Cosmology after the 2015 planck results

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on behalf of the Planck Collaboration

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

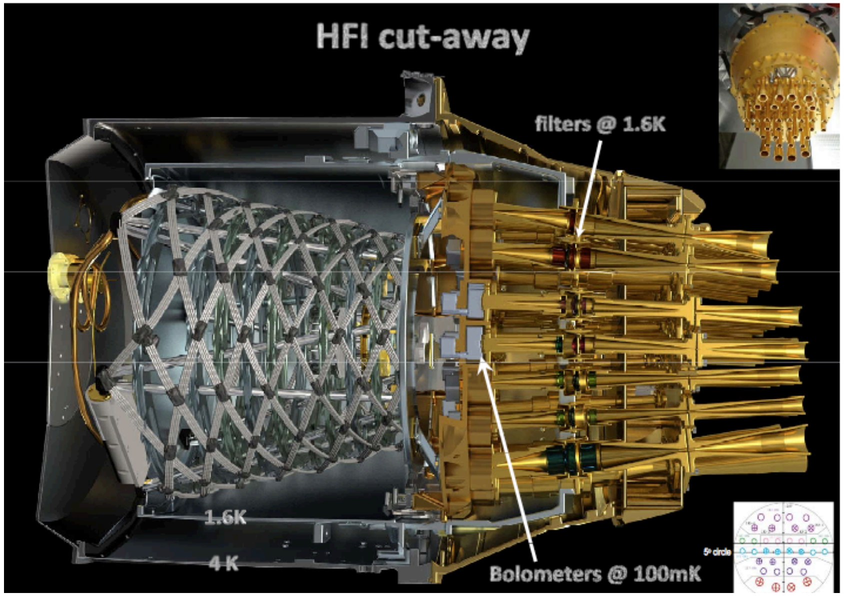
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific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

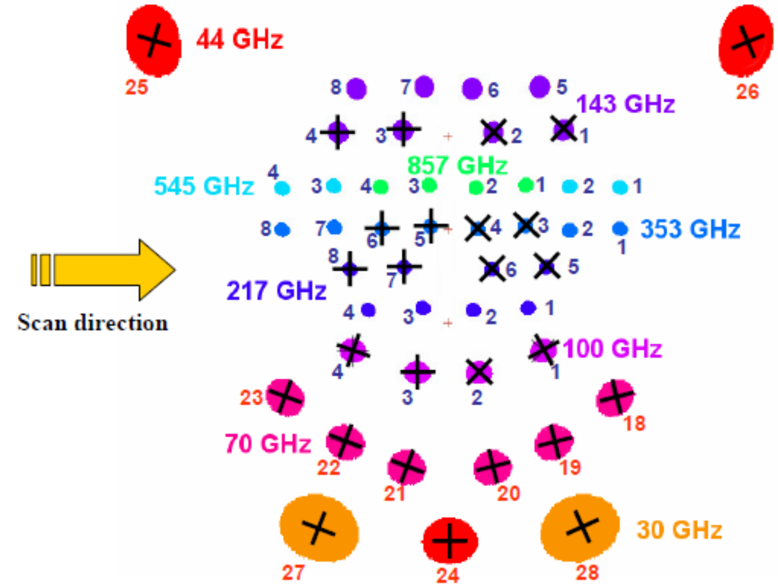
papers now out

planck

I. Overview of products and results (*this paper*)
II. Low Frequency Instrument data processing
III. LFI systematic uncertainties
IV. LFI beams and window functions
V. LFI calibration
VI. LFI maps
VII. High Frequency Instrument data processing: Time-ordered information and beam processing
VIII. High Frequency Instrument data processing: Calibration and maps
IX. Diffuse component separation: CMB maps
X. Diffuse component separation: Foreground maps
XI. CMB power spectra, likelihood, and consistency of cosmological parameters
XII. Simulations
XIII. Cosmological parameters
XIV. Dark energy and modified gravity
XV. Gravitational lensing
XVI. Isotropy and statistics of the CMB
XVII. Primordial non-Gaussianity
XVIII. Background geometry and topology of the Universe
XIX. Constraints on primordial magnetic fields
XX. Constraints on inflation
XXI. The integrated Sachs-Wolfe effect
XXII. A map of the thermal Sunyaev-Zeldovich effect
XXIII. The thermal Sunyaev-Zeldovich effect–cosmic infrared background correlation
XXIV. Cosmology from Sunyaev-Zeldovich cluster counts
XXV. Diffuse, low-frequency Galactic foregrounds
XXVI. The Second Planck Catalogue of Compact Sources
XXVII. The Second Planck Catalogue of Sunyaev-Zeldovich Sources
XXVIII. The Planck Catalogue of Galactic Cold Clumps

the Planck detectors

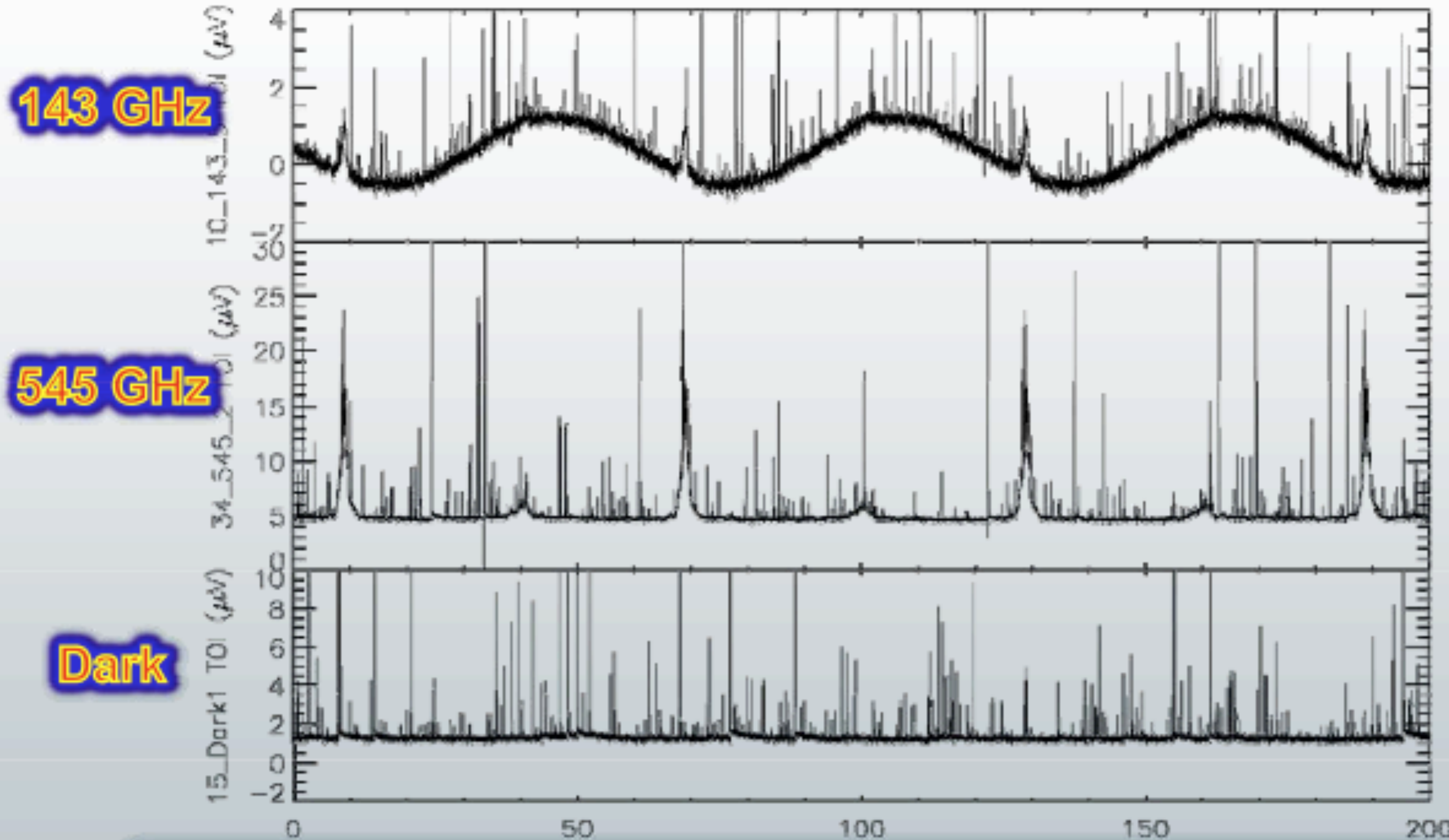




	30GHz	44GHz	70GHz	100GHz	143GHz	217GHz	353GHz
Angular resolution [arcmin]	33.2	28.1	13.1	9.7	7.3	5.0	4.9
Noise sensitivity [$\mu K_{CMB}\ s^{1/2}$]	148.5	173.2	151.9	41.3	17.4	23.8	78.8
NOISE/PIXEL							
From detector sensitivity [μK_{CMB}]	9.2	12.7	23.9	9.6	5.4	10.7	36.5
Measured from maps [μK_{CMB}]	9.2	12.5	23.2	11.2	6.6	12.0	43.2
Extended mission [months]	*48*	*48*	*48*	*29*	*29*	*29*	*29*
End-of-missioni [μK_{CMB}]	5.2	7.1	13.2	8.2	4.8	8.8	31.6
Measured End-of-Mission [$\Delta T/T$, $\mu K/K$]	**1.9**	**2.6**	**4.8**	**3.0**	**1.8**	**3.2**	**11.6**
2005: Blue book GOAL [$\Delta T/T$, $\mu K/K$]	**2.0**	**2.7**	**4.7**	**2.5**	**2.2**	**4.8**	**14.7**
1996: Red book GOAL [$\Delta T/T$, $\mu K/K$]				**~ 2**			

(nearly) raw data stream

planck

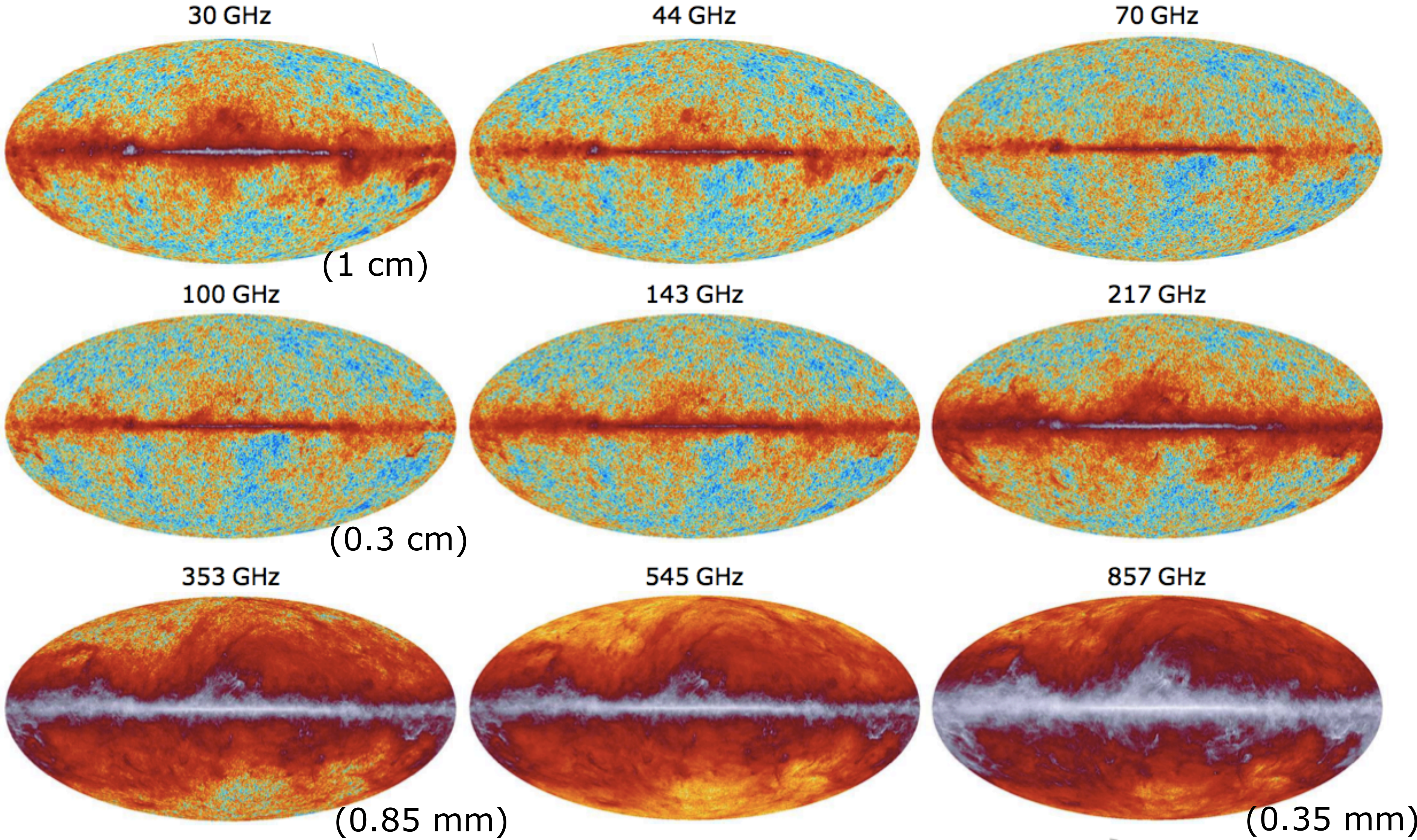


3 minutes of quasi ‘raw” data (i.e. only demodulated).The Solar (cosmological) dipole is clearly visible at 145GHz with a 60 seconds period (the satellite rotates at 1 rpm), while the Galactic plane crossings (2 per rotation) are more visible at 545 GHz than at 143 GHz. The Dark bolometer sees no sky signal, but displays a similar population of glitches from cosmic rays.

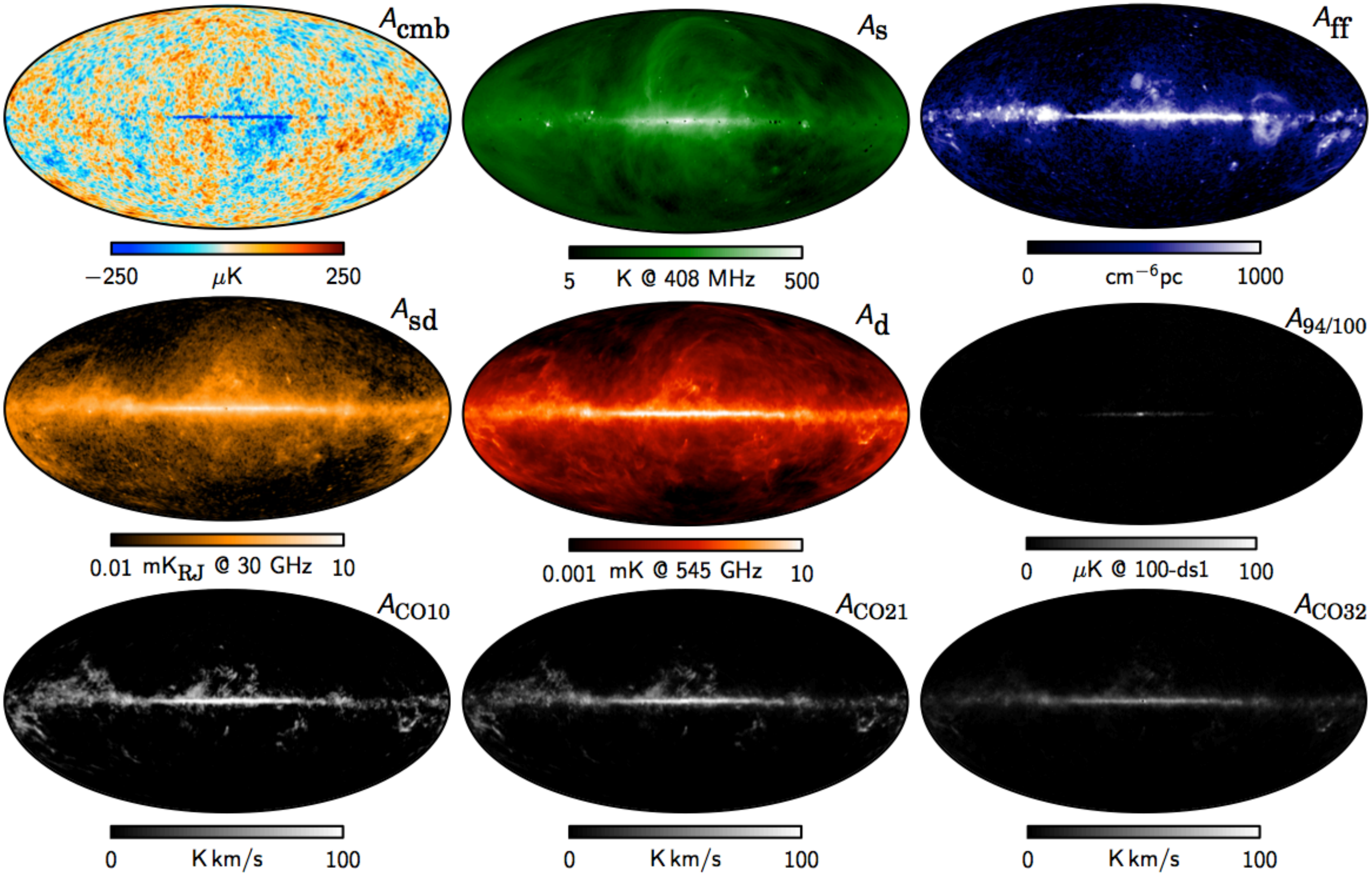
the sky seen by Planck

planck

Planck 2015 raw temperature maps

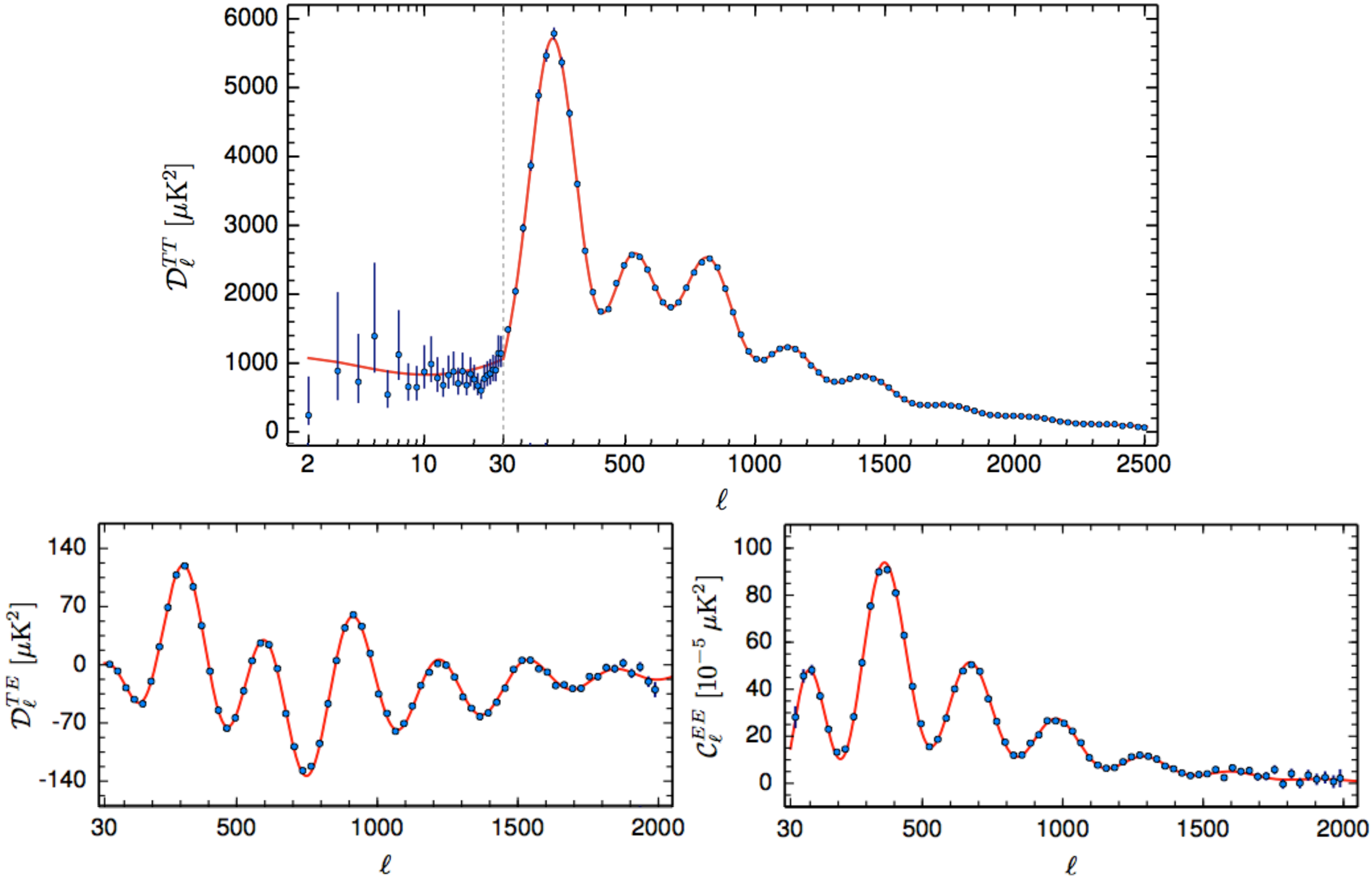


planck 2015 component maps



Maximum posterior intensity maps derived from the joint analysis of Planck, WMAP, and 408MHz observations

Planck data vs ΛCDM model



how to constrain parameters

planck

likelihood

posterior

prior

Bayes theorem: $$P(\theta|D,H) = \frac{P(D|\theta,H)P(\theta|H)}{P(D|H)}$$

data

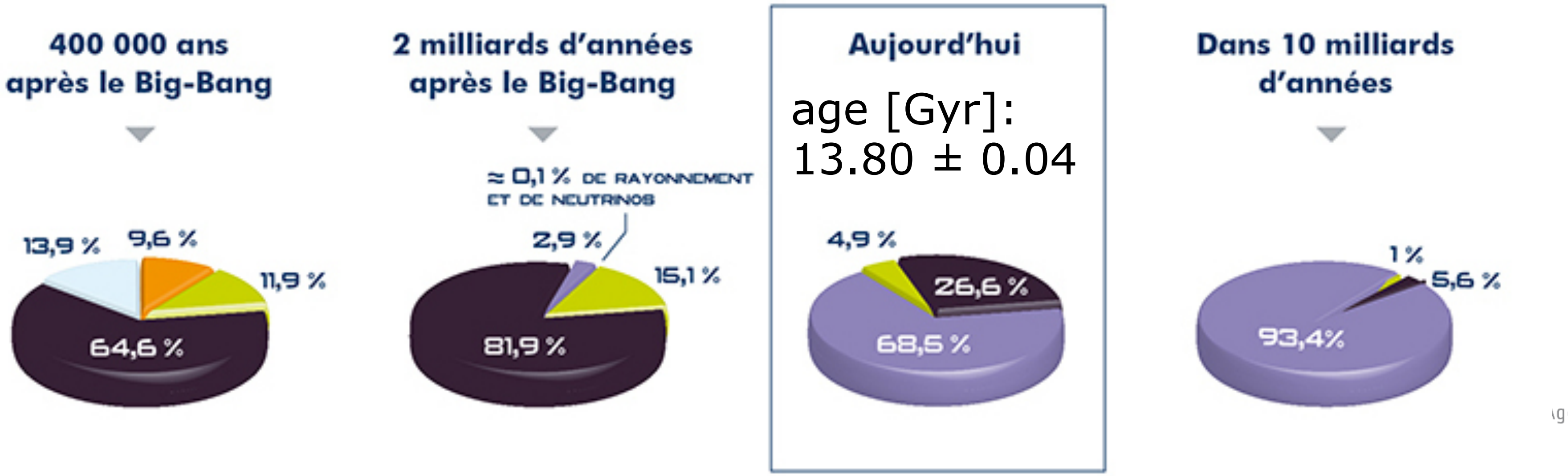
parameters

hypothesis
(e.g. model)

- pick a model H with parameters θ, decide on a prior
- get code to compute ‘observables’ (camb or CLASS for us)
- get likelihood (encapsulates data)
- explore posterior with MCMC (e.g. cosmomc)
- obtain credible intervals, model probabilities, etc.

flat LCDM model parameters

Parameter	[1] *Planck* TT+lowP	[4] *Planck* TT,TE,EE+lowP	
$\Omega_b h^2$	0.02222 ± 0.00023	0.02225 ± 0.00016	$\Omega_b \approx 5\%$
$\Omega_c h^2$	0.1197 ± 0.0022	0.1198 ± 0.0015	
$100\theta_{MC}$	1.04085 ± 0.00047	1.04077 ± 0.00032	0.03% !
τ	0.078 ± 0.019	0.079 ± 0.017	
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.094 ± 0.034	
n_s	0.9655 ± 0.0062	0.9645 ± 0.0049	$n_s \neq 1$
H_0	67.31 ± 0.96	67.27 ± 0.66	
Ω_m	0.315 ± 0.013	0.3156 ± 0.0091	



curvature

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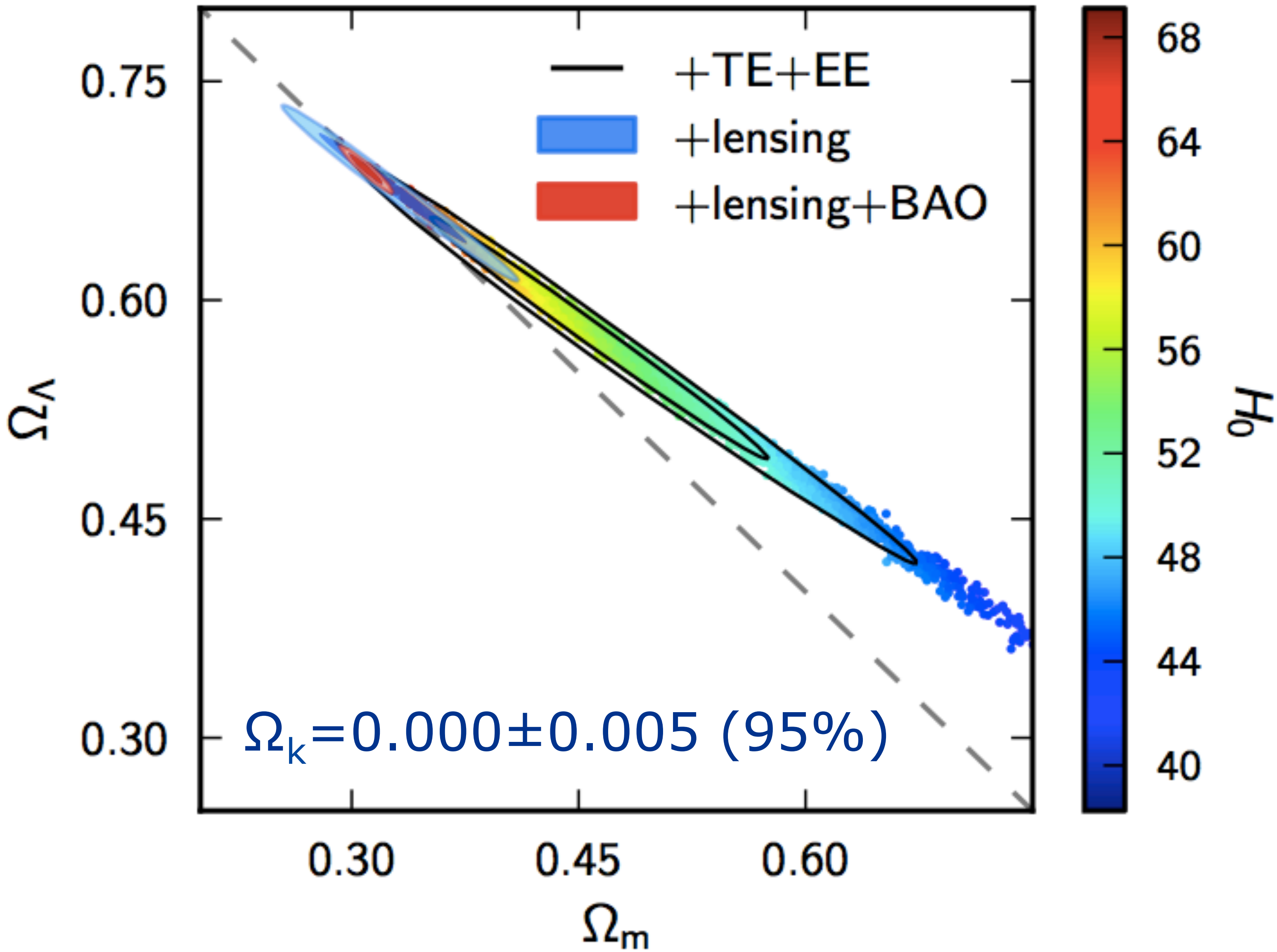

2013 → 2015 consistency

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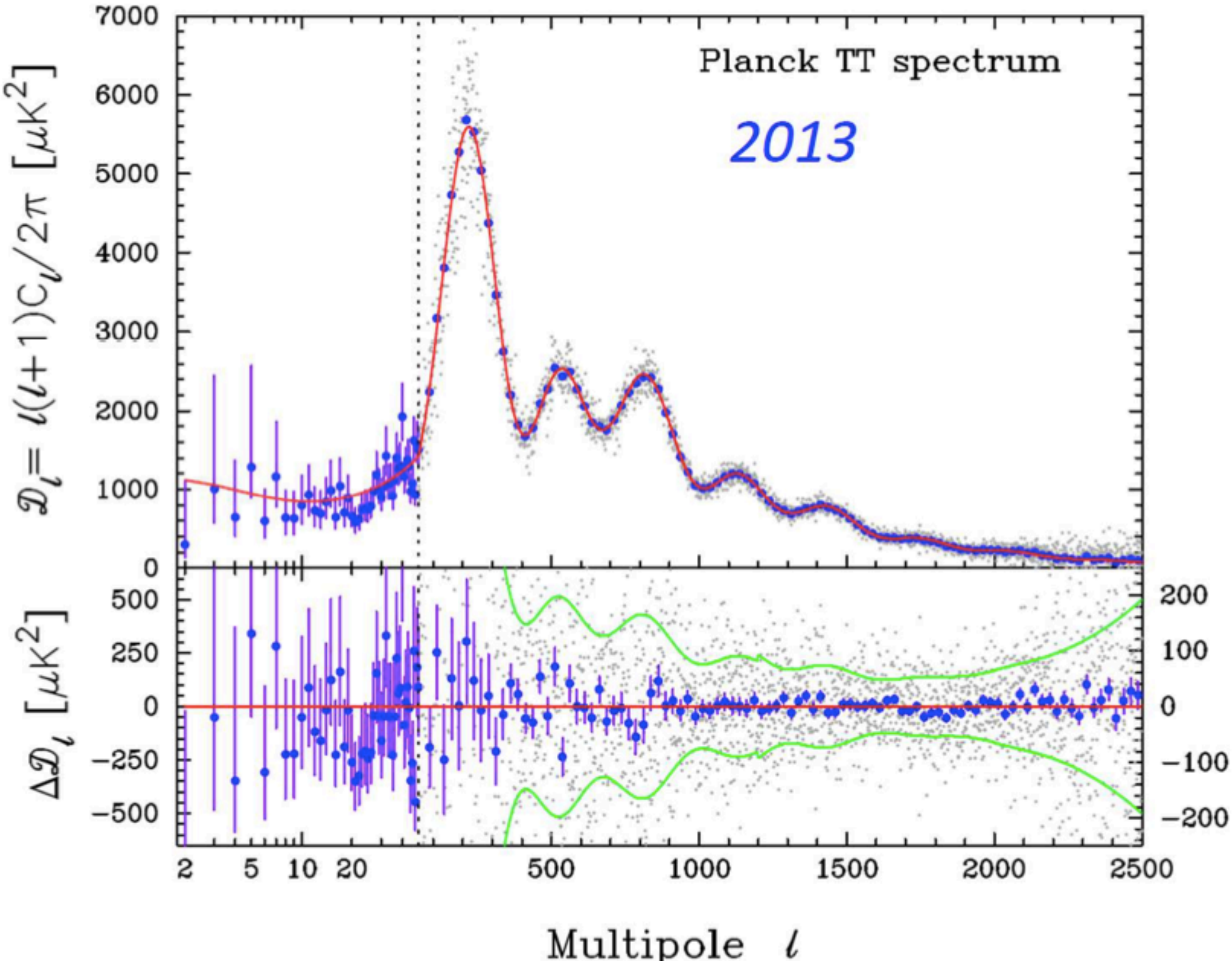
[1] Parameter	[2] 2013N(DS)	[3] 2013F(DS)	[4] 2013F(CY)	[5] 2015F(CHM)	[6] 2015F(CHM) (Plik)	$([2]-[6])/\sigma_{[6]}$	$([5]-[6])/\sigma_{[5]}$
$100\theta_{MC}$	1.04131 ± 0.00063	1.04126 ± 0.00047	1.04121 ± 0.00048	1.04094 ± 0.00048	1.04086 ± 0.00048	0.71	0.17
$\Omega_b h^2$	0.02205 ± 0.00028	0.02234 ± 0.00023	0.02230 ± 0.00023	0.02225 ± 0.00023	0.02222 ± 0.00023	−0.61	0.13
$\Omega_c h^2$	0.1199 ± 0.0027	0.1189 ± 0.0022	0.1188 ± 0.0022	0.1194 ± 0.0022	0.1199 ± 0.0022	0.00	−0.23
H_0	67.3 ± 1.2	67.8 ± 1.0	67.8 ± 1.0	67.48 ± 0.98	67.26 ± 0.98	0.03	0.22
n_s	0.9603 ± 0.0073	0.9665 ± 0.0062	0.9655 ± 0.0062	0.9682 ± 0.0062	0.9652 ± 0.0062	−0.67	0.48
Ω_m	0.315 ± 0.017	0.308 ± 0.013	0.308 ± 0.013	0.313 ± 0.013	0.316 ± 0.014	−0.06	−0.23
σ_8	0.829 ± 0.012	0.831 ± 0.011	0.828 ± 0.012	0.829 ± 0.015	0.830 ± 0.015	−0.08	−0.07
τ	0.089 ± 0.013	0.096 ± 0.013	0.094 ± 0.013	0.079 ± 0.019	0.078 ± 0.019	0.85	0.05
$10^9 A_s e^{-2\tau}$	1.836 ± 0.013	1.833 ± 0.011	1.831 ± 0.011	1.875 ± 0.014	1.881 ± 0.014	−3.46	−0.42

Main analysis changes:

- Beams, '4K' lines, orbital dipole calibration: change in amplitude
- low-l polarization: change in reionisation optical depth
- full mission data (29 months HFI, 48 LFI vs 15.5 both in 2013)
- more aggressive sky coverage
- minor changes to likelihood and foreground modeling

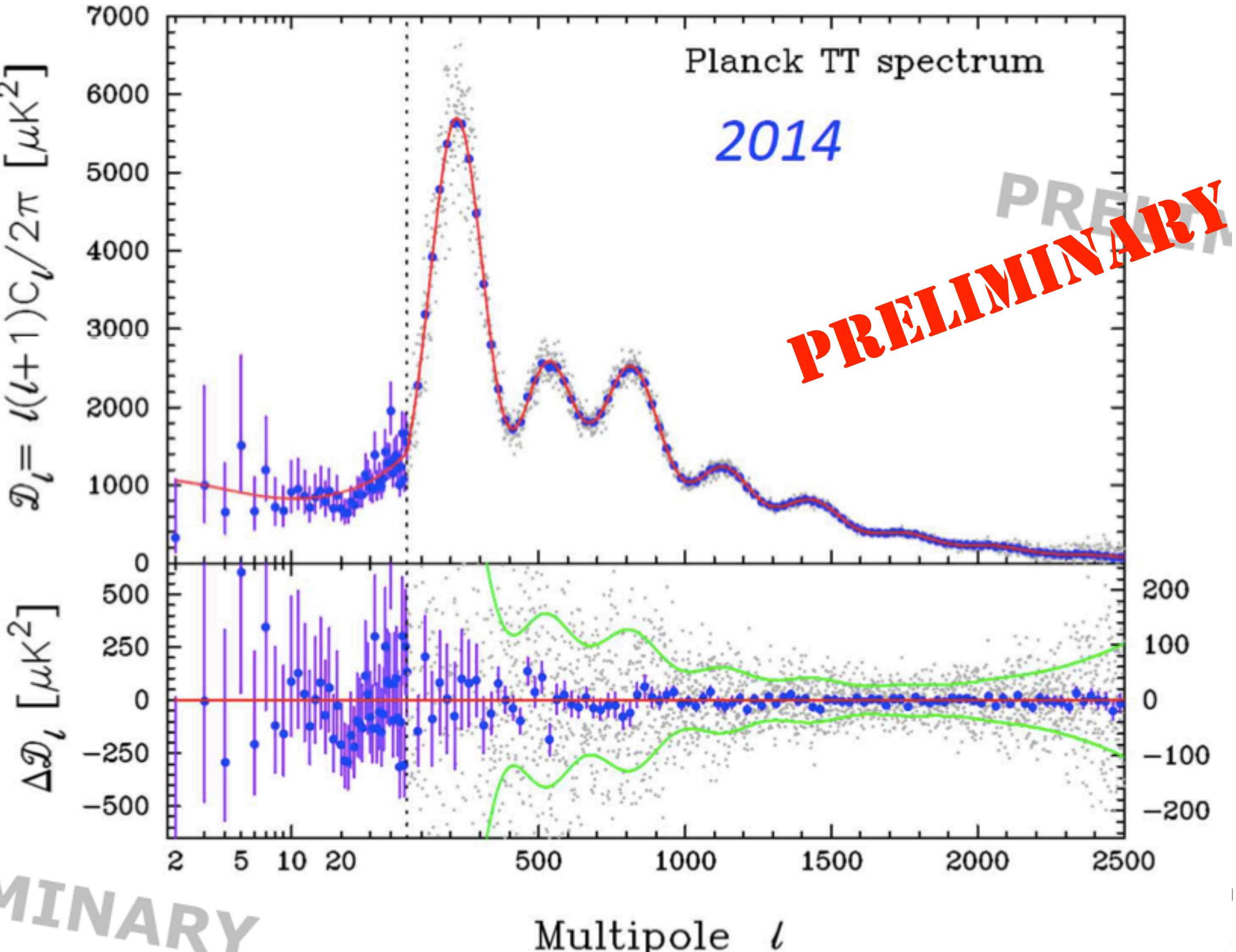
(note that shifts in amplitude and τ nearly compensate for σ_8!)

2013 TT power spectrum

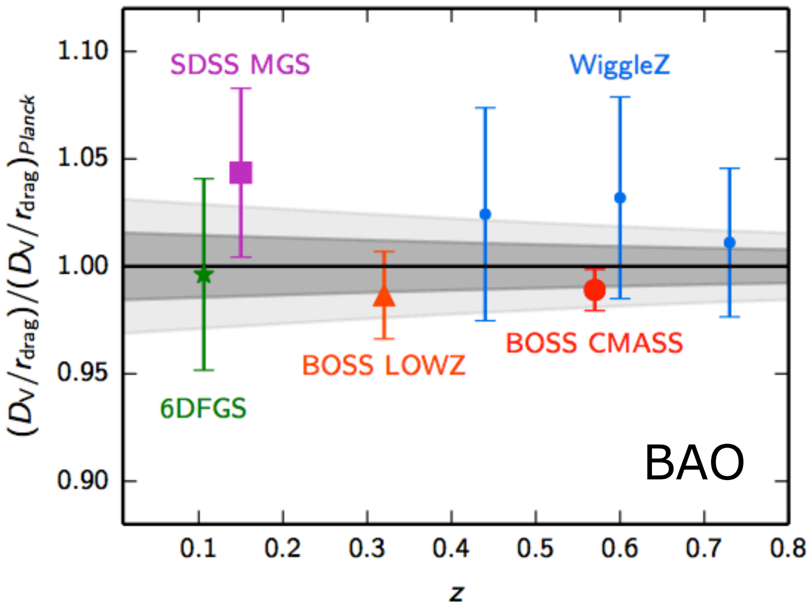


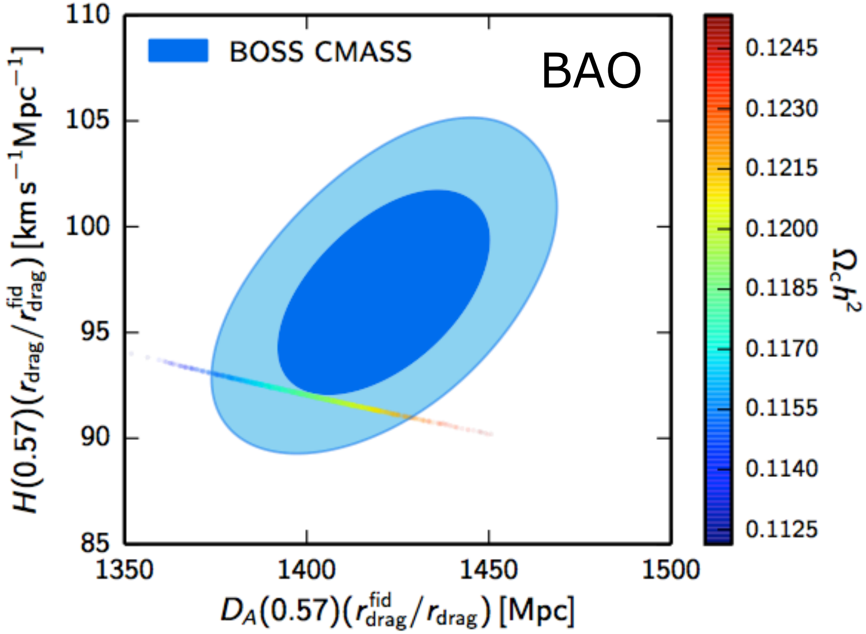
ency

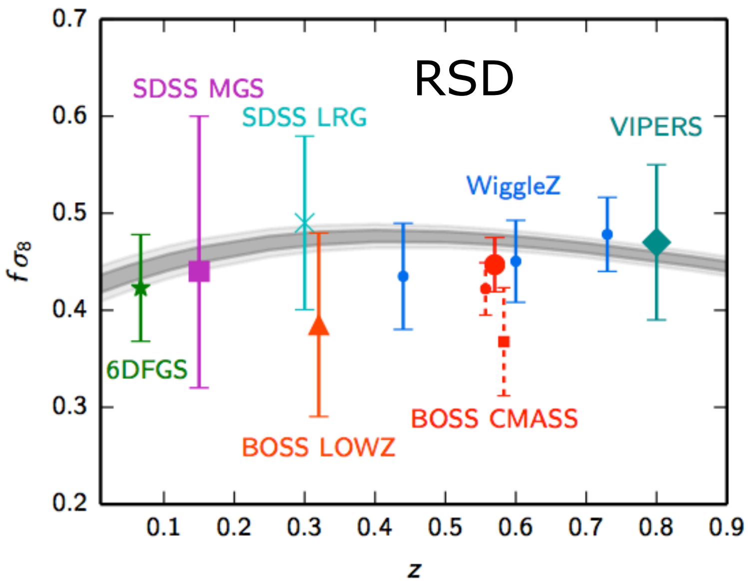
2014 TT power spectrum

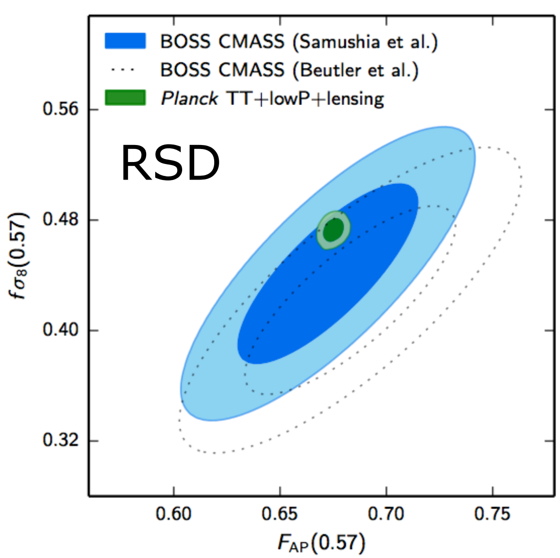


consistency with non-Planck data



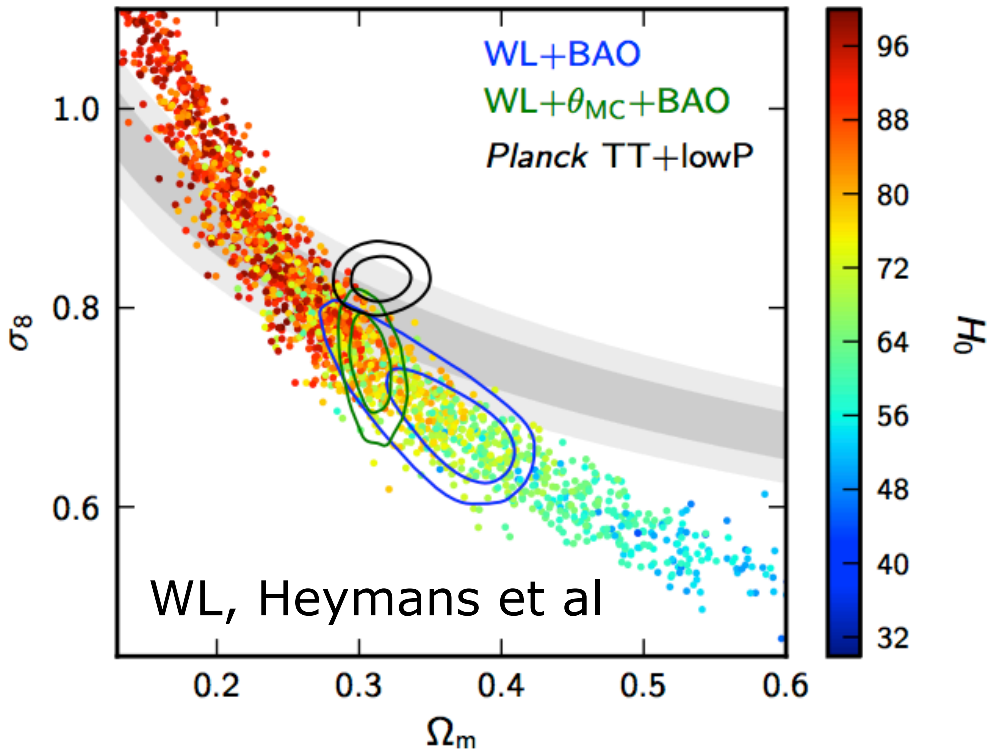




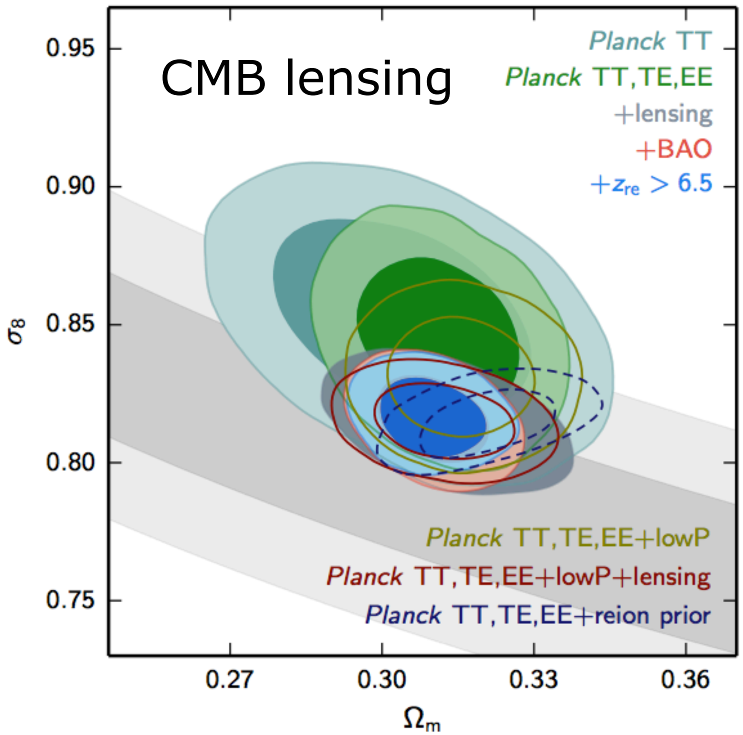


- BAO: good except in Ly-α
- JLA SN-Ia now also okay
- H_0 unchanged, revised anchor: H_0=70.6±3.3
- RSD okay-ish?

consistency with lensing data

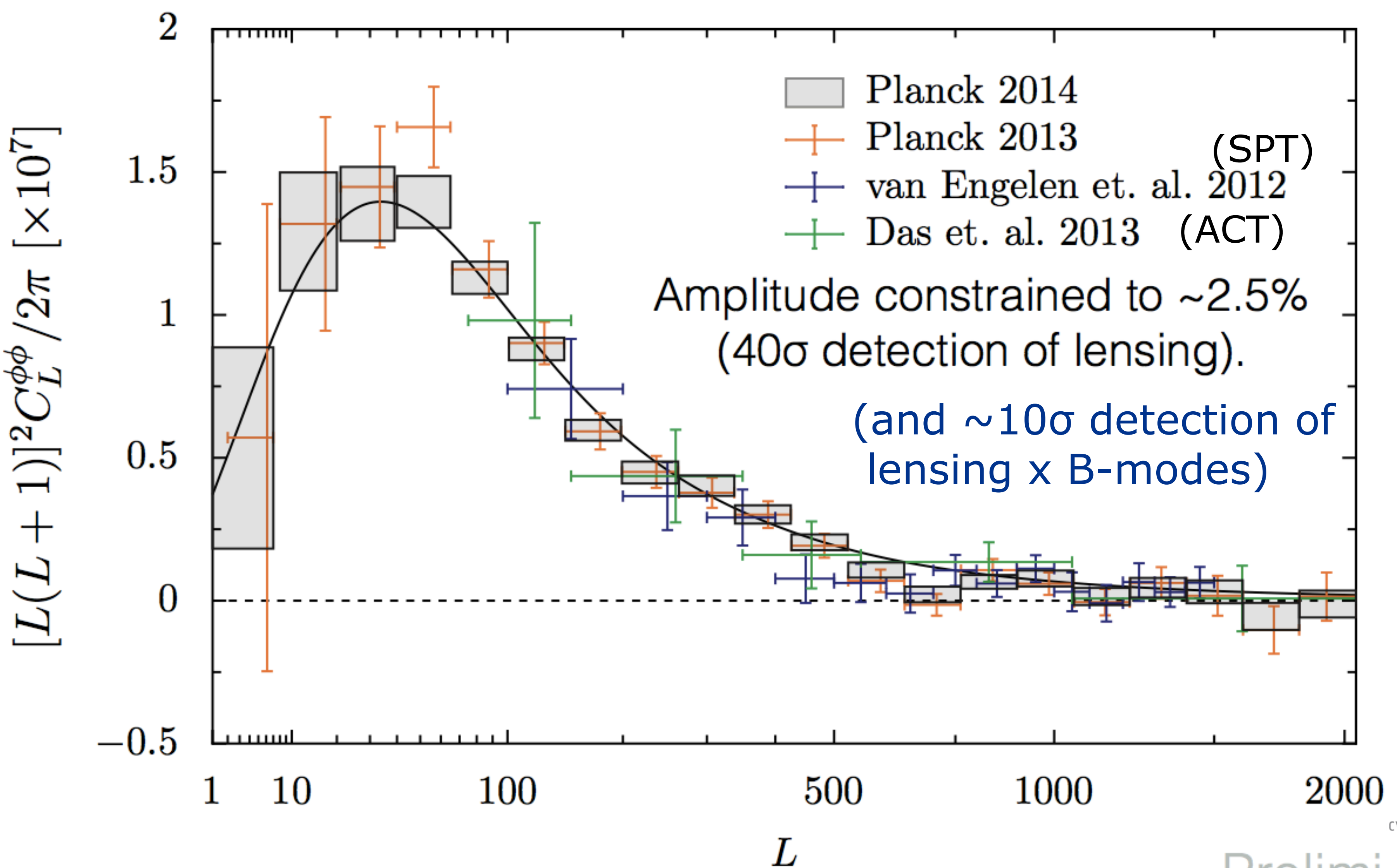


- WL still young technique
- CFHTLenS analyses marginally compatible with each other
- region ~Planck needs high H_0



- CMB lensing now quite mature
- relatively good agreement with primary CMB
- (still a slight 'lensing excess' in power spectrum)

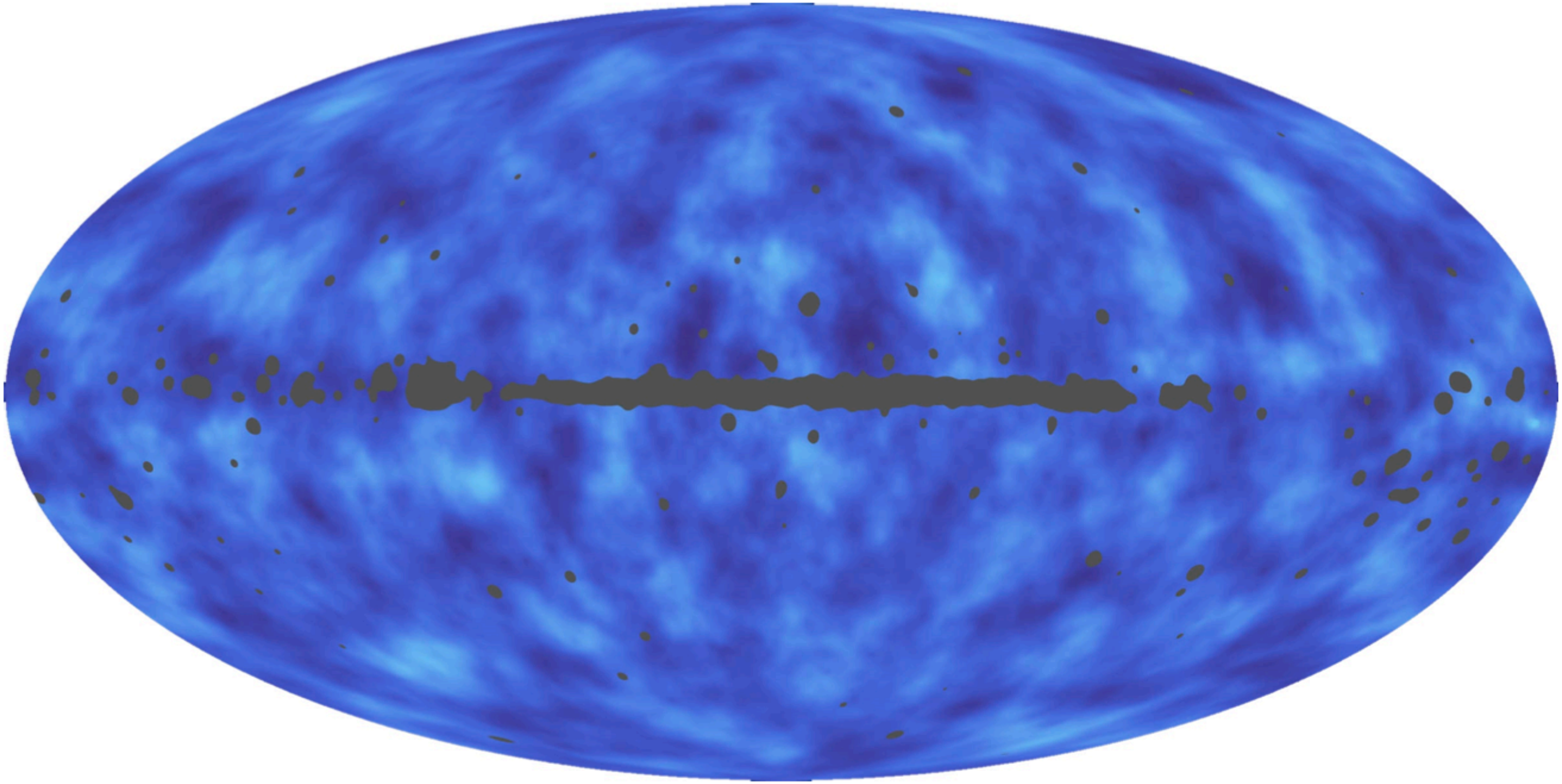
CMB lensing



planck
2
1.5
1
0.5
0
−0.5
1
10
100
500
1000
2000
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi\ [\times 10^7]$
L
Planck 2014
Planck 2013
van Engelen et. al. 2012
(SPT)
Das et. al. 2013
(ACT)
Amplitude constrained to ~2.5%
(40σ detection of lensing).
(and ~10σ detection of
lensing x B-modes)

all the structure in the universe (?)

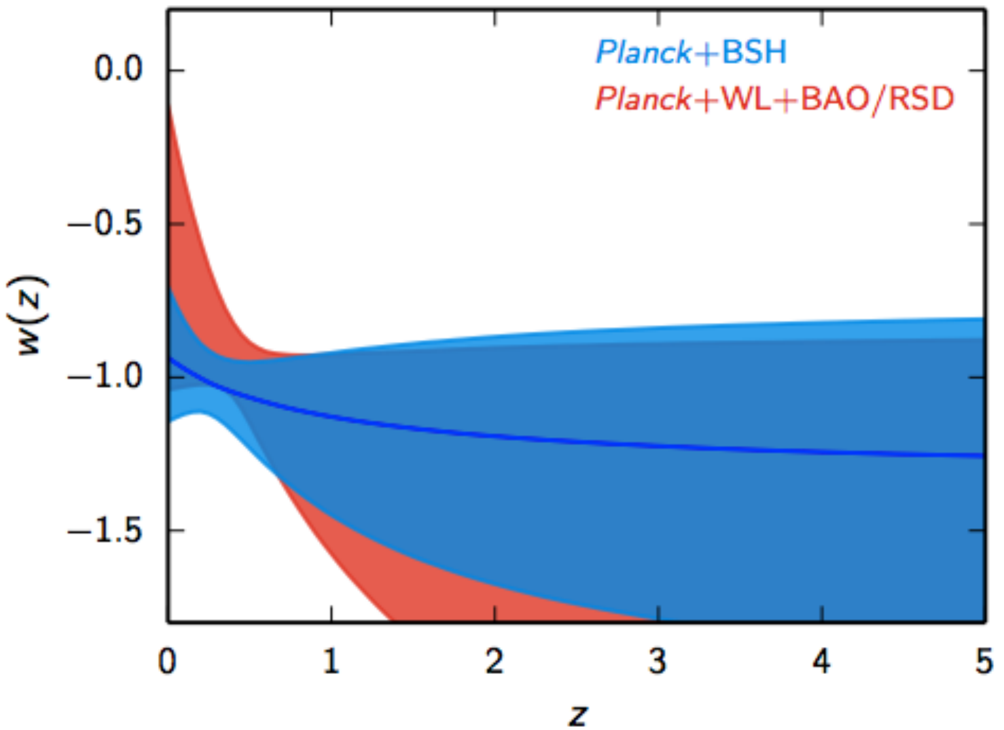
planck

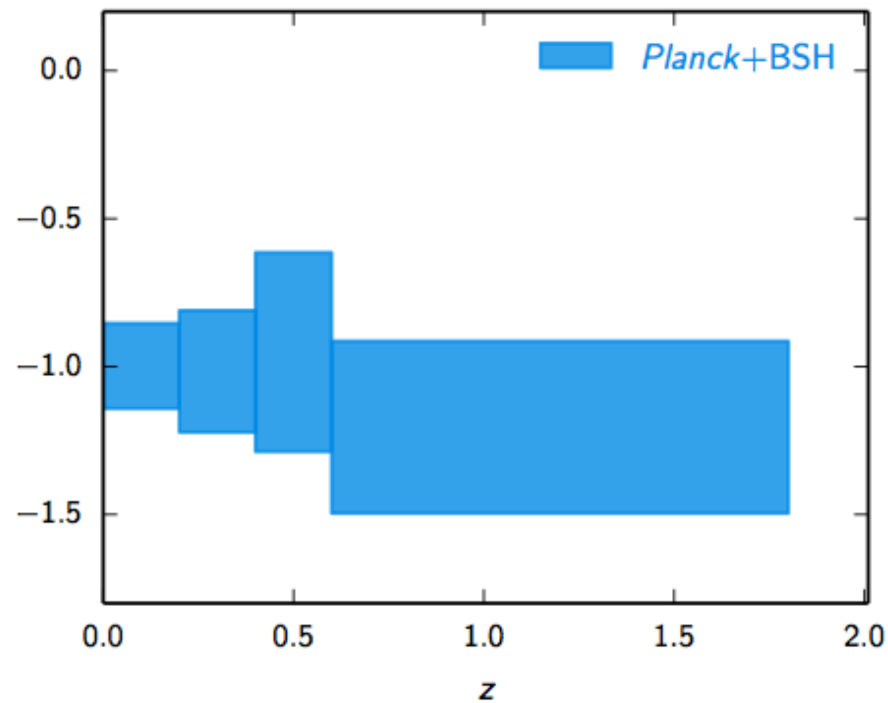


esa

European Space Agency

dark energy equation of state





from ensemble of
$w_0+(1-a)w_a$ curves
(we also tried cubic in a)

PCA
(we also tried more bins)

no deviation from w=-1

(constant w: w=-1.02±0.04)

European Space Agency

testing “modified gravity”

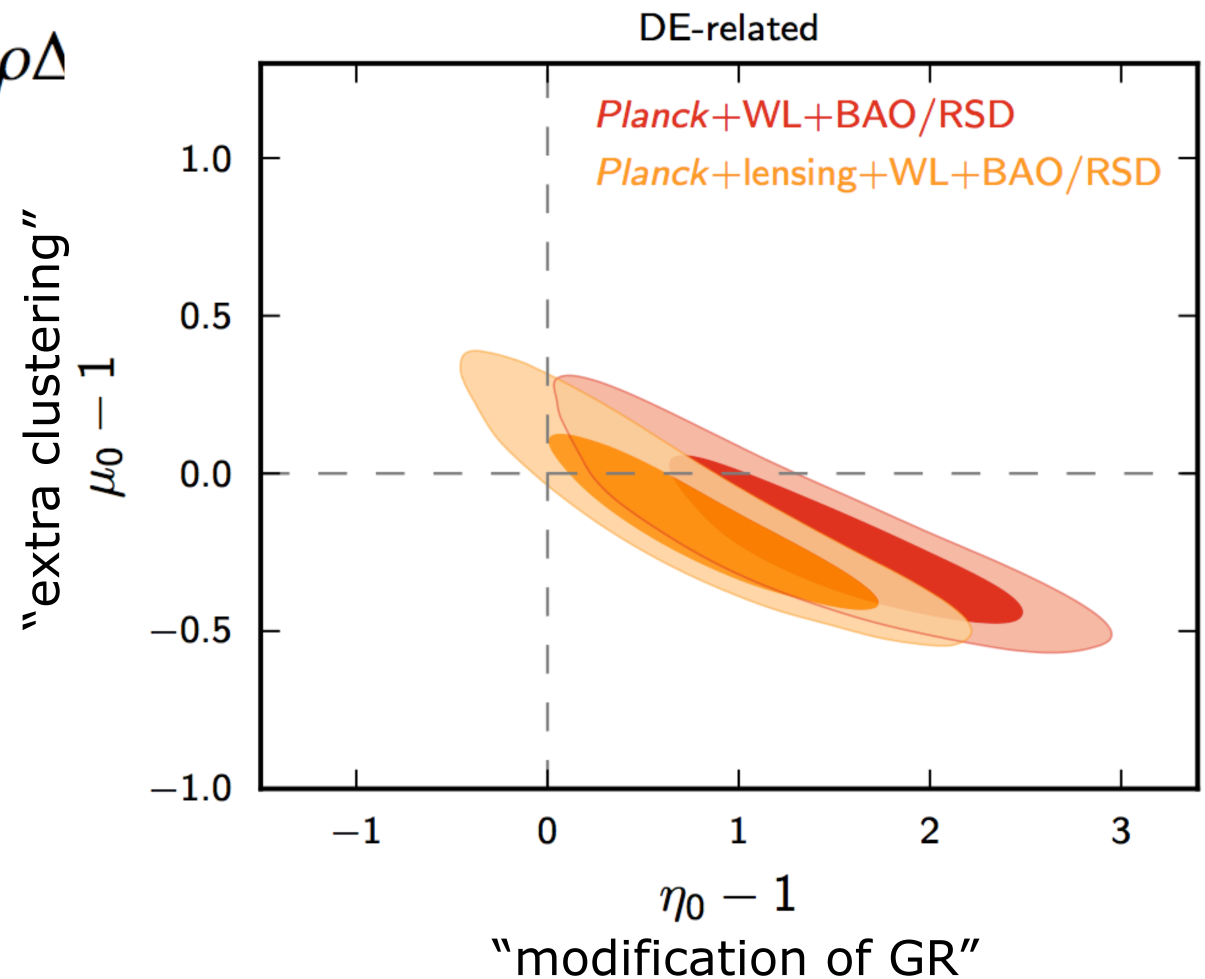
parameterisation of
late-time perturbations:

$$-k^2\Psi \equiv 4\pi G a^2 \mu(a,\boldsymbol{k})\rho\Delta$$

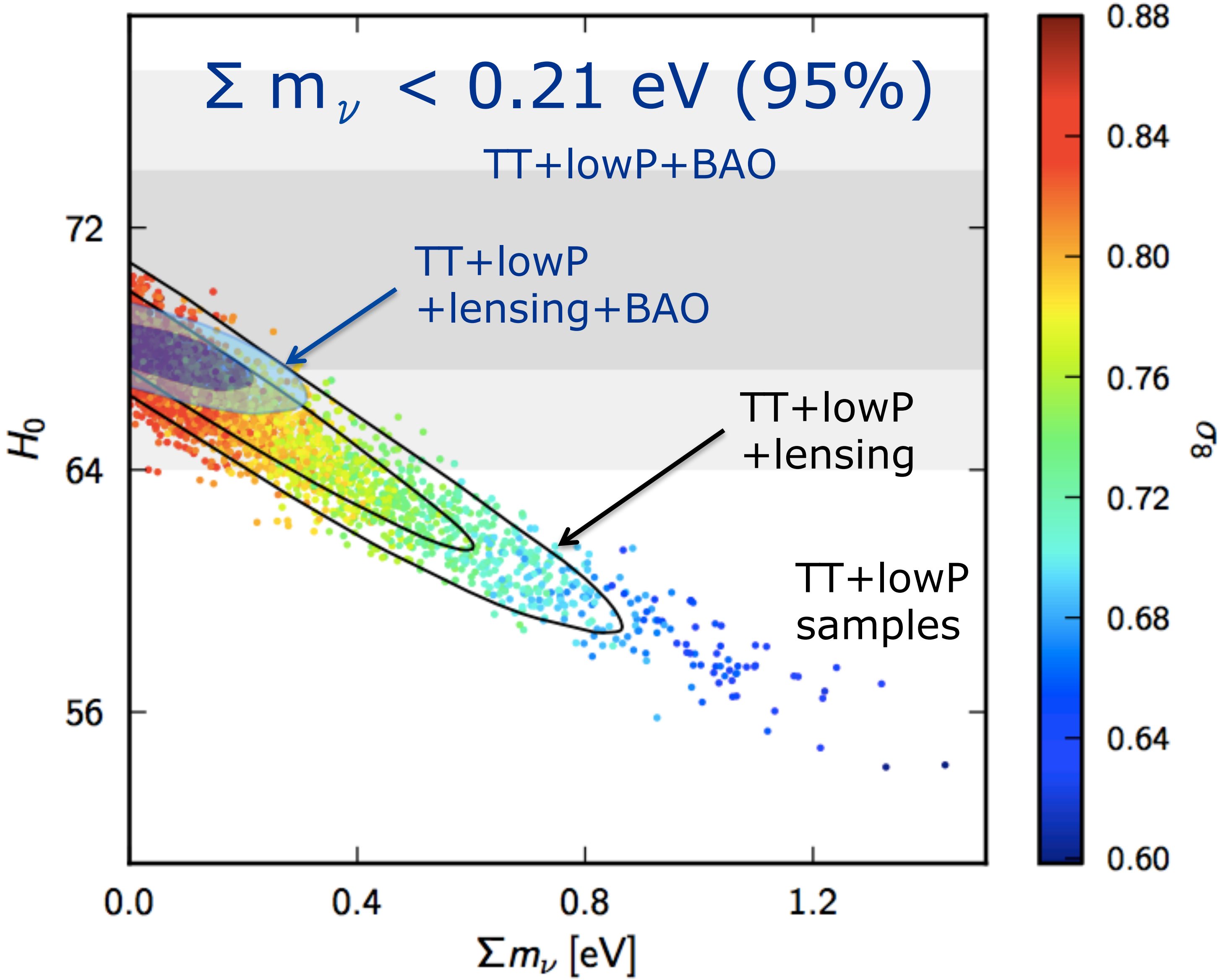
$$\eta(a,\boldsymbol{k}) \equiv \Phi/\Psi$$

functions ~ $\Omega_{DE}(a)$
ΛCDM background

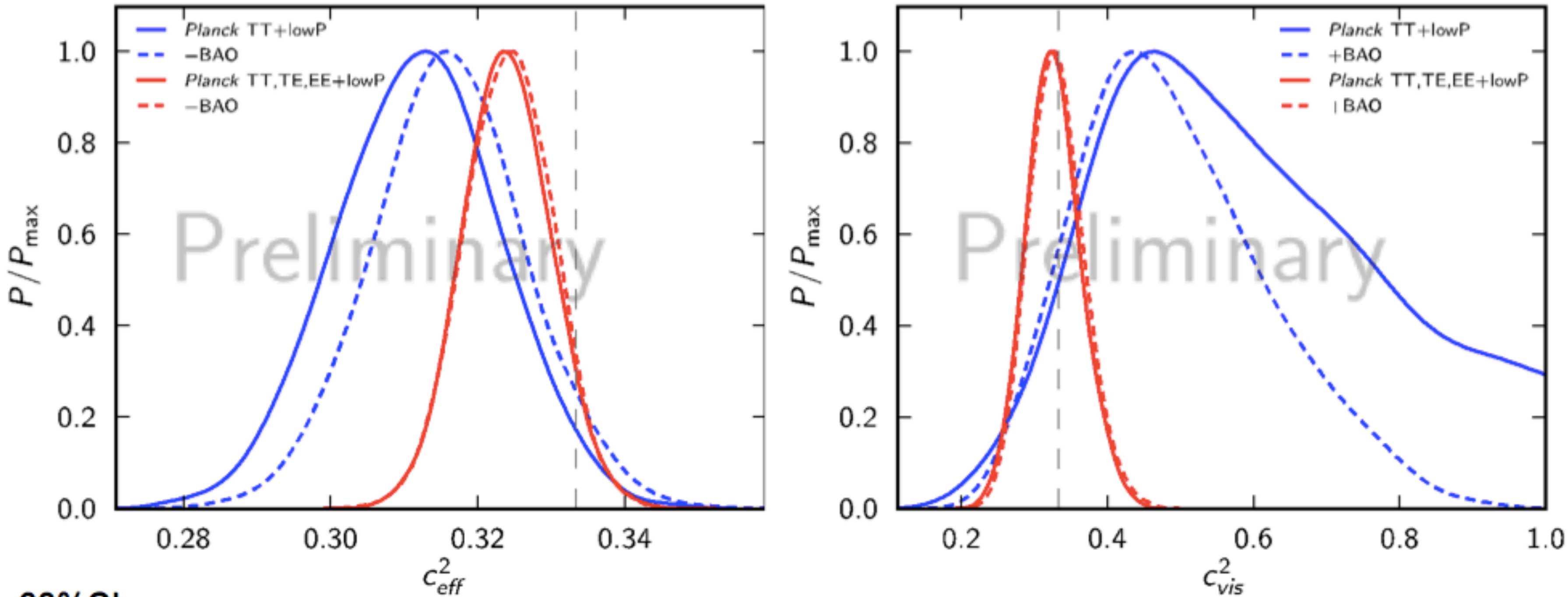
- no scale de-pendence detected
- deviation driven by CMB and WL
- CMB lensing pushes back to LCDM



neutrino masses



neutrino properties



68%CL

Parameter	TT+lowP	TT+lowP+BAO	TT,TE,EE+lowP	TT,TE,EE+lowP+BAO
$c^2_{\rm vis}$	$0.47^{+0.26}_{-0.12}$	$0.44^{+0.15}_{-0.10}$	0.327 ± 0.037	0.331 ± 0.037
$c^2_{\rm eff}$	0.312 ± 0.011	0.316 ± 0.010	0.3240 ± 0.0060	0.3242 ± 0.0059

- significant detection of “neutrino anisotropies”
- compatible with expected values

relativistic degrees of freedom

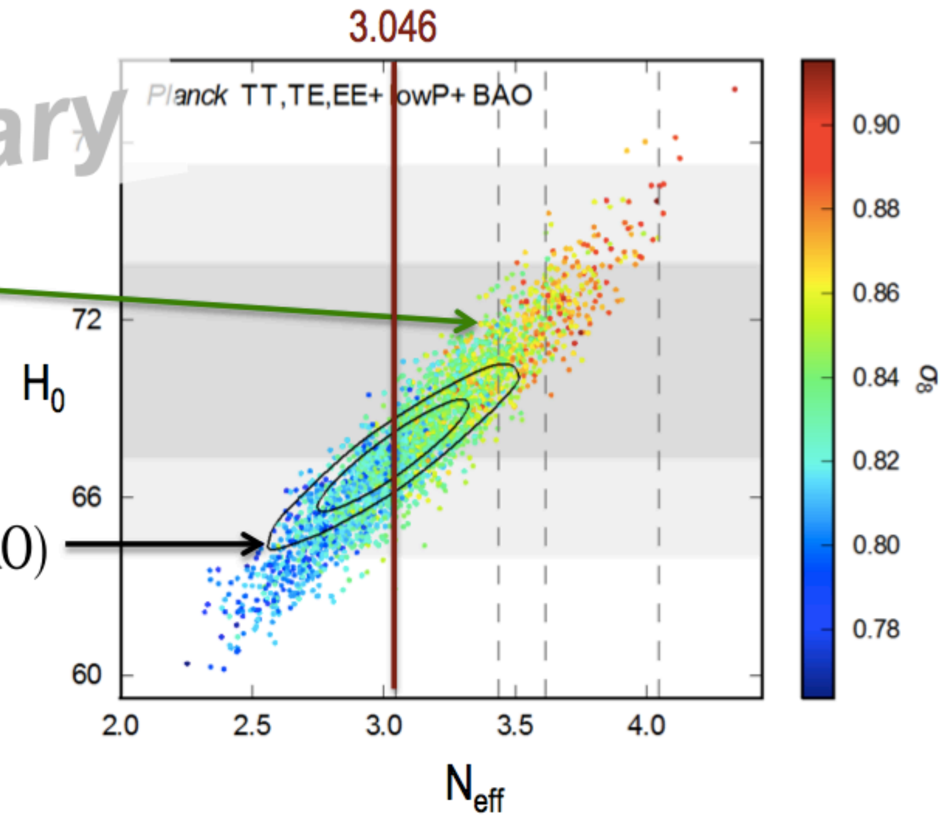
$N_{\rm eff} = 3.13 \pm 0.32$ (*Planck* TT+lowP)

$N_{\rm eff} = 3.15 \pm 0.23$ (*Planck* TT+lowP+ BAO)

$N_{\rm eff} = 2.98 \pm 0.20$ (*Planck* TT,TE,EE+lowP)

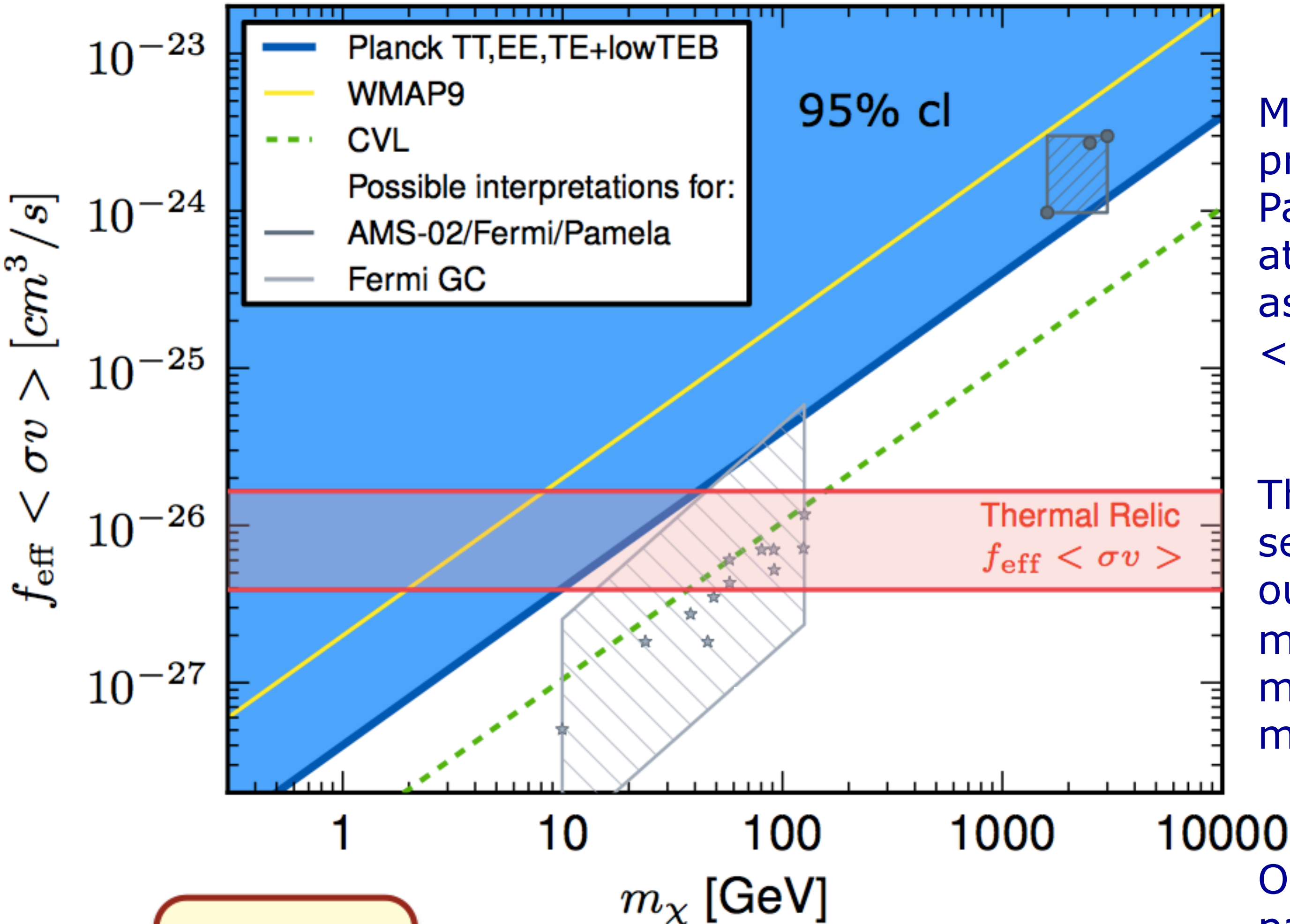
$N_{\rm eff} = 3.04 \pm 0.18$ (*Planck* TT,TE,EE+lowP+BAO)

(all at 68% CL, BAO from *6dFGS, SDSS-MGS, BOSS-LOWZ, BOSS-CMASS-DR11*)



- expected value consistent with data
- zero is not consistent
- $N_{\rm eff}$ = 4 starts to be excluded (but model dependent)
- no sign of any extra light degrees of freedom

dark matter annihilation



Most of parameter space preferred by AMS-02/ Pamela/Fermi ruled out at 95%, under the assumption
<σv>(z=100)=
<σv>(z=0)

Thermal Relic cross sections at z~1000 ruled out for:
m~<40 GeV (e-e+)
m~<20 GeV (μ+μ-)
m~<10 GeV (τ+τ-).

$$p_{ann} = \boxed{f_{eff} \frac{<\sigma v>}{m_\chi}}$$

no detection of any energy injection in data

Only a small part of the parameter space preferred by Fermi GC is excluded

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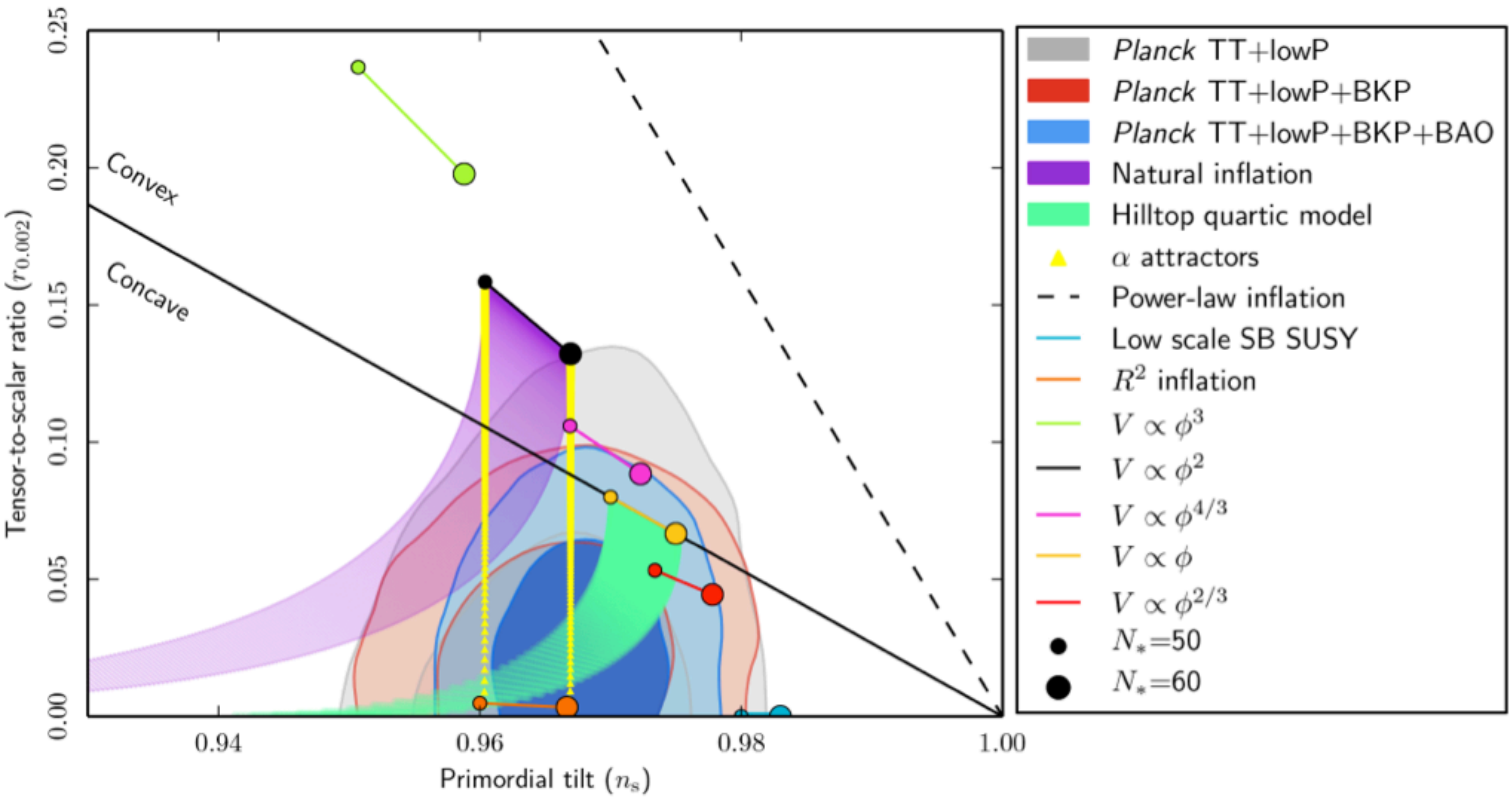
inflation



- 2015 consistent with 2013 results, Bicep2-Keck also consistent
- no significant evidence for features in initial power spectrum

primordial nG

planck

Shape and method	f_{NL}(KSW) 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**

and trispectrum:

$$g_{\mathrm{NL}}^{\mathrm{local}} = (-9.0 \pm 7.7) \times 10^4$$

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

- Constraints based on T+E (2015) confirm temperature results and reduce error bars significantly
- 2013 "hints" of non-Gaussianity in oscillatory feature models remain in temperature, but generally decrease in significance when polarization is included
- The 2015 analysis contains greatly extended template family

cosmic defects

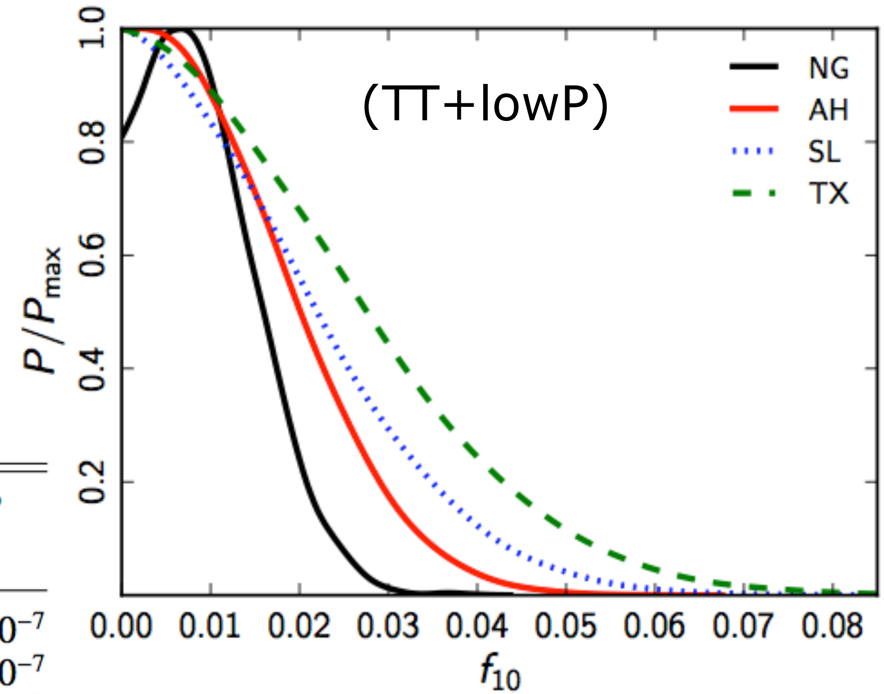
NG: Nambu Goto
AH: Abelian Higgs

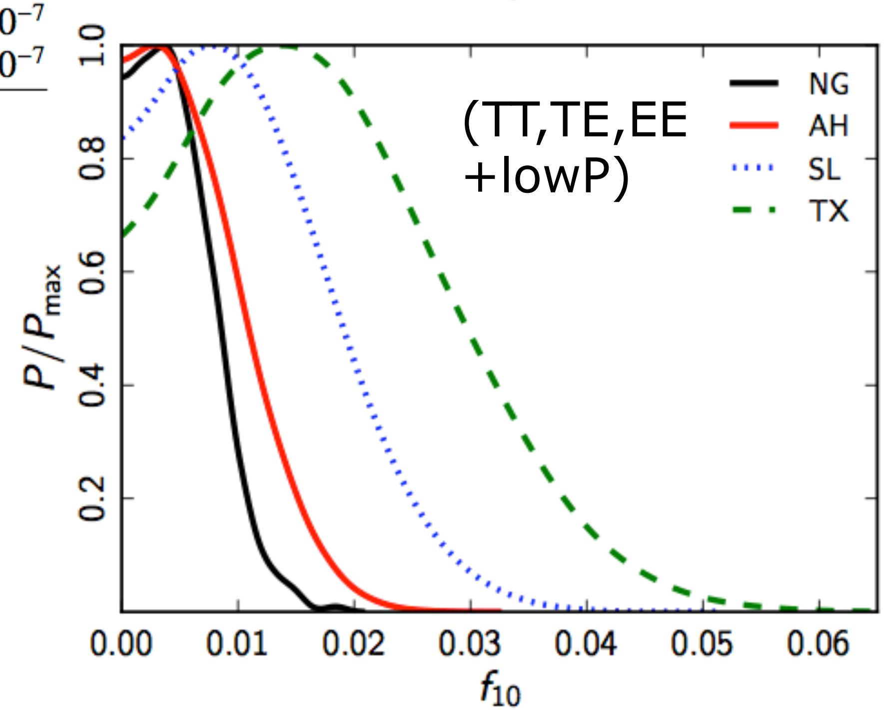
SL: semilocal
TX: texture

	TT+lowP		TT,TE,EE+lowP	
Defect type	f_{10}	$G\mu/c^2$	f_{10}	$G\mu/c^2$
NG	< 0.020	$< 1.8 \times 10^{-7}$	< 0.011	$< 1.3 \times 10^{-7}$
AH	< 0.030	$< 3.3 \times 10^{-7}$	< 0.015	$< 2.4 \times 10^{-7}$
SL	< 0.039	$< 10.6 \times 10^{-7}$	< 0.024	$< 8.5 \times 10^{-7}$
TX	< 0.047	$< 9.8 \times 10^{-7}$	< 0.036	$< 8.6 \times 10^{-7}$

- (NG model changed significantly)

- TT not so different from last year
- Polarisation has big impact
- (B-modes are nearly as strong)





conclusions

status:

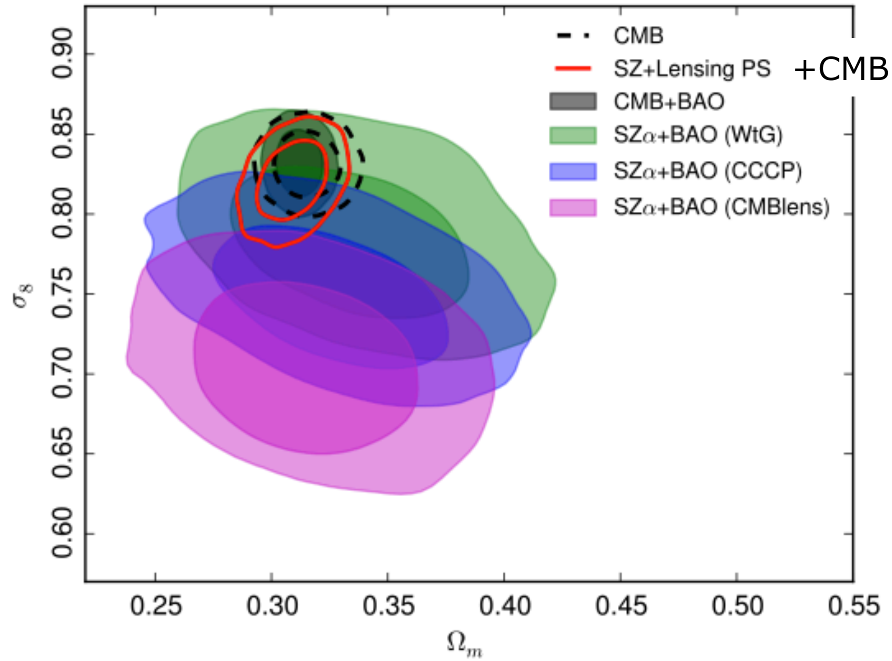
- new 2015 Planck data is a significant improvement over 2013 (better processing, more data, polarisation)
- flat ΛCDM continues to be a good fit to combined CMB, distance and large scale structure data
- scalar fluctuations consistent with pure adiabatic modes with featureless power spectrum
- no primordial non-Gaussianity detected, no defects, CMB anomalies similar to 2013
- no sign of extra light d.o.f., neutrinos behave as expected
- Planck 2015 release contains many more things!

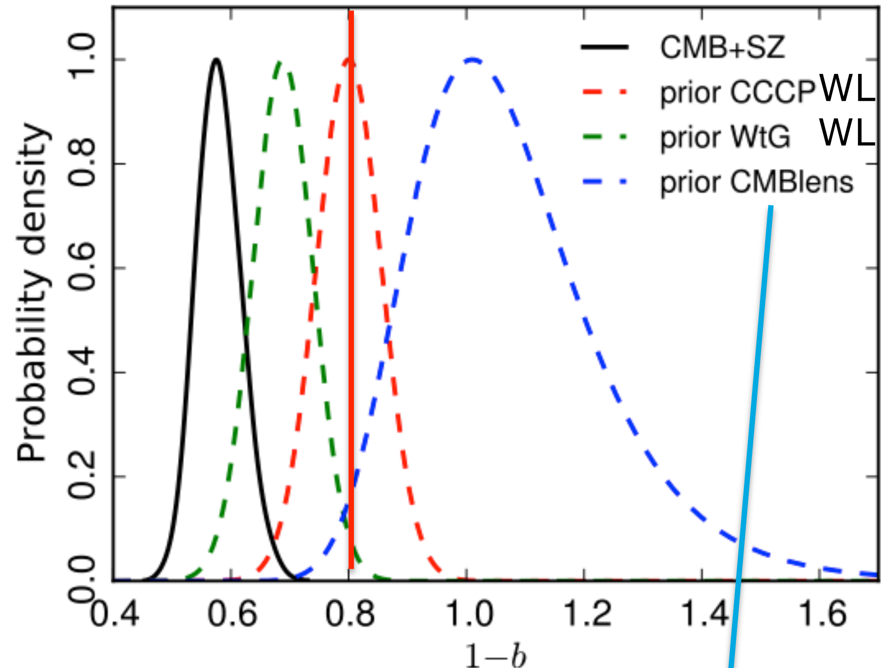
outlook:

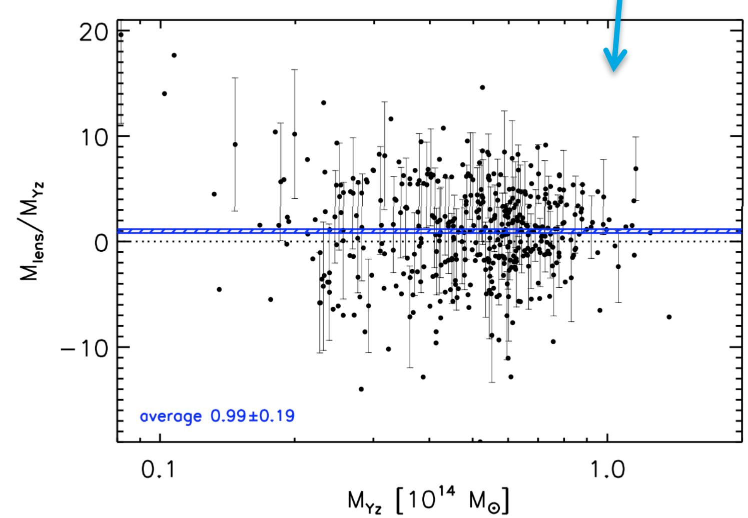
- CMB: Planck ends 2016, next: B-modes, lensing, spectral distortions
- LSS: DES ongoing, MS-DESI soon; Euclid satellite, SKA, LSST: 2020+

Thank you

SZ clusters







- cosmological constraints fully degenerate with mass bias
- widely varying results from different lensing approaches
- use spread as indication of systematics? if so then no disagreement with Planck CMB

ISW cross-corr.

(there is a funny issue when stacking CMB anisotropies at locations of known structures)

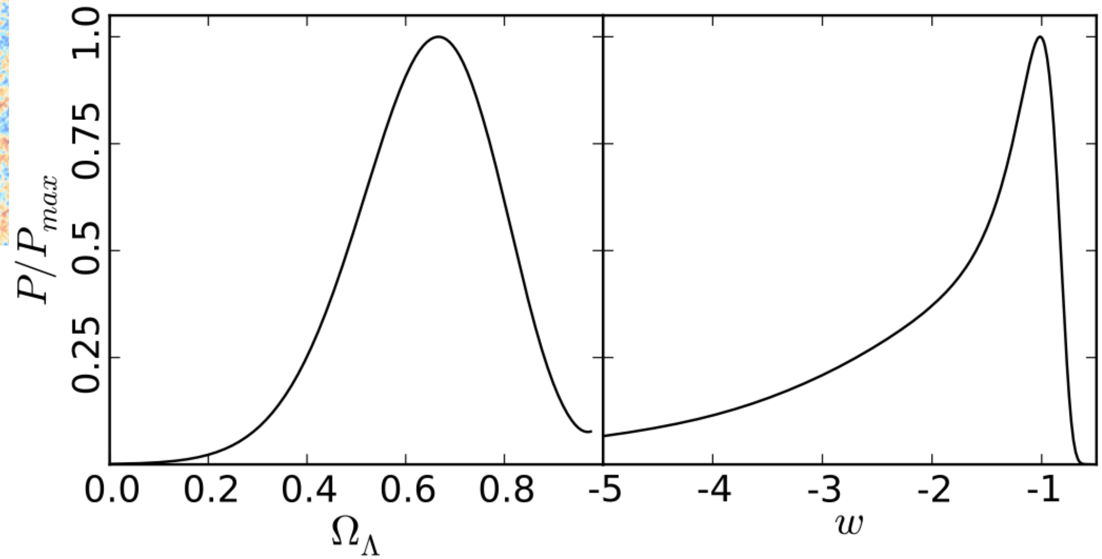
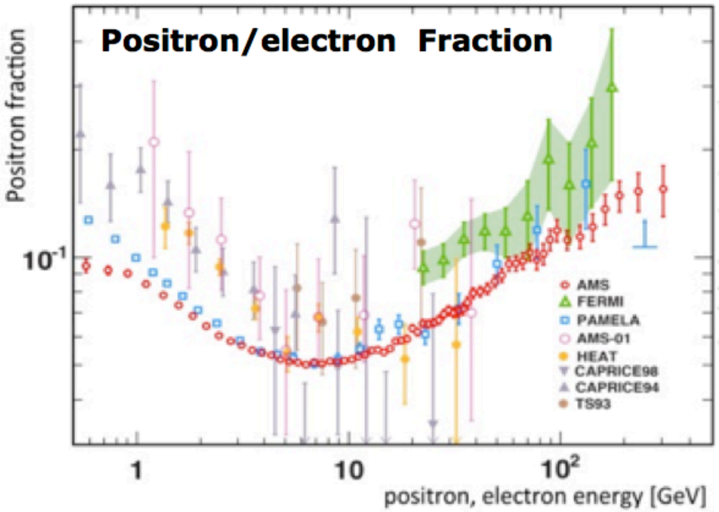
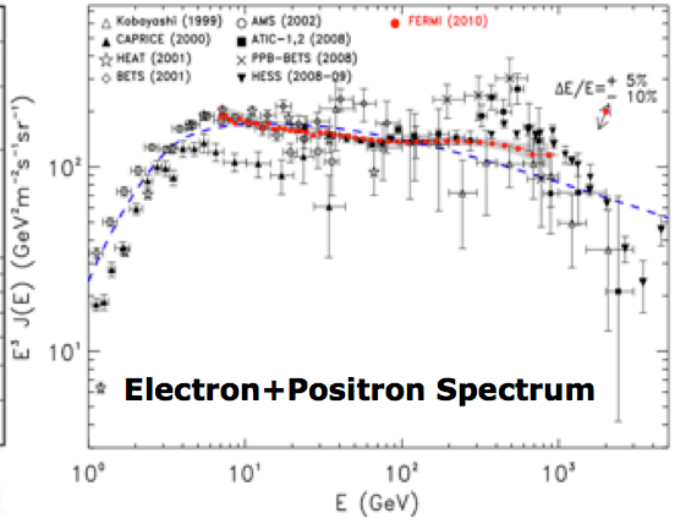


Table 2. ISW amplitudes A, errors σ_A, and significance levels S/N = A/σ_A of the CMB-LSS cross-correlation (survey-by-survey and for different combinations). These values are reported for the four *Planck* CMB maps: `COMMANDER`, `NILC`, `SEVEM`, and `SMICA`. The last column stands for the expected S/N within the fiducial ΛCDM model.

LSS data	`COMMANDER`		`NILC`		`SEVEM`		`SMICA`		Expected
	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	$A \pm \sigma_A$	S/N	S/N
NVSS	0.95 ± 0.36	2.61	0.94 ± 0.36	2.59	0.95 ± 0.36	2.62	0.95 ± 0.36	2.61	2.78
WISE-AGN ($\ell_{min} \geq 9$)	0.95 ± 0.60	1.58	0.96 ± 0.60	1.59	0.95 ± 0.60	1.58	1.00 ± 0.60	1.66	1.67
WISE-GAL ($\ell_{min} \geq 9$)	0.73 ± 0.53	1.37	0.72 ± 0.53	1.35	0.74 ± 0.53	1.38	0.77 ± 0.53	1.44	1.89
SDSS-CMASS/LOWZ	1.37 ± 0.56	2.42	1.36 ± 0.56	2.40	1.37 ± 0.56	2.43	1.37 ± 0.56	2.44	1.79
SDSS-MphG	1.60 ± 0.68	2.34	1.59 ± 0.68	2.34	1.61 ± 0.68	2.36	1.62 ± 0.68	2.38	1.47
Kappa ($\ell_{min} \geq 8$)	1.04 ± 0.33	3.15	1.04 ± 0.33	3.16	1.05 ± 0.33	3.17	1.06 ± 0.33	3.20	3.03
NVSS and Kappa	1.04 ± 0.28	3.79	1.04 ± 0.28	3.78	1.05 ± 0.28	3.81	1.05 ± 0.28	3.81	3.57
WISE	0.84 ± 0.45	1.88	0.84 ± 0.45	1.88	0.84 ± 0.45	1.88	0.88 ± 0.45	1.97	2.22
SDSS	1.49 ± 0.55	2.73	1.48 ± 0.55	2.70	1.50 ± 0.55	2.74	1.50 ± 0.55	2.74	1.82
NVSS and WISE and SDSS	0.89 ± 0.31	2.87	0.89 ± 0.31	2.87	0.89 ± 0.31	2.87	0.90 ± 0.31	2.90	3.22
All	1.00 ± 0.25	4.00	0.99 ± 0.25	3.96	1.00 ± 0.25	4.00	1.00 ± 0.25	4.00	4.00

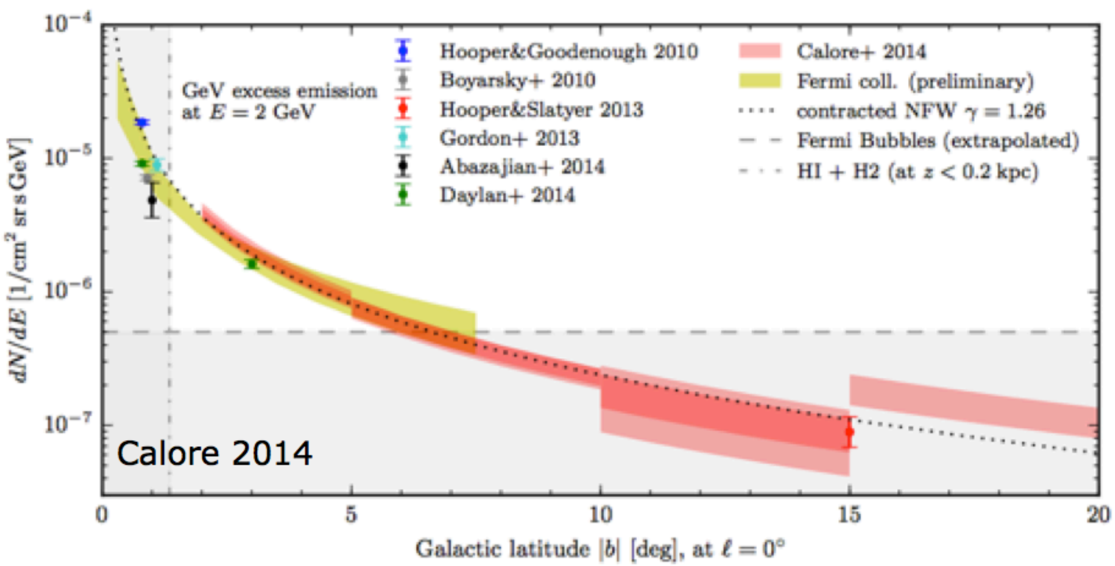
astroparticle signals





Cosmic rays excesses in PAMELA/FERMI/AMS-02

- Leptonic ann.chan.,
- Mass~ TeV,
- Large cross-section required (~10^{-23}cm^3/s).
- Need broken power law in electrons.



Fermi Galactic Center excess

- Many ann.chan. allowed.
- Mass ~few tens GeV,
- ~Thermal relic cross section (~10^{-26}cm^3/s)

annihilation and energy injection

planck

$$\frac{dE}{dt} = \rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 \, \boxed{f_{eff} \frac{<\sigma v>}{m_\chi}}$$

p_{ann}

$\chi_i \frac{dE}{dt}$

IONIZATIONS

$\chi_\alpha \frac{dE}{dt}$

LYMAN-α

$\chi_h \frac{dE}{dt}$

HEATING

χ are the fractions of absorbed energy going into heating, ionization and excitation of the medium.

Shull and Van Steenberg 1989, Chen & Kamionkowski 2004

f(z) is the fraction of overall annihilation energy absorbed by the medium.

In the following, we will assume f(z) constant with redshift, $f(z) \sim f_{eff}$.

(Galli 2009,2011, Slatyer 2009,Finkbeiner2012)

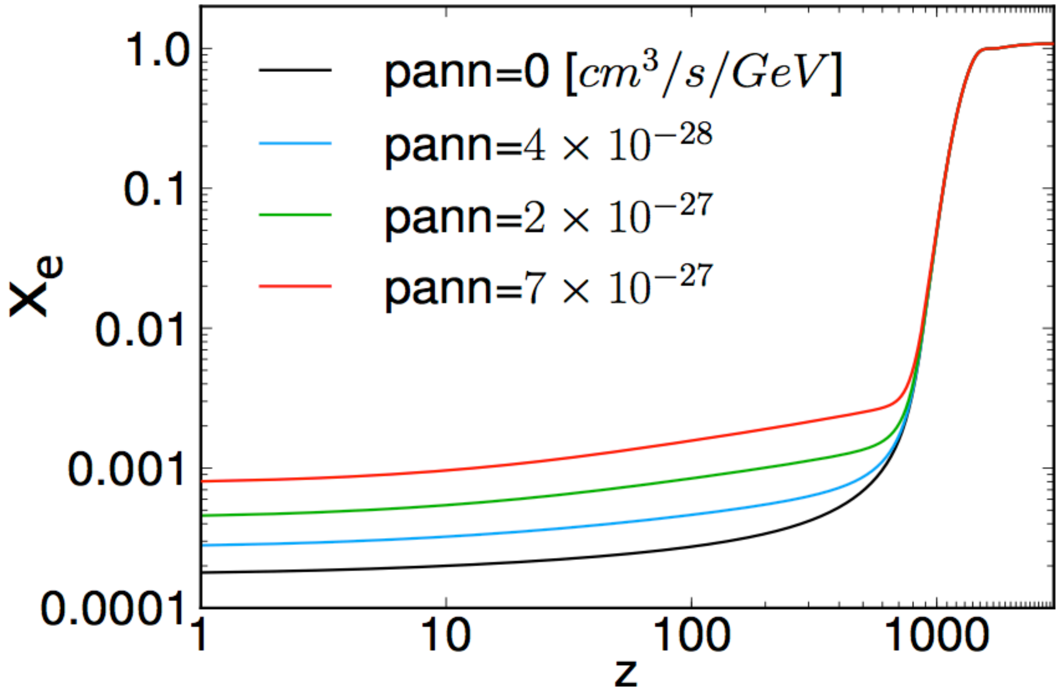
(effectively z~600)

energy injection and ionisation

planck

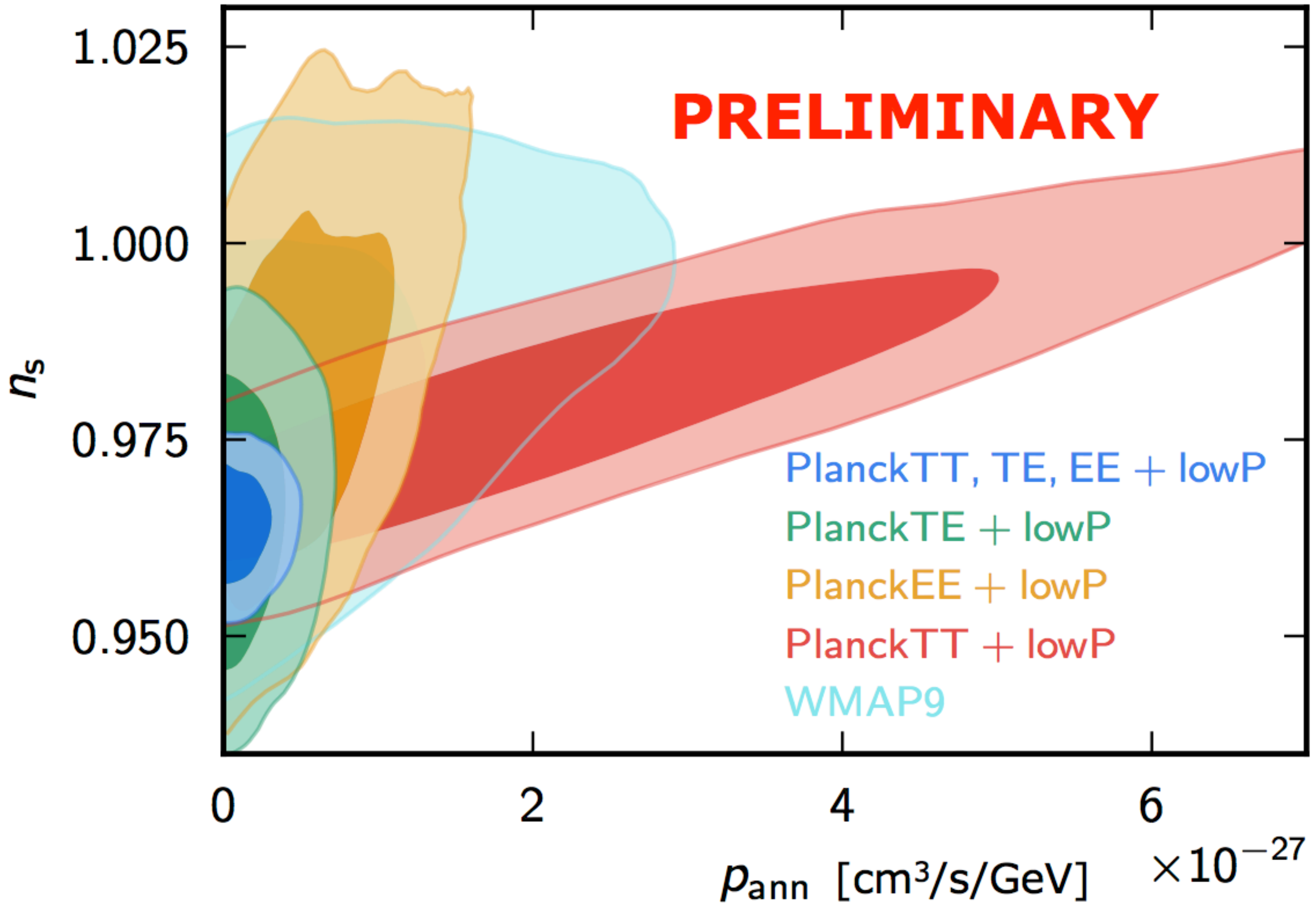
$$\frac{dE}{dt} = \rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 \boxed{f_{eff} \frac{<\sigma v>}{m_\chi}}$$

p_{ann}



The injected energy ionizes, excites and heats the medium. This affects the evolution of the free electron fraction.

annihilation constraints



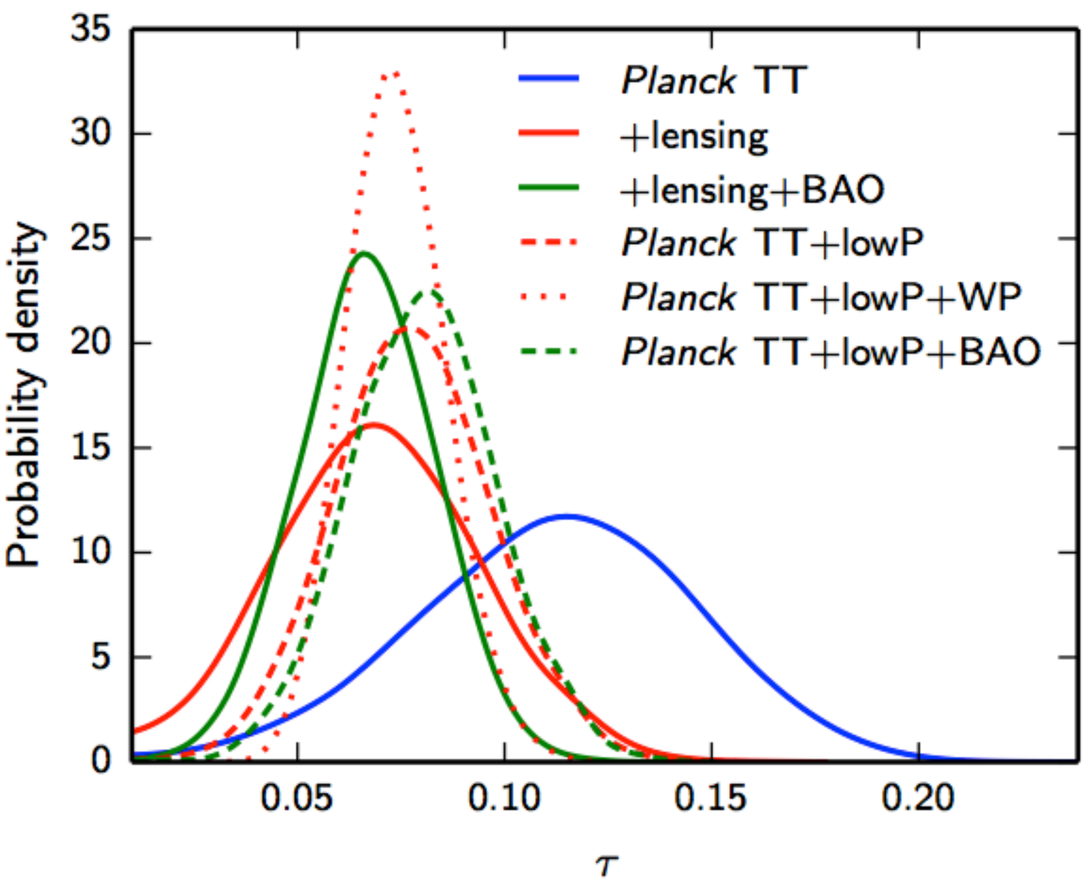
Polarization breaks degeneracies!

Planck TT,TE,EE set a constraint 5 times stronger than WMAP9, 4 times stronger than WMAP9+SPT

$$p_{ann} = f_{eff} \frac{<\sigma v>}{m_\chi}$$

reionisation

Ly-α opacity: reionisation complete by z ≈ 6
difficult to reconcile with high optical depth from WMAP

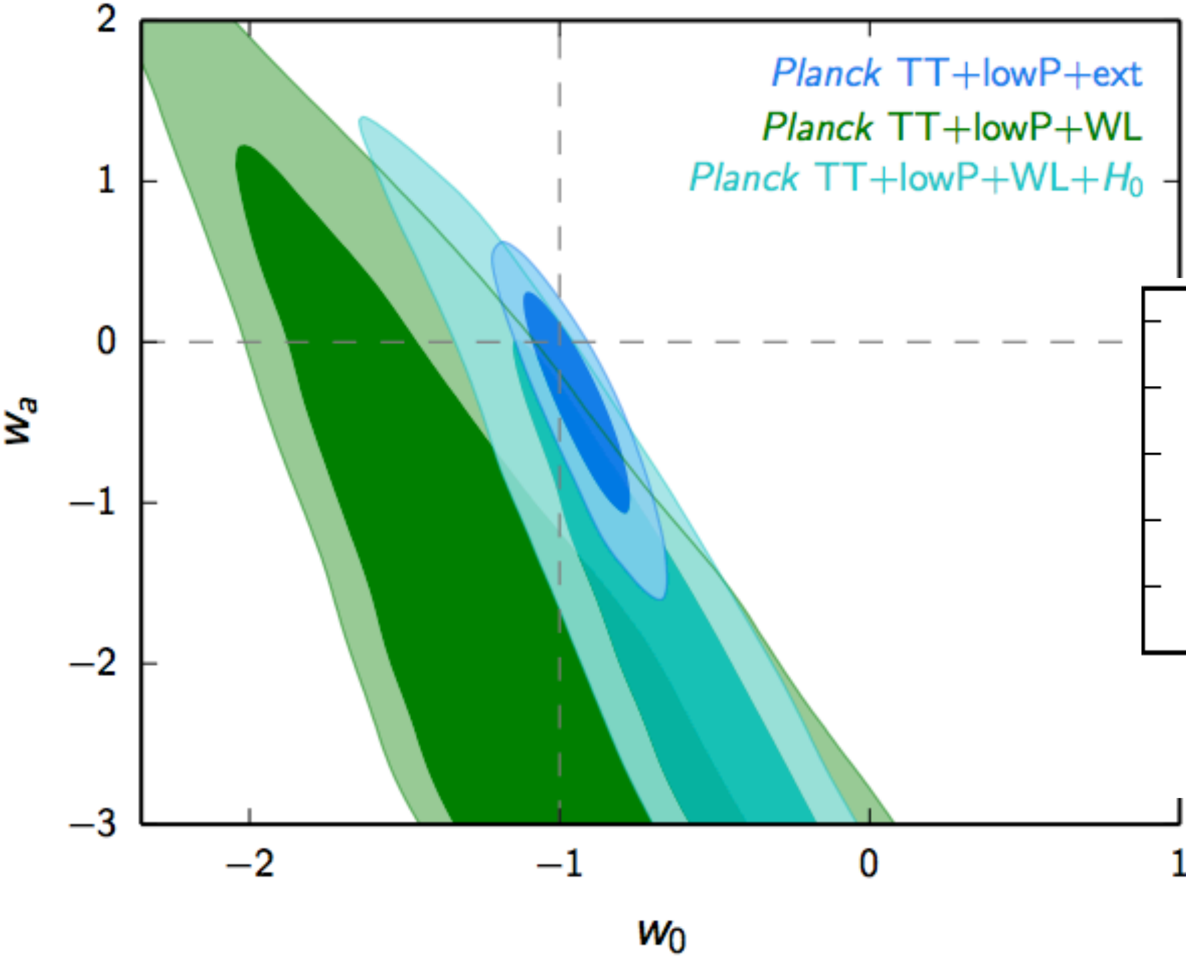


- low-l polarization is hard (systematics, polarized foregrounds)
- WMAP9: τ=0.089±0.014
- Planck 353GHz cleaned WMAP9: τ=0.075±0.013
- Planck low-l polarisation alone: τ=0.067±0.022
- TT+lowP: τ=0.078±0.019
- low-l polar independent TT+lensing+BAO: τ=0.067±0.016

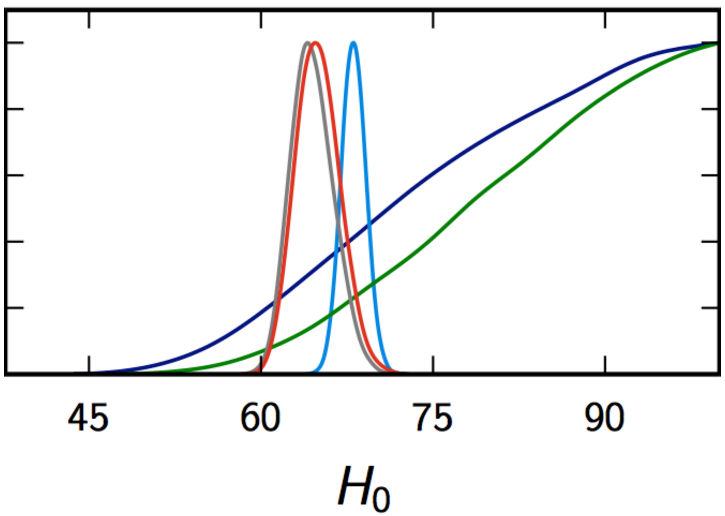
(CMB lensing breaks $A_s e^{-2\tau}$ degeneracy of TT)

→ reionization around z ≈ 8 to 10

dark energy



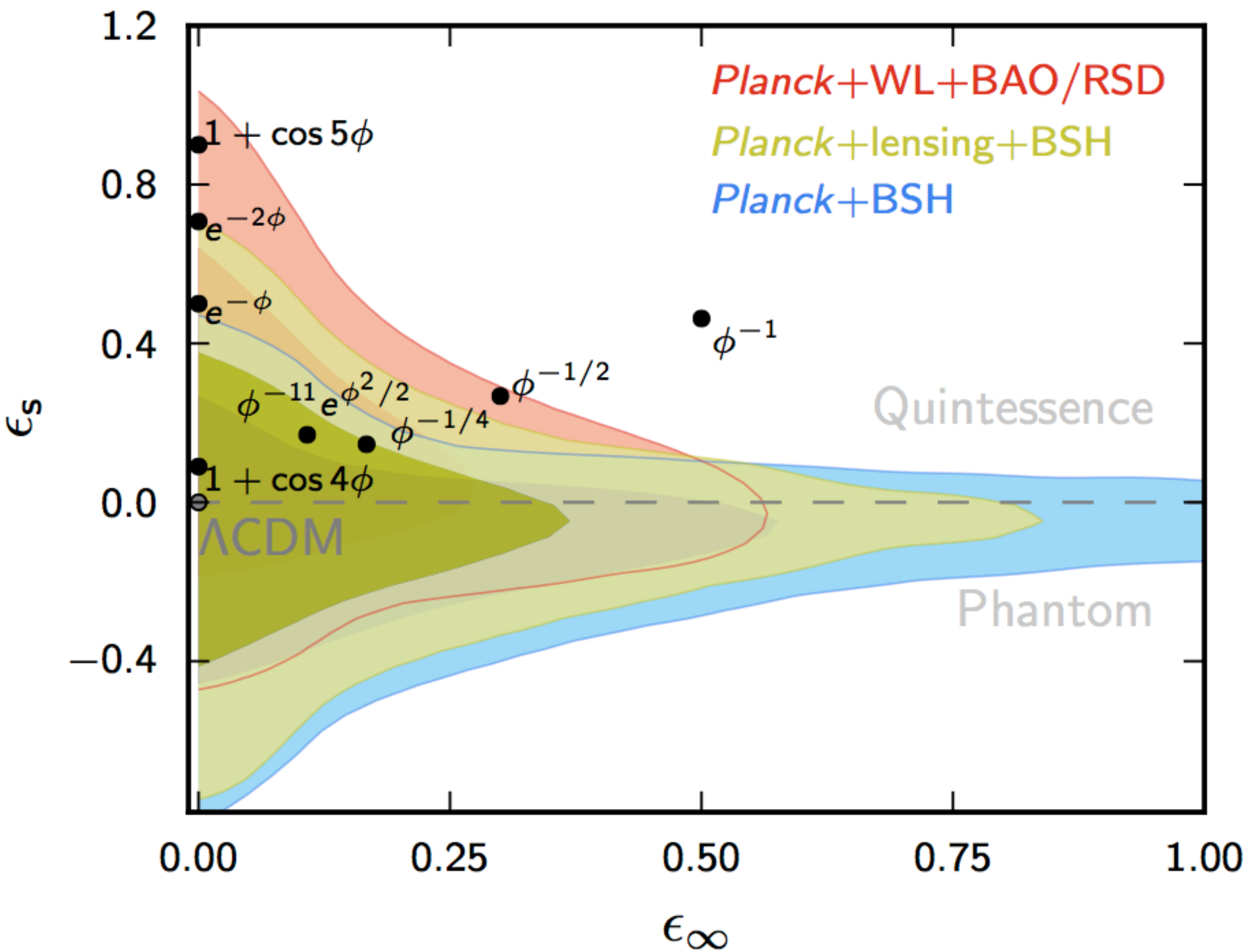
effective quintessence
$w(z) = w_0 + (1\text{-}a)w_a$



- Planck and WL prefer high H_0 and the 'phantom domain'
- no deviation from LCDM when adding BAO+JLA+H0
- const w: w=-1.02±0.04 (TT,TE,EE+lowP+lensing+ext)

cy

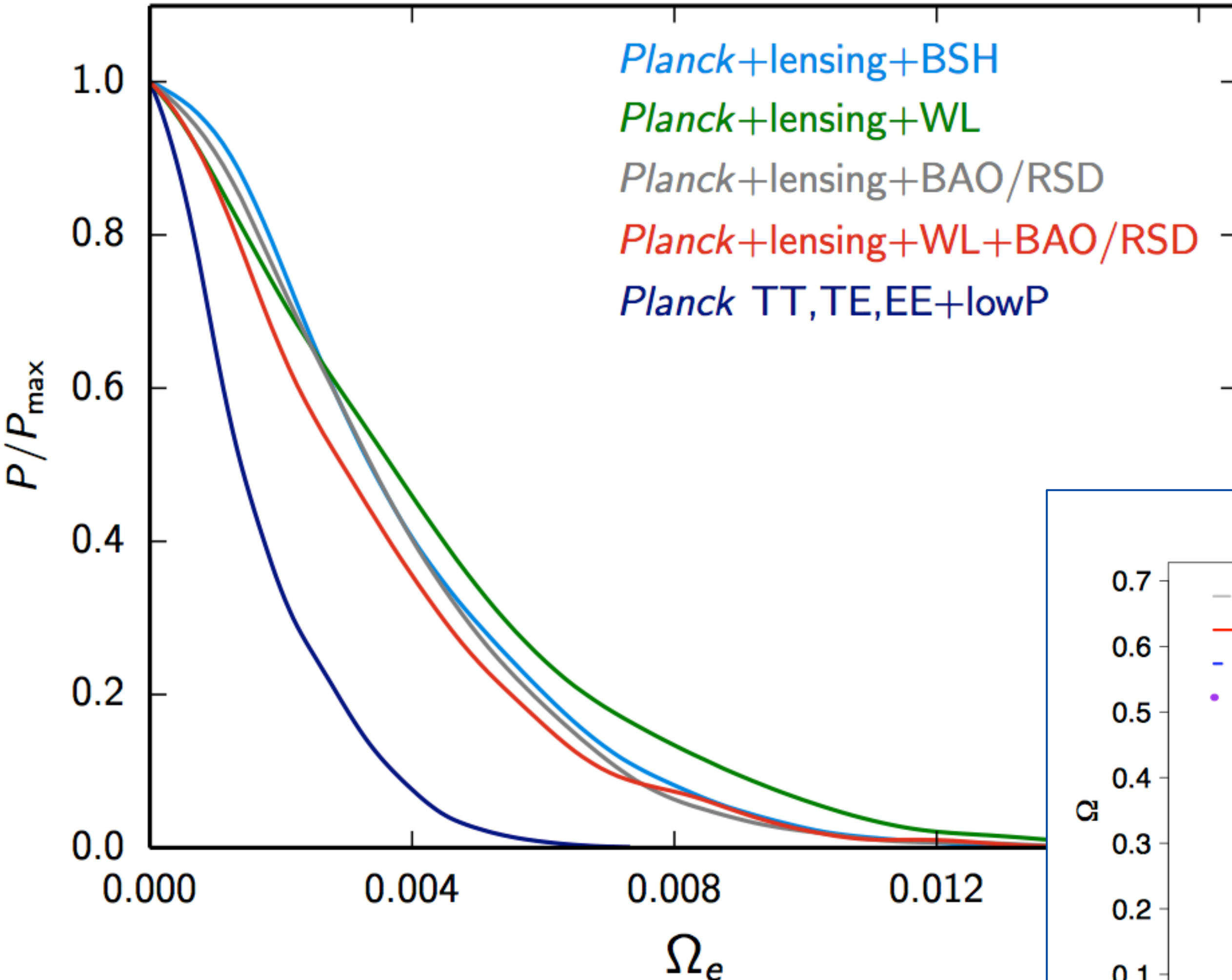
quintessence landscape



similar to scalar field inflation

$\varepsilon_s \approx 3/2(1+w)$
ε_∞ early time

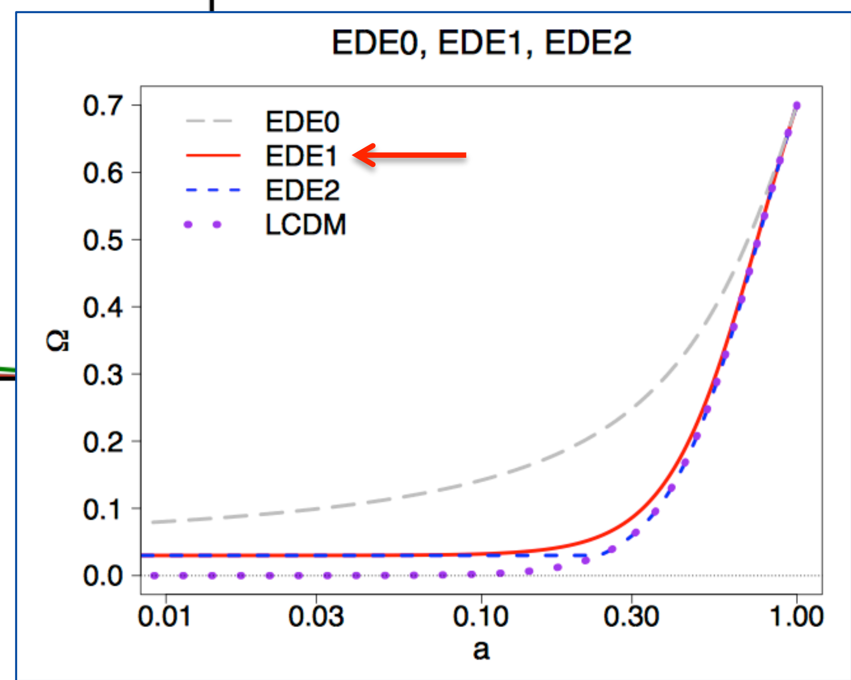
early dark energy



TT,TE,EE+lowP+BSH:

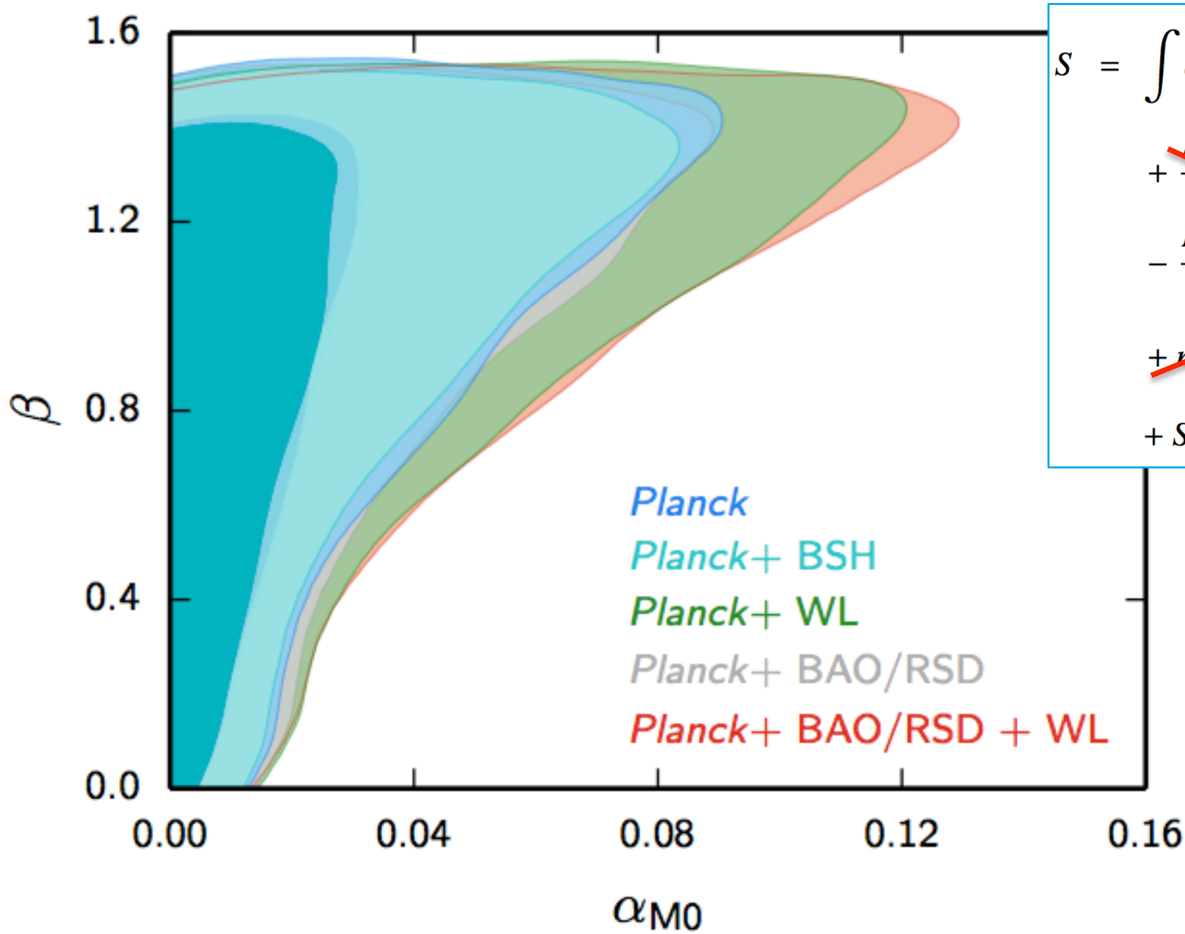
Ω_e < 0.0036 @95%

w_0 < -0.94 @95%



[if DE important for z ≤ 50 only then Ω_e ≤ 2% (95%CL)]

effective field theory of DE



$$
\begin{aligned}
S = & \int d^4x \sqrt{-g} \Big\{ \frac{m_0^2}{2}\left[1+\Omega(\tau)\right]R + \Lambda(\tau) - a^2 c(\tau)\delta g^{00} \\
& \cancel{+ \frac{M_2^4(\tau)}{2}\left(a^2\delta g^{00}\right)^2 - \bar{M}_1^3(\tau) 2a^2 \delta g^{00}\delta K^\mu_\mu} \\
& \cancel{- \frac{\bar{M}_2^2(\tau)}{2}\left(\delta K^\mu_\mu\right)^2 - \frac{\bar{M}_3^2(\tau)}{2}\delta K^\mu_\nu \delta K^\nu_\mu + \frac{a^2\hat{M}^2(\tau)}{2}\delta g^{00}\delta R^{(3)}} \\
& \cancel{+ m_2^2(\tau)\left(g^{\mu\nu}+n^\mu n^\nu\right)\partial_\mu\left(a^2 g^{00}\right)\partial_\nu\left(a^2 g^{00}\right)} \Big\} \\
& + S_{\mathrm{m}}[\chi_i, g_{\mu\nu}].
\end{aligned}
$$

$$\Omega(a) = \exp\left\{\frac{\alpha_{M0}}{\beta}a^\beta\right\} - 1$$

→ non-minimally coupled K-essence model

“modified gravity”

planck

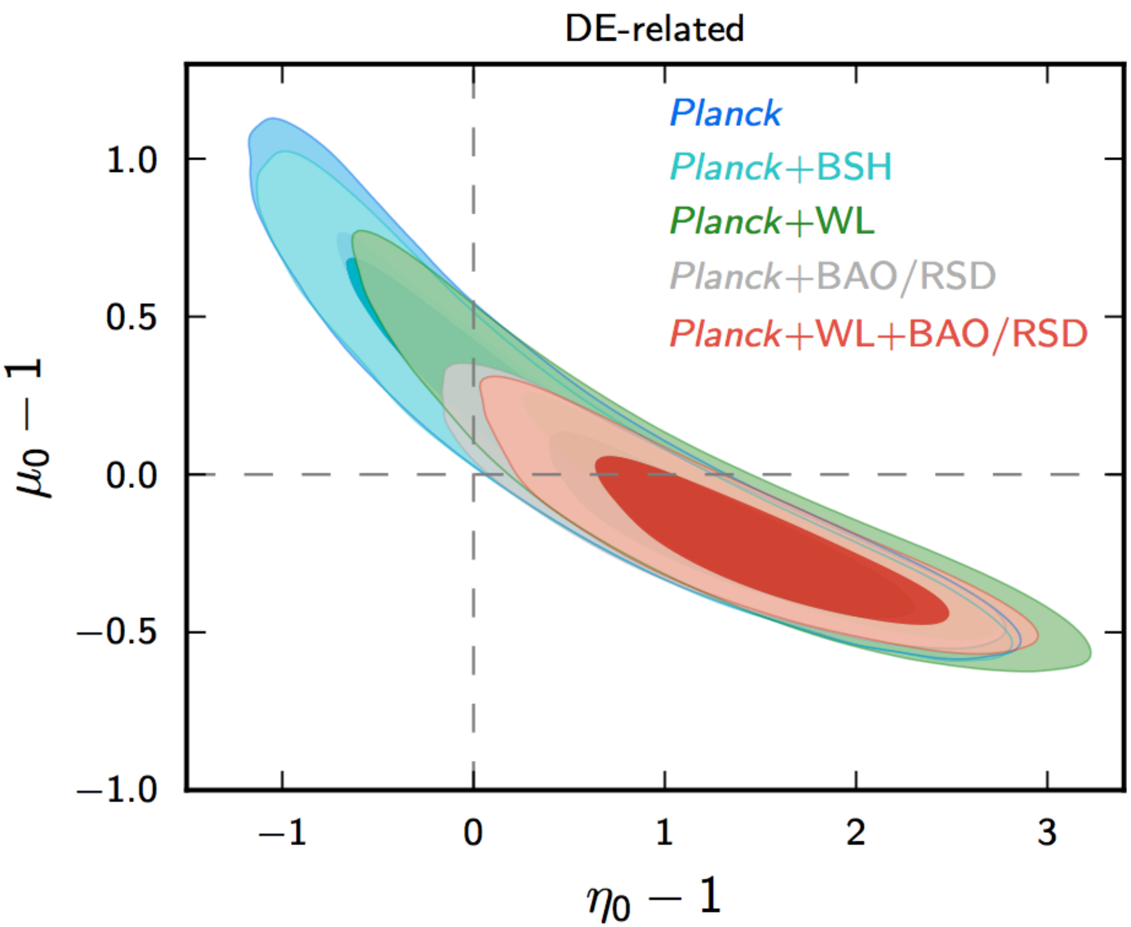
parameterisation of
late-time perturbations:

$$-k^2\Psi \equiv 4\pi G a^2 \mu(a, \boldsymbol{k}) \rho \Delta$$

$$\eta(a, \boldsymbol{k}) \equiv \Phi/\Psi$$

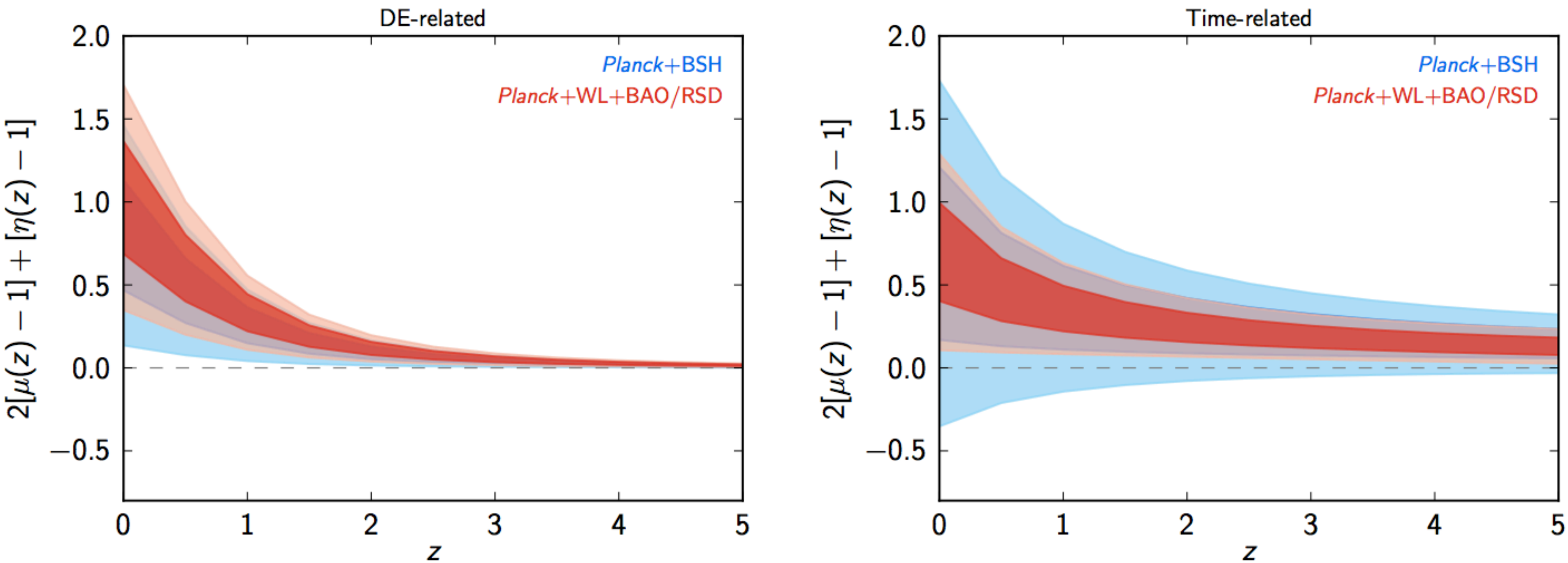
functions ~ $\Omega_{DE}(a)$
ΛCDM background

- no scale dependence detected
- deviation driven by CMB and WL



esa

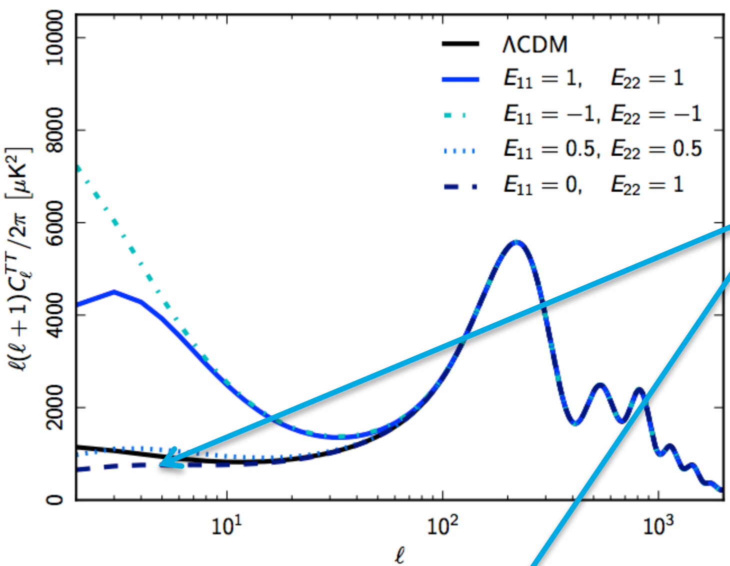
evolution of deviation

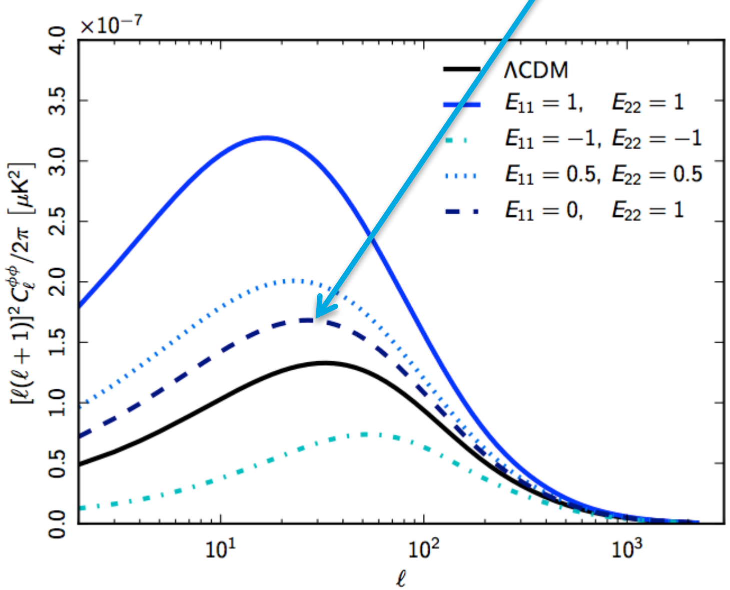


DE related parameterization:

- ΔX^2 = -6.3 (Planck TT+lowP)
- ΔX^2 = -10.6 (Planck TT+lowP+WL)
- ΔX^2 = -10.8 (Planck TT+lowP+WL+BAO/RSD)
- roughly 3σ when projected on single combination

MG impact on observables



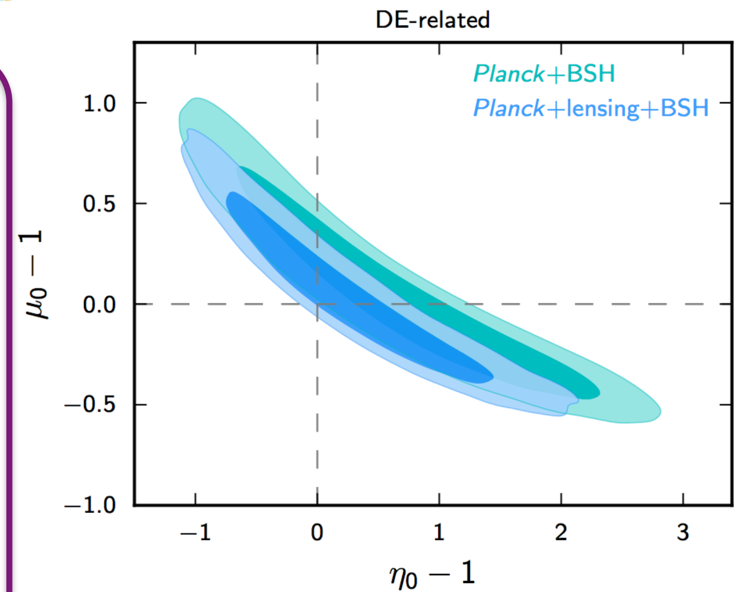


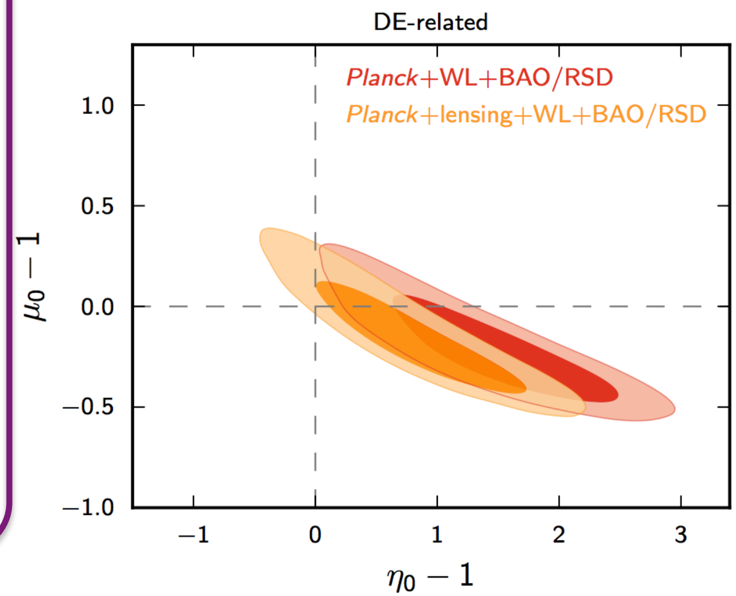
best-fit model is similar to -- model

CMB data prefers lower low-l value and higher lensing in TT

BUT NOT in the 4-point lensing → CMB lensing prefers LCDM!

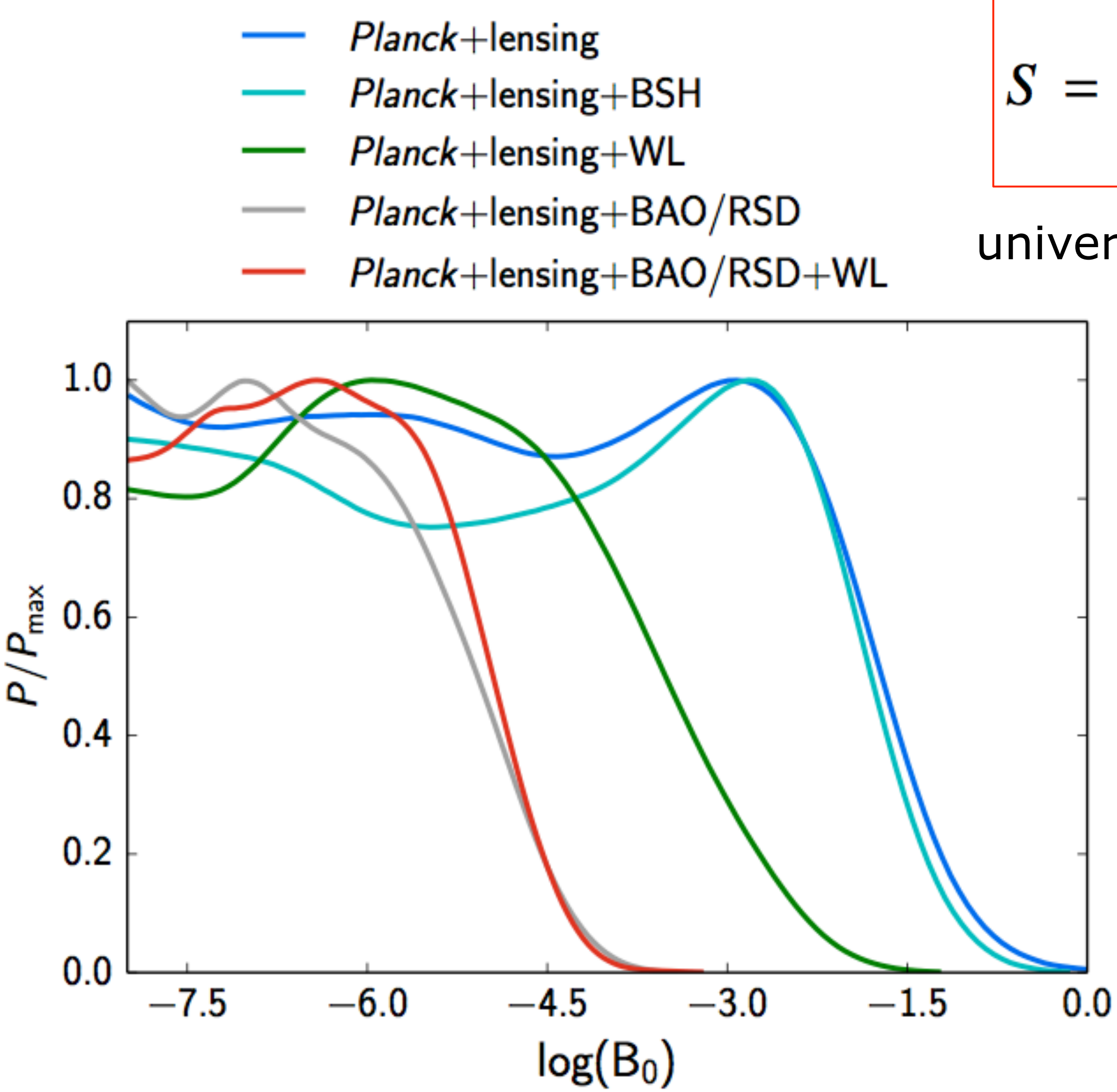
→ doesn't look very significant after all ☺





f(R) models

planck



$$S = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}(R + f(R))$$

universal but non-minimal coupling

LCDM background

$$B(z) = \frac{f_{RR}}{1+f_R}\frac{H\dot{R}}{\dot{H}-H^2}$$

4 orders of magnitude improvement from RSD!

best limit:
TT+lowP+lensing+WL
+BAO/RSD
$B_0<0.8\times10^{-4}$ (95% CL)

coupled quintessence

coupling strength β only to CDM
→ no screening mechanism
→ non-universal coupling

Planck+BSH give 2.5σ tension with LCDM

but no improvement in X²!
→ volume effect from marginalisation?