CMB Observations:

Current Status and Implications for Theory

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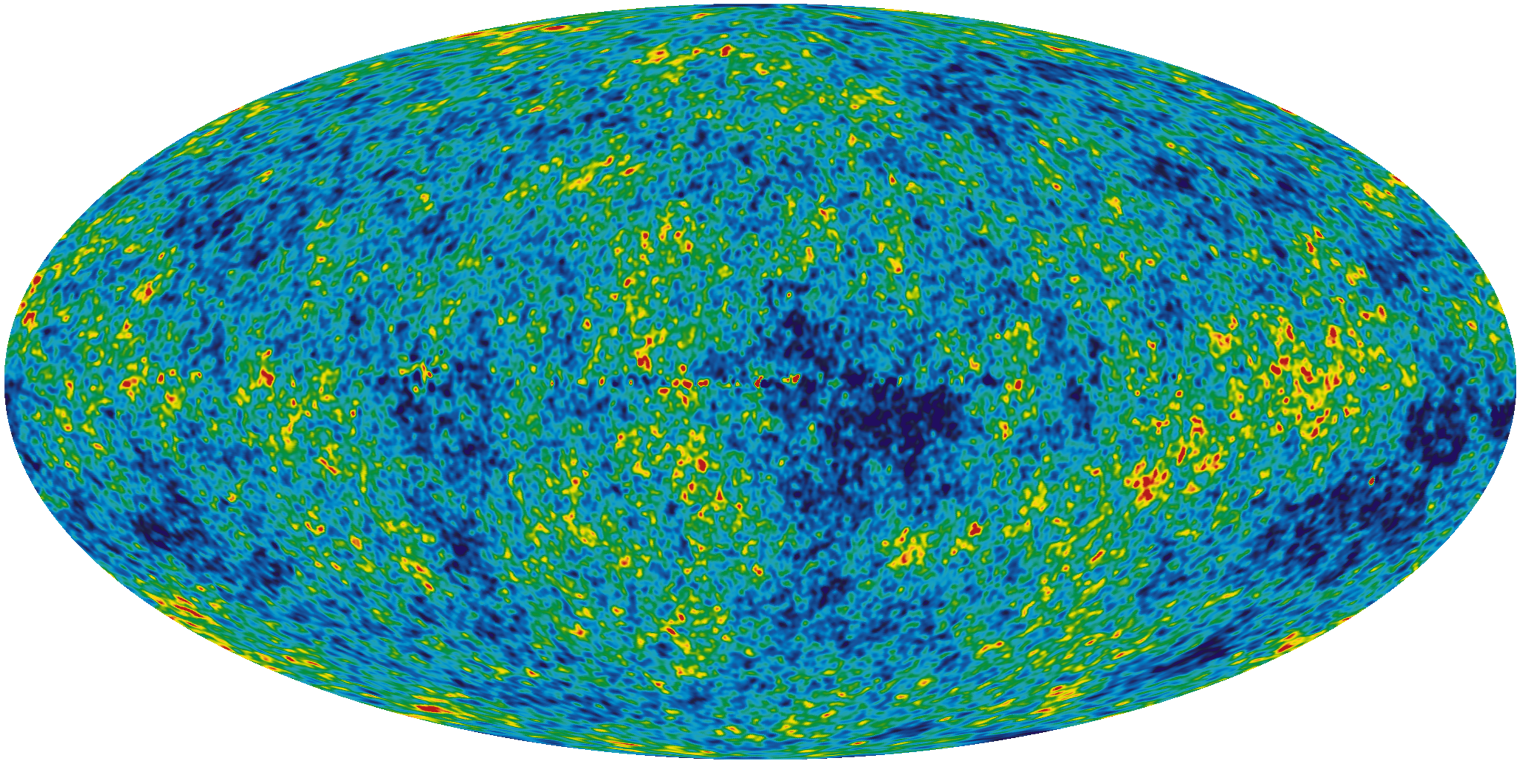
PLAN FOR TALK

- Will give an overview of current state of CMB observations and scientific implications
- Want to emphasize the ‘big questions’ that the CMB can help address
- Some new interesting polarisation results out from 2 current experiments (BICEP and QUAD)
- Will look at these and their implications
- And discuss some current secondary anisotropy experiments — first ‘blank field’ Sunyaev-Zeldovich detections appearing - will show you the first ones starting to come from the AMI experiment in Cambridge
- Note: thanks to Anthony Challinor and Anna Scaife for help with some of the slides

THE COSMIC MICROWAVE BACKGROUND

- The Cosmic Microwave Background (CMB), is a wonderful tool in modern cosmology
- A very significant fraction of all the information in cosmology over the last 10 to 15 years has come from it
- Has finally ushered us into an era of ‘precision cosmology’ (but also deep mysteries)



SOME BIG QUESTIONS

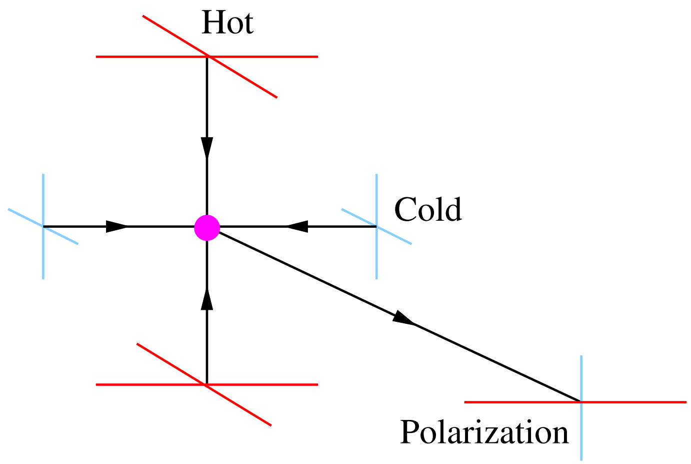
- What are some of the current big questions that current and forthcoming CMB observations will help us make progress in?
- The Dynamics and Energy Scale of Inflation
  - One key to this is B-mode CMB polarization, so need to look at this and the parameter r
  - Another key parameter is n_{run} — is the slope of the primordial spectrum fixed, or change with wavenumber?
  - Are the primordial fluctuations Gaussian? — it's now clear that estimators like f_{nl} (see later) are very good discriminators of the type of inflation (and important measurements soon)
- String Cosmology: are there any hopes of forming observational links with this (so can start to constrain quantum gravity)
- ...

Some Big Questions — Later Universe

- Can we find any evidence for
  - Defects?
  - Universal rotation?
  - Other departures from spherical symmetry?
- As regards secondary anisotropies
  - Sunyaev-Zeldovich (SZ) now coming of age
  - Time now poised as regards blank field surveys
  - What is σ_8? (may be becoming clearer)

CMB POLARIZATION

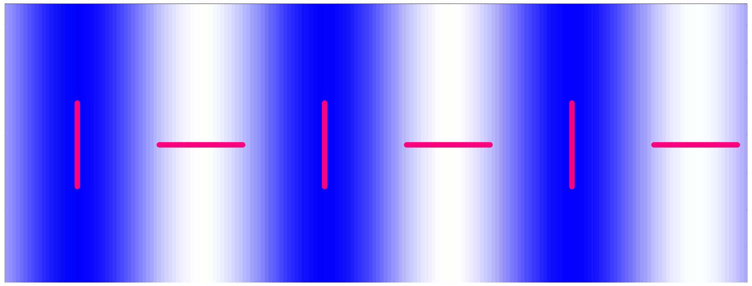
- Photon diffusion around recombination $\longrightarrow$ local temperature quadrupole
  - Subsequent Thomson scattering generates (partial) linear polarization with r.m.s. $\sim 5\,\mu$K from density perturbations

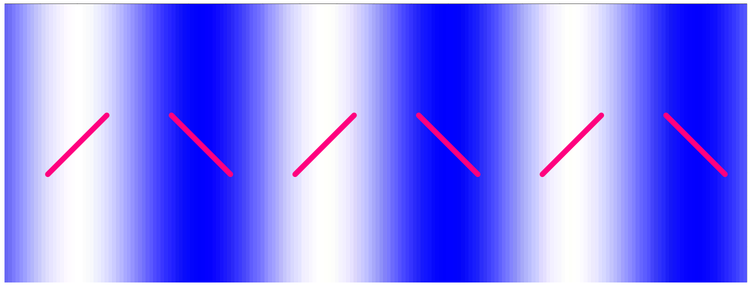


- Decomposition of polarization tensor into E and B modes:

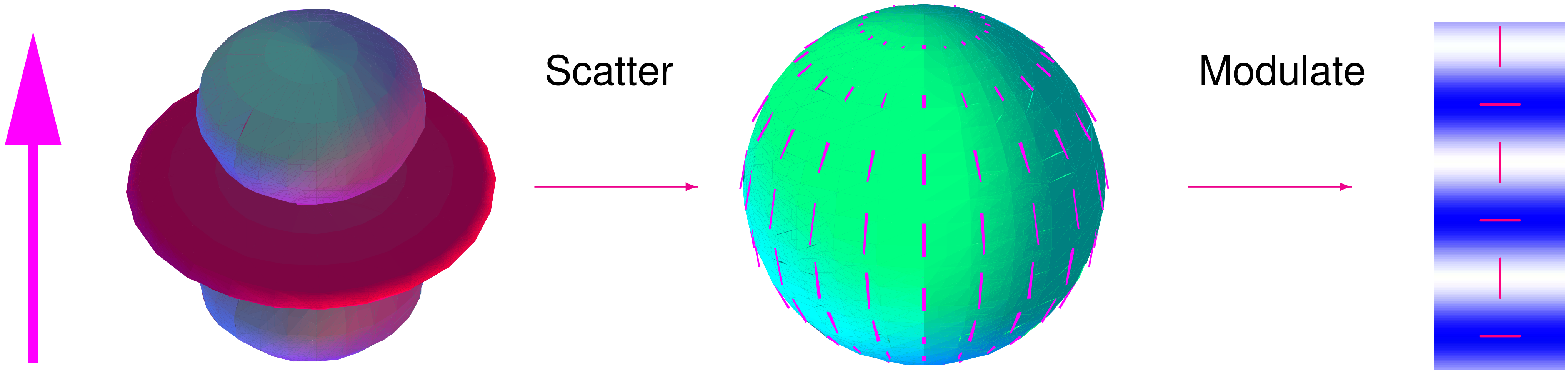
$$\mathcal{P}_{ab}(\hat{\boldsymbol{n}}) \equiv \frac{1}{2}\begin{pmatrix} Q & U \\ U & -Q \end{pmatrix} = \nabla_{\langle a}\nabla_{b\rangle}P_E + \epsilon^c{}_{(a}\nabla_{b)}\nabla_c P_B$$

  - Only three power spectra if parity respected in mean: C_l^E, C_l^B and C_l^{TE}





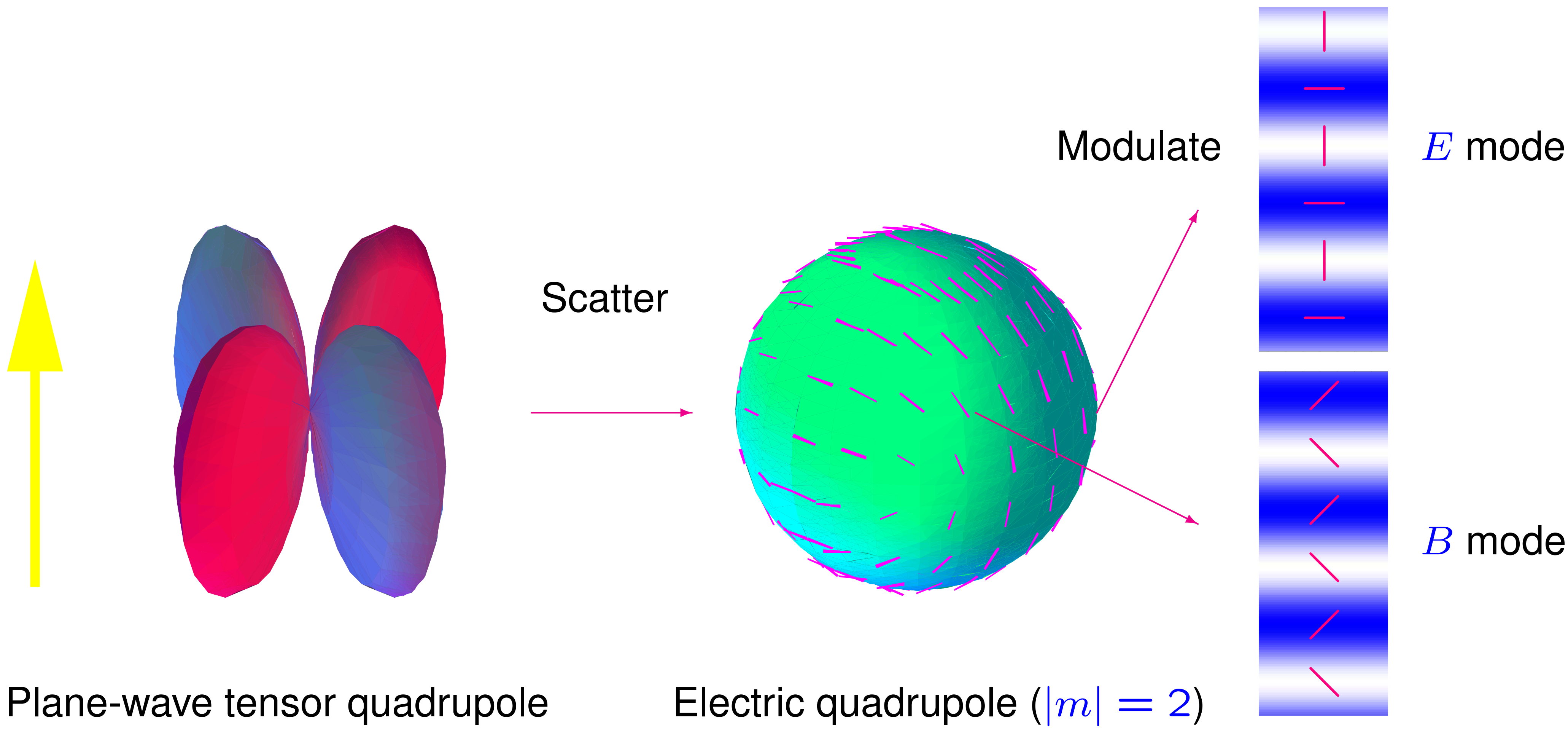
PHYSICS OF CMB POLARIZATION: SCALAR PERTURBATIONS



Plane-wave scalar quadrupole — Electric quadrupole ($m = 0$) — Pure E mode

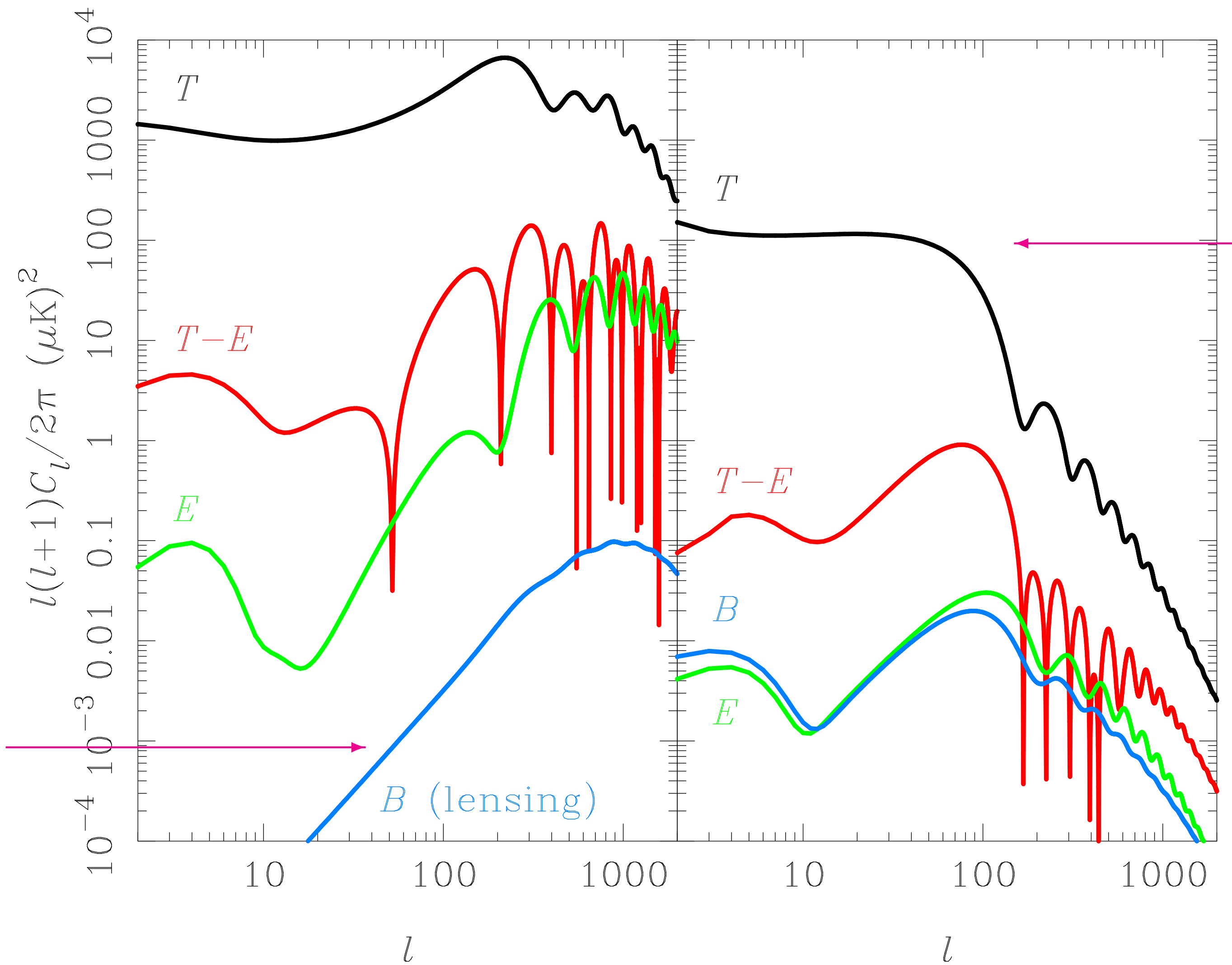
- Linear scalar perturbations produce only E-mode polarization (Kamionkowski et al. 1997; Seljak & Zaldarriaga 1997)
- Mainly traces baryon velocity at recombination $\Rightarrow$ peaks at troughs of ΔT

Gravity waves in CMB polarization: physics



- Gravity waves produce both E- and B-mode polarization

POWER SPECTRA



Lens-induced B modes ($\sqrt{C_l^B} \approx 1.3$ nK)

Effects only on large scales since gravity waves damp inside horizon

WHAT WOULD A DETECTION OF PRIMORDIAL GRAVITY WAVES TELL US?

- Strong evidence that inflation happened
- The amplitude of the power spectrum $\mathcal{P}_{\rm grav}(k)$ is a model indepedent measure of the energy scale of inflation

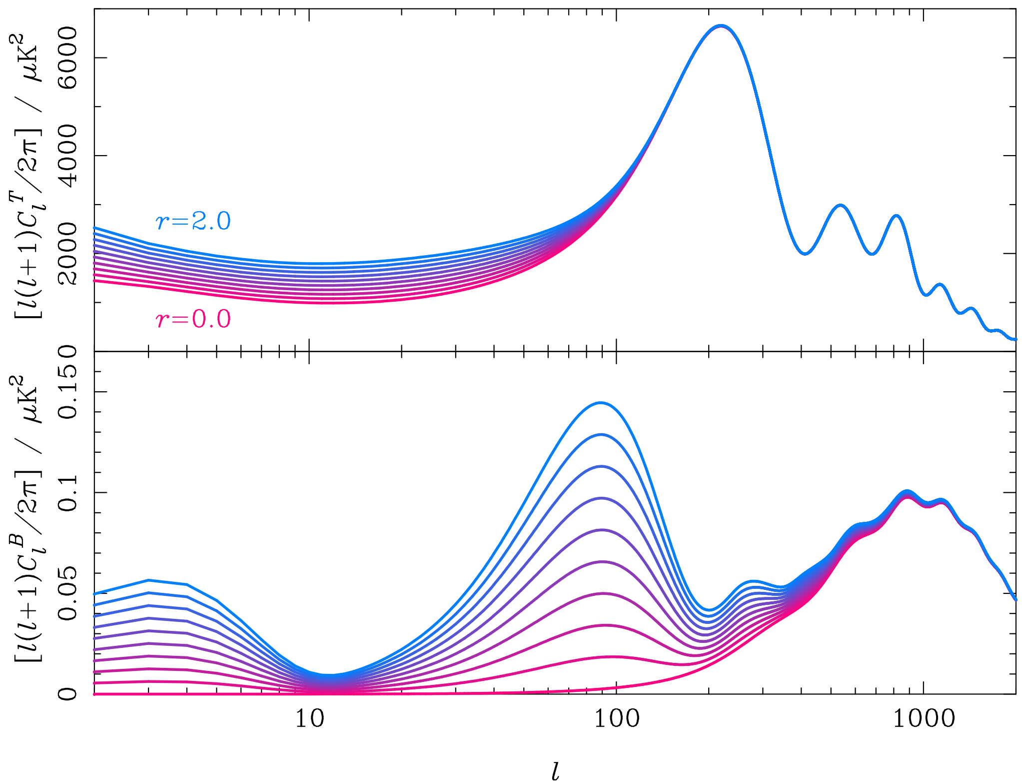
$$\mathcal{P}_{\rm grav} = \frac{8}{M_{\rm Pl}^2}\left(\frac{H}{2\pi}\right)^2 = 1.92\times 10^{-11}\left(\frac{E_{\rm inf}}{10^{16}\,{\rm GeV}}\right)^4$$

- Here H is the Hubble parameter through slow-roll (roughly constant)
- Define the tensor to scalar ratio r, via the ratio of the tensor to scalar power spectrum at some given k (typically a low value like $k = 0.001\,{\rm Mpc}^{-1}$ chosen)
- Find

$$r = 0.008\left(\frac{E_{\rm inf}}{10^{16}\,{\rm GeV}}\right)^4$$

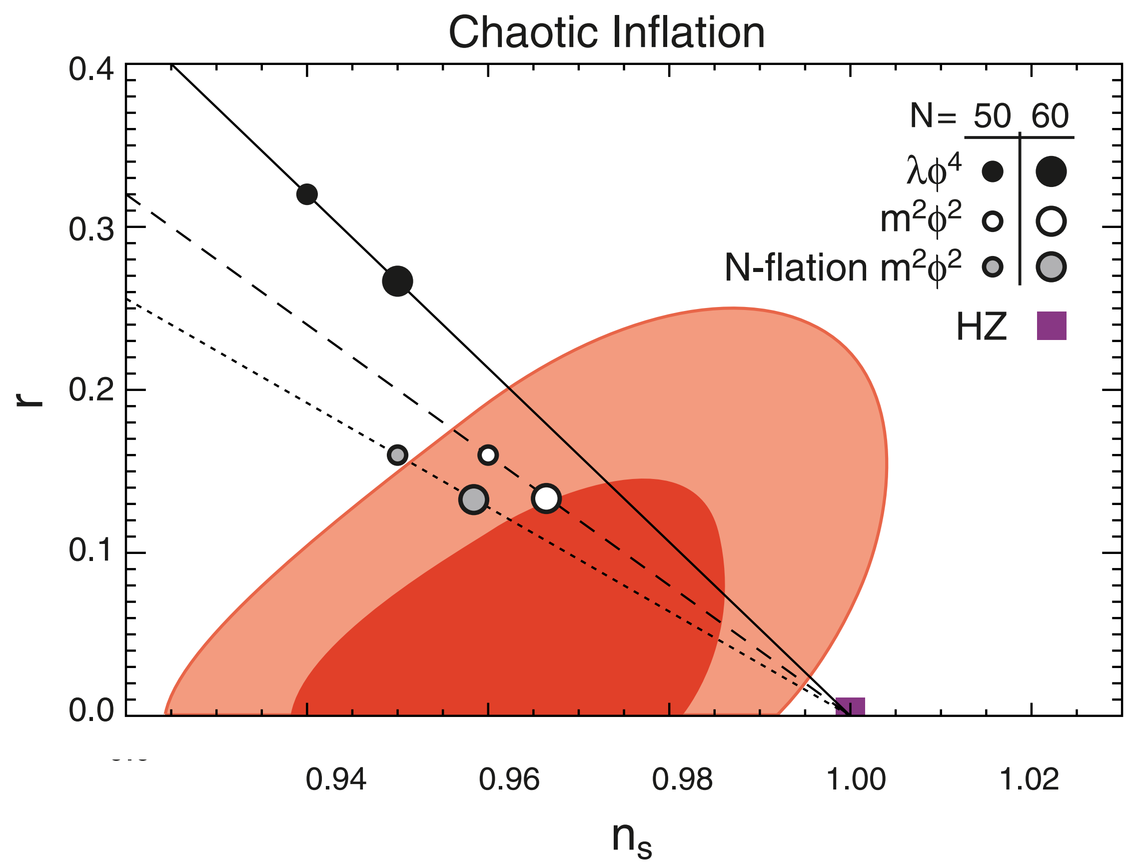
- Thus detectable gravity waves ($r > 0.01$ say) would mean inflation occurred at the GUT scale
- We would then be accessing particle physics at a scale about at least 10^{12} higher than those achievable at LHC
- This high energy scale has its own problems however — will discuss the 'Lyth bound' below

EFFECT OF r ON T AND B



(Anthony Challinor)

- This illustrates vividly how B helps with cosmic variance
- If trying to estimate r from TT (or TT plus EE), then get a fundamental limits of $\Delta r = 0.07$ (or $\Delta r = 0.02$)
- No such limit if use BB directly



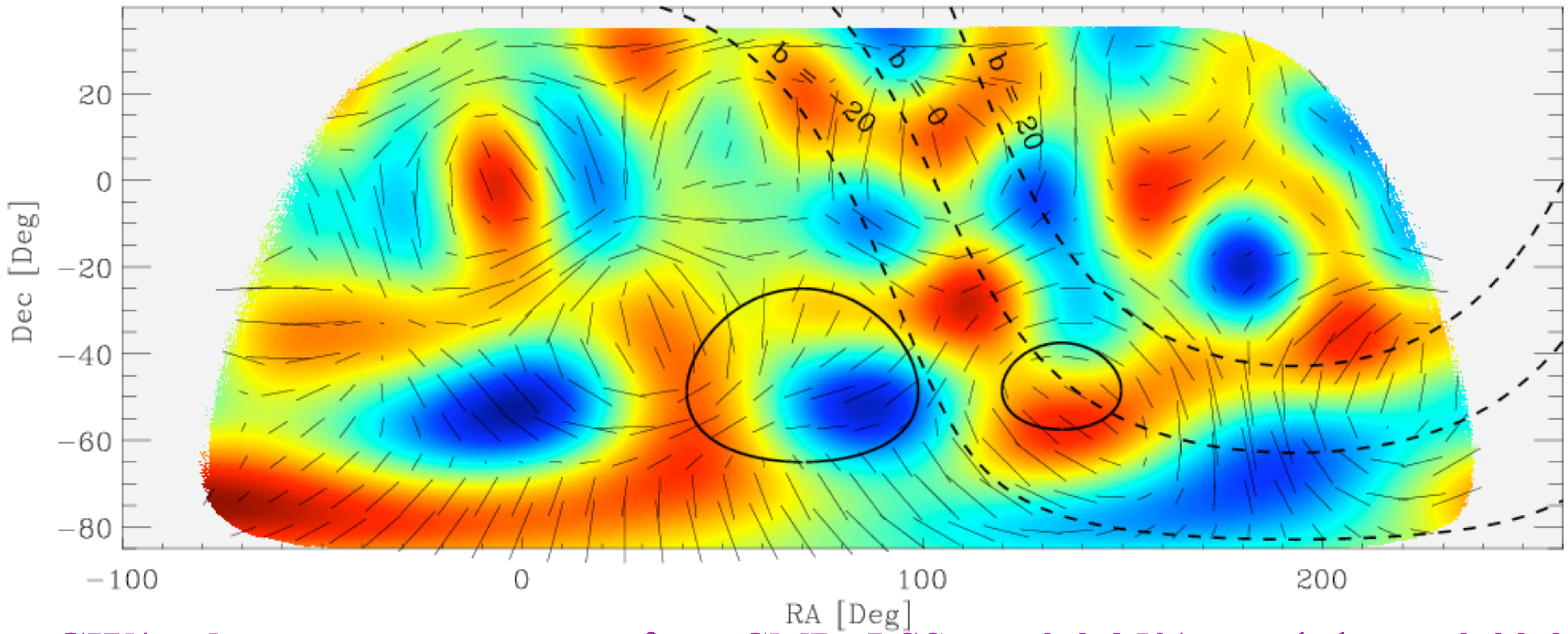
- Observational constraints shown are from WMAP5 (Komatsu et al., 2008)
- Basic results we need to understand this diagram are

$$r = \frac{4\alpha}{N}, \qquad n_s = 1 - \frac{2+\alpha}{2N}$$

  if $V(\phi) = \lambda\phi^\alpha$.
- However, if $V(\phi) = V_0(1 - (\phi/\phi_e)^p)$ then can get r as small as one wants

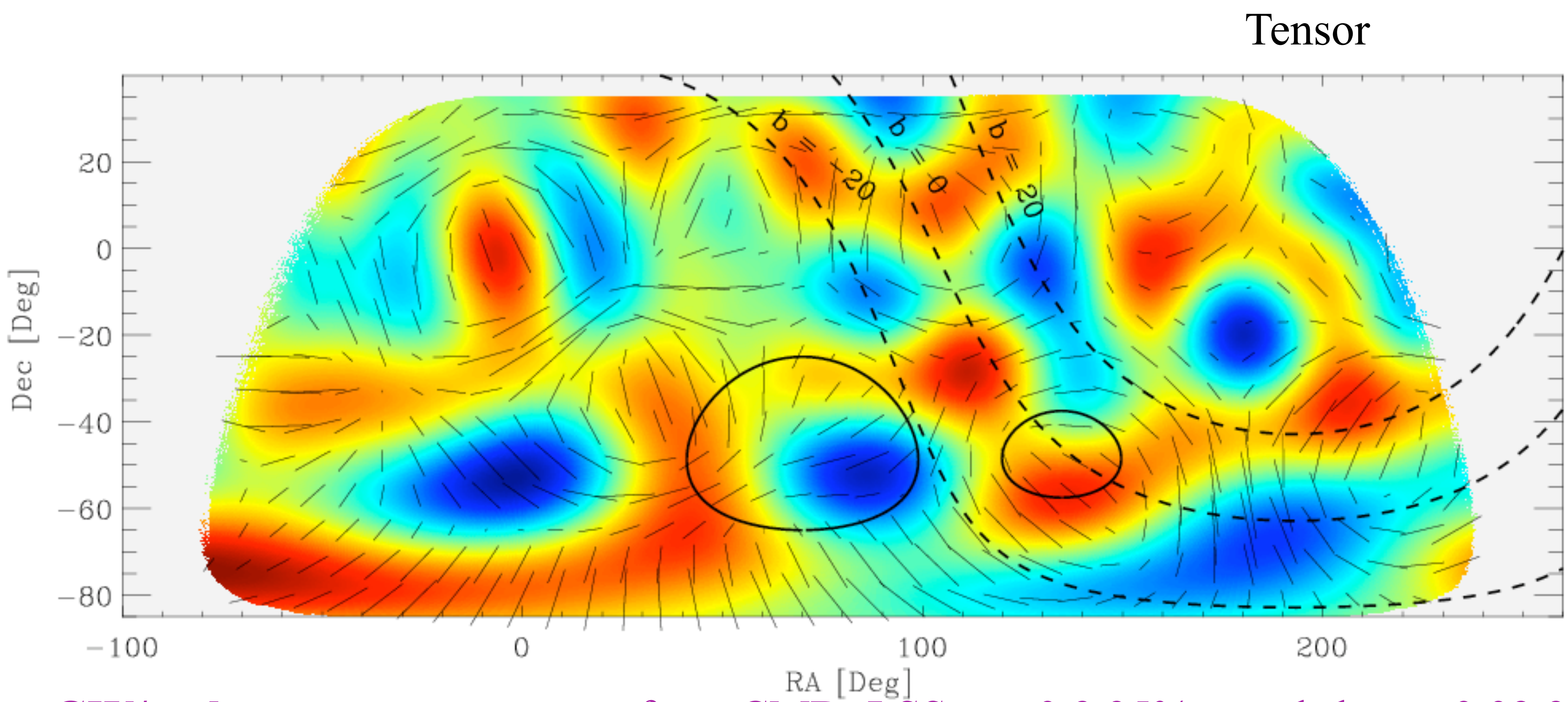
Sky with and without tensors

No Tensor



http://www.astro.caltech.edu/~lgg/spider_front.htm

SKY WITH AND WITHOUT TENSORS



http://www.astro.caltech.edu/~lgg/spider_front.htm

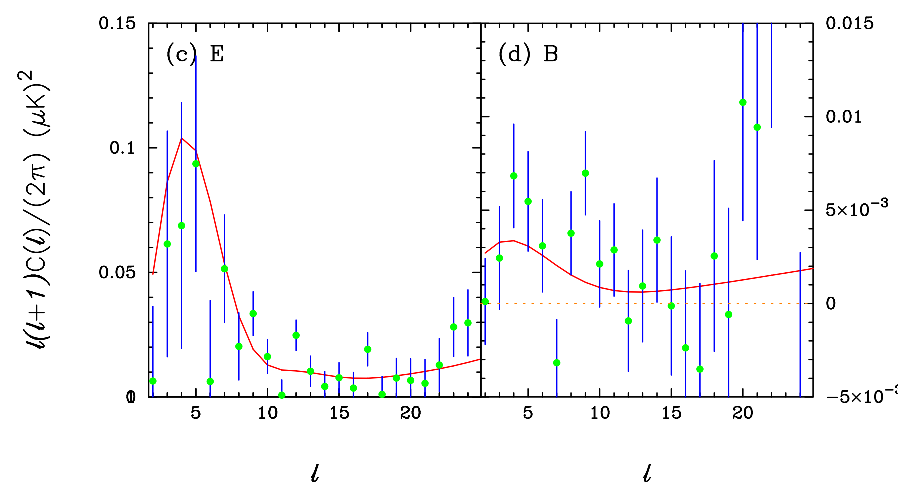
Some Current/Future CMB Polarisation Experiments

Name	Type	Detectors	ℓ range	r target	Start Date
QUAD	ground	bolometer	$200 < \ell < 3000$		completed
BICEP	ground	bolometer	$50 < \ell < 300$	0.1	2007
QUIET	ground	MMIC	$\ell < 1000$	0.05	2008-2010
CLOVER	ground	bolometer	$20 < \ell < 600$	0.01	??
EBEX	balloon	bolometer	$20 < \ell < 1000$	0.03	2009
SPIDER	balloon	bolometer	$\ell < 100$	0.025	2009-2010
BPOL	space	bolometer	$\ell < 200$	1–5 $\times 10^{-3}$	??
QUIJOTE	ground	MMIC	$\ell < 80$	0.1/0.05	2008
POLARBEAR	ground	bolometer	$20 < \ell < 2000$	0.05	2009

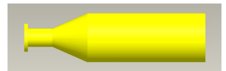
Discuss here

- CLOVER — Cardiff, Cambridge, Oxford, Manchester, B-mode bolometric experiment
- QUAD — some new interesting results just appeared
- QUIJOTE — Tenerife, Cambridge, Manchester, Santander foregrounds and B-mode HEMT
- BICEP — Caltech, Princeton, JPL, Berkeley + others — first B mode direct limit starting to be competitive with indirect limits

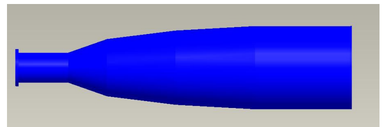
- Planck was launched May 14th
- Has reached L2 and can begin a First Light Survey soon
- Reno will be able to give us a full report
- B-mode polarisation — with two-year mission (currently being applied for) predictions are that could detect B-modes at $r = 0.05$ (and would set an upper limit around $r < 0.03$ if r small) (Efstathiou & Gratton, astro-ph/0903.0345)
- Will also be able to improve over WMAP greatly as regards parameter constraints (cosmic variance limited to much higher ℓ) (good for inflation parameters) and in non-Gaussianity (see later)



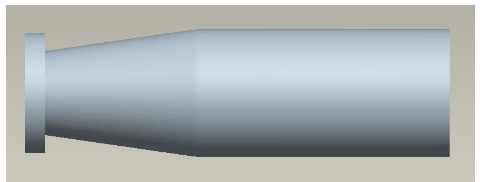
QUIJOTE



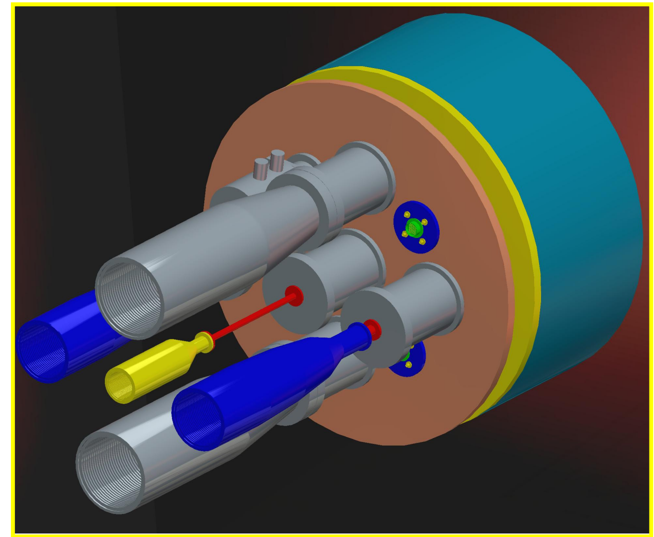
26-36GHz Horn



14-20GHz Horn



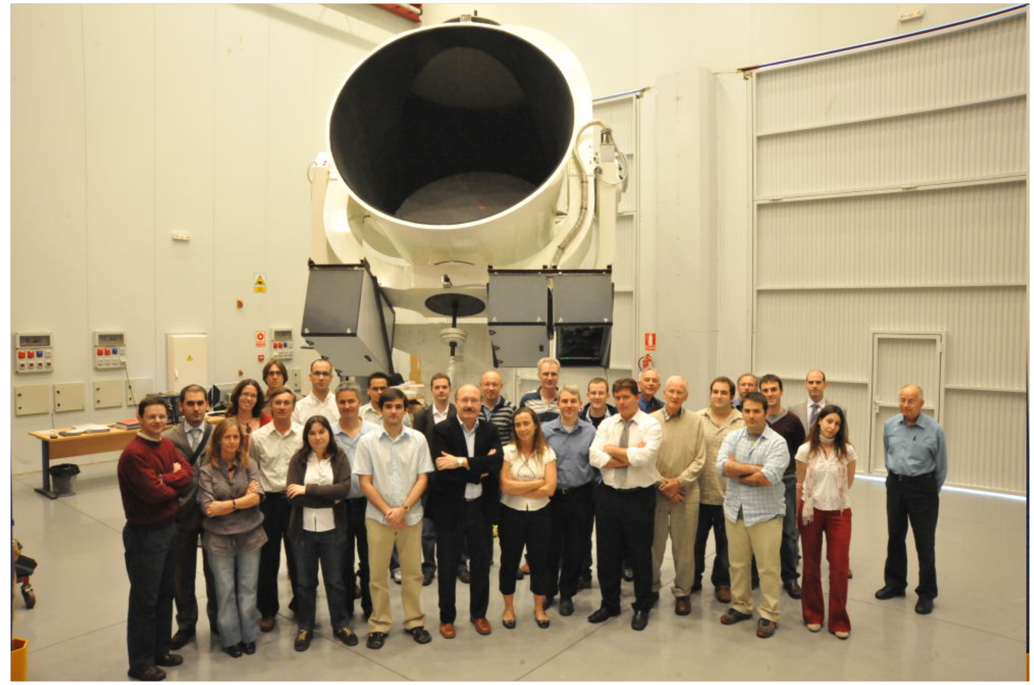
10-14GHz Horn



QUIJOTE 1 : Focal Plane Distribution

- Rafa Rebolo was going to give a lecture on this — will highlight a few key aspects
- IAC (Tenerife)-Cambridge-Manchester-Santander collaboration
- With the demise of CLOVER, is probably now the premier ground-based European experiment
- Comes in 3 stages:
  Phase 1: First Instrument: Horns and frequencies as in picture
  Phase 1: Second Instrument: 16×30 GHz horns substituted

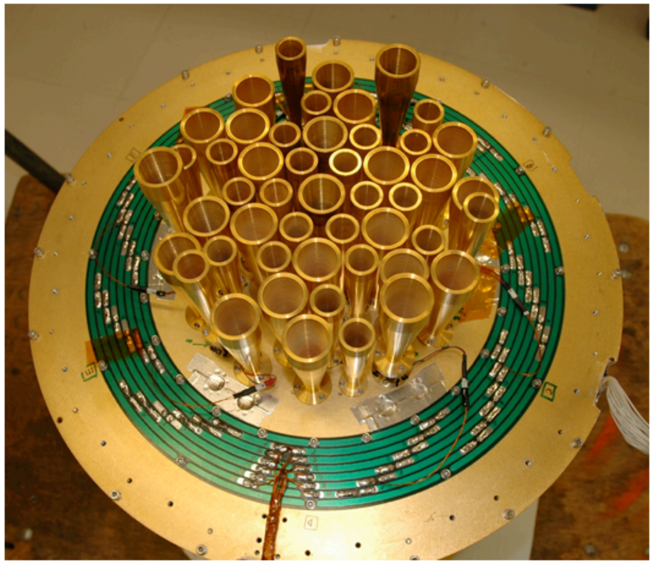
QUIJOTE (CONTD.)

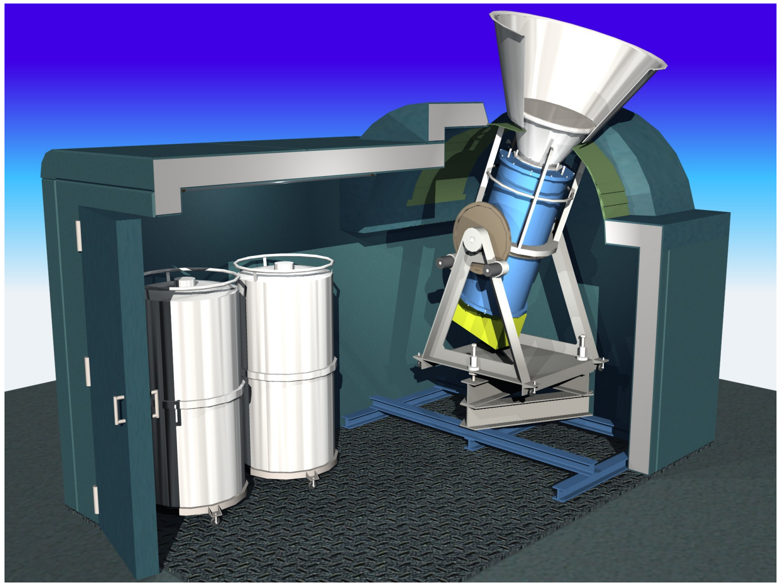


- Will use spinning mount to achieve good sky coverage
- Aprrox. 1 degree resolution
- Main aims: frequency coverage 10–36 GHz ideal for mapping and understanding properties of spinning dust and other foregrounds
- Also, in principle could detect B-modes if large ($r \sim 0.1$)
- Observations start ~September!
- Following this (currently being applied for):
  Phase 2: 50 horns at 42 GHz plus an interferometric pathfinder

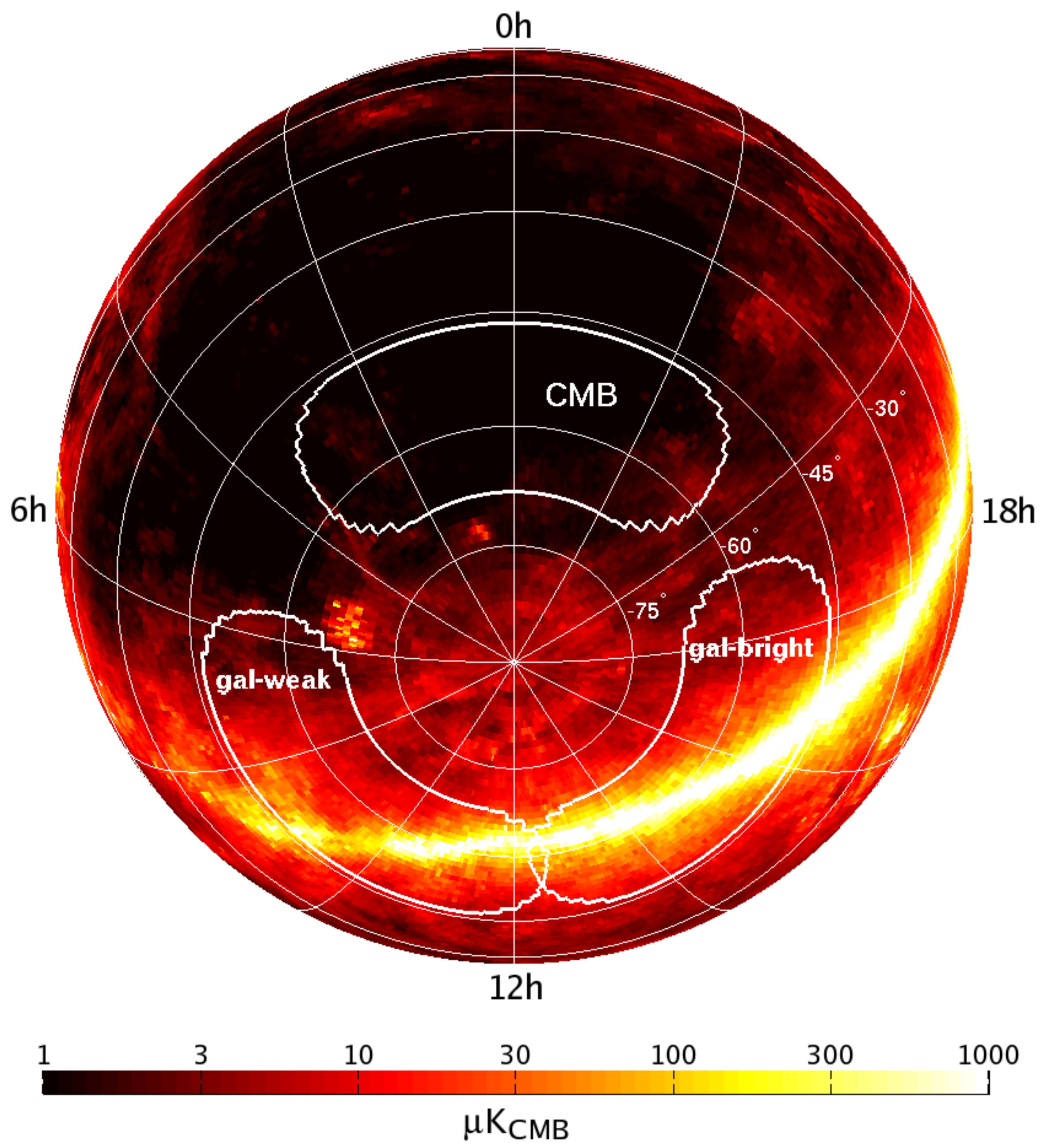
BICEP

- BICEP Background Imaging of Cosmic Extragalactic Polarization
- Caltech, Princeton, JPL, Berkeley and others collaboration
- 100 and 150 GHz polarization sensitive bolometers, illuminated via a 2 lens system (so is a refractor!)
- At South Pole, in a mounting which maximises how much of telescope is easily accessible
- Going after polarisation anisotropy at larger scales than other ground-based designs so far
- Beams = 0.93° at 100 GHz and 0.60° at 150 GHz
- (Cf. QUAD, which has about 4 armin resolution)

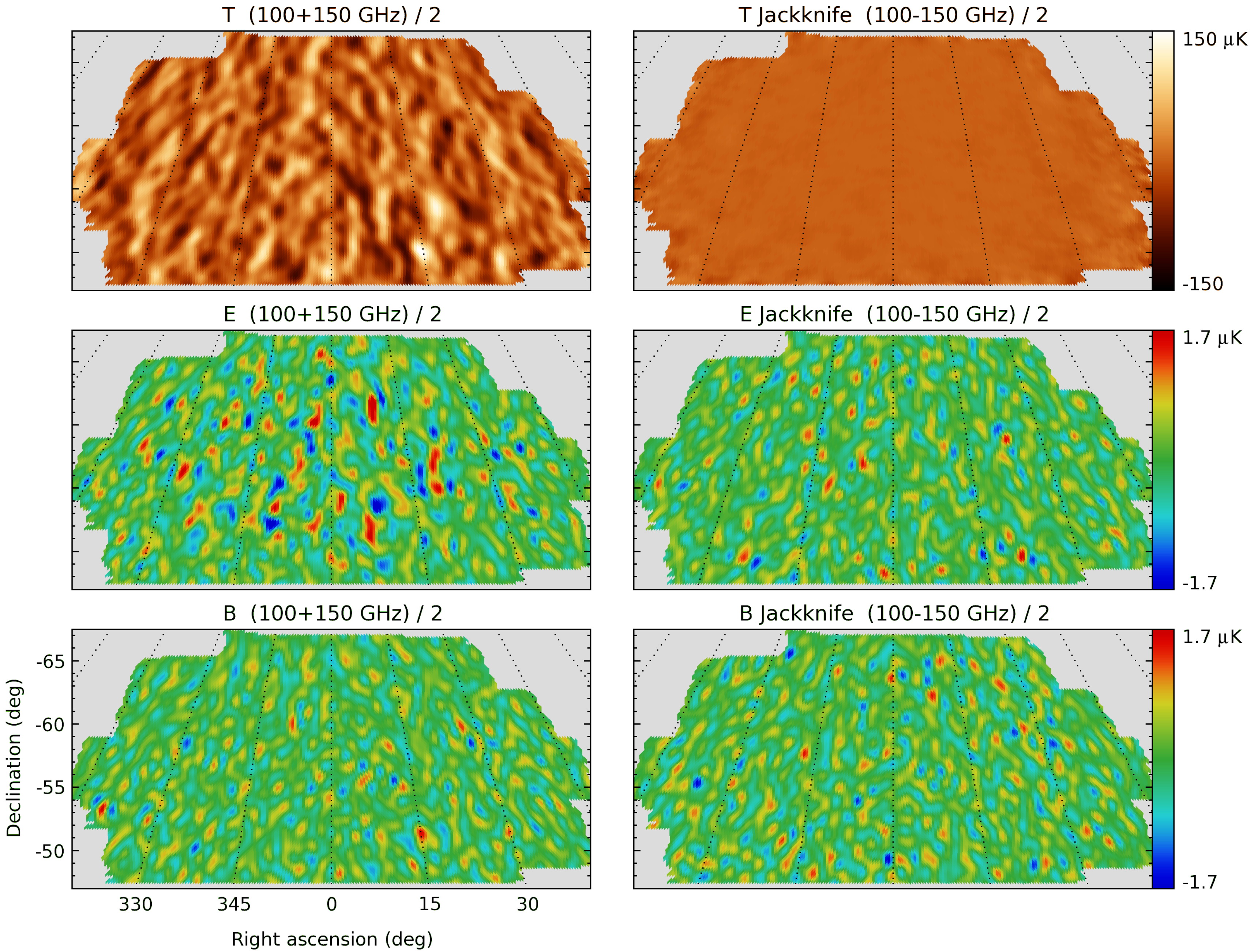




BICEP OBSERVING REGIONS

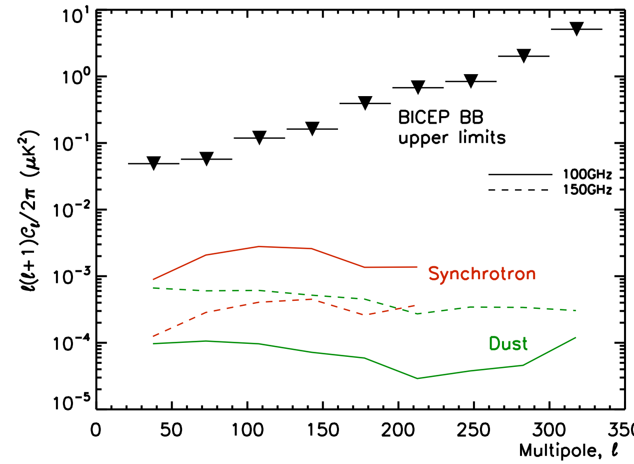


BICEP T, E AND B MAPS AND DIFFERENCES



BICEP RESULTS

- Results from 2007-2008 campaigns have appeared recently in Chiang et al. (astro-ph/0906.1181)
- Important that foregrounds look to be under control in what's being called the 'Southern Hole'
- They are claiming the first detection of the peak in EE at $\ell \sim 140$
- Main result is a much improved limit on r of $r < 0.73$ (95% conf.)
- This may not look exciting compared to $r < 0.43$ (Dunkley et al. WMAP5 CMB only result or $r < 0.33$ (QUAD CMB only result)
- However, this is by far most significant *direct* limit on r so far
- WMAP5 data analysed same way gives $r < 6$ (95% conf.)!



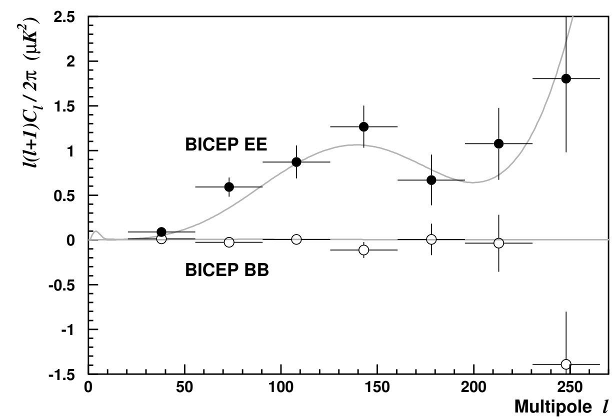
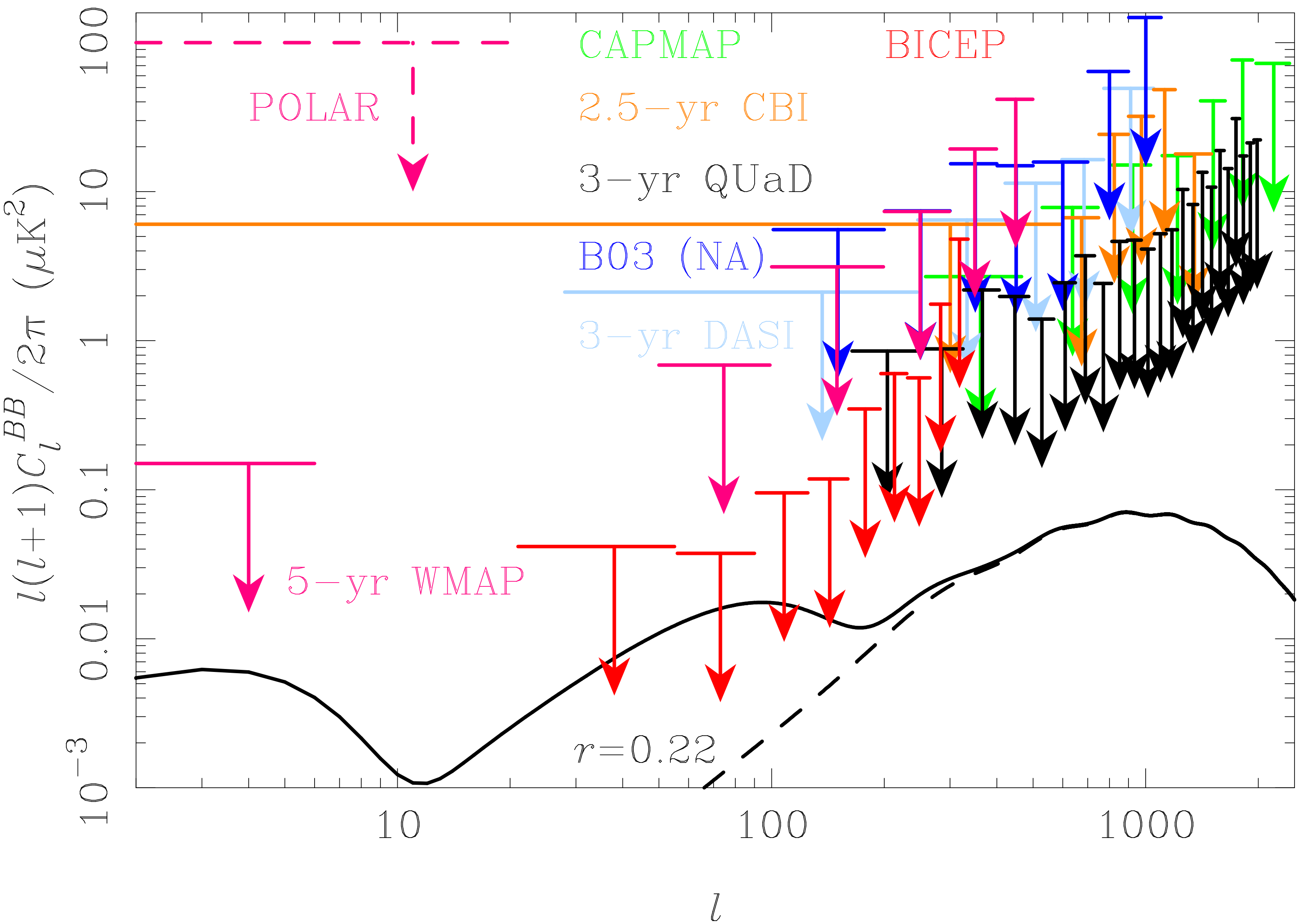


FIG. 12.— BICEP measures EE polarization (black points) with high signal-to-noise at degree angular scales. The BB spectrum (open circles) is overplotted and is consistent with zero. Theoretical ΛCDM spectra (with $r = 0.1$) are shown for comparison.

SUMMARY OF CONSTRAINTS ON BB



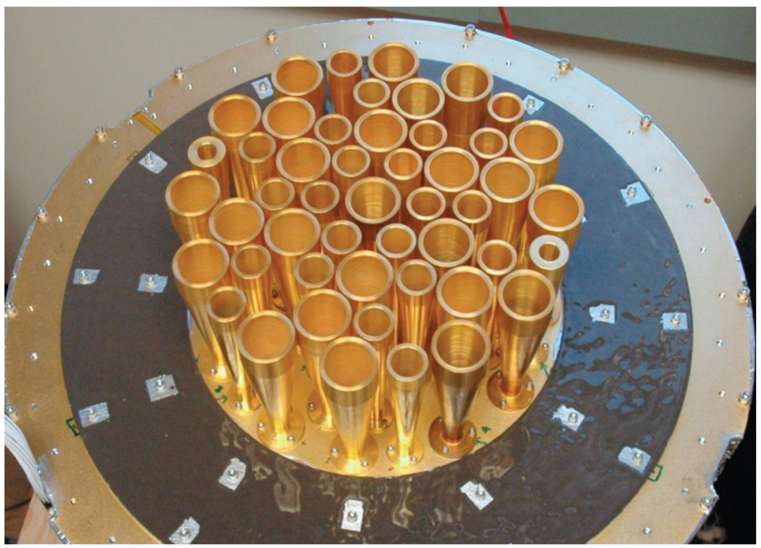
(Anthony Challinor)

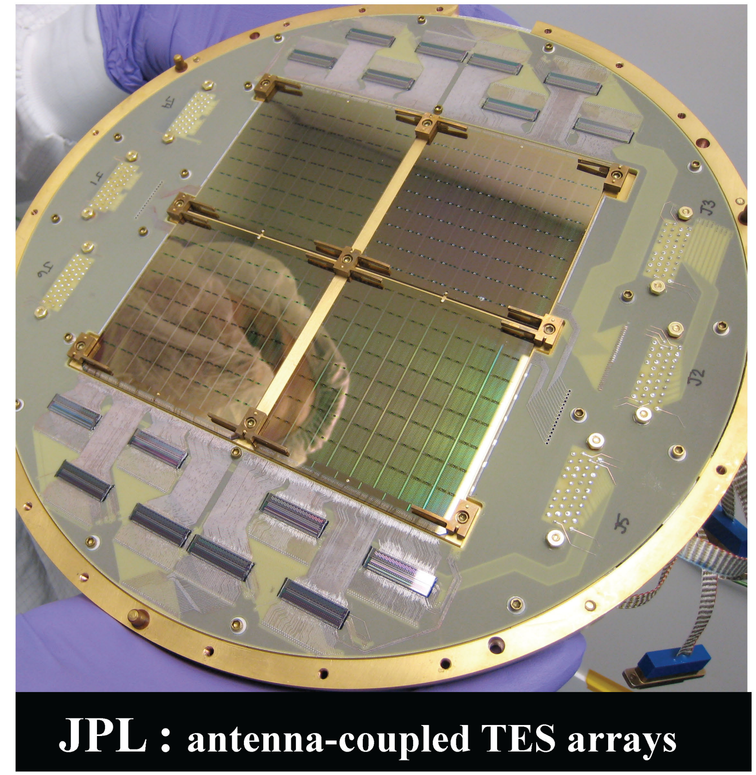
BICEP PLANS

- BICEP2 will deploy to South Pole in November 2009
- 512 detectors at 150 GHz only
- 10 times the mapping speed of BICEP1 (similar scales and ℓ-range aims)
- Funding exists for a third array (called the Keck array), which will have 3 further telescopes deployed by November 2010
- Frequencies TBD (depending on what is seen by then!)

THE TRANSITION BICEP1 TO BICEP2 (SLIDE FROM J. KOVAC)

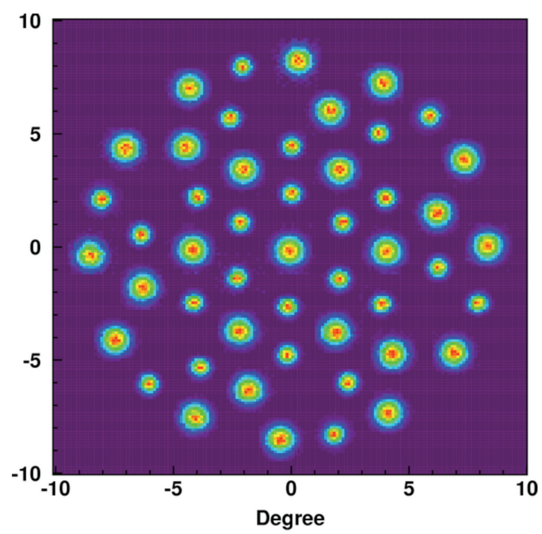
BICEP2: 10-fold increase in mapping speed:

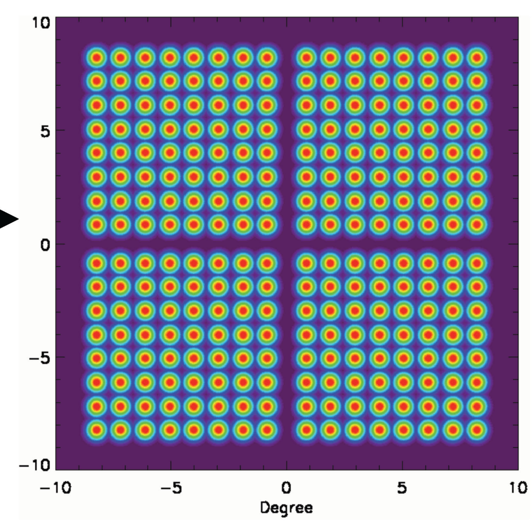




BICEP1

48
150 GHz detectors



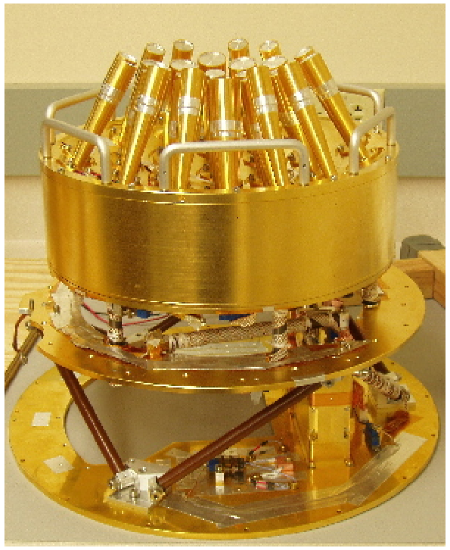


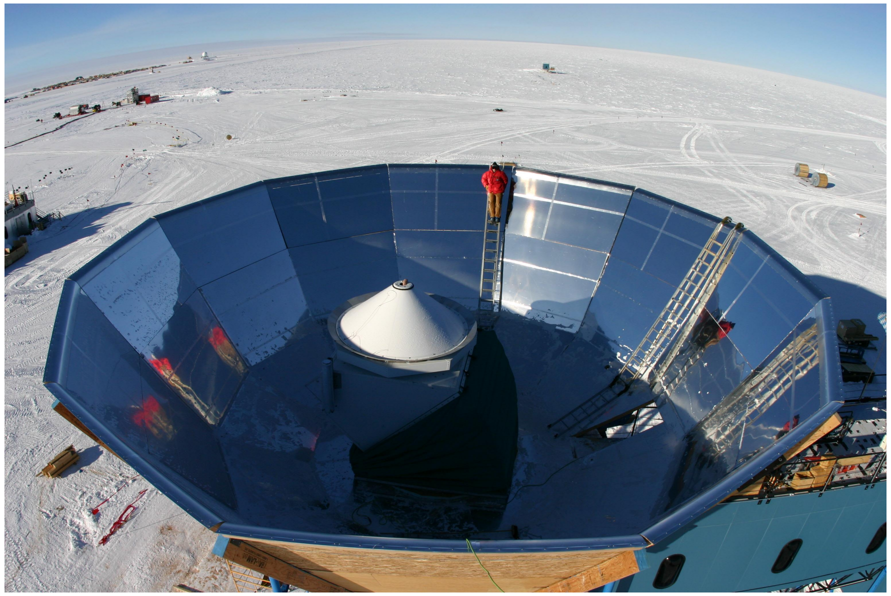
BICEP2

512
150 GHz detectors

QUAD

- QUAD – Quest at DASI
- Cardiff, Stanford, Chicago, Edinburgh and others collaboration
- 100 and 150 GHz polarization sensitive bolometers, feeding 2.6 m primary
- On DASI mount at South Pole
- Has been good for E-mode anisotropy at 4 arcmin scale
- New analysis recently appeared (Brown et al, arXiv.0906.1003v2)
- This has effectively doubled effective sky area, by not having to use lead/trail differencing, with some interesting new results





QUAD RESULTS

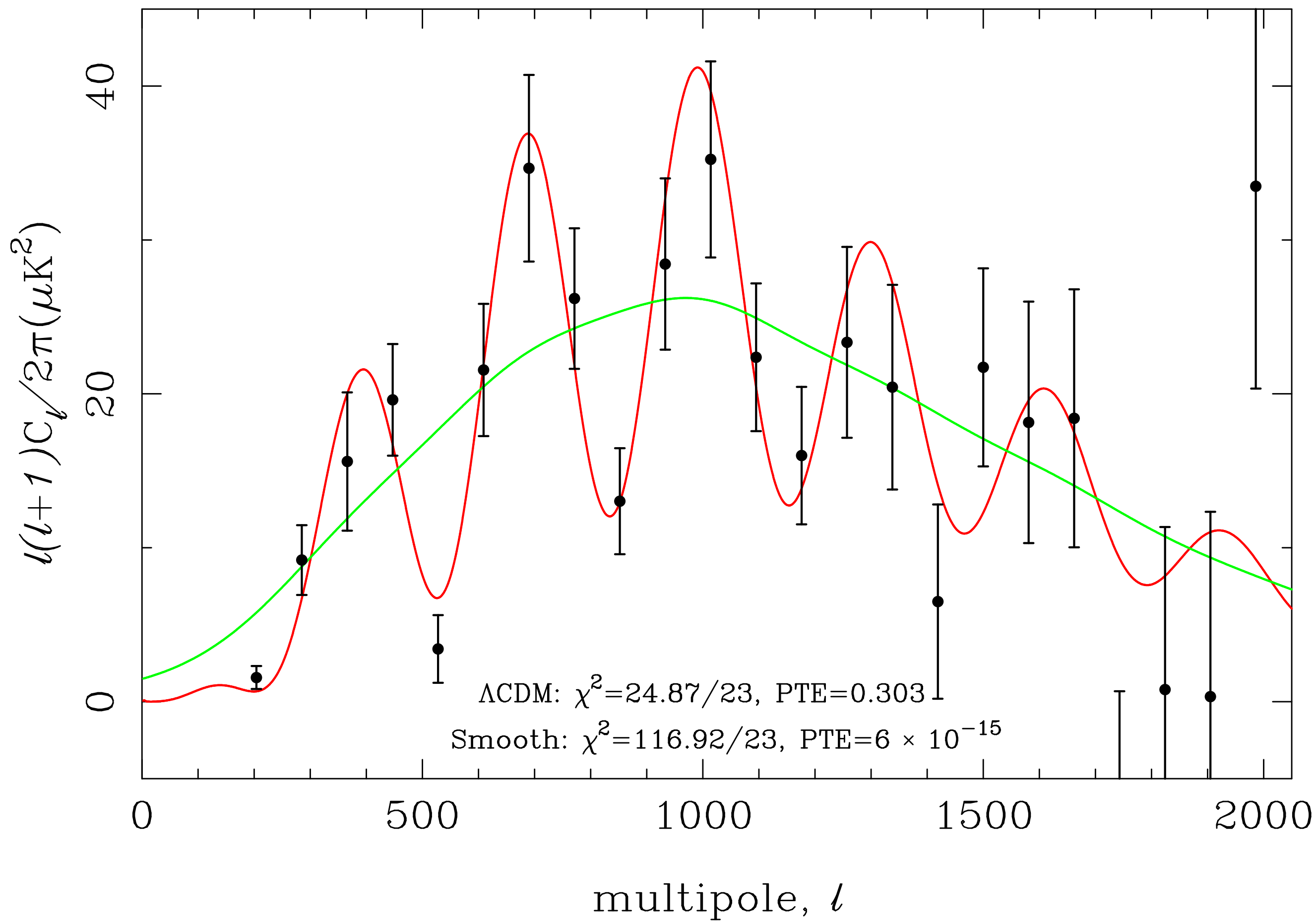
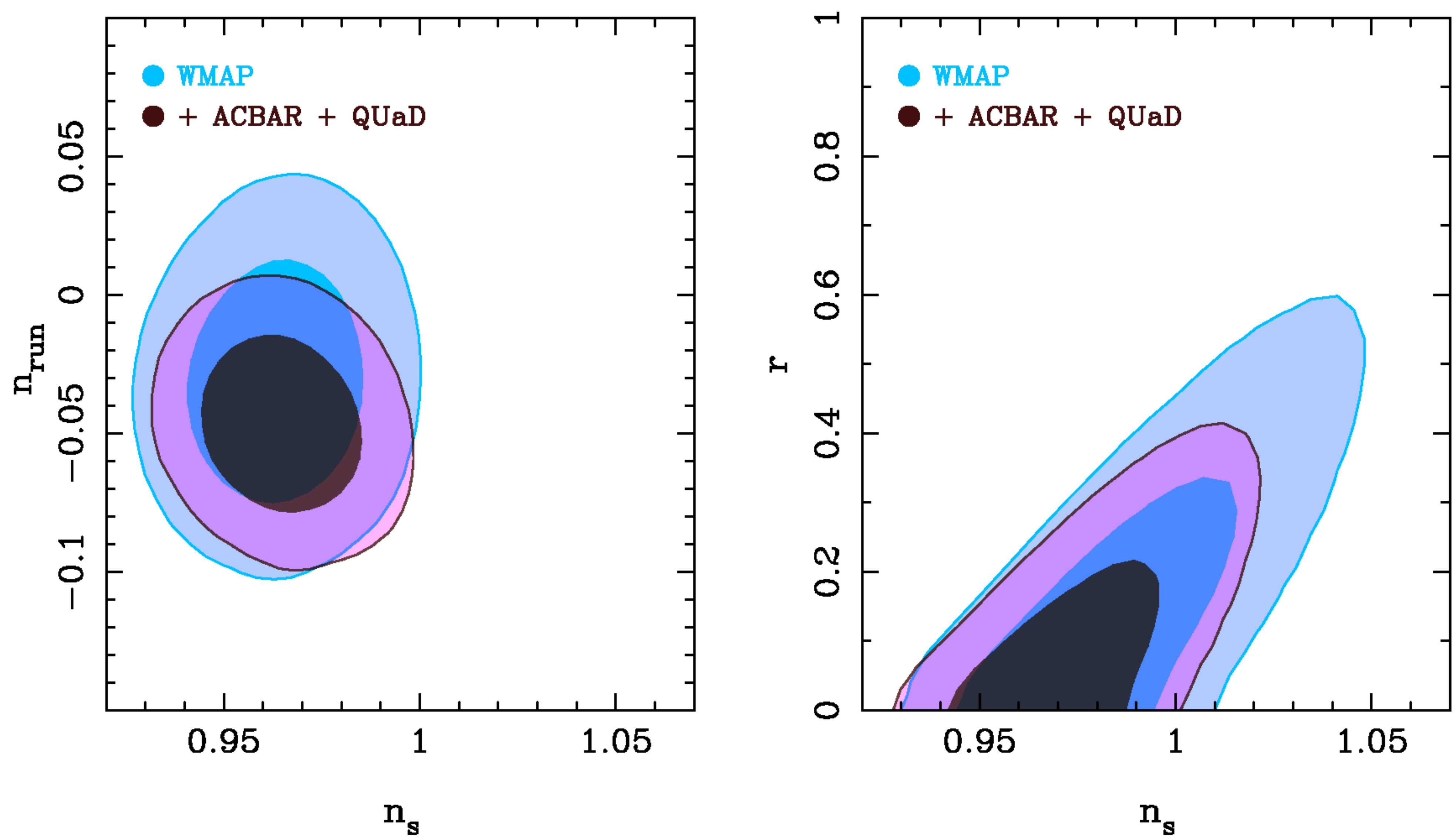


FIG. 13.— QUaD's measurements of the *EE* spectrum (black points) compared to the ΛCDM model (red curve) and a model without peaks (green curve). The data are incompatible with the no-peak scenario — the probability that the smooth curve is correct is $< 10^{-14}$.

- E.g., now have a definitive detection of the 'peaks' in the EE spectrum

QUAD RESULTS



- Also, very interestingly, evidence is starting to come back for running of the spectral index n_s! (and constraints in r vs. n_s plane are tightened)

- Have been doing recent work with Sylvain Brechet and Mike Hobson (Cambridge) on the question of initial conditions for inflation
- Related to work by Sanchez, de Vega, Boyanovsky & Destri concerning effects of a fast roll period before the usual slow roll of inflation
- Idea is that there is a natural boundary condition for inflation, namely, that the boundary condition for the scalar field evolution is that it emerges from the Big Bang singularity
- Can argue for this in exactly the same way as for ordinary perfect fluid evolution: if evolve backwards in time, then at a certain point the density starts to behave as

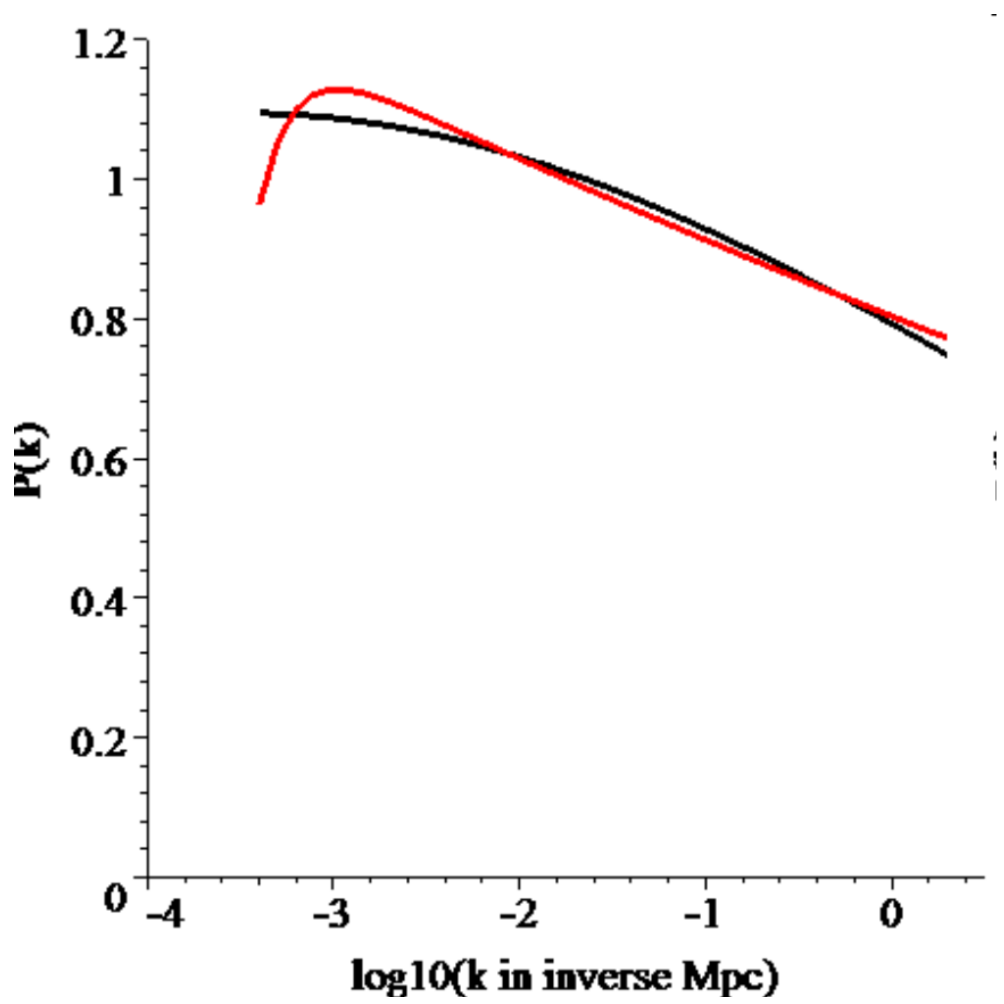
$$\rho \propto \frac{1}{(t-t_0)^2}$$

- We identify t_0 as the Big Bang. Exactly the same happens for the energy density of a scalar field. Evolving backwards, find there's always (except in some closed models, and Bianchi models (see Dechant, Lasenby & Hobson, Phys.Rev.D79:043524,2009), where can avoid singularity) a point where it behaves this same way

SHAPE OF THE PRIMORDIAL SPECTRUM (CONTD.)

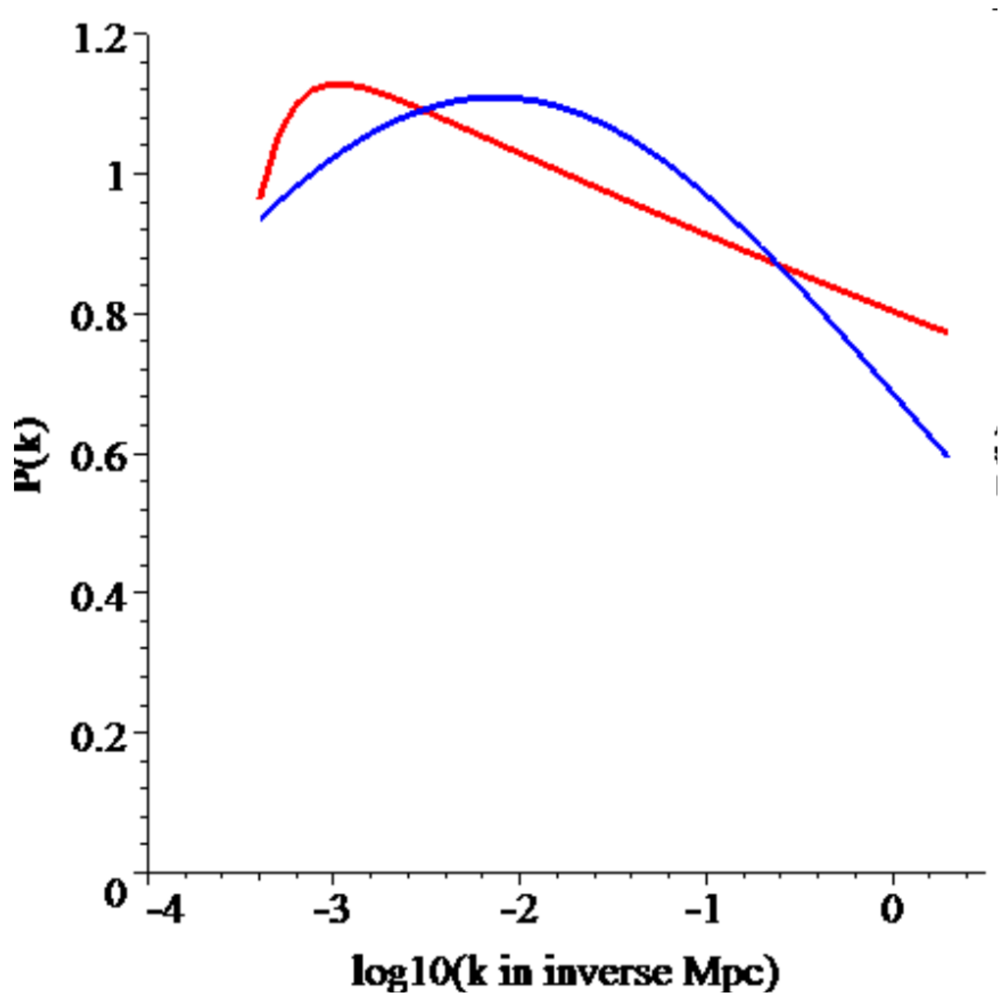
- Crucial (technical) question is whether this happens at a point where we are still allowed to treat its overall background evolution as classical
- In Lasenby & Doran (Phys.Rev.D, **71**, (2005) 063502) we showed in the context of a slightly closed ($\Omega_{\rm tot} \sim 1.02$) singular model with $V(\phi) = (1/2)m\phi^2$ ('chaotic potential') that indeed the background evolution was still in the classical regime at points where the observable perturbations today were laid down
- In this model, get a quadrupole suppression, and overall good agreement with the CMB and matter power spectra
- Point we've now got clear on (in Brechet et al., in prep) is that this type of spectrum is generic for any potential and works equally with a flat model (note still need fine-tuning in 2 params of potential to get e-folds and normalisation)
- Important point is that the (power series) expansion out of the singularity is enough to set conditions in which fast roll precedes slow roll (get $H(t) \sim 1/(3t)$, $\phi \frac{1}{\sqrt{24\pi}} \ln(t)$ as generic initial conditions)
- Now want to compare this type of spectrum with one having n_{run}

LASENBY + DORAN SPECTRUM WITH BEST FIT n_{run} (-0.01)



Note if didn't include low-k region with suppression, best fit n_{run} is about -0.001 (due to high-k power spectrum being linear in $\ln k$, rather than a power law)

LASENBY + DORAN SPECTRUM VS. $n_{\text{run}} = -0.04$



This illustrates how dramatic the effects of an n_{run} as big as -0.04 are. (QUAD value is -0.046 ± 0.021 using WMAP+QUAD+ACBAR.)

INFLATION AND STRING THEORY

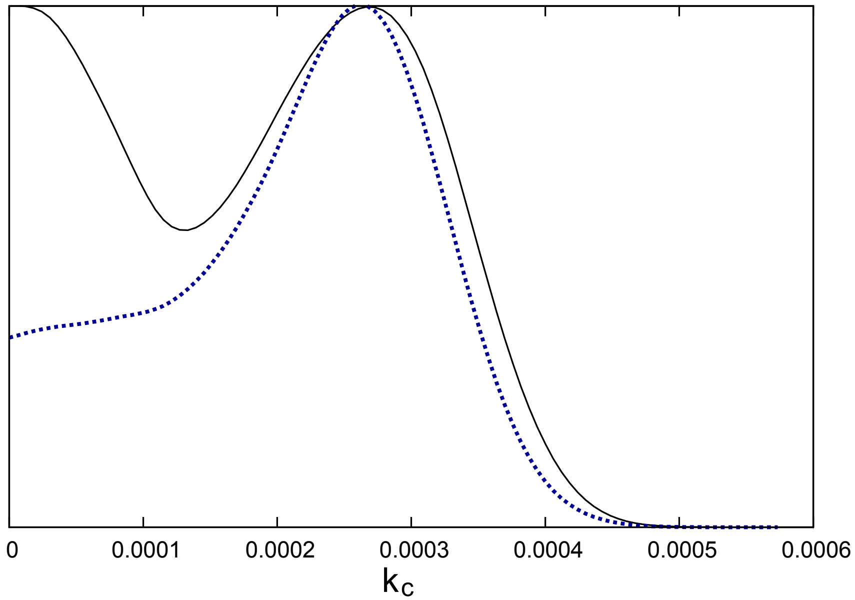
- Mentioned this last year as well, but would like to update
- In canonical single field models, Lyth (1997) showed

$$r = \frac{8}{M_{\mathrm{Pl}}^2}\left(\frac{d\phi}{dN}\right)^2$$

- Thus field evolution of 50–60 e-folds implies $\Delta\phi \sim (r/0.002)^{1/2}$
- Detectable gravity waves means inflaton evolved through a super-Plankian distance
- There may be geometrical effects in string theory moduli which makes this difficult
- Also now believed that having a smooth potential over $\Delta\phi > M_{\mathrm{Pl}}$ problematic for effective field theory with a cutoff $\Lambda < M_{\mathrm{Pl}]}$ unless shift symmetry removes higher order corrections
- Daniel Baumann (see e.g. hep-th/0901.0265), now very strong on this — detectable tensor modes means a shift symmetry must exist for the potential
- First 'stringy' models incorporating this (with axion-like potentials) now starting to appear (e.g. Flauger et al. hep-th/0907.2916 - Axion Monodromy model)
- These may lead to a broad ϕ^2 type potential, but with superposed oscillations — observable effects in CMB?

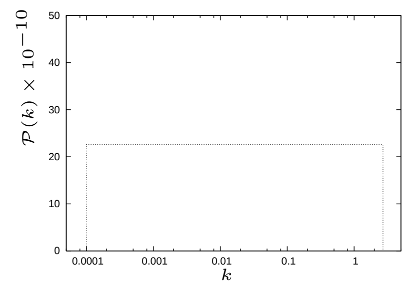
- Bridges, Feroz, Hobson and ANL (astro-ph/0812.3541) looked at optimal Bayesian reconstruction of the primordial power spectrum
- As first step looked at the evidence for some standard models using CMB (WMAP5 + ACBAR + CBI) and LSS (SDSS LRG+ 2dF)
- Evidence is the Bayesian way of trading off 'goodness of fit' against Occam's razor penalisation of extra parameters
- Cutoff favoured at about the same level as tilt

Model	CMB	CMB + LSS
H-Z	0.0 ± 0.3	0.0 ± 0.3
$n_{\rm s}$	$+1.6 \pm 0.3$	$+1.1 \pm 0.3$
$n_{\rm run}$	$+0.4 \pm 0.3$	-0.4 ± 0.3
k_c	$+1.5 \pm 0.3$	$+1.3 \pm 0.3$

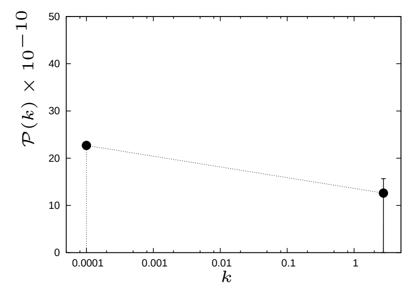


Marginalised posterior probability of the large scale spectral cutoff k_c using CMB plus LSS data (solid) and CMB data alone (dotted)

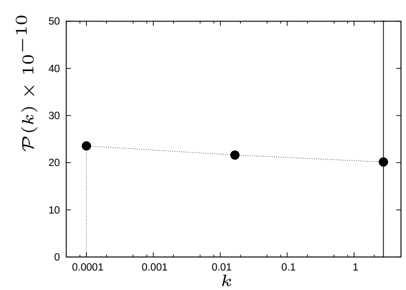
- Then looked at specification of the power spectrum via a series of nodes
- At each level of complexity worked out evidence for introduction of an extra node between two existing nodes
- Surprisingly, peaks at just 3 nodes! (so basically favouring a tilt — cut-off is assumed)



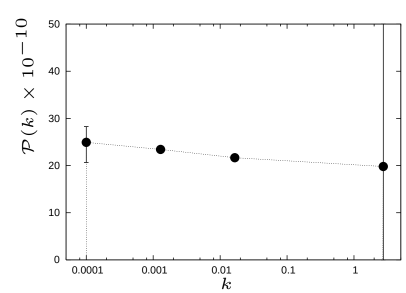
(a) **1:** $\mathcal{B}_{11} = 0.00 \pm 0.30$



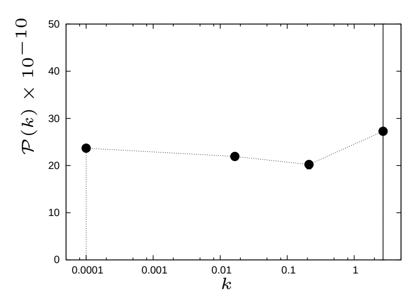
(b) **2:** $\mathcal{B}_{21} = +0.66 \pm 0.30$



(c) $\mathbf{3}$: $\mathcal{B}_{31} = +1.08 \pm 0.30$

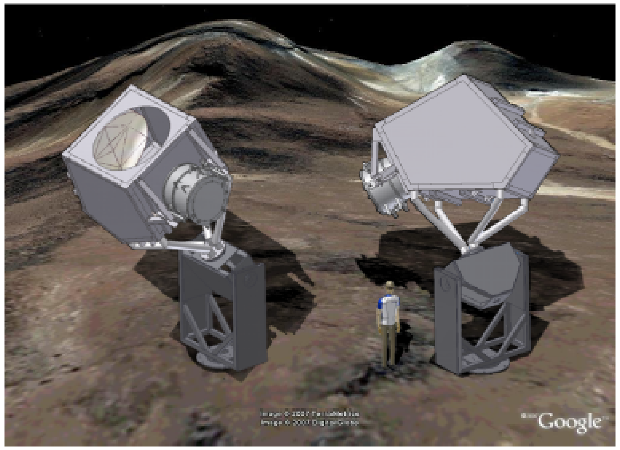


(d) $\mathbf{4}_{\rm I}$: $\mathcal{B}_{4_{\rm I}1} = -0.34 \pm 0.30$

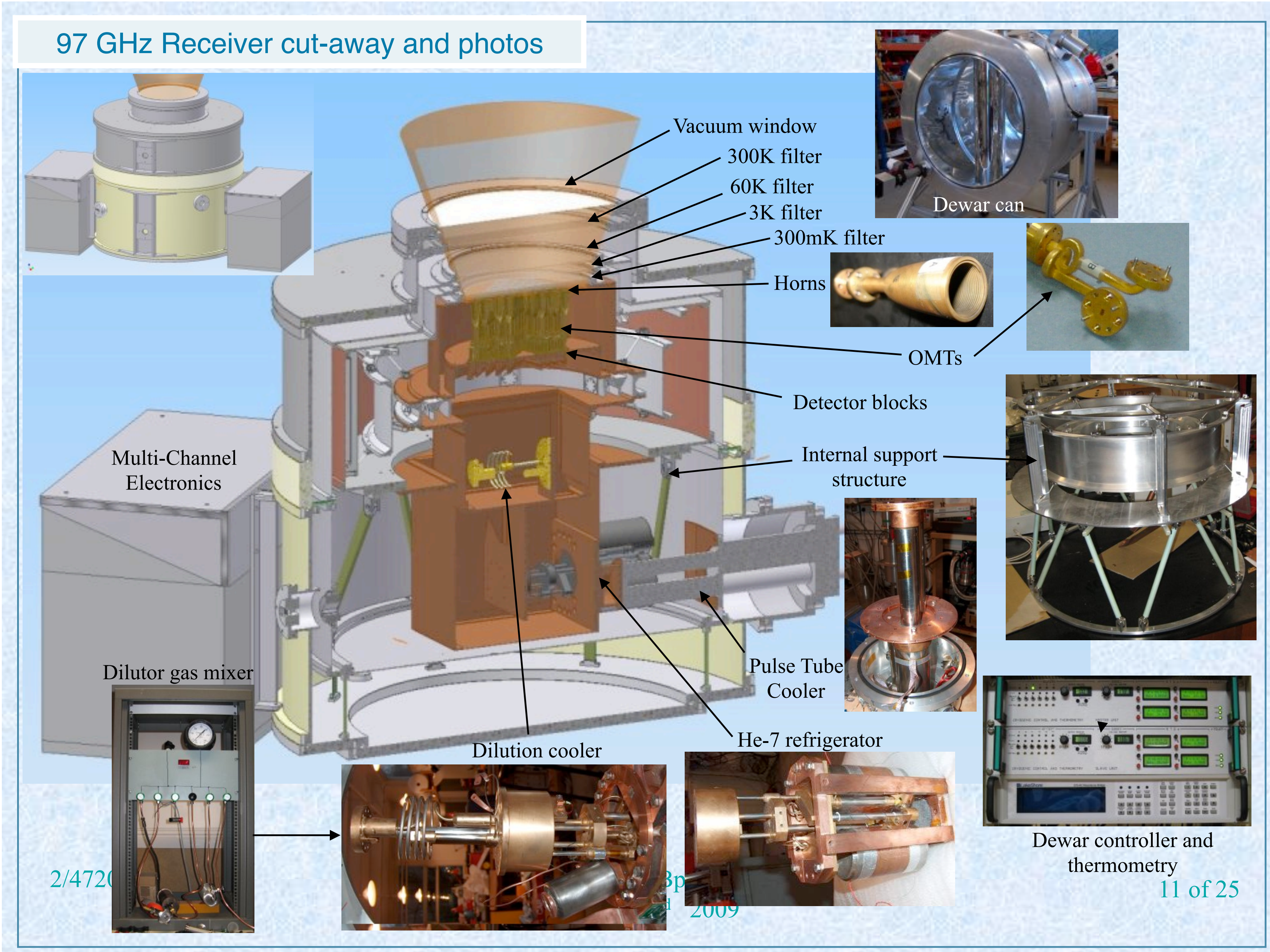


(e) $\mathbf{4}_{\rm II}$: $\mathcal{B}_{4_{\rm II}1} = -1.41 \pm 0.30$

CLOVER SUMMARY



- Cardiff-Cambridge-Manchester-Oxford collaboration (+ NIST & UBC)
- Clean, highly-sensitive polarimetry ($\sim 5\,\mu$K-arcmin imaging at 97 GHz)
- 600 background-limited TES detectors
- Multiple levels of modulation (HWP, scanning and boresight rotation)
- Two instruments: one at 97 (7.5 arcmin); one with mixed focal plane at 150 and 225 GHz (5.5 arcmin)
- Two years observing from Atacama, Chile; commissioning to start end-2009
- Most of hardware for first instrument and telescope now completed
- Unfortunately project has been canceled by UK funding council
- A big blow for UK (and European) cosmology


97 GHz Receiver cut-away and photos
Vacuum window
300K filter
60K filter
3K filter
300mK filter
Horns
OMTs
Detector blocks
Internal support structure
Dewar can
Multi-Channel Electronics
Dilutor gas mixer
Dilution cooler
Pulse Tube Cooler
He-7 refrigerator
Dewar controller and thermometry
11 of 25
2009

(Walter Gear)

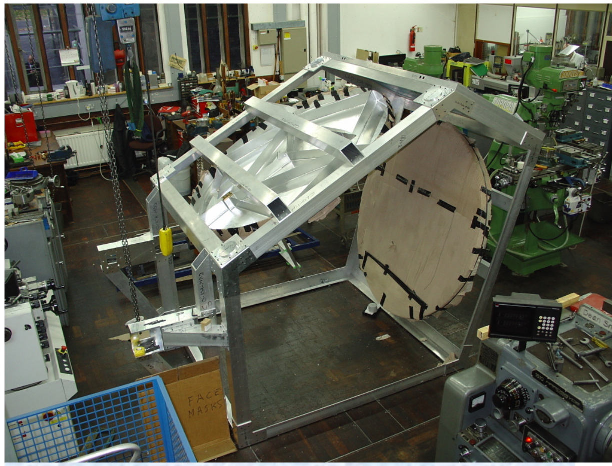
97 GHz Horns

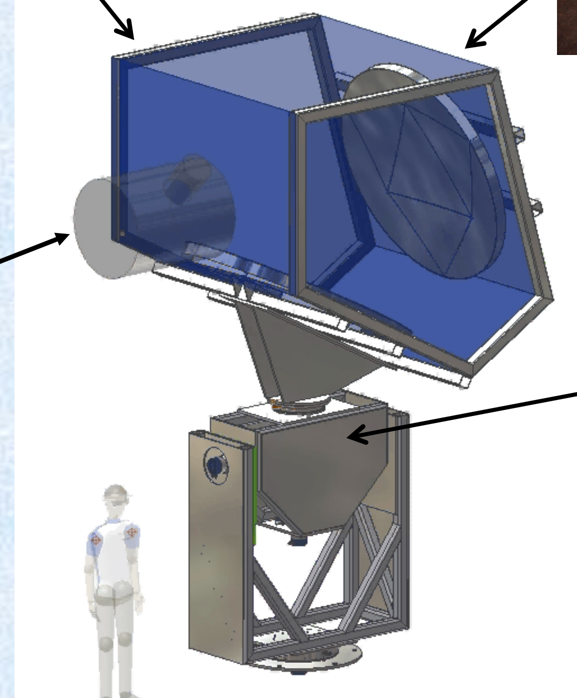
All 96 horns have been delivered

of 25

(Walter Gear)

Hardware almost complete
AIV underway





(Walter Gear)

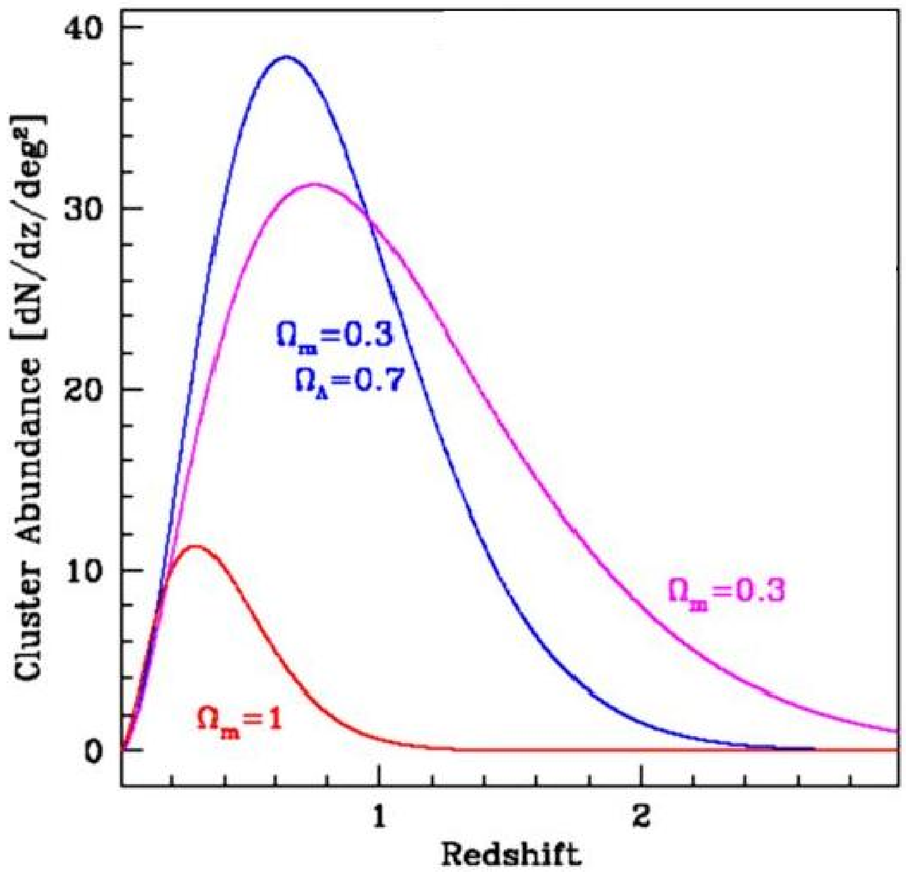
AMI

- The AMI Small Array
- Ten 3.7 m dishes
- Has been working fully for 2 year

- The AMI Large Array
- The Eight 13 m dishes of the old Ryle Telescope
- Reconfigured to make a compact array for source subtration for Small Array SZ surveys
- Key for measuring radio source contamination

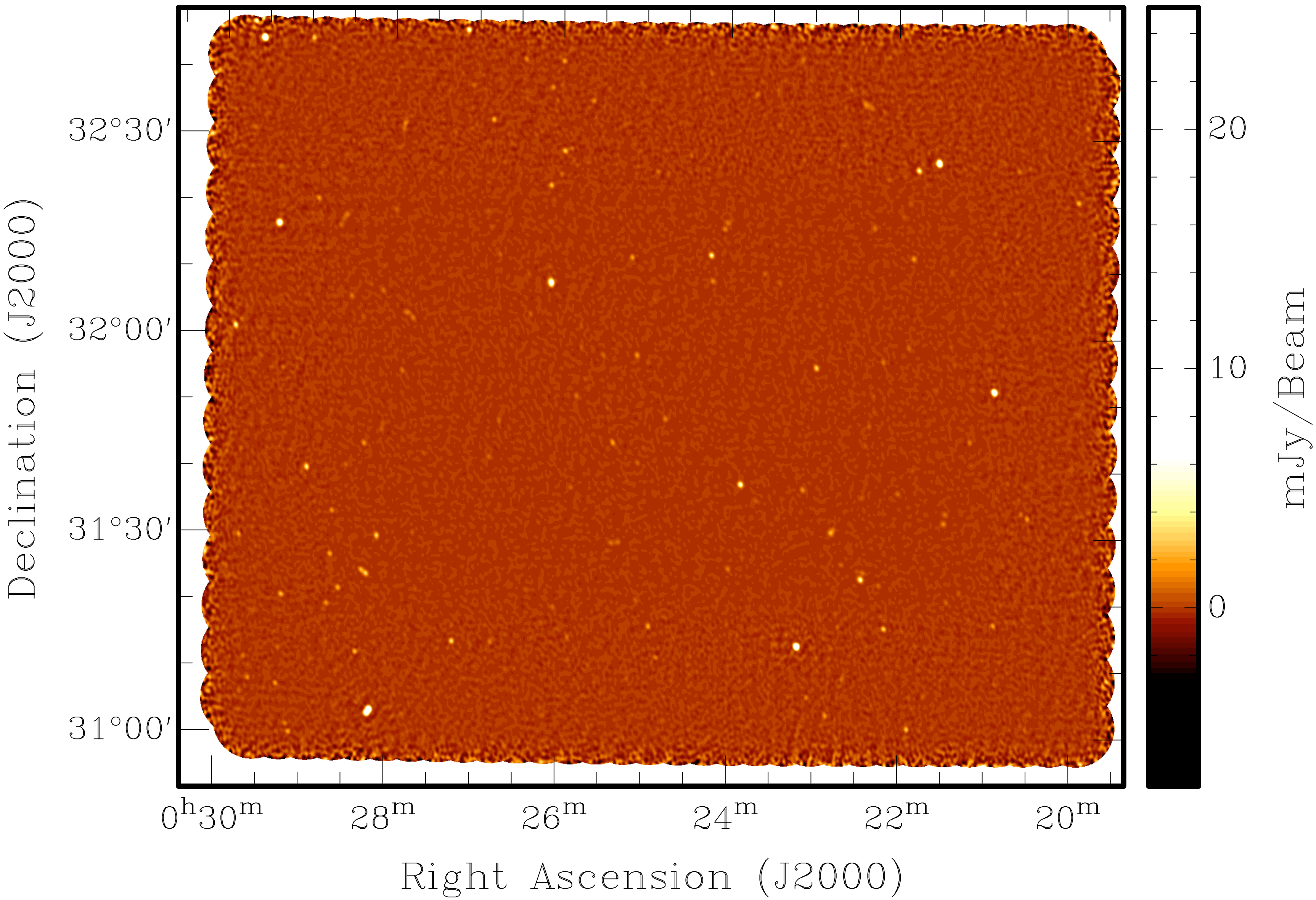
CLUSTER NUMBER COUNTS

- Measure $\frac{\mathrm{d}n(M,z)}{\mathrm{d}z}$ to constrain cosmology
- Probes volume-redshift relation
- Probes abundance evolution
- Cluster structure and evolution



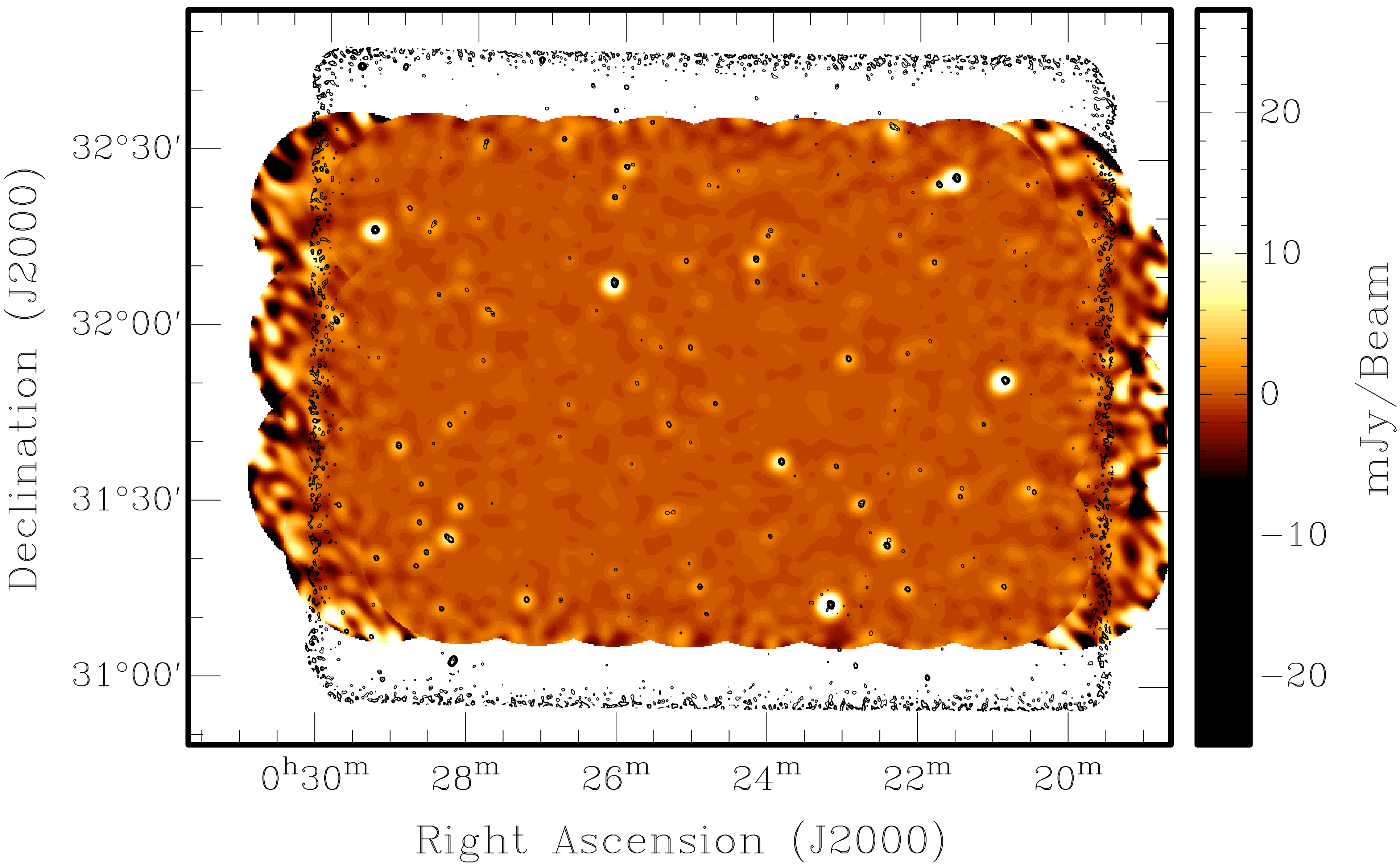
(Anna Scaife)

SURVEY FIELDS



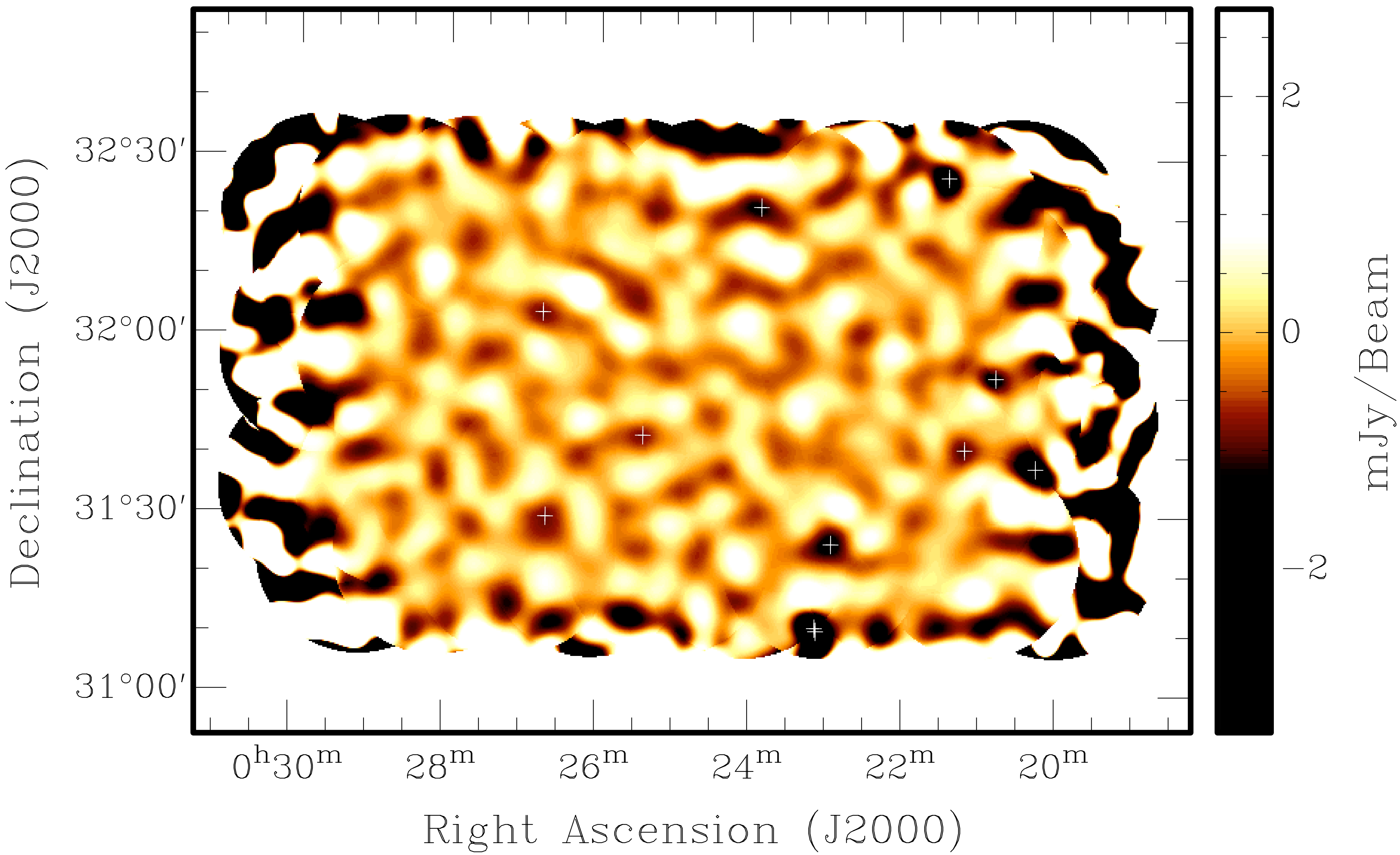
Large Array data on approx. 2 deg^2 survey field

SURVEY FIELDS



Small Array data (colour greyscale) with Large Array data superposed (contours)

SURVEY FIELDS

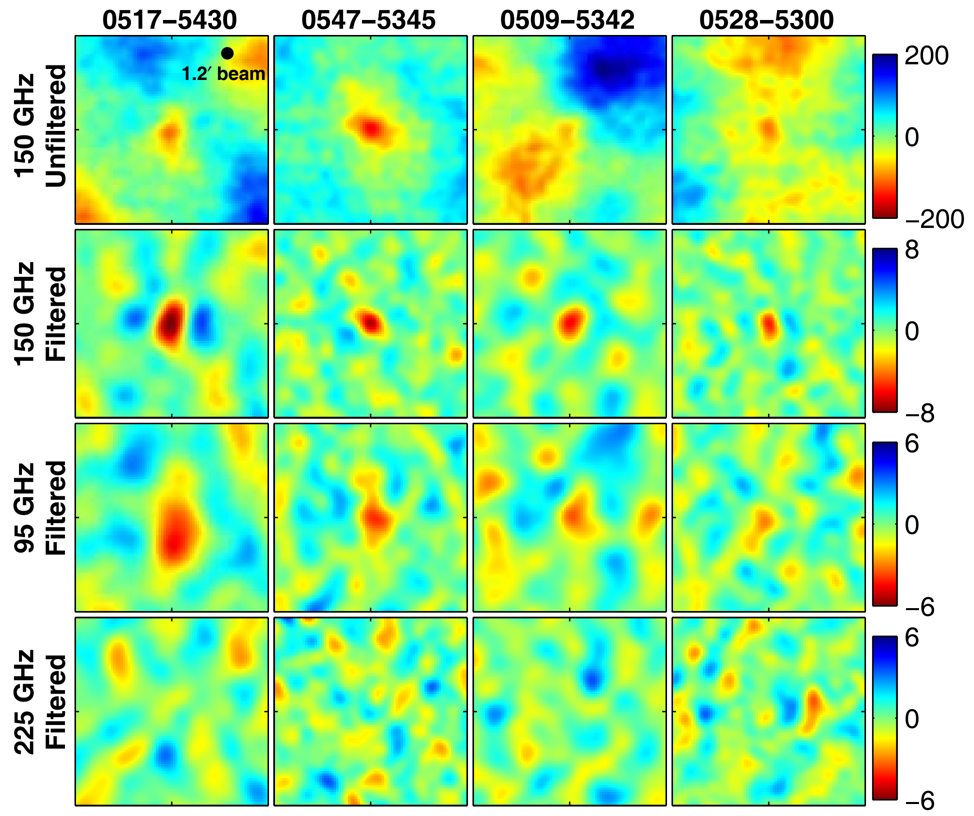


After source subtraction. About 4 decrements at $> 6\sigma$ at positions unlikely to be affected by source-subtraction effects

The South Pole Telescope

- South Pole Telescope (10m) has been carrying out first surveys
- These are at 150 and 220 GHz, covering two 100 deg^2 fields — still some problems with 90 GHz channel
- Telescope will only be used for a while for this, since then becomes a general purpose instrument operating at higher frequencies (extremely good surface)
- However, clear it has lots of sensitivity to detect 'blank field' clusters

THE SOUTH POLE TELESCOPE — LATEST

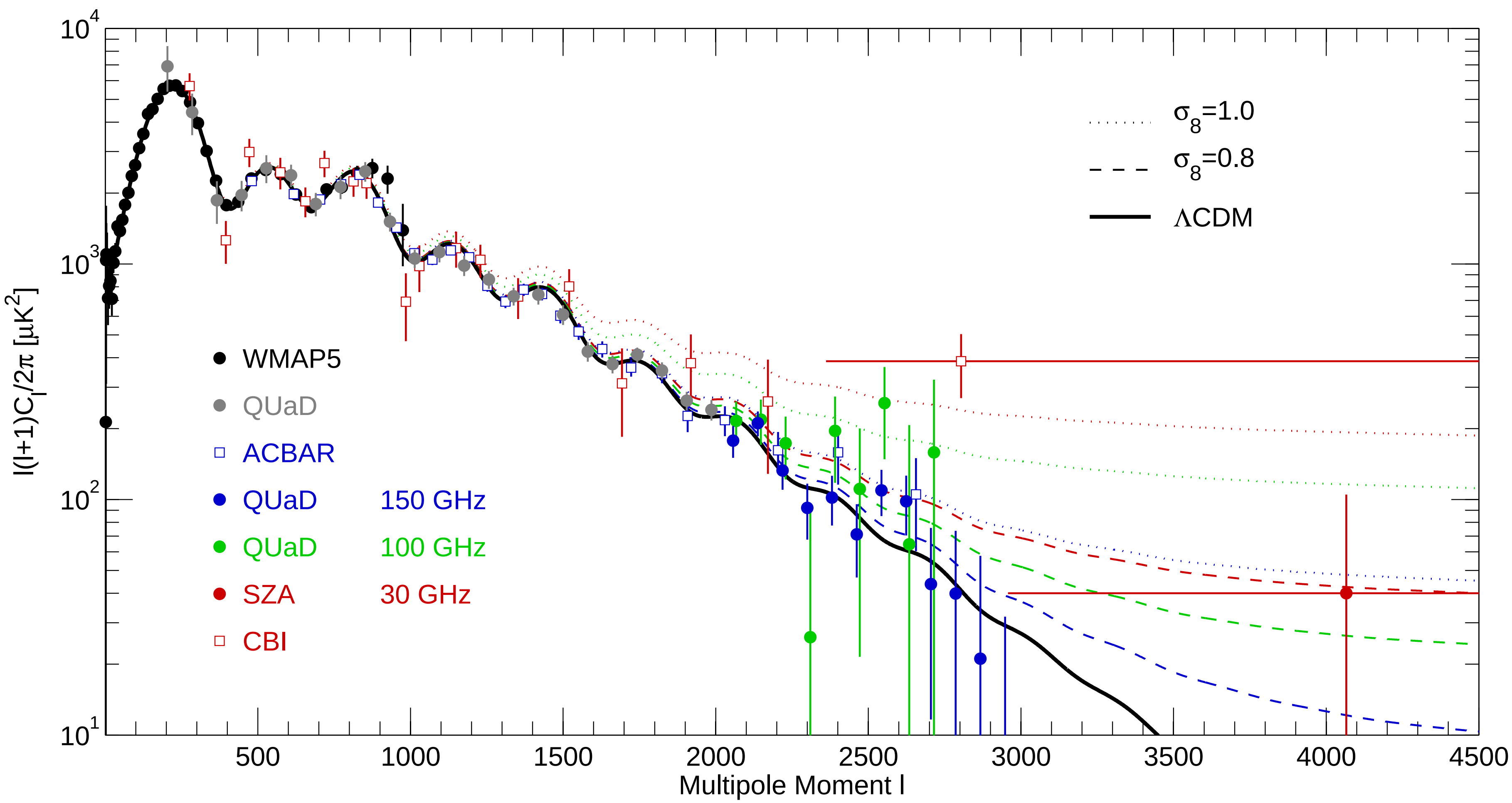


- 4 detections published so far (Staniszewski et al., astro-ph/0810.1578)
- Reports that may be ~ 100 more candidates by now
- SZA does not seem to have found any as yet
- Currently believe SPT mass cutoff will be about $6 \times 10^{14} M_\odot$ — AMI much smaller fields, but could go to $\sim 2 \times 10^{14} M_\odot$

Damping tail and CBI excess

- Photon diffusion suppresses photon density fluctuations below $\sim 3\,\mathrm{Mpc}$ at last scattering; $80\,\mathrm{Mpc}$ width of last scattering surface further washes out projection to ΔT
- Predicted exponential decline seen by CBI (30 GHz) and ACBAR (150 GHz) but ...
  - CBI and BIMA see excess emission at $l > 2000$: interpreted as SZ gives $\sigma_8 \approx 1.0$

DAMPING TAIL AND CBI EXCESS — LATEST QUAD RESULTS



Taken from Friedman et al. (2009) (astro-ph/0901.4334).

QUAD now disagrees with CBI

Consistent with $\sigma_8 = 0.8$ rather than 1

Is CBI estimated source correction underestimated?