Constraints on Primordial Gravitational Waves Using Planck, WMAP, and New BICEP2/Keck Observations through the 2015 Season

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BICEP2 / *Keck Array* X: Constraints on Primordial Gravitational Waves using *Planck*, WMAP, and New BICEP2/*Keck* Observations through the 2015 Season

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We present results from an analysis of all data taken by the BICEP2/*Keck* CMB polarization experiments up to and including the 2015 observing season. This includes the first *Keck Array* observations at 220 GHz and additional observations at 95 & 150 GHz. The Q/U maps reach depths of 5.2, 2.9 and 26 $\mu\mathrm{K}_{\mathrm{CMB}}$ arcmin at 95, 150 and 220 GHz respectively over an effective area of ≈ 400 square degrees. The 220 GHz maps achieve a signal-to-noise on polarized dust emission approximately equal to that of *Planck* at 353 GHz. We take auto- and cross-spectra between these maps and publicly available WMAP and *Planck* maps at frequencies from 23 to 353 GHz. We evaluate the joint likelihood of the spectra versus a multicomponent model of lensed-ΛCDM+r+dust+synchrotron+noise. The foreground model has seven parameters, and we impose priors on some of these using external information from *Planck* and WMAP derived from larger regions of sky. The model is shown to be an adequate description of the data at the current noise levels. The likelihood analysis yields the constraint $r_{0.05} < 0.07$ at 95% confidence, which tightens to $r_{0.05} < 0.06$ in conjunction with *Planck* temperature measurements and other data. The lensing signal is detected at 8.8σ significance. Running maximum likelihood search on simulations we obtain unbiased results and find that $\sigma(r) = 0.020$. These are the strongest constraints to date on primordial gravitational waves.

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Introduction.—It is remarkable that our standard model of cosmology, known as ΛCDM, is able to statistically describe the observable universe with only six parameters (tensions between high and low redshift probes notwithstanding [1]). Observations of the cosmic microwave background (CMB) [2] have played a central role in establishing this model and now constrain these parameters to percent-level precision (see most recently Ref. [3]).

The success of this model focuses our attention on the deep physical mysteries it exposes. Dark matter and dark energy dominate the present-day universe, but we lack understanding of both their nature and abundance. Perhaps most fundamentally, the standard model offers no explanation for the observed initial conditions of the universe: highly uniform and flat with small, nearly scale-invariant, adiabatic density perturbations. Inflation is an extension to the standard model that addresses initial conditions by postulating that the observable universe arose from a tiny, causally-connected volume in a period of accelerated expansion within the first fraction of a nanosecond, during which quantum fluctuations of the spacetime metric gave rise to both the observed primordial density perturbations and a potentially-observable background of gravitational waves (see Ref. [4] for a recent review and citations to the original literature).

Probing for these primordial gravitational waves through the faint B-mode polarization patterns that they would imprint on the CMB is recognized as one of the most important goals in cosmology today, with the potential to either confirm inflation, and establish its energy scale, or to powerfully limit the space of allowed inflationary models [5]. Multiple groups are making measurements of CMB polarization, some focused on the gravitational wave goal at larger angular scales, and others focused on other science at smaller angular scales—examples include [6–9].

In principle B-mode polarization patterns offer a unique probe of primordial gravitational waves because they cannot be sourced by primordial density perturbations [10–12]. However, in practice there are two sources of foreground: gravitational deflections of the CMB photons in flight leads to a lensing B-mode component [13], and polarized emission from our own galaxy can also produce B-modes. The latter can be separated out through their differing frequency spectral behavior, so extremely sensitive multi-frequency observations are needed to advance the leading constraints on primordial gravitational waves.

Our BICEP/*Keck* program first reported detection of an excess over the lensing B-mode expectation at 150 GHz in Ref. [14]. In a joint analysis using multi-frequency data from the *Planck* experiment it was shown that most or all of this is due to polarized emission from dust in our own galaxy [15, hereafter BKP]. We first started to diversify our own frequency coverage by adding data taken in 2014 with *Keck Array* at 95 GHz, yielding the tightest previous constraints on primordial gravitational waves [16, hereafter BK14].

In this letter [hereafter BK15], we advance these constraints using new data taken by *Keck Array* in the 2015 season including two 95 GHz receivers, a single 150 GHz receiver, and, for the first time, two 220 GHz receivers. This analysis thus doubles the 95 GHz dataset from two receiver-years to four, while adding a new higher frequency band that significantly improves the constraints on the dust contribution over what is possible using the *Planck* 353 GHz data alone. The constraint on primordial gravitational waves parametrized by tensor to scalar ratio r is improved to $r_{0.05} < 0.057$ (95%), disfavoring the important class of inflationary models represented by a ϕ potential[4, 5].

Instrument and observations.—*Keck Array* consists of a set of five microwave receivers similar in design to the precursor BICEP2 instrument [17, 18]. Each receiver employs a $\approx$ 0.25 m aperture all cold refracting telescope focusing microwave radiation onto a focal plane of polarized antenna-coupled bolometric detectors [19]. The receivers are mounted on a movable platform (or mount) which scans their pointing direction across the sky in a controlled manner. The detectors are read out through a time-domain multiplexed SQUID readout system. Orthogonally-polarized detectors are arranged as coincident pairs in the focal plane, and the pair-difference timestream data thus traces out changes in the polarization signal from place to place on the sky. The telescopes are located at the South Pole in Antarctica where the atmosphere is extremely stable and transparent at the relevant frequencies. The data are recorded to disk and transmitted back to the US daily for analysis.

To date we have mapped a single region of sky centered at RA 0h, Dec. $-57.5°$. From 2010 to 2013, BICEP2 and *Keck Array* jointly recorded a total of 13 receiver-years of data in a band centered on 150 GHz. Two of the *Keck* receivers were switched to 95 GHz before the 2014 season, and two more were switched to 220 GHz before the 2015 season. The BK15 data set thus consists of 4/17/2 receiver-years at 95/150/220 GHz respectively.

Maps and Power Spectra—We make maps and power spectra using the same procedures as used for BK14 and previous analyses [14]. Briefly: the telescope timestream data are filtered and then binned into sky pixels with the multiple detector pairs being co-added together using knowledge of their individual pointing directions as the telescope scans across the sky. Maps of the polarization Stokes parameters Q and U are constructed by also knowing the polarization sensitivity angle of each pair as projected onto the sky.

After apodizing to downweight the noisy regions around the edge of the observed area, the Q/U maps

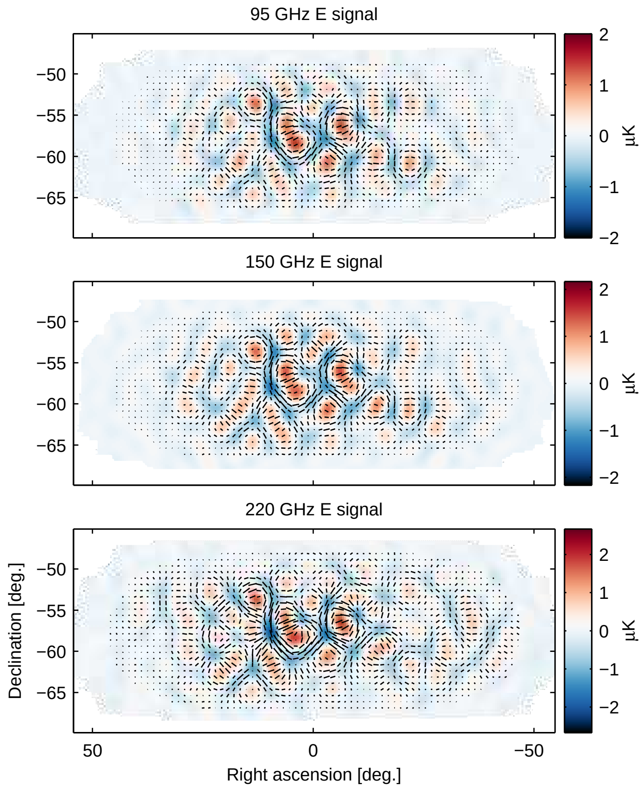

FIG. 1. Maps of degree angular scale E-modes ($50 < \ell < 120$) at three frequencies made using *Keck Array* data from the 2015 season only. The similarity of the pattern indicates that ΛCDM E-modes dominate at all three frequencies (and that the signal-to-noise is high). The color scale is in μK, and the range is allowed to vary slightly to (partially) compensate for the decrease in beam size with increasing frequency.

are Fourier transformed and converted to the E/B basis in which the primordial gravitational wave signal is expected to be maximally distinct from the standard ΛCDM signal.

Two details worth noting are the deprojection of leading order temperature to polarization leakage terms, and the adjustment of the absolute polarization angle to minimize the EB cross spectrum. See Ref. [14] for more information.

For illustration purposes we can inverse Fourier transform to form E/B maps. Fig. 1 shows E-mode maps formed from the 2015 data alone—the data which is being added to the previous data in this analysis. The similarity of the pattern at all three frequencies indicates that ΛCDM E-modes dominate, and that the signal-to-noise is high. The effective area of these maps is $\sim 1\%$ of the full sky. (See Appendix A for the full set of $T/Q/U$ maps [20].)

To suppress E to B leakage we use the matrix purification technique which we have developed [14, 21]. We then take the variance within annuli of the Fourier plane to estimate the angular power spectra. To test for systematic contamination we carry out our usual "jackknife" internal consistency tests on the new 95 GHz and 220 GHz data as described in Appendices B & C—the distributions of χ and χ^2 PTE values are consistent with uniform showing no evidence for problems.

In this paper we use the three bands of BICEP2/*Keck* plus the 23 & 33 GHz bands of WMAP [22][23] and all seven polarized bands of *Planck* [24][25]. We take all possible auto- and cross-power spectra between these twelve bands—the full set of spectra are shown in Appendix D.

Fig. 2 shows the EE and BB auto- and cross-spectra for the BICEP2/*Keck* bands plus the *Planck* 353 GHz band which is important for constraining the polarized dust contribution. The spectra are compared to the "baseline" lensed-ΛCDM+dust model from our previous BK14 analysis. Note that the BB spectra involving 220 GHz were not used to derive this model but agree well with it. The EE spectra were also not used to derive the model but agree well with it under the assumption that $EE/BB = 2$ for dust, as it is shown to be close to in *Planck* analysis of larger regions of sky [26, 27]. (Note that many of the BICEP/*Keck* spectra are sample variance dominated.)

Fig. 3 upper shows the noise spectra (derived using the sign-flip technique [14, 28]) for the three BK15 bands after correction for the filter and beam suppression. The turn up at low-ℓ is partially due to residual atmospheric $1/f$ in the pair-difference data and hence is weakest in the 95 GHz band where water vapor emission is weakest. In an auto-spectrum the quantity which determines the ability to constrain r is the fluctuation of the noise bandpowers rather than their mean. The lower panel therefore shows the effective sky fraction observed as inferred from the fractional noise fluctuation. Together, these panels provide a useful synoptic measure of the loss of information due to noise, filtering, and EE/BB separation in the lowest bandpowers. We suggest that other experiments reproduce this plot for comparison purposes.

Likelihood Analysis.—We perform likelihood analysis using the methods introduced in BKP and refined in BK14. We use the Hamimeche-Lewis approximation [29, hereafter HL] to the joint likelihood of the ensemble of 78 BB auto- and cross-spectra taken between the BICEP2/*Keck* and WMAP/*Planck* maps. We compare the observed bandpower values for $20 < \ell < 330$ (9 bandpowers per spectrum) to an eight parameter model of lensed-ΛCDM+r+dust+synchrotron+noise and explore the parameter space using `COSMOMC` [30] (which implements a Markov chain Monte Carlo). As in our previous analyses the bandpower covariance matrix is derived from 499 simulations of signal and noise, explicitly setting to zero terms such as the covariance of signal-only bandpowers with noise-only bandpowers or covariance of BICEP/*Keck* noise bandpowers with WMAP/*Planck* noise bandpowers [15]. The tensor/scalar power ratio r is evaluated at a pivot scale of 0.05 Mpc^{-1}, and we fix the tensor spectral index $n_t = 0$. The `COSMOMC` module containing the data and model is available for download at `http://bicepkeck.org`. We make only one change to

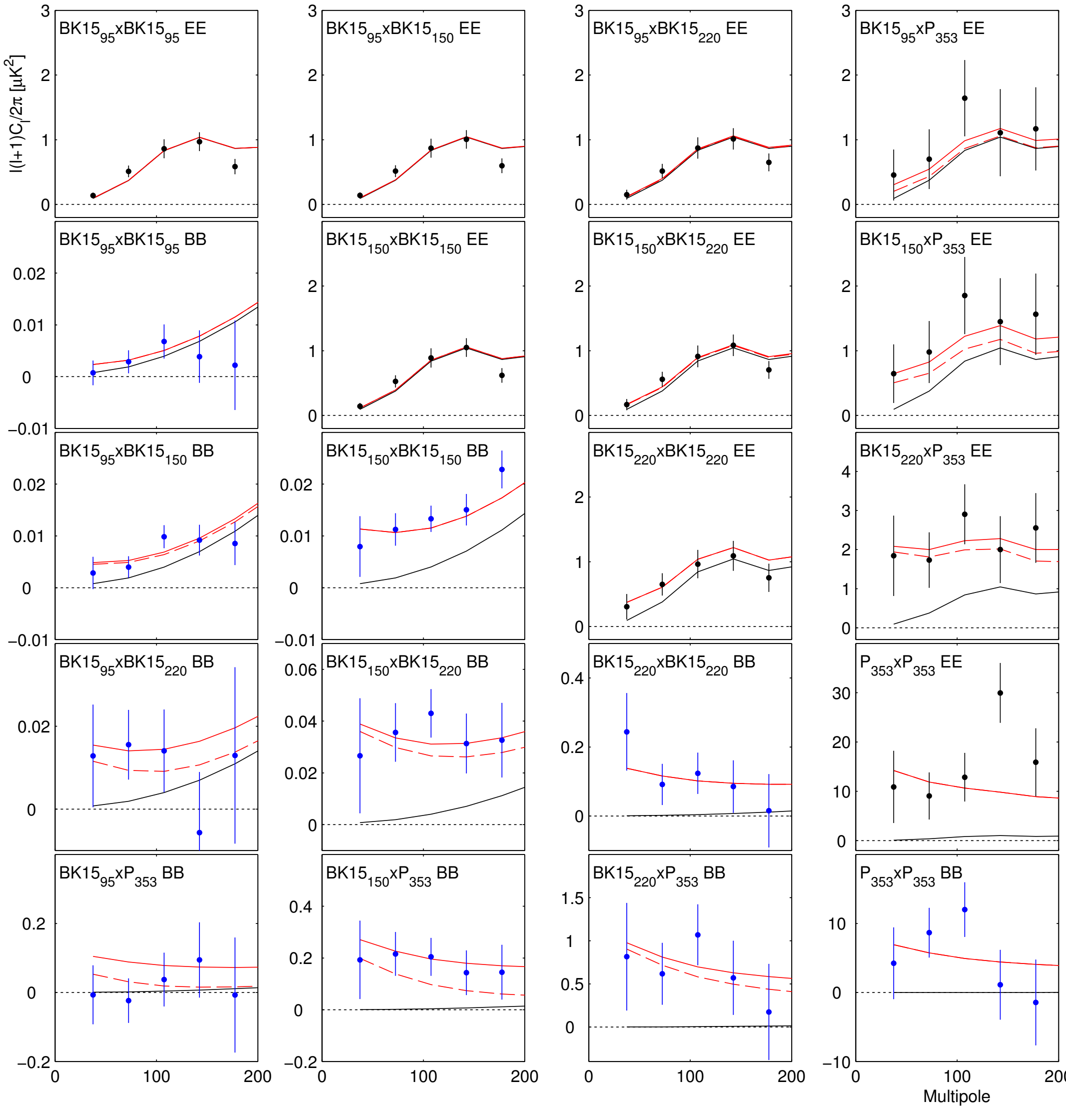

FIG. 2. EE and BB auto- and cross-spectra calculated using BICEP2/*Keck* 95, 150 & 220 GHz maps and the *Planck* 353 GHz map. The BICEP2/*Keck* maps use all data taken up to and including the 2015 observing season—we refer to these as BK15. The black lines show the model expectation values for lensed-ΛCDM, while the red lines show the expectation values of the baseline lensed-ΛCDM+dust model from our previous BK14 analysis ($r = 0$, $A_{\mathrm{d},353} = 4.3\,\mu\mathrm{K}^2$, $\beta_\mathrm{d} = 1.6$, $\alpha_\mathrm{d} = -0.4$), and the error bars are scaled to that model. Note that the model shown was fit to BB only and did not use the 220 GHz points (which are entirely new). The agreement with the spectra involving 220 GHz and all the EE spectra (under the assumption that $EE/BB = 2$ for dust) is therefore a validation of the model. (The dashed red lines show the expectation values of the lensed-ΛCDM+dust model when adding strong spectral decorrelation of the dust pattern—see Appendix F for further information.)

the "baseline" analysis choices of BK14, expanding the prior on the dust/sync correlation parameter. The following paragraphs briefly summarize.

We include dust with amplitude $A_{\mathrm{d},353}$ evaluated at 353 GHz and $\ell = 80$. The frequency spectral behavior is taken as a modified black body spectrum with $T_\mathrm{d} = 19.6$ K and $\beta_\mathrm{d} = 1.59 \pm 0.11$, using a Gaussian prior with the given 1σ width, this being an upper limit on the patch-to-patch variation [15, 31]. We note that the latest *Planck* analysis finds a slightly lower central value of $\beta_\mathrm{d} = 1.53$ [27] (well within our prior range) with no detected trends with galactic latitude, angular scale or EE vs. BB. The spatial power spectrum is taken as a power law $\mathcal{D}_\ell \propto \ell^{\alpha_\mathrm{d}}$ marginalizing uniformly over the (generous) range $-1 < \alpha_\mathrm{d} < 0$ (where $\mathcal{D}_\ell \equiv \ell\,(\ell+1)\,C_\ell/2\pi$). *Planck* analysis consistently finds approximate power law behavior of both the EE and BB dust spectra with exponents ≈ -0.4 [26, 27].

We include synchrotron with amplitude $A_{\mathrm{sync},23}$ evaluated at 23 GHz (the lowest WMAP band) and $\ell =$

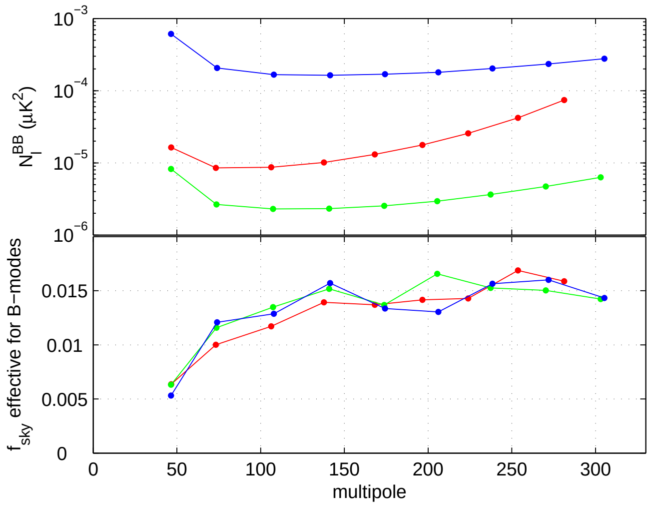

FIG. 3. *Upper:* The noise spectra of the BK15 maps for 95 GHz (red), 150 GHz (green) and 220 GHz (blue) after correction for the filtering of signal which occurs due to the beam roll-off and timestream filtering. (Note that no ℓ^2 scaling is applied.) *Lower:* The effective sky fraction as calculated from the ratio of the mean noise realization bandpowers to their fluctuation $f_{\rm sky}(\ell) = \frac{1}{2\ell\Delta\ell}\left(\frac{\sqrt{2}\bar{N}_b}{\sigma(N_b)}\right)^2$, i.e. the observed number of B-mode degrees of freedom divided by the nominal full-sky number. The turn-down at low ℓ is due to mode loss to the timestream filtering and matrix purification.

80, assuming a simple power law for the frequency spectral behavior $A_{\rm sync} \propto \nu^{\beta_{\rm s}}$ with a Gaussian prior $\beta_{\rm s} = -3.1 \pm 0.3$ [32]. We note that recent analysis of 2.3 GHz data from S-PASS in conjunction with WMAP and *Planck* finds $\beta_{\rm s} = -3.2$ with no detected trends with galactic latitude or angular scale [33]. The spatial power spectrum is taken as a power law $\mathcal{D}_\ell \propto \ell^{\alpha_{\rm s}}$ marginalizing over the range $-1 < \alpha_{\rm s} < 0$ [34]. The recent S-PASS analysis finds a value at the bottom end of this range (≈ -1) for BB at high galactic latitude.

Finally we include sync/dust correlation parameter ϵ (called ρ in some other papers [27, 33, 35]). In BK14 we marginalized over the range $0 < \epsilon < 1$ but in this paper we extend to the full possible range $-1 < \epsilon < 1$. The latest *Planck* analysis does not detect sync/dust correlation at high galactic latitude and the ℓ range of interest [27].

Results of the baseline analysis are shown in Fig. 4 and yield the following statistics: $r_{0.05} = 0.020^{+0.021}_{-0.018}$ ($r_{0.05} < 0.072$ at 95% confidence), $A_{\rm d,353} = 4.6^{+1.1}_{-0.9}\,\mu{\rm K}^2$, and $A_{\rm sync,23} = 1.0^{+1.2}_{-0.8}\,\mu{\rm K}^2$, ($A_{\rm sync,23} < 3.7\,\mu{\rm K}^2$at 95% confidence). For r, the zero-to-peak likelihood ratio is 0.66. Taking $\frac{1}{2}\left(1 - f\left(-2\log L_0/L_{\rm peak}\right)\right)$, where f is the χ^2 CDF (for one degree of freedom), we estimate that the probability to get a likelihood ratio smaller than this is 18% if, in fact, $r = 0$. As compared to the previous analysis, the likelihood curve for r shifts down slightly and tightens. The $A_{\rm d}$ curve shifts up very slightly but remains about the same width (presumably saturated at sample variance), and the $A_{\rm sync}$ curve loses the second bump at zero.

The maximum likelihood model (including priors) has parameters $r_{0.05} = 0.020$, $A_{\rm d,353} = 4.7\,\mu{\rm K}^2$, $A_{\rm sync,23} = 1.5\,\mu{\rm K}^2$, $\beta_{\rm d} = 1.6$, $\beta_{\rm s} = -3.0$, $\alpha_{\rm d} = -0.58$, $\alpha_{\rm s} = -0.27$, and $\epsilon = -0.38$. This model is an acceptable fit to the data with the probability to exceed (PTE) the observed value of χ^2 being 0.19. Thus, while fluctuation about the assumed power law behavior of the dust component is in general expected to be "super-Gaussian" [27], we find no evidence for this at the present noise level—see Appendix D for further details.

We have explored several variations from the baseline analysis choices and data selection and find that these do not significantly alter the results. Removing the prior on $\beta_{\rm d}$ makes the r constraint curve slightly broader resulting in $r_{0.05} < 0.079$ (95%), while using the BICEP/*Keck* data only shifts the peak position down to zero resulting in $r_{0.05} < 0.063$. Concerns have been raised that the known problems with the LFI maps [36] might affect the analysis—excluding LFI the r constraint curve peak position shifts down to $r = 0.012^{+0.022}_{-0.012}$ ($r_{0.05} < 0.065$, with zero-to-peak likelihood ratio of 0.90, and 32% probability to get a smaller value if $r = 0$), while the constraint on $A_{\rm sync,23}$ becomes $2.4^{+1.9}_{-1.4}\,\mu{\rm K}^2$. The shifts when varying the data set selection (e.g. omitting *Planck*) are not statistically significant when compared to shifts of lensed-ΛCDM+dust+noise simulations—see Appendices E 1 and E 2 for further details. Freeing the amplitude of the lensing power we obtain $A_{\rm L} = 1.15^{+0.16}_{-0.14}$, and detect lensing at 8.8σ significance.

The results of likelihood analysis where the parameters are restricted to, and marginalized over, physical values only can potentially be biased. Running the baseline analysis on an ensemble of lensed-ΛCDM+dust+noise simulations with simple Gaussian dust we do not detect bias. Half of the r constraint curves peak at zero and the CDF of the zero-to-peak likelihood ratios closely follows the idealized analytic expectation. When running maximum likelihood searches on the simulations with the parameters unrestricted we again obtain unbiased results and find that $\sigma(r) = 0.020$. See Appendix E 3 for further details.

We extend the maximum likelihood validation study to a suite of third-party foreground models [37–39]. These models do not necessarily conform to the foreground parameterization which we are using, and when fit to it are in general expected to produce bias on r. However, for the models considered we find that such bias is small compared to the instrumental noise—see Appendix E 4.

Spatial variation of the frequency spectral behavior of dust will lead to a decorrelation of the dust patterns as observed in different frequency bands. Since the baseline parametric model assumes a fixed dust pattern as a function of frequency such variation will lead to bias on r. Dust decorrelation surely exists at some level—the question is whether it is relevant as compared to the current experimental noise. For the third-party foreground

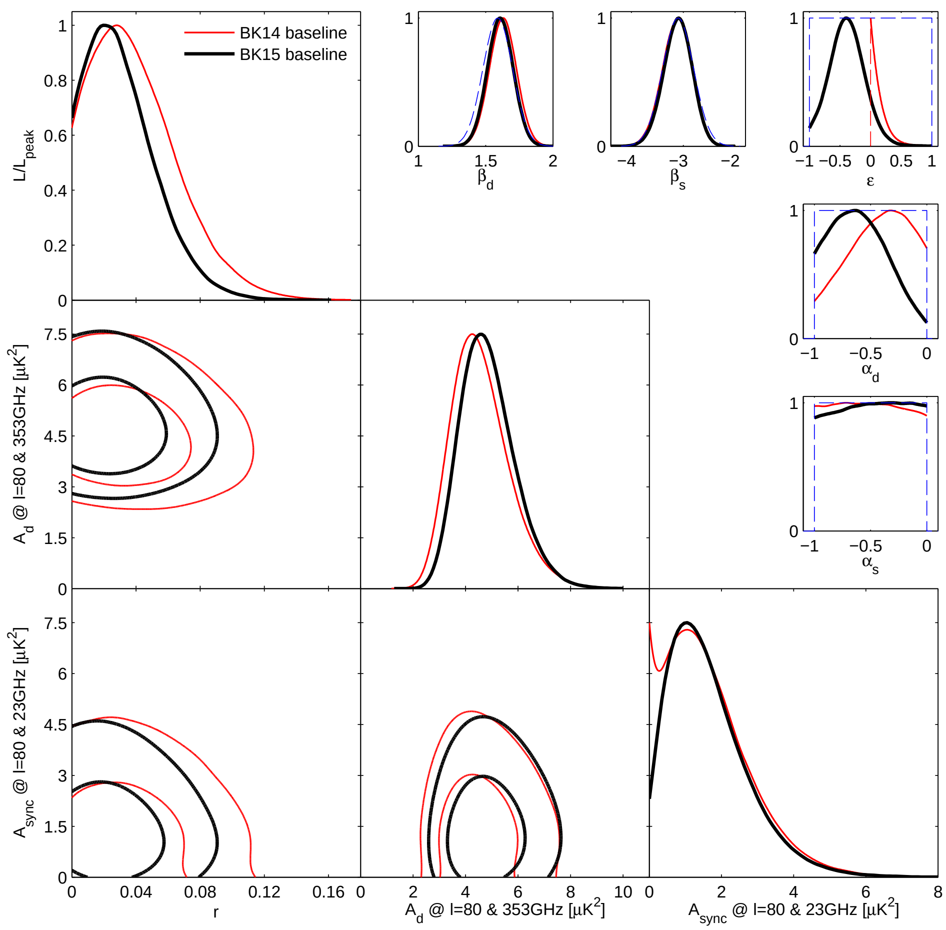

FIG. 4. Results of a multicomponent multi-spectral likelihood analysis of BICEP2/*Keck*+WMAP/*Planck* data. The red faint curves are the baseline result from the previous BK14 paper (the black curves from Fig. 4 of that paper). The bold black curves are the new baseline BK15 results. Differences between these analyses include adding *Keck Array* data taken during the 2015 observing season, in particular doubling the 95 GHz sensitivity and adding, for the first time, a 220 GHz channel. (In addition the ϵ prior is modified.) The upper limit on the tensor-to-scalar ratio tightens to $r_{0.05} < 0.072$ at 95% confidence. The parameters $A_{\rm d}$ and $A_{\rm sync}$ are the amplitudes of the dust and synchrotron B-mode power spectra, where β and α are the respective frequency and spatial spectral indices. The correlation coefficient between the dust and synchrotron patterns is ϵ. In the β, α and ϵ panels the dashed lines show the priors placed on these parameters (either Gaussian or uniform). Broadening or tightening the uniform prior range on α_s and α_d results in very small changes, and negligible changes to the r constraint.

models mentioned above, decorrelation is very small. Since our previous BK14 paper *Planck* Intermediate Paper L [40] appeared claiming a detection of relatively strong dust decorrelation between 217 and 353 GHz. This was followed up by Ref. [41], which analyzed the same data and found no evidence for dust decorrelation, and *Planck* Intermediate Paper LIV [27], which performed a more sophisticated multi-frequency analysis and again found no evidence. In the meantime we added a decorrelation parameter to our analysis framework. Including it only increases $\sigma(r)$ from 0.020 to 0.021, but for the present data set this parameter is partially degenerate with r and including it results in a downward bias on r in simulations—see Appendix F for more details.

By cross correlating against the *Planck* CO map we find that the contamination of our 220 GHz map by CO is equivalent to $r \sim 10^{-4}$.

Conclusions.—The previous BK14 analysis yielded the constraint $r_{0.05} < 0.090$ (95%). Adding the *Keck Array* data taken during 2015 we obtain the BK15 result $r_{0.05} < 0.072$. The distributions of maximum likelihood r values in simulations where the true value of r is zero give $\sigma(r_{0.05}) = 0.024$ and $\sigma(r_{0.05}) = 0.020$ for BK14 and BK15 respectively. The BK15 simulations have a median 95% upper limit of of $r_{0.05} < 0.046$.

Fig. 5 shows the constraints in the r vs. n_s plane for *Planck* 2015 plus additional data ($r_{0.05} < 0.12$) and when adding in also BK15 ($r_{0.05} < 0.057$). In contrast to the BK14 result the ϕ model now lies entirely outside of the 95% contour.

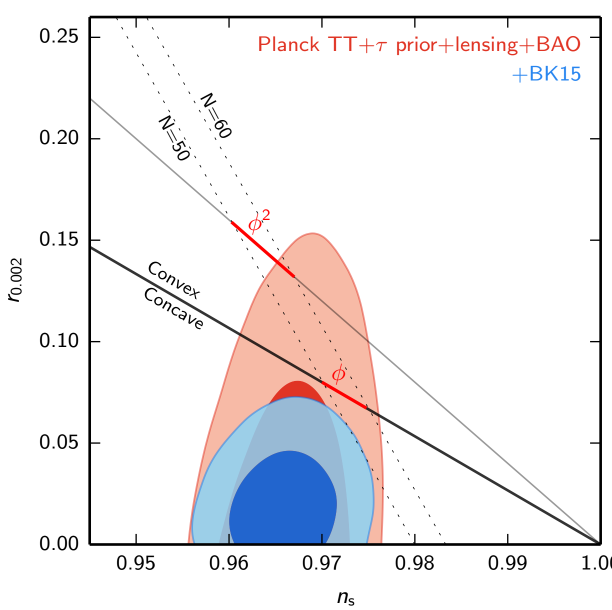

FIG. 5. Constraints in the r vs. n_s plane when using *Planck* plus additional data, and when also adding BICEP2/*Keck* data through the end of the 2015 season—the constraint on r tightens from $r_{0.05} < 0.12$ to $r_{0.05} < 0.06$. This figure is adapted from Fig. 21 of Ref. [3], with two notable differences: switching *lowP* to *lowT* + a τ prior of 0.055 ± 0.009 Ref. [42] and the exclusion of JLA data and the H_0 prior.

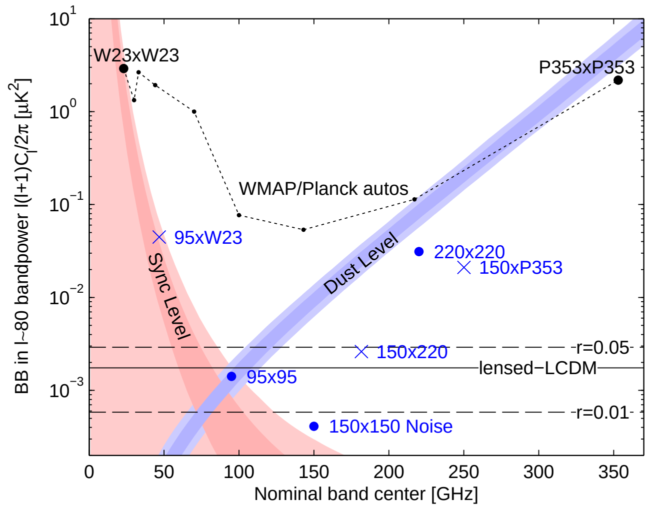

FIG. 6. Expectation values and noise uncertainties for the $\ell \sim 80$ BB bandpower in the BICEP2/*Keck* field. The solid and dashed black lines show the expected signal power of lensed-ΛCDM and $r_{0.05} = 0.05$ & 0.01. Since CMB units are used, the levels corresponding to these are flat with frequency. The blue/red bands show the 1 and 2σ ranges of dust and synchrotron in the baseline analysis including the uncertainties in the amplitude and frequency spectral index parameters ($A_{\mathrm{sync},23}, \beta_s$ and $A_{\mathrm{d},353}, \beta_\mathrm{d}$). The BICEP2/*Keck* auto-spectrum noise uncertainties are shown as large blue circles, and the noise uncertainties of the WMAP/*Planck* single-frequency spectra evaluated in the BICEP2/*Keck* field are shown in black. The blue crosses show the noise uncertainty of selected cross-spectra, and are plotted at horizontal positions such that they can be compared vertically with the dust and sync curves.

Fig. 6 shows the BK15 noise uncertainties in the $\ell \approx 80$ bandpowers as compared to the signal levels. Note that the new *Keck* 220 GHz band has approximately the same signal-to-noise on dust as *Planck* 353 GHz with two receiver-years of operation. In 2016 and 2017 we recorded an additional eight receiver-years of data which will reduce the noise by a factor of 5 & $\sqrt{5}$ for 220×220 & 150×220 respectively.

As seen in the lower right panel of Fig. 4 with four *Keck* receiver-years of data, our 95 GHz data starts to weakly prefer a non-zero value for the synchrotron amplitude for the first time. In 2017 alone BICEP3 recorded nearly twice as much data in the 95 GHz band as is included in the current result. We plan to proceed directly to a BK17 result which can be expected to improve substantially on the current results.

Dust decorrelation, and foreground complexity more generally, will remain a serious concern. With higher quality data we will be able to constrain the foreground behavior ever better, but of course we will also need to constrain it ever better. The BICEP Array experiment which is under construction will provide BICEP3 class receivers in the 30/40, 95, 150 and 220/270 GHz bands and is projected to reach $\sigma(r) < 0.005$ within five years.

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