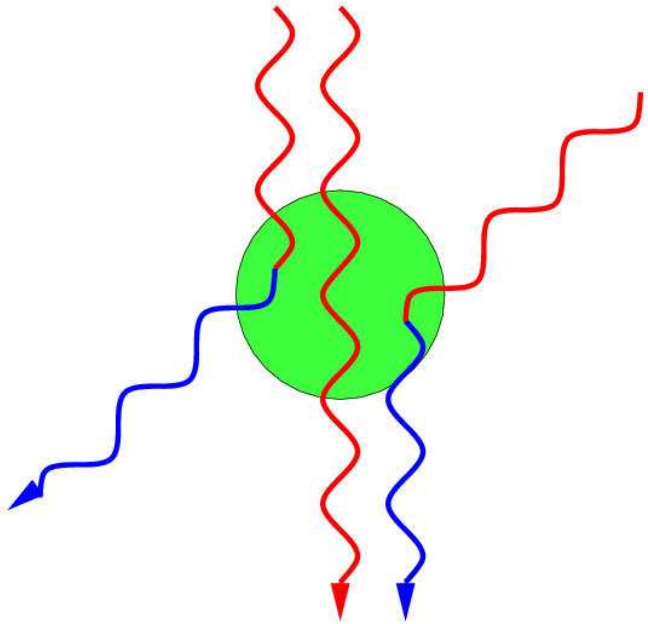
Surveying for Clusters through SZ

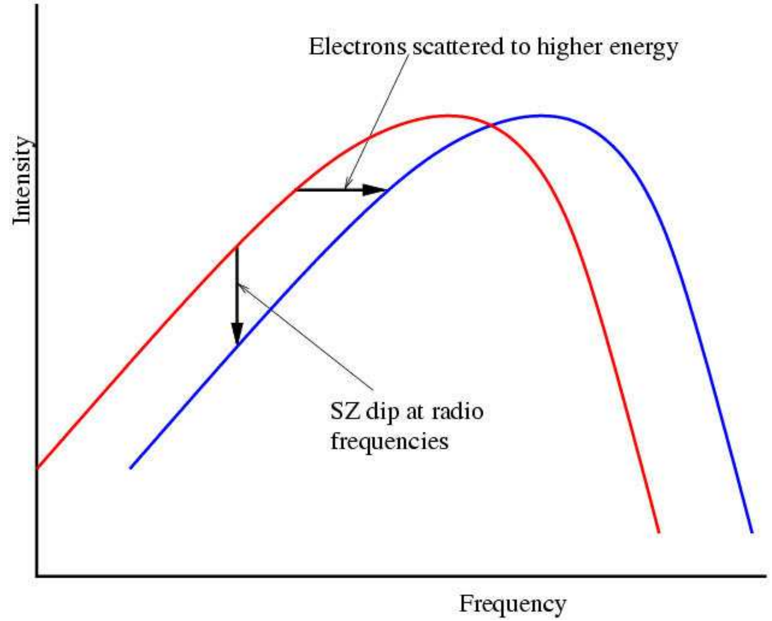
Keith Grainge
(with thanks to John Carlstrom)

Overview

- Introduction to the Sunyaev-Zel'dovich (SZ) effect
- History of SZ observations
- SZ surveys
  - Motivation
  - Instruments
  - Cosmology
- …. Second talk on AMI.

The Sunyaev-Zel'dovich Effect





- Scattering of CMB photons from intra-cluster plasma
- **SZ brightness independent of redshift**

Sunyaev-Zel'dovich Effect

complements X-ray and lensing

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

- Cluster physics
  - *measure integrated pressure*
- Peculiar velocities at high z
  - *Current best limits* $\sigma(v_{pec}) \sim 1000 km/s$
- Cluster gas mass fraction, Ω_b / Ω_M
  - *clean measure of baryon gas mass*
- Distances, H(z)
  - *combined with x-ray* → $D_A(z)$
- Cluster surveys:
  - *exploit redshift independence*
  - *constrain* Ω_M, Ω_Λ, σ_8, w, w(t)…

$$S \propto \int \Delta T_{SZE} d\Omega$$

$$\propto \frac{1}{D_A(z)^2} \int n_e T_e dV$$

Experimental Challenge

- Small signal, large angular size
  - Need to make differential measurements
  - Synchronous offsets

    → like intrinsic CMB anisotropy experiments
- Contamination
  - Point sources in radio – synchrotron emission (variable and correlated with clusters)
  - Point sources in mm/submm – dust emission
  - CMB on large angular scales
- Systematics, systematics & systematics
  - Like CMB, best done with with instruments designed specifically designed instruments. Most (all?) measurements done to date on telescopes designed for other purposes.

SZE instruments

Existing/past SZE instruments:

Interferometers: Ryle (15 GHz), OVRO/BIMA (30 GHz), CBI, VSA

Single dish radio: OVRO 40m, OVRO 5m, Nobeyama 45m, OCRA on Turan 32m

Single dish bolometers: SuZIE on CSO 10m (SuZIE I,II,III) , Diabolo on IRAM 30m, SEST 15m, SCUBA on JCMT 15m, MITO 2.6 m (MAD 4 MITO), ACBAR on Viper 2.5m

Upcoming:

OCRA 2 [10] [100?] 30 GHz HEMT array on Toran 32m (Birkinshaw et al)

Bolocam 144 element bolometer on CSO 10m

MAD 4 MITO 4 bands x 9 bolometers on MITO 2.6 m, SuZIE III on CSO

APEX-SZ 330 element bolometric array on APEX 12m

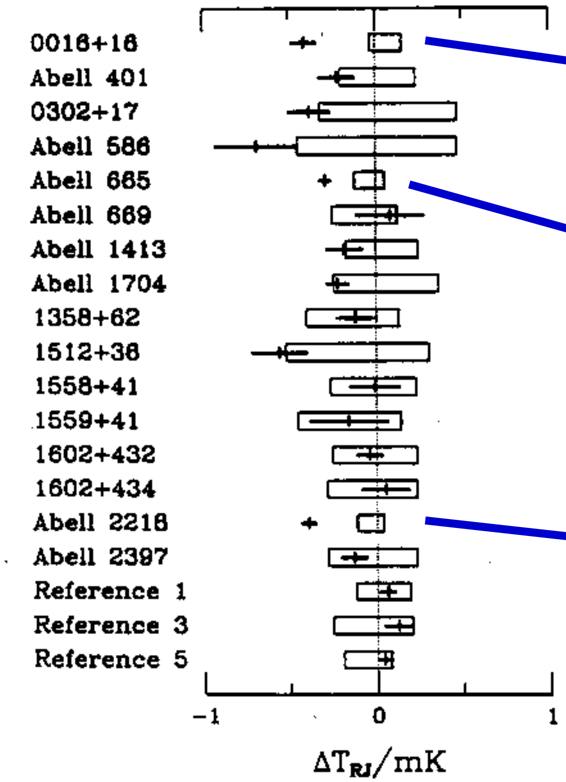
Penn 8x8 bolometer array on the NRAO GBT 100 m

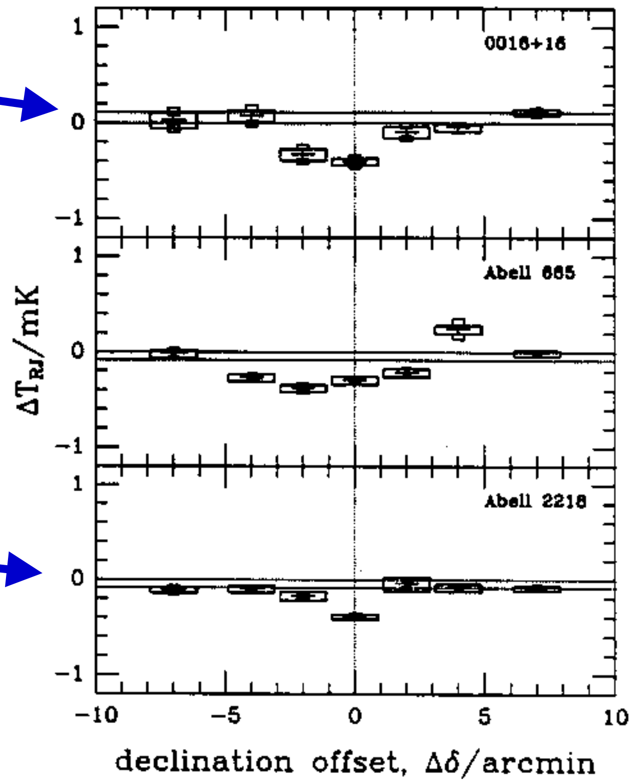
Next generation SZE *telescopes* and receivers:

Interferometers: SZA, AMI, 'AMiBA'

Single Dish Bolometer: South Pole Telescope (10m),
Atacama Cosmology Telescope (6m)
'Planck Surveyor Satellite'

1980’s: Pioneering Work by Birkinshaw and Collaborators
using the OVRO 40 m radio telescope using Dicke switching
and leading / trailing fields





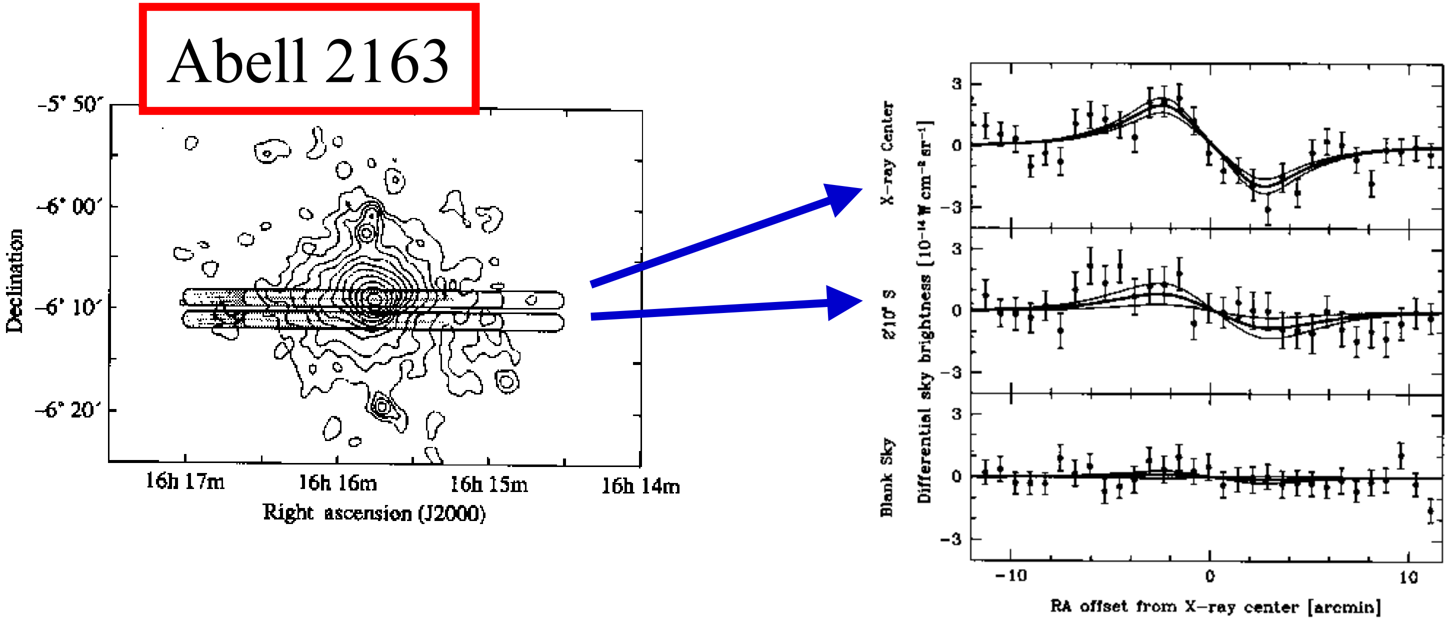
See Birkinshaw 1991 – review of SZE measurements

1990’s: Followed up with the OVRO 5m (7′ beam with 22′ chop) by Caltech group: (Readhead, Myers, Herbig, Mason)
Birkinshaw now working on OCRA 30 GHz focal plane array

SuZIE Multiband Bolometric Observations

Pioneered A/C – Chopped Bolometers, Drift scans on the CSO

1.2 mm & 2.1 mm channels, ***First detection of SZE increment***



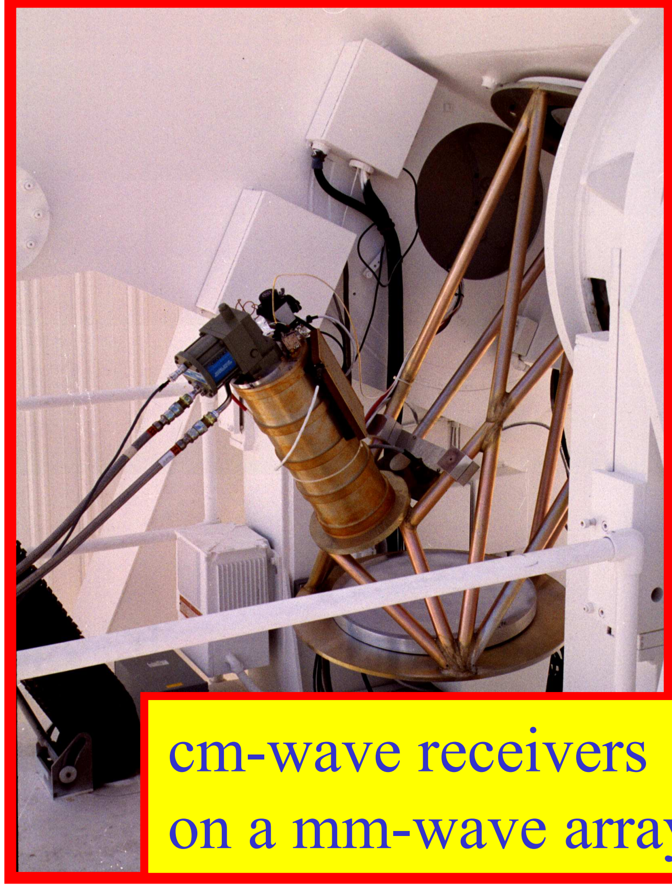
drift scans with CSO

Holzapfel et al. 1997, ApJ 480, 449, astro-ph/9702224

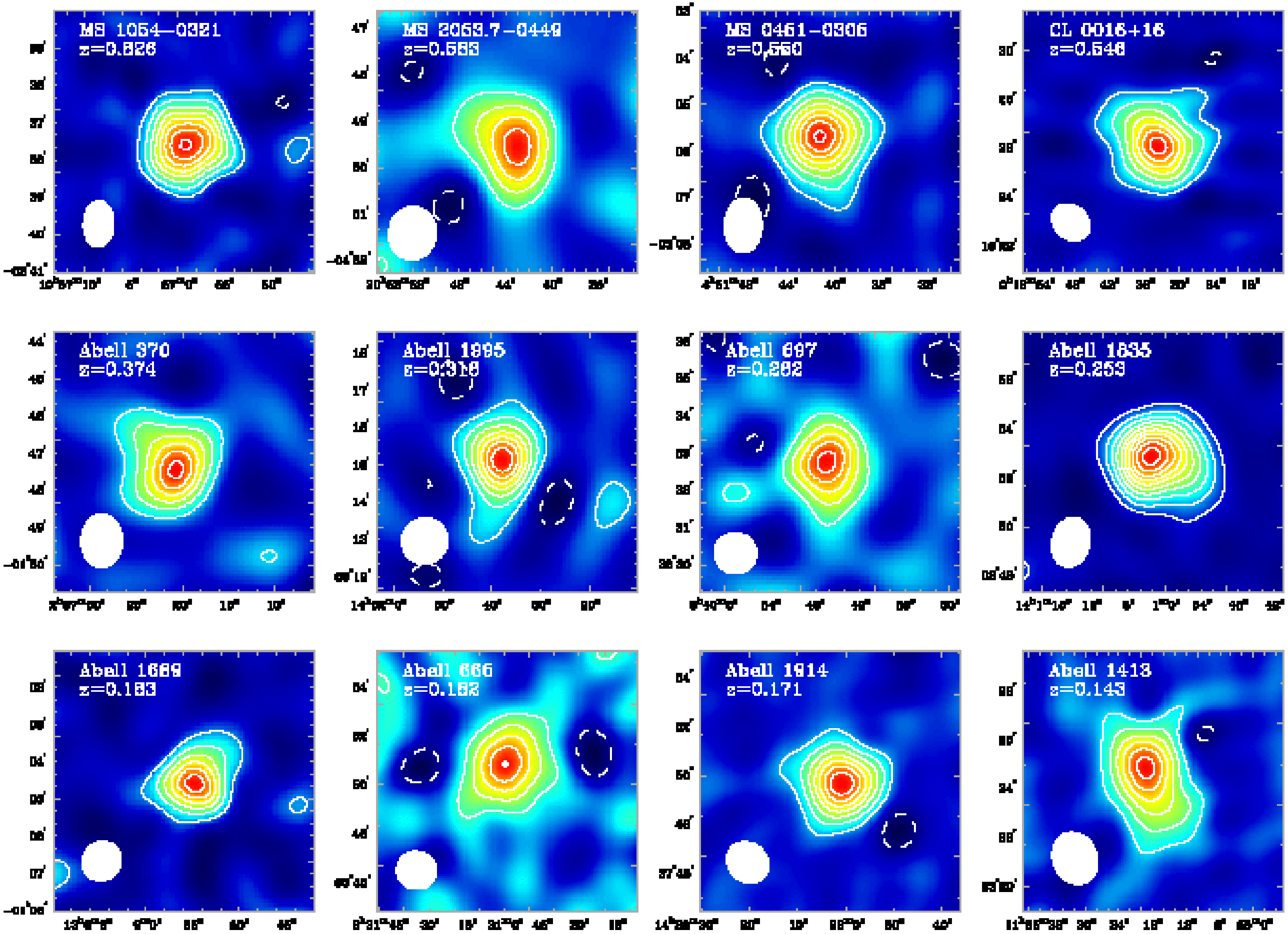
A/C bolometers on SEST and IRAM : Andreanni et al 1999, Desert et al, 1998, Pointecouteau et al., 1999, 2001

on MITO 2.6 m telescope: De Petris et al. 2002, astro-ph/0203303

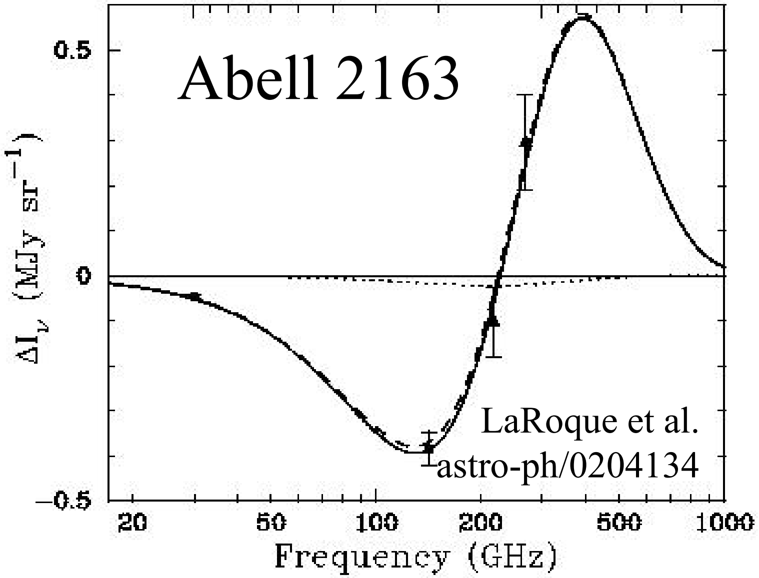
OVRO / BIMA SZE imaging



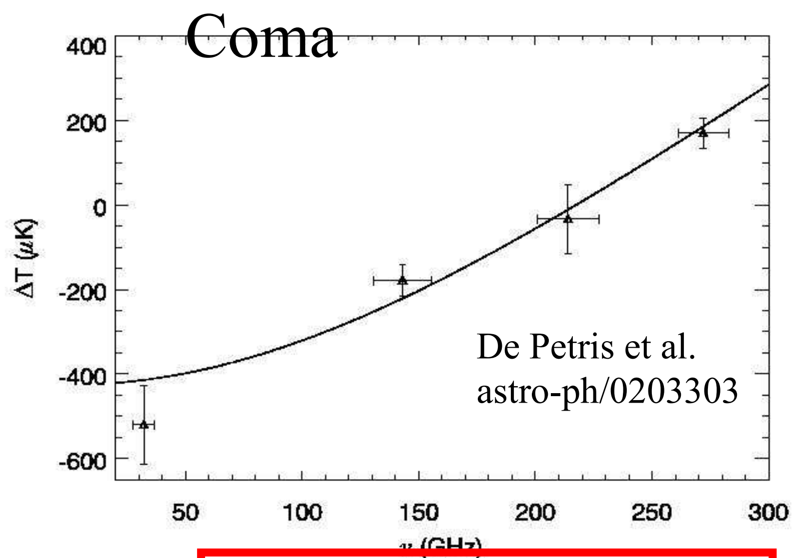
Sample of the 60 OVRO/BIMA imaged clusters, 0.07 < z < 1.03



Measured SZE Spectra

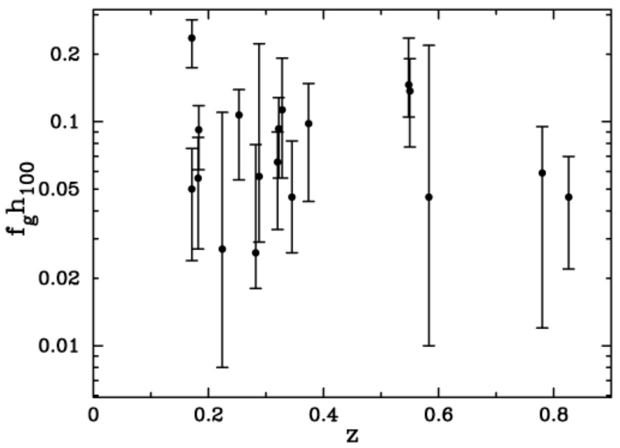


SuZIE & OVRO/BIMA Interferometer



OVRO 5m & MITO

For 10 more spectra see Benson, Church et al., Aug 1st 2003, ApJ

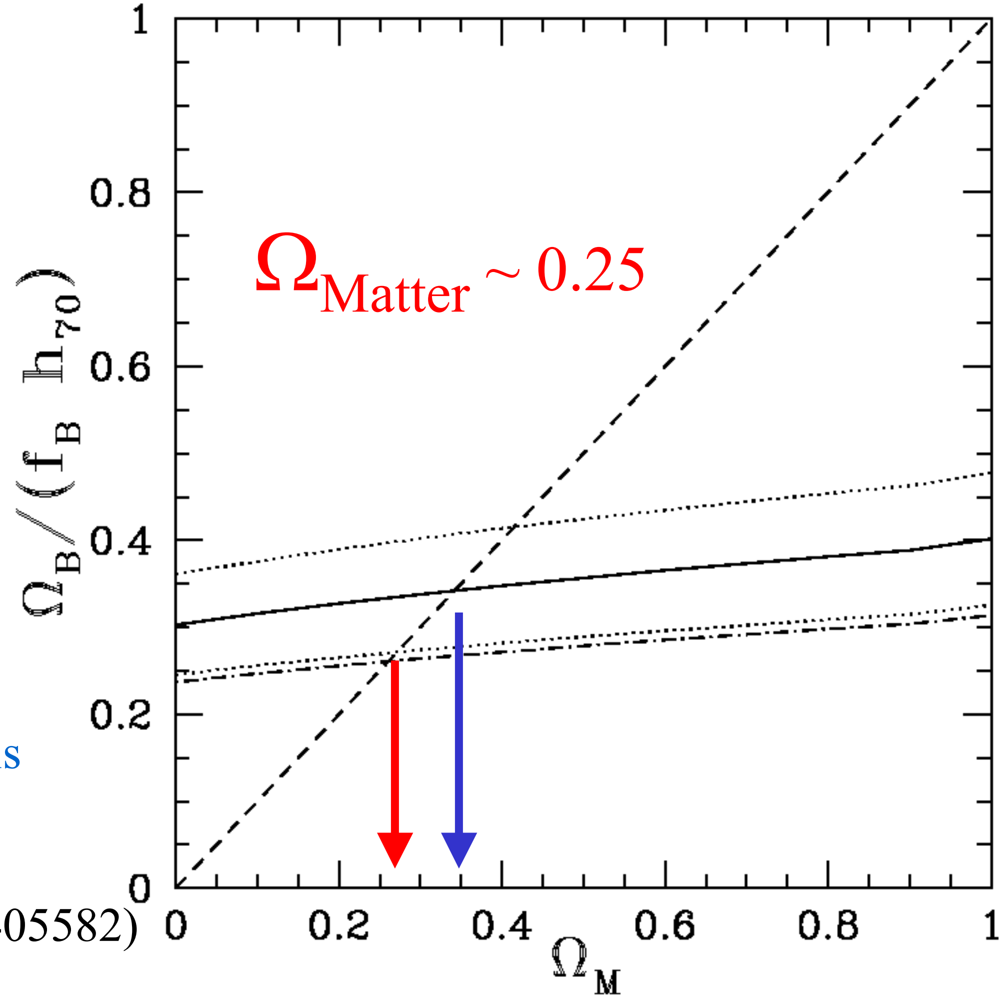


SZE Gas mass fractions

Ω_{Matter} from SZE derived gas mass ratios

- Total mass from SZE imaging and assumption of hydrostatic equilibrium.
  (No x-ray imaging data)
- Results agree with X-ray, M/Light, LSS

$$\mathbf{f_g = 0.081^{+0.009}_{-0.011} h^{-1}}$$



From sample of 18 BIMA clusters
Grego et al, 2001, ApJ 552,2
astro-ph/0012067 & Grego Ph.D. thesis

See also: Myers et al. '97
VSA low-z clusters (Lancaster et al. 0405582)

Distances from SZE and X-Ray

SZE: $\Delta T_{SZ} \propto n_e T_e L$

X-Ray $I_x \propto n_e^2 L$

Eliminate n_e and solve for L

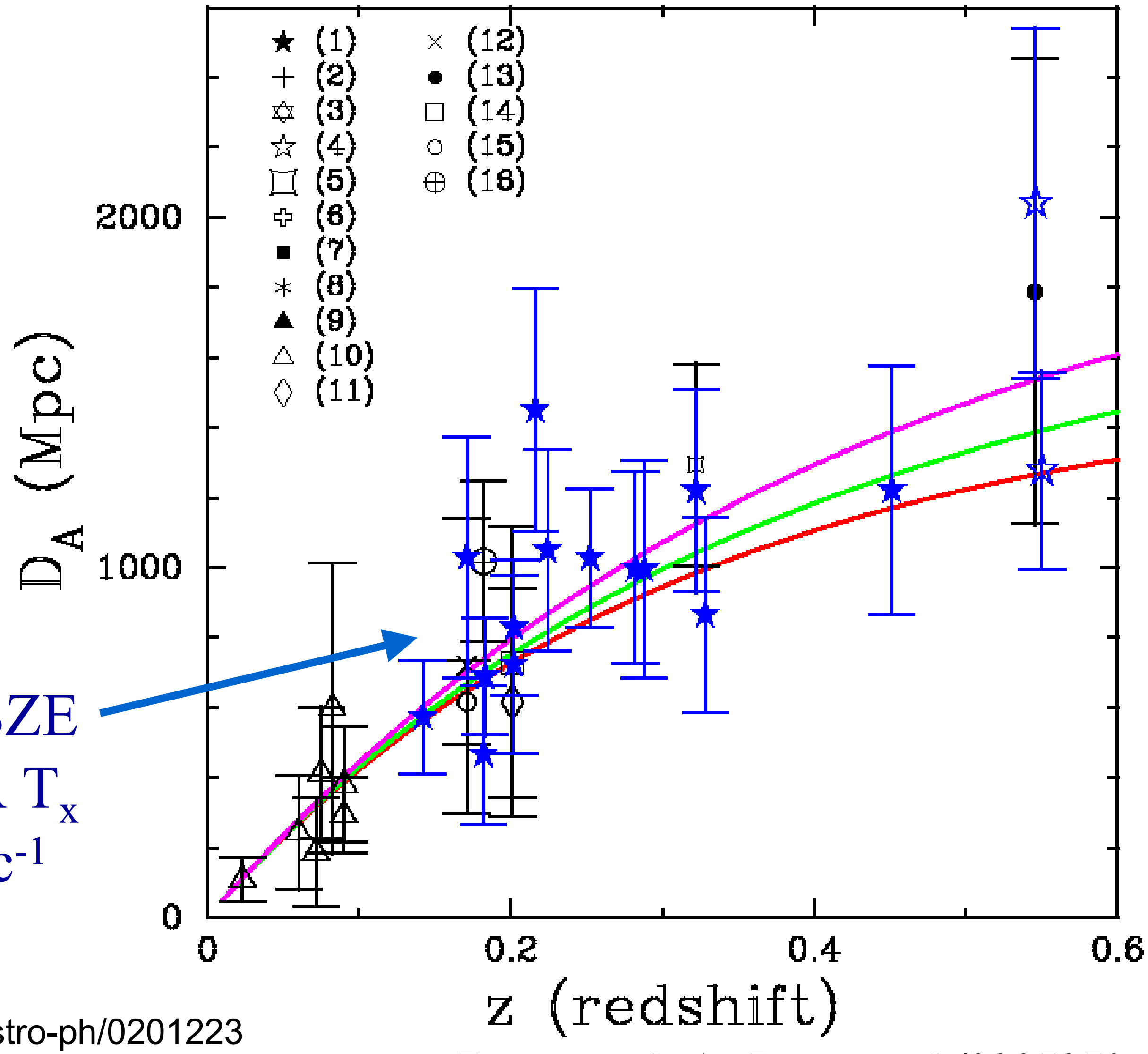
$L \propto (\Delta T_{SZ})^2 / I_x T_e^2$

Compare $L_{l.o.s.}$ to $\theta_{cluster} \rightarrow D_A$

$$H_0 \propto I_x T_e^2 / (\Delta T_{SZ})^2$$

Blue pts: OVRO/BIMA SZE + ROSAT X-ray + ASCA T_x

$H = 60 \pm 4 \pm 13$ km s^{-1} Mpc^{-1}



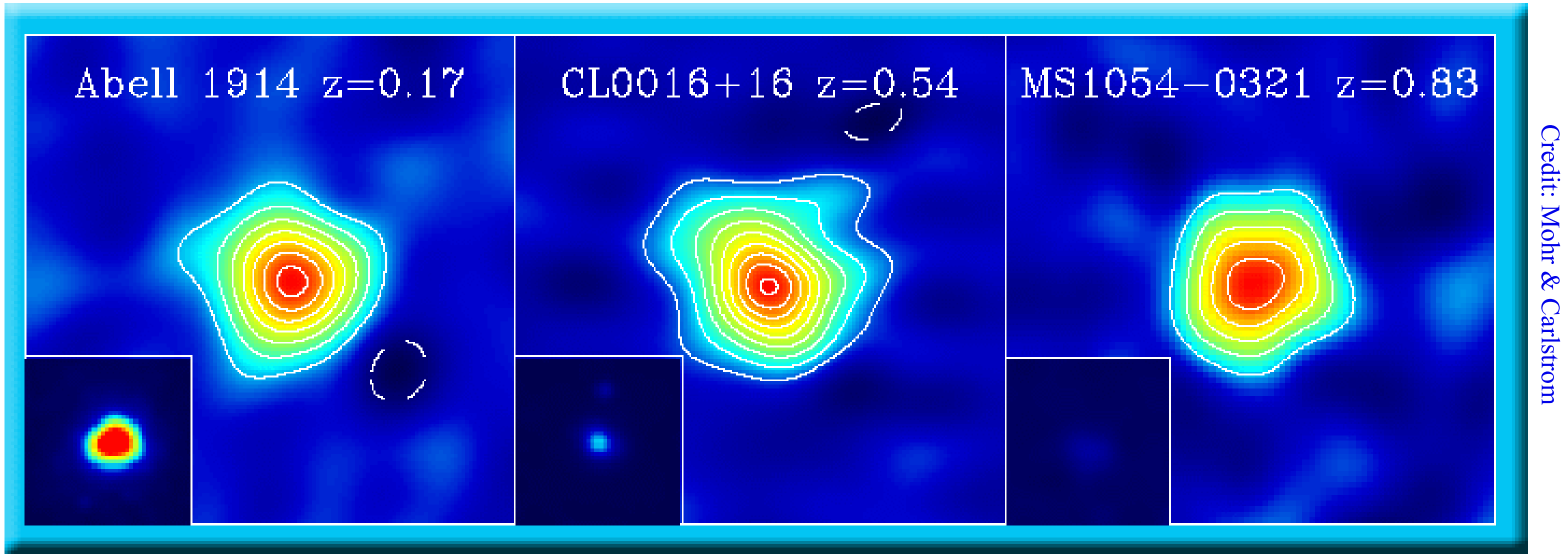
See Molnar, Birkinshaw & Mushotzky astro-ph/0201223 for an optimistic discussion on parameter constraints from SZE+X-ray distances for a sample of ~100 Clusters to z=2

Reese et al. ApJ, astro-ph/0205350

Reese PhD Thesis, (refs in ARAA)

SZE Surveys
Exploit SZE redshift independence

Use SZE as a Probe of Structure Formation
and to provide well defined high-z cluster sample

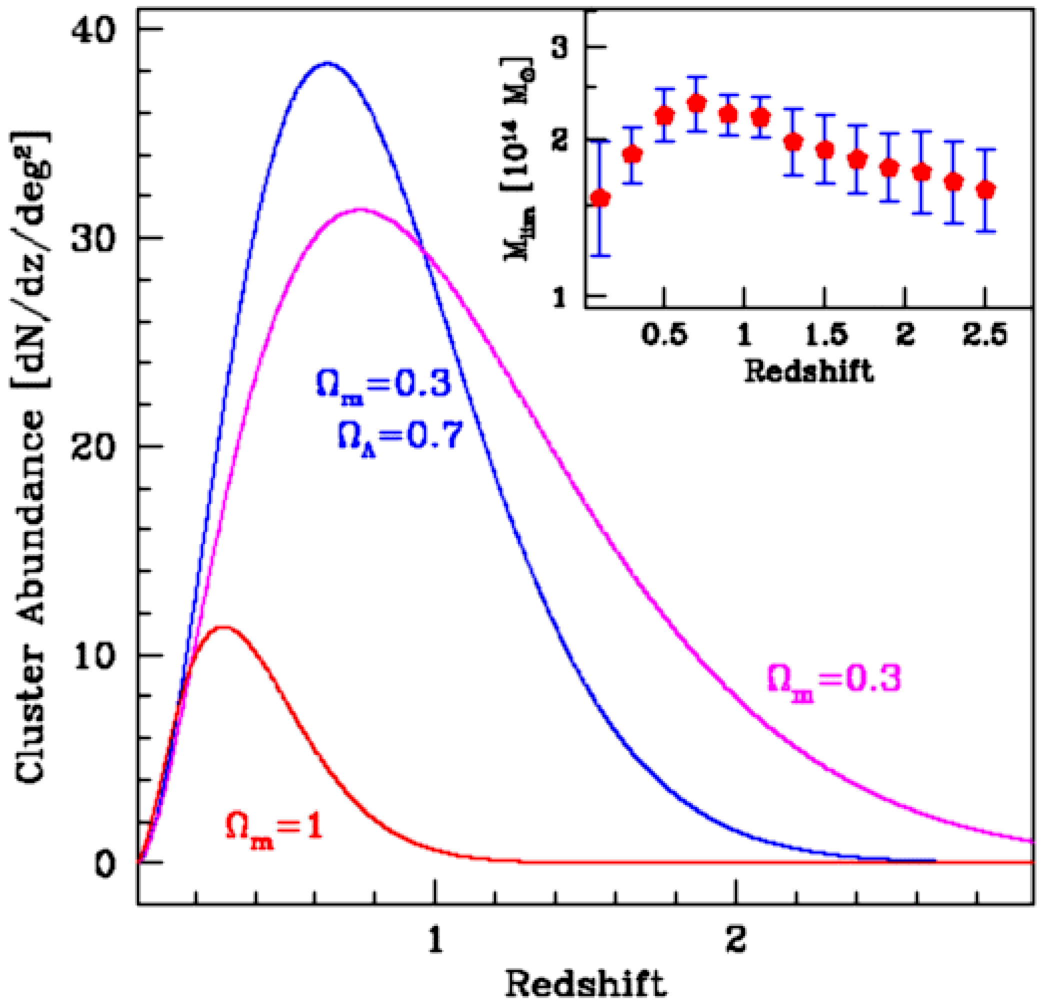


SZE contours every 75μK. Same range of X-ray surface brightness in all three insets.

$$\text{SZE Flux}: \; S \propto \frac{1}{d_A(z)^2}\int n_e T_e \, dV$$

Proportional to total thermal energy

Mass limits and yields for a SZE Survey



- Mass is most important variable
- Yields are highly sensitive to cosmology . . .

Mock SZA-like observations from
Holder et al. 2000, ApJ 544, 629

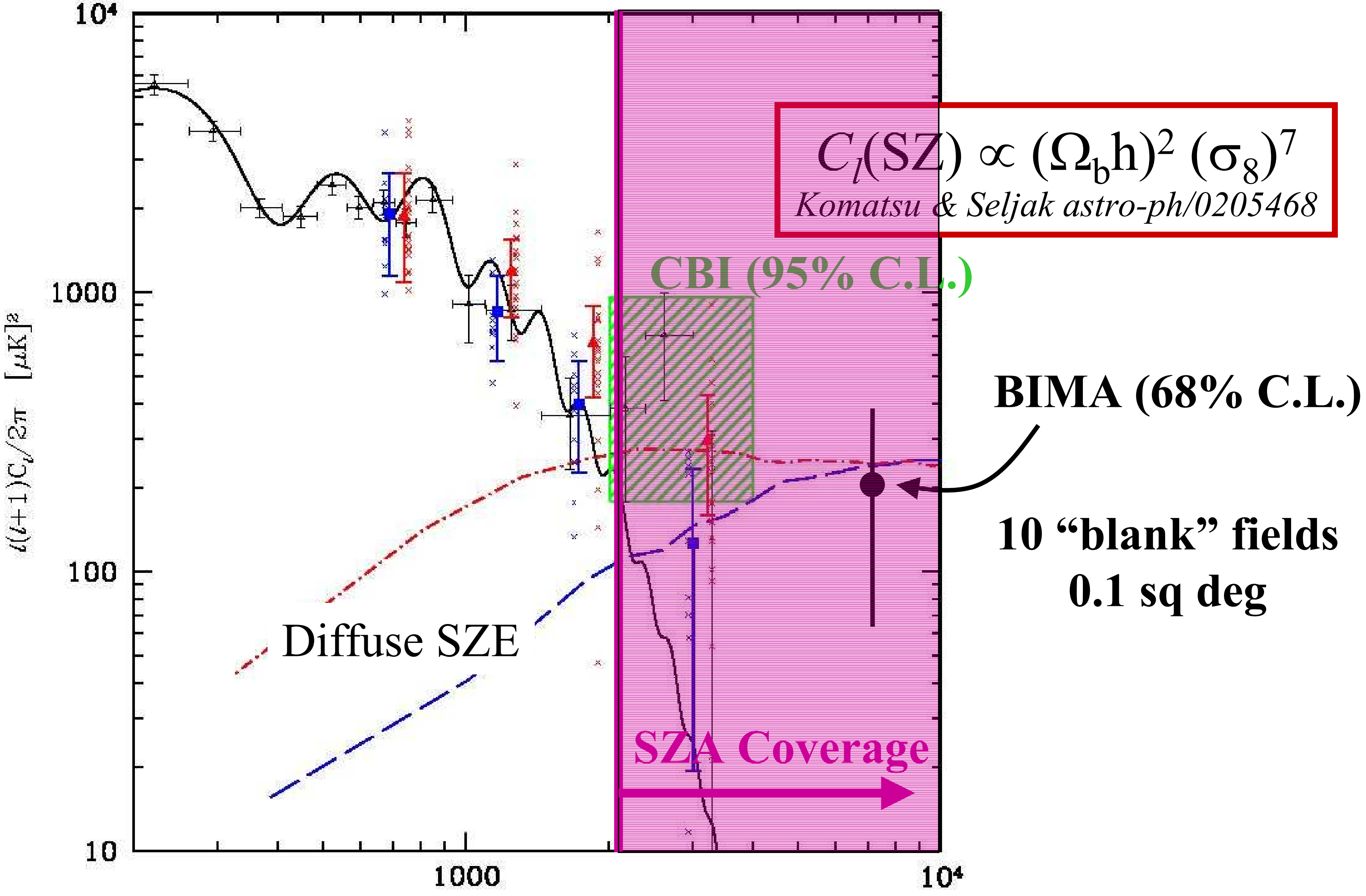
The **SZA:** *eight <u>3.5m</u> telescopes*

(from the OVRO/BIMA SZE program)

- For 1 cm ≤ λ ≤ 1 mm observing:
  - 30 um RMS surface
  - 1 arcsec rms pointing spec
- Allow close pack configuration:
  - 1.2 diameter minimum spacing
- 8 GHz correlation bandwidth
- 26–36 GHz & 85 – 115 GHz
- Stand alone array
  → 12 square degree SZE survey
- Heterogeneous array with CARMA
  → sensitive, high resolution,
  5 – 10” SZE imaging
- **Now WORKING!! First astronomical map with 8 elements and full correlator made 3/1/05**

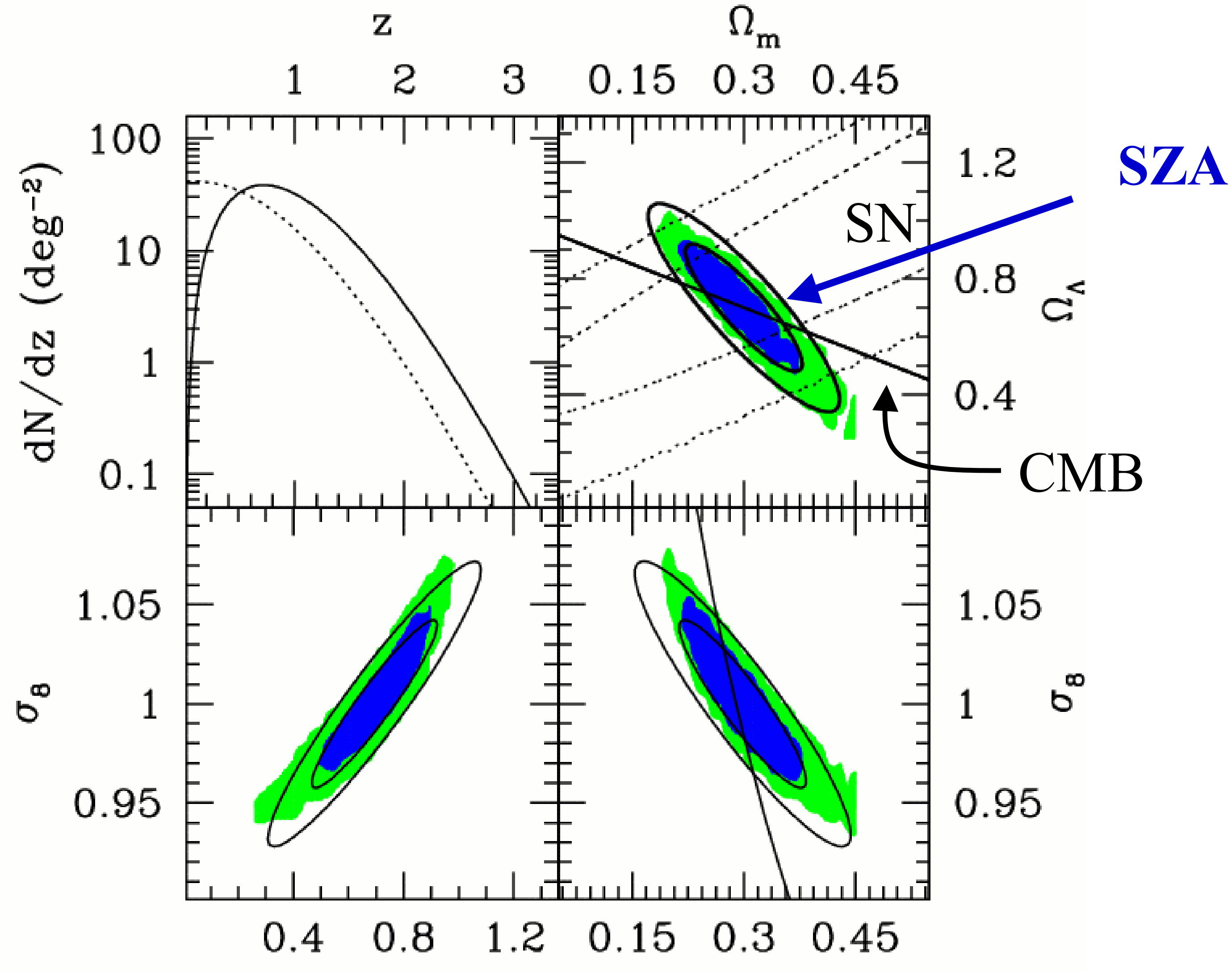
Chicago, Caltech, NASA/MSFC,Columbia
Telescope designed with Vertex/RSI, lead designer: Eric Chauvin, based on initial design by Dave Woody


Sunyaev-Zel'dovich Array
(Eastern Sierra near Bishop CA)



CBI & simulations: Bond et al. 2002, astro-ph/0205386
BIMA: Dawson et al. 2002 astro-ph/020601

Expected Cosmological Constraints from 1 year, 12 sq deg SZA Survey

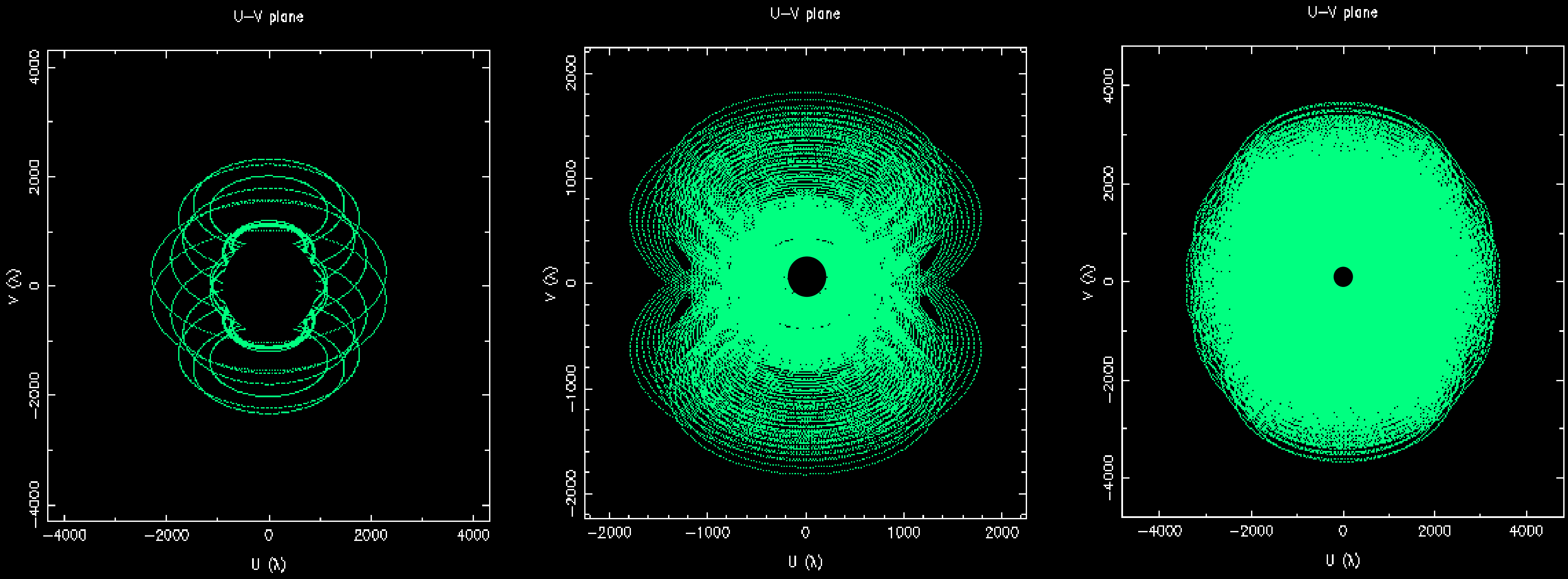


Holder, Haiman & Mohr astro-ph/0105396

Combined Array for Research in Millimeter-Wave Astronomy

CARMA: OVRO+BIMA+SZA

dramatically improved imaging



OVRO SZA CARMA + SZA

→ Will allow detailed SZE imaging at 5” resolution(!)

Useful to address cluster gas properties and evolution

SZE Bolometer Arrays in Progress

Bolocam

- Caltech 144 element array at 2mm for the CSO
  Exists, science runs in progress
- UMASS Bolocam-2 array for the 50-m LMT in Mexico

APEX (12 meter ALMA prototype)

- U.C. Berkeley 300 element array on the Max Planck prototype ALMA 12m telescope at Atacama

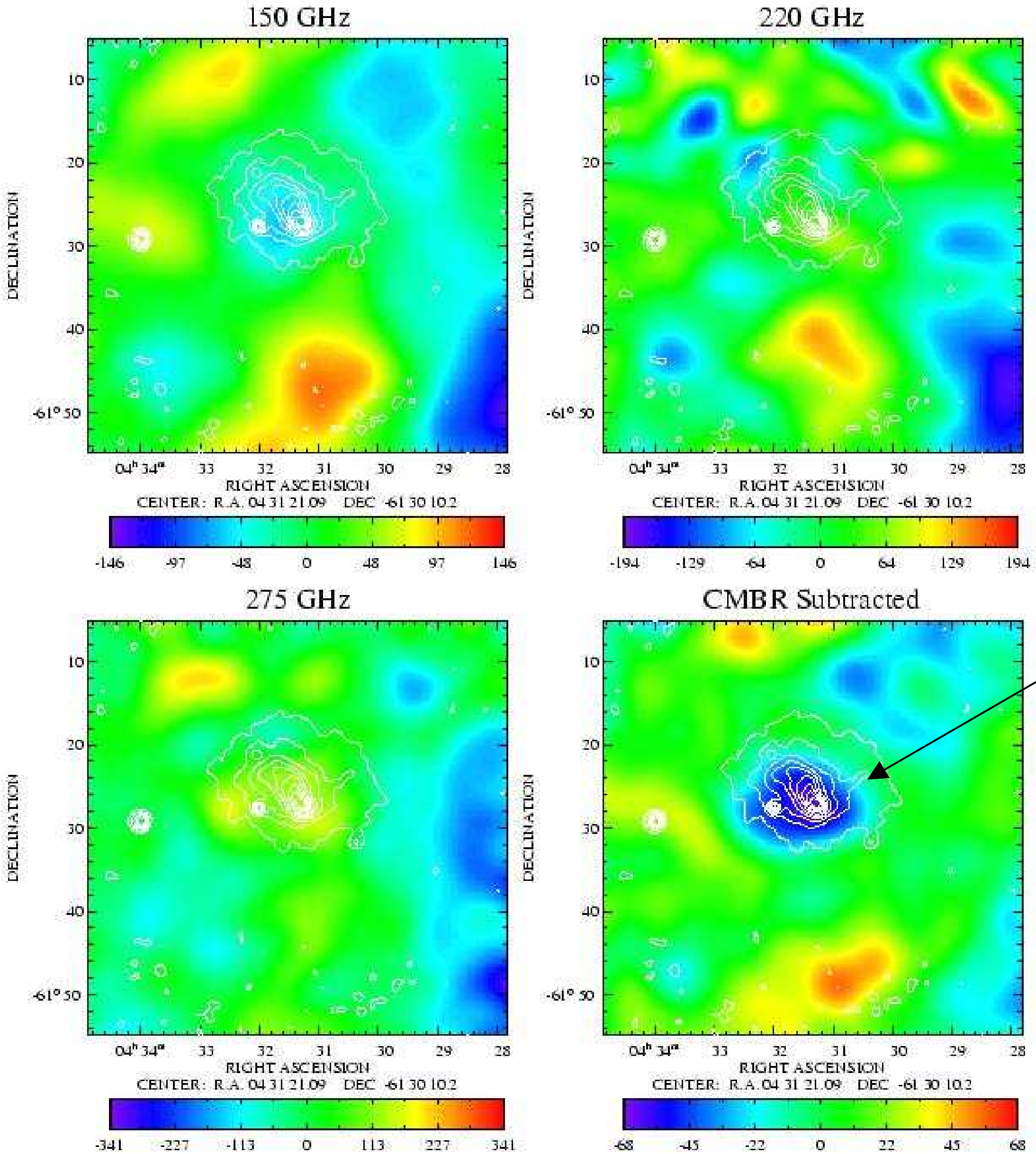
SPT (South Pole Telescope; 8/10 meter)

- with 1000 element array being developed at U.C. Berkeley

ACT (Atacama Cosmology Telescope; 6 meter)

- with 1000 element array being developed at NASA/Goddard

ACBAR SZE Measurements at 5′ resolution
Use SZE spectral signature to remove CMB temperature fluctuations



Abell A3266

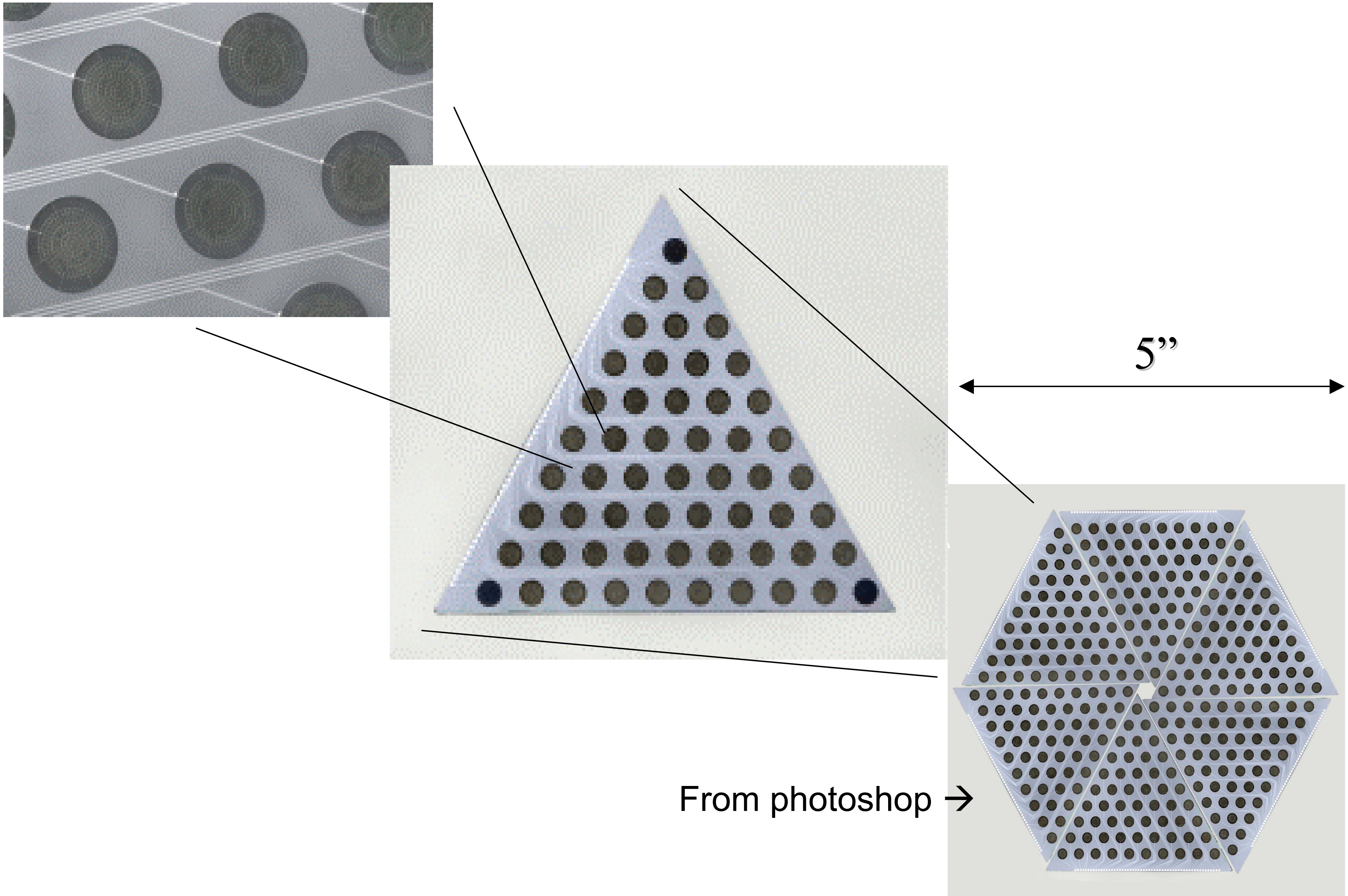
z = 0.059

Gomez et al, astro-ph/0301024

Form a linear combination of maps that minimizes CMB + instrument variance.

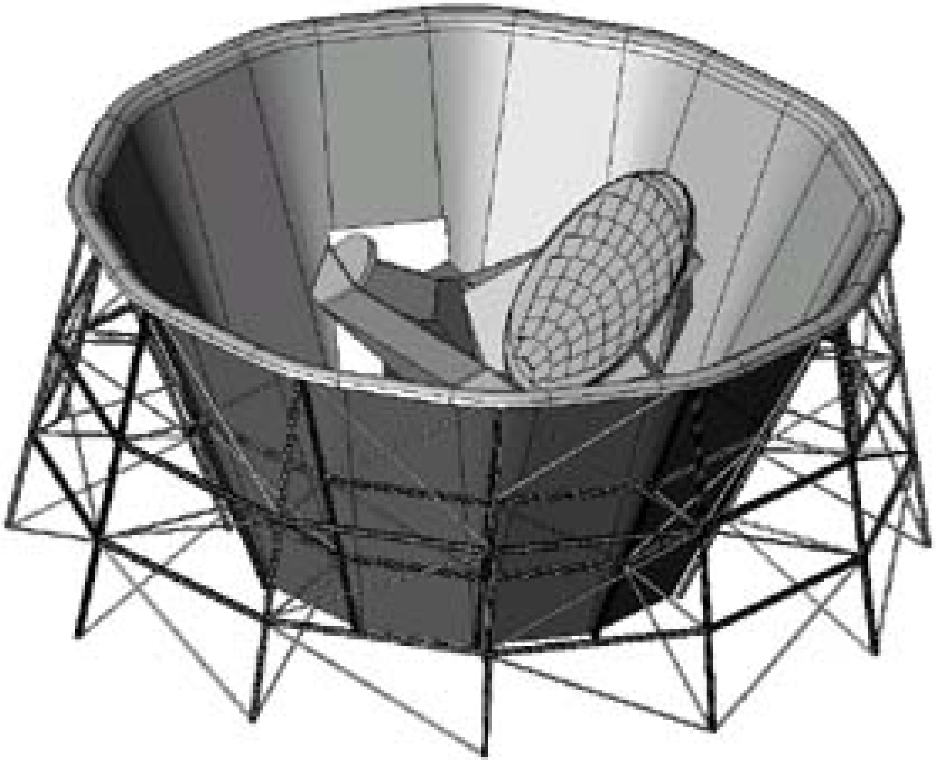
ACBAR 150 GHz SZE Survey
Marcus Runyan PhD thesis
No convincing detections due to high mass limit from 5’ beam

APEX-SZ 330 element Spiderweb TES Bolometer Array



Atacama Cosmology Telescope (ACT)

- 6m off-axis dish with ground screen
- 1000 element bolometric arrays (pop-ups)
- Deploy near ALMA site, Chile
- Fully operational ~2008
- NSF Funded



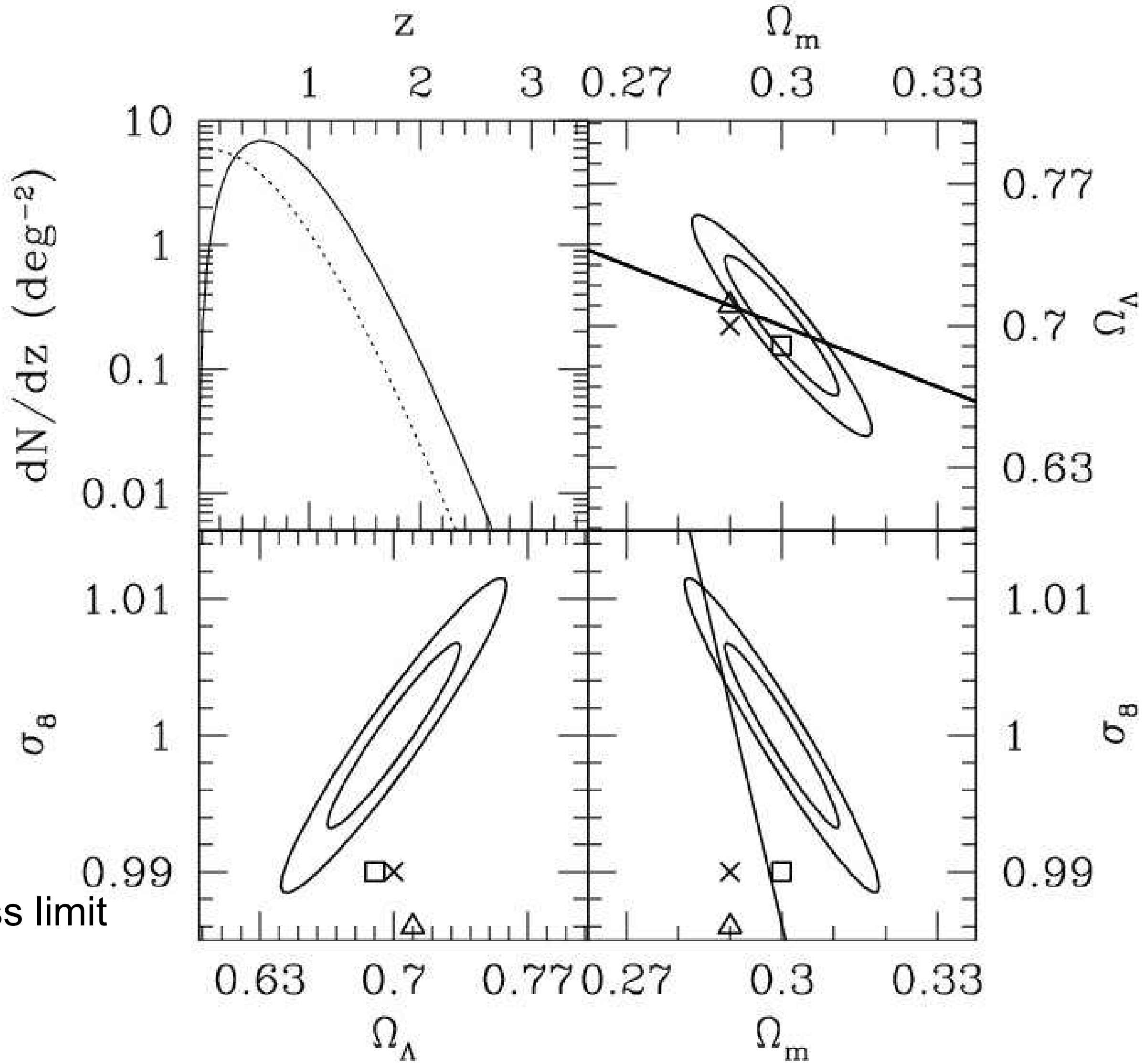
Collaboration:

Cardiff	Columbia	CUNY	Drexel	Haverford	NASA/GSFC
Penn	Princeton	Rutgers	Univ. de Catolica	UMASS	

Cosmology with SPT-SZ

Holder, Haiman & Mohr
2001, astro-ph/0105396

for ~17,000 clusters



Systematics:
□ -Tilt in mass function
Δ -10% reduction in mass fnc
x - 5% reduction of SZE mass limit

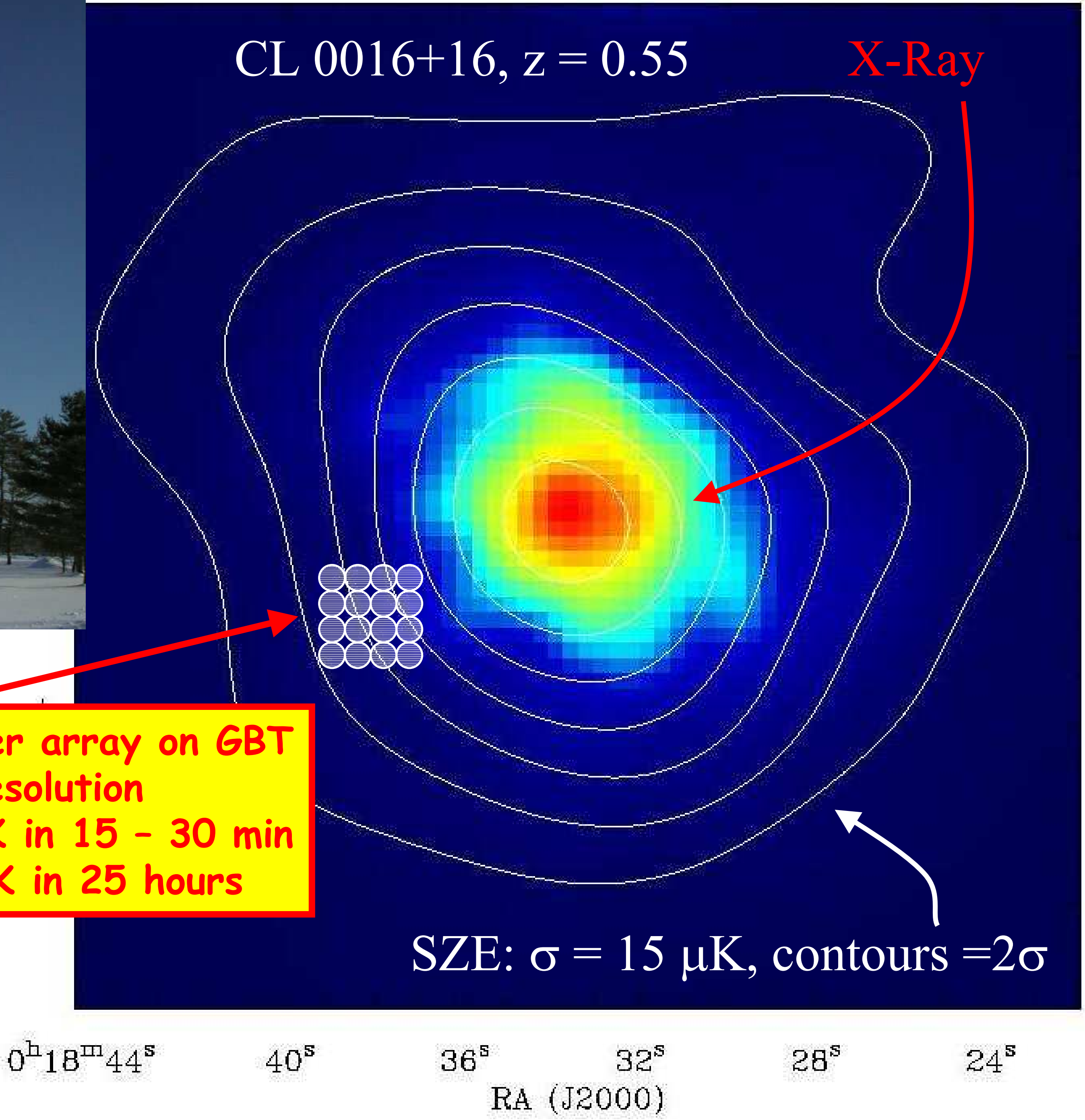
Summary

Observations of the SZE have improved, but cosmology with the SZE is just starting:

- Deep, fairly narrow, SZE surveys will be done in the very near future.
- Detailed, precise, high resolution SZE imaging in a couple years.
- Very large, deep SZE surveys will be done in a few years

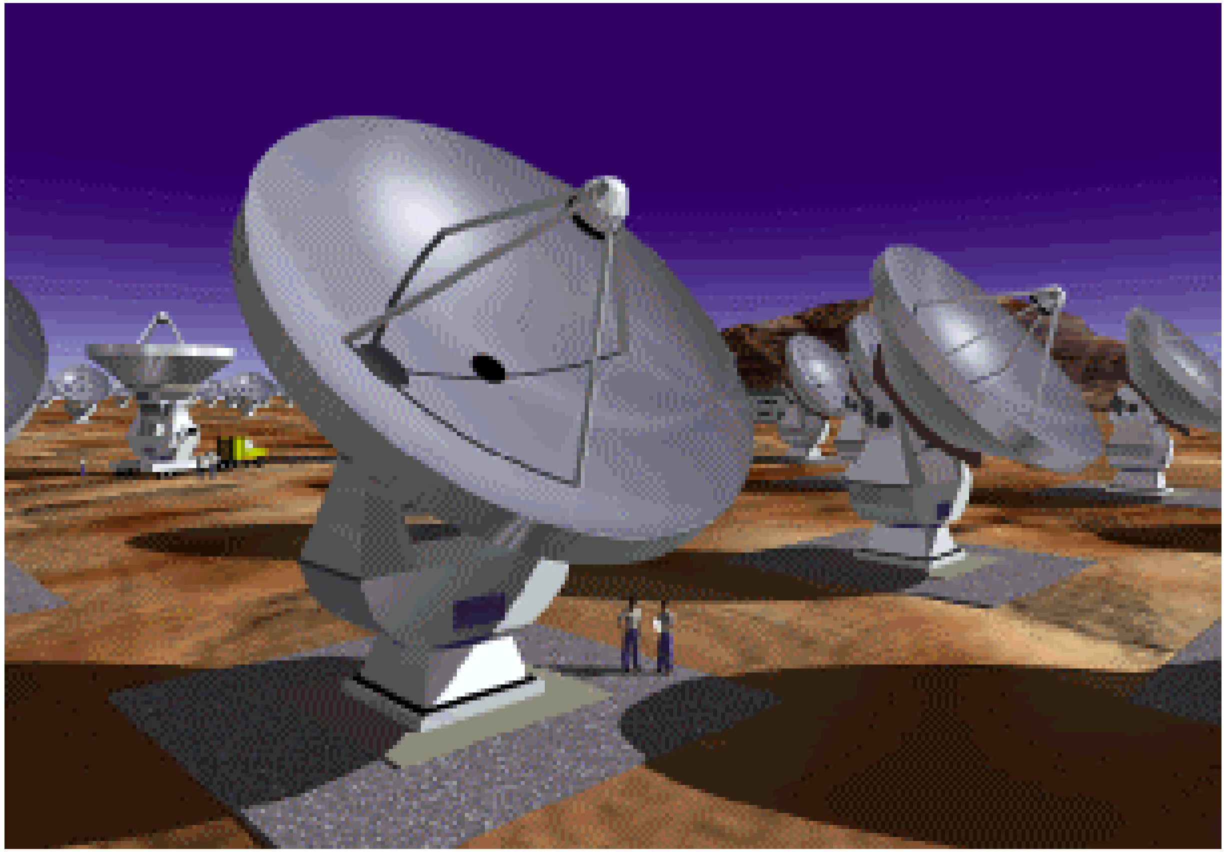
There is a lot of work to do:

- Confronting real clusters
  - Understand going from observables to cluster mass: understanding scatter in mass observable relation, testing self-calibration, detailed SZE imaging, simulations.
  - Develop a better way to comparison observations with predictions from cosmological models?
- Redshifts for large SZE surveys

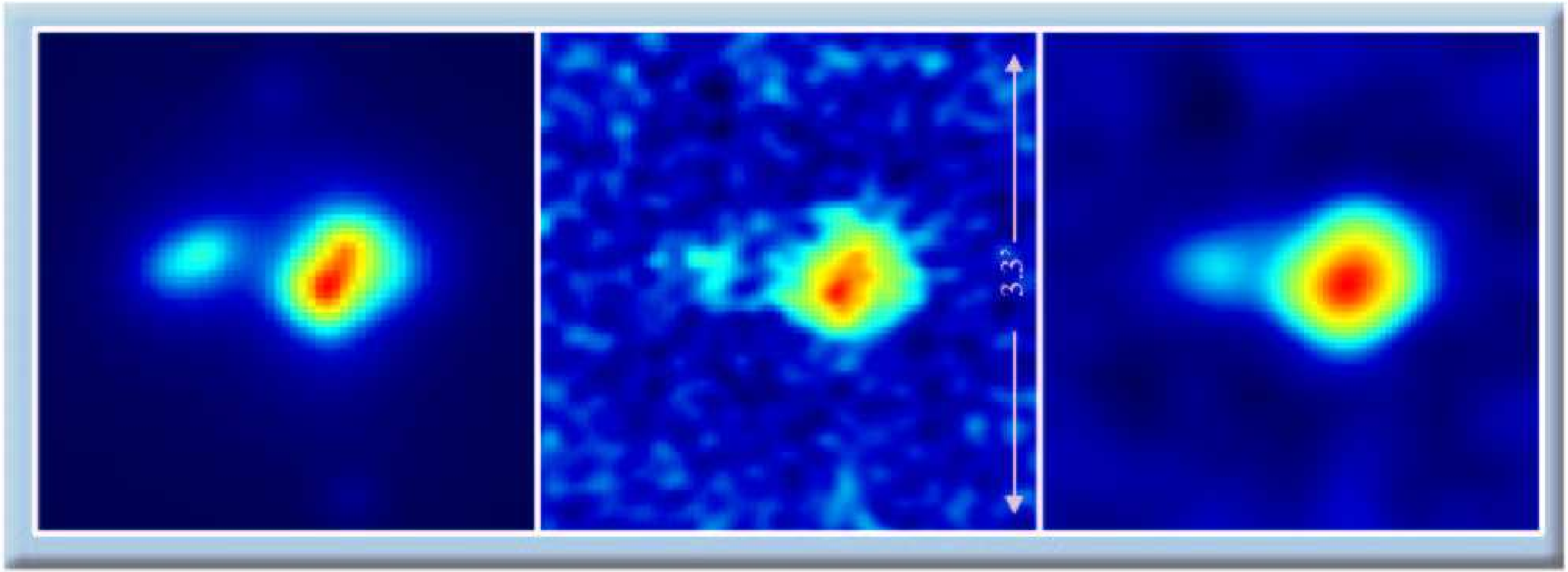


Penn 90 GHz bolometer array on GBT
8" resolution
10 μK in 15 – 30 min
1 μK in 25 hours

ALMA: 64 -12m telescopes, Atacama, Chile



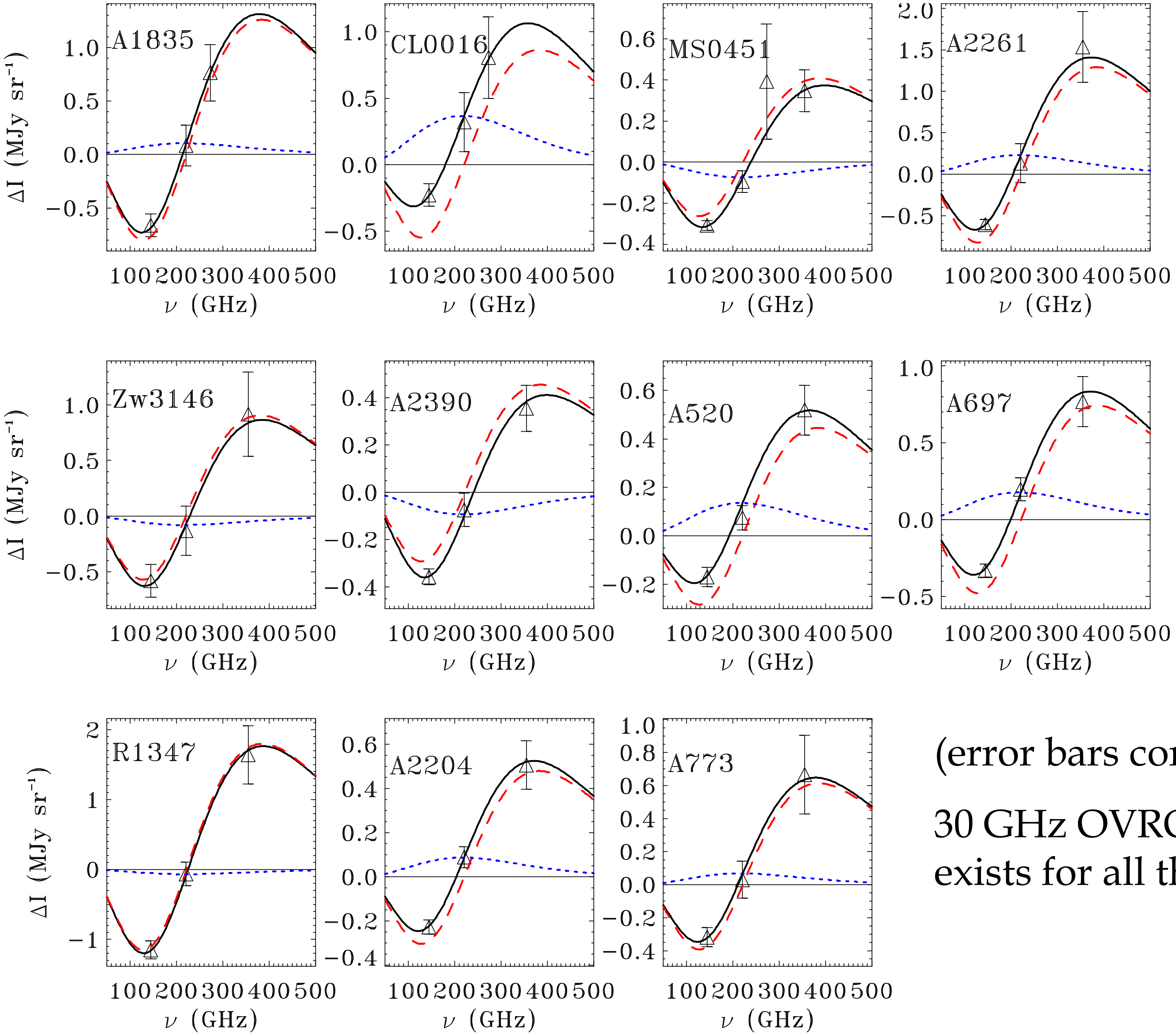
ALMA observations of the Sunyaev-Zel'dovich Effect using 30-43 GHz receivers



• SZE mock observation with ALMA in compact configuration. The simulated cluster (left panel) is $2.5 \times 10^{14}\ M_o$ at $z = 1$ and would be detected at 5σ in the SZA survey. ALMA equipped with 30 – 43 GHz receivers would image this cluster easily with high resolution, 10″ and 14 μK rms, in a couple hours (center panel) and the same data smoothed to 22″ results in 2.7 μK rms (right panel).

• Japan may join ALMA and build a sub array of 12 seven meter telescopes for ALMA making it fantastic for SZE measurements.

SuZIE Spectral Measurements



Between 4 and 20 hours per cluster

Benson, Church et al., Aug 1st 2003, ApJ

thermal

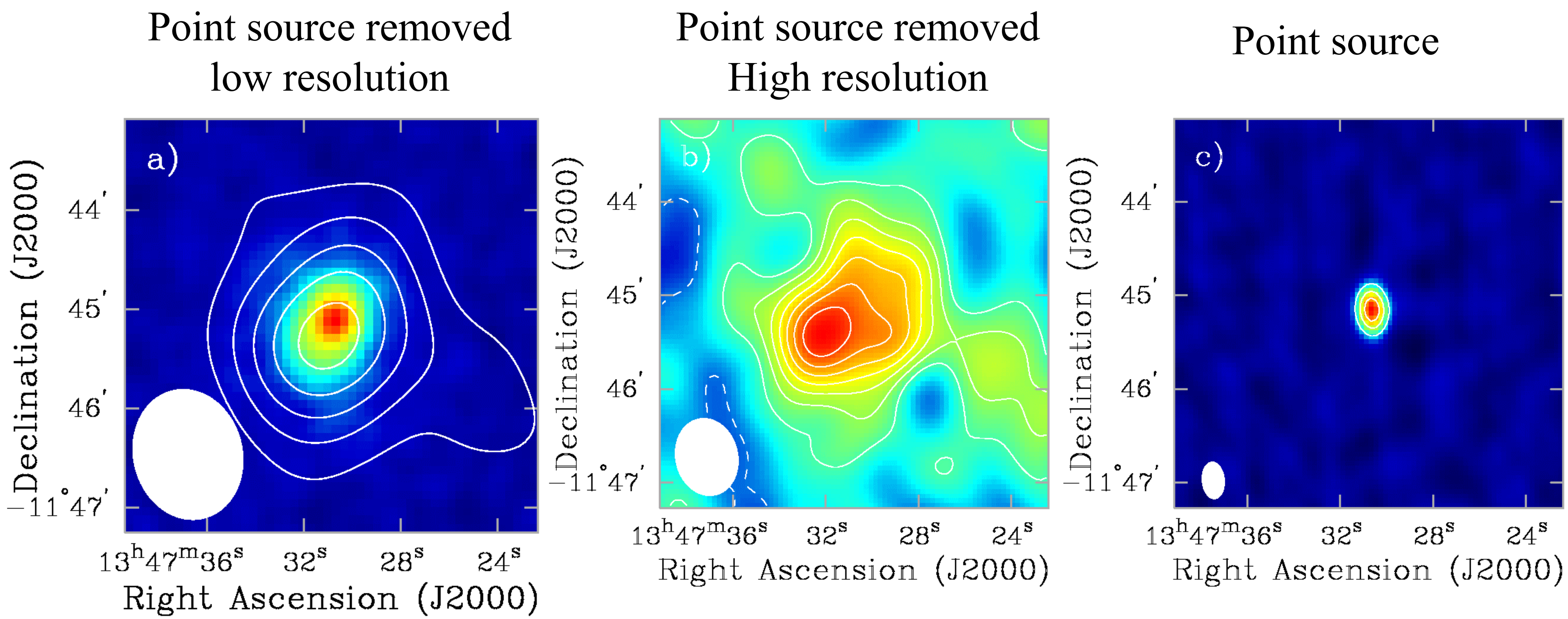
kinematic

total

(error bars correlated at 5-20%)

30 GHz OVRO/BIMA data exists for all these clusters..

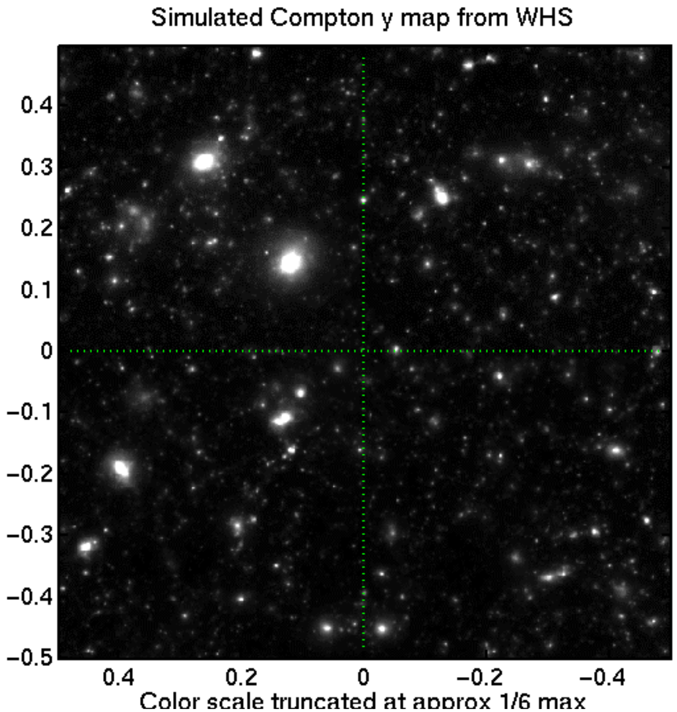
Example of spatial separation of SZE and point source emission

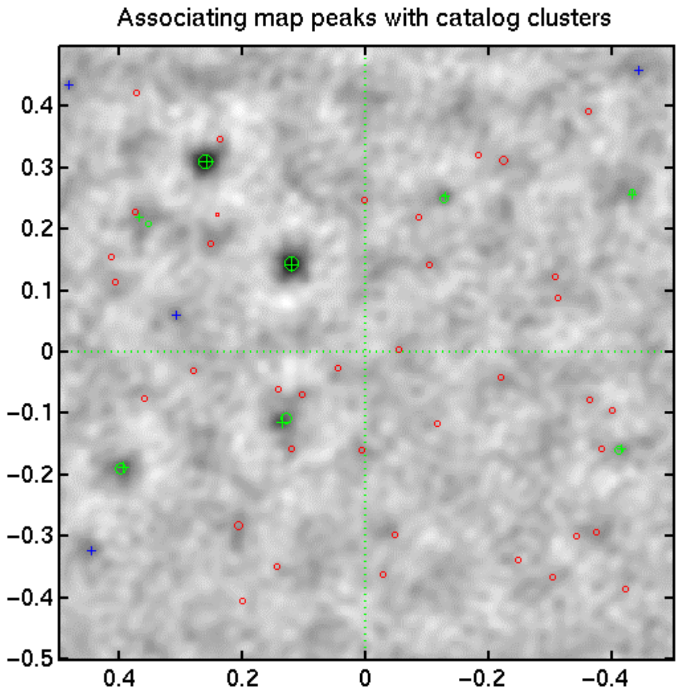


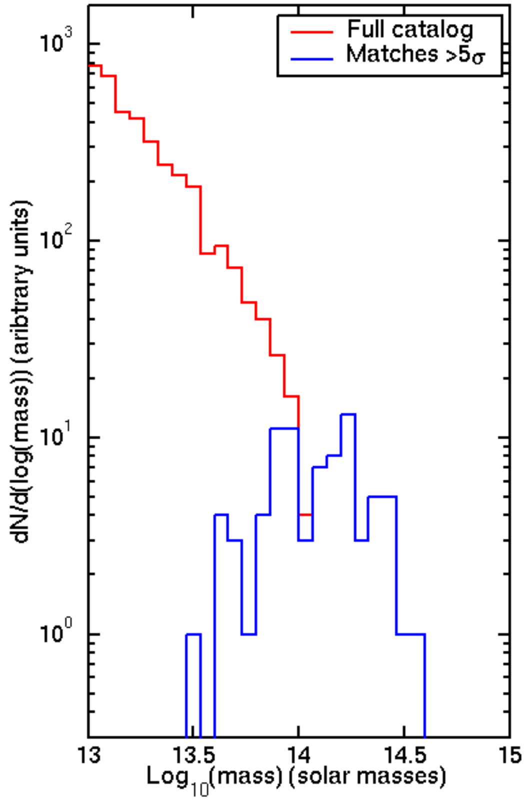
BIMA Observations of RX J1347-1145

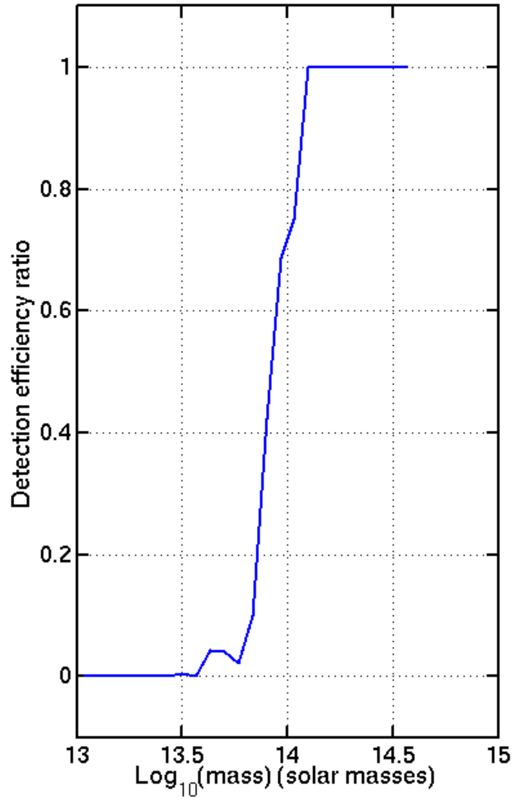
Testing mass limit with mock SZA surveys

(by Clem Pryke)



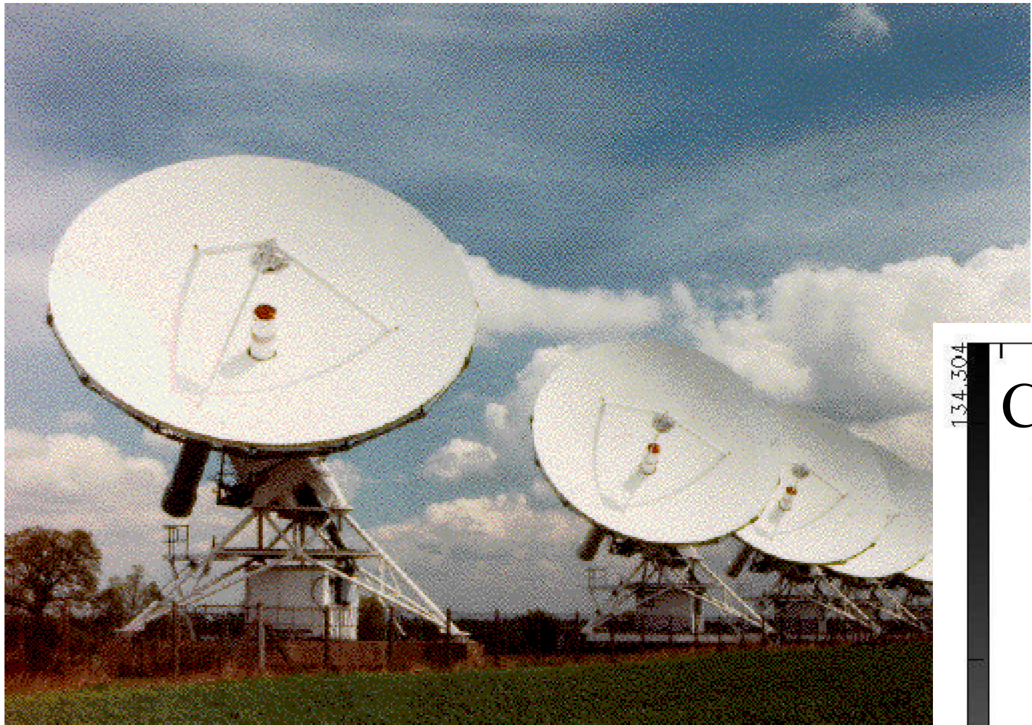




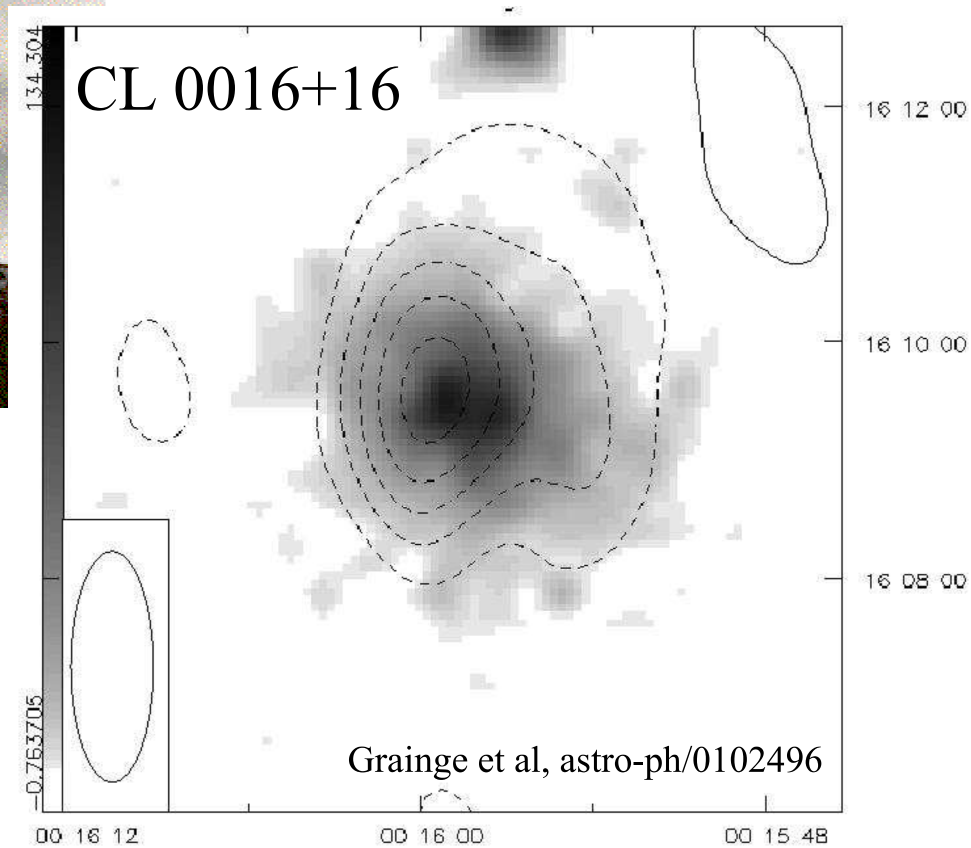


Ryle Telescope, MRAO

Made first interferometric SZE image in 1993, Abell 2218



- 8 13m telescopes
- 15 GHz
- E-W configurations



Grainge et al, astro-ph/0102496

AMI Instrument Specs

- Arcminute Microkelvin Imager
- MRAO/Cavendish/Cambridge group
- 10 x 3.7m at 15 GHz
- NRAO HEMT receivers, ~13K noise, ~25K system noise
- 6 GHz analog correlator
- FOV_{FWHM} ~ 21', $Beam_{FWHM}$ ~ 4.5'
- concurrent point source monitoring by Ryle Telescope (8 x 13m), *no heterogeneous correlation*
- *Almost online, should find ~100 clusters*