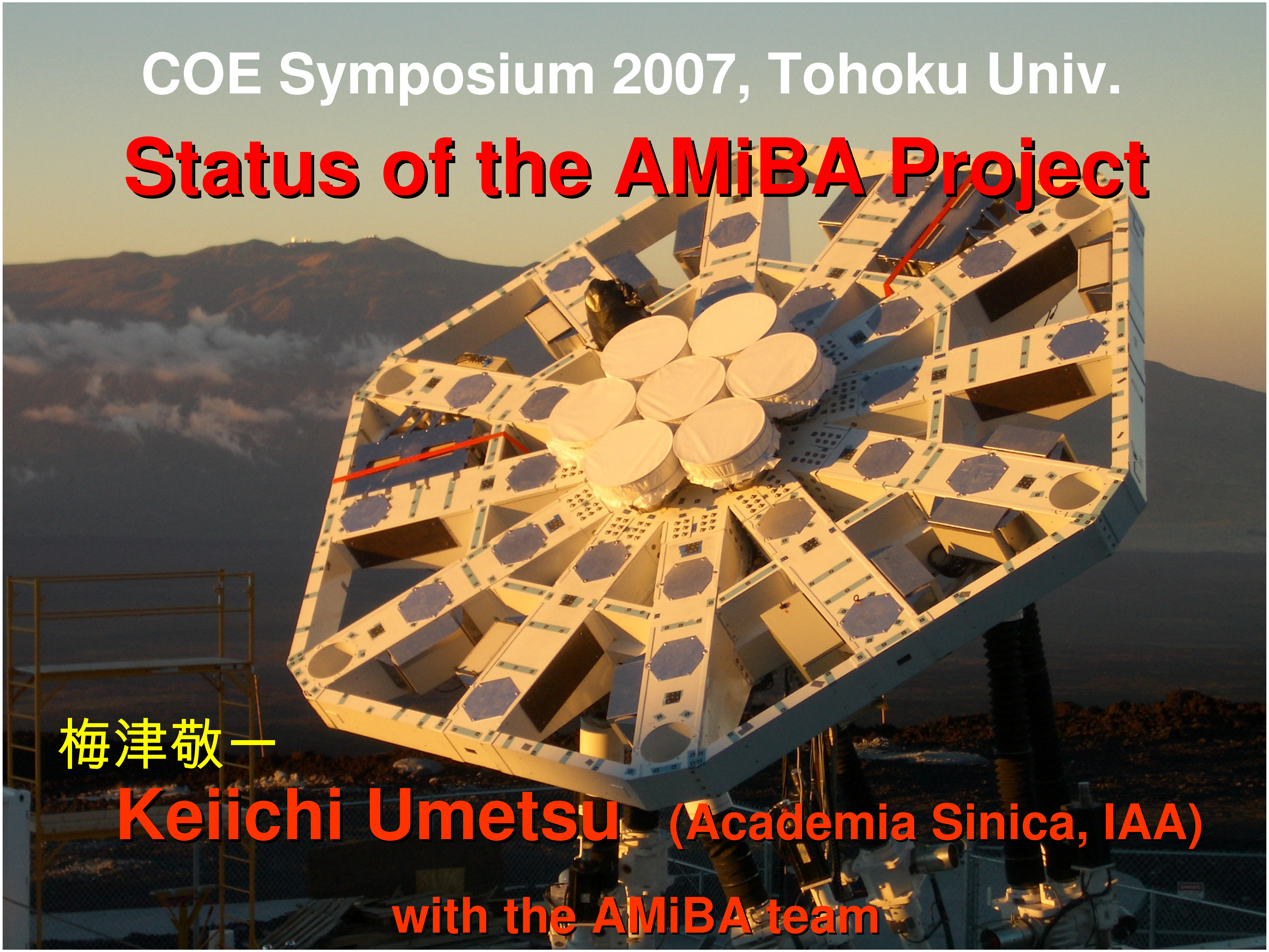

COE Symposium 2007, Tohoku Univ.
Status of the AMiBA Project
梅津敬一
Keiichi Umetsu (Academia Sinica, IAA)
with the AMiBA team

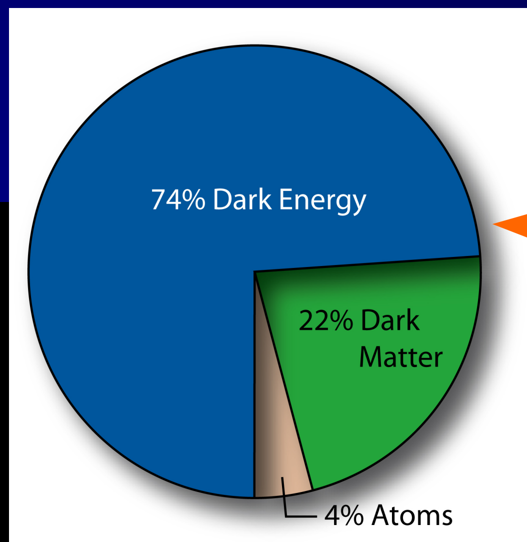
Outline

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

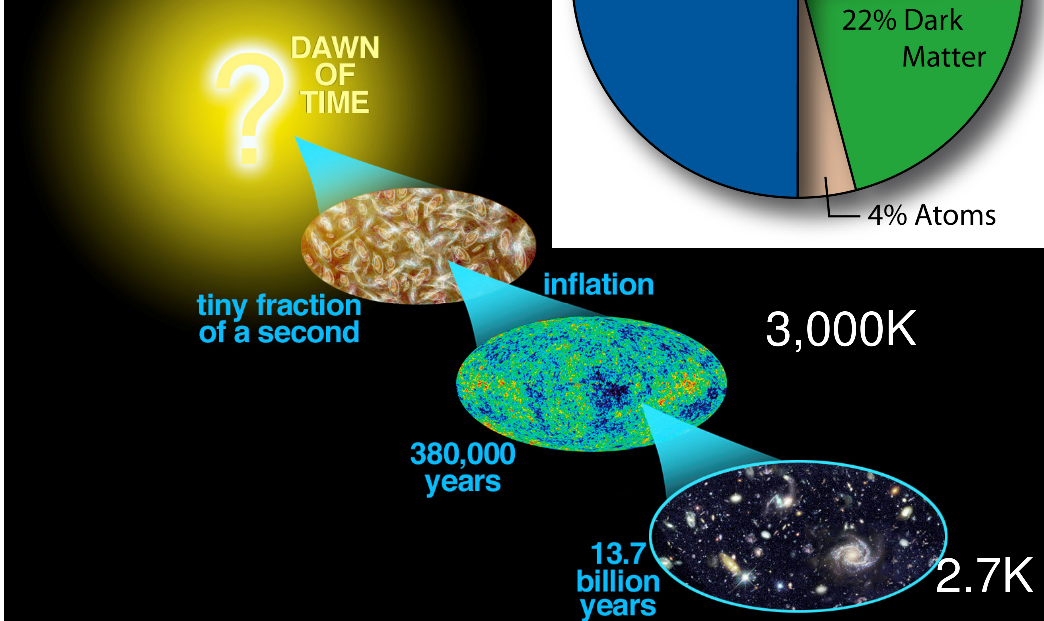
Cosmic Microwave Background: Powerful Probe of Cosmology

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

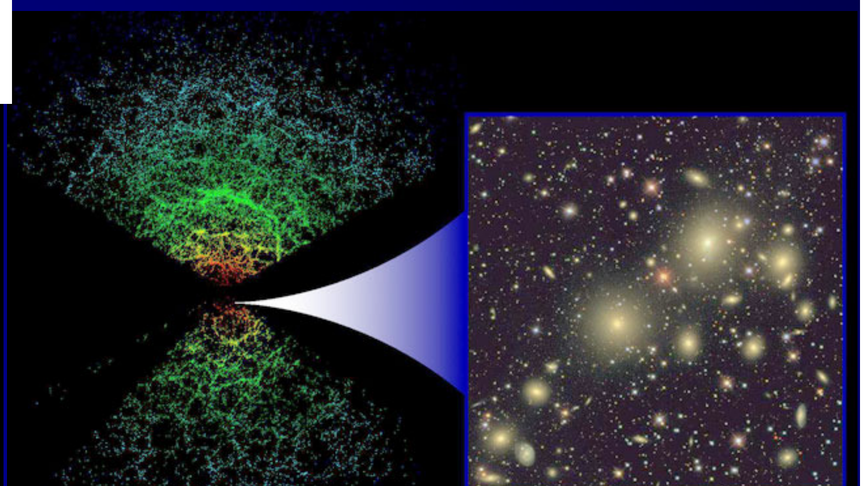


Total density = critical density

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 Dark Matter? Self-interaction?
- **Nature of Dark Energy** [Λ 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 and light
- **Initial conditions of the Universe: inflation model**
  Gravitational Wave
  Primordial power index: P(k)=Ak^ns

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

Angular Power Spectrum, C_l

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

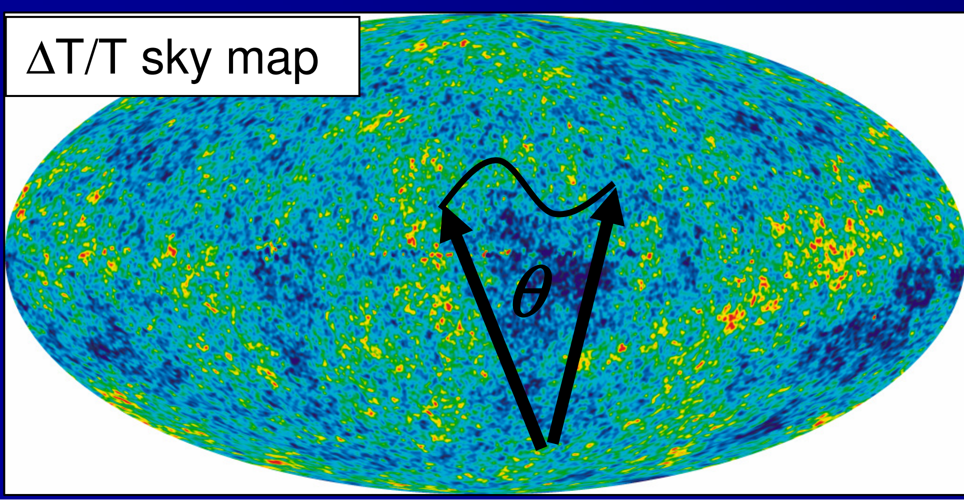
$$\frac{\Delta T(\theta,\phi)}{T} = \sum_{l}^{\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\theta,\phi)$$

"Fourier transform" of anisotropy on the sphere

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

Angular power spectrum

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

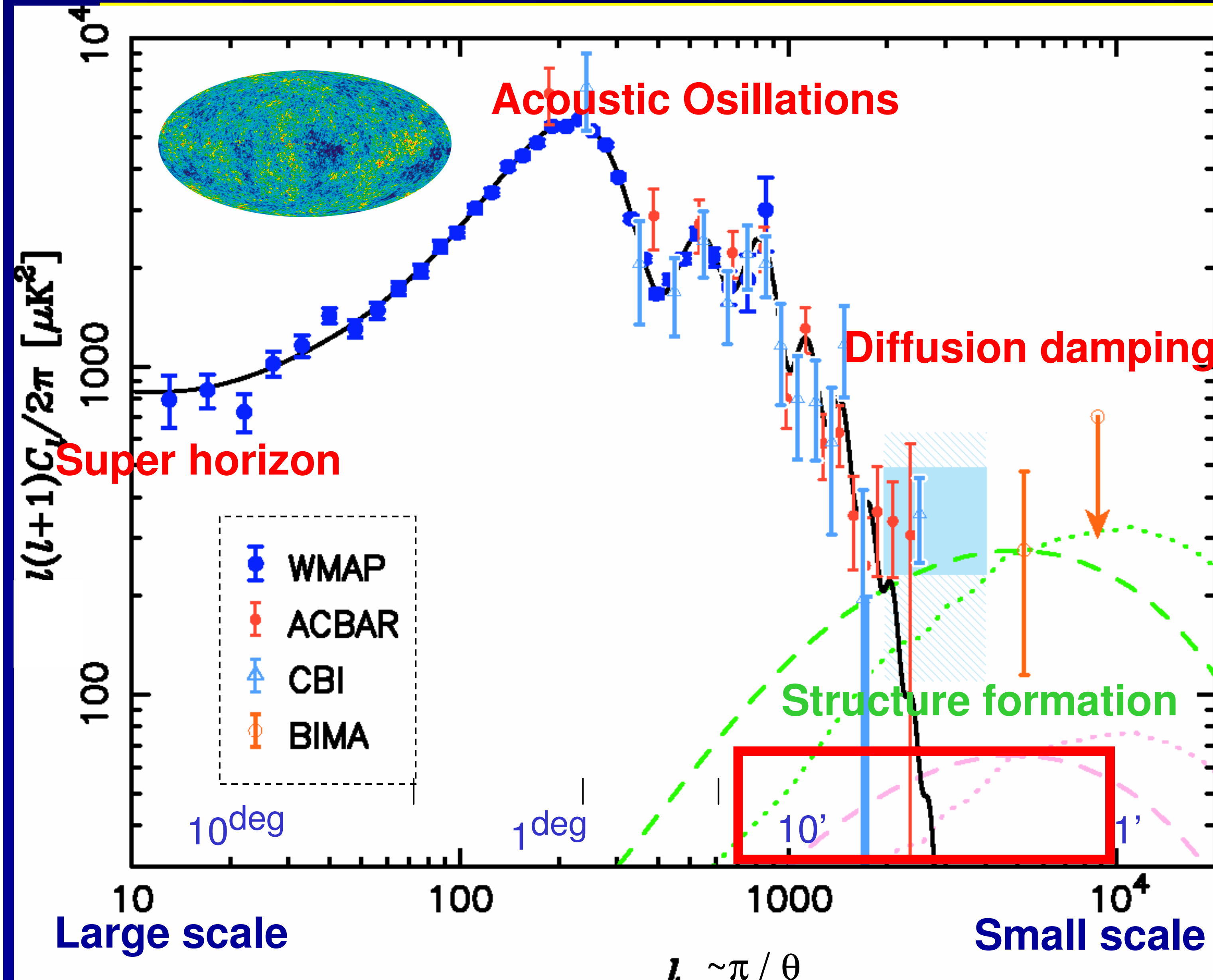


C_l is the variance of structures on scale l,

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

$\Delta T \sim 100\ \mu K$

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

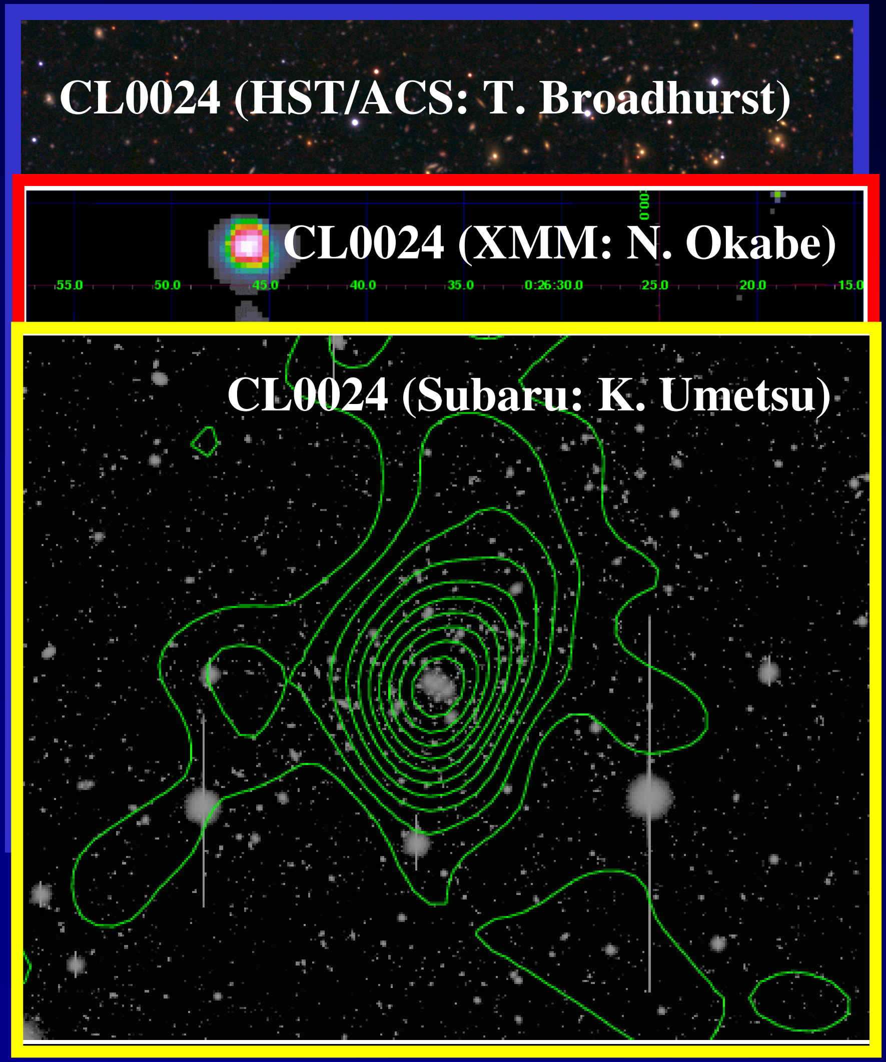
Galaxy Clusters

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

- contain:
  - 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:



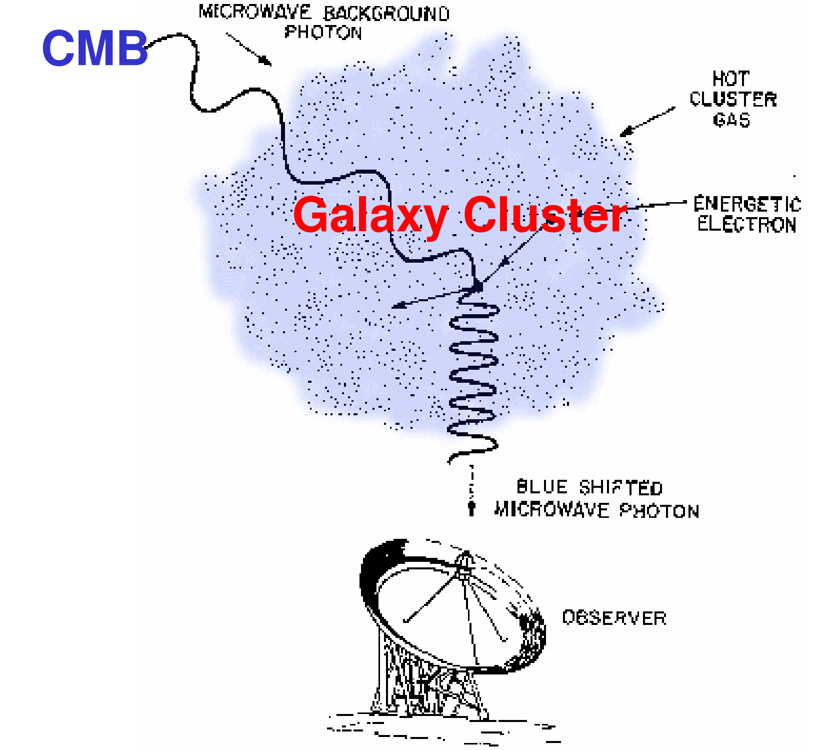
- **Weak Gravitational lensing**
- **Sunyaev-Zel'dovich Effect**

Thermal Sunyaev-Zel'dovich Effect (SZE)

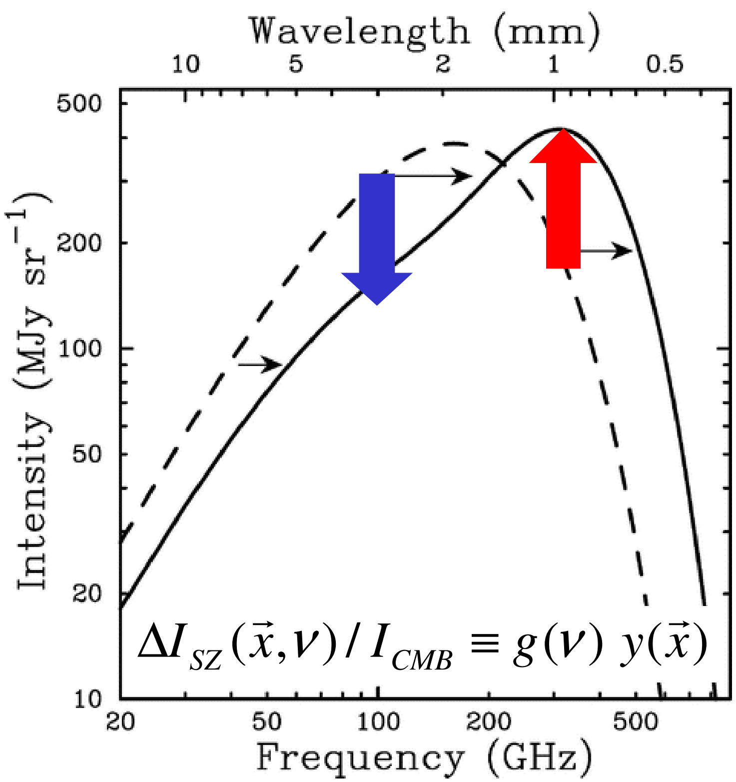
10^-2 10^-2

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

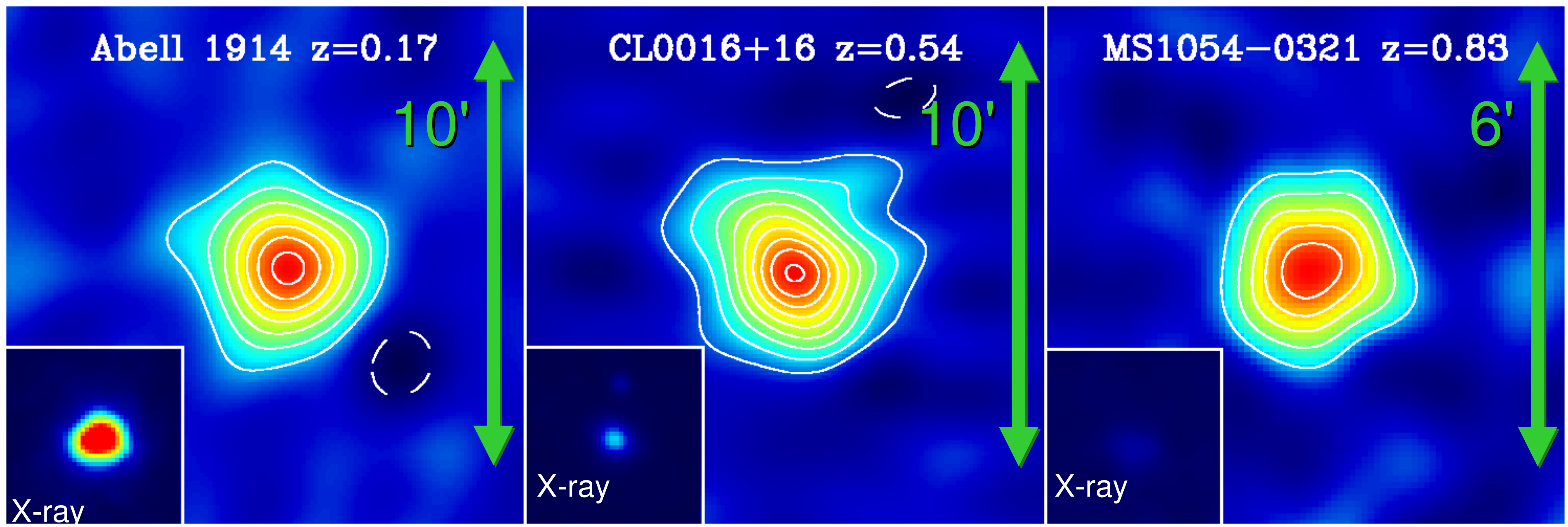
Energy transfer from **hot cluster gas** to **cold CMB** via inverse Compton scattering



Spectral distortion of CMB spectrum



Power of SZE



(Carlstrom et al. 1999)

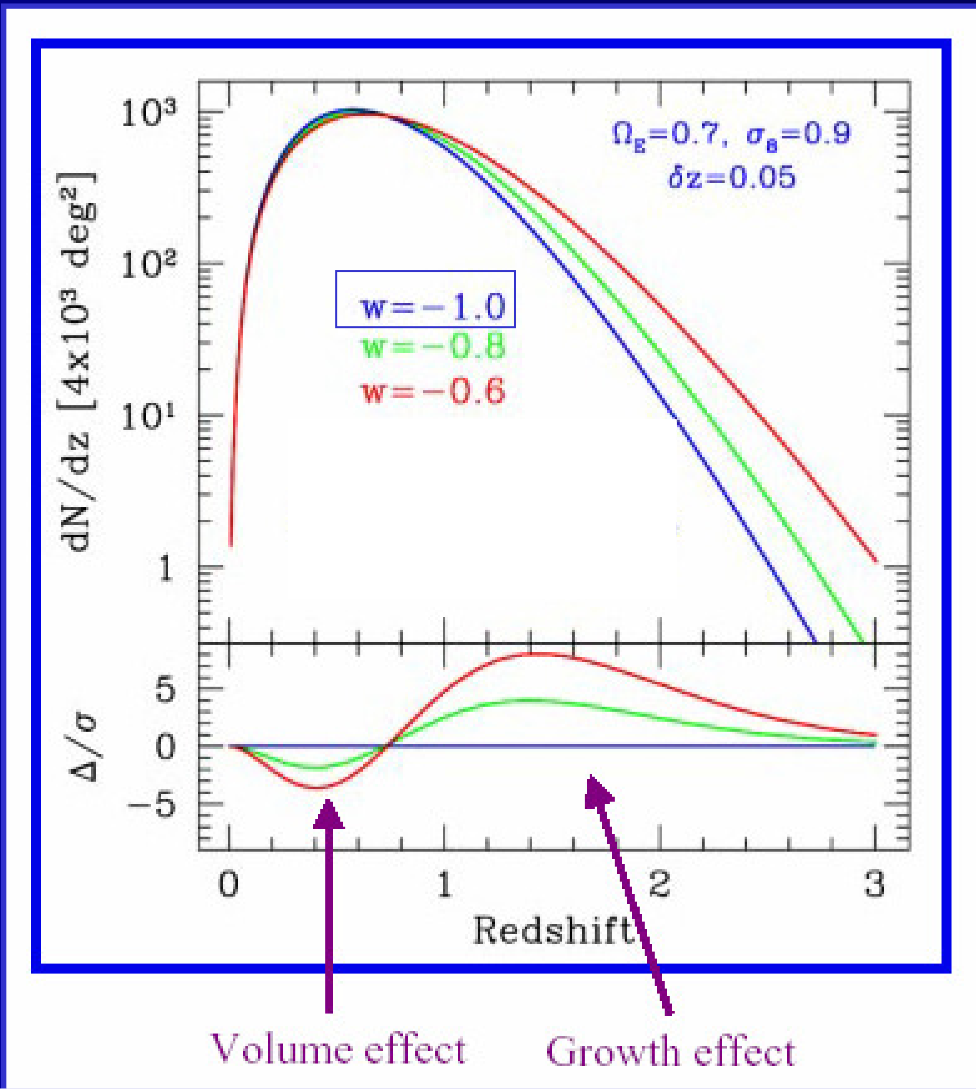
SZE brightness independent of distance (z),

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



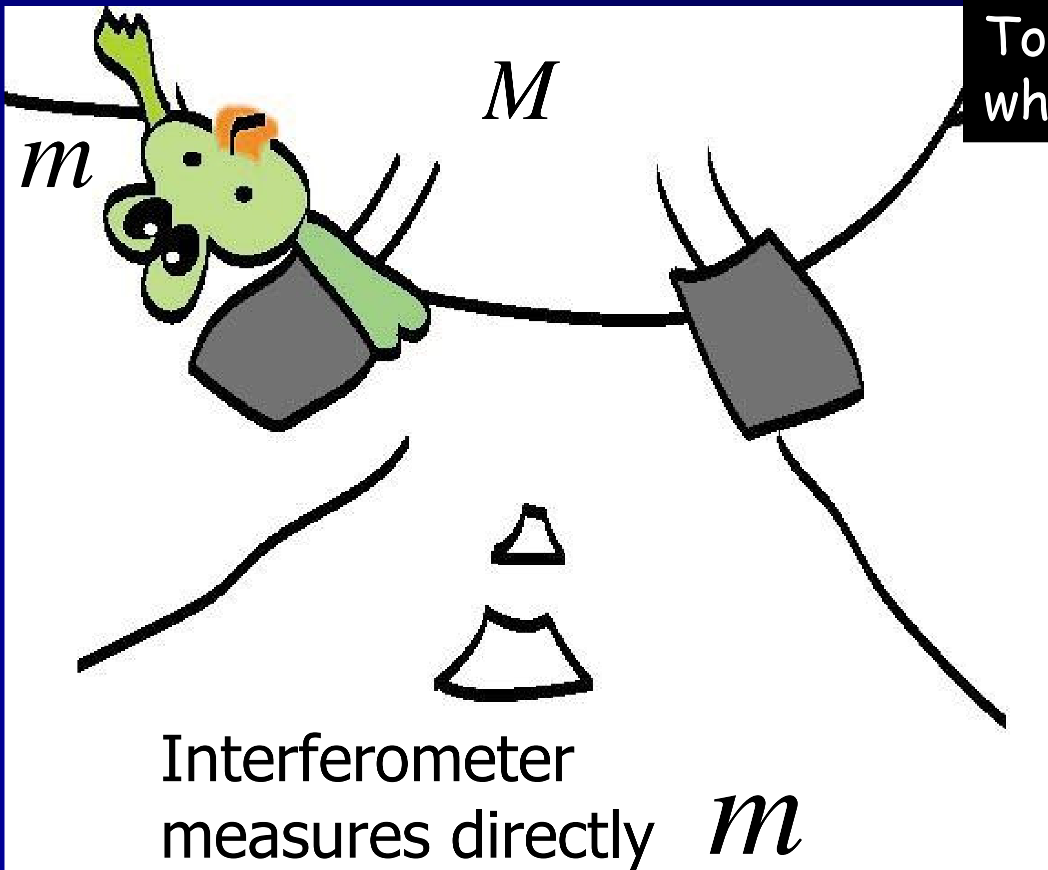
Cosmological test with structure formation (0<z<a few)

Complementary to CMB constraints on cosmology

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

2. CMB and Interferometer

CMB vs. Interferometer



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;

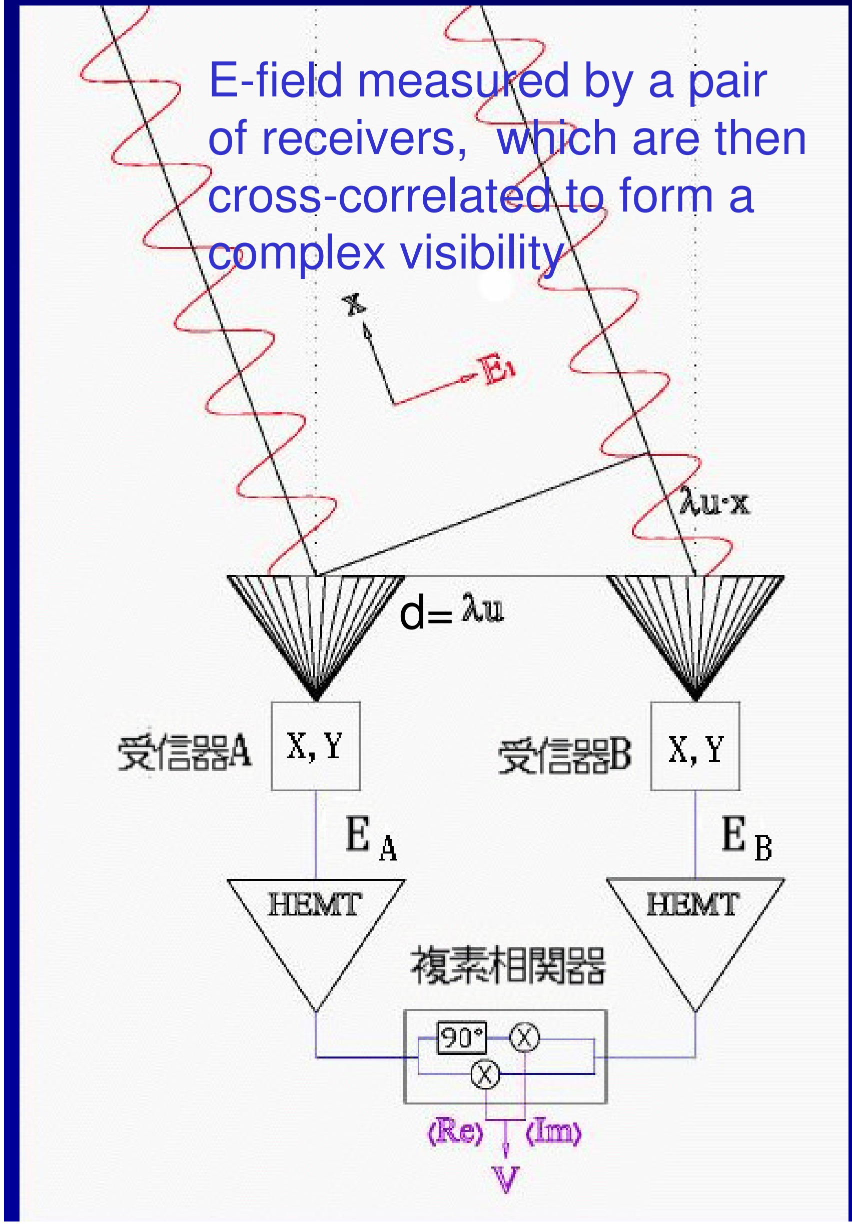
$$(M+m)-M^{'}=m$$

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)

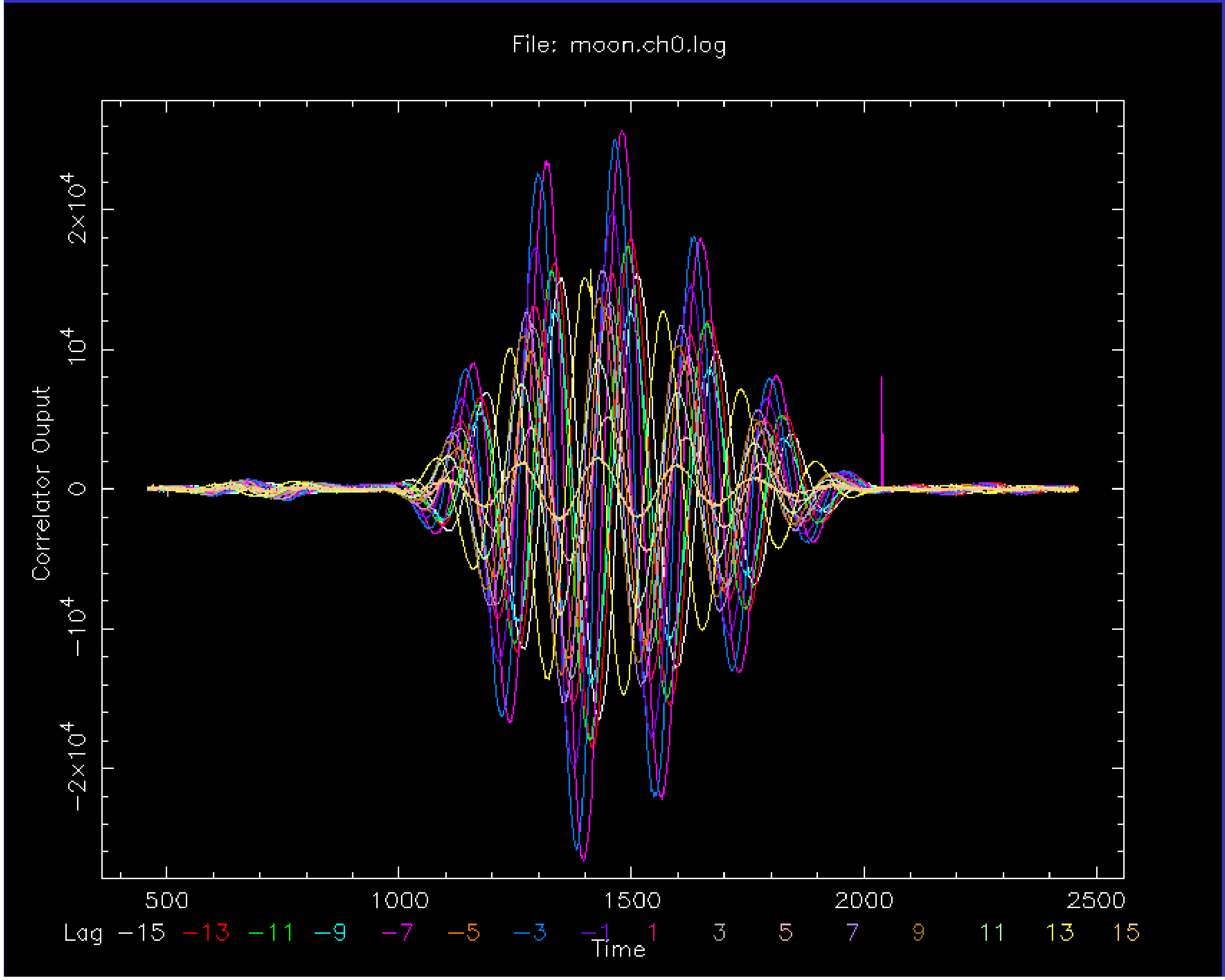
$$V(\vec{u}) = \mathbf{FT}[A(\vec{x}) I(\vec{x})]$$

Angular power spectrum directly measured by interferometer!!

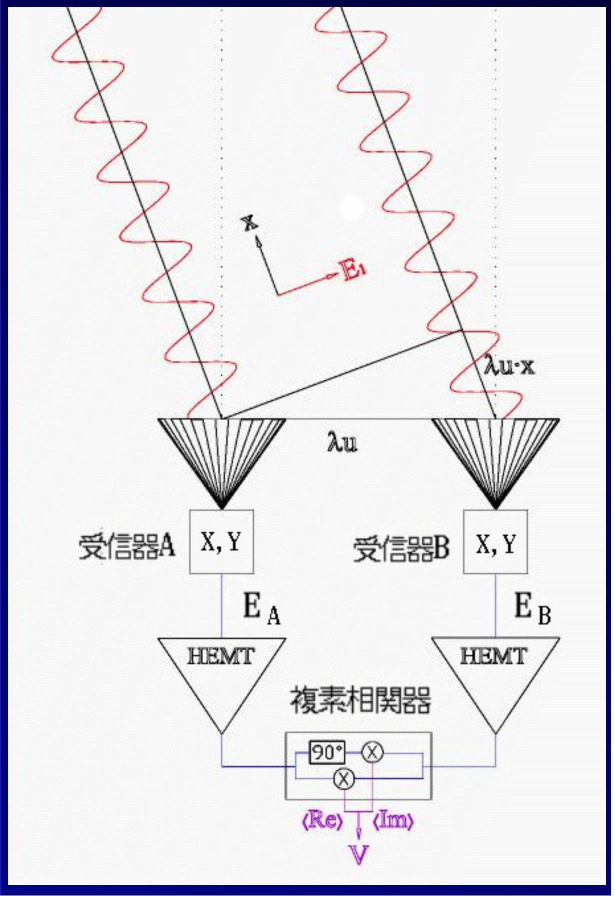
$$C_l\, \big|_{l=2\pi u} \approx \left\langle V(\vec{u}) V^*(\vec{u}) \right\rangle$$

Fringes from Drift-Scanning

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



transit

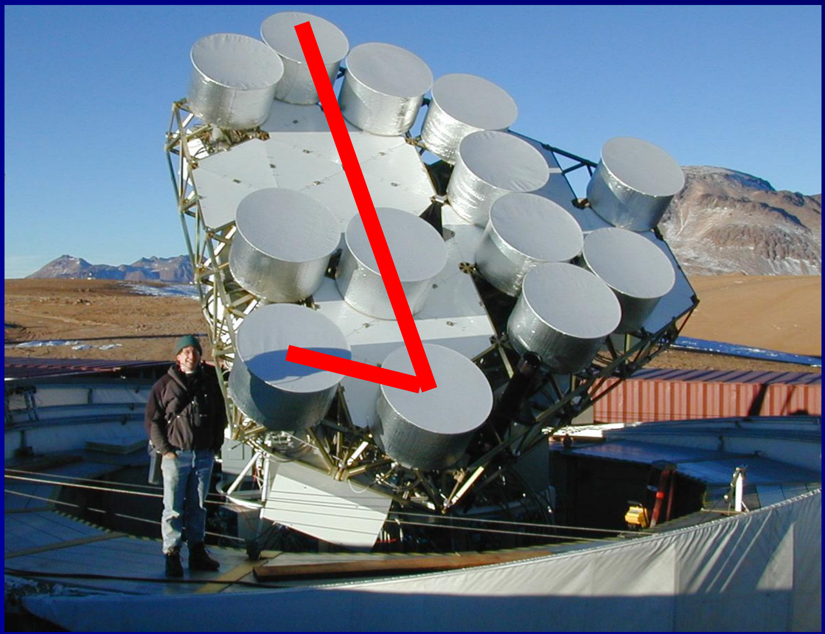


CMB Interferometers

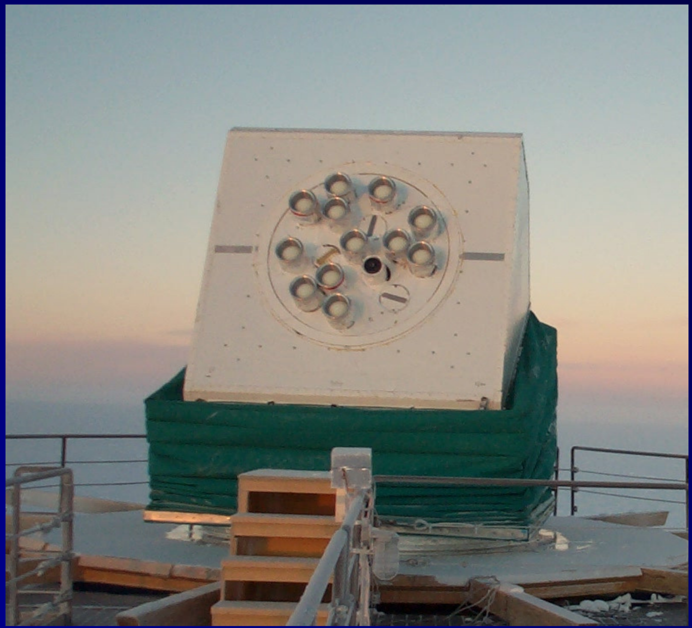
- Typical angular sizes ~ 1degree – 10 arcmin
  → small antennas, and/or, low frequency (10-100GHz)

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

- 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]

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'

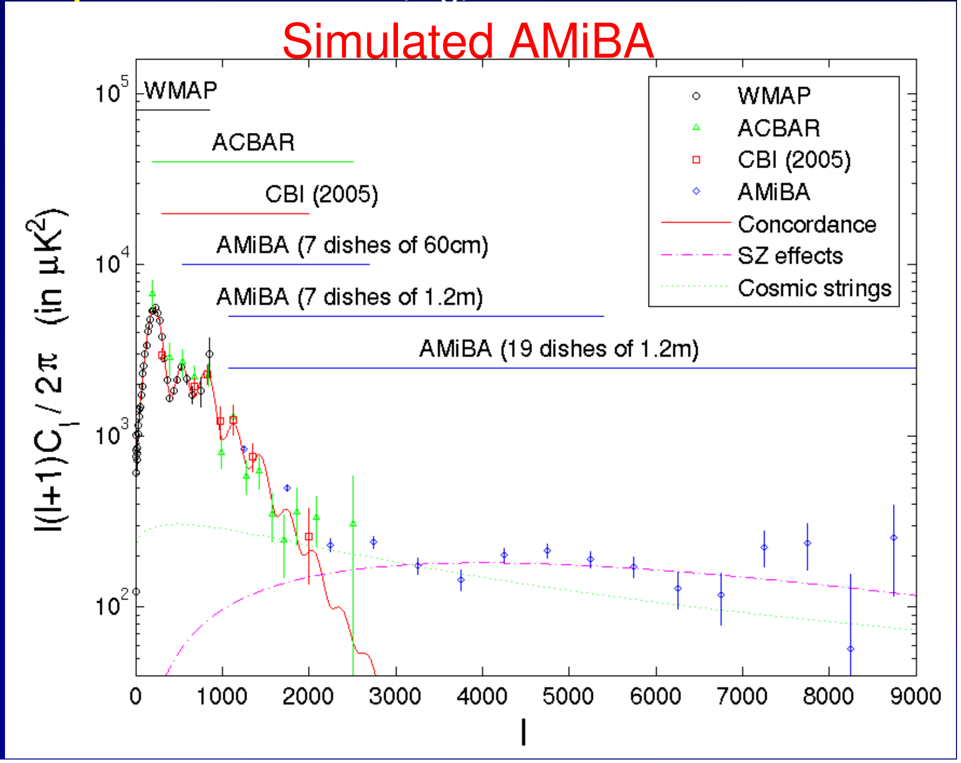
(1) CMB Power Spectrum and Structure at high-l [small scales]

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

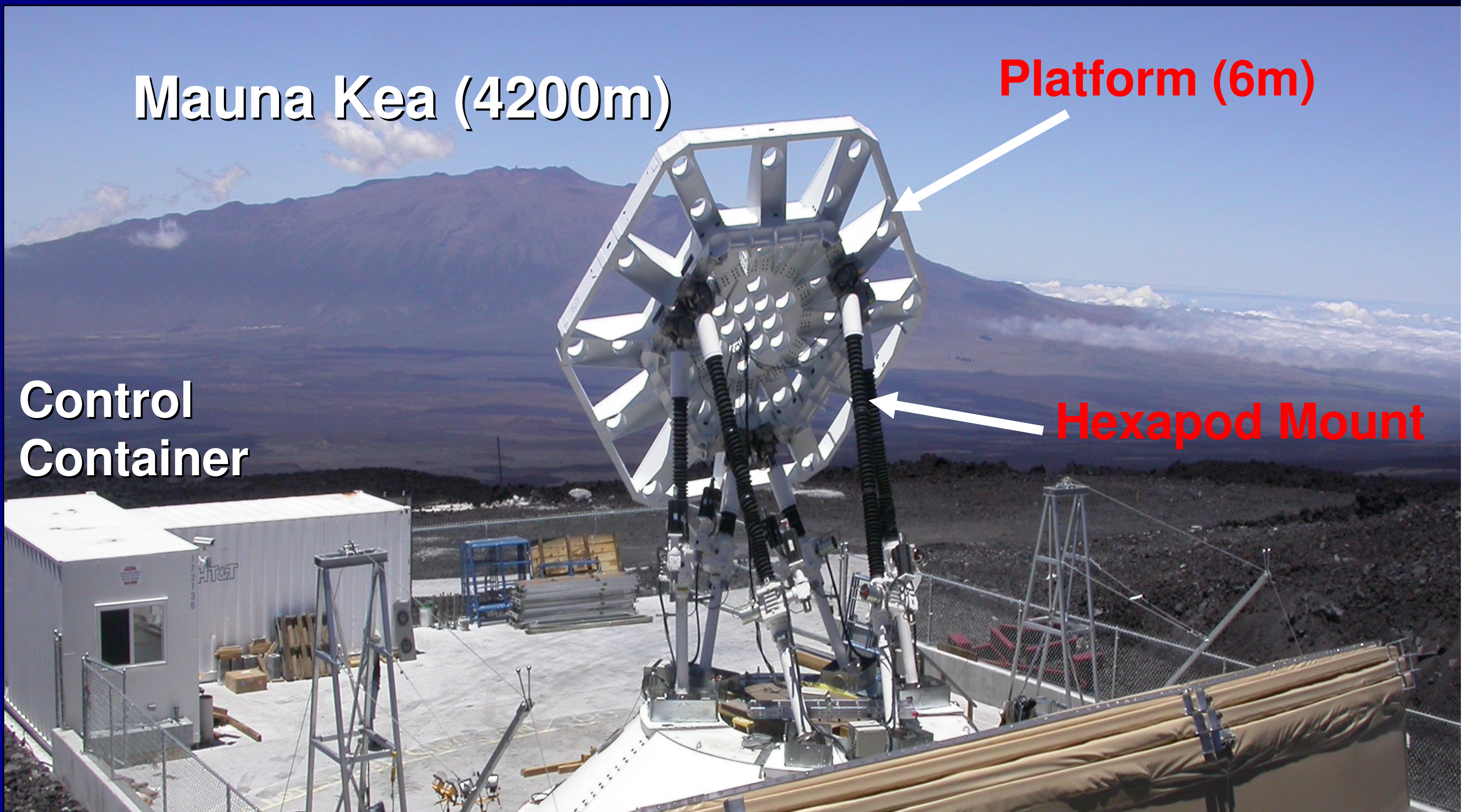
→ Initial condition of DM density fluctuations (σ_8)

(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)

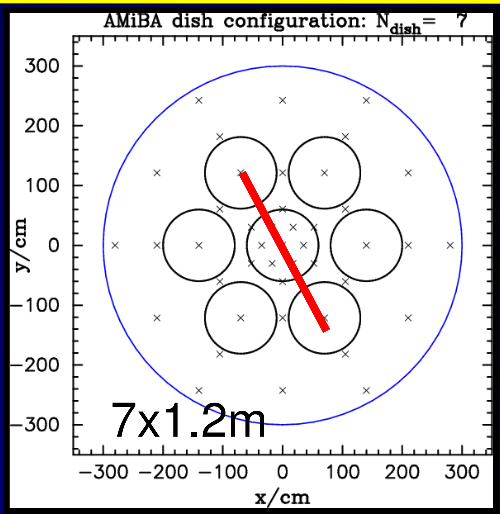


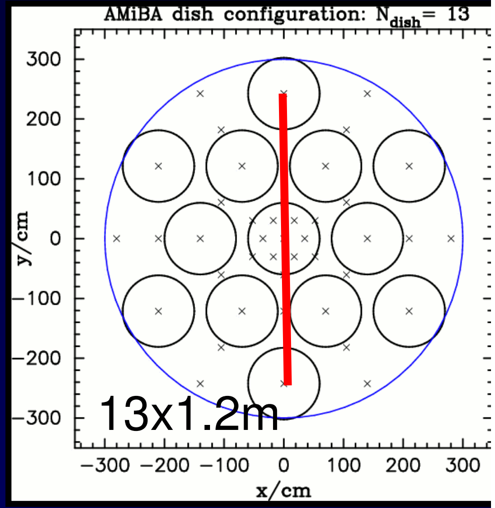
AMiBA Site: Mauna-Loa (3400m)



AMiBA Specifications

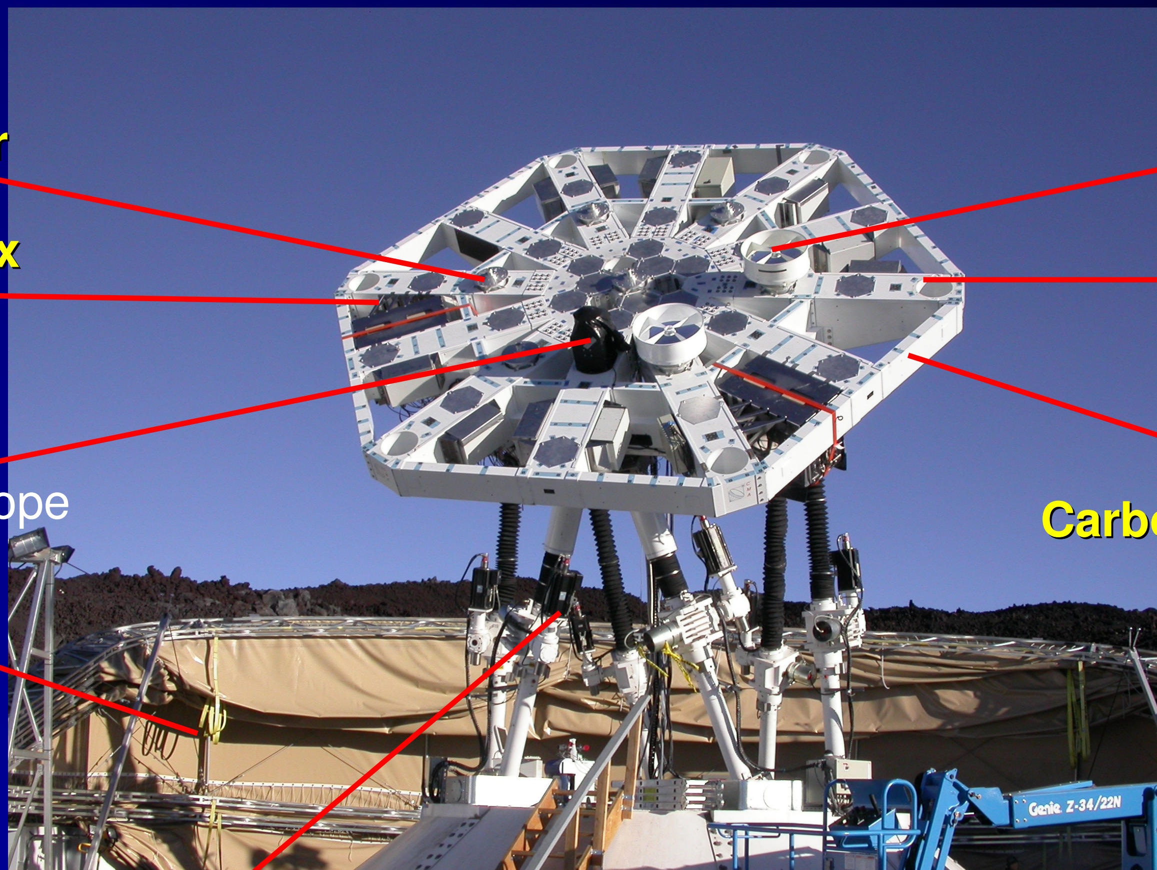
- **7 / 13 / 19-element interferometer**
  - Co-mounted on a 6m platform
  - 21 / 78 / 171-baseline
  - Cassegrain D=60,120cm antennas
- **Dual channel 84-104GHz** (3mm)
  - HEMT cooled to 15K
  - Tsys = 80K
- **Full polarization capability**
  - Dual polarizer: Linear X,Y
- **Correlator**
  - Analog,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

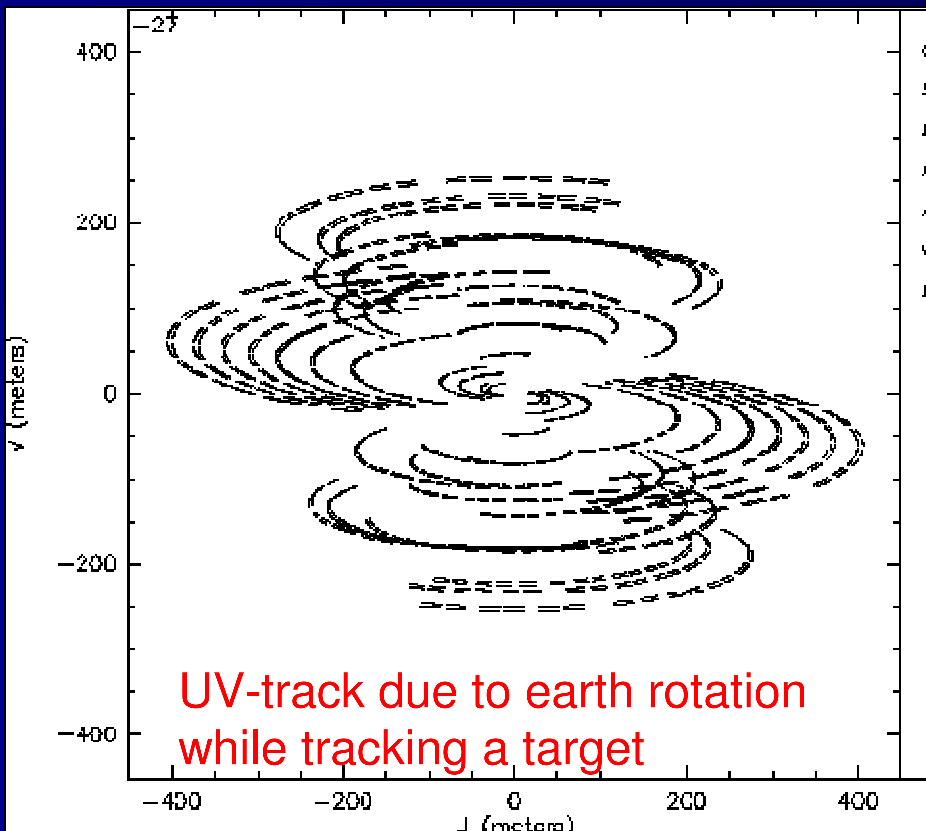
0<Azimuth<360deg, Elevation > 30deg

Polarization: +/-30deg

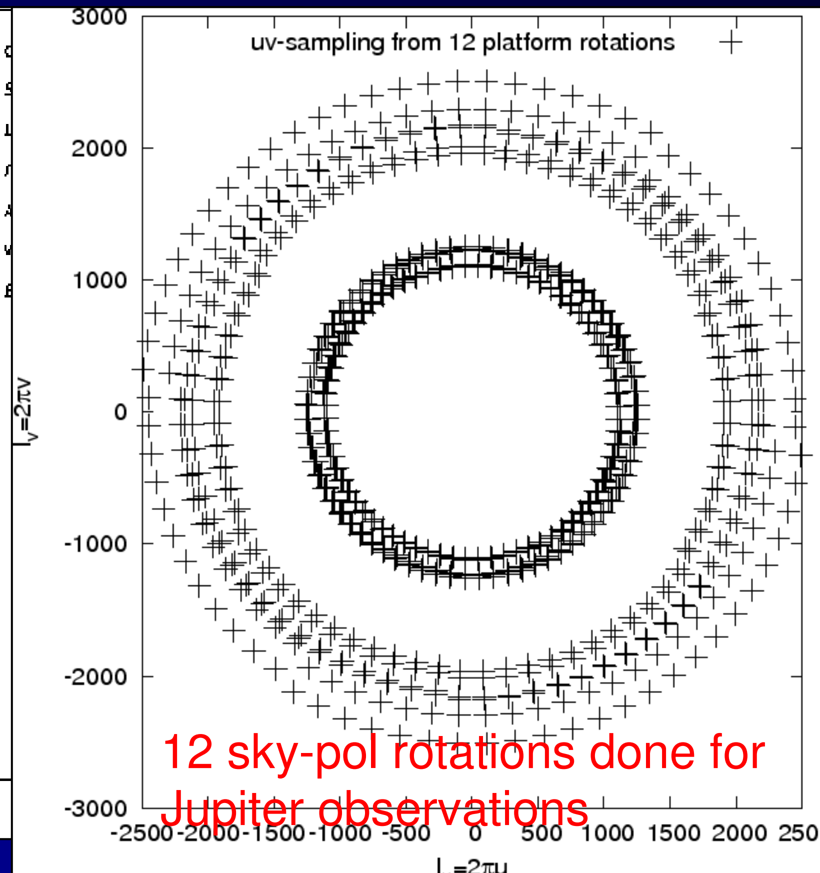
(june, 2006)

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

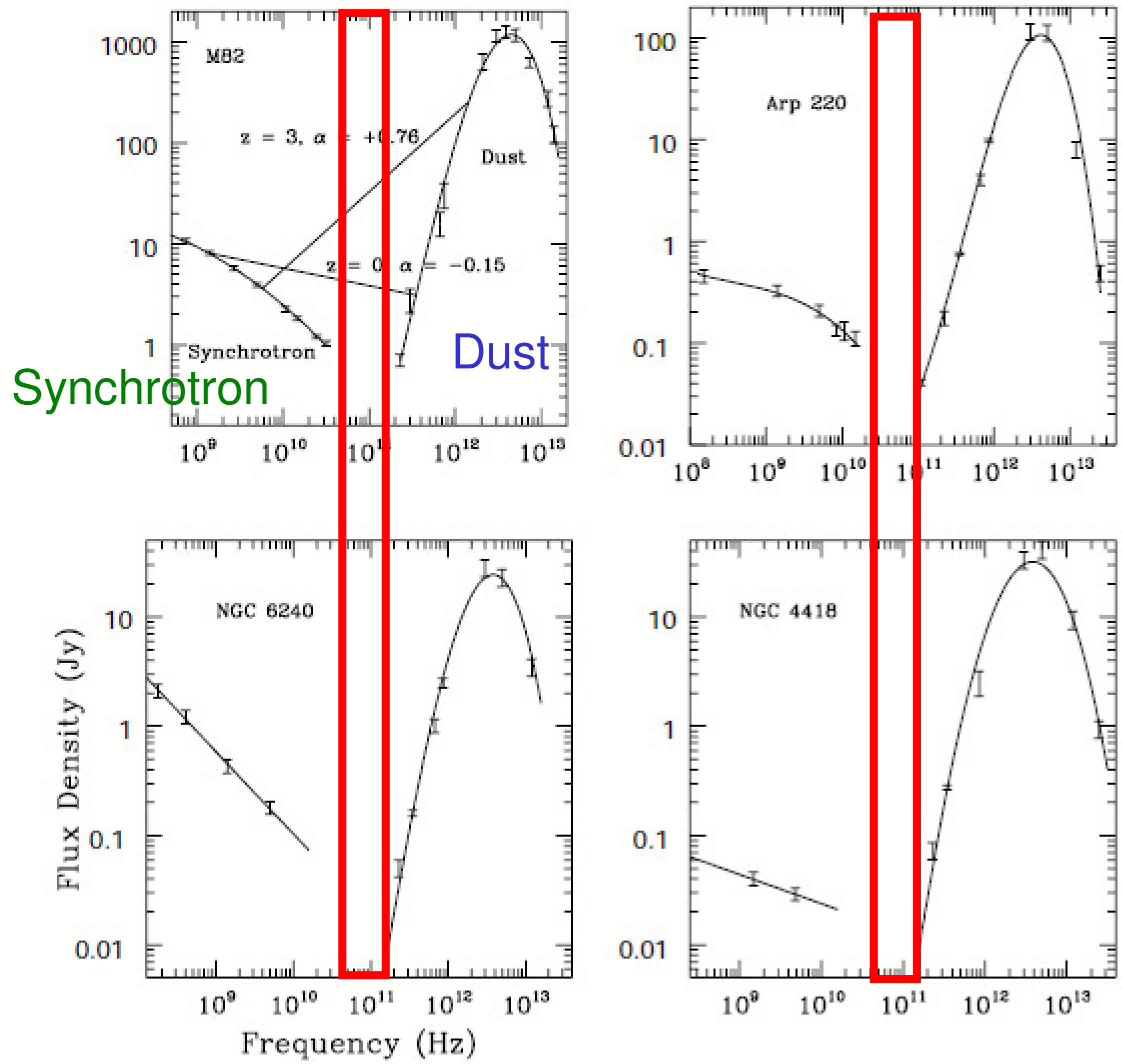
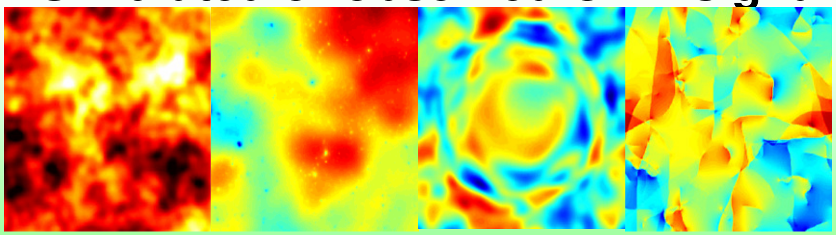


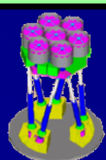
FIG. 1.—Data points show the radio through infrared spectral energy distributions of four representative galaxies from our sample of 17 listed in Table 1. The data are obtained from NED (*IRAS* data points), the NRAO VLA Sky Survey (Condon et al. 1998), the Westerbork Northern Sky Survey (Rengelink et 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:



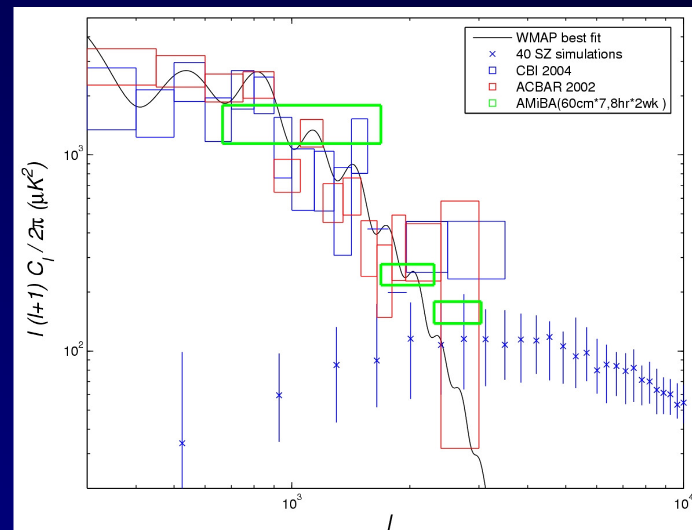
Inflationary | SZ effects | Lensing effects | Cosmic strings



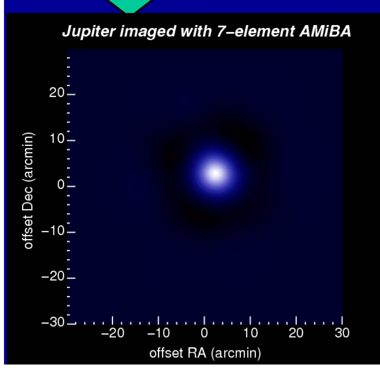
Data Taking
(with AMiBA configuration)

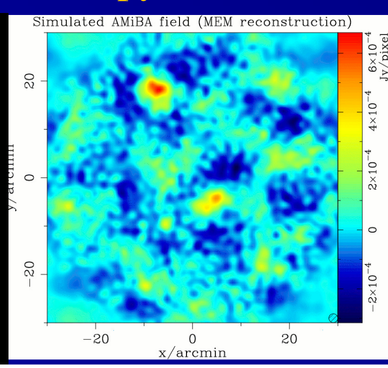
Fringe/lag data to visibilities

Power-Spectrum Estimation
(maximum-likelihood analysis)



Map Making
(maximum-entropy method, etc.)





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

(Ω_{tot} Ω_b Ω_{cdm} Ω_{DE} H_0 σ_8 w n_S n_T τ_c etc.)

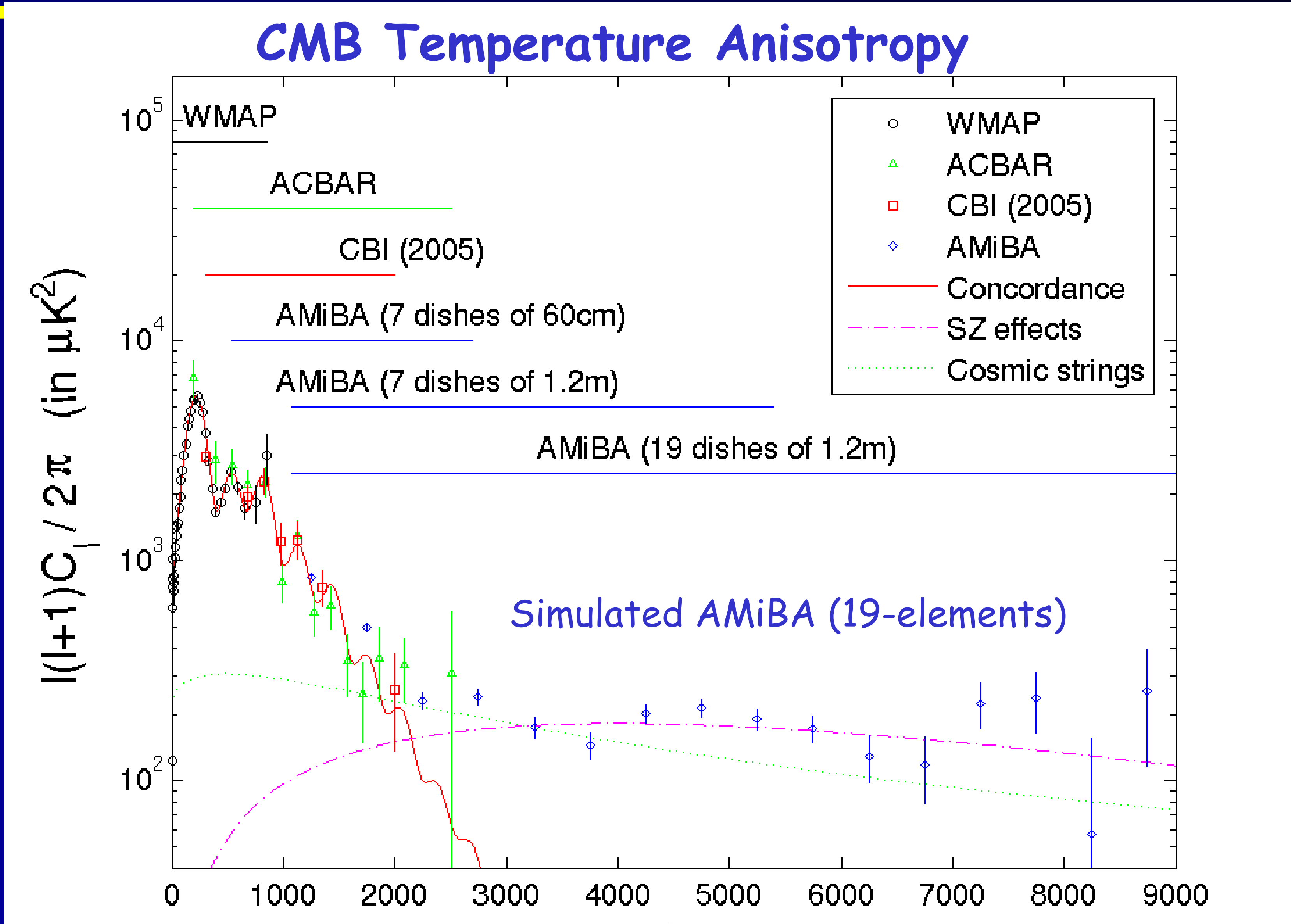
Expected Performance of AMiBA

AMiBA Science (1)

Measurement of

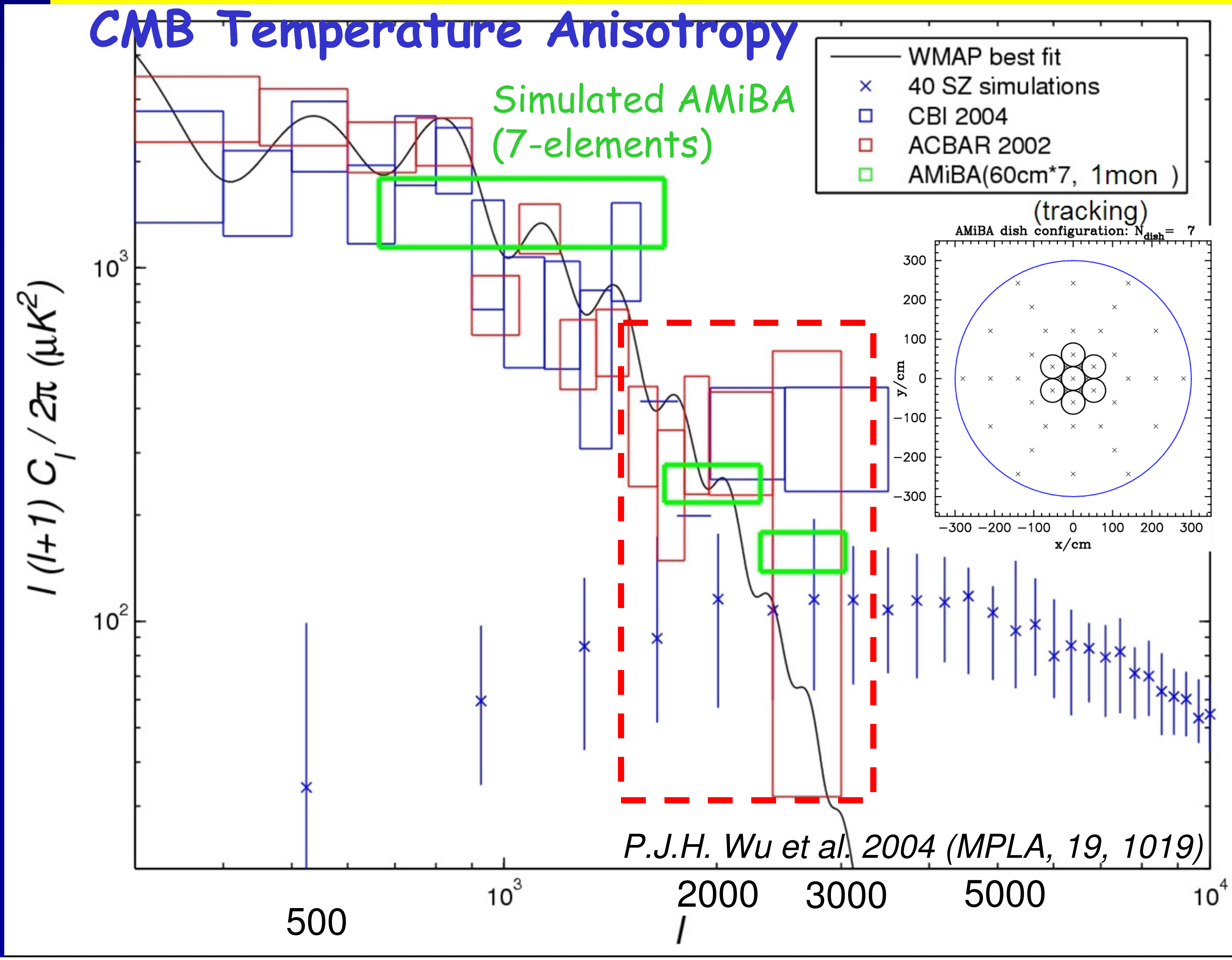
CMB Angular Power Spectra

Full 19-elements Performance



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

7-element Performance in 1month



Expected Performance of AMiBA

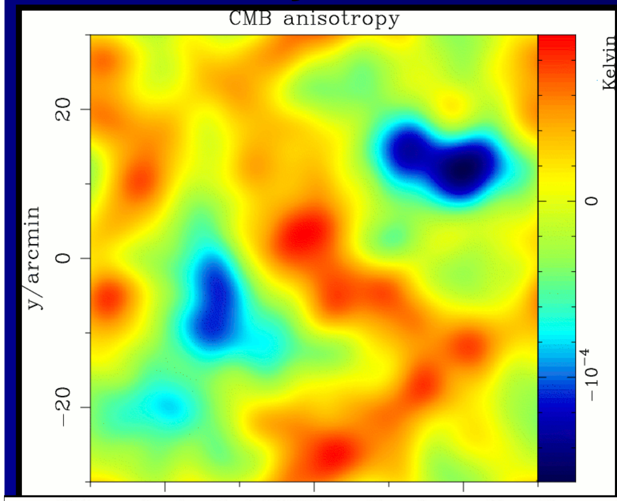
AMiBA Science (2)

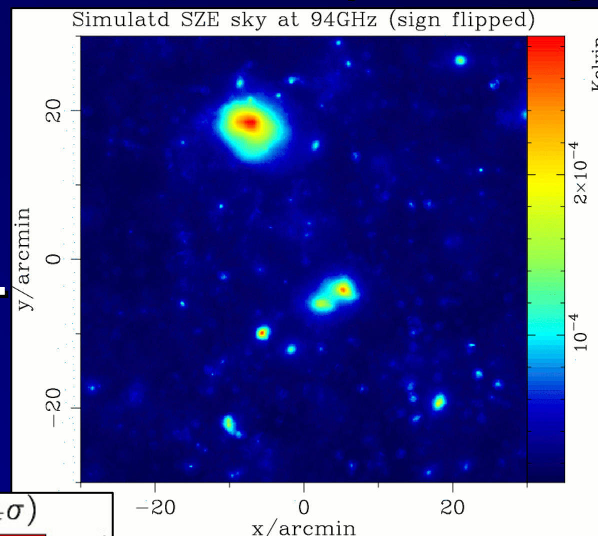
Search for High-z Galaxy Clusters

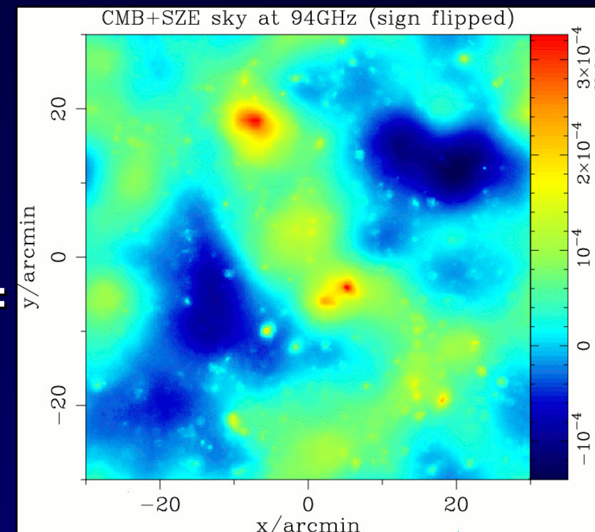
via the Sunyaev-Zel'dovich Effect

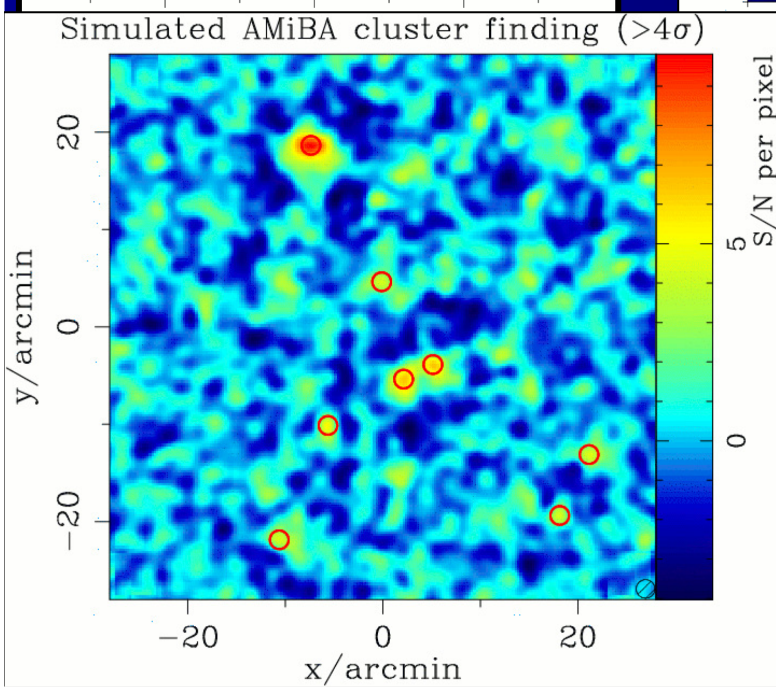
Simulated AMiBA Deep Survey

Primary CMB + **T-SZE** (ΛCDM, preheating) = **CMB+TSZE sky @94GHz**

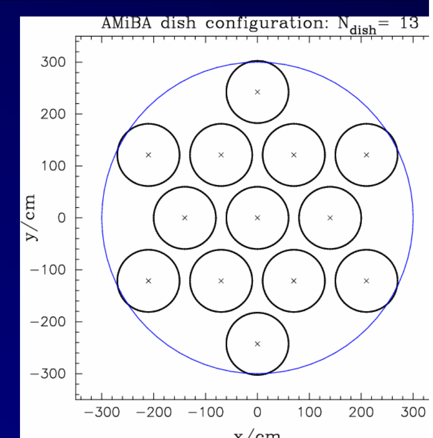








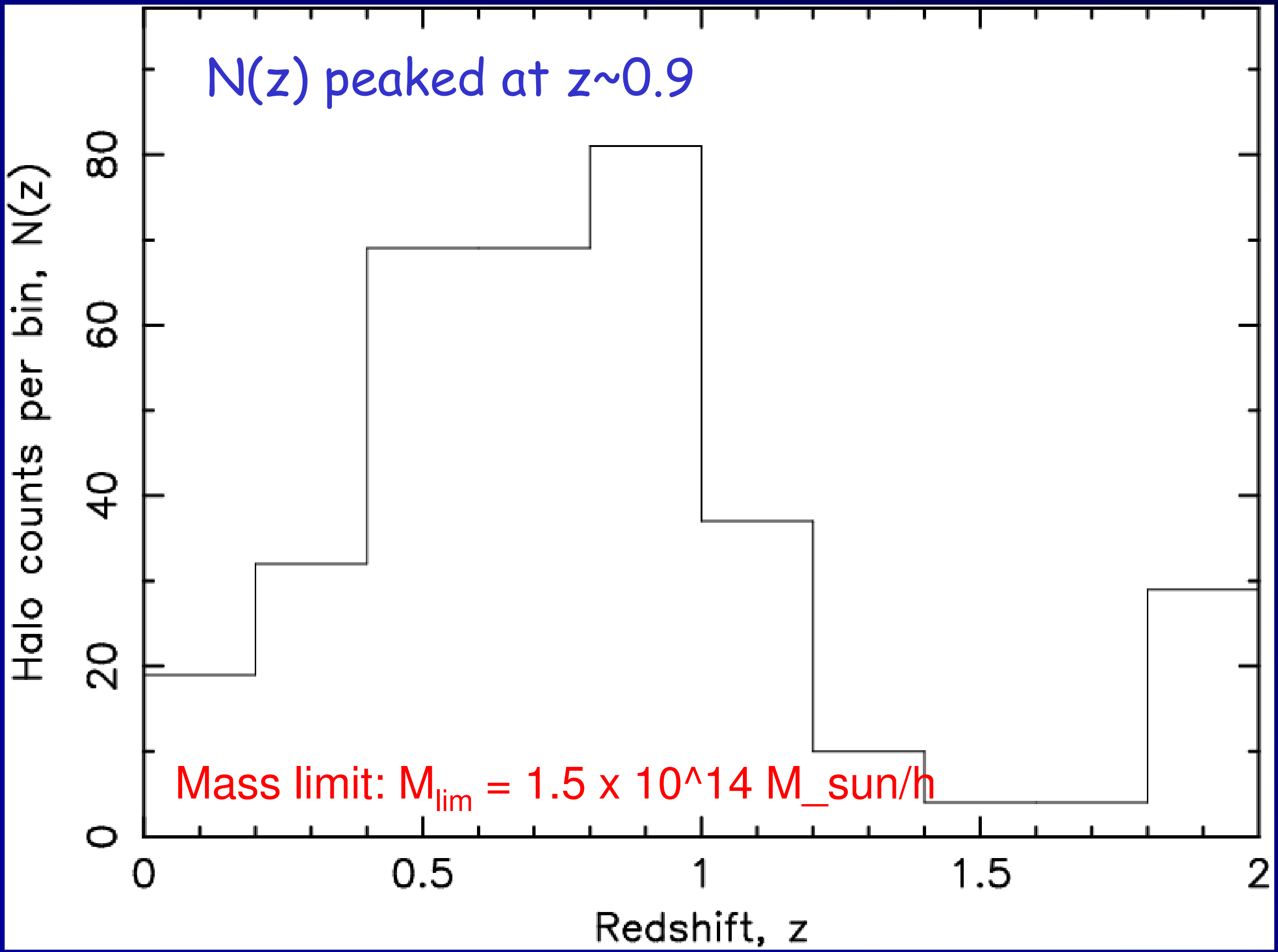
Simulated AMiBA survey



- 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

Redshift distribution of SZE Clusters from a simulated AMiBA deep survey

AMiBA will detect ~100 clusters (Ω=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

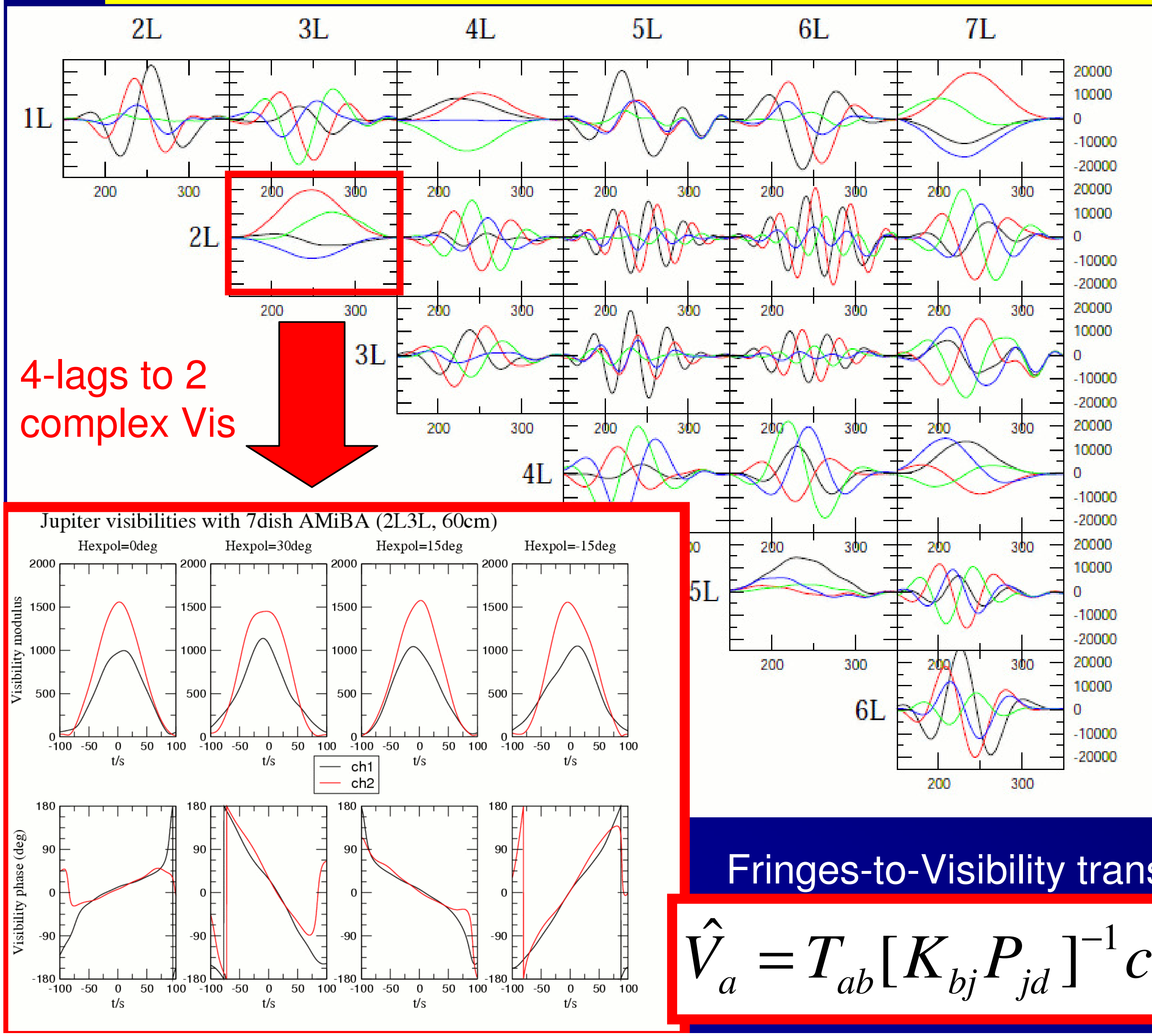
Mount commissioning: started in jan 2005
Receiver and correlator on-site testing since late 2005


August 2006


August 2005


Feb 2005

First Planet Fringes (Sep 8, 2006)



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

Jupiter

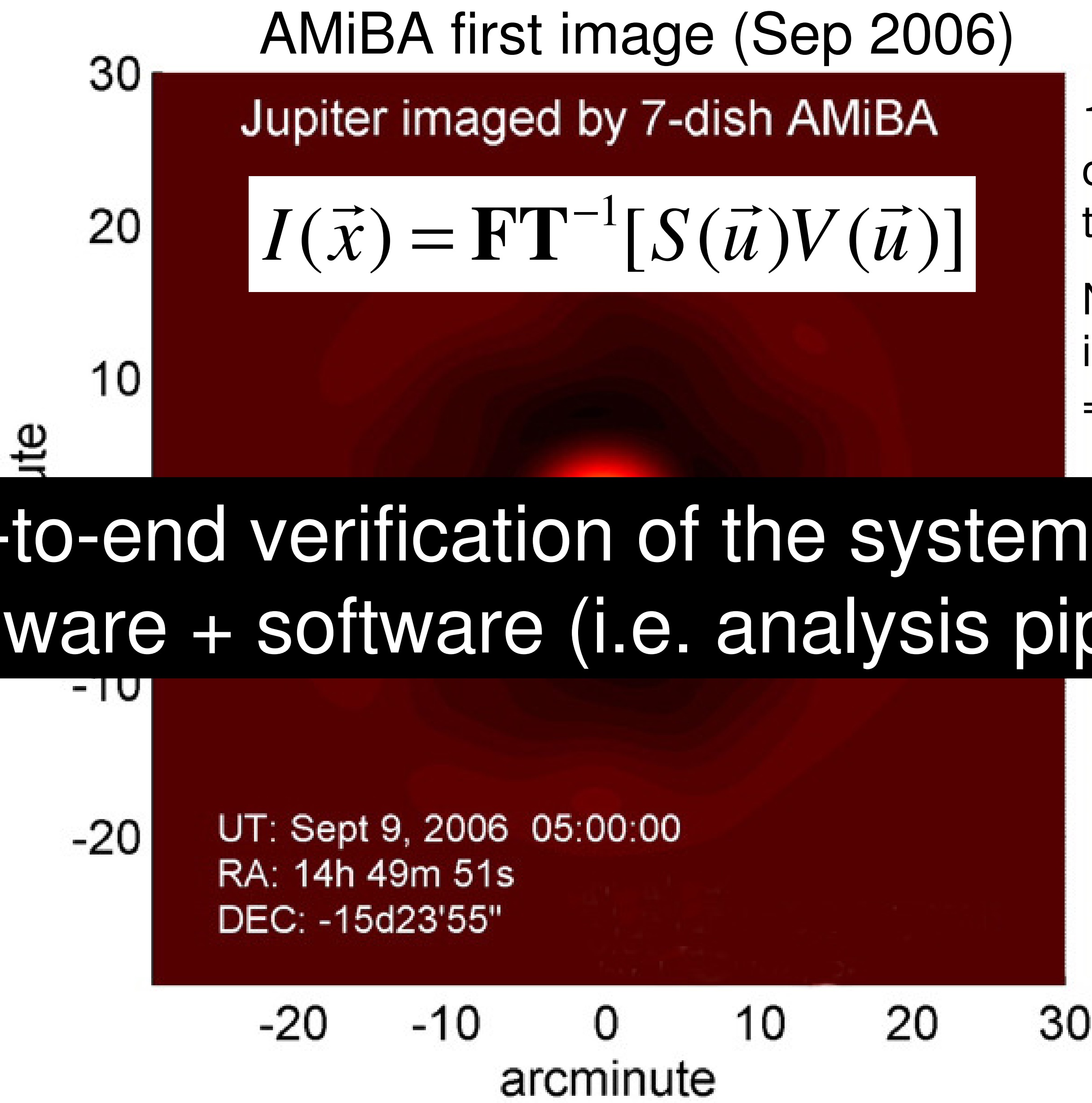
(point source for AMiBA):

850Jy @94GHz

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

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

First Image: Jupiter (Sep 2006)



12 scans combined at transit

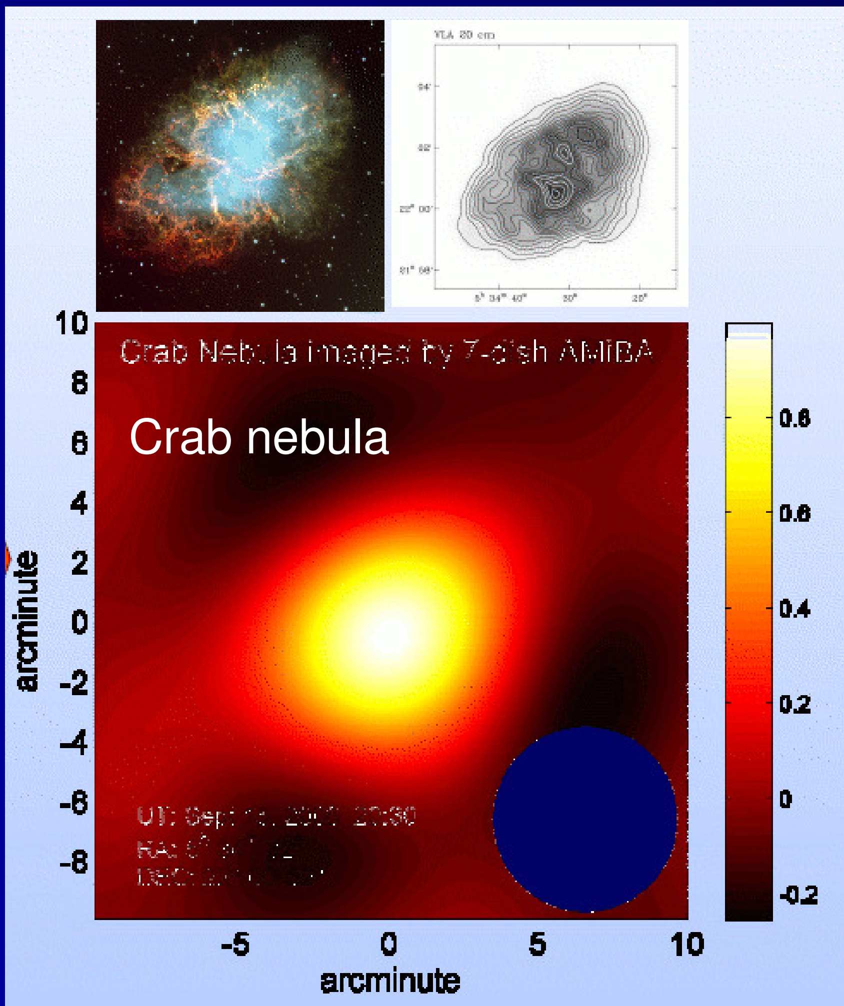
Net integration = 12s

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

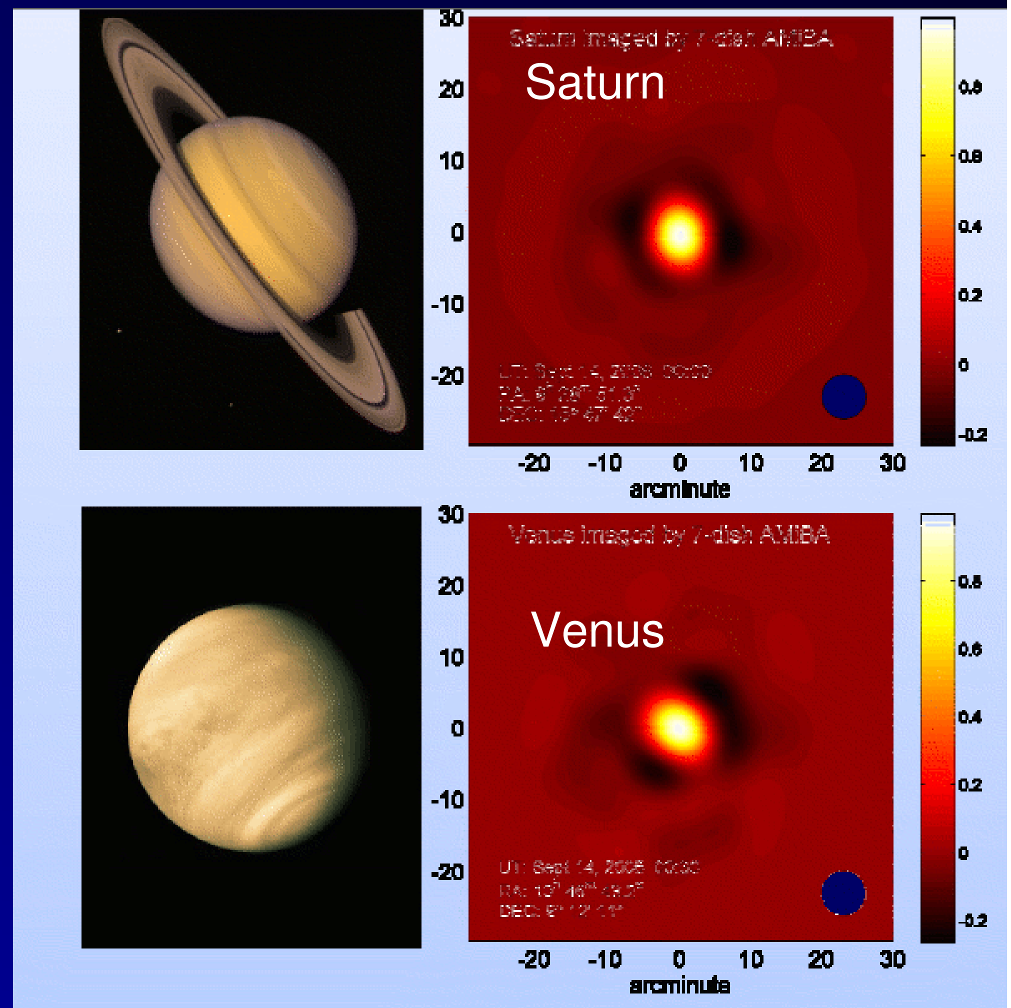
Synthesized beam FWHM (6')

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)

Current Faintest Target: Uranus (7.3Jy)

- No signal seen in fringe domain for < 40Jy sources
- Signal only seen after image synthesis → faint

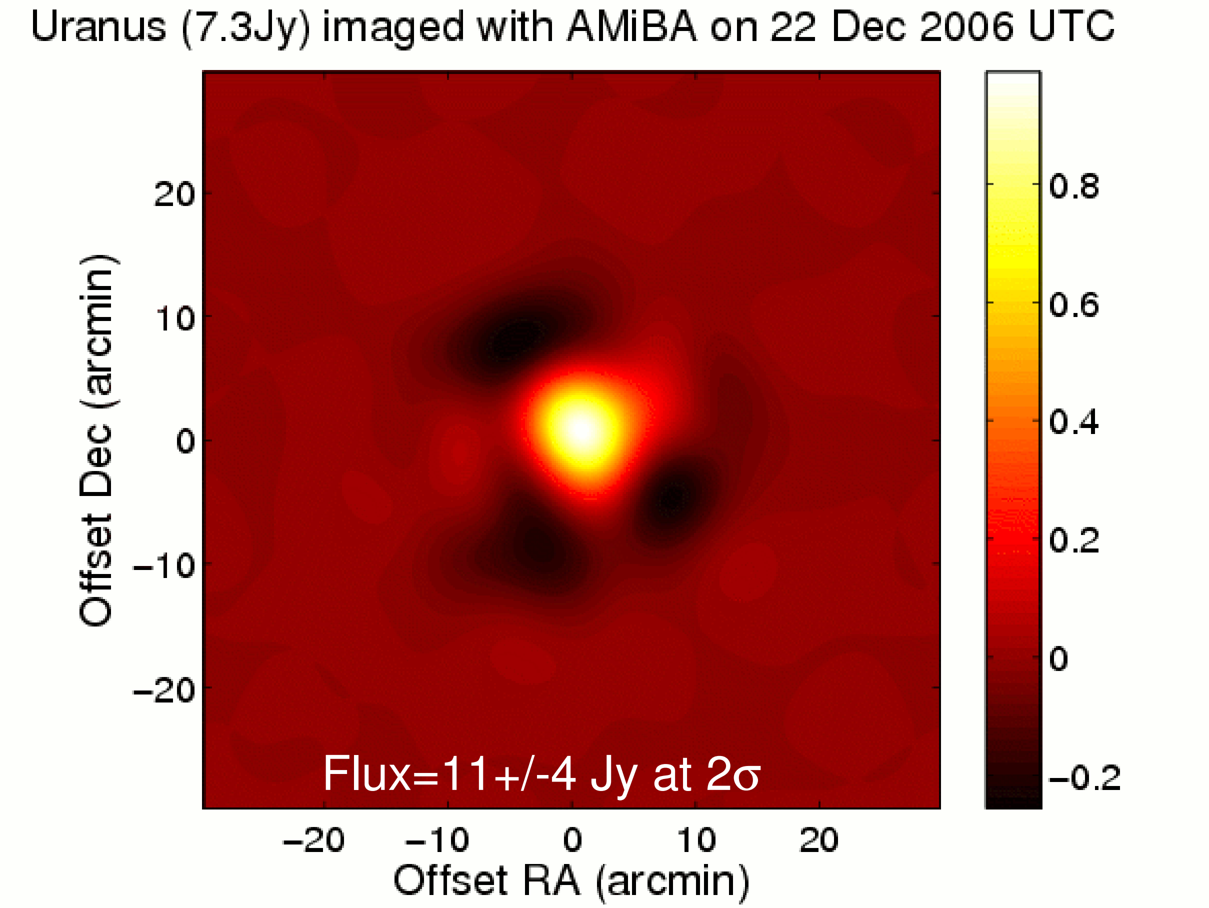


Image reconstruction from 16 drift-scans, with a net integration of 16s

Only 23 (/ 42) baselines available, having a poor UV-coverage, accordingly distorted image

Next Steps and Key Issues

Next Targets: aiming at starting CMB observations in 2-3 months

→ Quasars (100-1000mJy) *: a few days of integration*

→ Bright SZE clusters (10-100mJy) *: a few weeks*

→ CMB ΔT power spectrum *: ~1 month*

Key Issues:

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

Summary