Keck Array and BICEP2 data analysis

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Keck-Array Rational

- Take the search for gravity waves to the next level (again)
- Maximally exploit existing infrastructure at Pole:
 DASI mount and compressor room (and MAPO)
- Maximally exploit technology developed for BICEP2:
 - Detectors, focal-plane, telescope
- Switch from liquid helium to new technology Pulse Tube Coolers

Cool to 4K using electric power (8kW each)

Keck-Array Collaboration

• Minnesota

Cryostats, Mount adaptation, science analysis

• Harvard

Optics, beam mapping, science analysis

• Stanford

• Camera inserts, integration, science analysis

• Caltech/JPL

Detectors, focal-planes, science analysis

- Plus:
 - NIST: SQUIDS
 - UBC: Readout electronics
 - Toronto: House-keeping electronics
 - Case Western: waveplates
 - Plus many specialized commercial vendors...

Core B2/Keck Team in March 2012



Keck Array



- Five "copies" of BICEP2 on the old DASI platform
 2500 TES detectors.
- Pulse tube coolers no more liquid helium!
- 2011 season had 3 receivers, 2012 onwards 5 receivers



Receiver Production Line





- Minnesota outfit cryostat shell and test
- Caltech/JPL make detectors and integrate focal-plane and test
- Ship both to Stanford to integrate with camera assembly and test
- Ship to Harvard for beam mapping
 And on to Pole!...

MAPO a Hive of Activity



- Big team on site (14 max simultaneous)
- Push to get all receivers working by station close

Keck in Feb 2012

Tired and happy team with five working receivers!



Keck at Sunset

Keck also has a Far Field Flat Mirror...





• Redirects beams to cal source on mast 200m away

Keck 2013 On Sky Sensitivity



• array sensitivity 9.5 uK \sqrt{s}

Room for improvement as 2 rx better than rest...

BICEP2 Analysis Status

- Took data 2010, 2011, 2012
 Total 17,000 scansets under analysis
- 18TB raw data (including some cal. data)
- Sophisticated automatic cut framework implemented
 - Cope with weather...
 - ...and "fussy" SQUID based readout system

Low Level "Reduc Plot" – Goodish Weather



- This plot made for every 50 minute "scanset" x-axis time, top panel: telescope azimuth motion, middle panel: detector pair sum timestream, bottom panel: pair diff.
- Outer panels bracketing elnod calibrations ("mini skydips")
 - ▶ Use these to normalize relative gains note clean pair diff. elnods

Low Level "Reduc Plot" – Baddish Weather



- Way more atmospheric structure in pair sum
 - Think scanning over lumpy clouds which are drifting by
- But pair diff. looks the same as good weather
 - Atmosphere is clearly largely unpolarized

Cut Plots

cut parameter elnod_ab_ba, All Rxs



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- This parameter ratio-of-ratio of elnod pair gains before/after scanset
 - We cut on 20 odd parameters (although many highly correlated with weather)

Cumulative Weights





- Sensitivity improved greatly 2010 to 2011 (tuning of detectors and readout!)
- Small boost in late 2011

Basic Analysis flow

- Deconv, deglitch etc
- Equalize channel gains using elnods
- Pair difference
- Segment into half scans and apply some scan-wise filtering:
 - Subtract 3rd order poly from each
 - Bin in azimuth to form scan sync. template and subtract
- Accumulate into "pairmaps" (basically scansets binned in RA)
- Also accumulate deprojection templates
- Sum up over 10 elevation steps and then regress templates and subtract

B2 3-year Q Map

0641/real_3yr_filtp3_weight3_gs_jack0 - weighted rms 0.256 uK-deg over area 390.8 sq deg

map



B2 3-year U Map

0641/real_3yr_filtp3_weight3_gs_jack0 - weighted rms 0.267 uK-deg over area 390.8 sq deg

map



Apodize using 1/var map

0641/real_3yr_filtp3_weight3_gs_jack0 - min noise 0.22 uK

1/varmap



Fourier Transform and Square





• (Apologizes for saturated color scales)

Rotate Q&U to E (&B)



Perform 1st/2nd Half Jackknife



Perform "Deck" Jackknife



Why does Deck Jack Fail so Bad?

- Deck jack is difference of subset maps formed from instrument angles 0/45 deg and 180/225 deg
- Primary beam imperfection is A/B centroid offset
 - This largely cancels when adding equal amounts of data taken 180 deg apart – grad(T) leaks equally to +/-Q/U
- But Deck jack throws the effect into stark relief (doubles it)
- However deprojection can remove this...

Deck Jack E-modes with Diff. Point Deprojection



- Deprojection performed per detector pair for groups of 10 scansets (at 10 elevation steps)
- At the moment coefficients allowed to vary with time
 - Although for diff. point they empirically do not...

Simulations

• We do full blown timestream level signal and noise sims

Signal sims sample from Synfast curved sky input maps

- So all E/B mixing effects are included (flat map, sky cut, filtering, deprojection etc. are included)
- Can "debias" the resulting B-mode spectra using these
 But can do better...
- We find that using Kendrick Smith style "Pure-B" estimator is useful

Eliminates sky-cut induced E/B mixing

- Improved estimators under development
 - Use the sims themselves to find which modes are pure (Kirit Karkare)
 - Eventual goal is full matrix based analysis

Compare jacks to s+n sims

- Basically they pass...
- So we're done right?
- Well maybe there is residual beam mismatch which corrupts the non-jack spectra but somehow evades the jackknifes...
 - For instance differential ellipticity which was uniform across the focal plane could do this...
- So we have run many special simulations of different hypothetical beam mismatch effects
 - Cannot find anything remotely plausible which would cause false B at a level significant compared with the noise...
- Have now achieved sufficient signal to noise in per channel beam maps to just input these into sims...

Signal+noise sim B-modes LCDM



Signal+noise sim B-modes LCDM+r=0.1



Real E-mode Map

0641/real_2yr_filtp3_weight3_gs_jack0 apodized map (filtered)



Real B-mode Map

0641/real_2yr_filtp3_weight3_gs_jack0 apodized map (filtered)



Conclusions

- Keck-Array is taking data and working well
 Instrument NET is 9.5 uK √s
- BICEP2 analysis is advanced:
 - Data selection procedure in place
 - 3-year Q/U maps have noise of 0.12 uK-deg over 390 sq. deg. (effective)
 - Careful simulations constructed
 - With diff. point deprojection Jackknifes pass
 - We are fretting extensively about possible jackknife evading deprojection residuals...