The Sunyaev-Zeldovich Effect with ALMA Band 1

and some current observational results from the CBI…

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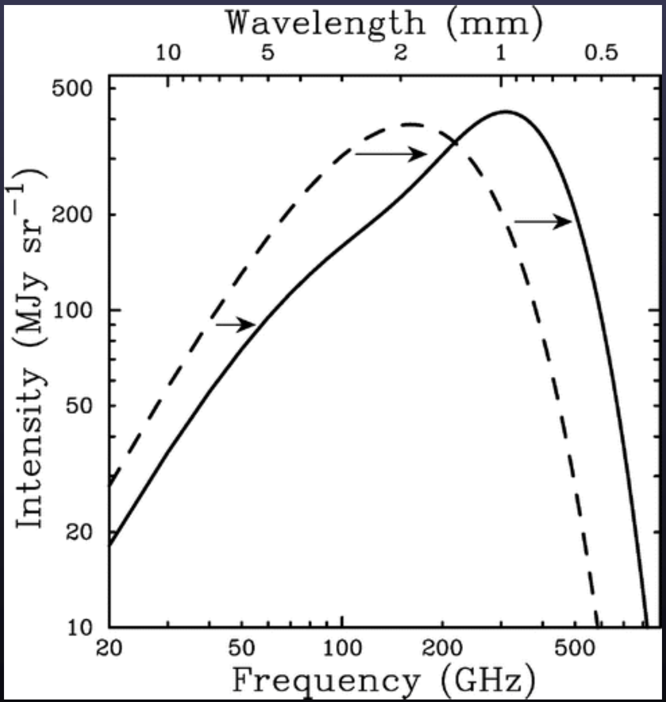
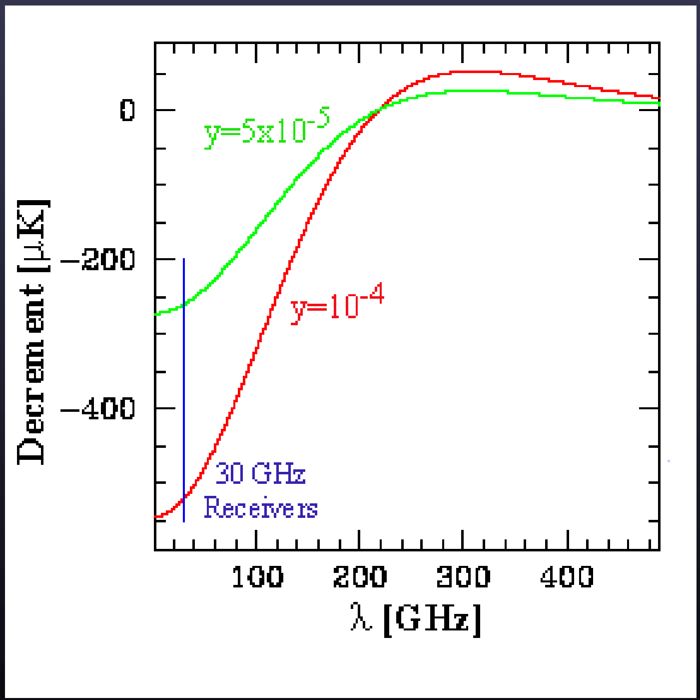
State of the art

SZ and CMB…

The SZE: a refresher

- The Sunyaev-Zeldovich Effect
  - Compton upscattering of CMB photons by keV electrons
  - decrement in I below SZ null (220 GHz), increment above
  - negative extended sources (absorption against 3K CMB)
  - massive clusters mK, but shallow profile $\theta^{-1} \rightarrow$ -exp(-v)





SZE vs. X-rays: a refresher

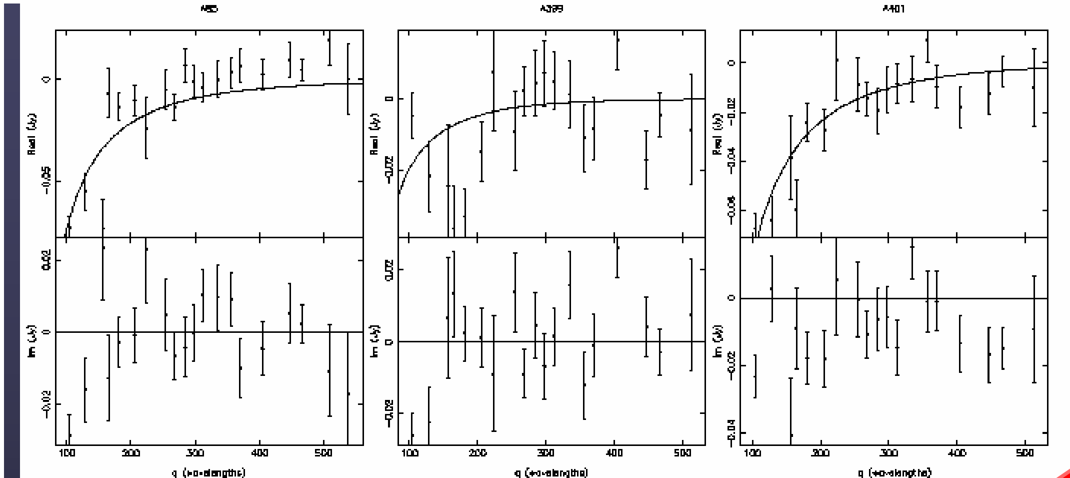
- gas density profiles: $$n_e(r) = n_{e0}\left(1+\frac{r^2}{r_0^2}\right)^{-3\beta/2}$$
- X-ray surface brightness: $$b_X(E) = \frac{1}{4\pi(1+z)^3}\int n_e^2(r)\Lambda(E,T_e)\,dl$$
- SZE surface brightness: $$\Delta I_{\mathrm{SZE}} \propto T_e \int n_e\,dl$$
- dependence on parameters:

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

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

$D_A \sim h^{-1}$ $n_{e0} \sim h^{1/2} \rightarrow$ $\Delta I_{SZE} \sim h^{-1/2}$ $\Delta I^2_{SZE} / b_X \sim D_A \sim h^{-1}$

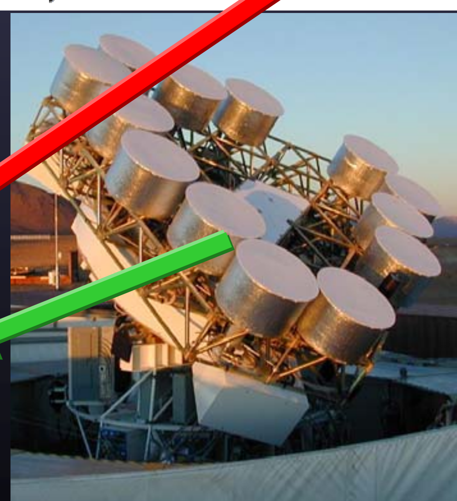
Example: z<0.1 SZE @ 30 GHz w/CBI

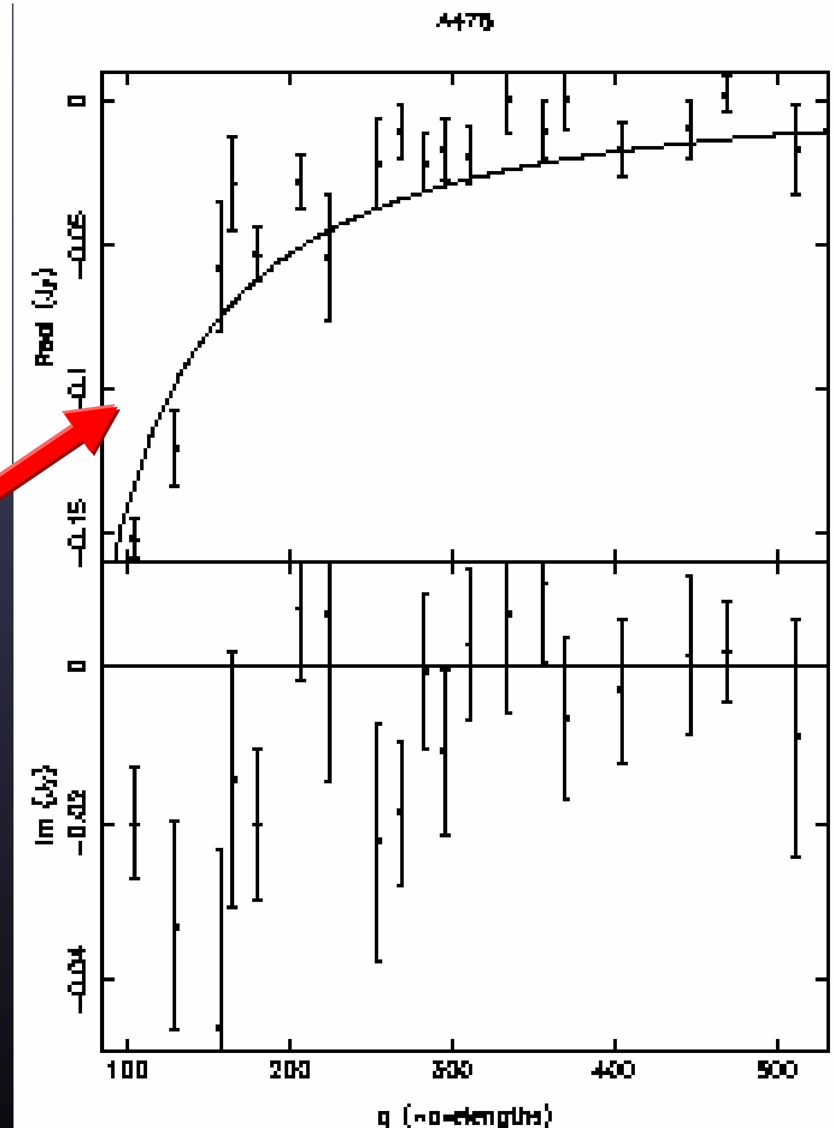


$$V(u,v) = I_0 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} B(\theta) \left(1 + \frac{\theta^2}{\theta_0^2}\right)^{-\frac{3}{2}\beta + \frac{1}{2}} e^{2\pi i(ux+vy)}\, dx\, dy$$

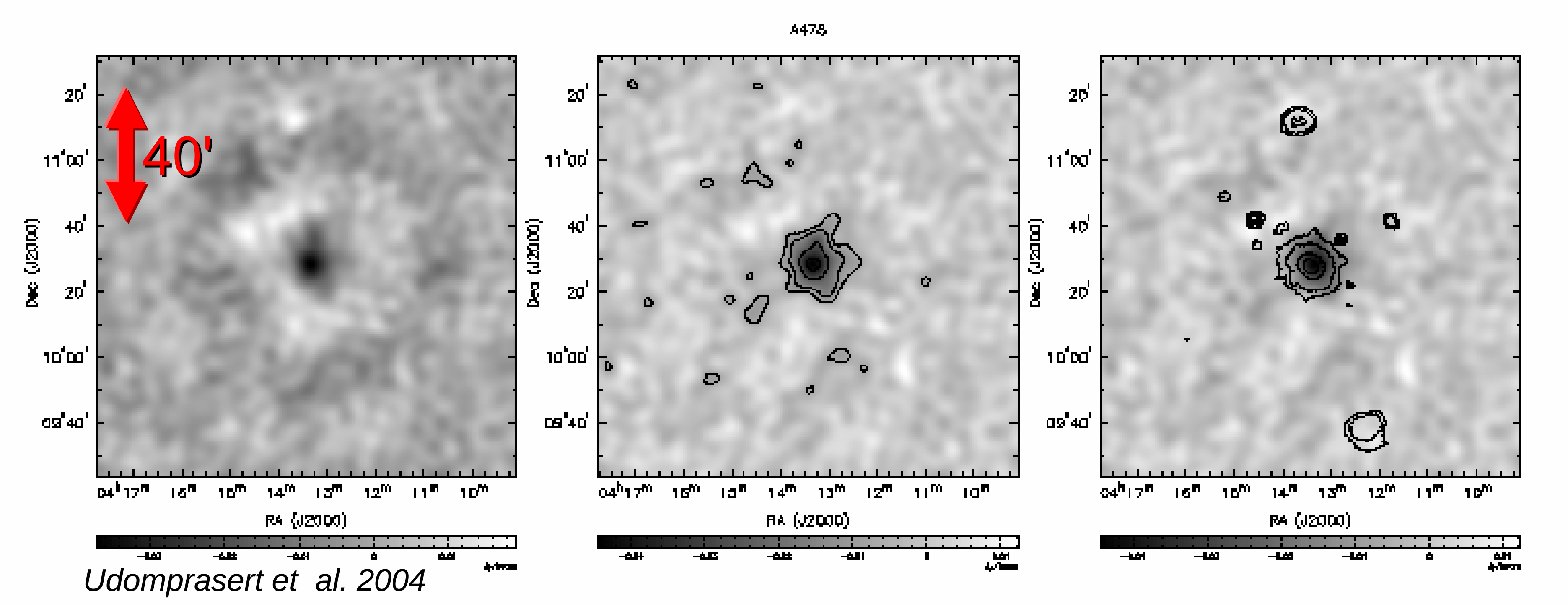
<u>SZ Visibility functions</u>

- Xray: θ^{-3} ($\beta \sim 2/3$)
- SZE: $\theta^{-1} \rightarrow$ -exp(-v)
- dominated by shortest baselines (1m=100λ for CBI at 30 GHz)





Example: **A478 (*z*=0.088) with CBI**



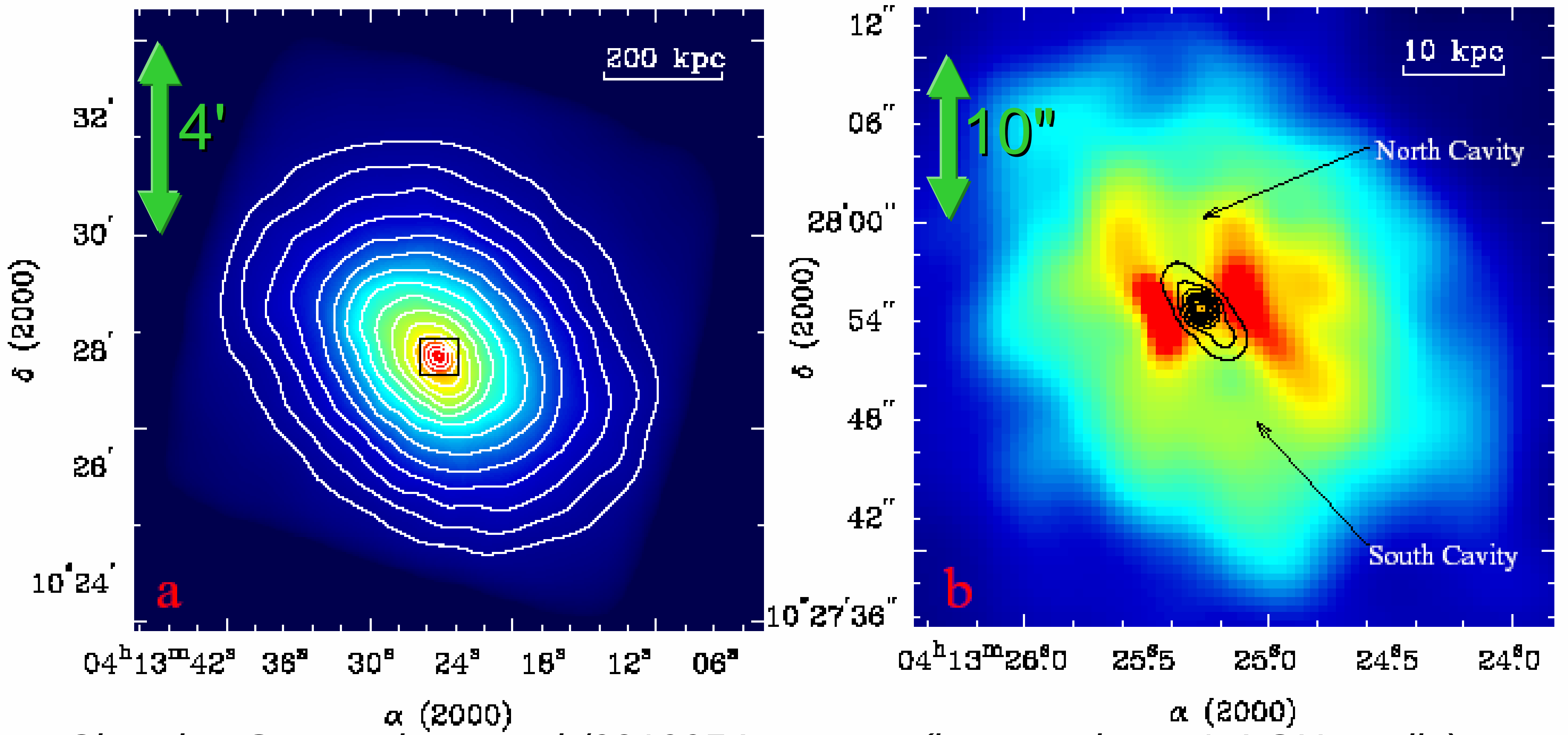
(left) Raw CBI Image (center) CLEAN source-sub CBI Image (right) CBI w/ROSAT

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

SZE measures IGM pressure → baryon surface density × kT

comparison with X-ray → effective path length ($L \sim \Sigma^2_{SZ}/\Sigma_X$)

Example: **A478 (*z*=0.088) in X-rays**



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

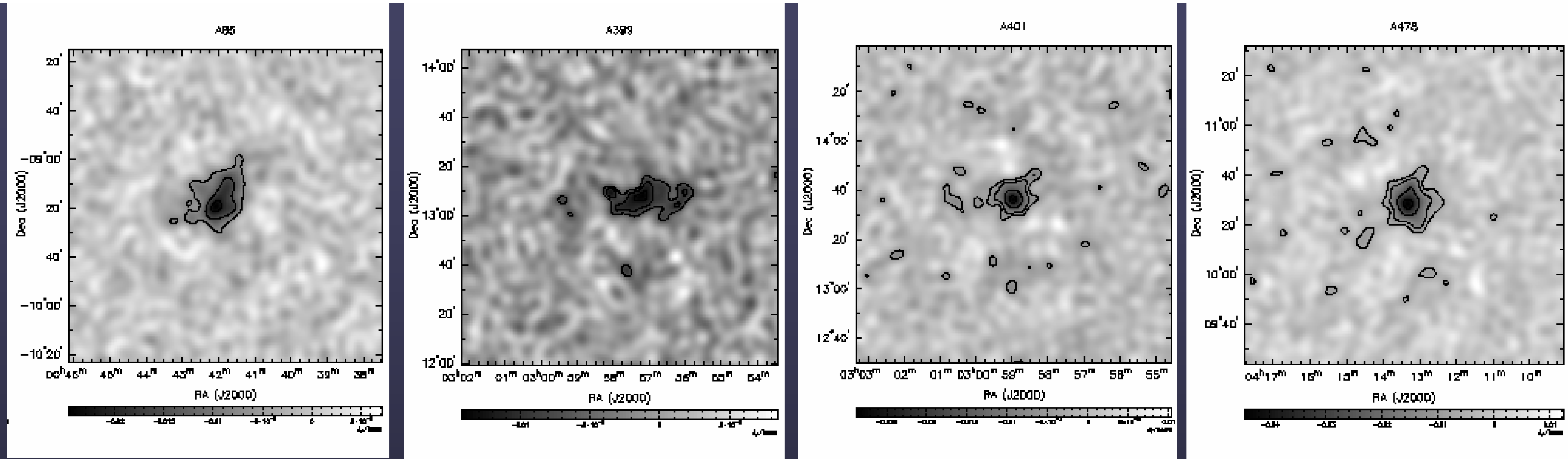
A478 – relaxed cooling flow cluster, X-ray cavities from AGN

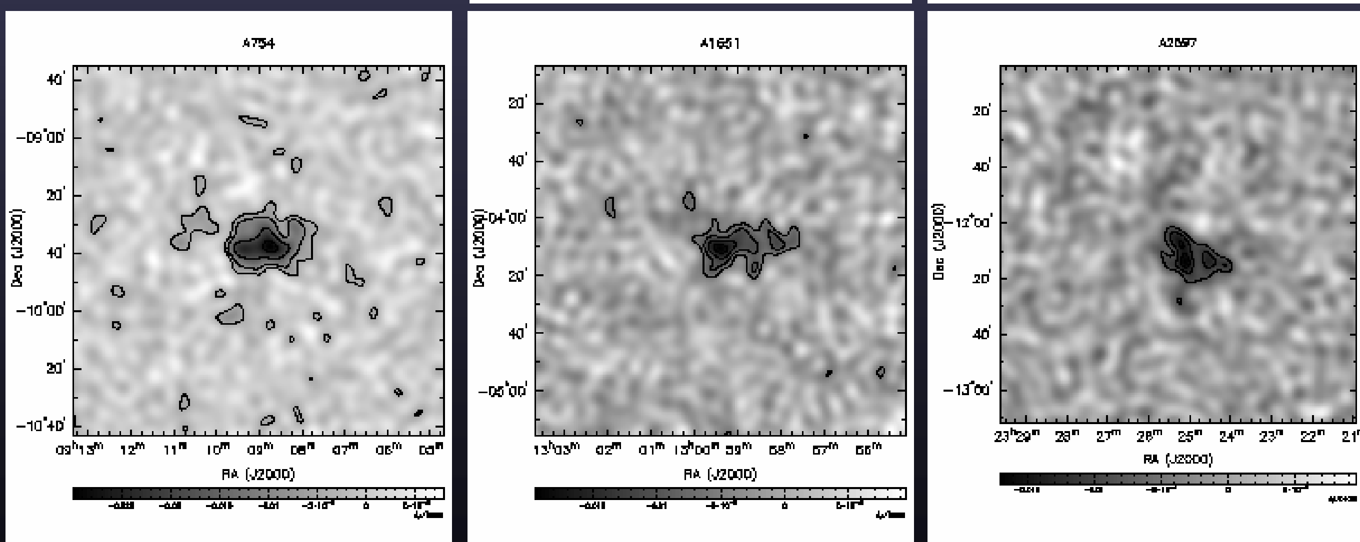
Compare substructure in SZ with Xray to determine pressure

Example: **CBI SZ program**

- Udomprasert et al. 2004 (and PhD thesis)
  - drawn from ROSAT (Ebeling et al. 1996, 1998; de Grandi et al. 1999; Boehringer et al. 2003)
  - define sample of 24 clusters accessible to CBI
    - $f_{0.1\text{-}2.4\mathrm{keV}} > 1.0 \times 10^{-11}$ erg cm^{-2} sec^{-1}
    - $z < 0.1$
    - $L_{0.1\text{-}2.4\mathrm{keV}} > 1.13 \times 10^{44}\ h^{-2}$ erg s^{-1}
    - declination $-70° < \delta < 24°$
  - sub-sample of 15 most luminous observed by CBI
  - reported results for 7 clusters:
    - A85, A399, A401, A478, A754, A1651, A2597
    - covers a range of luminosities and cluster types
  - would like to study similar samples out to high redshift!
    - should scale like CBI with D_A (e.g. ALMA = 12 × CBI)

Example: **CBI SZ cluster gallery**

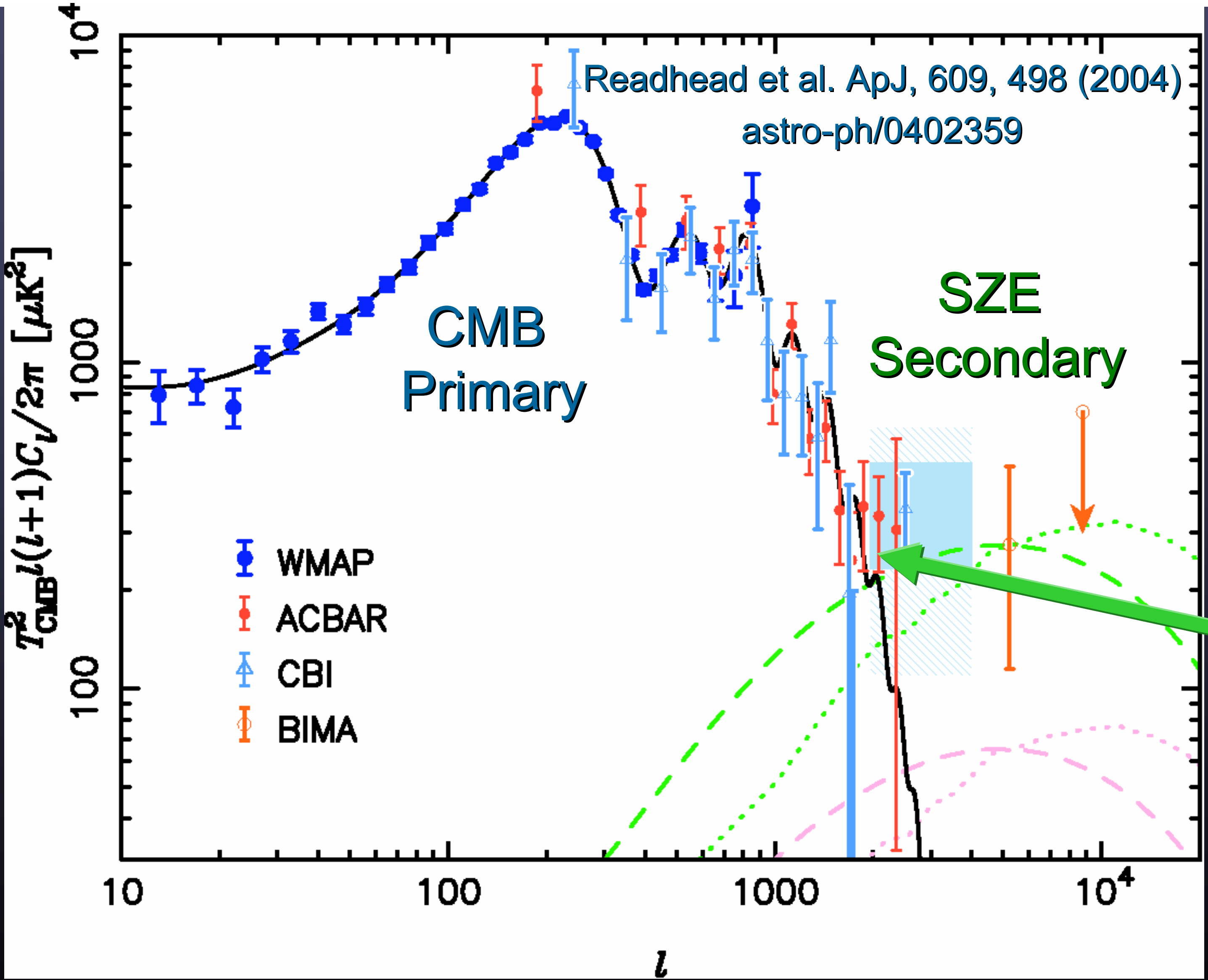




Integration time 11-16 hours split between cluster and lead and trail fields

CLEANed images (after point source subtraction)

The SZ CMB foreground



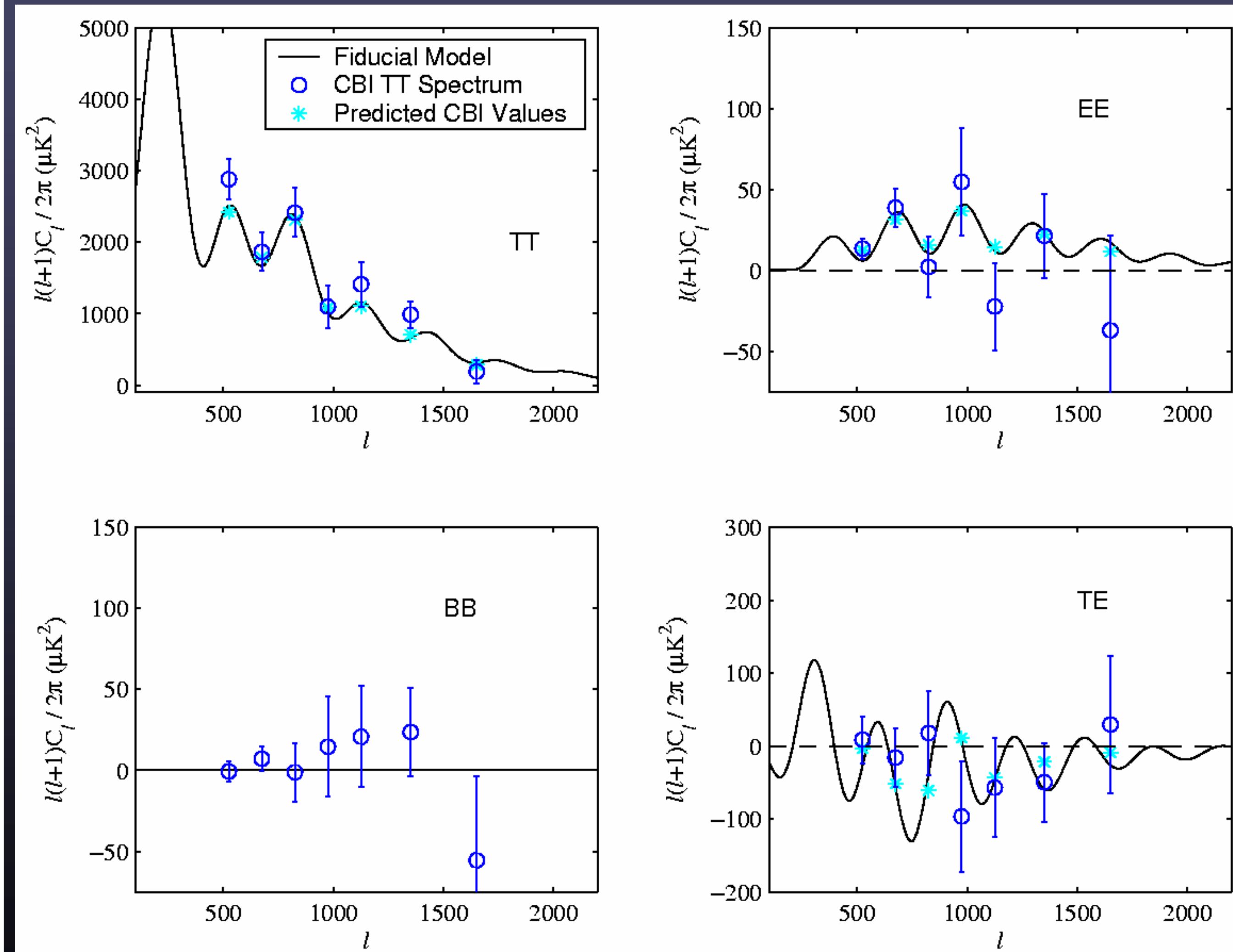
CMB/SZ x-over

l=2πB/λ~1500

B~250λ

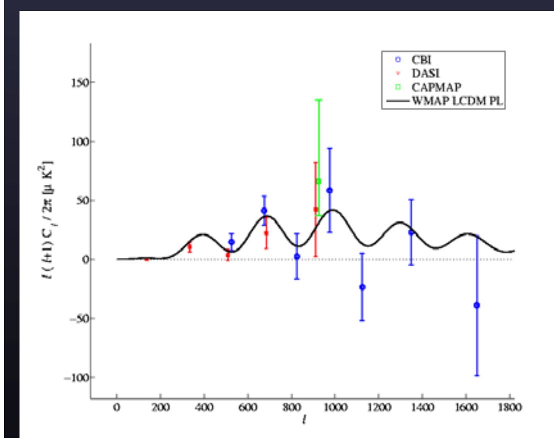
Arcminute CMB Polarization Results

7-band fits (Δl = 150 for 600<l<1200) matched to peaks



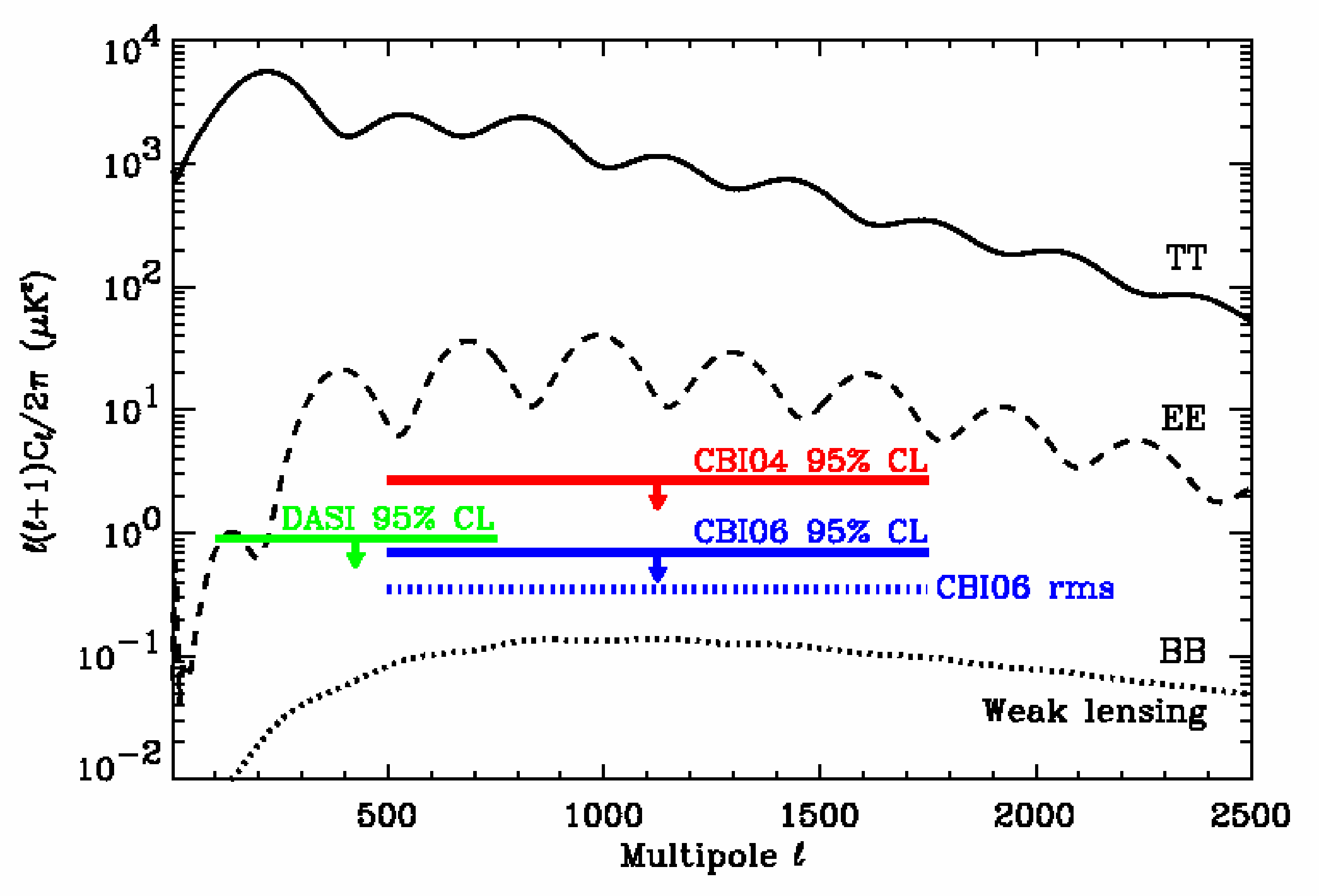
Interferometers are able to measure μK polarization signals!

astro-ph/0409569
(24 Sep 2004)
Science **306**, 836-844

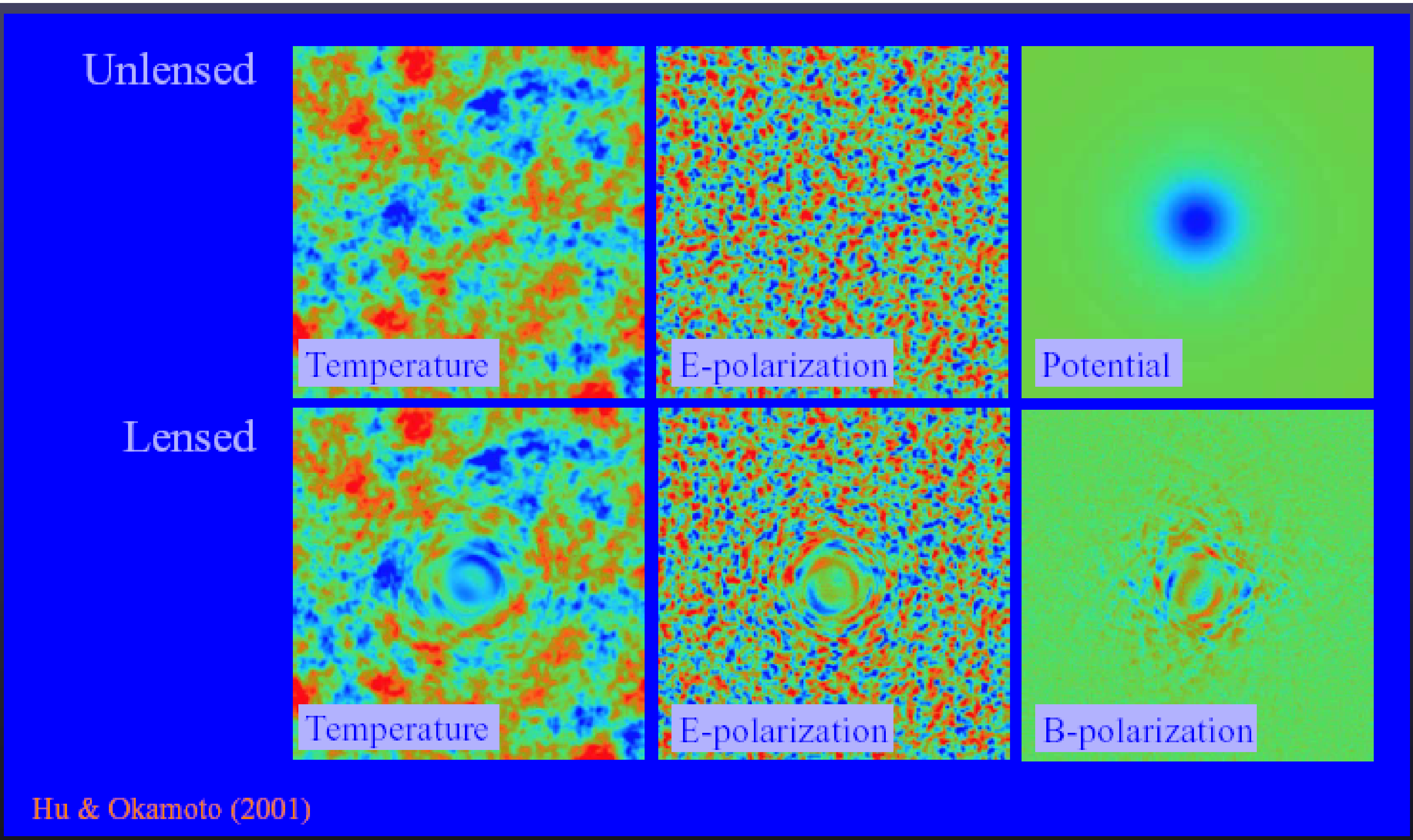


Arcminute CMB Polarization goals

BB-lensing within reach of ground-based instruments



Future: **Cluster CMB lensing**



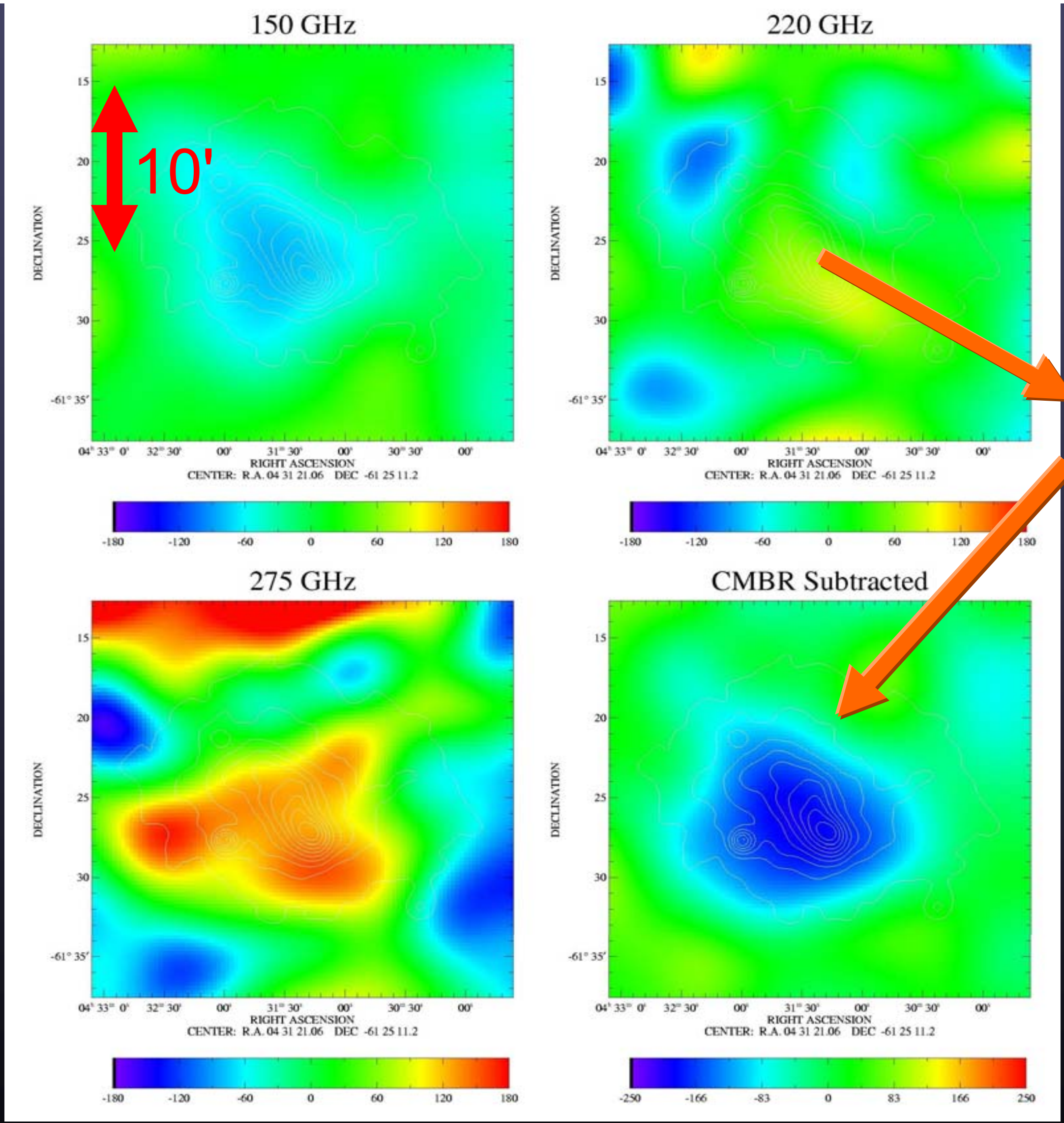
Note: clusters will lens CMB polarization signal

might prove interesting for probing nearby cluster potentials

SZE Interferometry Issues

- Analysis issues
  - currently limited in sensitivity & angular dynamic range
  - joint SZ & Xray modelfitting (MCMC code)
  - removal of contamination
    - CMB sub-dominant beyond 250λ → l >1500
    - point radio sources
  - substructure! more sensitivity on small scales…
- ALMA!
  - shortest baselines 1200λ at 1cm (shadowing limit)
  - many short baselines
    - good surface brightness sensitivity
  - long baselines for source subtraction
  - <u>science driver is cluster astrophysics rather than cosmology</u>

Example: ACBAR SZ A3266



Use 220 GHz (SZ null) to remove CMB signal

First ACBAR Cluster Image: A3266

z=.0545

T_x=6.2 keV

L_x=9.5x10^{44}

Courtesy ACBAR group

Arcminute-scale SZE @ 30 GHz

BIMA for SZE

- 600λ diameter antennas

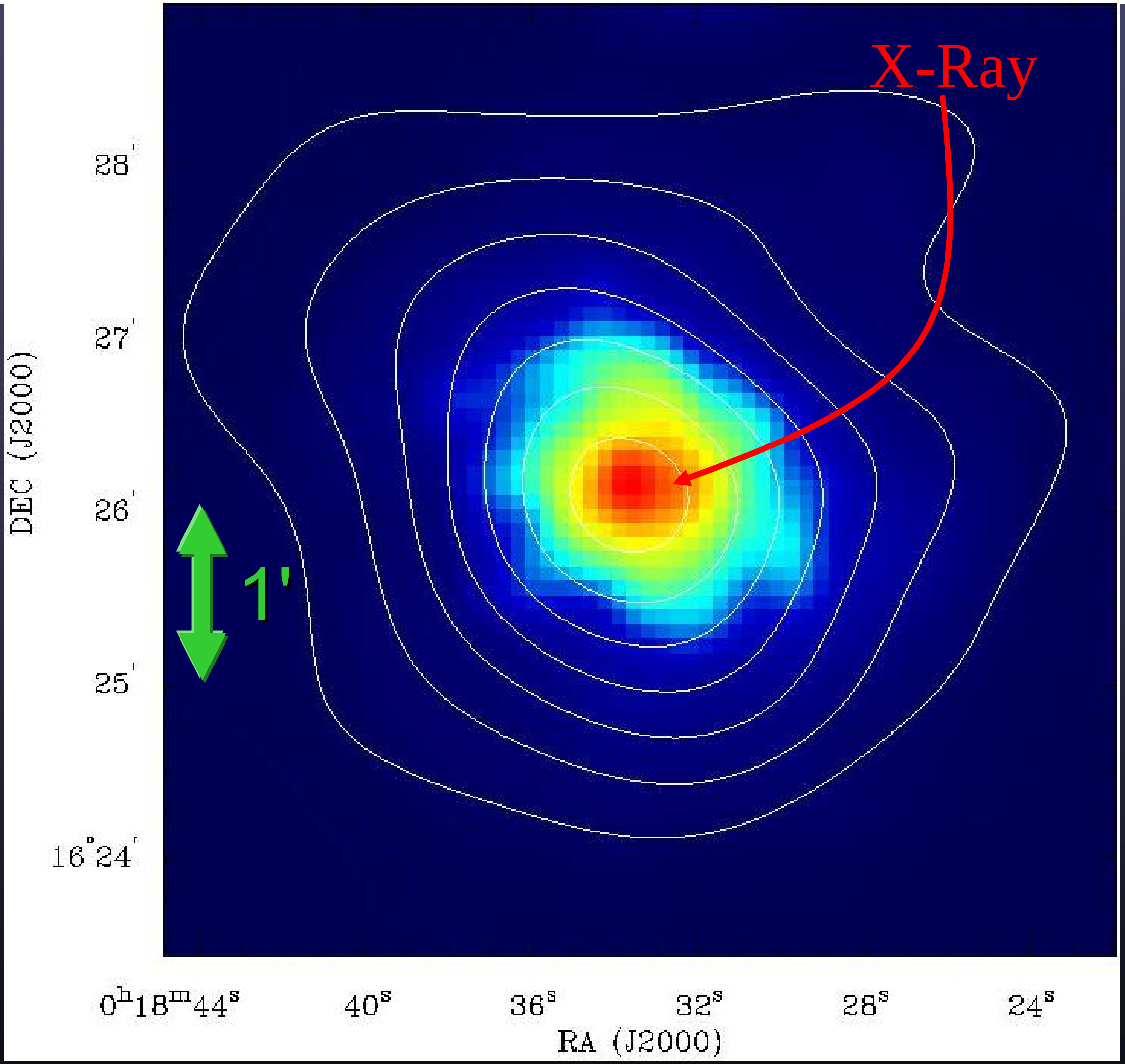
OVRO for SZE

- 1050λ diameter antennas

cf. ALMA for SZE

- 1200λ diameter antennas
- 700λ for ACA

Note that astrophysics is now limited by attainable sensitivity over a range of angular scales!

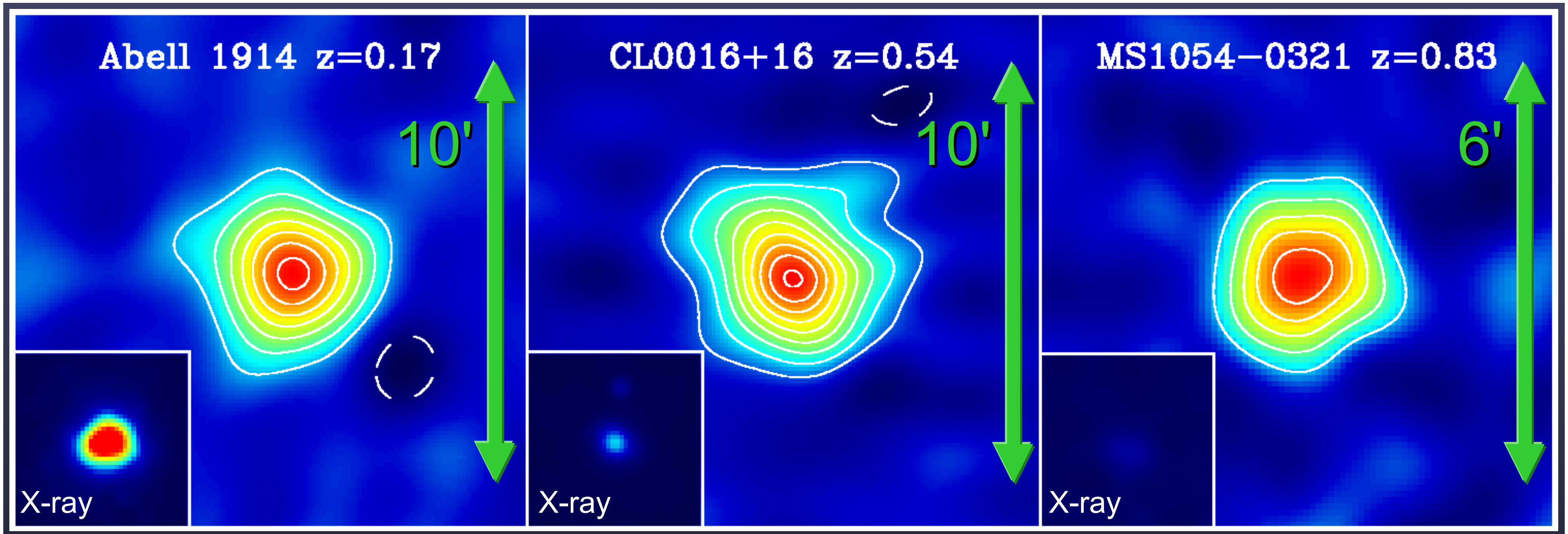


CL 0016+16, z = 0.55 (Carlstrom et al.)

ALMA Band 1 SZE

the case and some questions...

The power of SZ observations



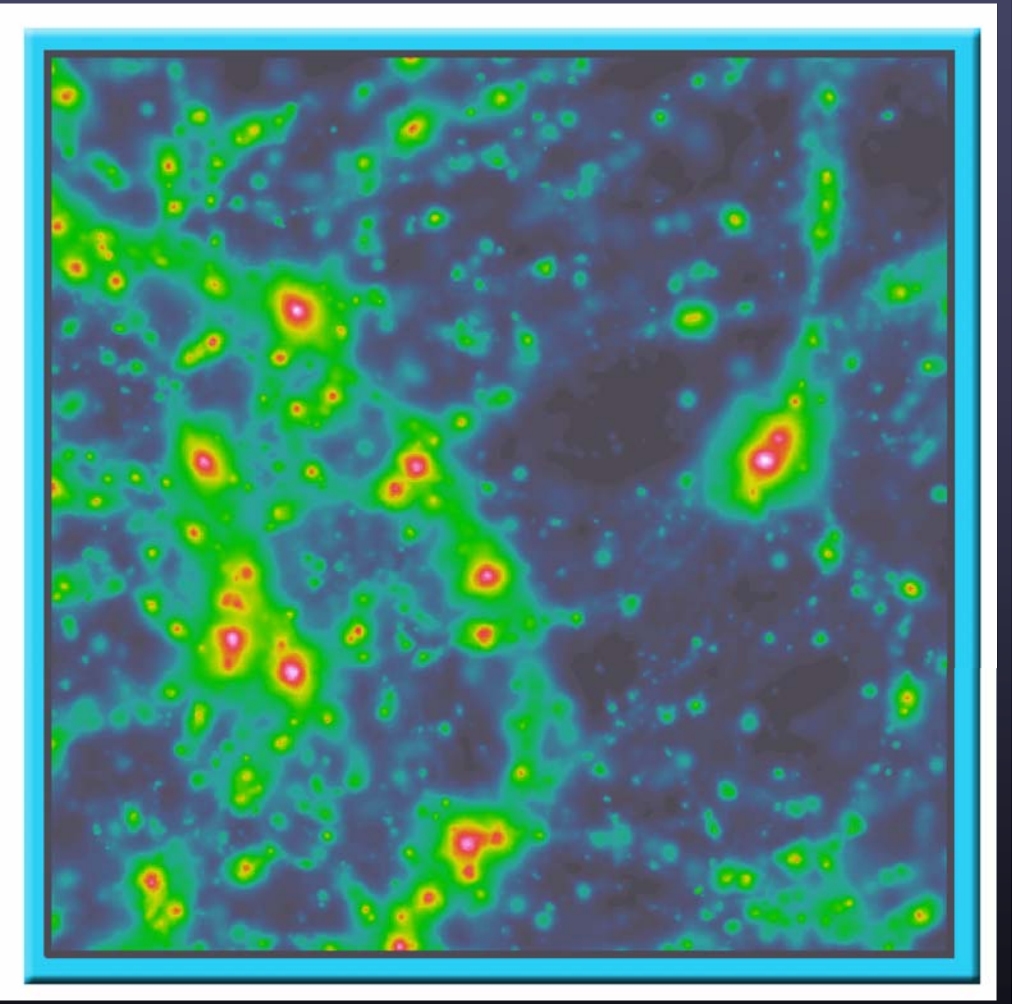
<u>OVRO/BIMA SZE vs. X-ray (insets)</u>

- X-ray emission brightness falls off sharply with distance
- SZE brightness independent of distance ($h\nu/kT_{cmb}$ const.)
  - only depends on profile (potential well growth) with *z*
  - can locate very distant clusters, if they exist…

The Cosmic Web

Chart the Cosmic Web

- clusters lie at the center of the filamentary web
- hierarchy of substructure
- mergers and groups
- ALMA would study individual (sub)structures



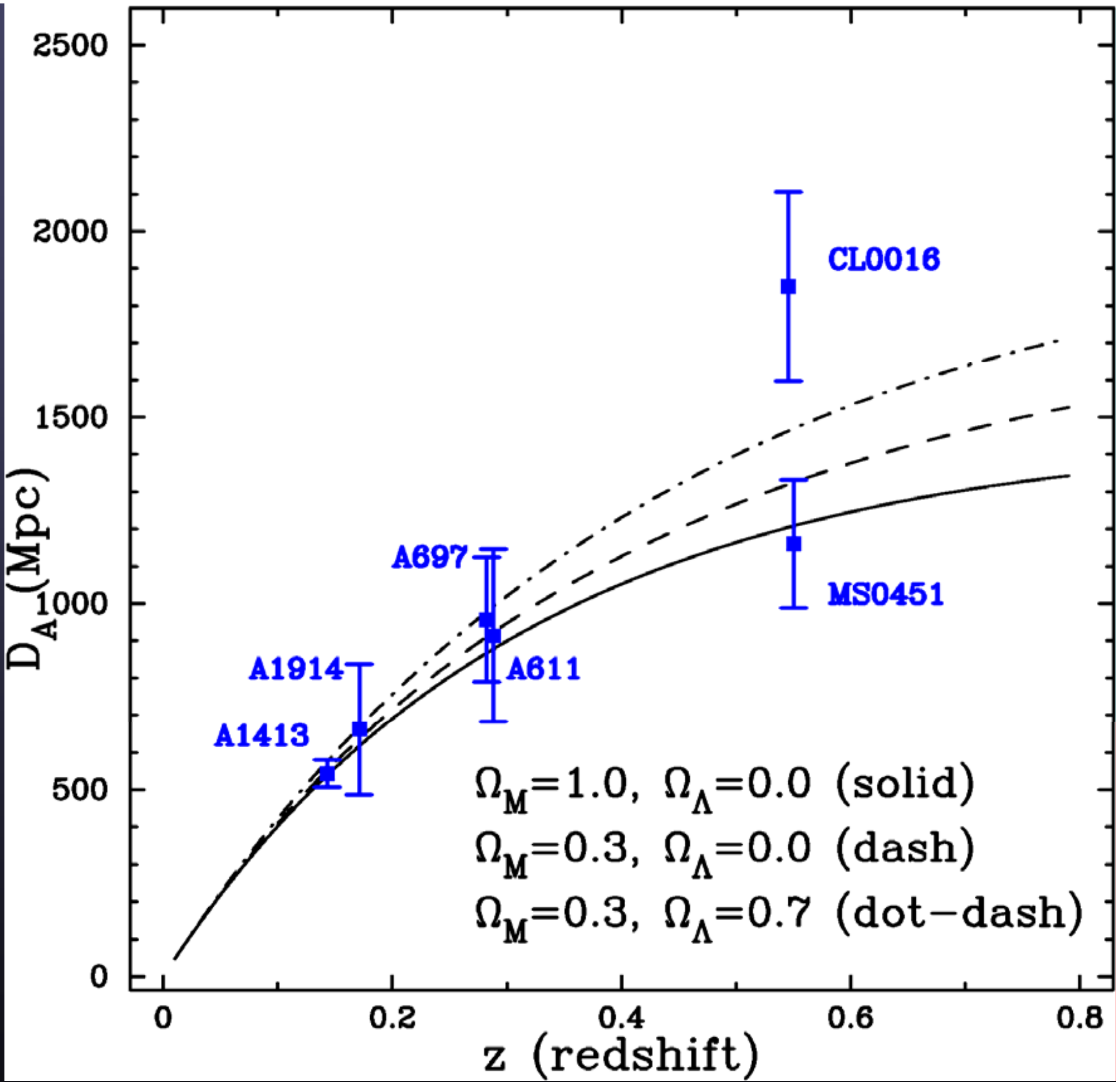
The SZE sky

- SZE simulation (hydro)
- supercluster!

A Universal Surveyor

Angular Diameter Distances

- SZE + Xray → standard candles
- need X-ray satellite!
  - Chandra/XMM now
  - what in 2012+???
- astrophysical scatter
  - very large samples



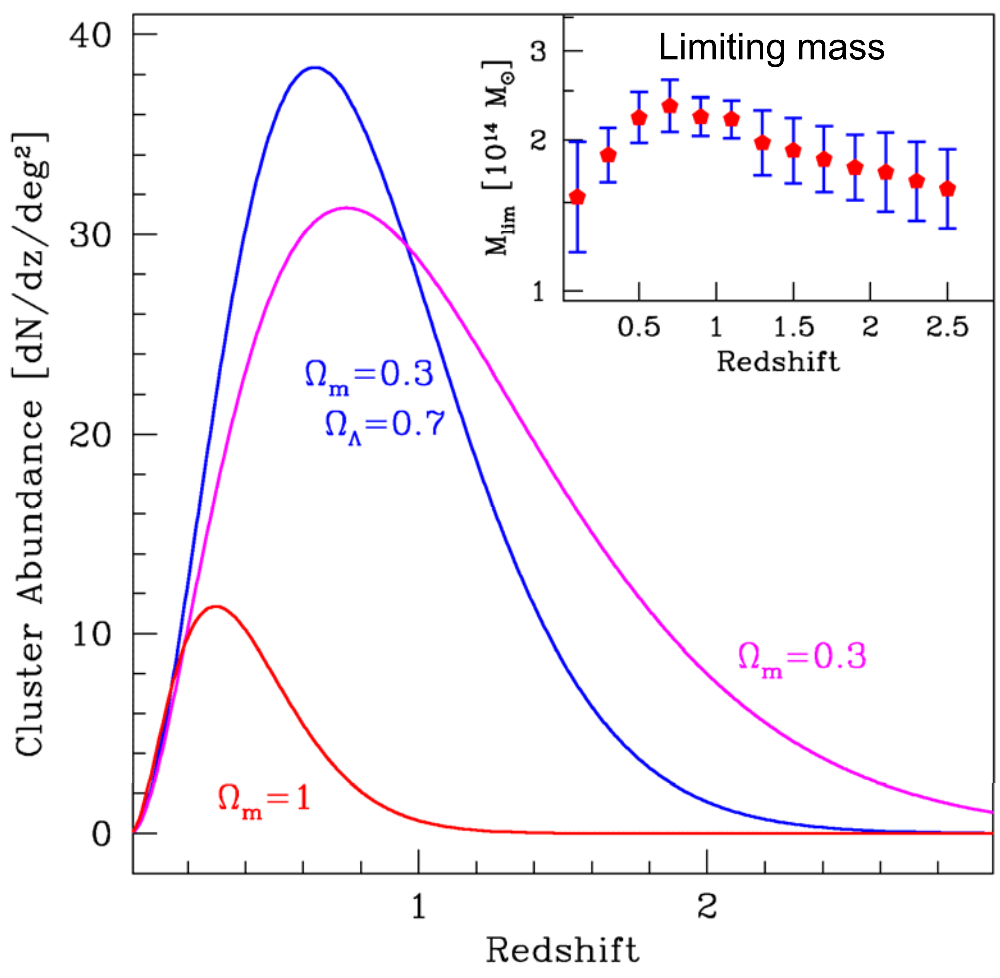
Illuminating the Dark Sector

Dark Energy Dark Matter

- SZE probes largest bound objects
- growth & volume factors sensitive to cosmology
- controlled by dark matter Ω_m and dark energy Ω_Λ (and its equation of state *w*)

SZ Survey

- fast bolometer array or interferometer
- e.g. SPT,APEX,SZA,AMI



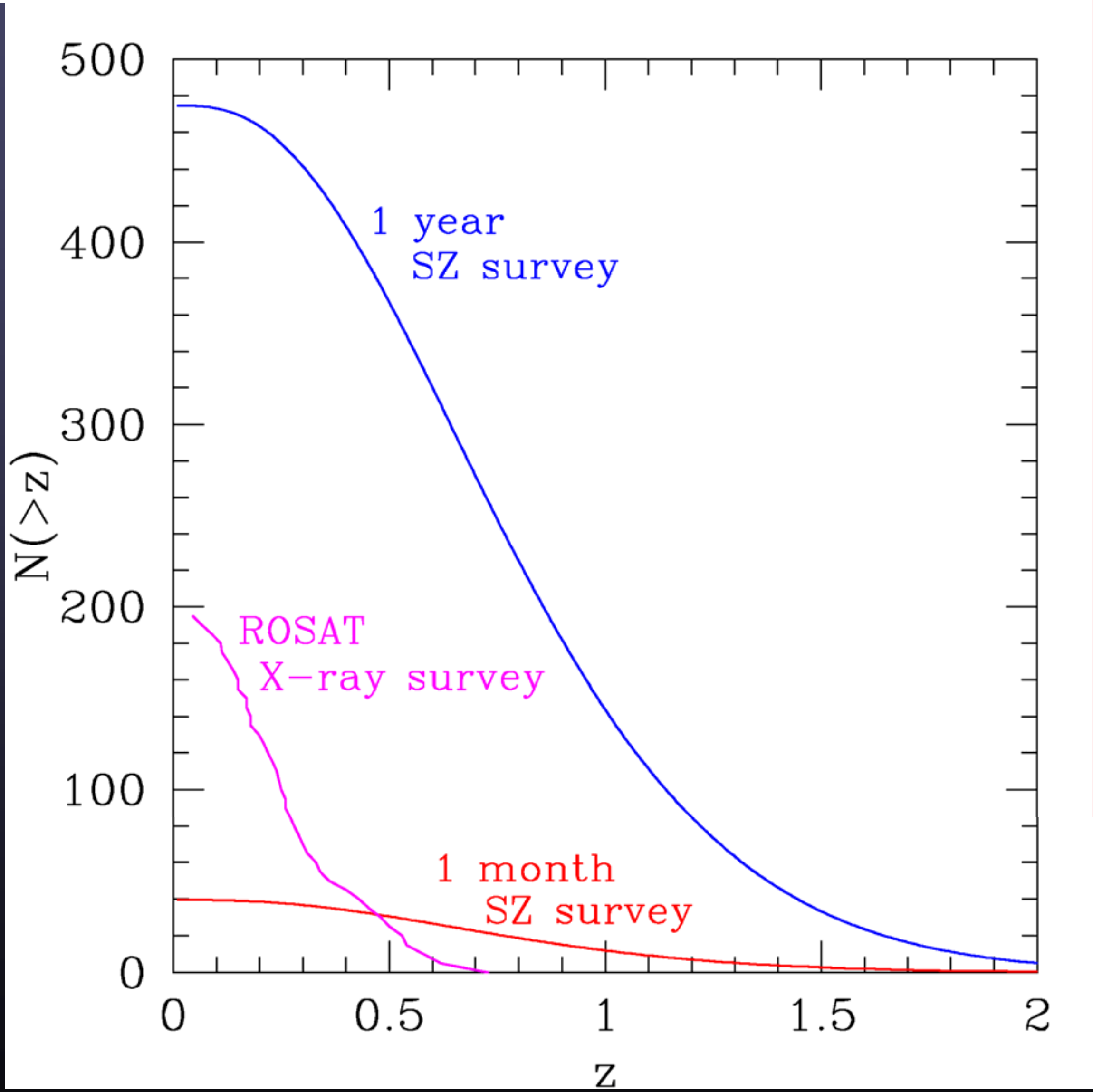
SZE Surveys: high yield!

Finding clusters

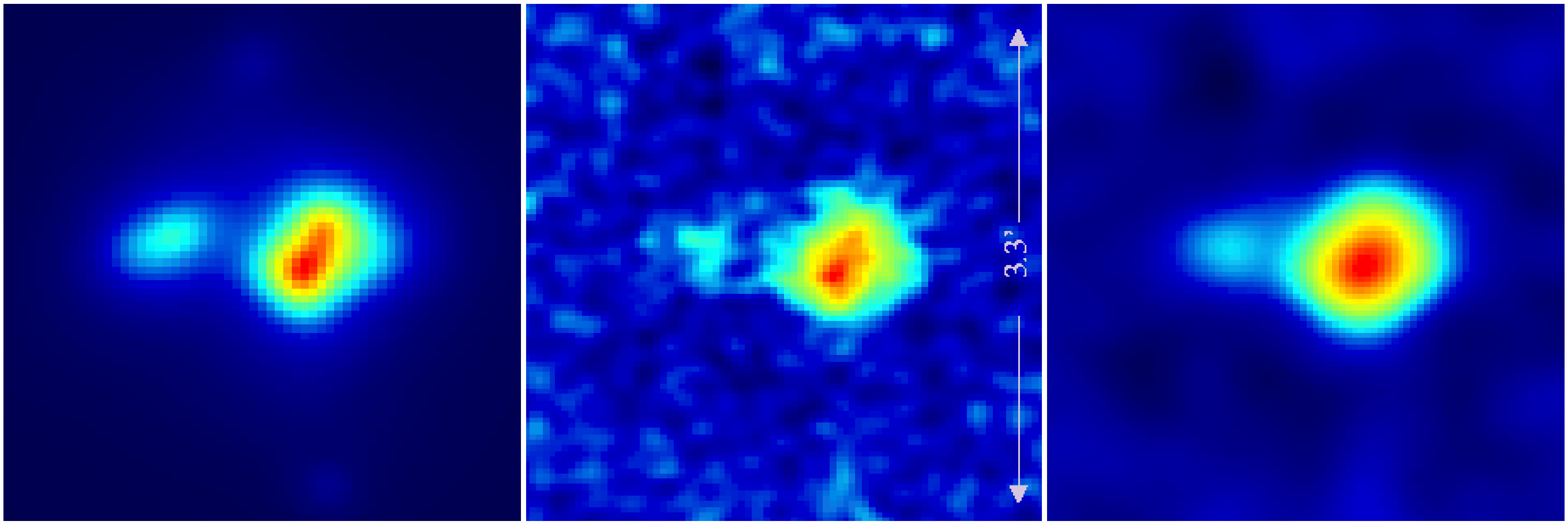
- fast instruments
- single dishes with bolometer camers
  - SPT, APEX, ACT, etc.
- or small interferometers
  - SZA, Amiba, etc.
- ALMA for follow-up!

SZ Survey

- fast bolometer array or interferometer
- e.g. SPT,APEX,SZA,AMI



Imaging the SZE with ALMA Band 1



ALMA observes SZE

SZE simulation (left)	4 hours ALMA (center)	after 4kλ taper (right)
2.5×10^{14} Msun z=1	34 GHz in compact config.	equiv. 22" FWHM
~5σ SZA survey detection	1.5 μJy (14 μK) 9.7" beam	2.8 μJy (2.7 μK)

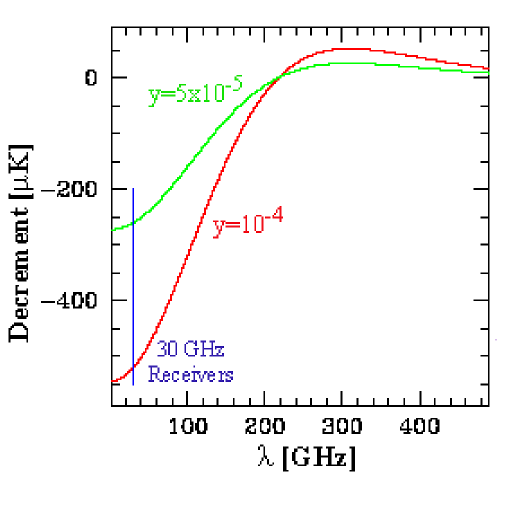
ALMA will provide images of high redshift clusters identified in surveys from other instruments like AMI, SZA, SPT, APEX-SZ, ACT

ALMA Band 1 Issues

- Site proven!
  - TOCO, CBI, ATSE, APEX, eventually ACT, CCAT, …
- Cost
  - somewhat less than Band 3
  - estimated $7M - $10M (USD'05)?
  - possibly cheaper?? (would have to diverge from stand. cartridge)
- Who will build this?
  - technology is straightforward (current CMB groups capable)
- Complementary instruments
  - survey telescopes
  - big dishes + FPA (GBT, LMT, CCAT, etc.)
  - optical / IR survey telescopes (CFHT, LSST, …)
  - X-ray survey telescopes (Con-X too far away)

ALMA Band 1 Issues (continued)

- Multi-bands
  - ALMA Band 3 dish diameter ~3600λ (array 3" untapered)
- SZE spectrum
  - SZE ΔT down by 20% at 90 GHz, 50% at 150 GHz
  - allow CMB subtraction and kinetic SZE
  - want matching resolution out to SZ null (220 GHz) and beyond
  - 50m dish w/FPA (LMT) at ~200 GHz
  - 25m dish w/FPA (CCAT) at 90-150 GHz
  - also IRAM 30m, GBT 100m with bolo arrays



ALMA is complimentary with other intruments:
A powerful global suite of telescopes
for cluster astrophysics & cosmology!

Open questions

- What do realistic simulations tell us?
  - What is the level of substructure from various astrophysical sources (shocks, fronts, jets, lobes)?
  - Is an interferometer like ALMA a good way to image these?
  - Need to simulate ALMA interferometer data and reconstructed images – not just convolved images – data is in Fourier domain! May need to develop new imaging algorithms…
- How strong a case should we make for Band 1?
  - A number of us feel that this would be a very powerful cosmology tool (not just for SZ!)
  - How to proceed?
  - Historical note: Band 1 was ranked 2nd among bands beyond first 4 for further development
- What about Band 2?
  - My guess this is not as useful as Band 1 (quite close to Band 3)