CMB interferometry

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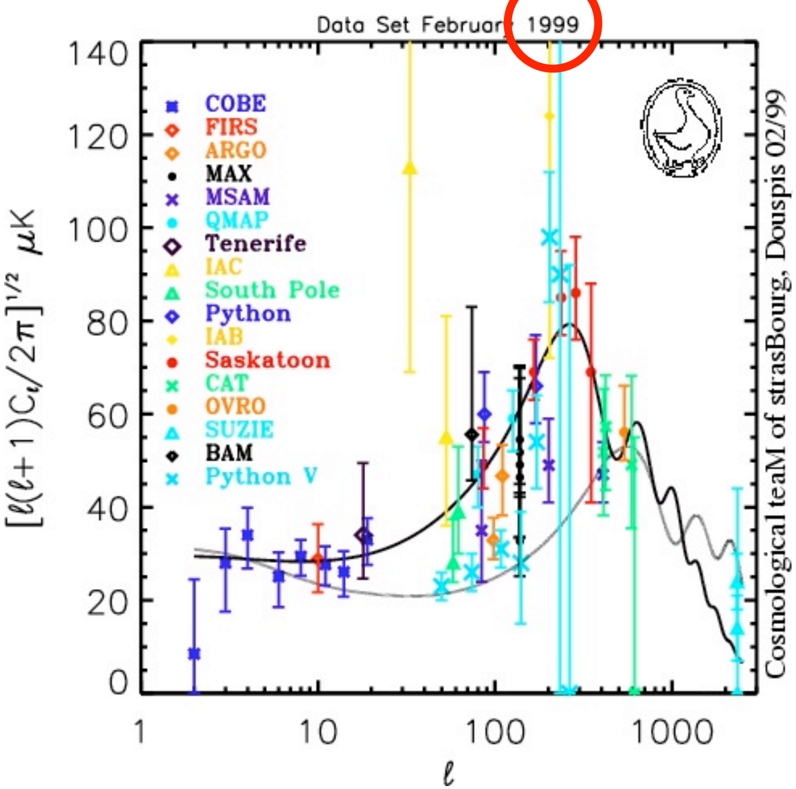
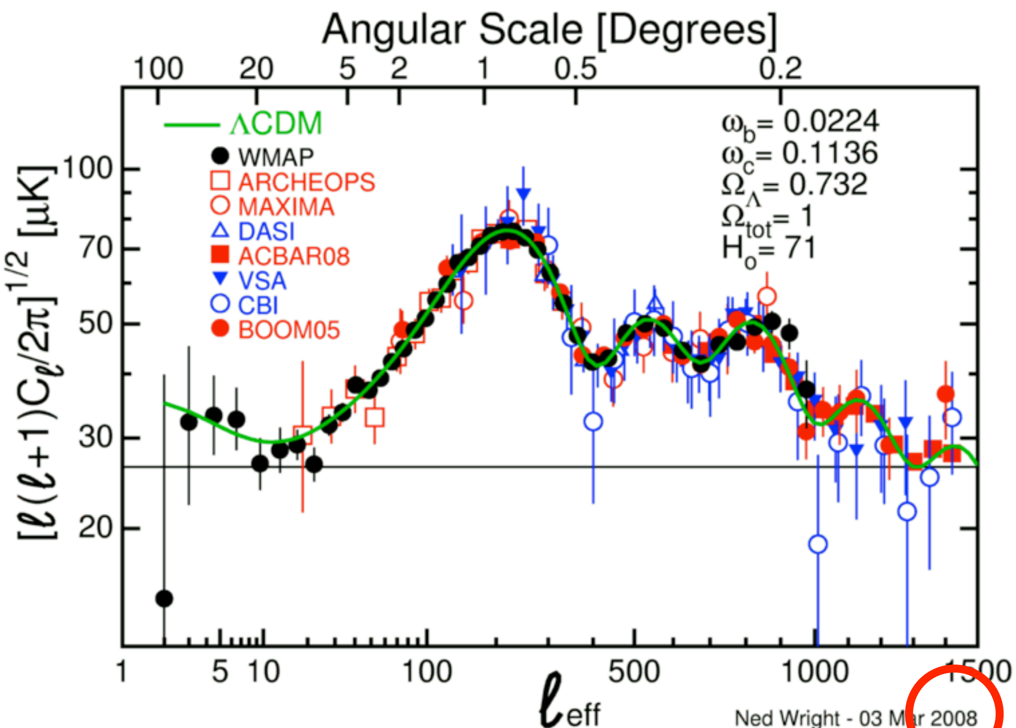
CMB power spectrum measurements

- We have come a long way in just a few years!
- Interferometers have made a big impact
  - IAC interferometer, CAT, VSA, CBI, DASI
- CMB provides accurate constraints on cosmology
  - Lambda-CDM model fits well

multipole l~1/θ





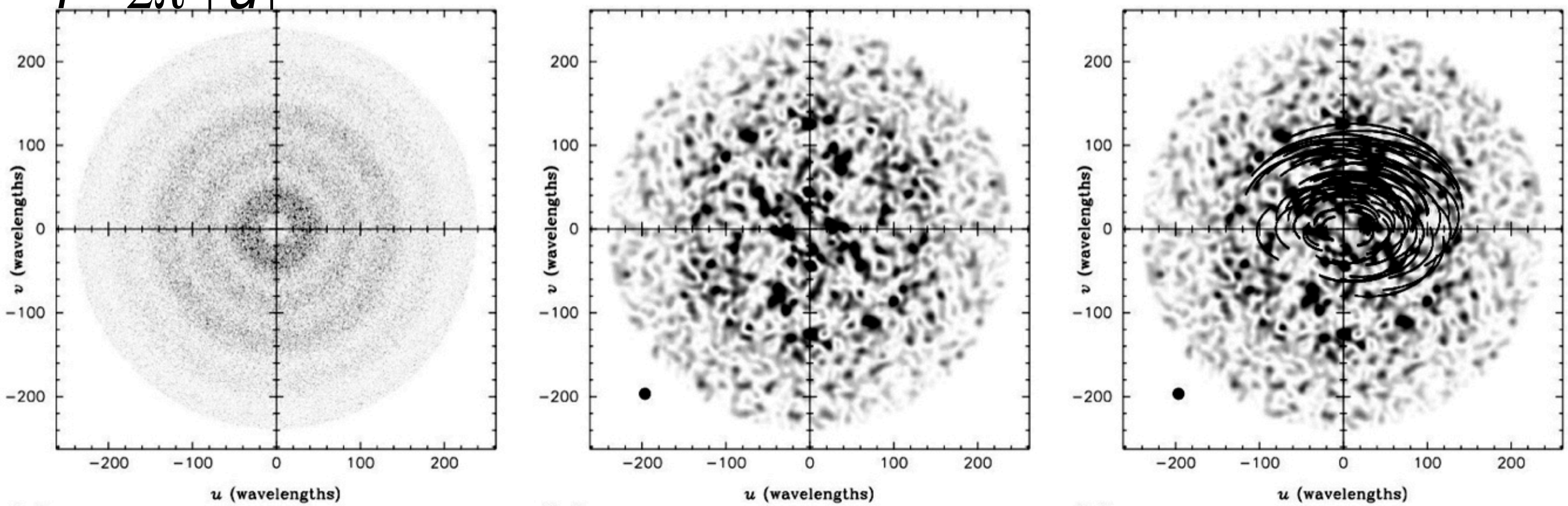
What an interferometer measures

- **Each baseline measures a Fourier component of the sky**
  - **Measures the correlation of 2 antennas**
- **Arrays sample the F.T. of the sky (the "u,v plane" for flat-sky) convolved with the aperture function**
- **Power spectrum is basically averaging in annuli and subtracting off the noise bias**
  - **Multipole window function governed by primary beam (can reduce by mosaicing)**

Van Cittert Zernike equation:

$$V_{\mathbf{y}}^{X}(\boldsymbol{u}) = b_\nu \int d\boldsymbol{x} A(\boldsymbol{x}-\boldsymbol{y}) X(\boldsymbol{x}) e^{2\pi i \boldsymbol{u}\cdot\boldsymbol{x}}, \quad (1)$$

$$l = 2\pi\,|u|$$



(a) (b) (c)

Interferometers: Advantages & disadvantages

- Advantages:-
  - Wide-range of angular scales via array configuration
  - Easy access to small angular scales
  - Accurate calibration
  - Accurate beam knowledge
    - Synth beam -> u,v coverage
    - Primary beam -> window function
  - Good rejection to systematics
    - no baseline drifts
    - strong rejection to "outside" signals
    - Insensitive to 1/f noise (averages out)
    - Pointing accuracy determined by primary beam
  - High dynamic range
  - Direct access to power spectra (Fourier modes)
  - Synthesis imaging to look for sources/SZ/ non-Gaussianity etc.

- Disadvantages:-
  - Not as sensitive to the larger angular scales
    - Single dish filling factor f=1!
    - f~N(D/d)^2
  - Largest angular scales more difficult
    - Curved sky (u-v-w plane)
    - Shadowing
  - Maps difficult to interpret for extended emission ("flux loss" or "resolving out") and correlated noise
  - n(n-1)/2 baselines
    - Large correlators!

Interferometer sensitivity

- You need to put lots of small antennas in a close-packed (almost touching) configuration
  - Also low Tsys and large bandwidth
- Point source sensitivity (Jy)

$$\Delta S = \frac{2kT_{\rm sys}}{\eta A(n(n-1)\Delta\nu\tau)^{1/2}}$$

- Surface brightness sensitivity to extended emission (Kelvin) can be approximated with a filling factor f

$$\Delta T \approx \frac{f\Delta S\lambda^2}{2k\Omega} \qquad f = N(d/D)^2$$

- Most interferometers are very bad for measuring low surface brightness extended objects!
  - e.g. VLA D-array f~0.01
  - e.g. e-MERLIN f~10^{-6}
  - Of course u,v tapering can help a lot in some cases

The first interferometric CMB measurement (published)

THE ASTROPHYSICAL JOURNAL, **277**:L23–L26, 1984 February 15

LIMITS TO THE SMALL-SCALE FLUCTUATIONS IN THE COSMIC BACKGROUND RADIATION

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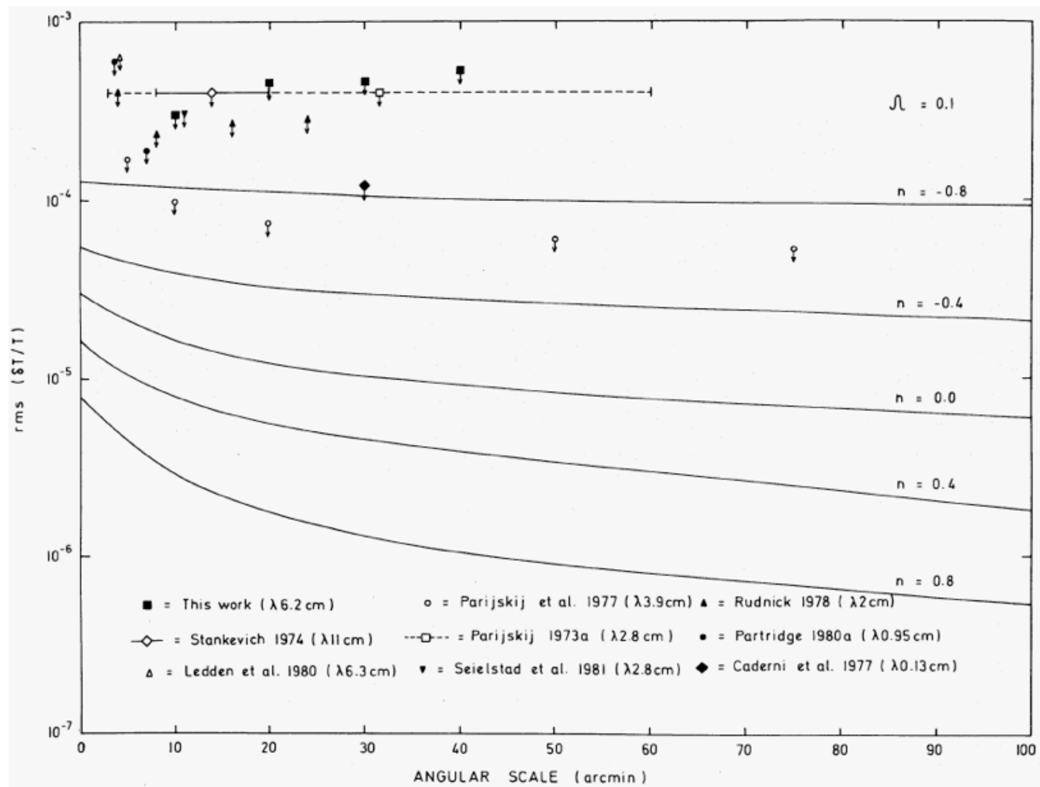
ABSTRACT

We have used the Very Large Array at 4.9 GHz to measure the fluctuations in the cosmic background radiation by examining a radio field of 10′ diameter. The rms sensitivity level of 14 μJy (0.0022 K at 18″ resolution), reached in 40 hours of integration, was limited equally by receiver noise and low-level interference signals between the antennas. These spurious signals produced excess fluctuations near the field center, not unlike those caused by possible sky fluctuations. An analysis of these excess fluctuations leads to the following limits: no fluctuations in the 2.7 K background greater than 0.10%, 0.08%, and 0.05% (95% confidence level) at 18″, 30″, and 60″ resolutions respectively.

Early CMB interferometer experiments (1)

- I used to think the first interferometric CMB measurements were by R.D. Davies & A.N. Lasenby at Jodrell Bank (U. Manchester)
  - Mk1/Mk2 baseline was unpublished due to lack of sensitivity (and probably other issues!)
- But I was wrong!
  - They instead published 5GHz single dish "wagging" (Lasenby & Davies, 1983, MNRAS, 203, 1137)



Early CMB interferometer experiments (2)

INTERFEROMETRIC OBSERVATION OF CMB ANISOTROPIES

TABLE 1

CURRENT EXPERIMENTS TO MEASURE CMB TEMPERATURE ANISOTROPIES WITH INTERFEROMETERS

Name	Location	N_{dish}	Frequency (GHz)	Bandwidth (GHz)	Primary Beam	ℓ
OVRO[a]	US	6	30	2.0	4′	6750
VLA[b]	US	27	8	0.2	5′	6000
Ryle[c]	England	8	15	0.4	6′	4500
BIMA[d]	US	10	30	0.8	6′	4300
ATCA[e]	Australia	6	9	0.1	8′	3400
T-W[f]	US	2	43	...	2°	20–100
CAT[g]	England	3	13–17	0.5	2°	339–722
VSA[h]	Canary Islands	15	26–36	2.0	4°	130–1800
DASI[i]	South Pole	13	26–36	10.0	3°	125–700
CBI[j]	Chile	13	26–36	10.0	44′	630–3500

High resolution

Low resolution

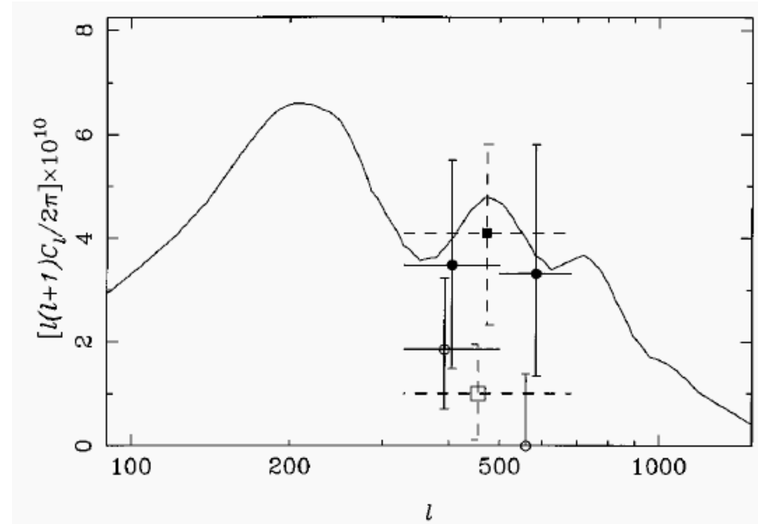
NOTE.—There are published upper limits from VLA, Ryle, and ATCA. The CAT has published a detection, while VSA, DASI, and CBI are expected to begin operations around 1999–2000. The location, number of dishes/horns, frequency, and (approximate) coverage in ℓ space are listed.

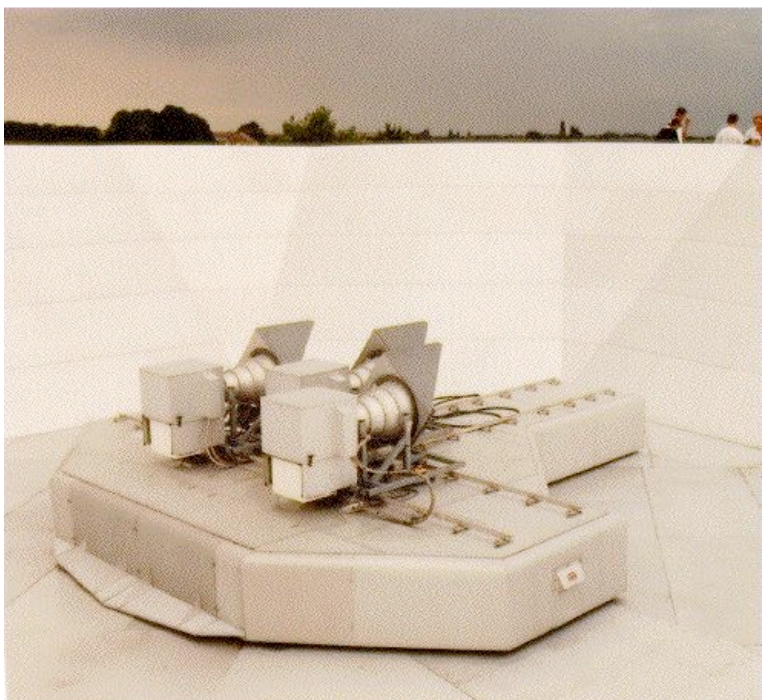
[a] Carlstrom, Joy, & Grego 1996.
[b] Fomalont et al. 1984, 1988, 1993; Knoke et al. 1984; Martin & Partridge 1988; Hogan & Partridge 1989; Partridge et al. 1997.
[c] Jones 1997.
[d] Cooray et al. 1997.
[e] Subrahmanyan et al. 1993, 1998.
[f] Timbie & Wilkinson 1990.
[g] O'Sullivan et al. 1995.
[h] See Jones 1996.
[i] See Halverson et al. 1998.
[j] http://astro.caltech.edu/~tjp/CBI/.

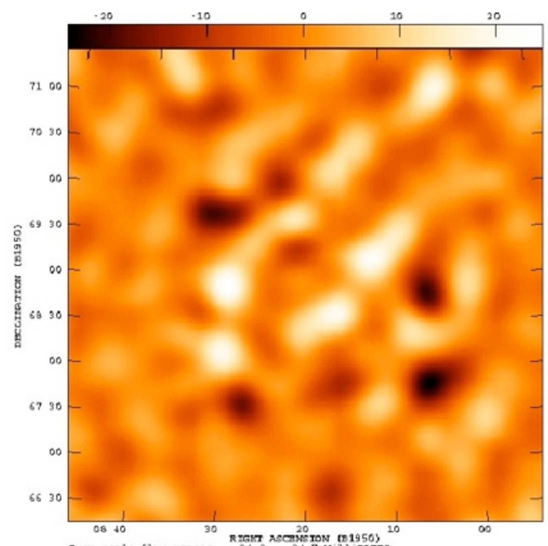
Taken from M. White et al. (1999)

First CMB anisotropy detection with an interferometer

- **First detection by an interferometer was Cambridge Anisotropy Telescope (CAT)**
  - Cambridge/Jodrell Bank/IAC collaboration
  - 3-horn reflector antennas at Cambridge (UK!)
  - 15.5/16.5 GHz, ~2deg primary beam
  - Careful attention to detail (e.g. ground screen)
  - Measurements at l~500 (e.g. Scott et al. 1996)

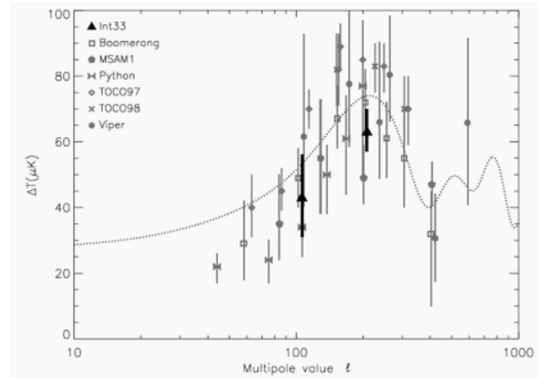






Jodrell Bank single baseline experiments

- **Jodrell Bank-IAC 33 GHz interferometer (Melhuish et al. 1999; Dicker et al. 1999; Harrison et al. 2000)**
  - Single E-W baseline
  - 31-34 GHz
  - ~1-2 deg angular scales



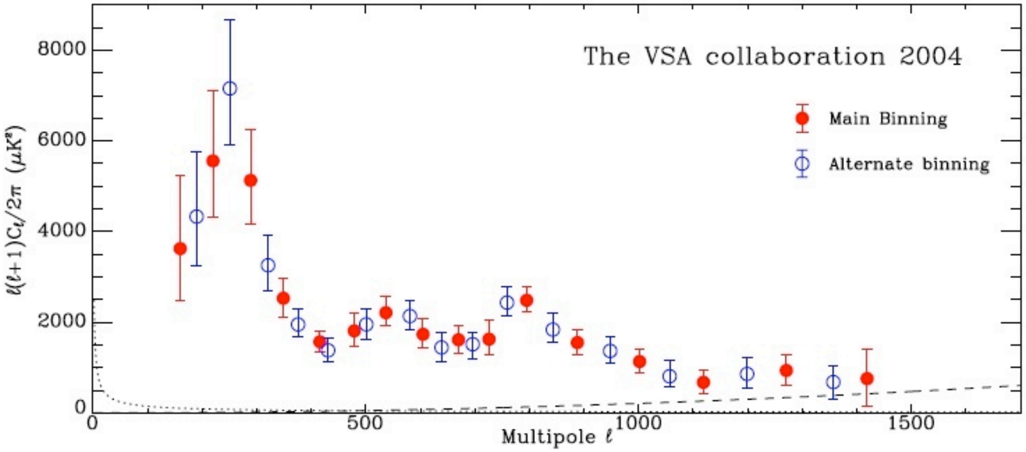
- **Jodrell Bank 5 GHz interferometer (Melhuish et al. 1997; Giardino et al. 2001)**
  - Single E-W baseline
  - 397 MHz bandwidth
  - Too low a frequency to be useful (foregrounds!)

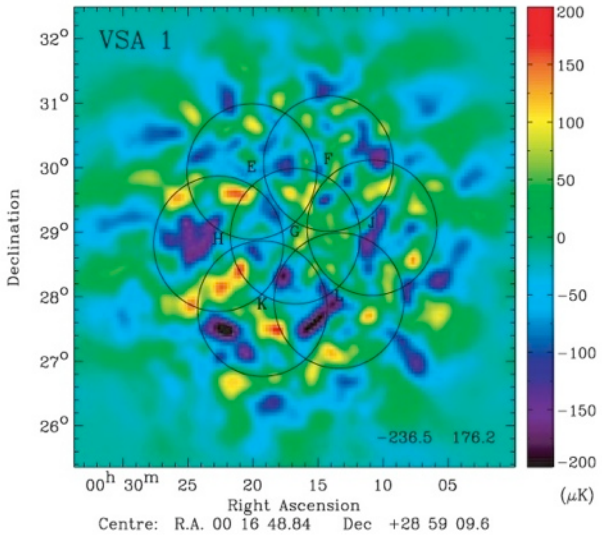
Interferometer arrays: VSA

- **Very Small Array (VSA) located at Tenerife**
  - Cambridge/Jodrell Bank/IAC
  - 14 elements -> n(n-1)/2 = 91 baselines!
  - 26-36 GHz tunable, 1.5 GHz bandwidth
  - Multiple configurations: l~130-2000
  - High filling factor to give good surface brightness sensitivity

$$\Delta T \approx \frac{f \Delta S \lambda^2}{2k\Omega}$$

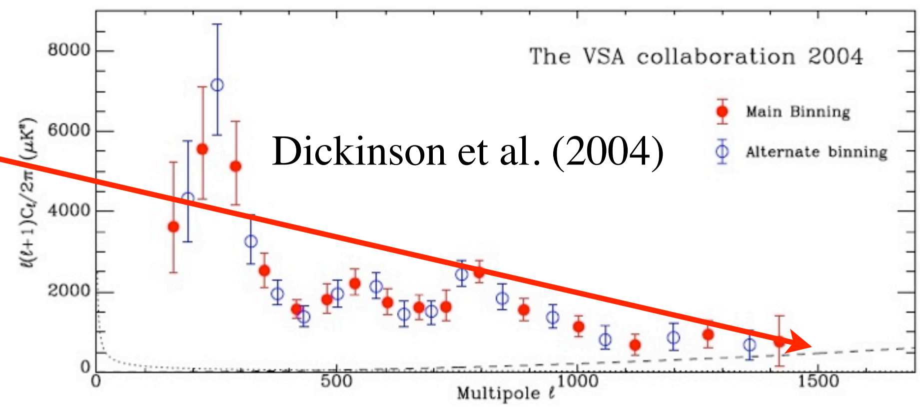
Dickinson et al. (2004)





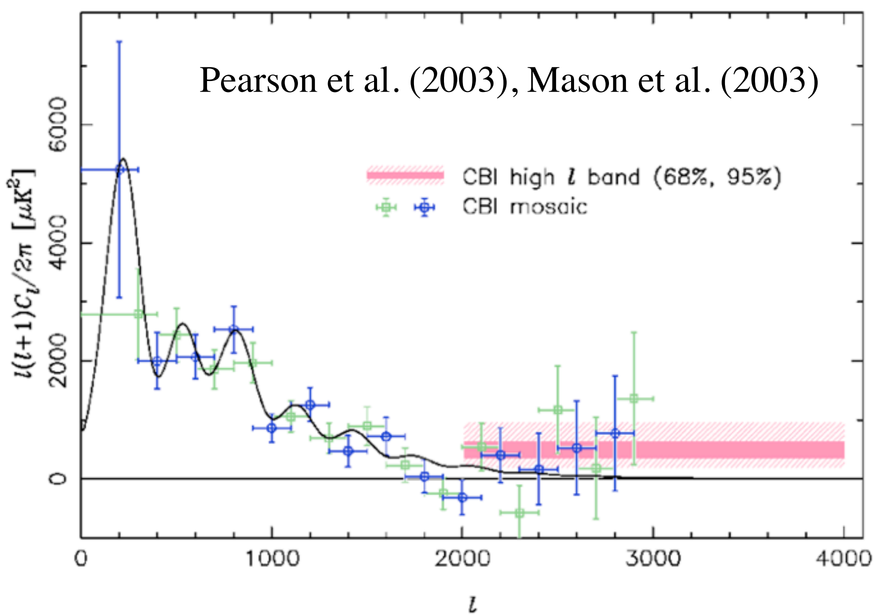
VSA source subtractor

- **Foregrounds are significant**
  - Galactic emission, extragalactic radio sources...
- **VSA employed a single N-S baseline interferometer**
  - Two 3.4 m dishes @ 34 GHz
  - Measure sources at the same frequency and at the same time
- **Worked beautifully!**
  - Survey of 453 sources (~1/week)
  - Extragalactic sources were negligible after subtraction
  - Source counts, variability (Cleary et al. 2006)
  - BUT, ultimately, was not absolutely required in the end! :-(



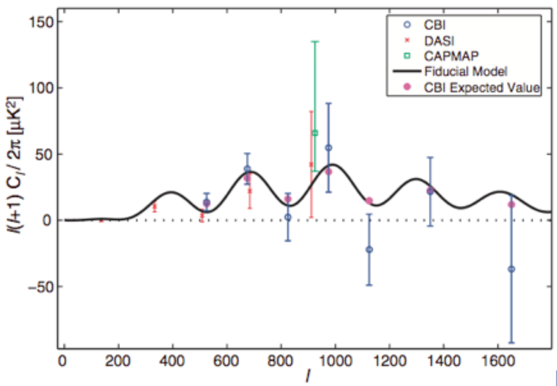
Interferometer arrays: CBI & DASI

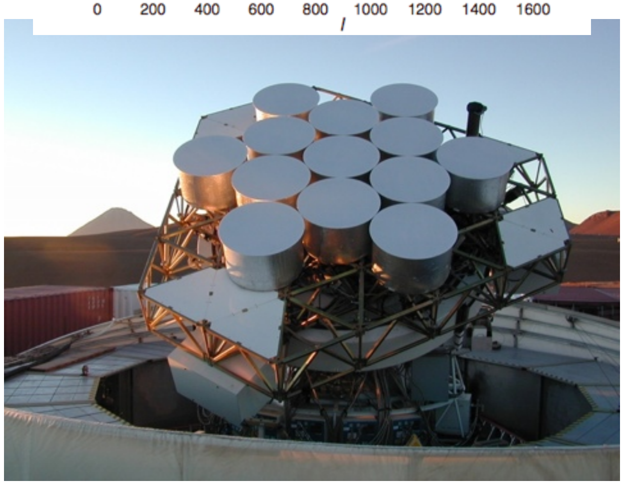
- **Degree Angular Scale Interferometer (DASI) & Cosmic Background Imager (CBI)**
  - Sister instruments (many parts in common)
  - 13 antennas 26-36 GHz band (1GHz band to limit bandwidth smearing)
  - DASI l~100-1000 at South Pole
  - CBI l~500-3500 (~5-30 arcmin) in Chile
- **CBI was first to show CMB damping tail at l>1500**
  - CBI high-l excess?

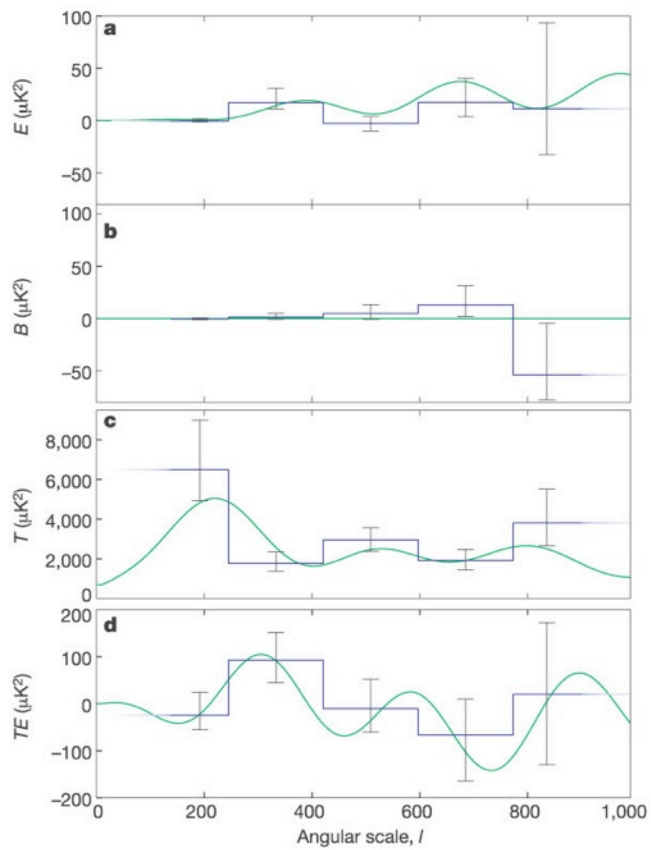


First CMB polarization detections! (DASI & CBI)

- First polarization detection by DASI
  - Kovac et al. (2002); Leitch et al. (2002)
- Confirmation by CBI
  - Readhead et al. (2004); Sievers et al. (2007, 2009)



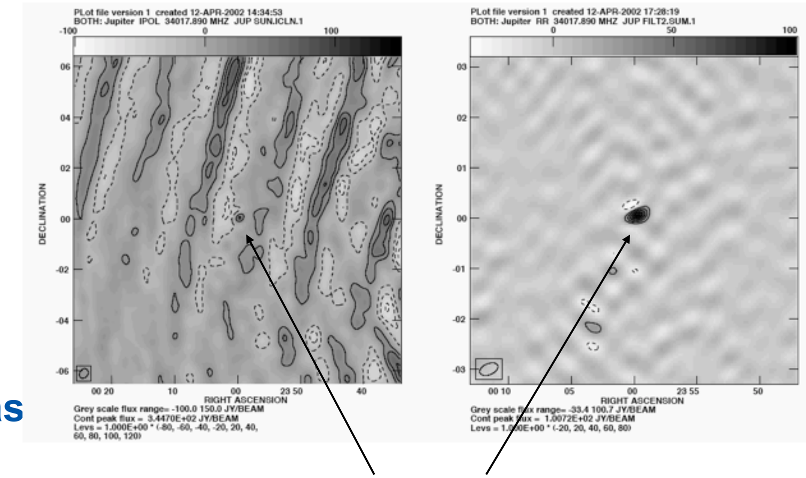




VSA & CBI experience

- VSA & CBI data are remarkably easy to analyze once geometry is worked out
  - No 1/f noise to worry about
  - Integrated for years (literally!)
  - Look for “bad” data and flag
  - Correlated emission (e.g. clouds!) easy to identify
  - Check calibration carefully
  - Average data in u,v-plane (~10000 samples)
  - Approximate covariance matrix and likelihood

- VSA suffered from “spurious correlated signal”
  - Probably *direct* cross-coupling between antennas
  - Worst on short baselines
  - Fringe-rate filtering worked very well!!!
  - Also filter other sources e.g. Sun & Moon!

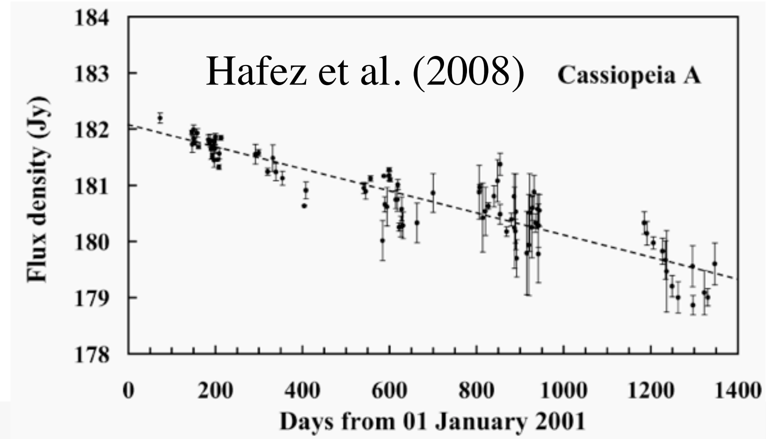


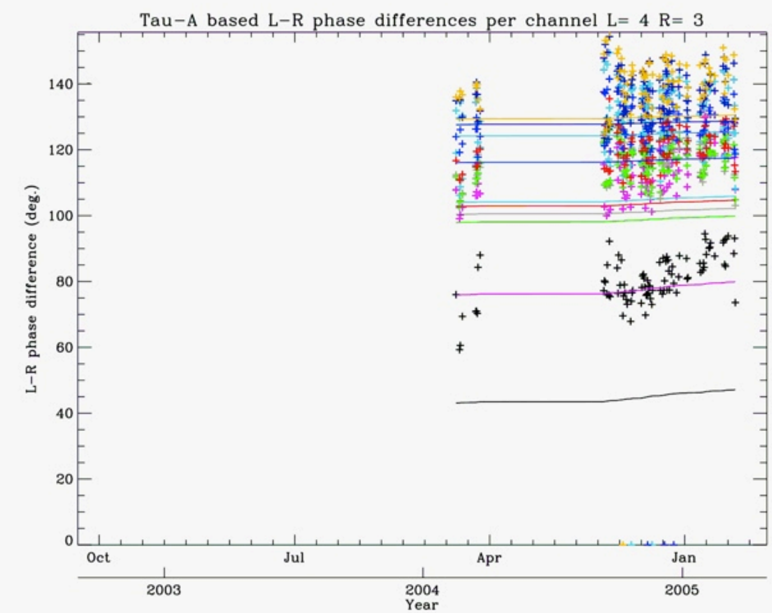
Jupiter
(Sun elongation 12deg!)

- CBI suffered from ground spillover
  - Comounted has benefits (constant u,v) but does not allow fringe-rate filtering!!
  - Lead/trail subtraction or multi-field projection worked well but reduced sensitivity

Amplitude / phase calibration

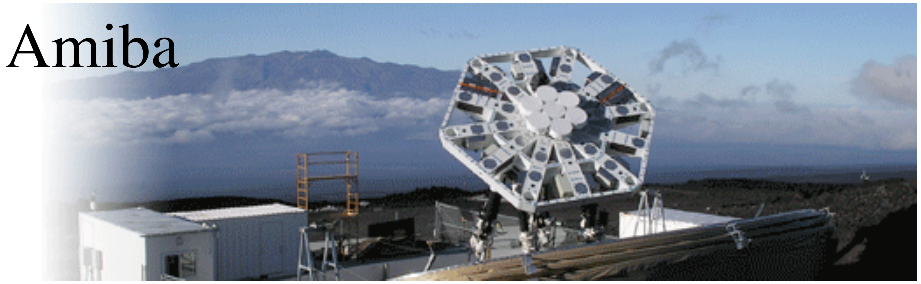
- **VSA & CBI were remarkably stable instruments**
  - Good sites helped!
  - Flux calibration accurate to typically ~1% or better (e.g. Hafez et al. 2008)
- **Phase calibration was stable for many hours**
  - No need for regular “phase tracking” (e.g. as in VLA)
- **Integrate for day after day no problem…**
- **CBI polarization was particularly “easy”**
  - ~half receivers LCP and other half RCP
  - Baselines gave LL,RR,LR,RL
  - Deck rotations gave full combinations
  - Total intensity calibration by LL/RR baselines independently
  - Only polarization calibration was L-R phase difference
    - ➢ Tau-A at -27.6 deg. (stable enough to interpolate over months!)





CMB interferometers today & tomorrow

- Mostly for "high resolution" (arcmin) scale CMB and Sunyaev-Zeldovich (SZ) surveys
  - Inverse Compton scattering of CMB photons off hot ICM gas in clusters
- Arcminute Microkelvin Imager (AMI)
  - Cambridge (Lords Bridge), 15 GHz, 6 GHz B/W, 10 3.7m dishes
- Sunyaev-Zeldovich Array (SZA)
  - 30 GHz, now part of CARMA array
- Array for Microwave Background Anisotropy (AMiBA)
  - 94GHz, 7,13 elements, at Mauna Loa
- Millimetre-wave Bolometer Interferometer
  - MBI, BRAIN, QUBIC
  - 1st bolometer interferometer? (Tucker et al. 2003)
- More on their way....
  - GUBBINS, CHIP...
  - Small-scale SZ fluctuations with ALMA!



Conclusions

- Interferometers are great!
- They have made a big impact for CMB studies
  - Accurate power spectrum measurements (at the time) from IAC, VSA, CBI, DASI....
  - First detection of CMB damping tail (CBI)
  - First CMB polarization detection (DASI)
  - Many SZ detections (Ryle, CBI, BIMA, SZA, AMI...)
- Not thought to be useful for primordial CMB anymore
  - CMB polarization is extremely weak!
  - Bolometer arrays at high frequencies not quantum limited and can be made into very large (>1000) arrays
- EXCEPT, bolometer interferometry being investigated for future CMB polarization interferometers
  - Non-coherent detectors but can get same visibilities in principle (Charlassier et al. 2008)
  - MBI, BRAIN, QUBIC

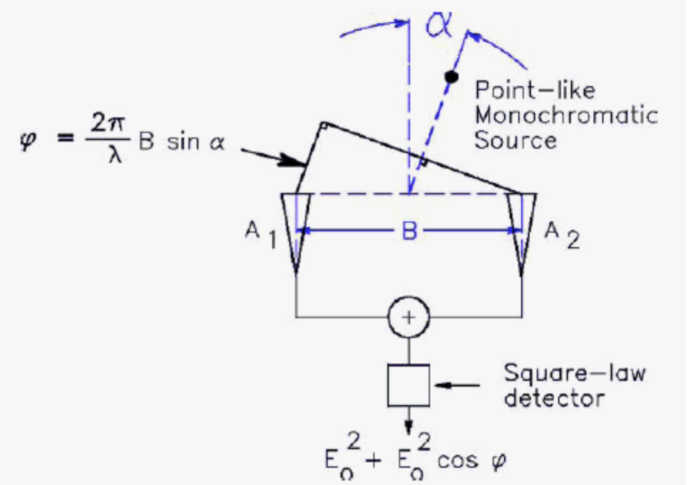
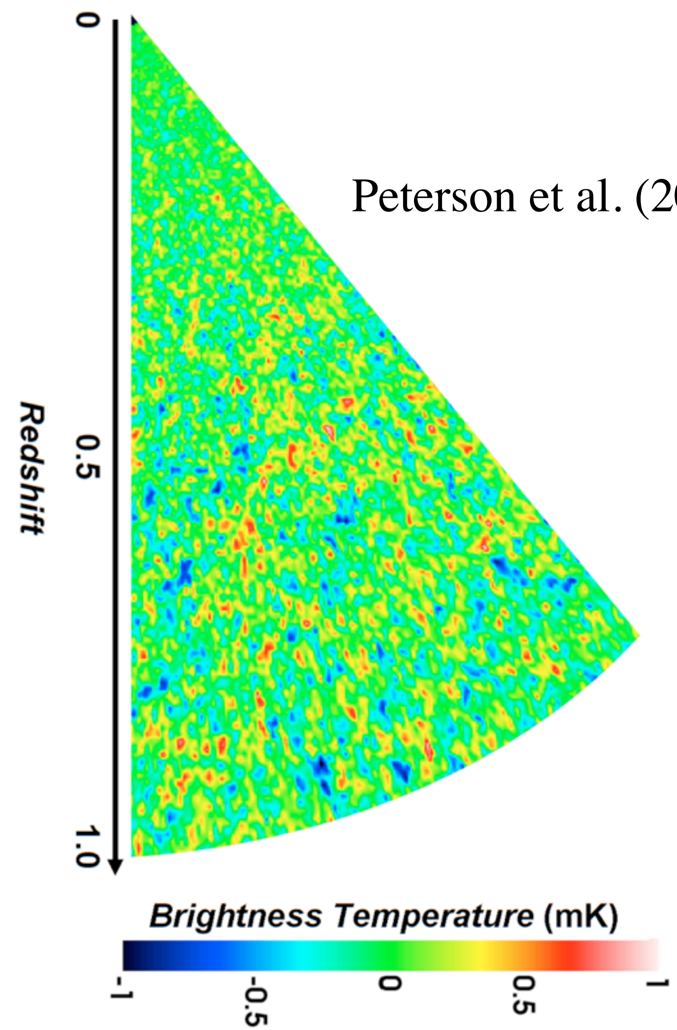


Fig. 2. Adding interferometer. At antenna A_2 the electric field is E_0, and at A_1 it is $E_0 e^{i\phi}$, where $\phi = kB \sin\alpha$ and $k = 2\pi/\lambda$. B is the length of the baseline, and α is the angle of the source with respect to the symmetry axis of the baseline, as shown. (For simplicity consider only one wavelength, λ, and ignore time dependent factors.) In a multiplying interferometer the in-phase output of the correlator is proportional to $E_0^2 \cos\phi$. For the adding interferometer, the output is proportional to $E_0^2 + E_0^2 \cos\phi$.

(Tucker et al. 2003)

The future: HI studies with interferometers

- **Interferometers are probably the best way for detecting hydrogen at high redshifts (EoR)**
  - **SKA, LOFAR, MWA, 21CMA.....**
- **Baryon Acoustic Oscillations (BAO)**
  - **HI intensity mapping at z~0.3-1 (Peterson et al. 2006)**
  - **Measure integrated hydrogen in large (~1deg) beams**
    - **~100s of micro-Kelvin signal**
  - **Power spectrum in 3D (as a function of frequency/redshift)**
- **Basically, a CMB experiment at ~1GHz!**
  - **e.g. Tianlai collaboration**
  - **~80-100 small dishes to measure BAO at z~1 (700 MHz)**
- **Foregrounds and systematics (calibration) will be the critical issue (also for EoR)**
- **I look forward to ongoing discussions with Richard Schilizzi on this topic as we look towards SKA!**



Peterson et al. (2008)