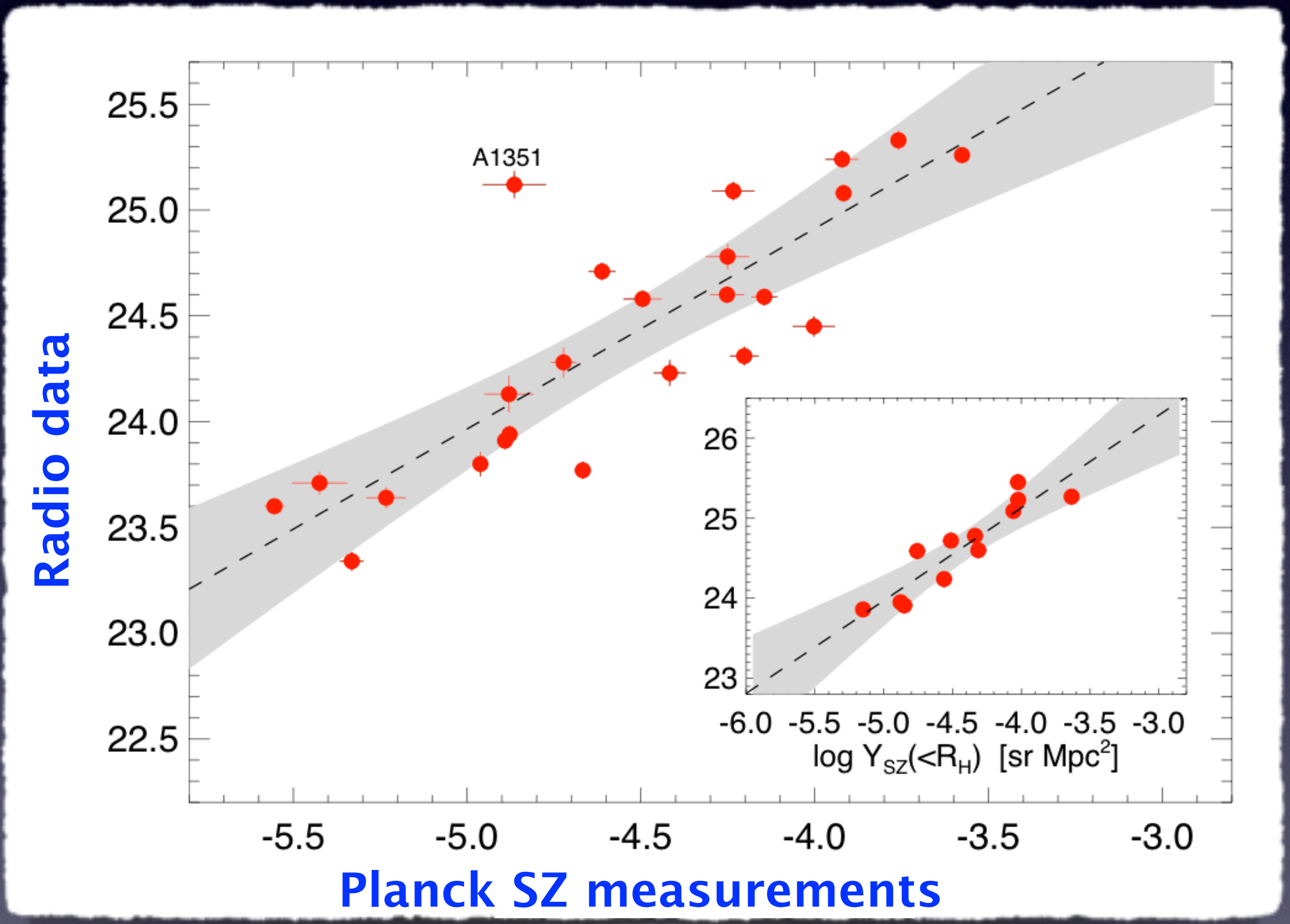
# AN SZ TAKE ON

# Cluster Diffuse Radio Emissions



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*With inputs from:*
Martin Sommer, Vyoma Muralidhara,
Jens Erler, Franco Vazza,
and many others

# In this talk..

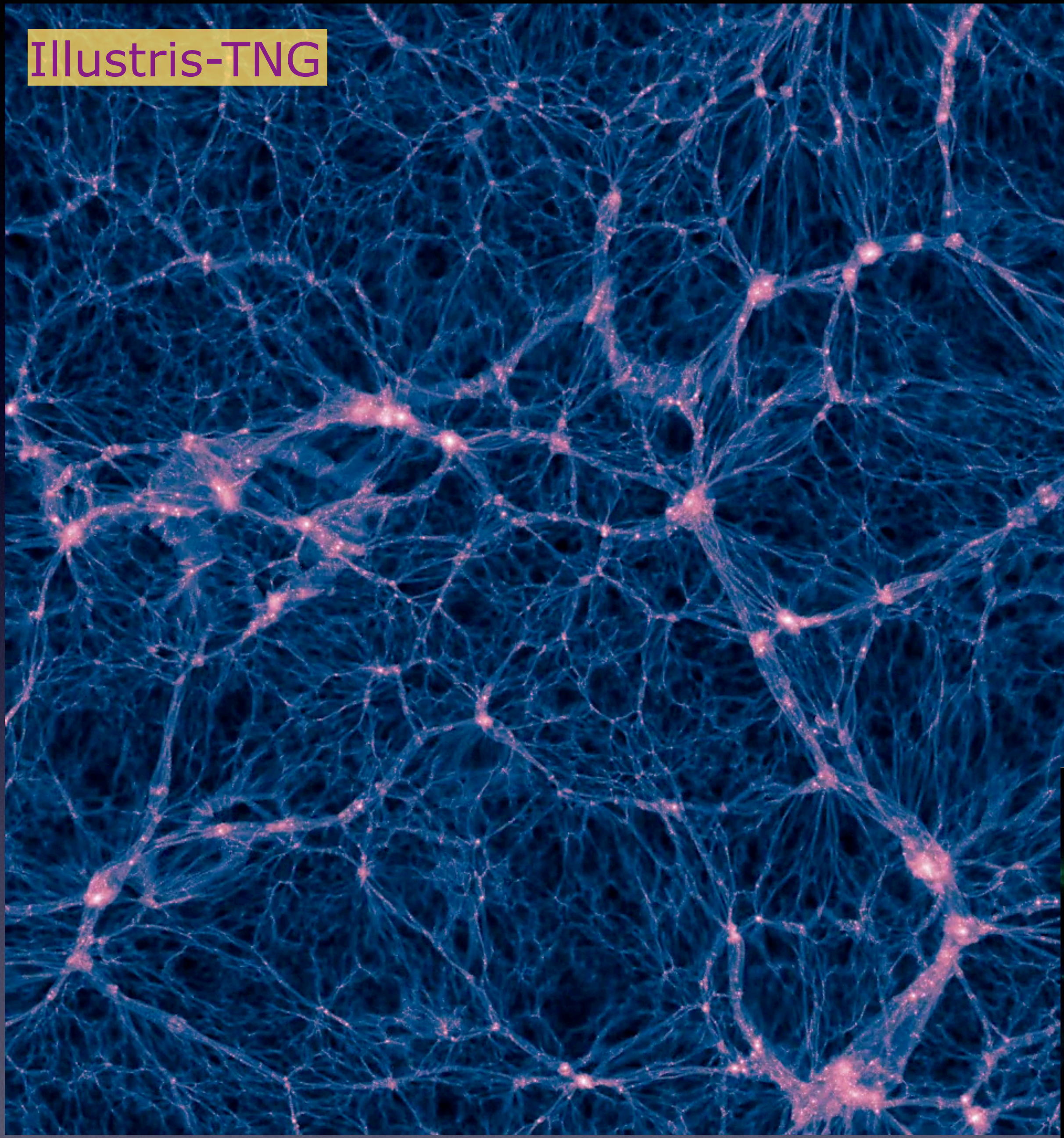
- We will learn about the two main types of diffuse synchrotron emissions in galaxy clusters, namely, radio halos and relics, and some open questions regarding them

- We will discuss the thermal SZ effect and how its measurements helped us to gain a better understanding of the nonthermal radio emission

- We will introduce the nonthermal SZ effect, which is caused by the relativistic electrons, and the prospects of measuring its signal

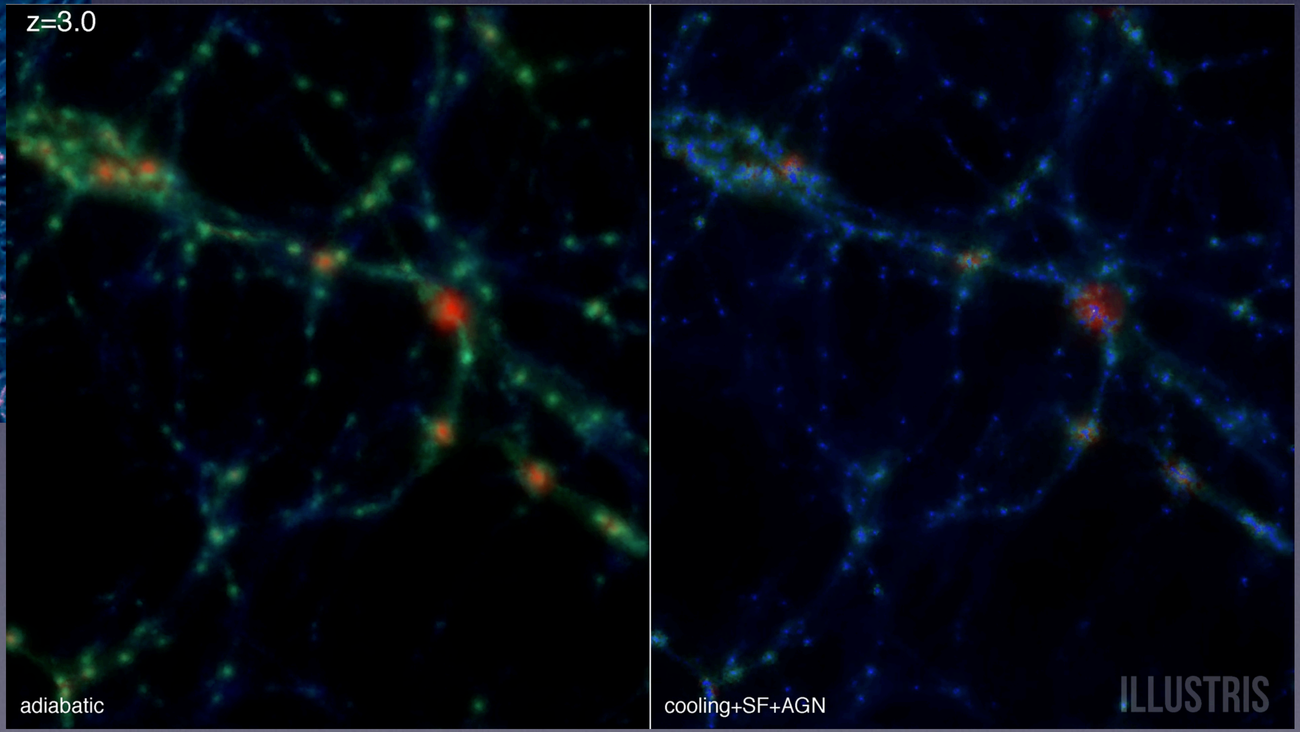
# The Big Picture

- How do large-scale structures in the Universe evolve? What role do the baryons play? Where are most of these baryons?
- Are nonthermal, ultra-relativistic particles (cosmic rays) also important in this cosmic evolution?
- What can we learn by cross-comparing the thermal and nonthermal emissions from the large-scale structures?



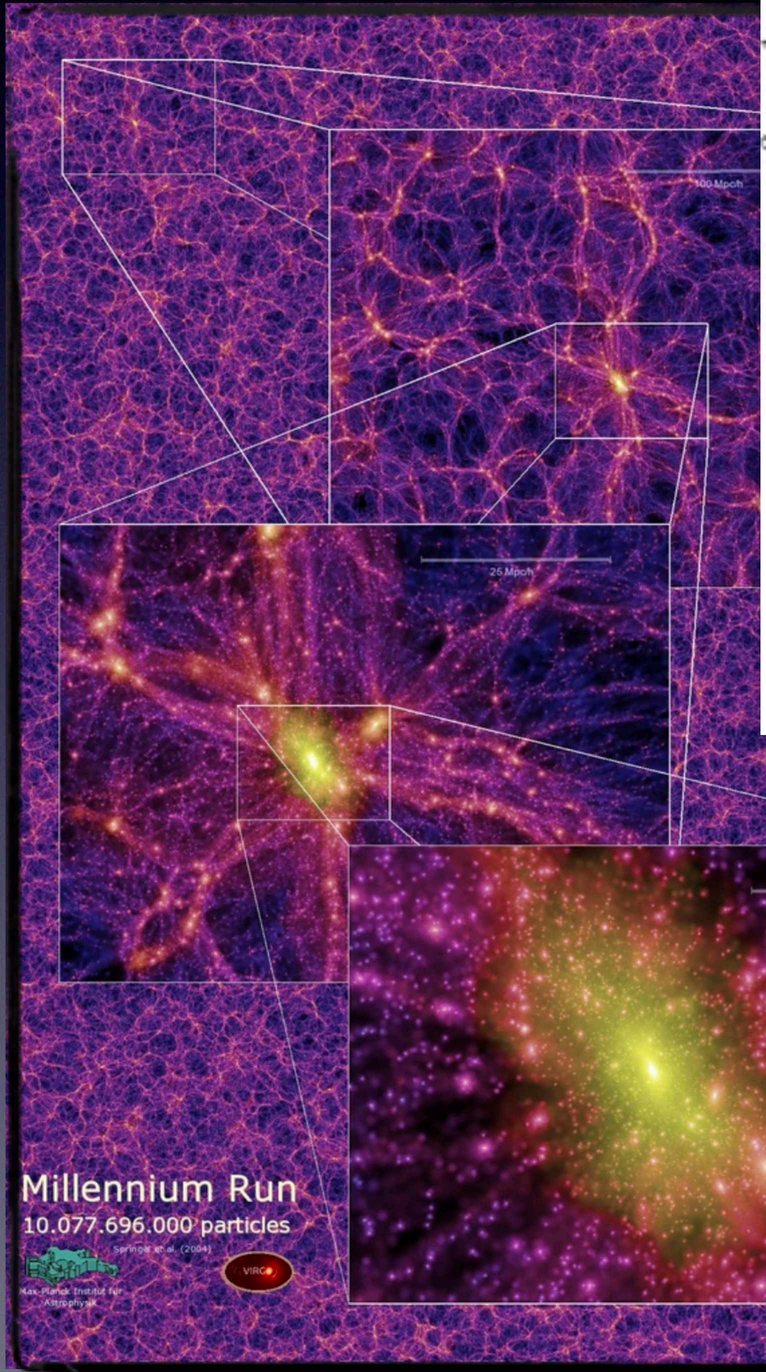
Slices of the universe at z=0 (DM only)

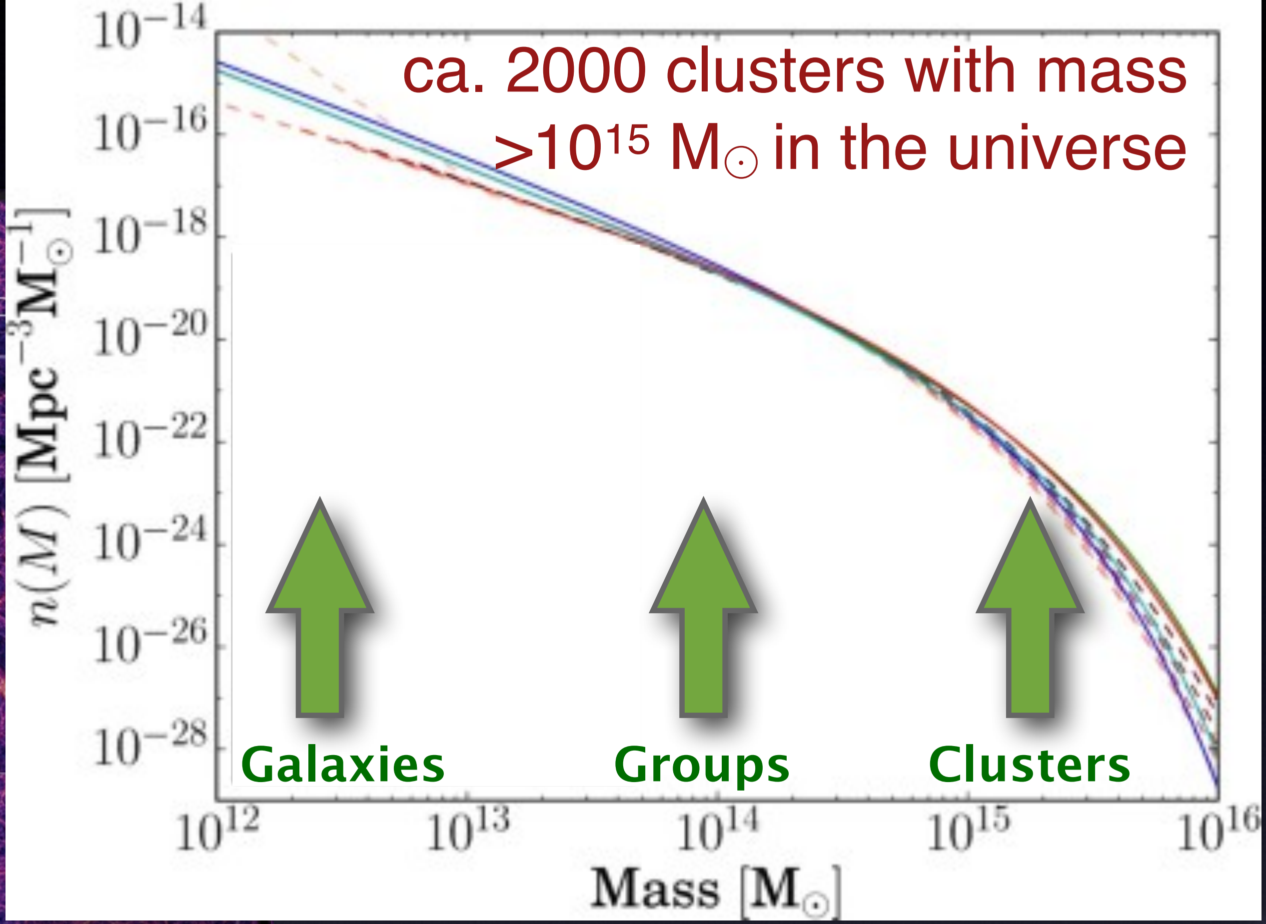
Impact of baryonic physics

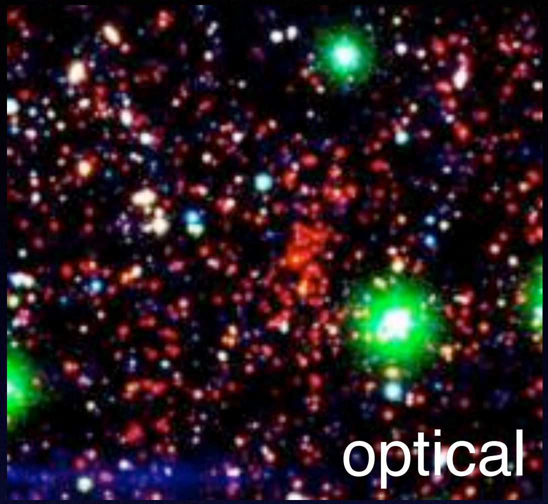


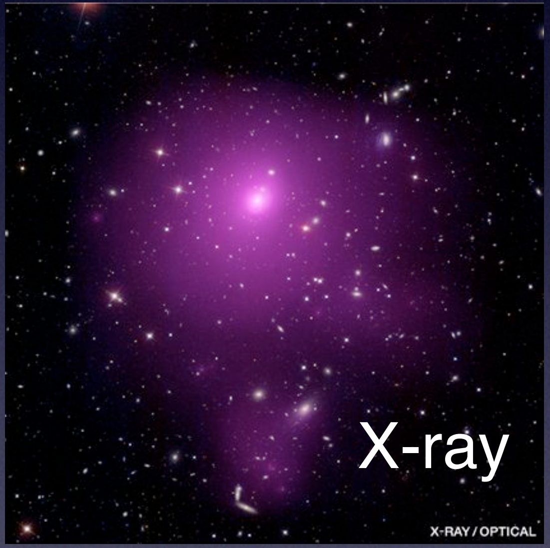
# Why Galaxy Clusters?

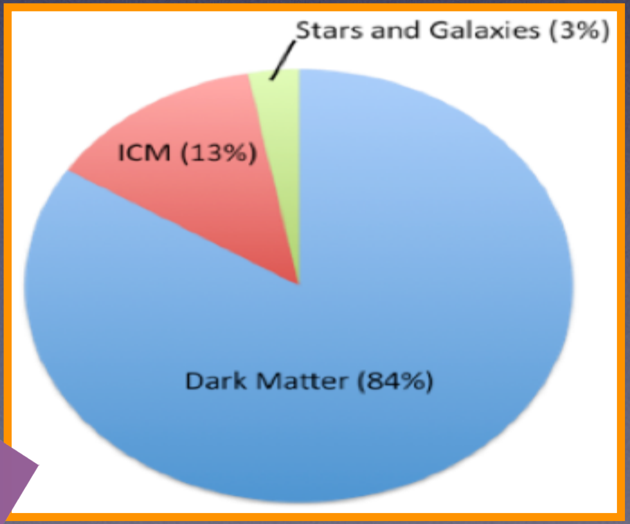
The “massive end” of the halo mass function.

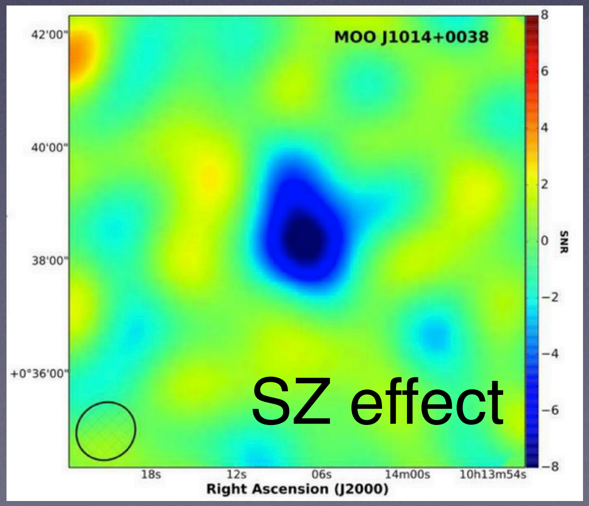



ca. 2000 clusters with mass $>10^{15}\ M_\odot$ in the universe

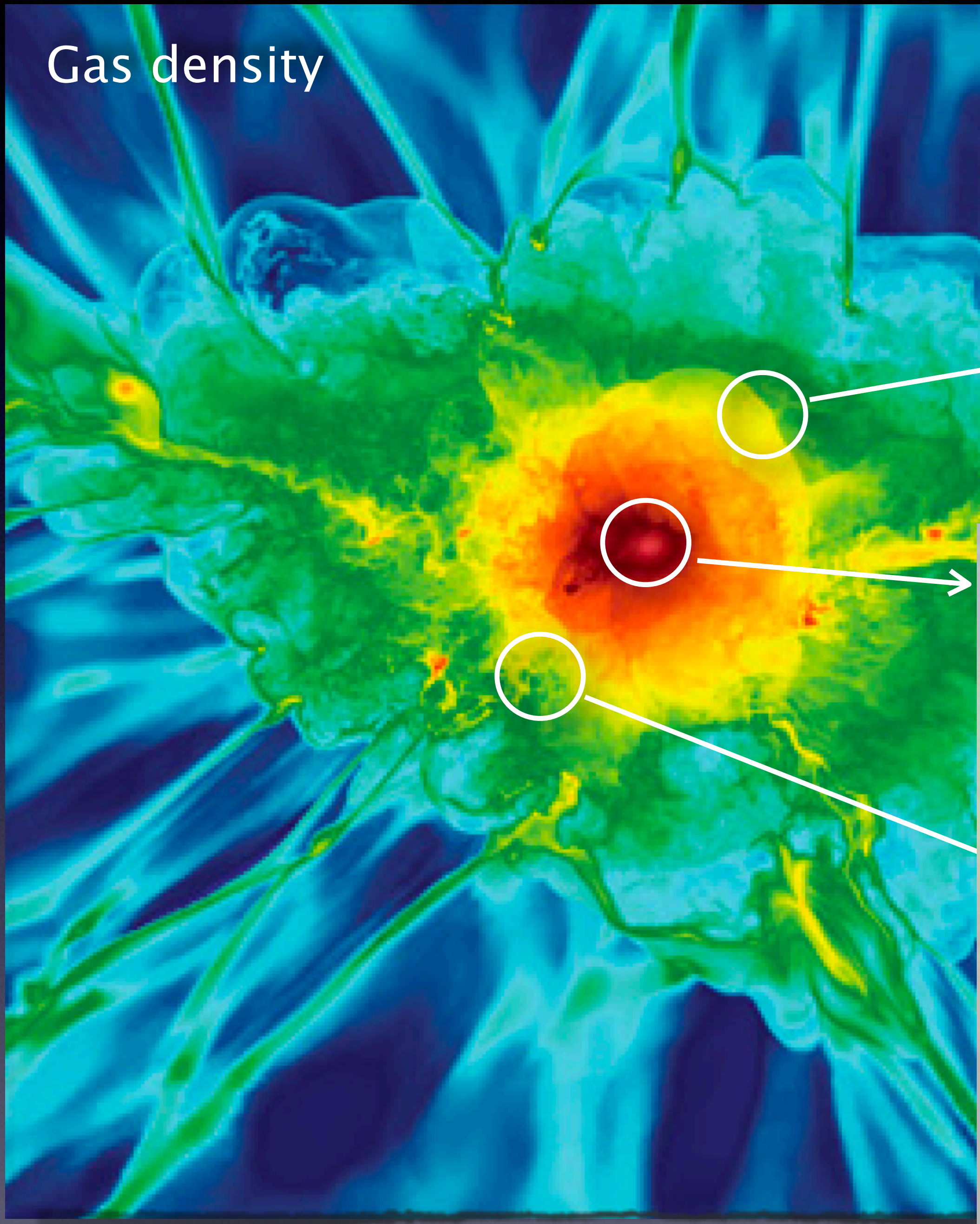




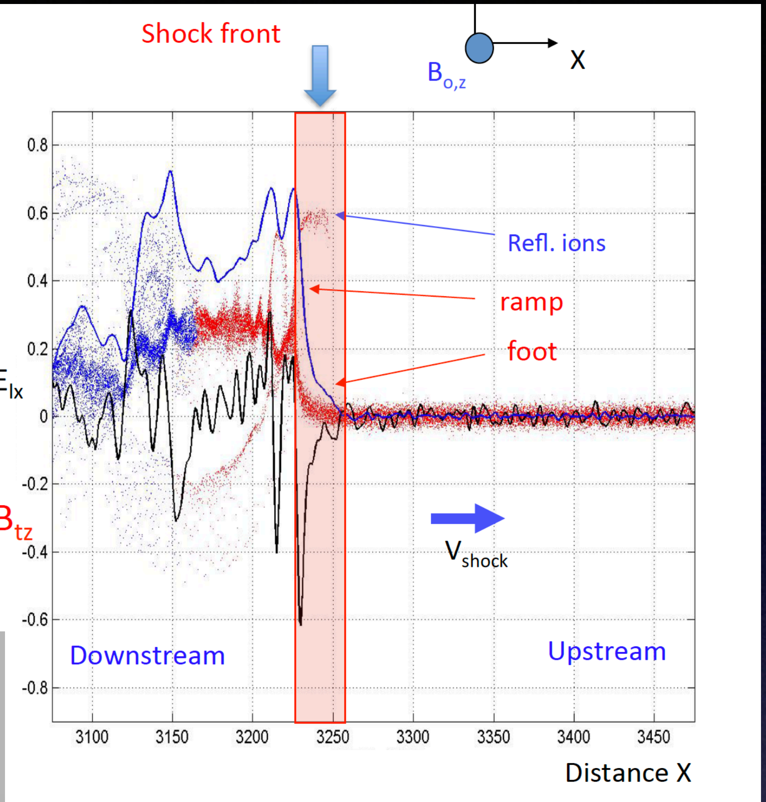




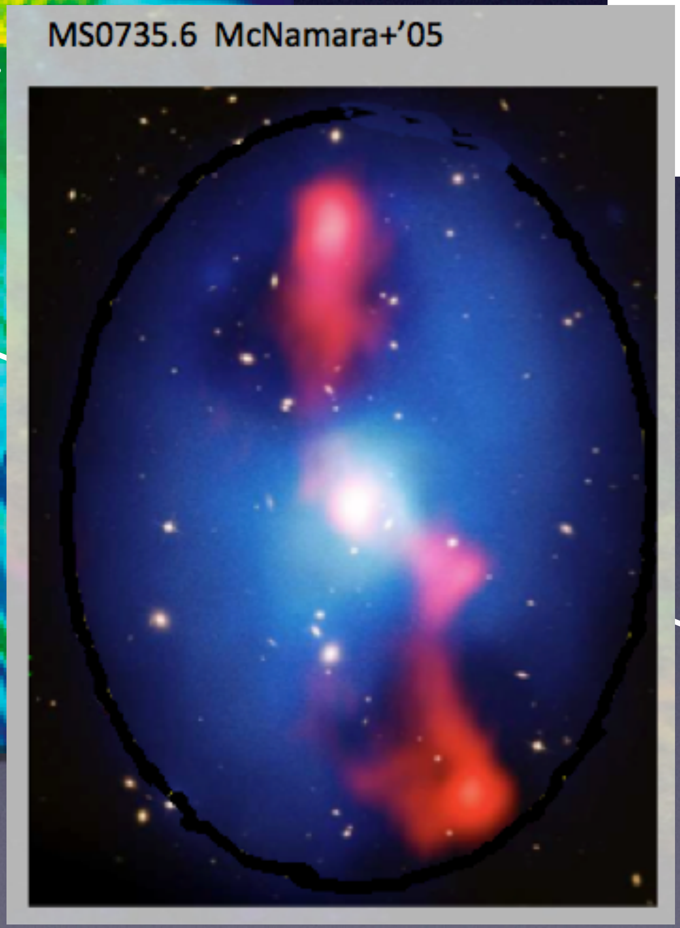
# Astrophysics of galaxy clusters

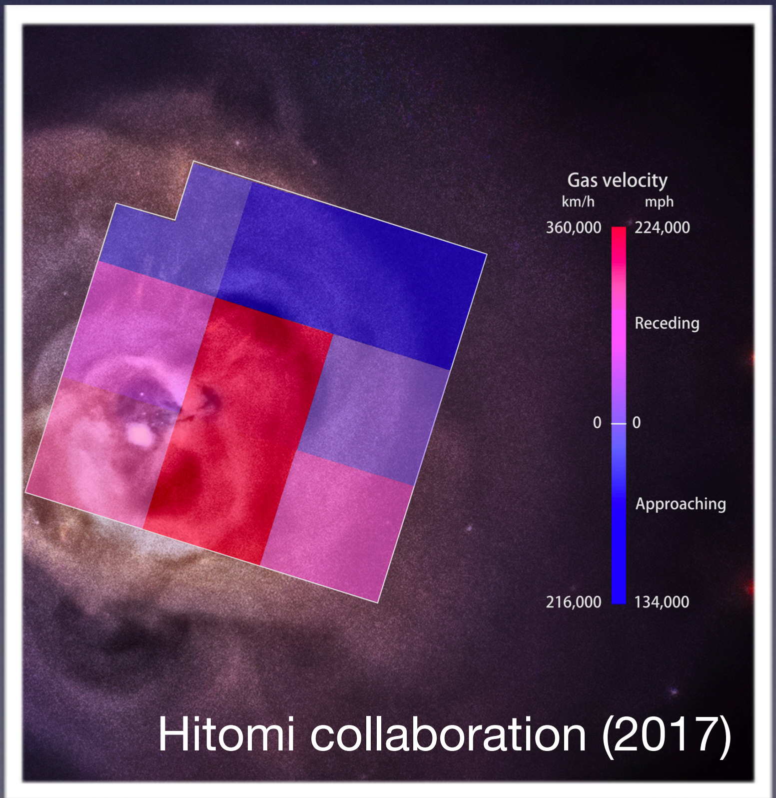


Matryoshka simulations (Miniati 2014)



Marcowith et al. (2012)

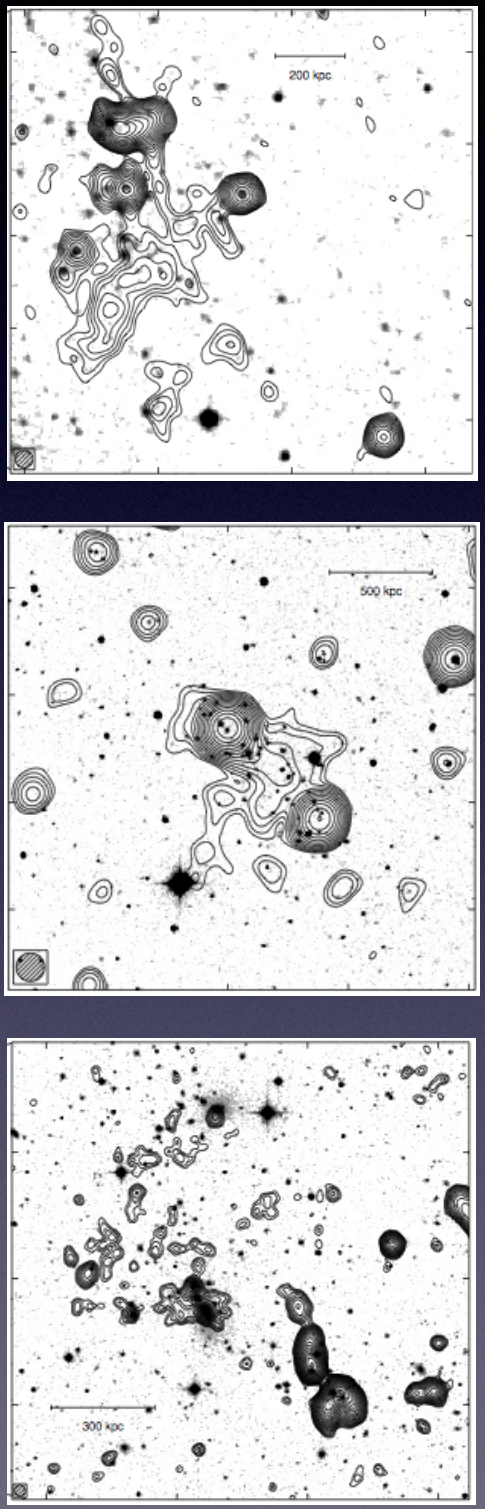


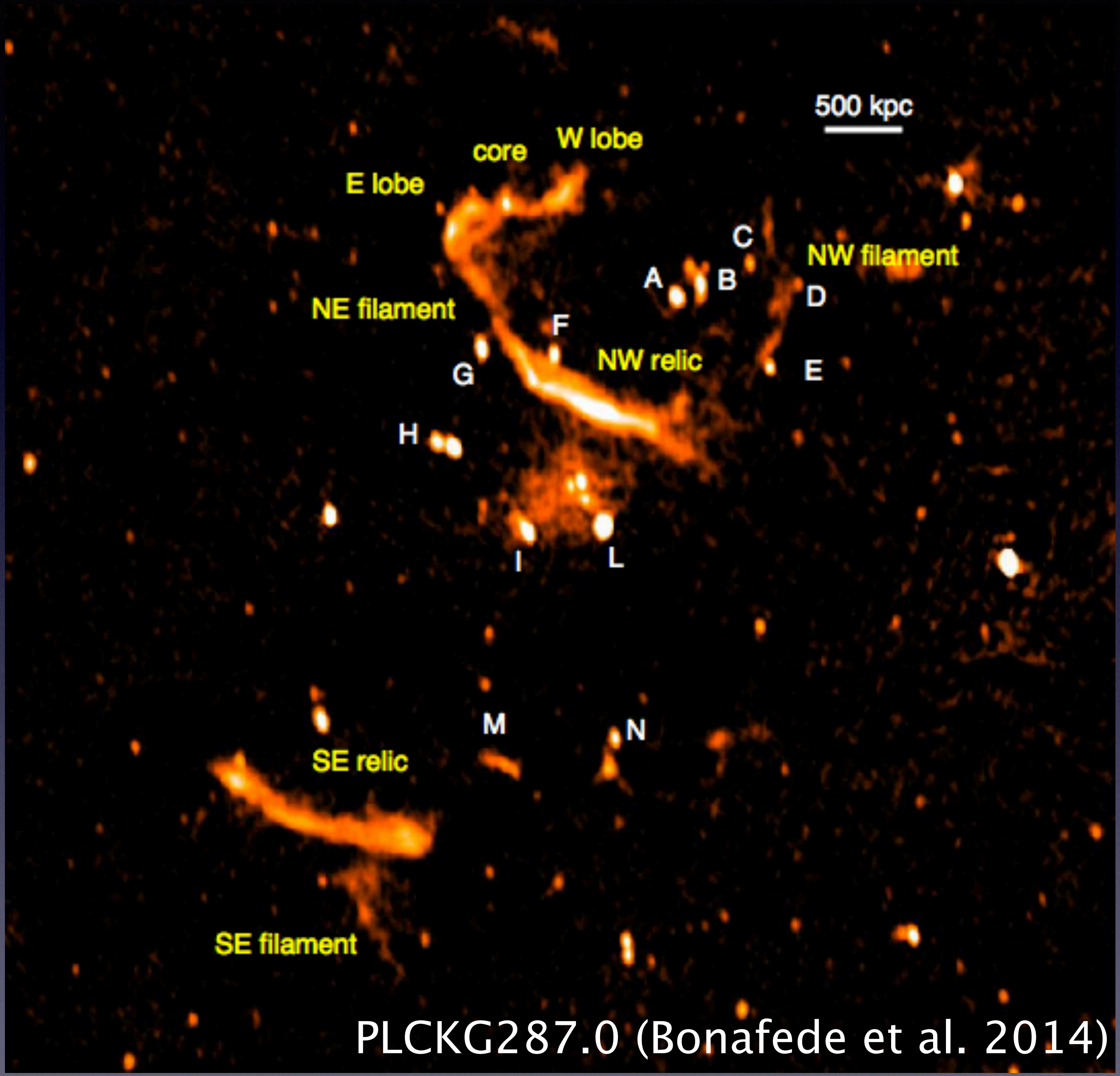


Hitomi collaboration (2017)

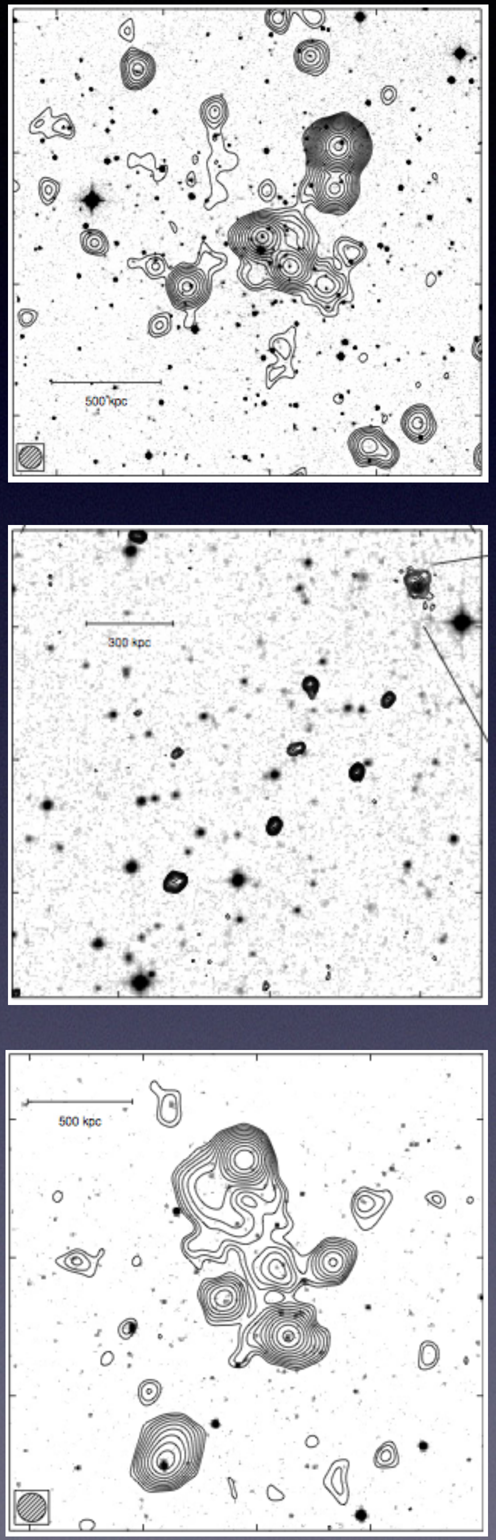
# Part I: Radio halos

# Radio emission from galaxy clusters





PLCKG287.0 (Bonafede et al. 2014)



All contour plots from Giovannini et al. (2009)

# The nonthermal ICM


CIZA J2242.8+5301
van Weeren et al. (2011)

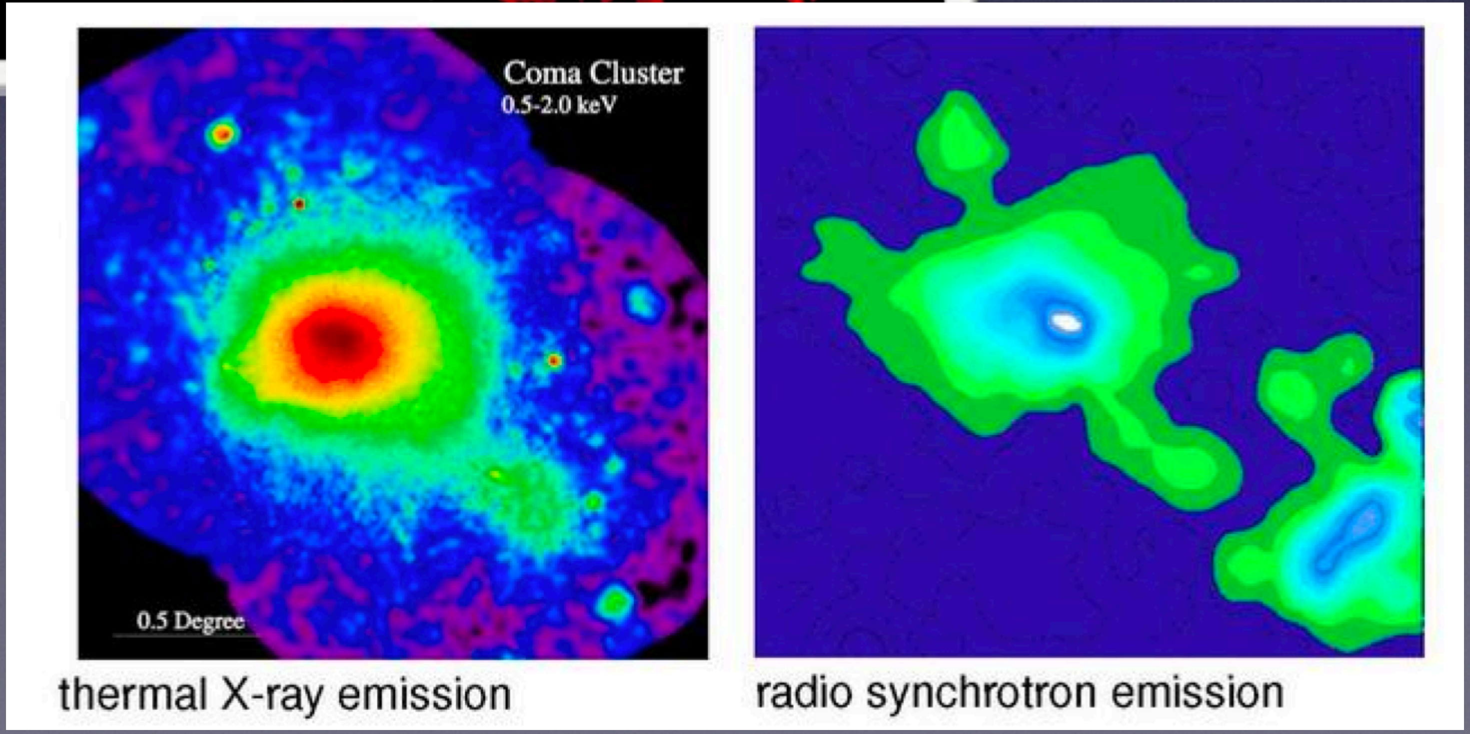
**AGN related**

Radio jets and lobes, WAT sources, plasma bubbles, AGN relics, radio BCGs, etc.


MS0735.6 McNamara+'05

**Diffuse radio emissions**

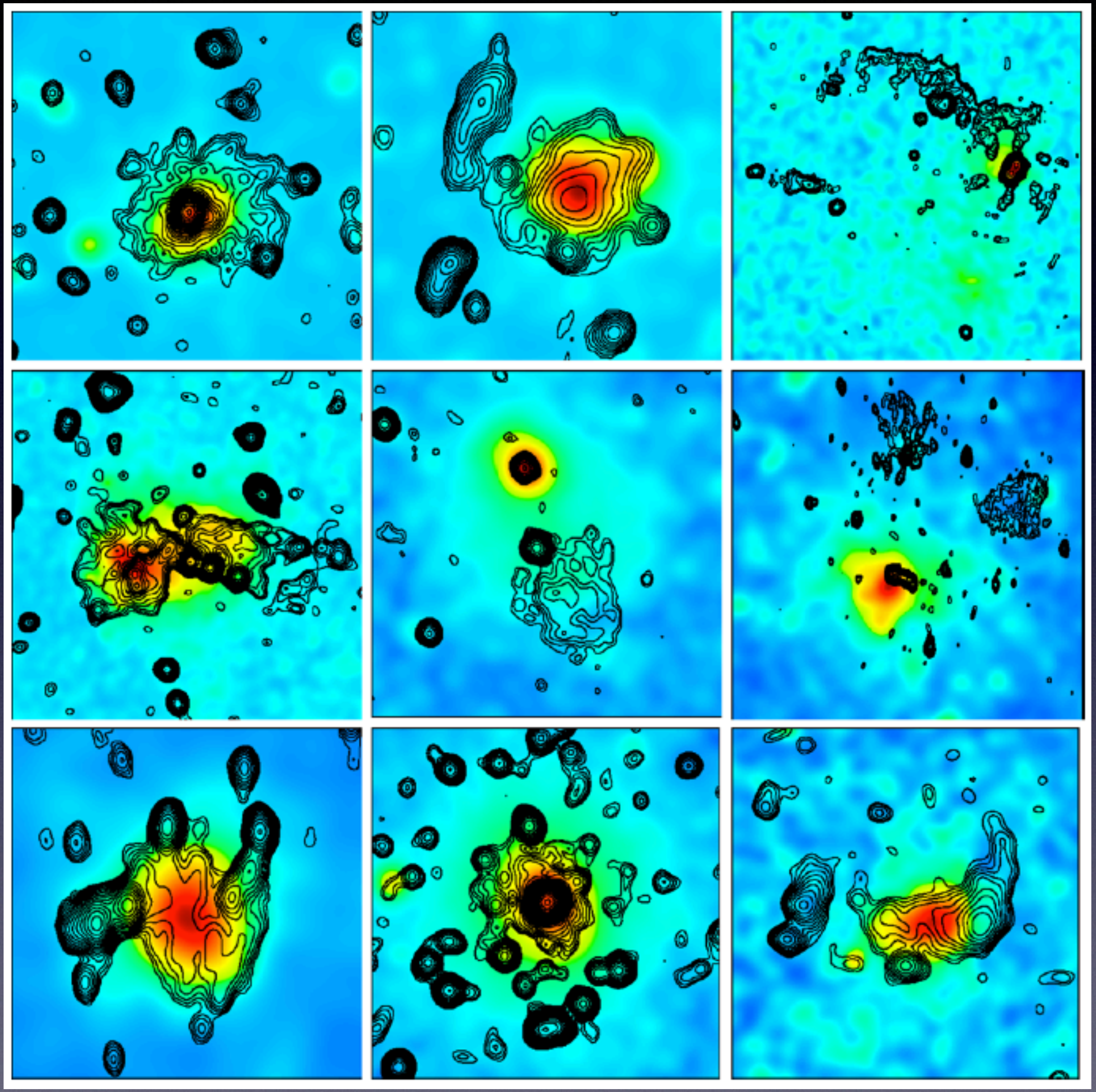
Radio halos, radio relics, mini halos, radio gischt, radio phoenix, etc.



thermal X-ray emission
radio synchrotron emission


3C75 in Abell 400
(Hudson et al. 2006)

# Radio halos and relics



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

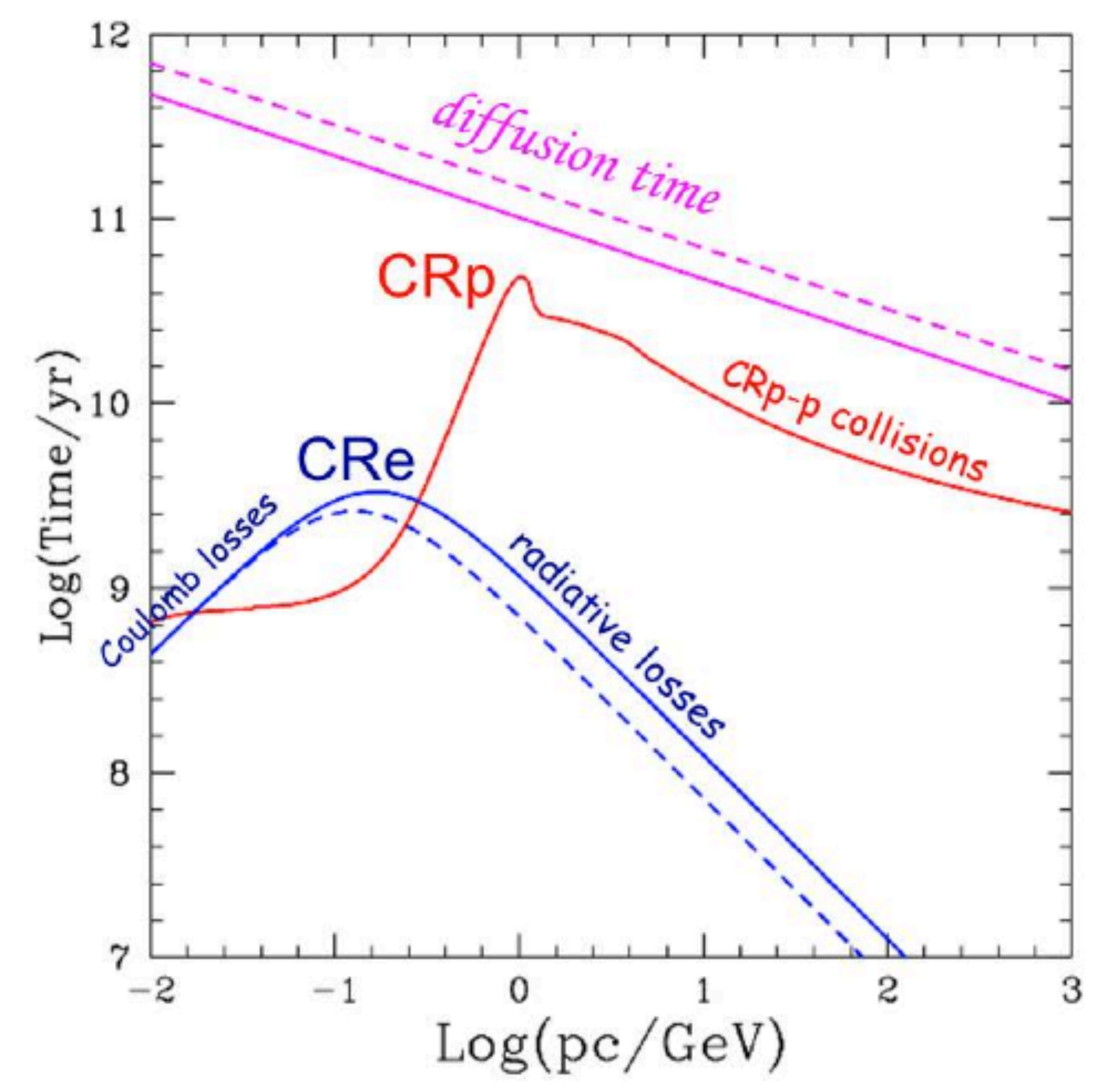
**Radio relics:** $L_{1.4\ \mathrm{GHz}} \sim 10^{23-25}$ W/Hz

- 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 "problem" with radio halos

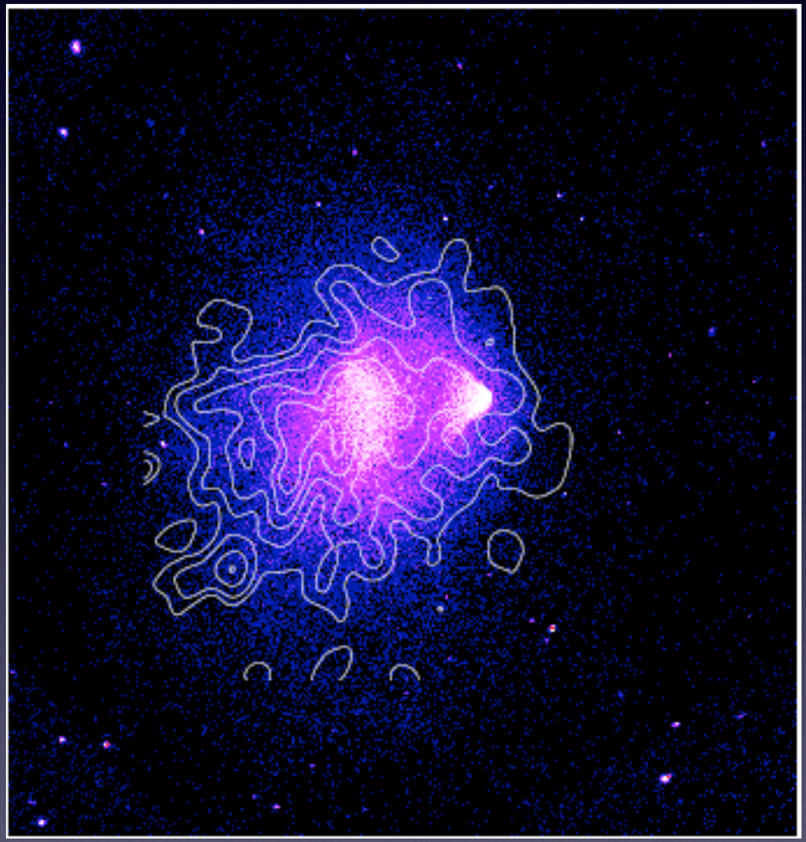
Radio halos imply GeV energy electrons filling up cluster volume (~ Mpc$^3$).
But CRe lifetimes are much shorter (~ $10^8$ years) than cluster dynamic timescales.

$t_{\text{merg.}}$ →



(Fig. from Brunetti & Jones 2014)

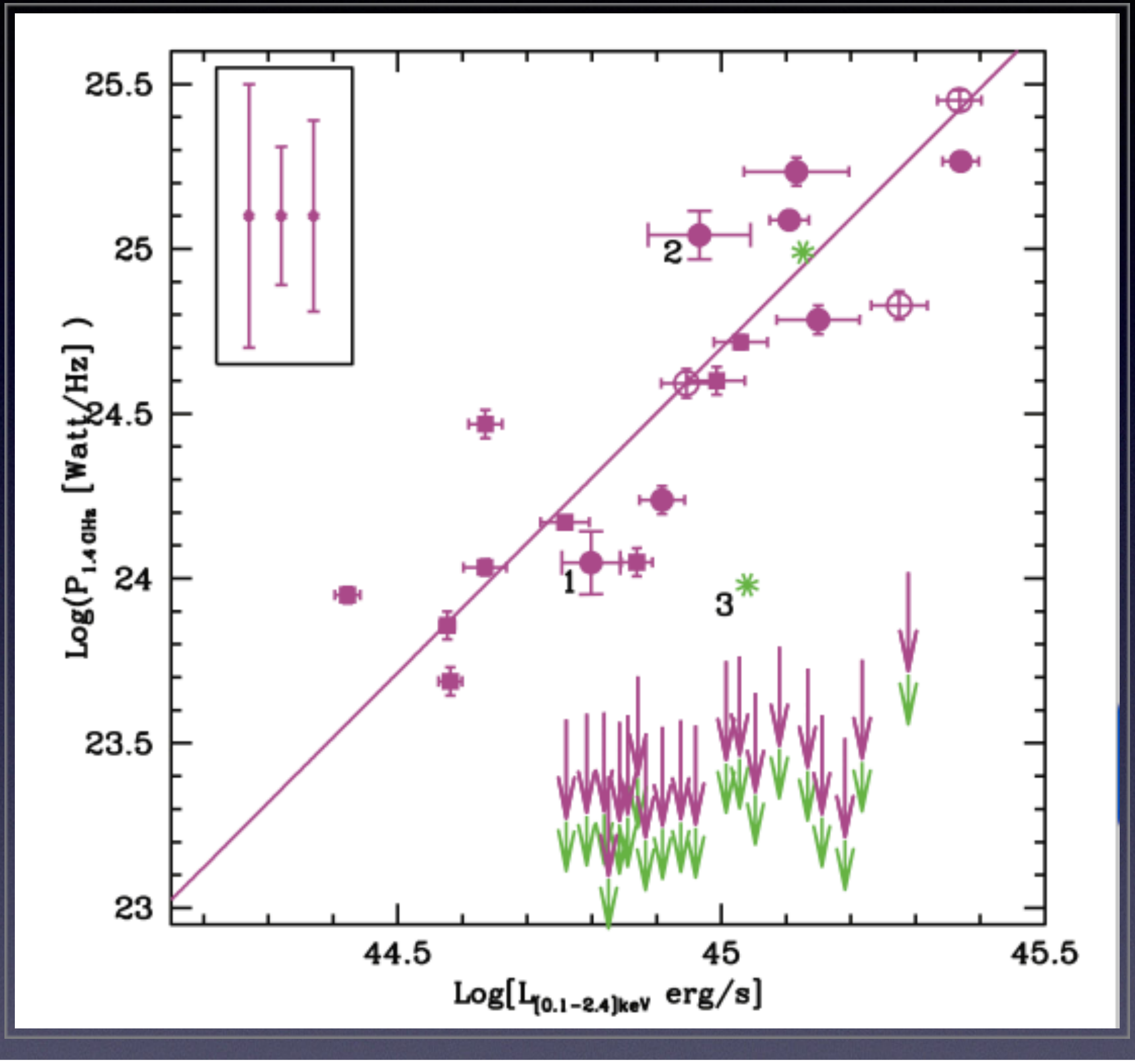
Some in-situ acceleration is necessary for the CRe



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

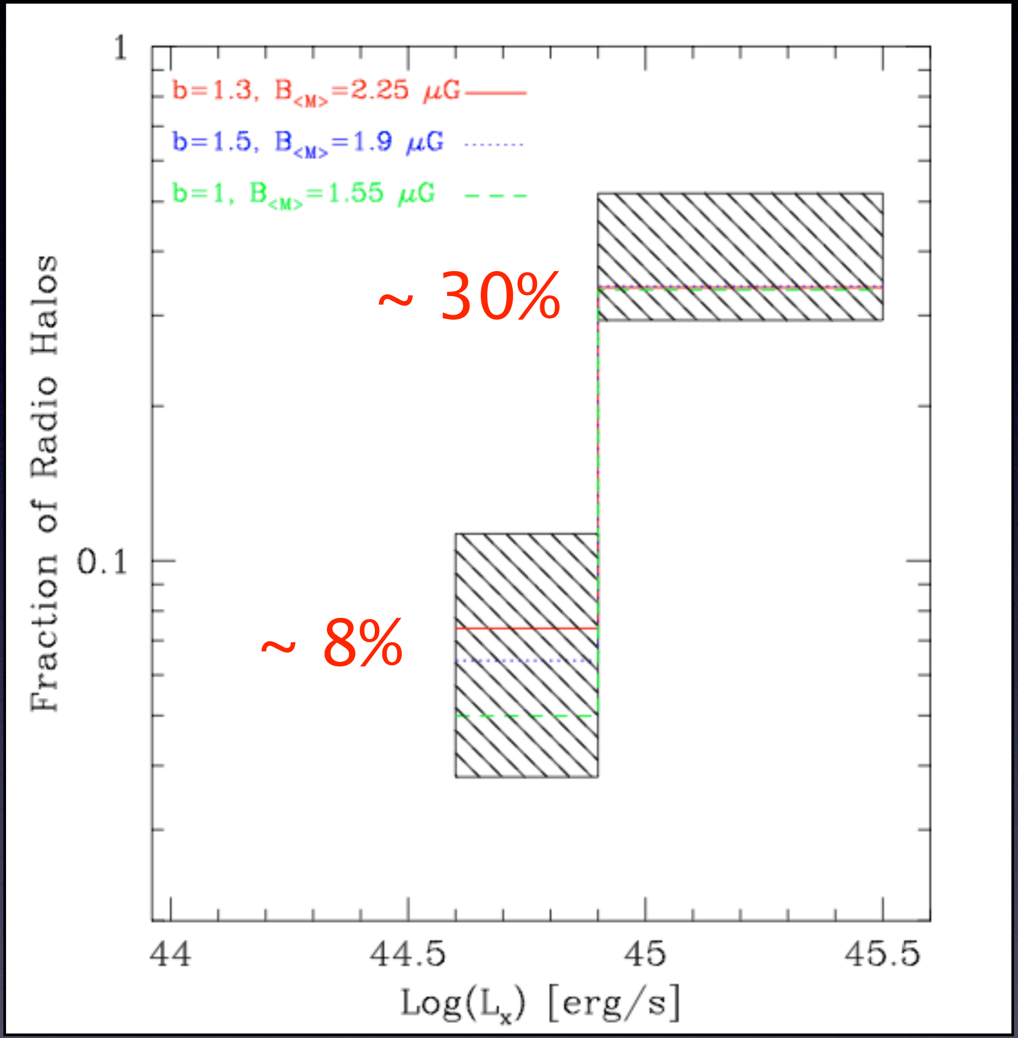
# The "consensus" for radio halos

There is a strong bi-modality



Brunetti et al. (2007)

They are rare ~60 known halos



Cassano et al. (2010)

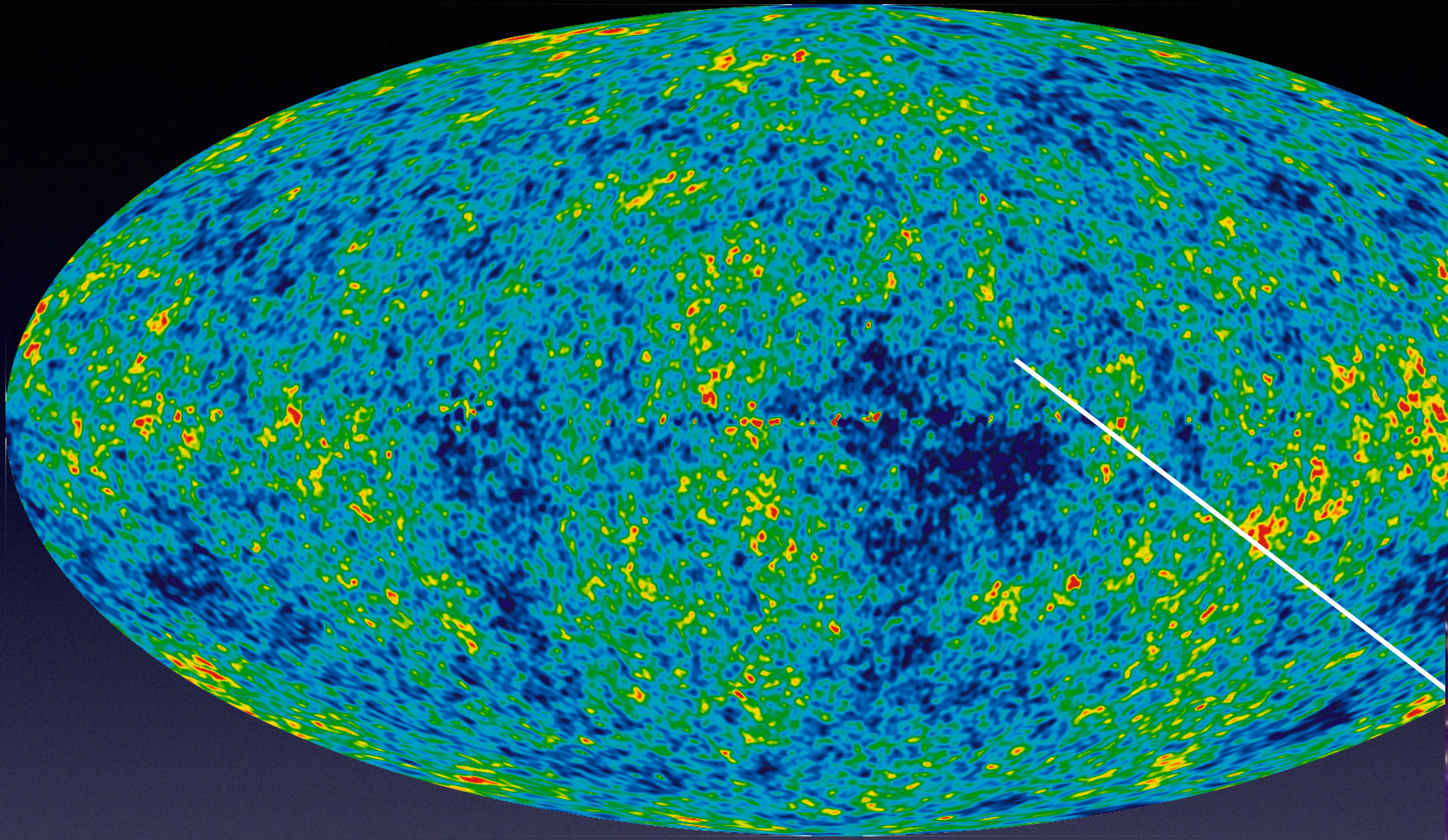
**Primary models** (or re-acceleration models):
electrons are accelerated in diffusive shocks via turbulence induced by cluster mergers, through inefficient Fermi-I process

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

**Two competing models for radio halo origin**
*(preference towards merger driven turbulence)*

# An “SZ take” on radio halos

# The Sunyaev-Zeldovich Effect



**tSZ Effect**

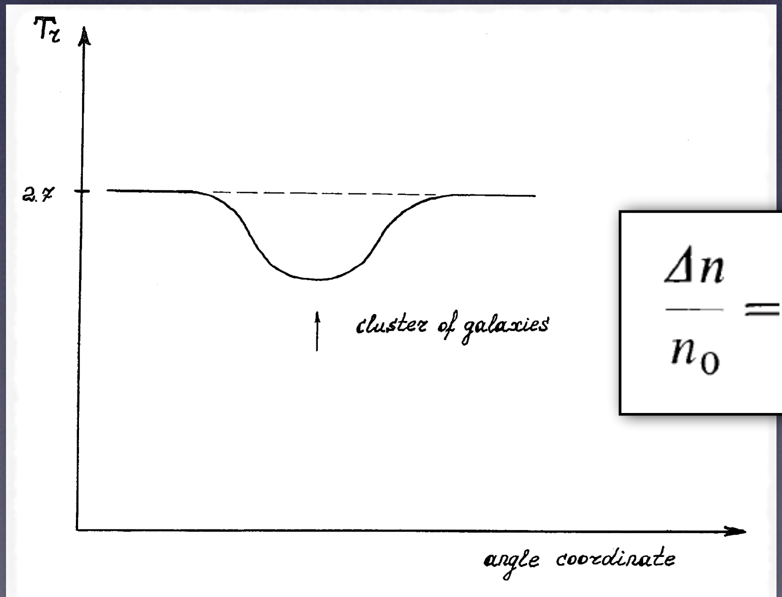
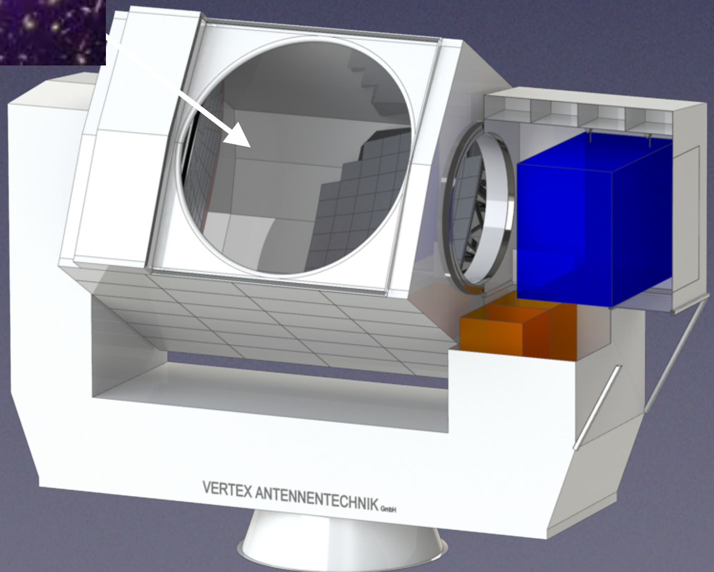


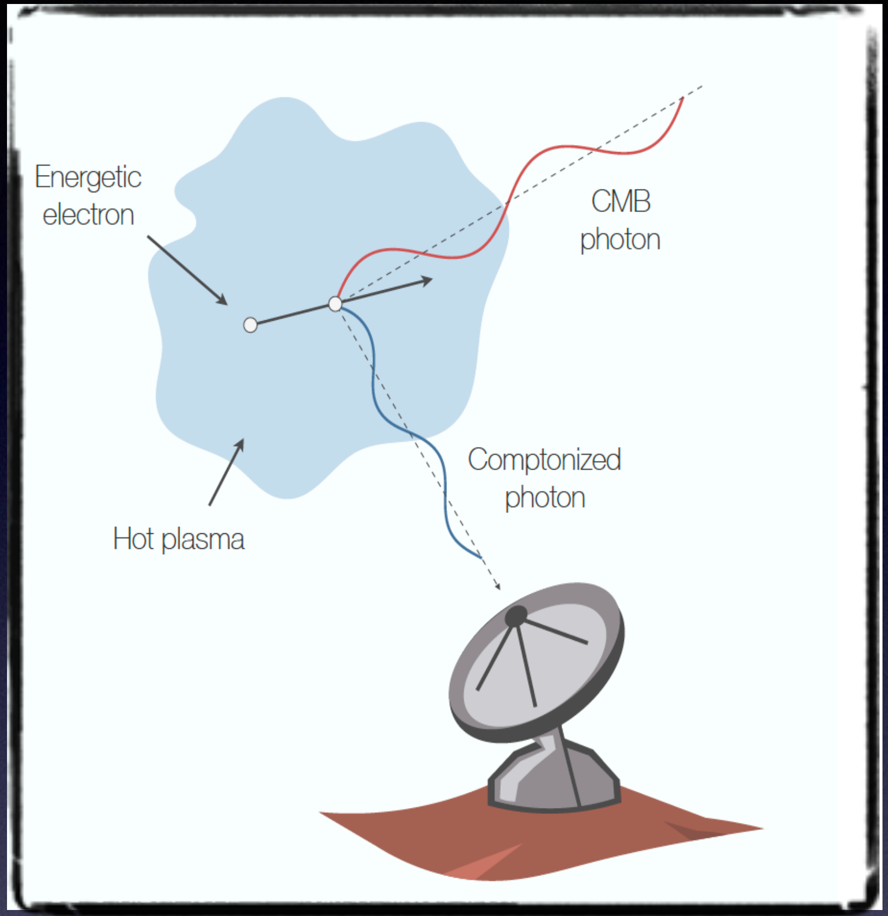
Fig. 1. The "hole" in the microwave background.

$$\frac{\Delta n}{n_0} = \frac{\Delta J}{J_0} = xy\,\frac{e^x}{e^x - 1}\left\{\frac{x}{\tanh(x/2)} - 4\right\}.$$

**R. A. Sunyaev & Ya. B. Zeldovich**
**Comments on Astrophysics & Space Physics, 1972**



# The Sunyaev-Zeldovich effect

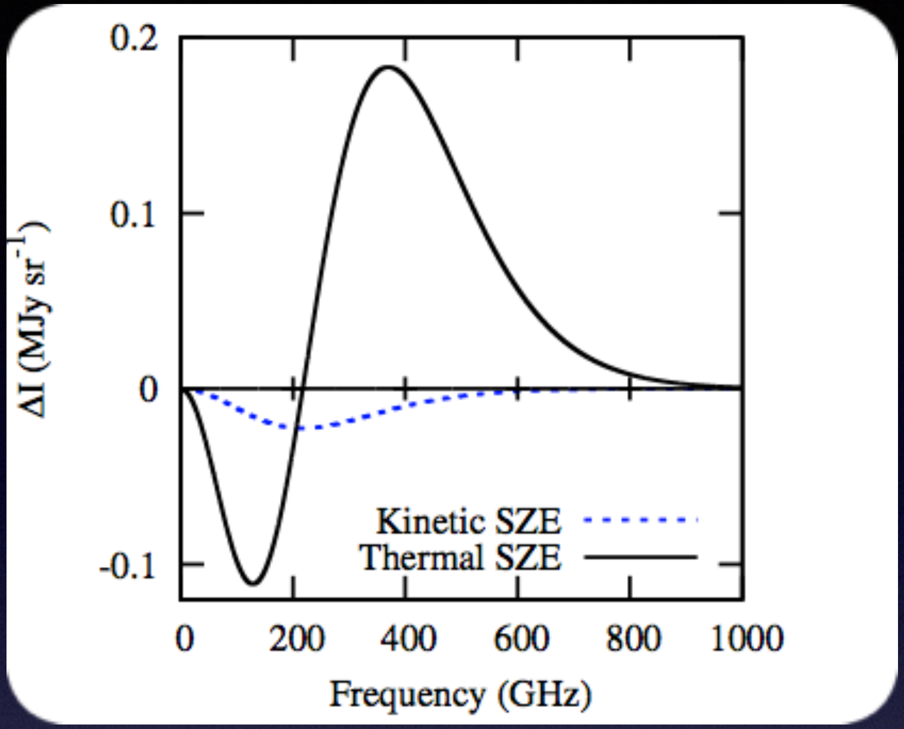


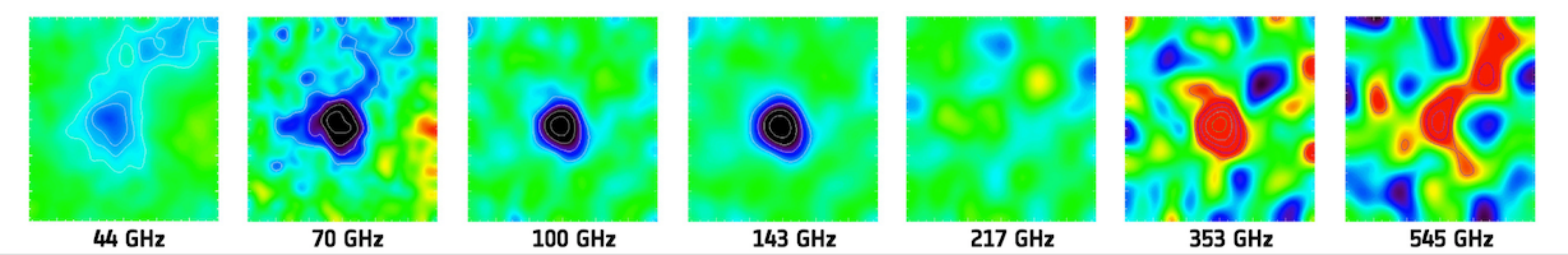
Carlstrom et al.

Inverse Compton scattering producing unique spectral distortion on the background CMB.

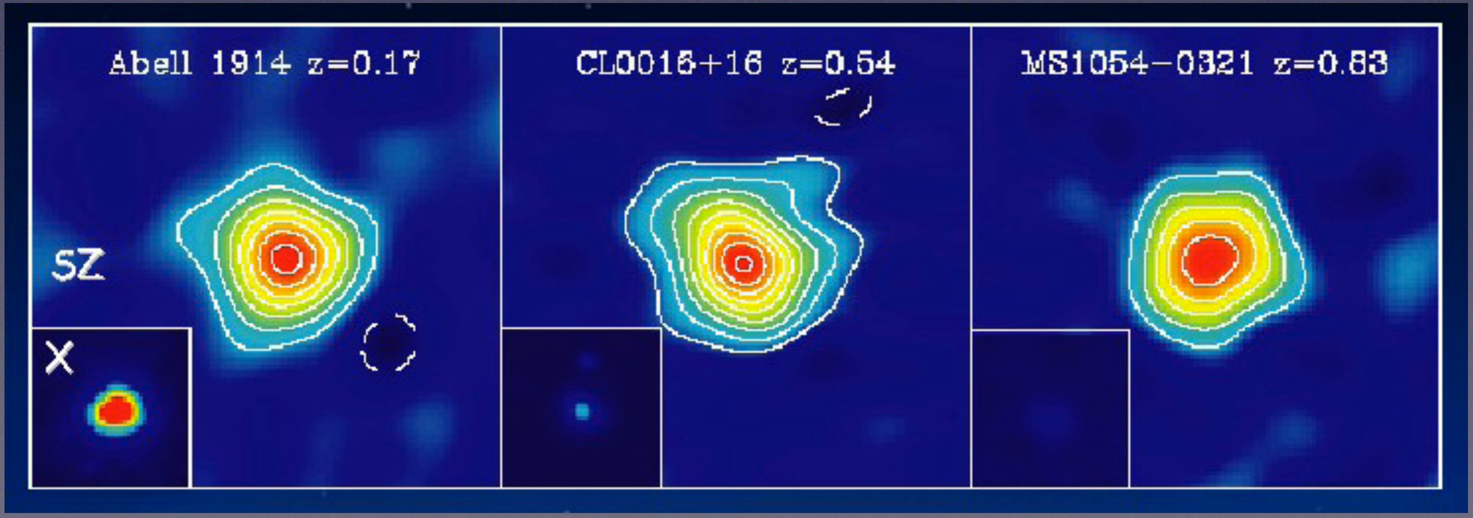
An ideal tool for finding and characterizing galaxy clusters.

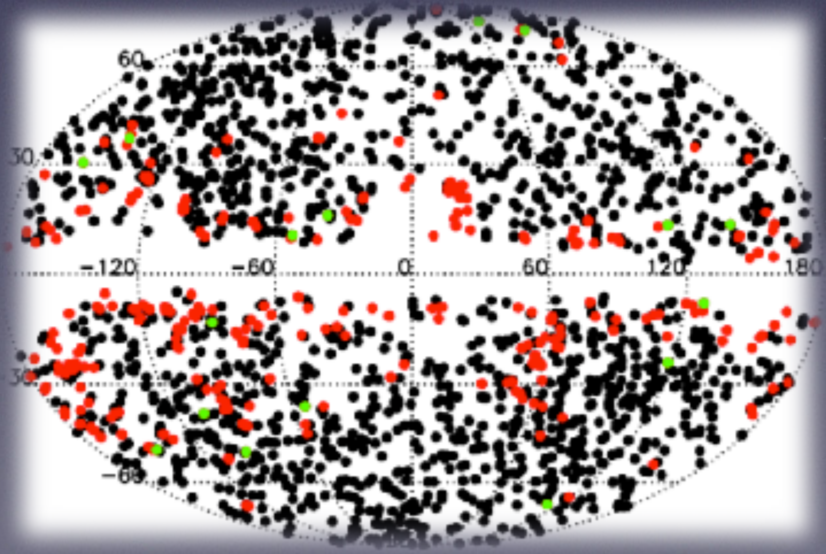
Resolved source flux is redshift independent and scales linearly with the gas density!

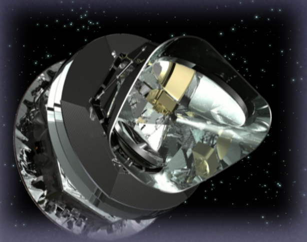




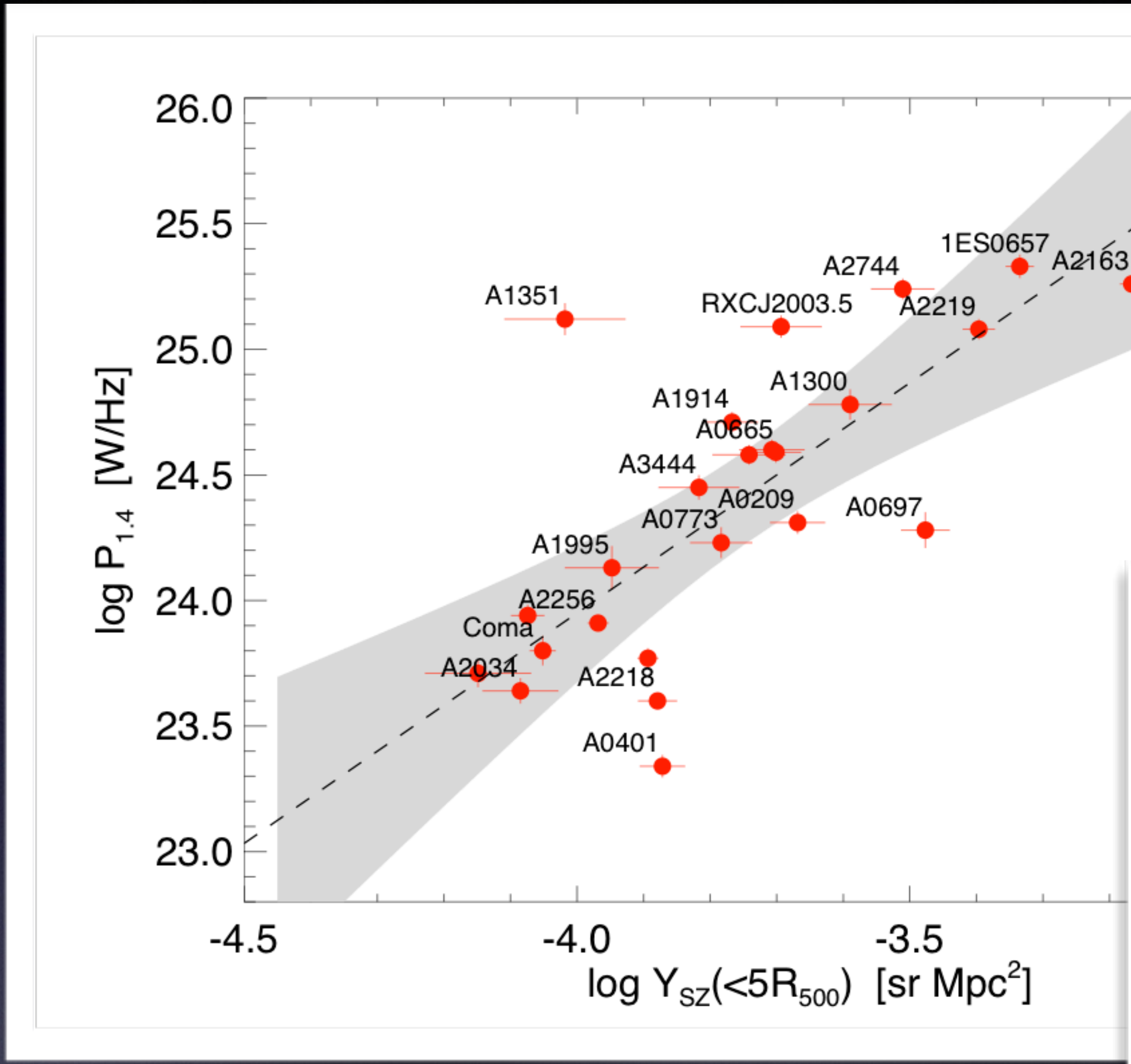
Credit: Planck collaboration





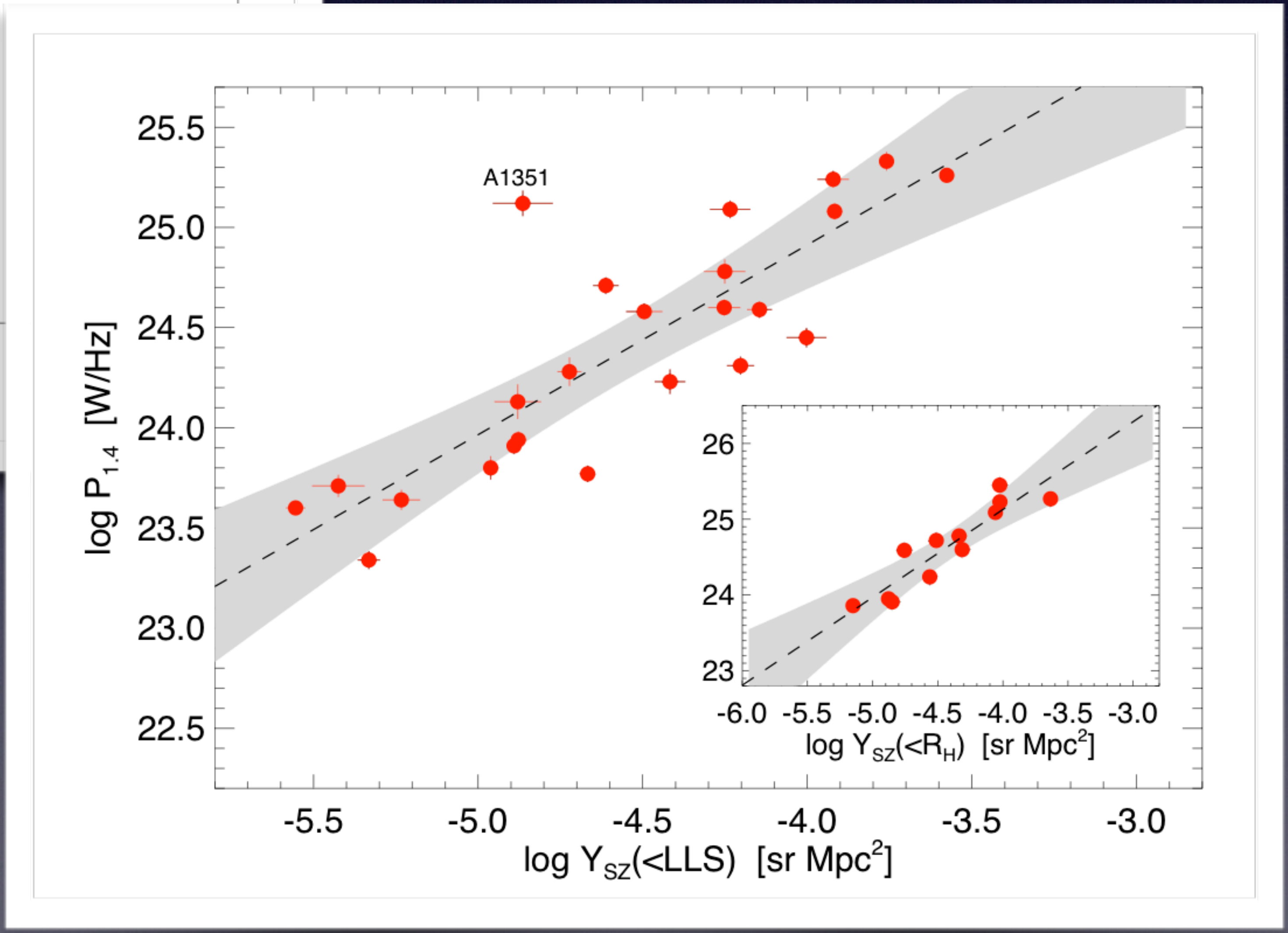


# SZ correlation for radio halos



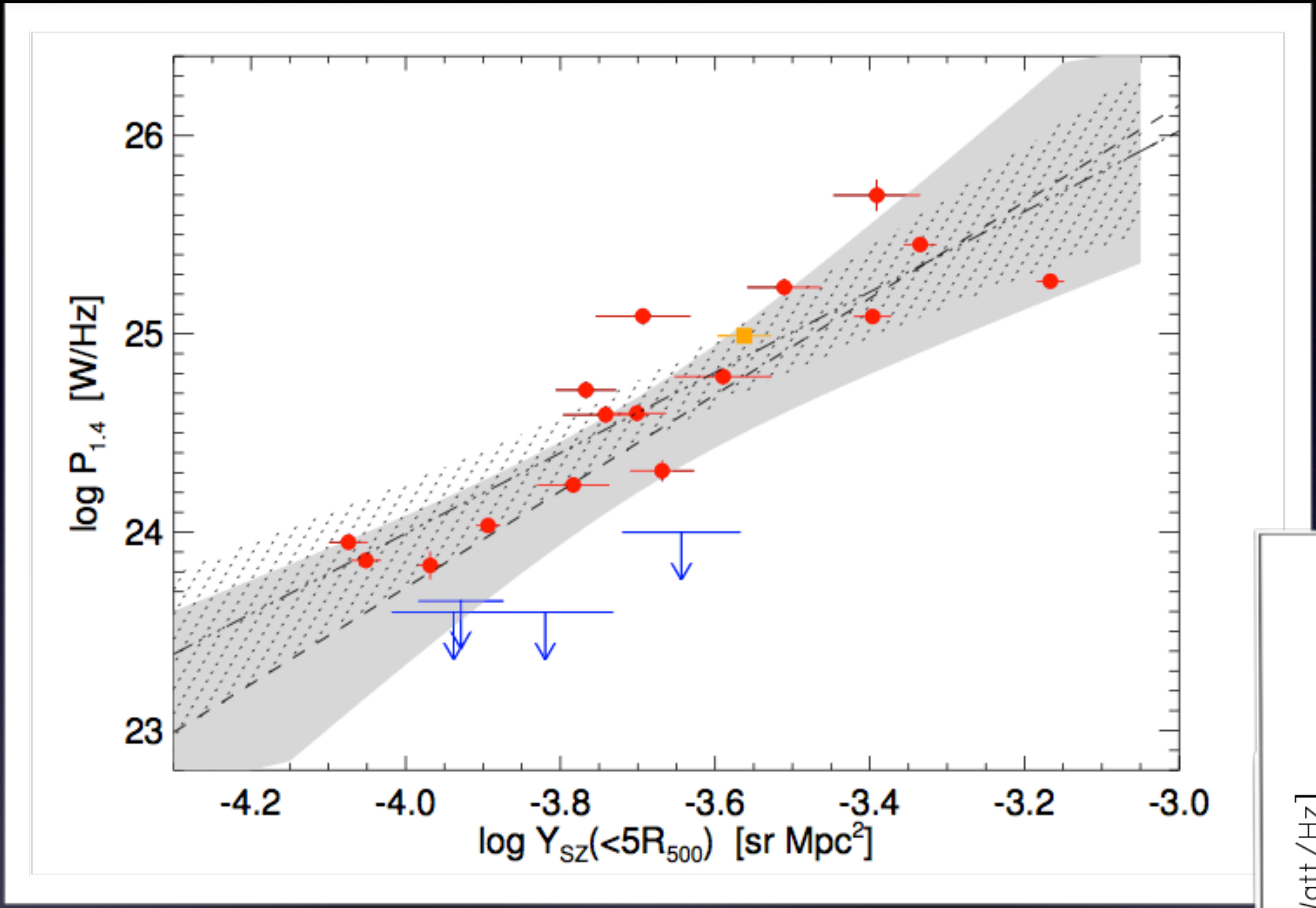
The cluster SZ signal and radio halo power are correlated (as expected from known X-ray correlation)

Basu (2012)



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

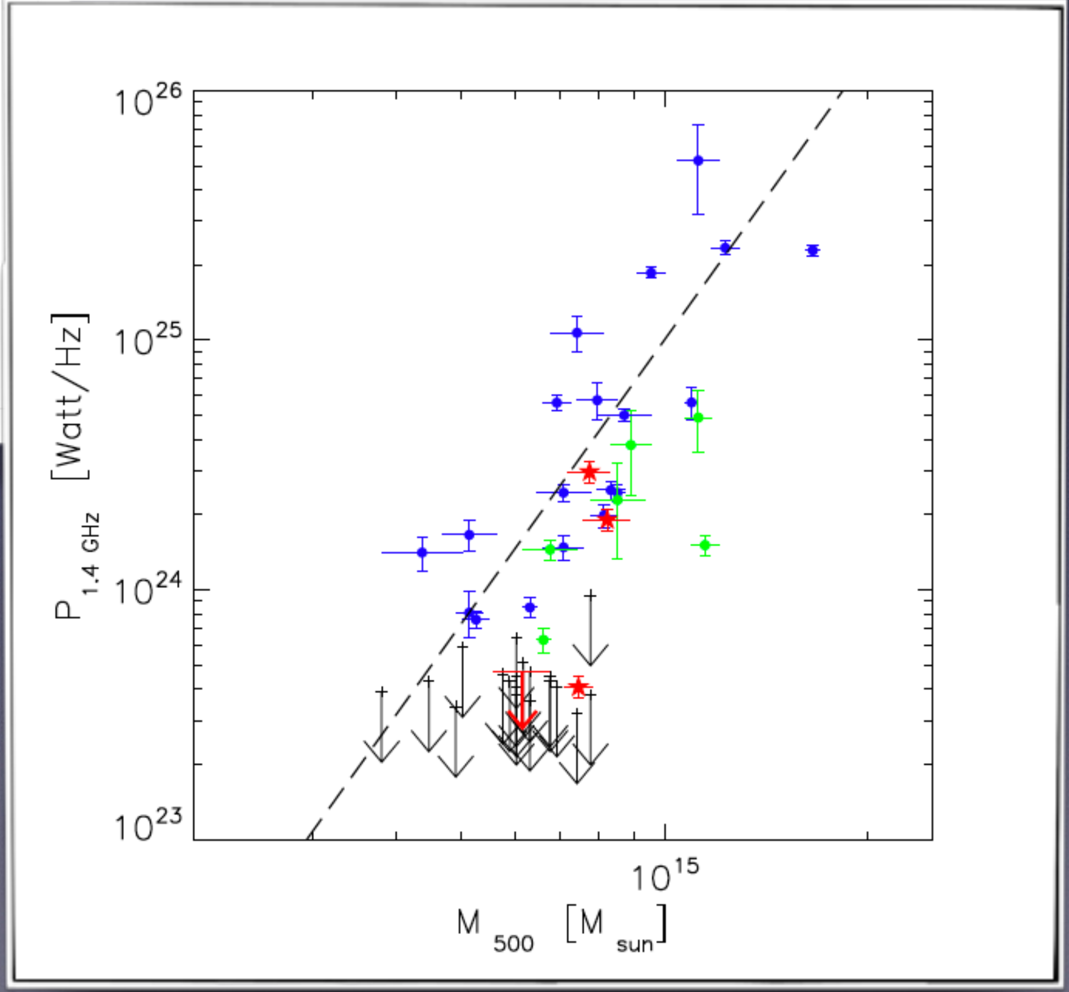
# No strong evidence for bimodality



Basu (2012)

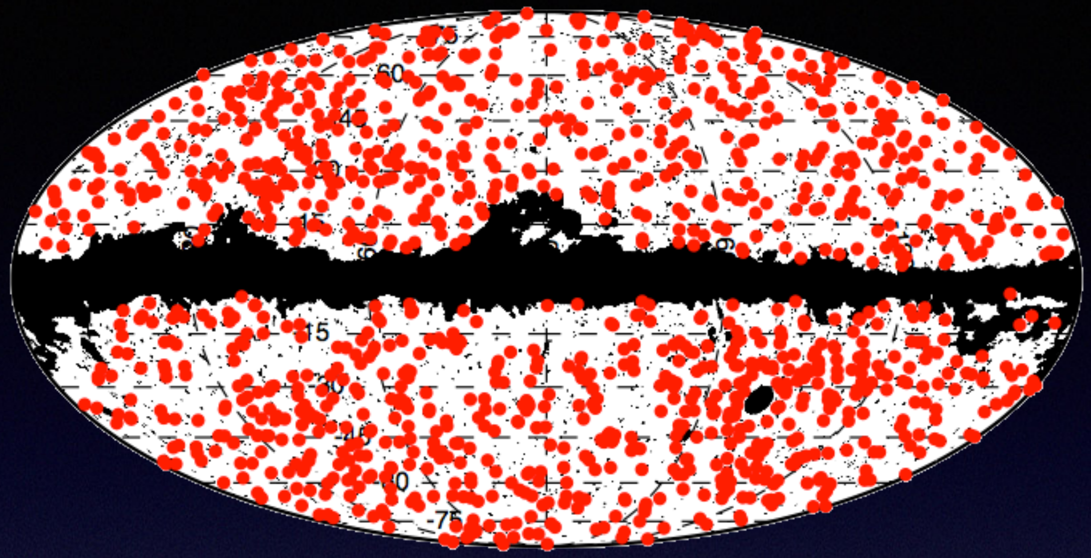
We found from a posteriori selection of radio halo clusters, taken from the Planck catalog, that the bi-modality is weak in the radio-SZ correlation.

This has now been independently verified by many other researchers!



Bonafede et al. (2015)
RHs from *Planck* cluster catalog

# Comparison between SZ/X-ray selection



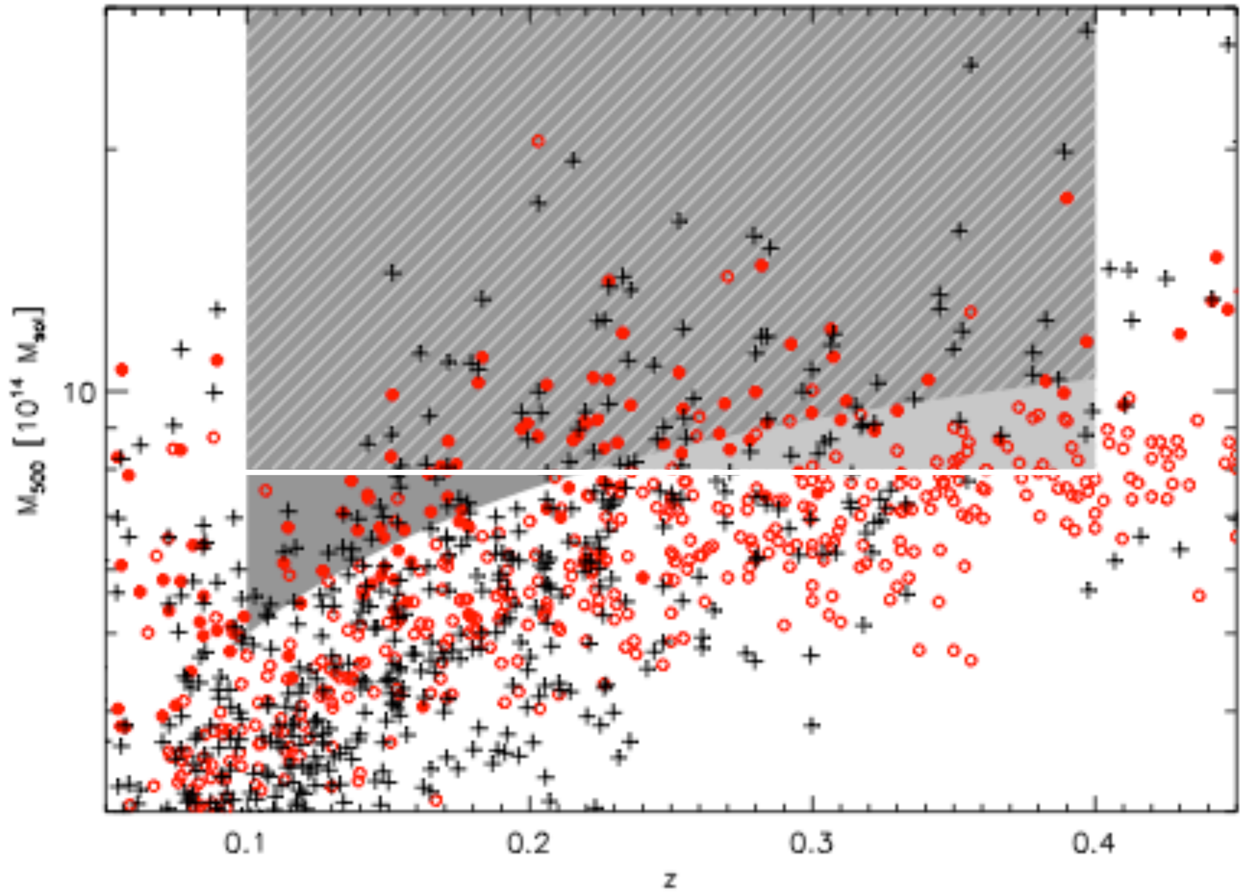
PSZ clusters (Planck coll. 2013)

We used low-sensitivity NVSS survey data to characterize radio halos. Most of these were non-detections, so we developed a regression method to particularly deal with that.

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.

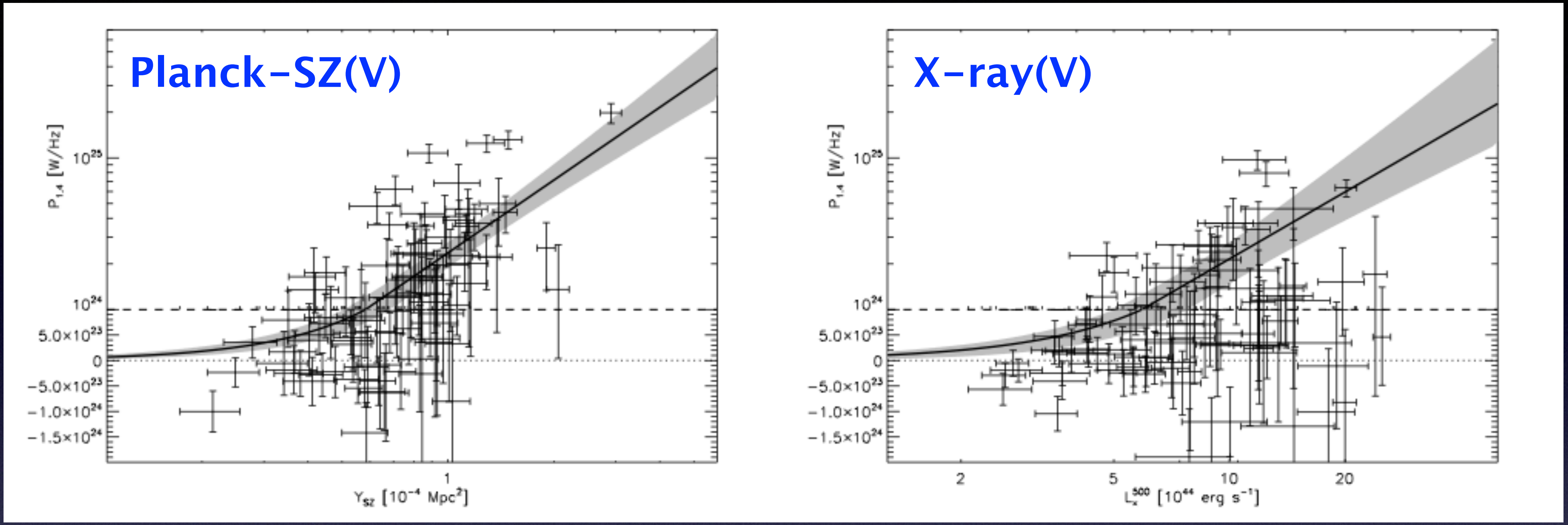
| Sub-sample | Mass limit | Primary selection | Flagged due to bad data | Final sample |
|---|---|---|---|---|
| PSZ(V) | $z$-dependent | 90 | 1 | 89 |
| X(V) | $z$-dependent | 86 | 1 | 85 |
| PSZ(C) | $8 \times 10^{14} M_\odot$ | 79 | 0 | 79 |
| X(C) | $8 \times 10^{14} M_\odot$ | 78 | 1 | 77 |

PSZ and REFLEX+eBCS+MACS



Sommer & Basu (2014)

# SZ vs X-ray selection



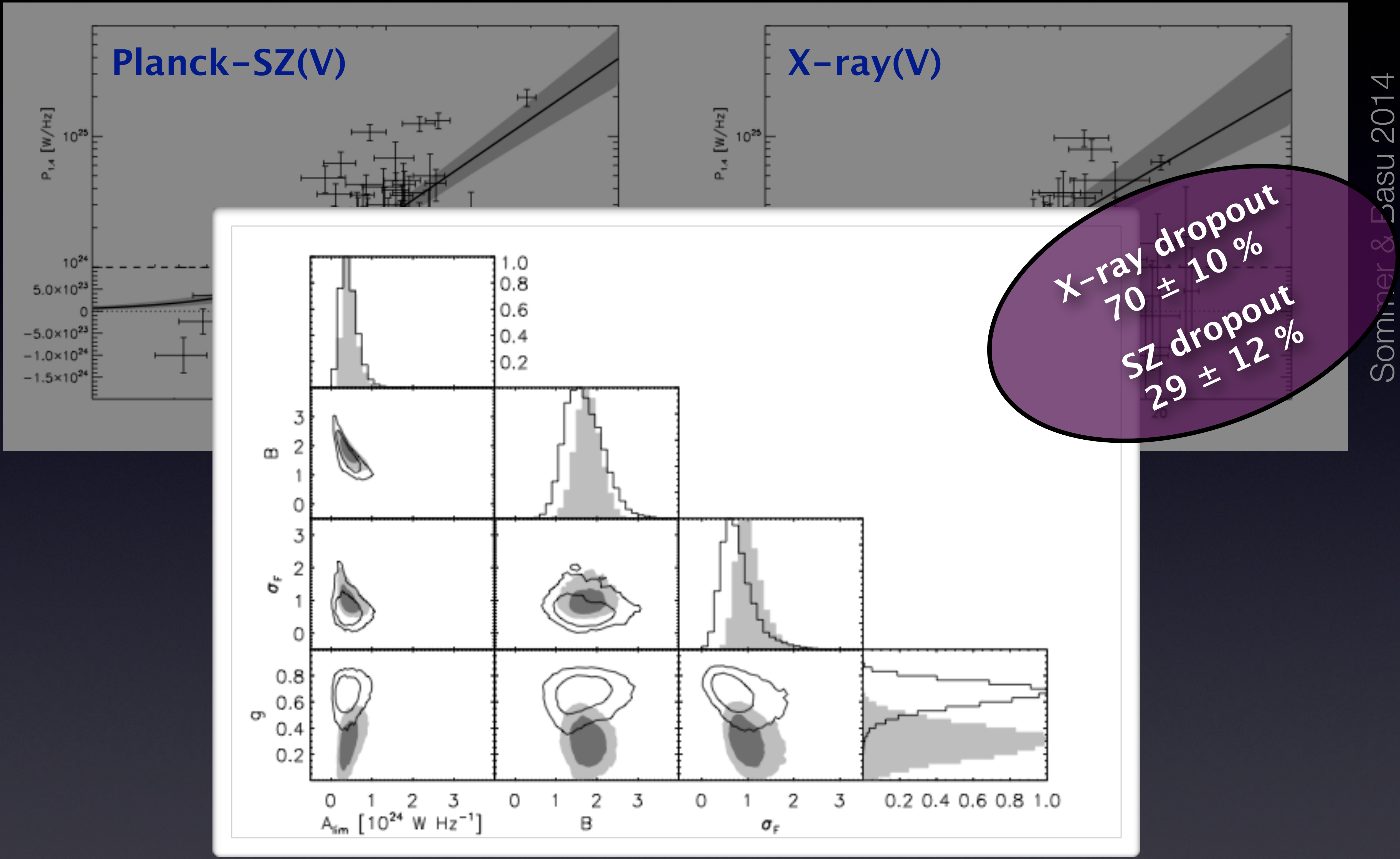
Sommer & Basu 2014

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!

# SZ vs X-ray selection



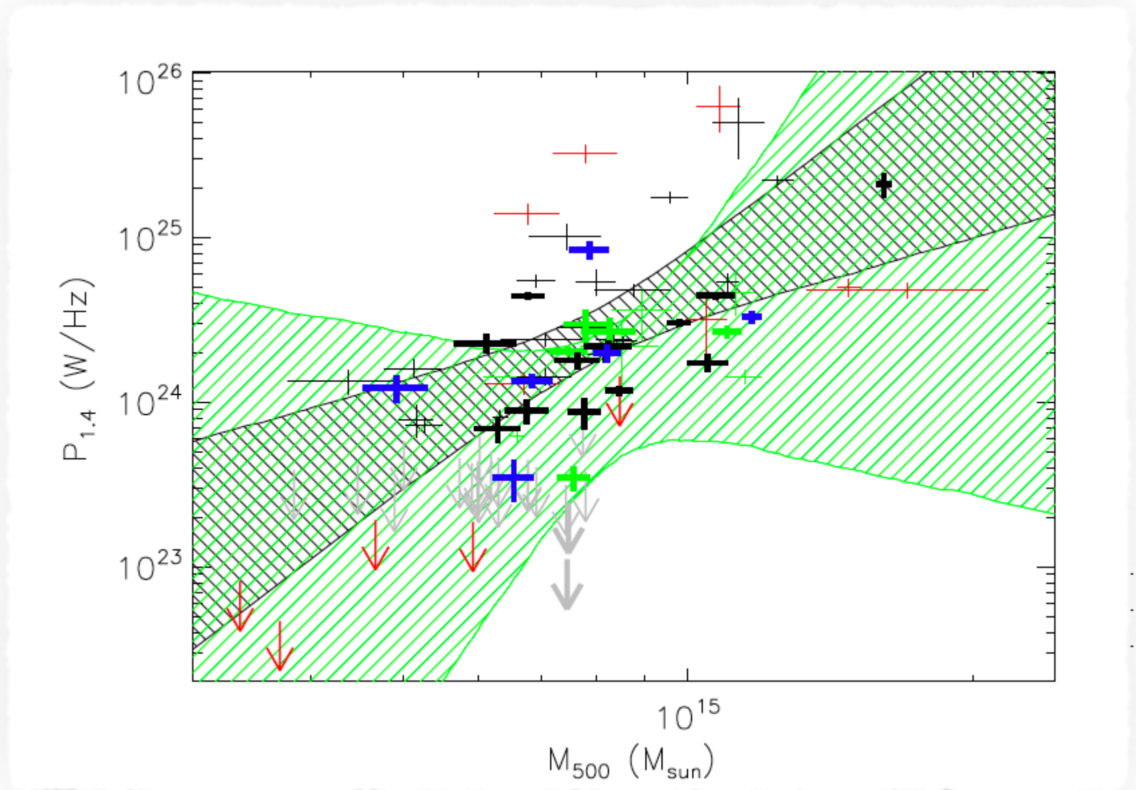
X-ray dropout 70 ± 10 %

SZ dropout 29 ± 12 %

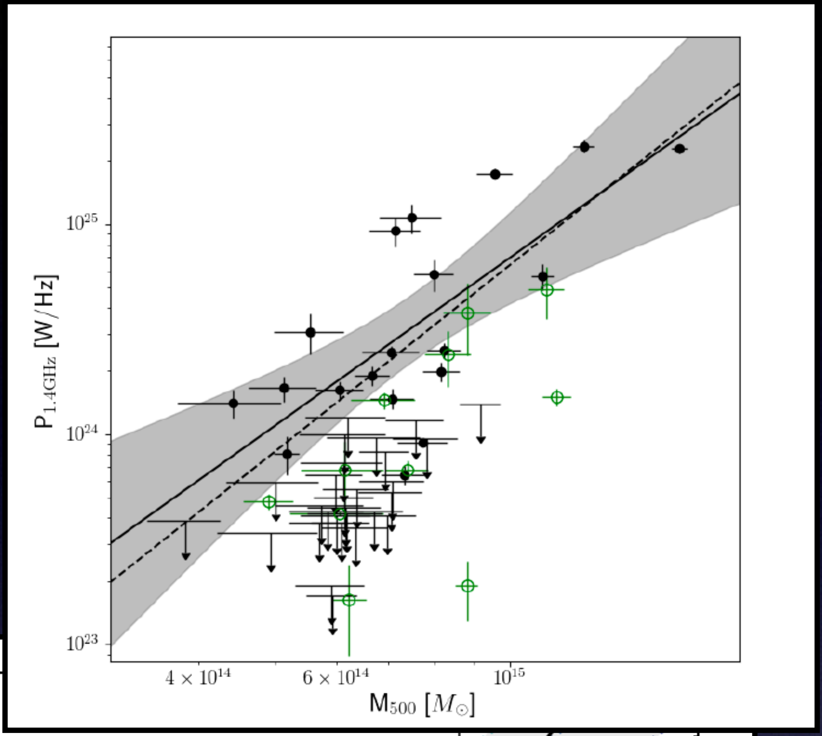
Sommer & Basu 2014

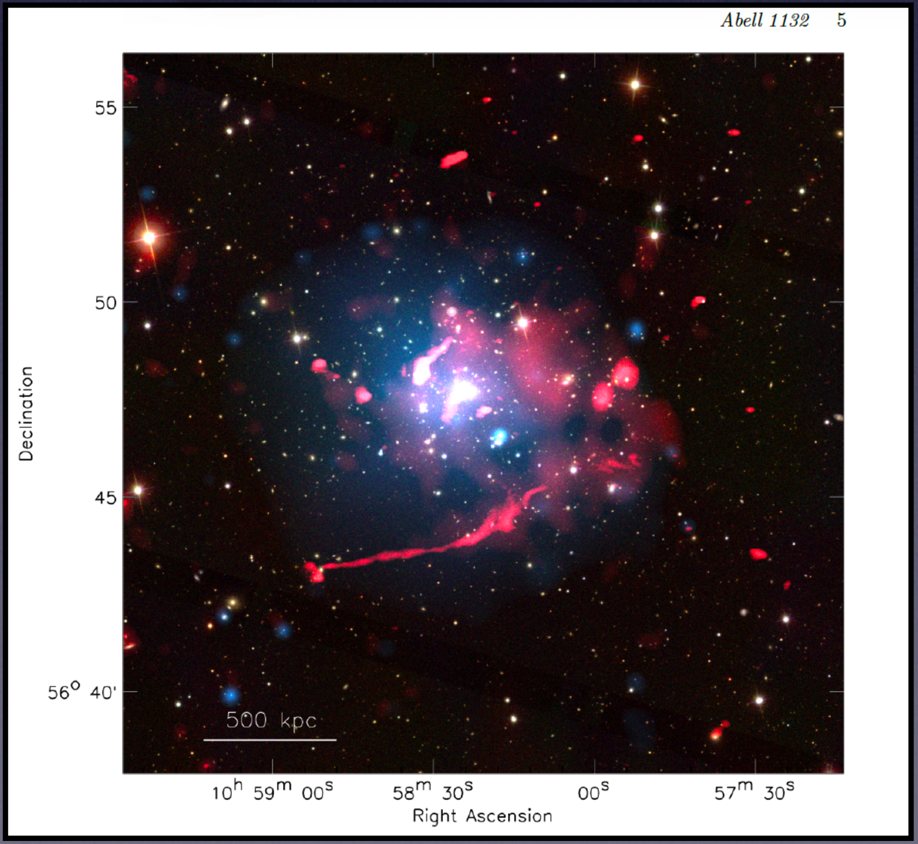
# State-of-the-art for radio halos

Sommer, Basu et al. (in prep.)



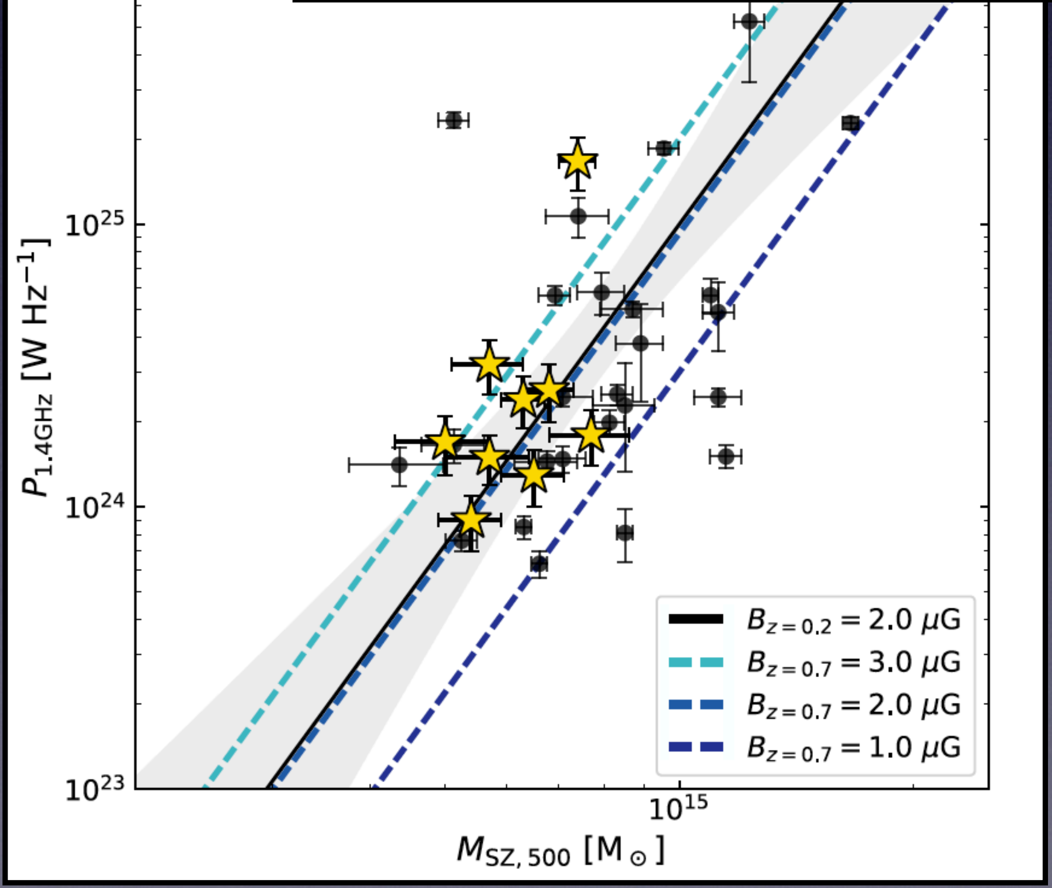
Radio halos in *Planck* selected & other clusters, Cuciti et al. (2021)





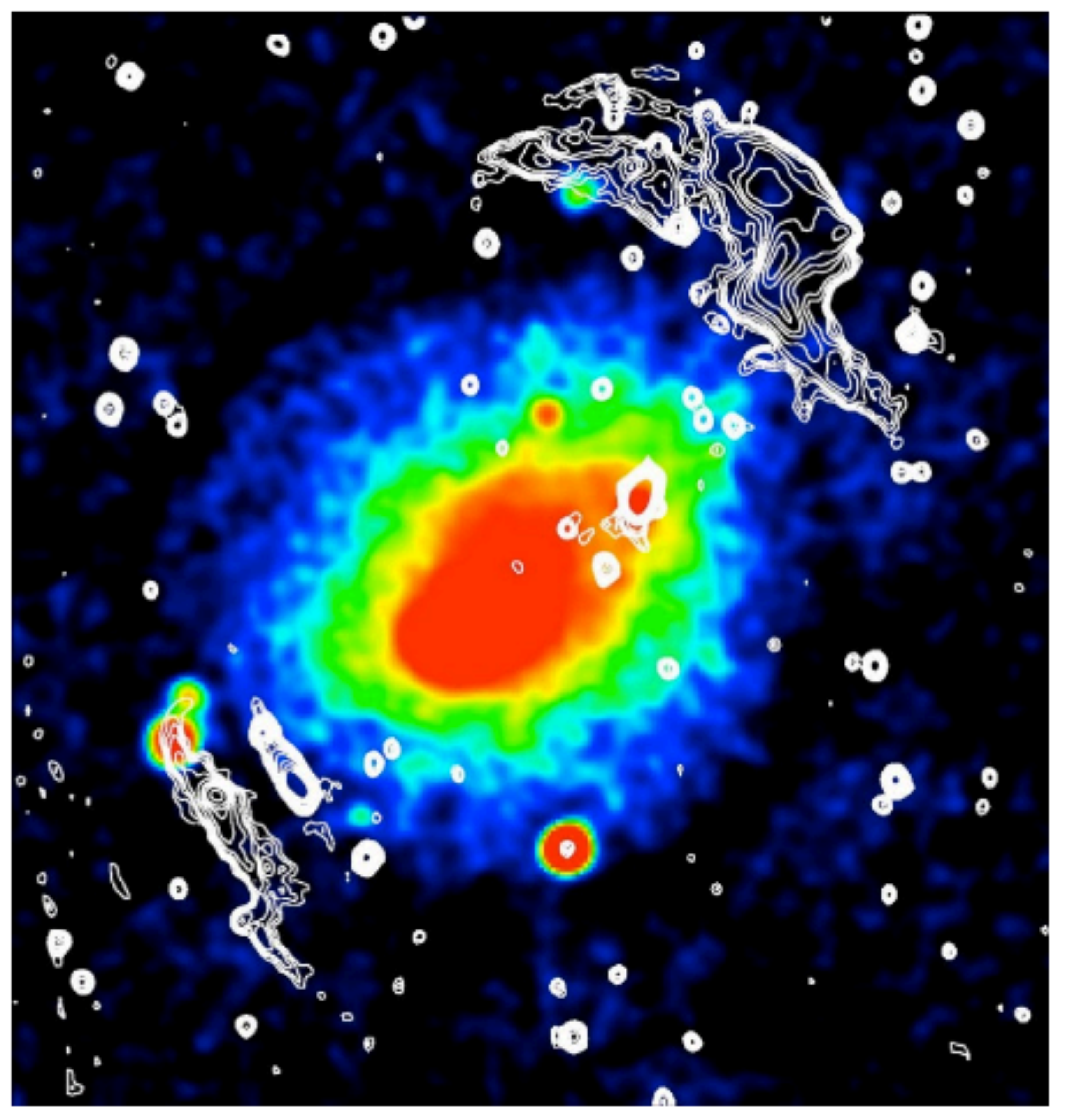
LOFAR observation of radio halos, from Wilber et al. (2018)

High-redshift (z ~ 0.6-0.9) radio halos from from Di Gennaro et al. (2020)



# Part II: Radio relics

# Radio relics in clusters



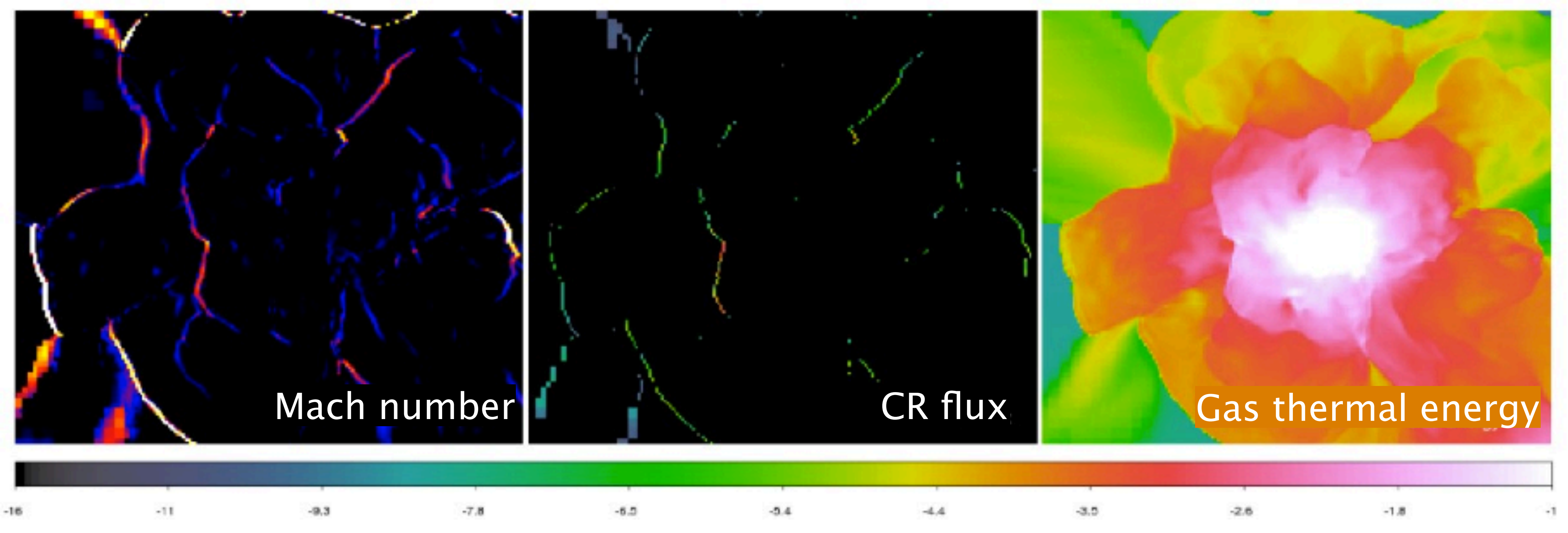
**Radio relics:** $L_{1.4\,\mathrm{GHz}} \sim 10^{23-25}$ W/Hz

- 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**

# Merger shocks & radio relics

Vazza et al. (2012)



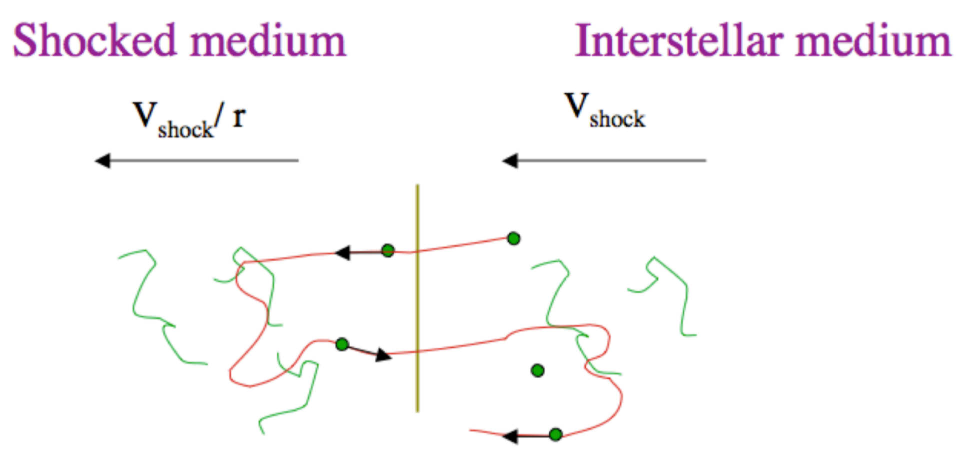
**Radio relics are thought to be associated to cluster merger shocks. The shock fronts accelerate electrons (and also protons) with the Fermi-acceleration mechanism, ans also compresses the magnetic fields. Those GeV electrons spiraling in the magnetic fields give rise to the synchrotron emission.**

- 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.

# “Problem” with radio relics

Diffusive Shock Acceleration (DSA) provides the correct CRe energy spectrum, but it is highly inefficient, needs “seed electrons” with relativistic energies

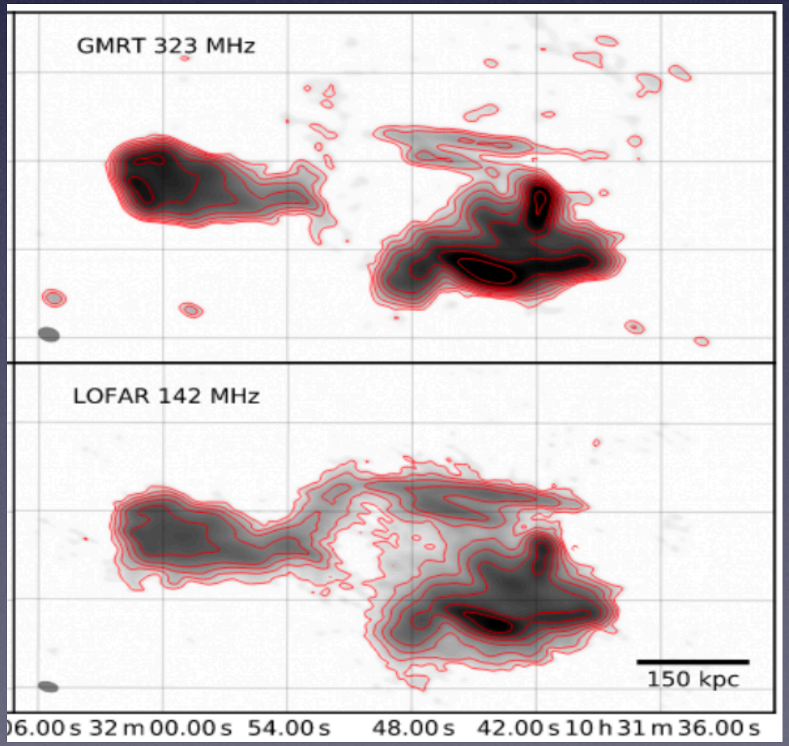


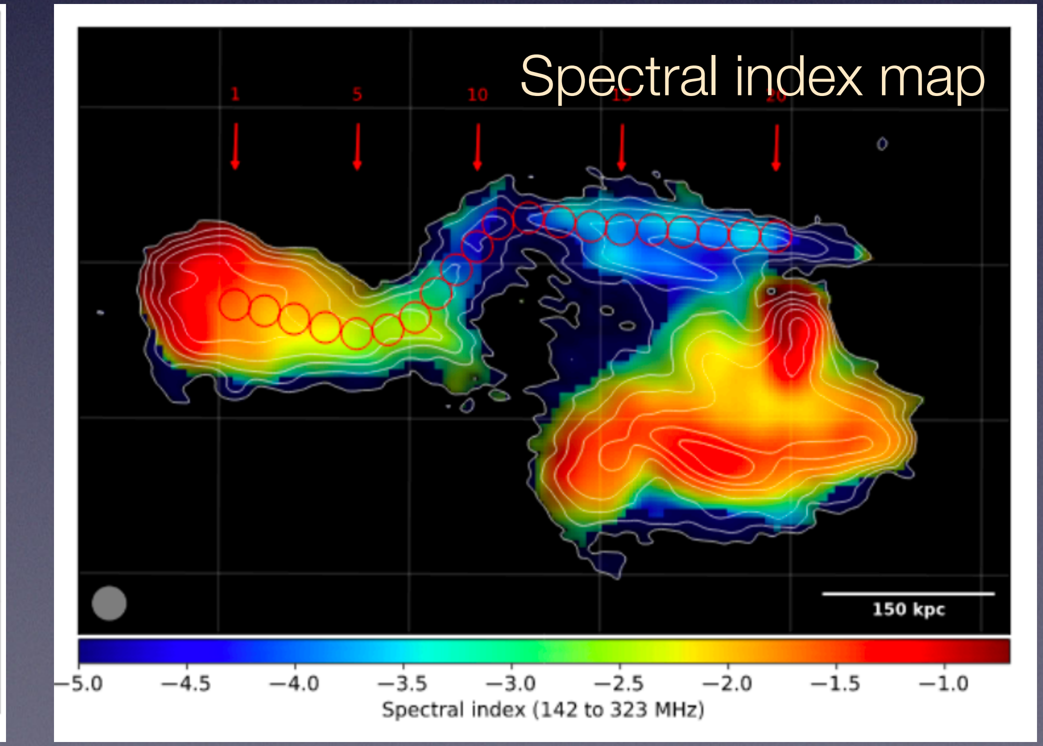
$$\langle \frac{\Delta E}{E} \rangle = \frac{4}{3}\beta = \frac{4}{3}\beta_{sh}\left(\frac{r-1}{r}\right)$$

- Linear dependence on shock Mach number
- Near-universal power law

$$n(E) = \left|\frac{dN(\geq E)}{dE}\right| = (x-1)\frac{N_0}{E_0}\left(\frac{E}{E_0}\right)^{-x}$$

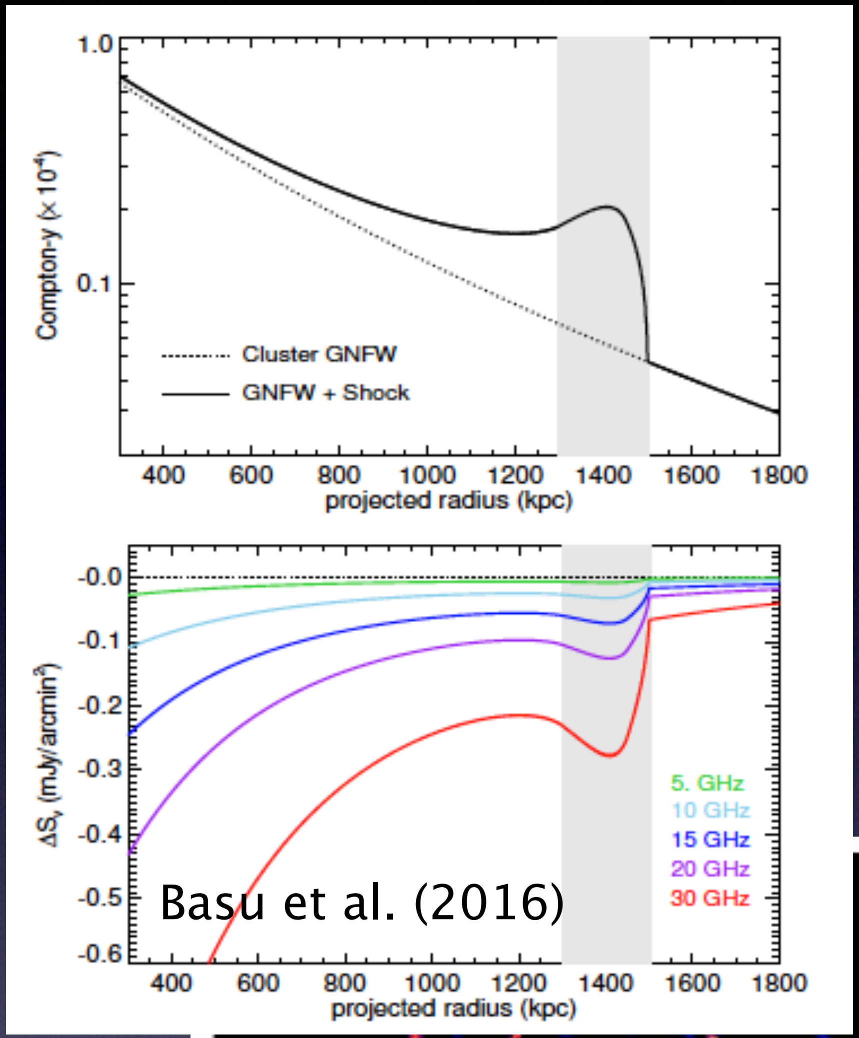
$$x = \frac{r+2}{r-1}$$





LOFAR observation of Abell 1033 cluster’s radio relic, from De Gasperin et al. (2017)

# SZ signal expected from cluster shocks

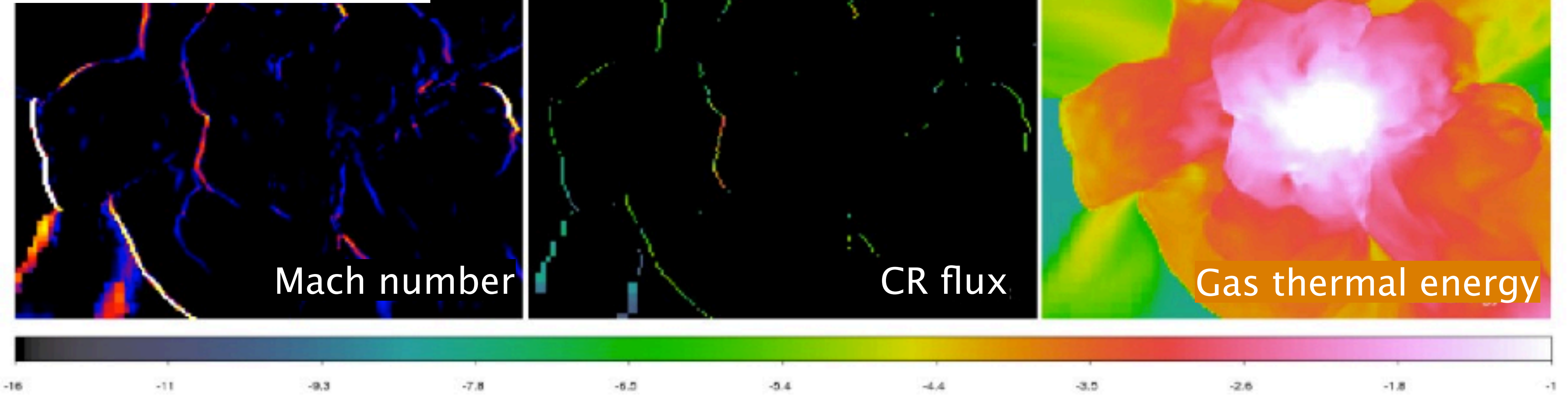


Basu et al. (2016)

Shocks create a pressure boost, which roughly scales as the **Mach number squared**

On projection ($\int P\, dl$ = Compton y parameter) this looks like a step function. This should be relatively easily detectable also in the cluster outskirts, and also out to high-z

Vazza et al. (2012)



Mach number

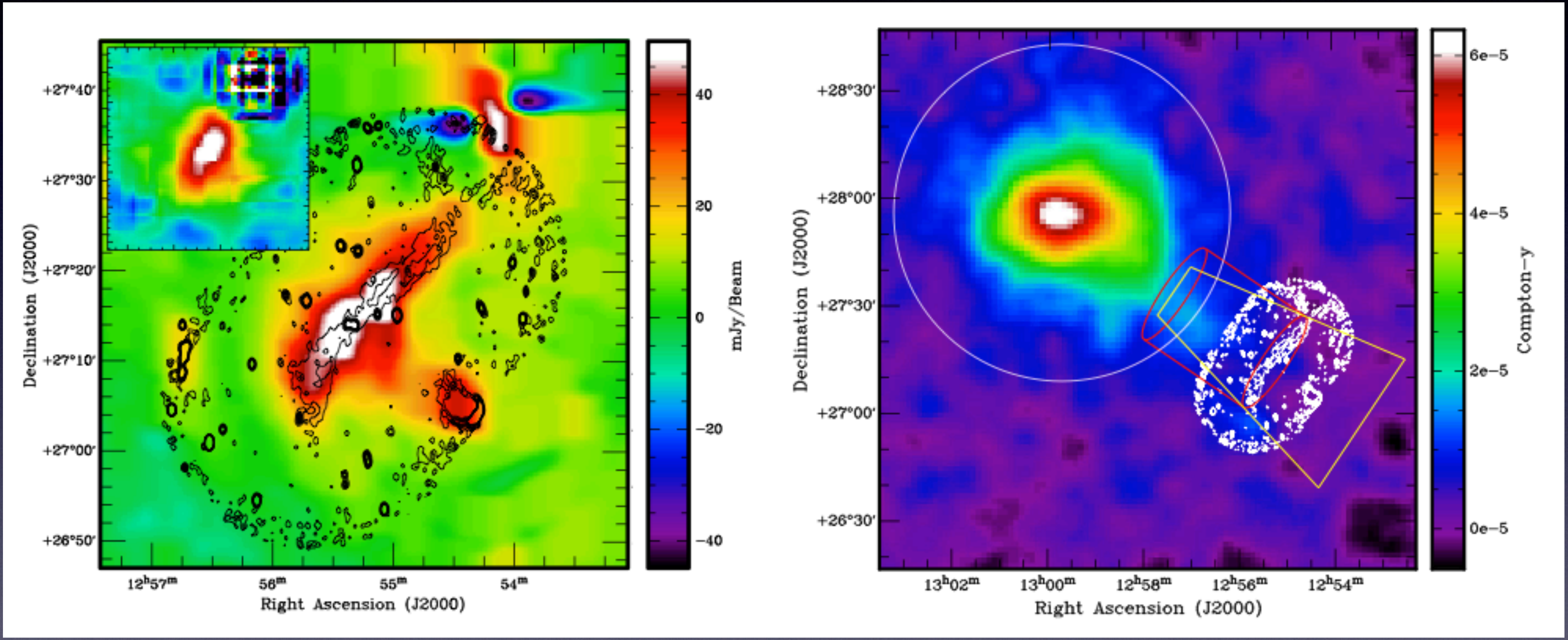
CR flux

Gas thermal energy

# Coma's radio relic with Planck

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

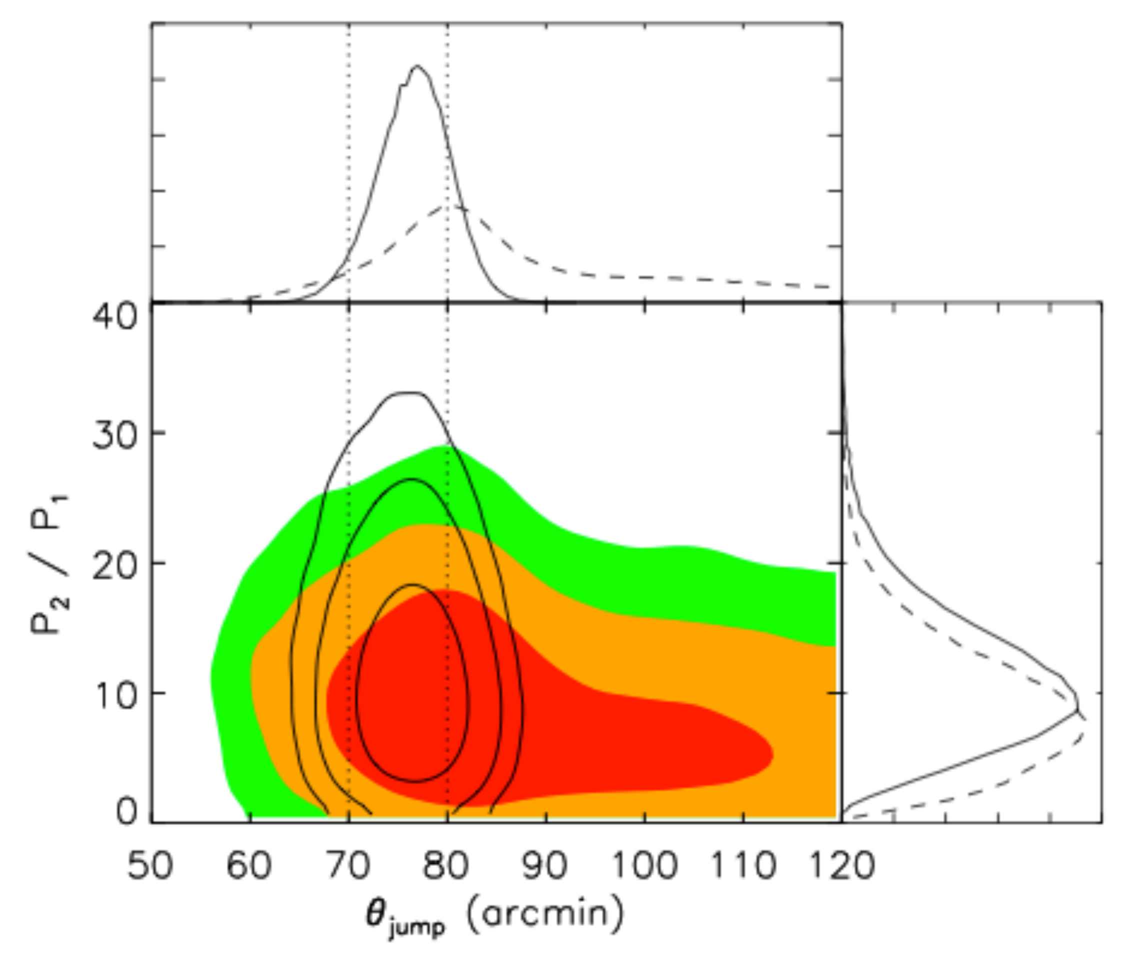
Erler, Basu et al. (2015), MNRAS, 447, 2497



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

# Results for Coma's 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 ratio and jump location are uncorrelated

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

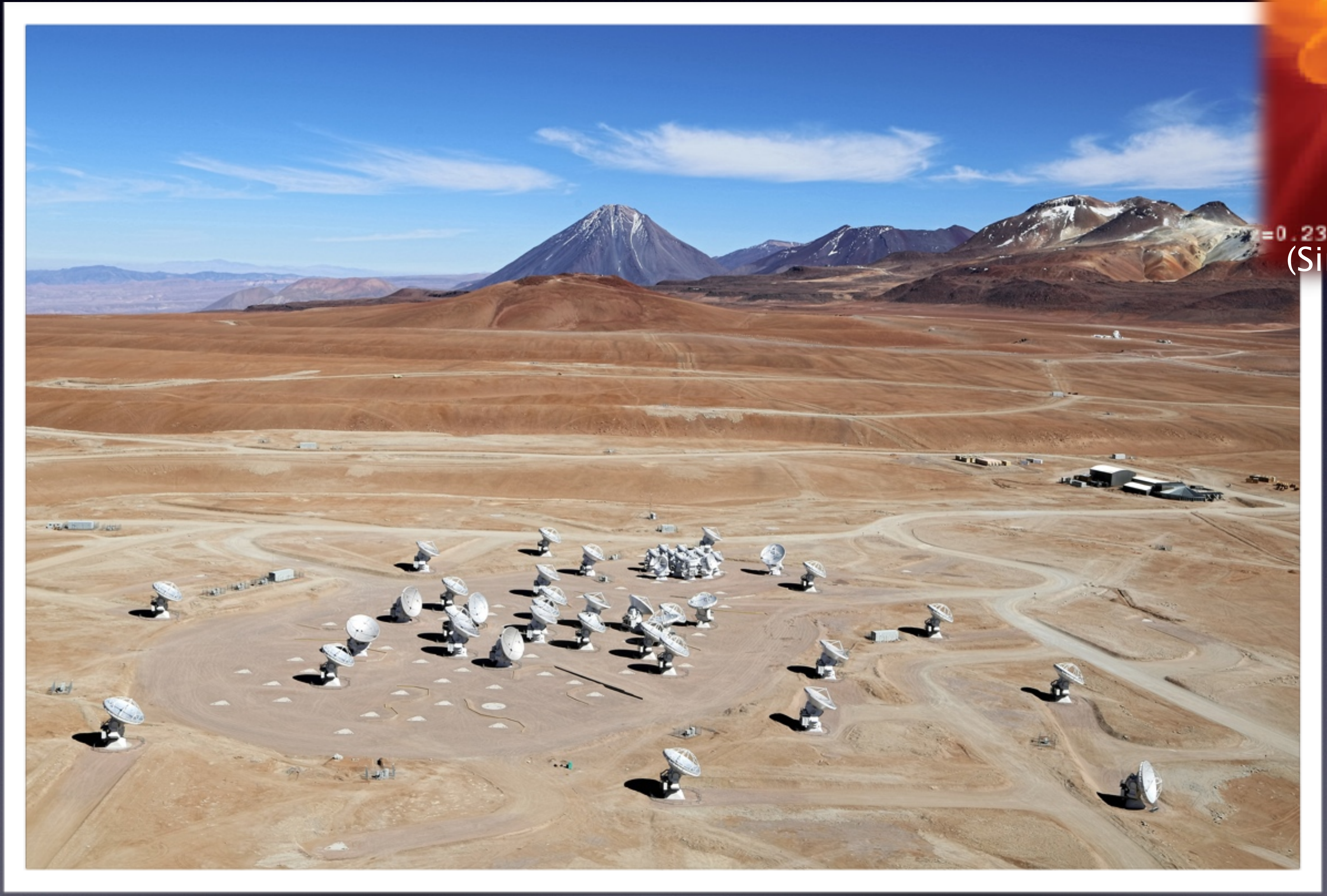
$$\mathcal{M} = 2.8^{+0.8}_{-0.6}$$

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 got Mach number M = 3.4±0.5 (pressure ratio $P_2/P_1$ = 14.3±4.5)**

# The finest imager for SZ shocks

Measuring SZ shocks with Planck is like observing radio sky with a single-dish antenna … we can do better



**Projected pressure map**

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

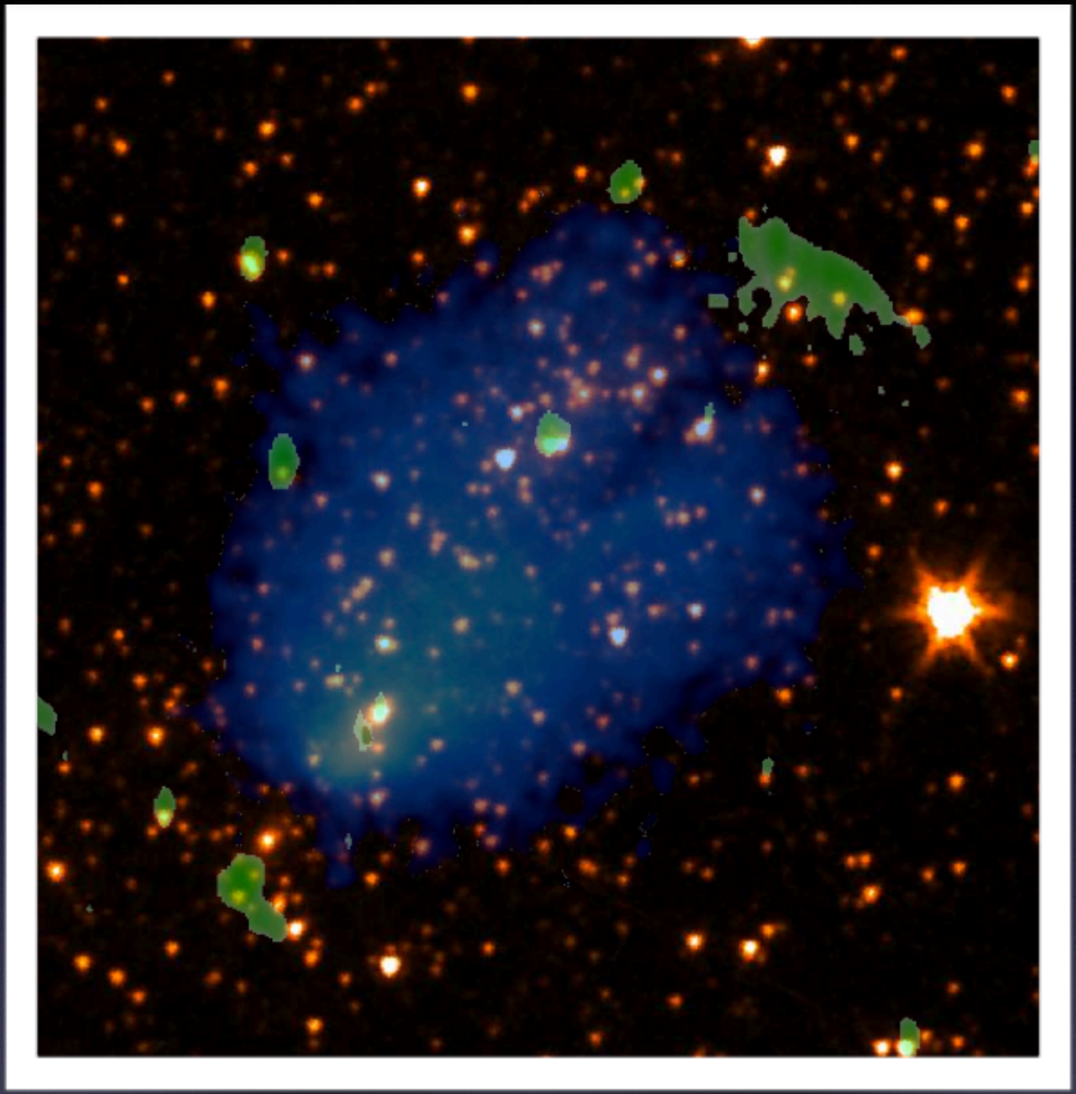
(Simulations by F. Vazza, 2012)

**First ALMA-SZ results:**

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

High-resolution single dish measurements are also on the way..

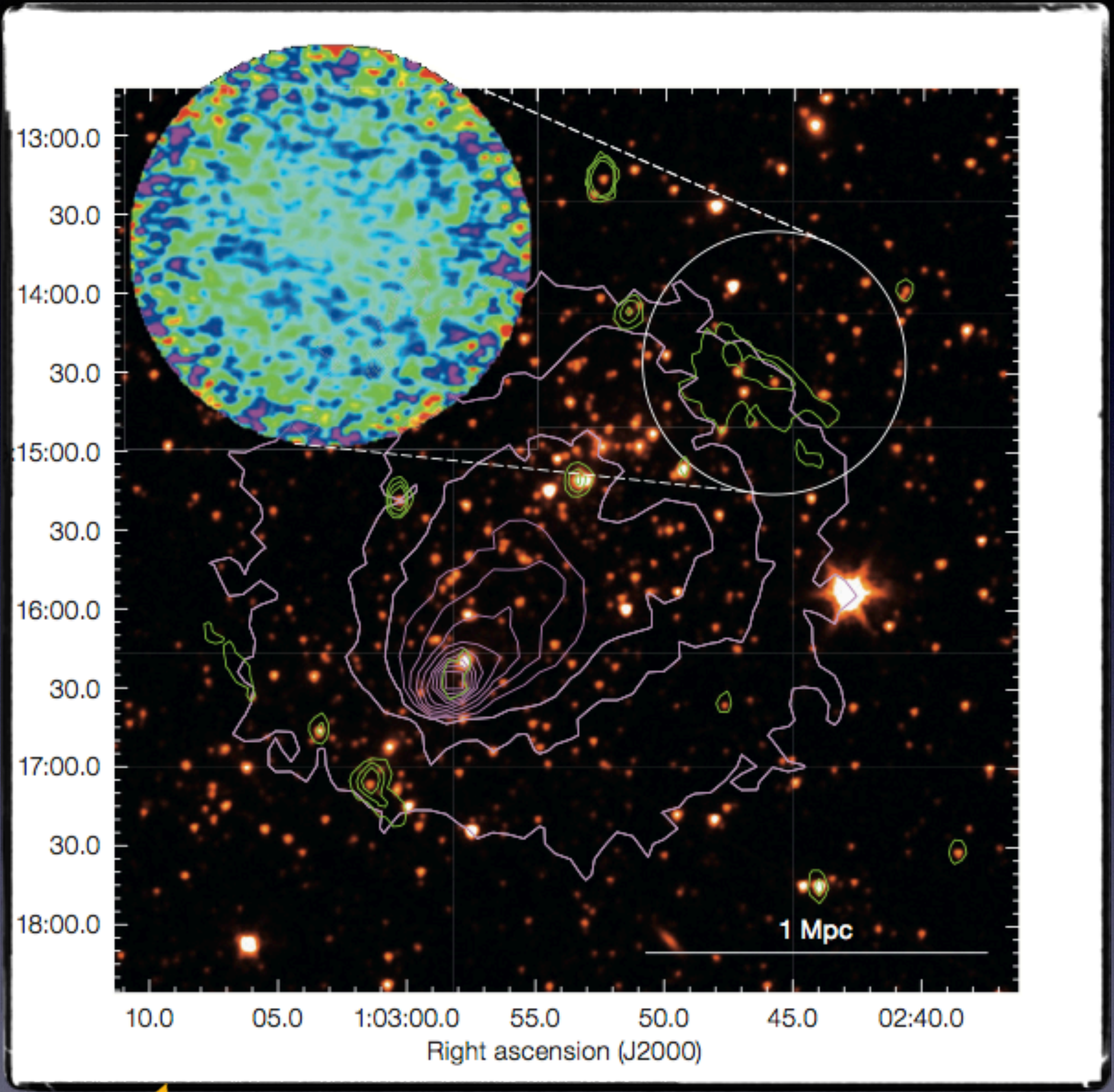
# A relic shock from at z=0.9



360 ks Chandra
(PI: J. Hughes)

+

ATCA 2.1 GHz radio
(Lindner et al. 2014)



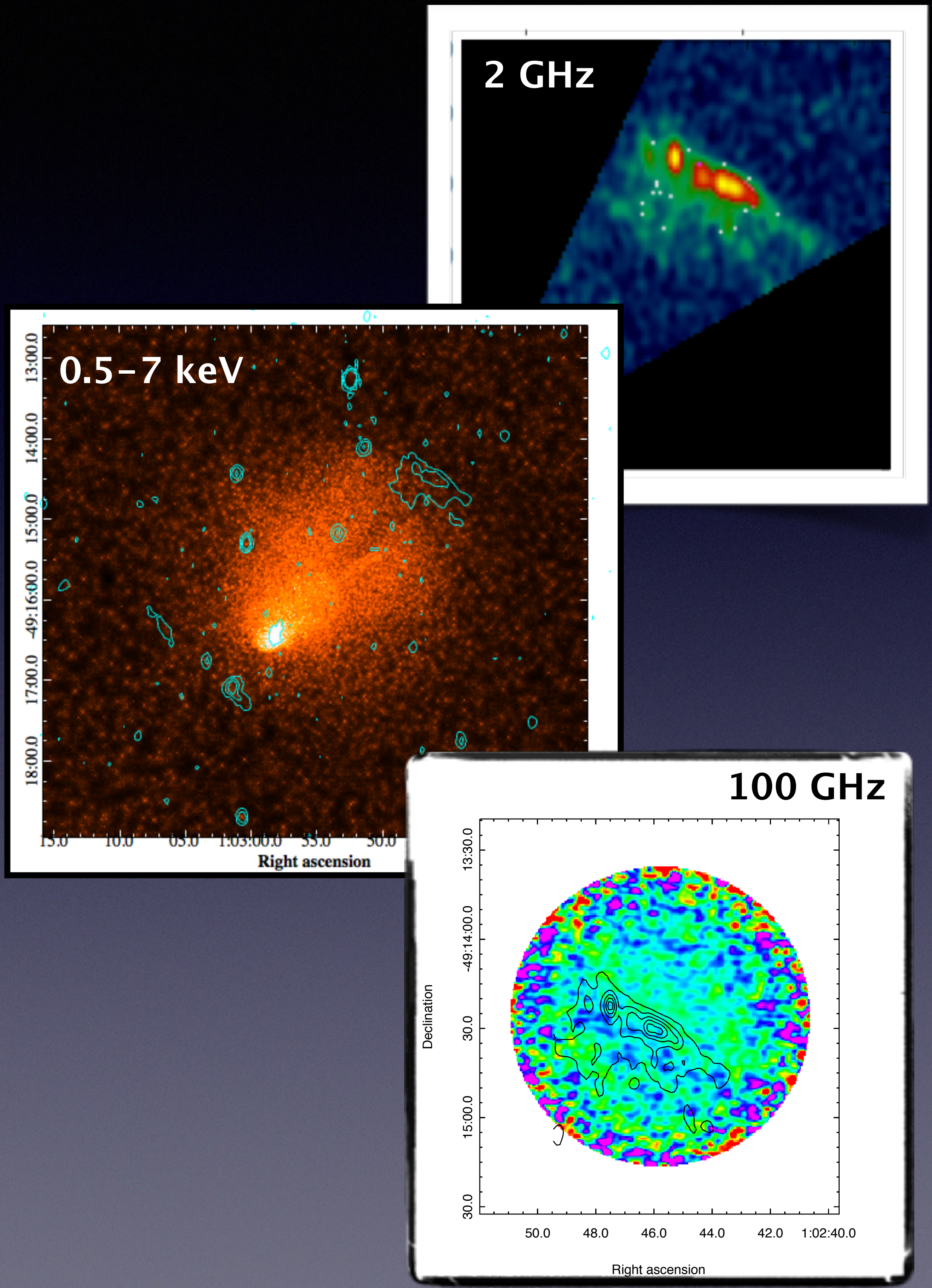
Basu et al. (2016), ApJ, 829

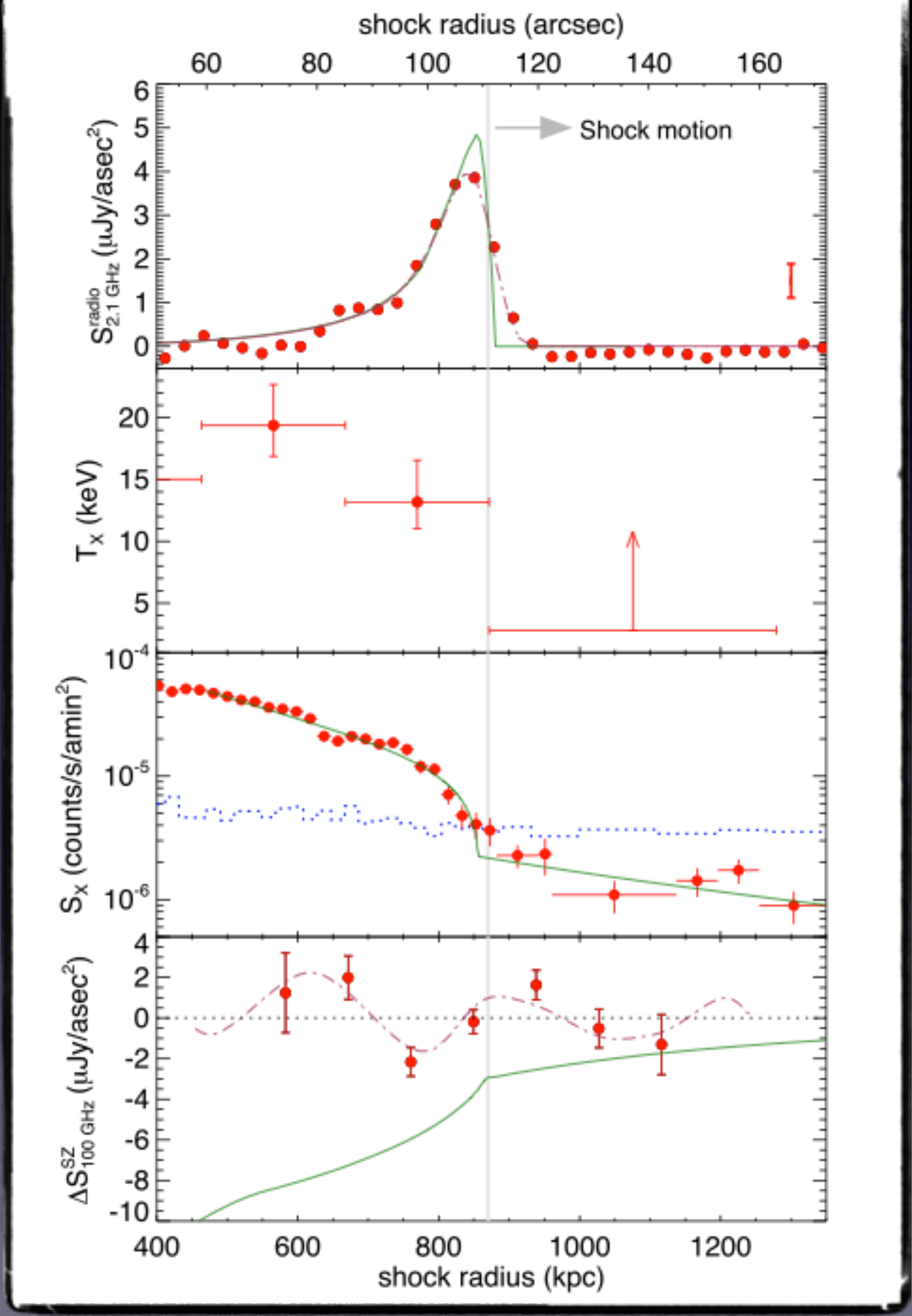
**ALMA data ~ 2h on-source**

**ALMA noise rms ~ 6 μJy/3” beam**

(enough to detect M~2 shock with >5σ)

# The multi-wavelength view





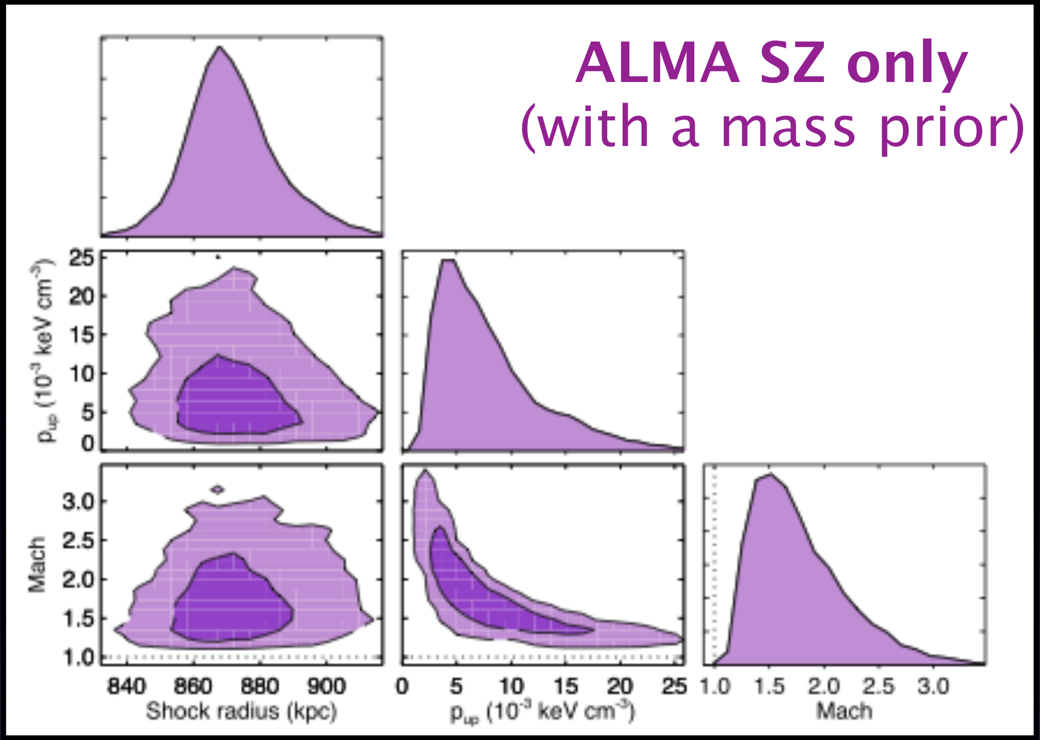
Basu et al. (2016), ApJ, 829

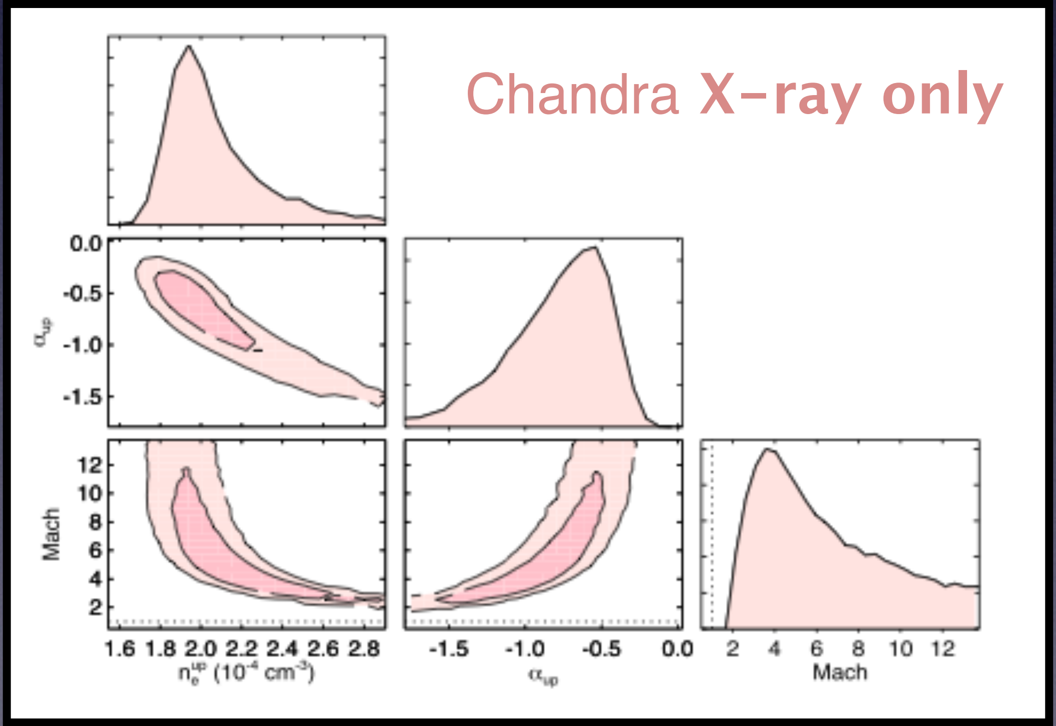
# SZ /X-ray joint modelling of relic shock

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

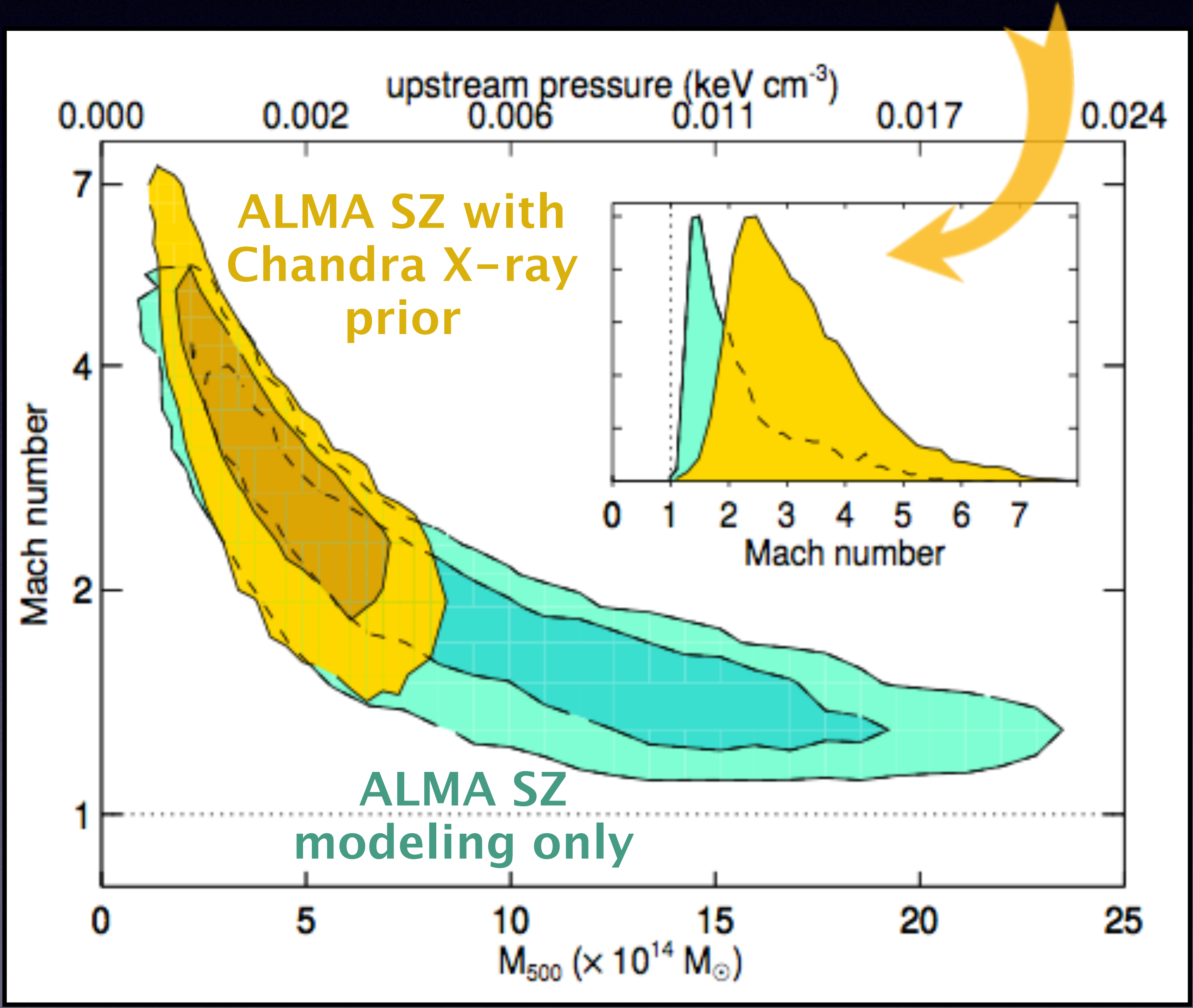
X-ray brightness jump suggests stronger: $\mathcal{M} = 3.5^{+6.4}_{-1.3}$

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



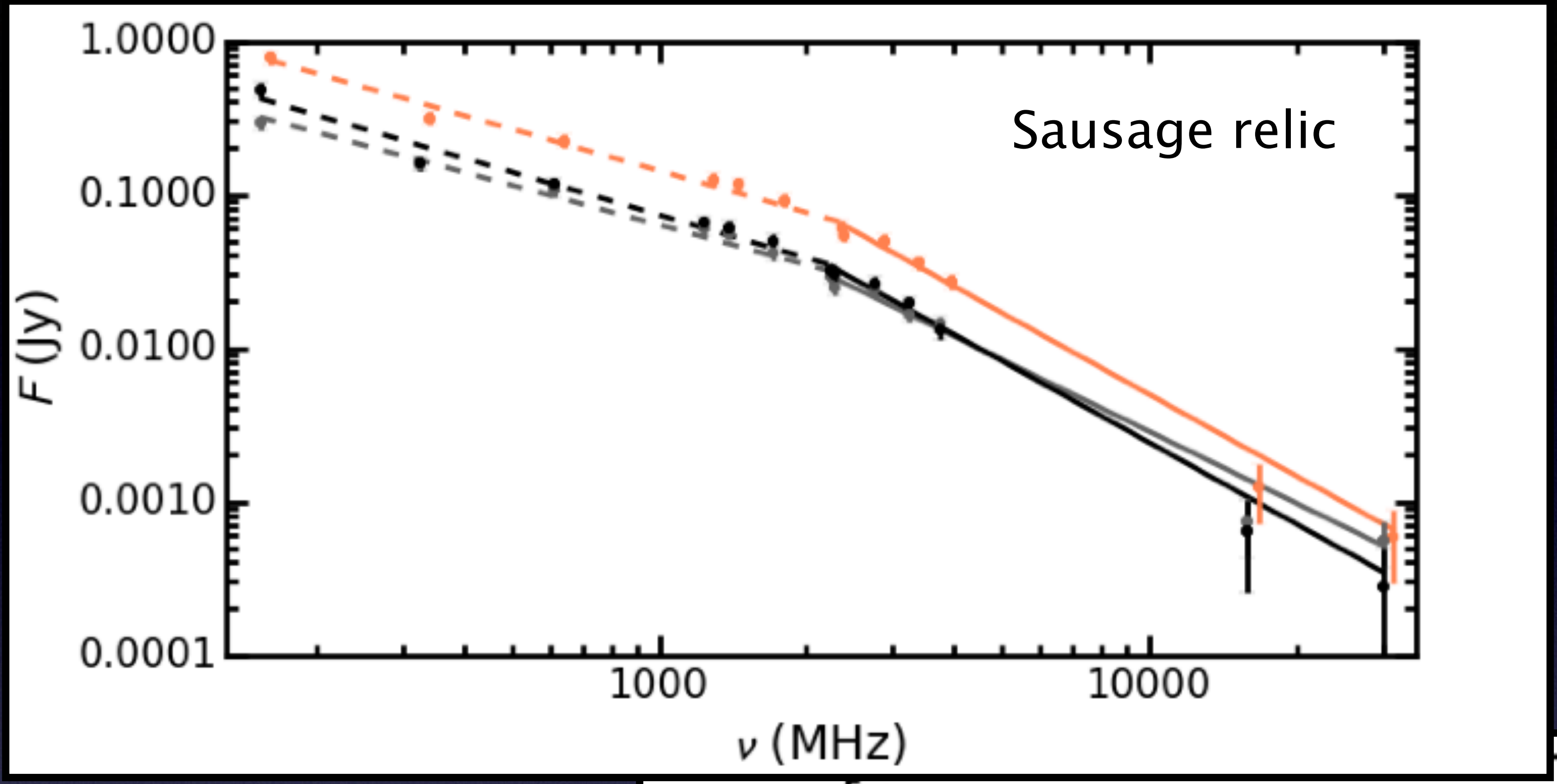


Basu et al. (2016), ApJ, 829



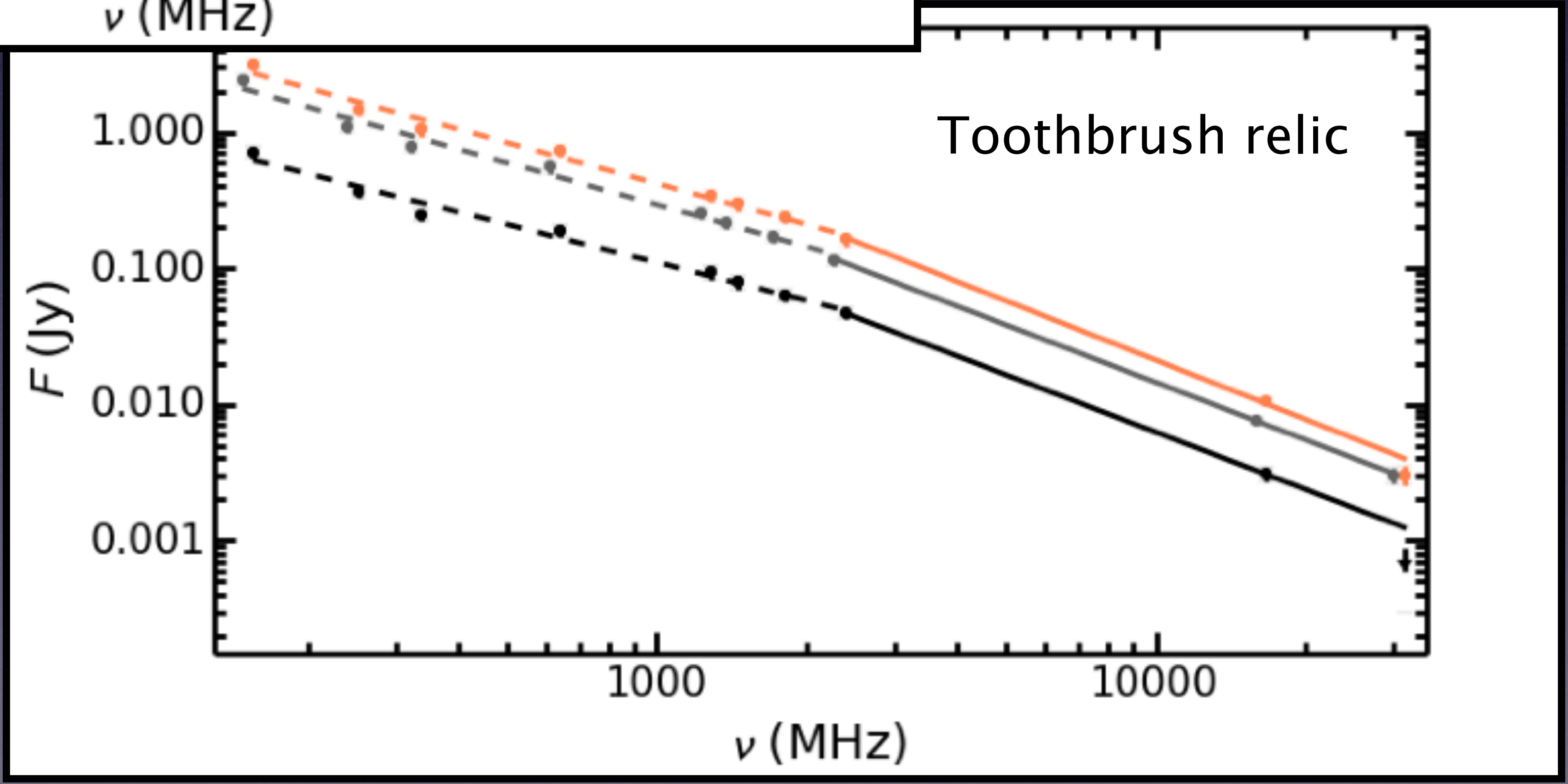
# “SZ contamination” on relic shocks

# Relic spectral steepening at >10 GHz



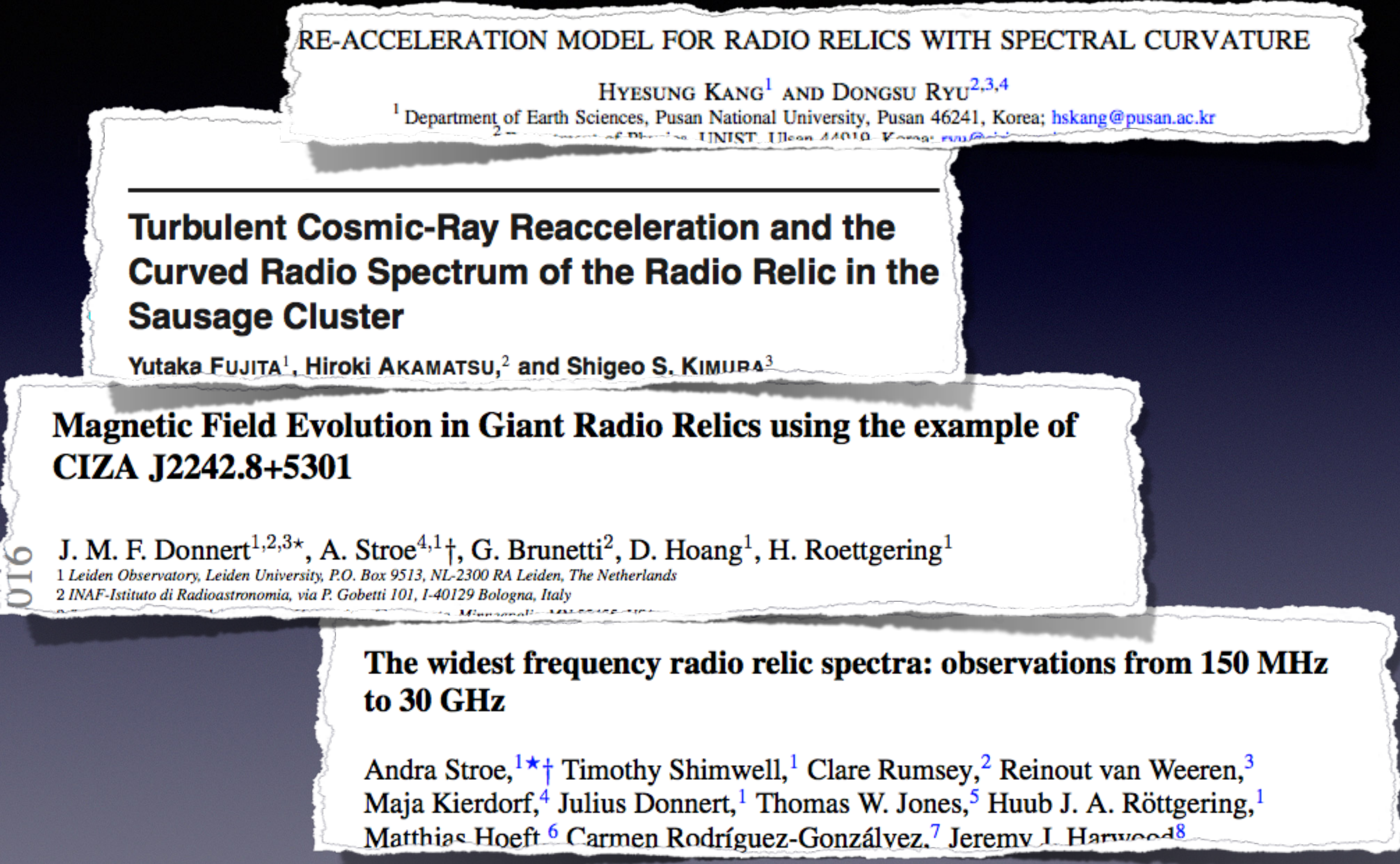
Stroe et al. (2015, 2016)

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 spectral steepening at >10 GHz



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

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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]

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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

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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]

# Relic spectral steepening at >10 GHz

RE-ACCELERATION MODEL FOR RADIO RELICS WITH SPECTRAL CURVATURE

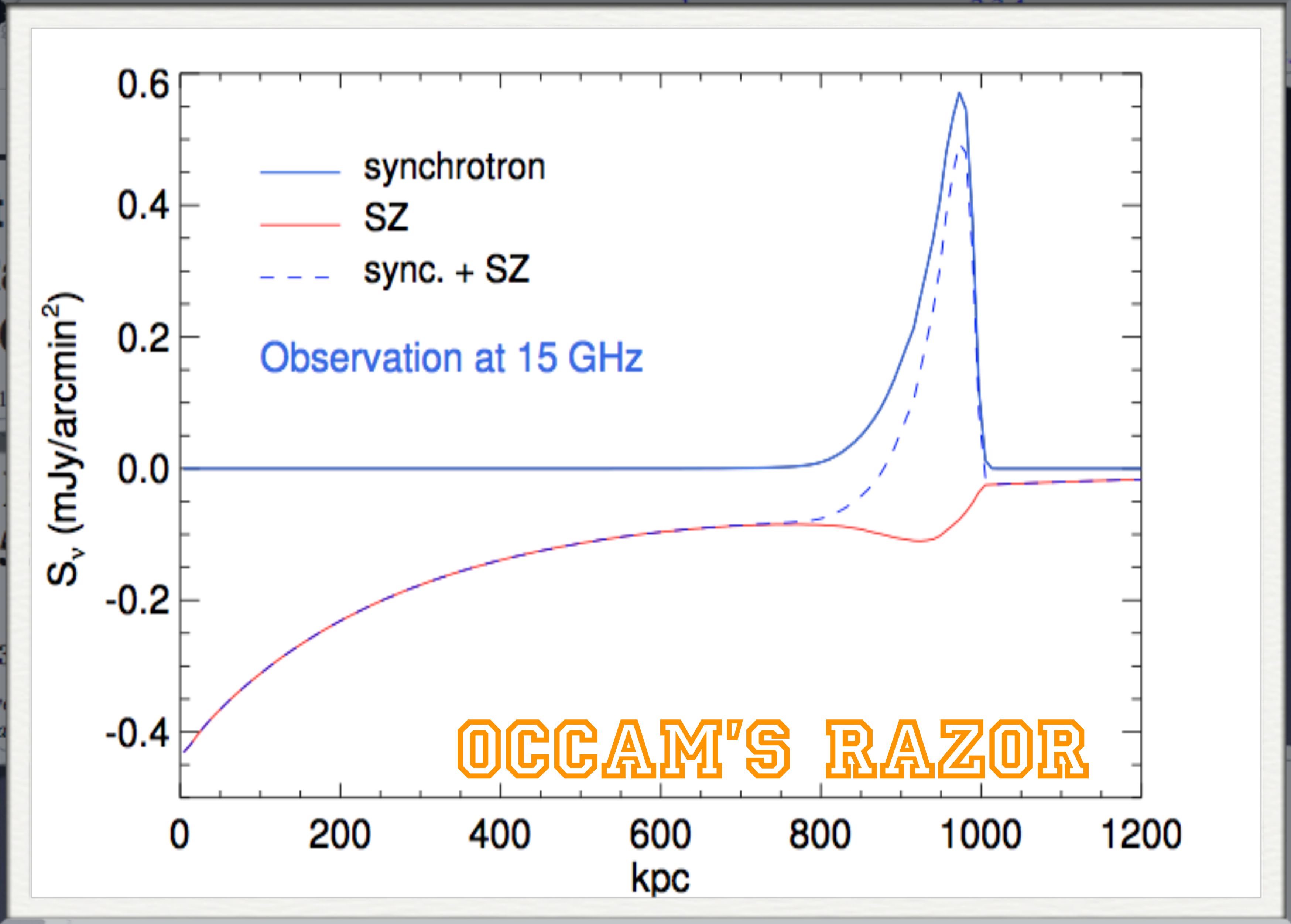
.kr

**Turbulent**
**Curved R**
**Sausage**

Yutaka FUJITA[1]

**Magnetic Field**
**CIZA J2242.8+**

J. M. F. Donnert[1,2,3]
1 *Leiden Observatory, Leiden Univ*
2 *INAF-Istituto di Radioastronomia*



OCCAM'S RAZOR

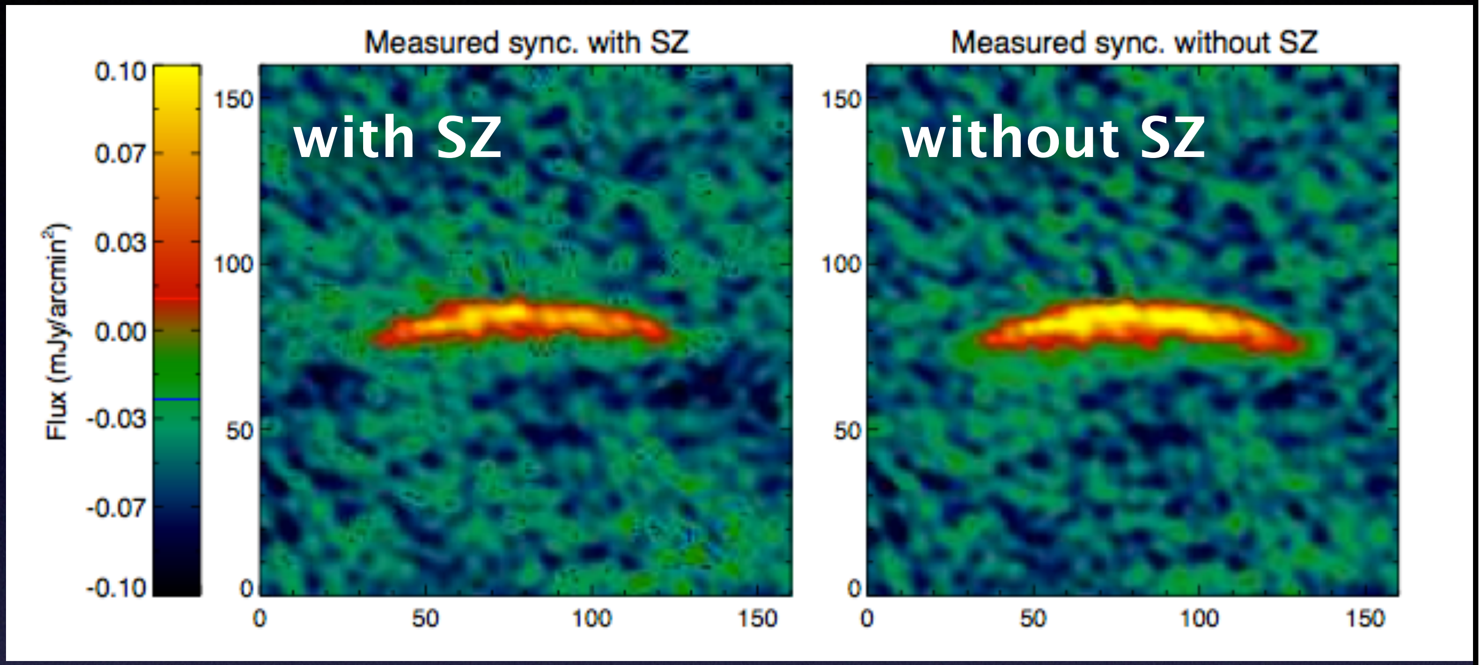
Basu et al. (2016), A&A, 591

**150 MHz**

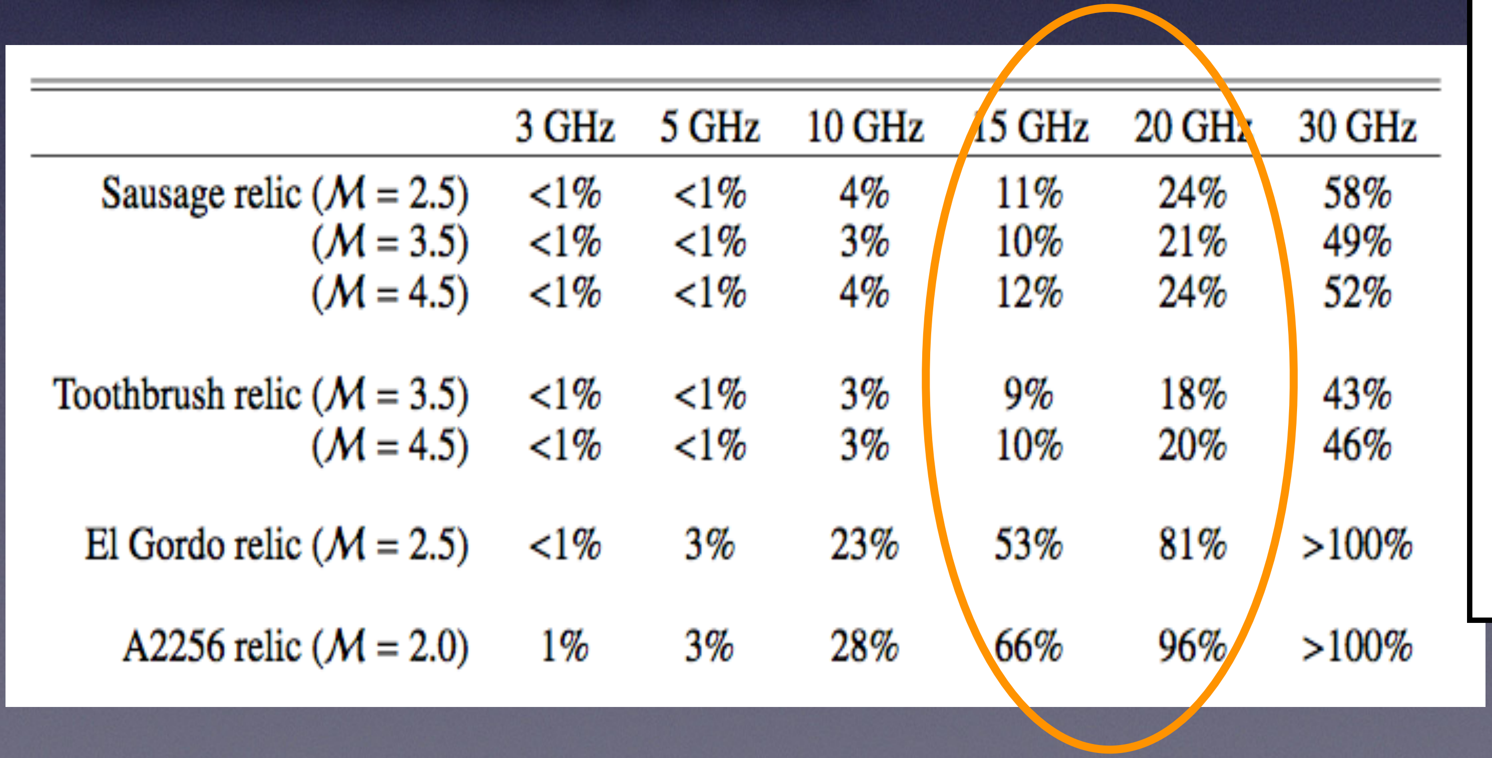
Andra Stroe,[1★†] Timothy Shimwell,[1] Clare Rumsey,[2] Reinout van Weeren,[3] Maja Kierdorf,[4] Julius Donnert,[1] Thomas W. Jones,[5] Huub J. A. Röttgering,[1] Matthias Hoeft,[6] Carmen Rodríguez-Gonzálvez,[7] Jeremy J. Harwood[8]

# A non-negligible effect at >10 GHz

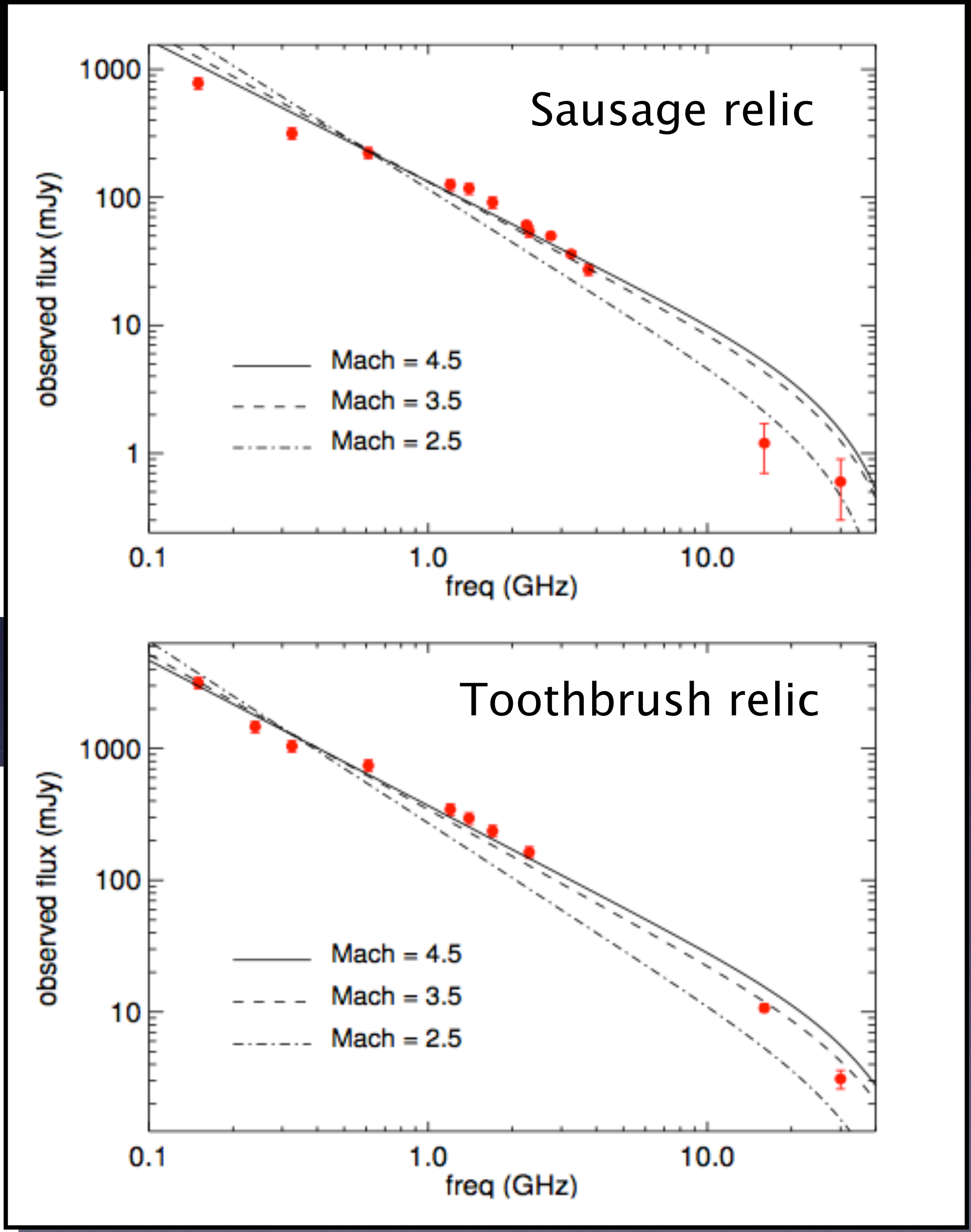
Simulated interferometric observation at 10 GHz



10%–50% flux loss at 10 GHz



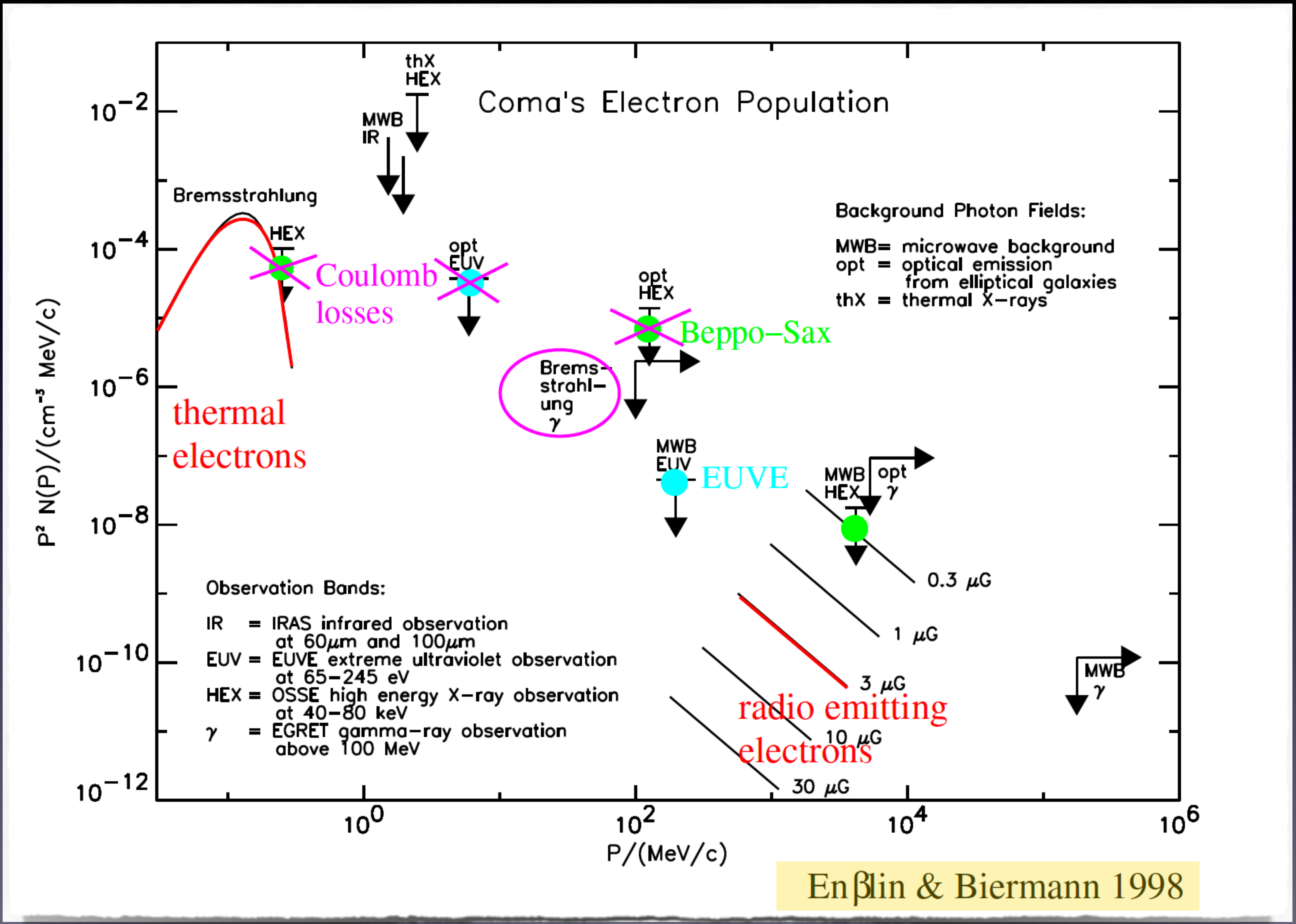
| | 3 GHz | 5 GHz | 10 GHz | 15 GHz | 20 GHz | 30 GHz |
|---|---|---|---|---|---|---|
| Sausage relic ($\mathcal{M}=2.5$) | <1% | <1% | 4% | 11% | 24% | 58% |
| ($\mathcal{M}=3.5$) | <1% | <1% | 3% | 10% | 21% | 49% |
| ($\mathcal{M}=4.5$) | <1% | <1% | 4% | 12% | 24% | 52% |
| Toothbrush relic ($\mathcal{M}=3.5$) | <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

# Part III: Nonthermal SZ

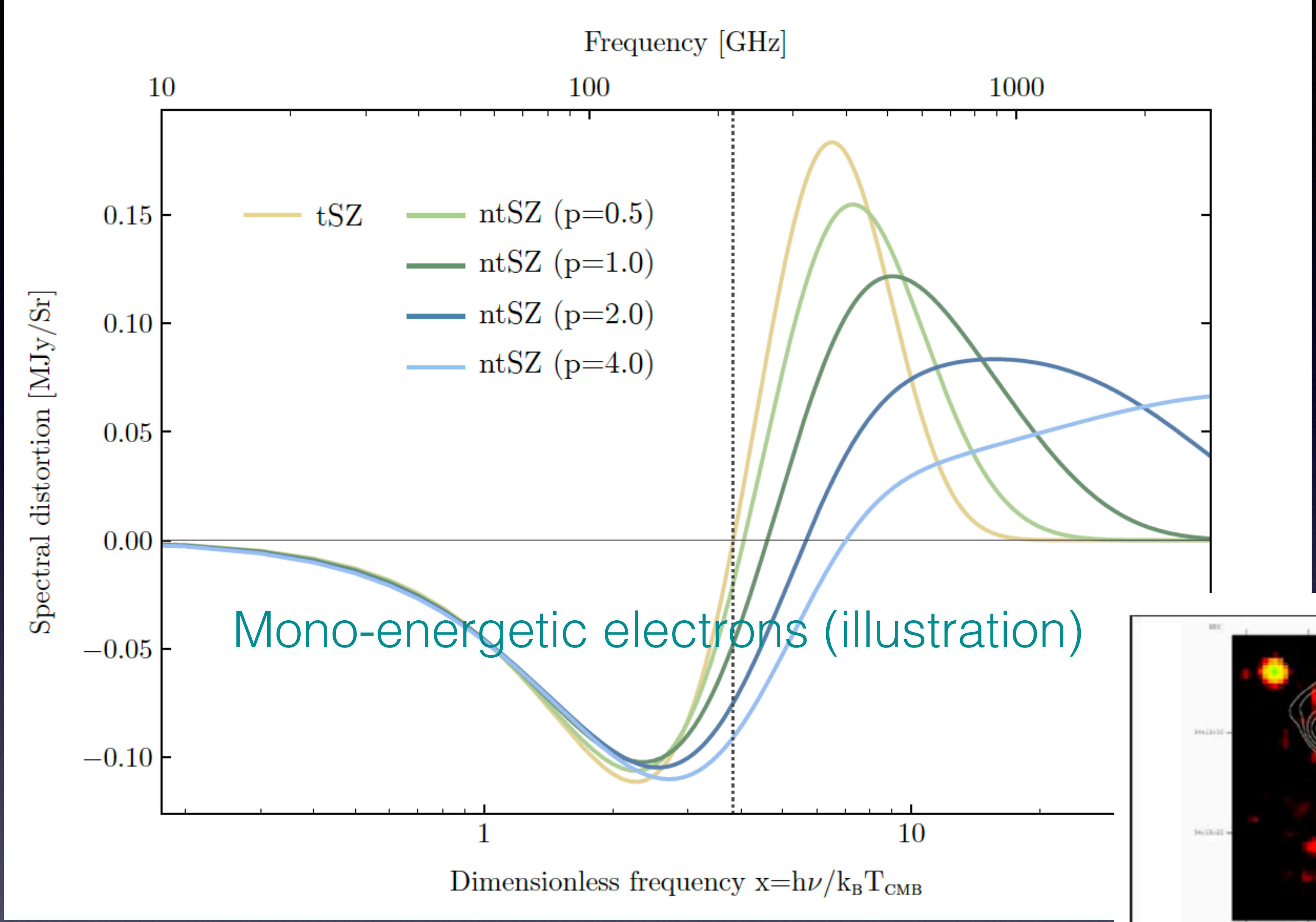
# Nonthermal electrons in clusters



Enβlin & Biermann 1998

*(reproduced in Enßlin 2004, with annotations)*

# Nonthermal SZ effect

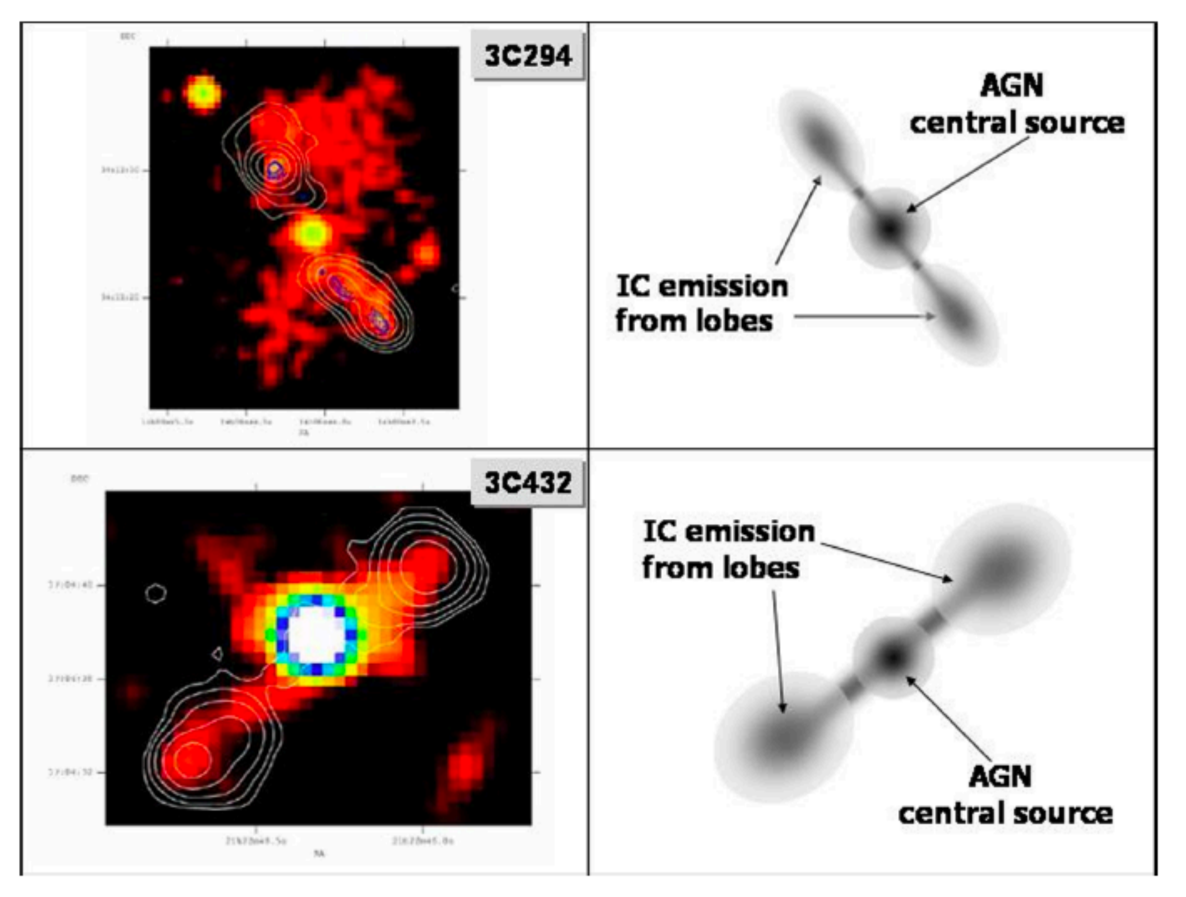


Mono-energetic electrons (illustration)

CMB photons will also scatter off other sources of free electrons, e.g. power-law distribution with a high-energy tail.

IC emission is routinely observed in hard X-ray band, from AGN lobes!

Fig. From Colafrancesco et al. (2013)

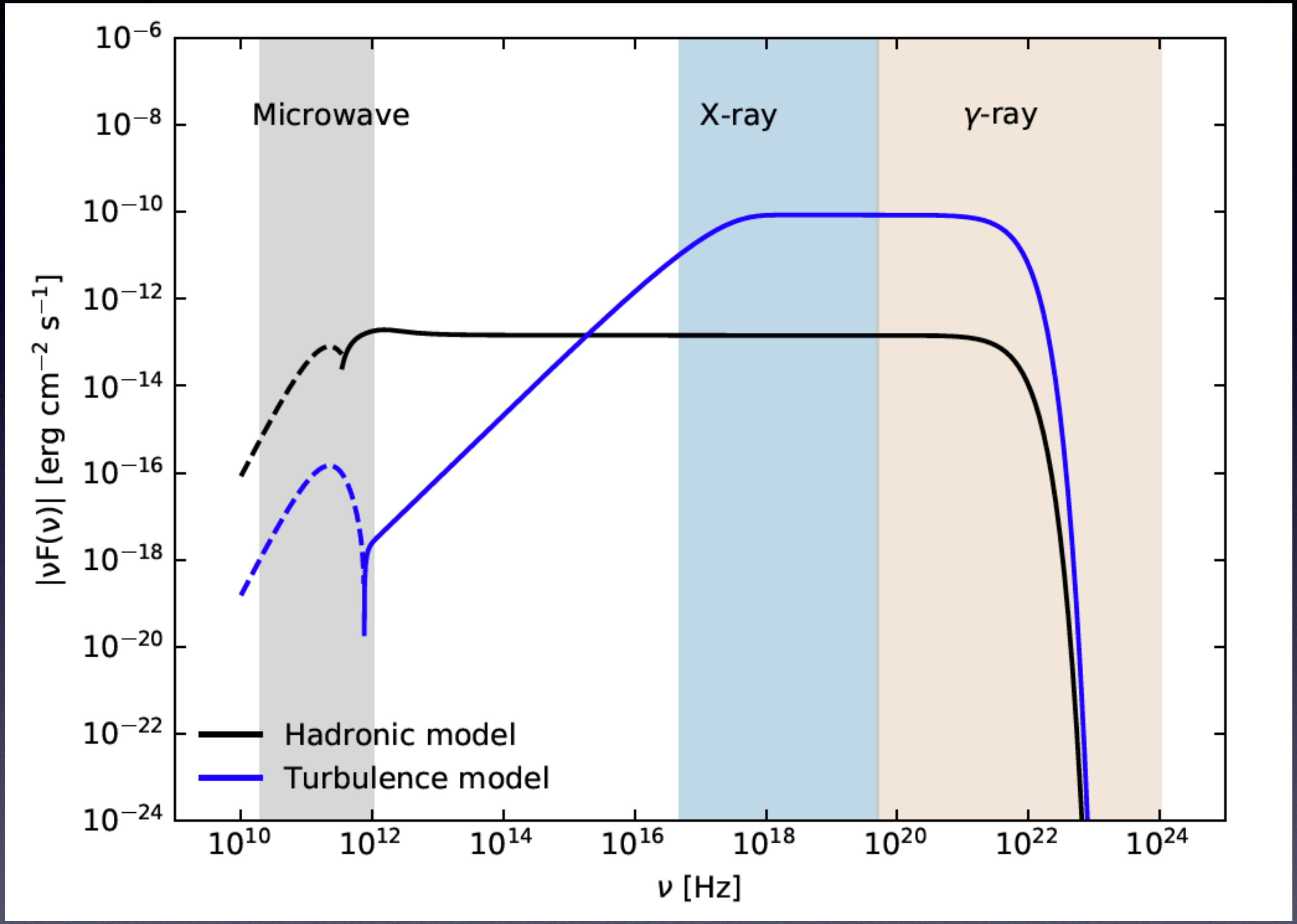


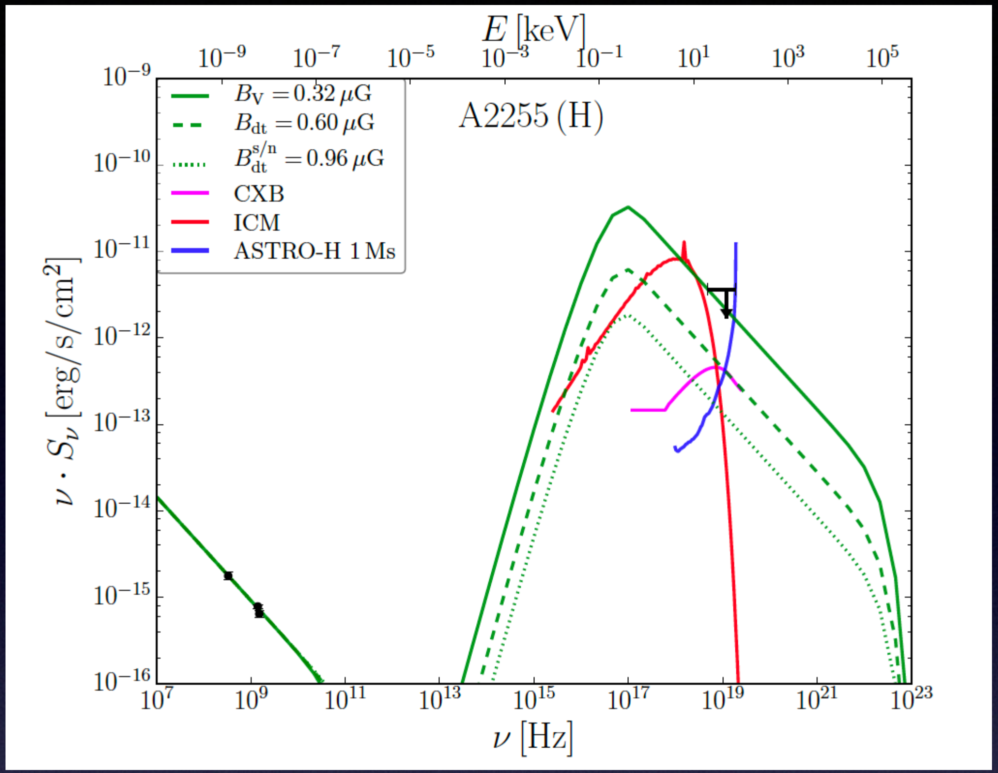
For a general isotropic momentum distribution *f(p)*:

$$\Delta I_\nu \approx I_0\, x^3\, \tau_e \int_0^\infty f(p) p^2 \mathrm{d}p \int_{-s_m(p)}^{s_m(p)} P(s,p)\, [n_{bb}(x\, e^s) - n_{bb}(x)]\, \mathrm{d}s.$$

Figure above shows four cases of mono-energetic electrons (i.e. delta function distributions)

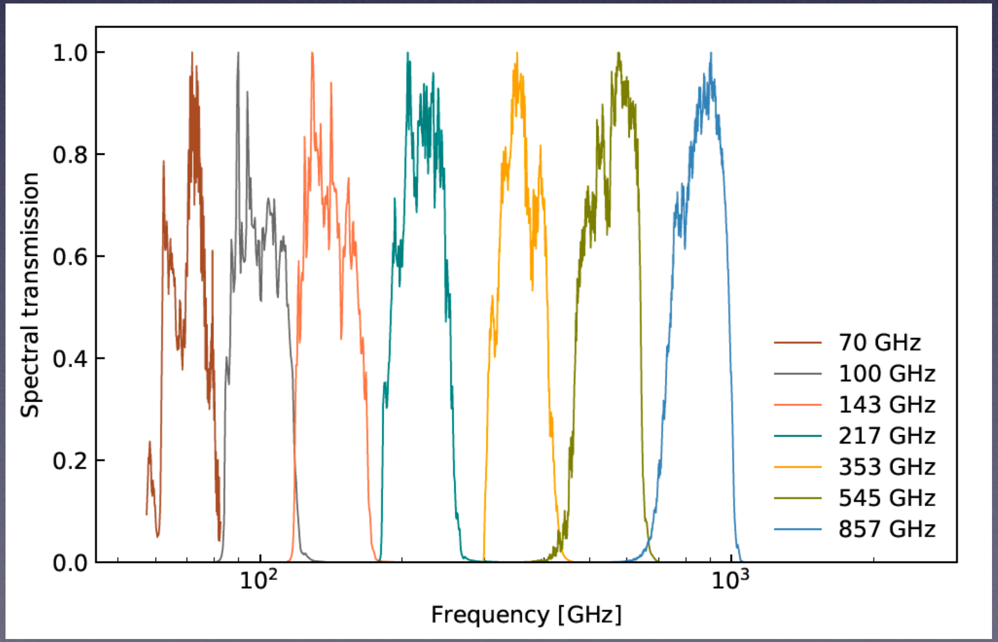
# The spectrum of ntSZ effect





X-ray IC predictions for RH clusters, from Bartels et al. (2018)

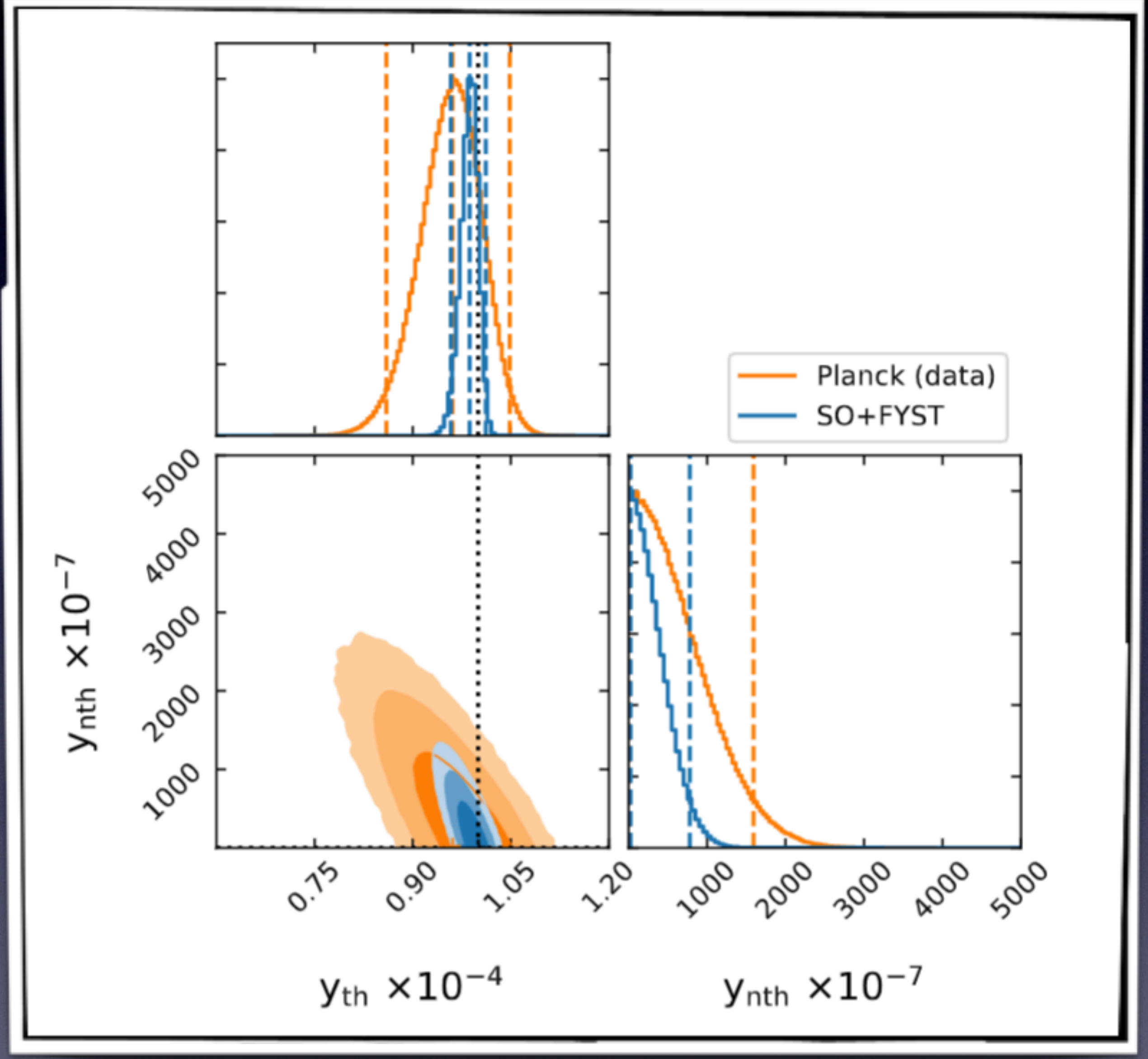
The same Inverse Compton signal is observable from millimeter-wave to gamma-ray energies!



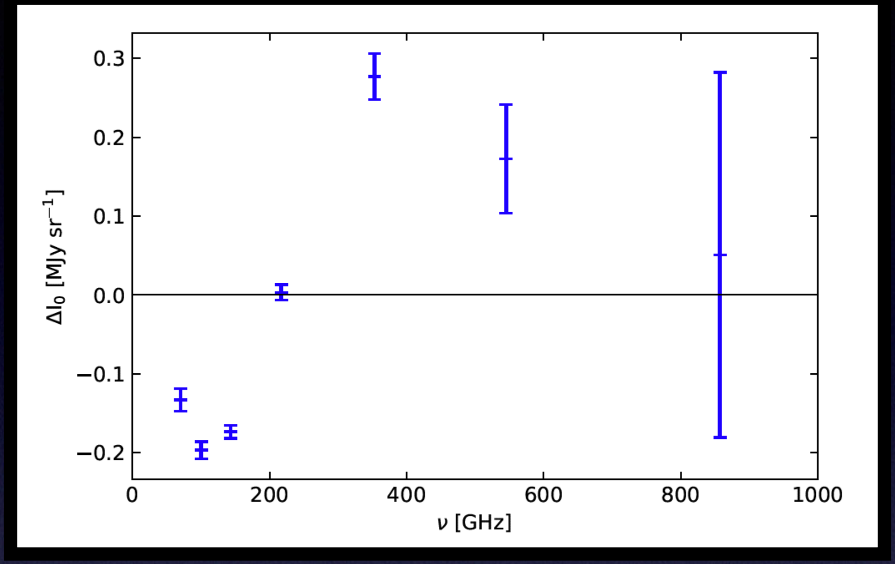
*Planck* frequency bands

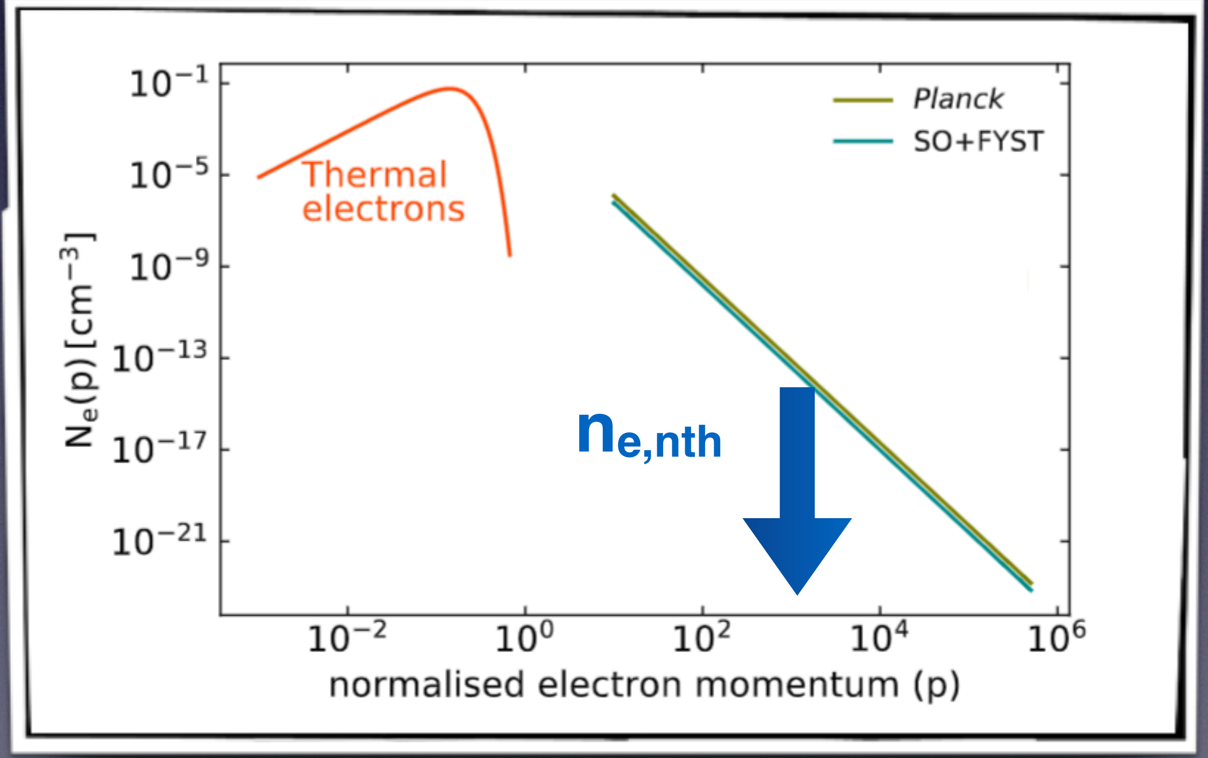
# Results from ~40 RH clusters

In clusters, ntSZ is ≲1% of the tSZ signal 🙁



Stacked spectrum of of 40 clusters from *Planck* data, after matched-filtering

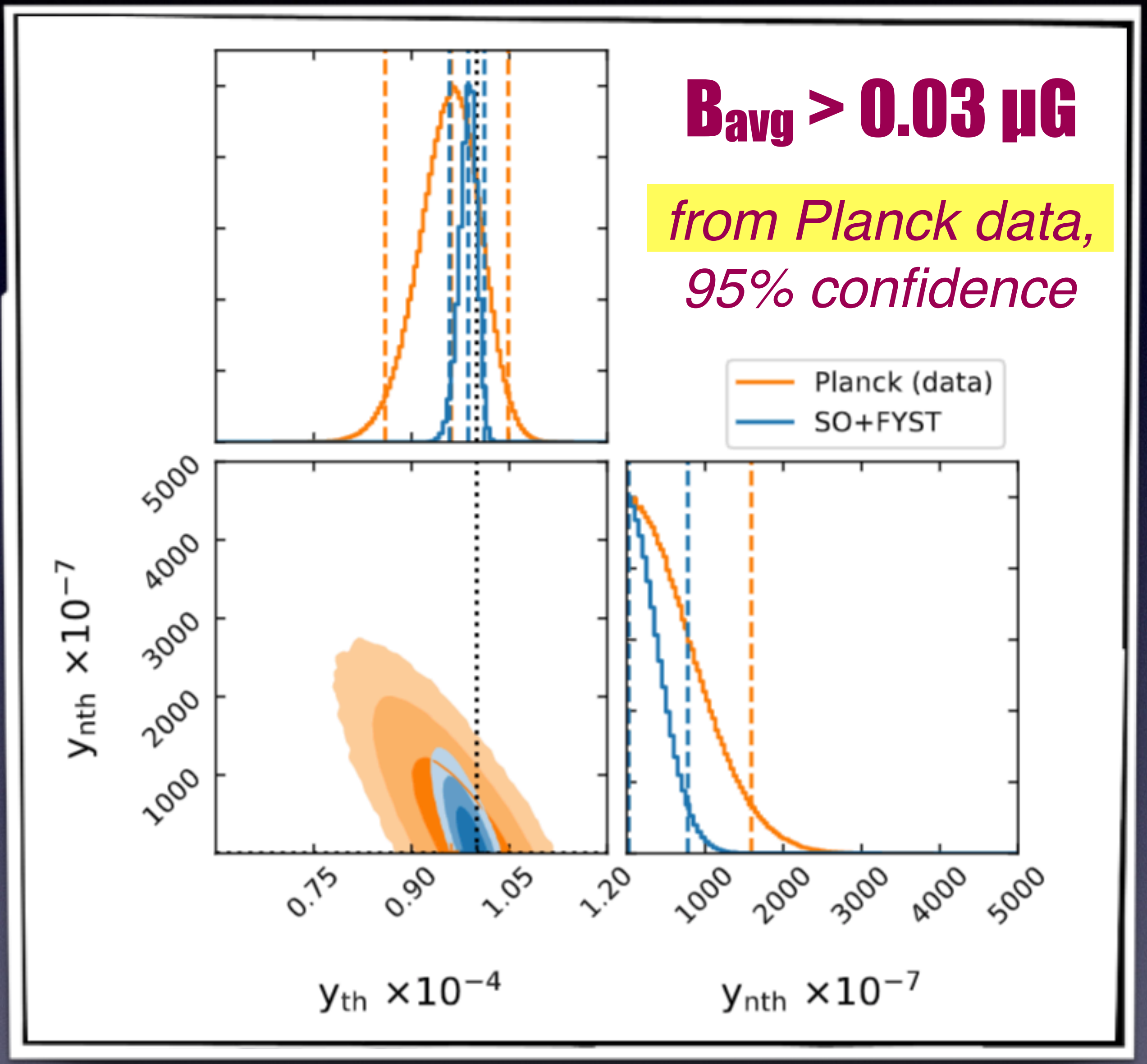




Muralidhara & Basu (in prep.)

# Results from ~40 RH clusters

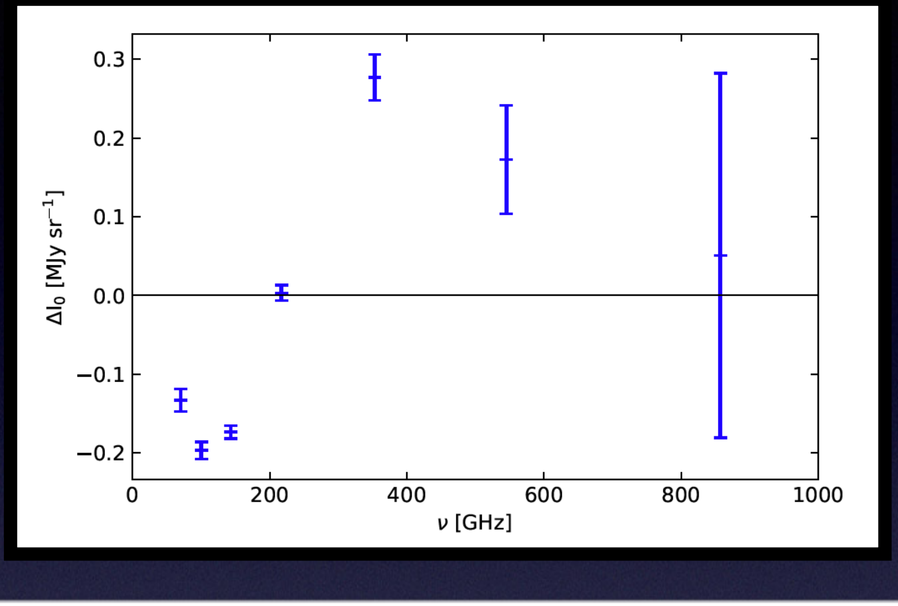
Muralidhara & Basu (in prep.)

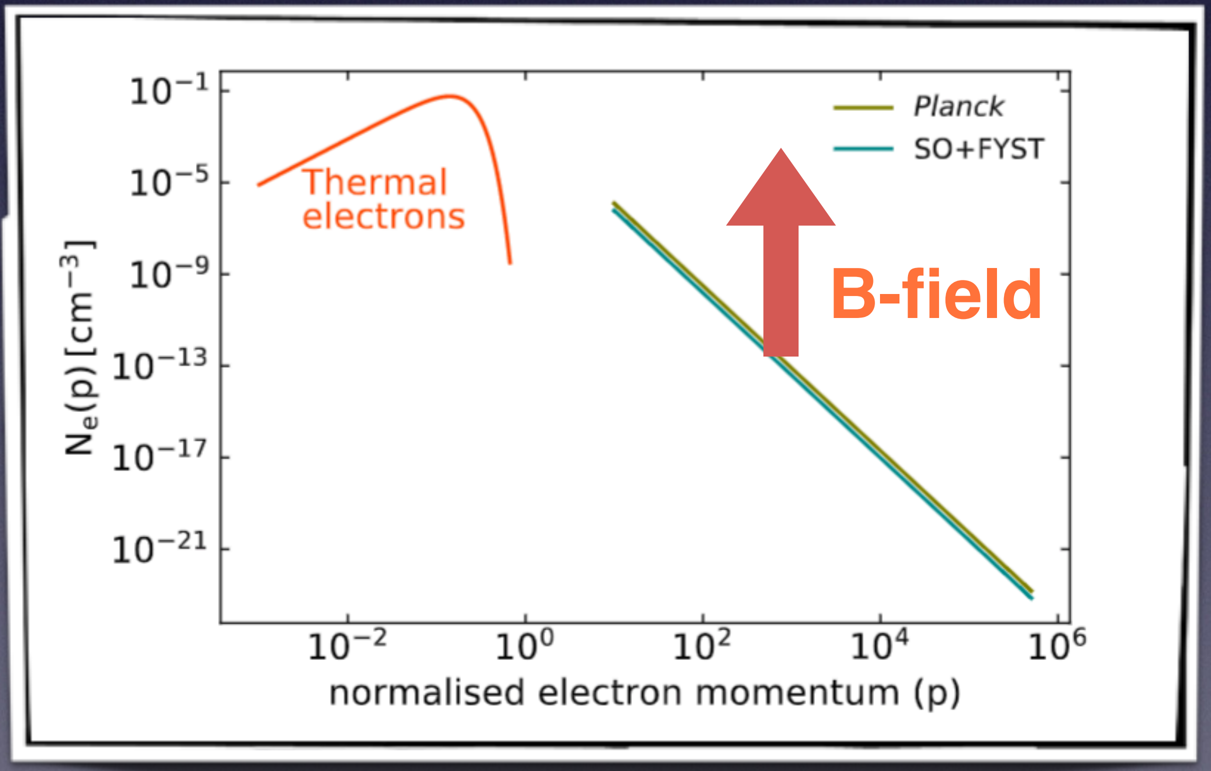


**$B_{avg} > 0.03\ \mu G$**

*from Planck data, 95% confidence*

Stacked spectrum of of 40 clusters from *Planck* data, after matched-filtering

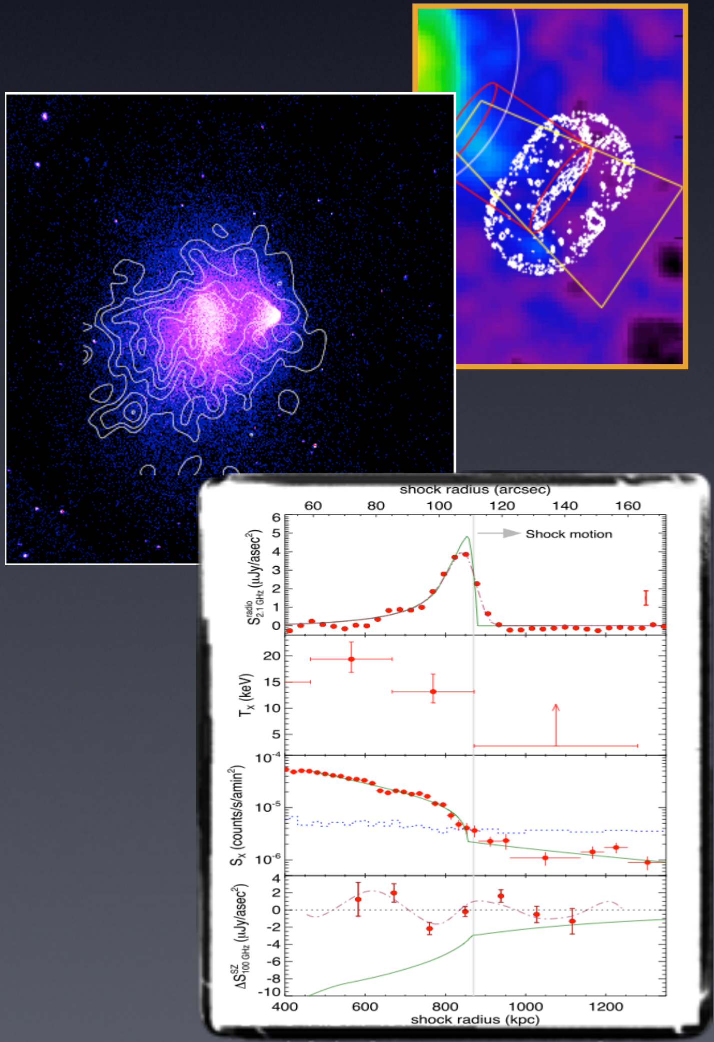




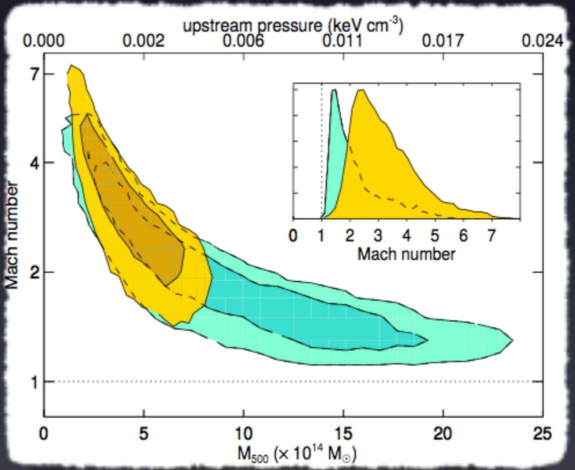
**With CCAT-prime and SO, order-of-magnitude better constraints on ntSZ-based B-field limits can be expected in the next ~5 years**

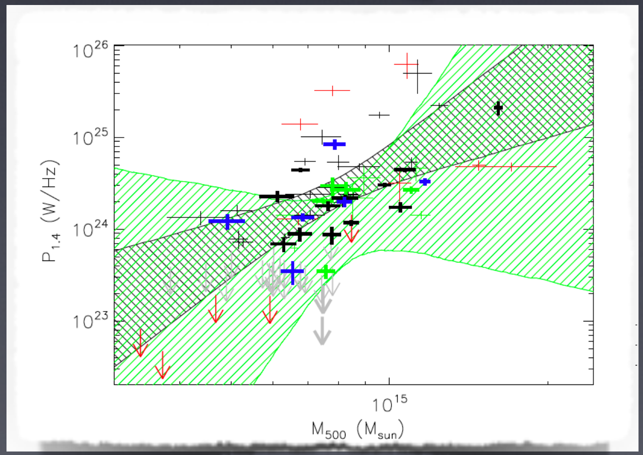
# Take home points

*Many questions unanswered for cluster diffuse radio emissions. Need to look beyond radio data.*



*SZ selection for radio halos provide unbiased statistics. SZ observation of radio relics measure the underlying shocks.*





*Nonthermal SZ measurement from next-generation CMB experiments is a potential new frontier.*