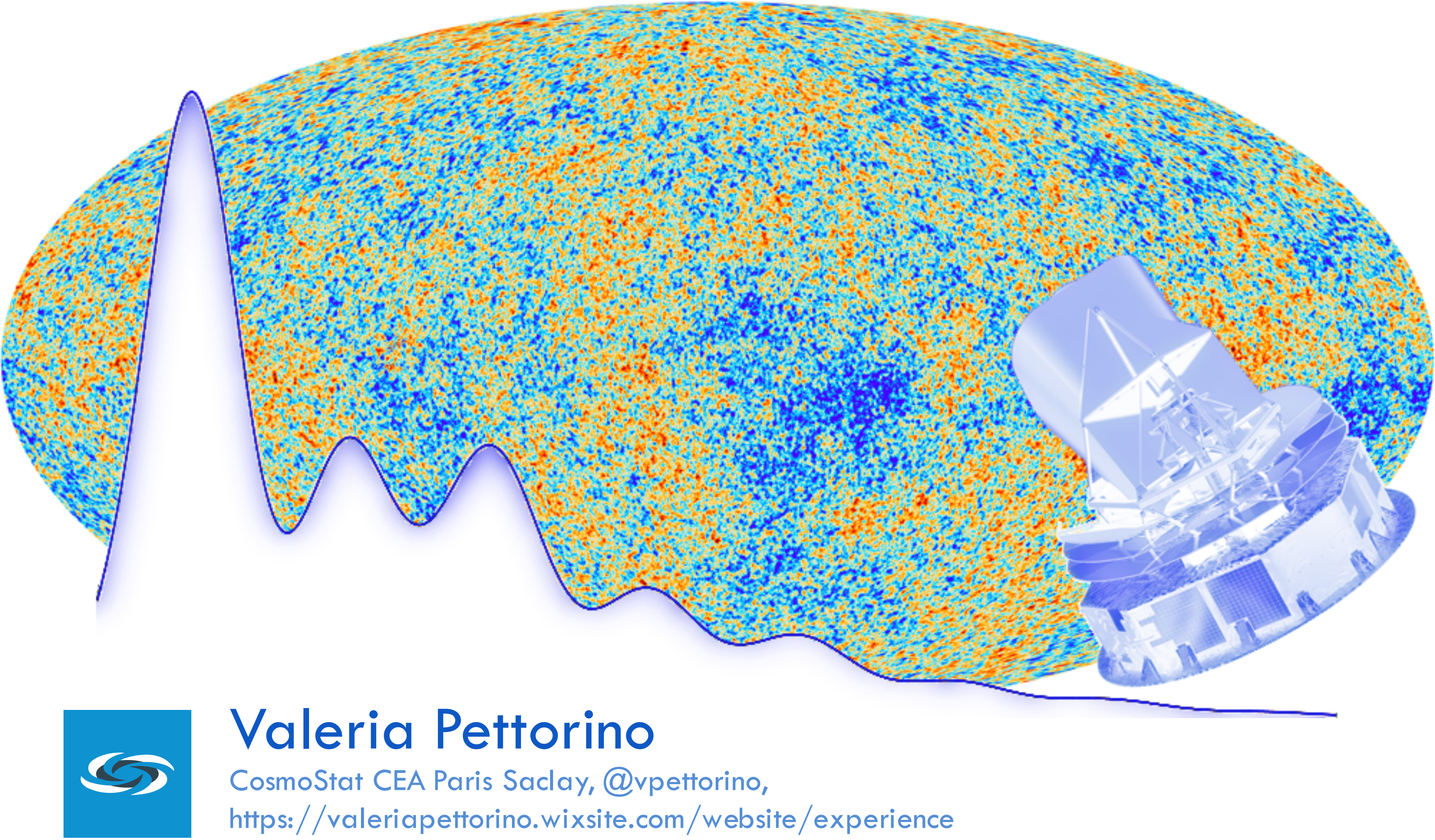
Planck 2018 results: cosmological parameters



Valeria Pettorino

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What's new

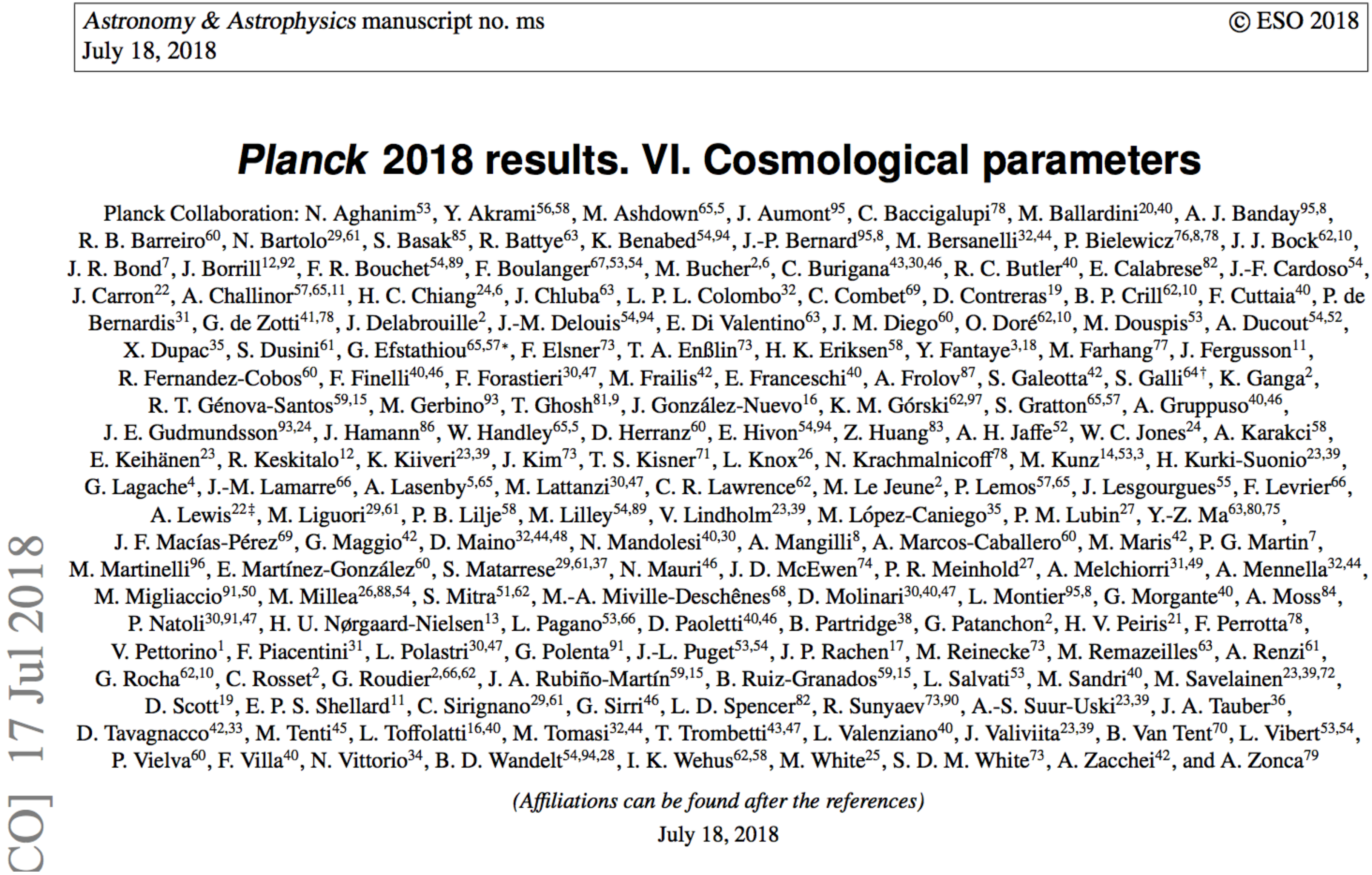
- **Results 2013**: temperature and CMB lensing from 15.5 months, combined with WMAP polarization at l < 23 to constrain τ
- **Results 2015**: full mission (29 months HFI), resolved calibration difference with WMAP, TT and preliminary TE EE. LFI polarization to measure τ
- **Results 2018**: same data as 2015; reduce systematics in HFI polarization at low l; new low-l likelihood to constrain τ. Better characterization of T to P leakage and relative calibrations of P spectra (with limitations).
- Very little effect on high-l TT TE EE wrt 2015. Difference mainly comes from low-l analysis.

9 new papers currently out

- **Planck 2018 results. I. Overview and the cosmological legacy of Planck**
- **Planck 2018 results. II. Low Frequency Instrument data processing**
- **Planck 2018 results. III. High Frequency Instrument data processing and frequency maps**
- **Planck 2018 results. IV. Diffuse component separation**
- **…**
- **Planck 2018 results. VI. Cosmological parameters**
- **…**
- **Planck 2018 results. VIII. Gravitational lensing**
- **…**
- **Planck 2018 results. X. Constraints on inflation**
- **Planck 2018 results. XI. Polarized dust foregrounds**
- **Planck 2018 results. XII. Galactic astrophysics using polarized dust emission**

3 more papers to come: V (Legacy Power Spectra and Likelihoods), VII (Isotropy and Statistics), and IX (Constraints on primordial non-Gaussianity) will be made public at a later time

https://arxiv.org/pdf/1807.06209.pdf



Astronomy & Astrophysics manuscript no. ms
July 18, 2018

Planck 2018 results. VI. Cosmological parameters

Planck Collaboration: N. Aghanim[53], Y. Akrami[56,58], M. Ashdown[65,5], J. Aumont[95], C. Baccigalupi[78], M. Ballardini[20,40], A. J. Banday[95,8], R. B. Barreiro[60], N. Bartolo[29,61], S. Basak[85], R. Battye[63], K. Benabed[54,94], J.-P. Bernard[95,8], M. Bersanelli[32,44], P. Bielewicz[76,8,78], J. J. Bock[62,10], J. R. Bond[7], J. Borrill[12,92], F. R. Bouchet[54,89], F. Boulanger[67,53,54], M. Bucher[2,6], C. Burigana[43,30,46], R. C. Butler[40], E. Calabrese[82], J.-F. Cardoso[54], J. Carron[22], A. Challinor[57,65,11], H. C. Chiang[24,6], J. Chluba[63], L. P. L. Colombo[32], C. Combet[69], D. Contreras[19], B. P. Crill[62,10], F. Cuttaia[40], P. de Bernardis[31], G. de Zotti[41,78], J. Delabrouille[2], J.-M. Delouis[54,94], E. Di Valentino[63], J. M. Diego[60], O. Doré[62,10], M. Douspis[53], A. Ducout[54,52], X. Dupac[35], S. Dusini[61], G. Efstathiou[65,57,*], F. Elsner[73], T. A. Enßlin[73], H. K. Eriksen[58], Y. Fantaye[3,18], M. Farhang[77], J. Fergusson[11], R. Fernandez-Cobos[60], F. Finelli[40,46], F. Forastieri[30,47], M. Frailis[42], E. Franceschi[40], A. Frolov[87], S. Galeotta[42], S. Galli[64,†], K. Ganga[2], R. T. Génova-Santos[59,15], M. Gerbino[93], T. Ghosh[81,9], J. González-Nuevo[16], K. M. Górski[62,97], S. Gratton[65,57], A. Gruppuso[40,46], J. E. Gudmundsson[93,24], J. Hamann[86], W. Handley[65,5], D. Herranz[60], E. Hivon[54,94], Z. Huang[83], A. H. Jaffe[52], W. C. Jones[24], A. Karakci[58], E. Keihänen[23], R. Keskitalo[12], K. Kiiveri[23,39], J. Kim[73], T. S. Kisner[71], L. Knox[26], N. Krachmalnicoff[78], M. Kunz[14,53,3], H. Kurki-Suonio[23,39], G. Lagache[4], J.-M. Lamarre[66], A. Lasenby[5,65], M. Lattanzi[30,47], C. R. Lawrence[62], M. Le Jeune[2], P. Lemos[57,65], J. Lesgourgues[55], F. Levrier[66], A. Lewis[22,‡], M. Liguori[29,61], P. B. Lilje[58], M. Lilley[54,89], V. Lindholm[23,39], M. López-Caniego[35], P. M. Lubin[27], Y.-Z. Ma[63,80,75], J. F. Macías-Pérez[69], G. Maggio[42], D. Maino[32,44,48], N. Mandolesi[40,30], A. Mangilli[8], A. Marcos-Caballero[60], M. Maris[42], P. G. Martin[7], M. Martinelli[96], E. Martínez-González[60], S. Matarrese[29,61,37], N. Mauri[46], J. D. McEwen[74], P. R. Meinhold[27], A. Melchiorri[31,49], A. Mennella[32,44], M. Migliaccio[91,50], M. Millea[26,88,54], S. Mitra[51,62], M.-A. Miville-Deschênes[68], D. Molinari[30,40,47], L. Montier[95,8], G. Morgante[40], A. Moss[84], P. Natoli[30,91,47], H. U. Nørgaard-Nielsen[13], L. Pagano[53,66], D. Paoletti[40,46], B. Partridge[38], G. Patanchon[2], H. V. Peiris[21], F. Perrotta[78], V. Pettorino[1], F. Piacentini[31], L. Polastri[30,47], G. Polenta[91], J.-L. Puget[53,54], J. P. Rachen[17], M. Reinecke[73], M. Remazeilles[63], A. Renzi[61], G. Rocha[62,10], C. Rosset[2], G. Roudier[2,66,62], J. A. Rubiño-Martín[59,15], B. Ruiz-Granados[59,15], L. Salvati[53], M. Sandri[40], M. Savelainen[23,39,72], D. Scott[19], E. P. S. Shellard[11], C. Sirignano[29,61], G. Sirri[46], L. D. Spencer[82], R. Sunyaev[73,90], A.-S. Suur-Uski[23,39], J. A. Tauber[36], D. Tavagnacco[42,33], M. Tenti[45], L. Toffolatti[16,40], M. Tomasi[32,44], T. Trombetti[43,47], L. Valenziano[40], J. Valiviita[23,39], B. Van Tent[70], L. Vibert[53,54], P. Vielva[60], F. Villa[40], N. Vittorio[34], B. D. Wandelt[54,94,28], I. K. Wehus[62,58], M. White[25], S. D. M. White[73], A. Zacchei[42], and A. Zonca[79]

(Affiliations can be found after the references)

July 18, 2018

Planck 2018 cosmology paper

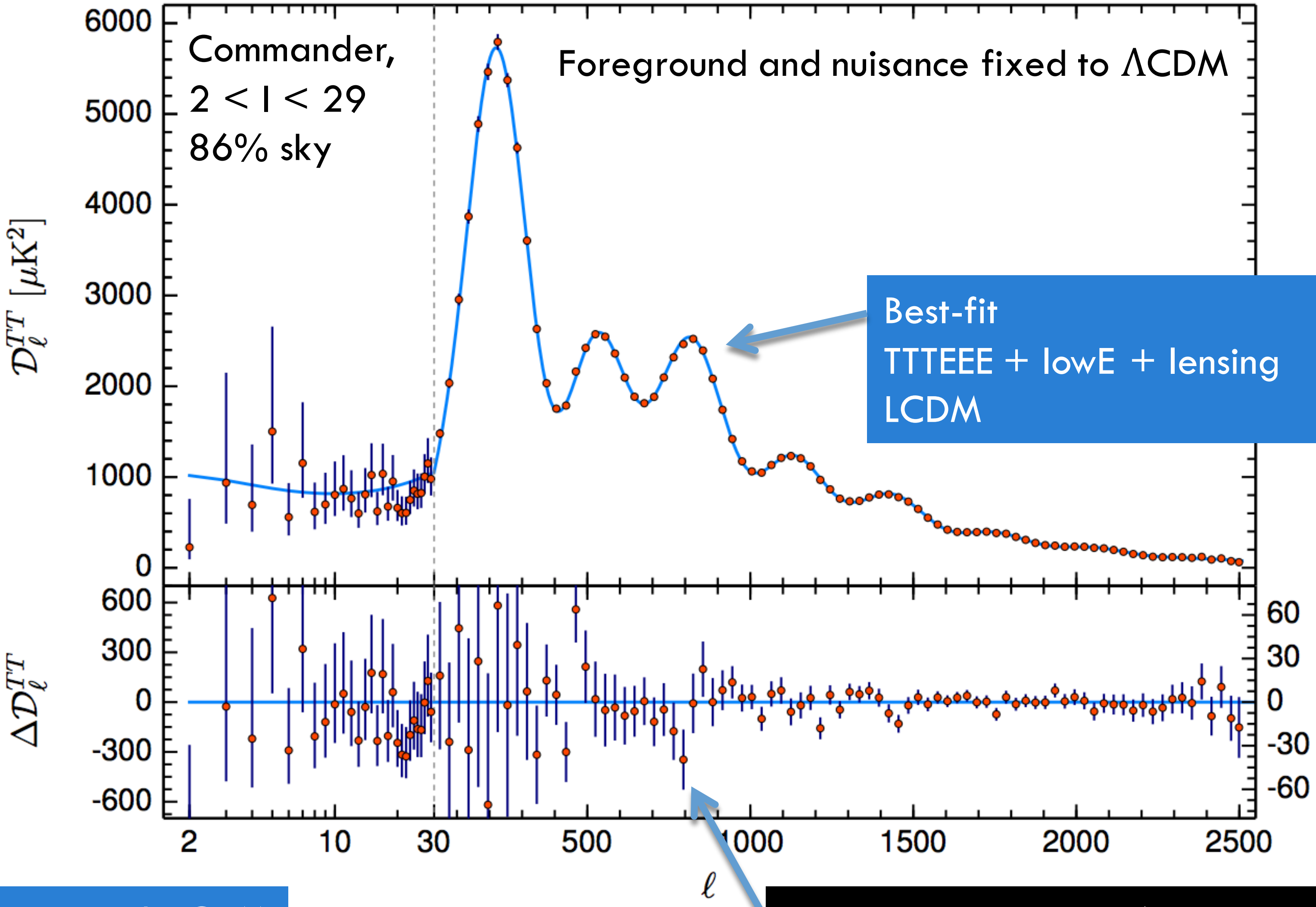
- Methodology and Likelihoods
- ΛCDM baseline results
- Comparison with high-l experiments (SPTPol, ACTPol)
- Comparison with external datasets
- Internal consistency in ΛCDM
- Extensions to ΛCDM
  - Early Universe
  - Curvature
  - Dark Energy and Modified Gravity
  - Neutrinos
  - BBN
  - Recombination
  - Reionization
  - Dark Matter annihilation

https://arxiv.org/pdf/1807.06209.pdf

TT spectrum

Log scale

Linear scale



Commander,
2 < l < 29
86% sky

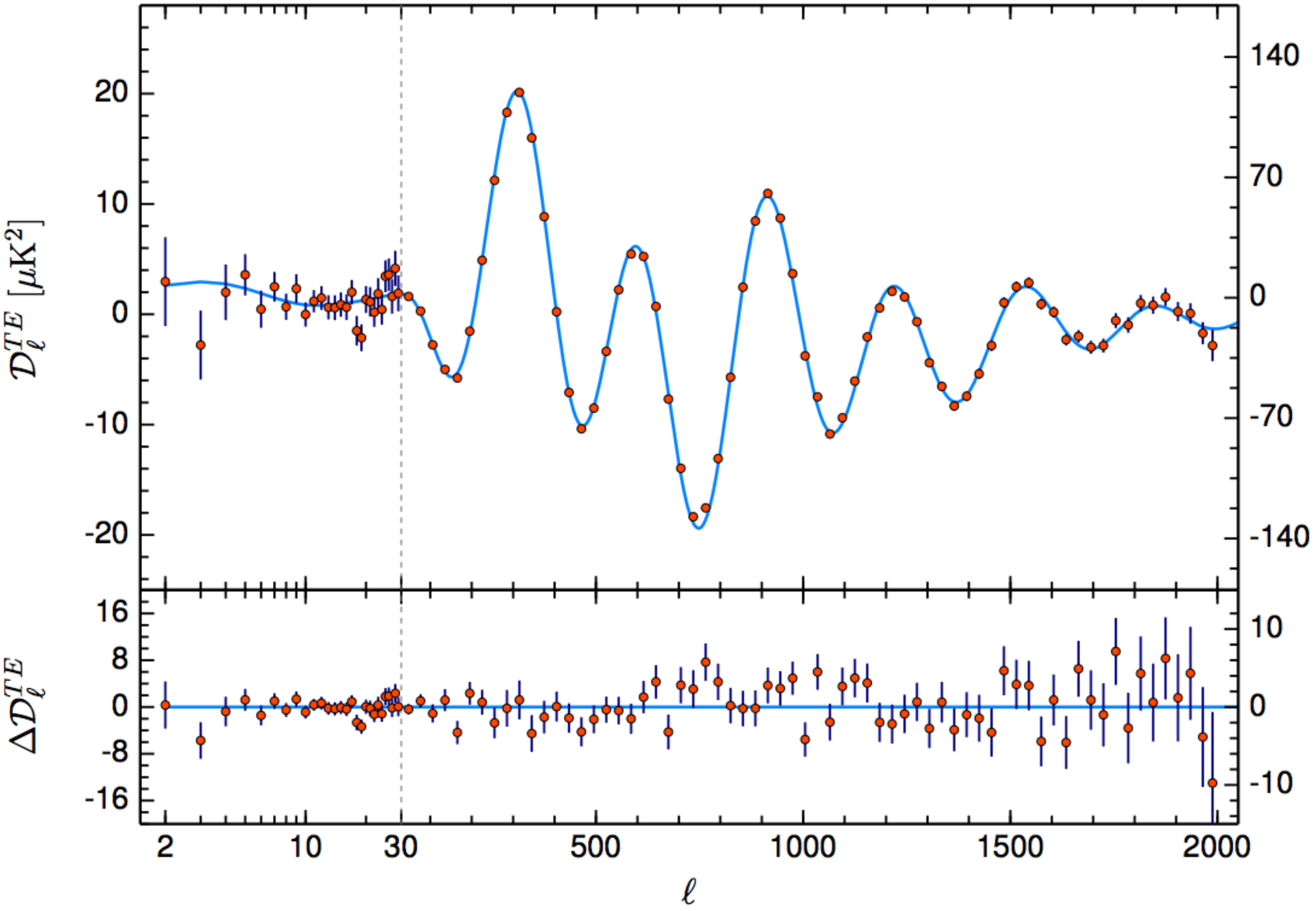
Foreground and nuisance fixed to ΛCDM

Best-fit
TTTEEE + lowE + lensing
LCDM

Agreement with LCDM

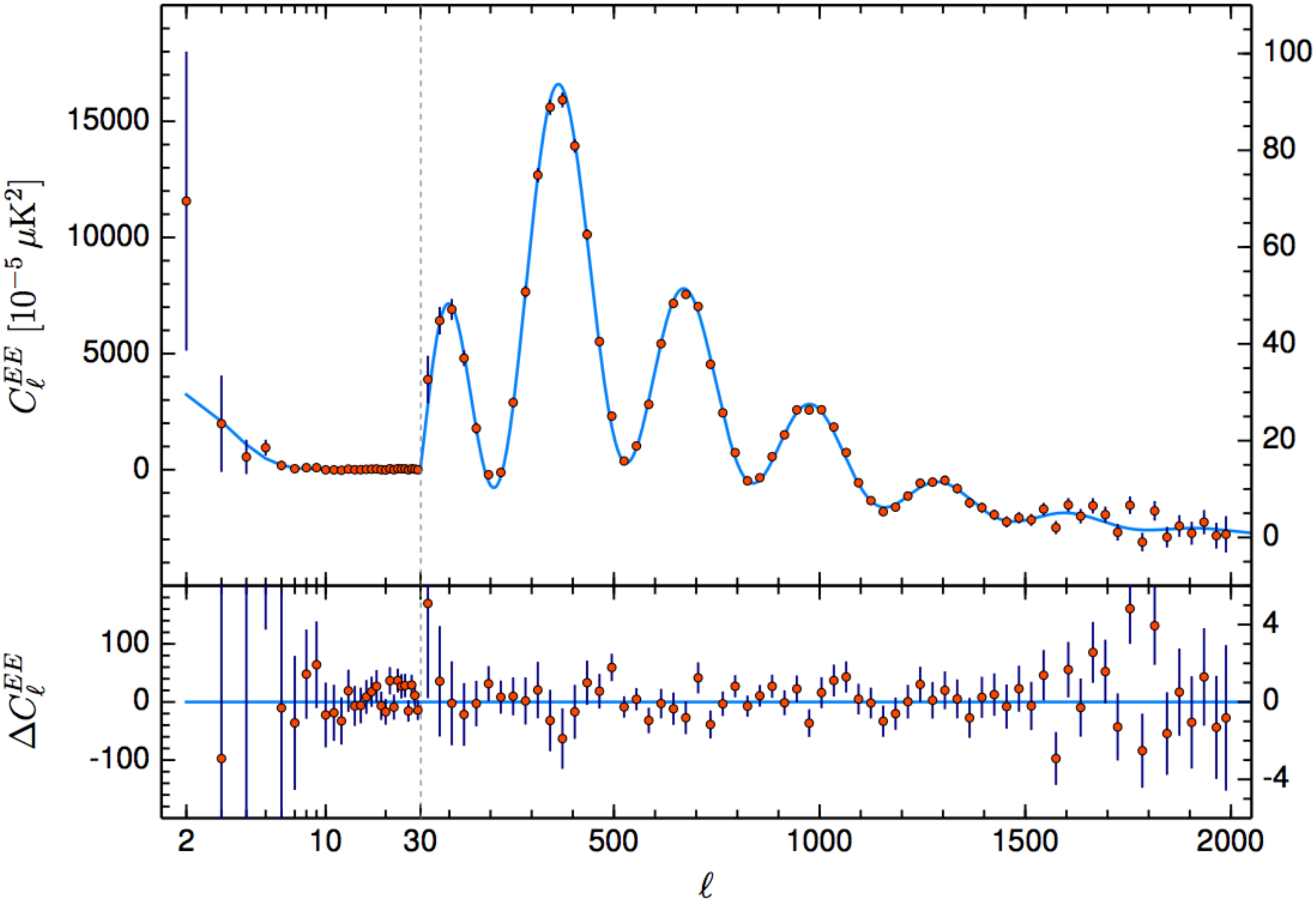
1 sigma uncertainties (cosmic variance)

TE spectrum



$\mathcal{D}_\ell^{TE}\ [\mu\mathrm{K}^2]$
20
10
0
-10
-20
140
70
0
-70
-140
$\Delta\mathcal{D}_\ell^{TE}$
16
8
0
-8
-16
10
0
-10
2
10
30
500
1000
1500
2000
ℓ

EE spectrum



$C_\ell^{EE}\ [10^{-5}\,\mu\mathrm{K}^2]$
15000
10000
5000
0
100
80
60
40
20
0
ΔC_ℓ^{EE}
100
0
-100
4
0
-4
2
10
30
500
1000
1500
2000
ℓ

Likelihood: hybrid analysis

l > 30 No component separation. Gaussian likelihood from cross-spectra.

Plik: baseline; 30 < l < 2508 TT; 30 < l < 1996 TE, EE
uses 100m 143, 217 GHz HFI maps

CamSpec: same maps; lcuts depend on cross spectra; TT same as 2015; P: different masks; different correction of systematic effects. Covariance matrices assume LCDM.

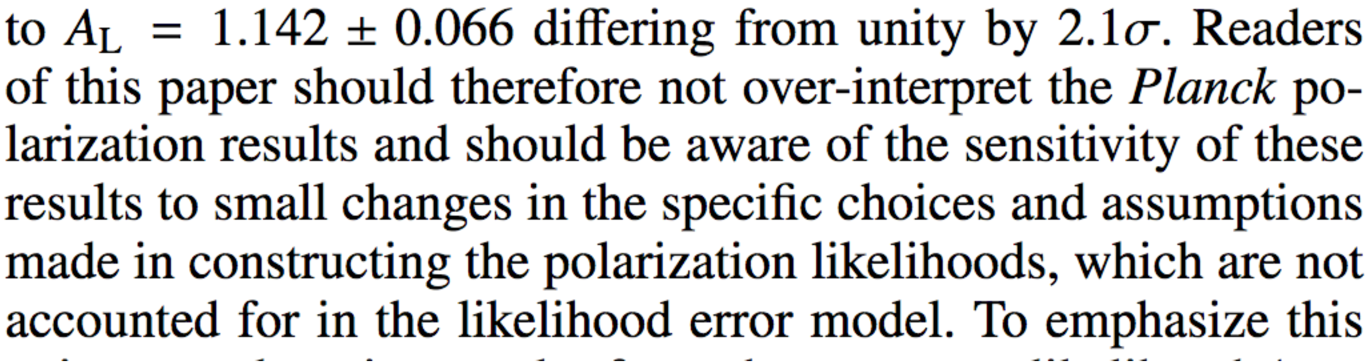
l < 30 TT: Comander component separation (86% coverage);
new EE likelihood (lowE) SimALL, maps produced with Sroll mapmaking algorithm (2018)

Correlation between low and high l are neglected.

CamSpec vs Plik

- Agreement in TT
- Small differences in TE and EE
- Correction of polarization efficiencies have largest uncertainty: recalibrated fitting in 200-1000 against a fiducial LCDM. The polarization efficiencies fitting TE or EE should be the same, however the ones from EE are 2σ lower than the ones from TE (statistics? Systematics?)
- Plik: assumes EE values for both (map-based)
- CamSpec: leaves T-to-P calibration free to vary (spectrum-based)
- Small shifts on LCDM ($<$ 0.5 σ) and $\sim$ 0.6 σ on A_L

A word of caution



to $A_L = 1.142 \pm 0.066$ differing from unity by 2.1σ. Readers of this paper should therefore not over-interpret the *Planck* polarization results and should be aware of the sensitivity of these results to small changes in the specific choices and assumptions made in constructing the polarization likelihoods, which are not accounted for in the likelihood error model. To emphasize this

CMB lensing likelihood

- Planck2018 increases the significance of the detection of lensing in the polarization maps from 5σ to 9σ. Combined with temperature, lensing is detected at 40σ.
- Spectra are always lensed
- *+ CMB lensing* means that the spectrum of the lensing potential is reconstructed from 4-point function, over $8 < l < 400$
- It probes $z < 2$
- Prefers less power at small scales than from other spectra
- Very compatible with LCDM
- Reconstruction assumes a fiducial LCDM; power spectrum corrected perturbatively in the normalization for changes in the fiducial.

Consistency with other datasets

Discussion on all data;
minimal use of external datasets in the analysis

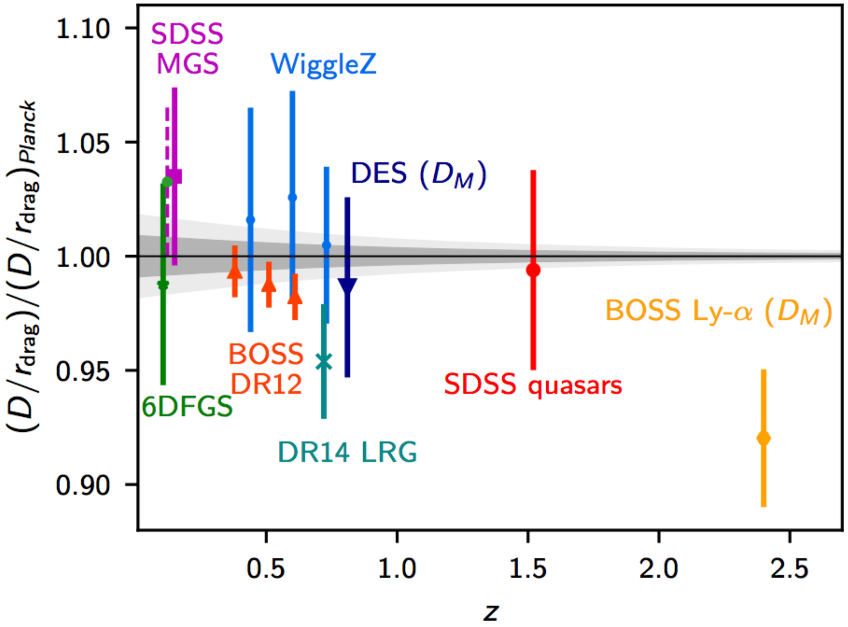
BAO: good agreement

Baryonic Acoustic Oscillations (BAO)

Measure the distance ratio:

Combination of
angular-diameter
distance and H(z)

Comoving sound horizon
at the epoch in which
baryons decouple
dynamically from
photons



Included: BOSS DR12, 6DFGS, SDSS MGS

Excluded: BOSS Ly-α (more complicated, assumptions)

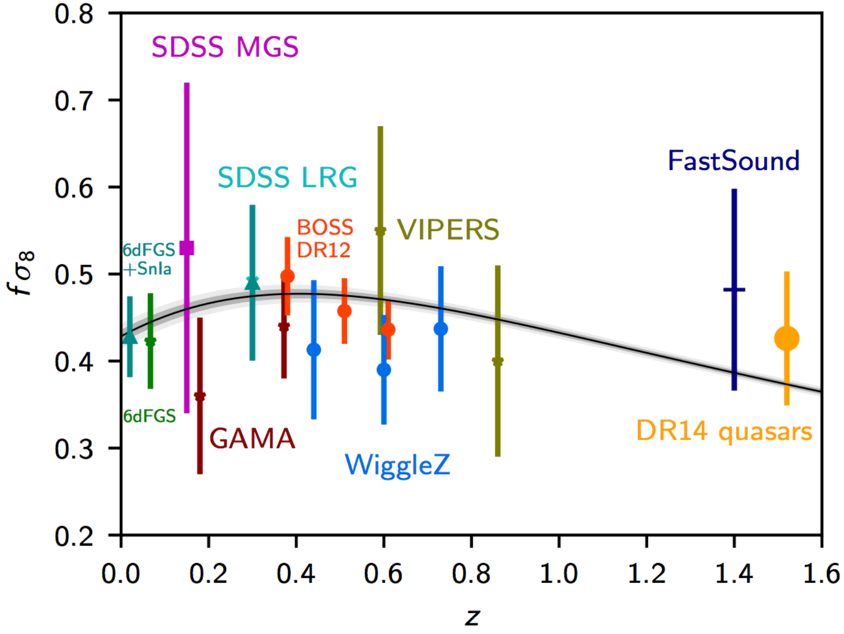
RSD: good agreement

Redshift Space Distortions (RSD)

Anisotropies induced by peculiar velocities: constraints f σ_8

Modelling non-linearities

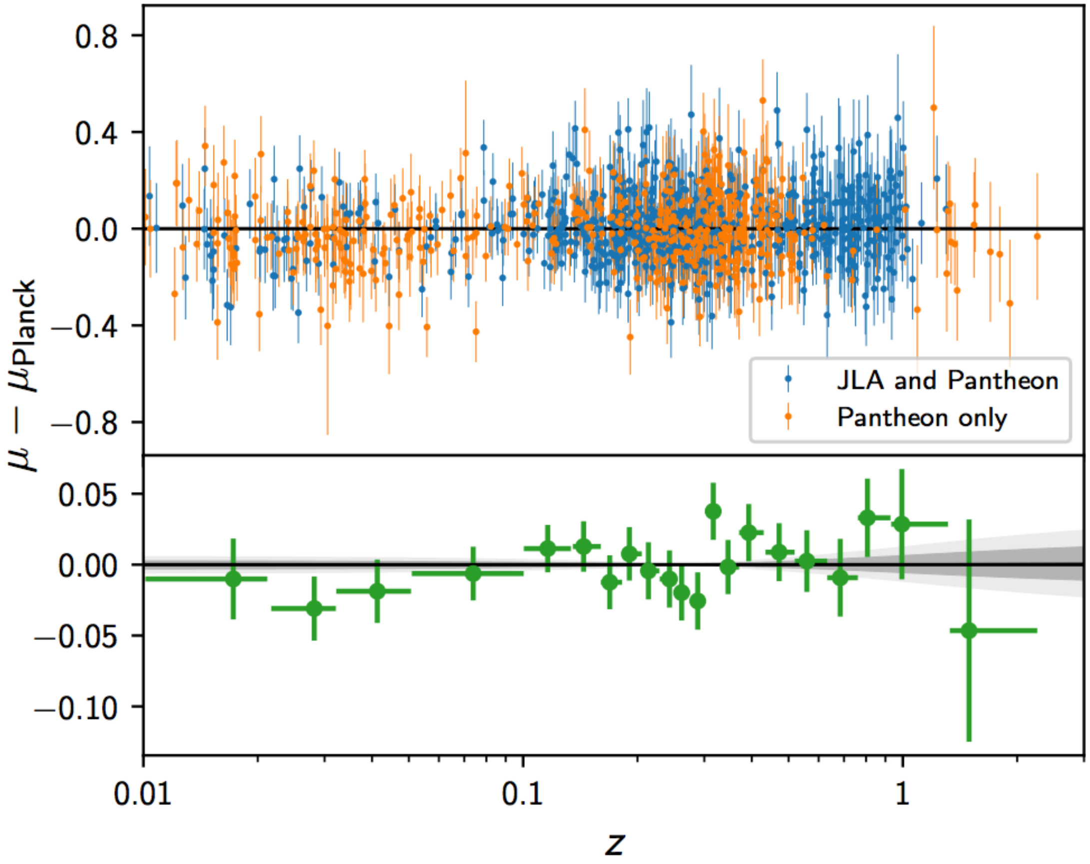
BOSS fits for (D_v/r_s, F_{AP}, f σ_8) where f is the growth rate, F_{AP} is the Alcock Paczynski parameter. $F_{\rm AP}(z) = D_{\rm M}(z)\frac{H(z)}{c}$.



Included: BOSS DR12 (Alam et al 2017)

<u>Not independent of BAO because</u> D_v/r_s is already used in the BAO likelihood

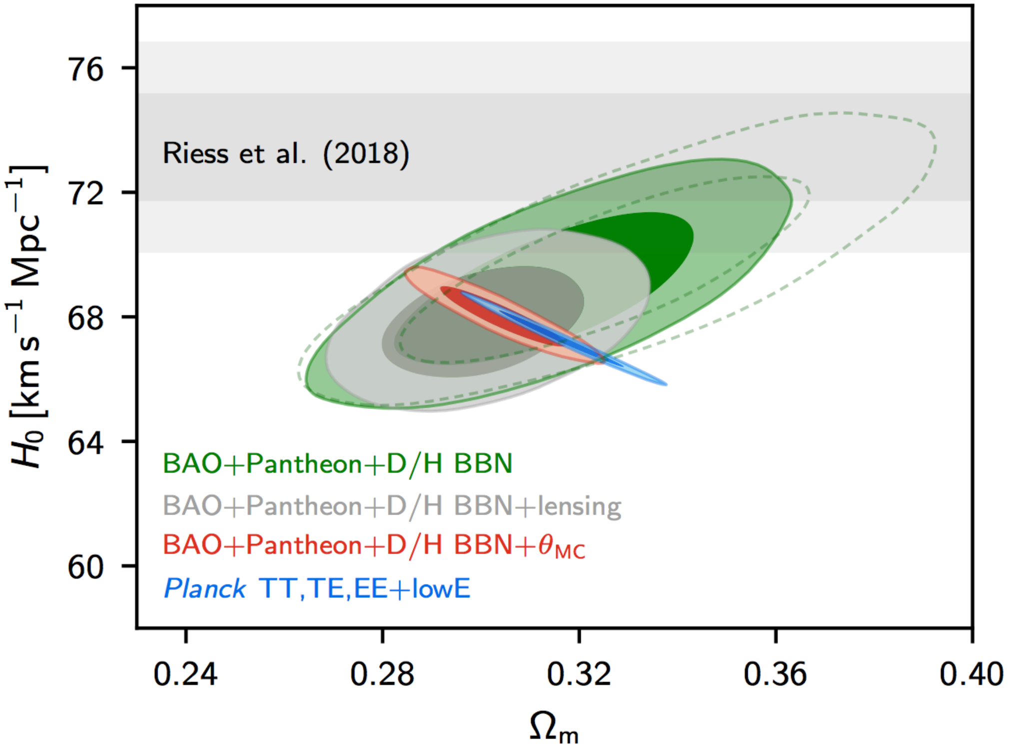
SNae Type Ia: good agreement



Included: Pantheon (1048 SNe SNLS SDSS Pan-STARRS1 ; 0.01 < z < 2.3)

H_0: 3.6 σ tension

Direct measurement of H_0



Planck TTTEEE+lowE+lensing 2018

$$H_0 = (67.27 \pm 0.60)\ \mathrm{km\ s^{-1} Mpc^{-1}}$$ LCDM

$$H_0 = (68.35 \pm 0.82)\ \mathrm{km\ s^{-1} Mpc^{-1}}, \quad (w_0 \text{ varying}),$$

$$H_0 = (68.34 \pm 0.83)\ \mathrm{km\ s^{-1} Mpc^{-1}}, \quad (w_0, w_a \text{ varying}).$$

Riess et al 2018

$$H_0 = (73.48 \pm 1.66)\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

(Riess etal 2018 not used for DE and MG beyond w0,wa)

Weak Lensing

Cosmic shear: distortion of shapes of distant galaxies due to LSS along the line of sight.

Galaxy - galaxy lensing: cross correlation between foreground (lens) galaxy positions and lensing shear of background source galaxies

Galaxy autocorrelation

CFHTLenS and KiDS:	tension $\sim 2\,\sigma$ (lower σ_8)
KiDS+GAMA GC (van Uitert et al 2018):	consistent with Planck
KiDS+ spectroscopy (2dFLS + BOSS) (joudaki et al 2018):	tension $\sim 2.6\,\sigma$ (lower σ_8)
KiDS (reanalysis by Troxel et al 2018):	consistent with Planck
DES (using improved modelling, DES 2017):	consistent with Planck
DES (joint shear-galaxy; galaxy – galaxy; shear)	tension (lower σ_8)

Included: DES1yr cosmic shear, redone in Planck *fixing neutrino masses*

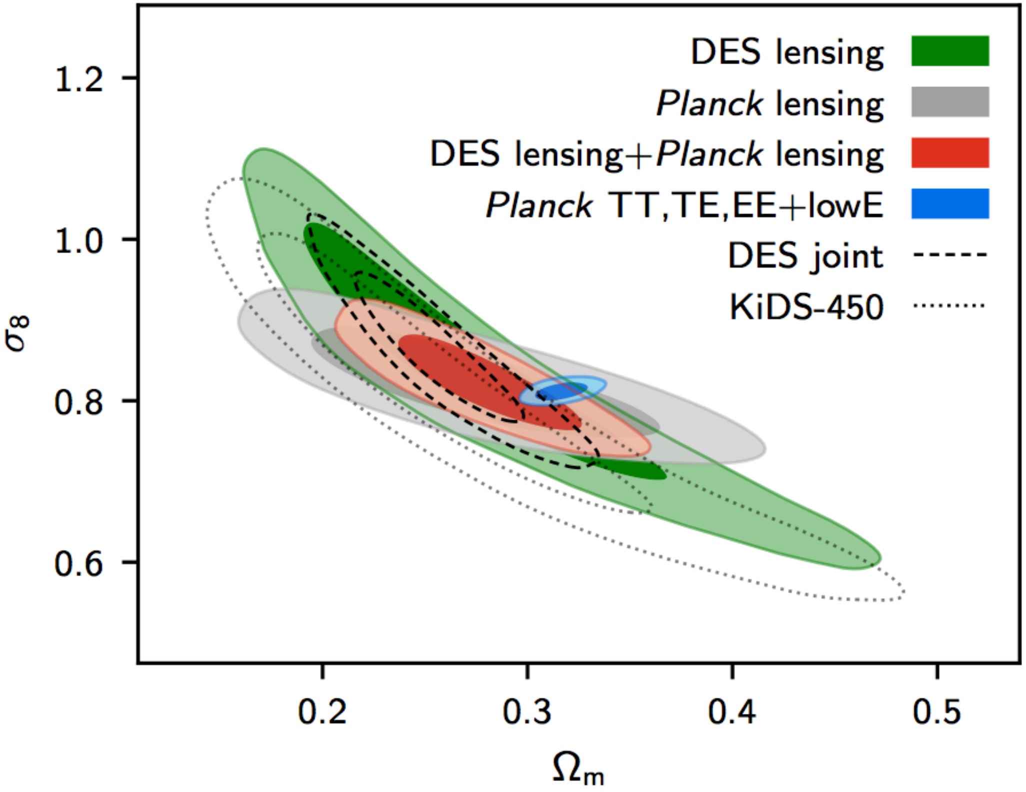
Excluded: DES1yr joint analysis

Non-linear regime: HMcode Mead etal 2016

Weak Lensing

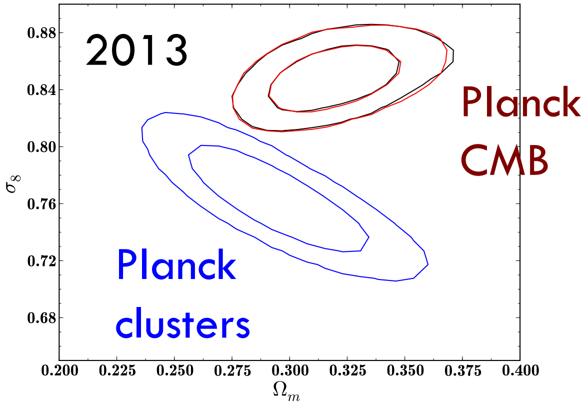
Included: DES1yr cosmic shear, redone in Planck fixing neutrino masses

Excluded: DES1yr joint analysis



Cluster Counts

- Calibration of cluster masses is the dominant uncertainty and essential to used them for cosmology
- Planck CMB-lensing & cluster count (Zubeldia & Challinor, in preparation): agreement with LCDM
- Not used in Planck 2018 (paper states: *no compelling evidence of tension*)



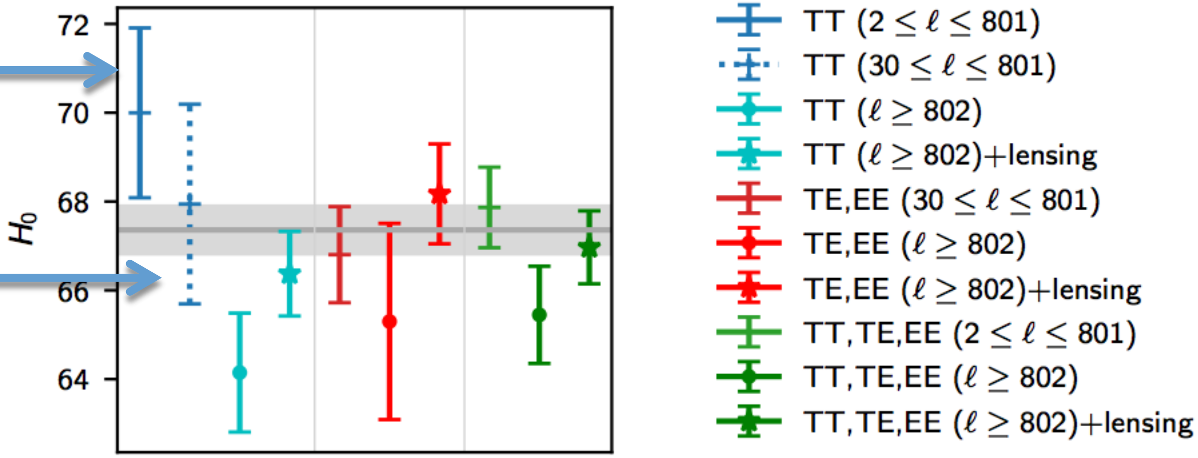
Internal consistency tests

High and low multipoles

- Agreement between WMAP (ell ~800) and Planck (ell ~2500) at scales measured by WMAP
- Dip at 20 < l < 30 (2013, WMAP, at multiple frequencies, identical feature in 2018)
- The high l (> 801) pulls parameters towards higher matter and lower H_0
- For temperature: low and high multipoles constraints differ at 2.8 σ
- Adding polarization: low and high multipoles are more consistent but still differ at 2 σ

With Commander

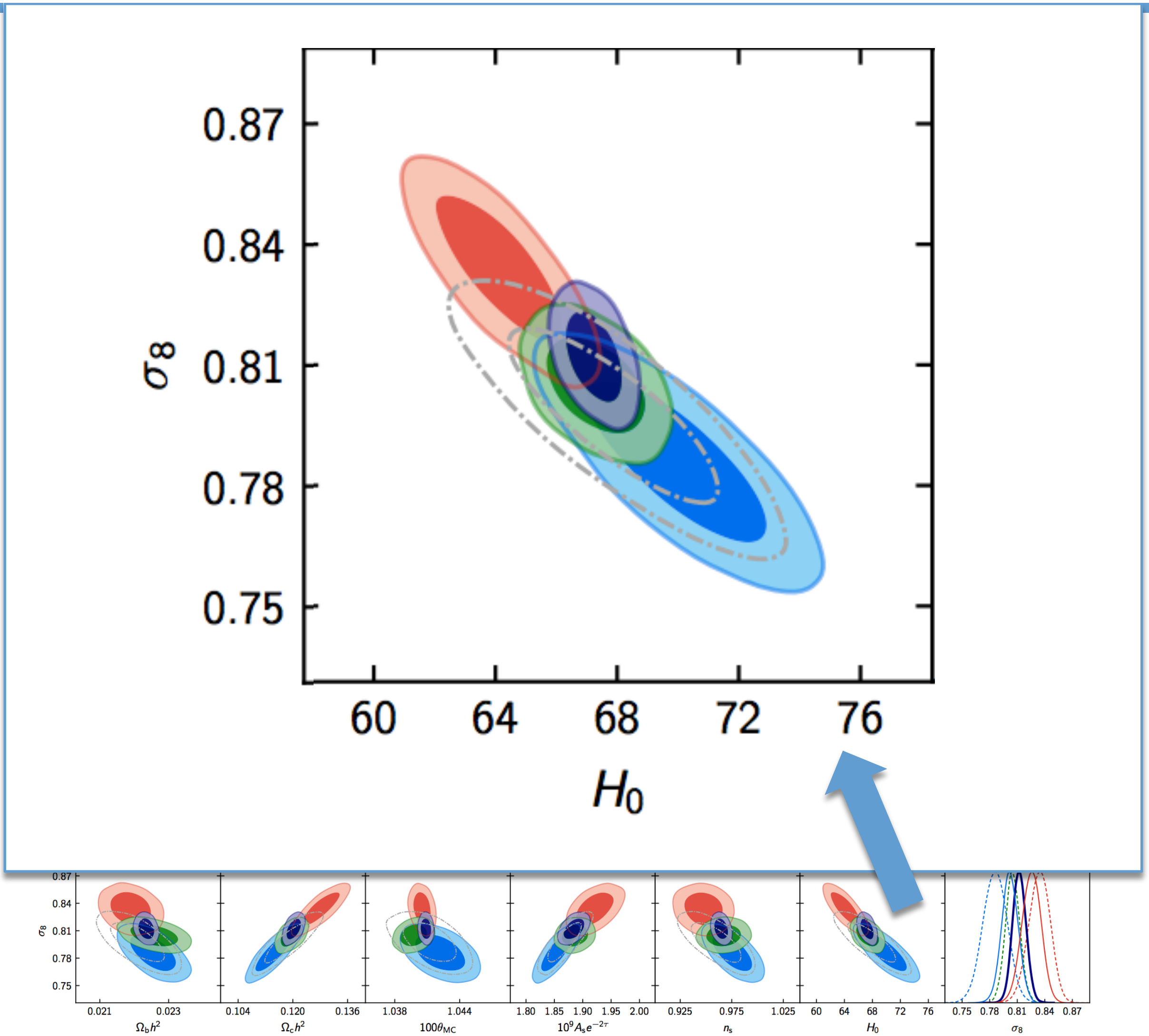
Without Commander



High and low multipoles

🟦 $2 \leq \ell \leq 801$ 🟥 $802 \leq \ell \leq 2508$ 🟩 EE+lensing+$(\Omega_b h^2 = 0.0222 \pm 0.0005)$ 🟦 TT,TE,EE $(2 \leq \ell \leq 2508)$

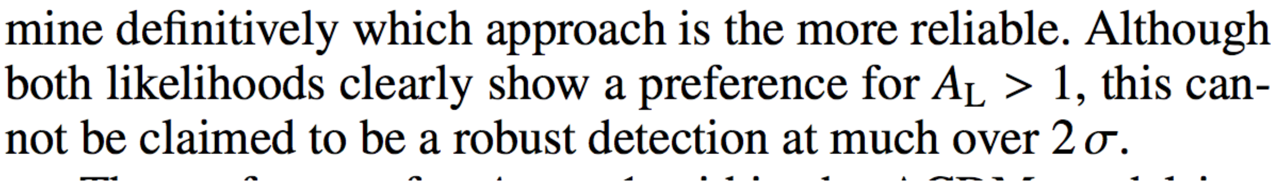
- For temperature: low and high multipoles constraints differ at 2.8 σ
- Adding polarization: low and high multipoles are more consistent but still differ at 2 σ



Lensing amplitude A_L

Parameter that rescales the amplitude of the lensing power spectrum. If the analysis is consistent, it has to be 1. No physical meaning, it is a consistency test.

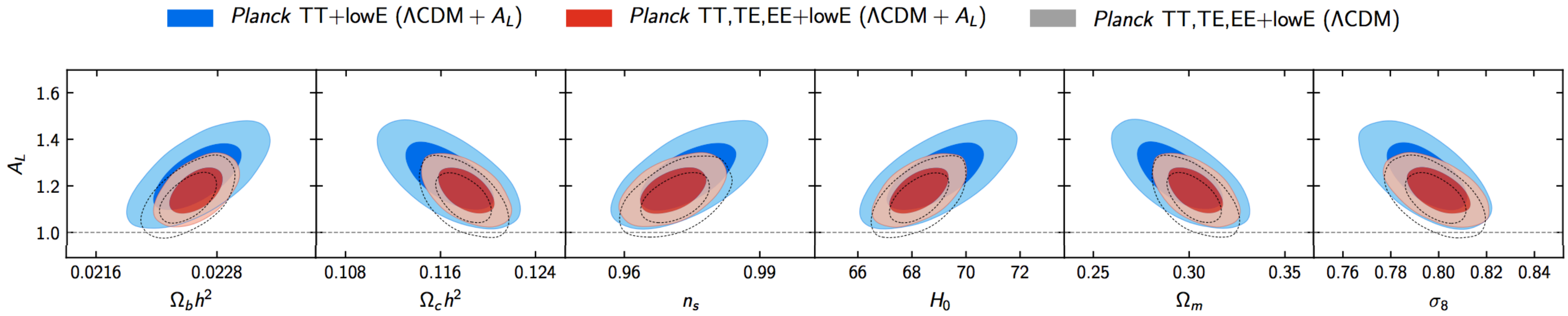
- A_L inferred from the CMB spectra:
  - TT: $A_L > 1$ at ~2 σ
  - TTTEEE + lowEE: $A_L > 1$ at ~2.8 σ (Plik) and at ~2 σ (CamSpec)
  - TTTEEE + lowEE + lensing: $A_L > 1$ at ~2 σ



mine definitively which approach is the more reliable. Although both likelihoods clearly show a preference for $A_{\mathrm{L}} > 1$, this cannot be claimed to be a robust detection at much over $2\,\sigma$.

Lensing amplitude A_L

- Degenerate with n_s, neutrinos, DE, MG (and anything modifying lensing amplitude)
- With A_L free to vary, fits prefer less matter, higher H_0, higher n_s (in a LCDM model)
- Higher A_L are also slightly preferred by the dip at low l
- Statistical fluctuation? Systematics? New Physics? Anything isotropic that mimics higher lensing amplitude, without affecting scale and shape



CMB as a probe for DE and MG

Shorter update with respect to the Planck DE & MG paper 2018

Models tested in 2015

Includes:

Background parametrizations

- a. w expansion and PCA
- b. Early Dark Energy
- c. Generic potentials

Perturbation parametrizations

- a. Effective Field Theory (EFT)
- b. Gravitational potentials

Examples of particular models

- a. Universal couplings
- b. Non universal couplings

Models updated in 2018

Includes:

Background parametrizations

a. ~~w expansion and PCA~~ w, w_0, w_a

b. ~~Early Dark Energy~~

c. ~~Generic potentials~~

Perturbation parametrizations

a. Effective Field Theory (EFT)

b. Gravitational potentials (only one parameterization)

Examples of particular models

a. ~~Universal couplings~~

b. ~~Non universal couplings~~

Data in 2015

Planck baseline: Planck TT + low-ℓ Polarization

Planck
Planck + BSH
Planck + WL
Planck + RSD
Planck + WL + RSD

Background:
BSH: BAO + SNe + H_0

Perturbations:
RSD: Redshift Space Distortions (BOSS DR11, Samushia etal 2014)
WL: Weak Lensing (CFHTLens, Kitching etal 2014, Kilbinger etal 2013, Heymans etal 2013 + ultraconservative cut of non-linear scales)

CMB lensing and TT TE EE polarization

Data in 2018 vs 2015

Planck baseline: Pl~~anck TT + low-ℓ Polariz~~ation

Planck TTTEEEE + lowEE +lensing

Background:

BSH: BAO + SNe ~~+ H_0~~

Planck
Planck + BS~~H~~
Planck + WL
Planck + RSD
Planck + WL + RSD

Perturbations:

DR12, Alam et al 2017

RSD: Redshift Space Distortions (BOSS ~~DR11, Samushia etal 2014~~)

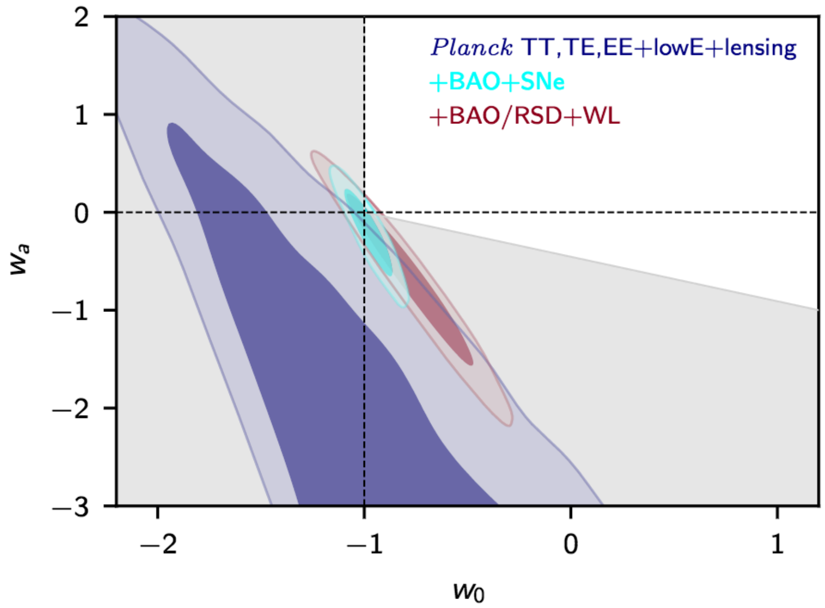
WL: Weak Lensing ~~(CFHTLens, Kitching etal 2014, Kilbinger etal 2013, Heymans etal 2013 + ultraconservative cut of non-linear~~ scales) DES shear (no galaxy-galaxy lensing)

CMB lensing and TT TE EE polarization

Results: equation of state

$$w(a) = w_0 + (1-a)w_a$$

Planck alone allows for a large region in parameter space.



$w_0 < -0.95$ (95 %, *Planck* TT,TE,EE+lowE +lensing+SNe+BAO).

Let's just fix $w_0 = -1$. Many models have a background close to -1. Perturbations?

Parameterizing MG

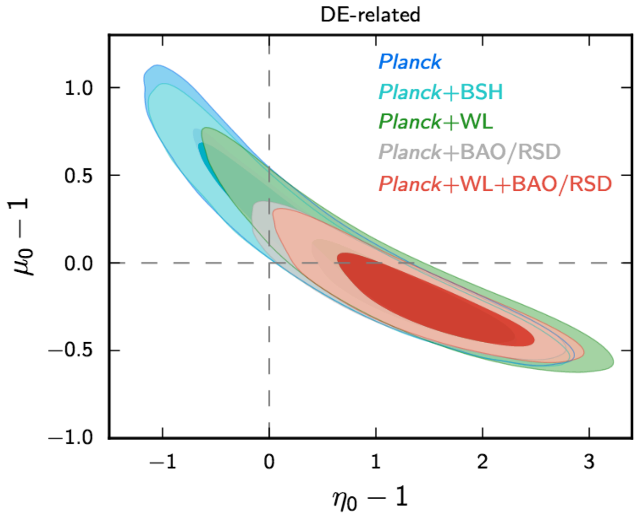
2 functions of scale and time:

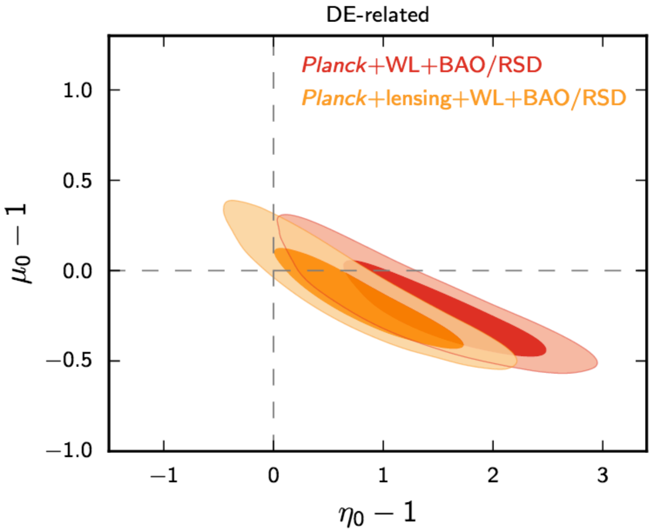
μ modifies the growth (higher μ -> higher σ_8)
η is the ratio of the gravitational potentials

Tension:

- Planck alone lies at the 2 sigma limit
- Higher tension with external datasets (WL)
- degenerate with optical depth and A_L
- WL+RSD will help to tighten constraints
- Tension reduced when including CMB lensing

2015 DE MG paper





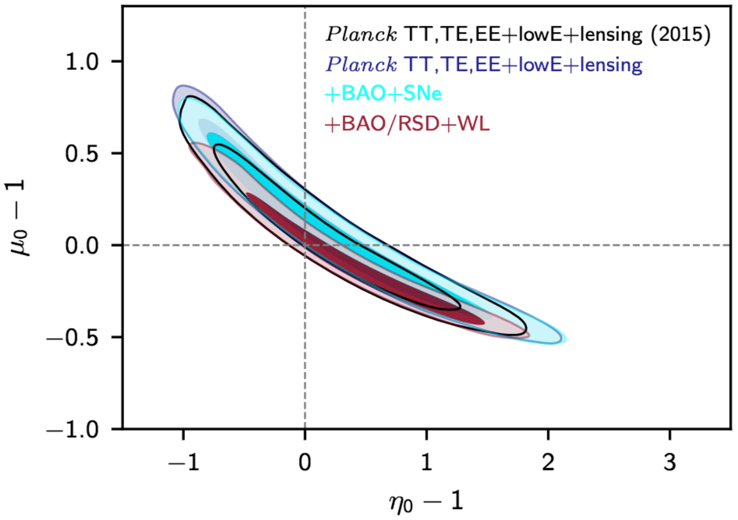
Parameterizing MG

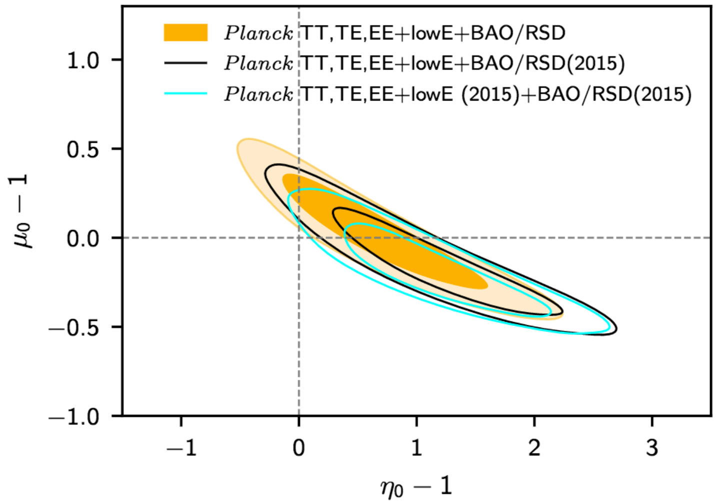
2018: consistent results with 2015

- Planck alone still lies at the 2 sigma limit (prefers higher lensing amplitude); constraints move along the degeneracy line
- New external datasets reduce the tension (DES disfavours higher lensing amplitudes)
- Degenerate with optical depth and A_L
- WL+RSD will help to tighten constraints
- Tension increases without CMB lensing reconstruction

Degeneracy direction corresponds to constant lensing amplitudes

2018 cosmology paper

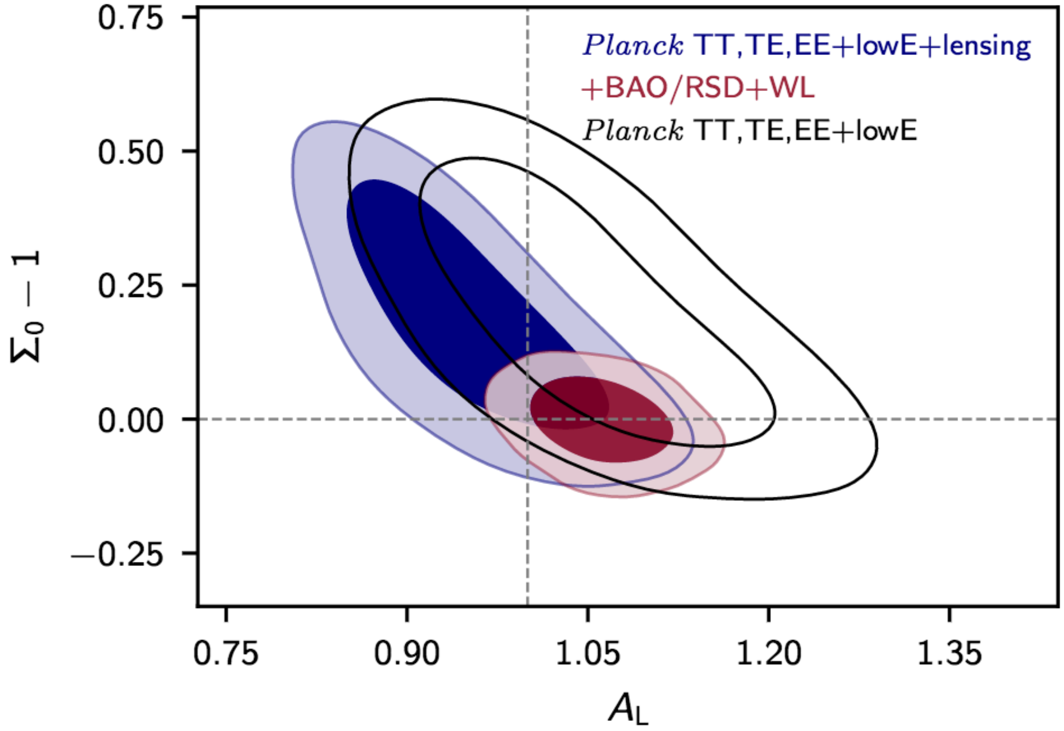


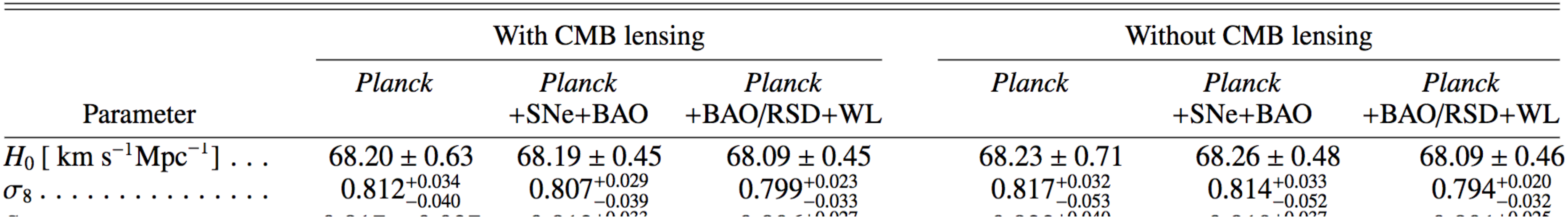


MG and lensing amplitude

MG ($\Sigma \neq 1$) are preferred if $A_L = 1$

with slightly higher values of H_0





Parameter	With CMB lensing			Without CMB lensing		
	Planck	*Planck* +SNe+BAO	*Planck* +BAO/RSD+WL	*Planck*	*Planck* +SNe+BAO	*Planck* +BAO/RSD+WL
H_0 [km s^{-1}Mpc^{-1}] . . .	68.20 ± 0.63	68.19 ± 0.45	68.09 ± 0.45	68.23 ± 0.71	68.26 ± 0.48	68.09 ± 0.46
σ_8	$0.812^{+0.034}_{-0.040}$	$0.807^{+0.029}_{-0.039}$	$0.799^{+0.023}_{-0.033}$	$0.817^{+0.032}_{-0.053}$	$0.814^{+0.033}_{-0.052}$	$0.794^{+0.020}_{-0.032}$

[Effective Field Theories (EFT)] f(R)

Gubitosi etal 2013

$$S = \int d^4x\sqrt{-g}\Bigg\{\frac{m_0^2}{2}[1+\Omega(\tau)]R+\Lambda(\tau)-a^2c(\tau)\delta g^{00}$$

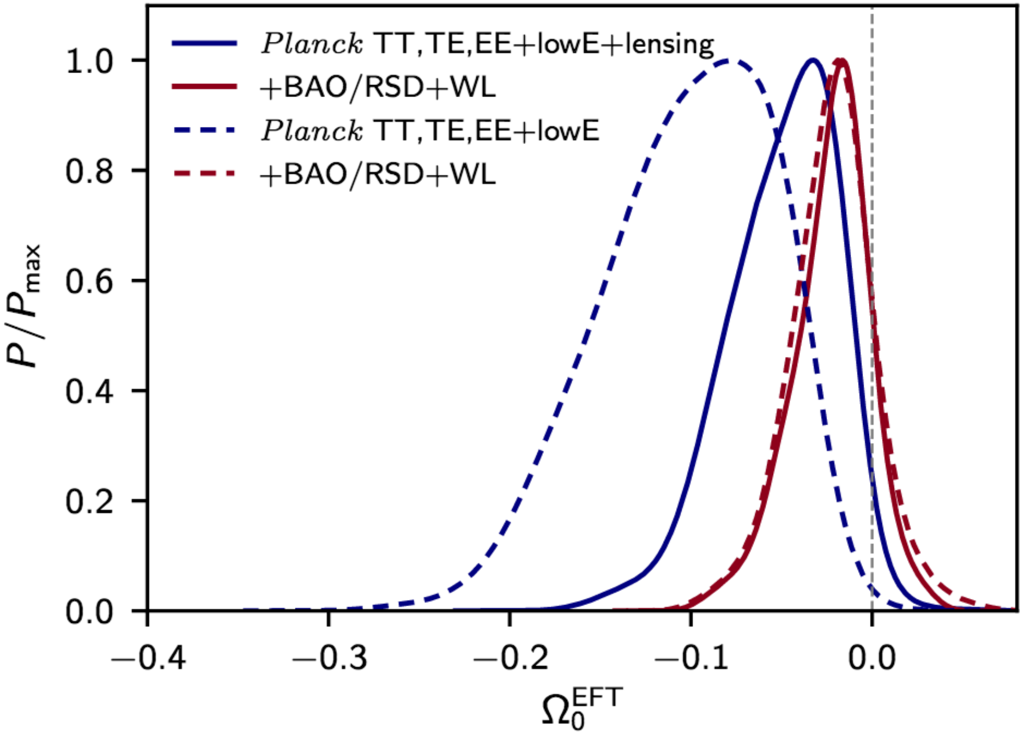
$$+\frac{M_2^4(\tau)}{2}(a^2\delta g^{00})^2-\bar{M}_1^3(\tau)2a^2\delta g^{00}\delta K_\mu^\mu$$

$$-\frac{\bar{M}_2^2(\tau)}{2}(\delta K_\mu^\mu)^2-\frac{\bar{M}_3^2(\tau)}{2}\delta K_\nu^\mu\delta K_\mu^\nu+$$

$$+m_2^2(\tau)(g^{\mu\nu}+n^\mu n^\nu)\partial_\mu(a^2g^{00})\partial_\nu(a^2g^{($$

Vary only 1

Planck alone prefers models with higher lensing amplitude



Conclusions

- Overall agreement between Planck and LCDM.
- New low-l polarization and better high-l polarization
- Tighter constraints on optical depth (and therefore on other parameters)
- Agreement with BAO, SNe, RSD BOSS DR12, WL DES cosmic shear

- Tensions with other external data sets:
  - Tension with H_0 ($\approx 3.6\ \sigma$, neutrinos don't help; MG helps)
  - Tension with other datasets at most 2.5 σ (DES galaxy-galaxy lensing lower σ_8,)

- Internal consistency checks:
  - low/high l, tension at 2σ
  - A_L more lensing than in LCDM (MG helps) ≈ 2-2.8 σ depending on likelihood
  - Polarization efficiencies: affects parameters at ~0.2- 0.8 σ depending on parameter
  - Plik vs Camspec: some difference mainly in m_ν, A_L, Ω_K

Be aware of choices in this story: in systematics, theories tested, data used, likelihood used

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

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planck

cnes

agenzia spaziale italiana

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a look back to the birth of Universe

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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.

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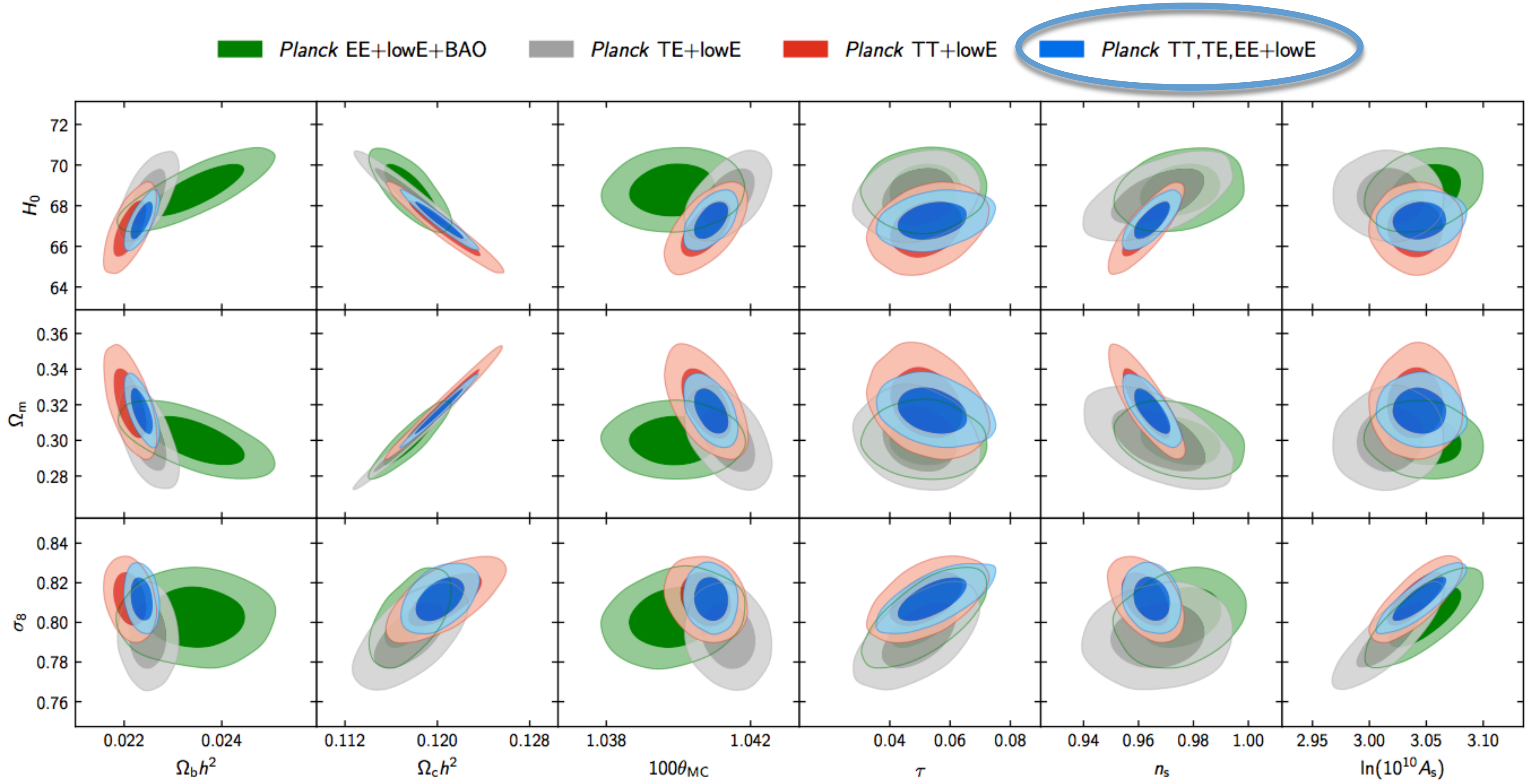
Planck parameters for ΛCDM

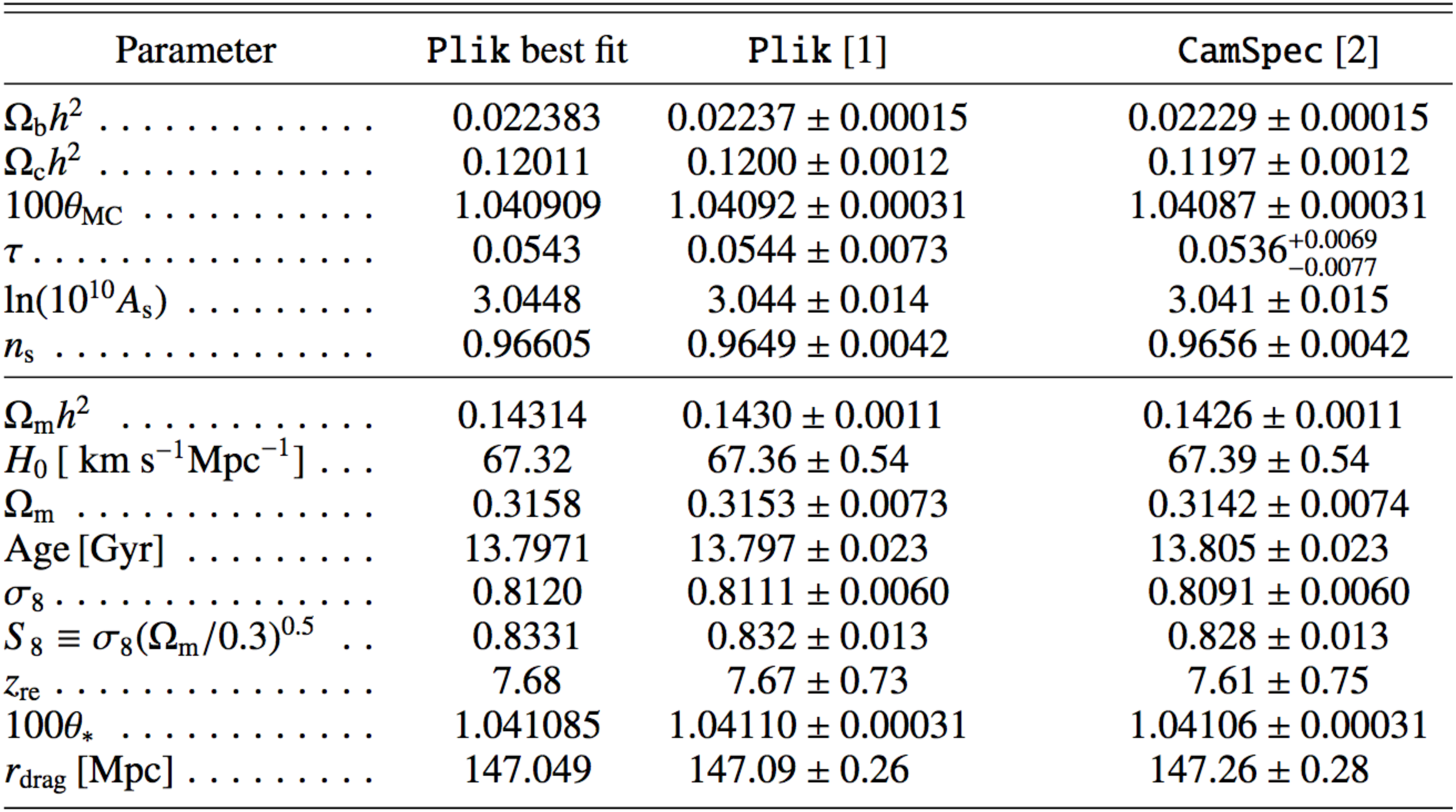


Neutrinos

Increasing the neutrino mass leads to lower values of H_0
-> increases tension with direct measurements

N_{eff} relativistic d.o.f.: a higher value, leads to smaller sound horizon, therefore higher H_0 (reduces tension, but less than DE or MG) but increases also σ_8 potentially increasing tension with WL

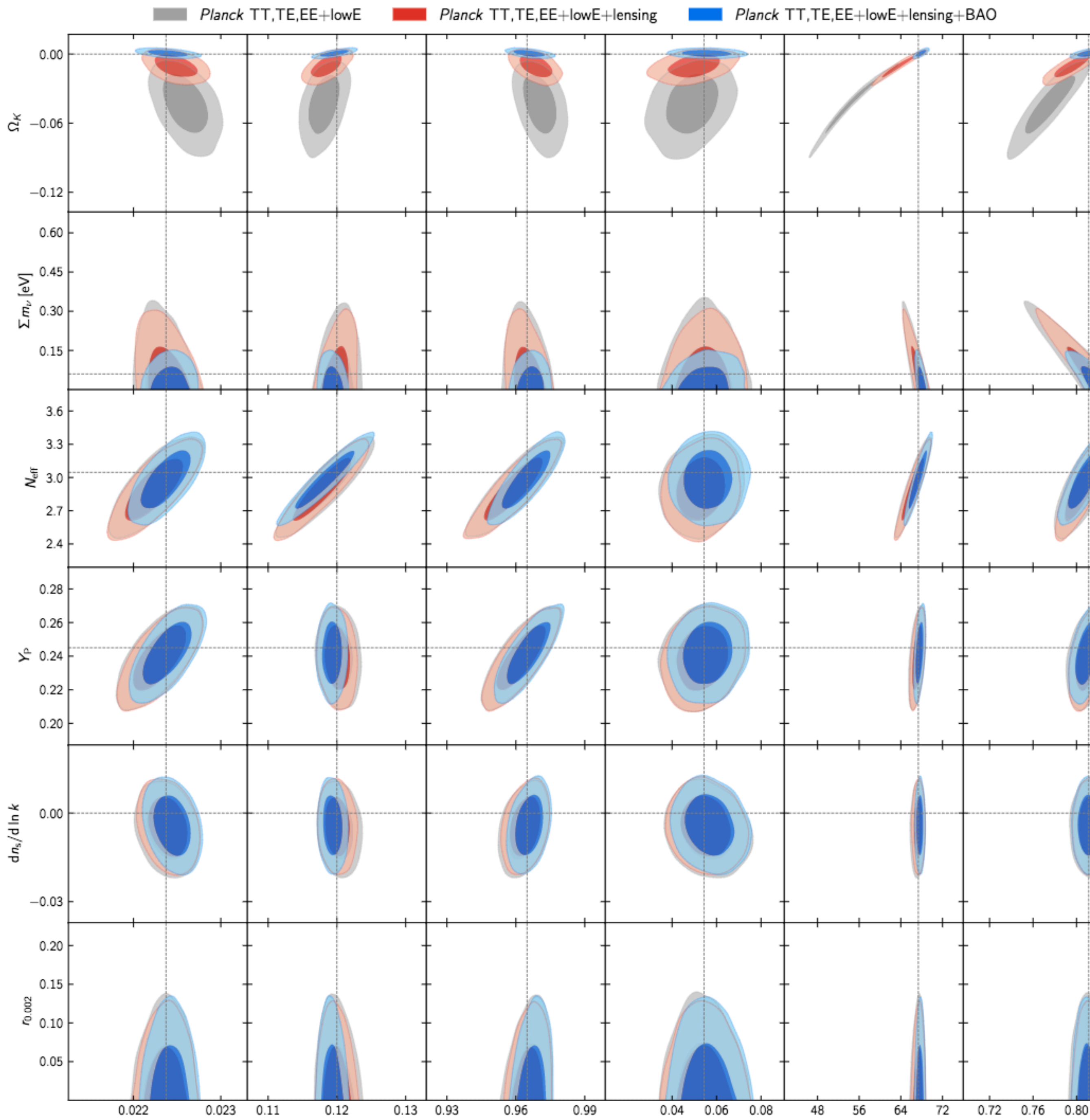
In numbers (baseline fit to LCDM)



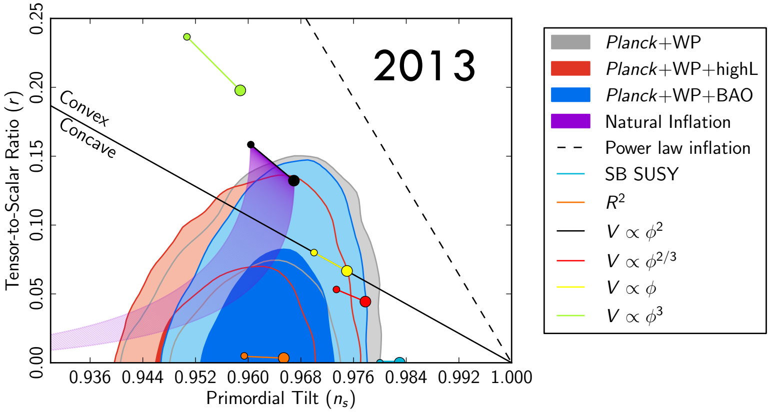
Parameter	`Plik` best fit	`Plik` [1]	`CamSpec` [2]
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}] . . .	67.32	67.36 ± 0.54	67.39 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.8331	0.832 ± 0.013	0.828 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28

1-parameter extensions

Overlap with LCDM in all minimal extensions (dashed lines)



Inflation



Dashed: Planck CamSpec

Solid: Planck Plik

-> part of the uncertainty depends on the likelihood

r < 0.07 at 2 σ