BICEP2 Instrumental Systematics
All systematic effects that we could imagine were investigated!

We find with high confidence that the apparent signal *cannot be explained* by instrumental systematics!
The BICEP2 Telescope

Telescope as compact as possible while still having the angular resolution to observe degree-scale features.

On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

Liquid helium cools the optical elements to 4.2 K.

A 3-stage helium sorption refrigerator further cools the detectors to 0.27 K.
BICEP2 on the Sky

Projection of the BICEP2 focal plane on the sky!
(Background is the CMB temperature map as measured with BICEP2)

Christopher Sheehy for the Bicep2 Collaboration
Each focal plane pixel is really two detectors — a horizontally polarized one and a vertically polarized one.

Measure CMB T by summing the signal from orthogonally polarized detector pairs.

Measure CMB polarization by differencing the signal.
Raw Data

Telescope Movement

Time (~1 hour)
Raw Data

Telescope Movement

Sum of detector pairs

time (~1 hour)
Raw Data

Telescope Movement

Sum of detector pairs

Difference of detector pairs

time (~1 hour)
Beam Systematics

➢ Each focal plane pixel is really two orthogonally polarized detectors
➢ Call these detectors “A” and “B”. They nominally point to the same location on the sky and have identical response to the CMB, i.e. have the same “beam”.
➢ If the CMB is unpolarized, the “pair difference” should be zero
➢ If the response to the CMB is different for A and B, then even if the CMB is unpolarized, the pair difference is non-zero. This is contaminates polarization!

Each focal plane pixel is really two detectors — a horizontally polarized one and a vertically polarized one.
Beam systematics
example: pointing center mismatch

“A” and “B” beams
Beam systematics
example: pointing center mismatch

“A” and “B” beams

A-B difference beam

Christopher Sheehy for the Bicep2 Collaboration
Beam systematics
example: pointing center mismatch

“A” and “B” beams

A and B’s path along the sky as the telescope scans

A-B difference beam

Planck T map

Christopher Sheehy for the Bicep2 Collaboration
Systematics removal: deprojection
example: pointing center mismatch

“A” and “B” beams

A-B difference beam

Planck dT/dDec. map

Christopher Sheehy for the Bicep2 Collaboration
Use the Planck 143 GHz map to form templates of leakage from mismatched elliptical Gaussian beams.

Fit these templates to the data and subtract.
We know our beam shapes

Far field beam mapping: microwave source mounted here

Detailed description in companion Instrument Paper

Christopher Sheehy for the Bicep2 Collaboration
We know our beam shapes

High fidelity beam maps of individual detectors

Christopher Sheehy for the Bicep2 Collaboration
We know our beam shapes

\[ \sqrt{p^2 + c^2} = 5\% \]

\[ \sqrt{\delta p^2 + \delta c^2} = 2\% \]

Christopher Sheehy for the Bicep2 Collaboration
Systematics removal: deprojection

Differences of elliptical Gaussians

Use the Planck 143 GHz map to form templates of leakage from mismatched elliptical Gaussian beams.

Fit these templates to the data and subtract.
Systematics removal: deprojection

Use the Planck 143 GHz map to form templates of leakage from mismatched elliptical Gaussian beams.

Fit these templates to the data and subtract.
We know our beam shapes

Because contamination from beam shape mismatch is entirely deterministic, we can both remove it (deprojection) and predict it in simulation using calibration data as input.

Calibration data for each detector
We know our beam shapes

Because contamination from beam shape mismatch is entirely deterministic, we can both remove it (deprojection) and predict it in simulation using calibration data as input.

Calibration data for each detector

Simulation
(implicit convolution with Planck T map)
We know our beam shapes

Because contamination from beam shape mismatch is entirely deterministic, we can both remove it (deprojection) and predict it in simulation using calibration data as input.

Calibration data for each detector

Simulation (explicit convolution with Planck T map)

Predictions of contamination

Christopher Sheehy for the Bicep2 Collaboration
Systematics removal: deprojection

Use the Planck 143 GHz map to form templates of leakage from mismatched elliptical Gaussian beams.
Fit these templates to the data and subtract.

Christopher Sheehy for the Bicep2 Collaboration
We know our beam shapes
example: slightly elliptical beams

Without ellipticity deprojection, predicted contamination in BB is negligible compared to noise level.

\[ r=0.2 + \text{lensing} \]
We know our beam shapes

beam ellipticity

\[ \sqrt{\delta p^2 + \delta c^2} = 2\% \]

differential ellipticity

\[ \sqrt{\delta p^2 + \delta c^2} = 5\% \]
We know our beam shapes
example: slightly elliptical beams

Without ellipticity deprojection, predicted contamination in BB is negligible compared to noise level

r=0.2 + lensing
We know our beam shapes
example: slightly elliptical beams

Without ellipticity deprojection, predicted contamination in BB is negligible compared to noise level

...but the focal plane inner/outer jackknife is still sensitive to it

real data

Christopher Sheehy for the Bicep2 Collaboration
We know our beam shapes
example: slightly elliptical beams

With ellipticity deprojection, predicted contamination in BB is still negligible

...and the jackknife cleans up exactly as simulations predict

r=0.2 + lensing

real data
All systematic effects that we could imagine were investigated!

We find with high confidence that the apparent signal cannot be explained by instrumental systematics!
Thanks