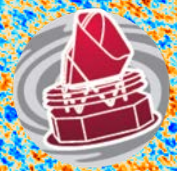
The Planck mission

Jan Tauber

Planck Project Scientist

on behalf of ESA and the Planck Collaboration

Contents



All the Planck Collaboration papers can be downloaded via

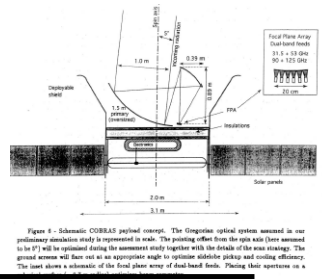
http://www.cosmos.esa.int/web/planck/publications

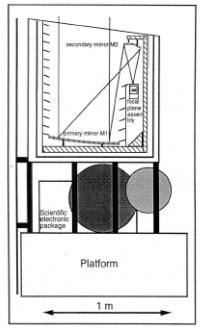
All the Planck data can be downloaded via

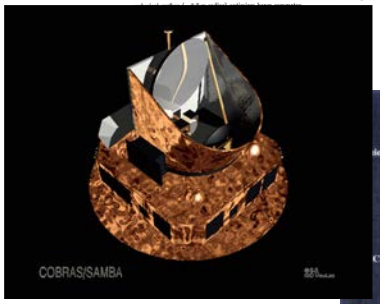
http://pla.esac.esa.int/pla

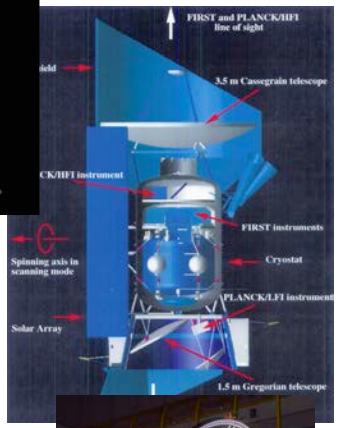
Development of the project

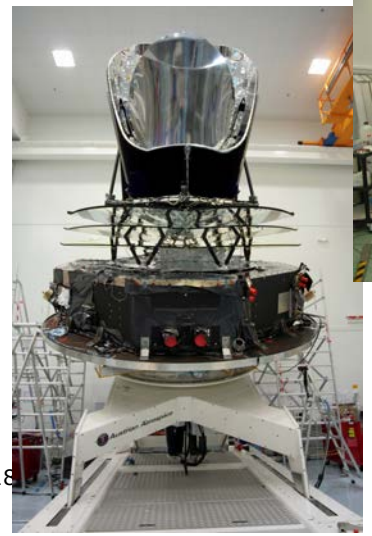
- COBRAS and SAMBA proposals were received in May 1993 in response to the call for mission ideas for the M3 element of Horizon 2000 programme
- Studies led to the selection of COBRAS/SAMBA in April 1996 with launch date 2003
- A period of uncertainty caused by programmatic issues led to the adoption of the FIRST/Planck project in Feb 1998 with launch date in 2007
- Industrial phase-B activities started in 2001
- Launch in 2009

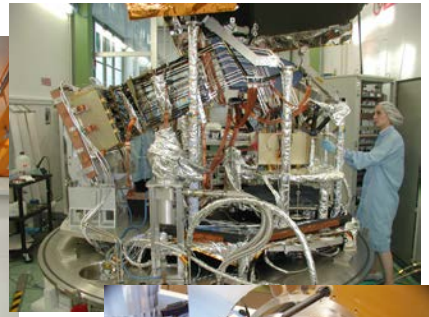








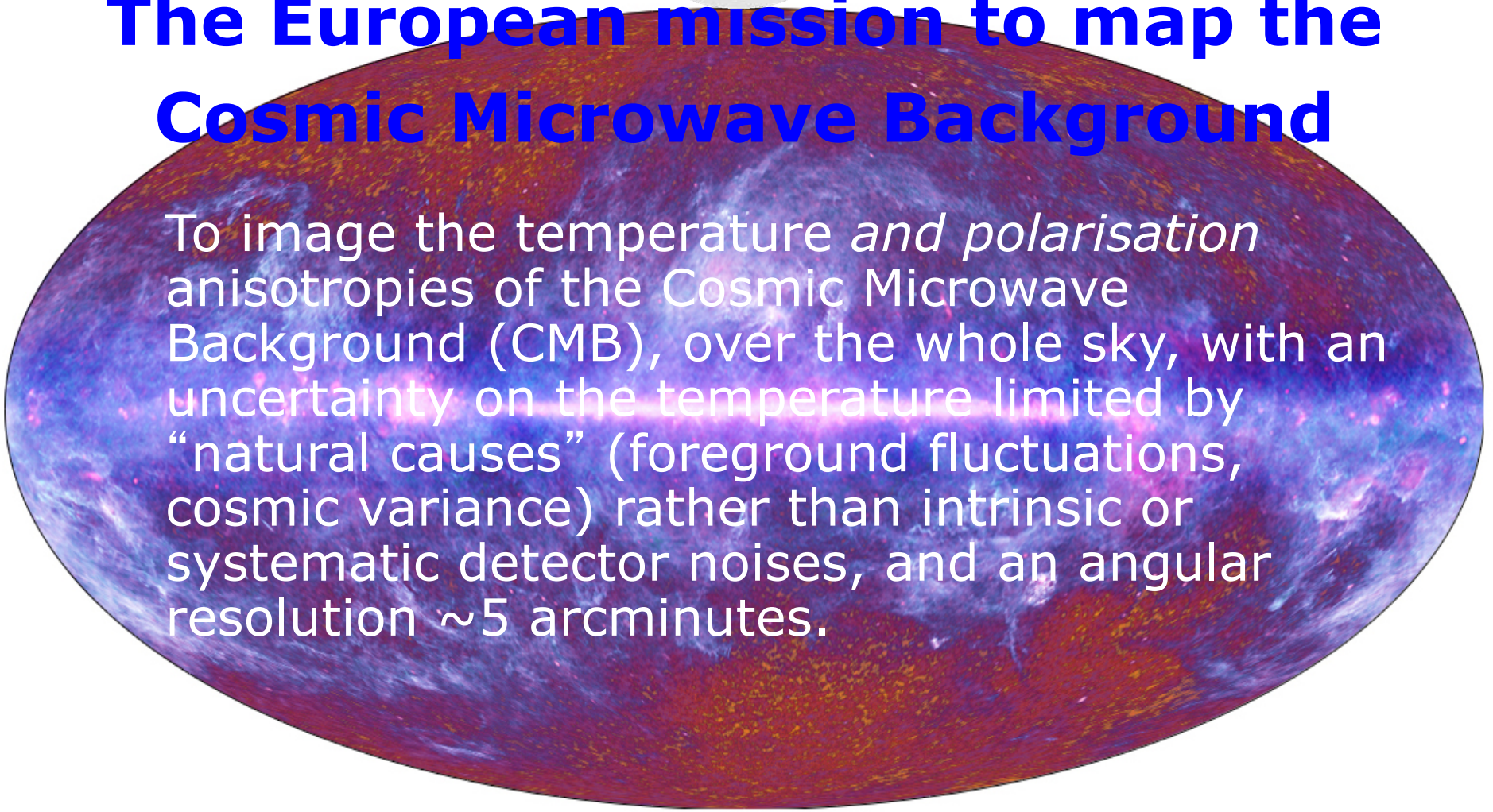




esa

planck

The European mission to map the Cosmic Microwave Background



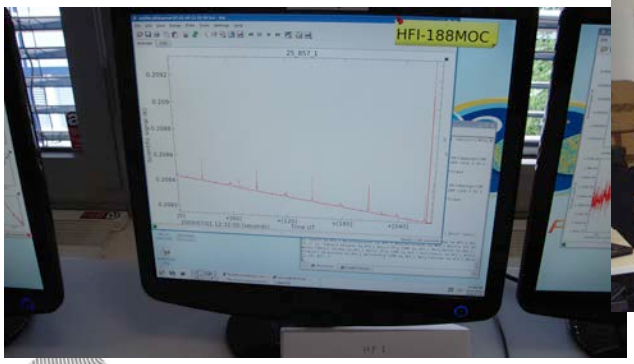
To image the temperature *and polarisation* anisotropies of the Cosmic Microwave Background (CMB), over the whole sky, with an uncertainty on the temperature limited by "natural causes" (foreground fluctuations, cosmic variance) rather than intrinsic or systematic detector noises, and an angular resolution ~5 arcminutes.

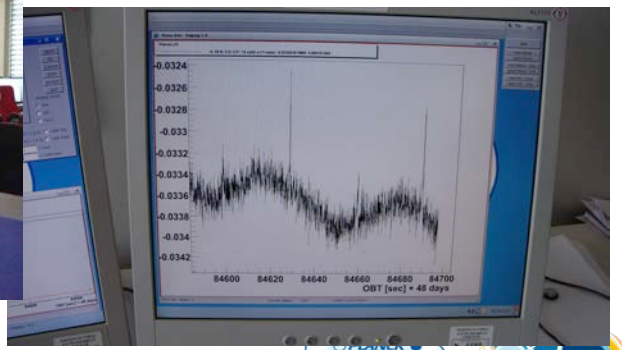
Technical challenges

- State-of-the art detectors
- Passive cooling with V-grooves
- Cooling to 0.1 K with active refrigerators
- A large CFRP telescope operating at 40 K
- Autonomous operation
- Distributed science ground segment

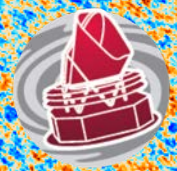
Operations

- Picture-perfect launch & early operations
- Commissioning and Performance Verification phases completed in time
  - All performances similar or better than predicted
  - First Light Survey became part of 1st survey
- Completely smooth routine operations between August 2009 and October 2013
  - 3 extensions of operations leading to 5 surveys with LFI+HFI, 8 with LFI
  - Cryo-chain worked continuously for more than four years
  - Only one instance of an interruption over four years





Planck data releases



- 2011: The Early Release Compact Source Catalogue
  - Intended as a "quick" product to enable follow-up of interesting sources, mainly with Herschel
- 2013: the first major release of data
  - Contained data products based on the first 15 months of observations, calibrated on the WMAP solar dipole
    - All-sky Temperature maps – by frequency
    - physical component maps and catalogues
- 2015: the first complete release of data
  - Data products using ALL the data acquired by Planck, calibrated on the orbital dipole
    - All-sky Temperature and Polarization maps – by frequency
    - Physical component maps and catalogues
    - Timelines of cleaned and calibrated data
- 2018: the "Legacy" release of data
  - Data products with improved handling of systematic effects, especially in polarization at large angular scales
  - "semi-raw" timelines

The 2018 release papers

I. Planck cosmological legacy

II. LFI data processing

III. HFI data processing

IV. CMB and foreground extraction

*V. Power spectra and likelihood**

VI. Cosmological parameters

*VII. Isotropy and statistics**

VIII. Lensing

*IX. Constraints on primordial non-Gaussianity**

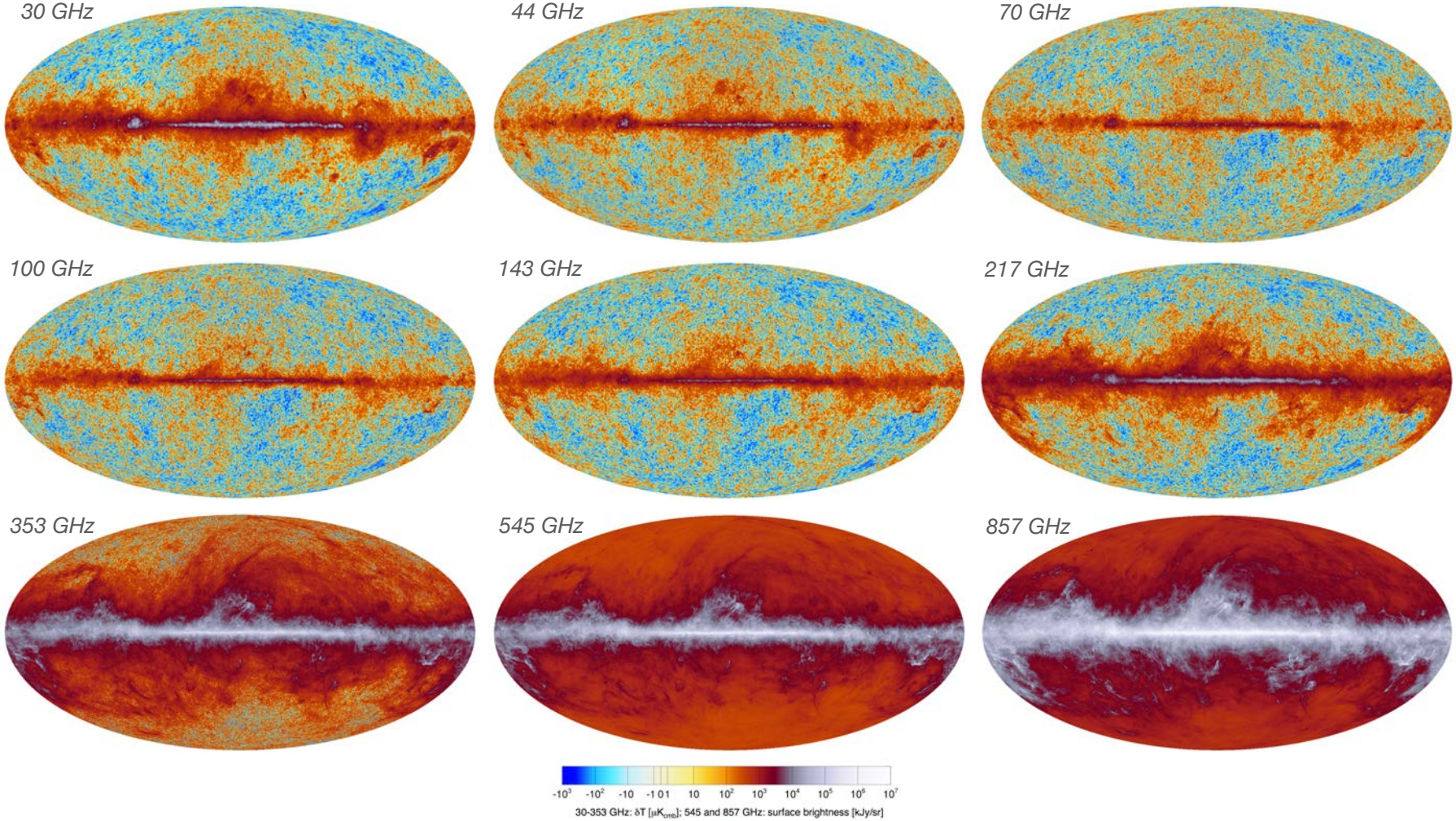
X. Inflation

XI. Polarized dust foregrounds

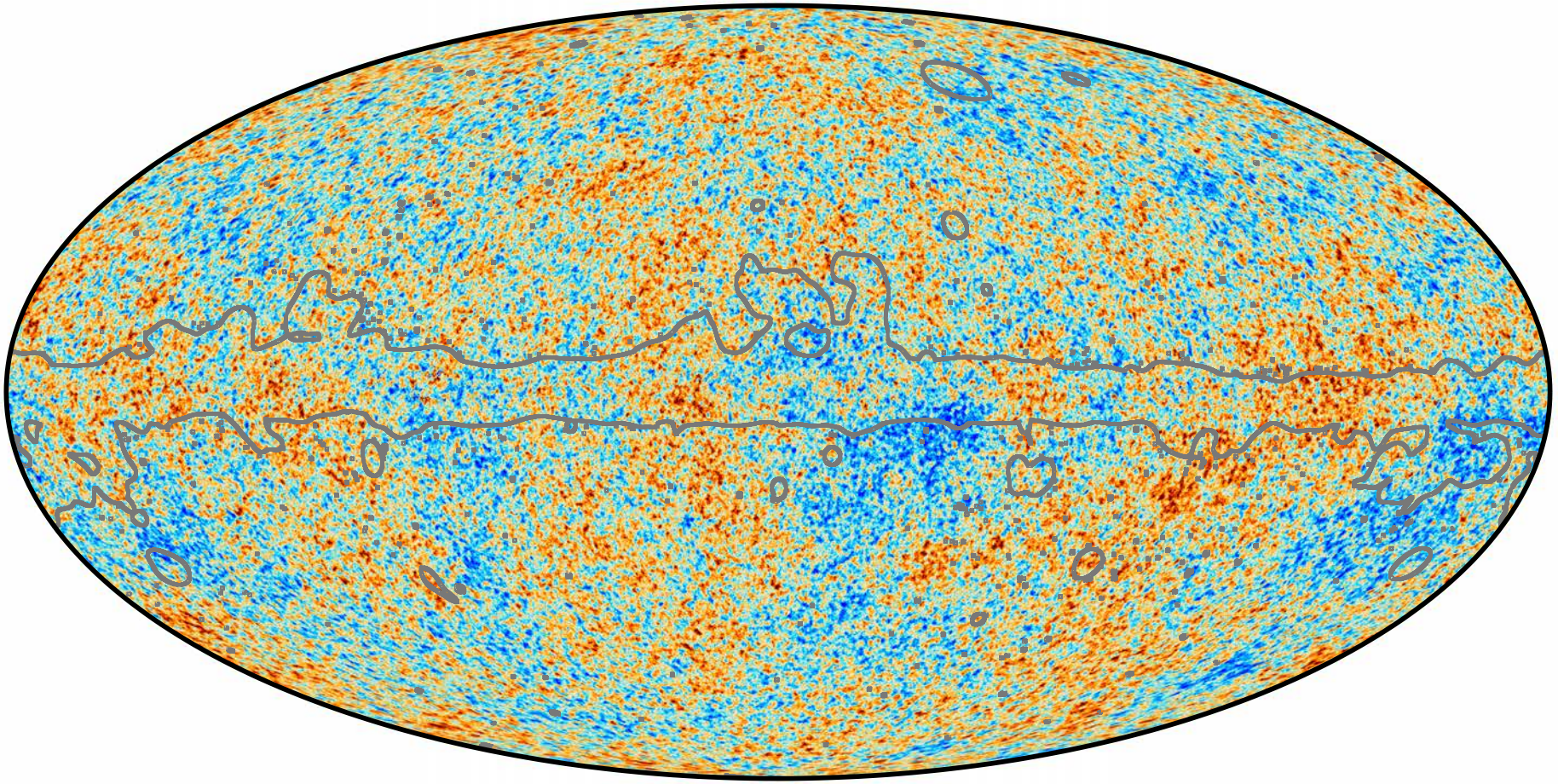
XII. Galactic astrophysics from polarization

** To be released in a few weeks*

2018 maps

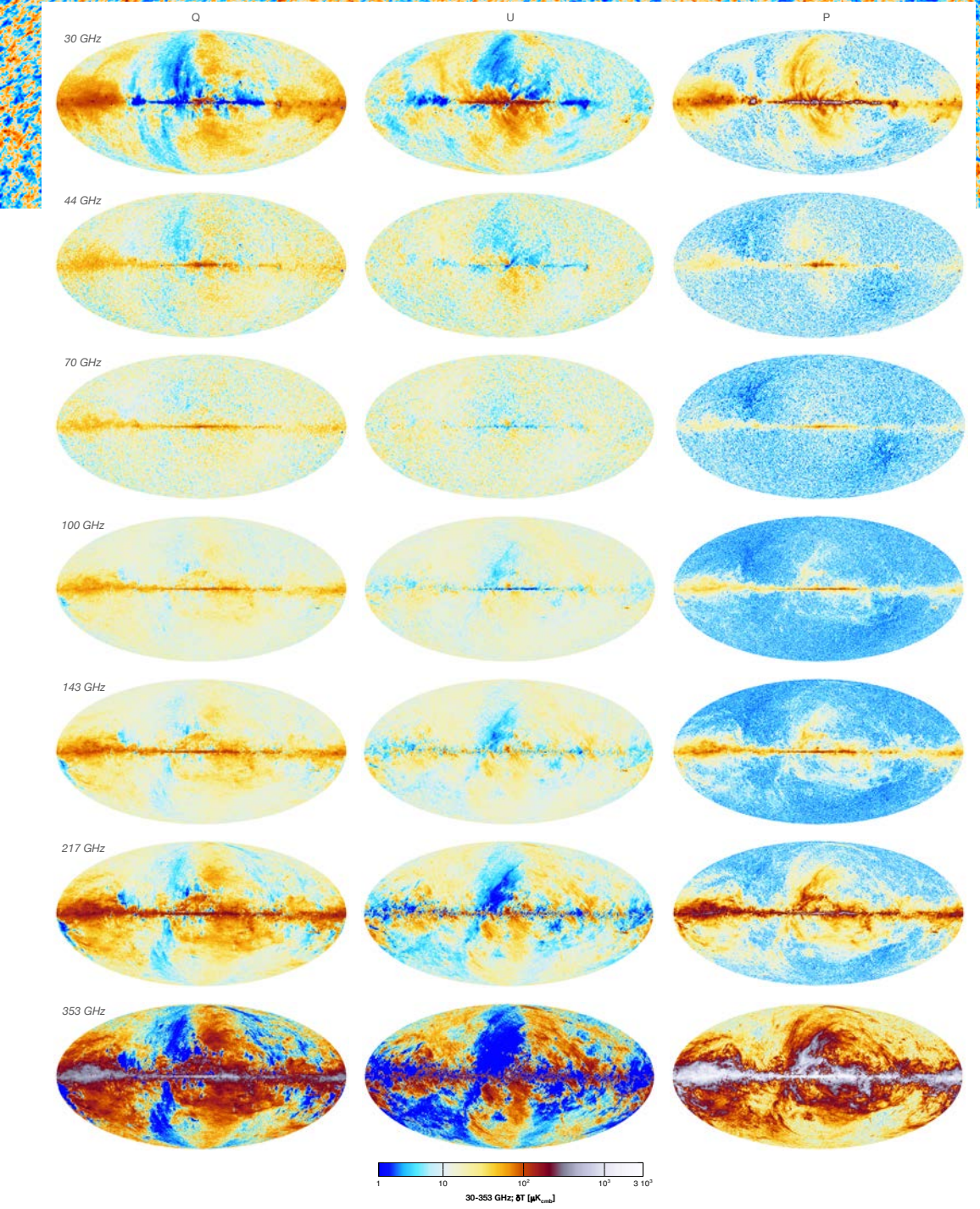

30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
-10³ -10² -10 -1 0 1 10 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷
30-353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]

The temperature fluctuations of the CMB



-300 300 μK

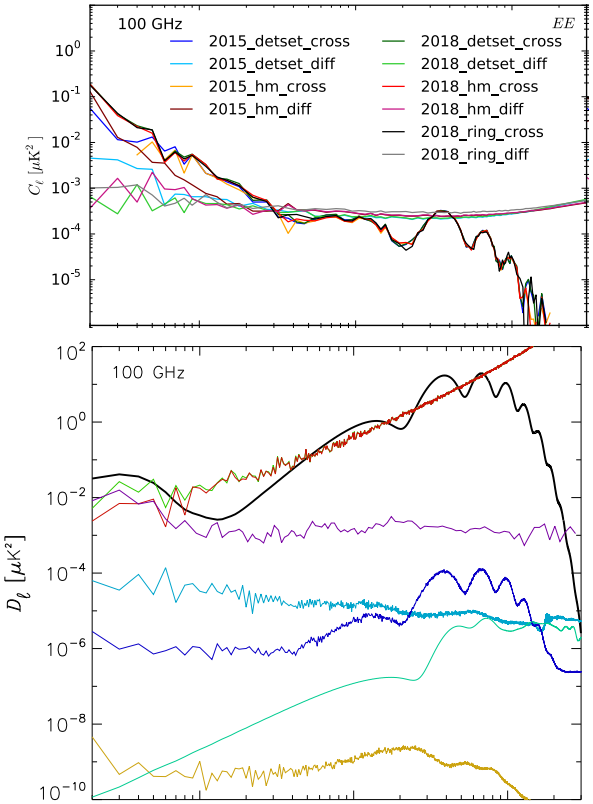
Jan Tauber, COSPAR 2018, July 2018



2018 polarized maps

planck

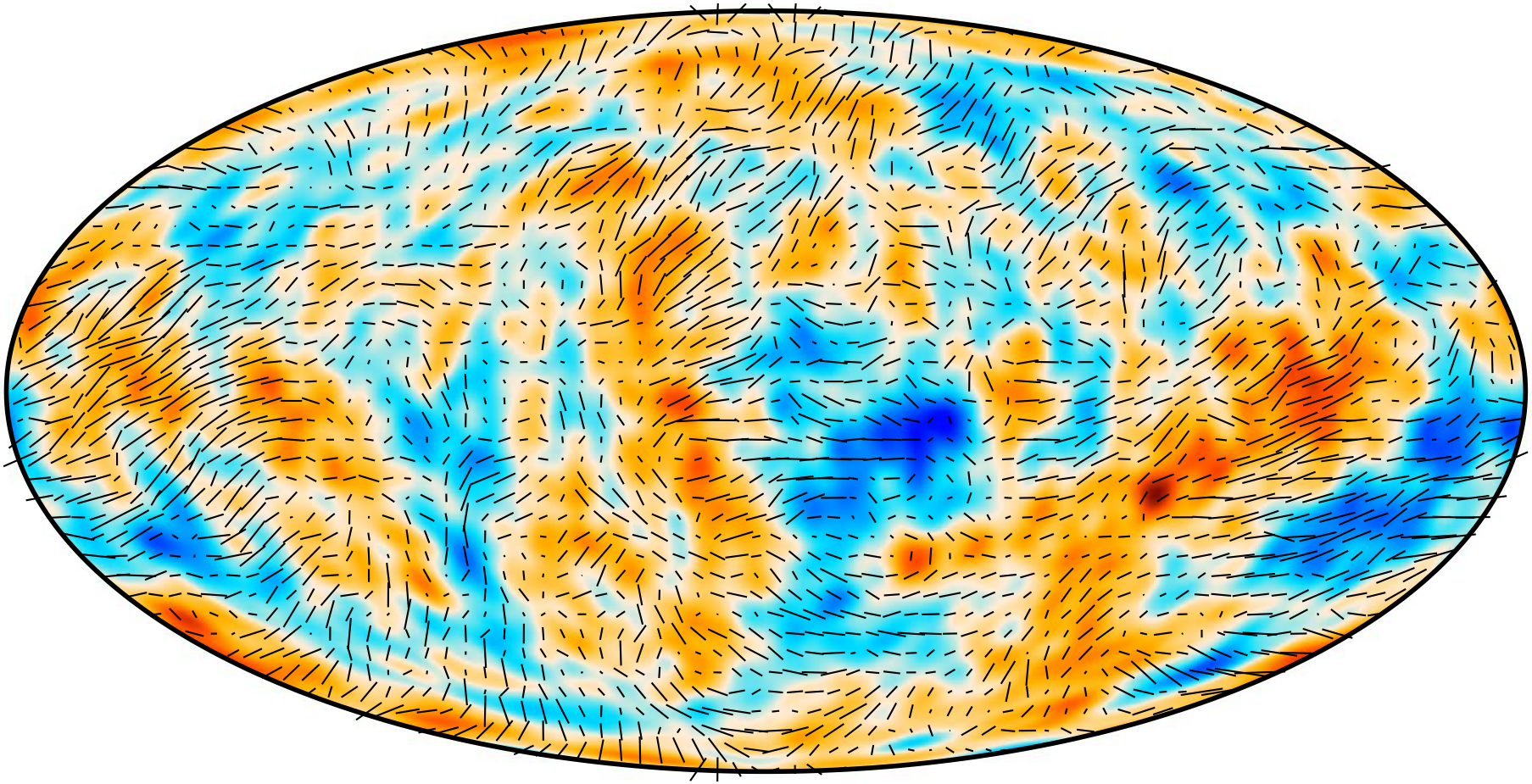
Large-scale polarization systematics have been reduced very considerably



PLANCK LFI

HFI PLANCK

The polarized CMB

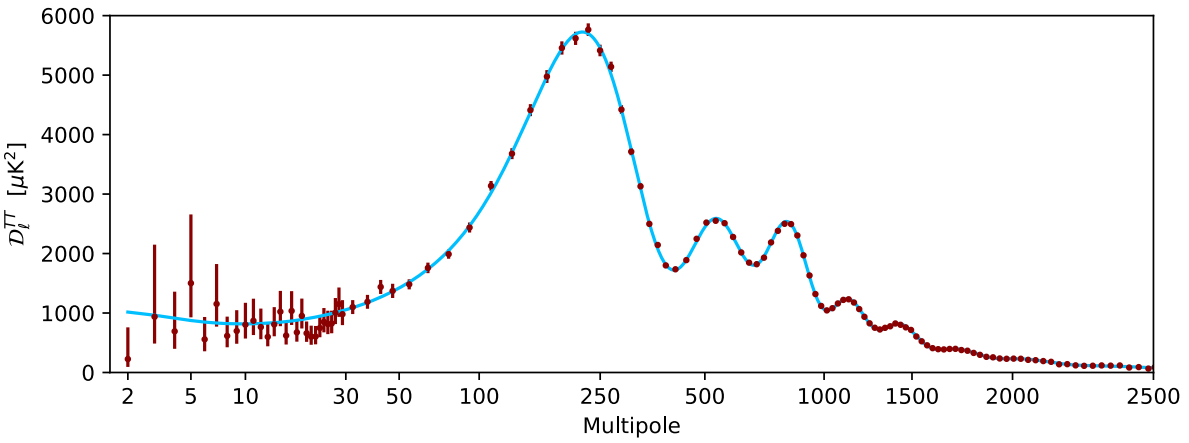


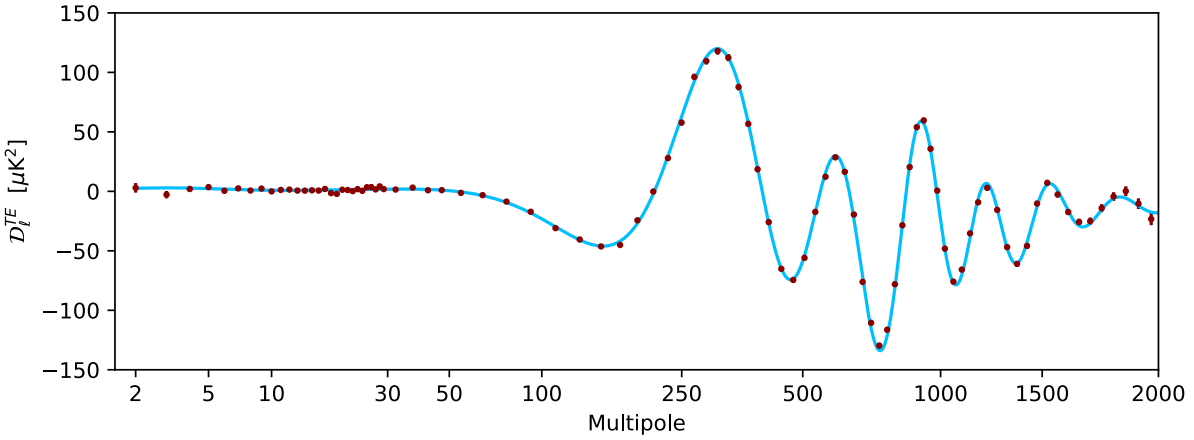
| 0.41 μK

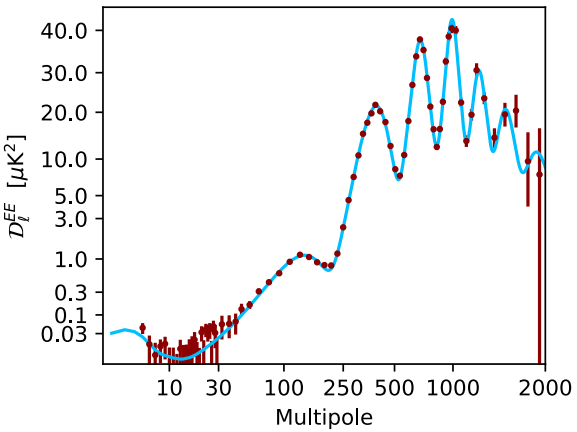
-160 160 μK

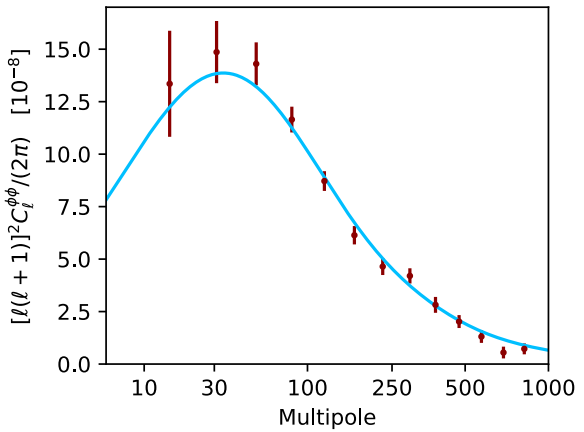
Best fit to TT, TE, EE+lowE+lensing

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_*[Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag}[Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
k_{eq}[Mpc^{-1}]	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

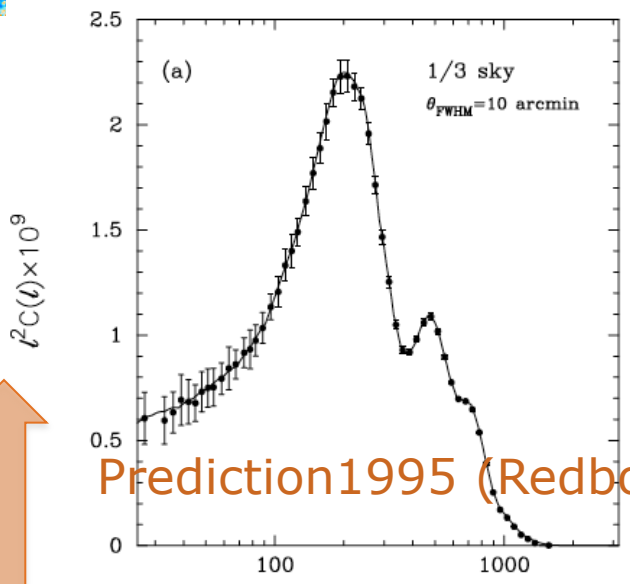




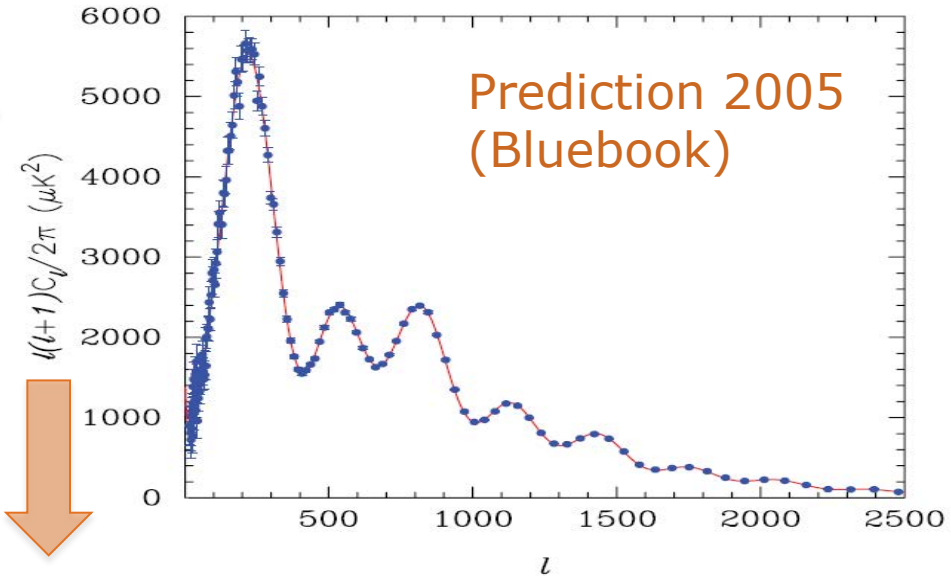


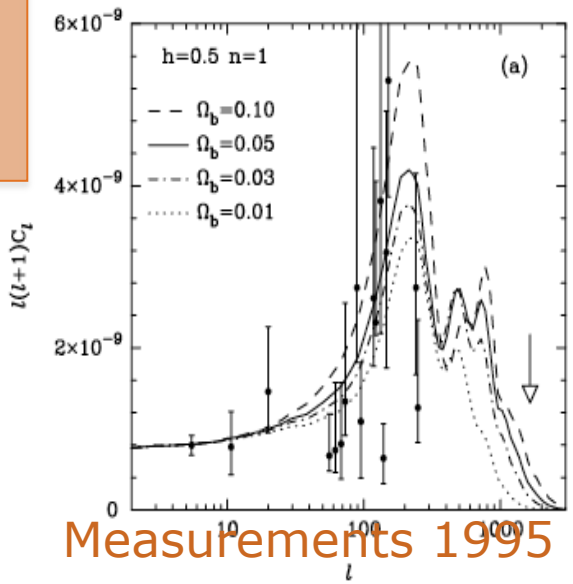


Expectations

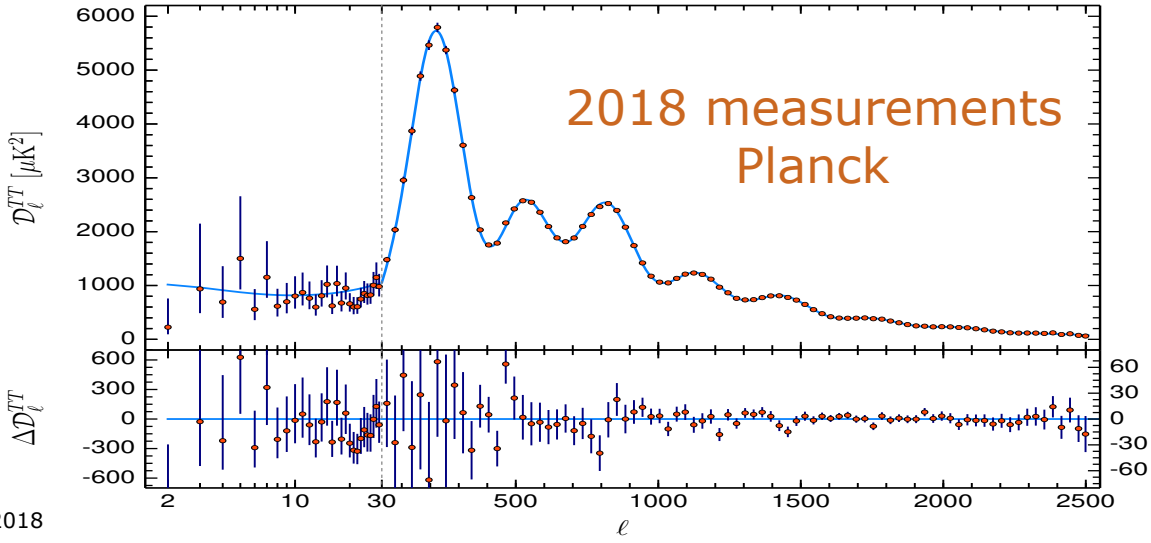


Prediction1995 (Redbook)



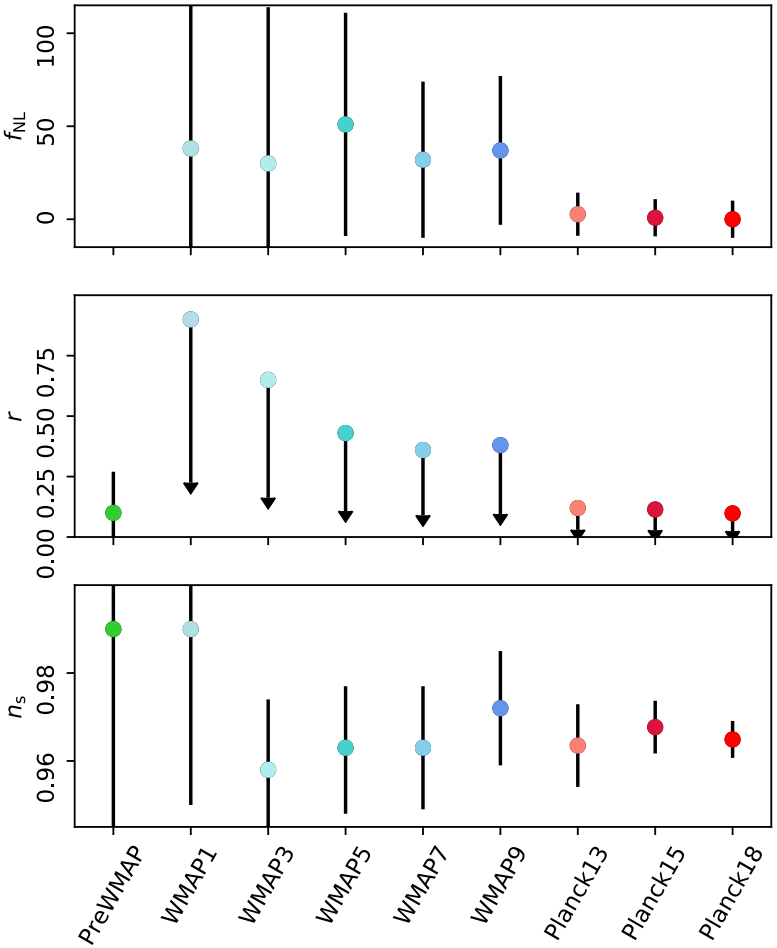


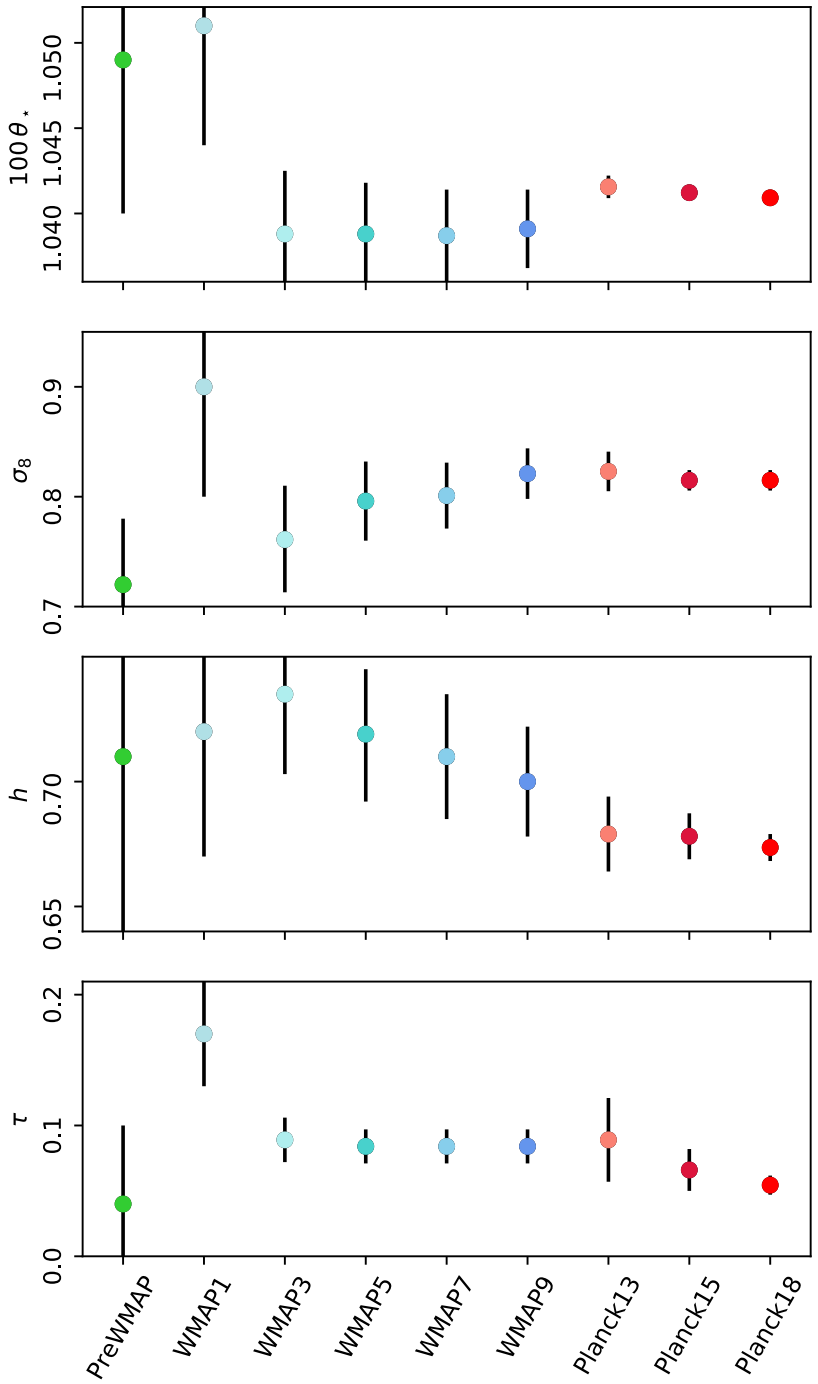
Measurements 1995



July 2018

Cosmological parameters over time

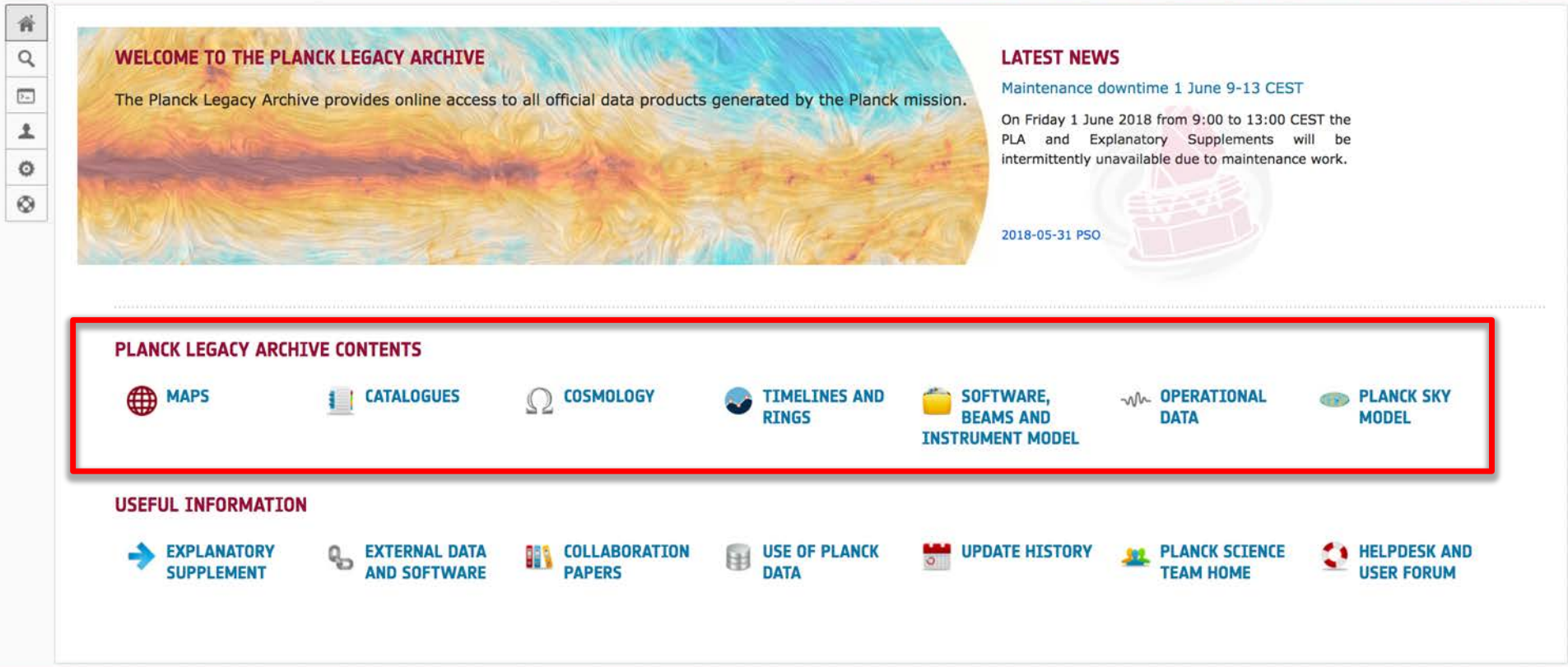




Planck Legacy Archive: the official repository of Planck data

Planck Legacy Archive

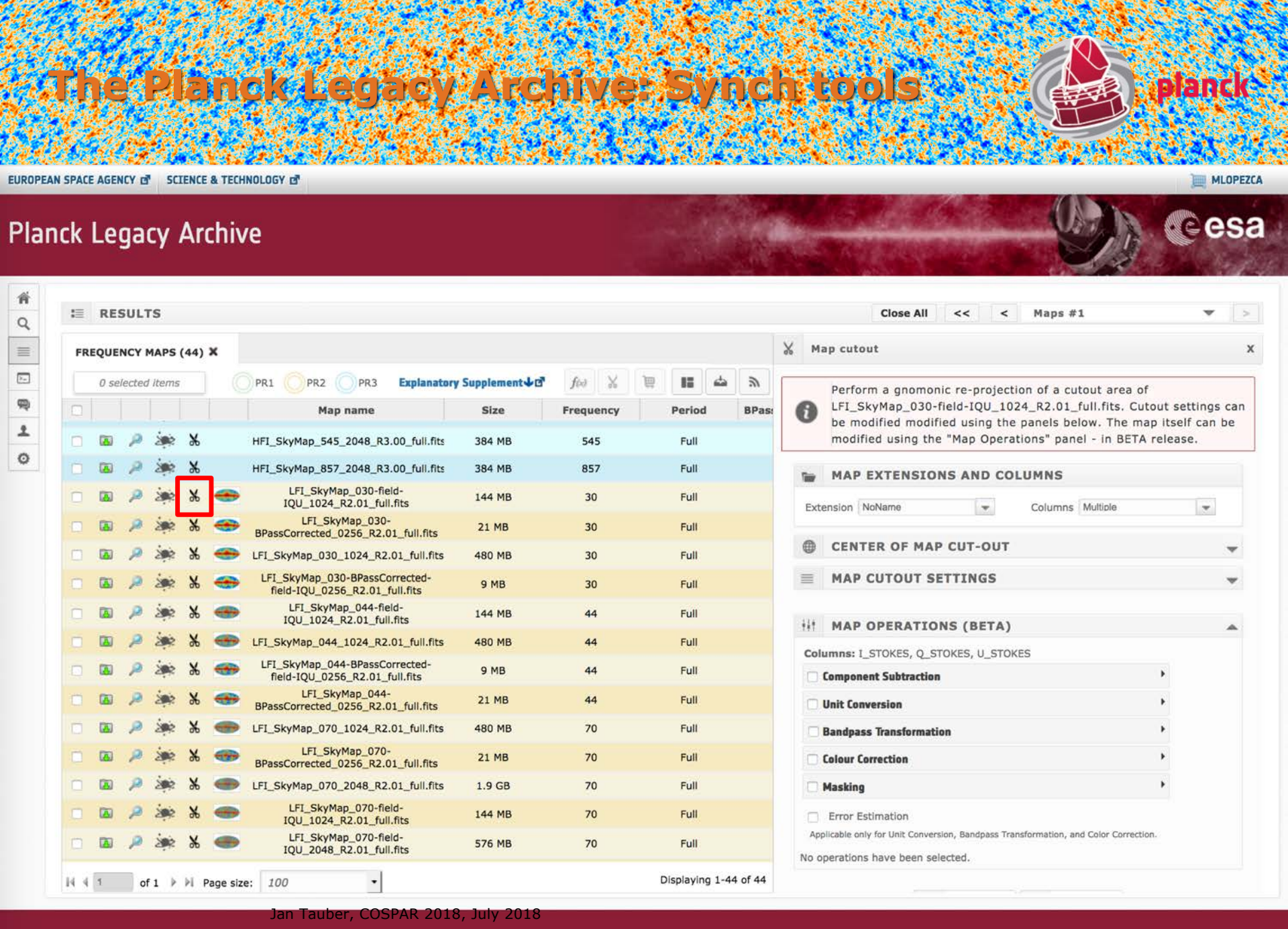
pla.esac.esa.int/pla



The Planck Legacy Archive

- The PLA contains thousands of data products
  - Types
  - methods
  - Releases
  - ancillary data products: corrections, Masks, Simulations …
- The PLA contains many useful tools to manipulate the products
  - Cut out small parts of the sky
  - Remove physical components
  - Change units, bandpasses, colour correct, mask, …
  - Estimate noise, beam shapes, …
- The PLA allows you to create new products using simple tools
  - Maps from timelines
  - Apply component separation
  - Create new simulated observations (using the PSM)
- The PLA interfaces easily with Aladin and Topcat

The Planck Legacy Archive: Synch tools



Planck Legacy Archive

LATEST NEWS

Maintenance downtime 1 June 9-13 CEST

On Friday 1 June 2018 from 9:00 to 13:00 CEST the PLA and Explanatory Supplements will be intermittently unavailable due to maintenance work.

2018-05-31 PSO

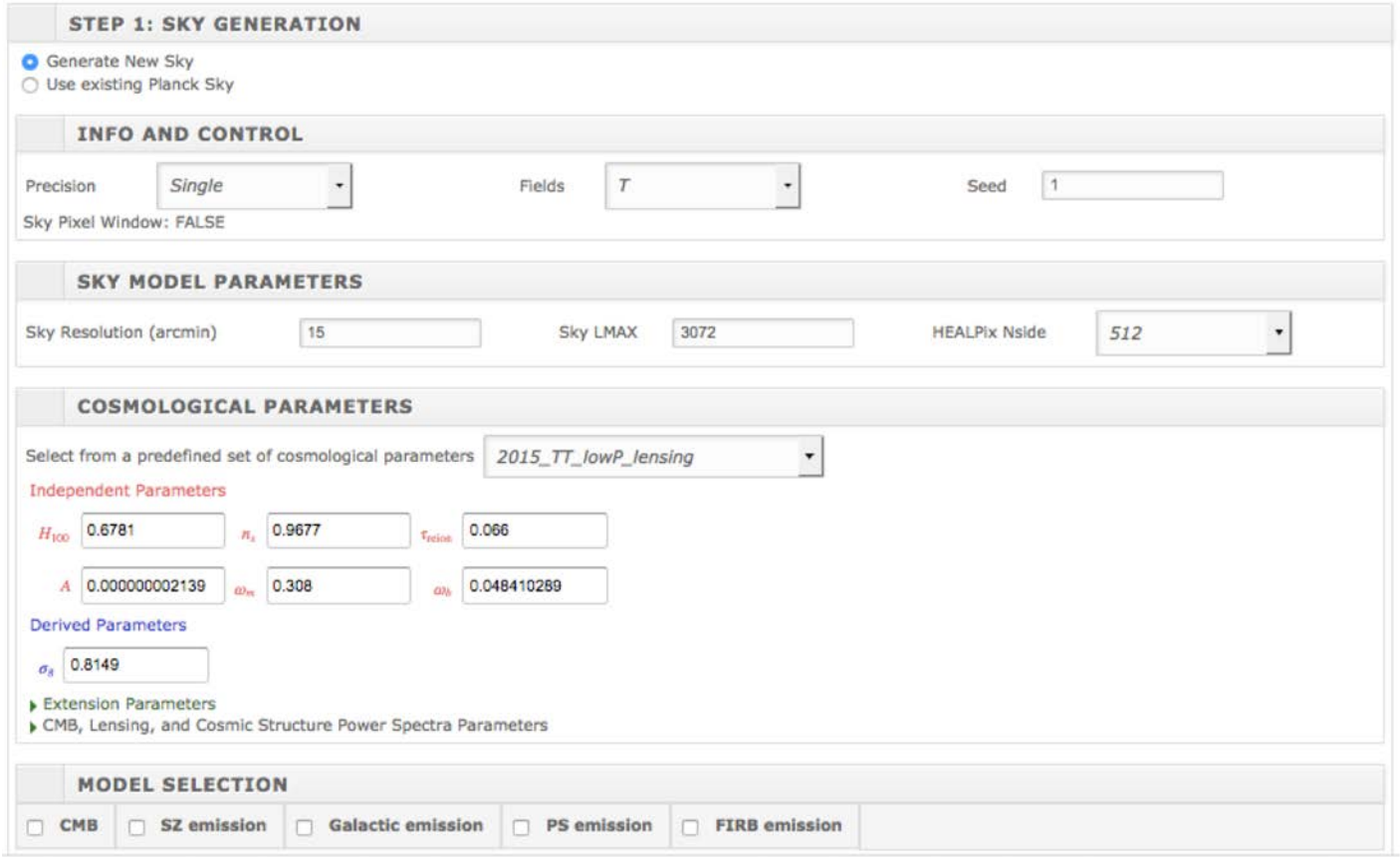
PLANCK LEGACY ARCHIVE CONTENTS

- MAPS
- CATALOGUES
- COSMOLOGY
- TIMELINES AND RINGS
- SOFTWARE, BEAMS AND INSTRUMENT MODEL
- OPERATIONAL DATA
- PLANCK SKY MODEL

USEFUL INFORMATION

- EXPLANATORY SUPPLEMENT
- EXTERNAL DATA AND SOFTWARE
- COLLABORATION PAPERS
- USE OF PLANCK DATA
- UPDATE HISTORY
- PLANCK SCIENCE TEAM HOME
- HELPDESK AND USER FORUM

1. Web interface for Planck Sky Model simulation software



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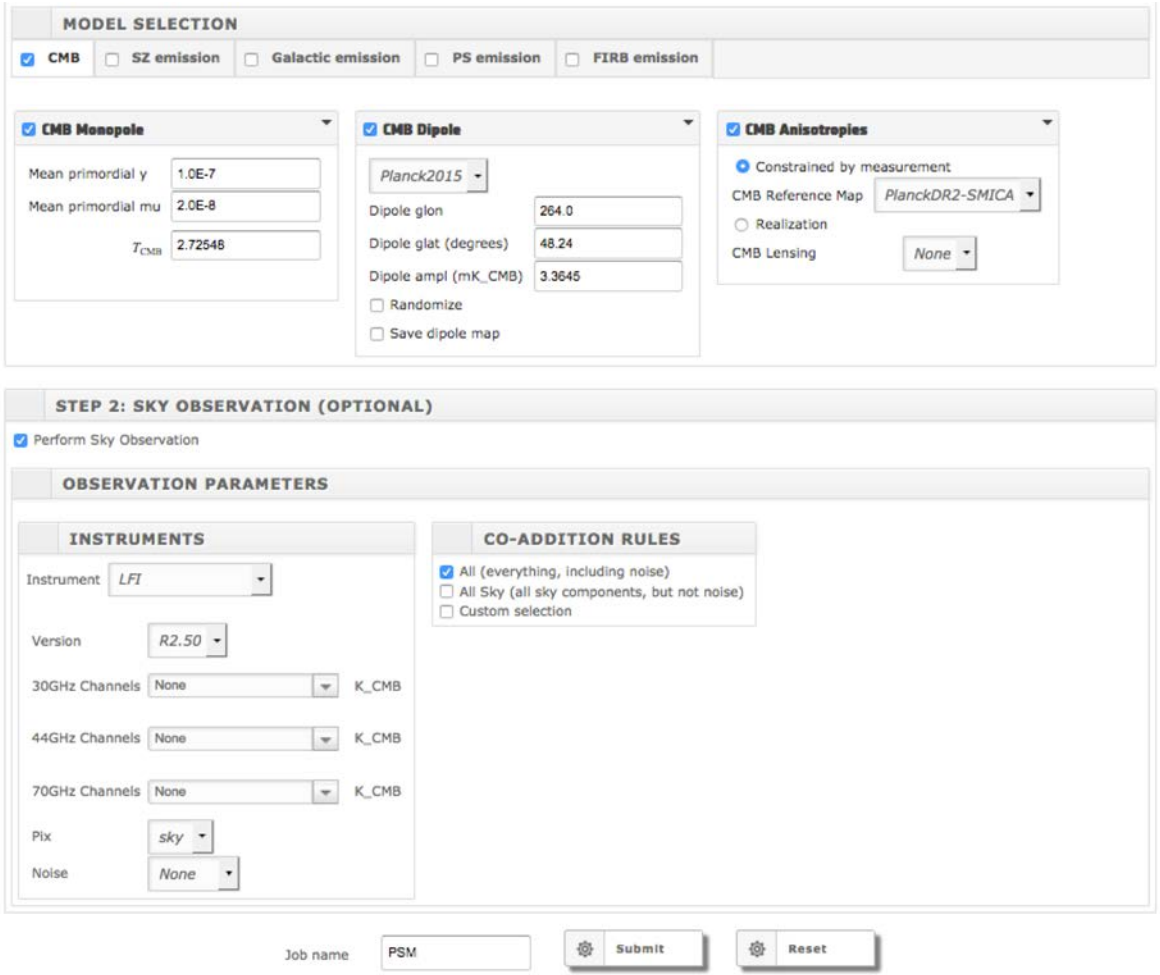

Wrap-up

- Planck has been an extremely challenging and successful mission
  - It has broken new ground technically and scientifically
  - It has met all its scientific goals and more
  - There are many Lessons Learned for other experiments
    - https://www.cosmos.esa.int/ web/planck/lessons-learned
- More than 1600 refereed papers using Planck data have been published
  - About 300 per year over the last four years
- We are now presenting the final release of the Planck Collaboration
  - All data products except the Likelihood code are available via the Legacy Archive
  - We expect to complete the release within 2 months
- There are still improvements to be made to the data
- There is a huge amount of science left to be done with the data, in cosmology and astrophysics

DOI: 10.1051/0004-6361/200912983
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Astronomy & Astrophysics
Special feature

Pre-launch status of the Planck mission

Planck pre-launch status: The *Planck* mission

Astronomy & Astrophysics manuscript no. ms
July 13, 2018
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Planck 2018 results. I.
Overview, and the cosmological legacy of *Planck*

Planck Collaboration: Y. Akrami[59,61], F. Arroja[63], M. Ashdown[69,5], J. Aumont[99], C. Baccigalupi[81], M. Ballardini[22,42], A. J. Banday[99,8], R. B. Barreiro[64], N. Bartolo[31,65], S. Basak[88], R. Battye[67], K. Benabed[57,97], J.-P. Bernard[99,8], M. Bersanelli[34,46], P. Bielewicz[80,8,81], J. J. Bock[66,10], J. R. Bond[7], J. Borrill[12,95], F. R. Bouchet[57,92], F. Boulanger[71,56,57], M. Bucher[2,6], C. Burigana[45,32,48], R. C. Butler[42], E. Calabrese[85], J.-F. Cardoso[57], J. Carron[24], B. Casaponsa[64], A. Challinor[60,69,11], H. C. Chiang[26,6], L. P. L. Colombo[34], C. Combet[73], D. Contreras[21], B. P. Crill[66,10], F. Cuttaia[42], P. de Bernardis[33], G. de Zotti[43,81], J. Delabrouille[2], J.-M. Delouis[57,97], F.-X. Désert[98], E. Di Valentino[67], C. Dickinson[67], J. M. Diego[64], S. Donzelli[46,34], O. Doré[66,10], M. Douspis[56], A. Ducout[57,54], X. Dupac[37], G. Efstathiou[69,60], F. Elsner[77], T. A. Enßlin[77], H. K. Eriksen[61], E. Falgarone[70], Y. Fantaye[3,20], J. Fergusson[11], R. Fernandez-Cobos[64], F. Finelli[42,48], F. Forastieri[32,49], M. Frailis[44], E. Franceschi[42], A. Frolov[90], S. Galeotta[44], S. Galli[68], K. Ganga[2], R. T. Génova-Santos[62,15], M. Gerbino[96], T. Ghosh[84,9], J. González-Nuevo[16], K. M. Górski[66,101], S. Gratton[69,60], A. Gruppuso[42,48], J. E. Gudmundsson[96,26], J. Hamann[89], W. Handley[69,5], F. K. Hansen[61], G. Helou[10], D. Herranz[64], E. Hivon[57,97], Z. Huang[86], A. H. Jaffe[54], W. C. Jones[26], A. Karakci[61], E. Keihänen[25], R. Keskitalo[12], K. Kiiveri[25,41], J. Kim[77], T. S. Kisner[75], L. Knox[28], N. Krachmalnicoff[81], M. Kunz[14,56,3], H. Kurki-Suonio[25,41], G. Lagache[4], J.-M. Lamarre[70], M. Langer[56], A. Lasenby[5,69], M. Lattanzi[32,49], C. R. Lawrence[66], M. Le Jeune[2], J. P. Leahy[67], J. Lesgourgues[58], F. Levrier[70], A. Lewis[24], M. Liguori[31,65], P. B. Lilje[61], M. Lilley[57,92], V. Lindholm[25,41], M. López-Caniego[37], P. M. Lubin[29], Y.-Z. Ma[67,83,79], J. F. Macías-Pérez[73], G. Maggio[44], D. Maino[34,46,50], N. Mandolesi[42,32], A. Mangilli[8], A. Marcos-Caballero[64], M. Maris[44], P. G. Martin[7], E. Martínez-González[64], S. Matarrese[31,65,39], N. Mauri[48], J. D. McEwen[78], P. D. Meerburg[69,11,100], P. R. Meinhold[29], A. Melchiorri[33,51], A. Mennella[34,46], M. Migliaccio[94,52], M. Millea[28,91,57], S. Mitra[53,66], M.-A. Miville-Deschênes[72], D. Molinari[32,42,49], A. Moneti[57], L. Montier[99,8], G. Morgante[42], A. Moss[87], S. Mottet[57,92], M. Münchmeyer[57], P. Natoli[32,94,49], H. U. Nørgaard-Nielsen[13], C. A. Oxborrow[13], L. Pagano[56,70], D. Paoletti[42,48], B. Partridge[40], G. Patanchon[2], T. J. Pearson[10,55], M. Peel[17,67], H. V. Peiris[23], F. Perrotta[81], V. Pettorino[1], F. Piacentini[33], L. Polastri[32,49], G. Polenta[94], J.-L. Puget[56,57], J. P. Rachen[18], M. Reinecke[77], M. Remazeilles[67], A. Renzi[65], G. Rocha[66,10], C. Rosset[2], G. Roudier[2,70,66], J. A. Rubiño-Martín[62,15], B. Ruiz-Granados[62,15], L. Salvati[56], M. Sandri[42], M. Savelainen[25,41,76], D. Scott[21], E. P. S. Shellard[11], M. Shiraishi[31,65,19], C. Sirignano[31,65], G. Sirri[48], L. D. Spencer[85], R. Sunyaev[77,93], A.-S. Suur-Uski[25,41], J. A. Tauber[38], D. Tavagnacco[44,35], M. Tenti[47], L. Terenzi[42], L. Toffolatti[16,42], M. Tomasi[34,46], T. Trombetti[45,49], J. Valiviita[25,41], B. Van Tent[74], L. Vibert[56,57], P. Vielva[64], F. Villa[42], N. Vittorio[36], B. D. Wandelt[57,97,30], I. K. Wehus[66,61], M. White[27], S. D. M. White[77], A. Zacchei[44], and A. Zonca[82]

(Affiliations can be found after the references)

July 13, 2018

ABSTRACT

…n Space Agen… *Planck* satellite, which was dedicated to studying the early Universe and its subsequent evolution, was launched …n 14 May 2009. It scanne… microwave and submillimetre sky continuously between 12 August 2009 and 23 October 2013, producing deep, …tion, all-sky m… in nine frequency bands from 30 to 857 GHz. This paper presents the cosmological legacy of *Planck*, which currently provides our strongest constraints on the parameters of the standard cosmological model and some of the tightest limits available on deviations from that model. The 6-parameter ΛCDM model continues to provide an excellent fit to the cosmic microwave background data at high and low redshift, describing the cosmological information in over a billion map pixels with just six parameters. With 18 peaks in the temperature and polarization angular power spectra constrained well, *Planck* measures five of the six parameters to better than 1 % (simultaneously), with the best-determined parameter (θ_*) now known to 0.03 %. We describe the multi-component sky as seen by *Planck*, the success of the ΛCDM model, and the connection to lower-redshift probes of structure formation. We also give a comprehensive summary of the major changes introduced in this 2018 release. The *Planck* data, alone and in combination with other probes, provide stringent constraints on our models of the early Universe and the large-scale structure within which all astrophysical objects form and evolve. We discuss some lessons learned from the *Planck* mission, and highlight areas ripe for further experimental advances.

Key words. Cosmology: observations – Cosmology: theory – cosmic background radiation – Surveys

Thanks to all Planck people !

The Planck Science Team and Managers

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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Mission accomplished !