Next Set of Lectures and Your next step

- Supernova and SuperNova Remnants

- Oral presentations: You will grade the presenters
  - clarity
  - coherence
  - organization
  - interest
  - 'style' (boring vs engaging)
  - Grade on a 1-5 scale (5 is best)- email me your grade

Sunayev-Zeldovich Effect

[redacted]

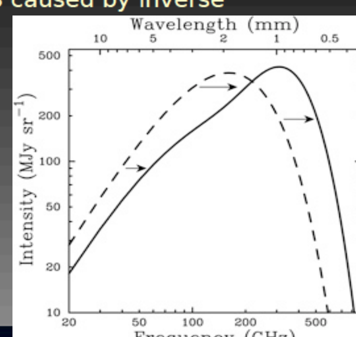
https://ned.ipac.caltech.edu/level5/Sept05/Carlstrom/Carlstrom2.html#2.1

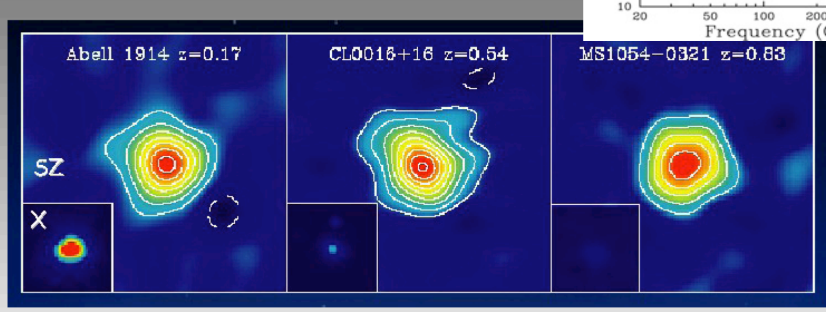
Thermal SZE is a small (<1 mK) distortion in the CMB caused by inverse Compton scattering of the CMB photons

$$\frac{\Delta T}{T_{\rm CMB}} = g(x) \int n_e(l) \frac{k_{\rm B} T_e(l)}{m_e c^2}\, dl$$

Total cluster flux density is independent of redshift!

$$\Delta S_\nu = \int \Delta I_\nu \, d\Omega \propto \frac{\int n_e T_e \, dV}{D_{\rm A}^2} \propto \frac{f_{\rm gas} M_{\rm tot} T_e}{D_{\rm A}^2}$$

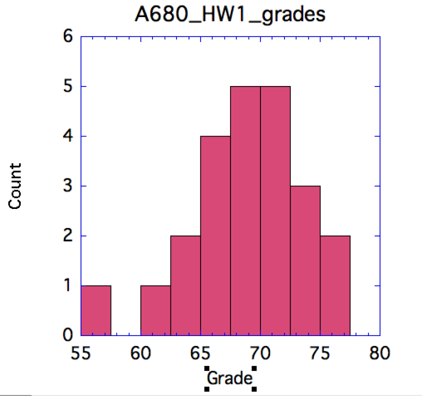




Carlstrom et al.

S-Z and x-ray images of clusters

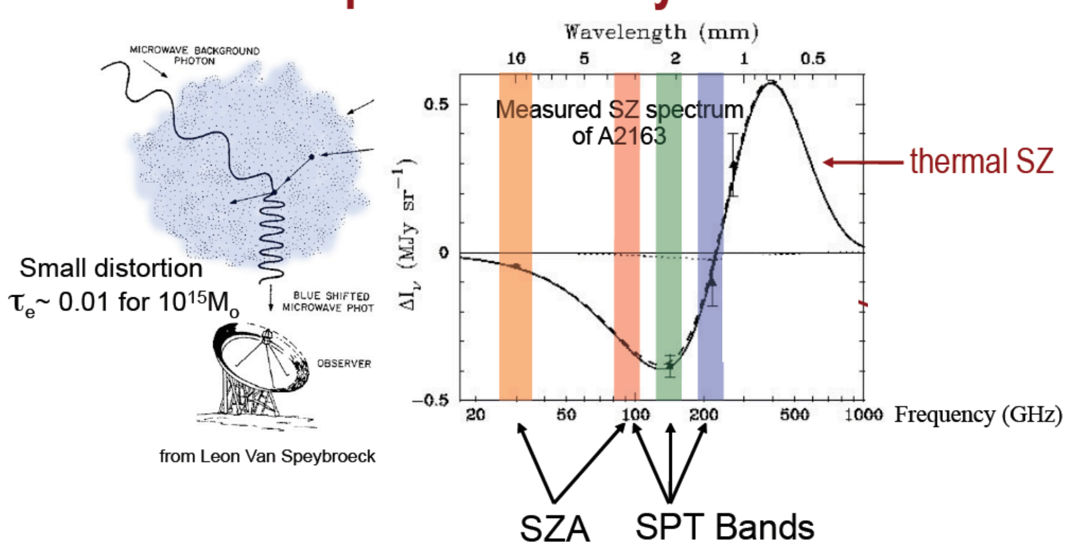
Homework- mean=median=68.5; variance 4.83



The mid-term will be delayed until Thursday March 14
No new 'oral' presentations until after spring break
Assignment will be made on Thursday March 7
New Homework due March 12

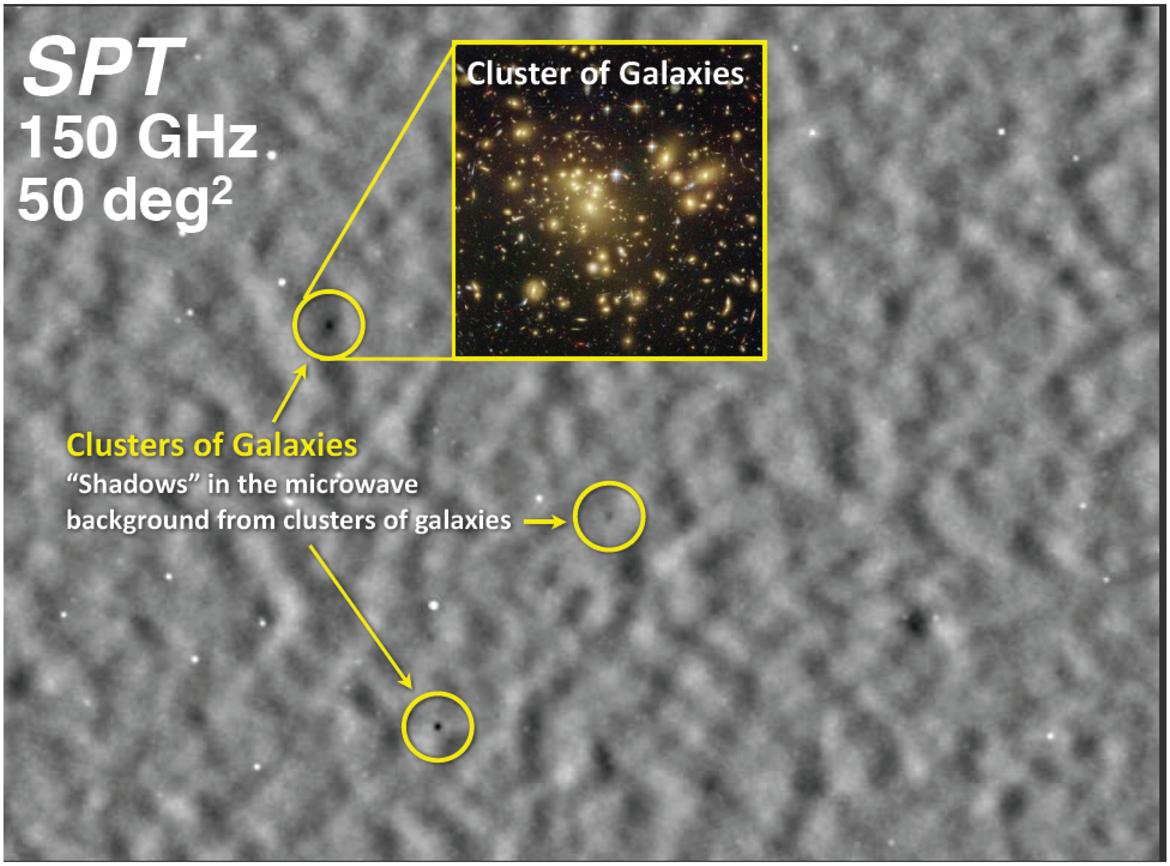
Sec 4.6 & 9.5 in Longair

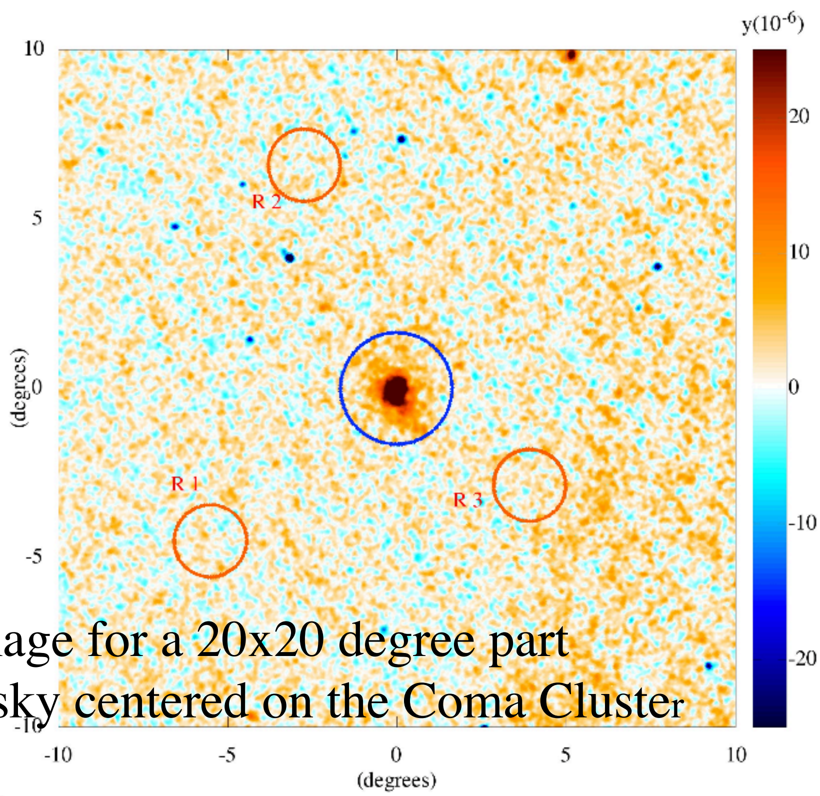
The Sunyaev-Zel'dovich Effect: probe of Galaxy clusters



Carlstrom

$$\boxed{\textit{Redshift independent:}\ \frac{\Delta T_{SZE}}{T_{CMB}} \propto \int n_e T_e dl}$$



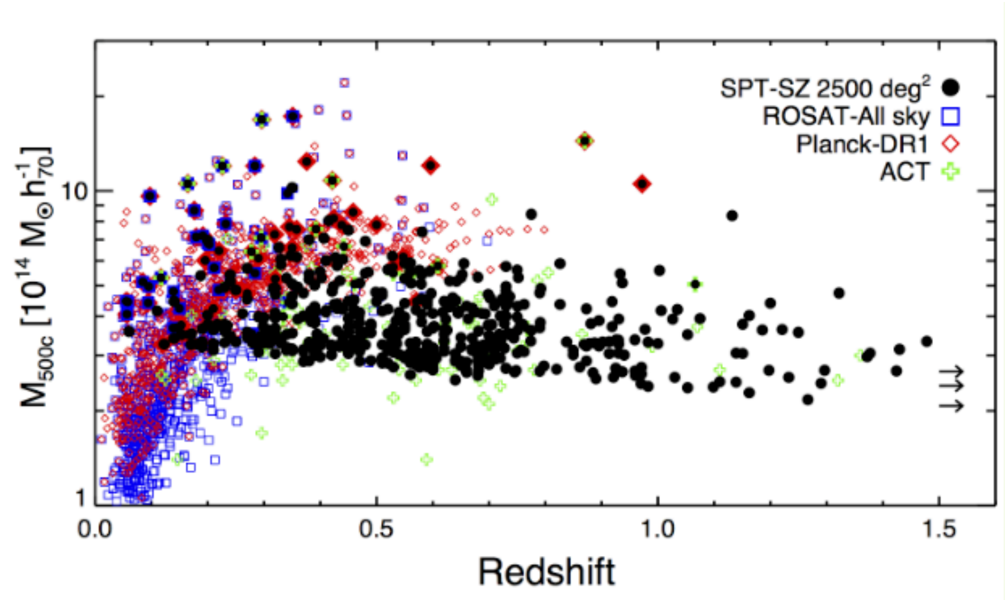


S-Z image for a 20x20 degree part
of the sky centered on the Coma Cluster

[!ht]

Figure 1. We show 20° × 20° region centered on the Coma cluster in LIL map. The $R_{200} \approx 2.62$ Mpc region is marked with a circle at the center of the map.

Modern Data



Large Sample of Objects Out to z~1.5
However these surveys have low angular resolution
(~1-10 arc minutes) compared to X-ray (0.5-5 arcsec).

Sunyaev-Zel'dovich Effect

Single Clusters

- *Measure of integrated pressure (total thermal energy)*
- *Distances, H_o, $H(z)$*
- *Cluster gas mass fractions, cluster structure, evolution studies*
- *Peculiar velocities at high z*

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

SZ Cluster Surveys

- *Exploit SZ redshift independence*
- *Measure growth of structure and large scale velocity fields to constrain Dark Energy*

$$S \propto \int \Delta T_{SZE}\, d\Omega$$
$$\propto \frac{1}{D_A(z)^2} \int n_e T_e dV$$

S-Z Effect: Khatri and Gaspari 2016

A change in the intensity $\Delta I_\nu = I_\nu - I_\nu^{Planck}$
of the CMB radiation is given by (Zeldovich & Sunyaev 1969)

$$\boxed{\Delta I_\nu = y \frac{2h\nu^3}{c^2} \frac{x e^x}{(e^x - 1)^2} \left[x \left(\frac{e^x + 1}{e^x - 1} \right) - 4 \right],}$$

where $x = h\nu/k_B T$, $T = 2.725(1+z)$ is the CMB temperature at redshift z, $\nu = \nu_0(1+z)$ is the frequency of CMB photon at redshift z, ν_0 is the observed frequency today ($z=0$), h is the Planck's constant, k_B is Boltzmann constant and c is the speed of light.

The amplitude of the distortion, y, is proportional to the integral of the pressure, P, along the line of sight**:**

$$\boxed{\mathbf{y = \sigma_T (m_e/c^2) \int ds\ n_e k_B T_e},}$$

where T_e and n_e are the electron temperature and electron number density respectively in the ICM plasma, m_e is the mass of the electron, σ_T is the Thomson scattering cross section, and *s* is the distance coordinate along the line of sight

The Kinetic Sunyaev-Zel'dovich Effect (kSZE) the "Other" S-Z Effect

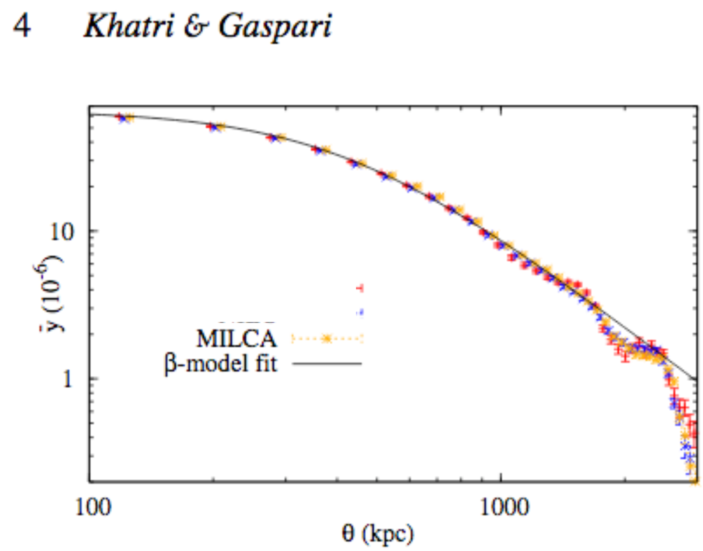
Another contribution to the change in energy of the CMB photons is the motion of the cluster with respect to the frame of reference of the CMB

It is linearly proportional to the line of sight peculiar velocity v_z and to the electron opacity τ_e as $dT_{kSZE} = -\tau_e(v_z/c)\, T_{CMB}$

The electron opacity-τ_e scales as the line of sight integral of electron density.

The kSZE is weaker than the tSZE.
However, since the kSZE does not depend (to first order) on temperature, the ratio of kSZE to tSZE is less small for cooler clusters and groups

T. Mroczkowski



Radial profile of y for Coma , solid line is β model for gas density

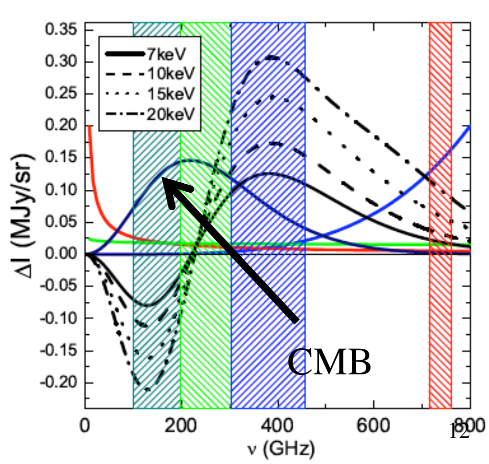
S-Z Simple Physics

- The optical depth for the S-Z effect is small
- the density of electrons is of order $n_e \sim 10^{-3}$ cm^{-3}, the path length through a cluster medium ~ several Mpc. With a Thomson cross section σ= 6.65 x10 $^{-25}$ cm^2,

 optical depth $\tau = n_e \sigma l \sim 0.005$; ~ 1% probability that a CMB photon crossing a rich cluster is scattered by an electron.

- Since the electron energy is much larger that the energy of the photon, to first order $\delta\nu/\nu \sim kTe/m_ec^2 = 1\%$. The resulting fractional temperature change of the CMB is of the order of 10^{-4},~300μk
- For a review see *Carnegie Observatories Astrophysics Series, Vol. 3: Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, 2004* Using the Sunyaev-Zelídovich Effectto Probe the Gas in Clusters MARK BIRKINSHAW

The spectrum of the thermal SZE has a characteristic shape
all interacting CMB photons get approximately a 1% boost in energy, the result is a transfer of photons in the CMB spectrum from lower to higher frequencies, resulting in a decrease of brightness at low frequencies



A Strange Fact

- The amplitude of the S-Z effect is independent of D_A the angular distance
- This is because the effect is a fractional change in the brightness of the CMBR, and the CMBR's energy density itself increases with redshift as $(1 + z)^4$, cancelling out the dimming effect of cosmology.

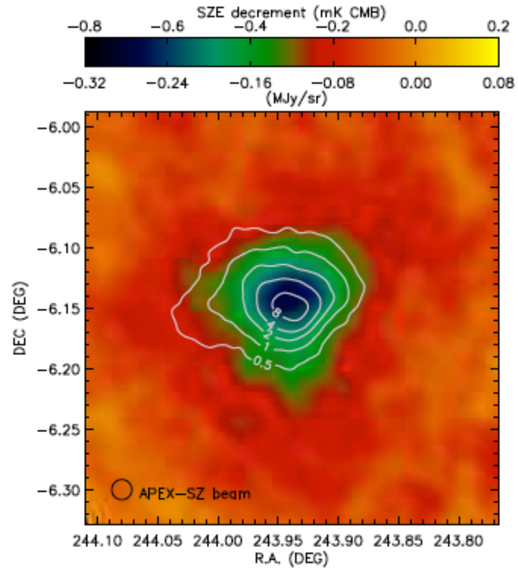
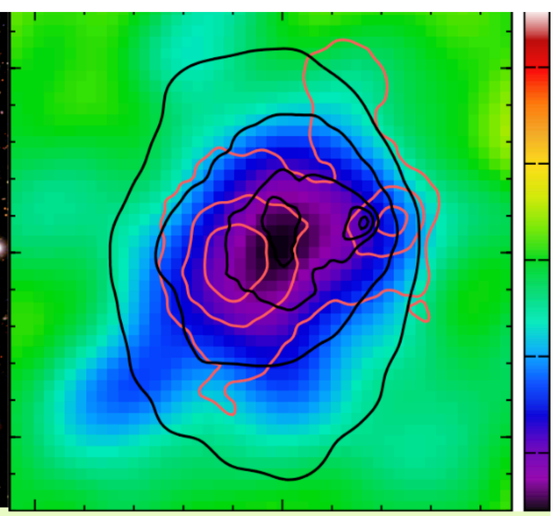


Fig. 1. Map of Abell 2163 at 150 GHz, overlaid with XMM-Newton X-ray contours (see Fig. 3) in units of 10^{-13} erg s^{-1}cm^{-2}arcmin^{-2}. Because the correlated-noise re-

Effect of Angular Resolution

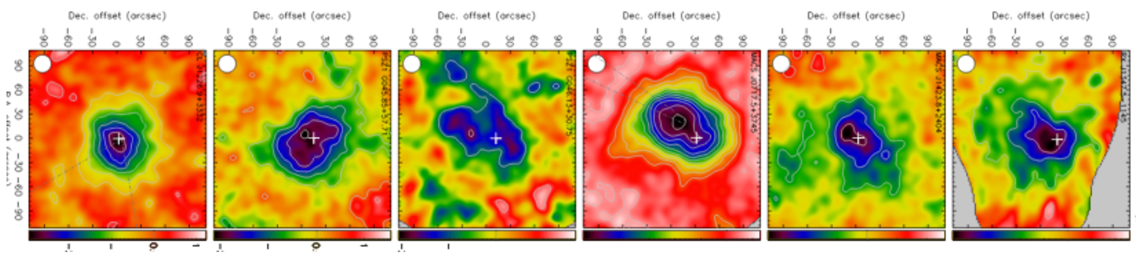
Credit: X-ray: NASA/CXC/CfA/Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/Clowe et al.



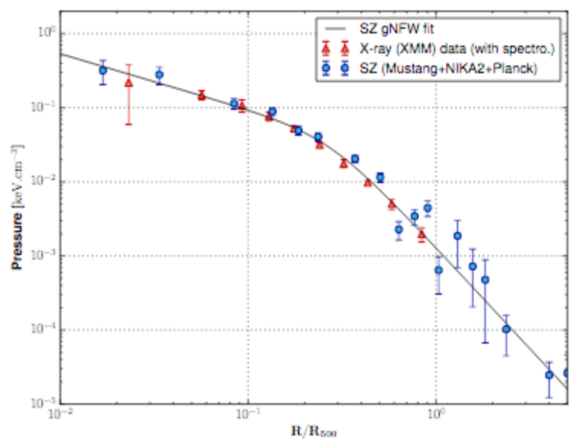
Hincks et al. ACT image with lensing (red) and X-ray (black) overlays

However new telescopes (ALMA, Mustang and NIKA 2 have much better angular resolution (~17" for NIKA 2- A&A 614,118, Adam et al

NIKA 2 Maps



Pressure profile from S-Z data compared to x-ray data − S-Z can extend pressure profile to large radii (where most of the mass is)



Sunyaev-Zeldovich Distances

- At present ~400 clusters have measured S-Z effect "decrements" and x-ray temperatures (Primarily from Planck and the South Pole Telescope and the Atacama Cosmology telescope)

Line integral of pressure

$$\Delta T \propto g(\nu) \int dz\, n_e(\mathbf{r})\, T_e(\mathbf{r}),$$

$$S_X \propto \frac{1}{(1+z)^4} \int dz\, n_e(z)^2\, T_e(z)\, \Lambda(T_e, Z_{ab}),$$

Geometry uncertainty

$$H_0 \propto \left(\frac{T_e}{\Delta T_{SZ}}\right)^2 \theta S_X \frac{\ell_\perp}{\ell_\parallel},$$

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

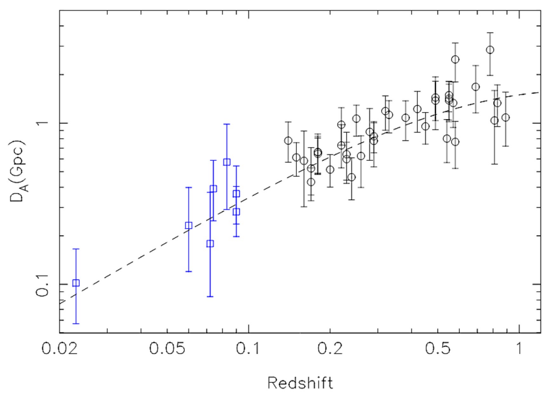
Angular distance D_A:ΔT_0 is the S-Z decrement, S_{X0} the x-ray surface brightness, T_{e0} the x-ray temperature, θ_c angular size and Λ the cooling function

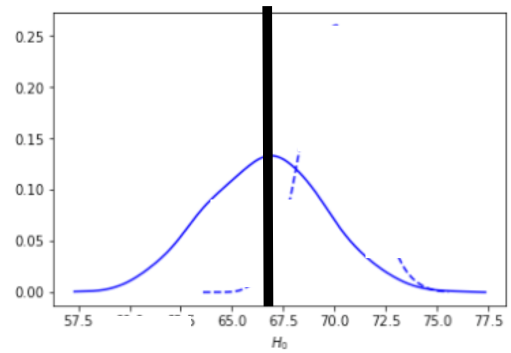
All quantities are directly measurable with an x-ray image, temperature map and S-Z image

S-Z Distances and H_0

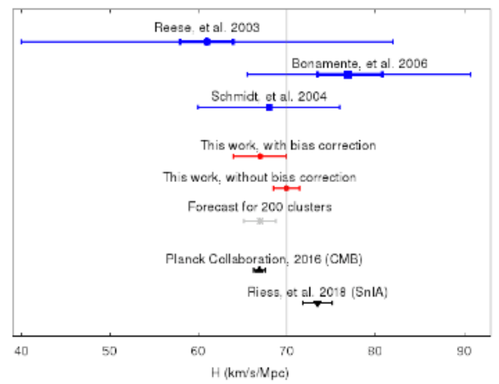
- Bonamente et al 2006 Kozmanyanet al 2018
- clusters with mass in the range $2.6\times10^{14}M \leq M_{500} \leq 1.8\times10^{15}M$,
- 26 clusters at z=0, 25 at z=0.25, 21at z=0.5.

$H_0=67\pm3$ kms^{-1}Mpc^{-1}





4 Posterior ons of H_0 for a flat ΛCDM universe

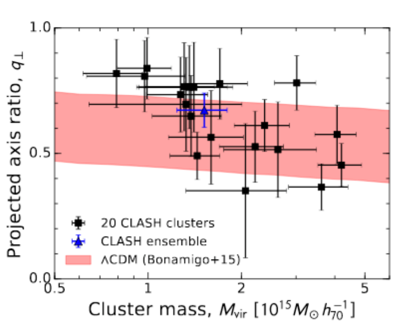


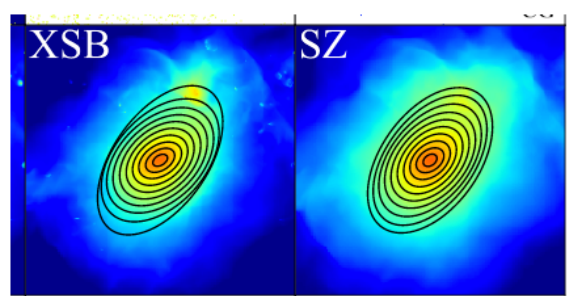
. Comparison of the result in this work (in red) with previous ents using clusters as probe (in blue) and with current most easurements of H_0 using other probes (in black). In gray w

3-D View of Clusters

- Since S-Z is proportional to path integral of pressure and x-ray to n^2xvolume the ratio is geometry dependent (Okabe et al 2018, Umetsu et al 2018)) and sensitive to non-thermal pressure terms

5.2.2. *Comparison with ΛCDM Predictions*



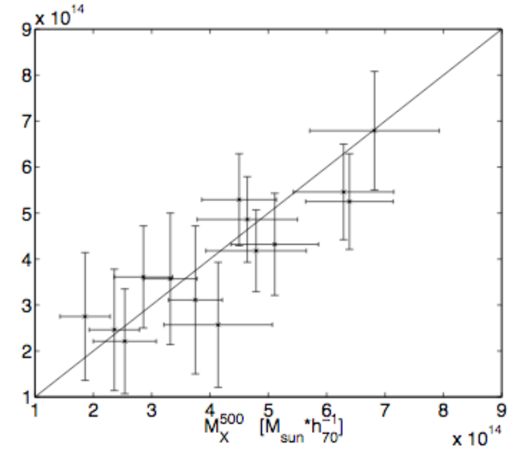


Projected image of x-ray surface brightness and S-Z y parameter

S-Z Effect and Cluster Mass

- The integrated S-Z signal 'Y_{SZ}' is determined primarily by the thermal energy of the ICM
- $Y_{SZ} = \int y \, d\Omega \ \alpha \ d^2_A \int P_e \, dV$;
- which is strongly connected to its mass (Saliwanchik et al 2015)

$M_{SZ} x 10^{14} M_{\odot}$

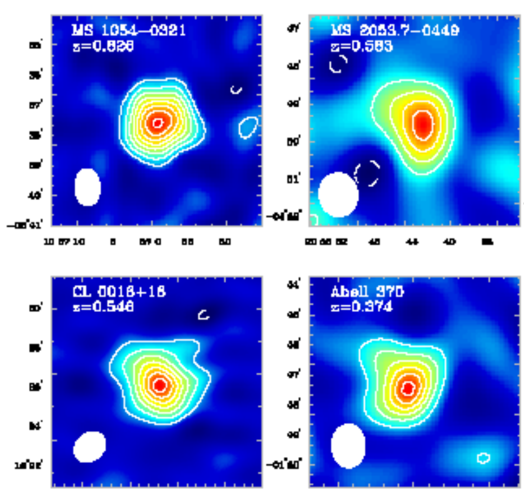


$M_x x 10^{14} M_{\odot}$

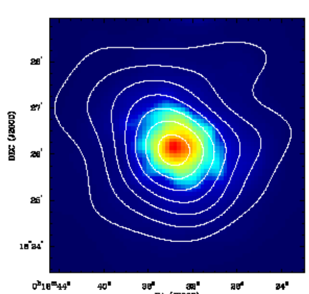
Sunyaev-Zeldovich effect

- The main technical limits are the long exposures required in both the x-ray band and the milli-meter (~1 day each for the highest z clusters)
- The S-Z decrement is independent of redshift, while the x-ray surface brightness drops as $(1+z)^4$

  Setting a practical limit to z~1.3 for the x-ray measurements
- In a massive cluster the typical optical depth is $\tau \sim 0.05$



S-Z contours images for a sample of clusters from z~0.3-0.9



X-ray image with S-Z contours for z=0.54 cluster