Measurements of the CMB and other continuum signals with coherent arrays

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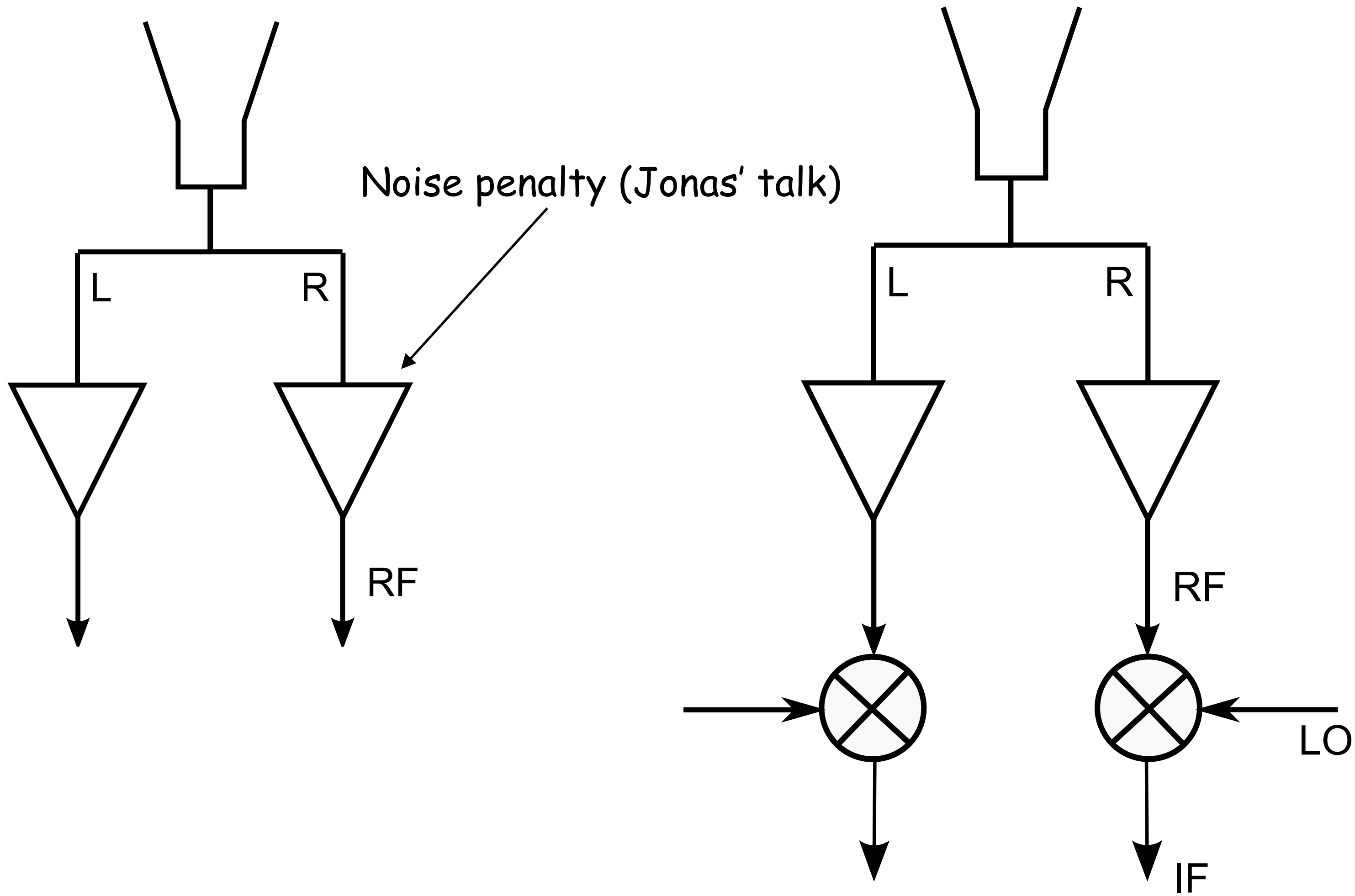
July 21st 2008

Outline

- Science from Measurement of the CMB
  - Existing and Straw-man Experiments using MMIC arrays
- Science from Measurement of the Sunyaev-Zel'dovich Effect
  - Straw-man experiment using MMICs
- In each case, technology development and challenges

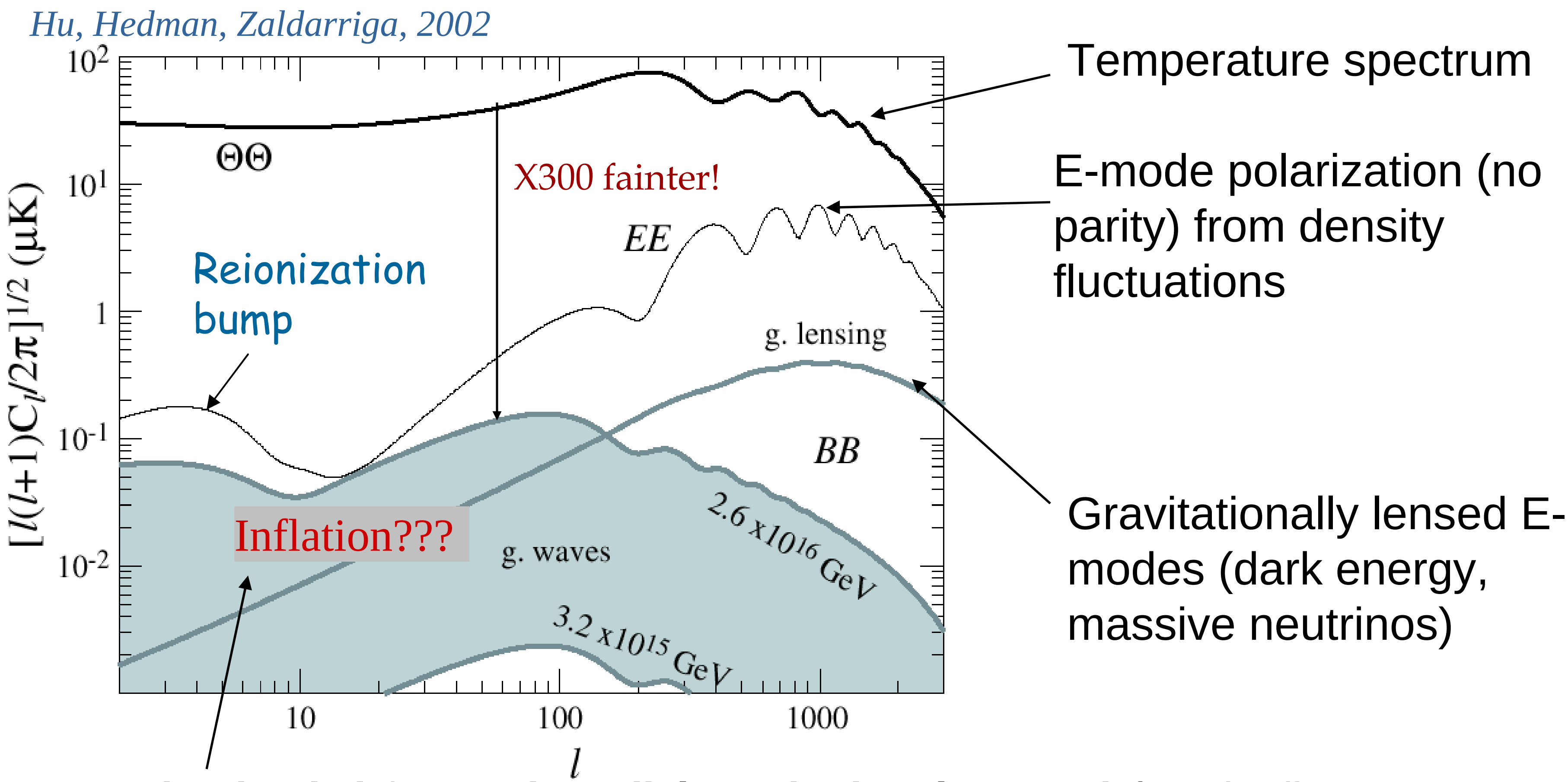
Using amplifiers to measure the CMB (or any other signal)



After this point, the signal can be split and processed in many different ways without a noise penalty (correlation radiometry, interferometry, spectroscopy)

Measurements of CMB polarization

The Science

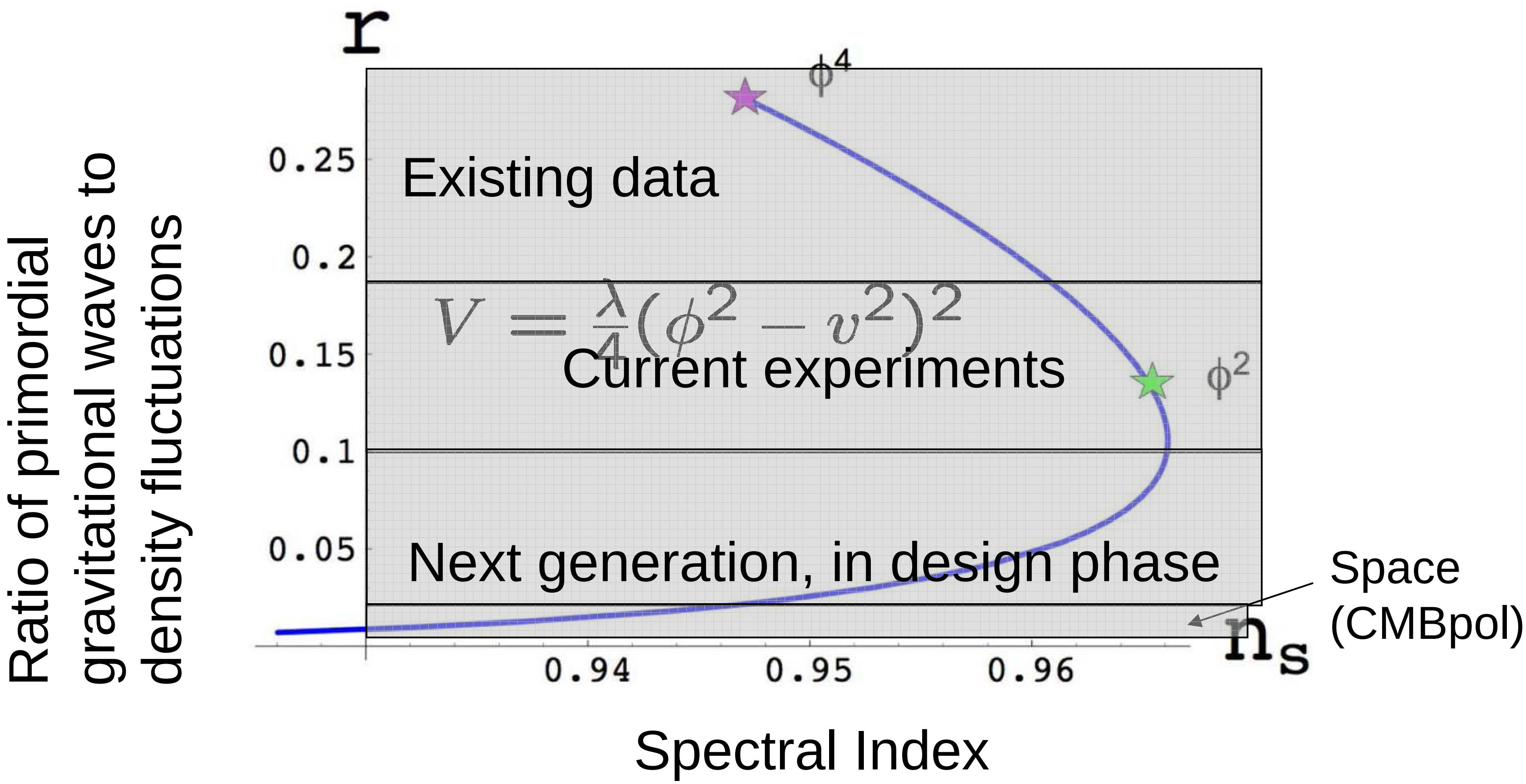


B modes (parity) from primordial gravitational waves (Blue shading spans current limits and minimum detectable from CMB)

Also very important tests of inflation from measurements of the gaussianity (or otherwise of the fluctuations)

The Goal: one class of inflationary model

Figure from Kallosh, Stanford Institute for Theoretical Physics



The Challenge

- Beyond $r \sim 0.1$ can only come from deploying hundreds of detectors
- Careful system engineering needed to minimize systematic effects that will otherwise dominate (signal < 1pt in 10^8 of background)
- Frequency discrimination is needed for foreground removal (Clive's talk)

Two Detector Solutions

- Low noise amplifiers and bolometers are the best technology at the moment for these measurements
- **Measurement methods are quite different – *different systematics***
- Different frequency ranges accessible with each, with a lot of overlap (Jonas's talk)

Frequencies and Foregrounds

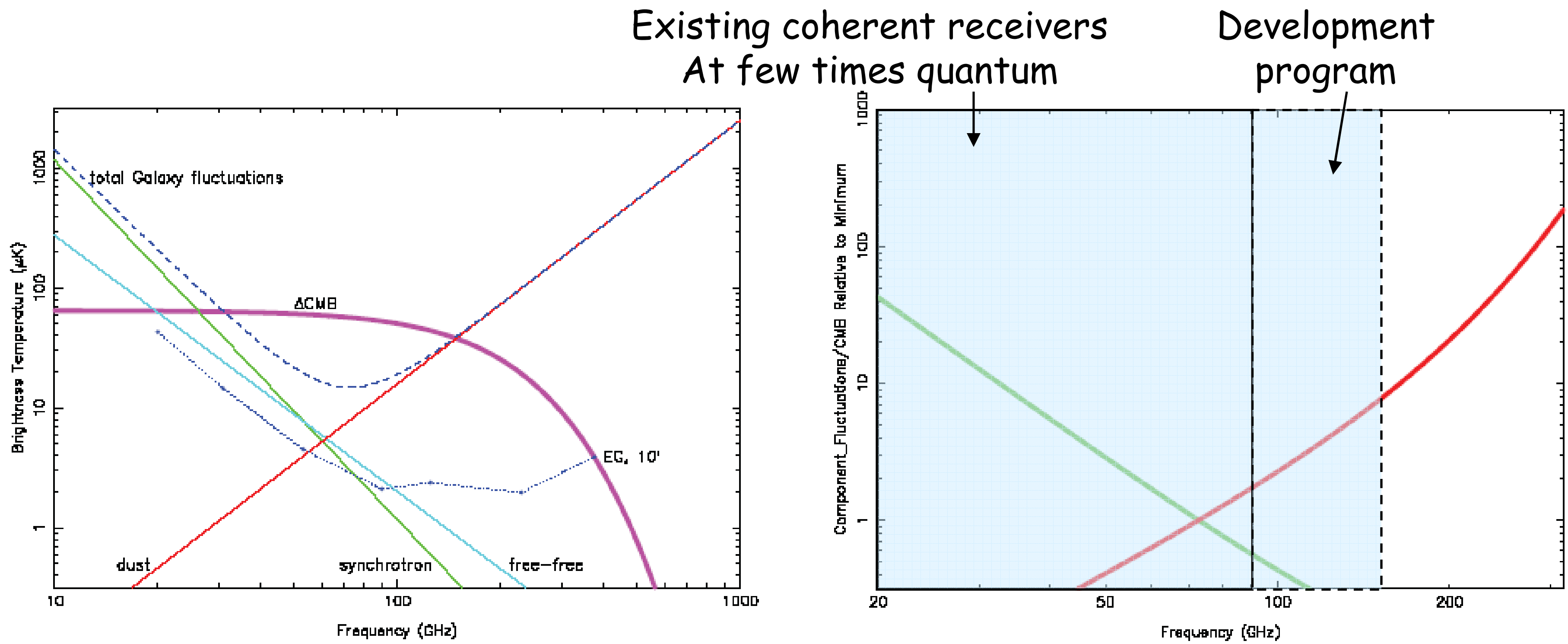


FIG 11.—Level of synchrotron and dust temperature fluctuations relative to CMB fluctuations, in absolute units (*left*) and normalized to the ratio at 70 GHz where the total diffuse foregrounds are a minimum (*right*). Too little is known about polarized foregrounds to support conclusive simulations; however, the same general behavior must apply, meaning that at high and low frequencies foreground fluctuations will dominate the measured signal. For example, at 40 and 130 GHz dust and synchrotron fluctuations are up by a factor of four over their values at the minimum. At 30 and 200 GHz the foregrounds are up by a factor of 10. By 300 GHz, dust fluctuations are up by two orders of magnitude compared to CMB fluctuations, which drop fast on the Wien side of the spectrum. Especially if the foreground spectra away from the minimum region are complicated, a very wide frequency range may be disadvantageous.

Slide from Charles Lawrence

What might be achieved

Development program

2005

TABLE 2

PROJECTED BOLOMETER & HEMT SENSITIVITIES, Q AND U PER FEED

Frequency [GHz]	SPACE 2010, FROM TFCR: Bolometer [μK s$^{1/2}$]	SPACE 2010, FROM TFCR: HEMT [μK s$^{1/2}$]	Predicted, this paper[c] [μK s$^{1/2}$]
40	51	51	<38
90	40	75	<39
140	42	...	<69
220	64	...	

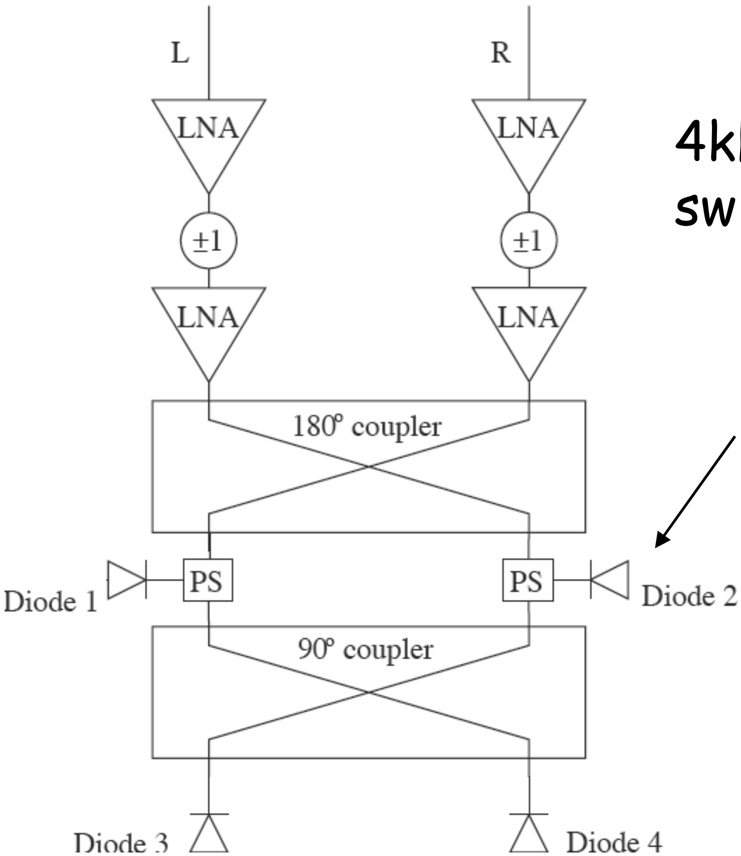
[a] (a) All sensitivities are $NET_{\rm cmb}$/feed = $NEQ_{\rm cmb}$/feed. The HEMT NET/feed is divided by $\sqrt{2}$ to provide a fair basis of comparison between the HEMT-based system, which can measure both the Q and U Stokes parameters simultaneously, and the bolometric system, which measures only Q or U at any given time. SPACE 2010 values are taken from the TFCR (2005).

[b] The convention for polarization sensitivity used is $(T_x - T_y)/2$.

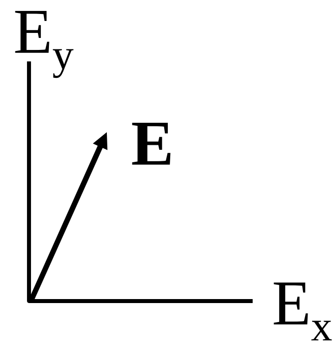
[c] Assuming noise from the model calculations shown in Figure 6, and 25% bandwidth.

Slide from Charles Lawrence

Technique -- correlation radiometer measurements (QUIET)



4kHz phase switching



$$|L \pm R|^2 = |(E_x + iE_y) \pm (E_x - iE_y)|^2 = 4E_x^2, 4E_y^2$$

Lock-in to phase switch frequency gives Q

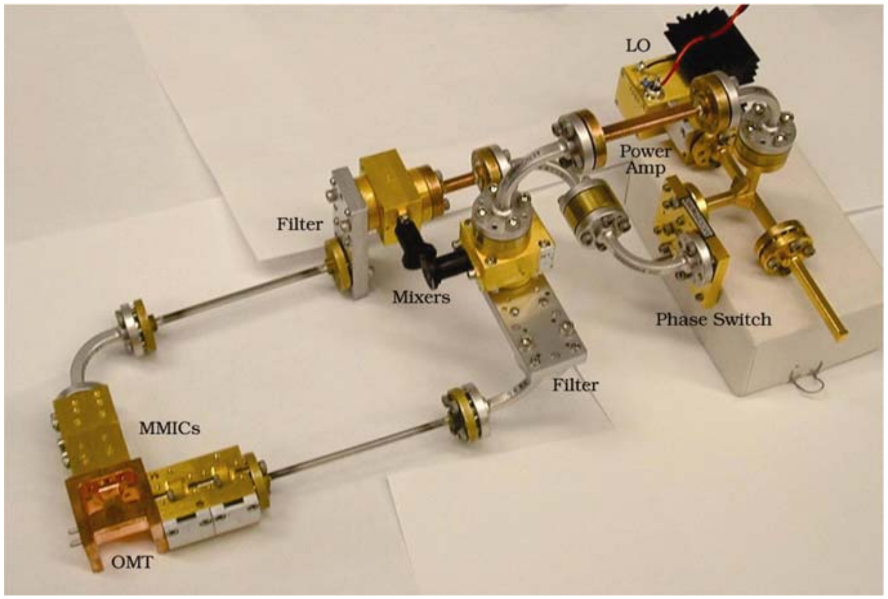
$$|(L \pm R) + i(L \mp R)|^2 = |L \mp iR|^2 = |L|^2 + |R|^2 \mp 2\,\mathrm{Im}(RL^*)$$

Lock-in to phase switch frequency gives Im(RL*), which is *U*

$$\mathrm{Im}(RL^*) = \mathrm{Im}(E_x + iE_y)^2 = 2E_xE_y$$

Q, U from same pixel, no noise penalty

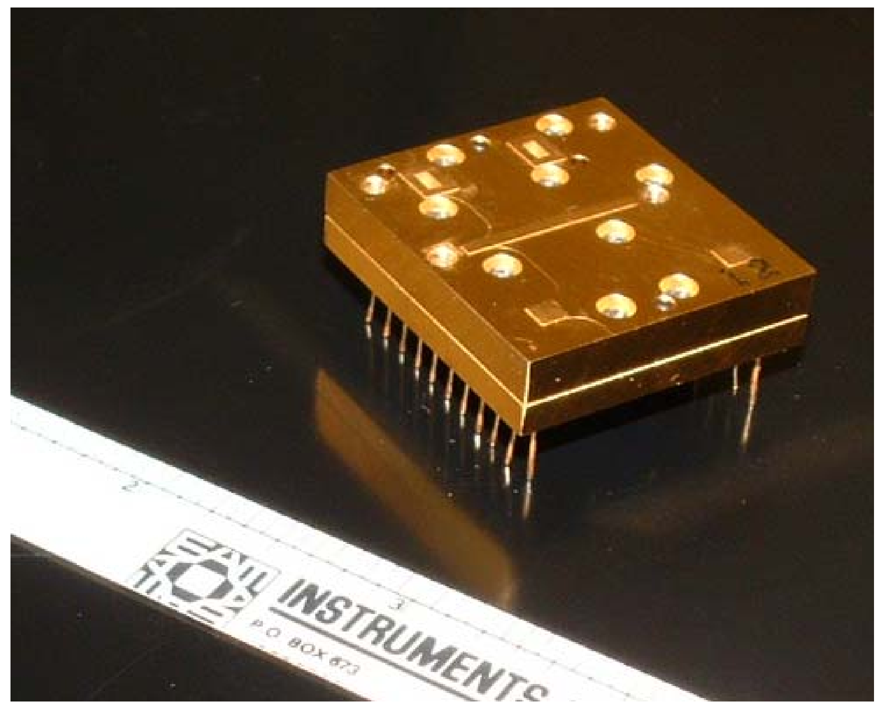
Advantage of Modular Radiometer



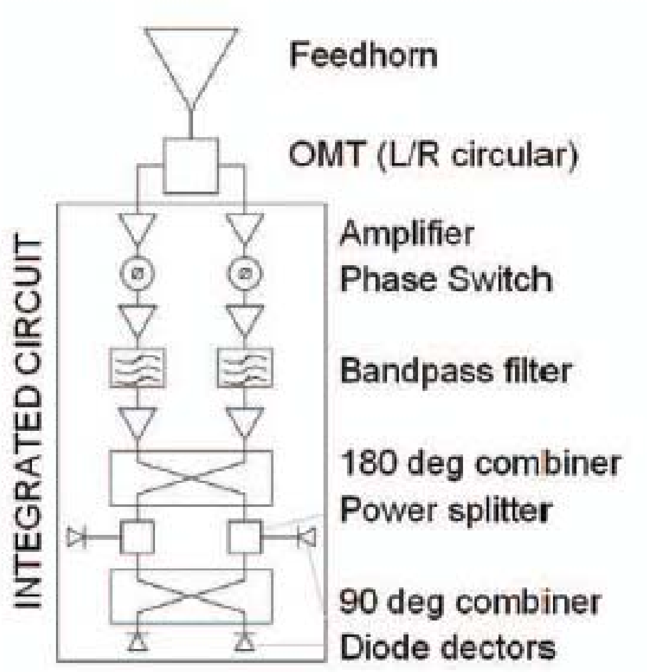
Quiet W band module

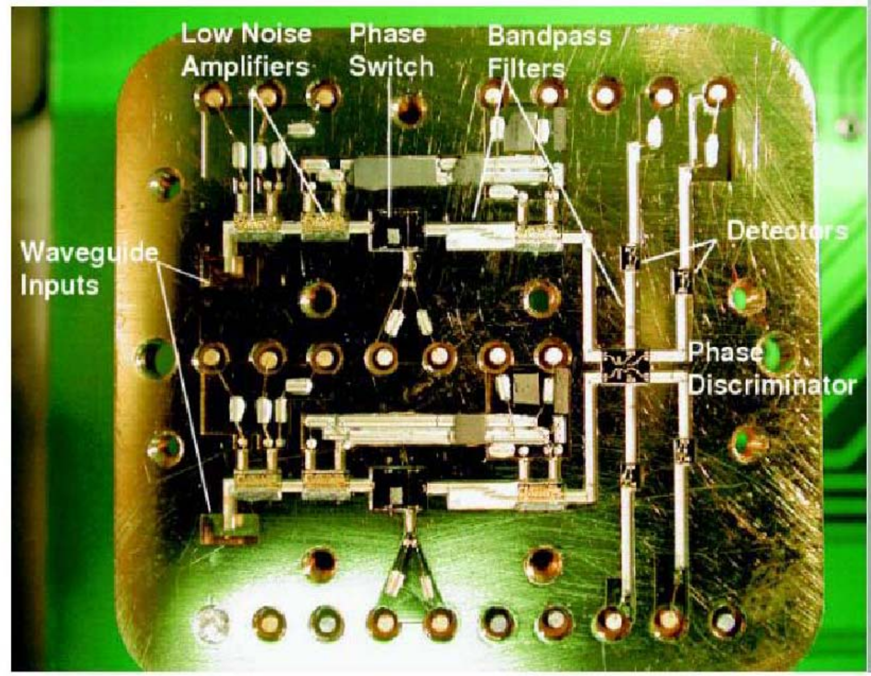
- 18 GHz band width
- Simultaneous Q/U measurements

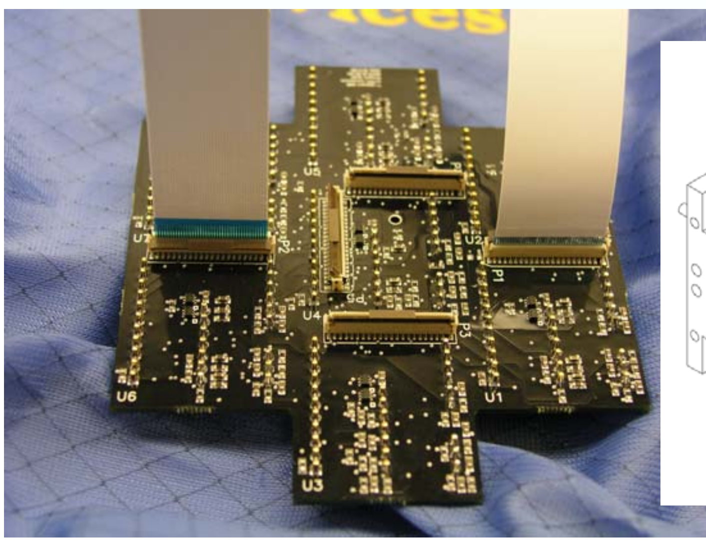
CAPMAP W-band correlation radiometer

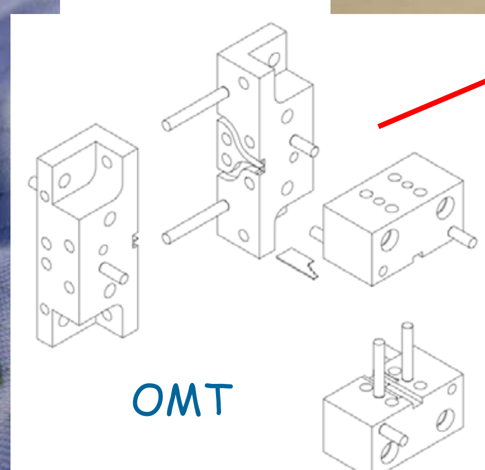


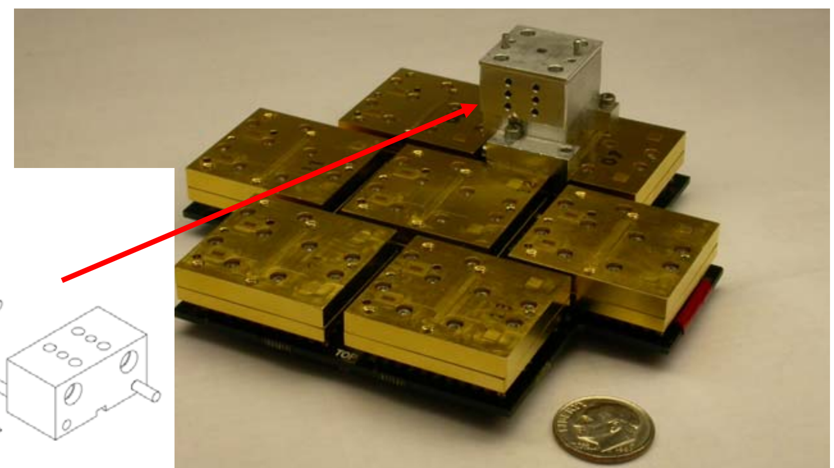
The QUIET modules











Existing and future correlation radiometers

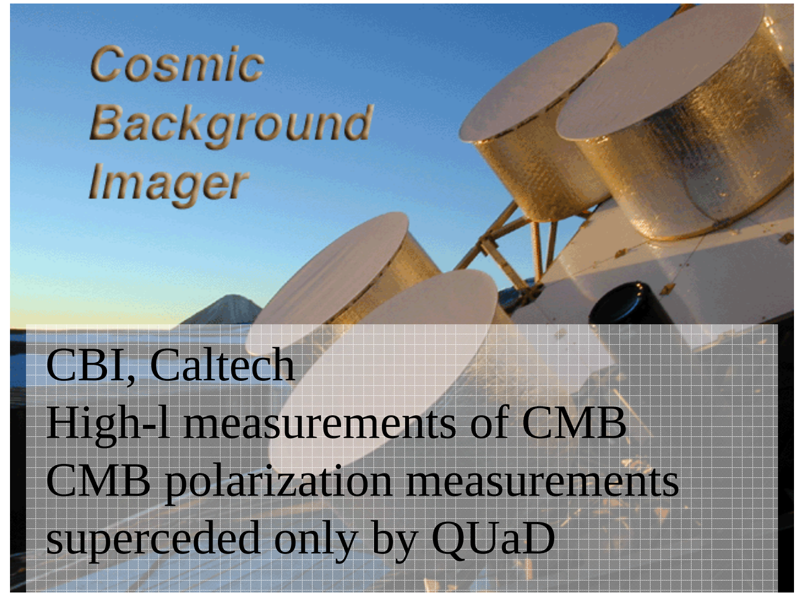
- QUIET
  - Phase I
    - 19 pixels, 40 GHz; 91 pixels 90 GHz
    - 1.4m telescope
  - Phase II
    - 200 pixels 40 GHz; 1000 pixels 90 GHz
    - 2m + larger telescope (TBD)
    - Possibly 30 GHz (Manchester MMICS), 150 GHz with new amplifier technology?
- Pathfinder to a space mission with similar technology
- Todd will speak about the program, but efforts in
  - Noise performance
  - Scalability (automated production of large numbers of modules)
  - Extension to higher frequencies

Systematics in a correlation radiometer

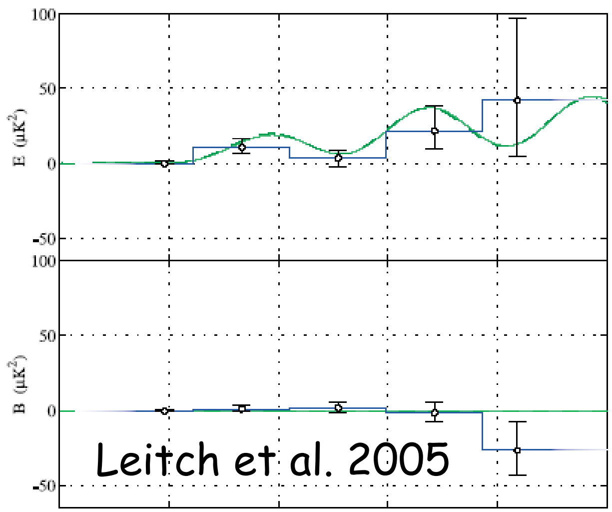
Parameter	Effect	Goal	Method
Cross-Polar Beam response	$E \rightarrow B$	< 0.003	Rotate Instrument, ~~Wave Plate~~
Main lobe ellipticity (0.5° beam)	$dT \rightarrow B$	$< 10^{-4}$	Rotate Instrument, ~~Wave Plate~~
Polarized sidelobes (response at Galaxy)	$dT \rightarrow B$	$< 10^{-6}$	Baffles/shielding/measure
Instrumental polarization	$dT \rightarrow B$	$< 10^{-4}$	Rotate Instrument, ~~Wave Plate~~
Polarization angle	$E \rightarrow B$	$< 0.2°$	Measure
Relative pointing (of differenced samples)	$dT \rightarrow B$	$< 0.1''$	Dual-polarization pixels
Relative calibration	$dT \rightarrow B$	$< 10^{-5}$	Modulators
Relative calibration drift (scan synchronous)	$T \rightarrow B$	$< 10^{-9}$	Modulators
Lyot Stop Temperature (10% spill, scan synch.)	$dT_{opt} \rightarrow B$	$dT_{opt} < 30$ nK	Measure
Cold stage T drifts (scan synch.)	$dT_{CS} \rightarrow B$	$dT_{CS} < 1$ nK	Improve uniformity, measure

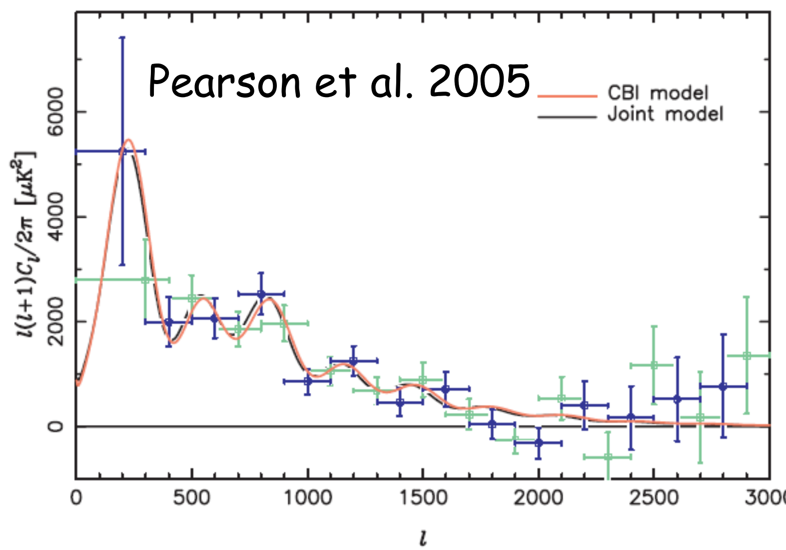
CMB taskforce report (assuming incoherent detectors, focal plane arrays)

Another approach -- interferometric measurements

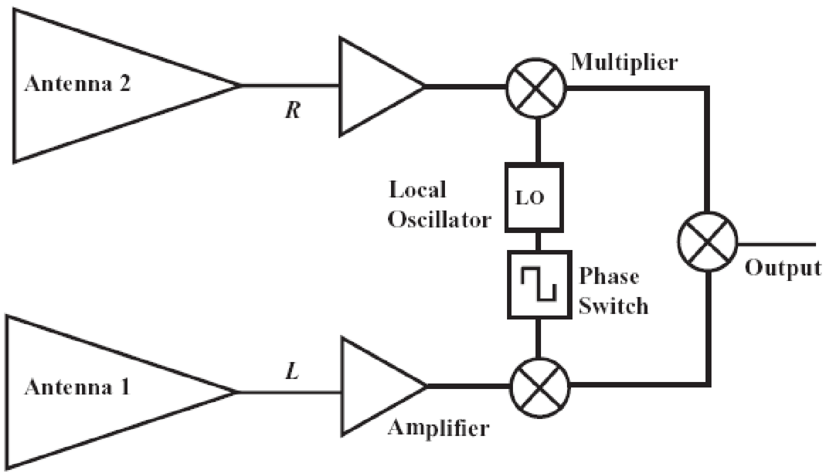


Radio interferometers played a key role in measurements of the CMB





How does an interferometer work?



L1 * L2 $\propto$ T + *i*V
R1 * R2 $\propto$ T - *i*V
L1 * R2 $\propto$ Q + *i*U
R1 * L2 $\propto$ Q - *i*U

Since each antenna can output both L and R polarization, all 4 Stokes parameters are *simultaneously measured* without noise penalty

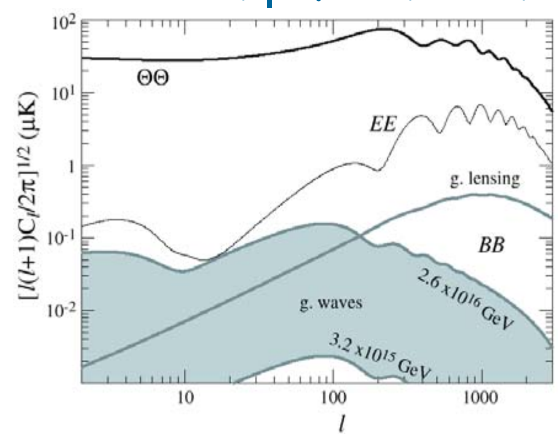
Correlate all possible baselines

Synthesize the equivalent aperture of the largest baseline

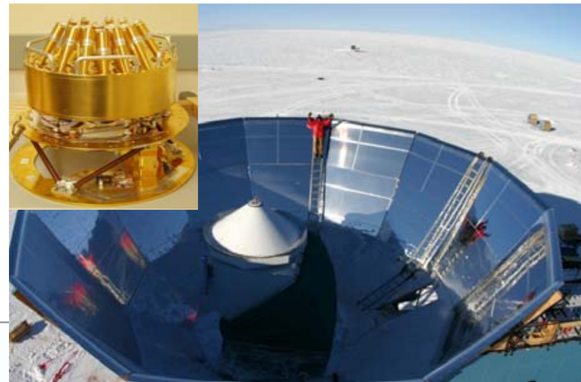
DASI interferometer
http://astro.uchicago.edu/cara/vtour/pole/darksector/cmbr/sunset.jpg

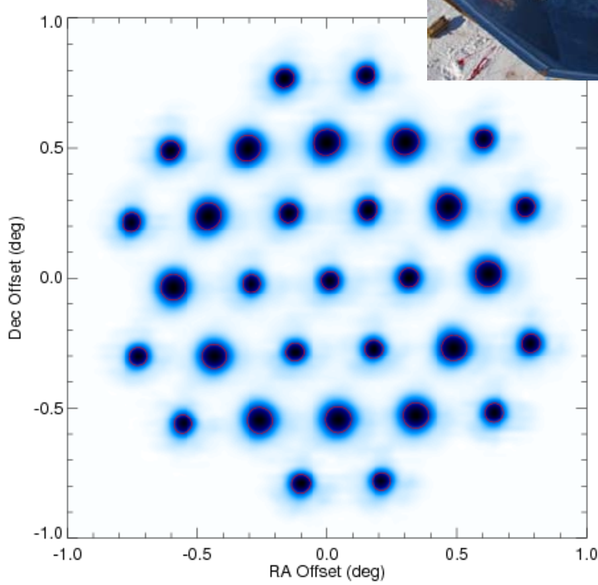
Interferometer compared to single dish measurements

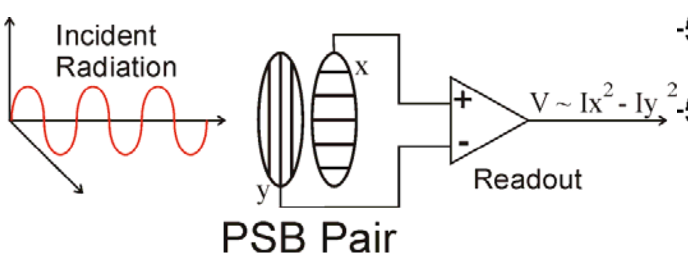
- Single-dish receivers and interferometers have completely equivalent in sensitivity in ell-space, or map space, **if**
  - Total number of detectors and amplifiers are the same
  - Noise per detector and per amplifier are equal
  - Each single dish pixel measures *both* Q *and U* without noise penalty (true for amplifiers)
  - ***One exception***: an interferometer has a low-ell cut-off. But a 10 degree field of view (2.5cm feed at 100 GHz) is quite adequate for measuring the ell=70-100 bump from B-mode polarization.



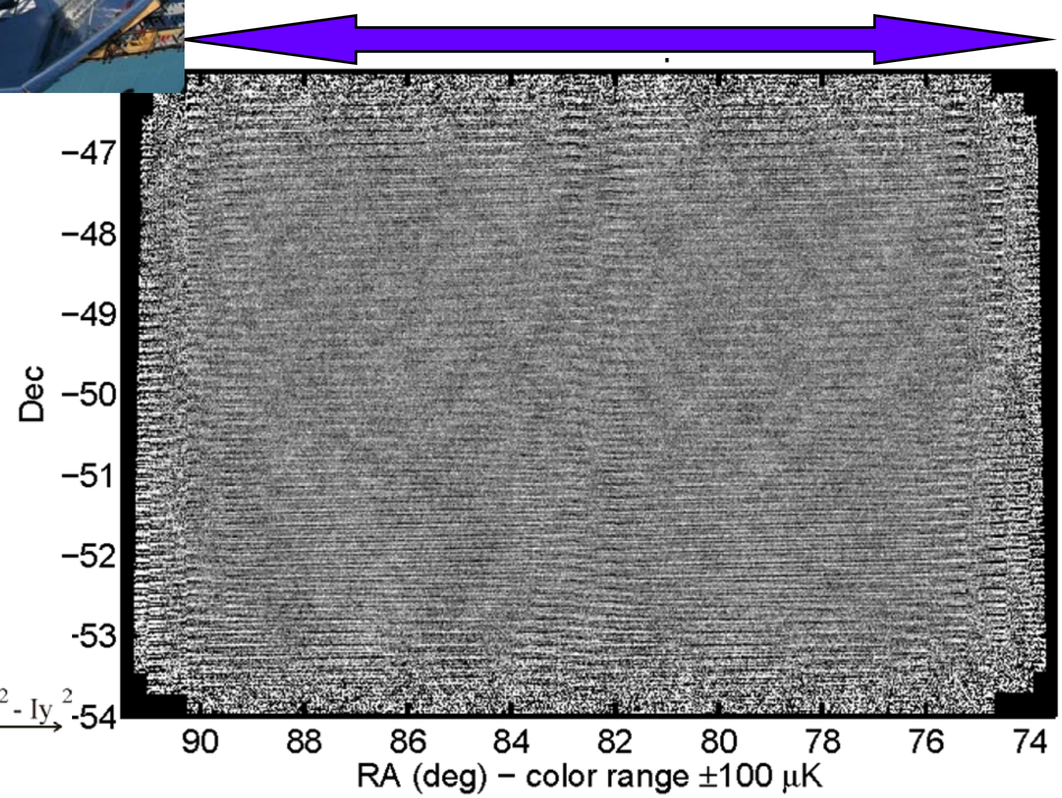
Compare to QUaD's method of measuring the CMB power spectrum



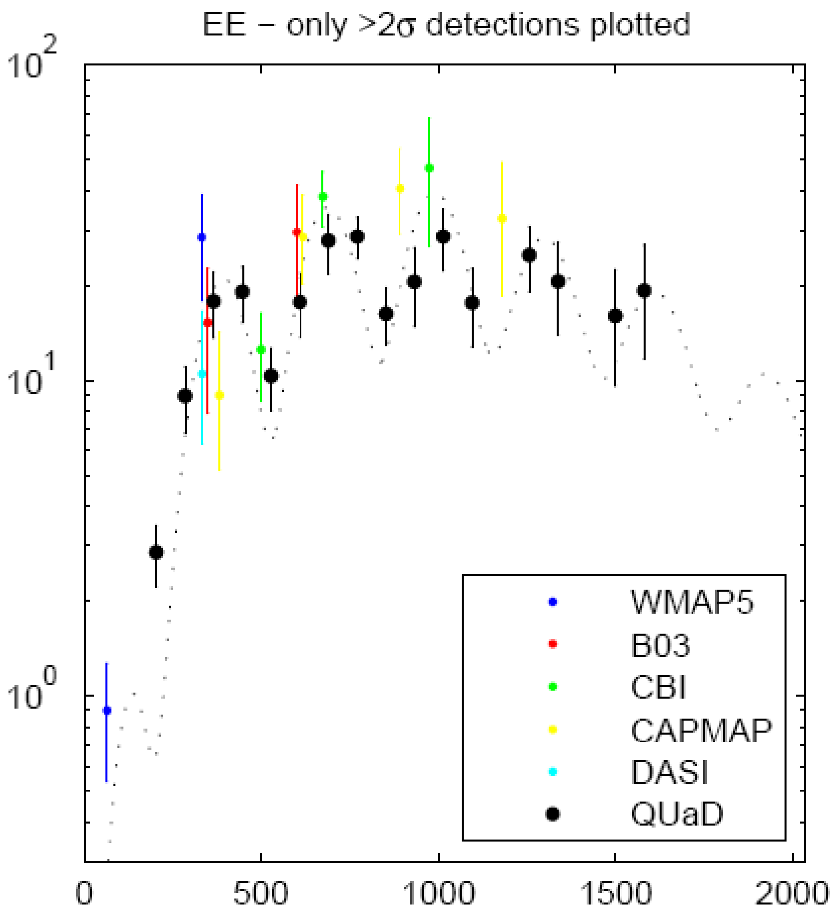


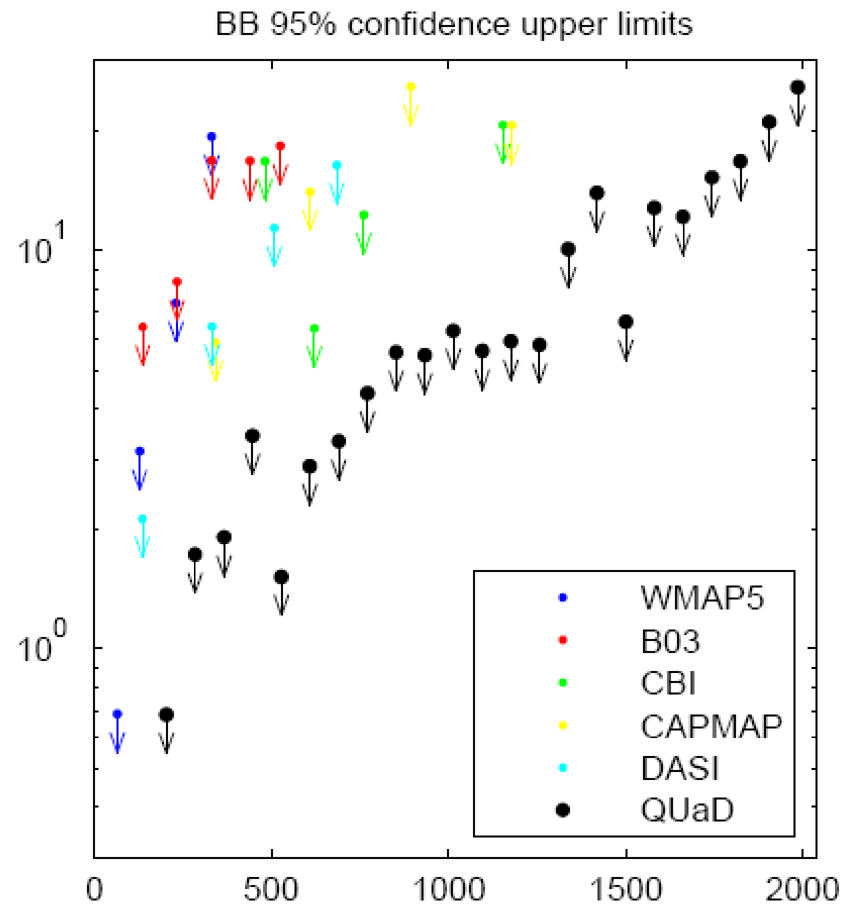


Scan backwards and forwards in azimuth



QUaD data


EE – only >2σ detections plotted
10^2
10^1
10^0
0
500
1000
1500
2000
WMAP5
B03
CBI
CAPMAP
DASI
QUaD

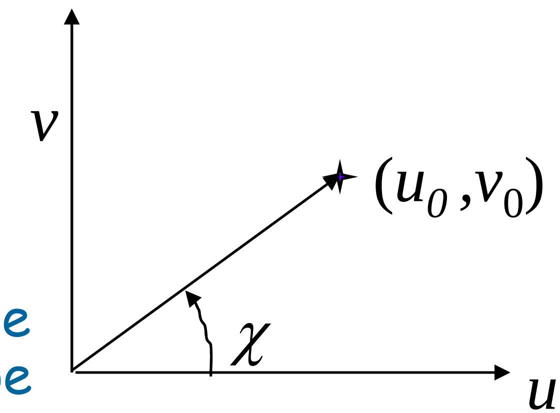

BB 95% confidence upper limits
10^1
10^0
0
500
1000
1500
2000
WMAP5
B03
CBI
CAPMAP
DASI
QUaD

Half the QUaD detectors map Q, half U

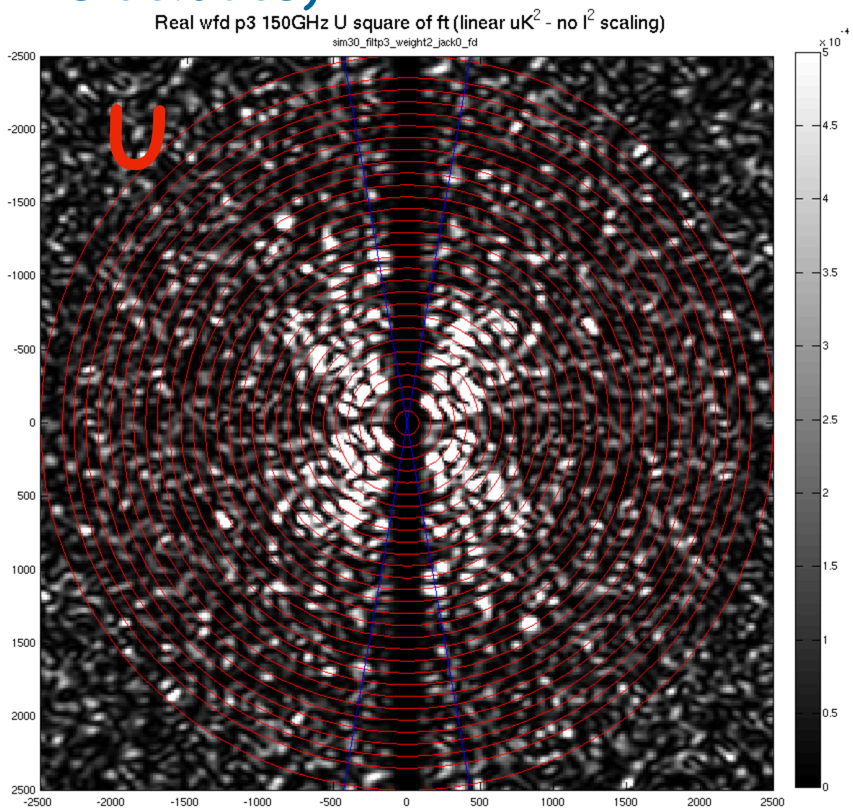
- Recover *E* and *B* modes from Fourier plane

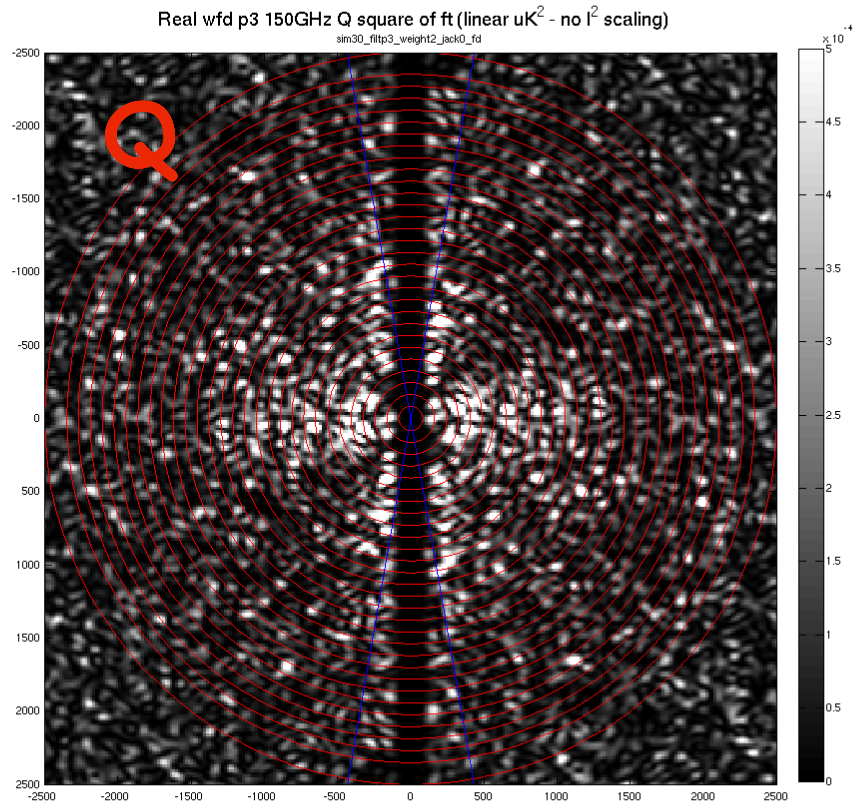
$$E = Q\cos 2\chi + U\sin 2\chi$$

$$B = -Q\sin 2\chi + U\cos 2\chi$$

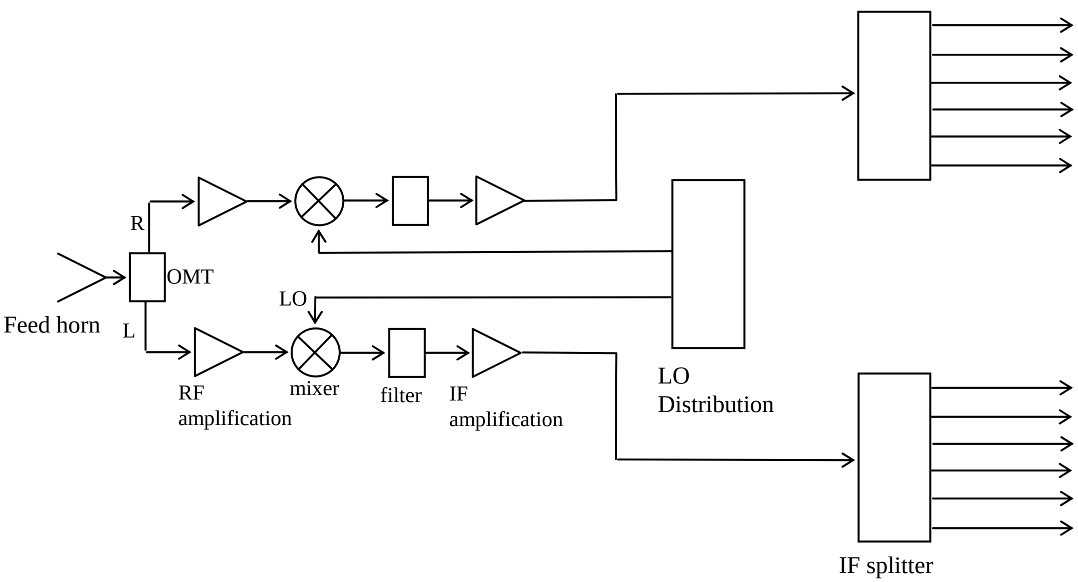


- Trench removes 1/f noise from atmosphere and detectors and ground pickup (telescope sidelobes)





An interferometer measures *I, Q, U* and *V* simultaneously



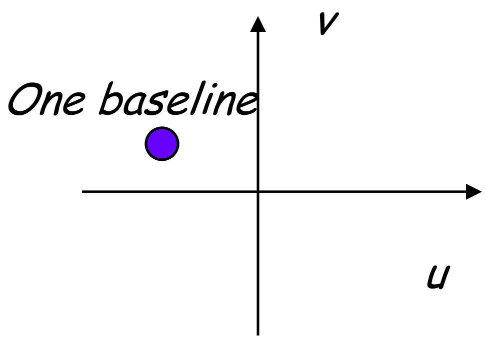
IF sub bands are digitized and cross-correlated with IF from second horn.

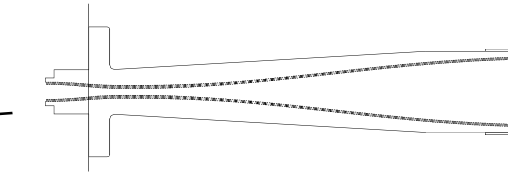
L1 * L2 $\propto$T + *i*V
R1 * R2 $\propto$T - *i*V
L1 * R2 $\propto$Q + *i*U
R1 * L2 $\propto$Q - *i*U

from which all 4 Stokes parameters can be recovered.

Why consider an interferometer for CMB polarization measurements? Systematics control is one argument

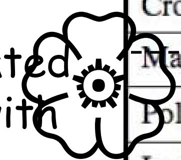
- Key for the next generation of experiments
- Interferometers have some advantages
  - Measurement is made in Fourier space; modeling the noise properties of the experiment is much more straightforward
  - I Q and U are measured simultaneously on same baseline
  - Large angular scales allow the use of corrugated feedhorns with very low spillover without the need for a telescope.
  - High resolution beams are synthesized – beam measurement errors reduced





Systematics in an Interferometer

Corrugated feeds with no transmissive or reflective optics



Parameter	Effect	Goal	Method
Cross-Polar Beam response	E → B	< 0.003	Rotate Instrument, ~~Wave Plate~~
~~Main lobe ellipticity (0.5° beam)~~	~~dT → B~~	~~< 10^{-4}~~	Rotate Instrument, ~~Wave Plate~~
Polarized sidelobes (response at Galaxy)	dT → B	< 10^{-6}	Baffles/shielding/measure
Instrumental polarization	dT → B	< 10^{-4}	Rotate Instrument, ~~Wave Plate~~
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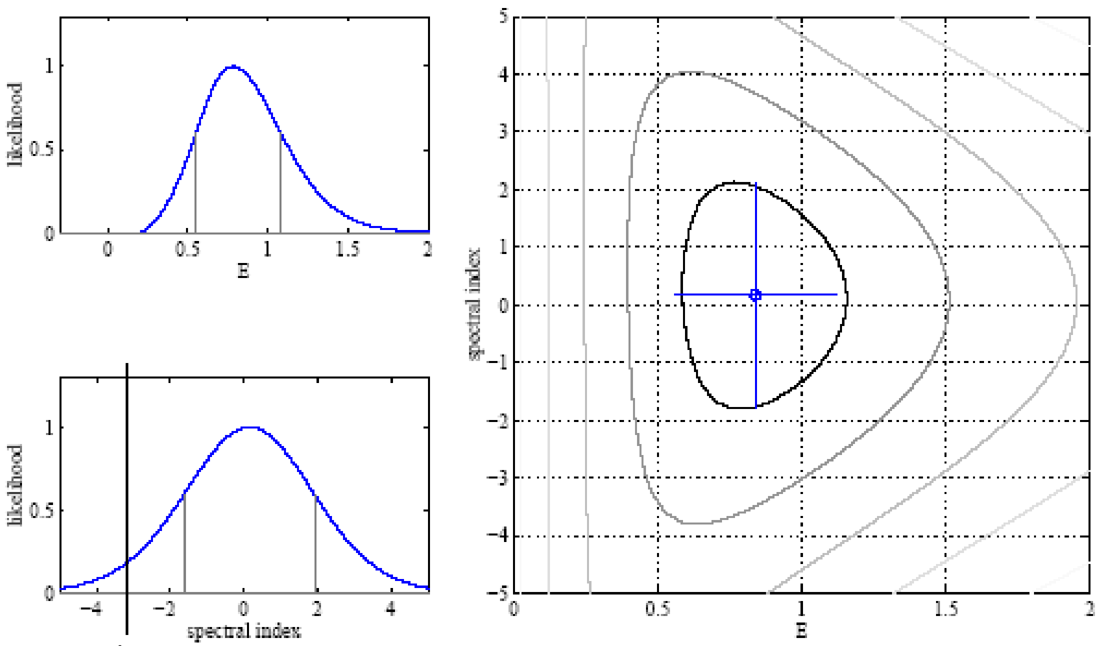
Relative pointing (of differenced samples)	dT → B	< 0.1″	Dual-polarization pixels
Relative calibration	dT → B	< 10^{-5}	Modulators
~~Relative calibration drift (scan synchronous)~~	~~T → B~~	~~< 10^{-9}~~	~~Modulators~~
~~Lyot Stop Temperature (10% spill, scan synch.)~~	~~dT_{opt} → B~~	~~dT_{opt} < 30 nK~~	~~Measure~~
~~Cold stage T drifts (scan synch.)~~	~~dT_{CS} → B~~	~~dT_{CS} < 1 nK~~	~~Improve uniformity, measure~~

CMB taskforce report (assuming incoherent detectors, focal plane arrays)

Why an interferometer? Foregrounds?

- Split IF into sub-bands to reduce chromatic aberration
- Retains additional spectral information each frequency band
- Useful for confirming that signal is CMB



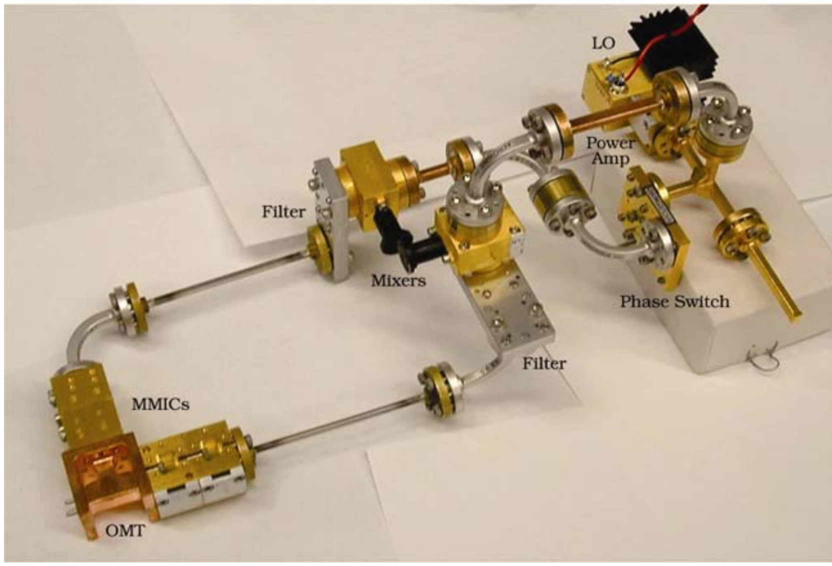
Synchrotron

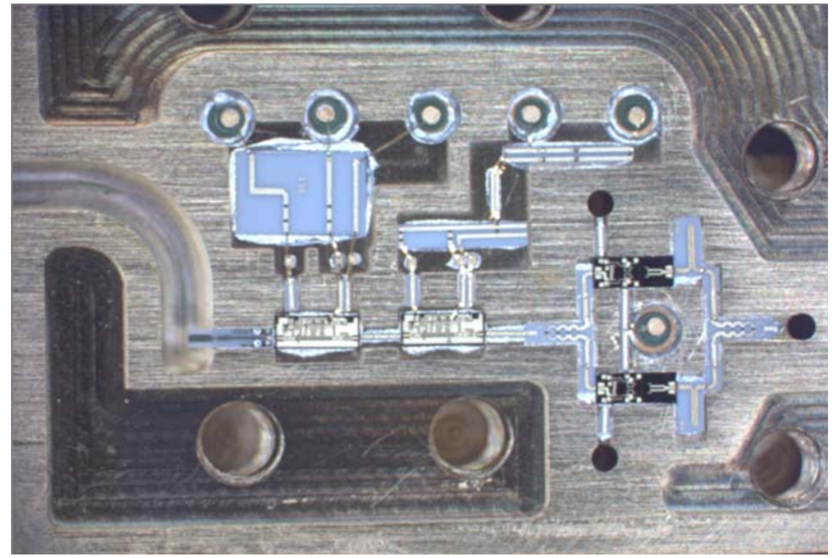
Spectral information helped to validate the DASI detection of polarization
Kovac et al. 2002

You might wonder……

- Interferometers are **complicated**
  - *N* antennas requires $N(N-1)/2$ correlations to recover all possible information
- **This program**
  - Few hundred element array with feedhorns is plausible
  - Correlating all baselines for such an instrument could be feasible, even in space (Ruf)

Heterodyne MMIC modules

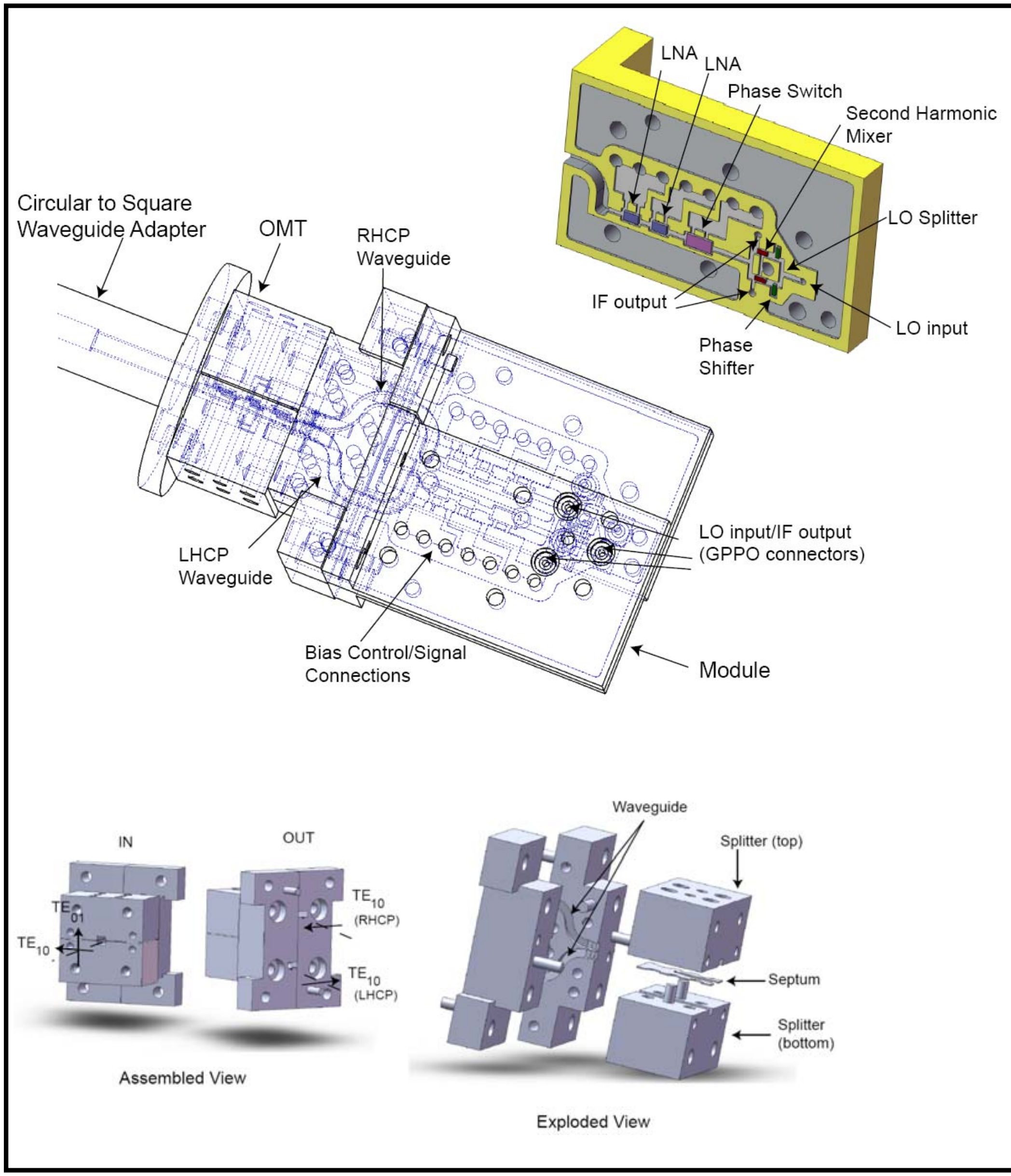


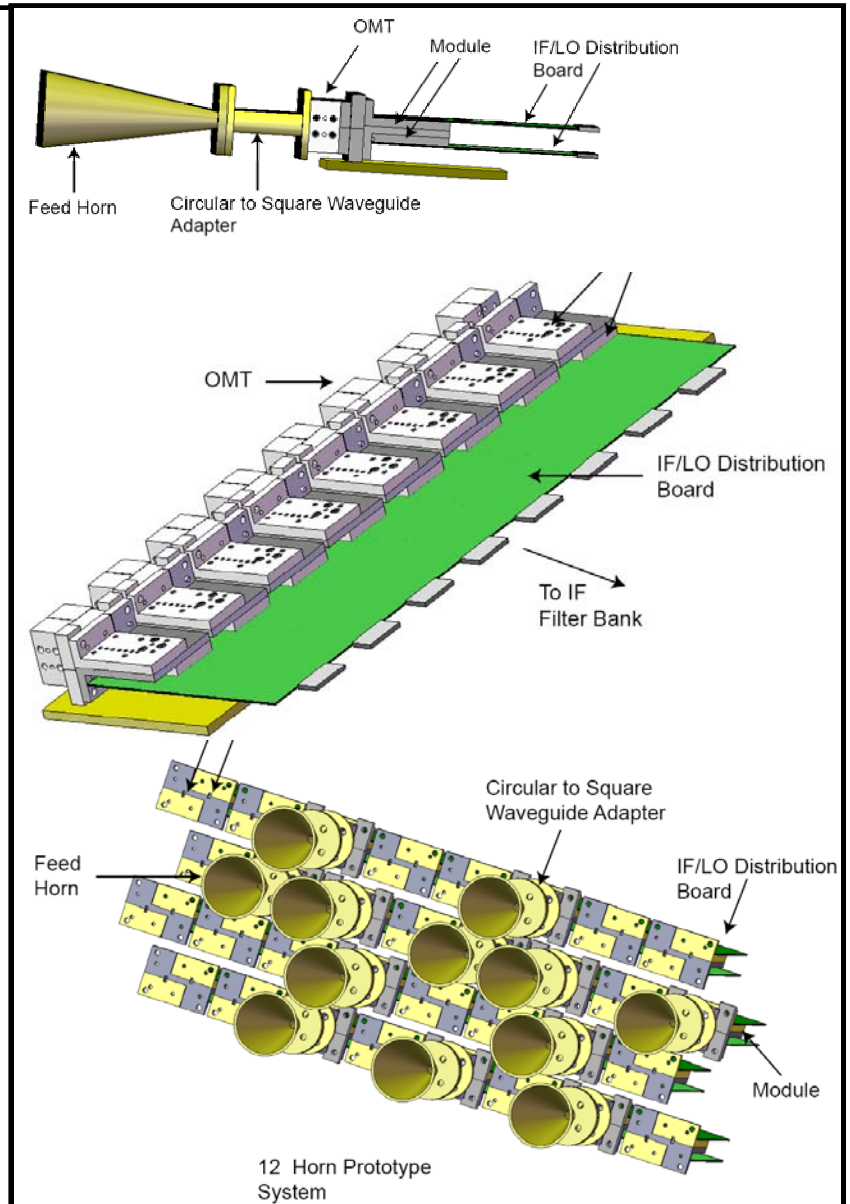


1.5 in

- Development of 90 GHz MMIC amplifier modules for a heterodyne spectrometer
- Only small modifications needed to make a module for an interferometer

Prototype array for heterodyne modules





Science from the Sunyaev-Zel'dovich Effect

The Sunyaev-Zel'dovich (SZ) effect

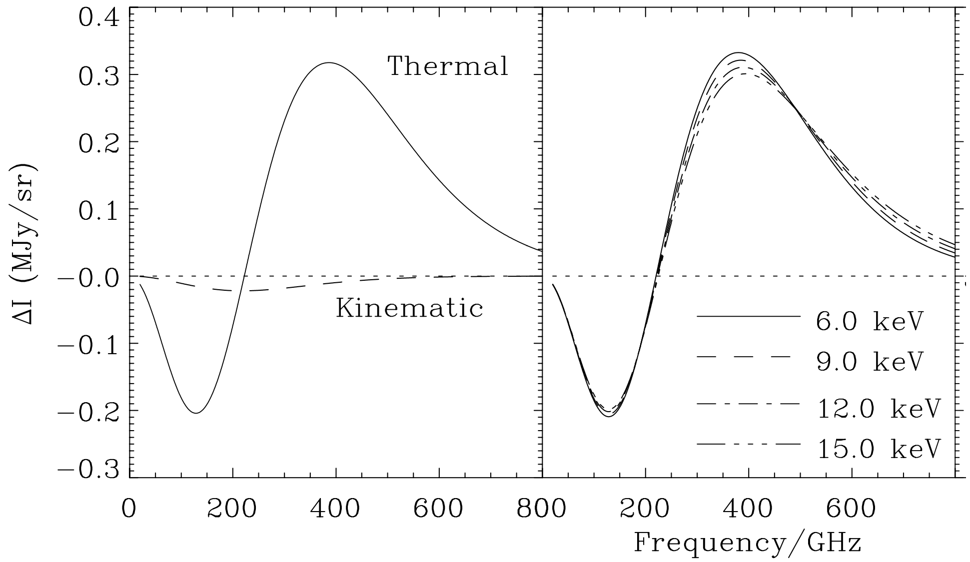
- thermal effect depends on electron temperature, T_e

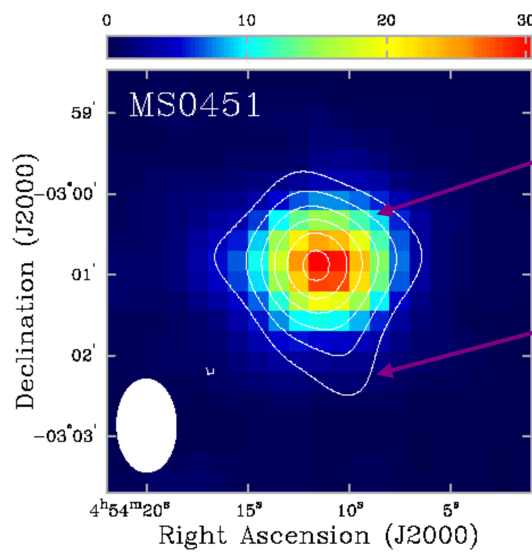
$$\frac{\Delta I_{th}}{I_{CMB}} \approx f(\nu, T_e) \times \tau \times \langle T_e \rangle$$

- the kinematic effect which depends on the cluster peculiar velocity, v_{pec}.

$$\frac{\Delta I_{kin}}{I_{CMB}} \approx g(\nu) \times \tau \times \frac{\langle v_{pec} \rangle}{c}$$

- τ is the optical depth of the cluster to Compton scattering
- *f* and *g* are different functions of frequency





Colors: X-ray emission

Contours: SZ effect

30 GHz OVRO/BIMA interferometric measurement
Reese et al. (2002) astroph/0205350

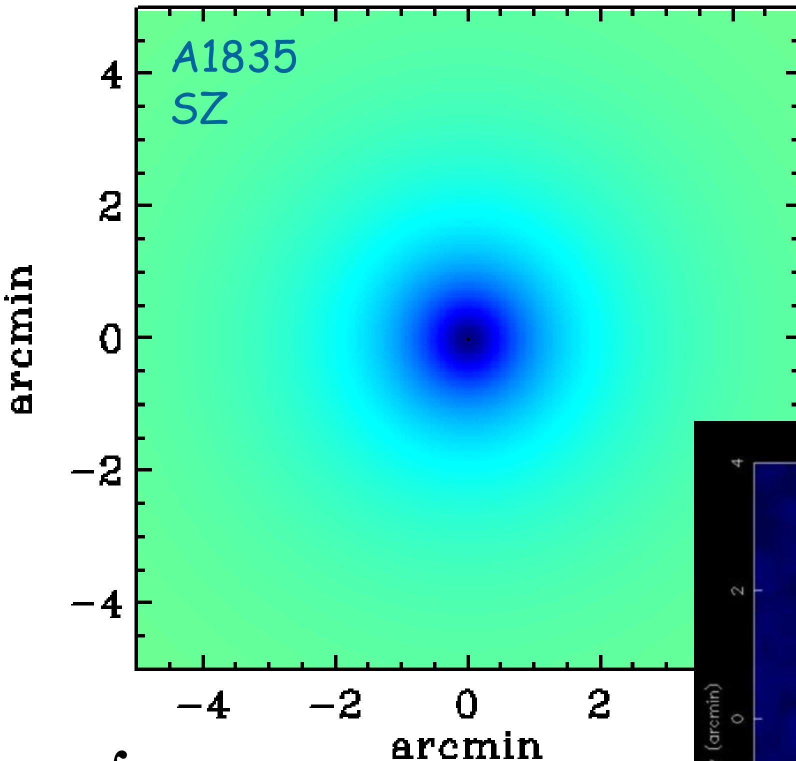
Model of SZ emission from a rich cluster

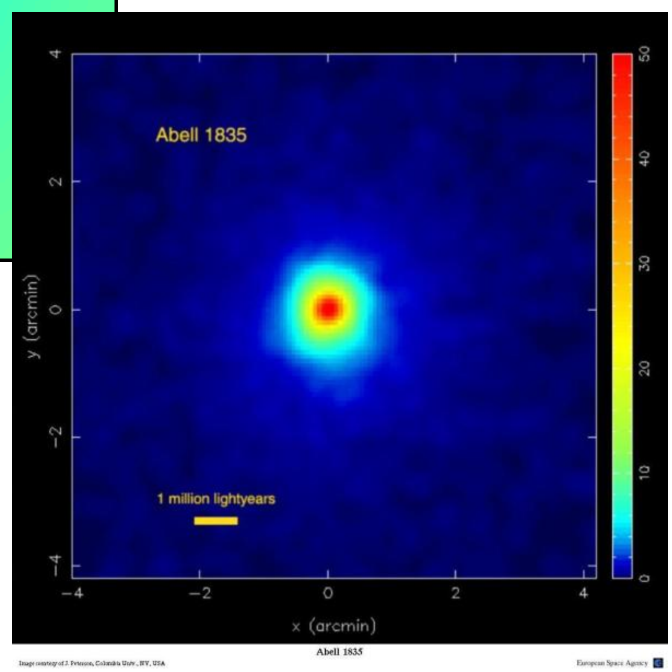
Based on a spherically symmetric model derived from a Chandra observation of A1835 (from Robert Schmidt)

$$S_X \propto \int n_e^2 \Lambda_e dl$$

S_X - peak X-ray flux

Λ_e - X-ray cooling function $\propto T_e^{1/2}$





XMM image (Peterson)

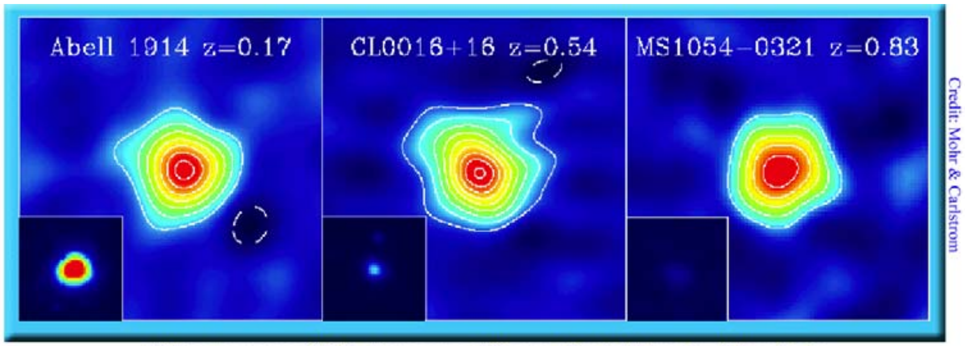
$$S_{SZ} \propto \int n_e T_e \, dl$$

S_{SZ} - SZ flux

T_e - gas temperature

$dl \sim D_A d\theta$ for a spherical cluster

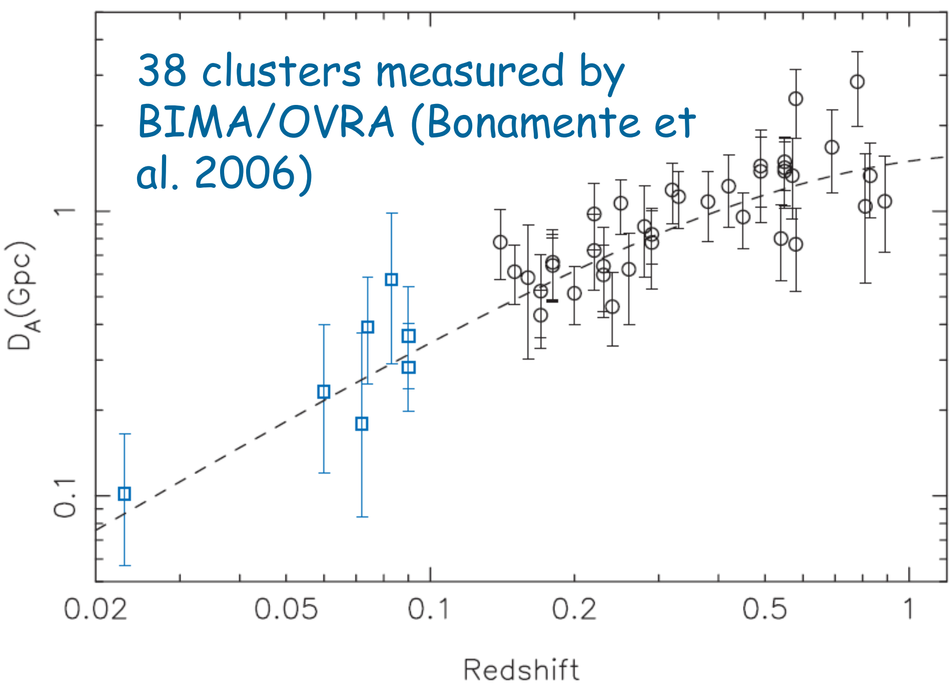
Using the SZ effect to measure D_A



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

$$S_{SZ} \propto \int n_e T_e D_A d\theta$$

$$S_X \propto \int n_e^2 \Lambda_e D_A d\theta$$



$$D_A \ \alpha \ \frac{S_{SZ}^2 \Lambda_e}{S_X T_e^2}$$

S_{SZ} - peak SZ flux

S_X - peak X-ray flux

Λ_e - X-ray cooling function $\propto T_e^{1/2}$

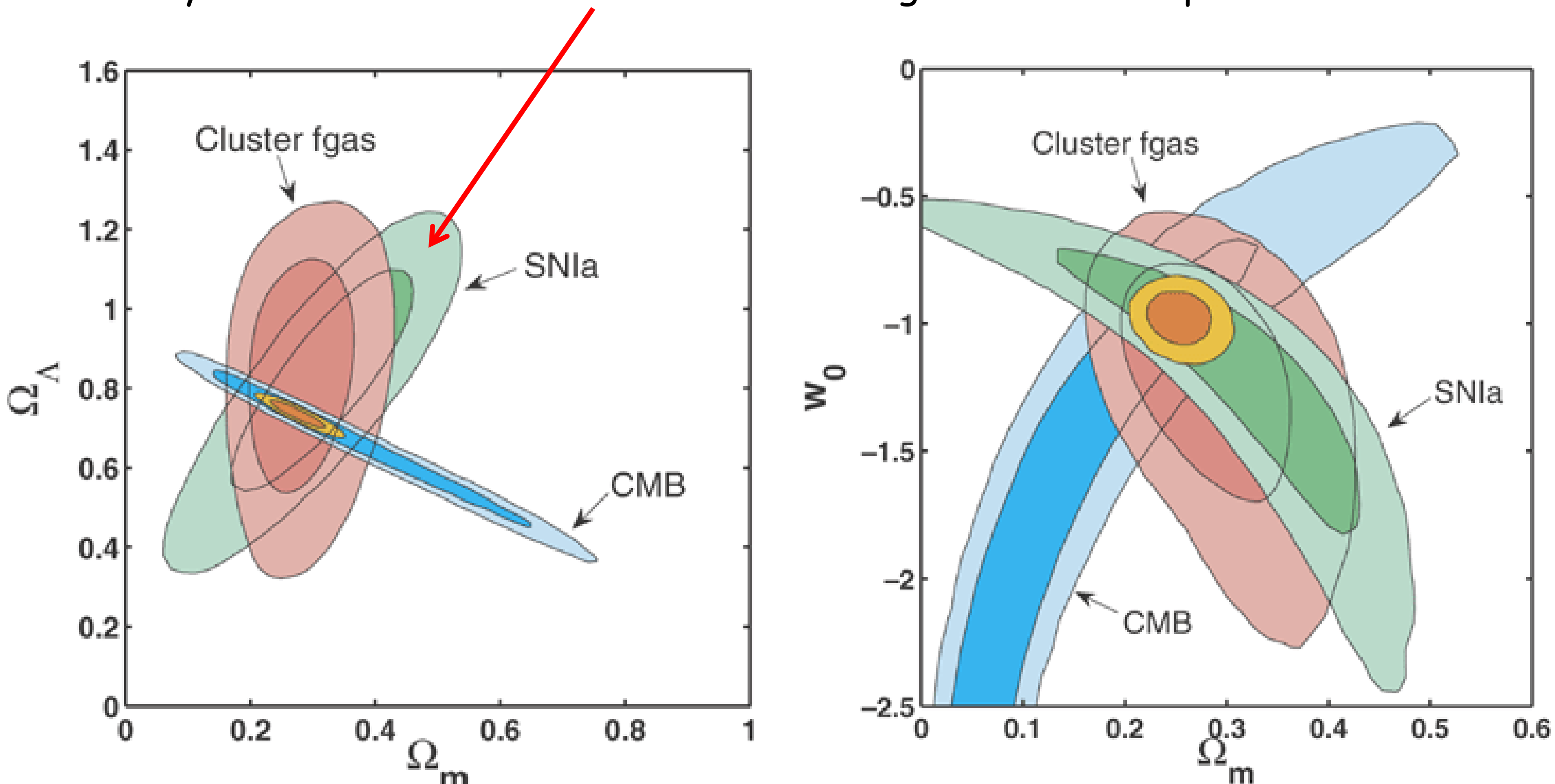
T_e - X-ray temperature

Science From Studies of the SZ Effect in Individual Clusters

- **Large Relaxed Systems**
  - Combine SZ and X-ray measurements to determine angular diameter distances
  - Measure gas masses and baryon fractions by combining with X-ray measurements
- Non-relaxed systems
  - Probe the gas distribution to understand the gas physics
- Calibrate SZ-flux to mass scaling relationships
  - Important step for cluster surveys that aim to use such scaling relations to probe dark energy
- Measure cluster gas temperatures through the relativistic correction to the SZ effect??
- Measure gas velocities from the kinematic SZ effect??

Constraining dark energy will be hard – multiple techniques neededc

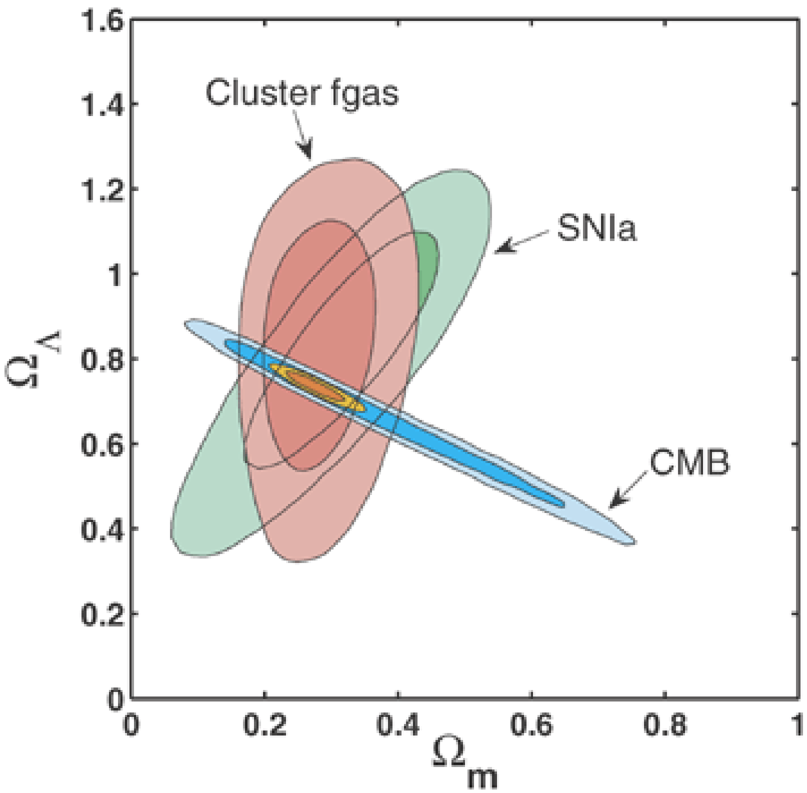
SZ/X-ray Measurements of individual clusters give similar shaped constraints to SN1a



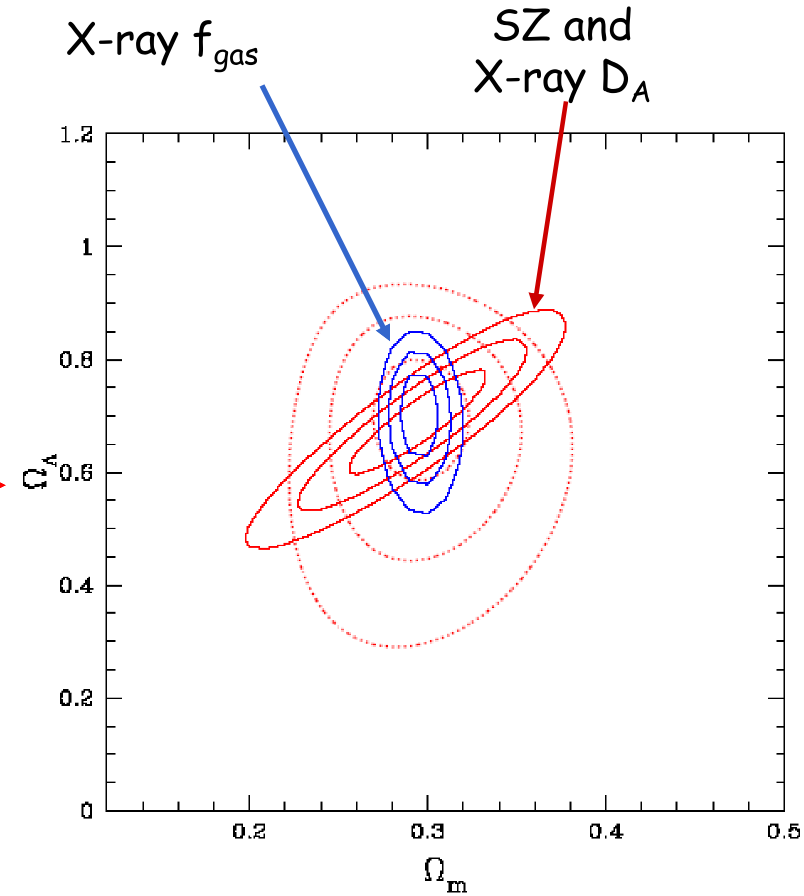
Allen et al., 2008 arXiv:0706.0033

Current Constrains on Dark Energy with X-ray Measurements of Individual Clusters

Add SZ/X-ray of 1000 clusters



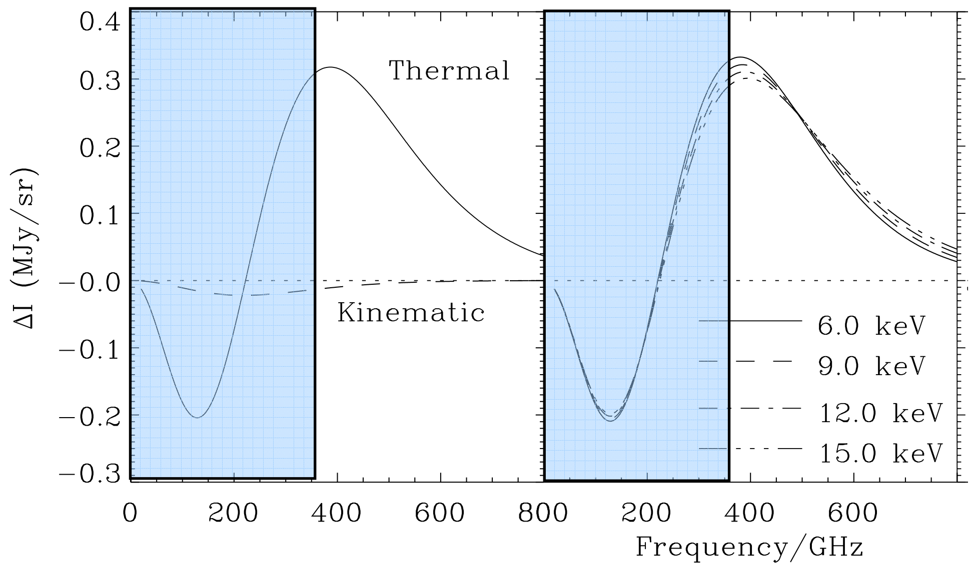
Allen et al., 2008 arXiv:0706.0033



Rapetti et al., 2006 arXiv:0608.0009

Less sensitive to models of cluster gas physics than cluster counting with SZ surveys

If you want to make accurate SZ measurements you need to know about other sources



- At radio/millimeter wavelengths we need to include
  - SZ thermal + kinematic
  - CMB
  - Dusty galaxies
  - Radio galaxies
  - (galactic emission)

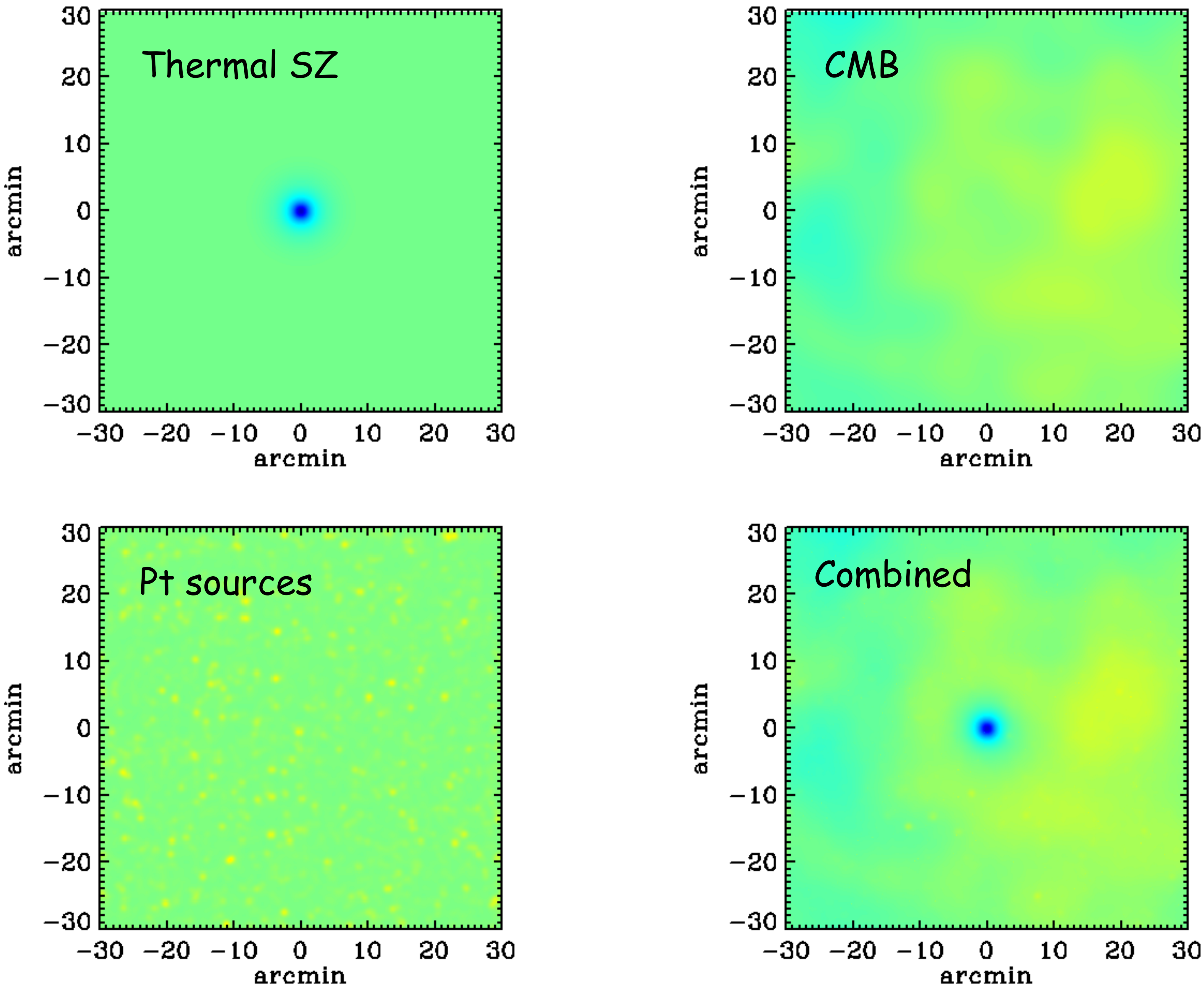
What does the sky look like at millimeter wavelengths?

- SZ thermal + kinematic
- CMB
- Dusty galaxies
- Radio galaxies
- (galactic emission)

- Following slides show how the components change with frequency

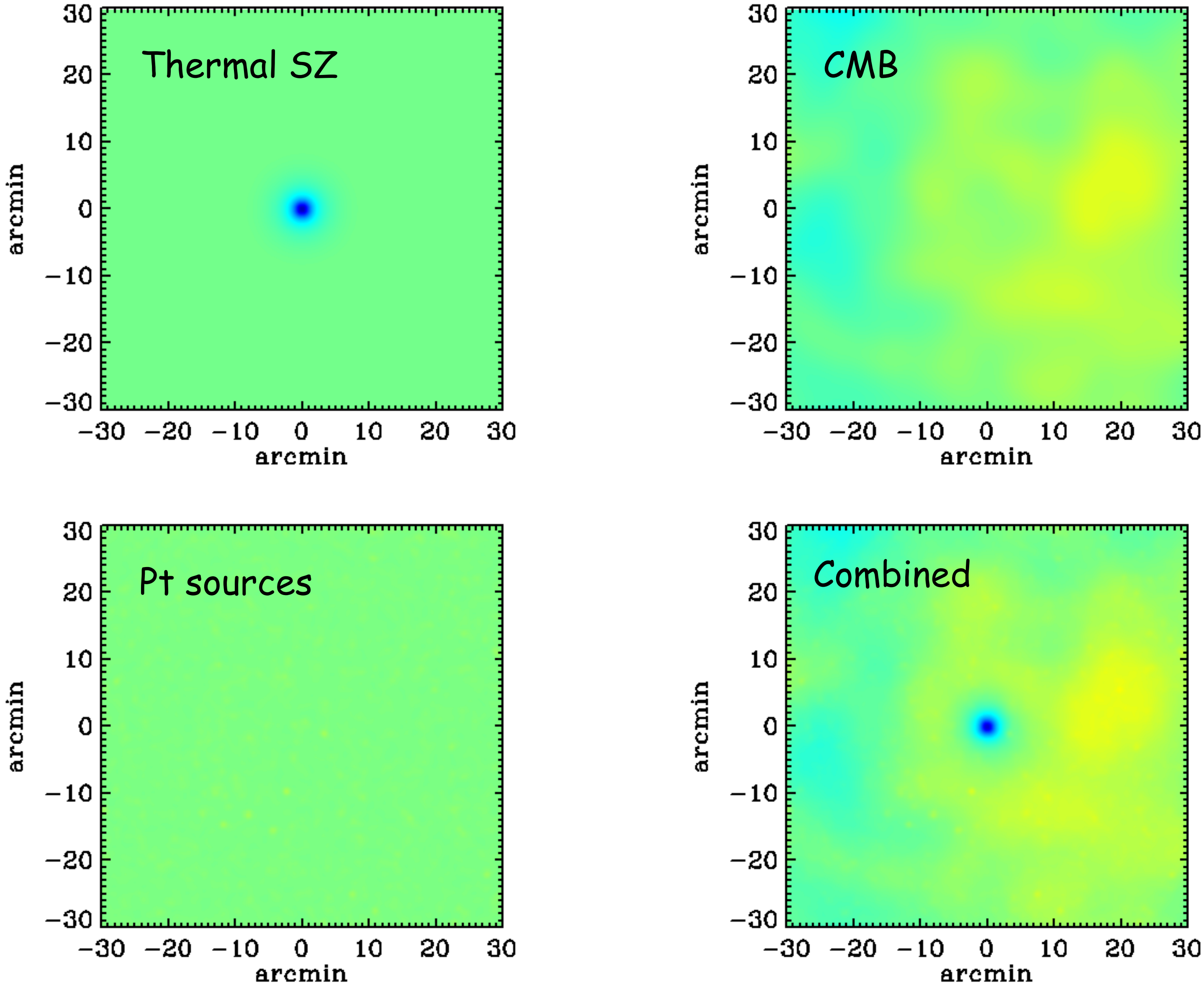
30 GHz

Color: Mjy/sr

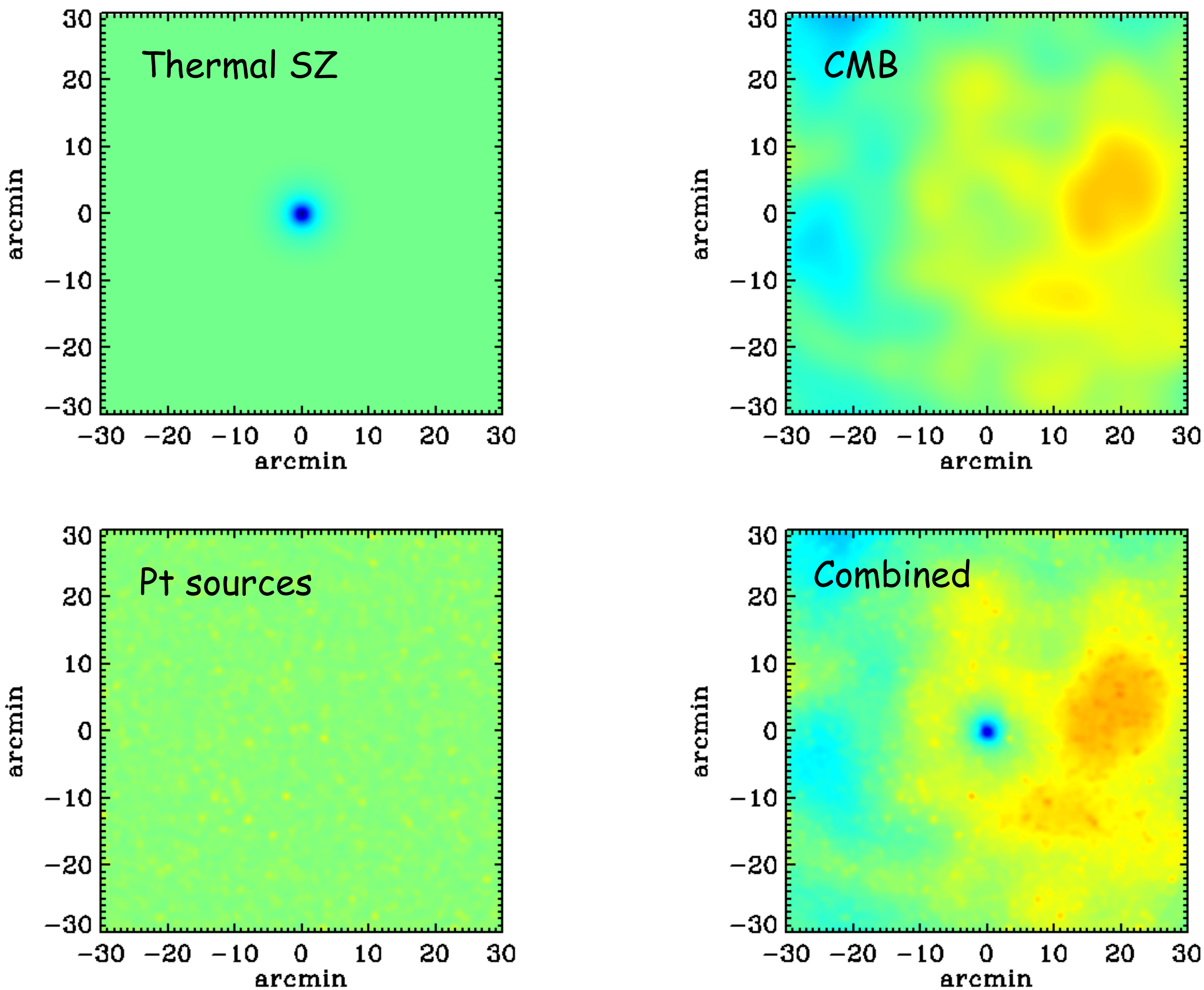


90 GHz

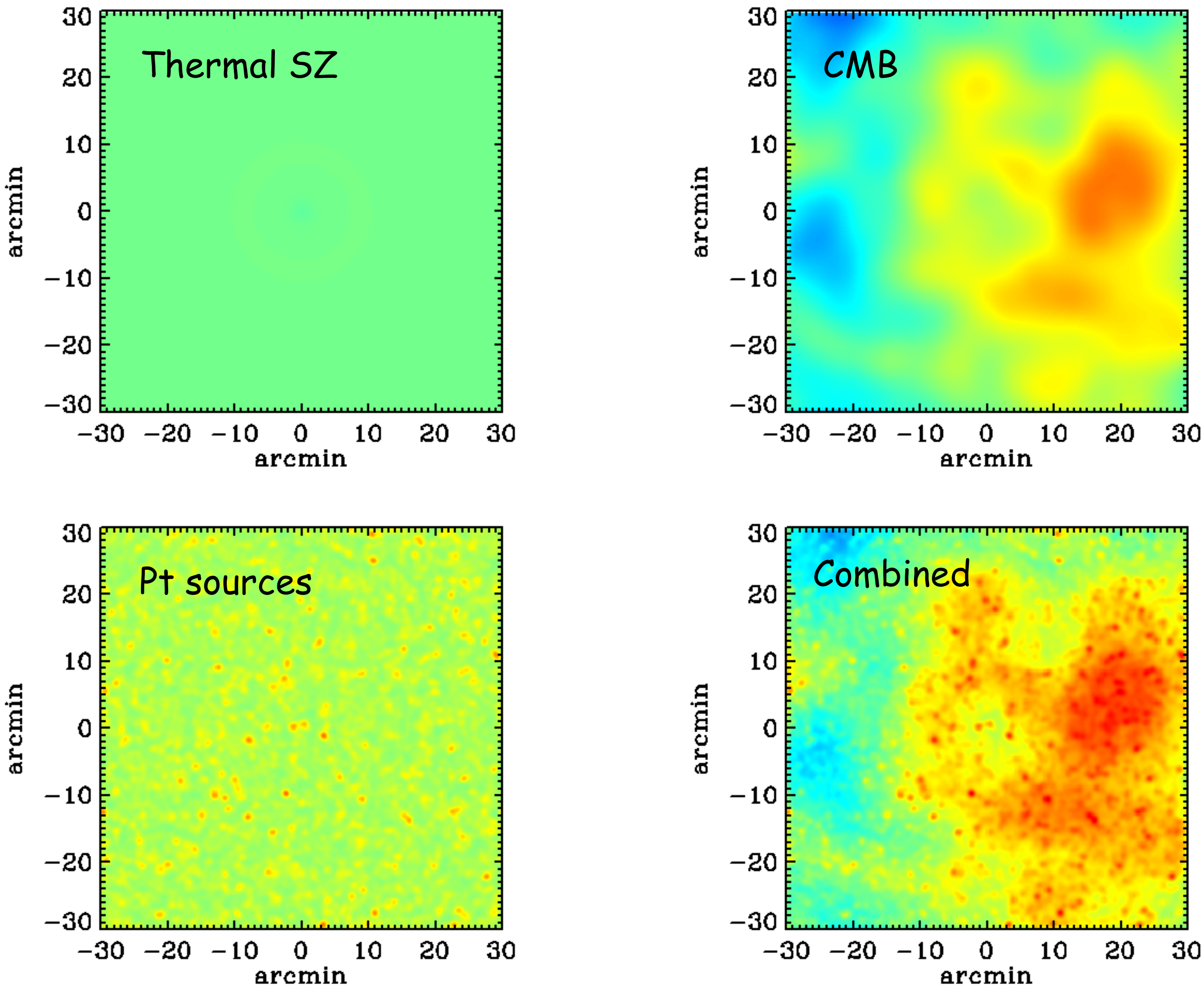
Color: Mjy/sr



150 GHz Color: Mjy/sr

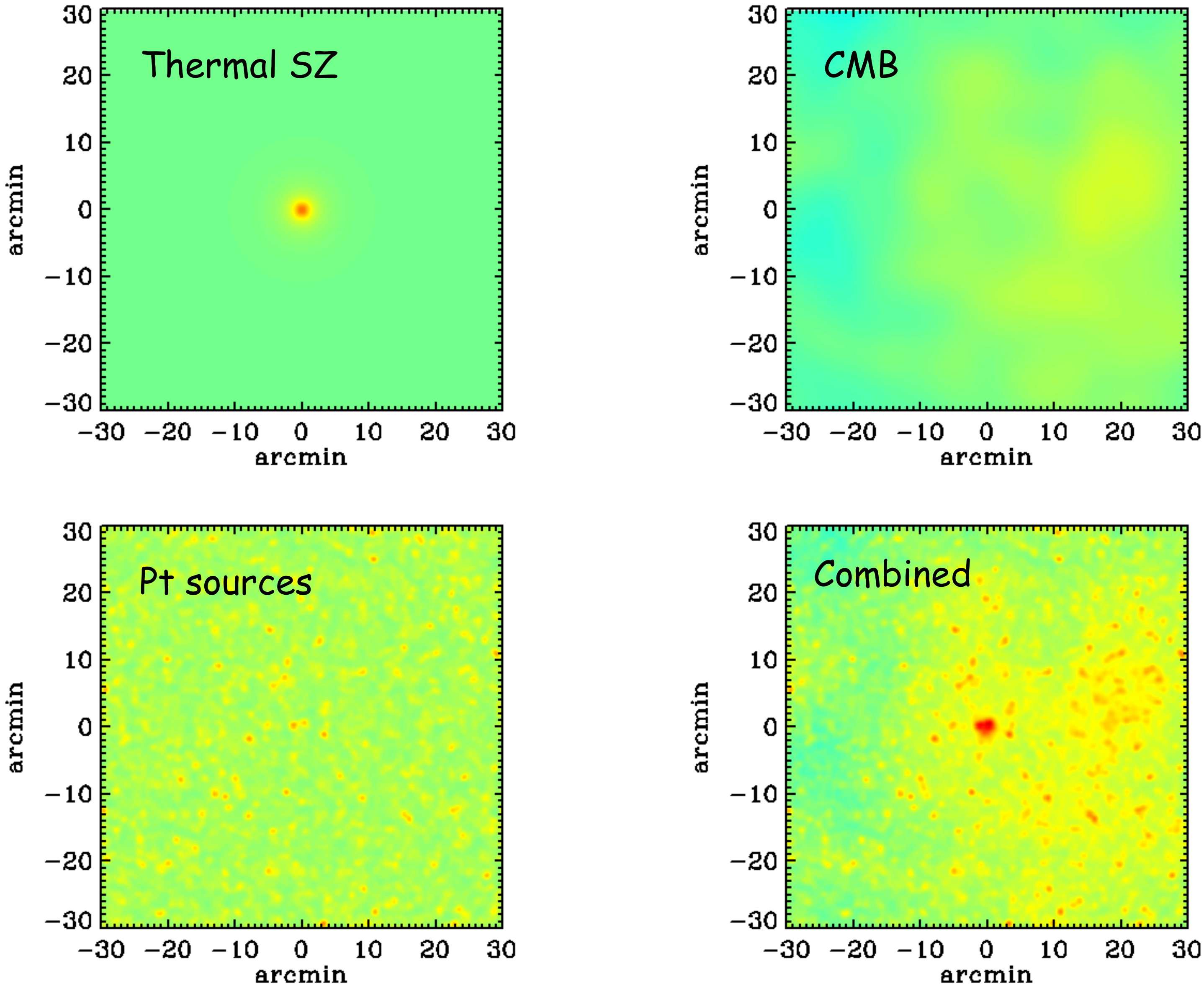


220 GHz Color: Mjy/sr

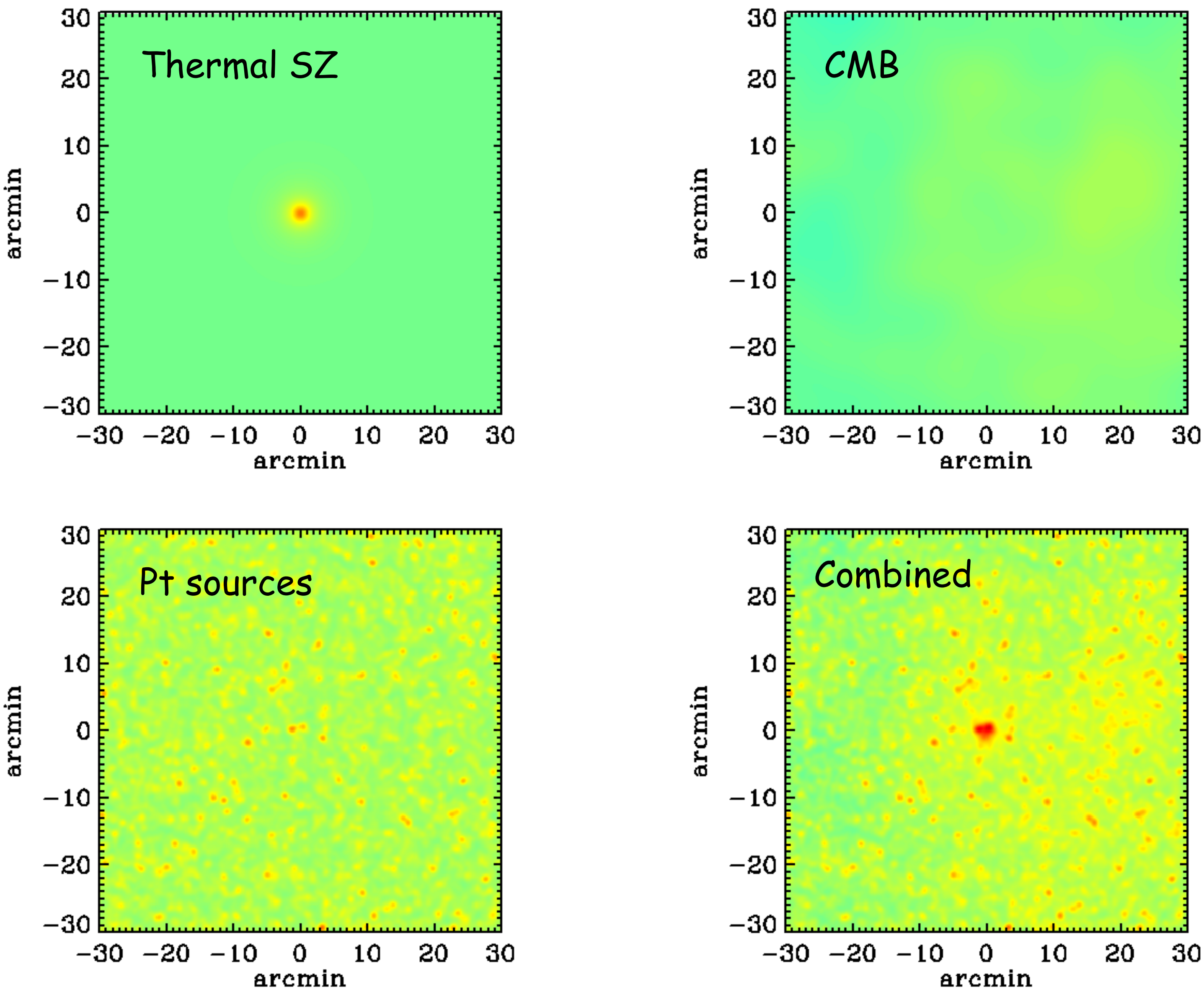


300 GHz Color: Mjy/sr

Re-scaled



350 GHz Color: Mjy/sr

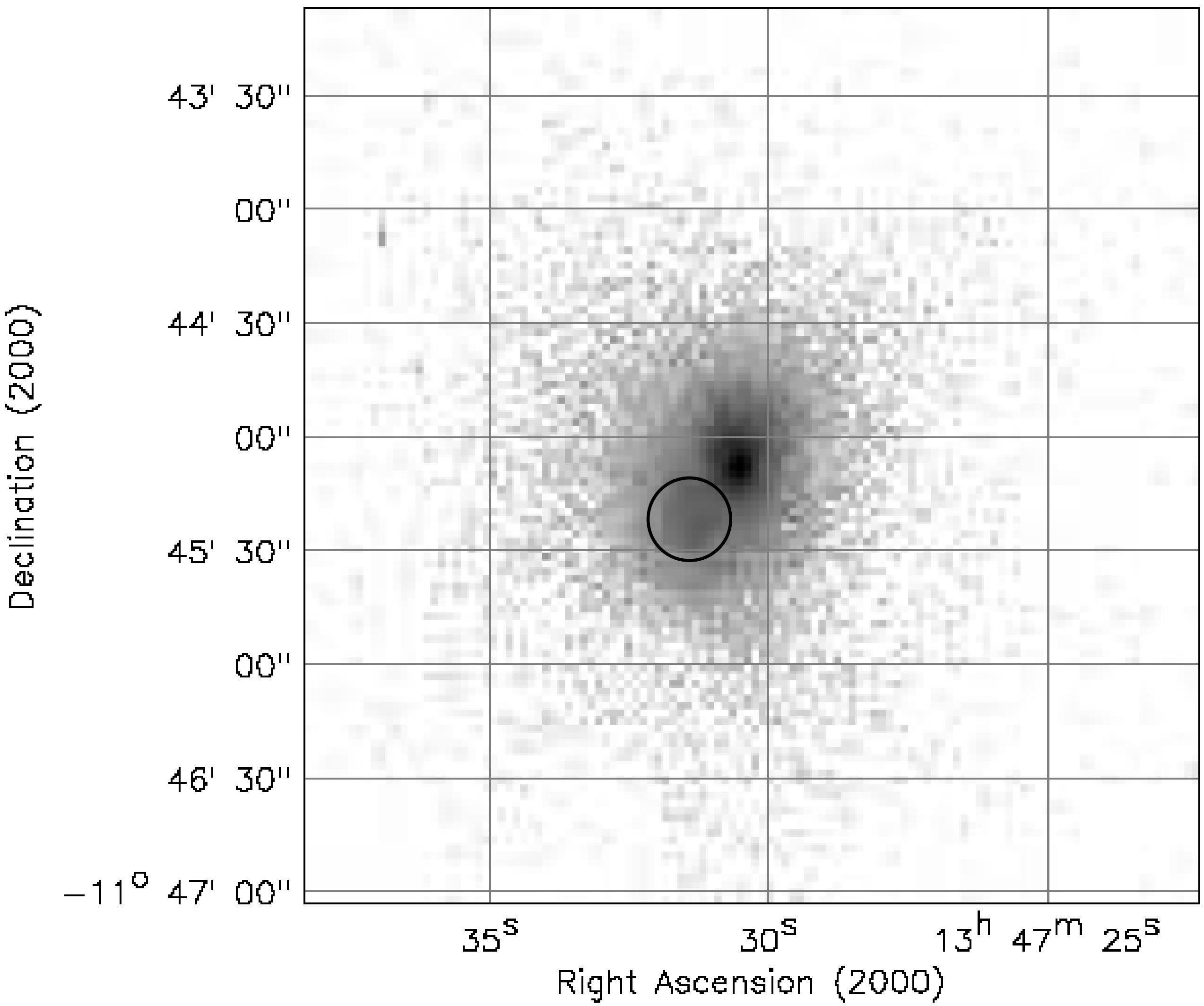


What would we like for angular diameter distance measurements?

- A large set of clusters at $z > 0.2$
- Very accurate measurement of the SZ flux, because D_A is proportional to the square of the flux
- Angular resolution of ideally 10" to allowed detailed comparison with X-ray data and exclusion of hot clumpy gas in the X-ray maps
- Separation of the SZ effect from other foregrounds

X-ray map of cluster RXJ1347-1145

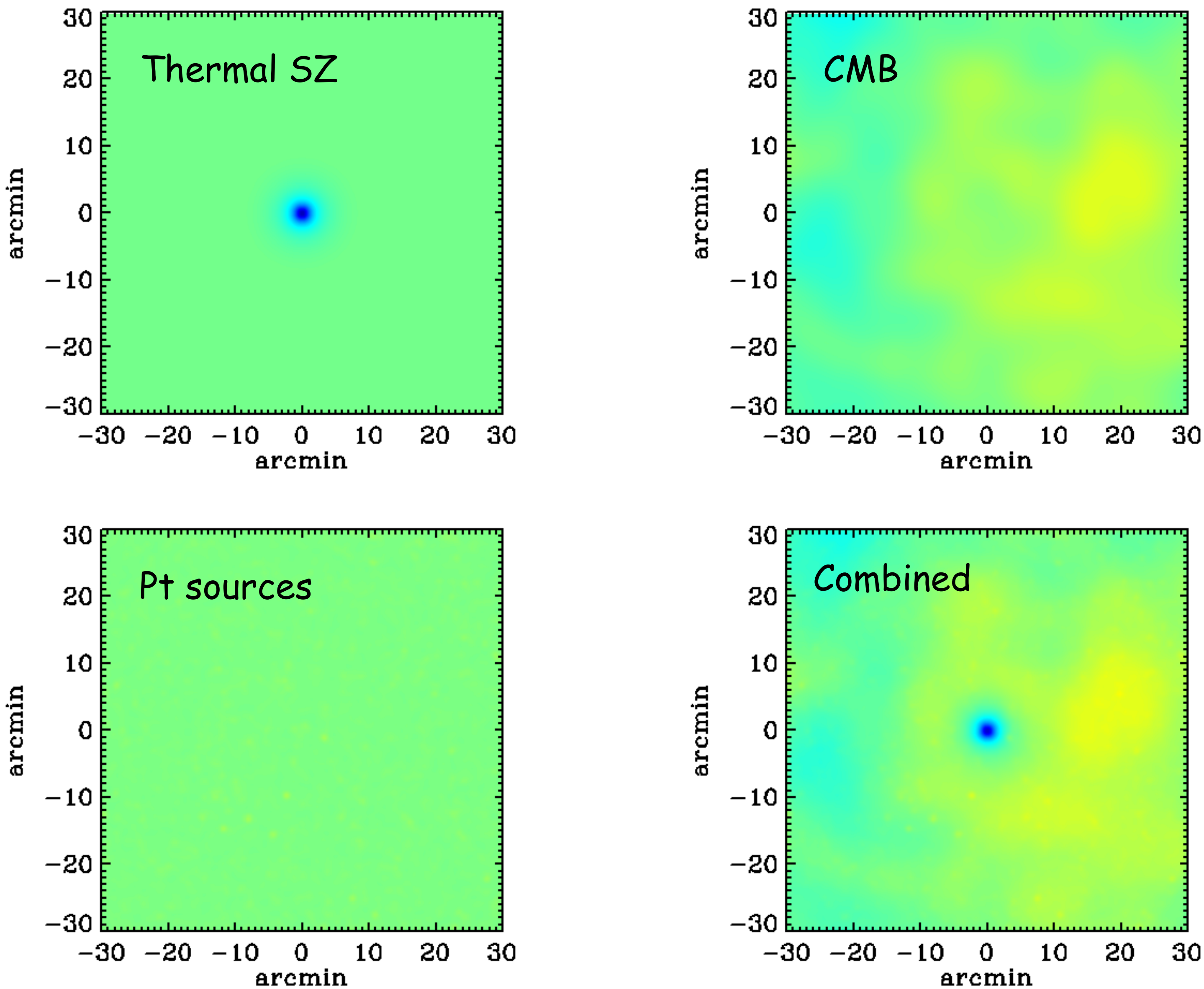
Allen, Schmidt, Fabian(2005)



90 GHz

Color: Mjy/sr

Sweet spot?



Current and Future Instruments for Single Cluster Measurements

- Current instruments have limited angular resolution (~ 1′), limited field of view or limited sensitivity
  - SZA – interferometer; only 8 antennas;
  - AMI (UK) – inteferometer; 13 antennas
  - South Pole Telescope – bolometer array on 10m telescope
  - Atacama Telescope – bolometer array on 10m telescope
  - ALMA – very high resolution interferometer; but field of view at 90 GHz ~ 1′
- Future
  - Caltech-Cornell Telescope (25 m telescope) equipped with a bolometer array at 150-350 GHz would have resolution 25″ at 150 GHz
  - **SZ interferometer with many dishes? (1m-6m foveated array with ~ 100 elements). Aim to image 10″-10′**

Interferometers for SZ

- Advantages
  - Angular resolution and field of view can be tailored by size and position of dishes.
  - Atmosphere is in near field of array and is strongly filtered
  - Ground signal is strongly attenuated, especially by a tracking array
  - Heterodyne detector technology lends itself naturally to spectroscopy so each band can be split into many sub-bands without loss of sensitivity (although with added cost and complication)
- Disadvantages:
  - Fourier filtering of **large-scale** SZ signal (hence ALMA not really suitable)
  - expense of correlator electronics; separate telescopes; receivers

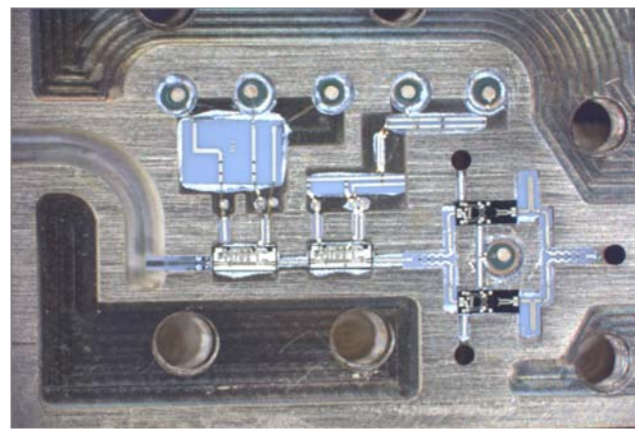
Comparing Single Telescopes and Interferometers for SZ

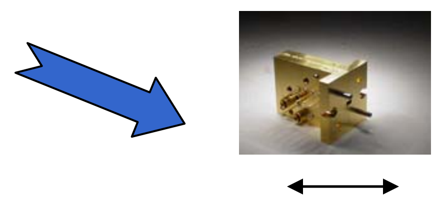
- An interferometer has the same sensitivity as a single dish to SZ if
  - The same number of elements in the interferometer is the same as the number of elements in a focal plane array
  - The area of interferometer is the same as the area of the single dish
  - The sensitivity of the detectors are equivalent
- In practice there are trade-offs and each has its advantages
  - 1000-element interferometers are hard to build
  - 100m millimeter-wavelength singe dishes are hard to build

Technology requirements (Grainge)

- Miniaturized heterodyne module reduces the amount of mass to be cooled
  - Small cheap receiver for each telescope is possible
- Cheap mass produced Cassegrain telescopes developed for other applications can be used for interferometry

1.4m antenna with a foam mounted secondary built at Oxford



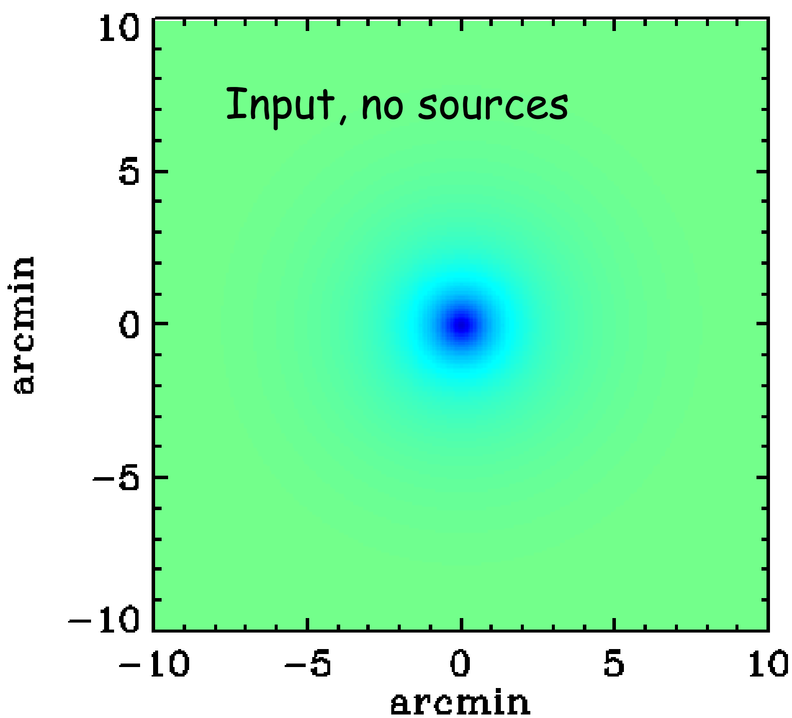


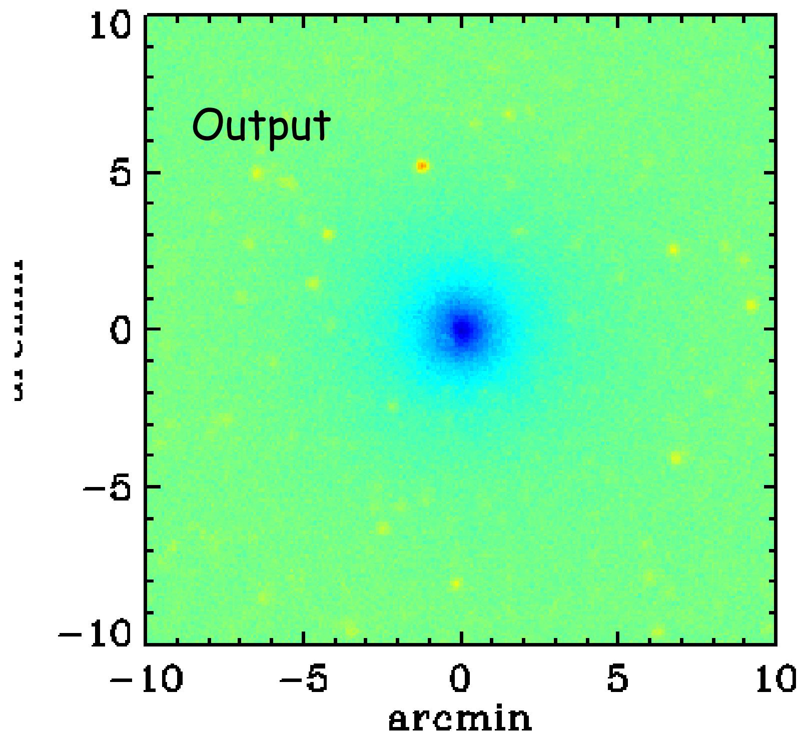
1.5 in

Foveated array benefits from MMIC arrays

- Several arrays with different primaries beams
  - Small dishes target large angular scales
  - Large dishes target small angular scales
- **Need small arrays on the large dishes for mapping speed**
- Reduces correlator requirements
  - Example 1m dish at 90 GHz has ~15′ primary beam
  - 1000 sq m collecting area requires ~ 10^7 correlations
  - But 100 1m dishes + 100 3m dishes where each 3m dish has 7 pixels, has 800 detectors, but requires ~ few x 10^5 correlations
- AMI and SZ/Carma are foveated arrays, but only few dozen pixels

A 6hr 90 GHz map made with such an interferometer





Combine with ALMA for even higher resolution