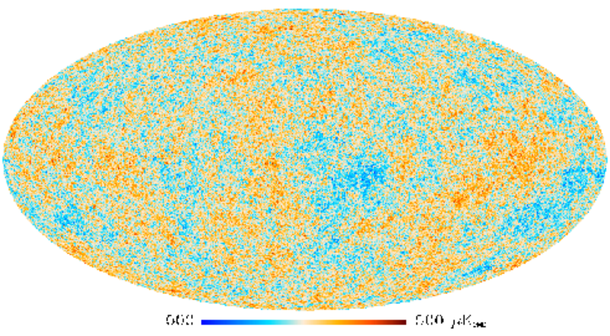


CMB Observations and their implications for cosmology

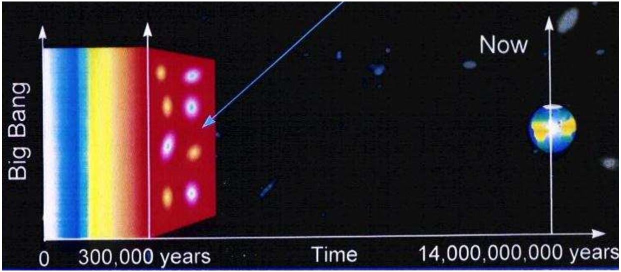
Anthony Lasenby, Astrophysics Group,
Cavendish Laboratory and Kavli Institute for Cosmology, Cambridge

(Paris Chalonge Meeting – July 2013)

Outline

- Last year has been a very good one for the CMB
- 9 year results from WMAP (will hear about from Eiichiro Komatsu)
- Results from SPT and ACT (talk by Sudeep Das)
- Release of first cosmology results from Planck
- Will devote a good fraction of today's talk to the Planck results, and there's also a talk on the Planck mission and cosmology results from Carlo Burigana — we have attempted to coordinate between these!
- Other thing I will highlight, since promises very interesting progress soon on 'tensor modes', is South Pole BICEP experiment

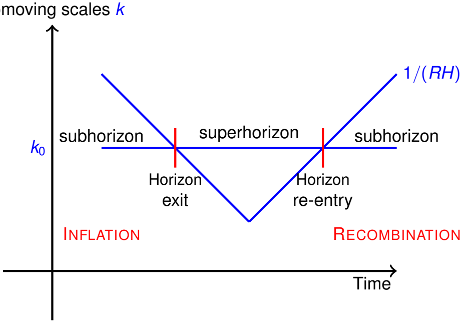
The cosmic microwave background



- The Cosmic Microwave Background (CMB) was emitted at about 300,000 years after the big bang and has been propagating to us ever since
- Embedded within it are the ‘seed fluctuations’, which go on to form galaxies and clusters of galaxies
- Going backwards in time, believe these seeds were laid down about about 10^{-36} seconds after the big bang as quantum fluctuations during inflation

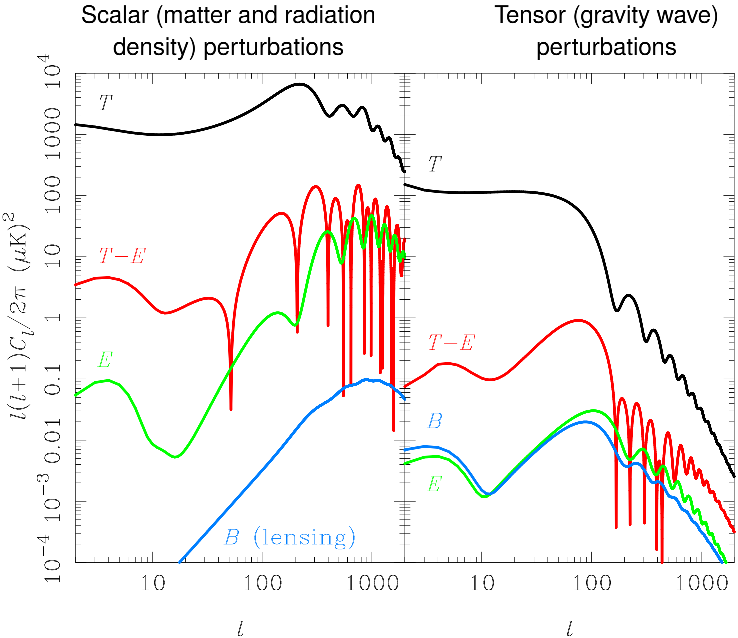
Inflation and the fluctuations

- Inflation boosts the perturbations to such a large scale that they lie outside the horizon scale (c/H) at very early times
- Equivalently, in comoving terms (divide by the scale factor R), inflation shrinks the comoving horizon, and perturbation scales which start inside (happily oscillating) then move outside and freeze
- Only re-enter the horizon and start to feel their own self-gravity (which for baryons and photons leads to oscillations), quite late (not long before recombination), and each mode when it re-enters effectively starts from rest



- This ‘phases up’ the fluctuations leading to a series of distinct peaks in the power spectrum

CMB Power spectra



Gravity waves

- Express the amplitude of gravity waves coming from inflation, relative to scalar modes from inflation, via their ratio r at some fiducial comoving wavenumber (typically low, e.g. $k = 0.001\,\mathrm{Mpc}^{-1}$)
- Key point is that if we decompose CMB polarization vector field on sky into a potential part E and curl part B (both of which are rotationally invariant, unlike Q and U Stokes parameters), the only primordial source of B are gravity waves!
- What would a detection of primordial gravity waves tell us?
- Strong evidence that inflation happened
- Find

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

- Thus detectable gravity waves ($r > 0.01$ say) would mean inflation occurred at the GUT scale
- We would then be accessing particle physics at a scale about at least 10^{12} higher than those achievable at LHC

Planck Cosmology Results

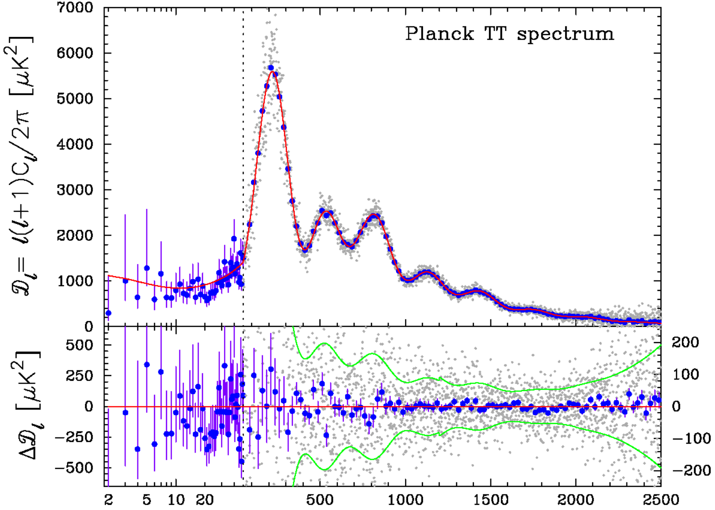
- The scientific results from Planck are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.
- Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

Planck Cosmology Results

- 28 papers plus associated data products released Mar 21
- Made headlines around the world, including front page of the NY Times
- Broad overview of results would be:
- Spectacular overall agreement with a simple 6-parameter ΛCDM cosmology
- But with some hints of departures in places
- And some tensions with other results

Planck Cosmology Results

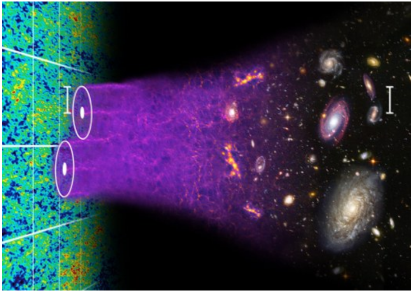
- Planck has produced a wonderful power spectrum of the fluctuations in the CMB sky
- Very big increase in accuracy (e.g. can now definitely say Dark Energy and Dark Matter exist, just from primordial CMB alone)



The standard model

What are the parameters of the standard model?

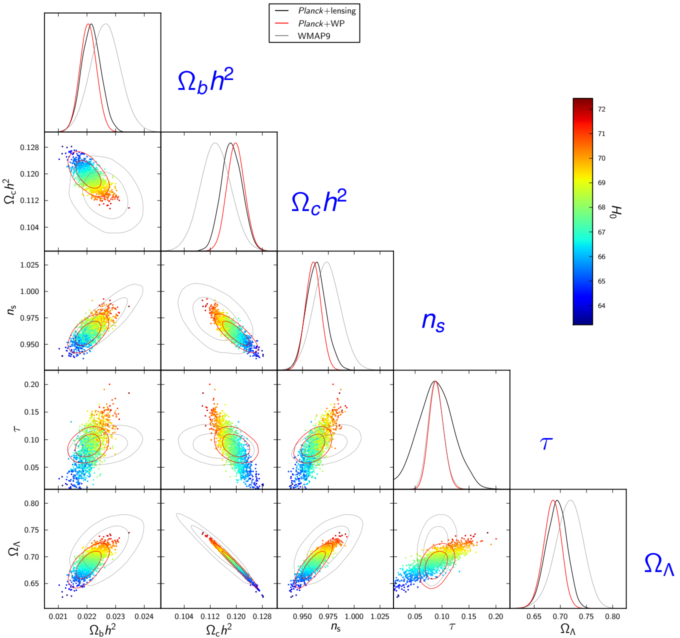
- Physical density in baryons $\Omega_b h^2$ ($h = H_0/100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$)
- Physical density in cold dark matter $\Omega_c h^2$
- $100\times$ angular diameter of sound horizon at last scattering $100\theta_*$
- Optical depth due to reionisation τ
- Slope of the primordial power spectrum of fluctuations n_s
- Amplitude of the primordial power spectrum (at a given scale) A_s



What is significance of detection?

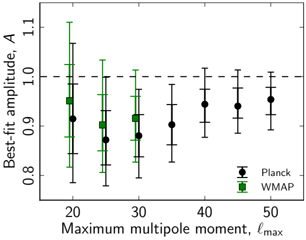
- 50 million pixels, compress to ~ 6 million spherical harmonic coefficients, and then to a power spectrum with close to 2000σ worth of signal
- All this well-fit by a model with just 6 parameters!

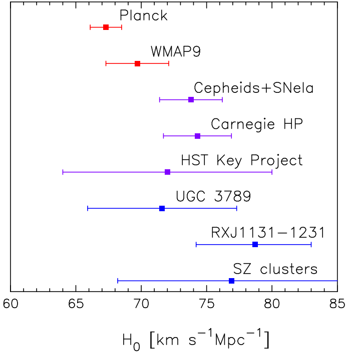
Comparison with WMAP9



Planck Cosmology Results

- Some hints of departures from simplest expectations on large scales
- Low-ℓ spectrum about 5–10% lower than expected cf. to best fit ΛCDM model at about 3σ significance
- Also H_0 from CMB now discrepant with recent HST + Spitzer determinations at about 2.5σ level
- (Universe has got slightly older Planck about 40 Myr $>$ WMAP9 value.)
- Some hints from SPT data for an extra neutrino species don't seem to be supported (though such a thing could help reconcile Planck H_0 determinations with others)

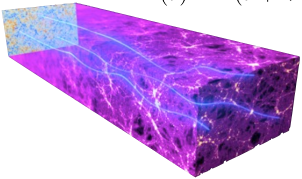


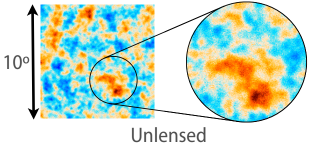


From Karim Benabed talk at Planck 2013 ESLAB Meeting

CMB lensing reconstruction

$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \ldots$$



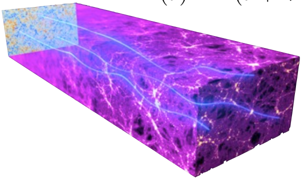


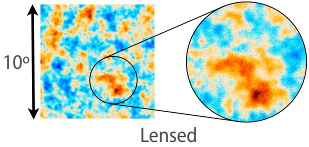
Gravitational lensing

From Karim Benabed talk at Planck 2013 ESLAB Meeting

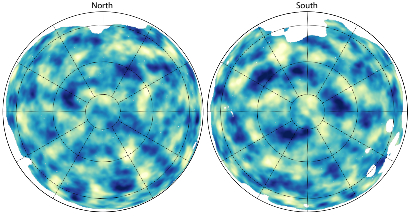
CMB lensing reconstruction

$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \ldots$$





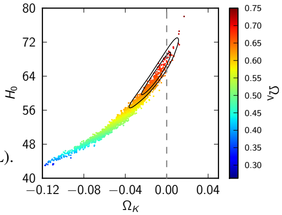
Gravitational lensing



- Maps of integrated Newtonian potential between here and last scattering surface
- Represents 25σ detection of lensing!
- Use power spectrum of this to generate a lensing likelihood

Breaking the geometrical degeneracy
2+fold improvement on the errorbar
3% precision determination of Dark Energy
from CMB alone

$$\Omega_\Lambda = 0.57^{+0.073}_{-0.055} \quad (68\%; \textit{Planck}\text{+WP+highL})$$
$$\Omega_\Lambda = 0.67^{+0.027}_{-0.023} \quad (68\%; \textit{Planck}\text{+lensing+WP+highL}).$$



From Karim Benabed talk at Planck 2013 ESLAB Meeting

Tension with clusters

- Can also attempt to get parameters like Ω_m and σ_8 (square root of variance in $8\,\mathrm{Mpc}$ spheres (derived from spectrum amplitude etc.)) via abundance of rich clusters
- This done in paper taking a sample 189 Planck clusters with good ancillary information
- Key difficulty is understanding the bias b in the relation between mass inferred from SZ signal and true cluster mass — can write schematically as

$$M_{500}^{Y_X} = (1-b)M_{500}^{\mathrm{true}}$$

- $1-b \approx 0.8$ is believable

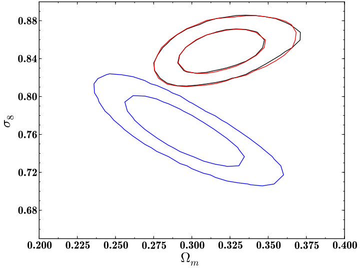


Fig. 11. 2D Ω_m–σ_8 likelihood contours for the analysis with *Planck* CMB only (red); *Planck* SZ + BAO + BBN (blue); and the combined *Planck* CMB + SZ analysis where the bias $(1-b)$ is a free parameter (black).

(From 'Planck 2013 results. XX. Cosmology from SunyaevZeldovich cluster counts', arXiv:1303.5080)

- However, to bring the cluster count results into line with what's inferred from the primordial CMB, need $1-b \approx 0.55$

Neutrino mass?

- This is difficult from cluster physics
- Can bridge gap if allow neutrino mass — e.g. $1 - b$ fixed to 0.8 then gives $\sum m_\nu = (0.58 \pm 0.20)\,\mathrm{eV}$
- If allow $1 - b$ to vary in range 0.7 to 1.0 (probably more sensible) and add in the Baryon Acoustic Oscillations (BAO) constraints, result sharpens up to $\sum m_\nu = (0.22 \pm 0.09)\,\mathrm{eV}$
- Intriguing, but really need to understand the cluster physics first

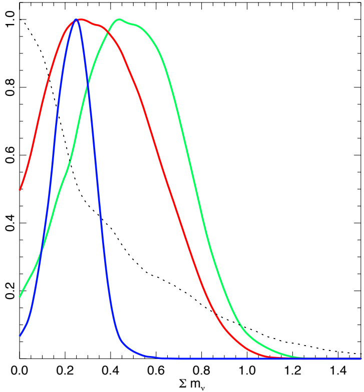
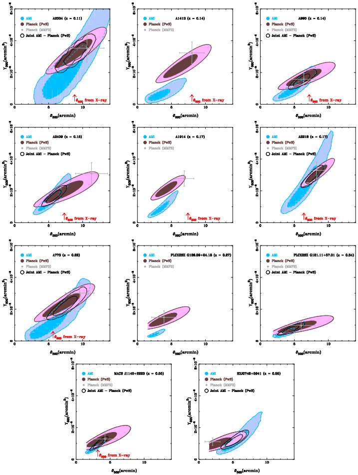


Fig. 12. Cosmological constraints when including neutrino masses $\sum m_\nu$ from: *Planck* CMB data alone (black dotted line); *Planck* CMB + SZ with $1 - b$ in [0.7, 1] (red); *Planck* CMB + SZ + BAO with $1 - b$ in [0.7, 1] (blue); and *Planck* CMB + SZ with $1 - b = 0.8$ (green).

AMI contribution to Planck cluster work

- In continuation of the work started for Early Release SZ catalogue, AMI used for candidate verification and follow-up in latest catalogue
- An initial set of ∼ 60 Planck candidates for follow-up were observed with AMI and results put into the catalogue
- 10 high-evidence confirmations of new clusters from AMI in this set, included in catalogue
- Many more results available now, since AMI team have been making follow-up observations of the full catalogue down to S/N 4.5 (about 300 clusters visible to AMI)



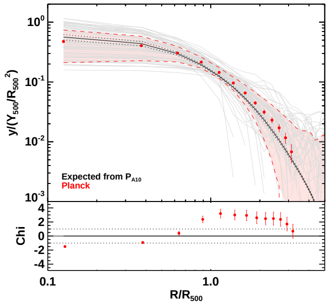
Planck vs. AMI comparison for an initial set of 11 clusters (arXiv:1204.1318)— should have well over 100 for this comparison shortly

Direct results on pressure profiles from Planck

The pressure profile used in Planck analysis (matched in AMI analysis) so far has been the Universal Pressure Profile of Arnaud et al, (A&A, **517**, A92,(2010)) a GNFW profile derived from X-ray observations and numerical simulations

$$P(r) = P_{500}\left(\frac{M_{500}}{3\times 10^{14}M_\odot}\right)^{\alpha_P}\frac{P_0}{(c_{500}x)^\gamma\left(1+(c_{500}x)^\alpha\right)^{\frac{\beta-\gamma}{\alpha}}}$$

- A particular set of the concentration and shape parameters $c_{500}, \alpha, \beta, \gamma$ etc., was derived by Arnaud et al.
- The evidence now from Planck and X-ray observations of 62 nearby clusters is that this profile underpredicts SZ effect in outer regions (main effect from β being too large)
- This would also potentially tie in with AMI results — Planck more sensitive to extended emission than AMI, so if UPP (used in the common analysis) is not the right profile, AMI would be thought to be giving on average too small results

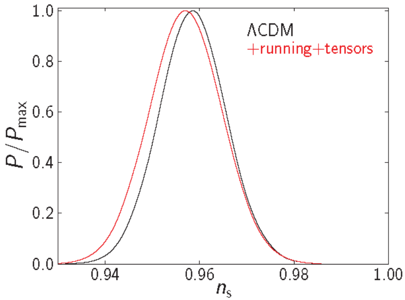


From Planck Intermediate Paper V: 'Pressure profiles of galaxy clusters from the Sunyaev-Zeldovich effect'

arXiv:1207.4061

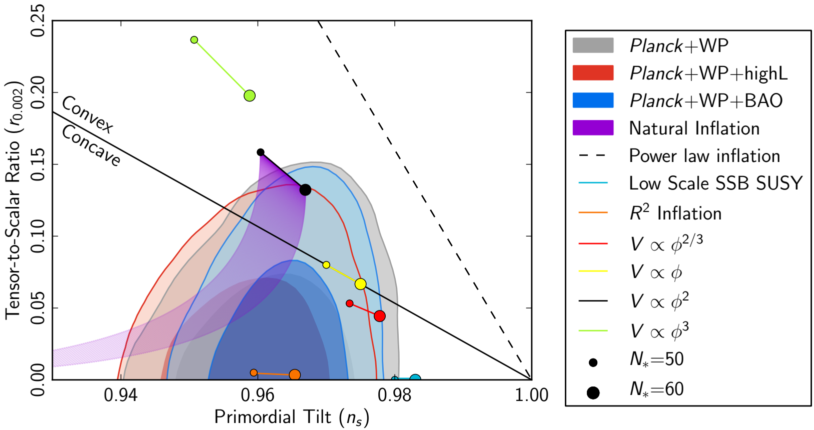
Planck Cosmology Results

- A key result for inflation is the restriction on the slope of the primordial power spectrum of perturbations
- Expressed by n_s, with scale-invariant being $n_s = 1$ — this was pre-inflation expectation
- Typical inflation models have $n_s < 1$, and Planck has now established this at 6σ
- Also Planck has shown CMB fluctuations are highly Gaussian, with 5 times tighter constraint than WMAP – eliminates several (more complicated!) inflation theories



$f_{\rm NL}$		
Local	Equilateral	Orthogonal
2.7 ± 5.8	−42 ± 75	−25 ± 39

Constraints in tilt vs. gravitational wave plane



- Pressure is beginning to mount on ϕ^2 theories!
- Lower power potentials still alright

Where do we stand on r results?

- BICEP 1's main result (Chiang et al 2010) was a much improved limit on r of $r < 0.73$ (95% conf.)
- This may not look exciting compared to $r < 0.36$ (Larson et al. WMAP7 CMB only result) or $r < 0.33$ (QUAD CMB only result)
- However, this is (still) by far most significant *direct* limit on r
- (QUIET gives $r < 0.9$, but they stress systematic error of ~ 0.1 is smallest yet.)
- An update from BICEP 1 is expected shortly corresponding to 1 more year of data compared to the 2 years used previously
- The result will be (Barkats et al., forthcoming) $r < 0.70$ (95% conf.)

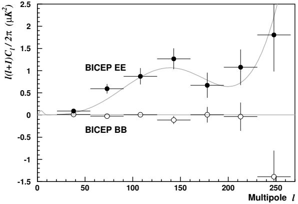
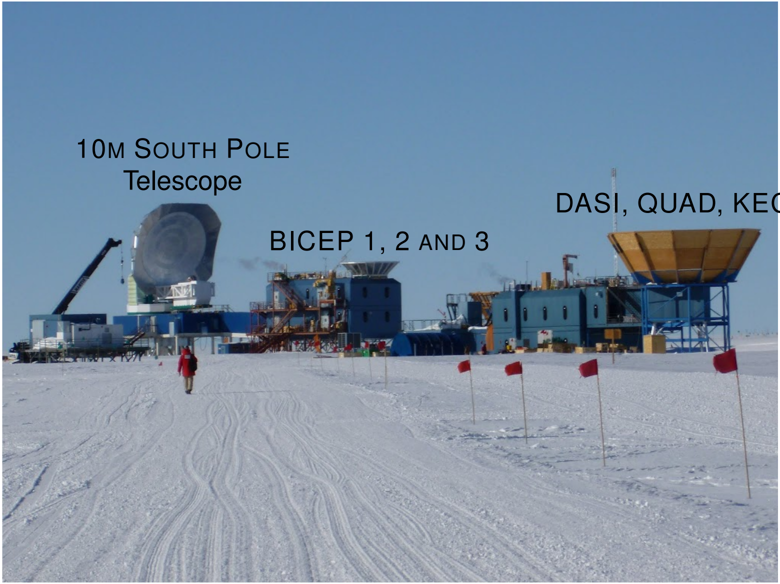


FIG. 12.— BICEP measures EE polarization (black points) with high signal-to-noise at degree angular scales. The BB spectrum (open circles) is overplotted and is consistent with zero. Theoretical ΛCDM spectra (with $r = 0.1$) are shown for comparison.

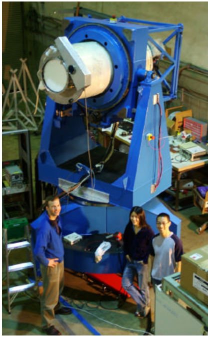
- (The statistics worked out so that there is not a big shift in the upper limit, despite 50% more data.)
- Planck limit (again indirect, but just CMB) is now $r < 0.12$ (95% conf.)
- However, something very interesting may be coming soon on direct limits

BICEP/KECK Programme



BICEP/KECK Programme

BICEP → BICEP2 → Keck-Array



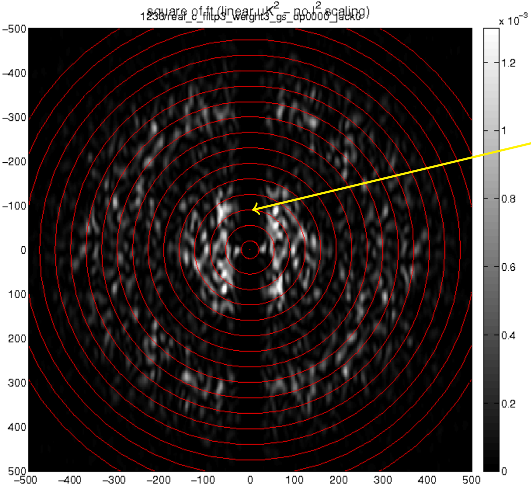
BICEP1 (2006 – 2008)
30cm refractor
96 NTD bolometers (same kind as Planck)
Best published limits on r from B-modes – r<0.72

BICEP2 (2010 – 2012)
Same optics as BICEP1
500 TES bolometers at 150 GHz
10x faster than BICEP1

Keck-Array (2011 – 2015)
5 BICEP2 like receivers
2500 TES bolometers
5x faster than BICEP2

(From Clem Pryke Moriond 2013 talk)

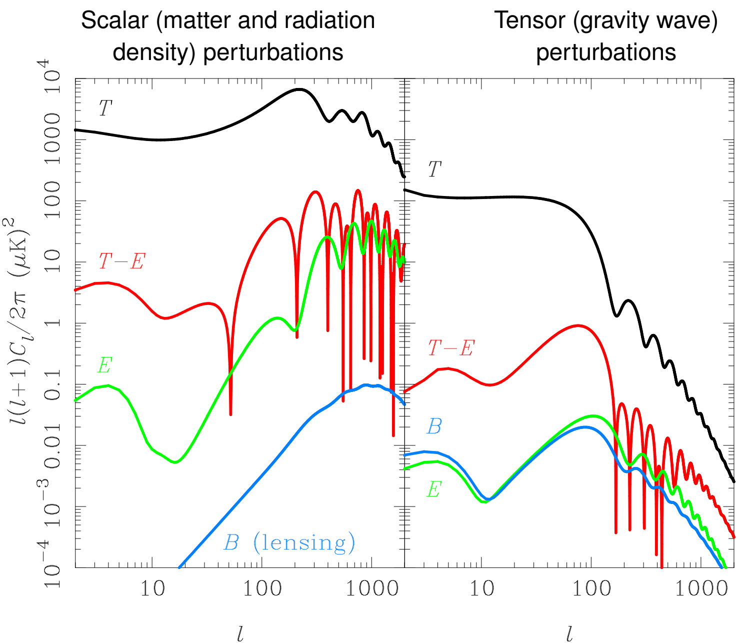
Rotate Q&U to E (&B)



Gap due to filtering in scan direction

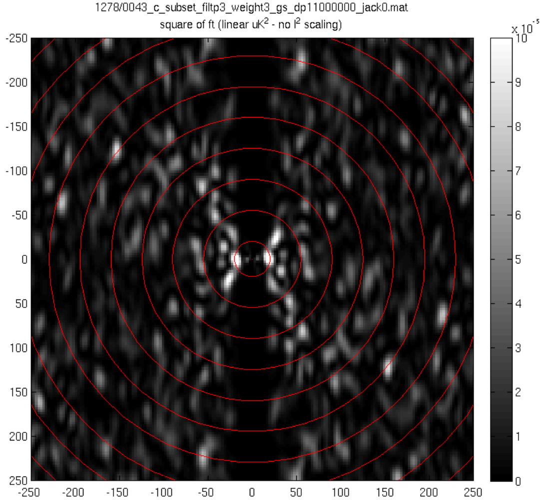
(From Clem Pryke June 2013 Santa Barbara talk)

CMB Power spectra



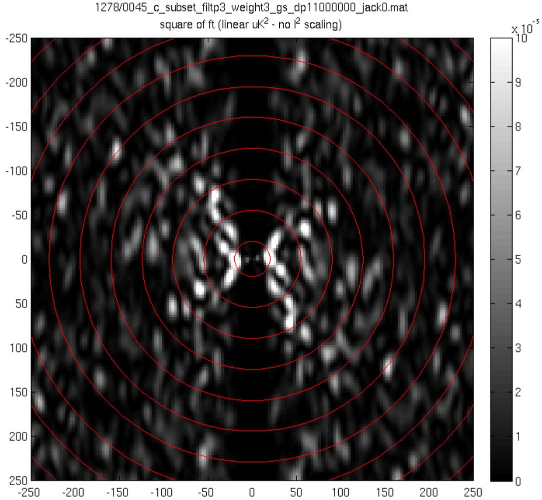
BICEP 2 Simulation

Signal+noise sim B-modes LCDM



From Clem Pryke June 2013 Santa Barbara talk

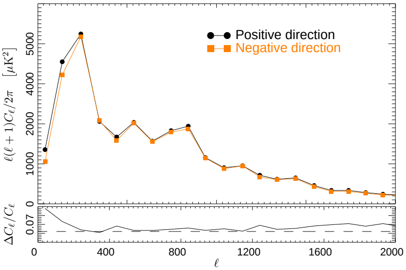
Signal+noise sim B-modes LCDM+r=0.1



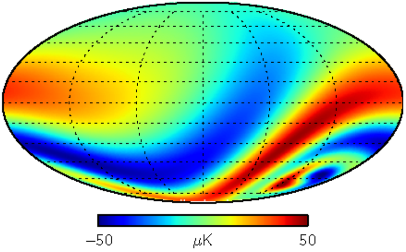
From Clem Pryke June 2013 Santa Barbara talk

Planck Cosmology Results (contd.)

- Several interesting features in large-scale CMB data – includes a fluctuation power asymmetry between hemispheres
- This had also been seen by WMAP — key here is that it seems to persist to higher multipoles — very difficult to think of a mechnism
- Also hints of a (possibly-linked) universal rotation latter v. small, $< 10^{-7}$ arcsec over history of universe
- However, parameters of model not in agreement with the real cosmological parameters
- To get the type of spiral implied, need $\Omega_m \sim 0.35$ (just ok), but $\Omega_\Lambda \sim 0.2$ — definitely not ok — model is very open



From ‘Planck 2013 results. XXIII. Isotropy and statistics of the CMB’, arXiv:1303.5083



(b) Best-fit Bianchi VII_h map.

Planck results: flat-decoupled-Bianchi model

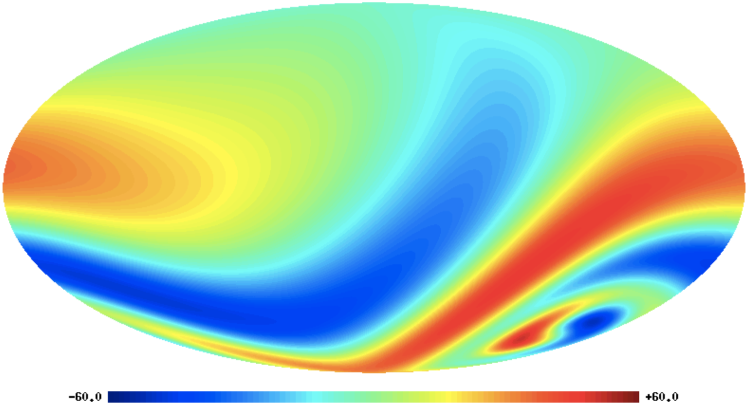


Figure: Best-fit template of flat-decoupled-Bianchi VII_h model found in *Planck* SMICA component-separated data.

Planck results: flat-decoupled-Bianchi model

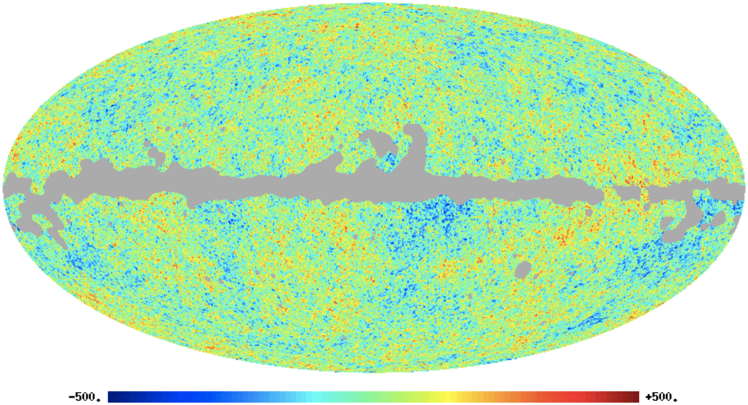


Figure: *Planck* SMICA component-separated data.

Planck results: flat-decoupled-Bianchi model

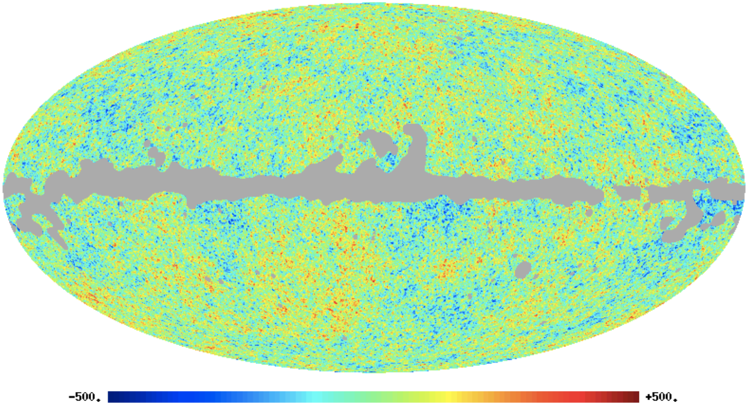
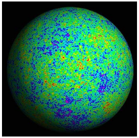


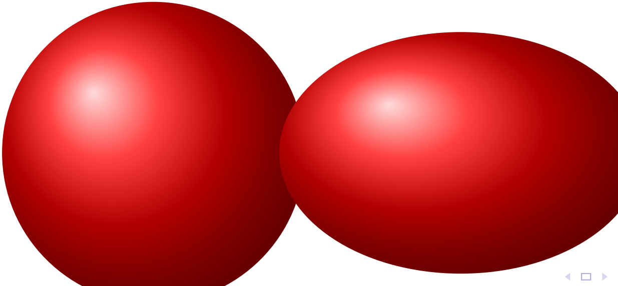
Figure: *Planck* SMICA component-separated data minus best-fit template of flat-decoupled-Bianchi VII$_h$ model.

Early time Bianchi Models?

- Homogeneous but anisotropic – generalise FRW
- Homogeneity generated by the 3-parameter Lie groups
- Bianchi IX (closed) vs Bianchi VII_h (open)
- Early-time (effects laid down during inflation) vs late-time (since recombination)
- Bianchi IX group is $SO(3)$ and group manifold is S^3
- Consider biaxially symmetric Bianchi IX so universe essentially a squashed 3-sphere

$$ds^2 = dt^2 - \frac{1}{4}R_1^2(\omega^1)^2 - \frac{1}{4}R_2^2\left[(\omega^2)^2 + (\omega^3)^2\right]$$





Bianchi IX dynamics

- Perfect fluid in Bianchi IX thought to generically lead to an oscillatory singularity (going back in time)
- The three axes tend to zero in a chaotic fashion (Mixmaster behaviour). (Evolution approximated by infinite sequence of successive Kasner epochs (Bianchi I solution).)

We worked with a setup including a scalar field

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa}\left(R + 2\Lambda\right) - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi + V(\phi)\right]$$

and with the assumption of biaxiality found two solutions (of definite parity) that have very simple dynamics — see Dechant, Lasenby & Hobson Phys. Rev. D 79, 043524 (2009) for details

- One odd-parity, pancaking solution
- One even-parity, bouncing solution

The Pancaking Solution

$R_1 \propto t$, $R_2 = R_3 \propto \text{const}$, $\phi = \text{const}$ through the 'Big Bang' at $t = 0$

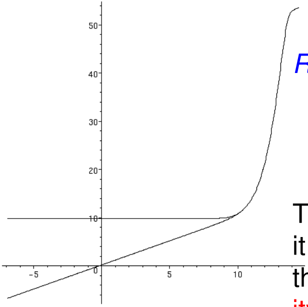
$$R_1(t) = t\left(a_0 + a_2 t^2 + a_4 t^4 + \ldots\right)$$

$$R_2(t) = R_3(t) = b_0 + b_2 t^2 + b_4 t^4 + \ldots \quad ,$$

$$\phi(t) = f_0 + f_2 t^2 + f_4 t^4 + \ldots$$

ln $(R_2(t))$

ln $(R_1(t))$



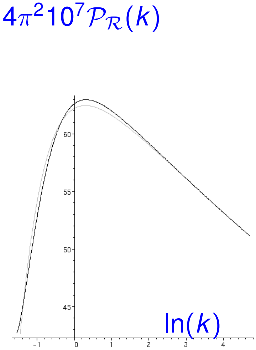
ln(t)

This solution has odd parity – it extends smoothly ($R_1 \sim t$) through the pancaking with a parity inversion and no singularities in any physical quantities. Late-time slope is $R \sim t^{2/3}$ as befits non-relativistic dust.

Consequences of early oblateness

- Isotropisation and Inflation overlap
- Universe is just oblate (at $\sim 0.2\%$ level) when perturbations on the scale of the current Hubble radius left the horizon
- Structure on the largest scales could stem from a time where the universe was still significantly oblate
- Could generate large-scale asymmetries and phase correlations?
- Isotropisation and Inflation make sure universe is close to isotropy and flatness at late times

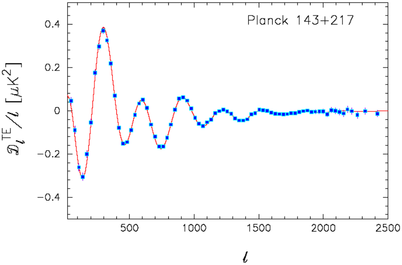
The power spectrum

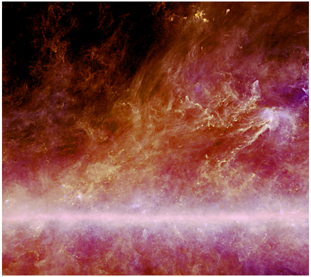


- Other features very similar to closed FRW case discussed in Lasenby & Doran (2005) — more generally low-k dip due to period of kinetic dominance, and this applies here equally as in cases with actual initial singularity (Will Handley currently working on this)
- Spectral index $n_s \sim 0.975$
- Tensor-to-scalar ratio $r \sim 0.15$
- low-ℓ dip: CMB power spectrum suppressed for low multipoles (exponential cutoff) due to low-k cutoff
- The grey line is the fit to an exponential cutoff proposed by Efstathiou (2003) on phenomenological grounds

Planck Results — still to come

- Quality of polarisation data on small angular scales already extremely impressive
- Line shown is not a fit, but predicted from Temperature data
- Also Planck, with its high resolution and large frequency coverage, is a very impressive instrument for Galactic studies
- First release, with about 1000 pages total, has just scratched the surface — definitely many mysteries remaining!
- Full Planck talk coming from Carlo Burigana





Planck image of dust in the Galaxy