Technological Requirements for a Next Generation SZ Imager

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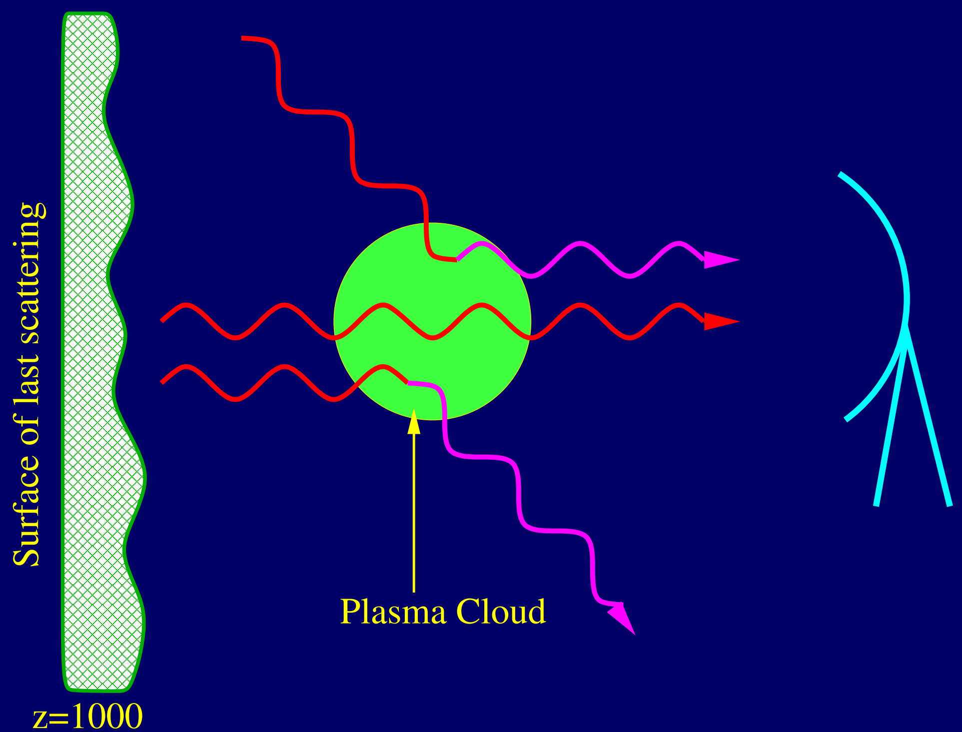
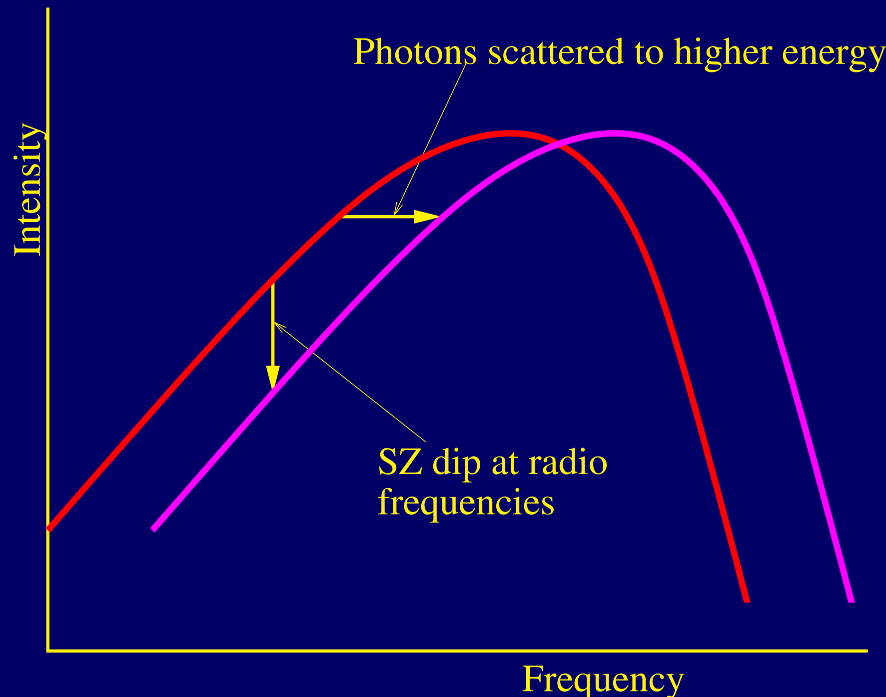
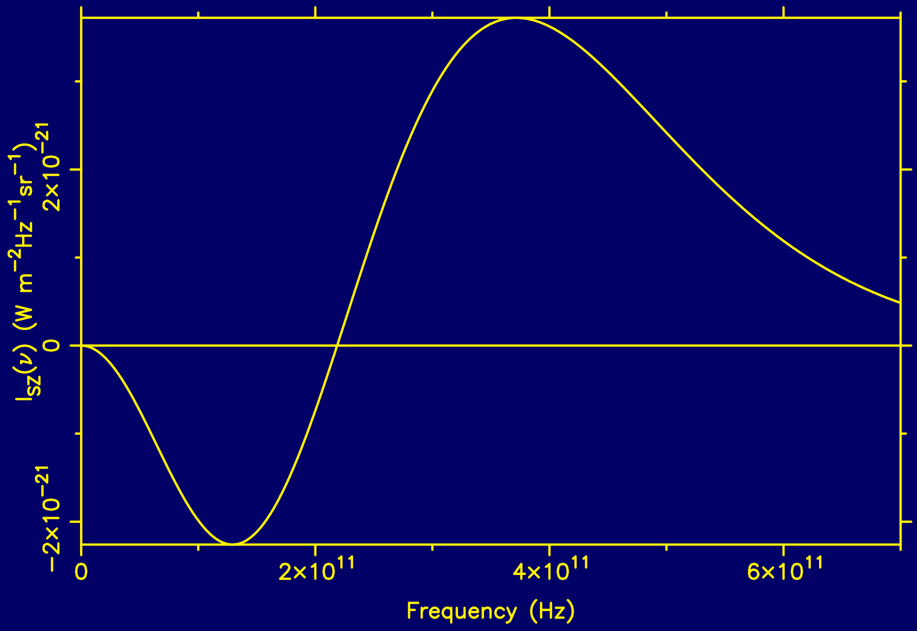
THE SUNYAEV-ZEL'DOVICH EFFECT



- Secondary anisotropy on the CMB
- Inverse Compton scattering from gas associated with galaxy clusters
- For a rich cluster:
  - $M_{\text{cluster}} \approx 10^{15} M_\odot$
  - $M_{\text{gas}} \approx M_{\text{cluster}}/10$
  - $r_{\text{vir}} \approx 1$ Mpc
  - $T_e \approx 10^8$ K $\cong$ 10 keV
  - $n_e \approx 10^4\ \text{m}^{-3}$
  - $\tau_e \approx 10^{-2}$
  - $(y \approx 2 \times 10^{-4})$
  - $(v_z \approx 1000\ \text{km s}^{-1})$

PHYSICS OF THE S-Z EFFECT





- CMB photons scattered to higher energies
- Photon number conserved
- Independent of redshift

$$\Delta I_\nu = \frac{xe^x}{(e^x-1)^2}\left(x\coth(x/2)-4\right) y B_\nu(T_0)$$

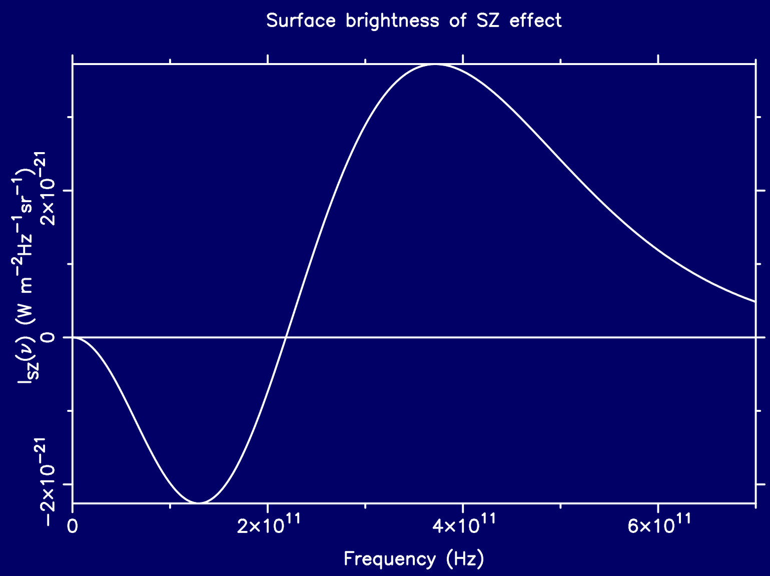
$$x = \frac{h\nu}{k_B T_0}$$

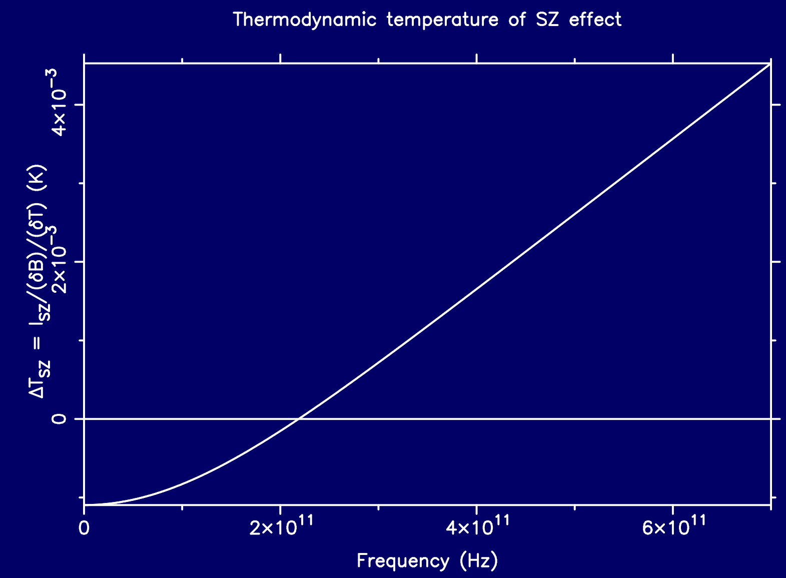
$$\theta_e = \frac{k_B T_e}{m_e c^2}$$

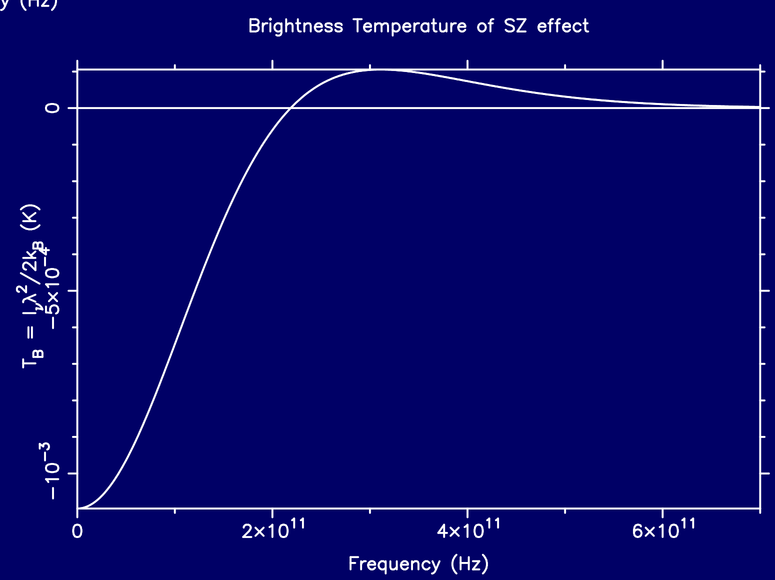
$$y = \frac{k_B \sigma_T}{m_e c^2}\int n_e T_e dl = \theta_e \tau_e$$

- In R-J region $\Delta T/T = -2y$.

THERMAL S-Z SPECTRUM

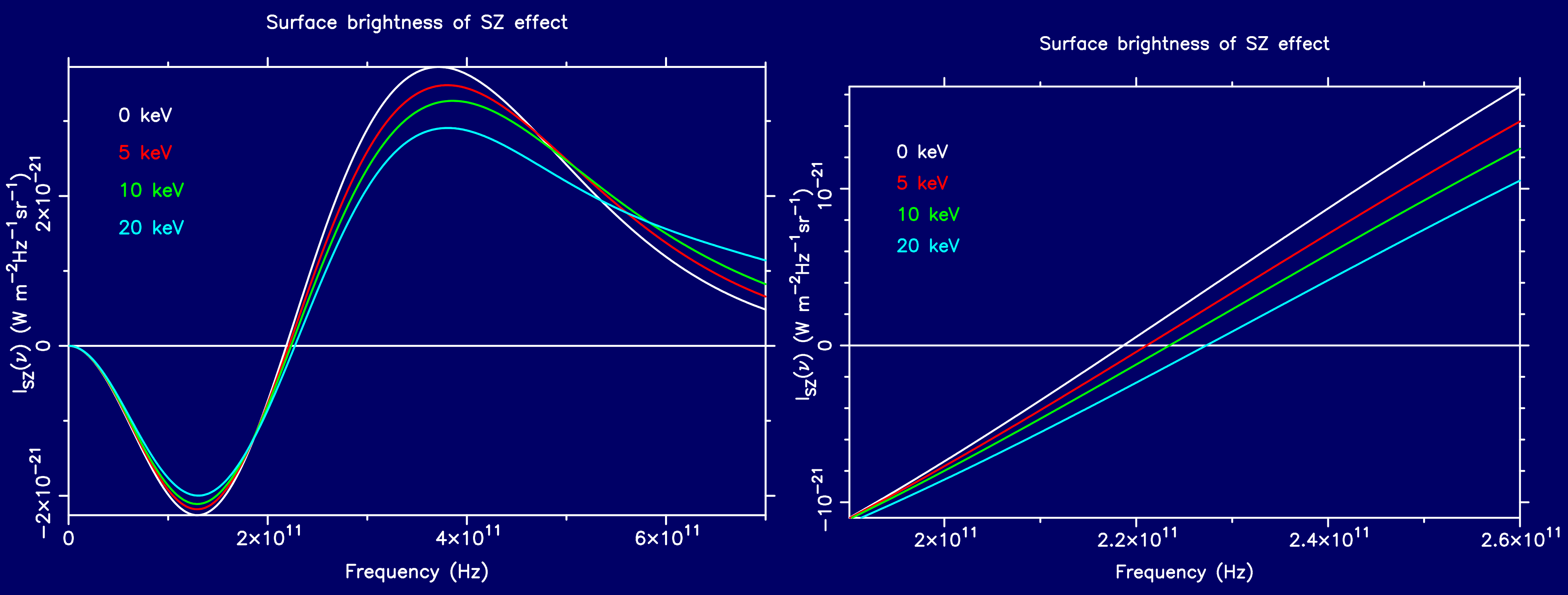






- Intensity; thermodynamic temperature; brightness temperature

Relativistic Correction to S-Z spectrum



Kinetic S-Z effect

- Essentially a Doppler shift due to motion of cluster along the line of sight.
- Photon number in direction towards observer changes, but is globally conserved.

$$\Delta I_\nu = B_\nu \tau_e \beta_z \left(\frac{x e^x}{e^x - 1} \right)$$

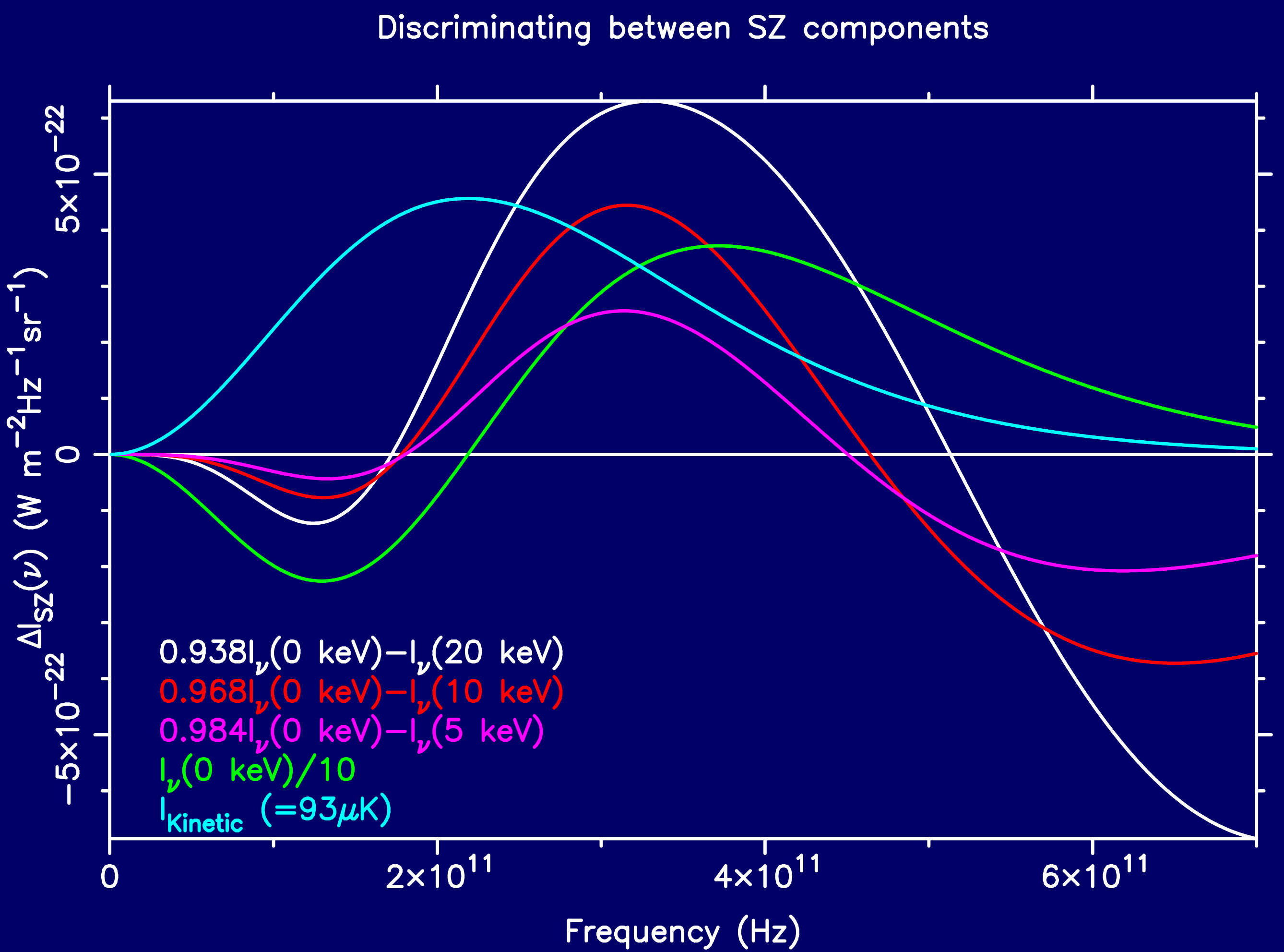
- i.e. same spectrum as a primordial fluctuation.

$$\left(\frac{\Delta T_{\mathrm{kinematic}}}{\Delta T_{\mathrm{thermal}}} \right)_{\mathrm{R-J}} = \frac{\beta_z m_e c^2}{2 k_b T_e}$$

$$\sim 0.085 (v_z / 1000\ \mathrm{km\,s^{-1}}) (k_B T_e / 10\ \mathrm{keV})^{-1}$$

- In the R-J region it is small compared to the thermal effect for a rich cluster.
- Becomes more important as you look at poor clusters/groups.

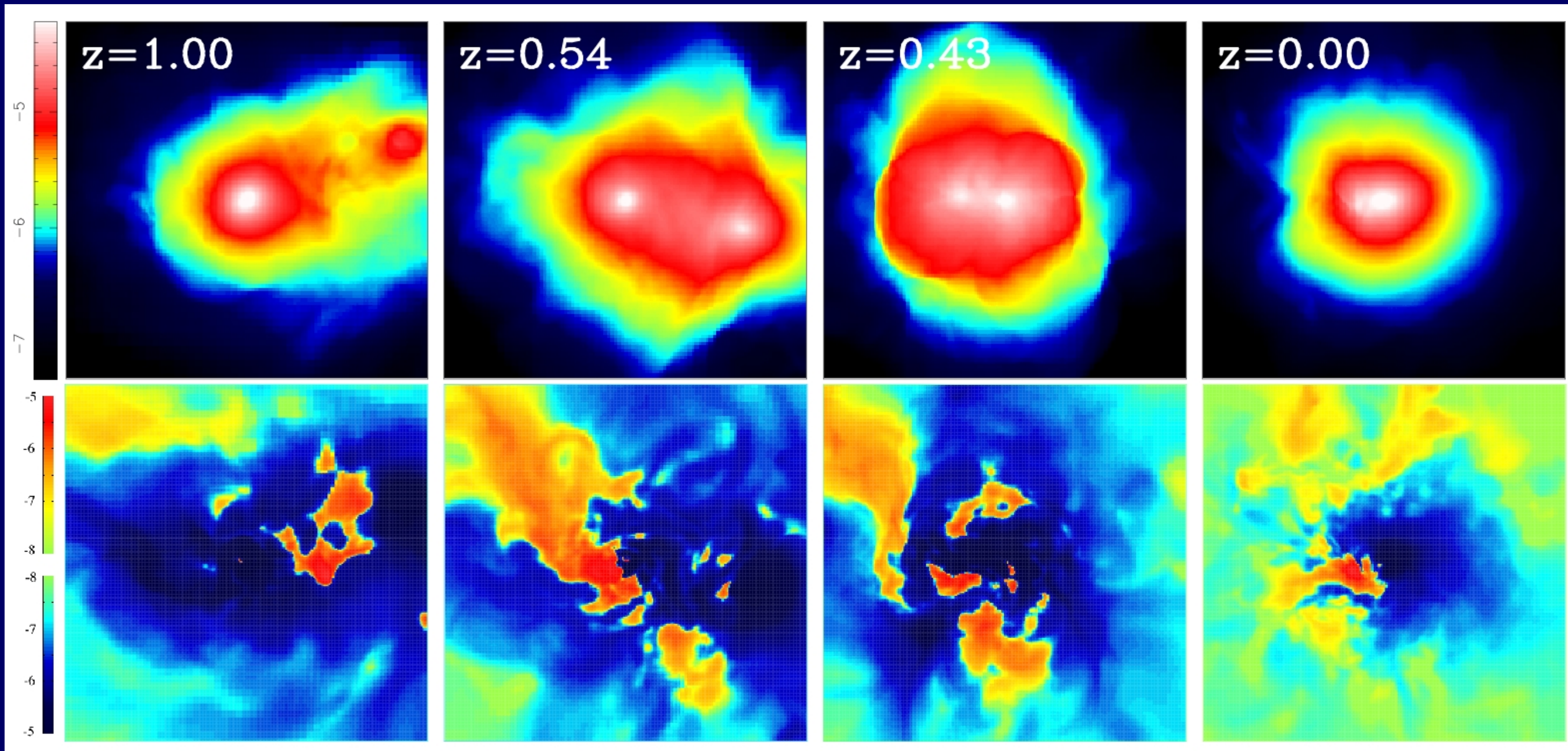
Separating S-Z Spectral Components



- Measure:
  - $\int n_e T_e dl$.

    (c.f. $\int n_e^2 f(T) dl$)
  - v_{gas}.
  - mass-weighted T_{gas}.
- NB large angular size

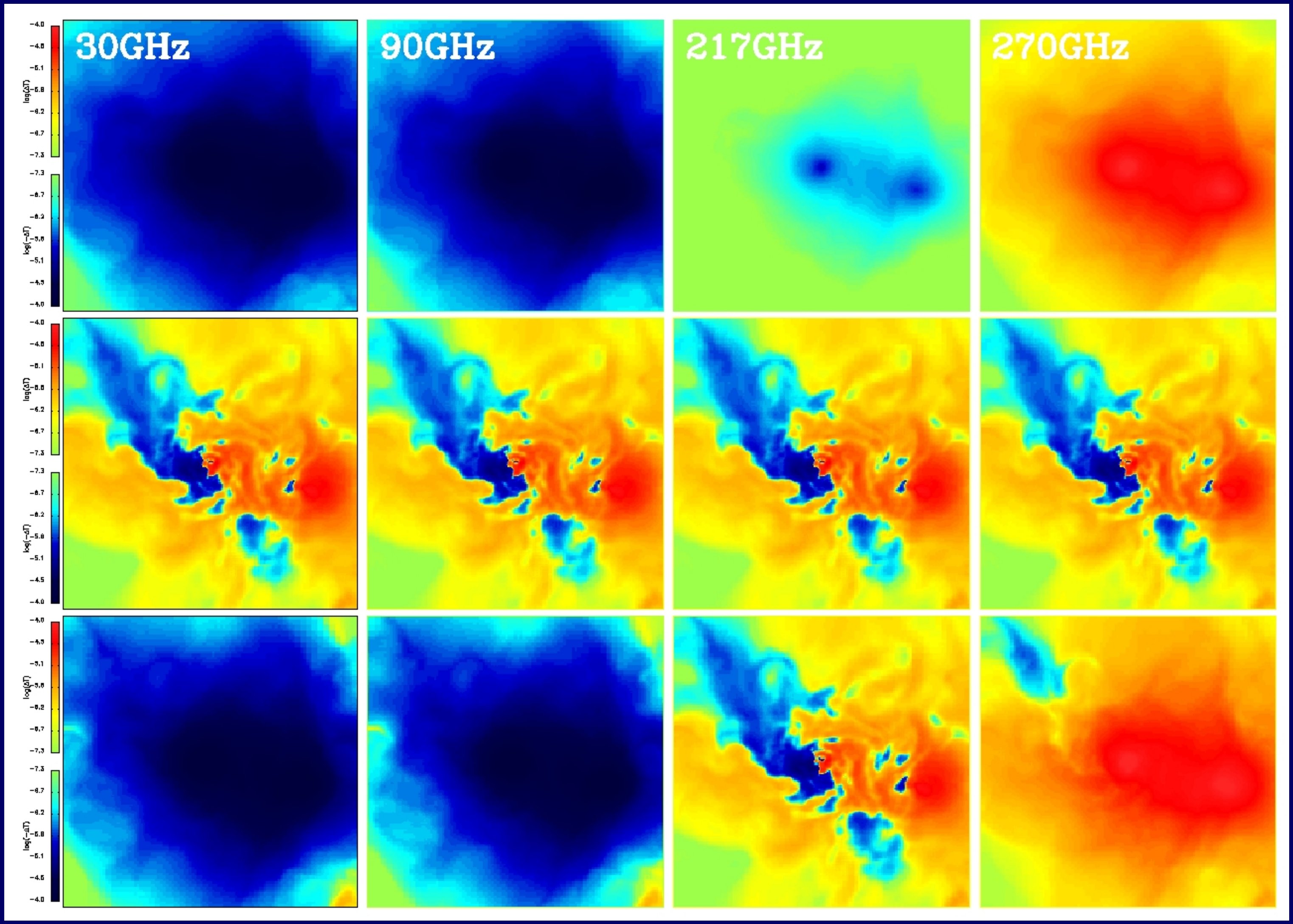
GALAXY CLUSTERS



(courtesy of Daisuke Nagai)

- Thermal (top) and kinematic (bottom) SZ effects
- $2h^{-1}$ Mpc region
- Logarithmic scale running from $\Delta T/T = 10^{-4}$

A MERGING CLUSTER



(courtesy of Daisuke Nagai)

- Thermal (top), kinematic (middle), summed (bottom) SZ effects
- $2h^{-1}$ Mpc region $\equiv$ 7.5’ at $z = 0.54$

Science from S-Z follow-up observations

- Follow up of Planck cluster catalogue ($\sim$ 2000-4000 detections).
- SPT/ACT clusters (4000 sq deg; clusters out to higher z)
- Measure $f_{gas}(z)$

— Method already used with X-rays (Allen 2008) — constrains w

— Main systematic is determining dynamical state — less important for SZ

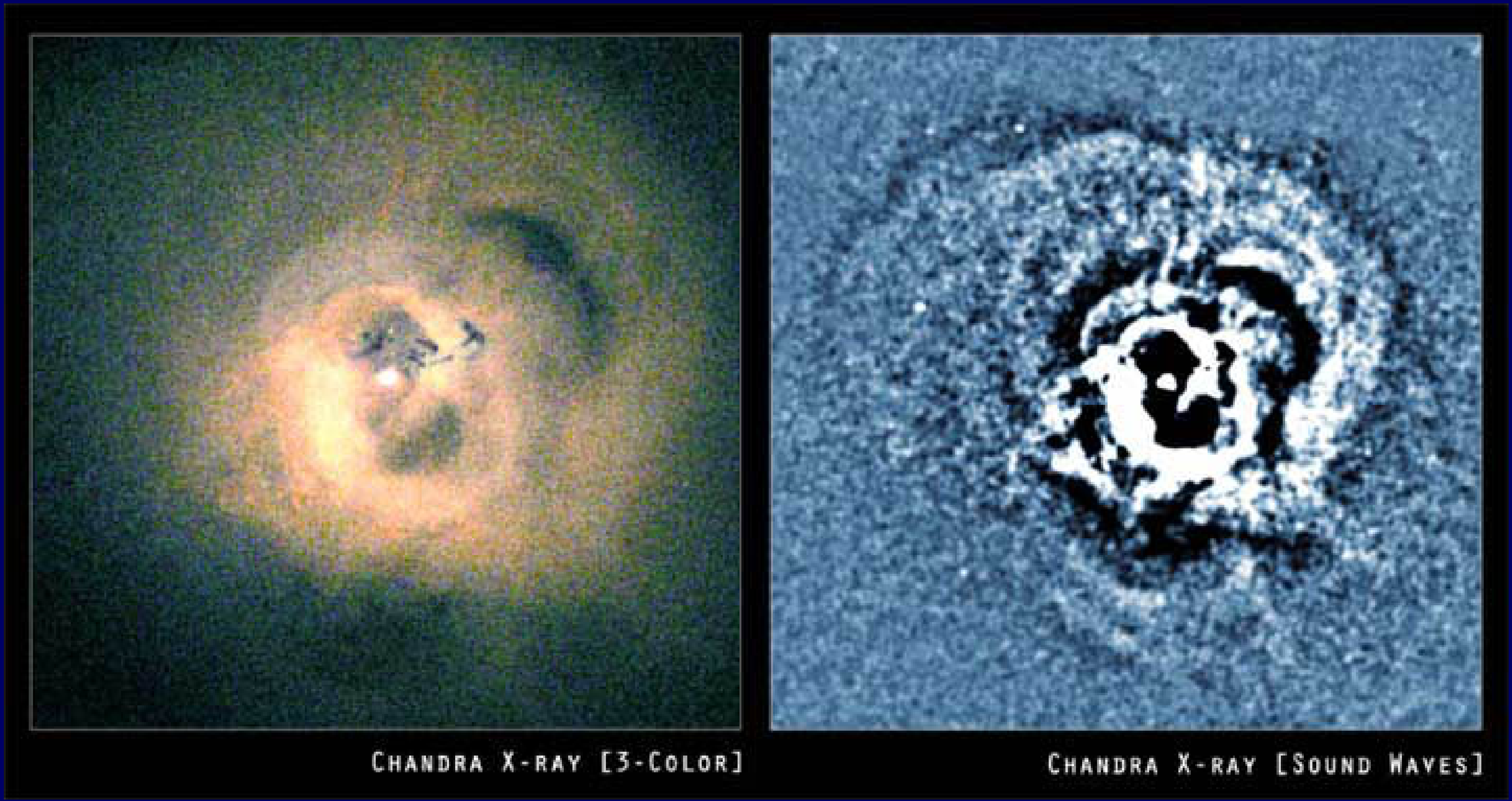
- Measure cluster peculiar velocity (e.g. Bhattacharya & Kosowsky 2008)

— Independent constraint on structure formation

— Constrains w

- Measure cluster masses — Y_X (e.g.Jeltema et al. 2007)
- Mass-weighted temperature — esp useful at high z
- Clusters interesting in their own right — investigate detailed astrophysics

SZ Science: Feedback in Clusters



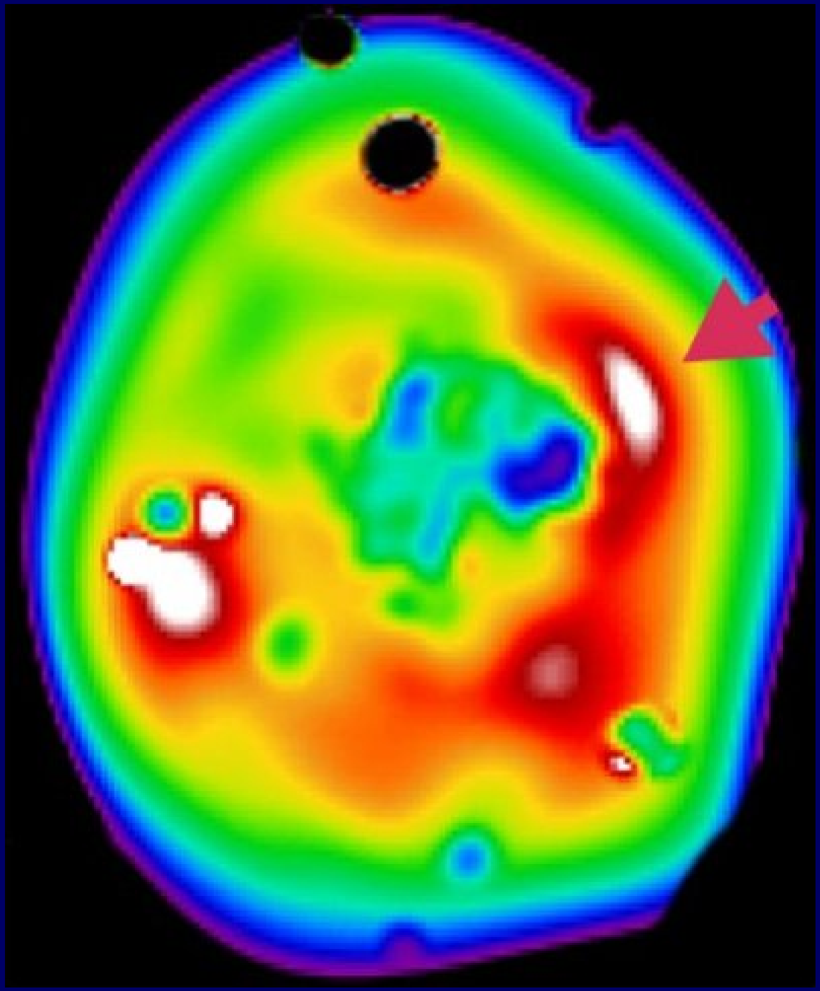
X-ray image of Perseus cluster (Fabian et al.)

- X-ray voids correlate with radio lobes.

$\Rightarrow$ Caused by bubbles of relativistic plasma from AGN.

- Bubbles rise, interrupting rapid cooling of central gas.
- Feedback process regulating cooling flows?

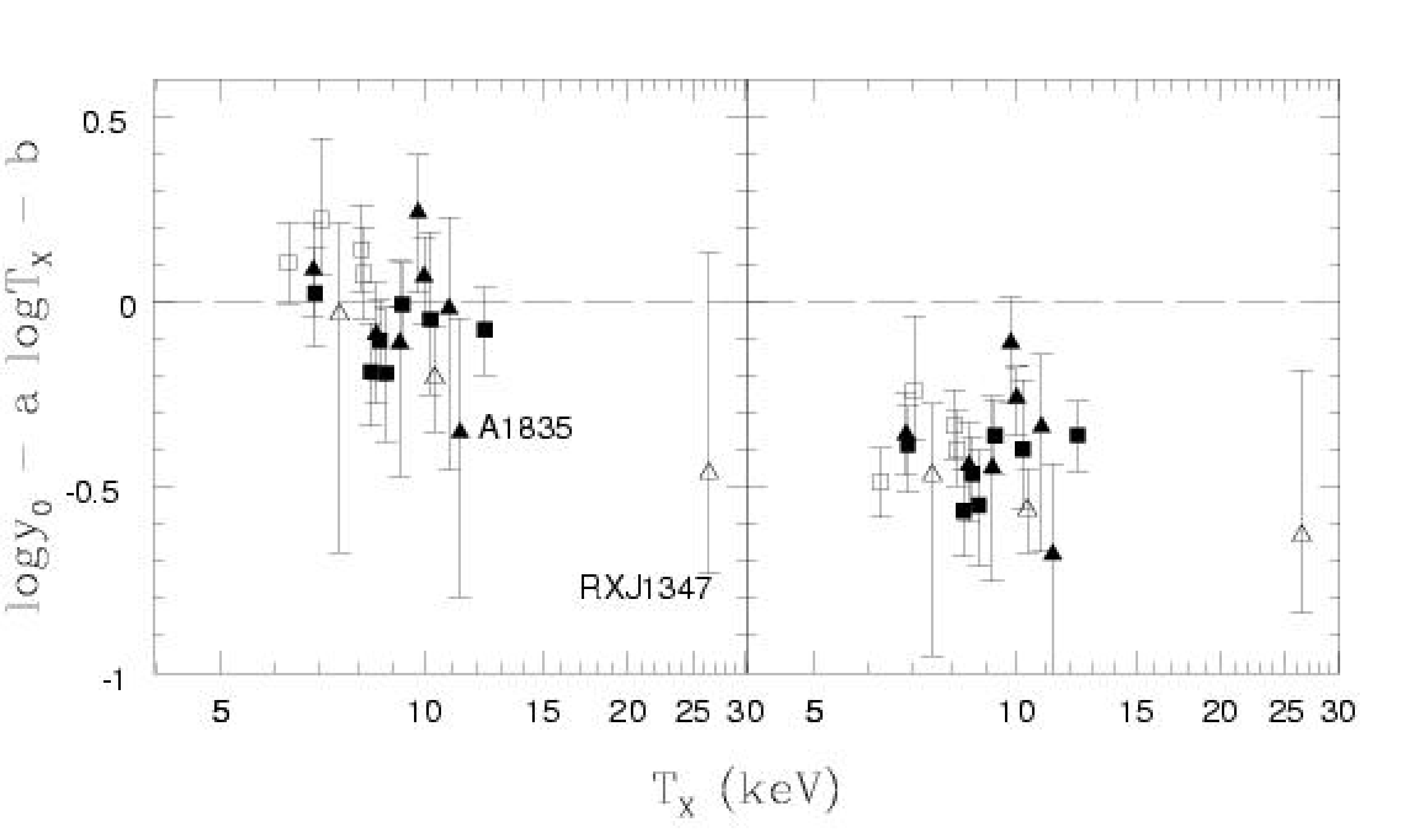
SZ Science: Cluster Mergers



XMM-Newton image of cluster undergoing merger (ESA website)

- Core of a sub-cluster flying through the main cluster body.
- Bow shock region due to sub-cluster supersonic speed.

S-Z Science: Scaling Relationships and Entropy Floor



$y_0 - T_X$ relation from existing SZ data (McCarthy et al. 2003)

- Left: residuals to model with $K_0 = 300\,\mathrm{KeV\,cm^2}$.
- Right: simple self-similar model.
- Nagai, Kravtsov, Vikhlinin (2007) include cooling and find no such effect.
- Chandra and XMM disagree at large radii from cluster core.
- More data required; SZ probes outer regions of gas well.
- Other scaling relations: $y_0 - L_X$, $y_0 - M(r_{500})$ etc

Other arc-minute scale anisotopies on the CMB

- Inhomogeneous reionisation.

- Integrated Sachs-Wolfe effect (gravitational redshift from linear growth).

- Rees-Sciama effect (gravitational redshift from non-linear growth).

- Gravitational lensing:
  - spatial perturbations in gravitational potential along line-of-sight.
  - does not generate fluctuations directly, but modifies existing background fluctuations.

- Topological defects.

Telescope Requirements

- Want higher sensitivity and resolution SZ observations.
- See Knox, Holder & Church 2004.
- At least 3 frequency bands for component separation

— Ideally 90, 150, 220, 270, (40), (350)

- High surface brightness sensitivity on scales between 10’ and 10”.

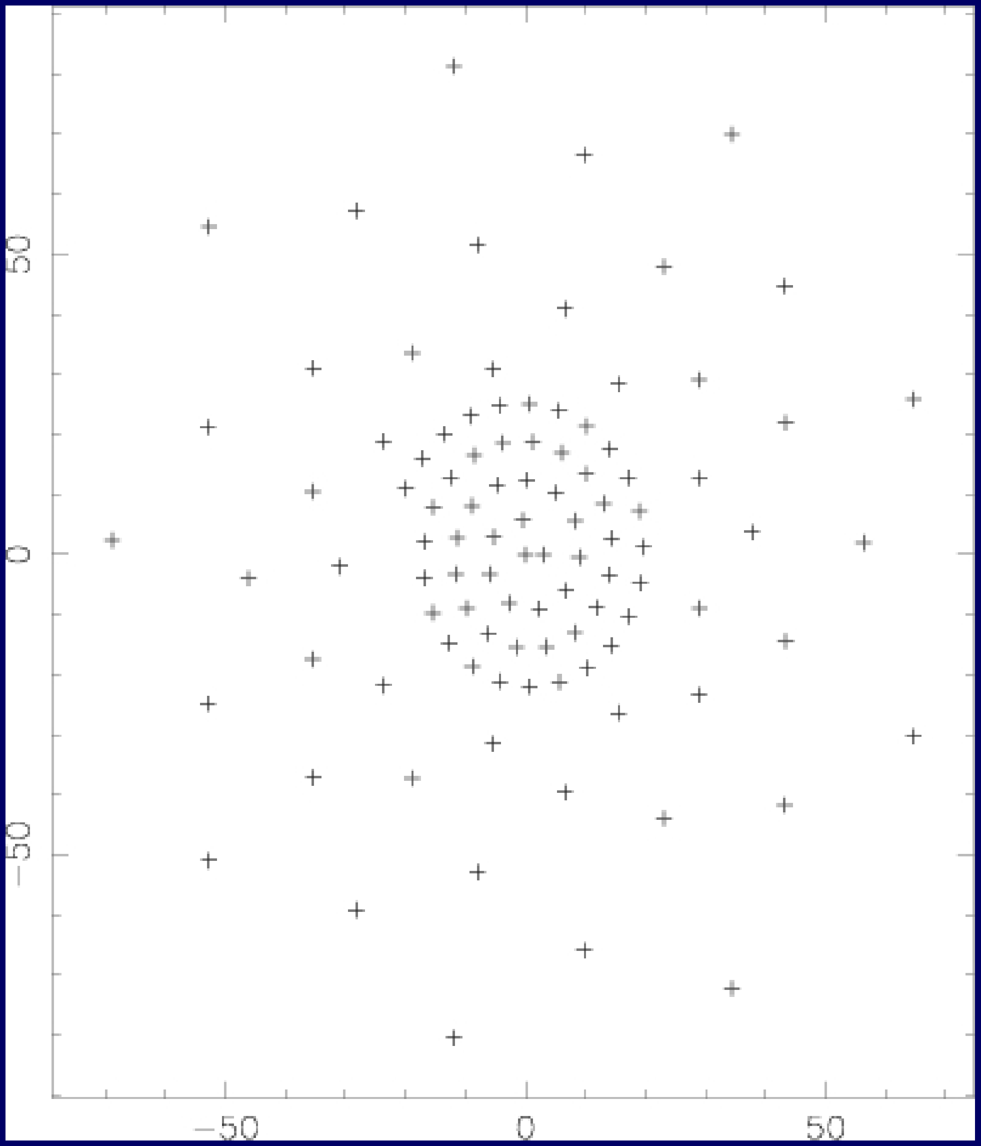
— High as possible bandwidth; some sub-channels useful

— low as possible amplifier T_{sys}

— Scaled telescope at each frequency

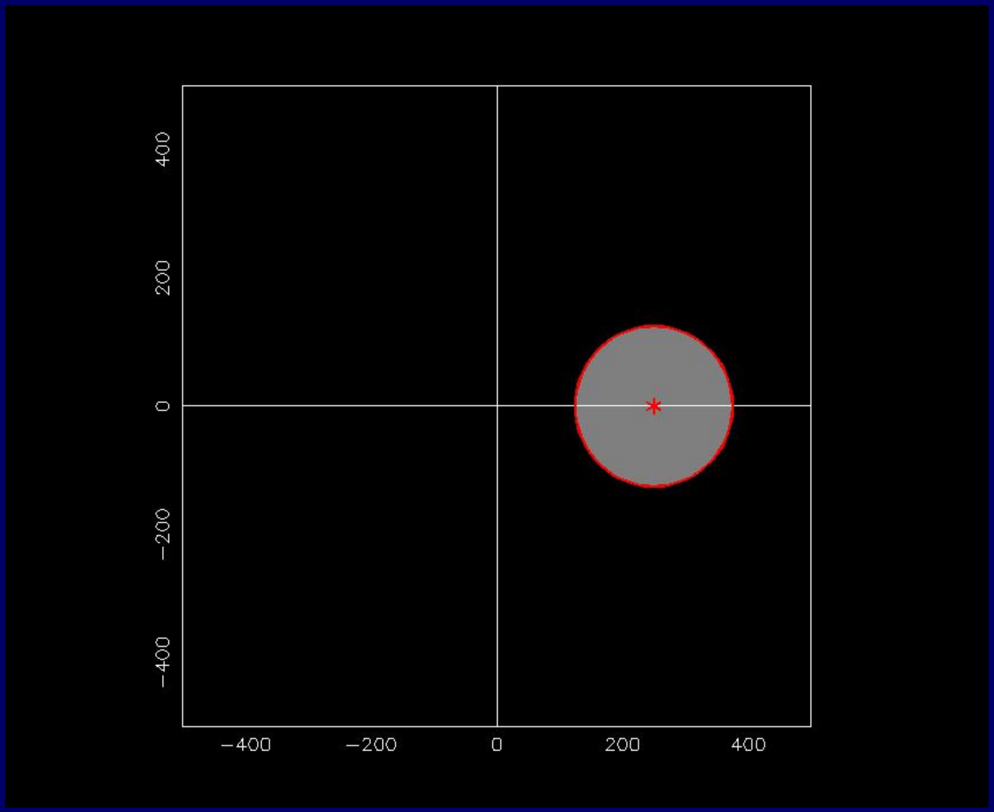
- Use a ground based interferometer

LARGE N SOLUTION

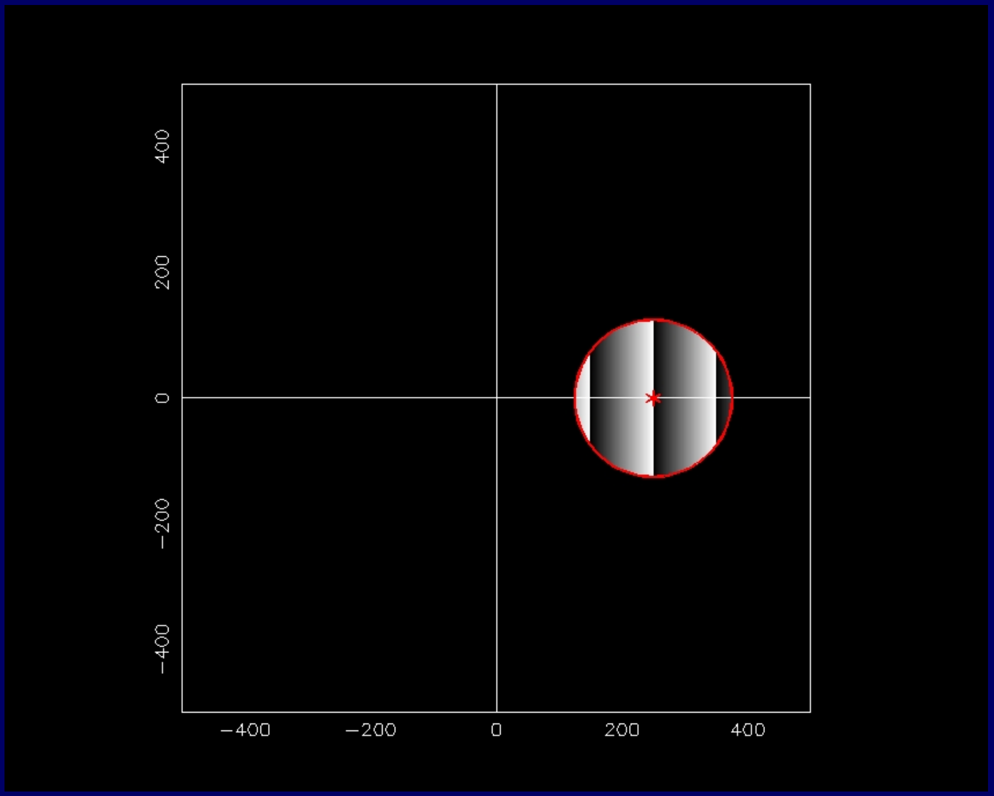


- Compact core
  → surface brightness sensitivity
- Logarithmic spiral
  → long baselines
- Stretch N-S (shadowing)
- 100 antennas at each frequency
- Coherent mosaicing instead?

COHERENT MOSAICING



uv point convolved with aperture illumination function



observation of same uv point for field offset to east

- Combine many offset pointings and can deconvolve aperture illumination function

$\Rightarrow$ Recover shorter baselines

- Limited by phase calibration and pointing

DETECTOR ARRAYS FOR INTERFEROMETERS

- Could put an array of feeds at focal plane of each interferometer element
- Alternatively:

— don't bring waves to a focus
— measure in aperture plane
— apply complex gains to signals and form beams on sky
— correlate with beams from other antennas

- Advantages:

— image region without stepping
— phase calibrate with a beam towards a bright source
— measure/adjust pointing with 5pt towards a bright source

- Does need beam forming hardware
- Number of correlations $N_A(N_A - 1)/2 \times n_{array}$
- Application for test system submitted.

"Straw-man" Design

- Build 10 antennas at 4 different sizes
- Close packed arrays; don't correlate between arrays
- number of array elements at each frequency:

	90 GHz	150 GHz	220 GHz	270 GHz
10 off 10m	64	64	-	-
10 off 3m	9	9	64	64
10 off 1m	1	1	9	9
10 off 0.3m	-	-	1	1

- 2880, 405, 45 correlations for arrays of 64, 9 and 1.
- 20% bandwidth (DSB) divided into 16 channels.

TECHNOLOGY DEVELOPMENTS REQUIRED

- Front end elements (HEMTs? SIS mixers?)
- Digital correlator
- These are common for a B-mode experiment (CHIP)
- An SZ experiment may be a natural pathfinder

— Would offer ancillary science (gravity waves and 10^{16} GeV not enough?)

Also....

- Beam former (NB SKADS)
- LO distribution
- Phase switches
- IF filter bank
- Feeds
- Simulations