Cosmology With Galaxy Clusters

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Cast of Characters

U of Chicago
- John Carlstrom
- Gil Holder
- Erik Reese
- Sam LaRoque
- Daisuke Nagai
- Amber Miller
- Mike Joffre

NASA/MSFC
- Marshall Joy
- Cheryl Bankston
- Sandy Patel (UAH)

UIUC
- Joe Mohr

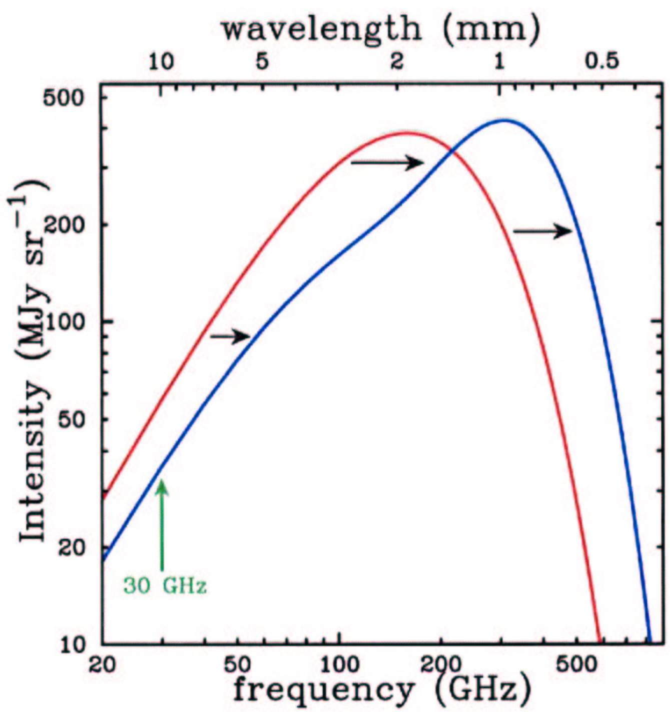
SAO/cfa
- Laura Grego

UC Berkeley
- Bill Holzapfel

Rutgers University
- Jack Hughes

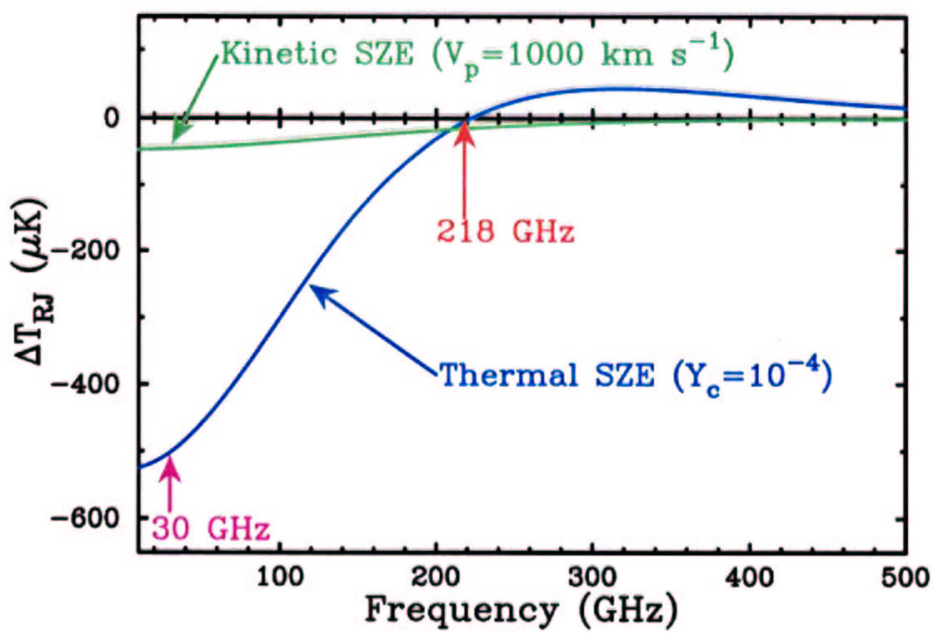
OVRO
- David Woody
- Steve Padin
- Steve Scott

BIMA
- Dick Plambeck
- John Lugten
- Rick Forster

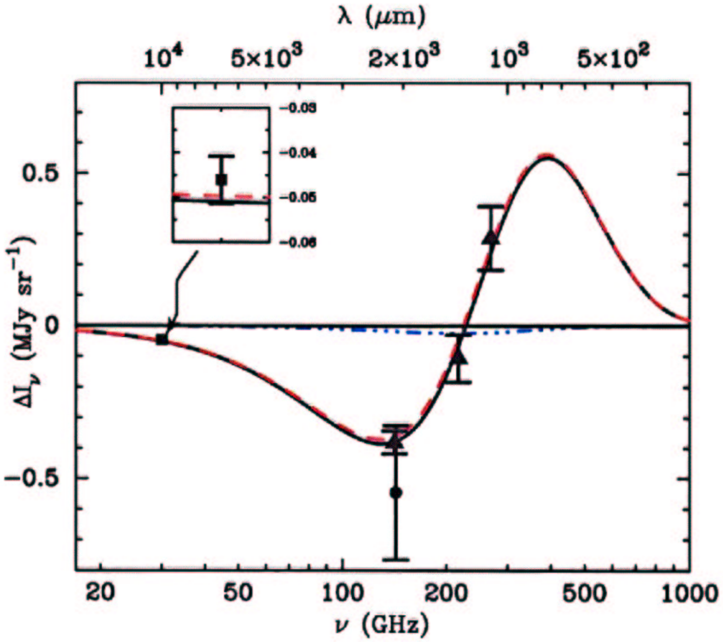


(Adapted from Sunyaev & Zel'dovich 1980 ARAA)

Observable ΔT –Brightness



A2163 SZE Spectrum



(LaRoque, Reese, Calstrom, et *al.* 2001)

$\frac{\Delta T_{sz}}{T}$ is independent of z

$\Rightarrow$ Good Cosmological Probe

Some Applications of SZE

- Distances with x-ray $\Rightarrow H_0, q_0$
  Independent of distance ladder
- Masses and gas fractions $\Rightarrow \Omega_M$
  $f_g \approx f_B = \Omega_B/\Omega_M \Rightarrow \Omega_M$
  (Myers et *al.* 1997; Grego et *al.* 2000, 2001)
- Peculiar Velocities
  (Holzapfel et *al.* 1997)
- T_e
- Inventory clusters in the distant universe $\Rightarrow$ geometry of universe (w, Ω_Q), structure formation models

⋆ Learn about galaxy clusters

Our Solution

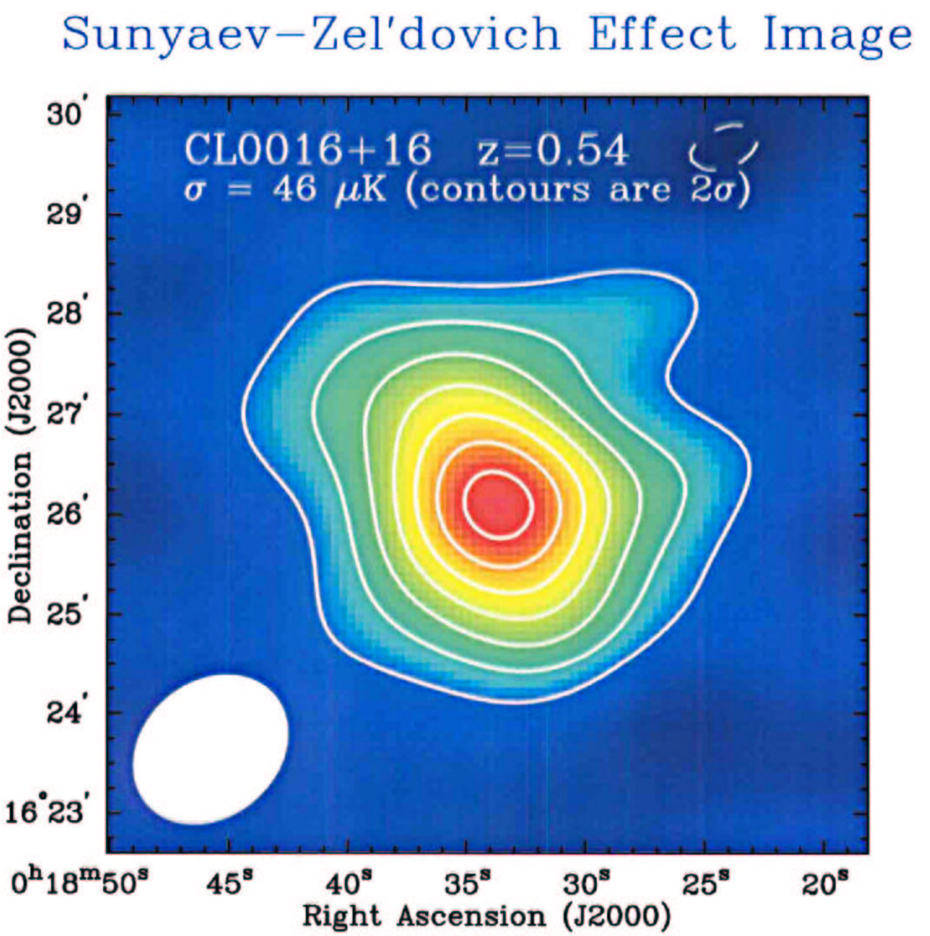
Use mm array at cm wavelengths

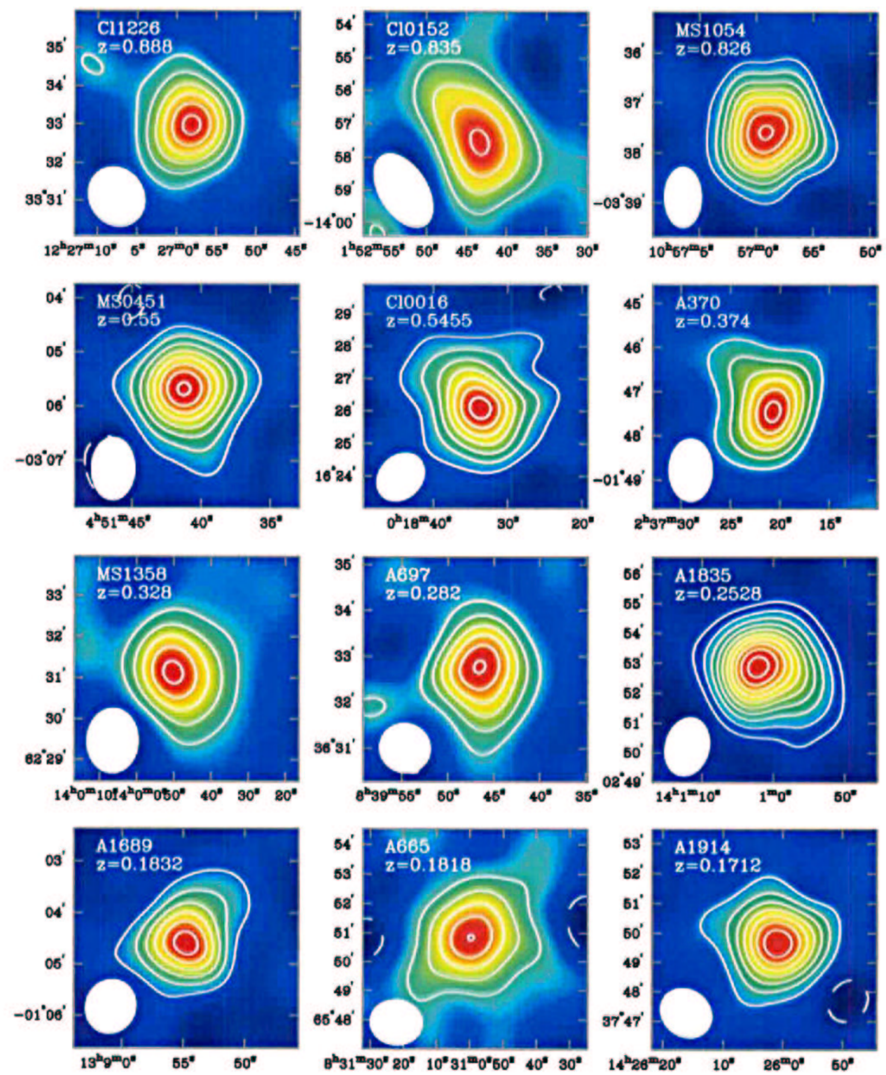
- low noise HEMT amplifiers
  $T_{RX} \approx 11$–20 K
- good λ for SZE ($\sim$ 30 GHz)
- large field-of-view 4′ and 7′
- large synthesized beams 1′-2′ ($\sim$ PSF)
  –arrays built for high resolution
- observe in non-ideal mm weather (summer)

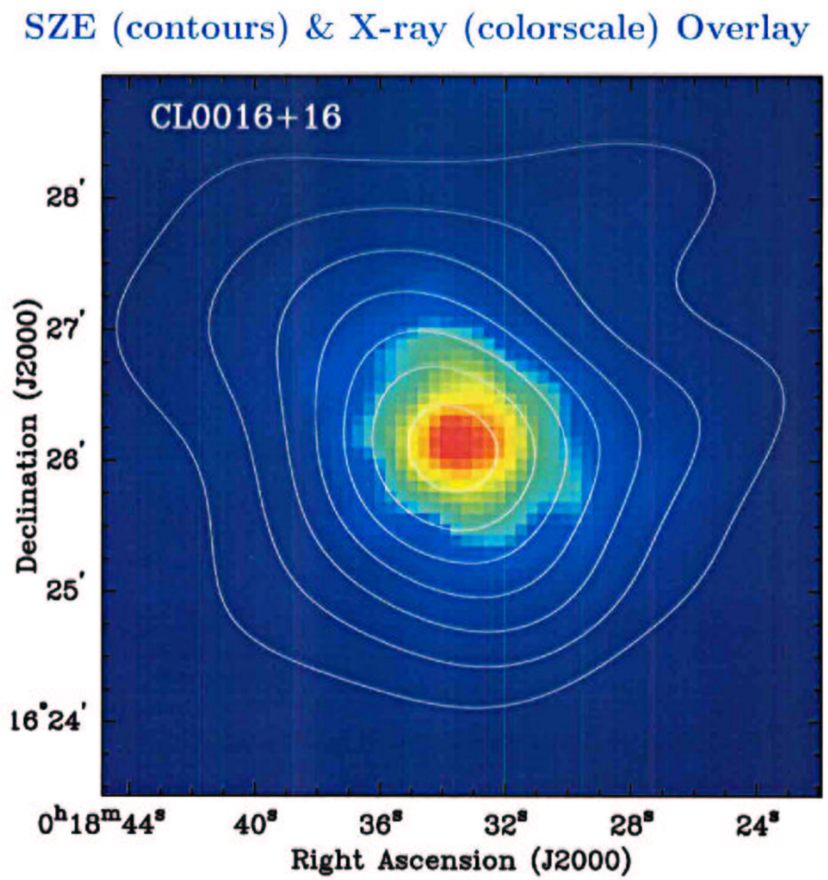
Benefits of Interferometry

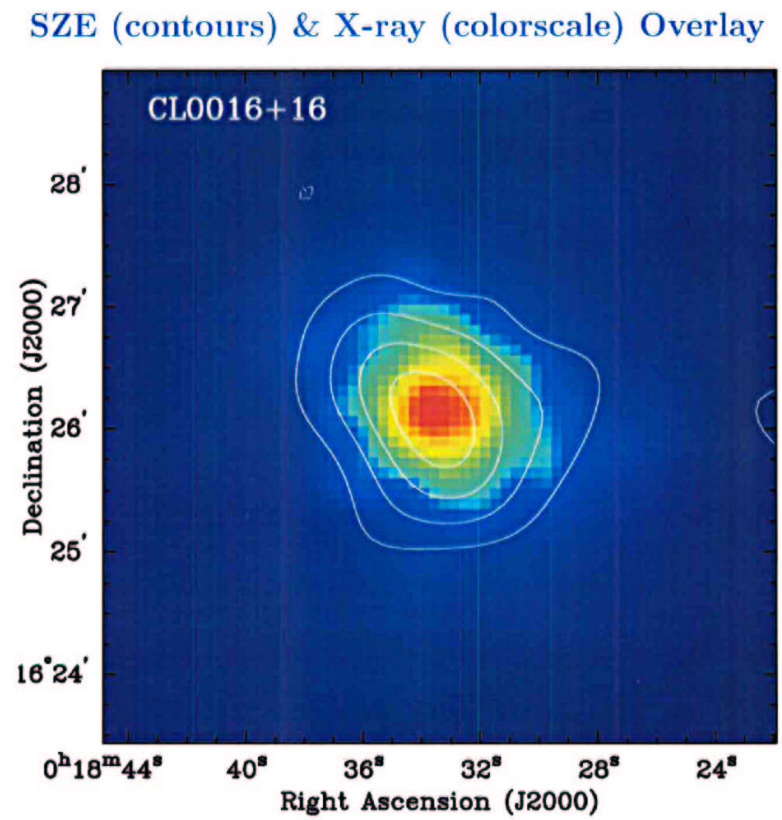
- stable, extremely low systematics
- produces 2-dimensional images
- measure point sources simultaneously
  –disentangle cluster & point source
- well defined filter

BIMA


Sunyaev–Zel'dovich Effect Image
CL0016+16 z=0.54
σ = 46 μK (contours are 2σ)
Declination (J2000)
Right Ascension (J2000)


Cl1226 z=0.888
Cl0152 z=0.835
MS1054 z=0.826
MS0451 z=0.55
Cl0016 z=0.5455
A370 z=0.374
MS1358 z=0.328
A697 z=0.282
A1835 z=0.2528
A1689 z=0.1832
A665 z=0.1818
A1914 z=0.1712


SZE (contours) & X-ray (colorscale) Overlay
CL0016+16
28'
27'
26'
25'
16°24'
Declination (J2000)
0h18m44s
40s
36s
32s
28s
24s
Right Ascension (J2000)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24s
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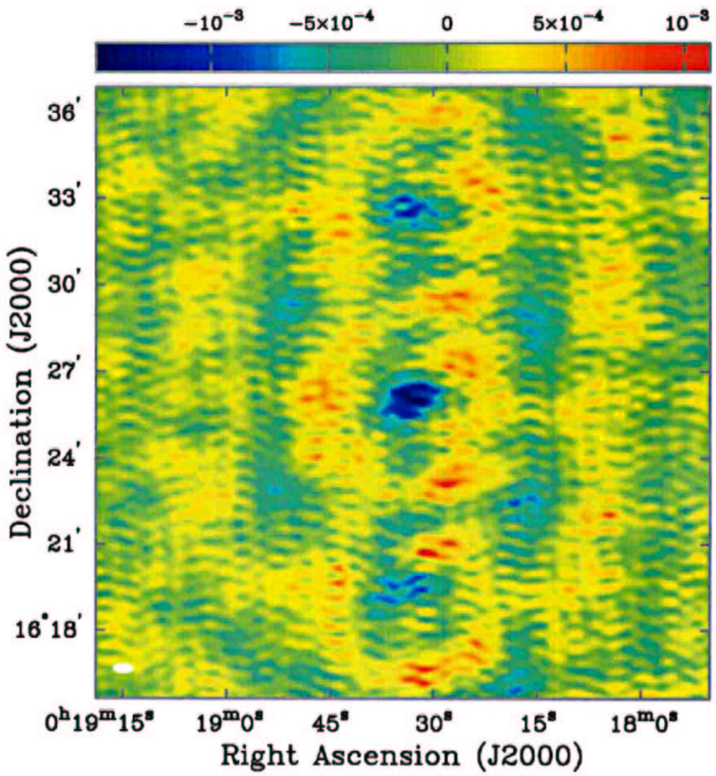
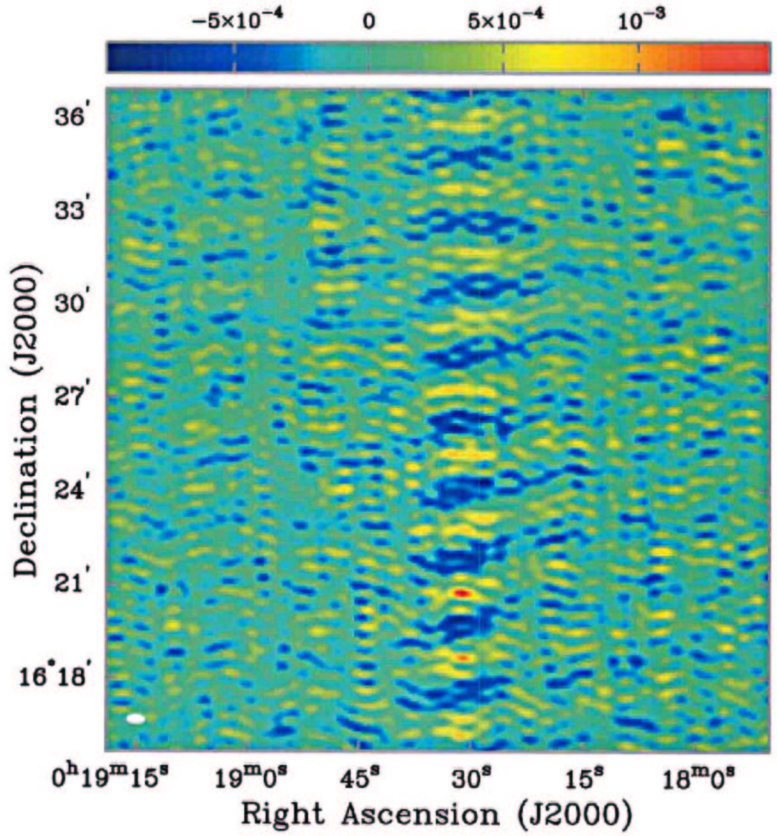
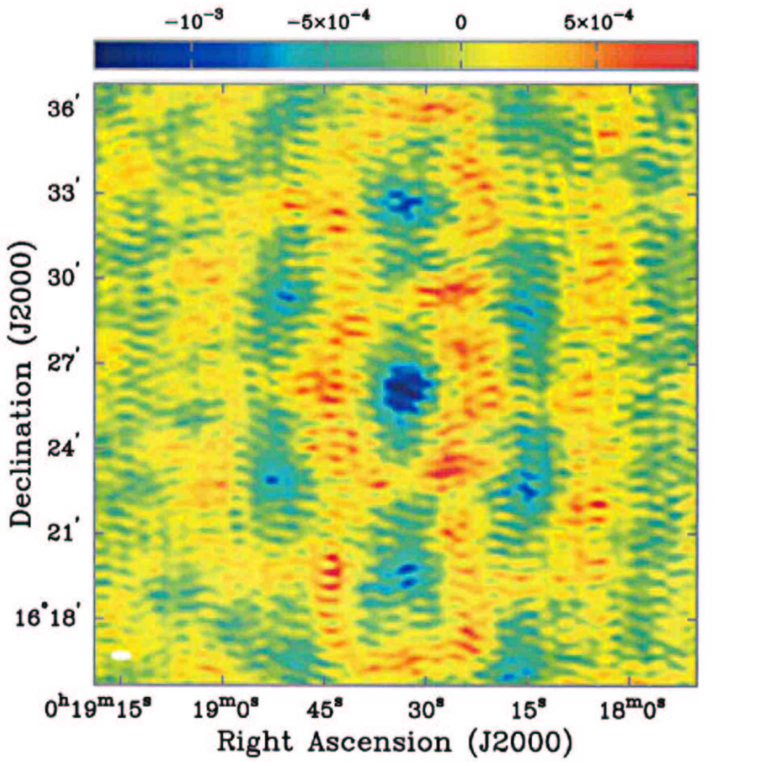
"Natural"



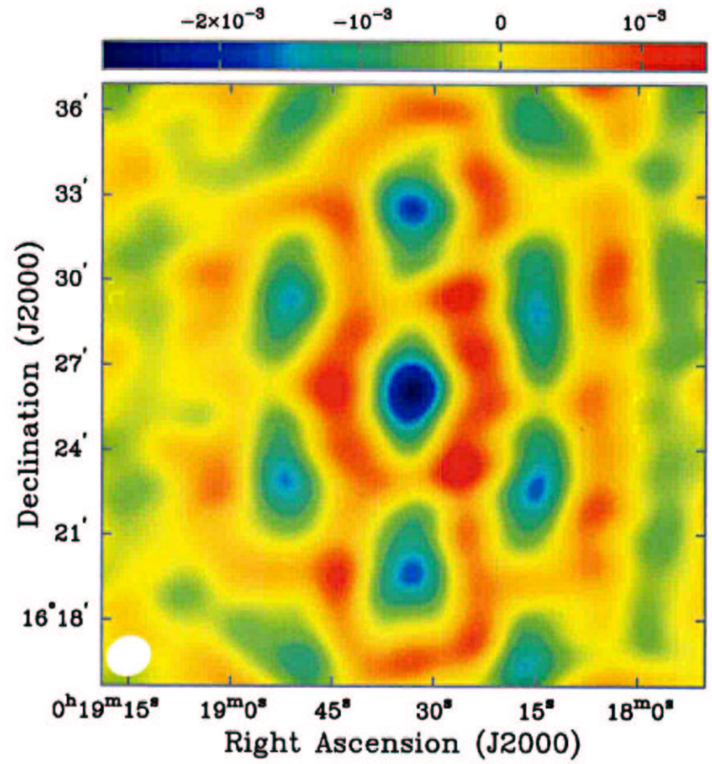
High Resolution



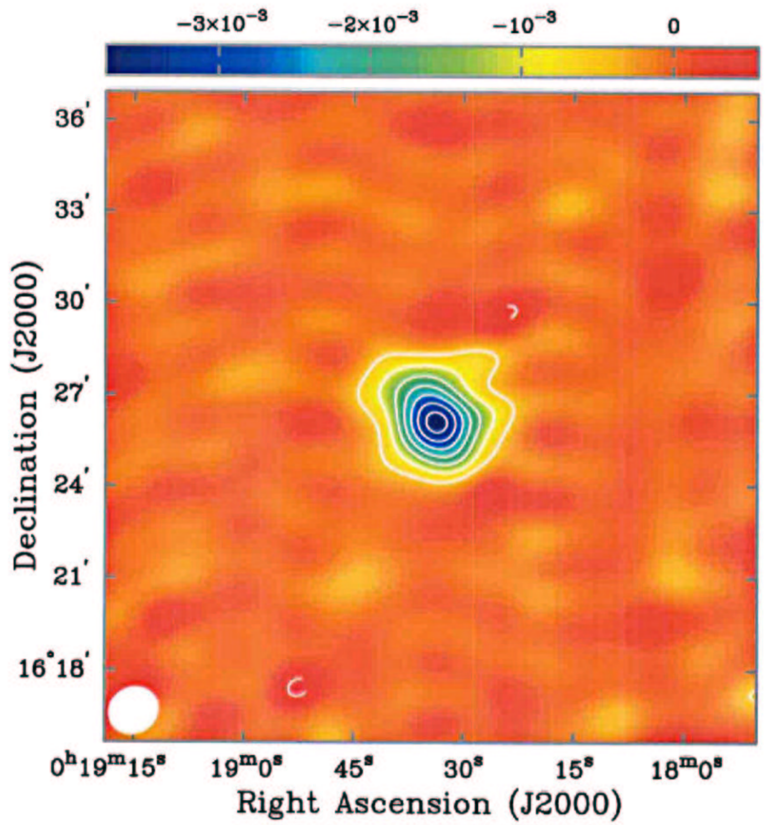
"Natural" No Point Source

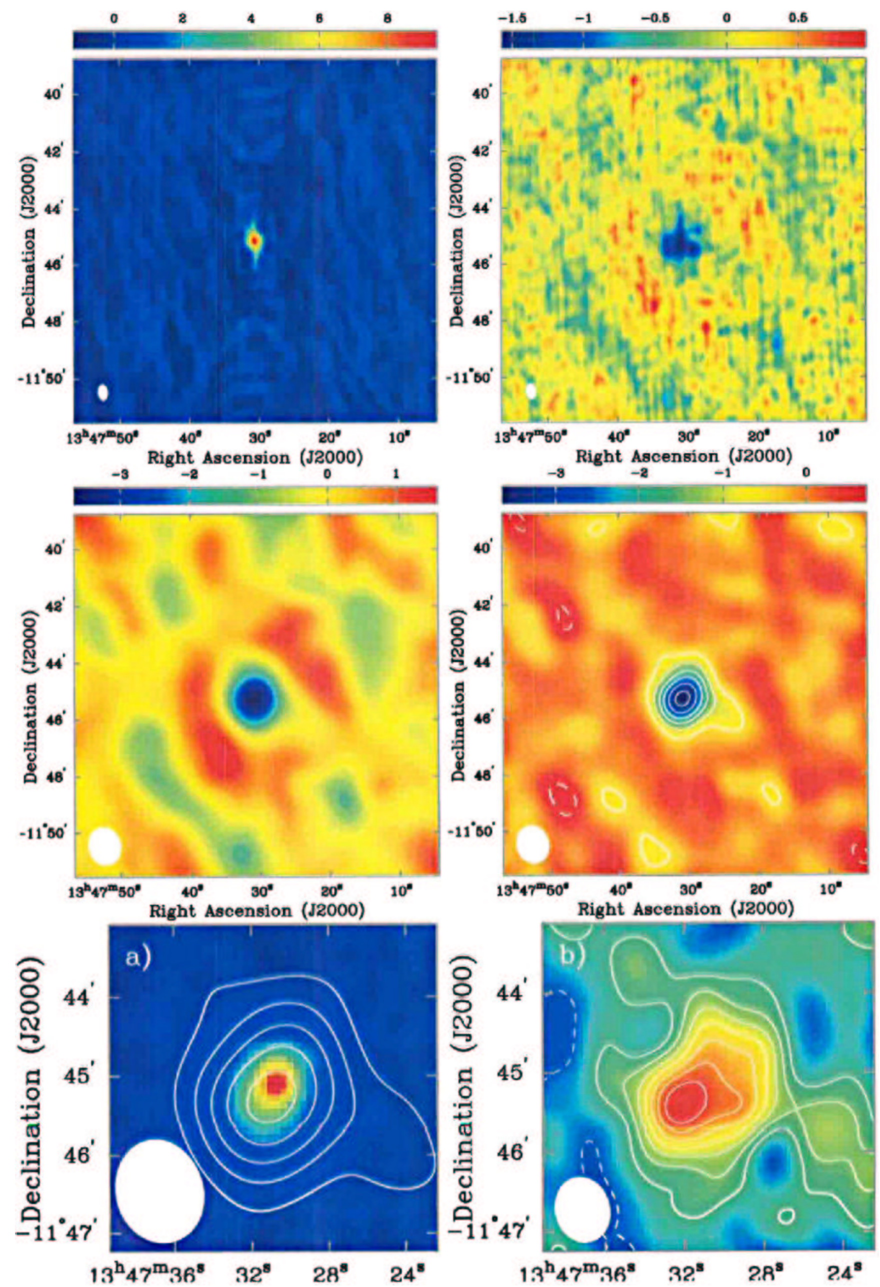


With Taper



Deconvolved With Taper





Hubble Constant

$$\Delta T \propto \int d\ell n_e T_e \Rightarrow \Delta T_0 \sim n_e T_e L$$

$$S_x \propto \int d\ell n_e^2 \Lambda \Rightarrow S_{x0} \sim n_e^2 \Lambda L$$

$$\Rightarrow L \propto \frac{(\Delta T_0)^2 \Lambda}{S_{x0} T_e^2}$$

with geometry of cluster

$$L = \theta D_A$$

with z and geometry of the universe

$$\Rightarrow H_0 \propto \frac{S_{x0} T_e^2}{(\Delta T_0)^2 \Lambda}$$

Independent of the distance ladder!

Analysis Method

Fit data with a spherical isothermal β-model

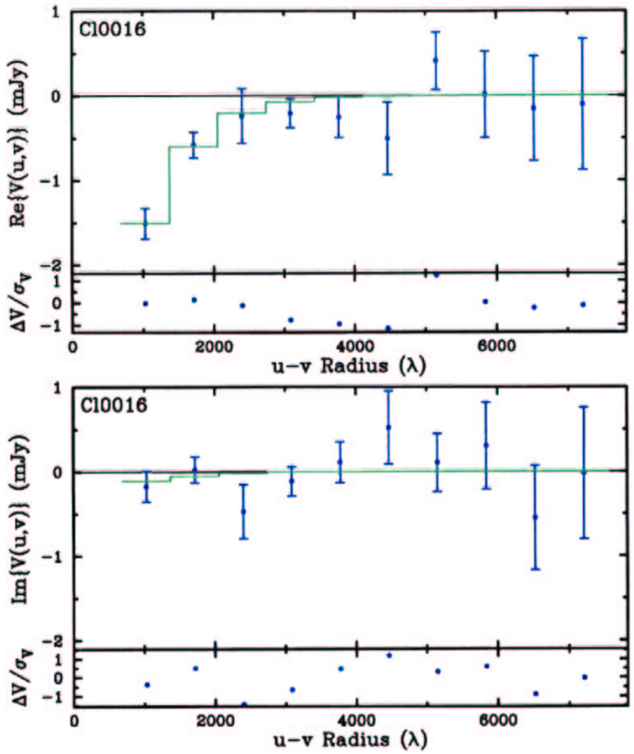
$$n_e(r) = n_{e0}\left(1 + \left(\frac{r}{r_c}\right)^2\right)^{-3\beta/2}$$

Maximum likelihood jointfit to SZE & X-ray data

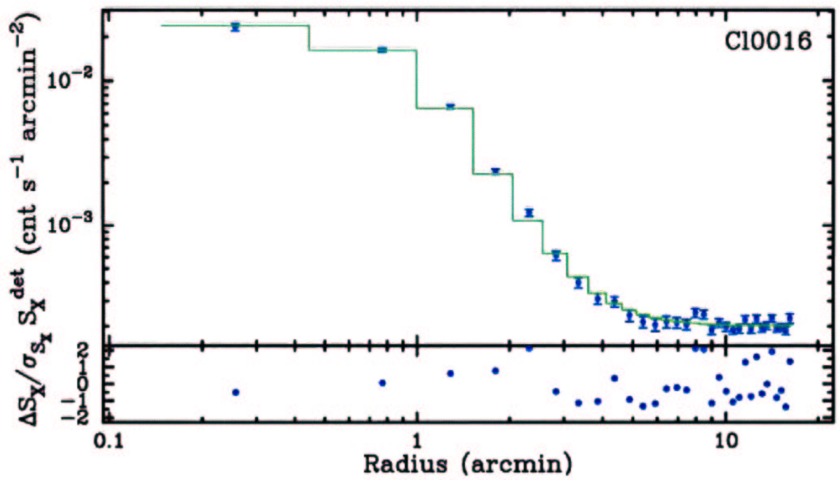
- SZE
  - data fit directly in Fourier plane
  - β-model + point sources
  - Gaussian statistics
- X-ray
  - Snowden ESAS reduction software (R4-R7 $\Leftrightarrow$ 0.5-2.0 keV)
  - β-model + background
  - mask point sources
  - Poisson statistics

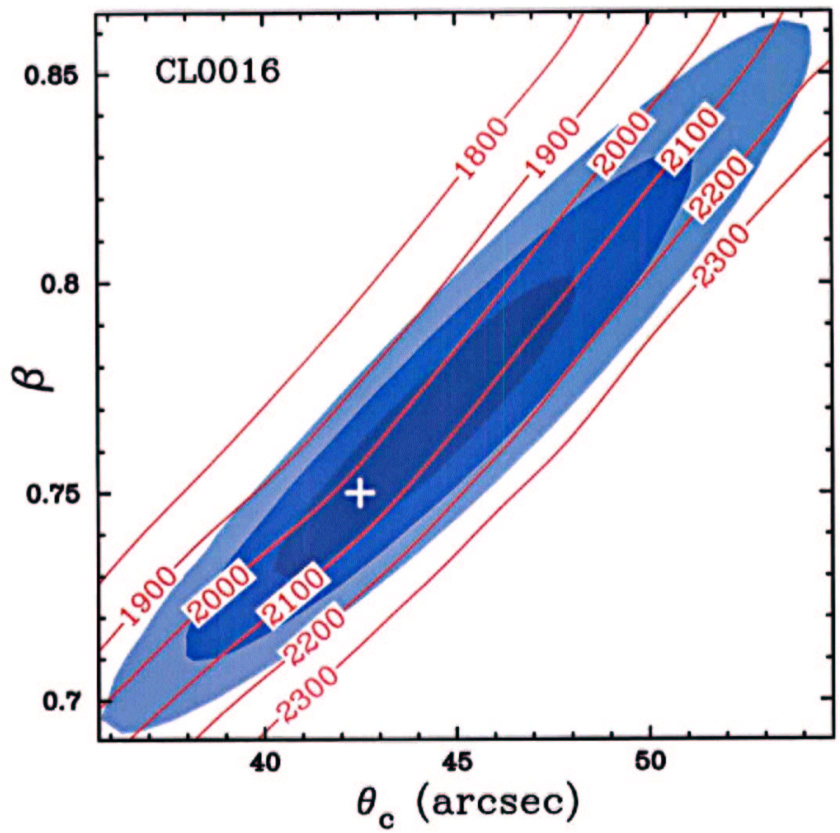
(Reese et al. 2000 ApJ 533 38)

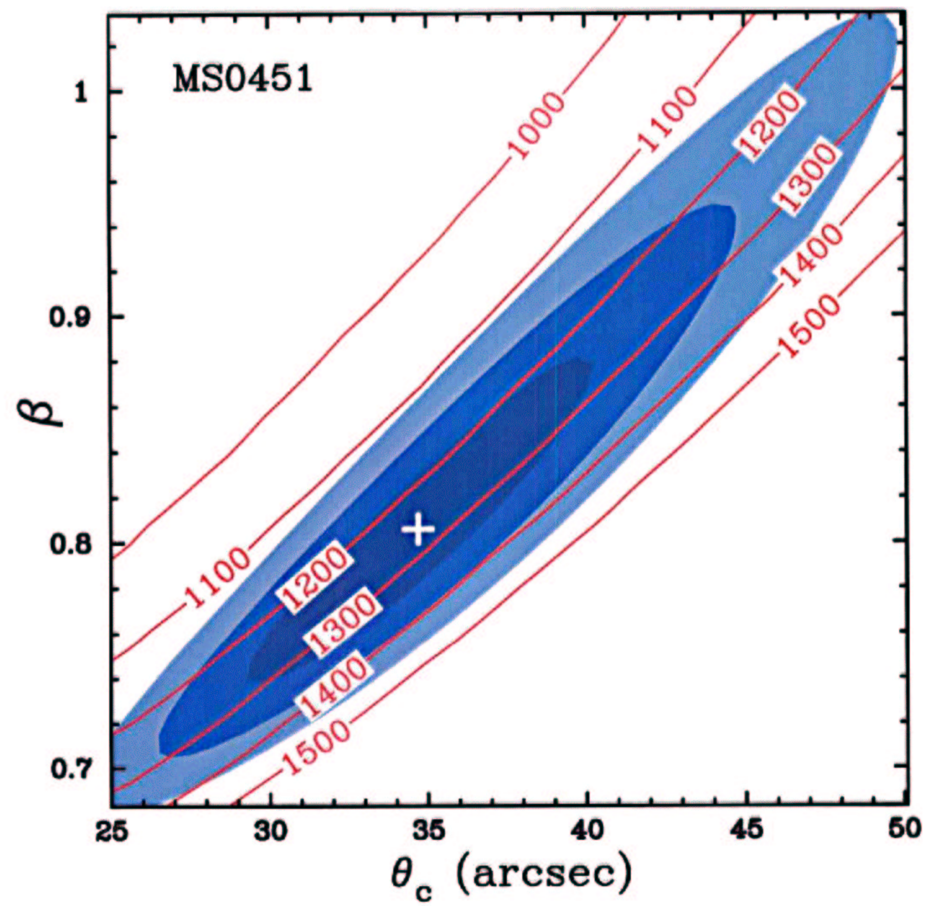
SZE *u-v* Radial Profile



X-ray Radial Profile




CL0016
0.85
0.8
0.75
0.7
β
40
45
50
θc (arcsec)
1800
1900
2000
2100
2200
2300


MS0451
1
0.9
0.8
0.7
β
25
30
35
40
45
50
θc (arcsec)
1000
1100
1200
1300
1400
1500

Uncertainties on H_0

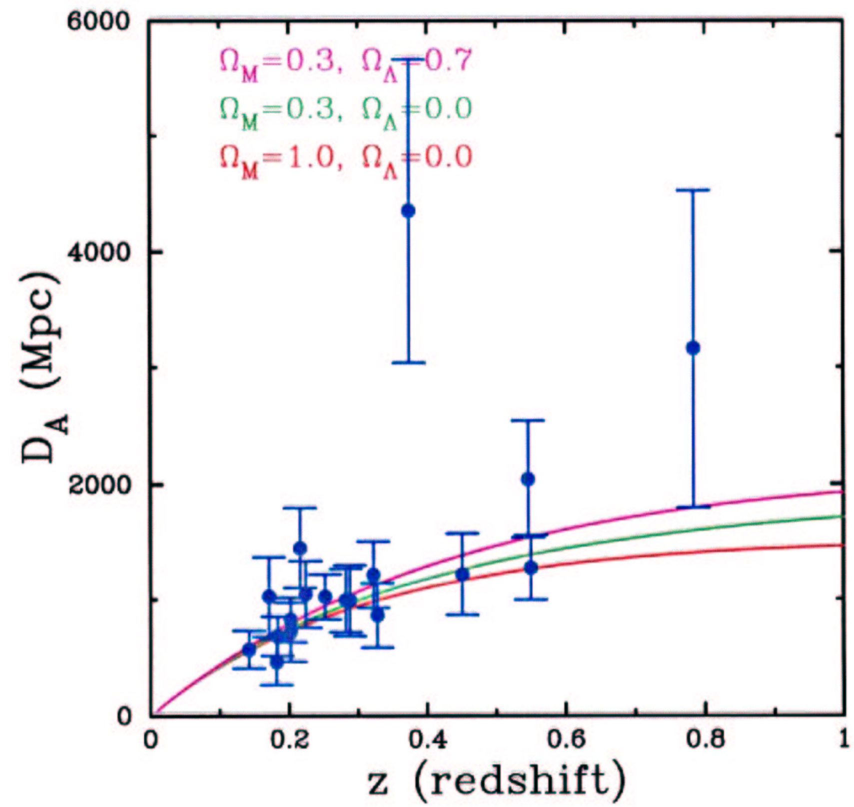
Statistical

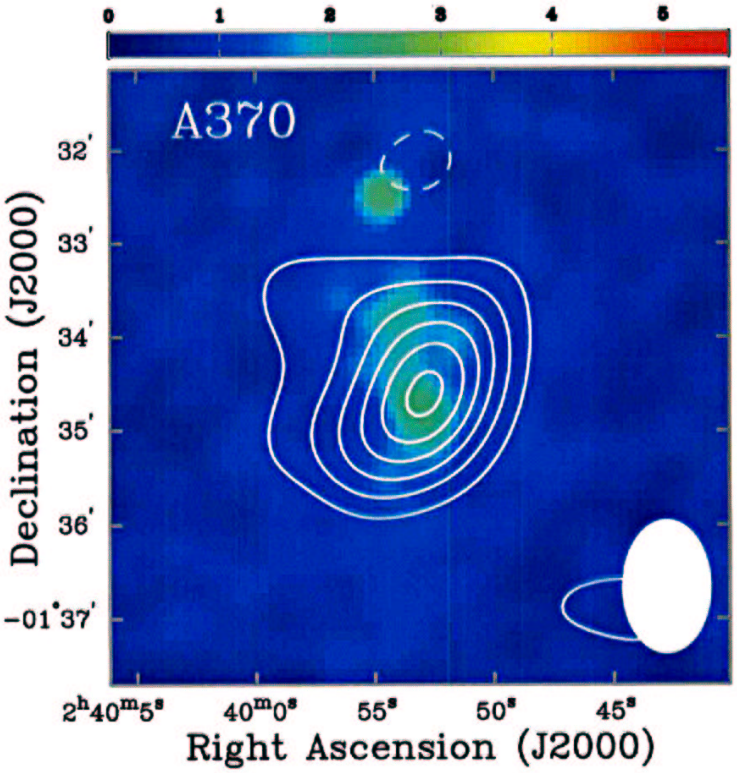
T_e ($H_0 \propto T_e^2$)	20%
Parameter fitting	15%
Metallicity	1%
N_H	1%

Systematic

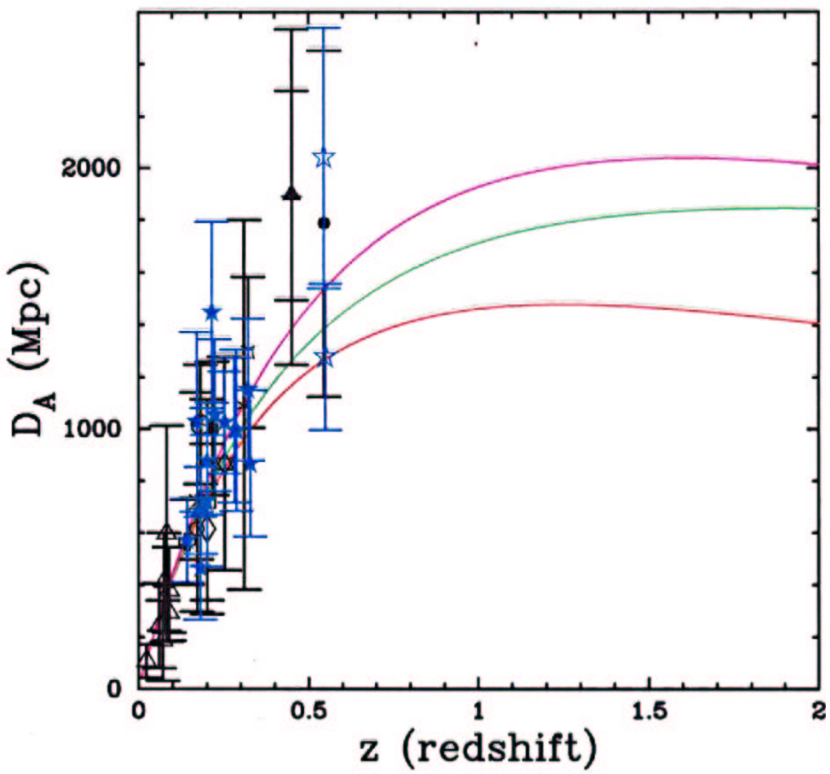
SZE calibration [$H_0 \propto (\Delta T_0)^{-2}$]	$\pm$ 8%
X-ray calibration	$\pm$10%
N_H	$\pm$ 5%
Asphericity•	$\pm$ 5%
Isothermality	$\pm$10%
Clumping	$-$20%
Undetected radio sources	$\pm$12%
Kinetic SZE•	$\pm$ 2%
Primary CMB	$\pm$ 1%
Radio Halos	$\pm$ 4%
Primay Beam	$\pm$ 3%
Total	+22% $-$30%

$$H_0 = \begin{cases} 60^{+4\ +13}_{-4\ -18}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}; & \Omega_M=0.3,\ \Omega_\Lambda=0.7 \\ 56^{+4\ +12}_{-4\ -17}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}; & \Omega_M=0.3,\ \Omega_\Lambda=0.0 \\ 53^{+4\ +12}_{-3\ -16}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}; & \Omega_M=1.0,\ \Omega_\Lambda=0.0 \end{cases}$$



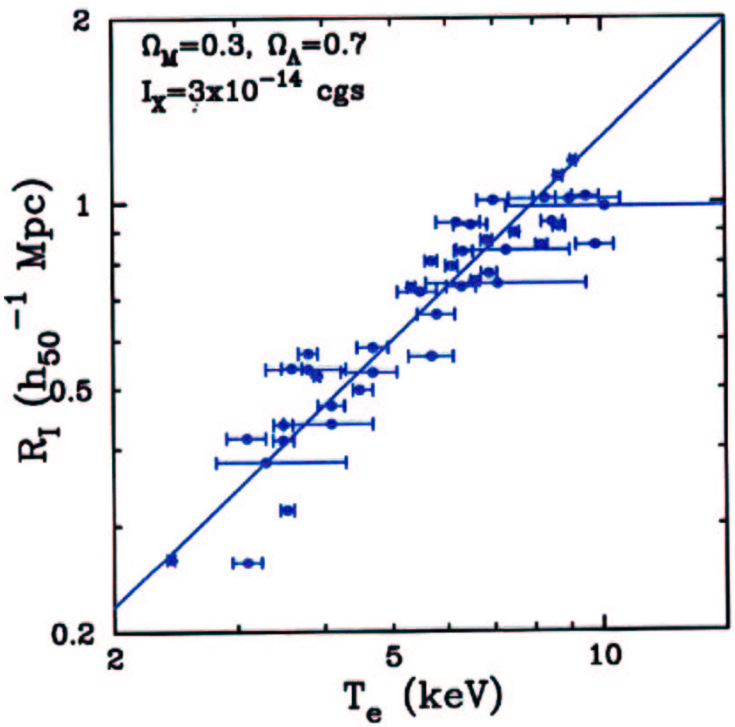


D_A Present & Future



Local ST Relation

$$R_I = \sqrt{\frac{A_I}{\pi}}$$



Motivation

- Start with self similar virialized clusters so that $R_\delta \propto T_e^{1/2} \rho_c^{-1/2}$
- Relate R_δ and R_I with the isothermal β model

$$I(R) = I_0 \left[1 + (R/R_c)^2\right]^{(1-6\beta)/2}$$

- Consider the region far from the core radius, $I(R) \propto R^{1-6\beta}$
- Therefore

$$R_I = R_\delta \left[\frac{I(R_\delta)}{I}\right]^{1/(6\beta-1)}$$

- Combining we find

$$R_I \propto T_e^\alpha \text{ where } \alpha = \frac{3\beta}{6\beta - 1}$$

- For the typical $\beta = 2/3$ (Jones & Forman 1984), $R_I \propto T_e^{2/3}$

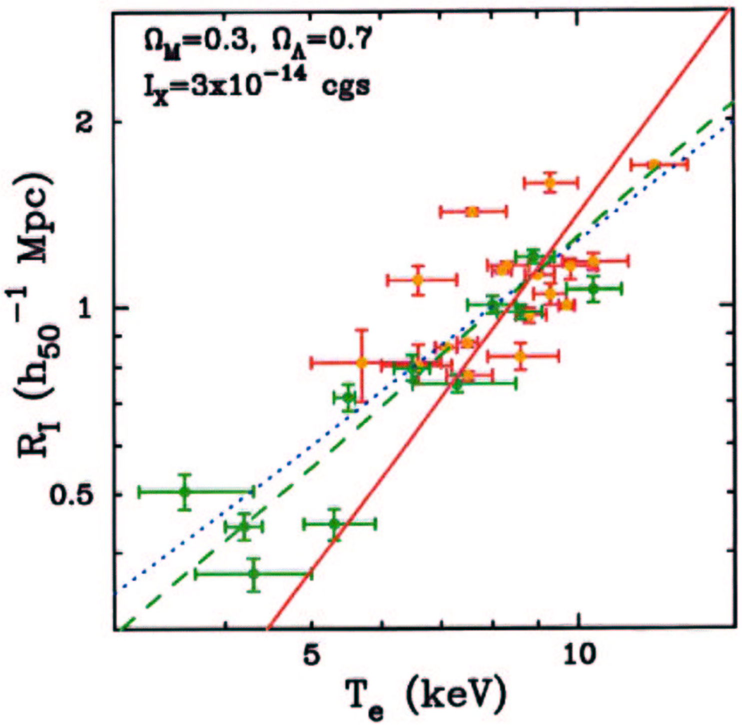
Local Relation

- $R_I = 0.74^{+0.01}_{-0.01} \left(\frac{T_e}{6\ keV}\right)^{1.09^{+0.04}_{-0.04}} h_{50}^{-1}$ Mpc
- Deviations from $R_I \propto T_e^{2/3}$ consistent with the trend of gas fraction with T_e (Mohr et al. 1999)
- Likely cause of trend is energy injection during galaxy formation

Evolution of the ST Relation

- Self similar model follows the evolution in the critical density, $\rho_c \propto E^2(z)$, where $E(z) = H(z)/H_0$
- $R_I(T_e, z) = R_I(T_e, 0)E^{\eta}(z)$, $\eta = \frac{4-6\beta}{6\beta-1}$
- For $\beta = 2/3$, $\eta = 0 \Rightarrow$ no evolution
- In principal, ST is ideal for measuring distances to high-redshift clusters

Distant ST Relation



Distant sample, Mohr et al. (2000), Local relation

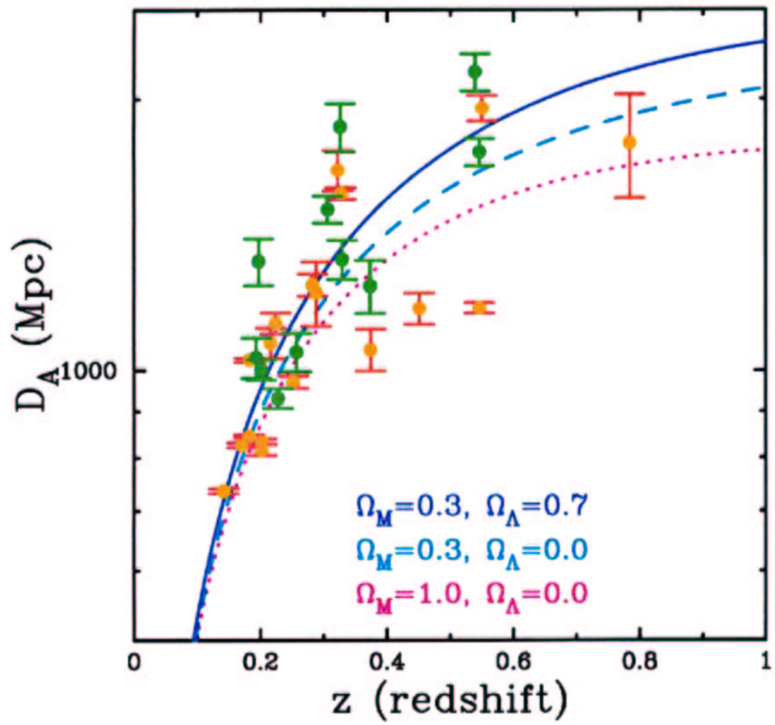
Distant ST Relation

- Sample of 18 distant $(0.14 \leq z \leq 0.78)$ galaxy clusters (ROSAT)
- Detailed β model analysis
- $R_I = (0.53^{+0.10}_{-0.15}) \left(\frac{T_e}{6\ \mathrm{keV}}\right)^{1.91^{+0.96}_{-0.51}} h_{50}^{-1}$ Mpc
- Steeper slope suggests possible evolution in the ST relation
- Require a larger sample to definitively test the standard cluster evolution model

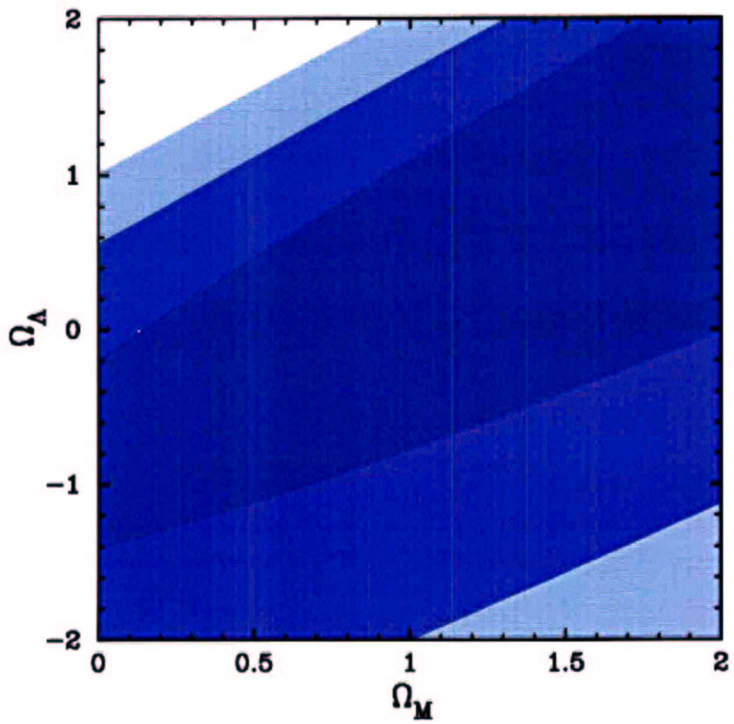
Cosmological Constraints

- ST relation is not expected to evolve with redshift
- Simple picture: $D_A = R_I^{local}/\theta_I^{distant}$
- Determine the geometry of the universe
- Turning this around, we can study the evolution of cluster structure if cosmology is known

Distances



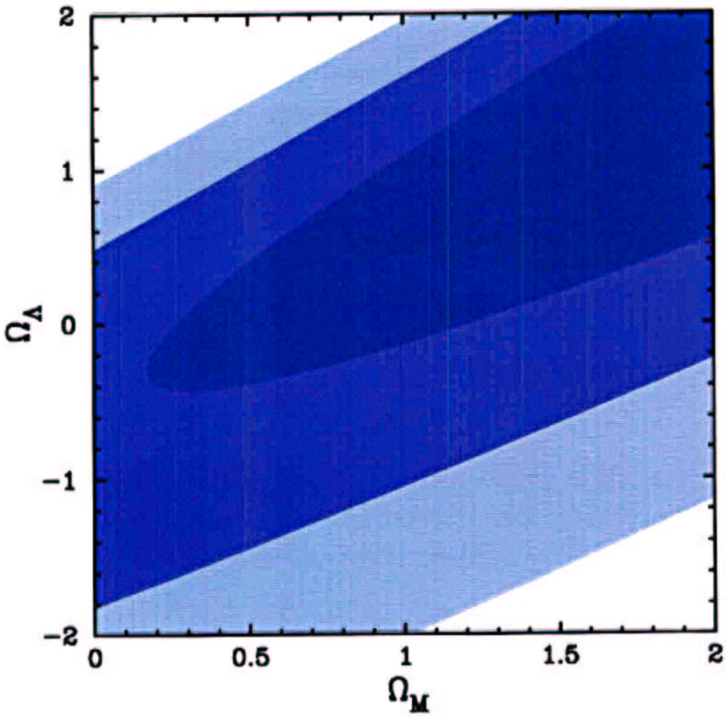
18 Cluster Sample



Combined Sample

- Need larger sample so combine our sample with Mohr et al. (2000) sample
- Combined sample of 26 clusters
- $R_I = (0.65^{+0.03}_{-0.03}) \left(\frac{T_e}{6\ \mathrm{keV}}\right)^{1.33^{+0.20}_{-0.13}} h_{50}^{-1}\ \mathrm{Mpc}$
- Again, the **hint** of evolution in the ST relation with redshift
- Combined sample cosmological constraints still weak

Combined Sample

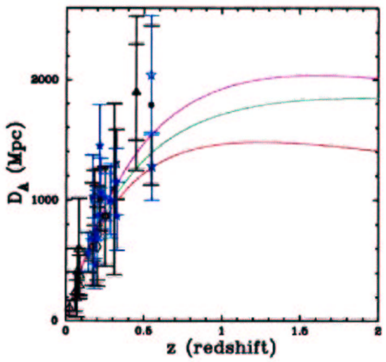


Summary

- Clusters are regular structures, as exhibited by tight correlations between observed global properties
- ST relation provides some evidence that clusters are not evolving according to the standard evolution model
- Cosmological constraints are weak but can potentially be overcome with a large sample of high redshift clusters

Summary

- H_0 independent of distance ladder
  $H_0 = 60^{+4}_{-4}{}^{+13}_{-18}$ km s^{-1} Mpc^{-1}; $\Omega_M, \Omega_\Lambda = 0.3, 0.7$
- Systematics are approachable
  Chandra/XMM-Newton, VLA, SZE calibration, Simulations...



- Ready to Determine Geometry of Universe
- SZE Surveys
  redshift independence of SZE