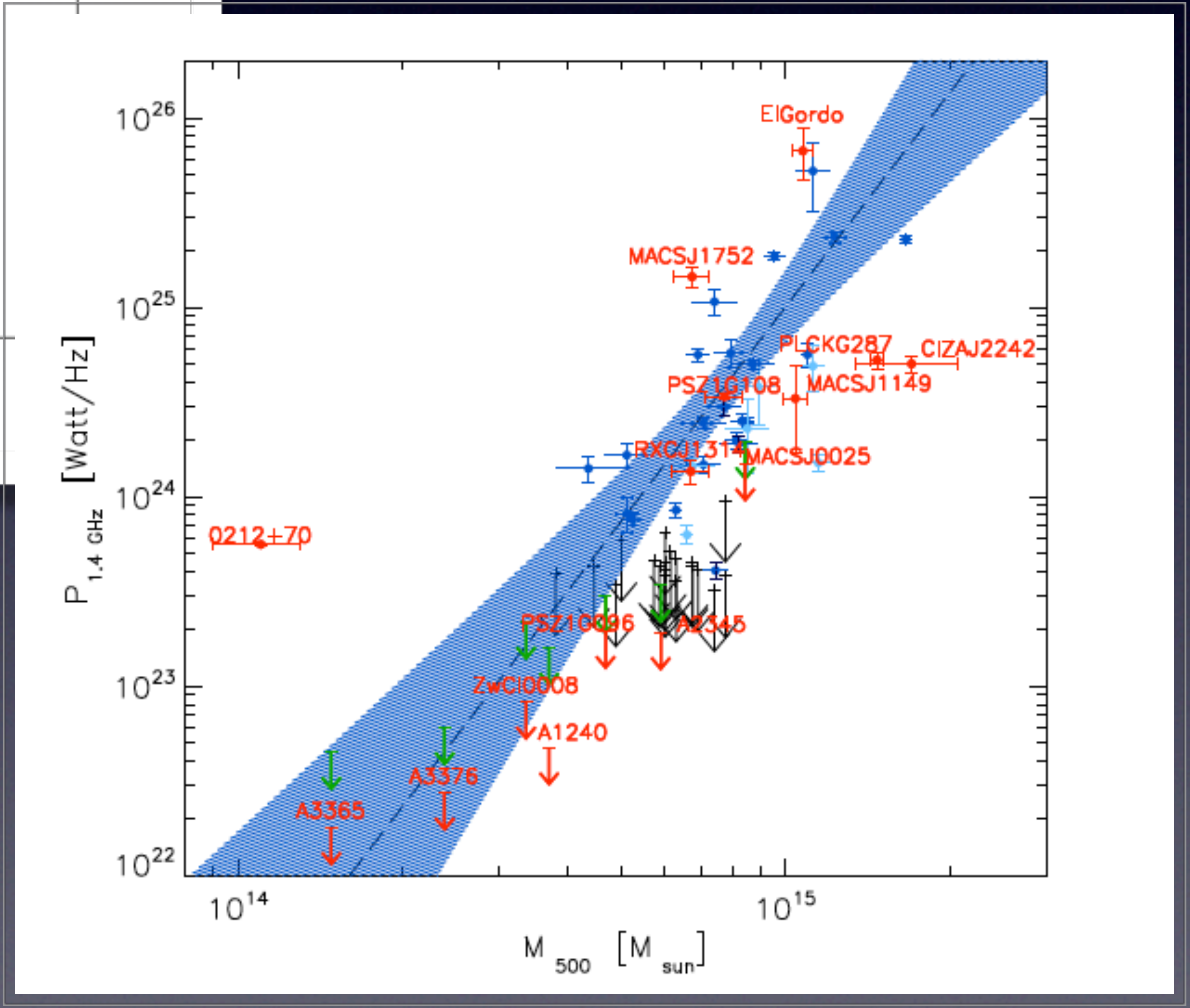
Reduced bi-modality in SZ



Basu (2012), MNRAS, 421

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.

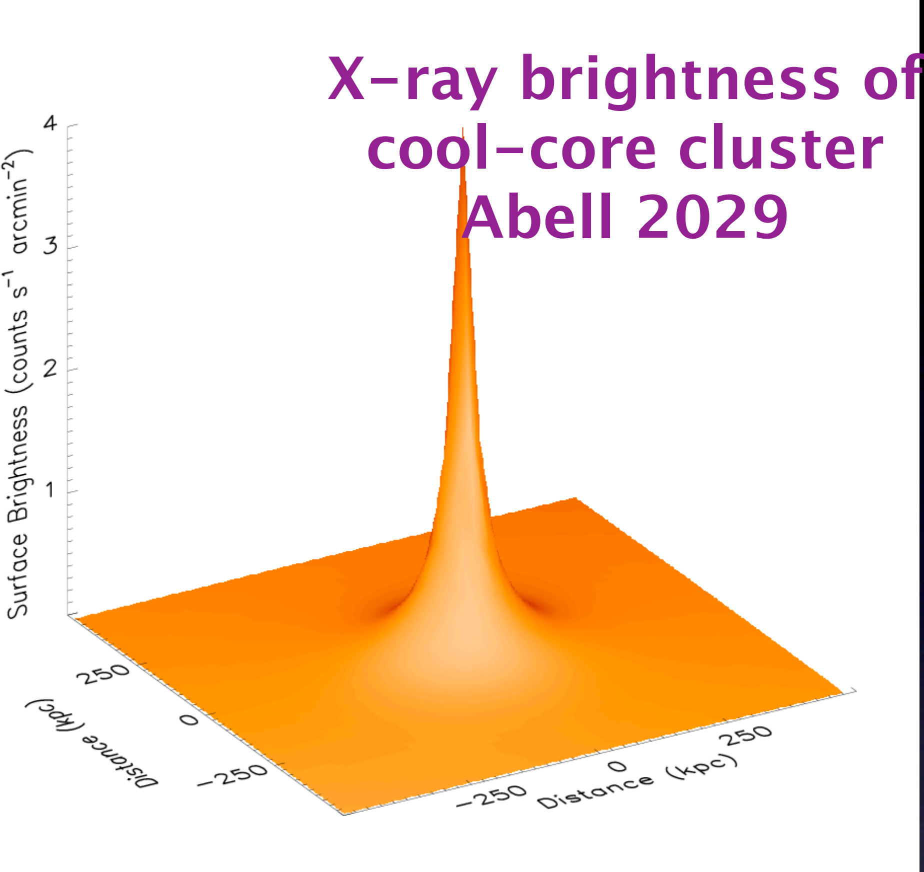
But this is not enough: we need statistics from *a priori* SZ selection



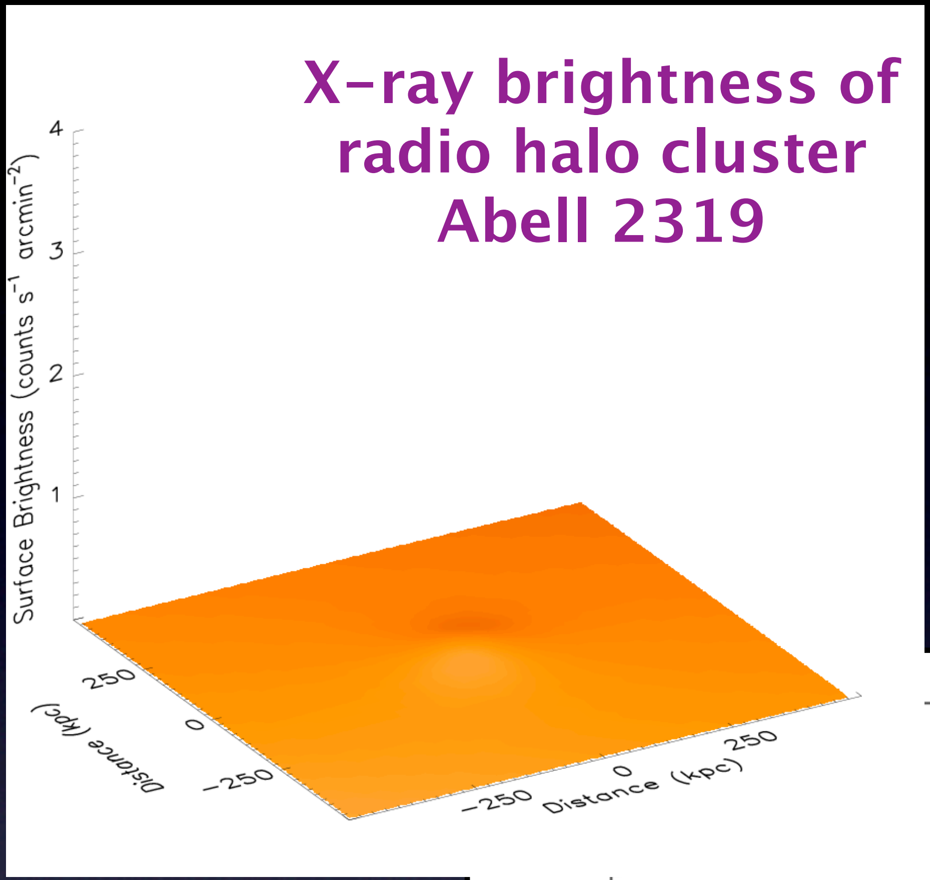
State-of-the-art
(Bonafede et al. 2017)

Appearance of strong bimodality: X-ray CC bias

Million & Allen (2009)



X-ray brightness of cool-core cluster Abell 2029

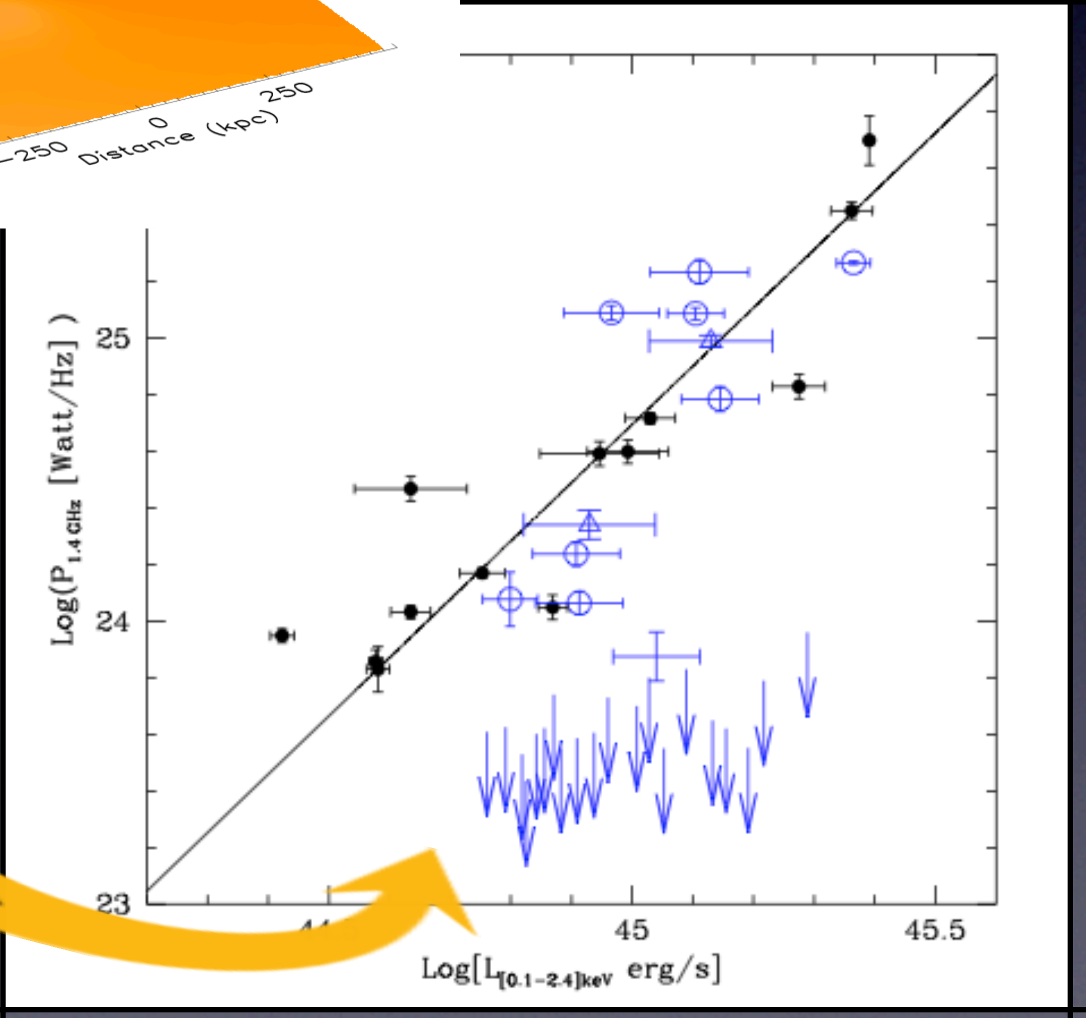


X-ray brightness of radio halo cluster Abell 2319

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

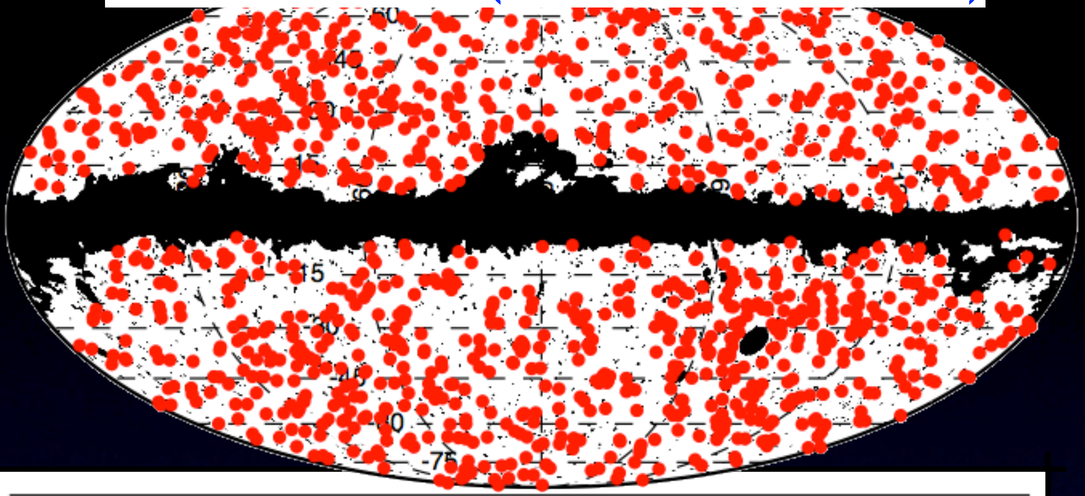
These systems generally do not host giant radio halos

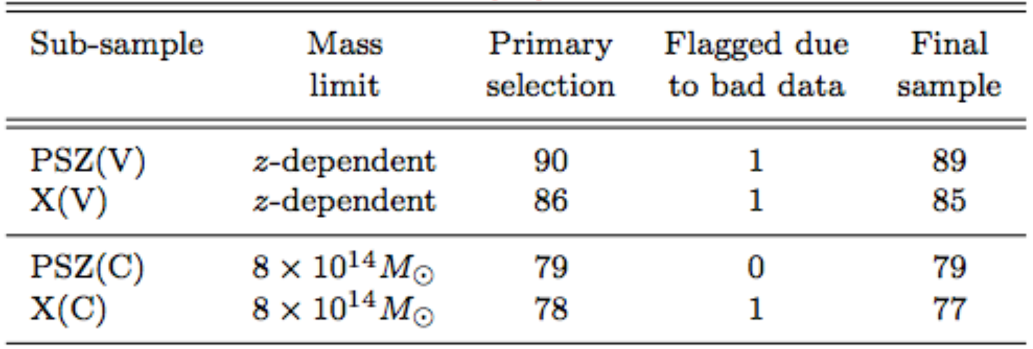
➜ producing a **strong** bi-modal distribution in X-rays



Towards a proper selection

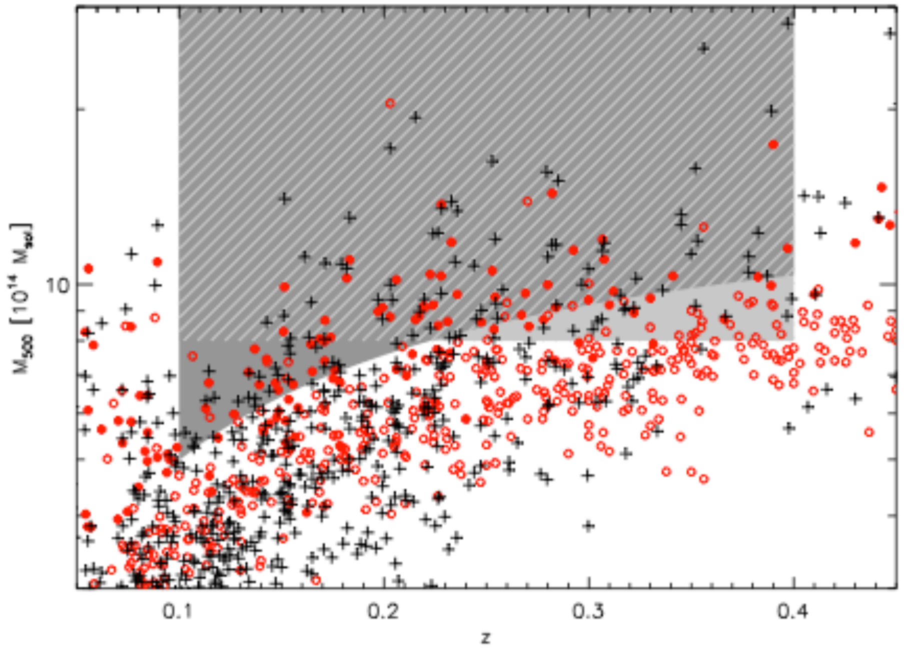
PSZ1 clusters (Planck coll. 2013)



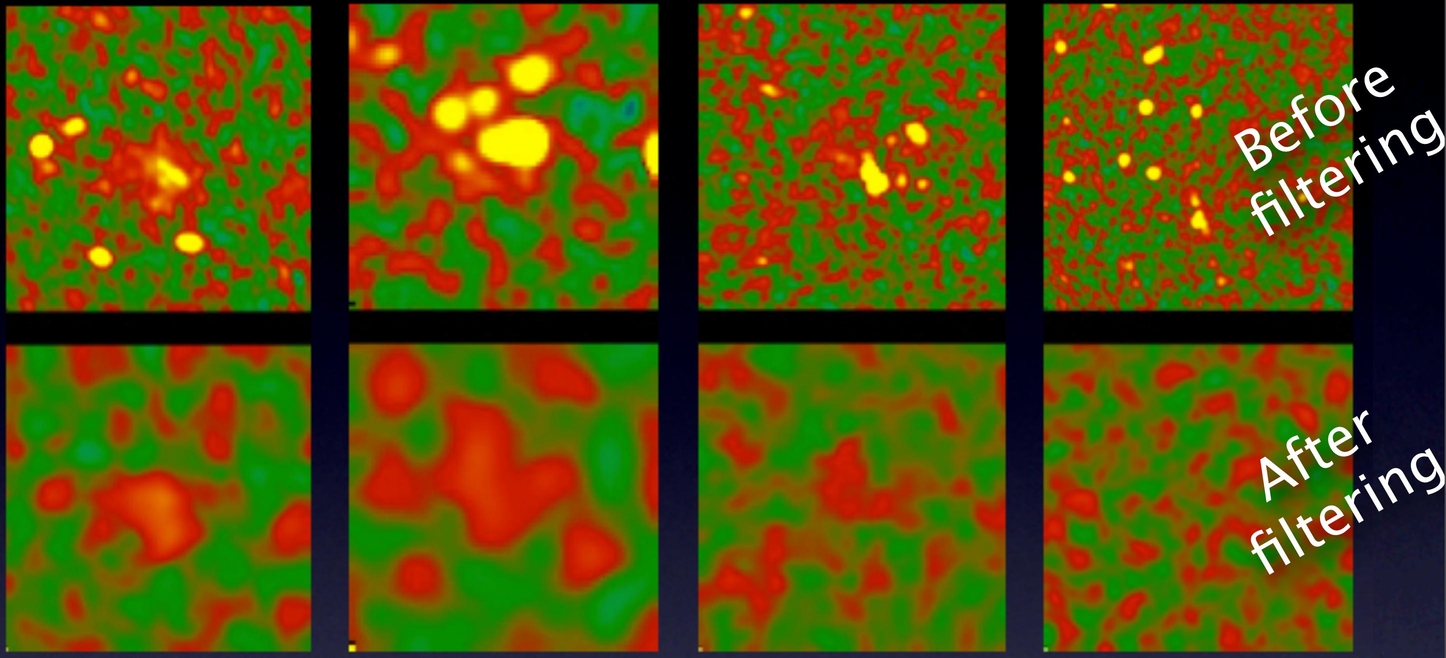


Sub-sample	Mass limit	Primary selection	Flagged due to bad data	Final sample
PSZ(V)	z-dependent	90	1	89
X(V)	z-dependent	86	1	85
PSZ(C)	$8 \times 10^{14} M_\odot$	79	0	79
X(C)	$8 \times 10^{14} M_\odot$	78	1	77

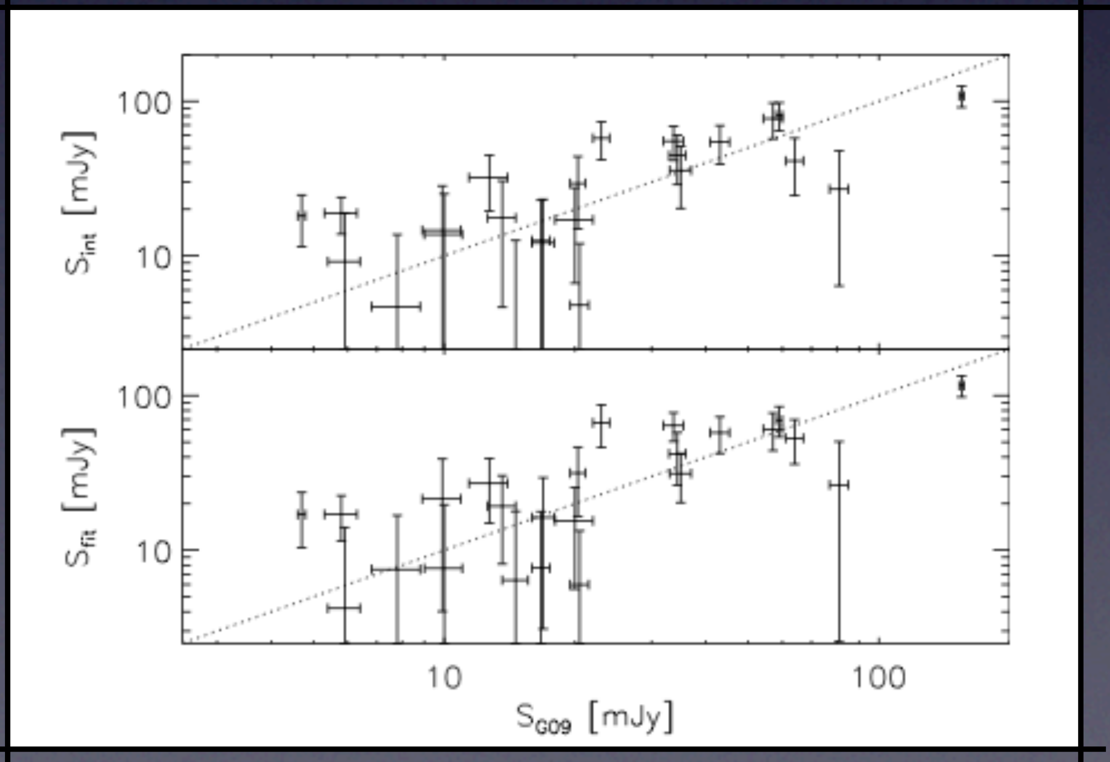
Sommer & Basu (2014), MNRAS, 437



For an unbiased comparison between SZ and X-ray selections, **we first used the NVSS data** (Sommer & Basu 2014)



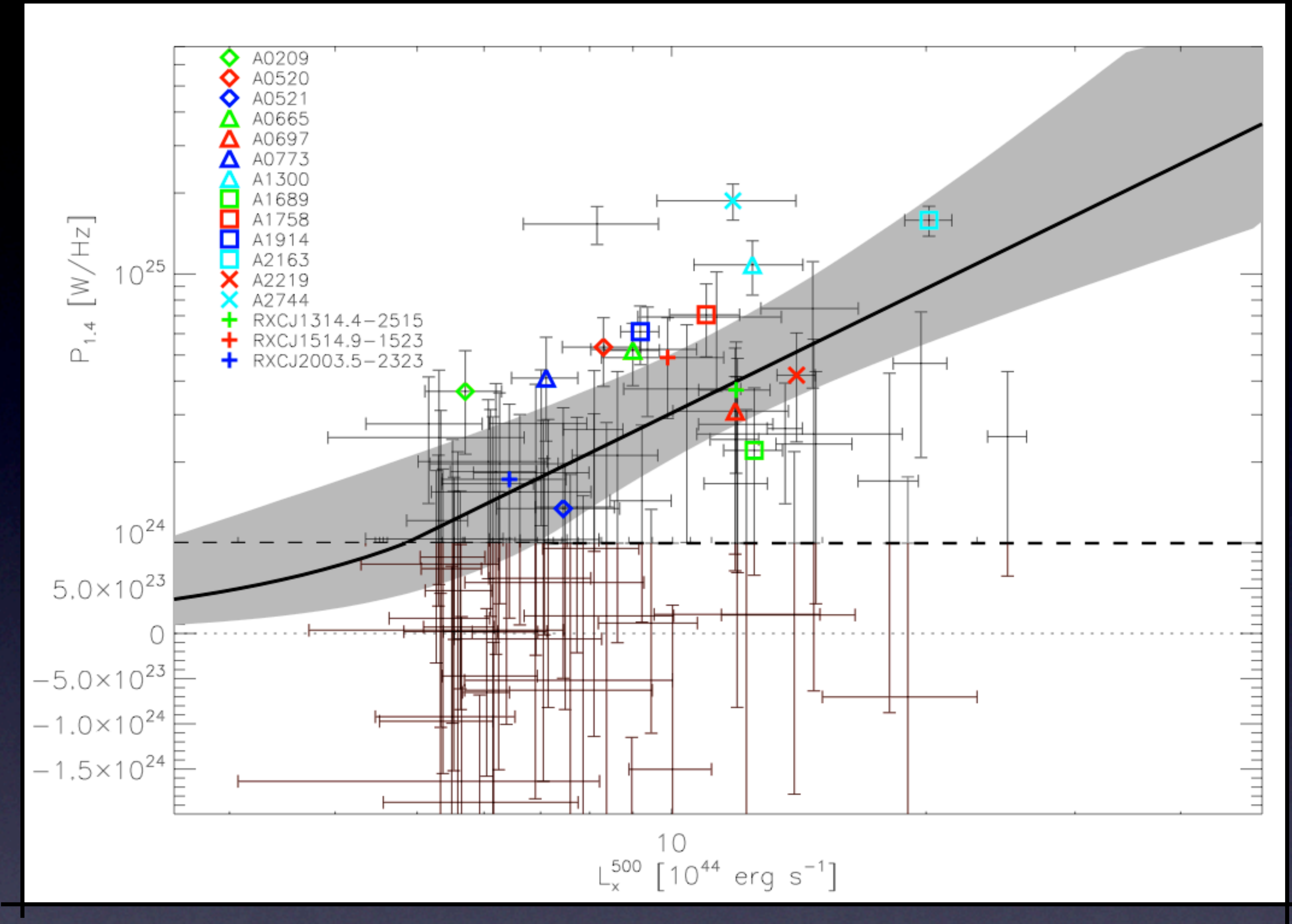
Flux comparison with individual detections (Giovannini et al. 2009)



Noisy detections with NVSS radio data

Most of our cluster radio halos from NVSS are non-detections. But we can find the $L_{1.4}$–Y_{SZ} scaling and the “off state” fraction statistically.

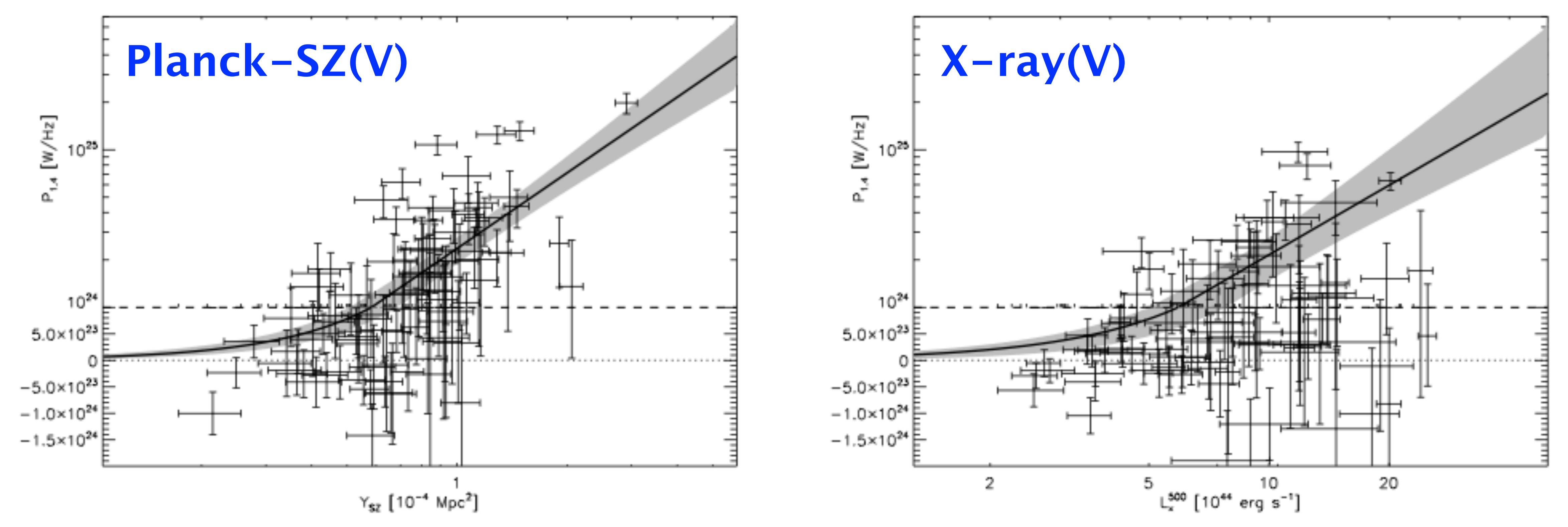
We ran extensive null tests and simulations for potential systematic biases.



Sommer & Basu (2014), MNRAS, 437

We fit a **regression model** that includes errors in both direction, intrinsic scatter, non-detections *and a dropout fraction* (i.e. zero population).

Results for SZ/X-ray selection



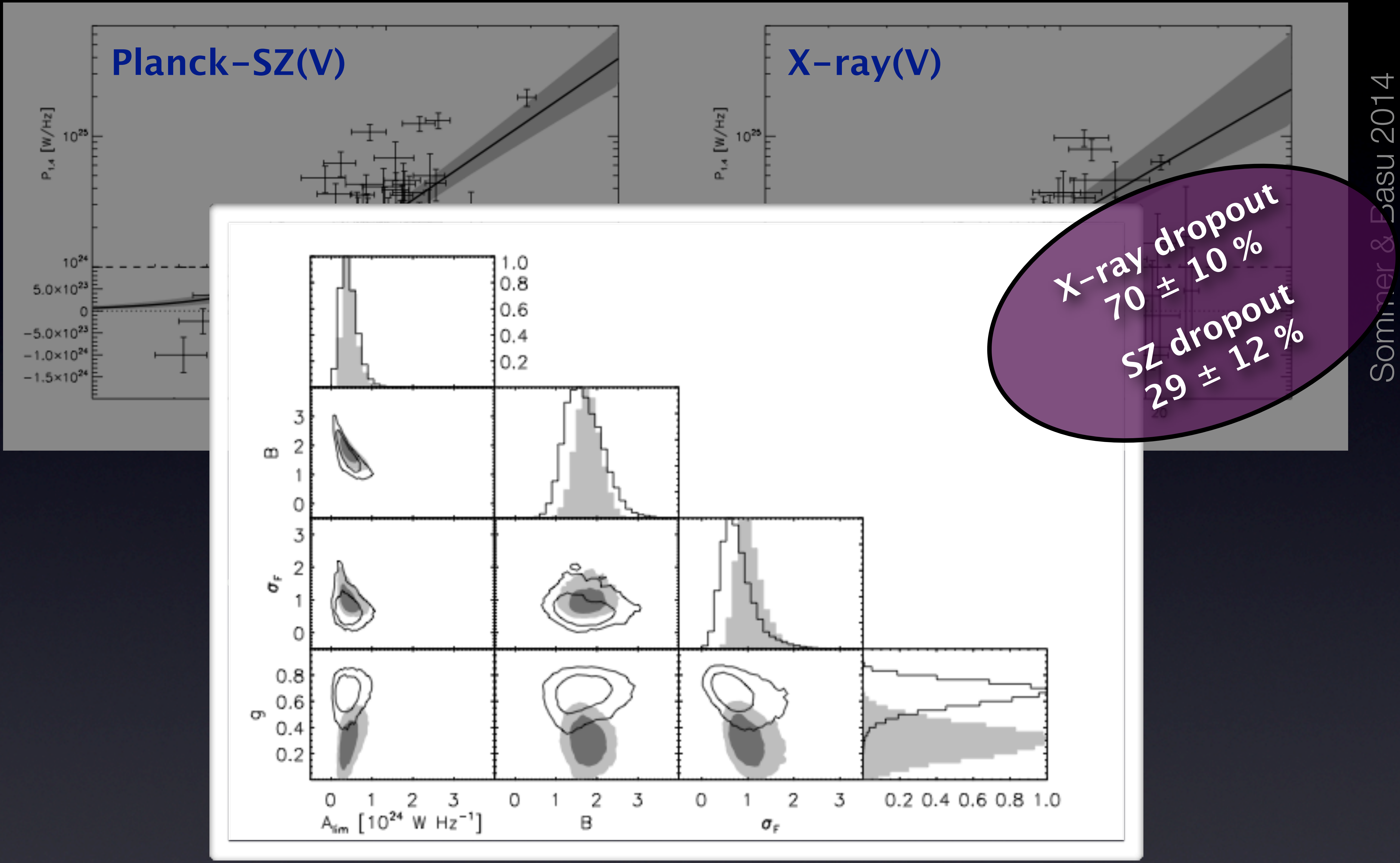
Sommer & Basu 2014

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 SZ/X-ray selection

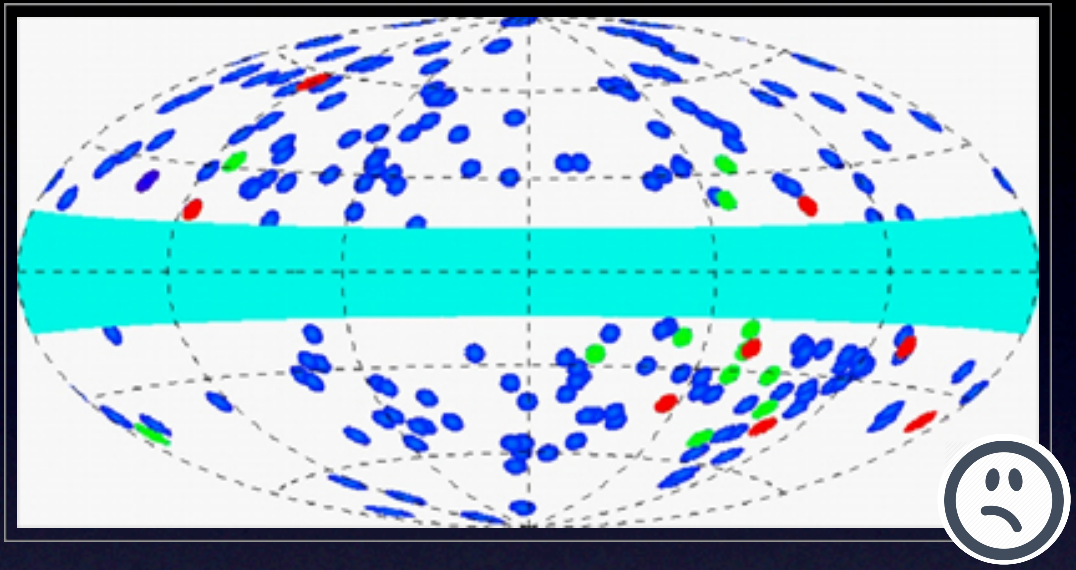


X-ray dropout
70 ± 10 %
SZ dropout
29 ± 12 %

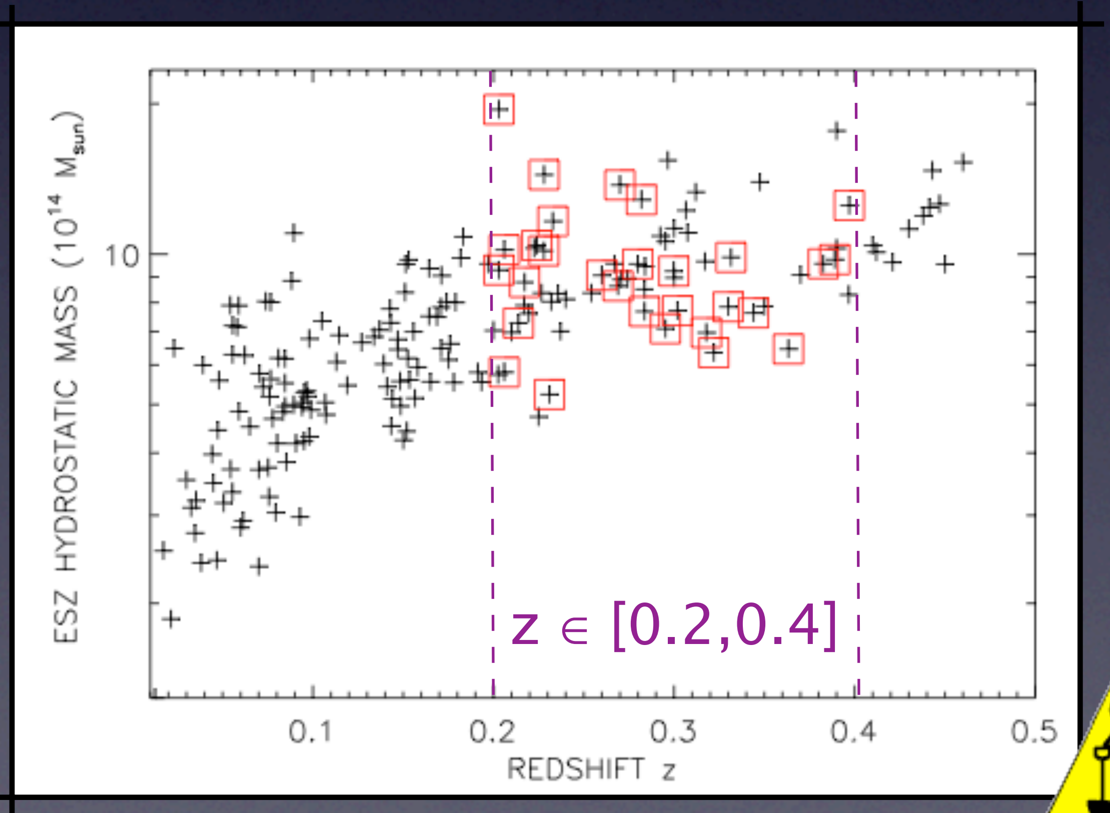
Sommer & Basu 2014

VLA follow-up of *26 Planck Clusters*

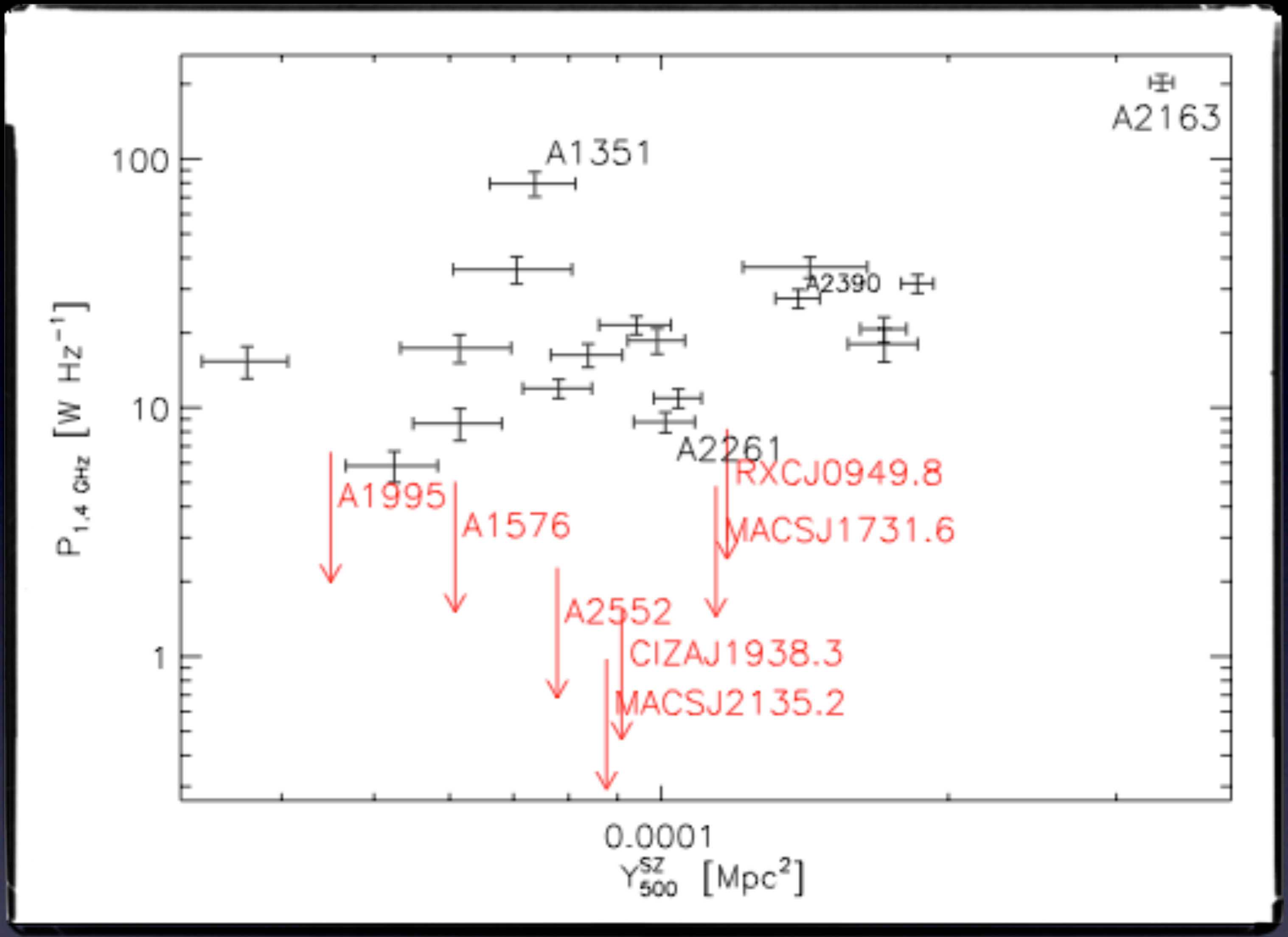
J-VLA follow up program (and some archival data) for ESZ clusters



ESZ clusters (Planck coll. 2011)



Sommer, Basu et al. 2017, in prep



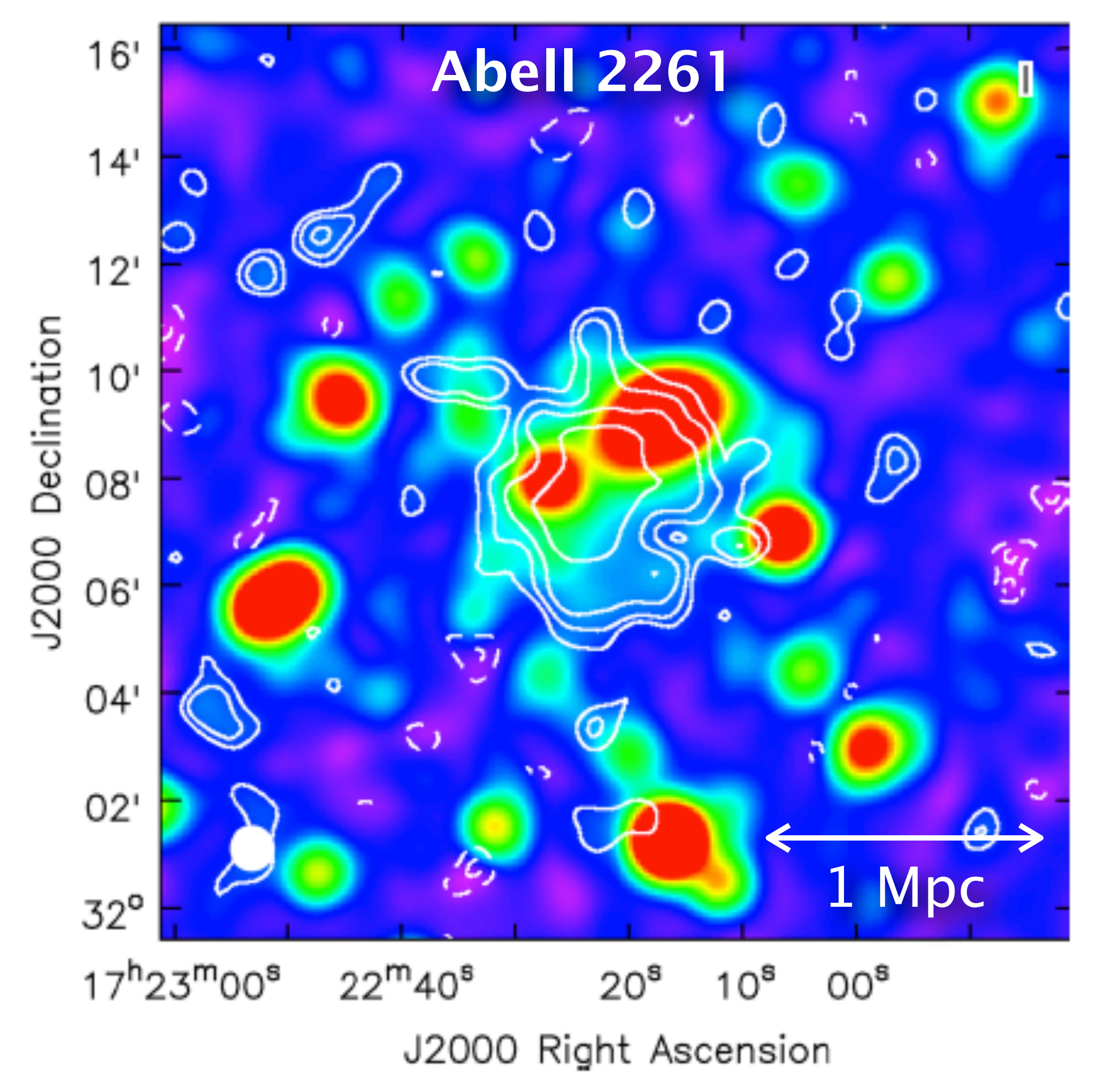
With deep radio data (and a uniform analysis), **18 out of 26** Planck selected clusters showing diffuse radio emission on ~1 Mpc scale.

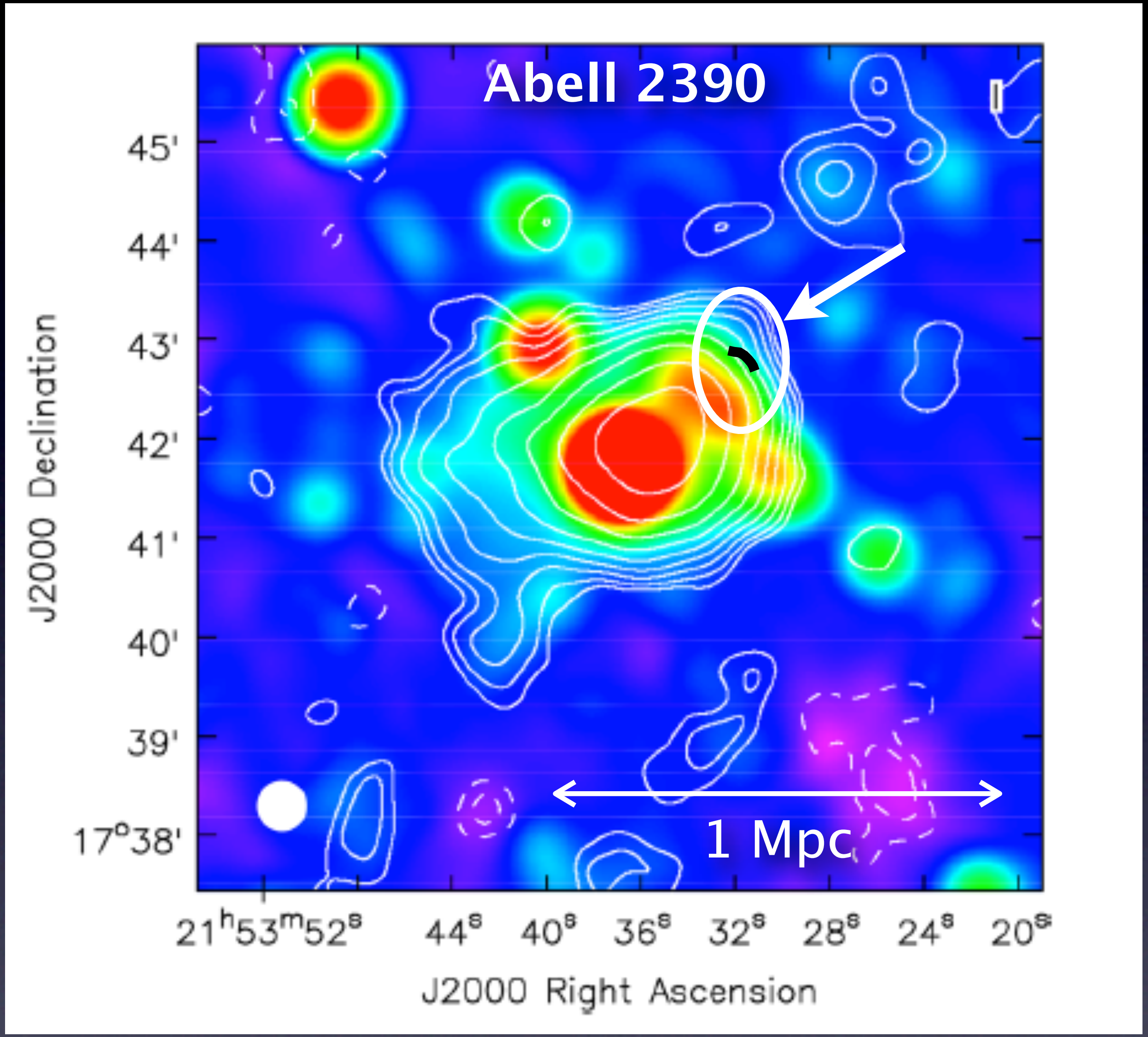
⇒ 70% !!

in prep

New radio halos in CC clusters

Sommer, Basu, Intema, et al. (2017)





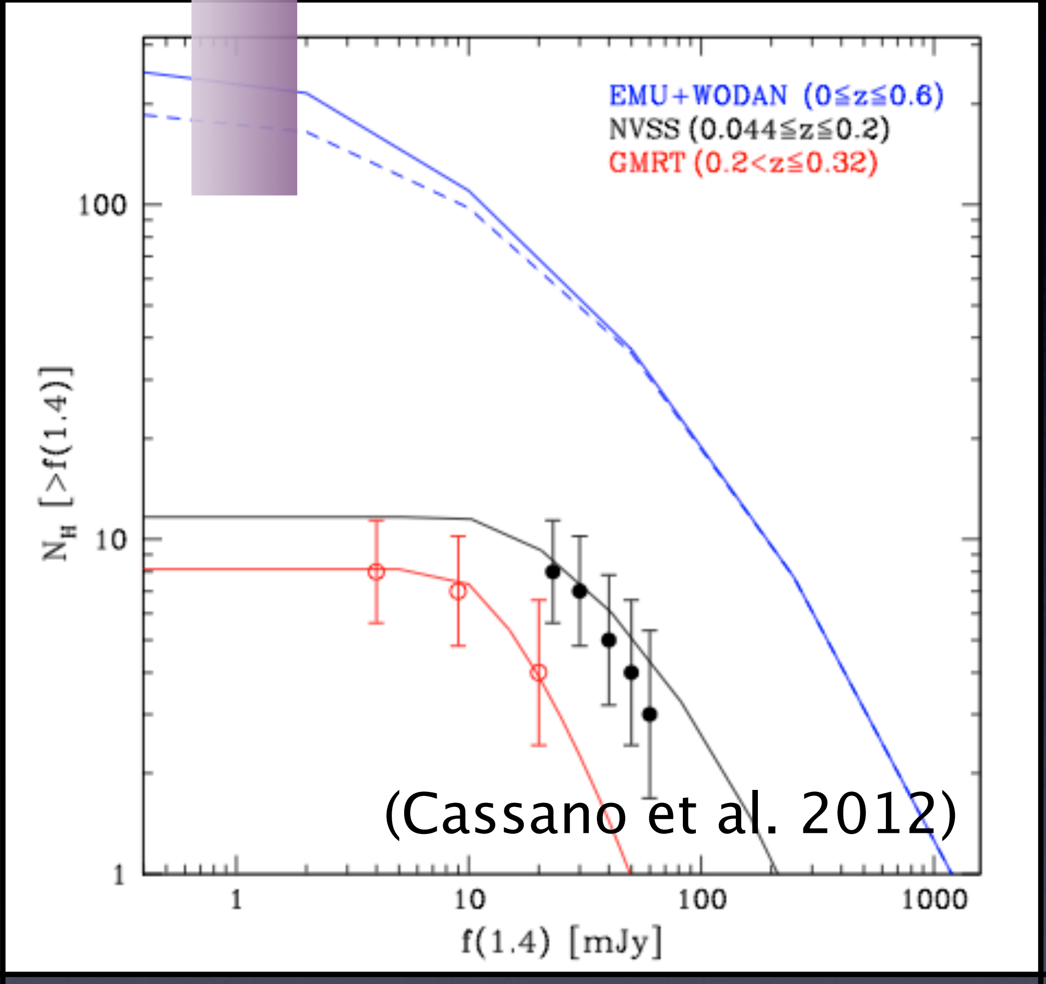
color → total radio emission
contours → diffuse emission

Probably not surprising, as these massive cool core clusters are fair targets for minor mergers

RH fraction with mass and redshift

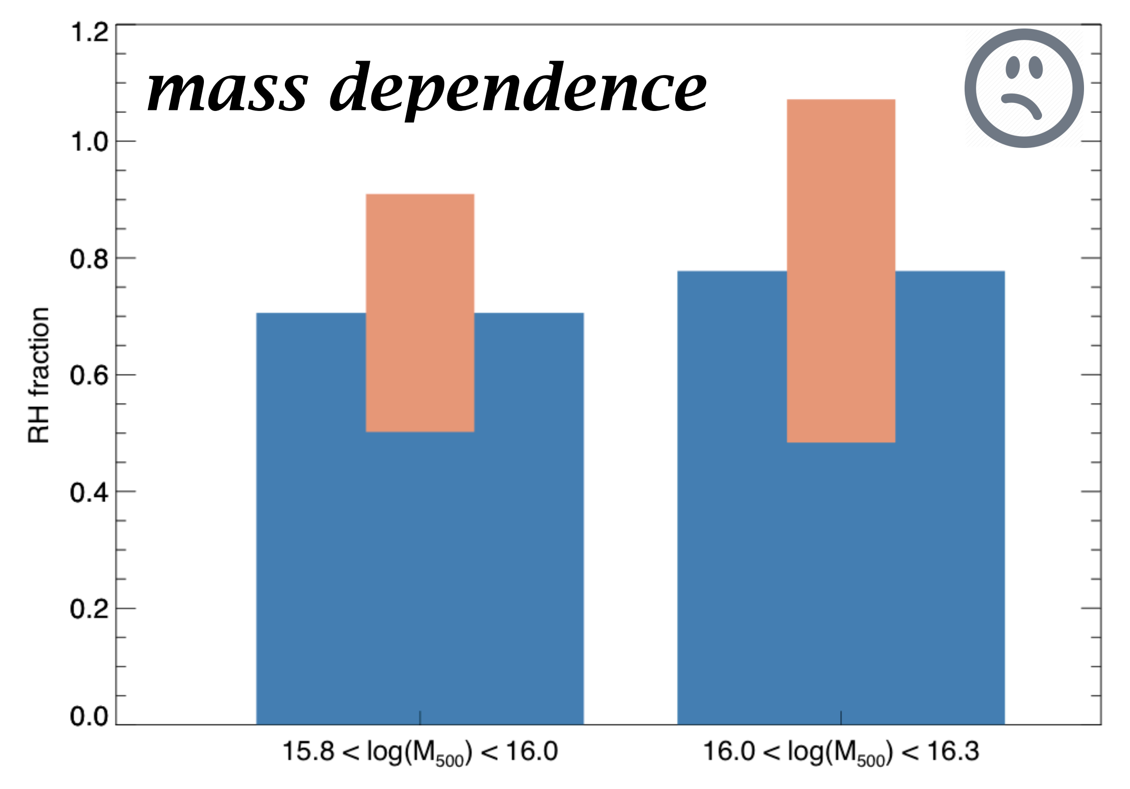
Up by factor ~5 or more

(several 100 RHs out to z=0.5, for $M_{500,c} > 4\times10^{14}\ M_\odot$)

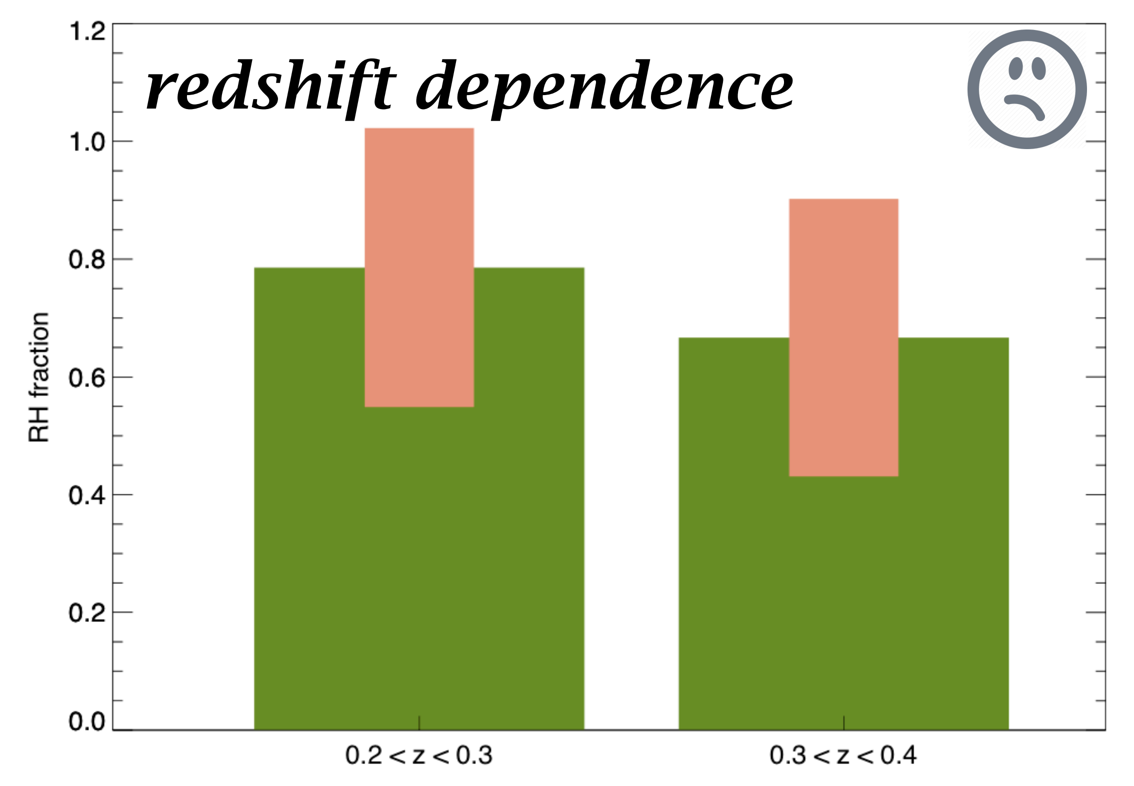


(Cassano et al. 2012)

Current prediction for 1.4 GHz RH expectations are conservative. *However..*



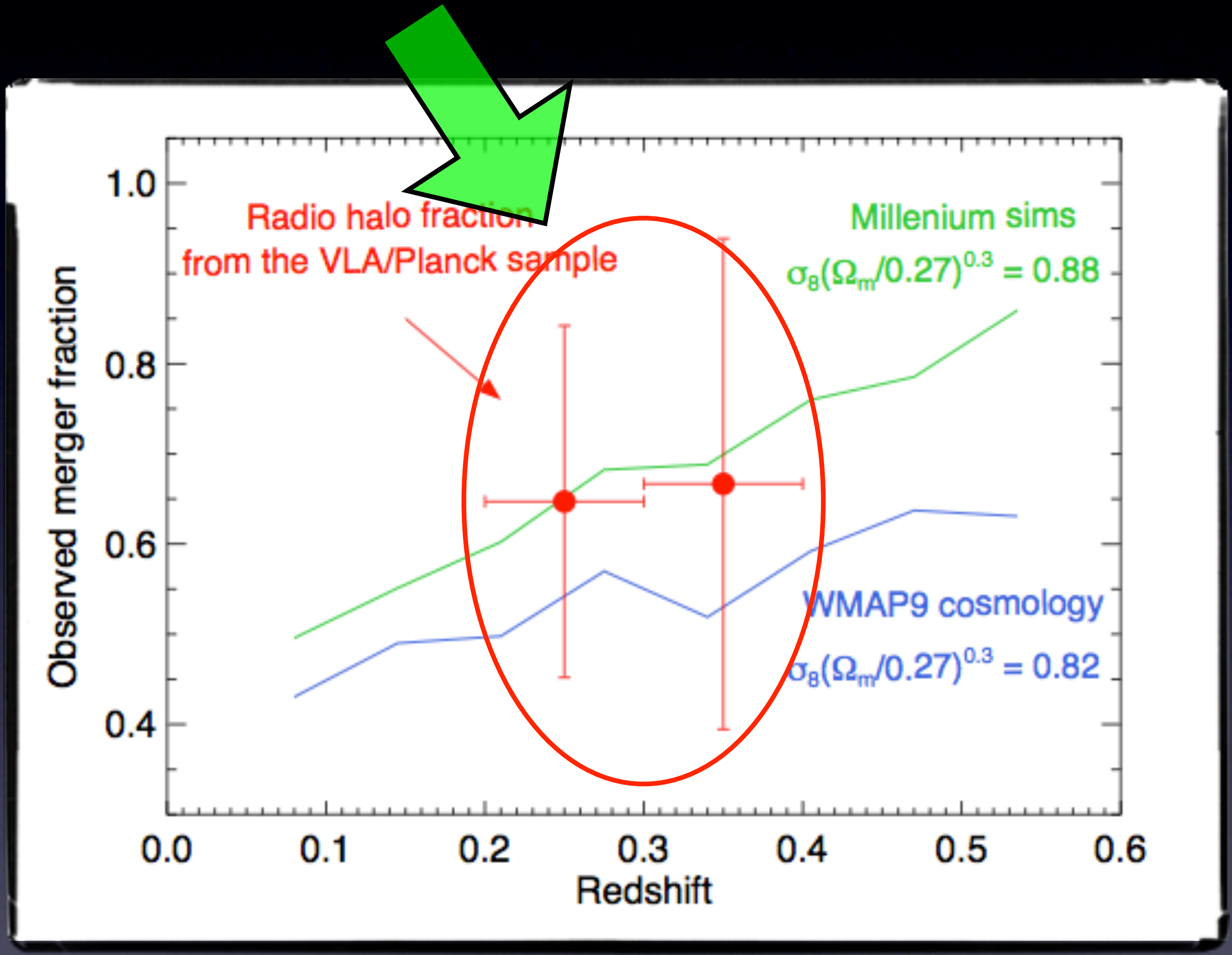
mass dependence



redshift dependence

Number of Radio Halos in the Sky

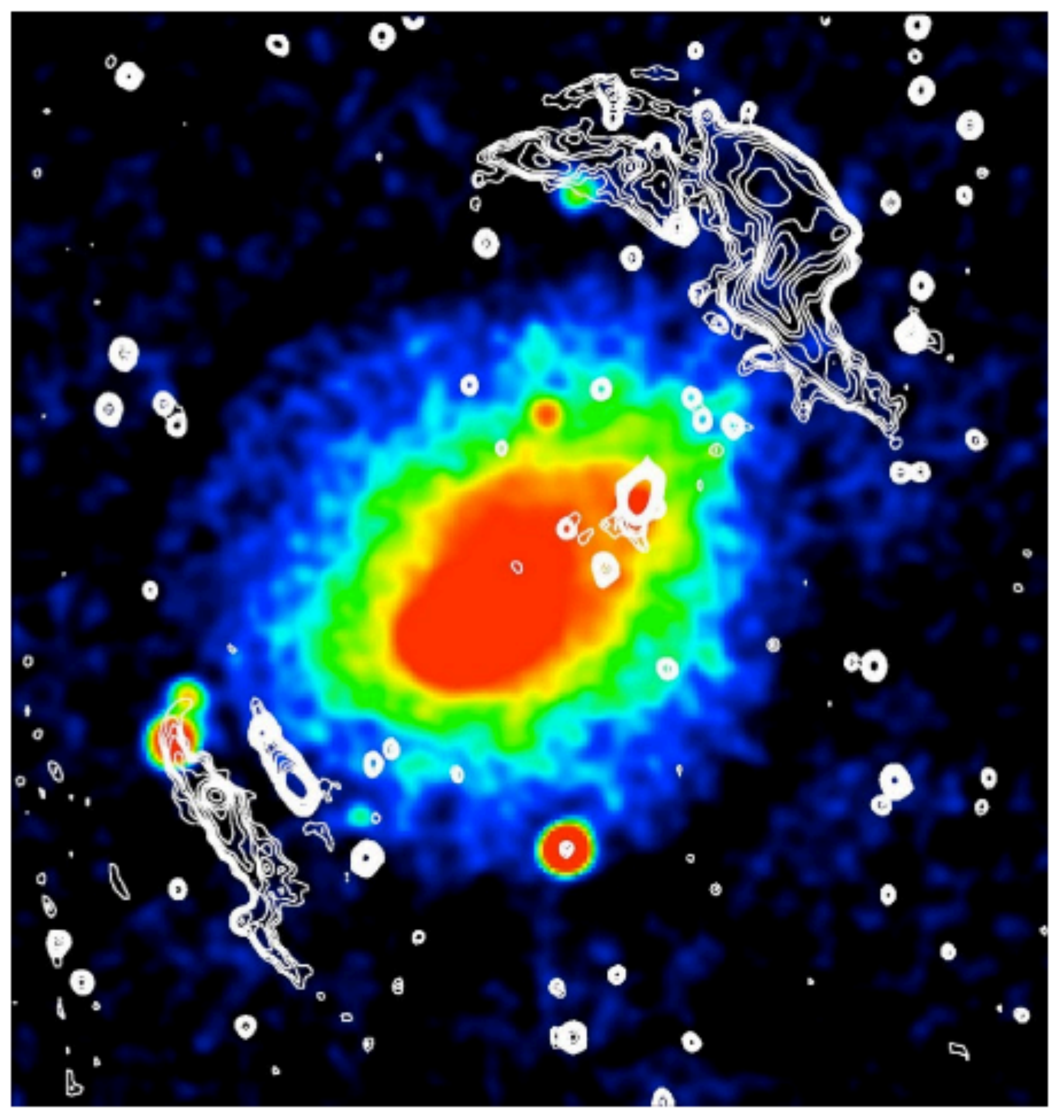
The SKA-Pathfinder Surveys (**ASKAP**/EMU and **MeerKAT**/MIGHTEE might be able to reduce these error bars by a factor of 3−5



To the cluster outskirts:

Radio Relic — SZ connection

Radio Relics ⇒ Shocks

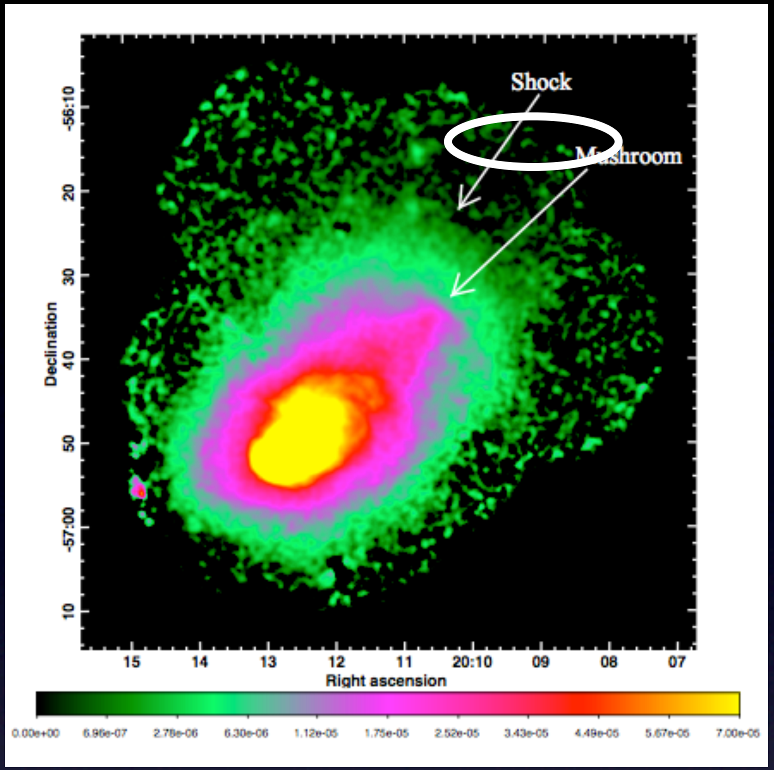


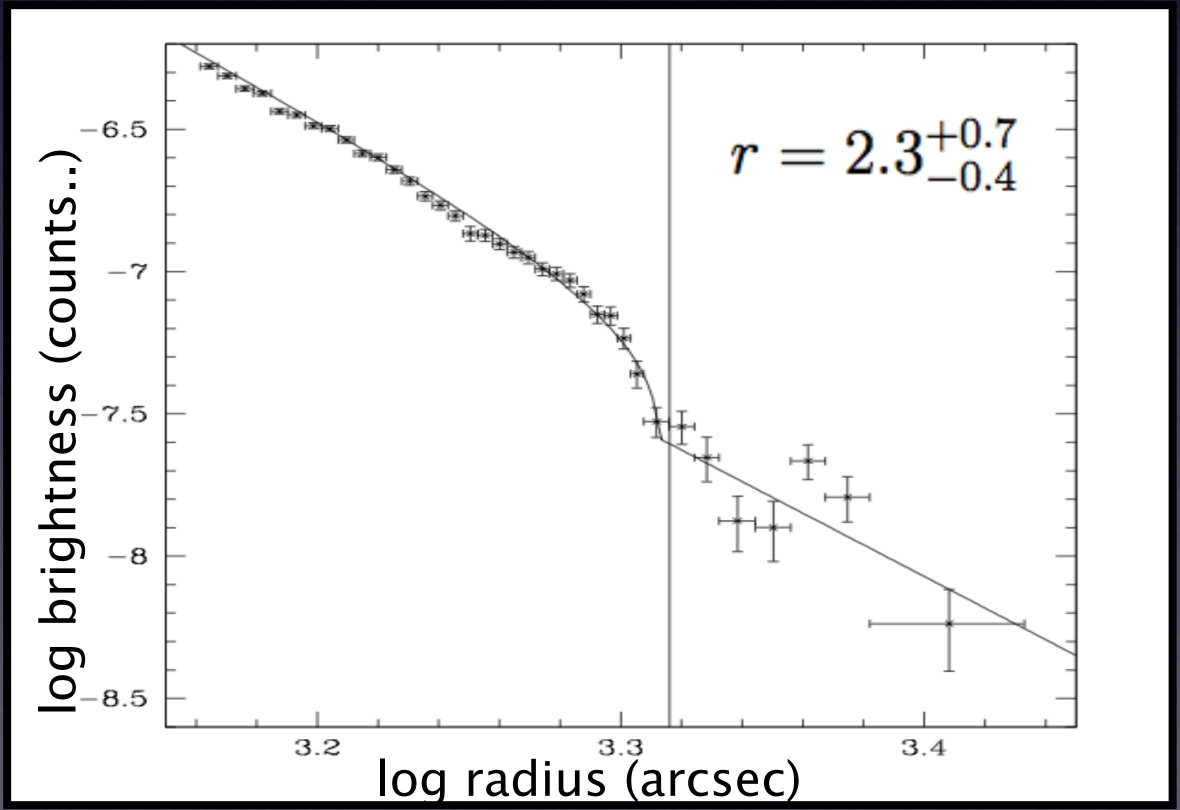
An example:

Abell 3667 (z = 0.05)

X-ray analysis
Finoguenov et al. (2010)
Sarazin et al. (2016)

Radio data:
Roettgering et al. (1997)



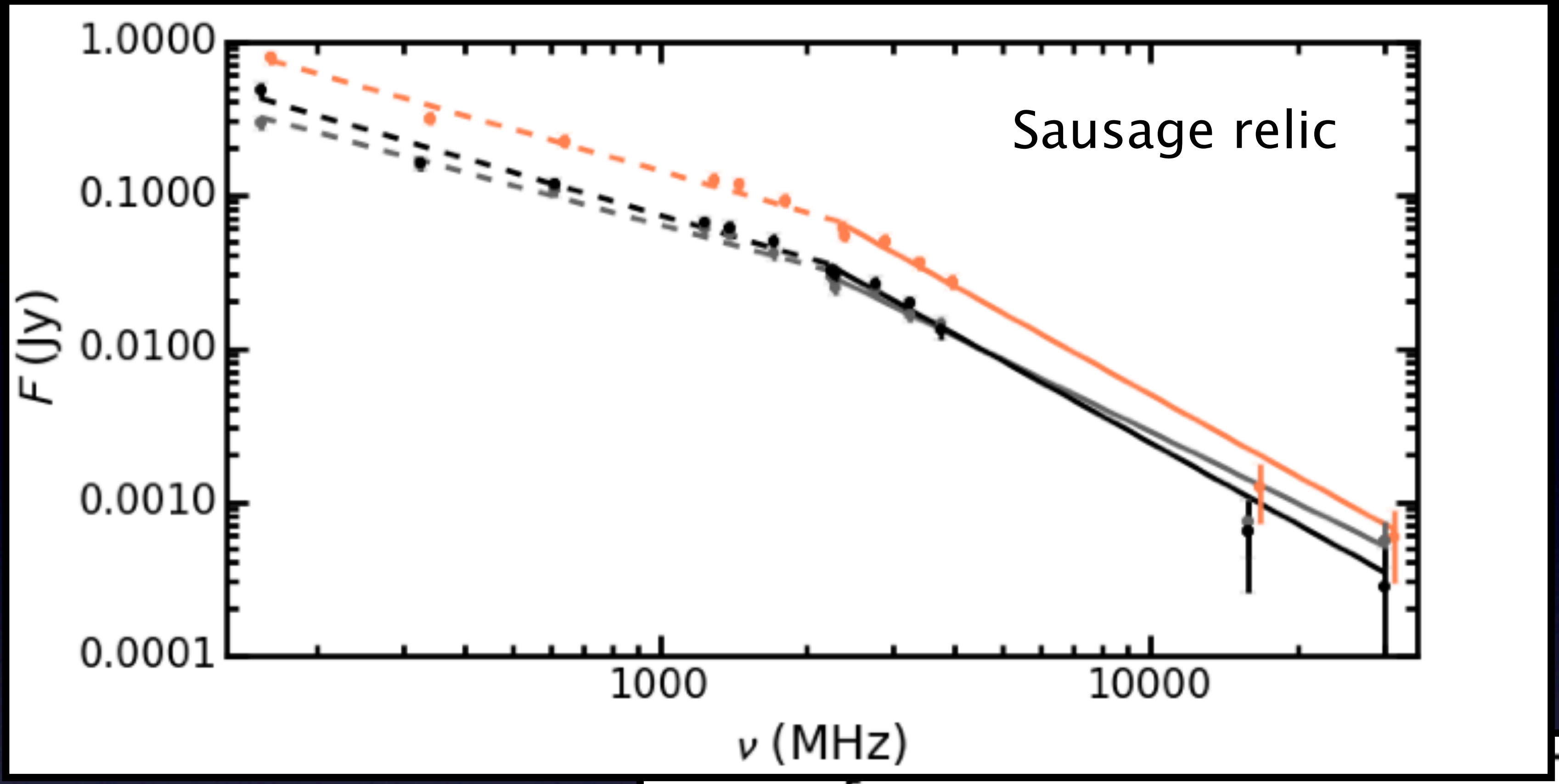


Sarazin et al. (2016)

Theoretical works:

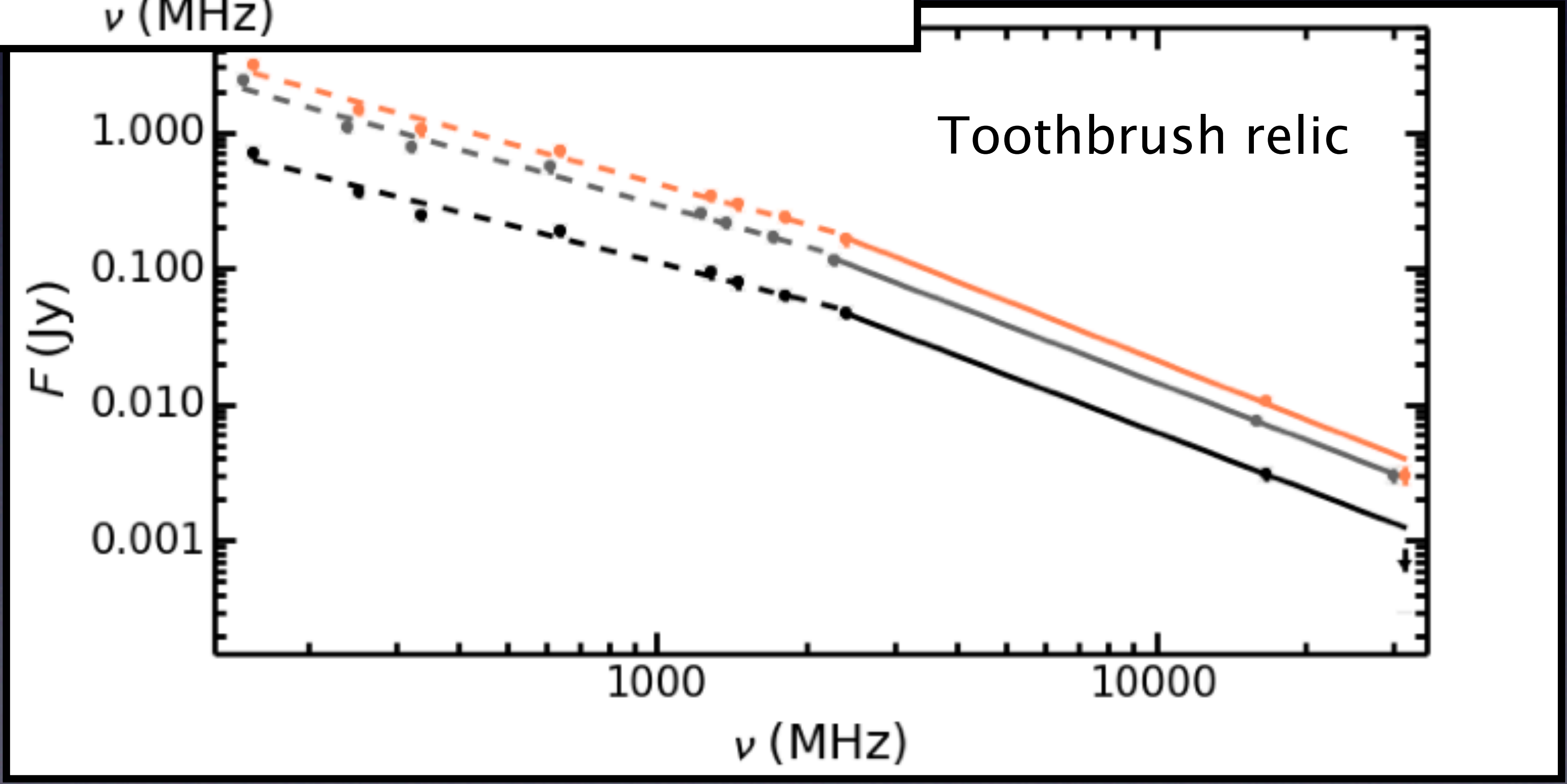
(To cite a few) Miniati et al. (2001); Hoeft & Brueggen (2007); Nuzza et al. (2012); Skillman et al. (2013); Vazza et al. (2014)

Relic Steepening Spectrum



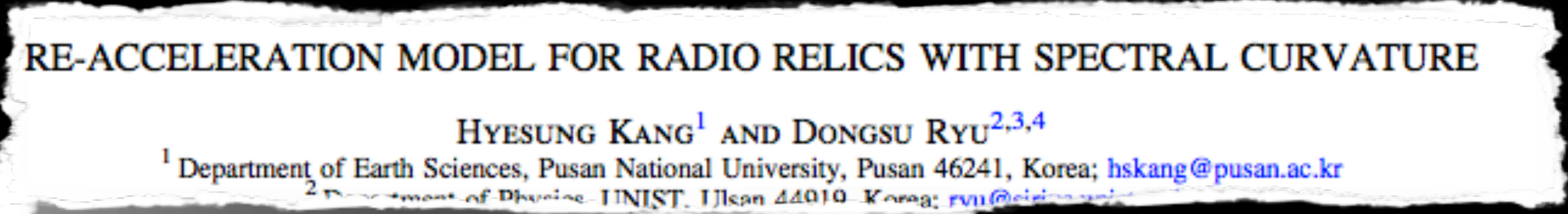
Stroe et al. (2015, 2016)

AMI (16 GHz) and
CARMA (30 GHz) data



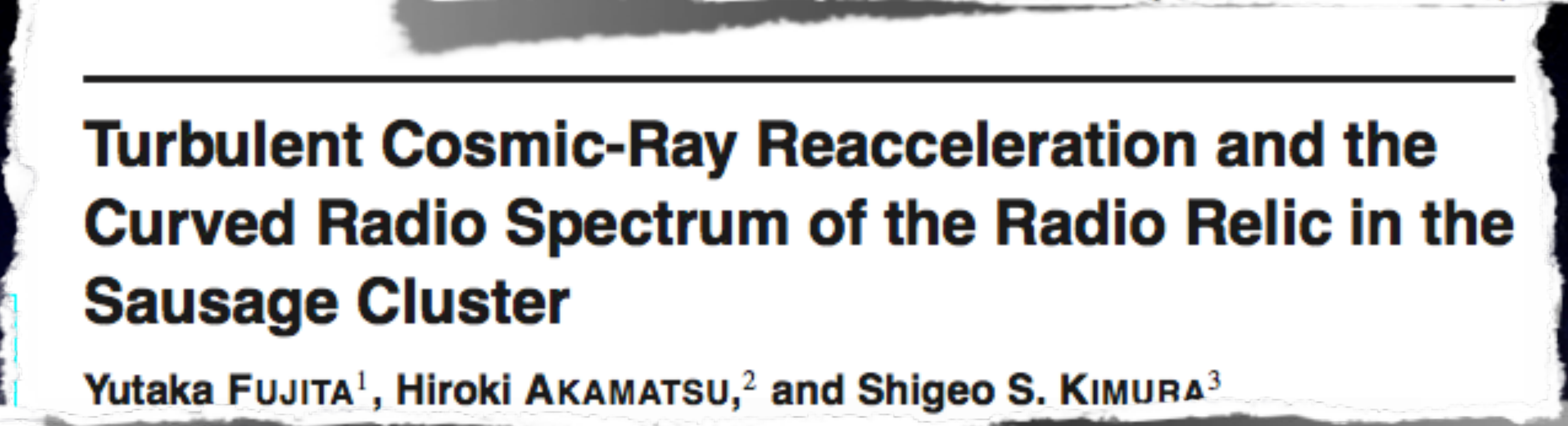
A *gradual* spectral steepening is observed above ~2 GHz, which cannot be explained from the standard DSA model.

Relic Steepening Spectrum



RE-ACCELERATION MODEL FOR RADIO RELICS WITH SPECTRAL CURVATURE

HYESUNG KANG[1] AND DONGSU RYU[2,3,4]
[1] Department of Earth Sciences, Pusan National University, Pusan 46241, Korea; hskang@pusan.ac.kr
[2] Department of Physics, UNIST, Ulsan 44919, Korea; ryu@sirius

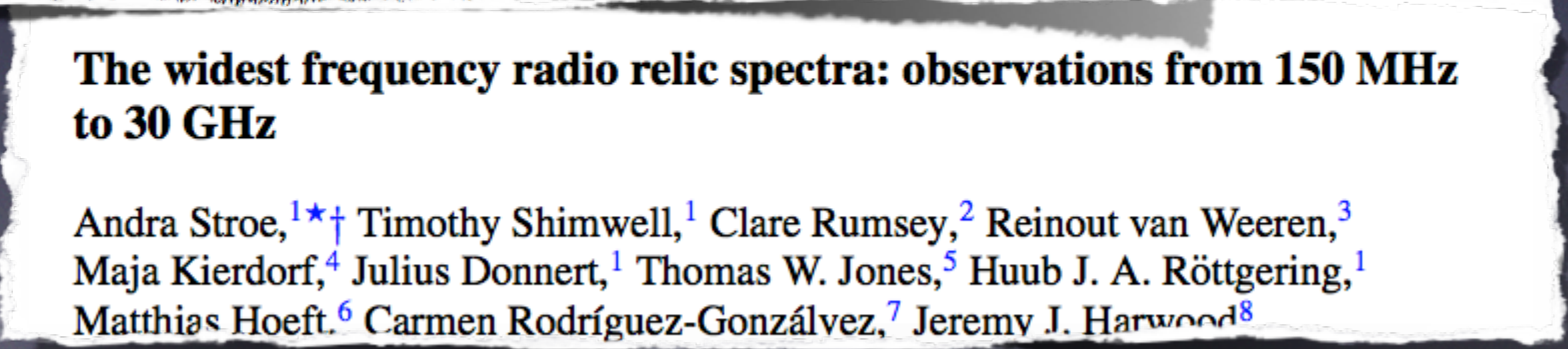


Turbulent Cosmic-Ray Reacceleration and the Curved Radio Spectrum of the Radio Relic in the Sausage Cluster

Yutaka FUJITA[1], Hiroki AKAMATSU,[2] and Shigeo S. KIMURA[3]

Magnetic Field Evolution in Giant Radio Relics using the example of CIZA J2242.8+5301

J. M. F. Donnert[1,2,3⋆], A. Stroe[4,1]†, G. Brunetti[2], D. Hoang[1], H. Roettgering[1]
1 *Leiden Observatory, Leiden University, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands*
2 *INAF-Istituto di Radioastronomia, via P. Gobetti 101, I-40129 Bologna, Italy*
3 *School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*



The widest frequency radio relic spectra: observations from 150 MHz to 30 GHz

Andra Stroe,[1⋆]† Timothy Shimwell,[1] Clare Rumsey,[2] Reinout van Weeren,[3]
Maja Kierdorf,[4] Julius Donnert,[1] Thomas W. Jones,[5] Huub J. A. Röttgering,[1]
Matthias Hoeft,[6] Carmen Rodríguez-Gonzálvez,[7] Jeremy J. Harwood[8]

Relic Steepening Spectrum

RE-ACCELERATION MODEL FOR RADIO RELICS WITH SPECTRAL CURVATURE

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Turbulent
Curved R
Sausage (

Yutaka FUJITA[1]

Magnetic Field
CIZA J2242.8+

J. M. F. Donnert[1,2,]
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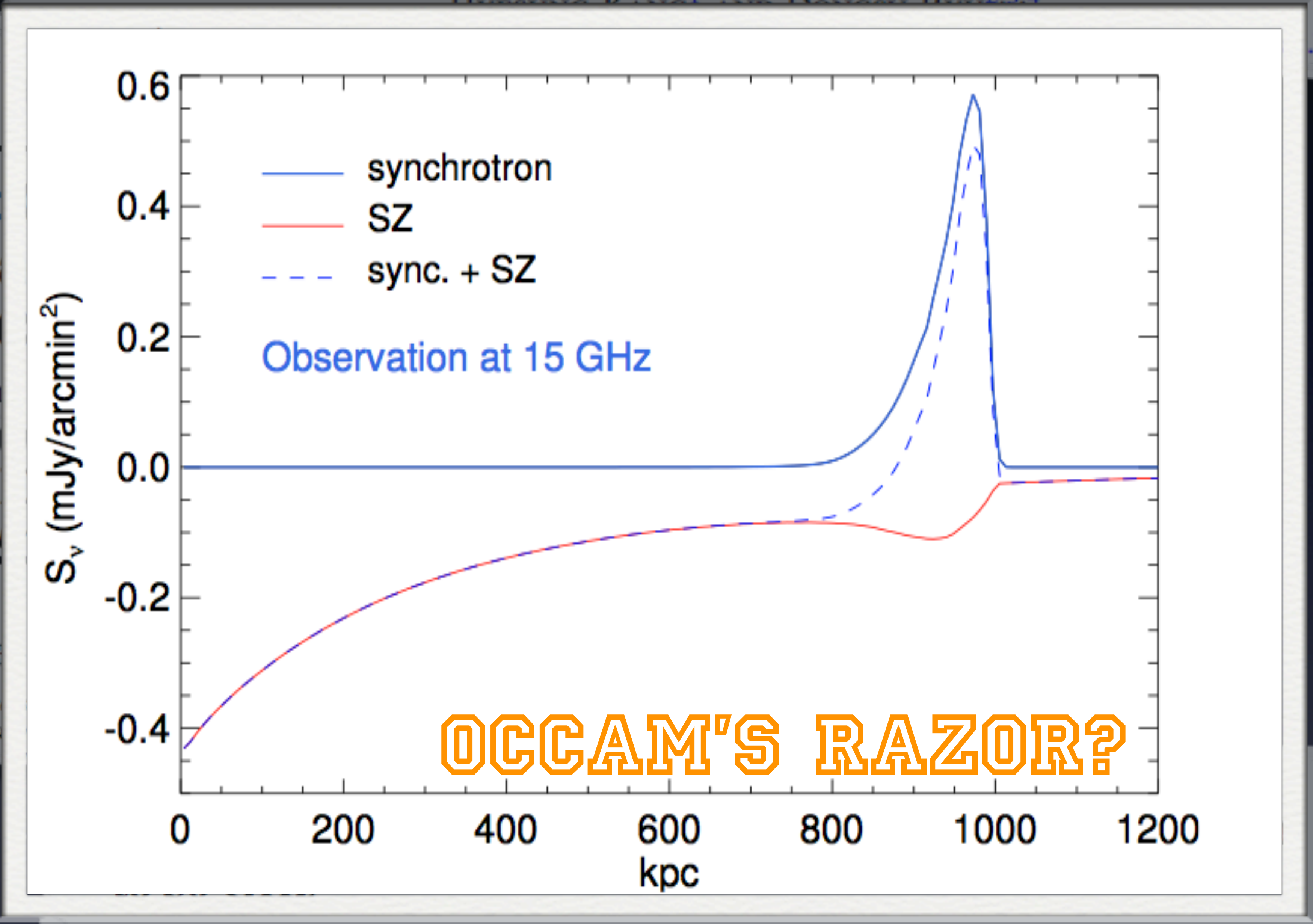

OCCAM'S RAZOR?

Basu et al. (2016), A&A, 591

150 MHz

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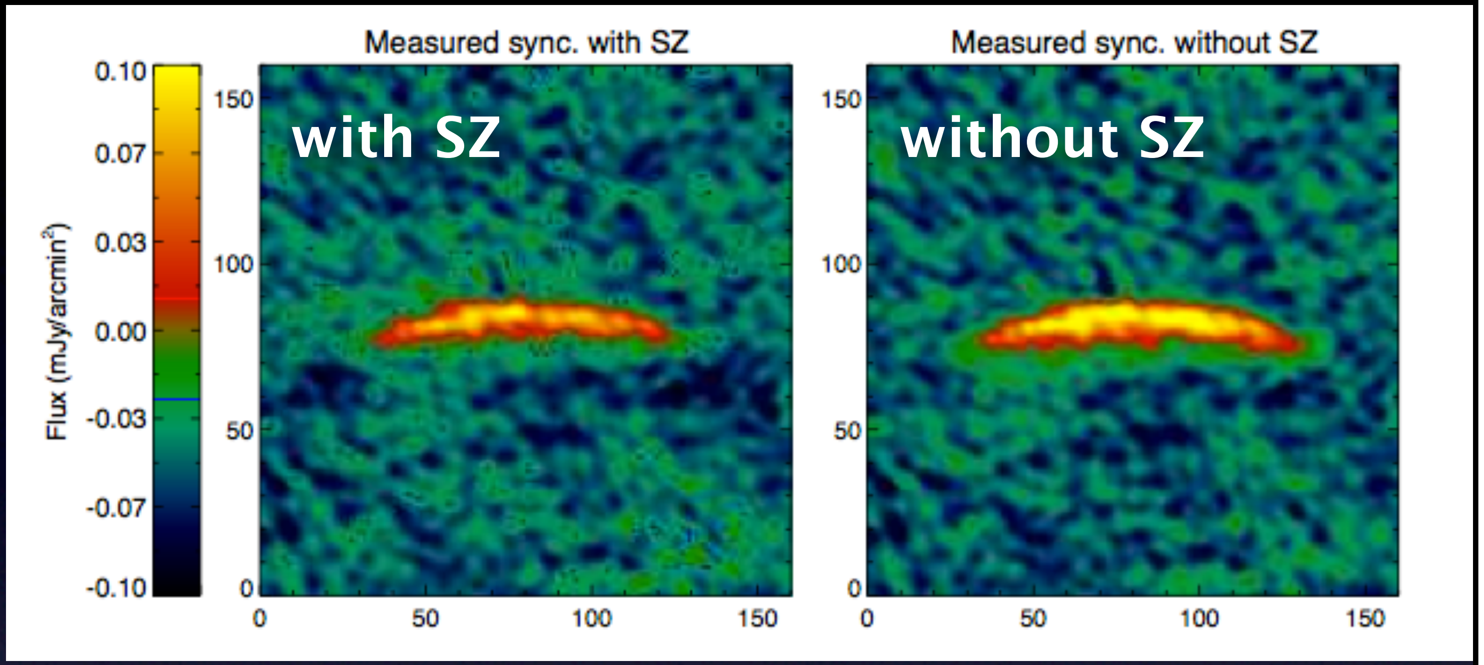
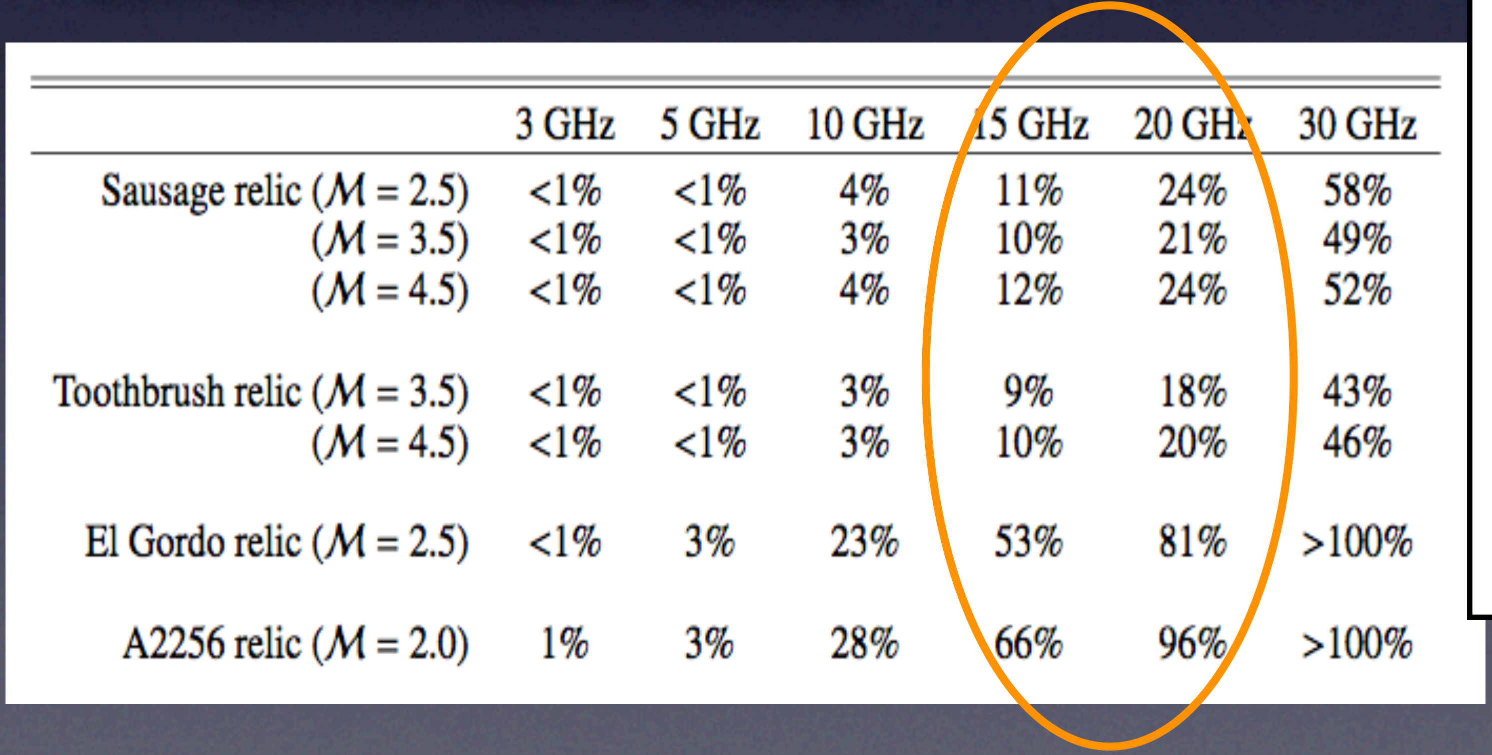
A Non-negligible Effect

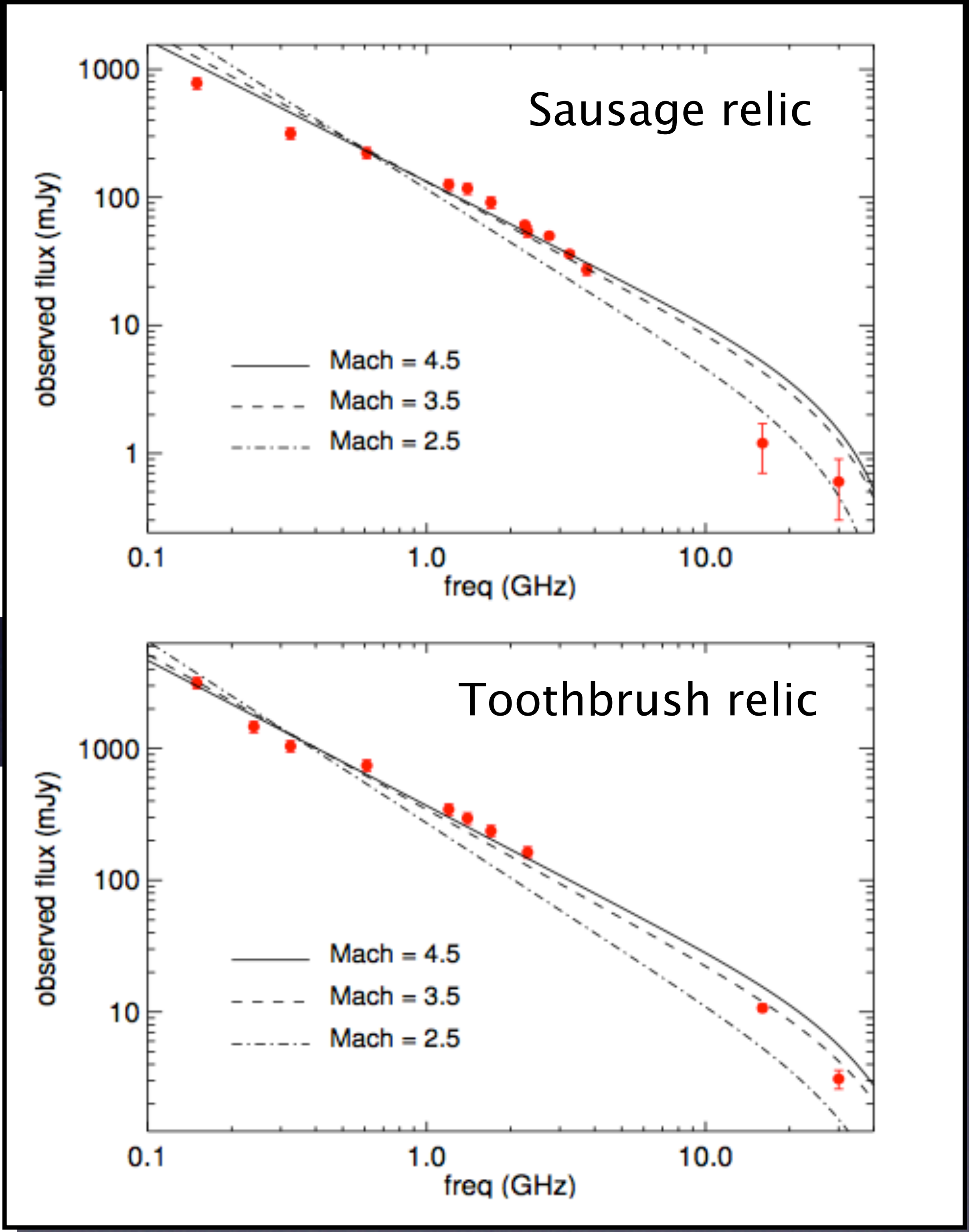
Simulated interferometric observation at 10 GHz



10%–50% flux loss at 10 GHz



	3 GHz	5 GHz	10 GHz	15 GHz	20 GHz	30 GHz
Sausage relic ($\mathcal{M} = 2.5$)	<1%	<1%	4%	11%	24%	58%
($\mathcal{M} = 3.5$)	<1%	<1%	3%	10%	21%	49%
($\mathcal{M} = 4.5$)	<1%	<1%	4%	12%	24%	52%
Toothbrush relic ($\mathcal{M} = 3.5$)	<1%	<1%	3%	9%	18%	43%
($\mathcal{M} = 4.5$)	<1%	<1%	3%	10%	20%	46%
El Gordo relic ($\mathcal{M} = 2.5$)	<1%	3%	23%	53%	81%	>100%
A2256 relic ($\mathcal{M} = 2.0$)	1%	3%	28%	66%	96%	>100%



Basu et al. (2016), A&A, 591

Synchrotron/SZ Flux Ratio

Make simplistic assumptions:

(1) The kinetic power of the shock:

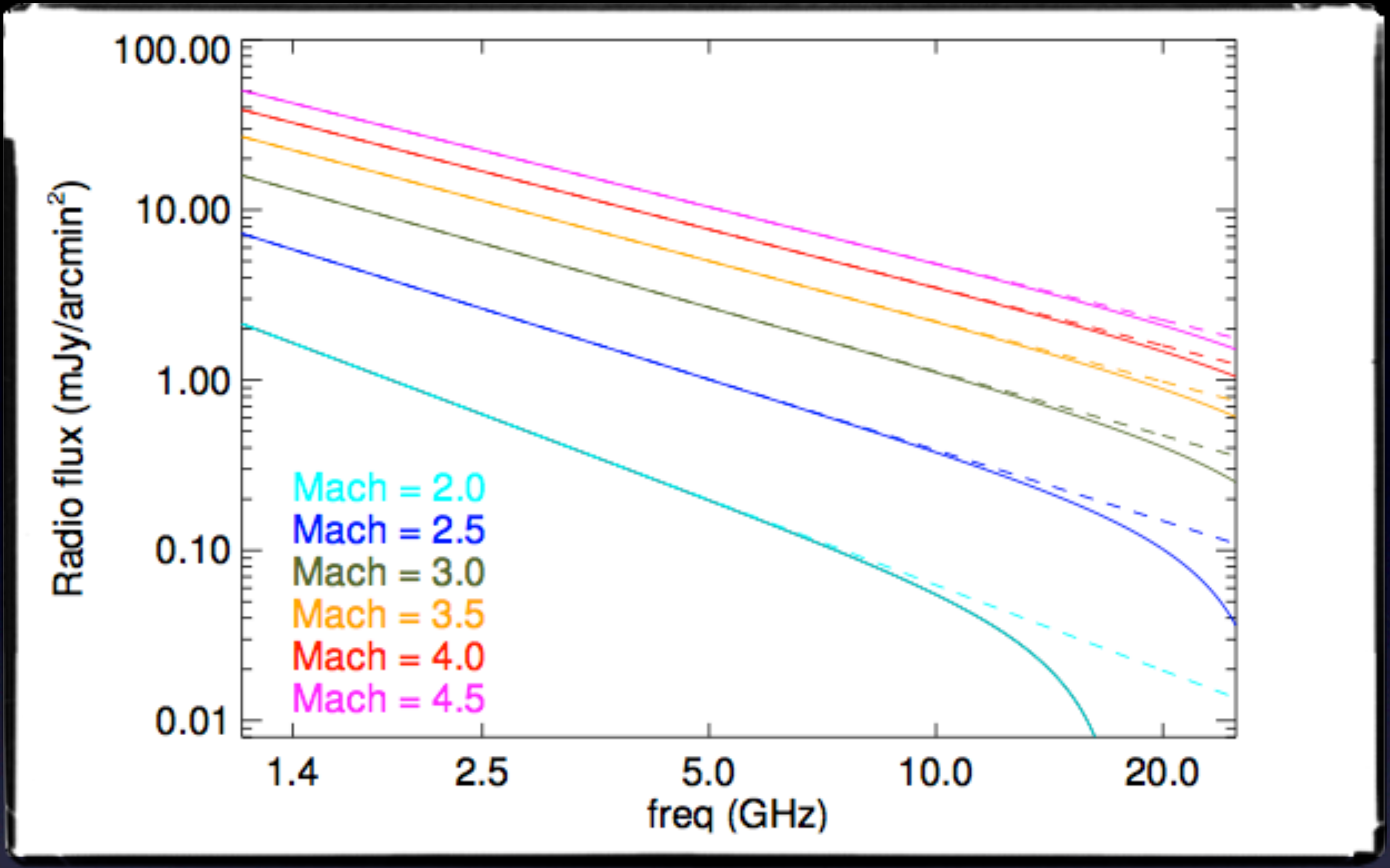
$$P_{\rm kin} = n_u v_s^3\, S/2 \quad (\text{where } v_s = \mathcal{M} c_s)$$

(2) A fraction of this kinetic power goes in proton acceleration:

$$P_{\rm CPp} = \eta(\mathcal{M})\, P_{\rm kin}$$

(3) Assume a fixed electron-to-proton ratio (ξ=0.05):

$$P_{\rm CPe} = \xi_{\rm e/p}\, \eta(\mathcal{M})\, P_{\rm kin}$$



$$\frac{S_\nu^{\rm sync.}}{S_\nu^{\rm SZ}} \approx -9\times 10^4 \left(\frac{\xi_{\rm e/p}}{0.05}\right)\left(\frac{\mathcal{M}}{3}\right)\left(\frac{T_{\rm u}}{1\,{\rm keV}}\right)^{1/2}\left(\frac{W}{100\,{\rm kpc}}\right)^{-1} \times (1+z)^{-(4+\delta/2)}\, \frac{B_{\rm relic}^{1+\delta/2}}{B_{\rm CMB}^2 + B_{\rm relic}^2}\left(\frac{\nu}{1.4\,{\rm GHz}}\right)^{-(2+\delta/2)}.$$

$$B_{\rm relic} \propto \left[-\left(\frac{S_\nu^{\rm sync.}}{S_\nu^{\rm SZ}}\right)\frac{W \nu_{\rm obs}^{2+\delta/2}}{\mathcal{M}\xi_{\rm e/p}\, T_{\rm u}^{1/2}}\right]^{2/(\delta-2)}$$

Basu et al. (2016), A&A, 591

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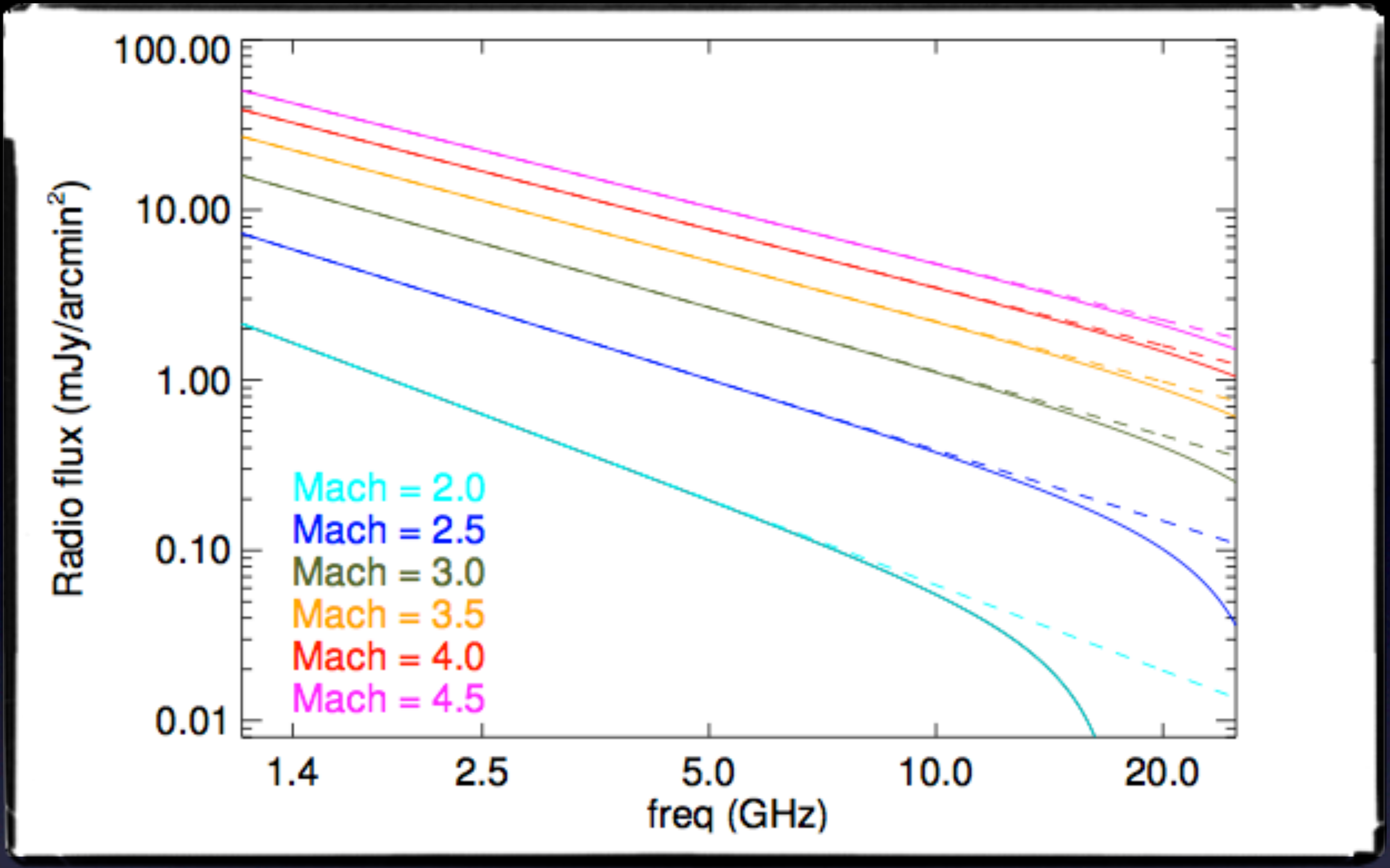

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⇒

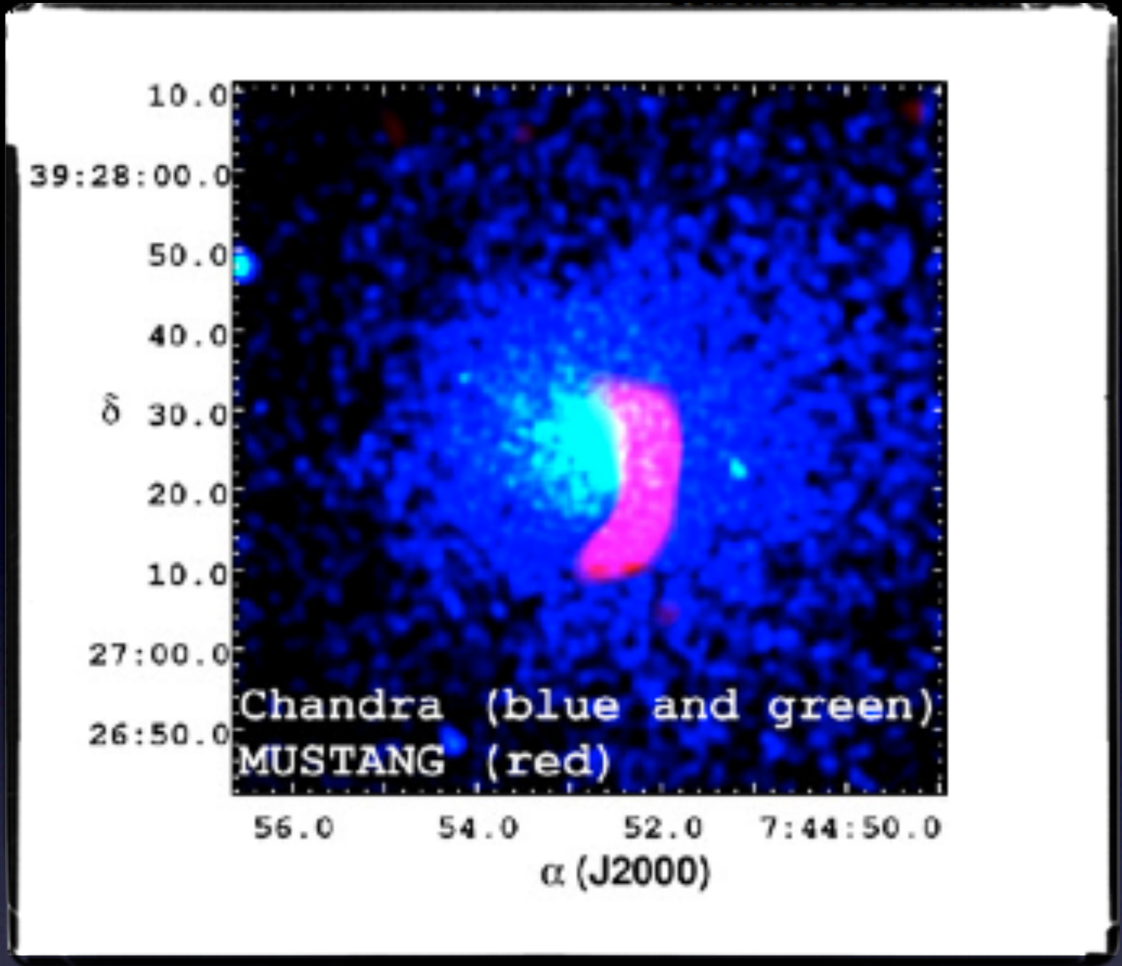
$$B_{\rm relic} \propto \left[-\left(\frac{S_\nu^{\rm sync.}}{S_\nu^{\rm SZ}}\right)\frac{W \nu_{\rm obs}^{2+\delta/2}}{\mathcal{M}\xi_{\rm e/p}\, T_{\rm u}^{1/2}}\right]^{2/(\delta-2)}.$$

Basu et al. (2016), A&A, 591

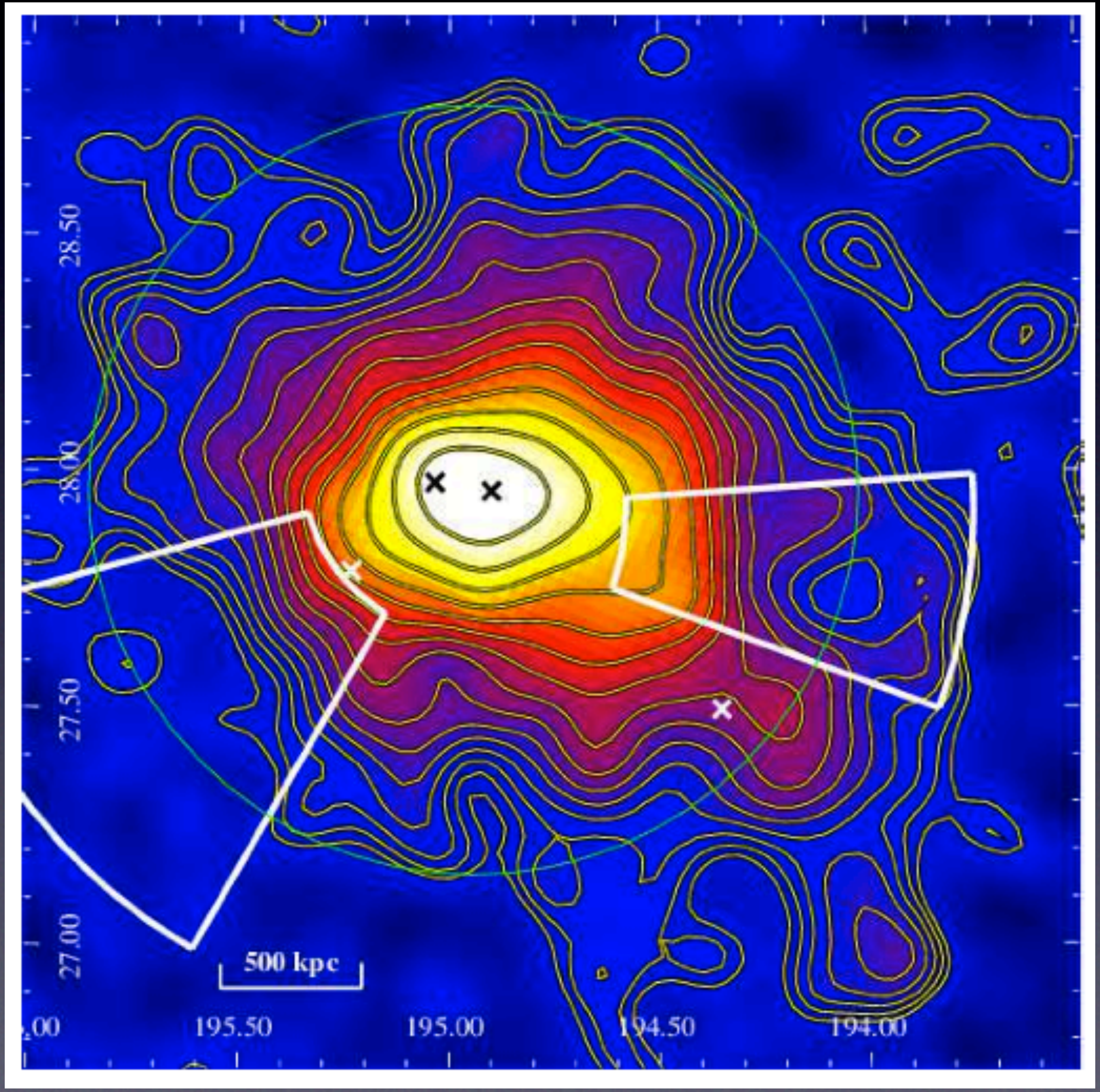
BUT, RELIC SHOCK IN SZ?

Shocks in SZ (within r_{500})

SZ shock modeling enabled by X-ray priors

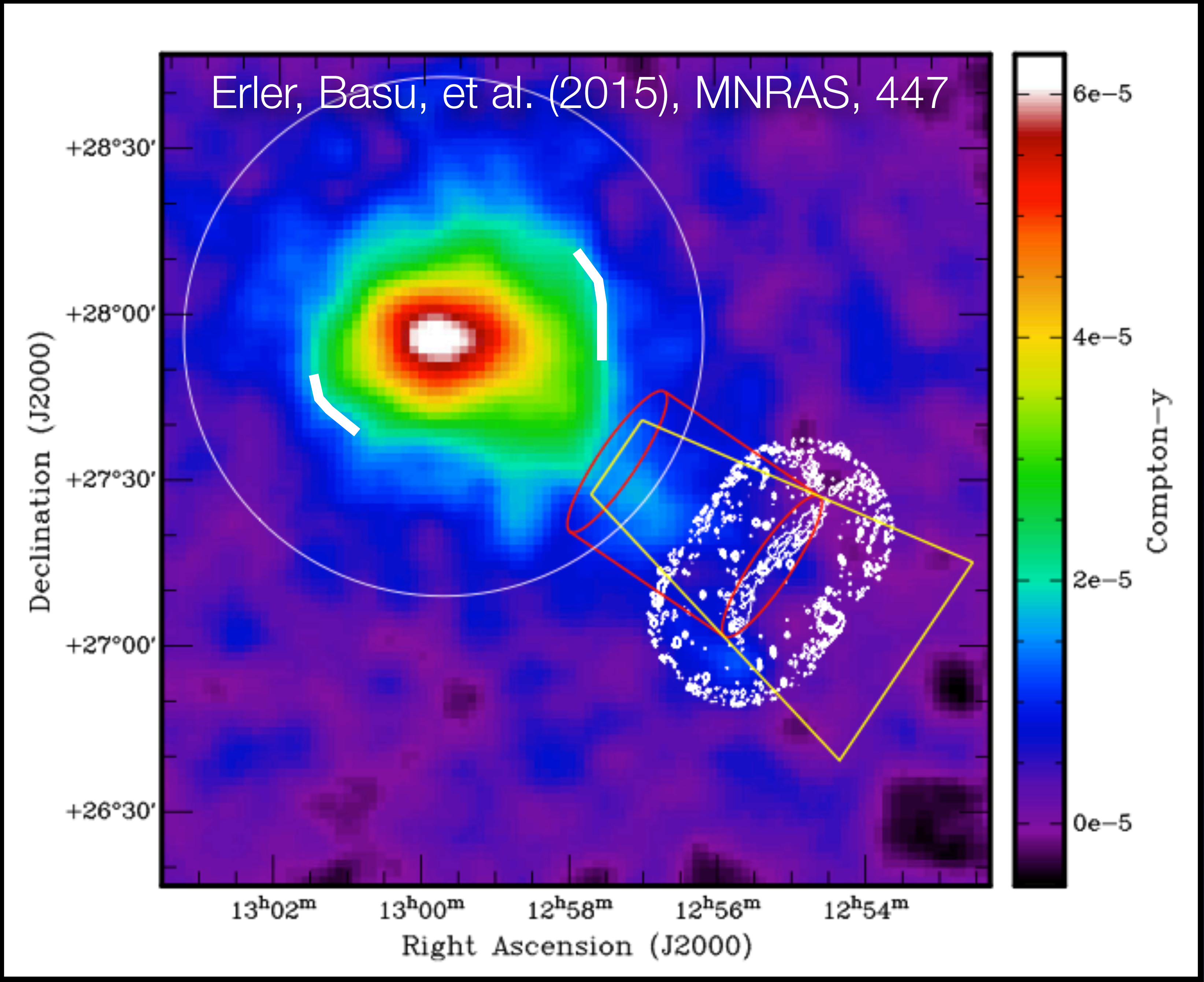


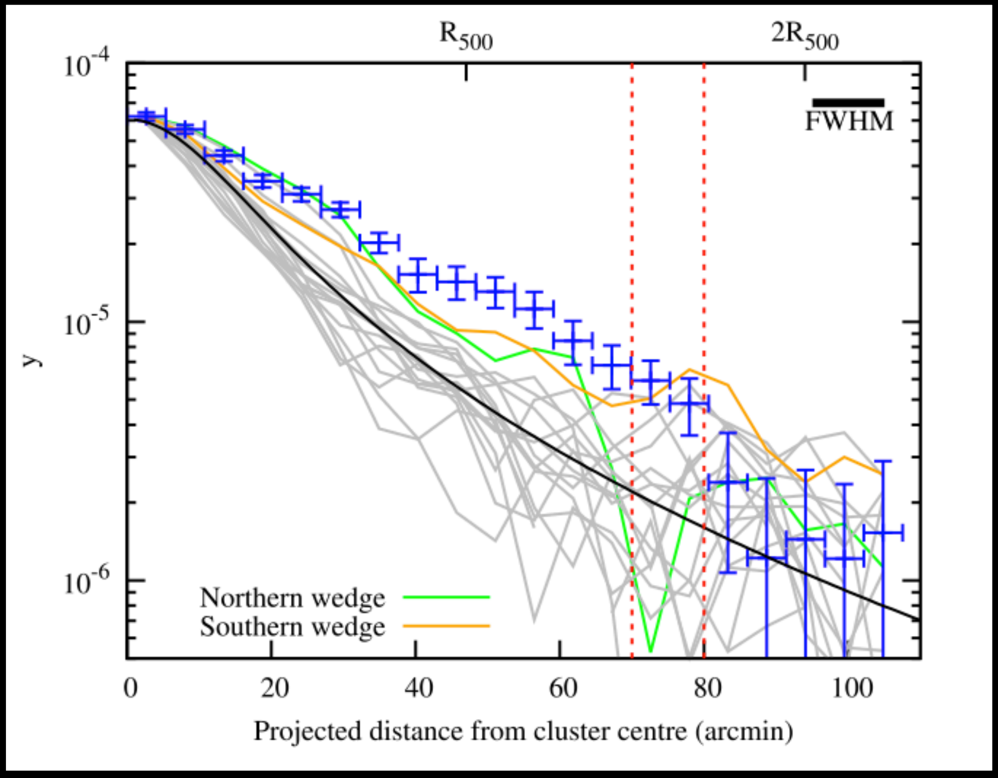
SZ shock in MACS J0744
(GBT/MUSTANG; Korngut et al. 2011)

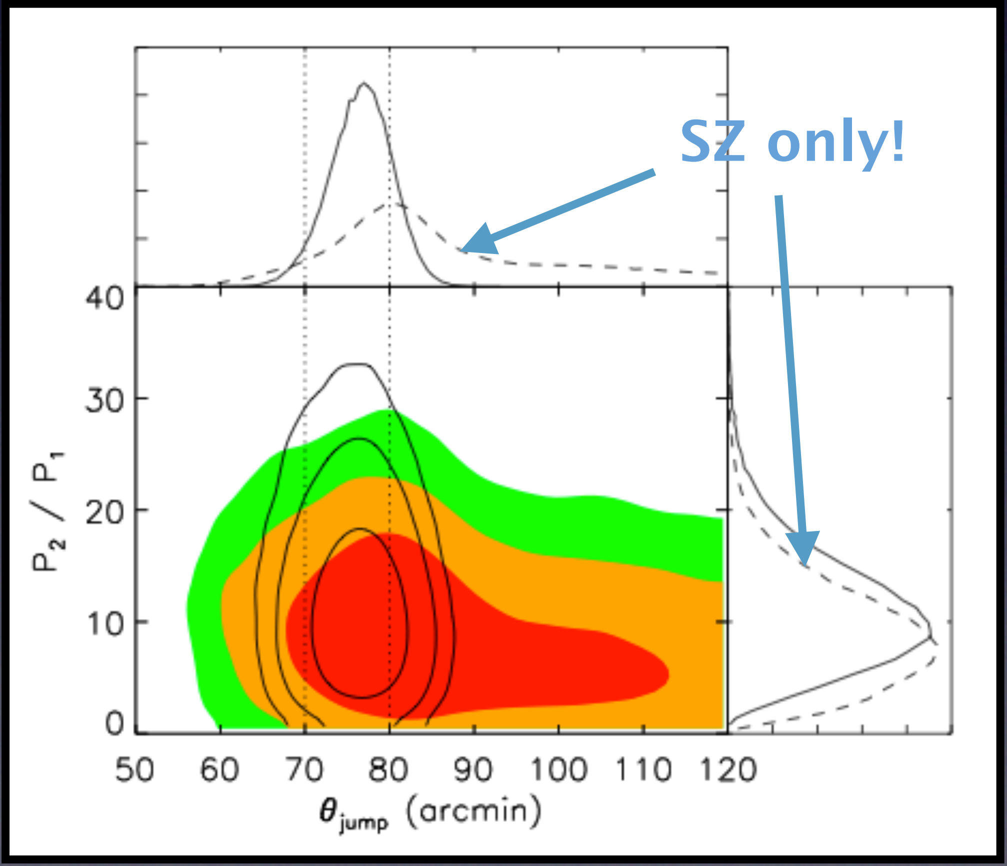


R ≤ R_{500} shocks in the Coma cluster
(Planck collaboration 2013)

Coma's Relic, with Planck


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



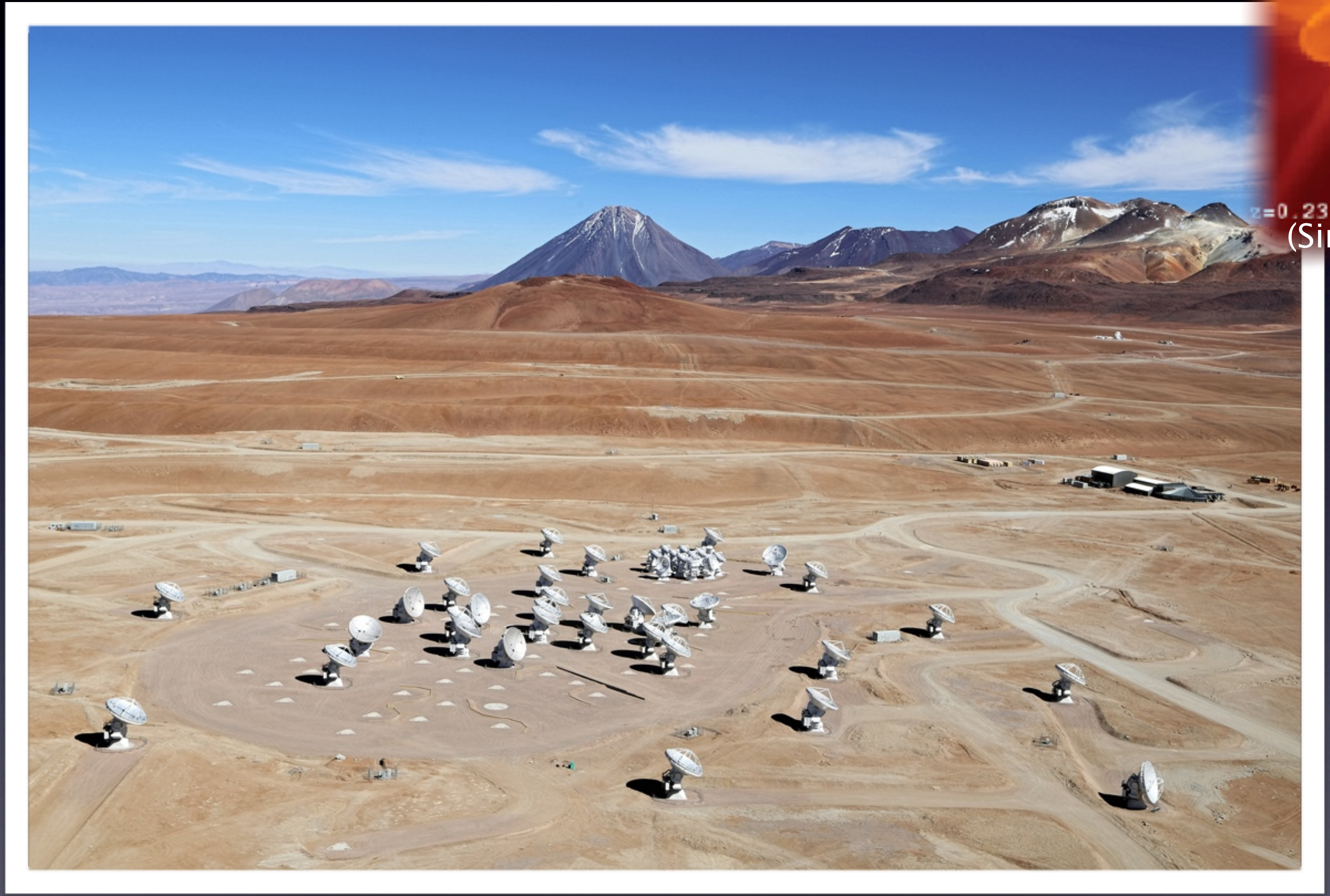

SZ only!

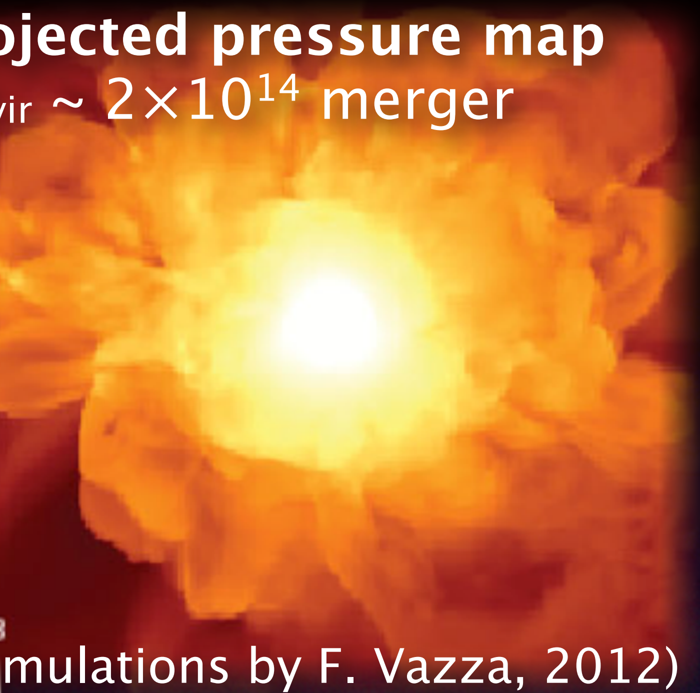
y–jump fits a shock, with $\mathcal{M} = 2.9^{+0.8}_{-0.6}$

[Using 2015 Planck data (and *spherical geometry*) $\mathcal{M} = 2.2 \pm 0.3$]

The ultimate SZ shock imager

Measuring SZ shocks with Planck is like measuring X-ray shocks with Uhuru... but now we can do better!





Projected pressure map

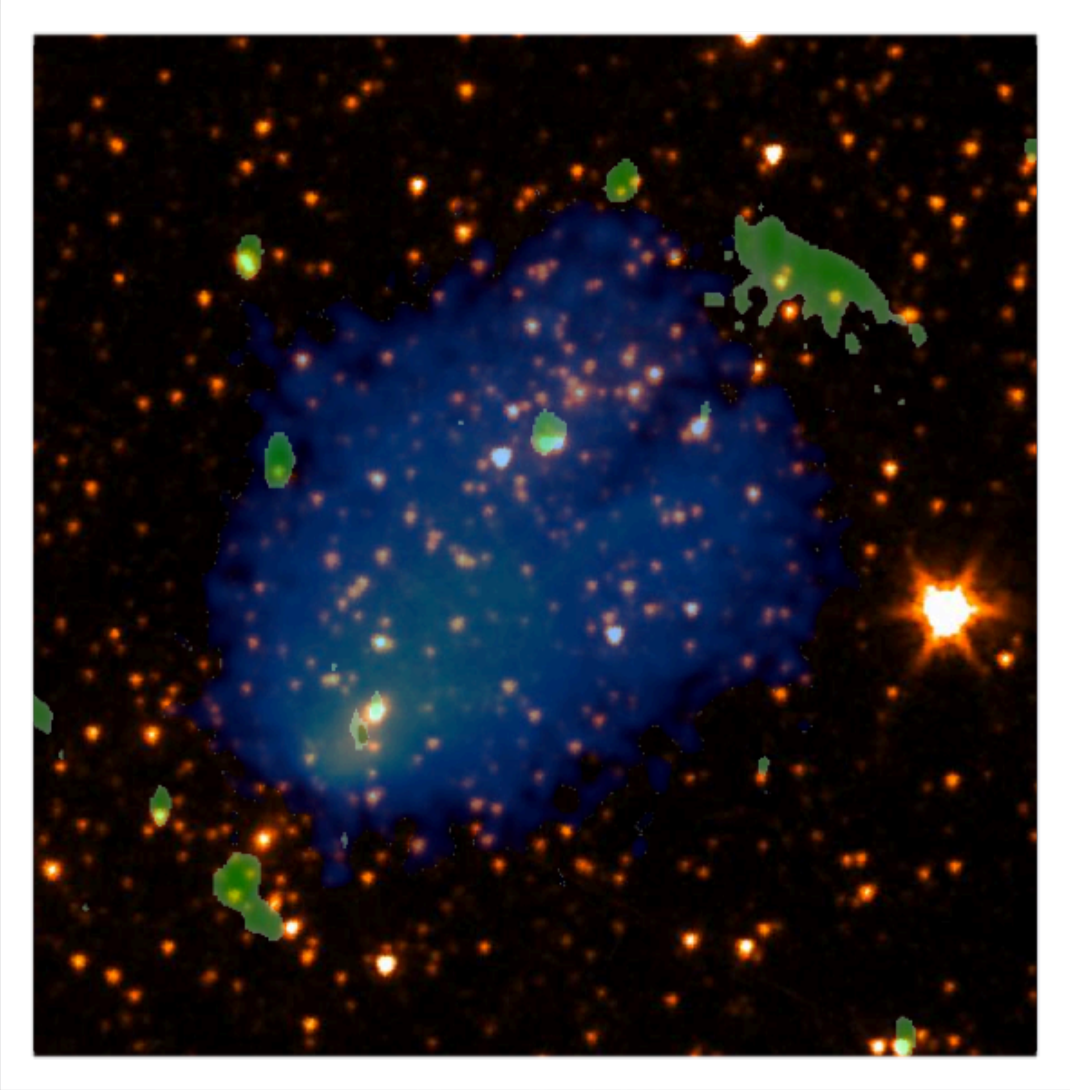
$M_{vir} \sim 2\times10^{14}$ merger

(Simulations by F. Vazza, 2012)

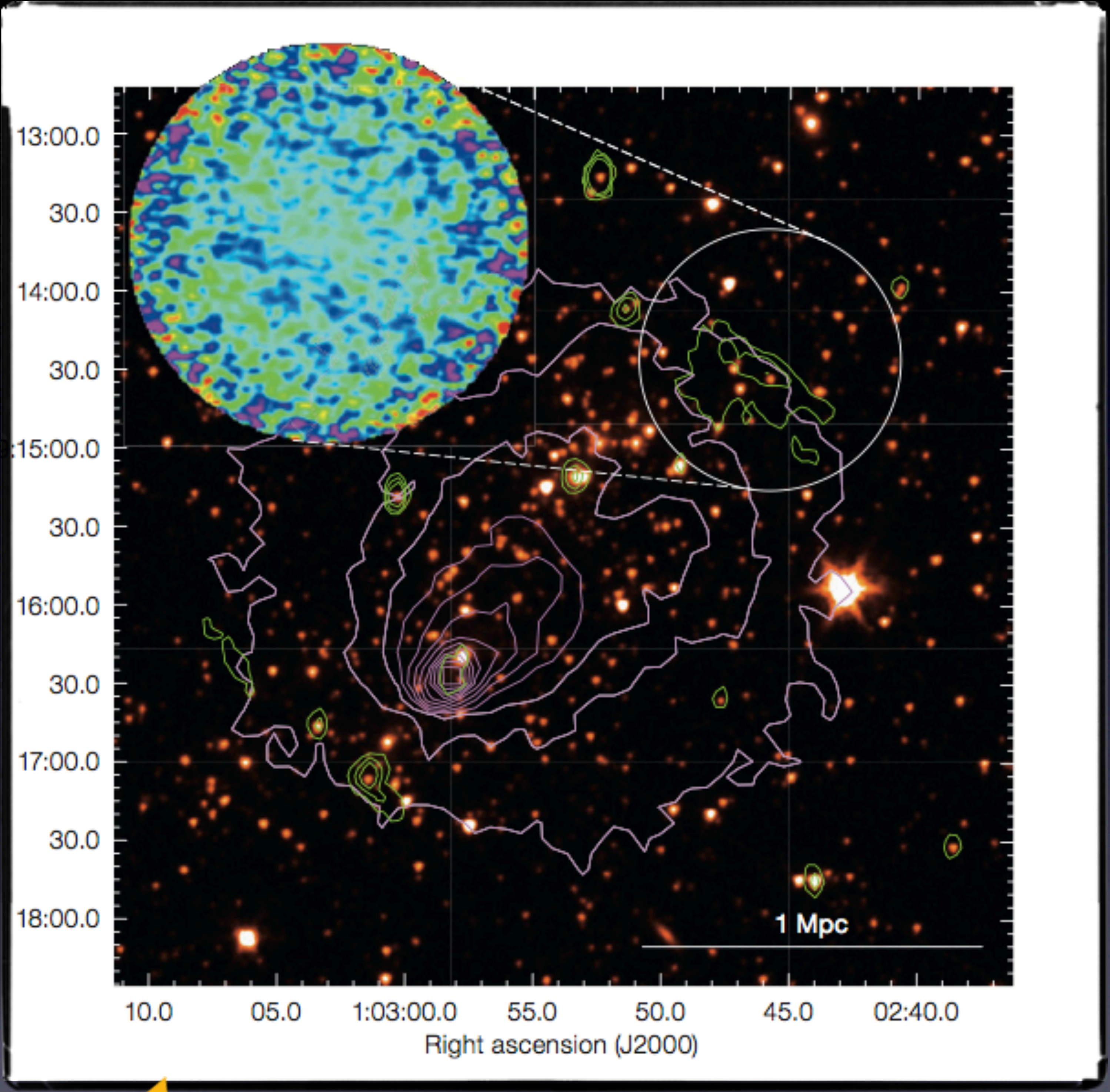
First ALMA-SZ results:

- ★ RXC J1347.5 core (Kitayama et al. 2016)
- ★ El Gordo relic shock (Basu et al. 2016)

A Relic-Shock with ALMA at z≈0.9



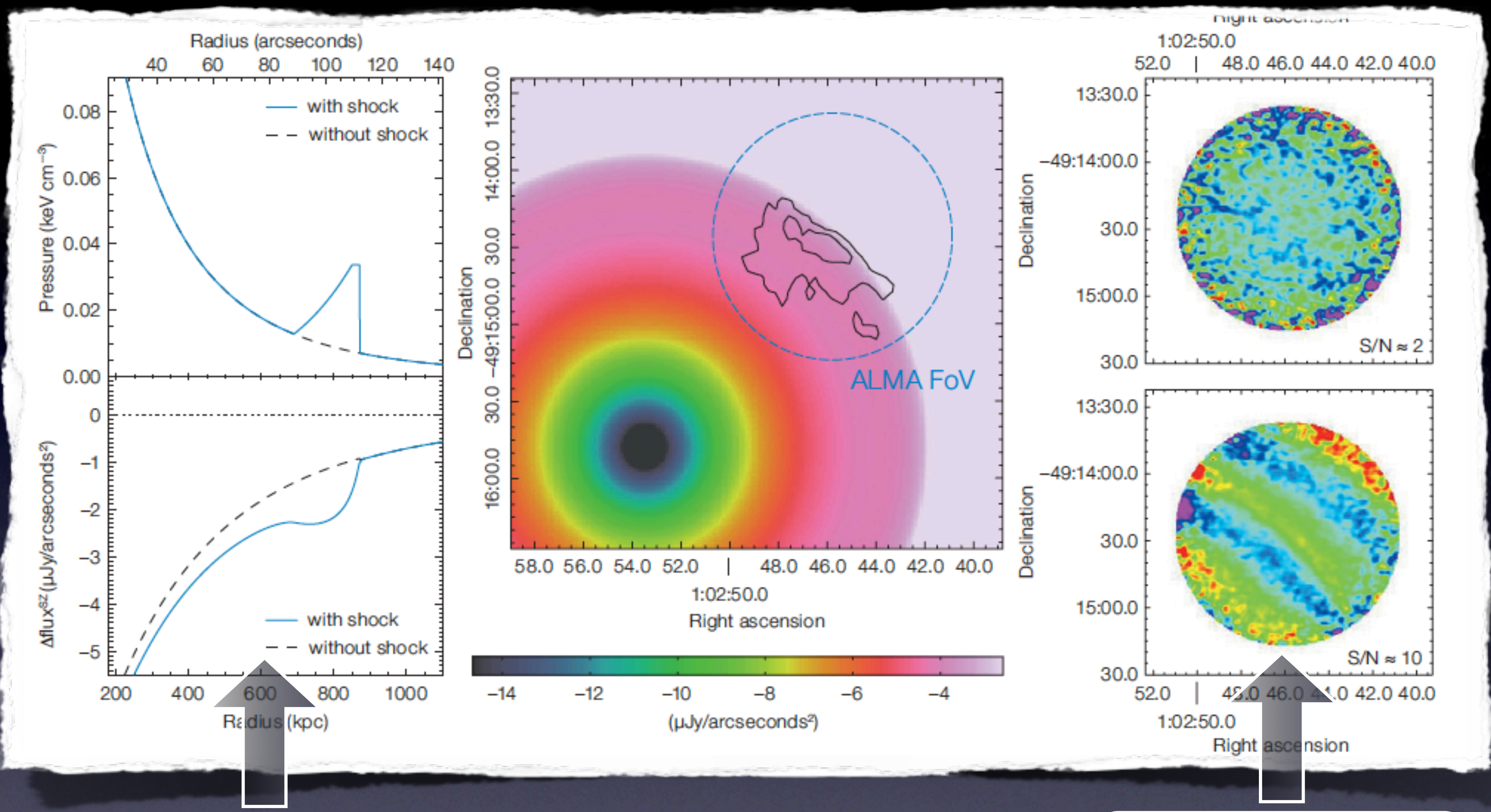
360 ks *Chandra* (PI: J. Hughes) + ATCA 2.1 GHz radio (Lindner et al. 2014)



ALMA data ~ 2h on-source
ALMA noise rms ~ 6 μJy/3” beam

Basu et al. (2016), ApJ, 829

How ALMA *sees* a Shock

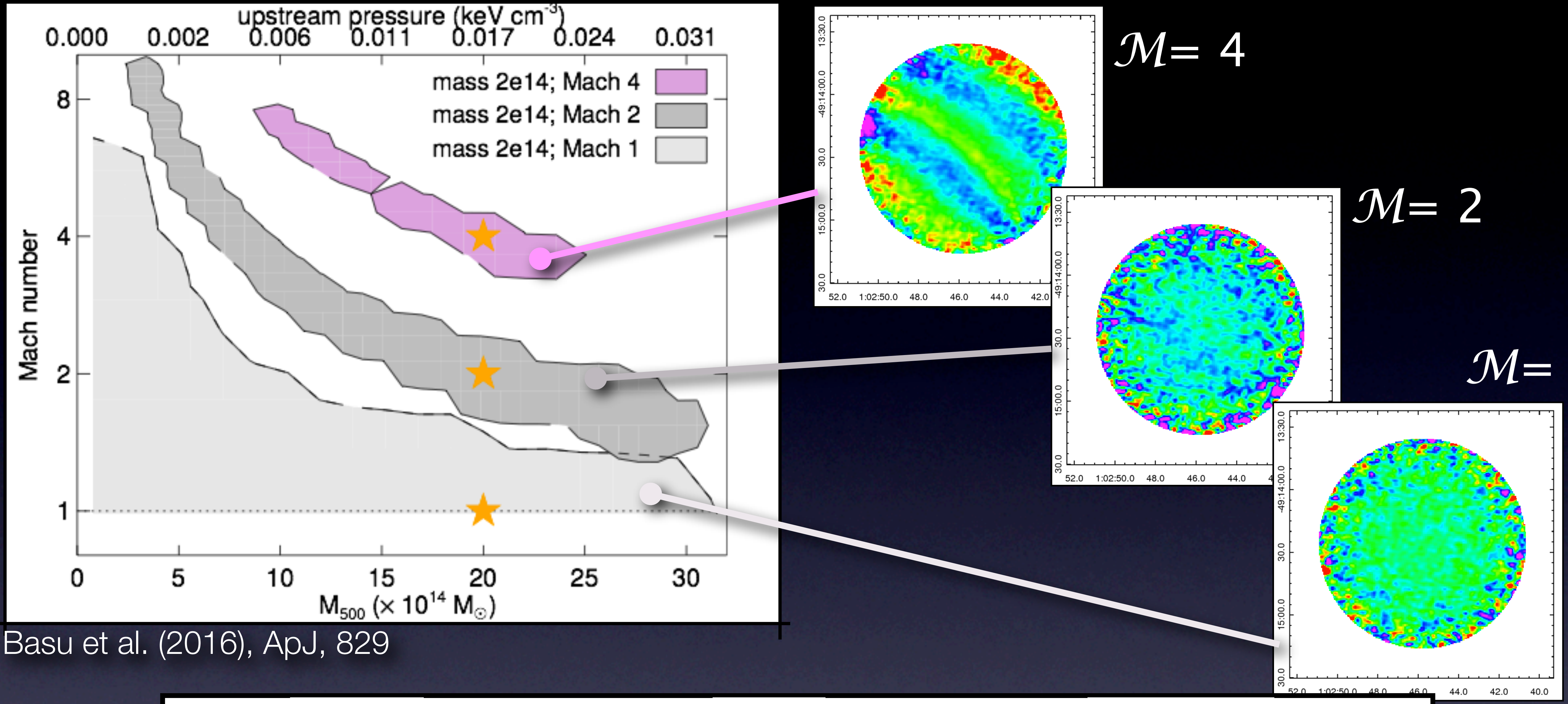


Step function-like jump in the SZ decrement

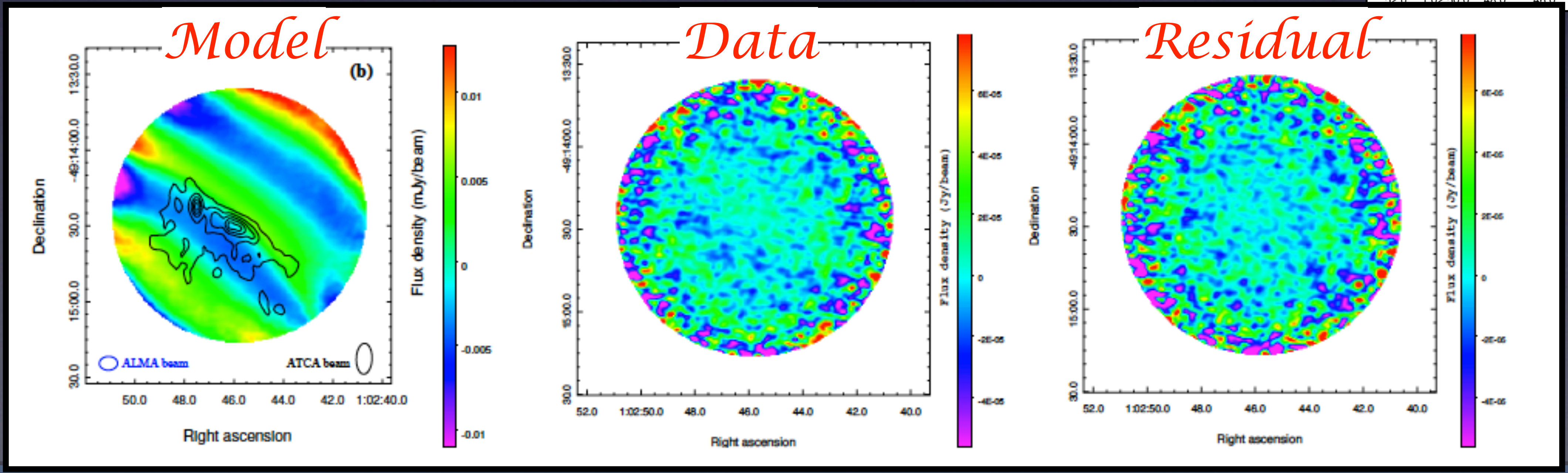
To avoid *interferometric imaging biases*, we fit our shock model directly to the visibility *("uv")* data, using a Bayesian MCMC method.

Deconvolved ("dirty") image produces ripple-like pattern

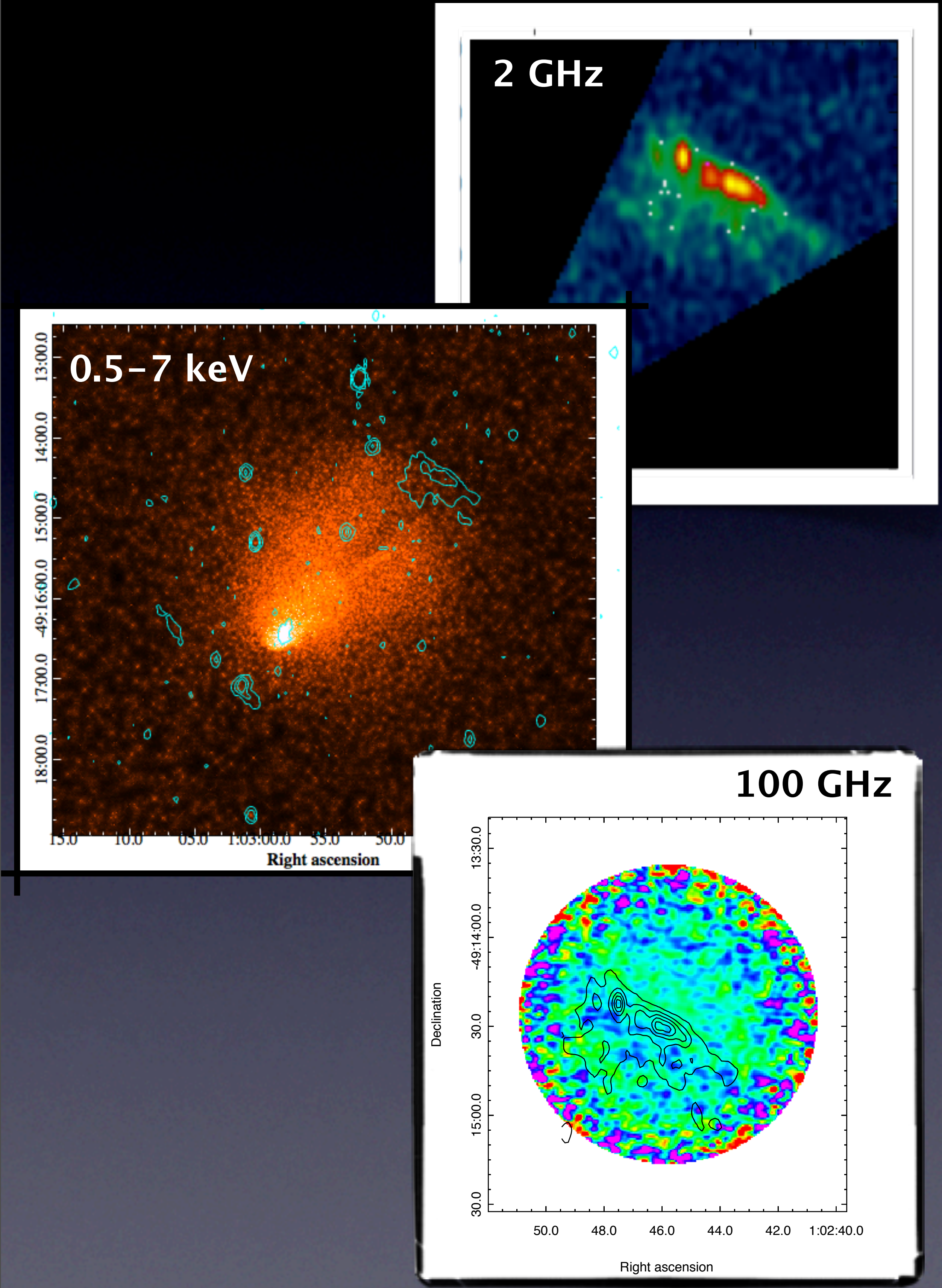
How ALMA *sees* a Shock

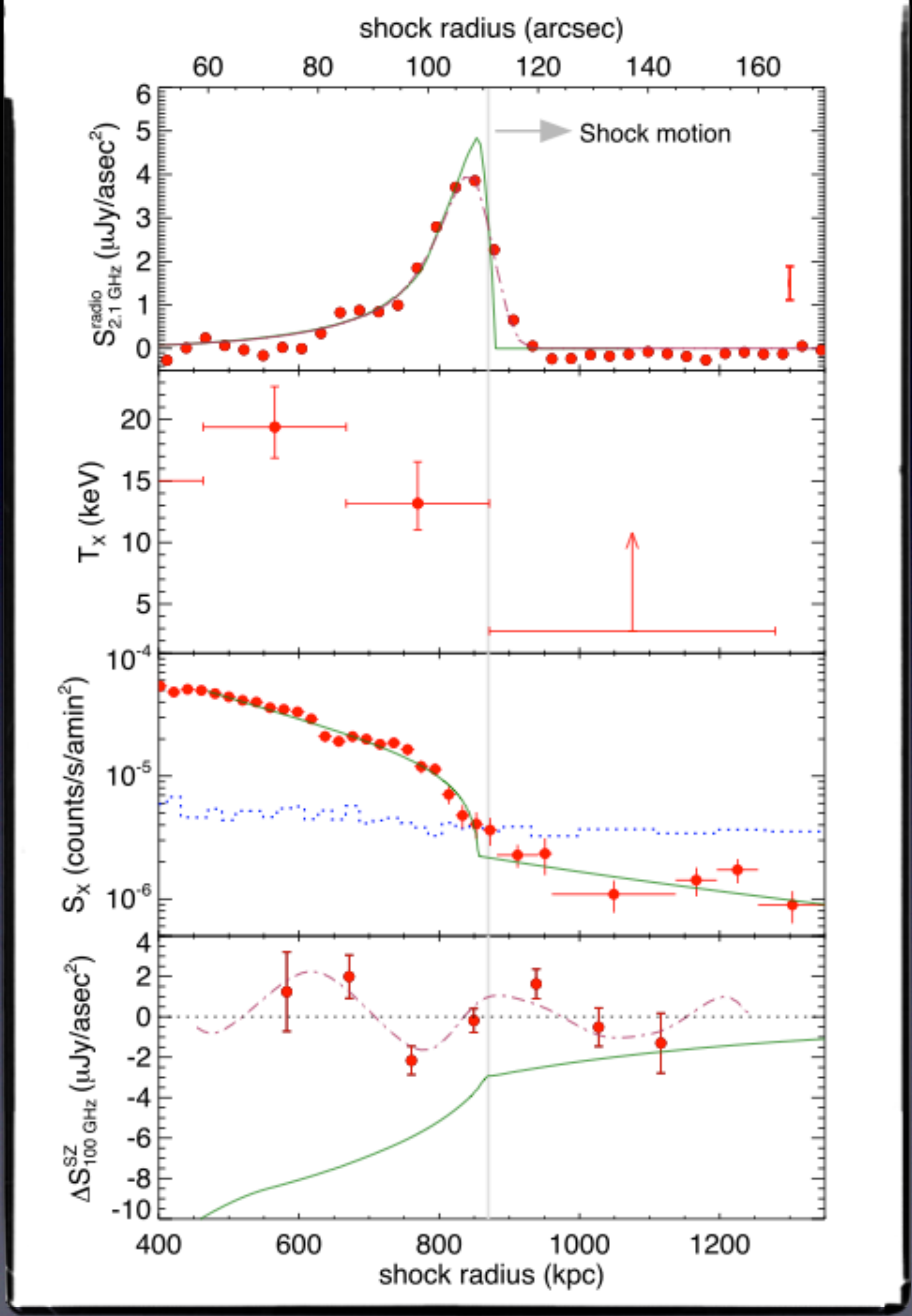


Basu et al. (2016), ApJ, 829



The Multi-Wavelength View

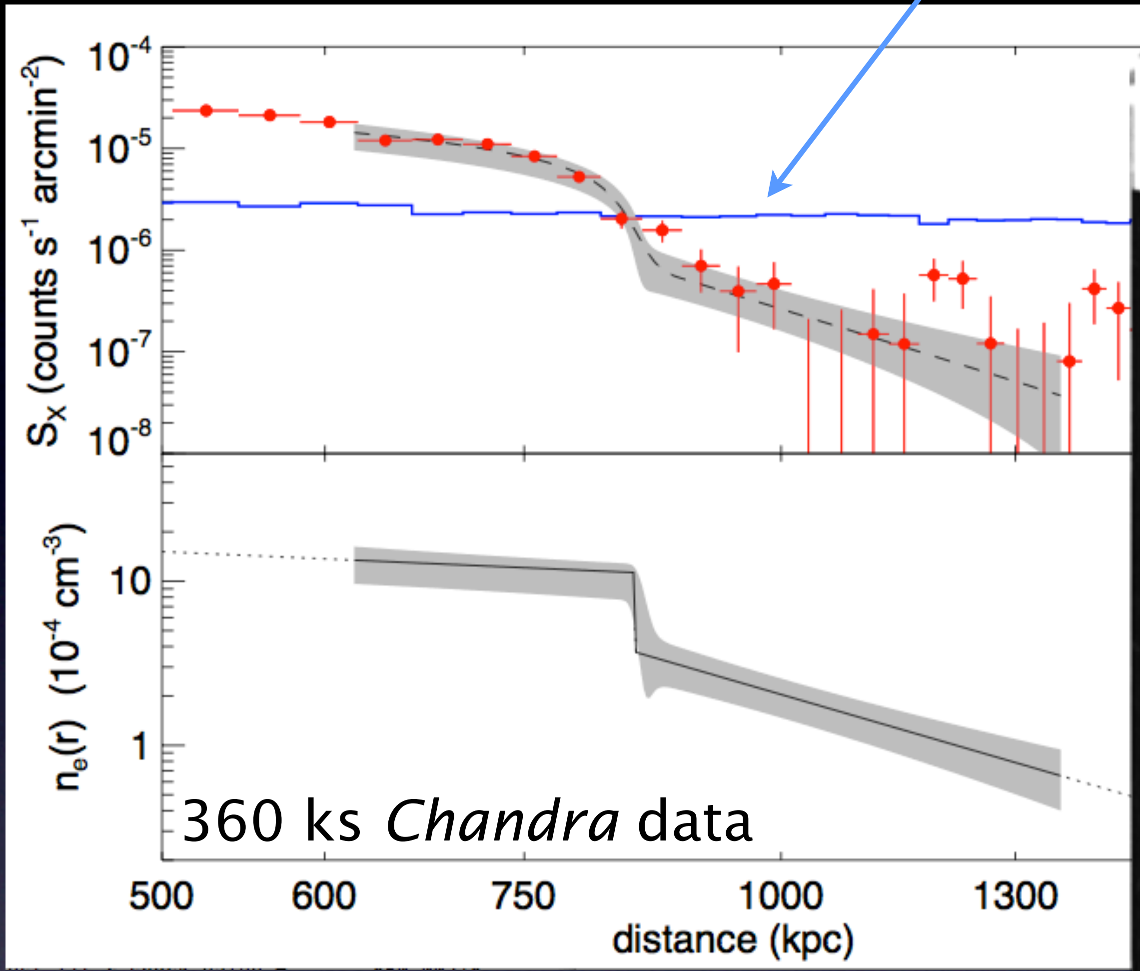




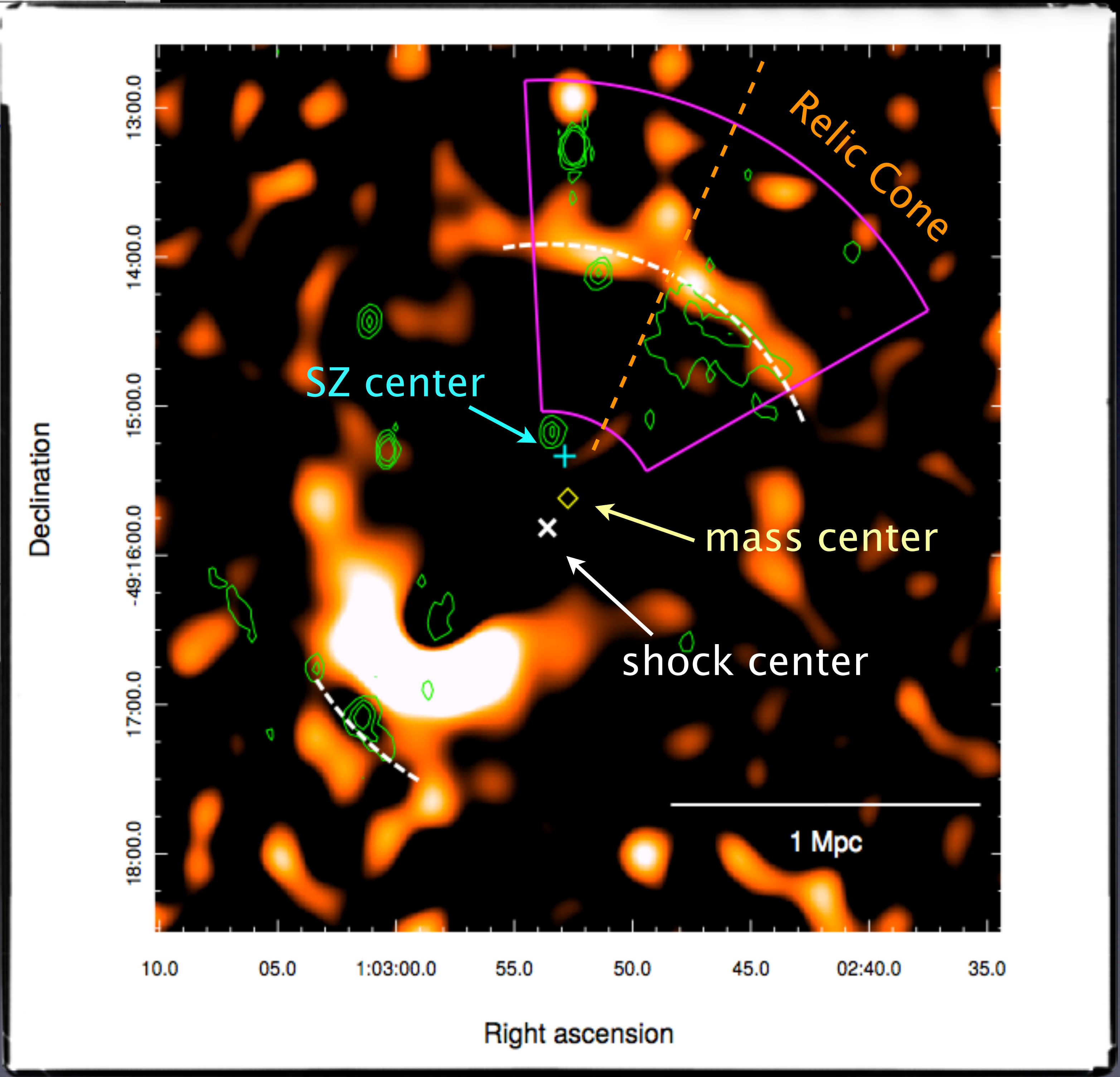
Basu et al. (2016), ApJ, 829

A wide shock, revealed in the X-rays

Background photon level



Basu et al. (2016), ApJ, 829



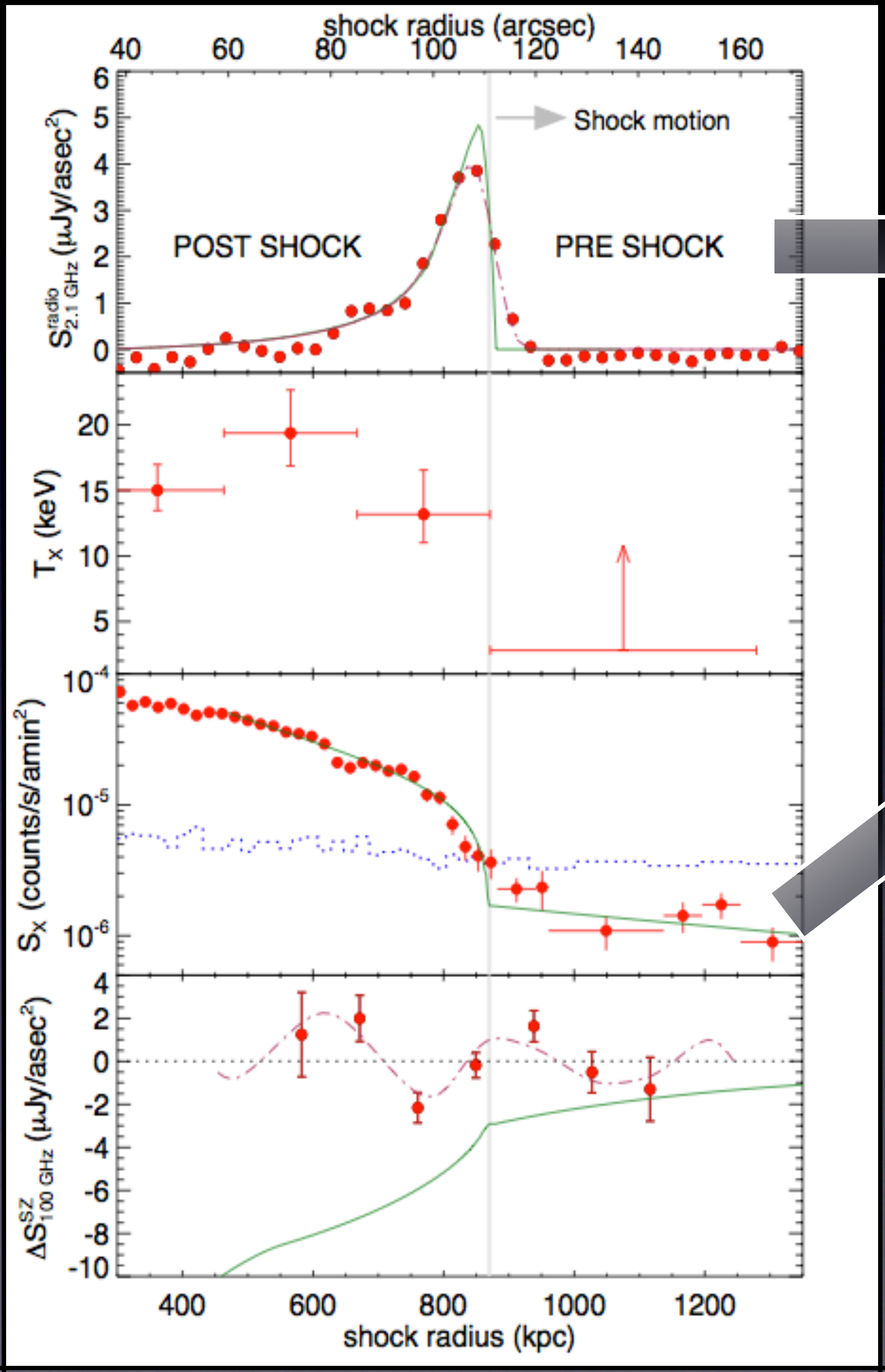
Mach number in the relic cone:

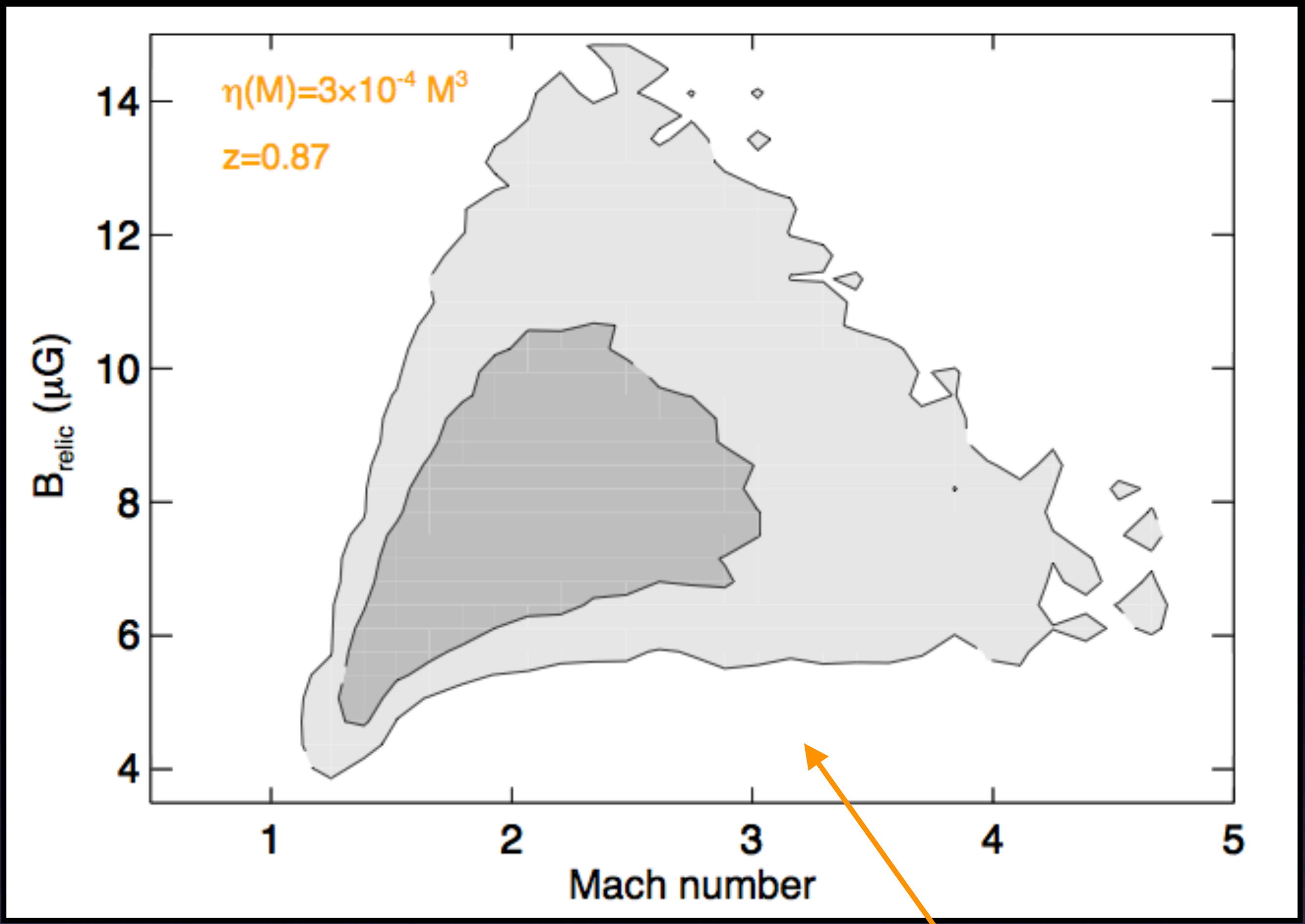
$$\mathcal{M} = 2.9^{+7.8}_{-0.9}$$

Mach number in the other half:

$$\mathcal{M} = 2.3^{+3.0}_{-0.8}$$

Magnetic Field at z≈0.9





DSA formula (Hoeft & Brueggen 2007), simplified:

$$S_\nu^{\rm sync.} = (1+z)^{1-\delta/2}\, P_\nu^{\rm sync.}/4\pi D_L^2$$

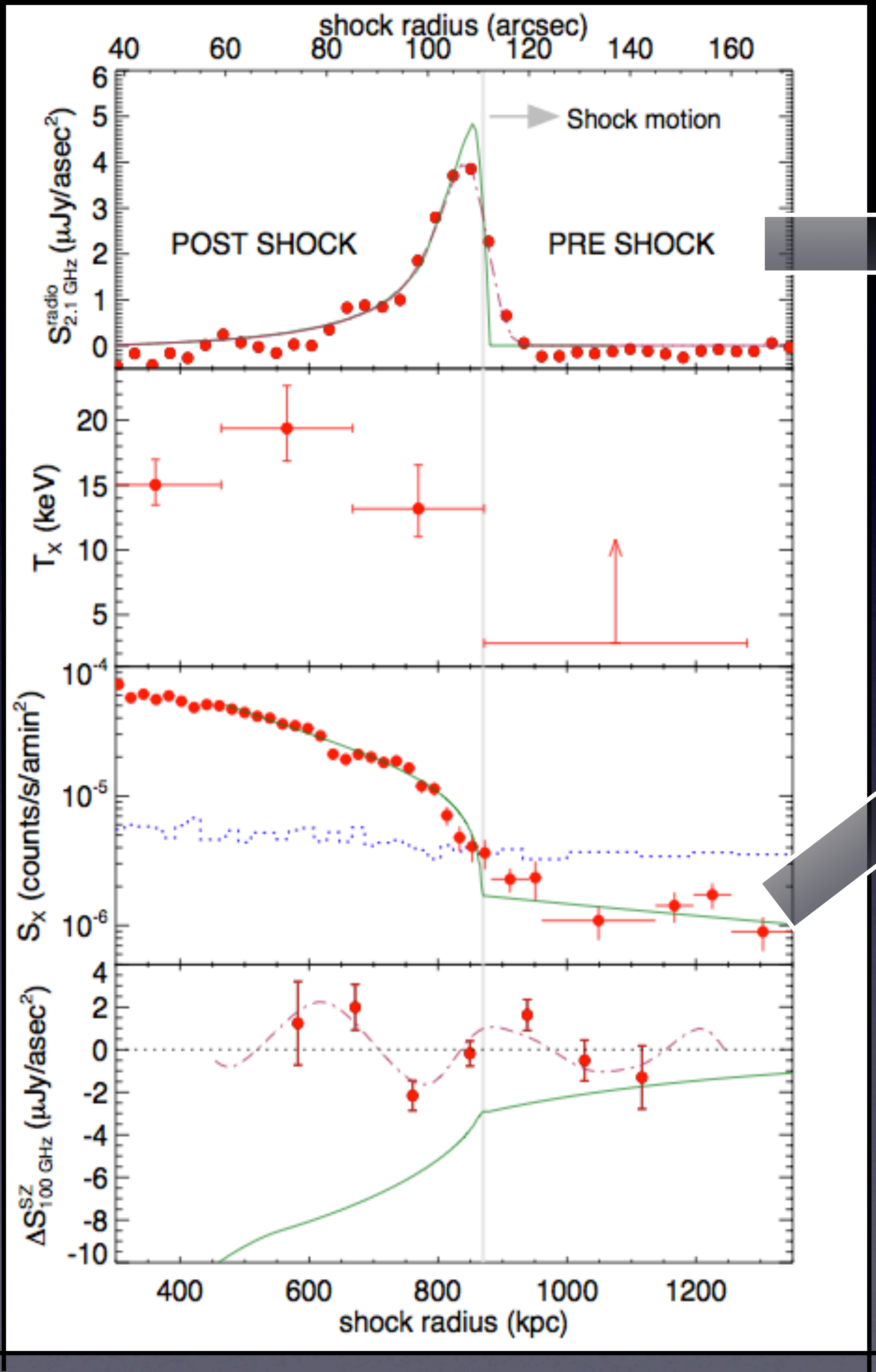
$$\approx 24\ {\rm mJy} \left(\frac{\mathcal{M}}{3}\right)^3 \left(\frac{\xi_{e/p}}{0.05}\right) \left(\frac{L^2}{1\ {\rm Mpc}^2}\right) \frac{B_{\rm relic}^{1+\delta/2}}{B_{\rm CMB}^2 + B_{\rm relic}^2}$$

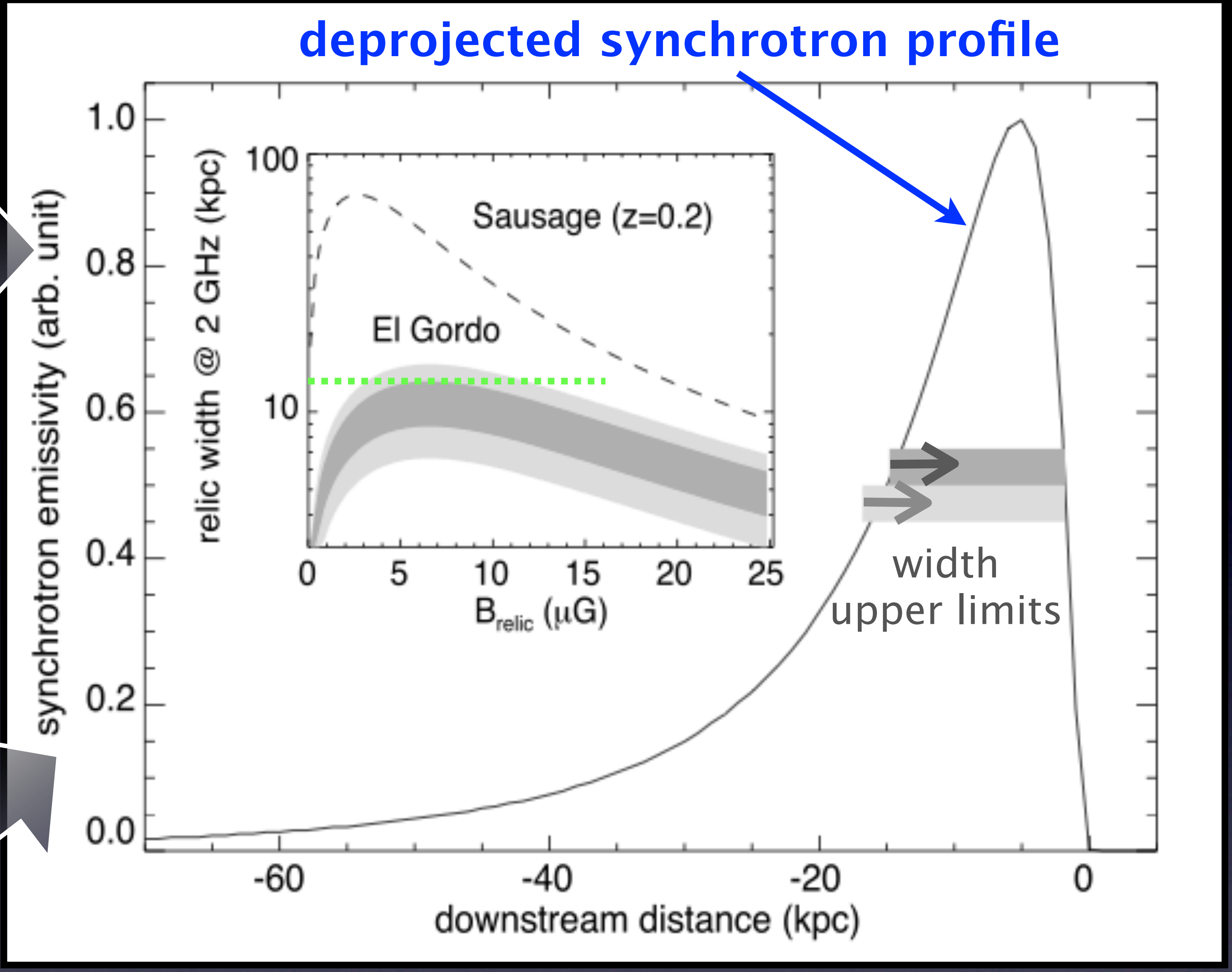
$$\times \left(\frac{n_{\rm u}}{10^{-4}{\rm cm}^{-3}}\right) \left(\frac{T_{\rm u}}{1\ {\rm keV}}\right)^{3/2} \left(\frac{D_L}{10^3\ {\rm Mpc}}\right)^{-2}$$

$$\times (1+z)^{1-\delta/2} \left(\frac{\nu}{1.4\ {\rm GHz}}\right)^{-\delta/2}$$

Basu et al. (2016)

Magnetic Field at z≈0.9





Relic width is related to the cooling time, i.e. the magnetic field:

$$\boxed{\mathcal{W}_{\rm relic} \approx v_d\, t_{\rm sync}}$$

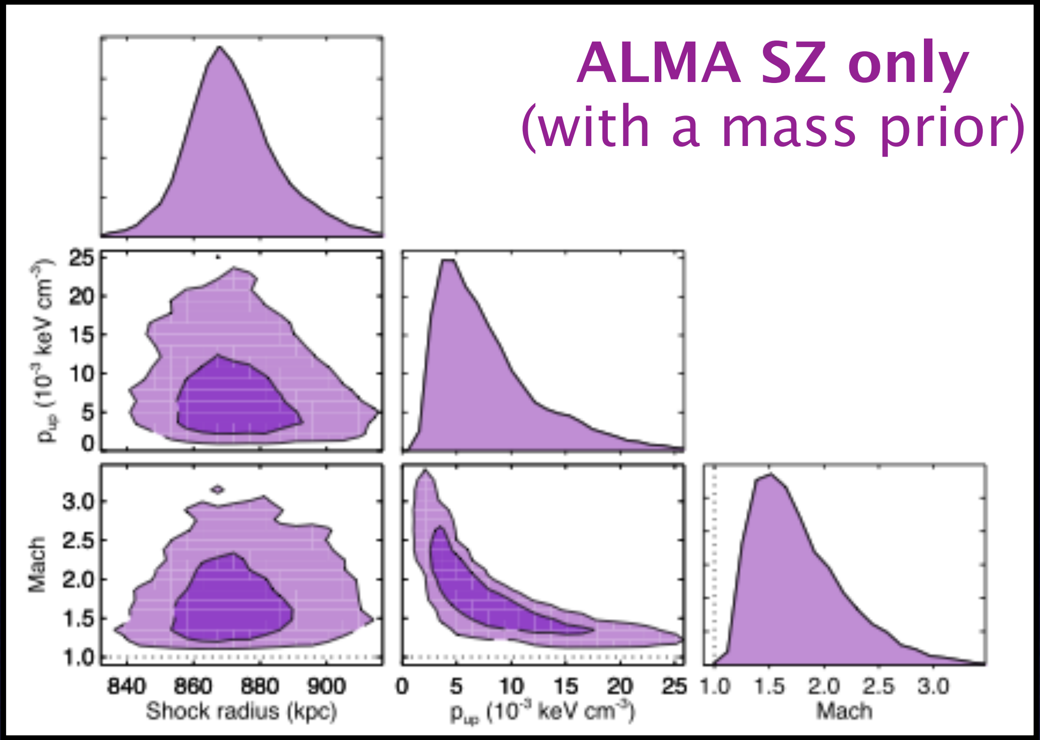
$$\boxed{t_{\rm sync} = 3.2 \times 10^{10}\ {\rm yr}\ \frac{B^{1/2}}{B^2 + B^2_{\rm CMB}}\ \frac{1}{\sqrt{\nu(1+z)}}}$$

The Shock Mach number

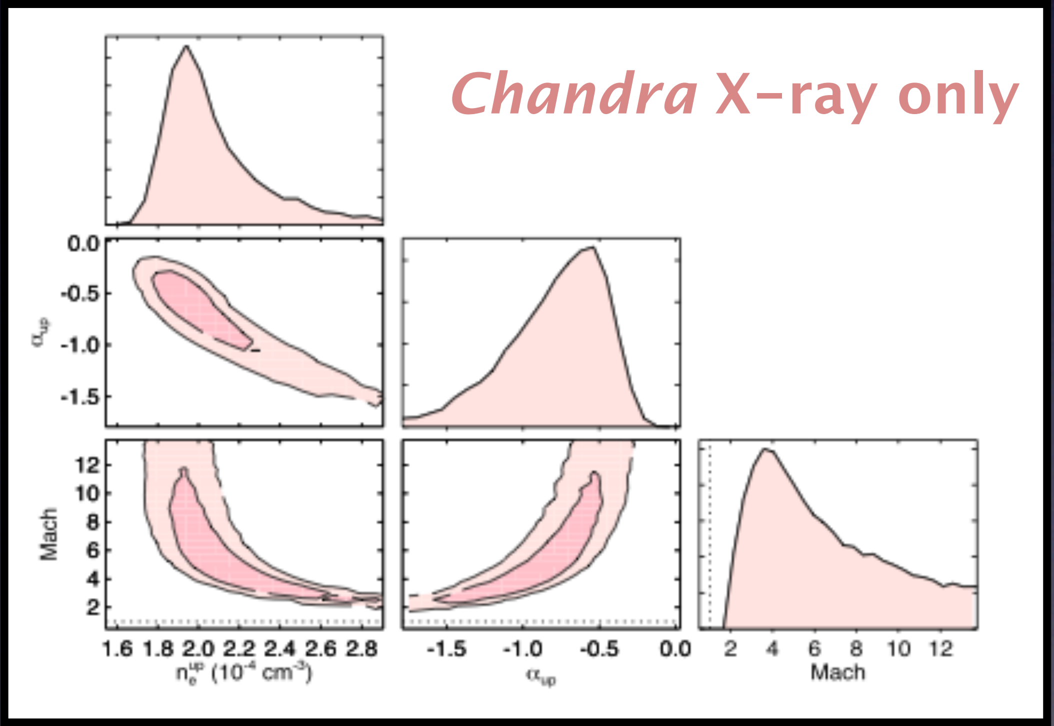
ALMA SZ data alone points to a weak shock: $\mathcal{M} = 1.4^{+1.2}_{-0.2}$

X-ray brightness jump suggests stronger: $\mathcal{M} = 3.5^{+6.4}_{-1.3}$

We use an X-ray pressure prior on the SZ modeling.

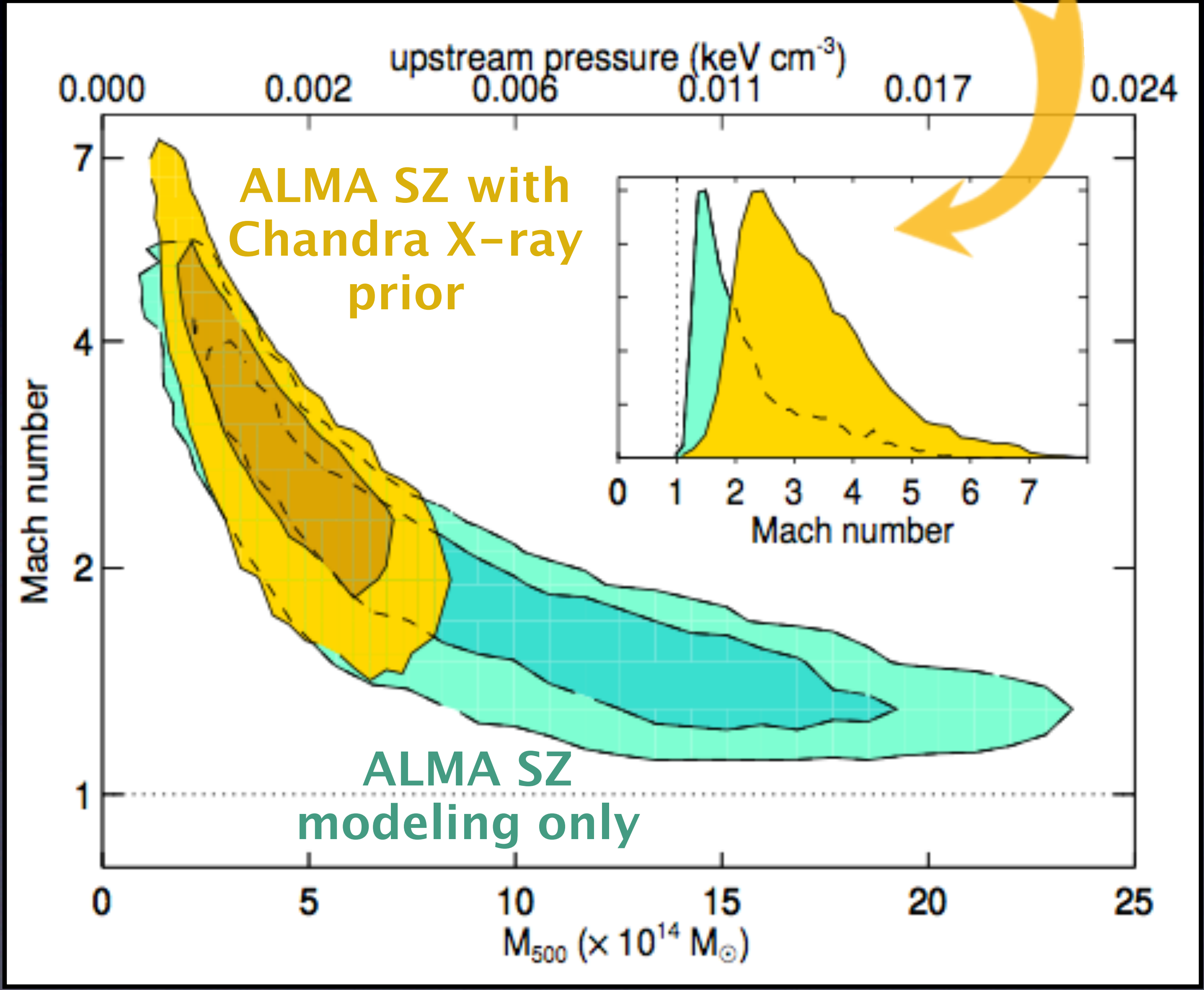


ALMA SZ only
(with a mass prior)



***Chandra* X-ray only**

Basu et al. (2016), ApJ, 829



ALMA SZ with Chandra X-ray prior

ALMA SZ modeling only

Summary

SZ connection for RADIO RELICS

- Thermal SZ/X-ray and non-thermal synchrotron are modeled self-consistently
- Shocks that underlie radio relics have now been measured also in the SZ
- Radio observations are affected by SZ at cm-wavelengths (1-30 GHz)
- ALMA is opening the SZ-substructure window in clusters

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SZ connection for RADIO HALOS

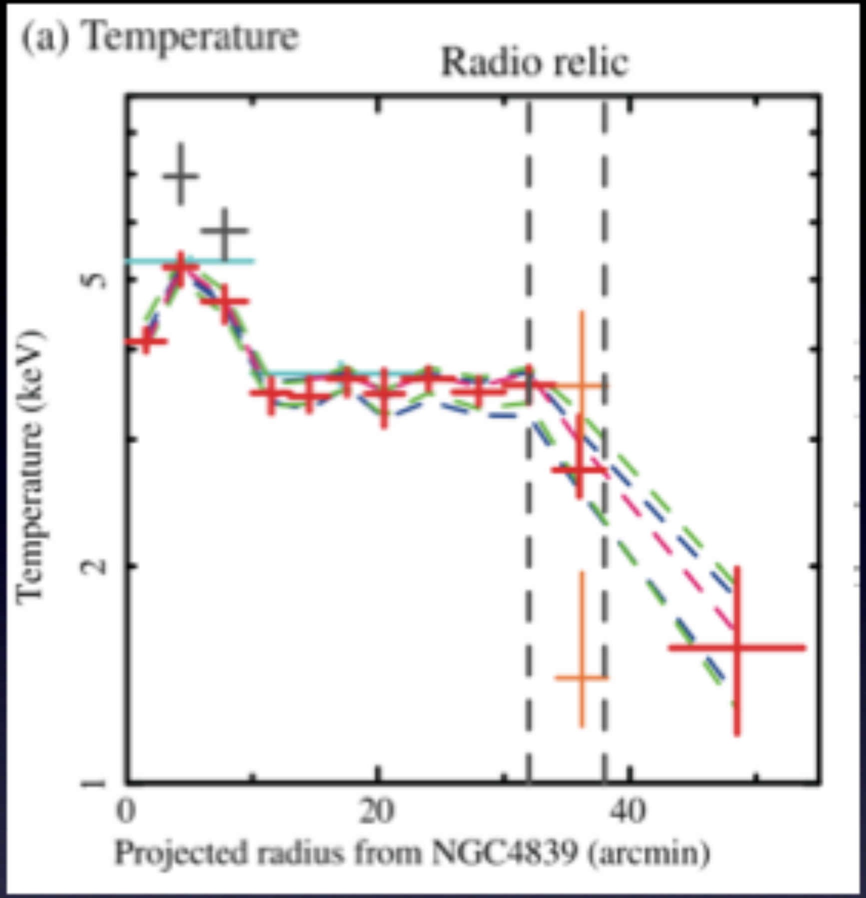
- First demonstration of the radio-SZ correlation for radio halos
- Reduced “apparent bimodality” in SZ selection, but certainly radio-off clusters
- SZ and X-ray selection in the high-mass end show significant difference with radio
- The SZ selection part (~70% RHs) no confirmed with deep radio data

Thank you!

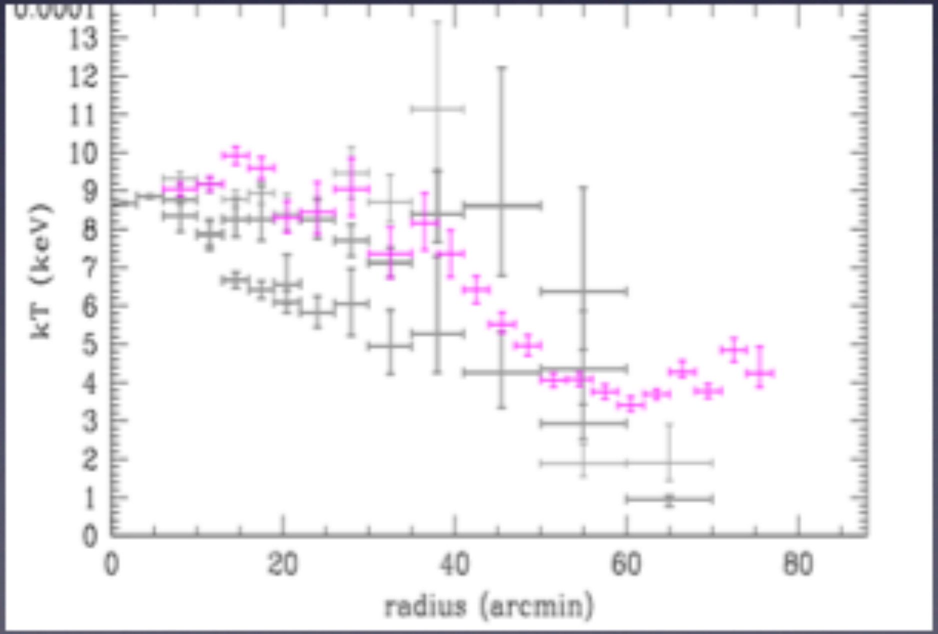
Thank you!

Additional Slides ➡

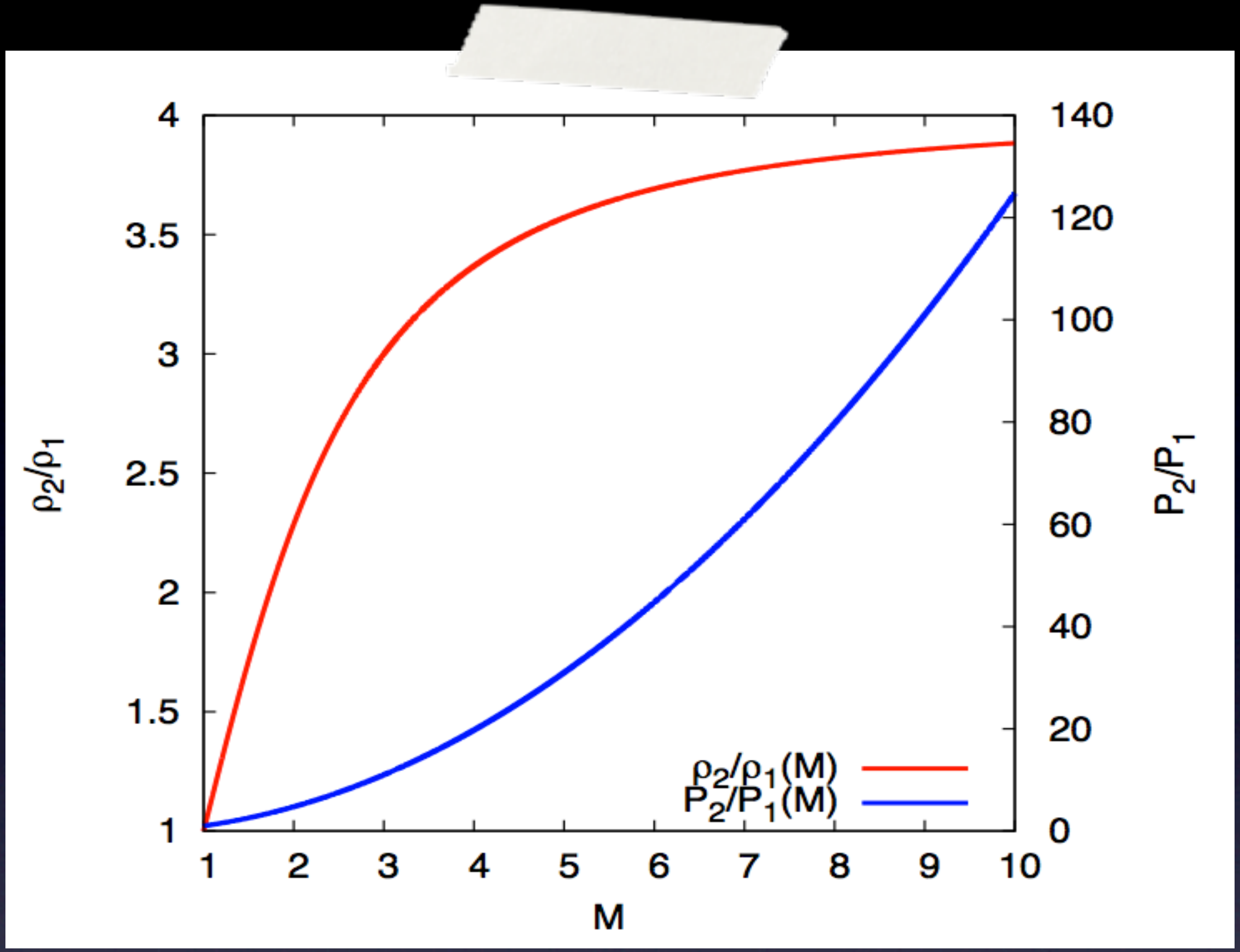
Shocks with X-rays at relics



Akamatsu et al. (2013)

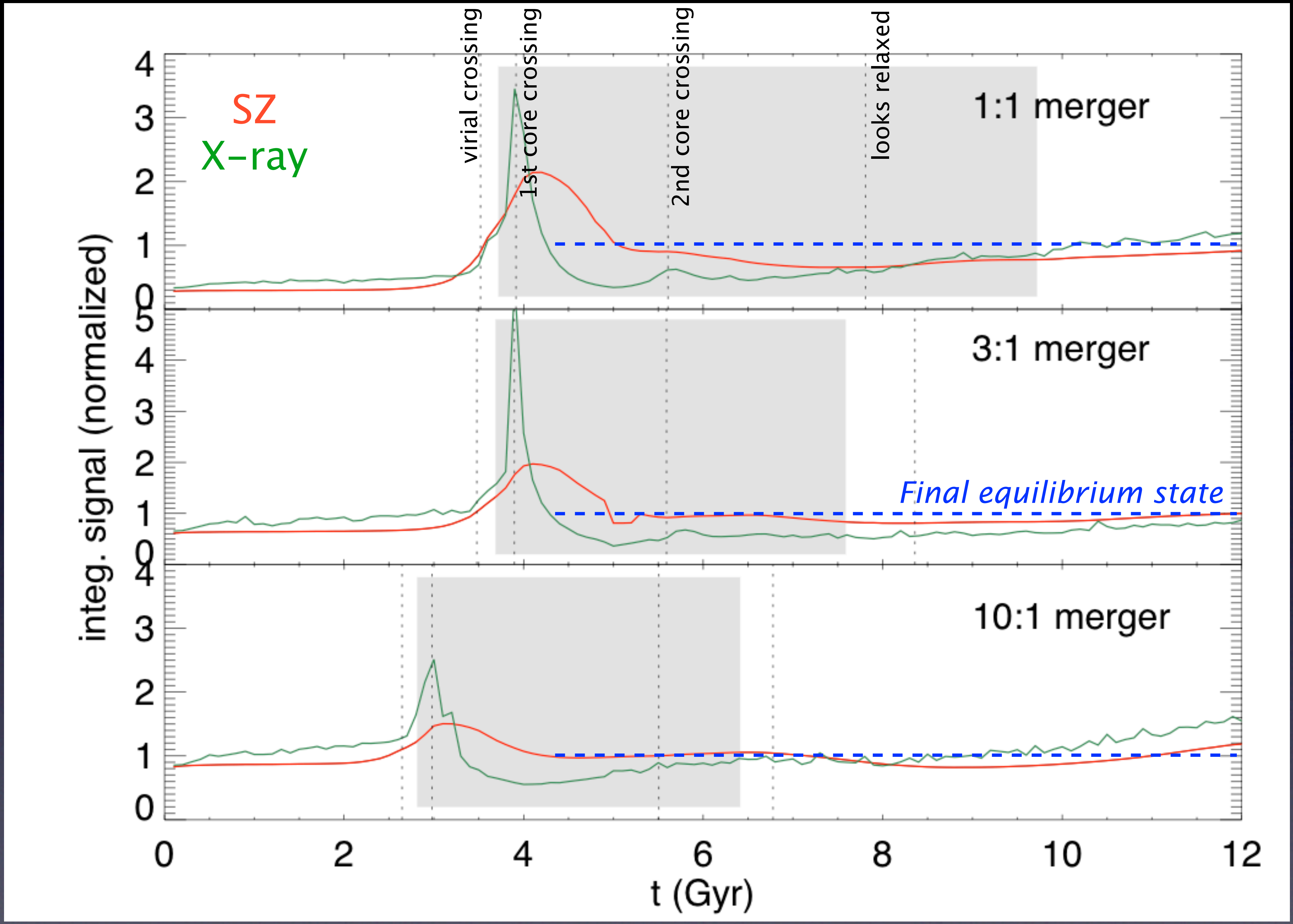


Simionescu et al. (2013)



- 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!*

SZ/X-ray Signal Variations during Mergers



Sommer & Basu (2014), MNRAS, 437

Based on N-body hydro simulation results by Poole et al. (2007)