Title: The Sunyaev-Zel'dovich effect as a probe of violent cluster mergers

Date: Apr 29, 2009 11:45 AM

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Abstract: In 2001 we made an unexpected discovery of a very bright SZ spot toward the X-ray luminous cluster RXJ1347-1145, which was significantly displaced from the center of the cluster's gravitational potential. One of the possible interpretations is that this spot is a signature of a violent merger in this cluster. This sypothesis has been confirmed by the subsequent Chandra X-ray observations. In this talk I will report on recent results from our follow-up observation of XJ1347-1145 with Suzaku X-ray telescope. Our studies show that the SZ effect, when it is mapped with a fine angular resolution of order 10 arc-seconds, provides a powerful probe of violent cluster mergers.

IPMU International Conference

# Dark Energy: Lighting up the Darkness

http://member.ipmu.jp/darkenergy09/welcome.html

June 22 – 26, 2009
At Institute for the Physics and Mathematics of the Universe
(IPMU), Kashiwa, Chiba, Japan

# The SZ effect as a probe of violent cluster mergers

Eiichiro Komatsu (Texas Cosmology Center, UT Austin)
SZ Workshop, Perimeter Institute, April 29, 2009

# Purpose of This Talk

- Show (hopefully, give an observational proof) that ***high-spatial resolution*** (~10") SZ mapping observations are a powerful probe of violent cluster mergers.

# Collaborators (1998–2008)

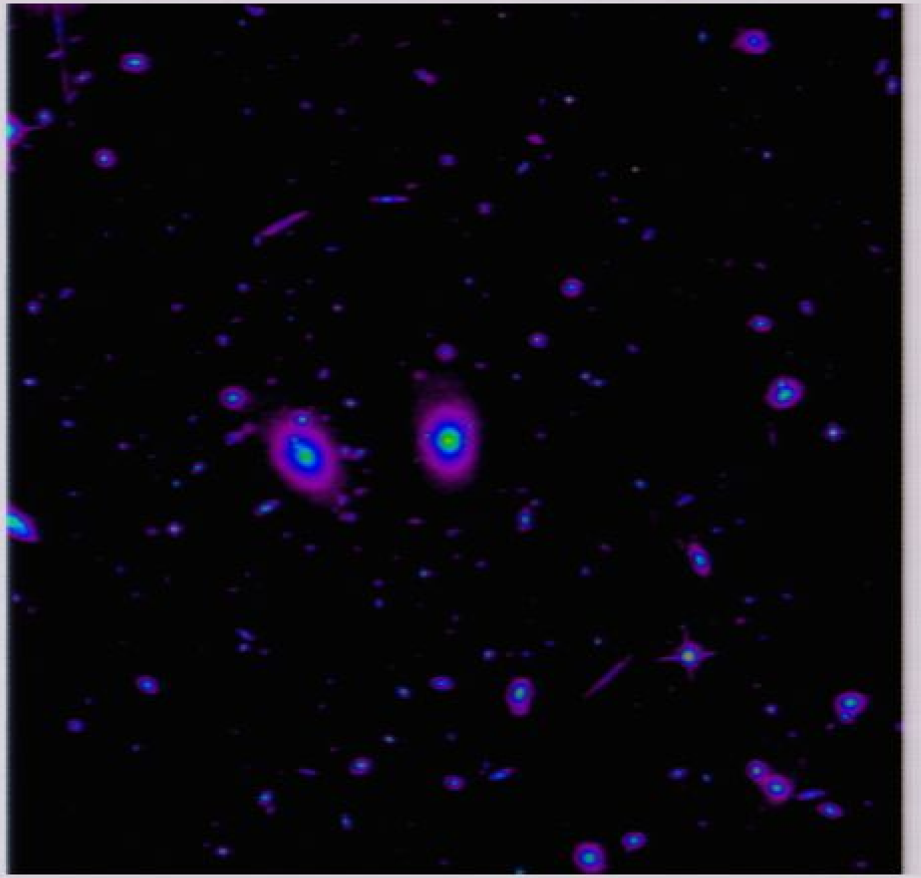
- Makoto Hattori (Tohoku Univ.)
- Ryohei Kawabe (NAOJ)
- **Tetsu Kitayama** (Toho Univ.)
- Kotaro Kohno (Univ. of Tokyo)
- Nario Kuno (Nobeyama Radio Observatory)
- Hiroshi Matsuo (NAOJ)
- Koichi Murase (Saitama Univ.)
- Tai Oshima (Nobeyama Radio Observatory)
- **Naomi Ota** (Tokyo Univ. of Science)
- Sabine Schindler (Univ. of Innsbruck)
- Yasushi Suto (Univ. of Tokyo)
- Kohji Yoshikawa (Univ. of Tsukuba)

# Papers

- Komatsu et al., ApJL, 516, L1 (1999) [SCUBA@350GHz]
- Komatsu et al., PASJ, 53, 57 (2001) [NOBA@150GHz]
- Kitayama et al., PASJ, 56, 17 (2004) [Analysis w/ Chandra]
- Ota et al., A&A, 491, 363 (2008) [Suzaku]

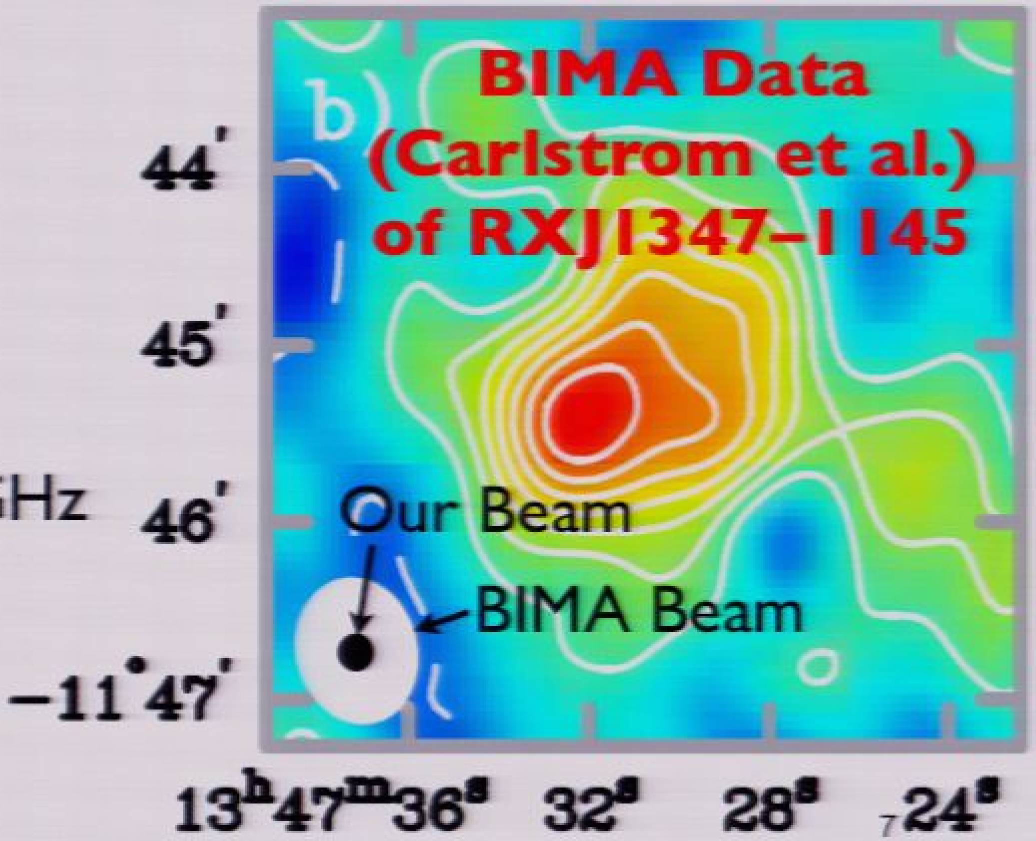
# Target: Bright, Massive, and Compact

- RXJ1347–1145
- $z$=0.451 (10”=59 kpc)
- $L_{X,bol}$~$2\times10^{46}$ erg/s
- $M_{tot}$(<2Mpc)~$1\times10^{15}M_{sun}$
- Cluster Mean $T_X$~13keV
- $\theta_{core}$~8 arcsec (47 kpc)
- $y$~$8\times10^{-4}$



# *High Spatial Resolution*
# SZ Mapping Observations

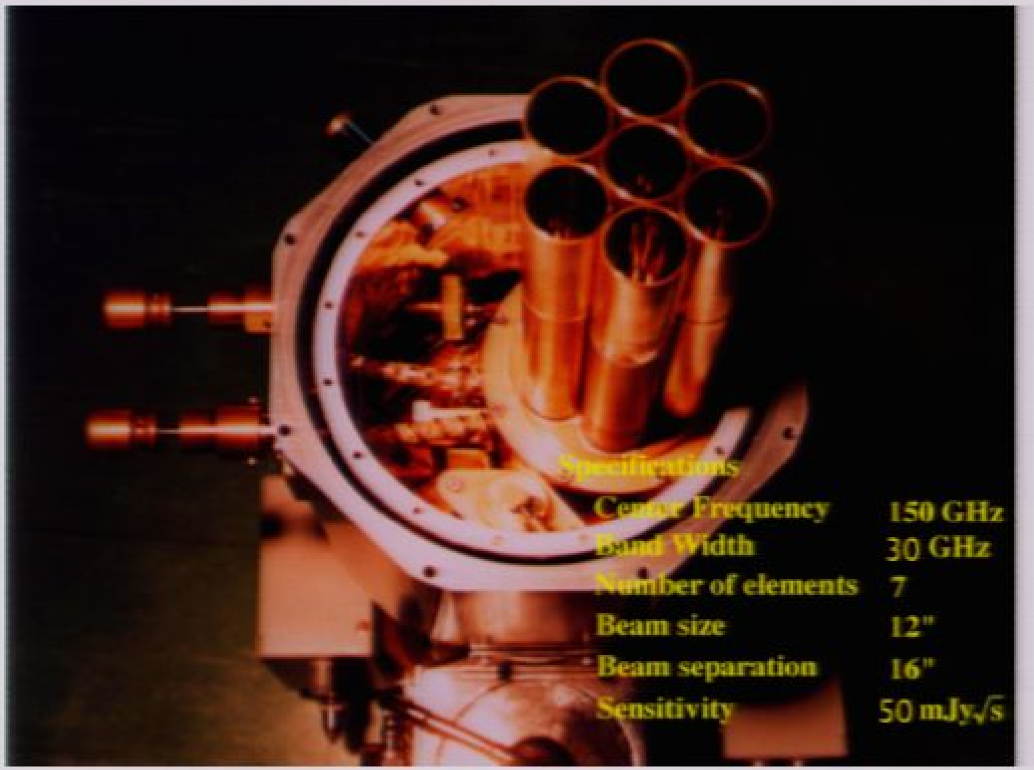
- **SCUBA**/JCMT@350GHz
    - ***15 arcsec*** FWHM Beam
    - Observed in 1998&1999
    - 5.3 mJy/beam (8 hours)
- **NOBA**/Nobeyama 45m@150GHz
    - ***13 arcsec*** FWHM Beam
    - Observed in 1999&2000
    - 1.6 mJy/beam (24 hours)



**BIMA Data (Carlstrom et al.) of RXJ1347–1145**

# Nobeyama Bolometer Array

- NOBA = 7-element bolometer array working at λ=2mm
- Made by Nario Kuno (NRO) and Hiroshi Matsuo (NAOJ) in 1993.
- Still available for general users at NRO



Specifications

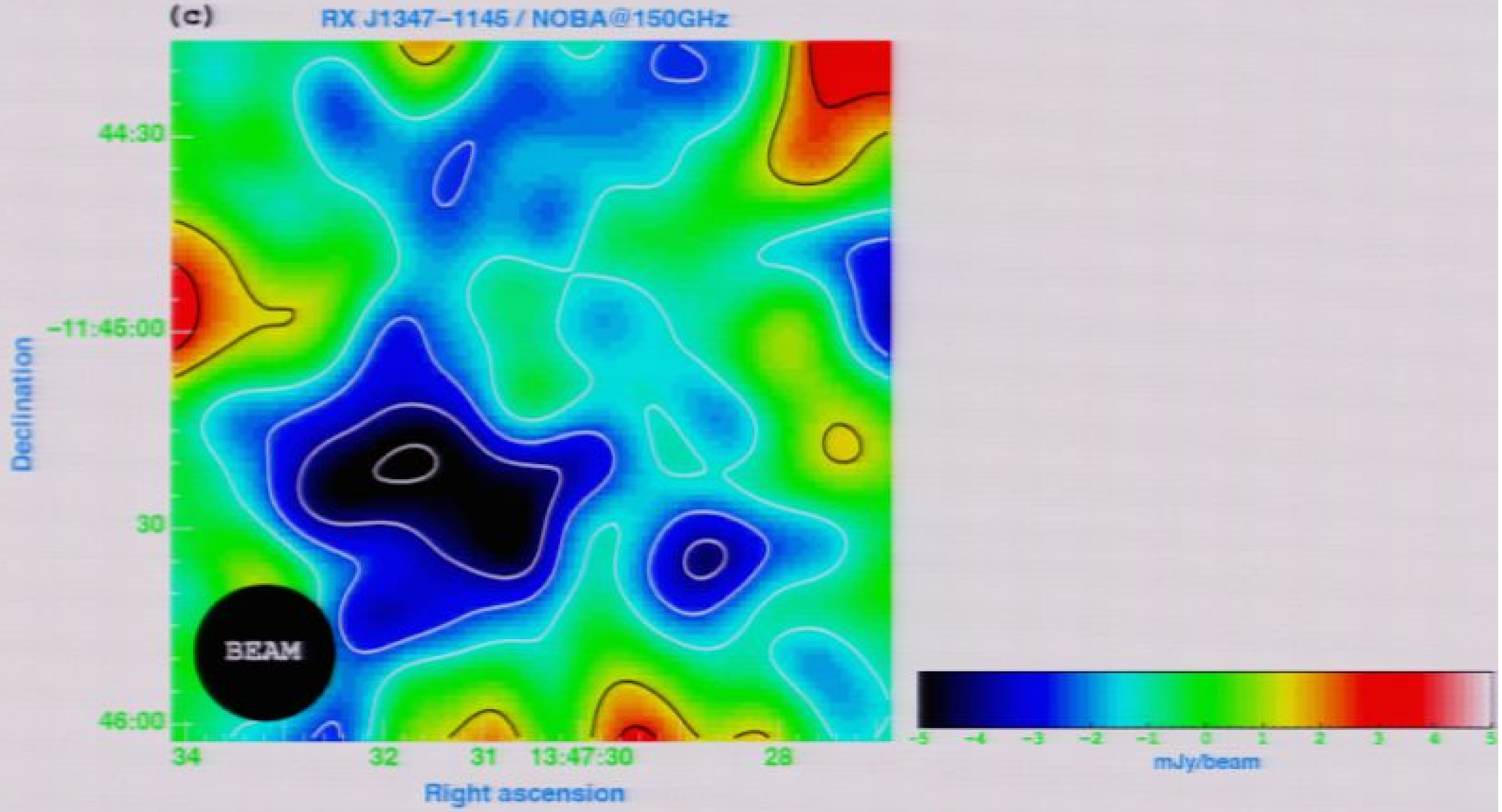
| | |
|---|---|
| Center Frequency | 150 GHz |
| Band Width | 30 GHz |
| Number of elements | 7 |
| Beam size | 12" |
| Beam separation | 16" |
| Sensitivity | 50 mJy$\sqrt{s}$ |

# X-ray Observations

- **ROSAT**, HRI (Schindler et al. 1997)
  - Sensitive up to ***~2 keV***
  - 35.6 ks (HRI)
- **Chandra**, ACIS-S3 (Allen et al. 2002), ACIS-I (archived)
  - Sensitive up to ***~7 keV***
  - 18.9 ks (ACIS-S3), 56 ks (ACIS-I)
- **Suzaku**, XIS and HXD (Ota et al. 2008)
  - Sensitive up to ***~12 keV*** (XIS); ***~60 keV*** (HXD/PIN)
  - 149 ks (XIS), 122 ks (HXD)

*Komatsu et al. (2001)*

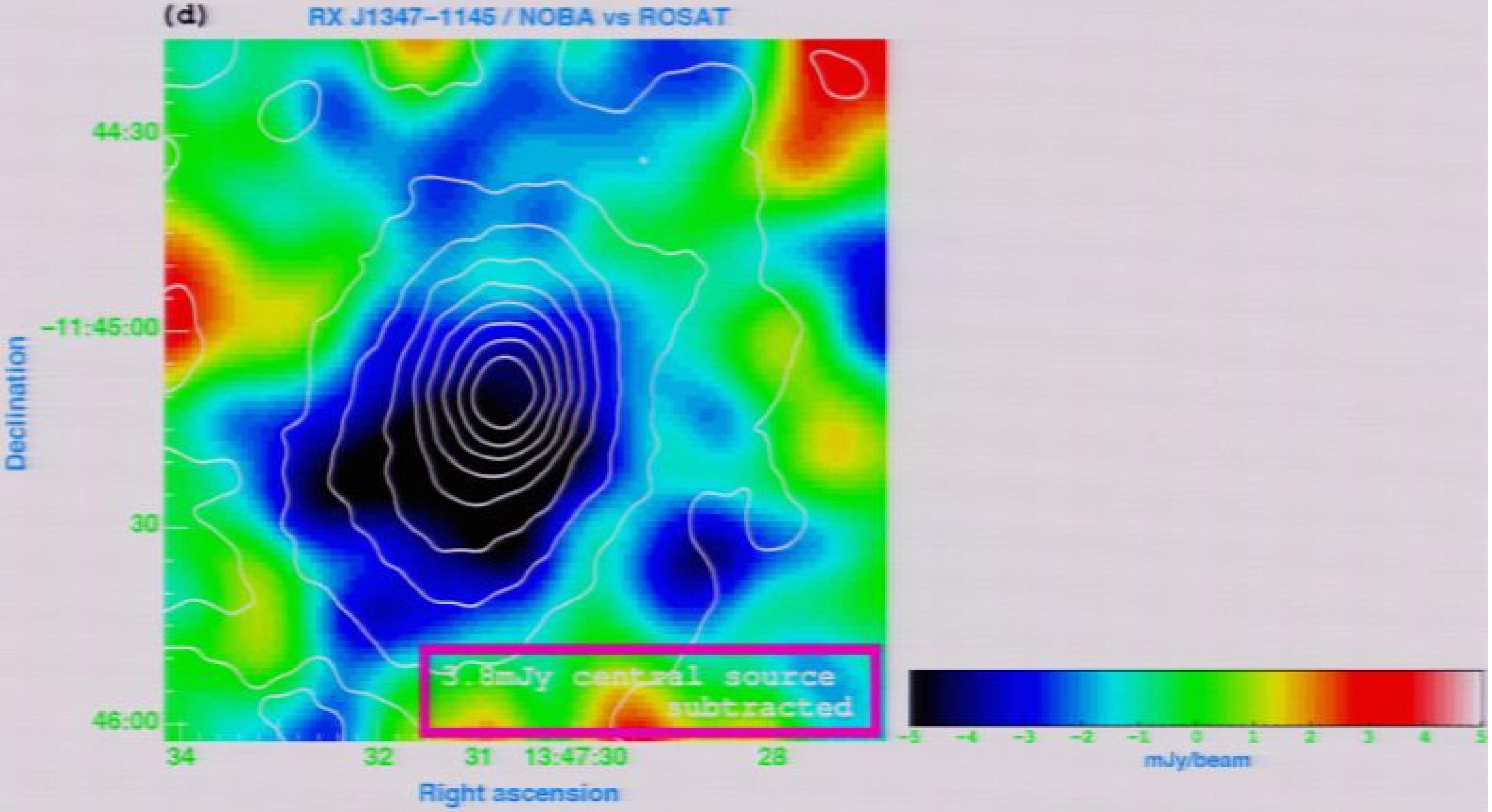
# SZ “Hot Spot”



- Significant offset between the SZ peak and the cluster center.

*Komatsu et al. (2001)*

# SZ saw it, but ROSAT missed



- ROSAT data indicated that this cluster was a relaxed, regular cluster. The SZ data was not consistent with that.

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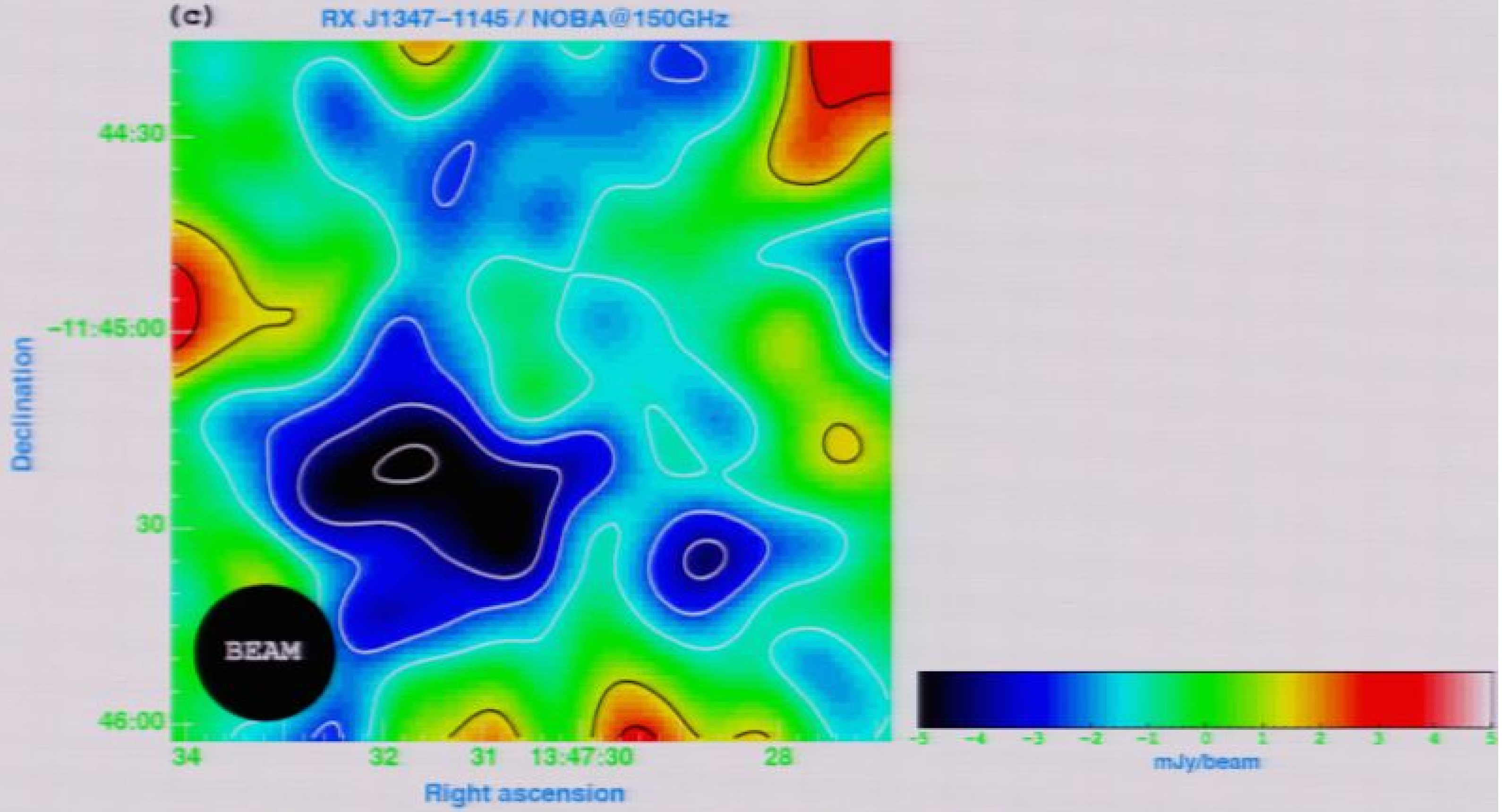

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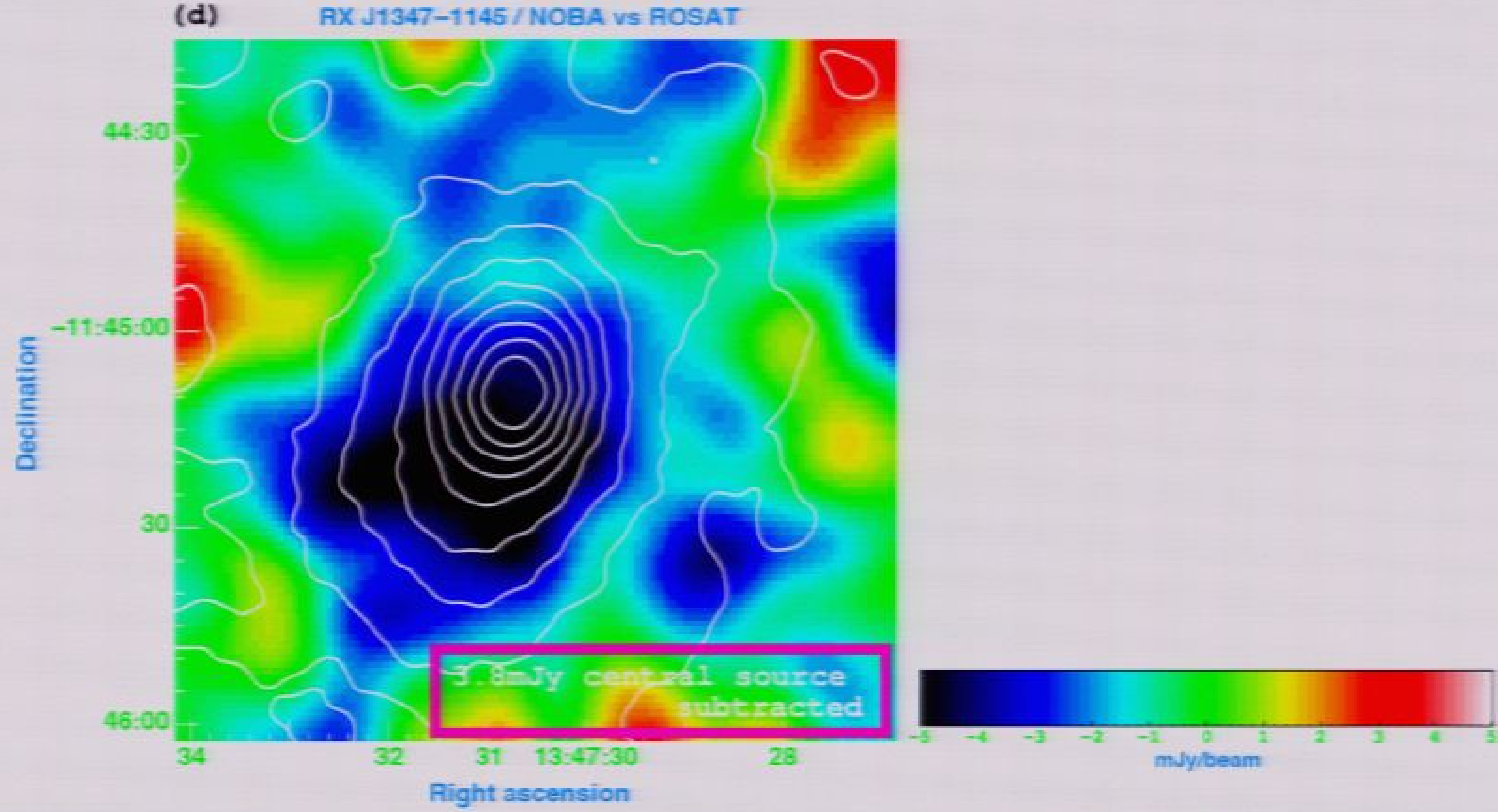


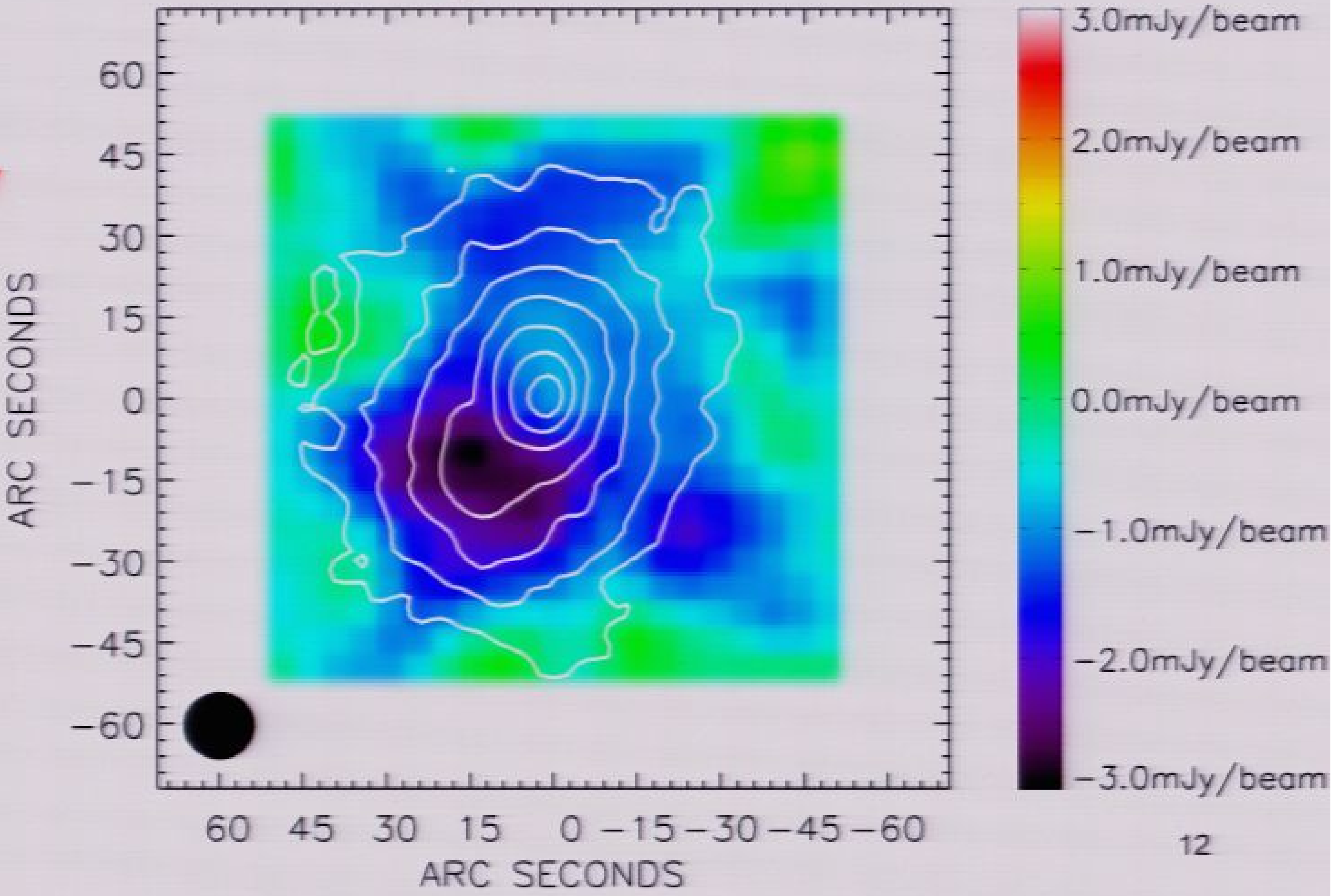
3.8mJy central source subtracted

- ROSAT data indicated that this cluster was a relaxed, regular cluster. The SZ data was not consistent with that.

*Allen et al. (2002); Kitayama et al. (2004)*

# Confirmed by Chandra

- Allen et al. (2002) estimated ~18 keV toward this direction from Chandra spectroscopy.
- But, Chandra is sensitive only up to ~7keV...



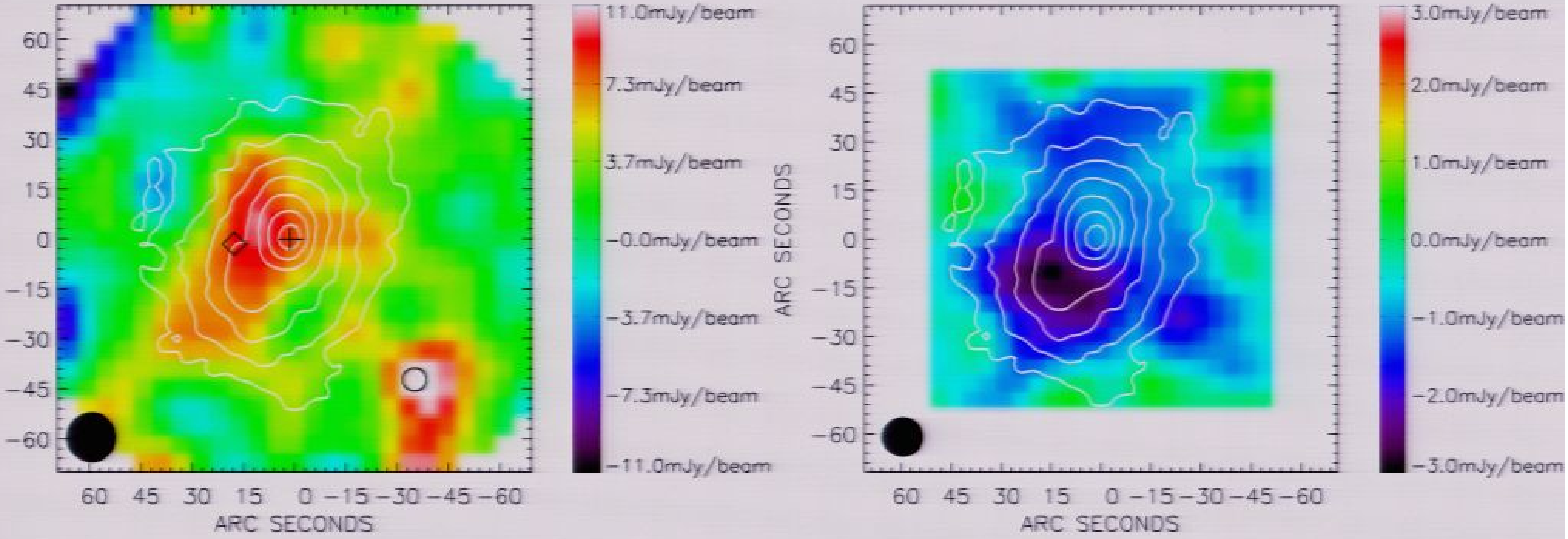
*Kitayama et al. (2004)*

# X-ray + SZ Joint

- The SZ effect is sensitive to arbitrarily high temperature.
- X-ray spectroscopy is not.
- Combine the X-ray brightness and the SZ brightness to derive the electron temperature:
    - $I_{SZ}$ is proportional to $n_eT_eL$, $I_X$ is proportional to $n_e^2\Lambda(T_e)L$ -> Solve for $T_e$ (and L)

*Komatsu et al. (1999, 2001); Kitayama et al. (2004)*

# Images of the SZ data

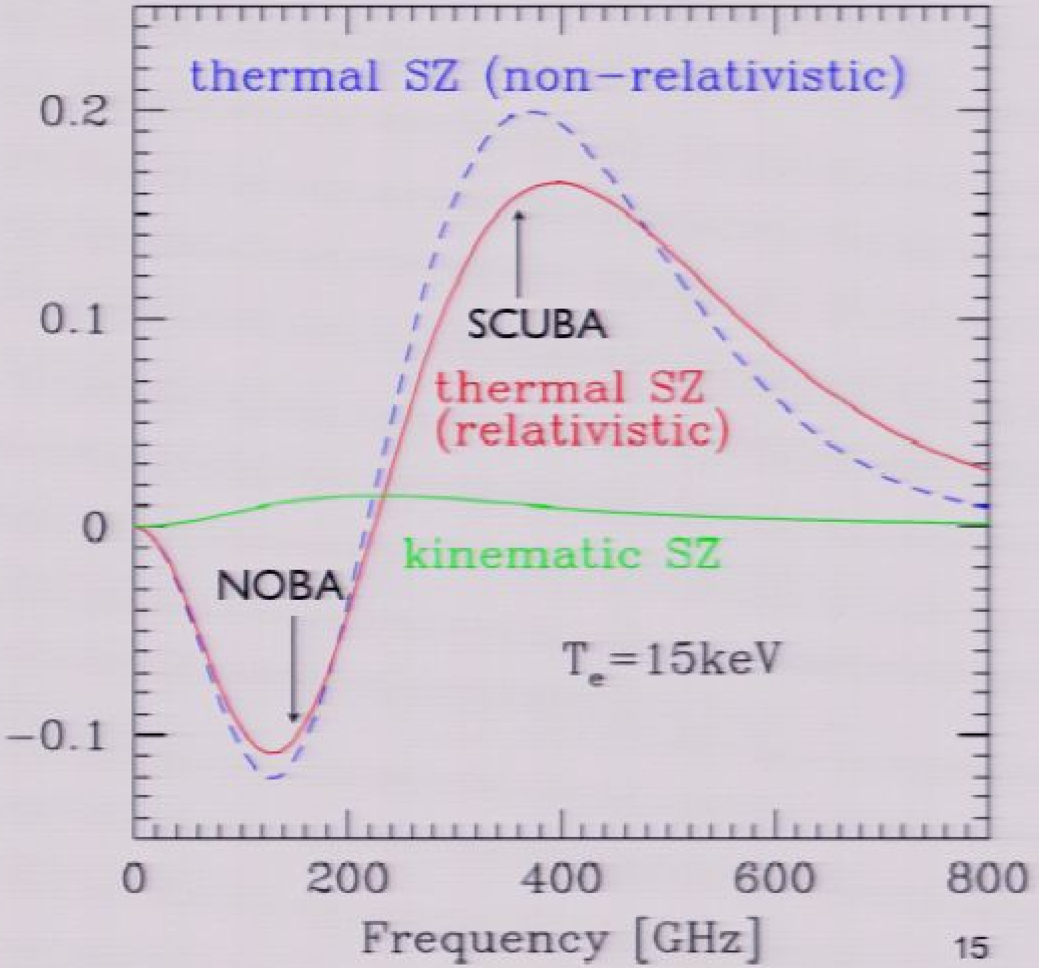


- Spatially resolved SZ images in 350 GHz (increment) and 150 GHz (decrement)

# Relativistic Correction

- At such a high $T_e$ that we are going to deal with (~30 keV), the relativistic correction must be taken into account.

- The suppression of the signal due to the relativistic correction diminishes the SZ at 350GHz more than that at 150GHz.



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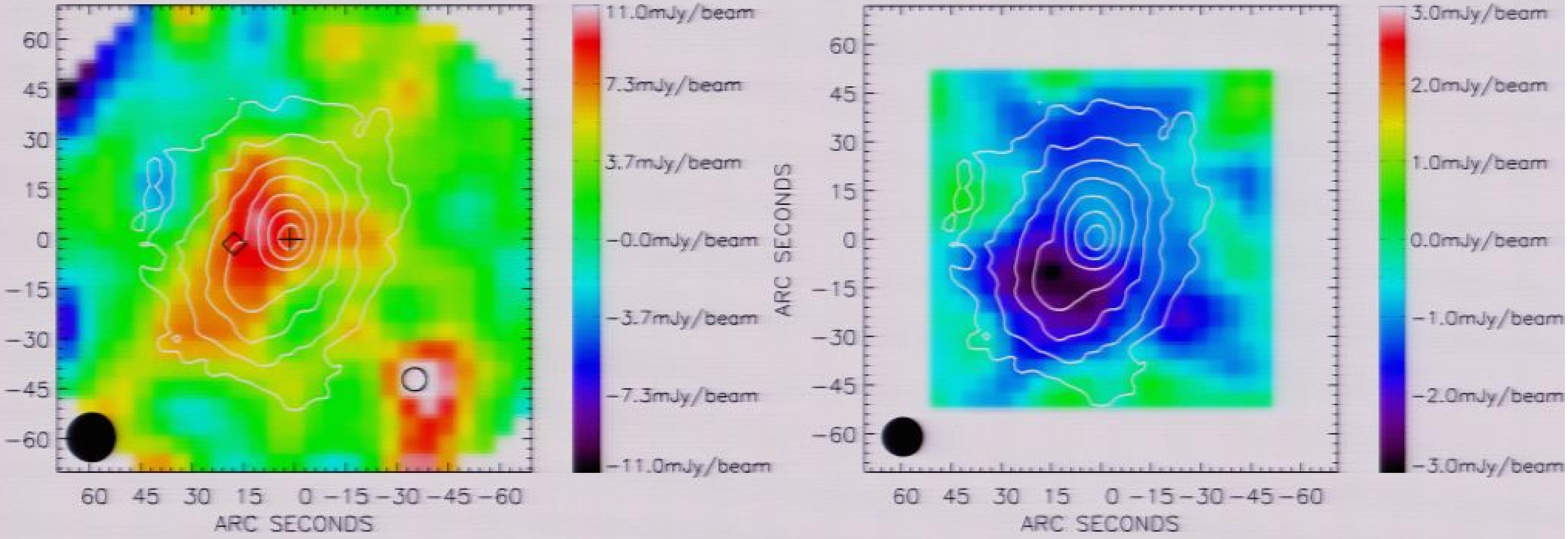

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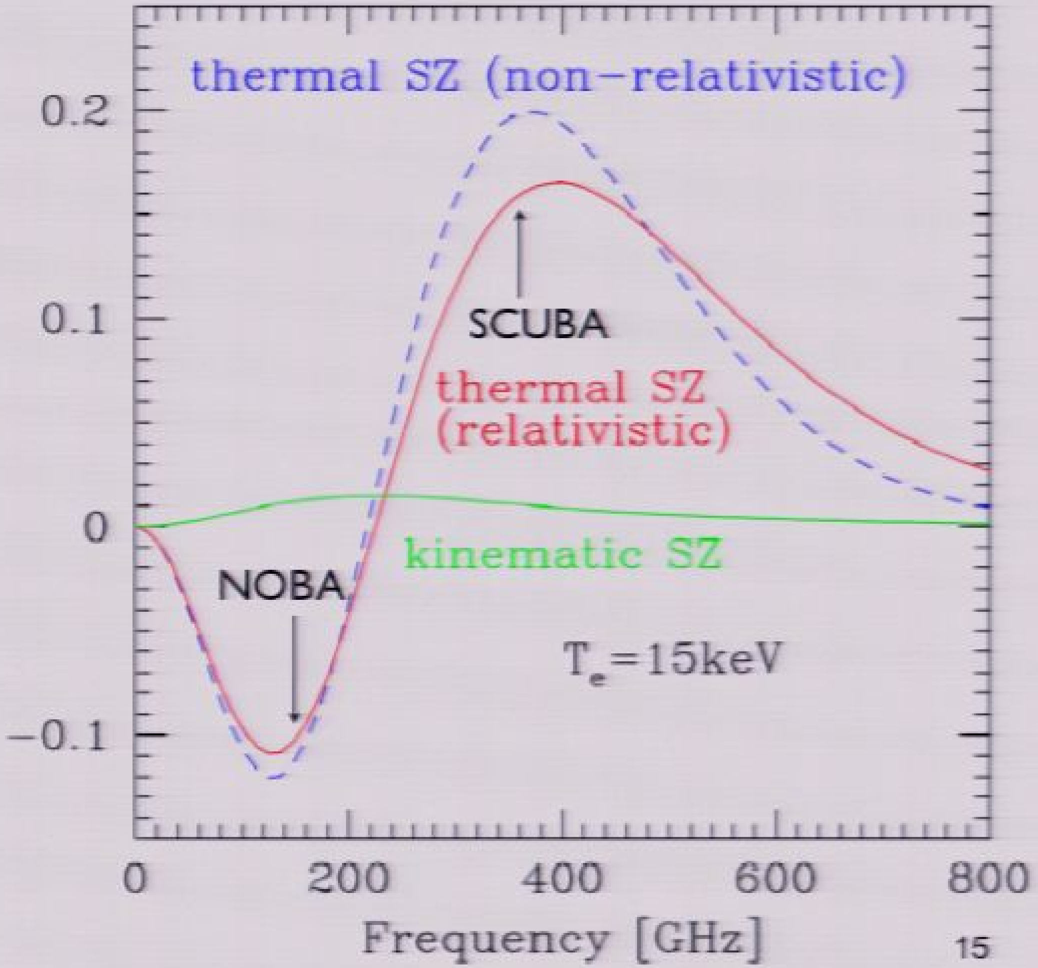
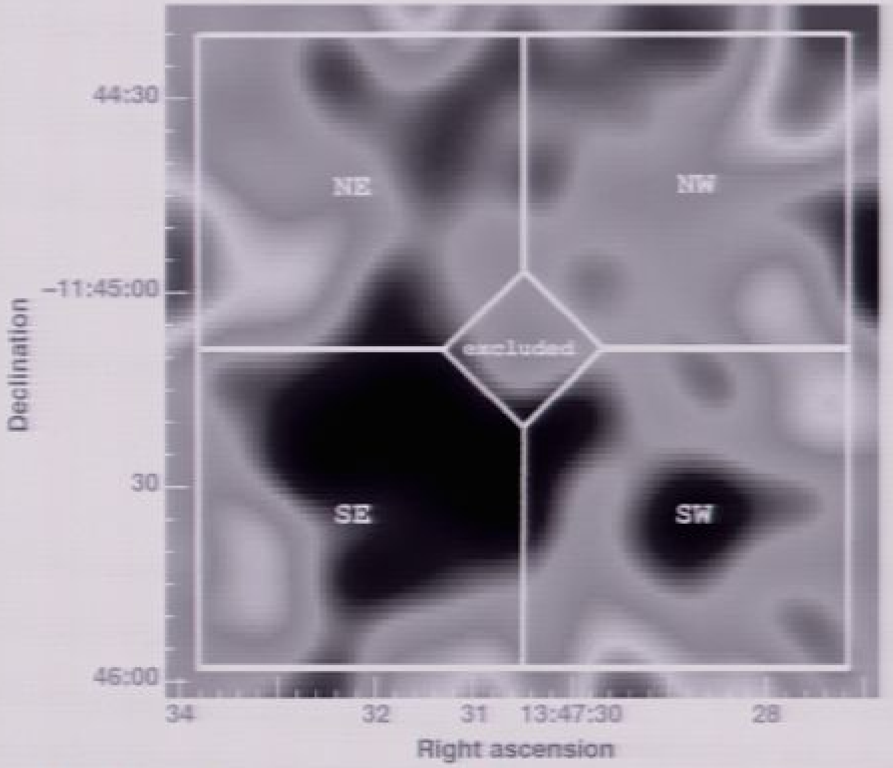


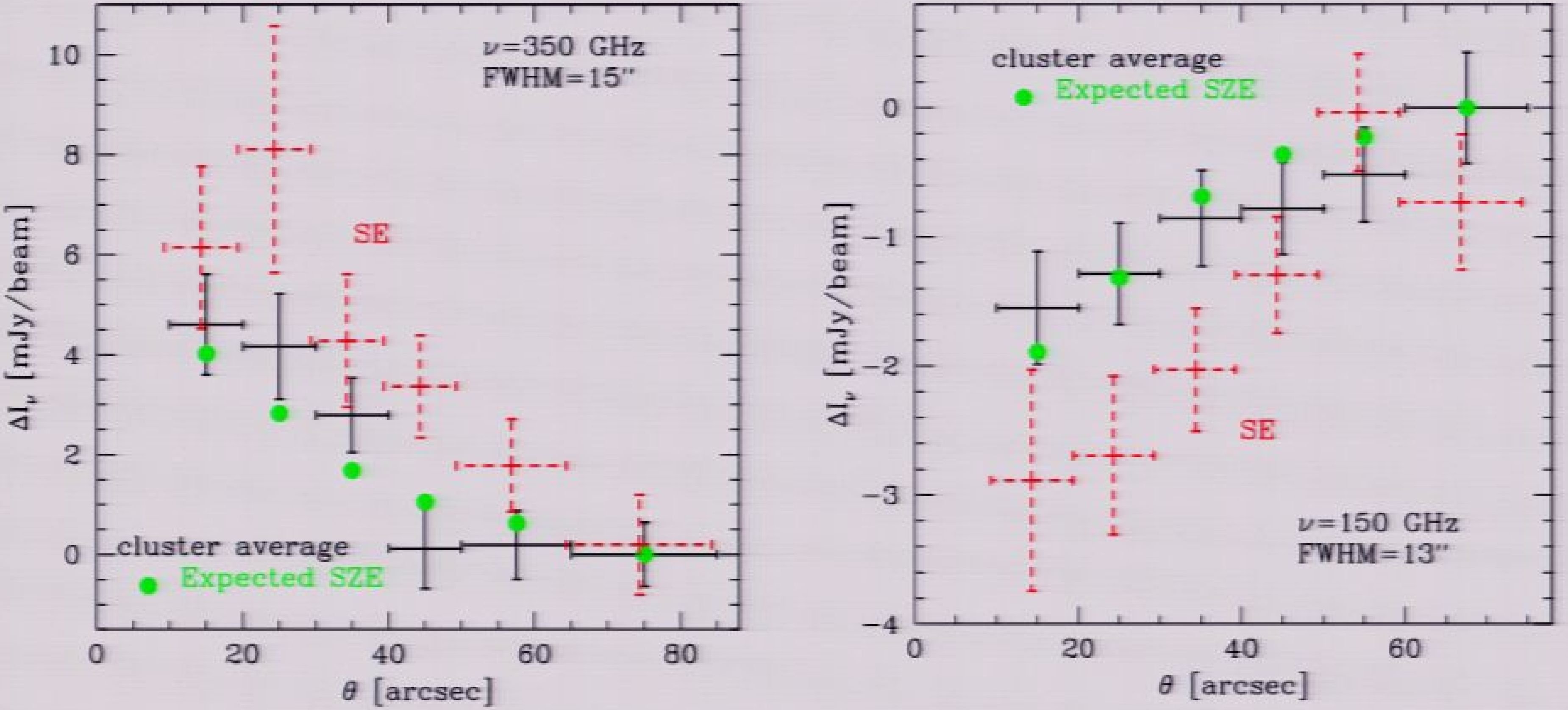
# "SE" (South-East) Quadrant



- We exclude the central part that is contaminated by the ~4mJy point source, and treat the SE quadrant separately from the rest of the cluster (which we shall call the "ambient component").

*Komatsu et al. (1999, 2001); Kitayama et al. (2004)*

# SZ Radial Profiles



- The excess SZ in the South-East quadrant is clearly seen.

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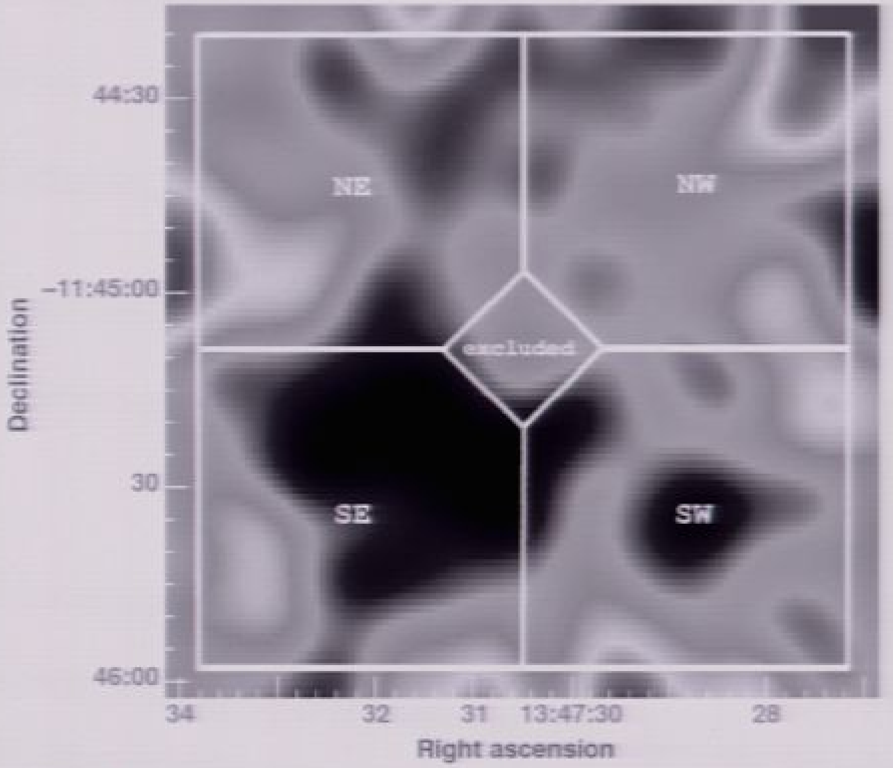

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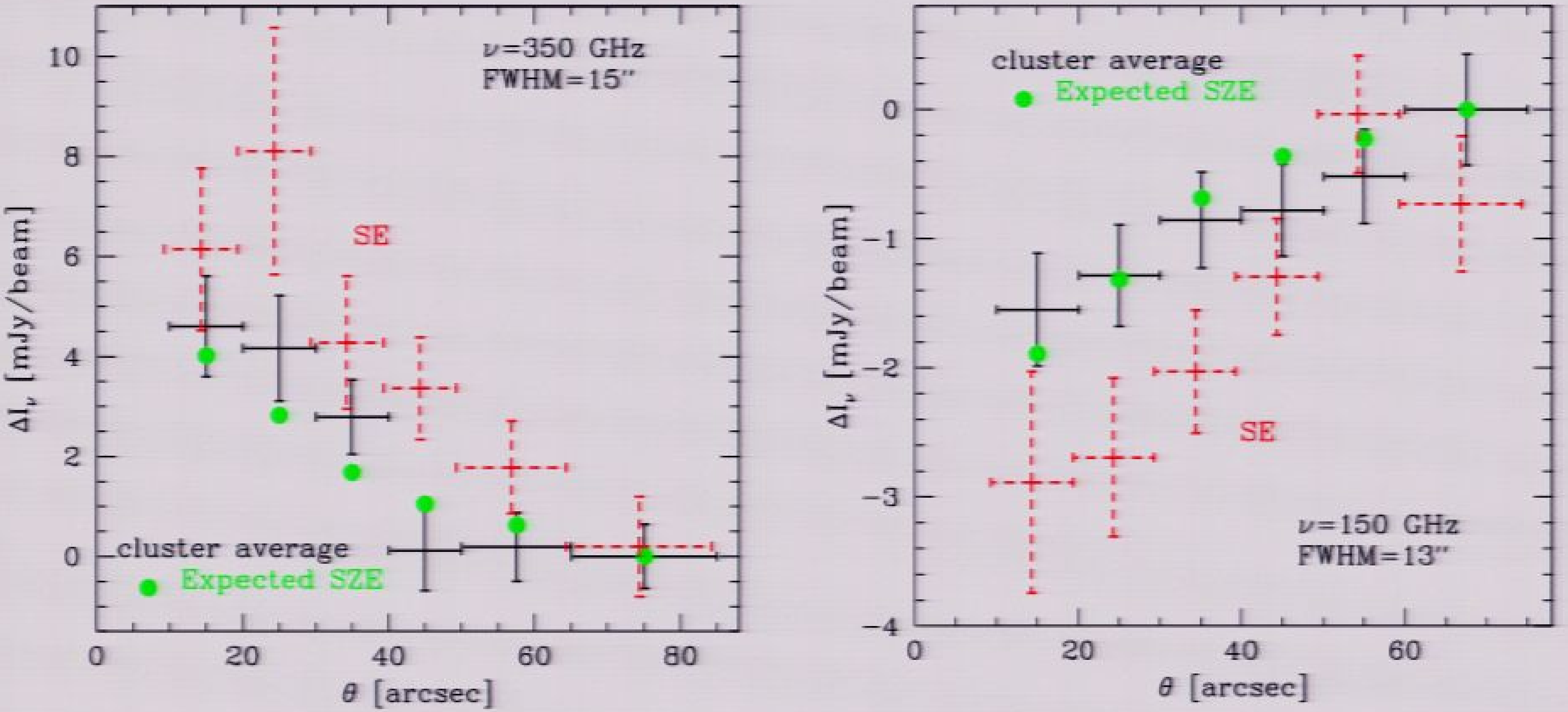

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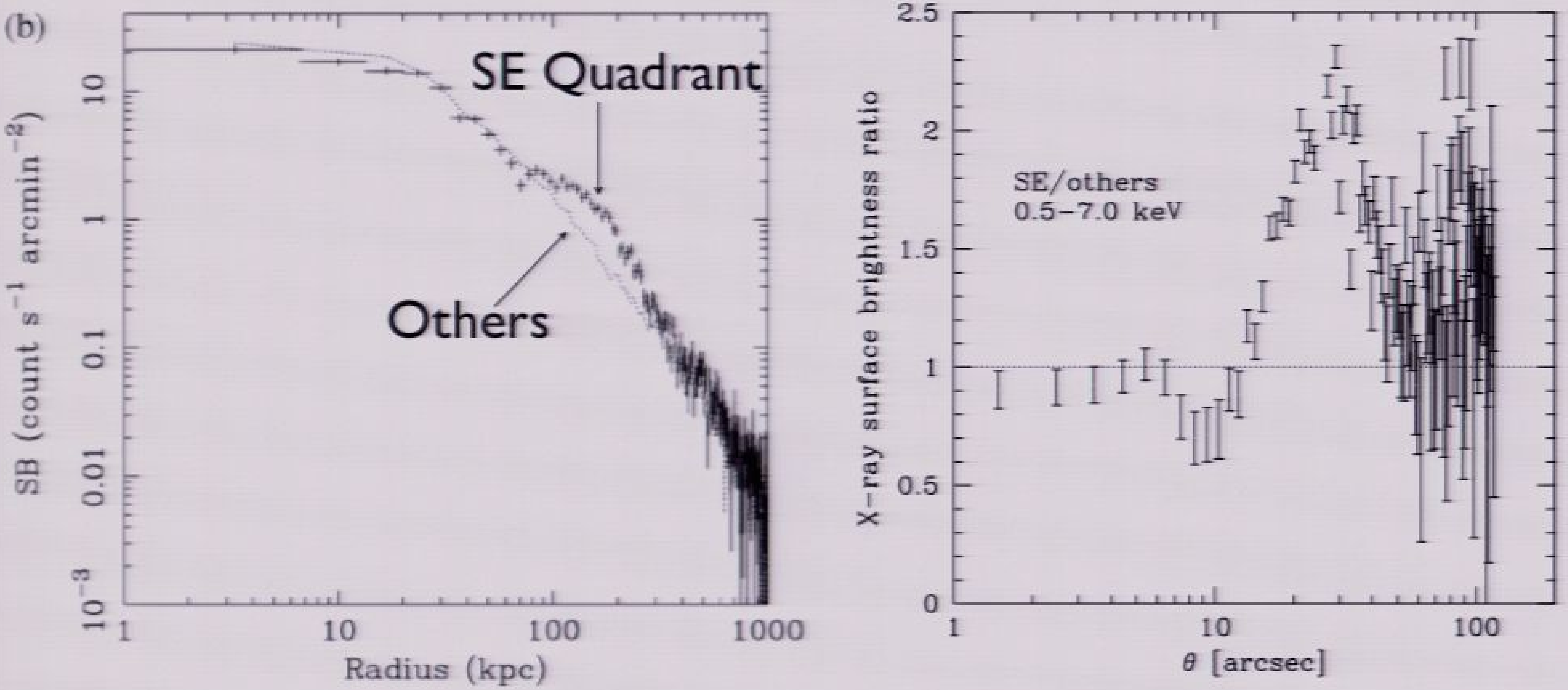
# X-ray Radial Profile

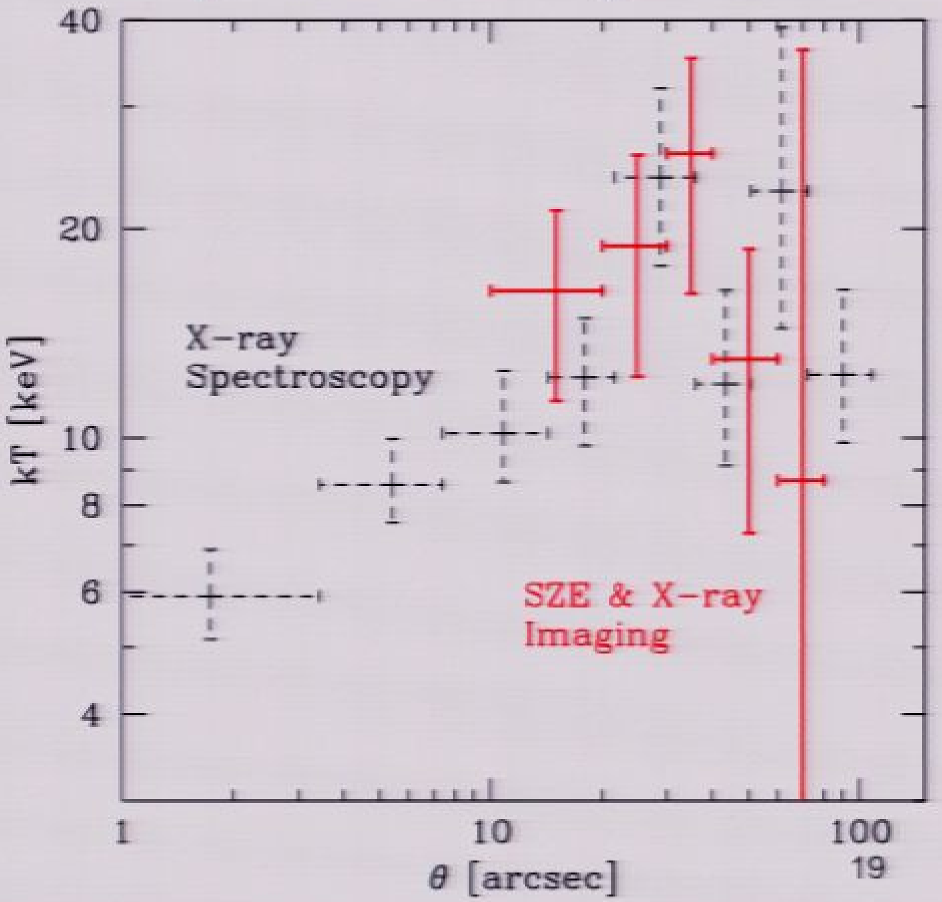


- The Chandra data also show the clear excess at ~20”.

*Kitayama et al. (2004)*

# Temperature Deprojection (Ambient Component)

- SE quadrant is excluded.
- **Black**: the temperature profile measured from the Chandra X-ray spectroscopy.
- **Red**: the temperature profile measured from the spatially resolved SZ data + X-ray imaging, without spectroscopy.



# What is this good for?

- Spatially-resolved SZ + X-ray surface brightness observations give you the temperature profile, *without spatially-resolved spectroscopic observations.*
- A powerful way of determining the temperature profiles from high-z clusters, where you may not get enough X-ray photons to do the spatially-resolved spectroscopy!
- Why need temperature profiles? For determining accurate *hydrostatic masses*.

Kitayama et al. (2004)

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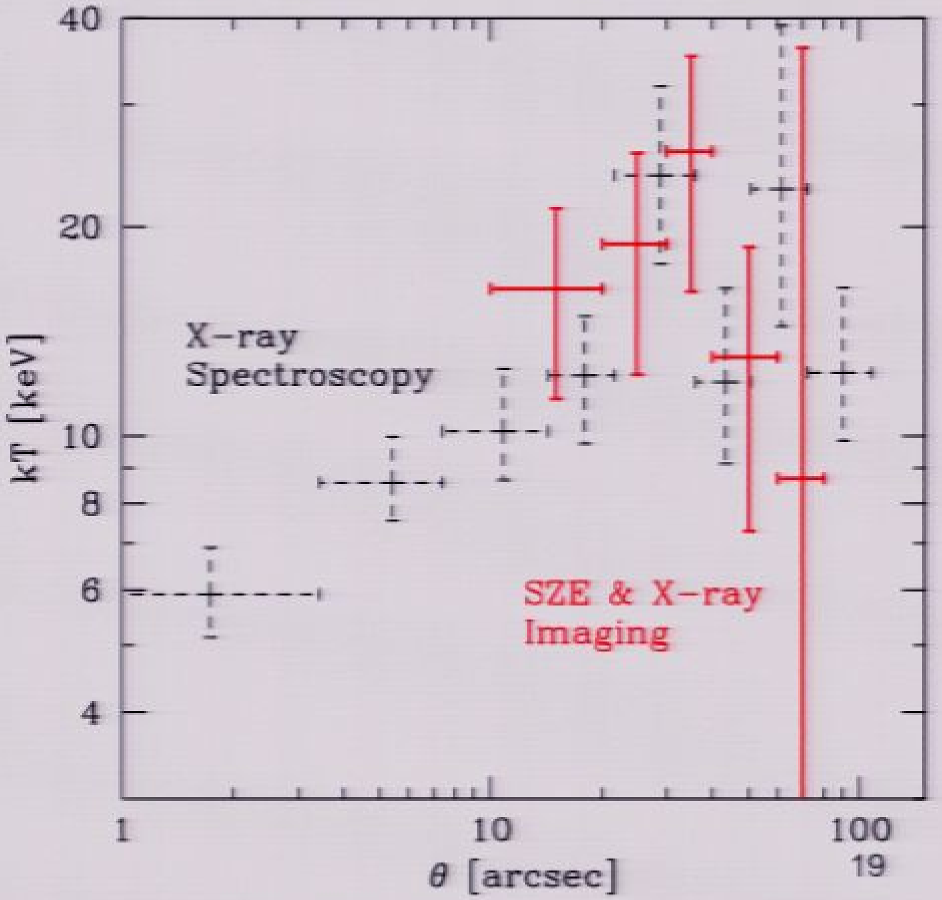

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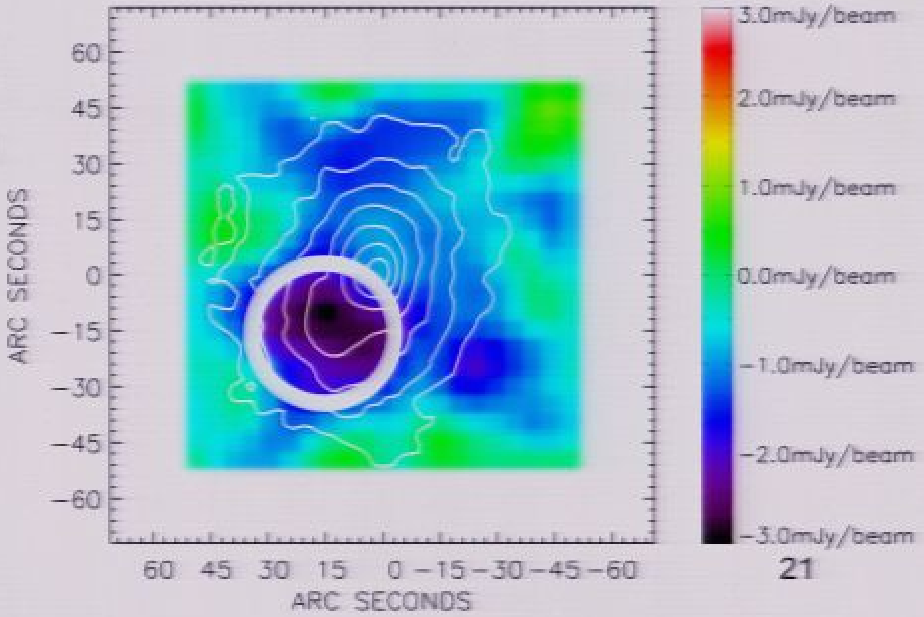
# Excess Component: Derived Parameters

- With the SZ data (150&350GHz) and the Chandra X-ray data
- $kT_{excess}$=28.5±7.3 keV
- $n_{excess}=(1.49\pm0.59)\times10^{-2}\ cm^{-3}$
- $L_{excess}$=240±183 kpc
- $y_{excess}\sim4\times10^{-4}$
- $M_{gas}\sim2\times10^{12}\ M_{sun}$



*Kitayama et al. (2004)*

# RXJ1347-1145 is a Bullet.

- A calculation of the shock (Rankine-Hugoniot condition) with:
  - pre-shock temp=$kT_1$=12.7keV; post-shock=$kT_2$=28.5keV
  - pre-shock density=$\rho_1$=free; post-shock=$\rho_2$=0.015 cm$^{-3}$
  - gamma=5/3

$$\frac{T_1\rho_1}{T_2\rho_2} = \frac{p_1}{p_2} = \frac{(\gamma+1)-(\gamma-1)\frac{\rho_2}{\rho_1}}{(\gamma+1)\frac{\rho_2}{\rho_1}-(\gamma-1)}$$

  - Solution: $\rho_1$~1/2.4 of the post-shock density

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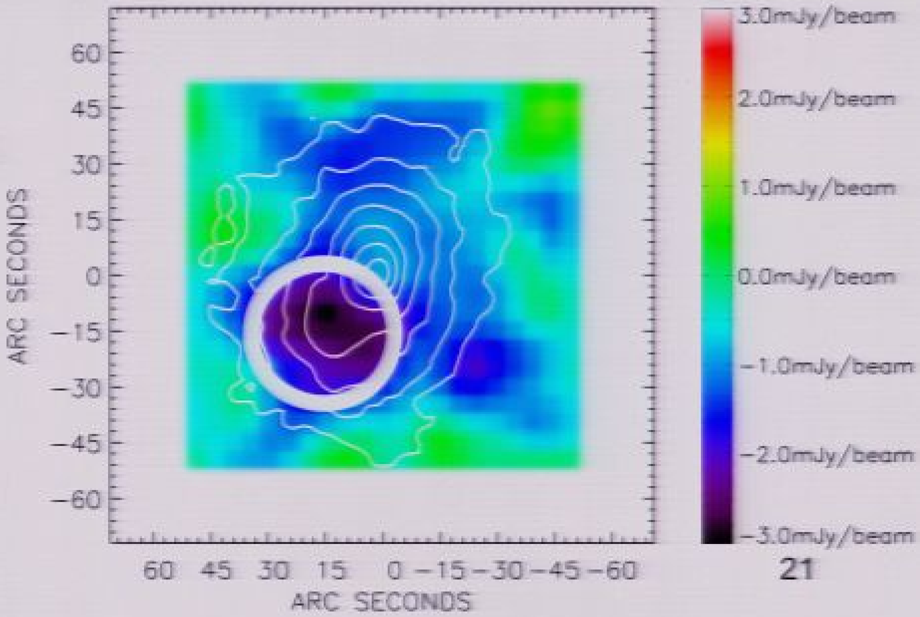

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- The Mach number of the pre-shock gas ~ 2, and the velocities of the pre-shock and post-shock gas are 3900 km/s & 1600 km/s.
    - For a head-on collision of equal mass, the collosion velocity is 4600 km/s!
- *This guy is a bullet** – just viewed from a "wrong" viewing angle.

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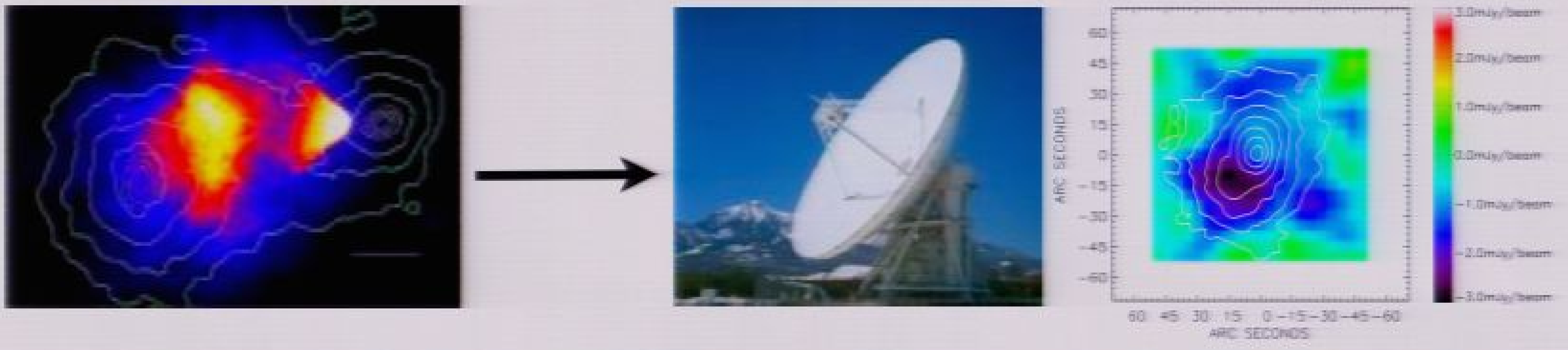


# A Big Question

- **Do you believe these results?**
- <u>**This is the only dataset**</u> for which the spatially-resolved, high-resolution SZ data were available, and used to extract the cluster physics.
- Can we get the same results using the X-ray data alone?
  - For Chandra, the answer is no: not enough sensitivity at >7keV.
  - **Suzaku can do this.**

# A Punch Line

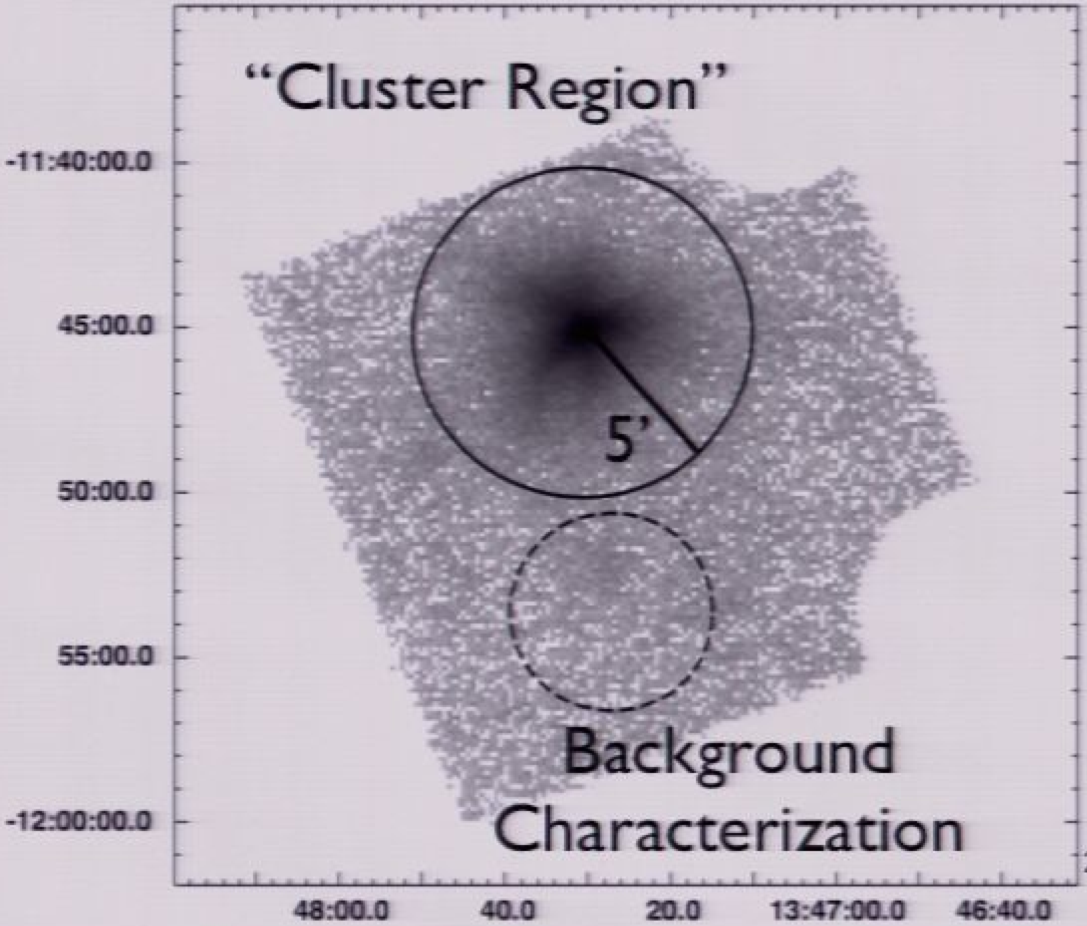
- With Suzaku's improved sensitivity at ~10 keV, we could determine the temperature of the excess component using the **X-ray data only**.
- And, the results are in an excellent agreement with the SZ+Chandra analysis.
- *Ota et al., A&A, 491, 363 (2008)*

# Suzaku Telescope

- Japan-US X-ray satellite, formally known as ASTRO-E2
- X-ray Imaging Spectrometer (XIS)
  - X-ray CCD cameras; FOV=18'x18'; Beam=2'
  - Three with 0.4–**12**keV; one with 0.2–**12**keV
  - Energy resolution~160eV at 6keV
- Hard X-ray Detector (HXD)
  - One with **10–60**keV; another with 40–600keV
  - FOV=30'x30' for 10–60keV, no imaging capability

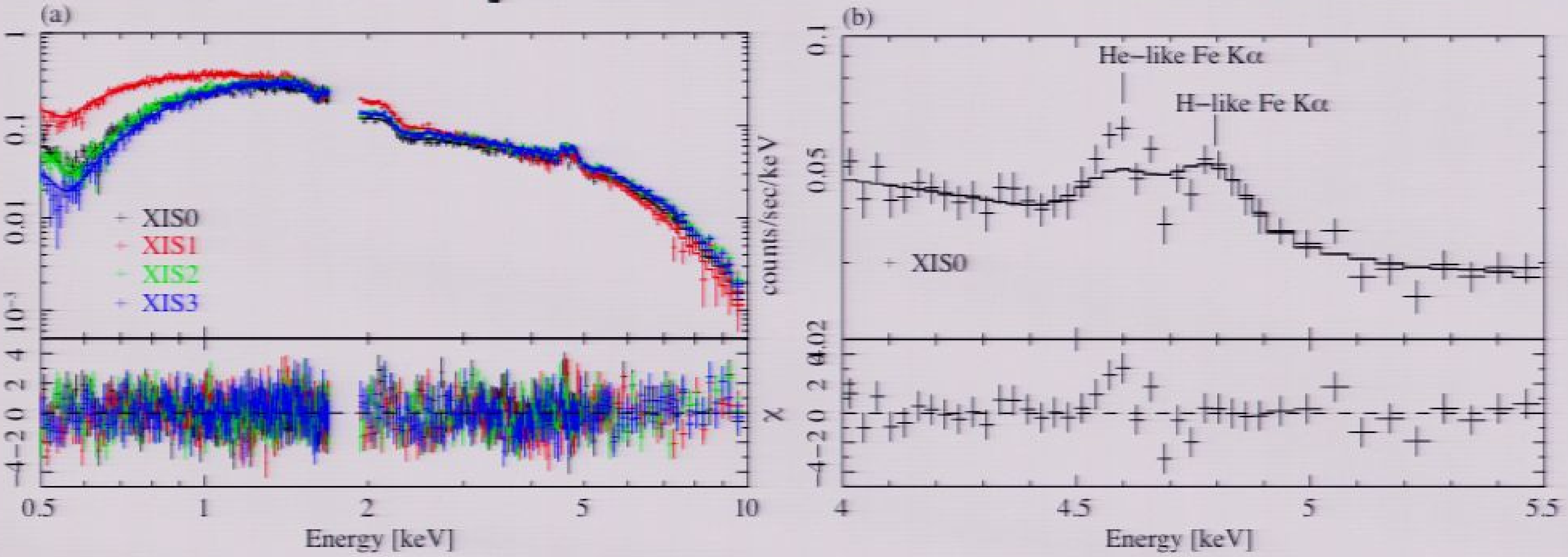
# XIS Image of RXJ1347–1145

- From one of the XIS cameras, in 0.5–10keV
- FOV=18'x18'



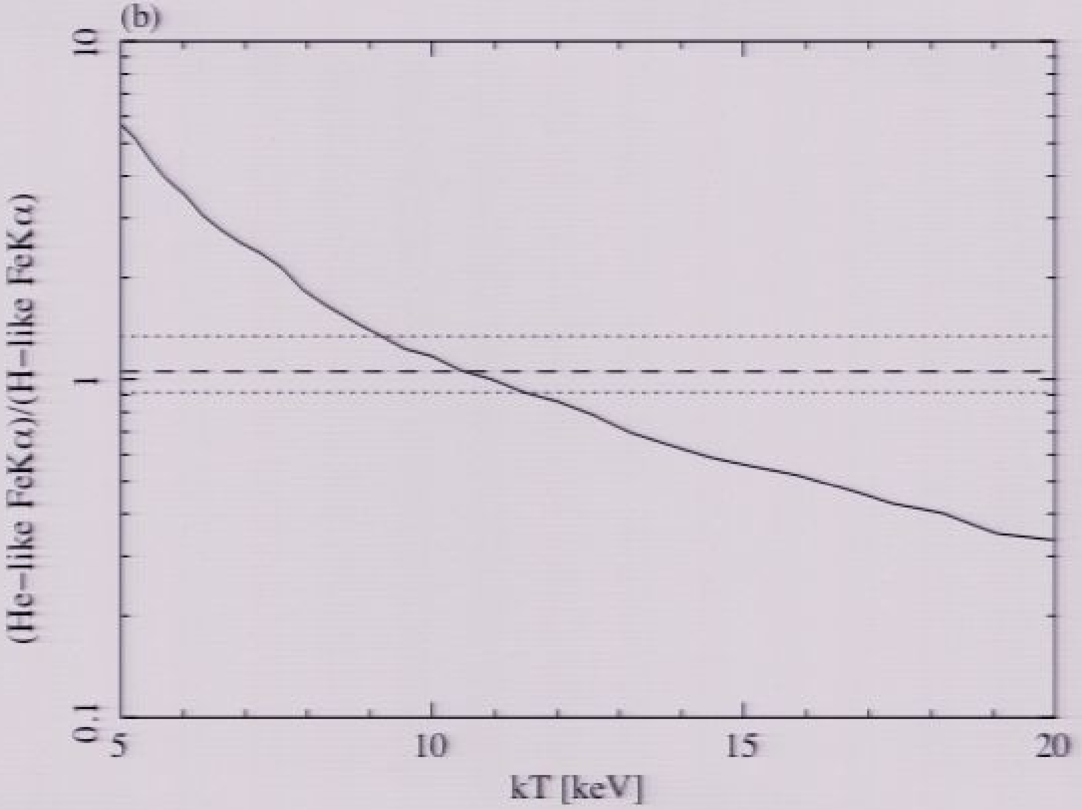
# XIS Spectra

H-like: rest frame 6.9 keV
He-like: rest frame 6.7 keV



- Single-temperature fit yields $kT_e = 12.86^{+0.08}_{-0.25}$ keV
- But, it fails to fit the Fe line ratios - $\chi^2 = 1320/1198$
  - The single-temperature model is rejected at 99.3% CL

# Temperature From Line Ratio

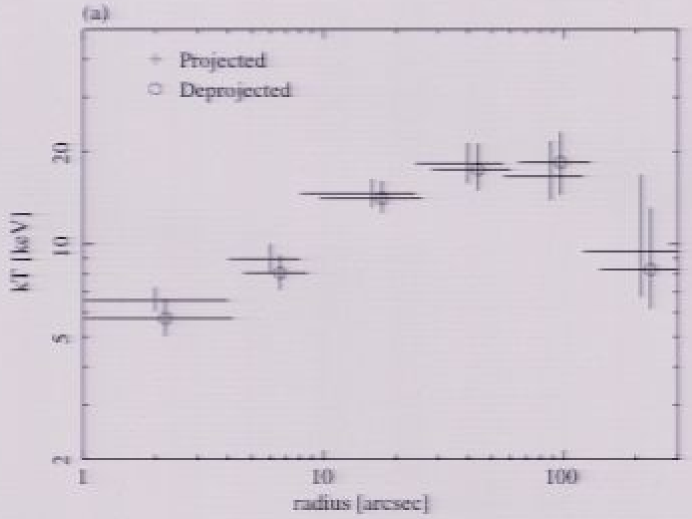


- $kT_e=10.4^{+1.0}_{-1.3}$ keV - significantly cooler than the single-temperature fit, $12.86^{+0.08}_{-0.25}$ keV.

# More Detailed Modeling

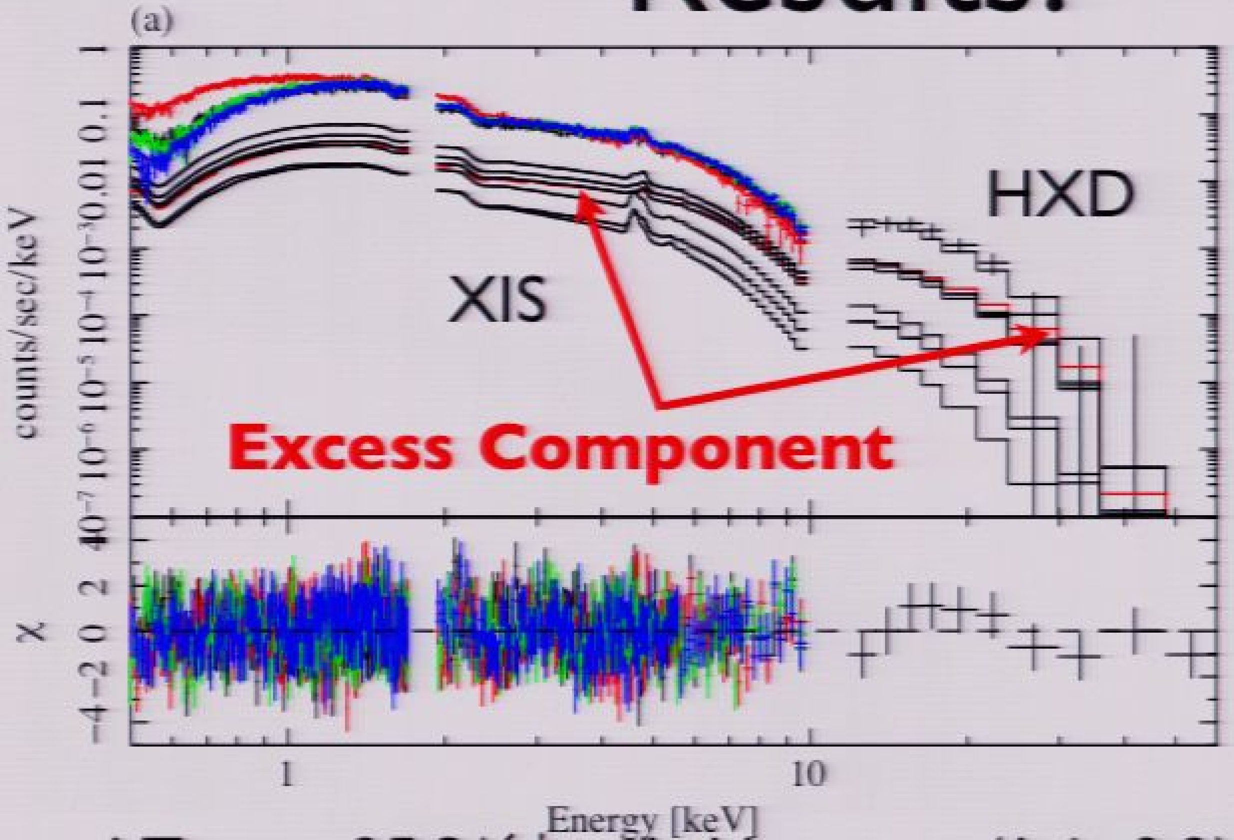
- We tried the next-simplest model: two-temperature model, but it did not work very well either.
- We know why: RXJ1347-1145 is more complicated than the two-component model.
    - The second component is localized, rather than distributed over the entire cluster.
- A joint Chandra/Suzaku analysis allows us to take advantage of the Chandra's spatial resolution and Suzaku's spectroscopic sensitivity.

# “Subtract Chandra from Suzaku”



- To make a long story short:
  - We use the Chandra data outside of the excess region (SE region) to get the model for the ambient gas.
    - 6 components fit to 6 radial bins from 0” to 300”.
  - Then, subtract this ambient model from the Suzaku data.
  - Finally, fit the thermal plasma model to the residual.
  - And...

# Results!



HXD data are consistent with the thermal model; we did not find evidence for non-thermal emission.

- $kT_{excess}=25.3^{+6.1}_{-4.5}$ keV; $n_{excess}=(1.6\pm0.2)\times10^{-2}\ \mathrm{cm}^{-3}$
  - Consistent with SZ+Chandra:
    - $kT_{excess}=28.5\pm7.3$ keV, $n_{excess}=(1.49\pm0.59)\times10^{-2}\ \mathrm{cm}^{-3}$

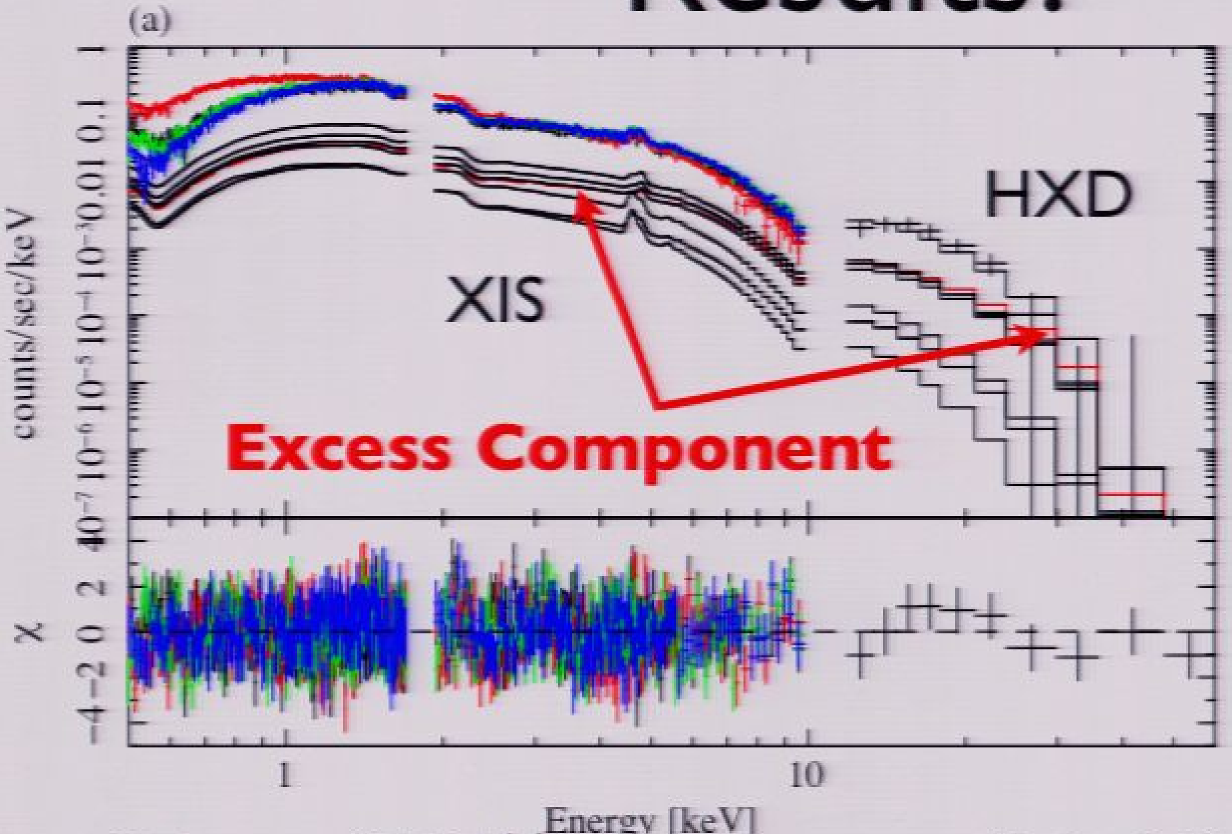
# Proof of Principle

- So, *finally*, we have a proof (and I can sleep better at night):
  - Yes, *the high-spatial resolution SZ mapping combined with the X-ray surface brightness indeed gives the correct result.*
- And, we have found a candidate for the *hottest* gas clump known so far!

# Lessons & Summary

- X-ray data may not capture (or measure) the temperature of very hot (>20 keV) components, if their band is limited to <10 keV.
- SZ is sensitive to arbitrarily high temperatures, which makes it *an ideal probe of violent cluster mergers.*
- As an added bonus, it should allow us to determine temperature profiles, hence masses, of clusters in a high-redshift universe, where X-ray spectroscopic observations are difficult.

# Results!



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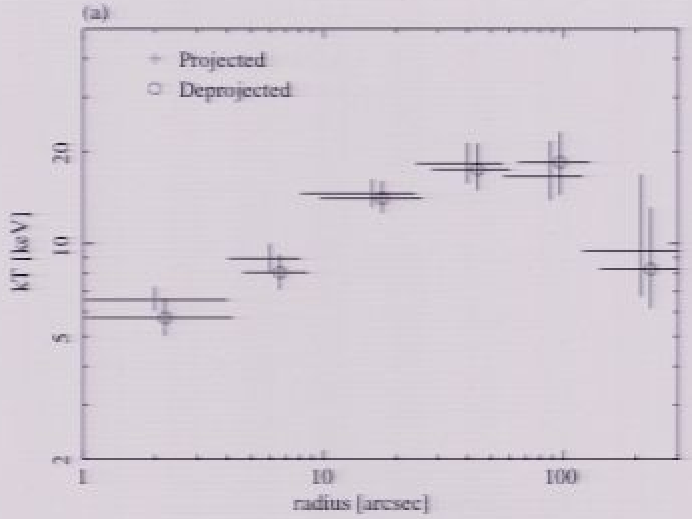

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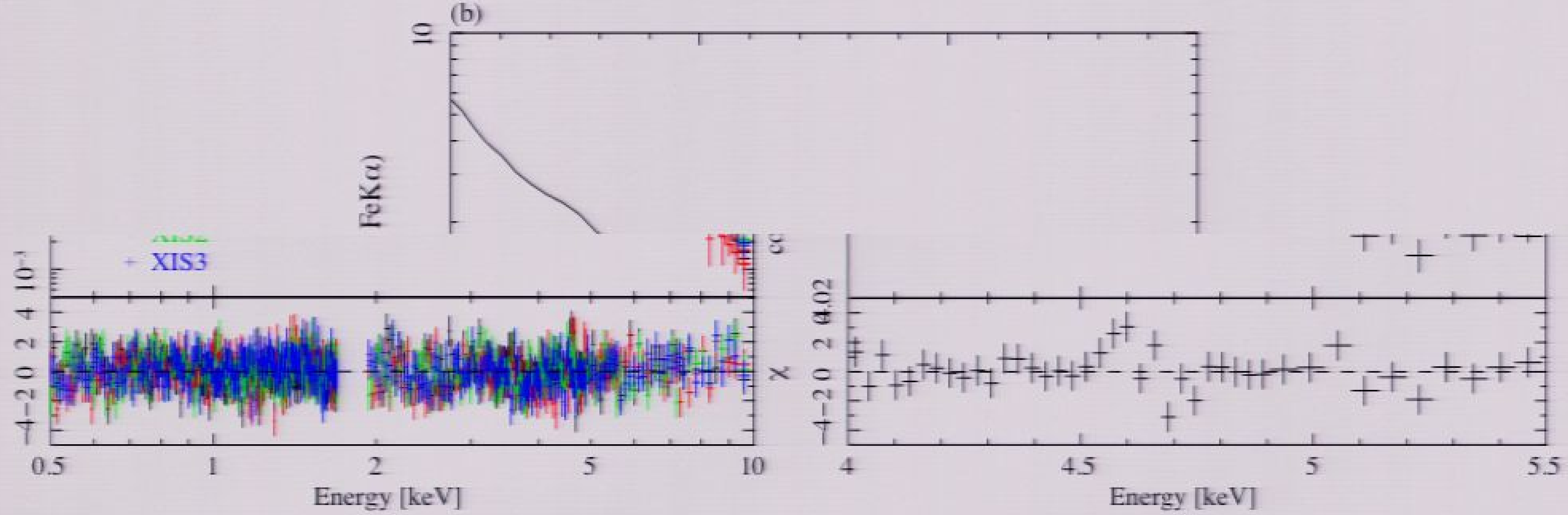

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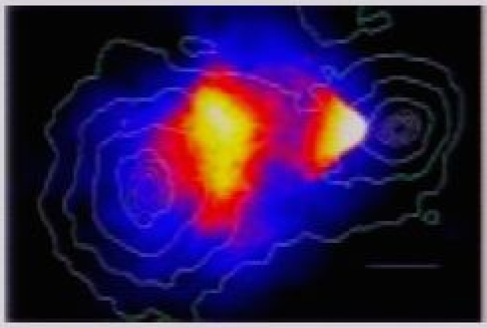
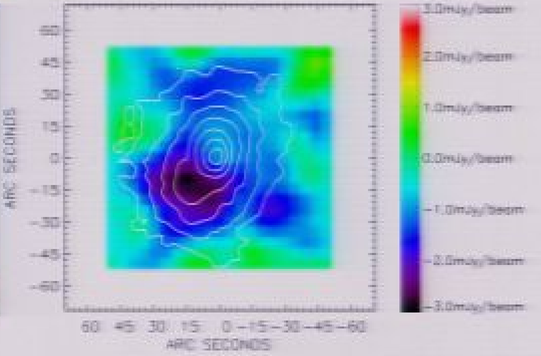
- *This guy is a bullet** – just viewed from a "wrong" viewing angle.

*Bullet Cluster has 4700km/s (Randall et al. 2008)

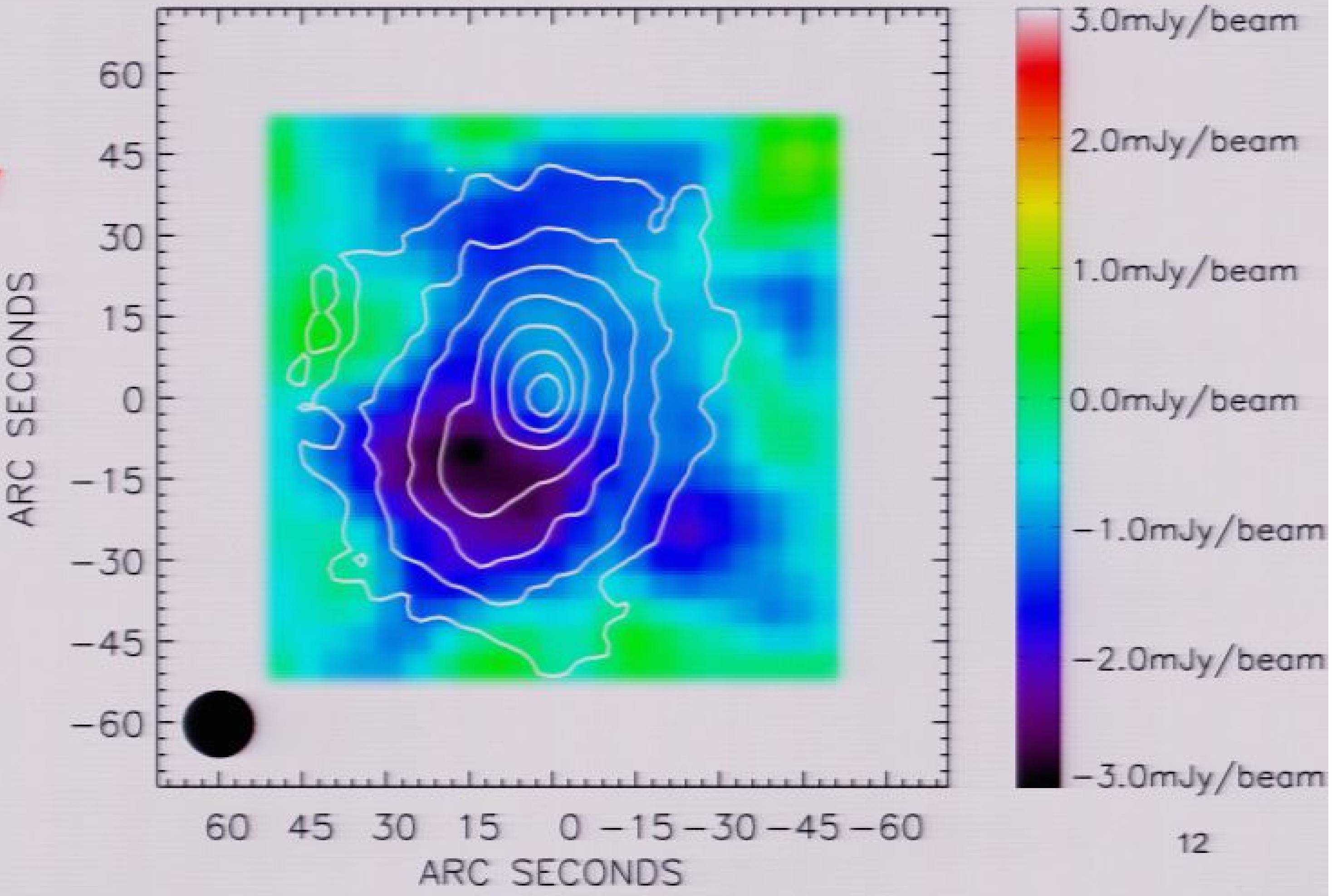




*Allen et al. (2002); Kitayama et al. (2004)*

# Confirmed by Chandra

- Allen et al. (2002) estimated ~18 keV toward this direction from Chandra spectroscopy.
- But, Chandra is sensitive only up to ~7keV...



# Target: Bright, Massive, and Compact

- RXJ1347–1145
- $z$=0.451 (10"=59 kpc)
- $L_{X,bol}$~$2\times10^{46}$ erg/s
- $M_{tot}$(<2Mpc)~$1\times10^{15}M_{sun}$
- Cluster Mean $T_X$~13keV
- $\theta_{core}$~8 arcsec (47 kpc)
- $y$~$8\times10^{-4}$