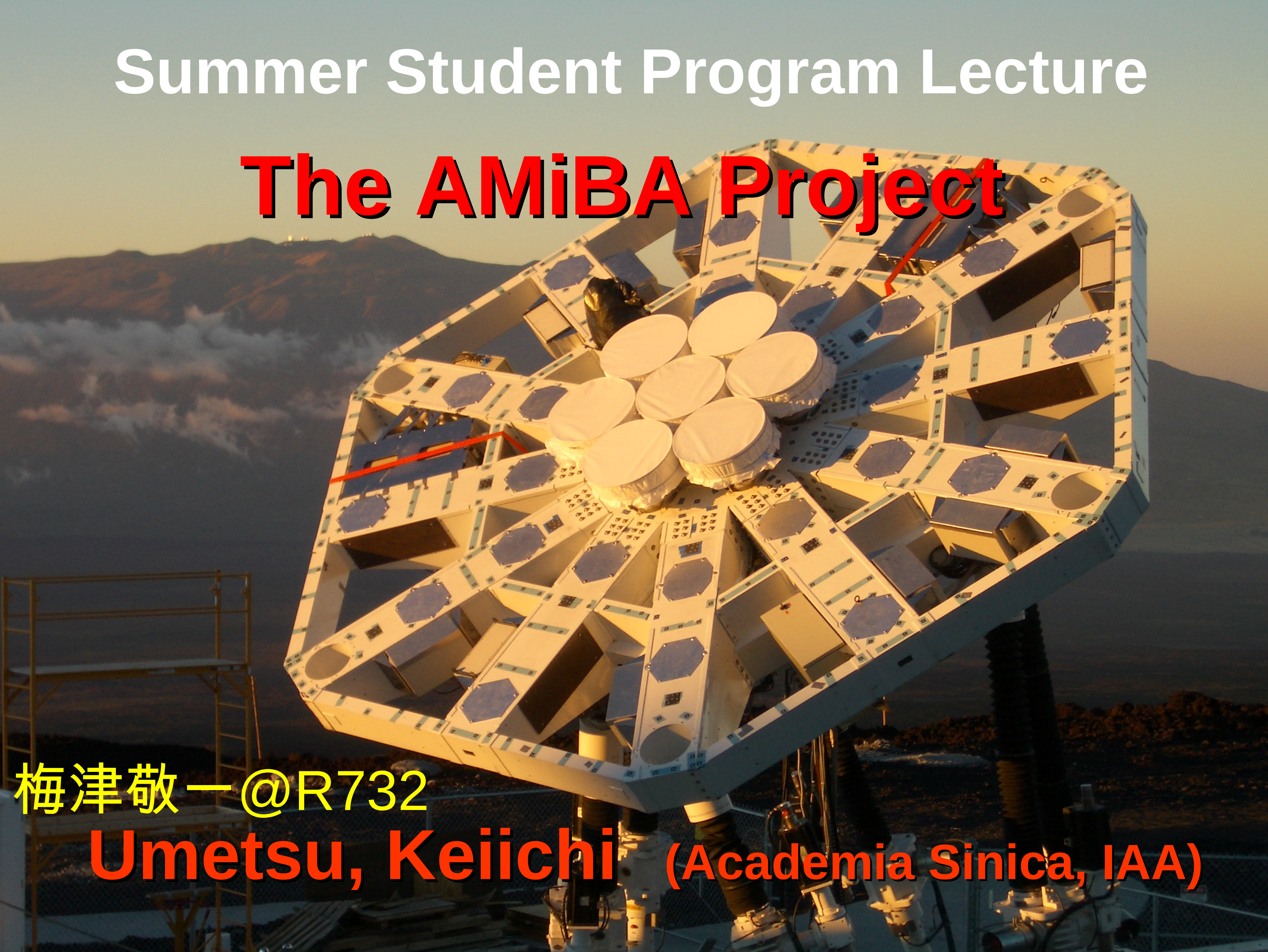


## Summer Student Program Lecture

# The AMiBA Project

梅津敬一@R732
**Umetsu, Keiichi** (Academia Sinica, IAA)

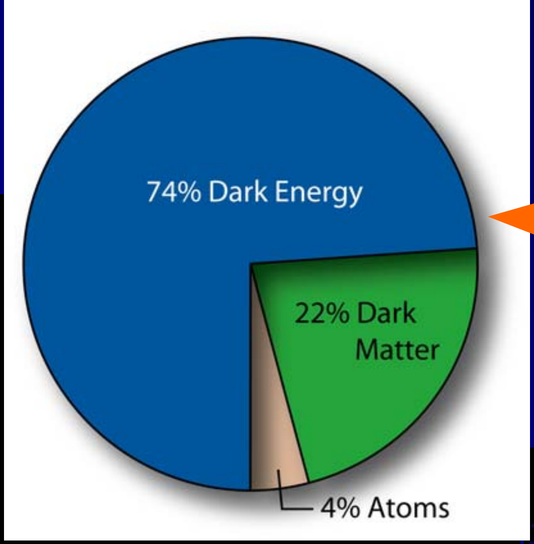
# Outline

1. **Introduction**
   - Cosmic Microwave Background (CMB)
   - Galaxy Clusters
2. **CMB and Interferometer**
3. **AMiBA:** Goals, Spec, Simulations
   - CMB Angular Power-Spectra
   - Galaxy Cluster Survey via the Sunyaev-Zel'dovich Effect (SZE)
4. **AMiBA Current Status**
5. **Summary**

# Introduction

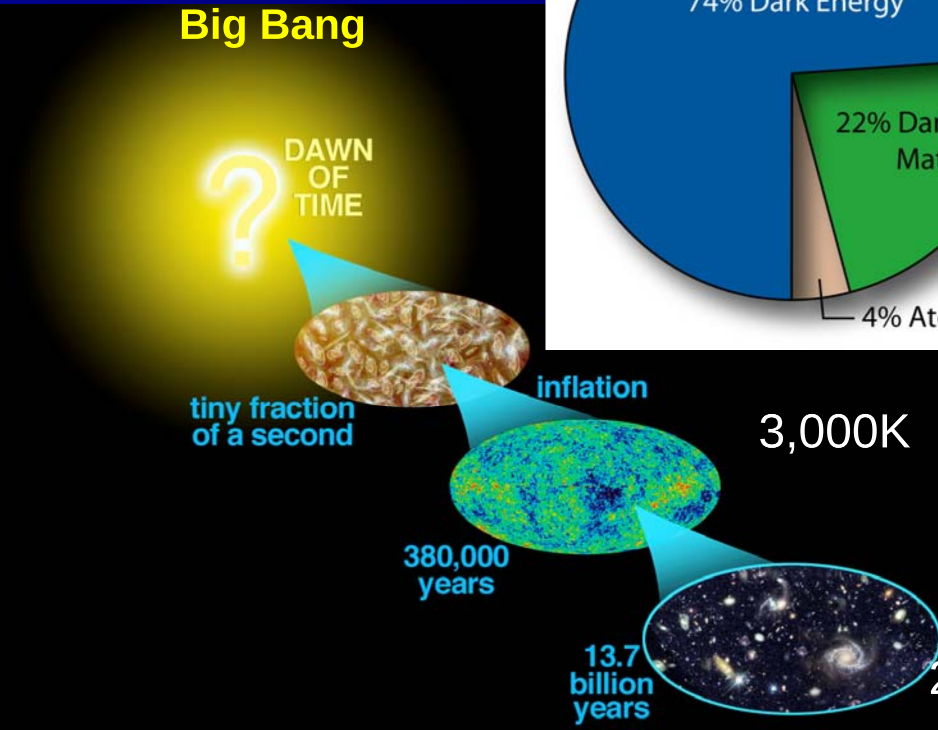
# Cosmic Microwave Background: Powerful Probe of Cosmology

CMB + complementary astrophysical data enable us to fix the fundamental cosmological parameters

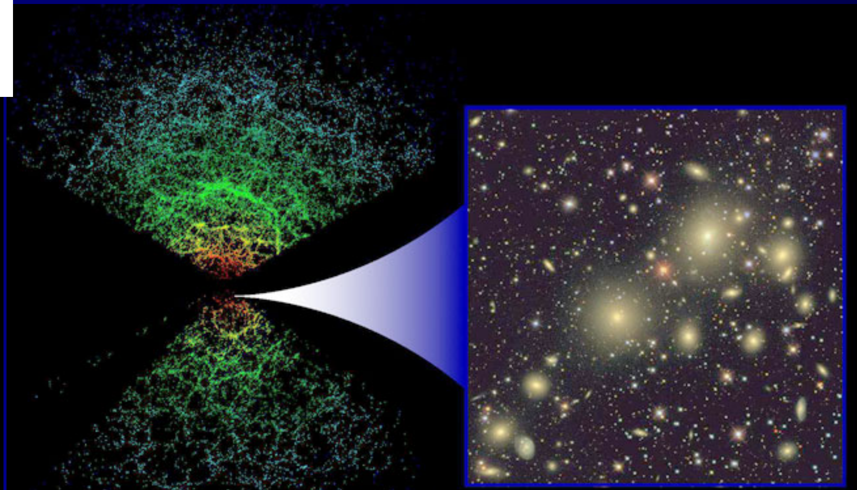



Total density = critical density

i.e. our universe is spatially flat




WMAP CMB experiment



SDSS galaxy survey

# What we don't know…

- **Nature of Dark Matter** [WIMPs or MACHO?]:

  Cold/Hot Dark Matter? Self-interaction?
- **Nature of Dark Energy** [$\Lambda$ or Q?]:

  DE Equation-of-State, $w=(P/\rho) < -1/3$, and its possible evolution
- **Re-ionization of the Universe: first stars/galaxies**

  When and How it happened?: z=11 to 6?
- **Cosmic structure formation**

  $\sigma 8$, biasing between mass (DM) and light (galaxies)
- **Initial conditions of the Universe: inflation model**

  Gravitational Wave

  Primordial power index: P(k)=Ak^ns

*Astrophysisits are proposing various methods for extracting observational evidence to answer the questions.*

# Angular Power Spectrum, $C_l$

- **Decomposing patterns of structures in spherical harmonics**

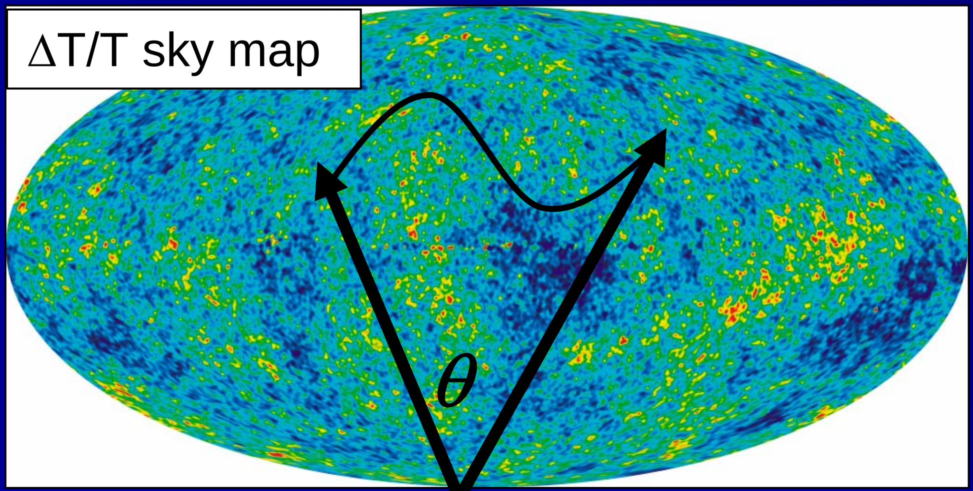
$$\frac{\Delta T(\theta,\phi)}{T} = \sum_l^{\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\theta,\phi)$$

*"Fourier transform" of anisotropy on the sphere*

- **Rotational invariance (**averaging over *m*)

**Angular power spectrum**

$$C_l = \frac{1}{2l+1} \sum_m \left\langle a_{lm} a_{lm}^{*} \right\rangle$$

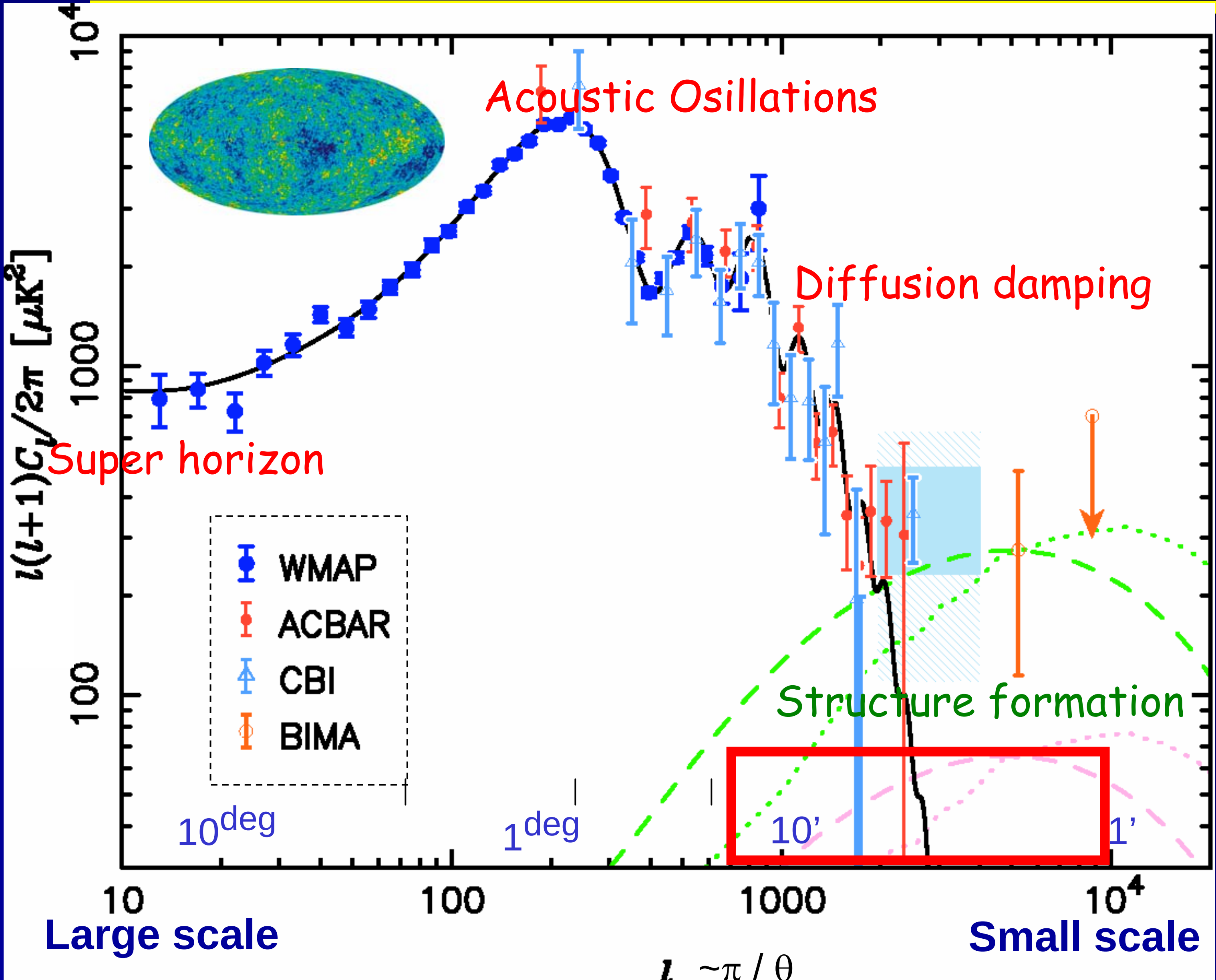



$C_l$ is the variance of structures on scale *l*,

$$l \sim 180 \left( \frac{\theta}{1\deg} \right)^{-1}$$

Δ T ~ 100 μK

# Observations of CMB T-Power Spectrum




**Primary CMB:**
Detailed physics worked out in cosmological perturbation theory

**2ndary CMB:**
Perturbations in non-linear regimes

Re-ionization from first stars and galaxies

Non-Gaussian signal

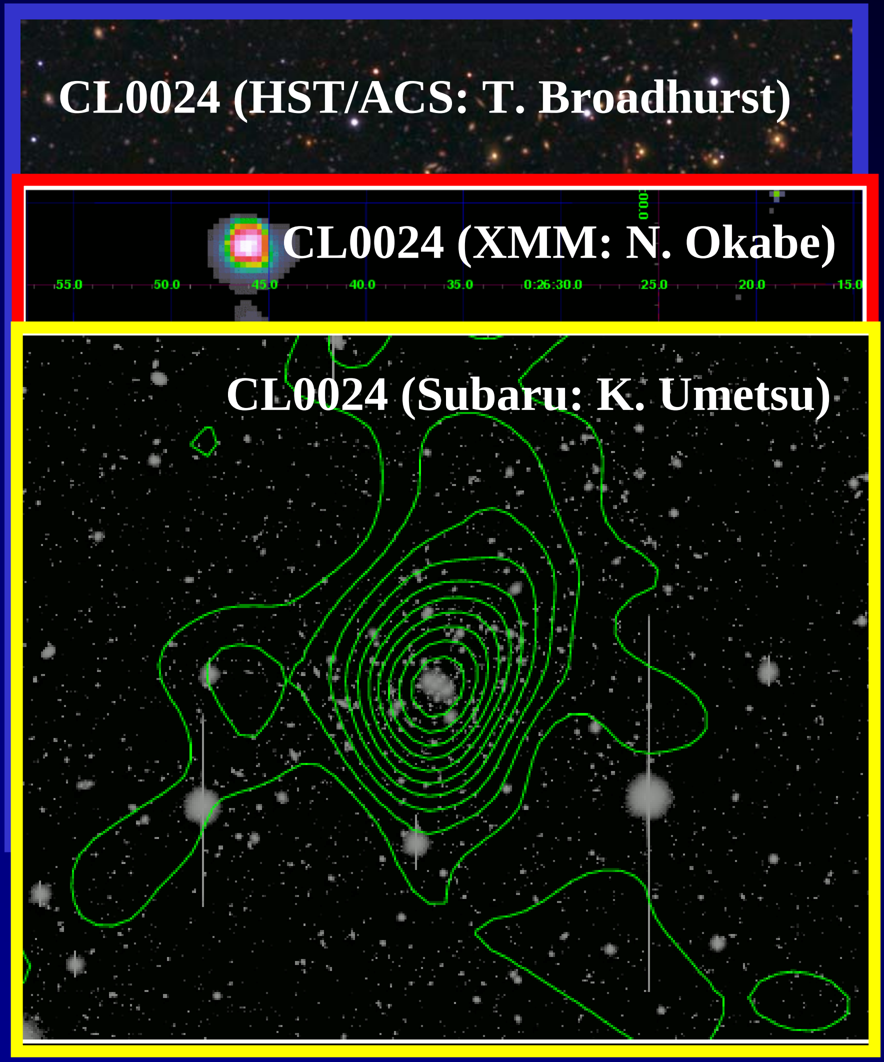
# Galaxy Clusters (星系団)

- being most massive, gravitationally-bound structures in the universe with **$M>10^{14}\ M_{sun}$**.

- contain:
  - Visible galaxies ($10^2$-$10^3$),
  - Diffuse ionized gas (1-10keV)
  - Dark Matter (80% in mass).

– sensitive cosmological probes, since they are the most rapidly evolving population.

– useful astrophysical probes, observed in many wavelengths:



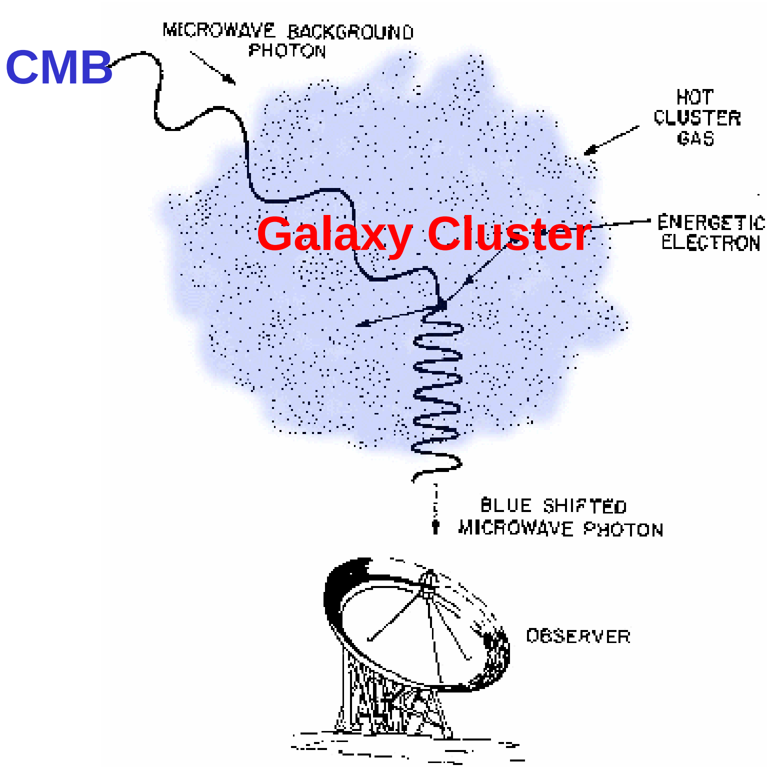

- **Weak Gravitational lensing**
- **Sunyaev-Zel'dovich Effect**

# Thermal Sunyaev-Zel'dovich Effect (SZE)

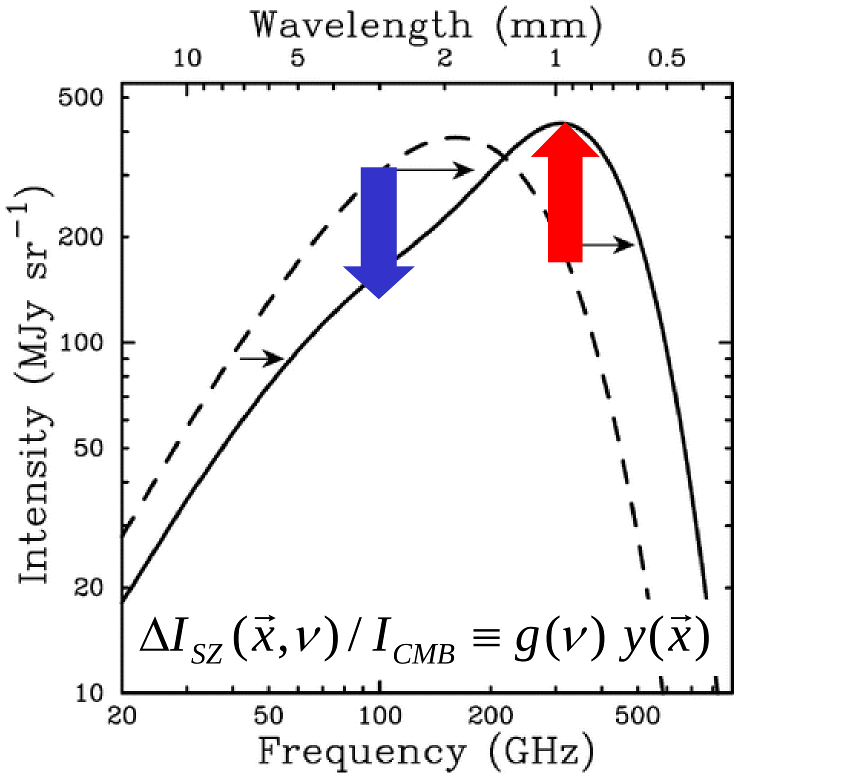
10^-2 10^-2

$$y \equiv \int_0^{\lambda_{\rm LSS}} d\tau \, \frac{k_{\rm B}(T_e - T_{\rm CMB})}{m_e c^2} \approx \int \frac{k_{\rm B} T_e}{m_e c^2} \sigma_{\rm T} n_e dl \propto \int dl \, P_e$$

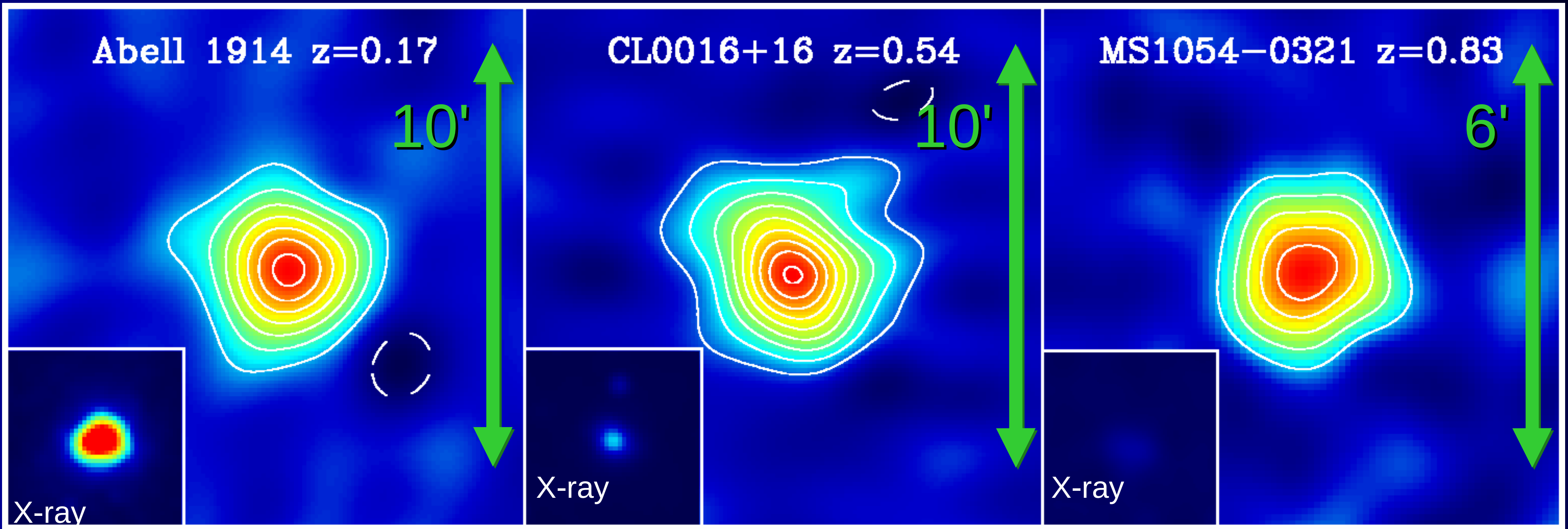
Energy transfer from **hot cluster gas** to **cold CMB** via inverse Compton scattering




**Spectral distortion of CMB spectrum**



# Power of SZE




(Carlstrom et al. 1999)

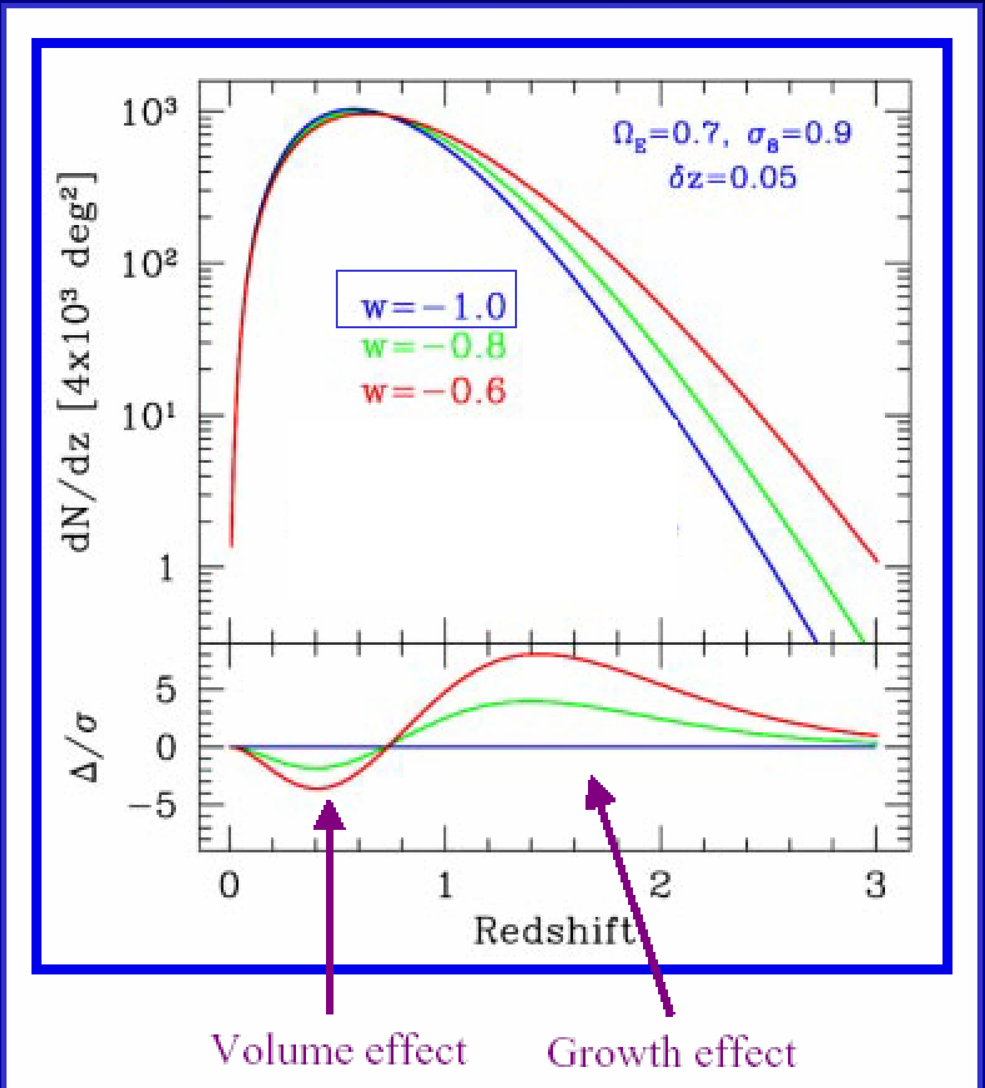
**SZE brightness independent of distance (z),**

**while X-ray/Optical/Lensing signal of clusters gets fainter**

What we seek for is a 10-100 μK weak signal!!

# Cluster Survey via the Thermal SZE

Evolution of Number Counts
of SZE Clusters



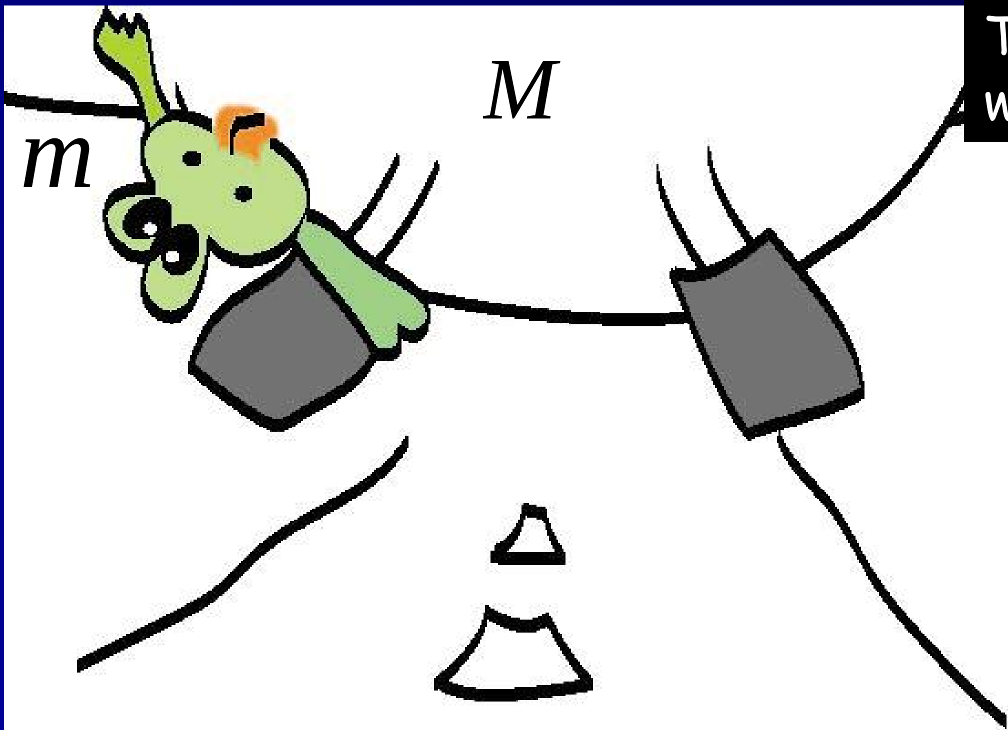

**Cosmological test with structure formation (0<z<a few)**

**Complementary to CMB constraints on cosmology**

*Figure from literature (simulated SZE survey with 8m SPT)*

# 2. CMB and Interferometer

# CMB vs. Interferometer




Interferometer measures directly $m$

Credit: Prof. Atsuto Suzuki;

Figure by Prof. Makoto Hattori

To measure the weight of a frog which is attached to a Jumbo-Jet:

In single-dish observations;

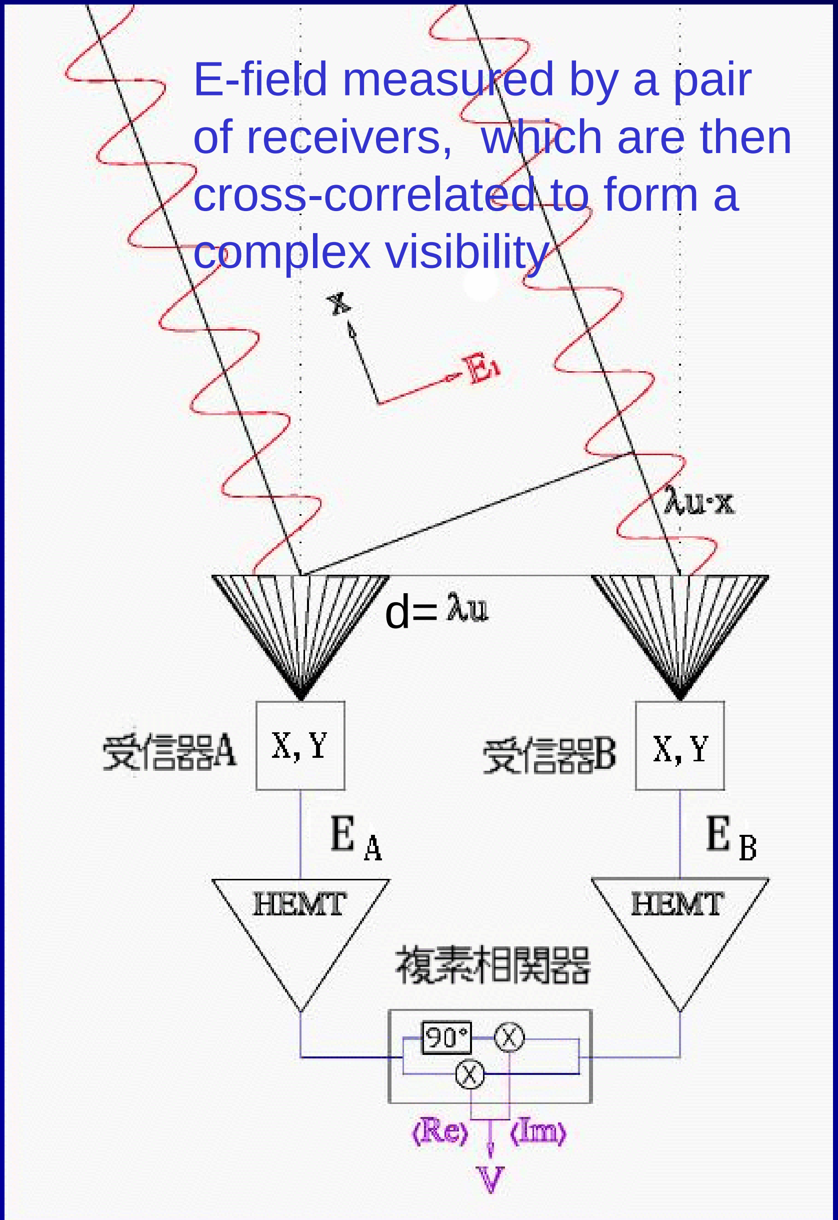
$$(M + m) - M' = m$$

$M$ : weight of Jumbo with frog

$M'$ : weight of Jumbo without frog

Measurement of CMB anisotropy: $\frac{m}{M'} < 10^{-5}$

# Observable: Complex Visibility, V(u,v)




$$V(\vec{u}) = \int d^2x\, A(\vec{x}) I(\vec{x}) \exp[2\pi\, i\vec{u}\cdot\vec{x}]$$

I(x) : intensity map on the sky

A(x) : antenna primary beam pattern

u = d/λ: baseline vector

Visibility is Fourier Transform of intensity pattern I(x) attenuated by A(x)

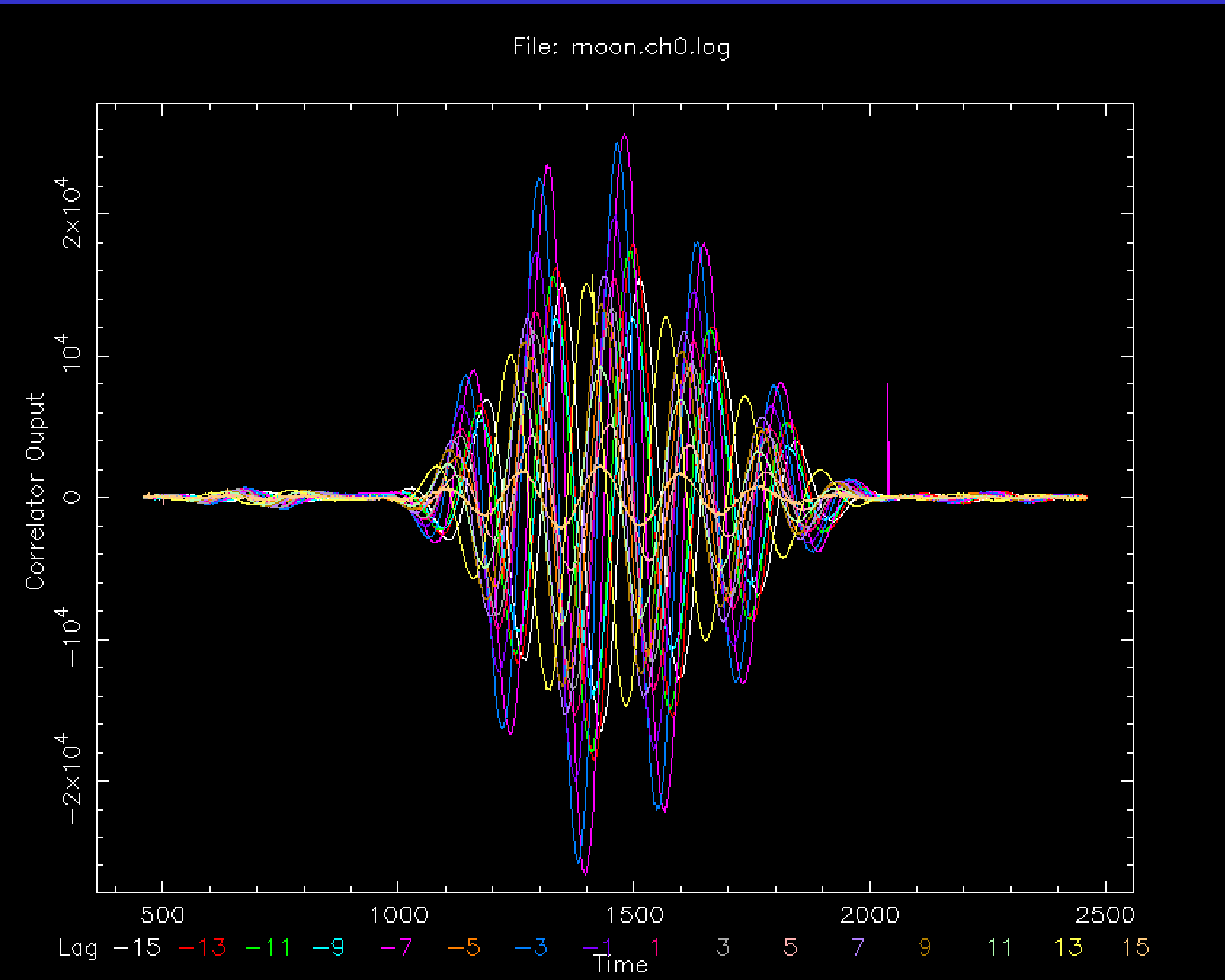
$$V(\vec{u}) = \mathbf{FT}[A(\vec{x}) I(\vec{x})]$$

*Angular power spectrum directly measured by interferometer!!*

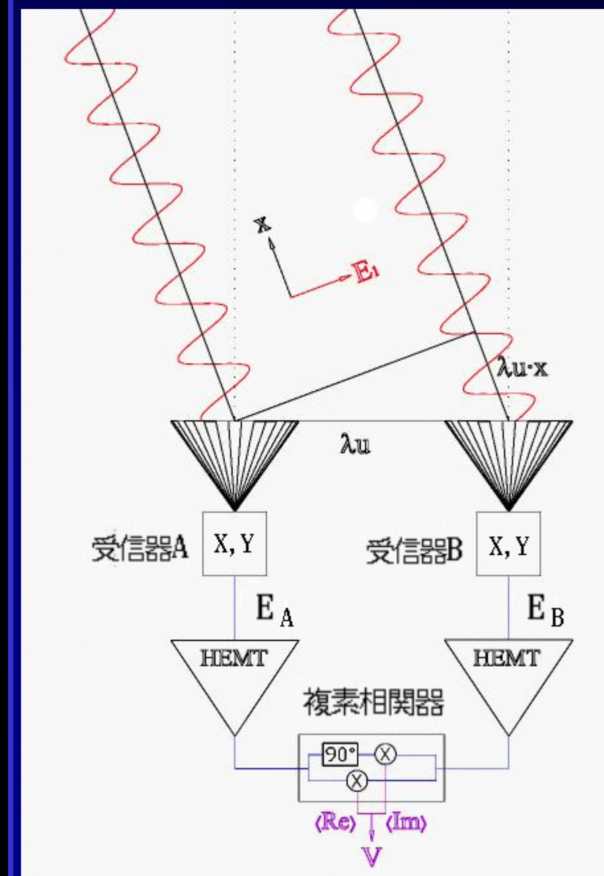
$$C_l \,\big|_{l=2\pi u} \approx \left\langle V(\vec{u}) V^*(\vec{u}) \right\rangle$$

# Fringes from Drift-Scanning

Fringes from 2-element AMiBA prototype (2002-2004)




transit

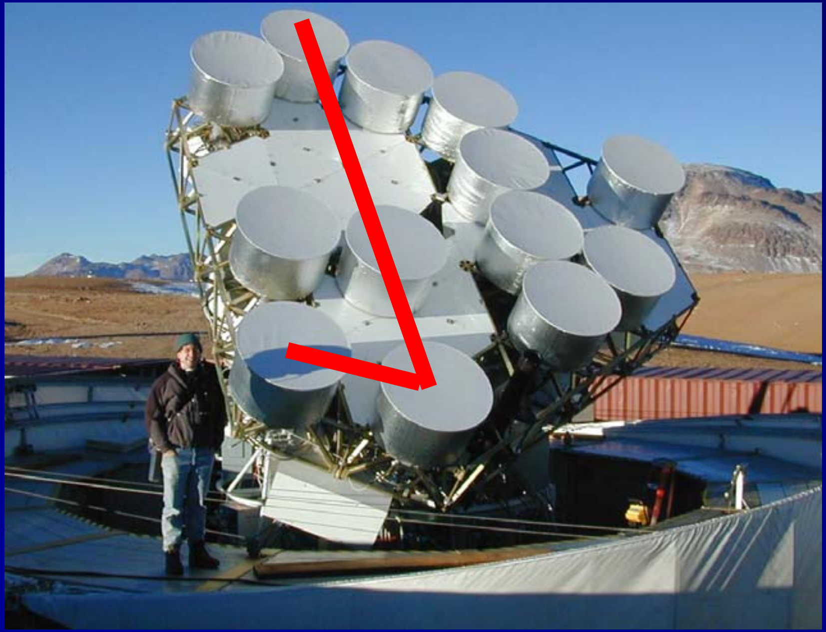


# CMB Interferometers

- Typical angular sizes ~ 1degree – 10 arcmin
  → small antennas, and/or, low frequency (10-100GHz)

$$\Delta\theta = \frac{1}{\Delta u} \approx 20' \left(\frac{d}{60\mathrm{cm}}\right)^{-1} \left(\frac{\lambda}{3\mathrm{mm}}\right)$$

- CMB anisotropy = diffuse, weak signal (10-100μK)
  → close-packed, or compact array to maximize sensitivity
- Observing strategies, different from traditional ones
  e.g., no geometrical delay to creat fringes when tracking



CBI @ 26-36 GHz, 13 elements, Chile (1999~)

DASI @ 26-36 GHz, 13 elements, South Pole (1999~)

# 3. Array for Microwave Background Anisotropy

**Positioned as the 1st astronomical project initiated, designed, and led by Taiwan (2000~)**

# AMiBA Collaboration

- AS  Institute of Astronomy & Astrophysics (ASIAA)
- NTU  Department of Physics/Astronomy
- NTU  Department of Electrical Engineering
- Australia National Telescope Facility
- University of Carnegie Mellon
- Jet Propulsion Laboratory/TRW
- Major Contractors:  ALONG, Vertex, CMA

2000-2004 MoE, Taiwan
2003-2008 Academia Sinica, Taiwan
2004-2008 NSC, Taiwan
[2000-2002 Design]
[2002-2005 Build]
[2005-2007 Commissioning/Operation]

# AMiBA Team: Dedication @ Mauna-Loa (3400m), Hawaii (Oct 2006)

# AMiBA Science Goals

## Science Objectives:

**CMB structure @ l=800-10,000:** **or** $\Delta \theta = 20' - 2'$

**(1) CMB Power Spectrum and Structure at high-l** [small scales]

Primary / Secondary (SZE) anisotropy (l=800-3000, l=1000-6000)

→ Initial condition of DM density fluctuations ($\sigma_8$)

**(2) Galaxy-Cluster Survey via the Sunyaev-Zel'dovich Effect (SZE)**

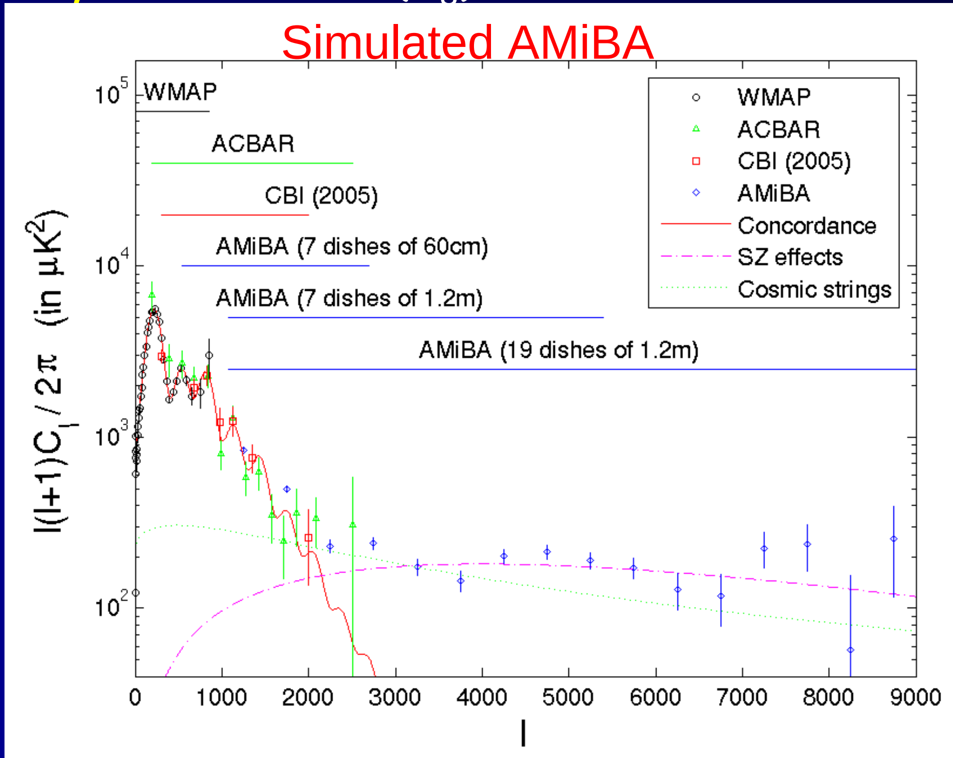
- Evolution of number counts of galaxy clusters, N(z)

  → Dark Energy Equation-of-State

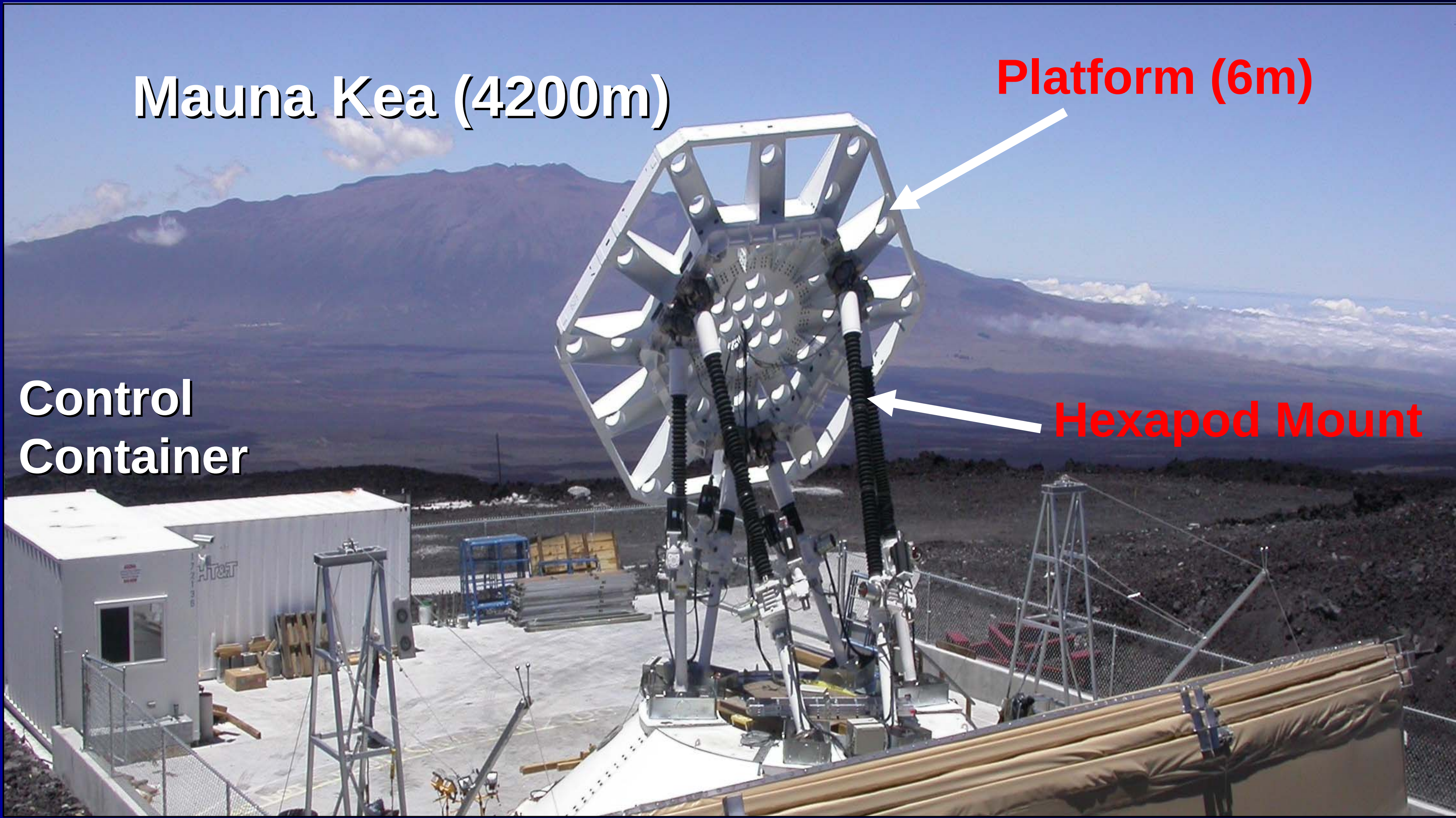
- Clustering properties of clusters

  → information of large-scale structure formation

- Probing high-z universe (z>1)

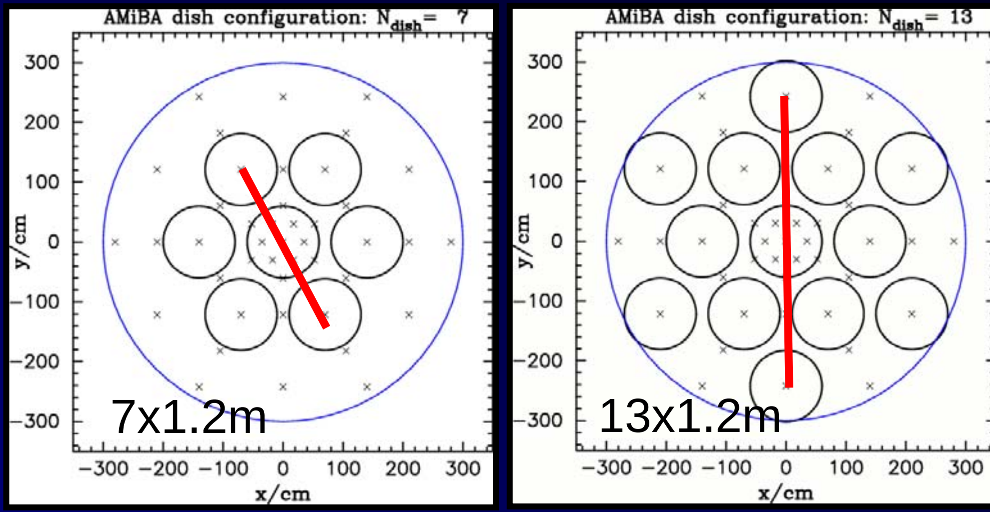


# AMiBA Site: Mauna-Loa (3400m)



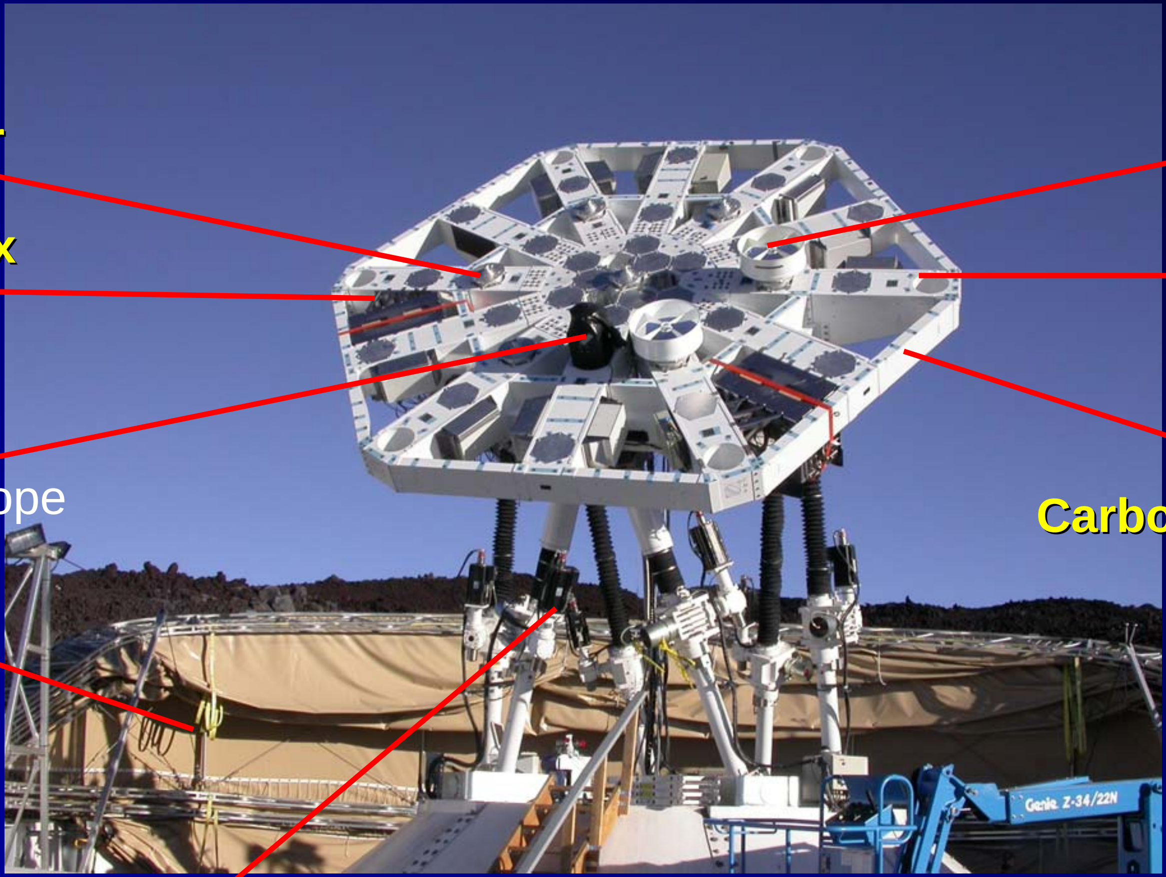
# AMiBA Specifications

- **7 / 13 / 19-element interferometer**
  - Co-mounted on a 6m platform
  - 21 / 78 / 171-baseline
  - Cassegrain D=60,120cm antennas
- **Dual channel 84-104GHz** (3mm)
  - HEMT cooled to 15K
  - Tsys = 80K
- **Full polarization capability**
  - Dual polarizer: Linear X,Y
- **Correlator**
  - Analog, complex, 4-lags
  - N = 42 / [156] / [342]-correlators
- **Angular scales and sensitivities**
  - FoV = 22’ (D=60cm), 11’ (D=120cm)
  - 2’ -6’ resolution
  - Down to 1.5mJy per 2’ beam in 1hr (15uK)




# AMiBA – A Hexapod Telescope

*http://amiba.asiaa.sinica.edu.tw*




Receiver

Correlator box

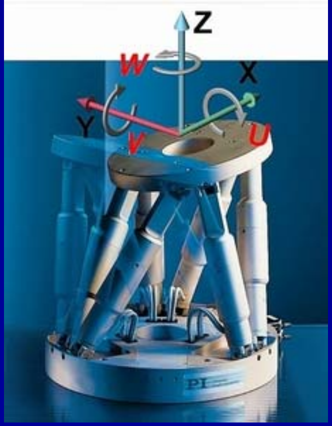
Optical telescope

Shelter

60cm antenna

Free Rx hole

Carbon fiber platform




Hexapod jack

0<Azimuth<360deg, Elevation > 30deg

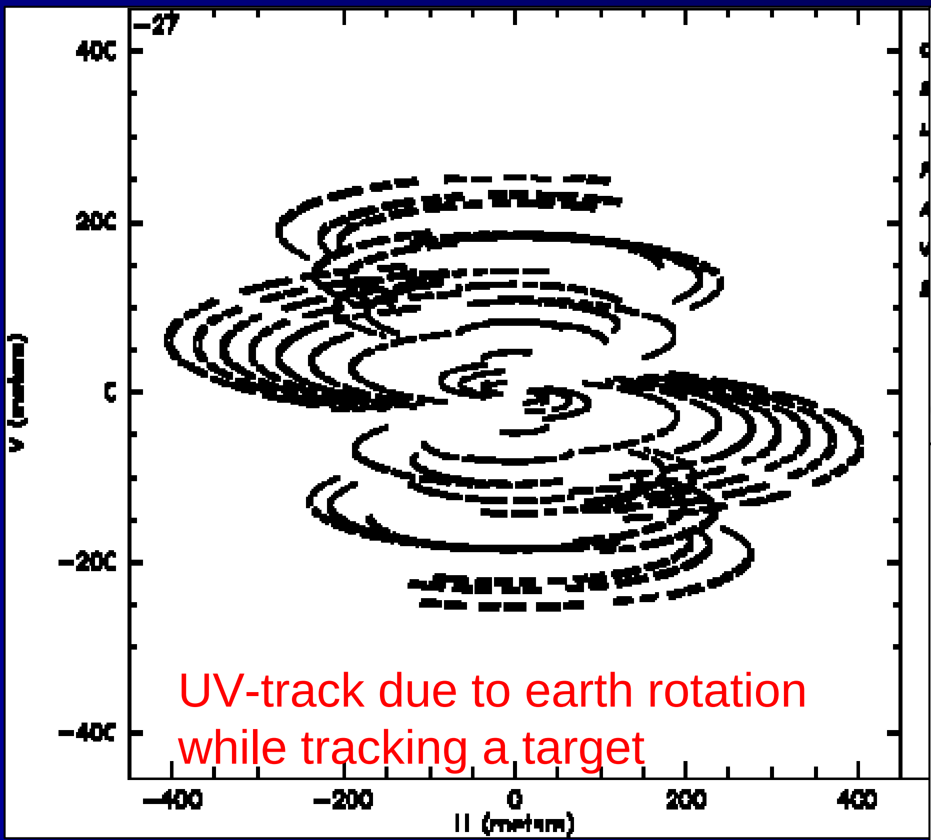
Polarization: +/-30deg

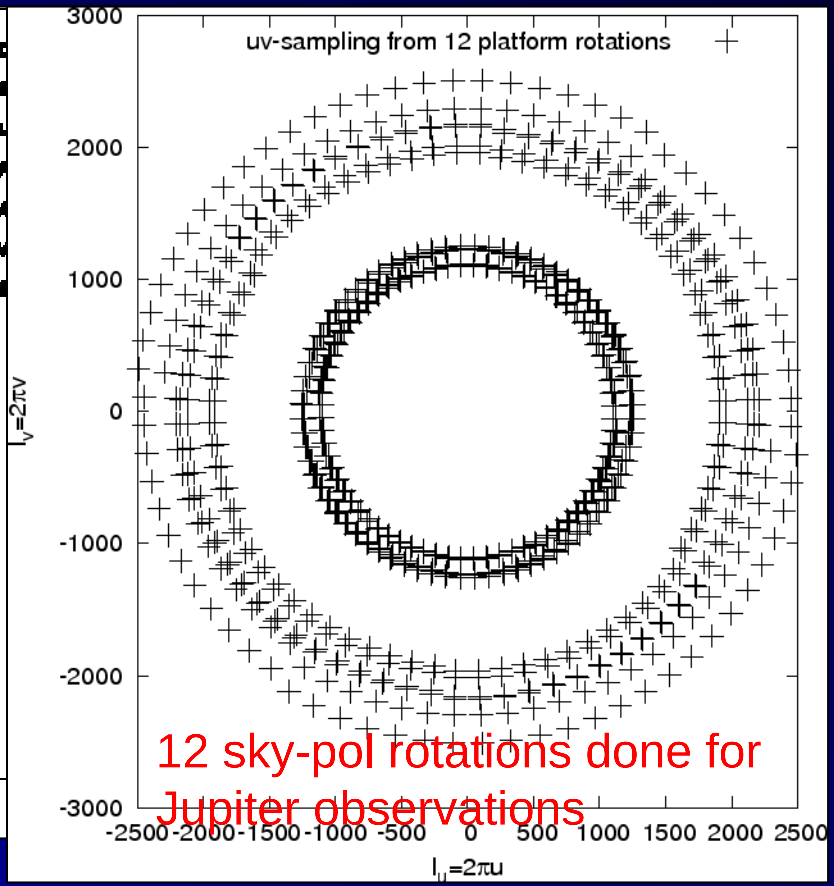
(June, 2006)

# AMiBA: Better uv-sampling: S(u,v)

Traditional interferometer
[2-axes: Azimuth, Elevation]

AMiBA with active platform rotations
[3-rotation DoF: Az, El, Pol ]




**PSF** is an **Inverse FT** of the uv-sampling function:

$$B(\vec{x}) = \mathbf{FT}^{-1}[S(\vec{u})]$$

# Dust/Synchrotron foreground emission minimized at 3mm

Typical SEDs of Galaxies

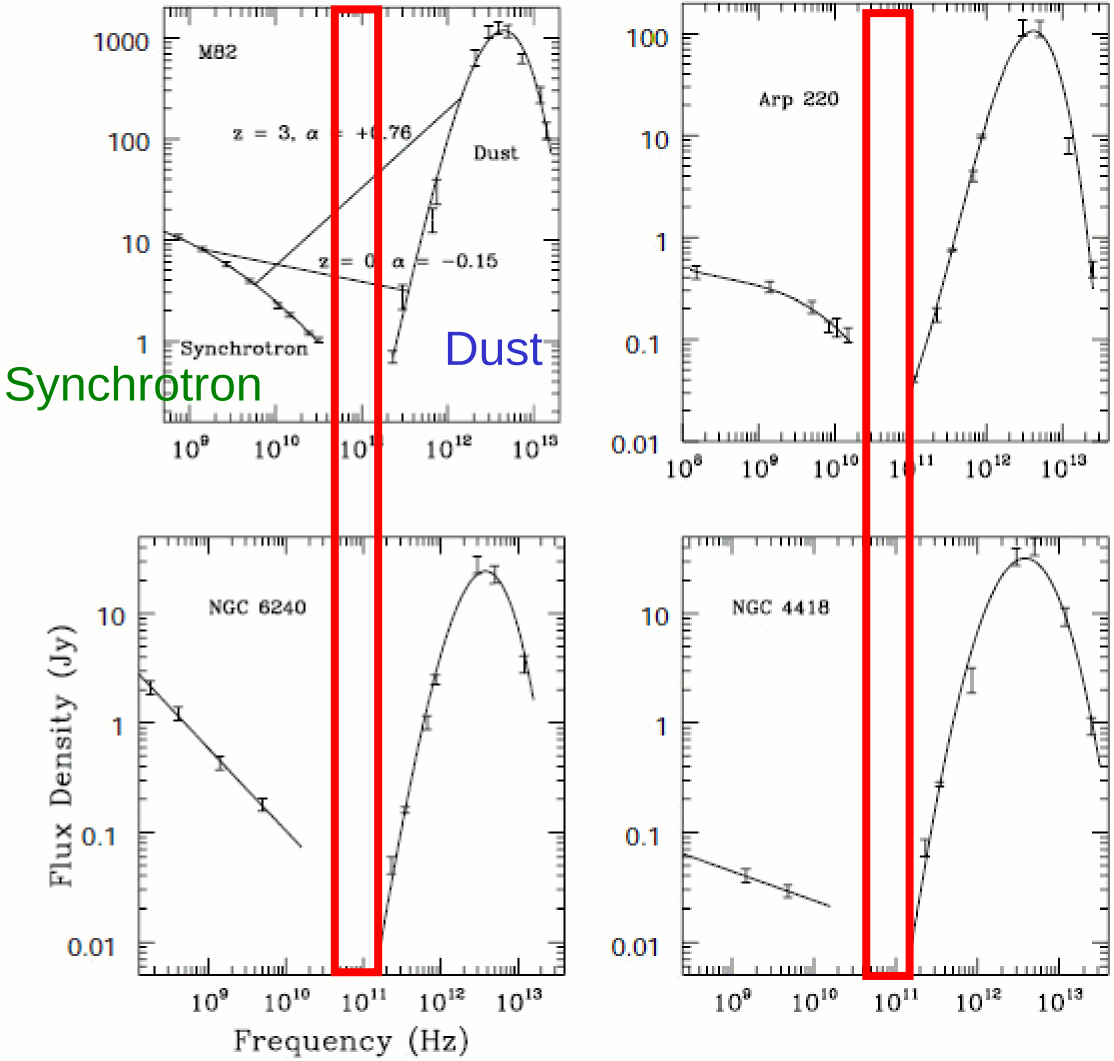
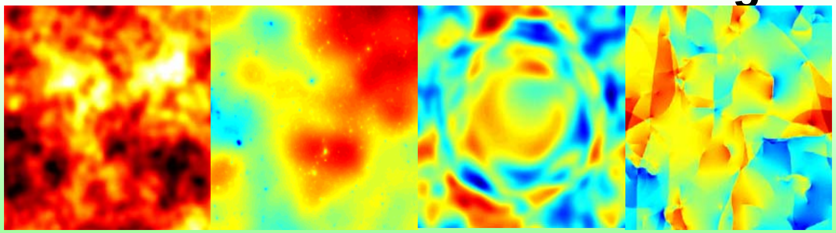


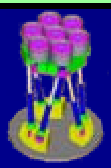

FIG. 1.—Data points show the radio through infrared spectral energy distributions of four representative galaxies from our sample of 17 listed in Table 1. The data are obtained from NED (*IRAS* data points), the NRAO VLA Sky Survey (Condon et al. 1998), the Westerbork Northern Sky Survey (Rengelink et al. 1997), and from Rigopoulou et al. (1996), Benford (1999), and Lisenfeld et al. (1999). The solid curves show polynimial fits to the data. For the M82 spectrum, the straight lines indicate the spectral index that would be derived for the source at $z = 0$ and $z = 3$ between observing frequencies of 1.4 and 350 GHz.

# AMiBA Data Analysis Flowchart

**Simulated or observed CMB signals:**



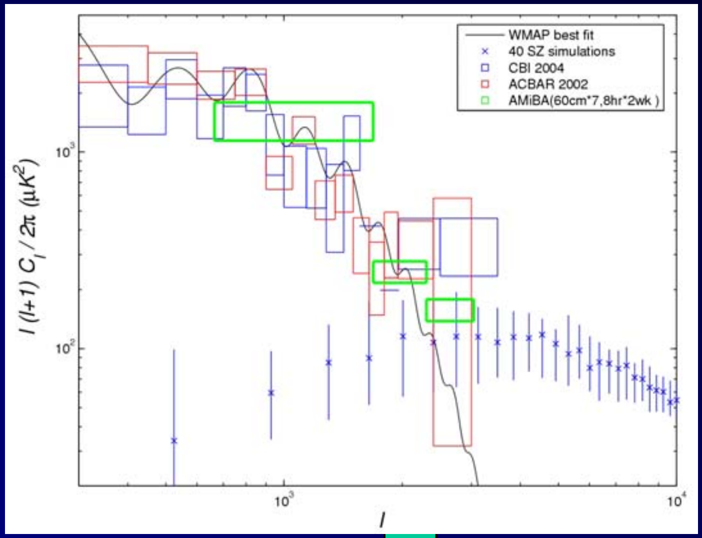
Inflationary SZ effects Lensing effects Cosmic strings



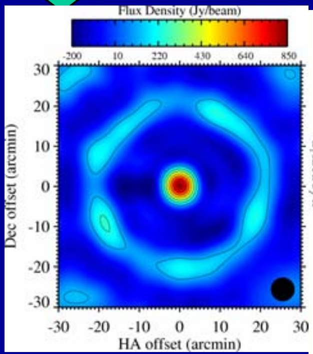
Data Taking
(with AMiBA configuration)

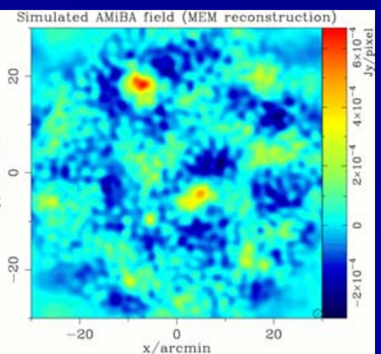
**Fringe/lag data to visibilities**

Power-Spectrum Estimation
(maximum-likelihood analysis)




Map Making
(maximum-entropy method, etc.)




1. **SZ Effects**
2. **Polarizations**
3. **Cosmological Parameters**

($\Omega_{tot}$ $\Omega_b$ $\Omega_{cdm}$ $\Omega_{DE}$ $H_0$ $\sigma_8$ $w$ $n_s$ $n_T$ $\tau_c$ etc.)

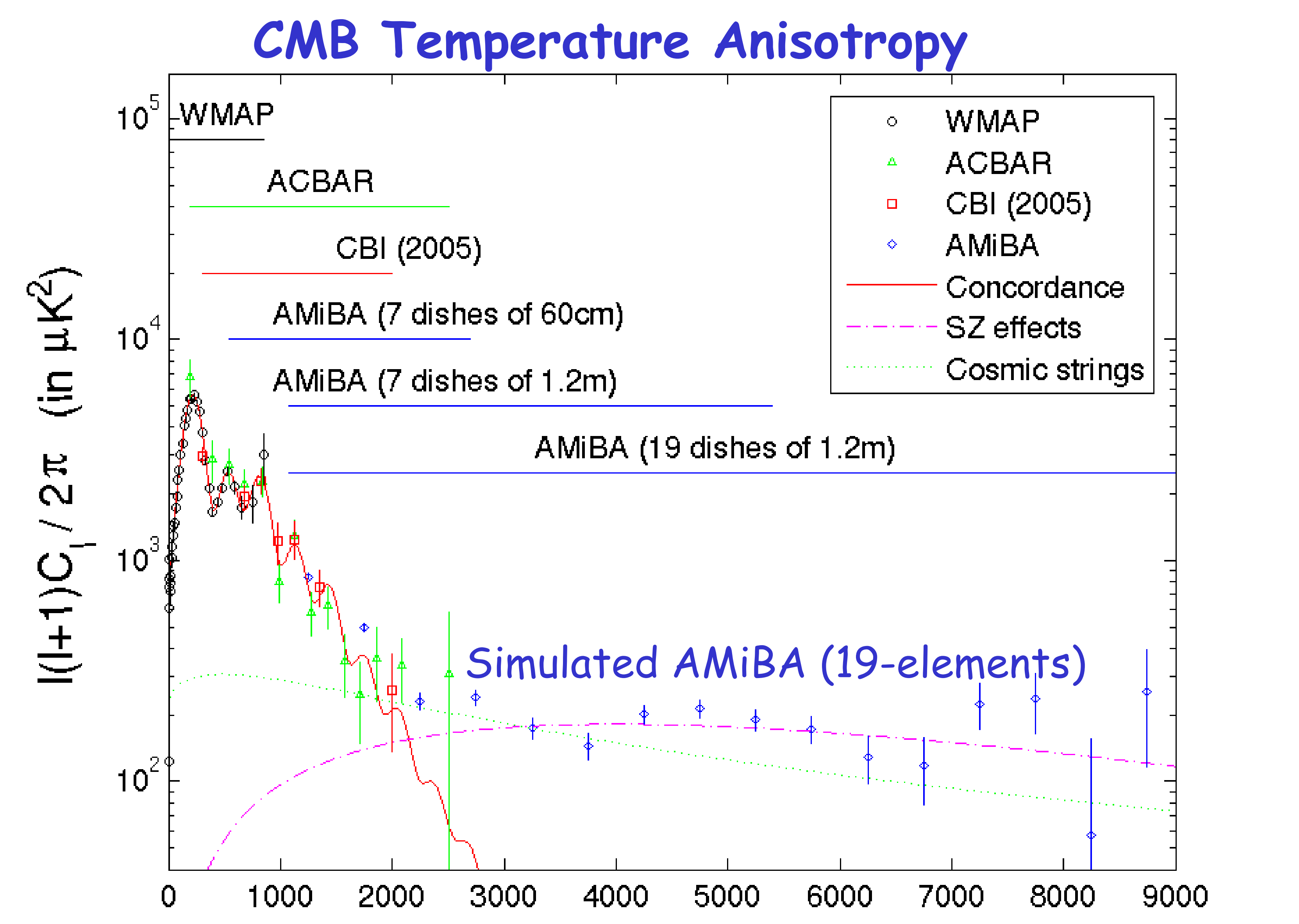
# Expected Performance of AMiBA

## AMiBA Science (1)

**Measurement of**

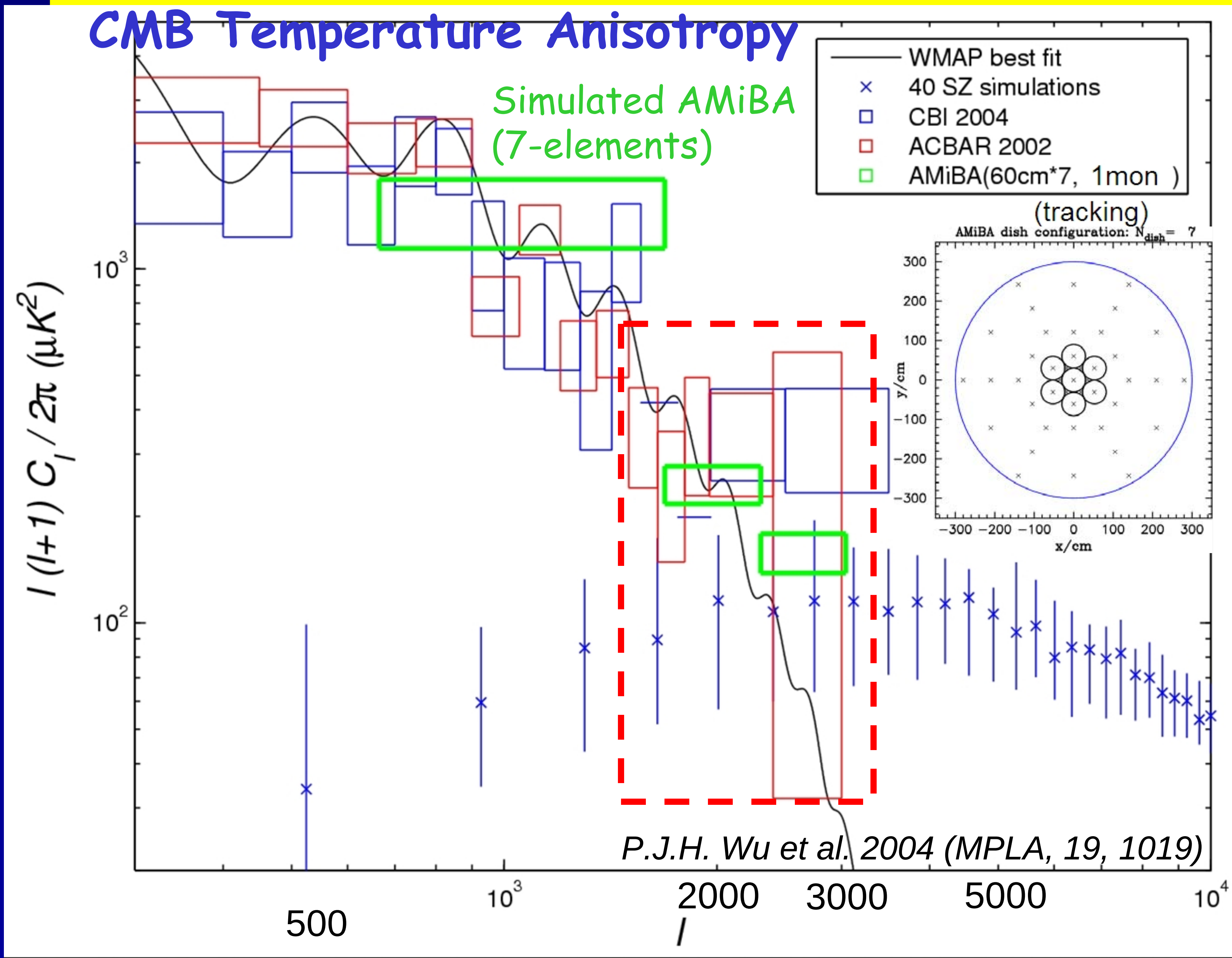
**CMB Angular Power Spectra**

# Full 19-elements Performance




*P.J.H. Wu et al. 2004 (MPLA, 19, 1019)*

# 7-element Performance in 1month



# Expected Performance of AMiBA

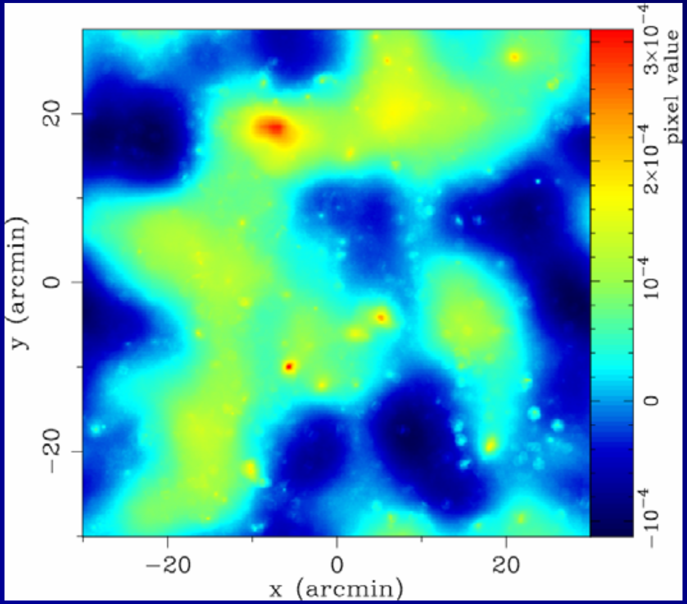
## AMiBA Science (2)

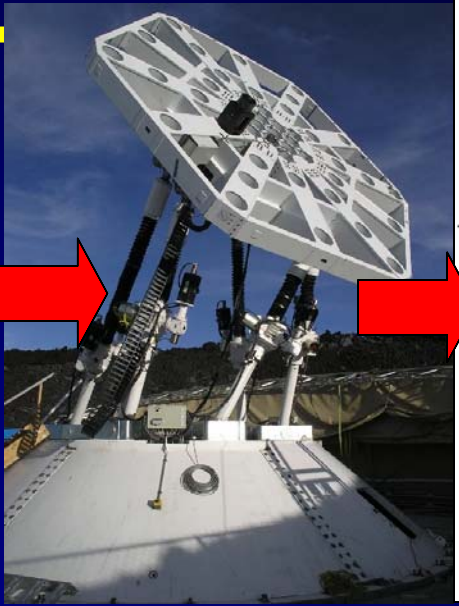
**Search for High-z Galaxy Clusters**

**via the Sunyaev-Zel'dovich Effect**

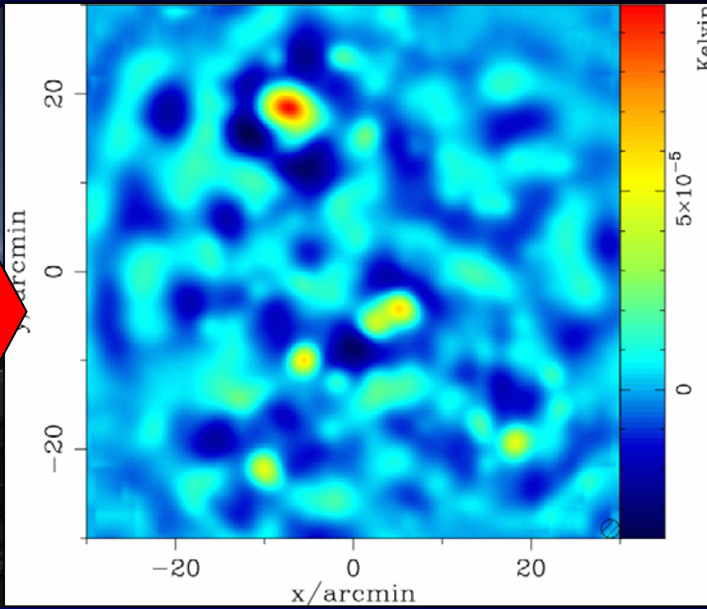
# AMiBA: Probing Small-Scale Anisotropy

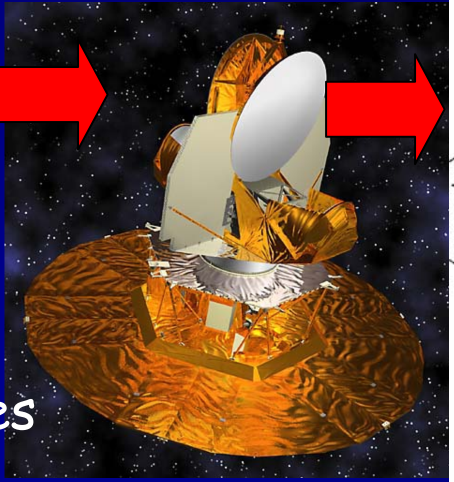
Input Primary + Secondary (CMB+SZE) sky @ 94GHz



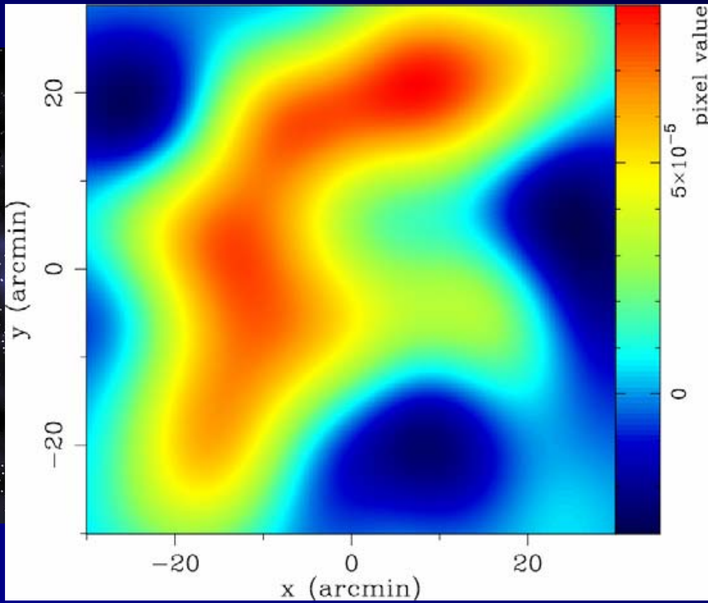



2' FWHM beam



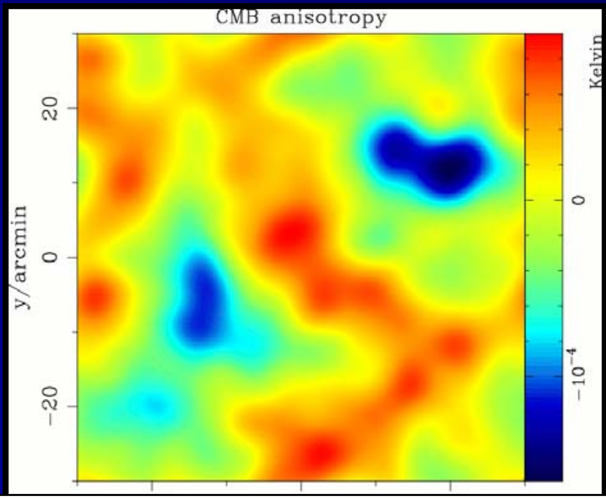
14' FWHM beam




**AMiBA** will target angular scales smaller than WMAP to study cluster-sized structures (~1Mpc) via the thermal **S-Z effect (T-SZE)**

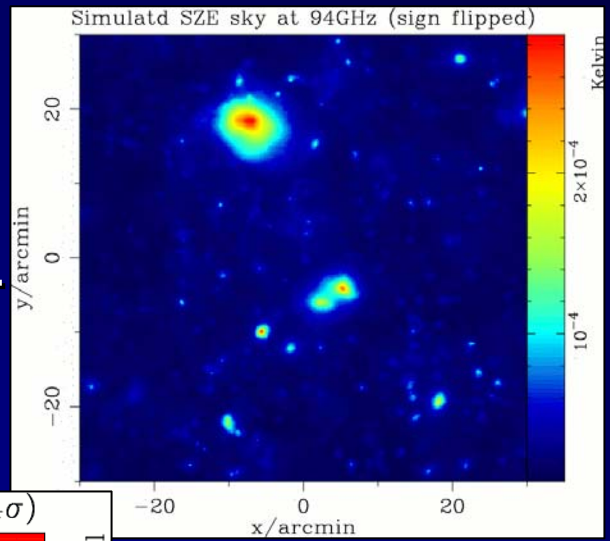
# Simulated AMiBA Deep Survey

**Primary CMB**



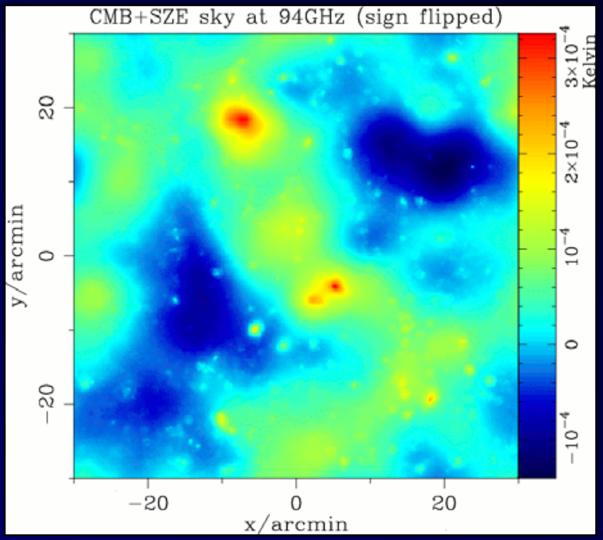

+

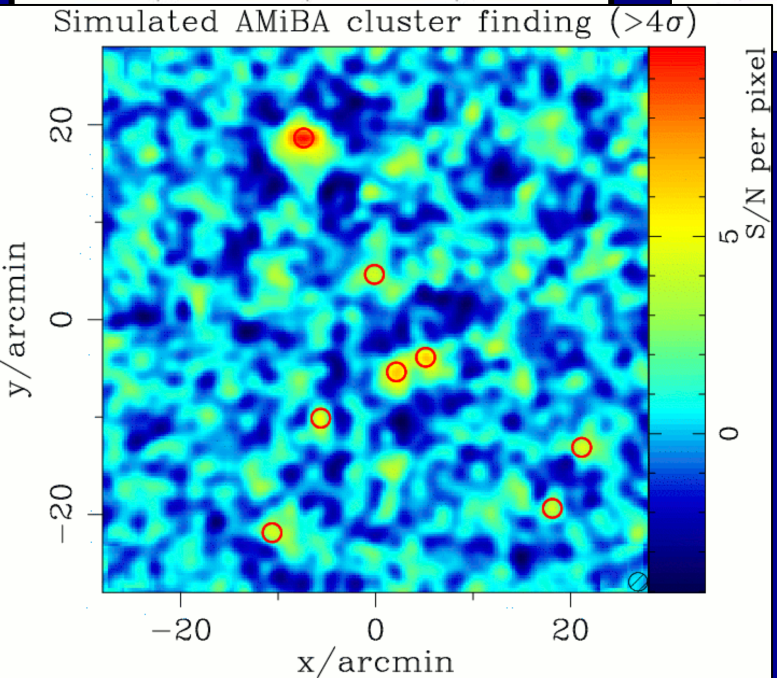
**T-SZE (ΛCDM, preheating)**




=

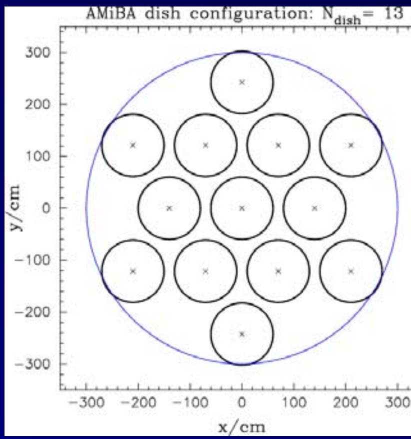
**CMB+TSZE sky @94GHz**




***Simulated AMiBA survey***

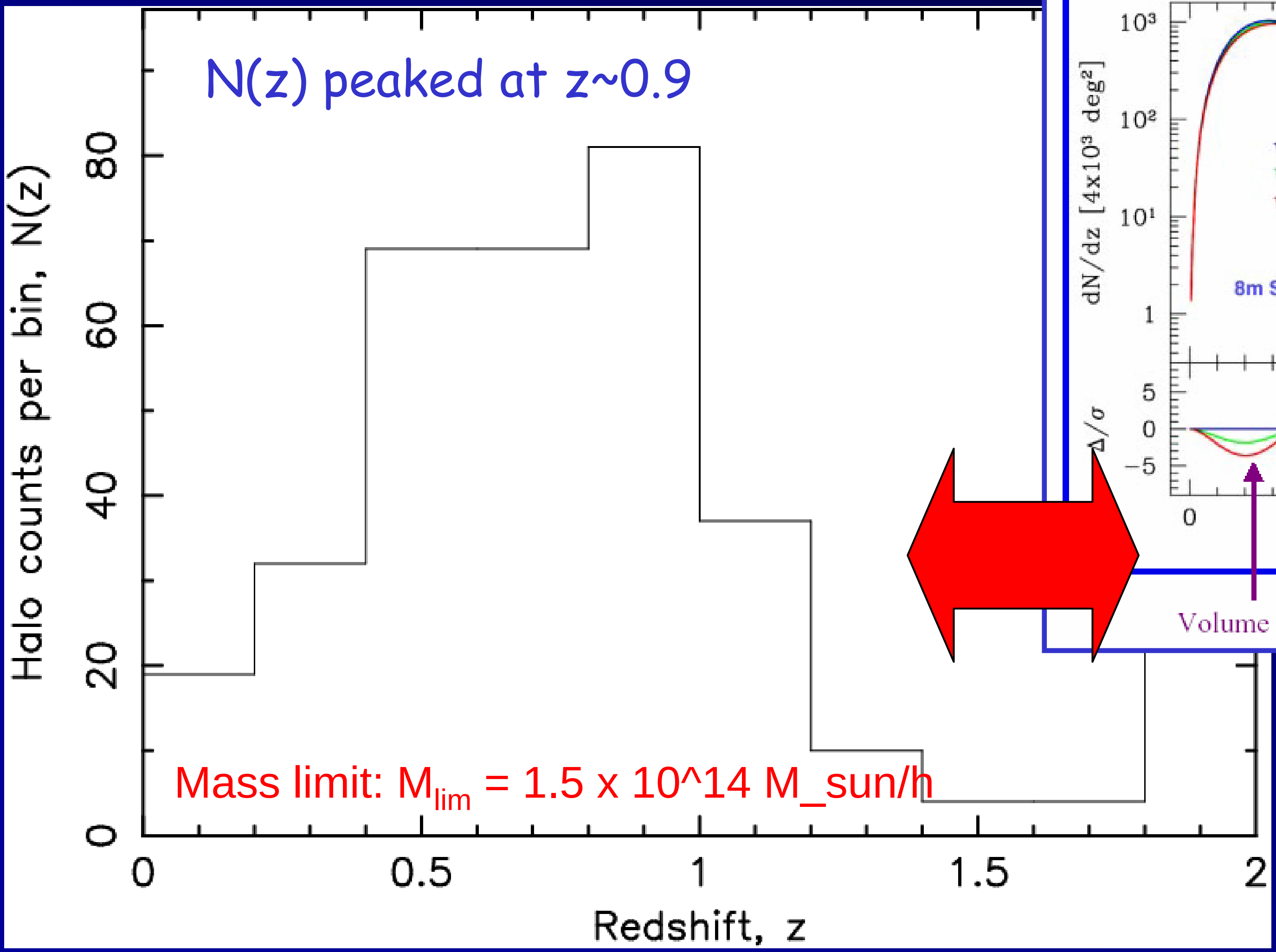
- 400ks integration over 1deg^2 (**14 nights**)
- 20cm gap between adjacent dishes filters out **primary CMB contamination**
- **Sensitivity**: 1.1mJy per 2' beam: 0.5mJy primary contribution included

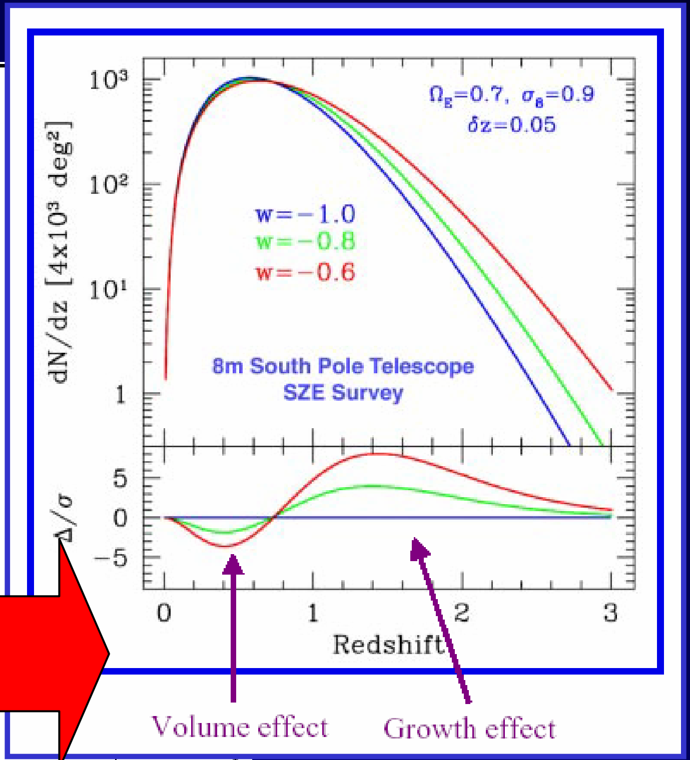



*K. Umetsu et al. 2004 (MPLA, 19,933)*

# Redshift distribution of SZE Clusters from a simulated AMiBA deep survey

AMiBA will detect ~100 clusters ($\Omega$=10deg^2) in 1 year,
…assuming 8hrs-integration per night




*K. Umetsu et al. 2004 (MPLA, 19,933)*

# 4. AMiBA Current Status

# Site Development: April 2004-August 2006


April 2004


October 2004


Nov 2004

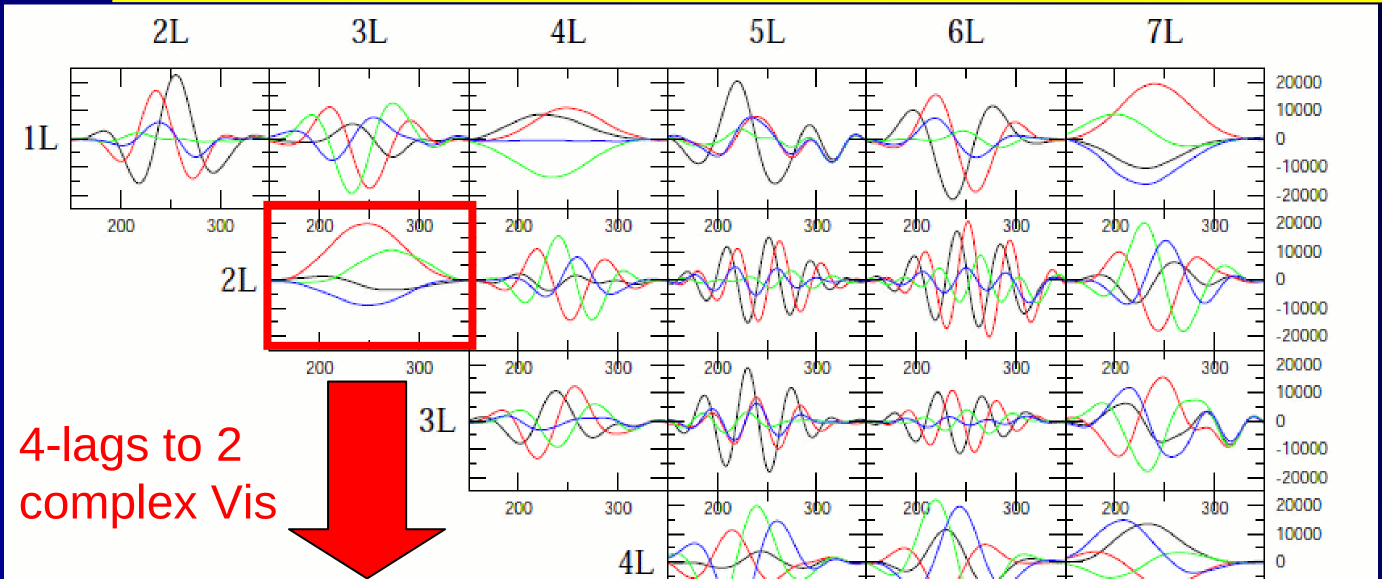
Mount commissioning: started in jan 2005
Receiver and correlator on-site testing since late 2005


August 2006

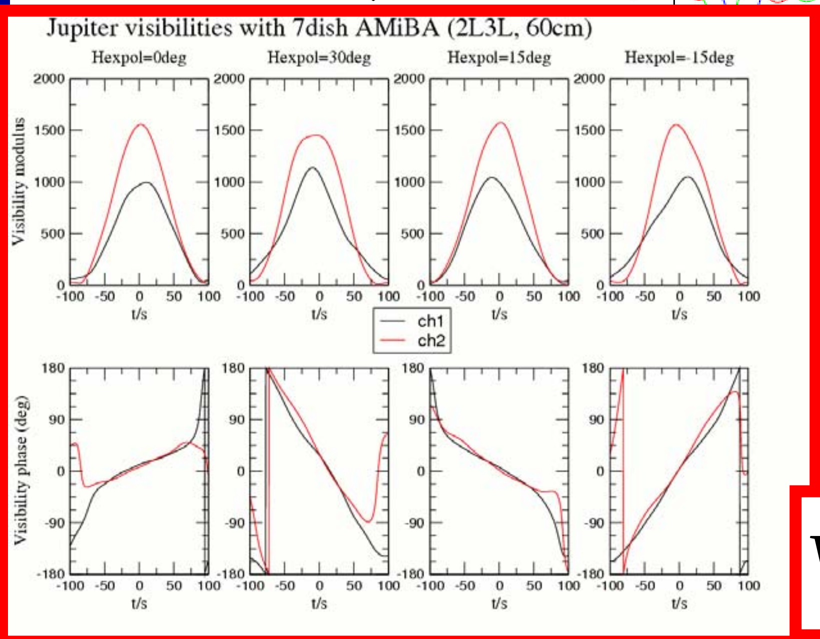

August 2005


Feb 2005

# First Planet Fringes: Jupiter




4-lags to 2 complex Vis




Sep 8, 2006

Noise-filtered fringes of Jupiter taken with drift-scan mode, shown for 21 (/ 42) baselines

**Jupiter**

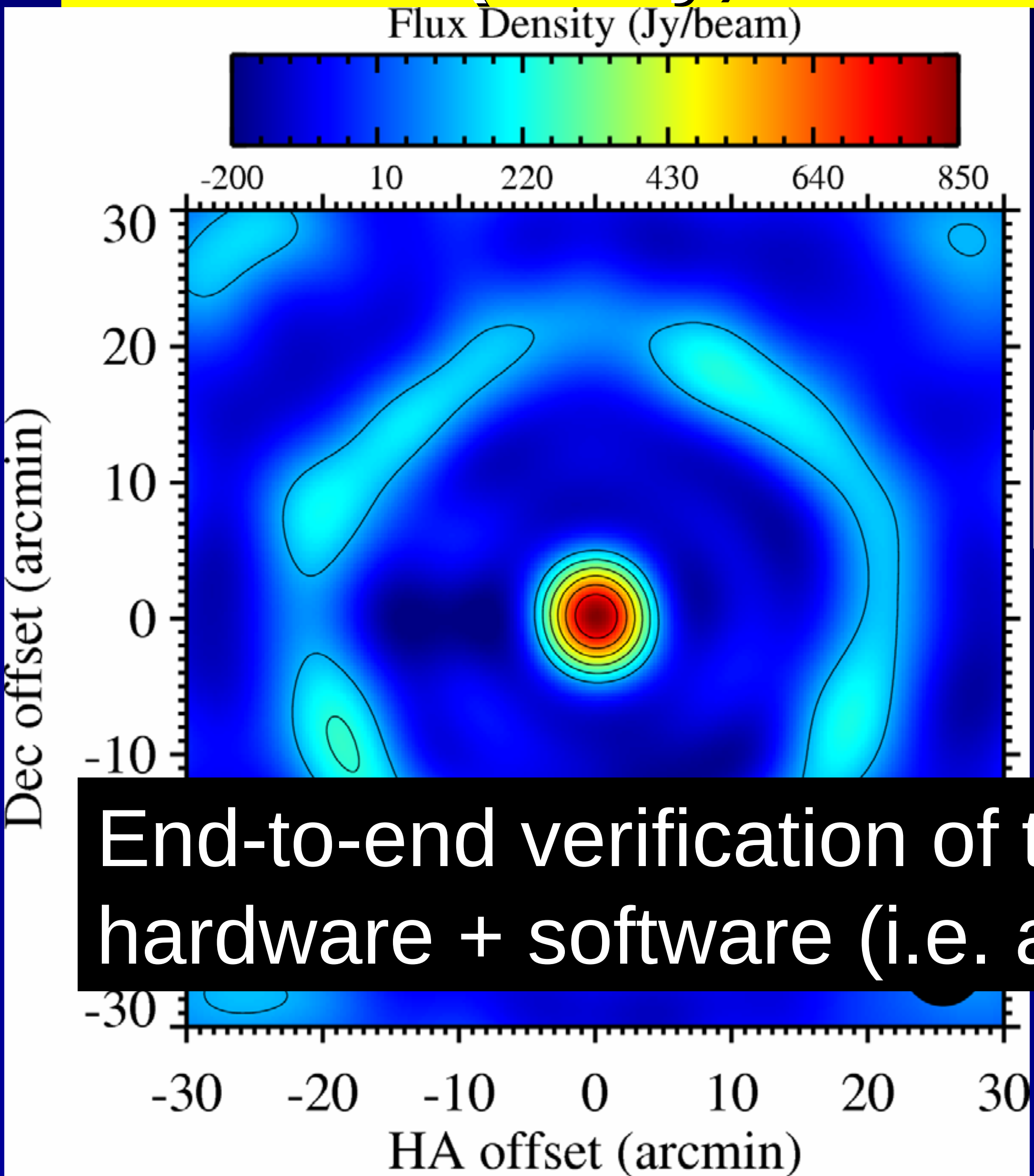
(point source for AMiBA):

850Jy @94GHz

Fringes-to-Visibility transformation (a=1,2,3,4)

$$\hat{V}_a = T_{ab}[K_{bj}P_{jd}]^{-1}c_d \equiv T_{ab}\left(\hat{K}^{-1}\right)_{bd}c_d$$

# AMiBA First Image: Jupiter (850Jy, Point source)




September 9, 2006

12 scans combined at transit

Net integration = "12s"

**Dirty image**

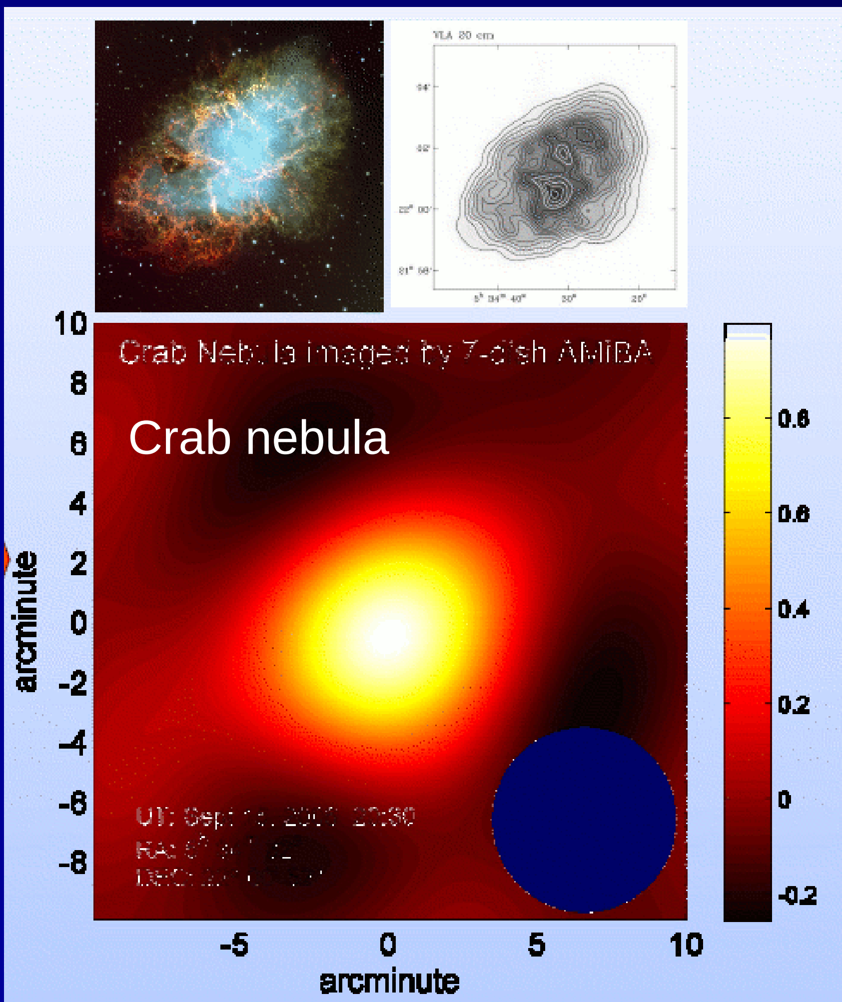
$$I(\vec{x}) = \mathbf{FT}^{-1}[S(\vec{u})V(\vec{u})]$$

End-to-end verification of the system = hardware + software (i.e. analysis pipelines)

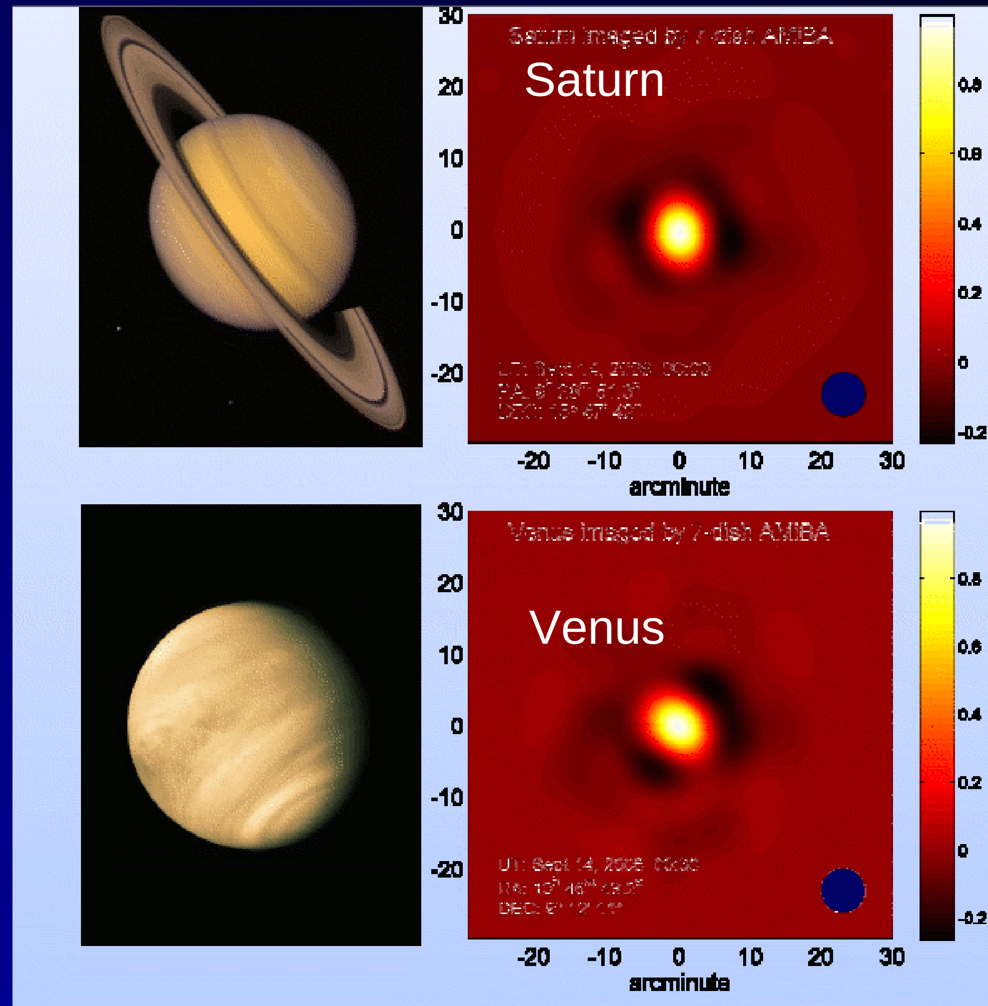
Synthesized beam FWHM (6')

# More First Images (Sep 2006)

Elongated structure of an extend source nicely recovered (Flux~200Jy @ 3mm)



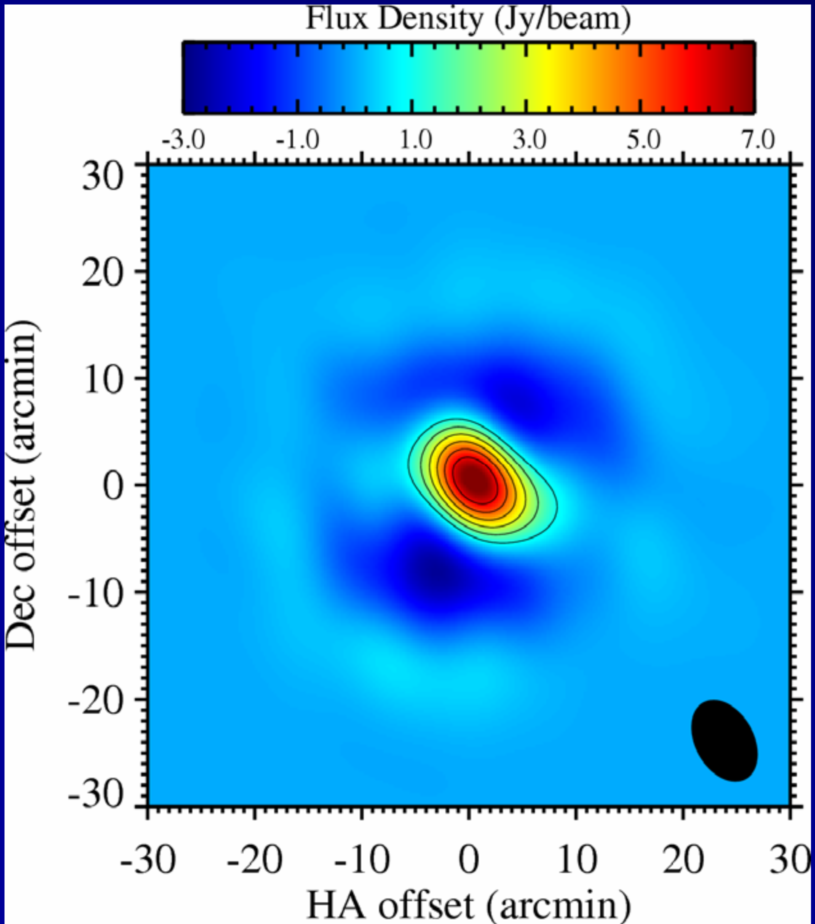

Fainter targets [point sources] with Flux~170Jy @ 3mm




*Figures here  from J.H. Proty Wu (NTU/Phys)*

# Fainter Target: Uranus (7.3Jy@94GHz)

- 16 drift scan observations
- No signal seen in fringes, for < 40Jy sources
- Signal only detected after image synthesis




Dec 22, 2006

Image reconstruction from 16 drift-scans, with a net integration of "16s"

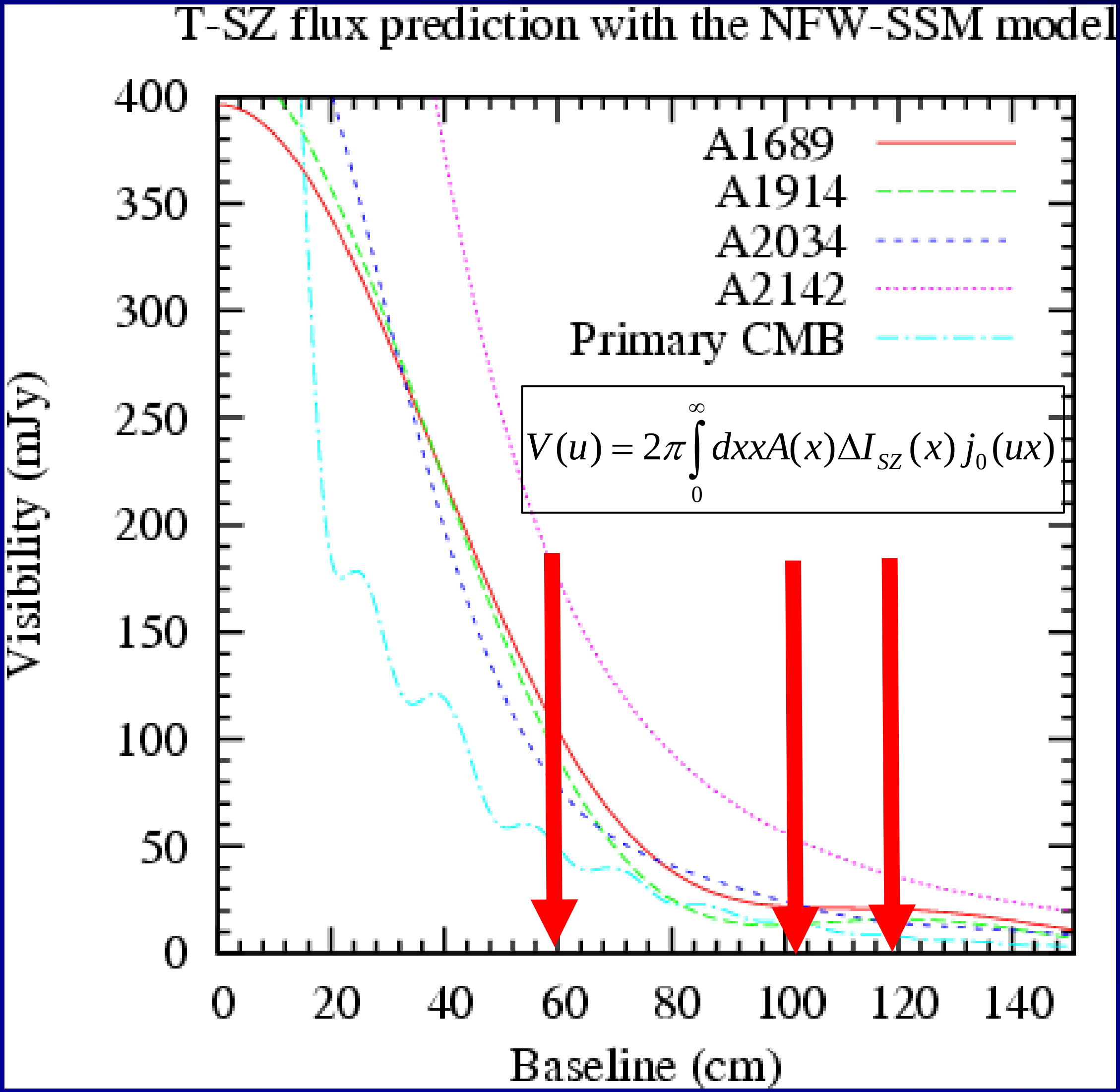
But took a few hours for completing 16 drift scans…

Only 23 (/ 42) baselines were available, resulting in a poor UV-coverage and a highly distorted image

Noise rms =~ 1Jy/beam (in 16s, 23 baselines)

# Next – SZ Effect Observations towards Clusters of Galaxies

Clusters are faint, extended radio sources

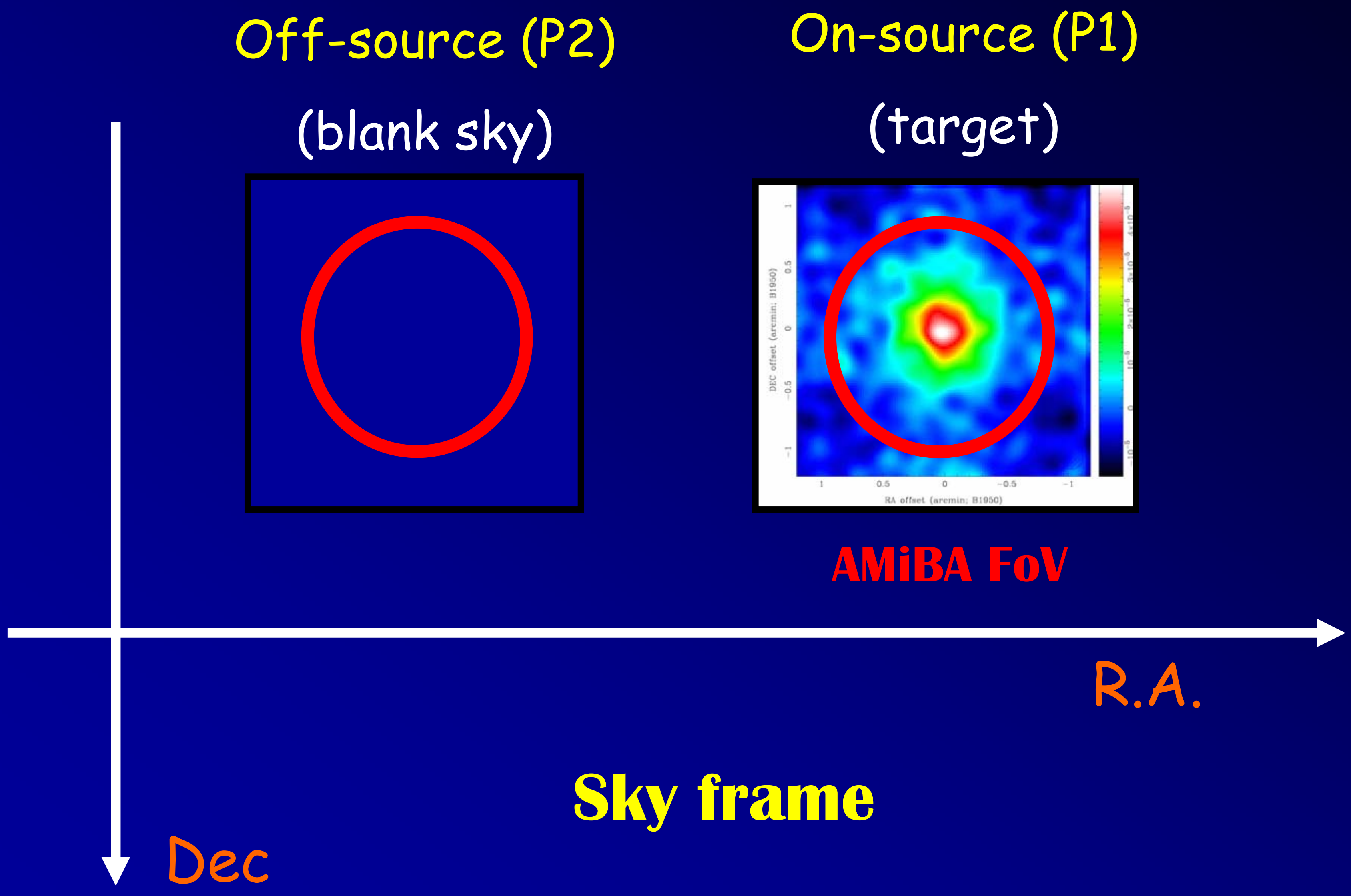



**Theoretical model predictions for the T-SZE towards nearby, massive clusters ::**

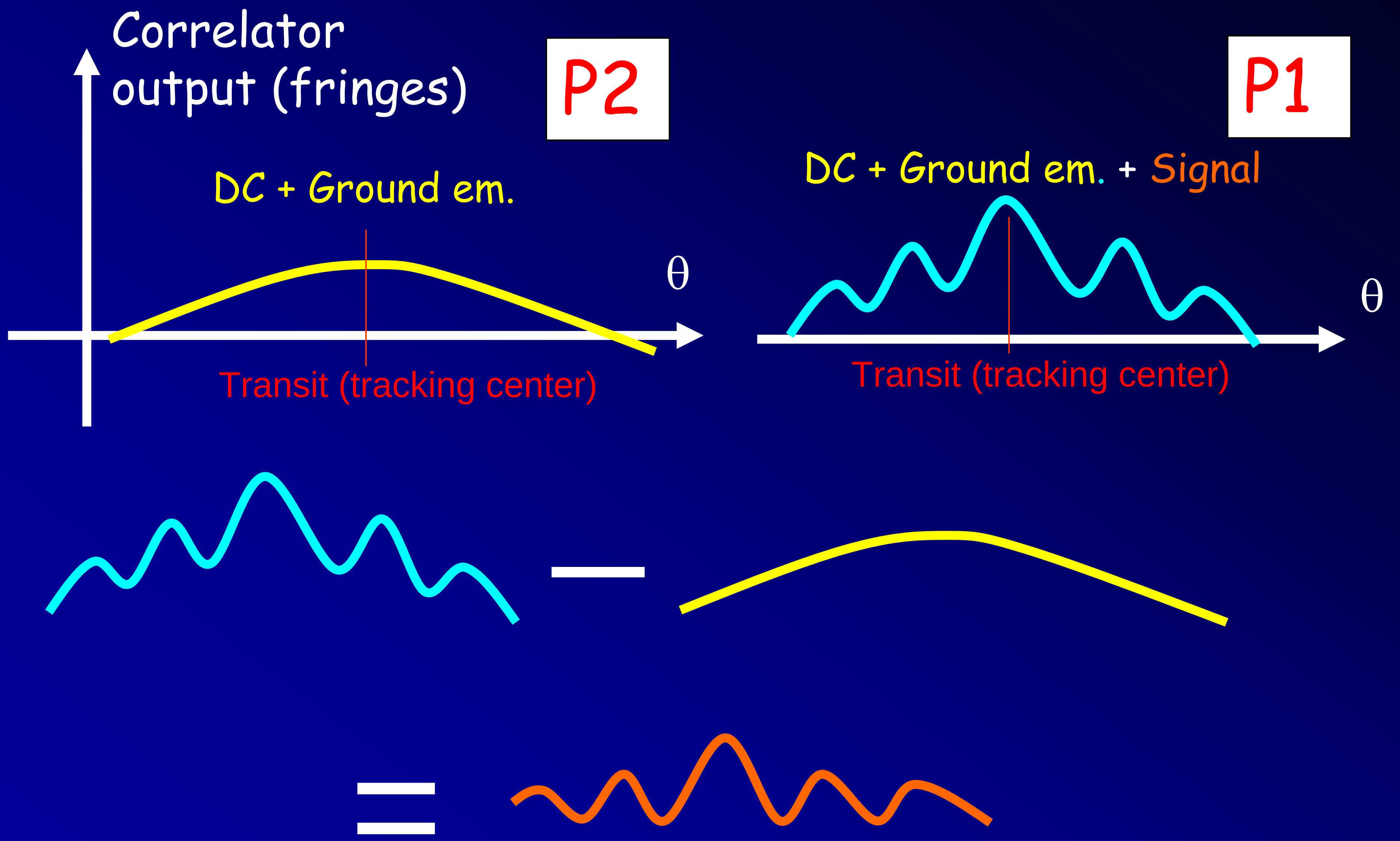
For AMiBA with 6′ synthesized beam, clusters at z=0.1-0.2 are extended sources..

Due to their large angular size, their fluxes at 60cm can be as large as 200-300mJy for very massive systems

# Two-Patch Tracking (1)



# Two-Patch Tracking (2)



# Two-Patch Tracking: Pros & Cons

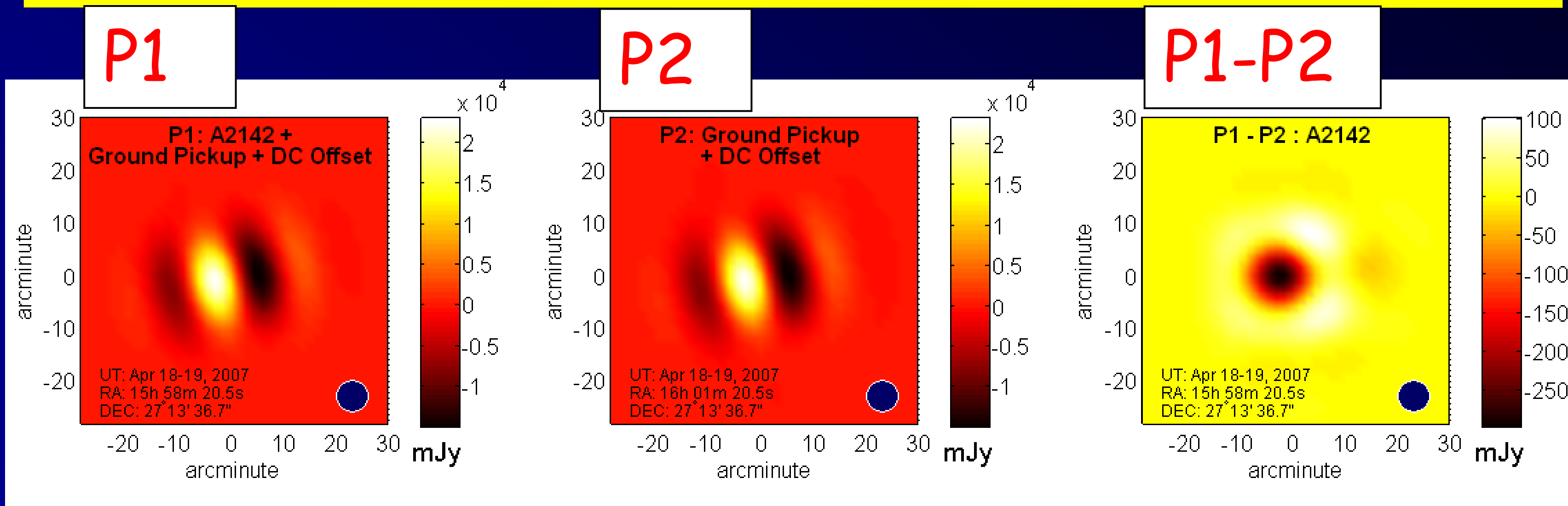
## Pros

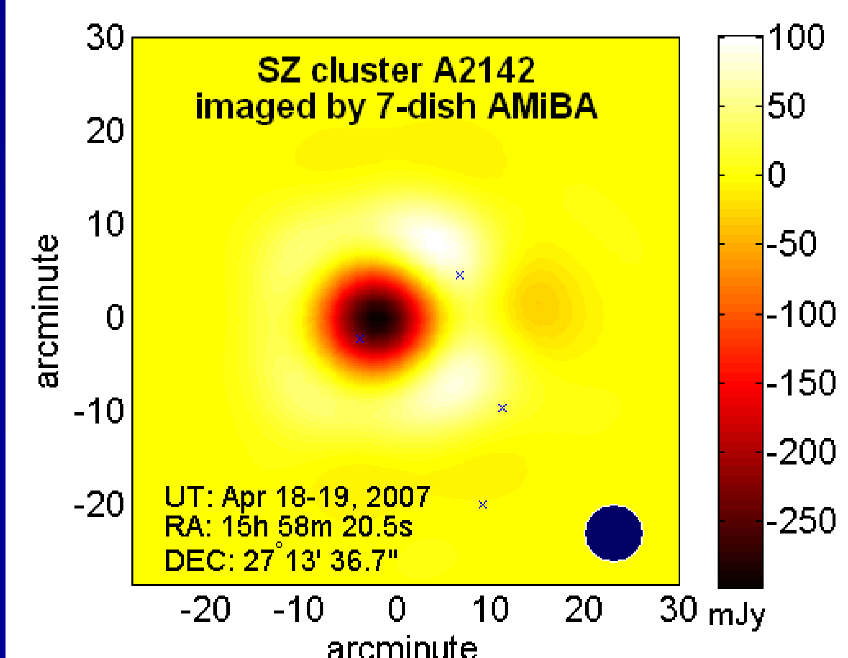
1. Allowing a **long on-source integration**, up to the limitation by the system stability (i.e., 1/f noise etc.)
2. Differentiate (P1-P2) in fringe domain, **removing the slowly-varying DC-signal** due to (1) the system and (2) ground emission

## Cons

- Observation time is twice of the single patch: cf. $\sigma \sim (s^2_b/t)^{1/2}$
- Differentiation (P1-P2) increases RMS noise by a factor of sqrt(2)
- In total, the net sensitivity is worse by a factor of (2^1/2)^2 = 2 → 100mJy/beam in 1hr
- However, the observing efficiency for extended, faint sources is much better than drift-scanning

# First SZ Effect Detection: A2142 (z=0.09)

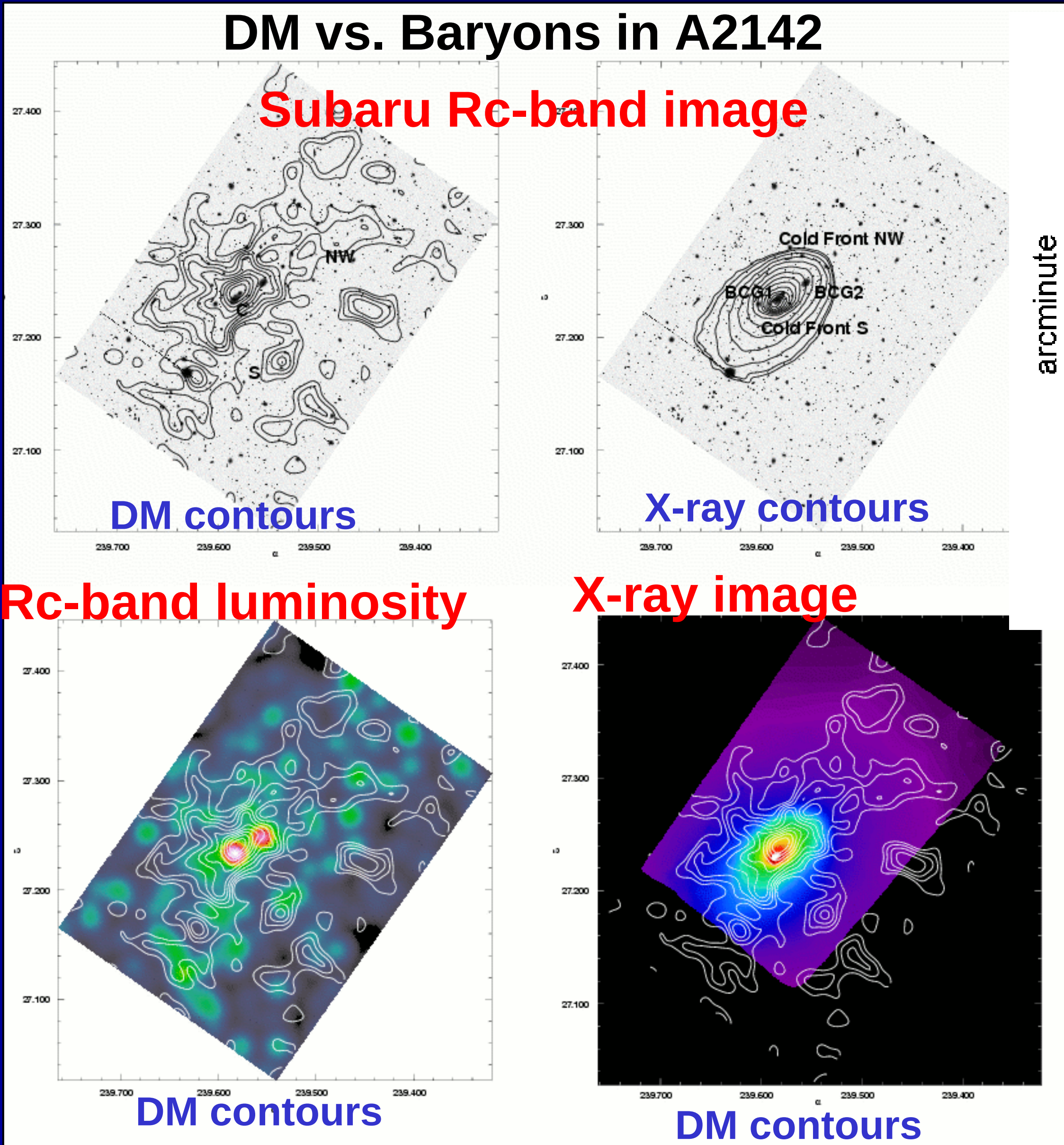


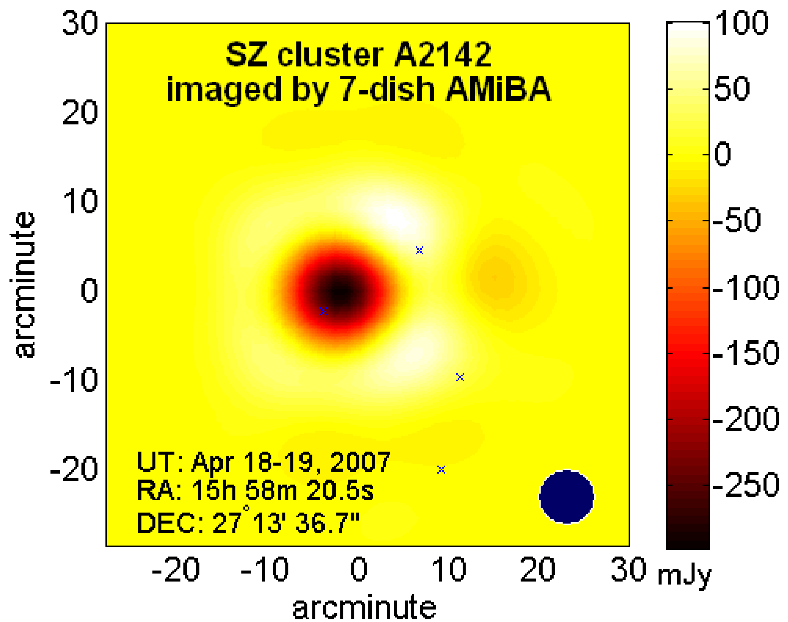




Estimated flux (@60cm, or u=200) is 300mJy, being consistent with the 30GHz observation by VSA

About 6σ detection in 5hr x 2P observations (2-3 nights)

# Possible Science with AMiBA
# "Multi-Wavelength Study of Clusters"




Lensing + X-ray + Optical + SZE,

probing the cluster physics

*Weak lensing, X-ray, and optical study of 7-merging clusters of galaxies by*

Okabe & Umetsu (2007)

# Next Steps and Key Issues

**Next Targets:** **Aiming at starting CMB observations in a few months**

→ Quasars (point like) (100 -1000mJy) : *< a-few hrs x 2-patch tracking*

→ Bright SZE clusters (100 - 300mJy) : *(5--50hrs) x 2-patch tracking*

→ Diffuse CMB power spectrum (rms<50mJy) *: ~ a few months?*

……Practically, t < 6-8hrs integration per night

## Key Issues:

- System efficiency improvement to increase "sensitivity":
  - Receiver-antenna alignment within 2-3 arcmin for <~2% efficiency loss
  - Currently, efficiency parameter $\eta = 0.3\text{–}0.4$, while ~0.6 expected
- Identify and minimize systematics, which limits the sensitivity
  - Ground-emission pickup measurement and shielding: cf. CBI found several $\mu$K contribution in a synthesized image
  - Stability of the system for a long integration: 1/f-noise, whiteness of noise

# Summary