BICEP2 and implications for inflation and dark energy

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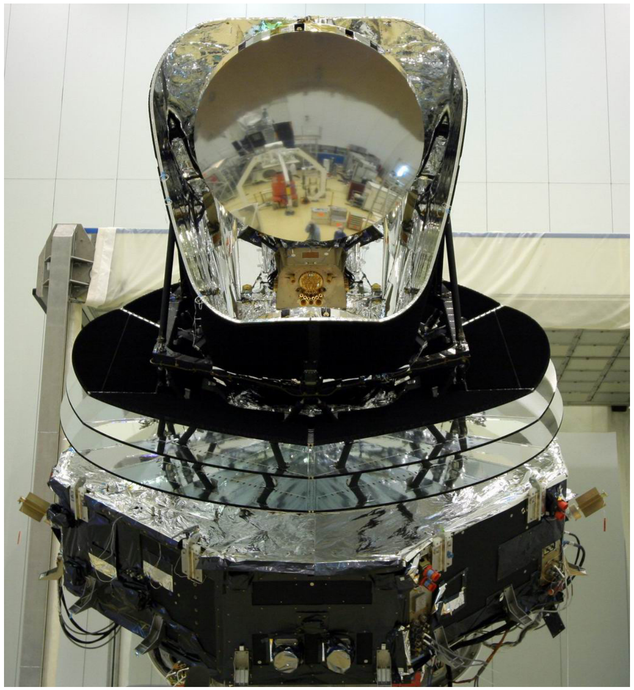
on behalf of the Planck Collaboration

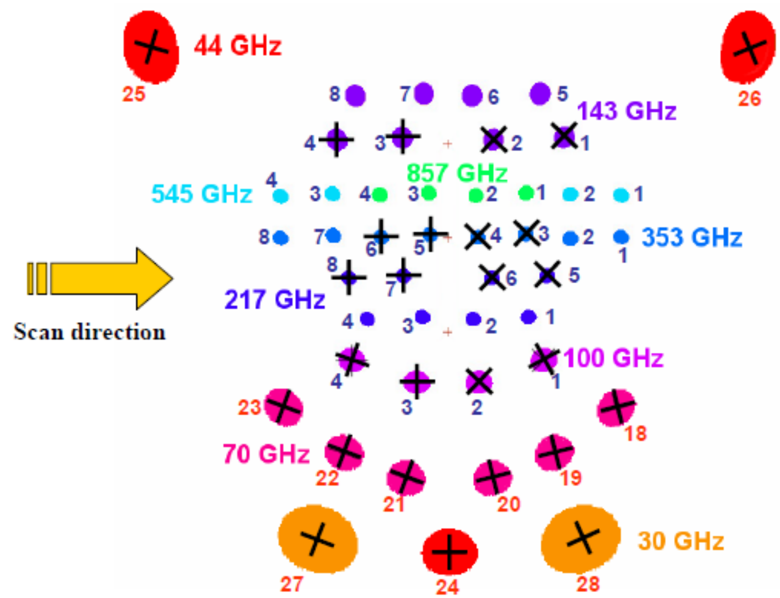
UNIVERSITÉ DE GENÈVE

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.

Planck: a microwave telescope

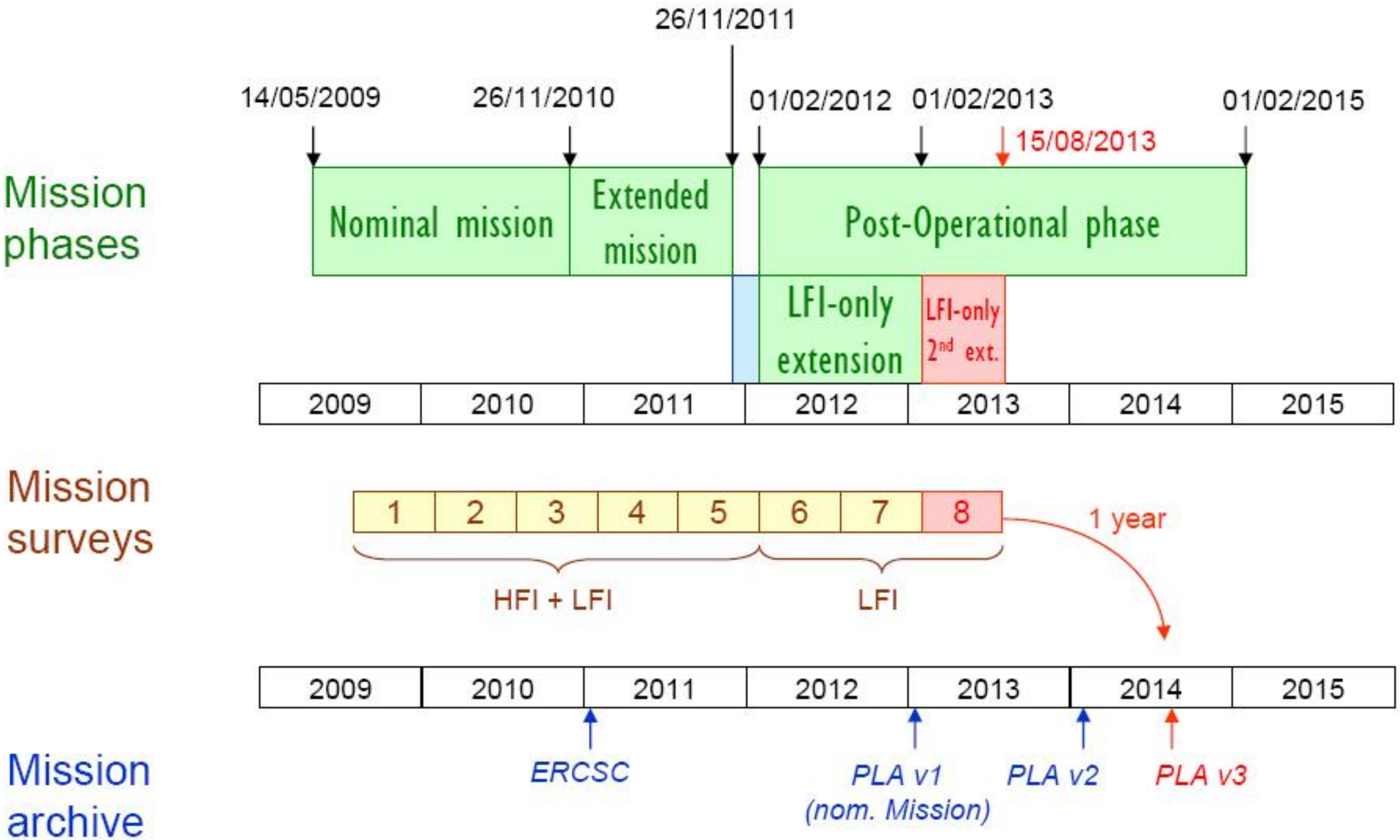




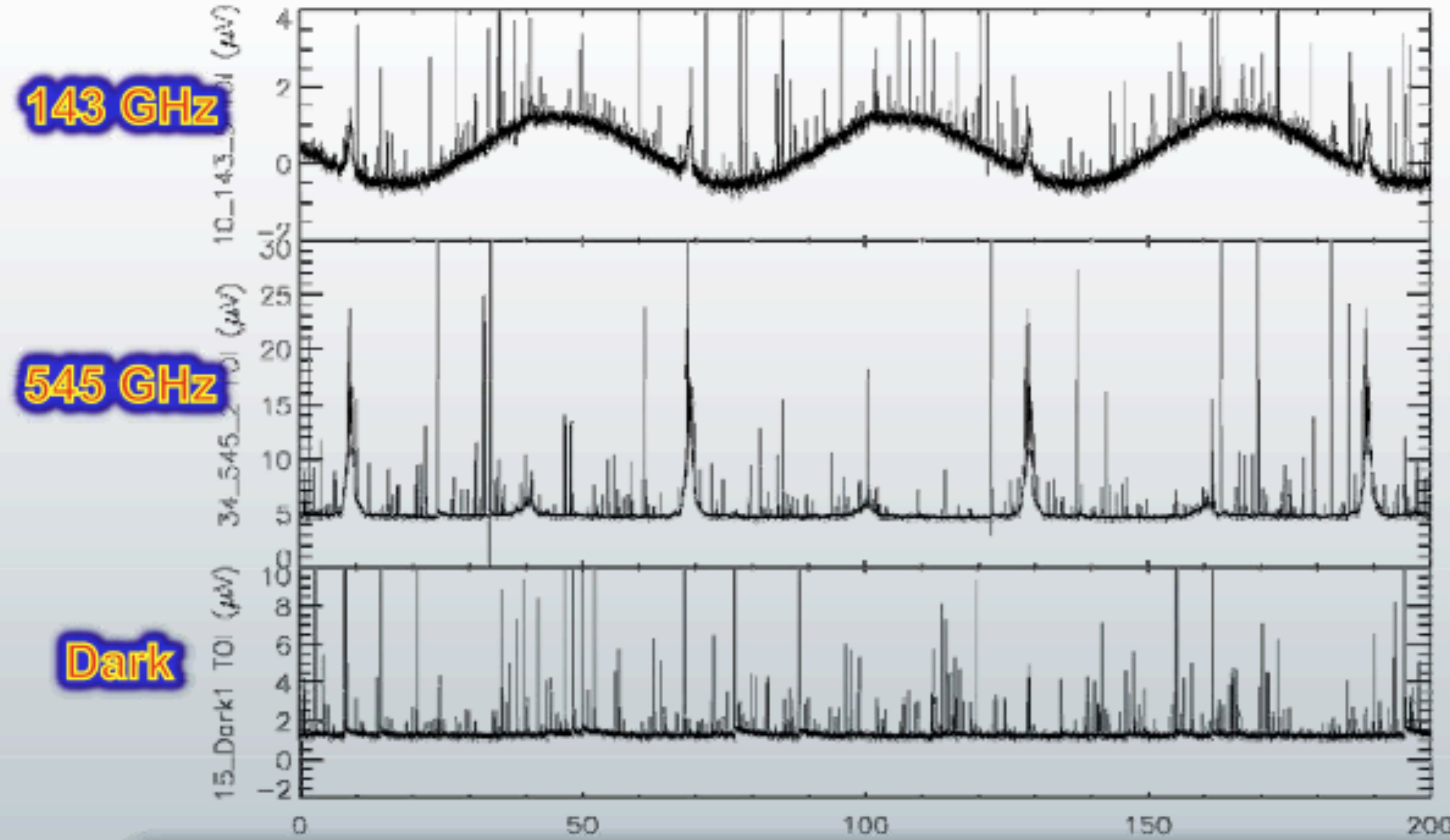
PLANCK	LFI			HFI					
Center Freq (GHz)	30	44	70	100	143	217	353	545	857
Angular resolution (FWHM arcmin)	33	24	14	10	7.1	5.0	5.0	5	5
Sensitivity in I [μK.deg] [$\sigma_{pix}\ \Omega_{pix}^{1/2}$]	2.7	2.6	2.6	1.0	0.6	1.0	2,9		
Sensitivity in Q or U [μK.deg] [$\sigma_{pix}\ \Omega_{pix}^{1/2}$]	4.5	4.6	4.6	1.8	1.4	2.4	7.3		

operational timeline

planck



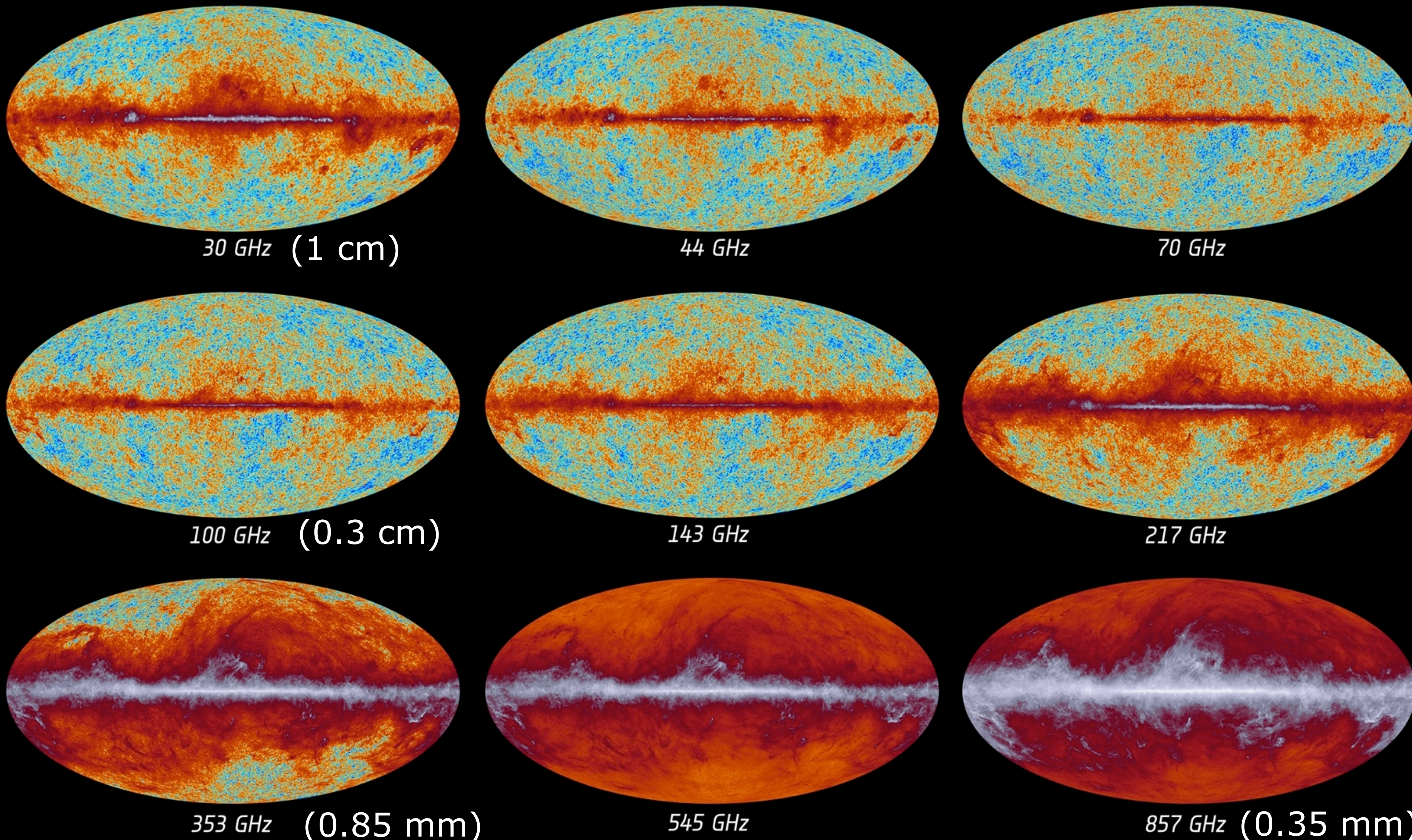
(nearly) raw data stream



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.

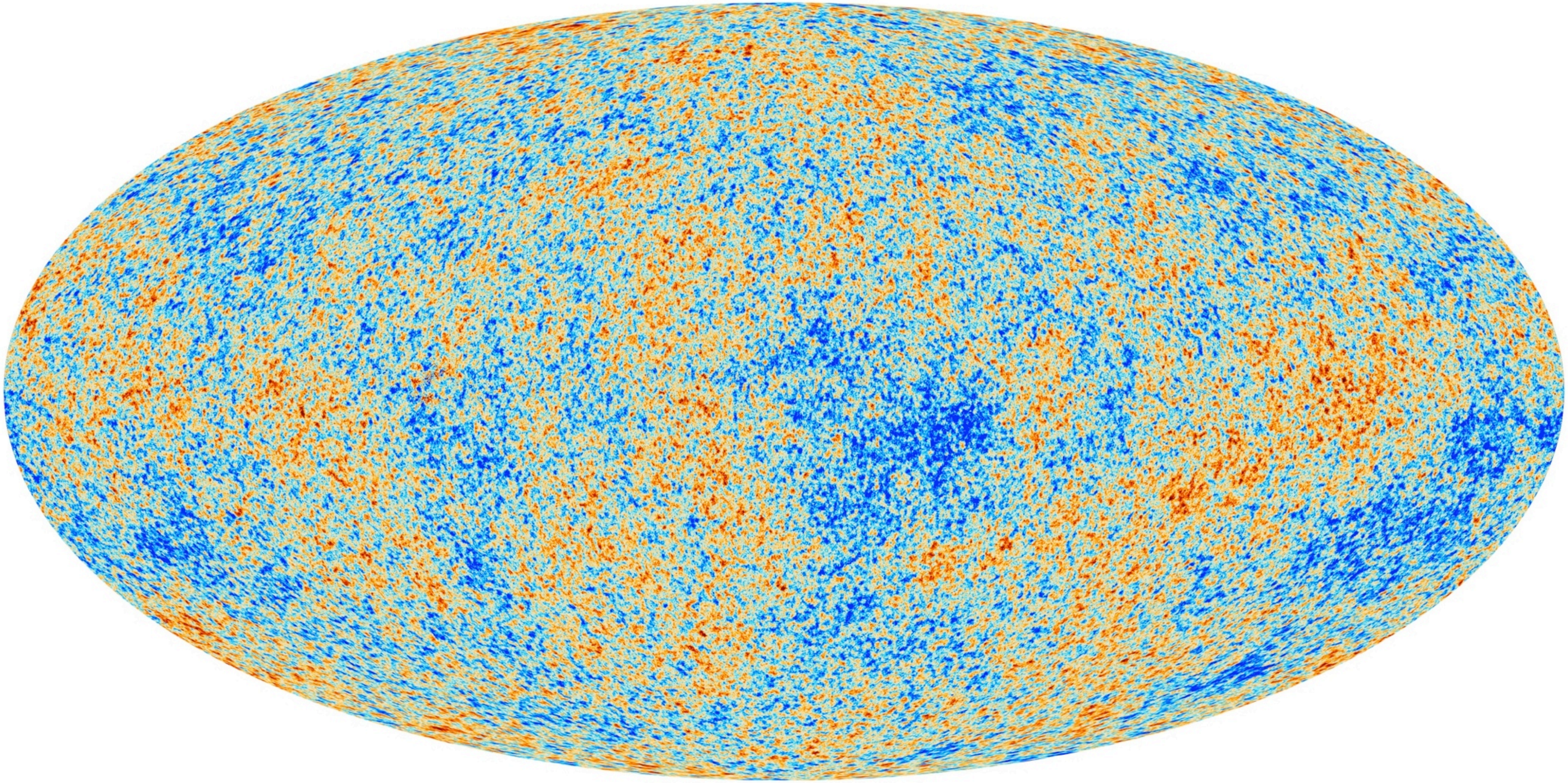
The sky seen by Planck

planck

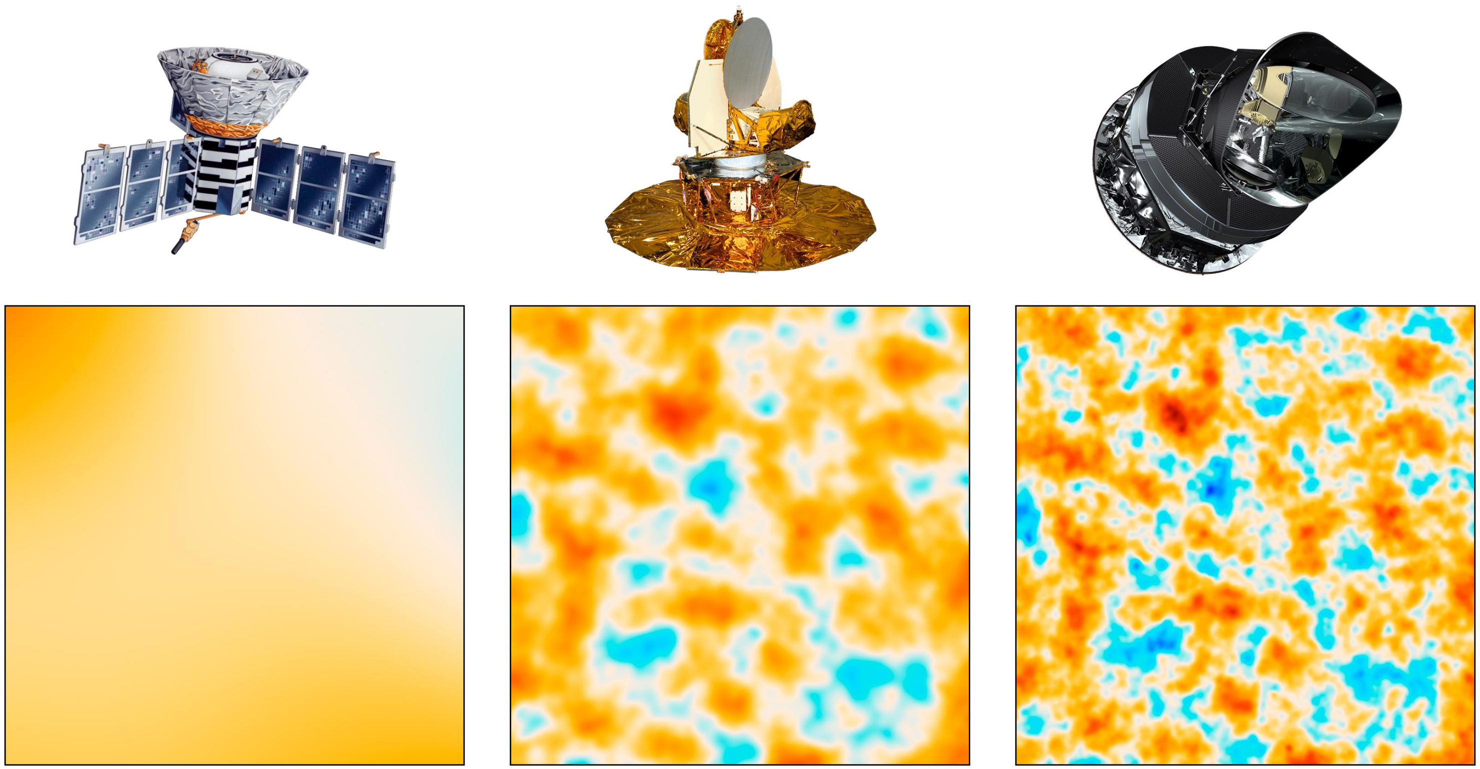


the Planck CMB map

‘SMICA’ CMB map (central 3% replaced w/ constrained realization)



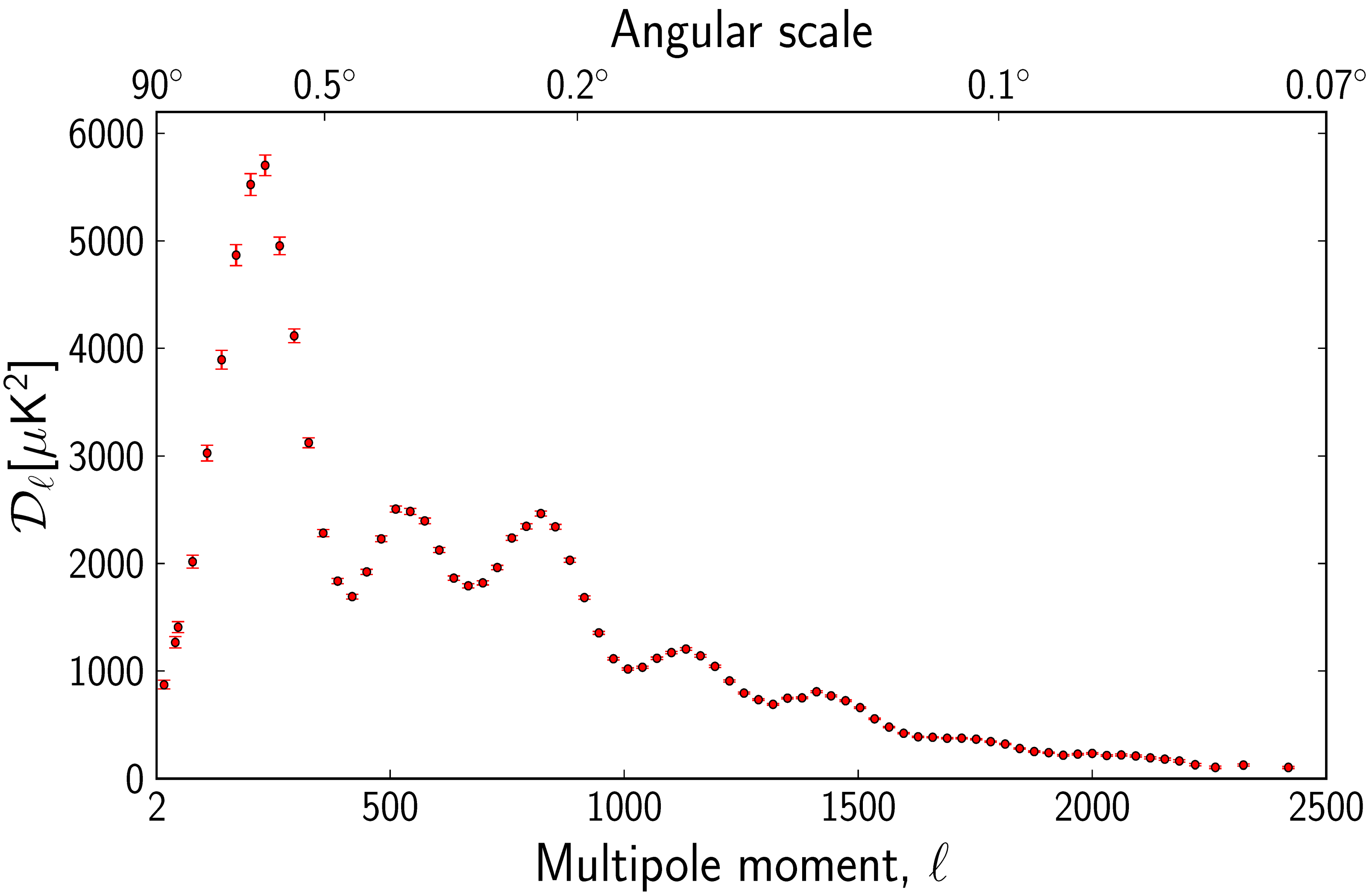
Planck: 3rd generation CMB satellite



COBE WMAP Planck

- Planck meets or exceeds goals ('blue book')
- improves on WMAP by a factor of 3 in angular resolution and 25 in instantaneous sensitivity

the Planck CMB power spectrum



Planck (or Planck+WP)

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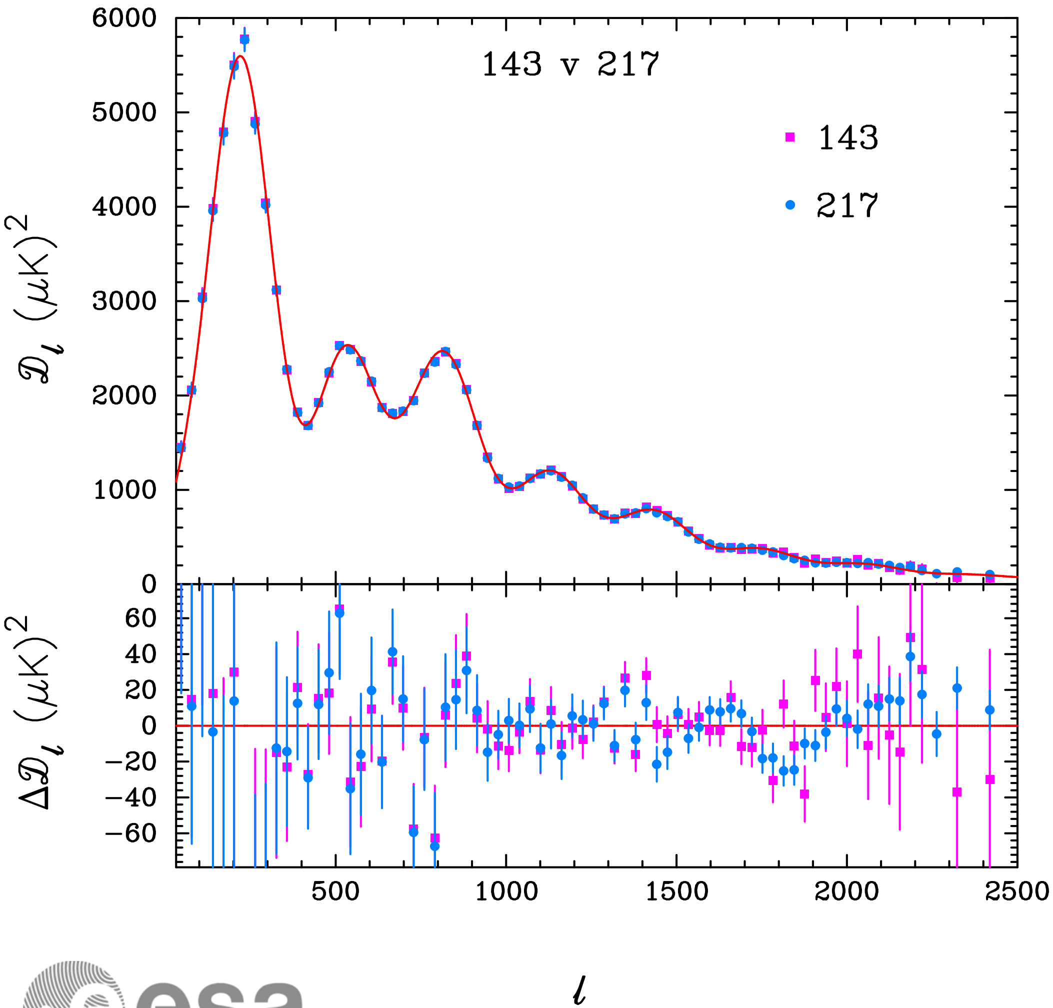
Planck spectrum vs ΛCDM model



red curve:
best fit 6-parameter ΛCDM model

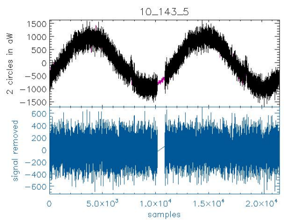
goodness of fit:

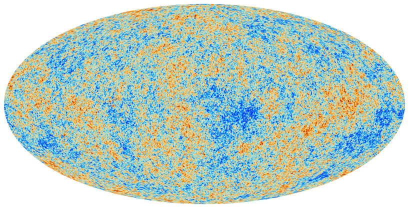
Spectrum	ℓ_{min}	ℓ_{max}	χ^2	χ^2/N_ℓ	$\Delta\chi^2/\sqrt{2N_\ell}$
100×100	50	1200	1158	1.01	0.14
143×143	50	2000	1883	0.97	−1.09
217×217	500	2500	2079	1.04	1.23
143×217	500	2500	1930	0.96	−1.13
All	50	2500	2564	1.05	1.62

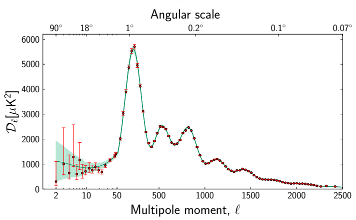
(no known model extension fits significantly better)

extreme compression!

planck







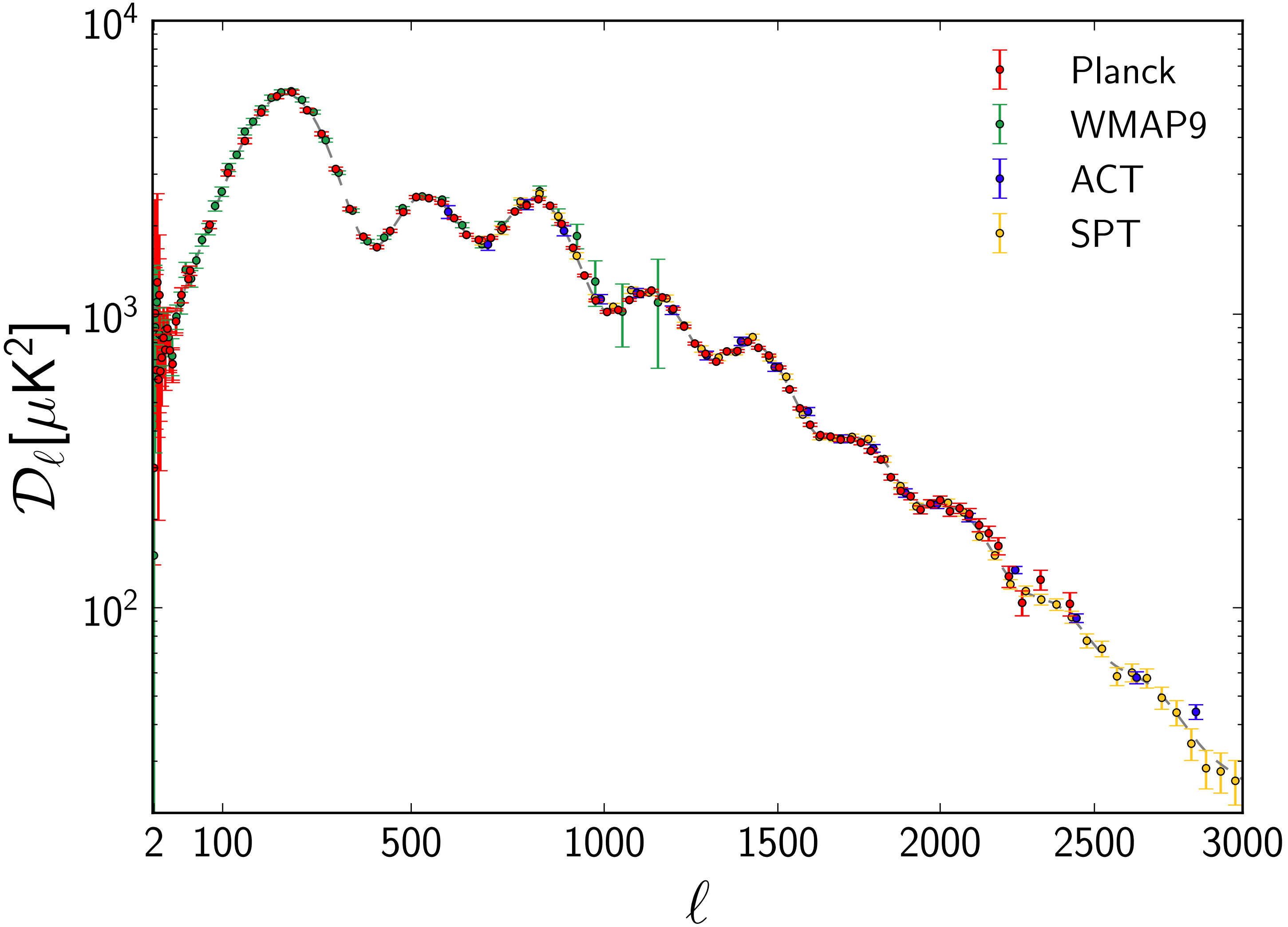
$\{\Omega_b,\Omega_\Lambda,H_0,A_s,n_s,\tau\}$

1. science samples: 530’632’594’653 (991’929’524’565 for full mission), a few terabytes
2. maps: ca 50 mega-pixels, compression 10’000:1
3. power spectrum: ca 2500 values, compression 20’000:1
4. model: 6 parameters, compression 400:1

total compression ca 10^{11}:1 !

(nearly 10^7:1 from map)

The full CMB power spectrum



Planck + WP + highL

Implications and outlook

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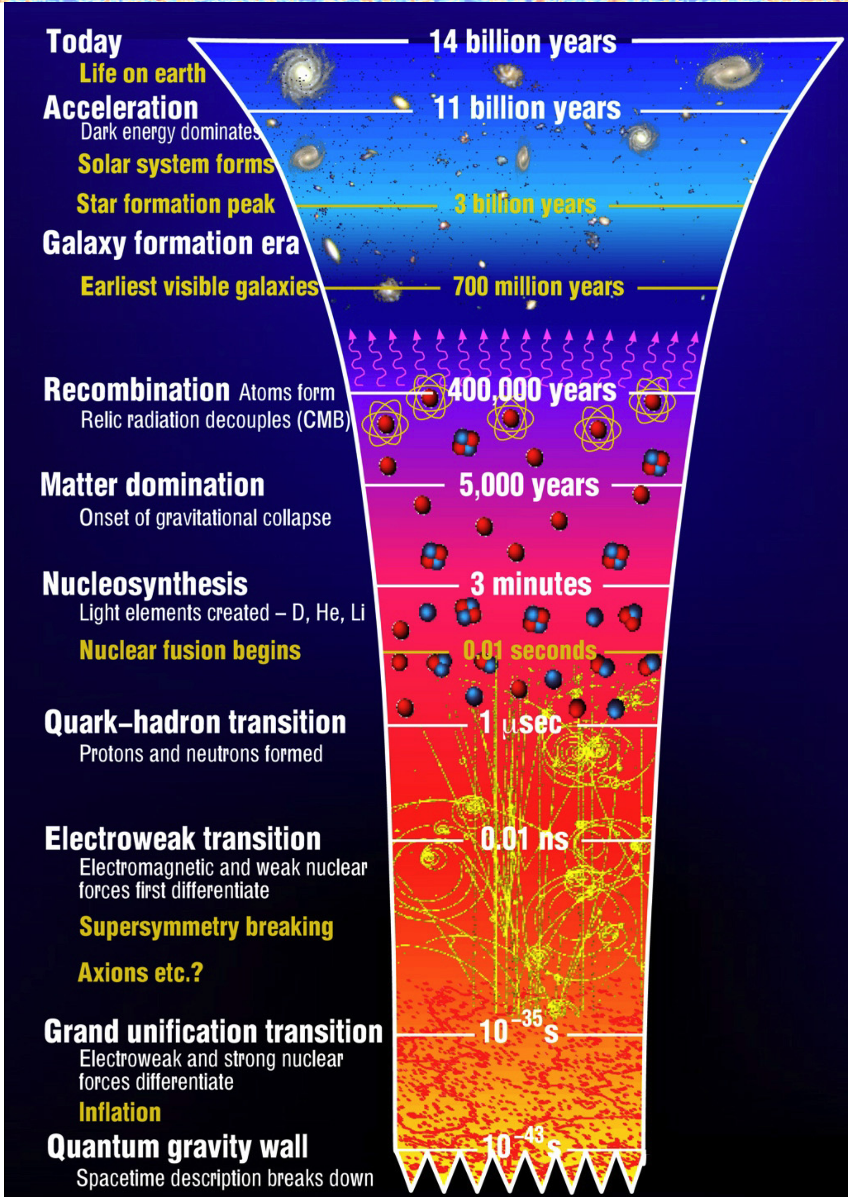
1. Parameter constraints from Planck
2. Beyond flat ΛCDM
   - curvature
   - dark energy
3. Looking into the fireball
   - formation of the light elements
   - neutrinos and N_{eff}
   - inflation
4. beyond Planck: BICEP2
5. outlook & conclusions



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The flat ΛCDM Universe

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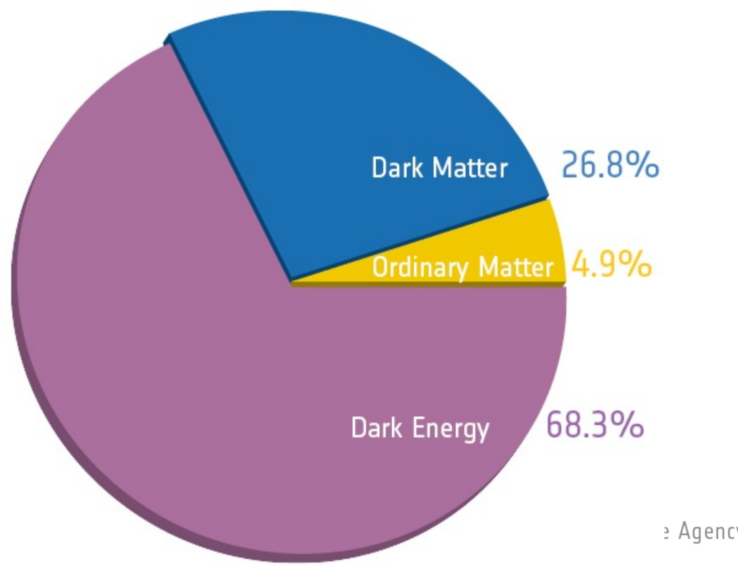
(T_{CMB} = 2.7255±0.0006K [COBE])

Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027 (2.3%)
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10}A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$ (2.5%)
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$
σ_8	0.8347	0.829 ± 0.012
z_{re}	11.37	11.1 ± 1.1
H_0	67.04	67.3 ± 1.2
Age/Gyr	13.8242	13.817 ± 0.048
$100\theta_*$	1.04136	1.04147 ± 0.00062
r_{drag}	147.36	147.49 ± 0.59

← looking back to the first few minutes, 1.3% precision ($\Omega_b h^2$)

← 0.06% precision on angular scale ($100\theta_{MC}$)

← 5.4σ detection (see later) (n_s)



weighing mass with light

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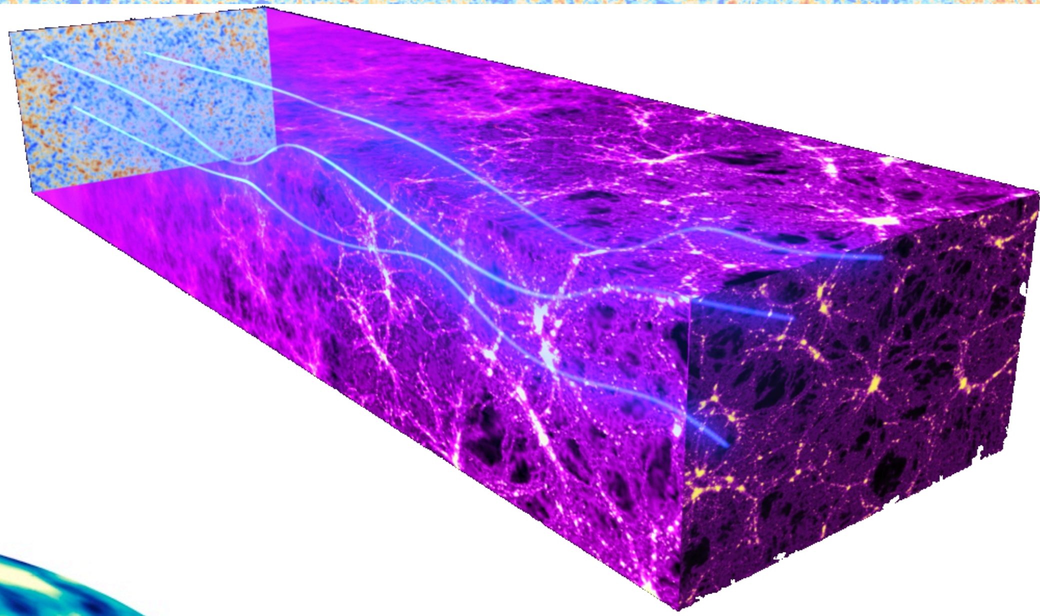
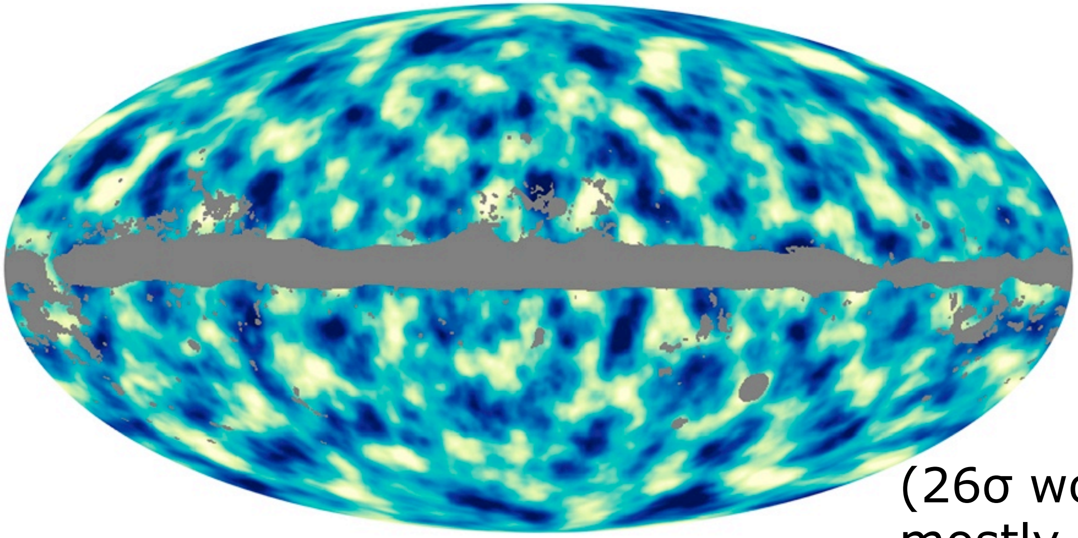
Gravity deflects light, including the CMB photons.

This modifies the CMB pattern subtly: we see the matter in the universe in front of the CMB backlight!





(Nearly) all the structure in the universe!

(26σ worth of signal, so we see mostly noise, but 10-20σ correlation with LSS and 42σ with CIB)

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Is space really flat?

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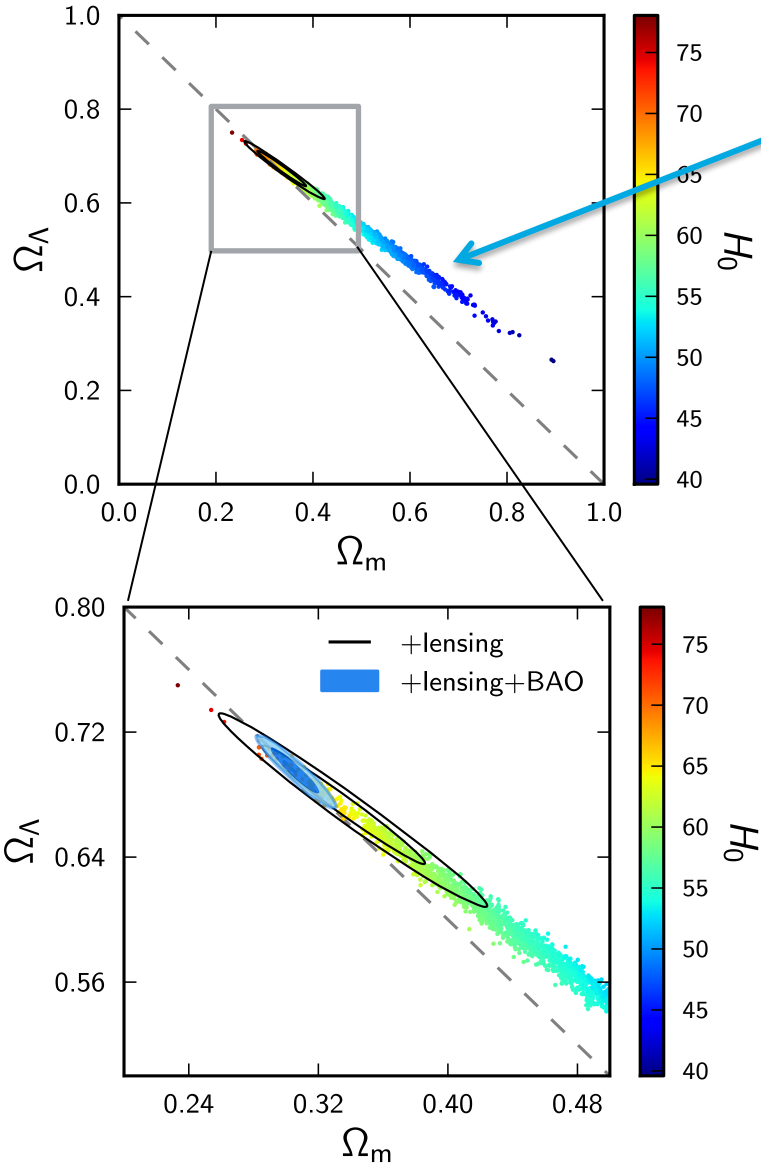

The 0.06% precision measurement of the sound horizon scale at last scattering gives us a known ruler!

A single measurement only gives one constraint → *geometric degeneracy*

The models in the tail have a higher lensing signal, and so CMB lensing breaks partially the geometric degeneracy, allowing us to rule out $\Lambda=0$ and constrain Ω_k at the percent-level with CMB data alone.

(first done by ACT/SPT in 2011/12)

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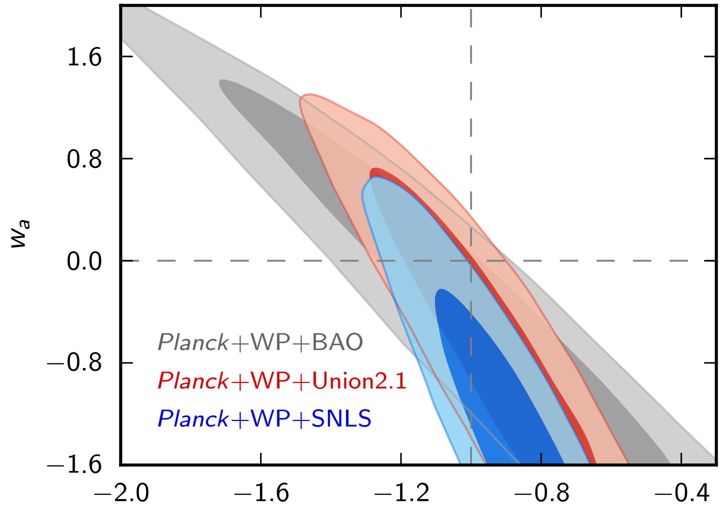
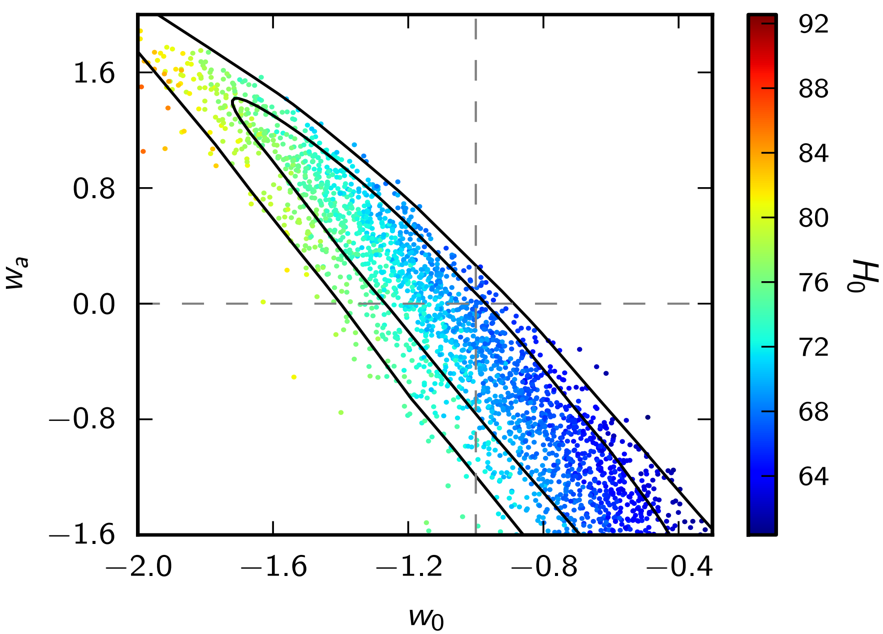
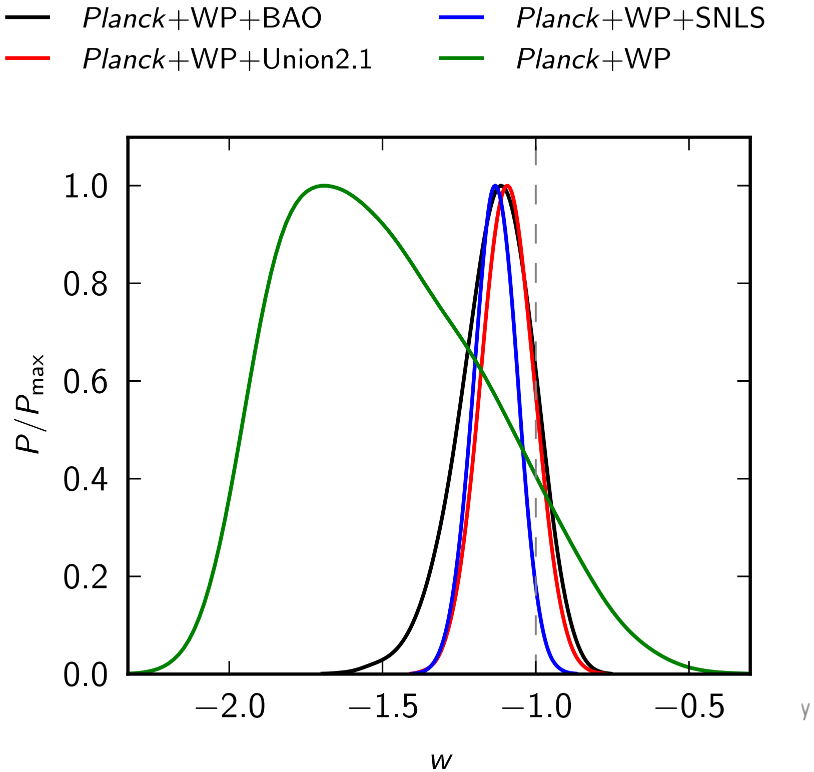
Planck & Dark Energy



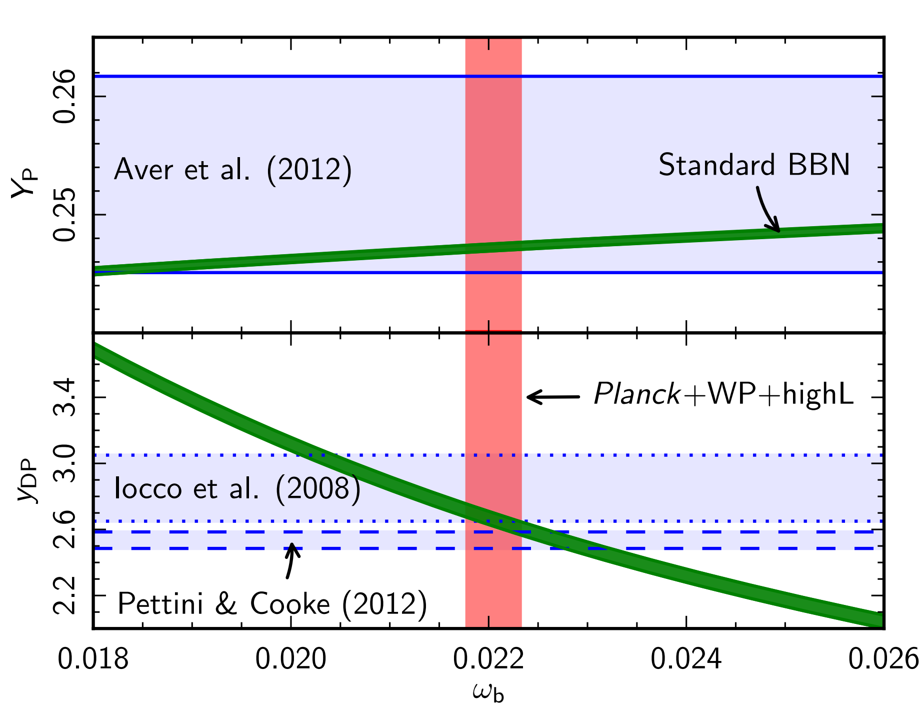
Planck is not the perfect DE experiment (that's why are working on Euclid) – but all DE experiments need Planck ☺

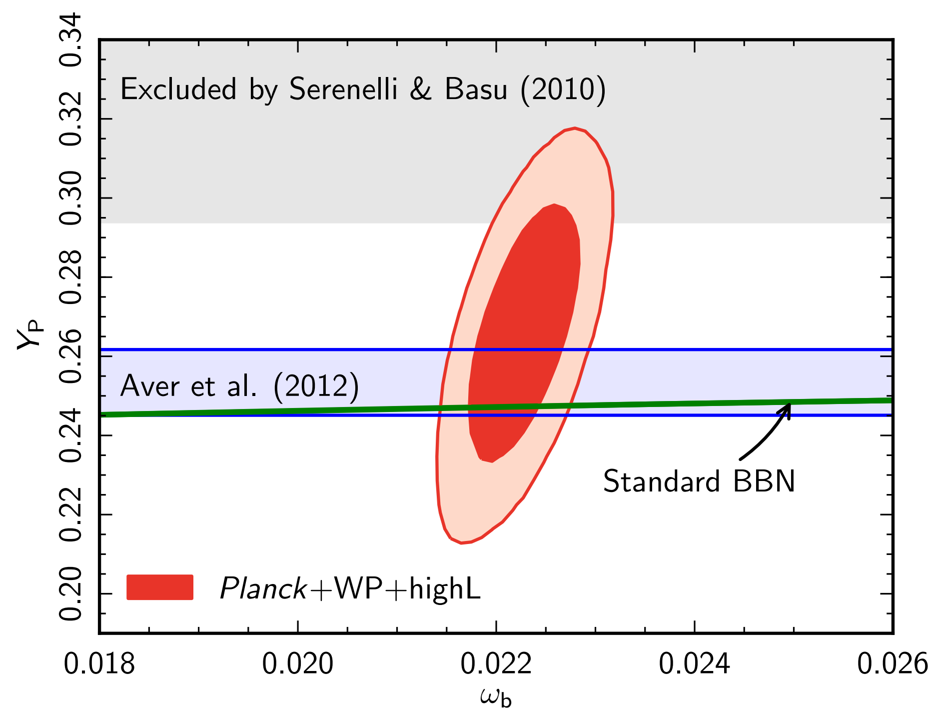




Looking into the fireball, back to the first three minutes

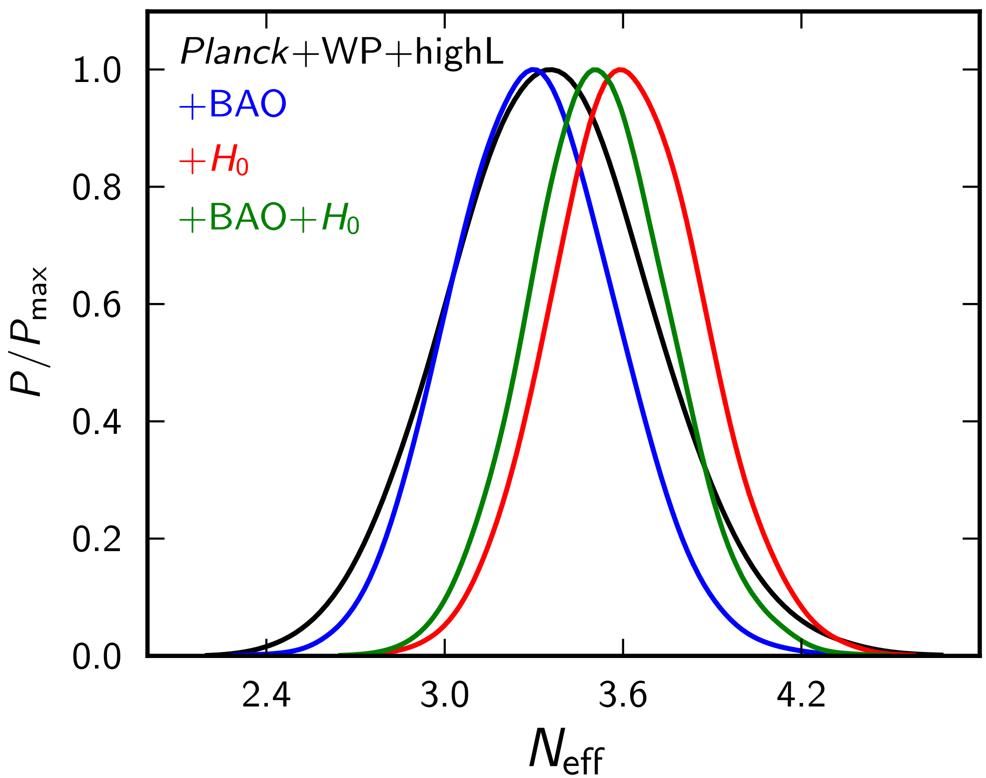
- at high energies the nuclei of heavier elements are kicked apart by the high energy photons, they can only form at ~ 0.1 MeV
- final abundance depends strongly on #baryons/#photons
- CMB measures both, so can compare to direct observations!

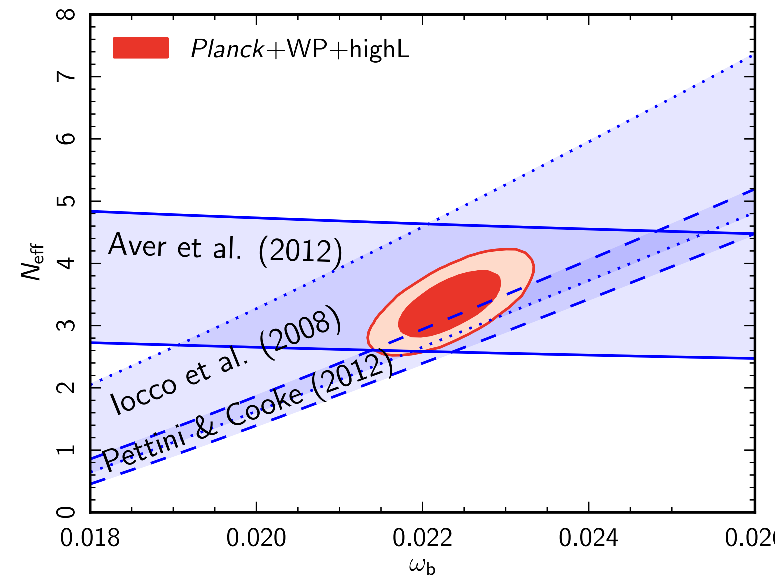


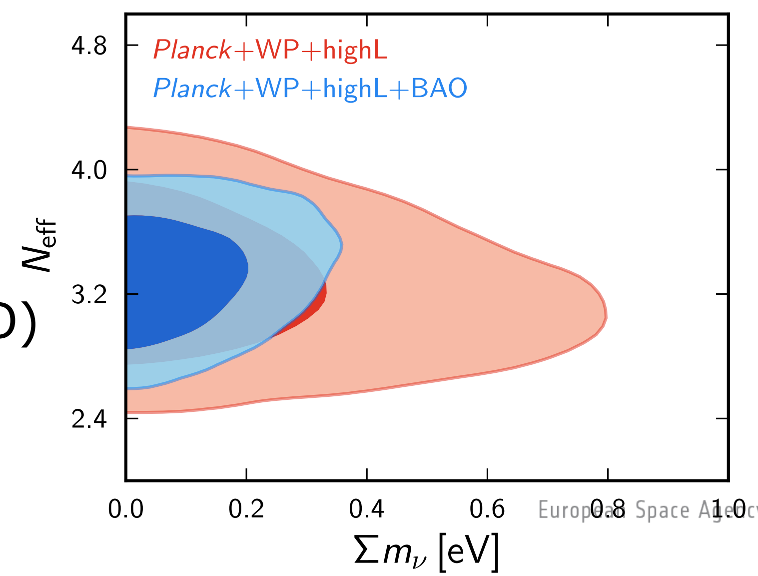


N_{eff} (or 'dark radiation')

planck







N_{eff} = 3.36±0.68 (95%, Pl+WP+hL)
3.30±0.54 (95%, Pl+WP+hL+BAO)
3.62±0.50 (95%, Pl+WP+hL+H_0)

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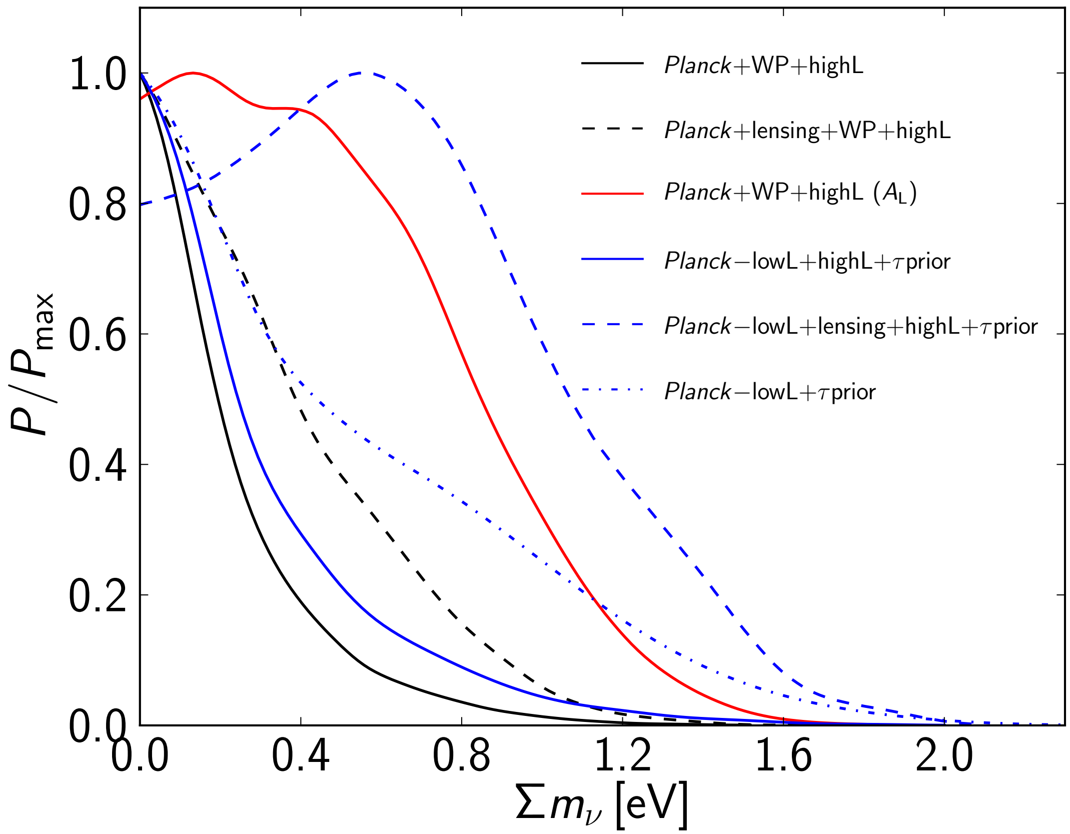
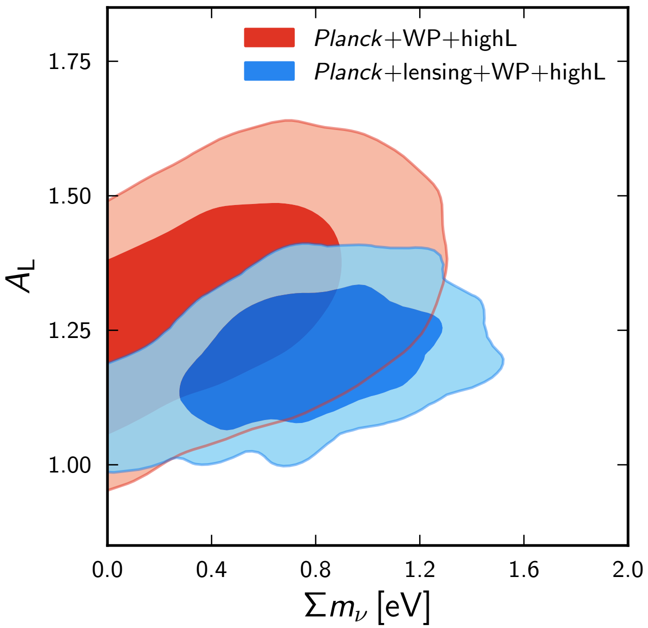
neutrinos





(A_L: lensing impact on power spectrum)

Limits on Σm_ν at 95%:

Limits on Σm_ν at 95%:	<0.66 eV	(Planck+WP+highL)
	<1.08 eV	(same, but marg. AL)
	<0.85 eV	(Planck+lensing+WP+highL)
	<0.23 eV	(Pl+WP+hL+BAO)

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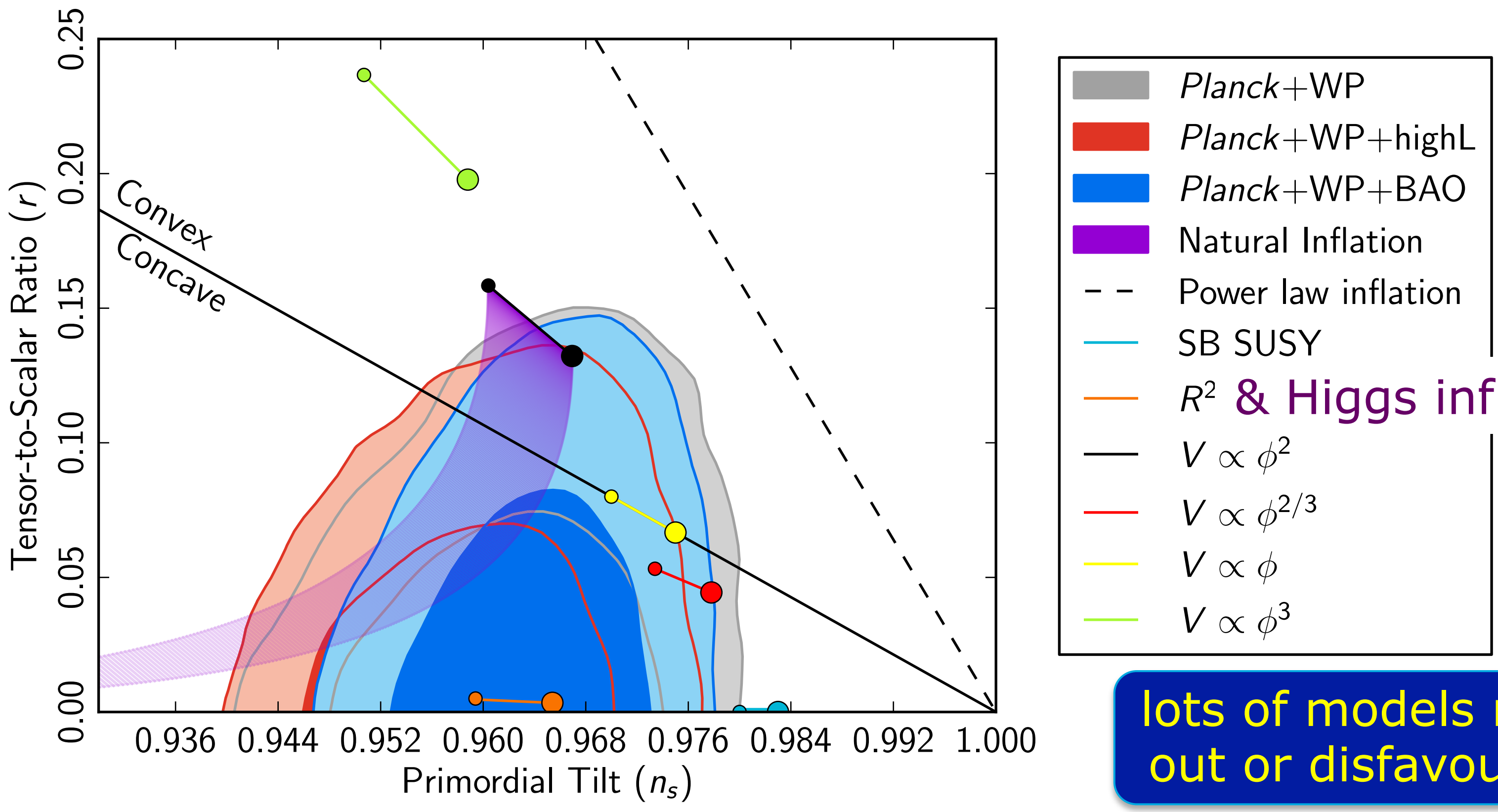
probing the first 10^{-xx} seconds…

Generic predictions of inflation:

- ✔ flat space
- ✔ nearly (but not quite) scale invariant perturbations (→ n_s)
- ✔ nearly Gaussian perturbations on all scales
- ? Gravitational waves (tensor perturbations → r parameter)



& Higgs inflation

lots of models ruled out or disfavoured!

probing inflation more deeply

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(probes interactions)

$n_s \neq 1$
no running
no features

exact shape of power spectrum

non-Gaussian perturbations

no detection
$f_{NL}[\text{local}] = 2.7 \pm 5.8$

no detection
$r < 0.11$

primordial gravitational waves

phase transition remnants (cosmic strings)

no detection
$f_{10} < 0.01$
(NG strings)

$V_* < (2\text{x}10^{16}\ \text{GeV})^4$

(probes energy scale)

(probes vacuum structure)

$G\mu < 1.3\text{x}10^{-7}$
(NG strings)

Constraints start to cut deeply into inflation parameter space!

‘standard’ bispec amplitudes

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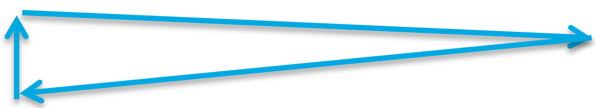
KSW: matched bispectrum filter

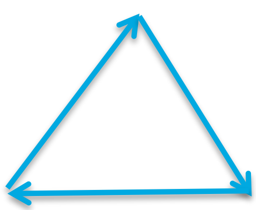
f_{NL}: amplitude parameter

main shapes:

	Independent KSW	ISW-lensing subtracted KSW
SMICA		
Local	9.8 ± 5.8	**2.7 ± 5.8**
Equilateral	−37 ± 75	**−42 ± 75**
Orthogonal	−46 ± 39	**−25 ± 39**

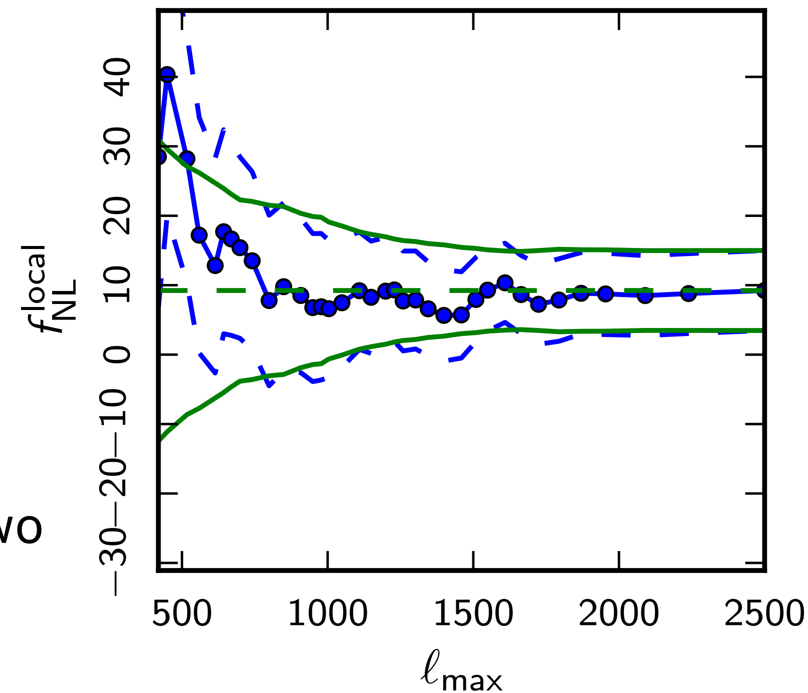


local
$k_1 << k_2, k_3$
multi-field



equilateral
$k_1 \sim k_2 \sim k_3$
non-canonical kinetic term

orthogonal: different from the other two



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Results summary

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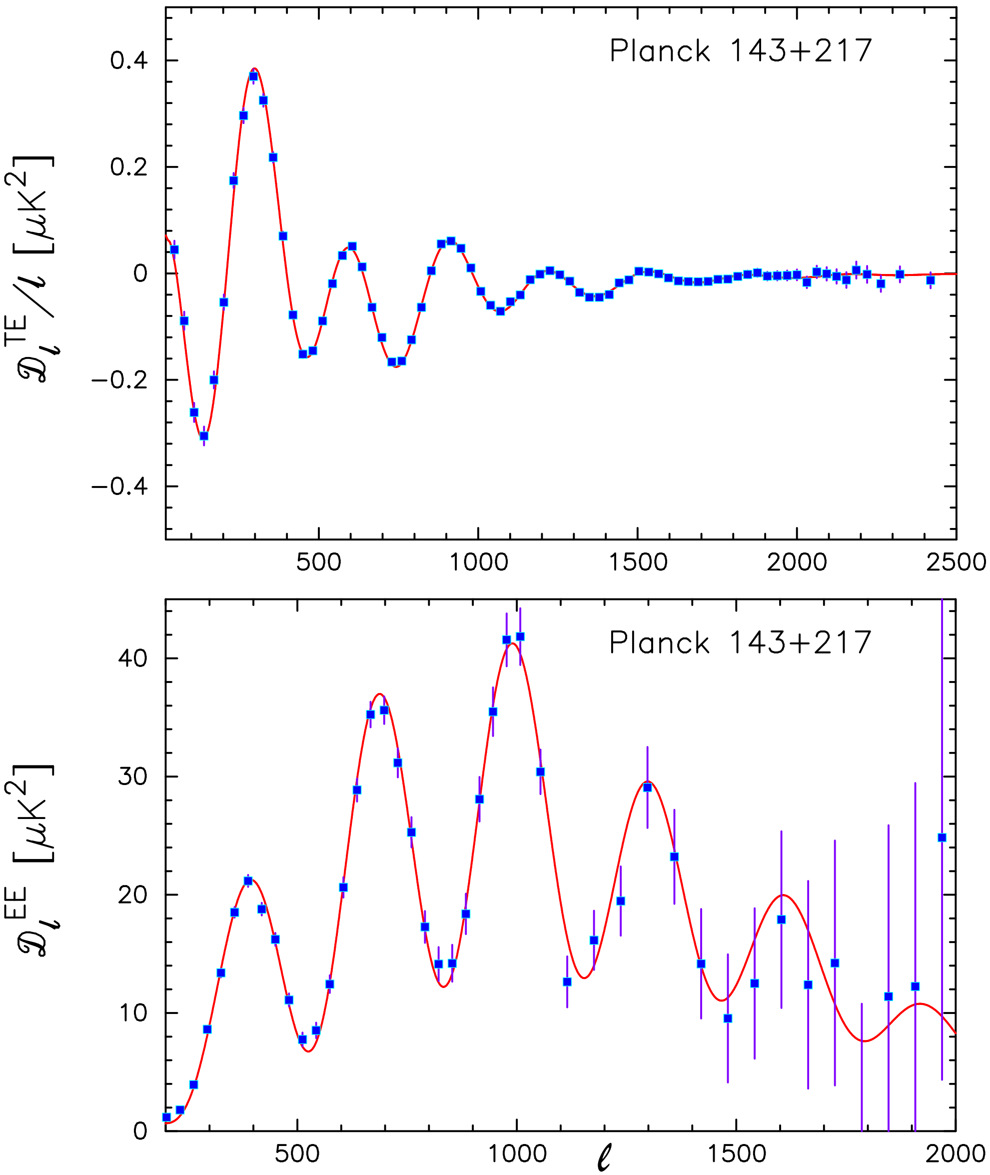
Planck nominal mission data (15.5 months, data available):

- stunning confirmation of ΛCDM 'standard model' (a few anomalies, but imnsho nothing to get too excited about at this point)
- composition: 5% normal matter, 27% dark matter, 68% dark energy
- BBN very consistent with theory and other measurements
- no extra light d.o.f. detected, N_{eff} <~ 4 at 95%
- neutrino mass constraints m_ν <~ 0.66 eV at 95%
- no sign of sterile neutrinos (but also not excluded if heavy enough or not thermalized), varying constants or decaying dark matter
- inflation: no gravitational waves, non-Gaussianity or phase-transition remnants detected, primordial power spectrum compatible with pure power law with index ns = 0.960±0.007

October 2014: full mission data set (29 months) + polarization!

Planck polarisation teaser



The Planck polarization data is excellent except on very large scales where we still have to clean it better.

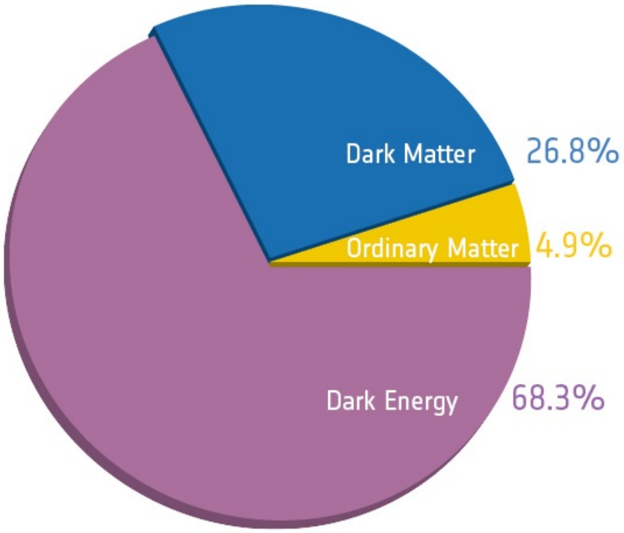
The red line is not a fit to the polarization data, but the predicted curve from the temperature data and the ΛCDM model!

Planck summary & outlook

planck

Things that worked:

1. the ***definitive*** temperature CMB data set for cosmology
2. amazing (unreasonable?) agreement with the flat **ΛCDM** model
3. no contradictions with **inflation** scenario (and detection of $n_s \neq 1$)
4. incredibly good constraints on model parameters, e.g.
   - age: 13.82±0.05 Gyr
   - curvature: $\Omega_k = -0.01 \pm 0.01$
   - sum of neutrino masses* < 0.23eV

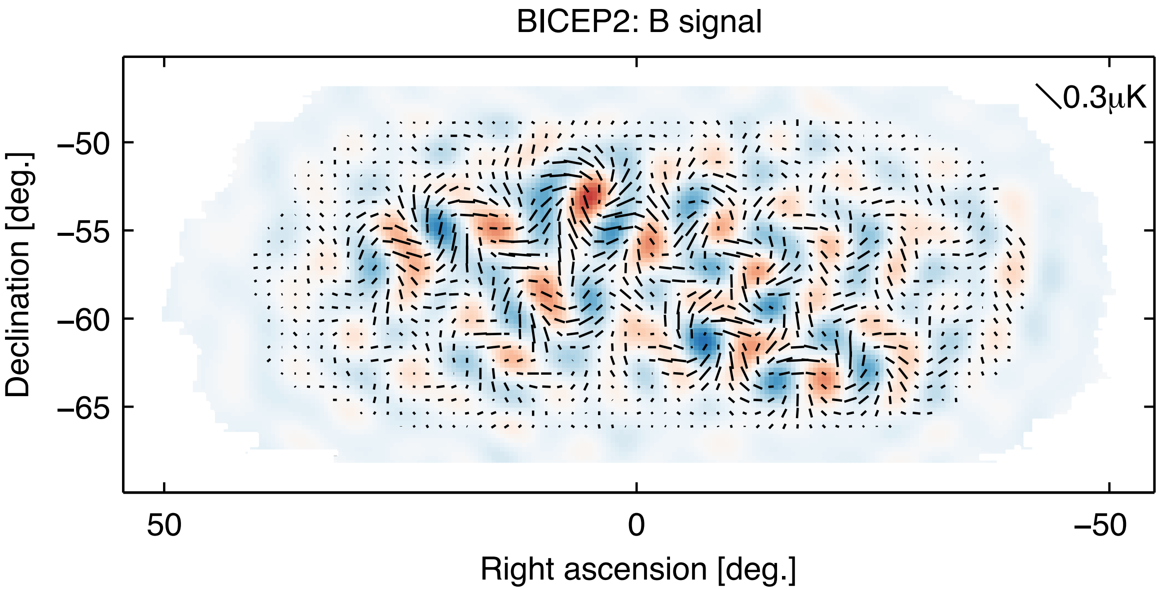


Things that still need work:

1. polarization data
2. funny anomalies on large scales
3. the other topic you are all waiting for …

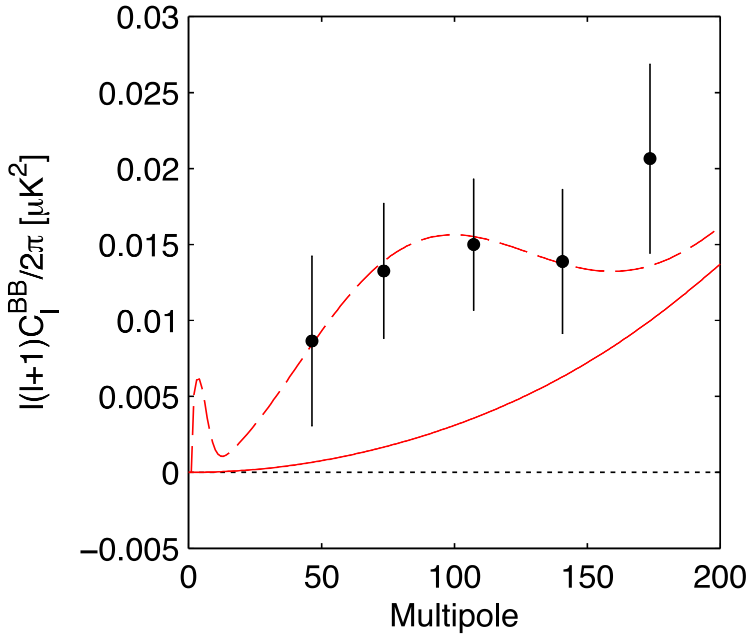
(*: uses extra non-CMB data, limit is 0.85eV else)

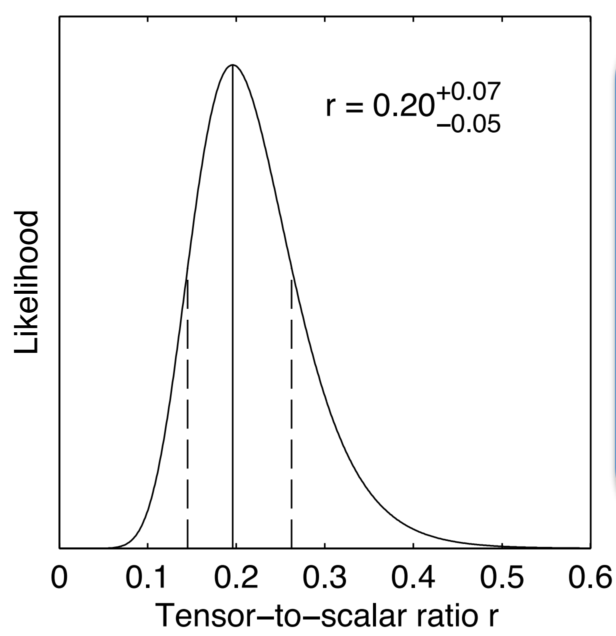
and now for something different



BICEP2 B-modes, arXiv:1403.3985

(since then: >90 papers on arXiv with BICEP2 in title; >200 with BICEP2 in abstract!)

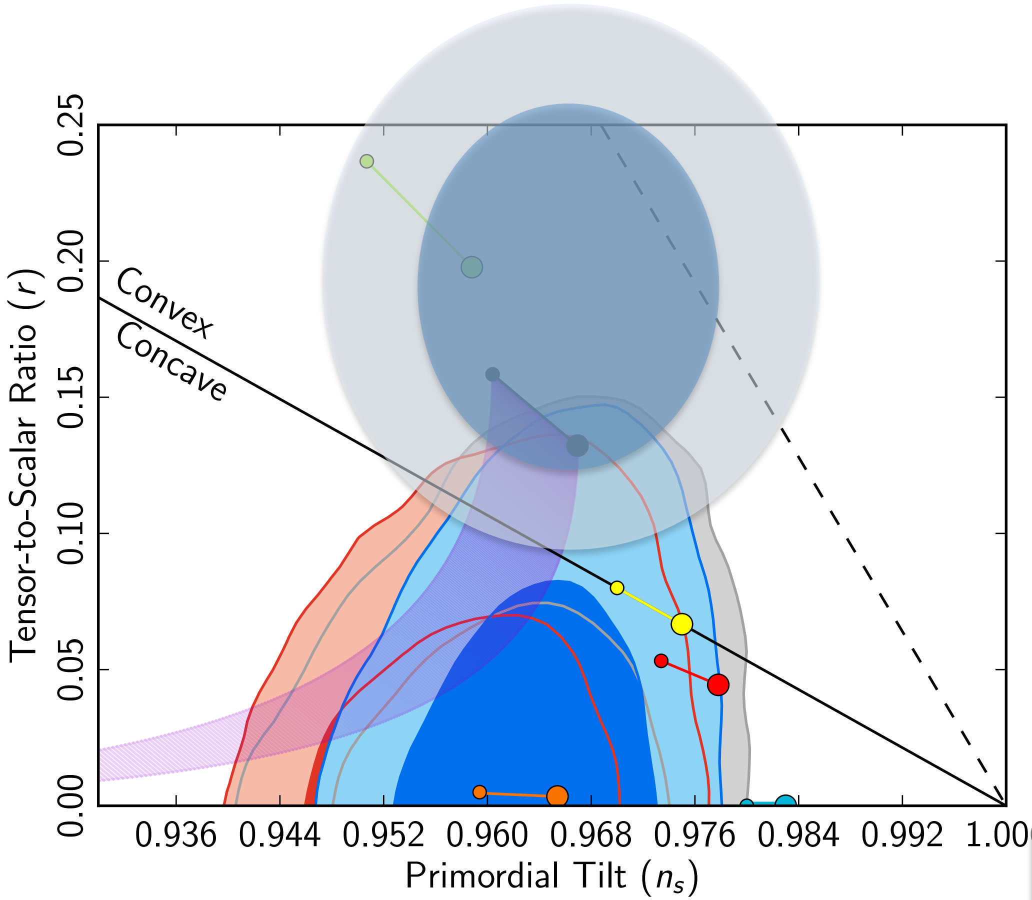




amazing sensitivity!

- what does it mean?
- is it primordial?

BICEP2 and inflation



Primordial tensor waves are expected in all 'inflation-like' models (all light d.o.f. acquire frozen-in quantum fluctuations)

→ **looking back to inflation!**

(other standard parameters only marginally affected when adding BICEP2 to Planck+WP)

$$V_*^{1/4} = 2.1 \times 10^{16} \mathrm{GeV} \left(\frac{r}{0.2}\right)^{1/4}$$

GUT scale

- determines energy scale of inflation, $P_T \sim H_*^2/M_p^2$
- large field excursion, $\Delta\varphi/M_p \sim 10$
- could test consistency relation $r = -8n_T$

caveat 1: likelihood + pivot

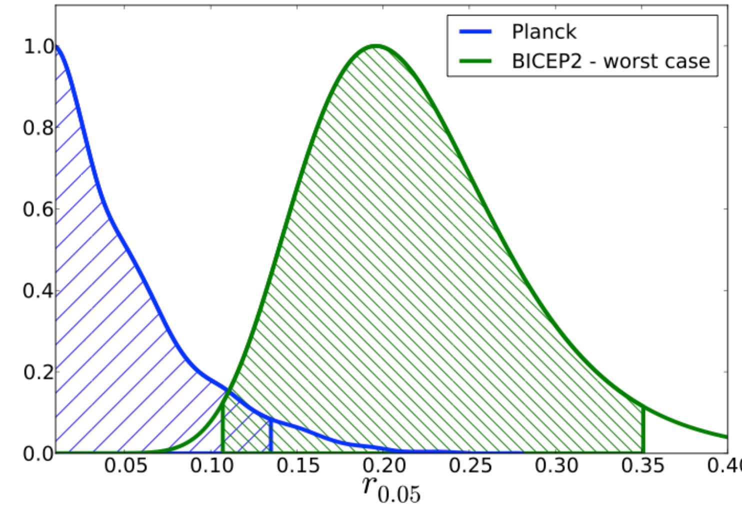
Audren, Figueora & Tram, arXiv:1405.1390

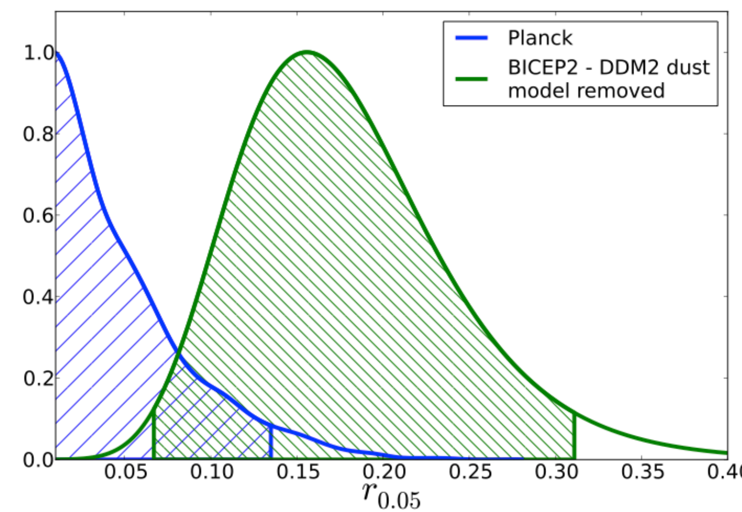
- BICEP2 pivot was actually 0.05 (not 0.002)
- n_t=0 vs consistency relation

→ Planck limit in this case is r < 0.135

- there is also some difference between the public and internal BICEP2 likelihoods

→ **Planck and BICEP2 are not very incompatible even w/o running**





caveat 2: radio loops

Liu, Mertsch & Sarkar, arXiv:1404.1899

→ There may be galactic foregrounds far from the galactic plane

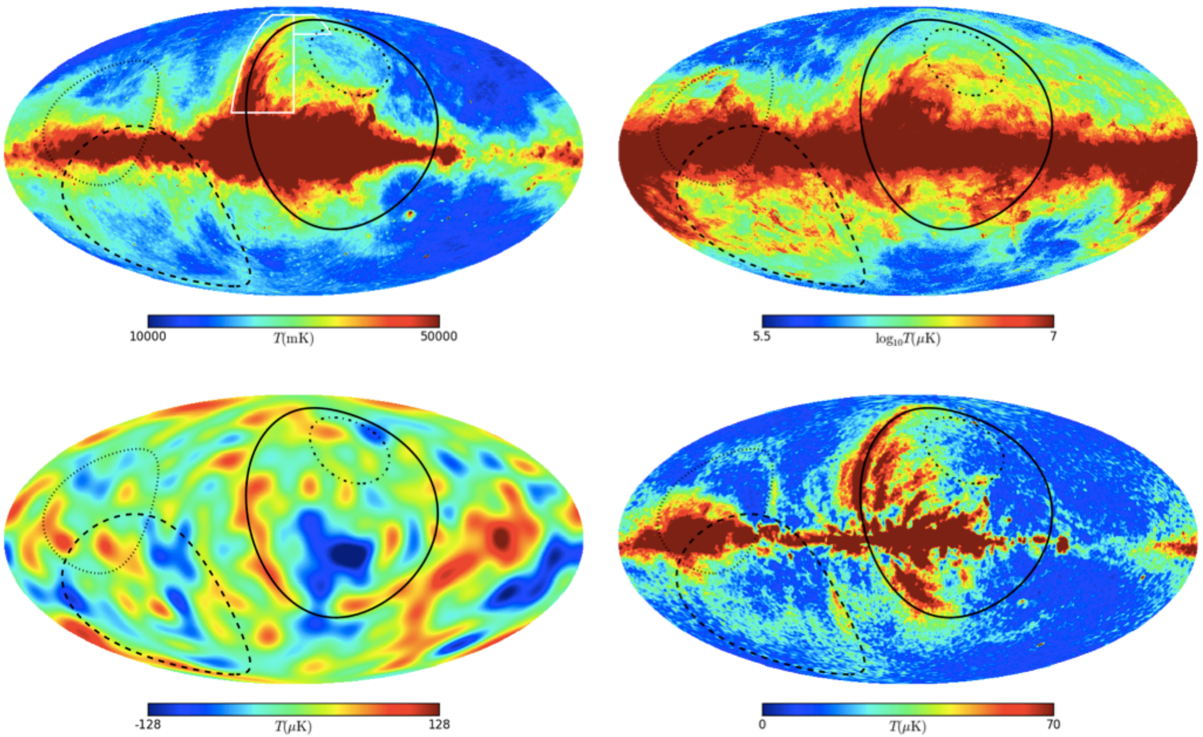


Figure 1. The 408 MHz survey (top left), the *Planck* 857 GHz map (top right) the low resolution ($l \leq 20$) WMAP9 ILC map (bottom left) and the WMAP9 K-band polarised intensity map (bottom right), with the positions of the radio loops indicated: Loops I-IV are indicated by the solid, dashed, dotted and dash-dotted line, respectively. The white outline (upper left panel) marks the NPS at 22 MHz.

caveat 3: dust

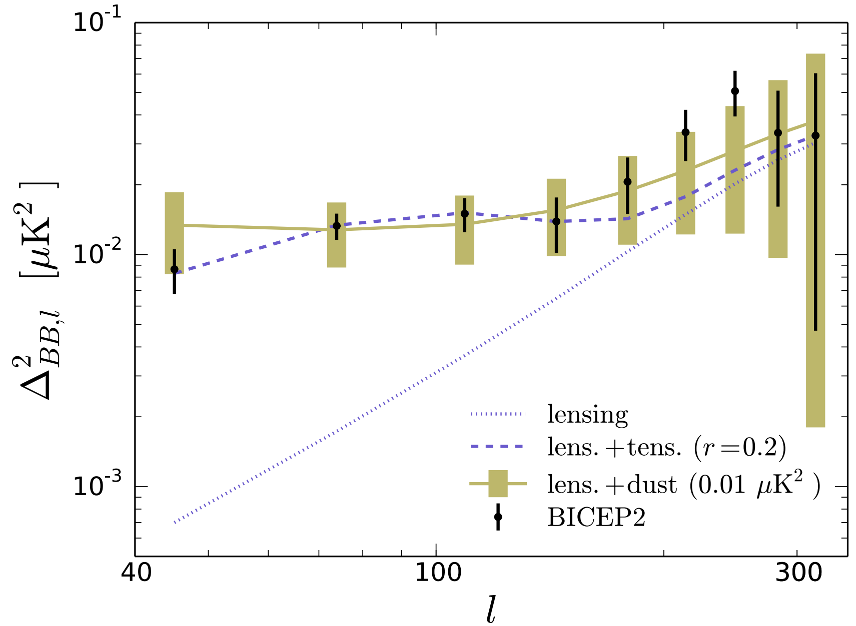
Flauger, Zaldarriaga, …

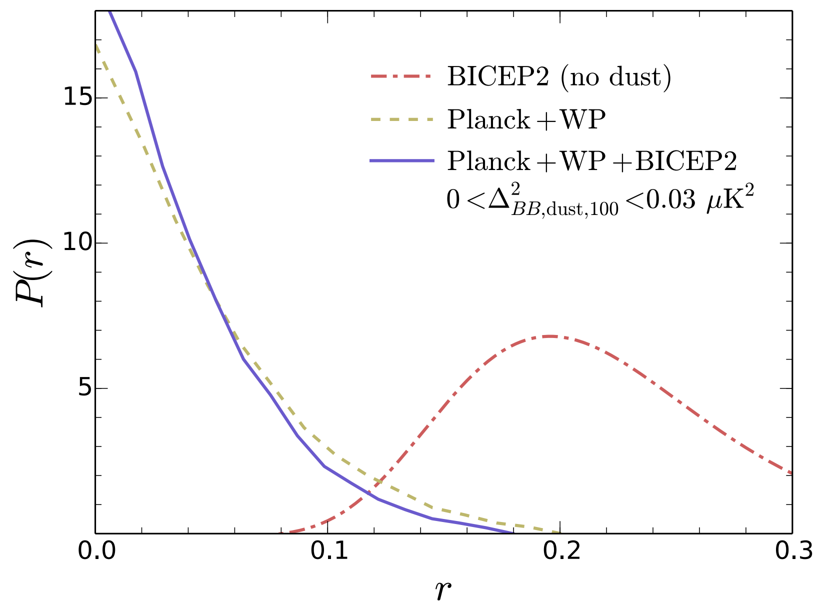
Mortonson & Seljak, arXiv: 1405.5857

- re-estimate of the dust contribution in BICEP2 field
- dust $C_l^{BB} \sim l^{-2.3}$ (Planck)
- early dust models are missing fluctuations (pol. angles / fraction)
- careful extrapolation from 353GHz needed

→ factor of 2 in pol. fraction is enough (CIB subtraction?)

→ **Need to understand dust contamination better (Planck?), atm status of BICEP2 detection unclear**





Other experiments to come

- BICEP2, Keck Array (South Pole)100GHz, 150 GHz
- POLAR-1, POLAR Array (South Pole) 150 GHz
- ABS (Atacama desert, Cile), wide band at 145GHz, 800 square degrees, $\ell = 25$ – 200,
- POLARBEAR-2 (South pole) $15^o \times 15^o$ patch, $\sigma(r) \sim 0.012$, 90/150/220GHz, 2nd run 2013-2016
- QUIET-II (Atacama desert, Cile), 43 GHz and 95GHz, radiometers, $\sigma(r) < 0.01$
- SPTpol (South Pole) 90GHz, 150 GHz, $\sigma(r) = 0.028$ at 1σ, anglular res.: arc-min to a few degrees.
- ACTpol Atacama Cosmology Telescope. 48 GHz, 218 GHz, and 277 GHz (small scales, lensing) ← arXiv:1405.5524
- Ballon: SPIDER (Austral summer of ~~2013~~/14 for a long duration (20 days) flight from Antarctica) 90GHz, 150 GHz, 280GHz, $\ell = 10$– 300, $\sigma(r) = 0.01$.
- Ballon: EBEX (very similar, austral summer 12/13, 11 days) 150, 250, and 410 GHz, 6000 square degrees observed, analysis ongoing. (Re-fly: with 90, 150, 240 GHz, want to achieve $\sigma(r) = 0.0035$.) ← 2016?
- Satellite: Planck, $\sigma(r) \le 0.025$, full sky, 7 polarisation frequencies from 30GHz to 353GHz.
- Satellie : LiteBird, 6 frequencies from 50GHz to 270GHz, $\sigma(r) < 10^{-3}$ (JAXA, Japanese, Chinese).
- Satellite: PRISM, CoRE M mission to be submitted to ESA this fall $\sigma(r) < 10^{-3}$.

Overall conclusions

planck

- ***Planck*** has performed beyond expectations
- Great TT data, CMB lensing, 'legacy' data (CIB, dust, …)
- ***BICEP2*** demonstrates the incredible increase in sensitivity from new detector technologies
- Detecting primordial tensor modes would be **amazing**
- Now it's all about systematics & foregrounds
- New results are on the way
    - Planck full data set incl. polar in October
    - many sub-orbital results are coming soon!

Thank you