BEYOND PLANCK

Nazzareno Mandolesi

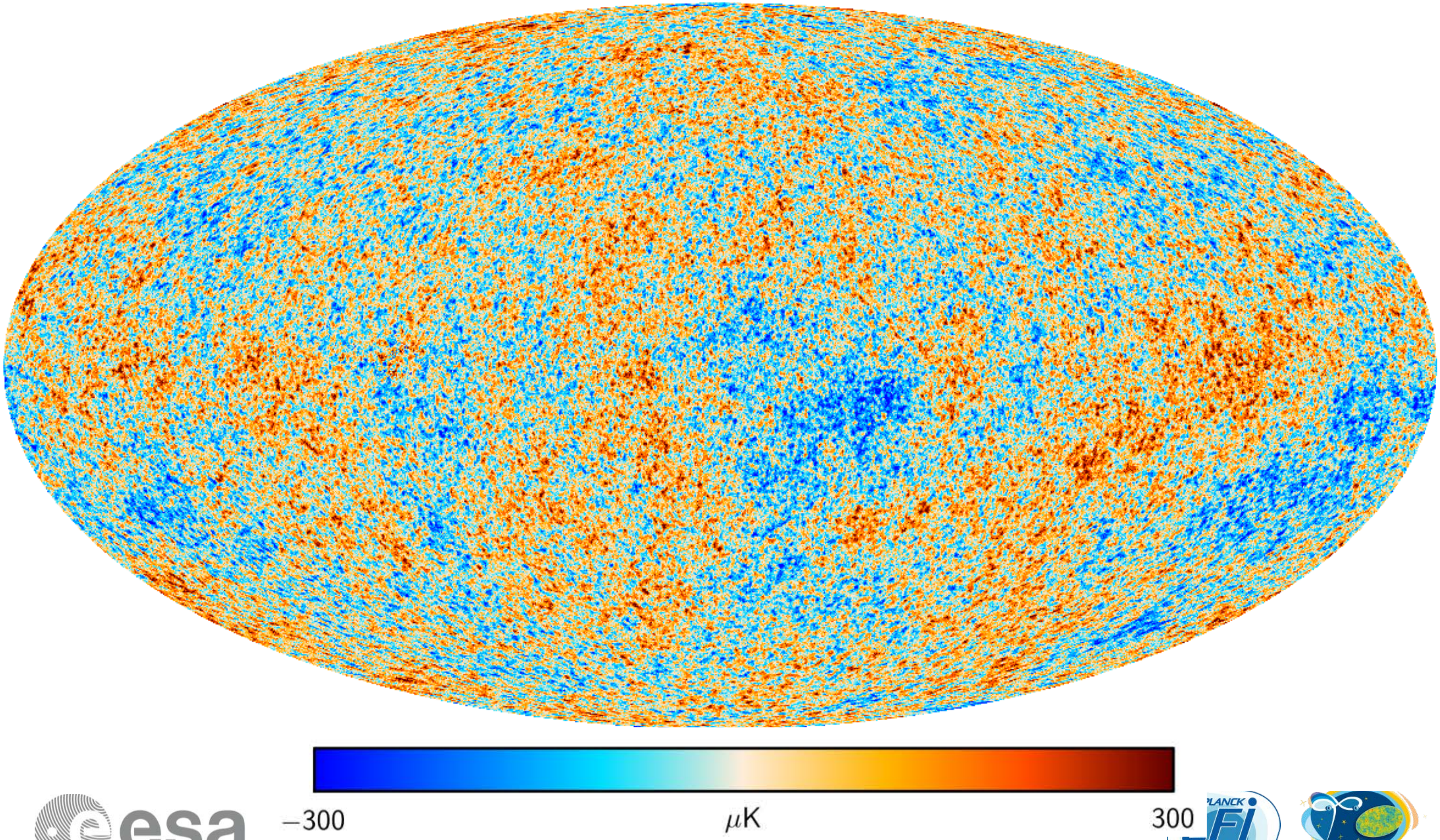
On behalf of the Planck Collaboration

N.Mandolesi University of Ferrara and INAF

The Planck Legacy

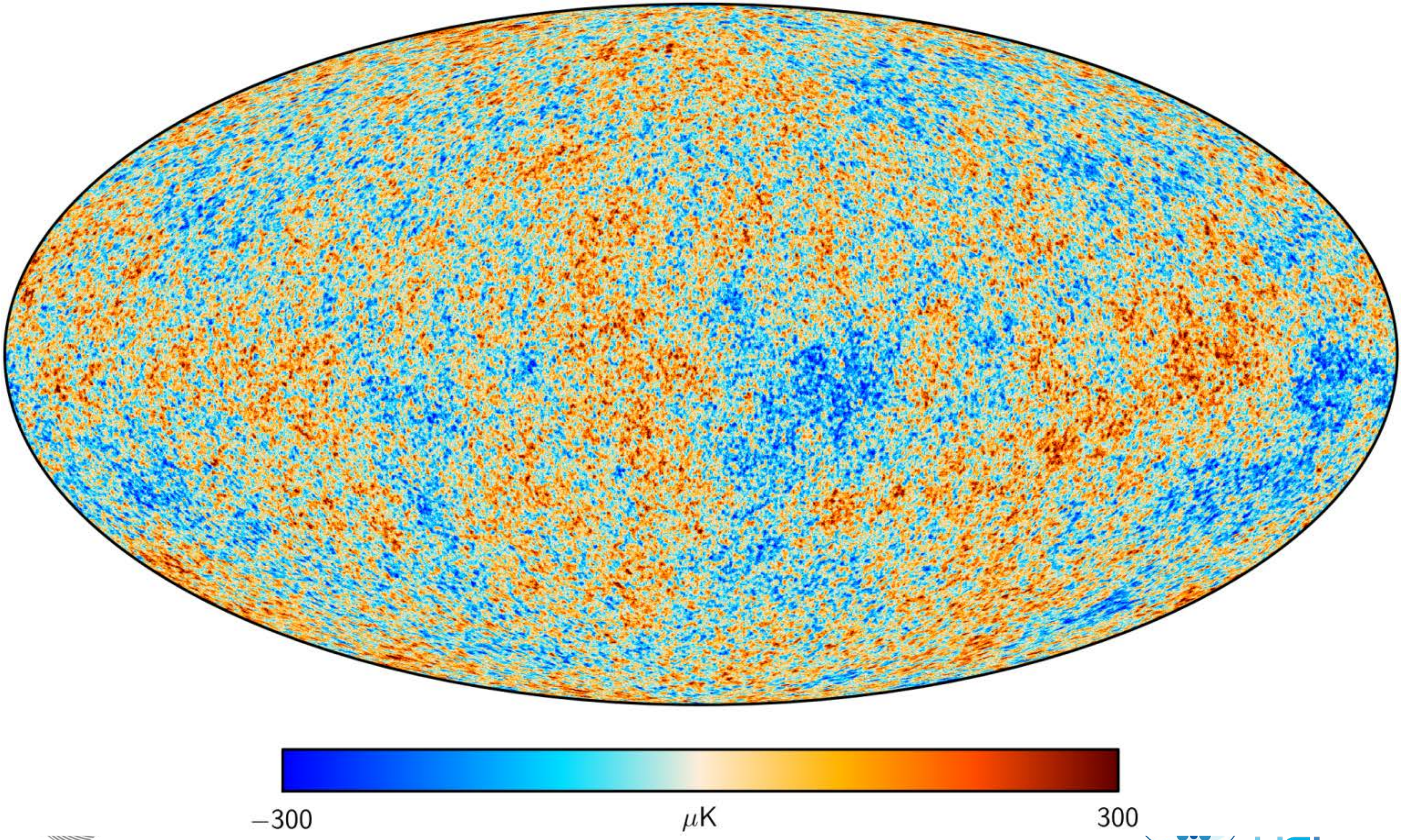
- Ultimate Anisotropy Temperature measurements at all CMB scales
- To date, unprecedented sensitivity Anisotropy Polarization full sky maps

2013



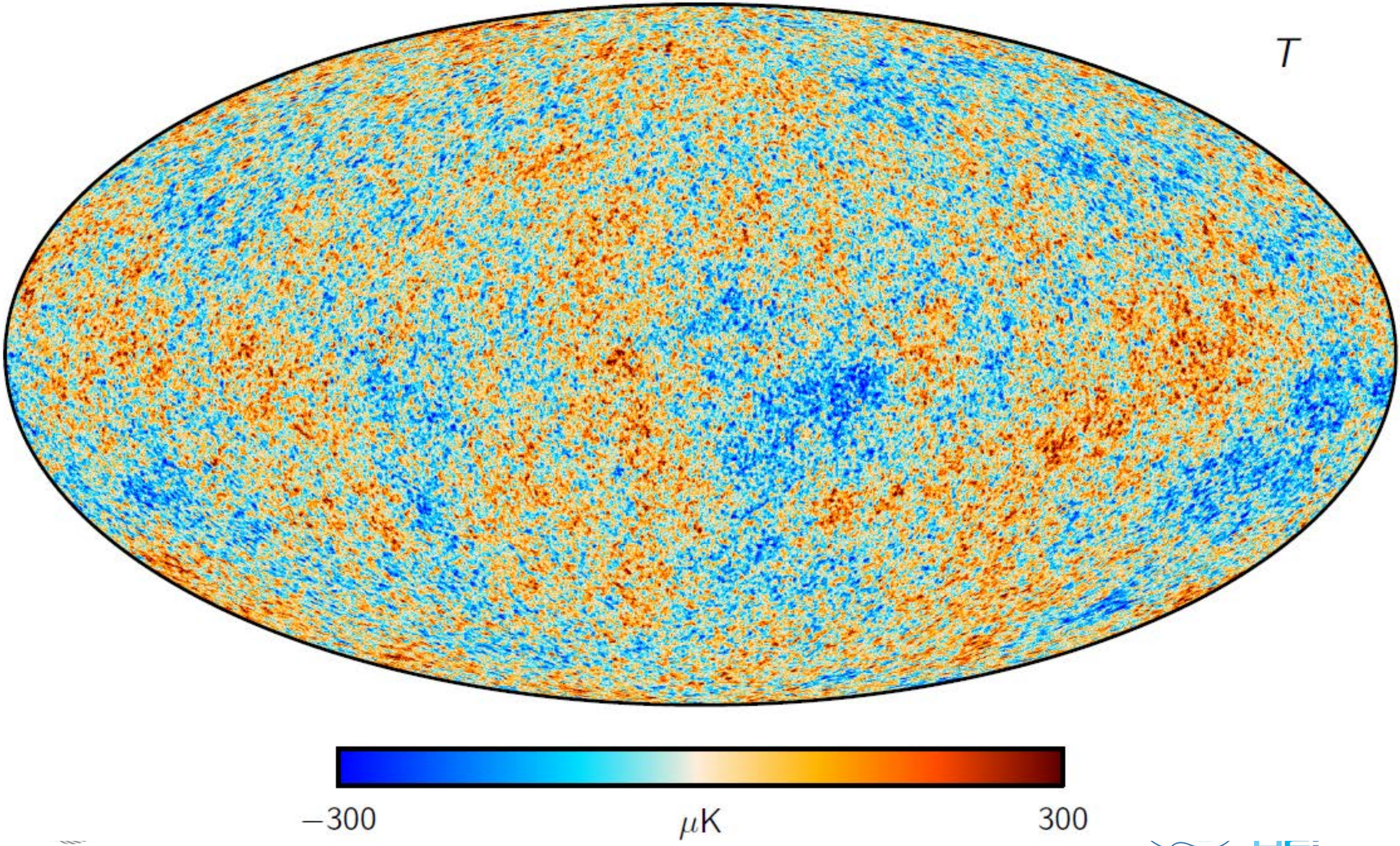
2015

planck



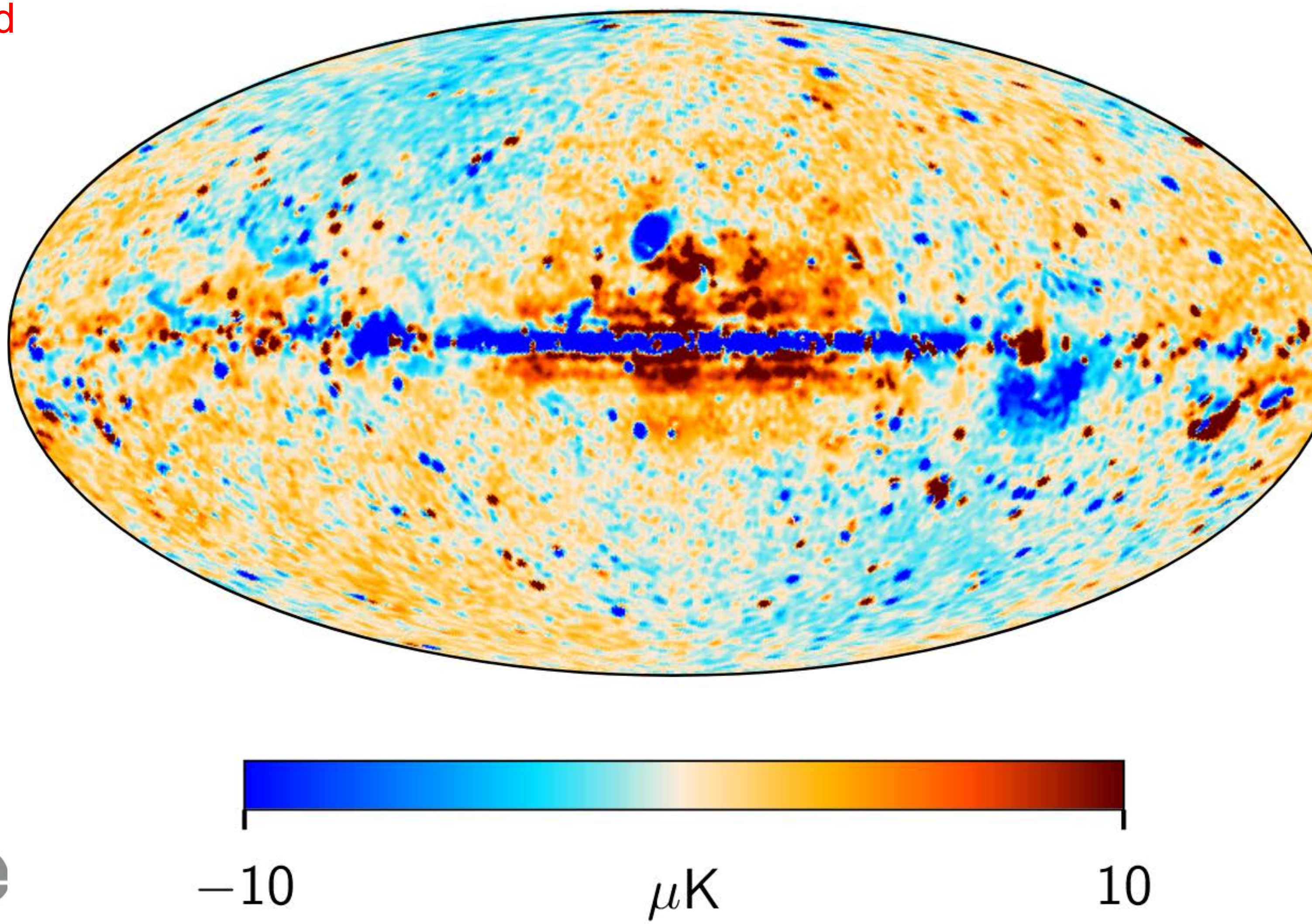
HFI PLANCK

2018

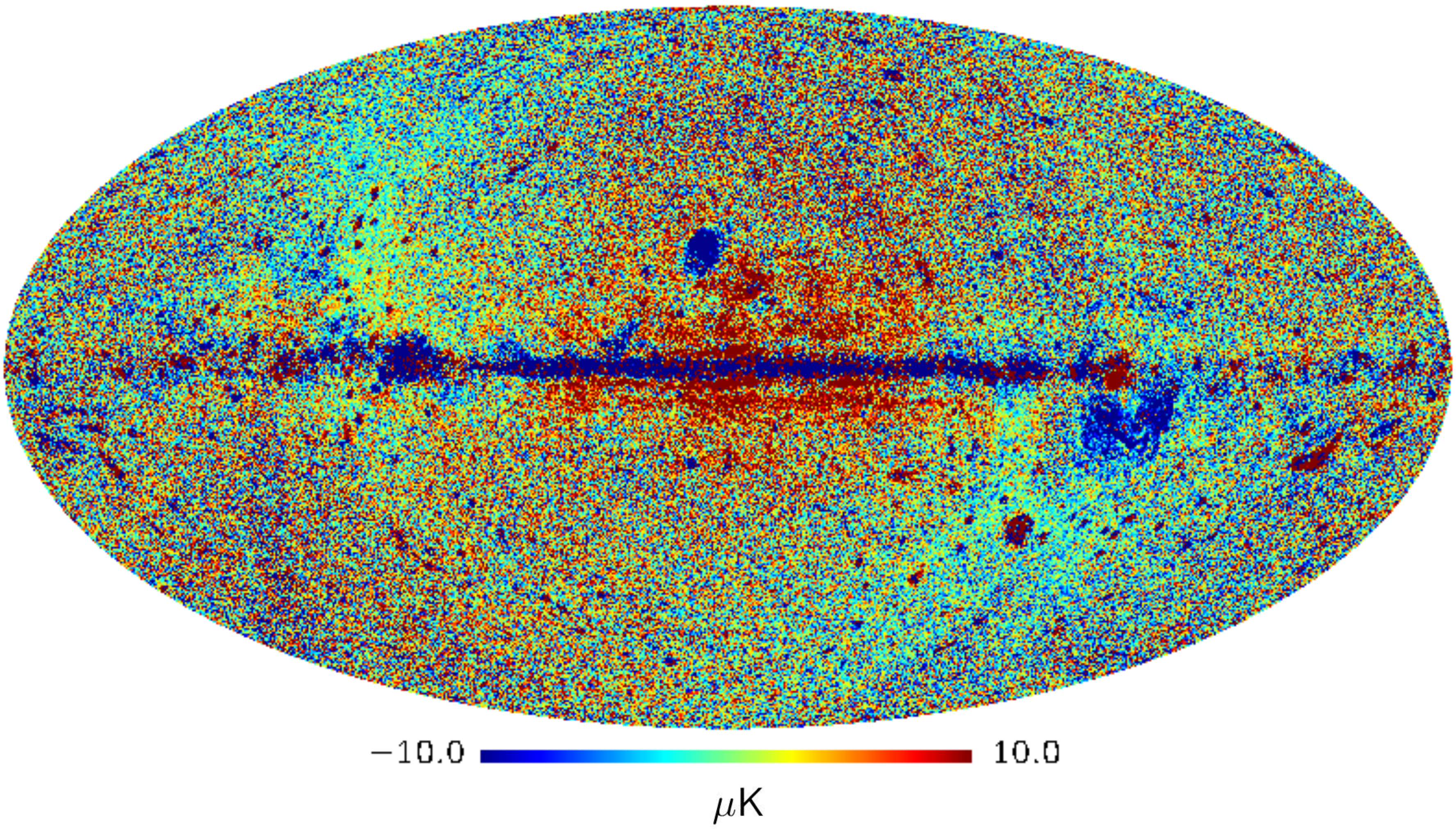


2015-2018 @ 80’

In 2018 sources are removed



2015-2018 @ 5’



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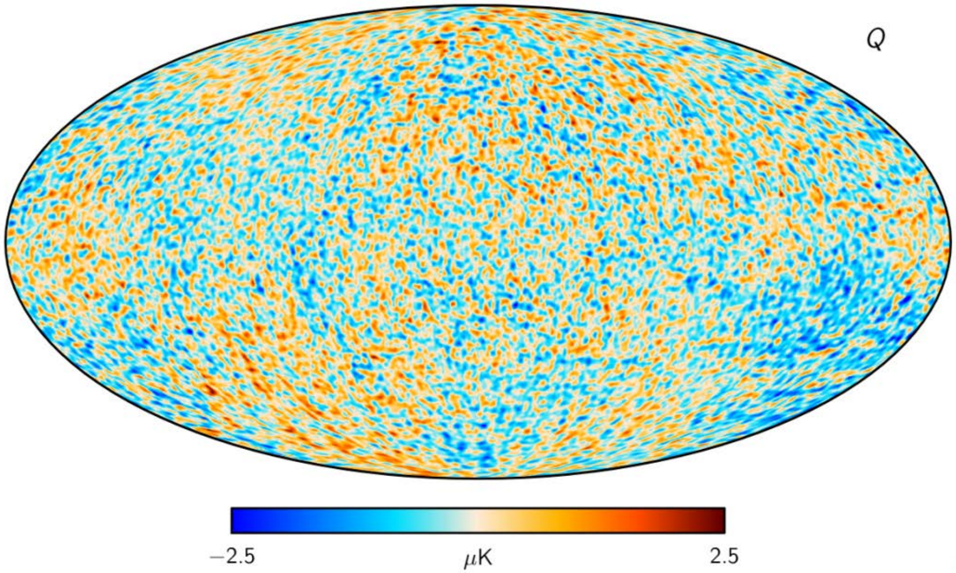
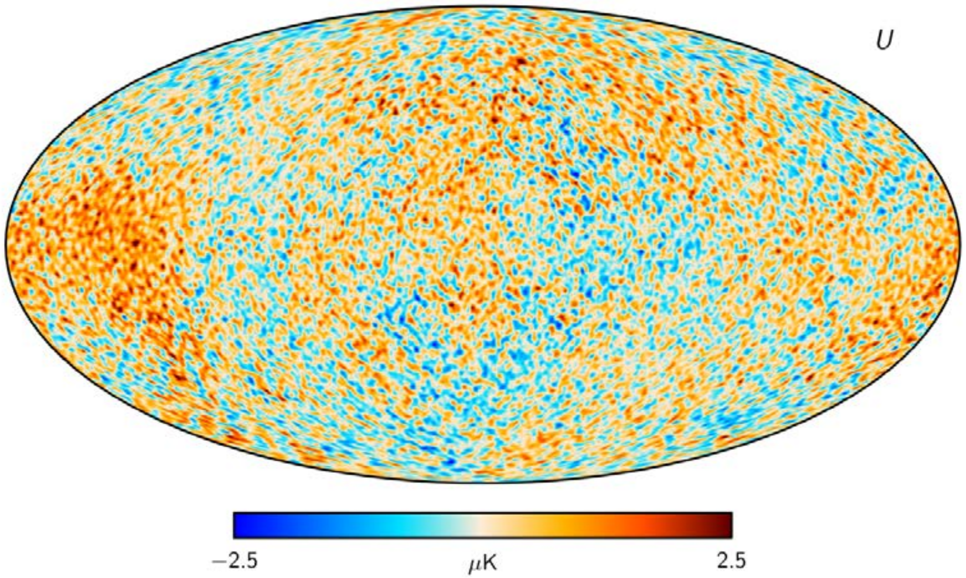
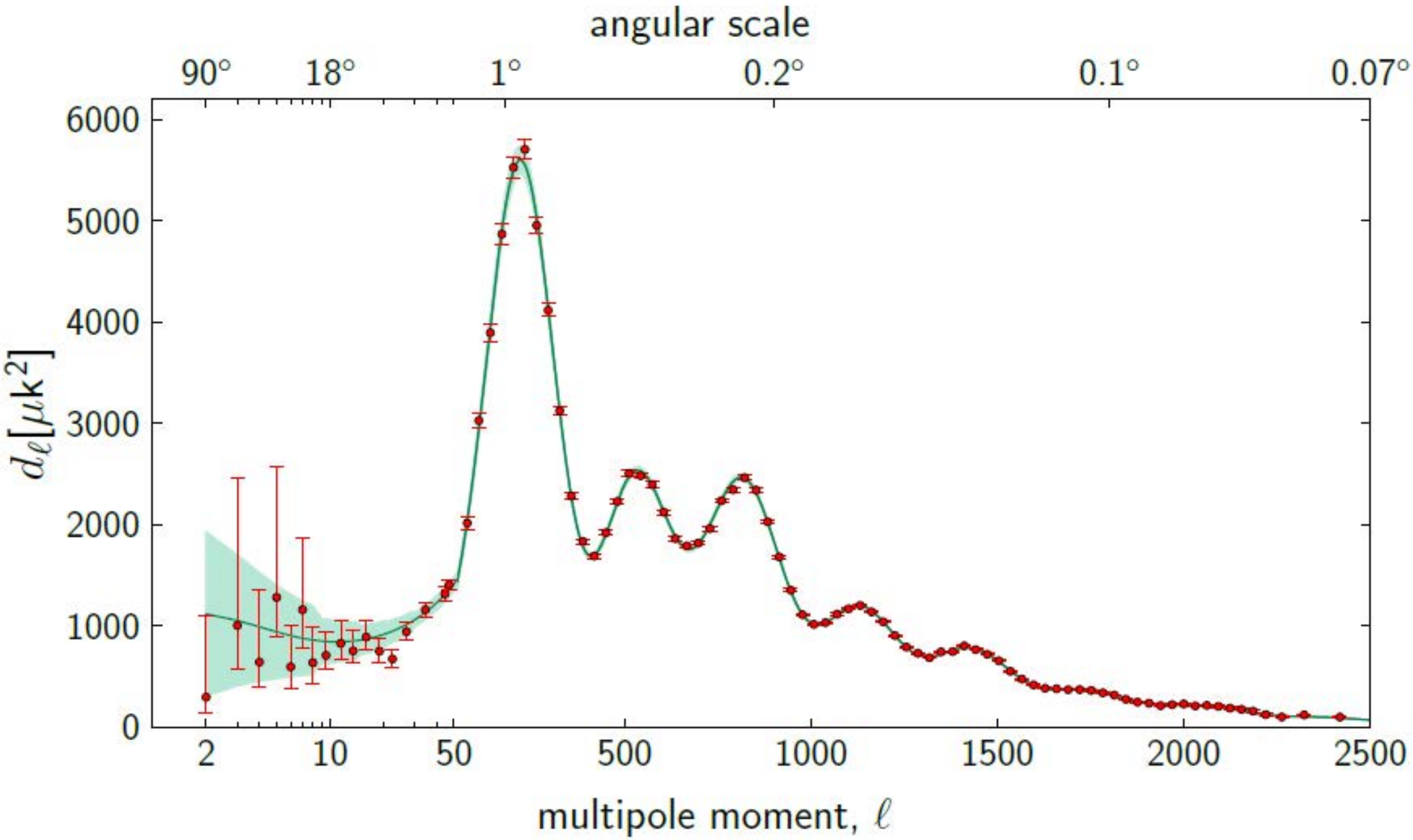
2018
Q and U @80’





2013 Planck TT



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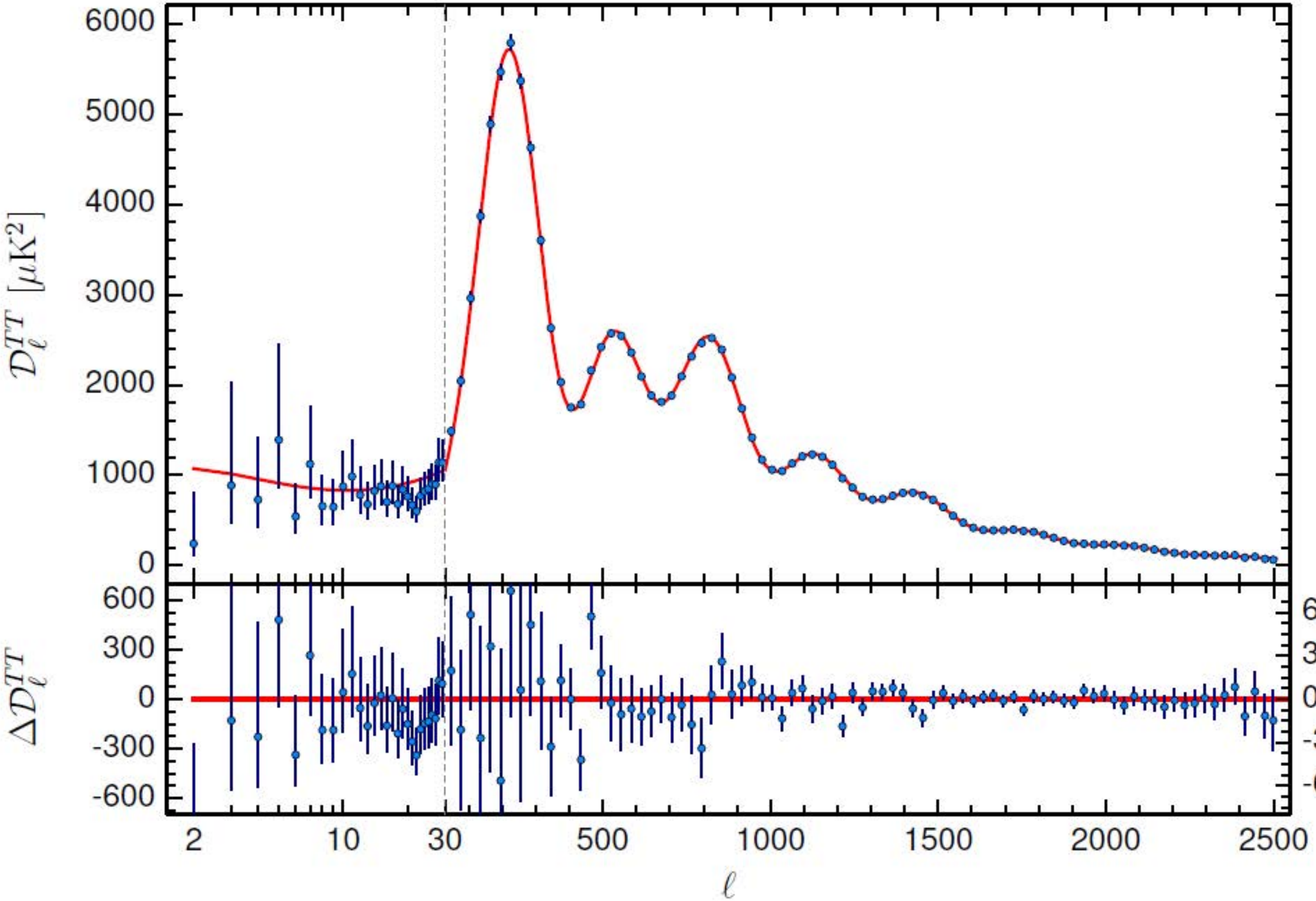
2015 Planck TT



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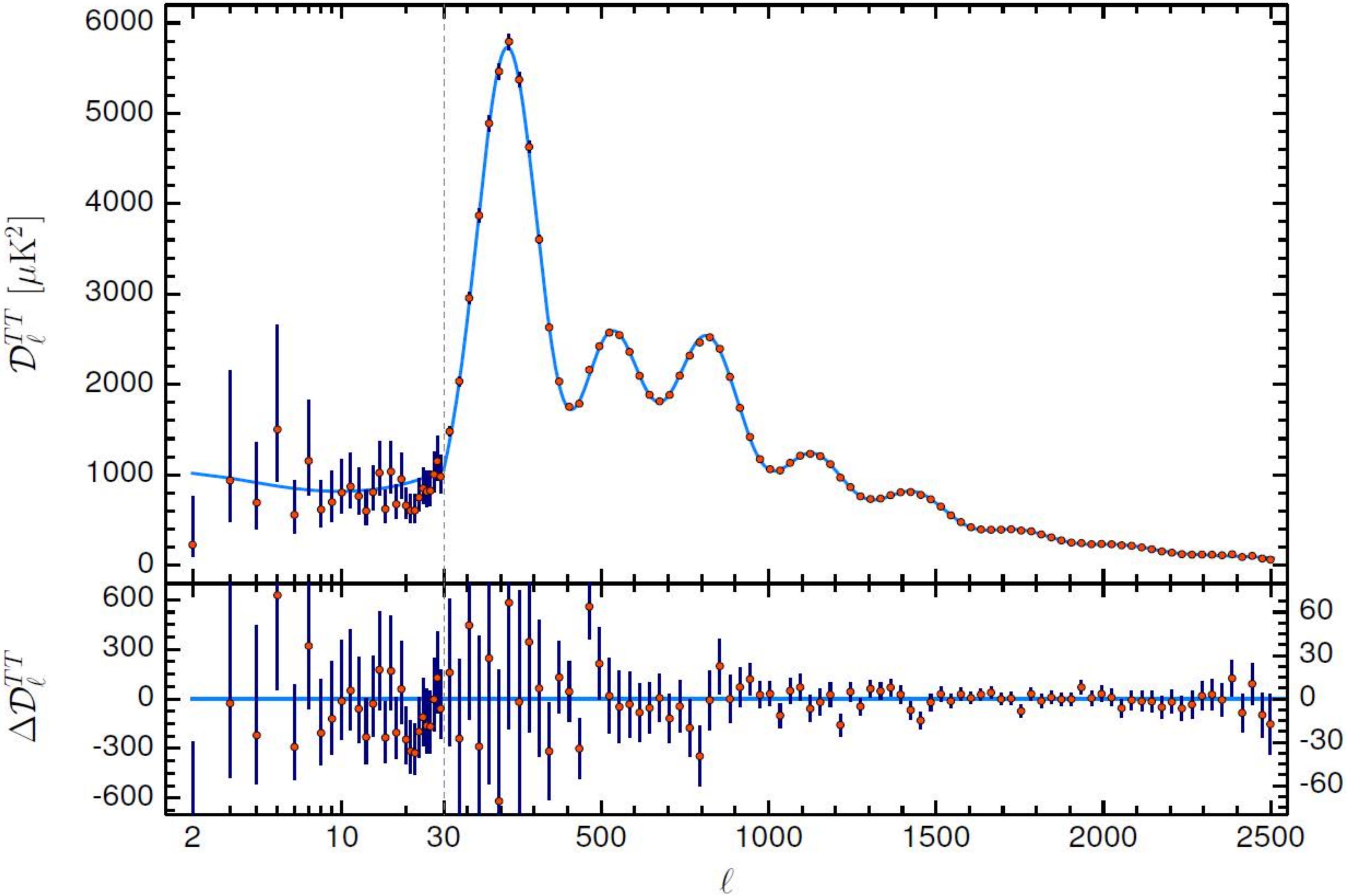
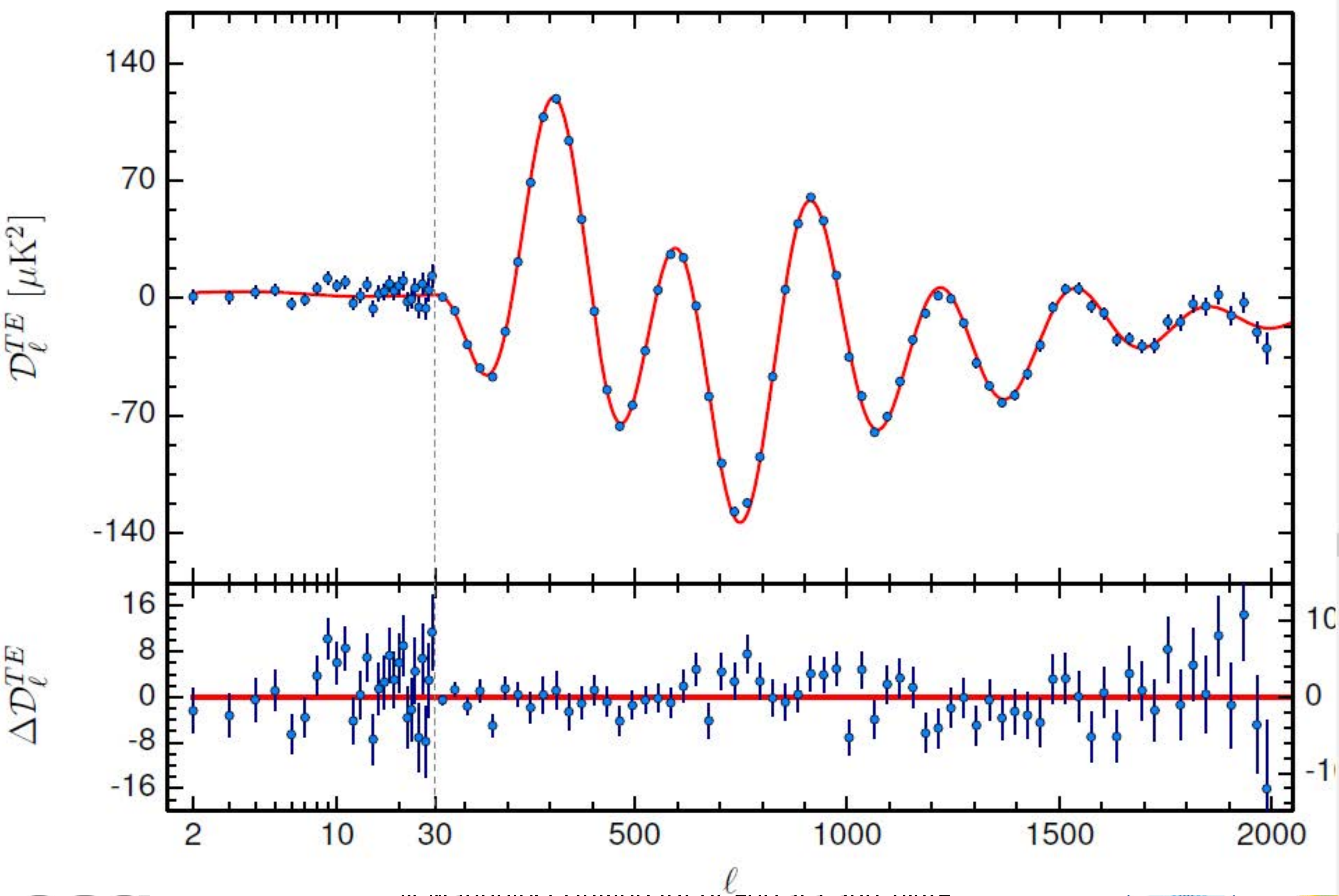
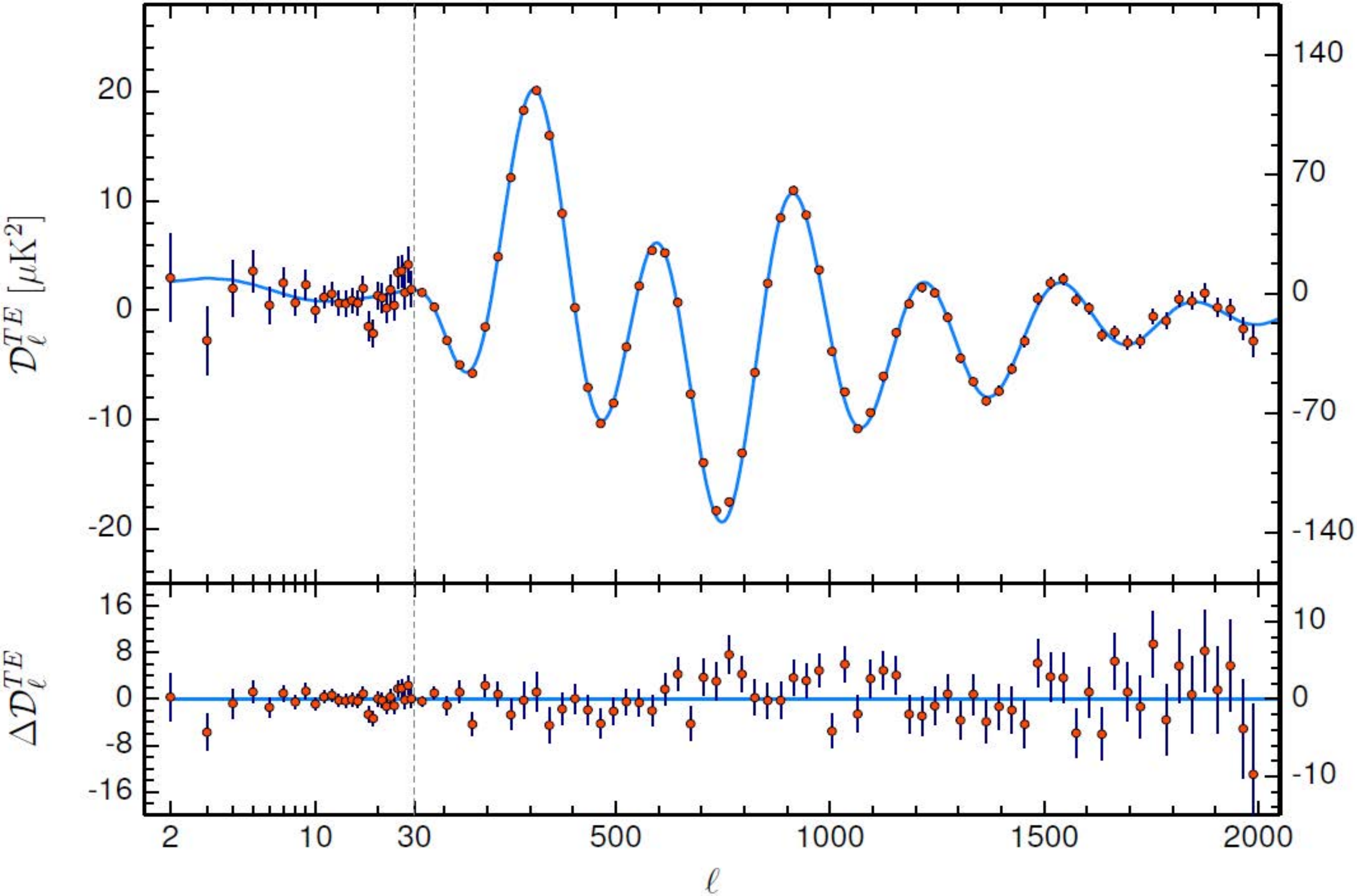
2018 Planck TT



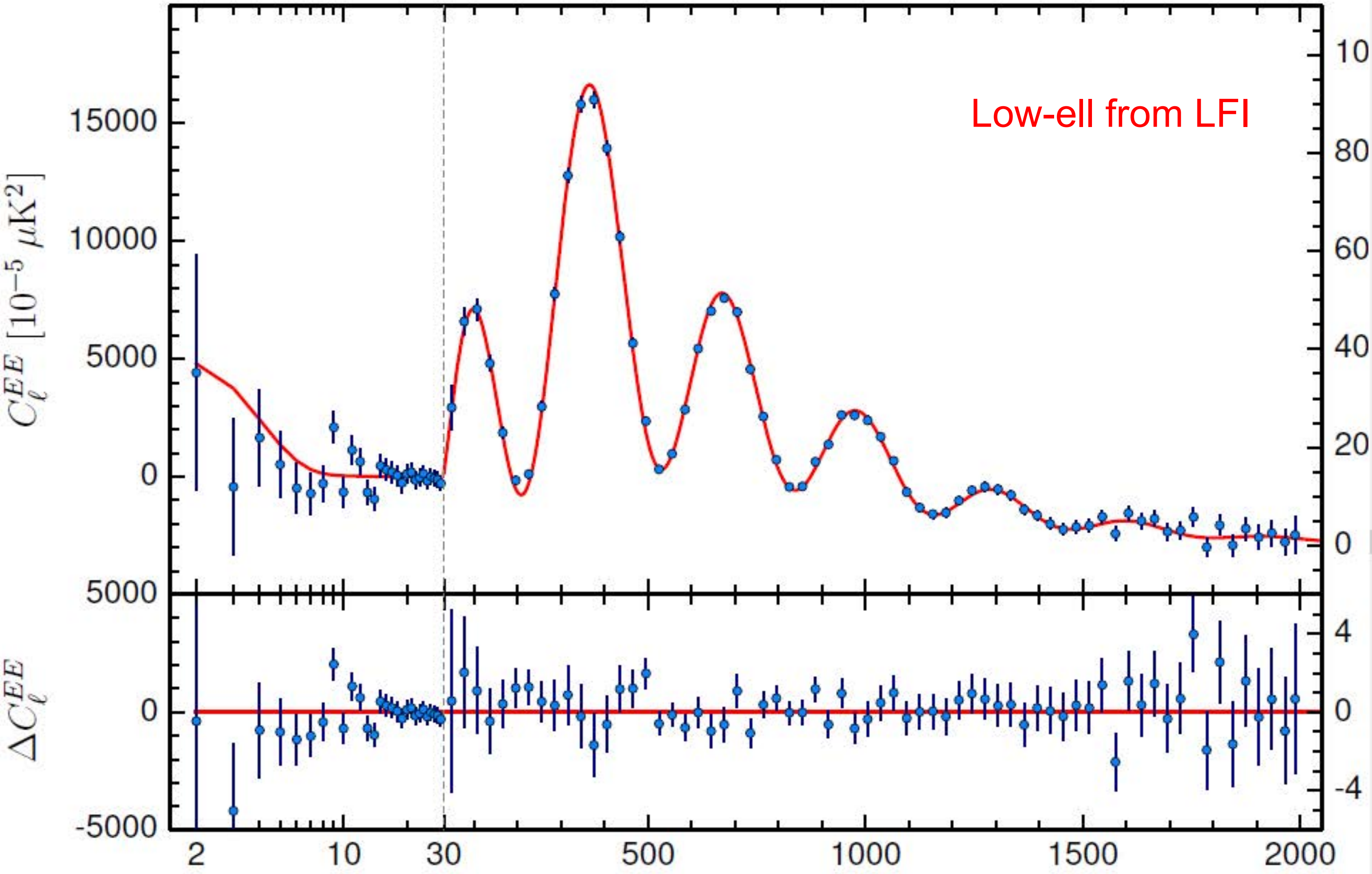
2015 Planck TE



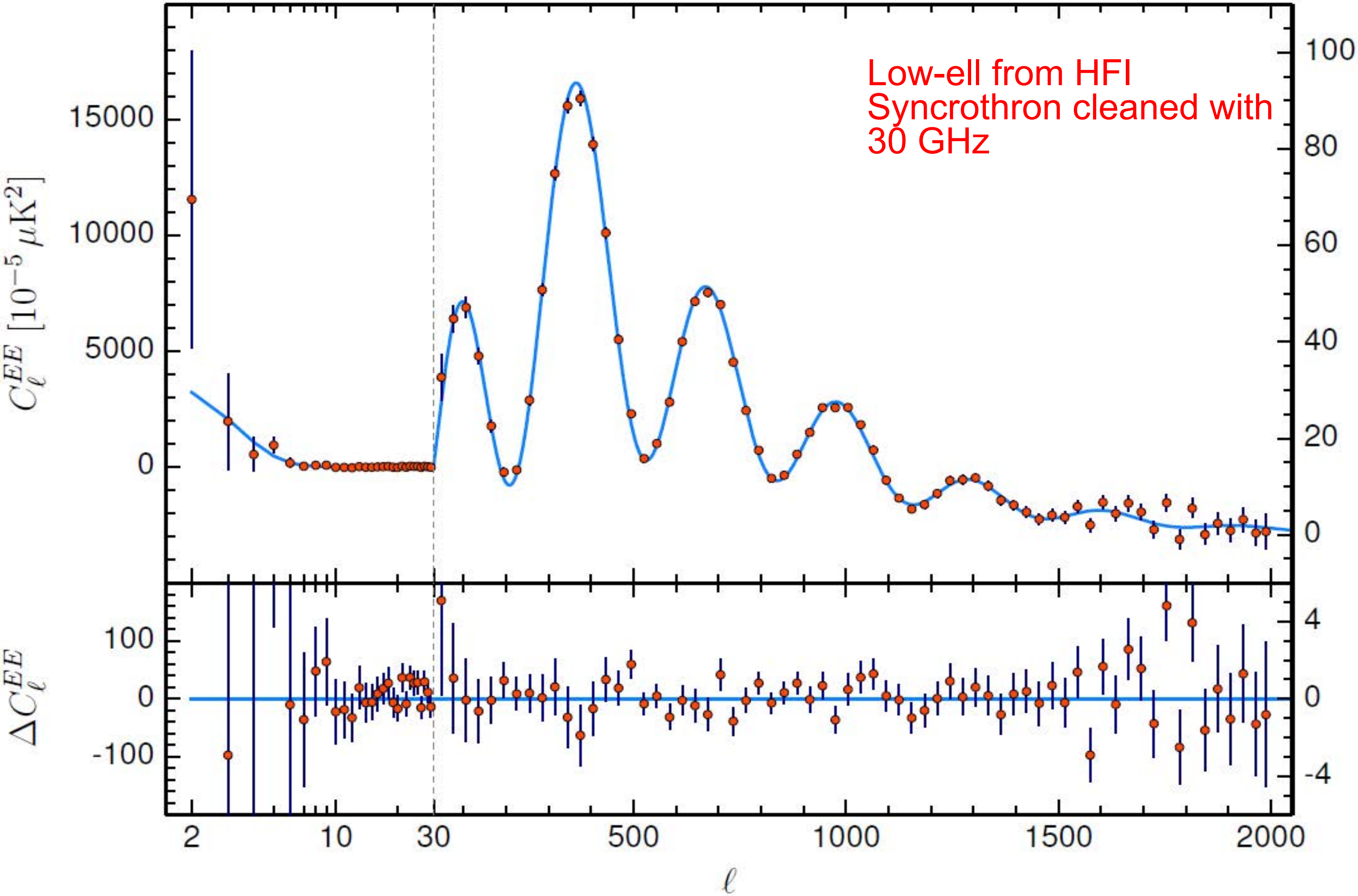
2018 Planck TE



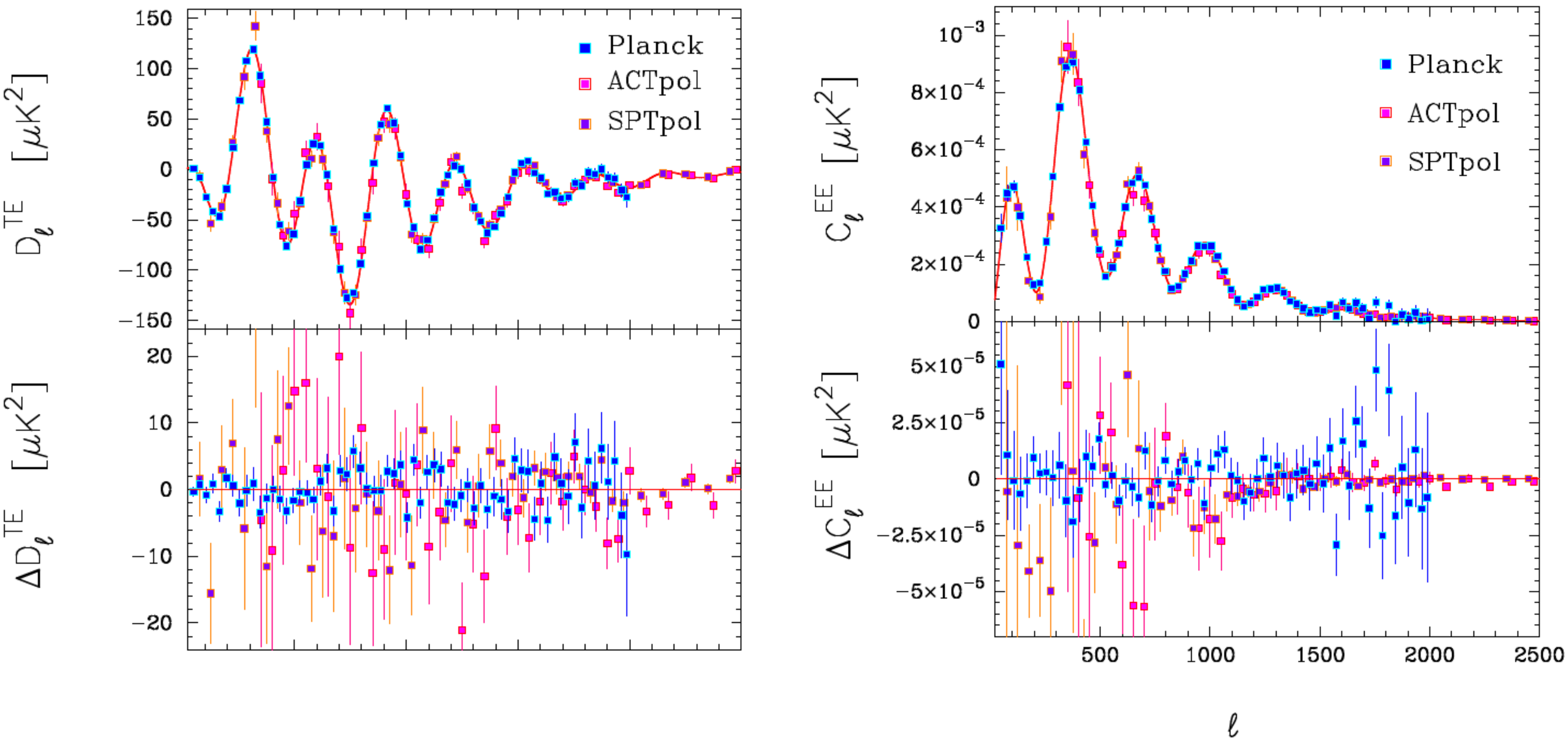
2015 Planck EE



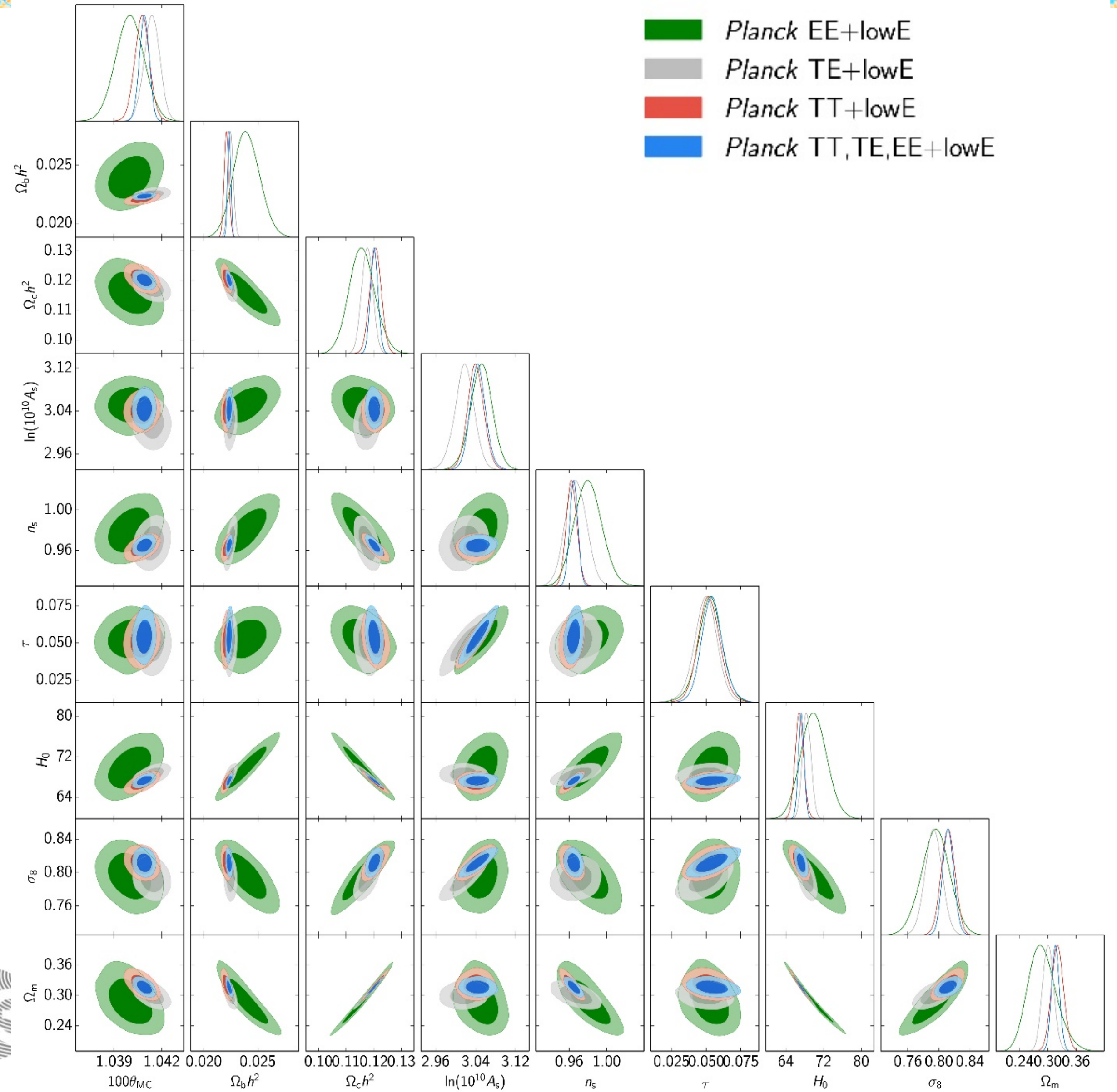
2018 Planck EE



Comparison with ground-based experiments



2018 Planck Internal Consistency



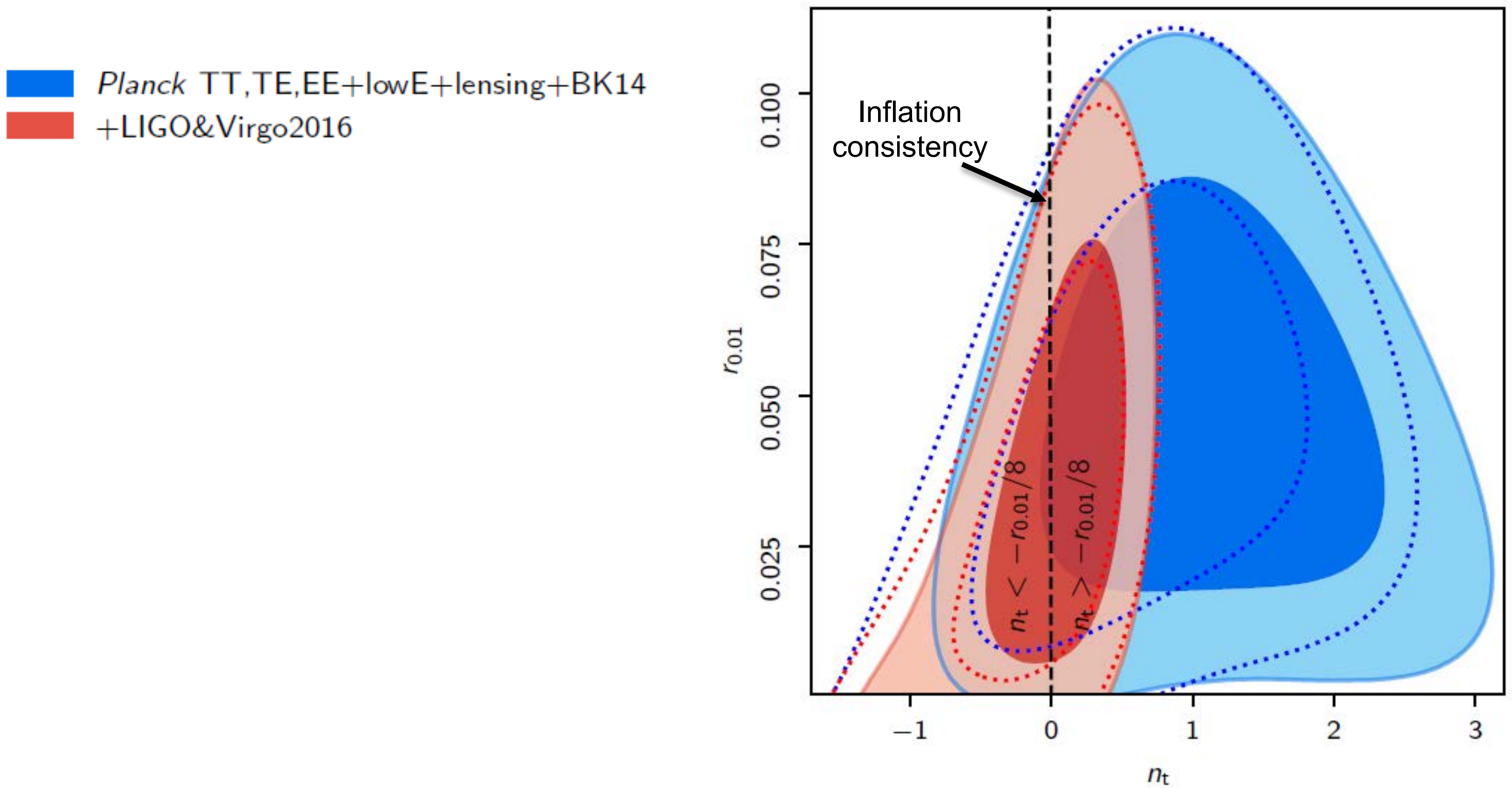
The Planck Legacy: what's next?

- ❑ Planck full sky maps represent the base for CMB studies for the next decade

- ❑ What remain to be done (few ideas):

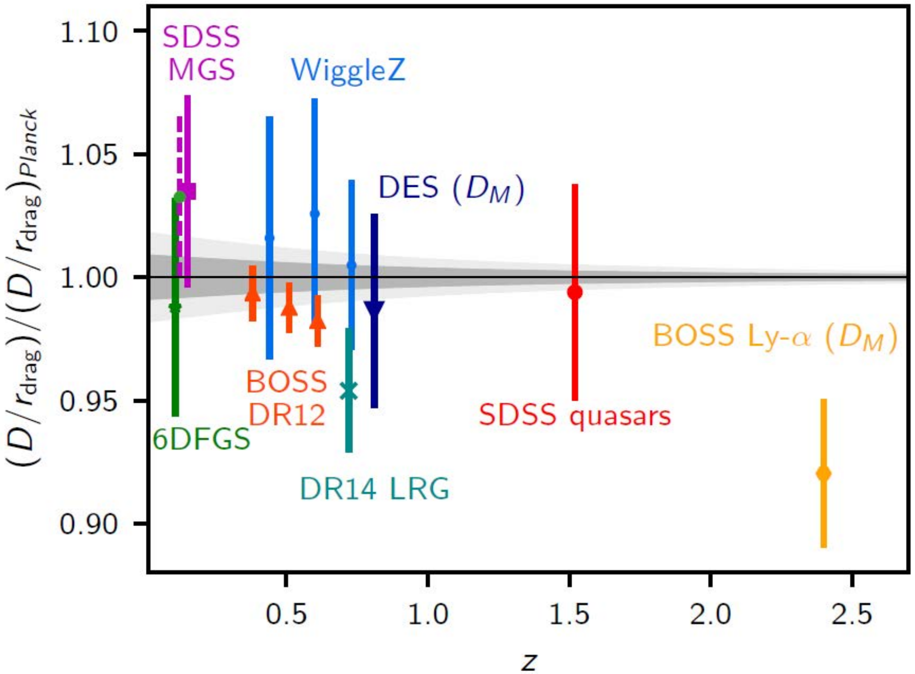
- ➢ Planck data will be one of the main stress-test for present and future cosmological and fundamental physics models
- ➢ Combination with lots of future data (multi-messenger):
  - e.g.combination with GW

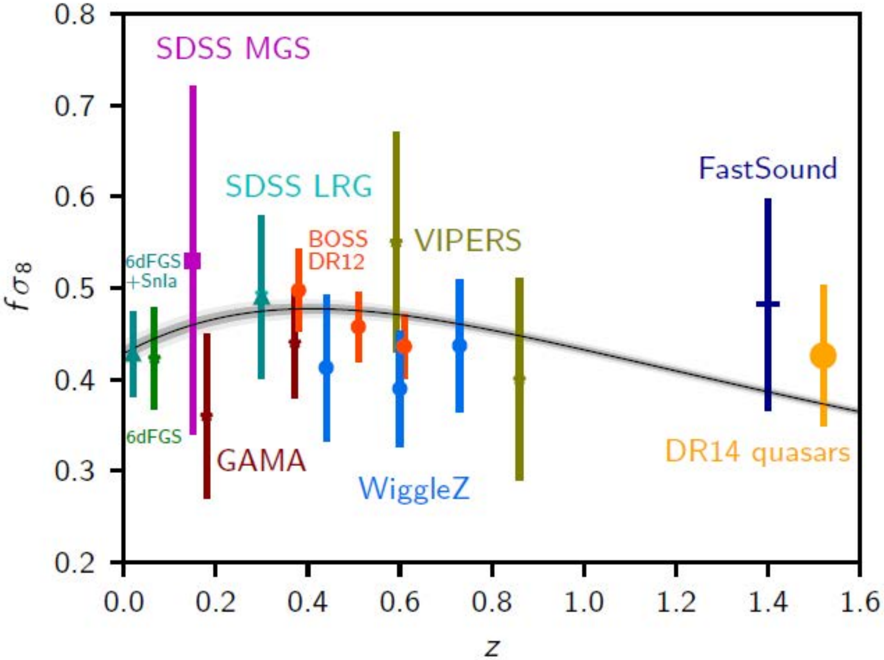
Combination with GW



$$\Omega_{GW}(k) = \frac{k}{\rho_{critical}} \frac{d\rho_{GW}}{dk} = \frac{A_t(k)}{24 z_{eq}} = \frac{A_{t1}(k/k_1)^{n_t}}{24 z_{eq}}$$

Consistency with other experiments





Beyond Planck
The OPEN (?) questions

- Anomalies at large angular scales
- Omega-k and Alens
- Tensions between large and small scales
- Tensions between low and high redshift probes

Need for full sky high precision measurements polarization

Anomalies – low-ell

planck

Features on large angular scales in the T pattern still present in the 2018 release at the level of about 2.5 sigma (consistent with COBE and WMAP).

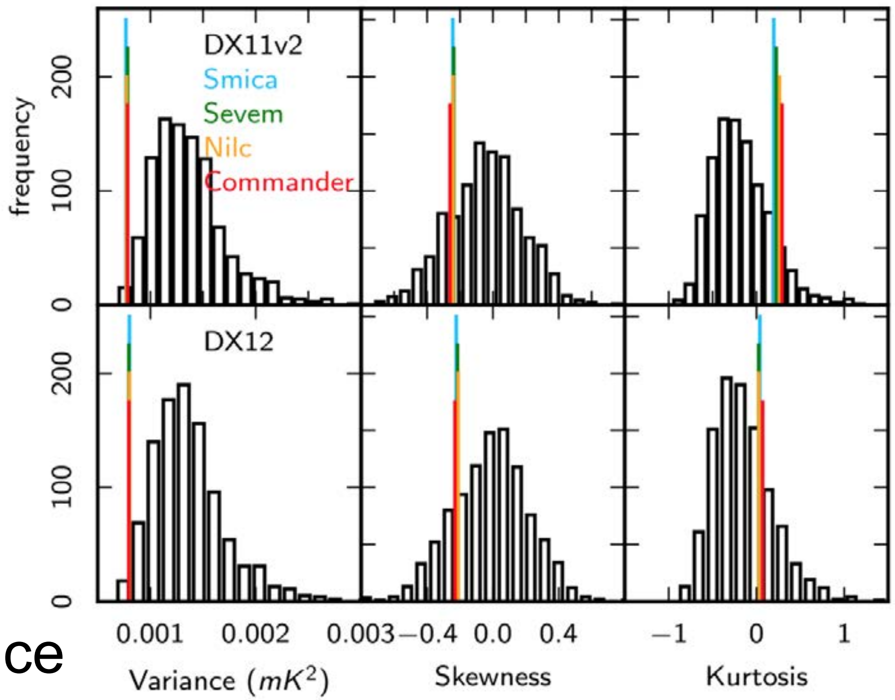
Lack of power (including l=20), Lack of correlation, Even-odd asymmetry+emispherical asymmetry (directional anomaly)

Compatible with a statistical fluke. If their origin is primordial their significance may increase including polarization information.

The counterpart analysis in polarization is limited by the low signal to noise ratio.

To be further investigated beyond Planck

They might reveal a new physics….

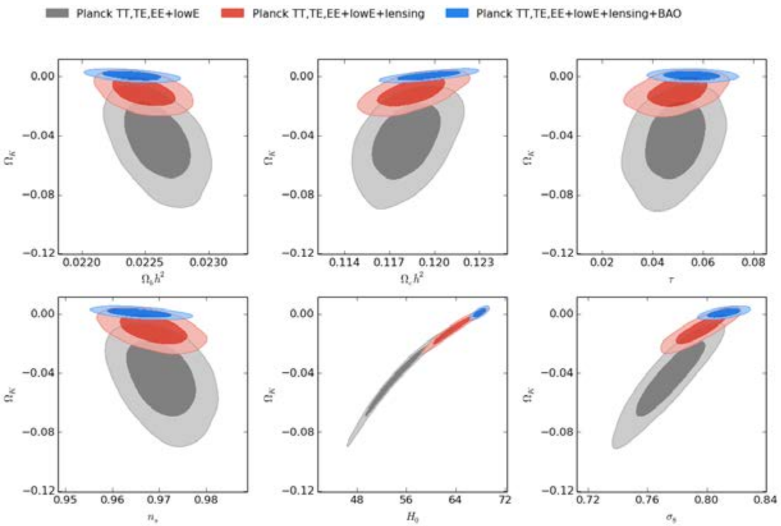


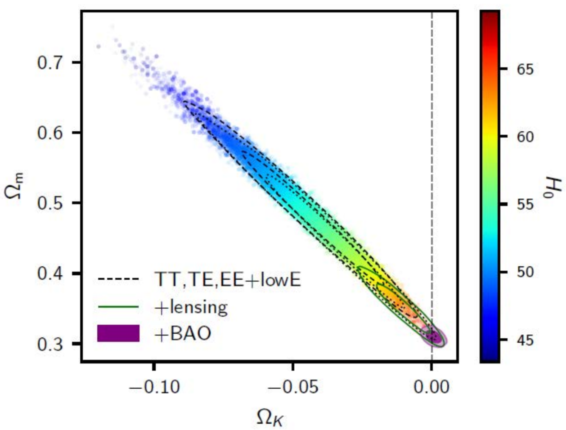
e.g.: Low variance

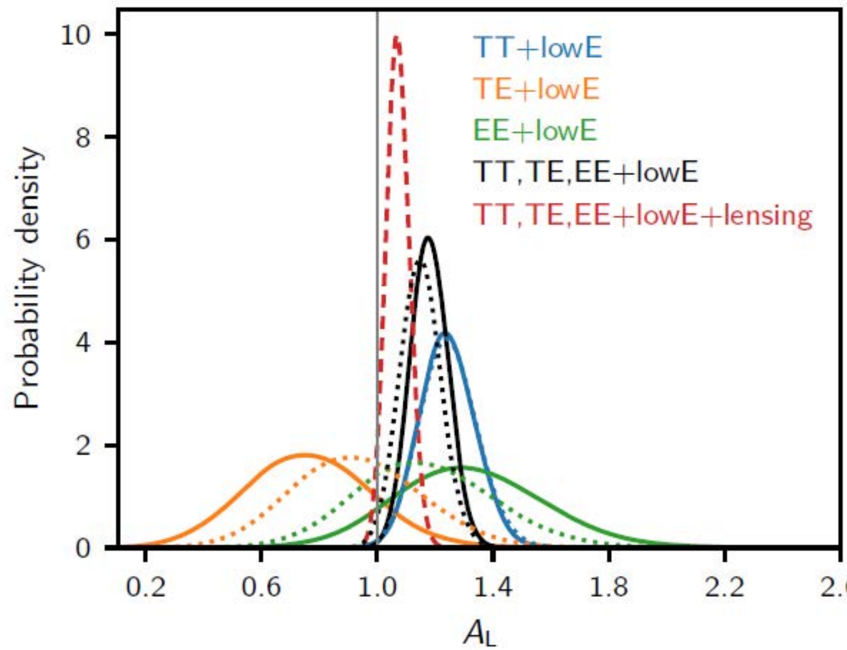
esa

PLANCK

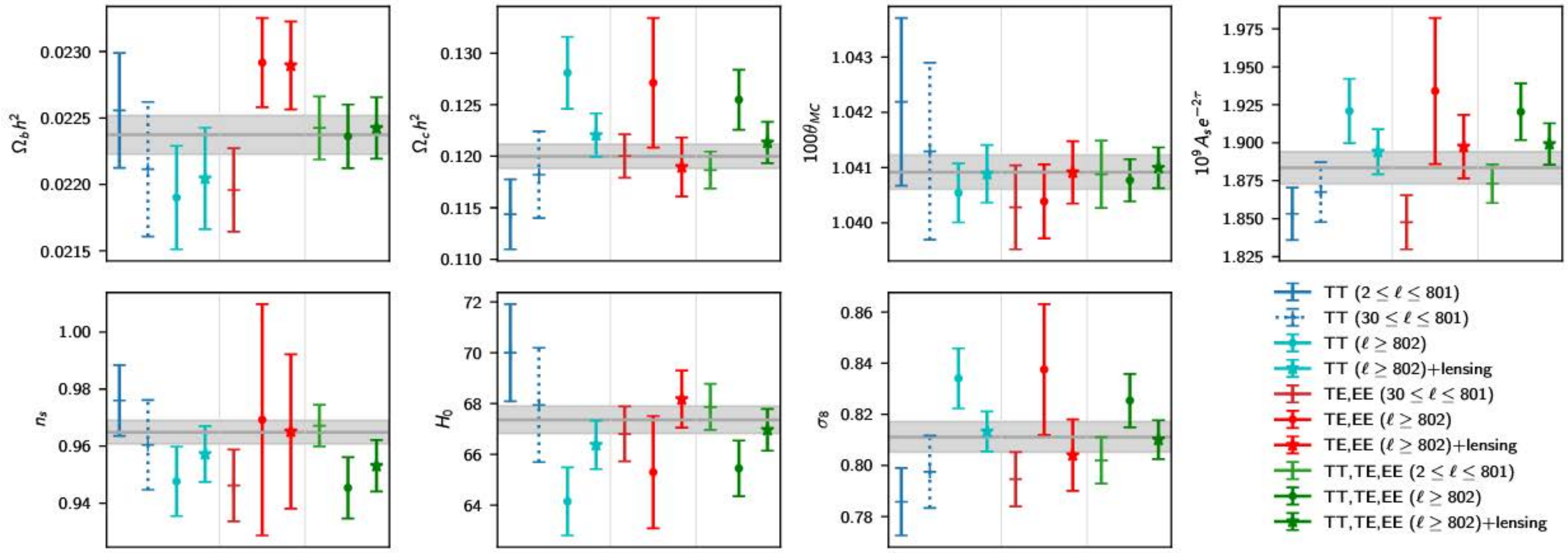
Curvature and Alens issue







Tensions Low-high ell ?



The results of Planck analysis comparing parameters measured from ell=30-1000 with those measured from 1000-2500 agree with what published in the Planck papers but are a bit cleaner because taking into account of reduced foregrounds. Therefore there is nothing anomalous -- the parameters shifts are consistent with expectations. There is, however, some tension when we add the low ells from ell=2-30 (LFI). (From G. Efstathiou)

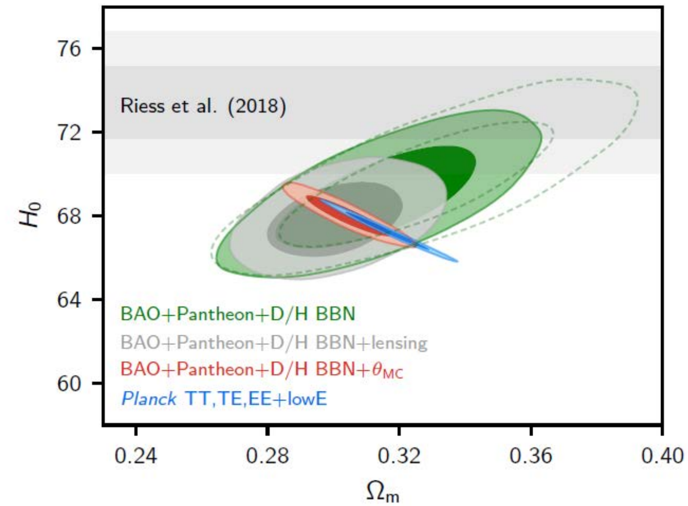
This might be just a consequence of the low amplitudes at ell<30 that we have known about since WMAP. It's possible that there is new physics that suppresses the low ell multipoles -- but the statistical significance is not high.

Tensions: H_0 (3.8 sigma)

Low-high redshift evolution?

New physics or systematics?

Primordial deuterium abundances allow to constrain the sound horizon and this gives constraints that agree with the base LCDM model. So, if we want to resolve the tension between CMB and H_0, we have to change the sound horizon while preserving BBN and the acoustic peak structure of the CMB.
Courtesy of G. Efstathiou



About the H_0 tension…

Prefer low H_0

- Planck
- Planck + SPT
- Planck + BOSS
- WMAP + BOSS
- SPT + BOSS
- ACT + BOSS
- r_d + SN + BOSS → This does not assume Λ
- BBN + BOSS
- BBN + DES + BOSS → These do not use CMB

Consistent with both

- SPT
- HOLiCOW
- LIGO GW

Prefer high H_0

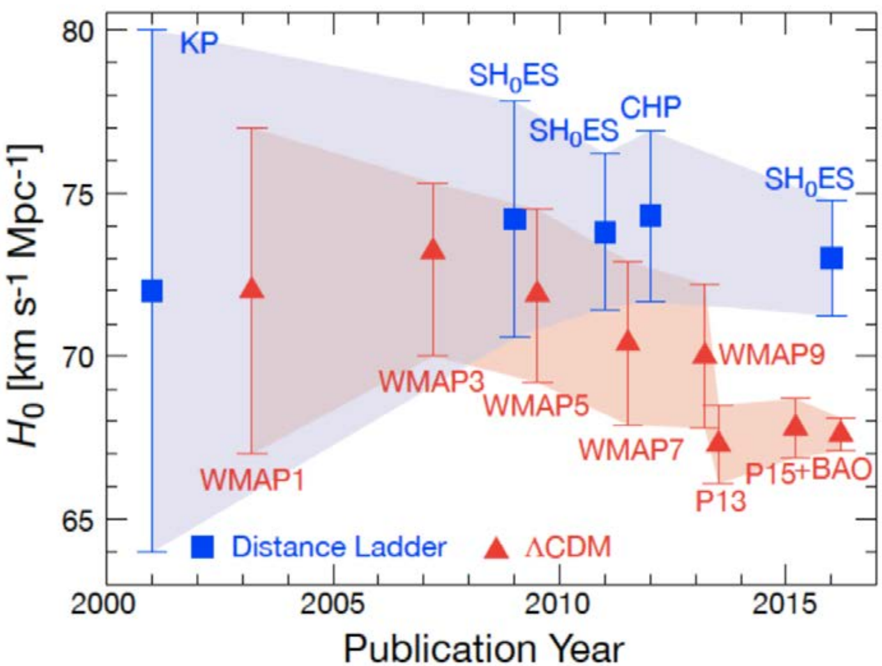
- Distance Ladder

```
WMAP9+ACT   r_d = 148.1 Mpc
WMAP9+SPT   r_d = 149.2 Mpc
WMAP9+ACT+SPT   r_d = 148.7 Mpc
PlanckTT   r_d = 147.1 Mpc
PlanckTTTEEE   r_d = 147.1 Mpc
PlanckTT+Low-P   r_d = 147.3 Mpc
```

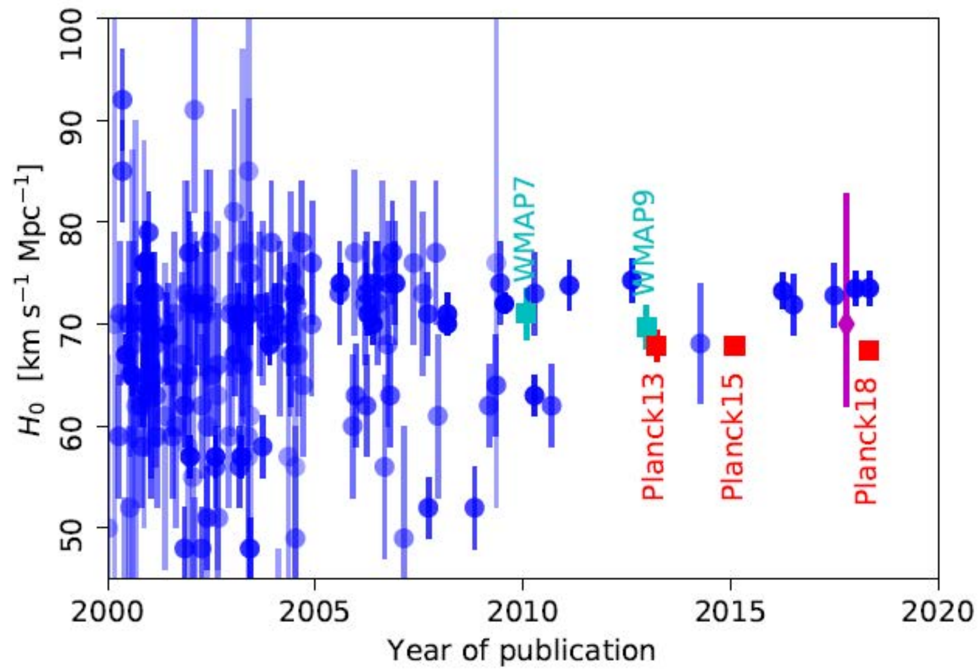
Parameters from Calabrese et al. (2017)

Agreement better than 1.4%

They all assume we understand early universe physics (to compute r_d)



W. Freedmann Nat. Astr. 1 2017



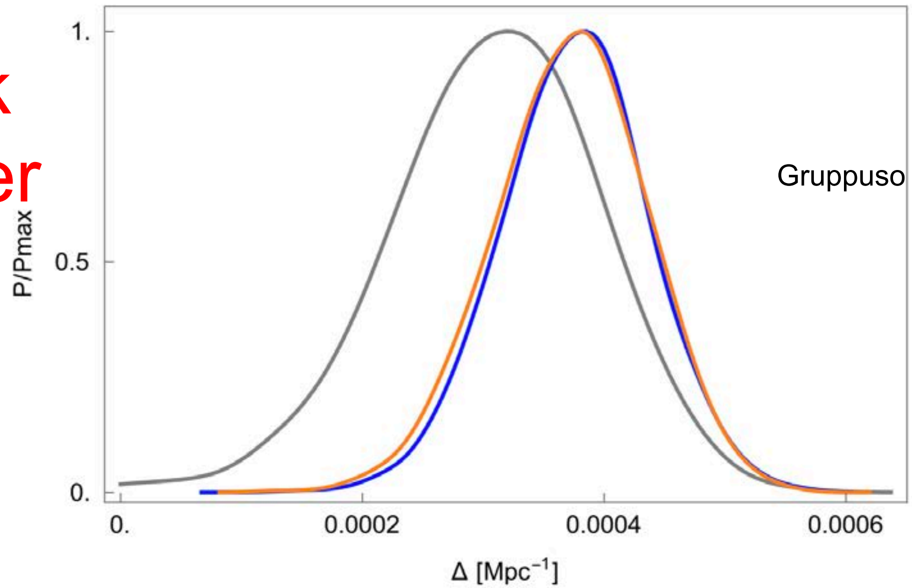
Planck exhausted the temperature
Polarization is the future

The search for B-modes and a cosmic variance limited -full sky E-mode measurement:

-Lack of power
-Reionization
-Primordial Universe
-Neutrinos

Will E-mode polarization confirm anomalies? Example:

Delta=0 -> no lack of power, the higher the more lack of power



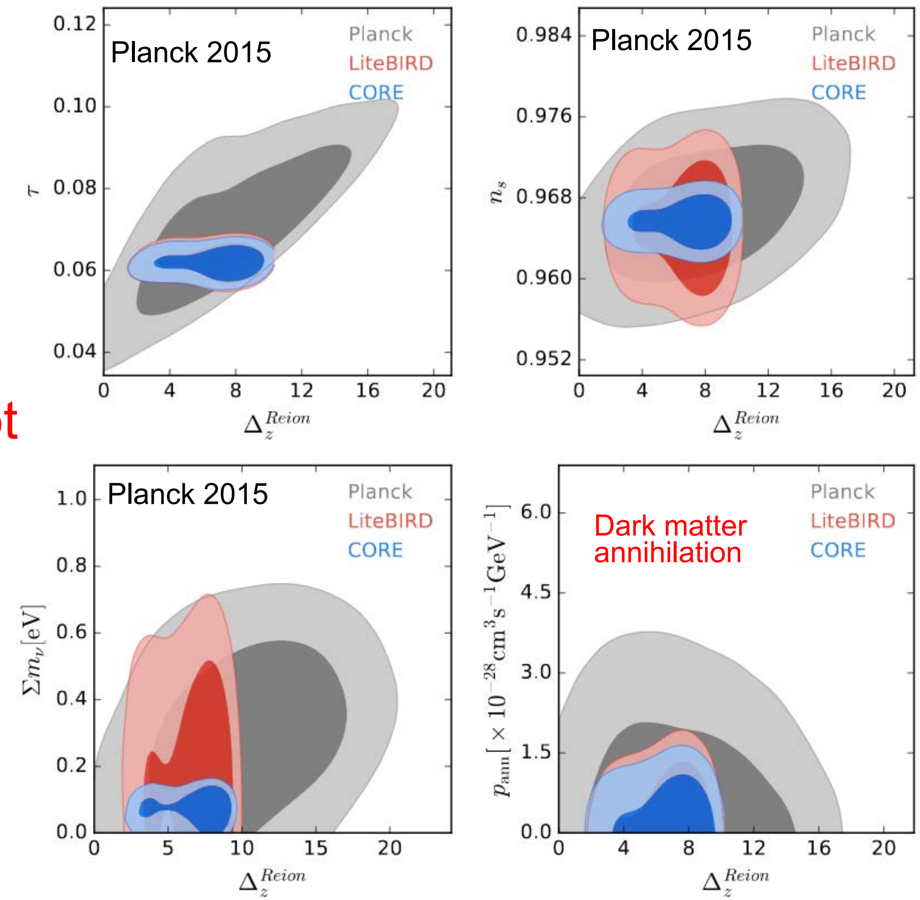
Gruppuso et Al. 2018 Phys. of the dark Univ.

Fig. 18. Expected estimates for Δ from future polarization- oriented experiments. The curves share the same underlying CMB realization, generated from a fiducial cosmological model with $\Delta = 0.37 \times 10^{-3}$. With PLANCK-like noise, standard mask in temperature and union mask in polarization, the detection level for Δ could grow up to about 3.5 σ (gray curve). With cosmic-variance-limited temperature and polarization data at large scales and the Ext_{30} masking, the detection level for Δ could rise up to about 6 σ (orange curve). Finally, with the same cosmic- variance-limited data, the standard mask in temperature and no mask in polarization, the detection level could increase even slightly beyond 6 σ (blue curve).

A tomography of the reionization history. Example:

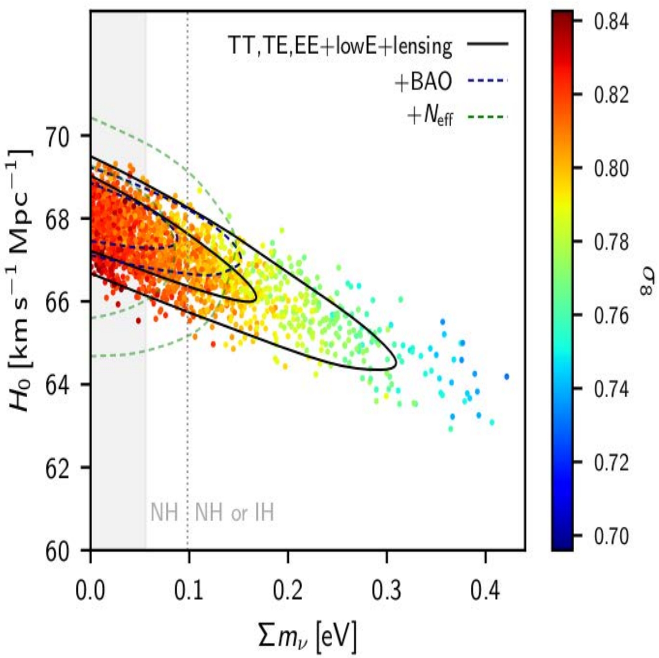
Breaking degeneracies with the Physics of the primordial Universe and extended models of reionization

Using the Poly-reion model (Hazra and Smoot 2015):



Hazra et al. 2018

The neutrino legacy of Planck (1)

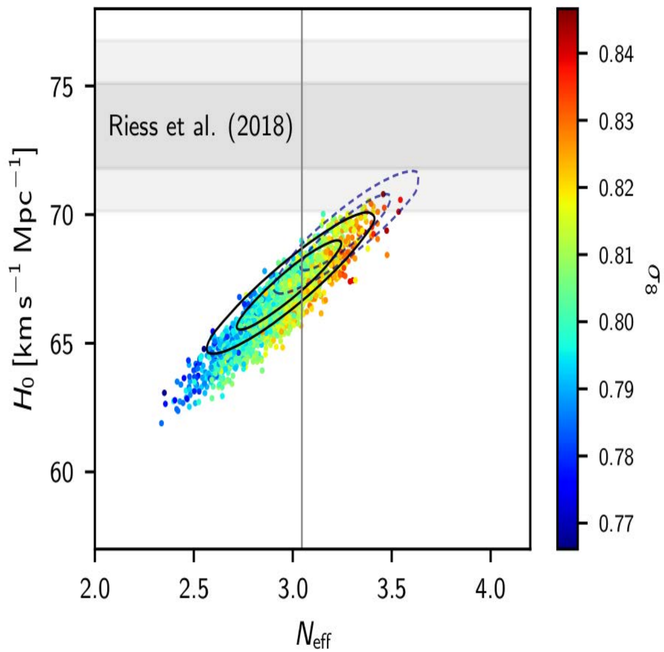


$M_\nu < 0.44$ eV (95%CL, TT + lowE + lensing)

$M_\nu < 0.13$ eV (95%CL,TT+lowE+lensing+BAO)

- Tightest constraint from a single experiment
- First constraint exploiting the information encoded in the CMB weak lensing
- One order of magnitude better than present kinematic constraints, already at the same level than future expectations for KATRIN
- The combined limits from Planck and large scale structure probes are starting to corner the inverted hierarchy scenario

The neutrino legacy of Planck (2)

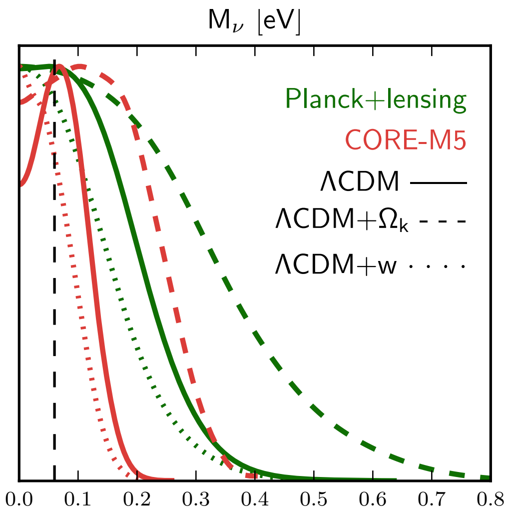


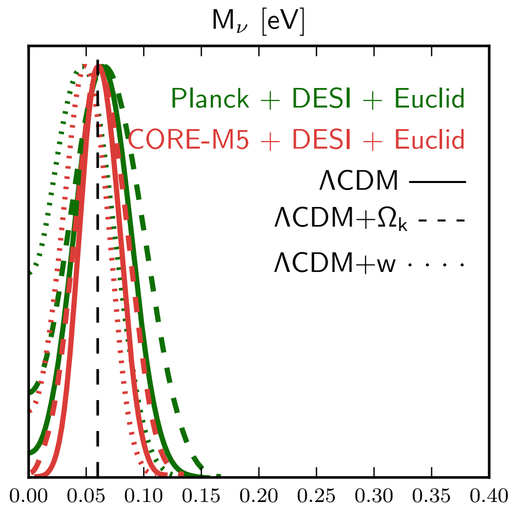
$N_{eff} = 3.00^{+0.57}_{-0.53}$ (95% CL, TT+lowE)

$N_{eff} = 3.11^{+0.44}_{-0.43}$ (95% CL, TT+lowE+lensing +BAO)

- Effective number of relativistic species is consistent with the standard expectation N_{eff} = 3.046
- Data are consistent with these relativistic species behaving as free-streaming neutrinos – a strong indication that they are indeed the SM neutrinos!
- A fourth thermalized species (N_{eff}=4) is excluded at 3.5 to 6 σ, depending on the dataset
- A light sterile neutrino species is allowed if not thermalized. Still, the sterile neutrino interpretation of the short-baseline anomalies is excluded by Planck

Neutrino: the Future





Expected uncertainty on M_ν from CORE (+LSS) in LCDM+M_ν

$\sigma(M_\nu)$ = 0.044 (0.016) eV

(similar figures for CMB-S4)

The combination of CMB and LSS, guarantees at least a 4 σ detection

Would allow to determine the hierarchy if the mass is close to

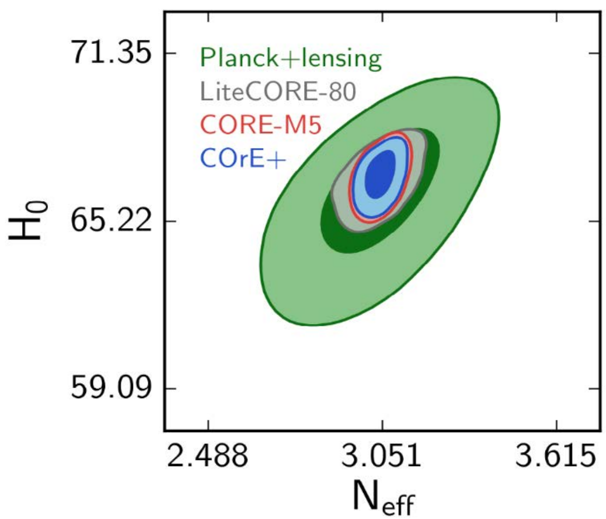
Effective number of relativistic species:

$\sigma(N_{eff})$ = 0.04 from CORE+DESI BAO

$\sigma(N_{eff})$ = 0.02 from CMB-S4+DESI BAO

Will allow to probe the physics of neutrino decoupling.

Also allows to detect thermal relics up to arbitrarily high decoupling temperatures (Baumann, Green, Wallisch 2017)



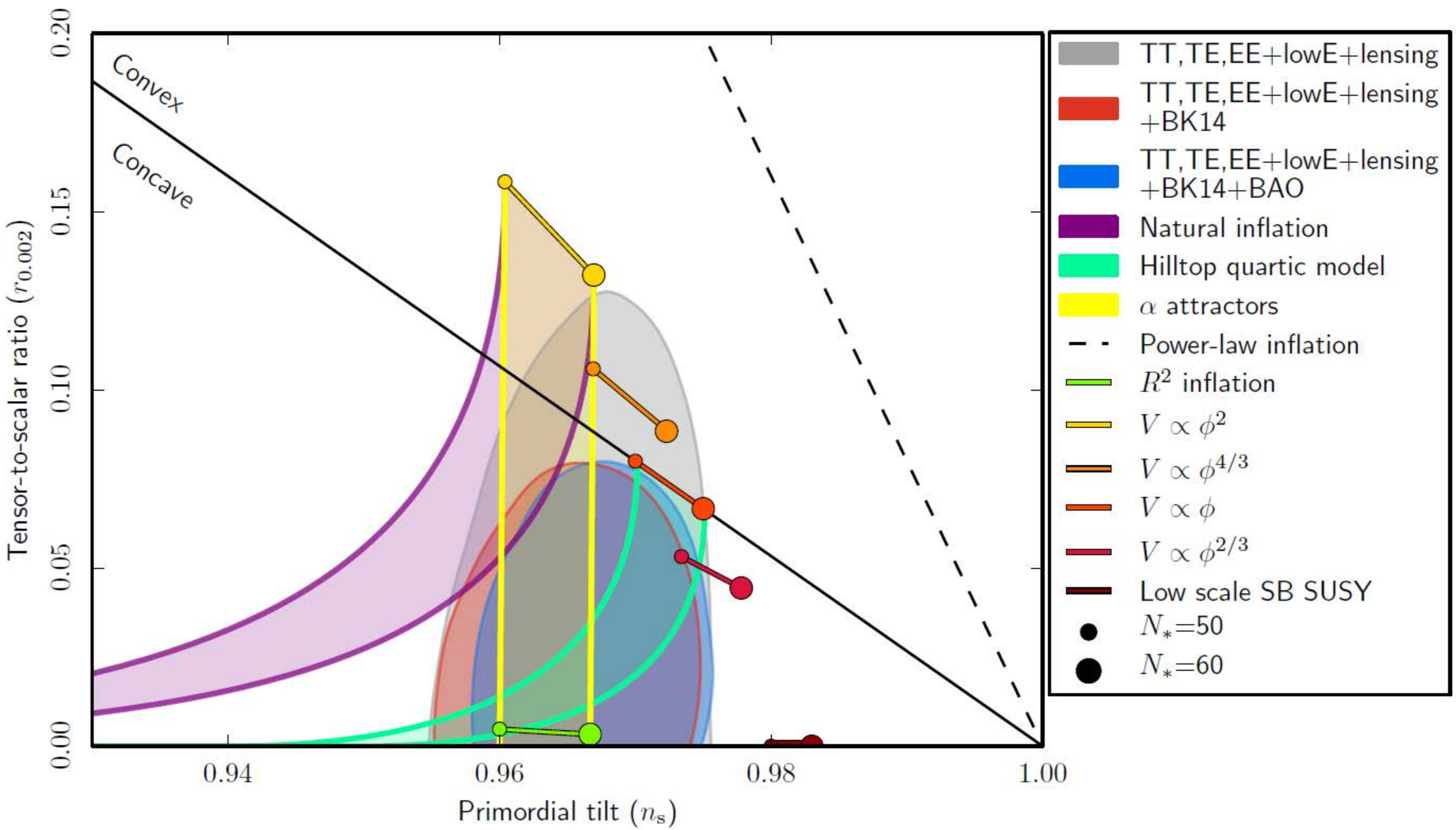
The quest for B-modes

Primordial tensor modes and the era of inflation

Primordial birefringence and the parity violations

Primordial magnetic fields and the origin of cosmic magnetism

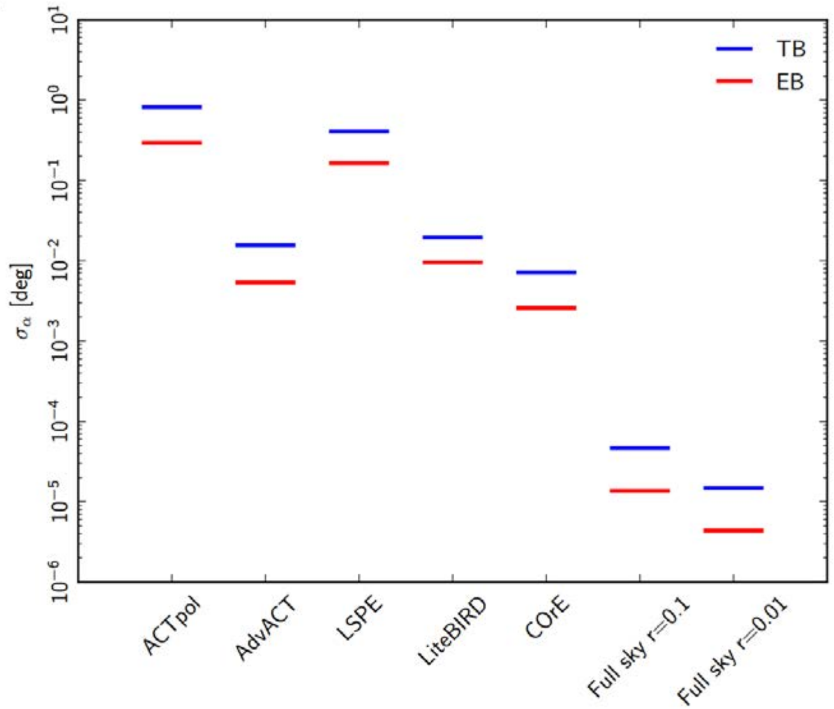
Inflation Physics



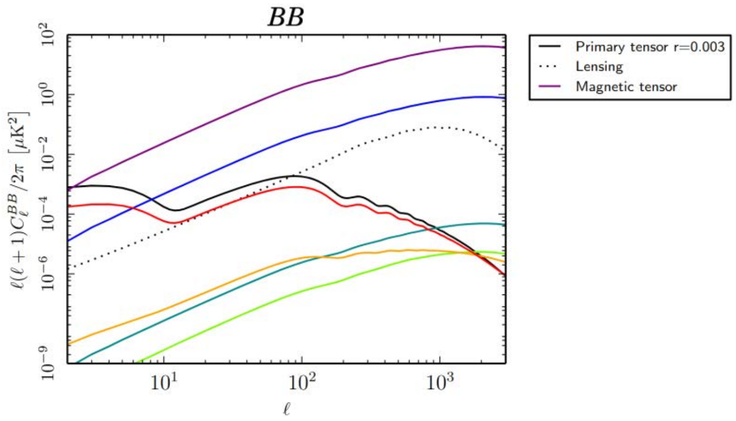
Parity violations Cosmic Birefringence

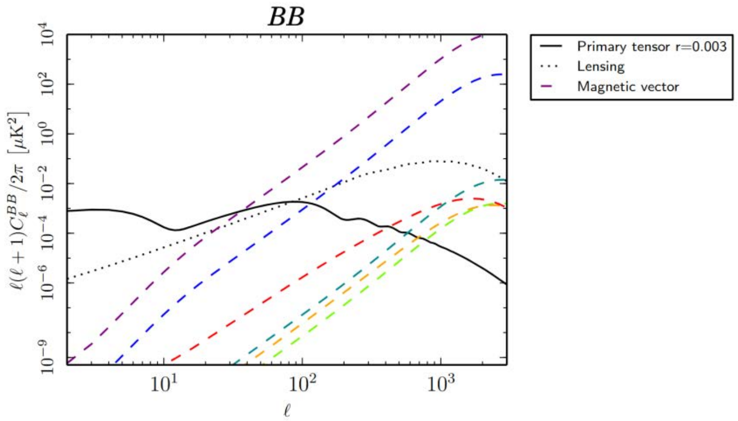
Origin of Cosmic Magnetism

Molinari et al. Phys. Dark Univ. 2016



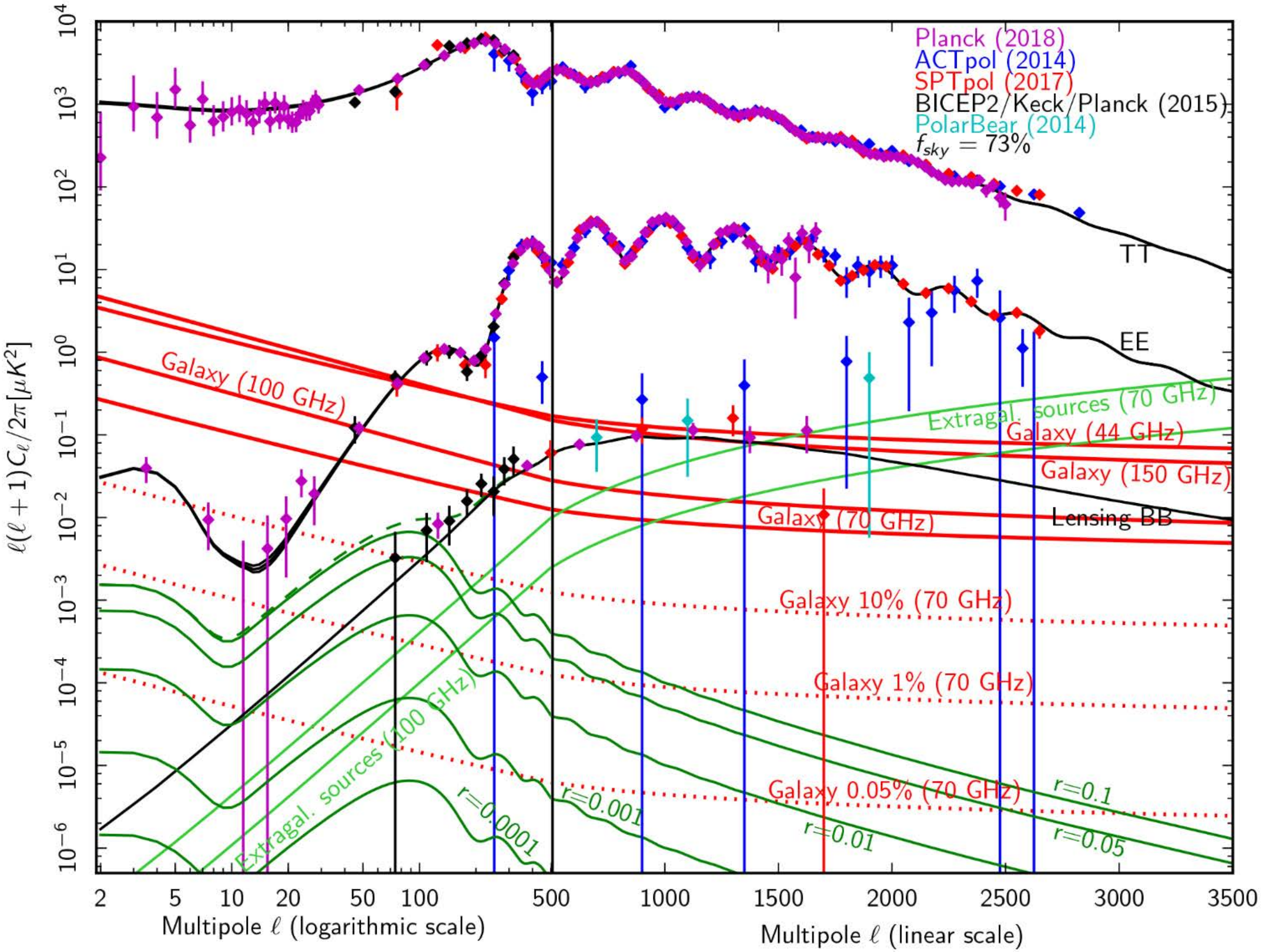
Future CMB experiments will be able to constrain birefringence angle better than 10^{-2} deg





Magnetic fields in the early Universe have a peculiar impact on both small and large angular scales B-mode

Deal with the foregrounds



Courtesy of Molinari, Mandolesi, Burigana

Breaking degeneracies , testing anomalies and constraining the Universe

The sinergies between CMB and LSS is crucial for the future

BAO
Galaxy Clusters
Galaxy Clustering
Weak lensing
Shear
Redshift space distortions

PLACK: LESSONS LEARNED

• A very long project (1992) and large teams to be managed and organized (issues of many types to solve, time and patience consuming)

• Need a combination of: credibility, charismatic leaders, support from the top, financial stability and ......FORTUNE

• Control of risks (fluctuating funding, technical challenging problems, schedule, crisis, etc.)

•Test Test Test

•A complex and challenging mission like Planck would not be possible in today’s (conservative) environment

•Despite of all these points Planck was a great success.

WHAT'S NEXT

The legacy of Planck not only represents the status of the art of full sky microwave observations but the path to the future of CMB:

POLARIZATION

Foregrounds in polarization are still very poorly known and this require a deep investigation. You will never be sure of a B-mode as long as foregrounds are not perfectly known beyond any doubt

TO PERFORM THE BEST POSSIBLE SEPARATION OF THE SKY COMPONENTS ARE REQUIRED AS MUCH FREQUENCY CHANNELS AS POSSIBLE.
AND THE WIDEST FREQUENCY RANGE IN ORDER TO DISENTANGLE LOW FREQUENCY FOREGROUND COMPLEXITY

Resolution. On small angular scales B-modes signal are dominated by the lensing. The only hope are delensing algorithms which need high resolution to be performant!

THE FUTURE OF THE CMB MIGHT BE PROMISING
BUT
COMPLEXITY WILL BE ORDERS OF MAGNITUDE HIGHER

Experiments Beyond Planck

- **Ground** (in this conference: PASIPHAE, CMB-S4, BICEP, POLARBEAR, Simons, SPT)
- **Balloon** (in this conference: PILOT)
- **Space** (in this conference: LiteBIRD, PICO, PIXIE)

CMB-Bharat

A proposal for a high-profile Indian CMB space mission submitted to the Indian Space Research Organisation by a consortium of ~100 Indian researchers (led by Prof. Tarun Souradeep, IUCAA, India), by the deadline of Apr. 26, 2018.

First review of proposal organised by ISRO on July 5-6, 2018

Aiming for a joint mission with other space agencies. Joint effort with CORE consortium currently being discussed.

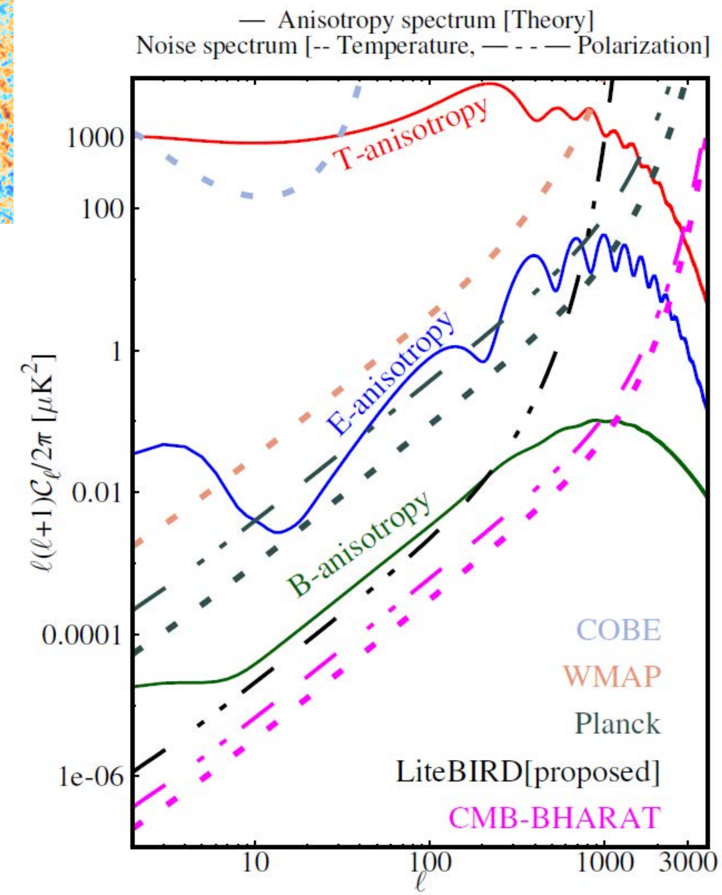
2400 detectors in the range 60-900 GHz

Polarization sensitivity down to 1μK.arcmin.

Under evaluation an additional 18 cm aperture Fourier Transform Spectrometer with a beam size of 3.6 degree and a frequency resolution of 12 GHz over the frequency range 36-3000 GHz.

Indian Launch Vehicle GSLV-III.
Target launch: 2029.

Assessment and evaluation underway



http://cmb-bharat.in/

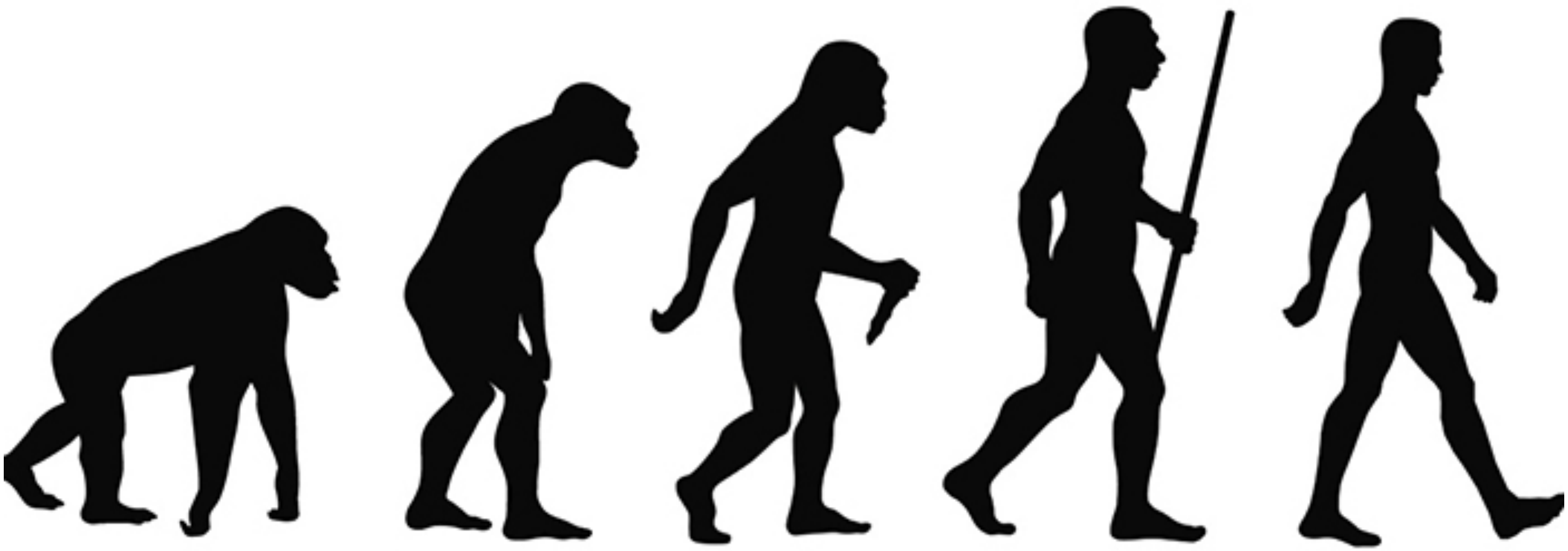
Science objectives:

- Primordial gravitational waves detection at 3-5 σ if r is 0.001.
- Neutrino physics: total neutrino mass, number of effective relativistic species
- The spectrometer in addition to the quest for spectral distortions might be used to clean from foregrounds

Future Space Mission

A LARGE MISSION IS NEEDED!

Where are we now with understanding our Universe?



The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.


Thank you
Contributions from D. Paoletti, D. Molinari and A. Gruppuso