CMB Observations, Anisotropies and Polarisation

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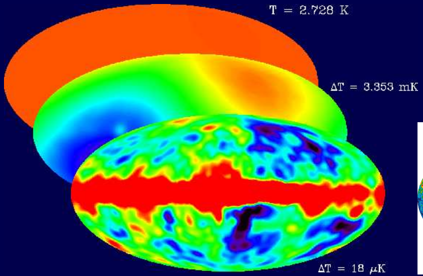
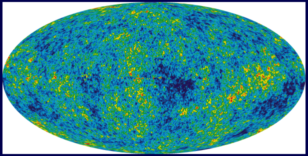
Overview

- 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 (but also for secondary anisotropies)
- Then briefly discuss the topic of evidence
- This has now become influential both in model selection and as a tool in thinking about experiment design
- Two things we apply it to are
  - The primordial power spectrum
  - Bianchi models
- Acknowledgements. Thanks to following for help with slides and slide material:
  - Anthony Challinor, Mike Hobson and Keith Grainge
  - And to many other colleagues involved in some of the experiments discussed here (e.g. Angela Taylor w.r.t some CLOVER material — see e.g. astro-ph/0610716, which has just been posted with a description of the CLOVER experiment)

The cosmic microwave background

- Thermal relic of hot big bang with almost perfect blackbody spectrum (COBE-FIRAS)
  - Temperature 2.726 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 ($\sim 10^{-5}$)





The cosmic microwave background

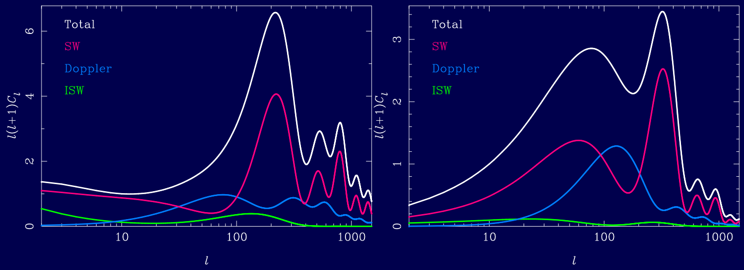
The big questions the CMB fluctuations can help us address include:

- What is the curvature of space — is the Universe open, closed or flat?
- Is the Universe rotating?
- Do we have any direct proof of inflation?
- When did the Universe re-ionize?
- What is the shape of the primordial power spectrum of density perturbations?
- Do cosmic defects exist?
- What is the nature of dark energy?

Will discuss how the CMB constrains some of these
Still the case that we don't actually have definite answers on any of these yet
— But getting close on several of them!

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:

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

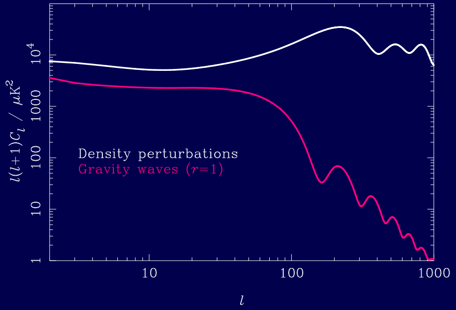
- Integrated effect of locally-anisotropic expansion (shear) of space generates temperature anisotropies after recombination:

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

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

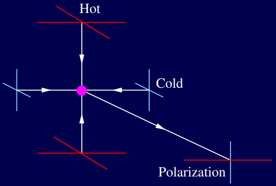
$$\Delta C_l = \sqrt{\frac{2}{2l+1}}C_l$$

limits $\Delta r = 0.07$

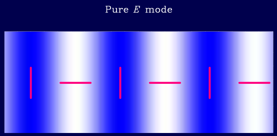


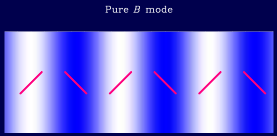
CMB polarization

- 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



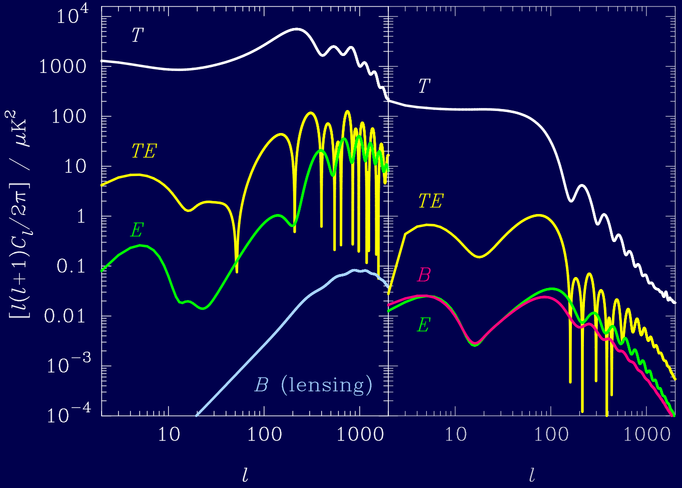
- Only three power spectra if parity respected in mean: C_l^E, C_l^B and C_l^{TE}





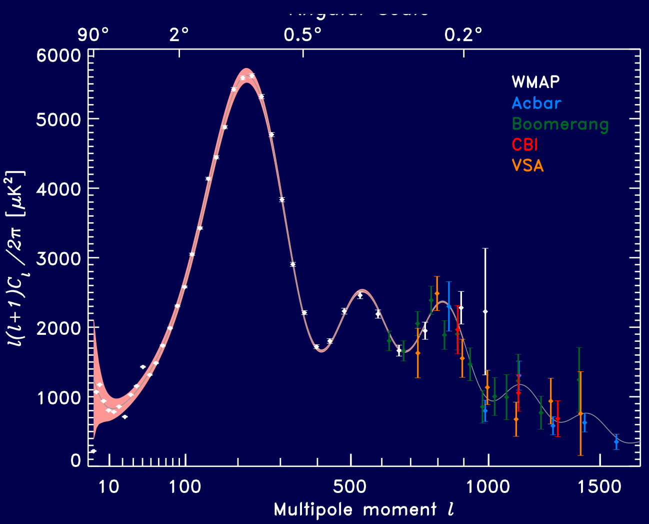
- Linear scalar perturbations produce only E-mode polarization
- Mainly traces baryon velocity at recombination $\Rightarrow$ peaks at troughs of ΔT
- Gravity waves produce both E- and B-mode polarization (with roughly equal power)

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



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

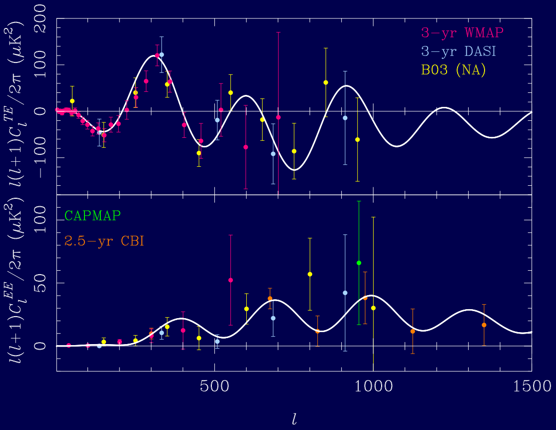
Current observations — ΔT



(Hinshaw et al. 2006)

Current observations — *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.

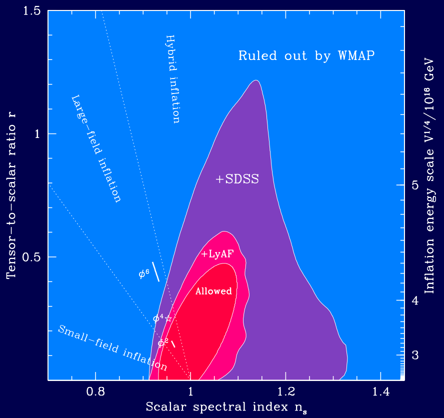


EXPERIMENTS DISCUSSED

- CLOVER — Cardiff, Cambridge, Oxford, Manchester B-mode bolometric experiment
- QUAD — Stanford, Chicago, Cardiff, Edinburgh
- QUIET — USA B-mode HEMT experiment
- AMI — SZ surveyor at Cambridge
- SZA — SZ surveyor in California
- 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, and this is now a key goal

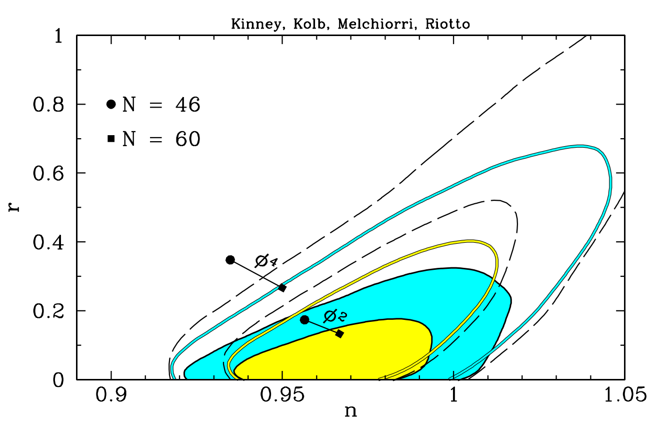
Inflation: r-n_s constraints (pre WMAP3 slide)

- 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)

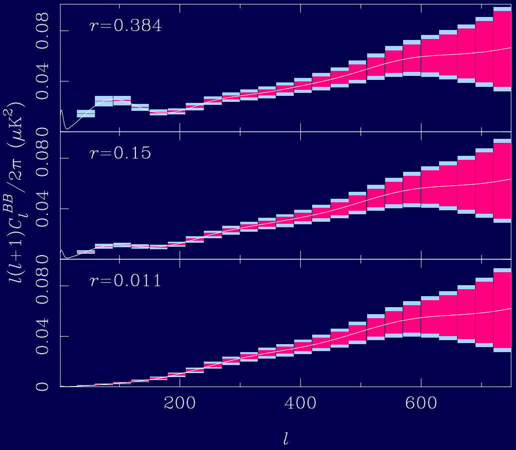
WMAP3 constraints on form of potential



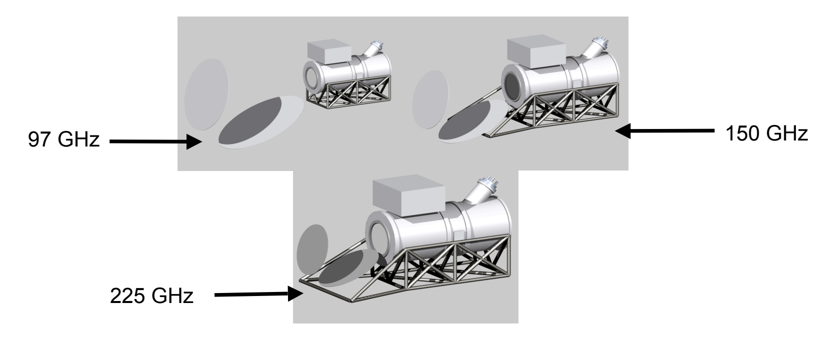
- Thus good evidence now starting to build up against ϕ^4 type theory or plain H-Z, and for ϕ^2
- This is in principle good news for B-mode detections! (typical $r \sim 0.15$ for ϕ^2)

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



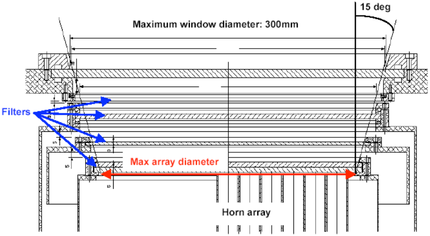
CLOVER EXPERIMENT

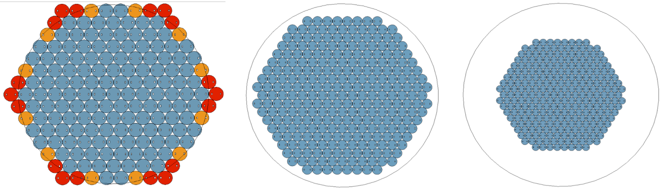


- Collaboration between
  - Cambridge — detectors, software
  - Cardiff — telescope, mount and integration
  - Oxford — optics
- Three independent scaled telescopes: 97, 150, 225 GHz
- 160, 256, 256 pixels, 8-arcmin resolution
- Transition Edge Sensor (TES) detectors at $\sim 100\,\mathrm{mK}$
- Three independent 3-axis mounts

CLOVER Focal Planes

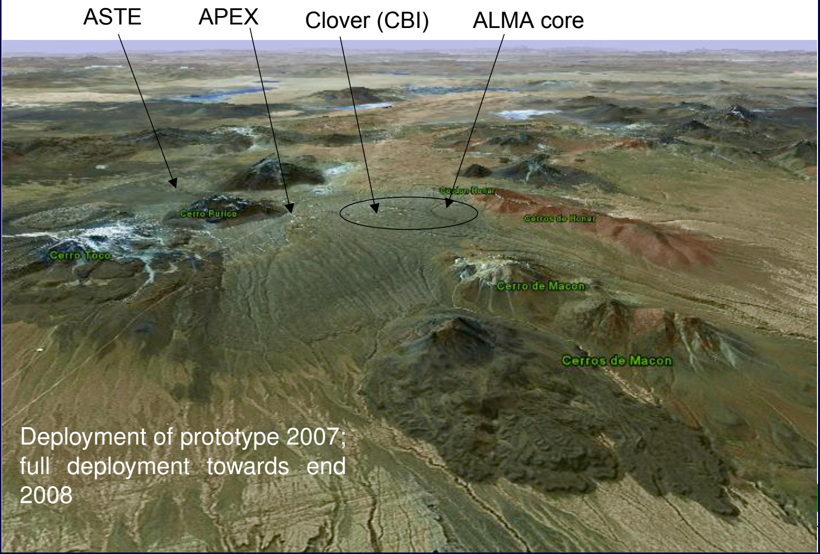
- Filter stack 300mm
- Limits array size





	97 GHz	150 GHz	220 GHz
No. horns:	160	256	256

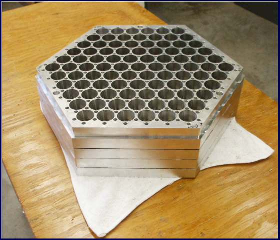
CLOVER Site



Deployment of prototype 2007; full deployment towards end 2008

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

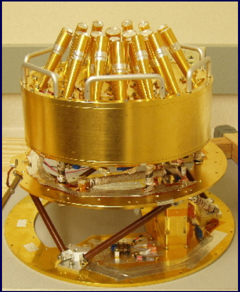


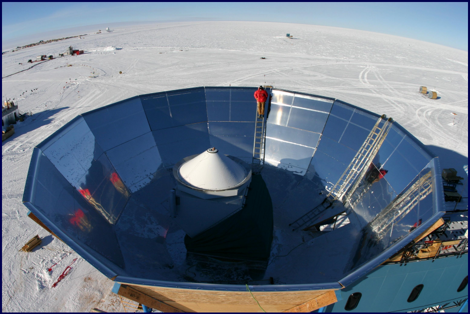
QUIET

- Lucent 7m telescope, currently in New Jersey and recently used for CAPMAP, will be moved to Chile for small angular scales (approx 4 arcmin)
- 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

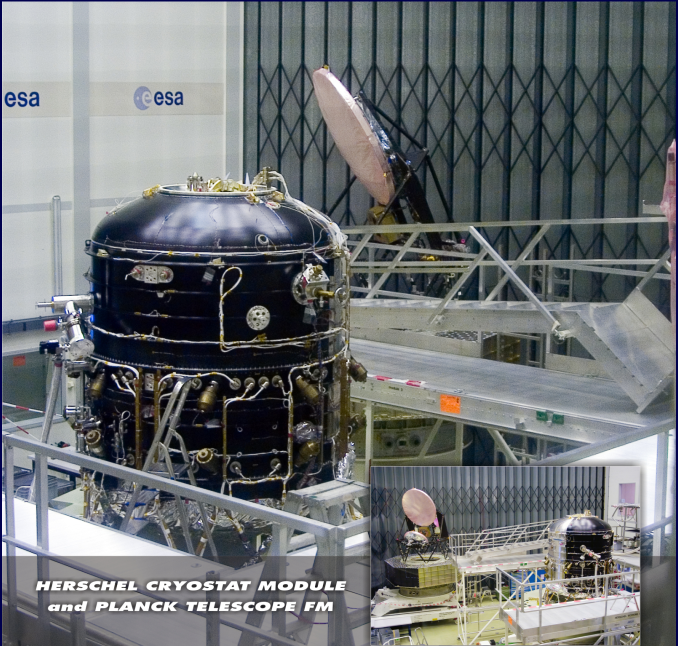
QUAD

- 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
- Second season underway
- First season analysis almost complete (December?)





Planck and Herschel meet at Estec




The Arcminute MicroKelvin Imager (Cambridge)

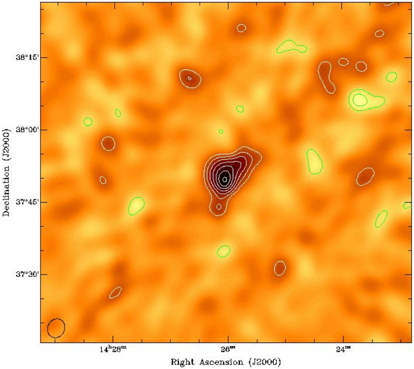
ARCMINUTE MICROKELVIN IMAGER – AMI

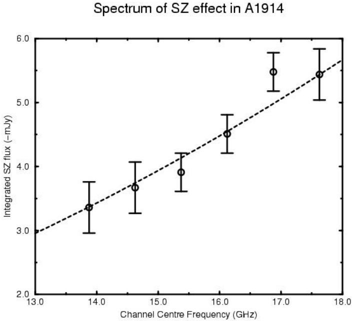
Small Array

Large Array

- Cluster survey instrument looking for SZ imprints
- Sited at Lords Bridge
- Small Array: ten 3.7m dishes
- Large Array: upgraded Ryle Telescope
- Supported on rolling grant until at least Mar 2010

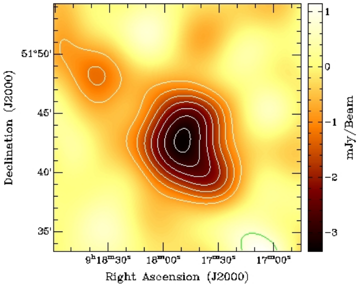
FIRST AMI SZ EFFECT

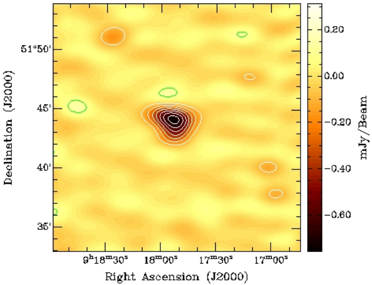




- Commissioning data – just 8 aerials; poor calibration etc.

SZ EFFECT IN A773





6 hour AMI image

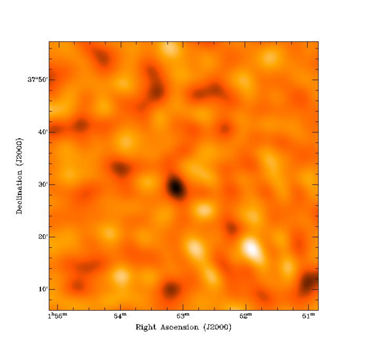
460 hour RT image

- Outer regions of gas now being detected.
- Telescope sensitivity matches theoretical prediction.

$\Rightarrow$ 10^3 improvement in survey speed over RT.

NORAS selected clusters

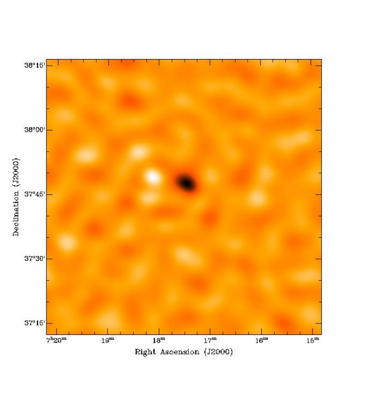
- Selected from a NORAS list with $L_X > 6.8 \times 10^{44}\,\mathrm{erg\,s^{-1/2}}$
- Map shows 10 hour observation of A263, $z = 0.3$; X-ray luminosity $L_X = 7.7 \times 10^{44}\,\mathrm{erg\,s^{-1/2}}$
- These observations will allow calibration of cluster scaling relations
- Can also combine with X-ray and lensing data $\rightarrow$ Detailed astrophysics of cluster plasma; fit for baryon fraction; H_0



A263, (Natasha Hurley-Walker)

MACS selected clusters

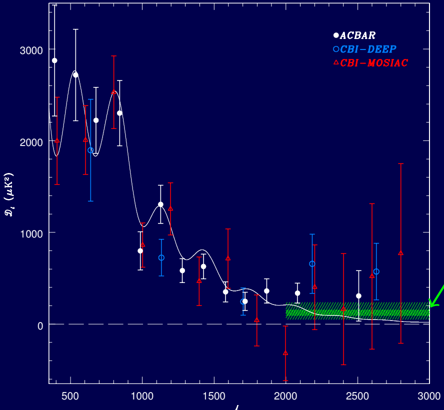
- Selected from MACS catalogue with $L_X > 10^{45}\,\mathrm{erg\,s^{-1/2}}$ and $z > 0.5$
- Map shows observation of $z = 0.545$ cluster
- Look for evolution of scaling relations
- In addition to this survey, we will also look at other high-z clusters from the literature



0717+374 (Jonathan Zwart)

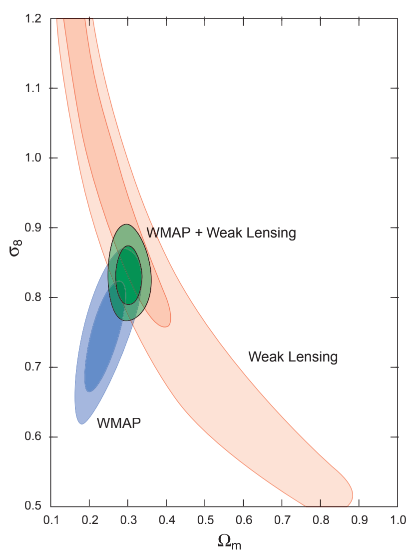
Damping tail and CBI excess

- 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)

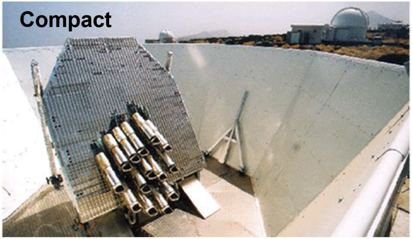
WMAP3 versus weak lensing

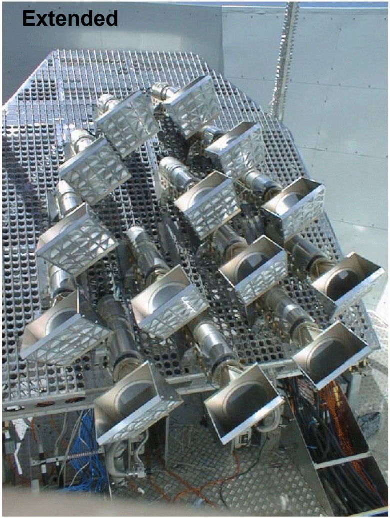


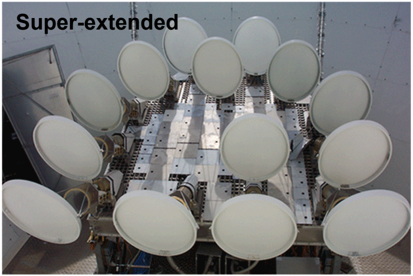
- A $\sigma_8 \approx 1.0$ would, however, now be a real problem
- Ok (in general) with weak lensing, but not now with WMAP3
- Combination of losing some optical depth and lower Ω_{cdm} means σ_8 now significantly lower
- $\sigma_8 = 0.92 \pm 0.1$ (WMAP1) now goes to $\sigma_8 = 0.76 \pm 0.05$ (WMAP3)
- This seems to be a real tension between models

The Very Small Array (VSA) – Main Array

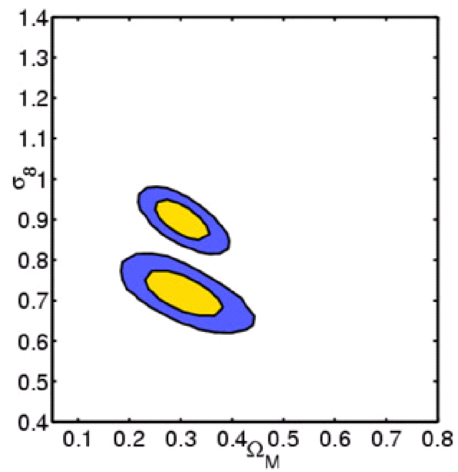
- 14-antennas interferometer → 91 baselines







Predicted AMI Cosmological Constraints



- 1 year, 100 square degrees AMI survey
- Other currently working experiment aiming at same thing 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)
- Currently taking science data
- SZA to be integrated with OVRO and BIMA telescopes (CARMA) will allow high resolution cluster imaging

Model selection and Bayesian evidence

- Evidence $\Pr(D|H)$ is the denominator in Bayes Theorem:

$$\Pr(\theta|D,H) = \frac{\Pr(D|\theta,H)\Pr(\theta|H)}{\Pr(D|H)}$$

  provides normalisation of the posterior

$$\Pr(D|H) = \int \Pr(D|\theta,H)\Pr(\theta|H)\,d\theta$$

- Can see that the evidence is the average of the likelihood with respect to the prior

  $\Rightarrow$ a model has a large evidence if more of its allowed parameter space is likely, given the data

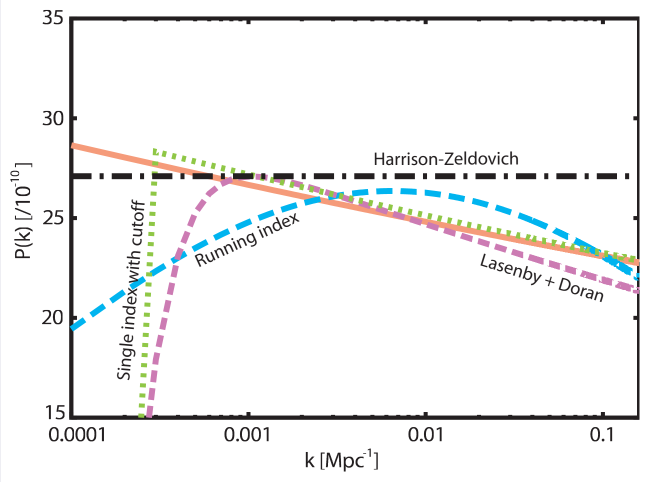
  $\Rightarrow$ a model has a small evidence if there are large areas of its allowed parameter space with low likelihood values

- Hence evidence naturally incorporates Occam's razor: a simpler theory is preferred to a more complicated one, unless latter is significantly better at describing the data
- Thus, the preferred model is that with the largest evidence

Two Examples in Cosmology

- Is there evidence for departures from scale invariance in the primordial power spectrum coming out of inflation and if so, which models are preferred (in a proper evidence sense)?
- Evidence for rotation of the universe
- Starting with first, this has been examined in astro-ph/0511573 (Bridges, Lasenby & Hobson)
- Plus another in July by same authors for WMAP3 (astro-ph/0607404)

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

Slightly closed models

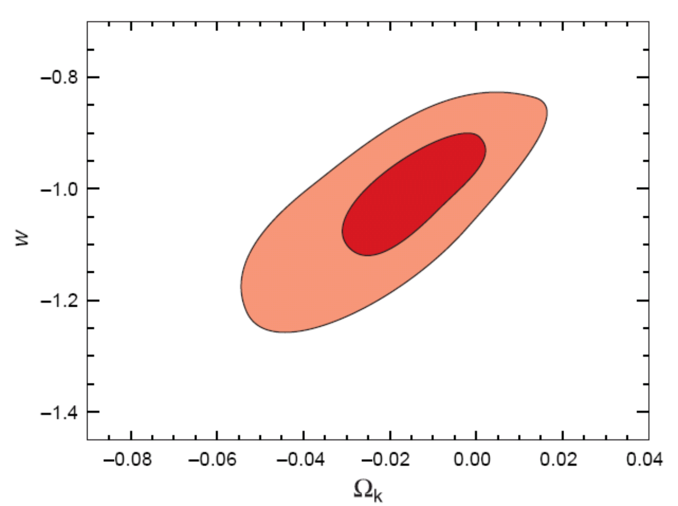
- At this stage, I ought to declare an interest
- With Chris Doran, I have developed a model in which a slightly closed universe (few percent level) emerges naturally
- ‘Closure’ during inflation naturally gives a low k cutoff in primordial spectrum
- Model has its basis in a conformal geometry approach to understanding Λ
- Works with a simple $m^2\phi^2$ scalar field potential
- Described in Phys.Rev.D **71, (2005) 063502** (Lasenby & Doran)
- The conformal geometry part gives a novel boundary condition at the ***end*** of the universe!
- Also gives natural linkage between Λ and number of e-folds N of inflation

$$\Lambda \sim \exp(-6N) \quad \text{which gives} \quad \sim 10^{-122} \quad \text{in natural units if} \quad N \sim 46$$

- Thus I am very interested in whether universe is indeed just closed, and want $w = -1$, so that Λ can be purely geometrical!

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

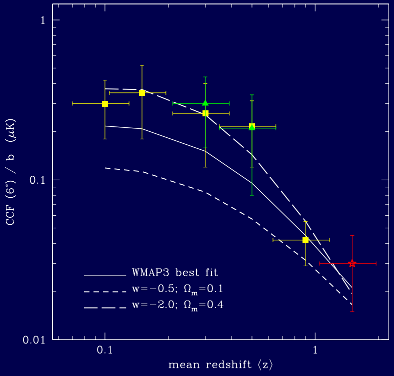


This is for full CMB data set+2dfGRS+SDSS+SN

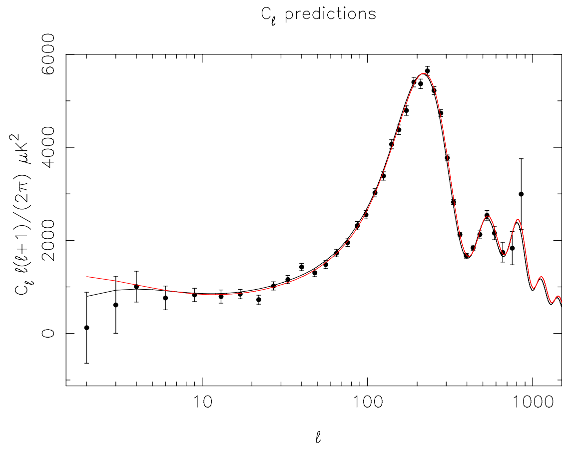
- get $w = -1.062^{+0.128}$, $\Omega_k = -0.024^{+0.016}$

ISW effect and dark energy

- Potentials decay once Λ comes to dominate $\Rightarrow$ positive correlation of ΔT with LSS tracer on large scales
- Many detections over range of redshifts – highest at $z \sim 1.5$ with quasars from SDSS (Giannantonio et al. 2006, astro-ph/0607572)



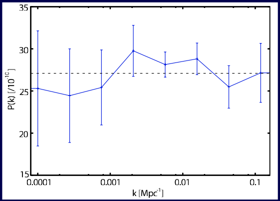
Comparison of L+D model with WMAP1 points



- Predicted CMB power spectrum for a model with $\Omega_{\text{tot}} = 1.04$
- Red line is WMAP best fit Λ CDM power law spectrum
- Catch is that our curve is for $H_0 = 60\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$!
- HST value is 72 ± 8, for comparison

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

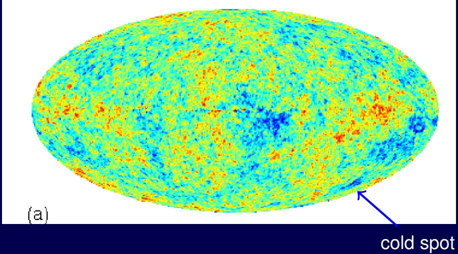


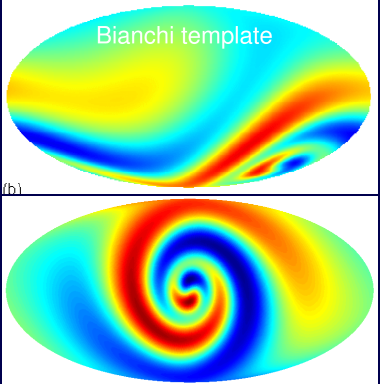
- Some sample evidence results were as in following:

Table: Differences of log evidences (for primordial parameters) for all models with respect to single index model within a current (near) concordance cosmology: $\Omega_0 = 1.024, \Omega_b h^2 = 0.0229, h = 0.61, \Omega_{cdm} h^2 = 0.118$, as compared to the Lasenby & Doran model (treated as a template)

Model	$\ln E_i - \ln E_0$
Constant n	0.0 $\pm$ 0.5
H-Z	-4.4 $\pm$ 0.5
Running	-0.8 $\pm$ 0.6
Cutoff	0.4 $\pm$ 0.5
Broken	-2.7 $\pm$ 0.6
Binned	-6.1 $\pm$ 0.6
Lasenby & Doran	4.1 $\pm$ 0.5

A Bianchi Model Universe?





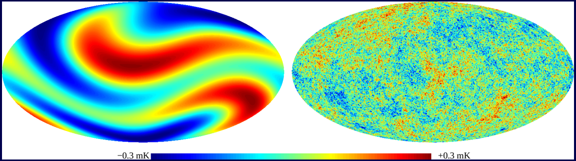
- Several authors have commented on significant North/South asymmetry in the WMAP data, plus strange alignment between low multipoles
- Jaffe et al. (astro-ph/0503213) fitted a Bianchi VIIh template to WMAP sky
- Found a best fit with $\Omega_0 = 0.5$
- Coldest part of template corresponds with a non-Gaussian 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
- Can one achieve the same in models including Λ?

Effects of including Λ

- Movie shows effects of changing Ω_Λ, with fixed other parameters ($h = 0.01$, $\Omega_\mathrm{m} = 0.26$)
- (Generally, putting in Λ has the effect of shortening conformal time available, and so need more drastic (small) h values in order to get similar smaller scale effects)

Evidence and Bianchi models

- Results (Jaffe et al. second paper (astro-ph/0512433)) are that it's not possible to find a good model in which the Bianchi template cosmology values match those of something which fits rest of data (e.g. acoustic peaks etc.)
- Supported by the full MCMC analysis in Bridges et al (astro-ph/0605325)
- However, still interesting to evaluate evidence for Bianchi VIIh model, just treating it as a template - how much do we really need it in our data??
- E.g., both of these are for a reasonable 'just open' cosmology $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.69$



- Can simulate different vorticities and see how well evidence can discriminate

The Bianchi versus CMB degeneracies

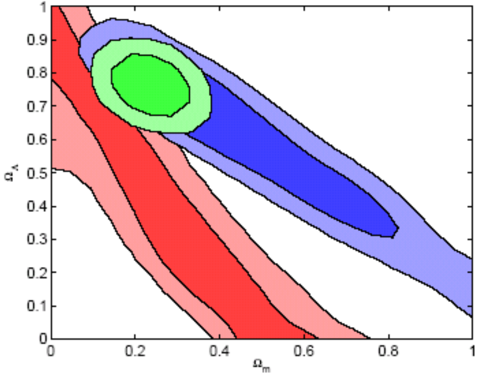
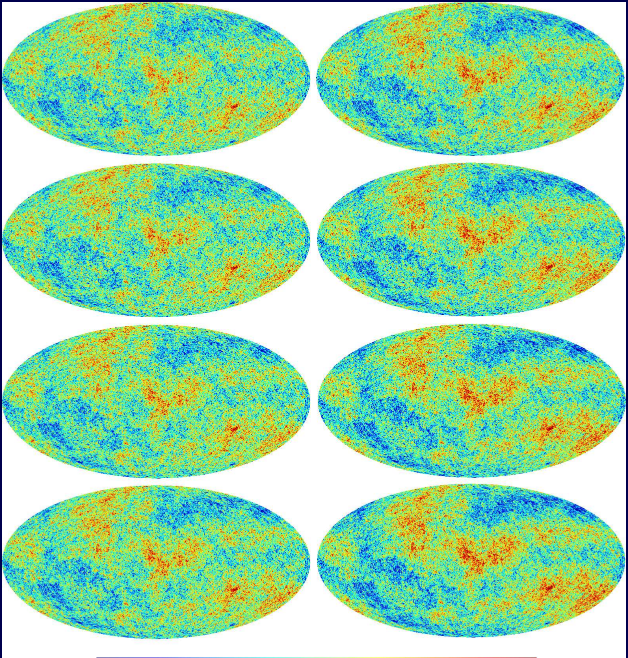


Figure 8. Comparison of the $\Omega_m - \Omega_\Lambda$ Bianchi degeneracy (shaded with 1 and 2σ contours) with the familiar CMB geometric degeneracy from WMAP first (blue) and third year + polarisation (green) data (with 1 and 2σ contours).

From Bridges et al (astro-ph//0605325)

Evidence for a Bianchi template in simulations



$\omega = 3 \times 10^{-10}$
$\Delta \ln E = -5$

$\omega = 4 \times 10^{-10}$
$\Delta \ln E = -3$

$\omega = 5 \times 10^{-10}$
$\Delta \ln E = -1$

$\omega = 6 \times 10^{-10}$
$\Delta \ln E = +1$

$\omega = 7 \times 10^{-10}$
$\Delta \ln E = +10$

$\omega = 8 \times 10^{-10}$
$\Delta \ln E = +7$

$\omega = 9 \times 10^{-10}$
$\Delta \ln E = +11$

$\omega = 10 \times 10^{-10}$
$\Delta \ln E = +18$

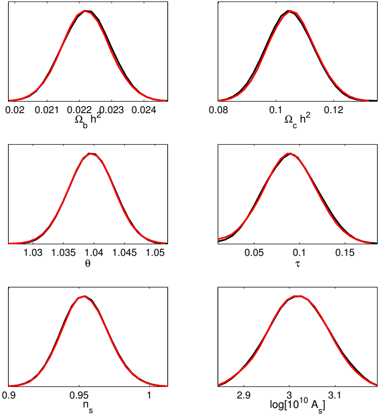
Evidence and Bianchi models

- So we start to be able to discriminate, at about the level of the original Bianchi template
- Indeed, considering this (no Λ now), we find that for both the WMAP1 and WMAP3 data such a template is needed by the data by a $\Delta \ln E$ difference which is positive but < 1 (so not definitive)
- So not clear if the data really warrant the introduction of these kinds of large scale features yet.

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 $V^{1/4} > \mathrm{few} \times 10^{15}\,\mathrm{GeV}$ (lensing, foregrounds, systematics?)
- Unresolved issues on large angles (topology, foregrounds, systematics, chance?)

CosmoNet: Accelerated cosmological parameter estimation using neural networks astro-ph/0608174

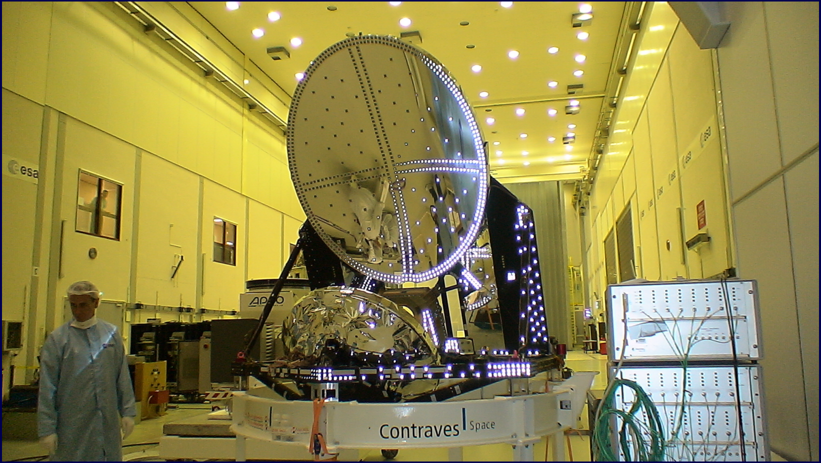


- CMB power spectra ($C_l^{TT,TE,EE}$) and WMAP 3-year likelihoods in microseconds for 6 parameter ΛCDM cosmology.
- Reduces total time required for parameter estimation with CosmoMc from $\sim$ 12 hours to $\sim$ 30 minutes.

Code available to download at:

`www.mrao.cam.ac.uk/software/cosmonet`

Progress with PLANCK II



Planck Telescope Flight Model at ESTEC after completion of videogrammetry test inside the Large Space Simulator.