CMB Anisotropies and Polarisation: Status Report and Future Perspectives

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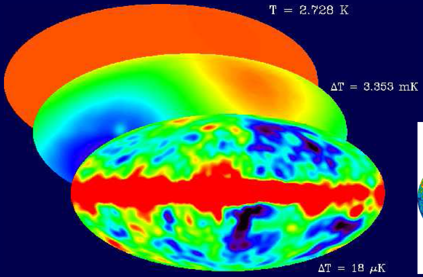
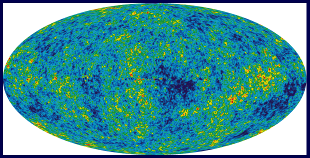
Overview

- Will give a brief introduction to current status of CMB observations and what we hope to learn from them
- Then discuss some current and near future CMB experiments and prospects, particularly for polarisation (also deal briefly with a couple of experiments for secondary anisotropies)
- Will also have some things to say on the theoretical front, e.g. about possible large scale anomalies, and current interest in Bianchi models
- Acknowledgements: would like to thank Anthony Challinor for help with some of the introductory slides

The cosmic microwave background

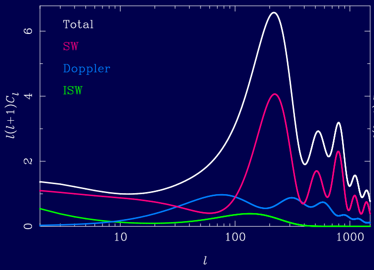
- Thermal relic of hot big bang with almost perfect blackbody spectrum (COBE-FIRAS)
  - Temperature $2.726\,\mathrm{K} \Rightarrow$ CMB photon number density $4 \times 10^{8}\,\mathrm{m}^{-3}$
  - $\sim$ 90% of CMB photons last interacted with matter at recombination ($z \sim 1000$); remaining suffered further Thomson scattering once Universe reionized around $z \sim 11 - 12$ (WMAP3)
- Fluctuations in photon phase space density and gravitational potential give rise to small temperature anisotropies ($\sim 10^{-5}$)

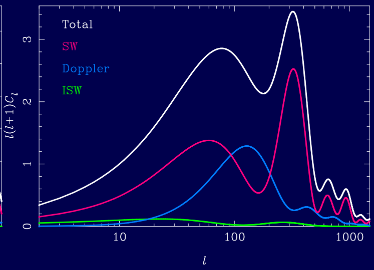




Adiabatic and isocurvature modes

- Adiabatic modes (e.g. single-field inflation) perturb number densities of all species in same way
  - Couple to cos oscillation in kr_s where $r_s =$ sound horizon distance $\Rightarrow$ peaks in direct temperature + gravitational effects at $kr_s = n\pi$
- Isocurvature modes (e.g. multi-field inflation, axion etc.) perturb relative number densities so that curvature *initially* vanishes
  - Sub-horizon behaviour $\approx$ sin oscillation $\Rightarrow$ peaks at $kr_s = \pi/2 + n\pi$





Gravity waves and CMB temperature anisotropies

- Gravity waves are transverse, trace-free perturbation to FRW metric:

$$ds^2 = dt^2 - a^2(\delta_{ij} + h_{ij})dx^i dx^j$$

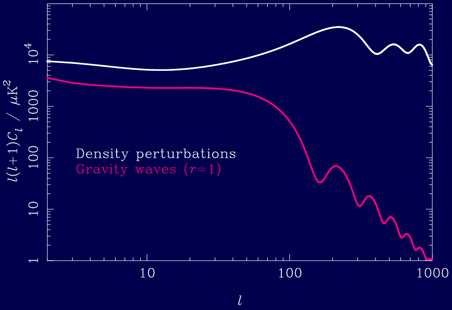
- Integrated effect of locally-anisotropic expansion (shear) of space generates temperature anisotropies after recombination:

$$\Delta T(\hat{n})/T = -\frac{1}{2}\int e^{-\tau}\dot{h}_{ij}\hat{n}^i\hat{n}^j\, dt$$

- Gravity waves damp inside horizon $\Rightarrow$ only affects large-angle ΔT
- Cosmic variance

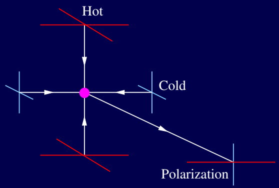
$$\Delta C_l = \sqrt{\frac{2}{2l+1}}C_l$$

limits $\Delta r = 0.07$

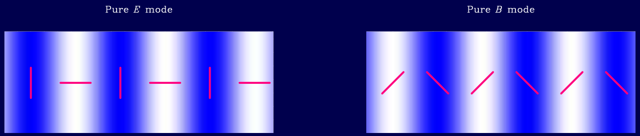


CMB polarization

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

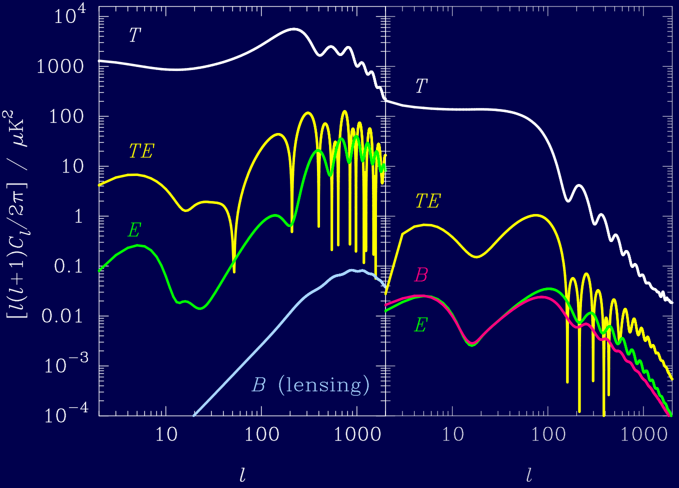


- Only three power spectra if parity respected in mean: C_l^E, C_l^B and C_l^{TE}



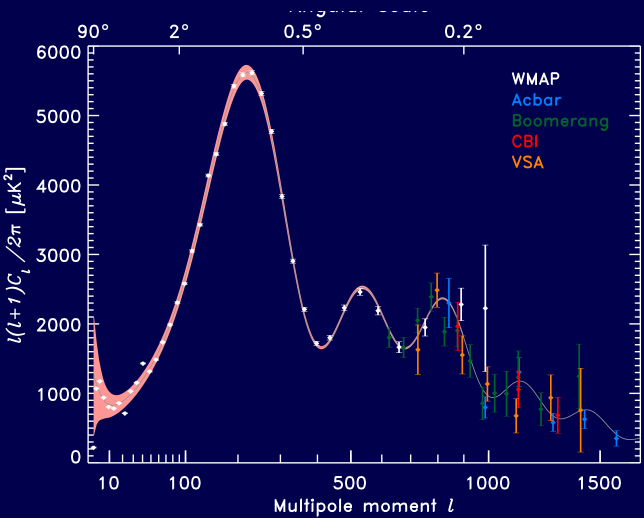
- Linear scalar perturbations produce only E-mode polarization
- Mainly traces baryon velocity at recombination $\Rightarrow$ peaks at troughs of ΔT
- Gravity waves produce both E- and B-mode polarization (with roughly equal power)

Scalar and tensor power spectra ($r = 0.36$)



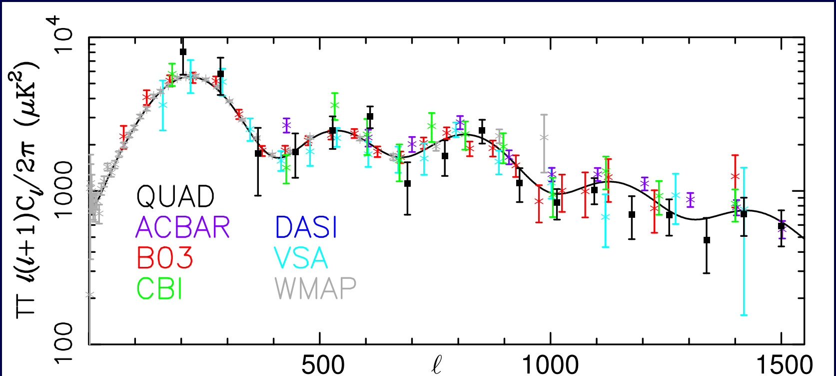
- *B*-mode polarization circumvents cosmic variance of dominant scalar component present in *T* and *E*

Observations 2006 — ΔT



(Hinshaw et al. 2006)

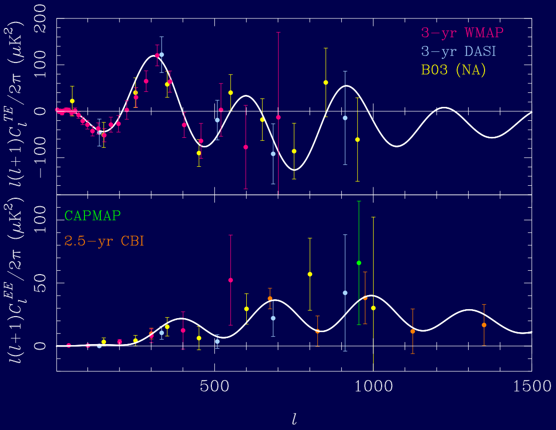
Observations 2007 — ΔT



Compilation from QUAD first season results paper:
Ade et al. astro-ph/0705.2359
ACBAR points are also new since last year:
Kuo et al. astro-ph/0611198

Observations up to 2006 — *E*-mode polarization

- Super-horizon correlations at last scattering surface from *TE* correlation ⇒ apparently acausal fluctuations
- Sign of correlation consistent with adiabatic i.c.
- Peak positions in *TT*, *TE* and *EE* all consistent, and with adiabatic i.c.



Future CMB Polarisation Experiments

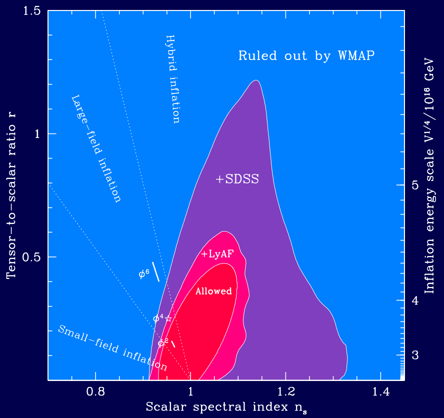
Name	Type	Detectors	ℓ range	r target	Start Date
BICEP	ground	bolometer	$50 < \ell < 300$	0.1	2007
QUIET	ground	MMIC	$\ell < 1000$	?	2008-2010
CLOVER	ground	bolometer	$20 < \ell < 600$	0.01	2008-2009
EBEX	balloon	bolometer	$20 < \ell < 1000$	0.03	2009
SPIDER	balloon	bolometer	$\ell < 100$	0.025	2009-2010
BPOL	space	bolometer	$\ell < 200$	$1\text{–}5 \times 10^{-3}$	2016?

Discuss here

- CLOVER — Cardiff, Cambridge, Oxford, Manchester B-mode bolometric experiment
- QUAD — Stanford, Chicago, Cardiff, Edinburgh (already has results)
- QUIET — USA B-mode HEMT experiment
- SPIDER — USA + Canada + UK B-mode experiment
- BPOL — proposed to ESA as an M-class mission
- But first, what are some of the science drivers as regards inflation?
- We know a key feature is that B-mode polarisation is a ‘smoking gun’ for tensor perturbations — what are specifics?

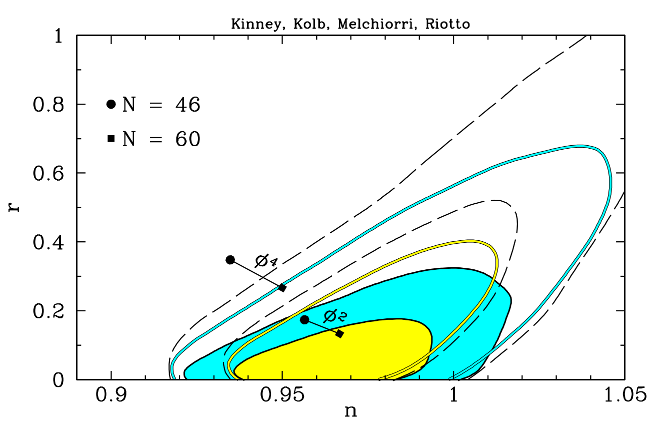
Inflation: r-n_s constraints (pre WMAP3 slide)

- Energy scale totally uncertain: $V^{1/4} < 2.6 \times 10^{16}$ GeV but could be as low as electroweak scale (100 GeV) but theoretical prior not uniform!
- No evidence for dynamics of inflation (data consistent with low-energy, flat potential giving $r \approx 0$ and $n_s \approx 1$)
- Some models already ruled out (e.g. ϕ^6 and ϕ^4)



(Tegmark et al. 2003; Seljak et al. 2004)

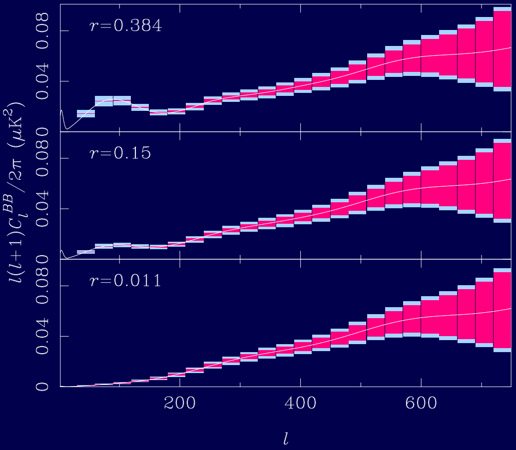
WMAP3 constraints on form of potential



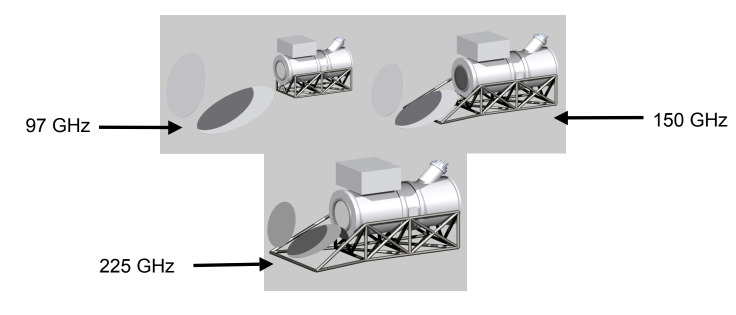
- Thus good evidence now starting to build up against ϕ^4 type theory or plain H-Z, and for ϕ^2
- This is in principle good news for B-mode detections! (typical $r \sim 0.15$ for ϕ^2)

Summary of CLOVER science goals

- Characterise *B*-mode polarization on scales $20 < l < 600$
  - Sufficient thermal sensitivity (magenta) to be limited by sample variance of lensing signal for $l < 200$
- Detect gravity waves if $r > 0.01$ (3σ; c.f. current 95% limit of ~ 0.36)
  - Hence measure energy scale of inflation if $> 1.0 \times 10^{16}$ GeV
- Place tight constraints on dynamics of inflation

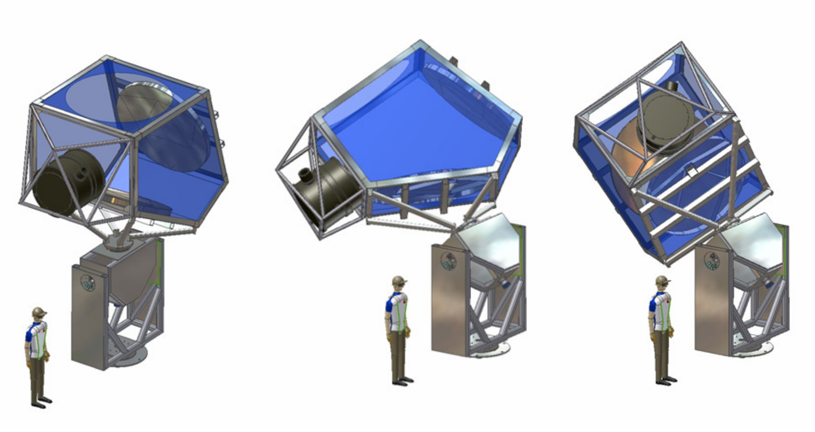


CLOVER EXPERIMENT



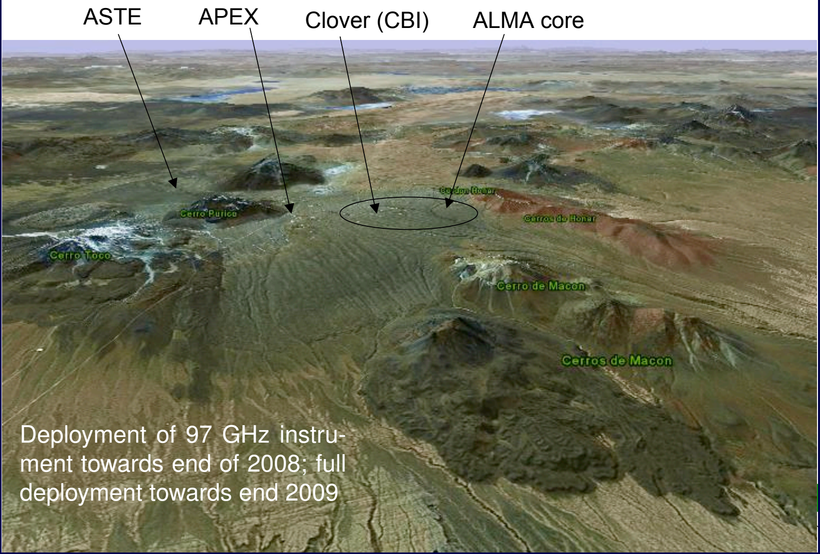
- Collaboration between
  - Cambridge — detectors, software
  - Cardiff — telescope, mount and high frequency instrument
  - Oxford — optics
  - Manchester — 97 GHz instrument
- Plan is now for 2 telescopes: 97 GHz (as before) and 150 + 225 GHz combined — all frequencies 8-arcmin resolution
- Will now have approx. 100 pixels at each frequency, with Transition Edge Sensor (TES) detectors at $\sim 100\,\mathrm{mK}$

CLOVER Mount



- Three views of the 97 GHz mount showing its ability to rotate around three axes
- The optical assembly, containing the 1.8 m mirrors, will be lined with an unpolarised absorber to reduce the effects of sidelobes

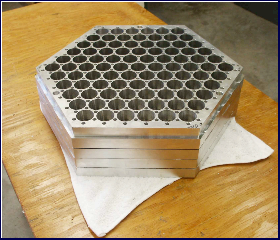
CLOVER Site



Deployment of 97 GHz instrument towards end of 2008; full deployment towards end 2009

QUIET

- HEMT receiver CMB polarization experiment
- Collaboration between Chicago, JPL, Miami, Princeton Caltech, Columbia, Stanford and Oxford
- Bruce Winstein (Chicago) PI
- Pathfinders: 100-element W-band (90 GHz) array on 1m telescope
- 37-element Q-band (40 GHz) array
- Two optical platforms: Novel 1m-scale telescope on CBI in Chile for large angular scales

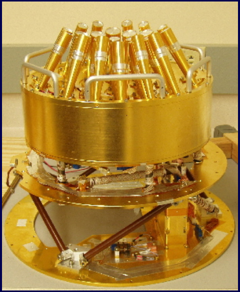


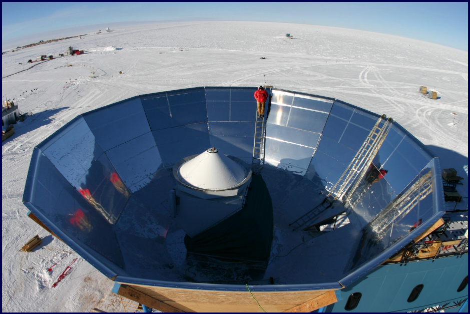
QUIET

- Previous proposal was that Lucent 7m telescope, currently in New Jersey and recently used for CAPMAP, will be moved to Chile for small angular scales (approx 4 arcmin) — not clear if this is now preferred route
- For ultimate instrument, two frequencies at each angular scale: 1000-element W-band arrays; 300-element Q-band arrays
- Operate for 3+ years
- Funding for first stages now agreed

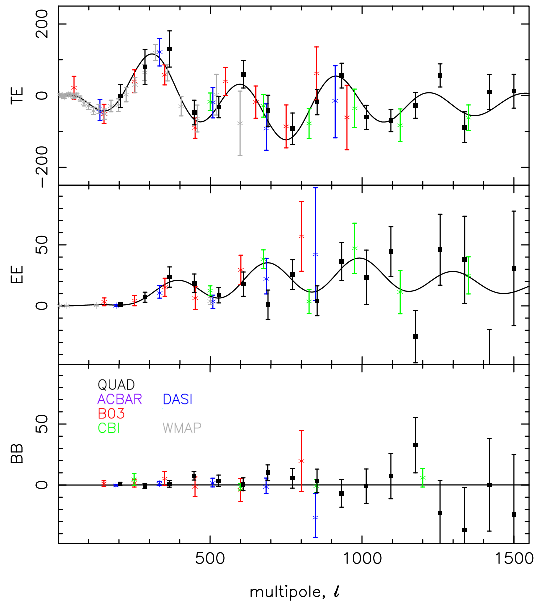
QUAD

- 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
- Going after E-mode anisotropy at 4 scale
- Third (final) season underway
- First season analysis came out recently

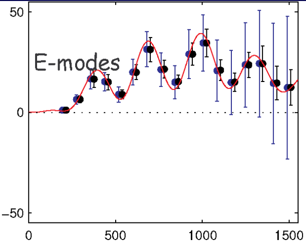




QUAD First Season Polarisation Results



Significant improvement expected re second season results

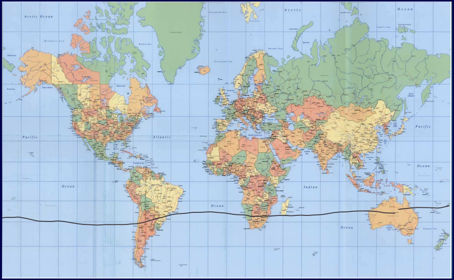


Above shows simulations of second season E-mode data, but with actual errors (in comparison to 1st season — offset for clarity)

SPIDER

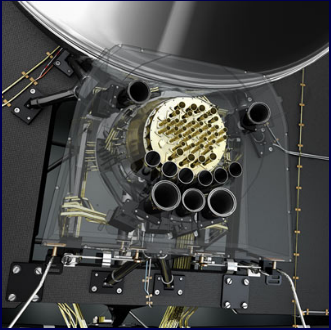
- 7 telescope system on spinning gondala
- Targetting relatively large angular scales $\ell < 100$

ν(GHz)	90	90	150	150	150	220	270
NET($\mu K\sqrt{s}$)	120	120	100	100	100	230	300
FWHM	70	61	53	53	53	36	28
N^{det}	256	256	512	512	512	512	512



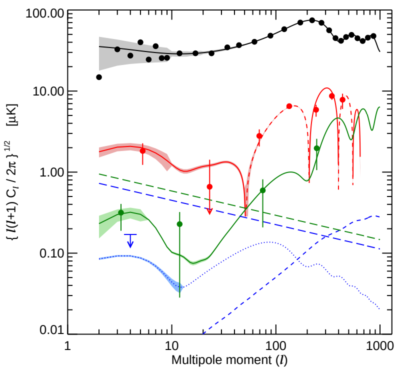
- Collaboration including Caltech, Cardiff, CITA, Imperial, UBC, U. Toronto
- Launch from Alice Springs, Australia
- Mid-latitude flight (-23°) taking about 25 days
- Spins in azimuth at night, anti-sun during day
- First LDB flight Autumn 2010

Planck and WMAP

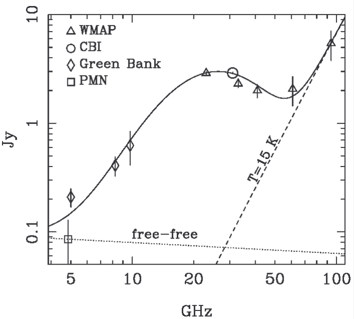


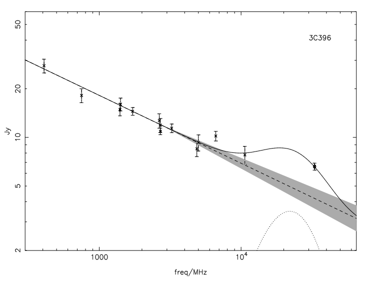
- Planck HFI and LFI instruments have now been integrated
- Launch August 2008

- WMAP showed how hard polarisation work will be
- Will need to dig deep into the foregrounds
- Following is from Page et al (2006)
- Dashed lines are the modelled foreground levels - dominate even EE



Spinning Dust





- Additional component seen in the 10-60 GHz range
- Strongly correlated with FIR maps
- Not conventional free-free (e.g. lack of Hα)
- Above, frequency spectrum of the Lynds Dark Cloud LDN1622

- Recent points are from the CBI (Casassus et al., astro-ph/0511283, Astrophys.J. 639 (2006) 951-964)
- On right, recent measurements with the Very Small Array (Cambridge/Tenerife/Manchester) of the dusty supernova remnant 3C396 (Scaife et al., astro-ph/0702473)

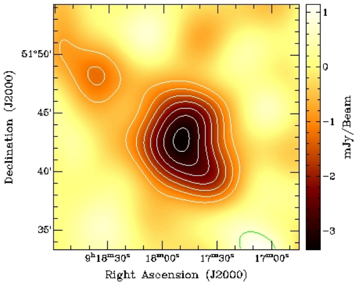
Secondary Anisotropies —
The Sunyaev–Zeldovich Effect
Arcminute MicroKelvin Imager (Cambridge)

AMI

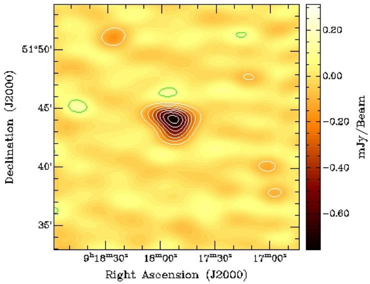
- The AMI Small Array
- Ten 3.7 m dishes
- Has been working fully for $>$ 1 year

- 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
- Will be complete and commissioned in about 1 month

SZ Effect in A773



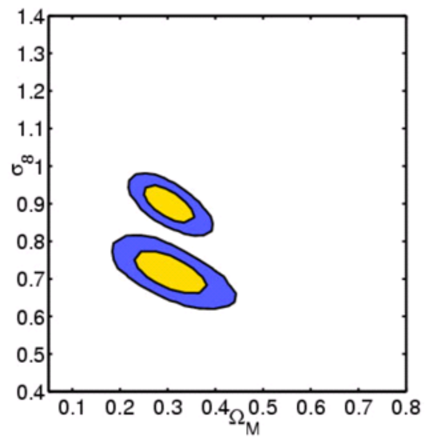
6 hour AMI Small Array image



460 hour RT image

- Outer regions of gas now being detected
- Telescope sensitivity matches theoretical prediction
- 10^3 improvement in survey speed over old Ryle Telescope
- New: Similar speed improvement now demonstrated for new Large Array source-mapping versus old RT

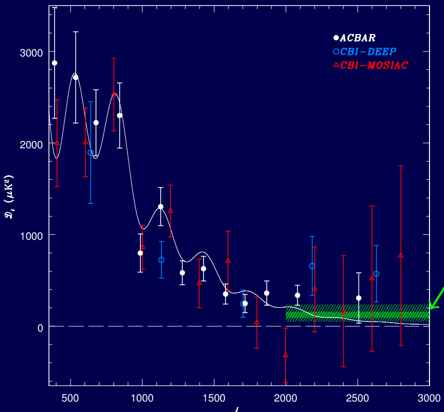
Predicted AMI Cosmological Constraints



- 1 year, 100 square degrees AMI survey
- We can start this as soon as Large Array is fully working (to detect and subtract the sources) — approx 1 month
- How many clusters will we find? Also what is the integrated SZ contribution to the primordial CMB tail?

Damping tail and CBI excess

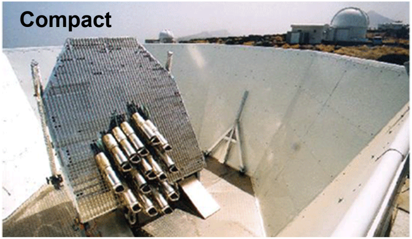
- Photon diffusion suppresses photon density fluctuations below $\sim 3\,\mathrm{Mpc}$ at last scattering; $80\,\mathrm{Mpc}$ width of last scattering surface further washes out projection to ΔT
- Predicted exponential decline seen by CBI (30 GHz) and ACBAR (150 GHz) but ...
  - CBI and BIMA see excess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

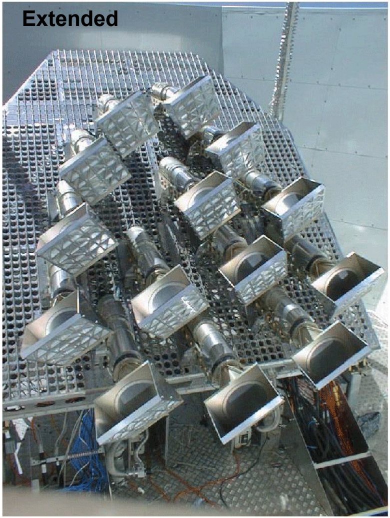


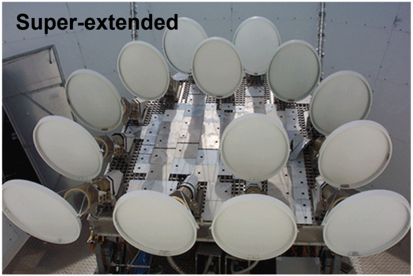
SZ expected at 150 GHz given CBI result (Kuo et al 2004). (About 1.2σ detection of this in latest ACBAR work (Kuo et al 2006))

The Very Small Array (VSA) – Main Array

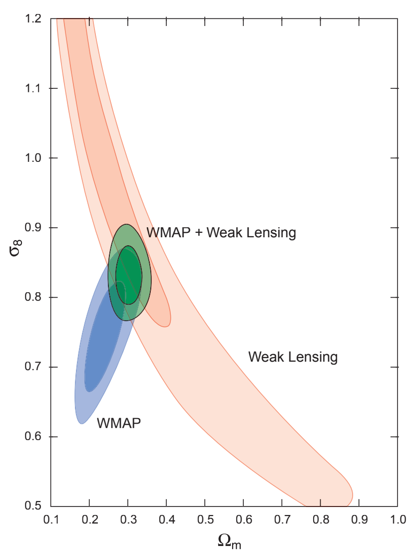
- 14-antennas interferometer → 91 baselines







WMAP3 versus weak lensing



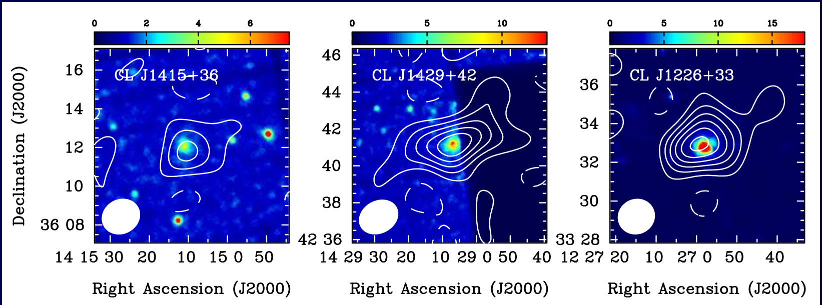
- A $\sigma_8 \approx 1.0$ would, however, now be a real problem
- Ok (in general) with weak lensing, but not now with WMAP3
- Combination of losing some optical depth and lower $\Omega_{\rm cdm}$ means σ_8 now significantly lower
- $\sigma_8 = 0.92 \pm 0.1$ (WMAP1) now goes to $\sigma_8 = 0.76 \pm 0.05$ (WMAP3)
- This seems to be a real tension between models
- Other (current) experiment able to address blank field SZ directly is the SZA

The SZA

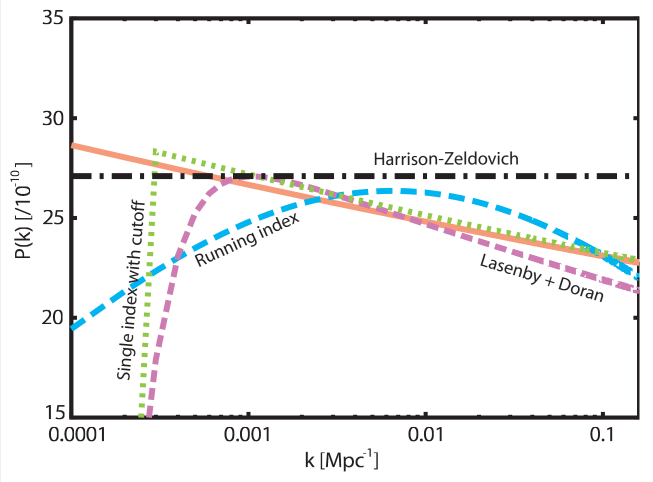
- Chicago, Columbia, Caltech/JPL collaboration
- P.I. John Carlstron
- Eight 3.5 m diameter telescopes
- Like AMI, close-packed configuration for high surface brightness (1.2 diameter spacings)
- 30 GHz Receivers (cluster survey) (cf. AMI 15Ghz)

The SZA (contd.)

- Has now begun on SZ survey
- Possible low σ_8 a worry!
- First results paper is on measurements in 3 high redshift clusters: ClJ1415.1+3612 ($z = 1.03$) ClJ1429.0+4241 ($z = 0.92$) ClJ1226.9+3332 ($z = 0.89$) in astro-ph/0610115 Muchovej et al. Astrophys.J. 663, (2007), 708
- SZA to be integrated with OVRO and BIMA telescopes (CARMA) will allow high resolution cluster imaging



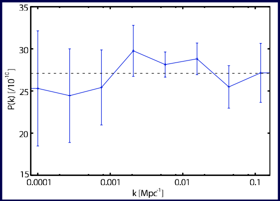
Evidence for different primordial spectra



- Figure shows some of the different type of spectra that were considered
- 'Lasenby + Doran' is for a particular model leading to a slightly closed universe (Described in Phys.Rev.D **71, (2005) 063502**.)

Evidence for different primordial spectra (contd.)

Also considered a free-form fit in 8 bins for the power spectrum, plus a 'broken spectrum' with two scale-invariant sections joined by a sloping line

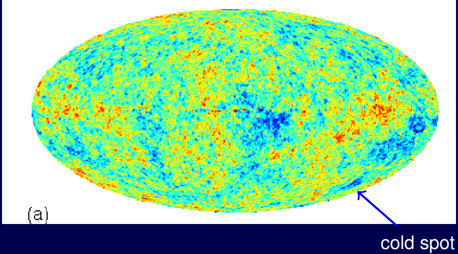


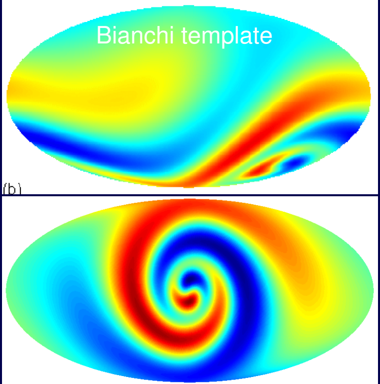
- Some sample evidence results were as in following:

Table: Differences of log evidences (for primordial parameters) for all models with respect to single index model within a WMAP3 concordance cosmology: $\Omega_0 = 1.039, \Omega_b h^2 = 0.022, h = 0.57, \Omega_{cdm} h^2 = 0.110$, as compared to the Lasenby & Doran model (treated as a template)

Model	$\ln E_i - \ln E_0$ WMAP1	$\ln E_i - \ln E_0$ WMAP3
Constant n	0.0 $\pm$ 0.5	0.0 $\pm$ 0.3
H-Z	-4.4 $\pm$ 0.5	-17.5 $\pm$ 0.9
Running	-0.8 $\pm$ 0.6	+1.4 $\pm$ 0.7
Cutoff	0.4 $\pm$ 0.5	0.6 $\pm$ 0.3
Broken	-2.7 $\pm$ 0.6	-0.3 $\pm$ 2.2
Binned	-6.1$\pm$ 0.6	-16.9$\pm$ 0.9
Lasenby & Doran	4.1 $\pm$ 0.5	5.2 $\pm$ 0.6

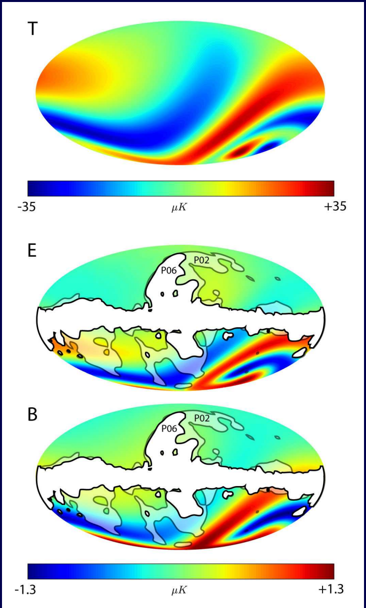
A Bianchi Model Universe?



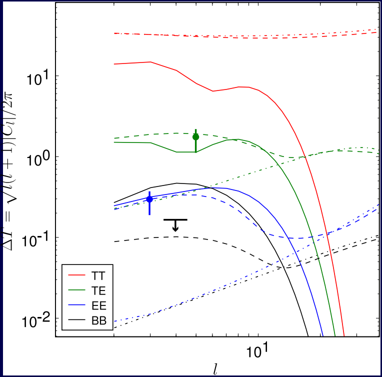


- Several authors have commented on significant North/South asymmetry in the WMAP data, plus strange alignment between low multipoles
- Jaffe et al. (astro-ph/0503213) fitted a Bianchi VIIh template to WMAP sky
- Found a best fit with $\Omega_0 = 0.5$
- Coldest part of template corresponds with a non-Gaussian spot found in Vielva et al. (astro-ph/0310273) and drawn attention to in Cruz et al. (astro-ph/0405341)
- But $\Omega_0 = 0.5$ in conflict with most other astrophysical indicators
- Even including Λ can't get a valid region in parameter space

Bianchi Polarisation



- Polarisation in Bianchi VII_h models recently considered by Pontzen & Challinor (astro-ph/0706.2075)
- Surprise is that predicted B-mode already rules them out!

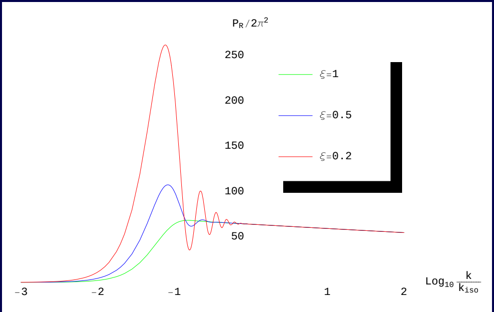


Effects of anisotropy during inflation?

- Preceding works have all been concerned with what we can call late time Bianchi models
- This is where our current universe is taken to have shear and rotation, and the effects are all laid down during recombination and during propagation to us from then
- An alternative, which has recently begin to be explored, is the effects of anisotropy during inflation itself
- Could some of the large scale anomalies in the CMB be laid down during inflation, during isotropisation from some earlier phase?
- Recent works on this from Gumrukcuoglu, Contaldi & Peloso (astro-ph/0707.4179) and Periera, Pitrou & Uzan (astro-ph/0707.0736)

Effects of anisotropy during inflation? (contd.)

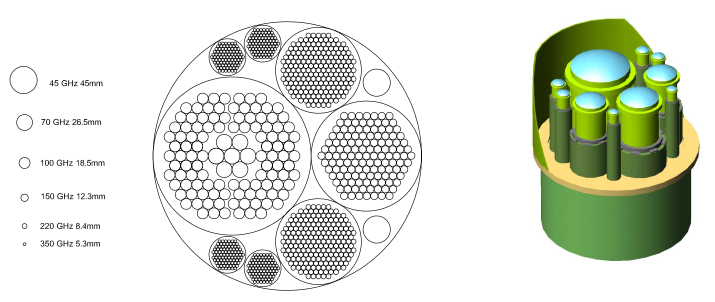
- E.g., in Gumrukcuoglu et al., they actually attempt to form the $P(k)$ spectrum that would be generated in an axisymmetric Bianchi I phase, with 60 e-folds of inflation in total
- They are able to demonstrate coupling between the low order modes (that would be independent in FRW)
- However, computations incomplete



- ξ above is the cosine of the angle between the k-mode and the direction of axisymmetry
- $P(k)$ becomes unbounded as $\xi \to 0$
- Both Gumrukcuoglu et al. and Periera et al. suggest that tensor mode will be crucial (non-standard effects)

BPOL

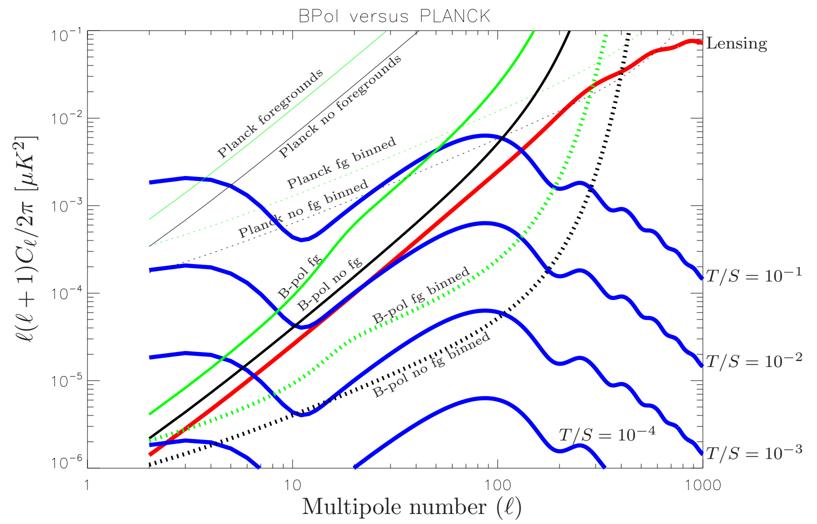
Proposal to ESA for a new M-class satellite mission



Concept is to go after relatively large angular scales, with high sensitivity and very good control of systematics

Freq. band (GHz)	45	70	100	143	217	353
$\Delta\nu$	30%	30%	30%	30%	30%	30%
ang. res.	15deg	68'	47'	47'	40'	59'
# horns	2	7	108	127	398	364
det. noise ($\mu K \cdot \sqrt{s}$)	57	33	53	53	61	119
Q & U sens. ($\mu K \cdot$ arcmin)	33	23	8	7	5	10
Tel. diam. (mm)	45	265	265	185	143	60

BPOL vs. Planck projected sensitivity



Time evolution of the CMB!

- This has been examined recently by Lange & Page (astro-ph/0706.3908)
- They find that small scale power grows
- But also large scale, due to ISW (and late-time domination by Λ)
- Lange & Moss propose an experiment to demonstrate expansion of universe by comparisons 1 century apart

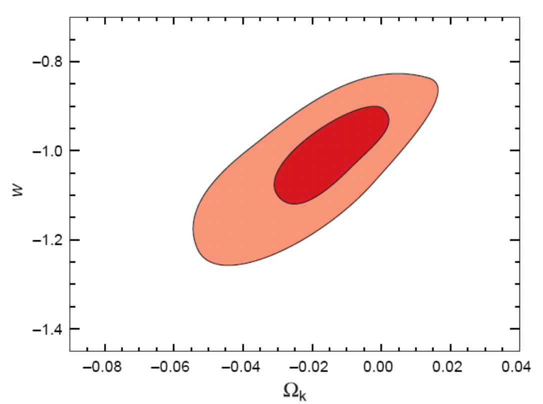
- Also, independently been looked at Zibin, Moss & Scott (astro-ph/0706.4482)
- C_ℓ animation is from latter
- Sensitivity of proposed experiment may be possible — variable foregrounds more likely to be real problem!

Conclusions as regards CMB and cosmology

- Basic predictions from CMB now impressively verified:
  - Large-scale Sachs-Wolfe effect and ISW
  - Acoustic peaks and diffusion damping
  - E-mode polarization, correlation with ΔT and reionization in TE
- In the near-future:
  - Better polarization; B-modes from lensing (and possibly gravity waves)
  - Physics of reionization, SZ surveys, defect searches from small-angle CMB
- Inflation holding up well and just starting to get evidence for dynamics during inflation
  - Character (adiabatic) and statistics (Gaussian) from high sensitivity CMB will be important future probes
  - Gravity waves from inflation should be detectable in B-mode polarization if $V^{1/4} > \text{few} \times 10^{15}\,\text{GeV}$ (lensing, foregrounds, systematics?)
- Unresolved issues on large angles (topology, foregrounds, systematics, chance?)

Nature of dark energy

- This, and slight closure of the universe, fit in fine with all current data, e.g. following from Spergel et al WMAP3



This is for full CMB data set+2dfGRS+SDSS+SN

- get $w = -1.062^{+0.128}_{-0.079}$, $\Omega_k = -0.024^{+0.016}_{-0.013}$