Results from Planck

Ben Wandelt

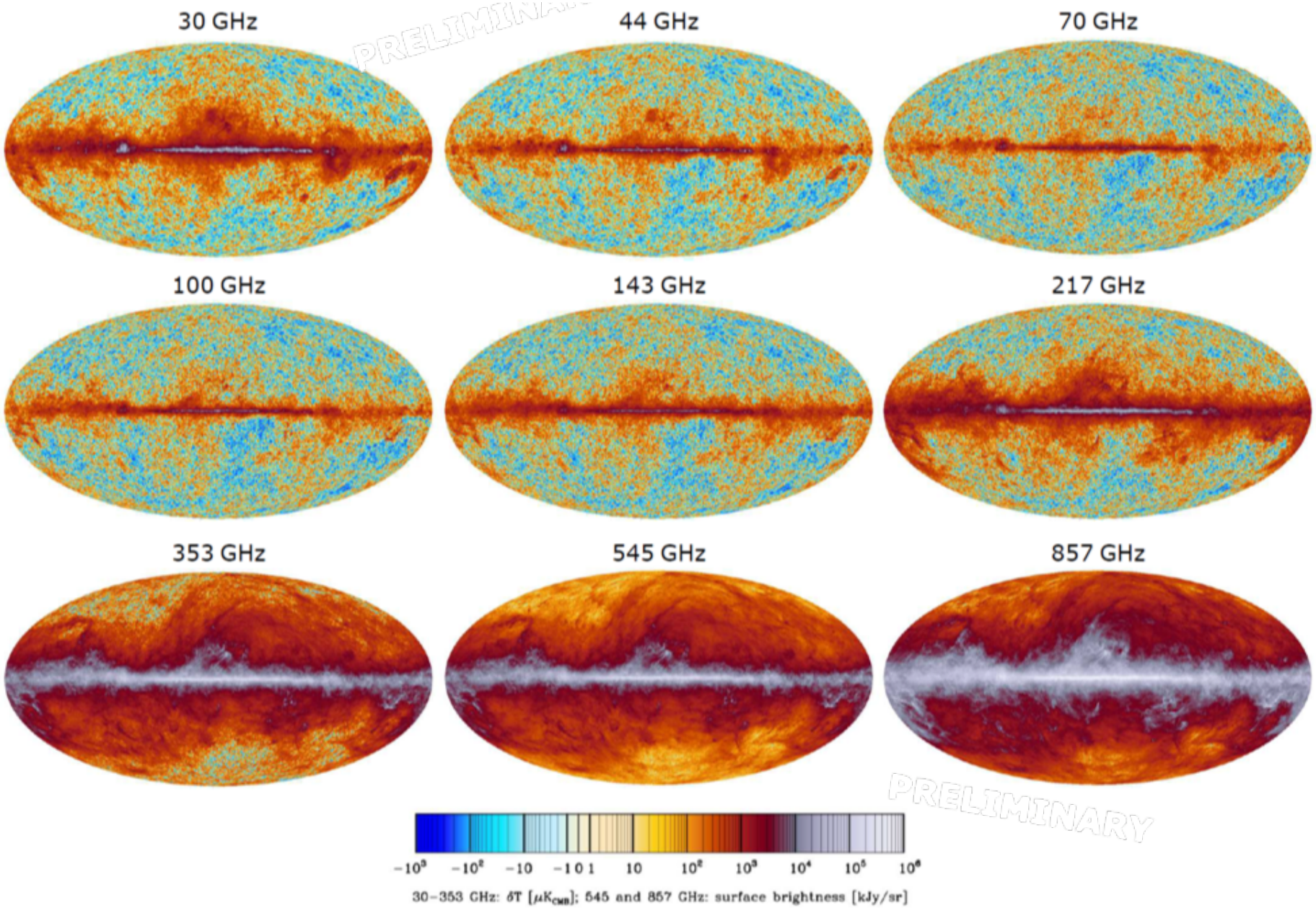
Planck results presented on behalf of the Planck collaboration

Institute for Astrophysics, Paris (IAP)

Lagrange Institute, Paris (ILP)

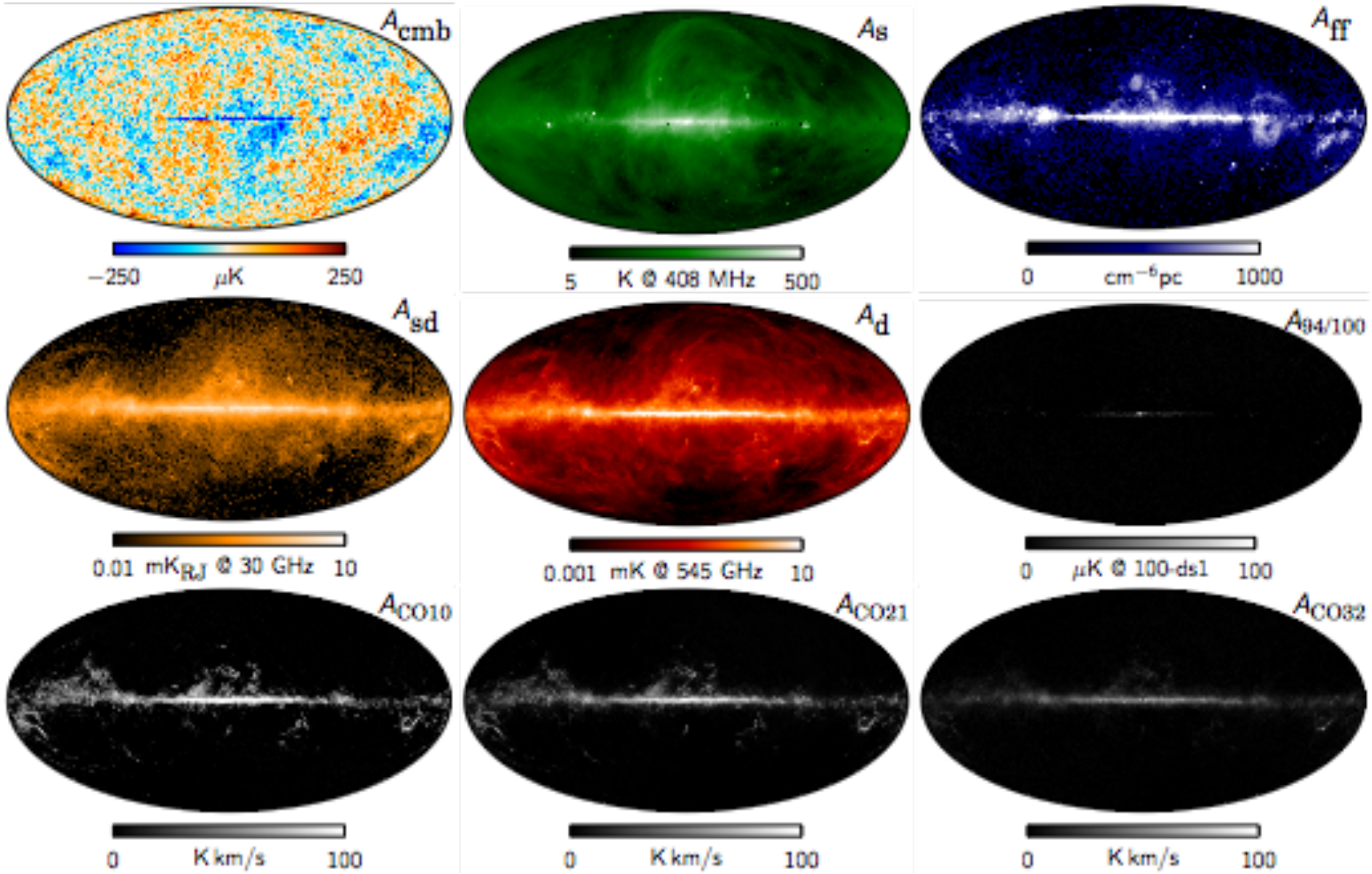
UPMC

Planck



Planck 2015

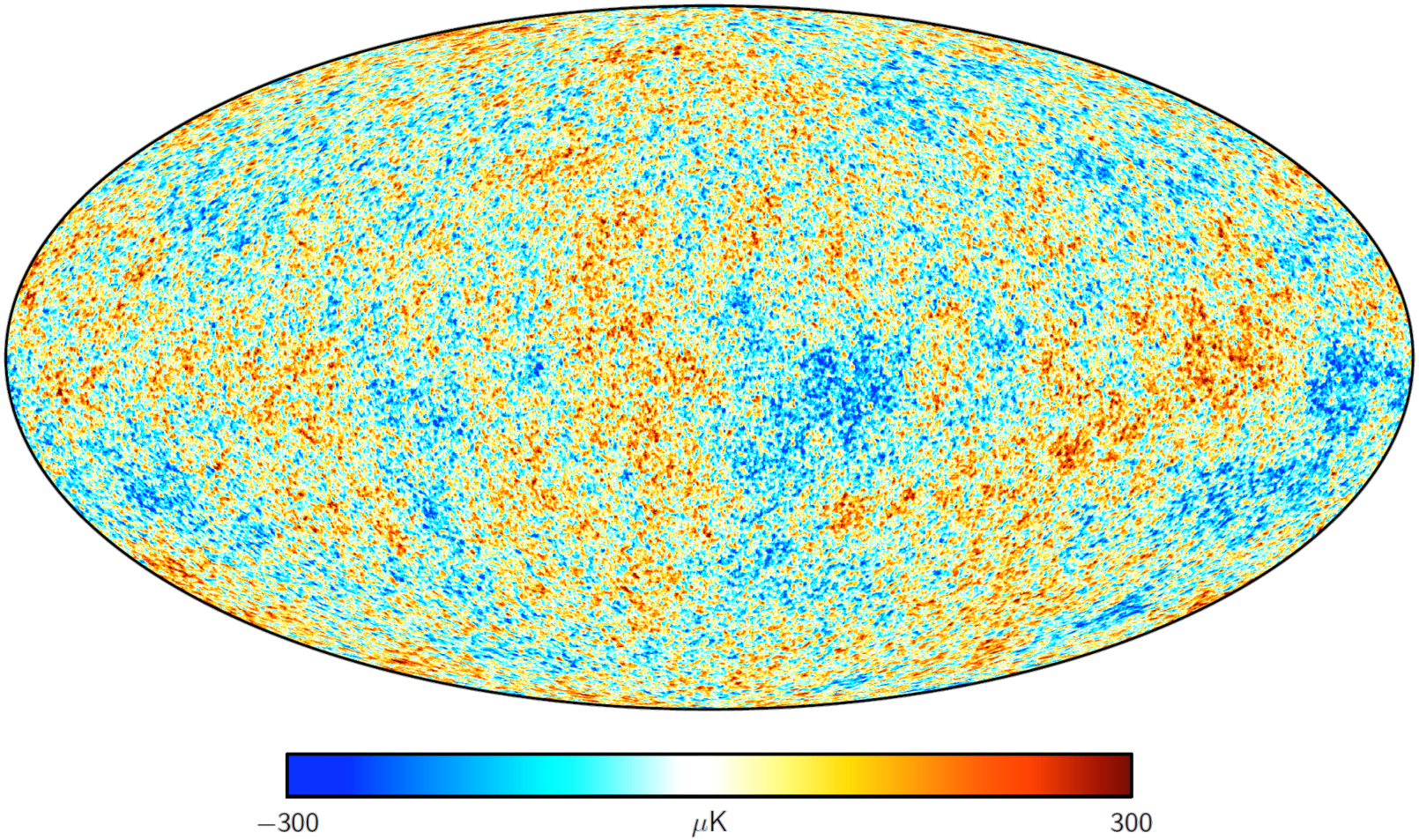
Microwave sky



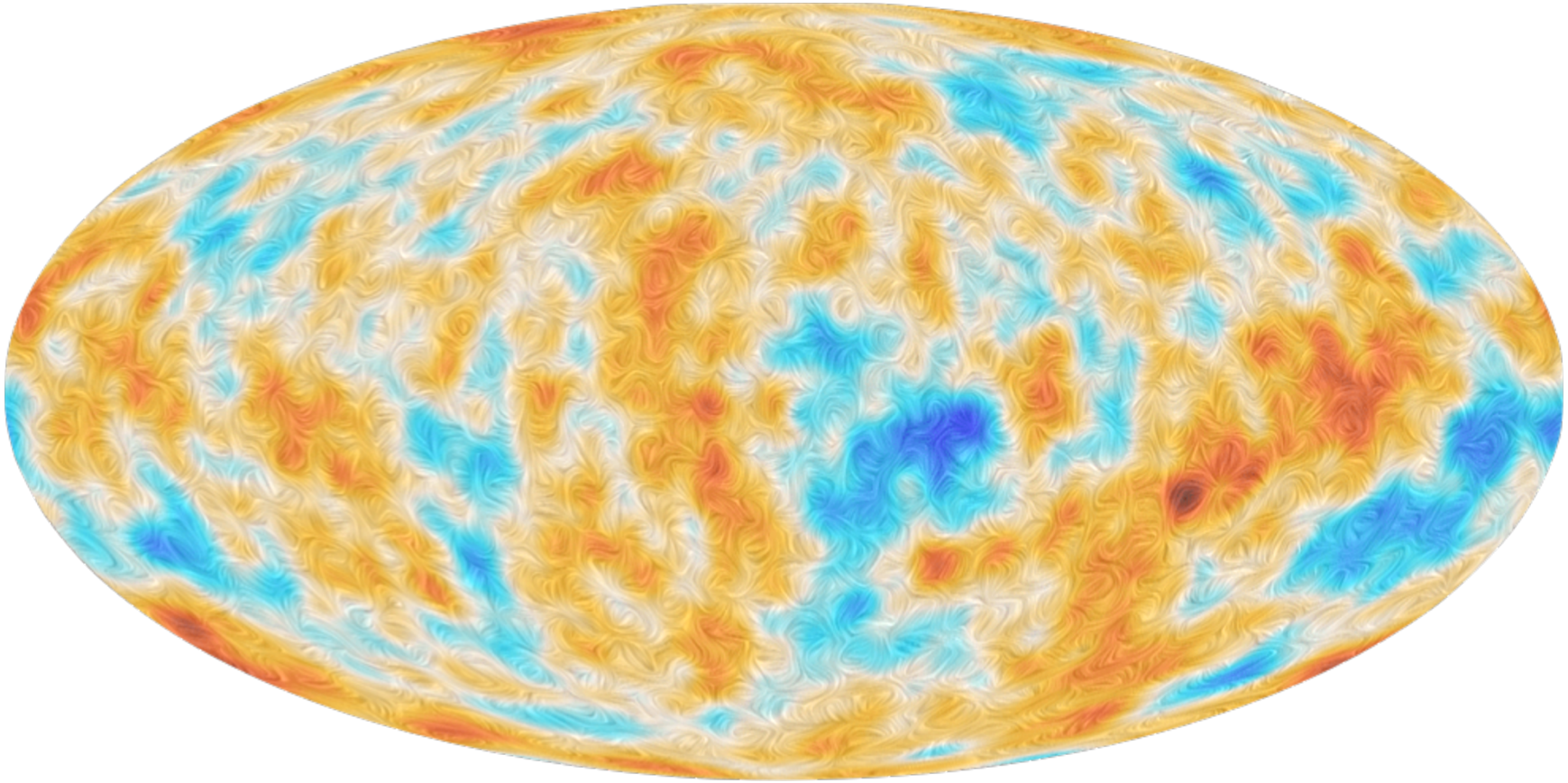
Planck 2015

Components in the microwave sky

The Planck 2015 temperature map



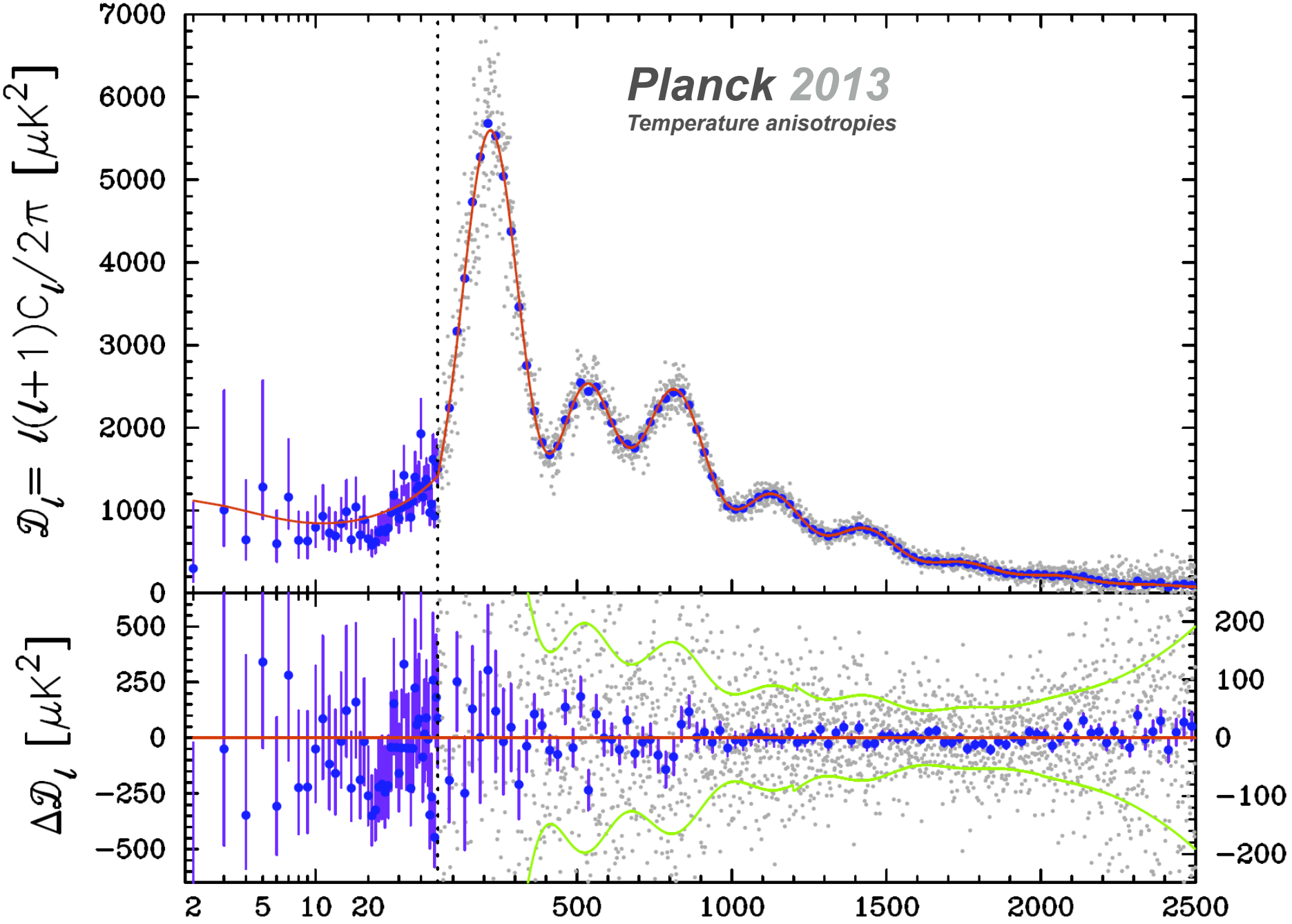
The Planck 2015 polarization map

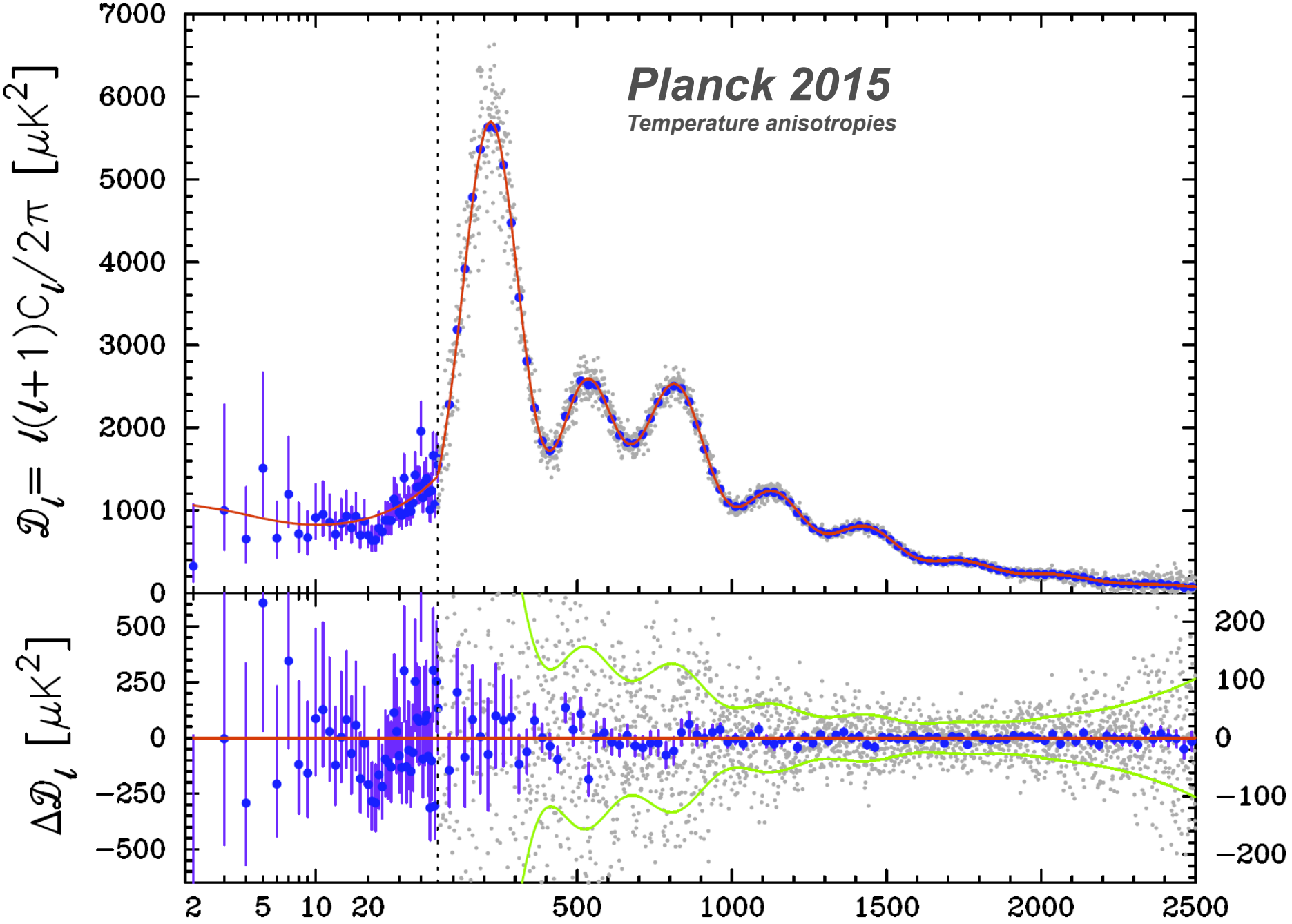


Fluctuations larger than 10 degrees have been removed

Health warning

- All results involving 2015 E-polarization are considered preliminary
- The idea is that if E results agree with/ reinforce T results, then it makes us feel good.
- No physics alarm bells ring if T and E do not agree - it could well be a residual systematic.
- The final 2016 polarization data set is expected to be much better characterized


Planck 2013
Temperature anisotropies
$\mathcal{D}_l = l(l+1)C_l/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_l\ [\mu K^2]$
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500


Planck 2015
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$\Delta\mathcal{D}_l\ [\mu K^2]$
7000
6000
5000
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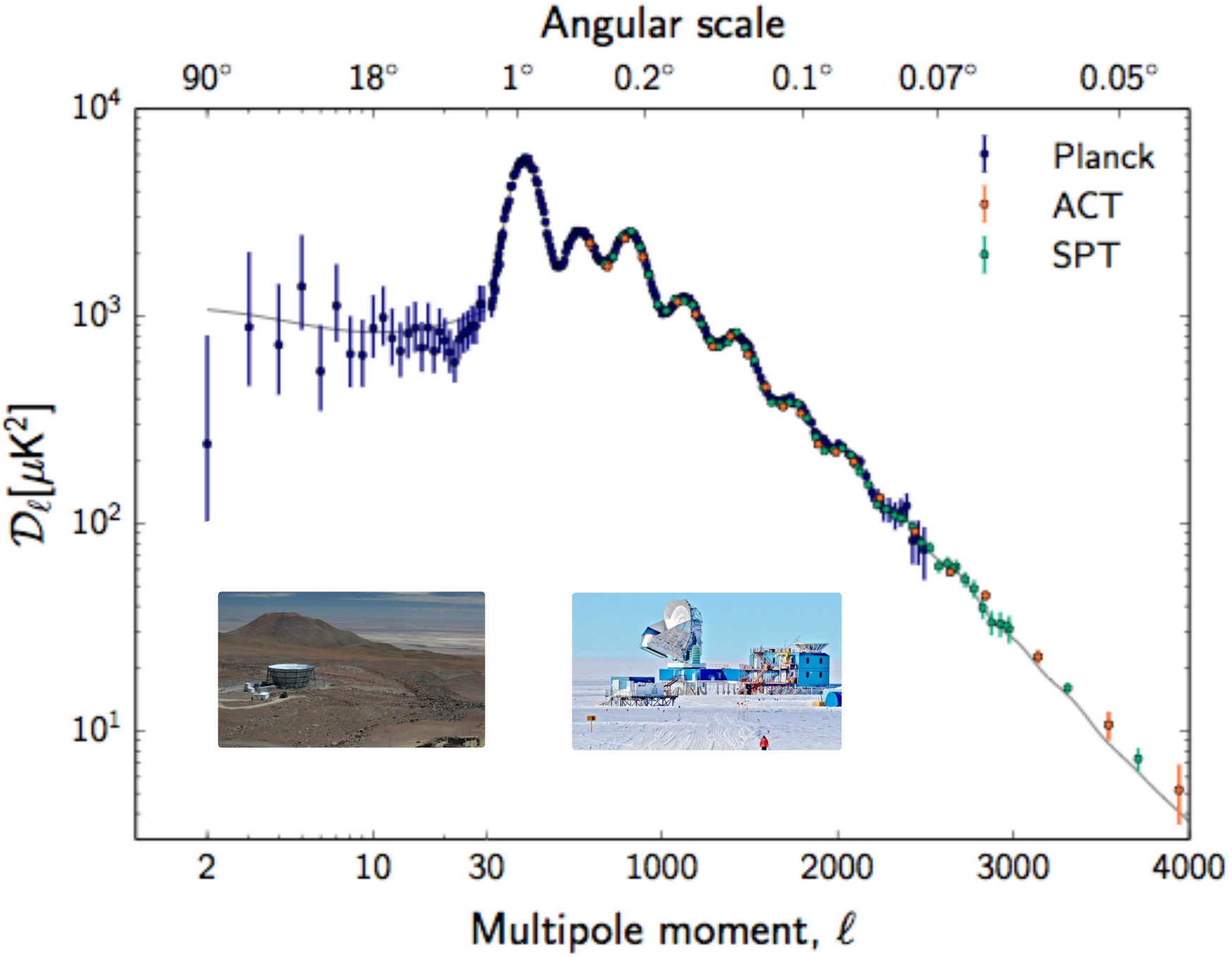
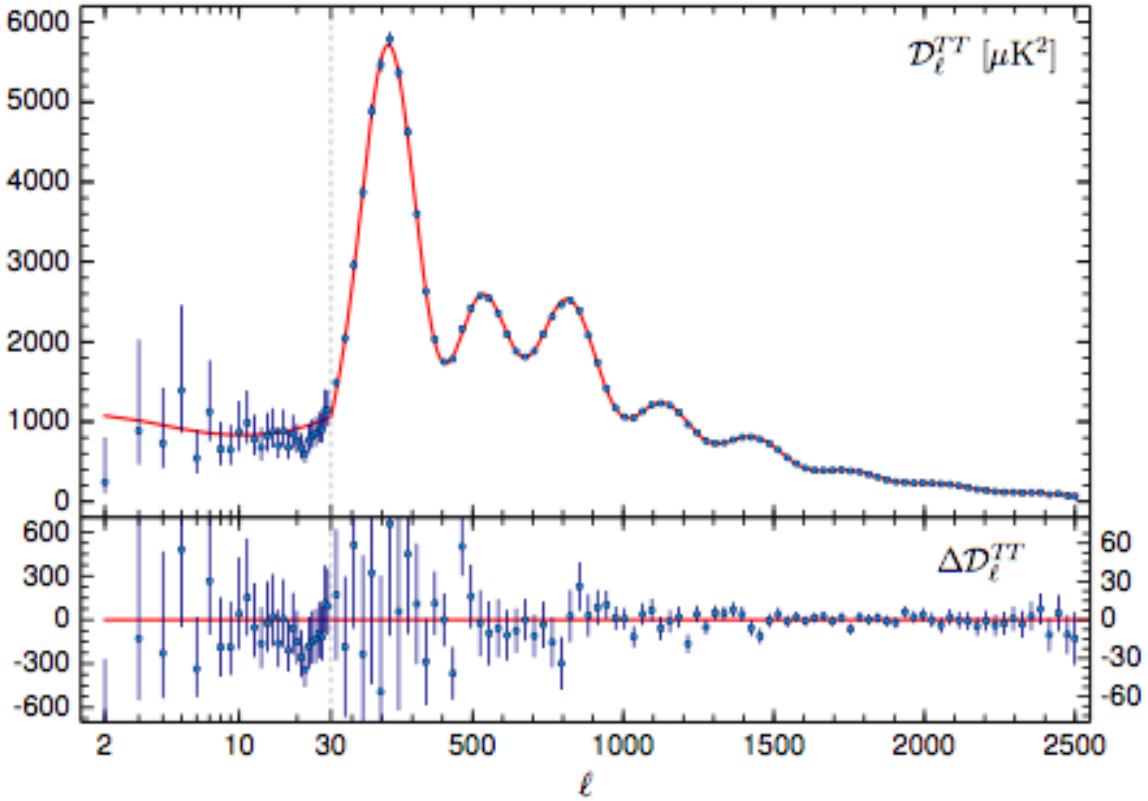
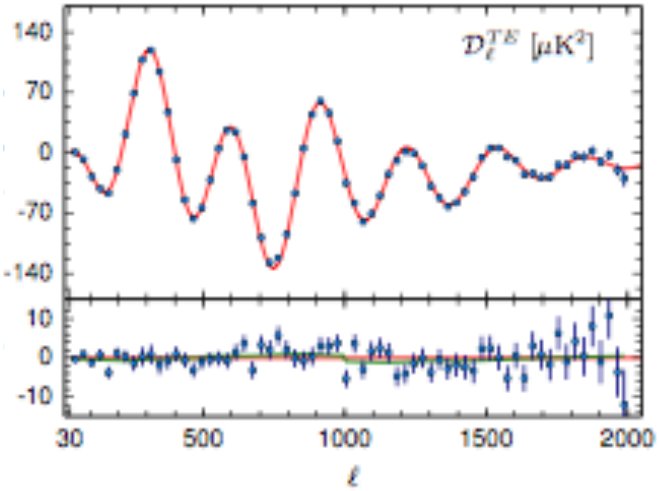
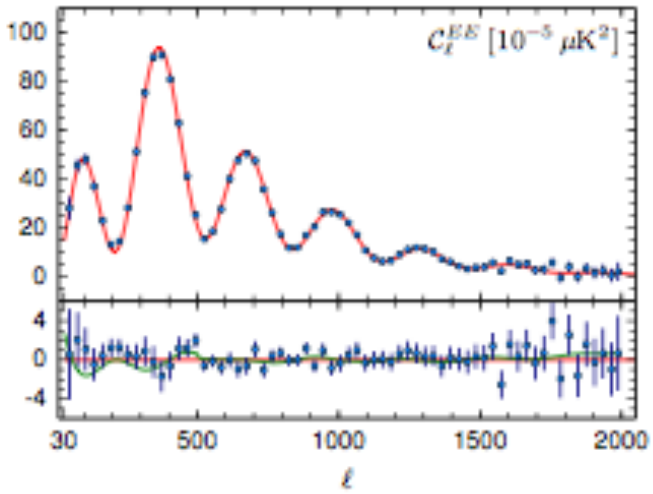
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
0.05°
10^4
10^3
10^2
10^1
$\mathcal{D}_\ell[\mu K^2]$
Planck
ACT
SPT
2
10
30
1000
2000
3000
4000
Multipole moment, ℓ







Best fit ΛCDM model

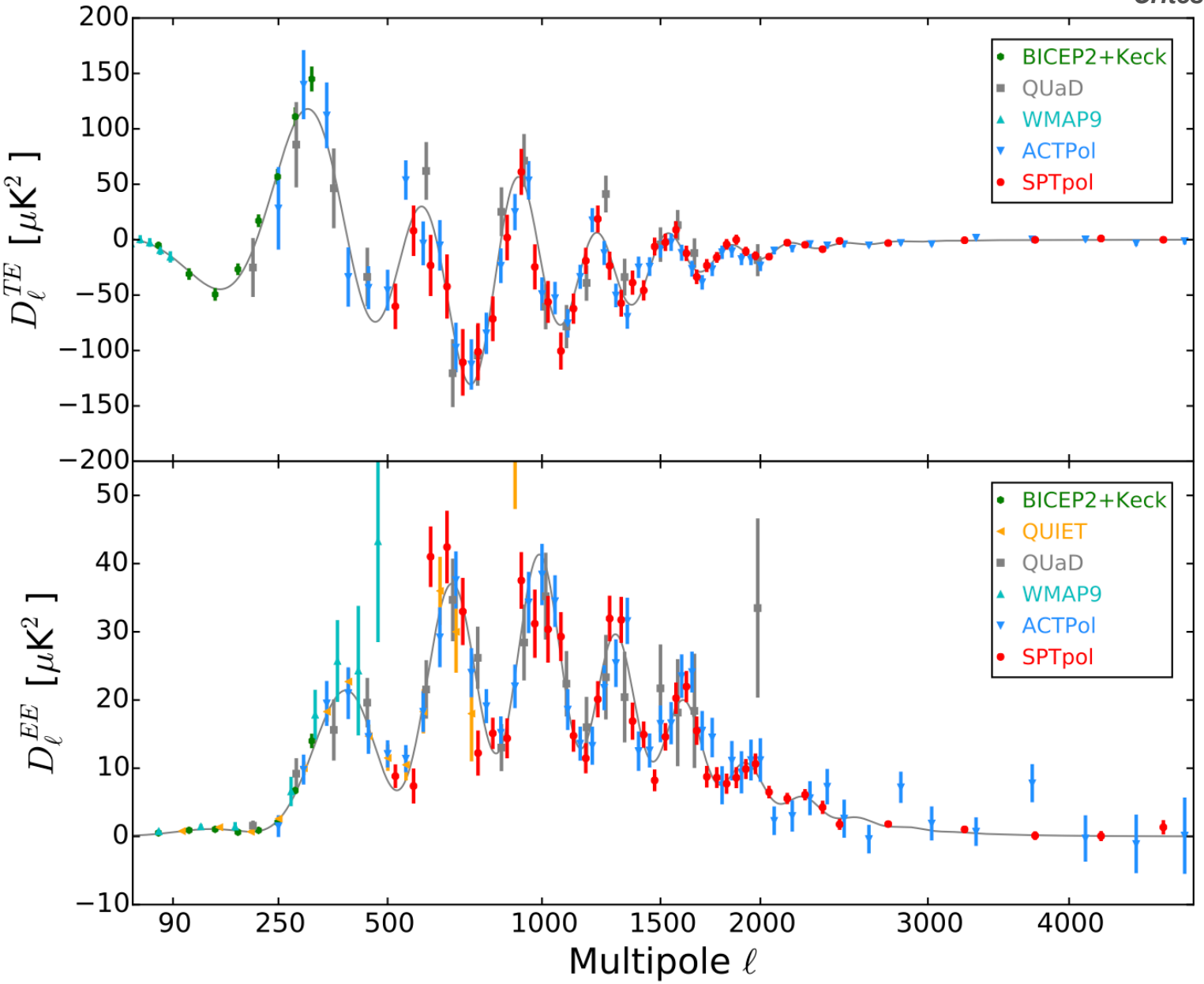
Coadded, foreground cleaned spectrum

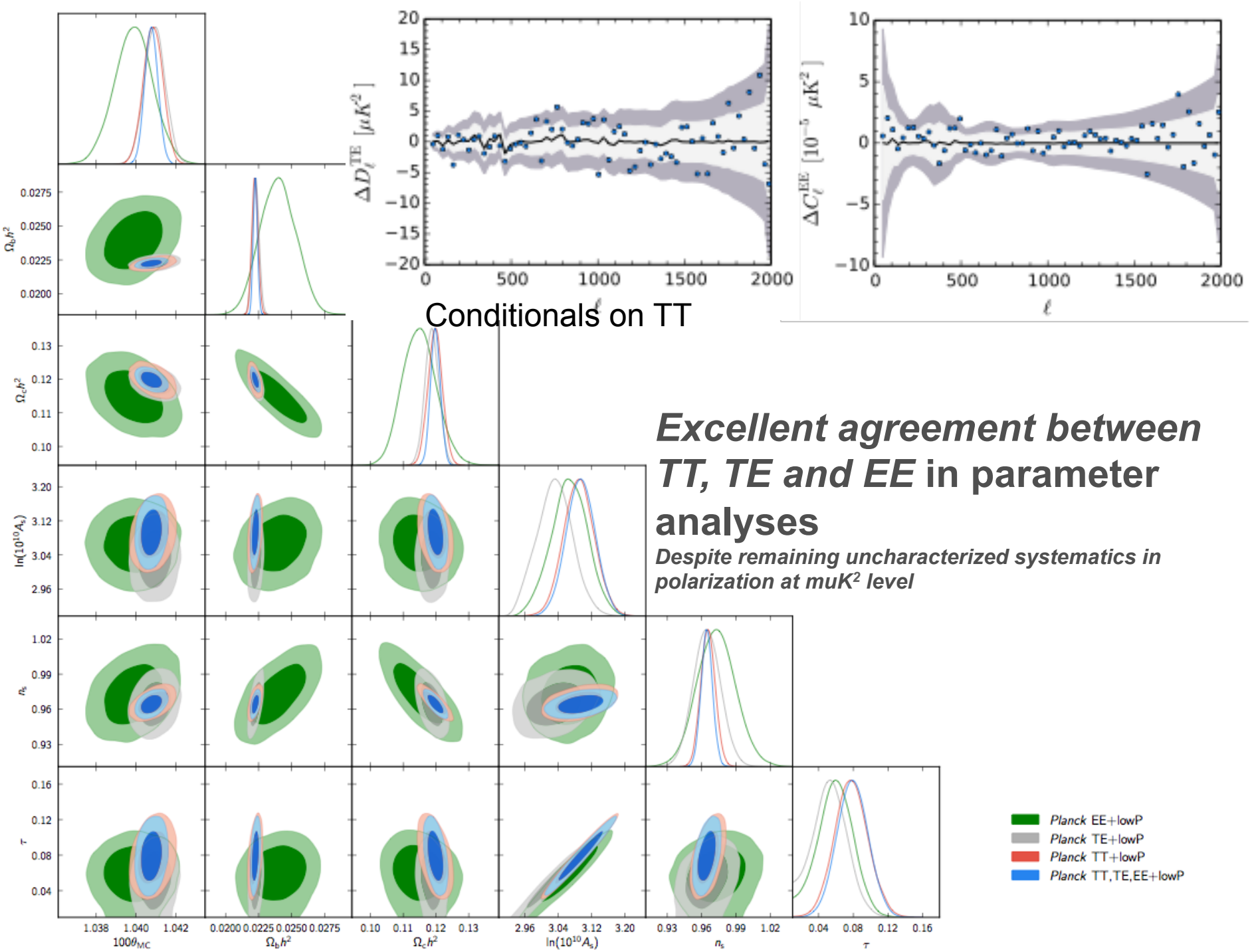
Residual beam mismatch

expected dominant residual contribution at muK^2 level

Pre Planck 2015 state of the art

Crites et al. 2014

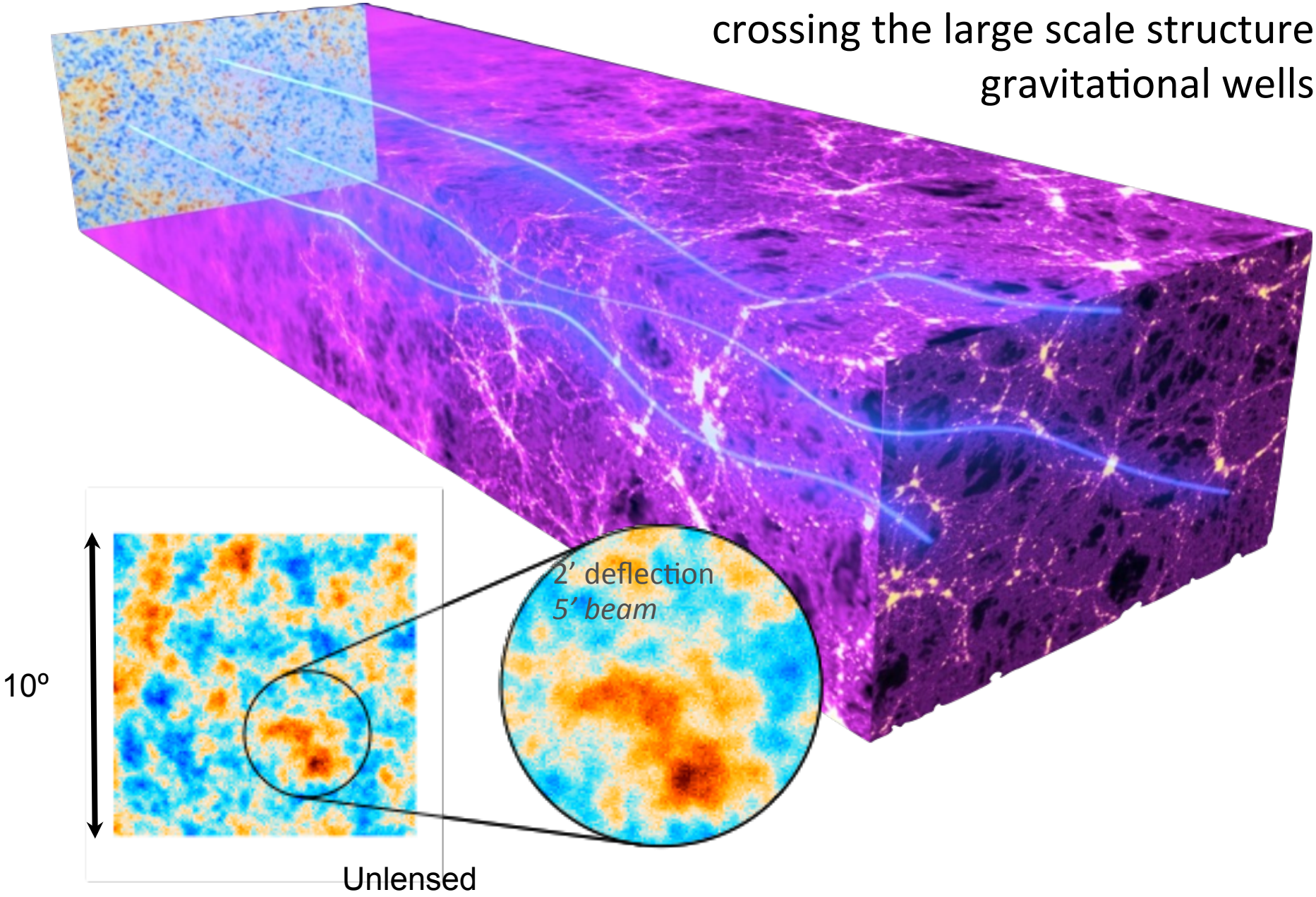




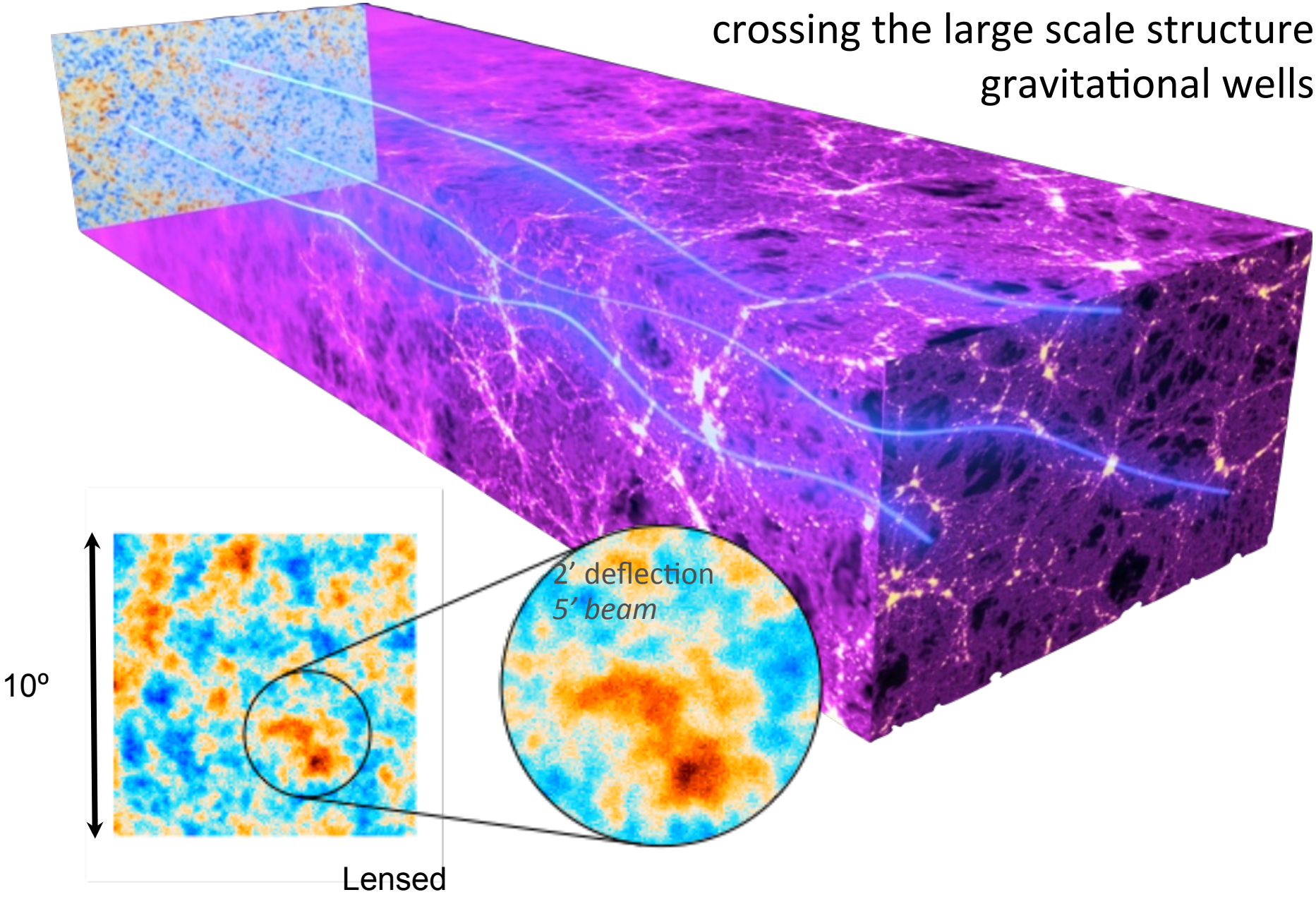
Excellent agreement between TT, TE and EE in parameter analyses

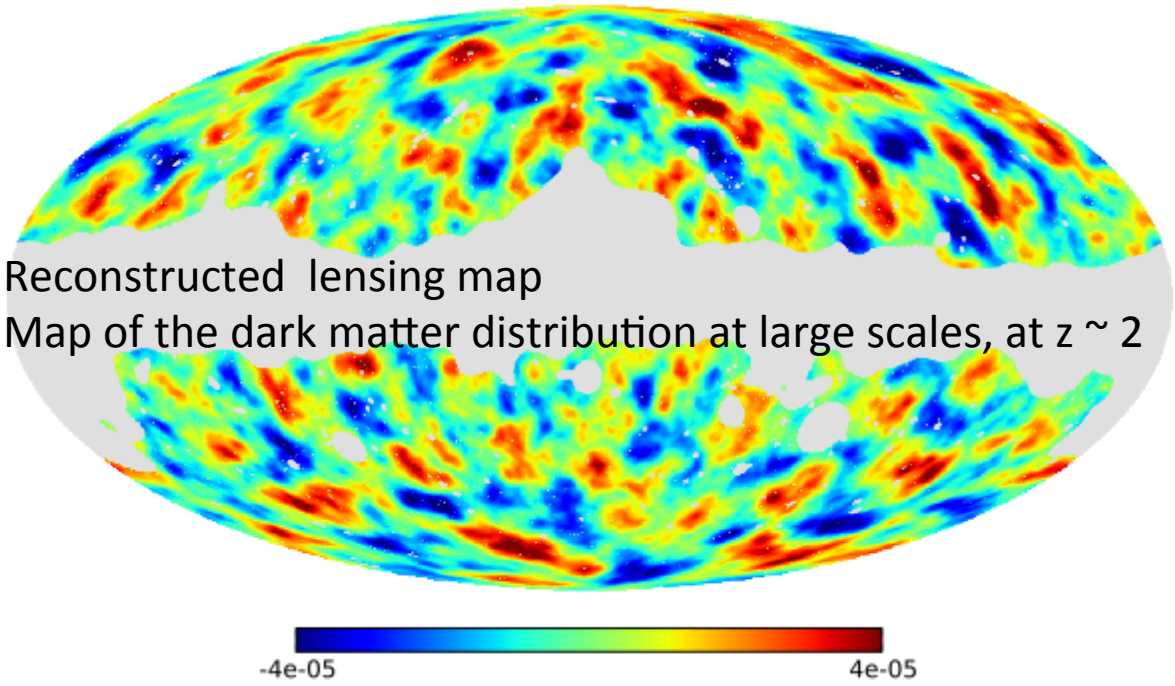
Despite remaining uncharacterized systematics in polarization at muK^2 level

Photon paths are deflected when crossing the large scale structure gravitational wells



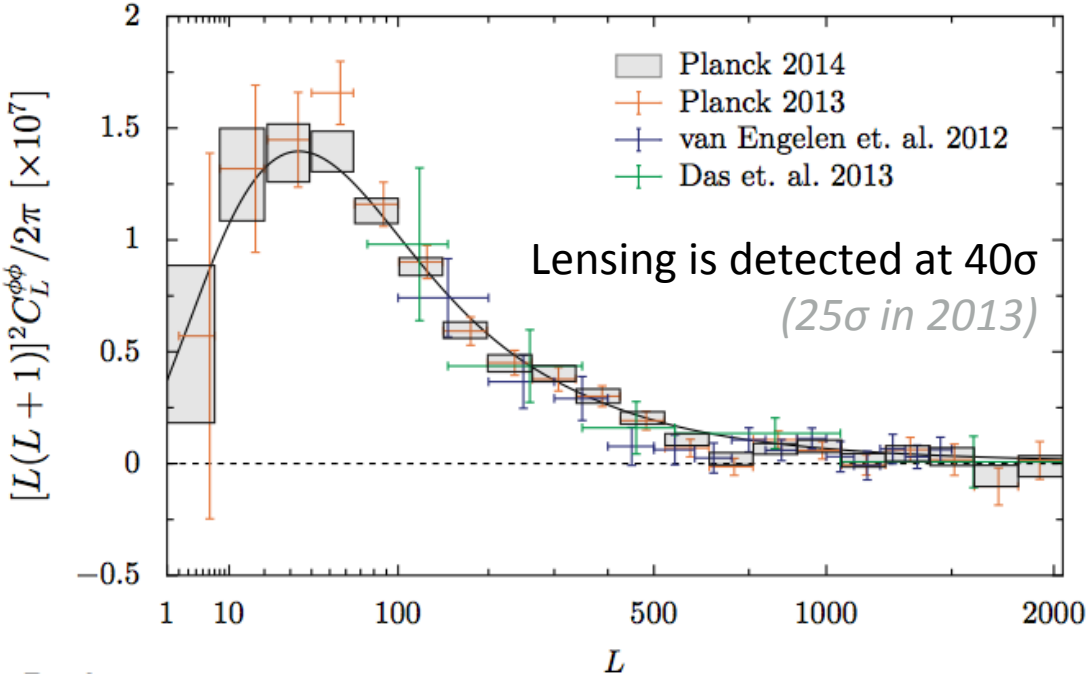
Photon paths are deflected when crossing the large scale structure gravitational wells

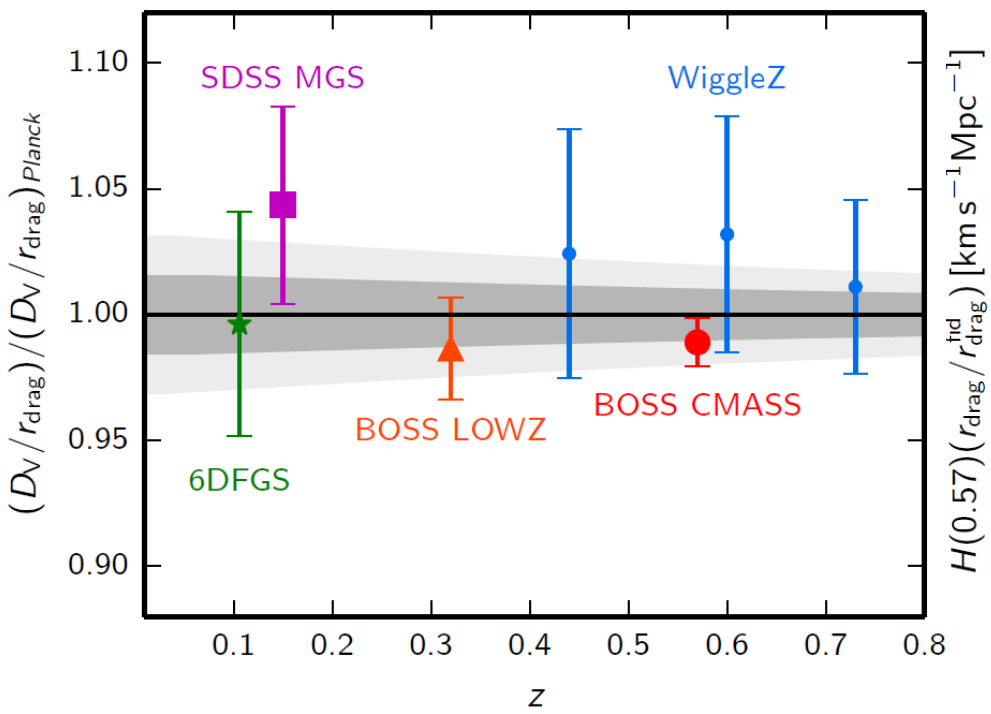


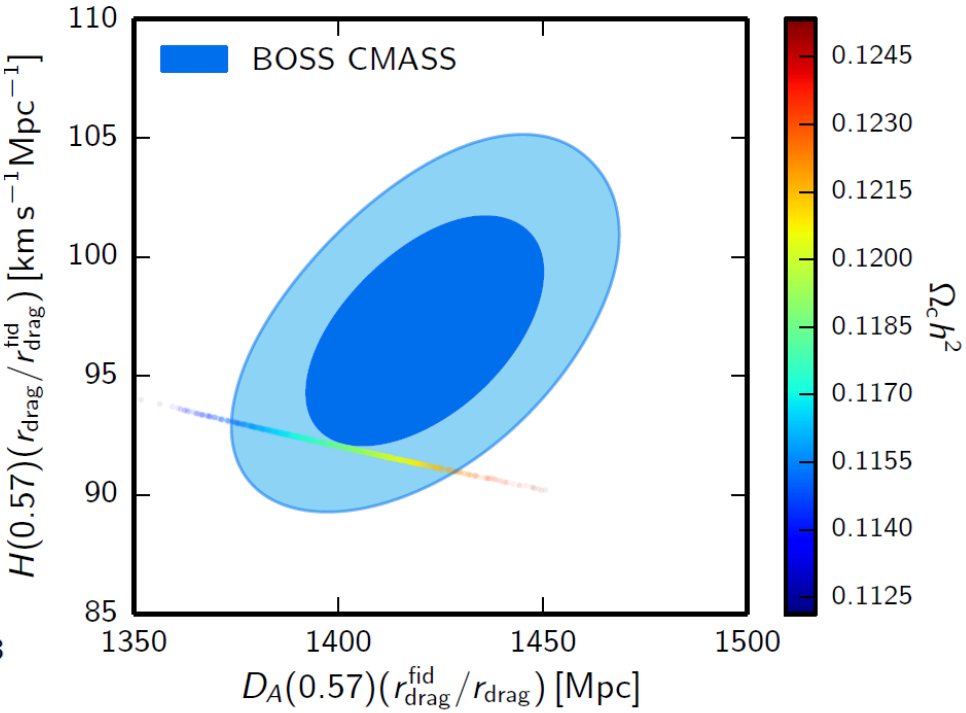


Reconstructed lensing map

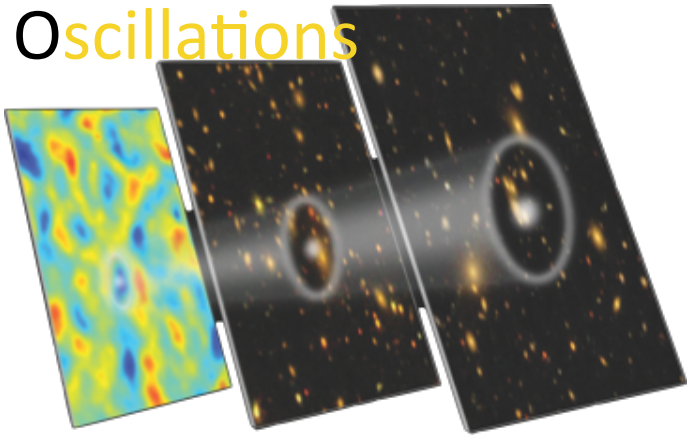
Map of the dark matter distribution at large scales, at z ~ 2







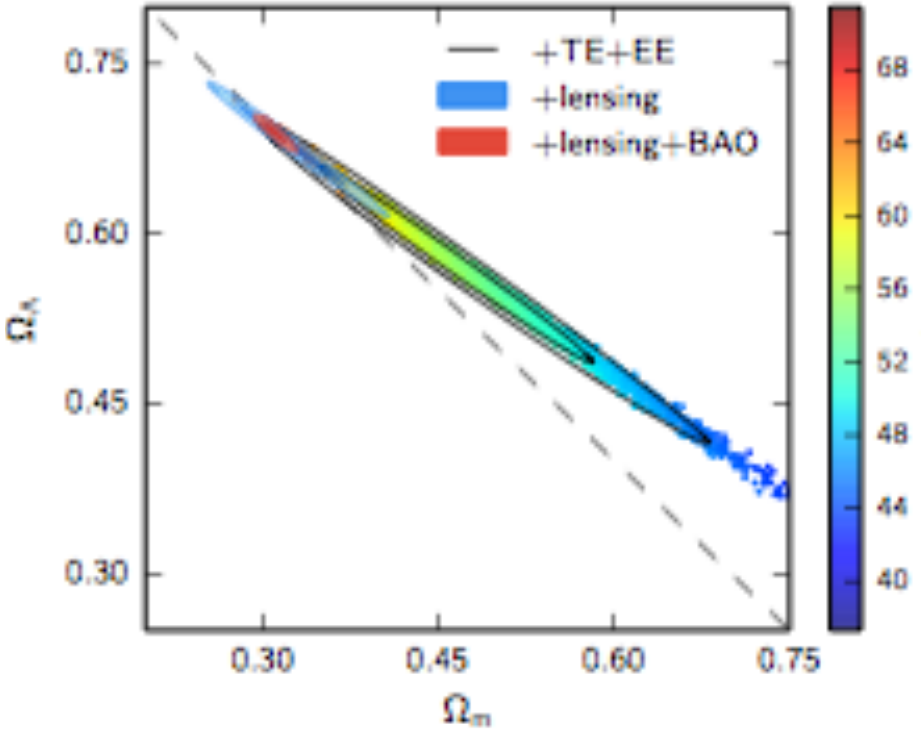
Baryon Acoustic Oscillations

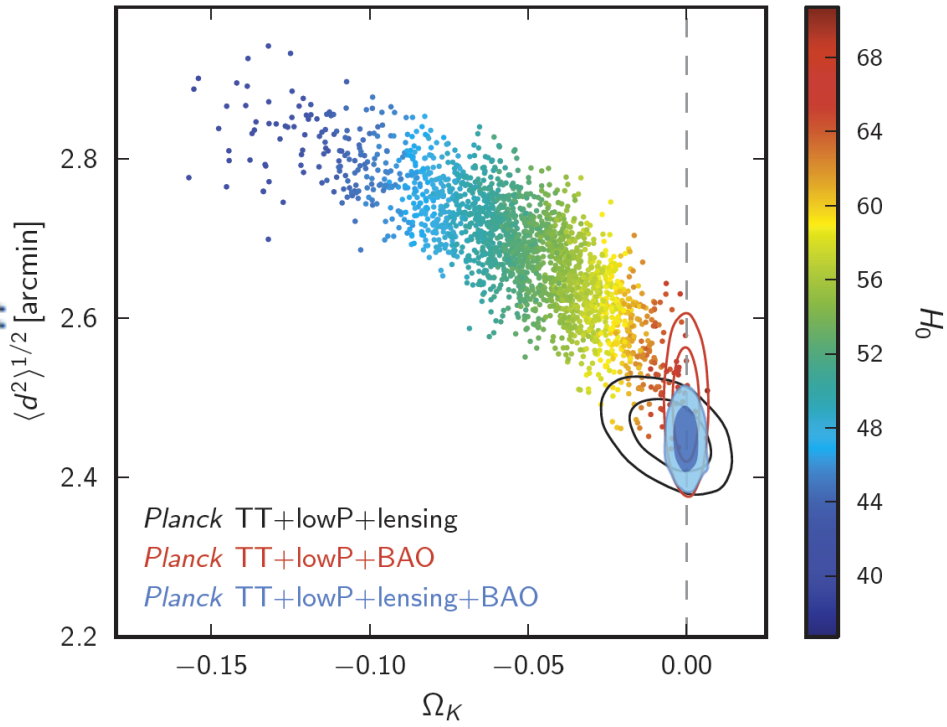


Good agreement between CMB and BAO.

BAO provides a geometrical constraint
BAO helps tighten the matter density constraints.

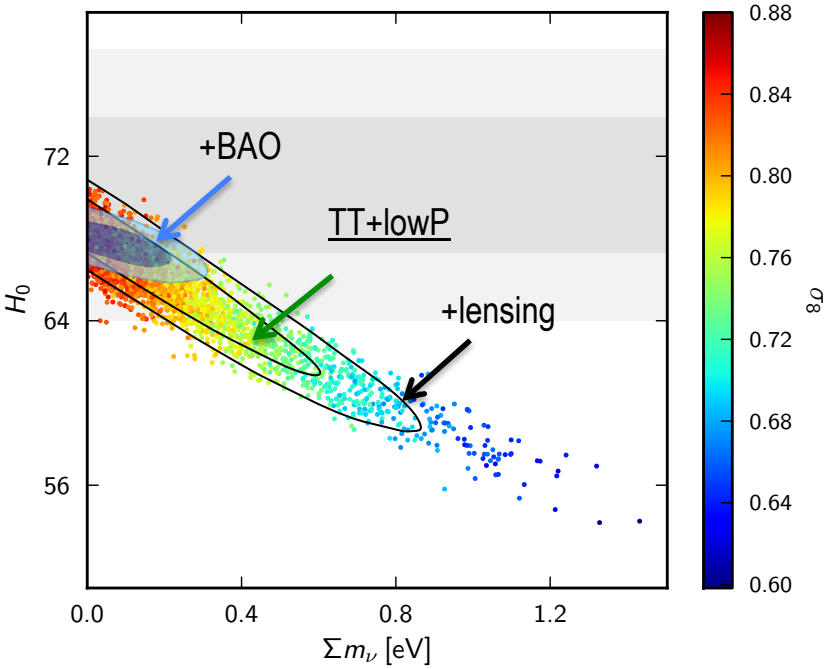
A flat universe with dark energy

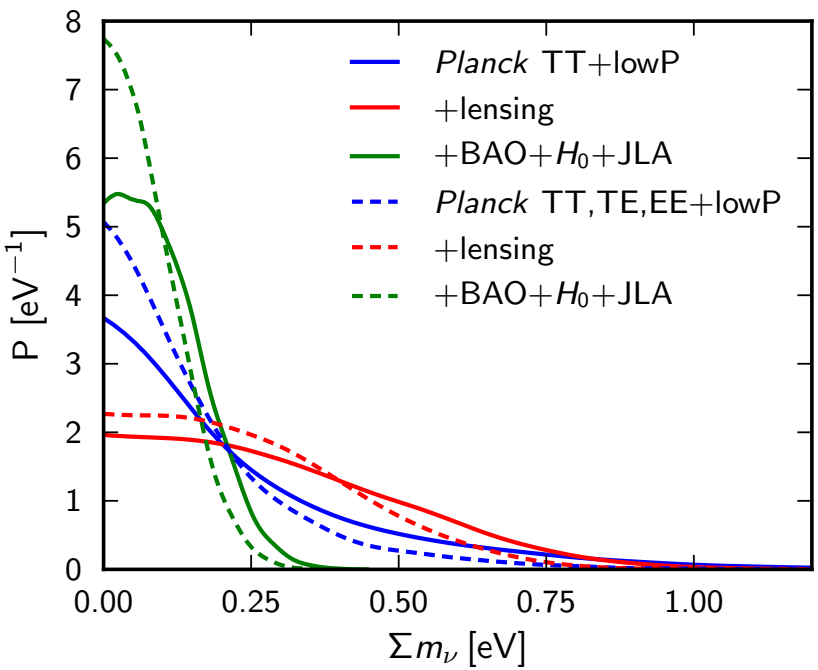




$$\Omega_K = 0.000 \pm 0.005 \ (95\%)$$

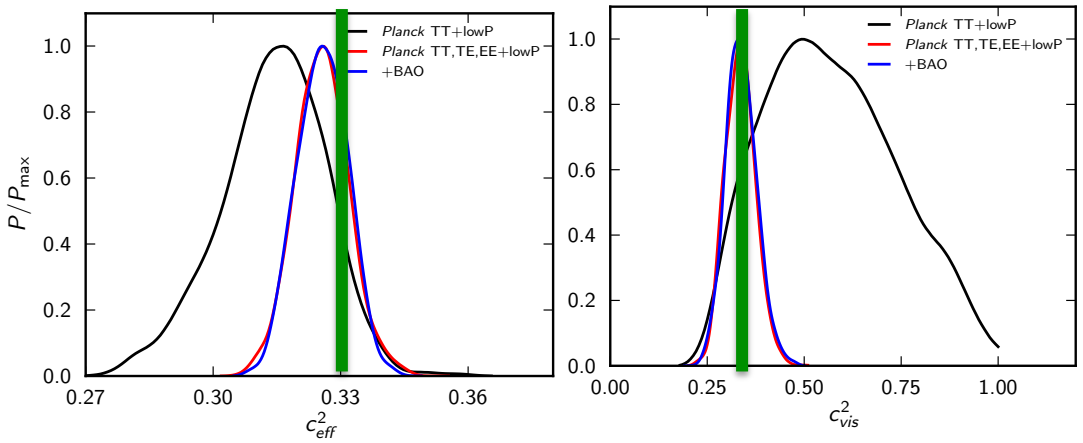
Neutrino masses





$$\sum m_\nu < 0.21 \text{ eV} (95\%)$$

Planck 2015 discovers anisotropies in the neutrino background!



- c_{eff} and c_{vis} parameterize non-ideal fluid:
  - Ideal fluid: (1/3,0)
  - Scalar field: (1,0)
  - **Free-streaming particles like neutrinos: (1/3,1/3)**

Atomic physics with Planck

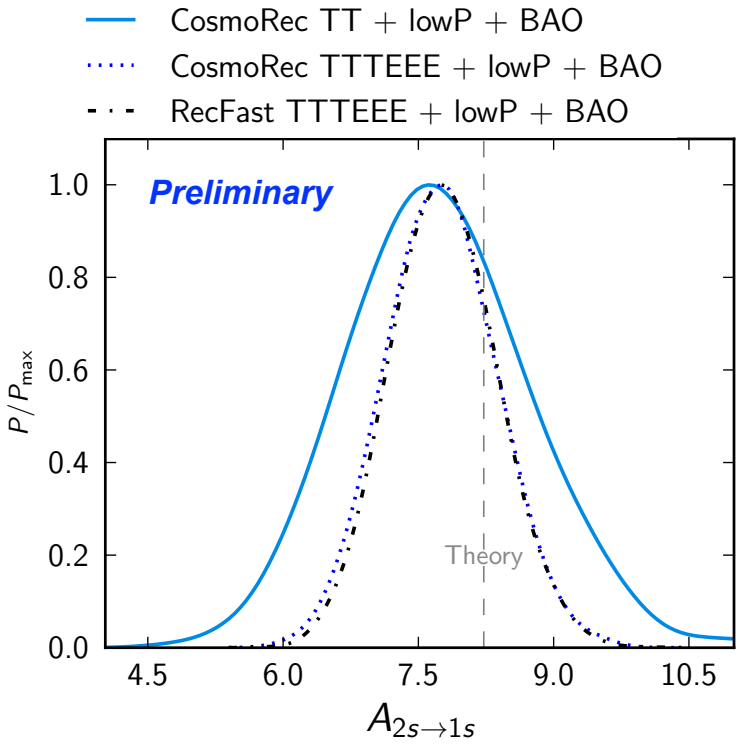
- The HI 2s-1s two photon rate is important for recombination dynamics
- Not well determined in the lab (error of ~40%)
- Theory says:

$$A_{2\mathrm{s}\to1\mathrm{s}}^{\mathrm{theory}} = 8.2206 s^{-1}$$

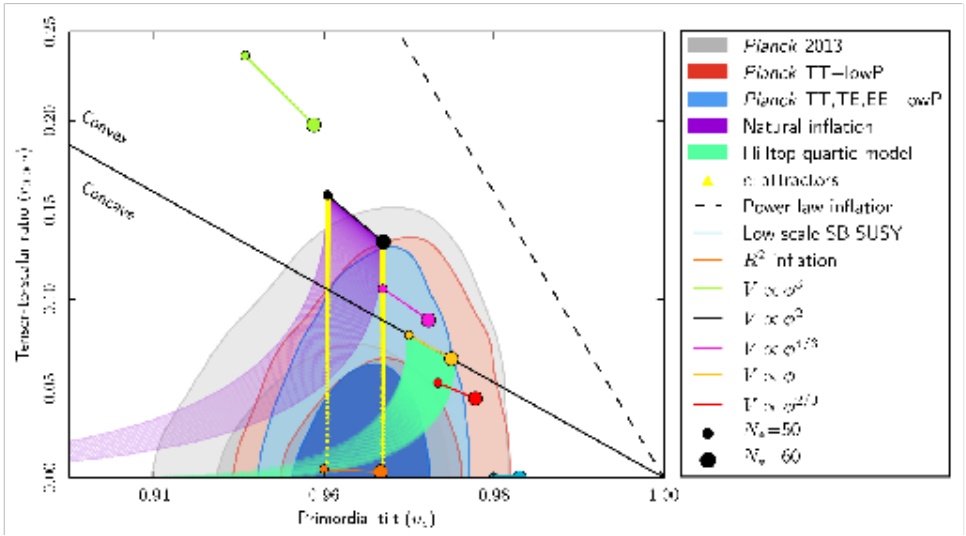
- Planck measures

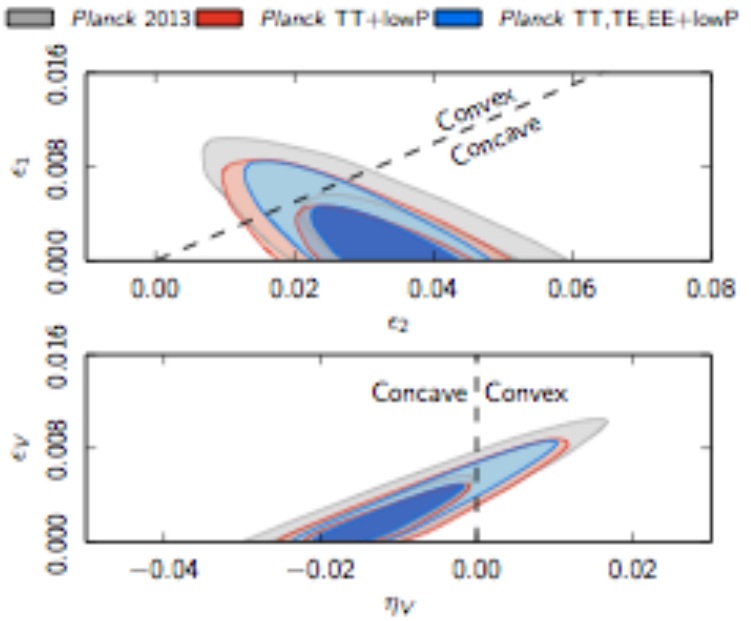
$$A_{2\mathrm{s}\to1\mathrm{s}} = 7.75 \pm 0.61 s^{-1}$$

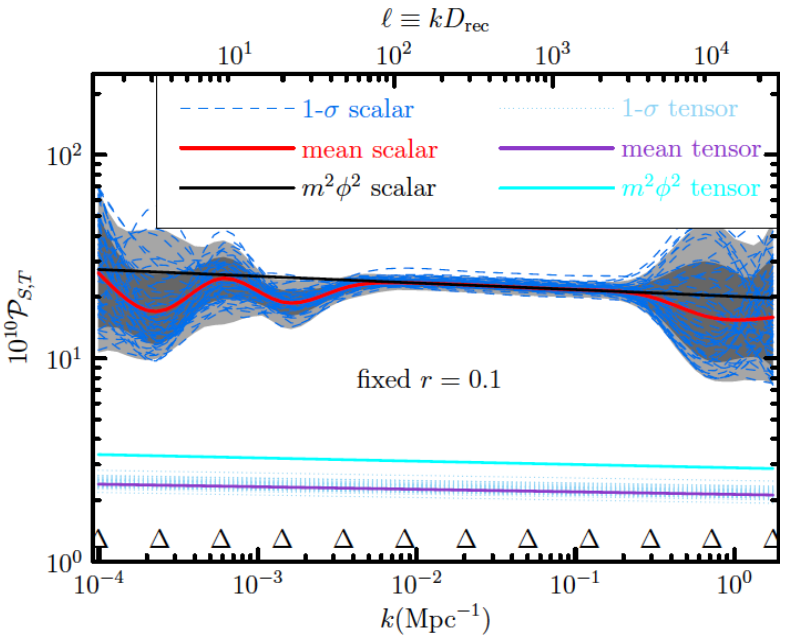
~8% error!

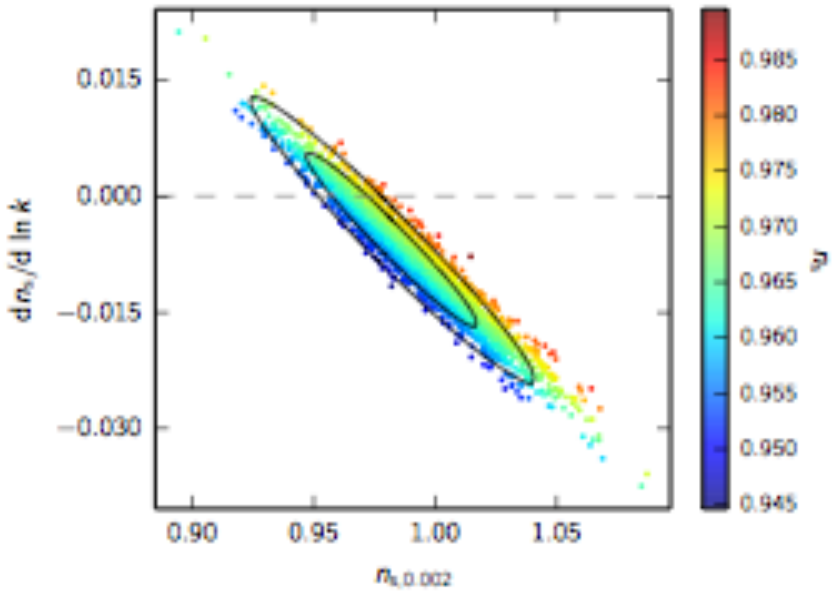


Constraints on Inflation



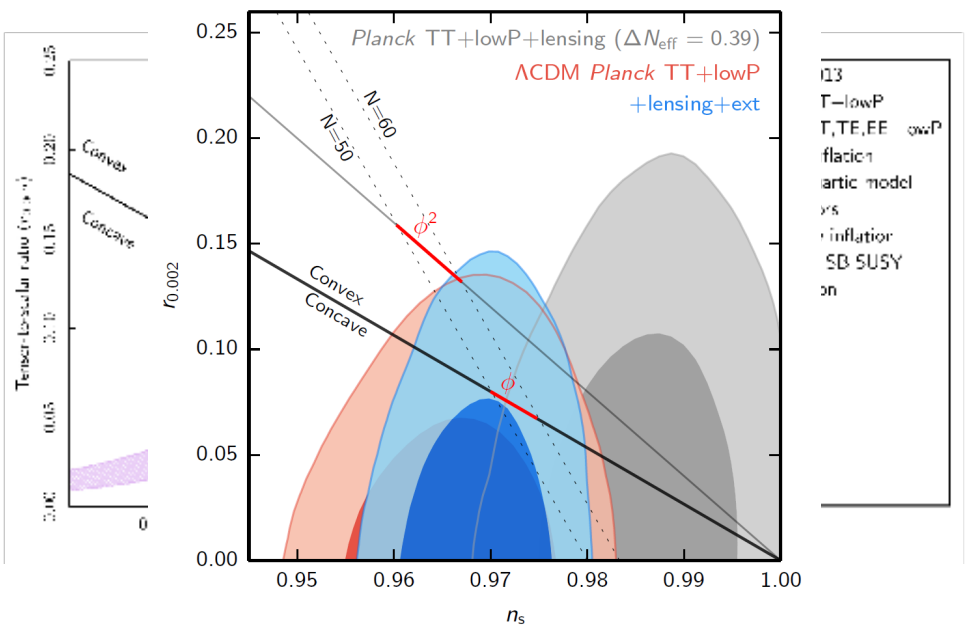


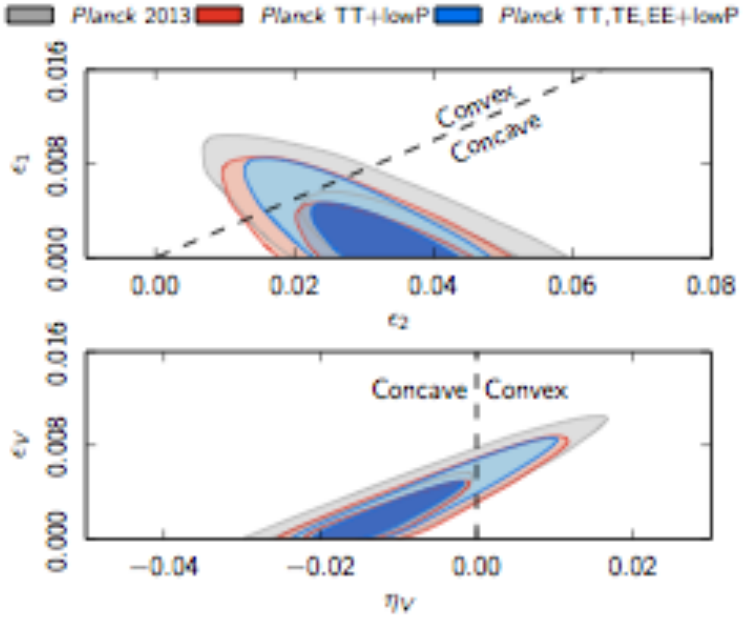


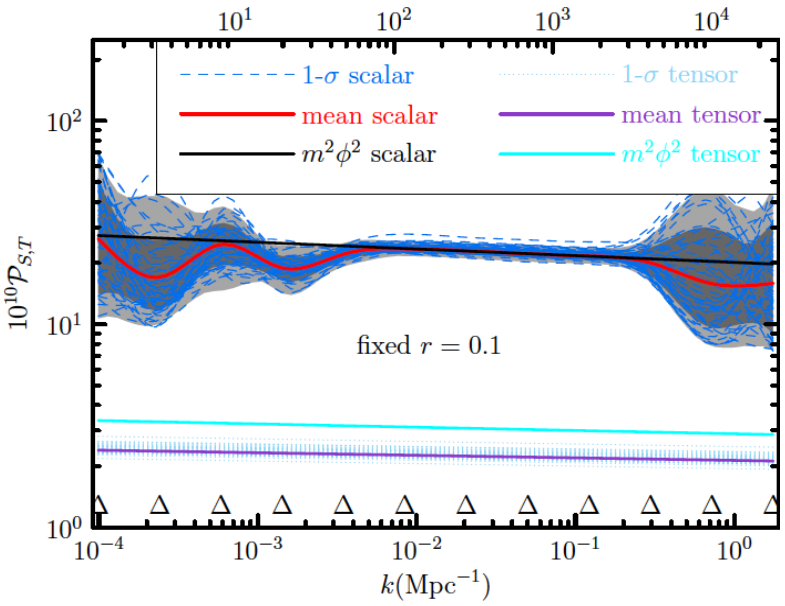


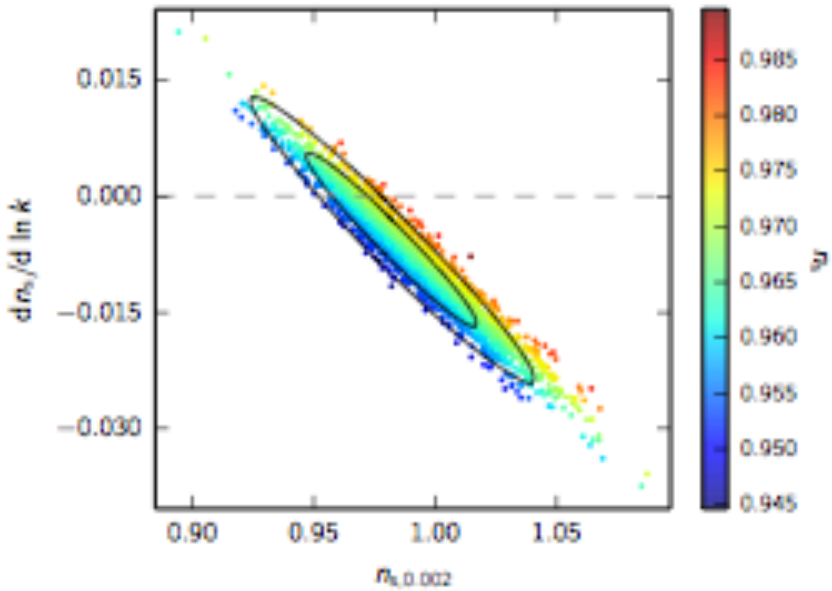
Constraints on Inflation

Beware that some results are model dependent…

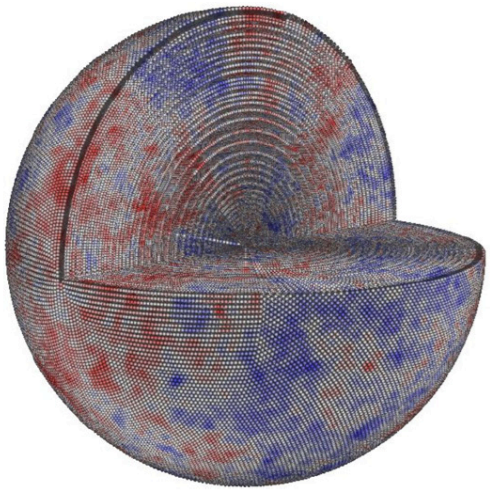






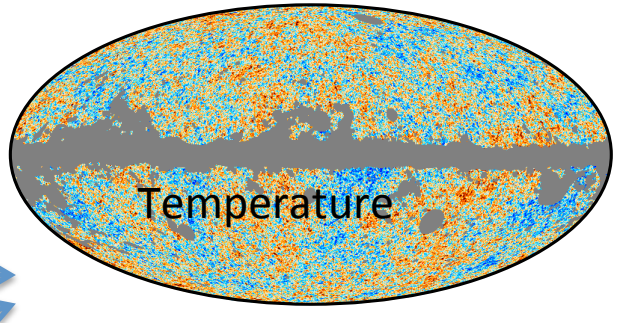


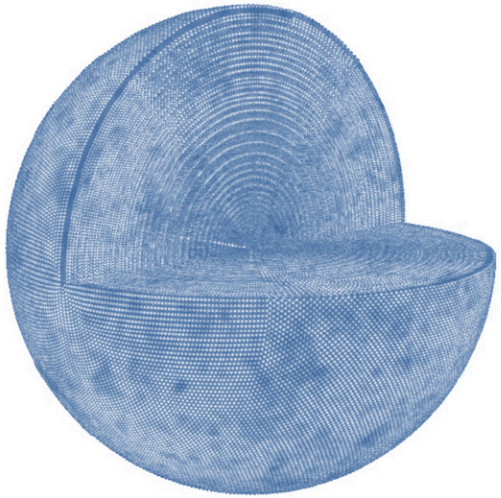
Polarization breaks isocurvature degeneracies



ζ

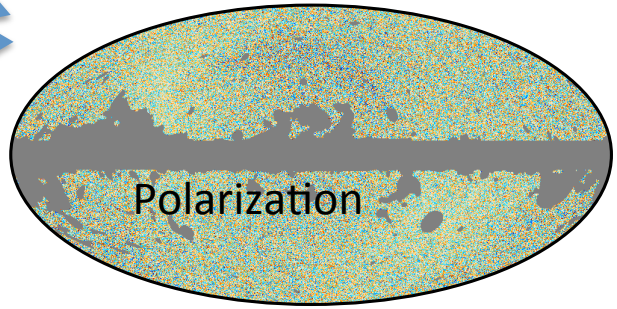
Radiative Transfer





S

Plasma Physics

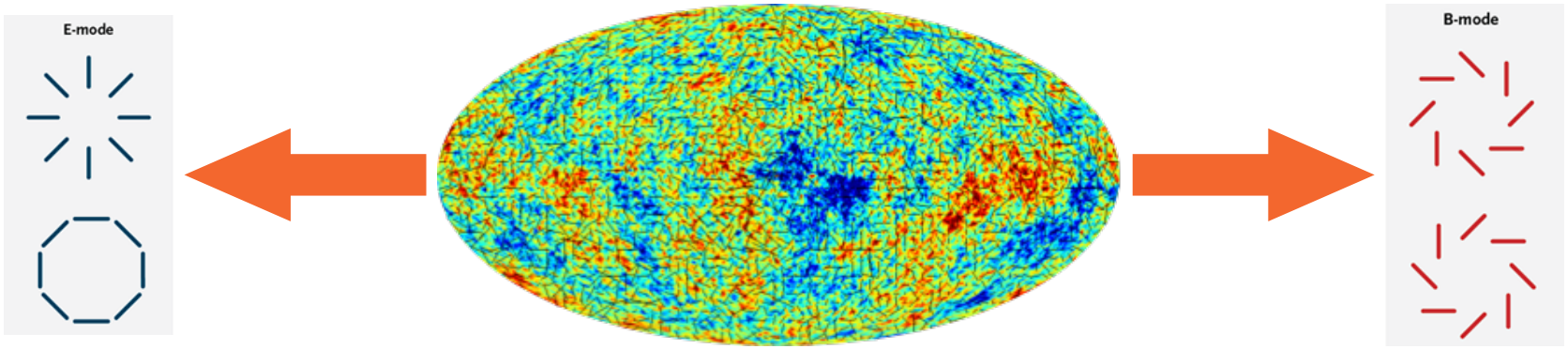


Isocurvature constraints

- Limits on Cold dark matter isocurvature, neutrino density isocurvature, and neutrino velocity isocurvature are now

$$|\alpha_{\text{non-adi}}| < 1.9\,\%,\ 4.0\,\%,\ \text{and}\ 2.9\,\%$$

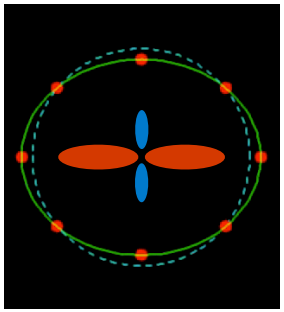
- Polarization improved non-Gaussianity constraints on isocurvature modes by large factors.

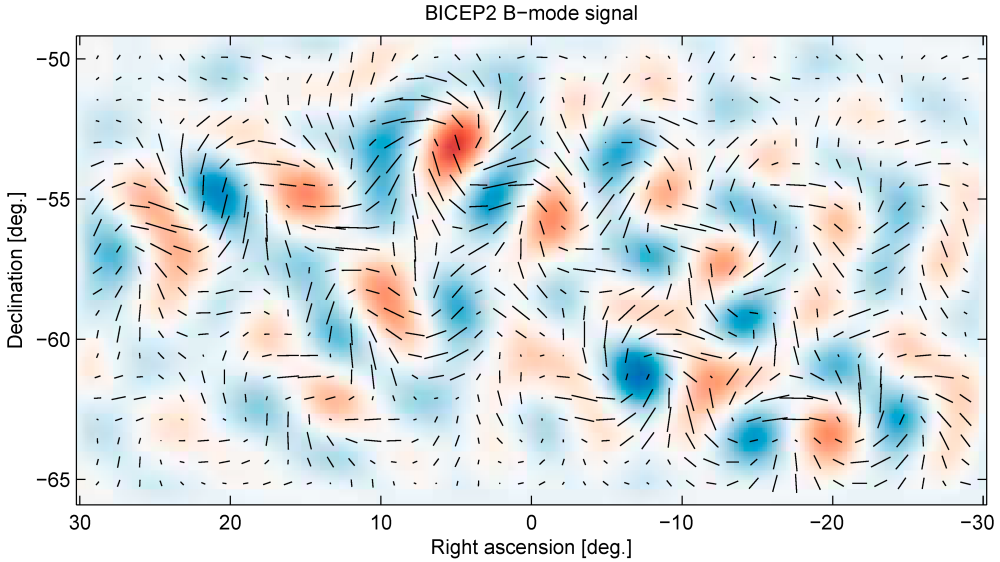


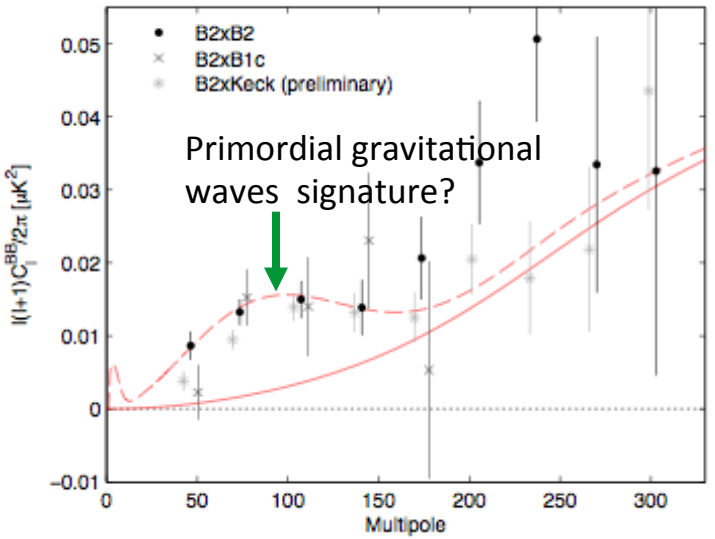
March 2014

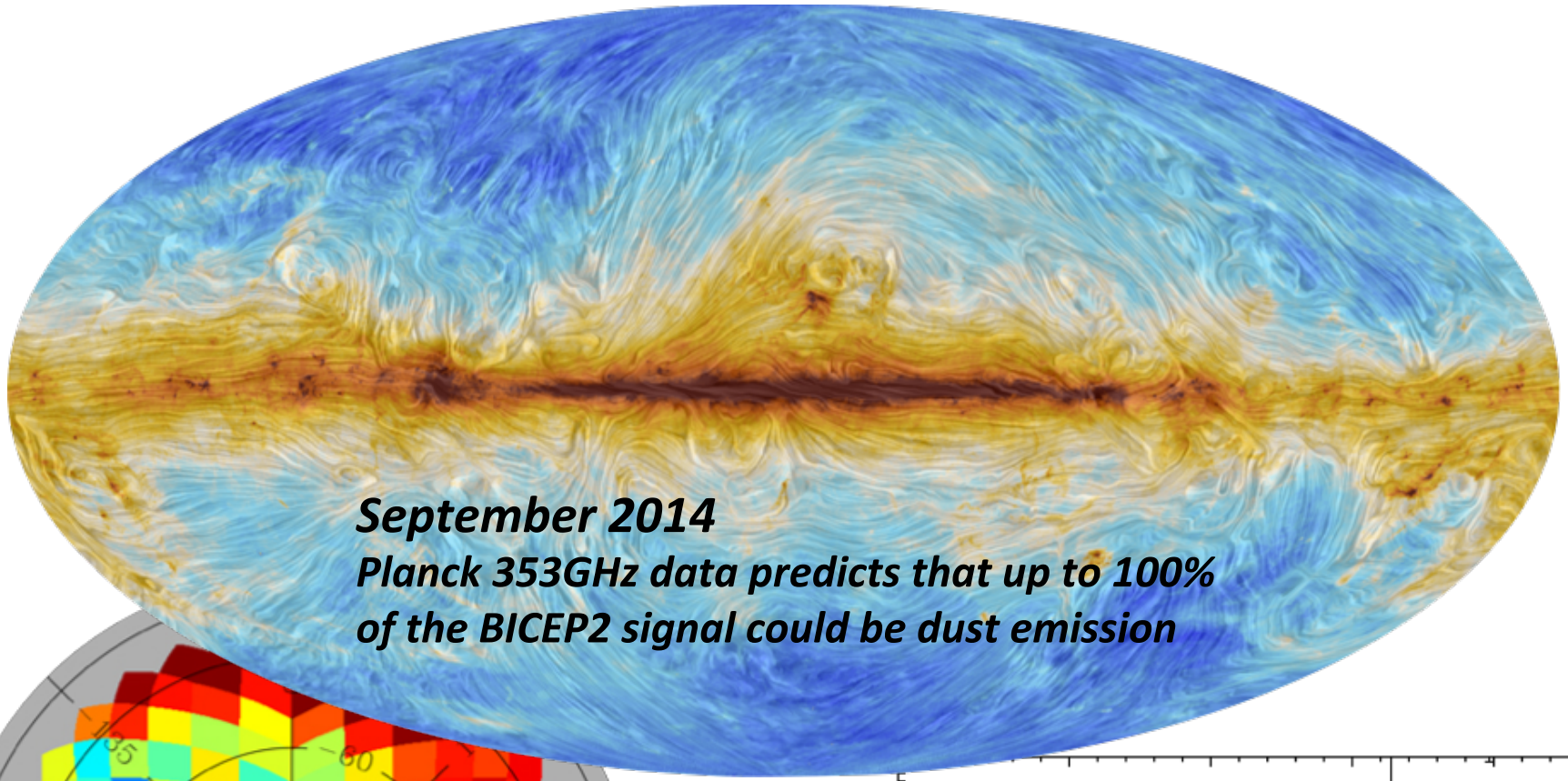
Bicep2 announced a detection of primordial B Polarization at large scale.

Large scale B polarization is a signature of the gravitational waves background



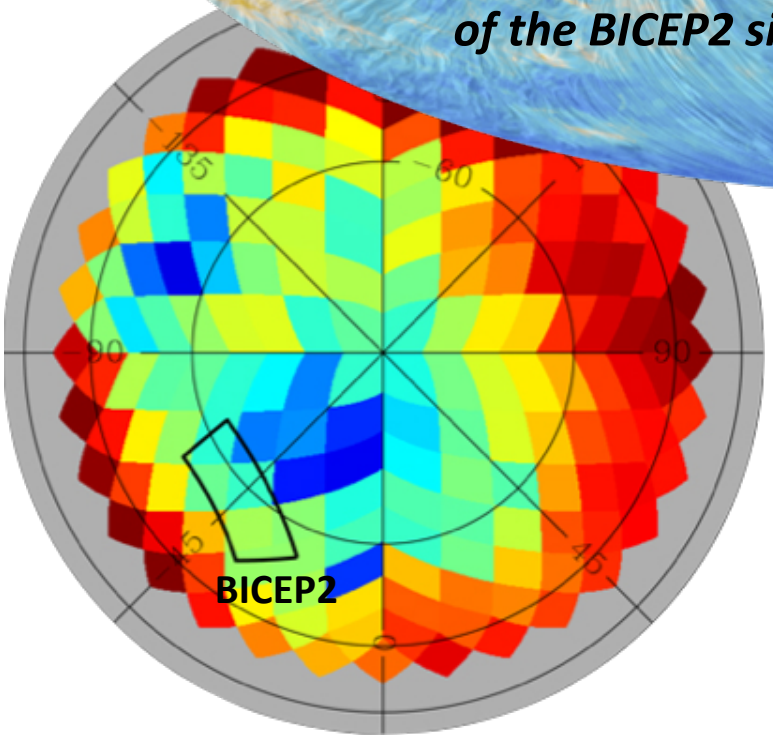


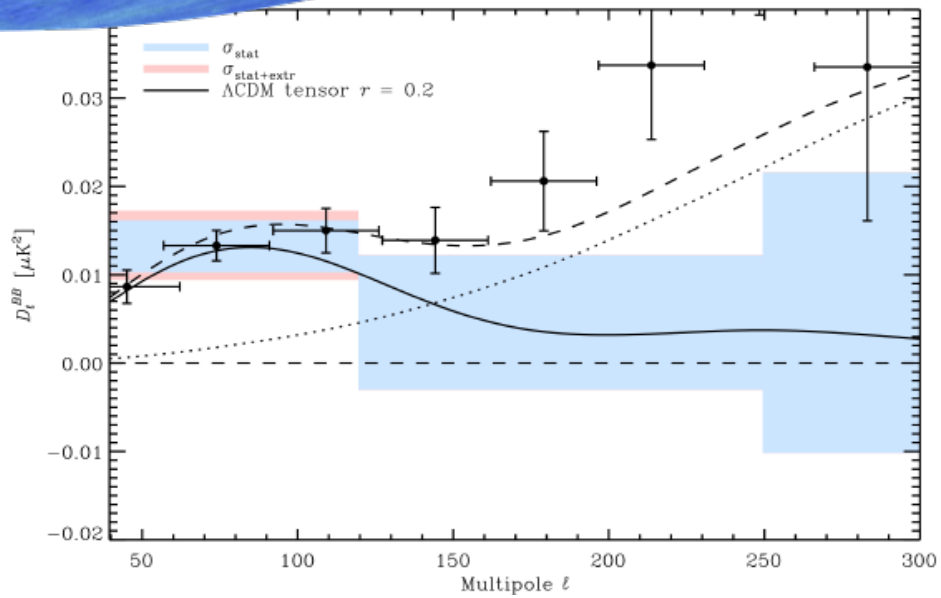




September 2014

Planck 353GHz data predicts that up to 100% of the BICEP2 signal could be dust emission



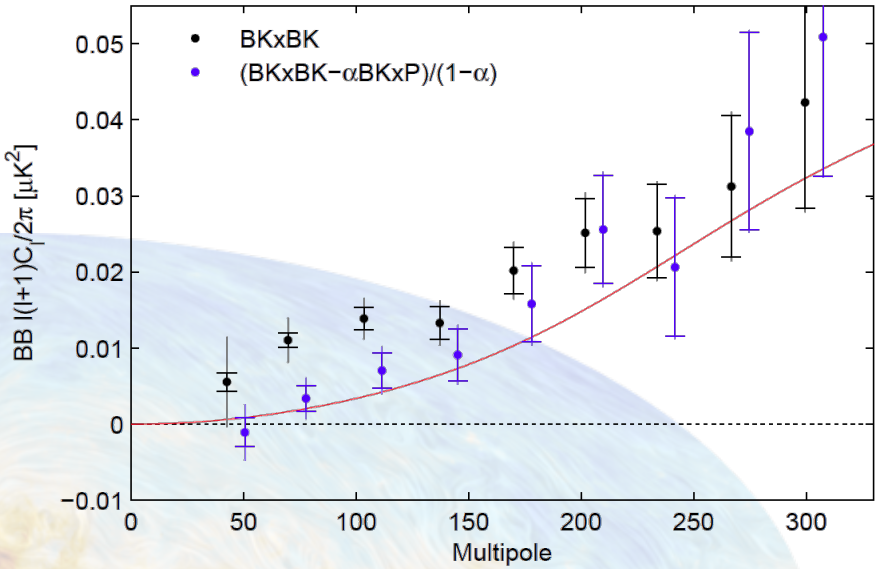


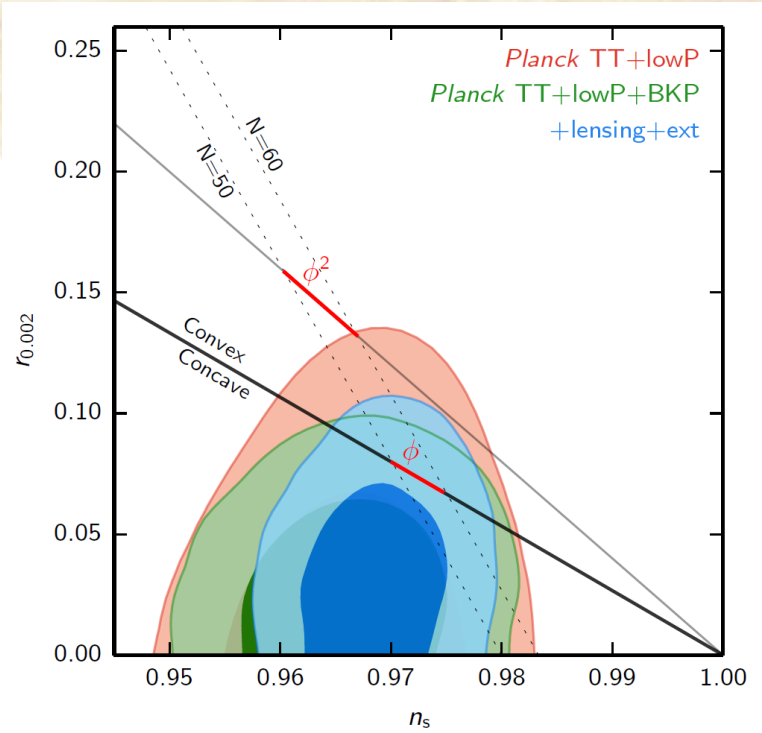
February 2015

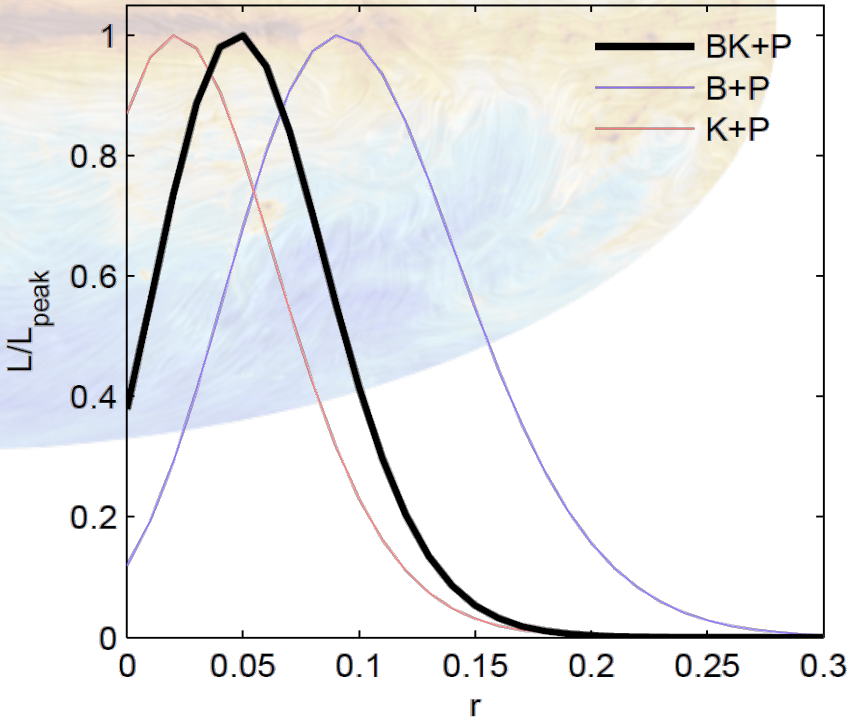
- *Joint Planck 353/Bicep2-Keck analysis*
- *No significant primordial B Polarization after 353GHz cleaning*
- *BKP constraint on r similar to Planck*
- *Joint constraint improves the upper limit*

$r_{0.002} < 0.11$, *Planck* TT+lowP+lensing+ext,
$r_{0.002} < 0.09$, *Planck* TT+lowP+lensing+ext+BKP.

- *Polarized dust emission is the key…*

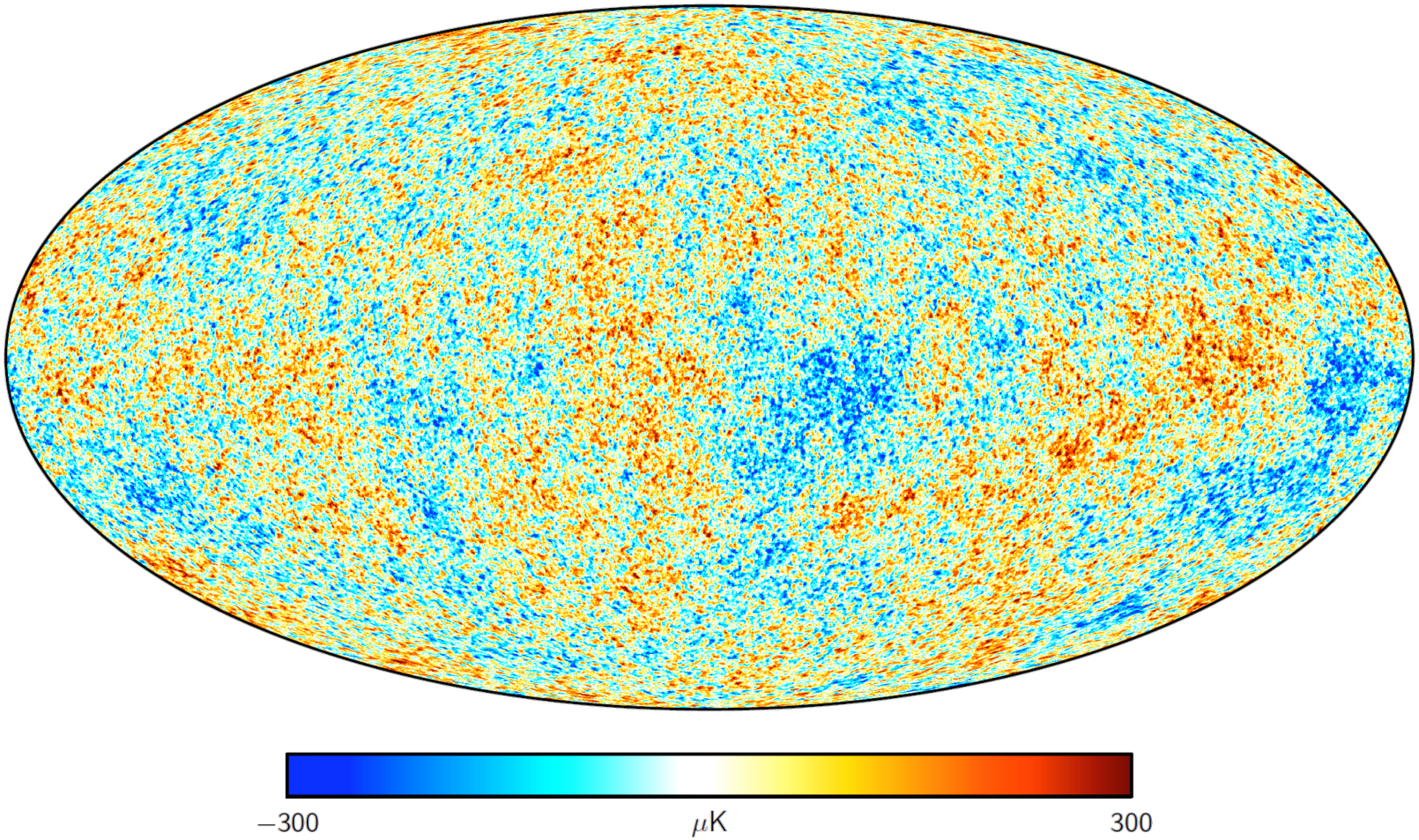




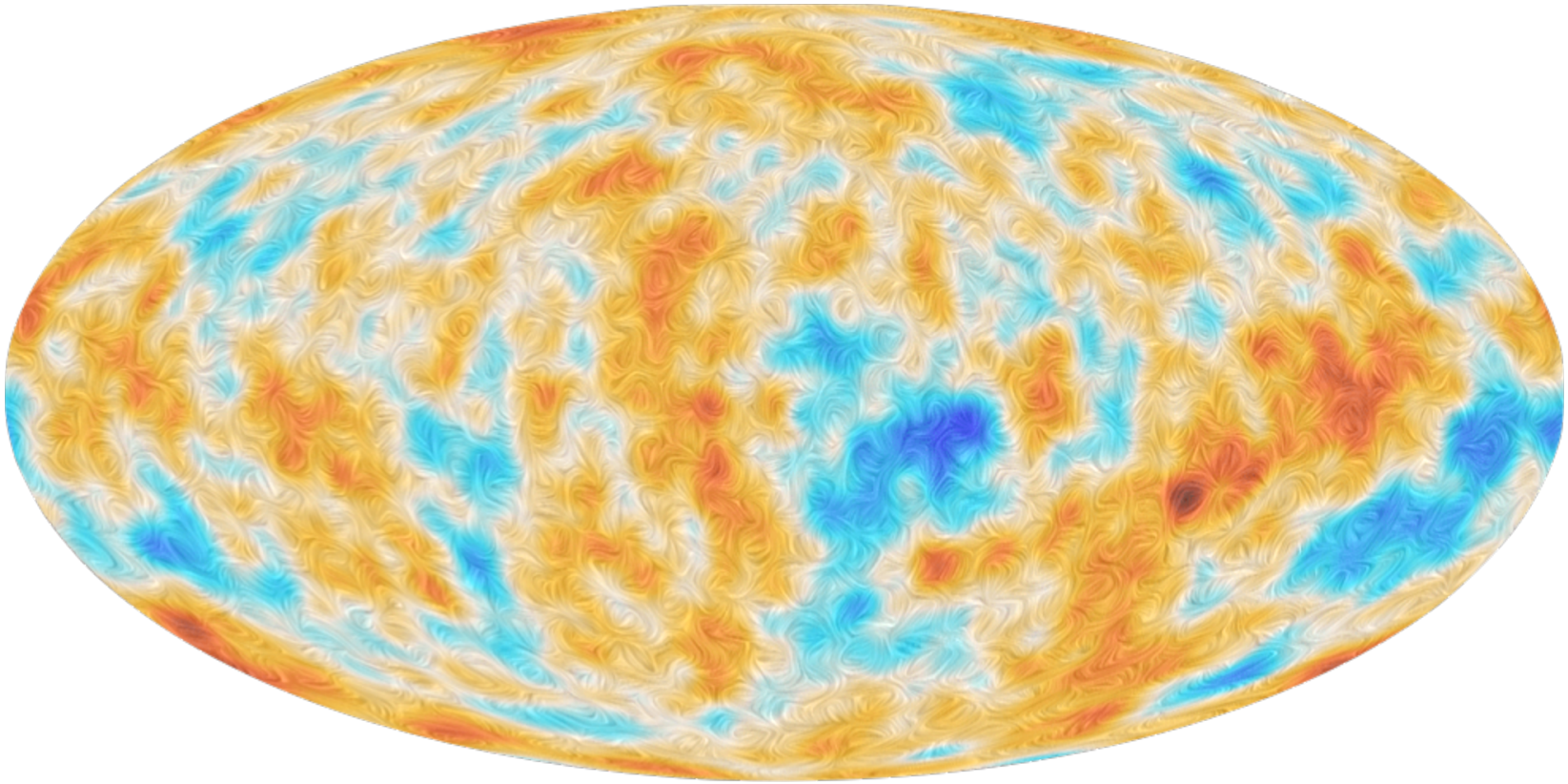


Beyond the power spectrum

The Planck 2015 temperature map

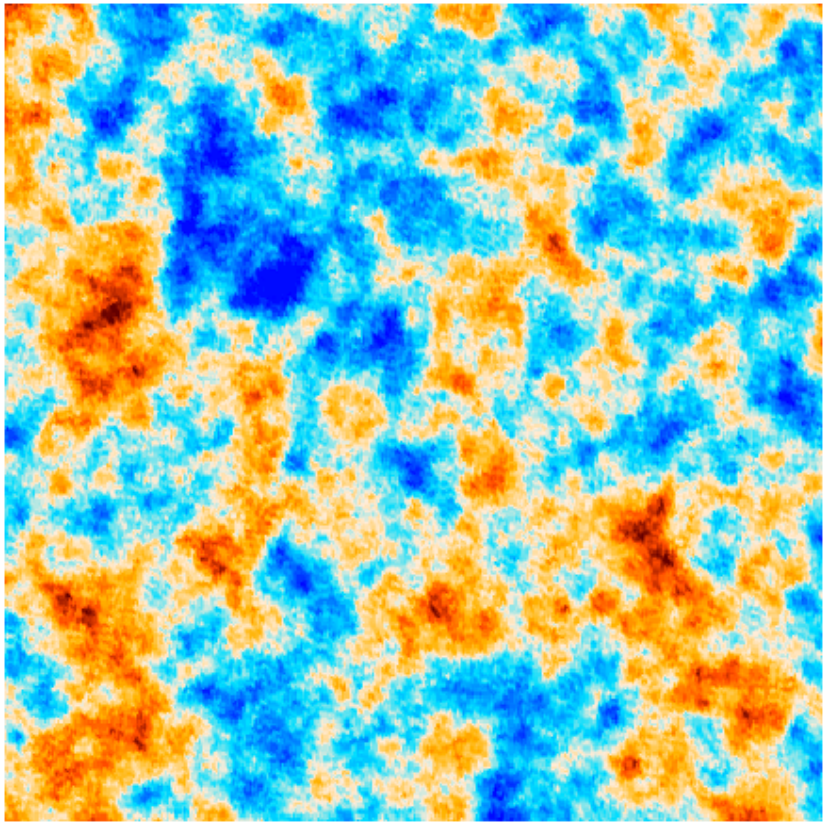


The Planck 2015 polarization map

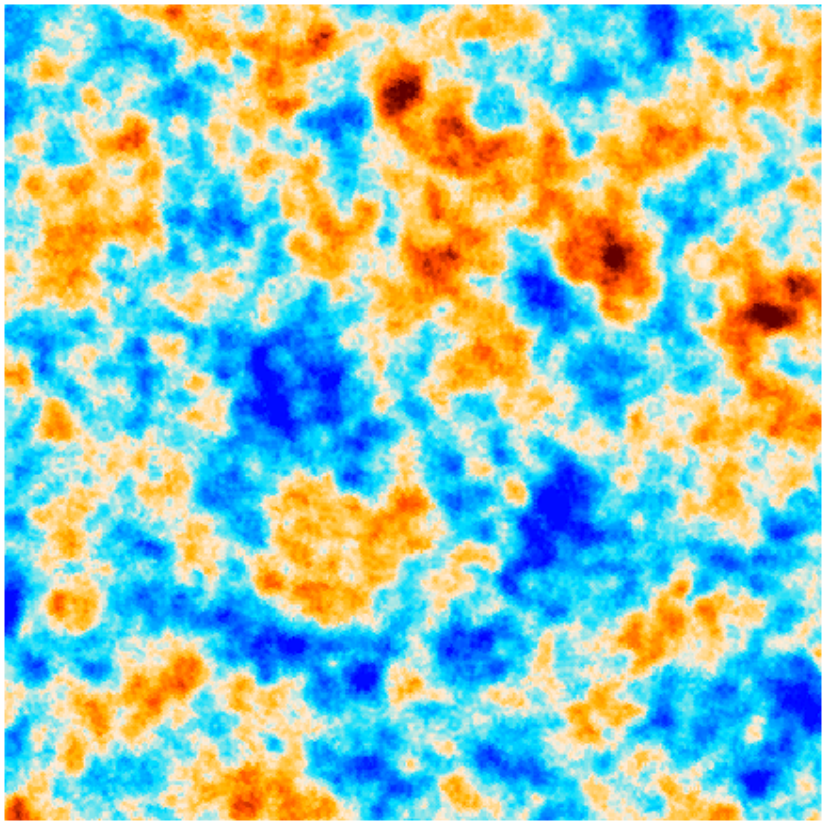


Fluctuations larger than 10 degrees removed

(glon,glat)=(139,43)

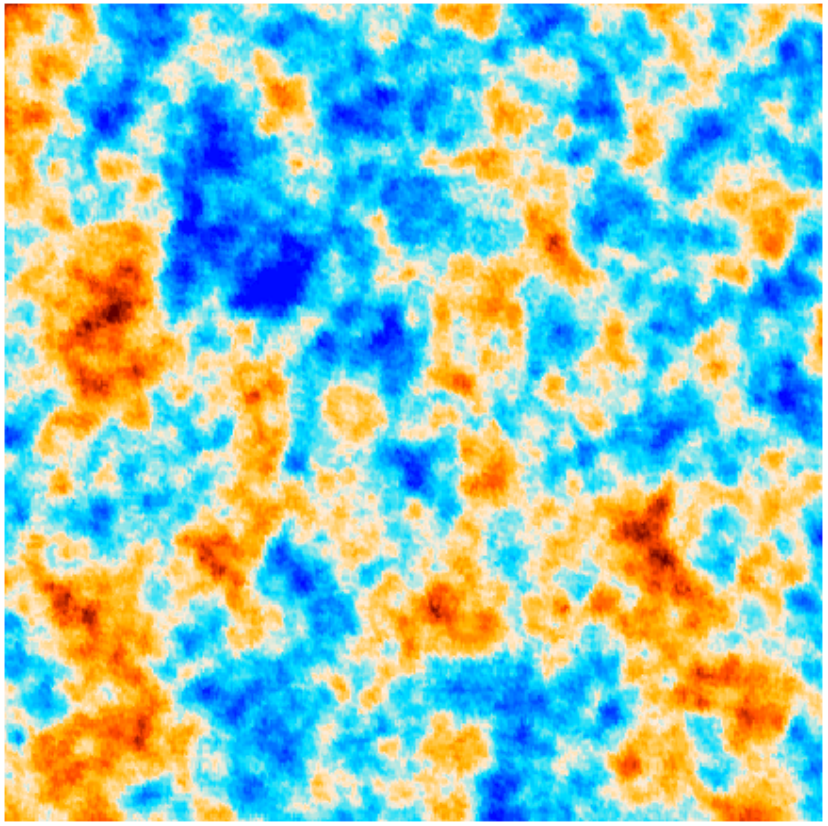


(glon,glat)=(99,-50)

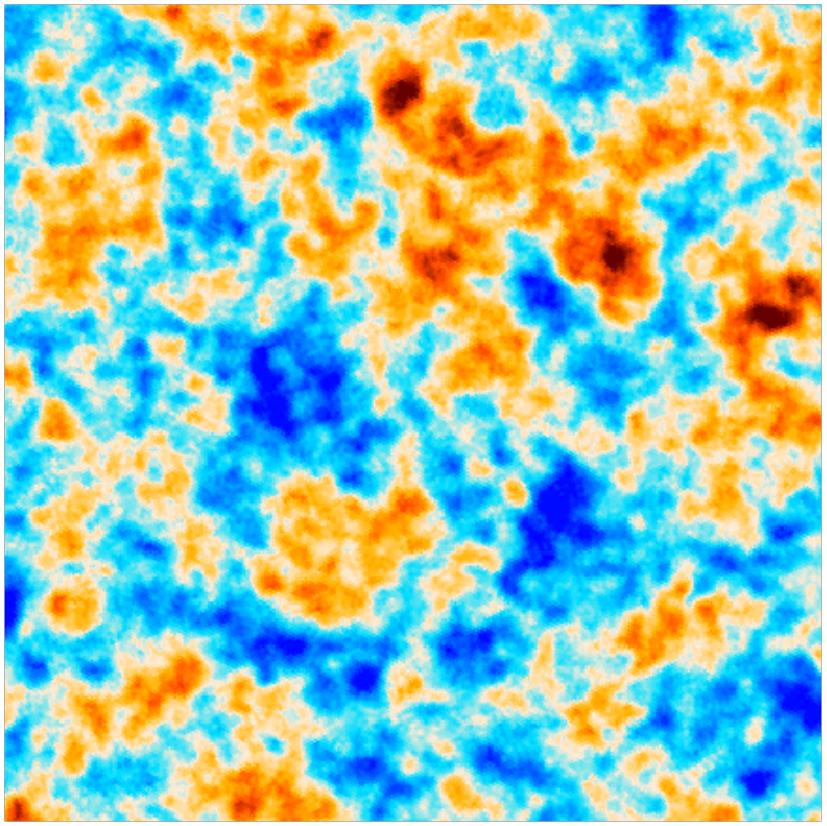


***Planck** 2013*

(glon,glat)=(139,43)

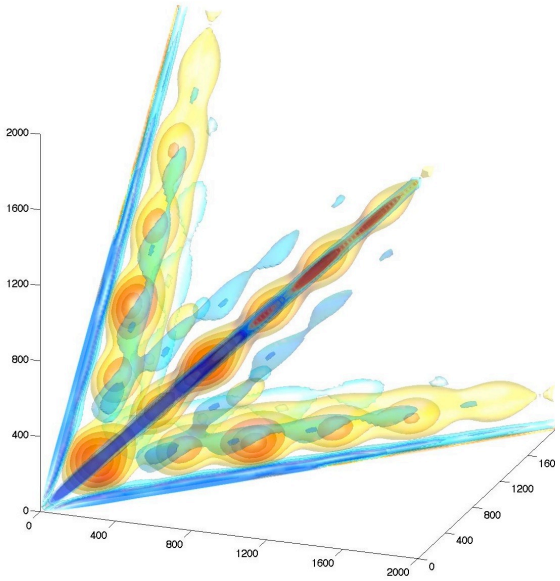


(glon,glat)=(99,-50)



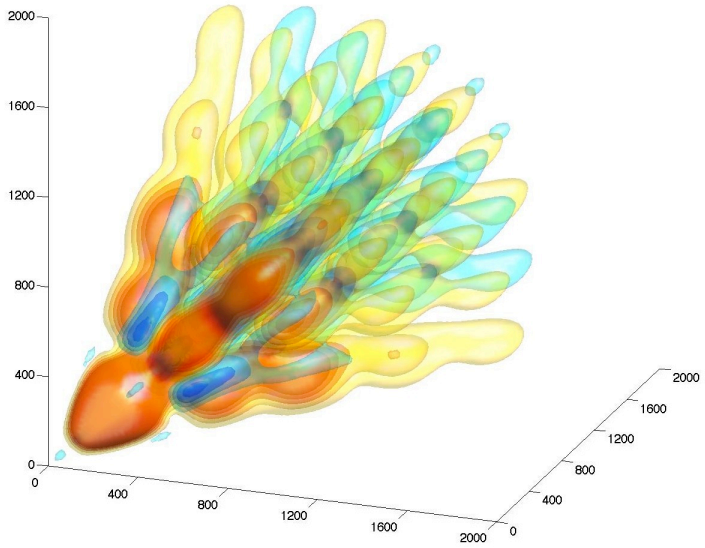
Planck 2015

Beyond the C_l: CMB bispectrum fingerprinting with Planck



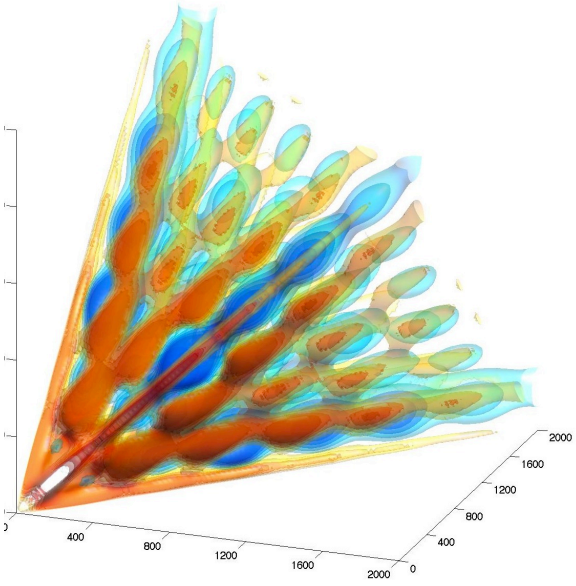
NG of ***local*** type:

- Multi-field models
- Curvaton
- Ekpyrotic/cyclic models



NG of ***equilateral*** type

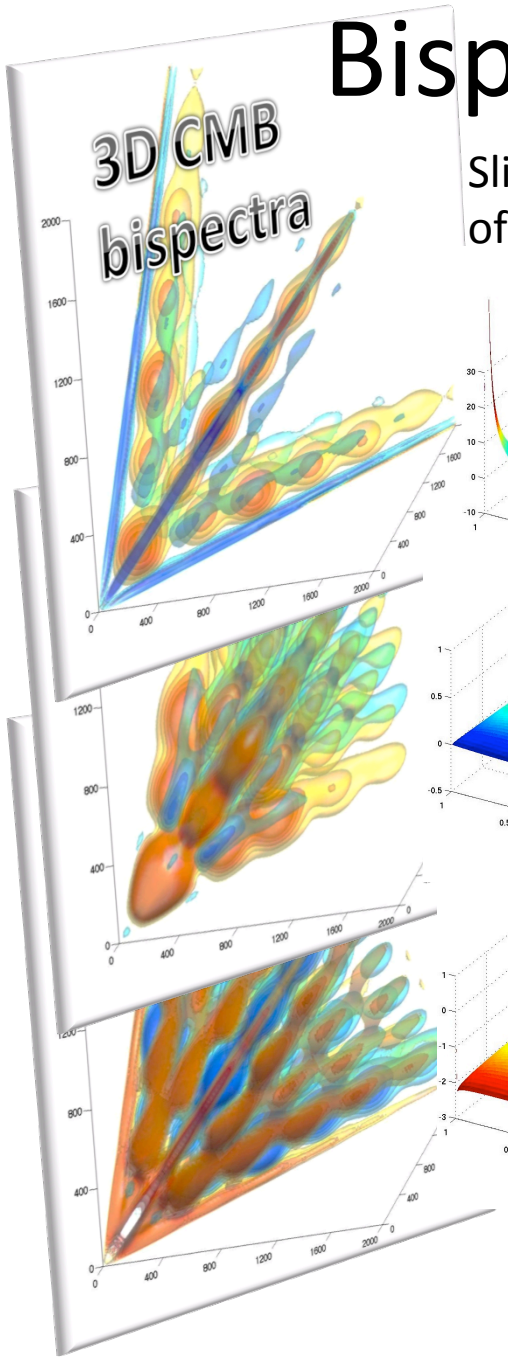
- Non-canonical kinetic term
  - K-inflation
  - DBI inflation
- Higher-derivate terms in Lagrangian
  - Ghost inflation
- Effective field theory



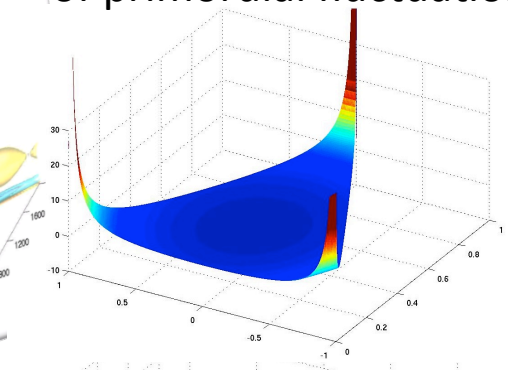
NG of ***orthogonal*** type

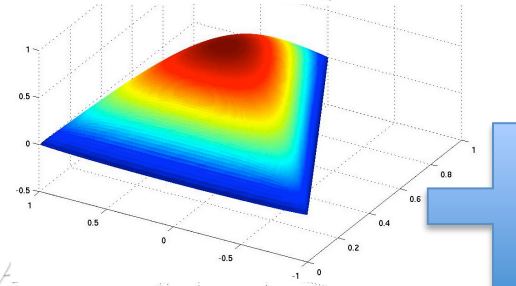
- Distinguishes between different variants of
  - Non-canonical kinetic term
  - Higher derivative interactions
- Galileon inflation

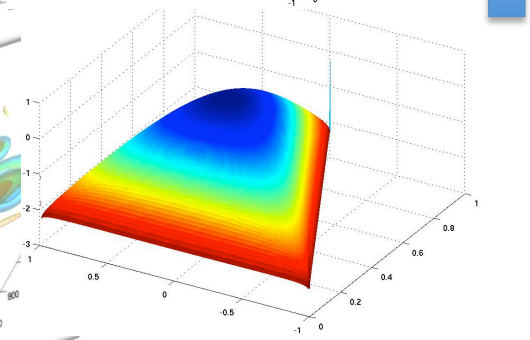
Bispectrum fingerprinting

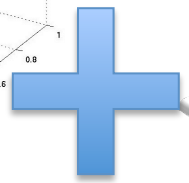


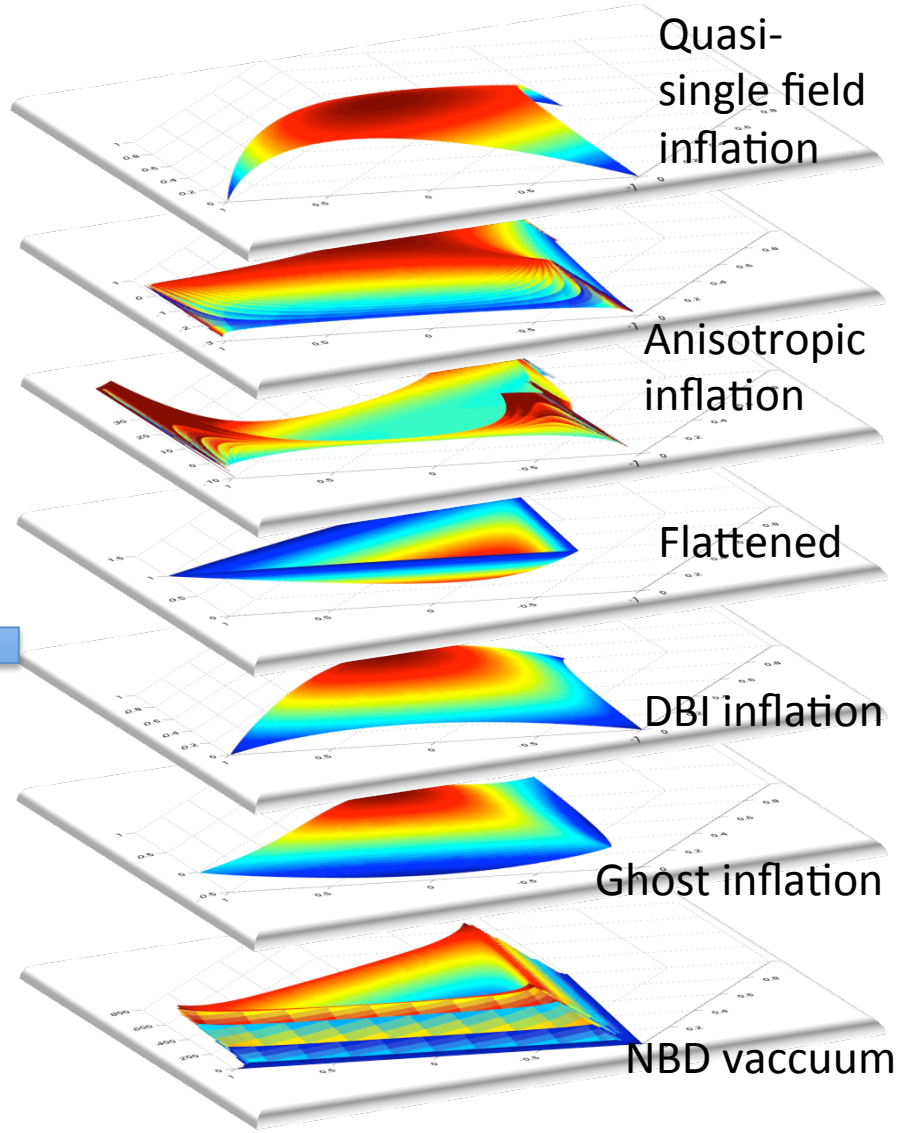
Slices through bispectra
of primordial fluctuations











• • •

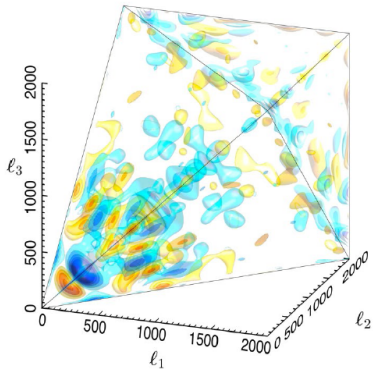
Planck 2013 headlines

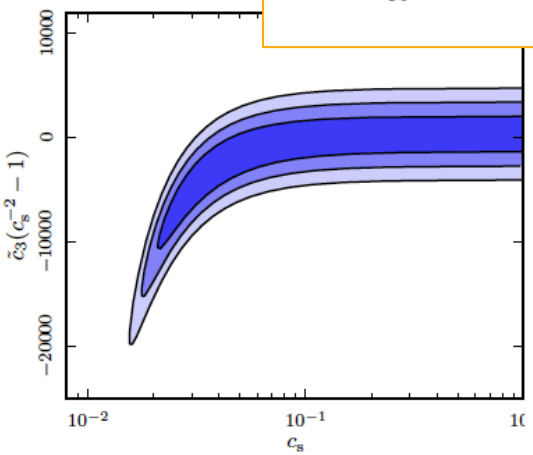
- **Tightest constraints on primordial non-Gaussianity so far: the highest precision test on the origin of cosmic structure**

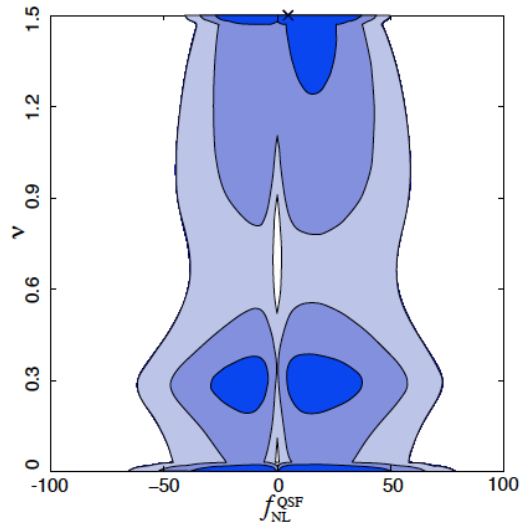
ISW-lensing subtracted		
KSW	Binned	Modal
2.7 ± 5.8	2.2 ± 5.9	1.6 ± 6.0
−42 ± 75	−25 ± 73	−20 ± 77
−25 ± 39	−17 ± 41	−14 ± 42

$$S = \int d^4x\sqrt{-g}\left[-\frac{M_{\rm Pl}^2\dot{H}}{c_{\rm s}^2}\left(\dot{\pi}^2 - c_{\rm s}^2\frac{(\partial_i\pi)^2}{a^2}\right) - M_{\rm Pl}^2\dot{H}(1-c_{\rm s}^{-2})\dot{\pi}\frac{(\partial_i\pi)^2}{a^2} + \left(M_{\rm Pl}^2\dot{H}(1-c_{\rm s}^{-2}) - \frac{4}{3}M_3^4\right)\dot{\pi}^3\right]$$

- **Consistent with a Gaussian Universe**
- Some hints of oscillatory features

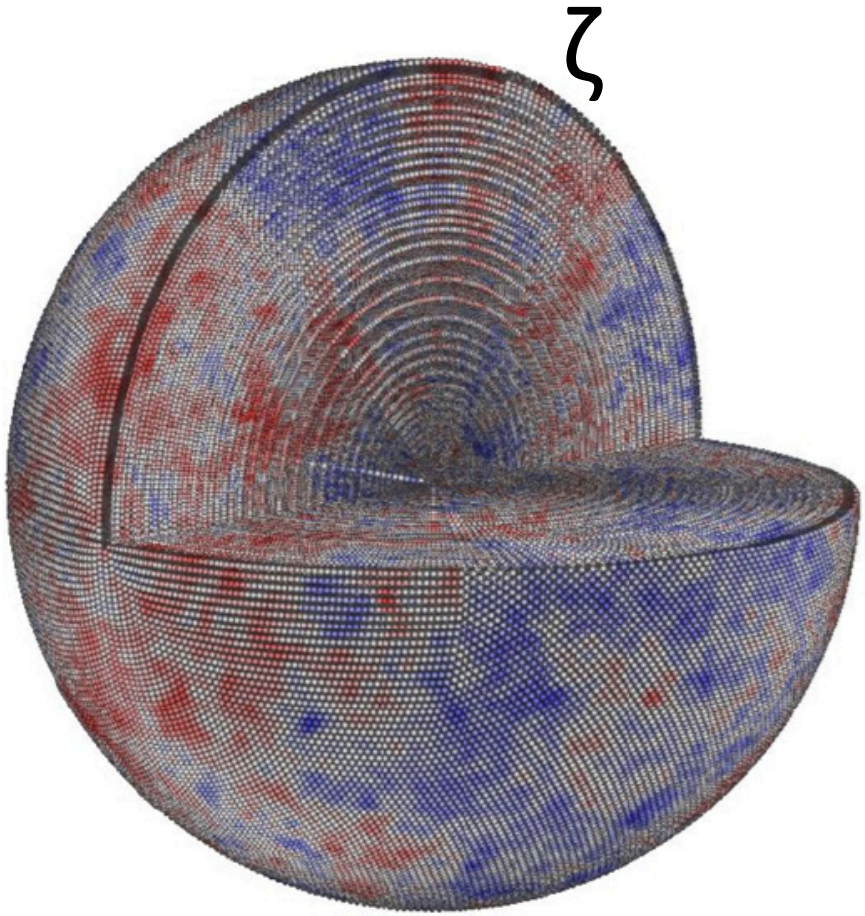




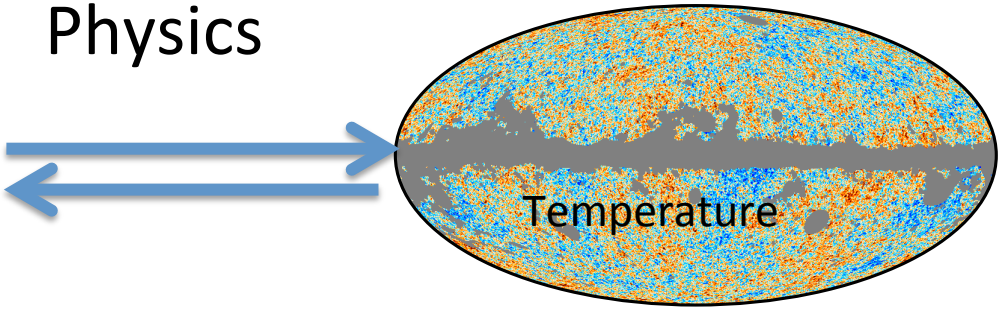


How does the CMB constrain the initial conditions?

Primordial curvature perturbations ζ give rise to the cosmic microwave background anisotropies

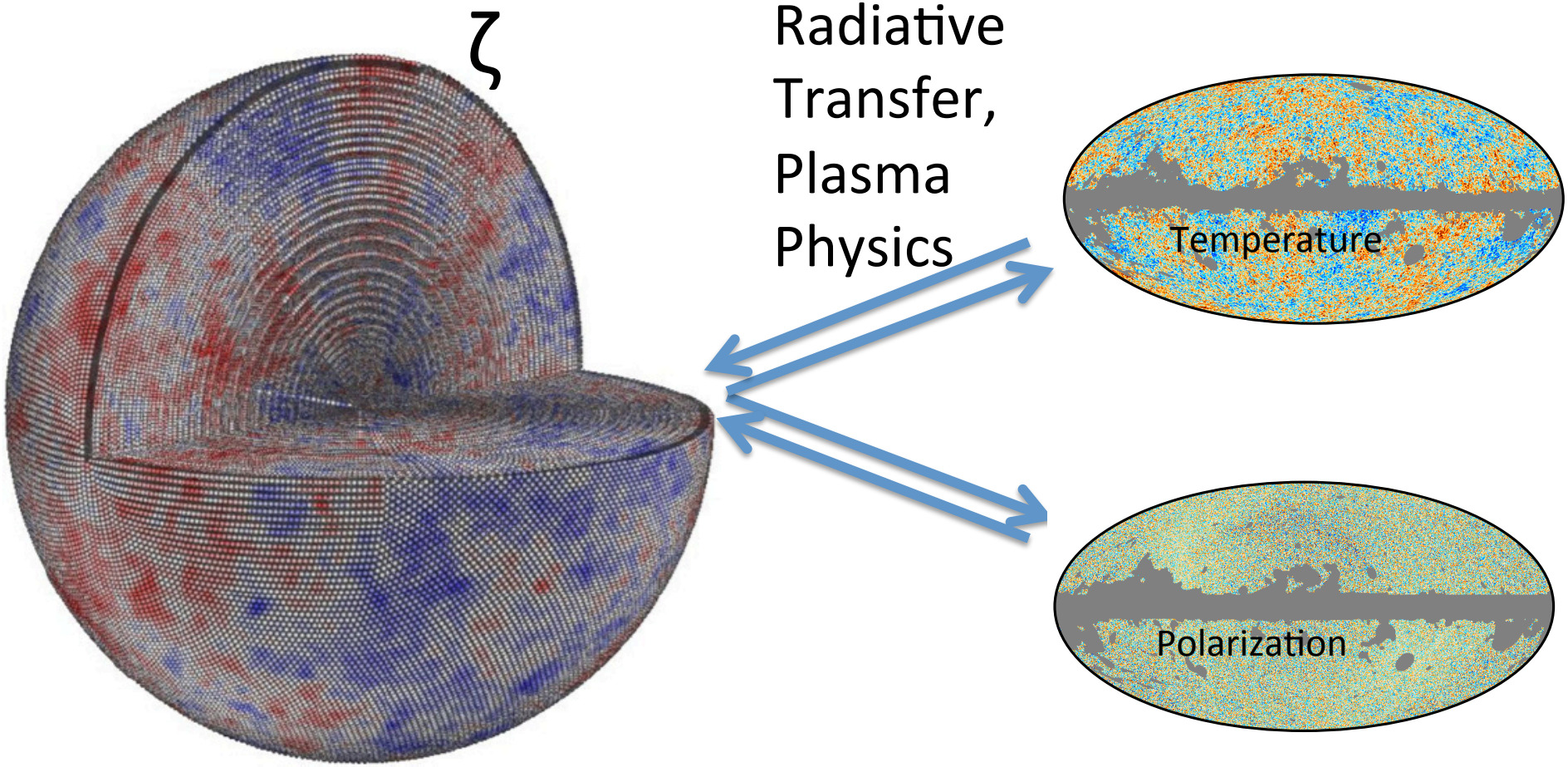


Radiative Transfer, Plasma Physics



Planck 2013

Primordial curvature perturbations give rise to the cosmic microwave background anisotropies



Planck 2015

First constraints on non-Gaussianity with CMB polarization data

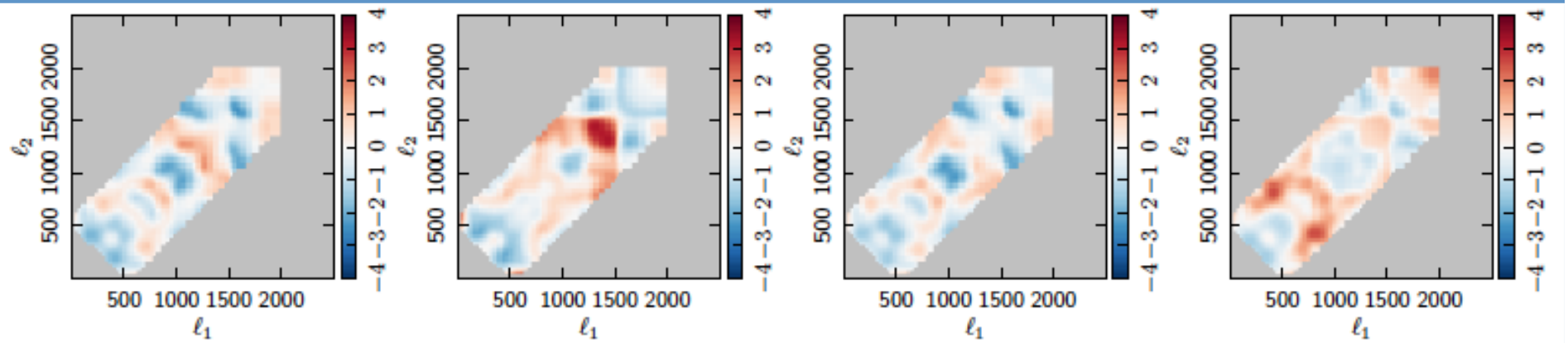
- Developed a set of cross-validated optimal or near-optimal estimators for **T, E** and **T+E**:
  - Komatsu Spergel Wandelt (KSW) for local, equilateral, and orthogonal (LEO) and other factorizable templates
  - Binned bispectrum
  - 2 modal bispectrum estimators
- An improved estimator based on Minkowski Functionals for **T**, **E** and **T+E**
- A KSW-style estimator of high-frequency linearly oscillatory features for **T, E** and **T+E**

The Planck 2014 binned bispectrum

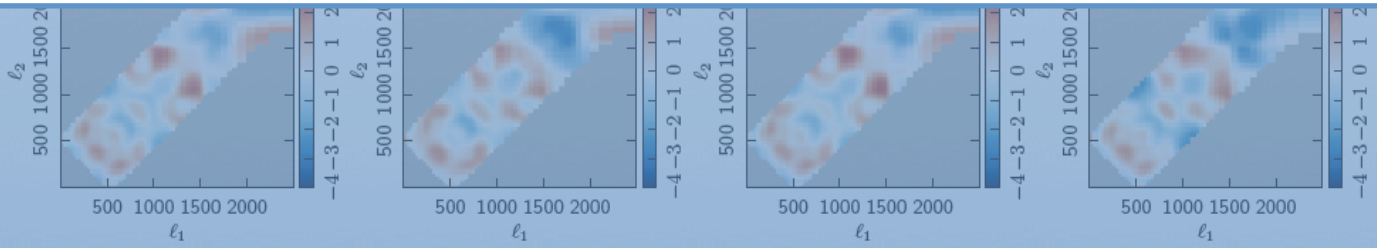
SMICA SEVEM NILC Commander

$\ell_3 \in [518, 548]$

One of the reasons why results based on E polarization are labeled preliminary



T2E



New bispectrum constraints using full mission data

Shape and method	f_{NL}(KSW) Independent	f_{NL}(KSW) ISW-lensing subtracted
SMICA (T)		
Local	10.2 ± 5.7	**2.5 ± 5.7**
Equilateral	−13 ± 70	**−16 ± 70**
Orthogonal	−56 ± 33	**−34 ± 33**

New bispectrum constraints using full mission data including polarization

	$f_{\rm NL}$(KSW)	
Shape and method	Independent	ISW-lensing subtracted
SMICA (T)		
Local	10.2 ± 5.7	**2.5 ± 5.7**
Equilateral	−13 ± 70	**−16 ± 70**
Orthogonal	−56 ± 33	**−34 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.0	**0.8 ± 5.0**
Equilateral	3 ± 43	**−4 ± 43**
Orthogonal	−36 ± 21	**−26 ± 21**

New bispectrum constraints using full mission data…

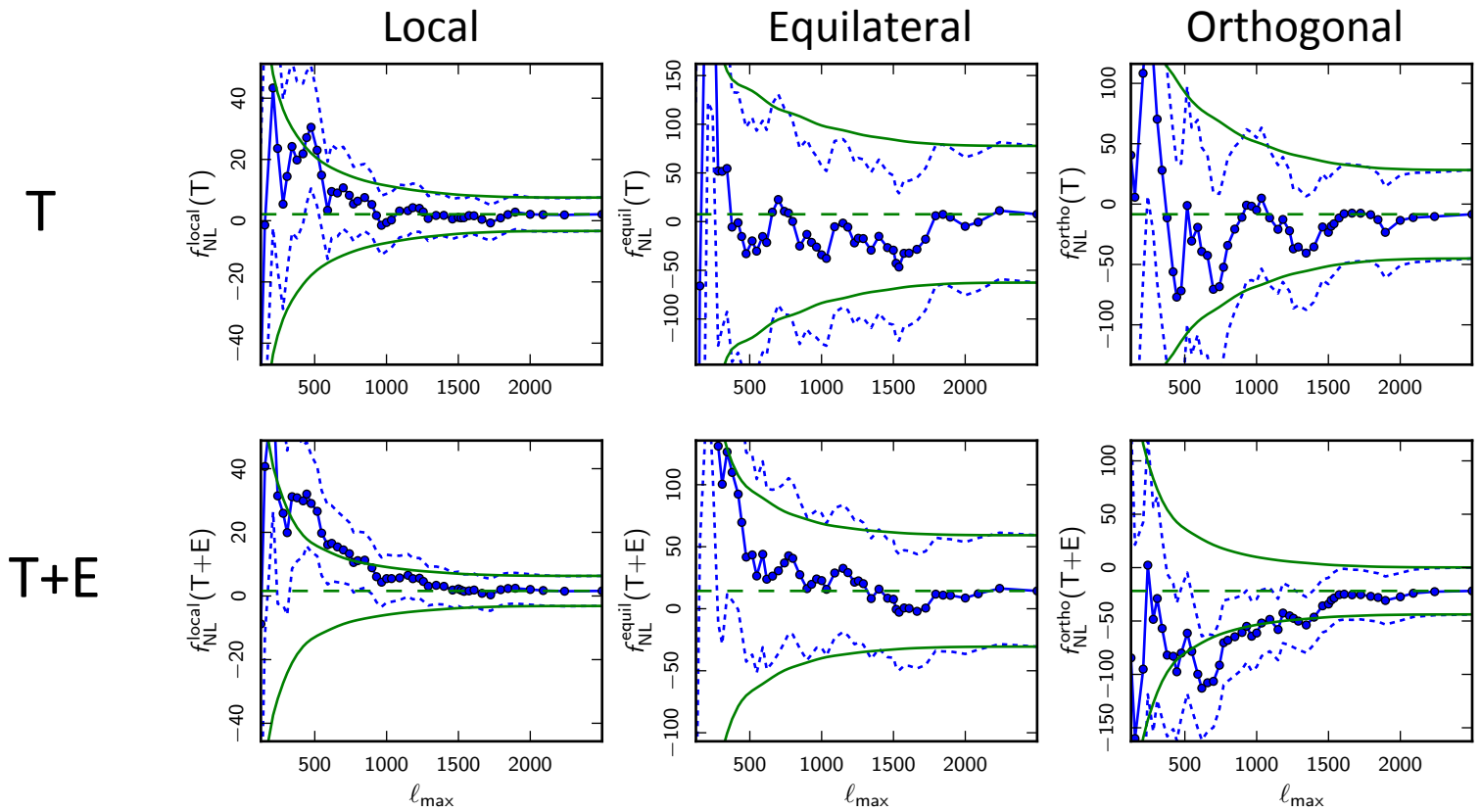
Shape and method	f_{NL}(KSW) Independent	f_{NL}(KSW) ISW-lensing subtracted
SMICA (T)		
Local	10.2 ± 5.7	**2.5 ± 5.7**
Equilateral	−13 ± 70	**−16 ± 70**
Orthogonal	−56 ± 33	**−34 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.0	**0.8 ± 5.0**
Equilateral	3 ± 43	**−4 ± 43**
Orthogonal	−36 ± 21	**−26 ± 21**

Planck 2013

ISW-lensing subtracted		
KSW	Binned	Modal
2.7 ± 5.8	2.2 ± 5.9	1.6 ± 6.0
−42 ± 75	−25 ± 73	−20 ± 77
−25 ± 39	−17 ± 41	−14 ± 42

Constraint volume in LEO space shrunk by factor of 3.

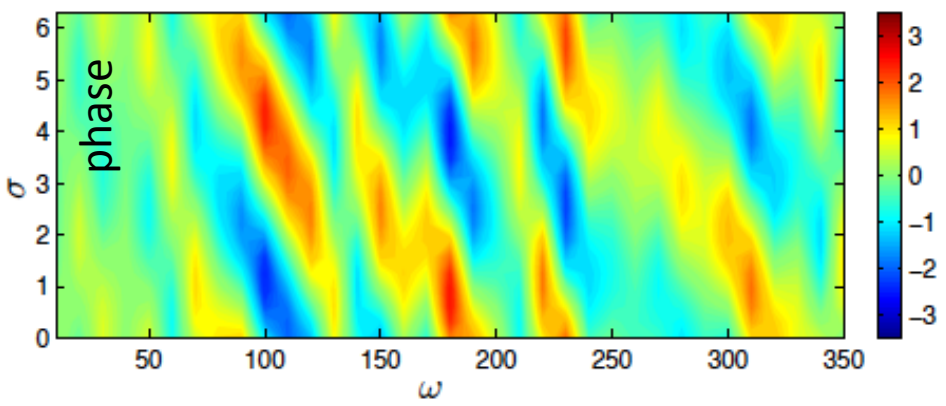
Results are stable as l_{max} increases

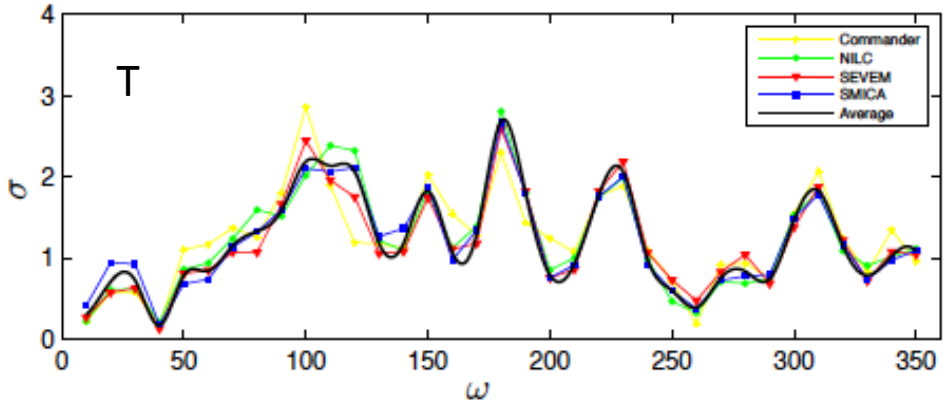


Beyond Local, Equilateral, Orthogonal Non-Gaussianity

- The 2015 results contain a greatly enlarged set of analyses of specific templates using the modal estimator
  - Resonant feature models
  - Generalized resonant models
  - Generalized feature models
  - Single field feature models Non-Bunch Davies models
  - …
- For any hints that appear upon combining T and E remember the health warning that comes with the polarization data in this release.
- New estimator for high-frequency oscillatory features

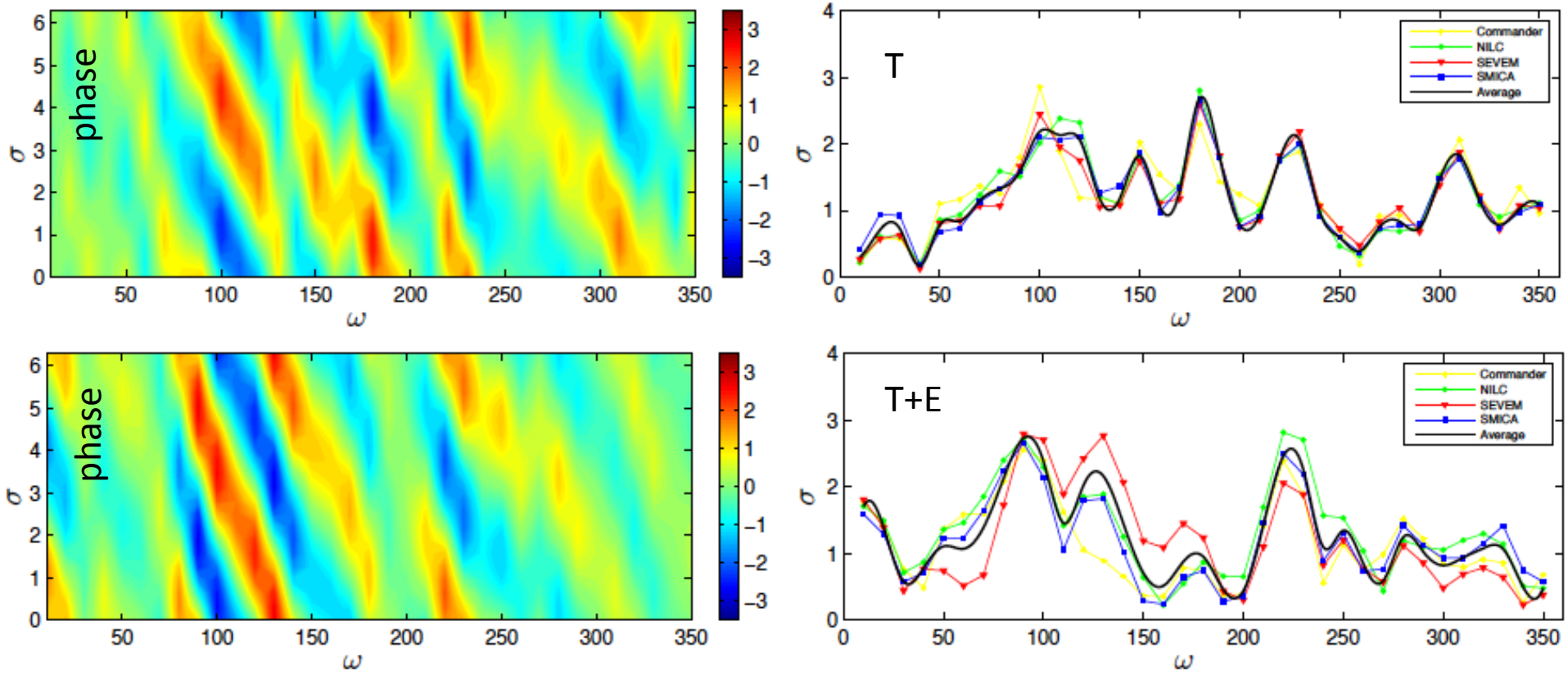
Linear oscillations





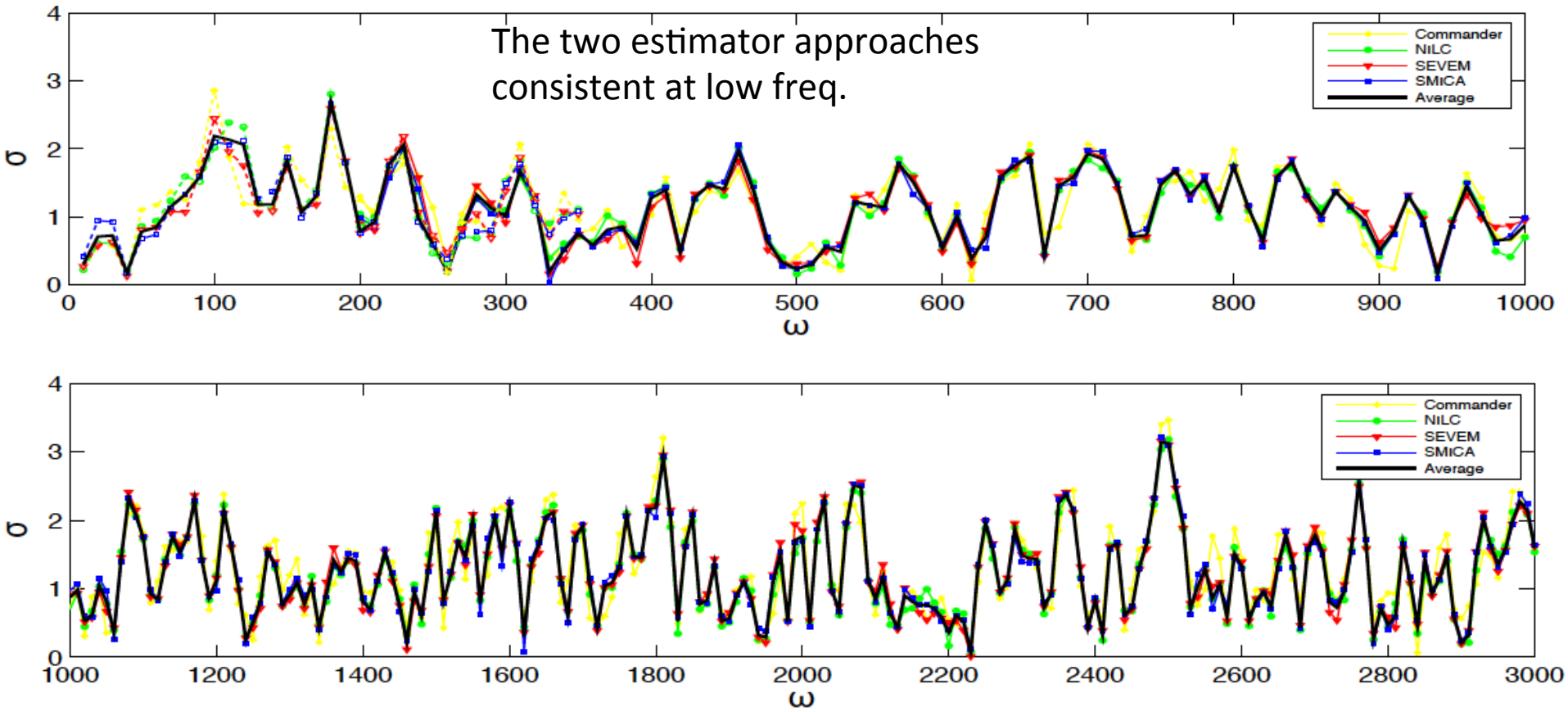
phase-maximized statistic

Linear oscillations



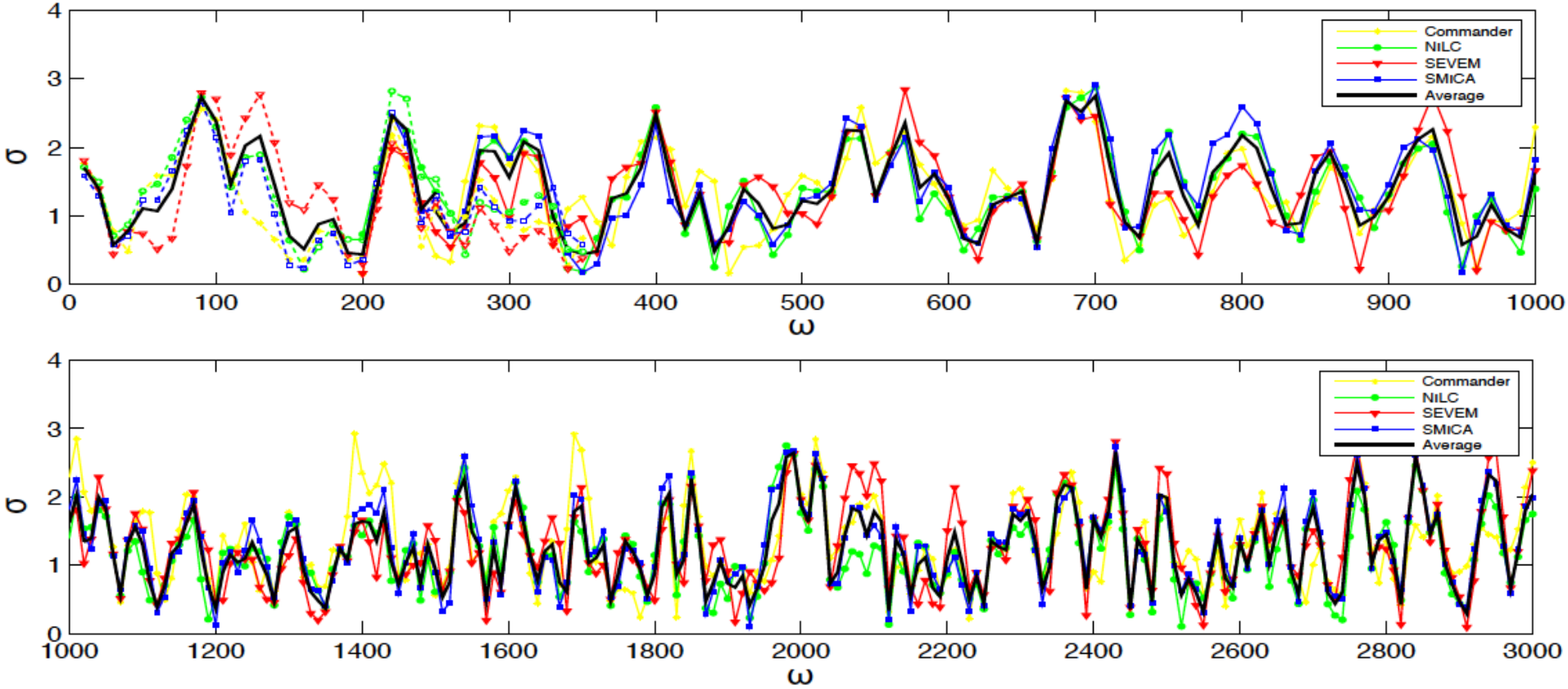
phase-maximized statistic

Linear oscillations – using targeted estimator to extend frequency range



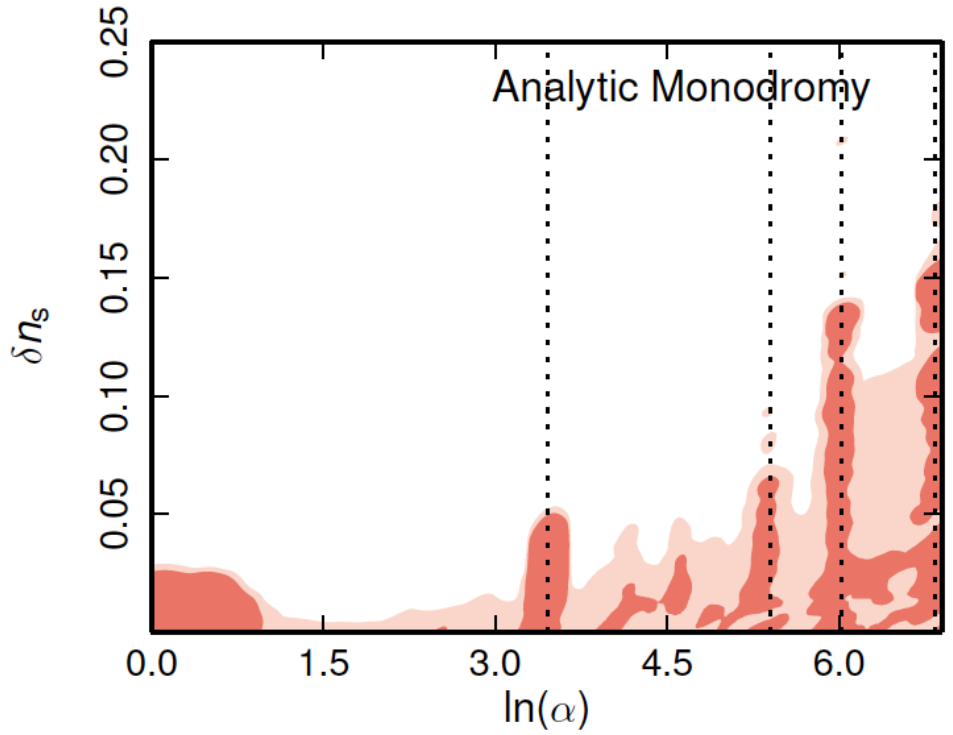
Targeted estimator (MBJW 2014) enables constraints to ~ 10x higher frequency

Linear oscillations – extended frequency range, T+E

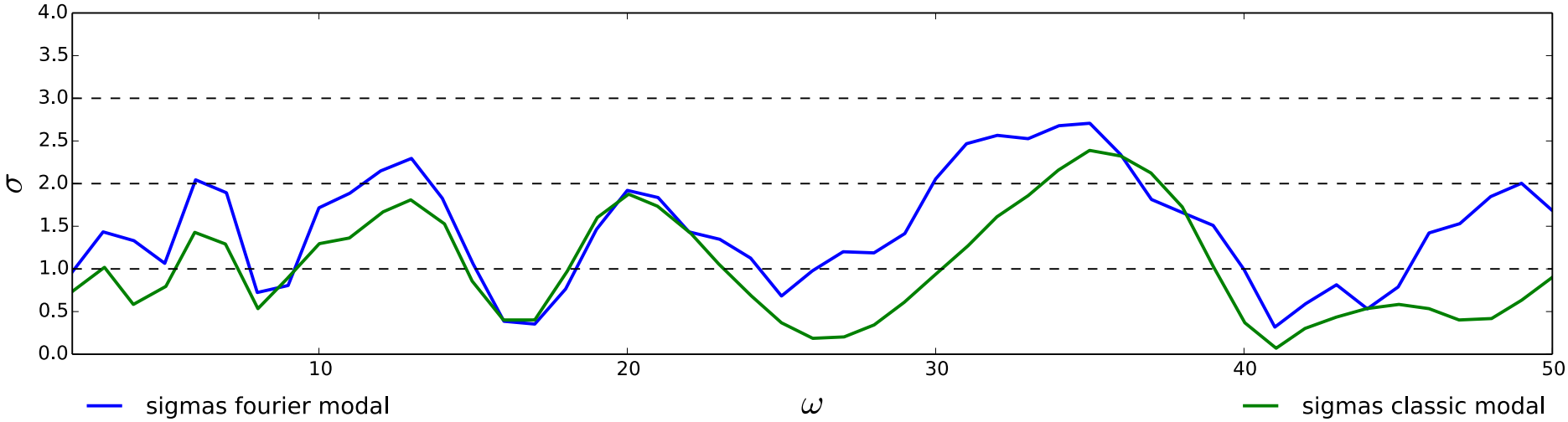


Log-oscillations

New estimator based on combinations of linear estimation modes allows estimating "log-oscillating" bispectra across the range probed in the power spectrum

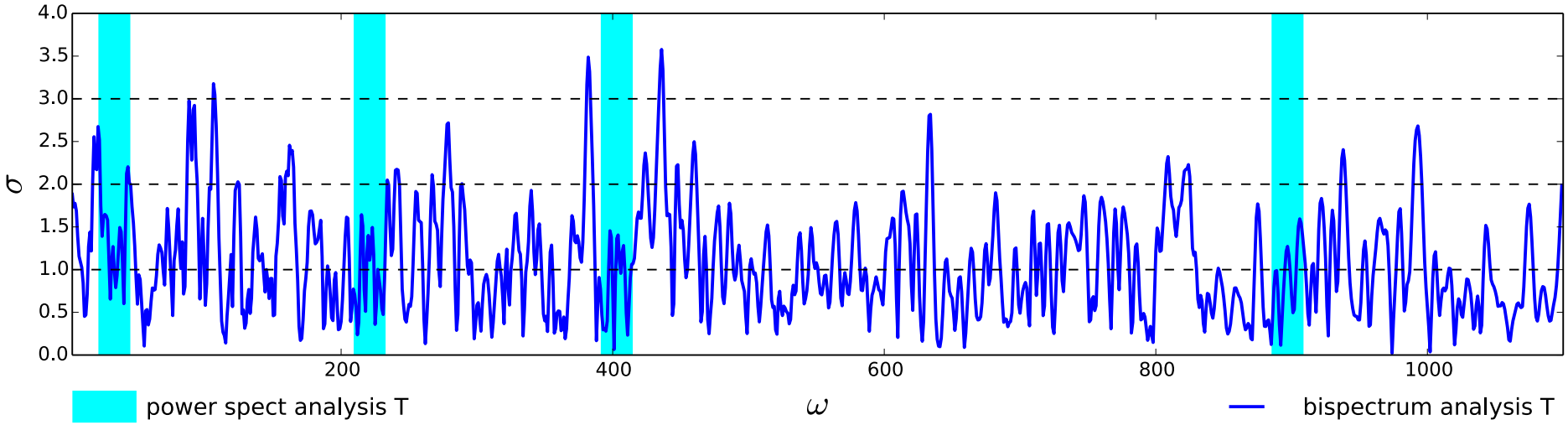


Comparison to modal estimator



Preliminary

Bispectrum of a Gaussian simulation



Conclusions

- The Planck has a lasting legacy as
  - a probe of the initial conditions of structure formation
  - the first all-sky view of matter perturbations through gravitational lensing
  - an anchor for "low-"redshift cosmology
- Planck temperature results largely consistent and enhanced with polarization results
- Stay tuned for more to come in the next year!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planck
cnes
agenzia spaziale italiana
NASA
cnrs
DTU Space
National Space Institute
Science & Technology Facilities Council
INAF ISTITUTO NAZIONALE DI ASTROFISICA
CSIC
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