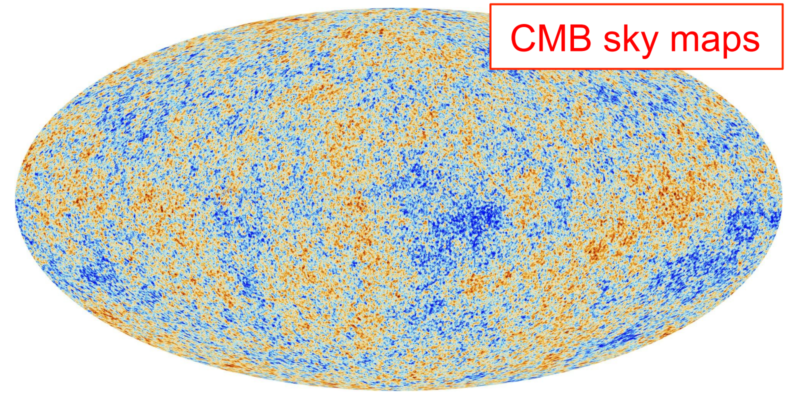
The Search for Inflationary B-modes: Latest Results from BICEP/Keck

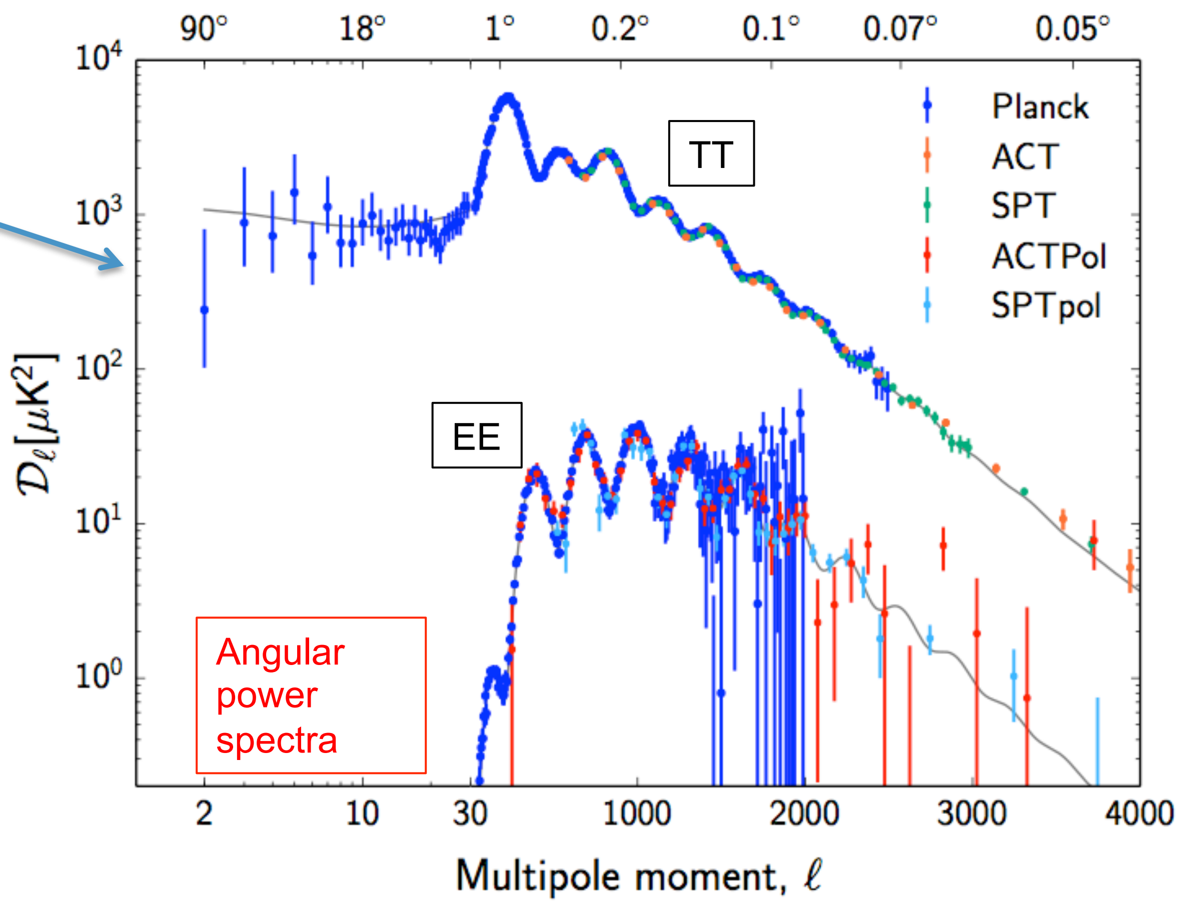
Clem Pryke (Minnesota) for the BICEP/Keck Collaborations – Blois June 1 2016

CMB Measurements Strongly Imply Inflation



CMB shows us structure of Universe at 380,000 years after the beginning – Gaussian random perturbations with contrast ratio of 1 part in 10^4

Given initial conditions (at *t*<<1sec) simple linear theory predicts the power spectra of the perturbations – superb agreement of theory and observations!



Initial conditions appear to have been a flat spectrum of adiabatic perturbations – the natural outcome of hyper inflated quantum fluctuations

The BICEP/Keck Collaboration

The Search for B-modes

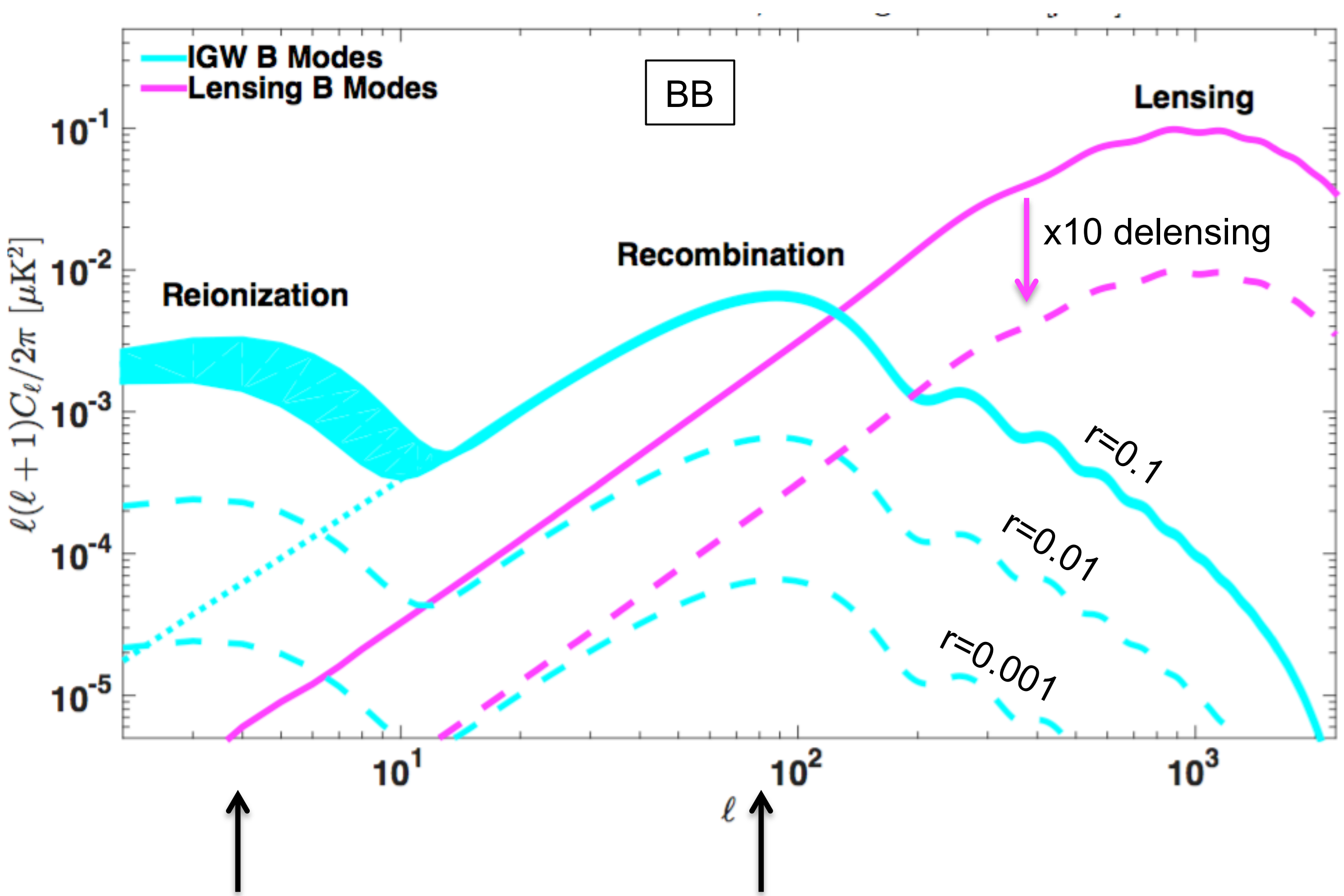
Inflation injects perturbations of all kinds into the fabric of spacetime – including gravitational waves

At combination/reionization these will produce a curl mode component in the CMB polarization pattern – a so-called B-mode

In simple inflationary gravitational wave models the **tensor-to-scalar ratio r** is the only parameter of the B-mode power spectrum.

So the experimental goal is to measure r – or set limits on it

B-modes induced by gravitational lensing are a foreground (background!) in this search



Reionization bump – need to cover most of the sky – typically from space

Recombination bump – only need to cover ~1% of the sky – can be done from the ground

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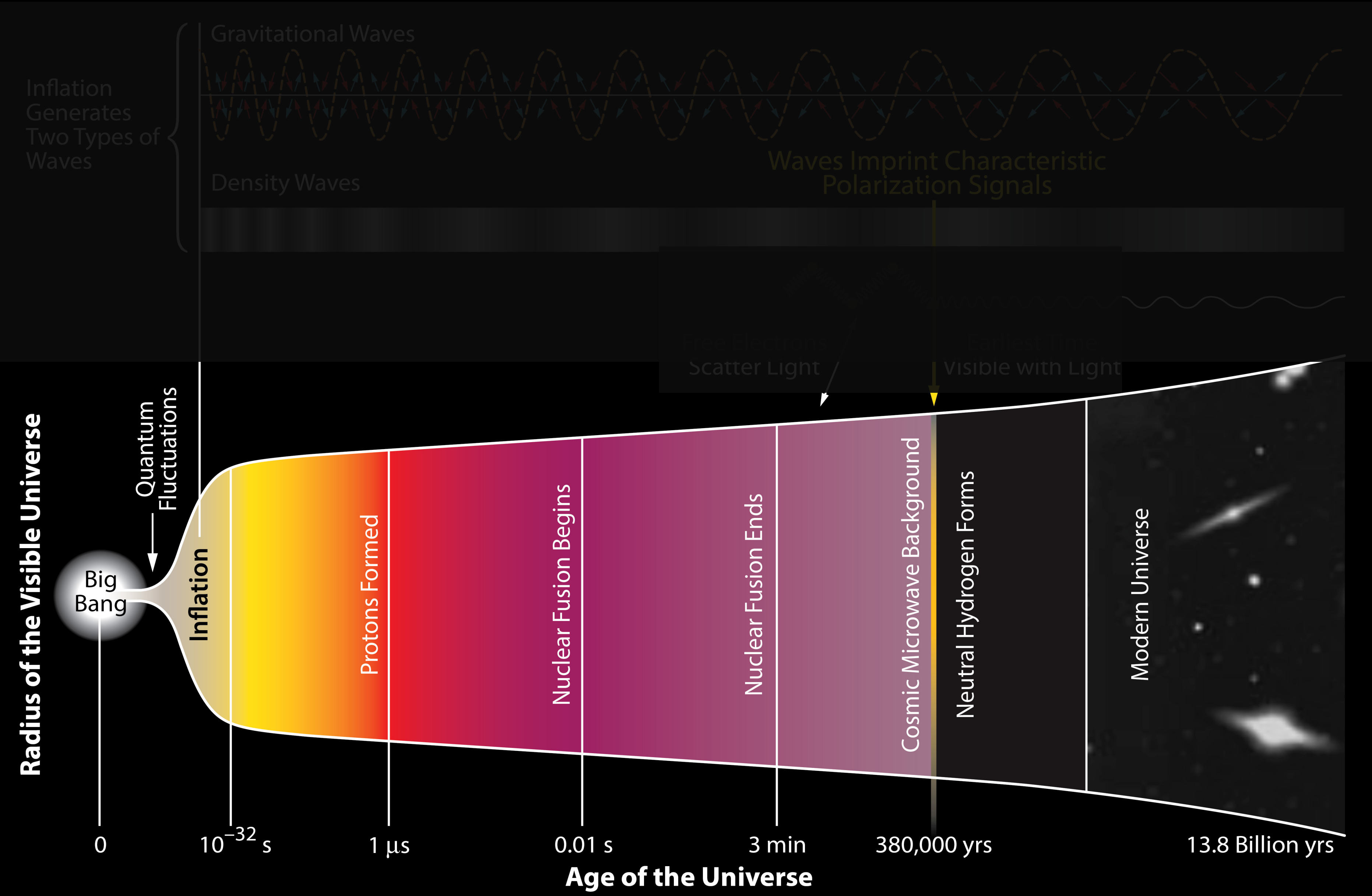
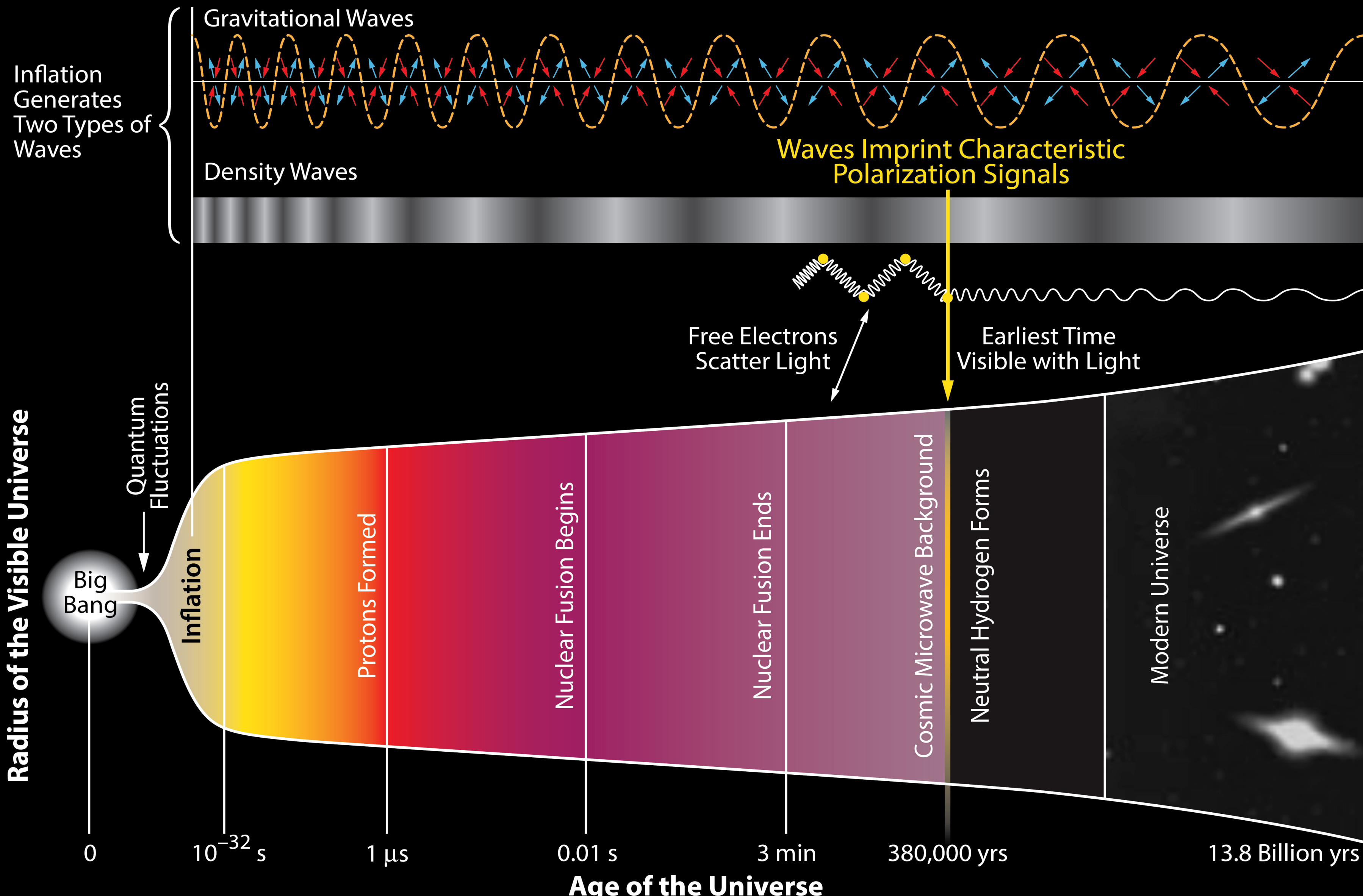
History of the Universe



History of the Universe



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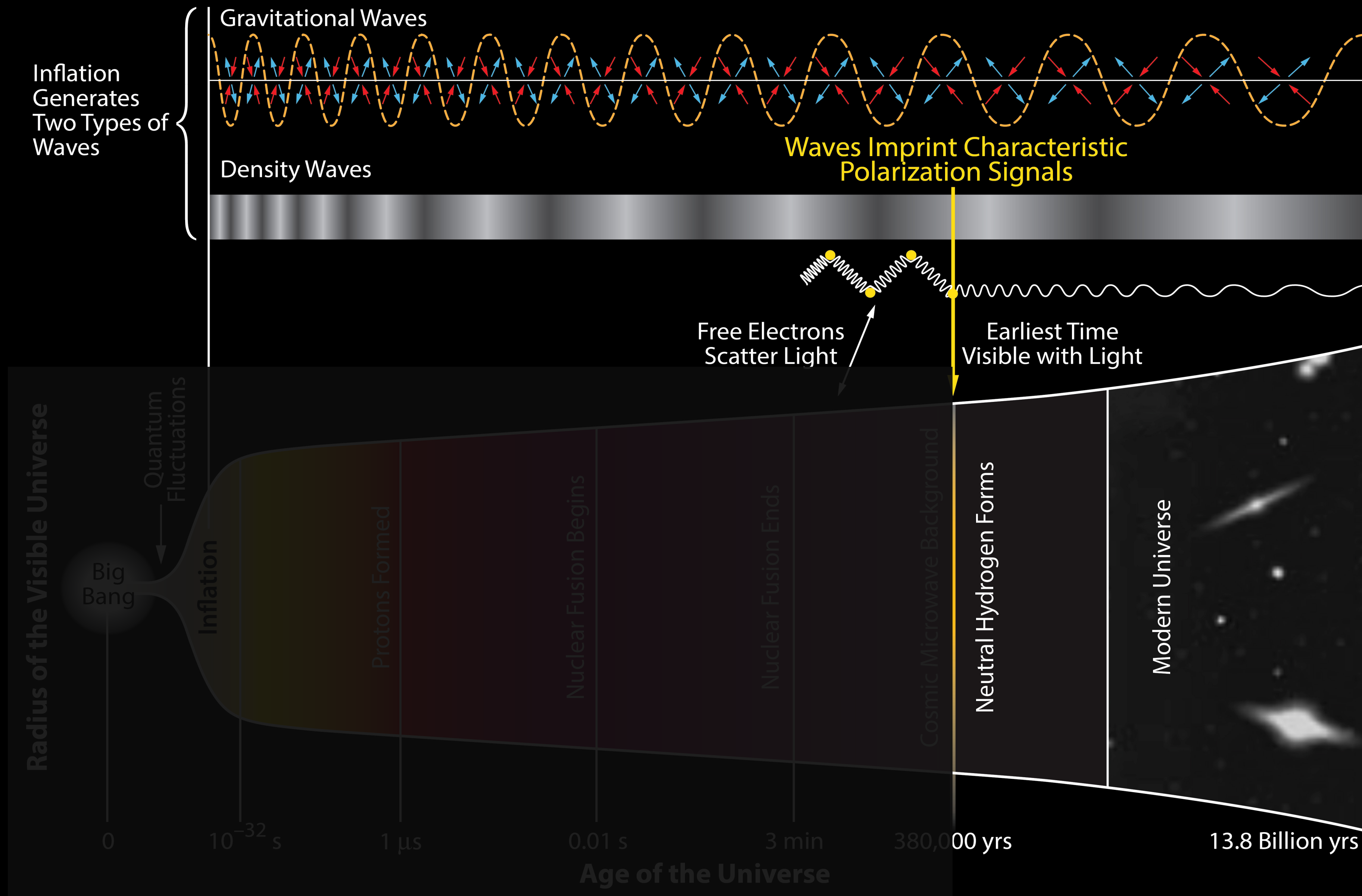

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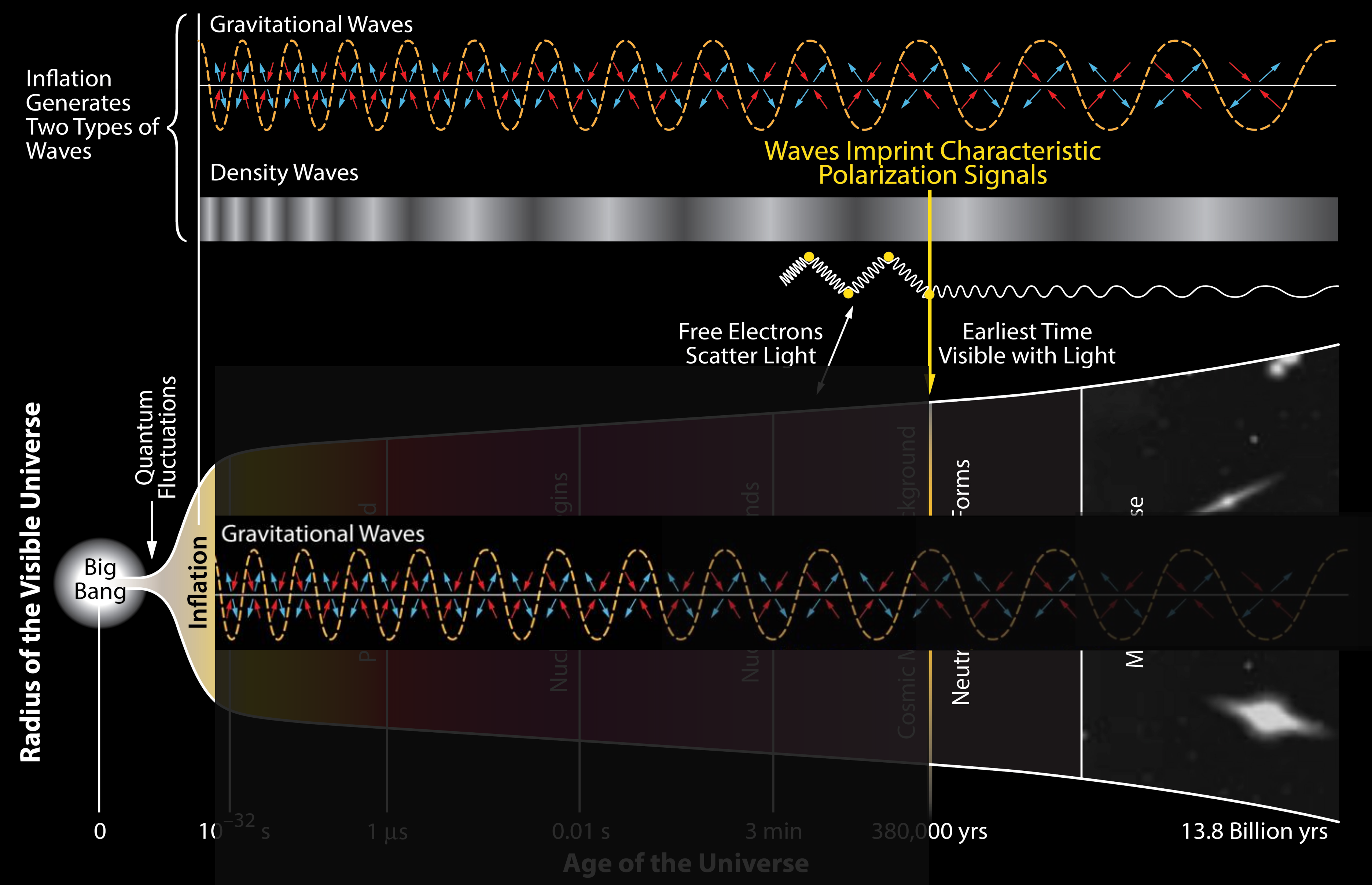

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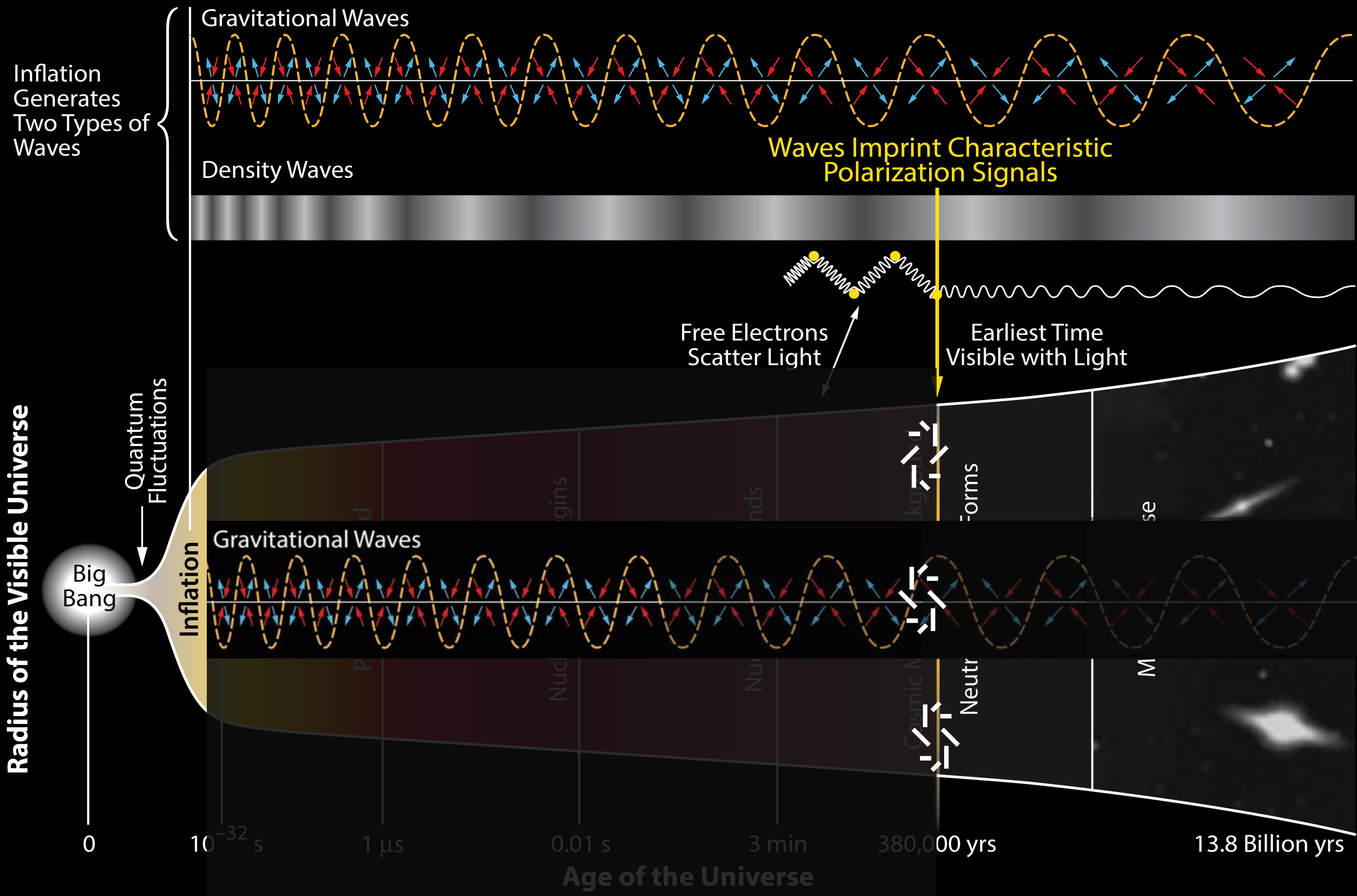


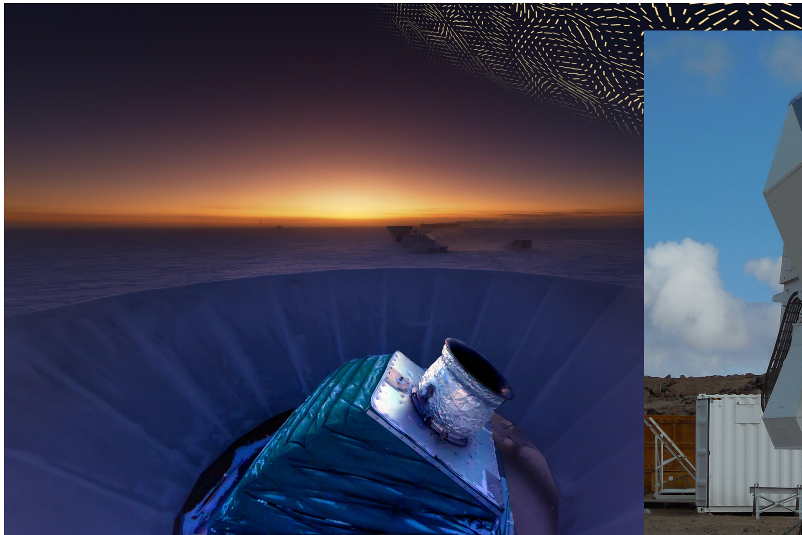
Can r be arbitrarily small?

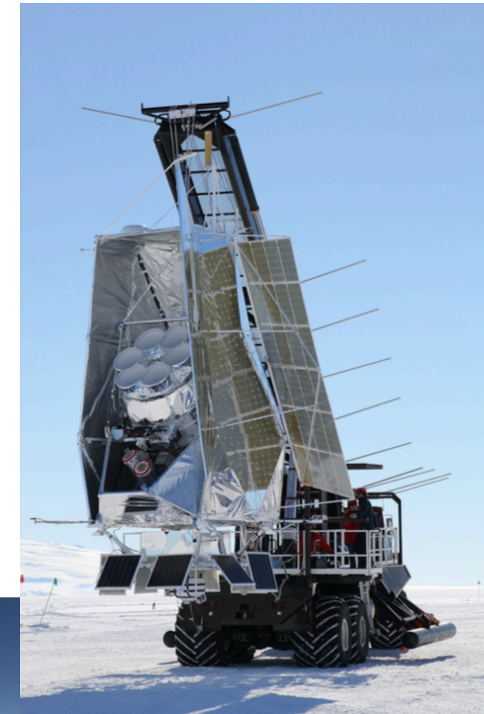
In principle yes – however see the following comment from Marc Kamionkowski:

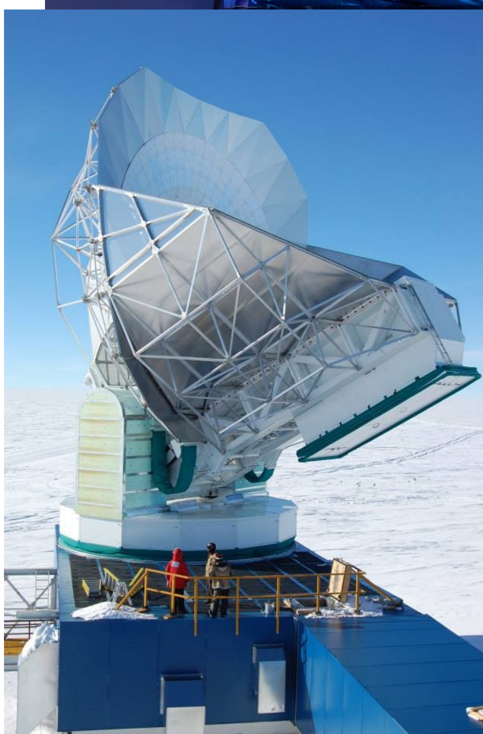
"The plot, however, has thickened over the past decade with the increasing evidence that the scalar spectral index is not unity. With these new constraints to n_s, there is a clear expectation from the prevailing single-field slow-roll paradigm that B modes will be detected by CMB-S4. If they are not, theorists will be forced to *very seriously* re-consider the prevailing models for inflation. If no B modes show up in CMB-S4, the models we all use when we teach inflation in classes will have to be discarded."

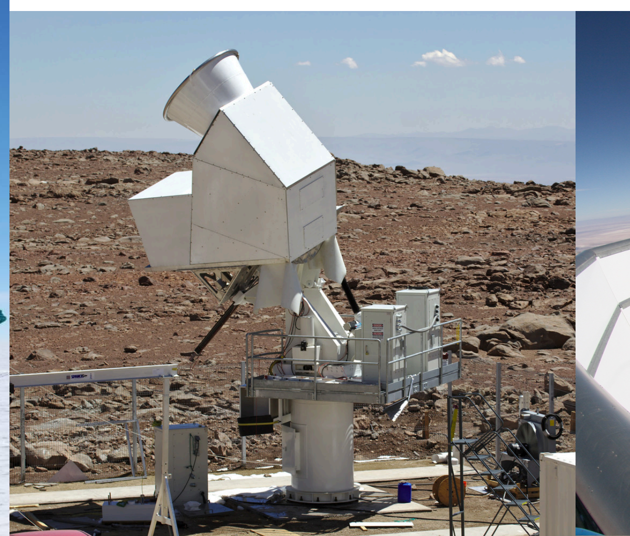
[CMB-S4 is projecting sensitivity to r>0.001]

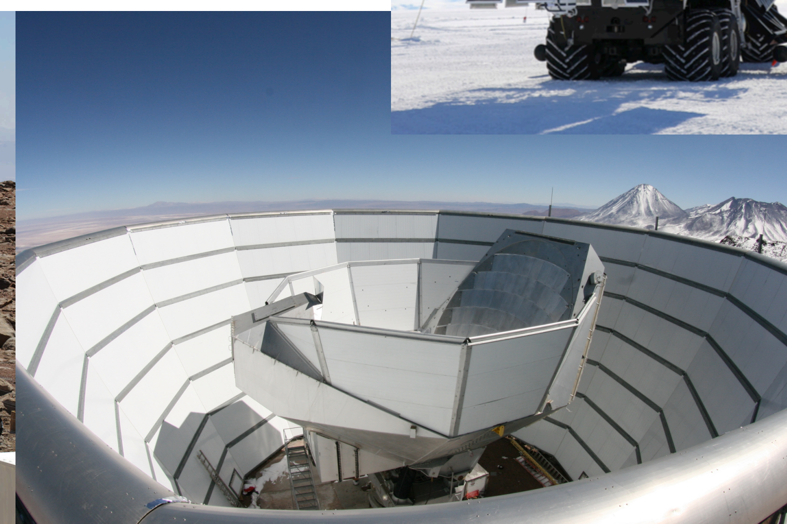
The Zoo of CMB Polarization Experiments





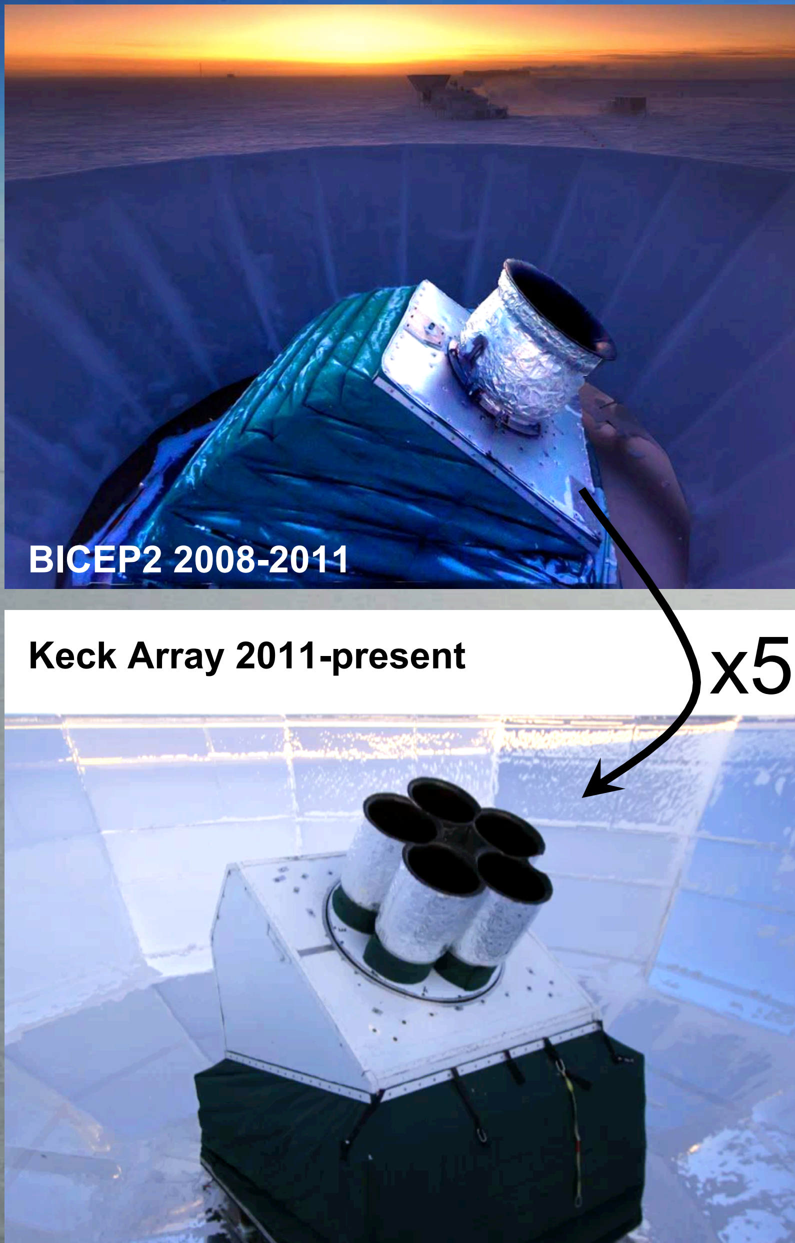






Big telescope = high angular resolution
- but not necessarily needed when trying to measure r

BICEP2 and Keck Array



Relentless observation of the CMB polarization from NSF's station at the geographic South Pole

Dry, stable atmosphere, high altitude + 24h coverage of the Southern Sky

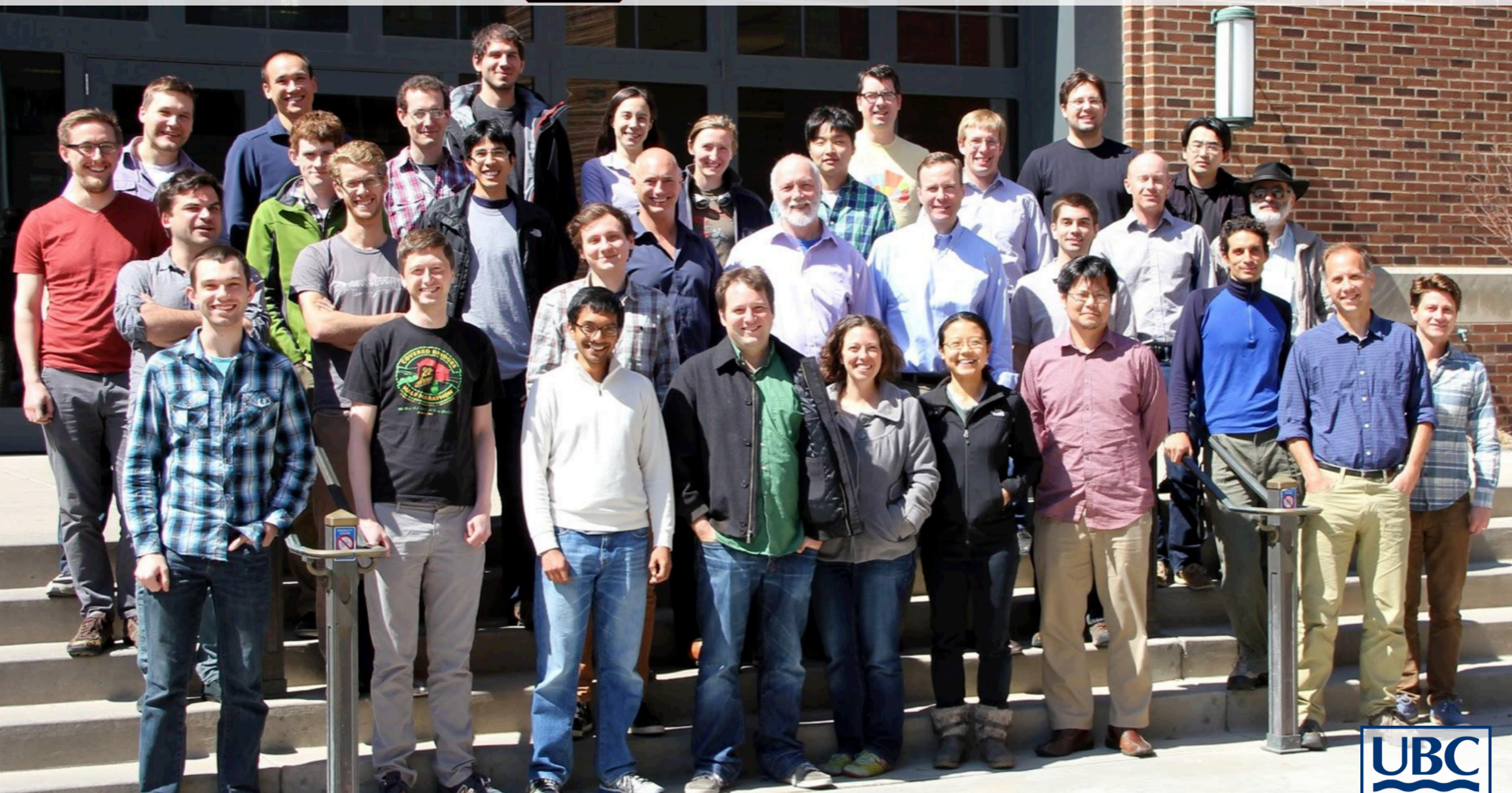
Compact cold refractive optics optimized for the angular scales of the potential inflationary signal

Superconducting phased antenna arrays

Focus on ~**400 deg^2** patch = 1% of the sky

VE RI TAS
HARVARD

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891



cea

UCSD

JPL

NIST

CARDIFF UNIVERSITY

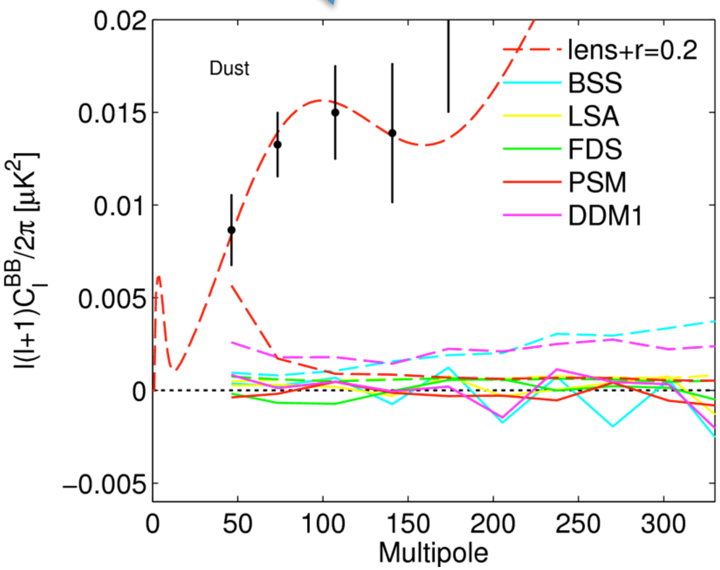
UNIVERSITY OF TORONTO

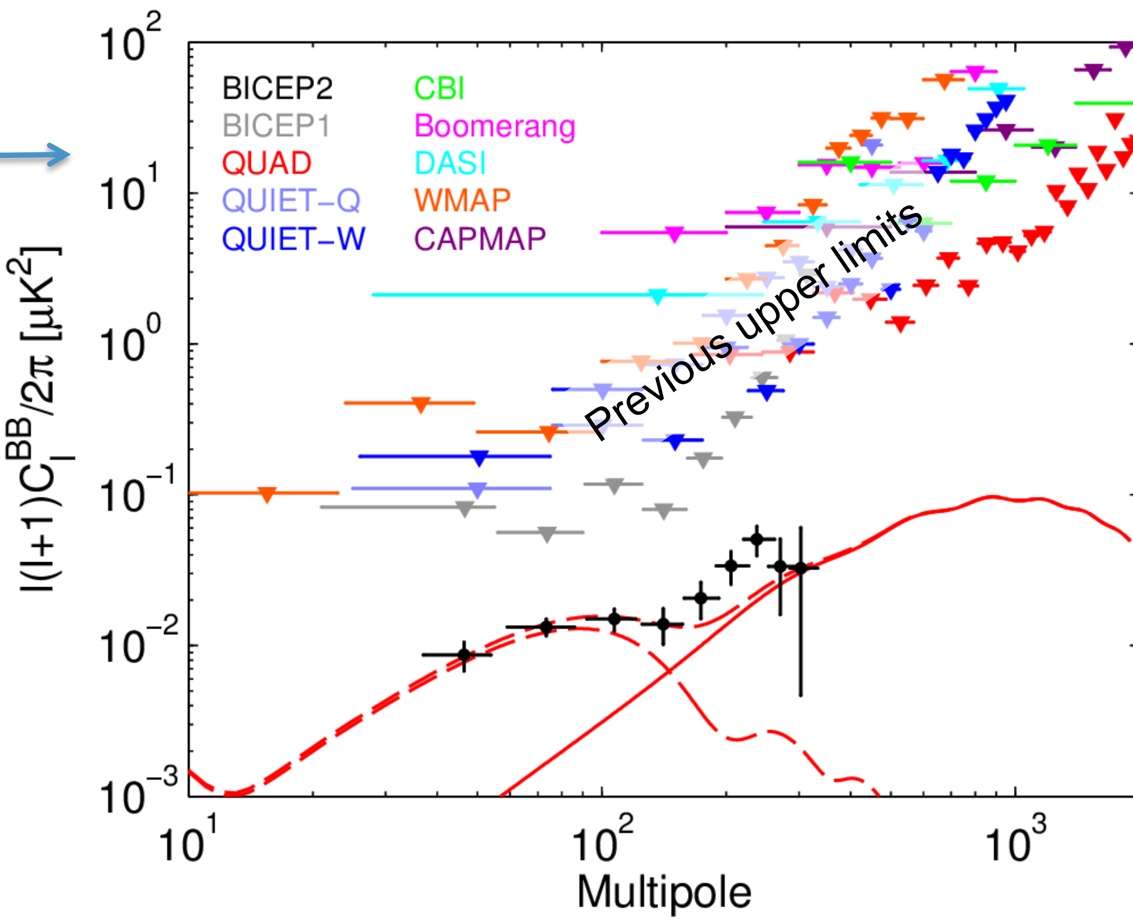
UBC

Results circa 17th March 2014

Data fit well to LCDM+r=0.2 expectation…

…and existing 3rd party foreground models indicated much lower levels of B-mode at 150GHz observation frequency…





But seemed odd given that Planck+ had already set indirect limit r<0.11 at 95% confidence...

…and of course it turned out the dust models were under-estimates!

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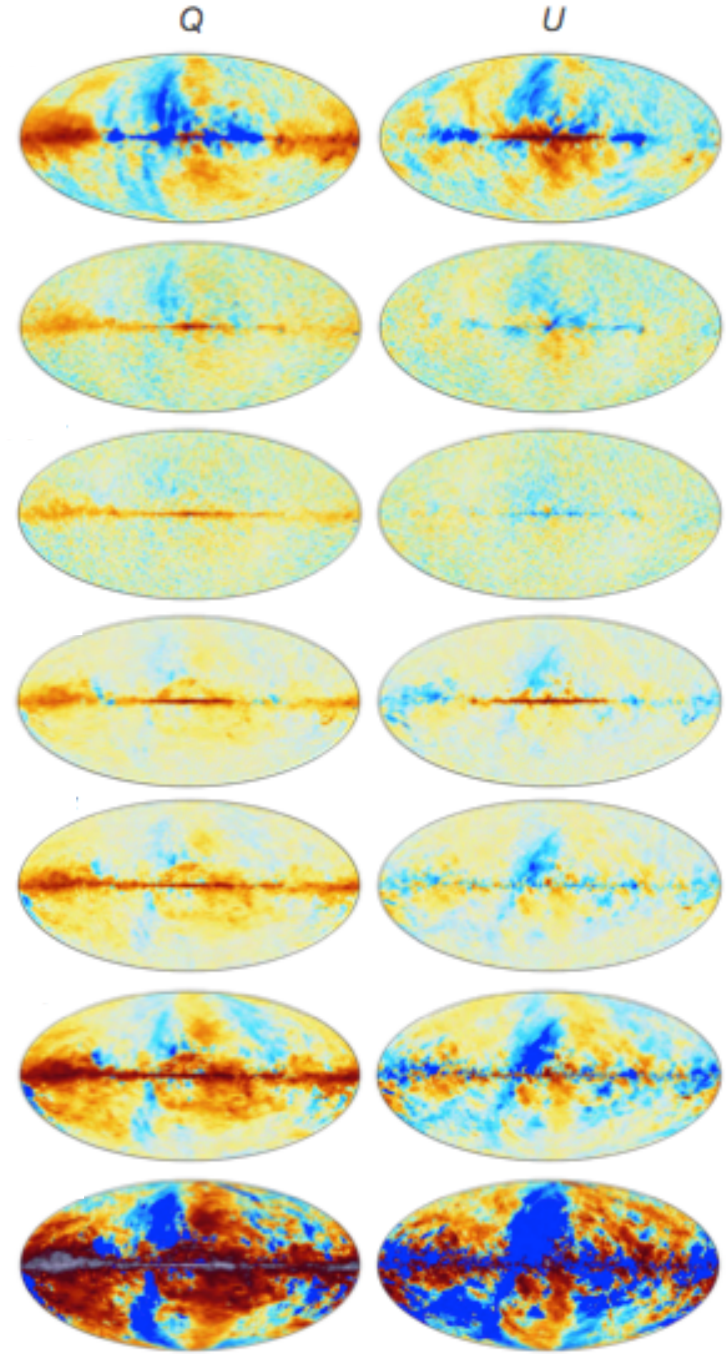
galactic **synchrotron** emission decreases with increasing frequency → 30 GHz

Planck space mission already had full sky polarization maps at 7 frequencies – but not made public until 2015

galactic **dust** emission increases with increasing frequency → 353 GHz



30 GHz

44 GHz

70 GHz

100 GHz

143 GHz

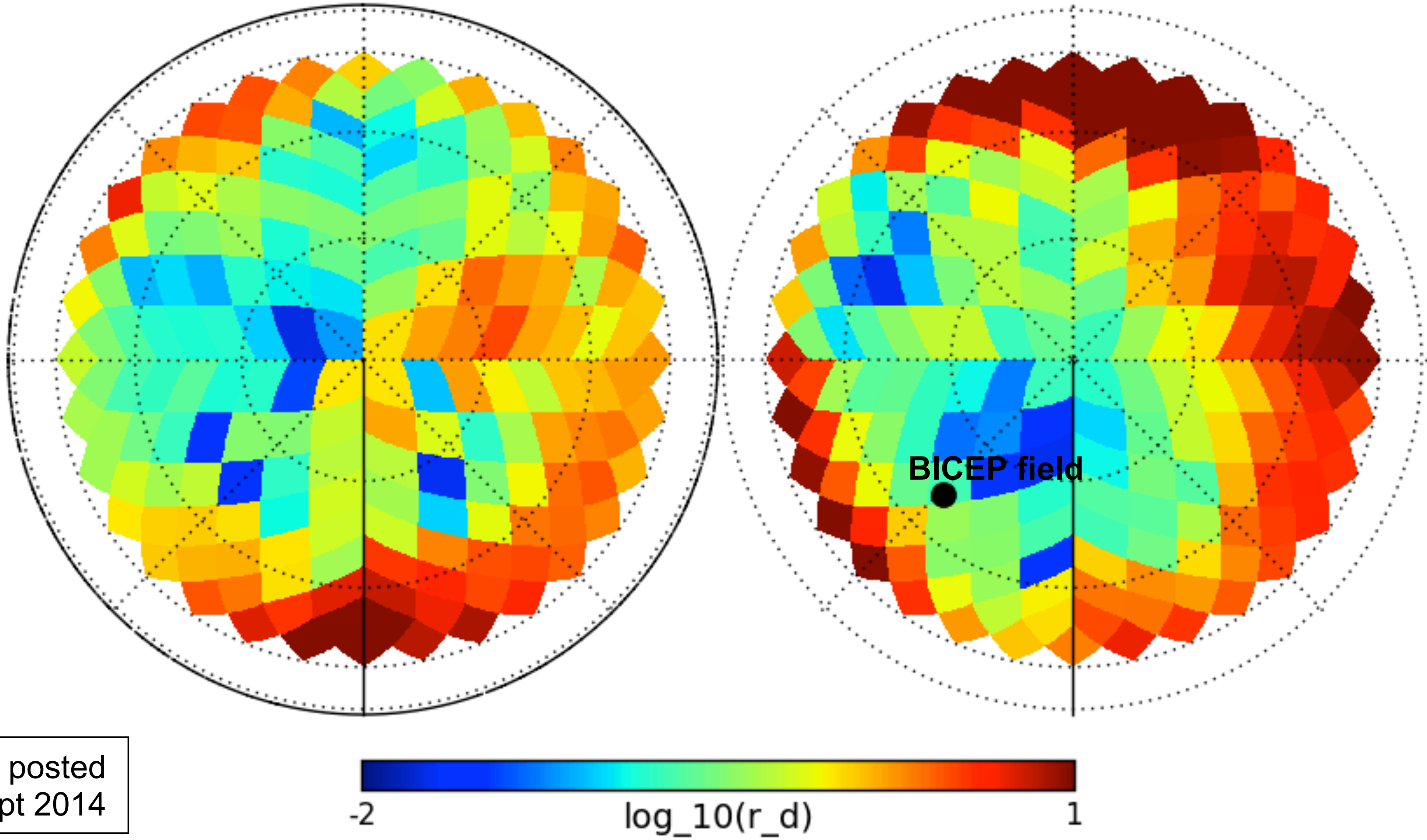
217 GHz

353 GHz

B2

Planck plot showing r equivalent dust level at 150GHz in all possible 1% sky patches

Made by extrapolating 353GHz maps down to 150GHz



Paper posted
19 Sept 2014

Fig8 of arxiv:1409.5738 (uses detector set data split)
Appears that there are cleaner regions – but may just be noise fluctuation

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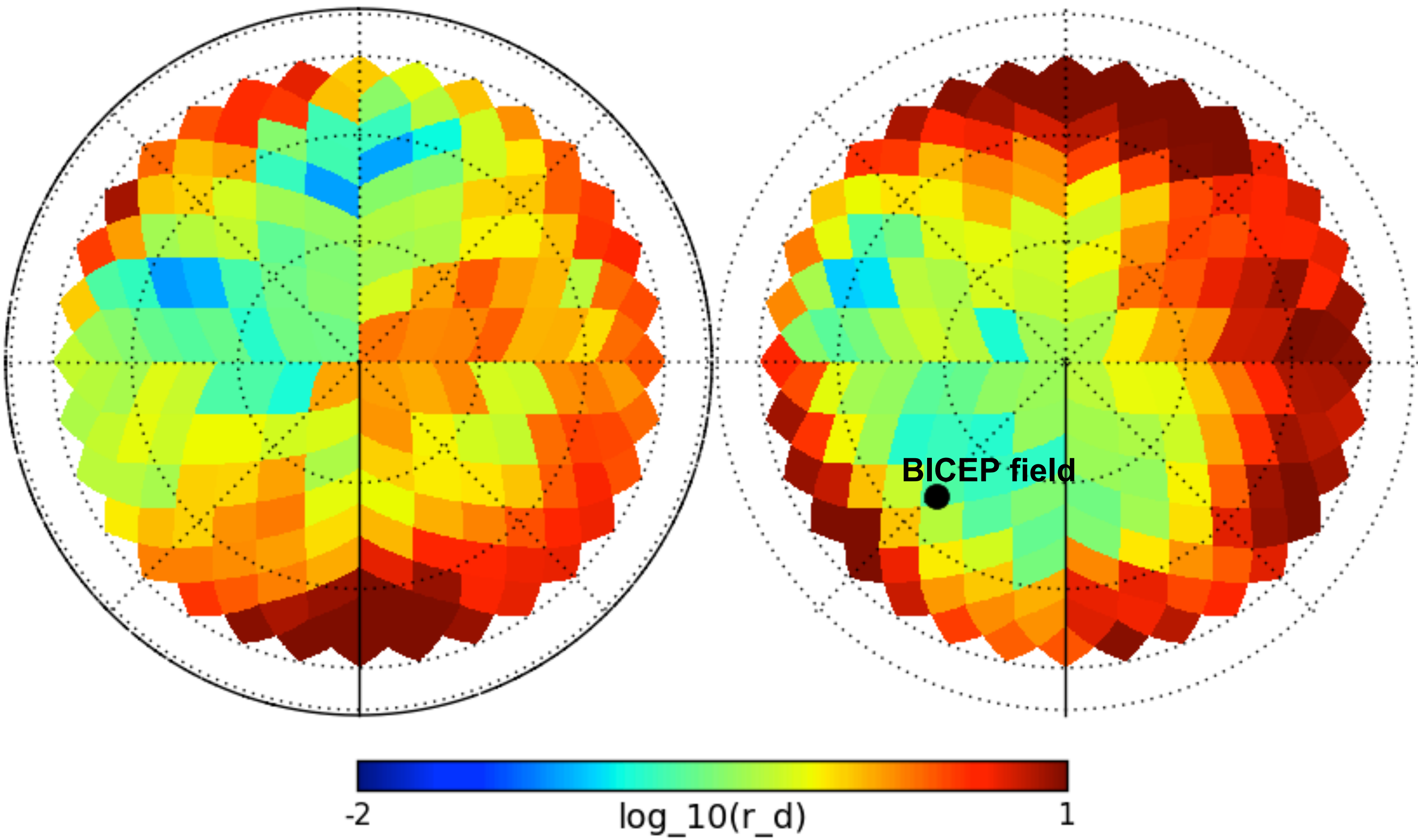
Aside: Our attempt to reproduce

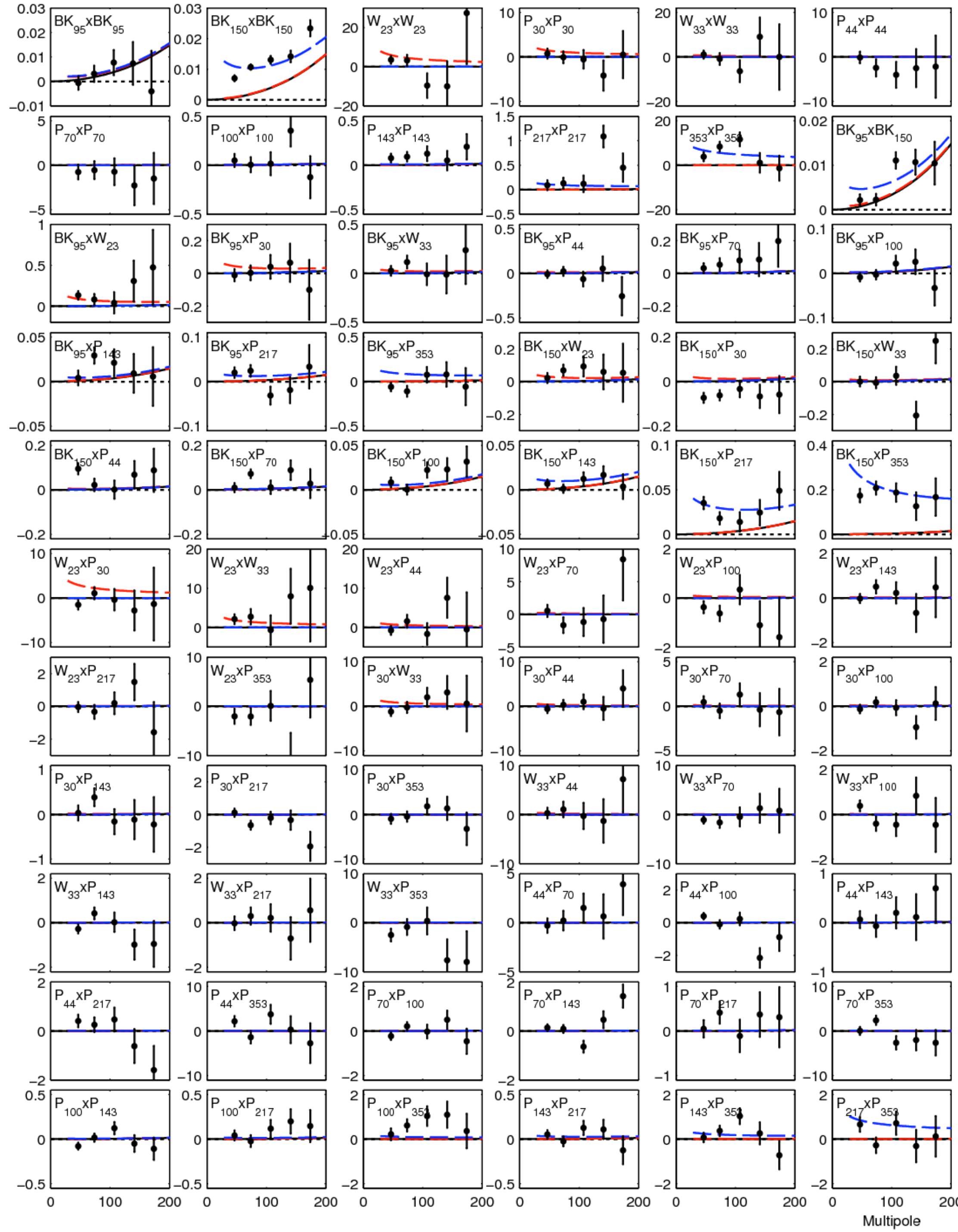


Our attempt to do an algorithmically identical analysis (using the year split)
Not clear there are any regions significantly better than our current one

Foreground separation technique:

Take all possible auto- and cross-spectra between BICEP/Keck, WMAP, and Planck bands (66 of them)

More powerful than map based cleaning



Multicomponent likelihood analysis

Take the joint likelihood of all the spectra simultaneously vs. model for BB that is the ΛCDM lensing expectation + 7 parameter foreground model + r

foreground model = dust + synchrotron

A_{dust} A_{synch} — amplitudes @ l=80

β_{dust} β_{synch} — frequency spectral indices

α_{dust} α_{synch} — spatial spectral indices

ε — dust/synch spatial correlation

Several steadily improving versions of the analysis:

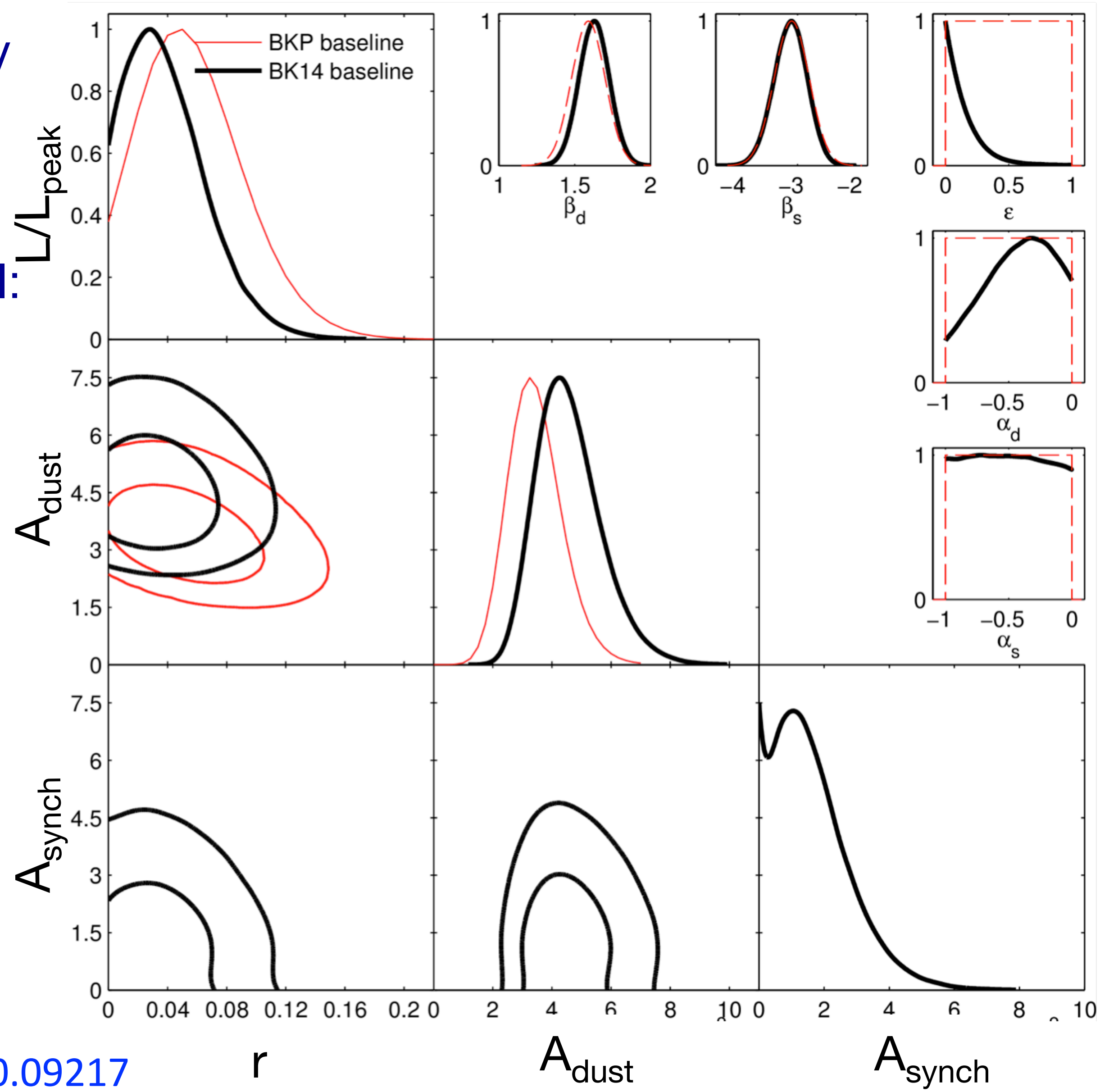
BKP = Feb 2015 analysis in conjunction with Planck

BK14 = Oct 2015 analysis adding in Keck Array 95GHz data

Take the joint likelihood of all the spectra simultaneously vs. 8 parameter lensing+dust +sync+r model:

Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation



dust vs. r degeneracy lifted

Marginalize over generous ranges in spatial spectral indices

Fig4 of arXiv:1510.09217

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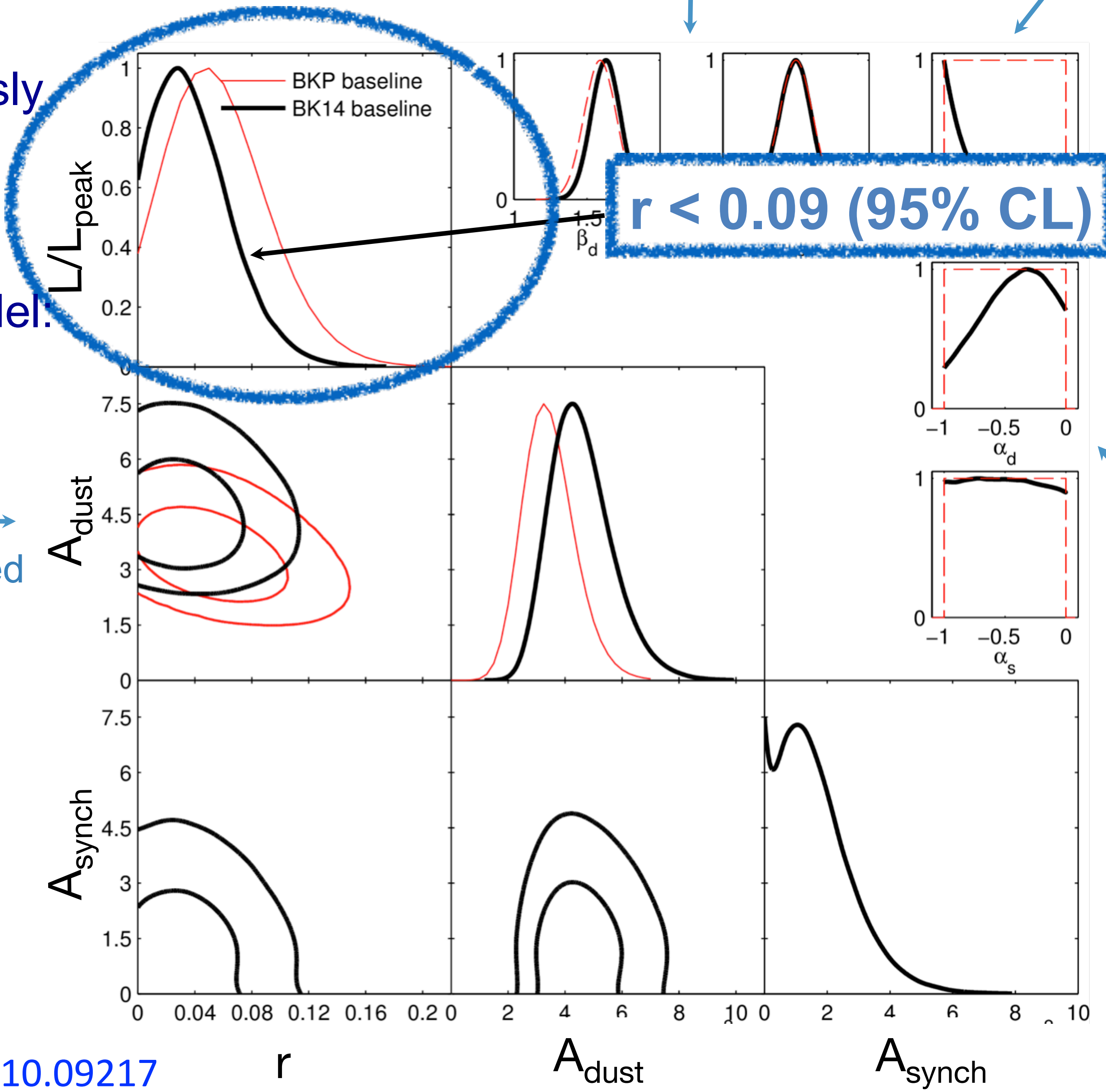

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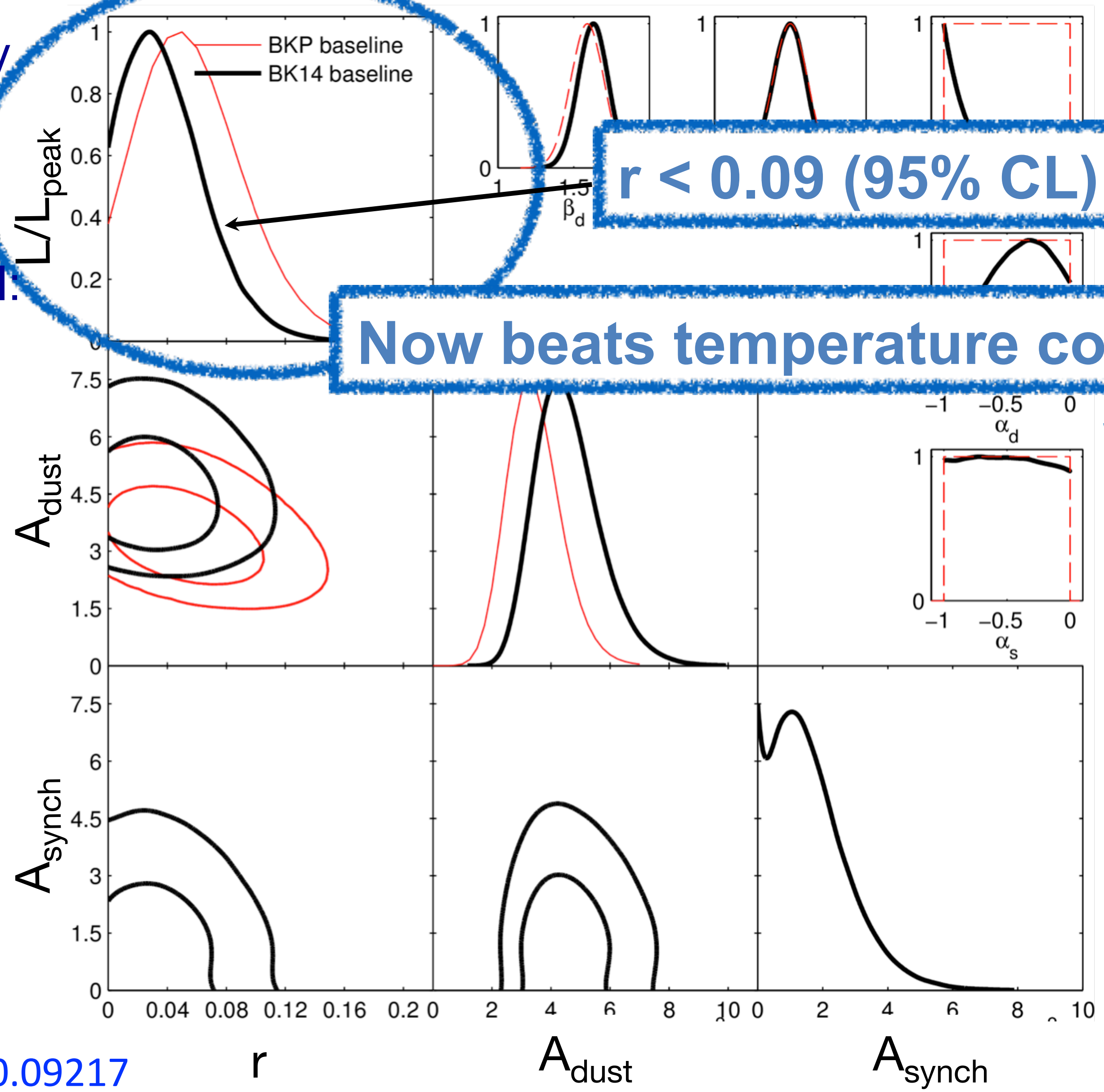

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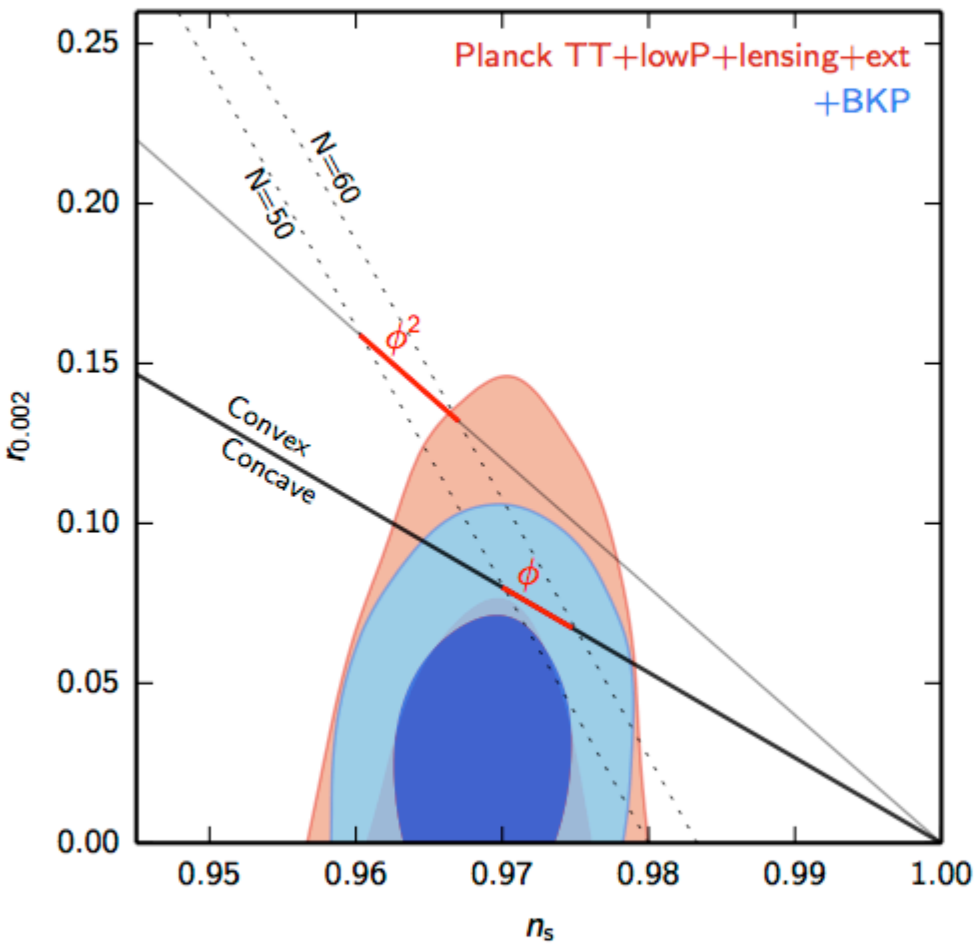
Planck full sky + BKP (Feb 2015)



Combined limit $r_{0.05}<0.09$

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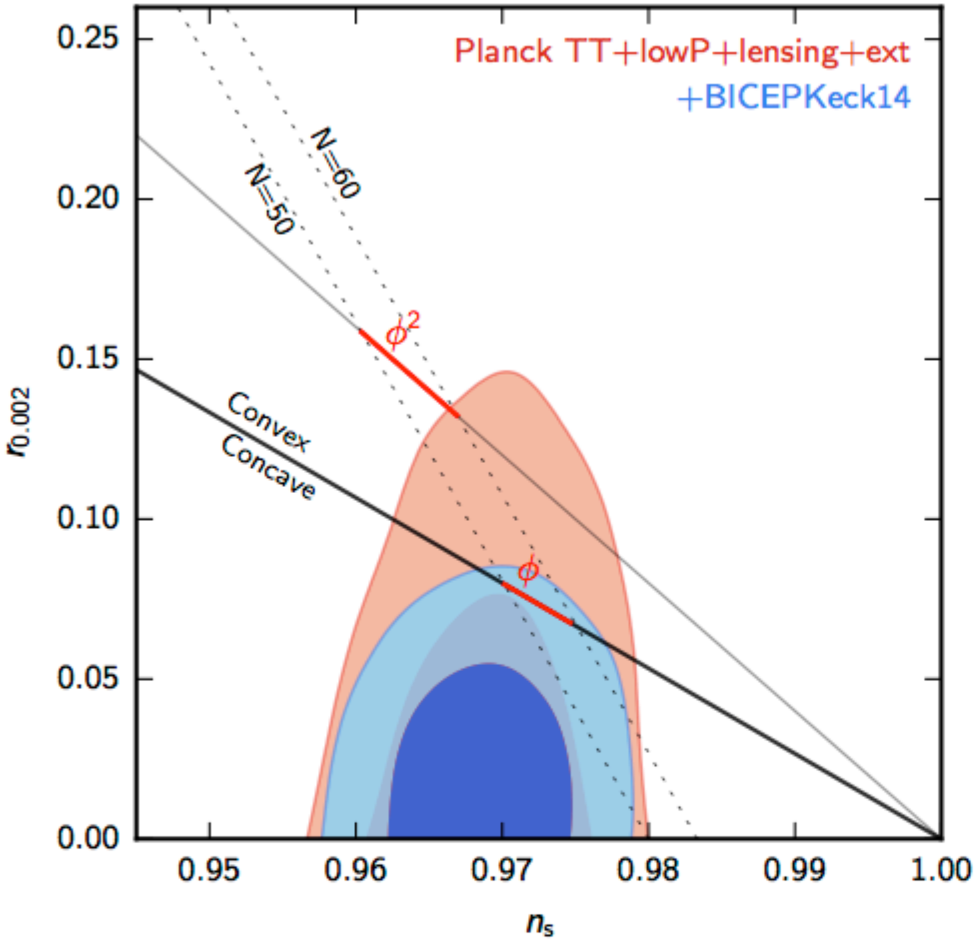
Planck full sky + BK14 (Oct 2015)



Combined limit $r_{0.05}<0.07$

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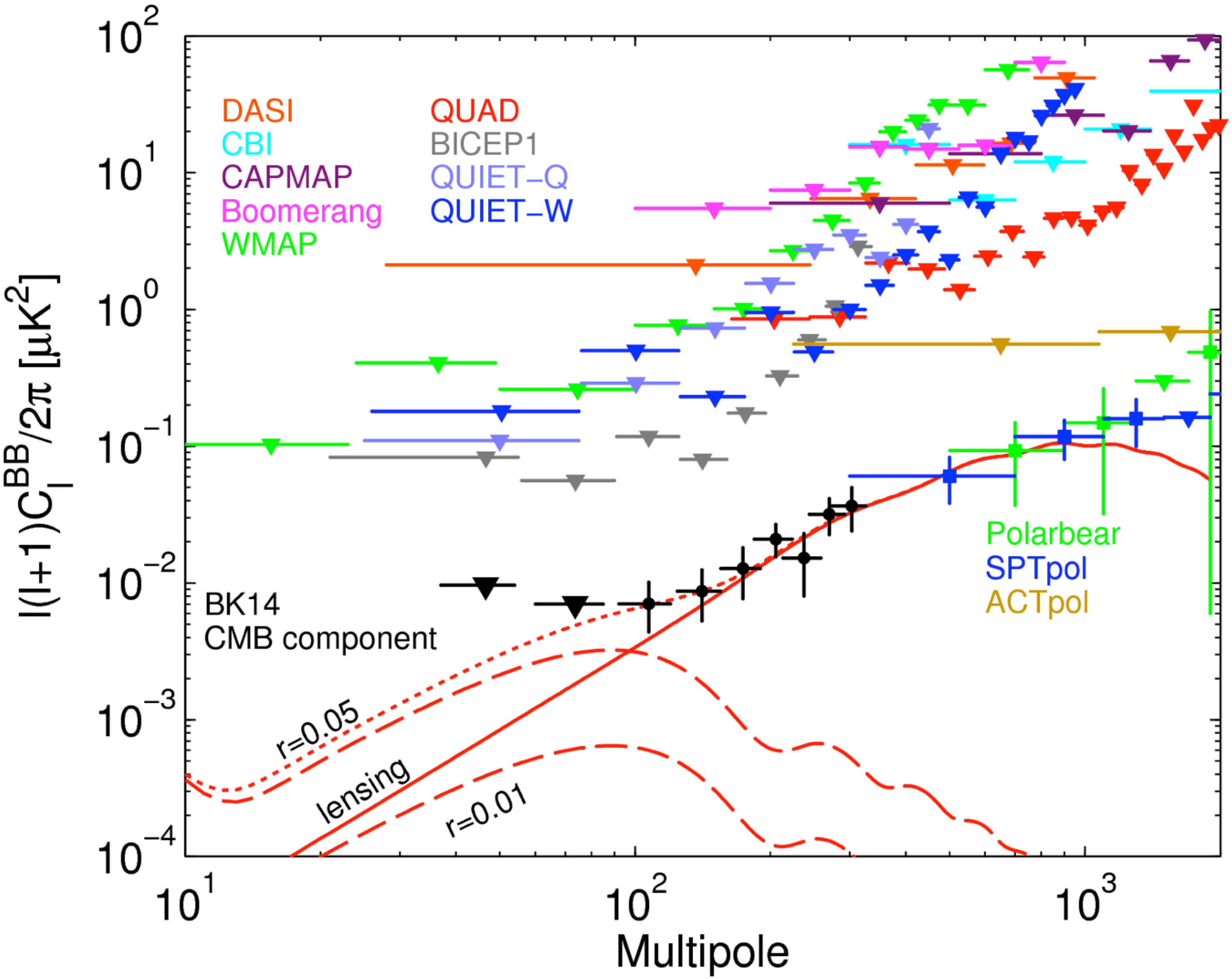
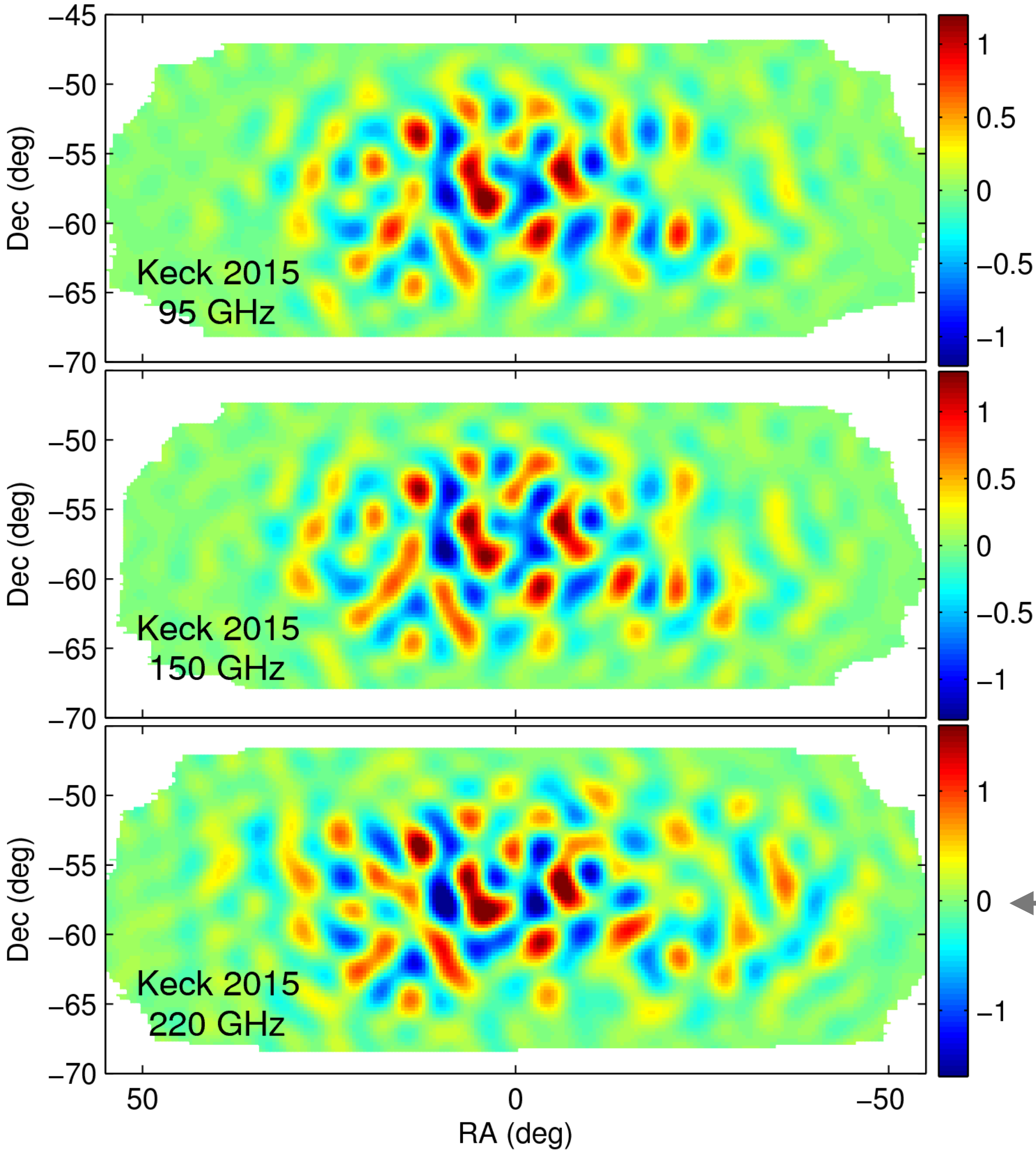
Component separated power spectrum (BK14)

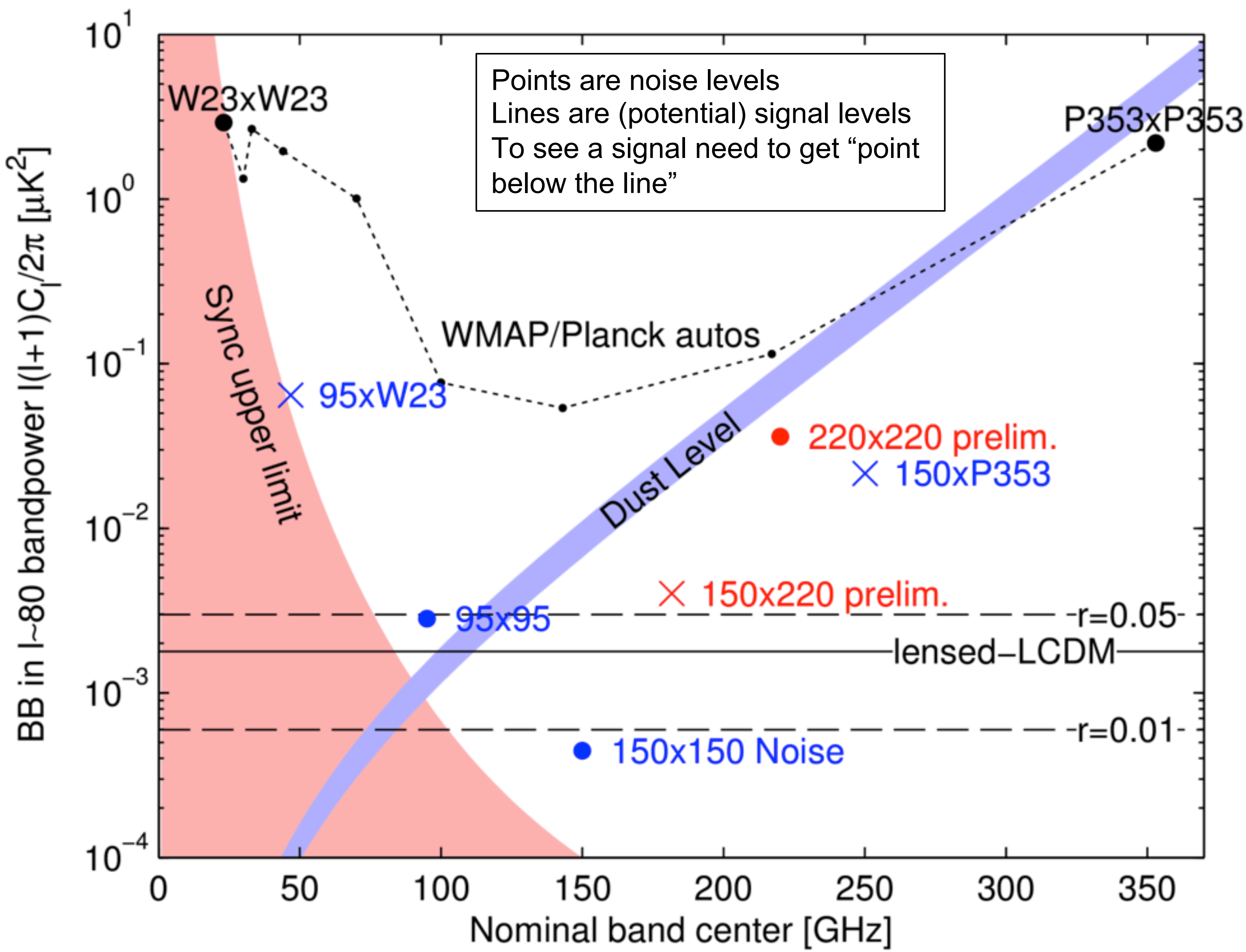


Teaser for the future: Keck 2015 E-mode maps



LCDM E-modes with high s/n at three frequencies in a single year!

Already deeper than Planck 217 GHz

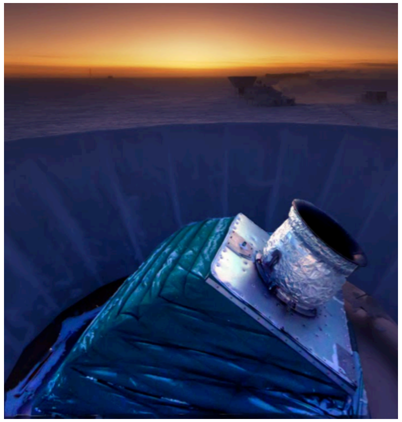


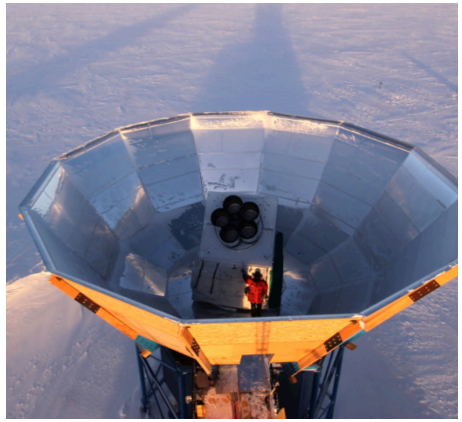
The current strength of the r-constraint is mostly dictated by the noise in the Planck 353GHz map – the result can get better quickly as the 220GHz measurements are brought to bear

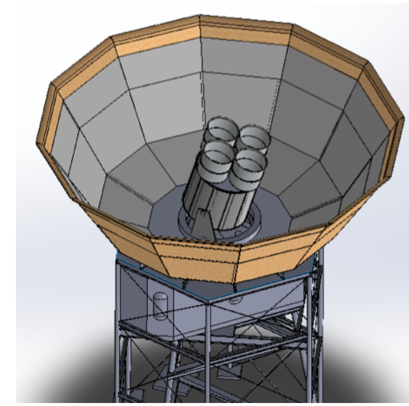
Our ongoing program – constantly scaling up and expanding frequency coverage

	BICEP2 (2010-2012)	**Keck Array** (2012-2017)	**BICEP3** (2015-)	**BICEP Array** (2018-)

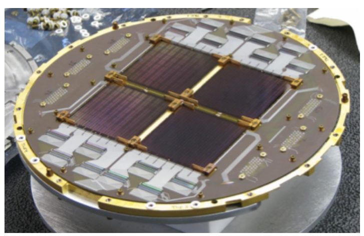
Telescope and Mount

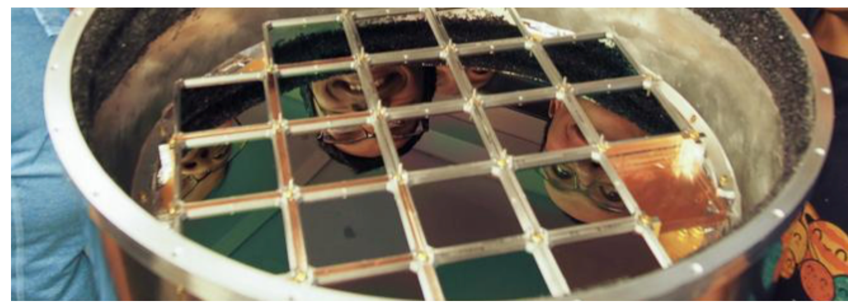




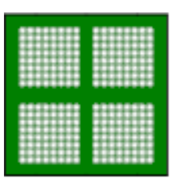


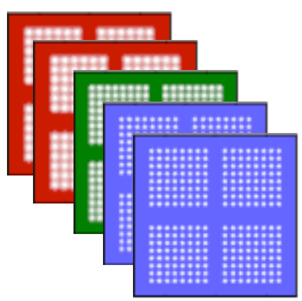
Focal Plane

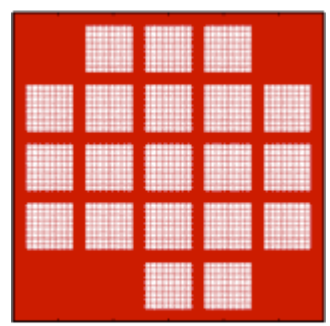


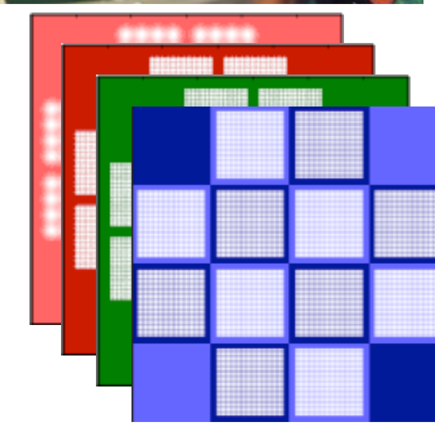


Beams on Sky









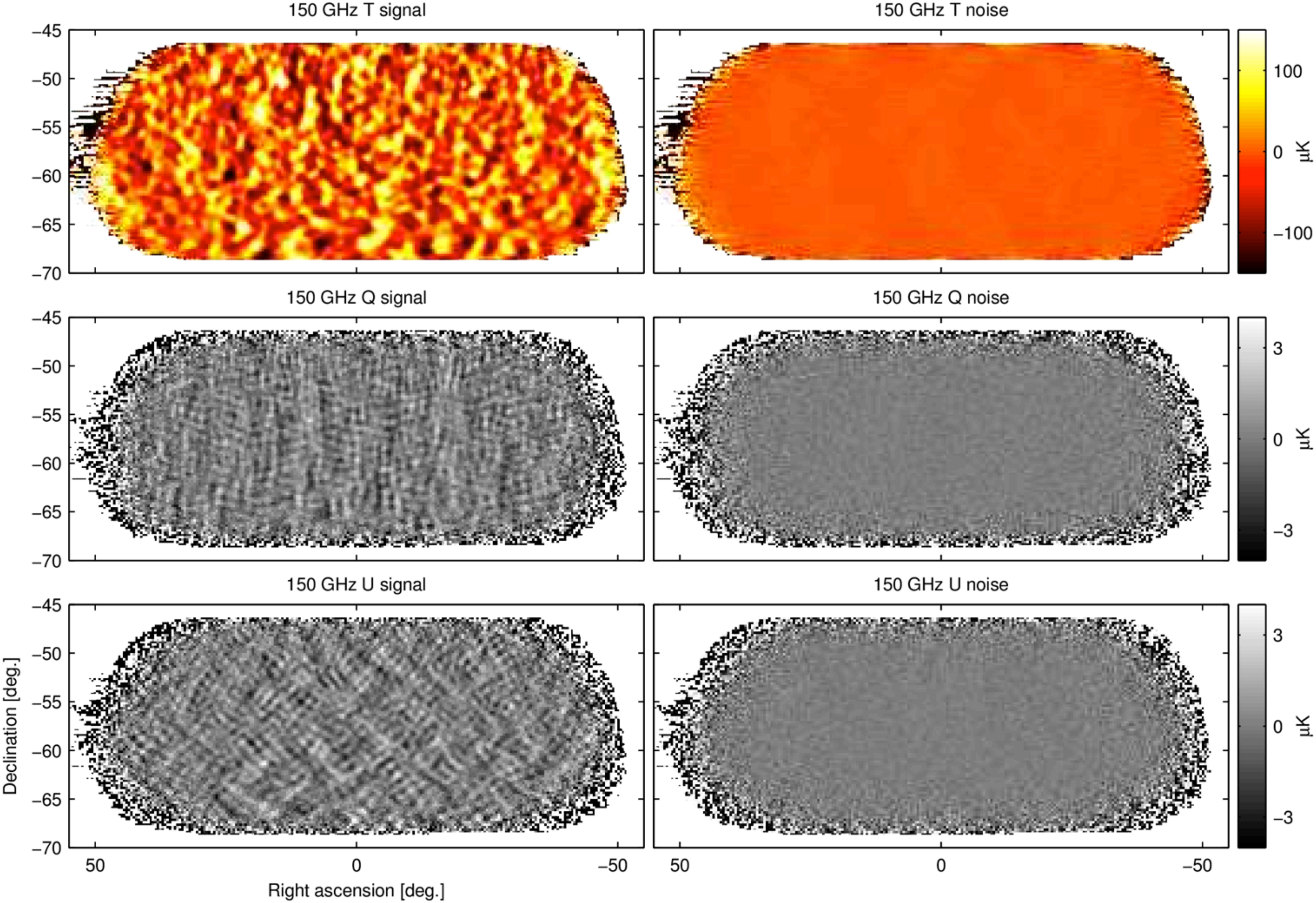
Conclusions

- BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:
- Best published sensitivity to date
- Best proven systematic control at degree angular scales
- (last pol. based result from another experiment was in 2012)

- Current BK14 analysis adds 95GHz data taken in 2014:
- Results in modest improvement: $r<0.12$ goes to $r<0.09$
- However this is an important milestone: for the first time B-mode only constraint exceeds the sensitivity of Planck TT derived constraint

- And we can go much further:
- 2015/16 data also includes 220GHz
- And BICEP3 “super receiver” is now online at 95GHz
- …and we have BIG plans for the BICEP-Array – $\sigma(r)<0.005$ by the end of the decade (delensing in conjunction w. SPT3G)

The end



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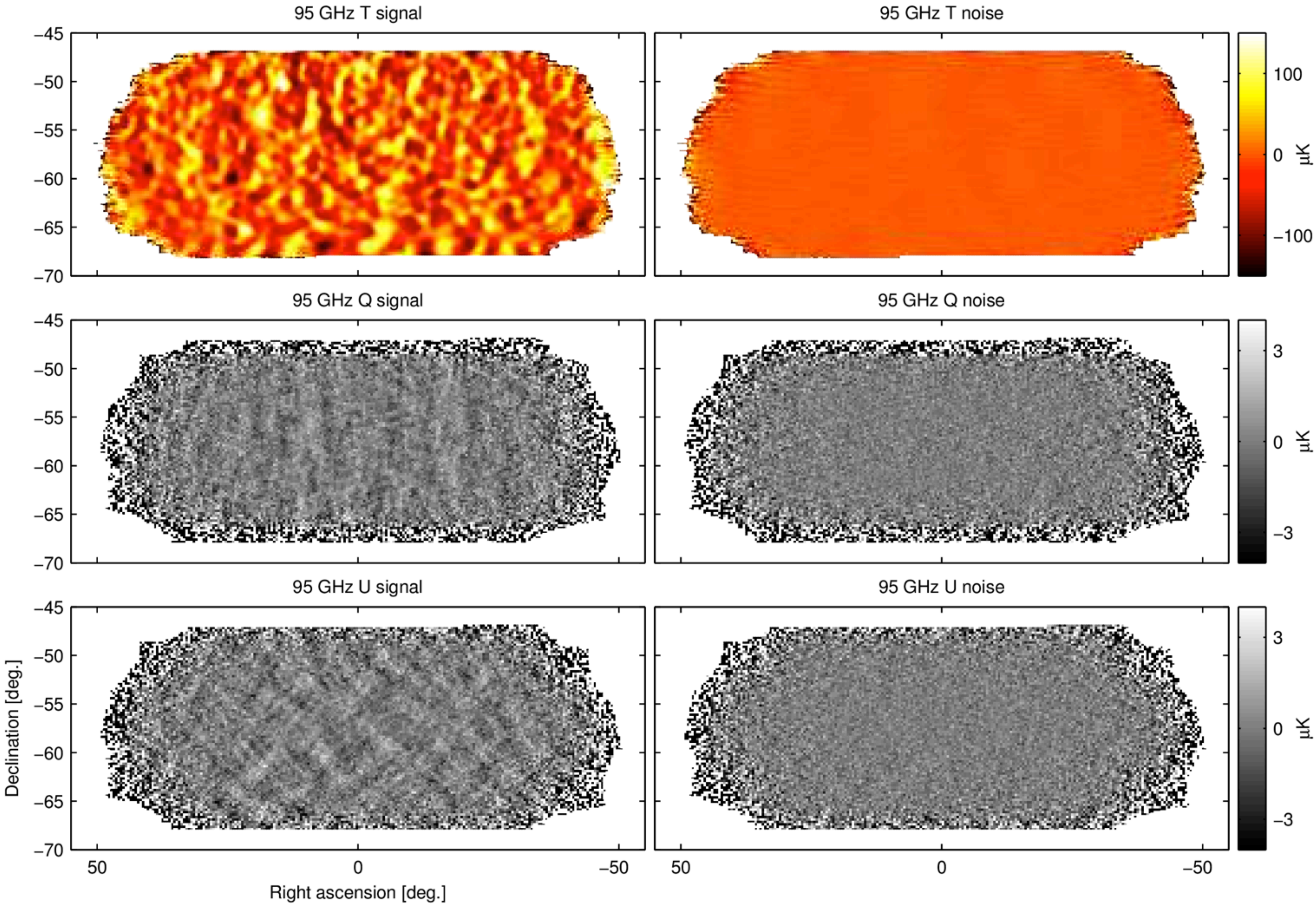
BK14 150GHz – 50 nK deg (3.0μK arcmin)



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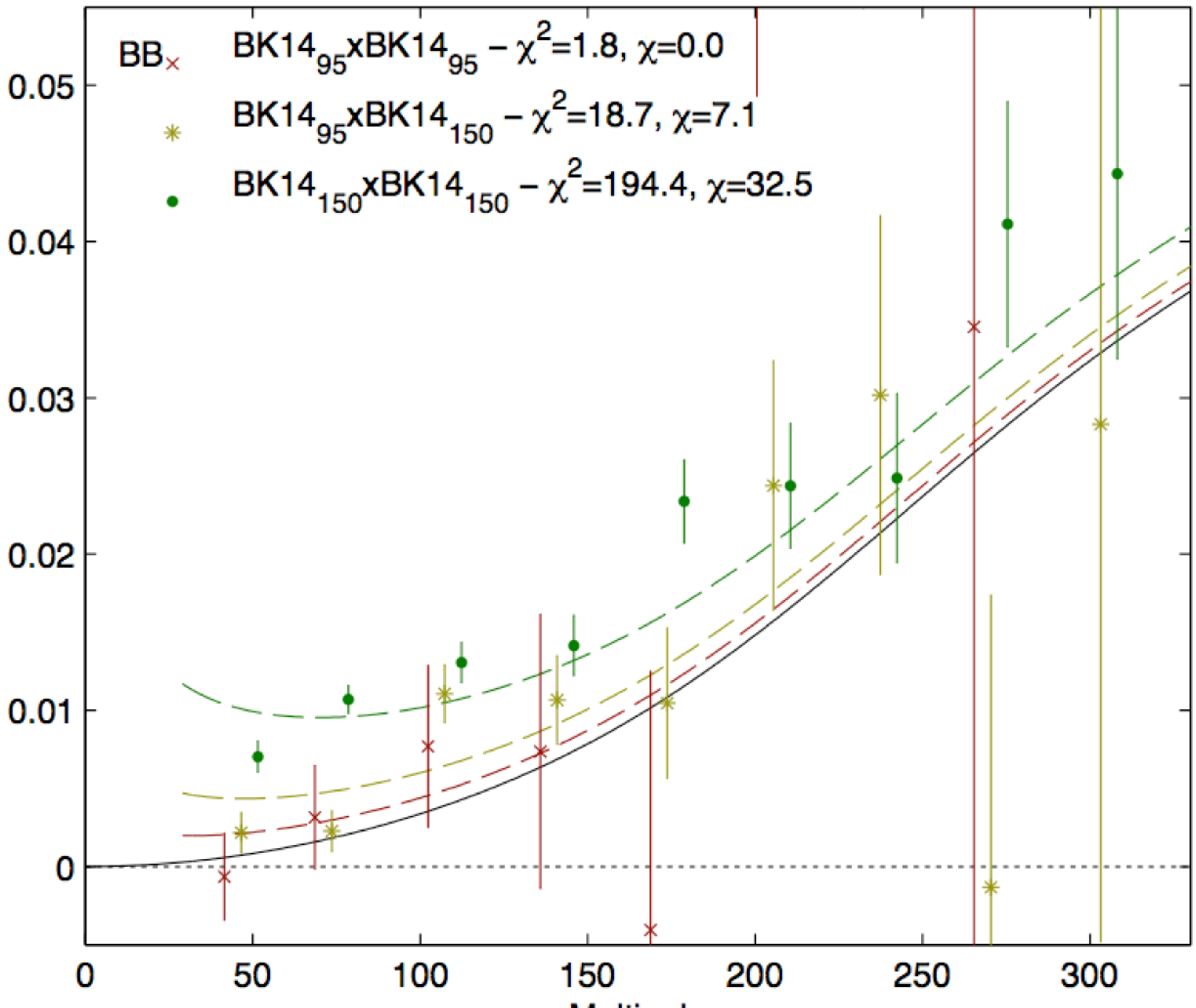
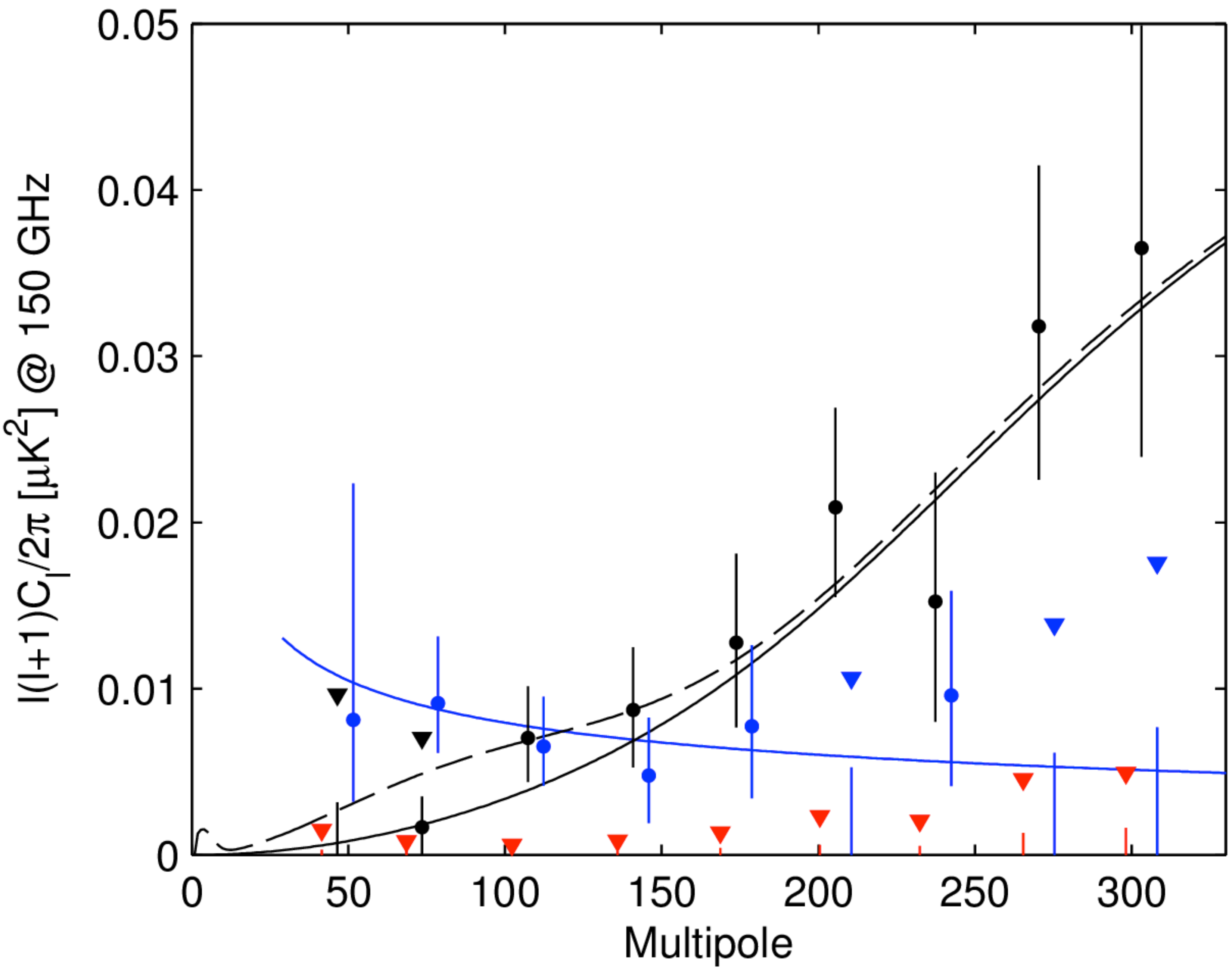
BK14 95GHz – 127 nK deg (7.6μK arcmin)

BK14 95/150GHz BB auto- and cross-spectra



The BICEP/

Alternate bandpower-by-bandpower dust/sync/CMB decomposition



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