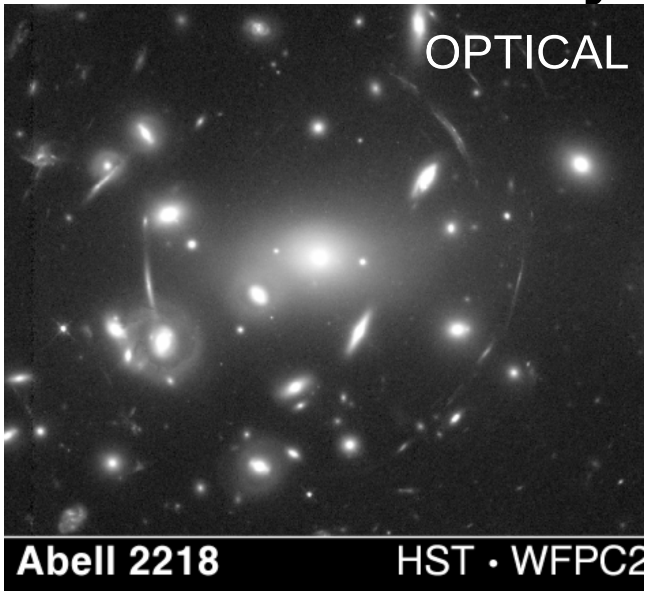
Cosmology with the Sunyaev-Zel’dovich Effect

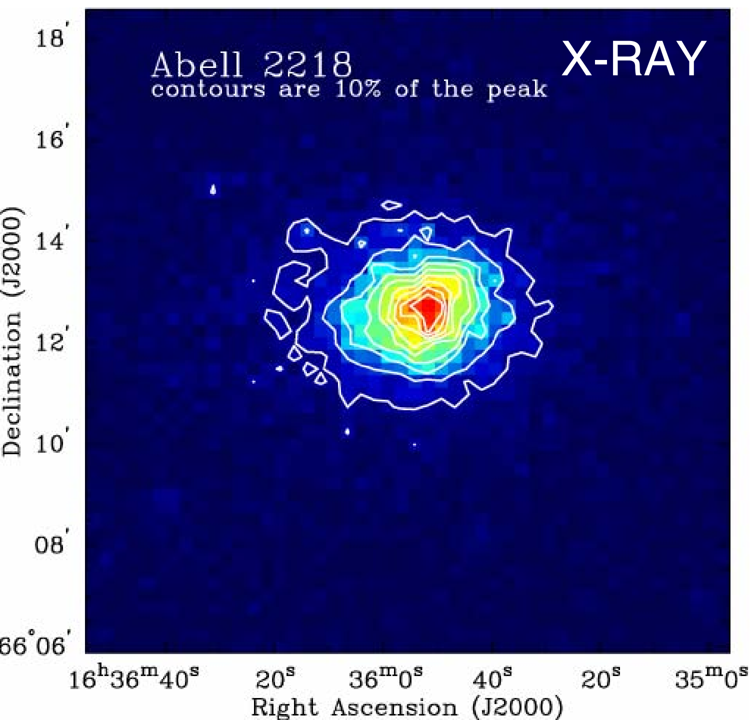
Status and Future Plans

John Carlstrom
Kavli Institute for Cosmological Physics
University of Chicago

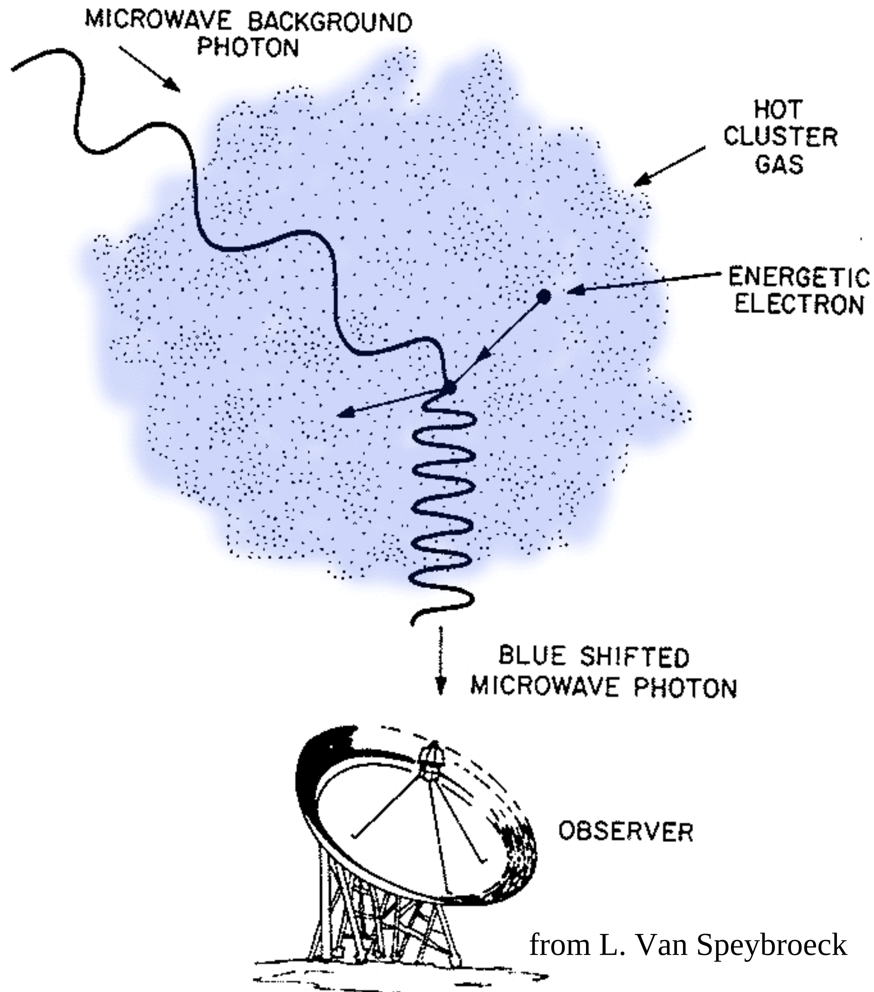
For a review see: Carlstrom, Holder & Reese, 2002, ARAA, 40, 643

The Sunyaev-Zel'dovich Effect

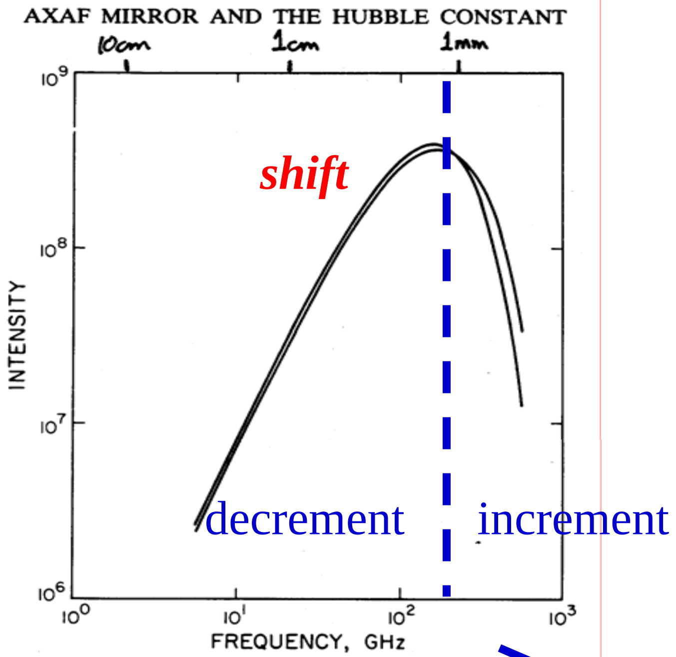




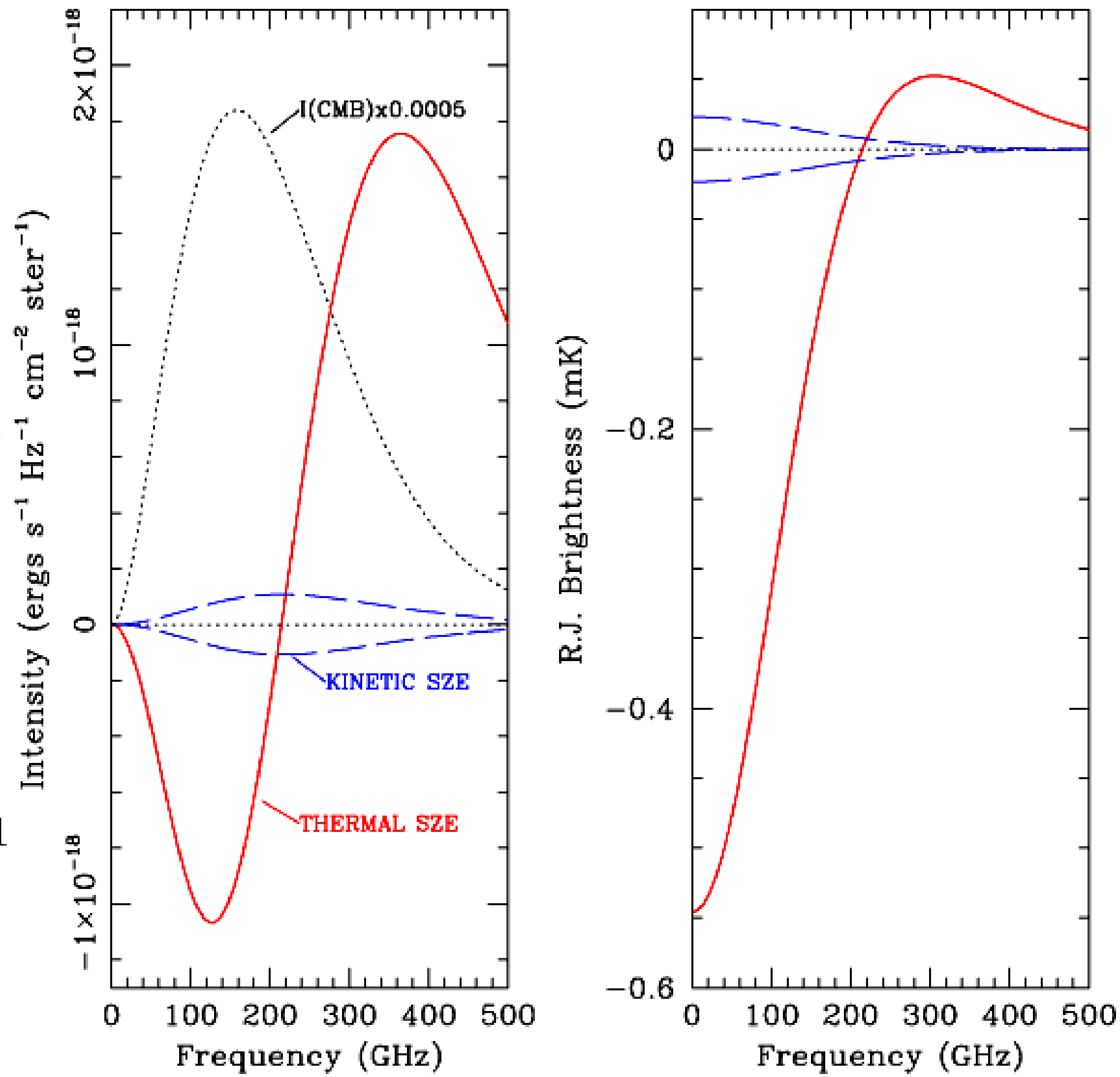
Clusters and the CMB



from L. Van Speybroeck



Sunyaev-Zel'dovich Effect
Spectral Distortion of CMB



Massive cluster:

$y = 1.0 \times 10^{-4}$

$T_e = 10$ keV

$V_{peculiar} = +/-500$ km s^{-1}

Sunyaev-Zel'dovich Effect

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

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)…

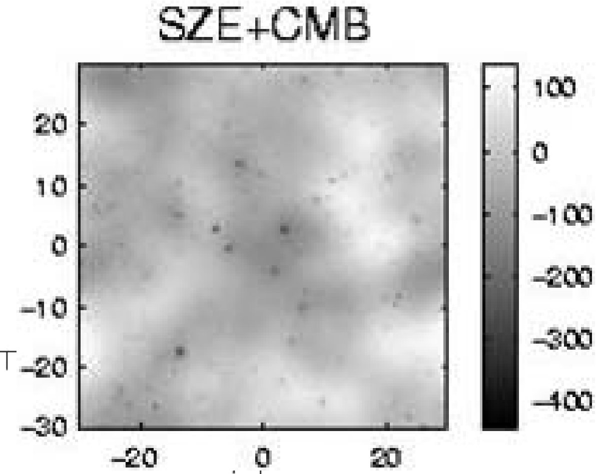
$$S \propto \int \Delta T_{SZE}\, d\Omega$$

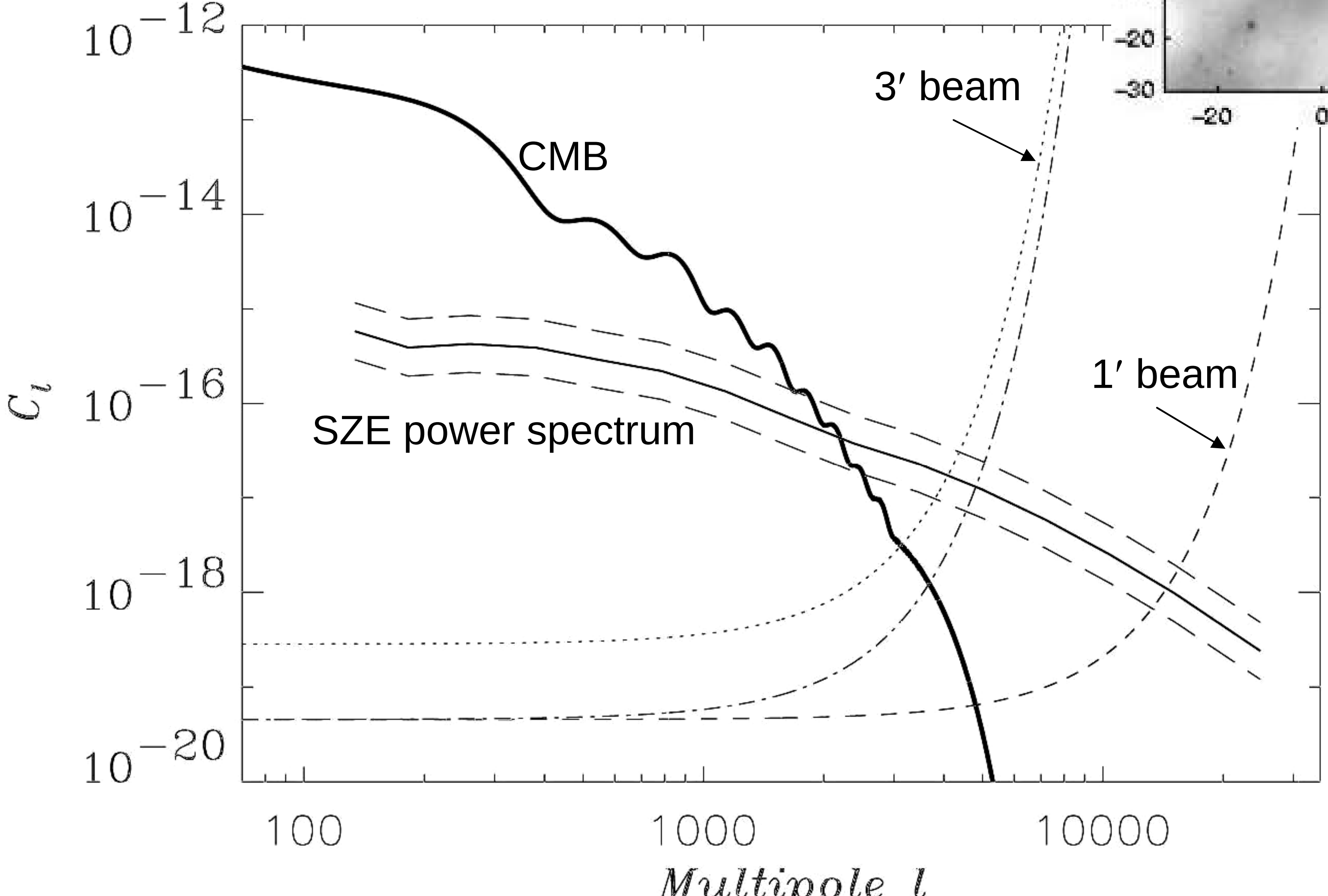
$$\propto \frac{1}{D_A(z)^2} \int n_e T_e dV$$

Experimental Challenge

- Small signal, large angular size
  - Need to make differential measurements
  - Synchronous offsets
    - → like intrinsic CMB anisotropy experiments
- Contamination (separate by angular filter and/or spectrum)
  - Point sources in radio – AGN synchrotron emission (variable and correlated with clusters)
  - Point sources in mm/submm – Dusty galaxies
  - 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.

Primordial CMB contaminates SZE





from Shulz & White astro-ph/0210667

SZE instruments

Existing/past SZE instruments:

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

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

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 2.5m

Upcoming:

Bolocam 144 element bolometer on CSO 10m (working now)

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

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

Penn 8x8 bolometer array on the NRAO GBT 100 m (10” res!)

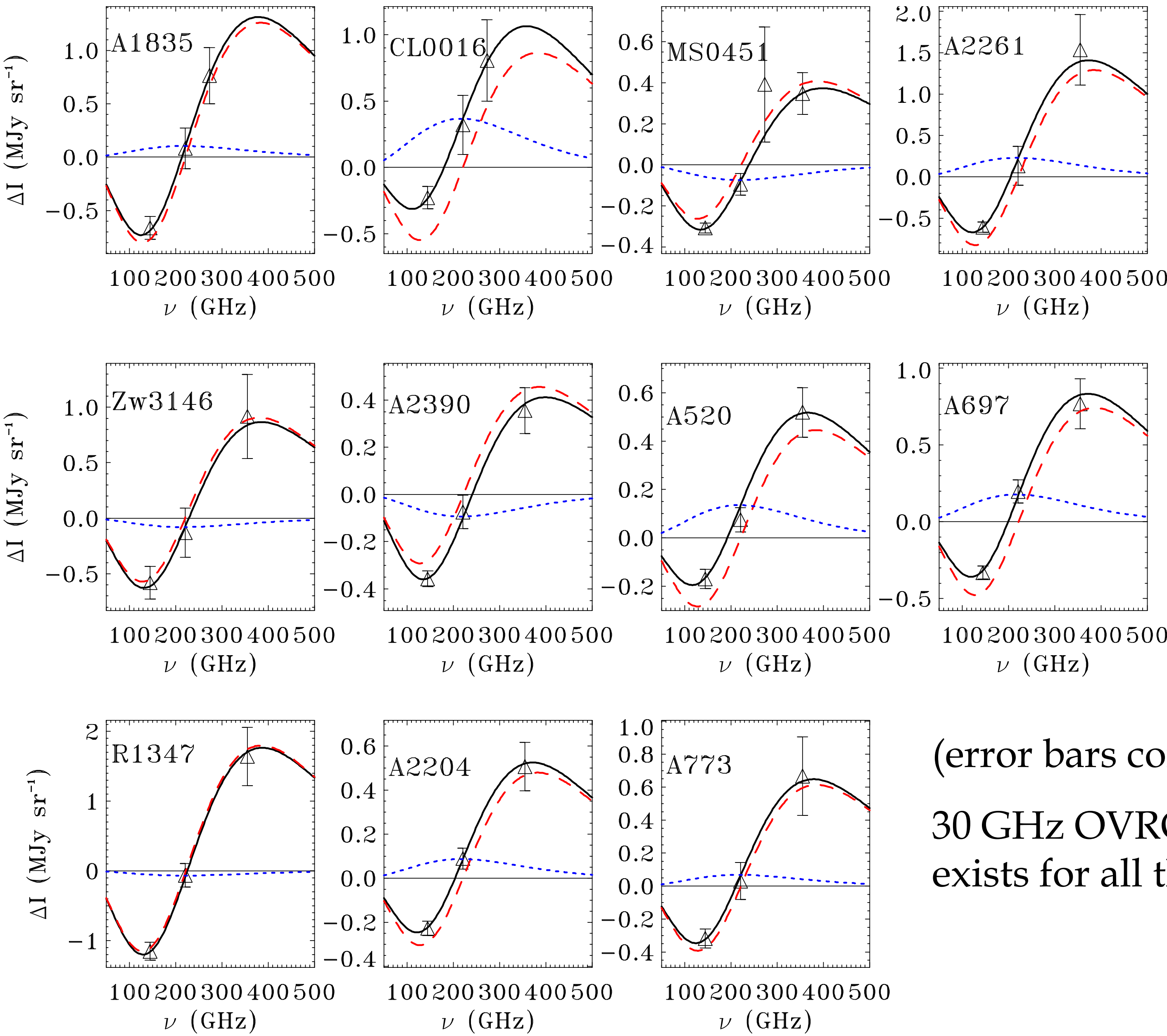
APEX-SZ 330 element bolometric array on APEX 12m in Chile

Next generation *SZE telescopes* and receivers:

Interferometers: SZA, AMI

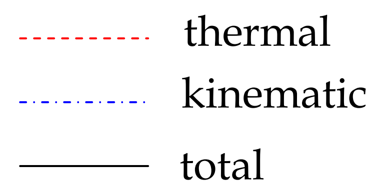
Single Dish Bolometric: South Pole Telescope (10m),
Atacama Cosmology Telescope (6m)
‘Planck Surveyor Satellite’

SuZIE Spectral Measurements



Between 4 and 20 hours per cluster

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

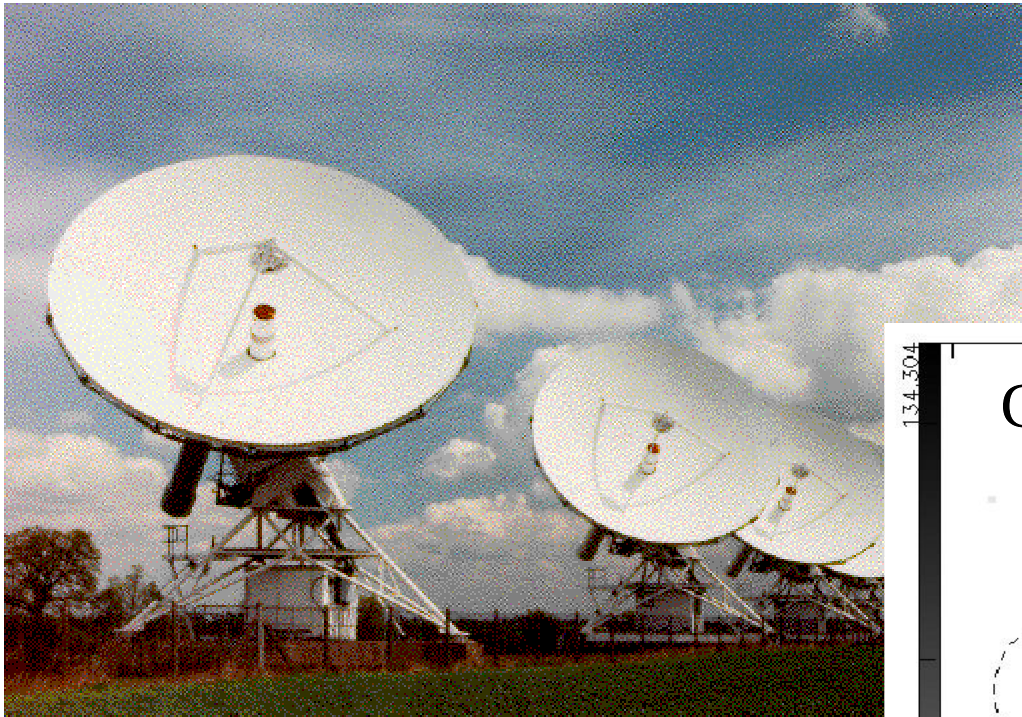


(error bars correlated at 5-20%)

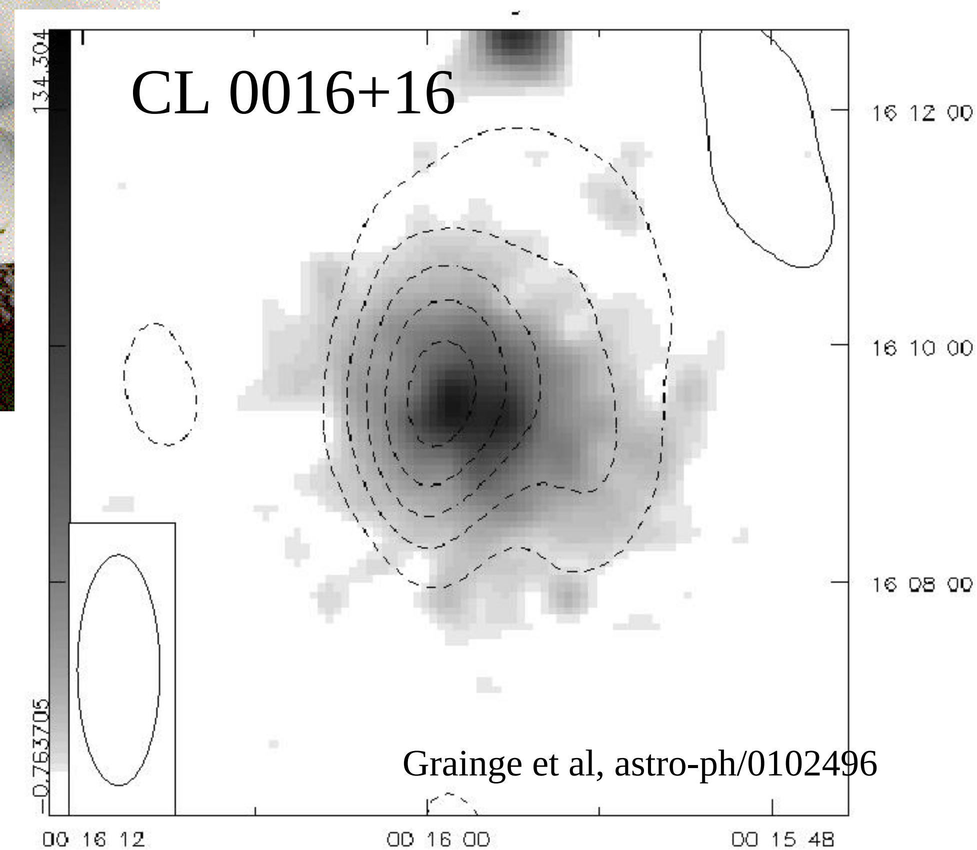
30 GHz OVRO/BIMA data exists for all these clusters..

Ryle Telescope, MRAO

Made first interferometric SZE image in 1993, Abell 2218



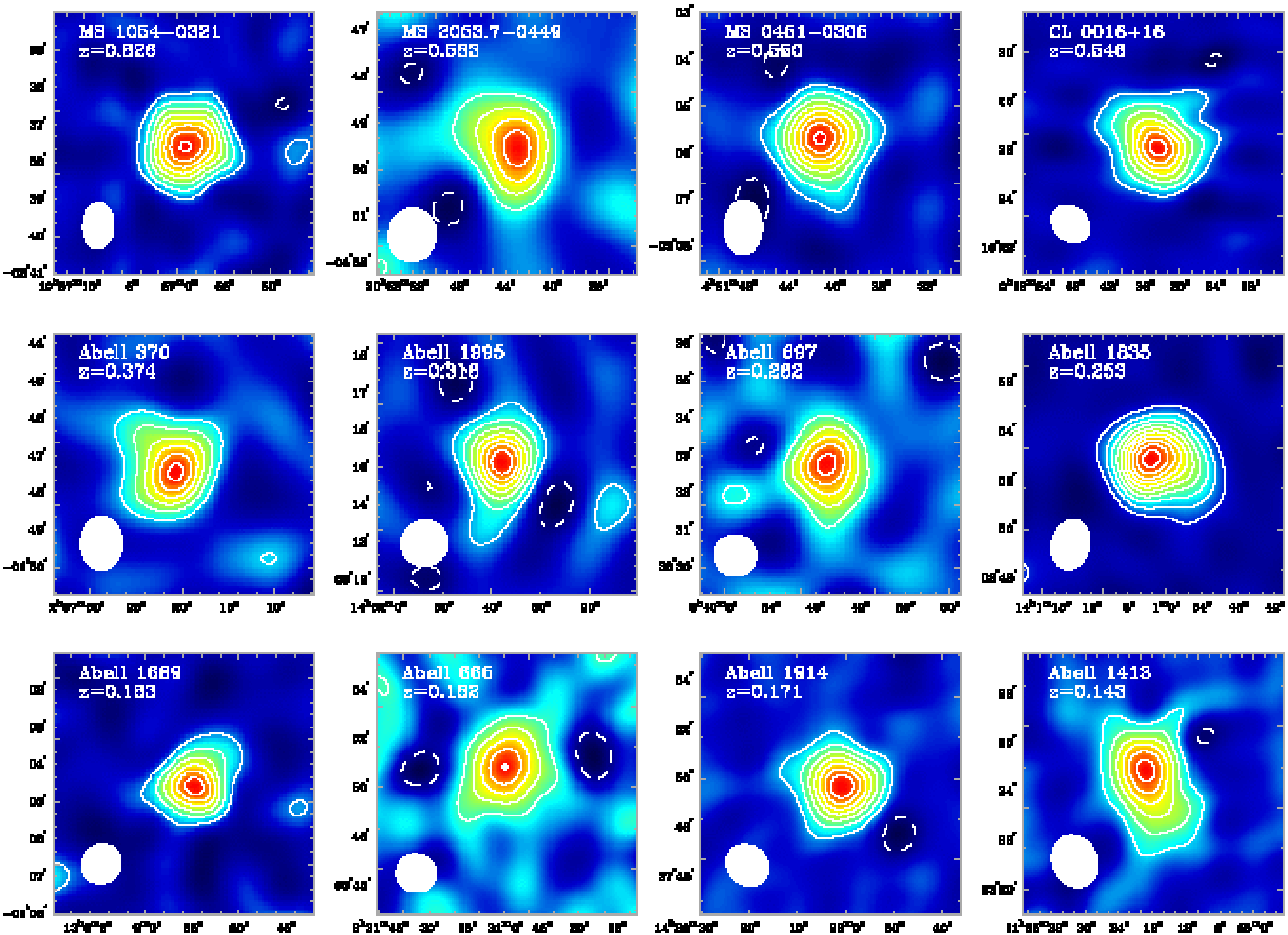
- 8 13m telescopes
- 15 GHz
- E-W configurations



Grainge et al, astro-ph/0102496

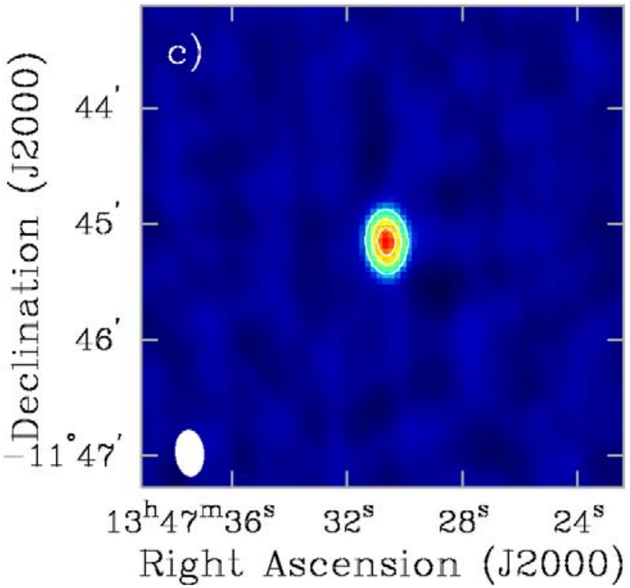
OVRO / BIMA SZE imaging

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

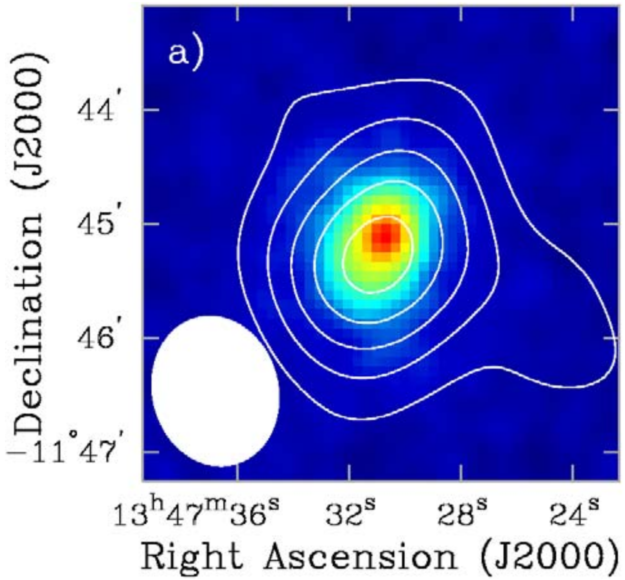


Example of spatial separation of SZE and point source emission

Point source imaged with long baselines



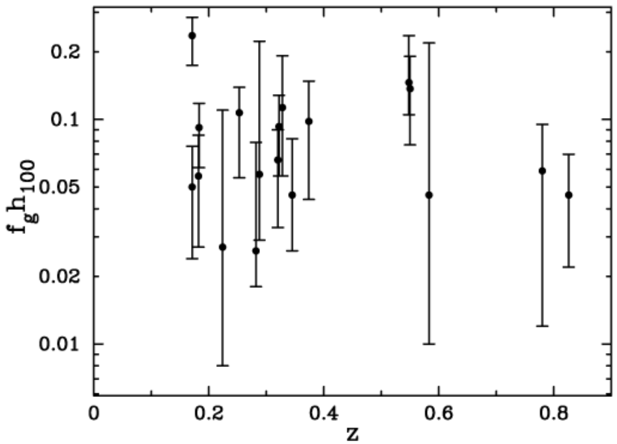
SZE imaged with corrected short baselines



BIMA Observations of RX J1347-1145

Ω_{Matter} from SZE derived gas mass ratios

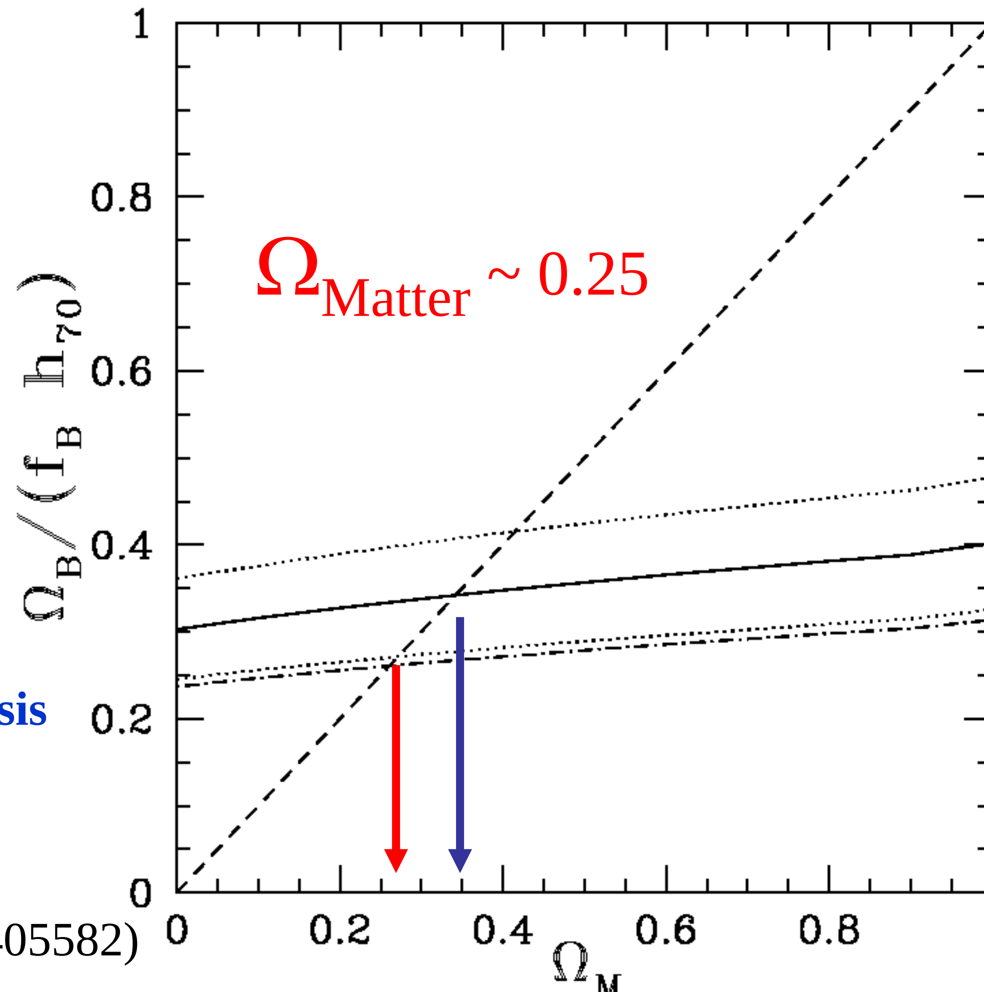
- Total mass from SZE imaging and assumption of hydrostatic equilibrium.
  (No x-ray imaging data)
- Results agree with X-ray, M/Light, LSS



SZE Gas mass fractions

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

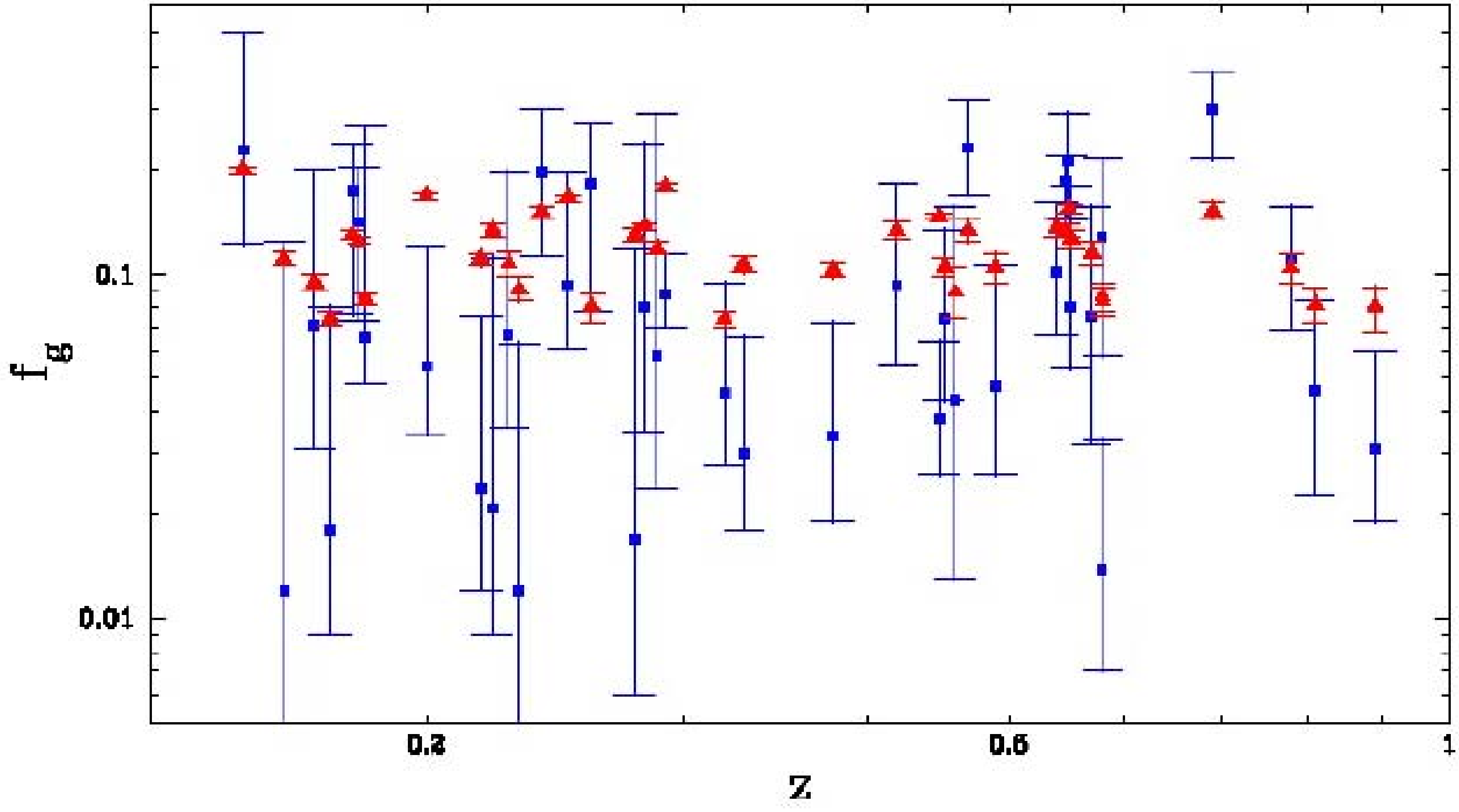
From sample of 18 BIMA clusters
Grego et al, 2001, ApJ 552,2
astro-ph/0012067 & Grego Ph.D. thesis



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

Work in progress - Sam LaRoque Ph.D. thesis

Chandra X-ray (Red) & **OVRO/BIMA SZE (Blue)**



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

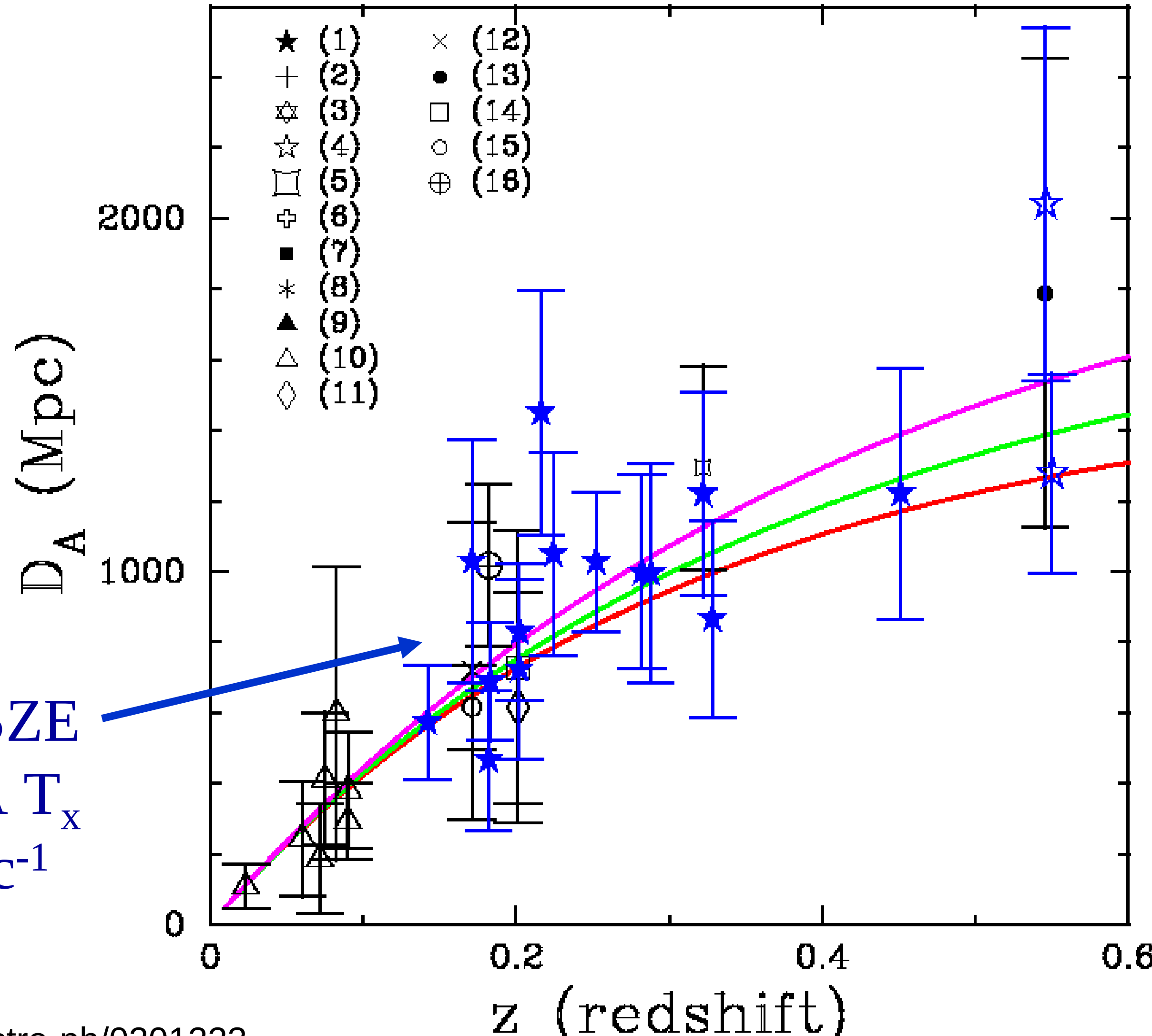
$L \propto (\Delta T_{SZ})^2 / I_x T_e^2$

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}



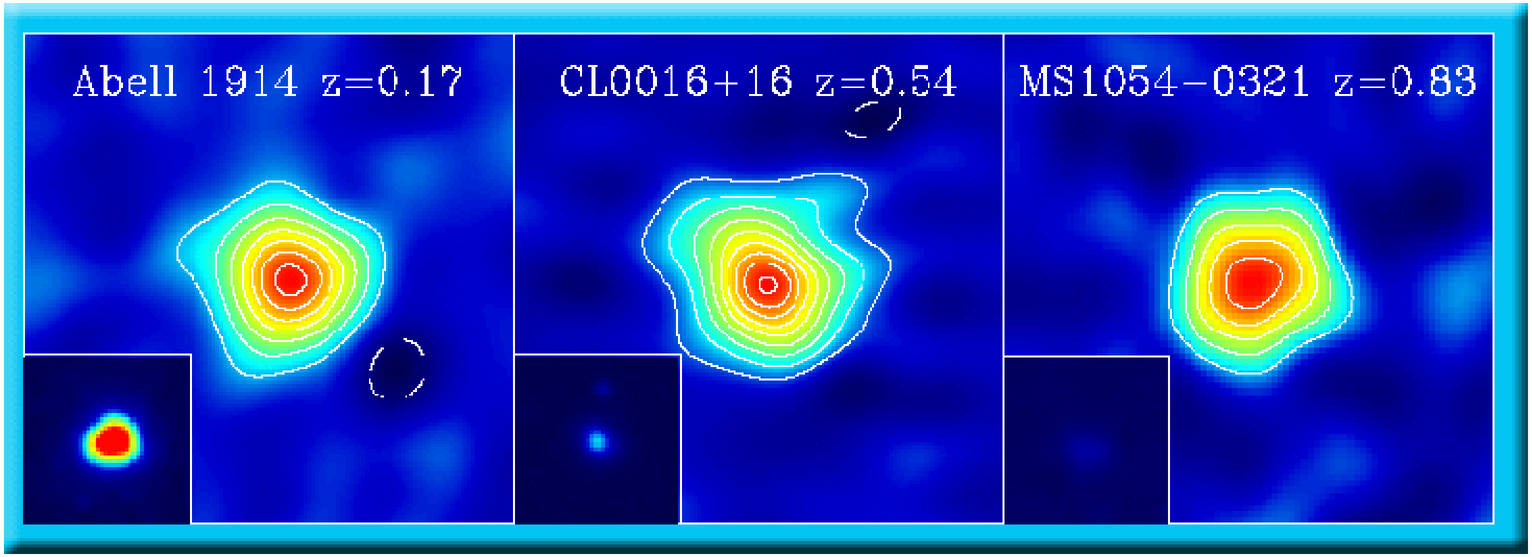
See Molnar, Birkinshaw & Mushotzky astro-ph/0201223 for an optimistic discussion on parameter constraints from SZE+X-ray distances for a sample of ~100 Clusters to z=2

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



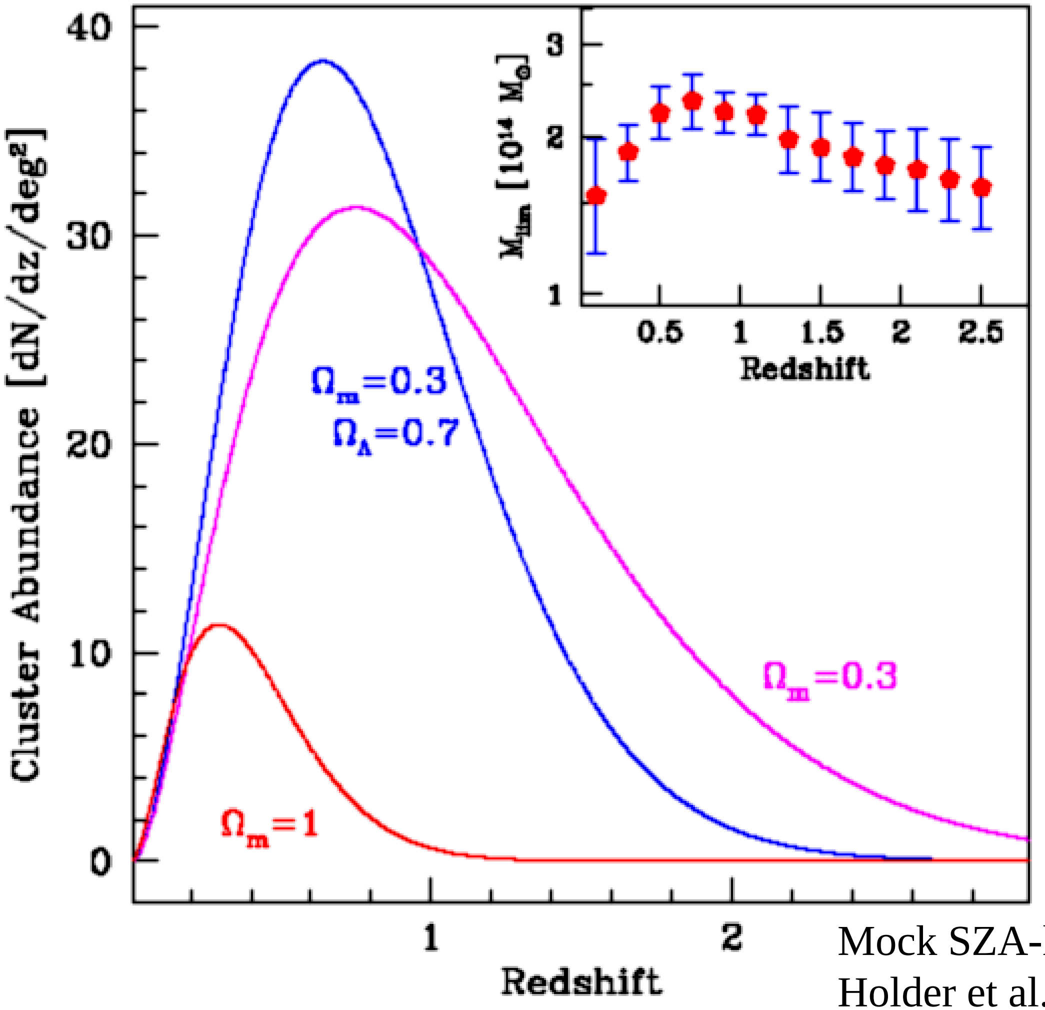
Credit: Mohr & Carlstrom

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

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

Simply proportional to the total thermal energy

Mass limits and yields for a SZE Survey

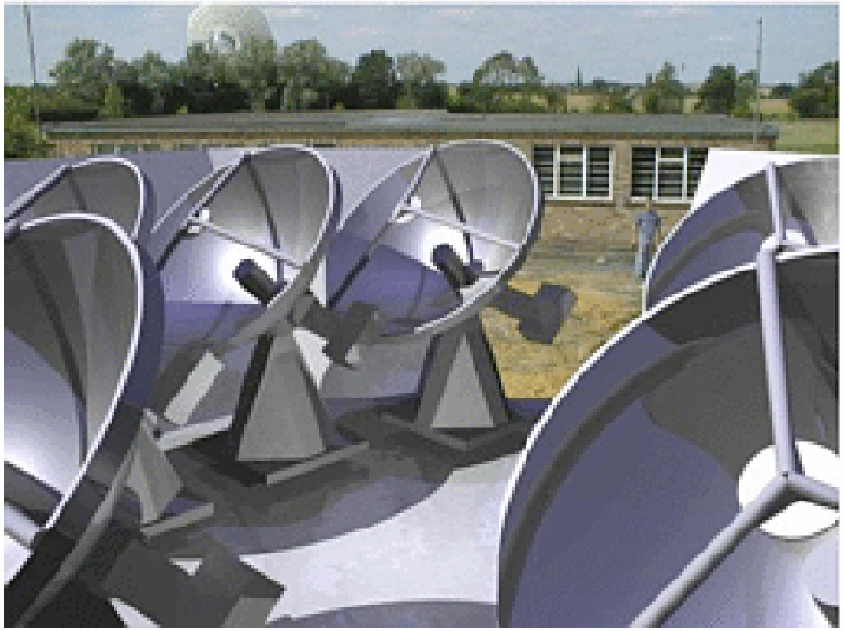


Mock SZA-like observations from Holder et al. 2000, ApJ 544, 629

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

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*

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

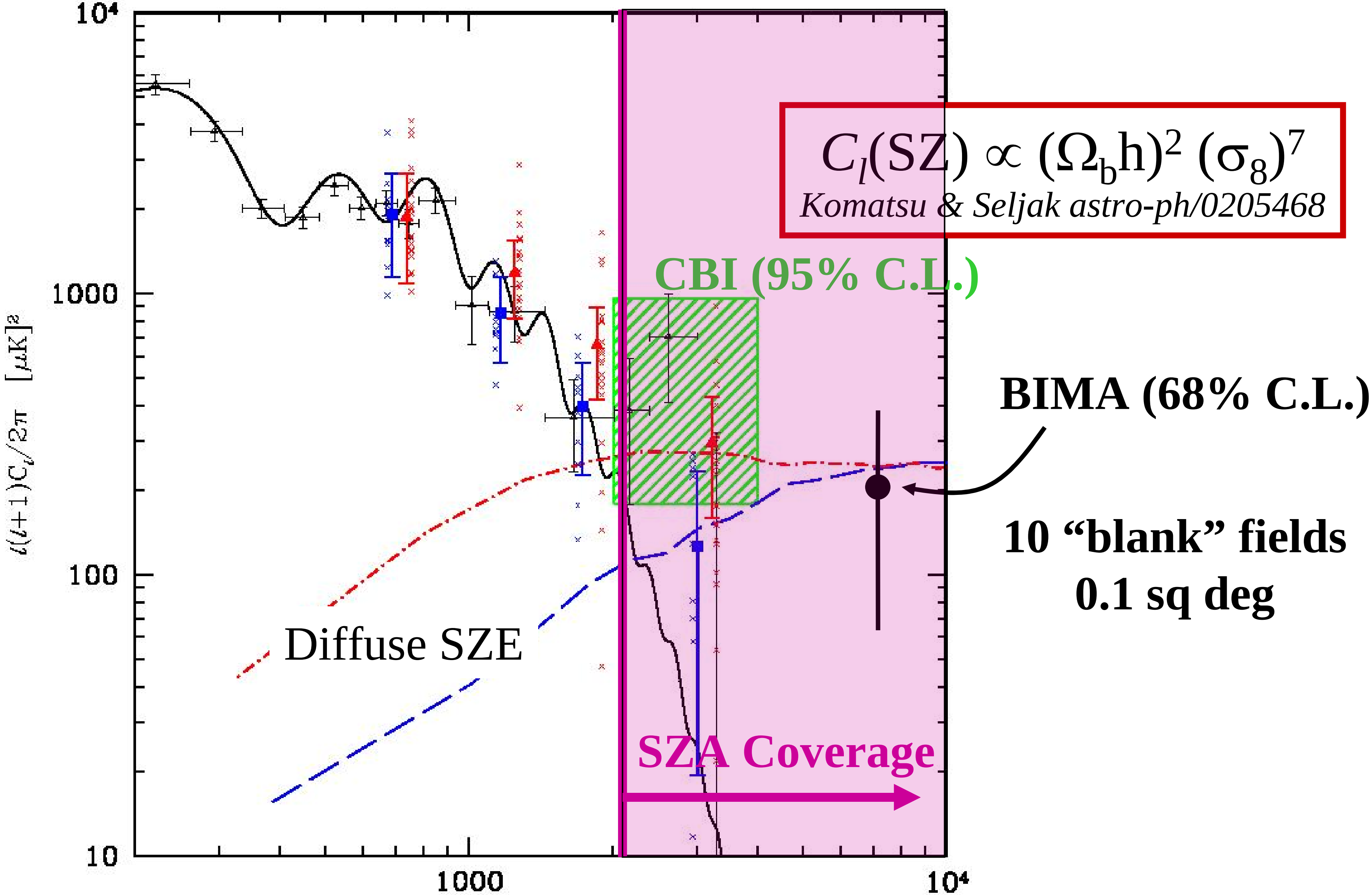
(from the OVRO/BIMA SZE program)

- 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
- <u>Survey about to start; should find ~100 clusters</u>

KICP/Chicago, Caltech, NASA/MSFC,Columbia

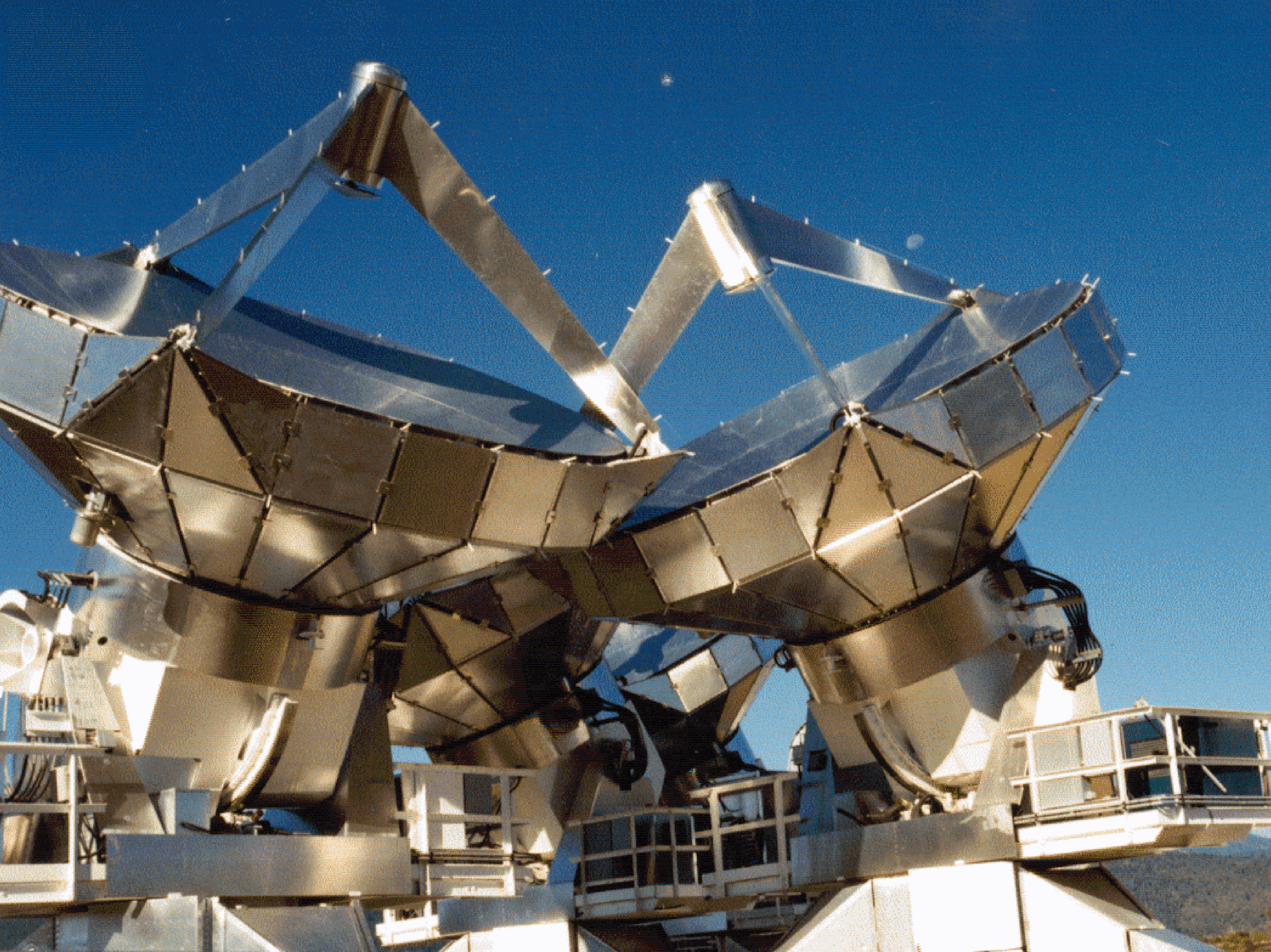
Telescope designed with Vertex/RSI, lead designer: Eric Chauvin, based on initial design by Dave Woody

SZA

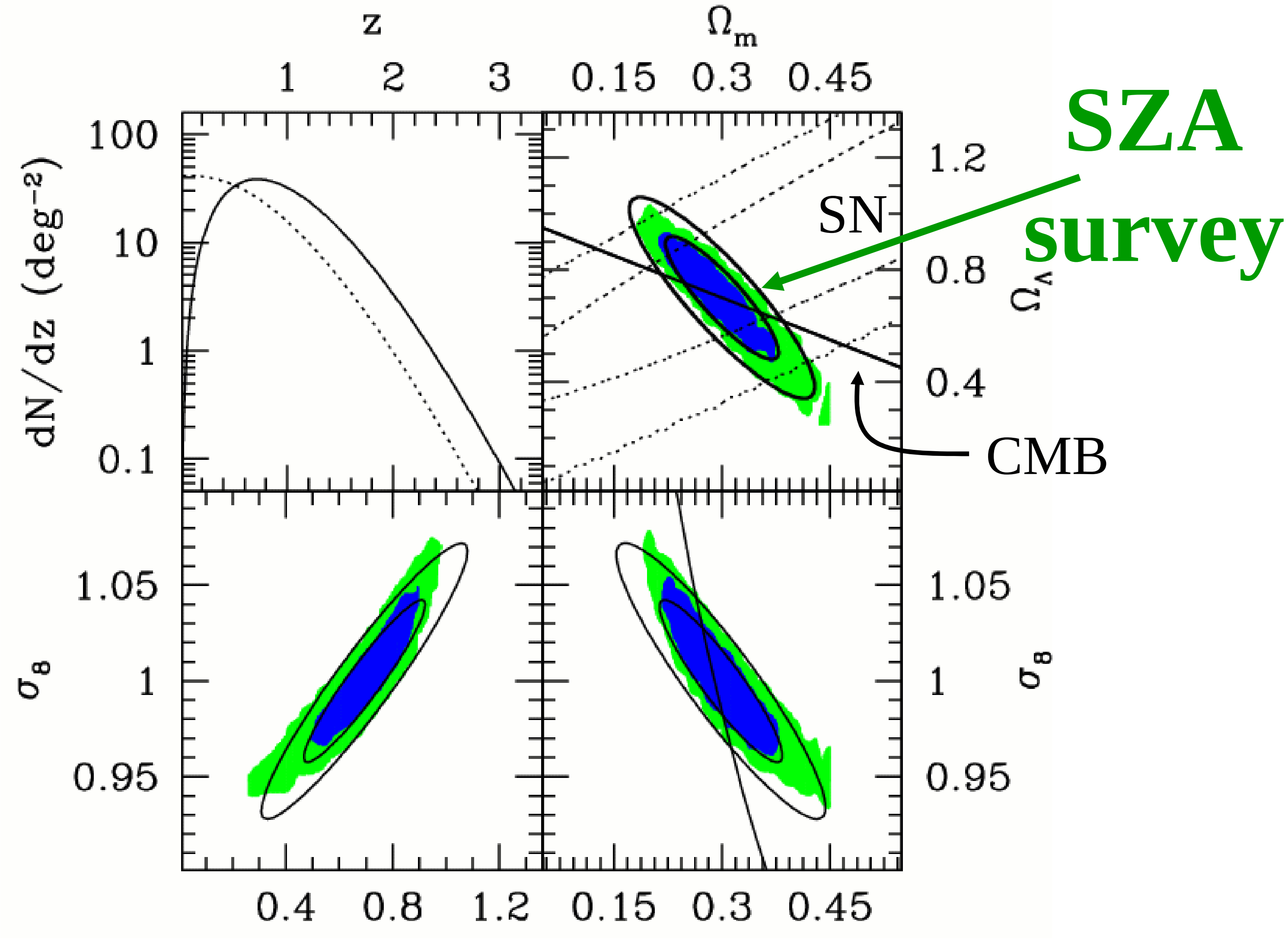


CBI & simulations: Bond et al. 2002, astro-ph/0205386

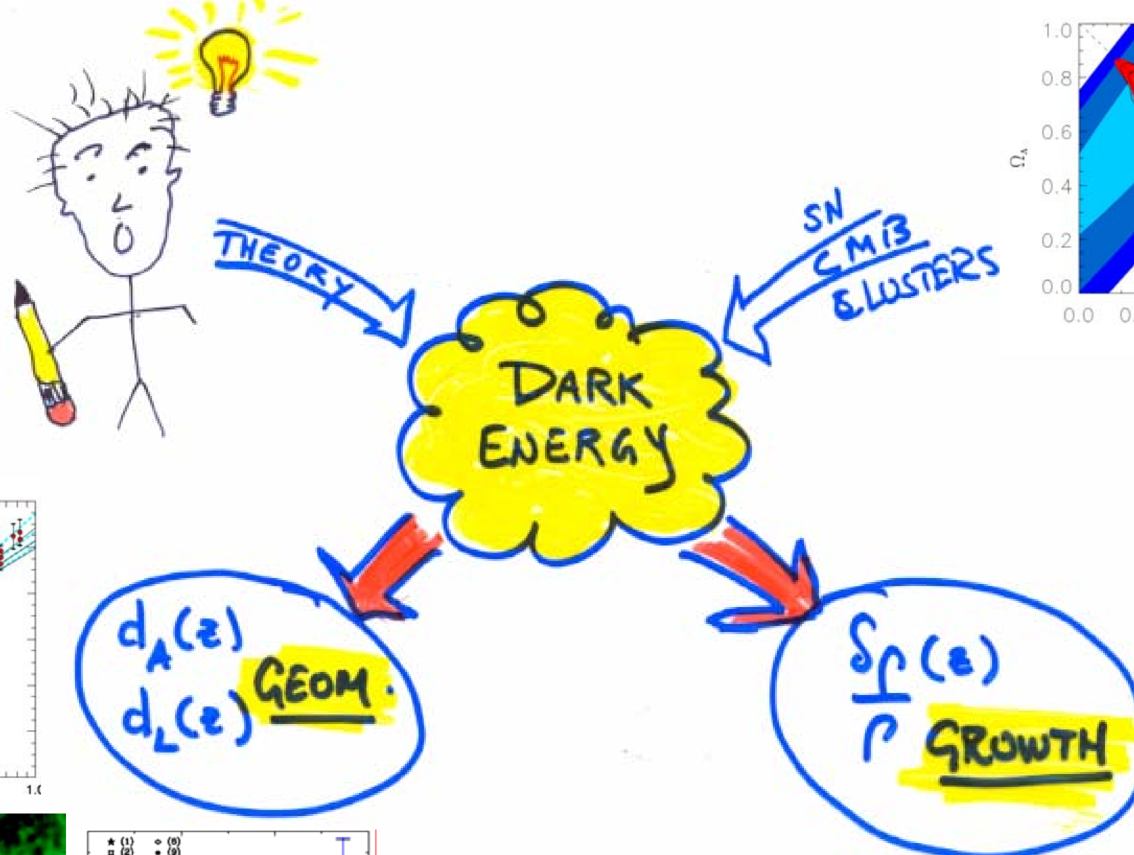
BIMA: Dawson et al. 2002 astro-ph/020601

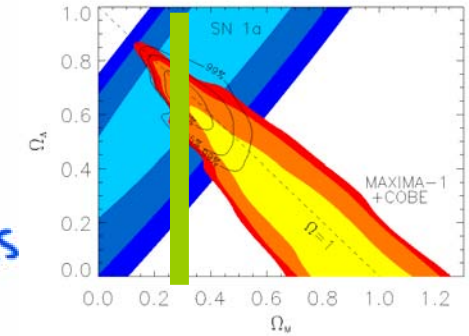


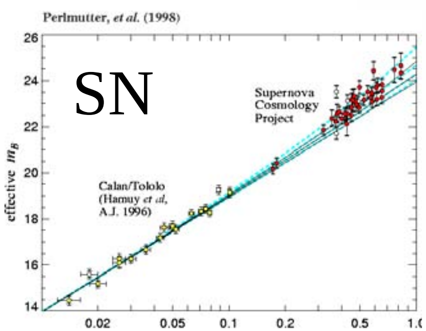
dN/Dz Cosmological Constraints from 1 year, 12 sq deg SZA Survey

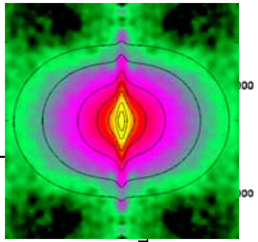


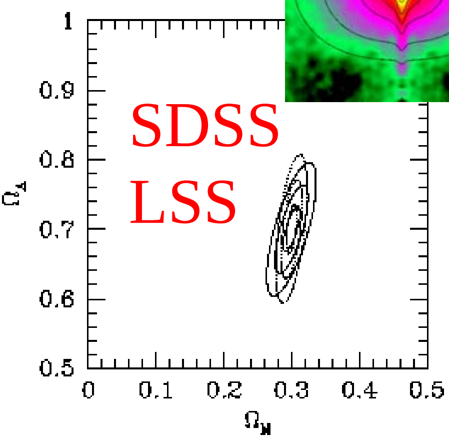
Holder, Haiman & Mohr astro-ph/0105396

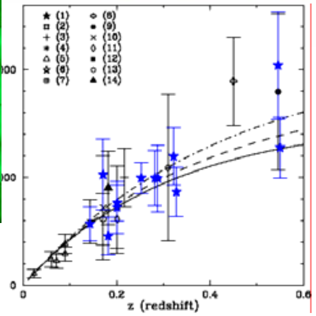

THEORY
SN
CMB
CLUSTERS
DARK ENERGY
$d_A(z)$
$d_L(z)$
GEOM.
$\frac{\delta\rho}{\rho}(z)$
GROWTH


SN 1a
MAXIMA−1 +COBE
Ω_Λ
Ω_M

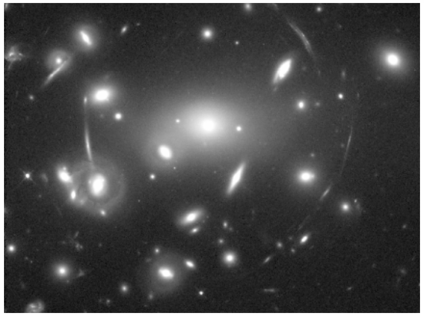

Perlmutter, et al. (1998)
SN
Supernova Cosmology Project
Calan/Tololo (Hamuy et al, A.J. 1996)
effective m_B

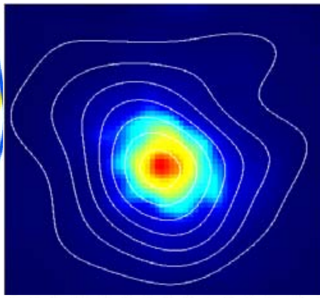


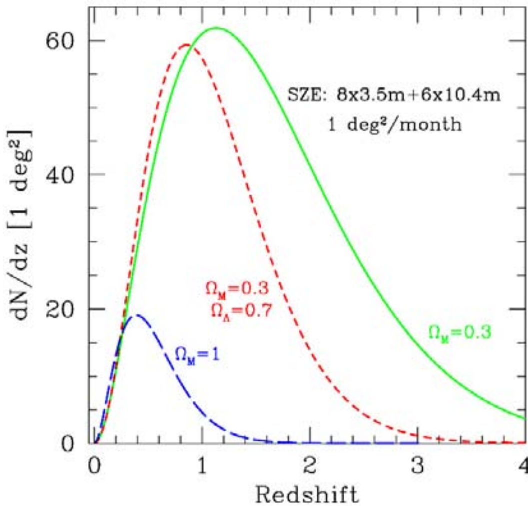

SDSS
LSS
Ω_Λ
Ω_M


z (redshift)

SZE






SZE: 8x3.5m+6x10.4m
1 deg²/month
dN/dz [1 deg²]
Ω_M=0.3
Ω_Λ=0.7
Ω_M=0.3
Ω_M=1
Redshift

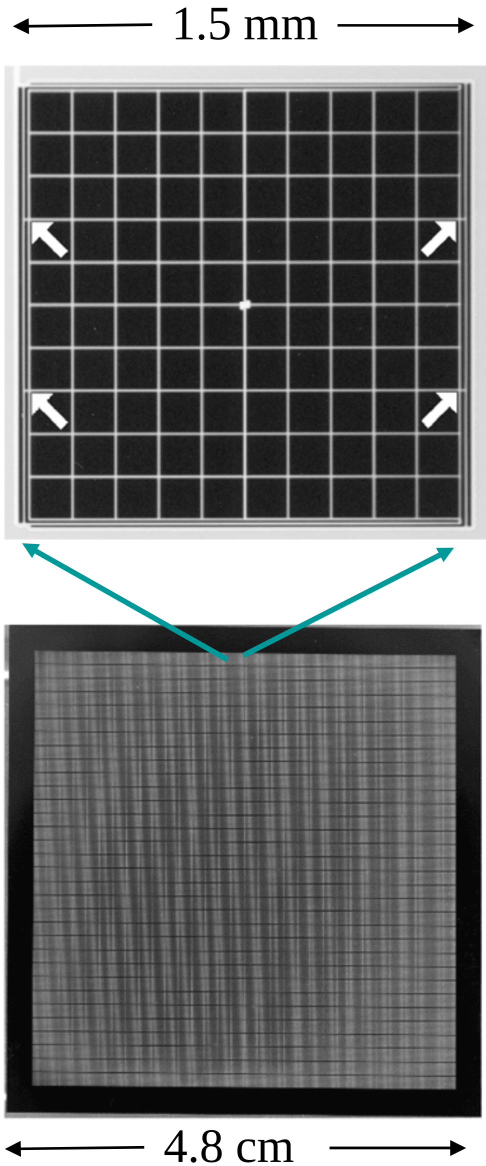
CARMA

Combined Array for Research in Millimeter-Wave Astronomy

23 Telescope Heterogeneous Array

Combine the 3 arrays at a new 7200’ elev. site

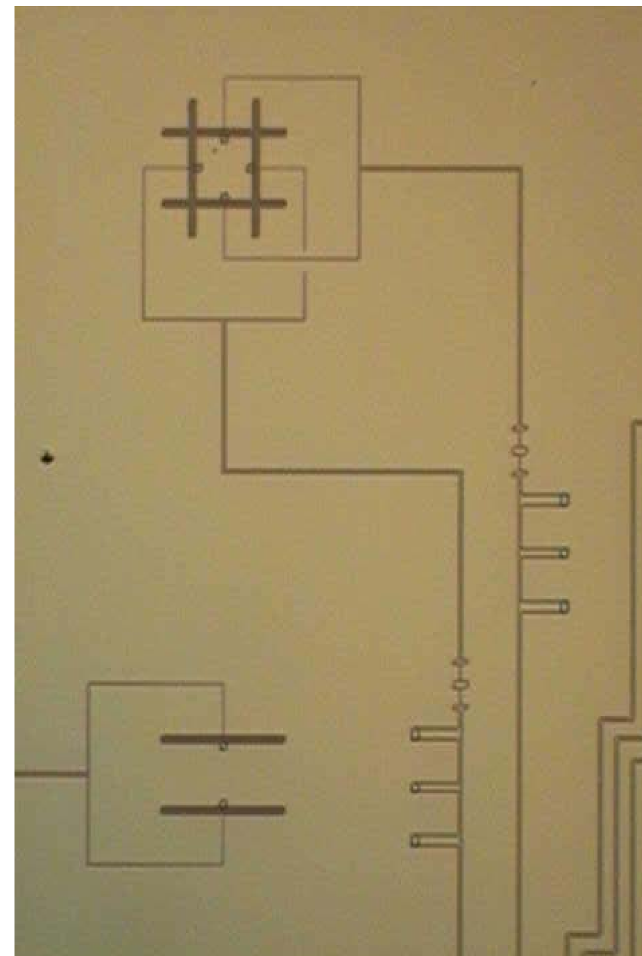
Revolution in Bolometer Array Technology



- 32 x 32 array of Si_3N_4 meshes built
- $>10^4$ pixels possible with multiplexed TES bolometers
- Frequency sensitive arrays, Frequency and polarization sens.

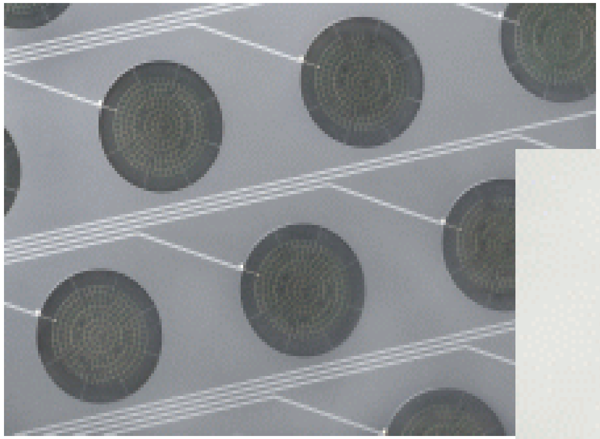
Antenna coupled bolometer arrays

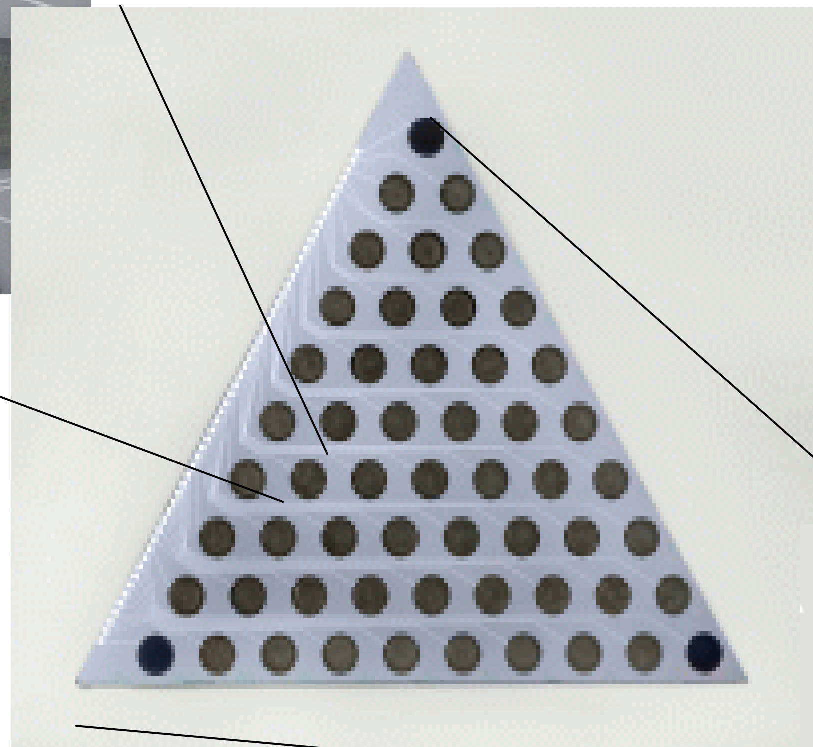
Dual polarization and multiple bands.



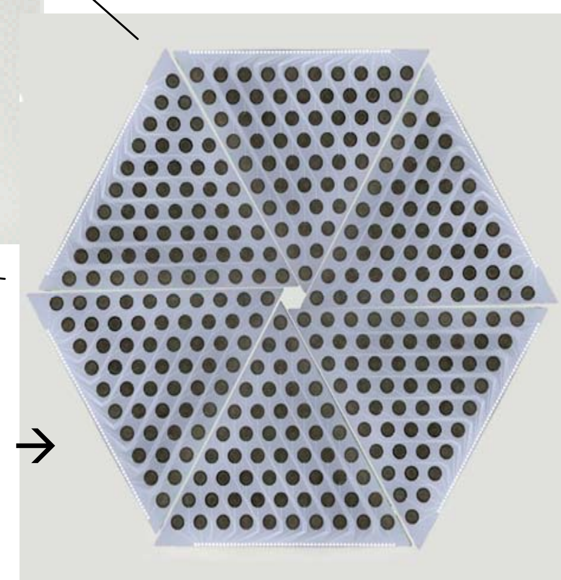
from A. Lee (U.C.Berkeley microfab lab). Research also being done at Caltech/JPL (i.e., SAMBA), NASA/Goddard, NIST…

APEX-SZ 330 element Spiderweb TES Bolometer Array





5”



From photoshop →

APEX-SZ

- Sunyaev-Zeldovich effect galaxy cluster survey.
- 330 element TES bolometer array camera on the 12-m APEX submm telescope in Chile
- <u>Survey 100-200 sq. degrees</u> to 10μK CMB sensitivity per 60" pixel, should find ~1000 clusters
- Demonstrate new technologies for SPT and other instruments
- First engineering tests in 2005

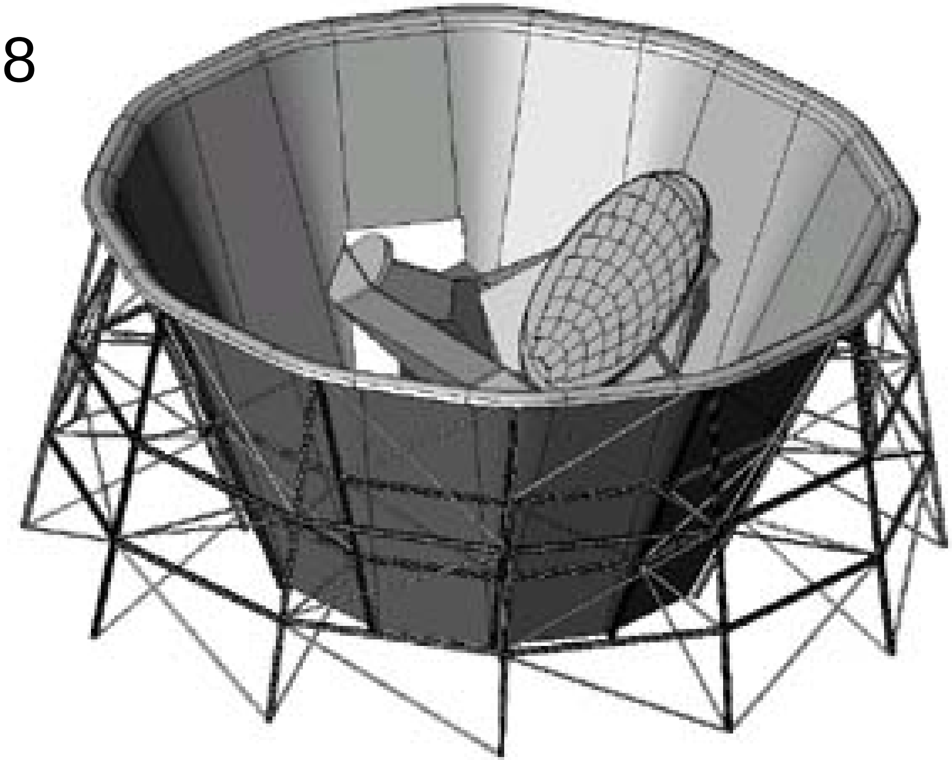
Berkeley University of California

BERKELEY LAB

Max-Planck-Institut für Radioastronomie

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	

10m South Pole Telescope (SPT) and 1000 element Bolometer Array

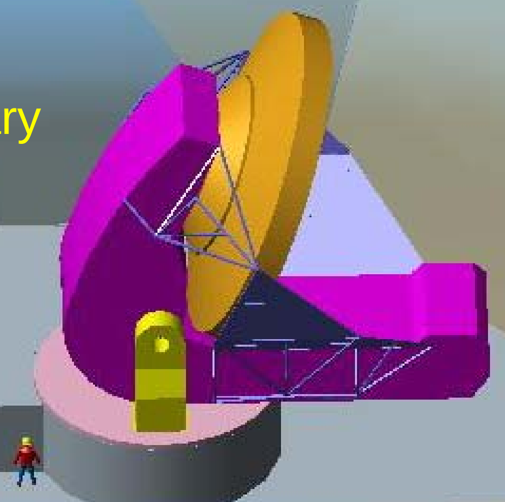
(see Ruhl et al. astro-ph/0411122)

Low noise, precision telescope

- 20 um rms surface
- 1 arc second pointing
- 1.0 arcminute at 2 mm
- ‘chop’ entire telescope
- 3 levels of shielding
  - ~1 m radius on primary
  - inner moving shields
  - outer fixed shields

SZE and CMB Anisotropy

- **4000 sq deg SZE survey**
- deep CMB anisotropy fields
- deep CMB Polarization fields



Collaboration

KICP/UChicago
UC Berkeley
Case Western
UIUC
SMA

1000 Element Bolometer Array

- multi-band focal plane made up of 90, 150, 250 & 270 GHz APEX-SZ style wedges of horn fed spider web absorbers

NSF-OPP funded
Nov 2006 deployment

SPT Collaborators

Principals:

John Carlstrom (KICP)
Bill Holzapfel (UCB)
Adrian Lee (UCB)
Erik Leitch (KICP)
Stephan Meyer (KICP)
Joe Mohr (UIUC)
Steve Padin (KICP)
Clem Pryke (KICP)
John Ruhl (Case-Western)
Helmuth Spieler (UCB)
Tony Stark (CfA)

With help from:

Wayne Hu (KICP)
Andrey Kravtsov (KICP)
Josh Frieman (KICP)
Martin White (UCB)

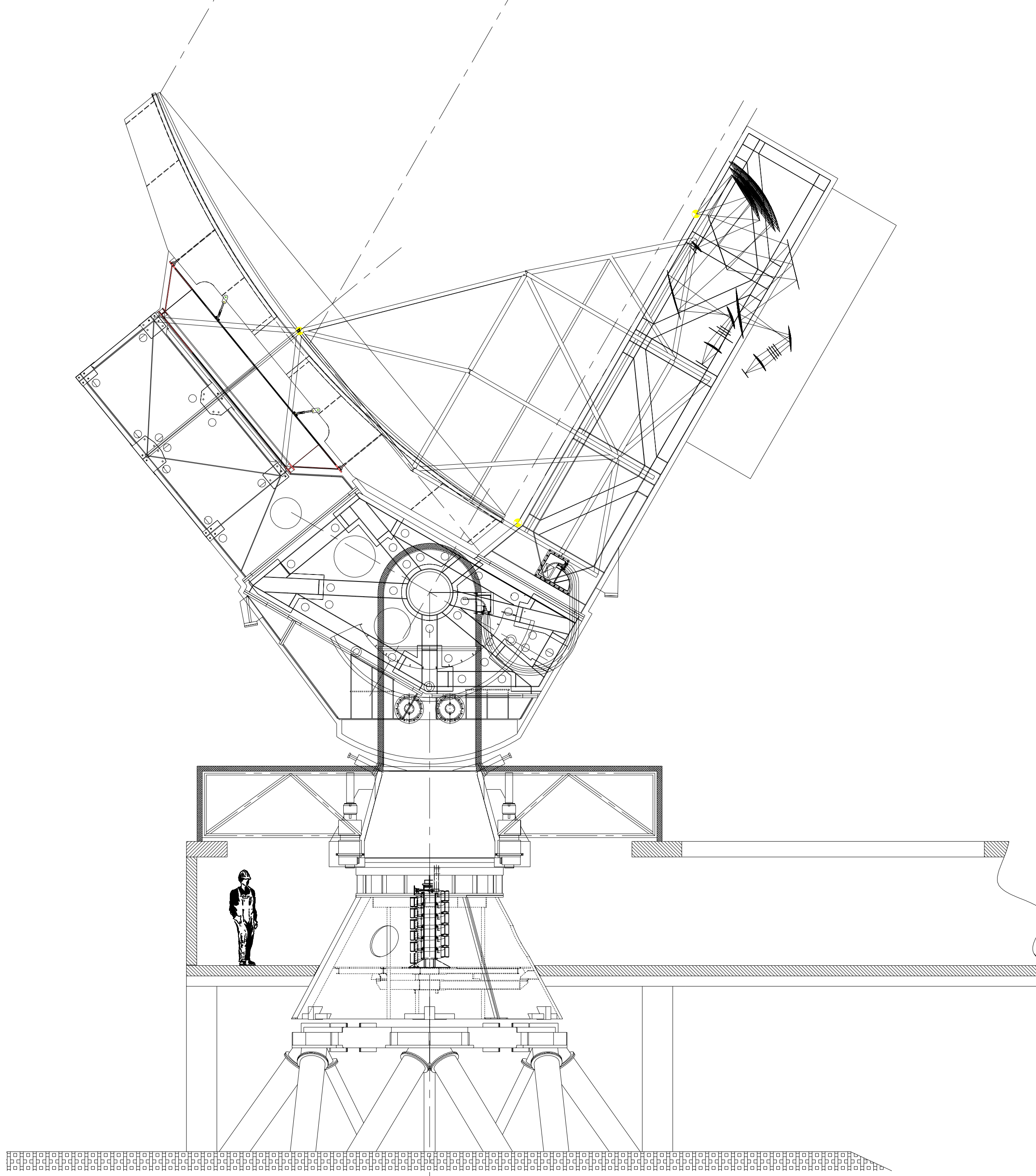
Postdocs:

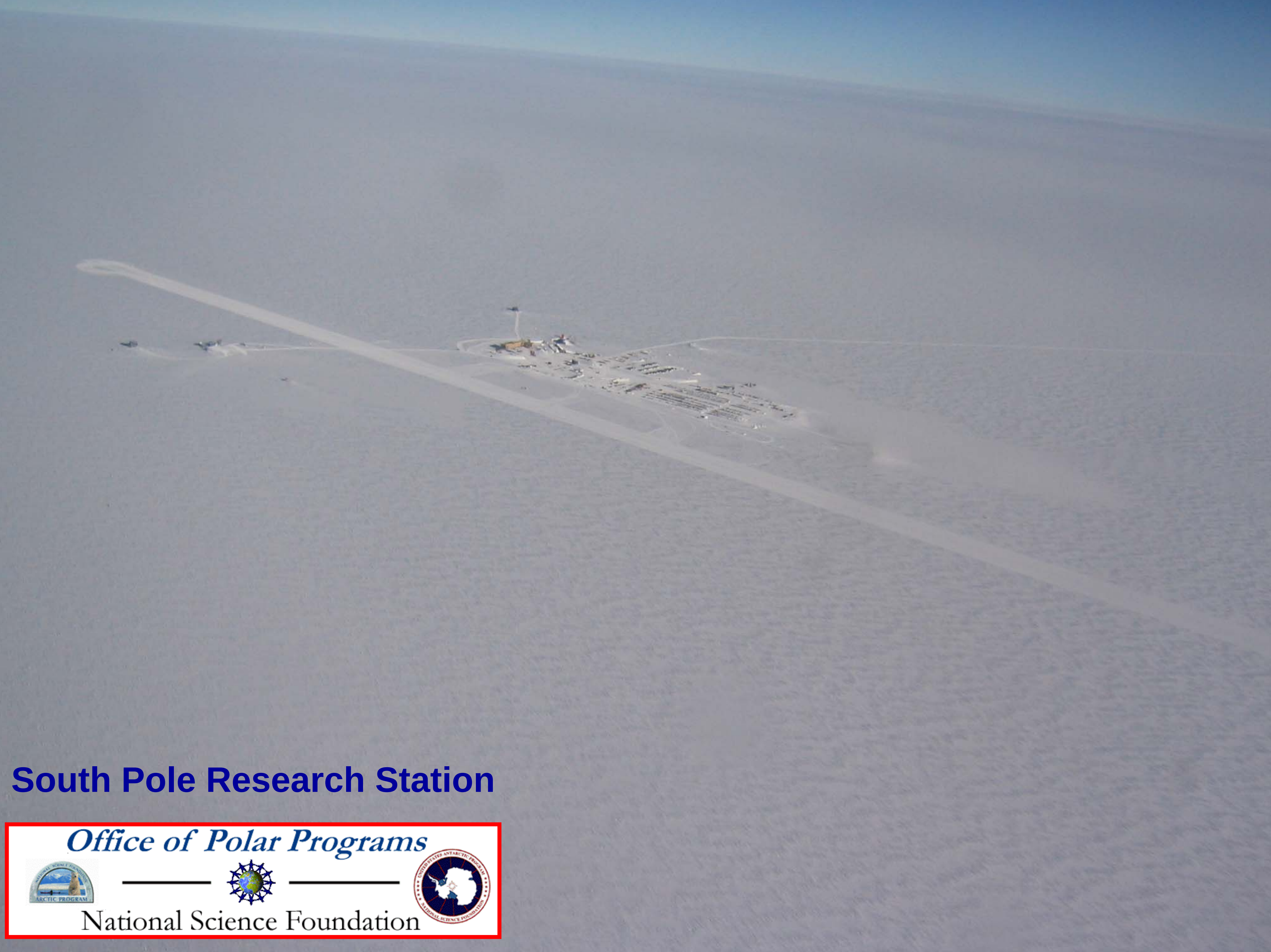
Tom Crawford (Chicago)
Sherry Cho (UCB)
Matt Dobbs (UCB)
Nils Halverson (UCB)
Subharbrata Majumdar (UIUC)
Marcus Runyan (KICP Fellow)

Students:

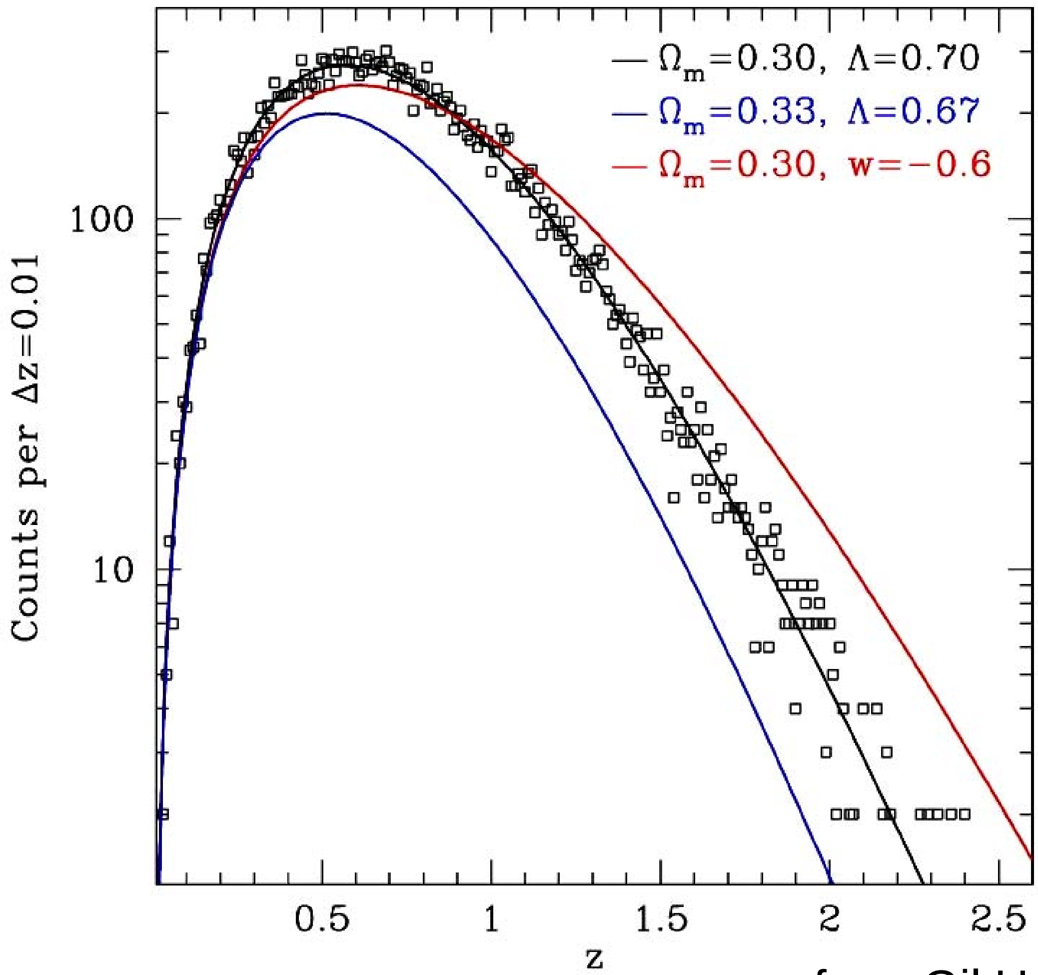
Chris Greer, Mathew Sharp, Sarah Hansen (KICP)
Po Kin Leung & Yen-Ting Lin (UIUC)
Jon Leong & Z. Staniszewski (Case)
Martin Lueker, Tom Plagge, Trevor Lanting, Jared Mehl, Dan Schwan, Erik Shirkoff (UCB)

KICP
NSF – OPP
Raytheon PSC




South Pole Research Station
Office of Polar Programs
National Science Foundation

Predicted dN/dz from a SPT 4000 sq deg SZE survey

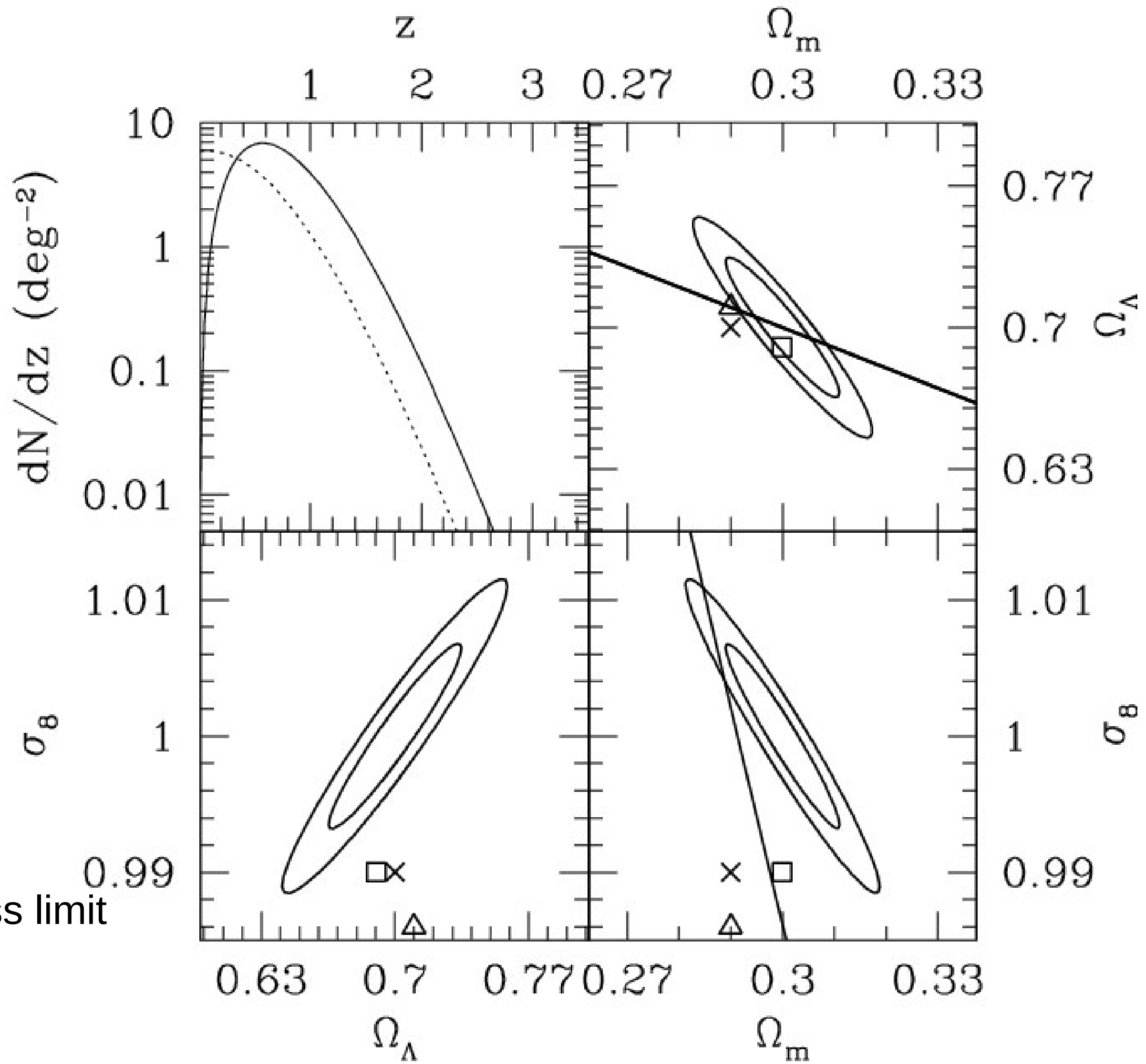


from Gil Holder

Cosmology with SPT-SZ

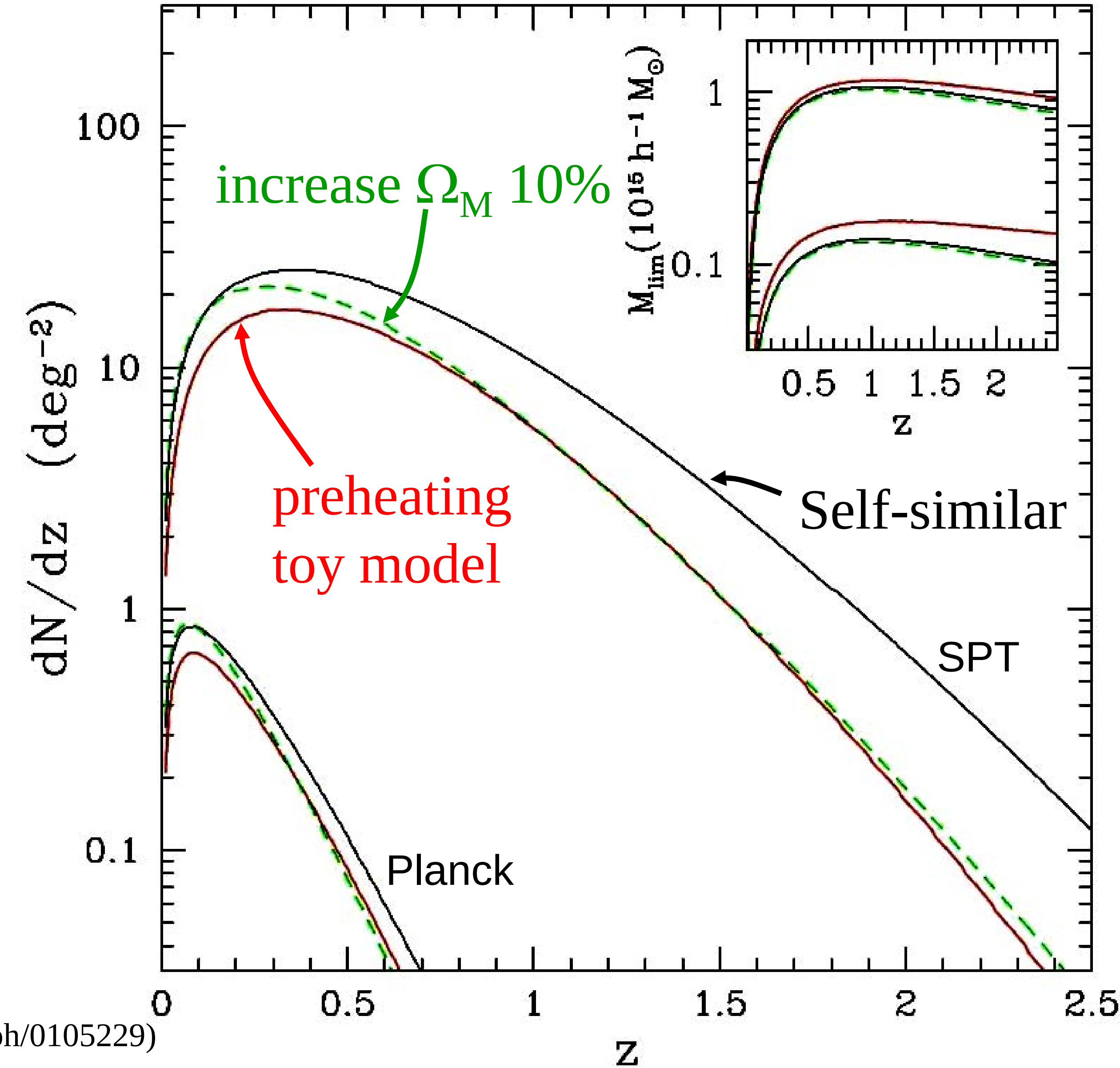
Holder, Haiman & Mohr 2001, astro-ph/0105396

for ~17,000 clusters



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

Analysis of cluster surveys need to account for evolution in the mass to observable relation.



from Gil Holder, JC ApJ, 558, 515. astro-ph/0105229)

‘Self-calibration’ of cluster surveys.

Use the cluster power spectrum in redshift bins

Mujumdar and Mohr astro-ph/0305341

Weng et al. astro-ph/0406331

And with limited mass follow-up

Mujumdar and Mohr astro-ph/0305341

Adding variance information from counts in 3-d cells

Lima & Hu 2004 astro-ph/0401559

Using shape of SZ luminosity-function in redshift slices

Hu 2003 astro-ph/0301416

Also see recent SZE forecasts:

Haiman, Mohr, Holder astro-ph/0002336

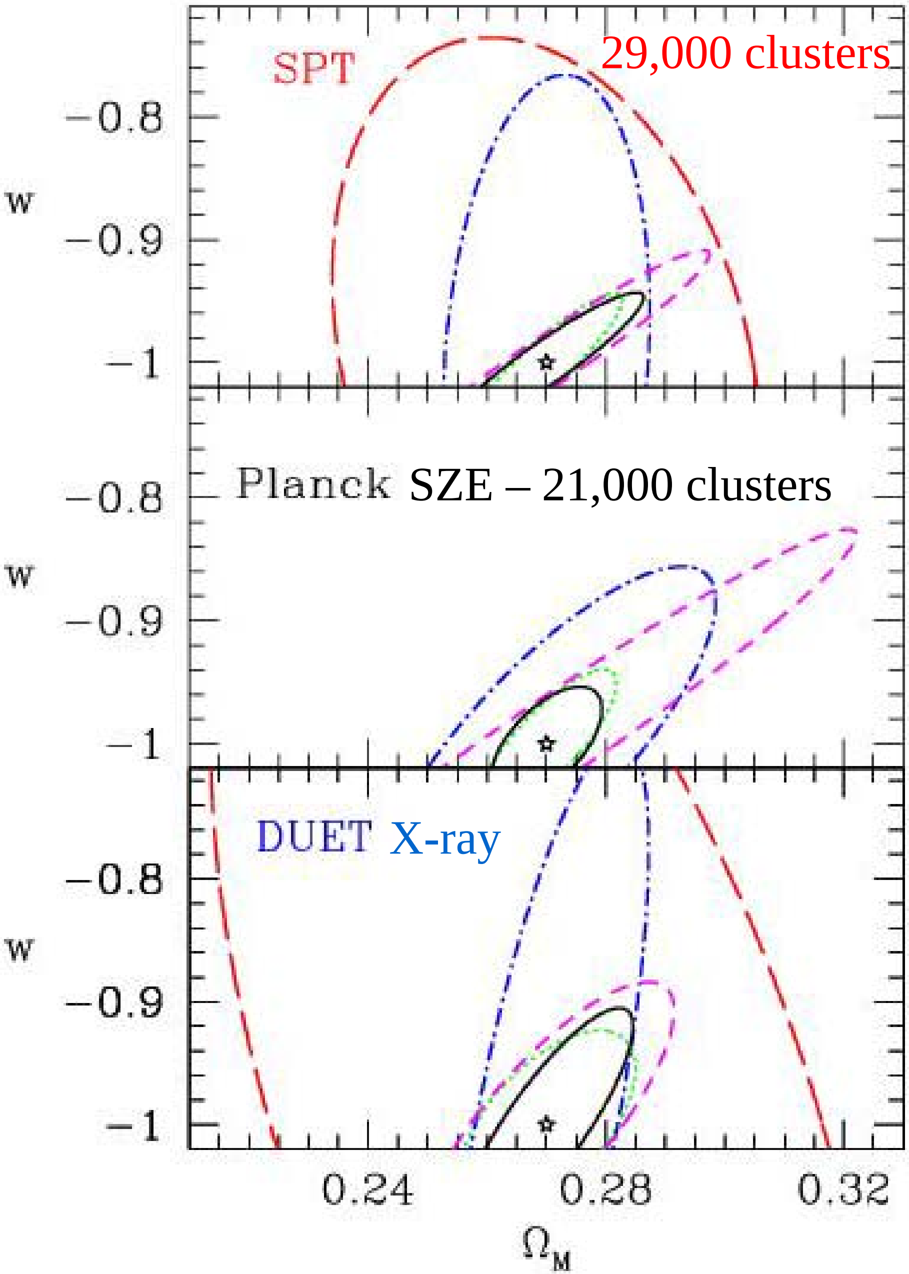
Kneissl et al astro-ph/0103042

Weller, Battye, Kneissl astro-ph/0110353

Holder, Haiman and Mohr astro-ph/0105396

Shulz and White astro-ph/0210667

Battye and Weller astro-ph/0305568



Mujumdar and Mohr astro-ph/0305341

Summary

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

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

There is a lot of work to do *(in addition to building the instruments!)*

- Finding/extracting Clusters from real surveys (systematics, point sources)
- 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 **(*Go Dark Energy Survey!*)**