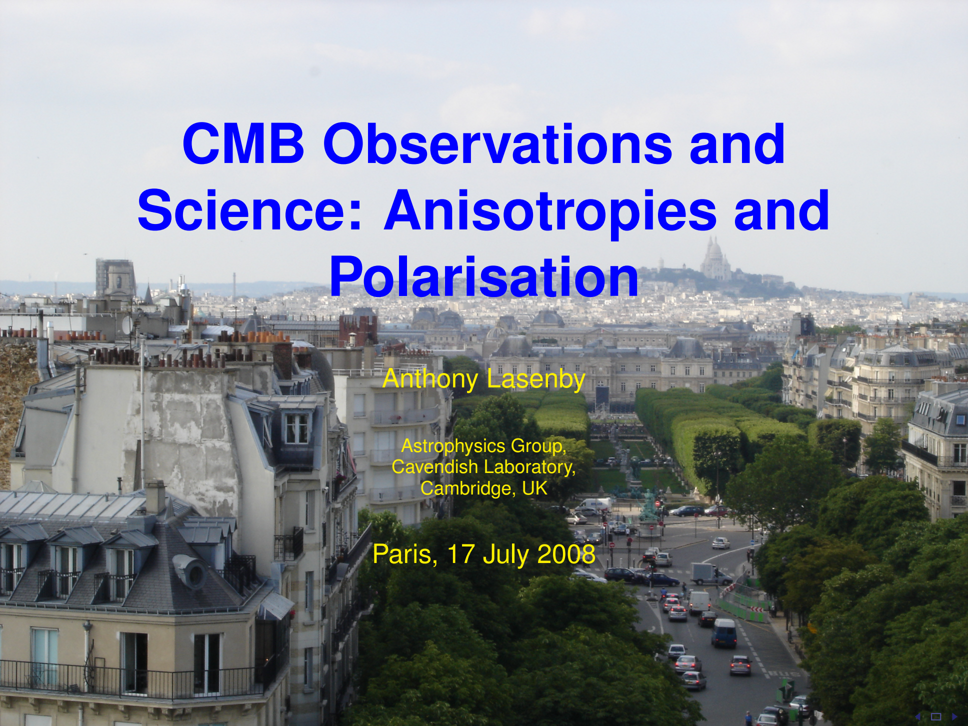


CMB Observations and Science: Anisotropies and Polarisation

Anthony Lasenby

Astrophysics Group,
Cavendish Laboratory,
Cambridge, UK

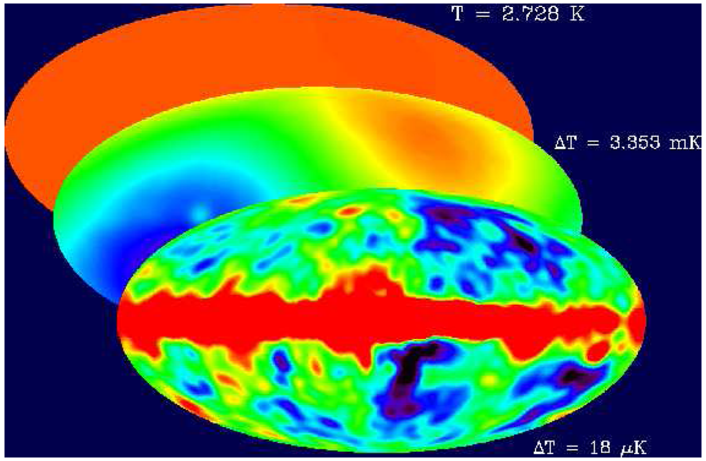
Paris, 17 July 2008

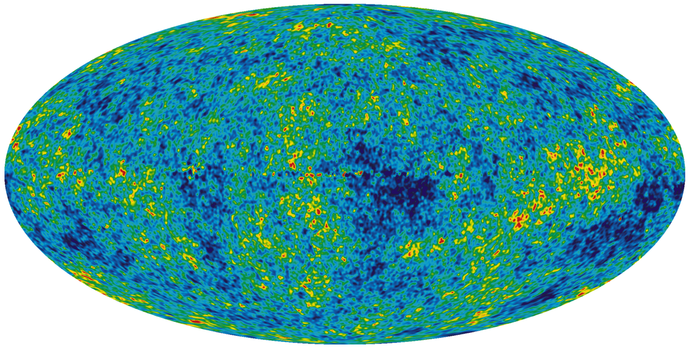
PLAN FOR TALK

- Will give an overview of current state of CMB observations and scientific implications, with particular emphasis on the contribution that CMB polarisation can make to fundamental physics
- This includes inflation, gravity waves, string cosmology, parity violation and universal rotation
- Also, will consider briefly some upcoming polarisation experiments
- And discuss some current secondary anisotropy experiments — just about to enter an interesting time as regards 'blank field' Sunyaev-Zeldovich experiments
- *Not* going to mention non-Gausianity — very interesting developments on this over past year — will leave to others here
- (Acknowledgements to Anthony Challinor for help with some of the slides.)

The cosmic microwave background

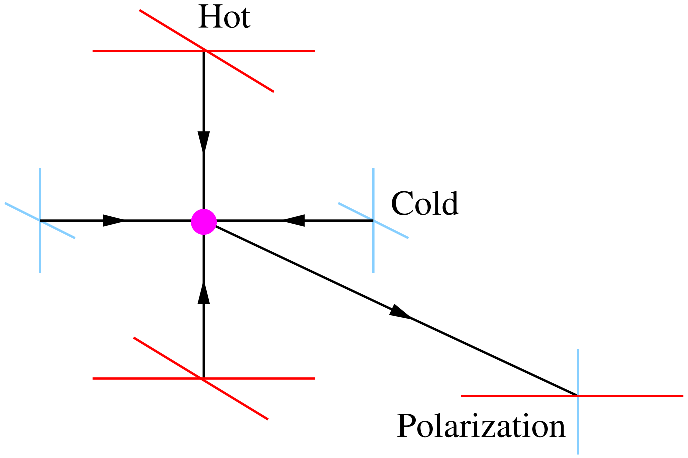
- Thermal relic of hot big bang with almost perfect blackbody spectrum (COBE-FIRAS)
  - Temperature $2.726\,\mathrm{K} \Rightarrow$ CMB photon number density $4 \times 10^8\,\mathrm{m}^{-3}$
  - $\sim$ 90% of CMB photons last interacted with matter at recombination ($z \sim 1000$); remaining suffered 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 ($\sim 10^{-5}$) — familiar with these — will concentrate on physics of polarisation anisotropies





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

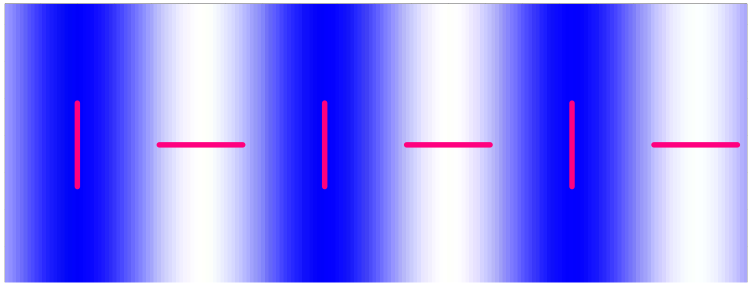


- Decomposition of polarization tensor into E and B modes:

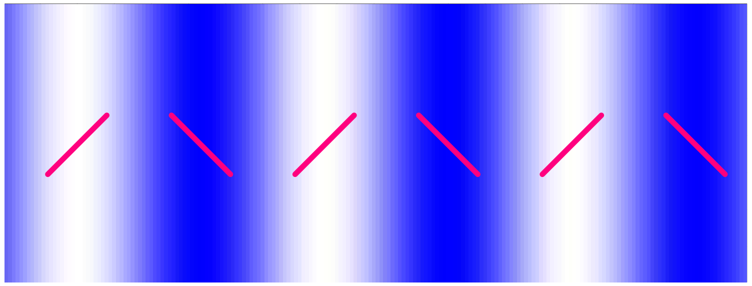
$$\mathcal{P}_{ab}(\hat{\boldsymbol{n}}) \equiv \frac{1}{2}\begin{pmatrix} Q & U \\ U & -Q \end{pmatrix} = \nabla_{\langle a}\nabla_{b\rangle}P_E + \epsilon^c{}_{(a}\nabla_{b)}\nabla_c P_B$$

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

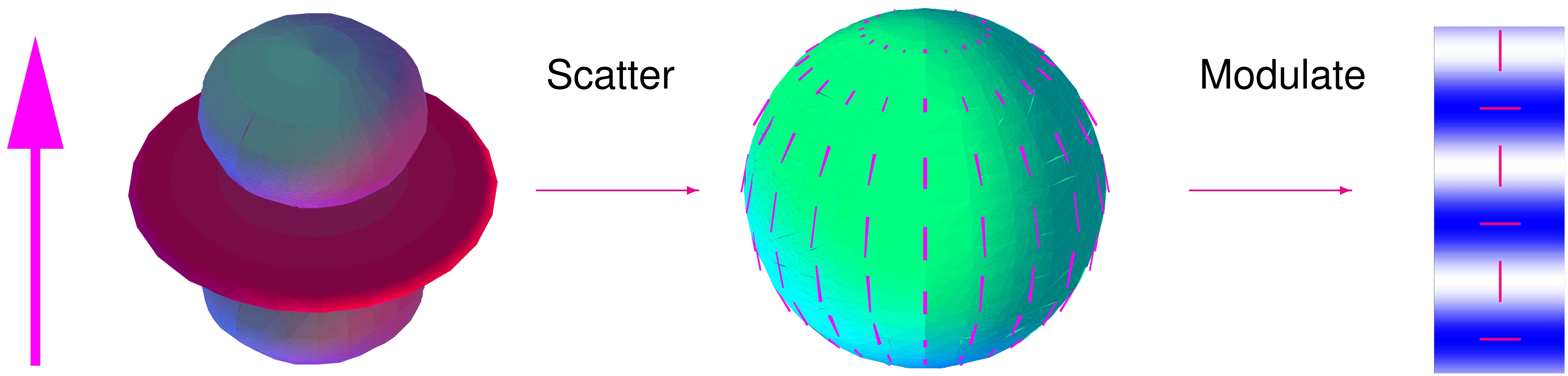
Pure E mode



Pure B mode



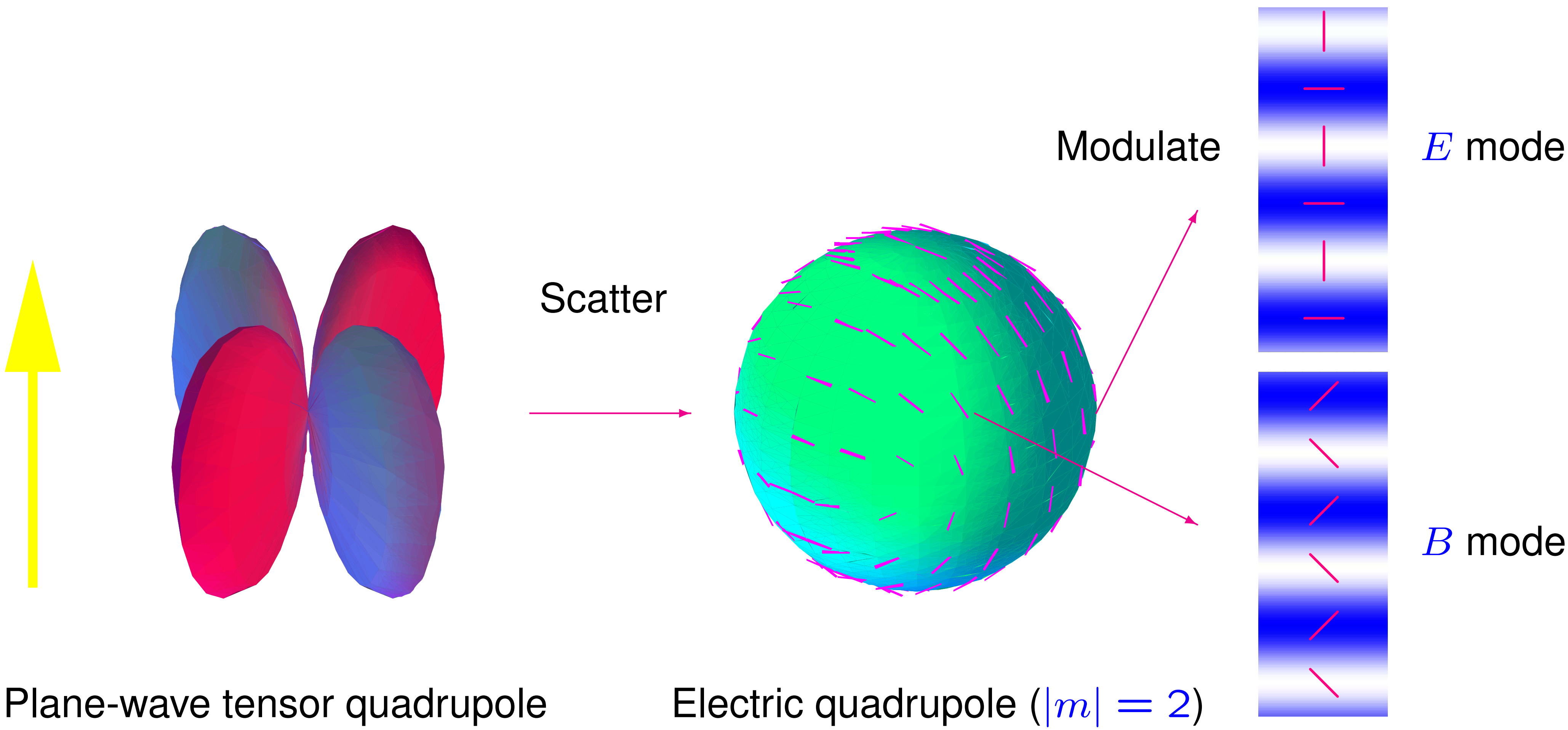
PHYSICS OF CMB POLARIZATION: SCALAR PERTURBATIONS



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

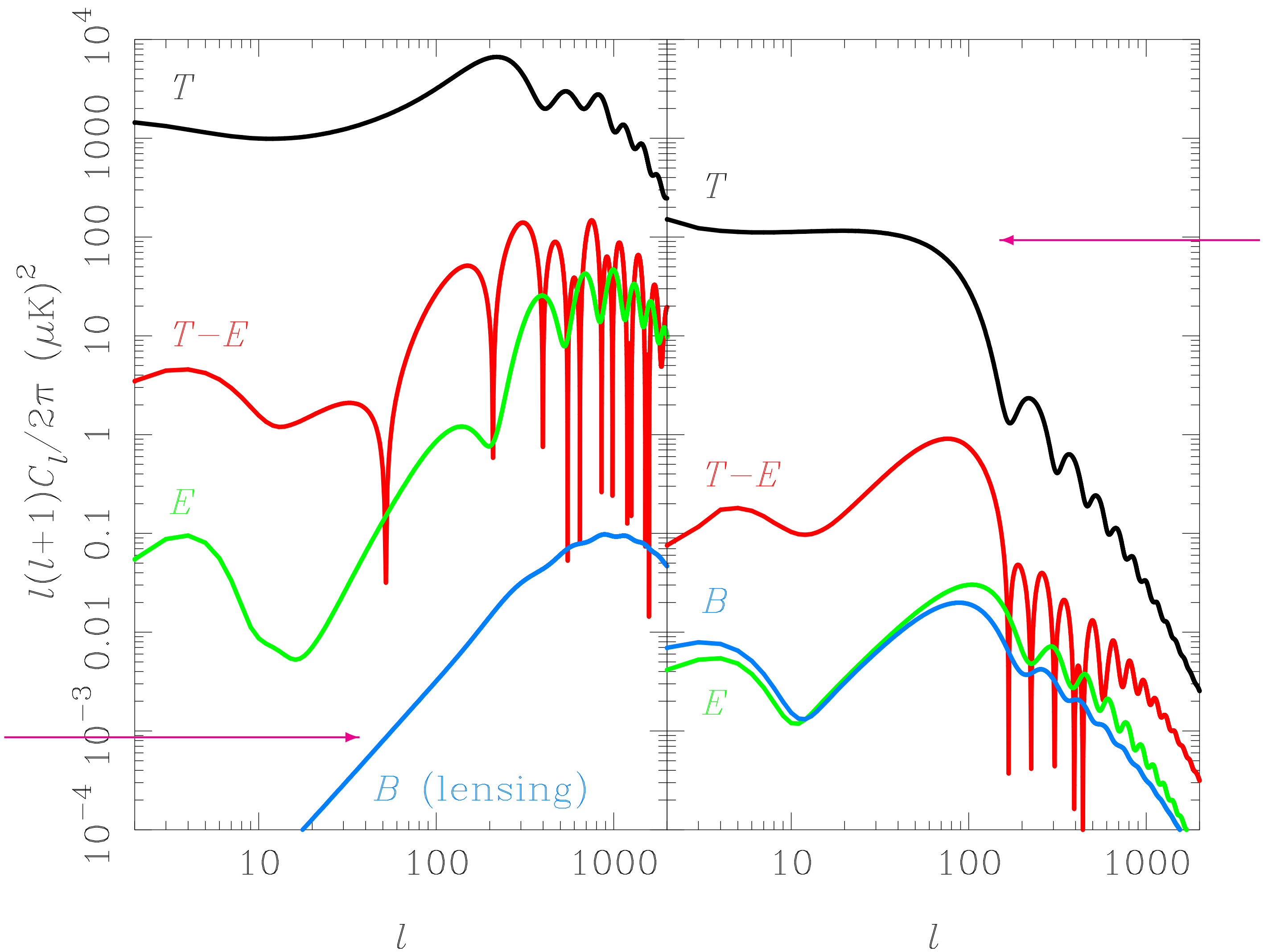
- Linear scalar perturbations produce only E-mode polarization (Kamionkowski et al. 1997; Seljak & Zaldarriaga 1997)
- Mainly traces baryon velocity at recombination $\Rightarrow$ peaks at troughs of ΔT

GRAVITY WAVES IN CMB POLARIZATION: PHYSICS



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

POWER SPECTRA



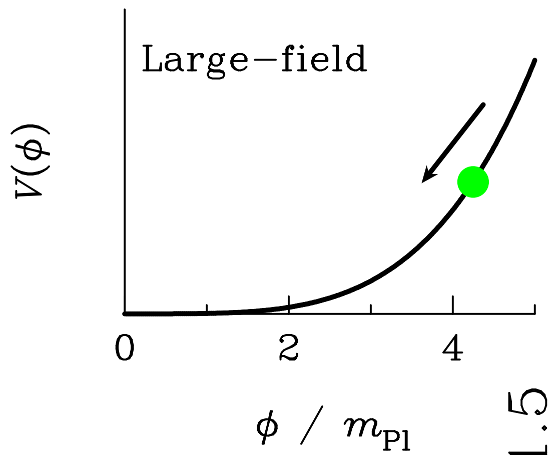
Effects only on large scales since gravity waves damp inside horizon

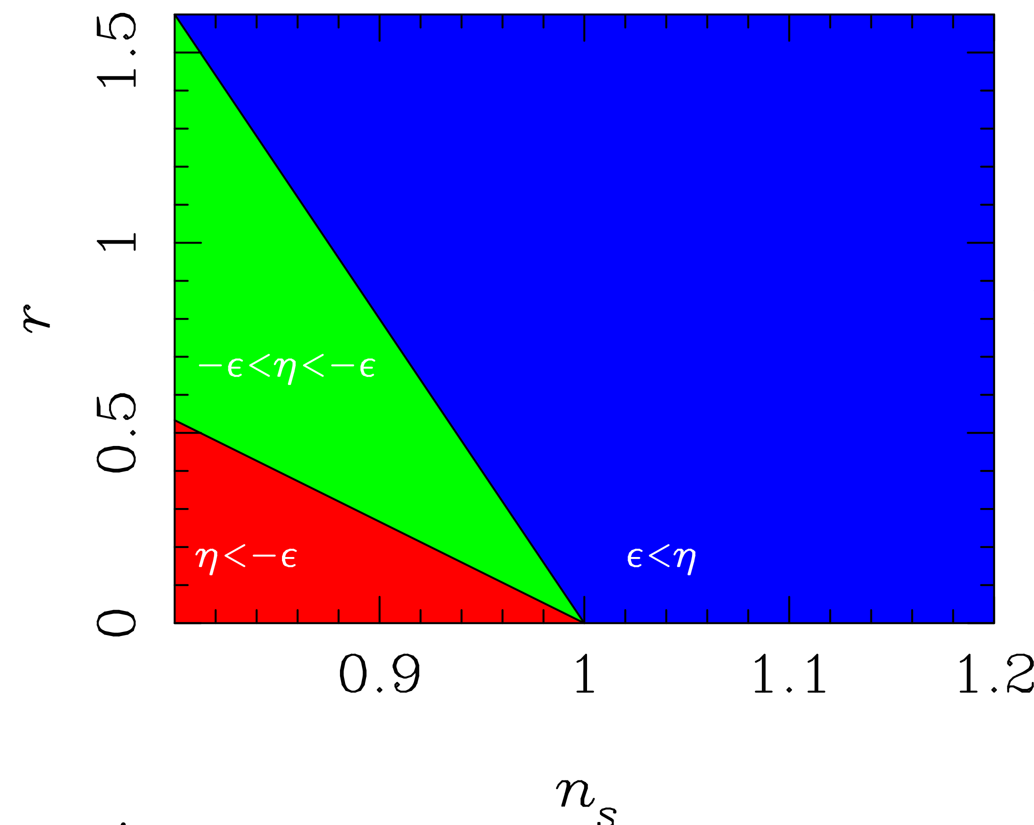
Lens-induced B modes ($\sqrt{C_l^B} \approx 1.3\,\mathrm{nK}$)

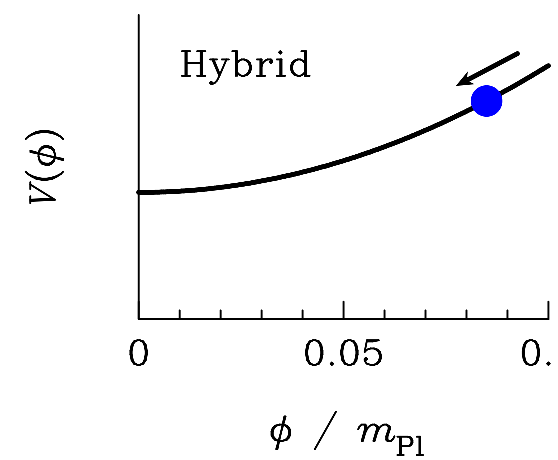
Single-field inflation phenomenology

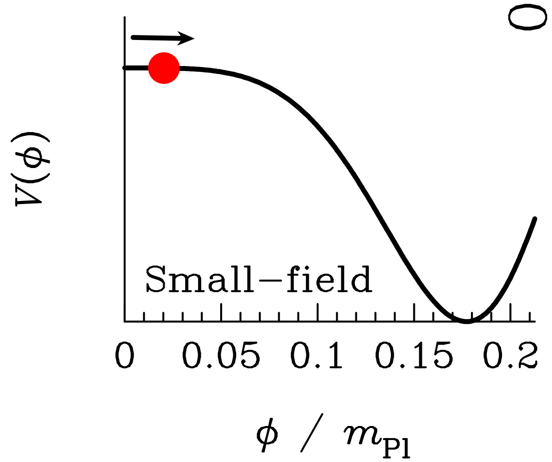
$$\mathcal{P}_h(k) \sim \left(\frac{H}{2\pi}\right)^2 \approx \frac{16H^2}{\pi m_{\rm Pl}^2} \equiv r\mathcal{P}_{\mathcal{R}}(k)$$

$$\mathcal{P}_{\mathcal{R}}(k) \sim \left(\frac{H}{2\pi}\right)^2 \left(\frac{H}{\dot\phi}\right)^2 \approx \frac{16H^2}{\pi m_{\rm Pl}^2} \times \frac{\pi}{m_{\rm Pl}^2}\left(\frac{V}{V'}\right)^2$$







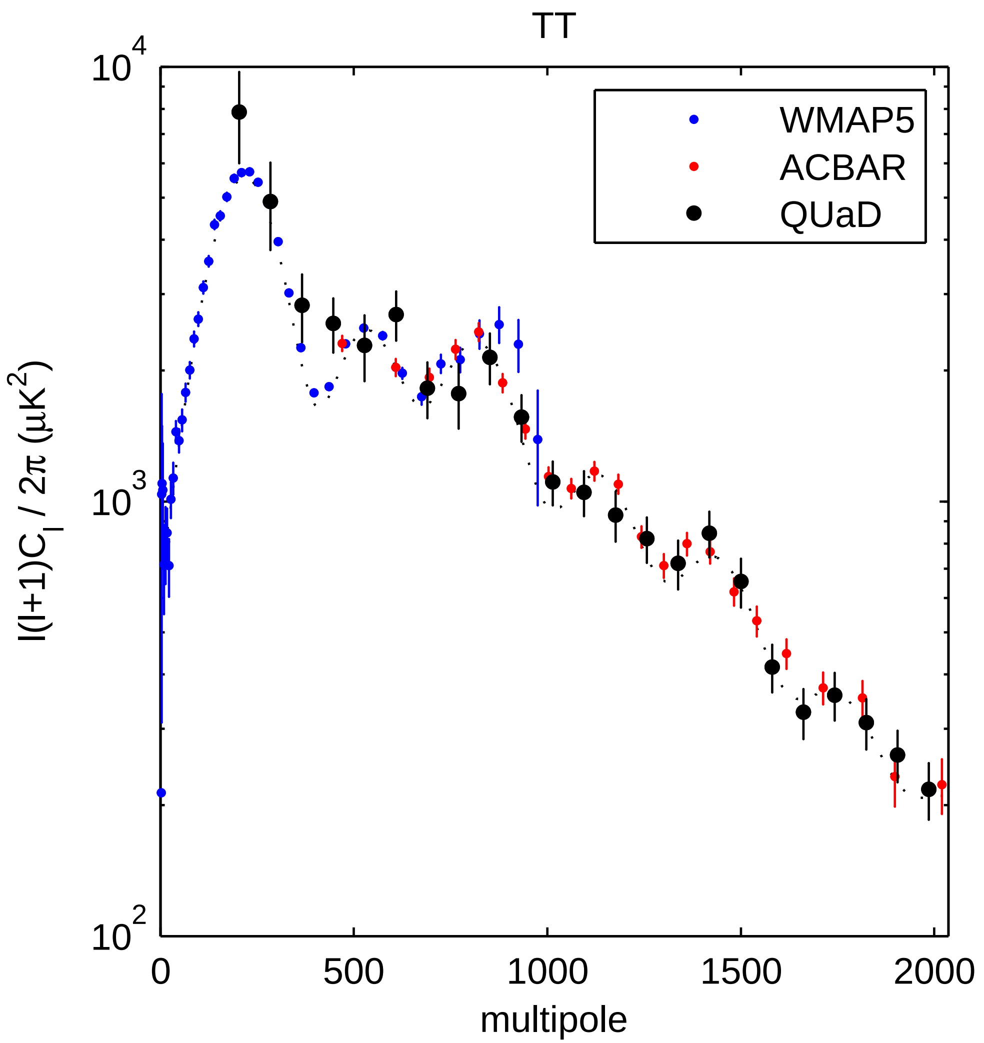


- r and power-law spectral index

$$n_s - 1 \approx (m_{\rm Pl}^2/4\pi)[V''/V - (3/2)(V'/V)^2]$$

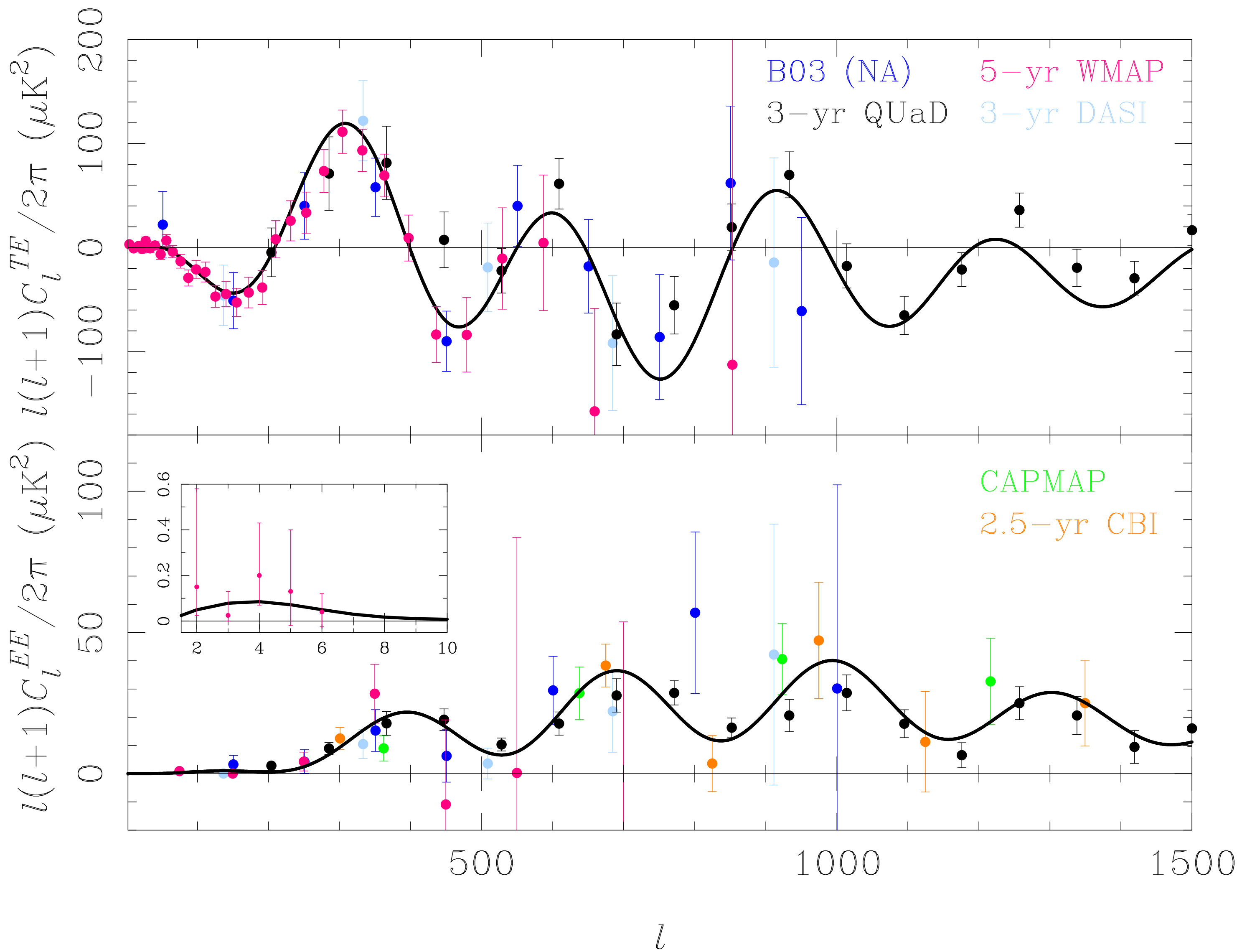
probe slope and curvature of potential

Current C_l constraints: TT



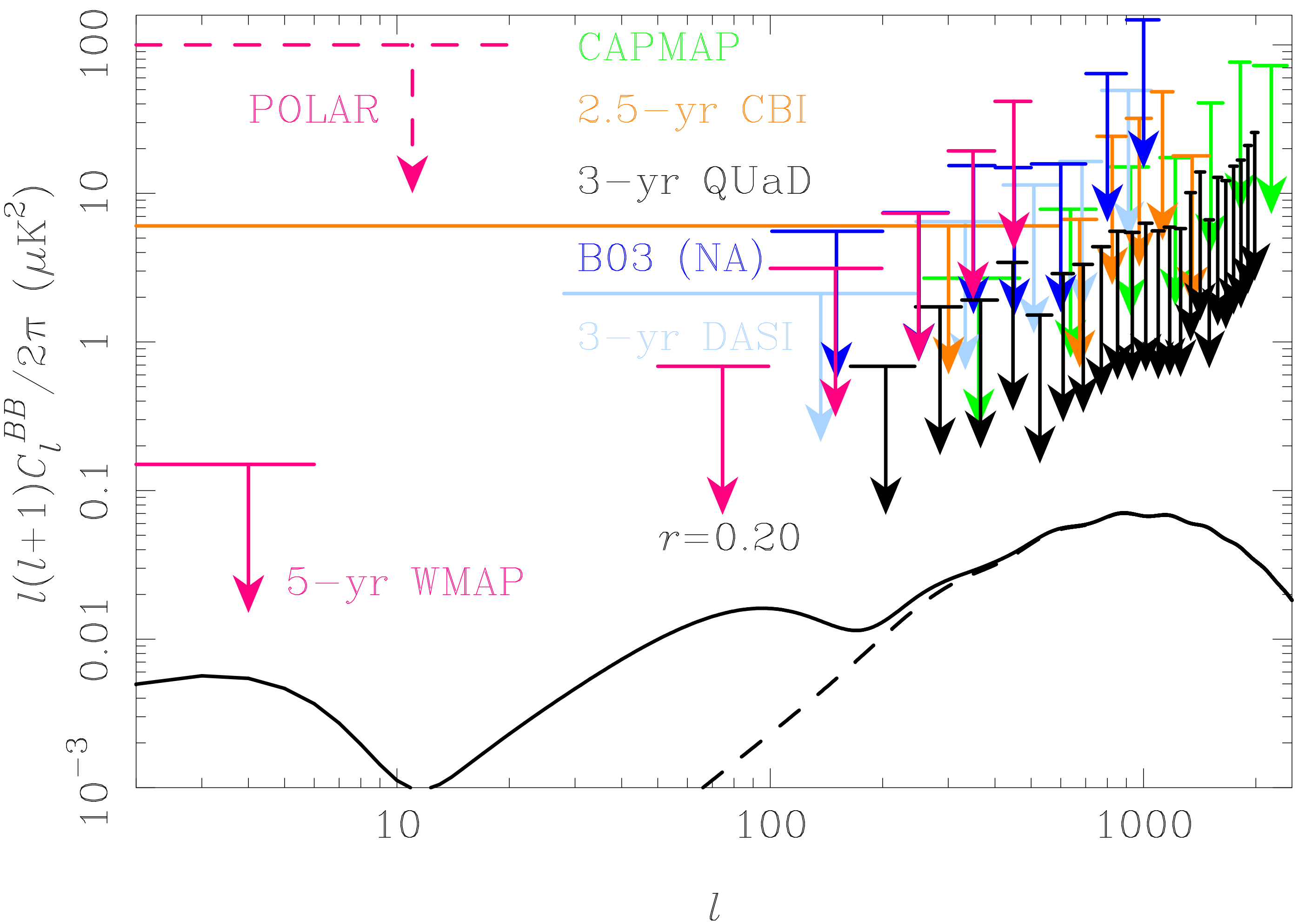
Taken from Pryke et al. (astro-ph/0805.1944) (latest QUAD results)
ACBAR (Reichardt et al 2008) claim $> 3\sigma$ detection of effects of lensing on TT spectrum — controversial — e.g. Calabrese et al (astro-ph/0803.2309) show amplitude about 3 times larger than expected

CURRENT C_l CONSTRAINTS: TE AND EE



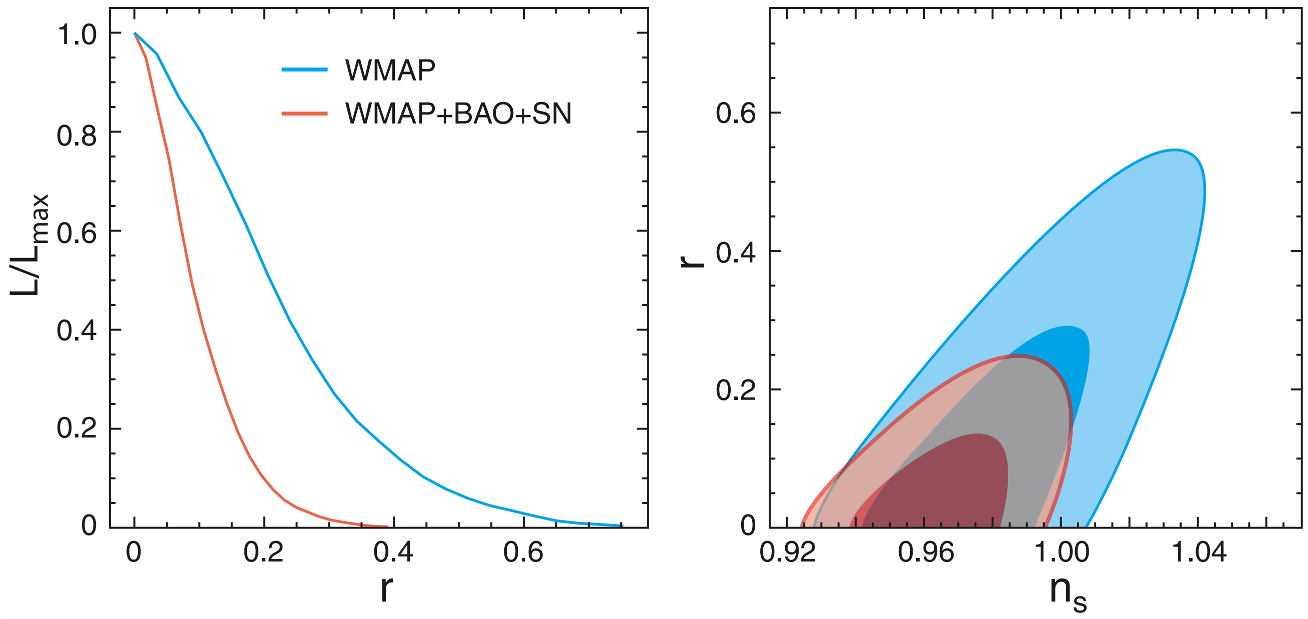
- Large-angle E-modes $\Rightarrow \tau = 0.09 \pm 0.03$ (Page et al. 2007)
- Latest is from WMAP 5 year: $\tau = 0.087 \pm 0.017$ (Dunkley et al.)

CURRENT C_l CONSTRAINTS: BB



- Due to inclusion of Ka band as well as Q and V band, plus two years extra data, $\ell = 2$–7 WMAP 5yr EE and BB 2.3 times smaller noise than 3 yr

WHERE DO RESULTS ON r STAND? (KOMATSU ET AL.)



- Due to improved optical depth determination, degeneracy between τ, scalar spectral index n_s and r now reduced, and constraint on r from WMAP + BAO + SN is

$$r < 0.20 \quad 95\% \text{ conf.}$$

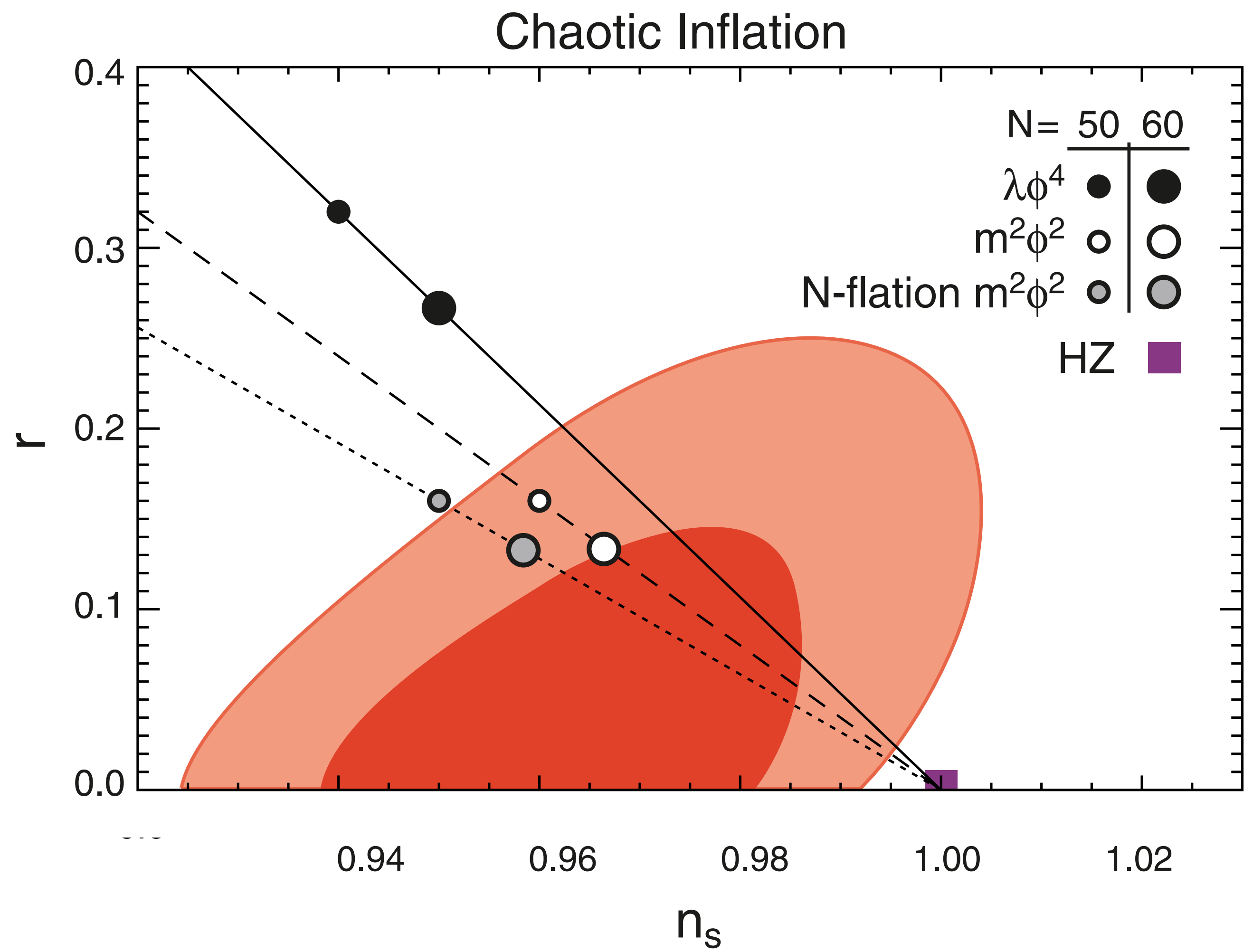
(compare about $r < 0.4$ previously)

- Note this relaxes quite a bit if running of the spectral index is allowed as well:

$$r < 0.54 \quad 95\% \text{ conf.}$$

- Previous limit implied energy scale of inflation $< 2.6 \times 10^{16}$ GeV (scales ar $r^{1/4}$)

WMAP5 CONSTRAINTS ON FORM OF POTENTIAL



- (N-flation model consists of many masive axion fields.)
- ϕ^4 theory now essentially ruled out (more than 99% confidence level)
- ϕ^2 model are still ok — in principle good news for B-mode detections! (typical $r \sim 0.15$ for ϕ^2) — but may be getting close to edge

ISSUES FOR B-MODE POLARIMETRY

- Small signal
- Instrumental systematic effects
- Foreground contamination
- Separating E and B for realistic surveys
- Confusion from non-linear effects (weak gravitational lensing) and other physics

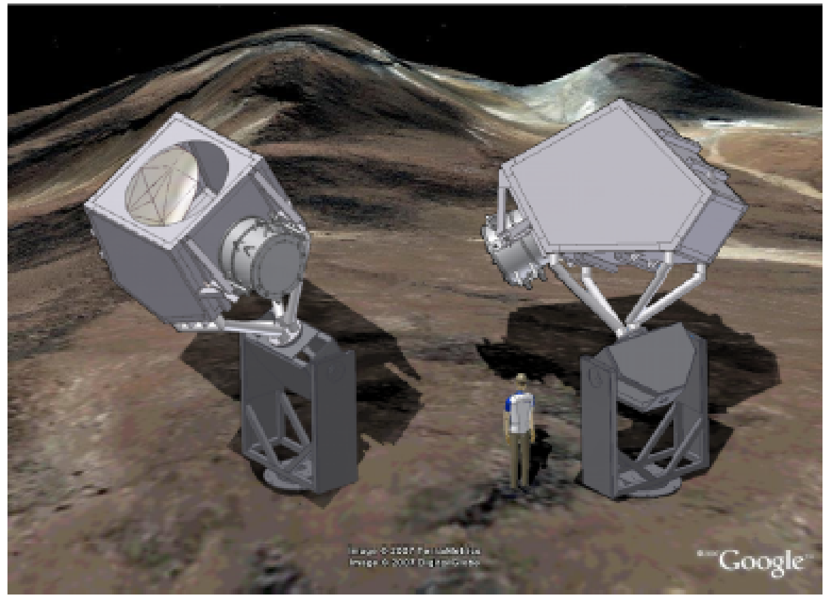
FUTURE CMB POLARISATION EXPERIMENTS

Name	Type	Detectors	ℓ range	r target	Start Date
BICEP	ground	bolometer	$50 < \ell < 300$	0.1	2007
QUIET	ground	MMIC	$\ell < 1000$	0.05	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	$\ell < 200$	1–5 $\times 10^{-3}$	2016?
QUIJOTE	ground	MMIC	$\ell < 80$	0.1	2008

Discuss briefly here

- CLOVER — Cardiff, Cambridge, Oxford, Manchester, B-mode bolometric experiment
- QUAD — reported final results May
- QUIJOTE — Tenerife, Cambridge, Manchester, foregrounds and B-mode HEMT
- SPIDER — USA + Canada + UK B-mode experiment
- PLANCK — will leave to Reno — but note Launch approaching (December 08/January 09)

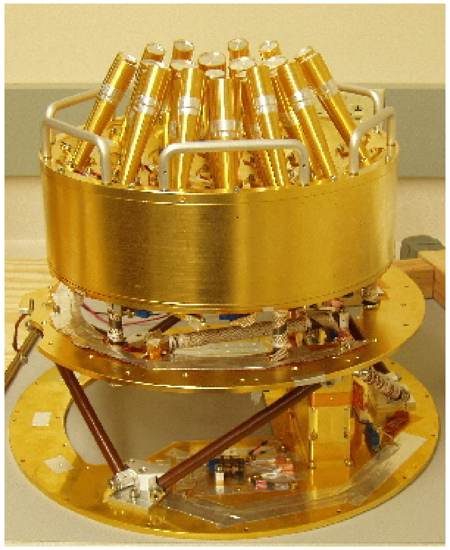
CLOVER SUMMARY

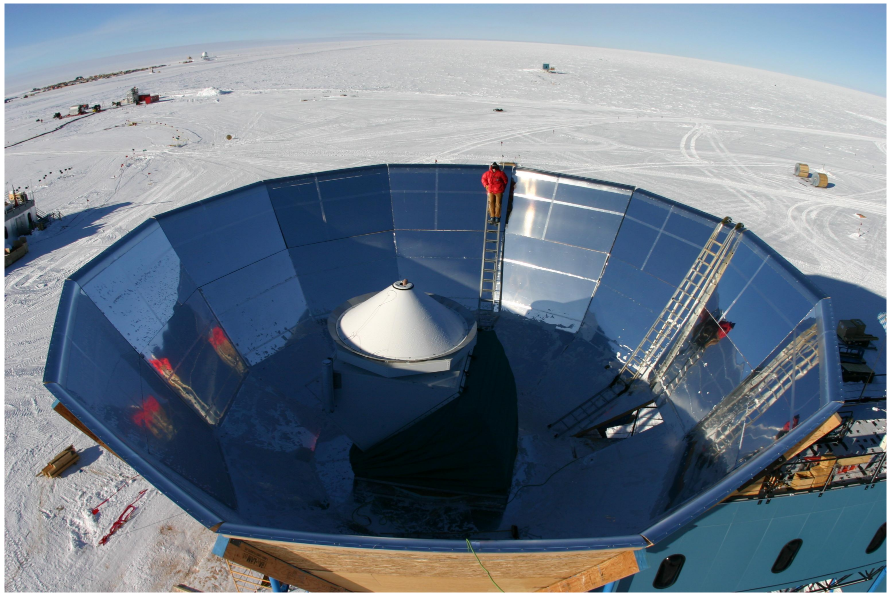


- Cardiff-Cambridge-Manchester-Oxford collaboration (+ NIST & UBC)
- Clean, highly-sensitive polarimetry ($\sim 5\,\mu$K-arcmin imaging at 97 GHz)
- 600 background-limited TES detectors
- Multiple levels of modulation (HWP, scanning and boresight rotation)
- Two instruments: one at 97 (7.5 arcmin); one with mixed focal plane at 150 and 225 GHz (5.5 arcmin)
- Two years observing from Atacama, Chile; commissioning from mid-2009

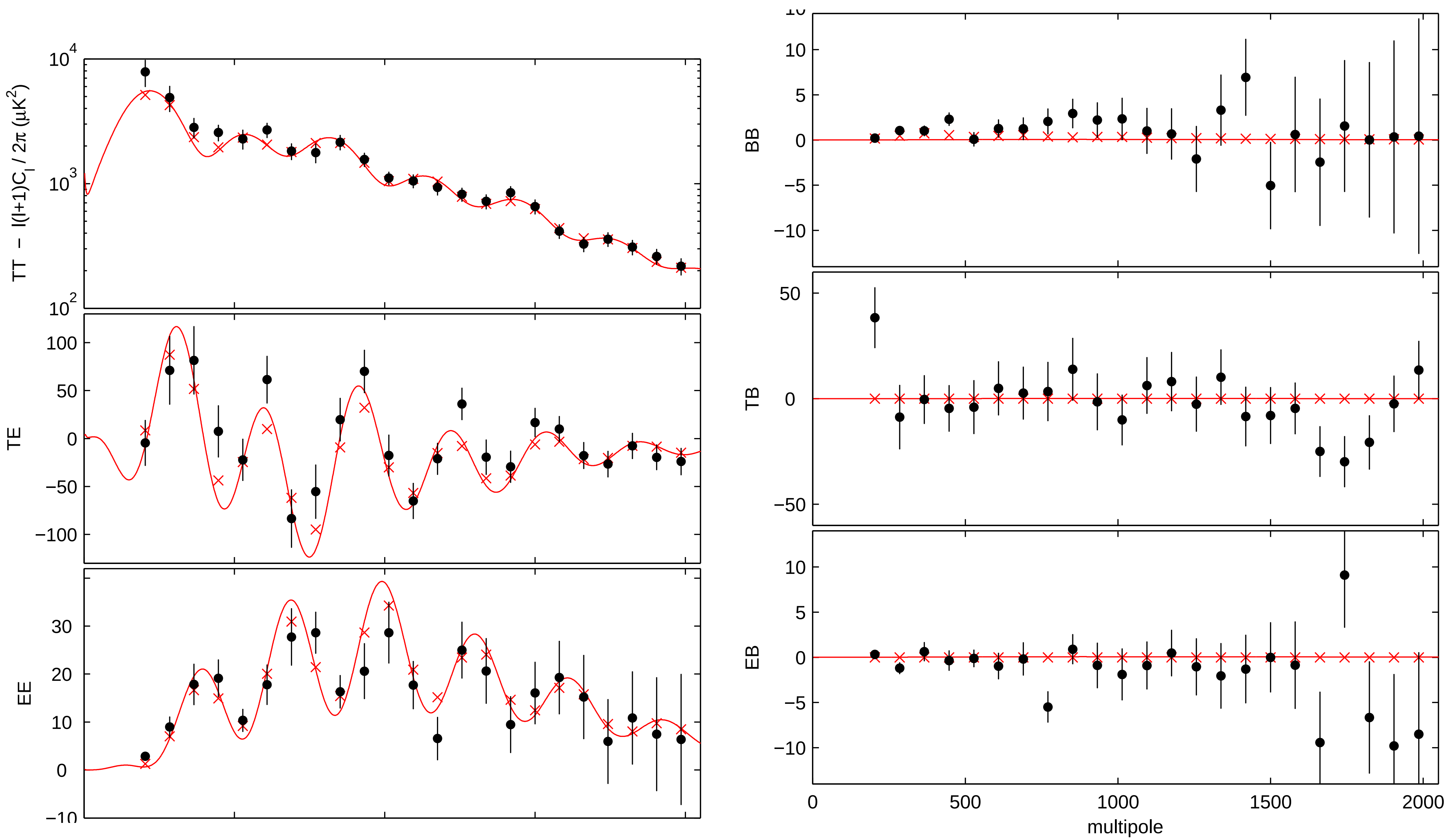
QUAD

- 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 arcmin scale
- Third (final) season now finished
- Final analysis came out recently

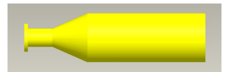




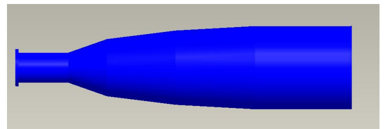
QUAD Final Results — Pryke et al. 2008



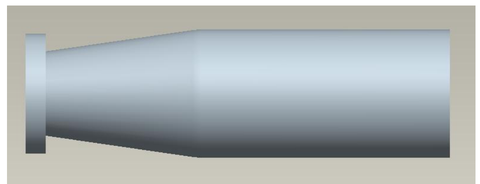
QUIJOTE



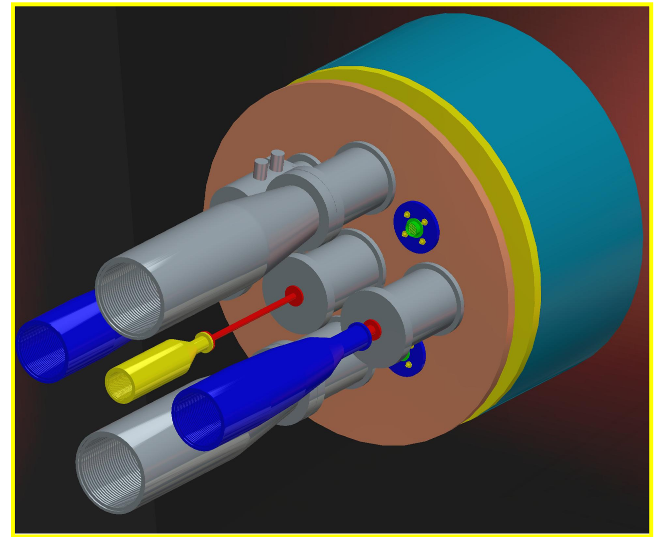
26-36GHz Horn



14-20GHz Horn



10-14GHz Horn



QUIJOTE 1 : Focal Plane Distribution

- IAC (Tenerife)-Cambridge-Manchester collaboration
- Will use spinning mount to achieve good sky coverage
- Planned layout for first stage shown
- 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 ($r \sim 0.1$)

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, Case Western
- 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

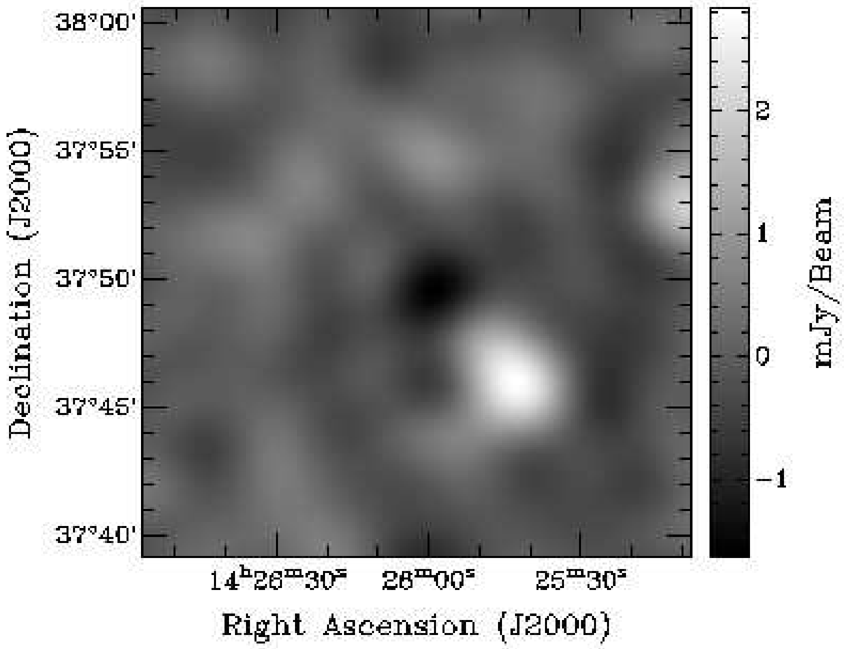
AMI

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

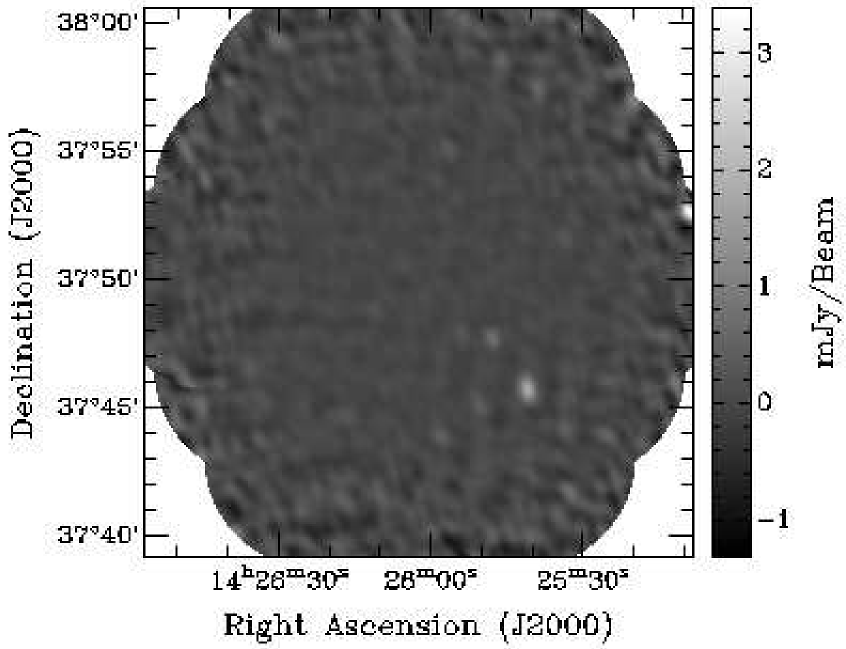
- The AMI Large Array
- The Eight 13 m dishes of the old Ryle Telescope
- Reconfigured to make a compact array for source subtration for Small Array SZ surveys
- Key for measuring radio source contamination

ARCMINUTE MICROKELVIN IMAGER (AMI) — LATEST

- Large Array now fully commissioned and blank field survey has commenced



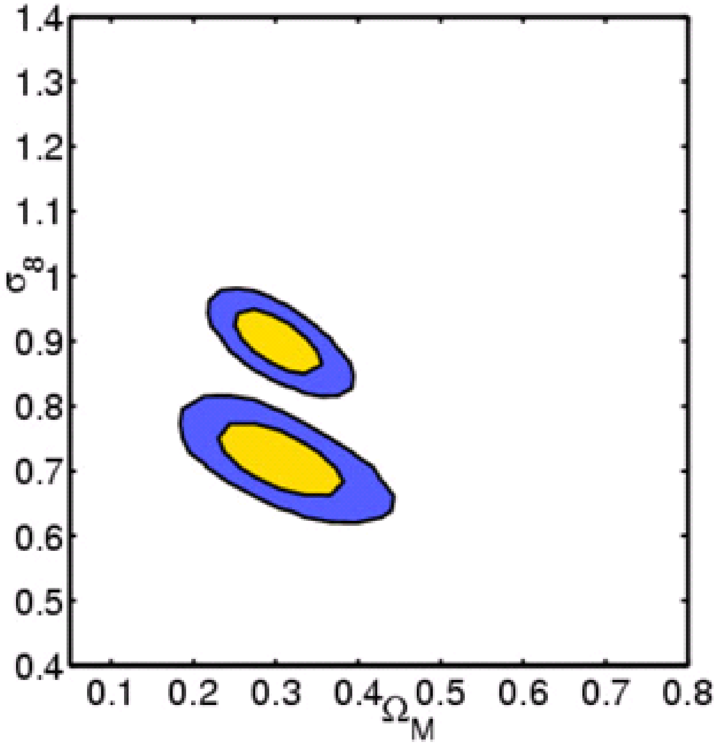
(a) Single-pointing SA map.



(b) LA map comprising a 7- and 19-point raster.

3 types of survey being undertaken — deep ($\sim 10\,\mathrm{deg}^2$); medium ($\sim 50\,\mathrm{deg}^2$) and shallow ($\sim 300\,\mathrm{deg}^2$) for the brightest population

PREDICTED AMI COSMOLOGICAL CONSTRAINTS

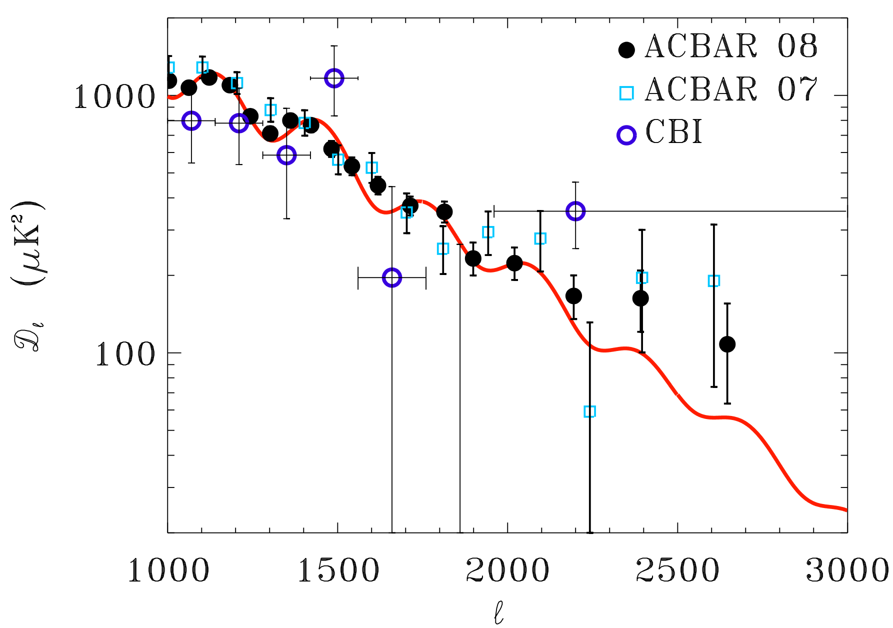


- 1 year, 100 square degrees AMI survey
- This type of survey now started - crucial thing is Large Array is fully working (to detect and subtract the sources)
- How many clusters will we find? Also what is the integrated SZ contribution to the primordial CMB tail?

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 $\sigma_8 \approx 1.0$

DAMPING TAIL AND CBI EXCESS — LATEST ACBAR RESULTS



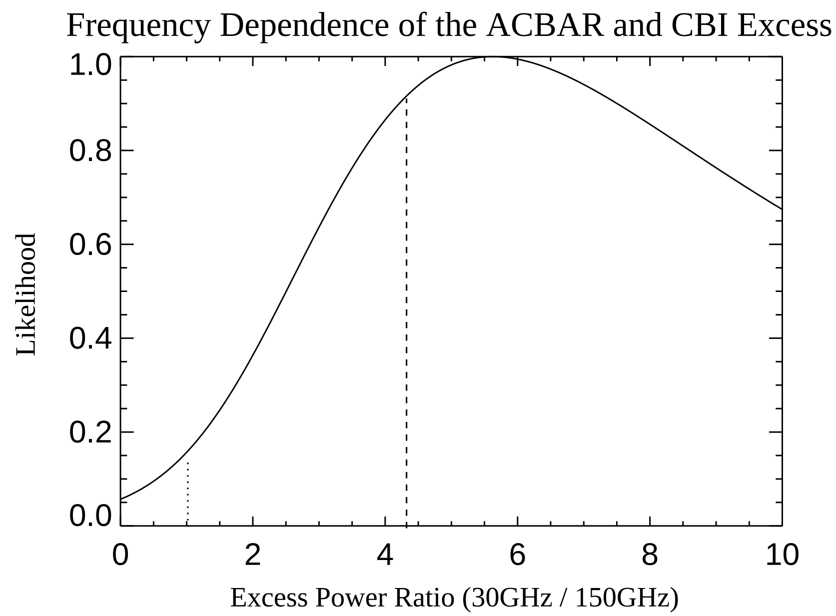


FIG. 7.— ACBAR results on the high-ℓ anisotropies. *Left*: The ACBAR band-powers above $\ell = 1000$ plotted against the best-fit ACBAR+WMAP3 model spectrum. The latest CBI results at 30 GHz and the previous ACBAR results are also shown. The ACBAR band-powers for $\ell > 1950$ are consistently above the model spectrum and below the CBI band-power. *Right*: The likelihood distribution for the ratio of the "excess" power, observed by CBI at 30 GHz and ACBAR at 150 GHz. The excess for each experiment is defined by a flat spectrum for $\ell > 1950$. The likelihood is estimated by examining the difference of the measured band-powers and the model band-powers. The vertical dashed line represents the expected ratio (4.3) for the excess being due to the SZ effect. If the excess power seen in CBI is caused by non-standard primordial processes, the ratio will be unity (blackbody), indicated by the dotted line. If the excess in ACBAR and CBI has a common origin, we conclude that it is 6 times more likely that the excess seen by CBI and ACBAR is caused by the thermal SZ effect than a primordial source.

Taken from Reichardt et al. (2008) (astro-ph/0801.1491). Significance of effect now $\sim 1.7\sigma$

The South Pole Telescope — Latest

- South Pole Telescope (10m) now complete and carrying out first surveys
- These are at 150 and 220 GHz, covering two 100 deg^2 fields — another to be done shortly
- 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

- Almost all models of string inflation give small levels of gravitational waves (Baumann & McAllister 2007; Kallosh & Linde 2007)
  - Lyth (1997) bound relates change in field $\Delta\phi$ to r

$$r = \frac{8}{N^2}\left(\frac{\Delta\phi}{m_{\rm Pl}}\right)$$

  - N is the efective number of e-folds of inflation, so as a minimum is about 45
  - Thus

$$r =< 0.004\left(\frac{\Delta\phi}{m_{\rm Pl}}\right)$$

    and ϕ has to move over a range comparable in scale to the Planck mass in order to give a measurable r. (Due to foregrounds, this probably means measurable at *any* point in the future.)
  - The problem is that $\Delta\phi \ll m_{\rm Pl}$ in essentially all microphysical models of inflation
  - E.g. in typical string models have geometric constraint on evolution of moduli
- Detection of gravity waves at sensitivity levels of upcoming B-mode experiments ($r \sim$ few $\times 10^{-2}$) $\longrightarrow$ trouble for string theory?

FURTHER LINKS WITH FUNDAMENTAL THEORY - PARITY VIOLATION?

- WMAP 5yr Komatsu et al. paper considers possibility of parity-violating interaction between photons and dark matter

- Lagrangian would be of the form

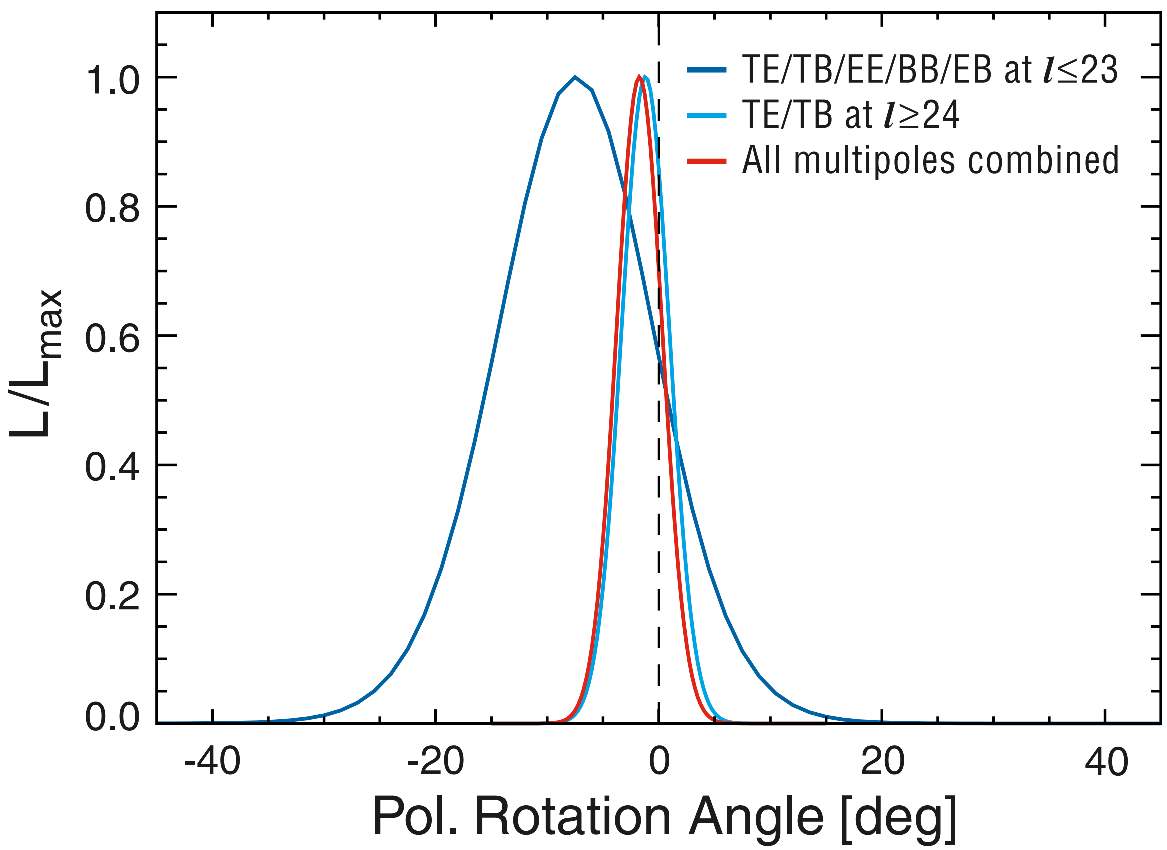
$$\mathcal{L} = -\frac{1}{2} p_\alpha A_\beta \overline{F}^{\alpha\beta}$$

- A_α is the standard EM vector potential, $\overline{F}^{\alpha\beta}$ is the dual of the standard Faraday tensor, and p_α is taken as the gradient of a light scalar field (standing in for some aspect of dark matter)

- This interaction (of Chern-Simons form) violates parity, and makes the two polarisation states of a photon propagate with different group velocities, and hence causes the polarisation plane to rotate (cosmological birefringence) (Carroll, 1998)

- This makes E transform into B (like lensing) and with a parity violation (unlike lensing), which means TB and EB cross-power spectra are produced (normally zero)

Parity violation (contd.)



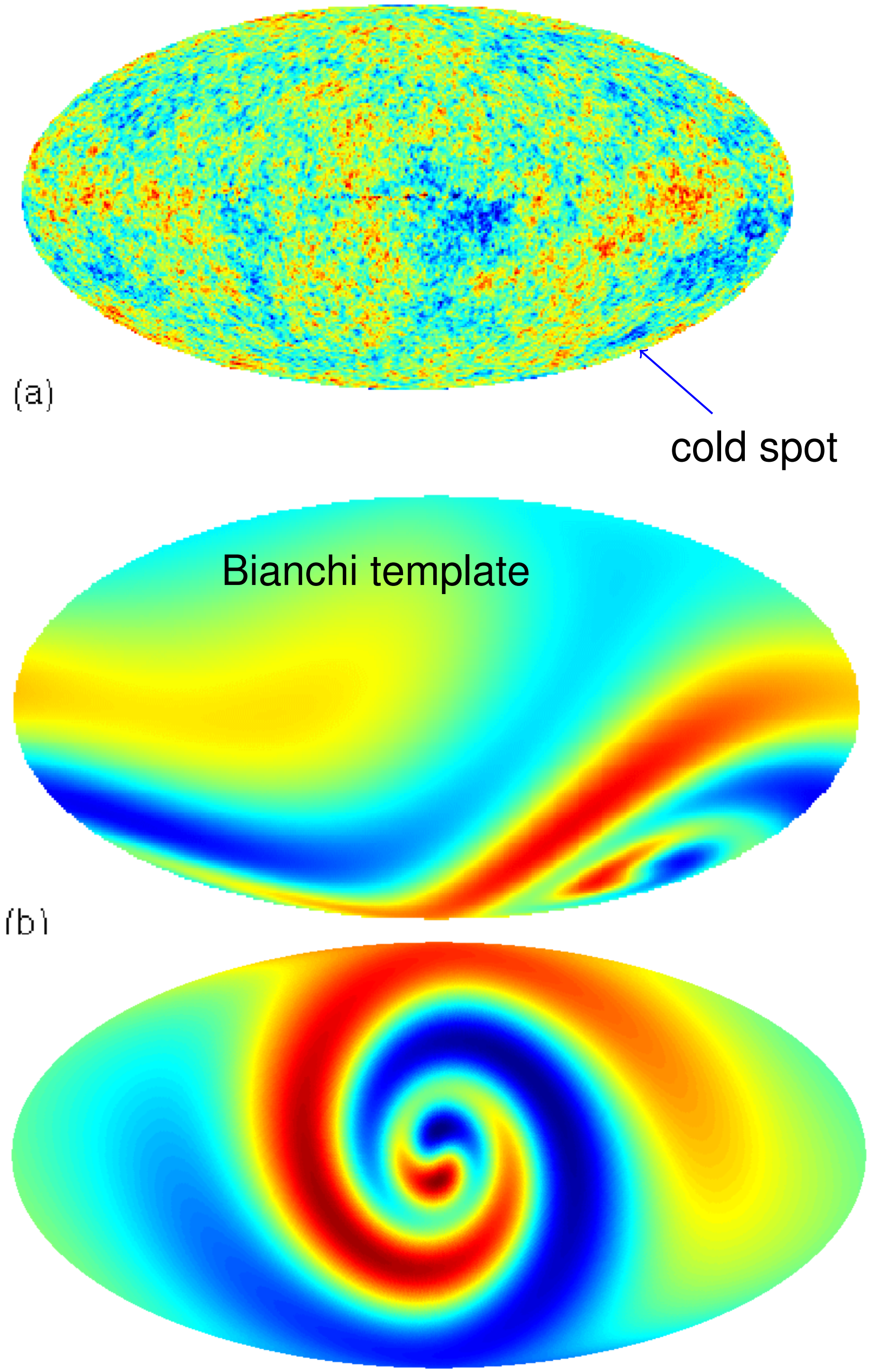
(Komatsu et al., 2008)

- So these spectra are included in the analysis for this purpose (Now distributed with the WMAP likelihod code.)
- No evidence for polarisation plane rotation found to

  $\Delta\alpha = -1.7^{\circ} \pm 2.1^{\circ}$ (95% conf.)

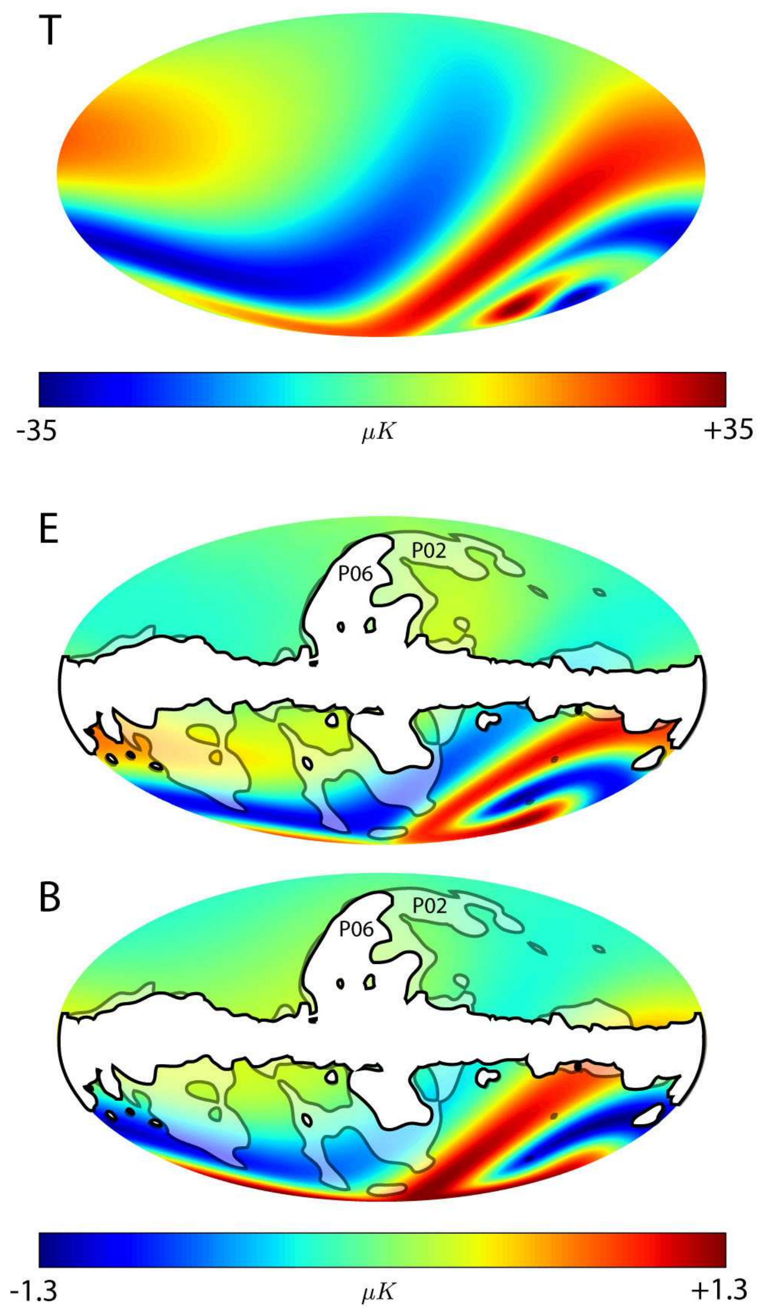
  when all ℓ ranges combined (lower ℓ measures rotation from reionisation to us, higher from decoupling to us)

A BIANCHI MODEL UNIVERSE?



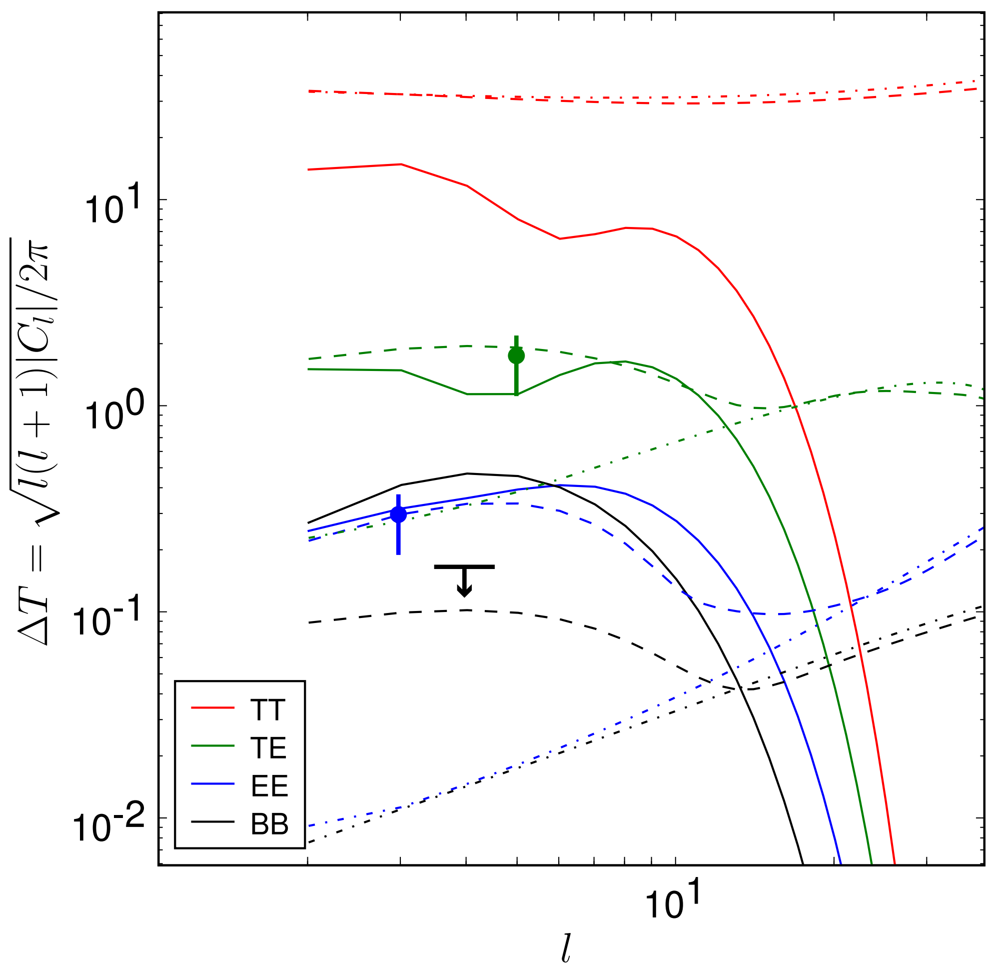
- Several authors have commented on significant North/South asymmetry in the WMAP data, plus strange alignment between low multipoles
- Jaffe et al. (astro-ph/0503213) fitted a Bianchi VIIh template to WMAP sky
- Found a best fit with $\Omega_0 = 0.5$
- Coldest part of template corresponds with a non-Gaussian 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)
- They extended Collins & Hawking (1973) type calculation to ful radiative transfer including polarisation
- There is a polarisation peak at low ℓ due to rapid decay of shear, with roughly equal E and B mode power

Bianchi Polarisation (contd.)



- Surprise is that this is big enough that B-mode already rules them out!
- Bridges, McEwen, Lasenby and Hobson are joining with Pontzen & Challinor to carry out more rigorous map-based MCMC analysis
- Requires extension of previous techniques to situation with mask present
- Gives the opportunity to include more modes in the Bianchi analysis as well (previous just one shear mode out of a total of 5 included)

Effects of anisotropy during inflation?

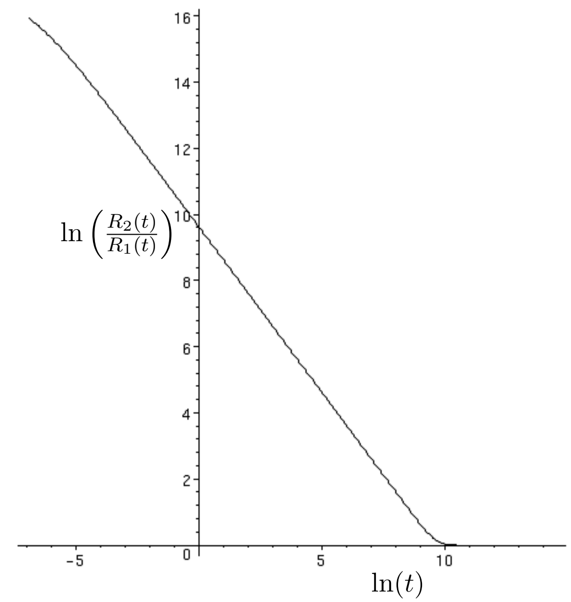
- Preceding works have all been concerned with what we can call late time Bianchi models
- This is where our current universe is taken to have shear and rotation, and the effects are all laid down during recombination and during propagation to us from then
- An alternative, which has recently begin to 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.)

- A different approach: Dechant, Lasenby & Hobson (submission in a few weeks) have been looking at closed Bianchi models (Bianchi IX) with scalar field

- Have got a biaxially symmetric model in which $R_1 \propto t$ while $R_2 = R_3 \mapsto$ const. (as does ϕ) as one approaches the big bang

- Surprise is that the model gets smoothly through 'big-bang', with no singularities in any physical quantities, to a symmetric (though presumably parity-inverted) universe beforehand

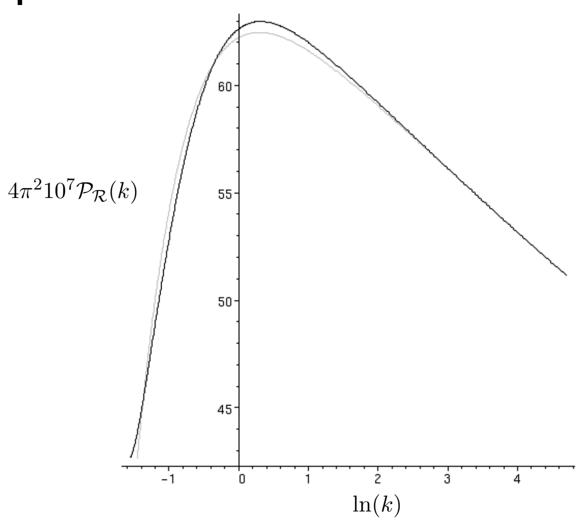


- The period of inflation due to the scalar field makes sure the universe is spherically symmetric by end of inflation, and also that Ω ends up close to 1

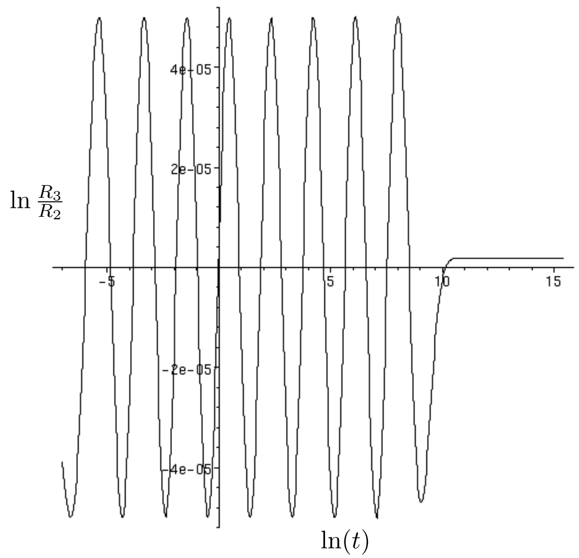
- However, on largest scales the universe is just oblate ($\sim$ 0.2% level) at the point where the perturbations are being laid down

EFFECTS OF ANISOTROPY DURING INFLATION? (CONTD.)

- This suggests will be able to get phase correlations and some lage-scale asymmetries present due to this
- However, doesn't prejudice actual power spectrum (computed crudely, at least), which still displays very nice fit to phenomenological form suggested by Efstathiou (MNRAS, **343**, L95 (2003)) in response to low WMAP quadrupole



- Tensor mode looks acceptable $r \sim 0.17$ (though note WMAP5+BAO+SN just starting to approach this level now)
- Investigating stability of this situation, find that full triaxial case with $R_3(t) = R_2(t)(1 + \delta(t))$, and δ small, oscillates until inflation kicks in, and then 'freezes out' in a fashion very similar to linear perturbation modes at horizon crossing in FRW



Fast roll inflation

- Want to briefly discuss something which we will hear about later at this meeting
- Work by Sanchez, de Vega, Boyanovsky & Destri concerning effects of a fast roll period before the usual slow roll of inflation
- This comes out of their 'effective field theory' approach, and has implications for a low quadrupole — also for r
- I want to demonstrate briefly here that such a thing comes out naturally in what I consider to be the obvious boundary conditions 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

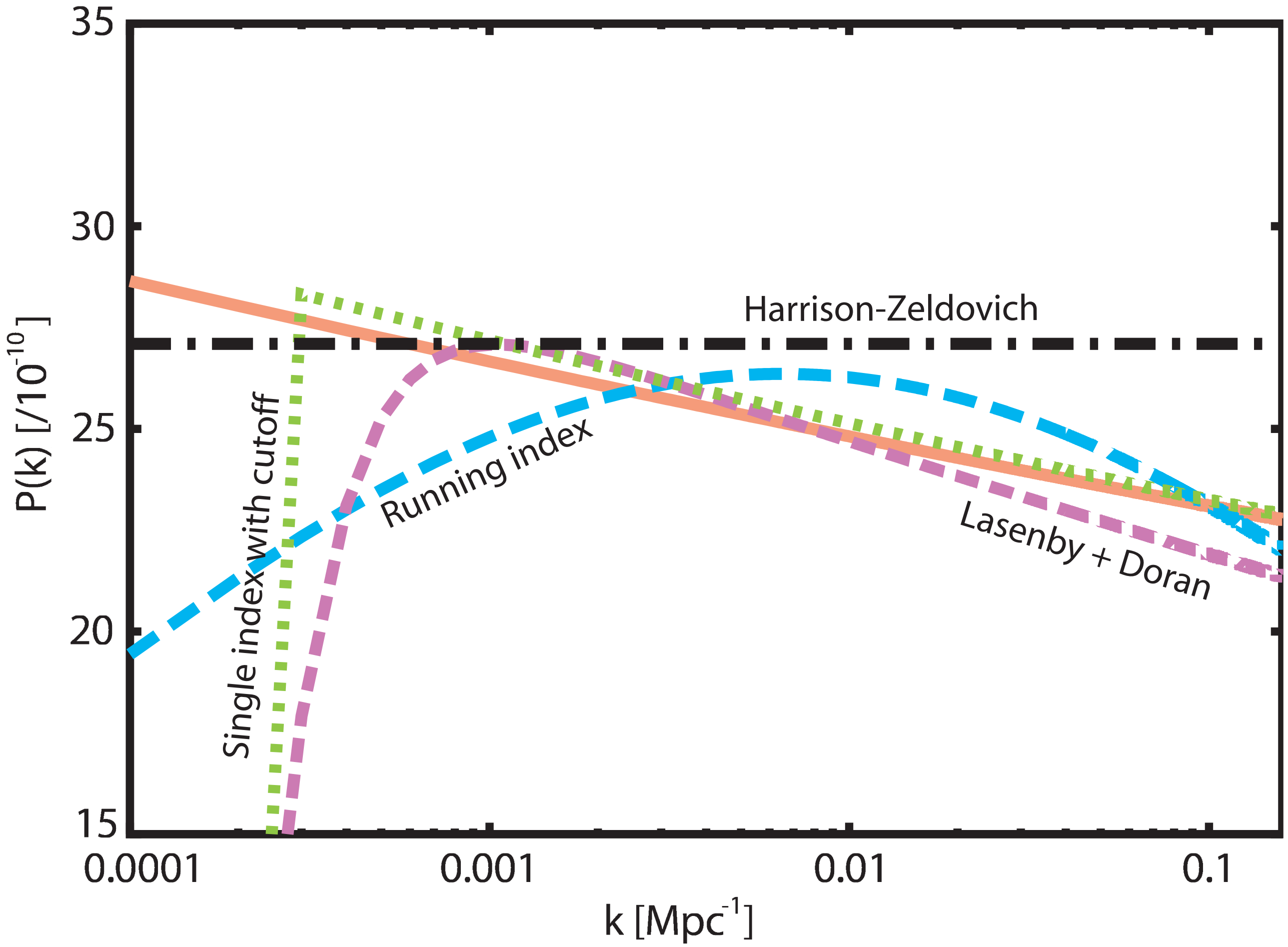
$$\rho \propto \frac{1}{(t-t_0)^2}$$

- 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, where can avoid singularity) a point where it behaves this same way

FAST ROLL INFLATION (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
- Later compared this model with other primordial power spectra in context of an 'Evidence' calculation

PRIMORDIAL SPECTRA



- Figure shows some of the different type of spectra that were considered (free-form binned also included)
- ‘Lasenby + Doran’ preferred at an evidence value (In of relative probability) of ~ 5 using WMAP3 data (see Bridges, Lasenby & Hobson, MNRAS, **381**, 68 (2007))
- HZ and binned dis-preferred at values of ~ -17

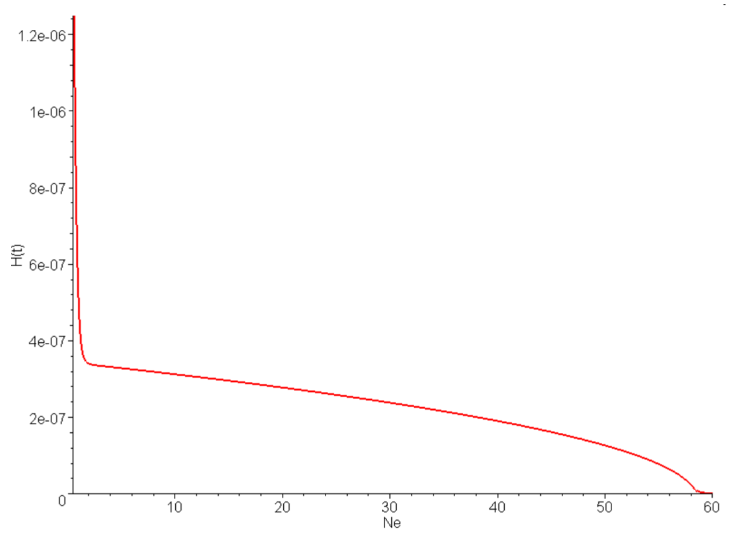
- Note, however, we showed major part of why good evidence results were obtained was due to high-ℓ behaviour, rather than low-ℓ cutoff
- Point I want to make here, is that what happens at low k isn't just due to the closed nature of the model
- Coming out of the singularity itself implies a 'fast-roll' period and quadrupole suppression, irrespective of curvature
- So have recently repeated relevant part of the calculations in a flat model to better compare with Sanchez, Boyanovsky & de Vega
- In flat case, series expansion of gravitational and scalar field equations out of singularity yields leading order behaviour of the form

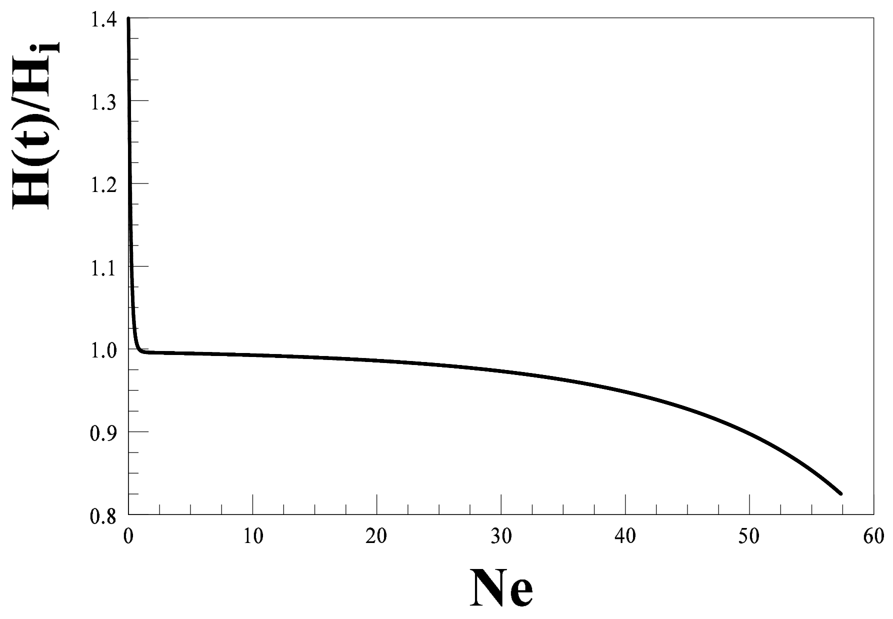
$$H \sim \frac{1}{3t} + \frac{8}{3} t\pi\, {b_0}^2 + \frac{2}{81} t + \frac{4}{27} t\sqrt{\pi}\sqrt{6} b_0 - 4/9 \ln(t)\, t\sqrt{\pi}\sqrt{6} b_0 - \frac{2}{27} \ln(t)\, t + 1/$$

$$\phi \sim -1/12 \frac{\ln(t)\sqrt{6}}{\sqrt{\pi}} - 1/6 \ln(t)\, t^2 b_0 + \frac{1}{432} \frac{\ln(t)\, t^2\sqrt{6}}{\sqrt{\pi}} + b_0 - \frac{11}{2592} \frac{t^2\sqrt{6}}{\sqrt{\pi}} - 1/$$

- Can see that ϕ energy is indeed initially kinetic dominated

- Find that remainder of terms in power series expansions depend on just one adjustable parameter! (we call b_0)
- This parameter is dimensionless, and controls the amount of inflation that occurs. Find get values appropriate to what we observe today (approximately 50 to 60 e-folds in typical flat model) with $b_0 \sim 1.8$ — i.e. works with values near 1!
- So can now compare the $H(t)$ dependence in this approach vs. that in Boyanovsky et al. ('CMB Quadrupole Suppression: II' — Phys.Rev. D74 (2006) 123007)





Very good match, and thus good match also in the generic form of primordial power spectrum predicted (though apparently different origin)

THINGS HAVE NOT TALKED ABOUT (JUST RE POLARISATION!)

- CMB polarimetry very rich field with many other applications and implications for fundamental physics
- Anti-correlation of T and E at $\ell \sim 150$ strong indicator of adiabatic nature of fluctuations, and origin in inflationary phase (phase coherence necessary for this)
- Stringy cosmologies suggest a renaissance for cosmic (super-)strings — B-mode effects may be best way of detecting these (Copeland)
- Ekpyrotic and Cyclic universe (Turok, Steinhardt et al.) predict a very small level of B-modes, essentially since H smaller comparatively during epoch when scalar perturbations are laid down — this a powerful discriminant for this case
- Then whole rich area of polarisation of secondary anisotropies (some with fundamental consequences, at least in principle, e.g. clusters reprocess the quadrupole they see locally to polarisation — evade cosmic variance on quadrupole?)