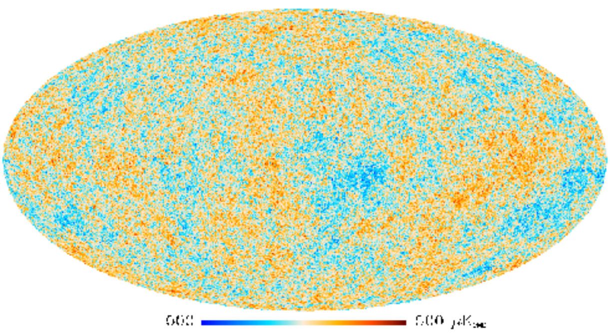

CMB Observations and Some Current Questions in Cosmology

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(Paris Chalonge Meeting – July 2016)

Outline

- Idea is to look at some current cosmological questions, particularly in the light of the CMB
- Can pose these as:
  - Does ΛCDM explain everything we see in the CMB?
  - Is there structure in the primordial power spectrum coming out of inflation?
  - Is late time evolution of the universe compatible with just a cosmological constant?
  - What is the optical depth due to reionization?
  - Can we find the time history of reionization?
  - When will we discover the background of gravitational waves, either directly, or indirectly via the CMB? (Update on BICEP)
  - Is the power spectrum of the matter distribution we see today compatible with the CMB (First DES results)

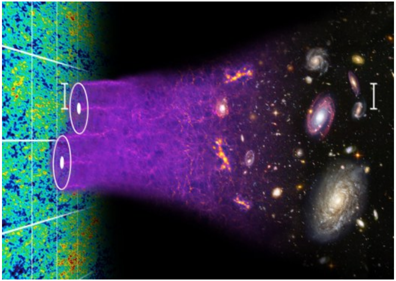
Planck Acknowledgements

- 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

ΛCDM model has 6 parameters

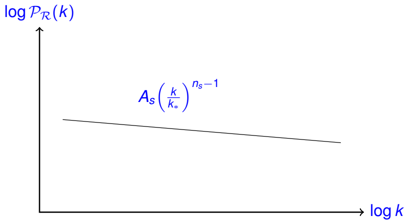
- Physical density in baryons $\Omega_b h^2$ ($h = H_0/100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$)
- Physical density in cold dark matter $\Omega_c h^2$
- $100\times$ angular diameter of sound horizon at last scattering $100\theta_*$
- Optical depth due to reionisation τ
- Slope of the primordial power spectrum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

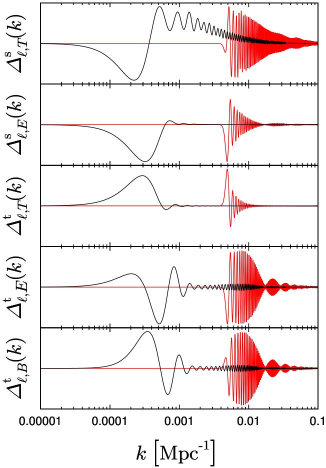


- Given these, can predict the power spectrum of the CMB, both in temperature and polarization
- Can supplement this, with measurements of effects of the same scale (how far the sound waves travelled by recombination) as traced by matter (BAO)

Standard Model (contd.)

- From the parameters, we can calculate the Transfer Function which goes between the initial power spectrum (in k) coming out of inflation and the CMB power spectrum in ℓ



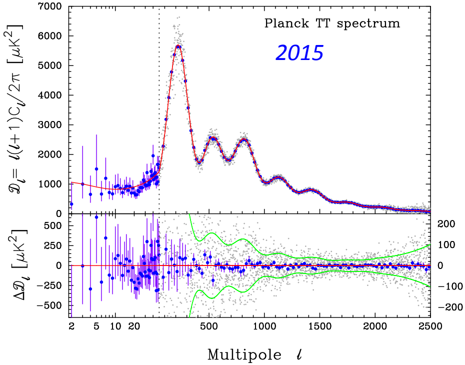


Example transfer functions for $\ell = 2$ (black) and $\ell = 65$ (red)

(From Planck 2015 Inflation paper, 1502.0211)

Power spectrum

- The measured Planck power spectra contain ~ 2500 independent modes
- They are overall in extremely good agreement with the predictions of the 6-parameter model!
- However, hint of a possible 'dip' between $\ell = 25$–30, and general depression at low ℓ



Primordial power spectrum reconstruction

- One can go about this either in terms of fitting parameterised features, or via a free-form reconstruction
- We did both in inflation paper, but here want to look at latter
- One way was a (frequentist-style) Maximum likelihood approach — can't in fact invert but can use a regularised likelihood incorporating penalty functions
- But what criteria can there be for choosing the parameters of the penalty function and deciding on the significance of the result
- So we carried out a Bayesian analysis, using a free-form function, in which Bayesian evidence is used to determine the number of 'features' allowed
- We have

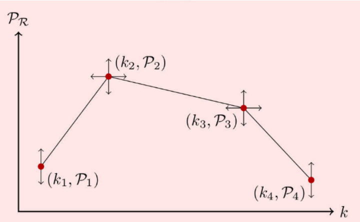
$$P(M|D) = \frac{P(D|M)P(M)}{P(D)}$$

where M = model and D = data, so in comparing models with the same data, and assuming the same prior probability of the models themselves we can compare their probability directly using

$$P(D|M) \quad \text{— the Evidence}$$

Primordial power spectrum reconstruction (contd.)

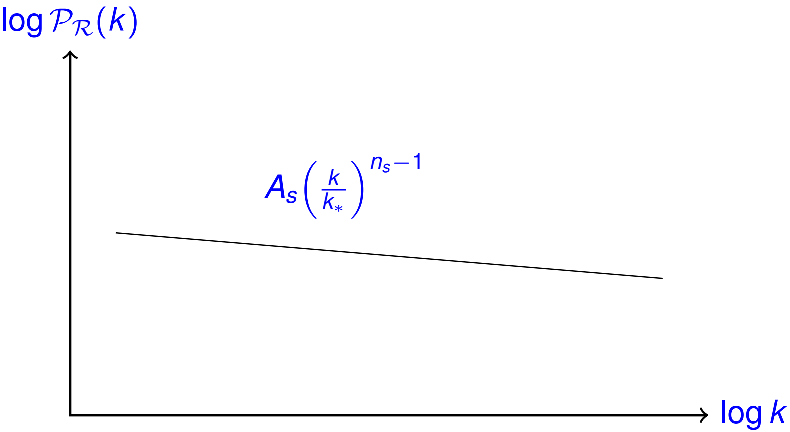
- Method is to lay down *N* 'nodes' with *N* variable and calculate evidence as a function of *N*
- Each node introduces two additional parameters, and resulting posterior distributions are generally multimodal
- Previous samplers, like that in CosmoMC, or MultiNest were not able to deal with the high-dimensionality



- So we introduced a new sampling method: 'PolyChord' (Handley, Hobson & Lasenby)
- arXiv:1502.01856 and 1506.00171
- Note (technical point) can deal well with fast/slow parameters
- Used in other parts of Planck Inflation paper as well

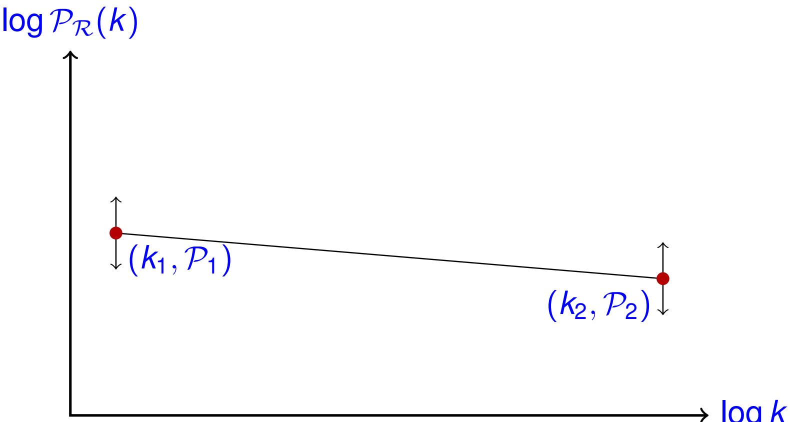
PolyChord in action

Primordial power spectrum $\mathcal{P}_\mathcal{R}(k)$ reconstruction



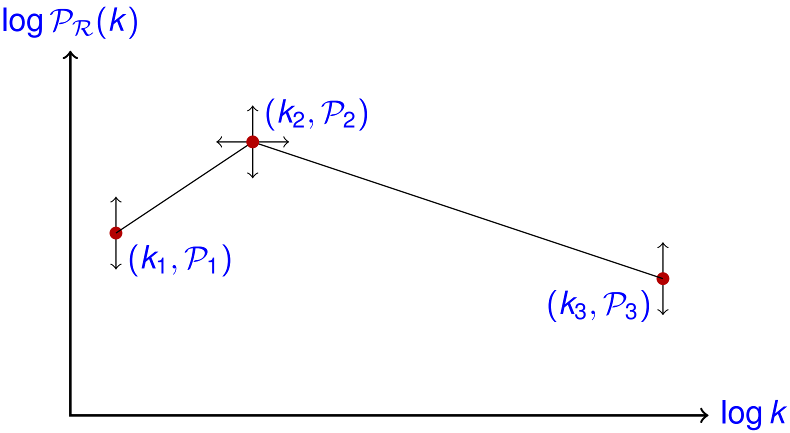
PolyChord in action

Primordial power spectrum $\mathcal{P}_\mathcal{R}(k)$ reconstruction



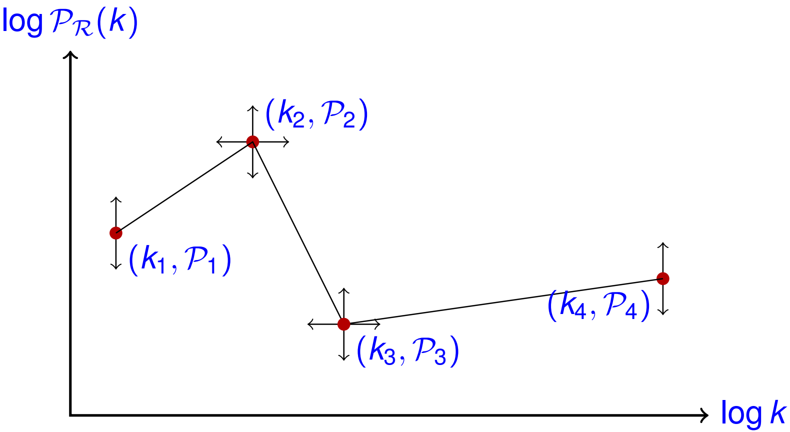
PolyChord in action

Primordial power spectrum $\mathcal{P}_\mathcal{R}(k)$ reconstruction



PolyChord in action

Primordial power spectrum $\mathcal{P}_\mathcal{R}(k)$ reconstruction



PolyChord in action

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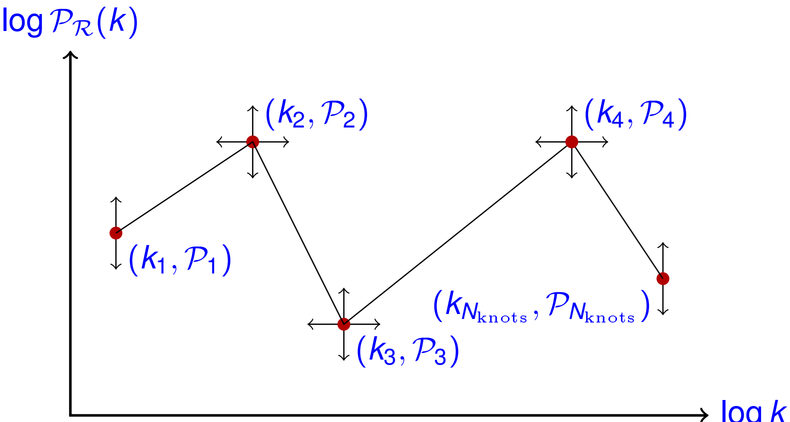
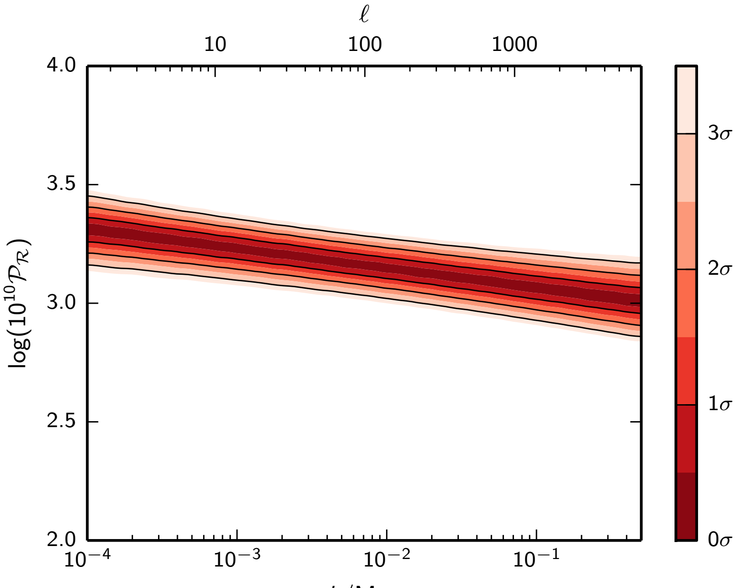


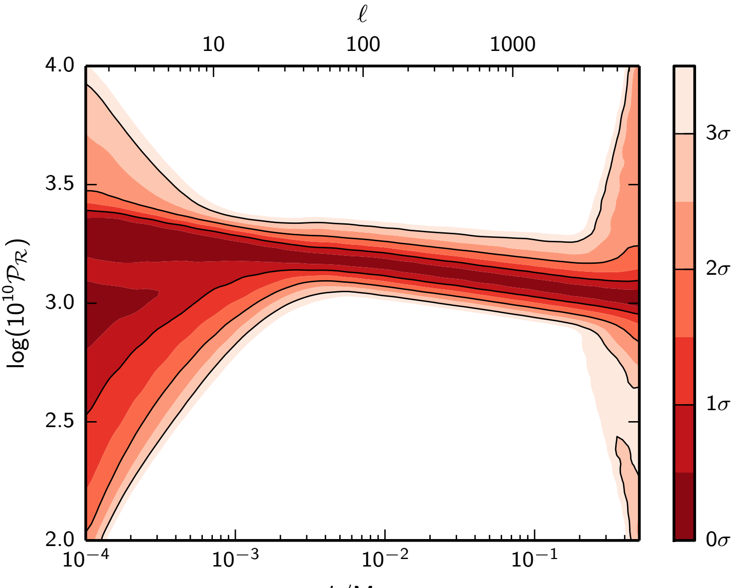
0 internal nodes

Primordial power spectrum $\mathcal{P}_\mathcal{R}(k)$ reconstruction



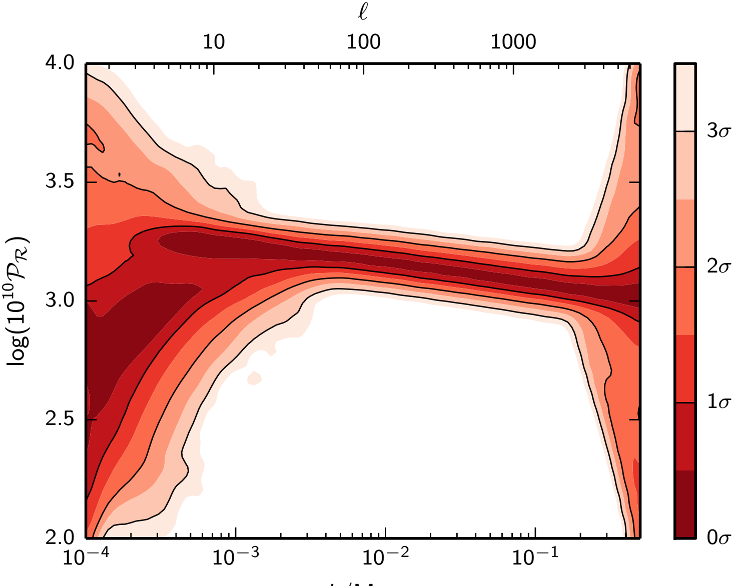
1 internal nodes

Primordial power spectrum $\mathcal{P}_{\mathcal{R}}(k)$ reconstruction



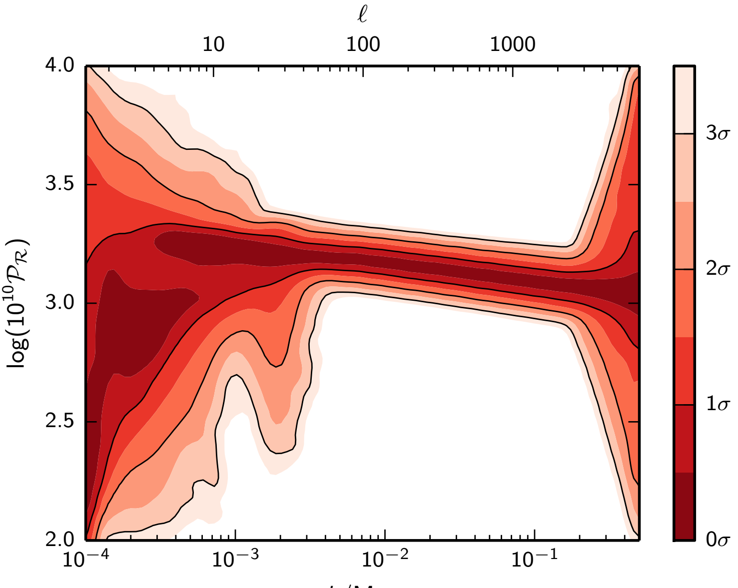
2 internal nodes

Primordial power spectrum $\mathcal{P}_\mathcal{R}(k)$ reconstruction



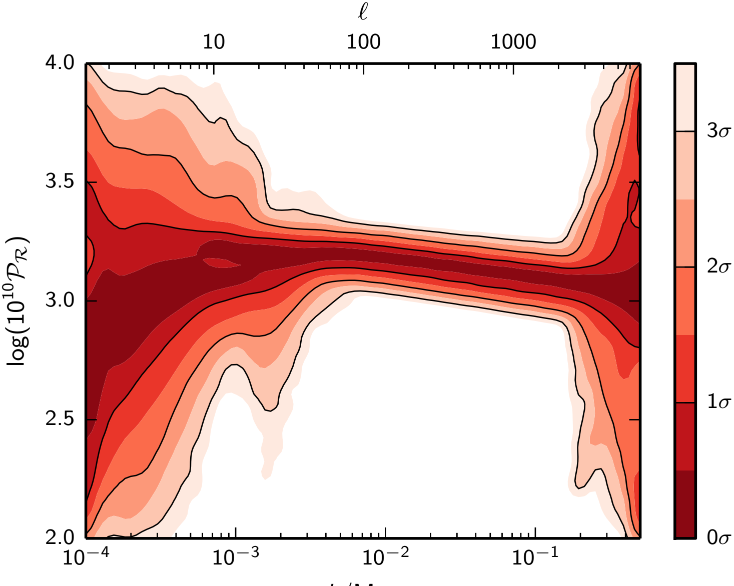
3 internal nodes

Primordial power spectrum $\mathcal{P}_\mathcal{R}(k)$ reconstruction



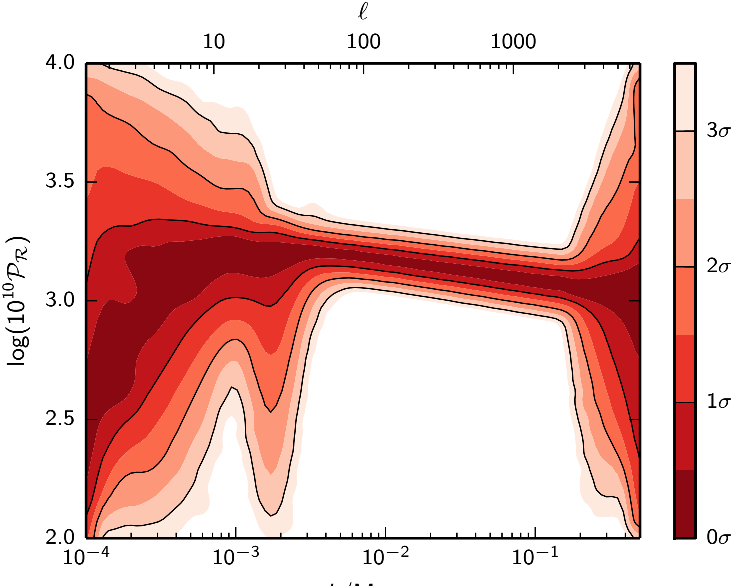
4 internal nodes

Primordial power spectrum $\mathcal{P}_\mathcal{R}(k)$ reconstruction



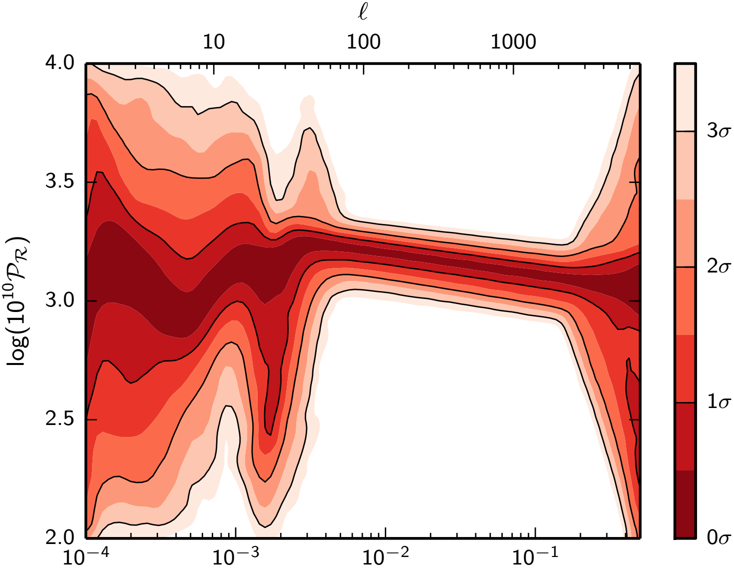
5 internal nodes

Primordial power spectrum $\mathcal{P}_\mathcal{R}(k)$ reconstruction



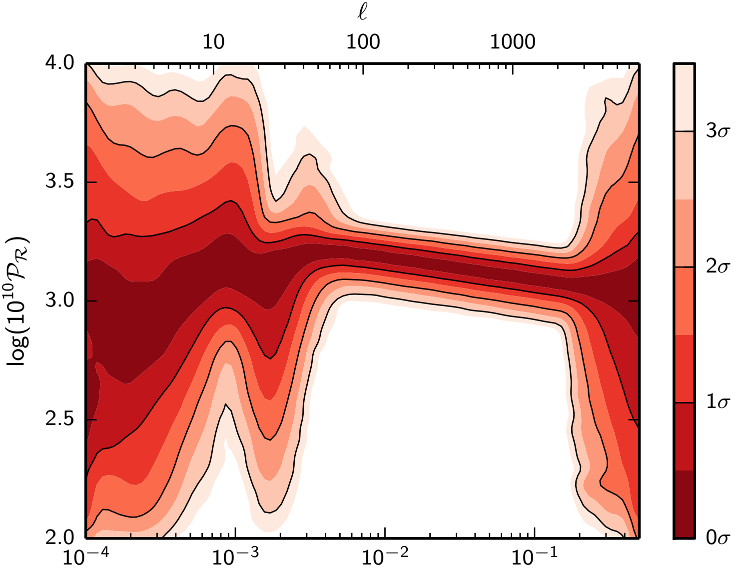
6 internal nodes

Primordial power spectrum $\mathcal{P}_{\mathcal{R}}(k)$ reconstruction



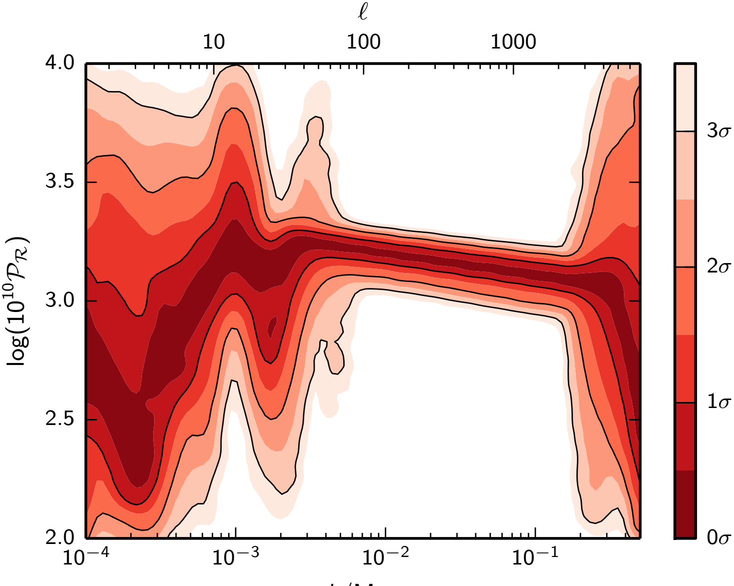
7 internal nodes

Primordial power spectrum $\mathcal{P}_\mathcal{R}(k)$ reconstruction



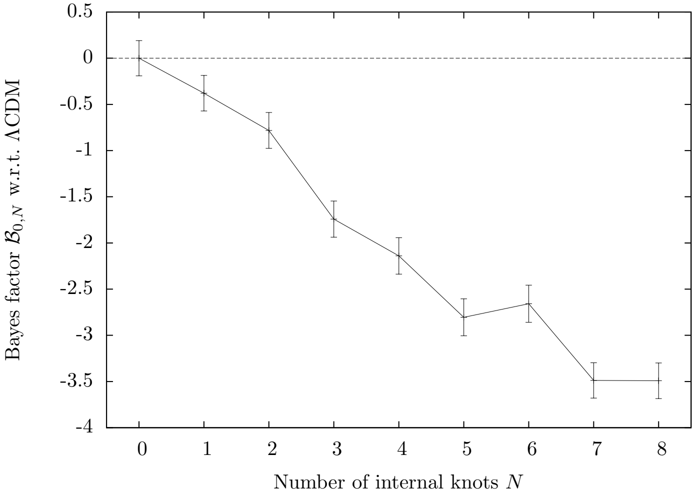
8 internal nodes

Primordial power spectrum $\mathcal{P}_\mathcal{R}(k)$ reconstruction



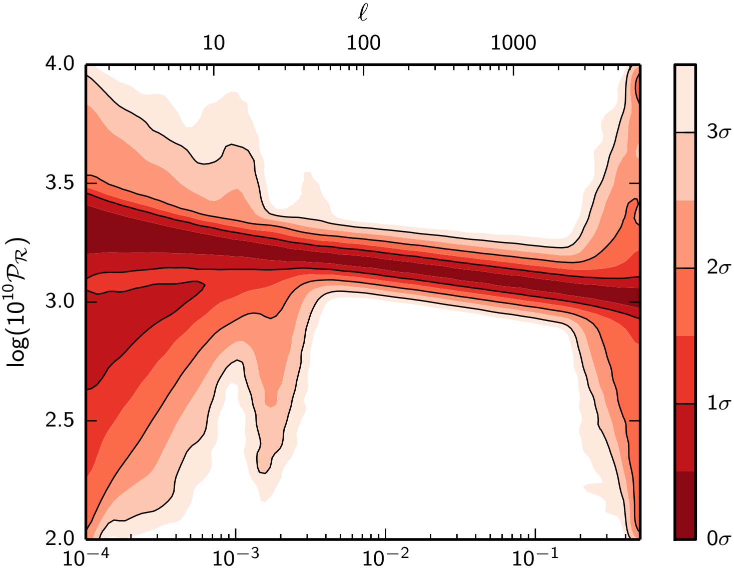
Bayes Factors

Primordial power spectrum $\mathcal{P}_{\mathcal{R}}(k)$ reconstruction



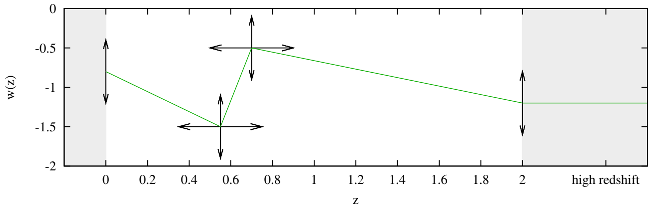
Marginalised plot

Primordial power spectrum $\mathcal{P}_\mathcal{R}(k)$ reconstruction



Model comparison

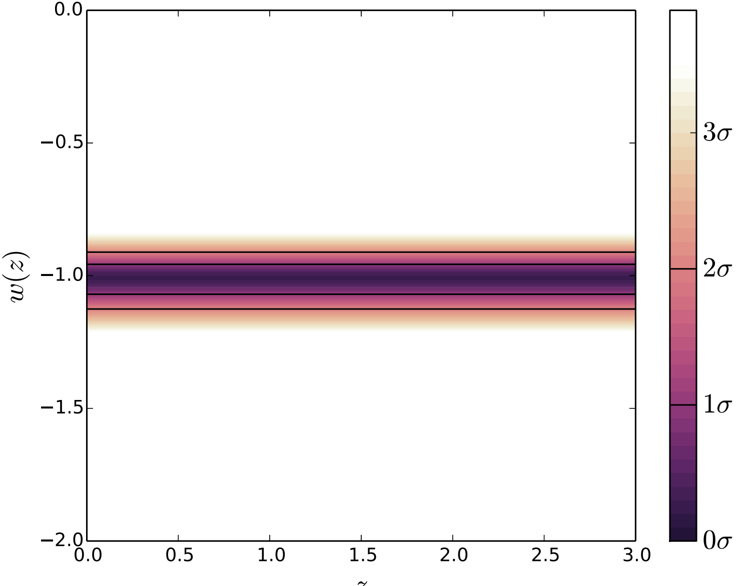
- We have also been applying these methods to the equation of state parameter *w* versus redshift
- This is in Hee, Vazquez, Handley, Hobson & Lasenby, recently submitted (arXiv:1607.00270)
- Data used is Planck 2015, BOSS DR 11, JLA supernovae and Font-Ribera *et al.* (2015) and Delubac *et al.* (2015) BOSS Lyα data



- So we set up cases with (a) no internal node and two end points the same (fixed *w*), (b) no internal nodes and end points can move (a 'tilt'), (c) 1 internal node, etc.

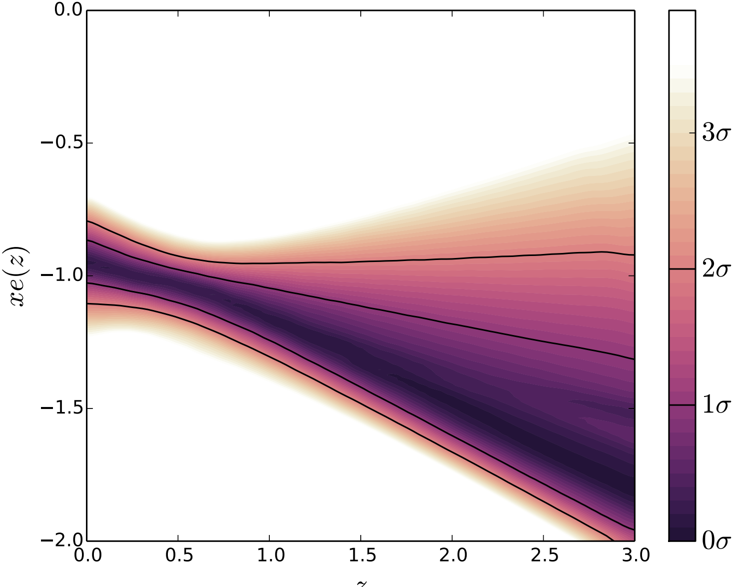
flat, variable *w*

w(*z*) reconstruction



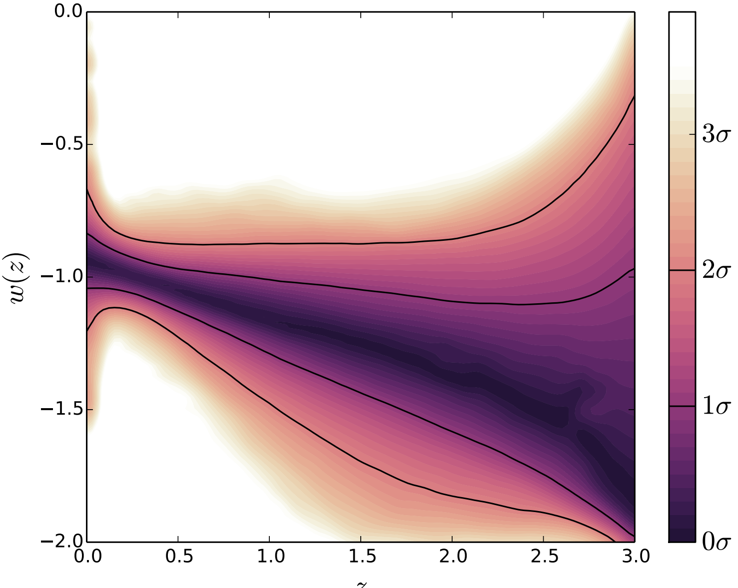
tilted

$w(z)$ reconstruction

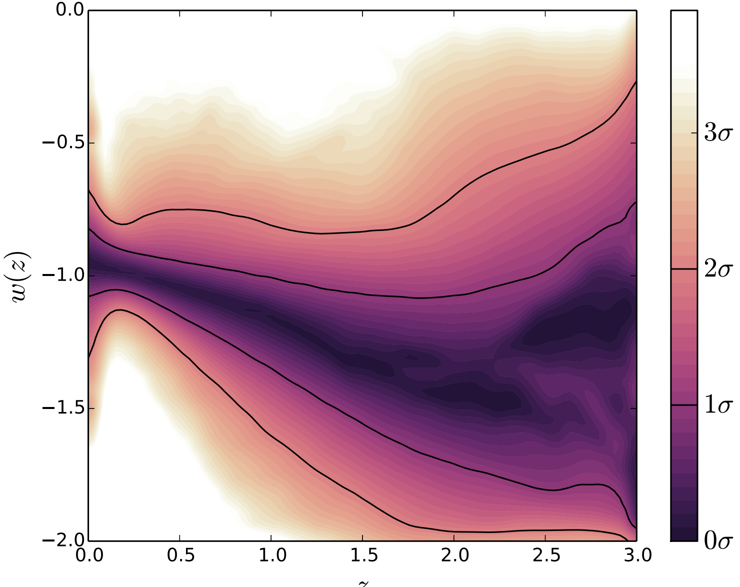


1 internal node

$w(z)$ reconstruction

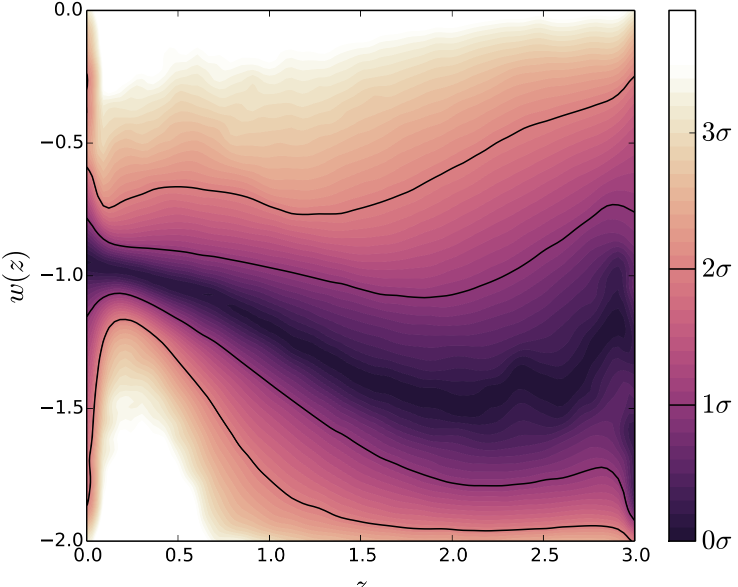


2 internal nodes
$w(z)$ reconstruction



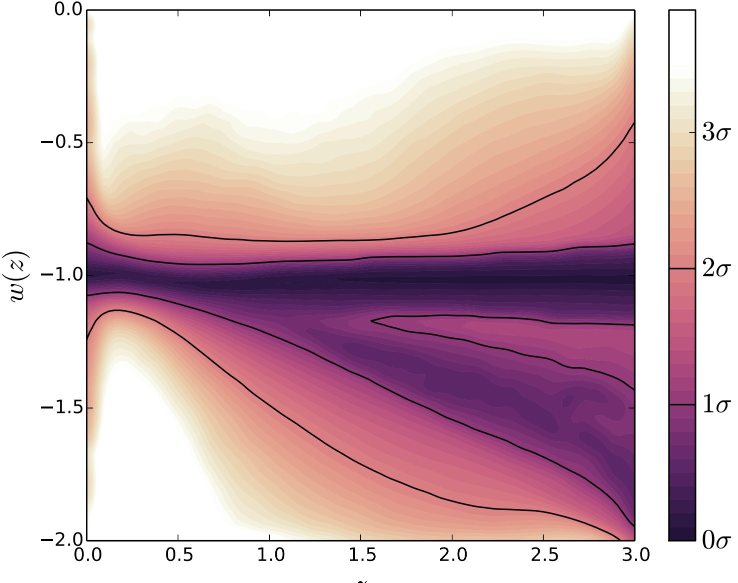
3 internal nodes

w(*z*) reconstruction



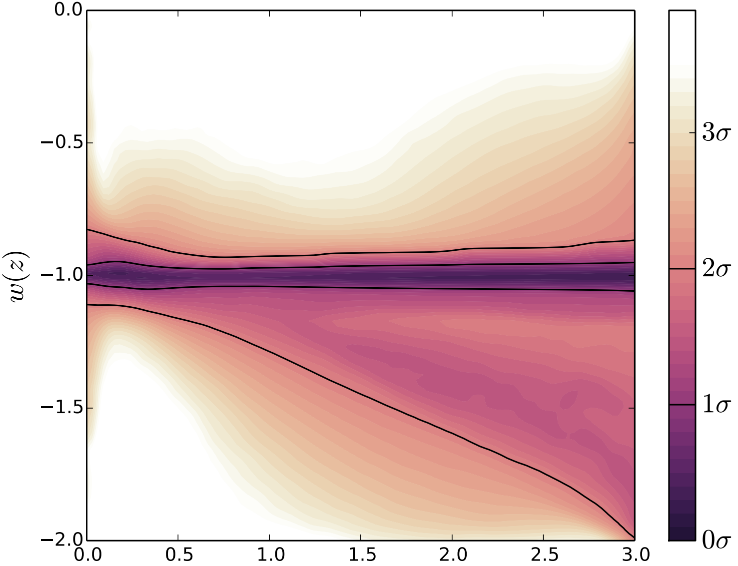
marginalised plot - just extension models

$w(z)$ reconstruction



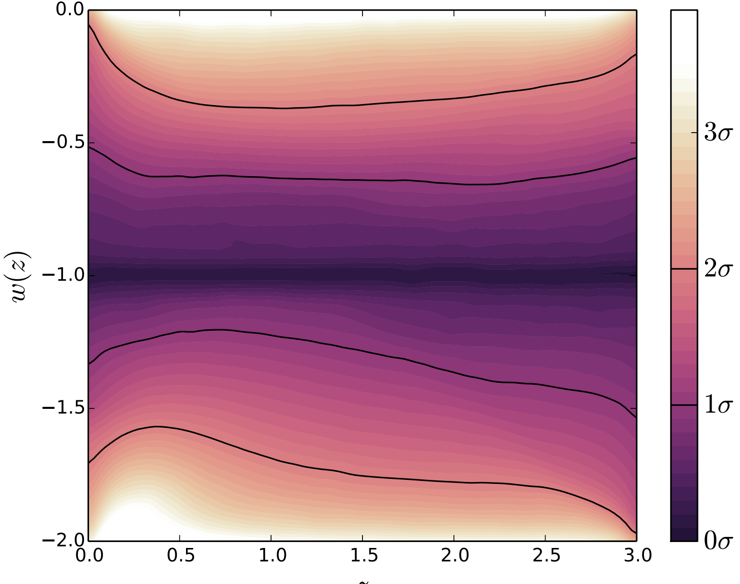
marginalised plot - including LCDM

w(*z*) reconstruction



prior

$w(z)$ reconstruction



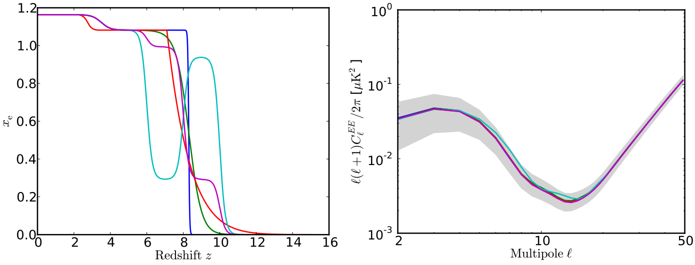
Kullback–Leibler divergence

- So ΛCDM wins in all cases (Bayes factors range from -2.3 to -3.4 over the examples considered), but preference for 'supernegative' values at higher z of interest
- We have also been looking at a quantitative measure of the information and constraining power in a given dataset
- The Kullback–Leibler divergence of a posterior distribution $Pr(w|z)$ from a prior $\pi(w|z)$ is

$$\mathcal{D}_{\mathrm{KL}}(z) = \int Pr(w|z) \ln \left[\frac{Pr(w|z)}{\pi(w|z)} \right] dw$$

- This provides the gain in information on w at each z. (We marginalise both the priors and posteriors over all other parameters before doing this.)
- By doing this with different datasets added/removed, provides an interesting way of understanding where (and which) data sets are most constraining in z
- Think this could be useful in survey design as well as analysis

Reconstruction of x_e history

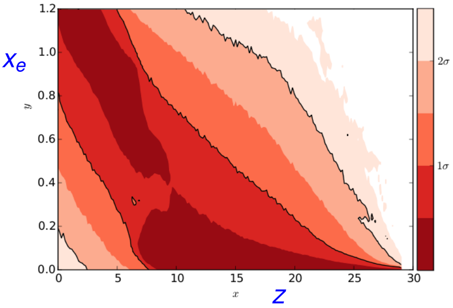


- Method also seems well-adapted to attempts to reconstruct the reionization history
- Above is from the recent Planck paper on 'Planck constraints on reionisation history', arXiv:1605.03507

- The different histories at the left all have the same τ ($= 0.06$) and give rise to the different *EE* spectra shown at the right
- Grey band is cosmic variance

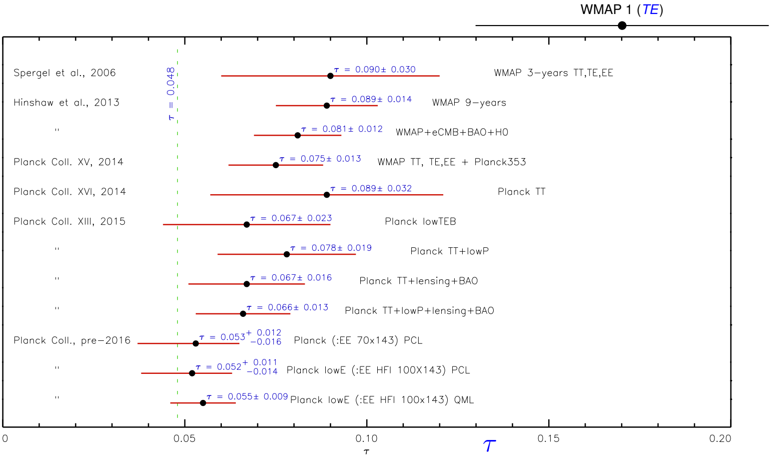
Reconstruction of x_e history

- Point about our method is that since evidence is used to determine the number of nodes, it's still of interest to attempt a reconstruction, just to see the 'confidence band' of models consistent with the data
- We use similar data as for the $w(z)$ reconstruction, including the Planck 2015 likelihoods and this time with Planck lensing as well (should help break the $A_s e^{-2\tau}$ degeneracy)



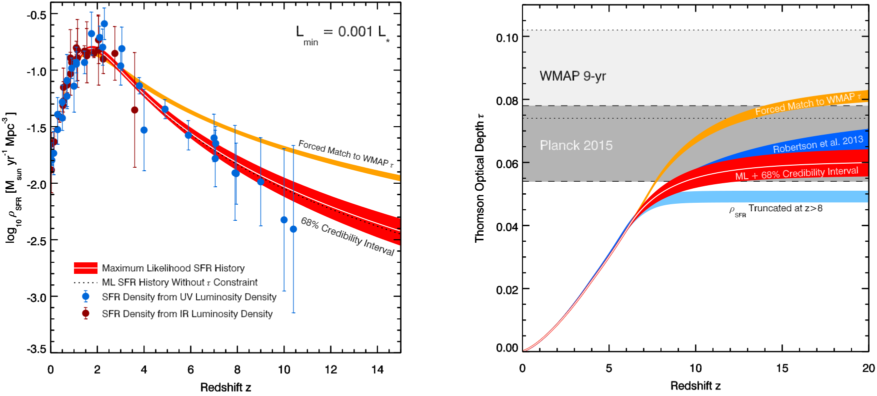
- Note this attempt just preliminary — known things wrong with it
- As HI reionization era data starts to come in from the experiments, will be very interesting to incorporate this data in such an approach

τ history



- Plot is from ‘Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth’, arXiv:1605.02985
- WMAP first year point (*TE* only) has been added in

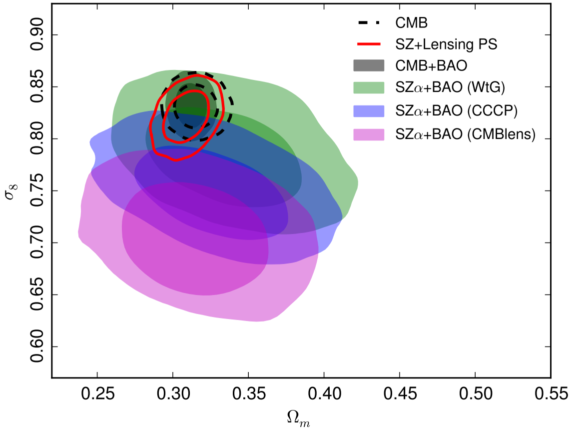
Cosmic reionization constraints



Plots from ‘Cosmic reionization and early star-forming galaxies: a joint analysis of new constraints from Planck and Hubble space telescope’, Robertson *et al.*, 2015 (arXiv:1502.02024)

Clustering

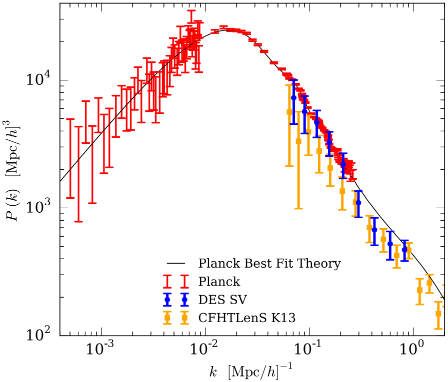
- Cosmology sample for 2015 release of Planck SZ clusters used 439 clusters *versus* 189 in 2013
- Still tensions between primordial CMB constraints and those from clusters, but very dependent on mass scaling used

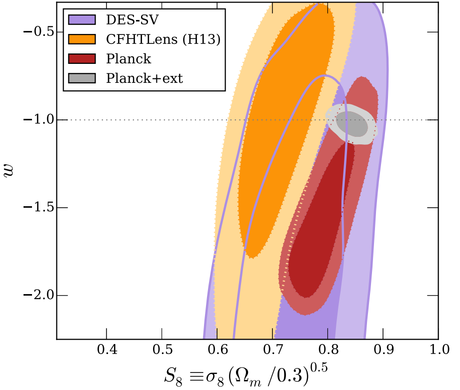


From Planck SZ Cosmology paper 2015 arXiv:1502.01597

WTG = Weighing the Giants, CCCP = Canadian Cluster Comparison Project, LENS = CMB lensing

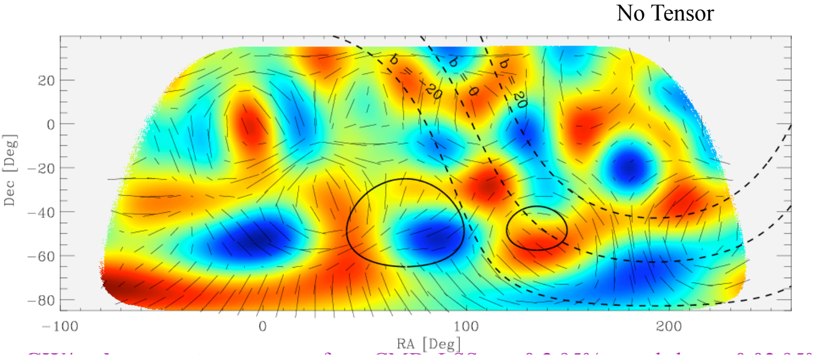
First Dark Energy Survey (DES) Cosmology Results





From 'Cosmology from cosmic shear with Dark Energy Survey Science Verification data' arXiv:1507.05552

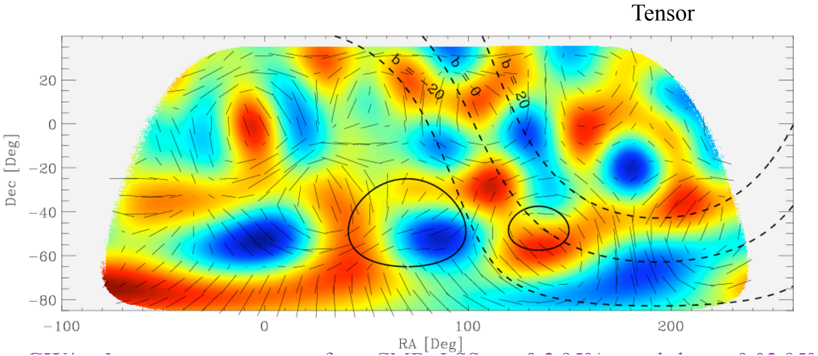
Sky with and without tensors



http://www.astro.caltech.edu/ lgg/

- Amplitude of tensor (gravity wave) component, is measured by the ratio r of tensor to scalar mode at some given scale
- This comparison is for $r = 0.1$

Sky with and without tensors



http://www.astro.caltech.edu/ lgg/

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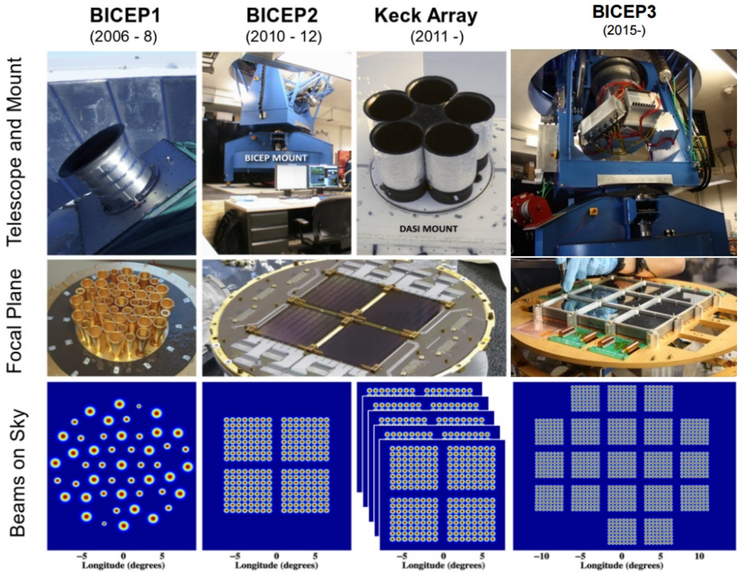
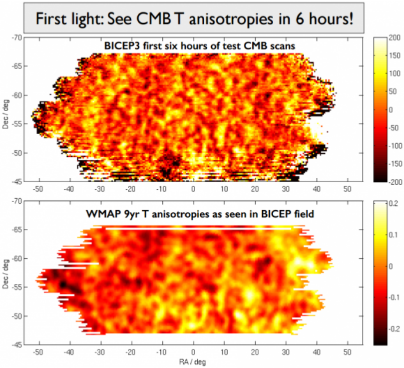
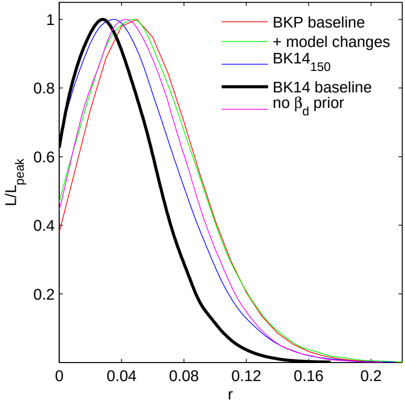
Update on BICEP



Latest BICEP results



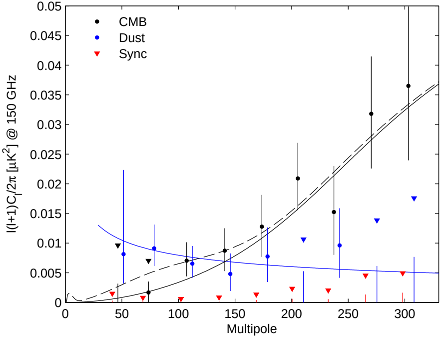


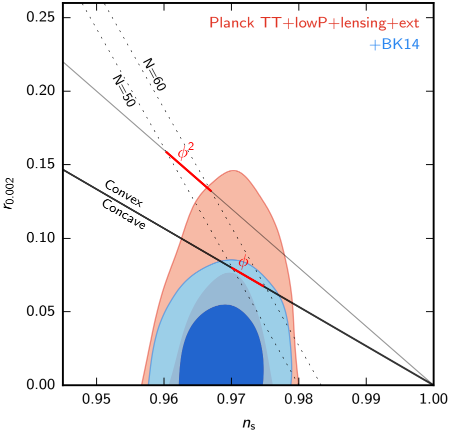
From 'BICEP2 / Keck Array VI: Improved Constraints On Cosmology and Foregrounds When Adding 95GHz Data From Keck Array' arXiv:1510.09217

- Six hours of BICEP 3 data compared to 9 years of WMAP (on a single patch)

- 'BK14' leads to best current r constraint of $r < 0.07$ at 95% confidence

Latest BICEP results (contd.)

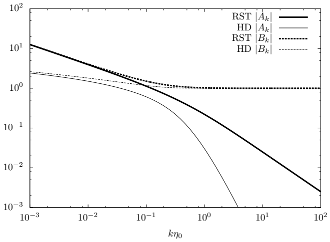




- Plots also from October 2015 BICEP paper arXiv:1510.09217
- Left shows constraints when splitting into spectral components (CMB, dust and Synch.)
- Right shows constraints on inflation in n_s-r plane

New proposal for initial conditions in inflation

- An issue for the generation of perturbations during inflation, is how one lays down the initial conditions
- Well within the horizon, i.e. for everything except low k, different methods, e.g. Hamiltonian diagonalization, adiabatic method . . . , give the same answer
- Not true for low k modes in a rapidly changing background, however
- Last week, Handley, Lasenby & Hobson (Phys.Rev. D, accepted, arXiv:1607.04148) have proposed a further method — minimization of the local energy density of the renormalised stress-energy tensor

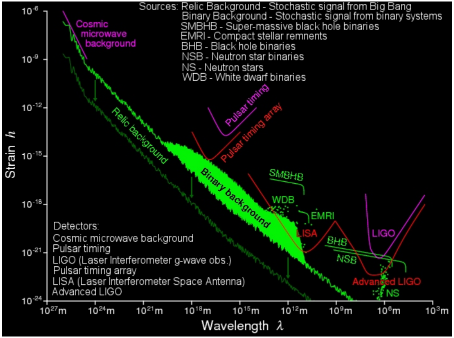


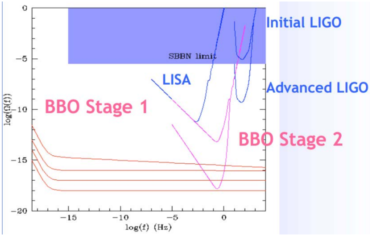
- This gives different predictions for the initial mode amplitudes than Hamiltonian diagonalization
- We work with

$$\chi_k(\eta) \propto \sqrt{\pi\eta}\left(A_k H_0^{(1)}(k\eta) + B_k H_2^{(1)}(k\eta)\right)$$

- Point is that such differences are in principle accessible to experiment

Direct Detection?





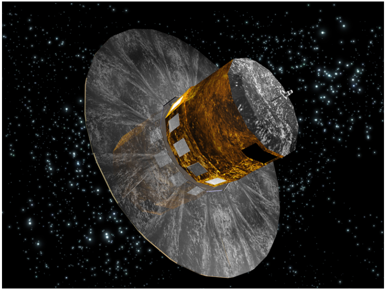
Top curve is for $r = 0.1$

From a talk on BBO by Gregory Harry (MIT)

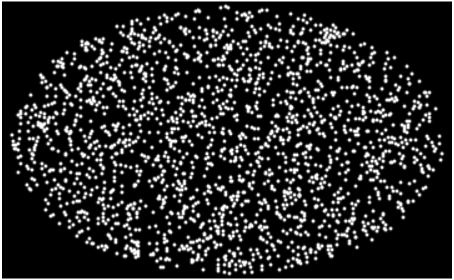
- Big problem is that most of portion of frequency space where we want to look is taken out by background of Binary Stars (in our and other galaxies)
- However, could be a window near 1 milliHz to 1 Hz, which could eventually be observed from space with required sensitivity if $r \gtrsim 0.001$ (Big Bang Observer proposed to do this - at least 30 years away?)

GAIA and gravitational waves

- Project with Gerry Gilmore, and student Deyan Mihaylov, to investigate use of GAIA proper motion data for constraints on gravitational wave background
- Have started on simulation of what could be observed as gravitational waves cause deflection of a screen of stars and/or quasars



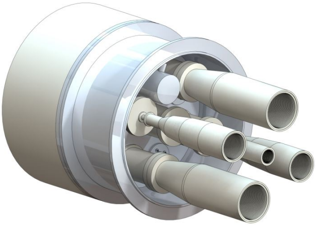
GAIA Satellite



- Typical levels certainly too small for detection of individual motions (swamped by intrinsic proper motions of stars anyway)
- Question is whether a statistical technique, tuned particularly to large scales, may be able to work

QUIJOTE

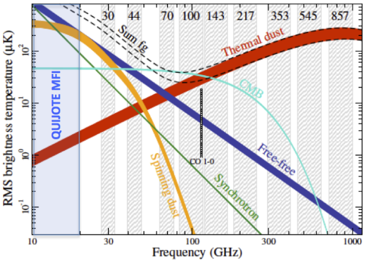
- QUIJOTE Spanish/UK ground-based experiment
- Currently one of only two ground-based CMB experiments with European leadership (other is QUBIC, led by APC, Paris)
- Tenerife, Santander, Manchester and Cambridge collaboration
- Two-fold aim: low frequency foreground mapping in polarization, plus in future 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 adds horns at 30 GHz (currently being commissioned)

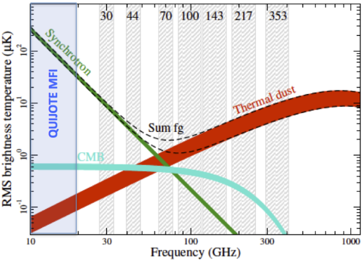


Horns of first receiver

Installation of second telescope

QUIJOTE/Planck Radioforegrounds Project





- Horizon 2020 project to use combination of QUIJOTE and Planck data to characterise foreground emissions

UNIVERSITY OF CAMBRIDGE

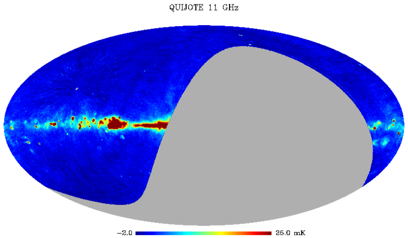
treelogic

QUIJOTE telescopes

QUIJOTE/Planck Radioforegrounds Project (contd.)

Combining Planck and QUIJOTE is to:

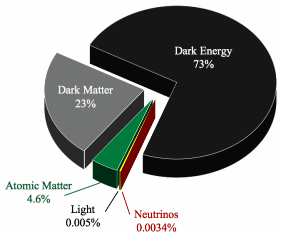
- Produce legacy maps of the synchrotron and AME (anomalous Microwave Emission) emissions in the Northern sky
- Characterize the synchrotron spectral index with high accuracy, fitting for the curvature of the synchrotron spectrum to constrain cosmic-rays electron physics
- Study the large-scale properties of the Galactic magnetic field



11 GHz map from QUIJOTE

- Model and characterize the level of a possible contribution of polarized anomalous microwave emission (AME);
- Characterize the population of radio sources measured by Planck by adding unique information in the frequency domain of 10-20 GHz;

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)

- Optical depth τ is somewhat lower than previously thought: $\tau = 0.055 \pm 0.009$
- Tensor ratio r is being constrained more tightly: $r < 0.07$ at 95% confidence
- This is starting to rule out mononomial inflation potentials ϕ^n for any $n > 1$
- Some evidence for a deficit in the level of clustering and matter power spectrum at smaller scales relative to best fit CMB model — possibly neutrino mass?