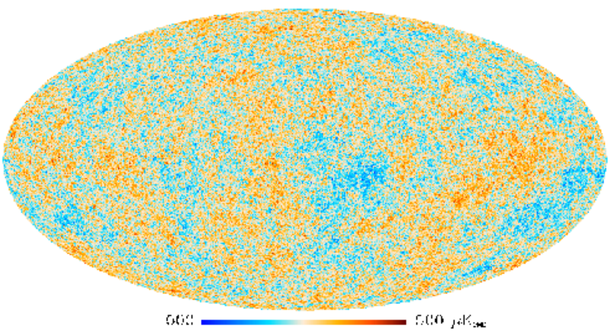

CMB Observations and their implications for cosmology

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(Paris Chalonge Meeting – July 2015)

Outline

- The CMB continues to be exciting!
- Since last year, we have had release of Planck 2015 Cosmology papers and data
- Constraints on departures from standard model becoming tighter
- Inflation constraints becoming interesting
- (Likelihood paper, and accompanying likelihood code, released last week, so people can now run the Planck 2015 likelihood for themselves.)
- Also resolution of whether BICEP2 had detected primordial B-modes
- Plus several other experiments in progress for B-mode detection

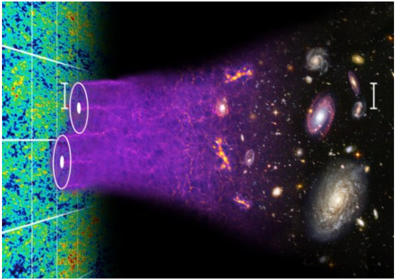
Planck Acknowledgements

- 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.

The standard model

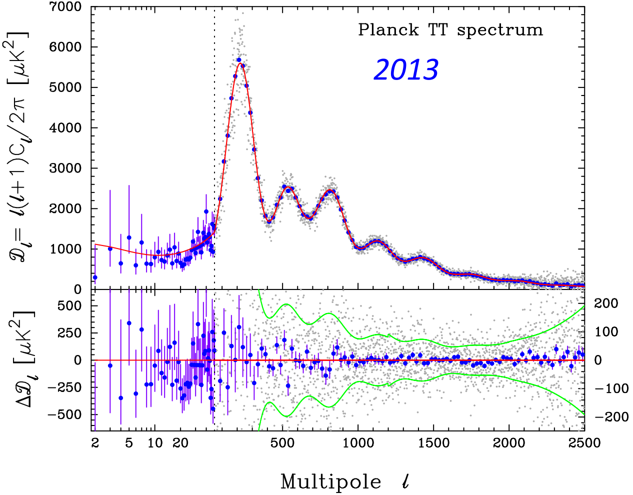
What are the parameters of the standard model?

- 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

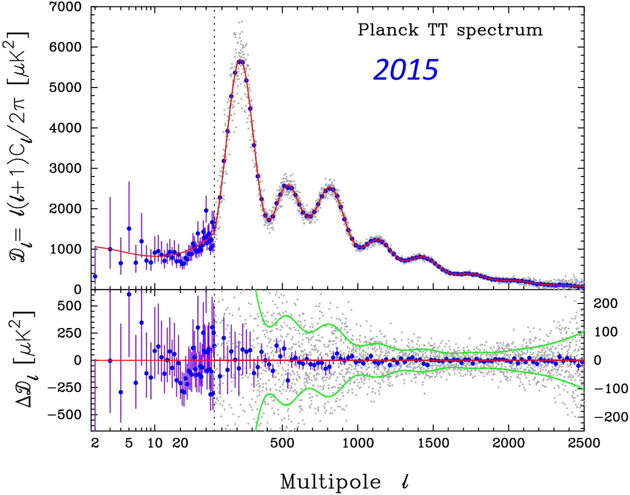


- The aim is to measure these from the power spectrum of the CMB, both in temperature and polarization
- Can supplement this, with measurements of effects of the same scale (how far the sound waves travelled by recombination) as traced by matter (BAO)

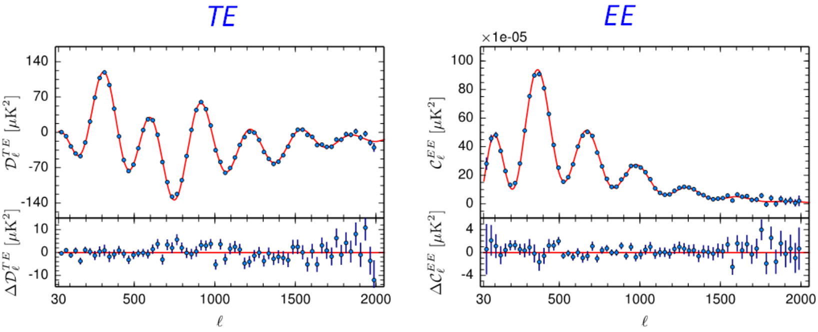
Planck spectrum results



Planck spectrum results



Planck polarization spectra



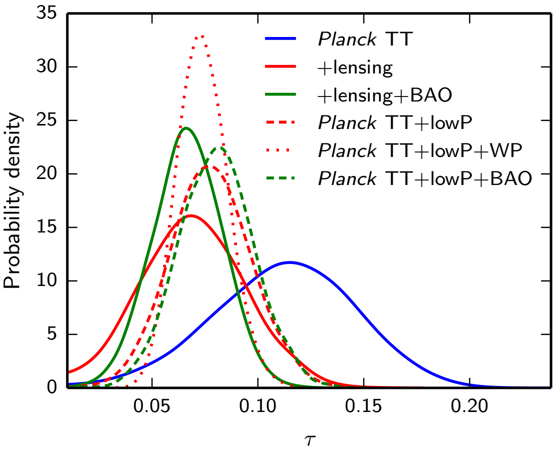
- The model shown in solid red, is not a fit to the polarization data, but a prediction from the best fit to the temperature data

Parameter consistency between TT and polarization

Parameter	TT + lowP	TT,TE,EE
$\Omega_b h^2$	0.02222 ± 0.00023	0.02224 ± 0.00015
$\Omega_c h^2$	0.1199 ± 0.0022	0.1199 ± 0.0014
$100\theta_*$	1.04086 ± 0.00048	1.04073 ± 0.00032
τ	0.078 ± 0.019	0.079 ± 0.017
n_s	0.9652 ± 0.0062	0.9639 ± 0.0047
H_0	67.3 ± 1.0	67.23 ± 0.64
Ω_m	0.316 ± 0.014	0.316 ± 0.009
σ_8	0.830 ± 0.015	0.831 ± 0.013
z_{re}	9.9 ± 1.9	10.7 ± 1.7

- lowP refers to using the low-ℓ ($\ell < 30$) Low Frequency Instrument polarization data to help constrain optical depth
- Note these are not the best final values (which for 'Planck alone' should include e.g. CMB lensing), but demonstrate consistency, plus improvement of statistical errors when including polarization
- Work still needs to be done to improve polarization systematics, however (final release next year)

Planck tau results

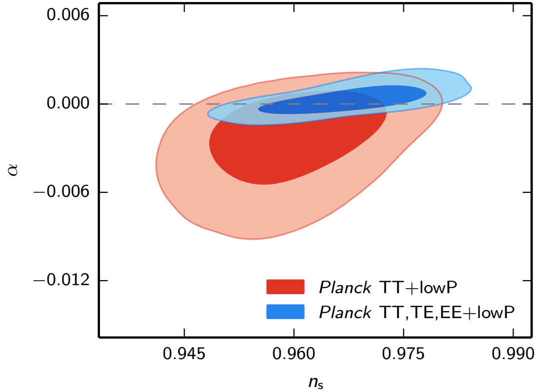


- Note the final WMAP 9-year data value for τ was 0.089 ± 0.014 so these results are for even lower τ than thought then
- Values here if include Planck TT+lowP+lensing+BAO are $\tau = 0.066 \pm 0.013$, $z_{\rm re} = 8.8^{+1.3}_{-1.2}$
- Implications for numbers of objects expected e.g. for JWST

Inflation after Planck

- Where do we stand on some predictions from Inflation, after Planck?
- (Note some, e.g. Steihnardt, are still saying inflation not a predictive theory, so useful to lay some of this out.)
- Probably reasonably good agreement that following should be true in simple versions of inflation:
  1. Primordial power spectrum slope should be slightly less then 1
  2. Universe should be flat to high accuracy
  3. Primordial perturbations should be adiabatic
  4. The perturbations should be Gaussian to good accuracy
  5. There should be B-modes due to gravitational waves with a fixed spectral shape in CMB ℓ-space, and amplitude dependent on a given theory
- Note the 'headline' values for curvature and non-Gaussianity are now $|\Omega_K| < 0.005$ and $f_{\mathrm{NL}}^{\mathrm{local}} = 0.8 \pm 5.0$
- Will now look at rest of these points in more detail

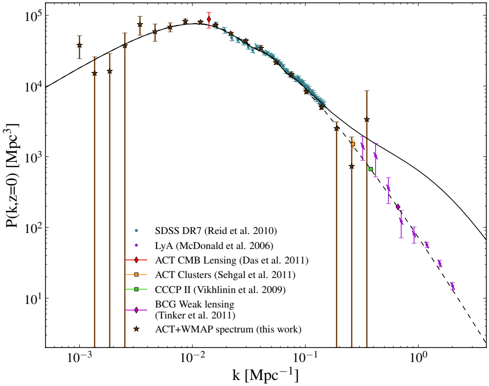
Planck Isocurvature constraints



- Expect adiabaticity in single field models of inflation (only one place where energy can be shared)
- Result shown is for constraints on the correlated matter isocurvature mode amplitude parameter α, where $\alpha = 0$ corresponds to purely adiabatic perturbations
- Polarization information makes a big difference here

The primordial spectrum

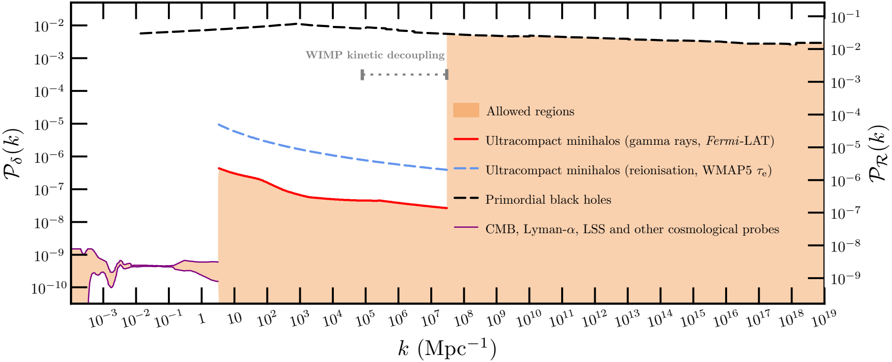
- The constraint on n_s from combination of Planck data with SN and BAO is now $n_s = 0.9667 \pm 0.0040$, i.e. 8σ away from the Harrison-Zeldovich value of 1
- Worth considering what we know about the primordial spectrum in more detail
- Following shows range of k space over which we have direct information from CMB and matter distribution



From Hlozek et al, arXiv:1105.4887

k ranges probed

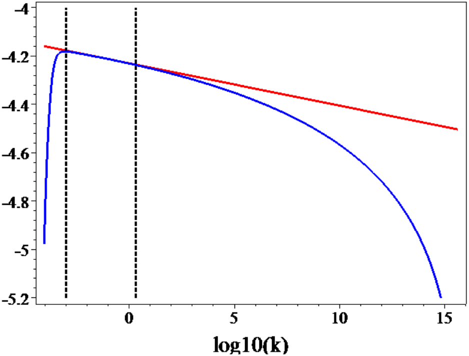
- This is actually a small fraction of the range which comes from inflation, and could be discussed



- From Bringmann, Scott & Akrami, arXiv:1110.2484v3

Primordial power spectrum slope

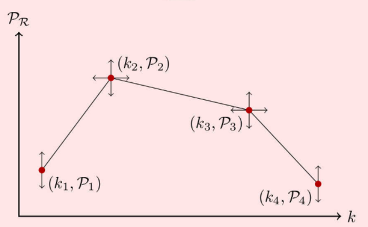
- As an illustration of theoretical expectations, following shows predicted power spectrum from inflation over a larger range than ordinarily shown



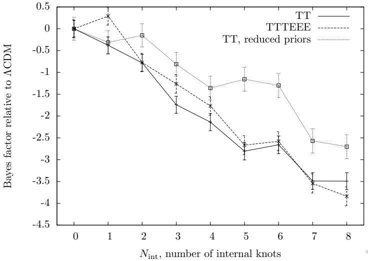
- Black dashed lines mark (currently) observable range, and red line is a spectrum with constant slope $n_s = 0.965$
- Note also cutoff in power at large spatial scales
- (Will discuss what underlying theory is shortly.)

Primordial power spectrum reconstruction

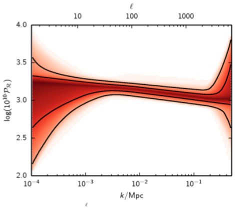
- For latest Planck release Inflation paper, Handley & Lasenby have been working on a novel method of primordial power spectrum reconstruction



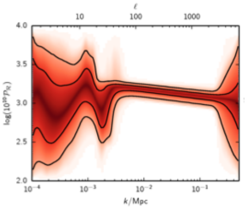
- Uses a new Bayesian sampling method called PolyChord (arXiv:1502.01856, developed by Handley, Lasenby & Hobson) (also used in other applications in the Inflation paper)
- Lay down *N* 'knots' with *N* variable and calculate evidence as a function of *N*
- Featureless spectrum still preferred by evidence (except Planck TTTEEE where slight preference for 1 internal knot)



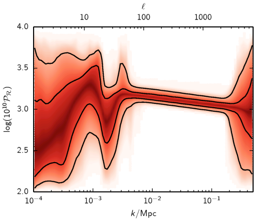
- However, interesting stable feature is present (found by the other two power spectrum reconstruction methods used as well), presumably associated with slight overall lack of large scale power plus dip in CMB spectrum around $20 < \ell < 30$



1 knot



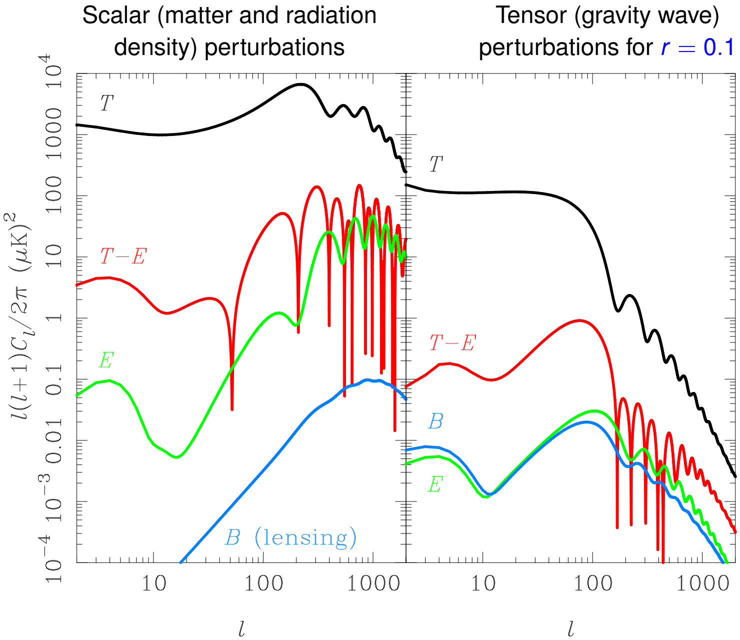
4 knot



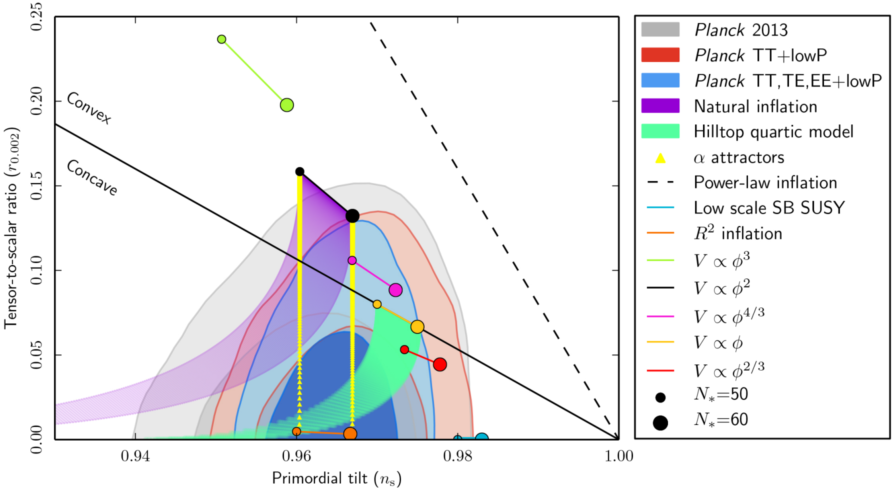
8 knots

From Planck 2015 ‘Constraints on Inflation’, arXiv:1502.02114

CMB Power spectra (Two parts separately)

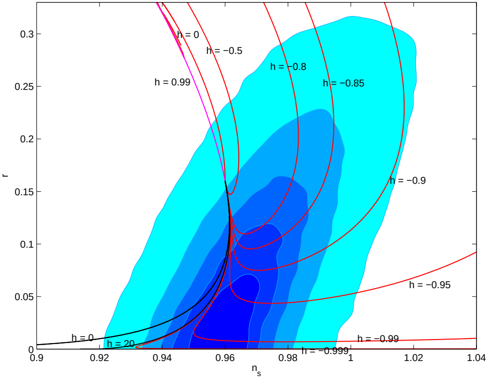


Planck 2015 results in $r - n_s$ plane



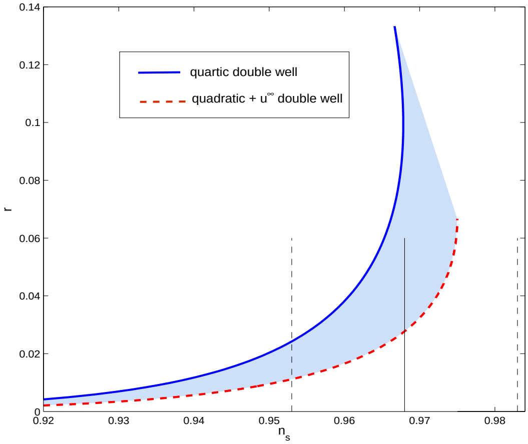
Expectations for r

- Want to emphasise that although things look bad for ϕ^2, ϕ^3 and ϕ^4 individually, their combination can be completely fine with current data
- This was something emphasised by de Vega, Sanchez, Destri et al
- In the following, from astro-ph/0703417, the h parameter controls the cubic (asymmetric) part of the potential



Expectations for r

- And here is the cosmic banana, which includes all possible higher order corrections in terms of a Ginsburg-Landau type effective field theory
- From Destri, de Vega, Sanchez, arXiv:0906.4102 (the vertical lines indicate the 1σ limits from the WMAP5 data)



Expectations for r

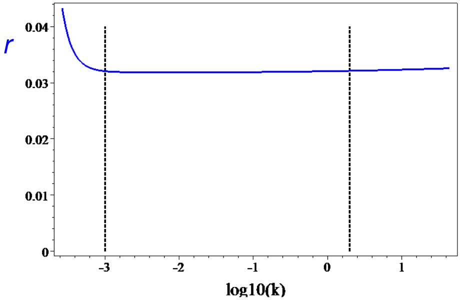
- Also want to emphasise that single field inflation can have some surprises in 'modified gravity' theories
- Have been working on a new scale-invariant gauge theory approach to gravity
- This generalises the Gauge Theory Gravity of Lasenby, Doran & Gull (see Phil. Trans. R. Soc. Lond. A, 356, 487 (1998)) to include scale invariance, as well as translation and rotation invariance
- Theoretical foundations will be described in a paper to appear in August: Lasenby & Hobson, Gauge theories of gravity and scale invariance. I. Theoretical foundations
- Scale invariance requires the introduction of a vector gauge field
- Turns out that this has the interesting effect in cosmology of generating a ϕ^4 term by itself, when all we put in 'by hand' is a standard $m^2\phi^2$ type potential term

Expectations for r

- Final effective potential is of the form

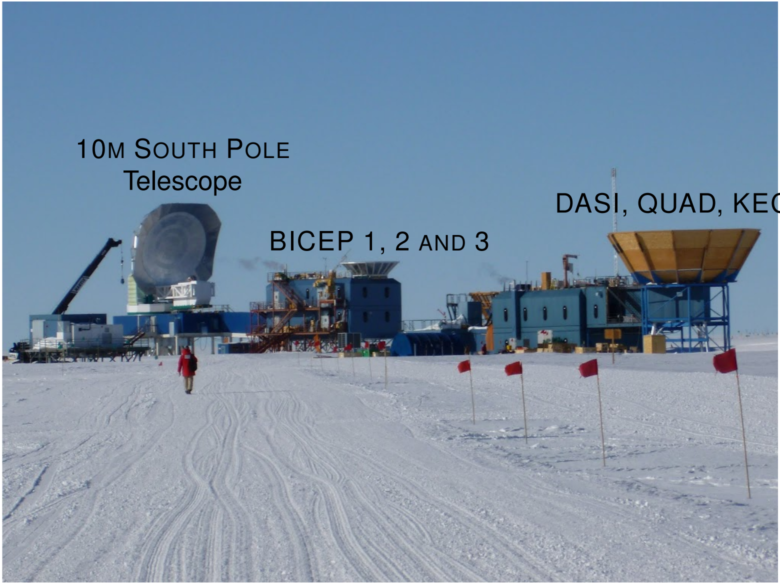
$$V(\phi) = \left(-\frac{3H^2}{\eta+6} + \frac{m^2}{2}\right)\phi^2 + \frac{m^2}{2(\eta+6)}\phi^4$$

- This produces the plot of scalar spectrum shown above, and can get perfectly sensible values of r from this



- r is shown here in a point by point comparison with scalar spectrum, and again dashed black lines represent extent of observability of scalar spectrum

Current situation on BICEP



Foregrounds?

- This was clearly the biggest potential problem
- Key foregrounds are Galactic dust at higher frequencies ($\gtrsim 70\,\mathrm{GHz}$) and Galactic synchrotron at lower frequencies ($\lesssim 70\,\mathrm{GHz}$)
- They worked at $150\,\mathrm{GHz}$ and based their analysis on existing, publically available maps of dust (e.g. from IRAS and Planck)
- Maps are in intensity, so they assumed a fixed 5% polarization fraction
- BICEP2 only has a single frequency, so can't discriminate spectra on this basis

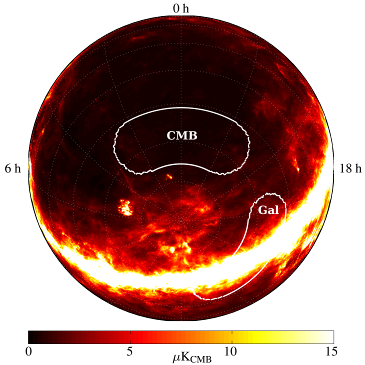
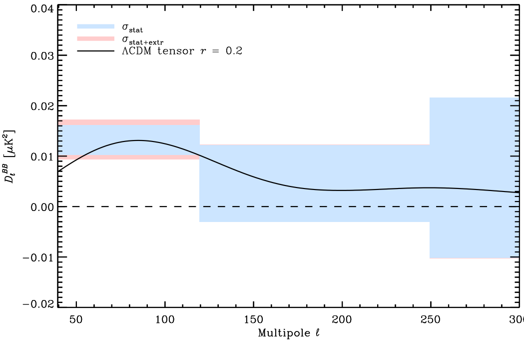


FIG. 20.— BICEP2 observing fields relative to the polarization amplitude predicted from FDS (Finkbeiner et al. 1999) model 8, assuming a 5% polarization fraction.

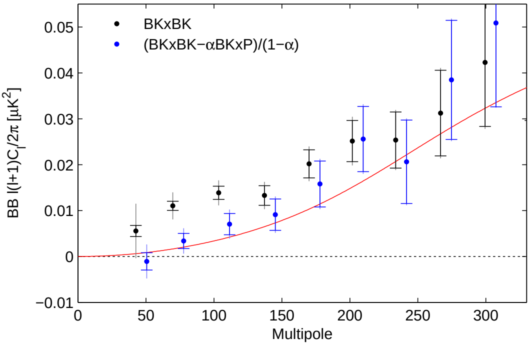
High latitude Planck dust results

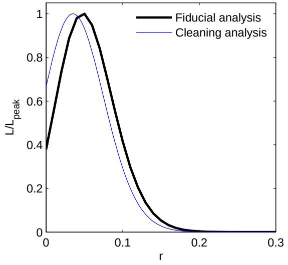
- The released Planck high latitude dust results from September last year indicated there could indeed be serious contamination (arXiv:1409.5738)



- The blue boxes represent 1σ uncertainties about the mean for extrapolating Planck $353\,\mathrm{GHz}$ measurements of dust to BICEP's observing frequency ($150\,\mathrm{GHz}$)
- Solid curve is what an $r = 0.2$ primordial B-mode would look like!
- Proper joint analysis of Planck and BICEP2 data then followed

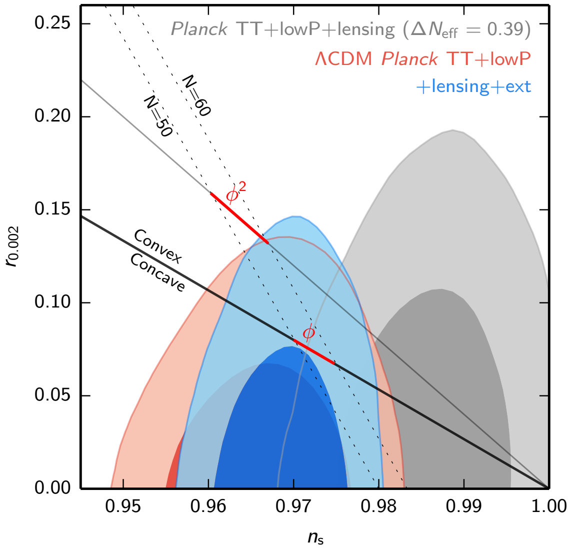
BICEP2 story



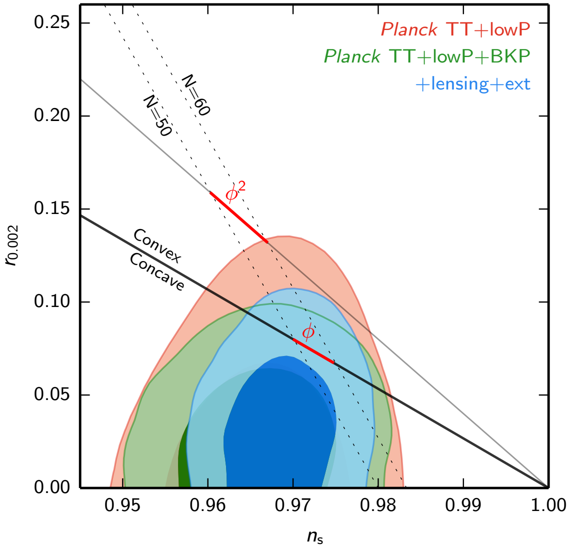


- Can see that's there's only really evidence for the lensing B-mode in BICEP's results so far
- For r, using Planck to clean dust, only get an upper limit $r < 0.12$ at 95% conf.
- So how does combination of Planck and (Planck-cleaned) BICEP likelihoods affect the n_s-r plane?

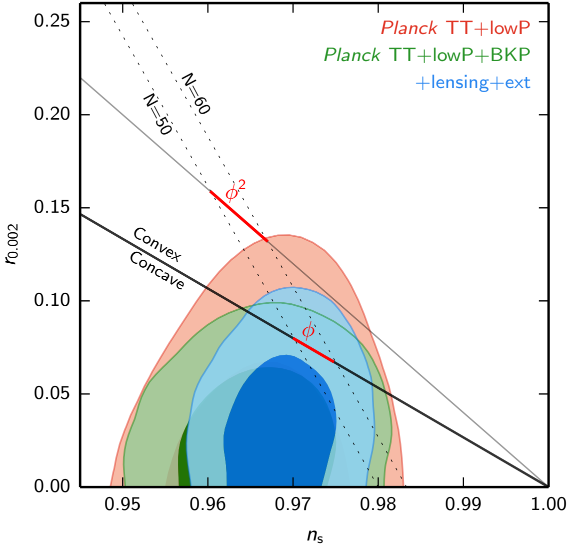
Planck results in $r - n_s$ plane



Planck results in $r - n_s$ plane

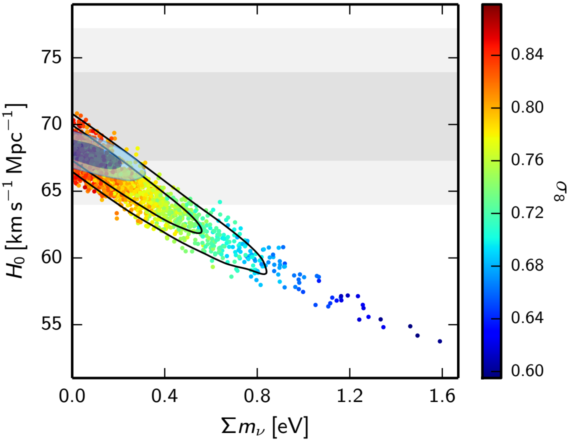


Planck results in $r - n_s$ plane



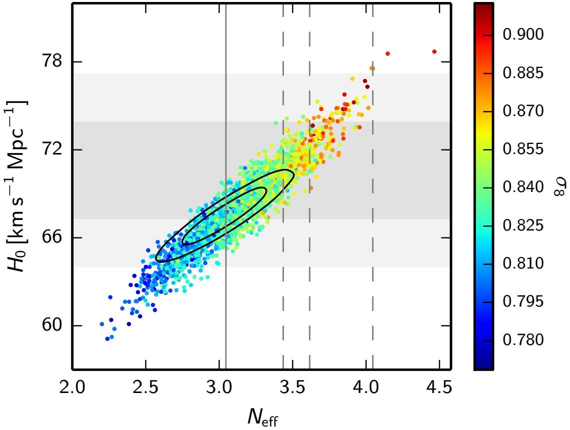
Note final r constraint from this (i.e. jointly using Planck CMB + BKP) is $r < 0.09$ (95% conf)

Constraint on neutrino masses



- Headline result (after combination with BAO) is $\sum m_\nu < 0.21\,\mathrm{eV}$ at 95%

Constraint on N_{eff}



- Results are $N_{eff} = 3.13 \pm 0.32$ (Planck TT alone)
- $N_{eff} = 3.04 \pm 0.18$ (Planck TT+polzn+BAO)
- (Note expect $N_{eff} = 3.046$ just on basis of 3 neutrino species due to effects at electron-positron annihilation.)

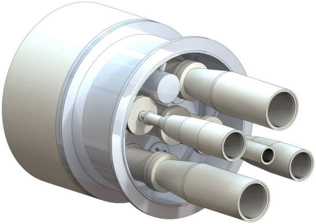
Future of B-mode measurements

- Only way to improve measurements of r is via direct detection of B-modes (Planck has already reached limit of what can be done from TT alone)
- Several experiments underway in this area
- BICEP/Keck is deepest measurement so far and progressing rapidly with further receivers and frequencies
- Will hear about this in detail from Clem Pryke
- Will mention briefly some others
- Two QUIJOTE telescopes were inaugurated by the King of Spain on June 27th

QUIJOTE Telescopes

QUIJOTE

- QUIJOTE Spanish/UK ground-based experiment
- Currently one of only two ground-based CMB experiments with European leadership (other is QUBIC, led by APC, Paris)
- Rafa Rebolo (IAC) is overall PI and ANL PI at Cambridge
- Two-fold aim: low frequency foreground mapping in polarization, plus in future versions sensitive to r at about 0.05 level.
- First telescope/receiver has 4 horns at 11, 13, 17 and 19 GHz and maps most of Northern sky
- Second telescope/receiver will add 32 horns at 30 GHz

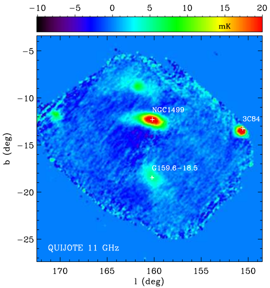


Horns of first receiver

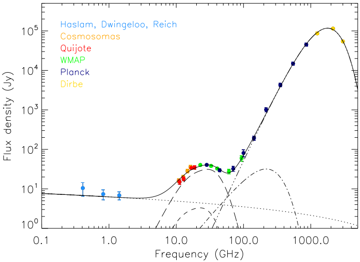
Installation of second telescope

QUIJOTE first results

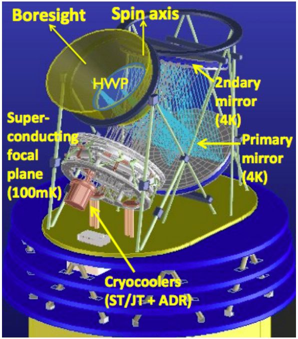
- First scientific results now published
- Concentrates on Perseus region, and in particular the IRAS dust cloud G159.6-18.5
- Intensity points fill in well the lower frequency part of the AME spectrum for this object
- Get limits on AME dust polarization fraction of $< 6.3\%$ at $11 - 13\,\mathrm{GHz}$ and $< 2.8\%$ at $17 - 19\,\mathrm{GHz}$
- Important in helping to rule out magnetic dipole mechanisms for spinning dust (prefers electric dipole)

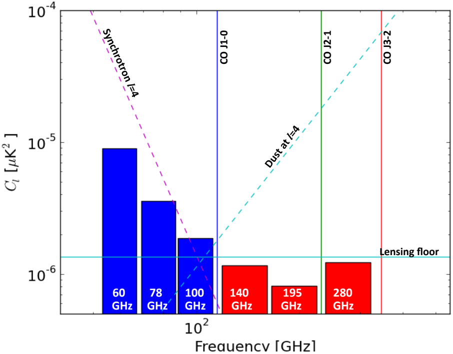


$11\,\mathrm{GHz}$ Intensity map of Perseus field



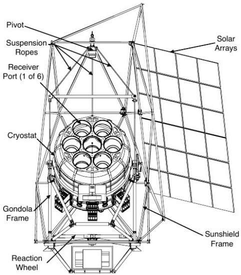
LiteBIRD

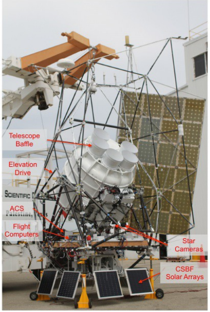


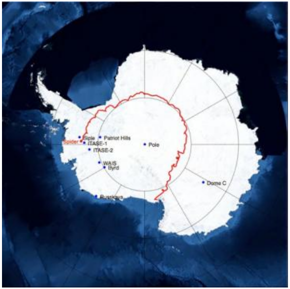


- LiteBIRD passed the JAXA downselection in June: 27 possible missions reduced to just 3 for further studies!
- Number of frequency bands could be increased further
- European B-mode mission (Core+/PRISM) unfortunately didn't make M4 selection recently — perhaps M5?
- In US, PIXIE (Al Kogut) of great interest (joint spectral/B-mode experiment)

SPIDER

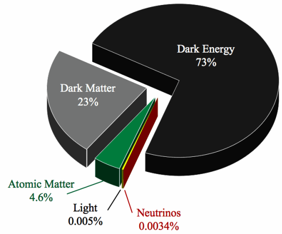






- Six 1° resolution telescopes at 100 GHz, 150 GHz, and 280 GHz
- SPIDER launched on first full flight January 1st 2015
- About 10% of sky mapped
- Flight duration 16 days - data currently being analysed

Summary



Plain vanilla ΛCDM survives very well as regards the CMB — (of course unfortunately this means we still don't know what about 95% of the universe is made of, but the accuracy with which the relative proportions have been determined continues to be impressive)

- BICEP2 results (which are certainly our most sensitive yet on B-modes) have demonstrated abundantly the enormous interest in this field
- However, we are still not much further forward as regards the amplitude of r
- Several experiments (including BICEP/KECK) poised to make big strides

Many other wonderful cosmological data coming in as well — golden age is far from over!