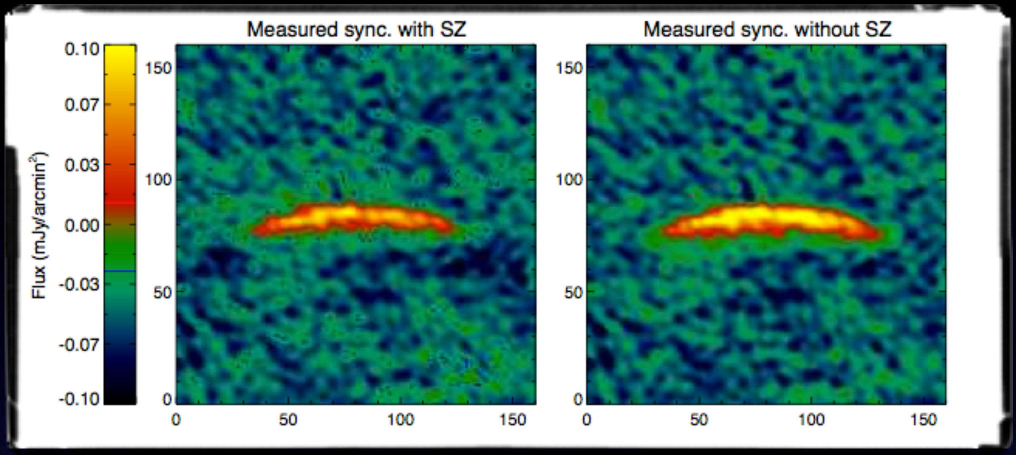
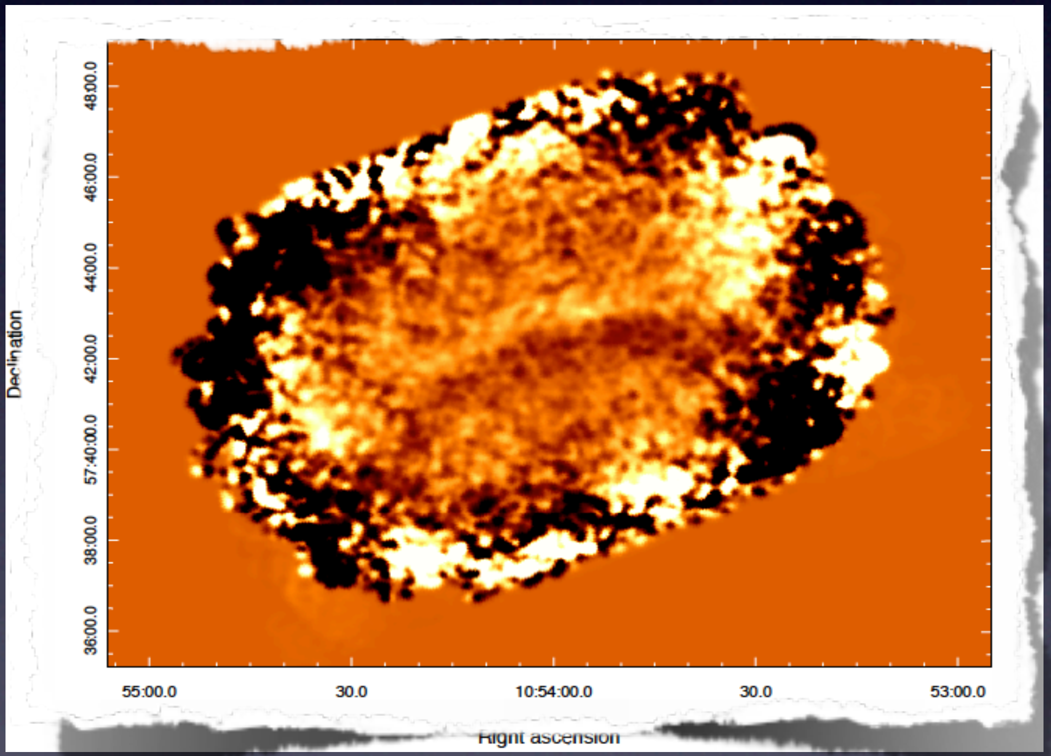
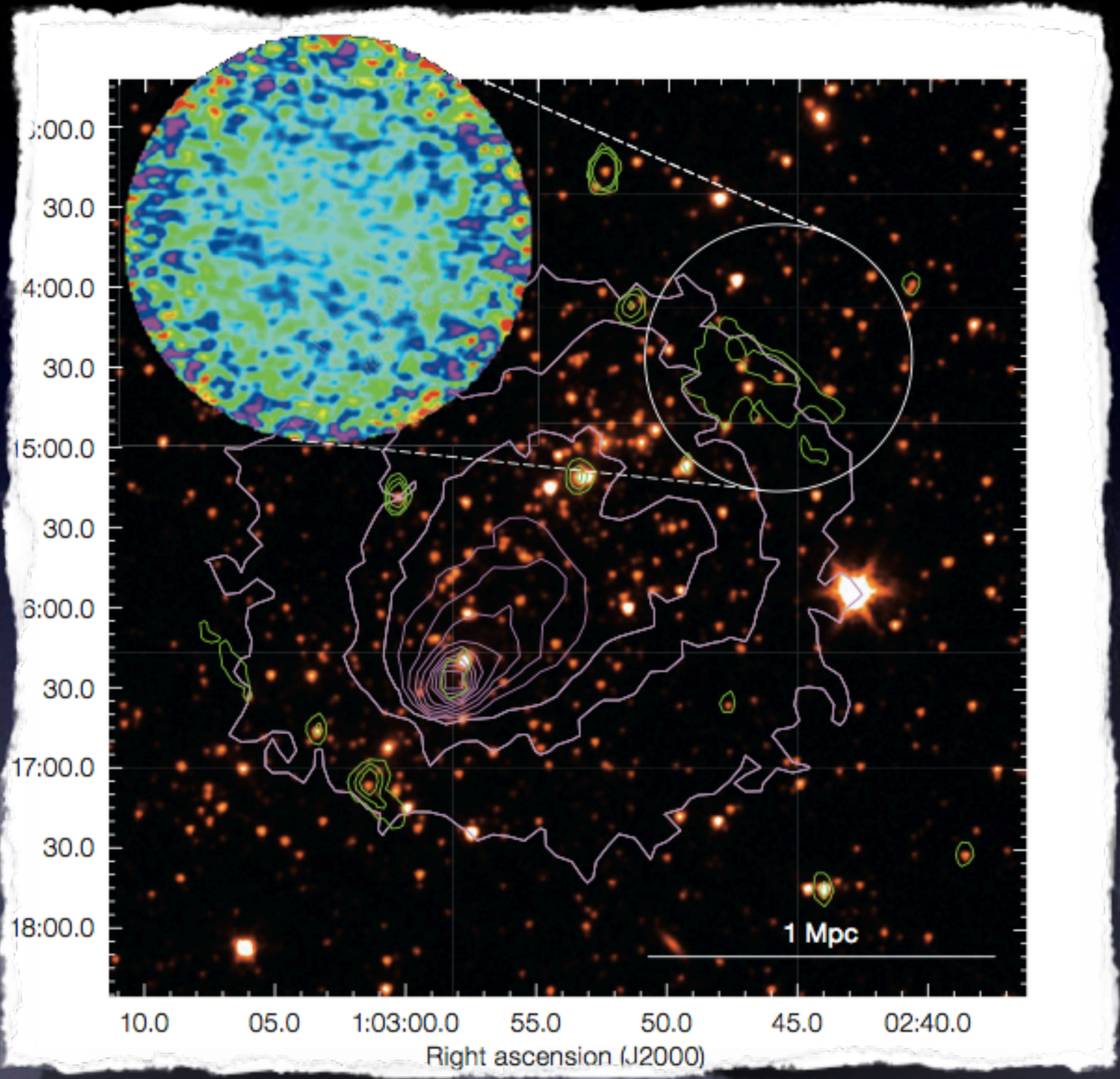
SZ observation of cluster *(relic)* shocks



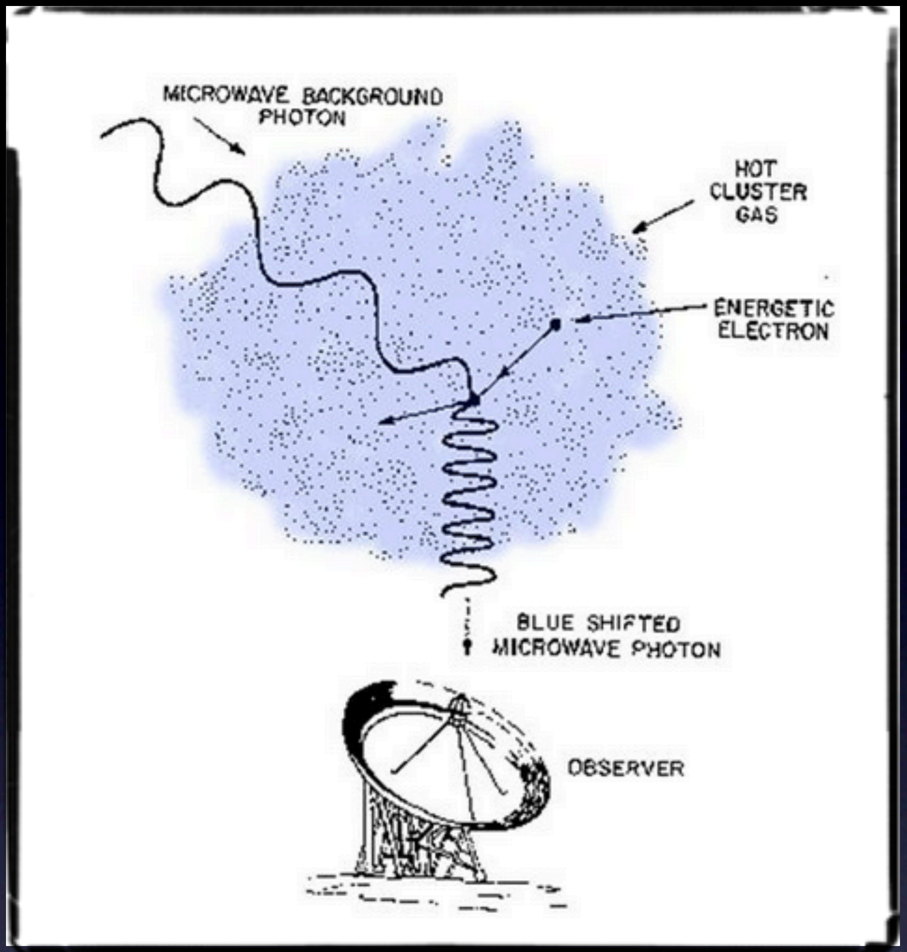




Kaustuv Basu (University of Bonn)

In collaboration with: Martin Sommer, Jens Erler, Franco Vazza, Dominique Eckert, and many others

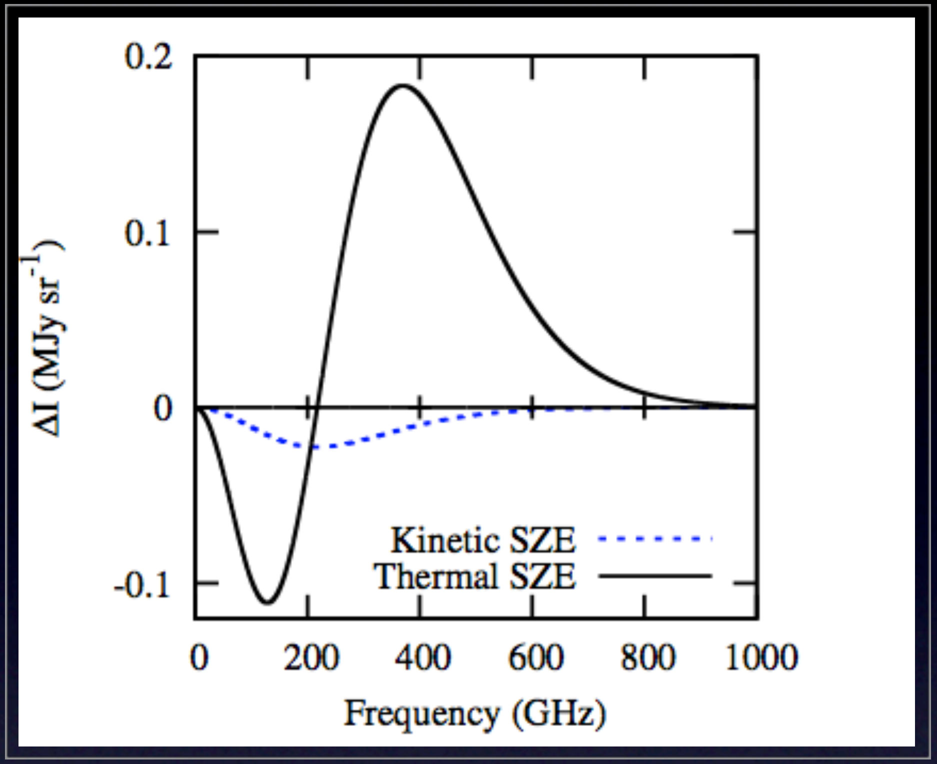
The Sunyaev-Zel'dovich effect

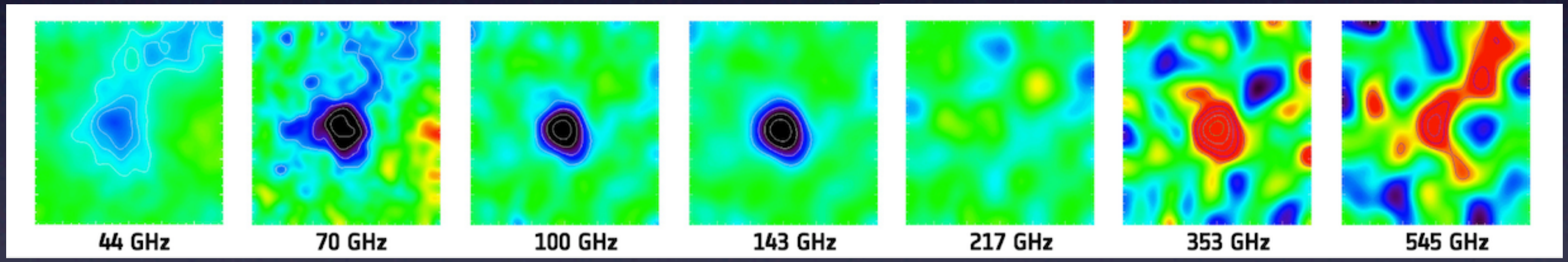


Inverse Compton scattering producing unique spectral distortion on the background CMB.

An ideal tool for finding and characterizing galaxy clusters.

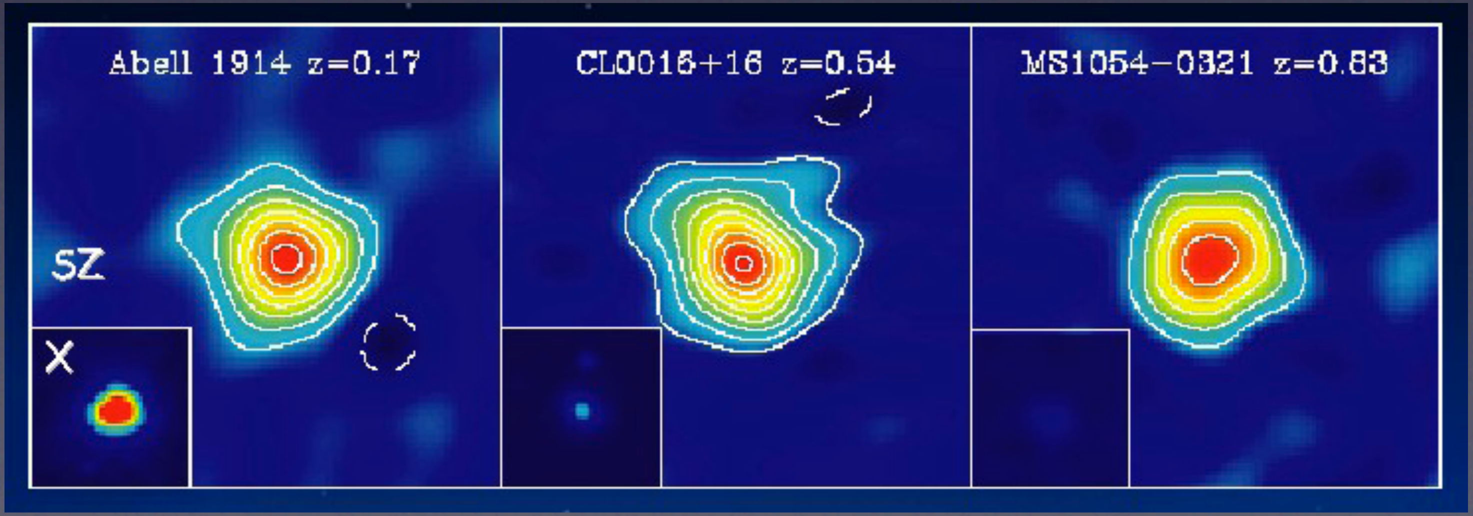
Resolved source flux is redshift independent and scales linearly with the gas density!



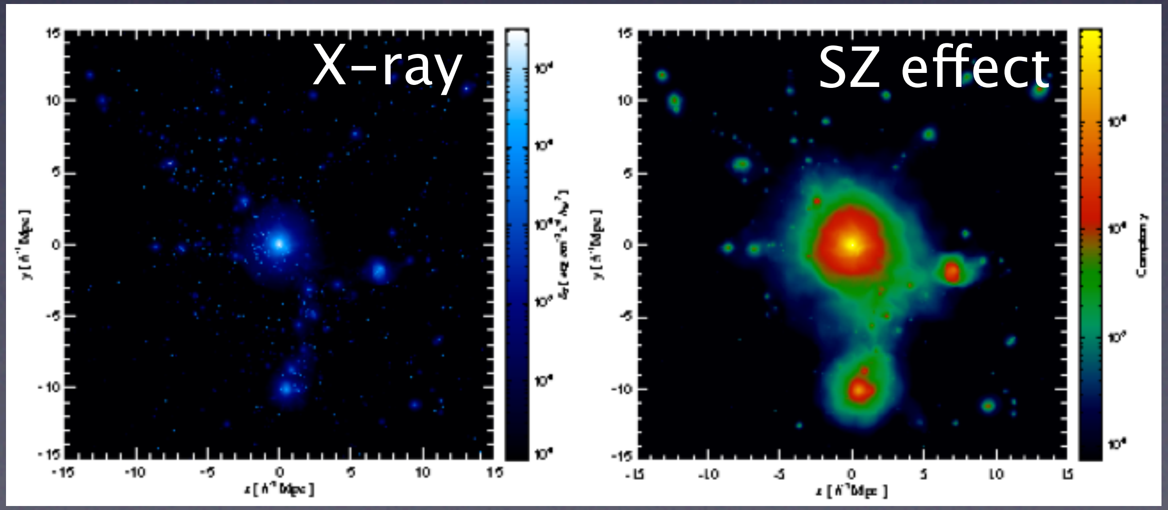


Credit: Planck collaboration

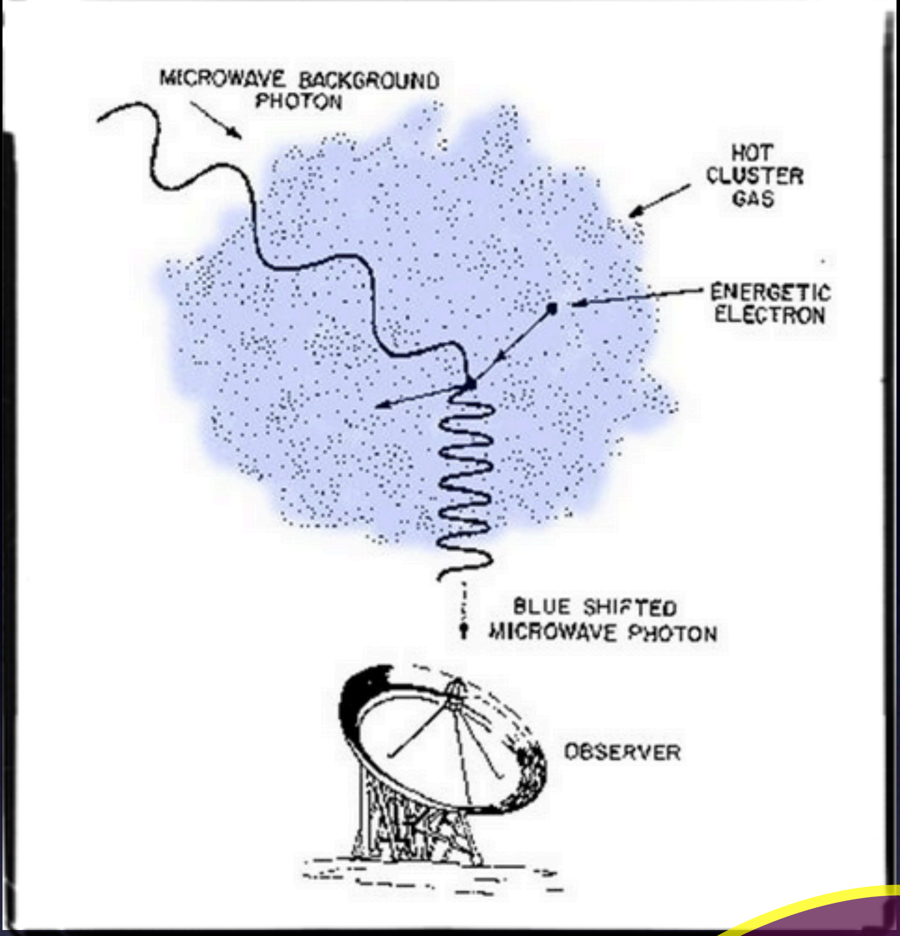
Carlstrom et al.



Sims: Pfrommer et al.



The Sunyaev-Zel’dovich effect



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

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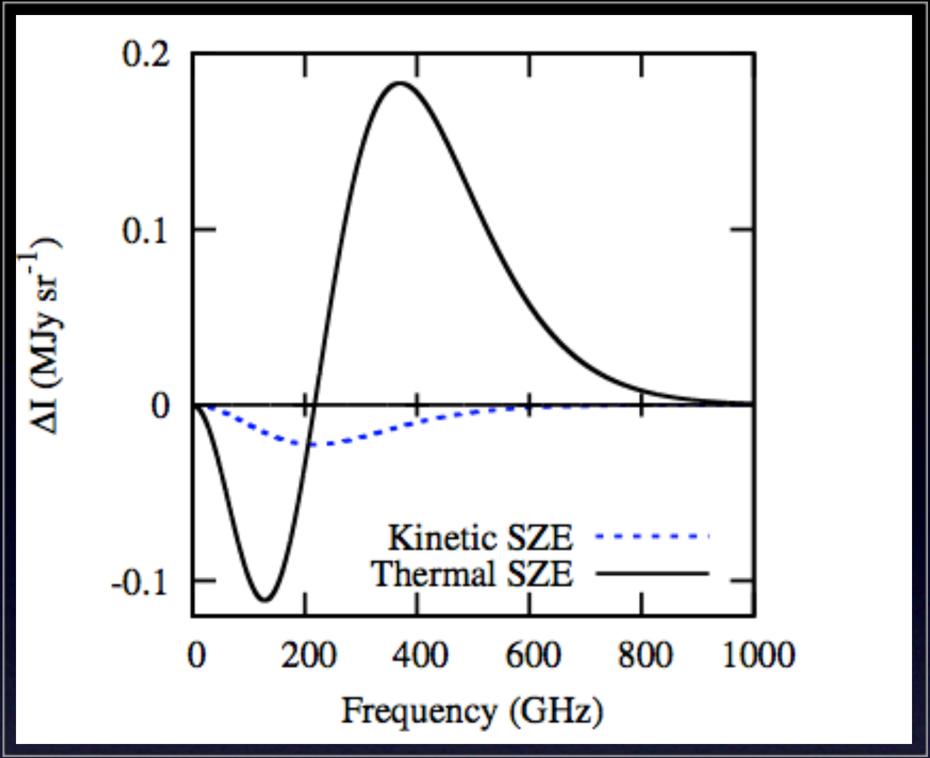
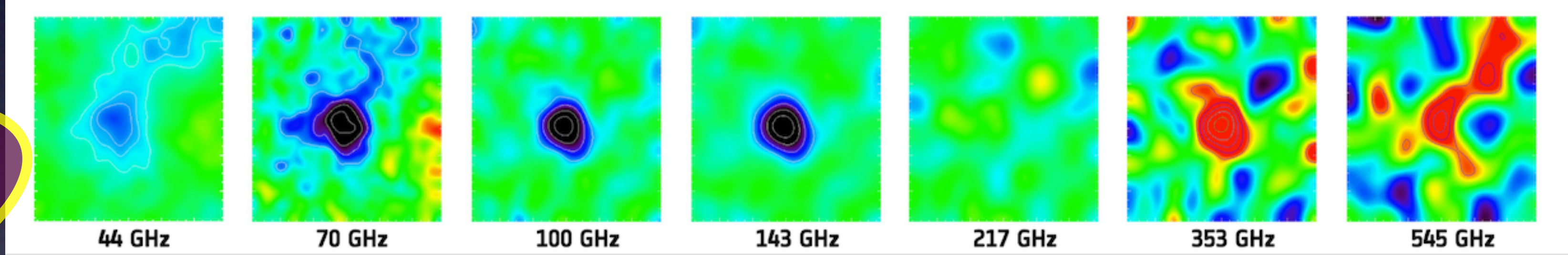
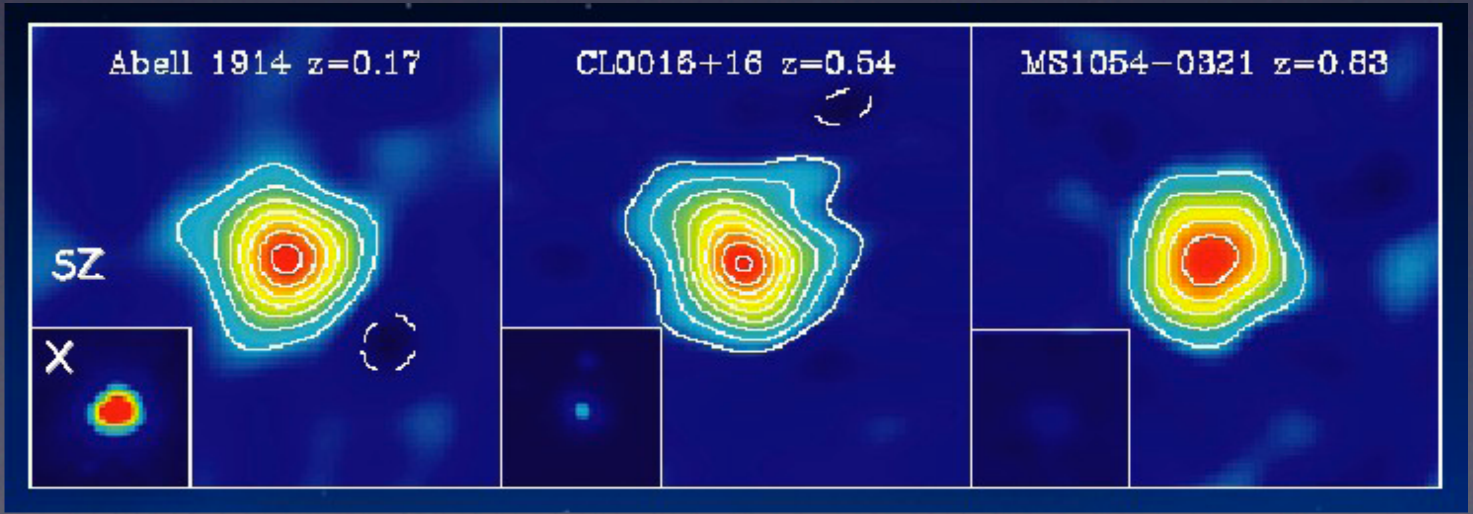


tSZ Effect

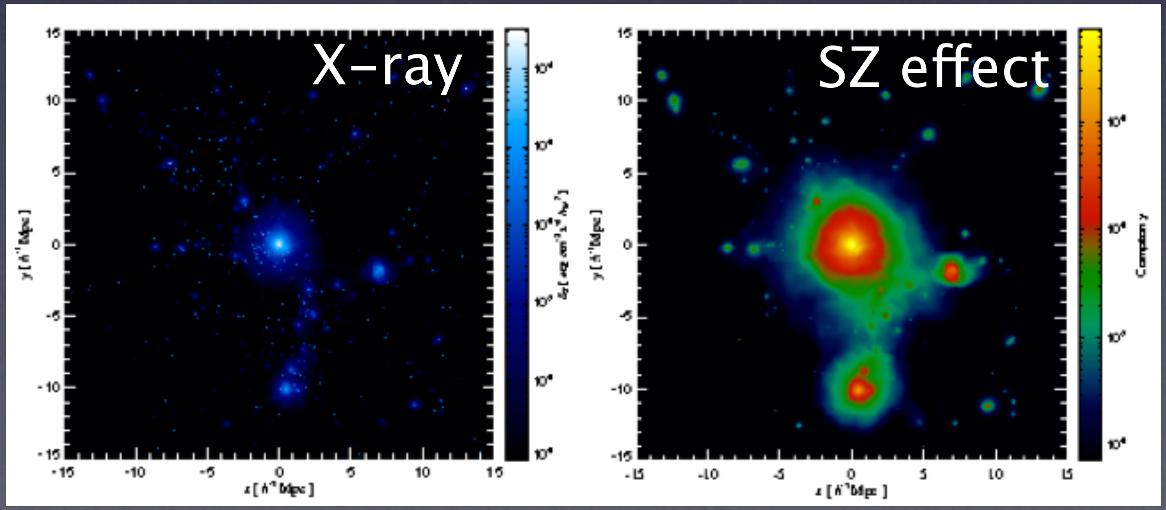


Credit: Planck collaboration

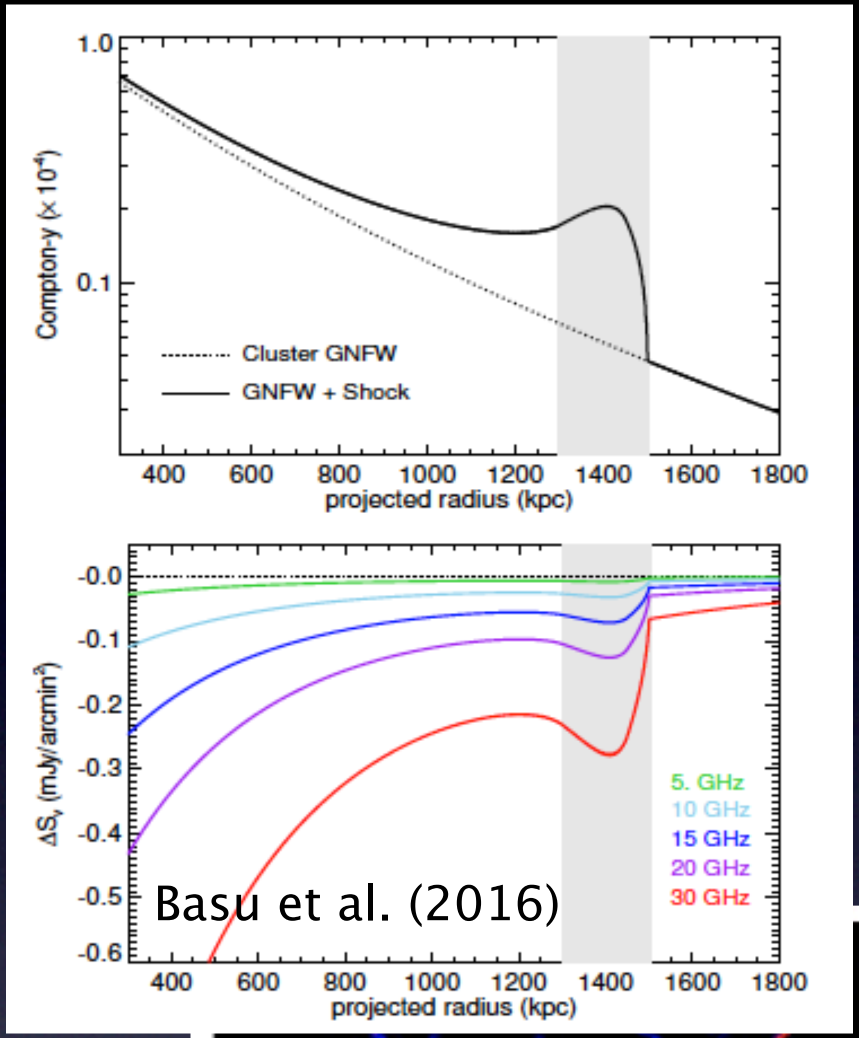
Carlstrom et al.



Sims: Pfrommer et al.



SZ effect to measure shocks

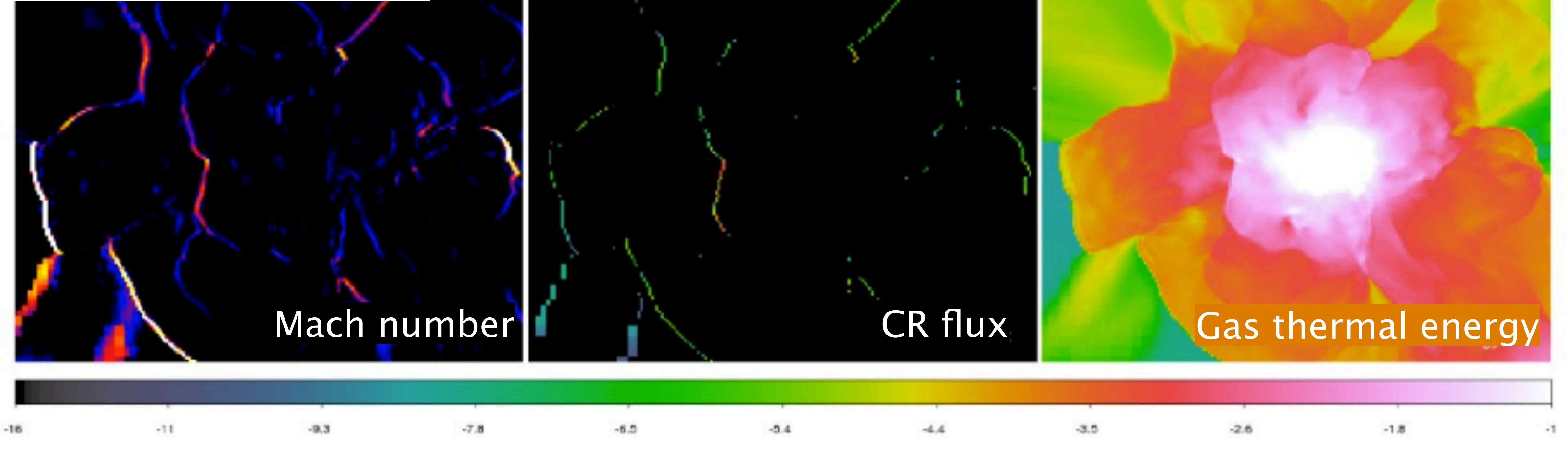


Basu et al. (2016)

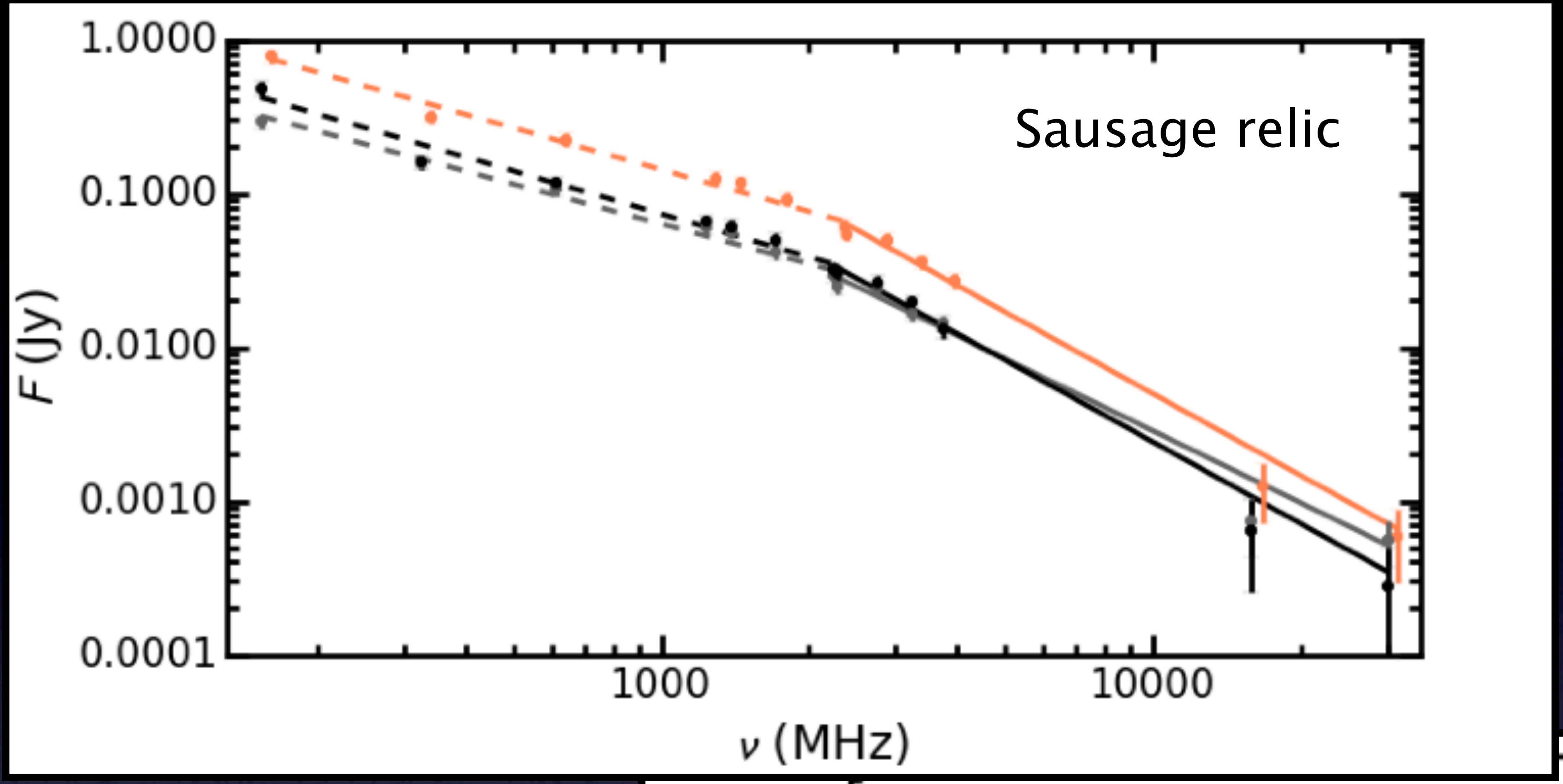
Shocks create a pressure boost, which roughly scales as the **Mach number squared**

On projection ($\int P\,\mathrm{d}l$ = Compton y parameter) this looks like a step function and relatively easily detectable also in the cluster outskirts

Vazza et al. (2012)

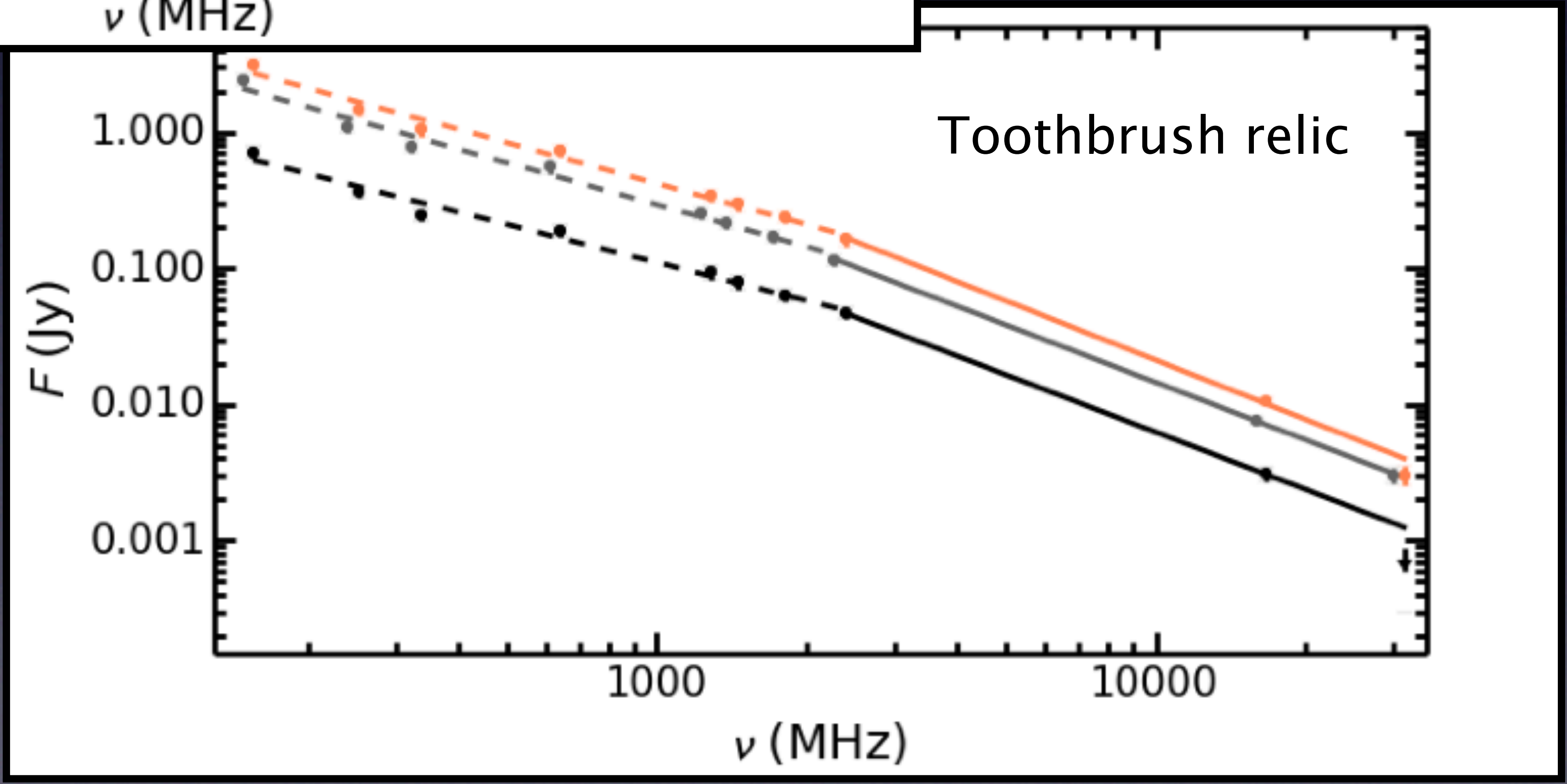


The steepening spectrum of some relics



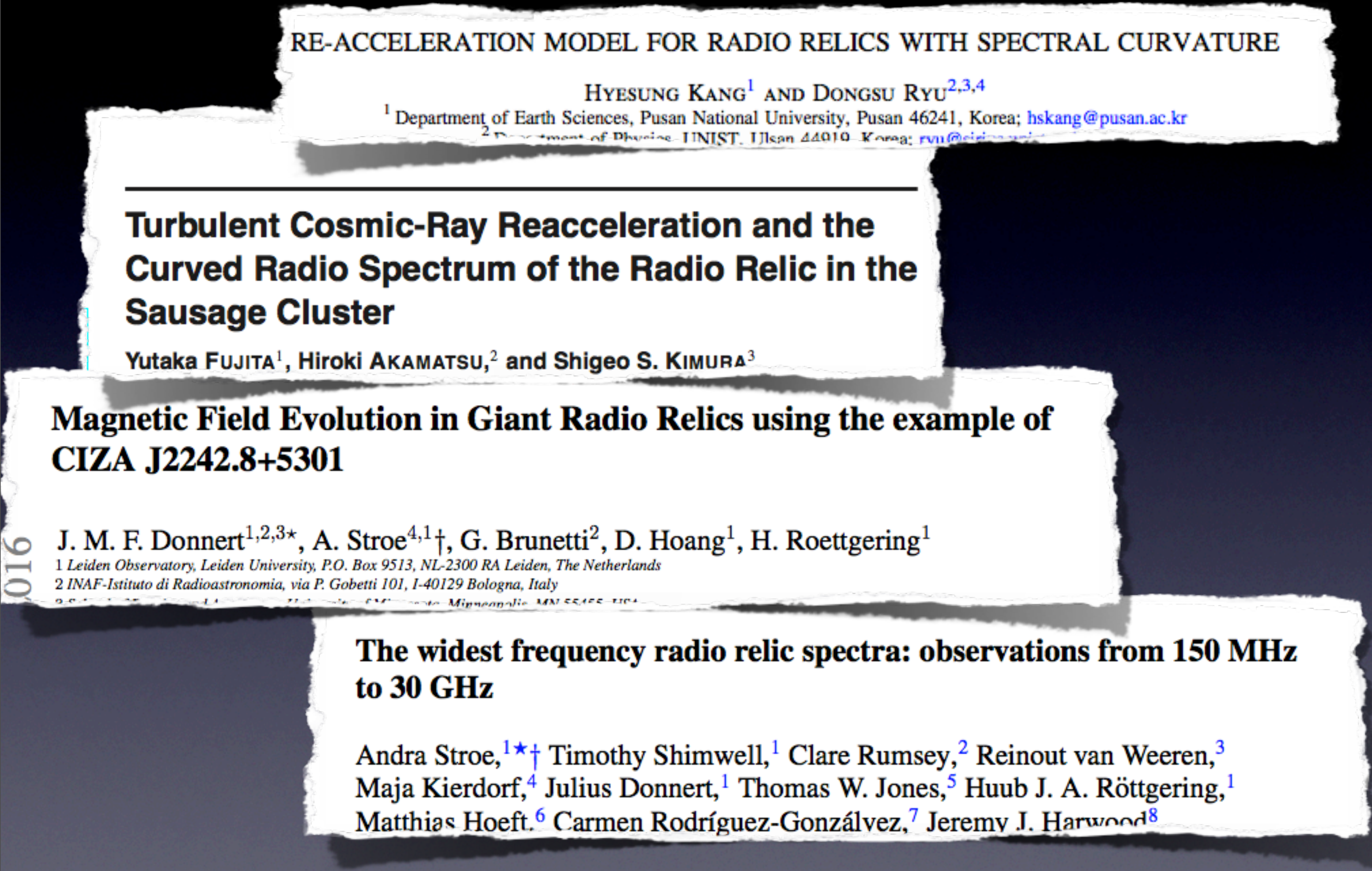
Stroe et al. (2015, 2016)

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.

The steepening spectrum of some relics



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

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*

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]

The steepening spectrum of some relics

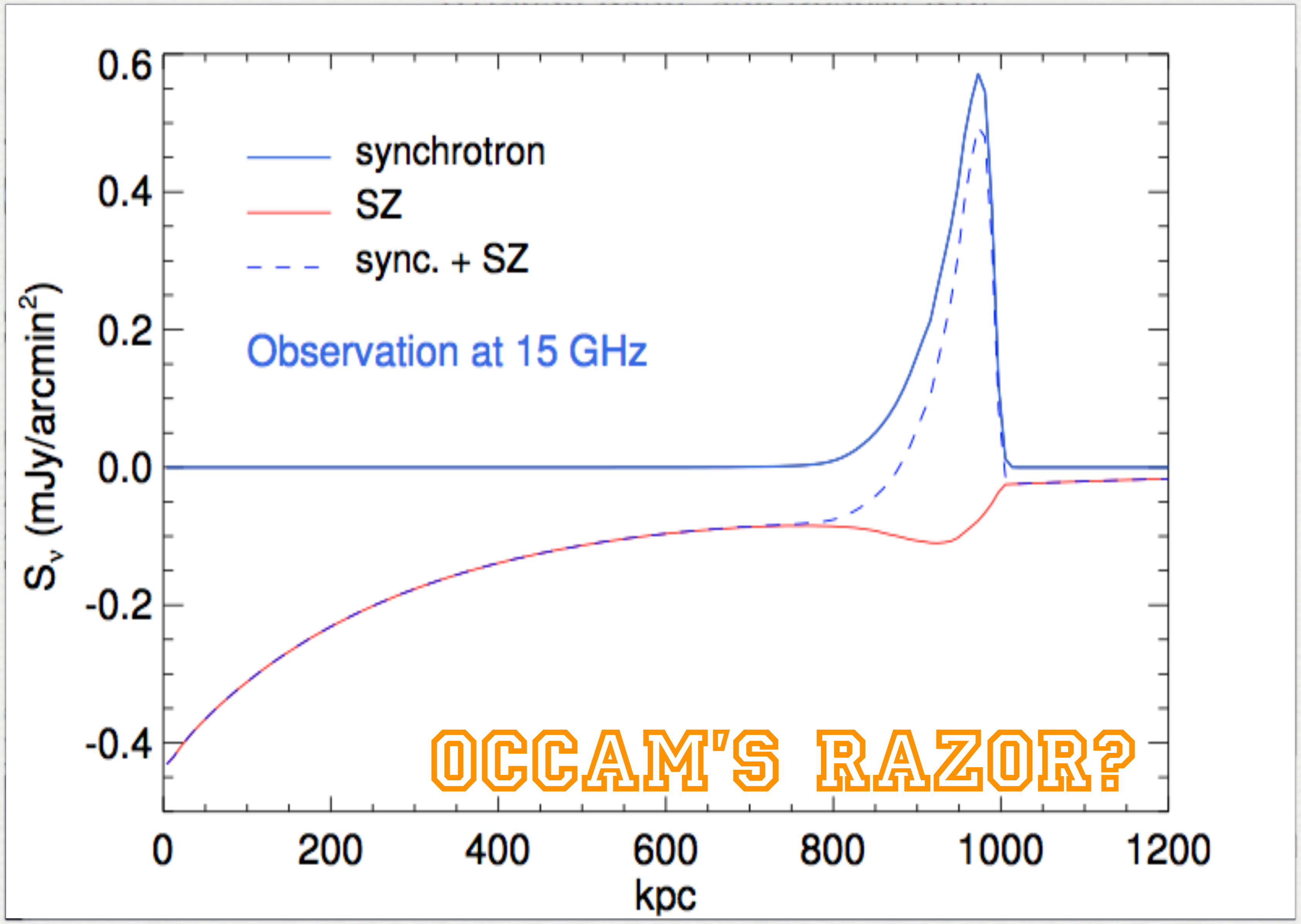
RE-ACCELERATION MODEL FOR RADIO RELICS WITH SPECTRAL CURVATURE

Turbulent
Curved R
Sausage

Yutaka FUJITA[1]

Magnetic Field
CIZA J2242.8+

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



OCCAM'S RAZOR?

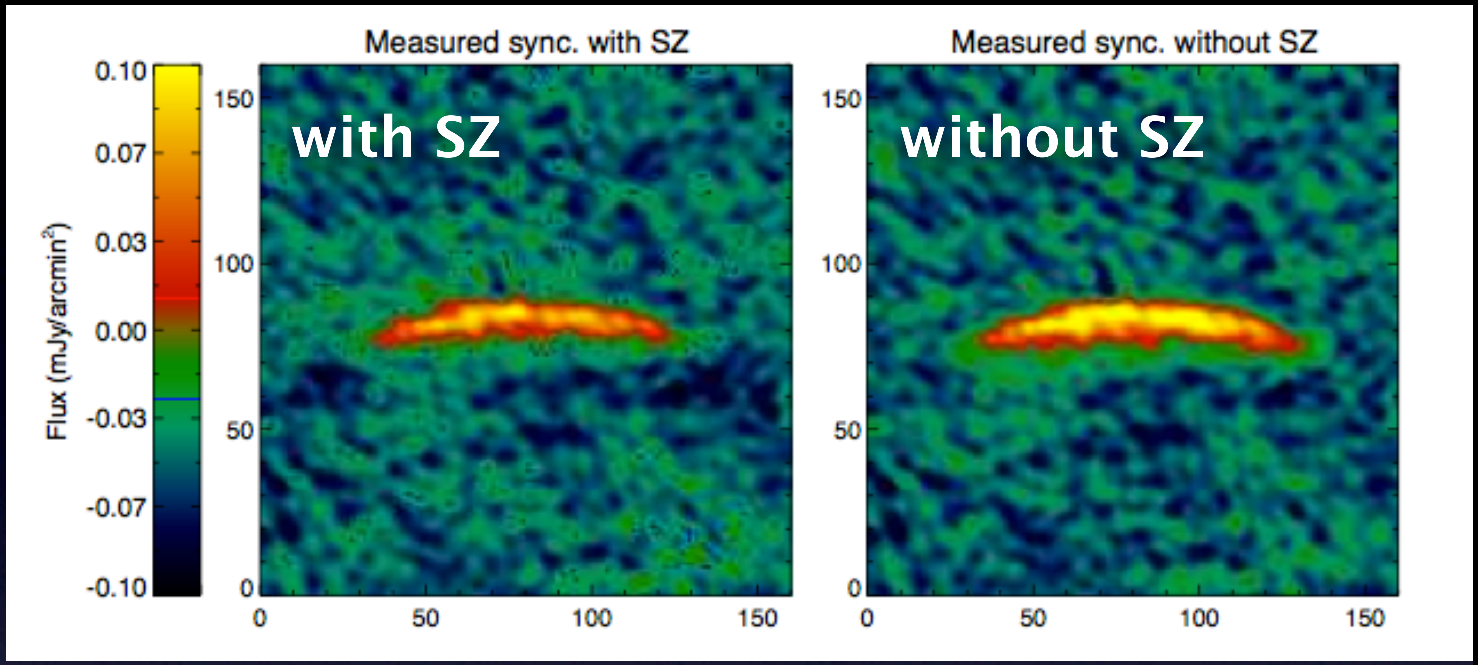
Basu et al. (2016), A&A, 591

150 MHz

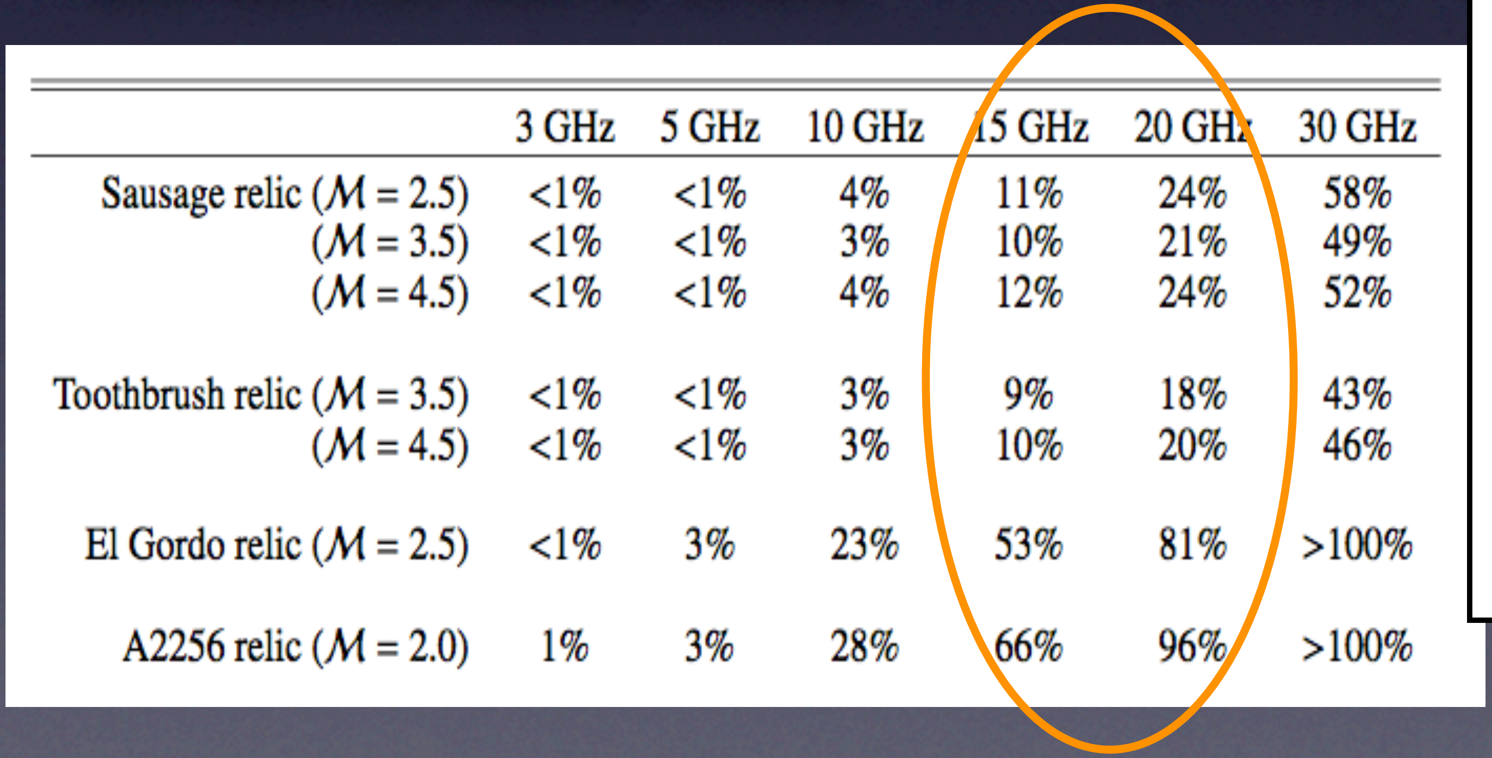
Andra Stroe,[1★†] Timothy Shimwell,[1] Clare Rumsey,[2] Reinout van Weeren,[3]
Maja Kierdorf,[4] Julius Donnert,[1] Thomas W. Jones,[5] Huub J. A. Röttgering,[1]
Matthias Hoeft,[6] Carmen Rodríguez-Gonzálvez,[7] Jeremy J. Harwood[8]

A non-negligible effect (≳10 GHz)

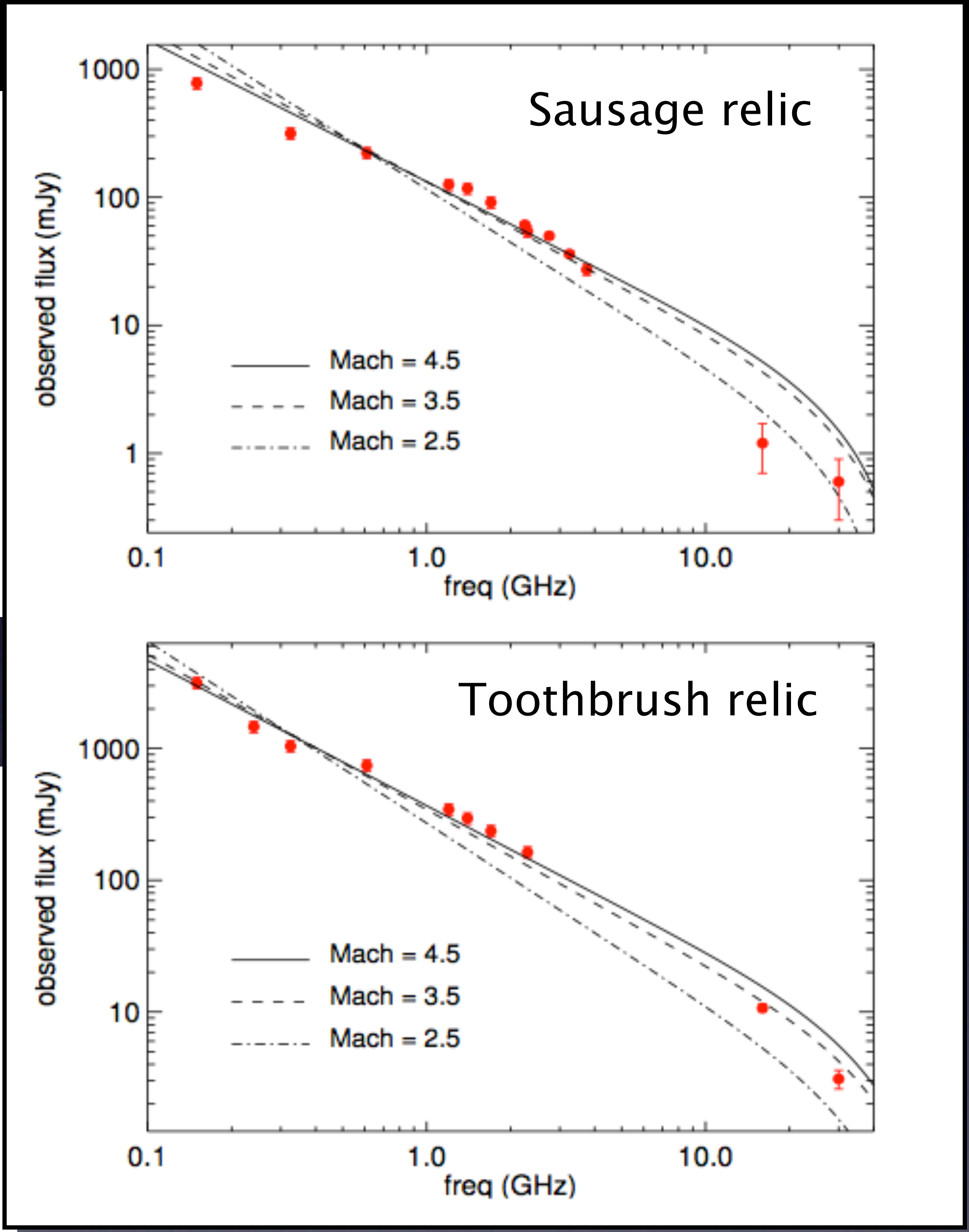
Simulated interferometric observation at 10 GHz



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

Synchrotron/SZ flux ratio

Make assumptions (following H&B 2007):

(1) The kinetic power of the shock:

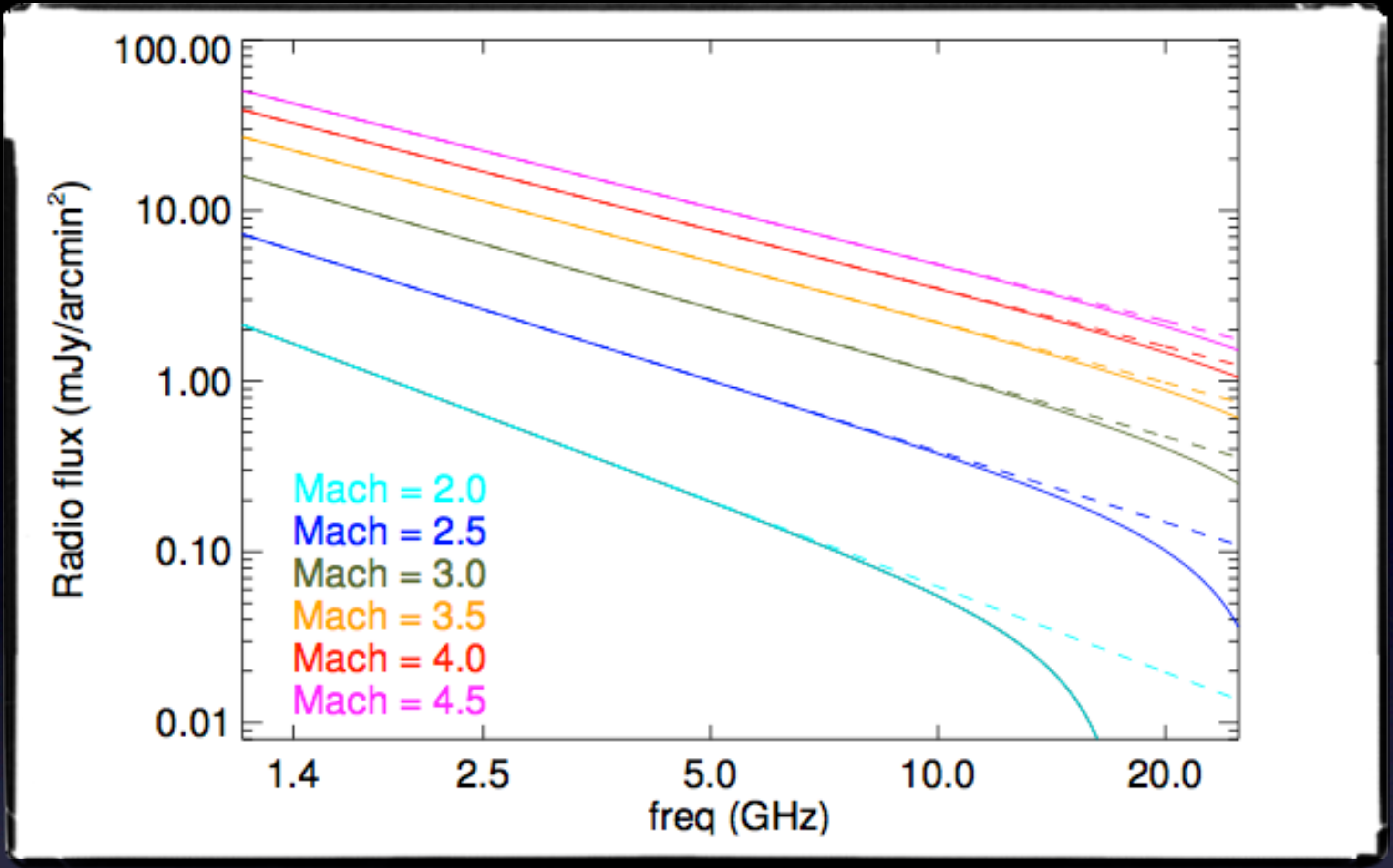
$$P_{\rm kin} = n_u v_s^3\, S/2 \quad (\text{where } v_s = \mathcal{M} c_s)$$

(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):

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



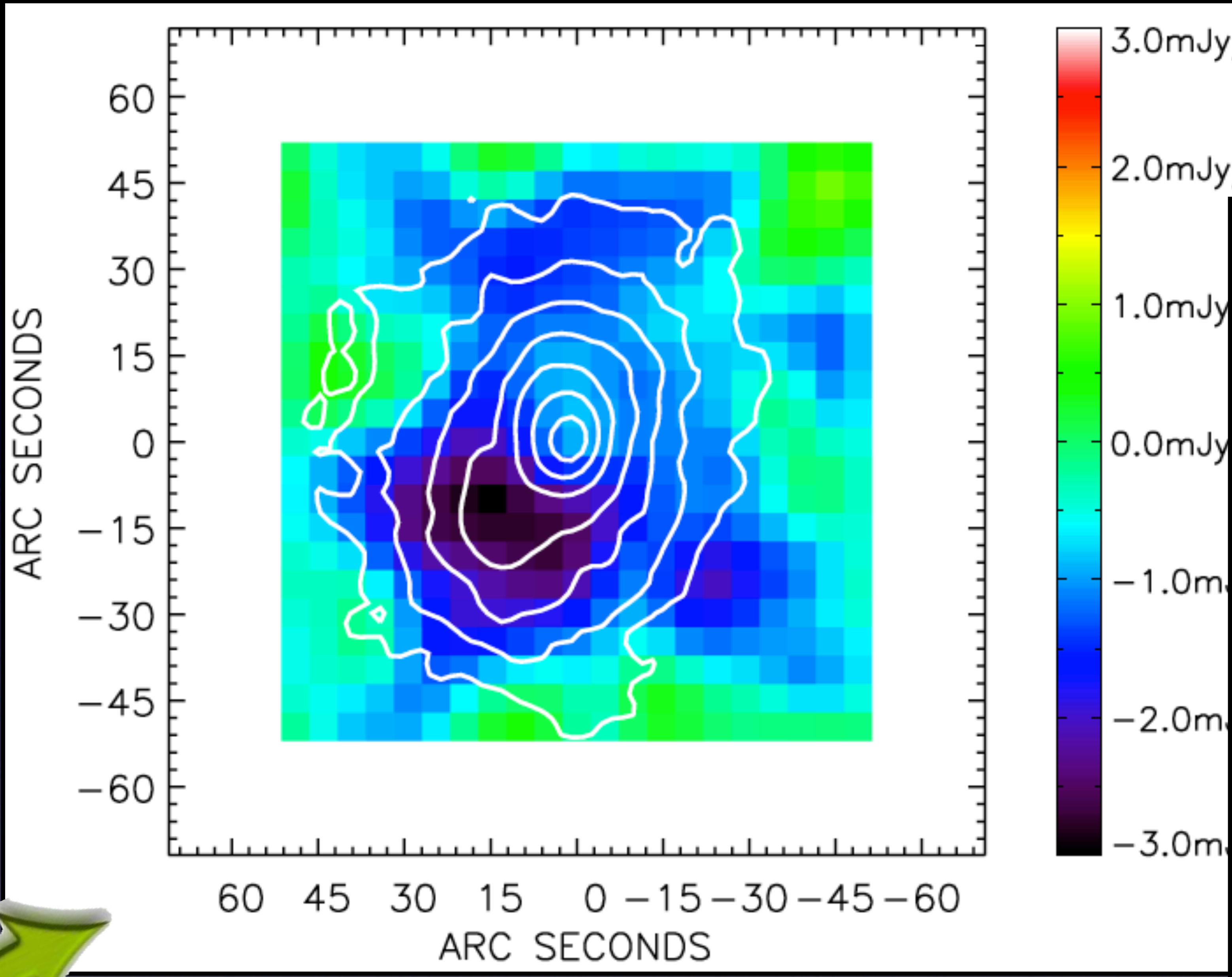
$$\frac{S_\nu^{\rm sync.}}{S_\nu^{\rm SZ}} \approx -9\times 10^4 \left(\frac{\xi_{\rm e/p}}{0.05}\right)\left(\frac{\mathcal{M}}{3}\right)\left(\frac{T_{\rm u}}{1\ {\rm keV}}\right)^{1/2}\left(\frac{W}{100\ {\rm kpc}}\right)^{-1} \times (1+z)^{-(4+\delta/2)}\, \frac{B_{\rm relic}^{1+\delta/2}}{B_{\rm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

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

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

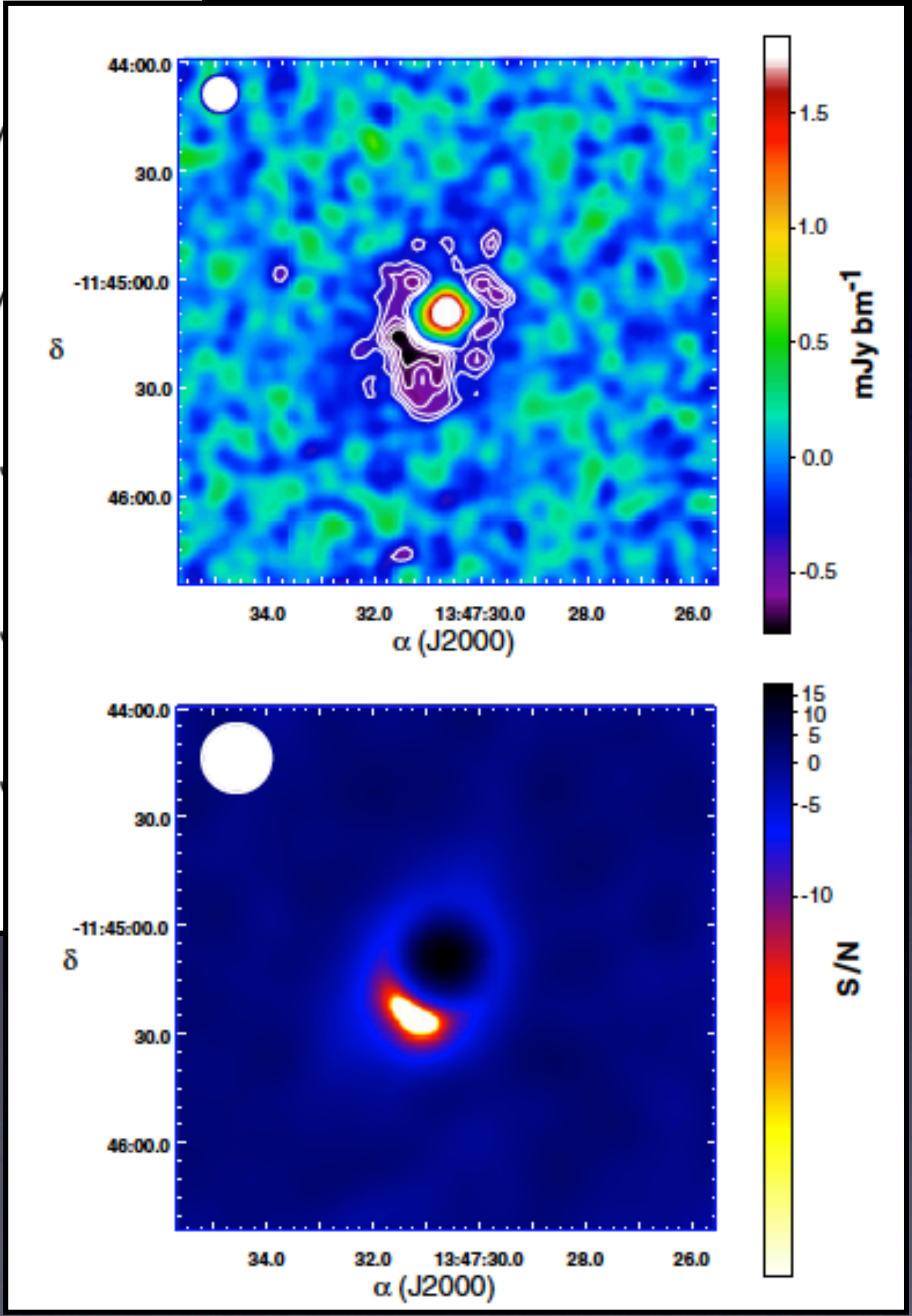
BUT, ACTUAL SHOCK IN SZ?

SZ substructures from shocks



Nobeyama 150 GHz

MUSTANG/GBT 90 GHz
(Korngut et al. 2011)



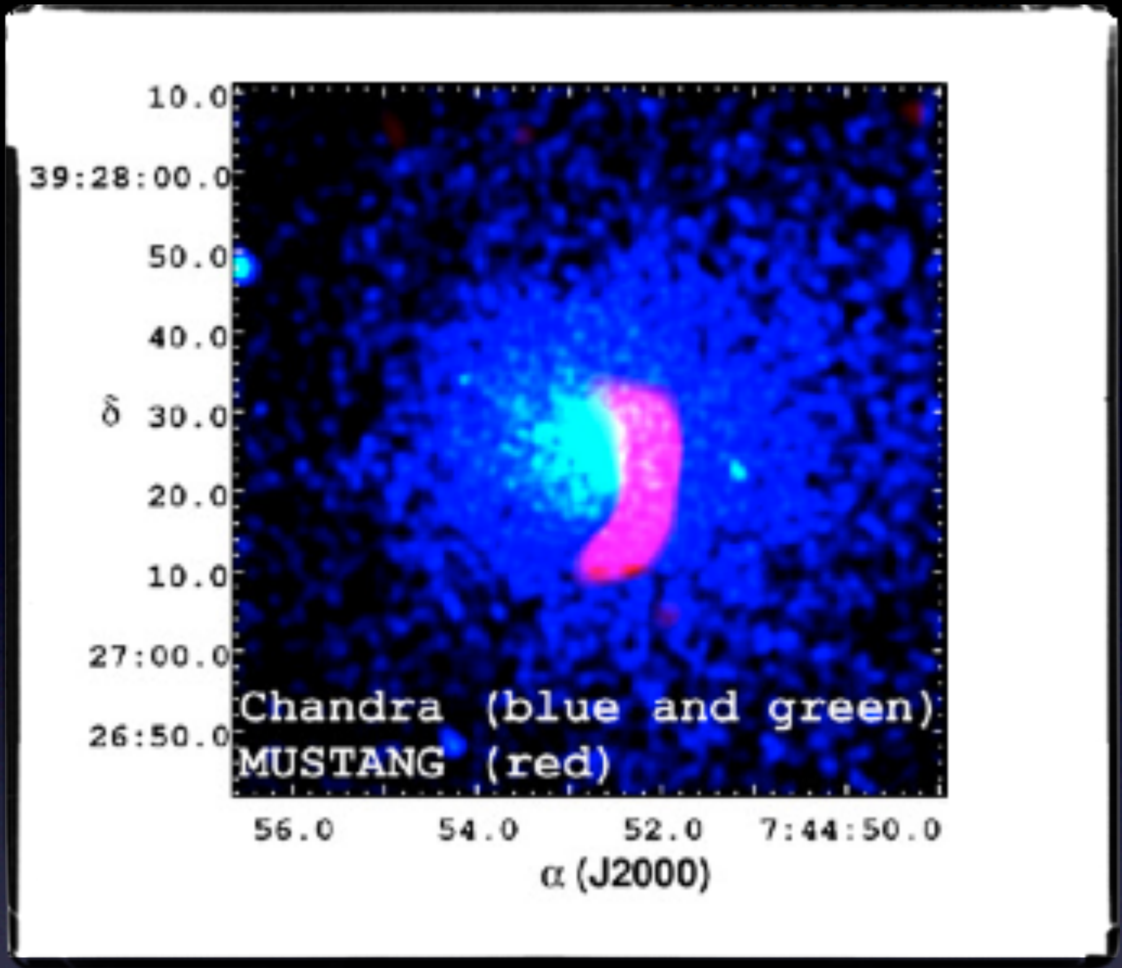
First measurement of shock heated gas in SZ

Kitayama et al. (2004) using Nobeyama telescope, in the galaxy cluster RXC J1347 (see also Ferrari et al. 2011)

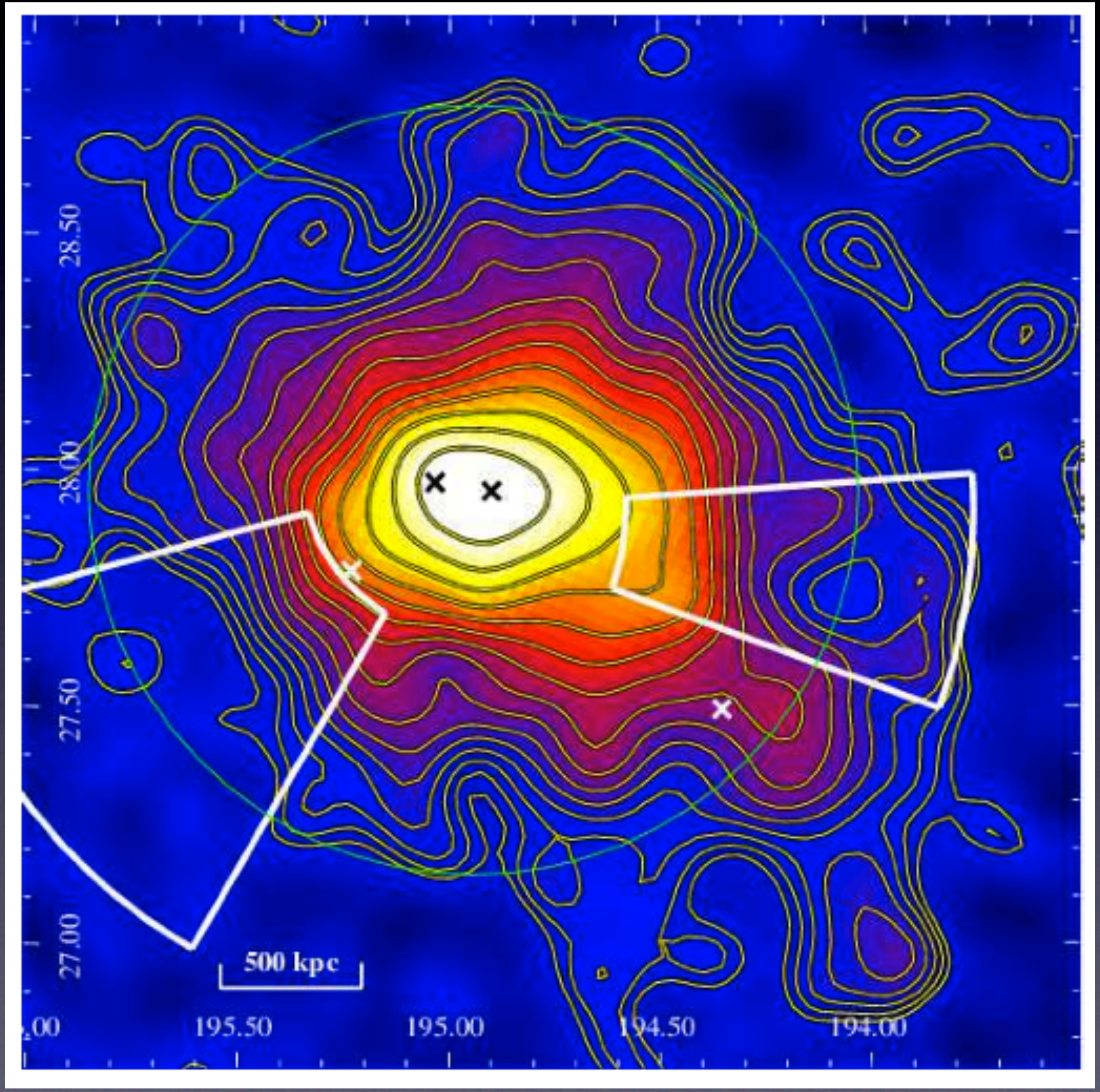
Direct detection of shock jump followed much later..

Shock fronts in SZ (within r_{500})

SZ shock modeling enabled by X-ray priors

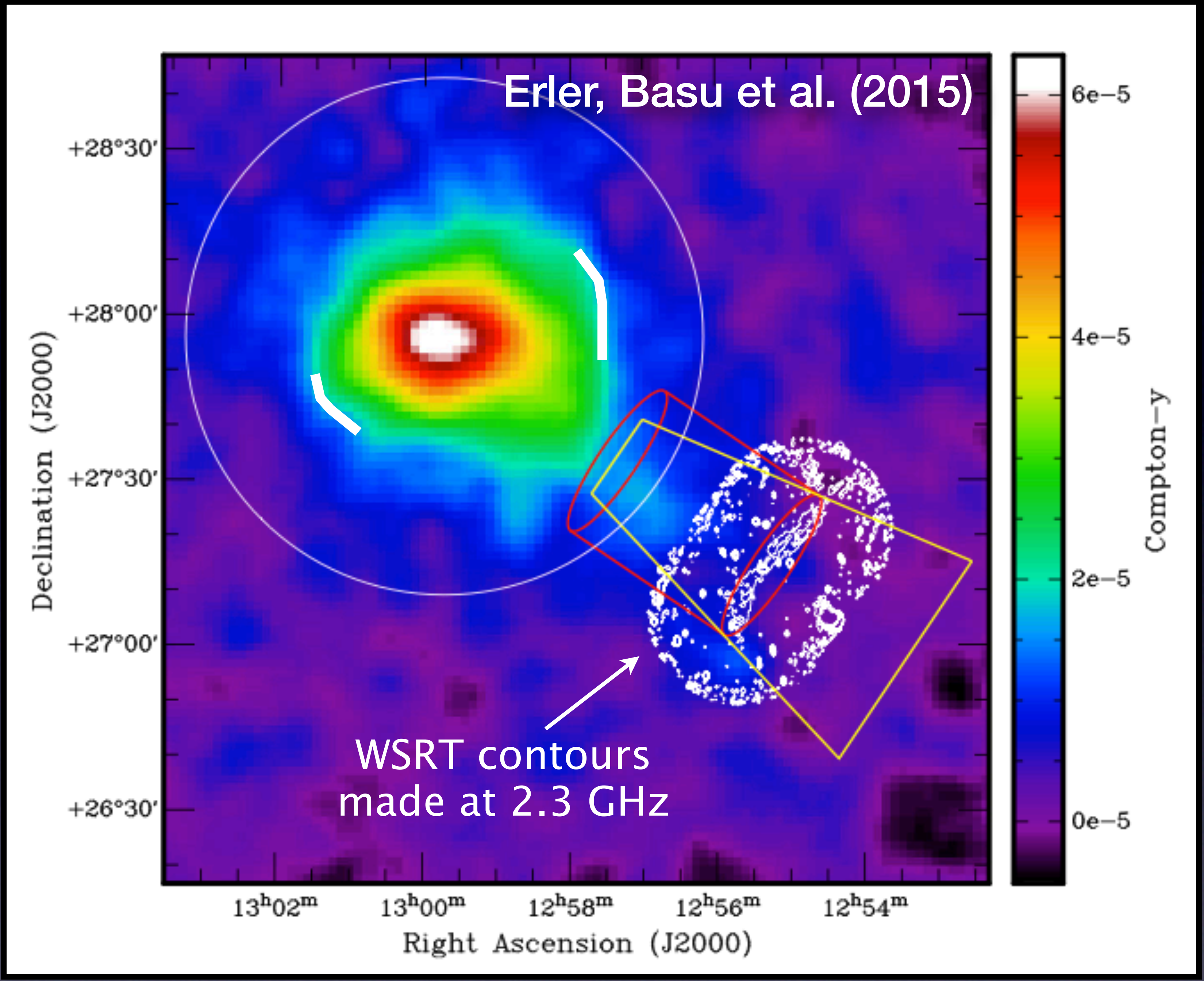


SZ shock in MACS J0744
(GBT/MUSTANG; Korngut et al. 2011)

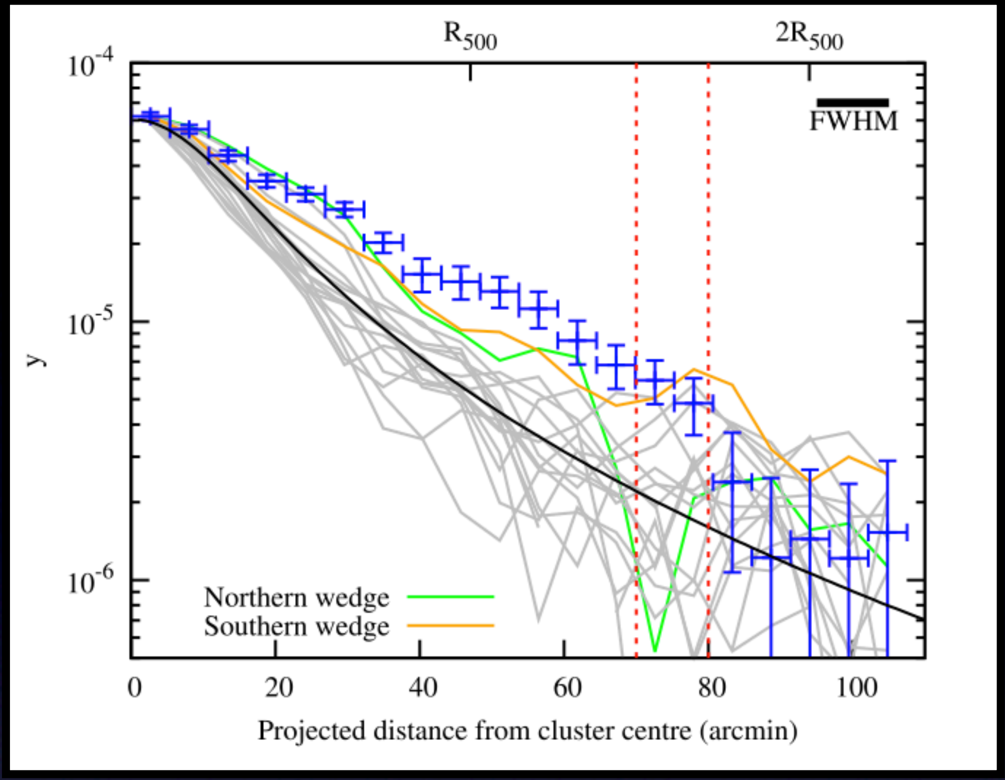


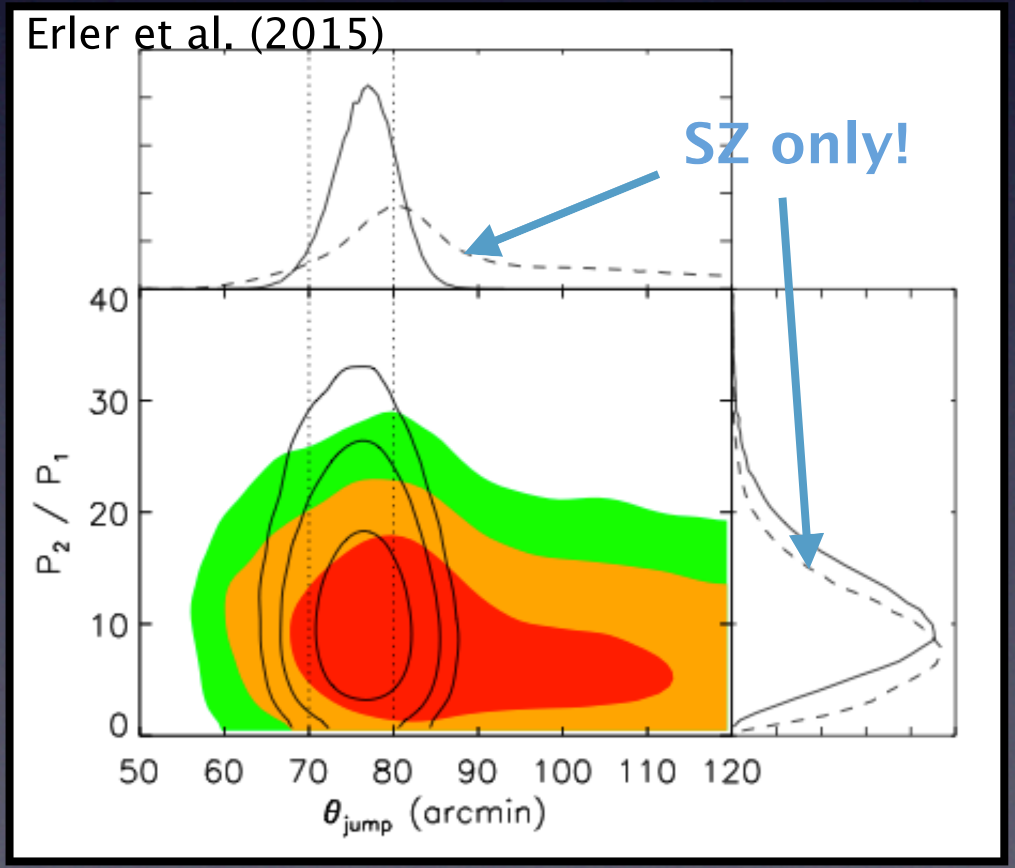
$R \leq R_{500}$ shocks in the Coma cluster
(Planck collaboration 2013)

Coma's relic, with Planck


Erler, Basu et al. (2015)

WSRT contours made at 2.3 GHz



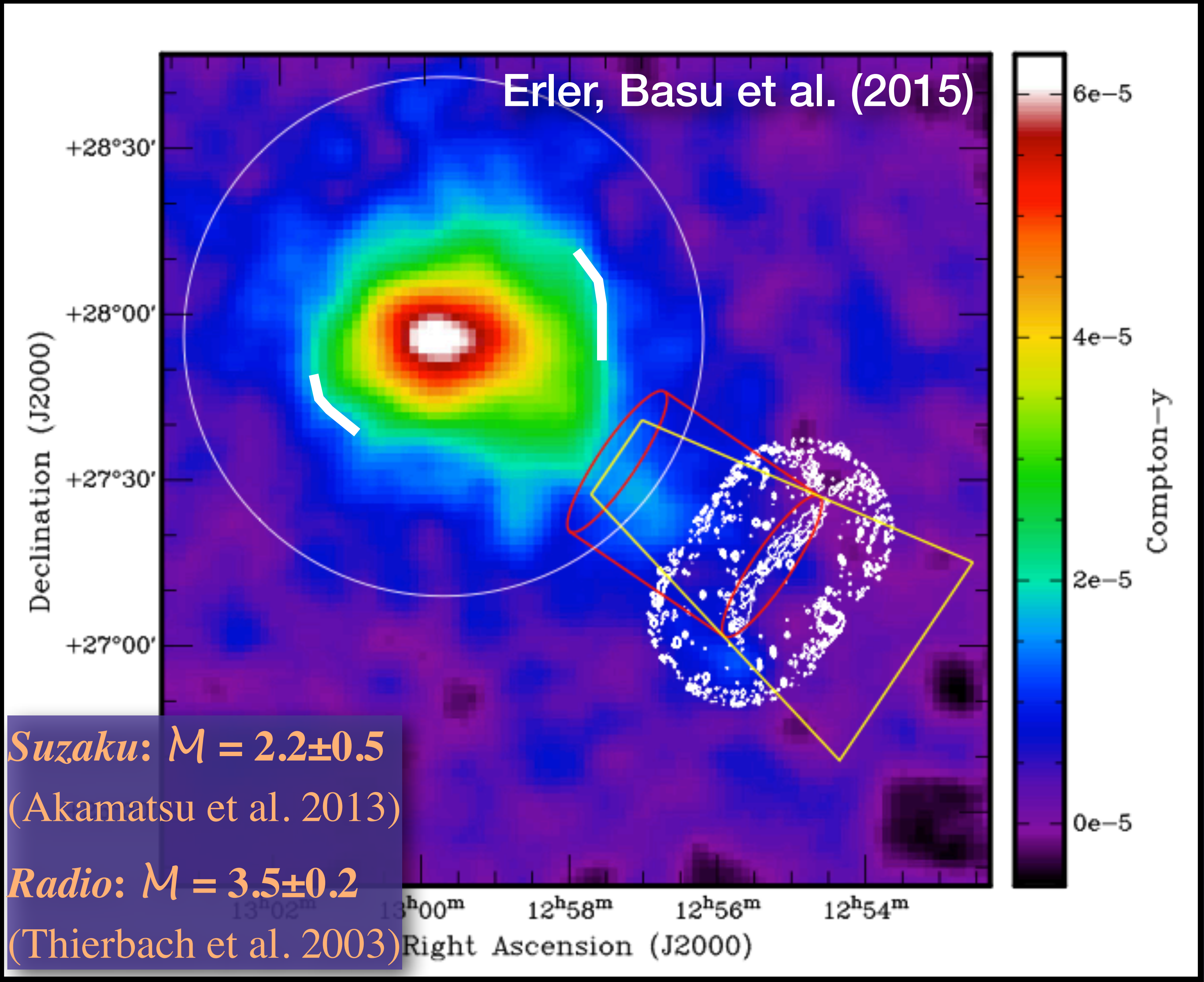

Erler et al. (2015)

SZ only!

The first measurement of a relic shock in SZ

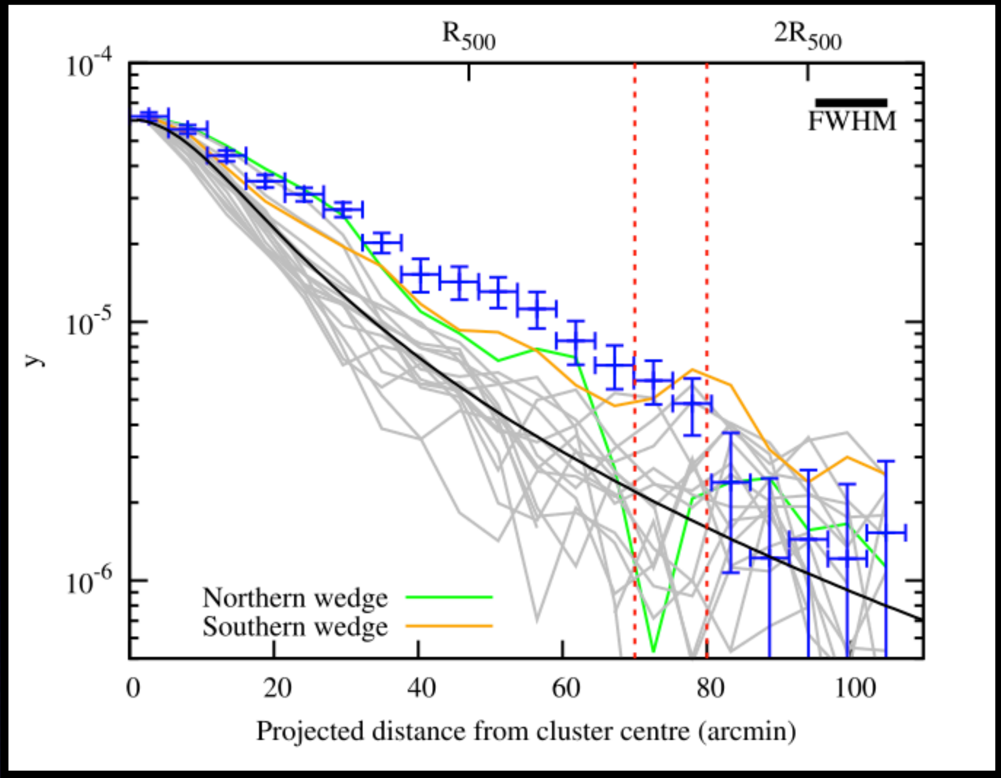
- Pressure boost confirmed with or without a radio prior
- Joint X-ray analysis rules out an inward-moving shock

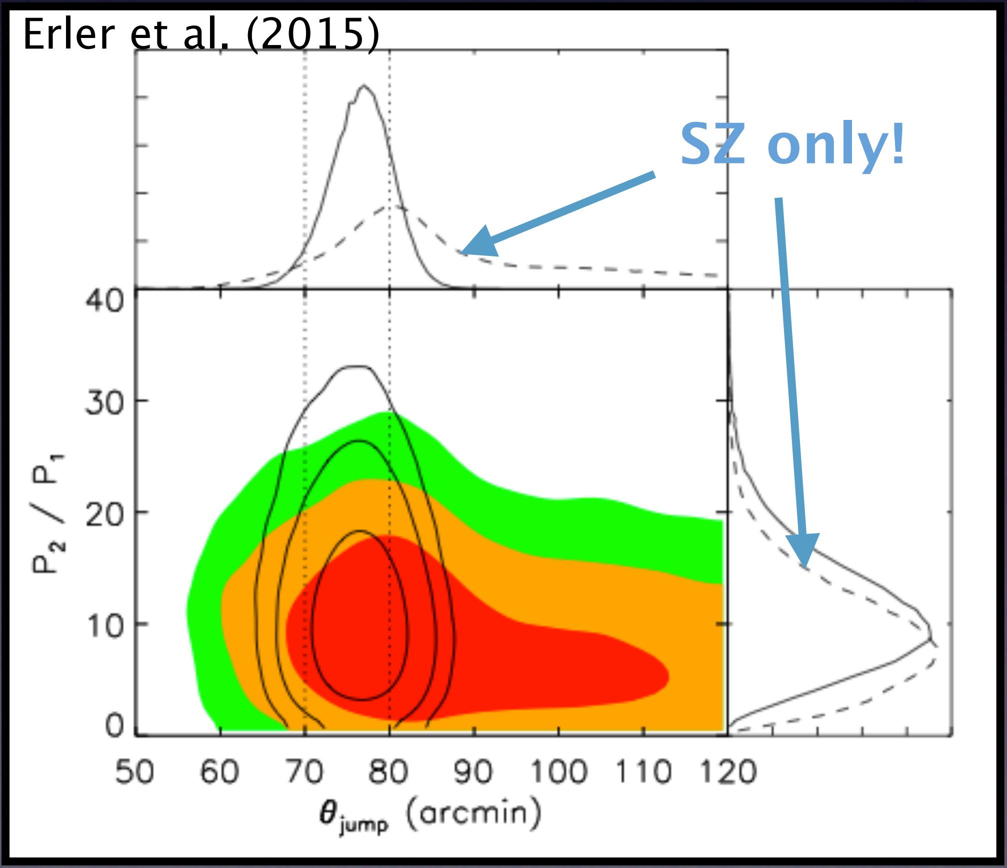
Coma's relic, with Planck



Suzaku: $\mathcal{M}$ = 2.2±0.5
(Akamatsu et al. 2013)

Radio: $\mathcal{M}$ = 3.5±0.2
(Thierbach et al. 2003)





Erler et al. (2015)

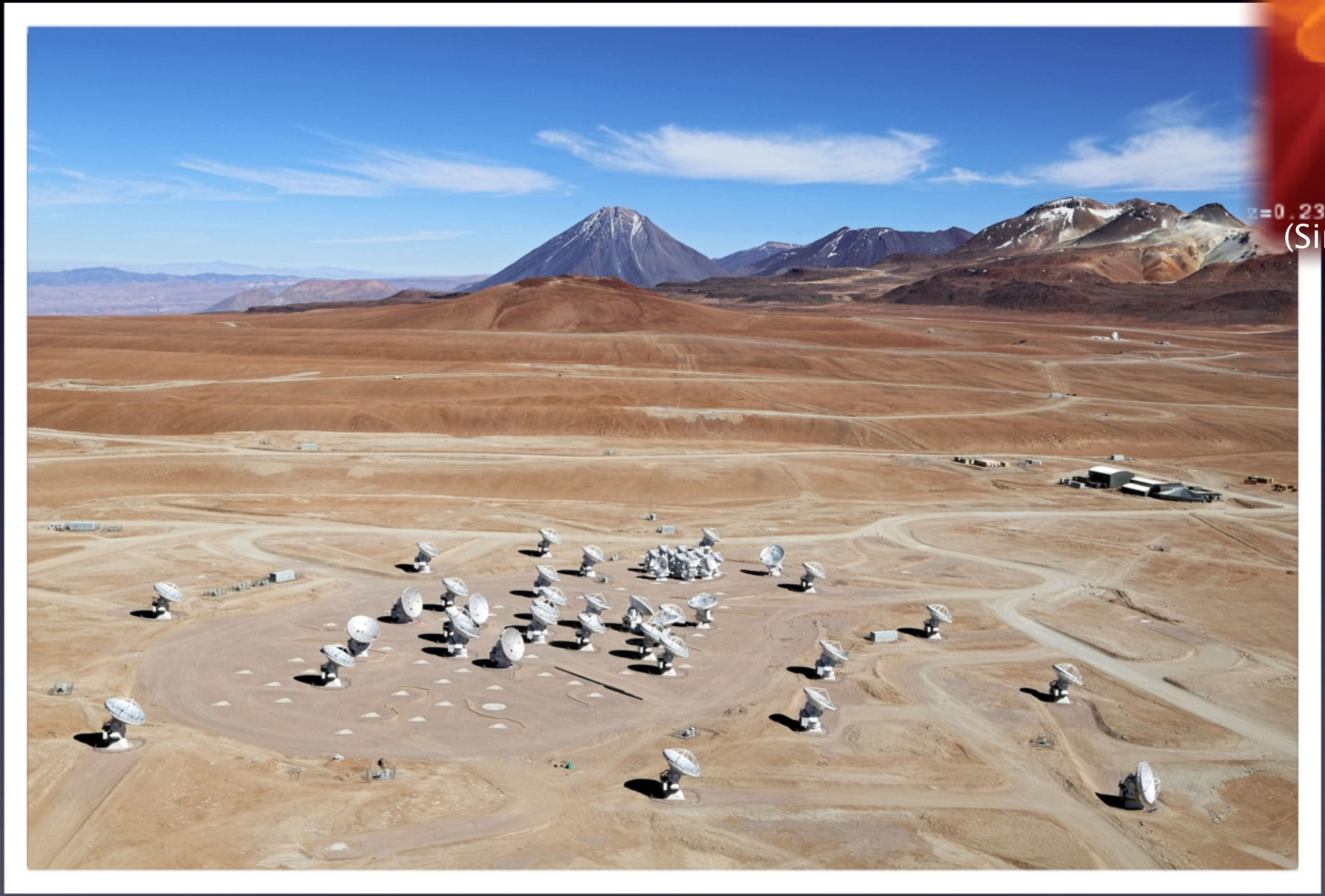
SZ only!

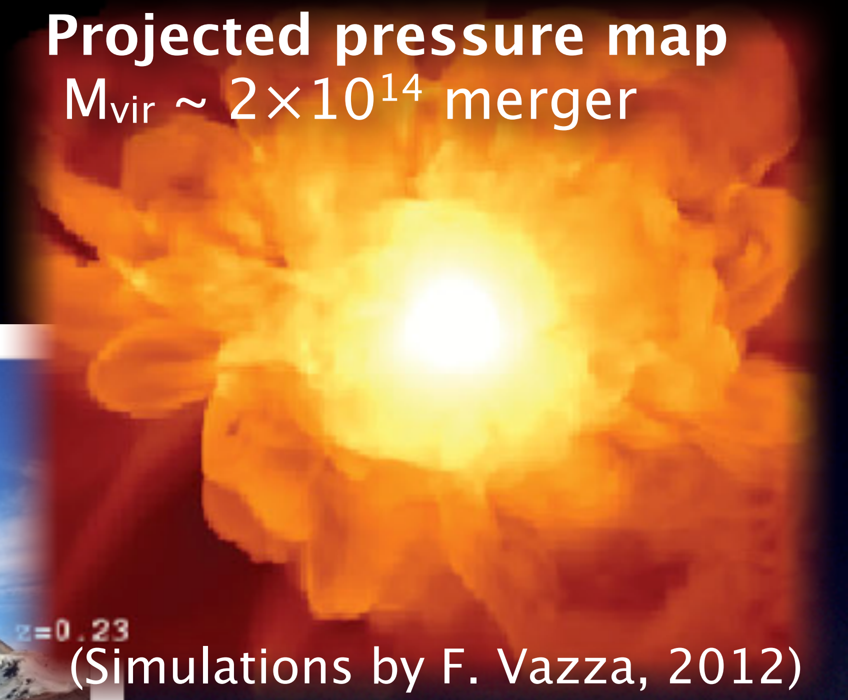
y–jump fits a shock, with $\mathcal{M} = 2.9^{+0.8}_{-0.6}$

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

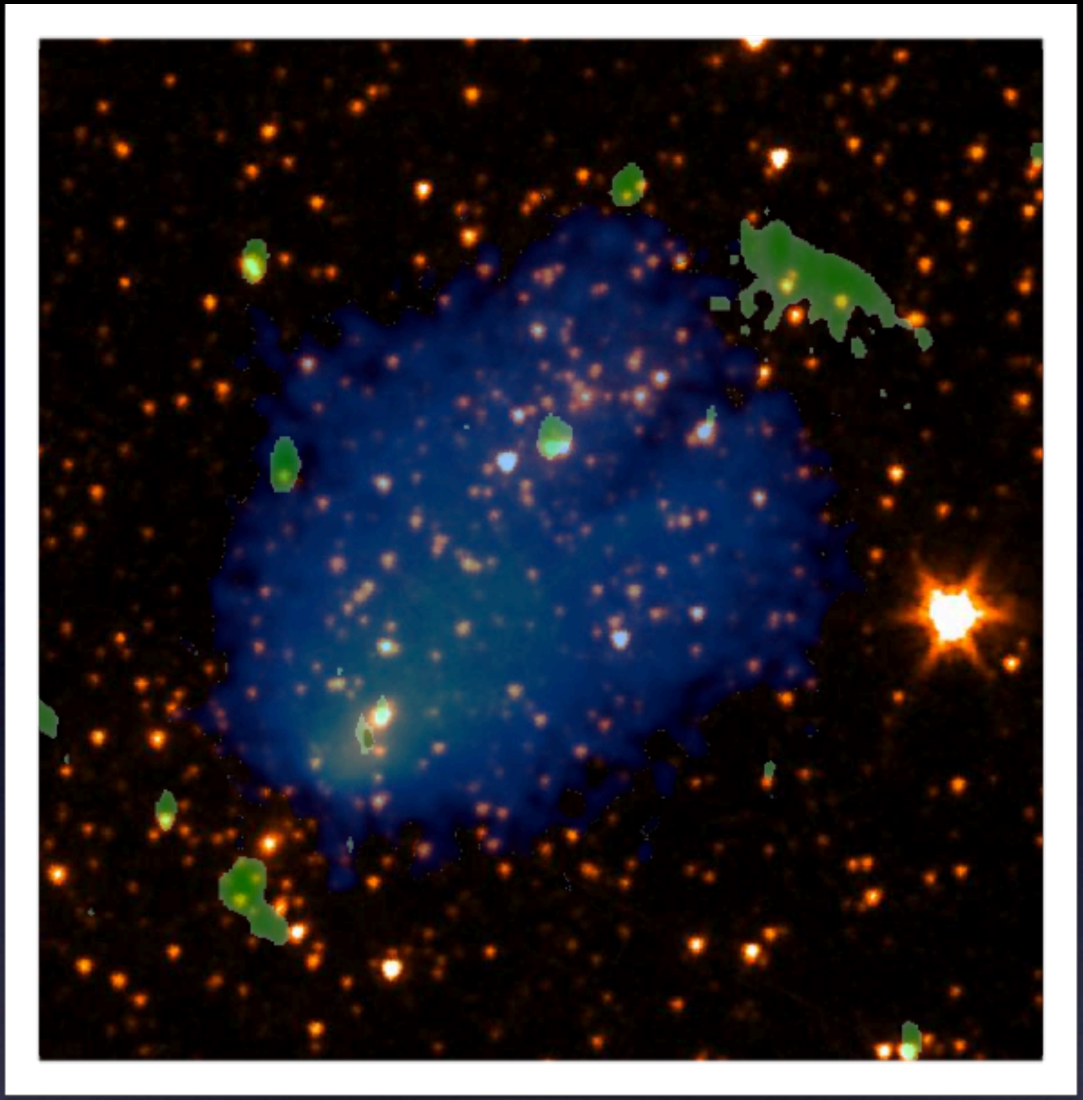
(Simulations by F. Vazza, 2012)

First ALMA-SZ results:

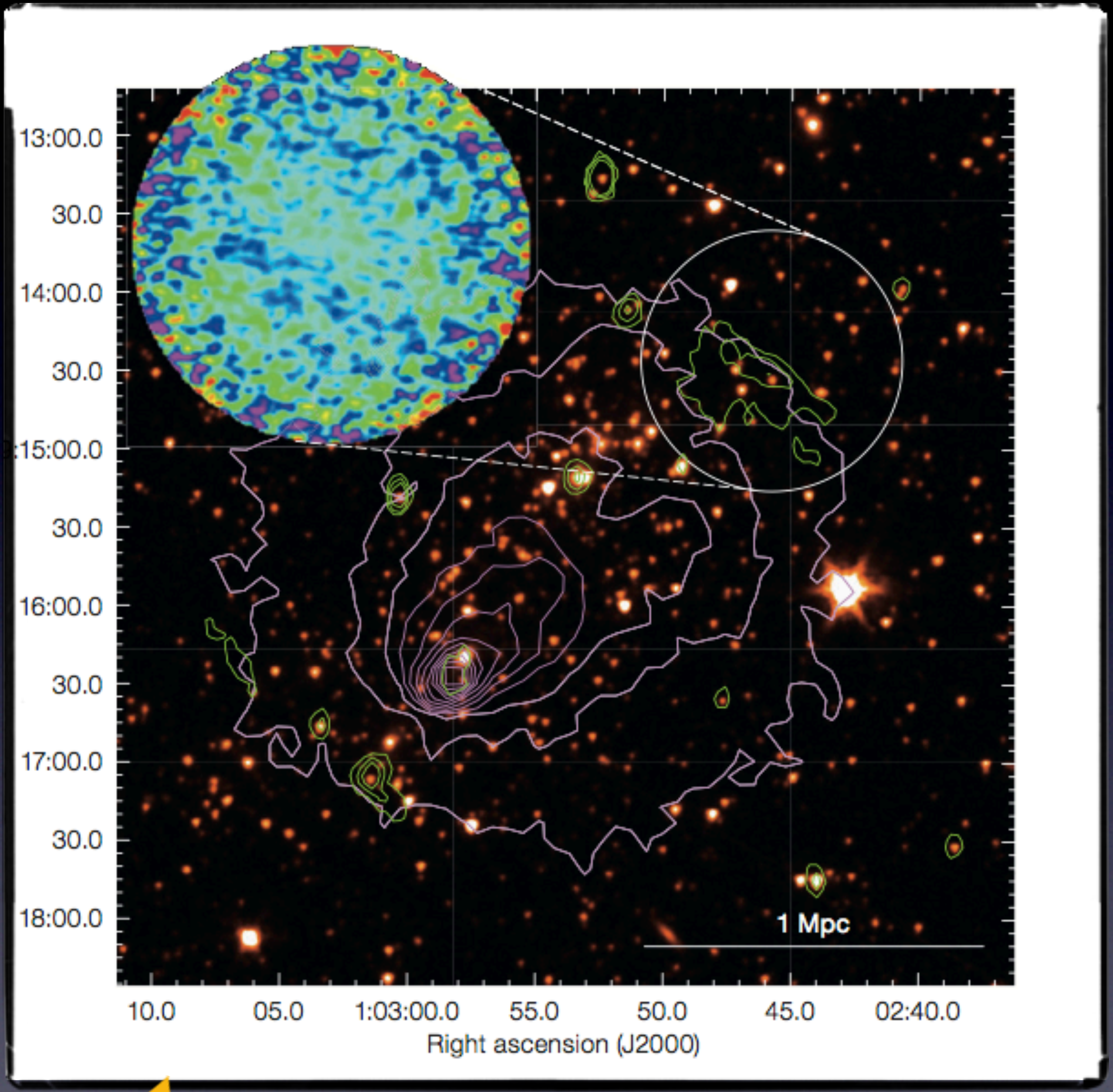
- ★ RXC J1347.5 core (Kitayama et al. 2016)
- ★ El Gordo relic shock (Basu et al. 2016)

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

A Relic-Shock with ALMA at z≈0.9



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



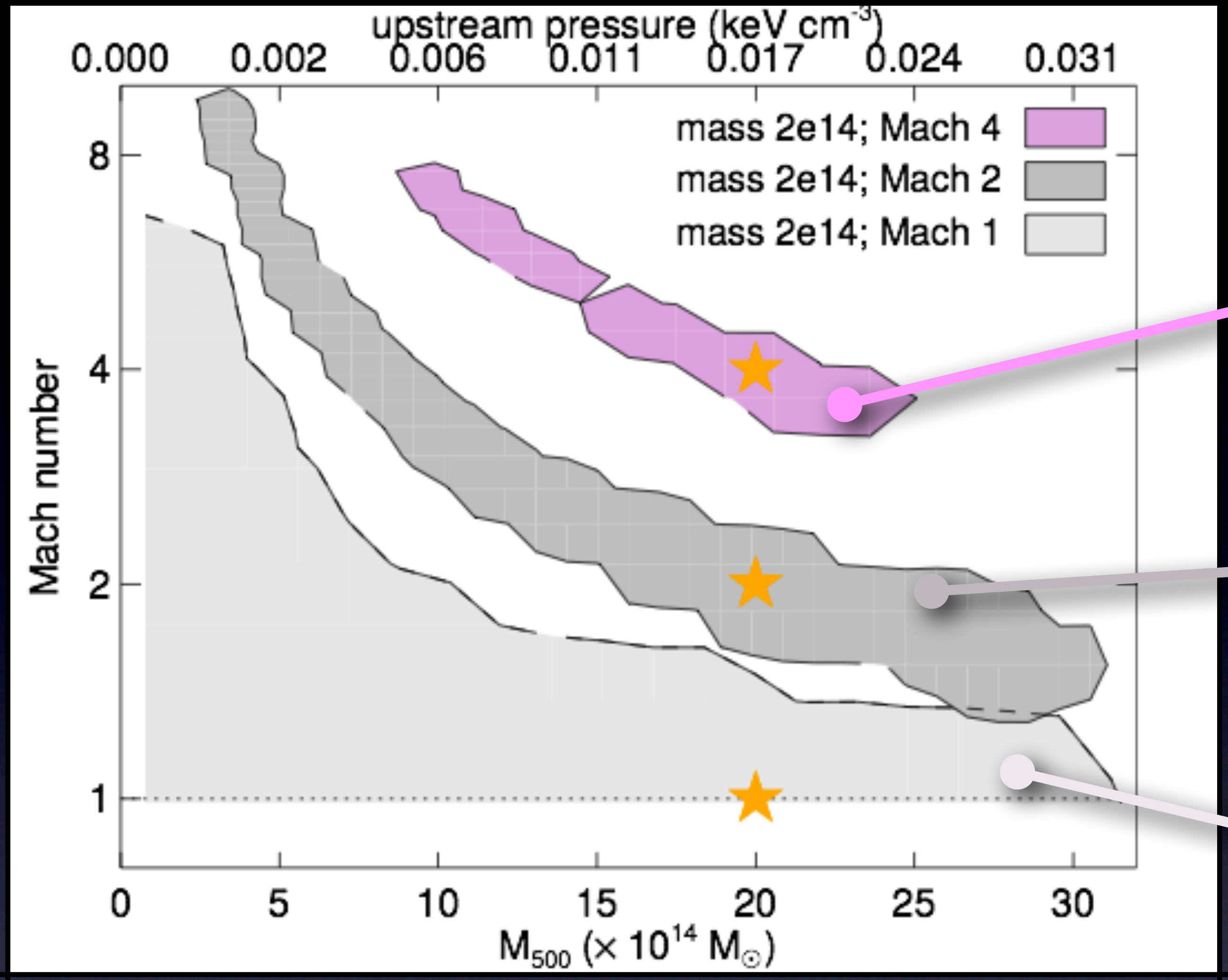
Basu et al. (2016), ApJ, 829

ALMA data ~ 2h on-source

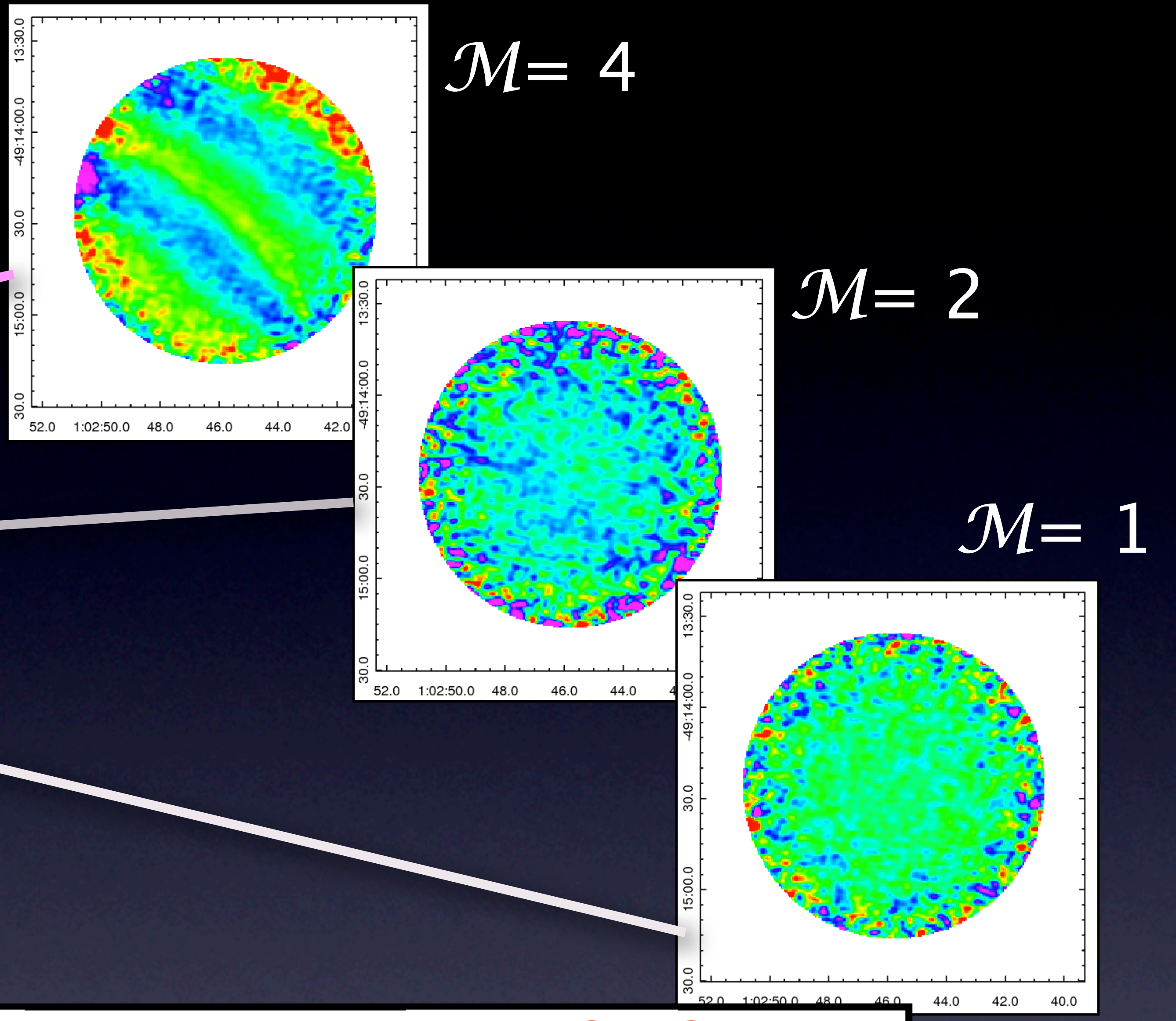
ALMA noise rms ~ 6 μJy/3” beam

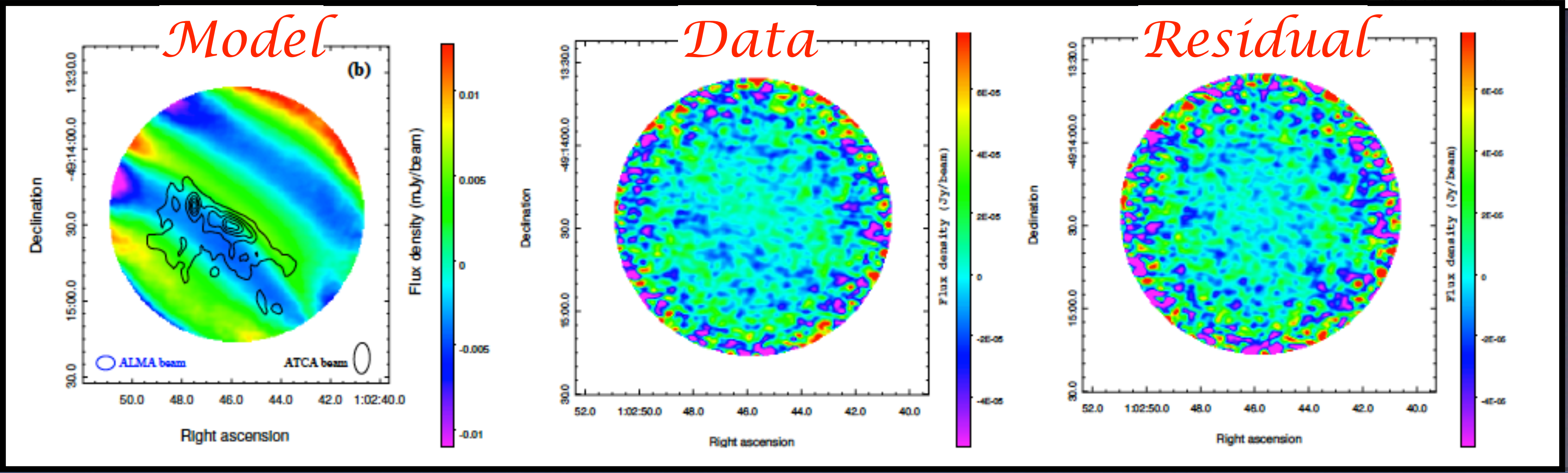
(enough to detect $\mathcal{M}$~2 shock with >5σ)

How ALMA *sees* a shock



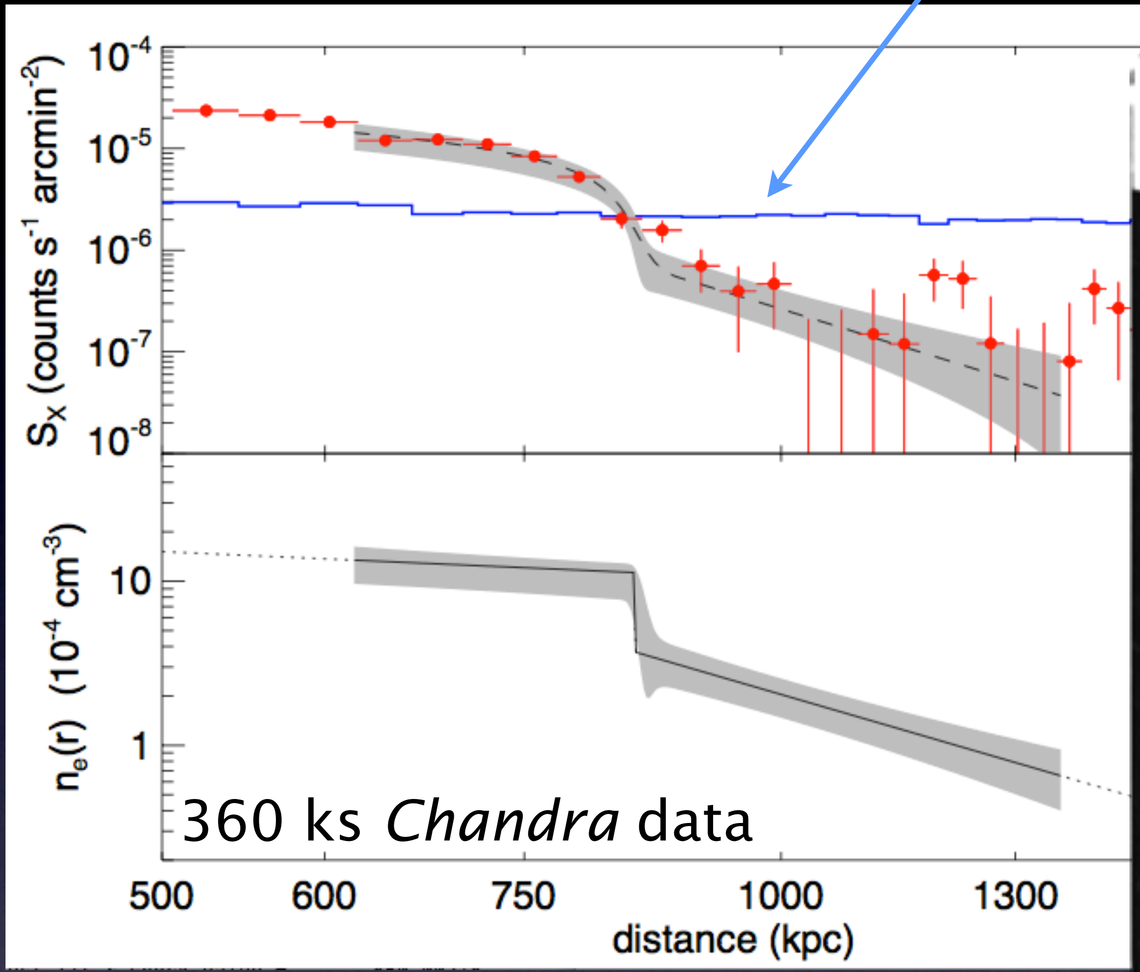
Basu et al. (2016), ApJ, 829



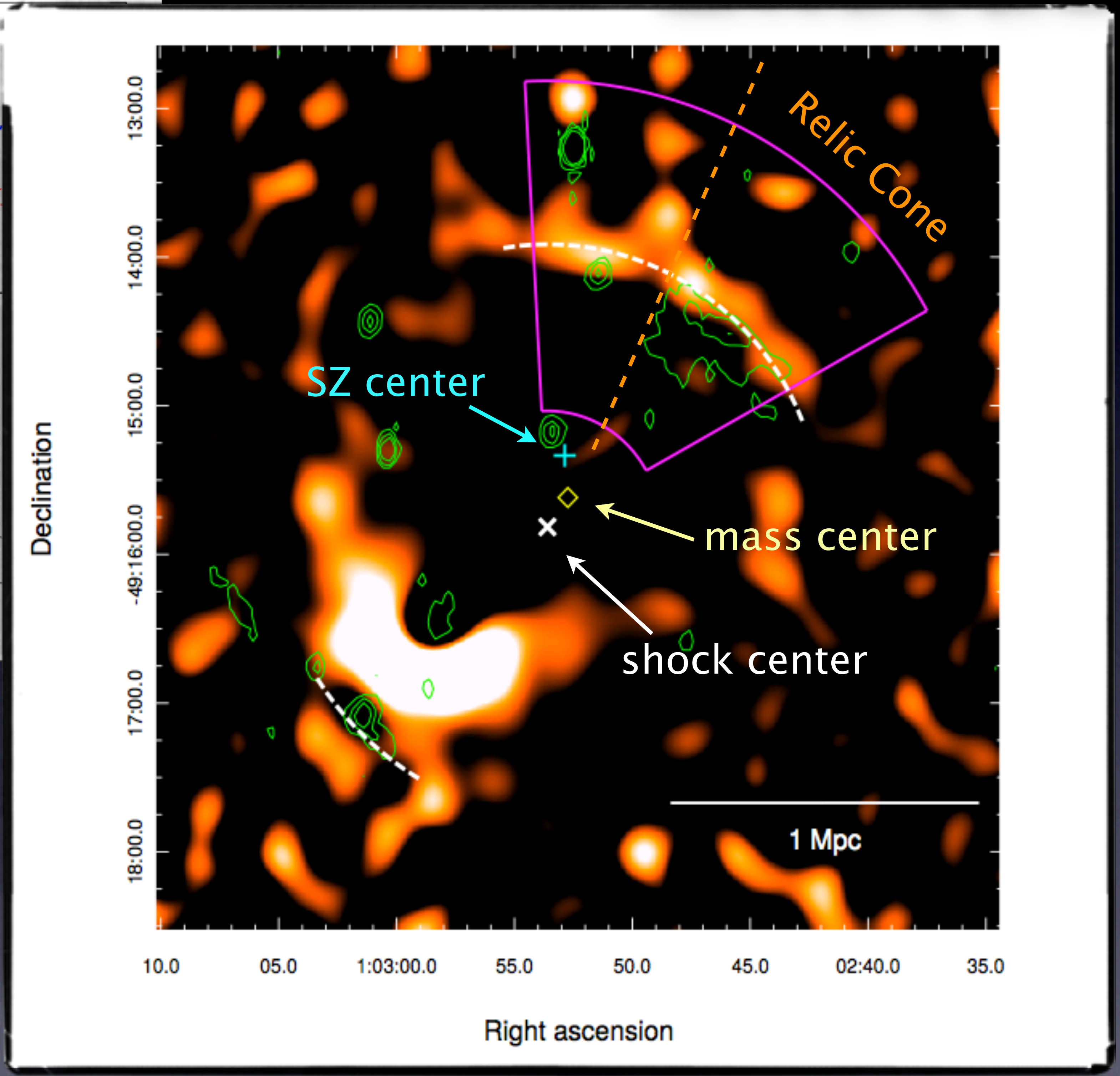


A wide shock, revealed in the X-rays

Background photon level



Basu et al. (2016), ApJ, 829



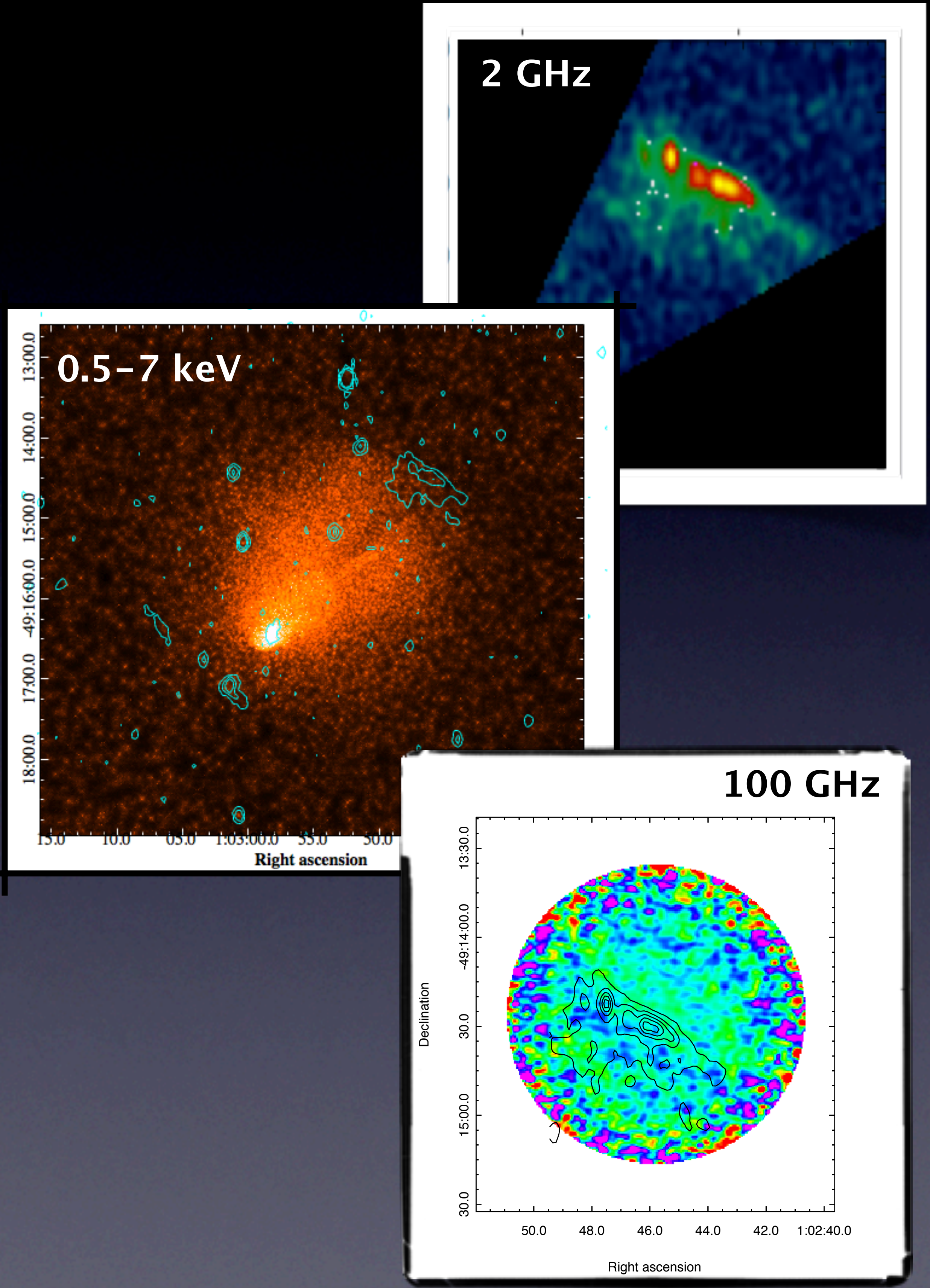
Botteon et al. (2016) first published the results from full archival Chandra data

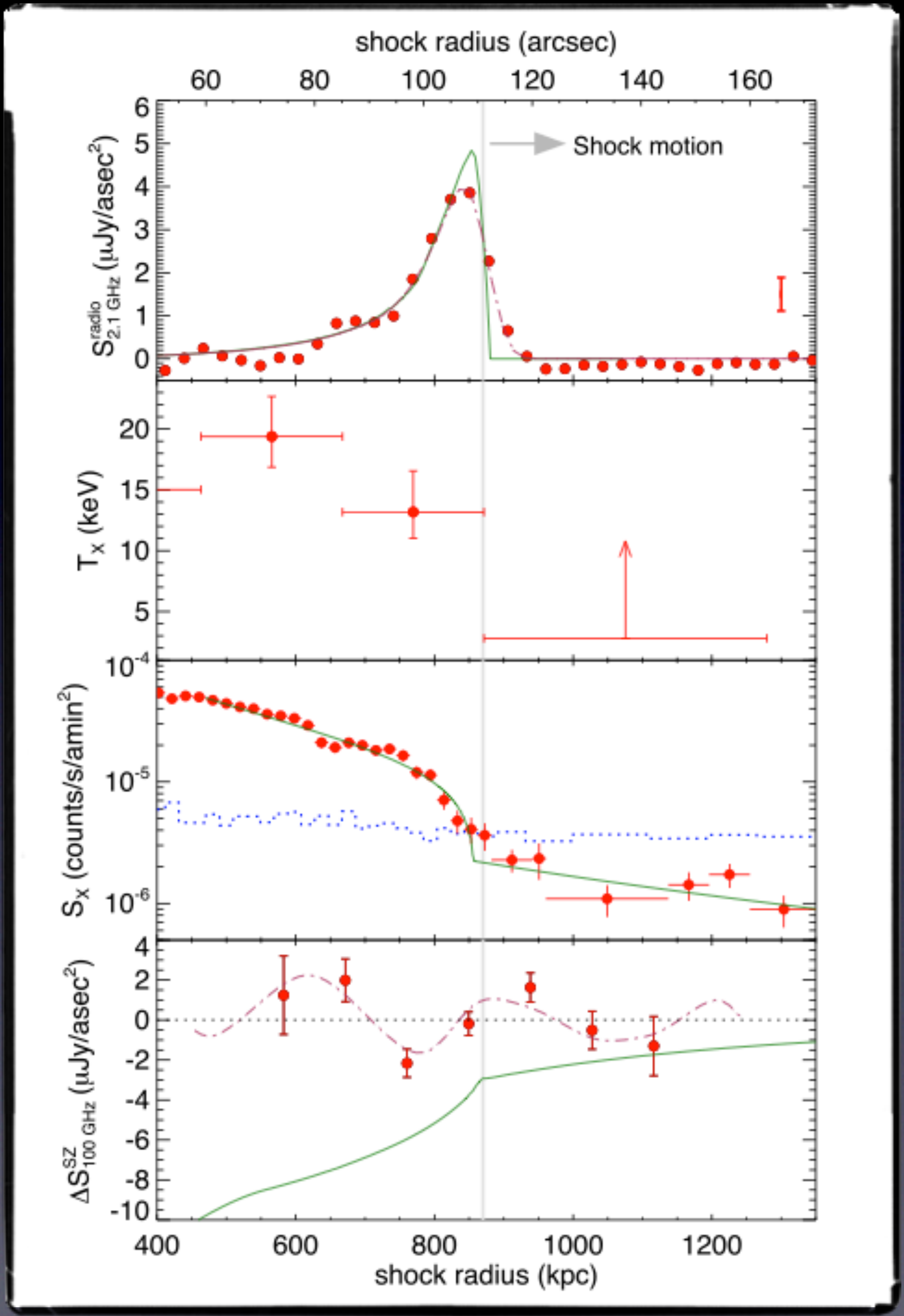
Our independent analysis also show *a much wider shock front in X-rays*

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

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

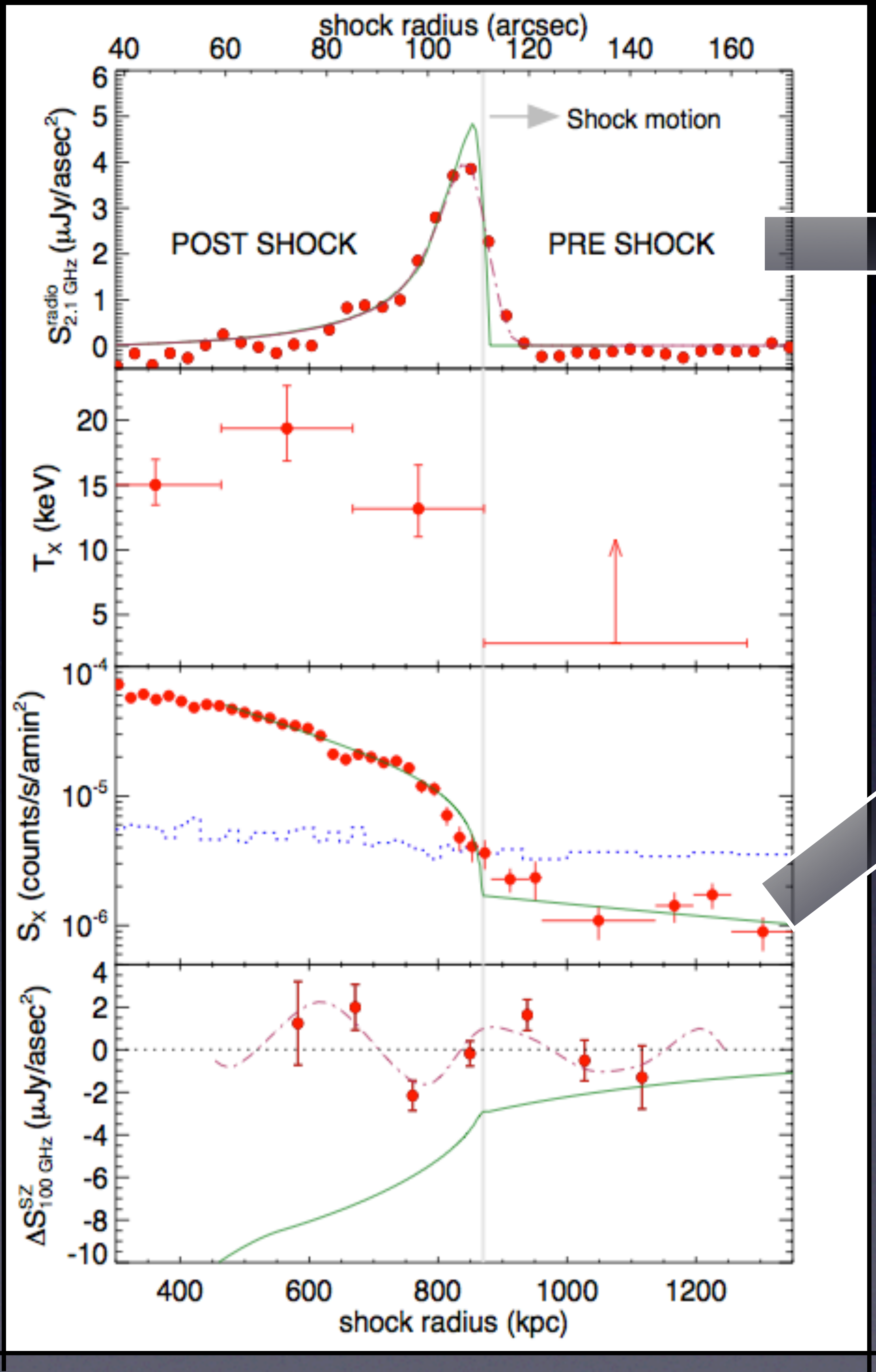
The “multi-messenger” view

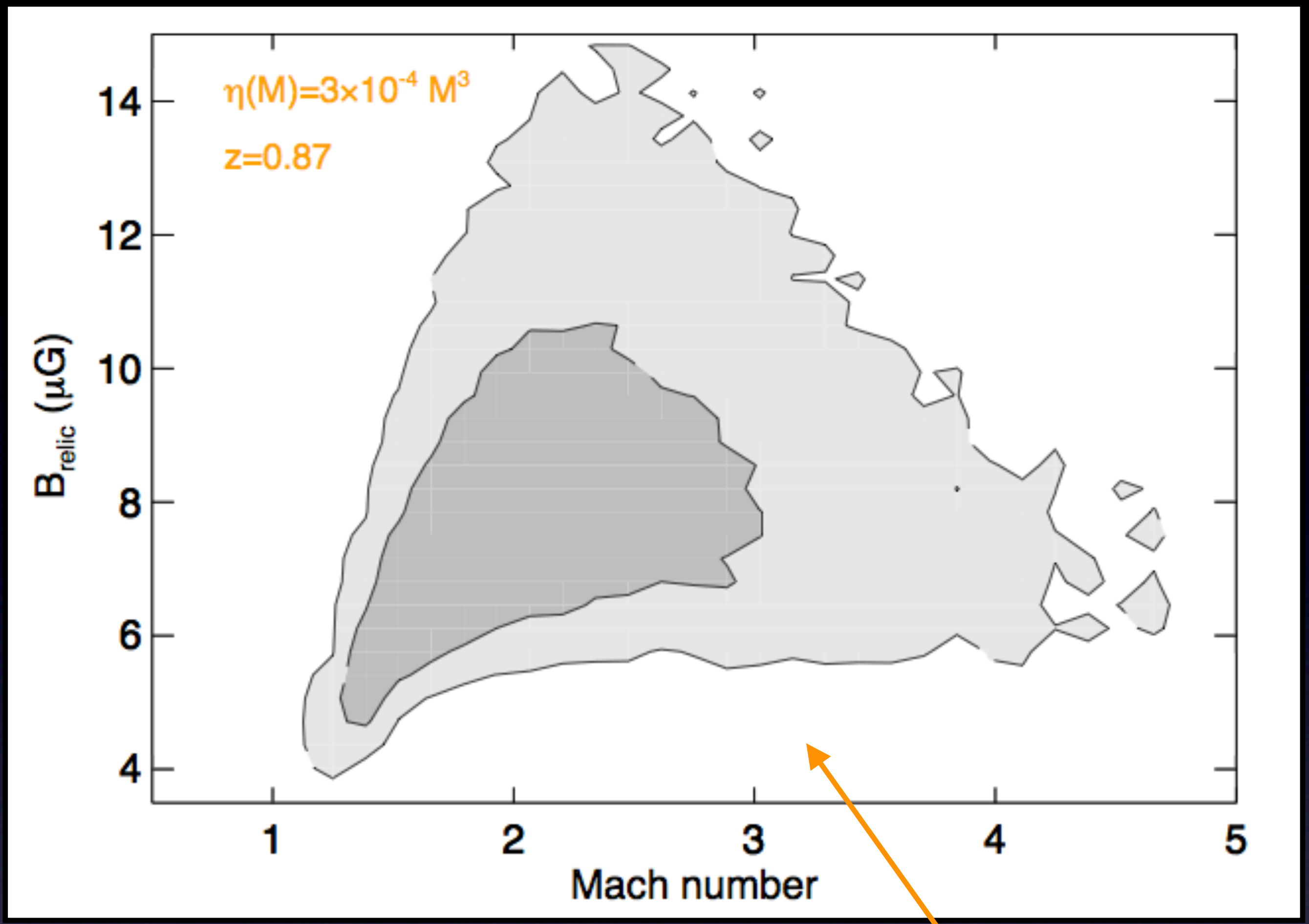




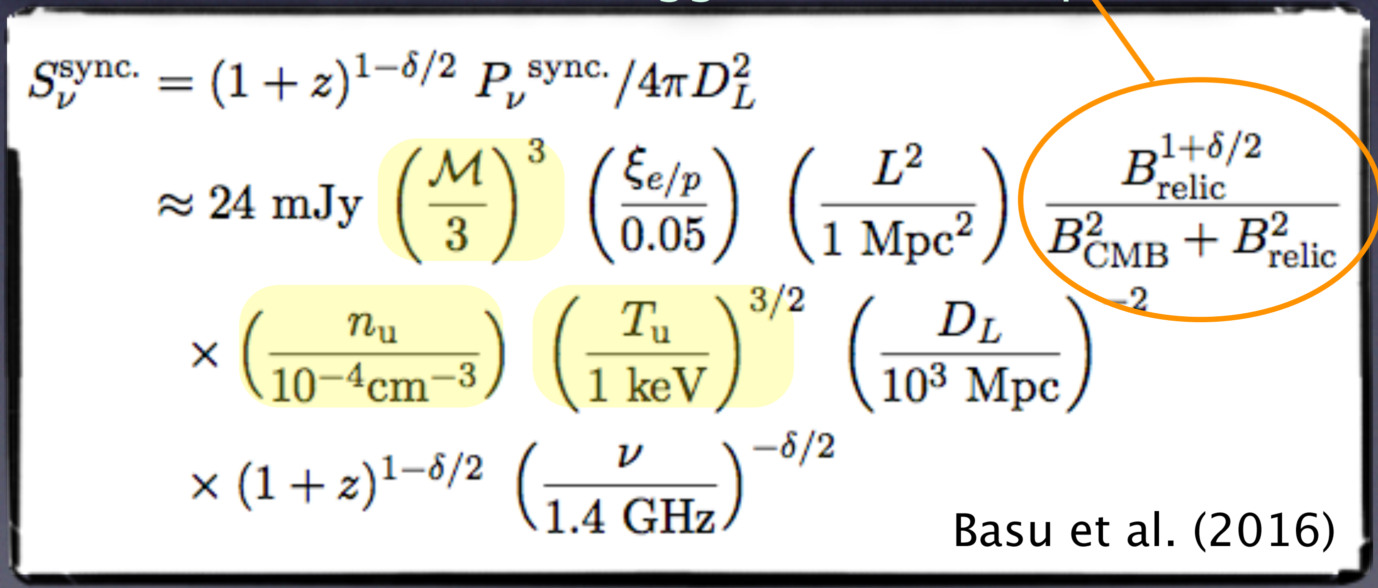
Basu et al. (2016), ApJ, 829

Magnetic field at z≈0.9





DSA formula (Hoeft & Brueggen 2007), simplified:



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

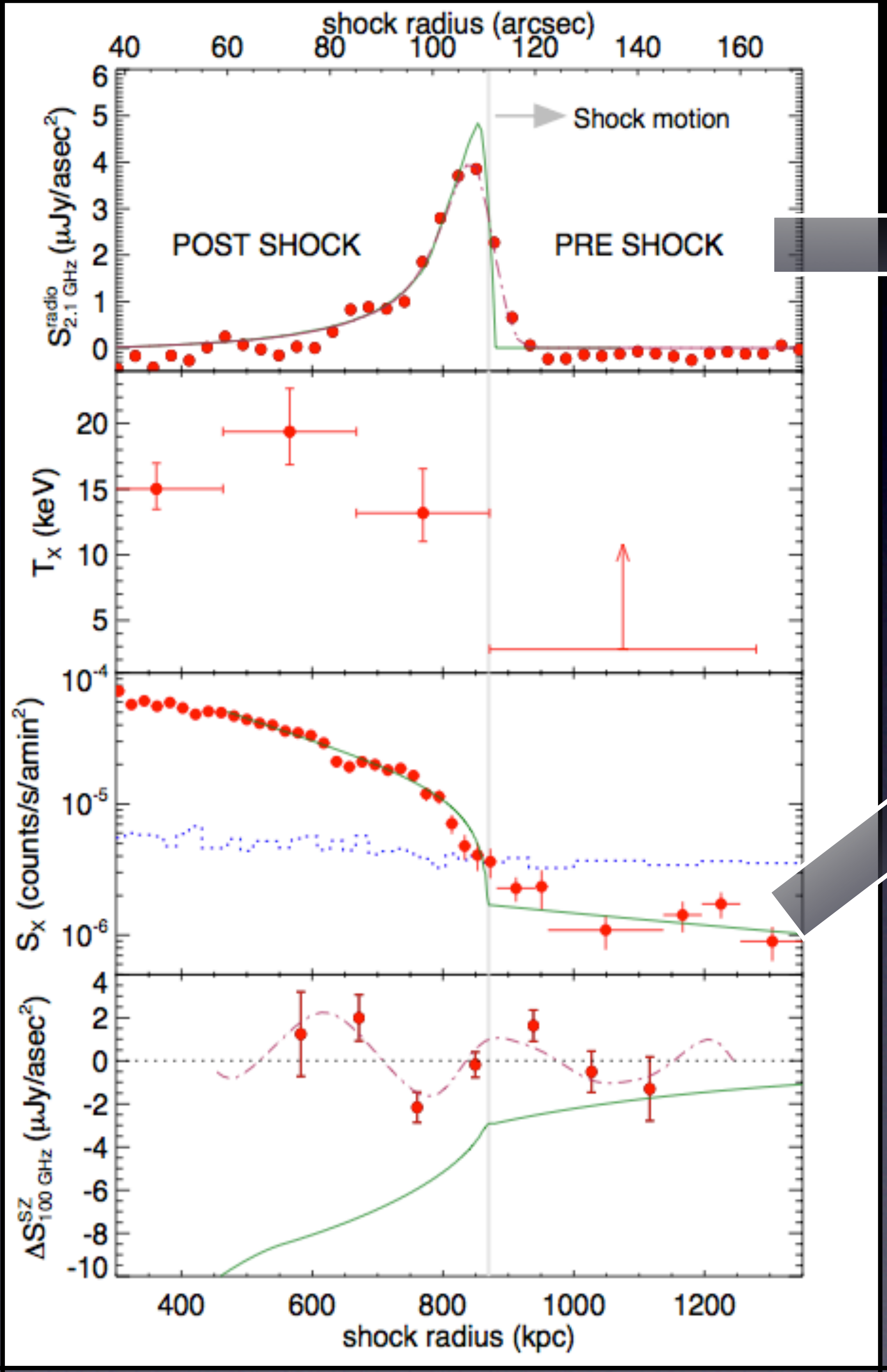
$$\approx 24\ \mathrm{mJy} \left(\frac{\mathcal{M}}{3}\right)^3 \left(\frac{\xi_{e/p}}{0.05}\right) \left(\frac{L^2}{1\ \mathrm{Mpc}^2}\right) \frac{B_{\mathrm{relic}}^{1+\delta/2}}{B_{\mathrm{CMB}}^2 + B_{\mathrm{relic}}^2}$$

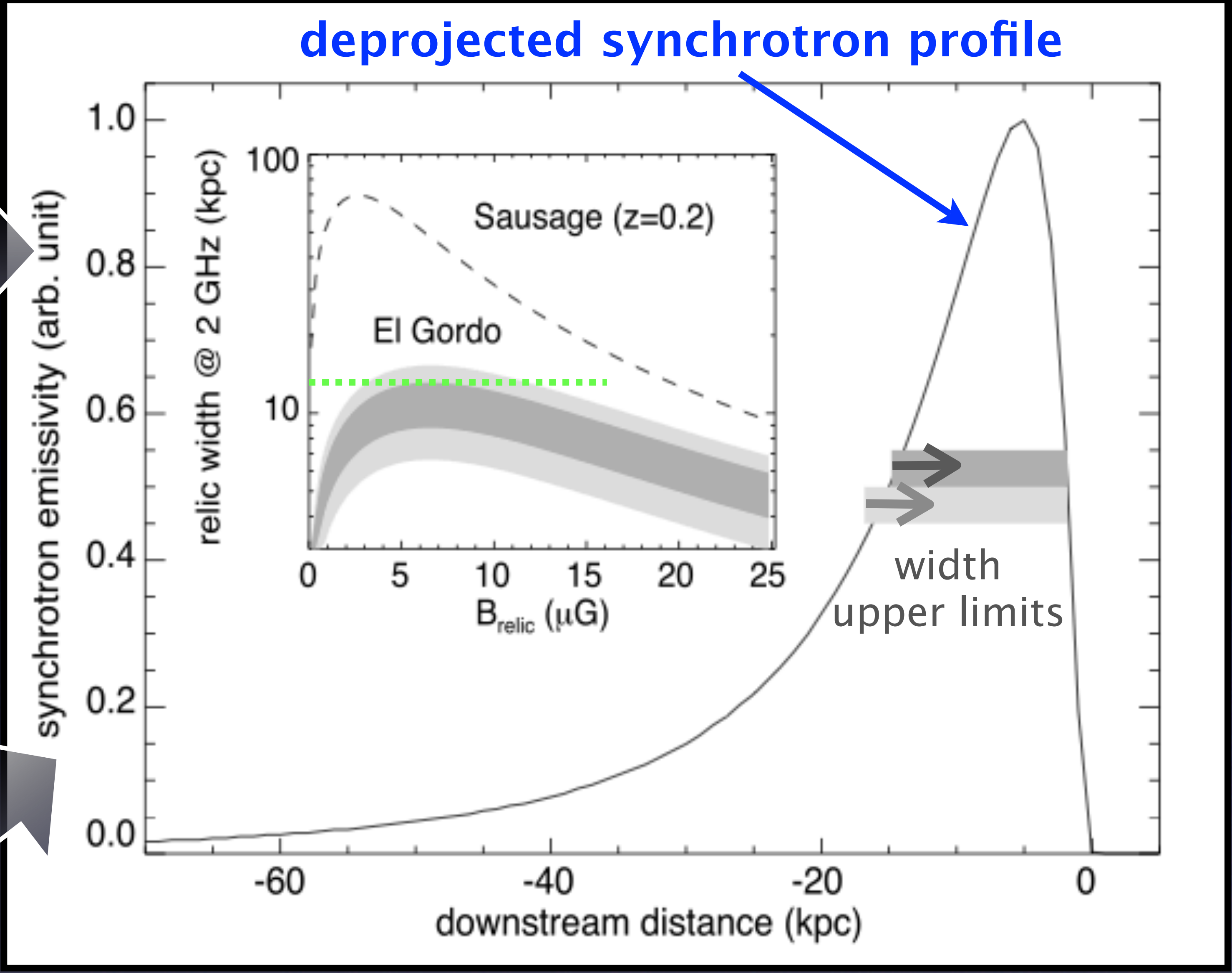
$$\times \left(\frac{n_{\mathrm{u}}}{10^{-4}\mathrm{cm}^{-3}}\right) \left(\frac{T_{\mathrm{u}}}{1\ \mathrm{keV}}\right)^{3/2} \left(\frac{D_L}{10^3\ \mathrm{Mpc}}\right)^{-2}$$

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

Basu et al. (2016)

Magnetic field at z≈0.9




deprojected synchrotron profile

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

$$\boxed{W_{\rm relic} \approx v_d\; t_{\rm sync}}$$

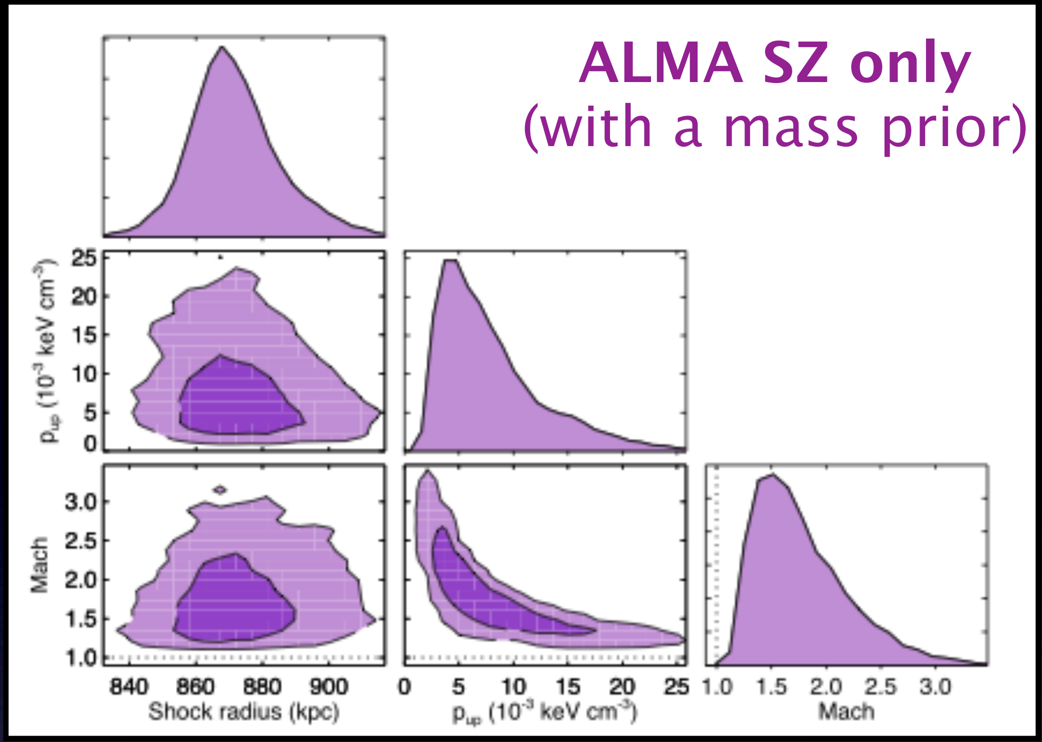
$$\boxed{t_{\rm sync} = 3.2 \times 10^{10}\ {\rm yr}\ \frac{B^{1/2}}{B^2 + B^2_{\rm CMB}}\ \frac{1}{\sqrt{\nu(1+z)}}}$$

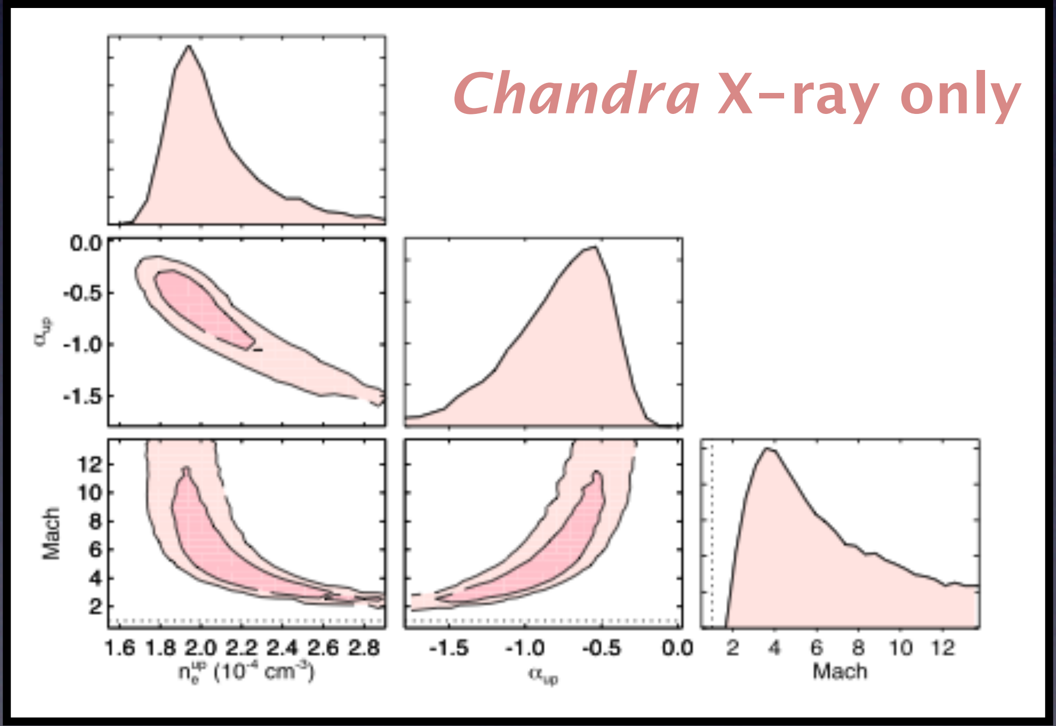
The shock Mach number

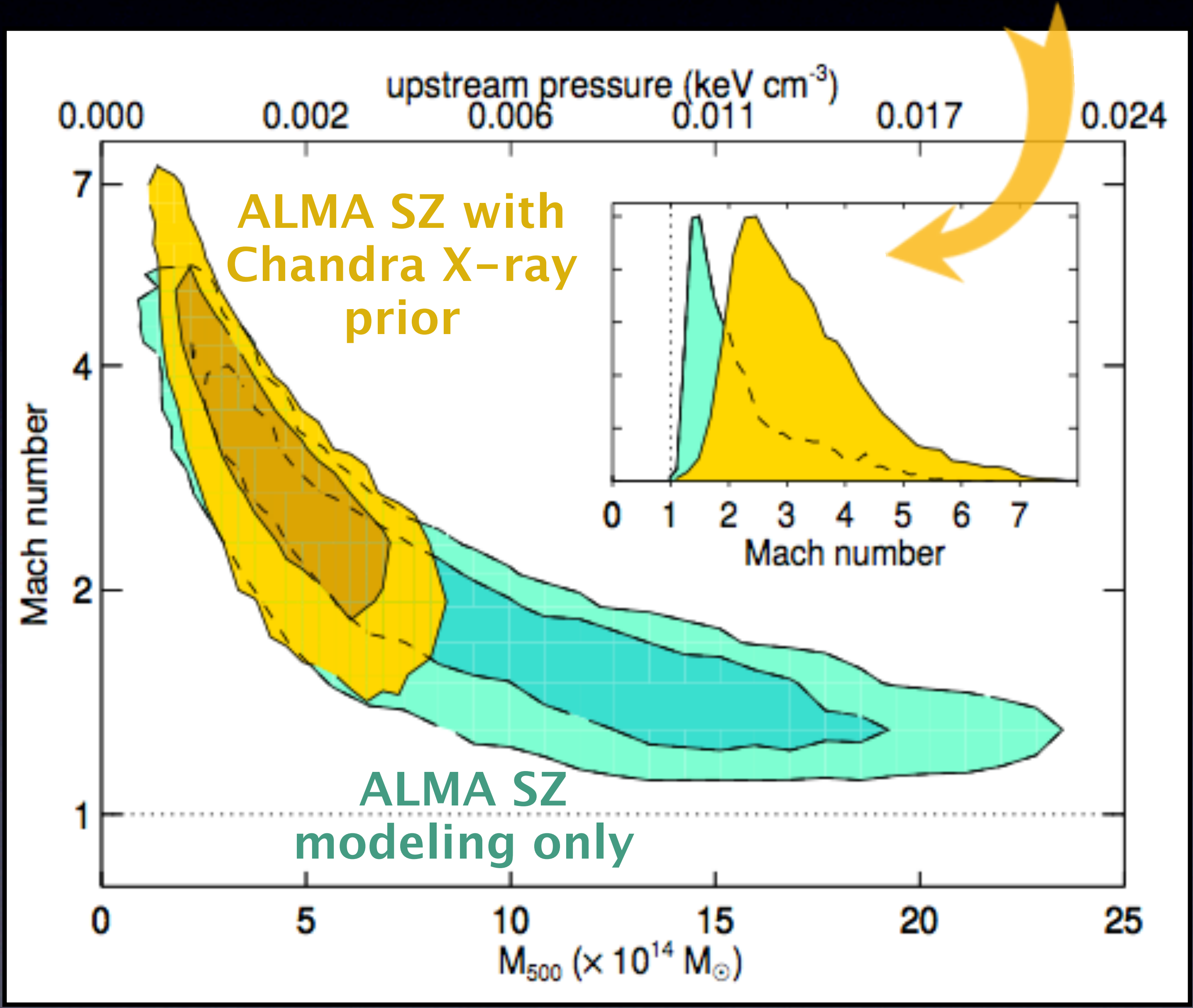
ALMA SZ data alone points to a weak shock: $\mathcal{M} = 1.4^{+1.2}_{-0.2}$

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**

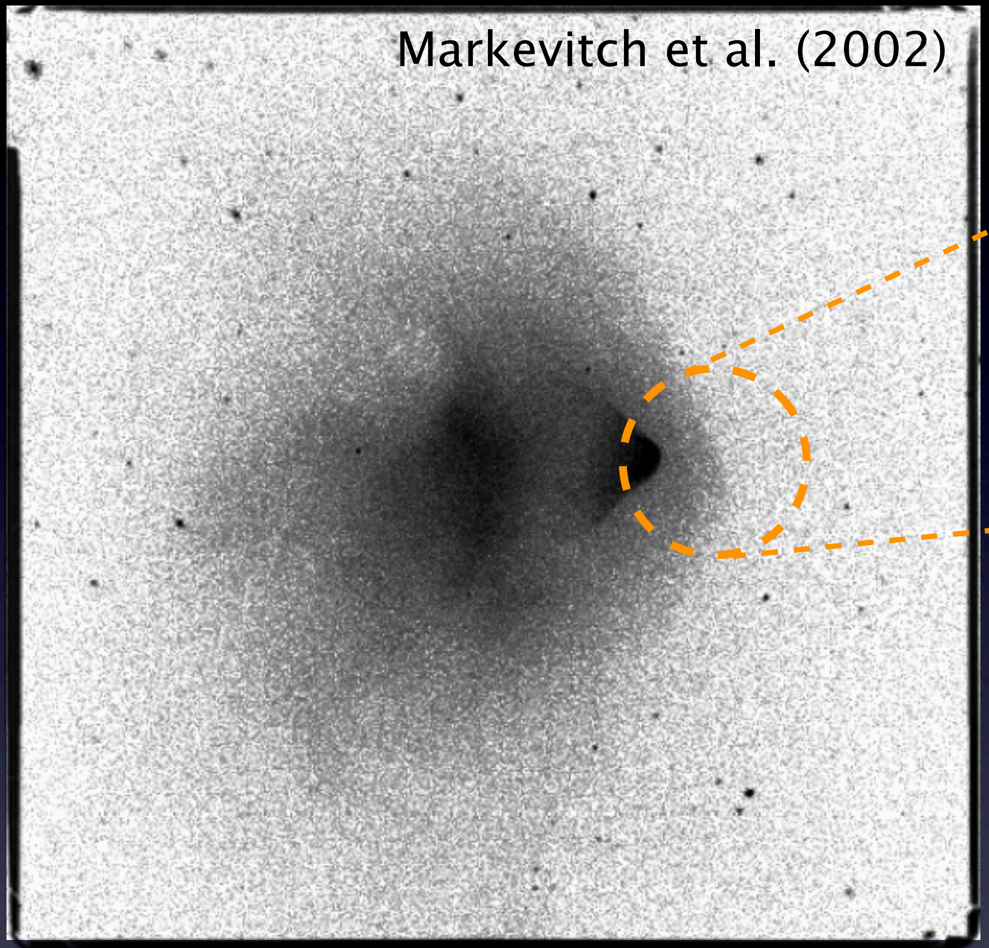

ALMA SZ with Chandra X-ray prior

ALMA SZ modeling only

Basu et al. (2016), ApJ, 829

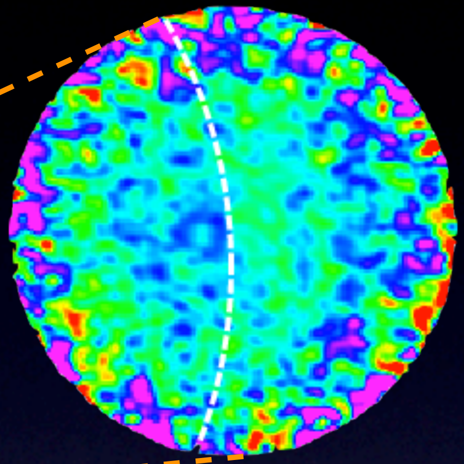
Upcoming results: Bullet cluster

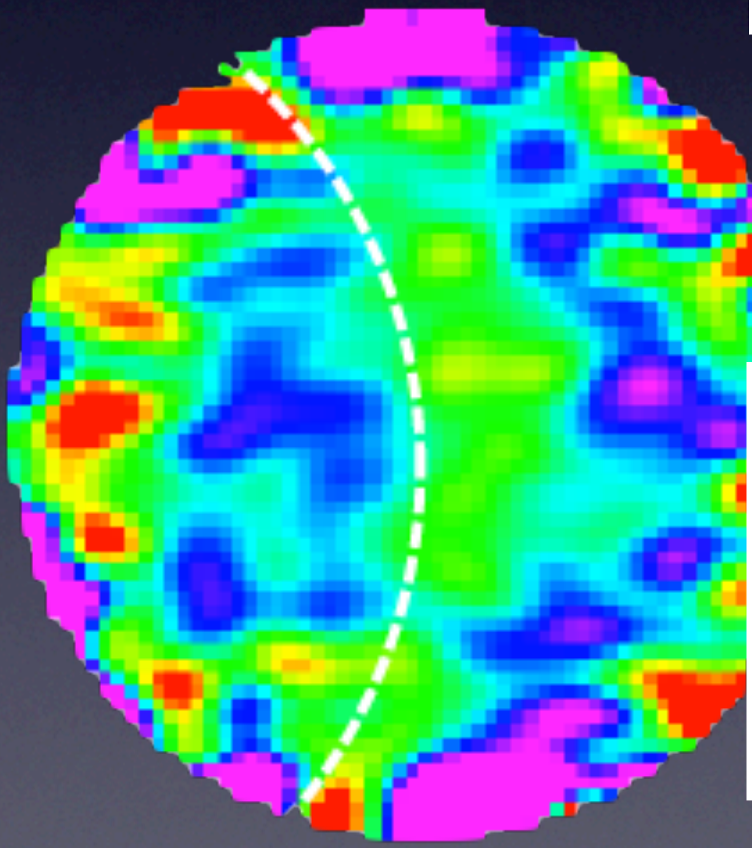
PI: T. Mroczkowski

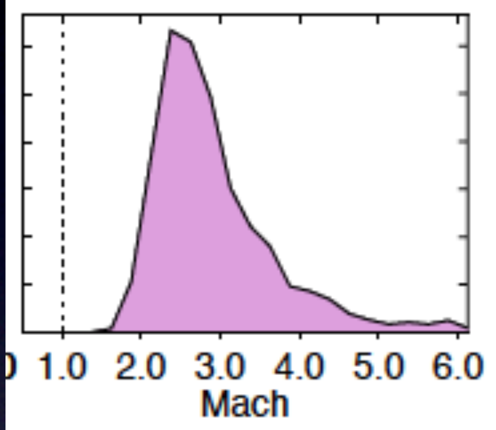


Deep ALMA pointing of the Bullet shock at 100 GHz
(Mroczkowski et al. in prep.)

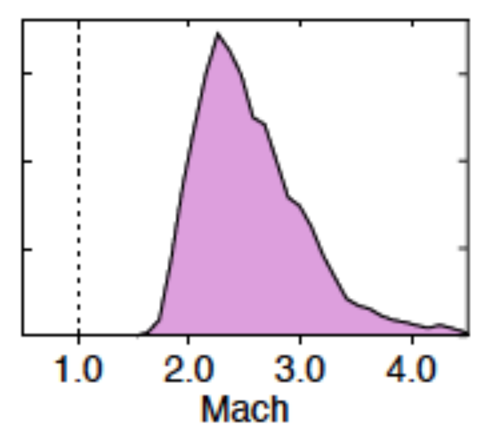
Spherical shock Mack number is around ~**2.5**, similar to the X-ray combined result of $\mathcal{M}$ = 2–3







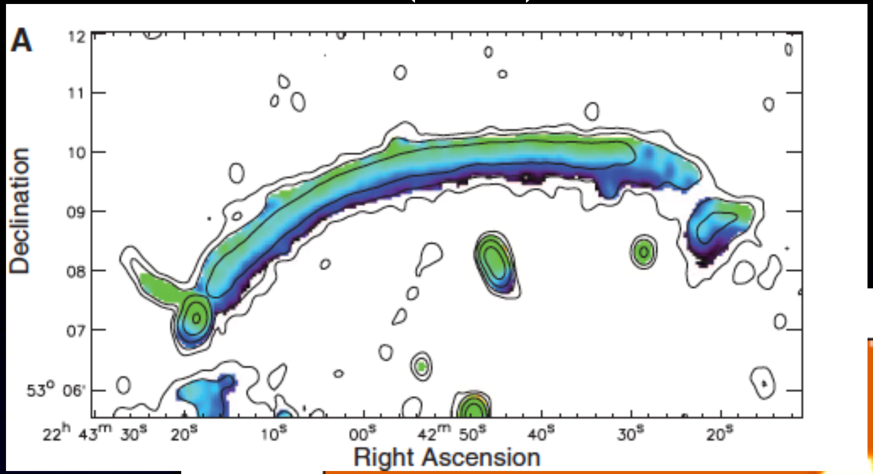
Main array data
FoV ~ 1.5′ (~400 kpc) at 100 GHz, 3″ resolution



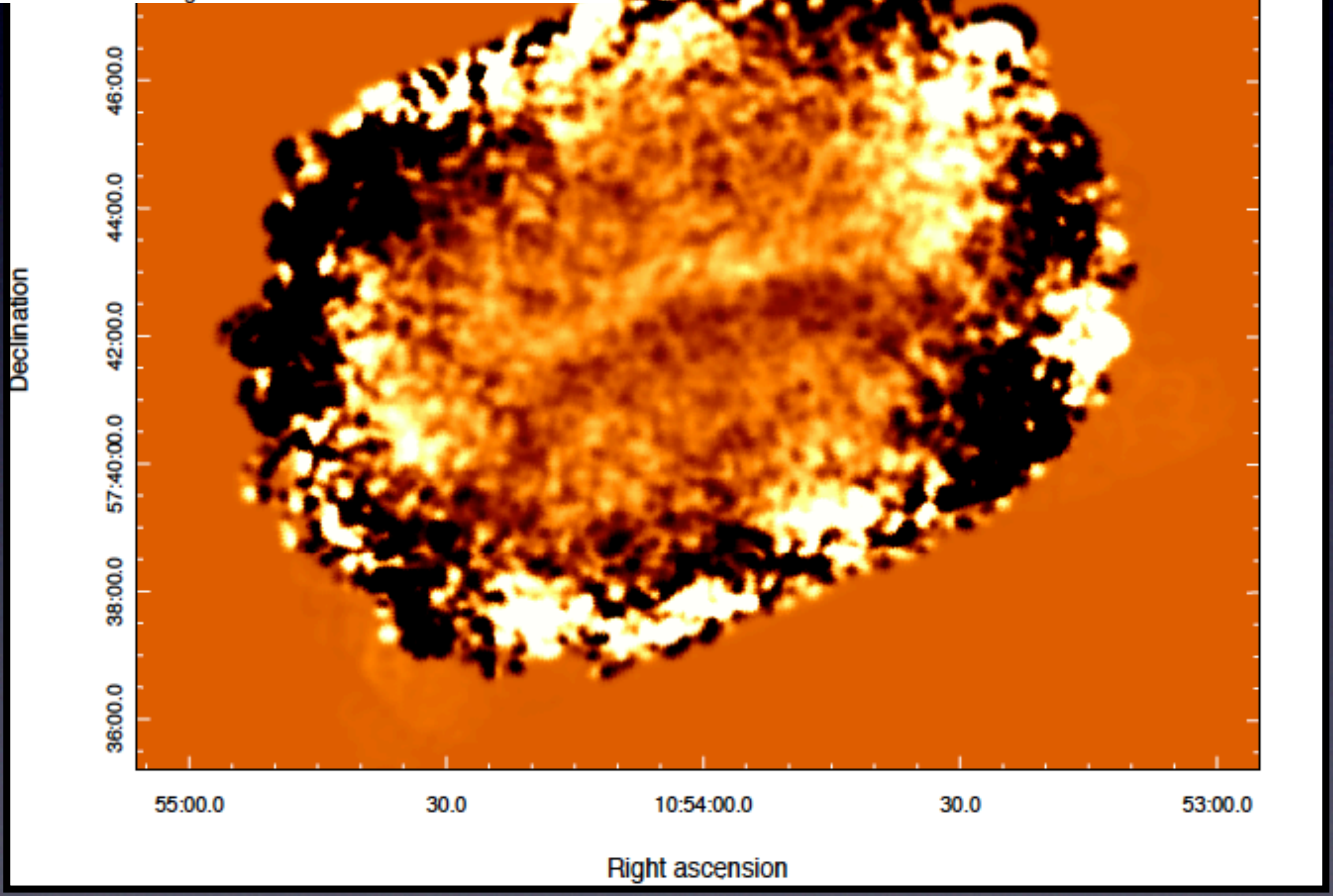
Compact array data
FoV twice larger

Upcoming results(?): *Sausage* relic

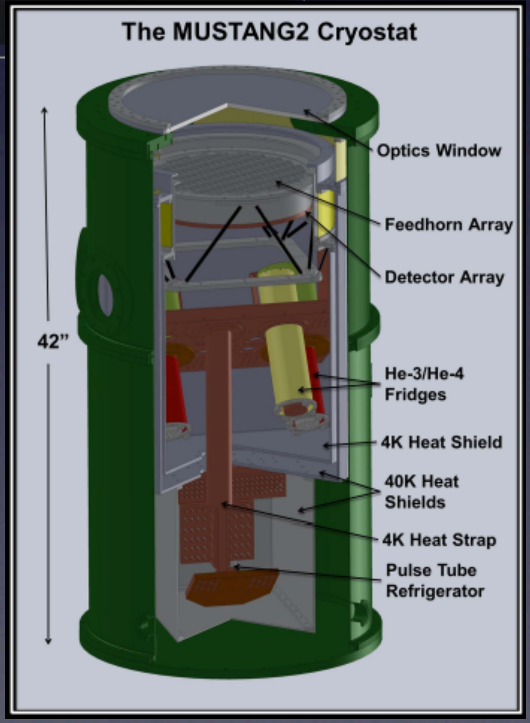
van Weeren et al. (2010)



MUSTNAG-2 at the GBT offers 9″ resolution SZ imaging at 90 GHz and excellent sensitivity



MUSTANG-2 receiver (currently being commissioned)



Simulated image of a $\mathcal{M}=3$ Sausage relic shock, 30 h integration

More than the thermal SZ: kSZ, rSZ

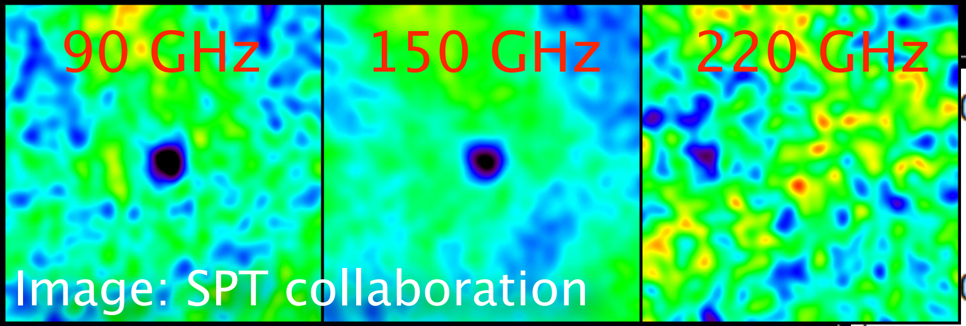
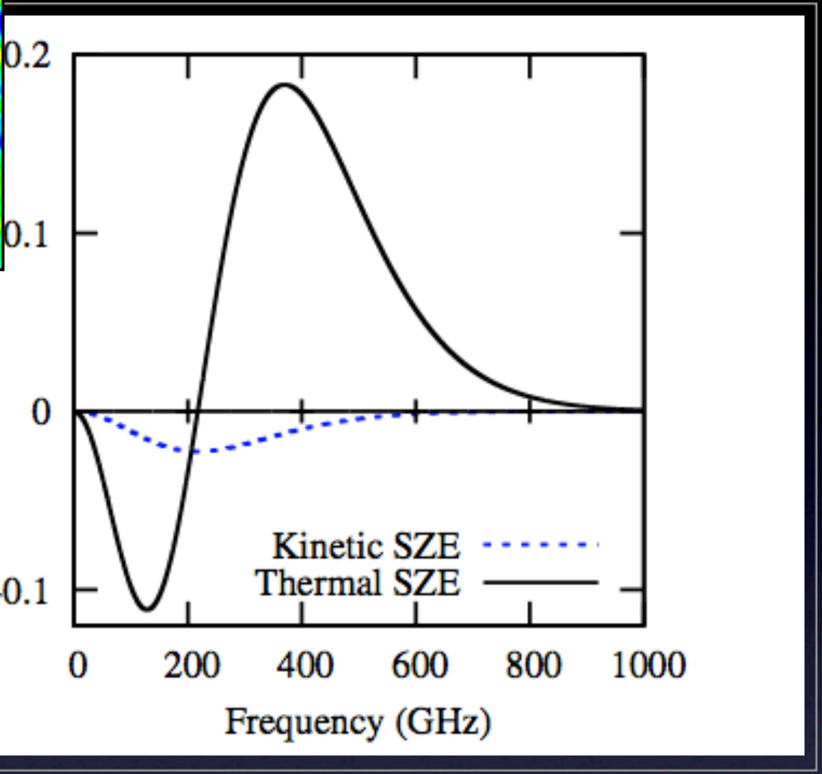


Image: SPT collaboration

The **thermal SZ (tSZ)** effect measures the line-of-sight electron pressure



The **kinetic SZ (kSZ)** effect measures the bulk motion of the scattering electrons

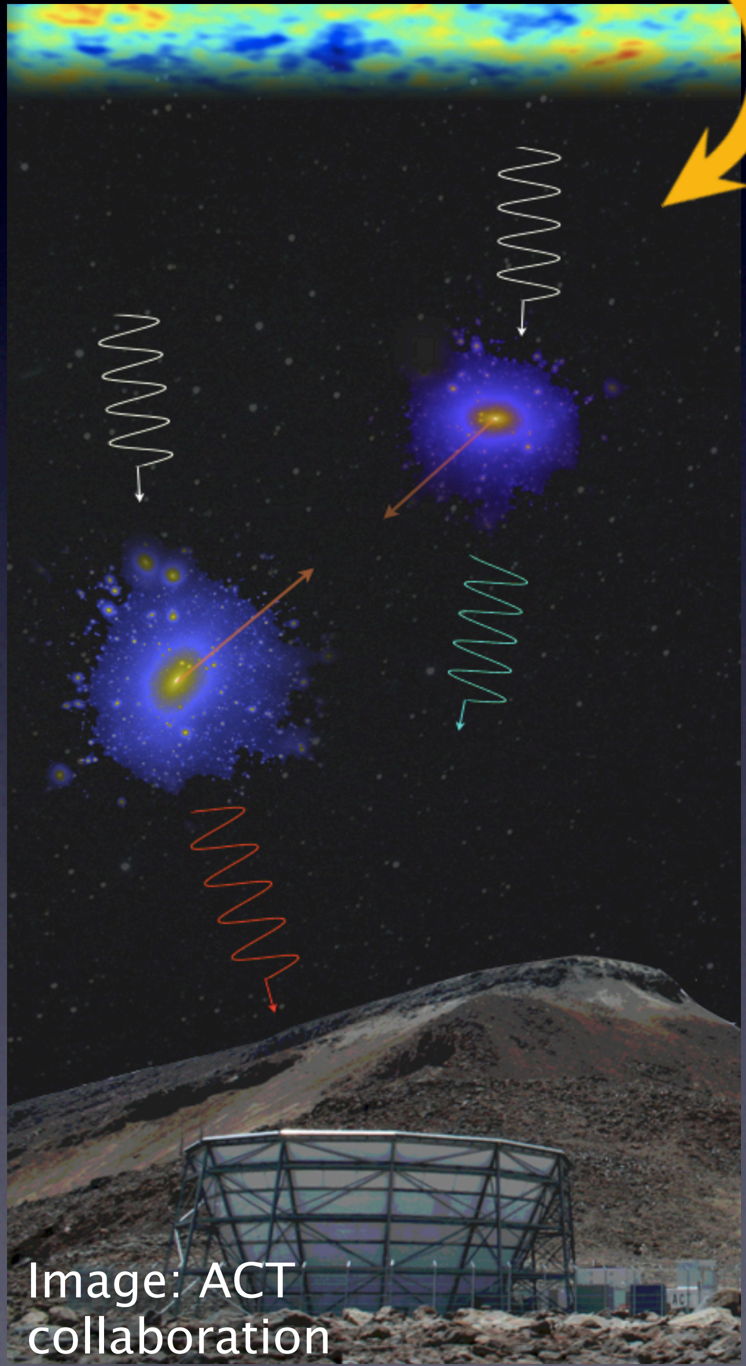
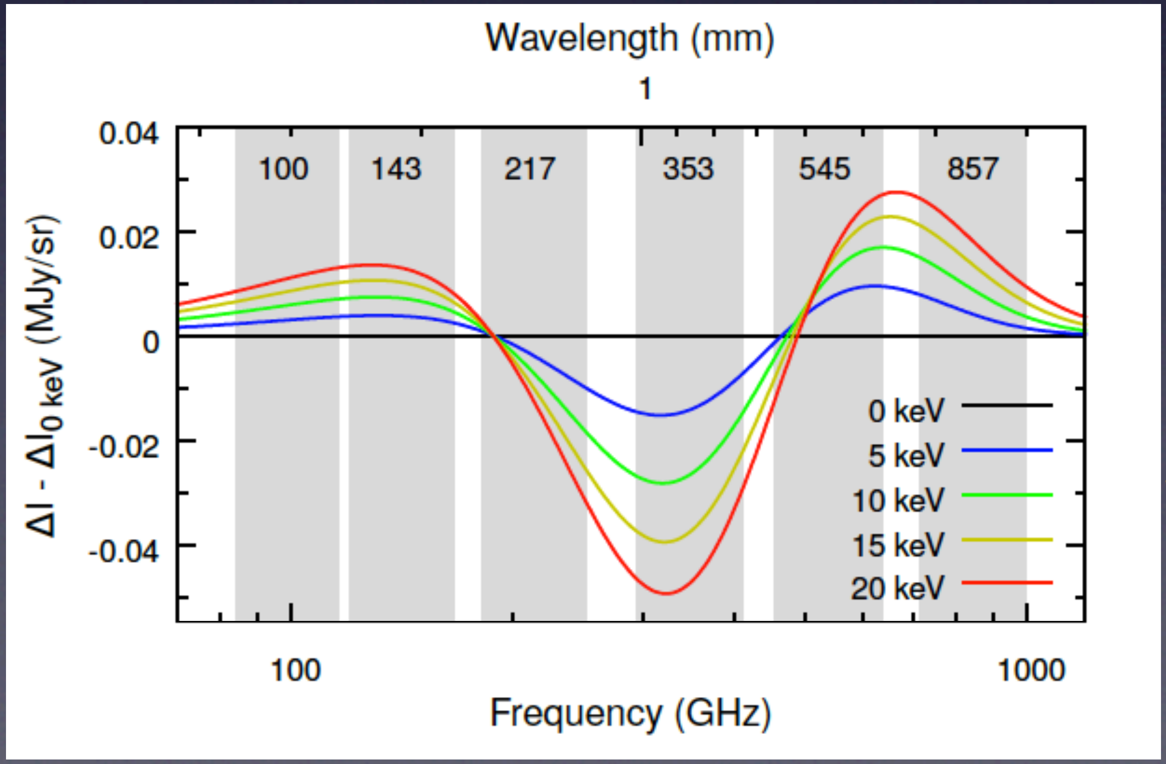


Image: ACT collaboration



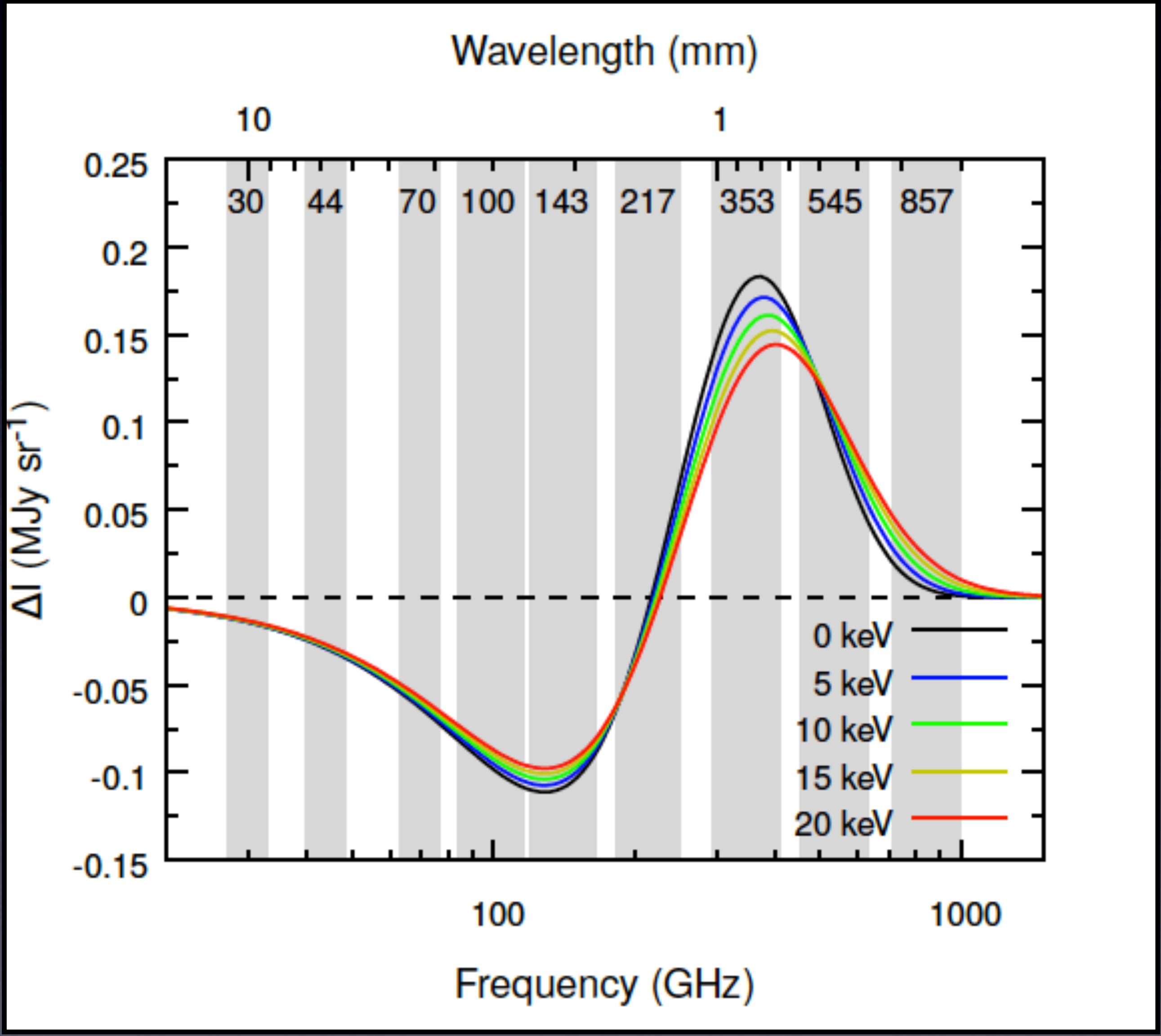
The **relativistic SZ (rSZ)** effect (or distortions) measures the electron temperature

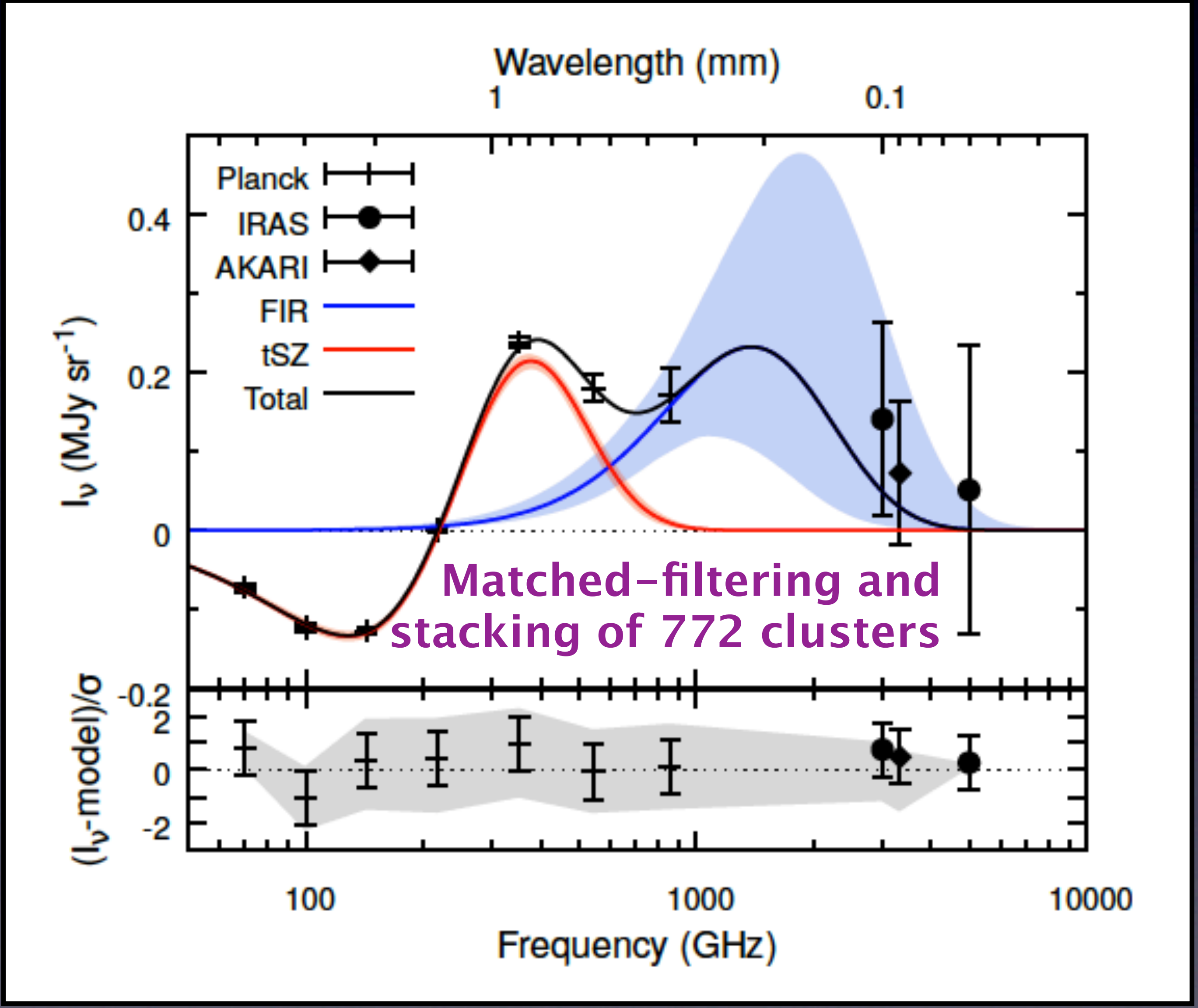
Clusters shocks in the rSZ effect?

Erler, Basu et al. (arXiv:1709.01187)

With current *Planck* data, roughly 2.3σ significance detection of cluster temperature can be obtained after stacking 772 clusters: $k_\mathrm{B}\langle T_\mathrm{SZ}\rangle = 4.4^{+2.1}_{-2.0}\ \mathrm{keV}$

With CCAT-prime the temperature of a ***single massive cluster*** *can be measured at 5–10 σ*





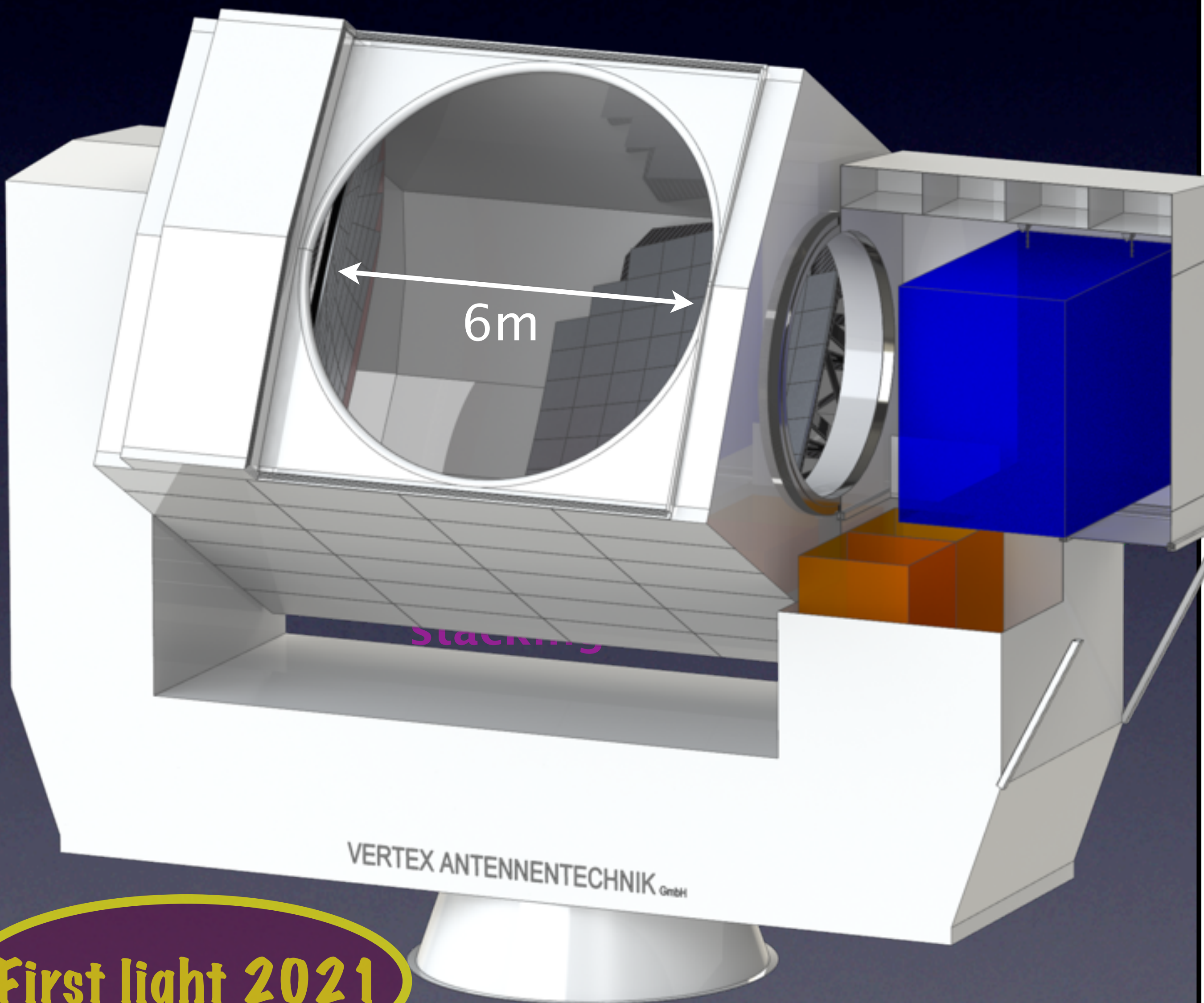
Matched–filtering and stacking of 772 clusters

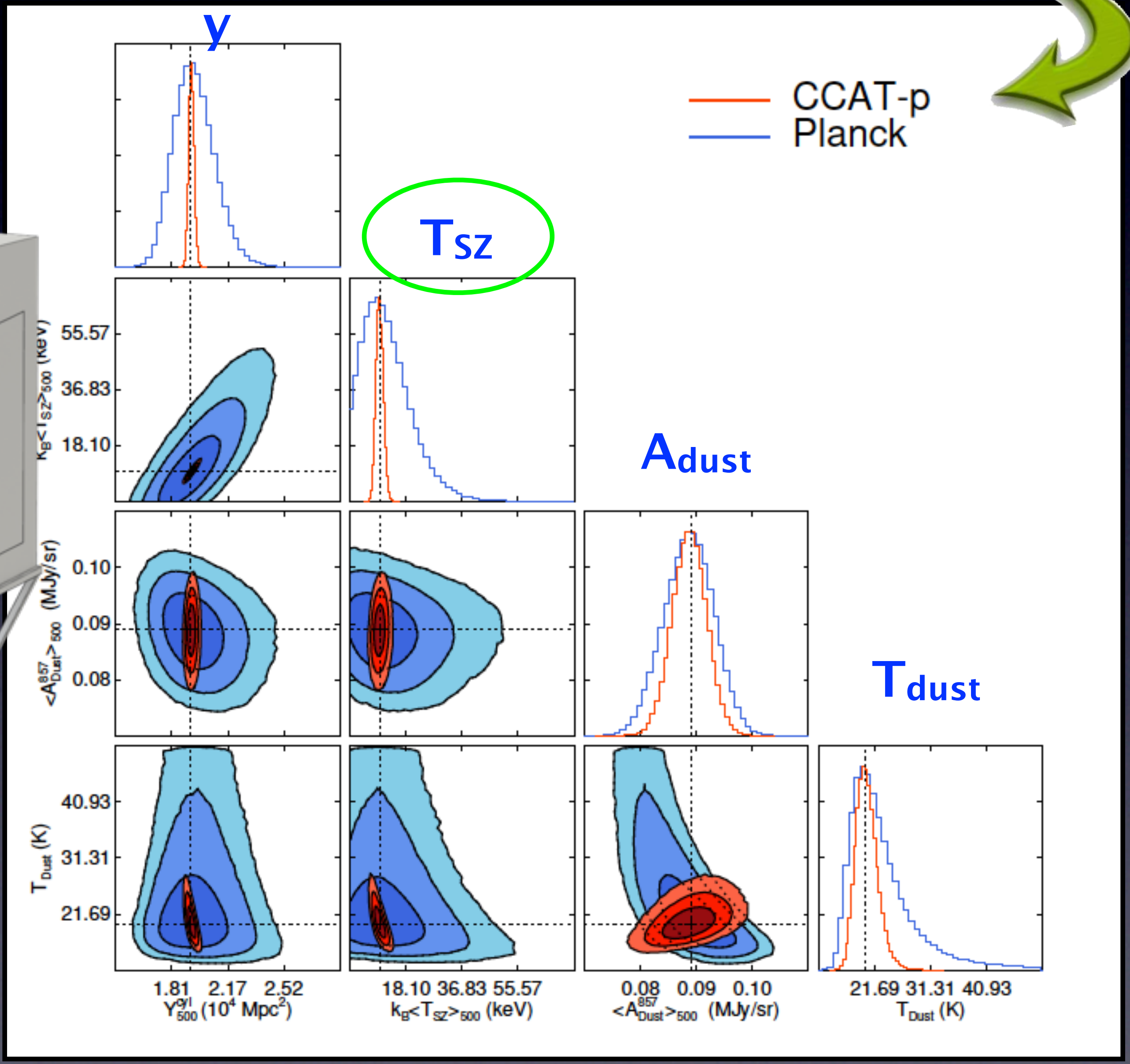
Clusters shocks in the rSZ effect?

Erler, Basu et al. (arXiv:1709.01187)

With current *Planck* data, roughly 2.3σ significance detection of cluster temperature can be obtained after stacking 772 clusters: $k_{\rm B}\langle T_{\rm SZ}\rangle = 4.4^{+2.1}_{-2.0}$ keV (Planck)

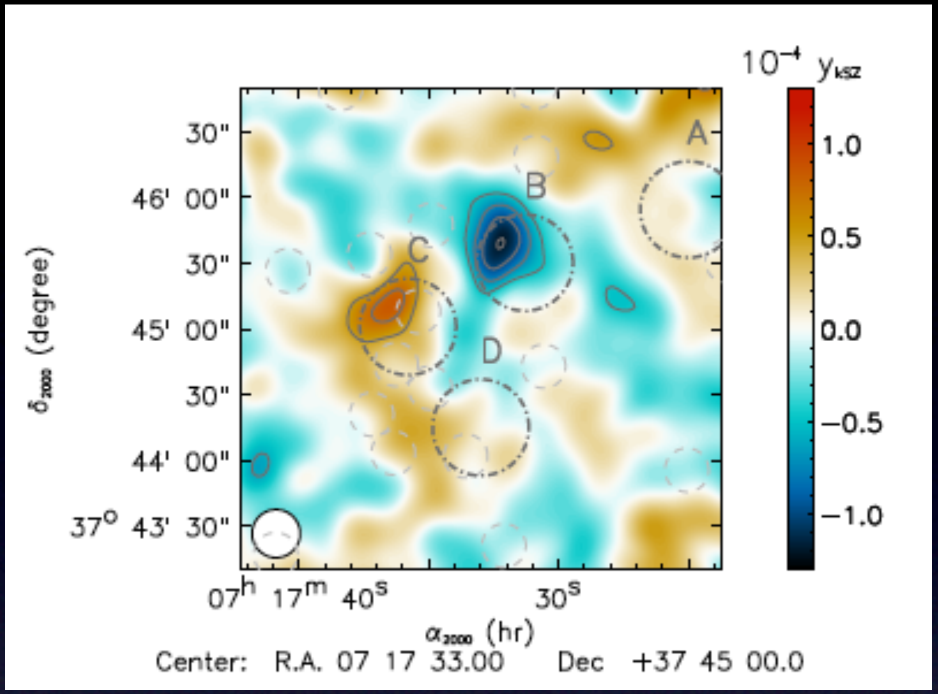
*With CCAT-prime the temperature of a **single massive cluster** can be measured at 5–10 σ*

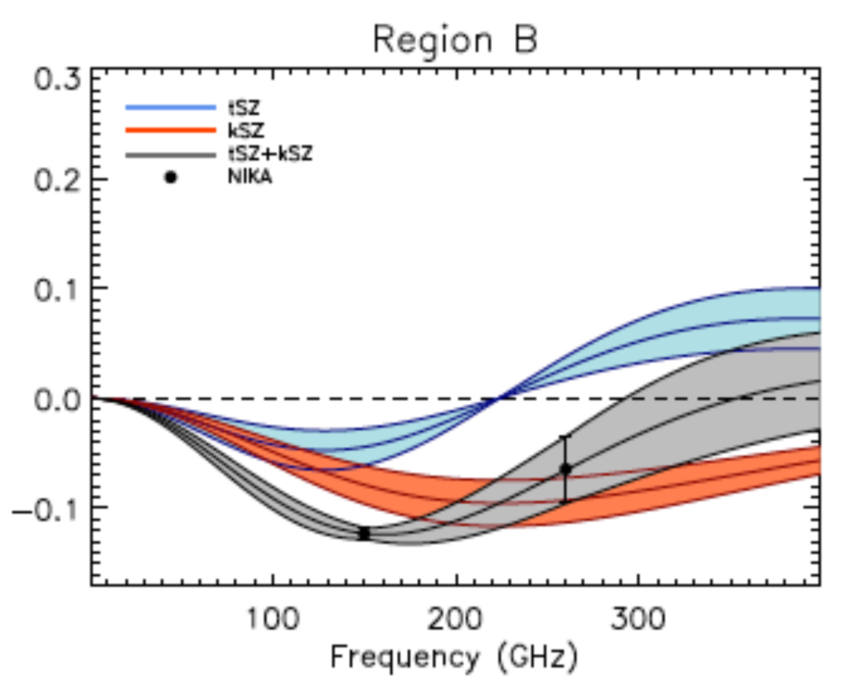




First light 2021

Cluster shocks in kSZ?





Figures from Adam et al. (2017)

kSZ effect probes the bulk motion of electrons along the line-of-sight.

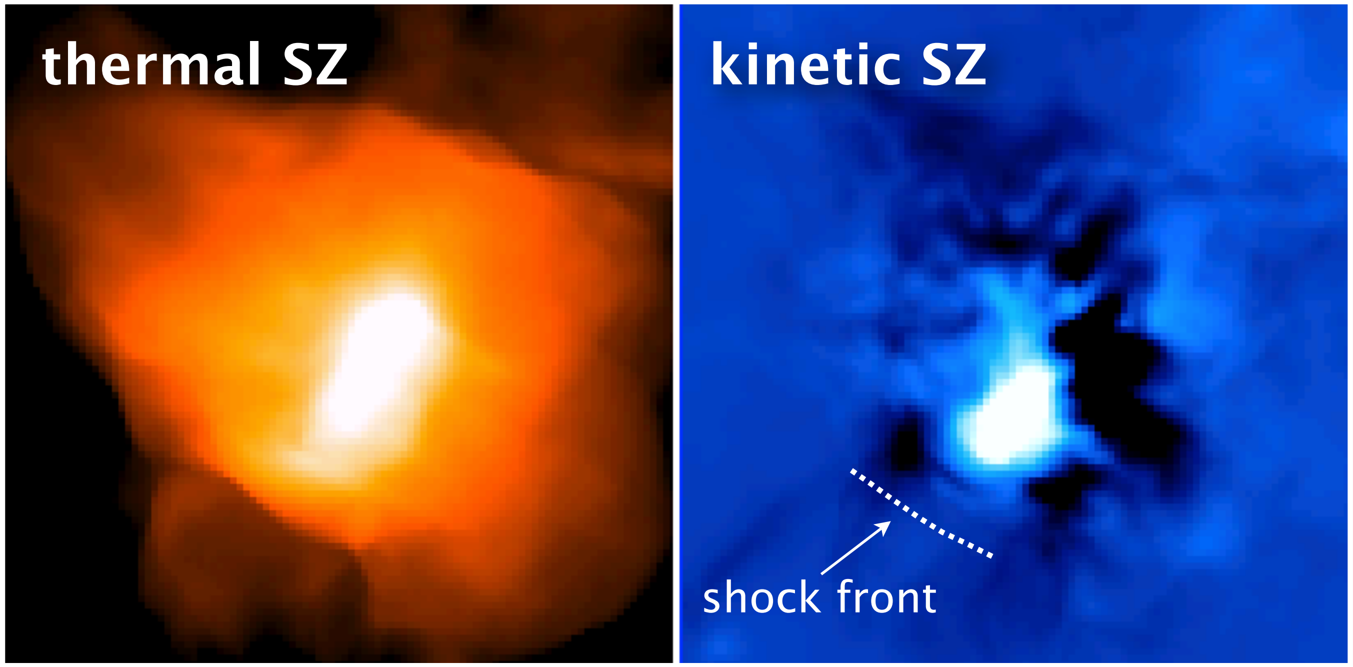
kSZ has been measured *internally* in galaxy clusters, for MACS J0717.5

(Mroczkowski et al. 2012, Sayers et al. 2013, Adam et al. 2017)

Current SZ measurements of (mostly transverse) are contaminated by kSZ at most 2-3% level

But under suitable projection angles the kSZ/tSZ ratio can be large

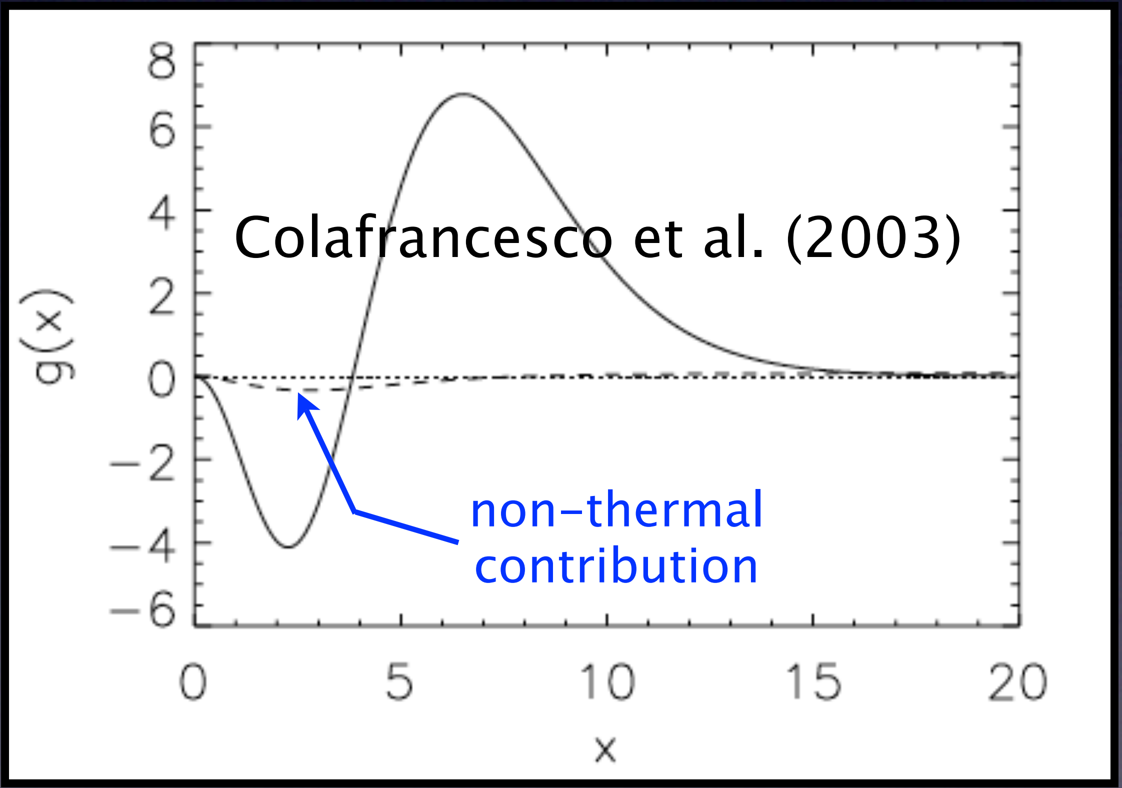
Simulations by Franco Vazza ⇨



ntSZ?? pSZ??

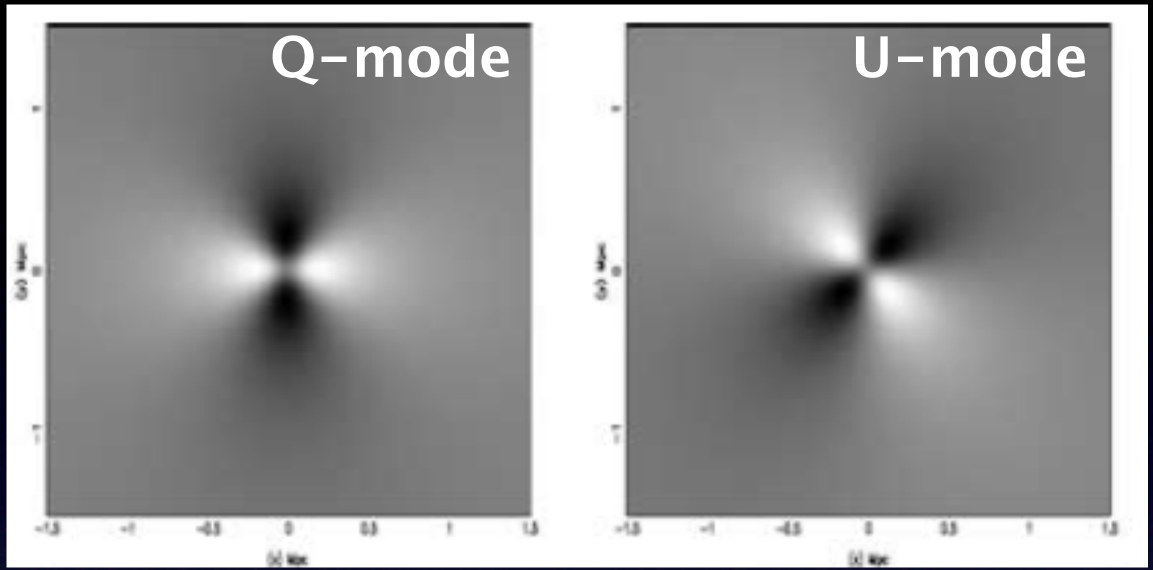
A **non-thermal SZ (ntSZ)** effect wil come from the scattering contribution of the relativistic, non-thermal plasma.

Effect is across the SZ spectral bands but *several orders of magnitude smaller* than the thermal signal (also accurate spectral models are lacking).



Colafrancesco et al. (2003)

non-thermal contribution



Q-mode

U-mode

Lavaux et al. (2004)

Polarized SZ (pSZ) effect can have several origins. The relatively dominant effect measures the *square of the tangential velocity* of the electrons (sometimes called the **kpSZ effect**).

Again a several-orders-of-magnitude smaller effect, and separation is complicated by other polarization signals.

with polarization sensitive bolometers in 10-20 years??

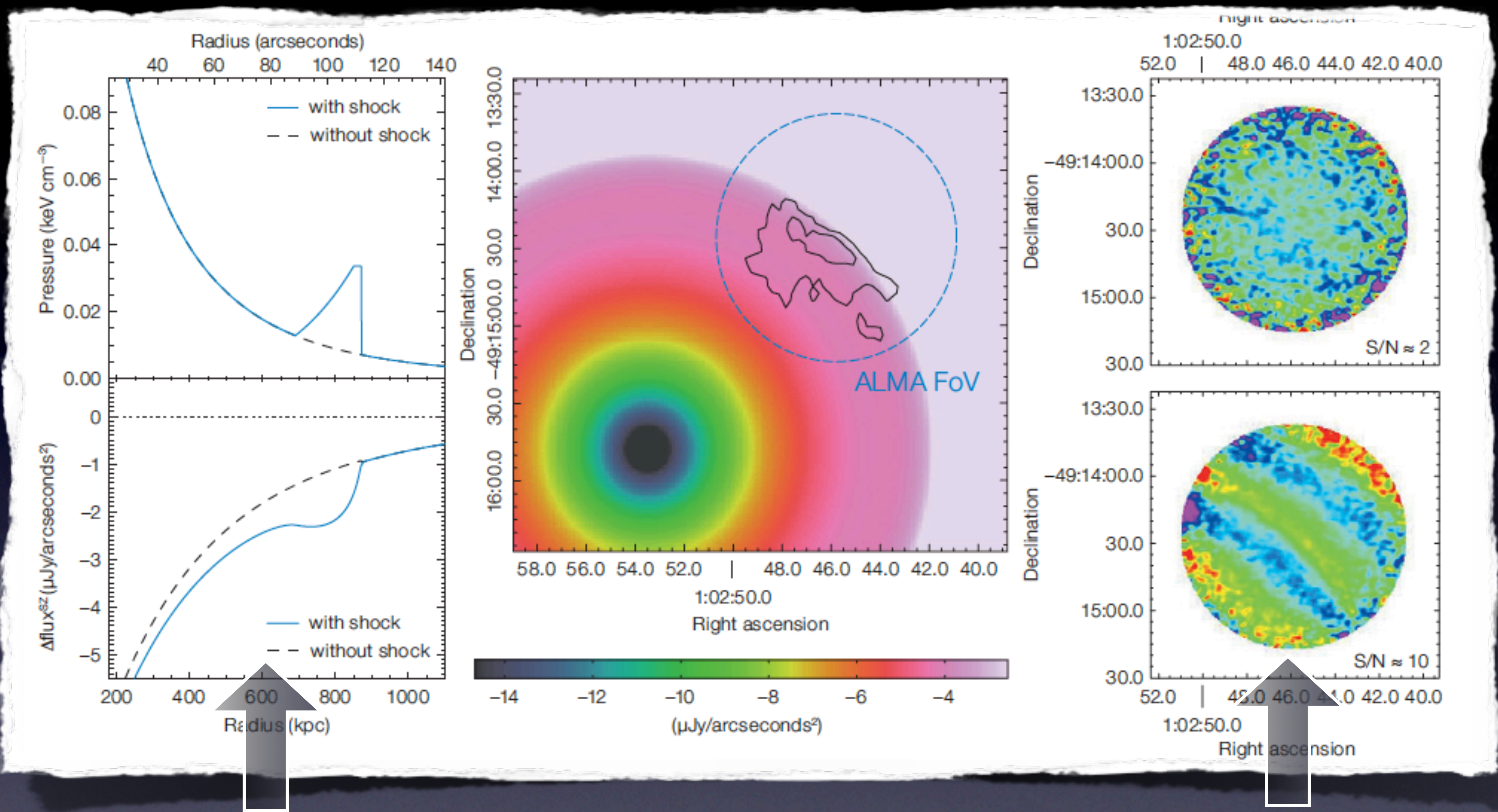
Summary

- The thermal SZ effect is a natural probe for measuring intracluster shocks
- Shocks underlying radio relics have now been measured in the SZ effect twice
- Radio observations at 10-20 GHz are already likely contaminated by the SZ

- ALMA is a great instrument for measuring SZ substructures like shock fronts
- Single-dish bolometer instruments (like MUSTANG2, NIKA2) also very promising
- SZ spectral measurement of T_e in shocked gas might be possible in 5-10 years
- Next frontiers: kSZ measurements of shocks, and even non-thermal & polarized SZ!

Additional Slides

How ALMA *sees* a shock

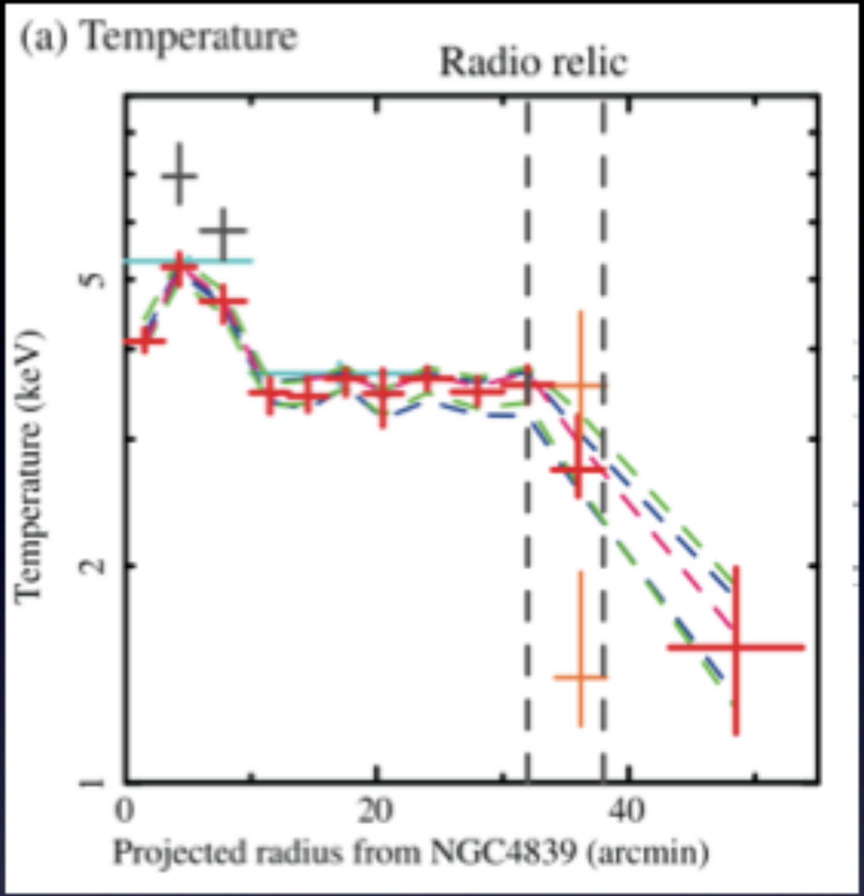


Step function-like jump in the SZ decrement

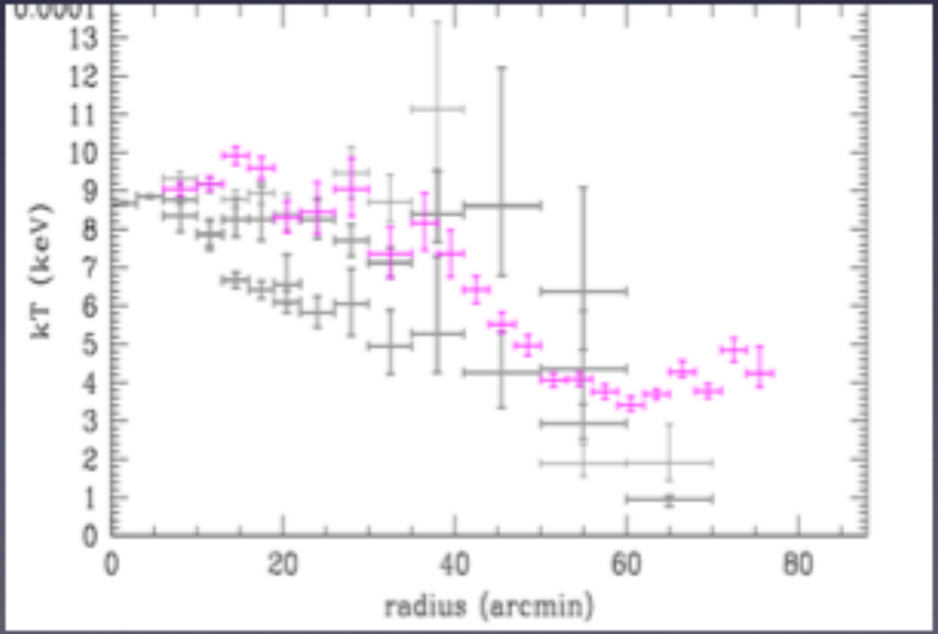
To avoid *interferometric imaging biases*, we fit our shock model directly to the visibility *("uv")* data, using a Bayesian MCMC method.

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

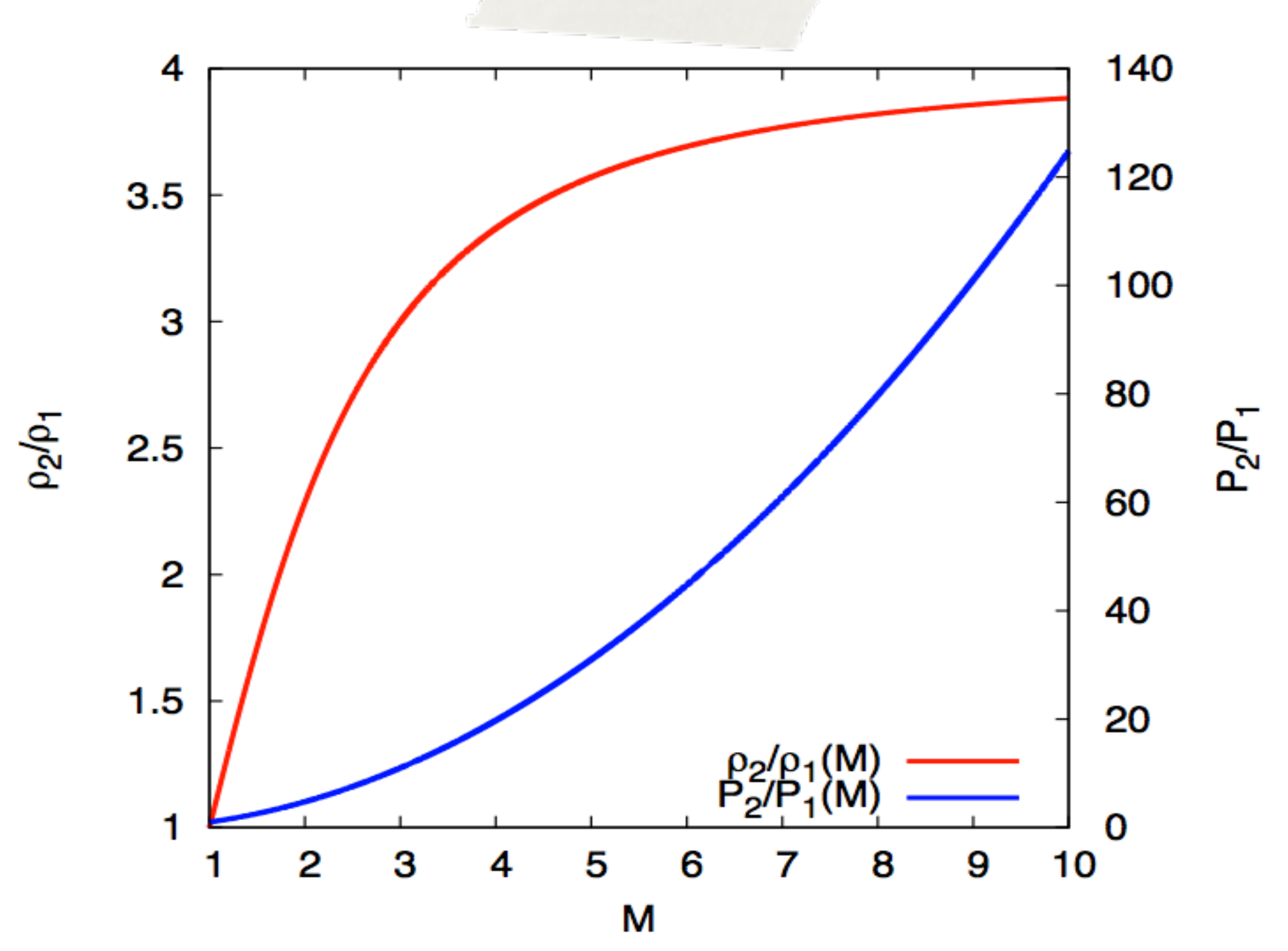
Shocks with X-rays at relics



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!*