

# The Sunyaev-Zel'dovich effect

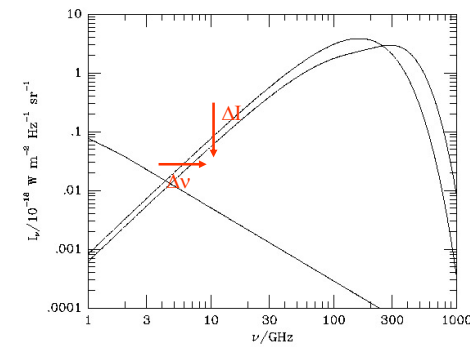
Mark Birkinshaw

1. The origin of the effect
2. SZ effect science: clusters
3. SZ effect science: cosmology
4. Sample SZ effect observations

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# Microwave background spectrum

1 deg<sup>2</sup>: CMB, exaggerated SZ distorted CMB, Cygnus A

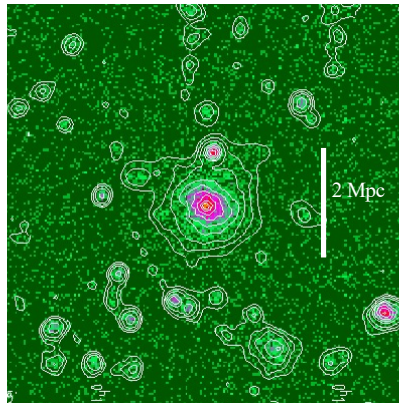


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## X-ray emission from clusters

Clusters of galaxies  
contain extensive hot  
atmospheres

$$T_e \approx 6 \text{ keV}$$
$$n_p \approx 10^3 \text{ protons m}^{-3}$$
$$L \approx 1 \text{ Mpc}$$



CL 0016+16; Hughes & Birkinshaw 1998

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## Inverse-Compton scatterings

- Cluster atmospheres scatter photons passing through them. Central iC optical depth

$$\tau_e \approx n_p \sigma_T L \approx 10^{-2}$$

- Scatterings changes the average photon frequency by a fraction

$$\Delta\nu/\nu \approx k_B T_e / m_e c^2 \approx 10^{-2}$$

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## Thermal SZ effect

- Fractional intensity change in the CMB (low  $\nu$ )

$$\Delta I/I = -2 y = -2 (\Delta\nu/\nu) \tau_e \approx 10^{-4}$$

- Effect in brightness temperature terms

$$\Delta T_{RJ} = -2 T_r (\Delta\nu/\nu) \tau_e \approx -300 \mu\text{K}$$

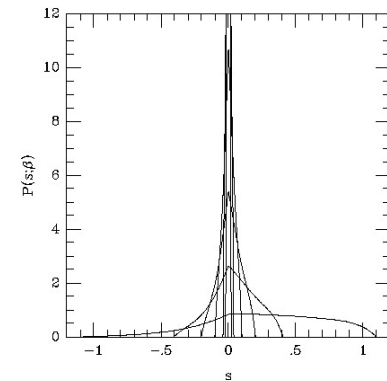
- Brightness temperature effect,  $\Delta T_{RJ}$ , is **independent of redshift**
- Flux density effect,  $\Delta S$ , decreases as  $D_A^{-2}$ , not  $D_L^{-2}$ , and **depends on redshift**

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## Compton scattering kernel

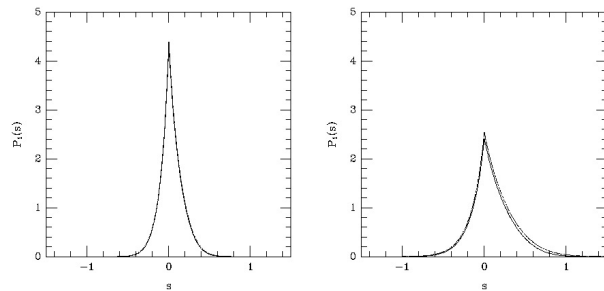
Probability that electron with dimensionless speed  $\beta$  causes frequency change  $s = \log(\nu'/\nu)$ . (Birkinshaw 1999).

$P(s;\beta)$  becomes broader and more asymmetrical as  $\beta$  approaches 1.



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## Compton scattering kernel

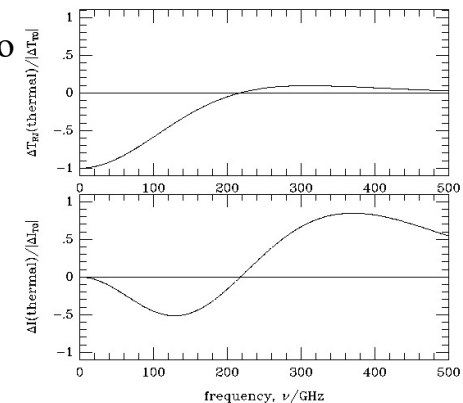


Distribution of  $s$  from a single scattering at 5 and 15 keV (Birkinshaw 1999). Asymmetry more pronounced at higher temperatures and deviates more from Kompaneets kernel.

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## Spectrum of thermal effect

- spectrum related to gradient of CMB spectrum
- zero at peak of CMB spectrum (about 220 GHz)
- Shape has weak dependence on  $T_e$



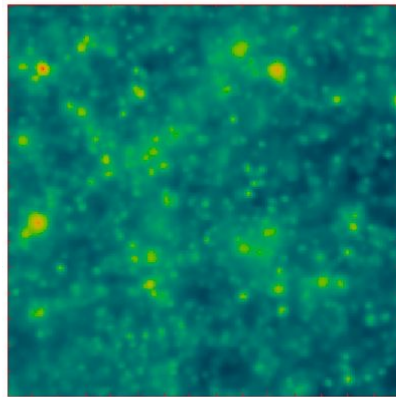
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## Predicted SZ effect sky

SZ sky predicted  
using structure  
formation code (few  
 $\text{deg}^2$ ,  $y = 0 - 10^{-4}$ , log  
colour coding)

CMB primordial  
fluctuations ignored

da Silva *et al.*



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## SZ effect and CMB power spectrum

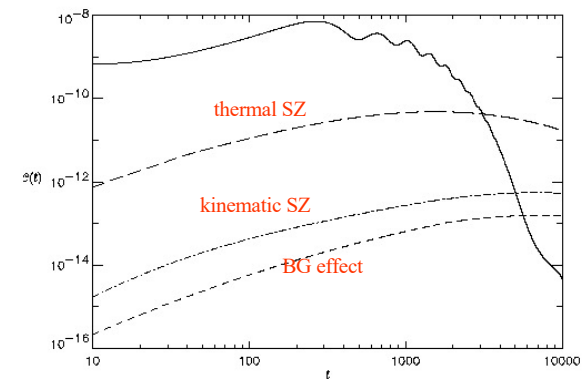


Figure from Molnar & Birkinshaw 2000  
SZ important on scales  $< 3$  arcmin.

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## Attributes of SZ effect

- $\Delta T_{\text{RJ}}$  is a redshift-independent function of cluster thermal energy, it is a calorimeter
- $\Delta T_{\text{RJ}}$  has a strong association with rich clusters of galaxies, it is a mass finder
- $\Delta T_{\text{RJ}}$  contains a weak redshift-independent kinematic effect, it is a radial speedometer
- $\Delta T_{\text{RJ}}$  has polarization with potentially more uses, but signal is tiny

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## SZ effect science: clusters

- Integrated SZ effects
  - total thermal energy content
  - total hot electron content
- SZ structures
  - not as sensitive as X-ray data
  - need for gas temperature
- Mass structures and relationship to lensing
- Radial peculiar velocity via kinematic effect

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## Integrated SZ effects

- Total SZ flux density

$$S_{RJ} \propto \iint d\Omega \int n_e T_e dz \propto U_{thermal}$$

Thermal energy content immediately measured in redshift-independent way

Virial theorem then suggests SZ flux density is good measure of **gravitational potential energy**

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## Integrated SZ effects

- Total SZ flux density

$$S_{RJ} \propto \iint d\Omega \int n_e T_e dz \propto N_e T_e$$

If have X-ray temperature, then SZ flux density measures electron count,  $N_e$  (and hence baryon count)

Combine with X-ray derived mass to get  $f_b$

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## SZ effect structures

- Gas currently only crudely measured by SZ methods (restricted angular dynamic range)
- X-ray based structures superior
- Structure more extended in SZ than X-ray:  $n_e$  rather than  $n_e^2$  dependence. SZ should show more about outer gas envelope, but need better sensitivity

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## SZ effects and lensing

Weak lensing measures ellipticity field  $\mathbf{e}$ , and so

$$\Sigma = -\frac{1}{\pi} \Sigma_{\text{crit}} \int d^2\boldsymbol{\theta}' K_i(\boldsymbol{\theta}', \boldsymbol{\theta}) e_i(\boldsymbol{\theta}')$$

Surface mass density as a function of position can be combined with SZ effect map to give a map of  $f_b \propto S_{\text{RJ}}/\Sigma$

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## Total and gas masses

Inside 250 kpc:

XMM +SZ

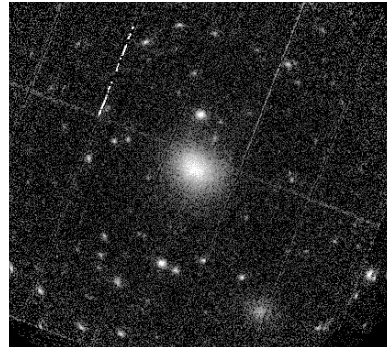
$$M_{\text{tot}} = (2.0 \pm 0.1) \times 10^{14} M_{\odot}$$

Lensing

$$M_{\text{tot}} = (2.7 \pm 0.9) \times 10^{14} M_{\odot}$$

XMM+SZ

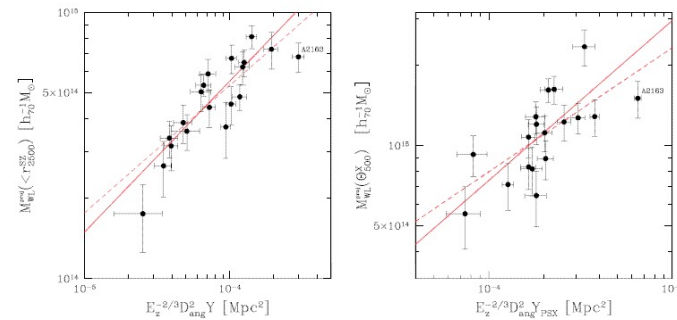
$$M_{\text{gas}} = (2.6 \pm 0.2) \times 10^{13} M_{\odot}$$



CL 0016+16 with XMM  
Worrall & Birkinshaw 2002

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## SZ mass estimates



Hoekstra *et al.* (2012); weak lensing mass correlates tightly with SZ signal (left Bonamente *et al.* sample; right Planck subsample). Note the logarithmic scales: a lot of scatter.

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## Cluster radial peculiar velocity

- Kinematic effect separable from thermal SZ effect because of different spectrum
- Confusion with primary CMB fluctuations limits velocity accuracy to about  $150 \text{ km s}^{-1}$
- Velocity substructure in atmospheres will reduce accuracy further
- Statistical measure of velocity distribution of clusters as a function of redshift in samples

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## Cluster radial peculiar velocity

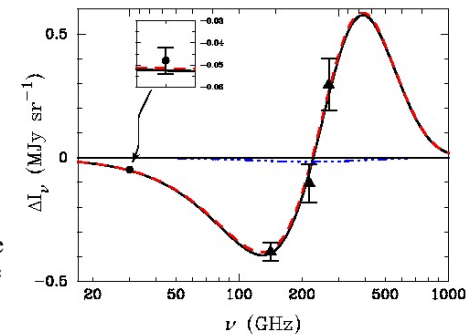
Need

- good SZ spectrum
- X-ray temperature

Confused by CMB structure

Sample  $\Rightarrow \langle v_z^2 \rangle$

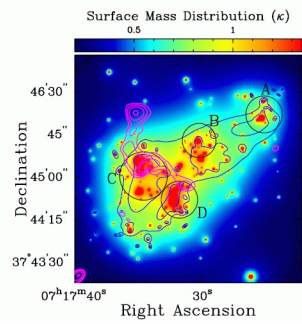
Few clusters so far, noise in measurements  $\delta v_z \approx 1000 \text{ km s}^{-1}$



A 2163; figure from LaRoque *et al.* 2002.

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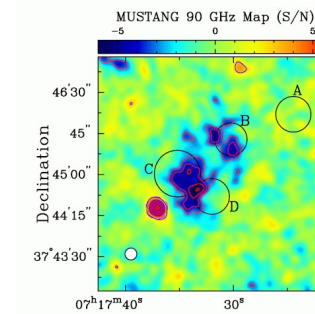
## Car-crash clusters; kinematic effect



X-ray and convergence; Mroczkowski *et al.* (2012).

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## Car-crash clusters; kinematic effect



90-GHz map, mostly SZ; Mroczkowski *et al.* (2012).  
Spectrum suggests about 3000 km s<sup>-1</sup> infall to south.

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## SZ effect science: cosmology

- Cosmological parameters
  - cluster-based Hubble diagram
  - cluster counts as function of redshift
- Cluster evolution physics
  - evolution of cluster atmospheres via cluster counts
  - evolution of radial velocity distribution
  - evolution of baryon fraction
- Microwave background temperature elsewhere in Universe

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## Cluster Hubble diagram

X-ray surface brightness

$$\Sigma_X \propto n_e^2 T_e^{1/2} L$$

SZ effect intensity change

$$\Delta I \propto n_e T_e L$$

Eliminate unknown  $n_e$

$$\Rightarrow L \propto \Delta I^2 \Sigma_X^{-1} T_e^{-3/2}$$

$$\Rightarrow H_0 \propto \Sigma_X \Delta I^{-2} T_e^{3/2} \theta$$

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## Cluster distances and masses

CL 0016+16

$$D_A = 1.36 \pm 0.15 \text{ Gpc}$$

$$H_0 = 68 \pm 8 \pm 18 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

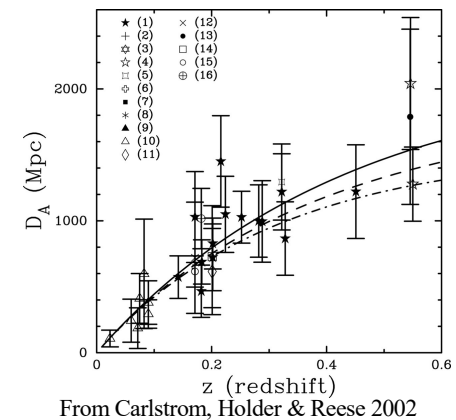


Worrall & Birkinshaw 2002

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## Hubble diagram

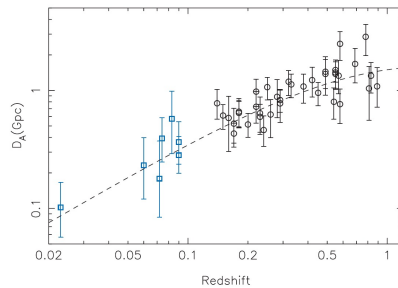
- poor leverage for other parameters
- need many clusters at  $z > 0.5$
- need reduced random errors
- *ad hoc* sample
- systematic errors



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## Hubble diagram

- poor leverage for other parameters
- need many clusters at  $z > 0.5$
- need reduced random errors
- *ad hoc* sample
- systematic errors



From Bonamente *et al.* 2006

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## Critical assumptions

- spherical cluster (or randomly-oriented sample)
- knowledge of density and temperature structure to get form factors
- clumping negligible
- selection effects understood

**need orientation-independent sample**

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## Blind surveys

- SZ-selected samples
  - almost mass limited and orientation independent
- Large area surveys
  - 1-D interferometer surveys slow, 2-D arrays better
  - radiometer arrays fast, but radio source issues
  - bolometer arrays fast, good for multi-band work
- Survey in regions of existing surveys
  - XMM-LSS survey region ideal, many  $\text{deg}^2$

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## Cluster counts and cosmology

Cluster counts and redshift distribution provide strong constraints on  $\sigma_8$ ,  $\Omega_m$ , and cluster heating.

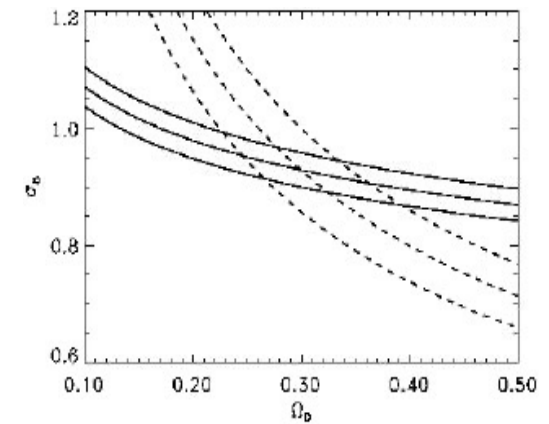


Figure from Fan & Chiueh 2000

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## Planck survey: SZ candidates

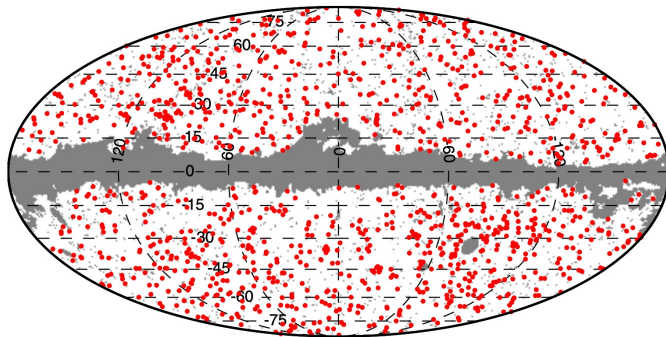


Fig. 2. Sky distribution of the 1227 *Planck* clusters and candidates (red dots), in a Mollweide projection with the Galactic plane horizontal and centred at longitude zero. Small grey dots show the positions of masked point sources, and grey shading shows the mask used to exclude the Galactic plane region. *Planck XXIX* (2014); 1227 candidates (red), Galactic coordinates.

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## Baryon mass fraction

$$S_{\text{RJ}} \propto N_e T_e$$

Total SZ flux  $\Rightarrow$  total  
electron count  $\Rightarrow$  total  
baryon content.

Compare with total  
mass (from X-ray or  
gravitational lensing)  
 $\Rightarrow$  baryon fraction

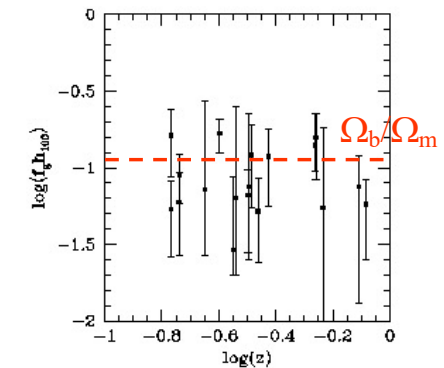


Figure from Carlstrom *et al.* 1999.

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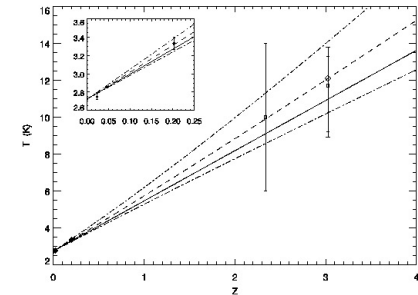
## Microwave background temperature

- Ratio of SZ effects at two different frequencies is a function of CMB temperature (with slight dependence on  $T_e$  and cluster velocity)
- So can use SZ effect spectrum to measure CMB temperature at distant locations and over range of redshifts
- Test  $T_r \propto (1+z)$

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## Microwave background temperature

- Test  $T_r \propto (1+z)$
- SZ results for two clusters plus results from molecular excitation



Battistelli *et al.* (2002)

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## SZ effect observations

- Interferometers: e.g., Ryle, SZA, ALMA
  - structural information should be good
  - baseline range limits
- Single-dish radiometers: e.g., OVRO 40-m
  - speed for single-object measurement
  - systematic errors from spillover
- Bolometers: e.g., SPT, ACT, Planck
  - speed
  - structural and spectral information
  - weather if ground-based; resolution if space-based

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## Ryle telescope

- first interferometric map
- Abell 2218
- brightness agrees with single-dish data
- limited angular dynamic range

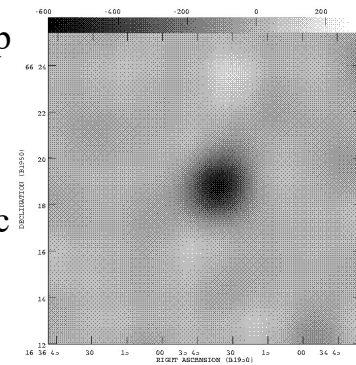


Figure from Jones *et al.* 1993

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## Interferometers

- restricted angular dynamic range
- high signal/noise (long integration possible)
- clusters easily detectable to  $z \approx 1$

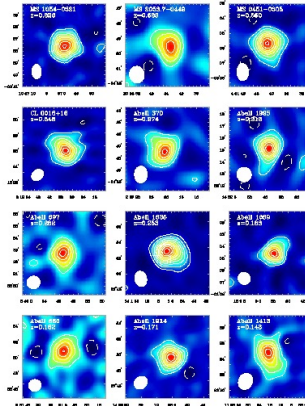
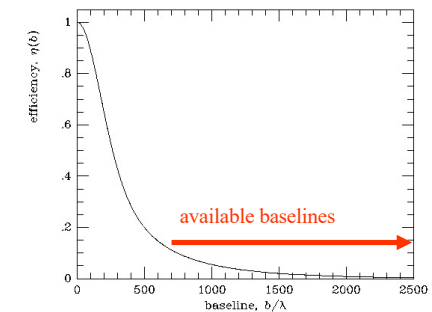


Figure from Carlstrom *et al.* 1999

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## Interferometers

- restricted angular dynamic range set by baseline and antenna size
- good rejection of confusing radio sources



Abell 665 model, VLA observation

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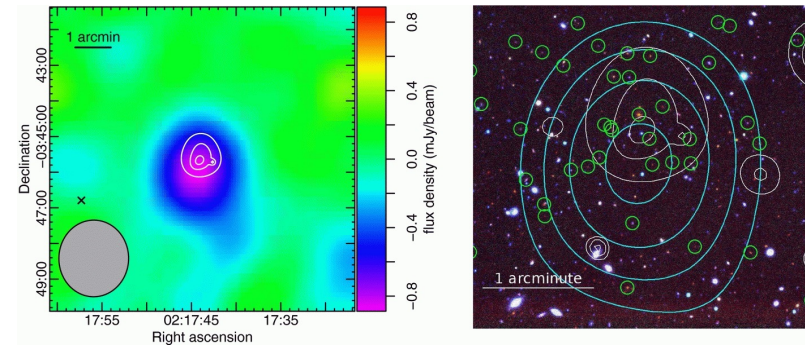
## SZA



SZA at OVRO in the Sierra Nevada, California (Leitch)

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## High- $z$ clusters



SZ effect – high sensitivity at high redshift, provided cluster has gas (Mantz *et al.* 2014; CARMA; XXL cluster at  $z = 1.9$ )

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## Single-dish radiometers

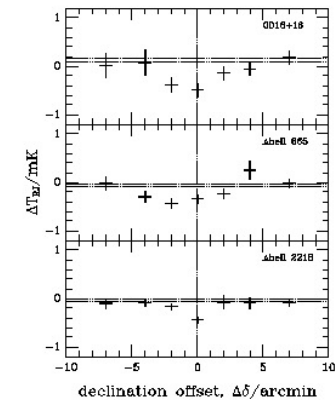
- Potentially fast way to measure SZ effects of particular clusters
- Multi-beams better than single beams at subtracting atmosphere, limit cluster choice
- Provided first SZ effects but less fashionable now: other techniques have improved faster
- New opportunities: e.g., GBT

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## Single-dish radiometers

- fast at measuring integrated SZ effect of given cluster
- multi-beam limits choice of cluster, but subtracts sky well
- radio source worries
- less used since early 1990s
- needs big telescopes

Figure from Birkinshaw 1999



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## Bolometers

- Fast way to survey for SZ effects
- Wide frequency range possible on single telescope, allowing subtraction of primary CMB structures
- Atmosphere a problem at every ground site
- Several experiments: SPT, ACT, Nika-2, etc.
- Space ideal: Planck survey; pointed in future?

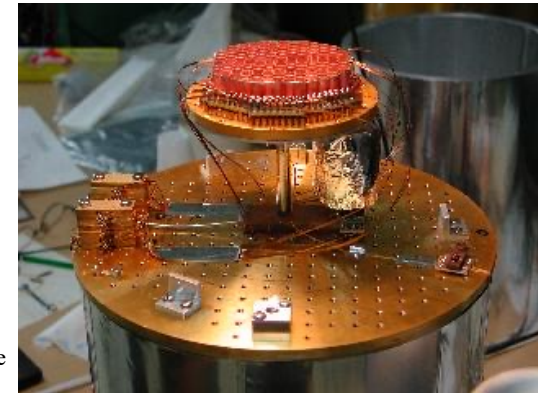
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## APEX

MPI project at  
Chajnantor

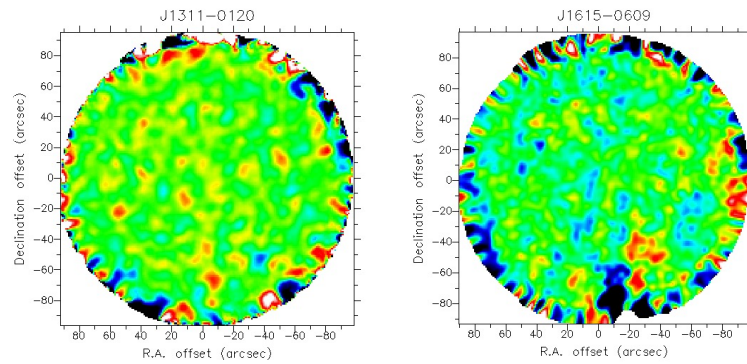
300-element  
bolometer  
array at 870  
 $\mu\text{m}$  ideal for  
SZ

(117-element prototype  
shown)



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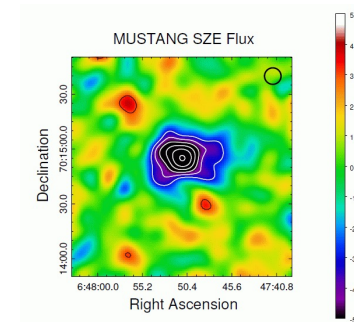
## SCUBA



850  $\mu\text{m}$  images: SZ effect measured in one; field too small

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## MUSTANG



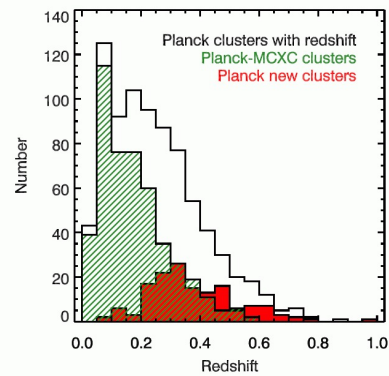
Multi-beam systems can make small maps in reasonable times – e.g., GBT + MUSTANG (Young *et al.* 2015)

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## Planck

Distribution of redshifts for the Planck cluster candidates. The strong drop-off at  $z > 0.4$  arises from the low angular resolution of the survey.

Planck XIX 2014.



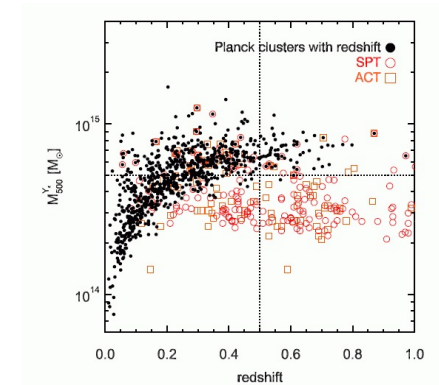
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## Planck cluster sample

Planck XXIX (2014).

Survey result - inferred mass versus  $z$  compared with results from higher-resolution ACT and SPT surveys.

Angular resolution limits maximum redshift. Need 15-arcsec survey.



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## Summary

- SZ effect relatively unbiased for study of clusters
- Improved SZ data (e.g., from SO) will give
  - outer structures and pressure features in clusters (thermal SZ effect)
  - radio source energetics (non-thermal SZ effect)
  - radial velocities of clusters (kinematic effect)
  - transverse velocities of clusters (intensity and polarization effect; Birkinshaw-Gull effect also)
  - detections of infalling filament gas possible