CBI Observations of the Sunyaev-Zeldovich Effect

Steven T. Myers*,

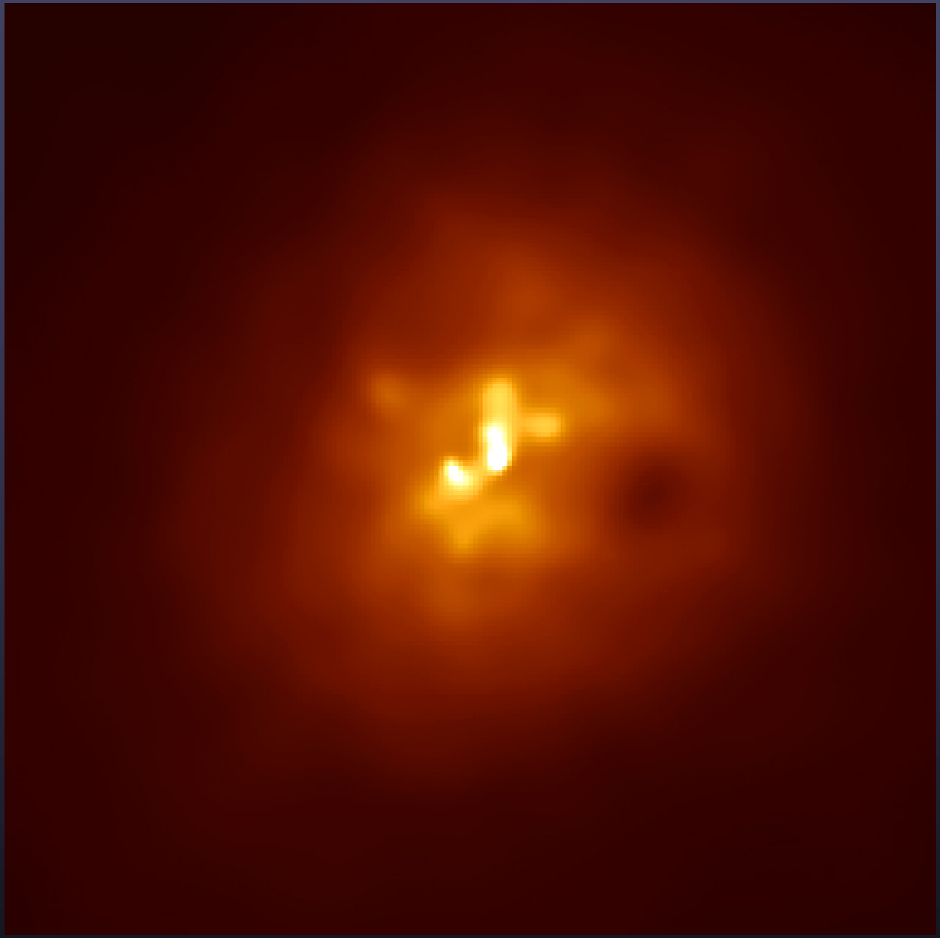
Patricia Udomprasert, and the CBI Team

***National Radio Astronomy Observatory**

Socorro, NM

The Sunyaev-Zeldovich Effect

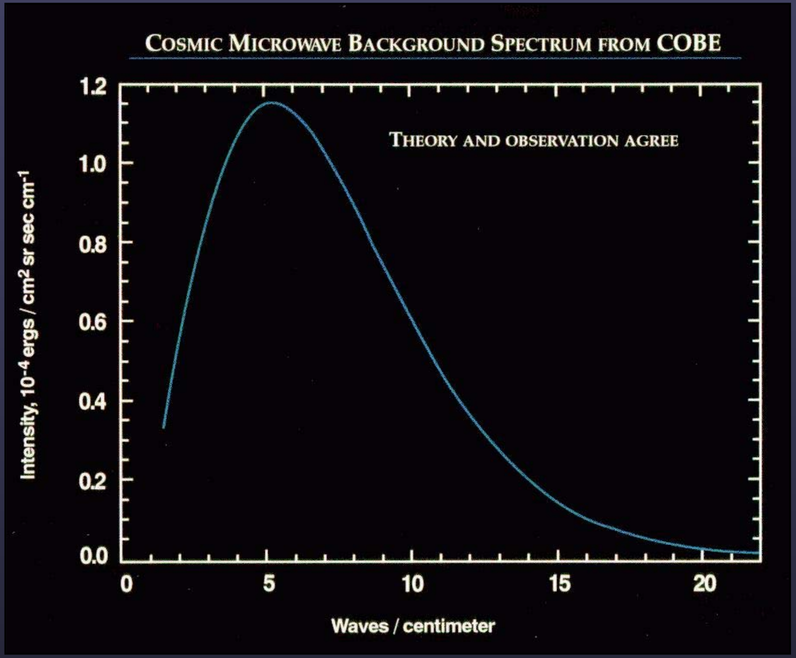
Behind clusters of galaxies is …

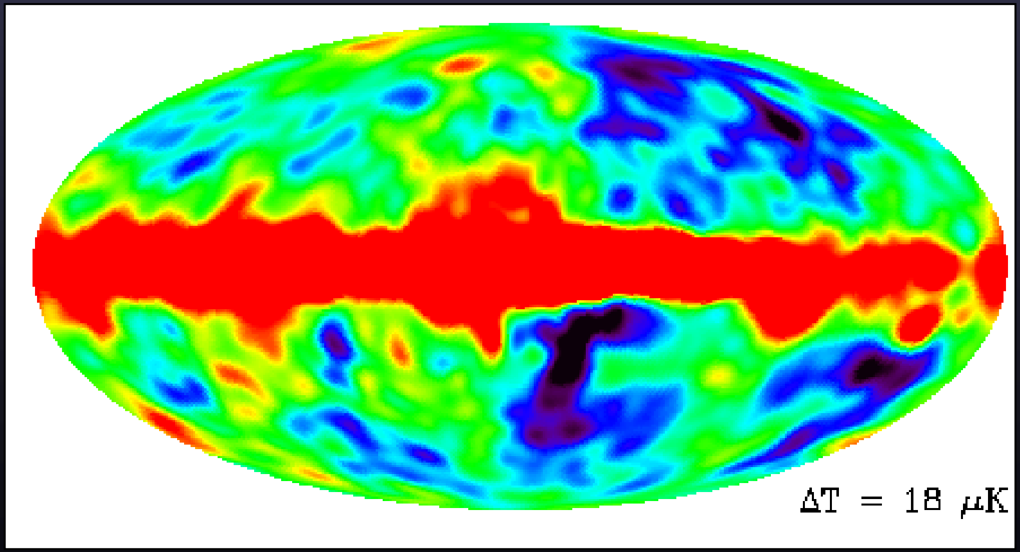


- *A2597 Chandra, courtesy NASA/CXC/Ohio U/B.McNamara et al.*

The Cosmic Microwave Background

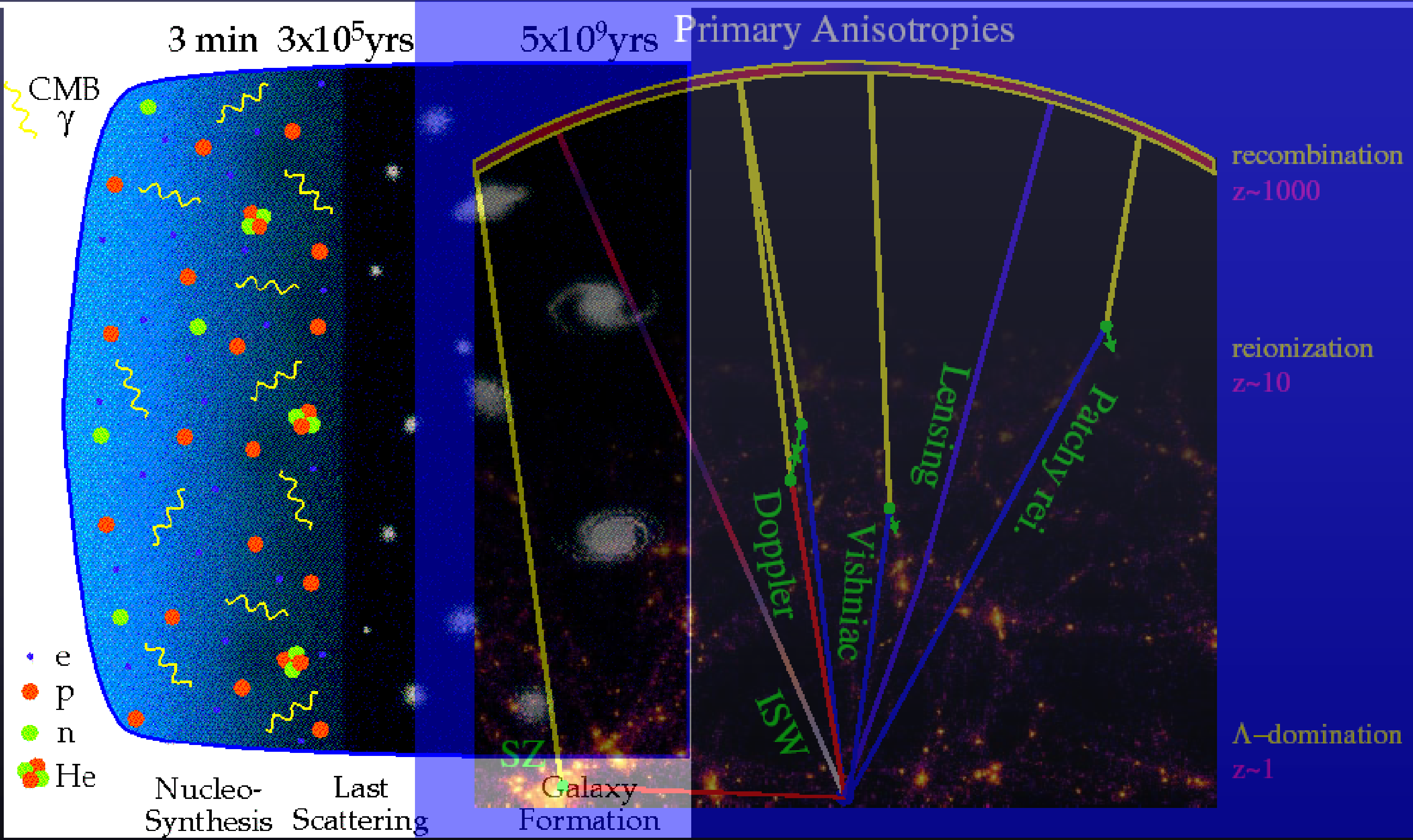
- Discovered 1965 (Penzias & Wilson)
  - 2.7 K blackbody
  - Isotropic
  - Relic of hot "big bang"
  - 3 mK dipole (Doppler)





- COBE 1992
  - Blackbody 2.725 K
  - Anisotropies 10^{-5}

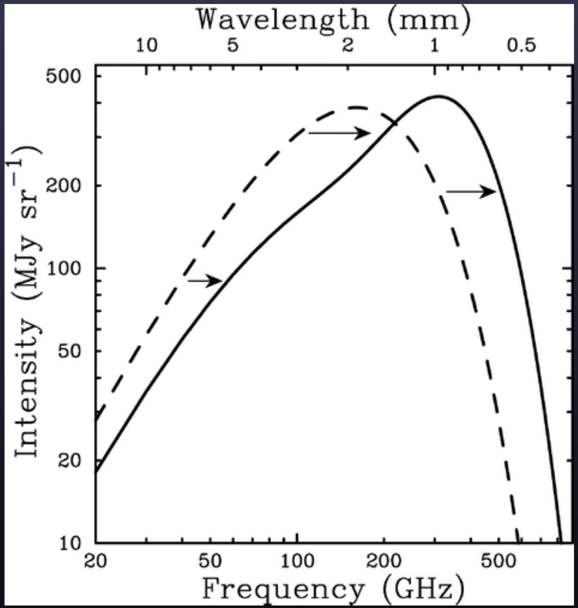
Thermal History of the Universe

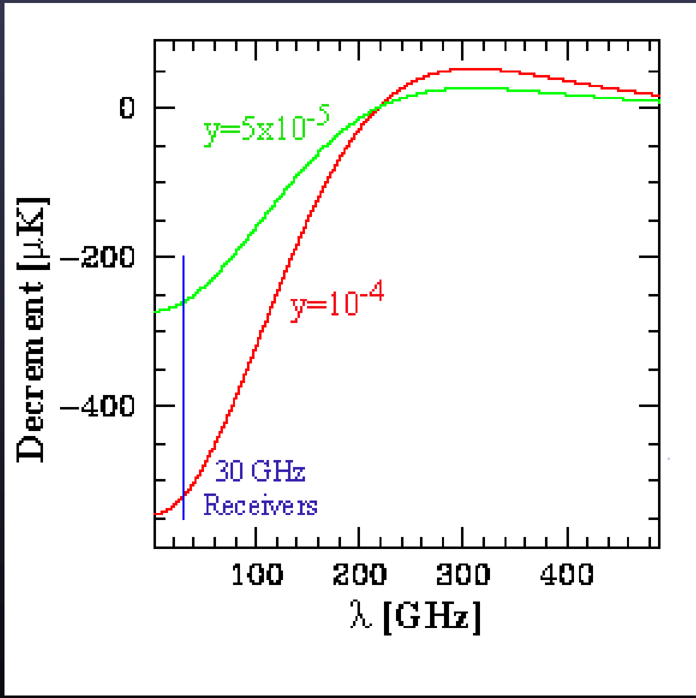


Courtesy Wayne Hu – *http://background.uchicago.edu*

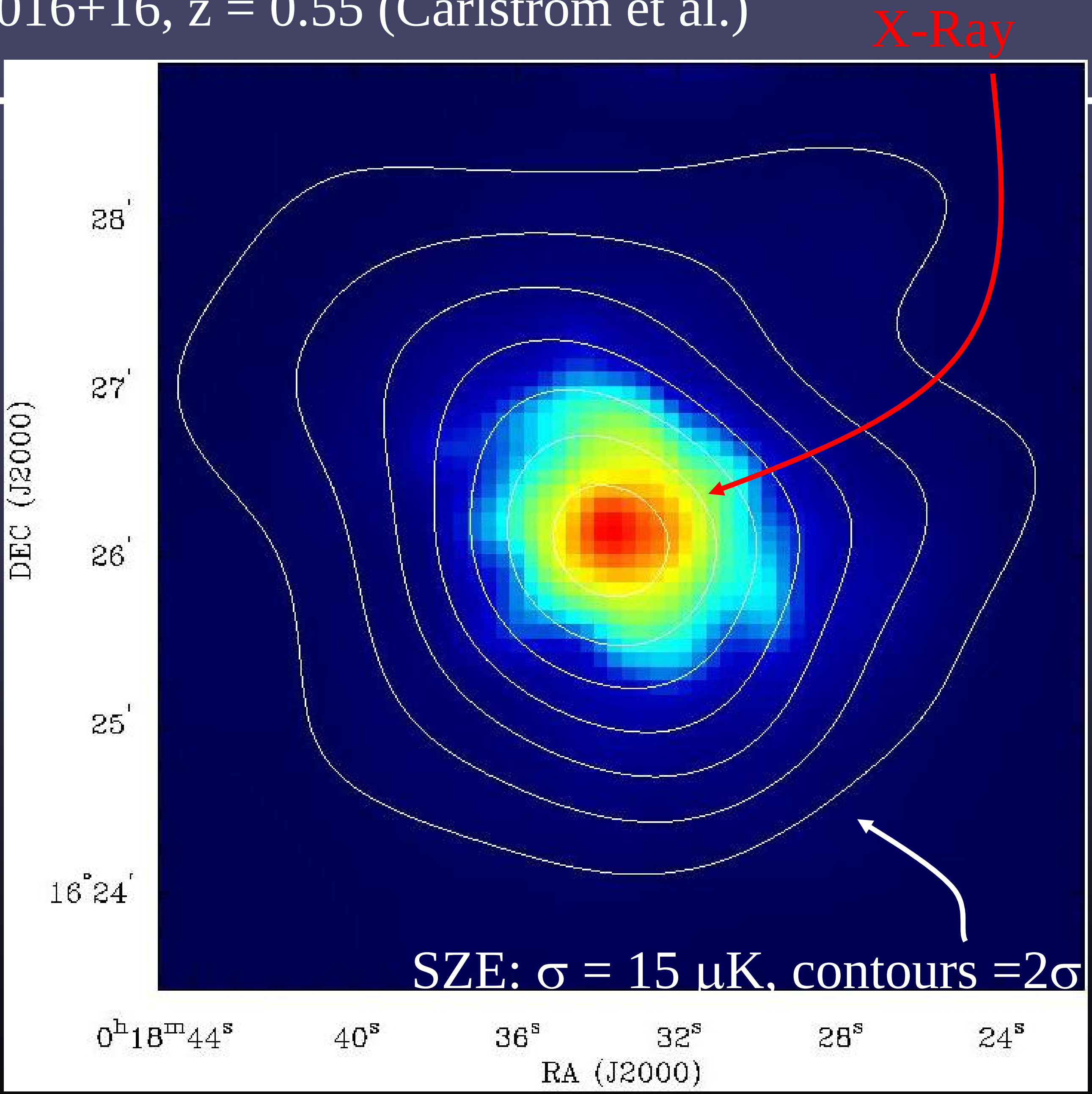
The SZE

- The Sunyaev-Zeldovich Effect
  - Compton upscattering of CMB photons by keV electrons
  - decrement in I below CMB thermal peak (increment above)
  - negative extended sources (absorption against 3K CMB)
  - massive clusters mK, but shallow profile $\theta^{-1} \rightarrow -\exp(-\nu)$

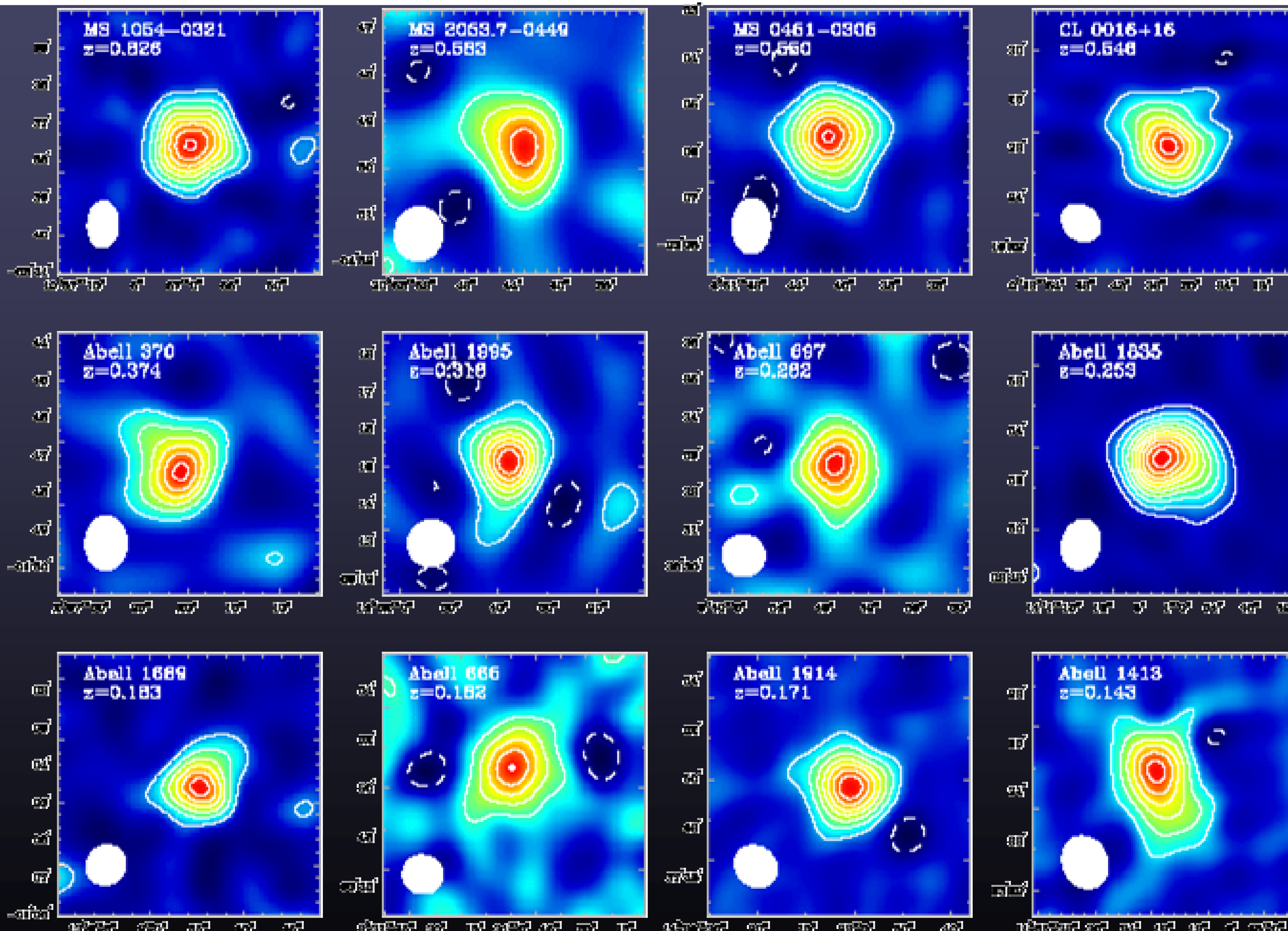




CL 0016+16, z = 0.55 (Carlstrom et al.)



Sample from 60 OVRO/BIMA imaged clusters, 0.07 < z < 1.03



The Cosmic Background Imager

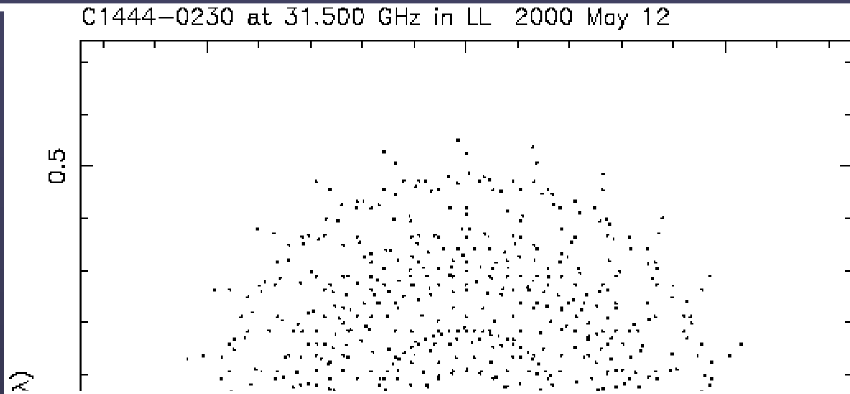
The Instrument

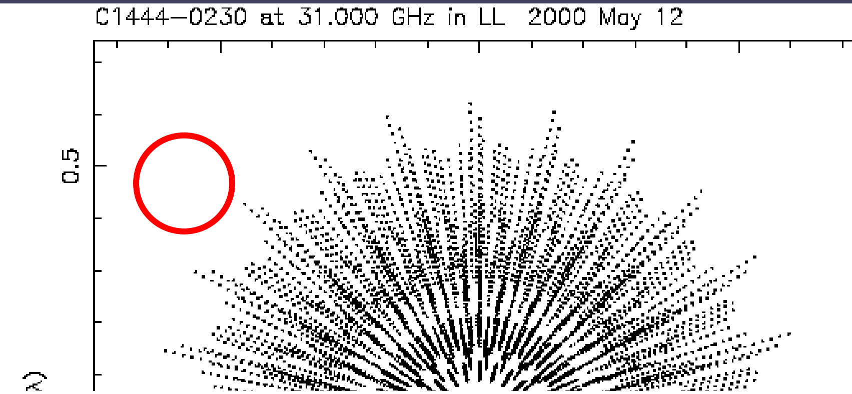
- 13 90-cm Cassegrain antennas
  - 78 baselines
- 6-meter platform
  - Baselines 1m – 5.51m
- 10 1 GHz channels 26-36 GHz
  - HEMT amplifiers (NRAO)
  - Cryogenic 6K, Tsys 20 K
- Single polarization (R or L)
  - Polarizers from U. Chicago
- Analog correlators
  - 780 complex correlators
- Field-of-view 44 arcmin
  - Image noise 4 mJy/bm 900s
- Resolution 4.5 – 10 arcmin

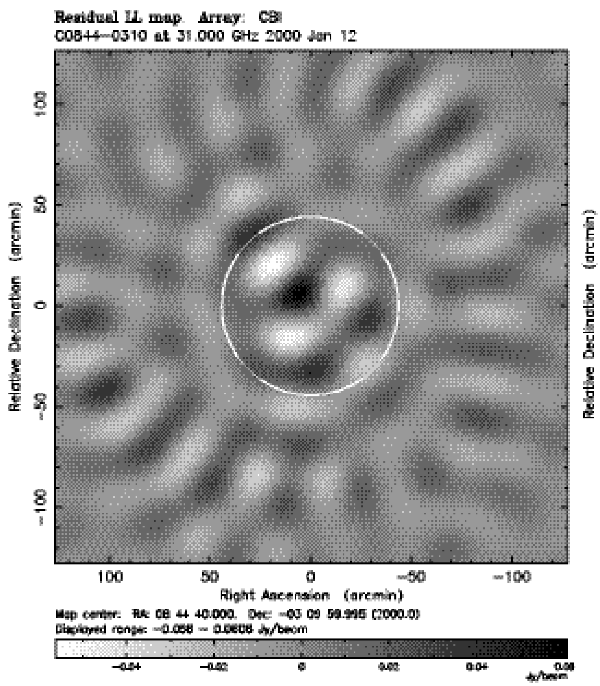
3-Axis mount : rotatable platform

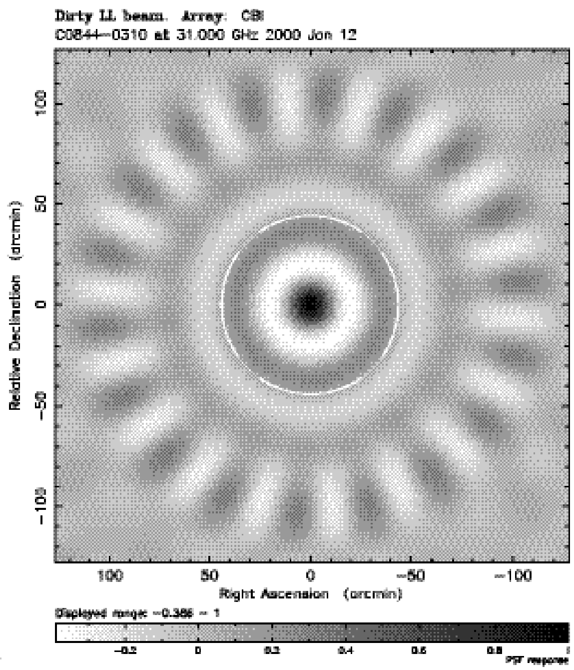
CBI Operations

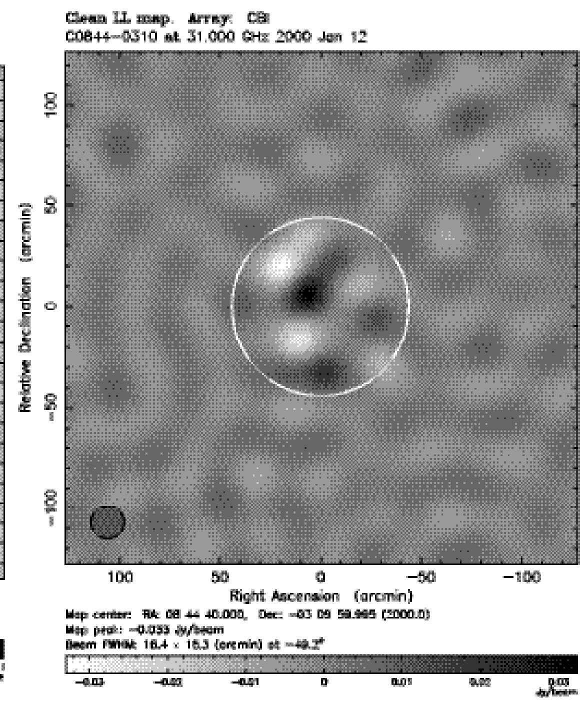
CBI Beam and *uv* coverage



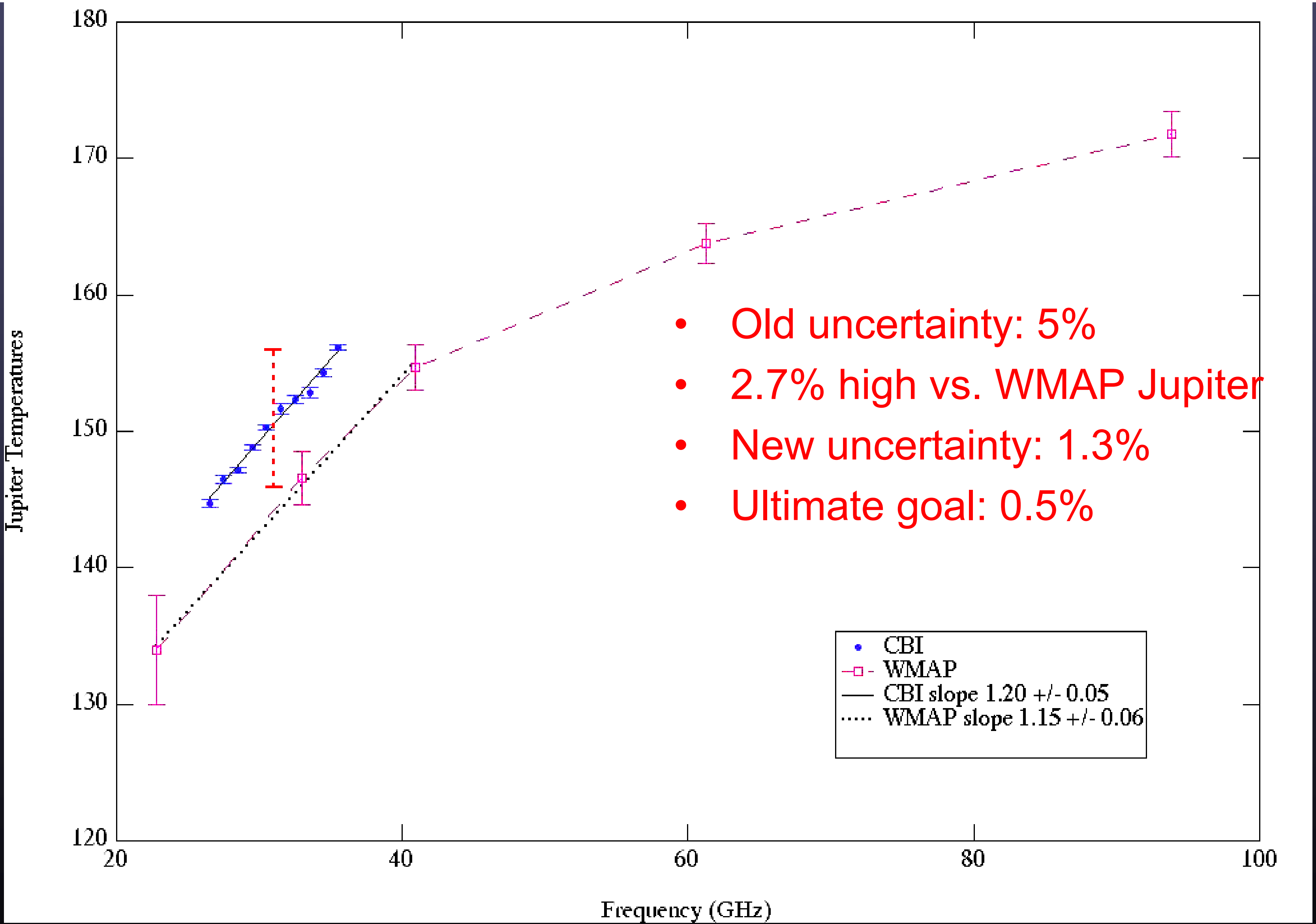








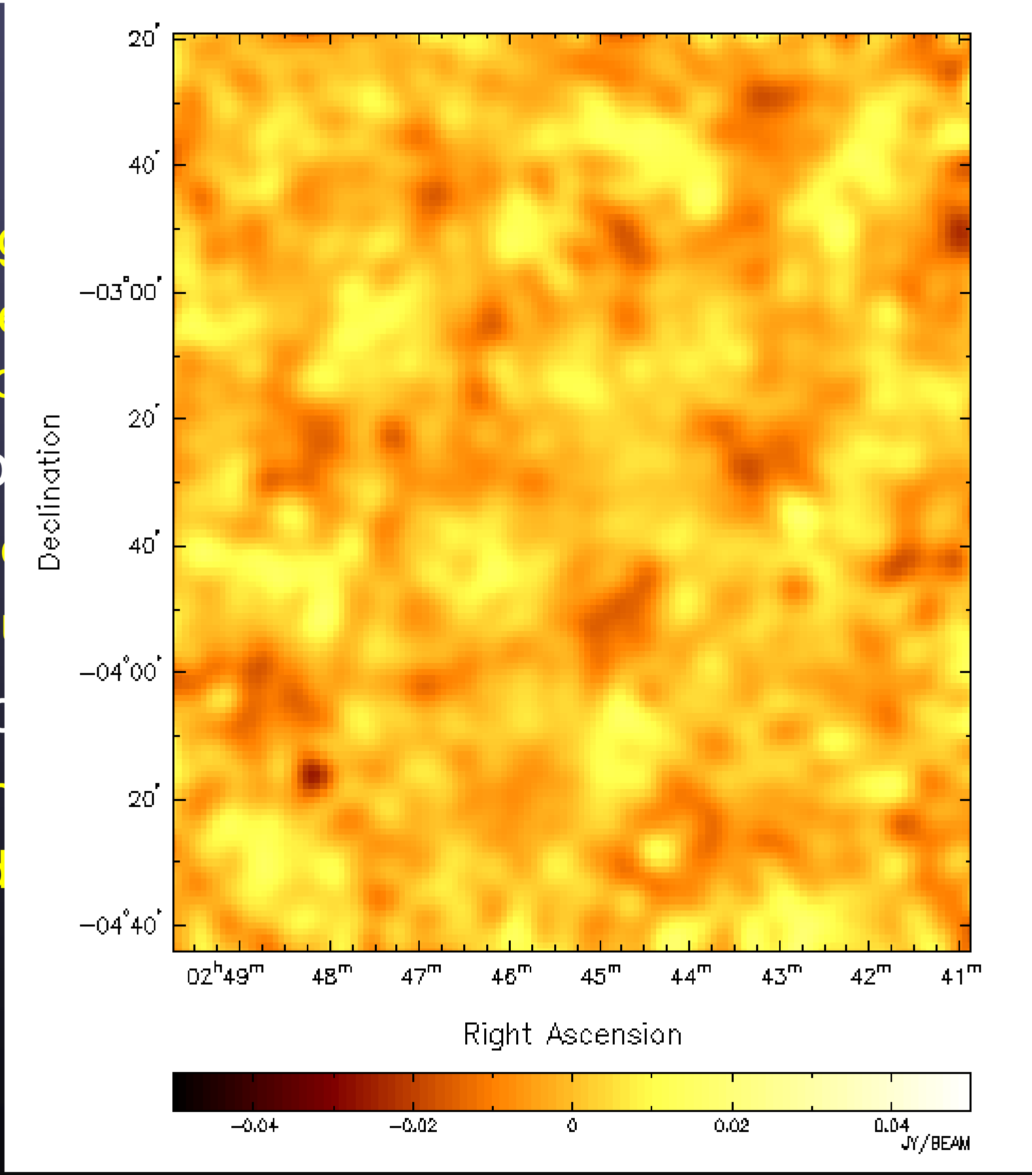
CBI Calibration from WMAP Jupiter



- Old uncertainty: 5%
- 2.7% high vs. WMAP Jupiter
- New uncertainty: 1.3%
- Ultimate goal: 0.5%

Decontamination

- Ground
  - Strong
  - Differe (9m to
- Foregro
  - Locate
  - Meas
- Backgro
  - domin
  - includ



The CBI SZE Program

The CBI SZE Sample

- led by Patricia Udomprasert (PhD. Thesis Caltech 2003)
- drawn from ROSAT (Ebeling et al. 1996, 1998; de Grandi et al. 1999; Boehringer et al. 2003)
- $f_{0.1\text{-}2.4keV} > 1.0 \times 10^{-11}$ erg cm^{-2} sec^{-1}
- $z < 0.1$
- $L_{0.1\text{-}2.4keV} > 1.13 \times 10^{44}\ h^{-2}$ erg s^{-1}
- declination $-70° < \delta < 24°$
- 24 clusters accessible to CBI
- primary sample 15 most luminous
- detailed in Udomprasert, Mason, Readhead & Pearson (2004) preprint

Cluster	z	$L_{0.1-2.4keV}$ ($h^{-2}10^{44}$ erg/s)[a]	*ROSAT*	*ASCA*	*XMM-Newton*	*Chandra*
A2029	0.775	3.84	P	y	G	S
A478	0.0881	3.24	P	y	G	S
A401	0.0737	2.47	P	y	G	I
A3667^S	[illegible]	2.32	P	y	G	I
A85	0555	2.15	P	y	B	I
A3827^S	0.0984	1.95	H		B	
A3571	0.0391	1.94	P	y	B	
A3266^S	[illegible]	1.89	P	y	G	I
A1651	0.0844	1.85	P	y		I
A754	[illegible]	[illegible]	P	y	G	I
A3112^S	0.0750	1.79	P	y	G	S
A399	0.0724	1.61	P	y	G	I
A1650	0.0845	1.61	P	y	B	
A2597	0.0852	1.48	P	y	G	S
A3558	0.0480	1.46	P	y	G	S
A3695	0.0894	1.44	H			
PKS1550-140	[illegible]	[illegible]				
A3158^S	0.0597	[illegible]	P	y		I
A3921^S	0.0936	1.32	P	y	G	
Z5029	[illegible]	1.32				
A780	0.0539	1.23	P	y	G	I,S
[illegible]^S	[illegible]	1.23	P			
A2420	0.0846	1.16				
A4010	0.0957	1.16				

[a] XBACs and REFLEX assume $h = 0.5$. Here we convert their luminosities to units of $h = 1$.
[S] Southern Source, not accessible with VLA or OVRO 40-m
ROSAT : P = Public PSPC, H = Public HRI only
ASCA : y = public data available
XMM-Newton : G = Guaranteed Time Target, B = General Observer Target
Chandra : I = ACIS-I, S = ACIS-S

Subsample 7 clusters

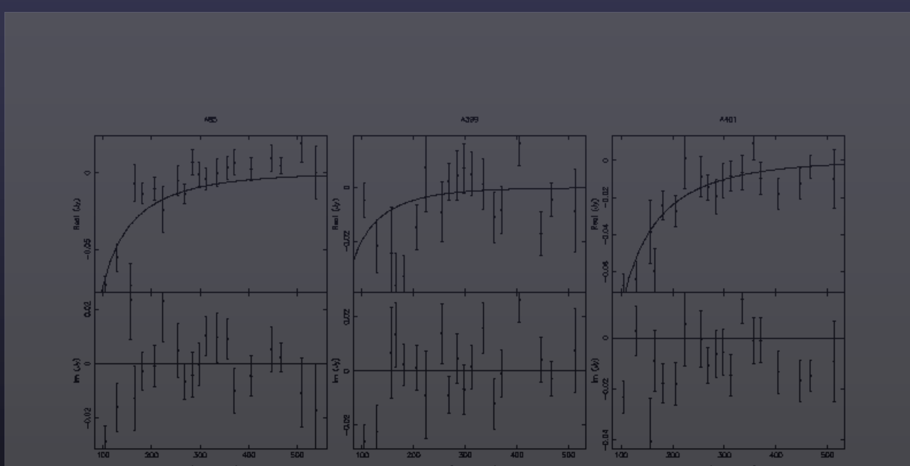
Cluster	R.A. (J2000)	Decl. (J2000)	L&T offsets (min)	Hours Observed (L+M+T)	rms noise (mJy/beam)	Beam FWHM
A85	00:41:48.7	−09:19:04.8	±16.5	16.6	1.8	5.3′
A399	02:57:49.7	+13:03:10.8	±12.5	15.6	2.0	5.4′
A401	02:58:56.9	+13:34:22.8	±12.5	15.7	2.0	5.4′
A478	04:13:26.2	+10:27:57.6	±10	12.2	2.4	5.2′
A754	09:09:01.4	-09:39:18.0	±9	16.0	1.9	5.4′
A1651	12:59:24.0	-04:11:20.4	±11	16.3	2.0	4.9′
A2597	23:25:16.6	-12:07:26.4	±15.5	11.6	2.3	5.5′

Cluster	θ_0 (arcm)	β	n_{e0} ($10^{-3} h^{1/2}$ cm^{-3})	*ASCA* Avg (keV)	*BeppoSAX* DM2002 (keV)	*BeppoSAX* & *ASCA* average	error in $h^{-1/2}$	Cooling Flow or Single Compon
A85	2.04±0.52	0.600±0.05	10.20±3.40	6.8±0.5	6.83±0.15	6.8±0.2	±2.9%	CF
A399	4.33±0.45	0.742±0.042	3.22±0.46	6.9±0.2			±2.9%	SC
A401	2.26±0.41	0.636±0.047	7.95±0.98	8.3±0.4			±4.8%	SC
A478	1.00±0.15	0.638±0.014	27.88±6.39	7.9±0.8			±10.1%	CF
A754	5.50±1.10	0.713±0.120	3.79±0.07	9.7±0.3	$9.42^{+0.16}_{-0.17}$	9.5±0.2	±2.1%	SC
A1651	2.16±0.36	0.712±0.036	6.84±1.79	6.2±0.2			±6.3%	SC
A2597	0.49±0.03	0.626±0.018	42.99±3.82	4.2±0.4			±9.5%	CF

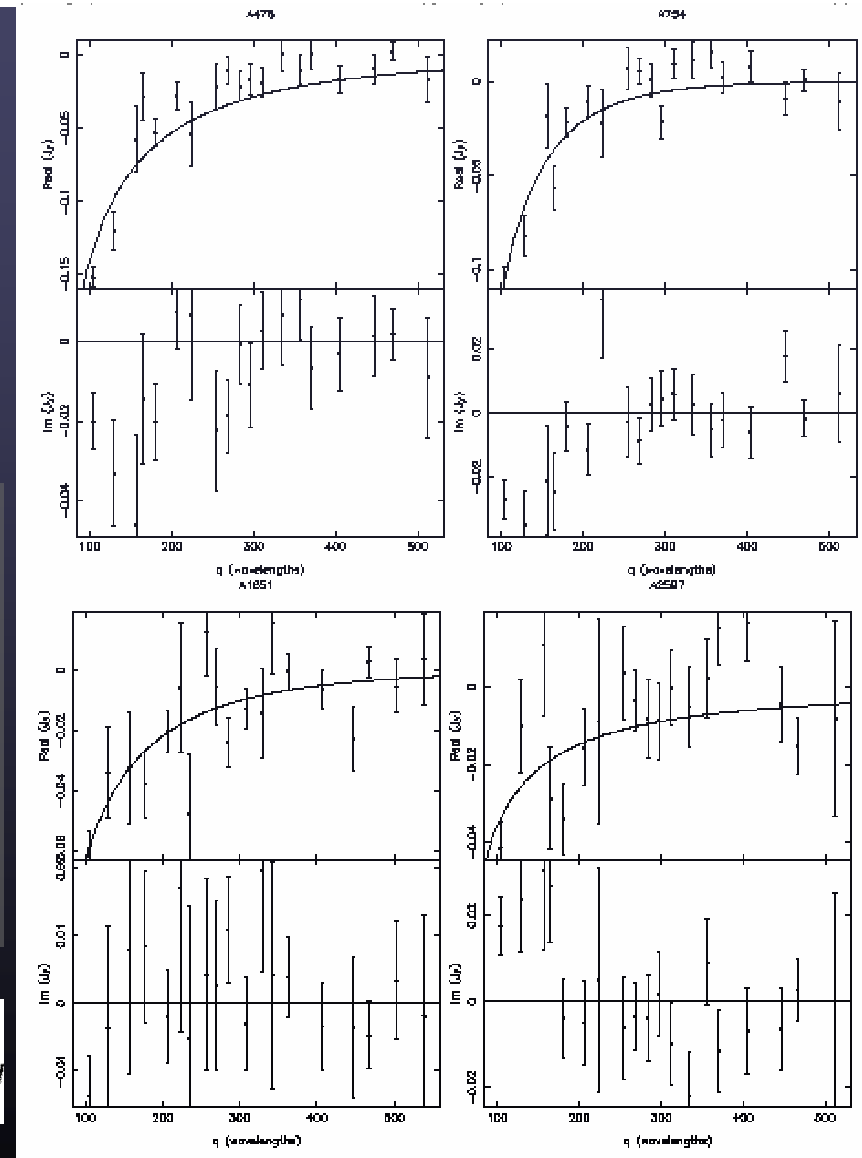
- covers a range of luminosities and cluster types

CBI SZE visibility function

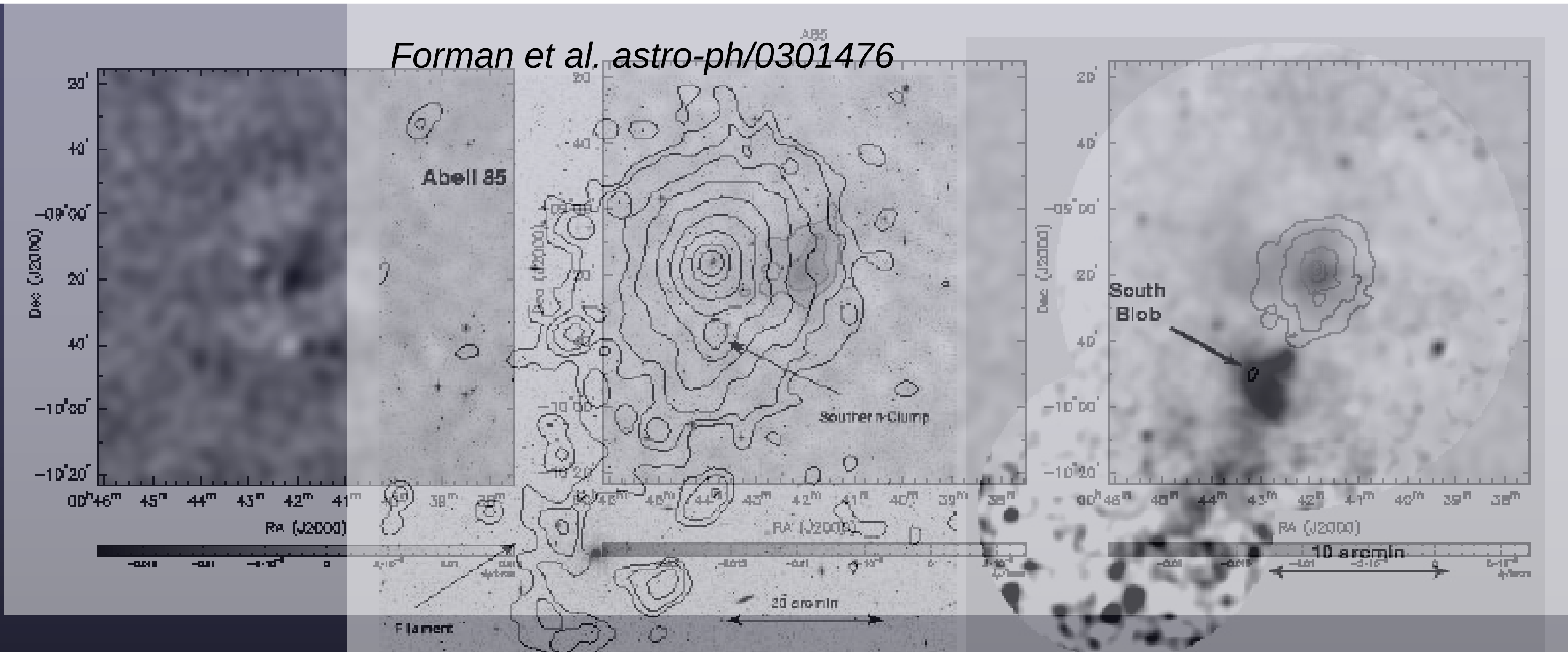
- Xray: θ^{-3} ($\beta \sim 2/3$)
- SZE: $\theta^{-1} \rightarrow$ -exp(-v)
- dominated by shortest baselines



$$V(u,v) = I_0 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} B(\theta)\left(1+\frac{\theta^2}{\theta_0^2}\right)^{-\frac{3}{2}\beta+\frac{1}{2}} e^{2\pi i(ux+vy)}\,dx\,dy$$



A85

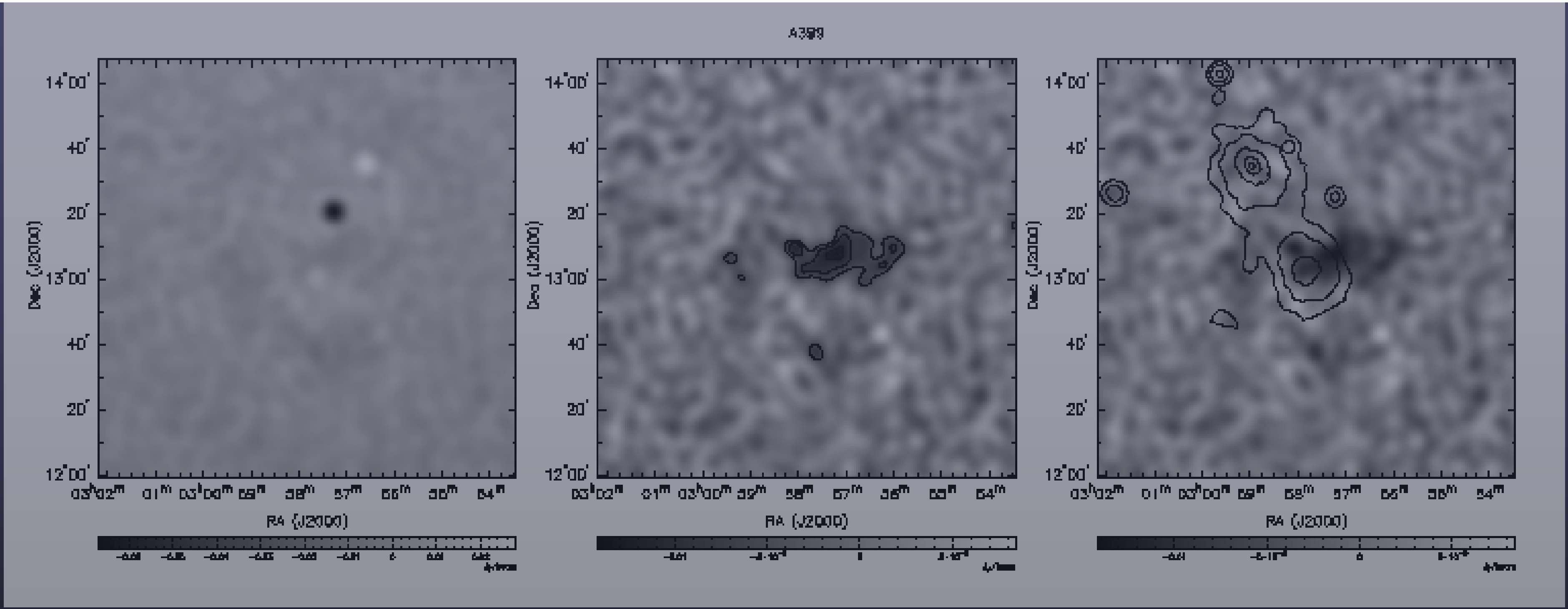


(left) Raw CBI Image (center) CLEAN source-sub CBI Image (right) CBI w/ROSAT

Figure 1. ROSAT and XMM-Newton observations of A85 (a) ROSAT PSPC iso-intensity contours (0.4-2.0 keV) are shown superposed on an optical image (adapted from Durret et al. 1998). A filamentary structure extends to the southeast. (b) The XMM-Newton MOS image shows the inner portion of the filament extending southeast from the South Blob (Southern Clump) (Durret et al. 2003).

- A85 – cluster with central cooling flow, some signs of merger activity, subcluster to south

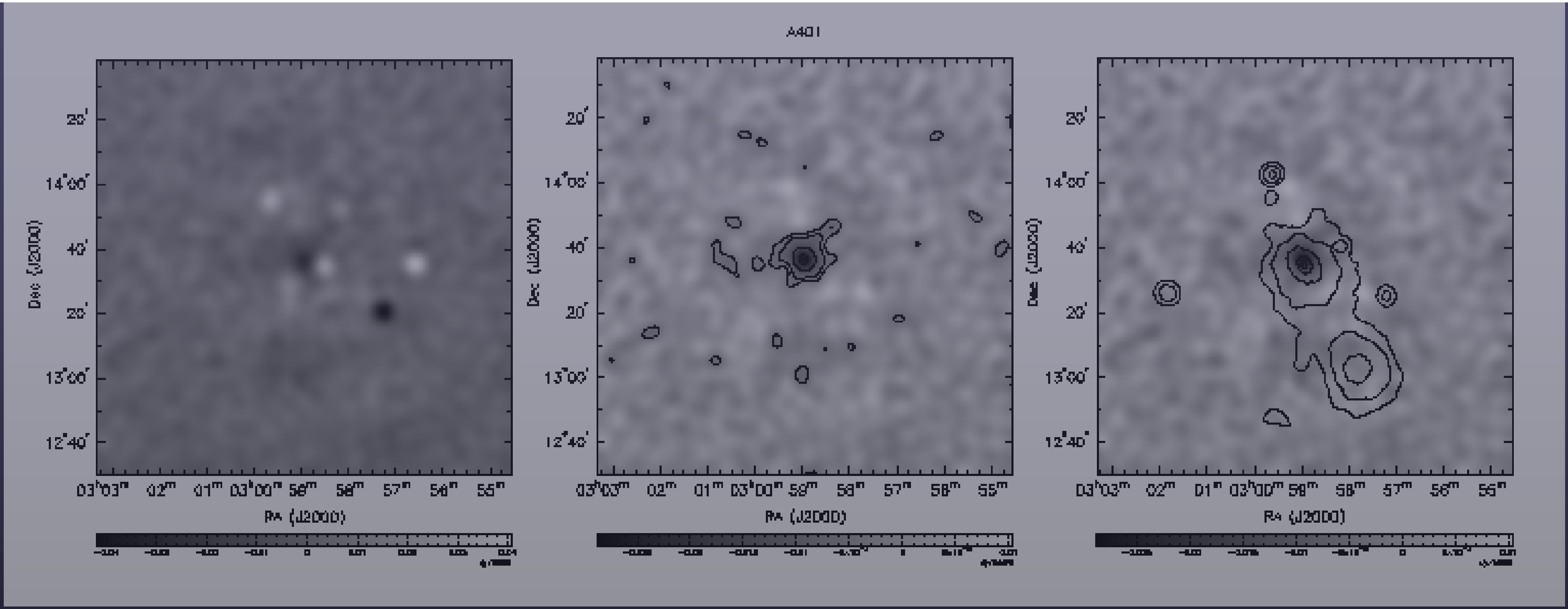
A399



(left) Raw CBI Image (center) CLEAN source-sub CBI Image (right) CBI w/ROSAT

- A399 – pair with A401

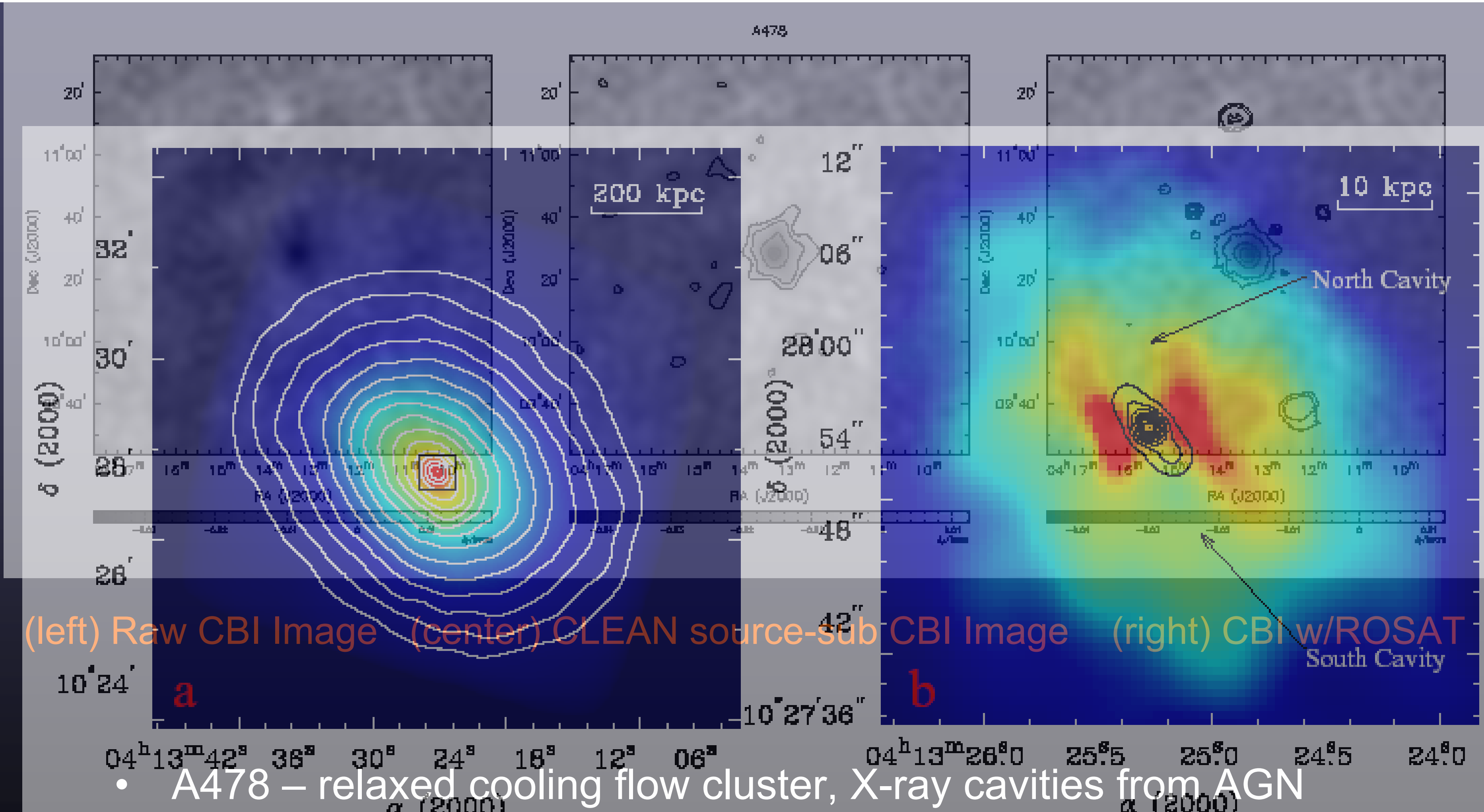
A401



(left) Raw CBI Image (center) CLEAN source-sub CBI Image (right) CBI w/ROSAT

- A401 – pair with A399, likely interacting now or in past, cooling flow disrupted?

A478

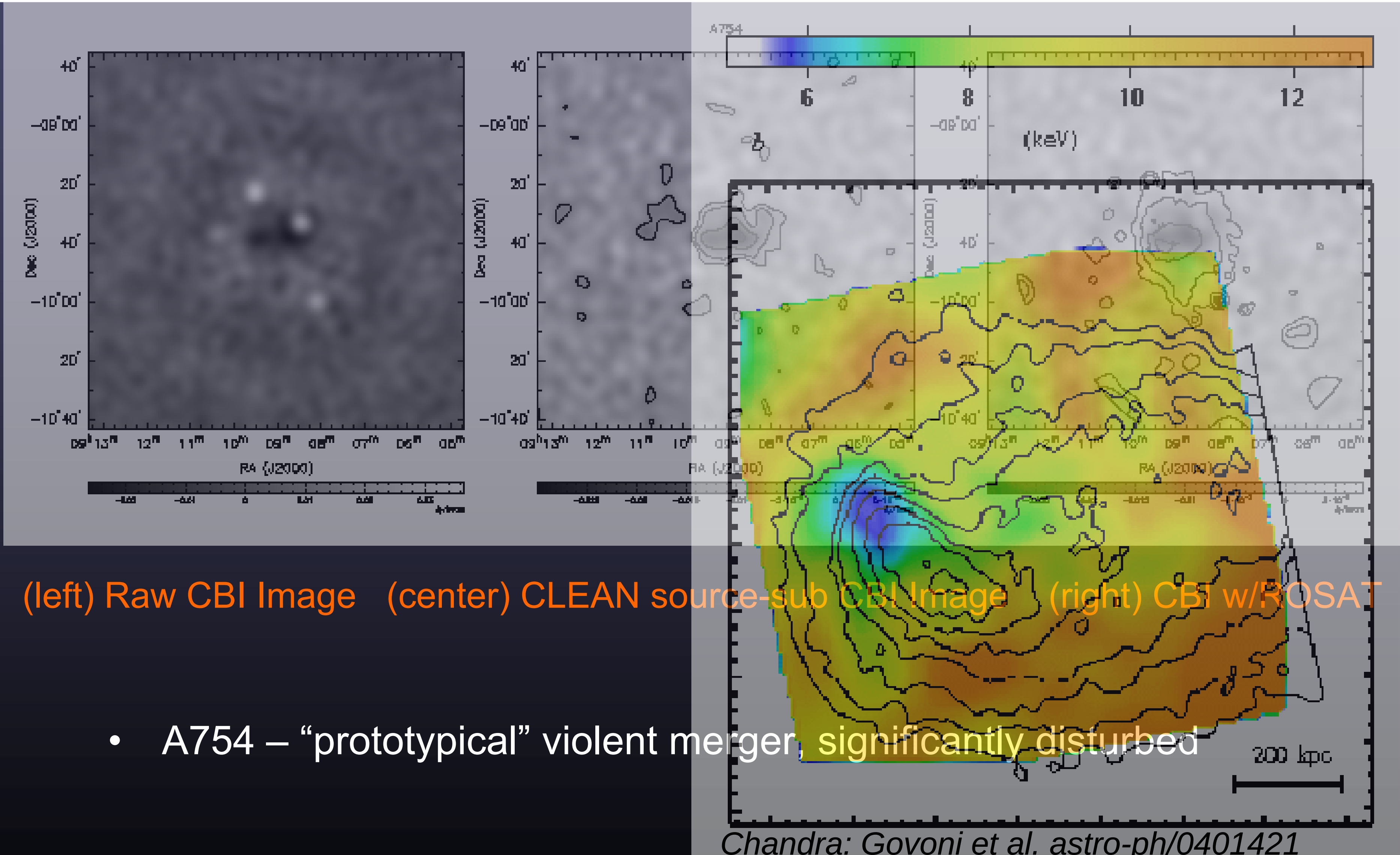


(left) Raw CBI Image (center) CLEAN source-sub CBI Image (right) CBI w/ROSAT

- A478 – relaxed cooling flow cluster, X-ray cavities from AGN

Chandra: Sun et al. astro-ph/0210054 *(inner region + 1.4 GHz radio)*

A754

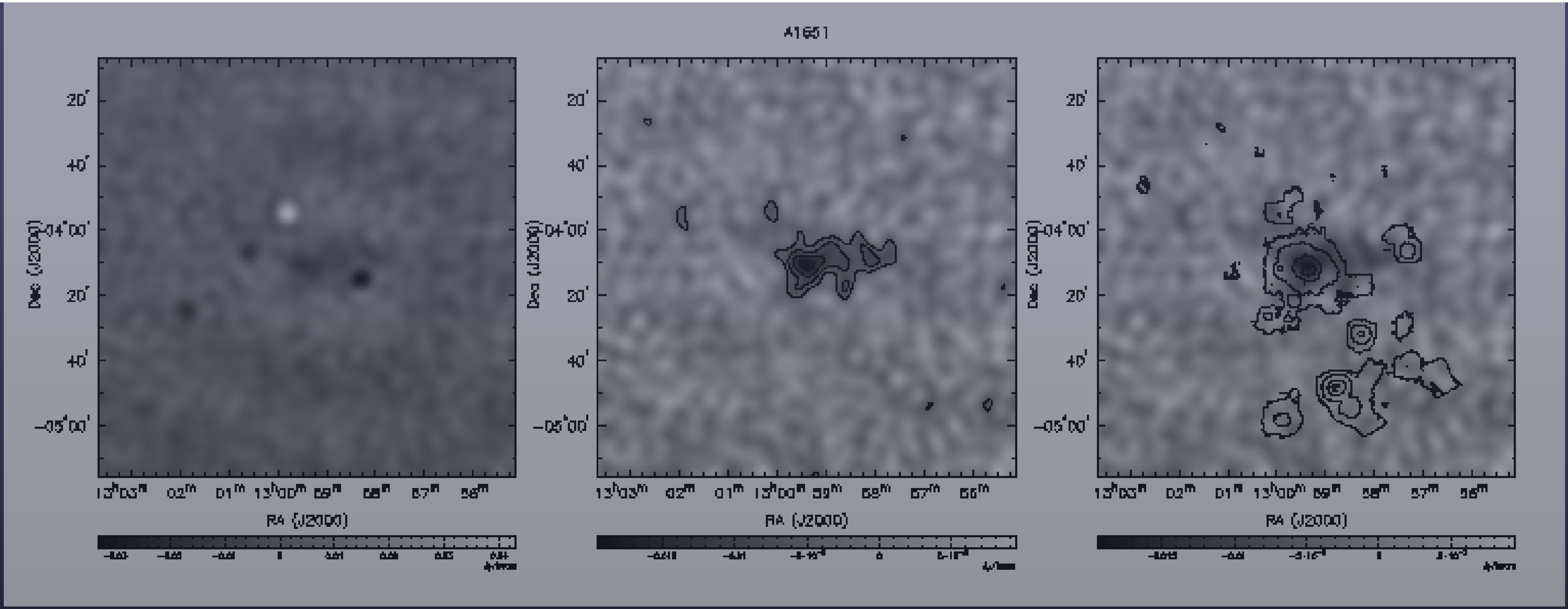


(left) Raw CBI Image (center) CLEAN source-sub CBI Image (right) CBI w/ROSAT

- A754 – “prototypical” violent merger, significantly disturbed

Chandra: Govoni et al. astro-ph/0401421

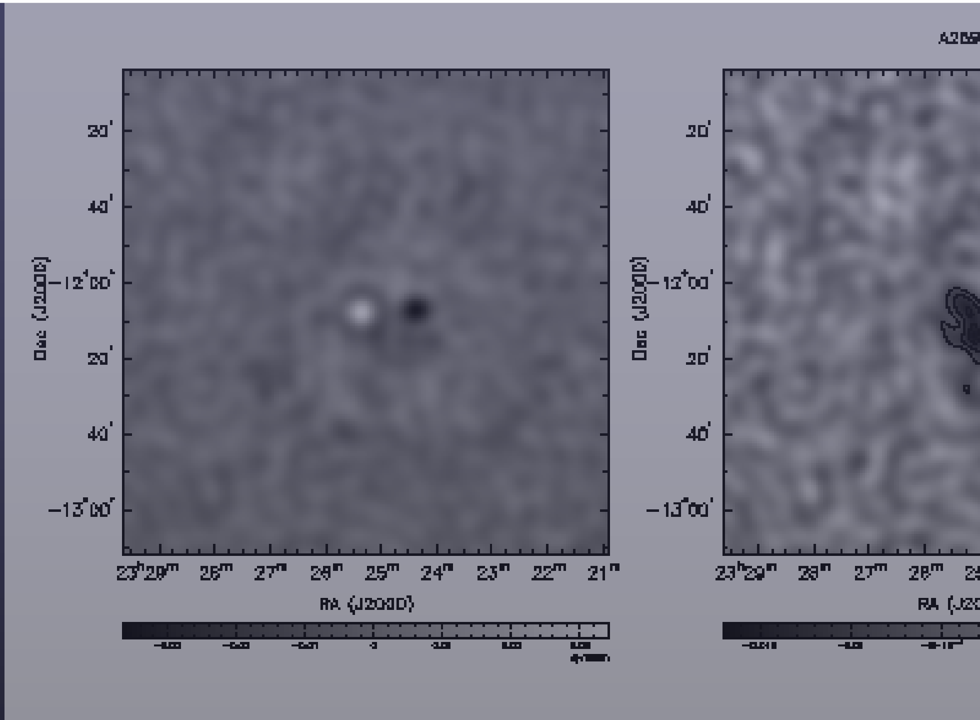
A1651

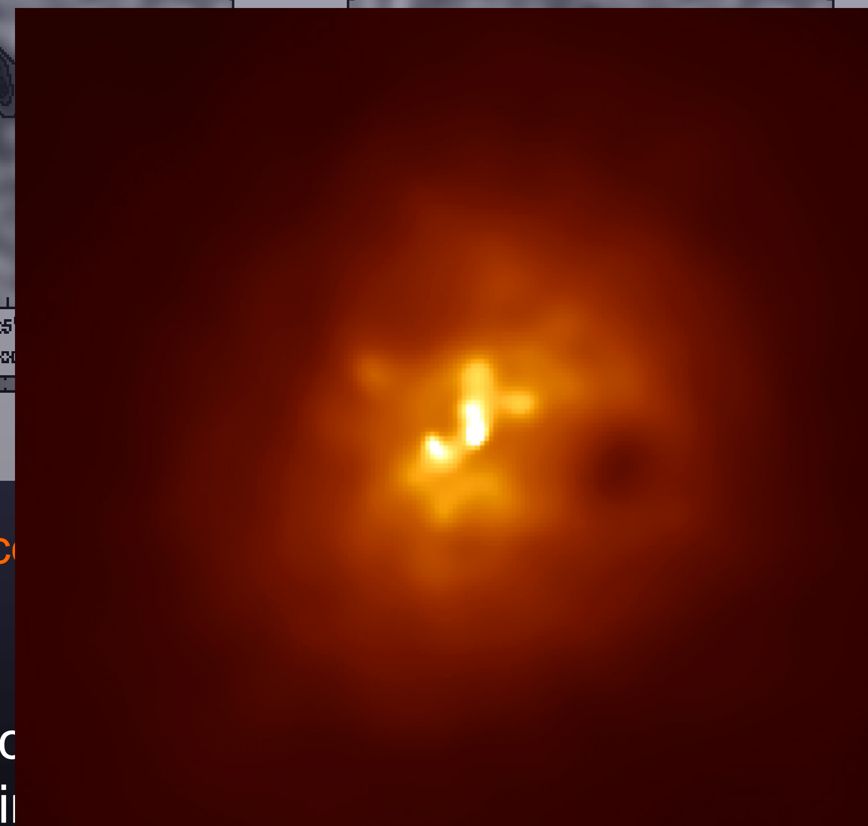


(left) Raw CBI Image (center) CLEAN source-sub CBI Image (right) CBI w/ROSAT

- A1651 – dynamically relaxed cD cluster, unremarkable

A2597





A2597 Chandra, courtesy NASA/CXC/Ohio U/B.McNamara et al.

(left) Raw CBI Image (center) CLEAN sourc

- A2597 – regular cD cluster with c
raw image) with X-ray shadows i

SZE vs. X-rays: The Main Event

- gas density profiles: $$n_e(r) = n_{e0}\left(1 + \frac{r^2}{r_0^2}\right)^{-3\beta/2}$$
- X-ray surface brightness: $$b_X(E) = \frac{1}{4\pi(1+z)^3}\int n_e^2(r)\Lambda(E,T_e)\,dl$$
- SZE surface brightness: $$\Delta I_{\rm SZE} \propto T_e \int n_e\,dl$$
- dependence on parameters:

$$b_X \propto n_{e0}^2\theta_0 D_A\left(1 + \frac{\theta^2}{\theta_0^2}\right)^{-3\beta+1/2}$$

$$\Delta I_{\rm SZE} \propto T_e n_{e0}\theta_0 D_A\left(1 + \frac{\theta^2}{\theta_0^2}\right)^{-\frac{3}{2}\beta+\frac{1}{2}}$$

- $D_A \sim h^{-1}$ $n_{e0} \sim h^{1/2}$ → $\Delta I_{SZE} \sim h^{-1/2}$

Results

- unweighted $H_0 = 67\ ^{+30}_{-18}\ ^{+13}_{-6}$ km/s/Mpc
- weighted $H_0 = 75\ ^{+23}_{-16}\ ^{+15}_{-7}$ km/s/Mpc
- uncertainties dominated by CMB confusion
- based on older X-ray data…

Cluster	Corrected $h^{-1/2}$ w/ total random error	ΔT_0 μK	Compton-y_0 ($\times 10^{-4}$)
A85	1.23±0.40	-580±190	1.13±0.37
A399	0.24±0.42	-80±130	0.15 ±0.26
A401	1.03±0.29	-620±170	1.20 ±0.34
A478	1.76±0.34	-1800±350	3.49±0.68
A754	1.09±0.31	-560±160	1.09±0.31
A1651	1.42±0.47	-520±170	1.00±0.33
A2597	1.74±1.10	-750±670	1.43±1.28
mean ± sd =	1.22±0.52		
(probability=21%)	$\frac{\chi^2}{\nu} = 1.47$ for 6 dof		
unweighted sample average: $h^{-1/2}$ =	1.22±0.20		
→	$h = 0.67^{+0.30}_{-0.18}$		
weighted sample average: $h^{-1/2}$ =	1.16±0.14		
→	$h = 0.75^{+0.23}_{-0.16}$		

Gastrophysics?

- “mergers” A85, A399/401, A754
  - A401 & A754 somewhat low, A399 very low (but uncertain)
- “cooling cores” A85, A478, A2597
  - A478 high, A2597 very high (but uncertain)

Cluster	Corrected $h^{-1/2}$ w/ total random error	ΔT_0 μK	Compton-y_0 ($\times 10^{-4}$)
A85	1.23±0.40	-580±190	1.13±0.37
A399	0.24±0.42	-80±130	0.15 ±0.26
A401	1.03±0.29	-620±170	1.20 ±0.34
A478	1.76±0.34	-1800±350	3.49±0.68
A754	1.09±0.31	-560±160	1.09±0.31
A1651	1.42±0.47	-520±170	1.00±0.33
A2597	1.74±1.10	-750±670	1.43±1.28
mean ± sd =	1.22±0.52		
(probability=21%)	$\frac{\chi^2}{\nu}$ = 1.47 for 6 dof		
unweighted sample average: $h^{-1/2}$ =	1.22±0.20		
→	$h = 0.67^{+0.30}_{-0.18}$		
weighted sample average: $h^{-1/2}$ =	1.16±0.14		
→	$h = 0.75^{+0.23}_{-0.16}$		

Error Budget

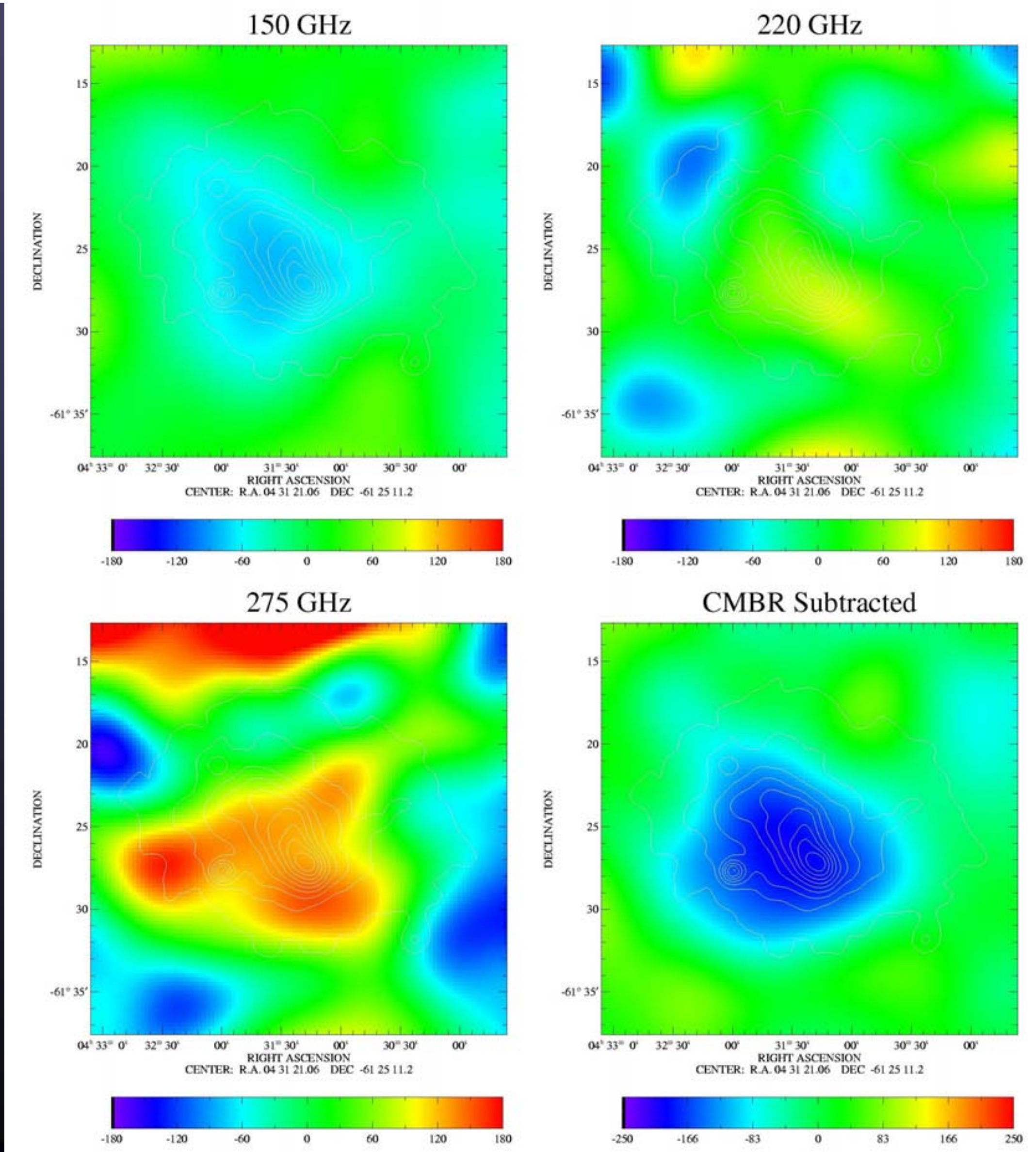
- CMB anisotropies – the dominant uncertainty
- density model – β models, some bias correction needed
- temperature profiles – assume isothermal, investigate deviations
- radio point sources – residuals small after using counts
- cluster asphericity – < 4%, could be worse in individual clusters
- clumpy gas distribution – $<n_e^2> / <n_e>^2$ 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+ptso 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

And the upshot is…

- Sample average H_0 consistent with canonical value
  - uncertainties dominated by CMB, then astrophysics
  - is there significant scatter among clusters?
  - finish the full sample!
- Gastrophysics not cosmology
  - turn it around – what does scatter say about clusters?
  - need to use latest Chandra & XMM-Newton data!
  - finish the full sample!
- What about the pesky CMB?
  - more distant clusters better, CMB less on smaller scales
  - measure CMB at SZE null (2mm)

CBI SZE Interferometry Issues



tion?)

mall scales…

th new 30GHz system!

E null (e.g. ACBAR)

First ACBAR Cluster Image: A3266

z=.0545

T_x=6.2 keV

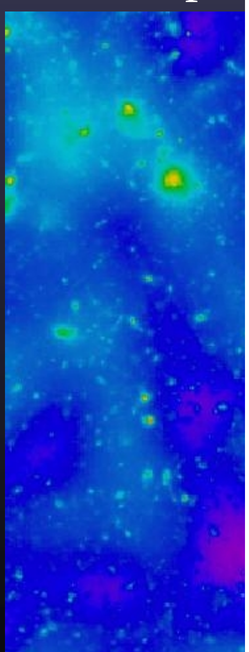
L_x=9.5x10^{44}

Courtesy ACBAR group

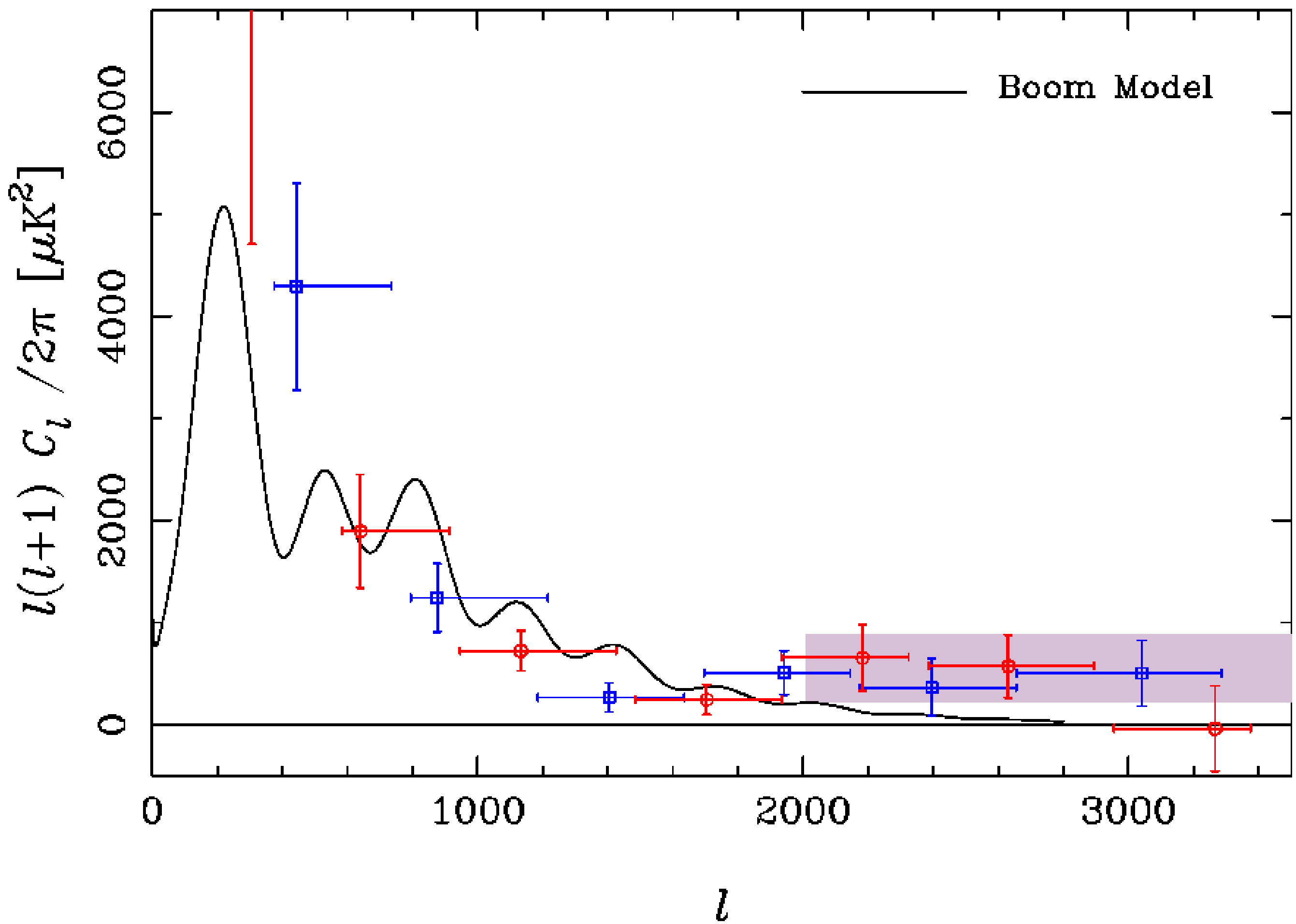
The SZE as a CMB Foreground

SZE Signatures in CMB

- Spectr
- Domin
clusters)
- Low-z
- z=1: ~
CMB or
- Ampli



Mason et al. 2003, ApJ, 591, 540

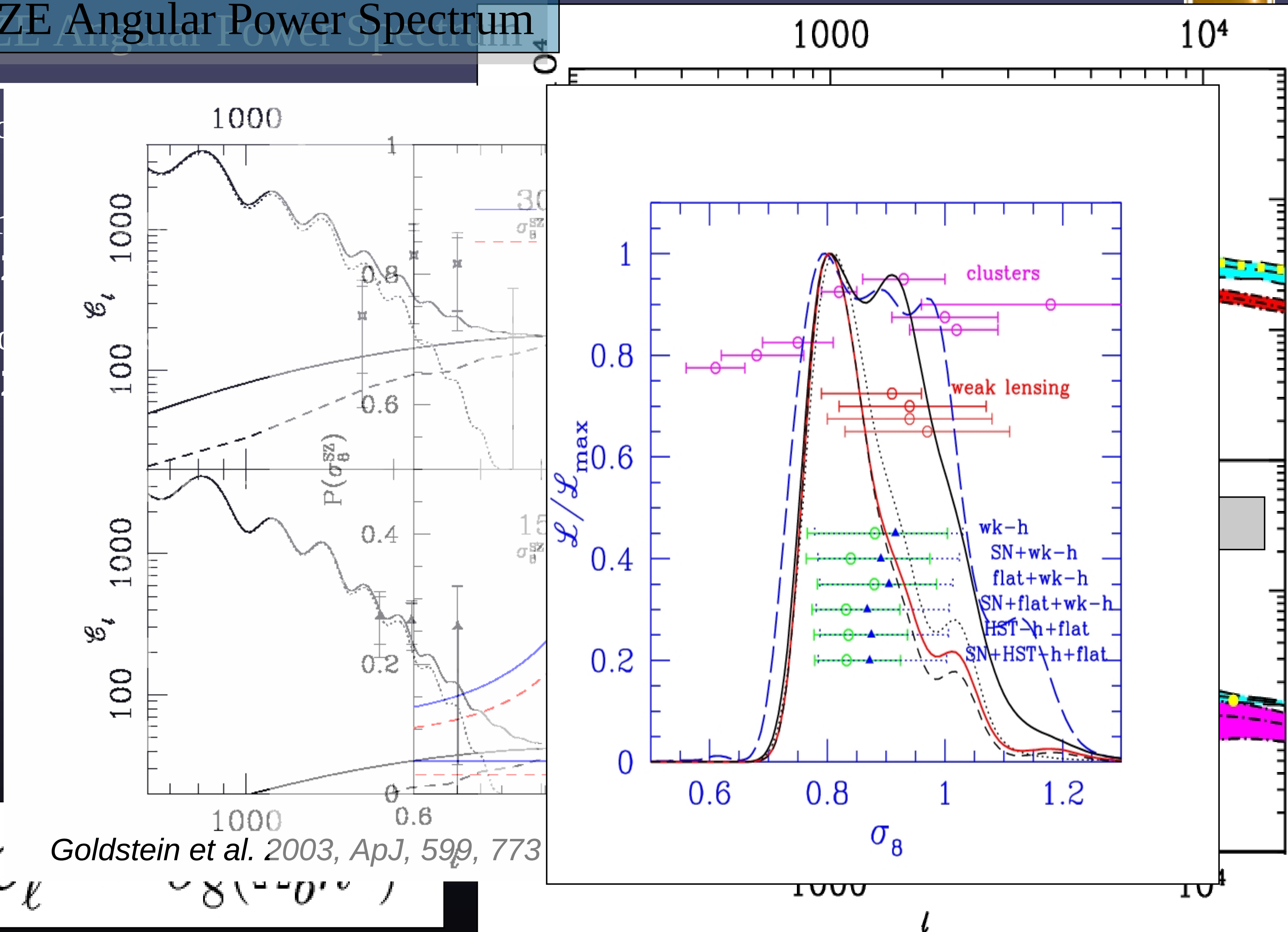


SZE Angular Power Spectrum

[Bo

•Sm
(51

•Mo
(51



Goldstein et al. 2003, ApJ, 599, 773

The CBI Collaboration

Caltech Team: Tony Readhead (Principal Investigator), John Cartwright, Alison Farmer, Russ Keeney, Brian Mason, Steve Miller, Steve Padin (Project Scientist), Tim Pearson, Walter Schaal, Martin Shepherd, Jonathan Sievers, Pat Udomprasert, John Yamasaki.
Operations in Chile: Pablo Altamirano, Ricardo Bustos, Cristobal Achermann, Tomislav Vucina, Juan Pablo Jacob, José Cortes, Wilson Araya.
Collaborators: Dick Bond (CITA), Leonardo Bronfman (University of Chile), John Carlstrom (University of Chicago), Simon Casassus (University of Chile), Carlo Contaldi (CITA), Nils Halverson (University of California, Berkeley), Bill Holzapfel (University of California, Berkeley), Marshall Joy (NASA's Marshall Space Flight Center), John Kovac (University of Chicago), Erik Leitch (University of Chicago), Jorge May (University of Chile), Steven Myers (National Radio Astronomy Observatory), Angel Otarola (European Southern Observatory), Ue-Li Pen (CITA), Dmitry Pogosyan (University of Alberta), Simon Prunet (Institut d'Astrophysique de Paris), Clem Pryke (University of Chicago).

The CBI Project is a collaboration between the **California Institute of Technology**, the **Canadian Institute for Theoretical Astrophysics**, the **National Radio Astronomy Observatory**, the **University of Chicago**, and the **Universidad de Chile**. The project has been supported by funds from the National Science Foundation, the California Institute of Technology, Maxine and Ronald Linde, Cecil and Sally Drinkward, Barbara and Stanley Rawn Jr., the Kavli Institute,and the Canadian Institute for Advanced Research.