Unveiling the composition of plasma bubbles with the SZ-effect

"The SZ Effect and ALMA"

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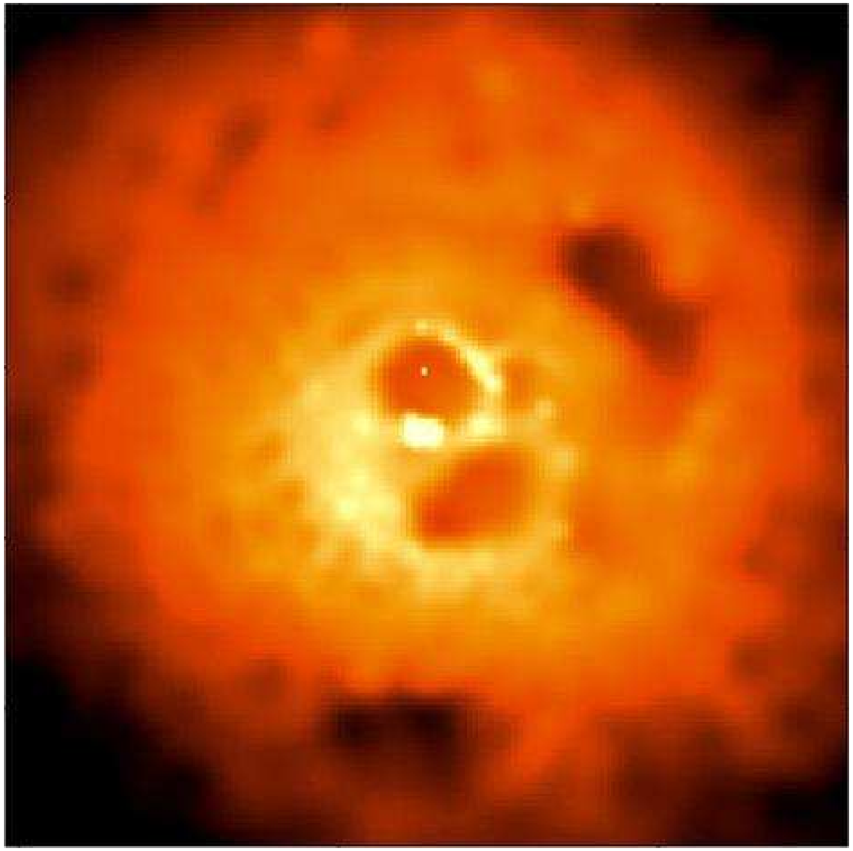
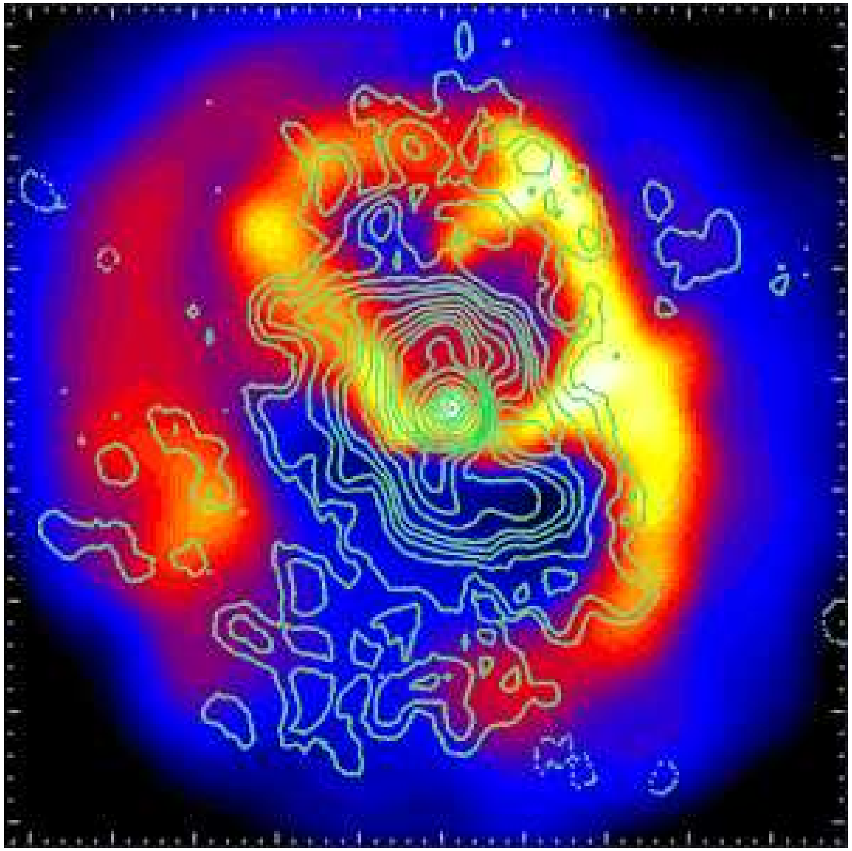
Plasma bubbles (1)



Perseus cluster

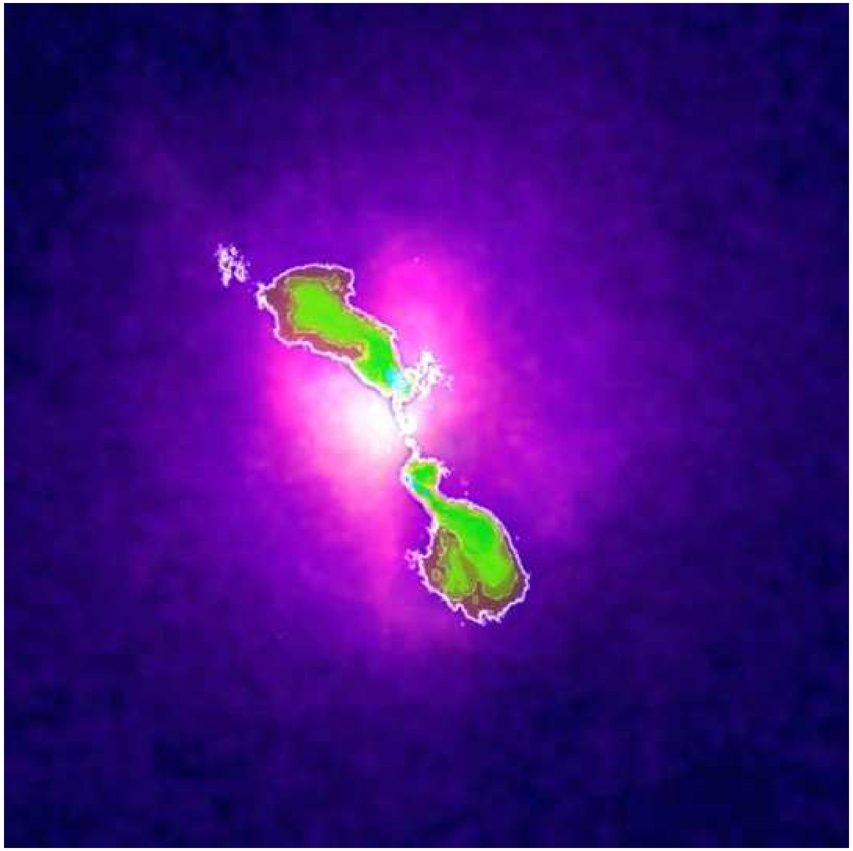
(NASA/IoA/A.Fabian et al.)

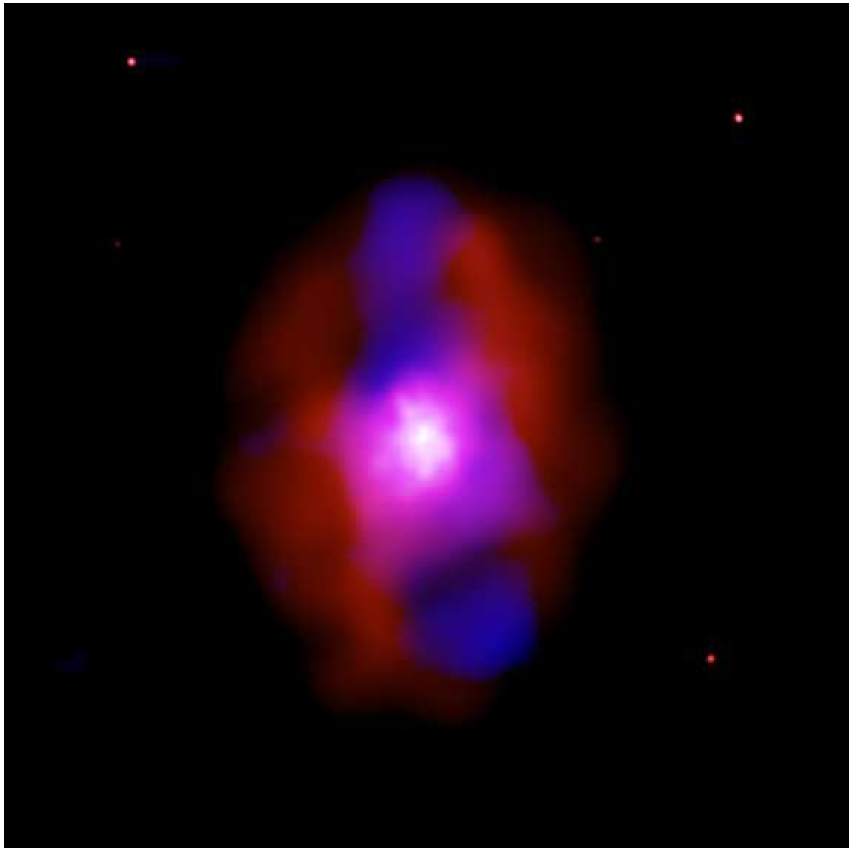


Abell 2052

(Blanton et al., 2001)

Plasma bubbles (2)





Hydra A cluster

(X-ray: NASA/CXC/SAO; Radio: NRAO)

MS 0735 cluster

(X-ray: NASA/CXC/Ohio U./
B.McNamara et al.; Radio: NRAO/VLA)

Why caring about plasma bubbles?

- minimum energy arguments show: $\varepsilon_{\mathrm{CRe}} \simeq 0.1\varepsilon_{\mathrm{th}}$
  $\longrightarrow$ where is the 'missing' pressure?
- radio plasma bubbles $\leftrightarrow$ ghost cavity transition:
  1. is there an influence on the dynamically dominant component?
  2. inferring the magnetic field configuration, cross field diffusivity
- composition of AGN jets: hadronic $\leftrightarrow$ leptonic scenario
- plasma bubble - cool core connection:
  cooling core cluster experienced only moderate accretion over the last Gyr (no major merger), cooling gas 'triggered' AGN activity

$\longrightarrow$ detailed physical understanding of governing processes

This work: C.P., Torsten Enßlin, & Craig Sarazin, 2005, A&A, 430, 799

Idea

Disadvantages of bubble X-ray observations: $L_{\mathrm{X}} \propto n_{\mathrm{e}}^2 \sqrt{kT_{\mathrm{e}}}$

- hot dilute gas does barely contribute to X-ray luminosity
- projected foreground and background emission contaminates weak signal
- projected substructure in outer regions could mock signal

Advantages of bubble SZ observations:

$$y \propto \int n_{\mathrm{e}} kT_{\mathrm{e}} \mathrm{d}l = \int P_{\mathrm{e}} \mathrm{d}l$$

- SZ effect measures directly the ‘missing’ quantity pressure
- possibility of bubble detections in outer cluster regions

SZ effect (1)

Planckian distribution function of the CMB $I(x)$:

$$I(x) = i_0 i(x) = \frac{2(kT_{\mathrm{CMB}})^3}{(hc)^2} \frac{x^3}{\mathrm{e}^x - 1},$$

The relative change $\delta i(x)$ in flux density as a function of dimensionless frequency $x = h\nu/(kT_{\mathrm{CMB}})$ for a line-of-sight through a galaxy cluster is given by

$$\delta i(x) = g(x)\, y_{\mathrm{gas}} - h(x)\, w_{\mathrm{gas}} + [j(x) - i(x)]\, \tau_{\mathrm{rel}}$$

thermal SZ effect

relativistic SZ effect

kinetic SZ effect

SZ effect (2)

- Amplitude of the thermal SZ effect:

$$y_{\mathrm{gas}} \equiv \frac{\sigma_{\mathrm{T}}}{m_{\mathrm{e}} c^2} \int \mathrm{d}l \, n_{\mathrm{e,gas}} \, kT_{\mathrm{e}}$$

- Amplitude of the kinetic SZ effect:

$$w_{\mathrm{gas}} \equiv \bar{\beta}_{\mathrm{gas}} \, \tau_{\mathrm{gas}} = \sigma_{\mathrm{T}} \int \mathrm{d}l \, n_{\mathrm{e,gas}} \, \bar{\beta}_{\mathrm{gas}},$$

- Amplitude of the relativistic SZ effect:

$$\tau_{\mathrm{rel}} = \sigma_{\mathrm{T}} \int \mathrm{d}l \, n_{\mathrm{e,rel}}.$$

Using the formalism of Enßlin & Kaiser (2000).

Relativistic SZ effect

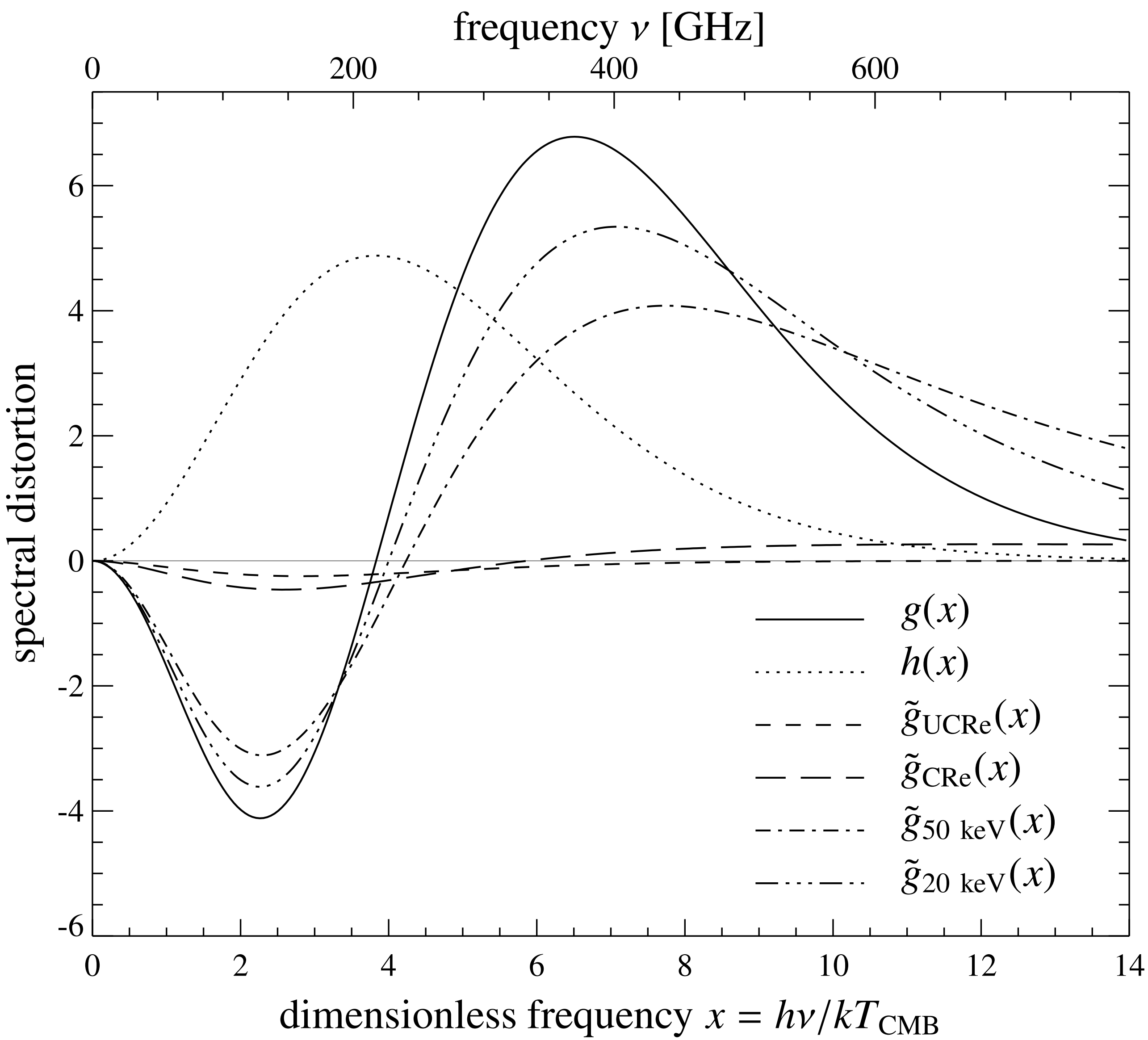
We introduce a relativistic Comptonization parameter $\tilde{y}$:

$$\delta i_{\rm rel}(x) = [j(x) - i(x)]\tau_{\rm rel} = \tilde{g}(x)\tilde{y},$$

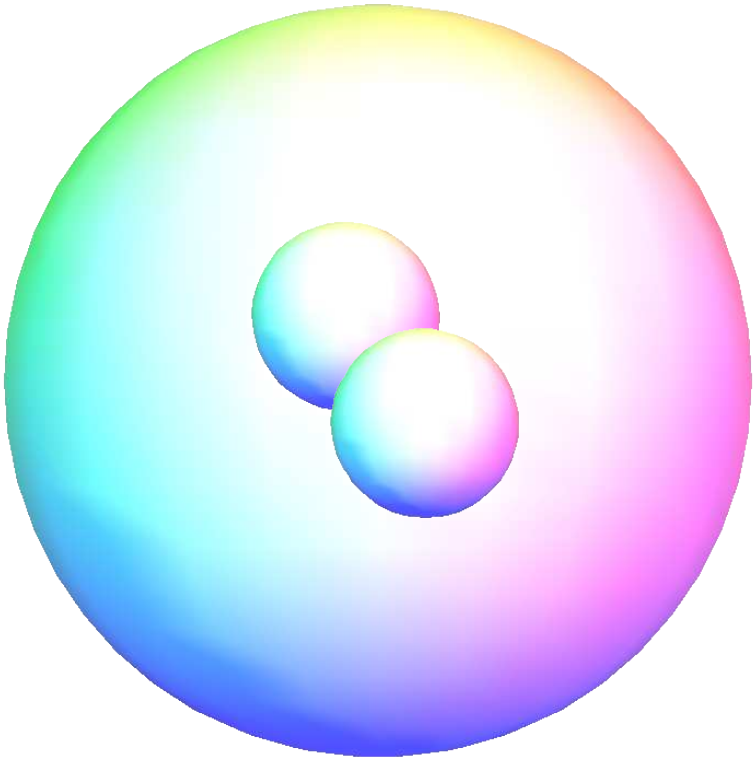
where

$$\begin{aligned}
\tilde{y} &= \frac{\sigma_{\rm T}}{m_{\rm e}c^2}\int {\rm d}l\, n_{\rm e}\, k\tilde{T}_{\rm e}\,, \\
k\tilde{T}_{\rm e} &= \frac{P_{\rm e}}{n_{\rm e}}\,, \\
\tilde{g}(x) &= [j(x) - i(x)]\,\tilde{\beta}(k\tilde{T}_{\rm e})\,, \\
\tilde{\beta}(k\tilde{T}_{\rm e}) &= \frac{m_{\rm e}c^2}{\langle k\tilde{T}_{\rm e}\rangle} = \frac{m_{\rm e}c^2\int {\rm d}l\, n_{\rm e}}{\int {\rm d}l\, n_{\rm e} k\tilde{T}_{\rm e}}\,.
\end{aligned}$$

Spectral distortions



Bubble model: visual



Pressure of the cooling core cluster is described by a multiple β-model, radio plasma bubbles are spheres cutting out the thermal pressure.

Bubble model: mathematical

- Unperturbed line-of-sight (not intersecting the bubble), the observed thermal Comptonization parameter reads

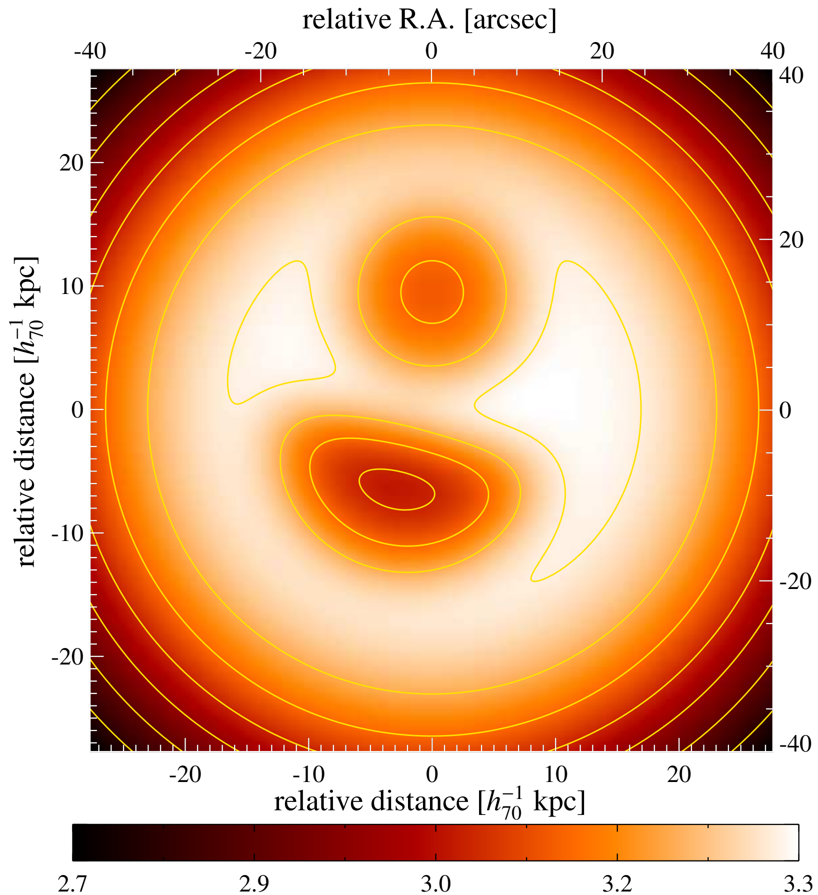
$$y_{\rm cl}(x_1,x_2)=\sum_{i=1}^{N} y_i\left(1+\frac{x_1^2+x_2^2}{r_{y,i}^2}\right)^{-(3\beta_{y,i}-1)/2}$$

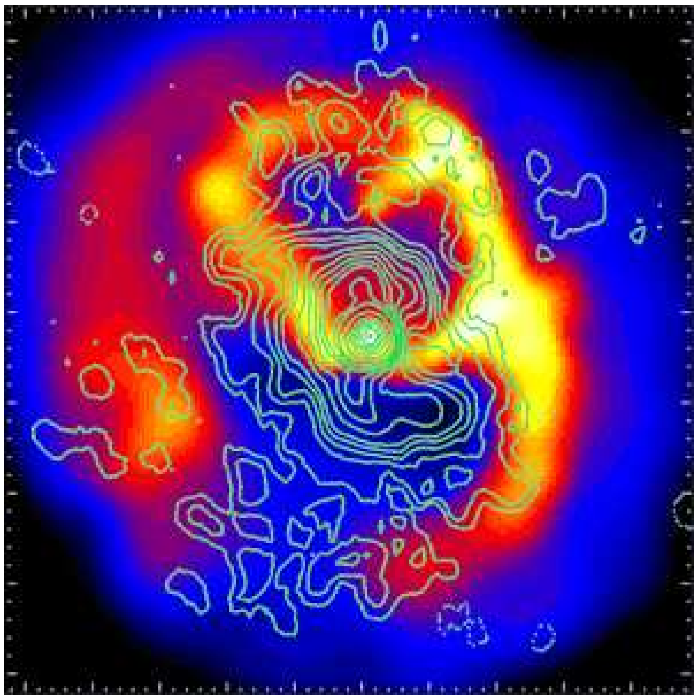
where $y_i=\sigma_{\rm T}(m_{\rm e}c^2)^{-1}P_i r_{y,i}\mathcal{B}\left(\frac{3\beta_{y,i}-1}{2},\frac{1}{2}\right)$.

- In the case of a line-of-sight intersecting the surface of the bubble, the area covered by the bubble reads

$$\begin{aligned} y_{\rm b}(x_1,x_2) &= y_{\rm cl}(x_1,x_2)-\sum_{i=1}^{N} y_i\left(1+\frac{x_1^2+x_2^2}{r_{y,i}^2}\right)^{-(3\beta_{y,i}-1)/2} \\ &\times\left[\frac{{\rm sgn}(z)}{2}\mathcal{I}_{q_{y,i}(z)}\left(\frac{1}{2},\frac{3\beta_{y,i}-1}{2}\right)\right]_{z_-}^{z_+} \end{aligned}$$

A2052: SZE versus thermal X-rays





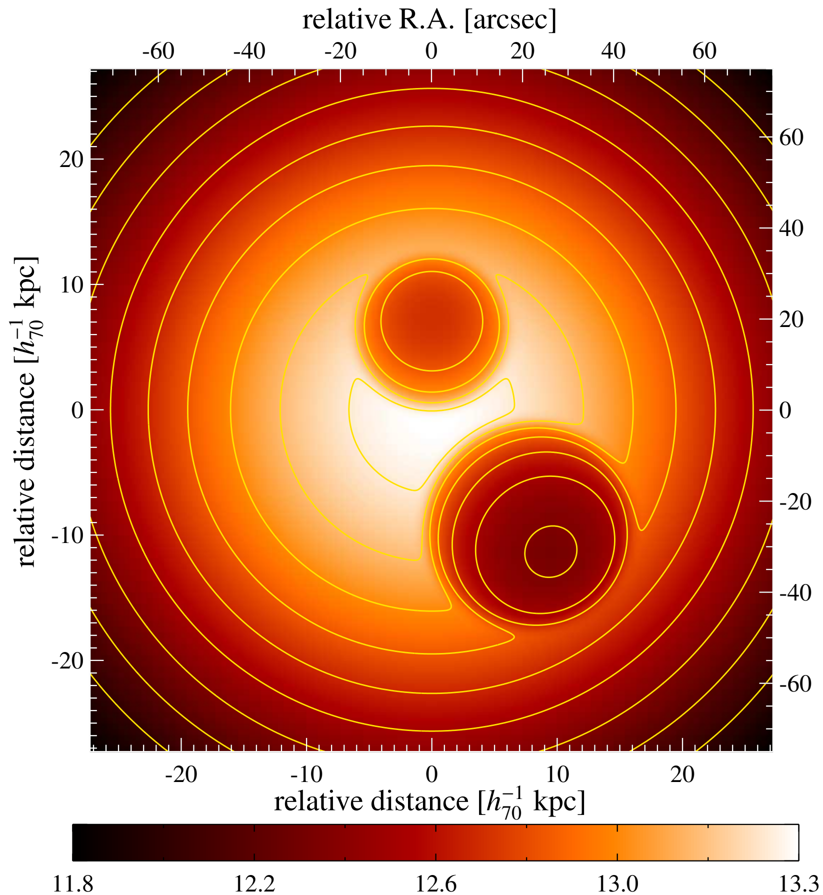
simulated GBT observation

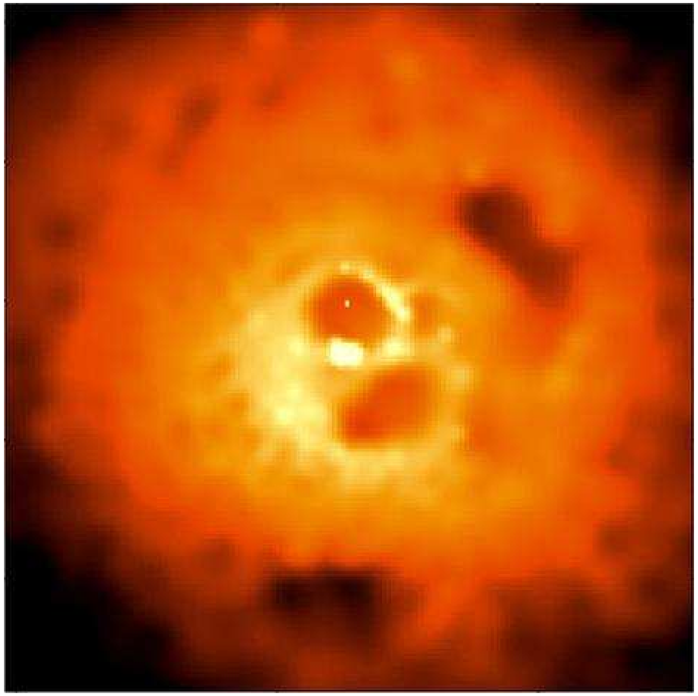
$\nu = 90$ GHz, size: $80'' \times 80''$

Chandra: $76'' \times 76''$

(Blanton et al., 2001)

Perseus: SZE versus thermal X-rays





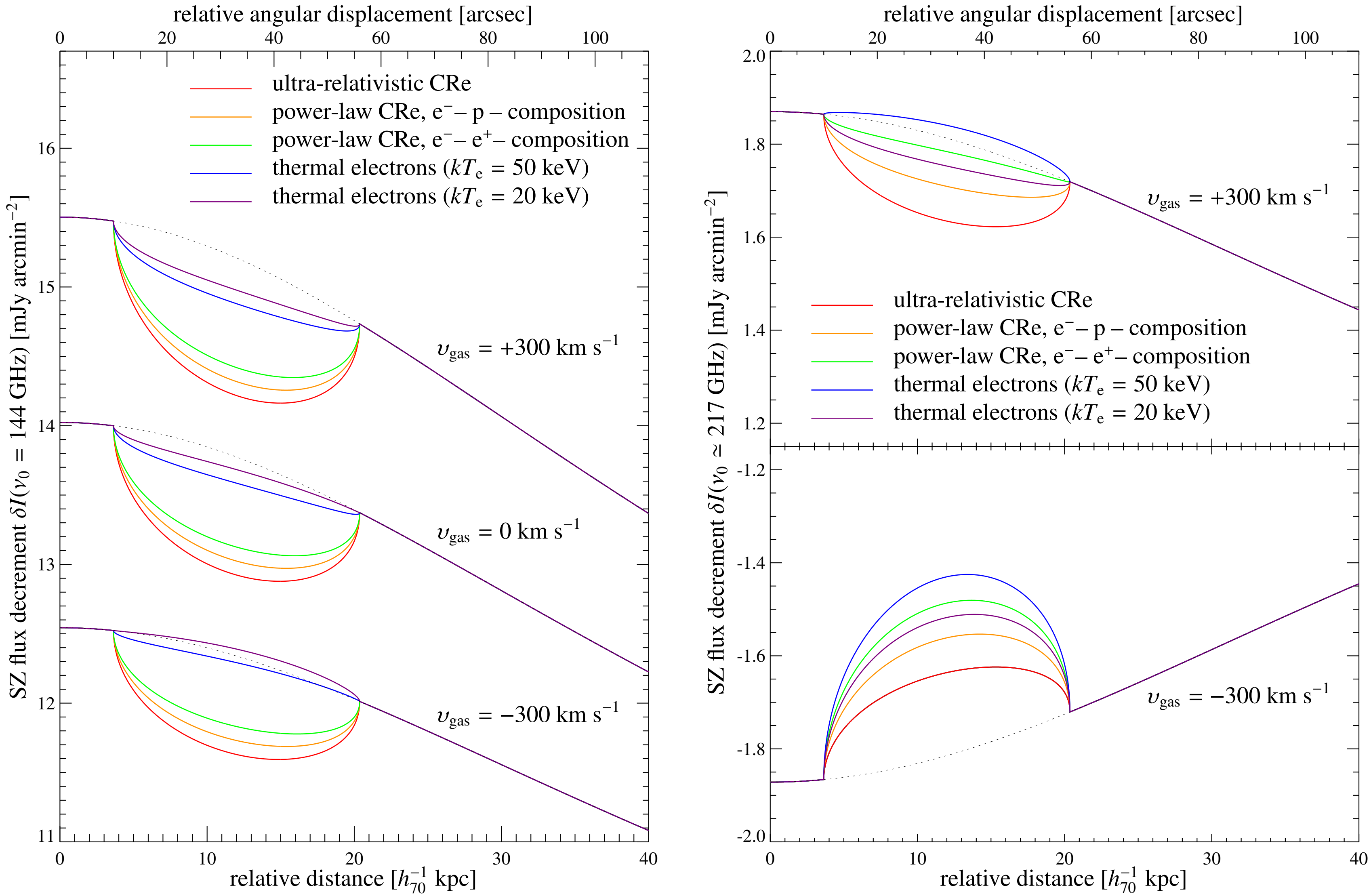
simulated ALMA observation

$\nu = 144$ GHz, size: $2.5' \times 2.5'$

Chandra: $6' \times 6'$

(NASA/IoA/A.Fabian et al.)

Unveiling the composition of bubbles



Conclusions

- SZ effect offers suitable tool for studying plasma bubble composition (SZ effect more sensitive to cluster outskirts compared to X-rays)
- Observations of SZ cavities possible for non-thermal pressure supported bubbles: Perseus $\sim$ 5 hours exposure, A2052 $\sim$ 30 hours exposure
- Detailed observations will reveal the dynamically dominant composition (relativistic electrons, protons magnetic fields, hot thermal gas)

$\longrightarrow$ Solving the cooling core riddle; indications how the heating mechanism proceeds by AGN bubbles

$\longrightarrow$ Indications for AGN jet composition (leptonic versus hadronic scenario)