SZ and CMB observations at high l with the VSA and AMI

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- The Very Small Array (VSA)
  - Current primordial observations
  - SZ cluster observations
  - Planned upgrades to the instrument
- The Arcminute Micro-Kelvin Imager (AMI)
  - Searching for SZ clusters
  - Cosmology with cluster surveys

The Very Small Array (VSA)

Collaboration between Cavendish Astrophysics Group, Jodrell Bank Observatory and Instituto de Astrofísica de Canarias.

Located at 2400m at the **Observatorio del Teide, Tenerife**: Transparency at 30 GHz $\approx$ 98 per cent; Excellent weather (<10 per cent data lost)

The instrument

• 14 individually **tracking** antennas $\Rightarrow$ 91 baselines

• dedicated **source subtraction** 2-element interferometer $\Rightarrow$ remove effect of extragalactic point sources

• Observing frequency $\nu = 26 - 36$ GHz; bandwidth $\Delta\nu = 1.5$ GHz

• **Compact** configuration: 143 mm horns; $\ell = 150 - 800$; $\Delta\ell \approx 90$ (without mosaicing); Sept 2000 – Sept 2001

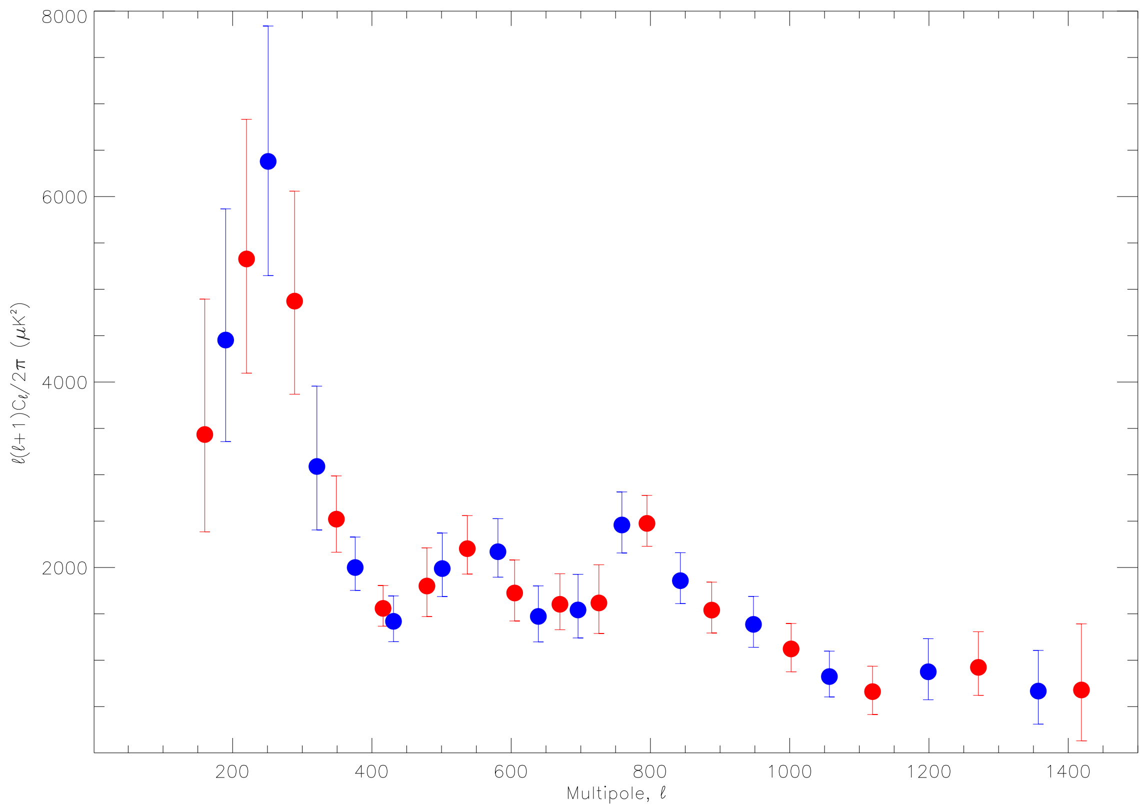
• **Extended** configuration: 322 mm horns; $\ell = 300 - 1800$; $\Delta\ell \approx 200$ (without mosaicing); Sept 2001 – present

VSA power spectrum of CMB anisotopies

- Combined power spectrum from:

– Two 3-field and one 2-field compact array mosaics (total sky area = 101 sq deg).

– Three 7-field and four 3-field extended array mosaics (total sky area = 81 sq deg).

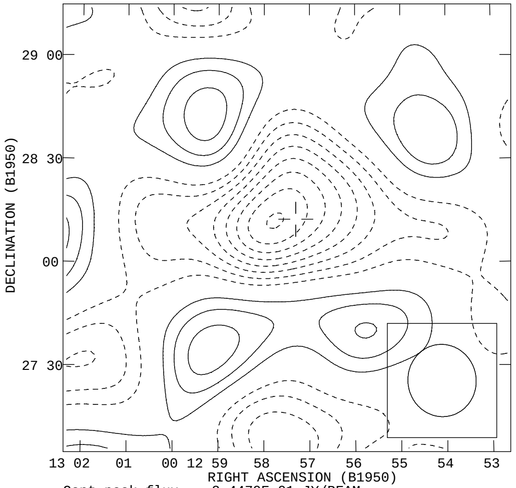


(Dickinson et al. 2004; parameters: Rebolo et al. 2004; non-Gaussian: Savage et al. 2003, Smith et al. 2004; Sources: Waldram et al. 2003)

VSA cluster program:

Coma, A1795, A399+A401, A478, A2142, A2244

PLot file version 1 created 28-MAY-2004 13:45:03
CONT: COMA C IPOL 33841.019 MHZ COMA-S test.ICL001.2



Cont peak flux = -2.4479E-01 JY/BEAM
Levs = 3.021E-02 * (-10, -9, -8, -7, -6, -5, -4, -3, -2, -1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10)

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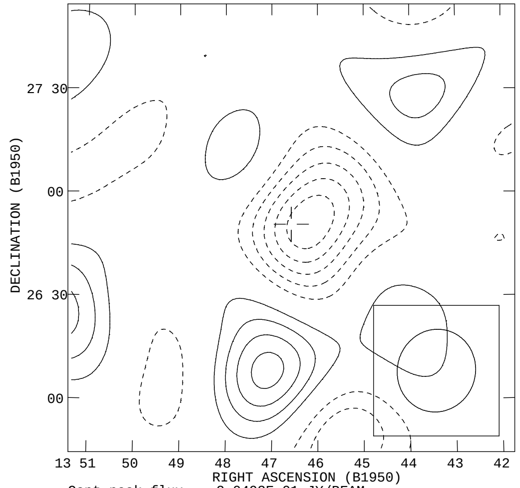

Cont peak flux = -2.0493E-01 JY/BEAM
Levs = 3.500E-02 * (-10, -9, -8, -7, -6, -5, -4, -3, -2, -1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10)

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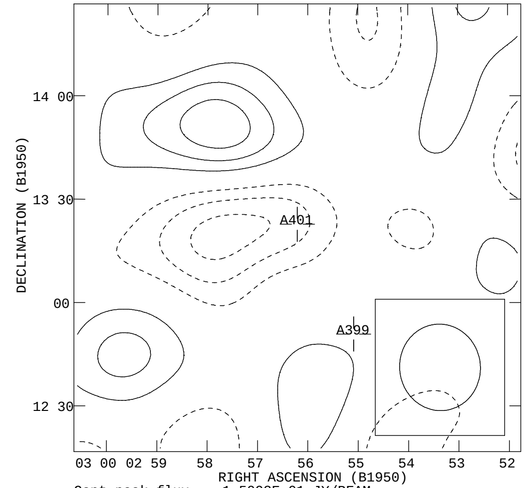

Cont peak flux = 1.5093E-01 JY/BEAM
Levs = 4.000E-02 * (-10, -9, -8, -7, -6, -5, -4, -3, -2, -1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10)

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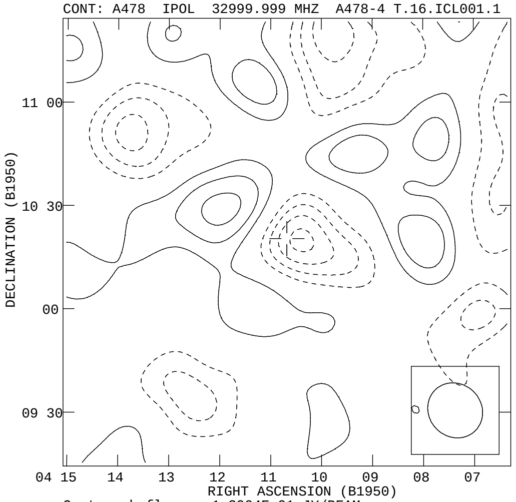

Cont peak flux = -1.3904E-01 JY/BEAM
Levs = 3.200E-02 * (-10, -9, -8, -7, -6, -5, -4, -3, -2, -1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10)

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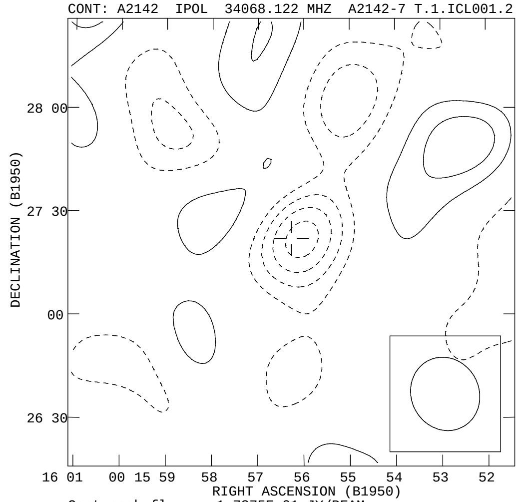

Cont peak flux = -1.7375E-01 JY/BEAM
Levs = 3.800E-02 * (-10, -9, -8, -7, -6, -5, -4, -3, -2, -1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10)

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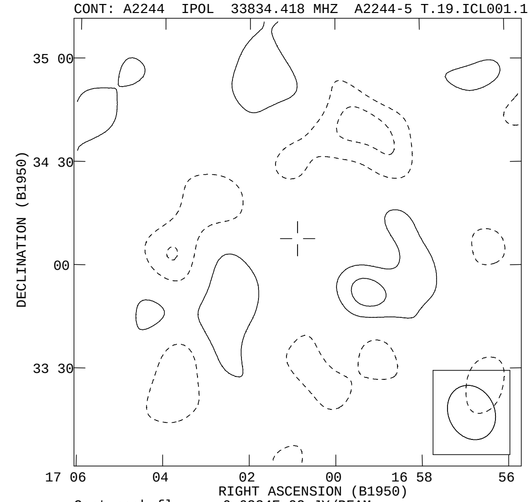
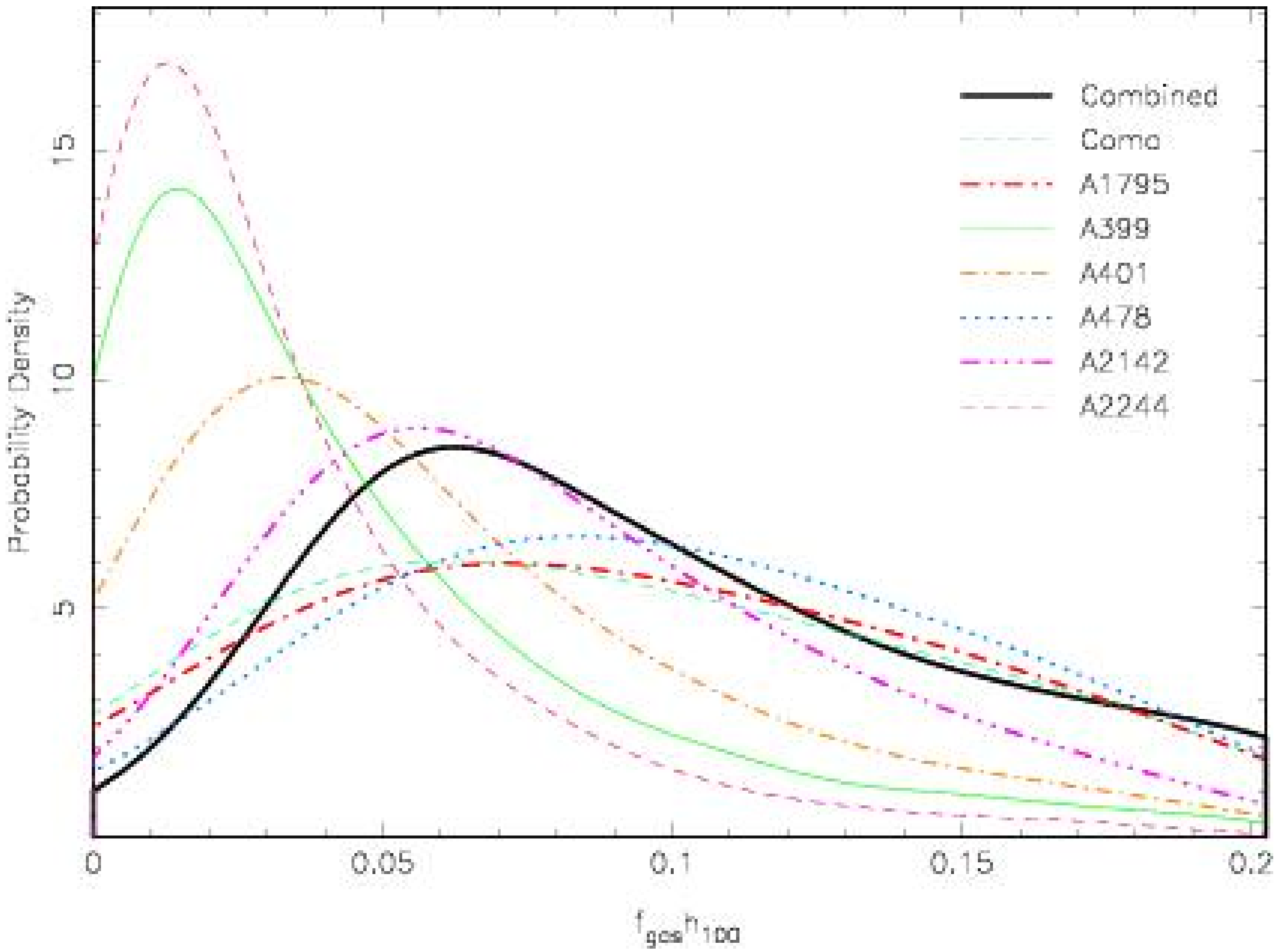


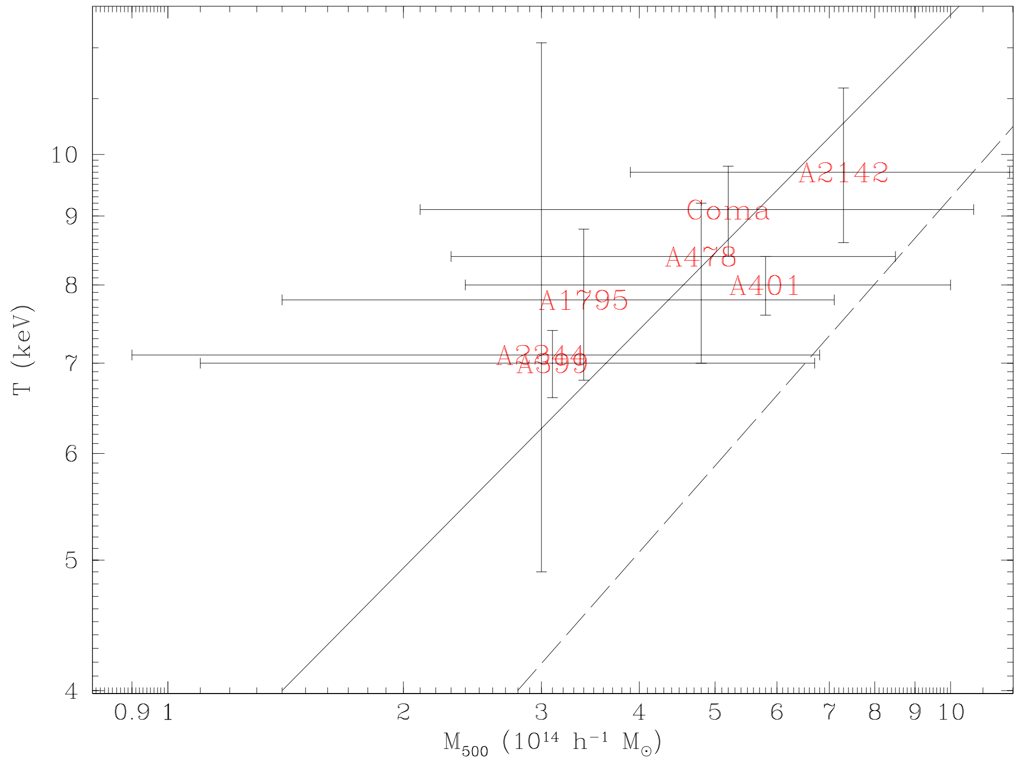
Cont peak flux = 6.6234E-02 JY/BEAM
Levs = 2.600E-02 * (-10, -9, -8, -7, -6, -5, -4, -3, -2, -1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10)

Gas fraction measurement



Combined constraints (from significant detections) on the gas fraction $f_g = 0.08^{+0.06}_{-0.04} h^{-1}$ (Lancaster et al., astro-ph/0405582)

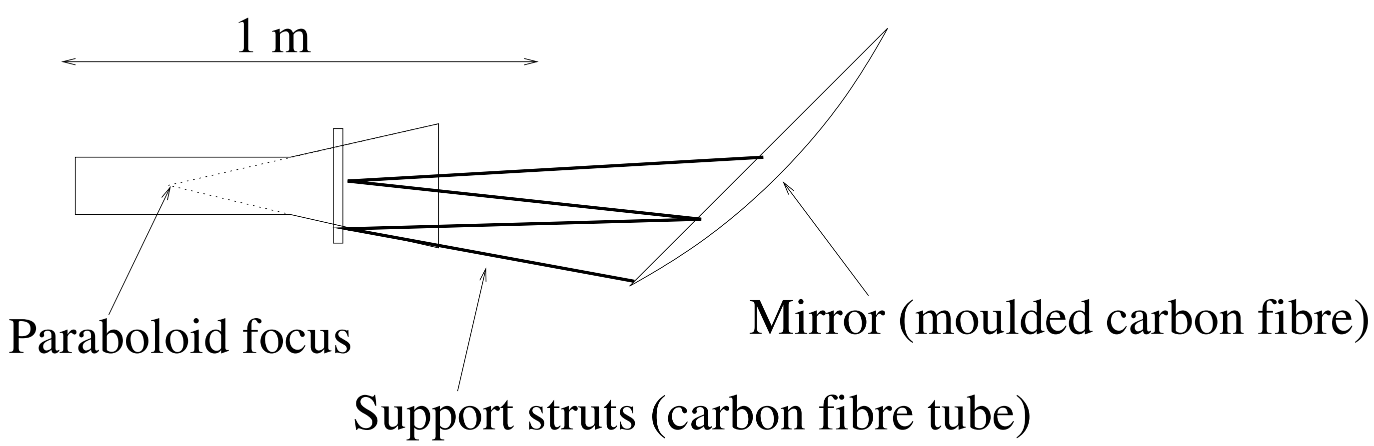
Mass - Temperature relation from (VSA) SZ data



In agreement with X-ray determinations, disagreement with predictions from adiabatic simulations - interesting, given the differences between X-ray and SZ.

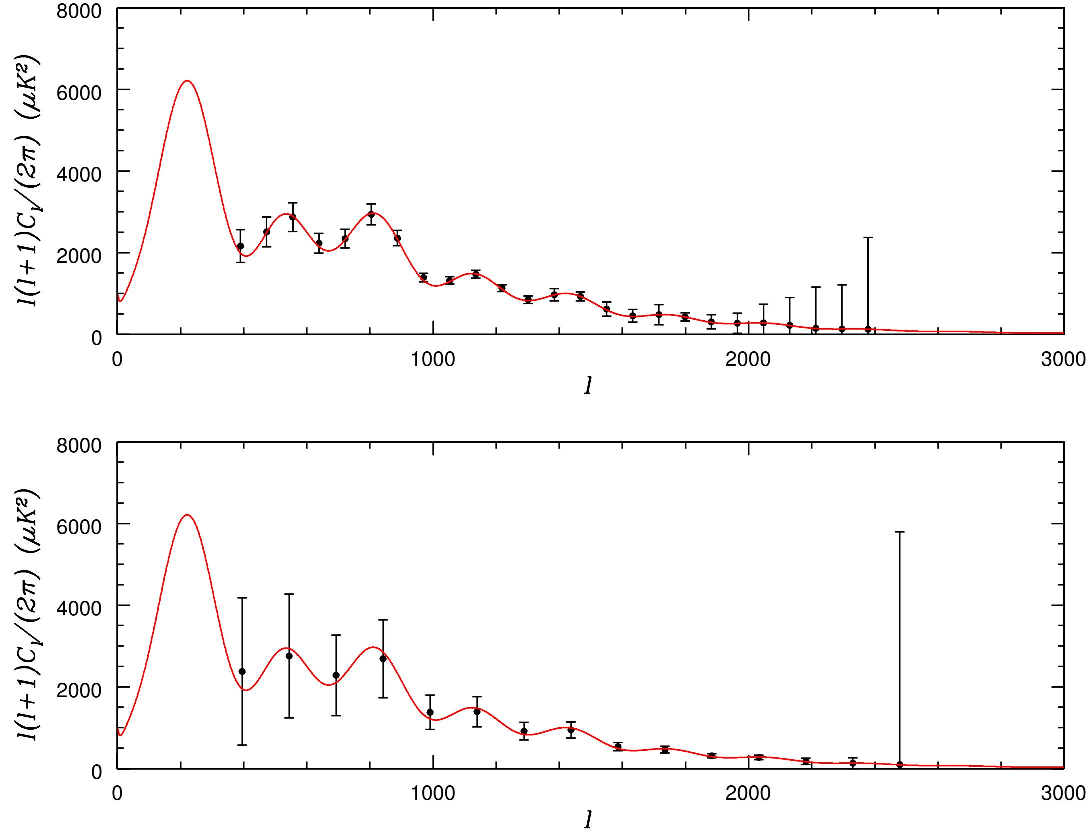
Understanding L_{SZ} - M relation, ie. M-T and f_g, will be essential for the blind SZ surveys.

The Future: The Super-Extended VSA



- Want to measure **high-ℓ** power spectrum with high sensitivity.
- Composite mirror with metallised surface supported by extension of existing struts.
- Replace front-end amplifiers with new devices: T_{sys} = 35K $\rightarrow$ 25 K.
- Fit a clone of the AMI correlator: $\Delta\nu$ = 1.5GHZ $\rightarrow$ 6GHz.
- Factor of 10 increase in observing speed

Science with the enhanced VSA



- Single binned, predicted performance of enhanced VSA (using known observing efficiency).
- Opportunity **before 2008** for a **high-ℓ** and **small-$\Delta\ell$** total-intensity experiment
- **beyond** WMAP resolution, with **low systematics** and ability to **subtract foregrounds**
- **Three** clear goals:

– determine **detailed structure** of CMB power spectrum out to $\ell \simeq 2000$

– determine **overall power level** of CMB power spectrum at $\ell > 2000$

– high-resolution, high-sensitivity **imaging** of CMB anisotropies

VSA summary and outlook

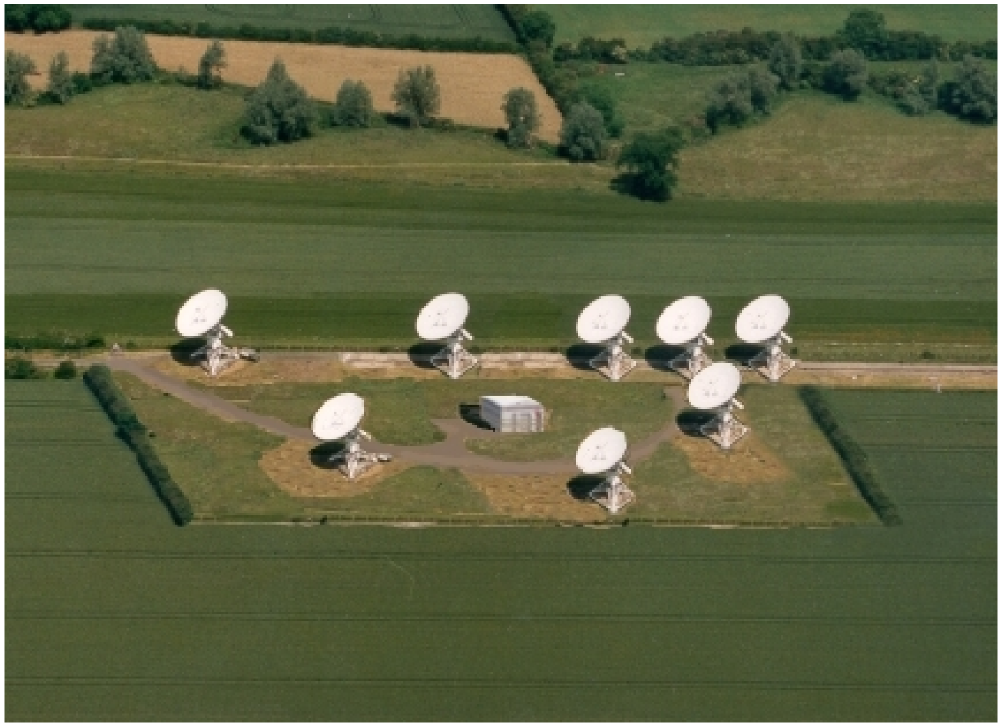
- The VSA has measured the CMB power spectrum from $\ell = 150 - 1600$.

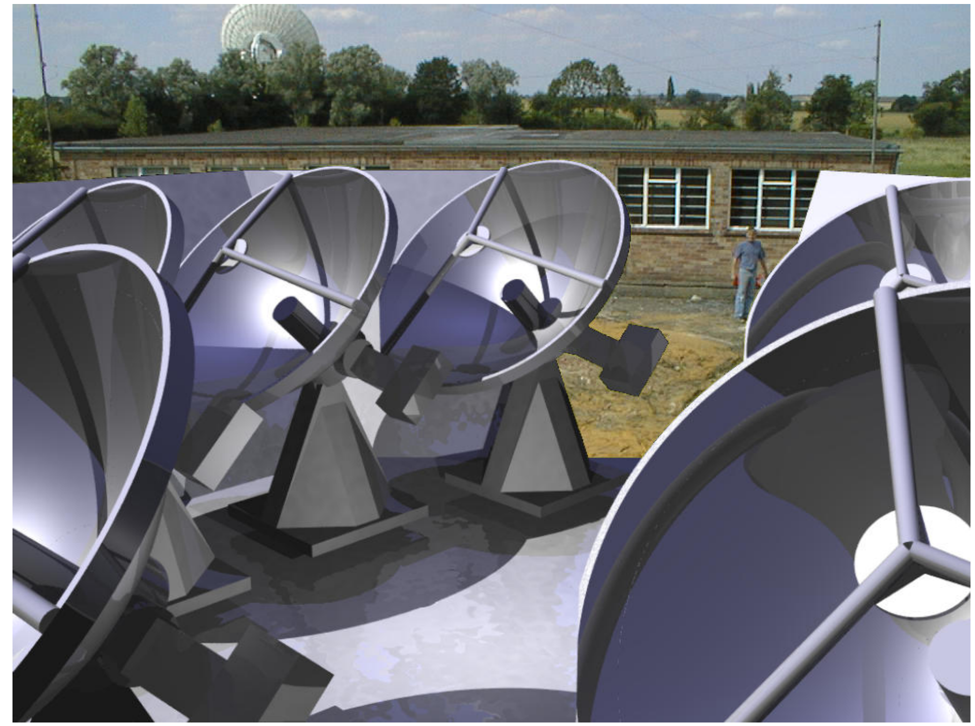
- Post-WMAP, there is still a huge amount to be learnt at high ℓ.
  - Measure 4th, 5th.... peaks — break degeneracies ($\triangle\ell$ critical).
  - Investigate **primordial fluctuation index** (n_{run}?; reject Harrison-Zel'dovich spectrum?)
  - Investigate **CBI excess** at $\ell > 2000$.
  - High-sensitivity searches for **topological defects**.

- The VSA can be enhanced to meet these challenges and has the advantage of excellent rejection of systematics.

- Upgrades not funded yet - an opportunity for agencies / collaboration with DASI could reduce costs.

The Arcminute Micro-Kelvin Imager

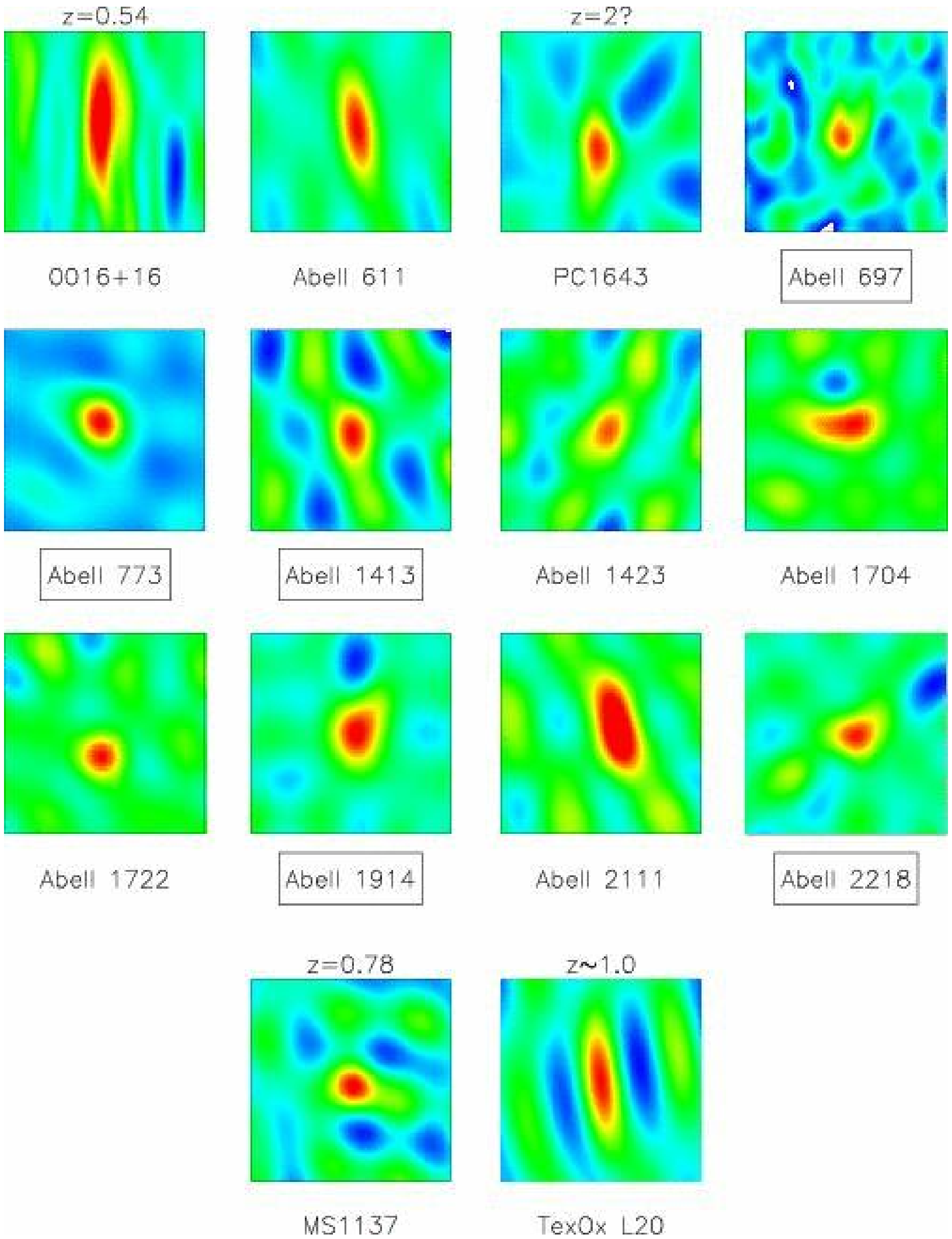




Roger Boysen, Tony Brown, Mike Crofts, Tom Culverhouse, Roger Dace, Ken Duggan, Will Flynn, Keith Grainge, Will Grainger, Jörn Geisbüsch, Richard Hills, Christian Holler, Roy Jilley, Mike Jones (PM), Tak Kaneko, Rüdiger Kneissl (PS), Anthony Lasenby (PI), Ian Northrop, Guy Pooley, Vic Quy, Richard Saunders (PS), Jack Schofield, Paul Scott, Clive Shaw, Angela Taylor, Dave Titterington, Simon West, Brian Wood, Jonathan Zwart

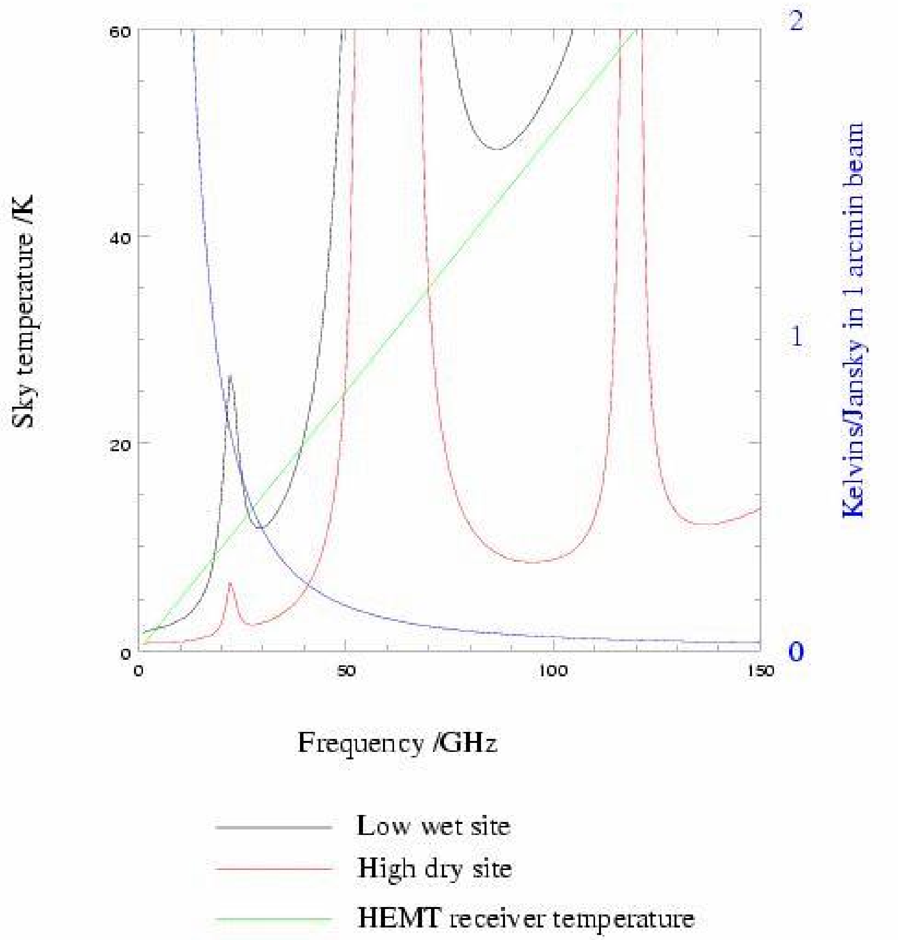
The Ryle Telescope

8 $\times$ 13-m antennas, **East-West** array, 5 compact, 350 MHz bandwidth @ 15 GHz



SZ clusters observed with the **Ryle Telescope** ($z = 0.1$–1).

The Ryle Telescope (80's technology) is too slow for surveying / no imaging of faint clusters.

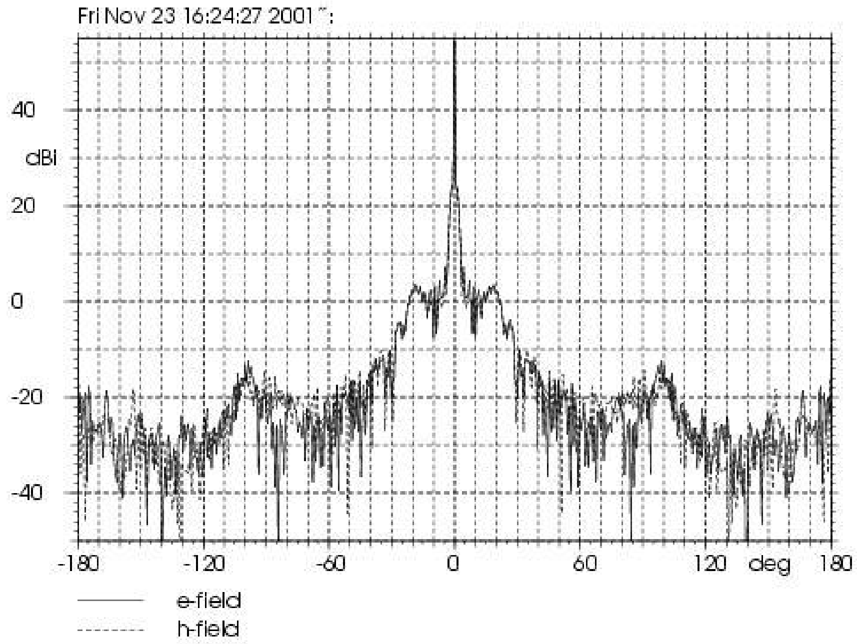


But, cost efficient design of AMI uses **large collecting area** to build SZ survey instrument at low frequency

- **Low** $T_{\rm sys}$ (atmosphere / receivers; 55K $\rightarrow$ 25K) + use **highest bandwidth** possible (0.35 GHz $\rightarrow$ 6 GHz)
- Move 3 distant Ryle antennas to gain **N-S resolution** and sensitivity
- **Infrastructure** of Lord's Bridge site
- Add **compact array of 3.7-m dishes**: Minimum baseline to **not resolve cluster** $\sim 200\lambda$ @ 2 cm (RT with 650λ resolves 90%)
- At 15 GHz **radio sources** are bright $\rightarrow$ **subtract** using Ryle antennas / surveys at neighbouring lower frequencies available

Antennas:

- 3.7-m Cassegrain, off-the-shelf single-piece paraboloidal primary
- shaped, over-size secondary gives $\eta \simeq 0.8$ over 12–18 GHz
- rim baffle and ground screen gives $T_{\mathsf{spill}} < 1$ K



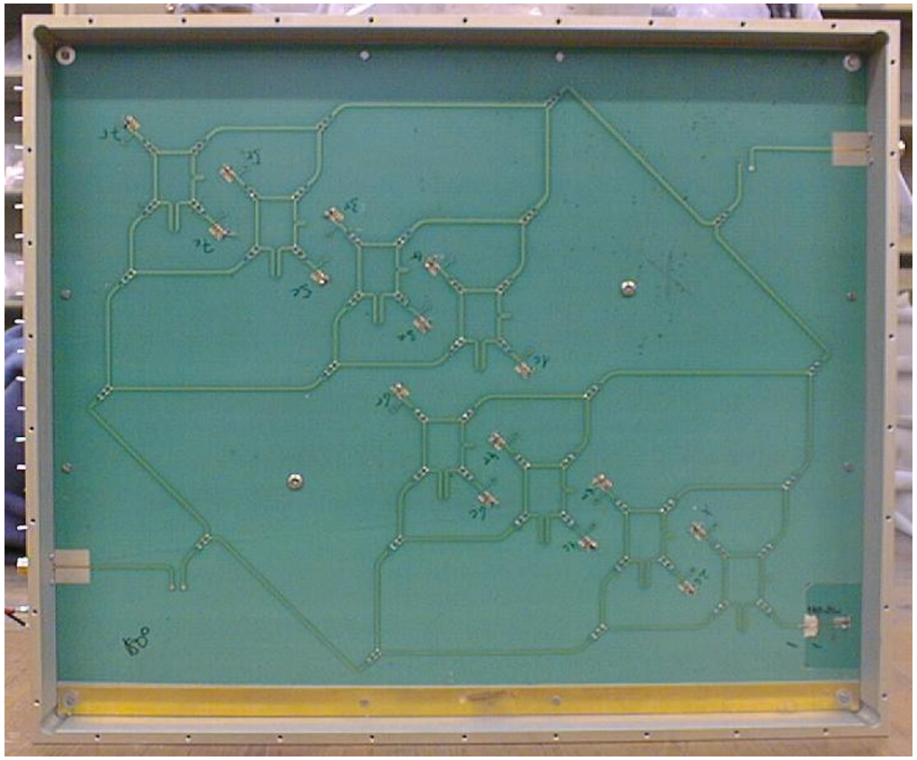
Receivers:

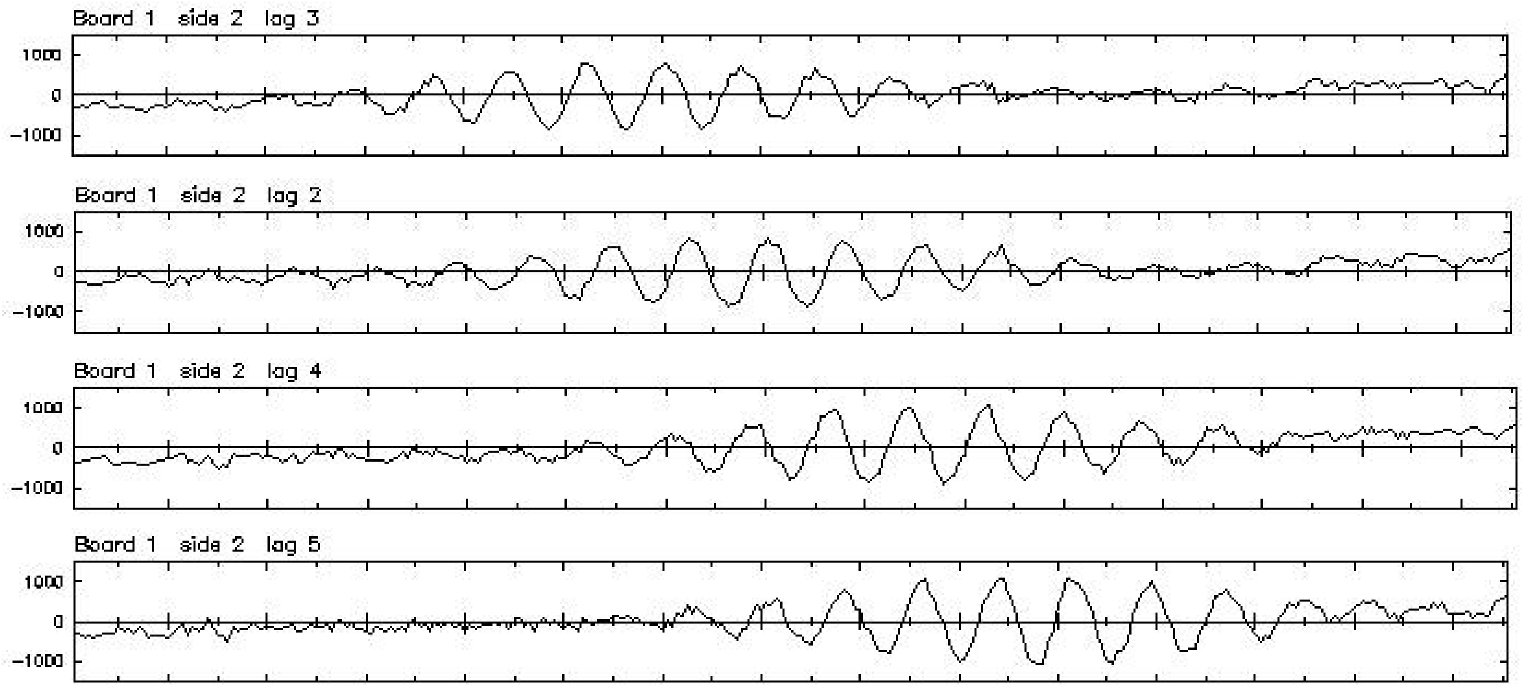
- NRAO 8–18 GHz amplifiers, $T_{\mathrm{amp}} = 6$ K
- fully cooled feedhorn

IF system: downconverters, amplifiers, filters, path compensator, gain control units for 6–12 GHz.

Correlator:

- 16-lag analogue correlator → 8 complex frequency channels
- detect phase-switched power with Schottky diodes

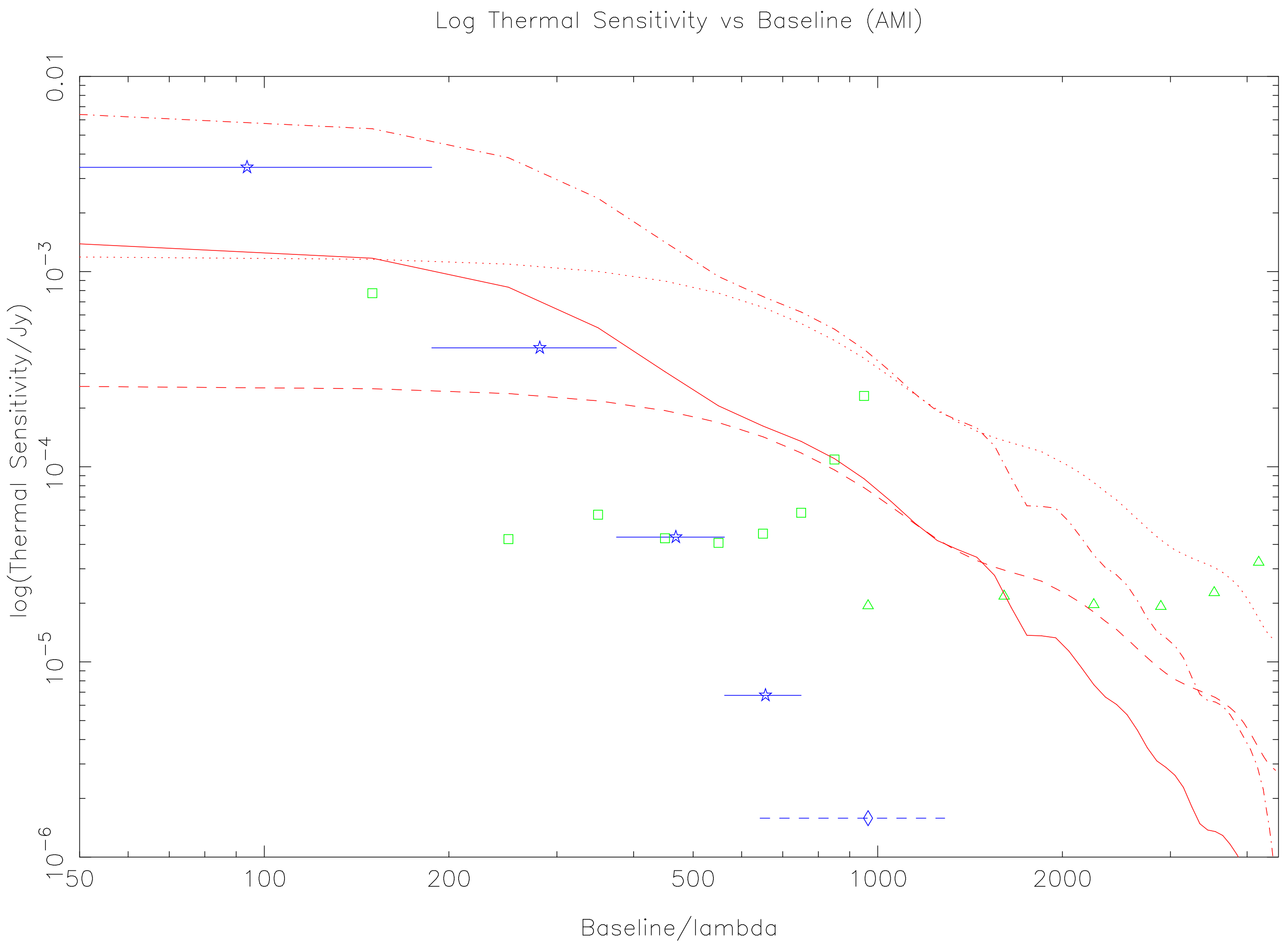




Fringes from Crab Nebula. Output by correlator lag – FT to get frequency

Commissioning (May 2004):

Sensitivity and CMB Confusion

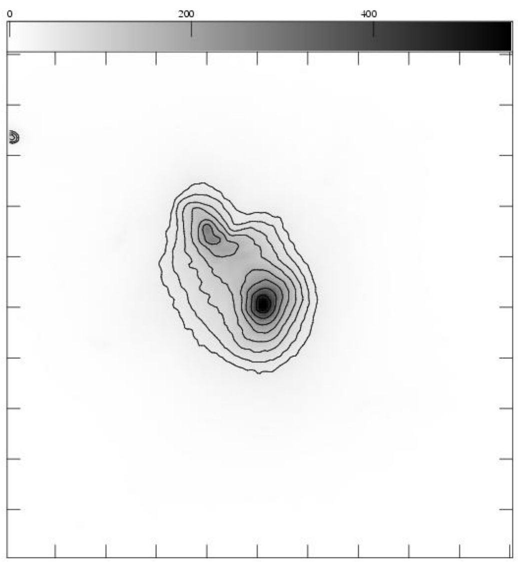


Thermal flux sensitivity (6 $\times$ 8-hours; within a 21 arcmin aperture) of the AMI 3.7-m and Ryle 13-m dishes compared to primordial CMB and 4 clusters with masses of $M = 2$ / 5 $\times 10^{14} M_{\odot}$ and at redshifts $z = 0.15/0.8$.

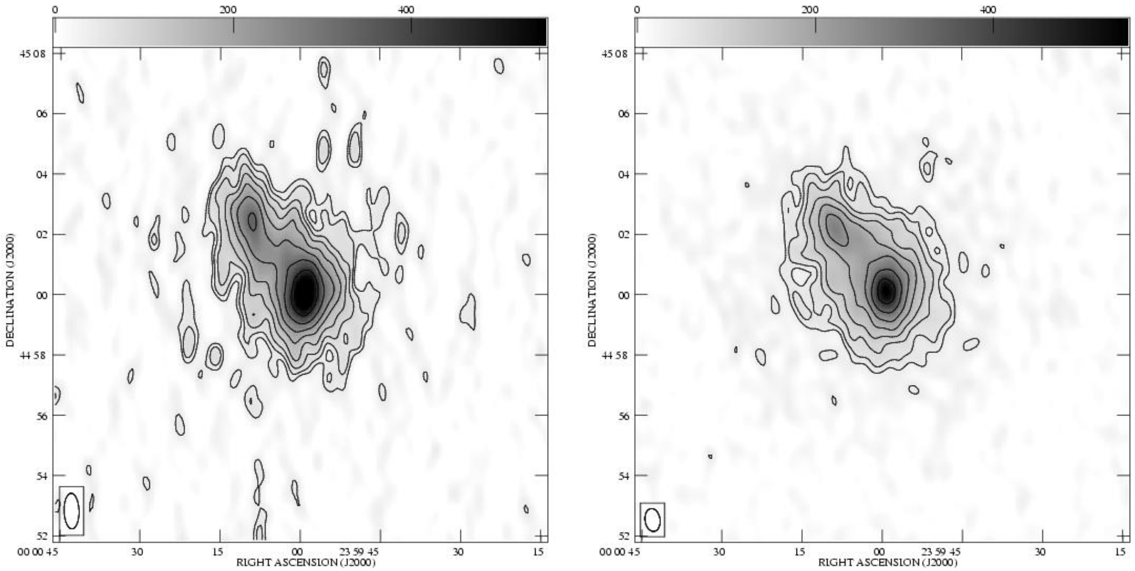
Imaging cluster substructure with AMI

Construction phase 3: Reconfiguring the Ryle telescope

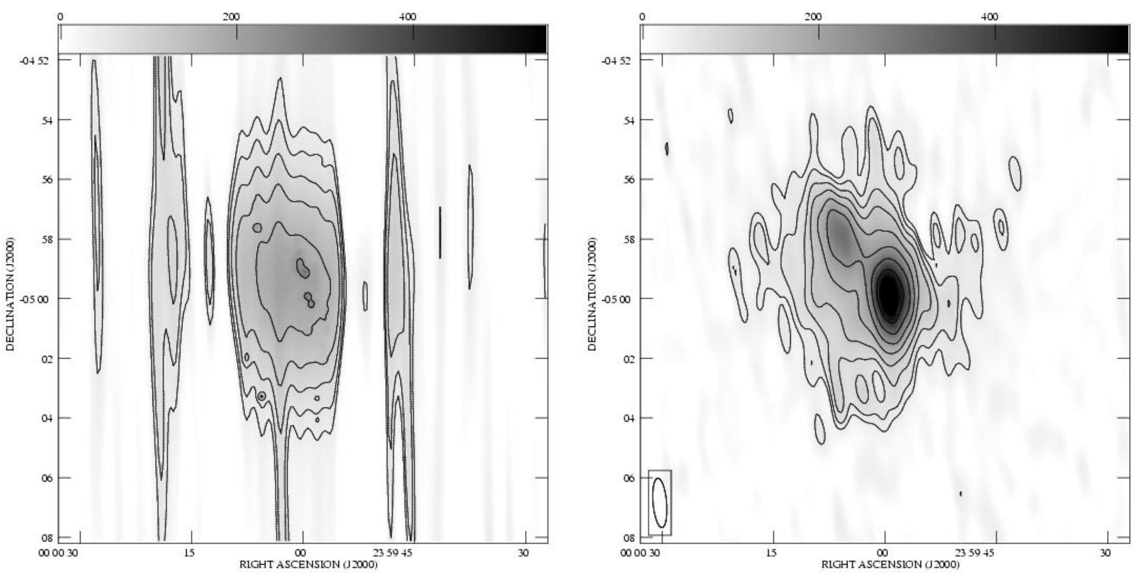
current wide East-West alignment



Hydrosimulation: 5×10^{14} $M_{\odot}$ merging cluster at $z = 0.155$.



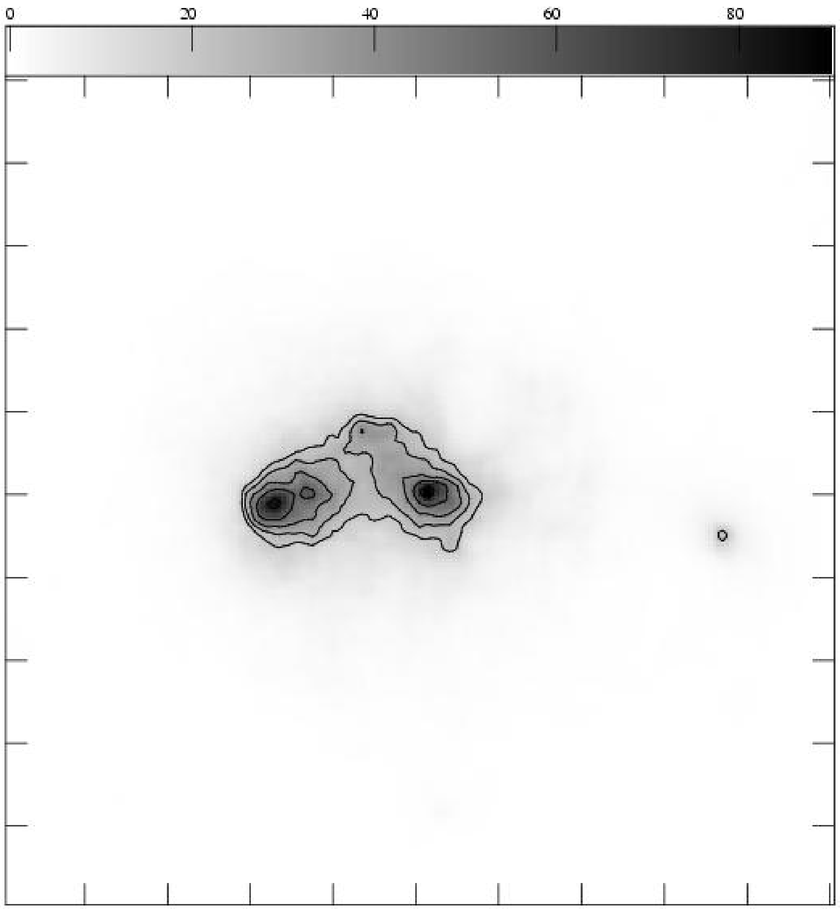
high declination (45 deg)



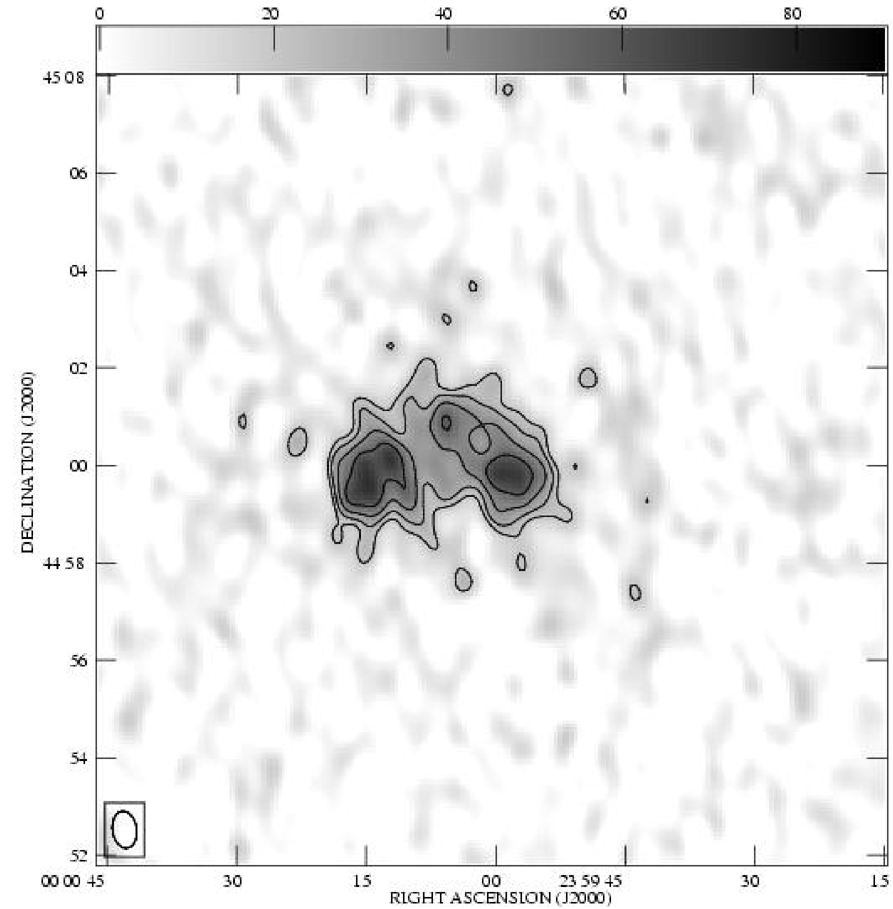
low declination (-5 deg)

more compact array with improved North-South resolution

Pointed high redshift cluster observations with AMI



Cluster merger at redshift 1.5 of total mass 2×10^{14} $M_\odot$ from a hydrodynamical simulation (G. Tormen); in y-units of 10^{-6}.



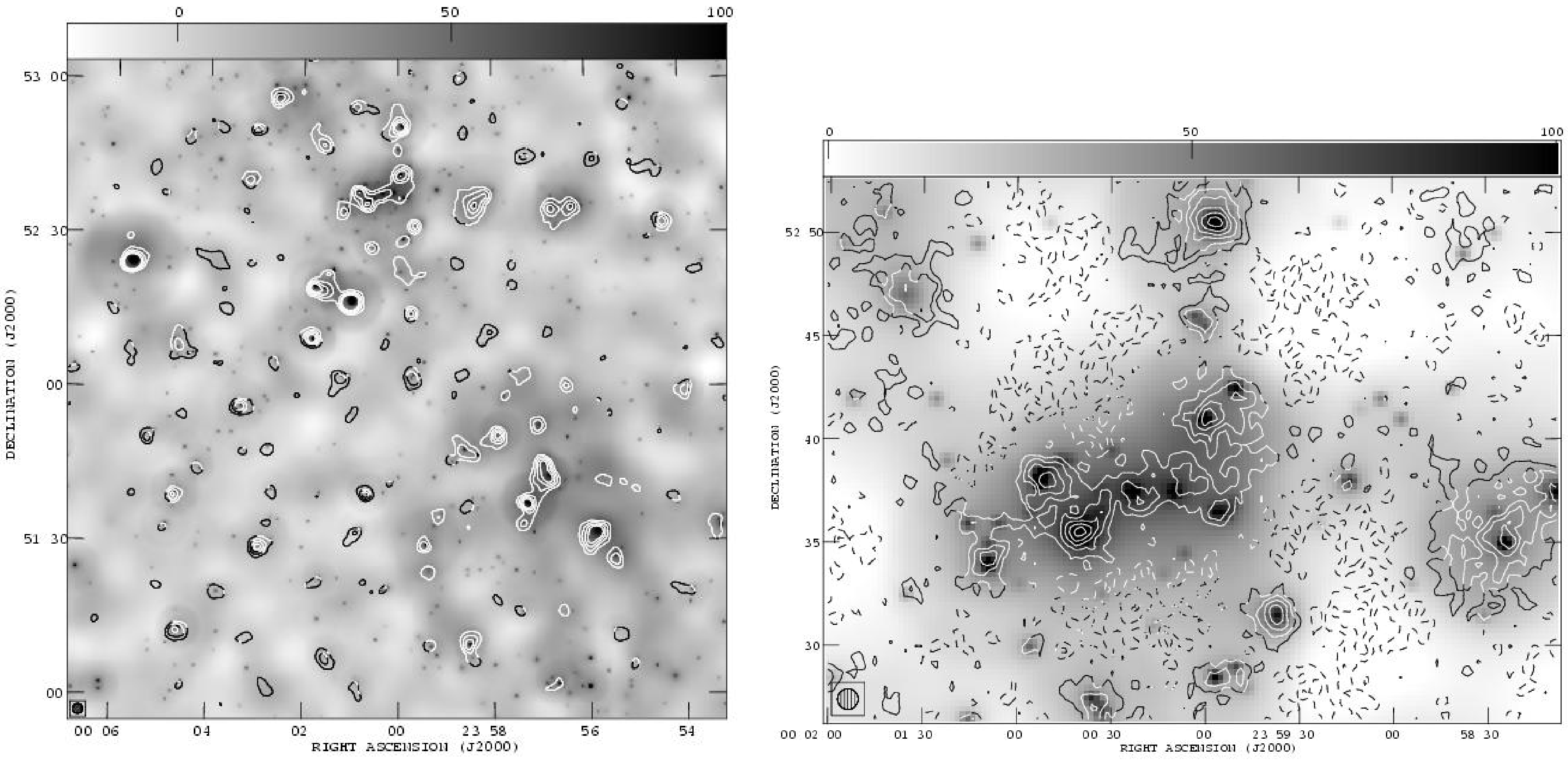
Simulated $14 \times 8{-}$h observation with compact array and Ryle mosaic; in μJy beam^{-1}.

Why SZ cluster surveys ?

- Cluster selection $\sim$ independent of mass over wide range of z
- Cluster $\frac{\mathrm{d}N}{\mathrm{d}M}$ as a function of z
- Sensitive to cosmological parameters: e.g. σ_8, Ω_M, Ω_Λ, dark energy
- Evolution of cluster properties, e.g. f_g and scaling relations, e.g. β_{TM}
- Total energy content of cluster independent of structure:

$$S_{\mathrm{SZ}} = \int \Delta T \mathrm{d}\Omega \propto \frac{1}{D_{\mathrm{A}}^2} \int n_{\mathrm{e}} T_{\mathrm{e}} \mathrm{d}V$$

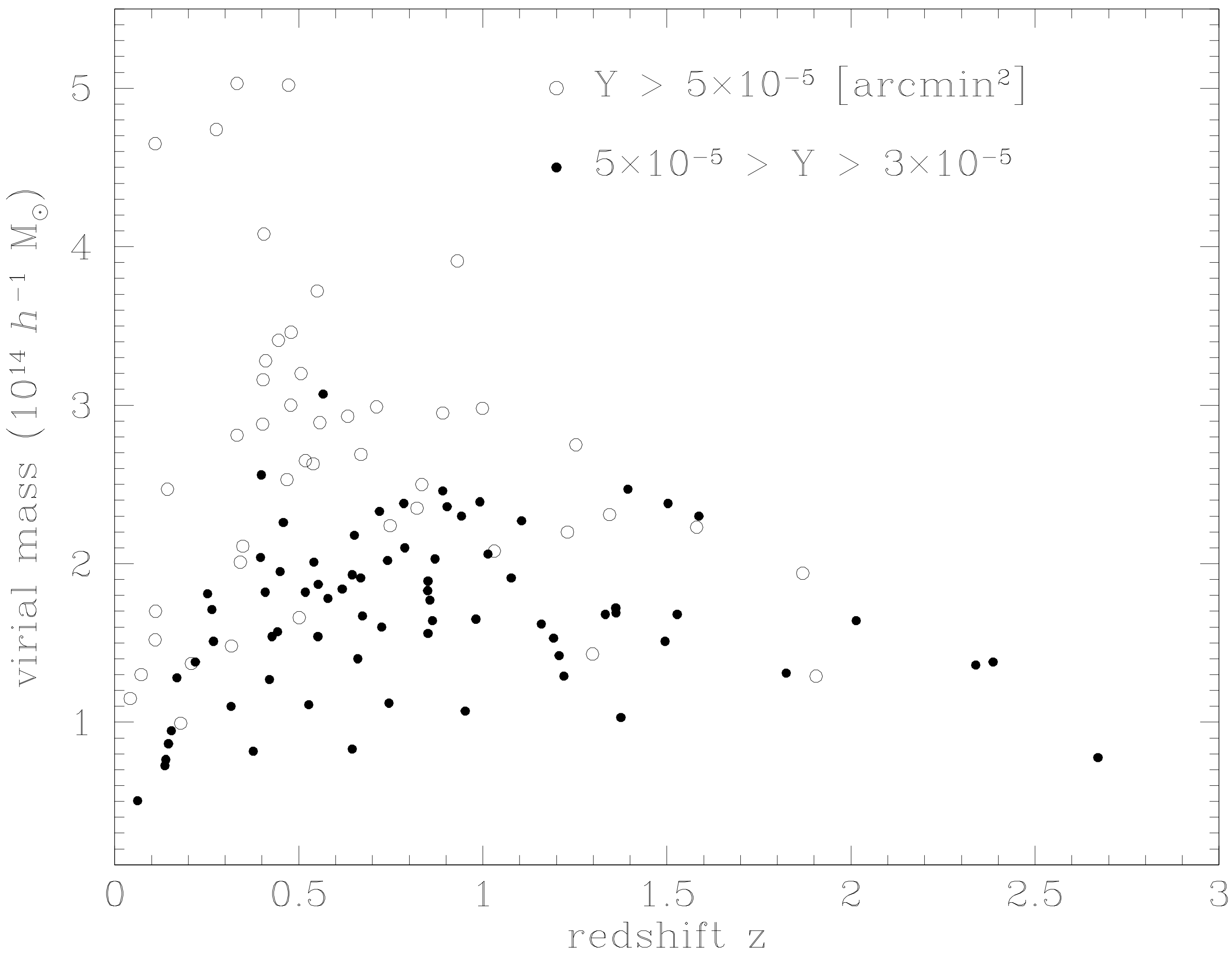
AMI cluster survey in the presence of primordial CMB



Grayscale image: Virgo cluster positions with scaled β model clusters, plus CMB

Contour overlay: 6 months survey, 2 arcmin resolution. Sources subtracted!

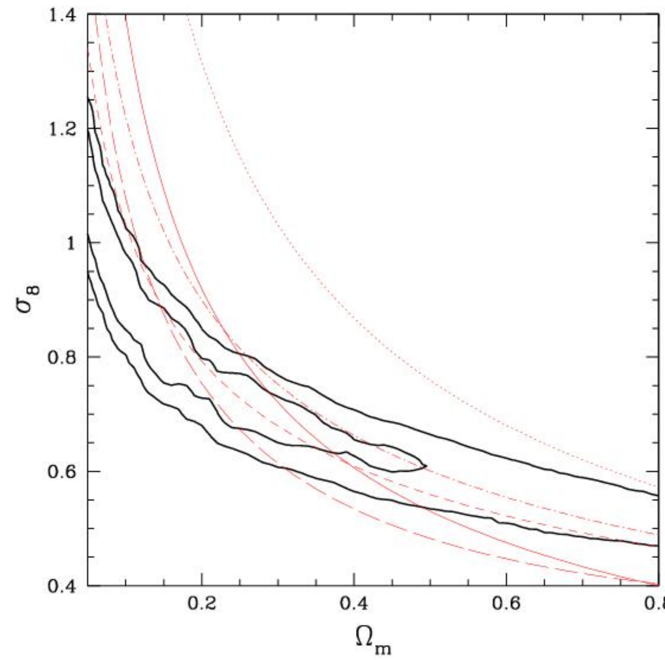
Masses and redshifts of AMI clusters



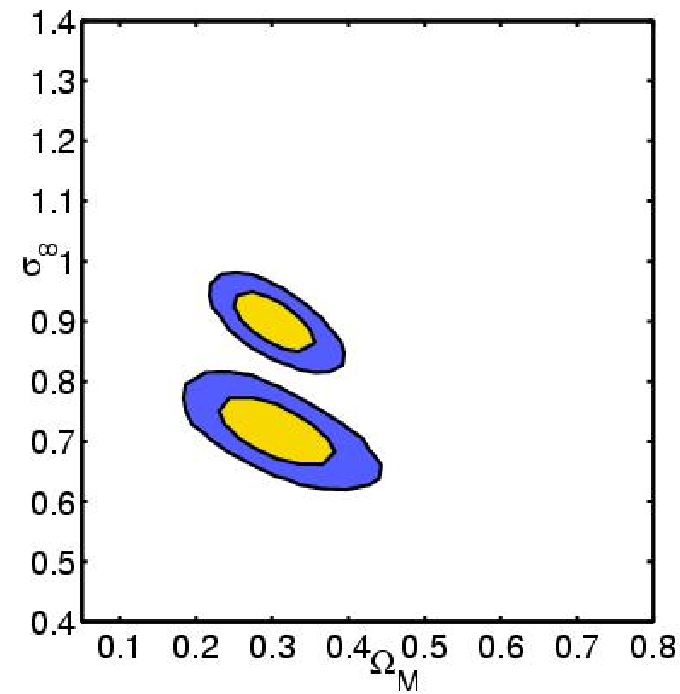
RK et al. 2001

Parameter estimation with AMI

- Two cases considered: $\sigma_8 = 0.9$ and $\sigma_8 = 0.7$ ($\Omega_{\rm M} = 0.3$)
- M-T relation is changed consistently with X-ray data
- Size of the error is roughly given by cluster numbers (300 and 150 clusters)
- Other cosmological parameters held fixed (e.g. $h = 0.72$ and $w = -1$)
- Follow-up: redshifts with $\Delta z = 0.1$ out to $z = 2$
- Well-determined cluster scaling relations (e.g. $\Delta f_g \sim 10\%$, $\Delta\beta \sim 10\%$)
- See Weller, Battye, RK (2002) for the method



X-ray cluster abundance (from Allen et al. 2002)

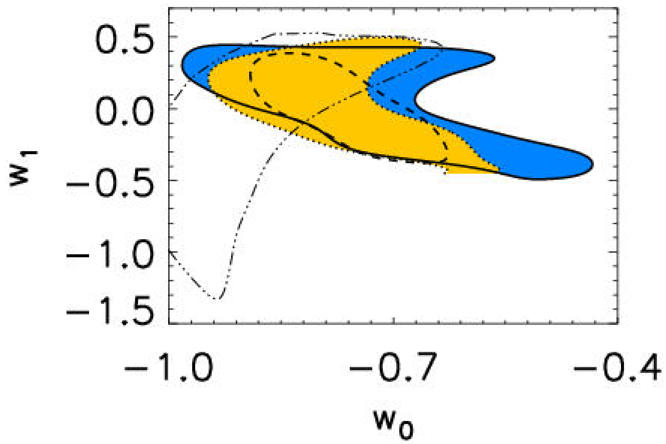


1-year AMI survey of 100 deg^2

Constraining dark energy with SZ clusters

The types of surveys and the number of clusters one would expect to observe in a fiducial cosmology $[h = 0.65, \sigma_8 = 0.925, \Omega_\mathrm{M} = 0.3, w_0 = -0.8, w_1 = -0.3; p = \rho(w_0 + w_1 z)]$.

	(I)	(II)	(III)	(IV)
S_lim	0.1	5	≈36	-
ν	15	30	≈100	-
$\Delta\Omega$	10	10^4	20600	4000
M_lim	1.5	≈ 7.0	≈ 6.0	2.5
N_tot	≈ 90	≈ 1970	≈ 5200	≈ 13600



Cluster evolution constraints from survey types II-IV compared with SNAP SNe (from Weller, Battye, RK 2002).

Necessary to take evolution of EoS into account, as expected in most physical models of quintessance.

Dark energy is an important aspect for SZ cluster surveys with interesting possibilities, but more a long term goal.

Conclusions

- AMI first science observations soon – full operation in early 2005
- AMI will provide interesting constraints on σ_8 and many high-z clusters
- Basic follow-up necessary for all clusters / detailed studies of interesting objects
- Pioneering SZ surveying and science extraction techniques for future instruments
- Combining SZ (survey) data with other (multifrequency) data, in particular X-ray, will be essential to
  - understanding the selection function of different cluster-finding methods
  - studying cluster scaling relations / cluster physics