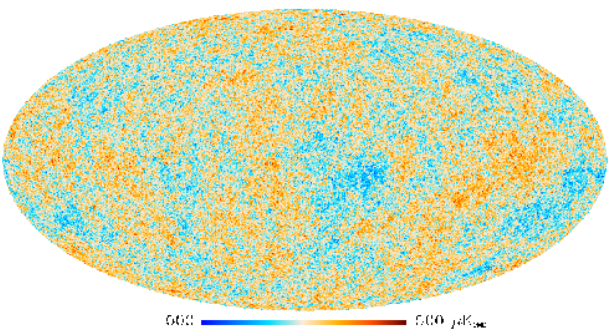


CMB Observations and their implications for cosmology

Anthony Lasenby, Astrophysics Group,
Cavendish Laboratory and Kavli Institute for Cosmology, Cambridge
(Paris Chalonge Meeting – July 2014)

Outline

- Last year has been an exciting one for the CMB!
- Clearly most excitement over the South Pole BICEP2 results
- Also continuing discussion and interest over Planck 2013 results, and release of 4 papers on polarized dust emission
- Very important results on lensing from SPT and POLARBEAR
- Also ACTPOL has produced its first polarisation results (excellent EE mode spectrum)
- Will aim to describe story of some of these and implications for cosmology

- Also: Period of kinetic domination leading to fast roll: results on why we should expect this in early universe

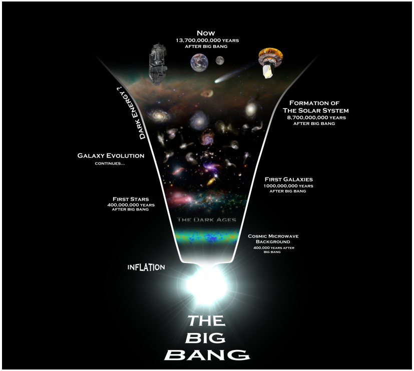
Planck Acknowledgements

- 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.

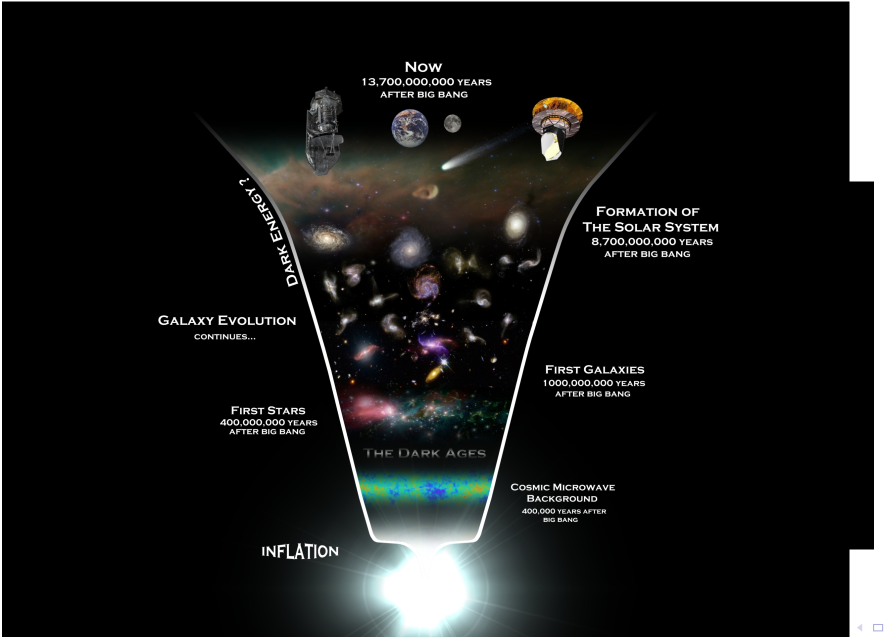
BICEP2 Results

- 'BICEP2 I: Detection Of B-mode Polarization at Degree Angular Scales', Ade et al.

- Paper submitted to the Archive 17th March (arXiv:1403.3985)
- Has caused huge interest by claiming discovery of primordial B-modes of the Cosmic Microwave Background (CMB)
- These are imprinted on the CMB during the 'Recombination' era, about 400,000 years after the Big Bang, but what imprints them are gravity waves generated at inflation itself (probably just 10^{-35} seconds after the Big Bang)

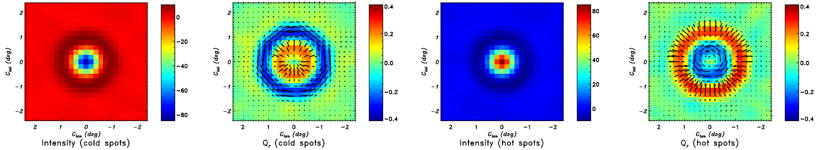


BICEP2 Results

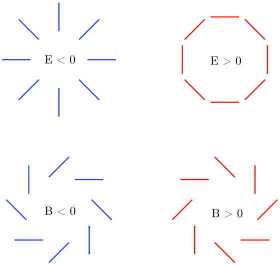


E and B modes

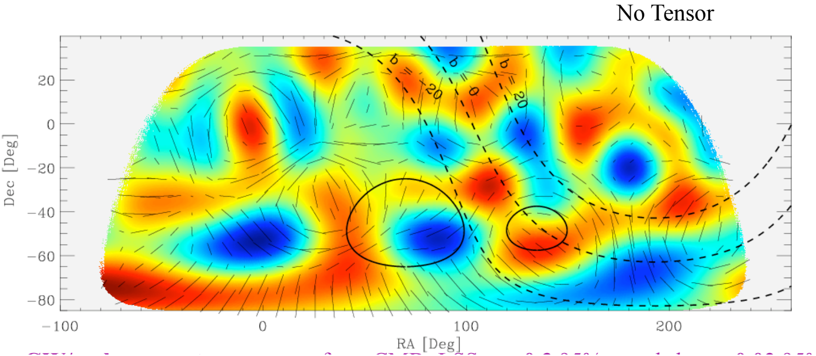
- Both arise from Thomson scattering at recombination
- Converts input quadrupoles in intensity $\Longrightarrow$ linear polarization
- Consider Planck hot and cold spots (from Planck 2013 Mission Paper)



- Pattern near peak is example of *E*-mode - like gradient of a potential
- *B*-mode is like a curl field
- Scalar (density) perturbations only give *E*-modes
- Gravity (tensor) waves produce both *E*- and *B*-mode polarization (latter have handedness)



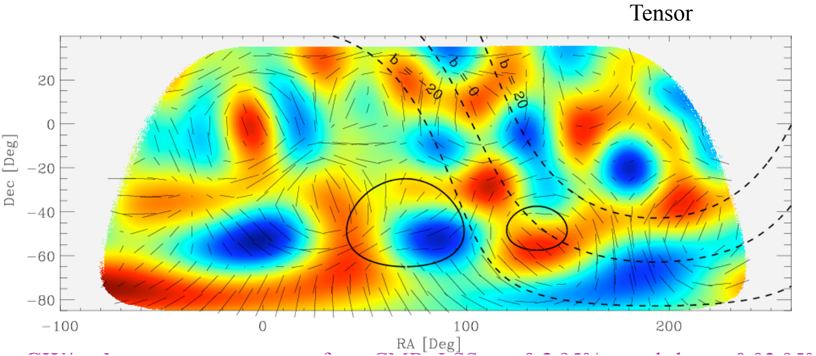
Sky with and without tensors



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 $r = 0.1$

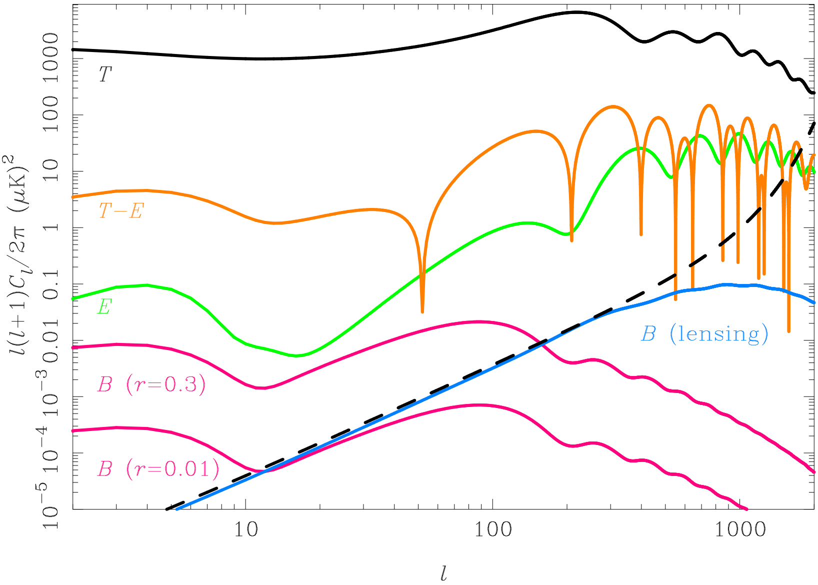
Sky with and without tensors



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

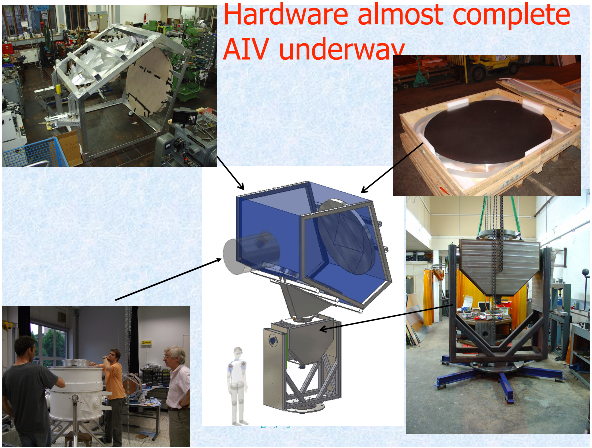
- Amplitude of tensor (gravity wave) component, is measured by the ratio r of tensor to scalar mode at some given scale
- This comparison is for $r = 0.1$

Predicted Spectra (sum)



CLOVER

- Dashed curve in previous plot was sensitivity level for CLOVER
- UK experiment (at 3 frequencies), cancelled in 2009 a few months before deployment in Chile

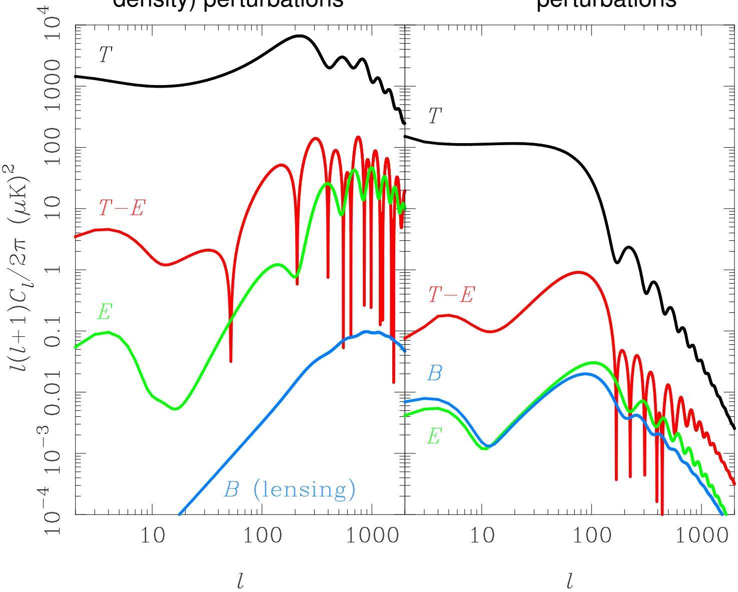


slide from 2009

CMB Power spectra (Two parts separately)

Scalar (matter and radiation density) perturbations

Tensor (gravity wave) perturbations



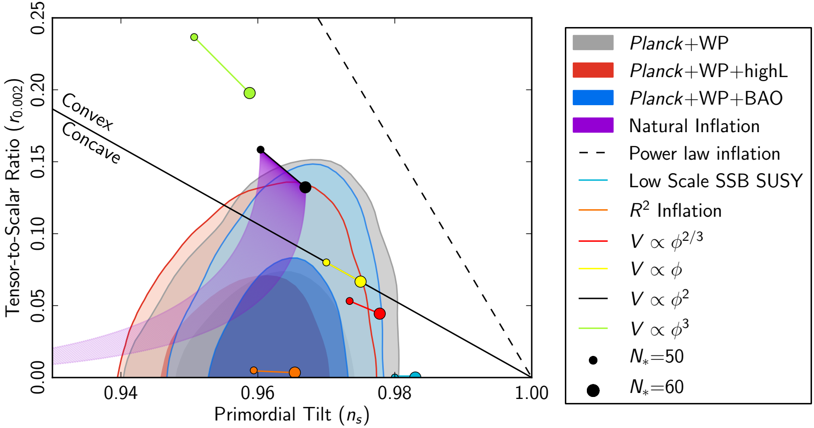
What would a detection of primordial gravity waves tell us?

- Strong evidence that inflation happened
- The tensor to scalar ratio r is directly related to the energy scale of inflation, which we don't know by other means:

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

- Thus detectable gravity waves ($r > 0.01$ say) would mean inflation occurred at the GUT scale ($\sim 10^{16}\,\mathrm{GeV}$)
- We would then be accessing particle physics at a scale about at least 10^{12} higher than those achievable at LHC
- Combination of r and slope of scalar primordial power spectrum (called n_s) is one of the most important ways important of discriminating between inflation theories
- Measurement of r provides the 'missing piece'

Constraints in tilt vs. gravitational wave plane

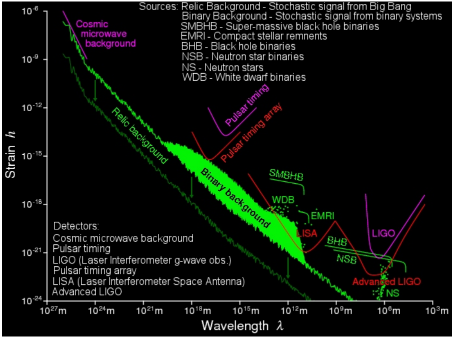


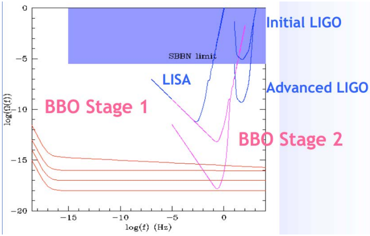
- These are results from Planck 2013 Inflation paper (arXiv:1303.5082)
- $r = 0.2$ would make a huge difference to this plot!

Inflation and string theory

- In simple single field models of inflation, Lyth (1997) showed that the field had to move through a super-Planckian distance if r was big enough to be observable
- Prediction is roughly $\Delta\phi \sim (r/0.002)^{1/2}$ for $\Delta\phi$ measured in Planck units $M_{\rm Pl}$
- There may be geometrical effects in string theory which makes this difficult
- Also now believed that having a smooth potential over $\Delta\phi > M_{\rm Pl}$ problematic for effective field theory with a cutoff $\Lambda < M_{\rm Pl}$ unless shift symmetry removes higher order corrections
- First 'stringy' models incorporating this (with axion-like potentials) appeared 5 years ago (e.g. Flauger et al. hep-th/0907.2916 - Axion Monodromy model)
- These may lead to a broad ϕ^2 type potential, but with superposed oscillations — observable effects in CMB?

Direct Detection?





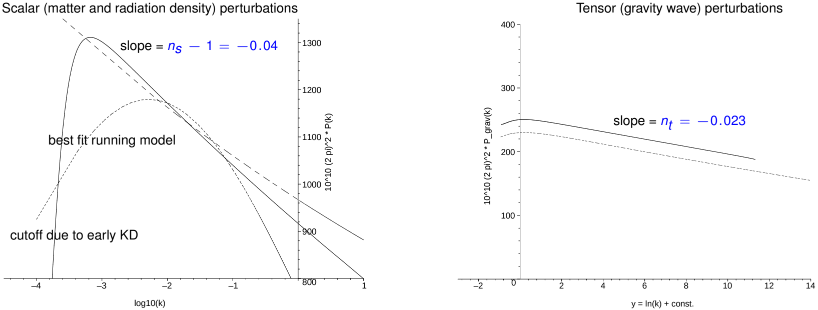
Top curve is for $r = 0.1$

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?)

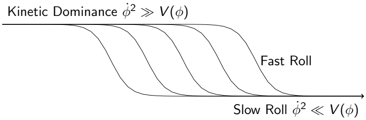
Tensor slope?

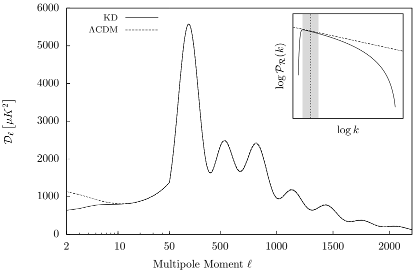
If r really is as big as ~ 0.2, then prospects also arise for checking the consistency relation $n_t = -r/8$



- These are two plots from Lasenby + Doran (Phys.Rev.D71:063502, 2005) arXiv:astro-ph/0307311
- Come from a model which naturally incorporates early Kinetic Dominance leading to suppression of power on largest scales
- Now believe KD is generic (see next slide), but r.h. plot illustrates that on smaller scales we still have the consistency relation, since r predicted here is about 0.19, therefore n_t should be $-0.19/8 = -0.02375$

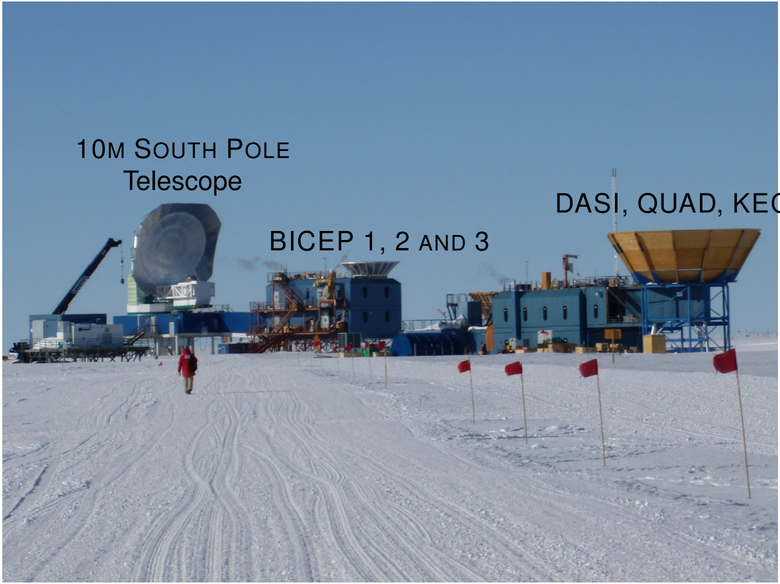
Kinetic Domination





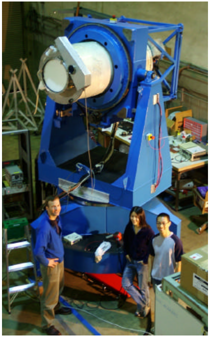
- In Handley et al., Phys. Rev. D 89 (2014) 063505 (arXiv:1401.2253) we have proved that the universe generically emerges from an initial singularity with the kinetic energy of the inflaton dominating its potential energy: $\dot{\phi}^2 \gg V(\phi)$.
- **Assumption**: there is some epoch prior to which the inflaton development is strictly monotonic: $0 < \varepsilon < |\dot{\phi}|$ (true for nearly all commonly considered potentials).
- Kinetic Dominance may be relevant to the apparent low-ℓ falloff in the CMB power spectrum (Planck 2013 results suggested about 5–10% shortfall over $\ell \lesssim 50$)
- Paper by Lello and Boyanovsky (JCAP05,029(2014) and arXiv:1312.4251) and talk later by Daniel Boyanovsky are very relevant

BICEP/KECK Programme



BICEP/KECK Programme

BICEP → BICEP2 → Keck-Array



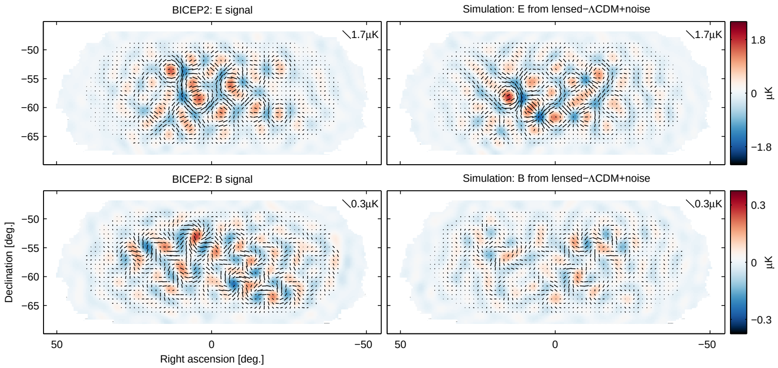
BICEP1 (2006 – 2008)
30cm refractor
96 NTD bolometers (same kind as Planck)
Best published limits on r from B-modes – r<0.72

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

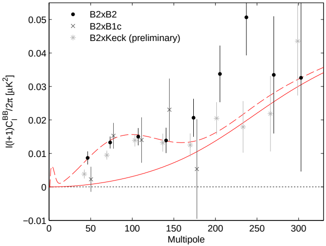
(From Clem Pryke Moriond 2013 talk)

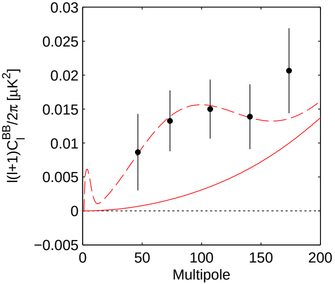
BICEP2 Results

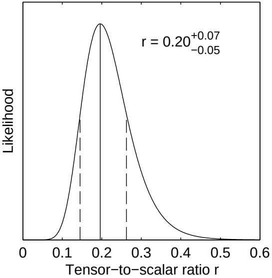


On comparing lower left and lower right panels can see enhancement in real detected signal vs. a simulation with just 'lensed' B-modes plus noise

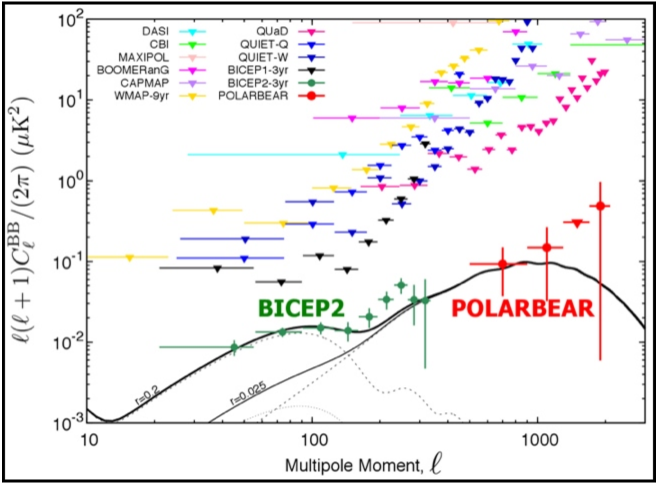
BICEP2 Results



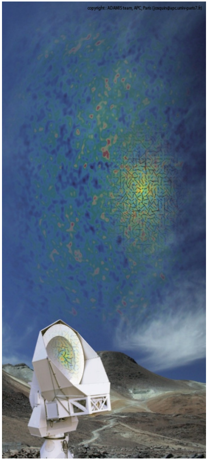




BICEP2 versus other experiments



POLARBEAR — first direct detection of lensing BB



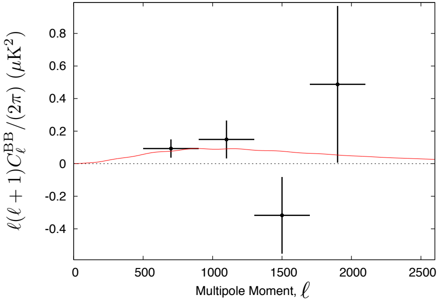


FIG. 12.— Binned C_ℓ^{BB} spectrum measured using data from all three patches ($\sim 30\,\mathrm{deg}^2$). A theoretical WMAP-9 ΛCDM high-resolution C_ℓ^{BB} spectrum with A_{BB}= 1 is shown. The uncertainty shown for the band powers is the diagonal of the band power covariance matrix, including beam covariance.

(From arXiv:1403.2369)

POLARBEAR is a project of UCSD, Berkeley and ~ 30 other institutions, sited in Atacama)

- Currently targeting higher resolution
- 3.5 arcmin beam, working at 150 GHz, 1274 bolometers currently
- Future plans: Multichroic pixels receiver in 2014: 7,588 detectors, 90/150 GHz
- Simons Array by 2018: 3 telescopes, 22,764 detectors, 90/150/220 GHz (details and picture from Giulio Fabbian 2014 Moriond talk)

BICEP2 Results

- Announcement made a huge impact, particularly in theoretical physics community
- Papers on arXiv citing it reached 200 just 5 weeks after announcement!
- Key feature is large value or r. Effectively unexpected both theoretically and observationally
- Points to problems in string theory (need 'large field' inflation)
- At face value disagrees with Planck 2013 data limit on r of < 0.11 at 95% confidence (based on temperature-only data)
- If both right, need to step outside standard 6-parameter cosmological model to reconcile them — therefore very exciting!

Foregrounds?

- This is 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 work at $150\,\mathrm{GHz}$ and base their analysis on existing, publically available maps of dust (e.g. from IRAS and Planck)
- Maps are in intensity, so they assume a fixed 5% polarization fraction
- BICEP2 only has a single frequency, so can't discriminate spectra on this basis

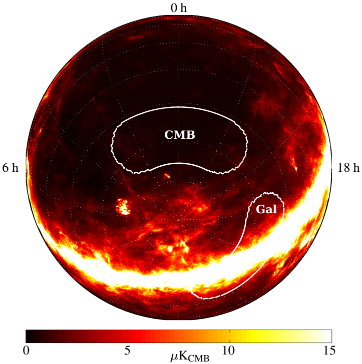
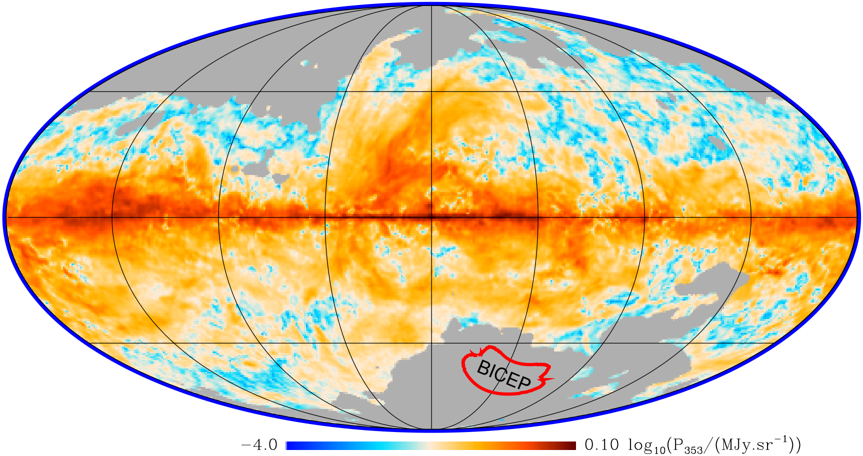


FIG. 20.— BICEP2 observing fields relative to the polarization amplitude predicted from FDS (Finkbeiner et al. 1999) model 8, assuming a 5% polarization fraction.

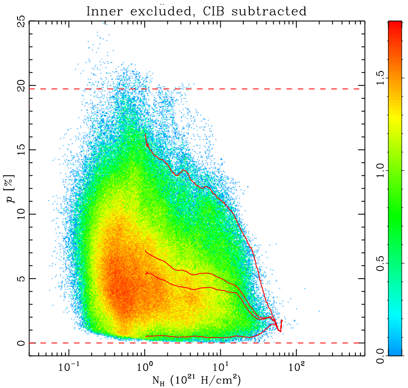
Planck PIP XIX map of 353 GHz Polarized Intensity



- Map is logarithmic plot of polarized intensity $p = \frac{\sqrt{Q^2+U^2}}{I}$
- Data only shown where the systematic uncertainties are small, and where the dust signal dominates total emission ($\sigma_p^{\mathrm{sys}} < 3\%$ and $f_{353} > 0.1\,\mathrm{MJy\,sr}^{-1}$)

Planck dust results

- Results from PIP XIX (arXiv:1405.0871), show that there is an anticorrelation between polarization fraction and column depth
- The curves show, from top to bottom, the evolution of the upper 1% percentile, mean, median and lower 1% percentile of p for pixels with $N_{\mathrm{H}} > 10^{21}\,\mathrm{cm}^{-2}$
- The top dashed line shows the best estimate of the maximum intrinsic polarization fraction ($p \sim 20\%$)
- Trends hypothesized to be due mainly to magnetic field configurations



- In 'Note added in proof' for published version of BICEP2 paper (PRL 112, 241101 (2014)), BICEP team acknowledge the trend to higher polarization fractions in regions of lower total dust emissivity
- BICEP field has $N_H \sim (1 - 2) \times 10^{20}\,\mathrm{H\,cm}^{-2}$

What next?

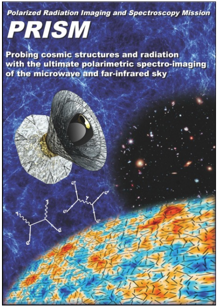
- Planck and BICEP teams now working together to produce a joint paper which analyses the BICEP field using Planck and BICEP data simultaneously
- Aim is that this joint paper will come out at the same time as the Planck cosmology release later this year (which will include the polarization data, as well as full mission temperature data)
- Several experiments coming up which could tell us more about these results, and crucially constrain dust contribution
- E.g. SPIDER and EBEX balloon-borne experiments to come (December 2014 flight for SPIDER — EBEX has already flown and results being analysed)
- Also QUIJOTE Spanish/UK ground-based experiment

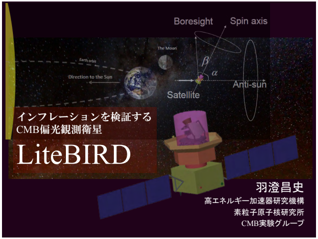
EBEX being recovered after flight

QUIJOTE

Further space missions?

- PRISM (Polarized Radiation Imaging and Spectroscopy Mission) was a European proposal for an L-class mission to be the ‘ultimate’ mapper of both temperature and polarisation for the CMB
- Lost out to Athena (X-ray) and eLISA (gravitatonal waves), but could come back in descoped form as an M-class mission





- Japanese have a proposed B-mode mission, LiteBIRD
- Degree-scales, 6 frequencies
- Selected as a “Priority large-scale research project” by Science Council of Japan on March 12th

Some current/upcoming polzn experiments

Name	Type	Detectors	ℓ range	r target	First Obs.
QUAD	ground	bolometer	$200 < \ell < 3000$		completed
BICEP	ground	bolometer	$50 < \ell < 300$	0.1	2007
BICEP2/KECK	ground	bolometer	$50 < \ell < 300$	0.05	2009
QUIET	ground	MMIC	$\ell < 1000$	0.05	completed
CLOVER	ground	bolometer	$20 < \ell < 600$	0.01	Cancelled
EBEX	balloon	bolometer	$20 < \ell < 1000$	0.03	2013
SPIDER	balloon	bolometer	$\ell < 100$	0.025	2014
CORE/PRISM	space	bolometer	$\ell < 2000$	$1\text{–}5 \times 10^{-3}$	??
QUIJOTE	ground	MMIC	$\ell < 80$	0.1/0.05	2012
POLARBEAR	ground	bolometer	$20 < \ell < 2000$	0.05	2013

+ polarization versions of ACT and SPT (typically targetting smaller angular scales)

Clusters

- Interesting recent results on clusters from Bocquet et al (arXiv:1407.2942)
- *Mass Calibration And Cosmological Analysis Of The SPT-SZ Galaxy Cluster Sample Using Velocity Dispersion σ_v And X-Ray Y_X Measurements*
- Gets better agreement between 'cluster abundance' and Planck primordial CMB parameters than Planck itself
- Non-zero sum of neutrino rest-masses helps bridge remaining gap (as for Planck)
- $\Sigma m_\nu = 0.148 \pm 0.081\,\mathrm{eV}$
- Definitely beginning to get impression that soon, by combination of CMB with smaller scale indicators like clusters and Lyα, we are going to start to get a real handle on neutrino mass

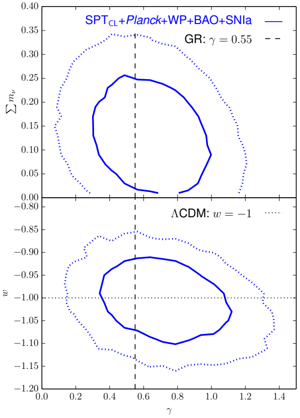


Figure 6. Likelihood contours (68% and 95%) for γ+ΛCDM with additional one-parameter extensions $\sum m_\nu$ (top), and w (bottom). The prediction for γ by GR and the ΛCDM value for w are indicated by the lines. The cosmological datasets combined exhibit no tension with a GR+ΛCDM description of the Universe.

From Bocquet et al, arXiv:1407.2942

Summary

BICEP2 results (which are certainly our most sensitive yet on B-modes) have demonstrated abundantly the enormous interest in this field. A verified B-mode detection means one has

- Discovered (indirectly) gravitational waves from the early universe
- Seen the furthest back in time we ever will
- Discovered the energy scale of inflation (close to GUT scale?)
- Provided first contact with 'predictions' from String Theory
- (If Planck and BICEP2 were both right) provided first indications that we have to step outside the Standard Model of Cosmology

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