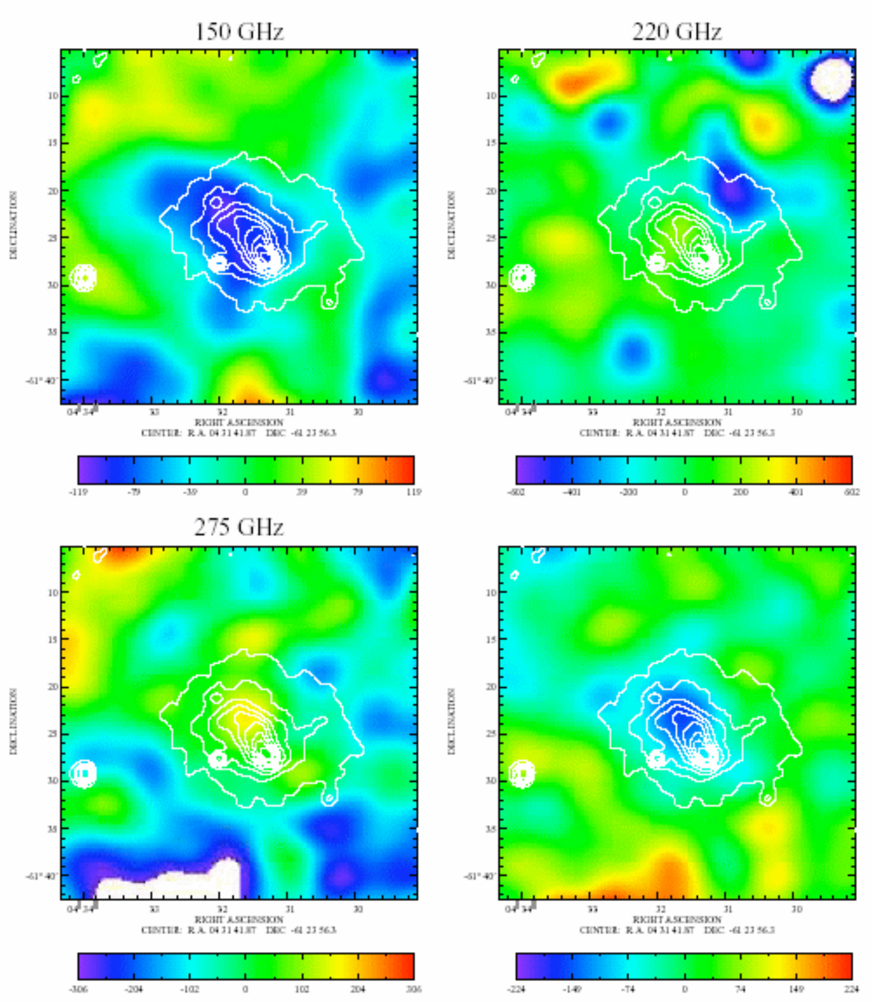
The Sunyaev-Zel’dovich (SZ) effect(s)



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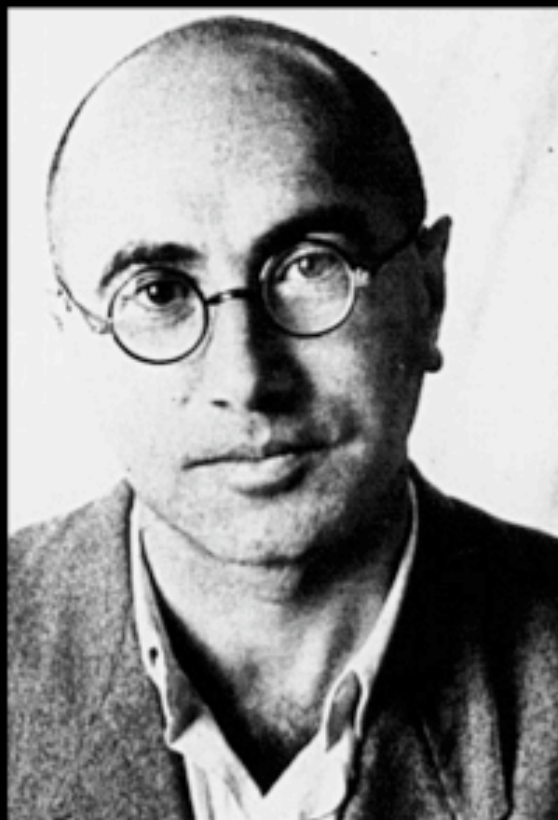
Bertinoro, 24-29th may 2009

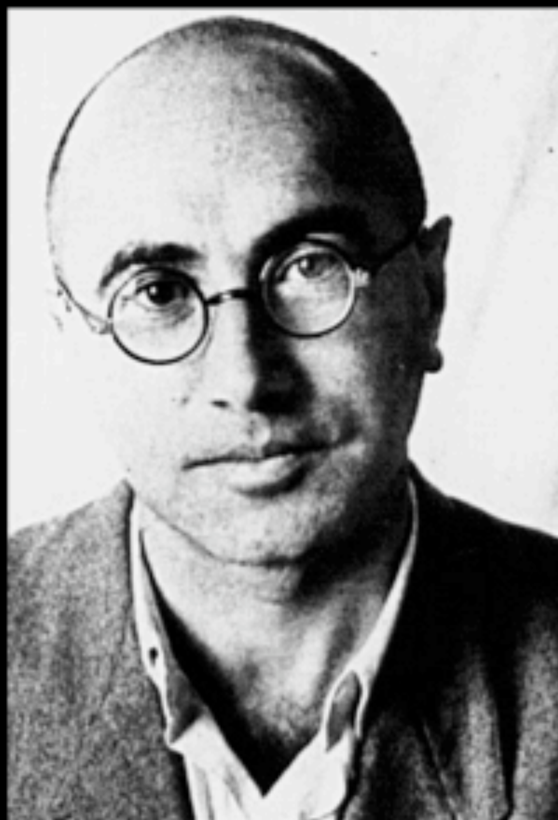
Outline

- What is the SZ effect?
- Derivation
- Properties
- Cosmological Relevance
- Observational Problems
- Present & Future Projects

What is SZ?




Rashid Sunyaev & Yakov Zel'dovich

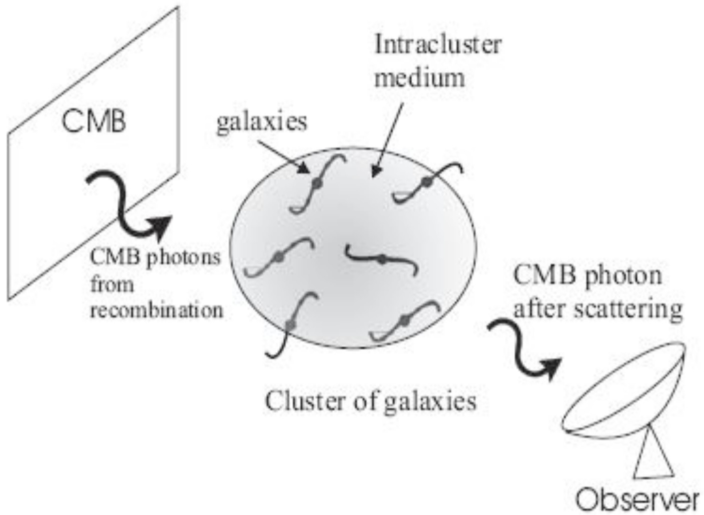


Yakov Zel'dovich
(1914-1987)

Rashid Sunyaev
(1943)

What is SZ?

- Clusters of galaxies
  - Galaxies
  - Intracluster Medium (ICM)
    - Hot electron gas



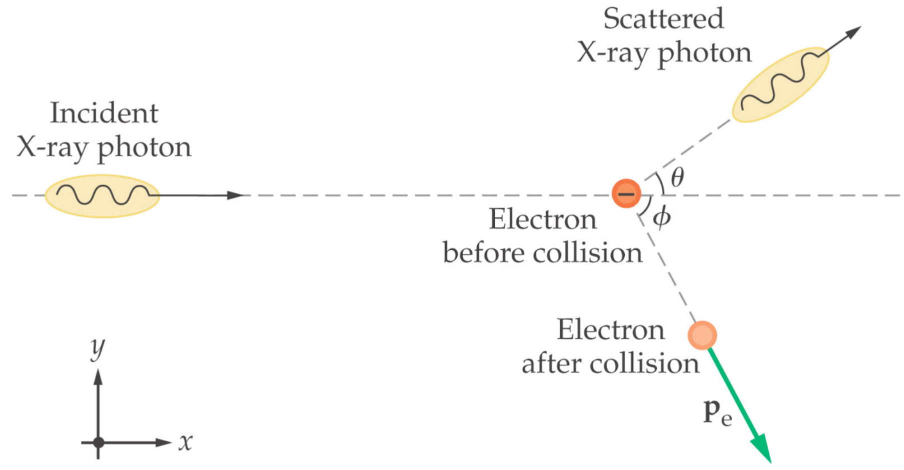
- Inverse Compton scattering of photons
  - Photons gain energy from electrons
  - Photons are moved from less to more energetic regions of black-body spectrum

Compton Scattering

- Photon scatters off of stationary e^-
  - *Loses* energy to electrons
  - Scatters by angle θ

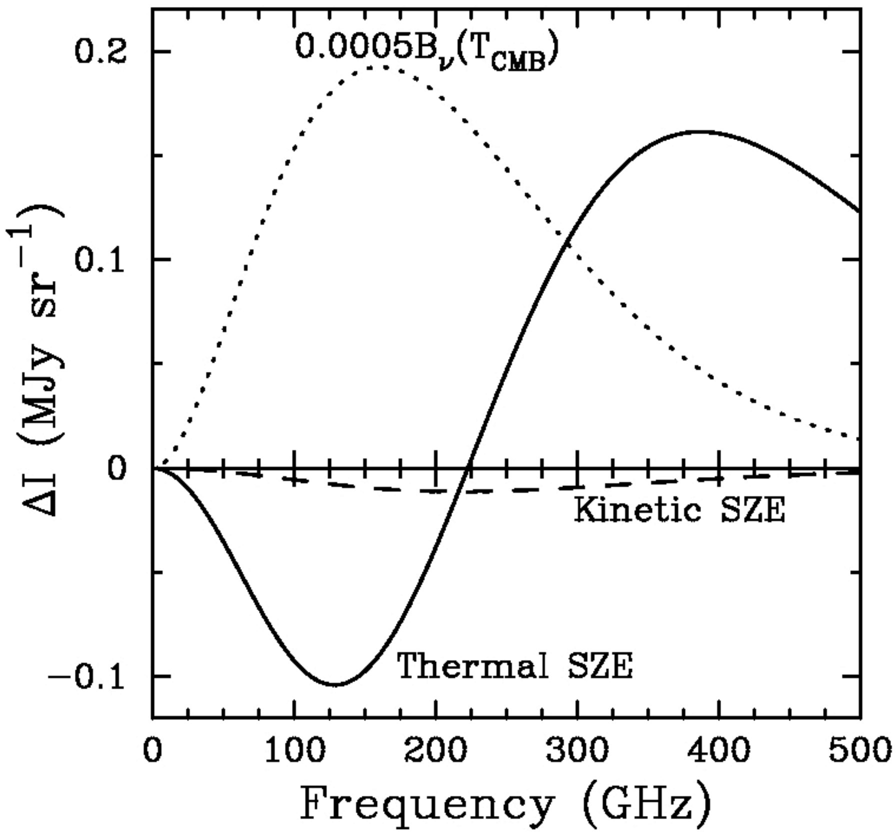
$$\Delta\lambda = \lambda - \lambda_0 = \frac{h}{mc}(1-\cos\theta)$$

  - λ_0 is initial wavelength
  - h is Planck's constant
  - $\Delta\lambda \geq 0 \rightarrow \nu$ **decreases**



Inverse Compton

- Photon scatters off of *moving* electrons
  - *Gains* energy from e^-
  - $\Delta\lambda \leq 0 \rightarrow \nu$ **increases**
- Decrement in Rayleigh-Jeans region
- Increment in Wien region



Derivation:
Thermal SZ Effect

A quantitative approach: the transport equation

- In a sparse astrophysical plasma, interactions between particles can be considered almost absent

=> no photon absorption or creation (photon conservation), but only a redistribution of their energies.

Some useful definitions

- $N(E)$: number density of photons
- Δ: photon energy change due to a single scattering
- $A \equiv \langle \Delta \rangle$: average change of photon energy per photon-electron collision
- $t_{c:}$ time between collisions

==> $AN/t_{c:}$ one-dimensional energy current

Conservation law

$$t_c \frac{dN}{dt} = -\frac{d(AN)}{dE}$$

but what about broadening of the energy spectrum?

Consider the probability distribution function p(Δ|E) and scatterings both **into and out** of the element dE:

$$\partial N = \int [N(E-\Delta)p(\Delta \mid E-\Delta) - N(E)p(\Delta \mid E)]d\Delta$$

If we Taylor expand N(E-Δ) and p(Δ|E-Δ), collect terms to 2nd order in Δ and define B≡ <Δ²>:

the Fokker-Planck equation

$$t_c \frac{dN}{dt} = -\frac{d(AN)}{dE} + \frac{1}{2}\frac{d^2(BN)}{dE^2}$$

- if A=0 => standard diffusion equation
- possible expansion to higher orders
- diffusive term significant when B≈AE

Using the Maxwell distr.

- Maxwellian distribution of electrons at *T*

$$p(v)dv = \sqrt{\frac{2}{\pi}}\left(\frac{m_e}{k_b T}\right)^{3/2} v^2 e^{\frac{-mv^2}{2k_b T}} dv$$

If $\hbar\omega << m_e c^2$ we obtain the appropriate A and B

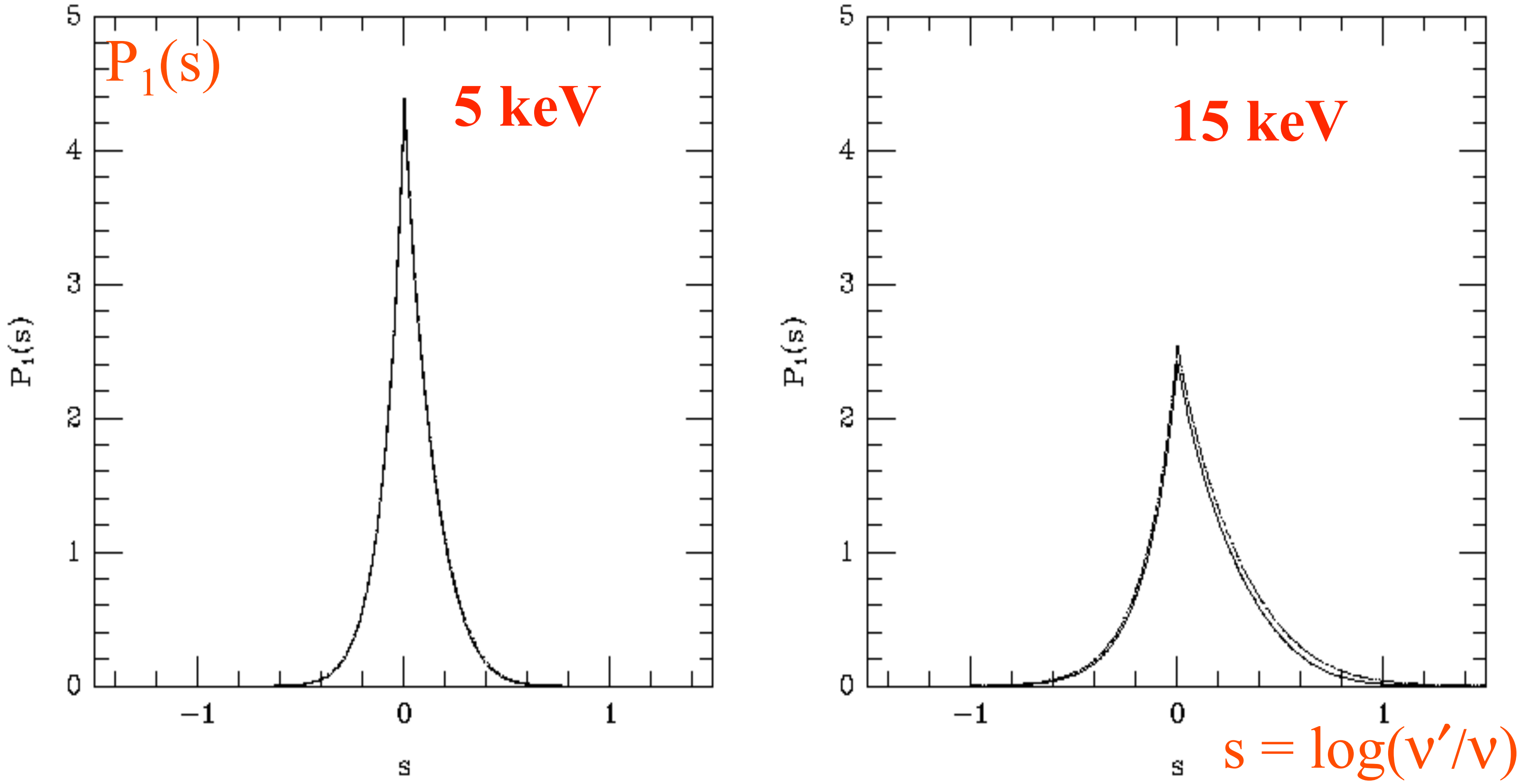
$$\frac{A}{\hbar\omega} = \left(4 - \frac{\hbar\omega}{kT}\right)\left(\frac{KT}{m_e c^2}\right)$$

$$\frac{B}{(\hbar\omega)^2} = 2\left(\frac{KT}{m_e c^2}\right)$$

and scattering time

$$t_c = \frac{1}{n_e c \sigma_T}$$

Single-scattering frequency shift



The distribution of scattered photon frequencies is significantly asymmetric, with a stronger upscattering tail than a downscattering tail: on average there is a frequency increase!

Including the quantum corrections

If photon occupation numbers are not small, we need to consider that bosons like to clump: stimulated transitions ensure that a final state is more probable if it is already occupied! The rate of scatterings from E and E+Δ becomes proportional to n(E)[1+n(E+Δ)].

The Fokker-Planck equation is modified as

$$t_c \frac{dN}{dt} = -\frac{d\left[AN(1+n)\right]}{dE} + \frac{1}{2}\frac{d^2(BN)}{dE^2}(1+n) - \frac{1}{2}BN\frac{d^2(1+n)}{dE^2}$$

Last change: in spite of N(E), consider n(ω), the photon phase-space occupation number:

$$N \propto \omega^2 n(\omega)$$

The Kompaneets equation

$$\frac{\partial n}{\partial t} = \left(\frac{\sigma_T n_e \hbar}{m_e c}\right)\frac{1}{\omega^2}\frac{\partial}{\partial \omega}\left\{\omega^4\left[n(1+n)+\frac{k_b T}{\hbar}\frac{\partial n}{\partial \omega}\right]\right\}$$

– Phase-space occupation number $n(\omega)$

– Angular frequency ω

– n_e electron number density

– σ_T Thomson cross section

Note: in the limit of many scatterings, we obtain the equilibrium Bose-Einstein distribution with non-zero chemical potential

Some simplifications

– Scattering chance small ~ 1%

  • Only one time per photon

– e^- gas much hotter than CMB photon

  • First term in { } of Kompaneets drops

$$\frac{\partial n}{\partial t} = \left(\frac{\sigma_T n_e \hbar}{m_e c}\right) \frac{1}{\omega^2} \frac{\partial}{\partial \omega} \left\{ \omega^4 \left[\frac{k_b T}{\hbar} \frac{\partial n}{\partial \omega} \right] \right\}$$

Derivation: the integration

- Integrate over time through cluster

$$\Delta n = \int \left(\frac{\sigma_T n_e \hbar}{m_e c} \right) \frac{1}{\omega^2} \frac{\partial}{\partial \omega} \left(\omega^4 \frac{k_b T}{\hbar} \frac{\partial n}{\partial \omega} \right) dt$$

- Note *c dt = dl*
- Define <u>*Compton y-parameter*</u>

$$y \equiv \int \sigma_T n_e \frac{k_b T}{m_e c^2} dl = \frac{\sigma_T}{m_e c^2} \int P_e \, dl$$

- Define <u>optical depth</u>

$$\tau_e \equiv \int \sigma_T n_e dl$$

- Passing to frequency:

$$\Delta n = \frac{y}{\nu^2}\frac{\partial}{\partial \nu}\left(\nu^4 \frac{\partial n}{\partial \nu}\right)$$

Using the Planck distrib.

- Recall Planck black-body formula:

$$I_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{k_b T}} - 1}$$

- Define parameter $x(\omega, T_{rad})$, a norm. frequency

$$x \equiv \frac{\hbar\omega}{k_b T_{rad}}$$

The final formula

- Final formula for *Thermal SZ effect*:

$$\frac{\partial I_\nu}{I_\nu} = \frac{\partial n}{n} = -y\,\frac{xe^x}{e^x - 1}\left[4 - x\coth\left(\frac{x}{2}\right)\right]$$

- At low frequencies:

$$\frac{\partial I}{I} = \frac{\partial T}{T} = -2y$$

Derivation: a review

- 2 important assumptions and 1 observation:

1. Optical depth τ low for hot ICM e^- gas
    - Photons scatter once
2. Because $T_{rad} < T_e \rightarrow n(n+1)$ goes away
3. CMB follows Planck law for black-body radiation

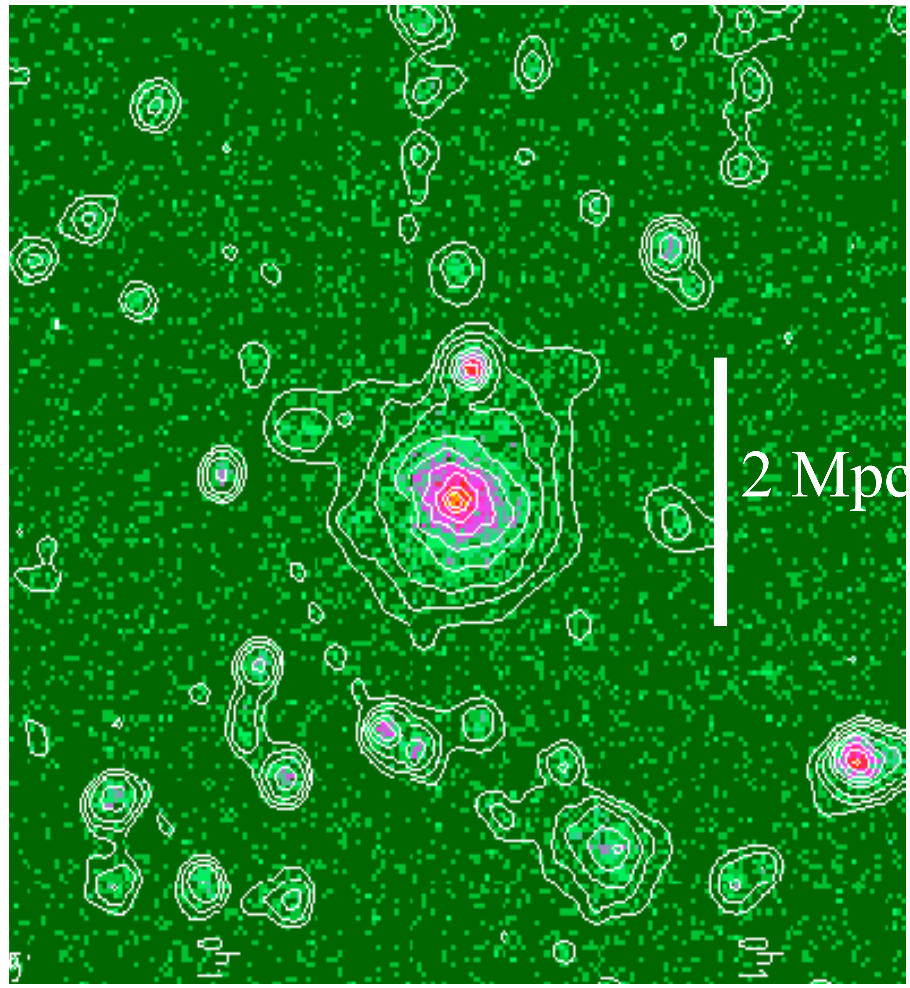
A first rough estimate of the thermal SZ effect from a cluster

Clusters of galaxies contain extended hot atmospheres

$T_e \approx 6$ keV

$n_p \approx 10^3$ protons m^{-3}

$L \approx 1$ Mpc



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

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

- Each scattering changes the photon frequency by a fraction

$$\Delta\nu/\nu \approx 10^{-2}$$

- The fractional intensity change in the background radiation

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

- Effect in brightness temperature terms is

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

Properties

Properties: Redshift

- *Practically* independent of redshift, z

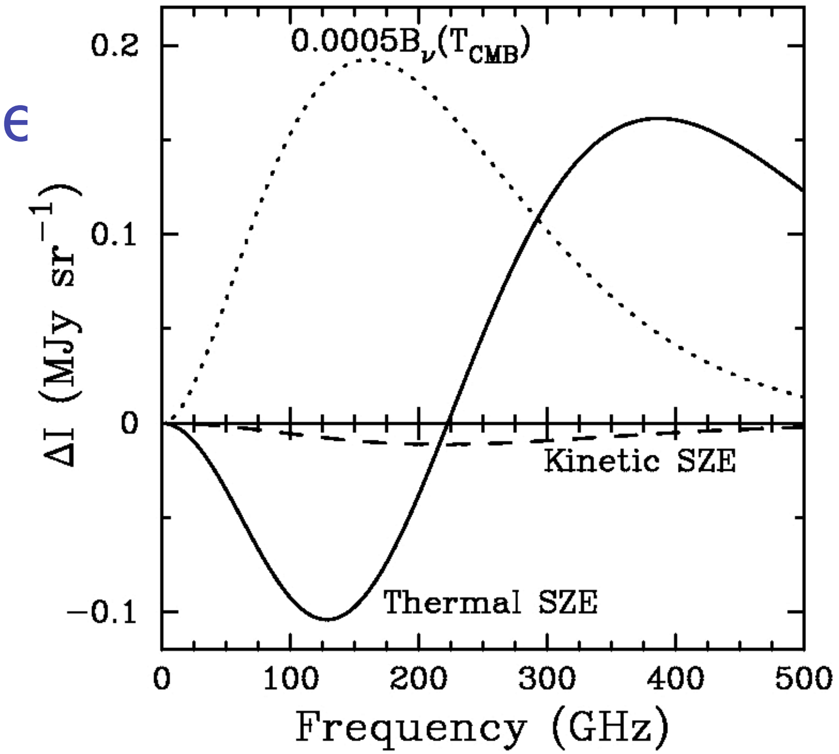
$$\frac{\partial I_\nu}{I_\nu} = \frac{\partial n}{n} = -y\,\frac{xe^x}{e^x - 1}\left[4 - x\coth\left(\frac{x}{2}\right)\right]$$

$$x \equiv \frac{\hbar\omega}{k_b T_{rad}}$$

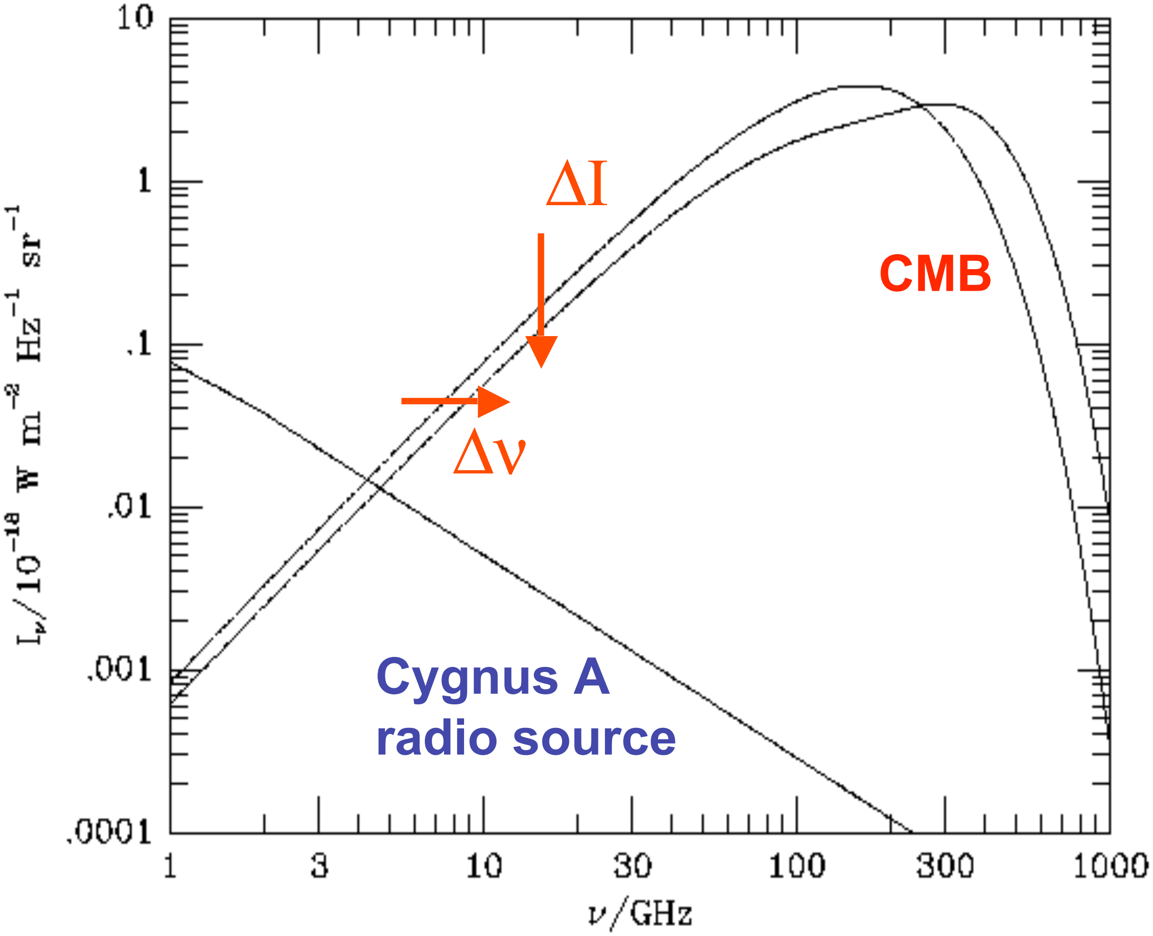
  – Very important observationally: all clusters equal

Properties: Photon Conservation

- Number of photons conserved
  - Only shifted from Rayleigh-Jeans to Wien regions of the black-body spectrum

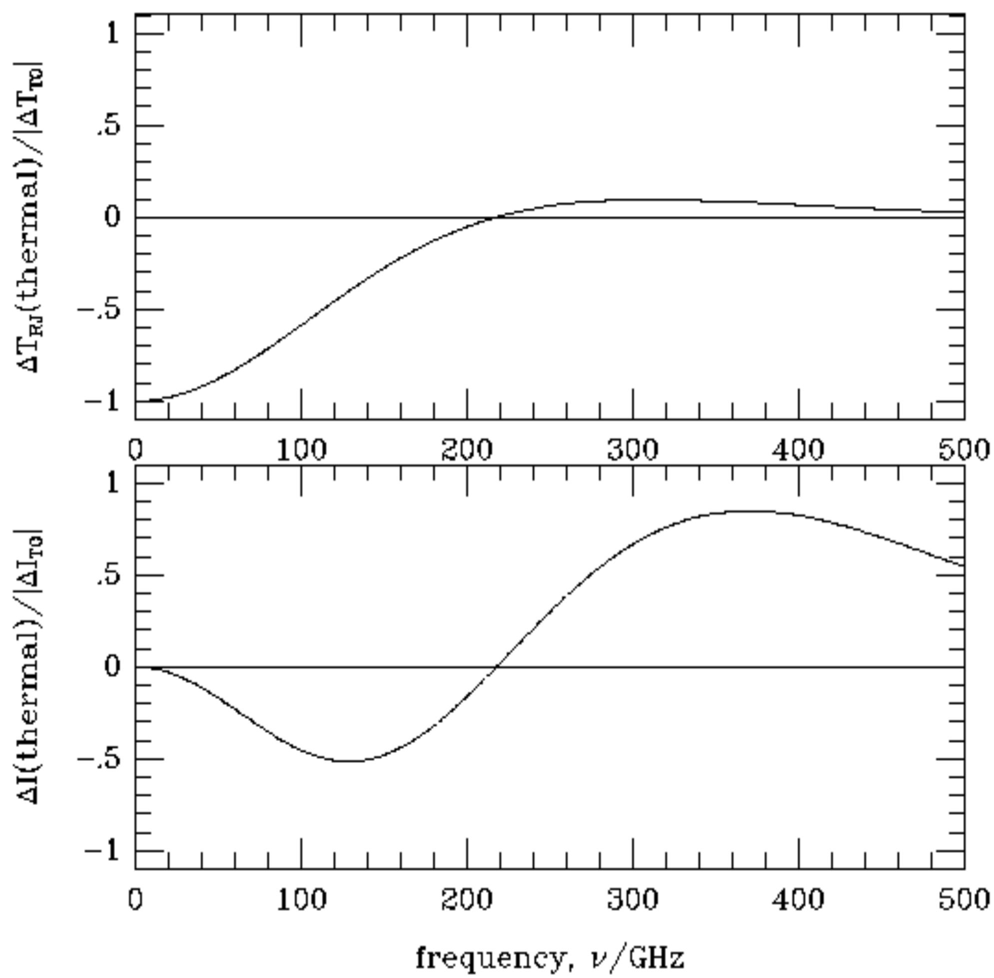


Microwave background spectrum



Spectrum of thermal effect

- effect caused by small frequency shifts, so the spectrum is related to gradient of CMB spectrum
- zero at peak of CMB spectrum
- Crossover frequency at 217 Ghz (x=3.83)



Relativistic corrections

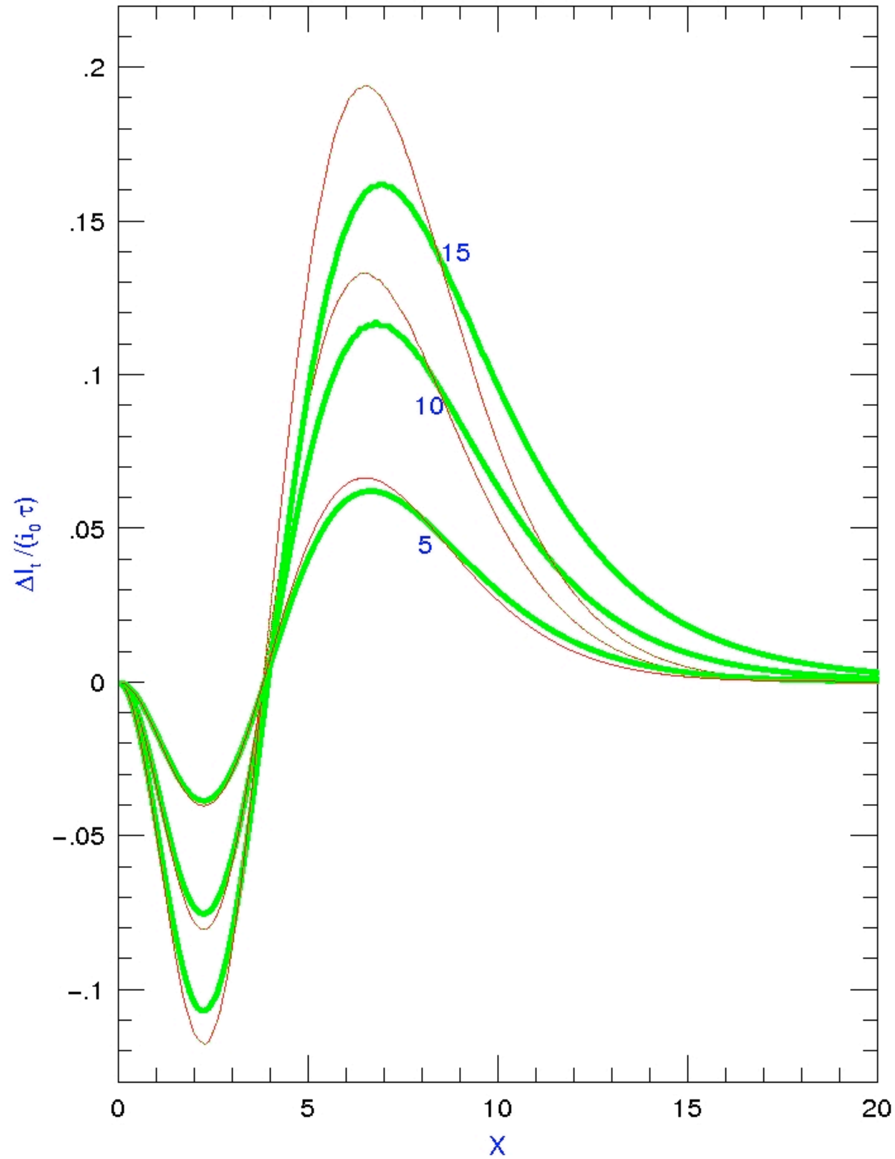
- Computed assuming a relativistic Maxwellian distribution of the electrons and/or generalizing the Kompaneets equation (e.g. Itoh et al. 2003)

$$\frac{\partial I_\nu}{I_\nu} = \left(\frac{\partial I_\nu}{I_\nu} \right)_{nonrel} + \delta(x, T_e)$$

- Relativistic corrections important for high-temperature clusters
- Effects in the Wien tail and at the crossover frequency: possible use for estimate the cluster temperature?

Temperature sensitivity

- T_e < 5 keV: e^- non-relativistic, effect independent of T_e
- T_e > 5 keV: enough e^- relativistic that spectrum is function of T_e



Itoh et al. 2003

Non-thermal SZ effect

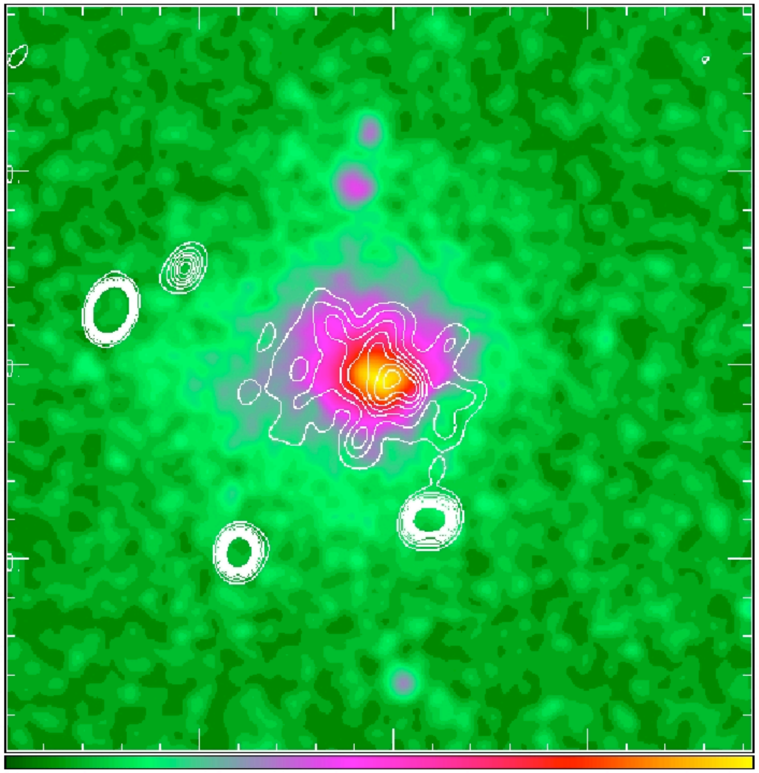
If the distribution of electron energies is non-thermal (i.e. power-law distribution like in radiogalaxies), you can have also the SZ effect, but with different properties.

Possible applications:

•Test for the low-end cutoff energy of relativistic electron spectrum

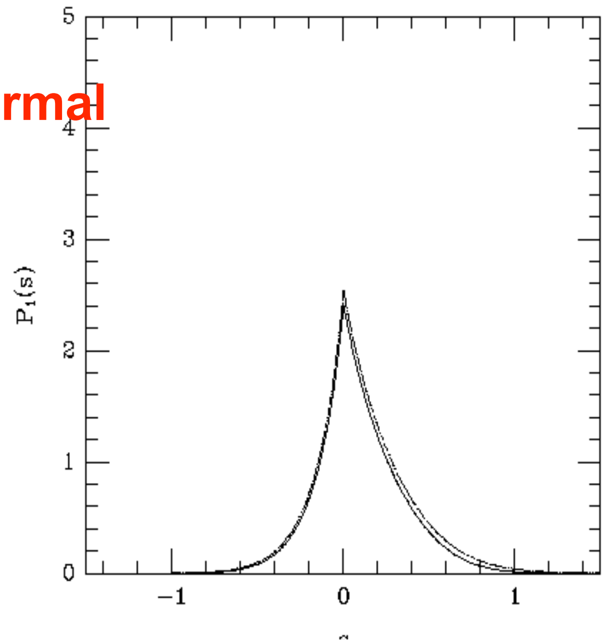
•Study of the energetics of the source

A cluster radio halo:
Abell 2163
Contours: radio @1400 MHz
Colours: soft X-ray



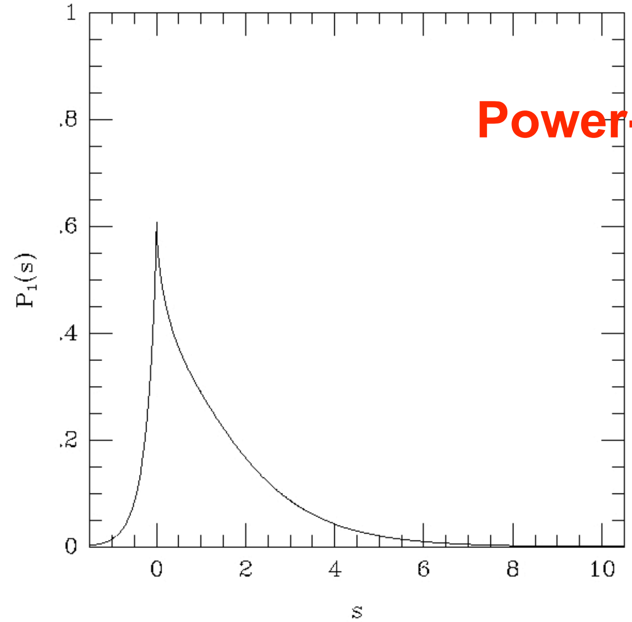
Thermal vs. non-thermal SZ

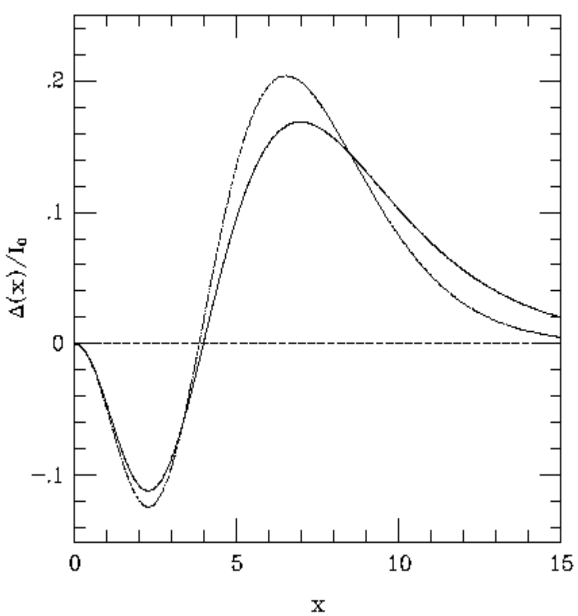
Thermal



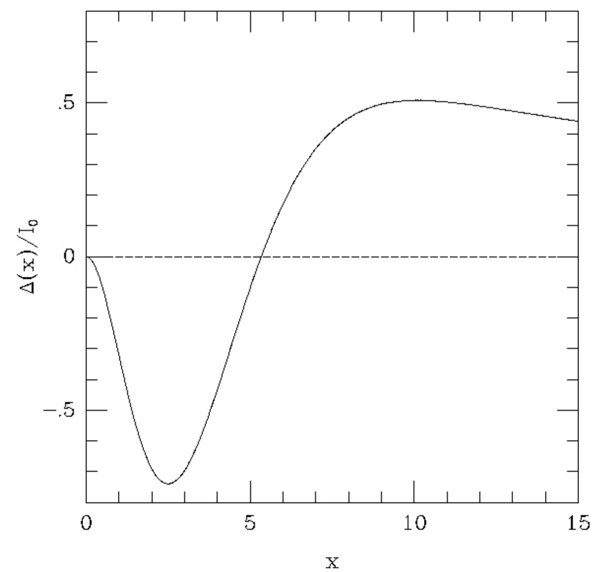
Scattering energy change

Power-law





Spectral deformation



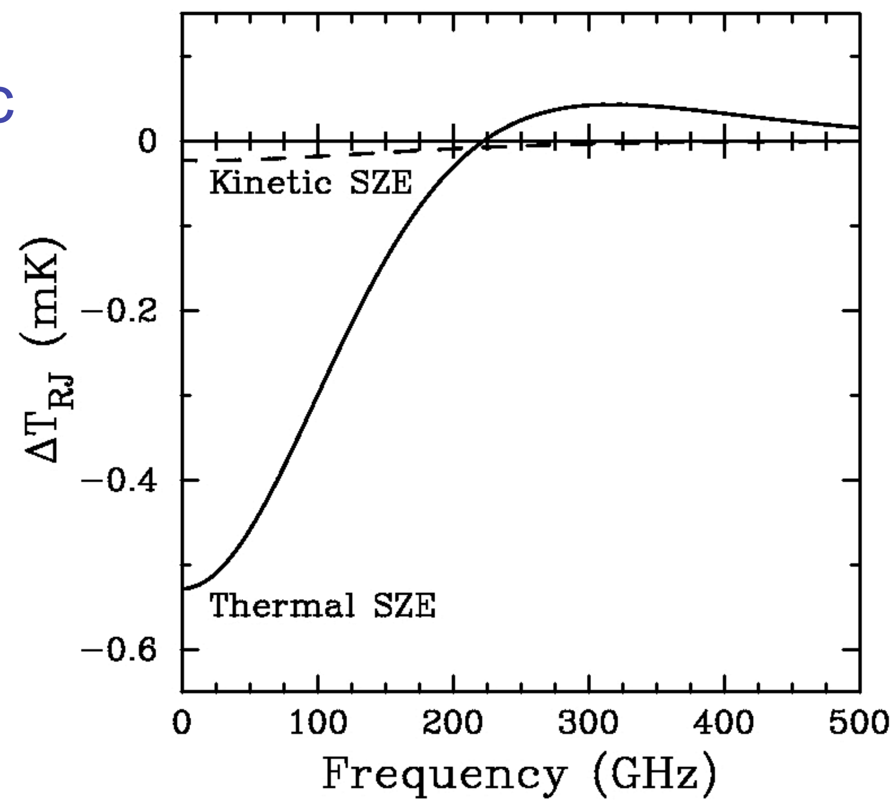
Properties: Kinetic SZ Effect

- e^- velocities distributed isotropically in ICM
  - Doppler effect cancels
- Cluster peculiar motion → net Doppler effect
  - Important: component of $v_{cluster}$ in line of sight
  - Doppler effect alteration is Kinetic SZ effect

Properties: Kinetic SZ Effect

- Retains the black-body shape, but changes temperature in non-relativistic limit

$$\frac{\Delta T}{T} = -\tau_e \left(\frac{v_{cluster}}{c} \right)$$



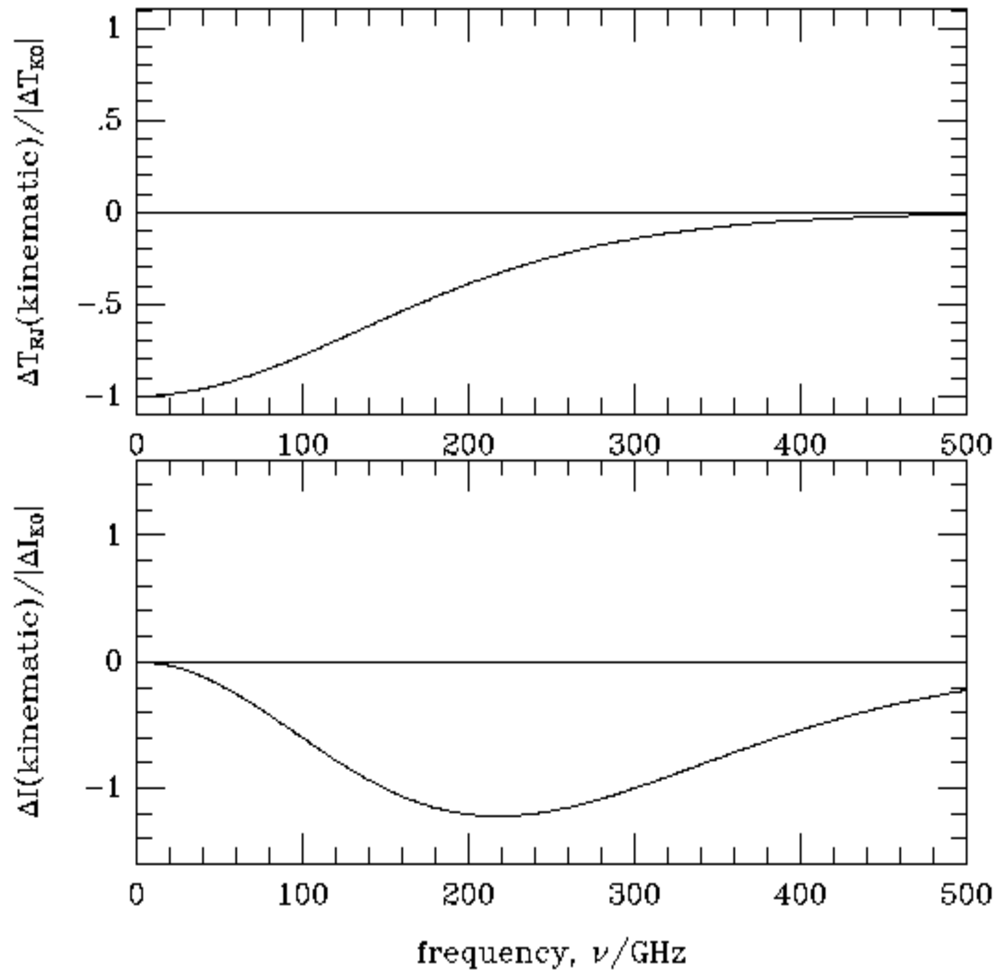
  – Positive $v_{cluster} \rightarrow$ lower temperature

  – Negative $v_{cluster} \rightarrow$ higher temperature

  – Much smaller than thermal SZE: for a (l.o.s) $v_{cluster}$ of 10^3 km/s (large!), $|\Delta T/T| \approx 3\ 10^{-5}$

Spectrum of kinetic effect

- effect caused by reference frame change, related to CMB spectrum
- No zero
- maximum at peak of CMB spectrum
- negative of CMB spectrum

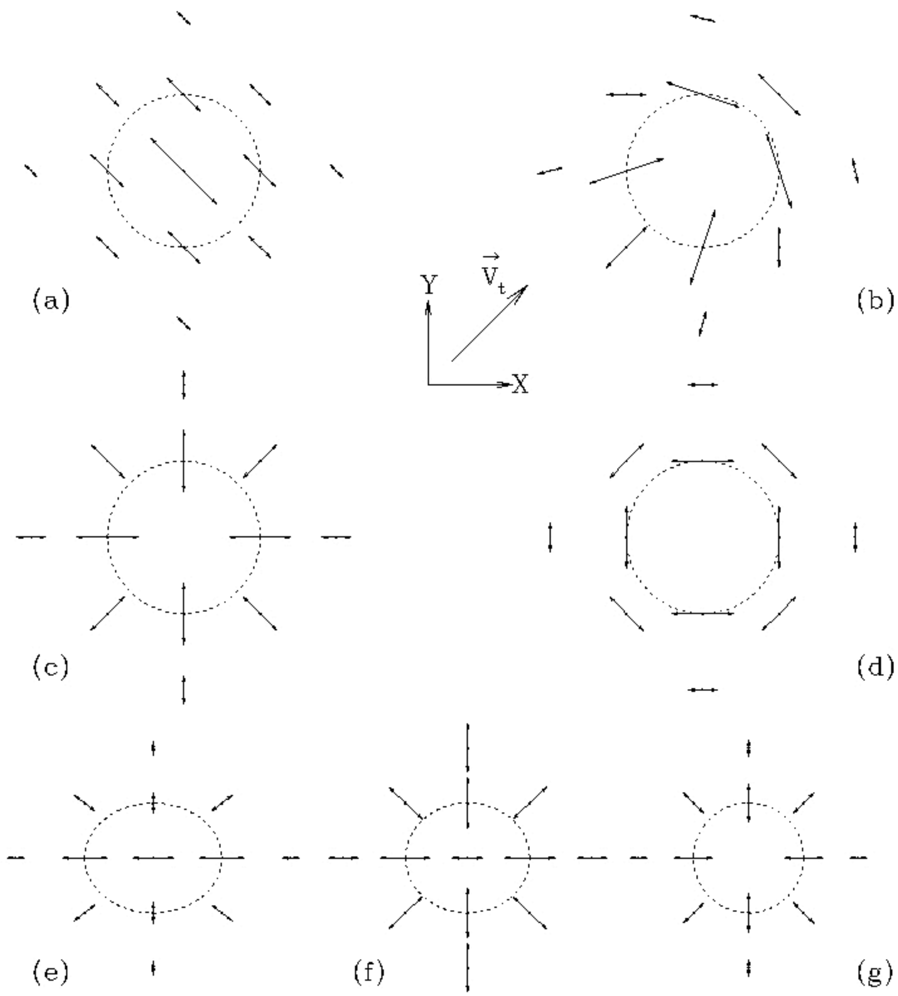


Polarization

Possible mechanisms to produce effects on the polarized intensity (Stokes Q, U and V):

- **Multiple scatterings** of photons within a scattering atmosphere
- **Scattering of the thermal SZ effect** by the same plasma producing the effect
- **single scatterings** of the quadrupolar term in the anisotropic radiation field seen in the frame of the moving cluster
- **Repeated scatterings** of the dipolar term

Effects depend on higher powers of the optical depth and velocity, then are expected to be much smaller than tSZ and kSZ, **not detectable with the current generation of experiments** (but non-thermal SZ?)



Rephaeli et al. 2005

Summary: the attributes of SZ effect

- ΔT_{RJ} is a redshift-independent function of cluster properties only. If the gas temperature is known, it is a <u>leptometer</u>
- ΔT_{RJ} contains a weak redshift-independent kinematic effect, it is a <u>radial speedometer</u>
- ΔT_{RJ} has a strong association with rich clusters of galaxies, it is a <u>mass finder</u>
- ΔT_{RJ} has polarization with potentially more uses, but signal is tiny

From Birkinshaw

Science results

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

Integrated SZE

- Total SZ flux density

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

==> we can measure in redshift-independent way the thermal energy

Virial theorem: SZ flux density could allow a good measurement of **gravitational potential energy**

Integrated SZE

- Total SZ flux density

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

If a (X-ray) estimate of the temperature is available, then SZ flux density measures electron count N_e (and hence baryon count)

Combine with X-ray derived mass to get f_b

SZ effect structures

- Currently only crudely measured by any method (restricted angular dynamic range)
- X-ray based structures superior
- Structure should be more extended in SZ than in X-ray because of n_e rather than n_e^2 dependence: ==> good SZ structure should extend out further and show more about halo
- Angular dynamic range issue: limitation of array sizes (radiometer, interferometer, bolometer), and CMB confusion
- Needed sensitivity: at μJy level on 10 arcsec to 120 arcsec scales

Science results: 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
- Evolution of the Microwave background temperature

Cosmological Parameters: H

- Galaxy Clusters emit in the X-ray band (bremsstrahlung)

  – The dependence on electron density n_e is different with respect to the thermal SZ effect:

$$\Delta T_{SZE} \propto \int n_e T_e dl$$

- Thermal SZ temperature fluctuation

$$S_x \propto \int n_e^2 \Lambda_{eH} dl$$

- X-ray emission
  – Λ_{eH} is X-ray cooling function

Cosmological Parameters: H

- but $dl = D_A \, d\zeta$

$$D_A \propto \frac{(\Delta T_0)^2 \Lambda_{eH0}}{S_{x0} T_{e0}^2} \frac{1}{\theta_c}$$

- Solving for D_A:
  - Quantities are computed through cluster center along the line of sight
  - θ_c: cluster angular scale along line of sight
    - Depends on the assumed density model for cluster

Cosmological Parameters: H

- 2 assumptions made:

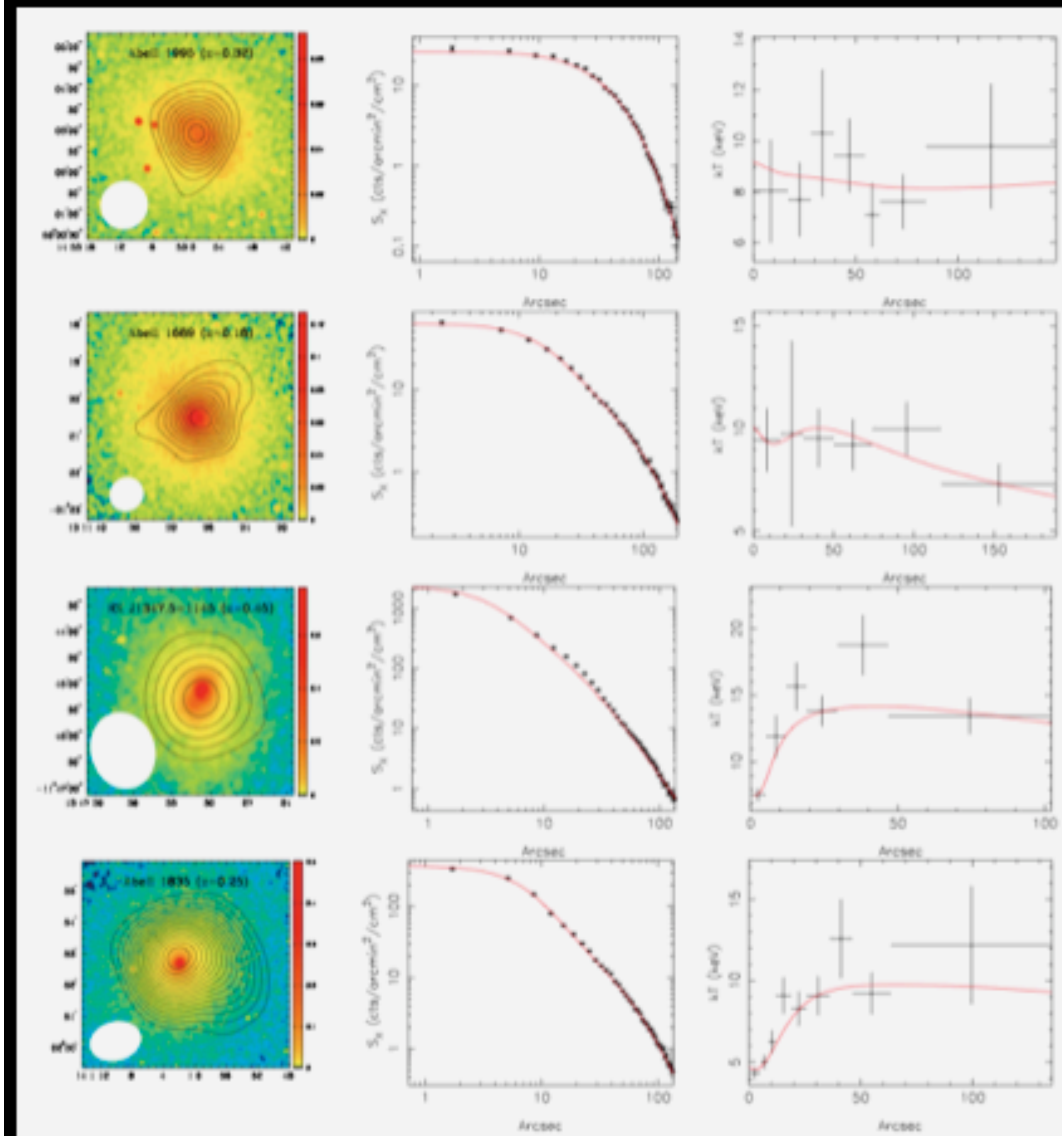
  1. θ_c assumed equal to angular scale subtended on sky by cluster

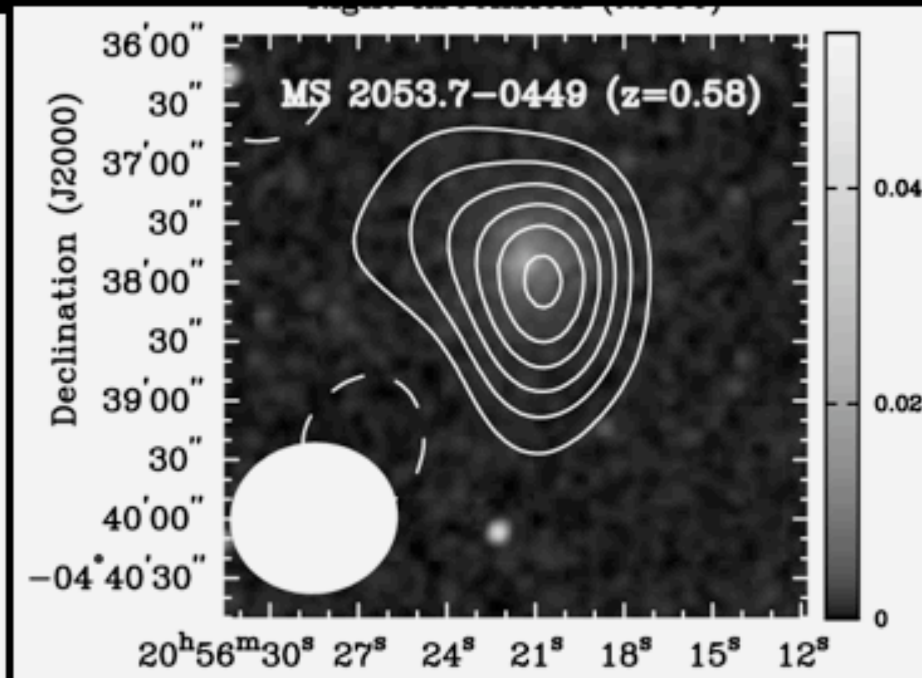
  2. Along line of sight through cluster, assume

$$\langle n_e^2 \rangle^{1/2} = \langle n_e \rangle$$

  – True when little substructure (homogeneous)

Measurements of H_0 with SZ

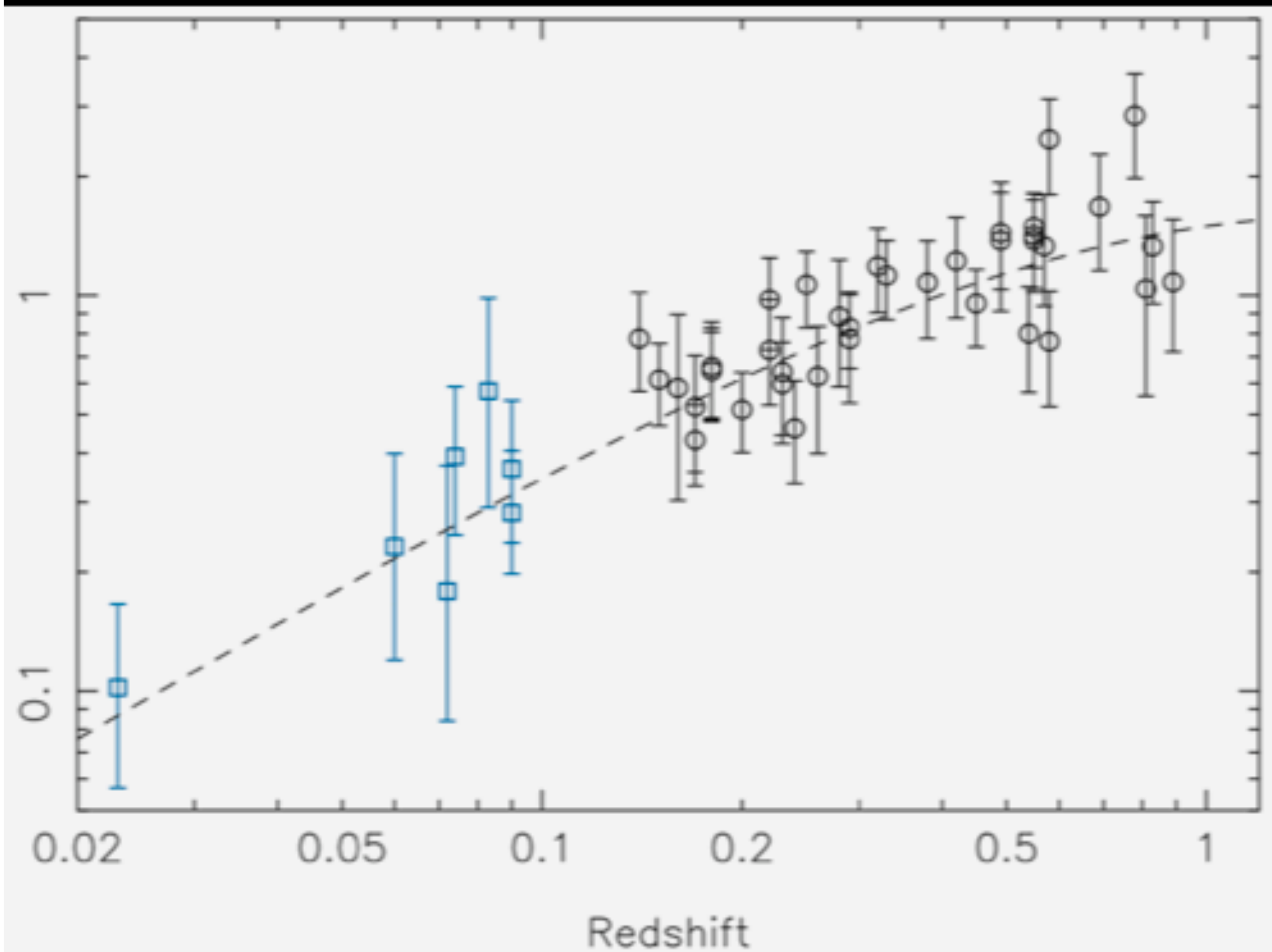




Bonamente et al. 2006

Used decrement to measure Hubble constant:
H_0= 77+/-10 km/s/Mpc

Measured distances



Bonamente et al. 2006

Measured Hubble constant:

H_0= 77+/-10 km/s/Mpc

Error Budget

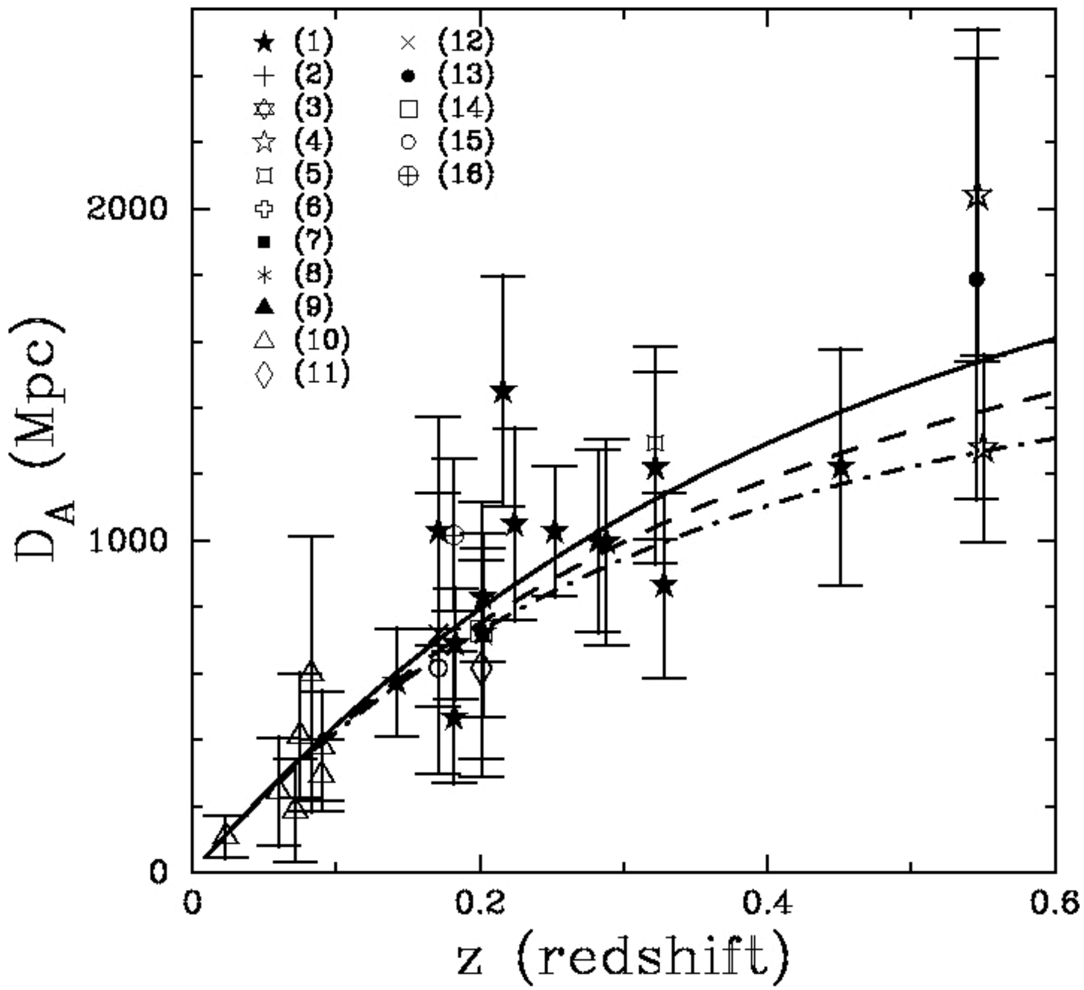
Myers

- CMB anisotropies – the dominant uncertainty
- density model – β models, some bias correction needed
- temperature profiles – assume isothermal, investigate deviations
- radio point sources – residuals small after using counts
- cluster asphericity – < 4%, could be worse in individual clusters
- clumpy gas distribution – $\langle n_e^2 \rangle / \langle n_e \rangle^2$ bias, substructure?
- peculiar velocities – no bias, 0.04% for even 1000 km/s!
- non-thermal Comptonization – unknown, model dependent

Cluster	CMB error	X-ray mod bias	pt src bias	T_e error	V_{pec} error	CMB+Ther+ptsc error
A85	±0.36	1.01	+0.00	0.03	0.05	±0.38
A399	±0.42	1.01	+0.02	0.03	0.05	±0.42
A401	±0.27	1.01	+0.03	0.05	0.04	±0.27
A478	±0.25	1.00	+0.00	0.10	0.04	±0.25
A754	±0.26	1.04	+0.02	0.02	0.04	±0.29
A1651	±0.43	1.00	+0.00	0.06	0.06	±0.44
A2597	±1.06	1.00	+0.01	0.09	0.08	±1.07

Cosmological Parameters: H

- Gives redshift z directly $\rightarrow$ $H(z)$
- Current data beginning to map out expansion history
  - More clusters $\rightarrow$ better statistics



Cosmological Parameters: Ω_M

- Can determine total mass contributing to gravity in cluster using thermal SZE data
  - ΔT_{SZE} and T_e of ICM gas
  - 2 assumptions
    - Hydrostatic equilibrium
    - Specific gas distribution

Cosmological Parameters: Ω_M

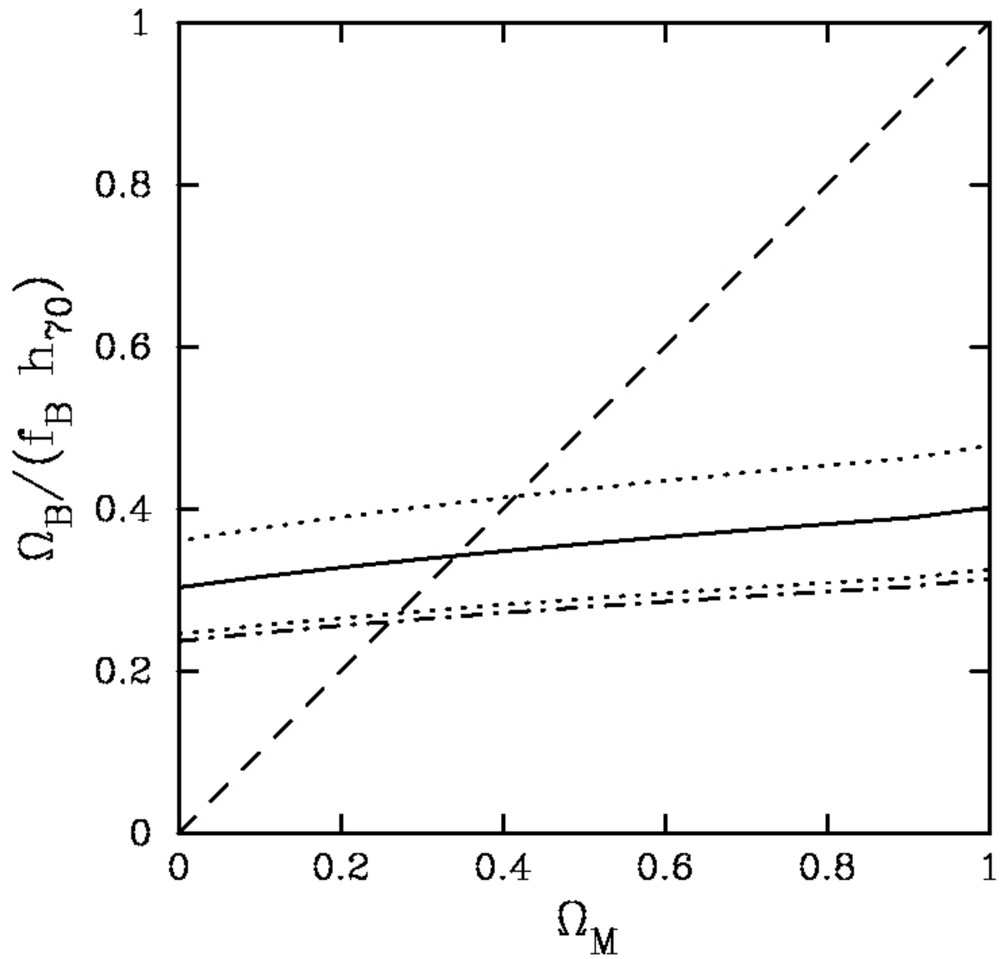
- Generally ICM contains most baryonic matter
- Divide by total gravitational mass yields gas mass fraction, f_g:

$$f_g \propto \frac{\Delta T_{SZE}}{T_e^2} \le f_B \equiv \frac{\Omega_B}{\Omega_M}$$

  - f_g assumed essentially the same as baryonic mass fraction of the universe, f_B
    - Lower bound for f_B

Cosmological Parameters: Ω_M

- Ω_B constrained by other observations
  - Gas mass fraction gives limits on Ω_M and Ω_{DM} as well if Ω_{Total} is known



Velocity field: v_z

- Kinetic effect can be separated from thermal SZE because of the different spectrum
- Confusion with primary CMB fluctuations limits v_z accuracy (typically to 150 km s^{-1})
- Velocity substructure can reduce accuracy further
- Statistical measure of velocity distribution of clusters as a function of redshift in samples

Velocity field: v_z

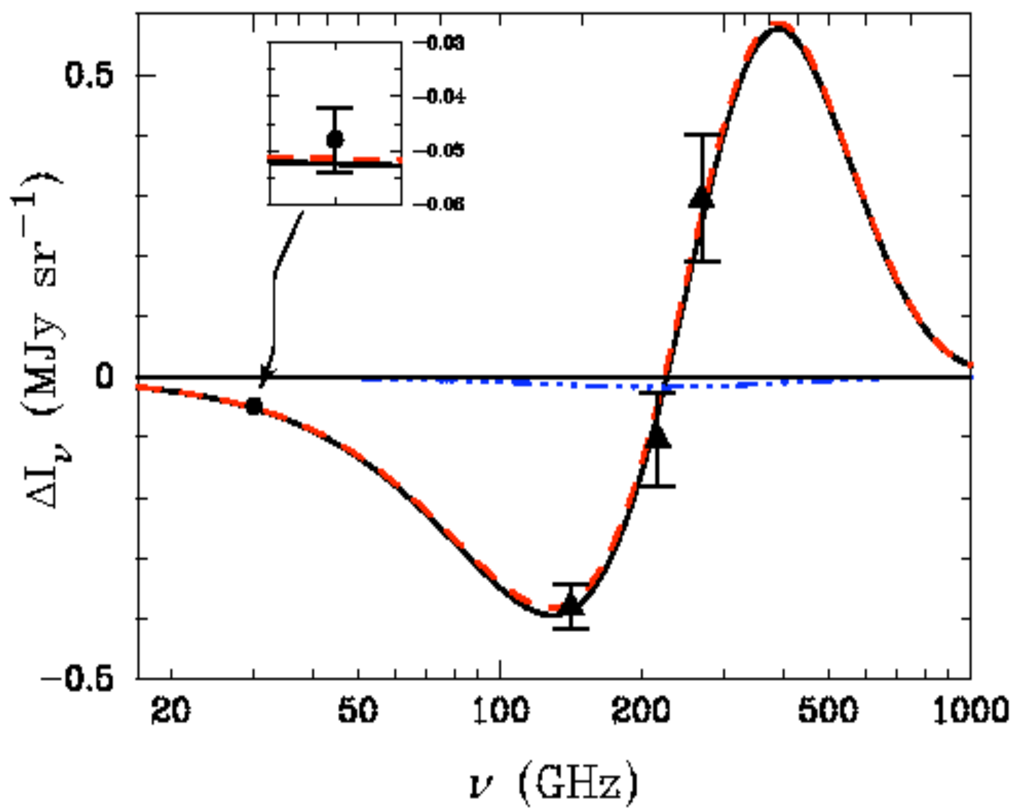
Need

- good SZ spectrum
- X-ray temperature

Confused by CMB structure

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

Errors $\approx$ 1000 km s^{-1} so far



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

SZ effect surveys

- SZ-selected samples needed for reliable cosmology
  - almost mass limited
  - flat redshift response
- X-ray samples
  - SZ follow-ups for X-ray-derived samples
- Optical samples
  - much used in past, line-of-sight confusion problem
- 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

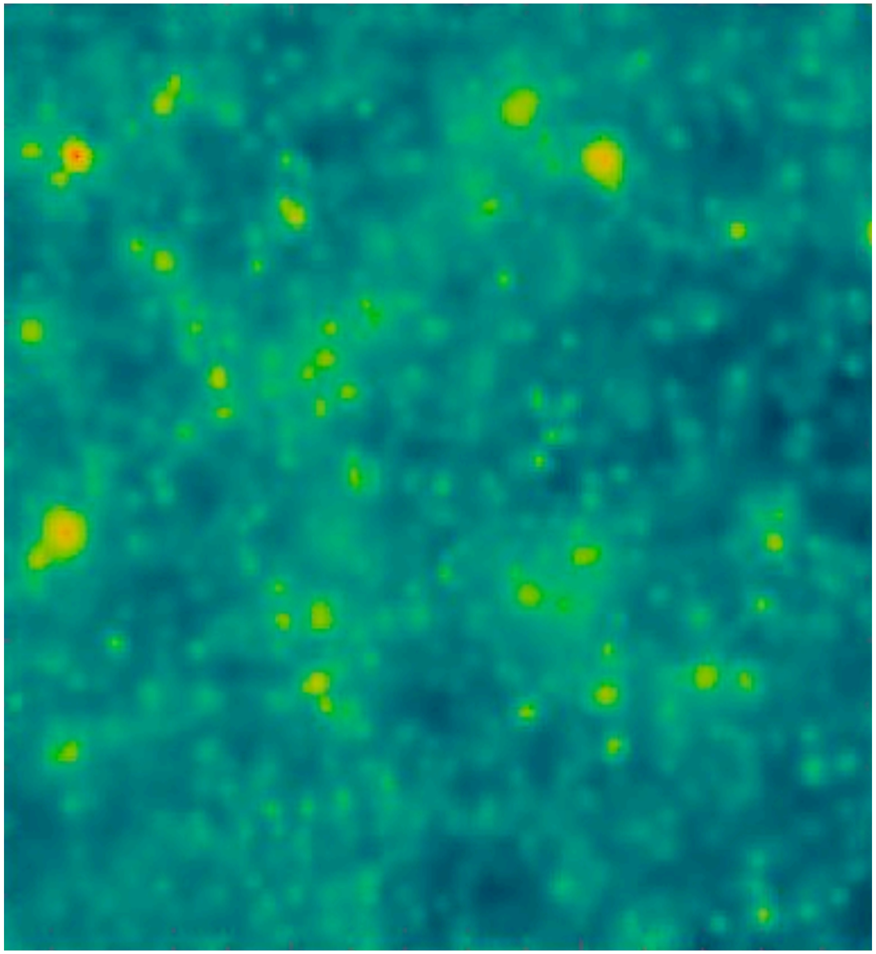
SZE sky

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

Primordial fluctuations ignored

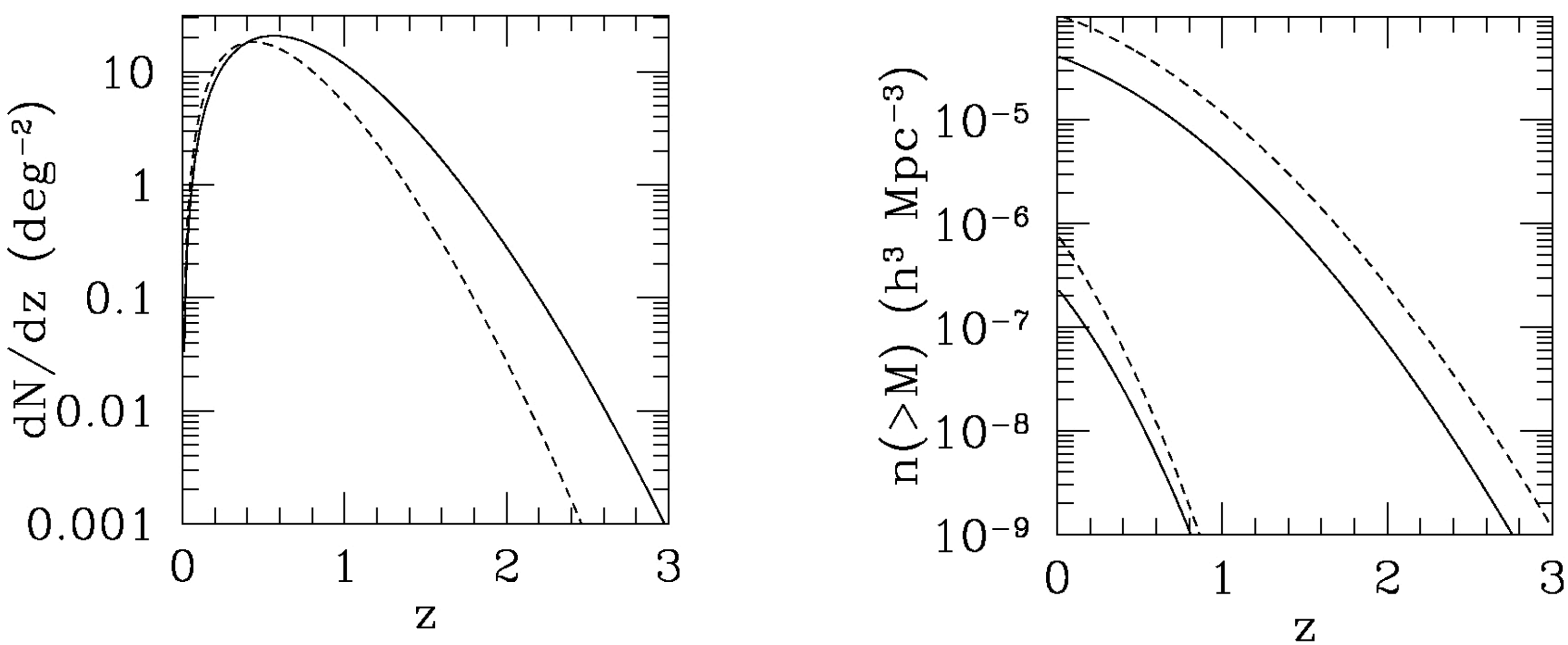
Cluster counts strong function of cosmological parameters and cluster formation physics.

Birkinshaw



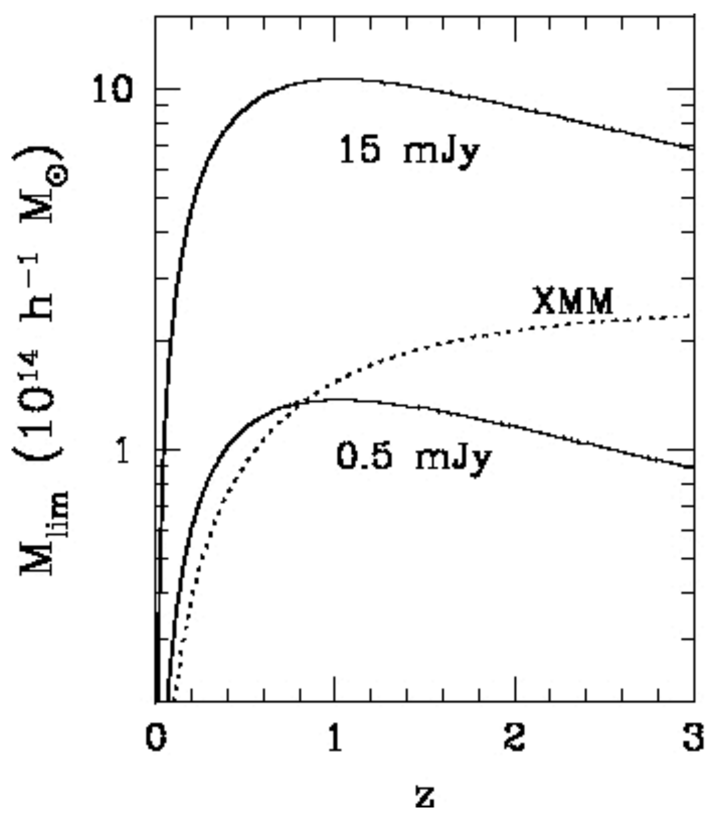
Cluster counts and cosmology

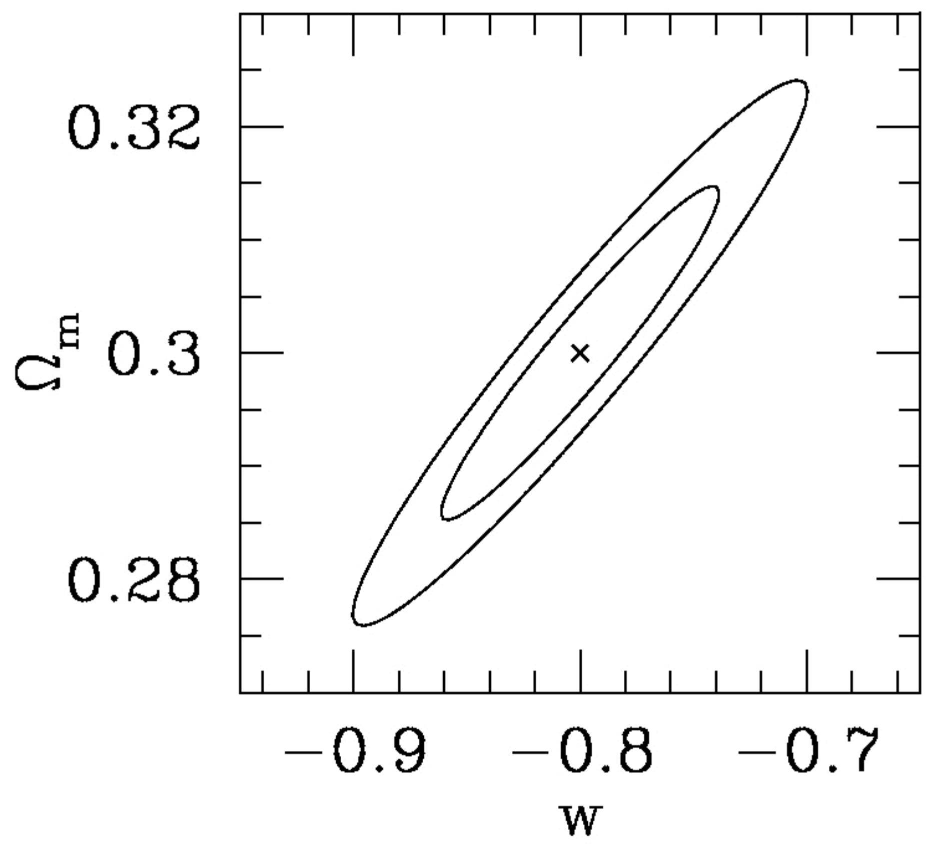
Cluster counts and redshift distribution provide strong constraints on σ_8, Ω_m and cluster evolution.



Carlstrom et al.

Cluster counts and cosmology





Carlstrom et al.

Evolution of the Microwave background temperature

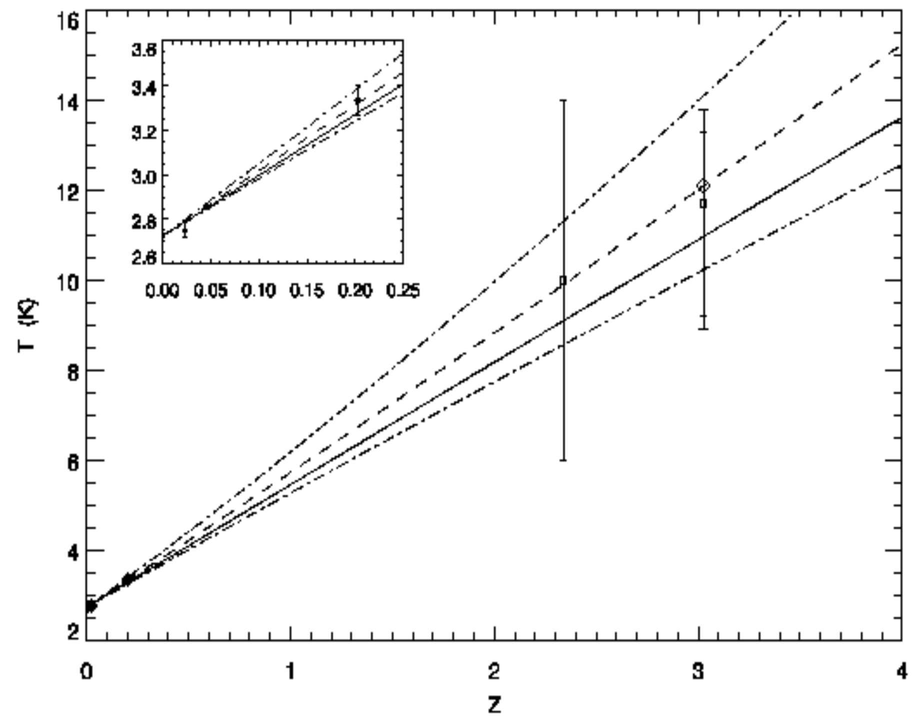
- Ratio of SZ effects at two different frequencies is a function of CMB temperature (with a slight dependence on T_e and cluster velocity)

==> use SZ effect spectrum to measure CMB temperature at distant locations and over range of redshifts

- **Test $T \propto (1 + z)$**

Microwave background temperature

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



Battistelli *et al.* (2002)

Requirements on observations

Use	Size (mK)	Critical issues
Energetics	0.50	Absolute calibration
Baryon count	0.50	Absolute calibration; isothermal/spherical cluster; gross model
Gas structure	0.50	Beamshape; confusion
Mass distribution	0.50	Absolute calibration; isothermal/spherical cluster
Hubble diagram	0.50	Absolute calibration; gross model; clumping; axial ratio selection bias

Birkinshaw

Requirements on observations

Use	Size (mK)	Critical issues
Blind surveys	0.10	Gross model; confusion
Baryon fraction evolution	0.10	Absolute calibration; isothermal/spherical cluster; gross model
CMB temperature	0.10	Absolute calibration; substructure
Radial velocity	0.05	Absolute calibration; gross model; bandpass calibration; velocity substructure

Birkinshaw

Requirements on observations

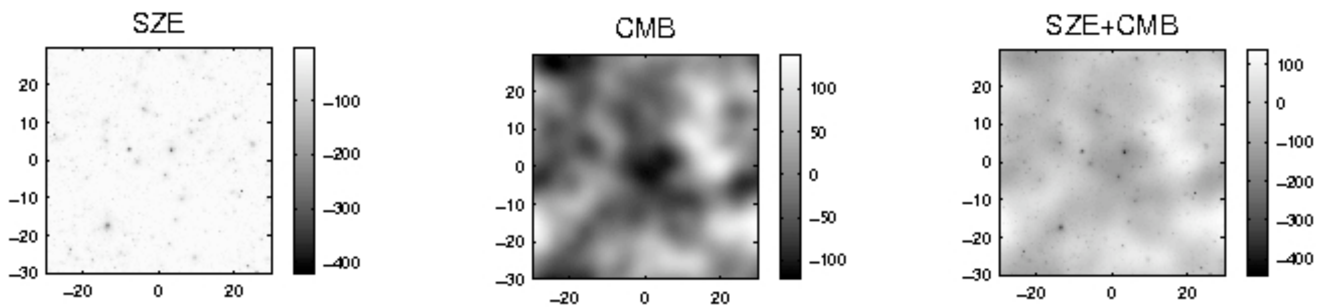
Use	Size (mK)	Critical issues
Cluster formation	0.02	Absolute calibration
Transverse velocity	0.01	Confusion; polarization calibration

Birkinshaw

Observational Problems

Systematics

The SZ signal is weak



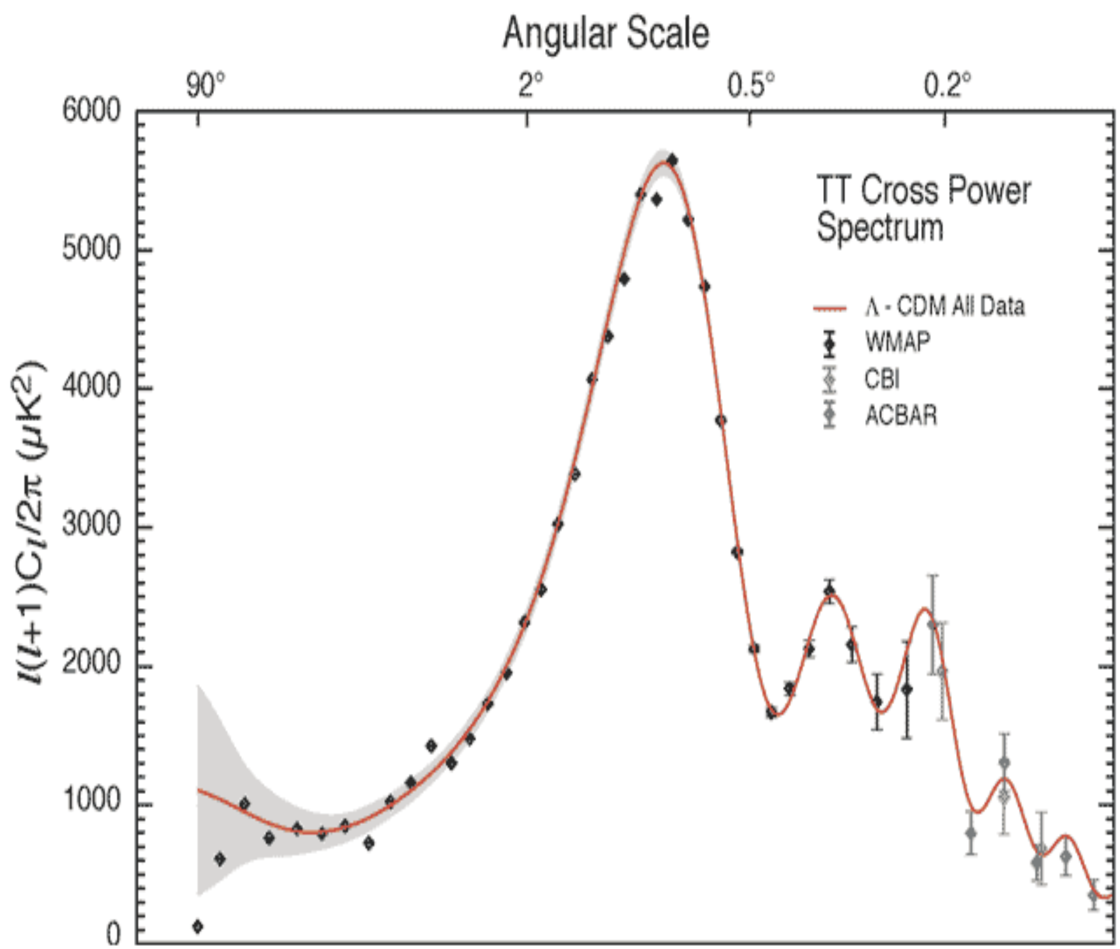
The SZ signals are dominated by systematics:
necessity of differential measurements

Possible sources of systematics:

- CMB anisotropies
- ground noise
- radio sources
- detector calibration
- earth atmophere

Observational Problems: Primary Anisotropies

- Recall the characteristics of the CMB power spectrum (see Balbi)
  - Prevalent at ~ degree scale
  - Begin damping at ~ arcminute scale

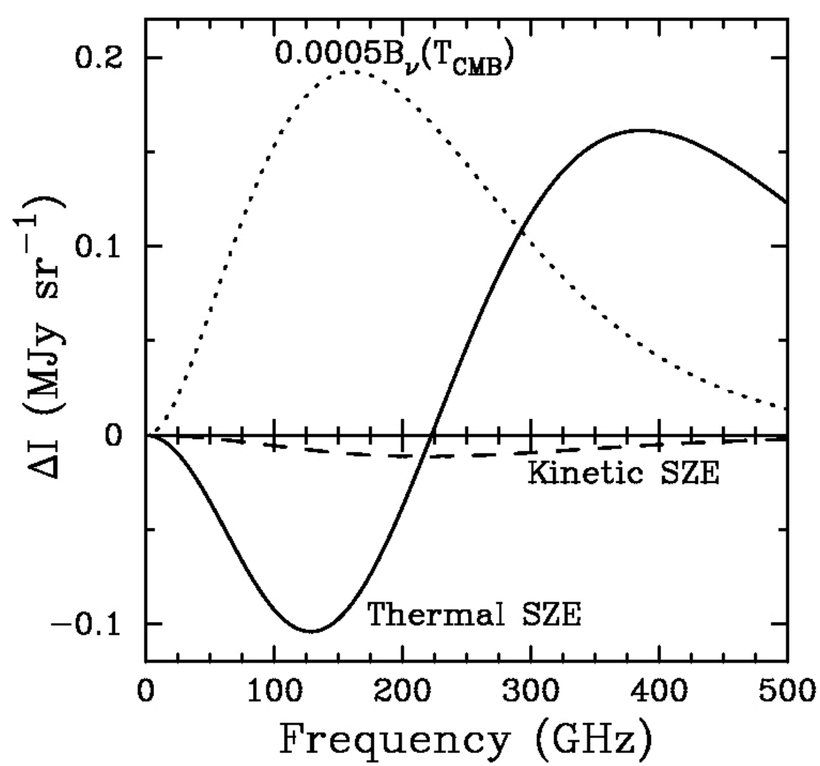


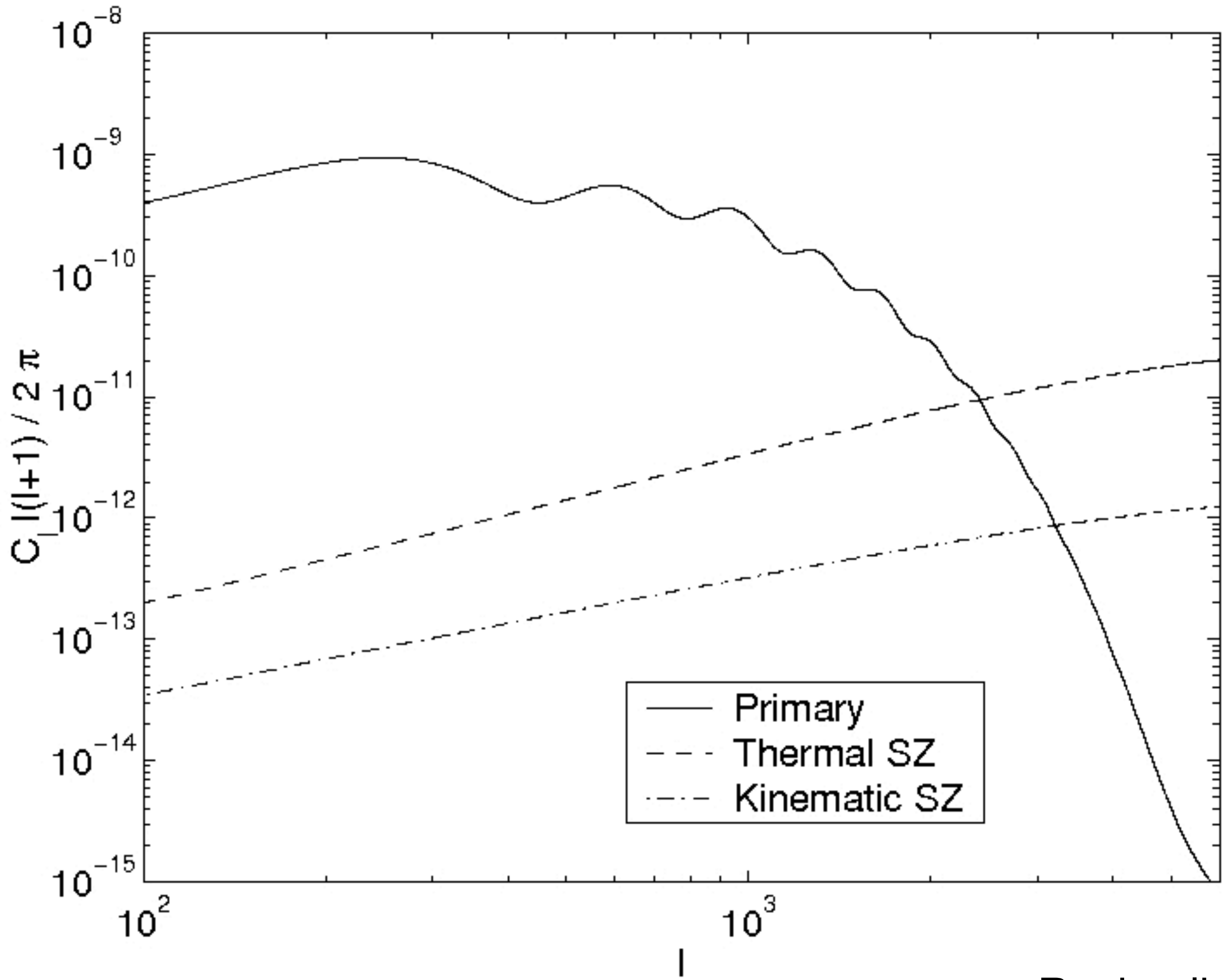
Observational Problems: Primary Anisotropies

- Thermal SZE very weak compared to acoustic peaks

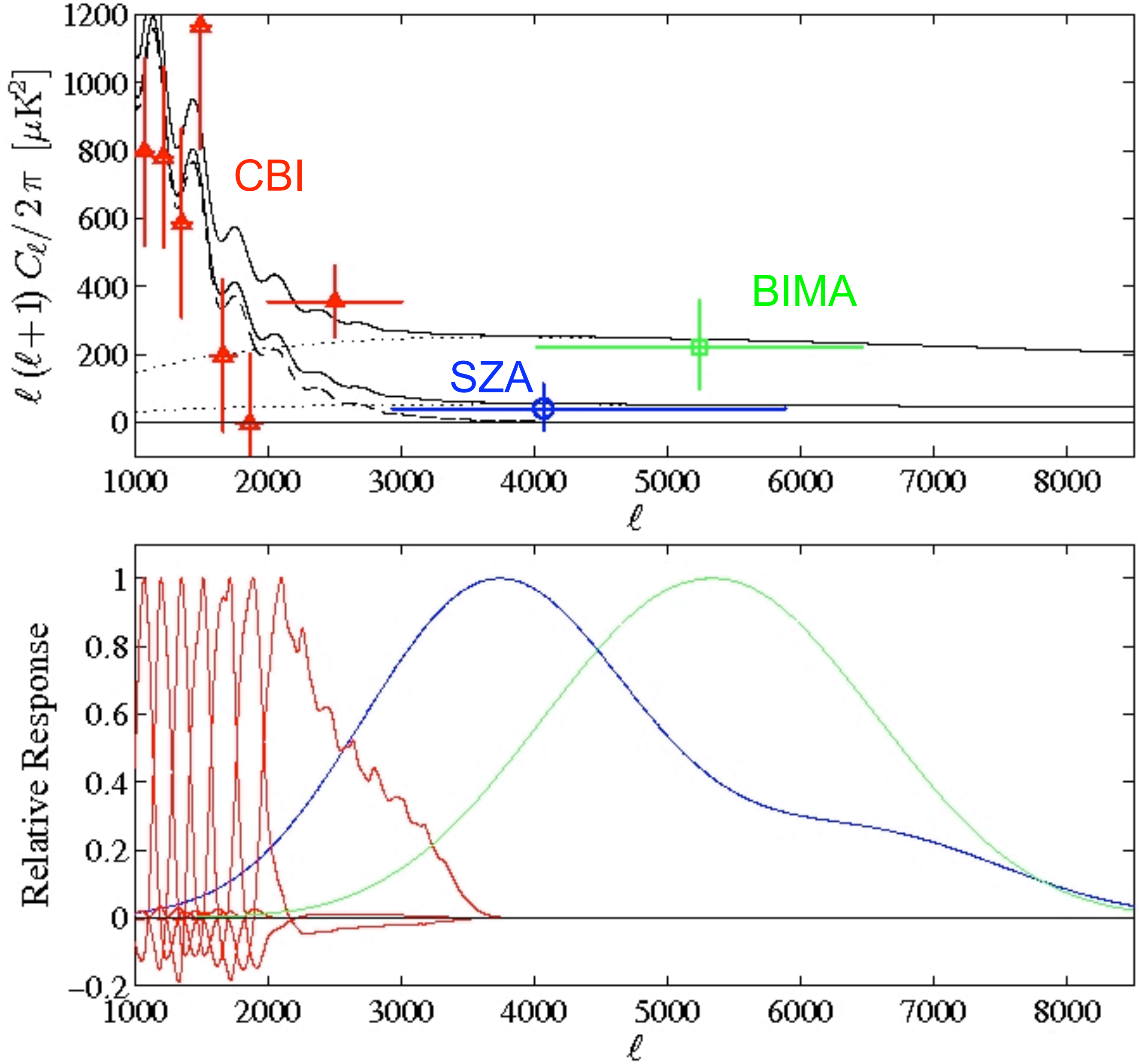
  – Requires great precision to see its effect

- Easiest to detect at small angular scales $\rightarrow$ High resolution





Rephaeli et al.



SZ measurement @ 30 GHz

Window funct.

Sharp et al. 2009

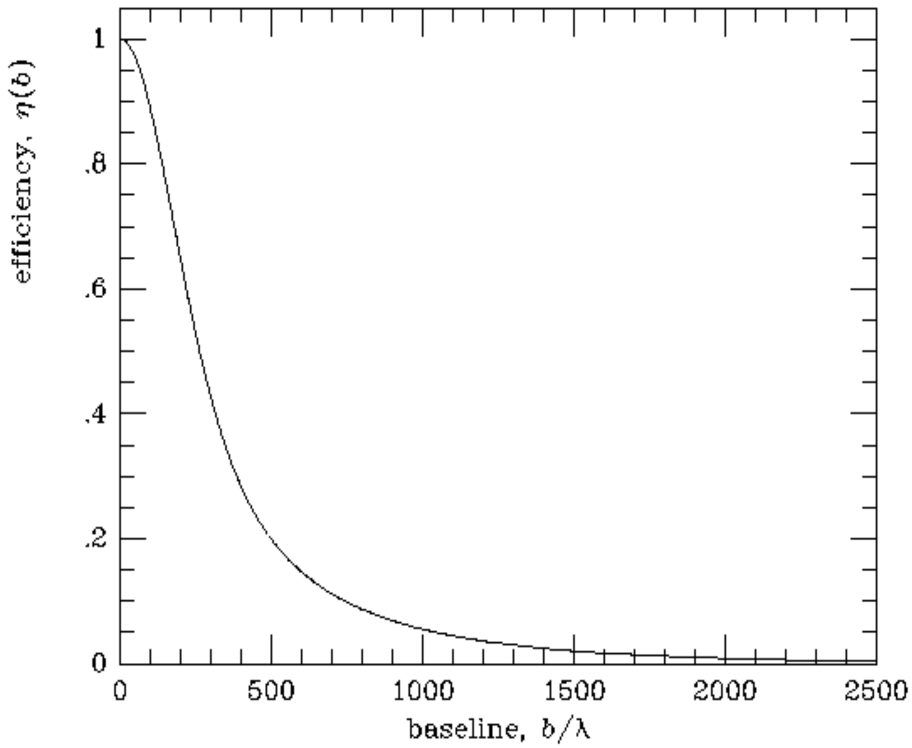
SZ observations today

- Interferometers
  - Structural information
  - Baseline range
- Single-dish radiometers
  - Speed
  - Systematic effects
- Bolometers
  - Frequency coverage
  - Weather

see Birkinshaw

Interferometers

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



Abell 665 model, VLA observation

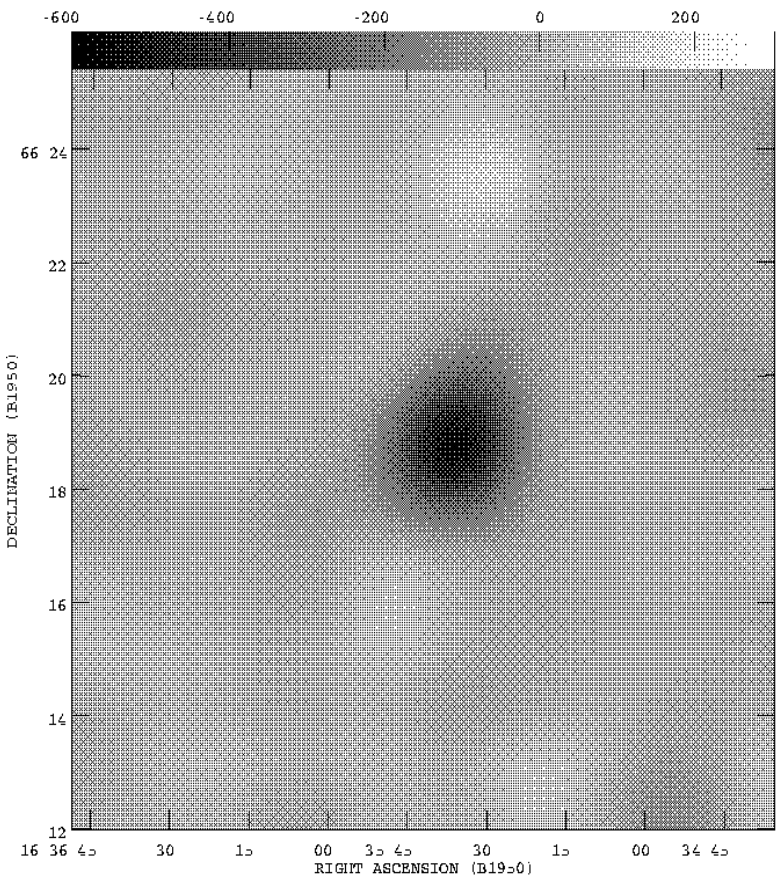
Interferometers

- good sky and ground noise rejection because of phase data
- long integrations and high signal/noise possible
- SZ detected for cluster redshifts up to $z=1$

Ryle telescope

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

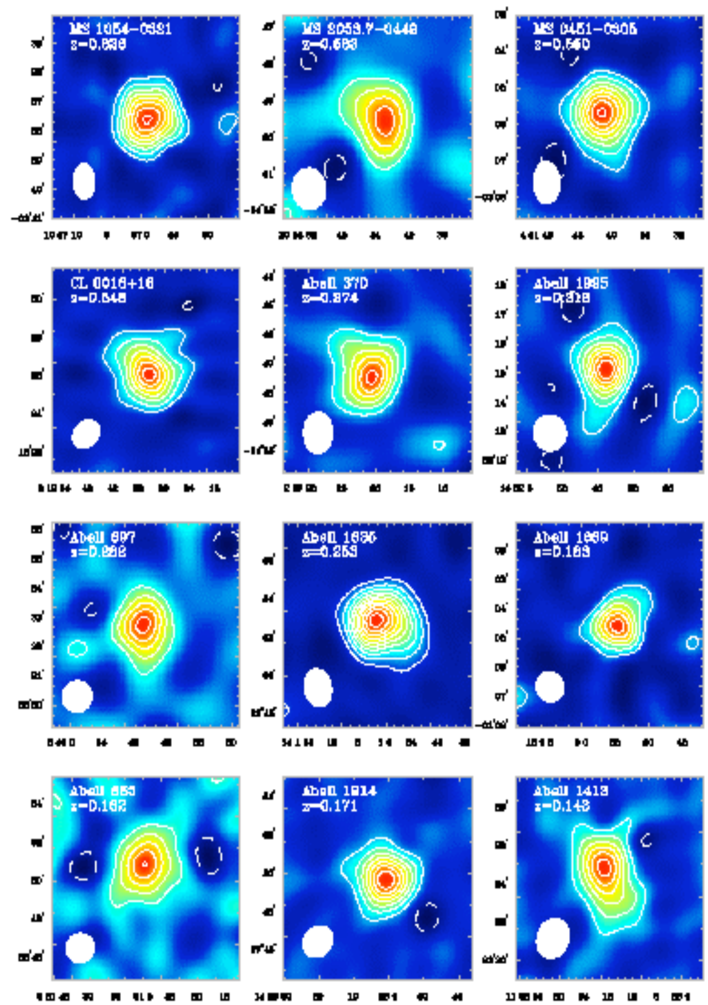
Jones *et al*. 1993



BIMA/OVRO

- limited angular dynamic range
- high signal/noise (with enough t_{int})
- clusters easily detectable to $z \approx 1$

Carlstrom *et al*. 1999



Single-dish radiometers

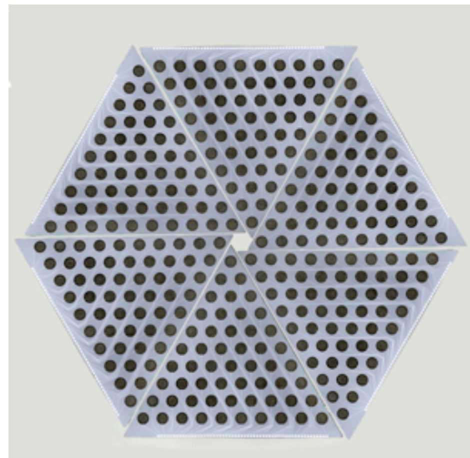
- Potentially fast way to measure SZ effects of particular clusters
- Multi-beams better than single beams at subtracting atmosphere, limit cluster choice
- Less fashionable now than formerly: other techniques have improved faster

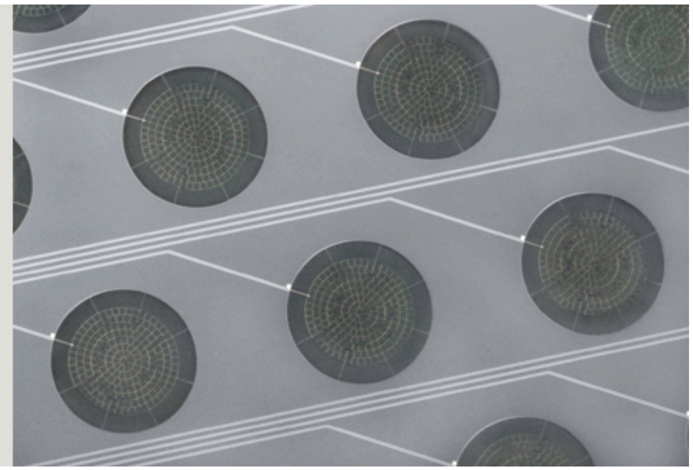
Bolometers

- Should be 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

The OVRO (Owens Valley Radio Observatory)
40-Meter and 5.5-Meter Telescope

APEX-SZ

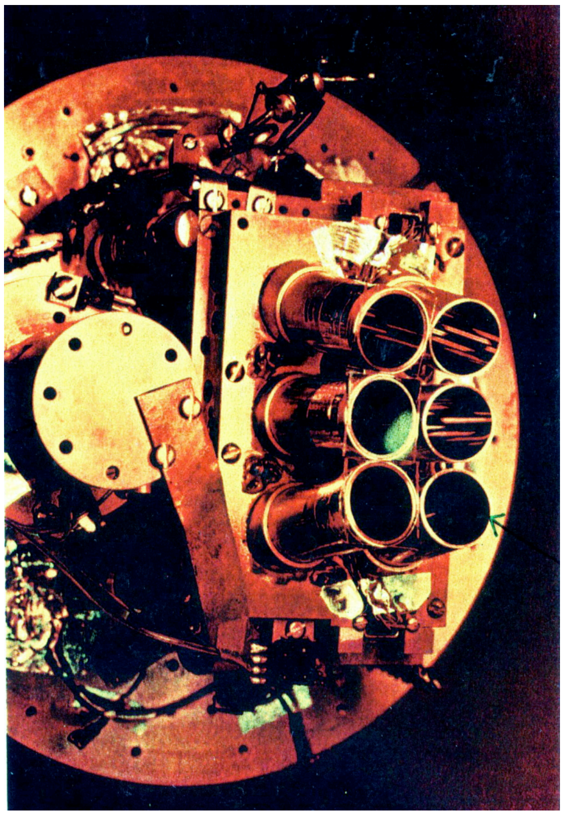


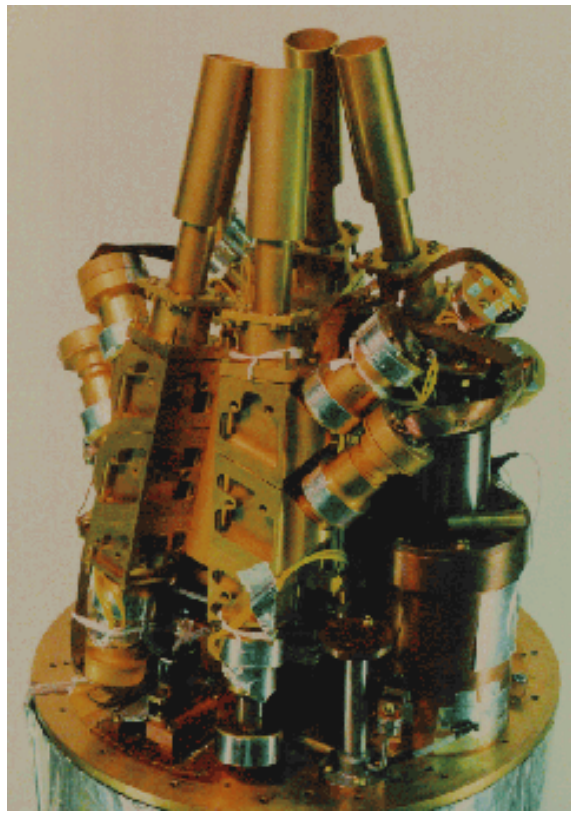


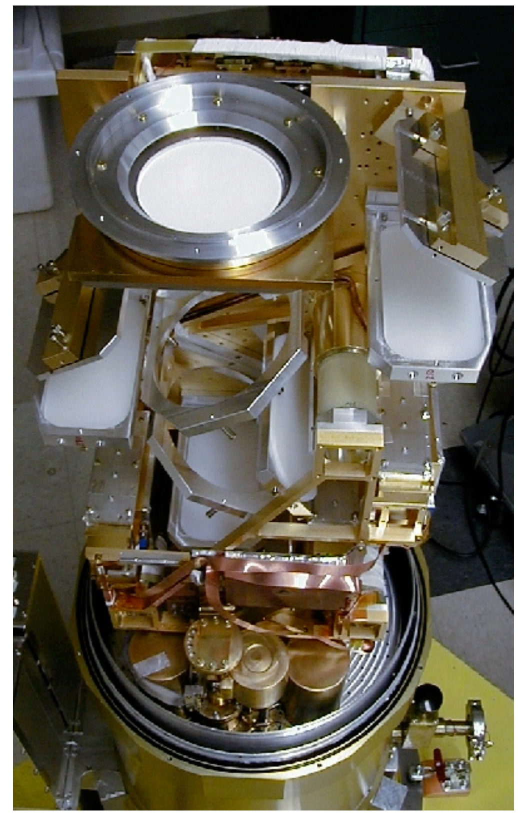
- 330 element transition edge sensor (TES) monolithic bolometer array
- 0.4 degree field of view
- Single color observations at 2 and 1.4 mm wavelengths
- Single-moded horn coupled array for RF and stray light shielding
- SQUID readouts on individual bolometers
- Survey 200 square degrees to 10 micro-K_CMB sensitivity per 0.8' pixel in two seasons at 2 mm wavelength
- Single detector NET of 350 micro-K √ s
- Pulse-tube cooler-based cryostat to eliminate liquid cryogens

SuZIE

The Sunyaev-Zel'dovich Infrared Experiment



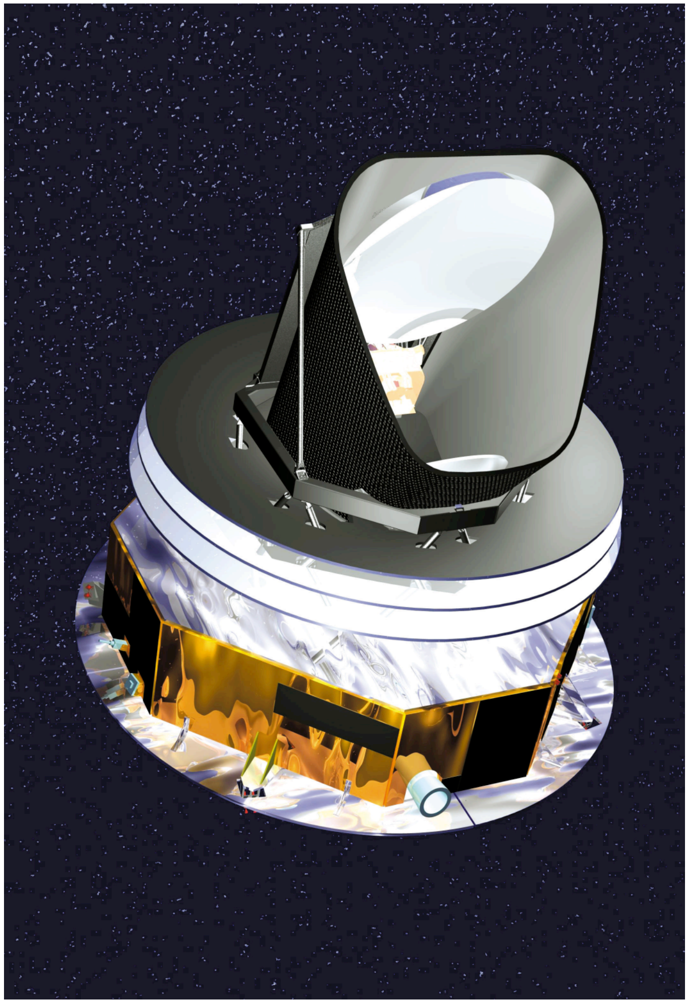




The SuZIE experiment measures the Sunyaev-Zel'dovich effect at multiple frequencies between 150 and 350 GHz, from the Caltech Submillimeter Observatory on Mauna Kea in Hawai'i.

OVMMA
(Millimeter-Wavelength Array)

The Planck Mission



The Planck Mission

Estimated Instrument Performance Goals

Telescope	1.5 m (proj. aperture) aplanatic; shared focal plane; system emissivity 1%								
	Viewing direction offset 85° from spin axis; Field of View 8°								
Instrument	LFI			HFI					
Center Freq. (GHz)	30	44	70	100	143	217	353	545	857
Detector Technology	HEMT LNA arrays			Bolometer arrays					
Detector Temperature	~20 K			0.1 K					
Cooling Requirements	H_2 sorption cooler			H_2 sorption + 4 K J-T stage + Dilution cooler					
Number of Unpol. Detectors	0	0	0	0	4	4	4	4	4
Number of Linearly Polarised Detectors	4	6	12	8	8	8	8	0	0
Angular Resolution (FWHM, arcmin)	33	24	14	9.5	7.1	5	5	5	5
Bandwidth (GHz)	6	8.8	14	33	47	72	116	180	283
Average $\Delta T/T_I$* per pixel#	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
Average $\Delta T/T_{U,Q}$* per pixel#	2.8	3.9	6.7	4.0	4.2	9.8	29.8		

* Sensitivity (1σ) to intensity (Stokes I) fluctuations observed on the sky, in thermodynamic temperature ($\times 10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

A pixel is a square whose side is the FWHM extent of the beam.

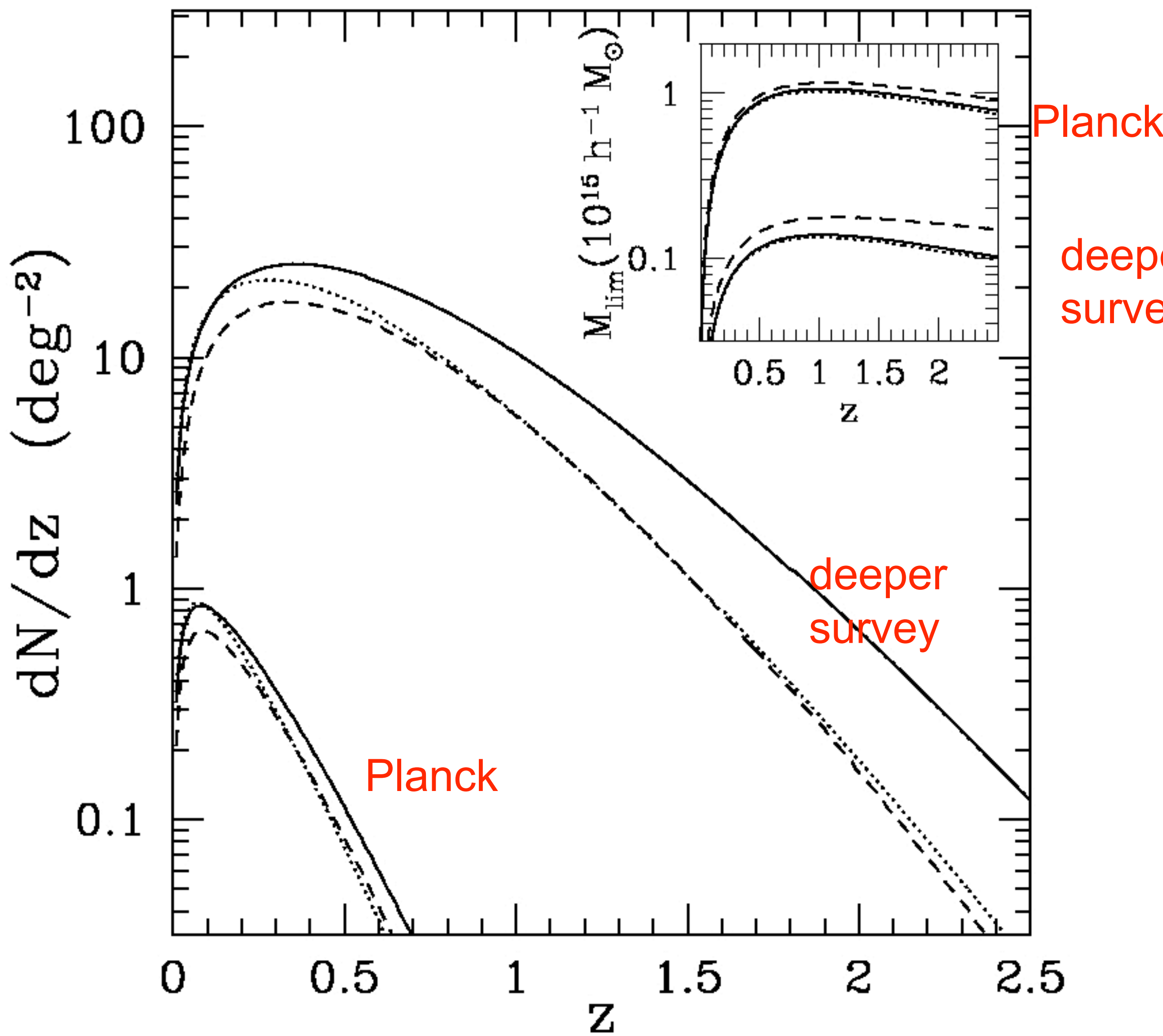
* Sensitivity (1σ) to polarised intensity (Stokes U and Q) fluctuations observed on the sky, in thermodynamic temperature ($\times 10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

PLANCK

Table last updated Feb. 2004

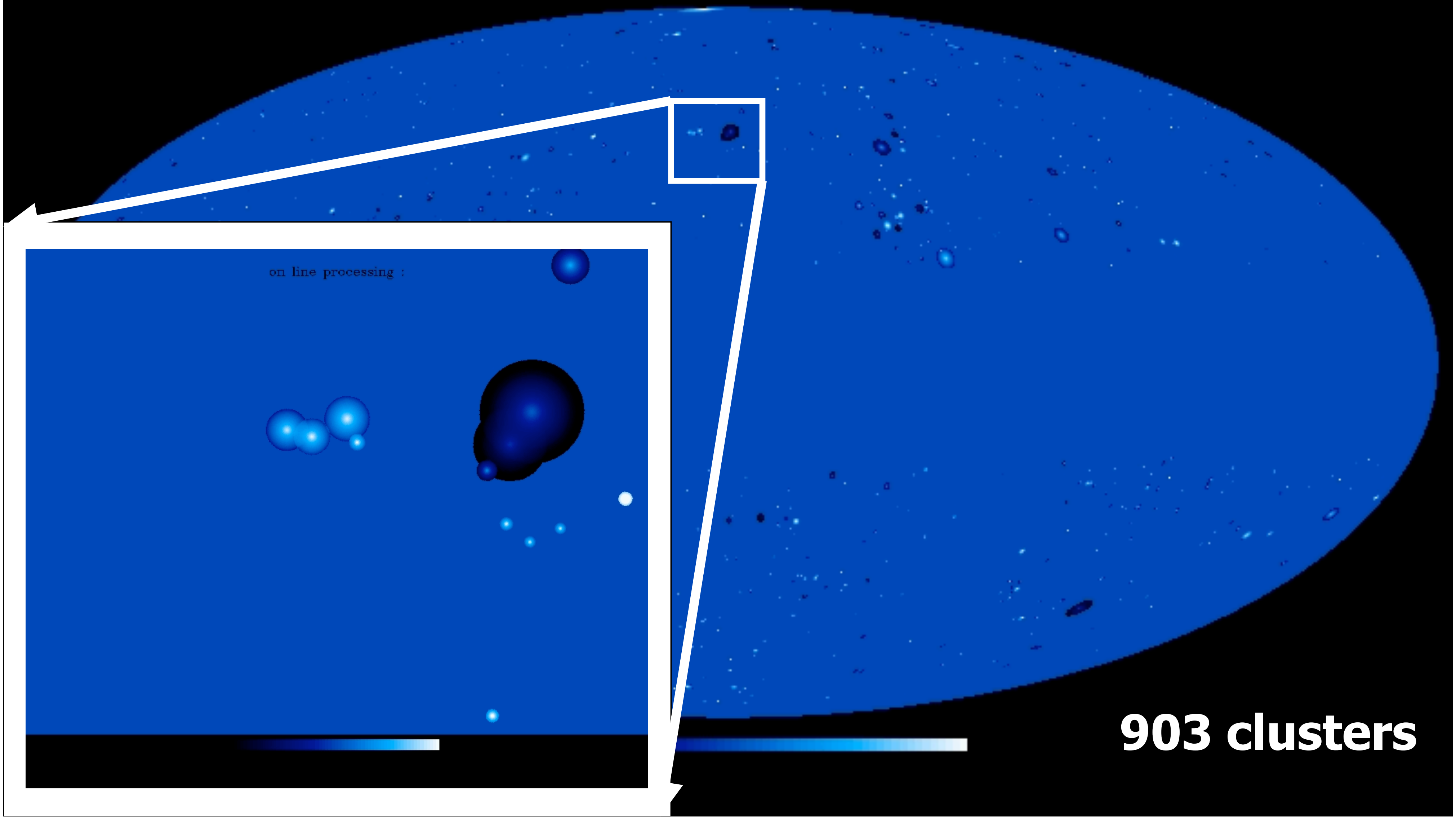
esa ASTROPHYSICS

“Optimistic” expected counts for Planck



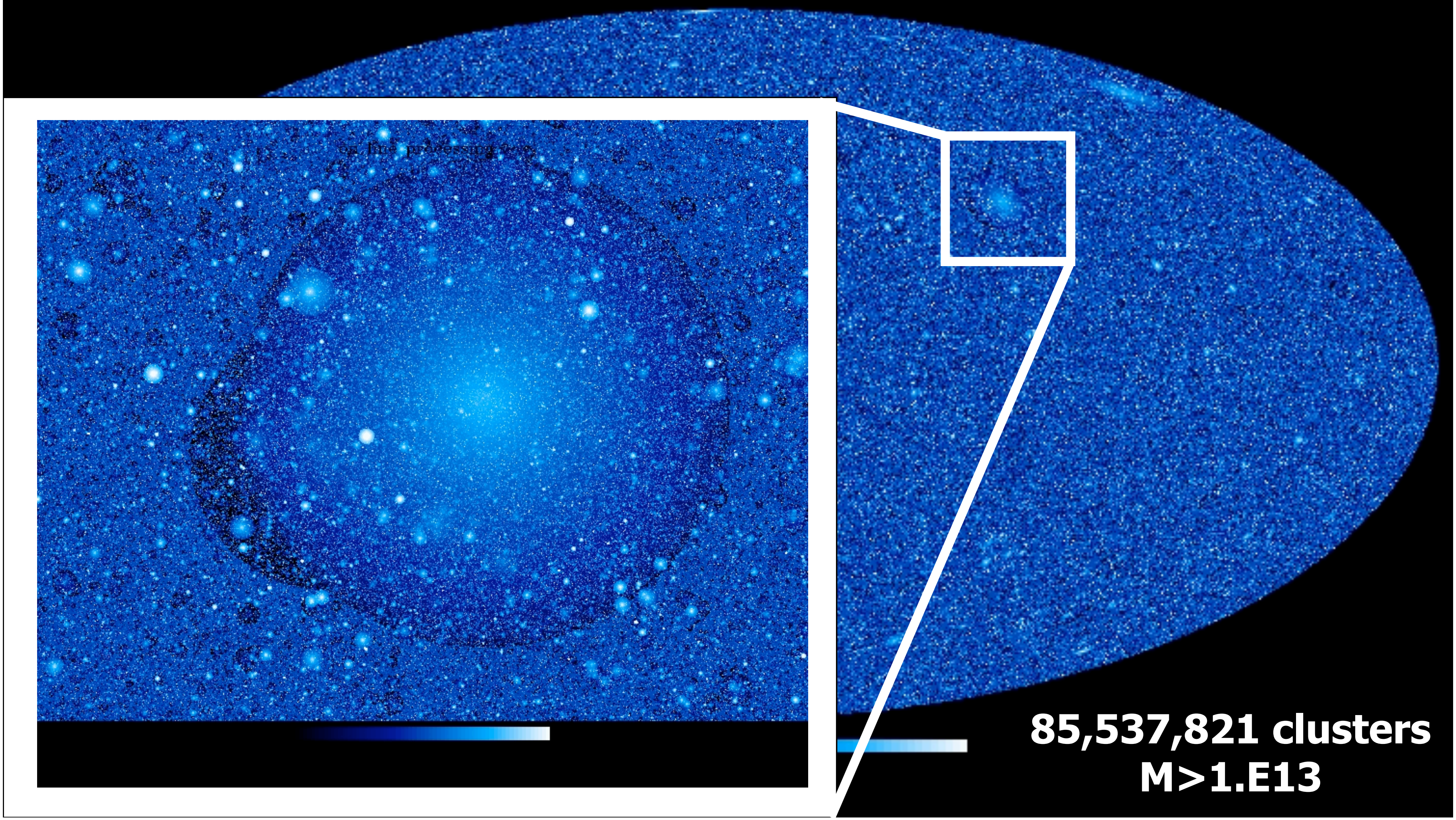
SZ sky of Known Clusters

Mazzotta



SZ sky including all clusters not detected in X-rays

Mazzotta



85,537,821 clusters
M>1.E13

An example of future project: SPT

SPT

- Joint project among:
  - University of Chicago
  - Case Western Reserve
  - University of Colorado: Boulder
  - Harvard-Smithsonian Astrophysical Observatory
  - Jet Propulsion Laboratory
  - McGill University
  - University of Illinois: Urbana-Champaign
  - University of California: Berkeley

http://spt.uchicago.edu

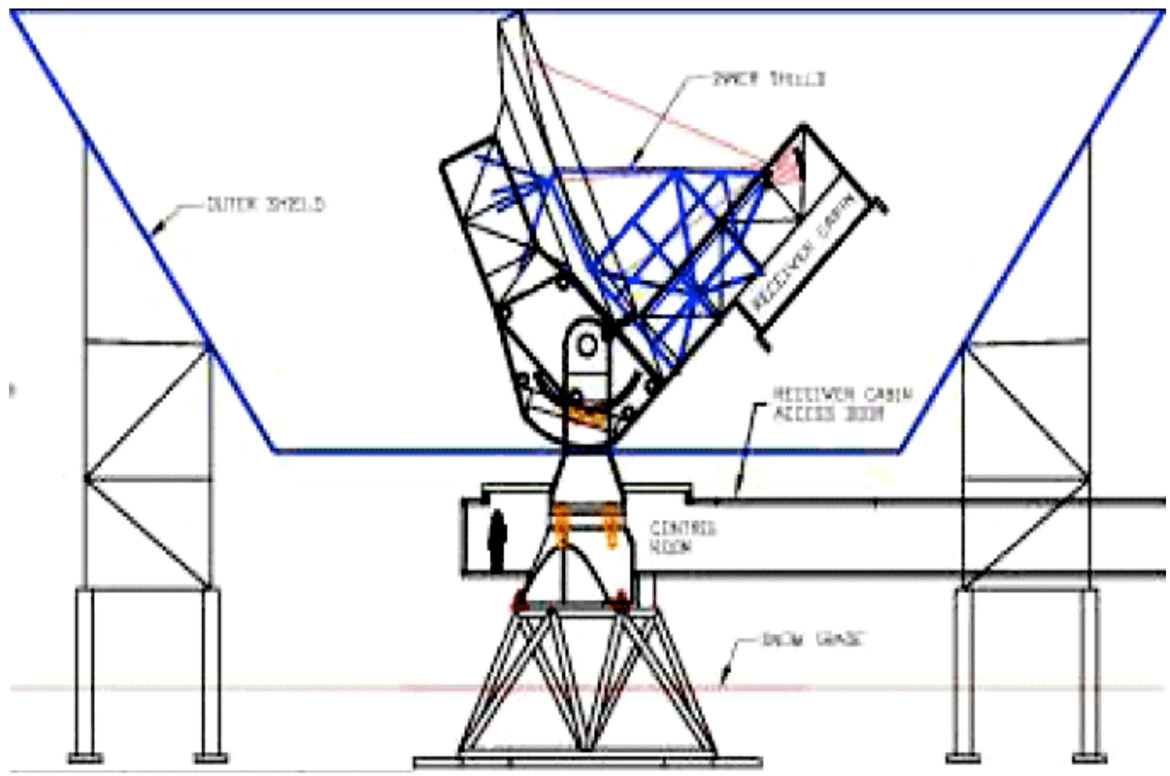
SPT

- Initial project is sky survey
  - 4000 degrees^2
  - First to *locate* clusters with SZE
    - Could find more than 20000 clusters
    - Masses higher than $2\times10^{14} M_{sun}$

http://spt.uchicago.edu

SPT

- Single dish – 10 meter diameter
  - mm & sub-mm wavelengths
    - As short as 200 μm
    - 2mm wavelength → resolution to arcminute



- Reflection screen for protection against local contaminants

Ruhl, et al., “The South Pole Telescope,” 2004, astro-ph/0411122 v1.

SPT

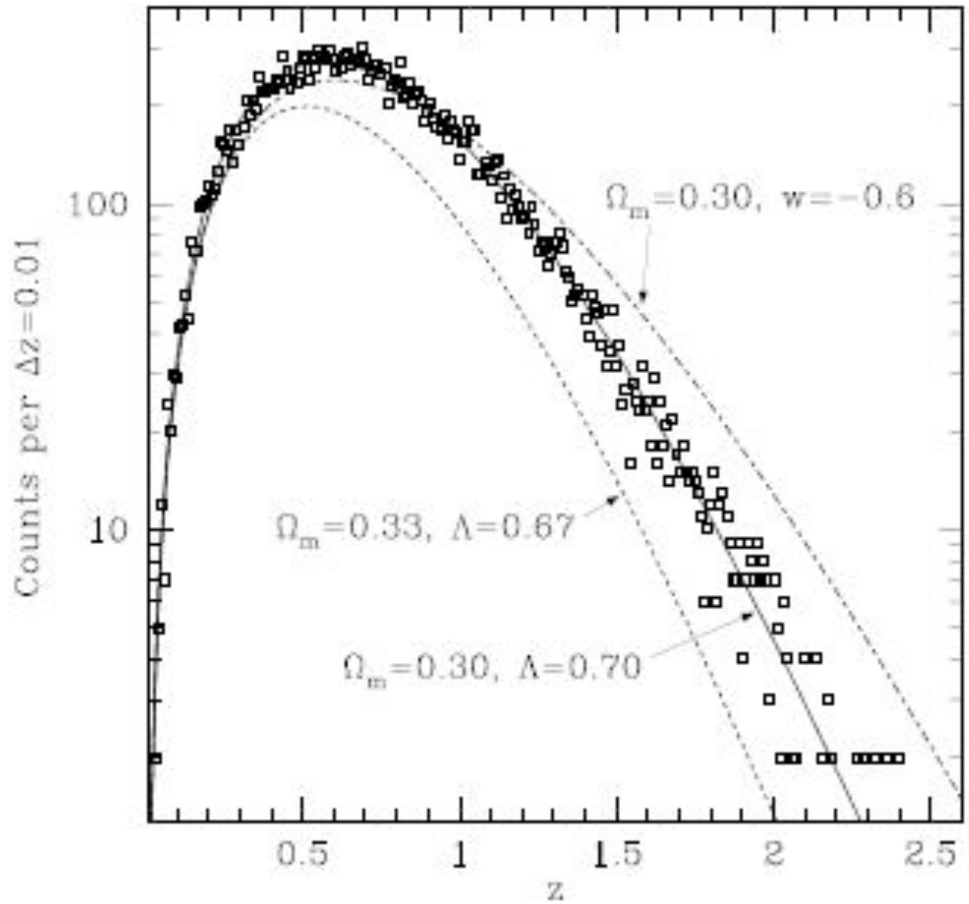
- Ideal location at South Pole
  - Minimal wind speed
    - Max 12 m/s for long periods 1957-1983
  - Sky simply rotates above the observer

  - Very little water vapor → easier to see weak signals (SZE)

Ruhl, et al., “The South Pole Telescope,” 2004, astro-ph/0411122 v1.

SPT

- Redshifts of sky survey clusters measured by follow-up experiments
  - Statistical power to pin dark energy equation of state to within 5% accuracy.



Ruhl, et al., “The South Pole Telescope,” 2004, astro-ph/0411122 v1.

Summary (1)

- SZ effects are now easily measurable to $z = 1$

- Measurements of Individual cluster SZ effects allow to estimate:
  - total thermal energy contents
  - total electron contents
  - structural information (especially on large scales)
  - peculiar radial velocities
  - cluster masses

Summary (2)

- Sample studies give
  - Hubble diagram and cosmological parameters
  - cluster number counts and cosmological parameters
  - baryon mass fraction
  - evolution of cluster properties
  - evolution of radial velocities
  - Redshift evolution of the microwave background temperature

Summary (3)

- Improved SZ data may give
  - radio source energetics (non-thermal SZ effect)
  - transverse velocities of clusters (polarization effect)
  - detections of gas in infalling filaments