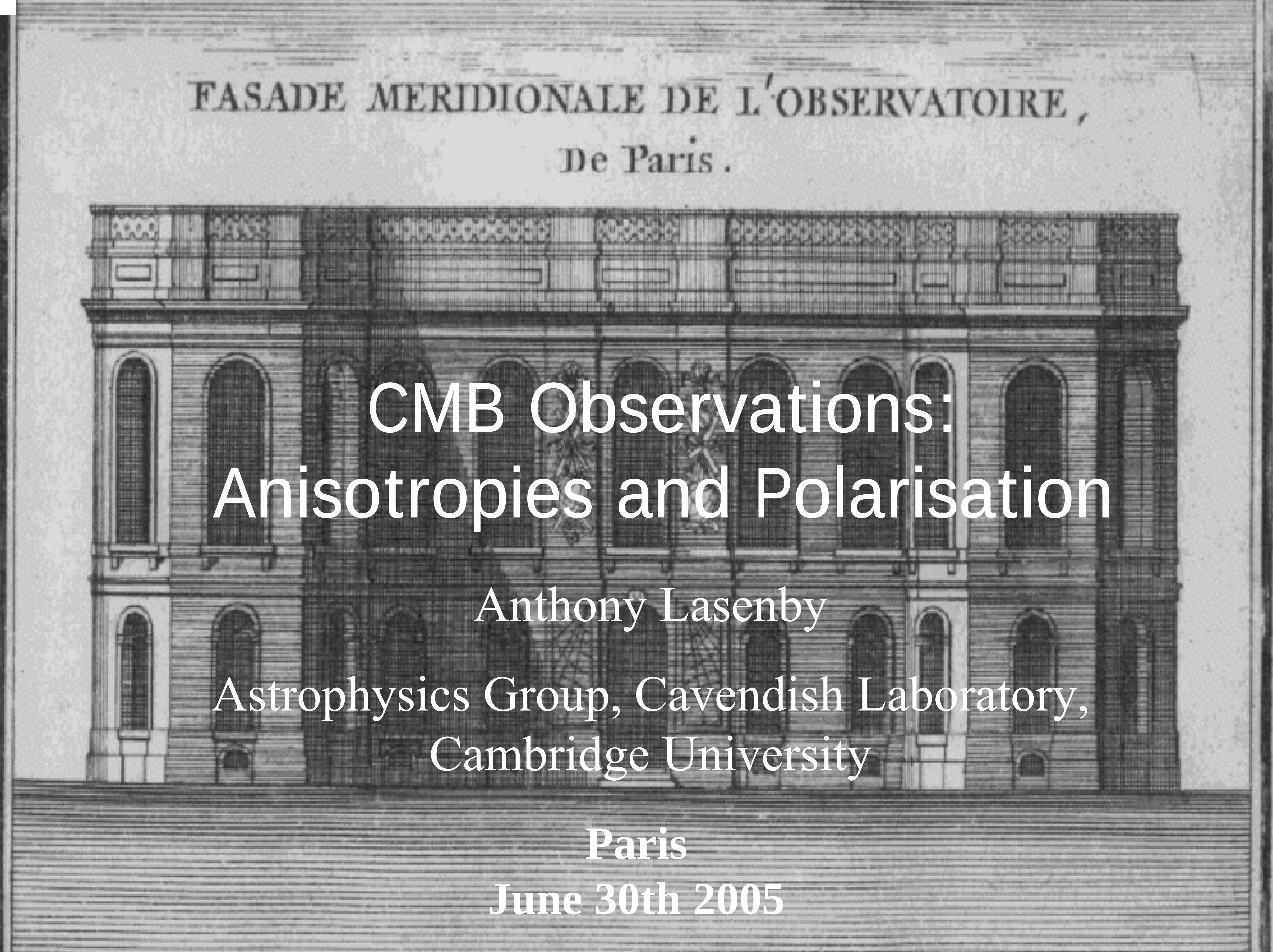

CMB Observations: Anisotropies and Polarisation

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Acknowledgments

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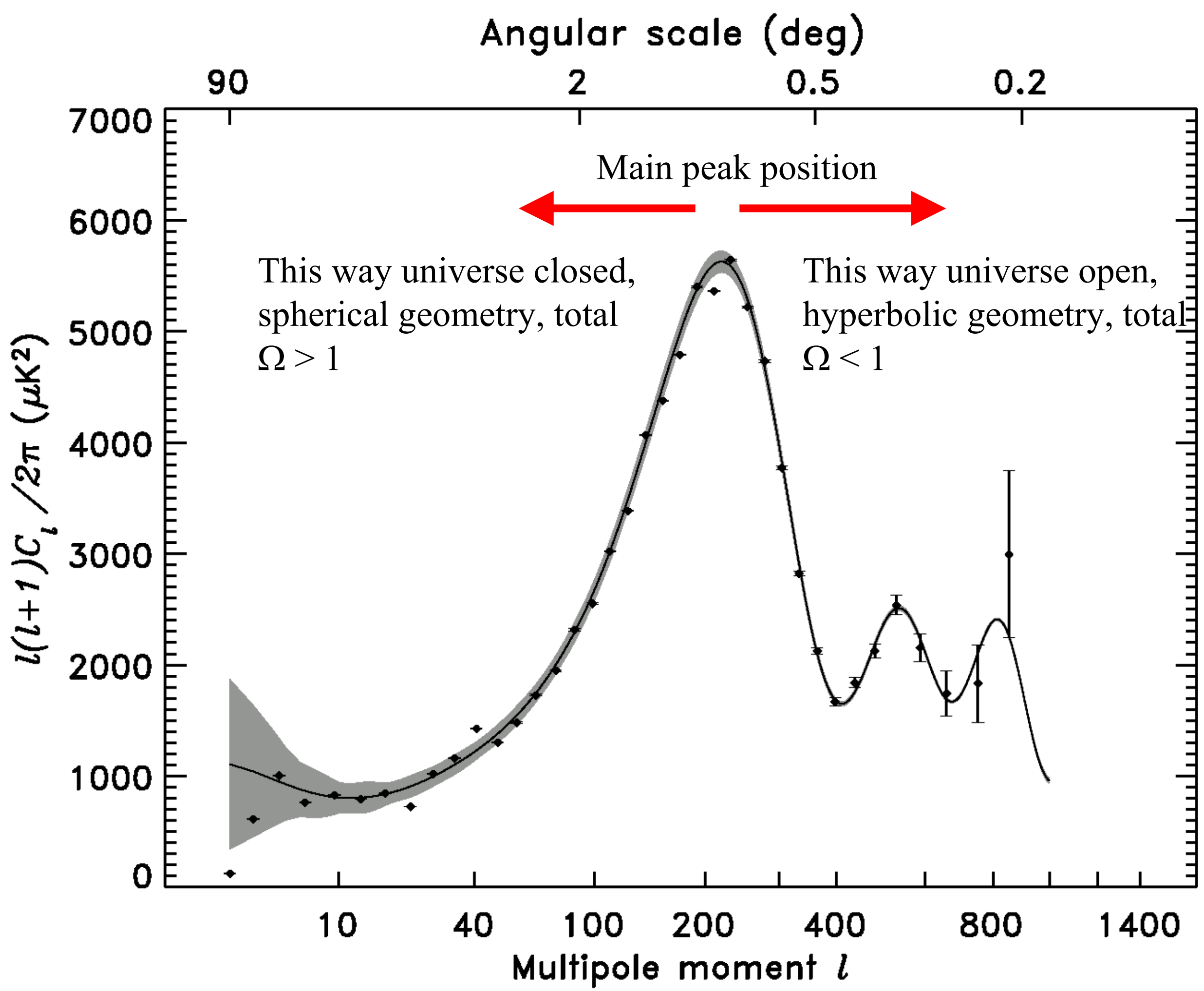
  - Anthony Challinor
  - Mike Hobson
  - Keith Grainge
- And to many other colleagues involved in some of the experiments discussed here

The Microwave Background

- Clearly a very exciting time for cosmology currently
- In a data-dominated phase
  - Large data sets
  - New instruments/techniques
- The CMB occupies an extremely important niche in this
  - (Though definitely still need other/complementary data sets)
- Experiments coming at a great rate!
- Going to concentrate here mainly on current/future ground-based experiments
- A few comments also on could the universe be closed? – will explain why interested, and some predictions
- Plus recent ideas re a non-isotropic universe

WMAP Results - WMAP Intensity Power Spectrum

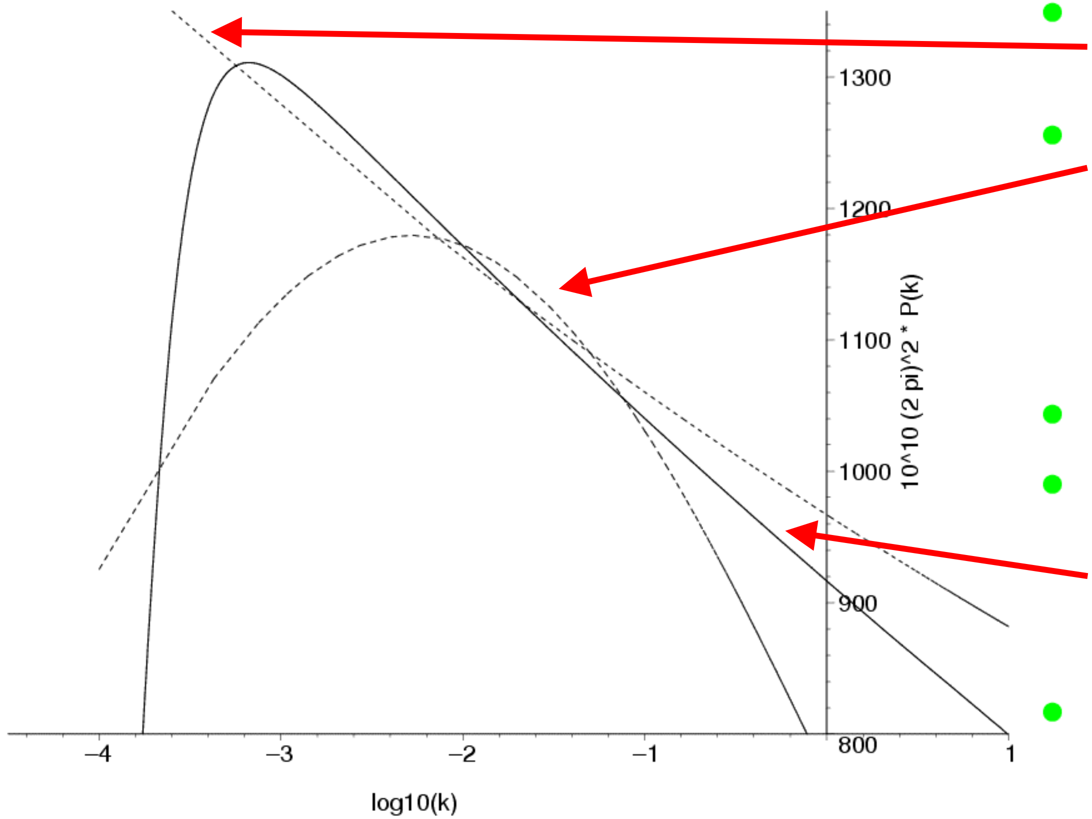


- Grey curve is ‘cosmic variance’ limit
- Errors are 1σ
- Note small ‘glitches’
- And low values at lowest multipoles

What do we still need to measure?

- To tie down inflation, then for next CMB measurements need:
  - Improved large scale measurements (low *l*) – cosmic variance means this is mainly a matter of improving frequency coverage to reduce foreground contamination – Planck will do a good job
  - This can help tell us about low *k* primordial spectrum
  - Measure total intensity CMB spectrum accurately at high *l*, with good resolution in *l* space
  - In conjunction with LSS data, this will tell use about departures from scale invariance, and possible n_{run}

Comparison of possible primordial power spectra



- A power law with $n_s = 0.96$ (dot-dash)
- The WMAP running spectral index best fit (dashed)

$$P(k) = P(k_0)e^{((n_s-1)\ln(k/k_0)+\frac{1}{2}n_{\rm run}(\ln(k/k_0))^2)}$$

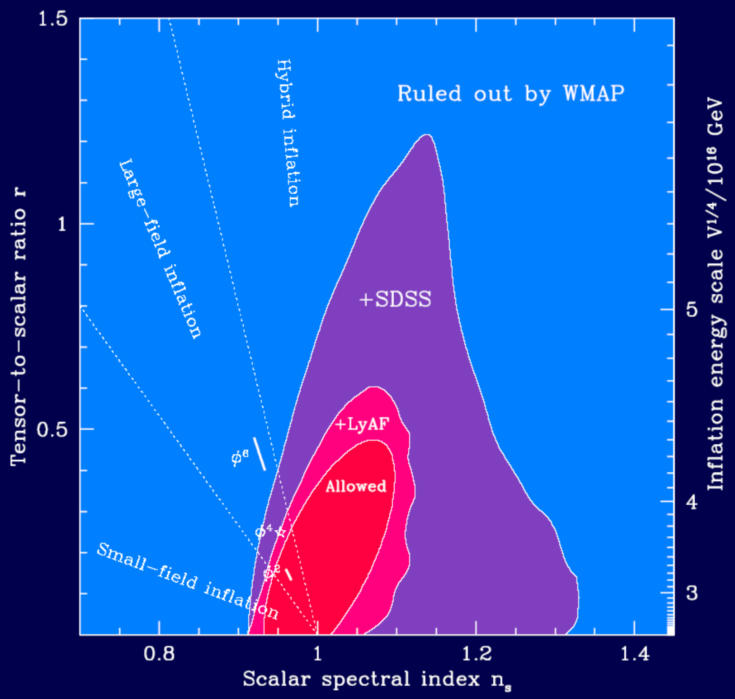
- ($n_s = 0.93$ and $n_{\rm run} = -.031$)
- Power spectrum computed for a slightly closed universe model (see later) with $\Omega = 1.02$ (solid line)
- Note the closed universe spectrum at high k is linear in $\ln k$ — not a power law!

What do we still need to measure (contd.)?

- Continuing with the theme of tying down inflation, let's think about what we now have as restrictions on inflation using e.g. WMAP + SDSS
- Will see that what comes out of this (as well as need for total intensity observations just discussed) is that we must:
  - Measure polarization spectrum in 'B-modes' to get tensor contribution – fixes directly energy scale of inflation and type of potential

Inflation post-WMAP and SDSS

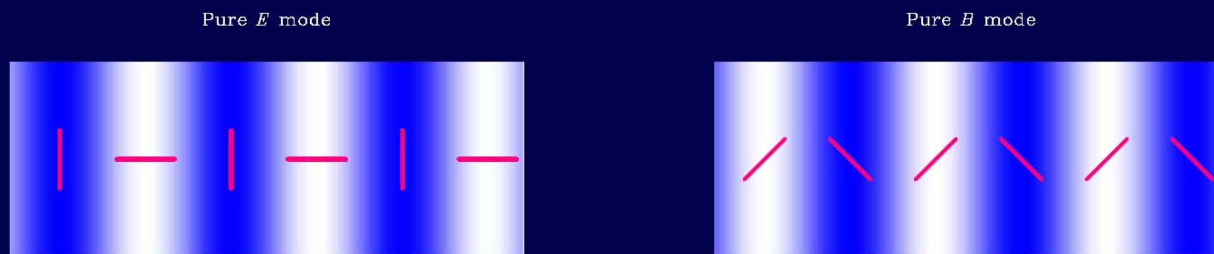
- Gaussian, adiabatic, super-horizon, nearly-scale-invariant density perturbations in flat universe
- Density perturbations A_s and n_s and gravitational waves with amplitude $A_t = rA_s \propto (V^{1/4}/m_{\rm Pl})^4$
- Energy scale totally uncertain: $100 < V^{1/4} < 2.6 \times 10^{16}$ GeV
- No evidence for dynamics of inflation (data consistent with low-energy, flat potential giving $r \approx 0$ and $n_s \approx 1$)
- Some large-field models already ruled out (e.g. ϕ^6 and ϕ^4)
- Sensitive GW searches key to determine physics of inflation



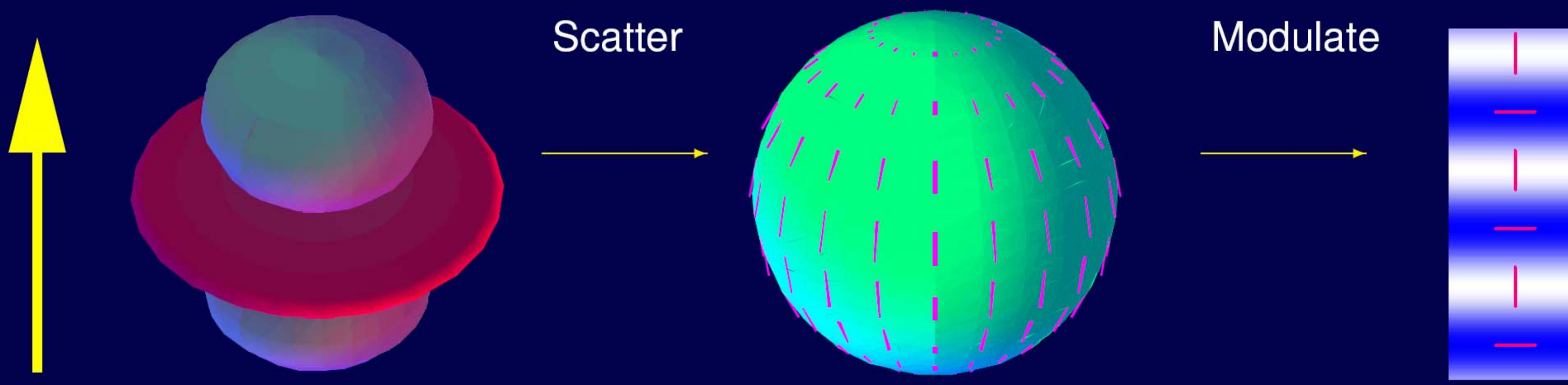
(Tegmark et al. 2003; Seljak et al. 2004)

CMB POLARIZATION

- Linear polarization (r.m.s. $\sim 6\,\mu$K) from Thomson scattering of anisotropic radiation around last scattering
  - Spin-2 decomposition into gradient-like modes with electric parity (E) and curl-like with magnetic parity (B):

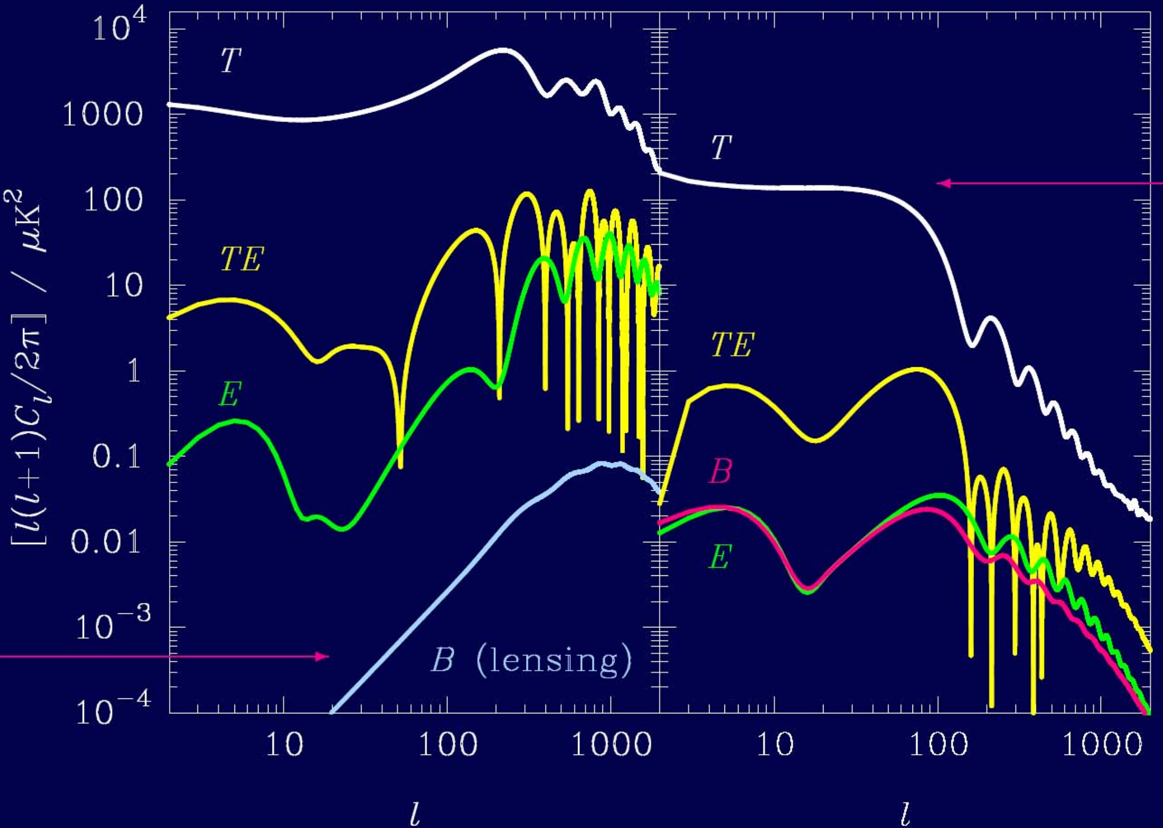


- Linear density perturbations produce no B modes $\Rightarrow$ 'smoking-gun' of gravity waves at recombination



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

GRAVITY WAVES AND THE CMB



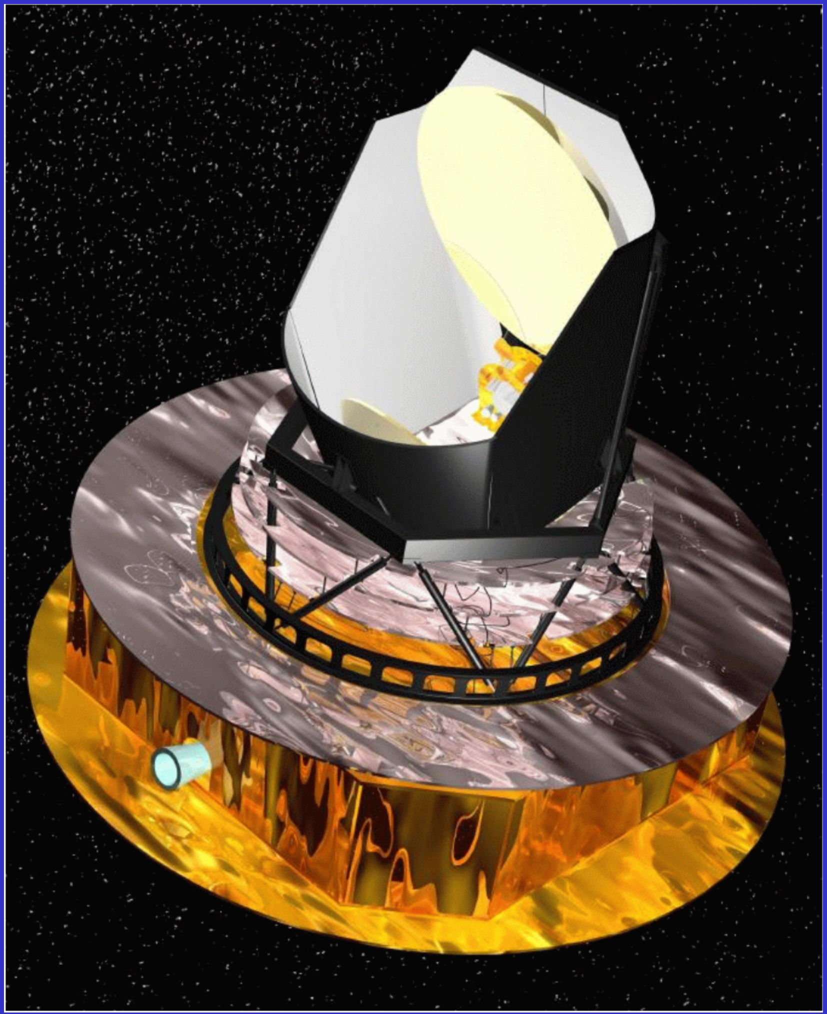
Effects only on large scales since gravity waves damp inside horizon

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

Should be limiting background for Clover

- B-mode polarization less troubled by sample variance of scalar perturbations c.f. E modes and ΔT
  - Limits of $\Delta r = 0.07$ with T only and 0.02 with E also

PLANCK

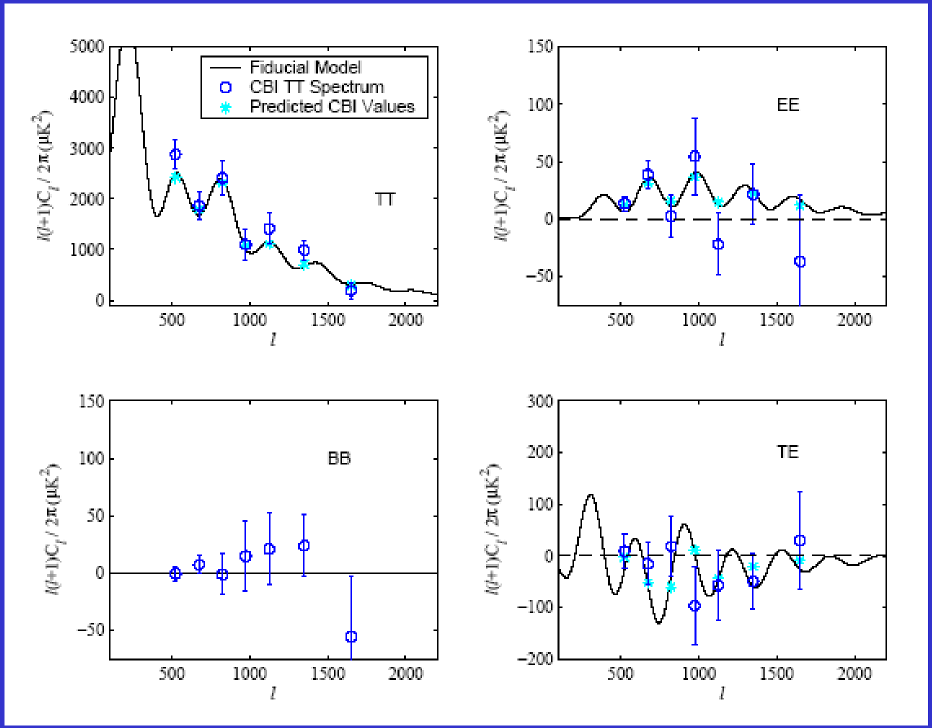


PLANCK (ESA Mission) – due for launch in late 2007

- Planck has ten frequency channels (30 – 800 GHz) and 5 arcmin resolution
- Should be able to achieve about 5 microK per beam area
- Should get intensity power spectrum extremely accurately to approx 8th peak
- Will probably be able to detect B polarization, but not find its spectrum accurately – other experiments needed for this
- Will be extremely good for E mode

The CBI (Cosmic Background Interferometer)

- Produced interesting new polarization results October 2004 (astro-ph/0409569) …

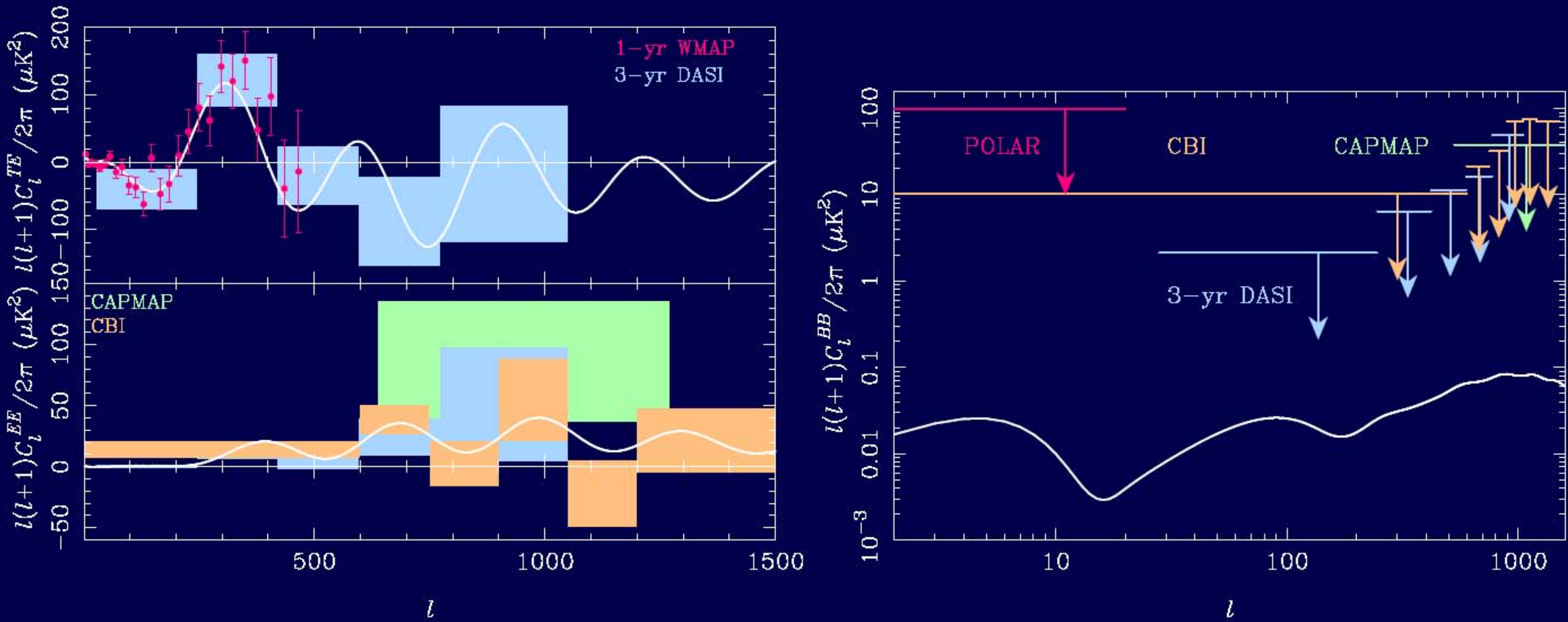


- CBI (Atacama Plain, Chile) in configuration used for polarization measurements

Latest CMB results - CAPMAP

- CAPMAP – Cosmic Anisotropy Polarization Mapper
- Chicago, Princeton, JPL, Caltech and others collaboration
- Four 84 – 100 GHz polarization receivers mounted in focal plane of a Lucent 7m telescope in New Jersey (Crawford Hill)
- Going after E-mode anisotropy at 4’ scale, in two wide bins
- First results reported recently (Barkats et al, astro-ph/0409380)
- Heterodyne technology and collaboration prototype for QUIET (see later)

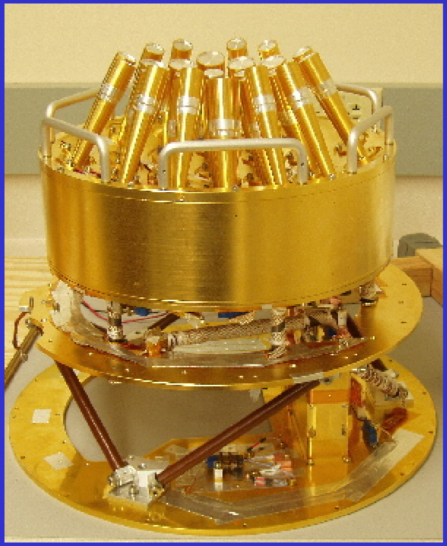
CURRENT STATUS OF CMB POLARIZATION MEASUREMENTS

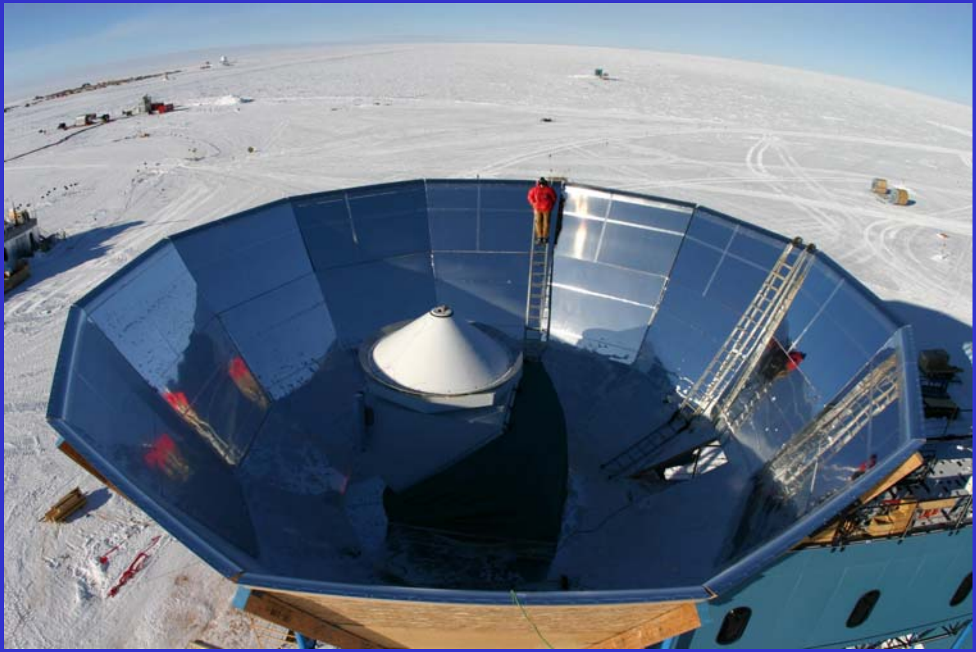


- Only upper limits on B-mode polarization at present: order of magnitude worse than constraints on r from ΔT (95% limit $r < 0.36$; Seljak et al. 2004)
  - R.m.s. of primordial $B < 0.25\,\mu$K

Current Experiments - 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
- Also going after E-mode anisotropy at 4’ scale
- Data-taking now underway over-winter at South Pole (currently -75 degrees C!)

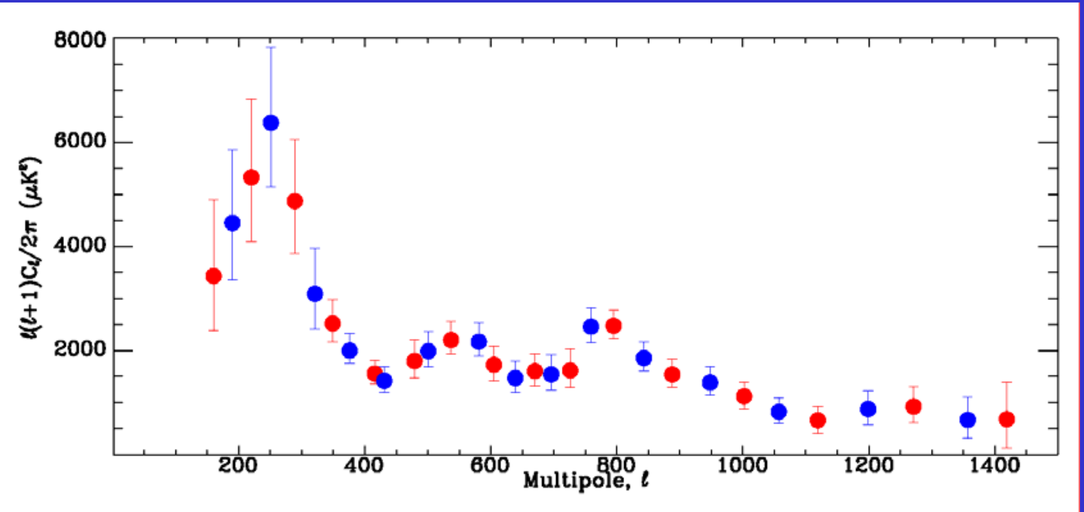




Current Status of VSA (Sited in Tenerife – built and run jointly by Cambridge and Jodrell Bank)

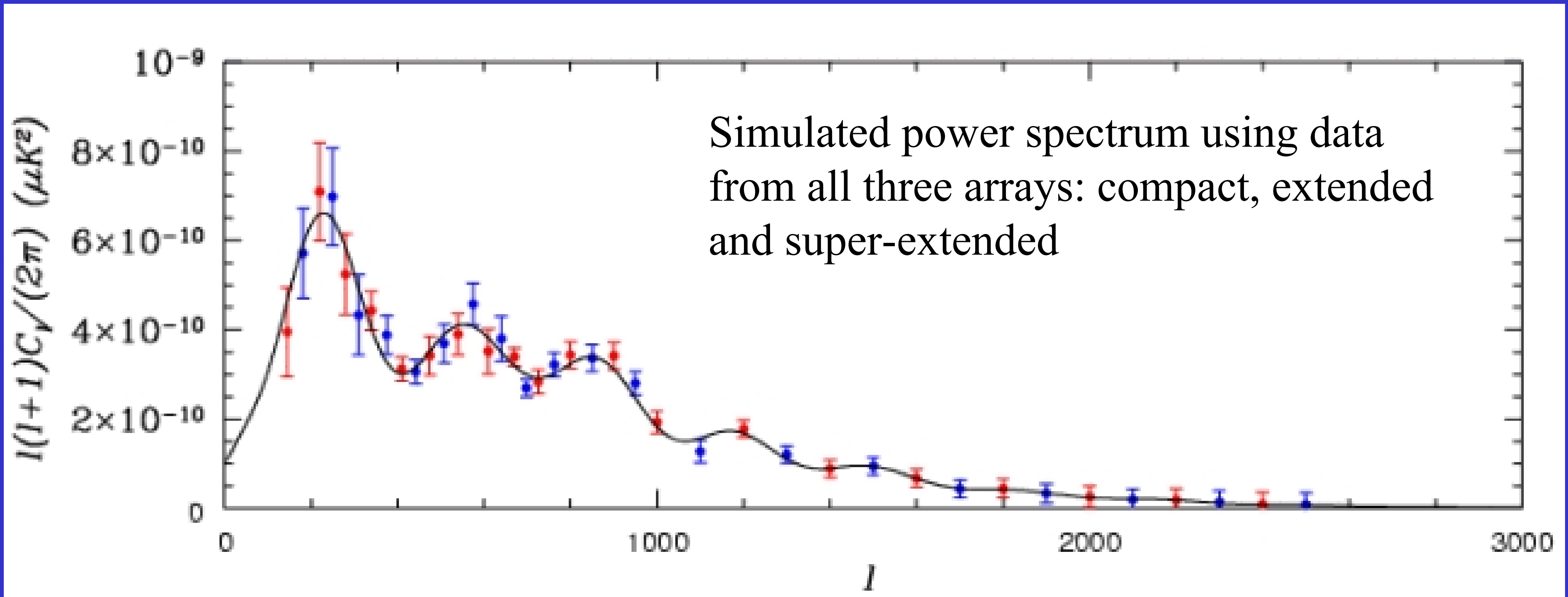
The extended array

Results from combined compact and extended arrays (Feb. 2004)

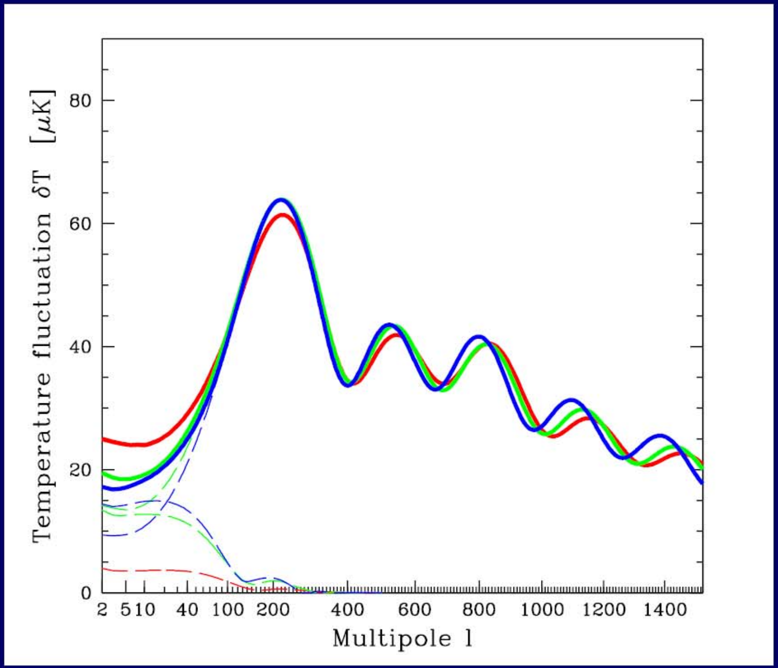


VSA plans – the Super-extended array

- Larger mirrors – new lightweight carbon-fibre design
- Upgraded front-end amplifiers (using Jodrell Bank experience of Planck amplifiers) – both this and mirrors nearly done
- Broadband correlator – 8 to 10 GHz vs. 1.5 GHz (also correlator of source subtractor) – this still awaits funding – may obtain correlator from CBI or DASI
- Could occupy key niche as regards *l* coverage at high *l* resolution

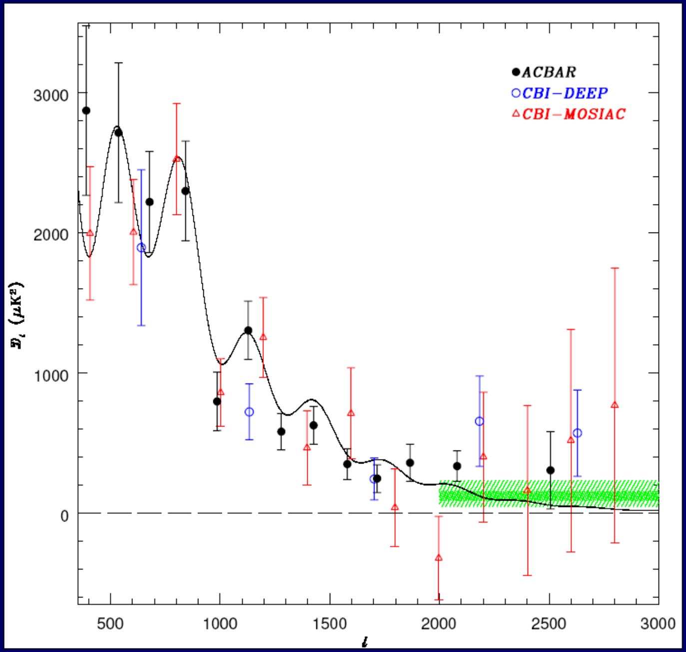


Detailed structure of power spectrum out to $\ell \simeq 2000$:



- Presence of further acoustic oscillations
- Form of damping tail $\Rightarrow$ recombination physics, damping mechanism, $\Delta z_{\rm rec}$ to 1%
- Form of primordial index $n_s(k)$ $\Rightarrow$ inflation dynamics, $\Delta n/n$ to 2%, scale-invariance
- Tighten existing parameter constraints, e.g. $(\omega_{\rm m}, \omega_{\rm b})$, $(n_{\rm s}, \tau)$
- Constrain Ω_ν $\Rightarrow$ limit on neutrino masses
- Set constraints on variable-α theories $\Rightarrow$ $\Delta\alpha/\alpha$ to 3%

Power level at $\ell > 2000$:



- Investigate excess power observed by CBI to $> 10\sigma$
- Determine contribution of integrated SZ effect:

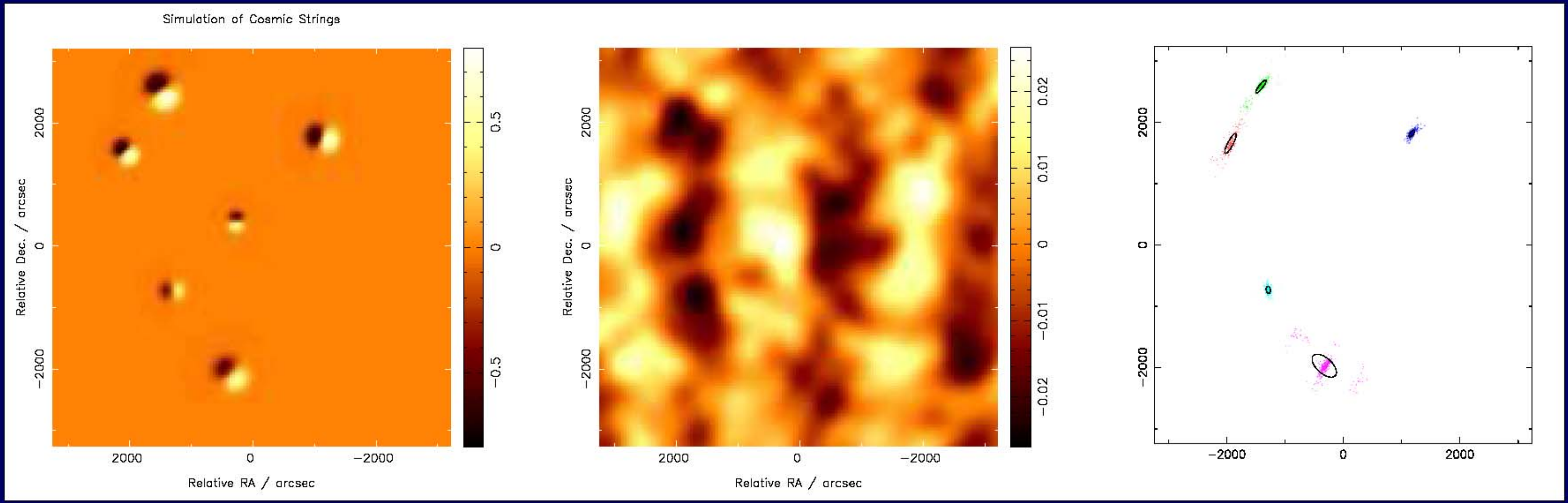
– low frequency (30 GHz) observations

– dedicated source subtraction

– direct mapping rather than differencing

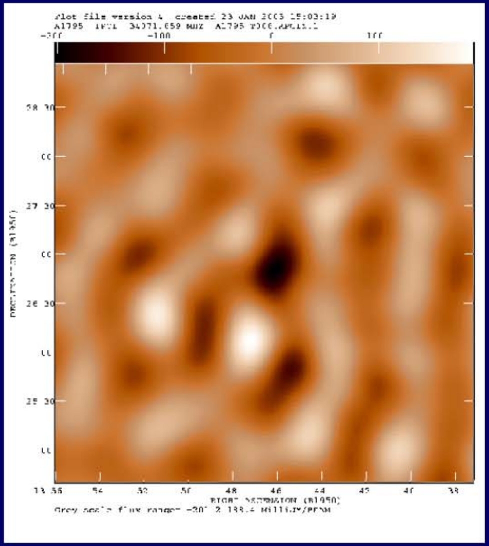
- If integrated SZ effect $\Rightarrow$ strong $\pm 2\%$ constraint on σ_8 (currently controversial)

High-resolution, high-sensitivity imaging of CMB anisotropies:

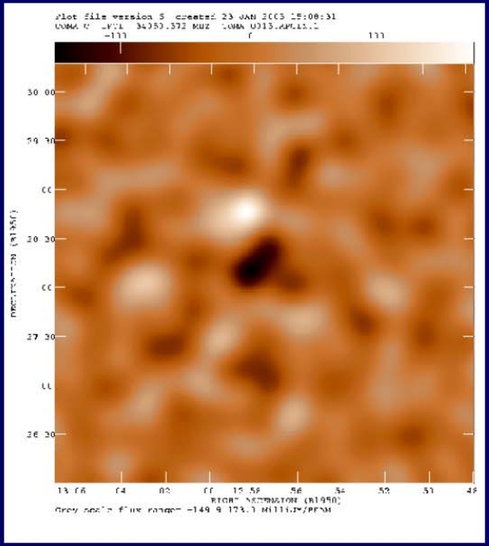


- Deep 3-field mosaic (5 deg^2) $\Rightarrow$ 1.5 μK per 5-arcmin beam (3$\times$ Planck sensitivity)
- Search for small-scale structures such as topological defects (cosmic strings)
- Sensitive tests for statistical non-Gaussianity
- Mapping SZ effect in nearly massive clusters

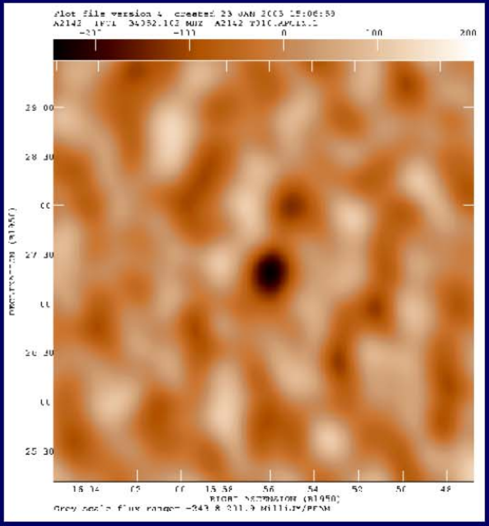
VSA SZ PROGRAMME: CLUSTER MAPS



A1795



Coma



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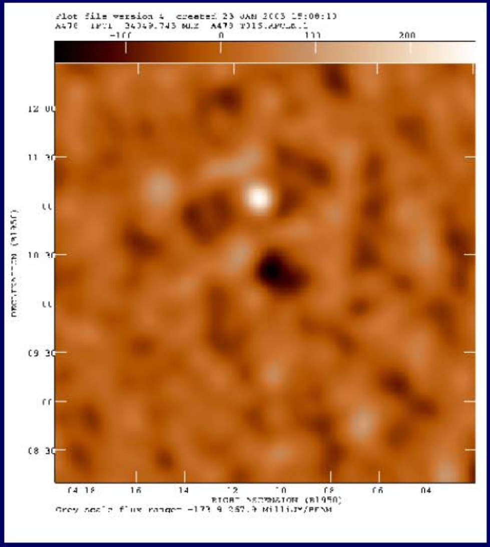


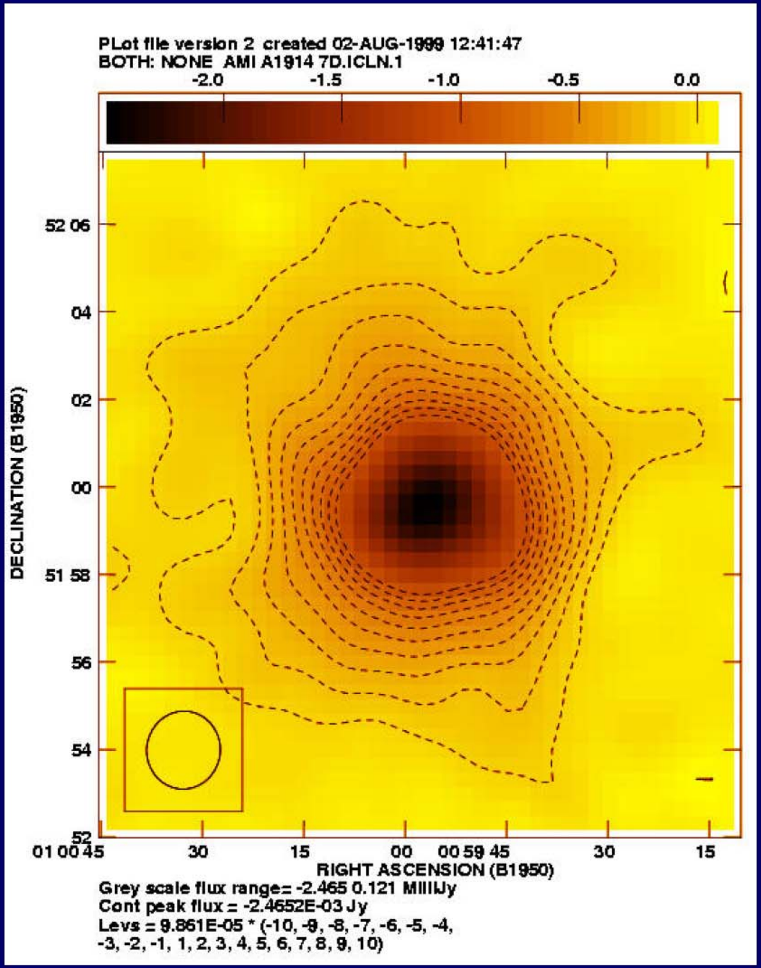
A478

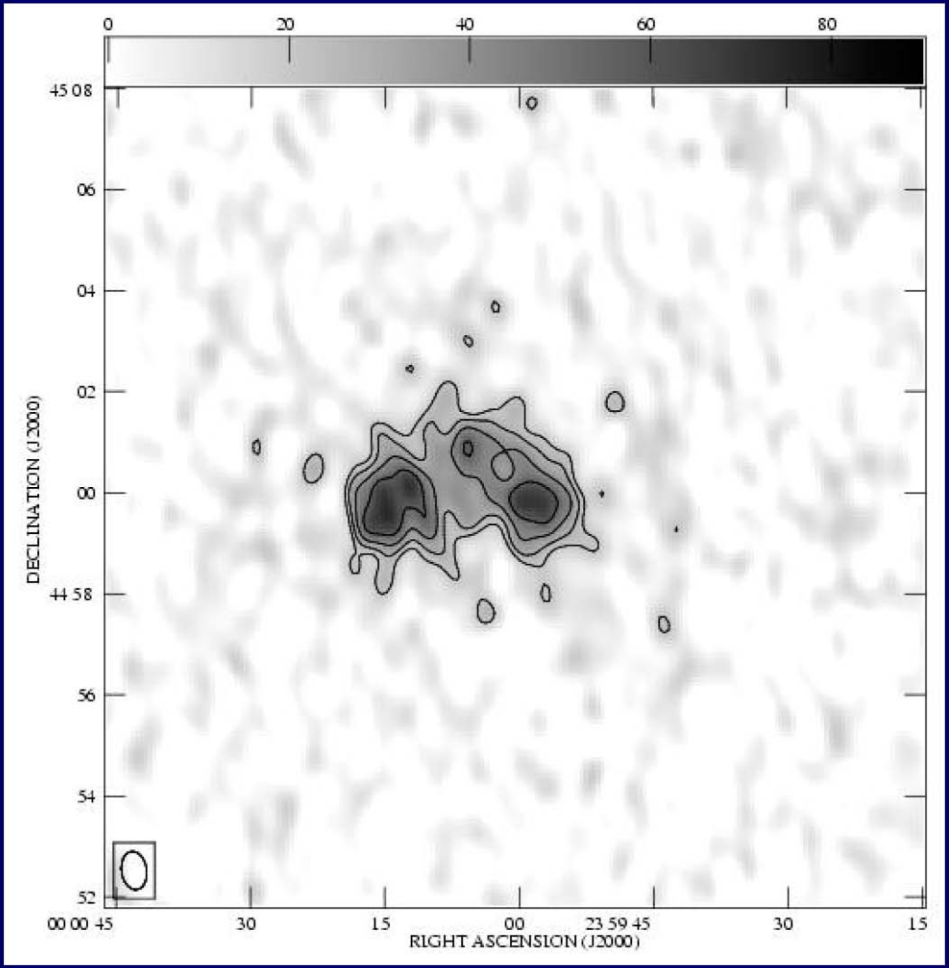
See Lancaster et al, astro-ph/0405582

New CMB projects - AMI

- Building of AMI (10 x 3.7m dishes + enhanced Ryle):
  - Next generation array for Sunyaev-Zeldovich and other CMB structures on arc-minute scales
  - Compact array nearly complete at Lords Bridge Cambridge
  - 3 outlier Ryle dishes have now been moved also (necessary for source subtraction and longer SZ baselines)
  - Gives images of clusters back to epoch of formation

PREDICTED PERFORMANCE – POINTED OBSERVATIONS

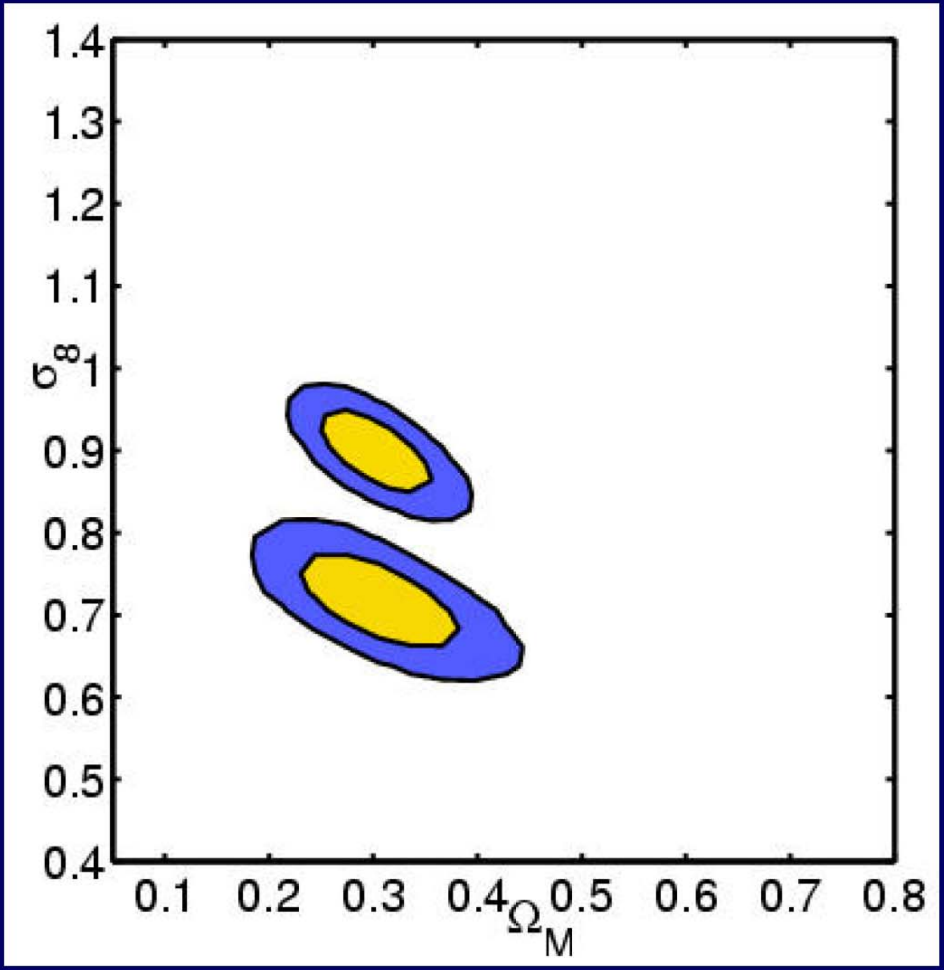




Simulation of A1914

Simulation of z=1.5, M = $2 \times 10^{14} M_{\circ}$ cluster

PREDICTED COSMOLOGICAL CONSTRAINTS



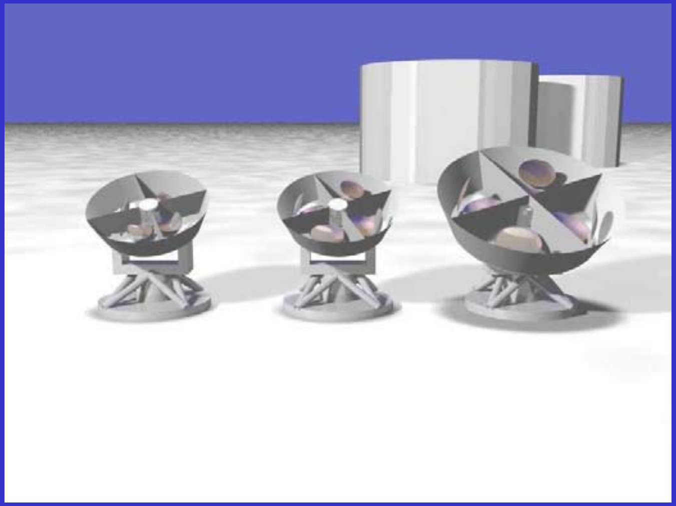
- 1 year, 100 square degree AMI survey

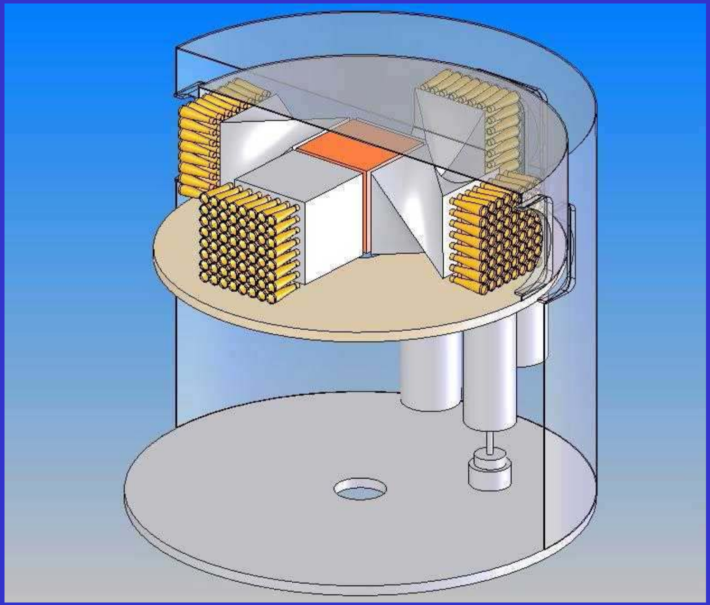
New CMB projects - AMIBA

- Taiwanese project – will be sited in Hawaii
- Array for Microwave Background Anisotropy (AMiBA)
- Planned as an interferometric array of 19 small radio telescopes mounted on a common hexapod platform
- One of the main science aims for AMIBA is measurement of polarization
- Will do this first, then move on to blank sky Sunyaev-Zeldovich survey

New CMB projects - CLOVER

- CLOVER
  - Joint project between Cambridge, Cardiff and Oxford
  - Aim is to image B-mode polarization of the CMB
  - ‘Smoking gun’ tensor mode perturbations (gravity waves) in early universe
  - Funded by PPARC – construction beginning





New CMB projects – CLOVER contd.

Specification summary for Clover.

Telescope freq.	90 GHz	150 GHz	220 GHz
Bandwidth	30 GHz	45 GHz	60 GHz
Pixel NET	170 $\mu Ks^{1/2}$	215 $\mu Ks^{1/2}$	455 $\mu Ks^{1/2}$
Array NET	10.5 $\mu Ks^{1/2}$	13.4 $\mu Ks^{1/2}$	28.5 $\mu Ks^{1/2}$
Beam FWHM	15 arcmin	15 arcmin	15 arcmin

- May be able to site at DOME C in Antarctica – 3200m elevation
- Will observe a few hundred square degrees
- Two-year observations imply 0.24 μK per resolution element
- Δr ¼ 0.004 possible
- Phased deployment – full instrument 2008

SECONDARY SCIENCE:

- Includes lensing (improves ‘dark’ parameters) and B-modes from new types of cosmic strings (e.g. Wyman et al, astro-ph/0503364)

New CMB projects - QUIET

QUIET – Heterodyne receiver CMB polarization experiment

• Pathfinders:

–100-element W-band (90 GHz) array on 1m telescope

–37-element Q-band (40 GHz) array on 1m telescope

• Later, two optical platforms:

–Lucent 7m telescope in Chile for small angular scales

–Novel 1m-scale telescope on CBI in Chile for large angular scales

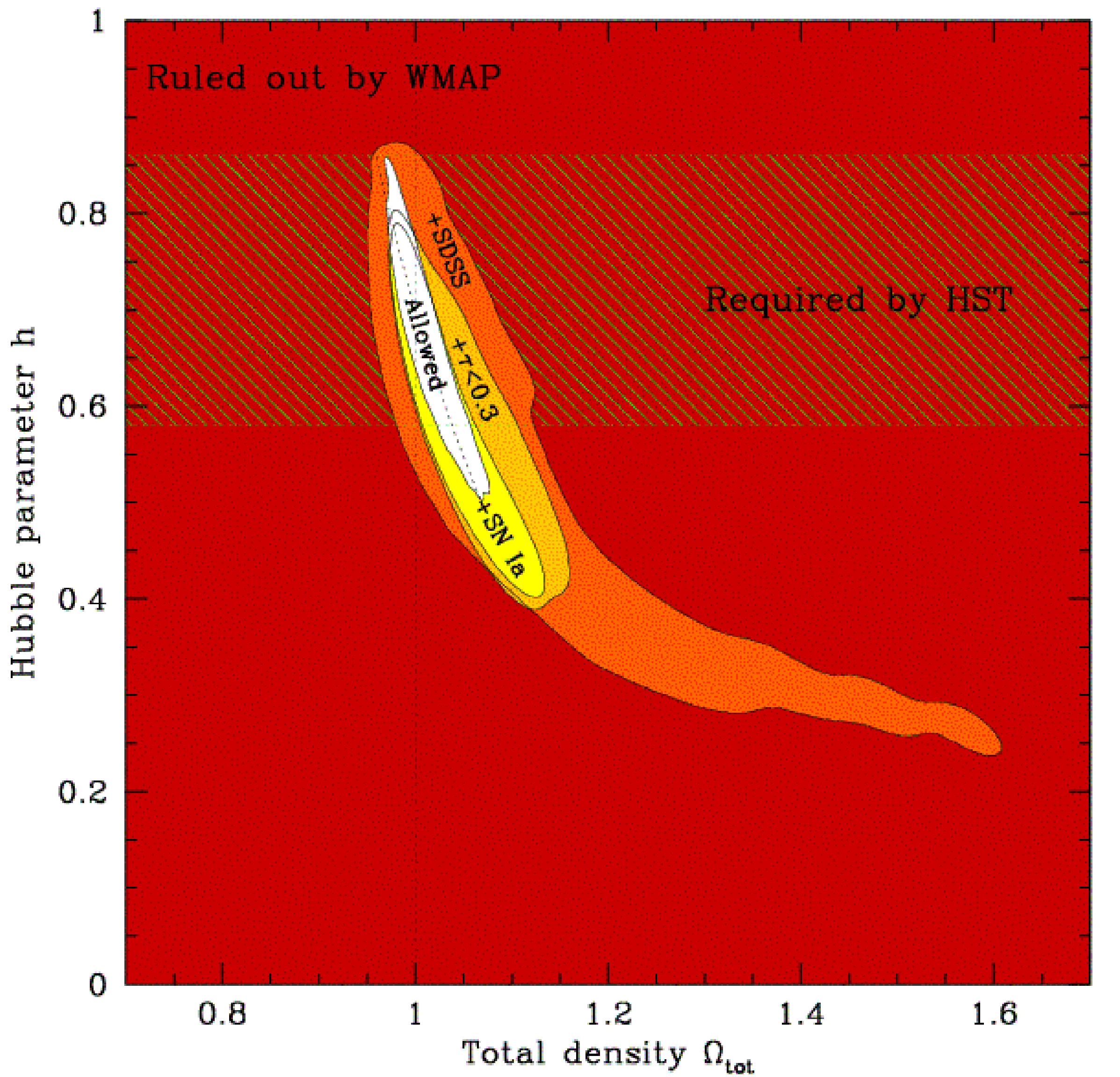
• Two frequencies at each angular scale:

–1000-element W-band arrays

–300-element Q-band arrays

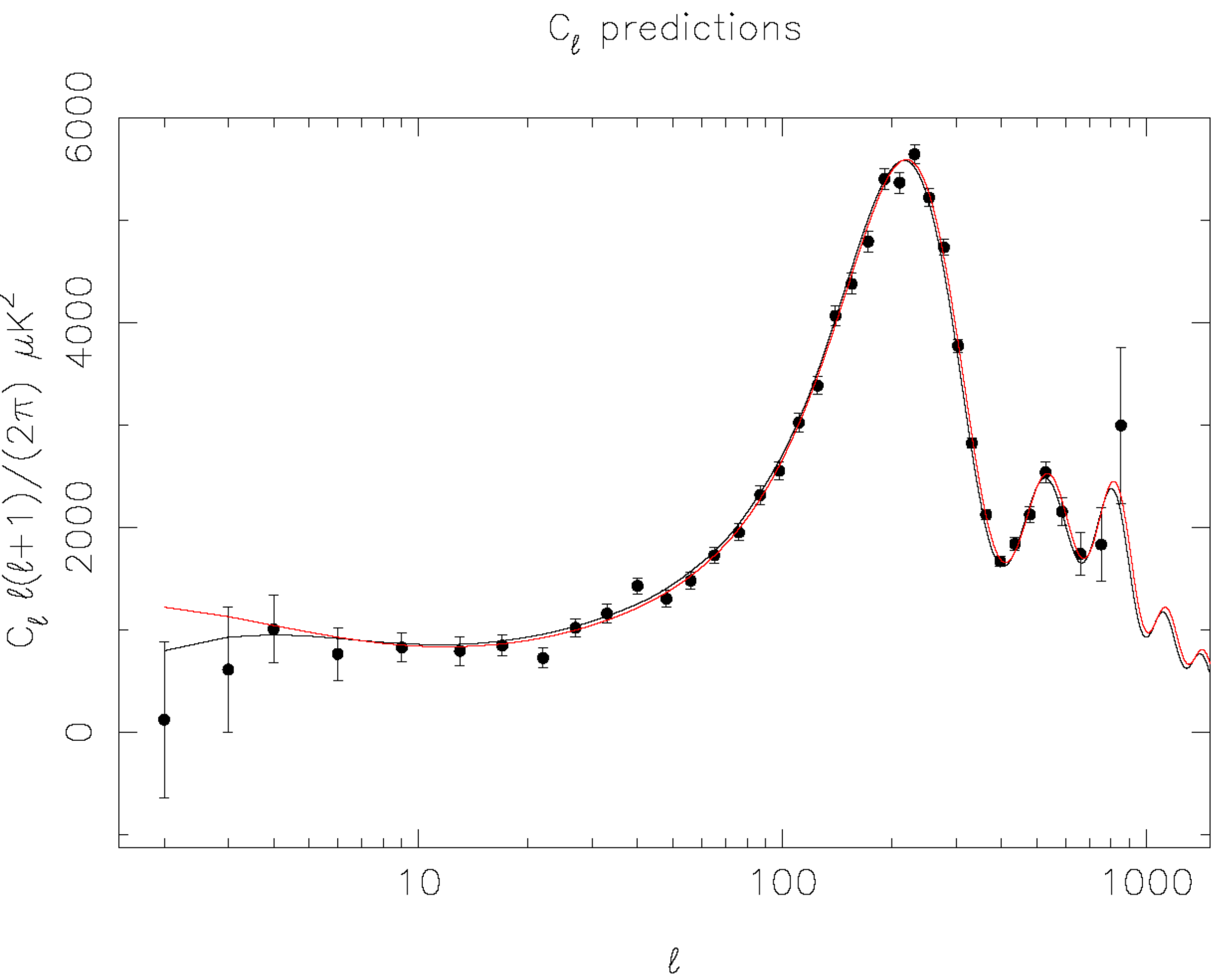
• Operate for 3+ years

Could the Universe be slightly closed?



- Not disallowed by current data (e.g. WMAP + SDSS – see Tegmark et al astro-ph/0310723)
- Lasenby + Doran (Phys.Rev.D, **71**, 063502 (2005)) have proposed a model which has generic curvature parameters going into inflation, but ends up slightly closed today

Another comparison with WMAP points



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

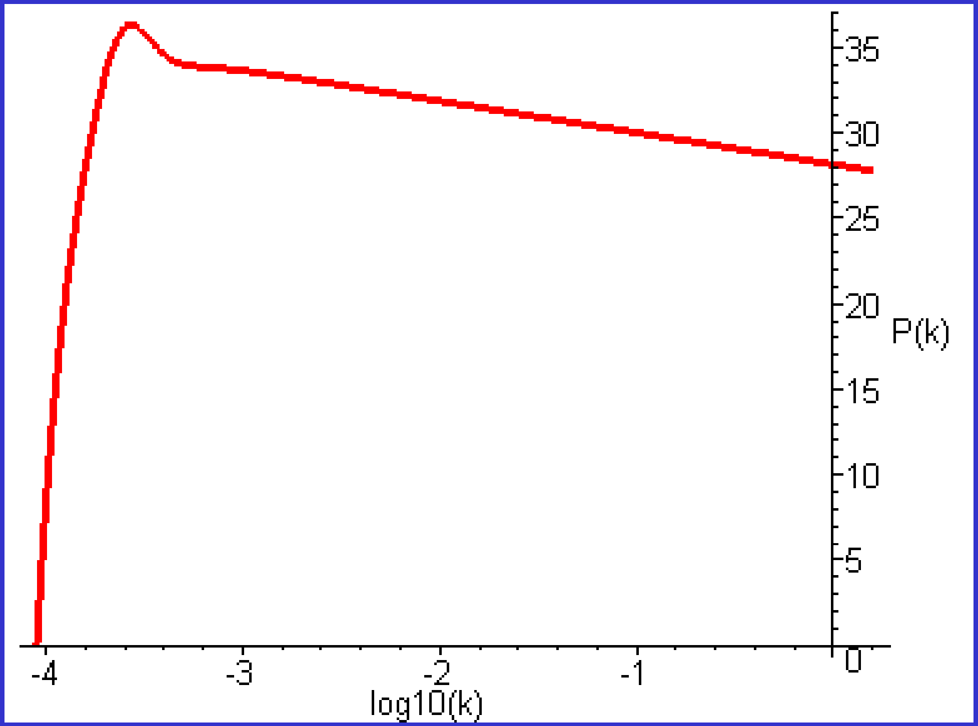
Evidence comparisons for different primordial spectrum models

Model	$\ln E(\text{model}) - \ln E_0$
Constant n	0.0 ± 1.70
Running	-0.84 ± 1.51
Cuto□	-0.40 ± 1.40
Broken	-5.17 ± 1.96
Binned	0.28 ± 1.53
Closed uni	3.62 ± 1.64

$\Omega_{tot} = 1.024$; $\Omega_b h^2 = 0.0229$;
$h = 0.61$; $\Omega_{cdm} h^2 = 0.118$

- Recent work by Bridges, Hobson + ANL (will be submitted shortly)
- ‘Evidence’ measures goodness of fit but also penalises properly for ‘too many parameters’
- Express it relative to some given model
- Work with overall best fit that we found for combined WMAP +VSA+2dF+ SDSS data

An exact primordial power spectrum for slightly closed model

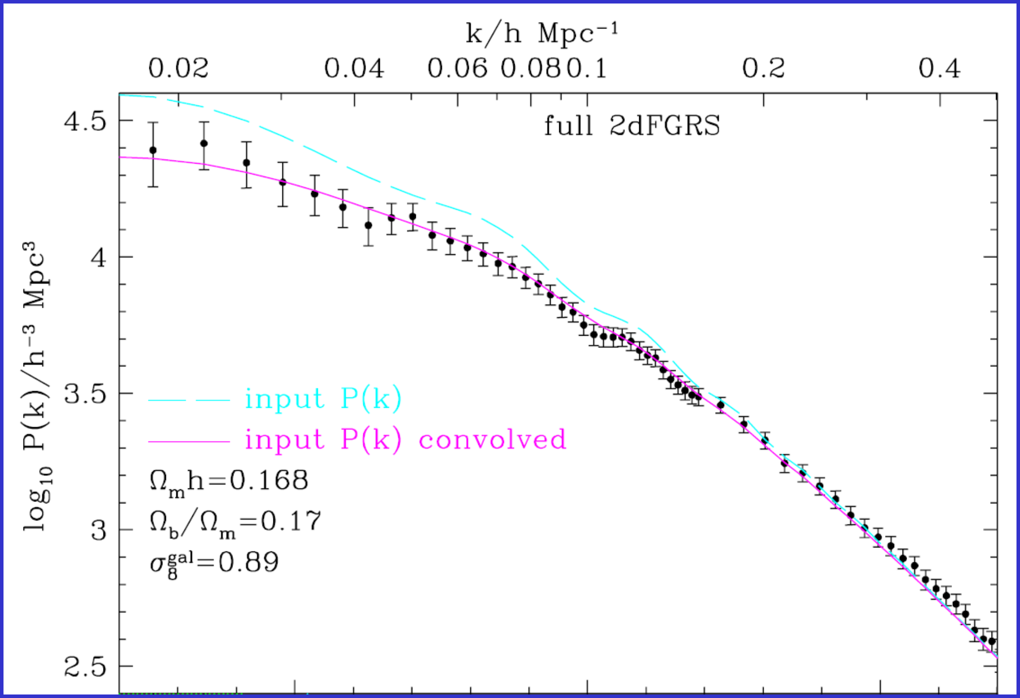


- CMB curve in previous slide was computed using an approximate primordial *P(k)* in the closed model
- Does the cutoff at low *k* survive if an exact computation is done?
- Yes, and shows an interesting signature as well
- Would need to defeat cosmic variance to see this – ultimately there may be ways

Results for parameters using 'baryon peak' LSS detection

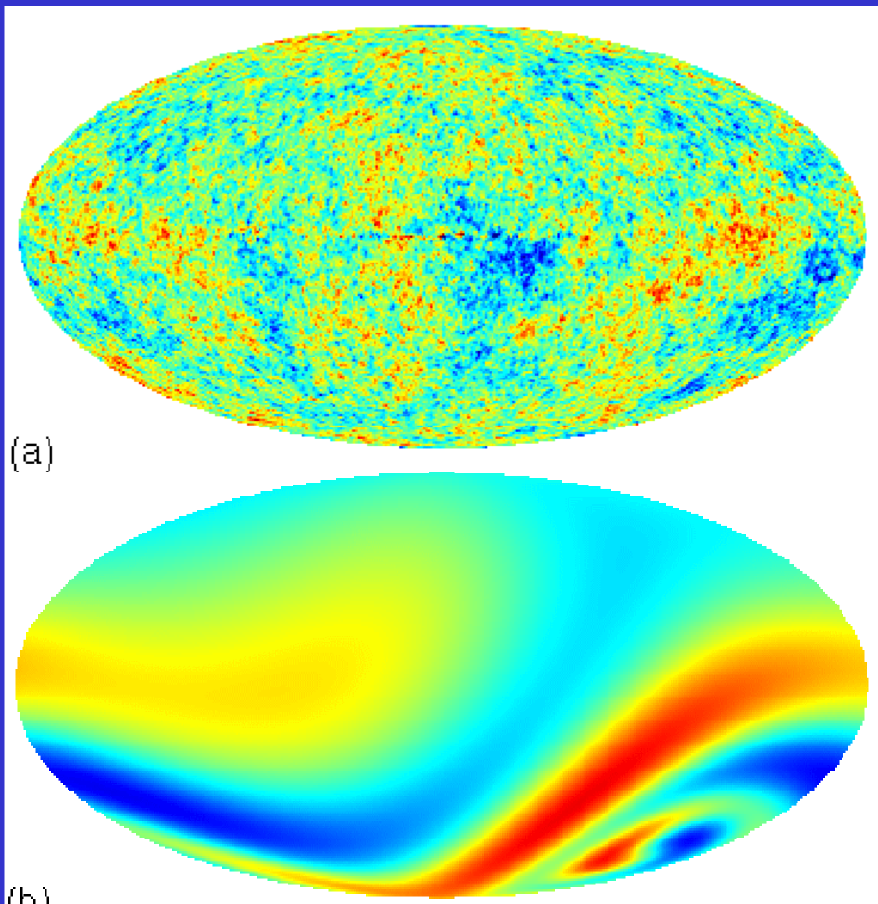
Joint Constraints on Cosmological Parameters including CMB data

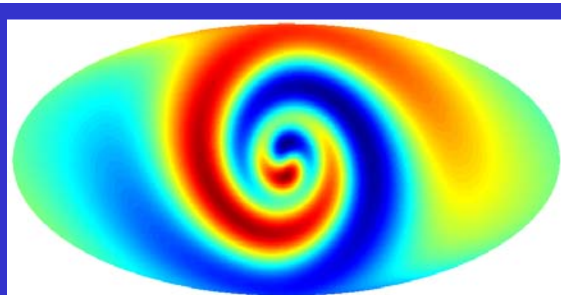
Parameter	Constant w flat WMAP+Main	Constant w flat +LRG	$w=-1$ curved WMAP+Main	$w=-1$ curved +LRG	$w=-1$ flat WMAP+Main	$w=-1$ flat +LRG
w	-0.92 ± 0.30	-0.80 ± 0.18	...	...	...	...
Ω_K	...	...	-0.045 ± 0.032	-0.010 ± 0.009	...	...
$\Omega_m h^2$	0.145 ± 0.014	0.135 ± 0.008	0.134 ± 0.012	0.136 ± 0.008	0.146 ± 0.009	0.142 ± 0.005
Ω_m	0.329 ± 0.074	0.326 ± 0.037	0.431 ± 0.096	0.306 ± 0.027	0.305 ± 0.042	0.298 ± 0.025
h	0.679 ± 0.100	0.648 ± 0.045	0.569 ± 0.082	0.669 ± 0.028	0.696 ± 0.033	0.692 ± 0.021
n	0.984 ± 0.033	0.983 ± 0.035	0.964 ± 0.032	0.973 ± 0.030	0.980 ± 0.031	0.963 ± 0.022



- Detection of baryon wiggle in 2dF power spectrum
- Above is results with and without LRG galaxies from latest Sloan data

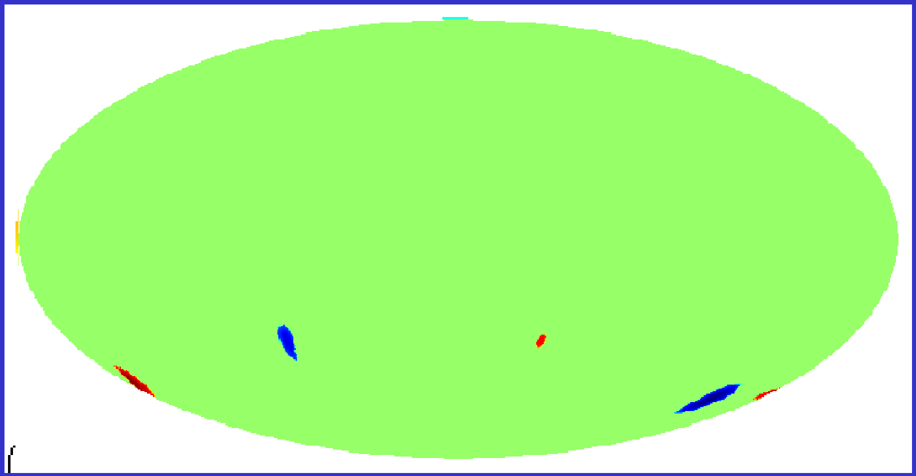
A Bianchi Model Universe?

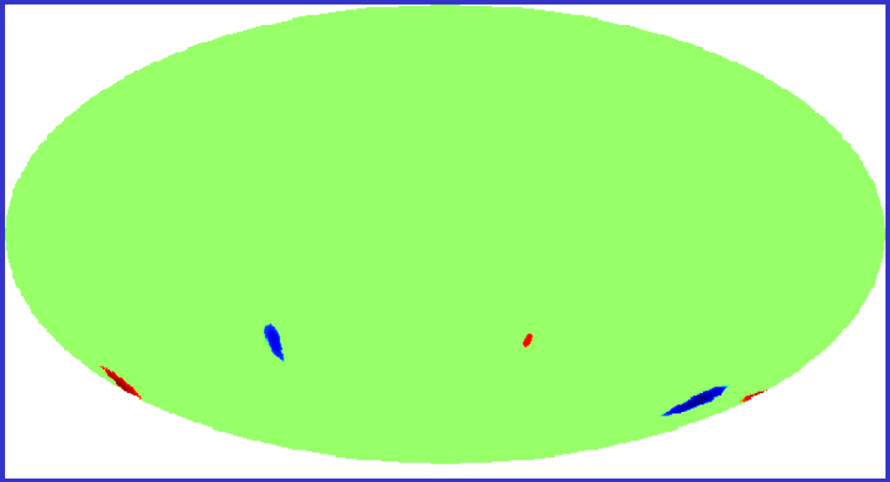




- Several authors have commented on a significant North/South asymmetry in the WMAP data, plus strange alignment between low multipoles
- Jaffe et al. (astro-ph/0503213) have fitted a Bianchi VIIh template to WMAP sky
- Find a best fit with $\Omega_0 = 0.5$
- Coldest part of template corresponds with a non-Gaussian spot found in in Vielva et al (astro-ph/0310273) and drawn attention to in Cruz et al (astro-ph/0405341)

A Bianchi Model Universe?





- Can also compare with results of directional wavelet analysis in McKewan et al (astro-ph/0406604)
- Same spot shows up – also other two main spots it finds could also be relevant
- But how to reconcile with having to mix Bianchi with a flat Lambda model to fit all the rest of the CMB data??

Conclusions

- Have yet to see any dynamics of inflation
- Total intensity spectrum still very relevant for this
- Serious B-mode experiments, for gravity wave detection and therefore energy scale of inflation, now under way
- Foregrounds big issue for these
- Some possible surprises/new physics maybe already hinted at in large scale data (e.g. 'just closed' universe, or rotating universe explanation for north/south asymmetry)