RESCEU Summer School

B-mode polarization of the CMB

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IMK
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素粒子宇宙起源研究機構

outline

- Introduction
  - Cosmic Microwave Background (CMB)
    - Cosmological density perturbations
      gravitational waves
- CMB polarizations
  - Q&U stokes paramters and E & B modes
- The sources of B-mode polarization
  - Gravitatinal waves (BICEP2)
  - Gravitational lensing (POLARBEAR, SPTPol)
- summary

Polarization of CMB photons

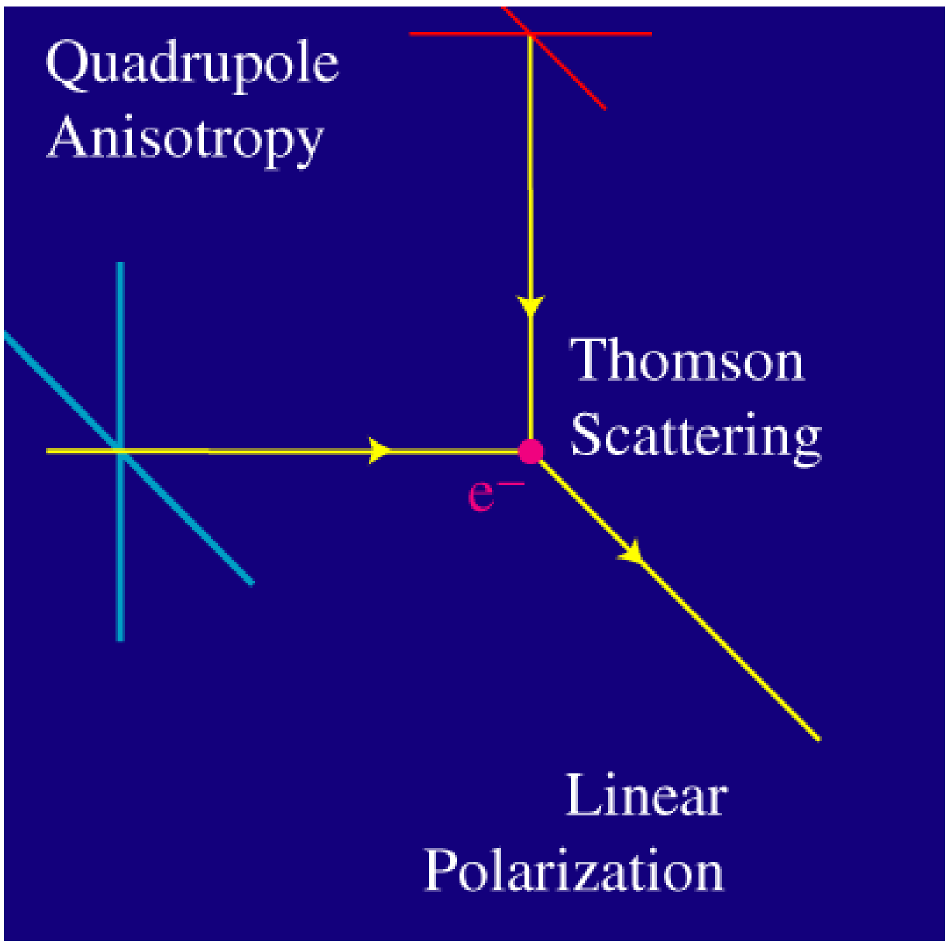
- Generated by the Thomson scattering
- Having information about Π_γ at the scattering
- Having characteristic polarization 'pattern' depending on the source of Π_γ
  - E- & B-mode (Seljak, ApJ, 1996; Kamionkowski+, PRL, 1997)

- E-mode detection by DASI (Kavoc et al., Nature, 2002)
- TE-correlation detection by WMAP (Kogut et al., ApJS, 2003)
- Lensing-B mode detection by SPTpol (Hanson+,PRL,2013)
  & PolarBear (Ade+, PRL, 2014)
- (Primordial)B-mode detection by BICEP2 (Ade+, PRL, 2014)

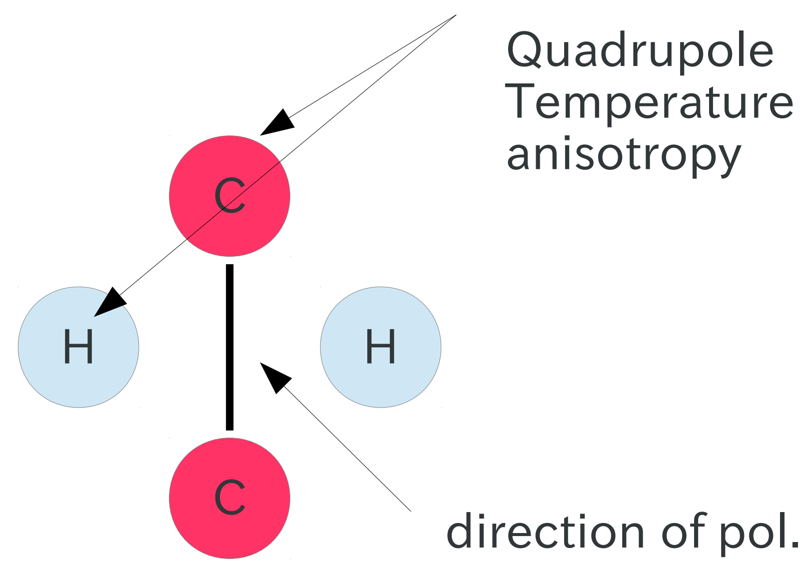
Polarization of scattered light



Generation of polarization



- No polarization without temp. anisotropy
- Quadrupole is the source

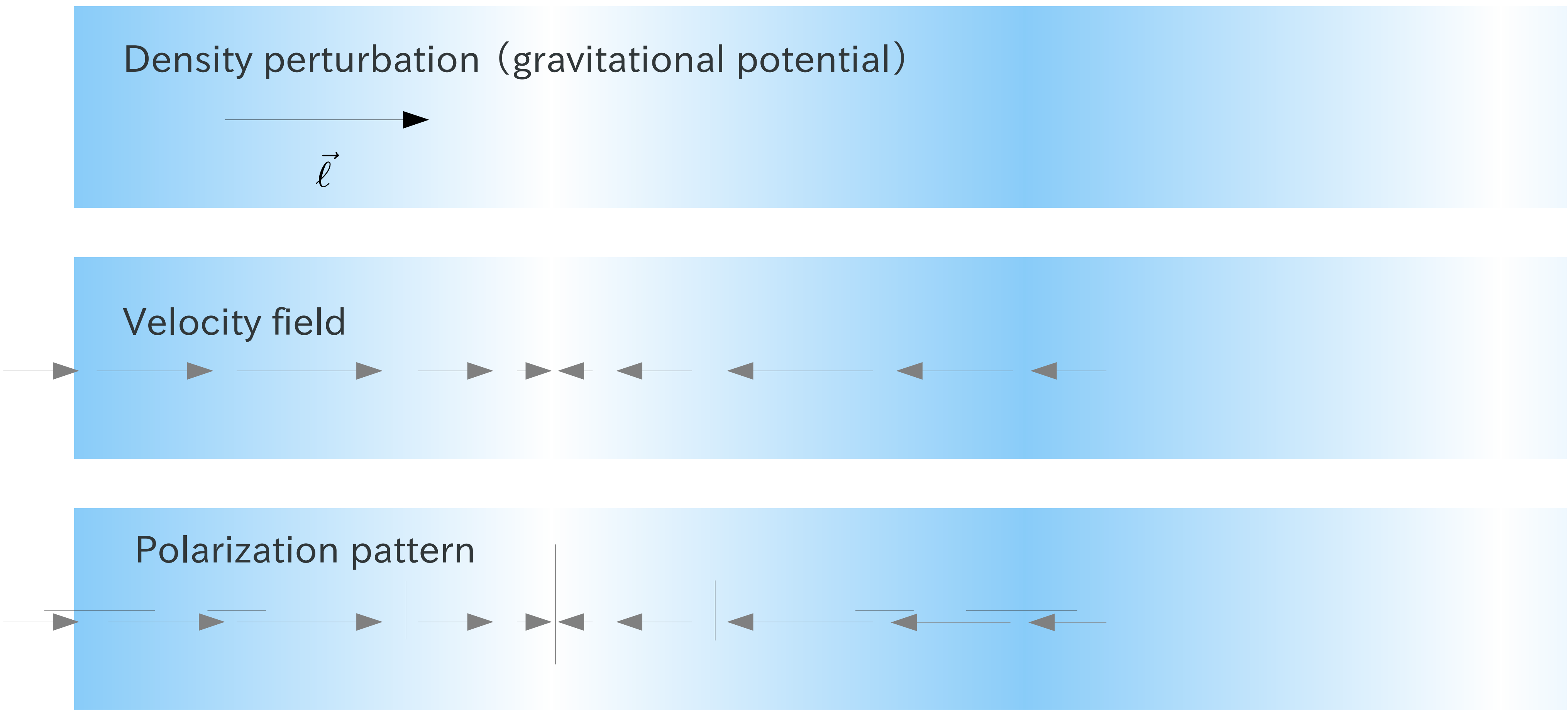


Credit: W. Hu

Polarization 'Pattern'

(inspired by E.Komatsu)

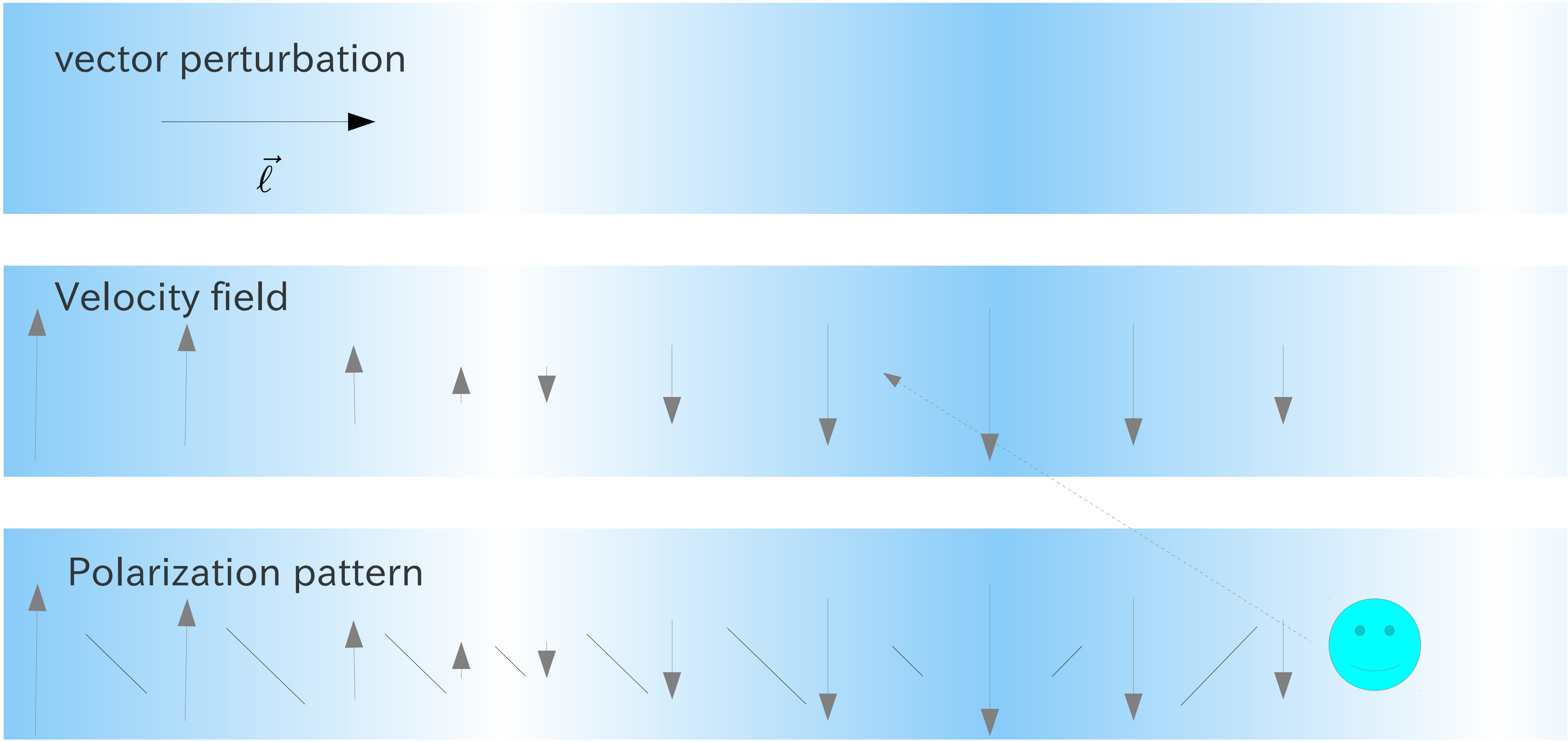
- Scalar-type : quadrupole = velocity gradient seen by e^-



Directions of polarization are parallel along or perpendicular to the direction of the Fourier mode (= E-mode)

Polarization 'Pattern'

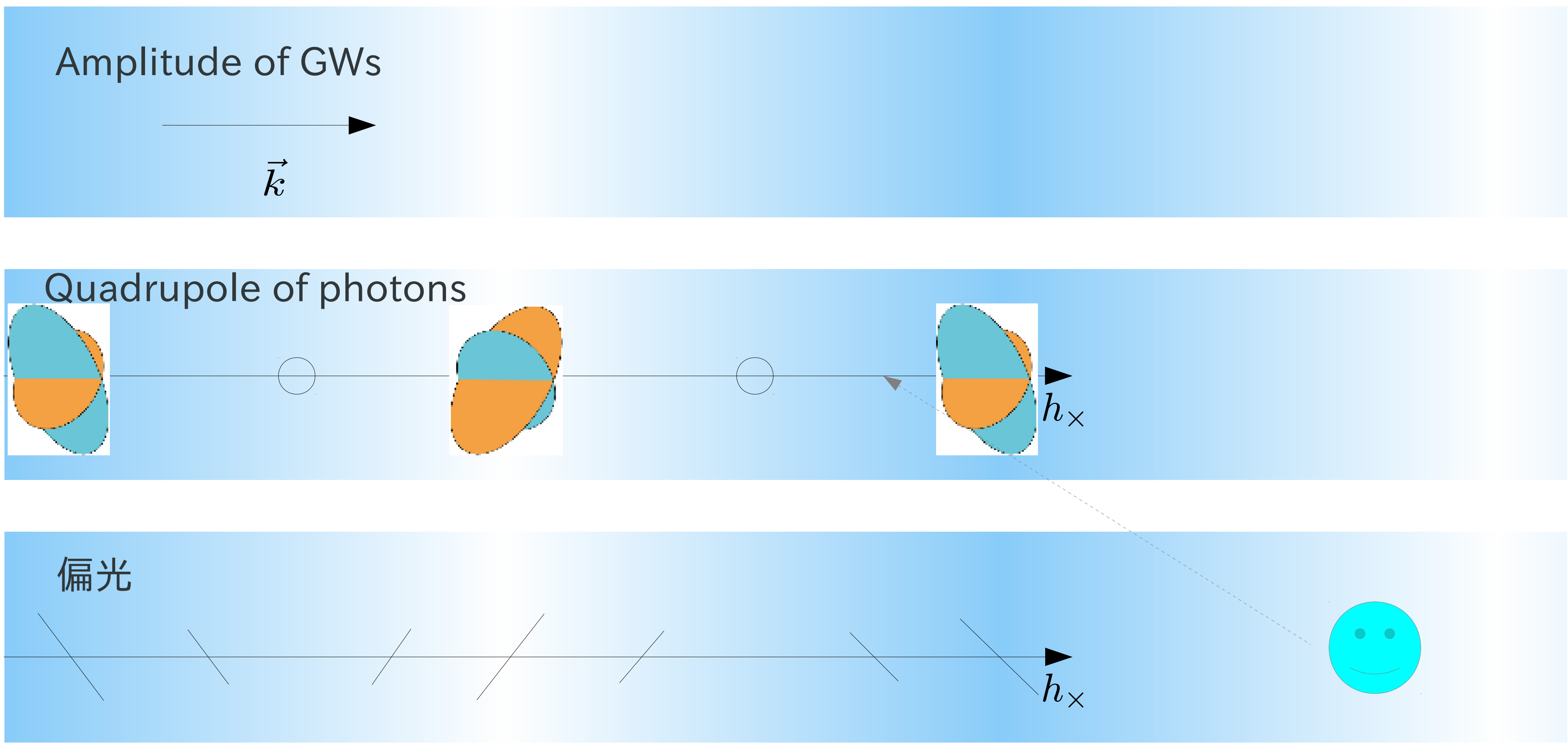
- Vector type : quadrupole = Doppler effect seen by e^-



Directions of polarization are inclined to the direction of the Fourier mode (= B-mode)

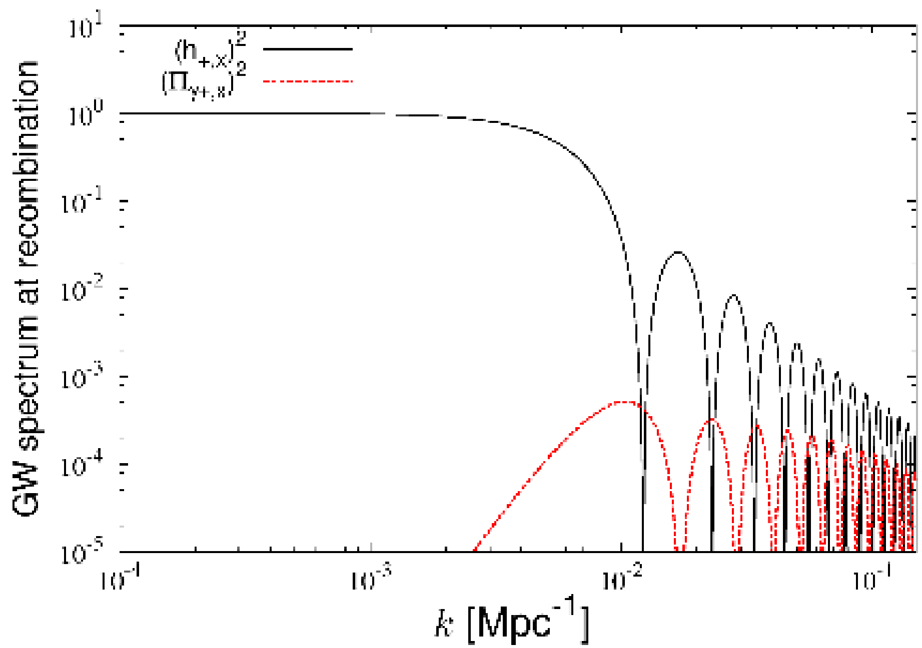
Polarization 'Pattern'

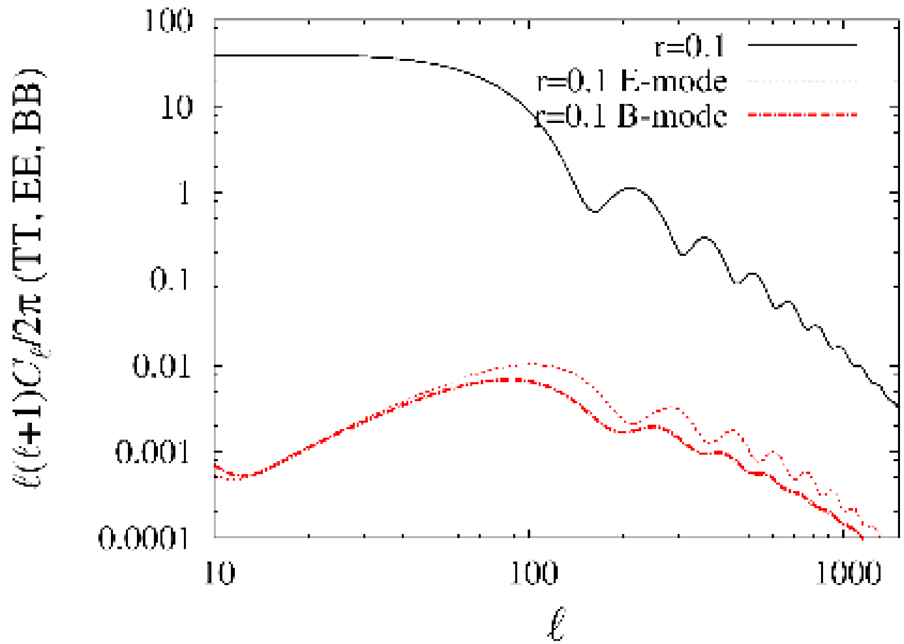
- Tensor-type：quadrupole from Gravitational waves (GW)



Directions of polarizations are inclined with respect to the direction of the Fourier mode (= B-mode)

$C_\ell^{\mathrm{EE,BB}}$ from GWs





Π_γ is driven by h , suppressed because of the tight coupling to baryons $\rightarrow$ $C_\ell^{\mathrm{EE,BB}}$ peak around l=100 with milder decline toward higher multipoles than temperature

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- (Primordial)B-mode detection by BICEP2 (Ade+, PRL, 2014)

BICEP1, BICEP2, and Keck Collaborators

Photo from Zak Staniszewski

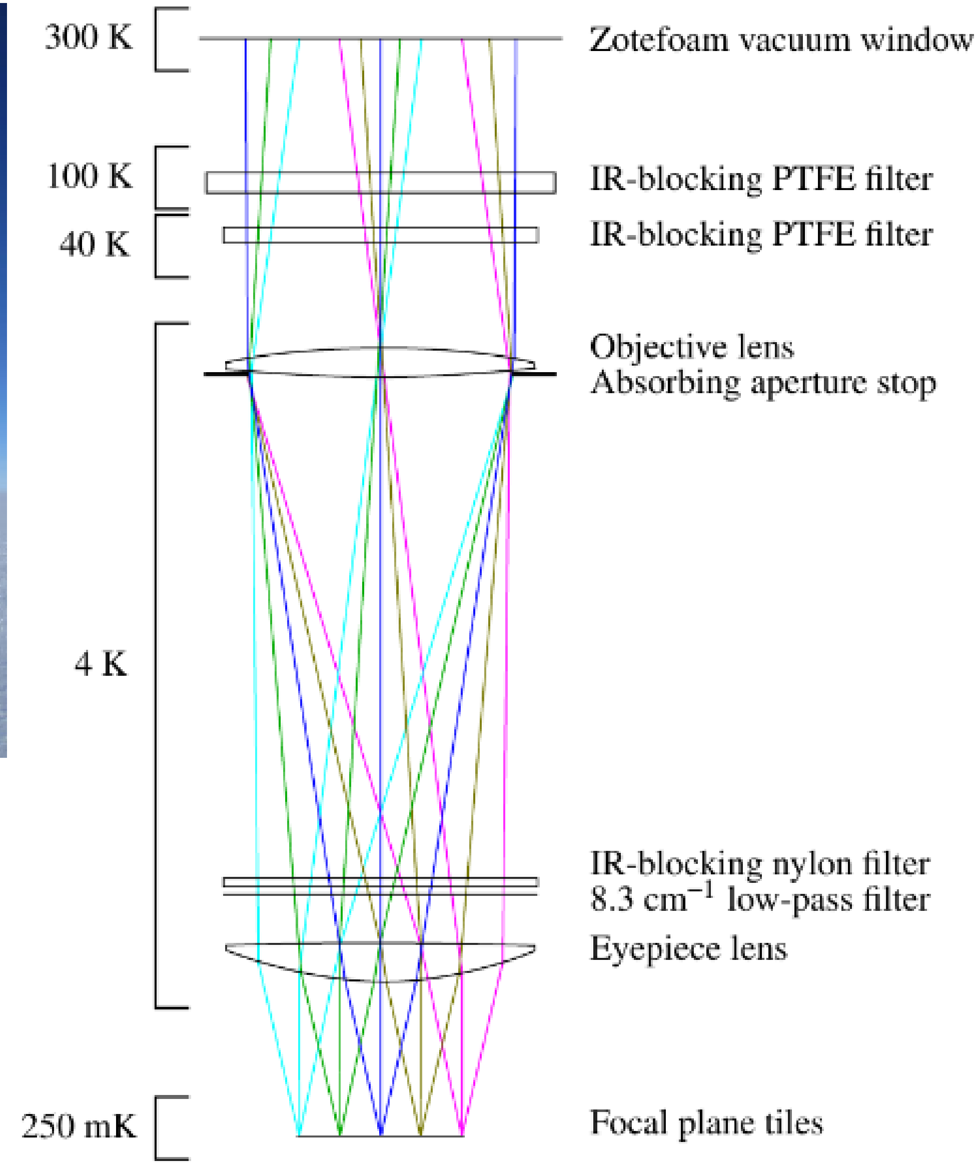
California Institute of Technology
Harvard University
JPL
KIPAC
Stanford University
University of Minnesota

Case Western Reserve University
NIST
University of British Columbia
University of Toronto
University of Chicago
UCSD
Wales Cardiff
CEA Grenoble

Thanks to National Science Foundation, W. M. Keck Foundation.

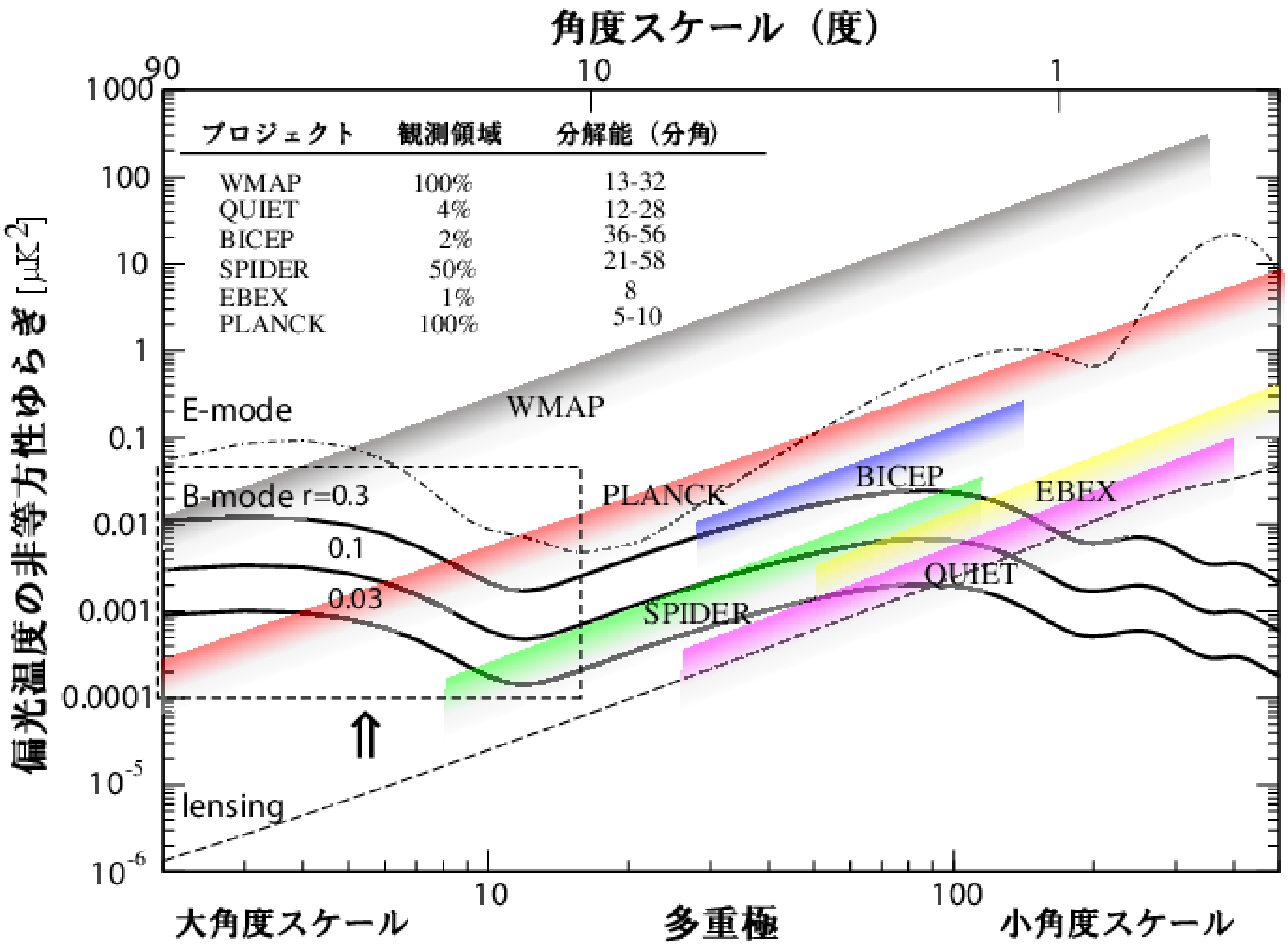
From slide by Immanuel Buder (CMB2013@沖縄)

BICEP2 at the South Pole

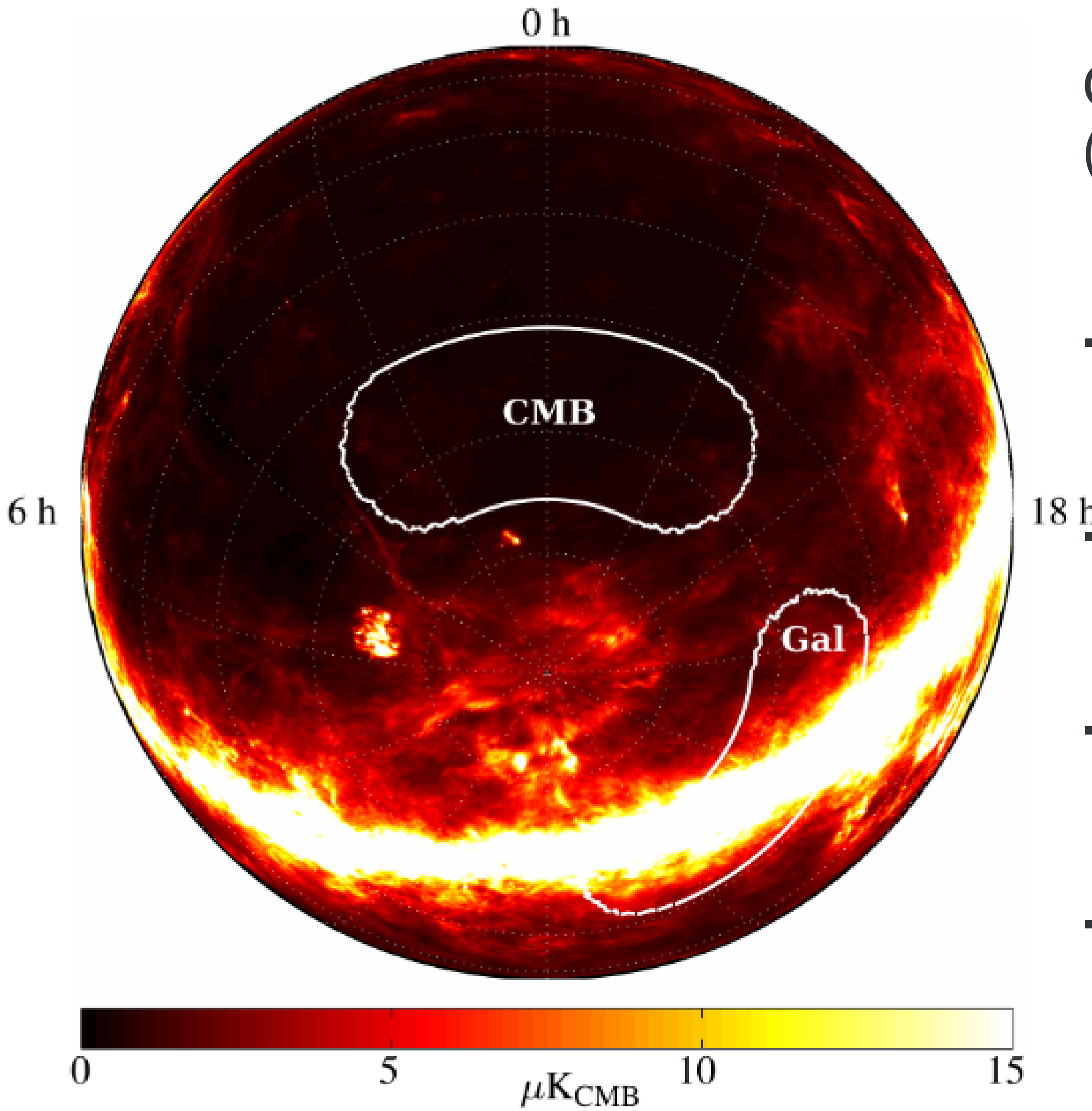


3yr observation '10-'12 from the SP
500 detectors, 150GHz band
Aperture 26.4 cm (resolution 12min)
sensitivity 5.2 μK･arcmin
(Planck ～60 μK･arcmin)
FoV 383.7 sq. deg.

2010年に作成した資料より



“Southern Hole” SKY from BICEP2



CMB Field
(1000 sq deg. 2% of the sky)

- RA=0hr, dec=-57.5 deg.
  $(\ell, b) = (316^\circ, -59^\circ)$
- very low dust emision region
  (<1% compared to median)
- Assume 5% polarization
  → B-mode r=0.02
- smaller synch polarization
  (based on scaling of WMAP)

T,Q,U maps

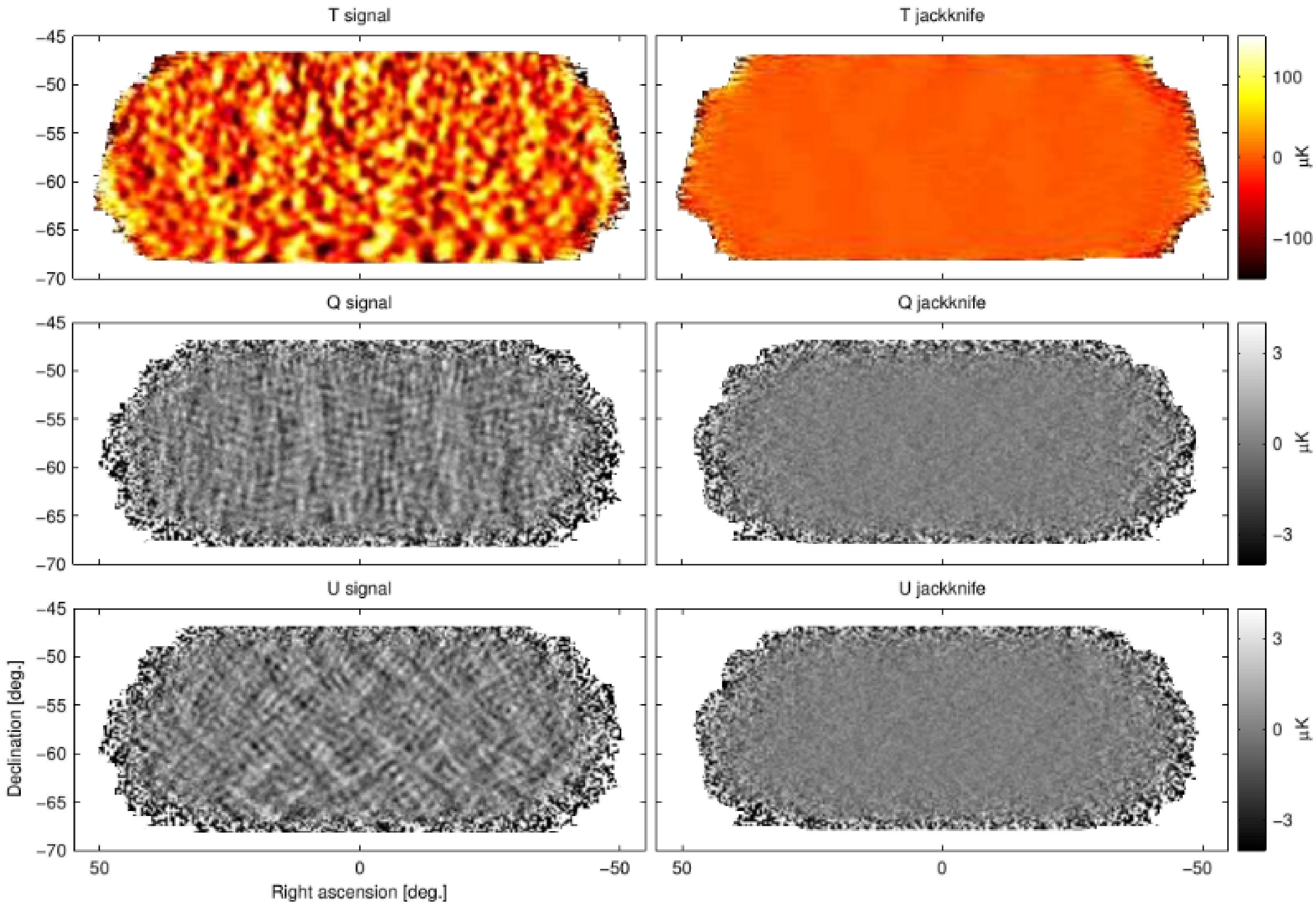
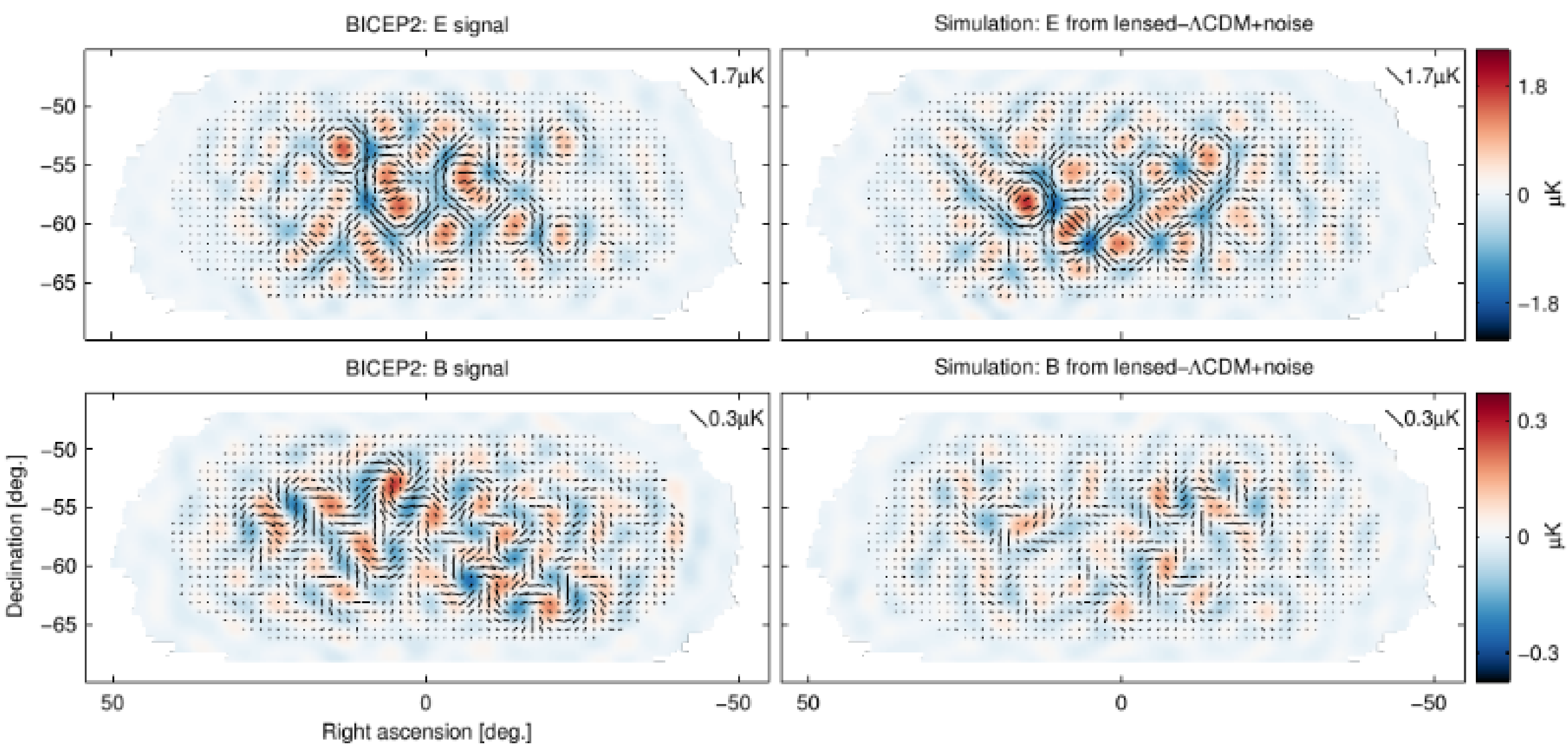


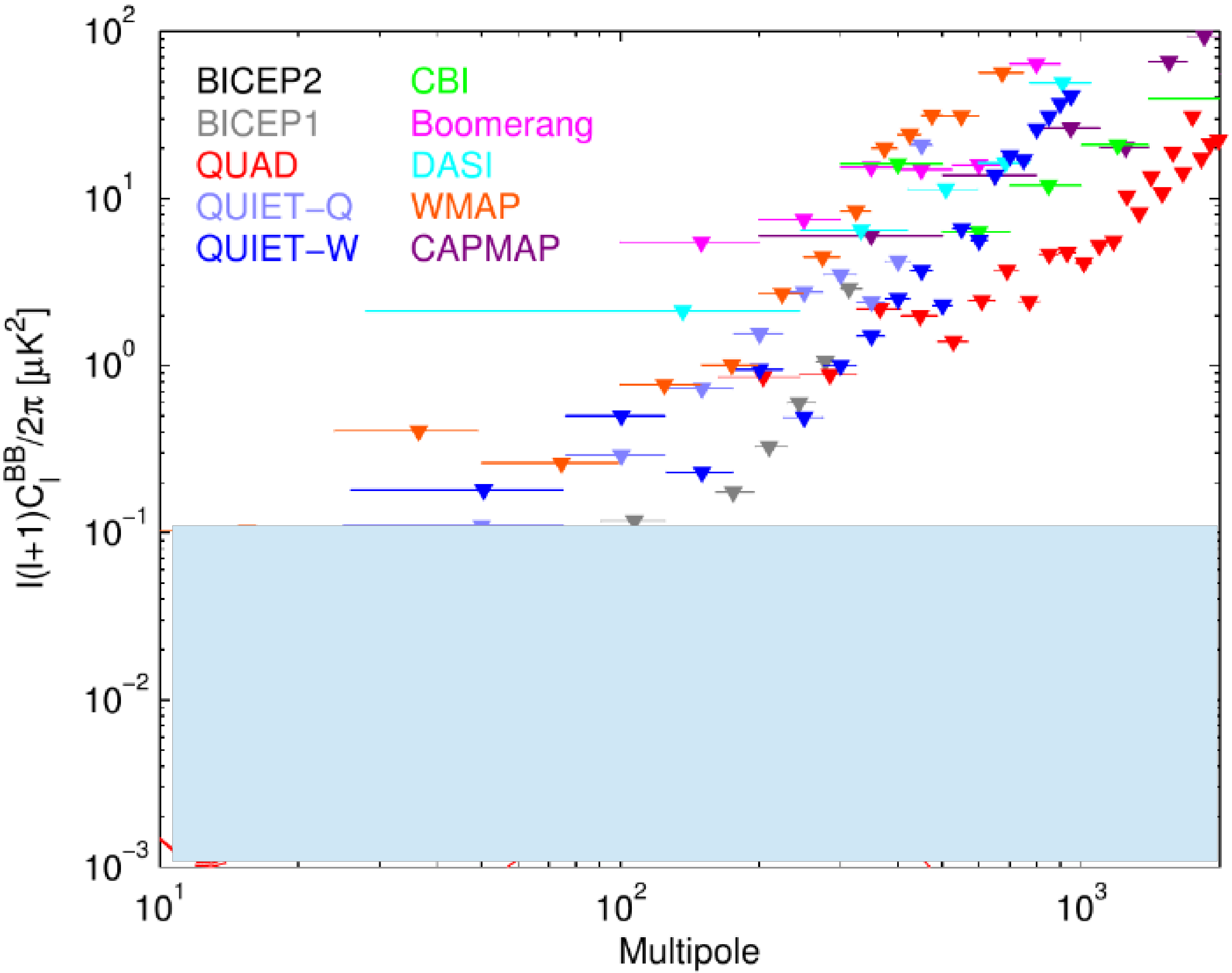
FIG. 1.— BICEP2 T, Q, U maps. The left column shows the basic signal maps with 0.25° pixelization as output by the reduction pipeline. The right column shows difference (jackknife) maps made with the first and second halves of the data set. No additional filtering other than that imposed by the instrument beam (FWHM 0.5°) has been done. Note that the structure seen in the Q&U signal maps is as expected for an E-mode dominated sky.

E&B maps filtered to 50<l<120

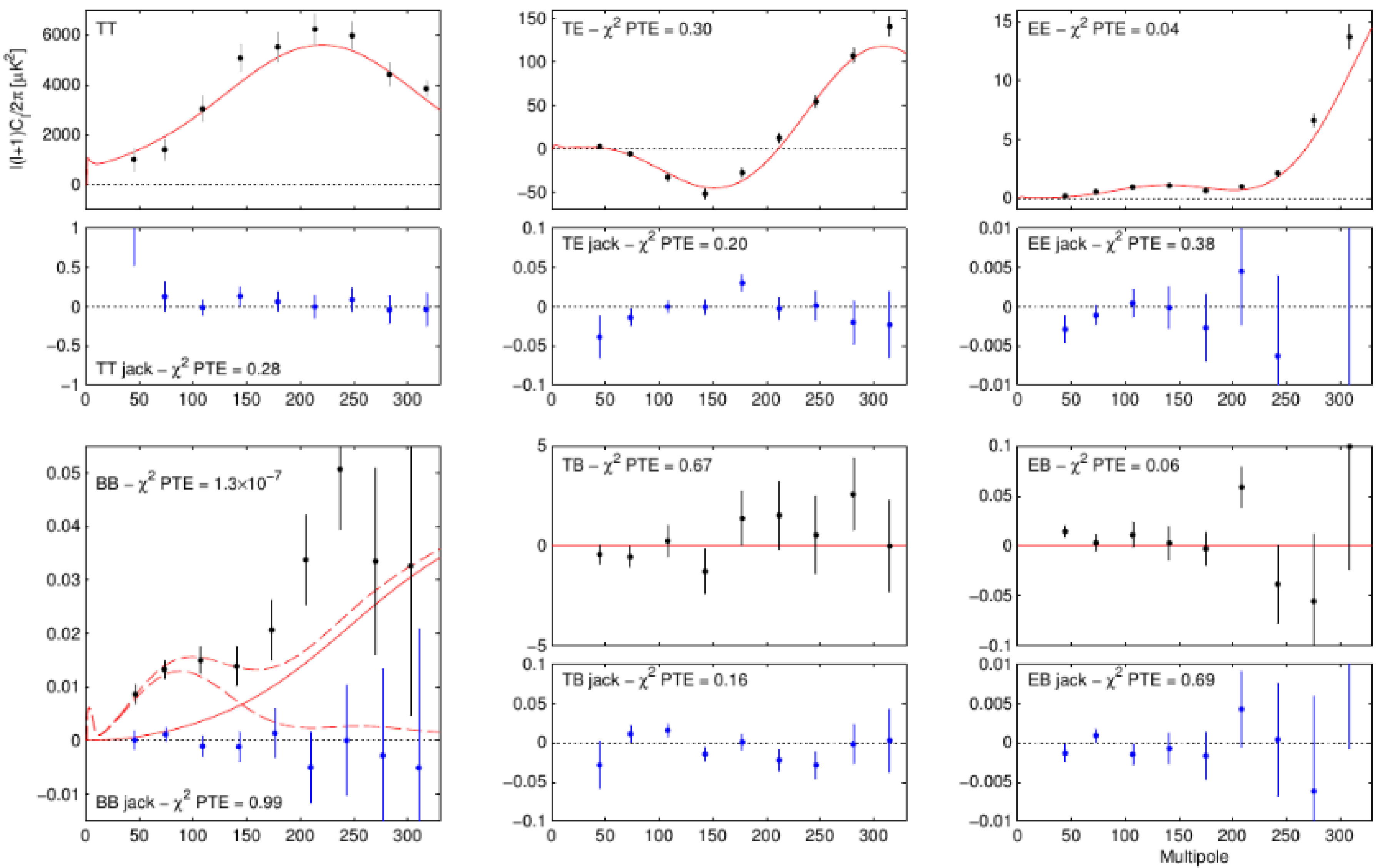
High signal-noise in the map
Signal appears to be evenly distributed over the field (and random Gaussian)



How impressive!



BICEP2 power spectra



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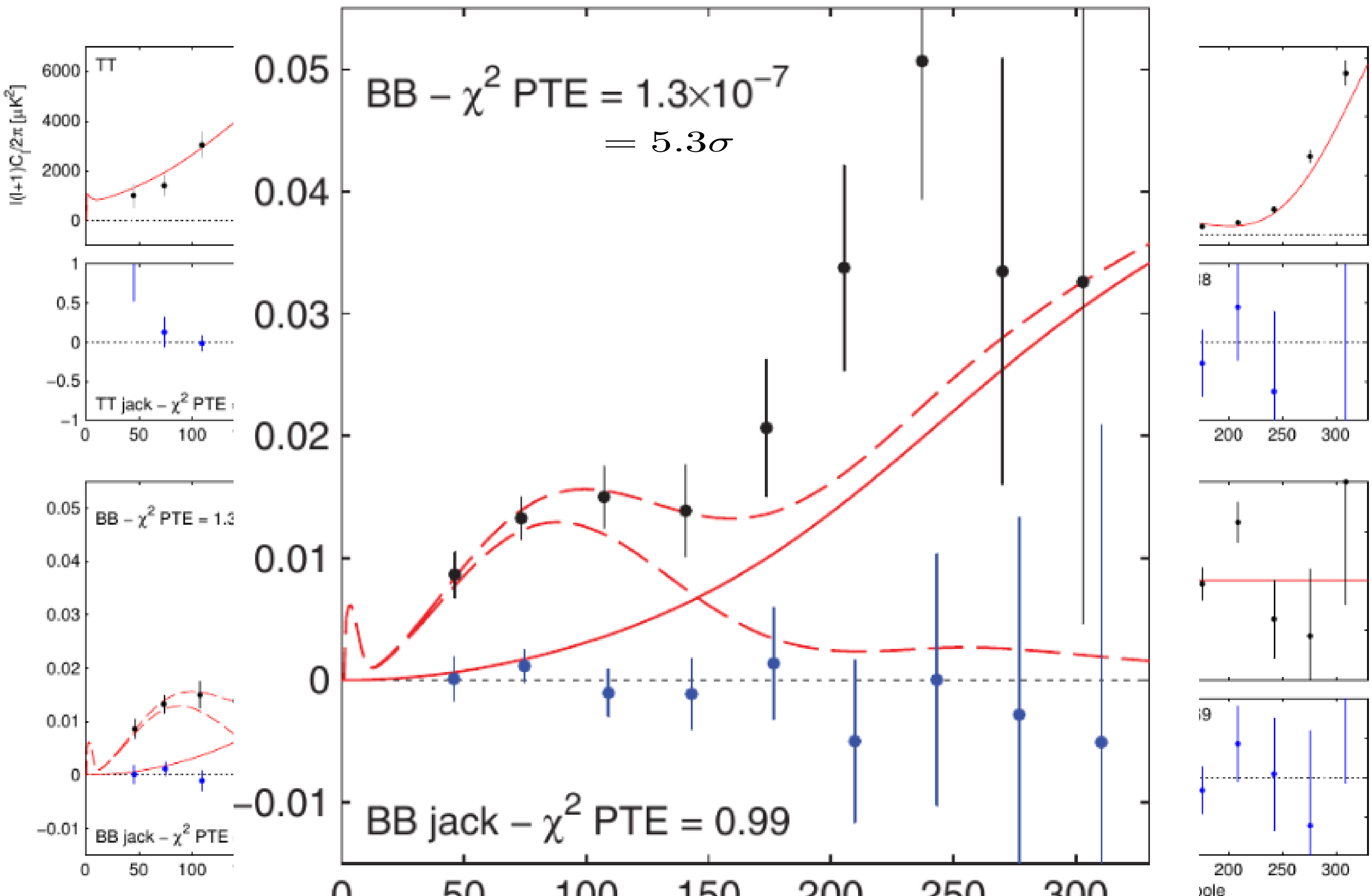
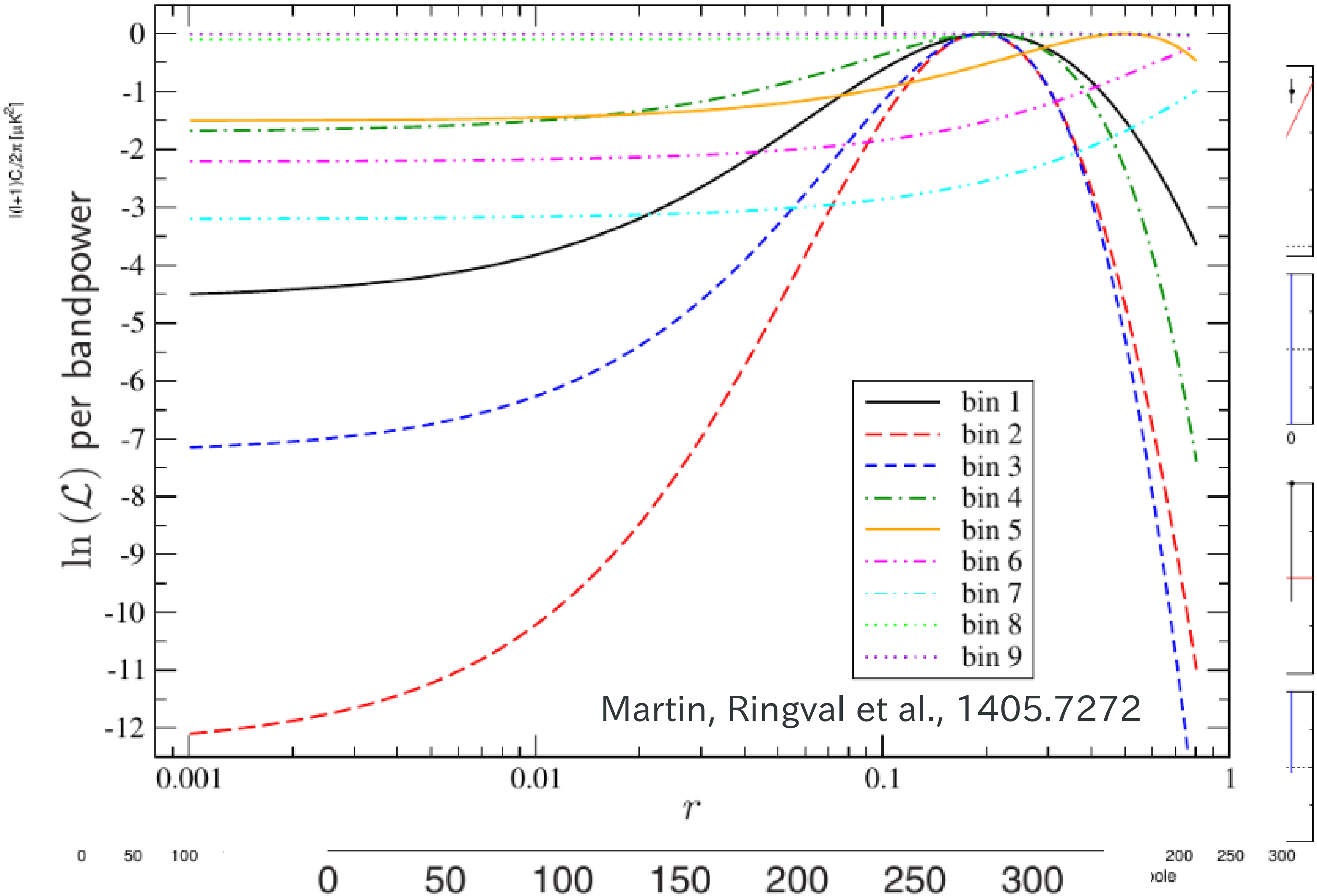


BICEP2 power spectra



Systematic uncertainties

Jackknife PTE values from χ^2 and χ (sum-of-deviation) Tests

Jackknife	Bandpowers 1–5 χ^2	Bandpowers 1–9 χ^2	Bandpowers 1–5 χ	Bandpowers 1–9 χ
Deck jackknife				
EE	0.046	0.090	0.164	0.299
BB	0.774	0.329	0.240	0.082
EB	0.337	0.643	0.204	0.267
Scan Dir jackknife				
EE	0.483	0.762	0.978	0.938
BB	0.531	0.573	0.896	0.551
EB	0.898	0.806	0.775	0.890
Temporal Split jackknife				
EE	0.541	0.377	0.916	0.958
BB	0.902	0.992	0.449	0.585
EB	0.477	0.689	0.856	0.615
Tile jackknife				
EE	0.004	0.010	0.000	0.002
BB	0.791	0.752	0.565	0.331
EB	0.172	0.419	0.962	0.790
Azimuth jackknife				
EE	0.673	0.409	0.136	0.339
BB	0.591	0.739	0.843	0.944
EB	0.529	0.577	0.840	0.659
Mux Col jackknife				
EE	0.812	0.587	0.196	0.204
BB	0.826	0.972	0.293	0.283
EB	0.866	0.968	0.876	0.697
Alt Deck jackknife				
EE	0.004	0.004	0.070	0.236
BB	0.397	0.176	0.331	0.086
EB	0.150	0.060	0.170	0.291
Mux Row jackknife				
EE	0.052	0.178	0.653	0.739
BB	0.345	0.361	0.032	0.008
EB	0.529	0.226	0.024	0.048
Tile/Deck jackknife				
EE	0.048	0.068	0.144	0.132
BB	0.908	0.840	0.629	0.269
EB	0.050	0.154	0.591	0.591
Focal Plane inner/outer jackknife				
EE	0.230	0.597	0.022	0.090
BB	0.216	0.531	0.046	0.092
EB	0.036	0.042	0.830	0.839
Tile top/bottom jackknife				
EE	0.289	0.347	0.459	0.599
BB	0.293	0.236	0.154	0.028
EB	0.545	0.683	0.902	0.932
Tile inner/outer jackknife				
EE	0.737	0.533	0.128	0.483
BB	0.255	0.096	0.421	0.036
EB	0.465	0.737	0.208	0.168
Moon jackknife				
EE	0.499	0.689	0.481	0.679
BB	0.144	0.287	0.898	0.858
EB	0.289	0.359	0.531	0.307
A/B offset best/worst				
EE	0.317	0.311	0.868	0.709
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.790

The deck jack … (68°,113°) vs (248°,293°)

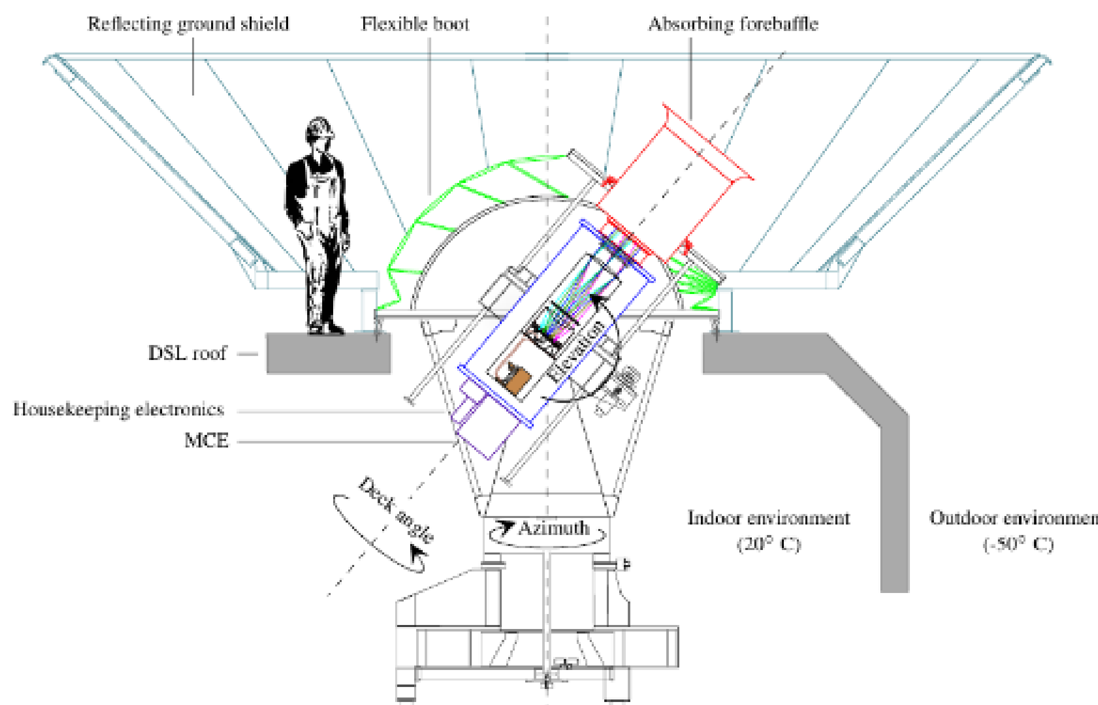
The alt. deck … (68°,293°) vs (113°,248°)

The temporal split … divide the data into two sequentially

The azimuth jack … divide the data based on seasons

The moon jack … divide the data based on moon position

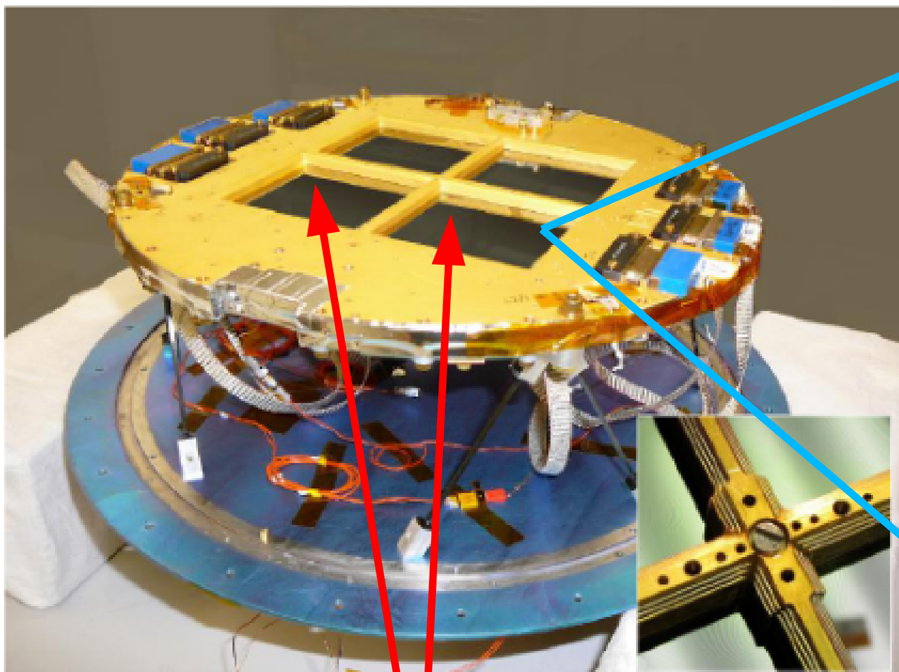
The tile jack … use different tiles



BICEP2 paper II

detectors

8x8 pixels in a tile



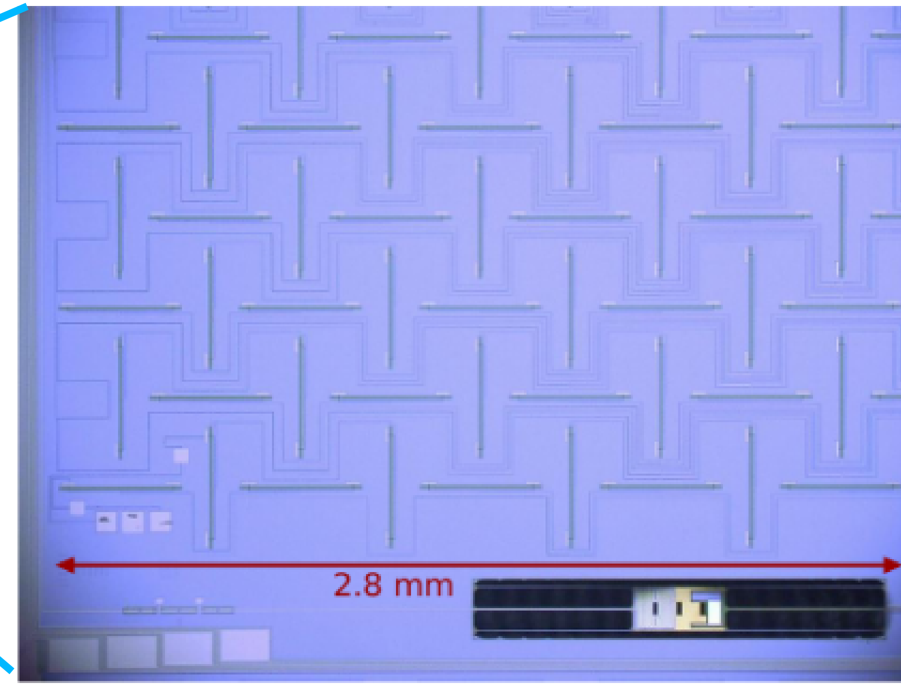
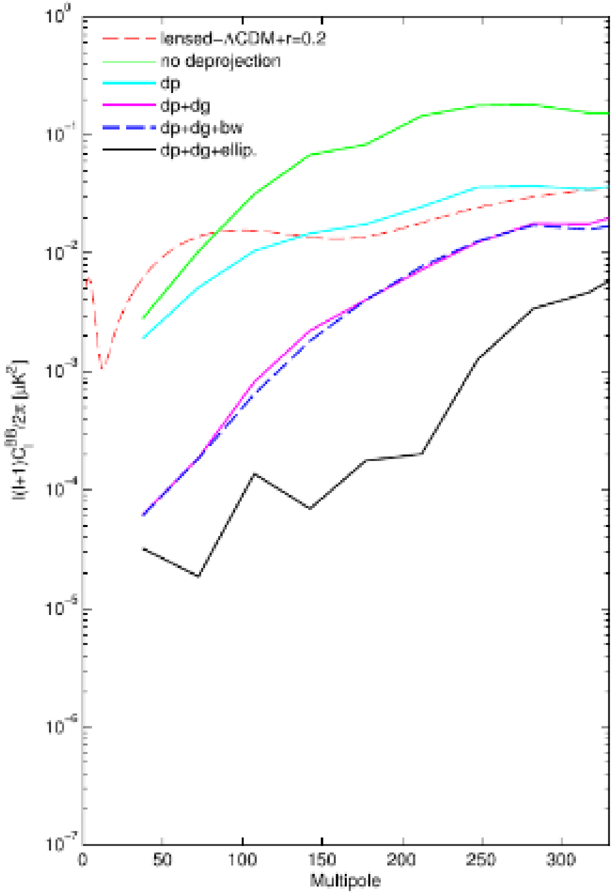


FIG. 8.— Partial view of one BICEP2 dual-polarization pixel, showing the

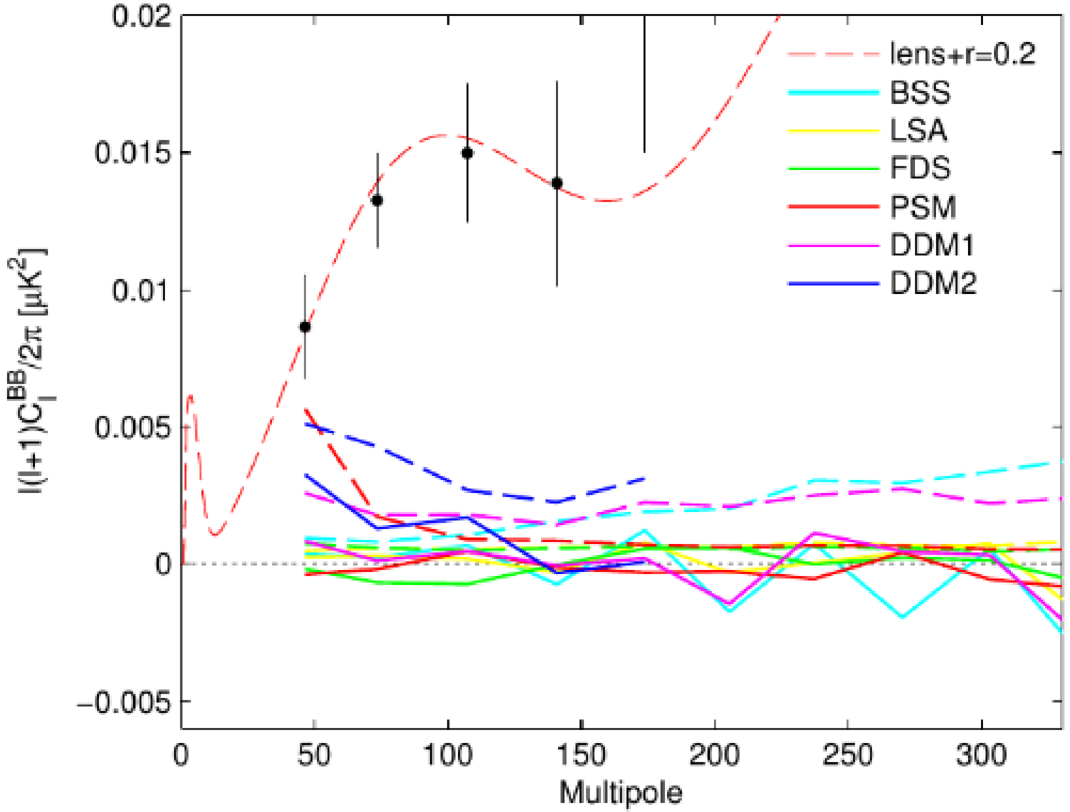
tiles

(4 tiles)x(8x8 pixels)=256 detectors

Other systematic and foregrounds

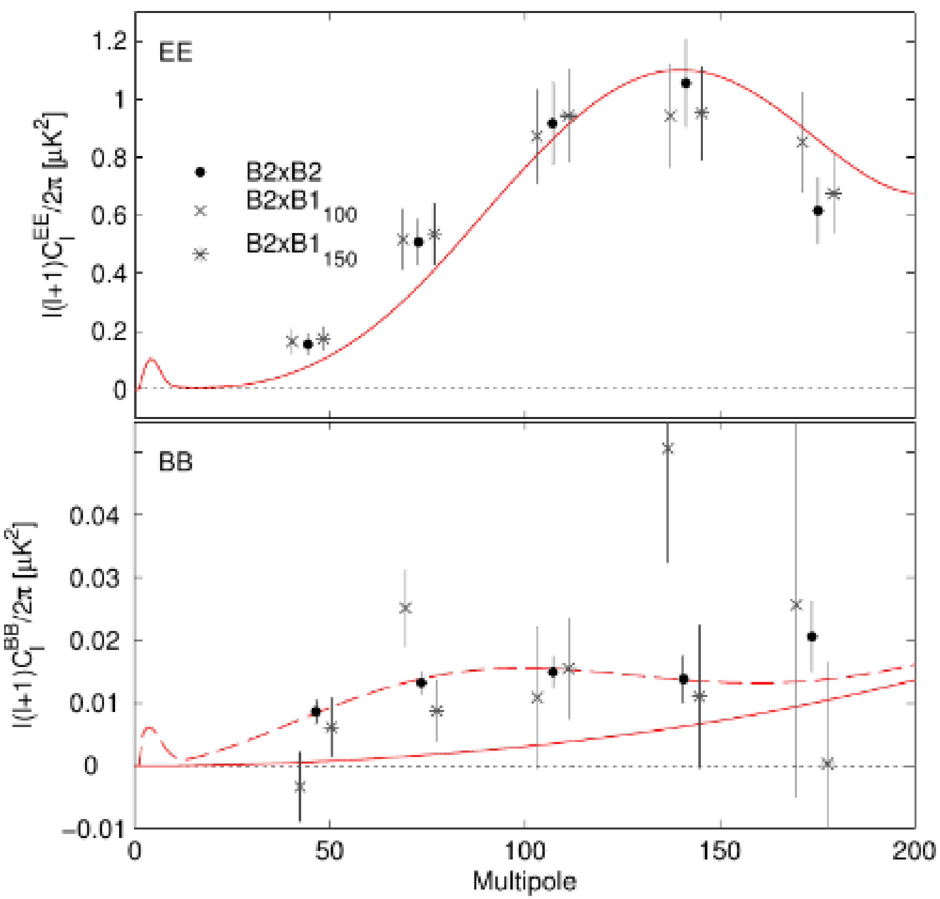


dp .. differential pointing
dg .. differential gain
bw .. differential beam width
ellip .. ellipticity of the beam

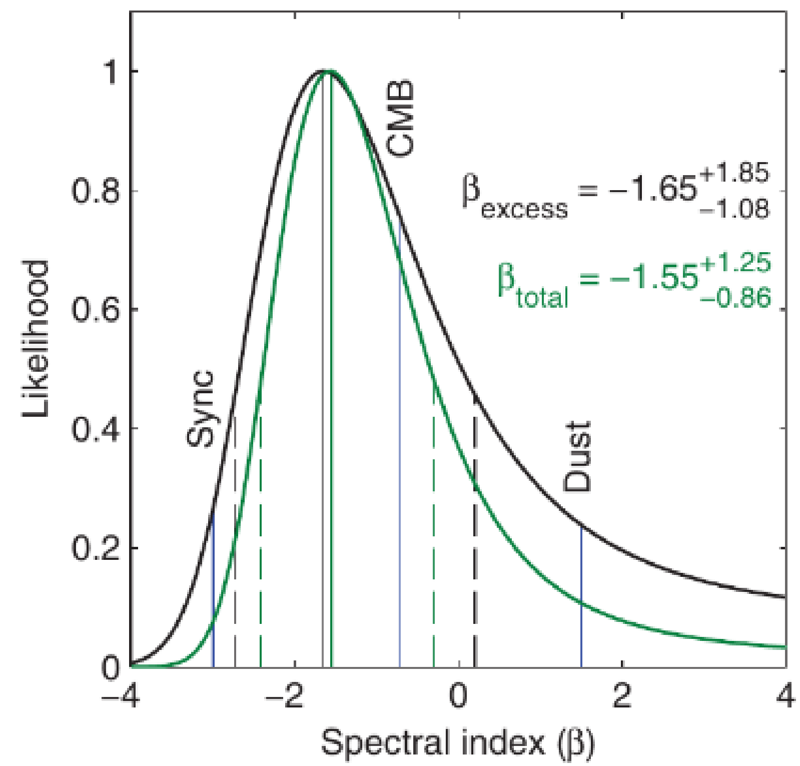


a-correlations (dashed) and x-correlations (solid) for various foreground models

Other systematics and foregrounds



cross correlations with another frequency (old) maps



Frequency scaling consistent with CMB (2.7K blackbody)

X-Correlations with other maps

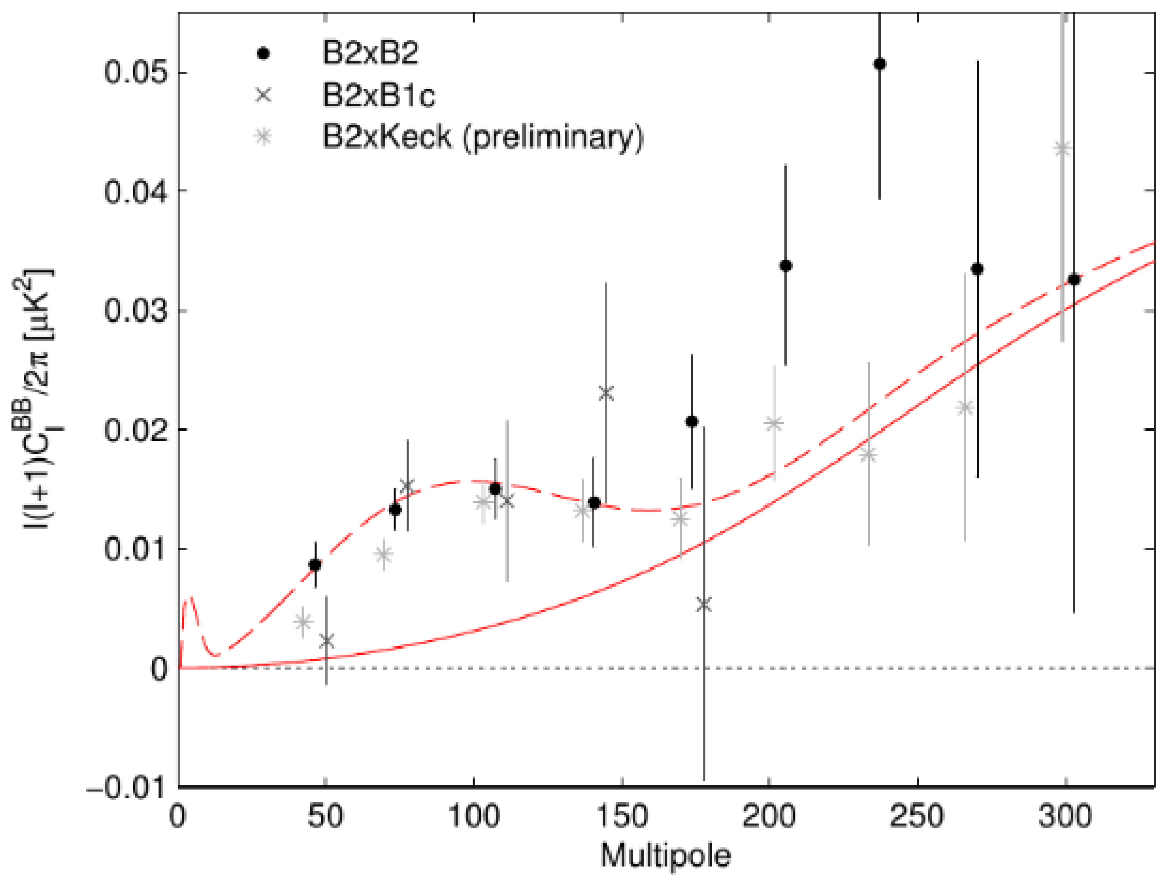
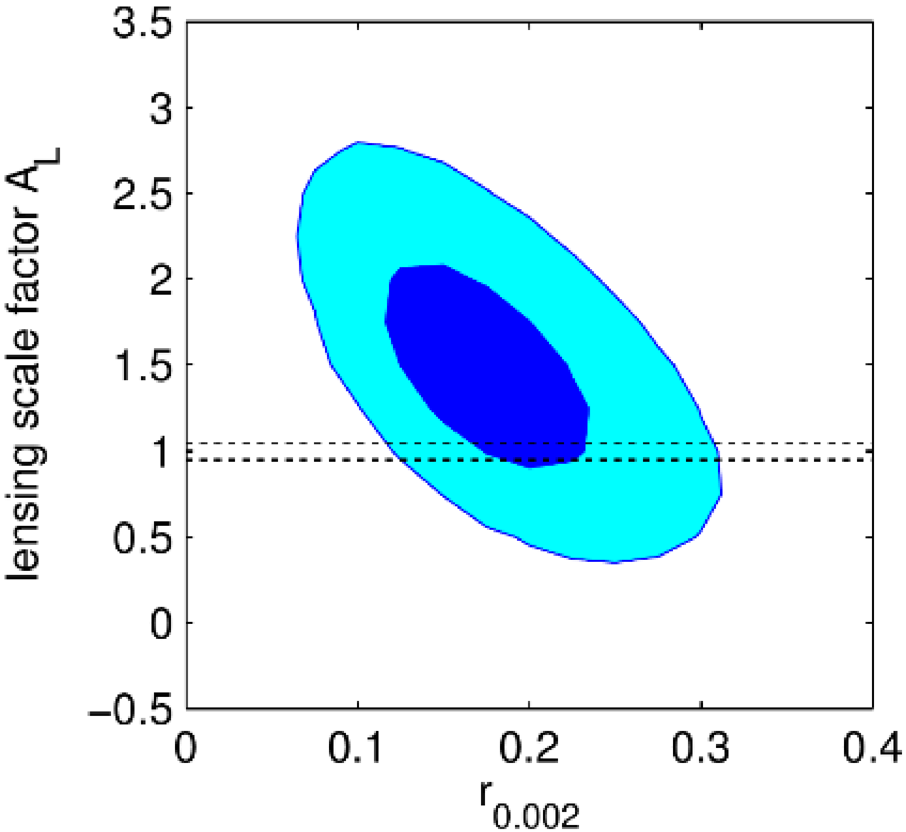


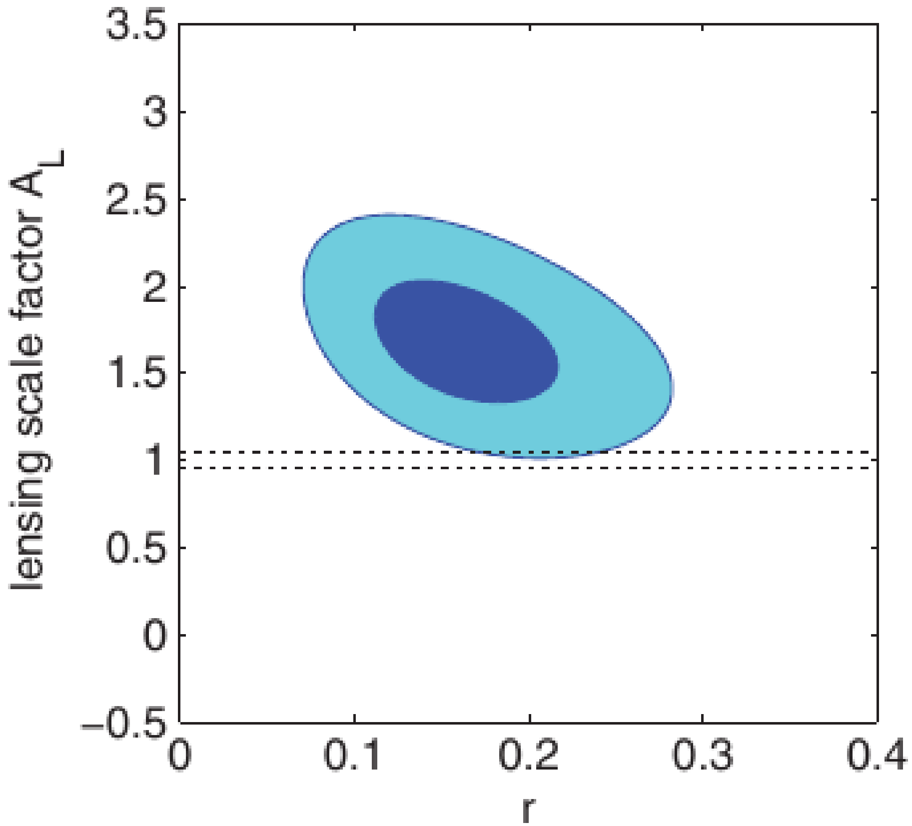
FIG. 9.— Comparison of the BICEP2 *BB* auto spectrum and cross spectra taken between BICEP2 and BICEP1 combined, and BICEP2 and *Keck Array* preliminary. (For clarity the cross spectrum points are offset horizontally and the BICEP2×BICEP1 points are omitted at $\ell > 200$.)

Cosmological interpretations



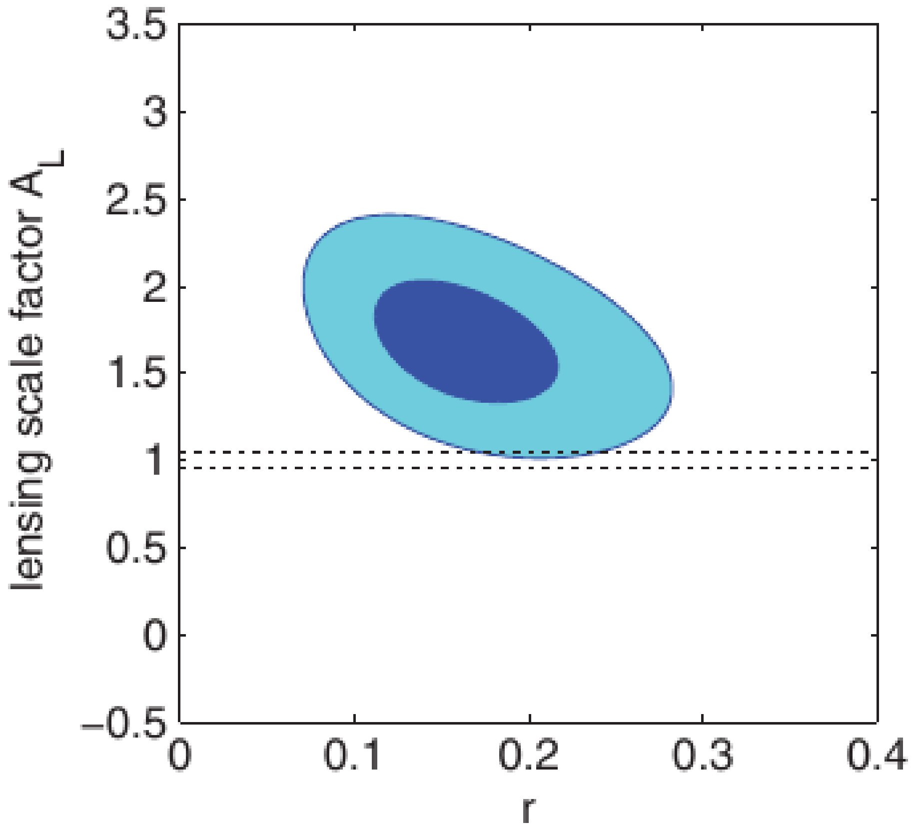
- Constraints using 1-5 bin
- CMB lensing can not explain all the signal

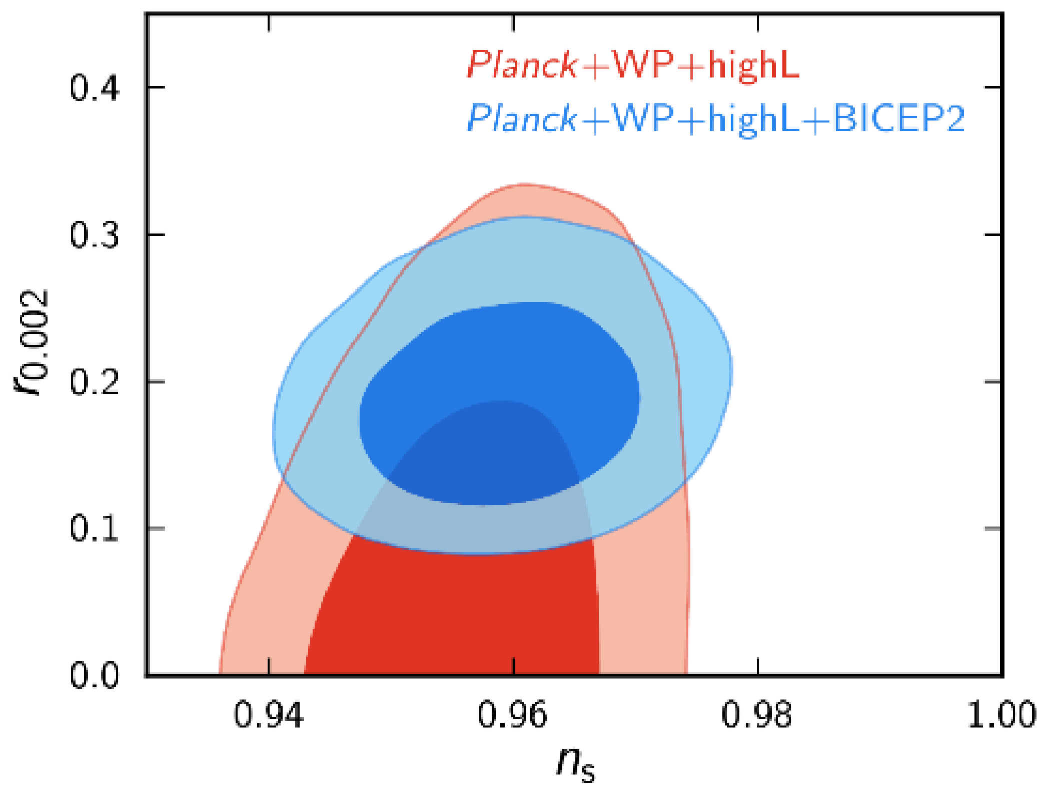
Cosmological interpretations



- Constraints using 1-9 bin
- CMB lensing can not explain all the signal

Cosmological interpretations

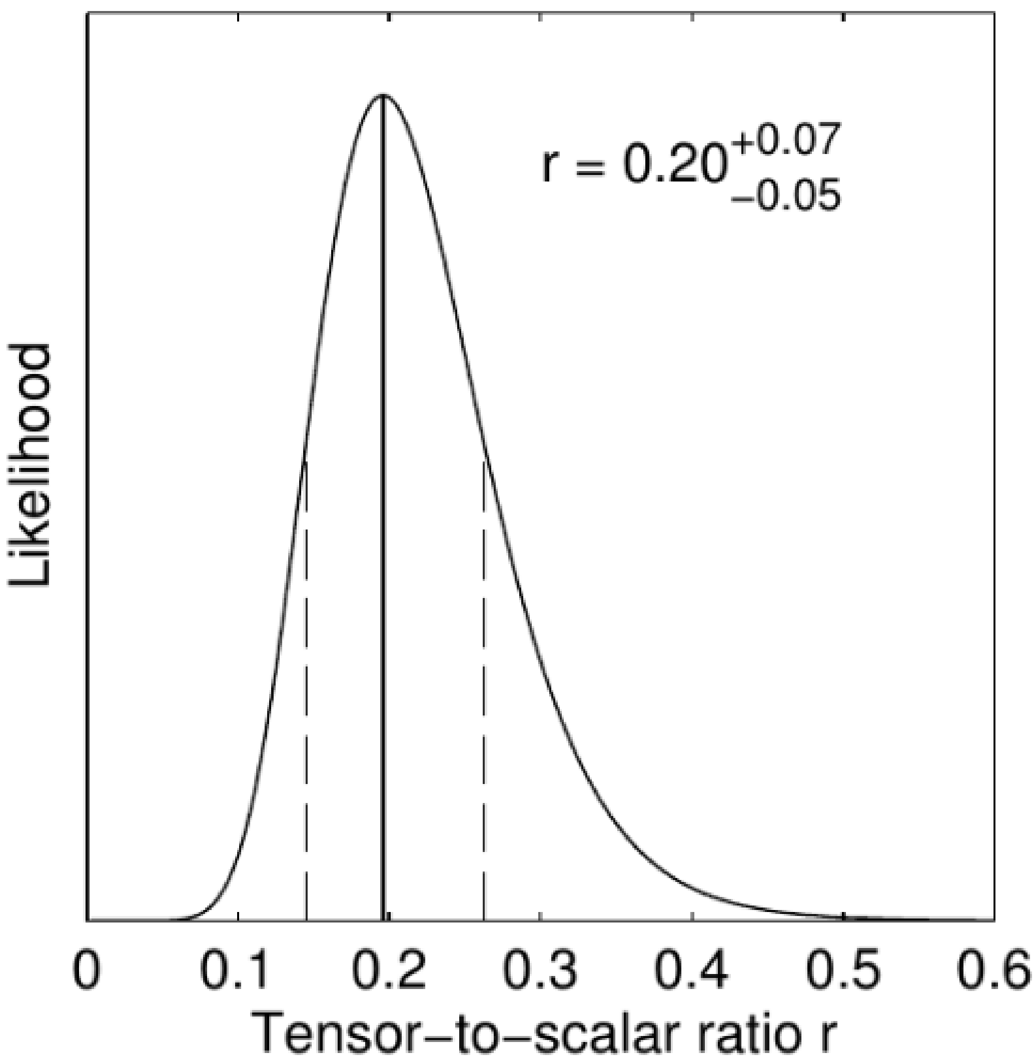


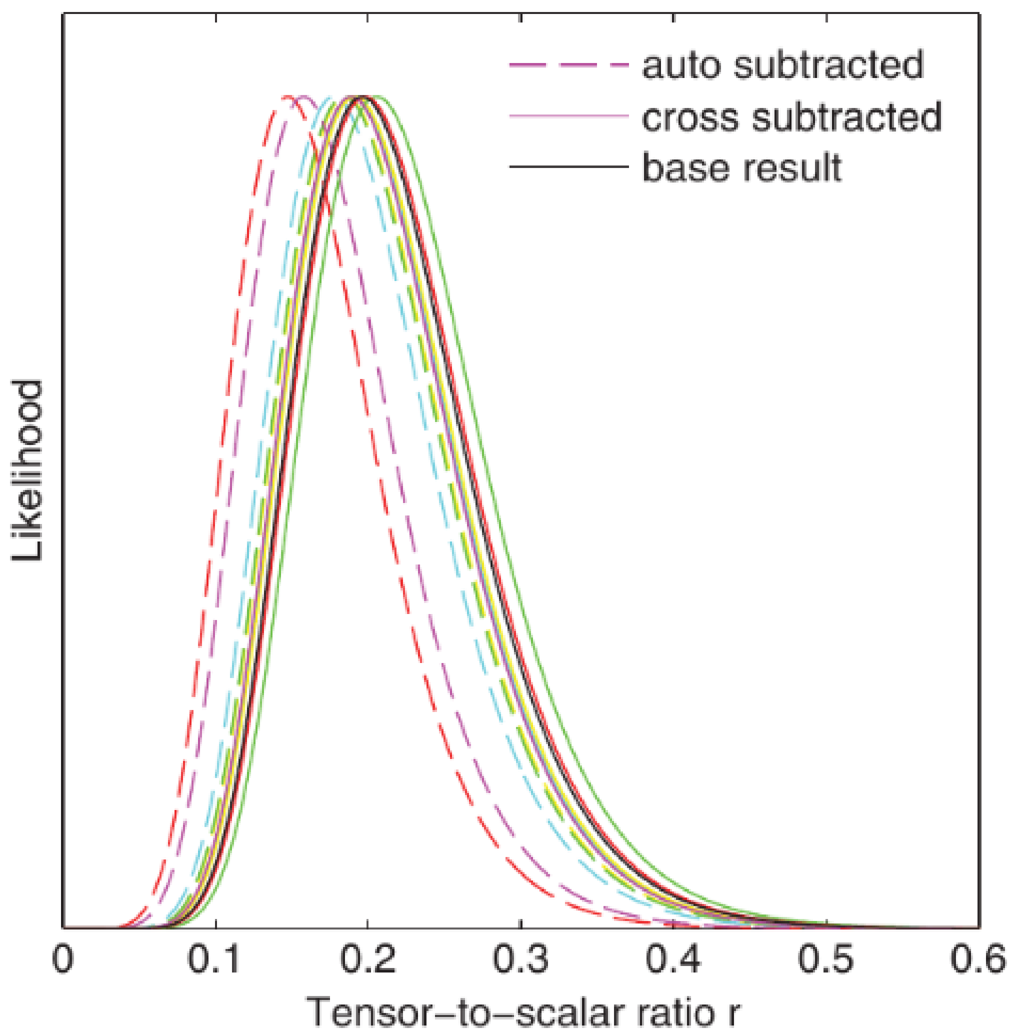


- Constraints using 1-9 bin
- CMB lensing can not explain all the signal

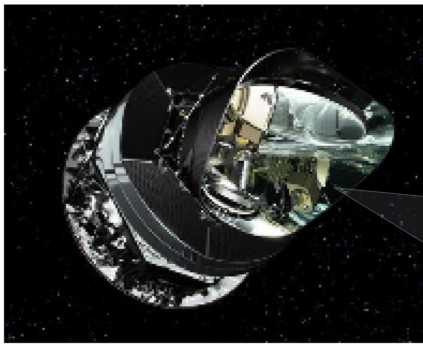
- BICEP2 signal is consistent with Planck temperature anisotropies if spectral running is included.

Likelihood & Foreground subtraction





new tension in cosmology?

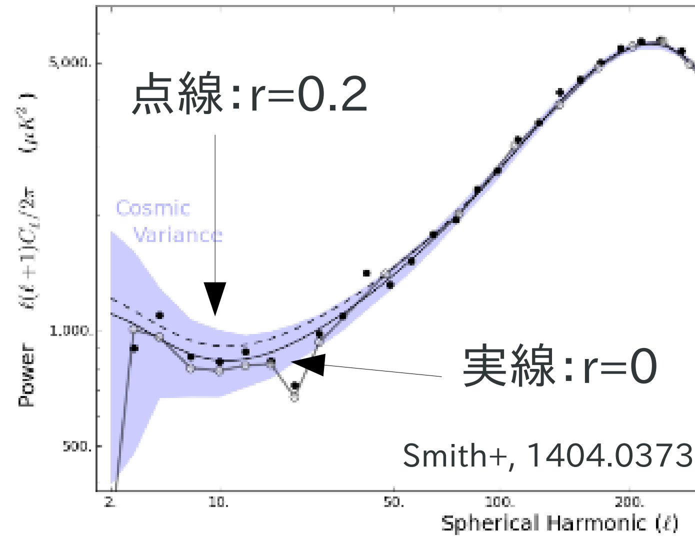


Planck 2013

We can not show pol. data yet, but

$$r \lesssim 0.11 \quad (95\%)$$

if the standard model is assumed, because we do not see fluctuations on large scales.



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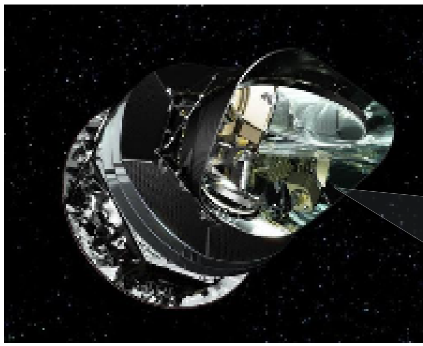

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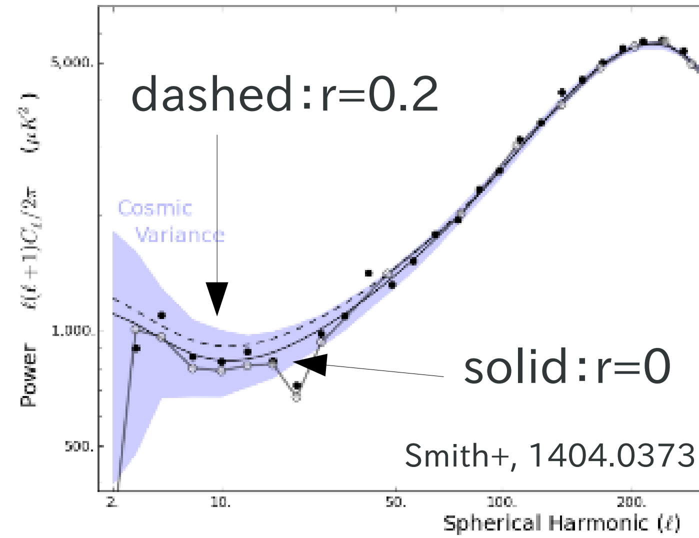


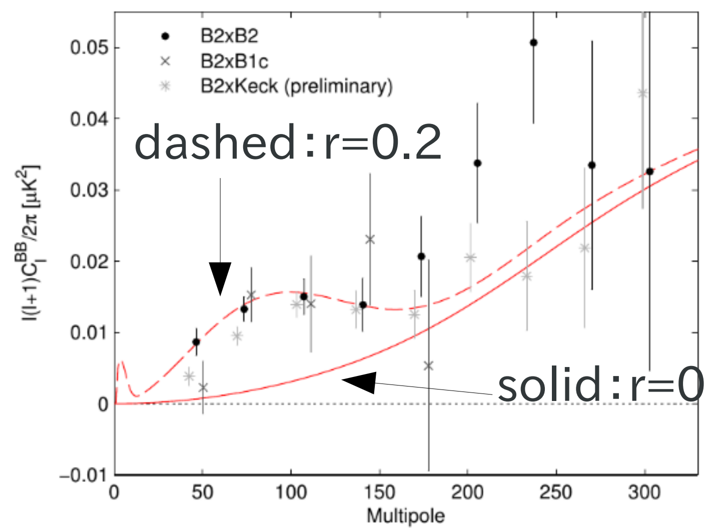
BICEP2 2014

We detect B-mode ! r should be

$$r = 0.2^{+0.07}_{-0.05}$$

The standard model seems slightly inconsistent....

many papers



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Many papers

Zotero - Mozilla Firefox

ファイル(F) 編集(E) 表示(V) 履歴(S) ブックマーク(B) ツール(T) ヘルプ(H)

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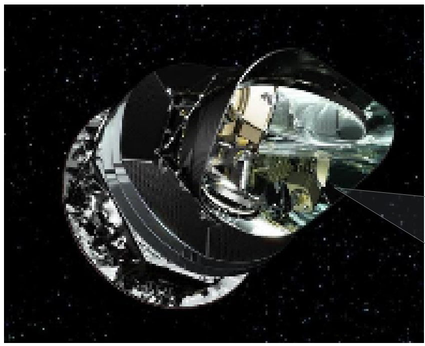
題名	編著者名	日時
Did BICEP2 see vector modes? First B-mode constraints on cosmic defects	Moss と Pogosian	2014/03/24
Compensation for large tensor modes with iso-curvature perturbations in CMB anisotropies	Kawasaki と Yokoyama	2014/03/24
High-Scale SUSY Breaking Models in light of the BICEP2 Result	Harigaya et al.	2014-03-24
Multi-Natural Inflation in Supergravity and BICEP2	Czerny et al.	2014-03-24
The Knotted Sky II: Does BICEP2 require a nontrivial primordial power spectrum?	Abazajian et al.	2014/03/24
Inflation and Alternatives with Blue Tensor Spectra	Wang と Xue	2014/03/23
Self-unitarization of New Higgs Inflation and compatibility with Planck and BICEP2 data	Germani et al.	2014-03-23
Blue Gravity Waves from BICEP2 ?	Gerbino et al.	2014/03/23
Self-complete chaotic inflation	Lee	2014/03/22
The challenge for single field inflation with BICEP2 result	Gong	2014-03-22
Cosmic Birefringence Fluctuations and Cosmic Microwave Background B-mode Polarization	Lee et al.	2014-03-21
Inflationary Magnetogenesis without the Strong Coupling Problem II: Constraints from CMB anisotropi...	Ferreira et al.	2014-03-21
The Imaginary Starobinsky Model	Ferrara et al.	2014-03-21
Reconstructing inflationary potential from BICEP2 and running of tensor modes	Choudhury と Mazumdar	2014-03-21
The Tilt of Primordial Gravitational Waves Spectra from BICEP2	Cheng と Huang	2014-03-21
Steps to Reconcile Inflationary Tensor and Scalar Spectra	Miranda et al.	2014/03/20
The Gravitational Wave Background and Higgs False Vacuum Inflation	Masina	2014-03-20
Polynomial inflation models after BICEP2	Kobayashi と Seto	2014/03/20
Inflation, Symmetry, and B-Modes	Hertzberg	2014/03/20
Higgs inflation still alive	Hamada et al.	2014/03/20
Non-trivial running of the primordial tensor spectrum	Gong	2014/03/20
Natural Inflation: Consistency with Cosmic Microwave Background Observations of Planck and BICEP2	Freese と Kinney	2014-03-20
Killing the Straw Man: Does BICEP Prove Inflation?	Dent et al.	2014/03/20
Excursion into Quantum Gravity via Inflation	Calmet と Sanz	2014/03/20
Inflationary Tensor Perturbations After BICEP	Caligiuri と Kosowsky	2014-03-20
Can topological defects mimic the BICEP2 B-mode signal?	Lizarraga et al.	2014/03/19
Remarks about the Tensor Mode Detection by the BICEP2 Collaboration and the Super-Planckian Excu...	Kehagias と Riotto	2014/03/19
Discovery of Large Scale Tensor Mode and Chaotic Inflation in Supergravity	Harigaya と Yanagida	2014/03/19
Relic Neutrinos, thermal axions and cosmology in early 2014	Giusarma et al.	2014/03/19
Is Higgs Inflation Dead?	Cook et al.	2014/03/19
Local Reconstruction of the Inflationary Potential with BICEP2 data	Ma と Wang	2014/03/18
Running Spectral Index from Large-field Inflation with Modulations Revisited	Czerny et al.	2014/03/18
Suppressing the impact of a high tensor-to-scalar ratio on the temperature anisotropies	Contaldi et al.	2014/03/18
Do Mixed States save Effective Field Theory from BICEP?	Collins et al.	2014/03/18
Comprehensive analysis of the simplest curvaton model	Byrnes et al.	2014/03/18
S-dual inflation: BICEP2 data without unlikeliness	Anchordoqui et al.	2014/03/18
Higgs Chaotic Inflation and the Primordial B-mode Polarization Discovered by BICEP2	Nakayama と Takahashi	2014/03/17
BICEP2 I: Detection Of B-mode Polarization at Degree Angular Scales	Collaboration et al.	2014/03/17

ADS 2014/08/01

new tension in cosmology?



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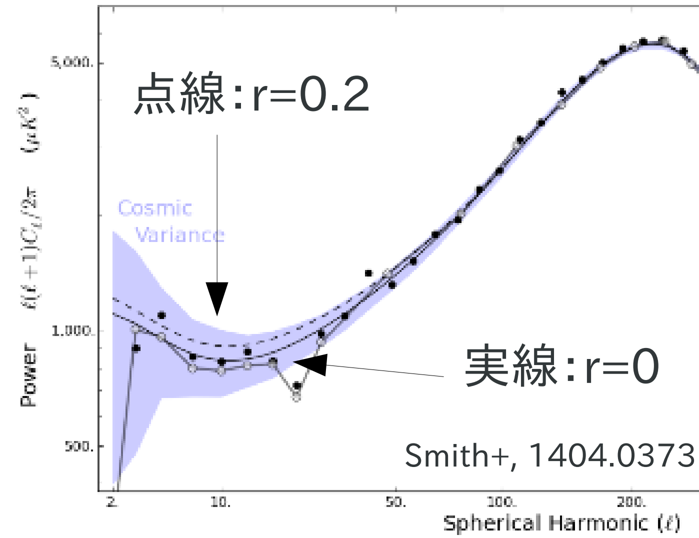

BICEP2 2014

We detect B-mode ! r should be

$$r = 0.2^{+0.07}_{-0.05}$$

The standard model seems slightly inconsistent....

many papers

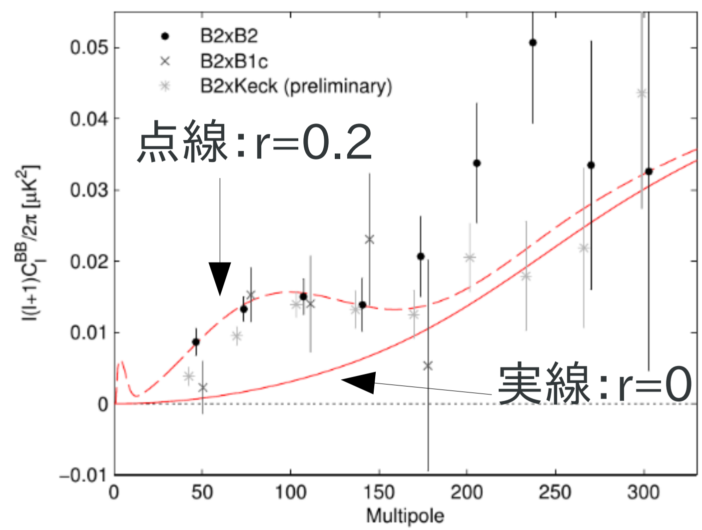

FIG. 9.— Comparison of the BICEP2 *BB* auto spectrum and cross spectra taken between BICEP2 and BICEP1 combined, and BICEP2 and *Keck Array* preliminary. (For clarity the cross spectrum points are offset horizontally and the BICEP2×BICEP1 points are omitted at $\ell > 200$.)

Many ideas

- Running spectral index (BICEP2+)
- Massive neutrinos (Dvorkin+, Zhang+)
- Correlated iso-curvature (Kawasaki+)
- Blue gravitational waves (Gerbino+)
- Modified P(k) (Hazra+,Abazajian+)
- Correlated Scalar&Tensor(Contaldi+,Zibin+,Emami+)
- Vector modes (Saga,Shiraishi,KI; see Saga-kun's poster)
- Foreground (Liu+, Mortonson+, Flauger+)
- Delayed scaling string (Kamada+)
- ...

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one possibility – massive neutrino

GWs generates temperature fluctuations on large scales（but they are not observed）

Consider bluer initial power spectrum to suppress fluctuations on large scales,
and a neutrino species to compensate the power on small scales Dvorkin+,1403.8049

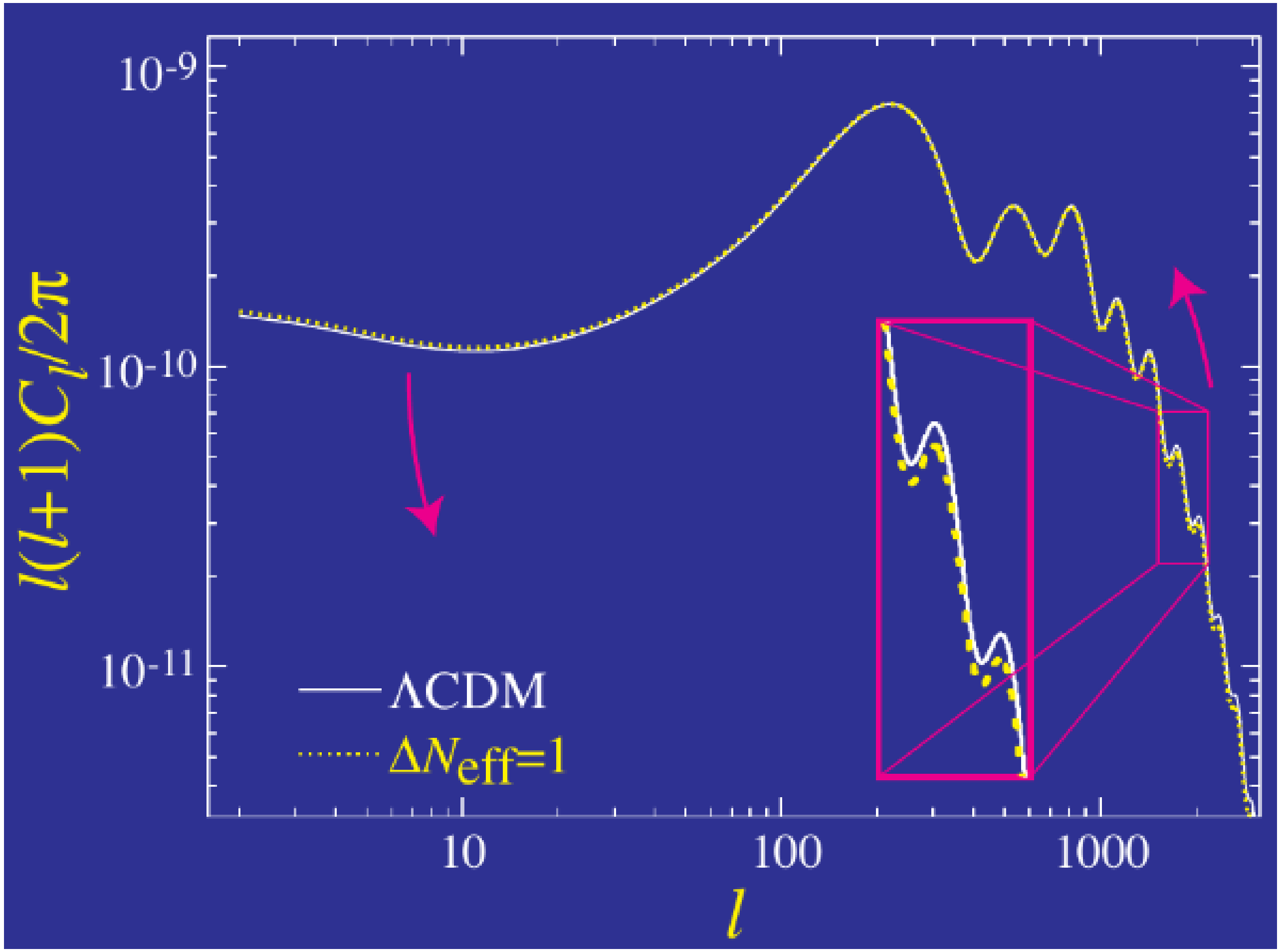


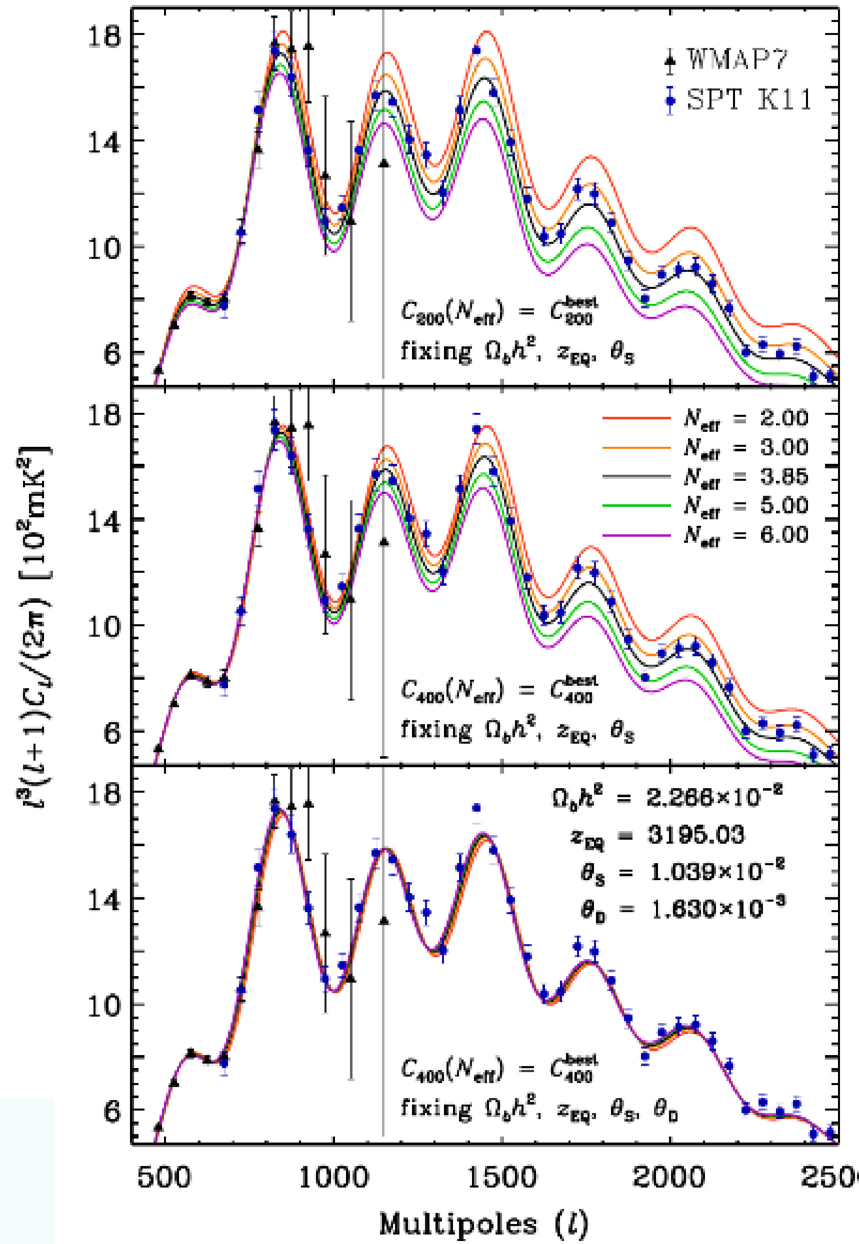
Figure by W. Hu

Why neutrinos?

- acoustic scale
  - $\theta_{\rm s} \propto c_s t \propto 1/H$
- diffusion scale
  - $\theta_{\rm diff} \propto l_{\rm mfp}\sqrt{N_{\rm scat}}$
    $\propto 1/\sqrt{H}$
- Hubble parameter
  - $H = (\rho_\gamma + \rho_m + \rho_\nu)^{1/2}$

CMB M-R Equality

Adding neutrinos makes the diffusion scale closer to the acoustic scale



Hou et al., arxiv:1104.2333

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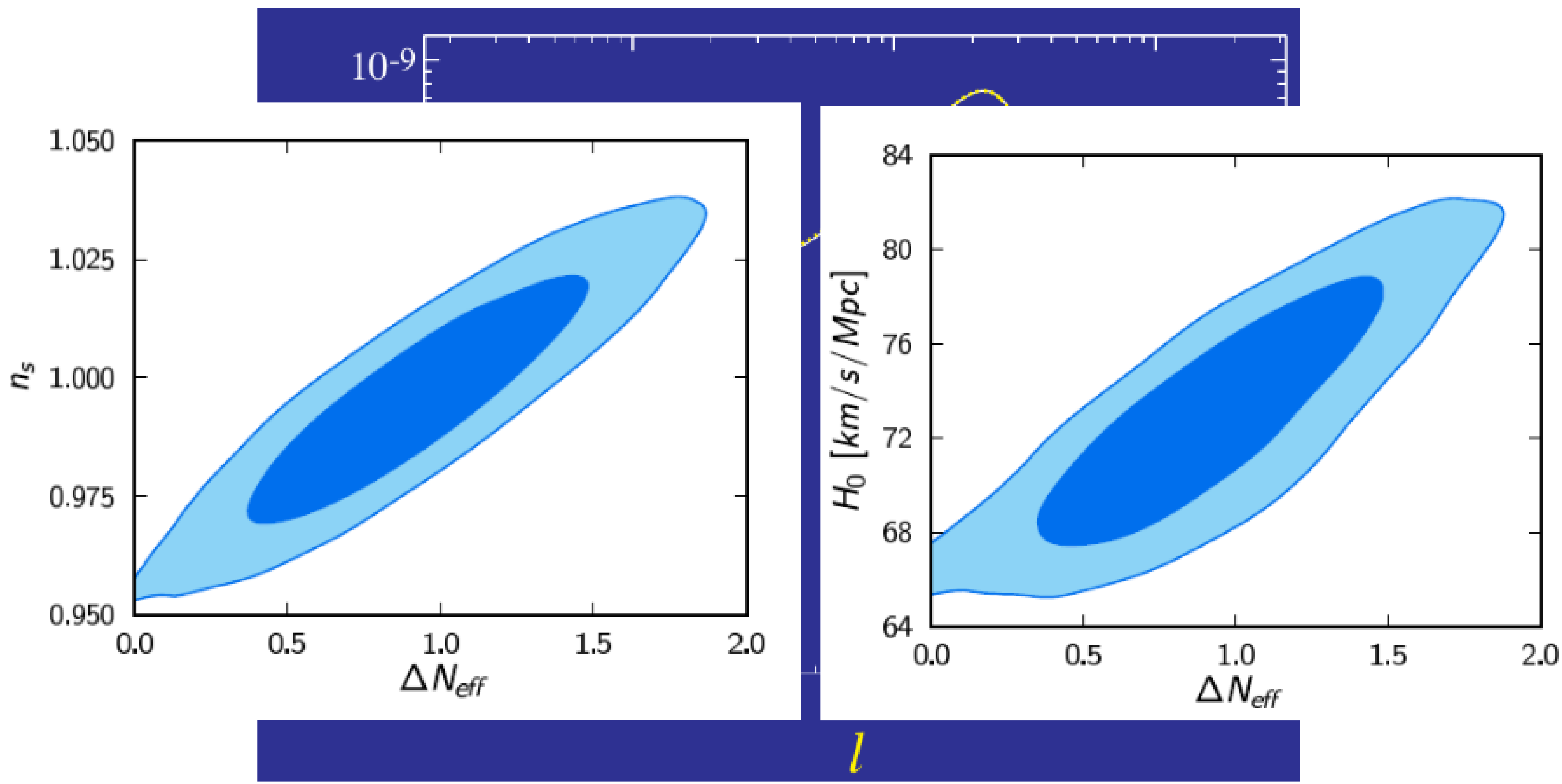


Figure by W. Hu

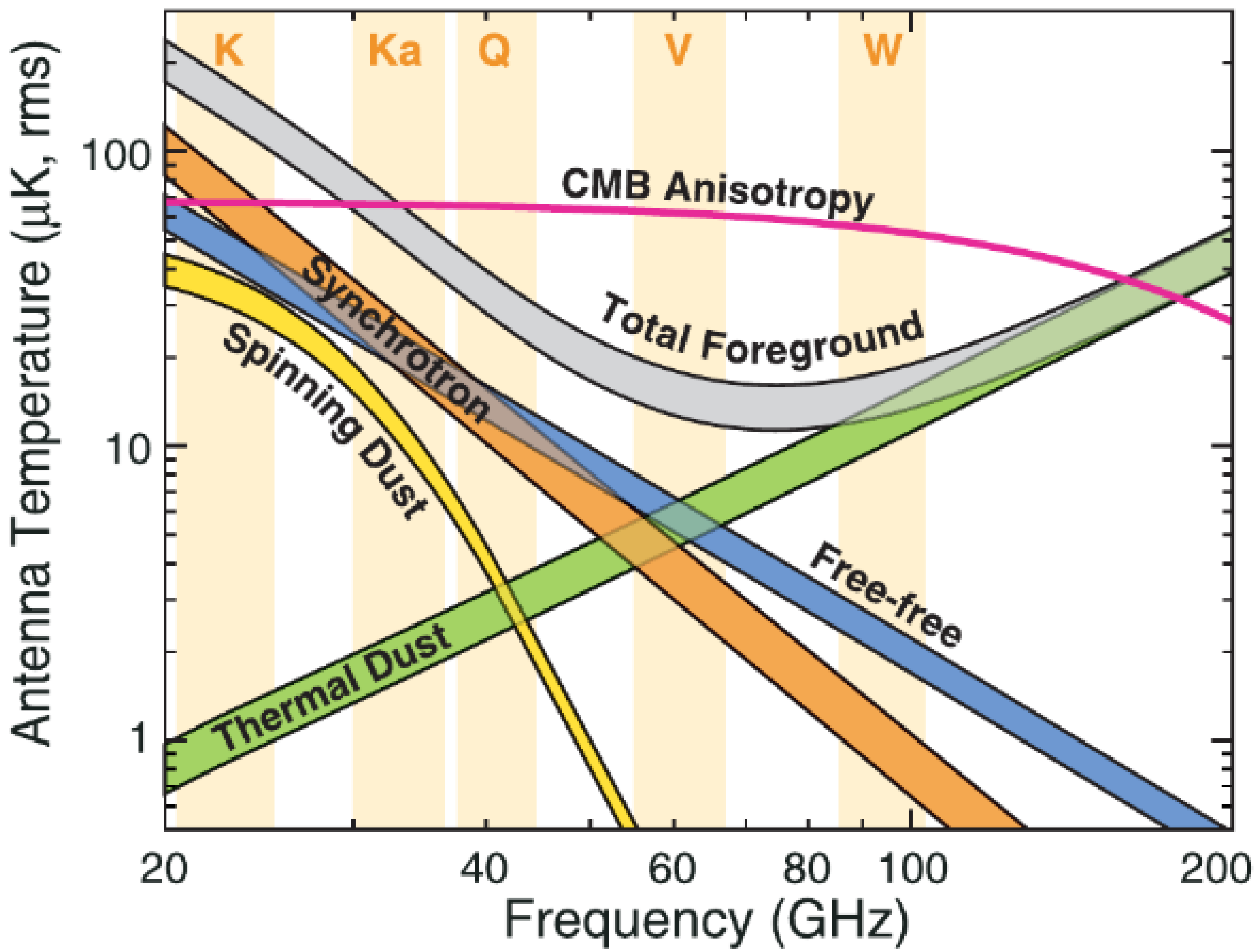
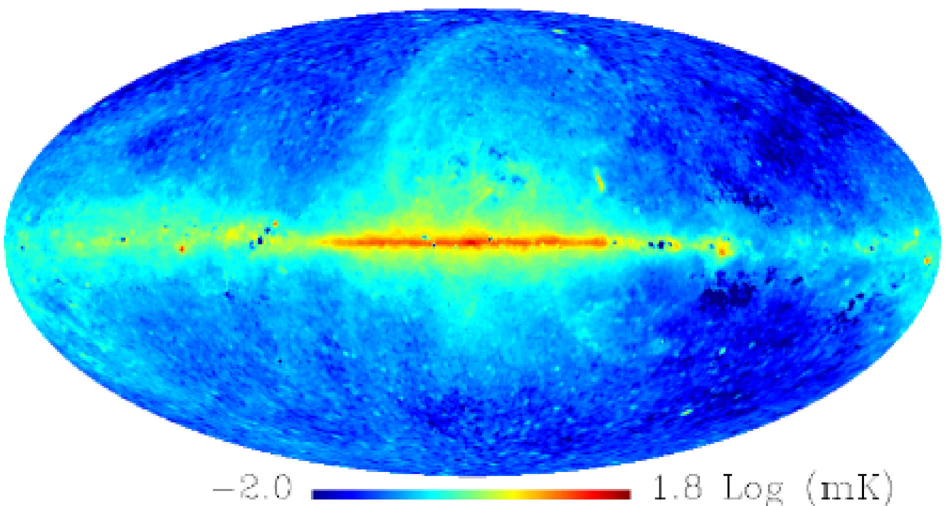


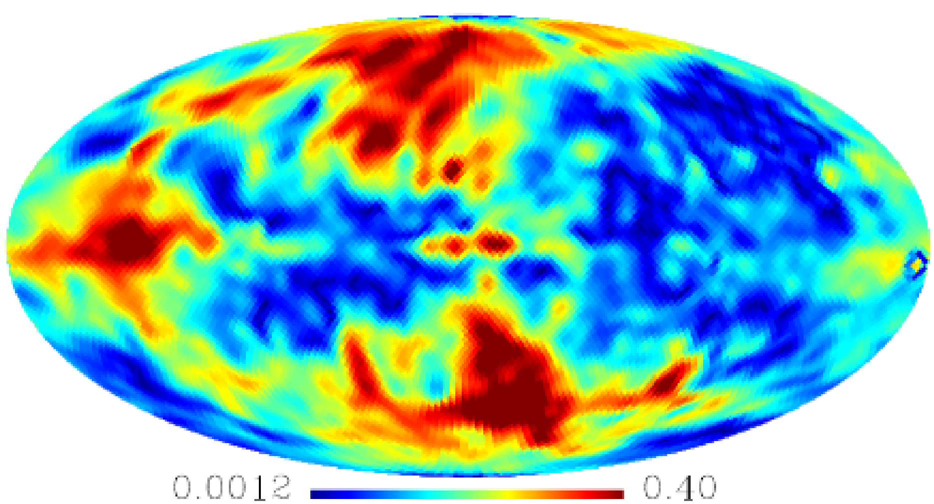
Fig. 1: The root-mean-square intensity of each foreground outside the KQ85 mask (upper curve) and the KQ75 mask (lower curve). Taken from Fig. 22 in [5]. Credit: C.L. Bennett et al., "Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Final Maps and Results", ApJS, Vol. 208, Issue 2, id. 20, 54 pp. (2013) © AAS. Reproduced with permission.

For a concise review, see K. Ichiki, PTEP, 2014

Synchrotron



intensity



(b) Polarization degree

Interaction between magnetic field and cosmic-rays

Polarized perpendicular to the projected field lines

$$T_{\mathrm{sync}} \propto \nu^{\beta}$$

radio $\beta \approx -2.5$

microwave $\beta \approx -3.0 \pm 0.2$

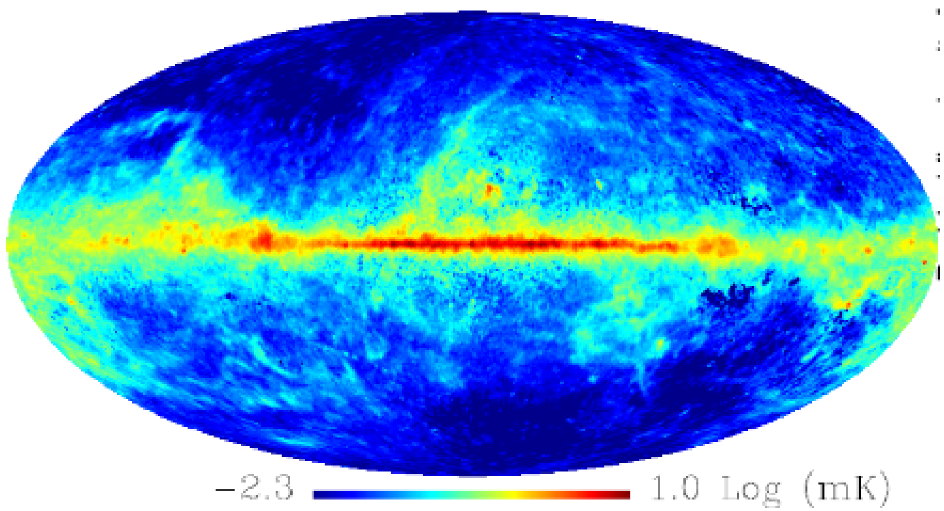
$$\Pi \sim 14\%$$

(Kogut et al., ApJ665, '07)

Synchrotron @ 23 GHz from WMAP 9yr result

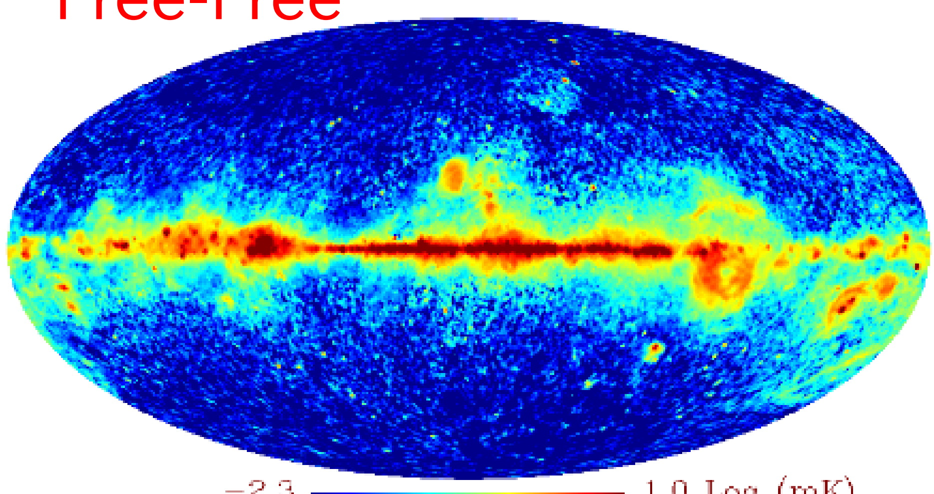
Free-Free & Spinning dust

Spinning dust



(a) estimate map for spinning dust at WMAP K band

Free-Free



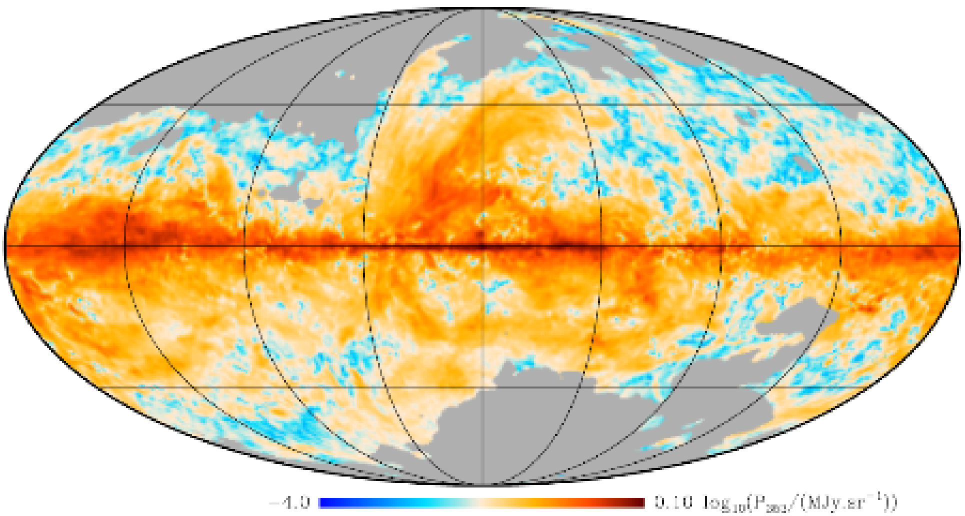
$\beta \approx -2.5$ around 20-30 GHz
falls rapidly above 60 GHz
(Macellari et al.,, MNRAS, 2011)

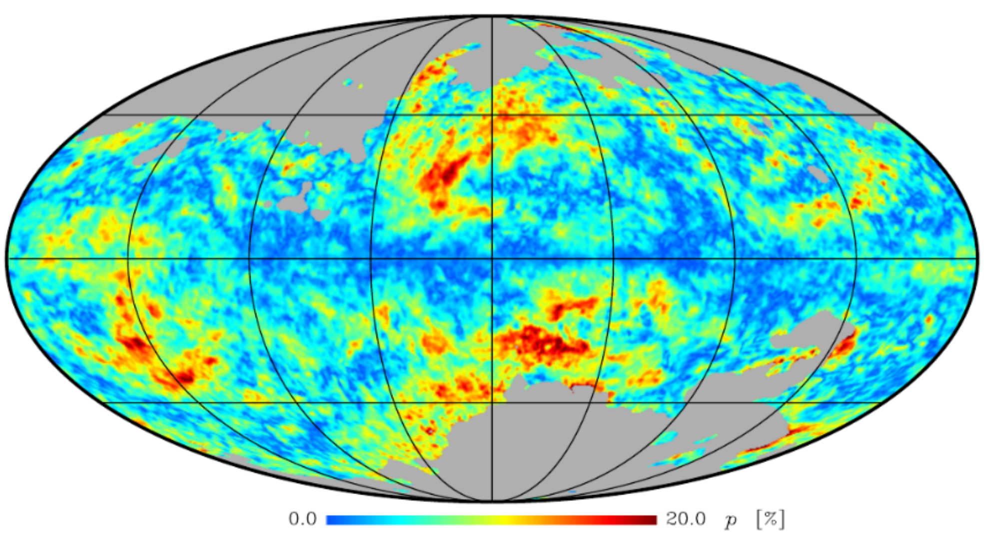
Unpolarized, less than 0.5% for $\gtrsim 30$ GHz
(Lazarian&Draine, ApJ, 2000)

Power law with $\beta \approx -2.1$
(Bennet et al.,, ApJS, 2011)

Unpolarized, with an upper limit $\lesssim 3.4\%$
(Macellari et al.,, MNRAS, 2011)

thermal dust (news from Planck)





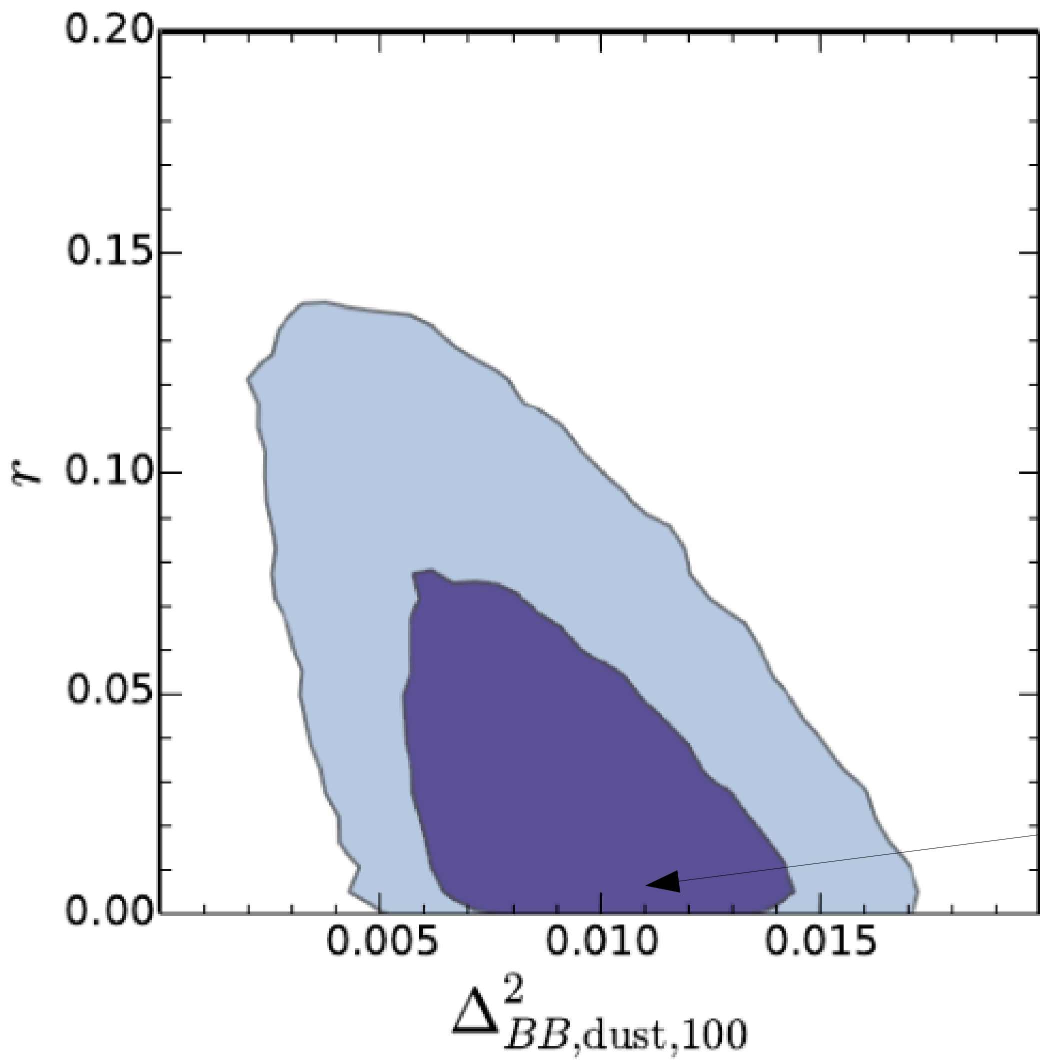
(Planck collaboration, arxiv:1405.0871)

- Polarized perpendicular to the projected field lines
- Possible correlation with synchrotron (Page et al., ApJS, '07)
- Polarization deg. as high as $\sim 20\ \%$

WMAP: $3.6 \pm 1.1\%$ (outside p06 mask)
(Kogut et al., ApJ, '07)

Archeops : $4–5\ \%$
(Benoit et al., A&A, '04)

Dust contrib. to the BICEP2 field



The dust power spectrum is used and fitted to the data:

$$\frac{\ell^2 C_\ell^{\mathrm{BB}}}{2\pi} = \Delta^2_{\mathrm{BB,dust}} \left(\frac{\ell}{100}\right)^{-0.3}$$

(2013 ESLAB conference)

The dust spectrum is totally consistent with the BICEP2 observation

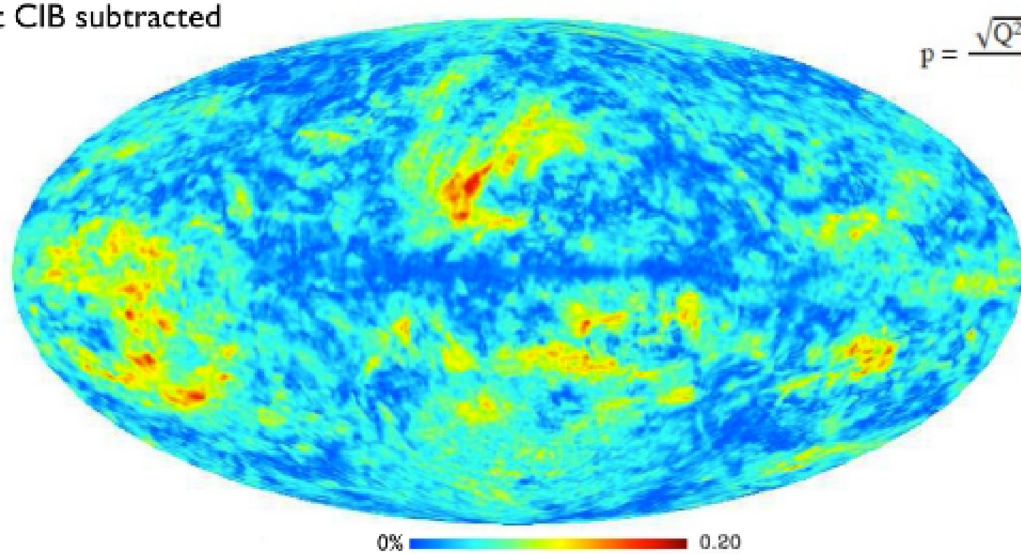
(Mortonson&Seljek arxiv:1405.5857)

Dust contrib. to the BICEP2 field

Apparent polarization fraction (p) at 353 GHz, 1° resolution

Not CIB subtracted

$$p = \frac{\sqrt{Q^2 + U^2}}{I}$$



p ranges from 0 to ~20%

Low p values in inner MW plane. Consistent with unpolarized CIB

Large p values in outer plane and intermediate latitudes

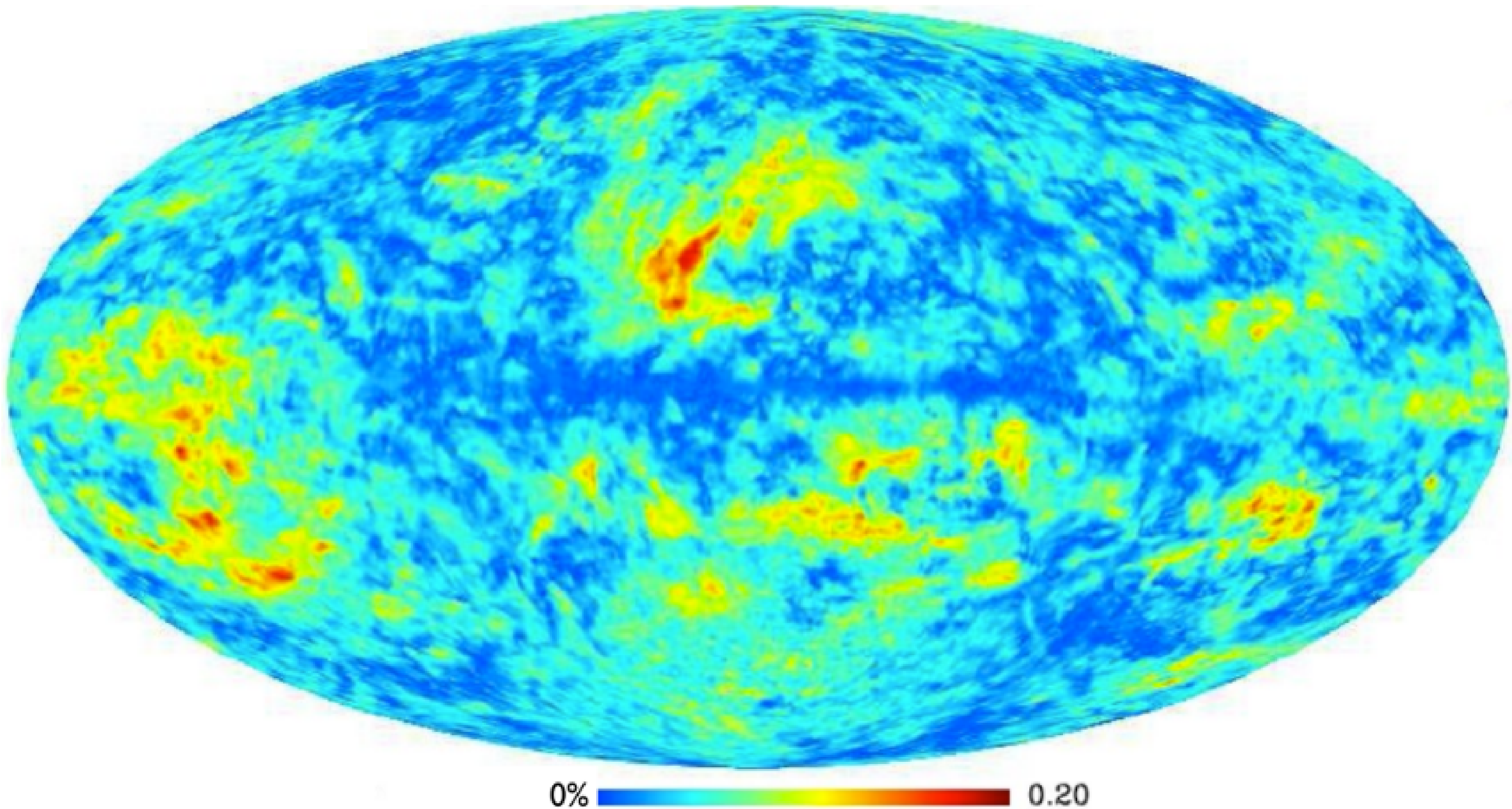
Bernard J.Ph., ESLAB 2013 6

$$\begin{aligned} p_{\rm Gal-B2} &= \frac{\sqrt{Q_{353}^2 + U_{353}^2}}{I_{353}} \\ &\approx \frac{\sqrt{Q_{\rm Gal}^2 + U_{\rm Gal}^2}}{I_{\rm Gal} + I_{\rm CIB} + I_{\rm CMB}} \\ &= \frac{I_{\rm Gal}}{I_{\rm Gal} + I_{\rm CIB} + I_{\rm CMB}} p_{\rm Gal-Actual} \, , \end{aligned}$$

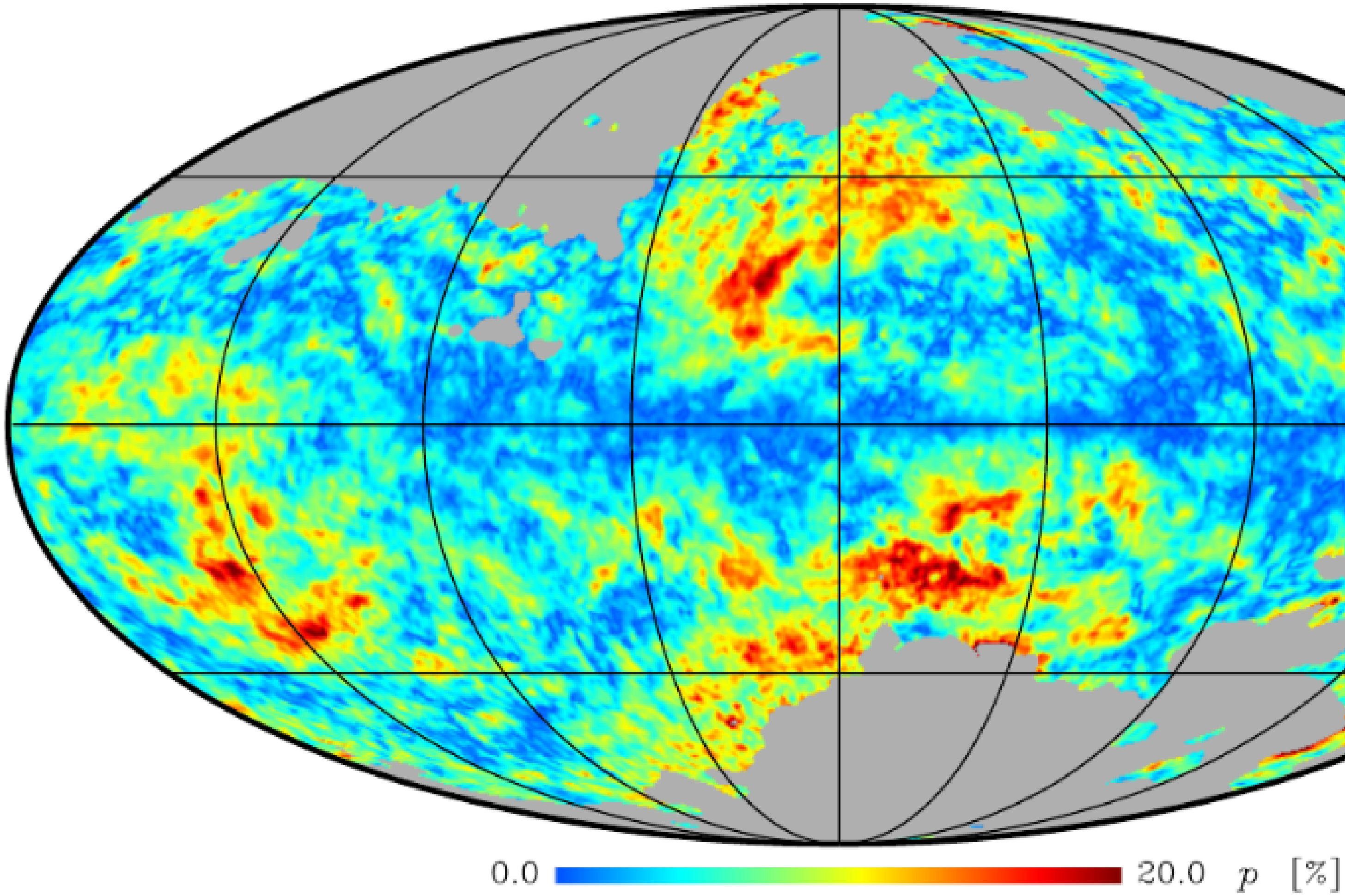
BICEP2 underestimated by this factor

Claim 1 --- DDM model in the BICEP2 analysis did not take into account the CIB (and CMB). (Flauger et al., arxiv:1405.7351)

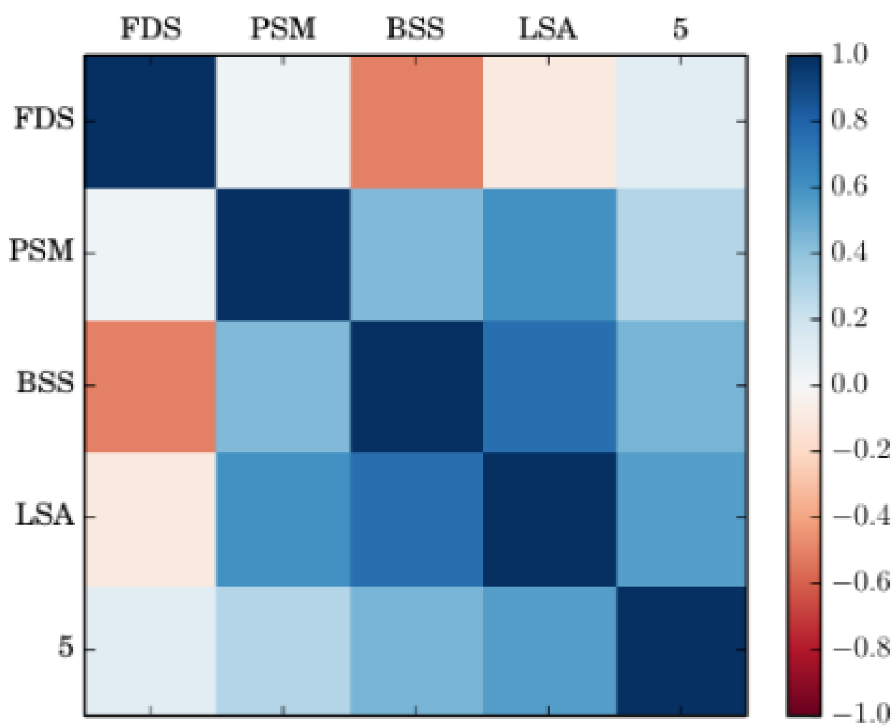
before



after



Dust contrib. to the BICEP2 field



(Flauger et al., arxiv:1405.7351)

Claim 2 --- cross correlation technique in BICEP2 requires:

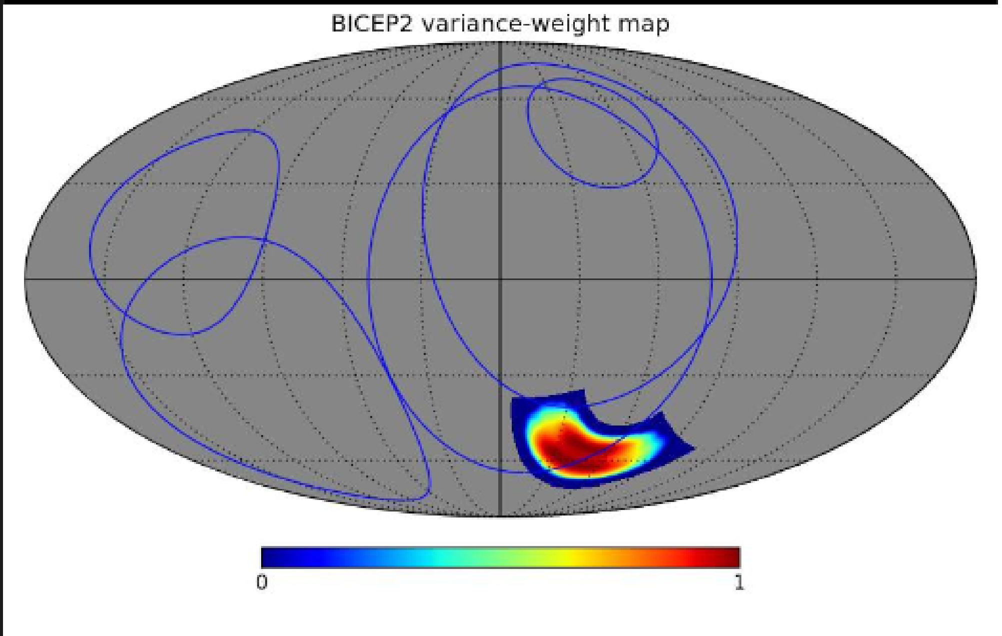
1) little noise in the template
2) accurate spatial structure

They found little correlations between the templates

At least some of the templates lead to the foreground underestimated by a factor of 10

Live Discussion of BICEP Press Conference - Mozilla Firefox

https://www.facebook.com/photo.php?fbid=10152153908664652&set=p.1015



Philipp Mertsch
4月9日

Sorry, just catching up with this now:

Hans Kristian, we have studied the Planck SMICA map, also the map by Starck et al. (arXiv:1401.6016 [astro-ph.CO]), but this part of the analysis didn't make it into the final paper. I'm confident that whoever repeats our analysis with those maps will find largely the same results.

Tom, please note that we did not claim a systematic in the BICEP2 measuremen... もっと見る

いいね!

4人がいいね!と言っています。

Liu et al., '14

Tom Crawford Phillip and Colin - Thanks very much for the clarification; I had not noticed that distinction.

Phillip - I absolutely think it's worth checking, but the way the conclusions were phrased ("Hence the cosmological significance *if any* of the de- tected B-mode signal needs further investigation") went well beyond "hey you should

Beyond linear – CMB lensing

"そんな観測は現時点では夢物語だが、、、
将来的にはこの効果は検出されるだろう"

(Blanchard & Schneider, 1987)

- CMB Lensing timeline
  - Cross correlation between CMB&LSS
    - WMAP+SDSS('07)
  - Smoothing effect on CMB power spectrum
    - ACBAR('08)
  - Lensing Power spectrum reconstruction
    - ACT('11),SPT('12),PLANCK('13)

CMB lensing

- Deflection angle by lenging α

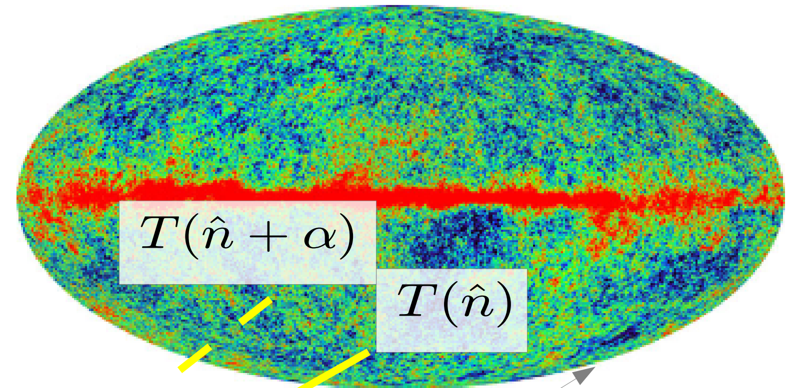
$$\alpha \sim 2\phi \times \sqrt{\frac{14000}{300}} \sim 2'$$

grav. potential   # of scattering

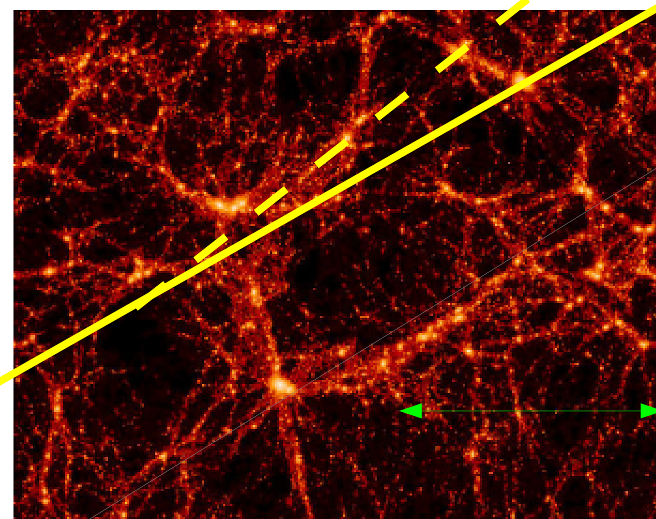
- coherent over

$300/(14000/2) \sim 2^\circ$

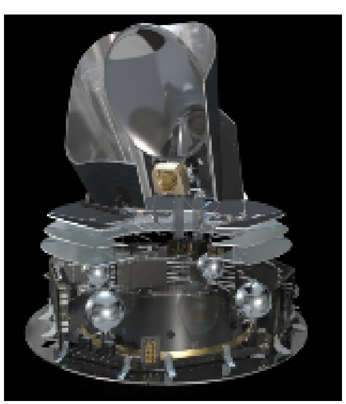
(=CMB peak scale)



Distance to CMB
$\sim 14000\mathrm{Mpc}$



Large scale structure $\sim 300\mathrm{Mpc}$ @z=2
(dark matter)



TO SEE IS TO BELIEVE

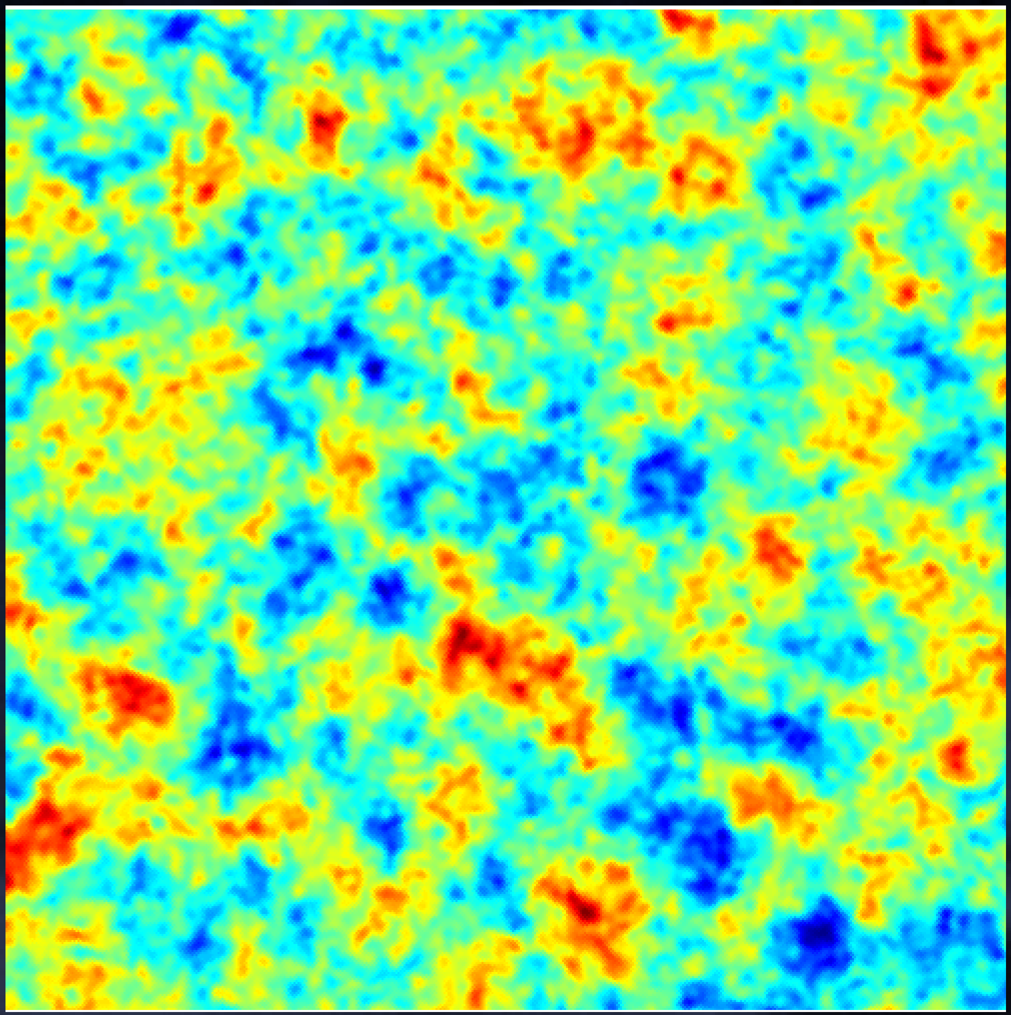
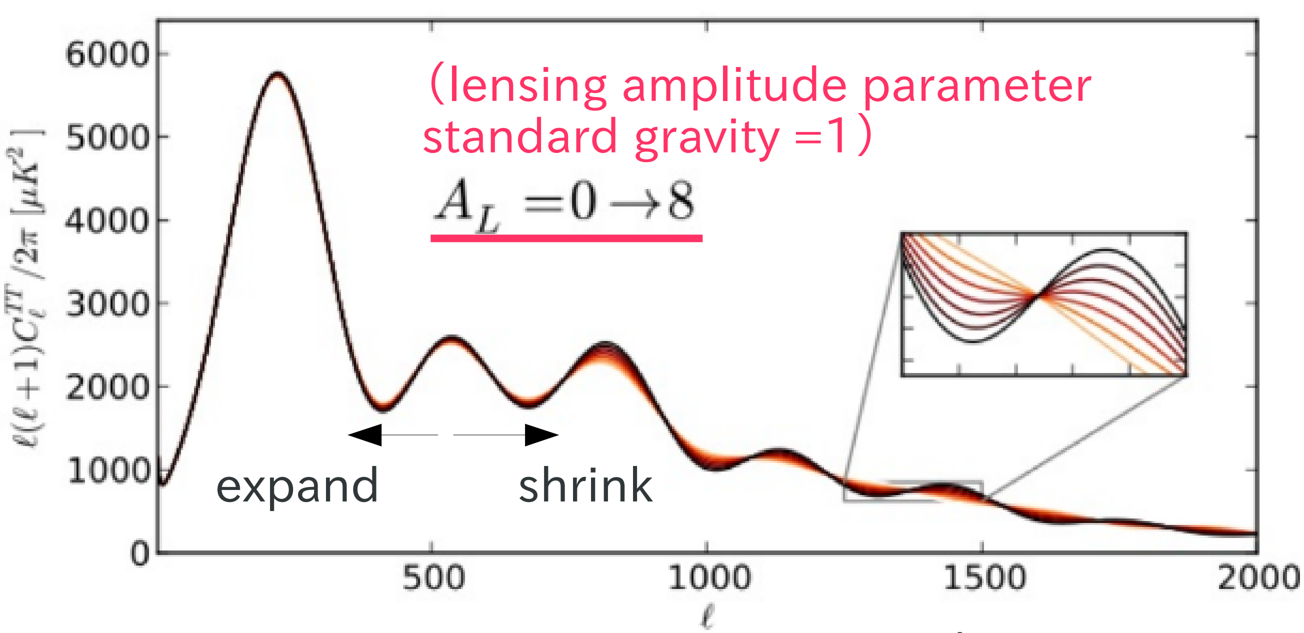
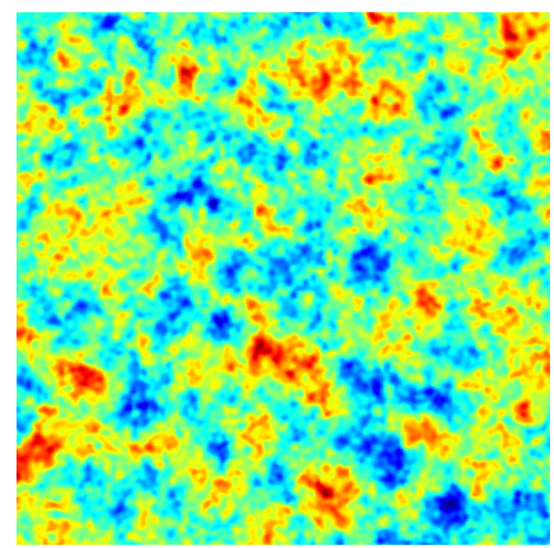


Image credit: erlyuniverse.org

Effects of CMB lensing

- Direction dependent magnification & shear (lens)
  - Smearing the acoustic structure (ACBAR+WMAP5 Reichardt, ApJ '09)
  - E-B mode polarization mixing
- Apparent breakdown of statistical isotropy of the CMB
  - Reconstruction of the lensing potential





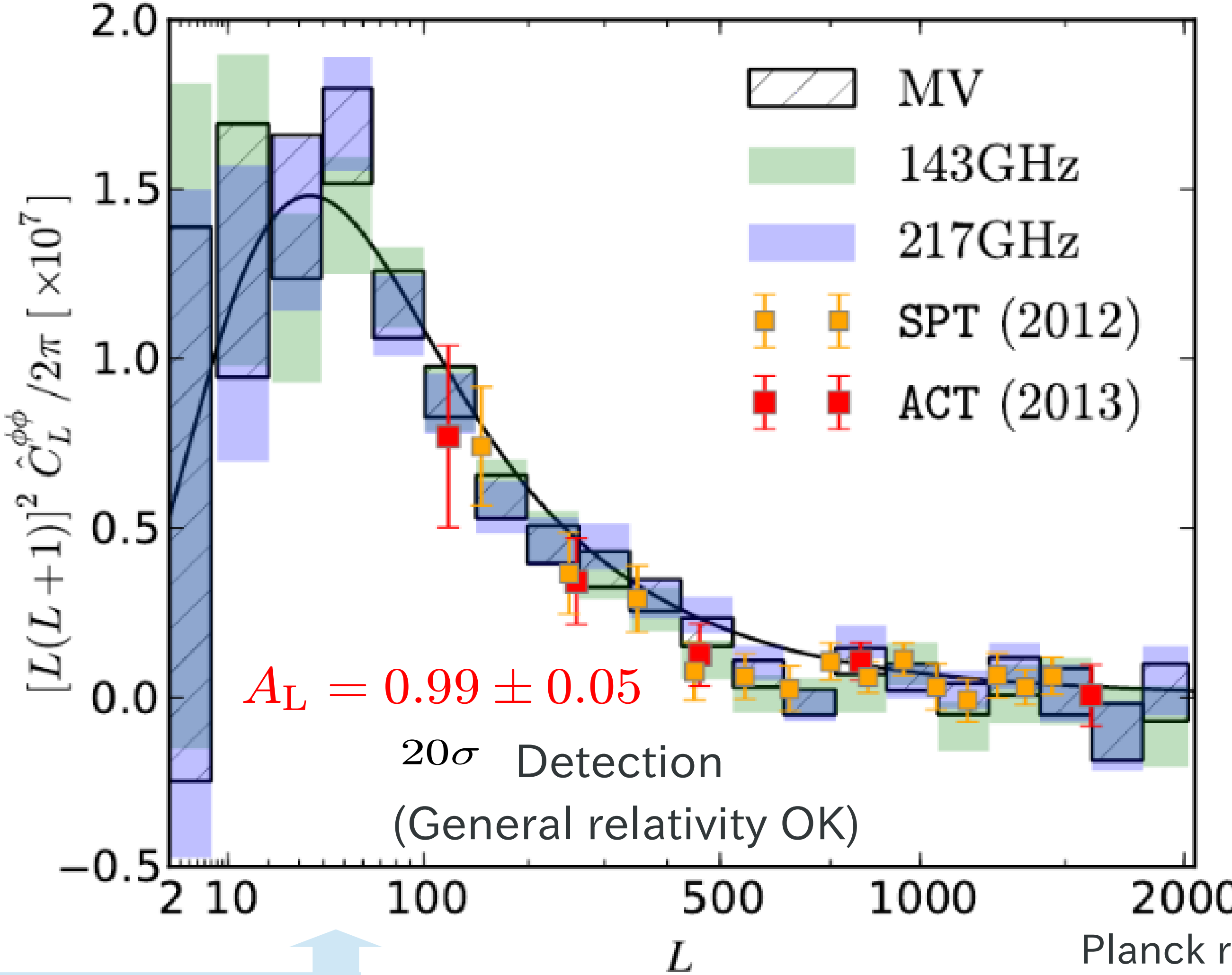
credit:Hanson

PLANCK lensing power spectrum

※info of CDM at z〜2

※deflection angle 〜2 arcmin

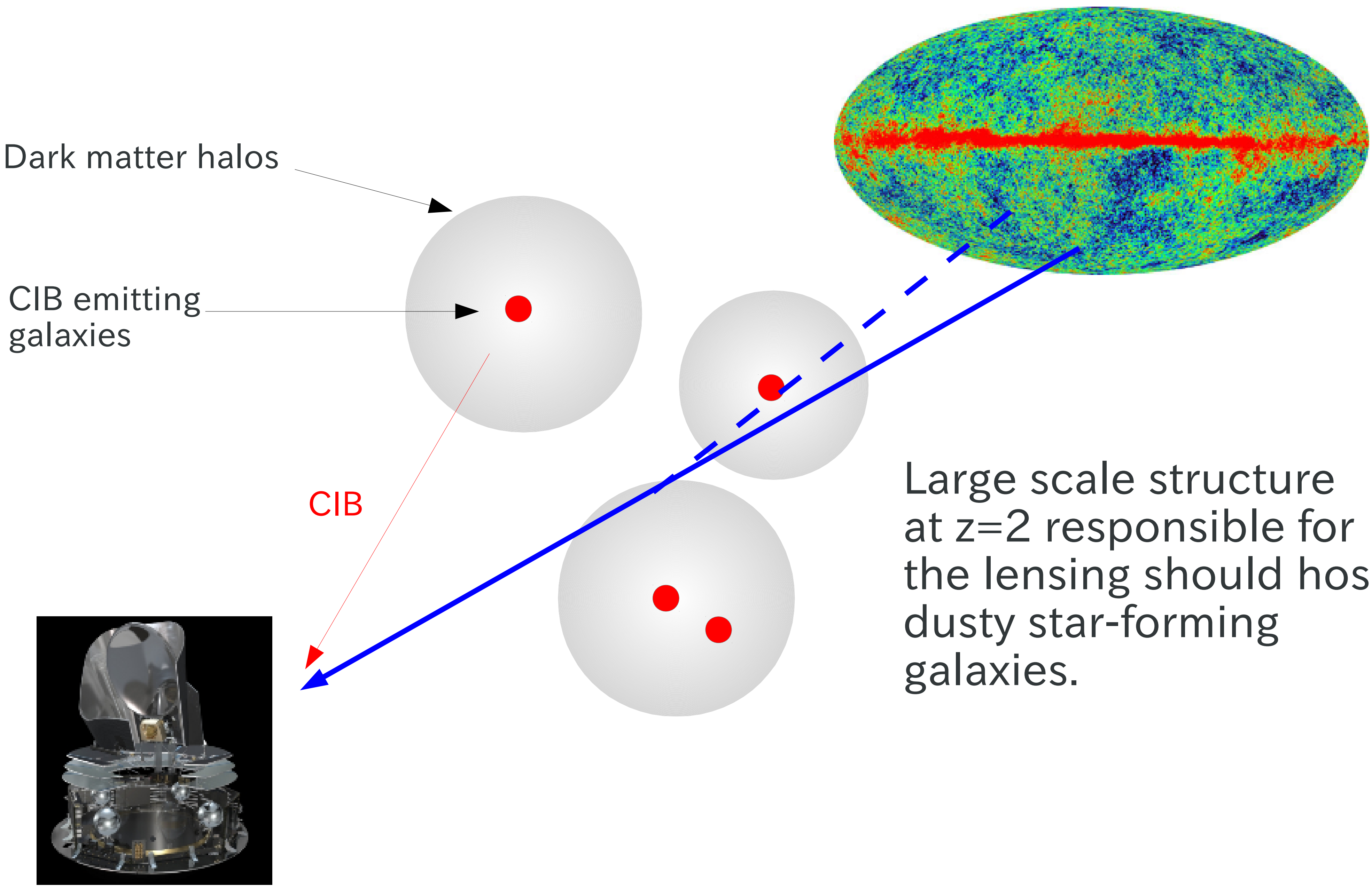
※coherent over 〜2 deg



Planck results 2013

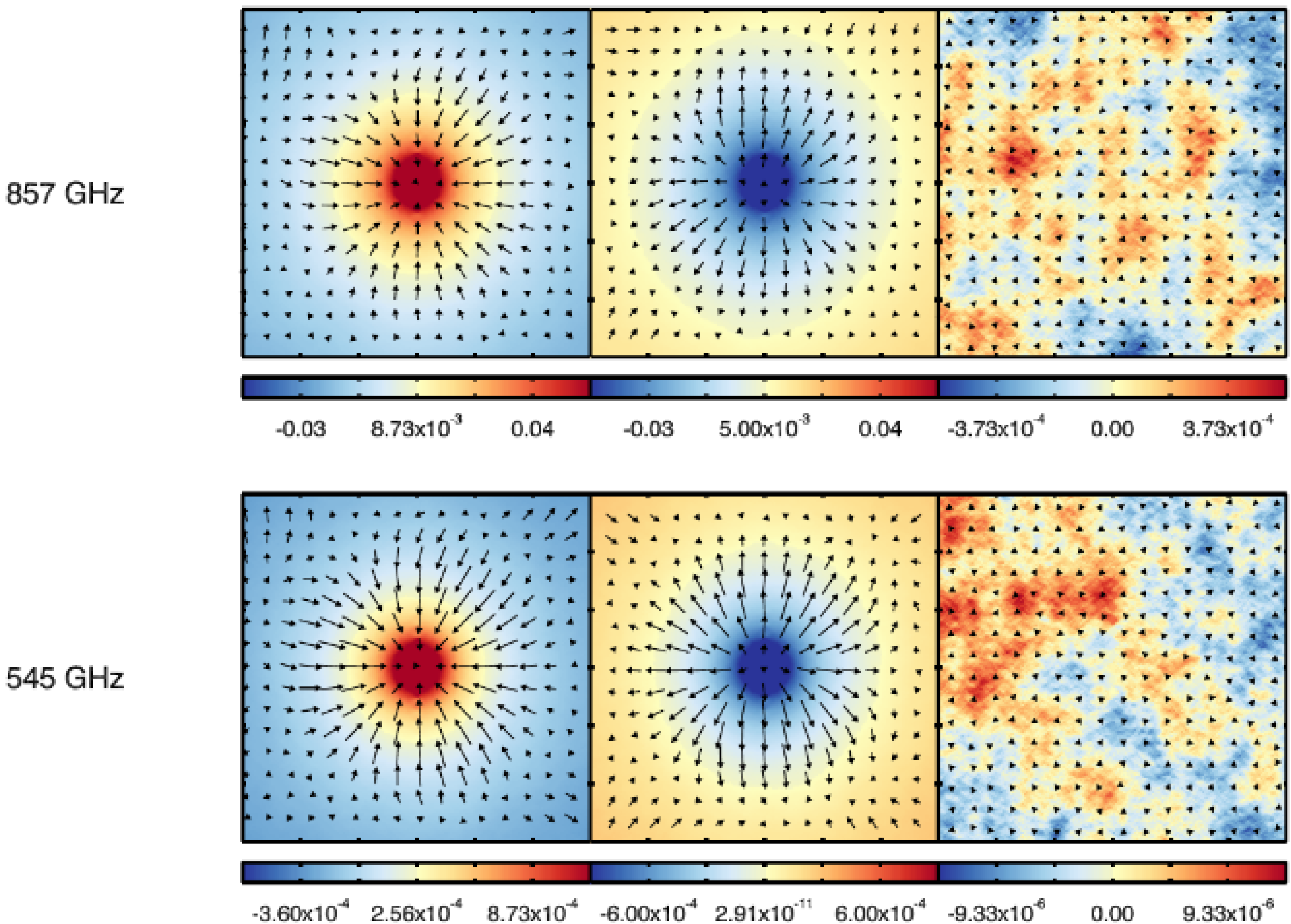
Take away key number: 〜2 (angle, correlation, redshift)

Lens-CIB x-correlation (Song et al., ApJ '03)



Large scale structure at z=2 responsible for the lensing should host dusty star-forming galaxies.

visualization (stacking technique)



CIB hot CIB cold random

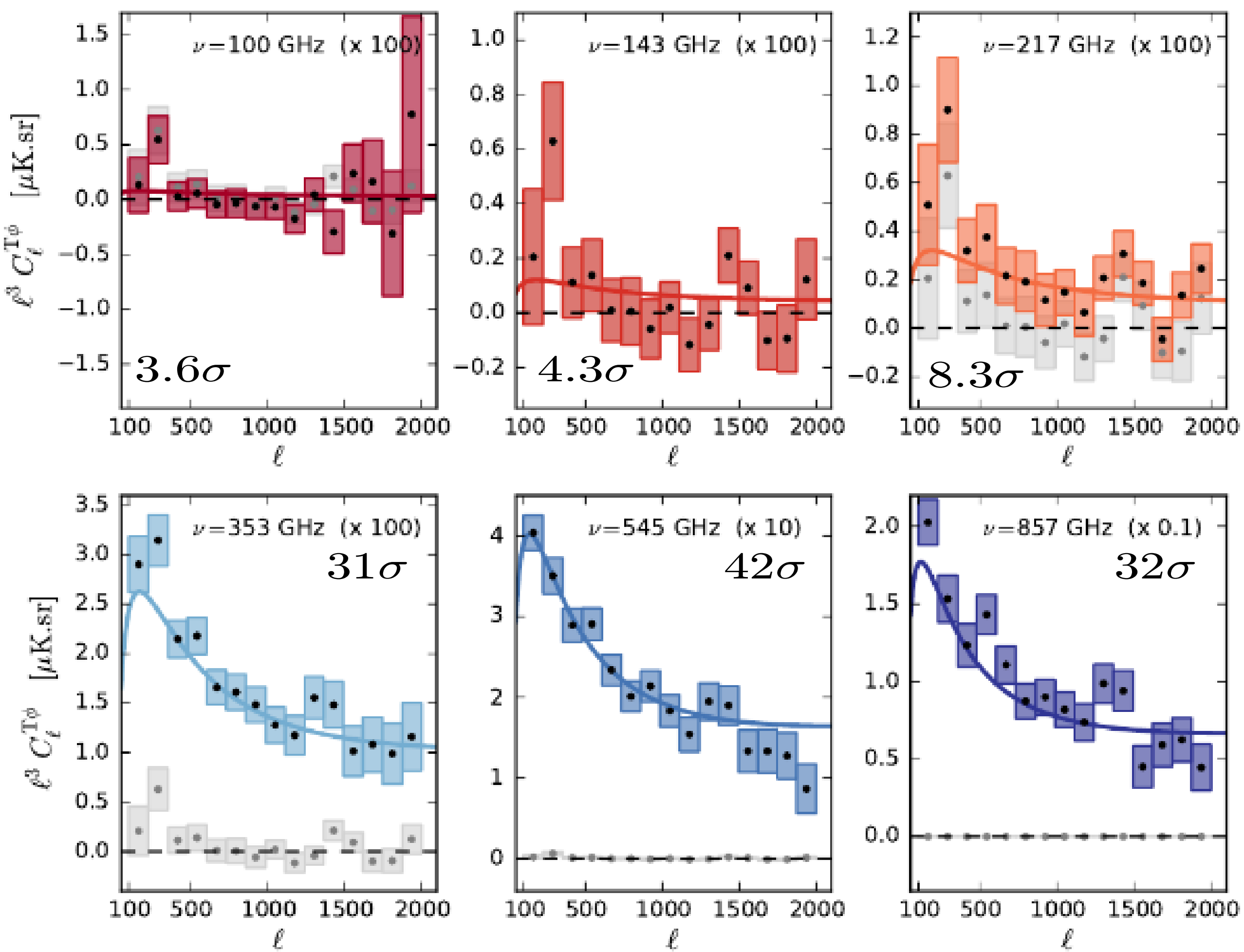
Stacking 1x1 deg. maps of CIB and lensing with the CIB peaks at the center

Maximum Deflection angle 6.3" in this map

(Planck 2013 results)

Cross correlation signal

- Cross correlation between CIB anisotropies and lensing potential anisotropies (Planck 2013 result)



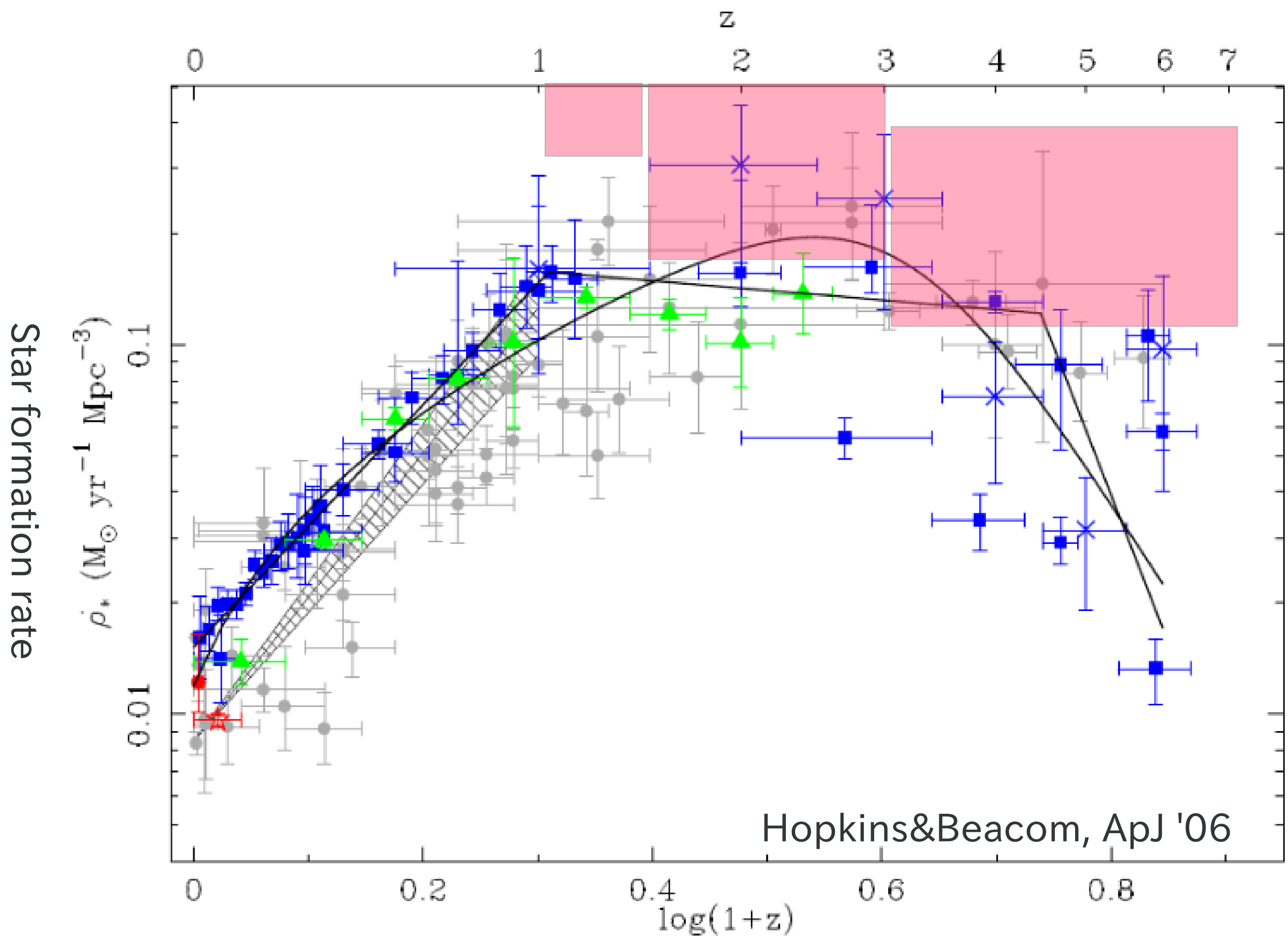
$$\hat{C}_\ell^{t\phi} = \frac{1}{2\ell+1}\sum \hat{t}_{\ell m}\hat{\phi}_{\ell m}$$

The lines are predictions, and Not fitted lines.

A new constraint on the Star formation history from the CMB satellite!

Fig. 3

New data points from Planck



B-mode polarization from lensing

- Lensing re-maps the unlensed sky

Lensing potential: given a line of sight integral of gravitational pot.

$$\tilde{P}_{ab}(\boldsymbol{x}) = P_{ab}(\boldsymbol{x} + \nabla\psi)$$

$$\approx P_{ab}(\boldsymbol{x}) + \nabla^c\psi\nabla_c P_{ab}(\boldsymbol{x})$$

yesterday once more

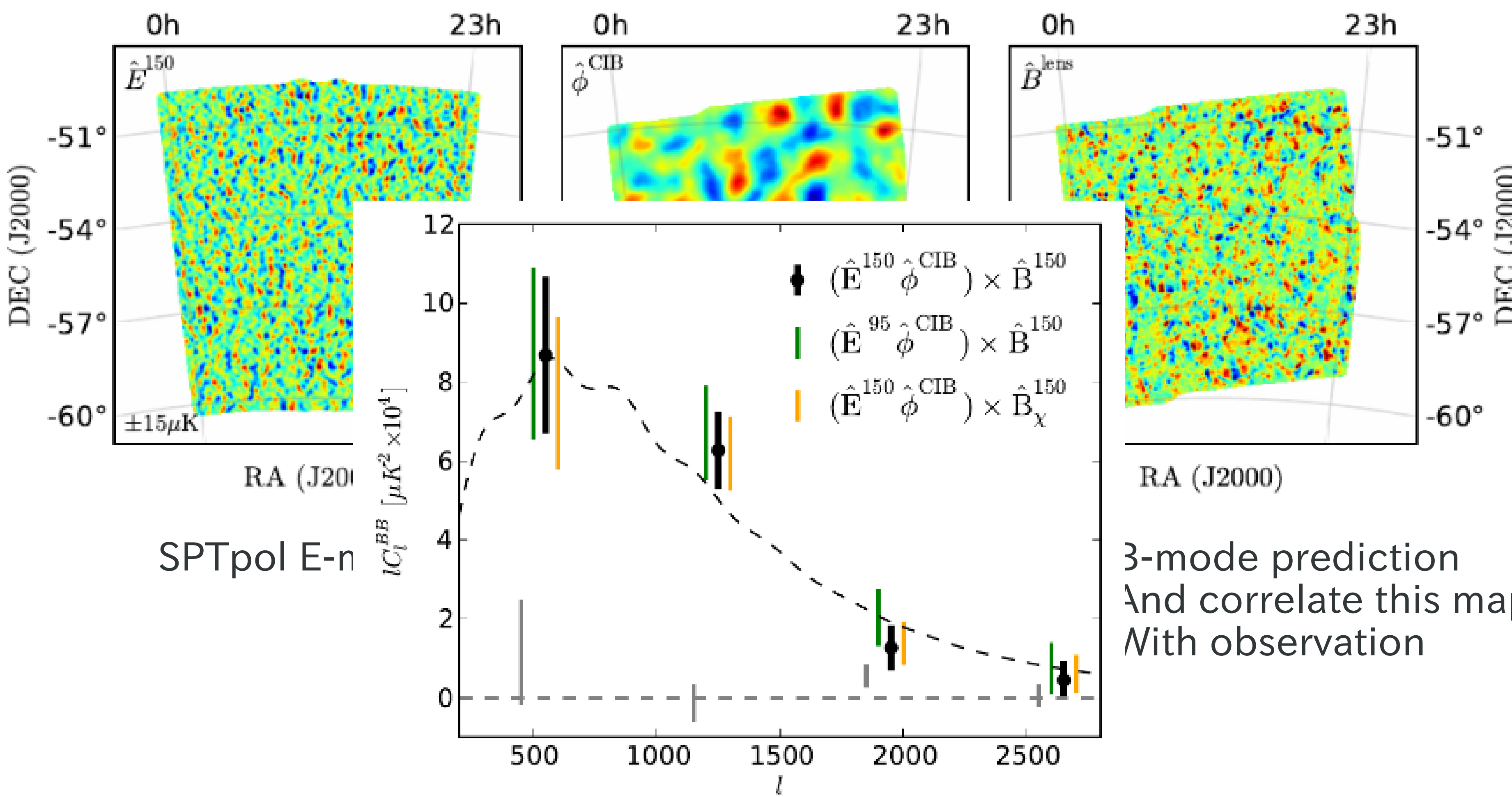
$$P_{++} \equiv (\boldsymbol{e}_+)^a(\boldsymbol{e}_+)^b P_{ab}^{(x,y)} = Q + iU$$

$$\tilde{E}(\boldsymbol{\ell}) \pm i\tilde{B}(\boldsymbol{\ell}) \approx E(\boldsymbol{\ell}) - \int \frac{d^2\ell'}{2\pi}\boldsymbol{\ell}' \cdot (\boldsymbol{\ell} - \boldsymbol{\ell}')e^{\pm 2i(\phi_{\boldsymbol{\ell}'} - \phi_{\boldsymbol{\ell}})}\underline{\psi(\boldsymbol{\ell} - \boldsymbol{\ell}')E(\boldsymbol{\ell}')}$$

(see e.g., Lewis & Challinor, 2006)

B-mode indirect detection --- SPTPol

$$B^{\rm lens}(\vec{l}_B) = \int d^2\vec{l}_E \int d^2\vec{l}_\phi W^\phi(\vec{l}_E, \vec{l}_B, \vec{l}_\phi) E(\vec{l}_E)\phi(\vec{l}_\phi), \quad (1$$



SPTpol E-n

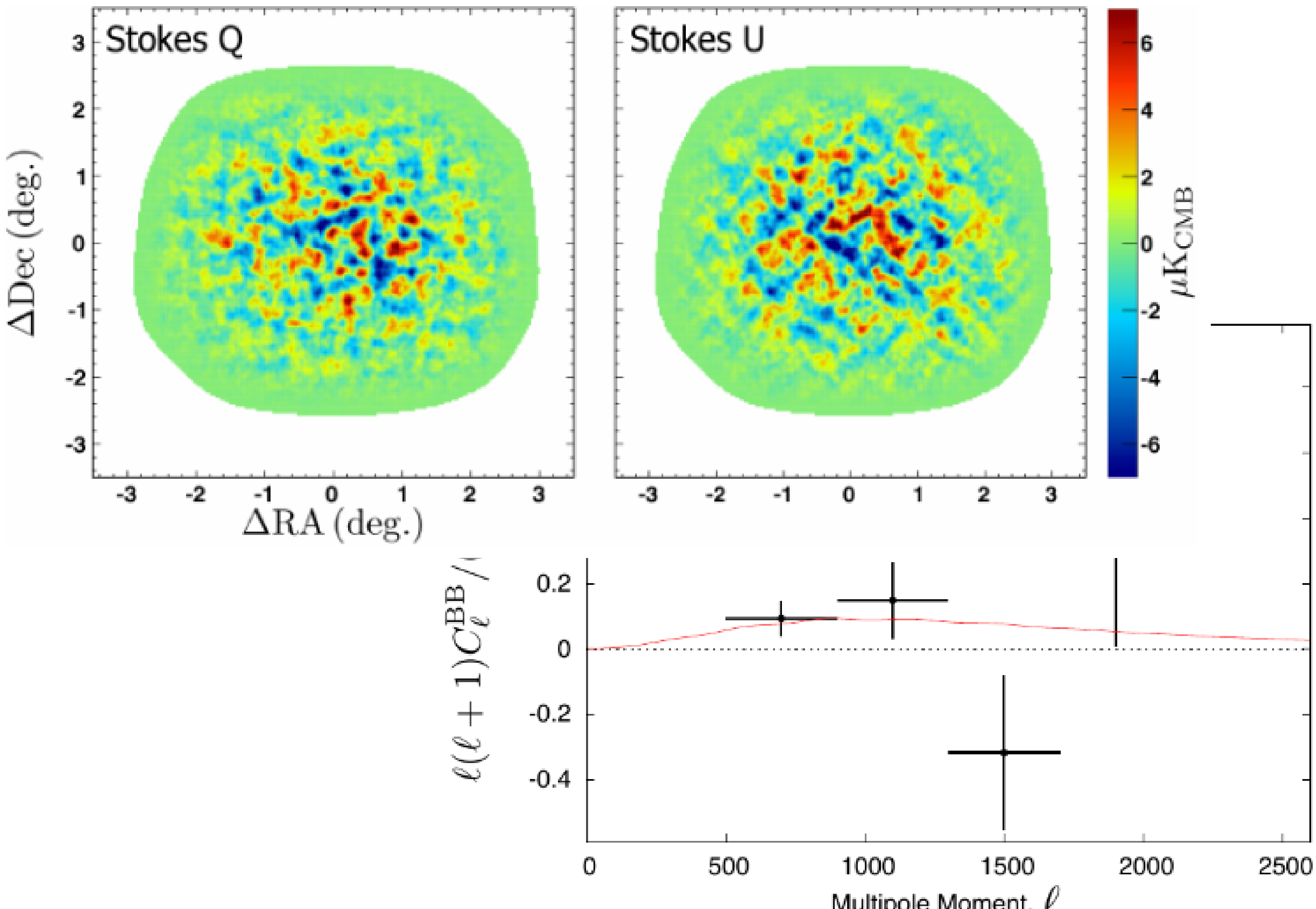
3-mode prediction
\nd correlate this map
Vith observation

7.7σ

Hanson et al., PRL111, '13

B-mode direct detection --- POLARBEAR

(arxiv: 1403.2369)



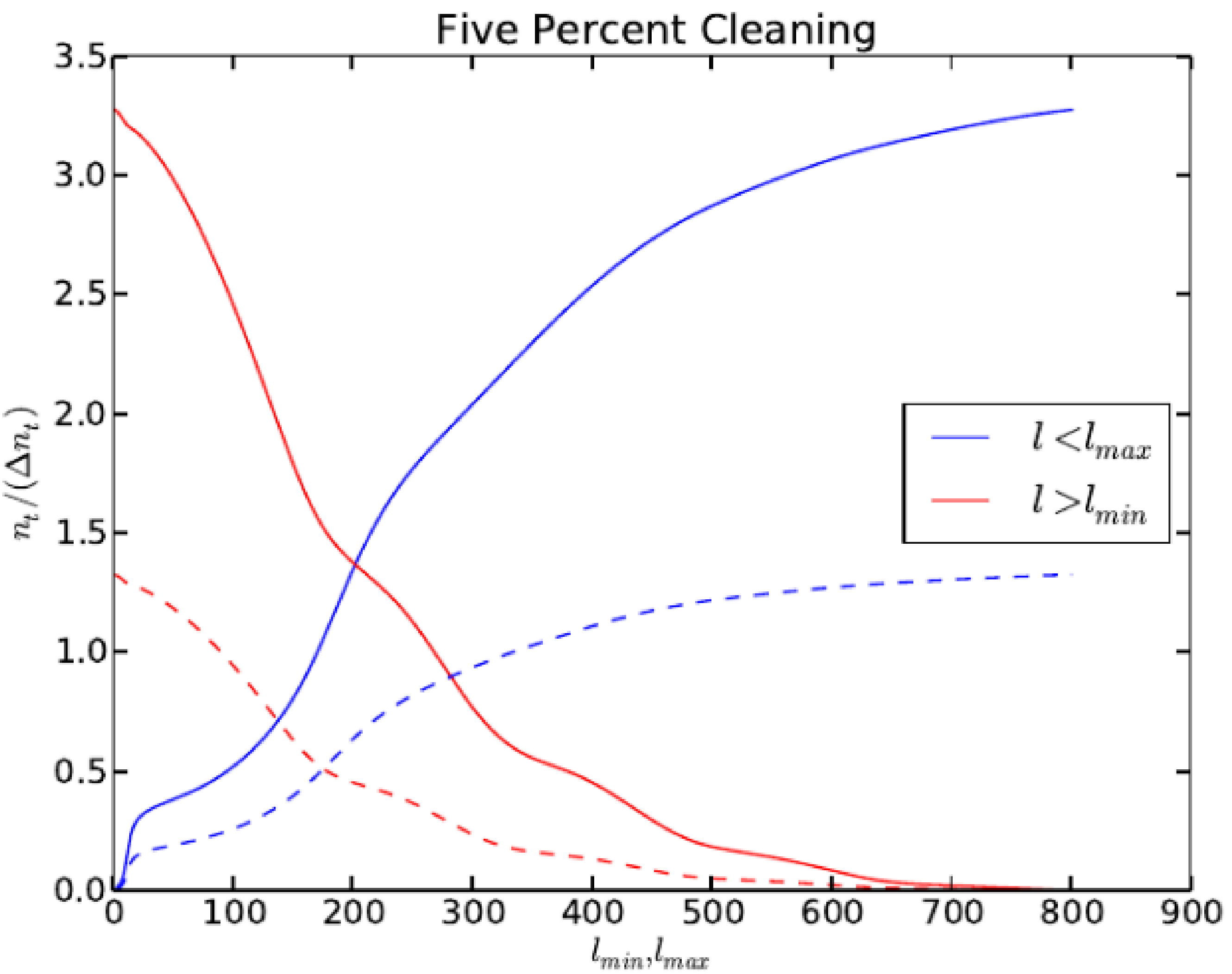
summary

- CMB is relic photons from the hot big-bang, and 10^{-5} level fluctuations in temperature, 10^{-6} in polarization
  - generated from scalar density mode from inflation
- Inflation also produce GWs, whose amplitude depends on its energy scale.
- CMB polarization is generated from Thomson scattering of photons off electrons with photon's quadrupole anisotropy
- Polarization pattern can be decomposed into E & B modes
  - E polarization are parallel along or perpendicular to the direction of the Fourier mode
  - B is rotated E by 45 degree.
- Because B mode is generated only from GWs, it can be considered as a smoking gun of inflation

summary

- This year, BICEP2 reported the B-mode polarization at degree scales, POLARBEAR at sub degree scales
- Tensor to scalar ratio $r = 0.20^{+0.07}_{-0.05}$
- Slightly inconsistent with observations of temperature anisotropies
  - many ideas
  - e.g.) massive neutrinos, foregrounds, etc....
- to confirm GWs as the origin of the B-mode, large scale correlations are essential
  - Bump from re-ionization at l = 10
  - Observation with larger sky coverage
  - Inflation consistency relations

What's the ultimate goal?

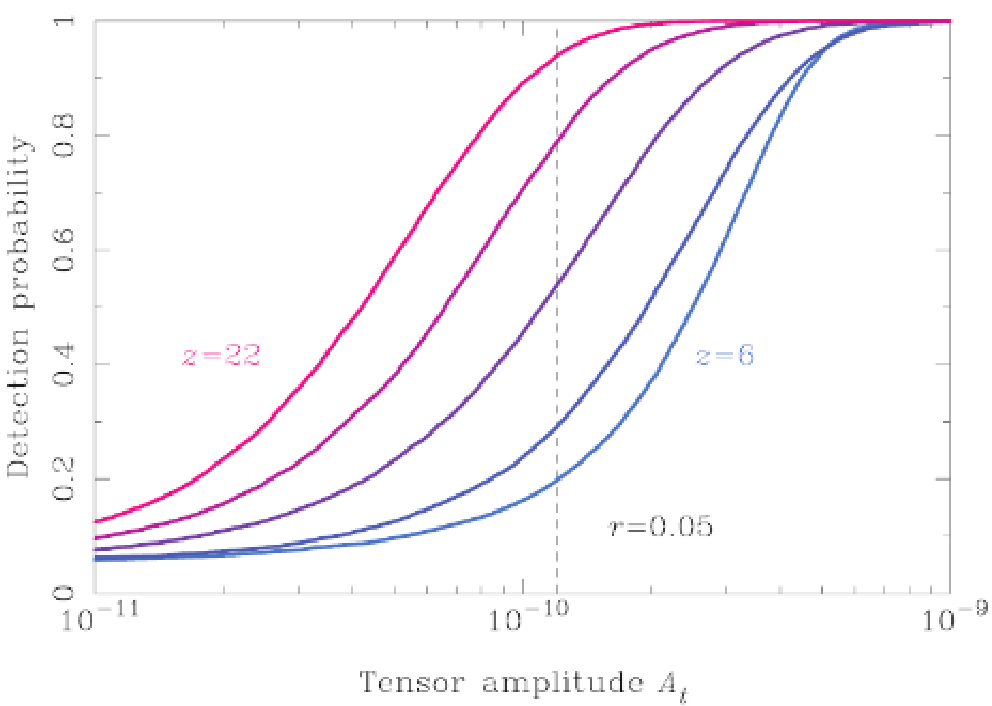


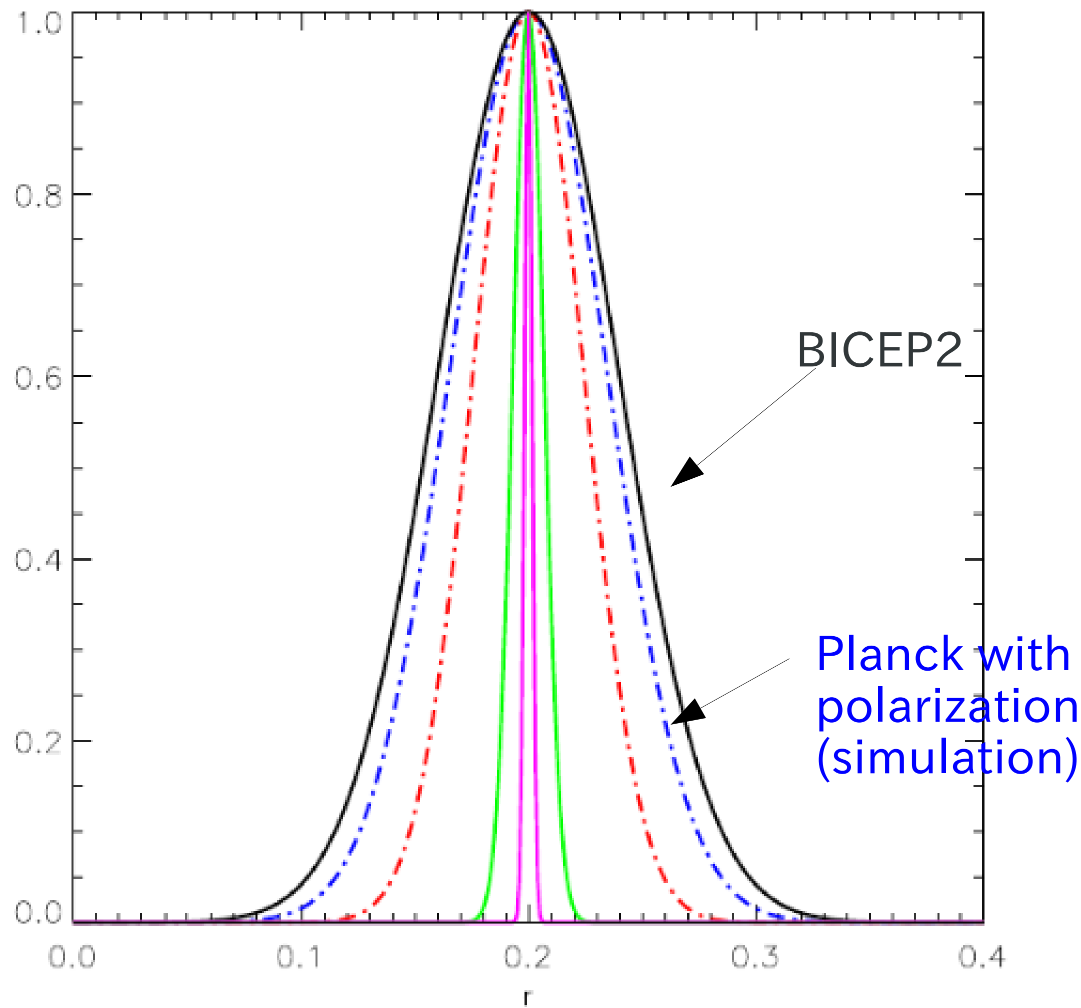
S. Dodelson, PRL, 2014

$$n_t = -8r$$

Can Planck confirm the signal?

Planck Blue Book (2006)





(Bonaldi et al., arxiv: 1407.0968)

Lens-CIB x-correlation (Planck 2013 result)

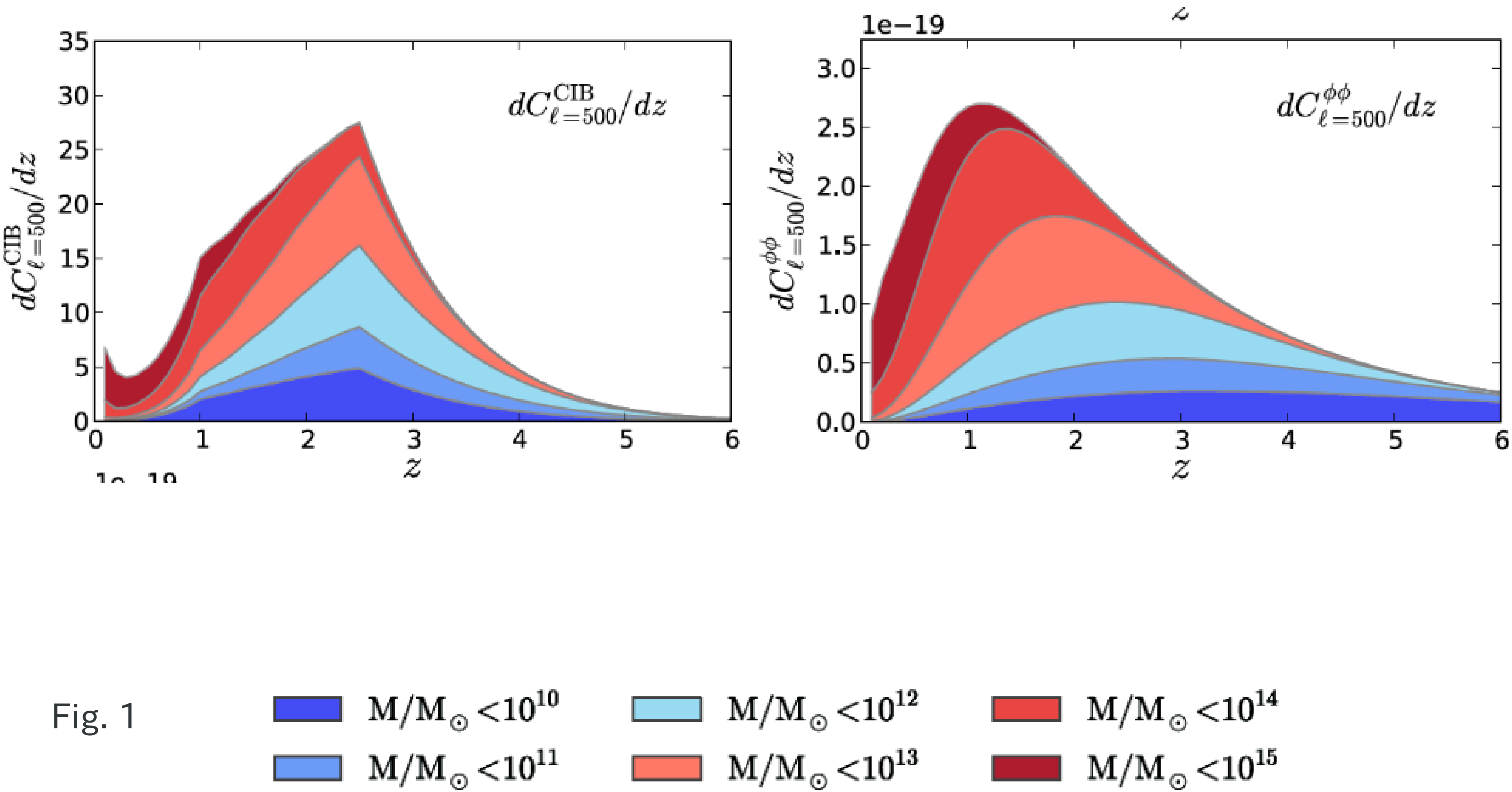


Fig. 1