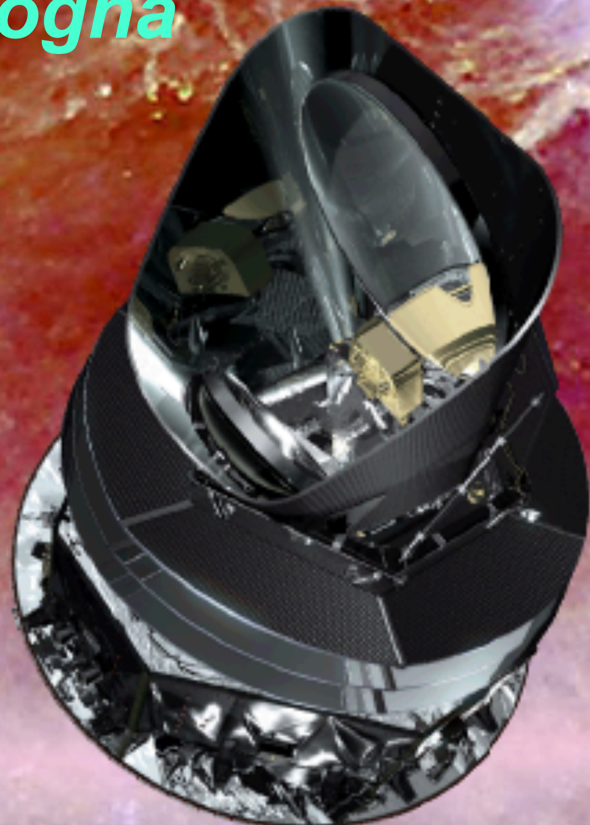
Recent results from the *Planck* satellite and their implications

Carlo Burigana @ INAF/IASF Bologna

On behalf of the *Planck* Collaboration



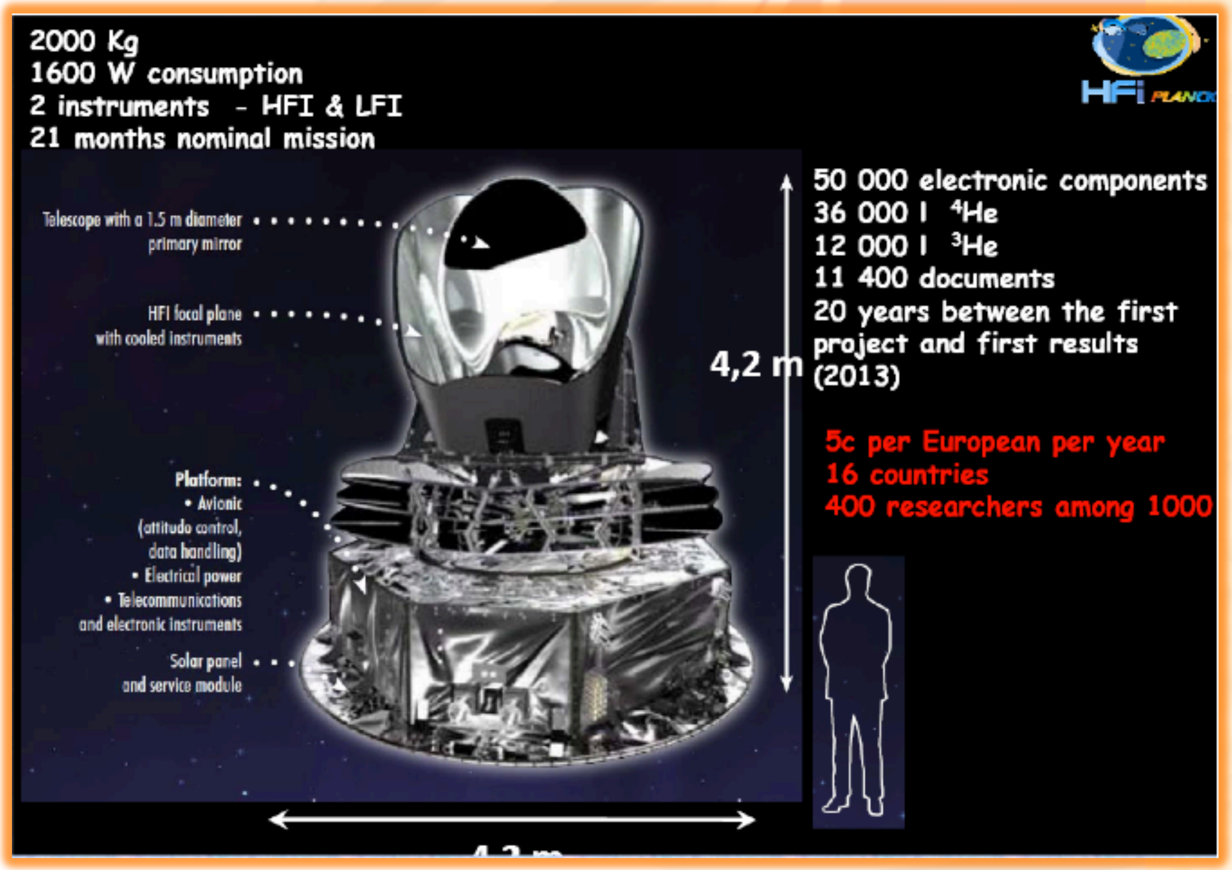
Special thanks to: M. Ashdown, F. Finelli, K. Ganga,
J. Gonzalez-Nuevo, N. Mandolesi,
S. Matarrese, D. Paoletti,
L. Toffolatti, T. Trombetti

The 17th Paris Cosmology Colloquium 2013
"The New Standard Model of the Universe:
Lambda Warm Dark Matter (ΛWDM)
Theory versus Observations",
The International School Daniel Chalonge
Observatoire de Paris, Paris campus, 24-26 July 2013

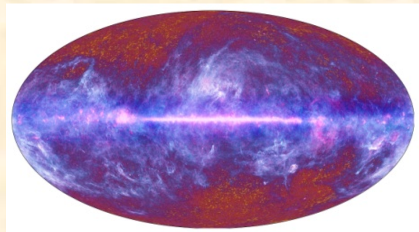
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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.

The European mission to map the Cosmic Microwave Background

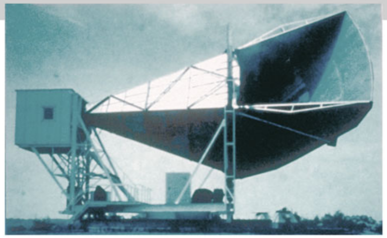


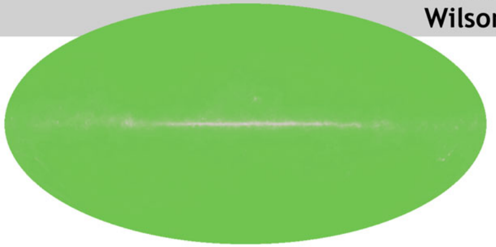
To image the temperature and polarisation anisotropies of the Cosmic Microwave Background (CMB), over the whole sky, with an uncertainty on the temperature limited by "natural causes" (foreground fluctuations, cosmic variance) rather than intrinsic or systematic detector noises, and an angular resolution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



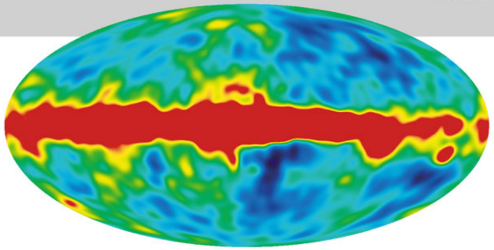
CMB space mission experiments overview – Planck: 3rd Generation

1965 Penzias and Wilson

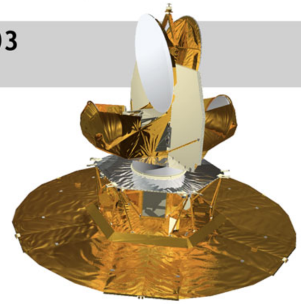


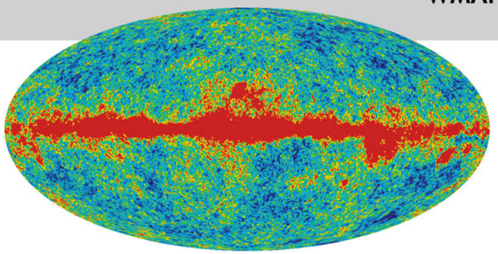


1992 COBE

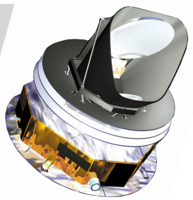


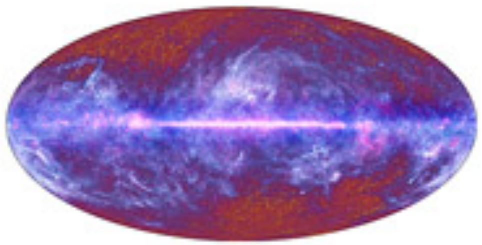
2003 WMAP





2009 *Planck*





The oldest light or the first light of the Universe

Discovered the remnant afterglow from the **Big Bang**.
→ **2.7 K**

Blackbody radiation,
Discovered the patterns (**anisotropy**) in the afterglow.
→ **angular scale ~ 7°** at a level $\Delta T/T$ of 10^{-5}

(Wilkinson Microwave Anisotropy Probe):
→ **angular scale ~ 15’**

→ **angular scale ~ 5’,**
$\Delta T/T \sim 2\times10^{-6}$, 30~867 Hz

Planck Scientific Objectives

The unrivalled accuracy of *Planck* on the whole sky will allow us to:

- **Pin down the basic characteristics of the Universe: age, contents, dynamics, geometry, …**
- **Examine the origins of the Universe and test inflation**
- **Probe physics at extremely high energies, e.g. superstrings, neutrinos**
- **Probe the birth of the first stars and galaxies**

& also

- **Understand the evolution of structures, galaxies and clusters of galaxies; Observe our own Galaxy as never seen before …**

→ Key non-CMB science with *Planck* includes:

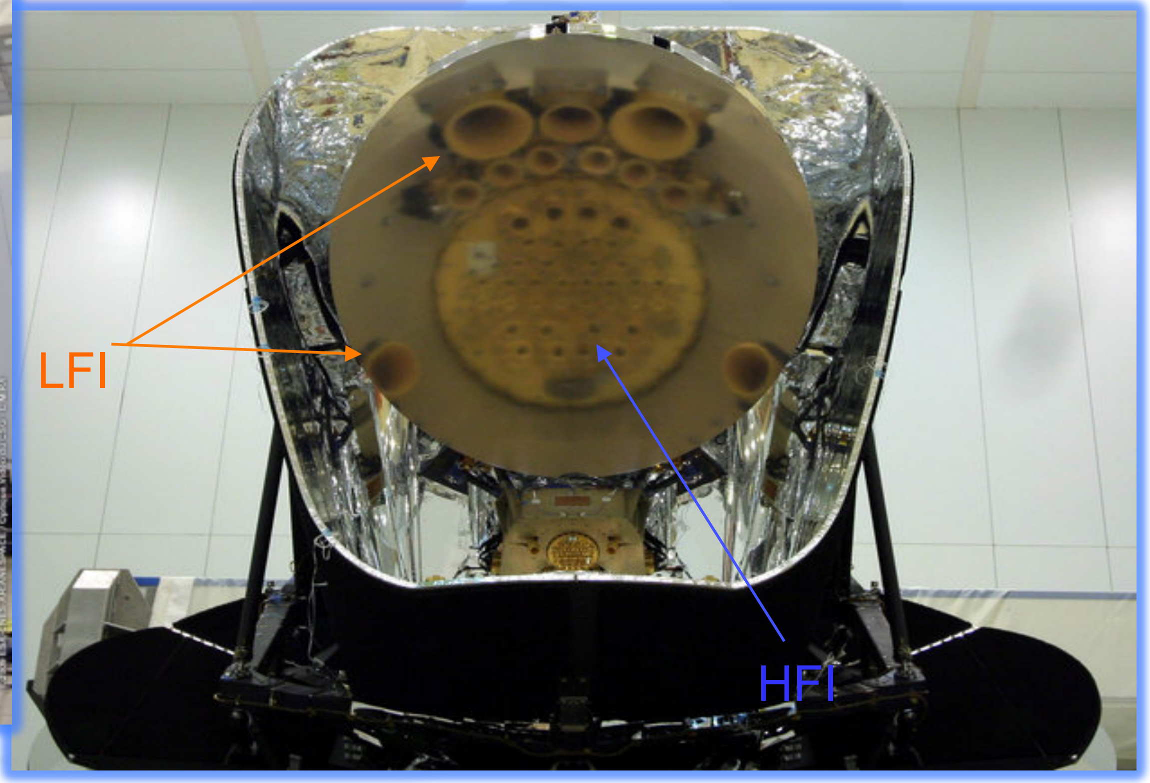
- ❖ **The Cosmic Infrared Background**
- ❖ **Sunyaev-Zeldovich selected sources**
- ❖ **Extragalactic sources and backgrounds**
- ❖ **Maps of Milky Way at frequencies 30-1000 GHz**

… and all related science ☺

Planck is composed by two instruments:

- The Low Frequency Instrument (LFI) based on EMT receivers and
- The High Frequency Instrument (HFI) based on bolometers

@ focal plane of a1.5 m Gregorian telescope



PLANCK HAS BEEN SUCCESSFULLY LAUNCHED ON THE 14 OF MAY 2009, TOGETHER WITH HERSCHEL, ON ARIANE 5 VECTOR

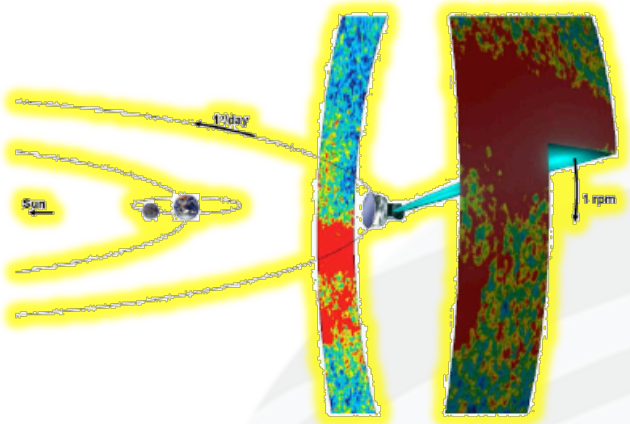
Is acquiring data since the 15 August 2009,

In January 2012 HFI was switched off and since then Planck is in LFI only mode

Survey	Instrument	Beginning	End	Coverage[a]
1	LFI & HFI	12 August 2009 (14:16:51 UT)	2 February 2010 (20:51:04 UT)	93.1 %
2	LFI & HFI	2 February 2010 (20:54:43)	12 August 2010 (19:27:20 UT)	93.1 %
3[b]	LFI & HFI	12 August 2010 (19:30:44)	8 February 2011 (20:55:55 UT)	93.1 %
4	LFI & HFI	8 February 2011 (20:59:10)	29 July 2011 (17:13:32)	86.6 %
5[c]	LFI & HFI	29 July 2011 (18:04:49)	1 February 2012 (05:26:29 UT)	80.1 %
6	LFI	14 January 2012	July 2012	
7	LFI	July 2012	Jan 2013	
8	LFI	Jan 2013	August 2013	

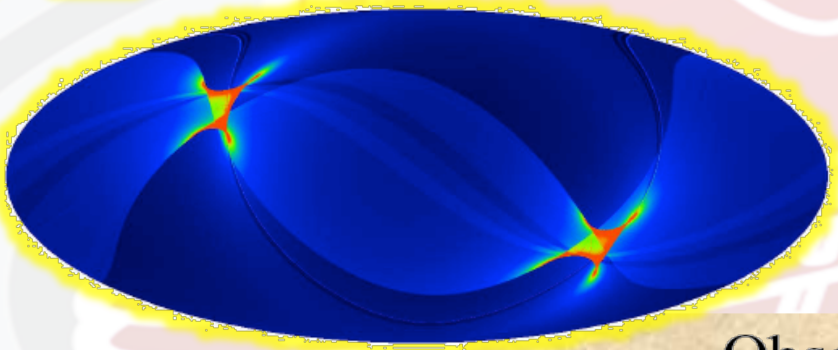
[a] Fraction of the sky covered by all frequencies
[b] End of Nominal period = 28 November 2010 (12:00:53 UT)
[c] End of data acquisition with HFI = 13 January 2012 (14:54:07 UT)

Planck Scanning Strategy



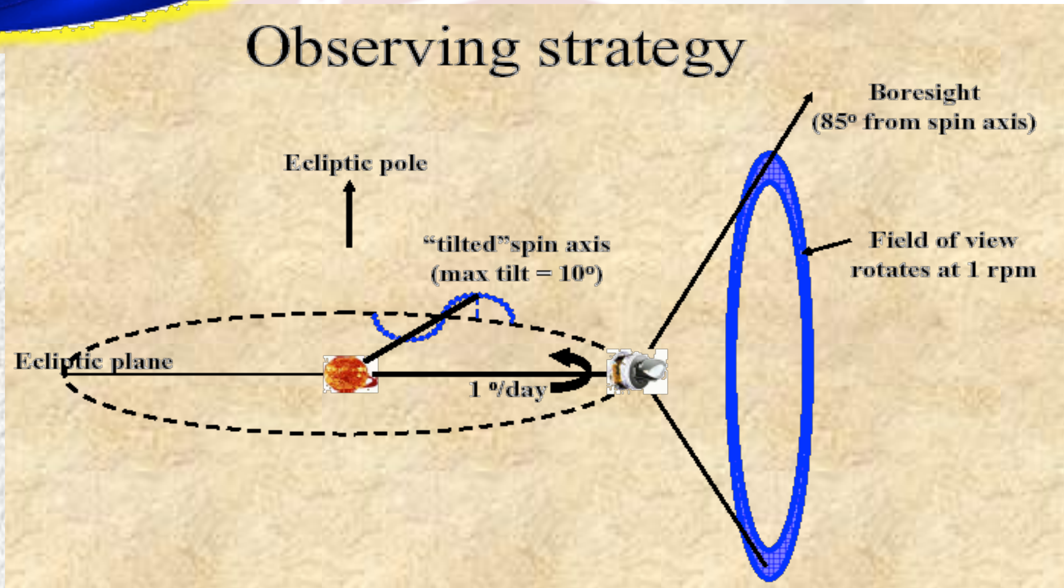
Planck is a survey mission

About 6 months are needed to cover ~95% of the sky.



Survey ≥ 5:
cycloid phase shifted by 90 deg.

During LFI only phase (surveys 6-8): scanning strategy combines standard mode with deep annuli on calibration sources to improve the quality of calibration and systematic effect control.



All the results are presented in 28 papers by the *Planck* Collaboration

- I — Overview of products & results
  - Frequency Maps
  - Component Maps
  - Power Spectra
  - Parameters
- II — LFI Processing
  - III — LFI Systematics
  - IV — LFI Beams
  - V — LFI Calibration
- VI — HFI Processing
  - VII — HFI Time Response & Beams
  - VIII — HFI Calibration
  - IX — HFI Spectral Response
  - X — HFI Particle effects
- XI — Consistency of the Data
- XII — Component Separation
  - XIII — Galactic CO
  - XIV — Zodiacal Emission
- XV — Power Spectra & Likelihood
- XVI — Cosmological Parameters
- XVII — Lensing by LSS
- XVIII — Lensing by Star-forming Galaxies
- XIX — The Integrated Sachs-Wolfe Effect
- XX — Cosmology from SZ Counts
- XXI — Compton Parameter Map
- XXII — Inflation
- XXIII — Isotropy & Statistics
- XXIV — Primordial Non-Gaussianity
- XXV — Strings & Other Defects
- XXVI — Background Geometry & Topology
- XXVII — Special Relativistic Effects on the Dipole
- XXVIII — Catalogue of Compact Sources
- XXIX — Catalogue of SZ Sources

Planck 2013 papers

Planck 2013 results. I. Overview of products and scientific results
Planck 2013 results. II. The Low Frequency Instrument data processing
Planck 2013 results. III. LFI systematic uncertainties
Planck 2013 results. IV. Low Frequency Instrument beams and window functions
Planck 2013 results. V. LFI calibration
Planck 2013 results. VI. High Frequency Instrument data processing
Planck 2013 results. VII. HFI time response and beams
Planck 2013 results. VIII. HFI photometric calibration and mapmaking
Planck 2013 results. IX. HFI spectral responseremoval, and simulation
Planck 2013 results X. Energetic particle effects: characterization, removal, and simulation
Planck 2013 results. XII. Component separation
Planck 2013 results. XIII. Galactic CO emission
Planck 2013 results. XIV. Zodiacal emission
Planck 2013 results. XV. CMB power spectra and likelihood
Planck 2013 results. XVI. Cosmological parameters
Planck 2013 results. XVII. Gravitational lensing by large-scale structure
Planck 2013 results. XVIII. Gravitational lensing-infrared correlation
Planck 2013 results. XIX. The integrated Sachs-Wolfe effect
Planck 2013 results. XX. Cosmology from Sunyaev–Zeldovich cluster counts
Planck 2013 results. XXI. Cosmology with the all-sky Planck Compton parameter y-map
Planck 2013 results. XXII. Constraints on inflation
Planck 2013 results. XXIII. Isotropy and statistics of the CMB
Planck 2013 results. XXIV. Constraints on primordial non-Gaussianity
Planck 2013 results. XXV. Searches for cosmic strings and other topological defects
Planck 2013 results. XXVI. Background geometry and topology of the Universe
Planck 2013 results. XXVII. Doppler boosting of the CMB: Eppur si muove
Planck 2013 results. XXVIII. The Planck Catalogue of Compact Sources
Planck 2013 results. XXIX. Planck catalogue of Sunyaev–Zeldovich sources
Planck intermediate results. XIII. Constraints on peculiar velocities

PLANCK IN SUMMARY: 9 FREQUENCIES BETWEEN 30 GHz AND 1 THz

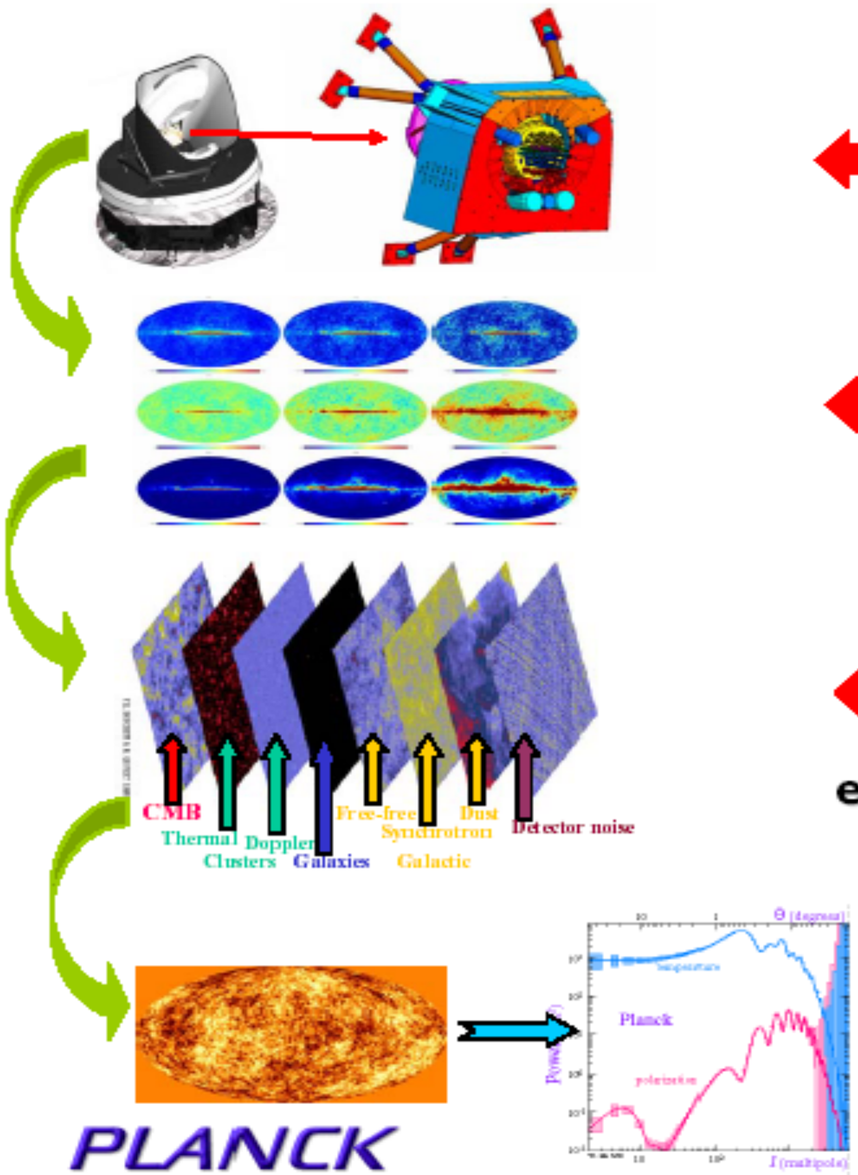
Channel	$N_{detectors}$ [a]	ν_{center} [b] [GHz]	Scanning Beam [c] FWHM [arcm]	Scanning Beam [c] Ellipticity	Noise [d] Sensitivity $[\mu K_{RJ}\,s^{1/2}]$	Noise [d] Sensitivity $[\mu K_{CMB}\,s^{1/2}]$
30 GHz	4	28.4	33.16	1.37	145.4	148.5
44 GHz	6	44.1	28.09	1.25	164.8	173.2
70 GHz	12	70.4	13.08	1.27	133.9	151.9
100 GHz	8	100	9.59	1.21	31.52	41.3
143 GHz	11	143	7.18	1.04	10.38	17.4
217 GHz	12	217	4.87	1.22	7.45	23.8
353 GHz	12	353	4.7	1.2	5.52	78.8
545 GHz	3	545	4.73	1.18	2.66	0.0259[d]
857 GHz	4	857	4.51	1.38	1.33	0.0259[d]

FOR TEMPERATURE ANALYSES

PLANCK SENSITIVITY AND ANGULAR RESOLUTION ARE ENOUGH TO BE ESSENTIALLY COSMIC VARIANCE LIMITED … BUT ALSO LIMITED (ONLY) BY THE CAPABILITY TO REMOVE THE CONTAMINATION BY ASTROPHYSICAL SIGNAL

WIDE FREQUENCY RANGE CLEARLY HELPS

HOW TO EXTRACT INFORMATION FROM THE MEASUREMENTS



Acquiring and processing time-ordered information

Converting time-ordered data to maps of the sky emission at many frequencies

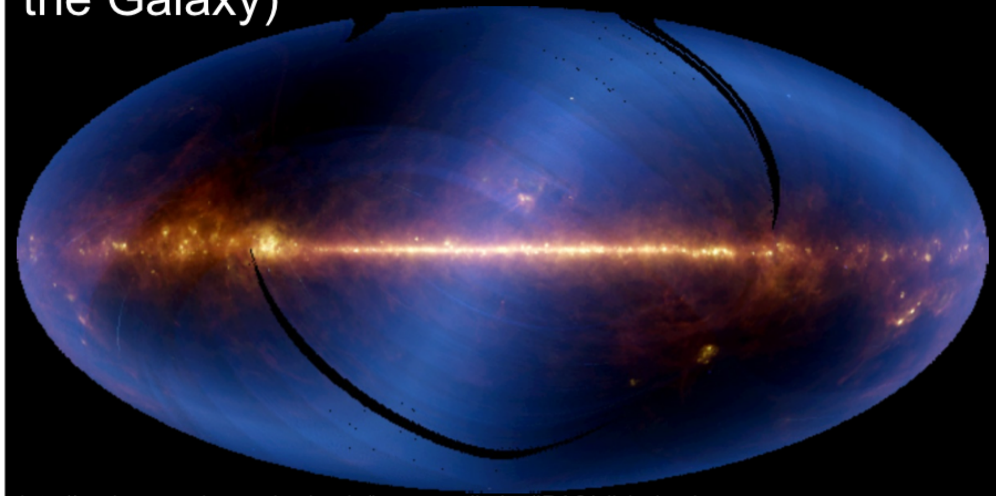
Converting frequency maps to component maps, e.g. the Cosmic Microwave Background

Estimating the CMB angular power spectrum and cosmological parameters

esa ASTROPHYSICS

Zodiacal emission

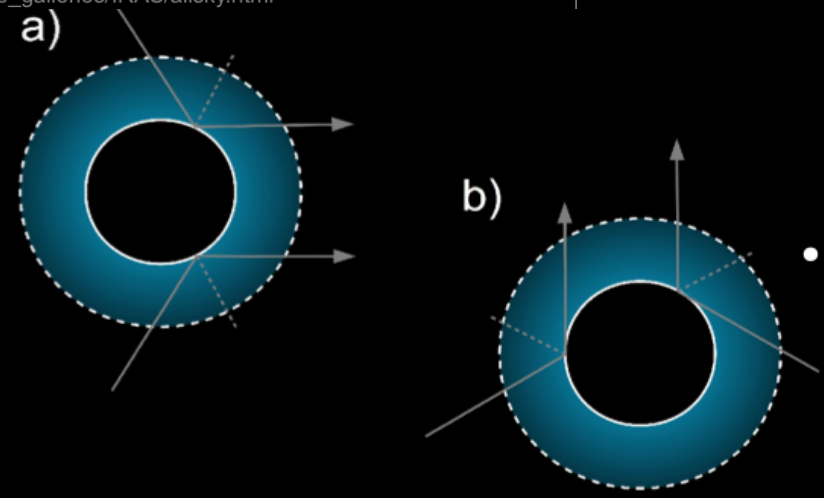
...measured by IRAS (it's the white 'S', not the Galaxy)



http://coolcosmos.ipac.caltech.edu/image_galleries/IRAS/allsky.html

Classical ZLE:

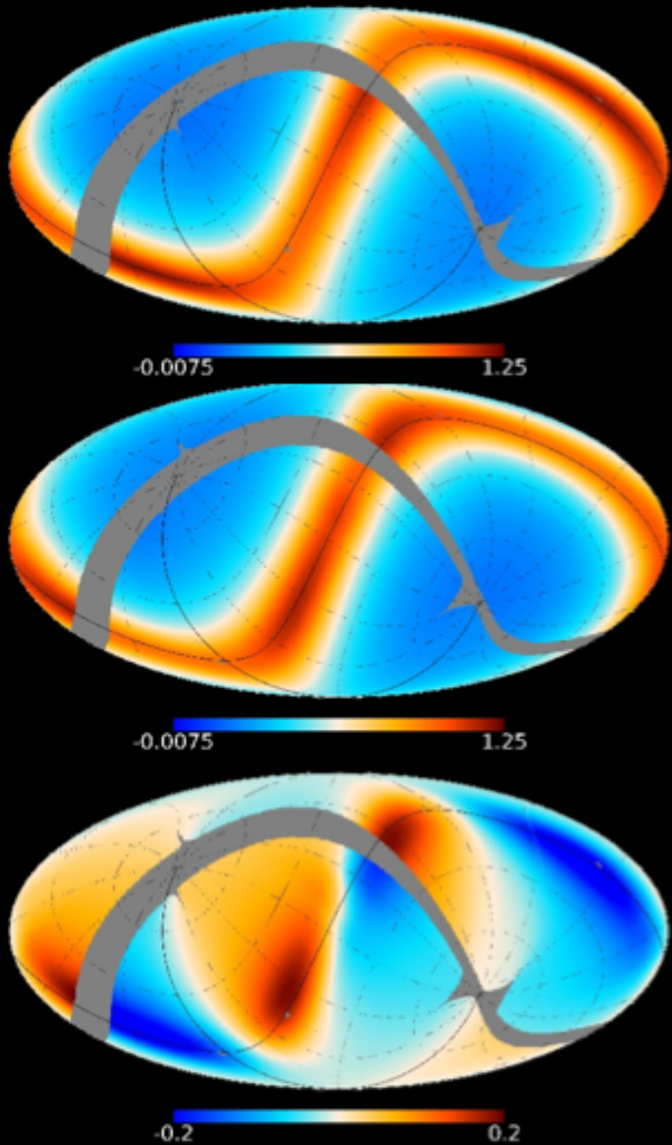
Separated in "time domain", for now simply exploiting differences in surveys



- In successive surveys we observe similar, but different total columns of interplanetary (local) dust (IPD)
- Making differences of successive surveys allows us to remove "contamination", but still be sensitive to the IPD

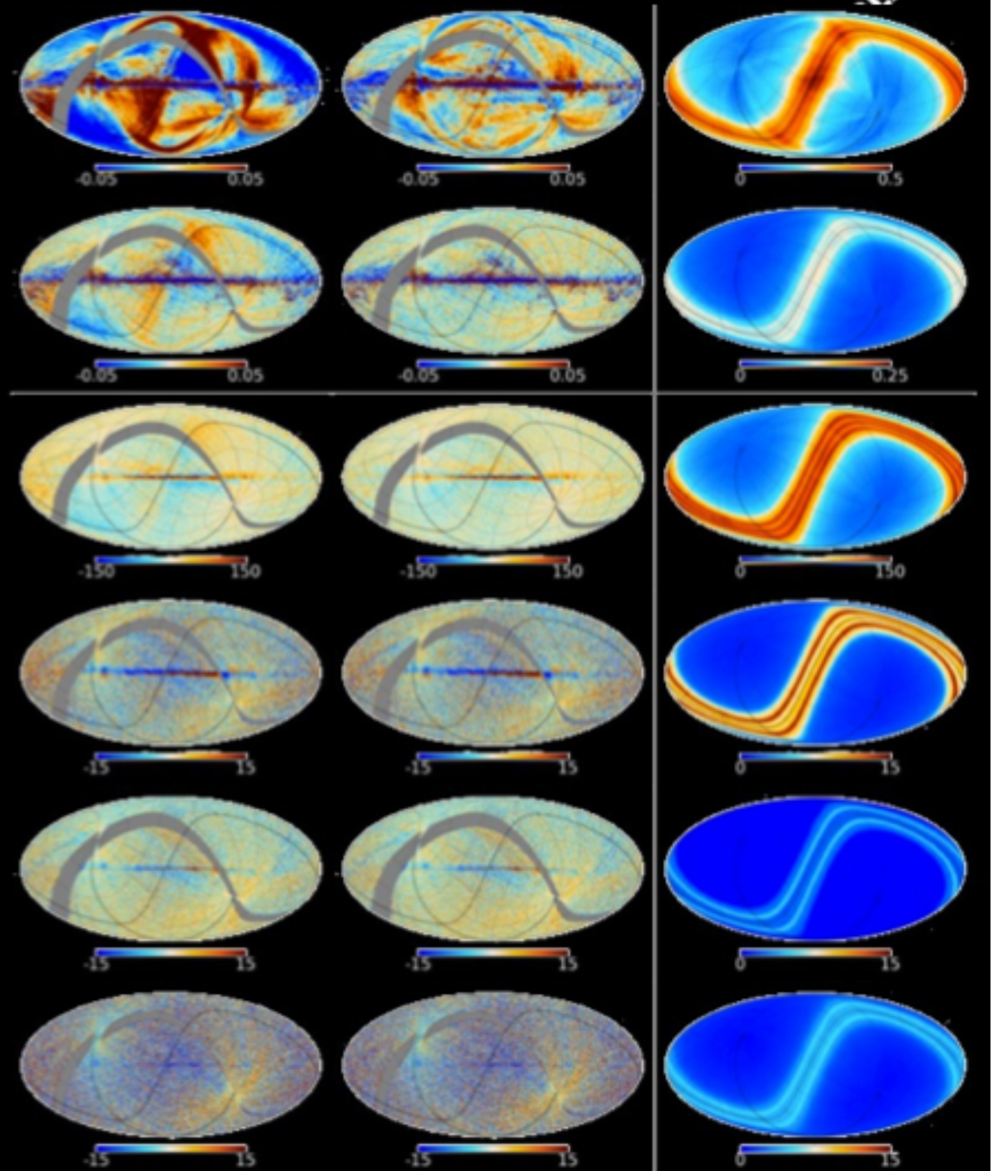
The Diffuse Cloud

- This is what we usually think about when we talk about the IDP
- It varies with our “cycloid” scanning strategy
- The difference is about what we will use to detect it.
- Top: Survey 1;
  Middle: Survey 2;
  Bottom: Survey Difference
  (Survey 2 minus Survey 1)

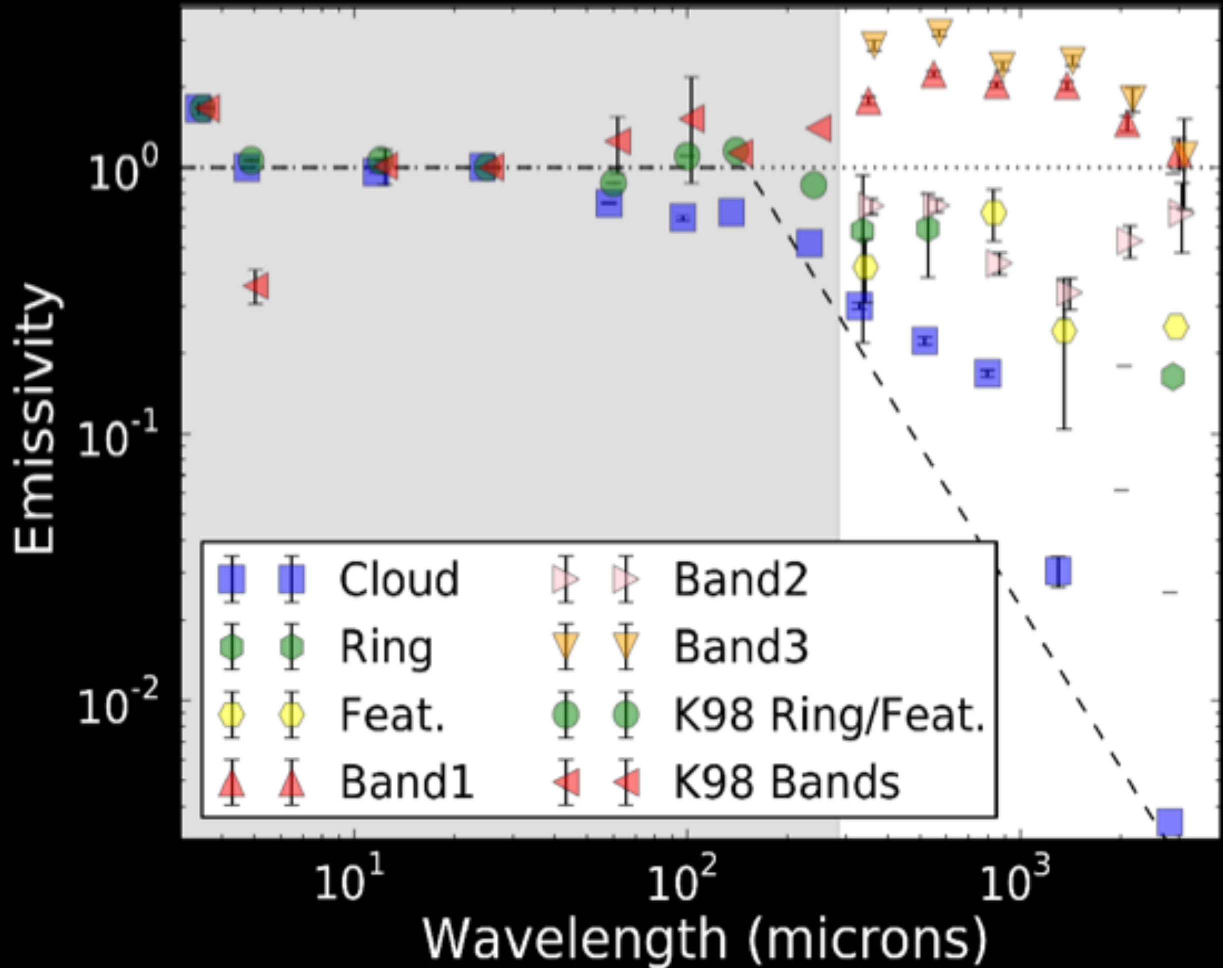


The data

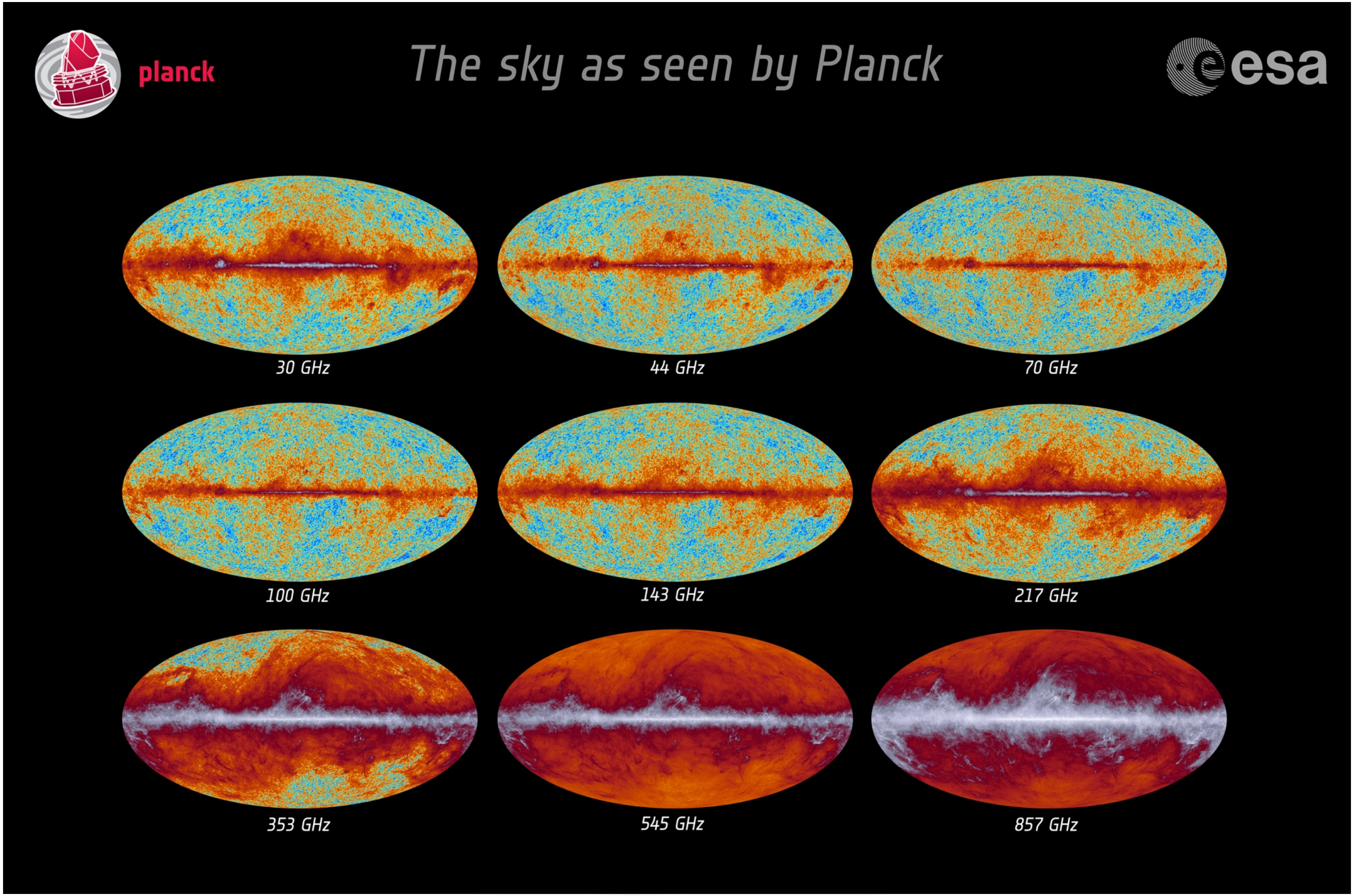
- We fit to the survey *differences*
- Left: Before Zodi Removal
- Middle: After Zodi Removal
- Right: Difference



Emissivities

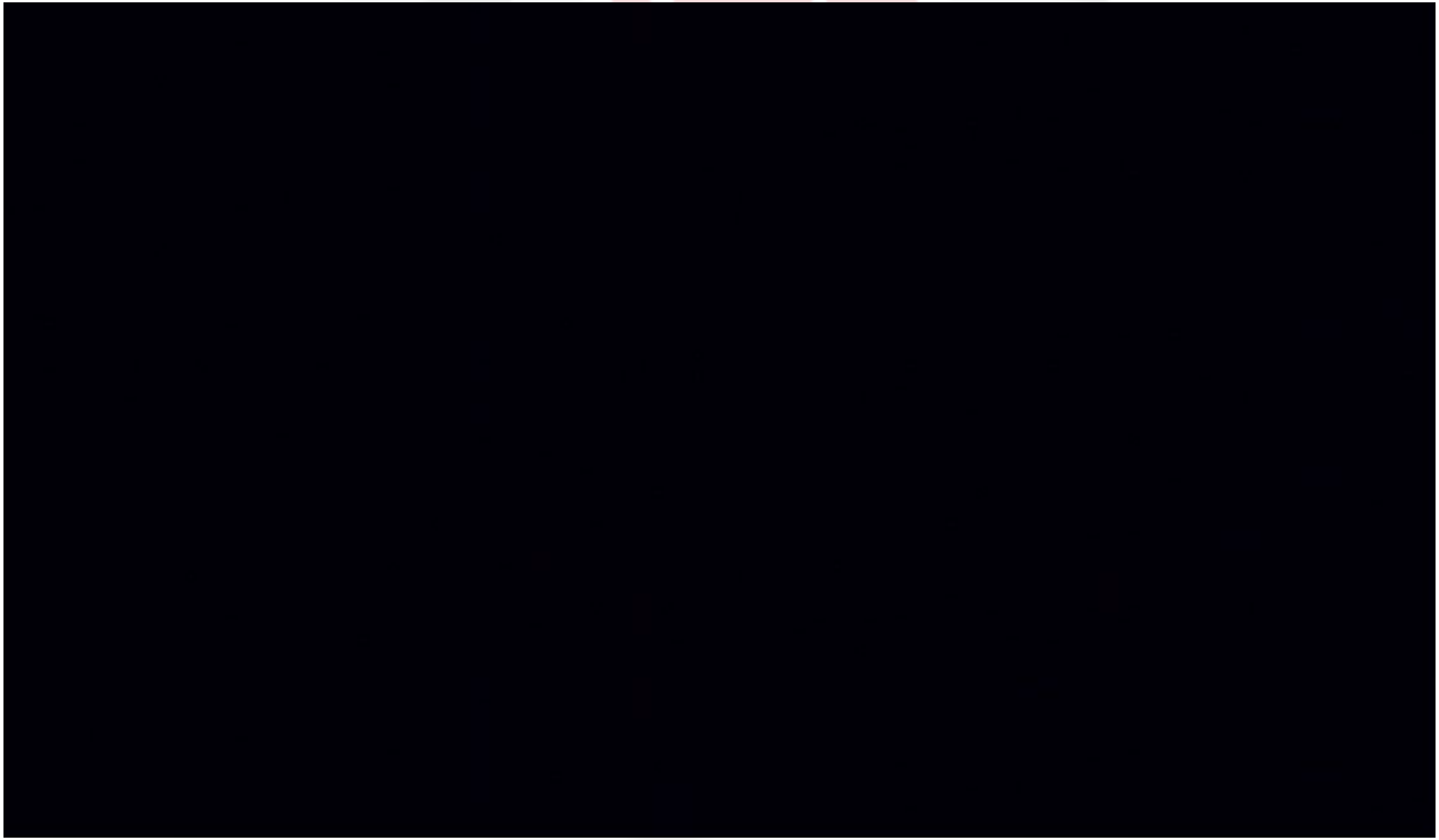


- The Diffuse Cloud descends as expected (Fixsen&Dwek)
- The Dust Bands are different
  - Band 2 is different from Bands 1 & 3
- I don't know what to make of the Ring and Feature


planck
The sky as seen by Planck
esa
30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz

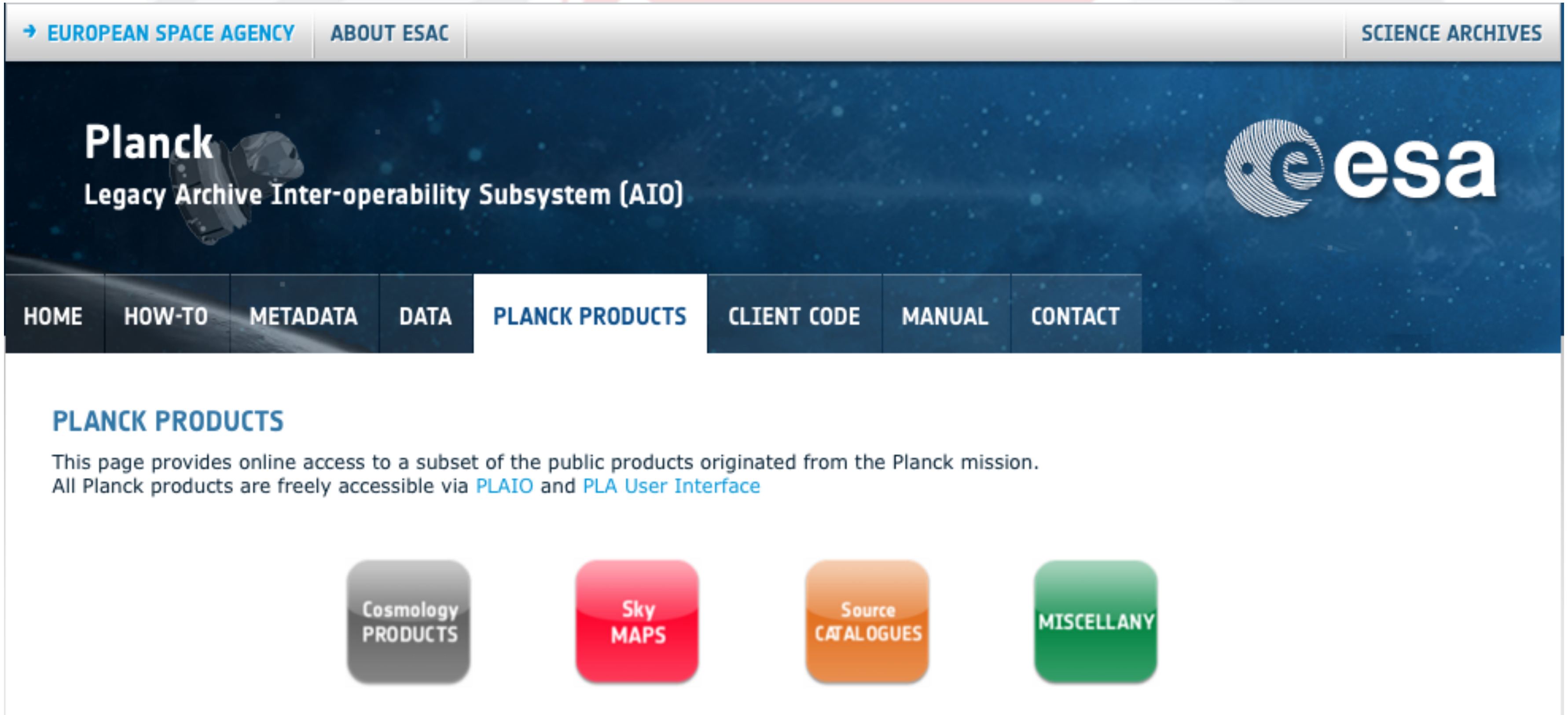
PLANCK MICROWAVE SKY

http://spaceinvideos.esa.int/Missions/Planck



Brief Overview of *Planck* Products

http://www.sciops.esa.int/index.php?project=planck&page=Planck_Legacy_Archive



Source Catalogues

[–]

Source Catalogues

ALIAS LINK	DESCRIPTION
PCCS_1.0	List of compact sources detected by Planck over the entire sky, and which contains both Galactic and extragalactic objects.
PCCS_SZ	A catalogue of galaxy clusters detected through Sunyaev-Zeldovich effect.
ERCSC	A list of high reliability sources, both Galactic and extragalactic, derived from the data acquired by Planck between August 13 2009 and June 6 2010.

PLANCK PRODUCTS

A catalogue of galaxy clusters detected through Sunyaev-Zeldovich effect.

PCCS_SZ

[–]

Total number of records available: 4

NAME	DATA_LINK	SIZE
COM_PCCS_SZ-MMF1_R1.11.fits	Retrieve Data	217399680
COM_PCCS_SZ-MMF3_R1.11.fits	Retrieve Data	231557760
COM_PCCS_SZ-PwS_R1.11.fits	Retrieve Data	224213760
COM_PCCS_SZ-union_R1.11.fits	Retrieve Data	129600

The *Planck* Catalogue (PCCS)

Table 1. PCCS characteristics

Channel	30	44	70	100	143	217	353	545	857
Freq [GHz]	28.4	44.1	70.4	100.0	143.0	217.0	353.0	545.0	857.0
λ [μm]	10561	6807	4260	3000	2098	1382	850	550	350
Beam FWHM[a] [arcmin]	32.38	27.10	13.30	9.65	7.25	4.99	4.82	4.68	4.33
S/N thresholds									
Full sky	4.0	4.0	4.0	4.6	4.7	4.8	...	...	...
Extragactic zone[b]	...	...	...	...	...	...	4.9	4.7	4.9
Galactic zone[b]	...	...	...	...	...	...	6.0	7.0	7.0
Number of sources									
Full sky	1256	731	939	3850	5675	16070	13613	16933	24381
$\|b\| > 30°$	572	258	332	845	1051	1901	1862	3738	7536
Flux densities									
Minimum[c] [mJy]	461	825	566	266	169	149	289	457	658
90 % completeness [mJy]	575	1047	776	300	190	180	330	570	680
Uncertainty [mJy]	109	198	149	61	38	35	69	118	166
Position uncertainty[d] [arcmin]	1.8	2.1	1.4	1.0	0.7	0.7	0.8	0.5	0.4

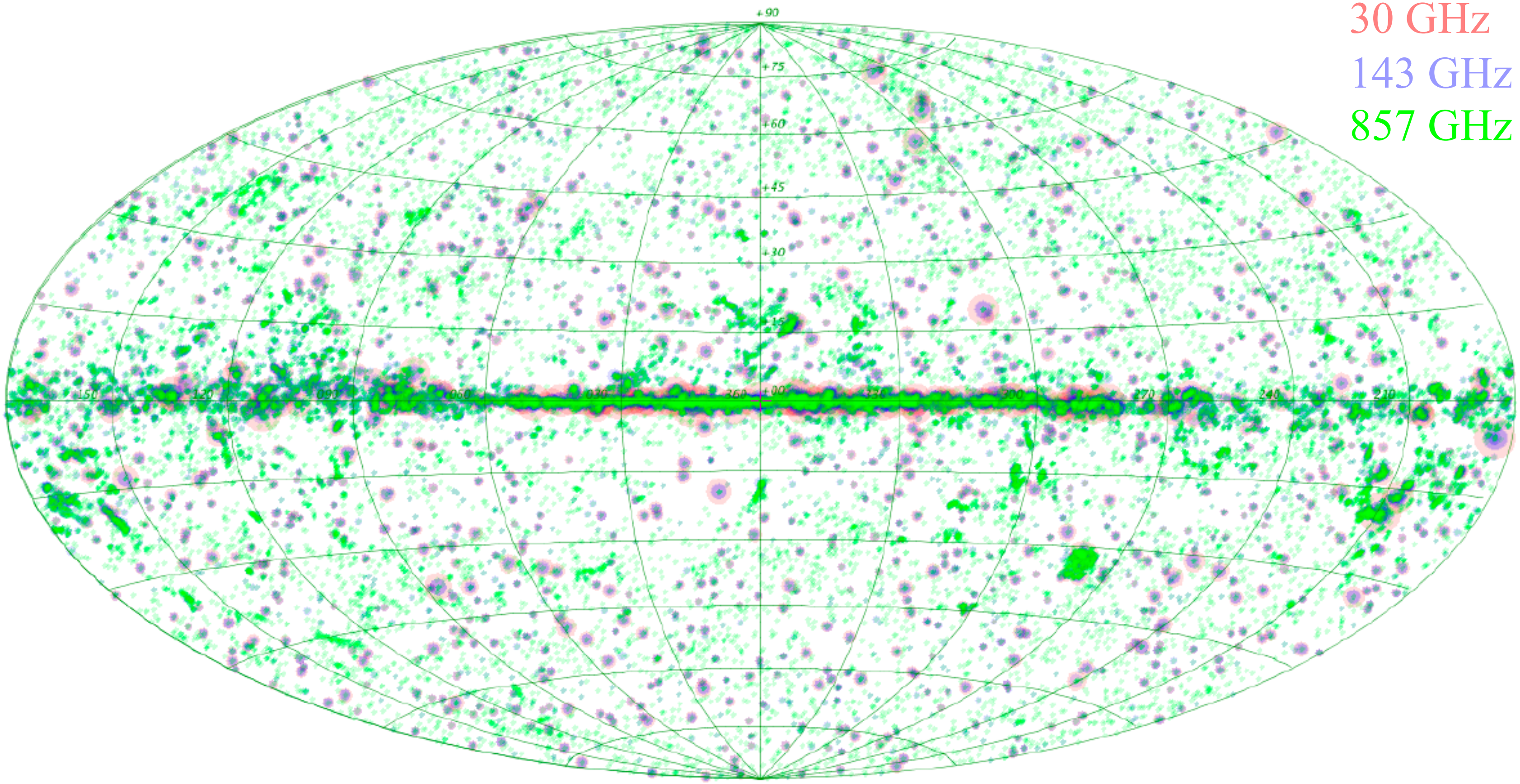
[a] FEBeCoP band-averaged effective beam. This table shows the exact values that were adopted for the PCCS. For HFI channels, these are the FWHM of the mean best-fit Gaussian. For the LFI channels, we use $FWHM_{\rm eff} = \sqrt{\frac{\Omega_{\rm eff}}{2\pi} 8 \log 2}$, where $\Omega_{\rm eff}$ is the FEBeCoP band-averaged effective solid angle (see Planck Collaboration IV 2013 and Planck Collaboration VII 2013 for a full description of the *Planck* beams). When we constructed the PCCS for the LFI channels we used a value of the effective FWHM slightly different (by $\ll 1\%$) of the final values specified in the Planck Collaboration IV (2013) paper. This small correction will be made in later versions of the catalogue.

[b] The Galactic and extragalactic zones are defined in Sect. 2.3.

[c] Minimum flux density of the catalogue at $|b| > 30°$ after excluding the faintest 10 % of sources.

[d] Positional uncertainty derived by comparison with PACO sample (Massardi et al. 2011; Bonavera et al. 2011; Bonaldi et al. 2013) up to 353 GHz and with *Herschel* samples in the other channels (see Sect. 3.2.3 for more details).

PCCS: Characteristics



Many of the Planck PCCS sources can be associated with stars with dust shells, stellar cores, radio galaxies, blazars, infrared luminous galaxies and Galactic interstellar medium features.

As expected, the high frequency channels (545 and 857 GHz) are dominated (> 90 %) by dusty galaxies and the low frequency ones are dominated (> 95 %) by synchrotron sources.

PCCS: Statistical properties

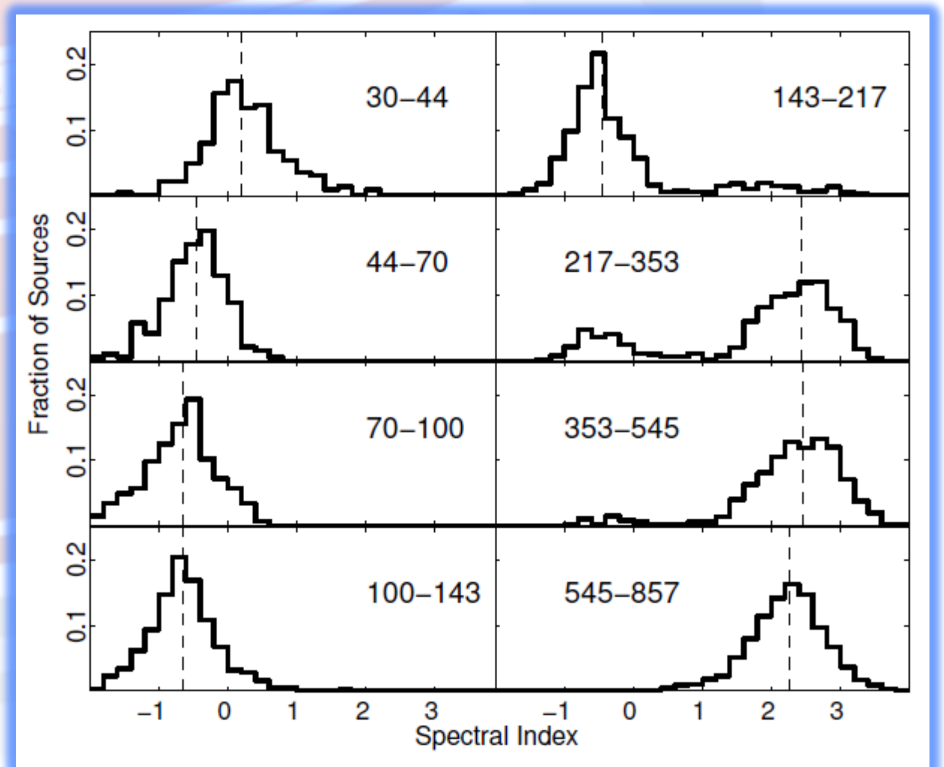
- Special effort to use simple selection procedures.
- With a common detection method and three additional photometries, spectral analysis can also be done safely.

- High level of matching sources between neighbouring channels
- Some of the previous results (Planck Collaboration XIII, 2011; Planck Collaboration Int. VII, 2013) are easily confirmed

Table 3. Summary of sources matched between neighbouring channels.

Channel	No. sources	No. matched		Frac. matched
		Above and below	Above or below	
30[a]	1256	...	629	50.1%
44.....	731	530	664	90.8%
70.....	939	552	815	86.8%
100....	3850	772	2758	71.6%
143....	5675	2454	4645	81.9%
217....	16070	3351	10624	66.1%
353....	13613	8029	12079	88.7%
545....	16933	9382	14535	85.8%
857[b] ..	24381	6904	18061	74.9 %

[a] The 30 GHz channel is only matched with the 44 GHz channel above.
[b] The 857 GHz channel is matched above with a catalogue extracted from the IRIS maps using the HFI–MHW. Both catalogues were cut with the IRIS mask prior to matching.

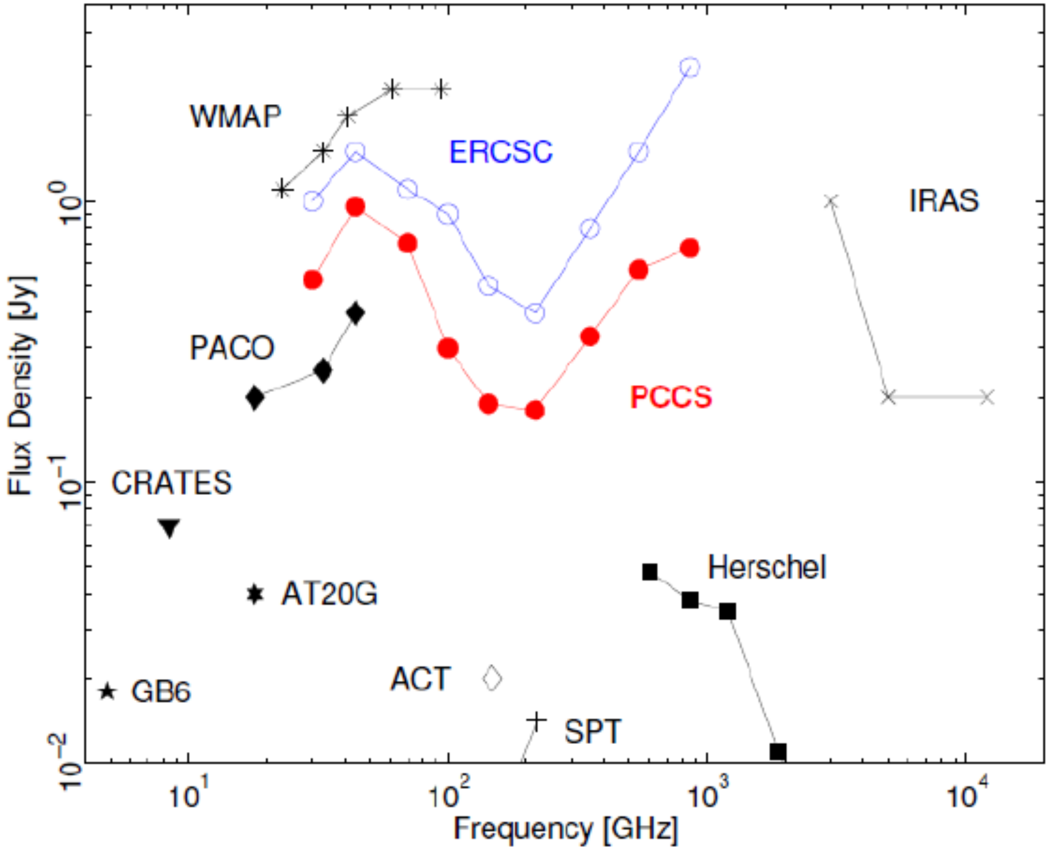


The *Planck* Catalogue (PCCS)

…but the PCCS has not been analyzed, yet! (future papers → 2014-15)

PCCS: Sensitivity

- PCCS is the most complete all-sky catalogue in the microwave band.



PCCS (2013) vs ERCSC (2011)

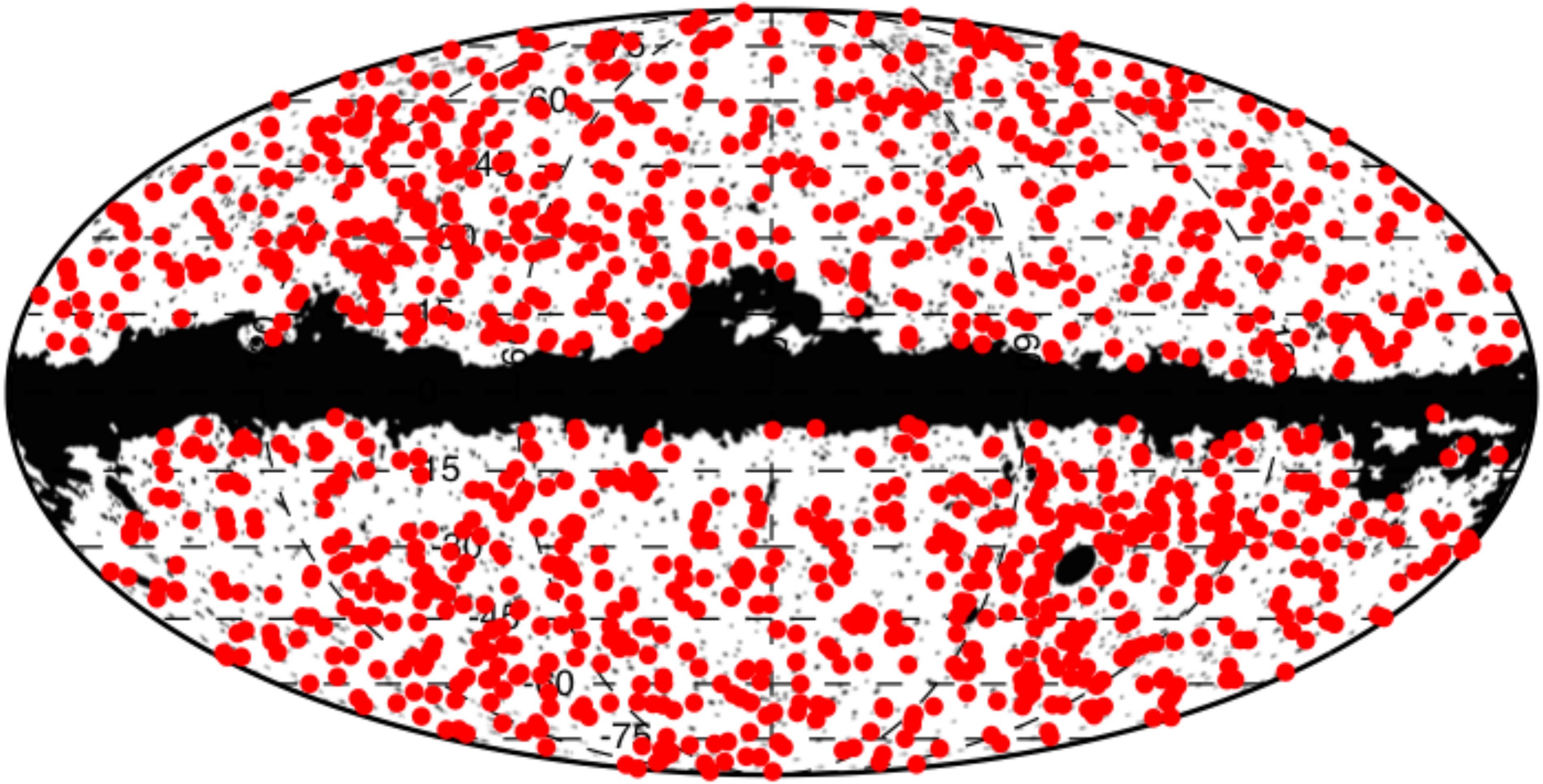
PCCS: Comparison with ERCSC

- One of the primary goals of the ERCSC was to provide an early catalogue of sources for follow-up observations with existing facilities, in particular *Herschel*, while they were still in their cryogenic operational phase.
- The PCCS differs from the ERCSC both in the data and the philosophy.
  - Data: 2.6 surveys vs 1.6 surveys, i.e., better sensitivity.
  - Better knowledge of the instruments, i.e., improved calibration and quality of the maps.
  - Better characterization of the beams (~2-8% variation with respect to the ERCSC beam solid angles)
  - Simplification of the selection procedure, i.e., easier statistical analysis
  - Relaxation of the Reliability constraint to ~80%
    - Higher number of detections per channel (a factor ~2-4 more sources) and better completeness.
    - Explore possibly interesting new sources at fainter flux density levels (unidentify blazars, high-z sources, lensed galaxies, …).

Planck 2013 results. XXIX. Planck catalogue of Sunyaev–Zeldovich sources

- The catalogue contains **1227 entries**, making it over six times the size of the Planck Early SZ (ESZ) sample and the largest SZ-selected deepest all-sky cluster ccatalogue to date.
- It contains **861 confirmed** clusters: 178 have been confirmed as clusters, mostly through follow-ups, and a further 683 are previously-known.
- 366 are cluster candidates: three classes according to the quality of evidence that they are likely to be true clusters.
- z to ≅ 1, broadest **range from (0.1 to 1.6) × 10^{15} $M_{\odot}$**.
- **Confirmation** of cluster candidates through comparison with existing surveys or cluster catalogues, catalogue statistical characterization in terms of completeness and statistical reliability. **Validation** process through additional information.
- This gives an ensemble of **813 cluster redshifts**, and for all these *Planck* clusters we also include a **mass** estimated from a newly-proposed SZ-mass proxy.
- Refined measure of the **SZ Compton parameter** for the clusters with X-ray counter -parts, **X-ray flux** for all the *Planck* clusters not previously detected in X-ray surveys.

Mollweide projection with the Galactic plane horizontal and the Milky Way centre in the middle, of the
1227 *Planck clusters and candidates across the sky (red thick dots).*
Masked point-sources (black thin dots), Magellanic clouds (large black areas), Galactic mask, covering a total of 16.3% of the sky and used by the SZ-finder algorithms to detect SZ sources.



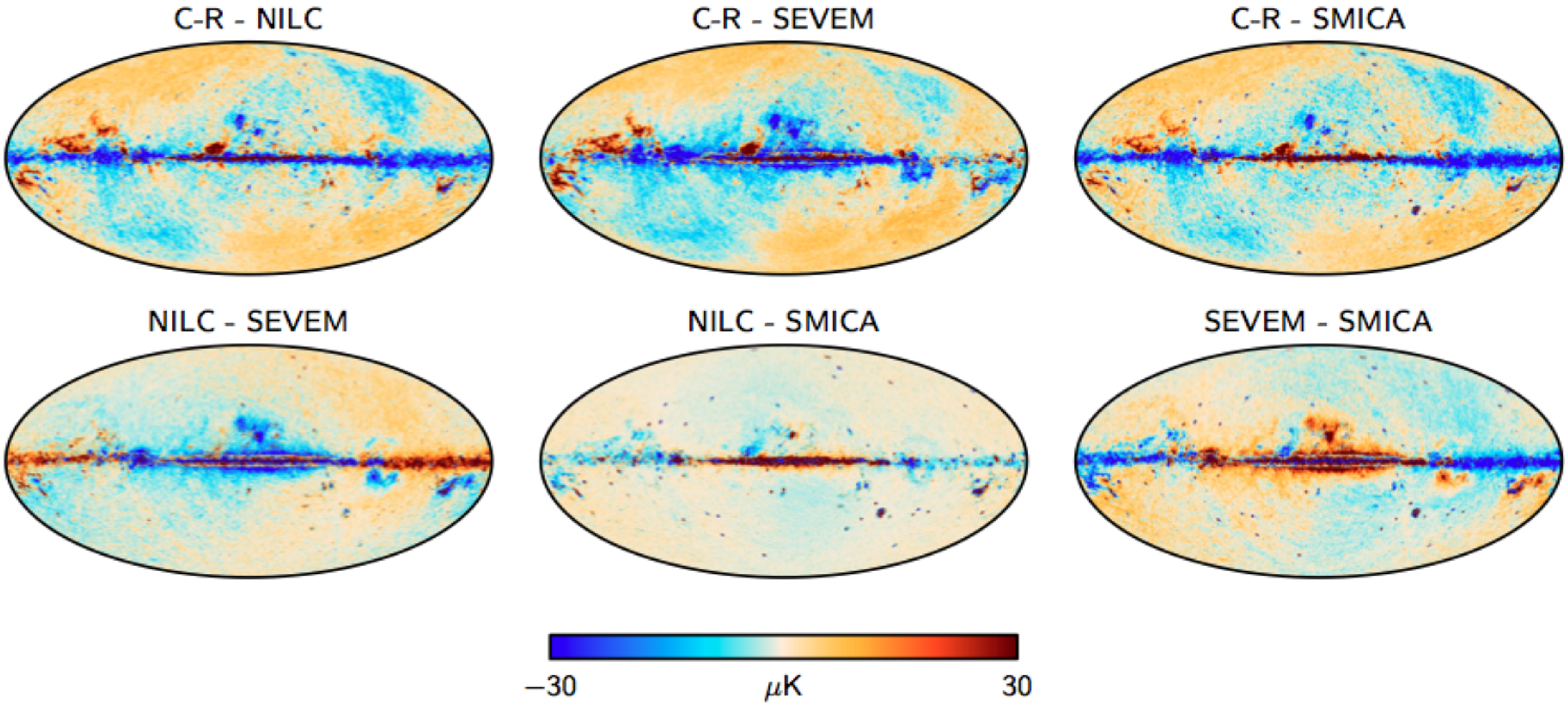
Component Separation of diffuse emissions in *Planck* – I

- Two algorithms based on model fitting
- Bayesian parameter fitting (Commander-Ruler, C-R)
  - Works in pixel domain
  - Fits parametrized model of the CMB and foregrounds to the data
  - Commander: MCMC sampling of amplitudes and spectral parameters at low resolution (40')
  - Ruler: solves for high-resolution amplitudes using Commander spectral parameters
  - 30 - 353 GHz channels
  - ~7.4' resolution
- Spectral matching (SMICA)
  - Work in harmonic domain
  - Fits model of CMB, generalized correlated foregrounds, and noise to the auto- and cross-spectra of the maps, then solves for amplitudes of CMB map
  - 30 - 857 GHz channels
  - 5' resolution, l_{max} = 4000
  - Version of CMB map filled with constrained realization in processing mask (3% of the sky)

Component Separation of diffuse emissions in *Planck* – II

- Two algorithms based on minimising the variance of CMB component
- Internal linear combination (NILC)
  - Works in needlet (wavelet) domain
  - Makes ILC at each needlet scale independently
  - 44 - 857 GHz channels
  - 5' resolution, $l_{max} = 3200$
- Template fitting (SEVEM)
  - Works in pixel domain
  - Uses internal templates produced by subtracting frequency channels after smoothing to common resolution: (30 - 44), (44 - 70), (857 - 535), (545 - 353)
  - Templates are used to clean 143 and 217 GHz maps
  - Combines maps afterwards in harmonic space to produce single CMB map
  - 5' resolution, $l_{max} = 3100$

Pairwise difference between CMB maps

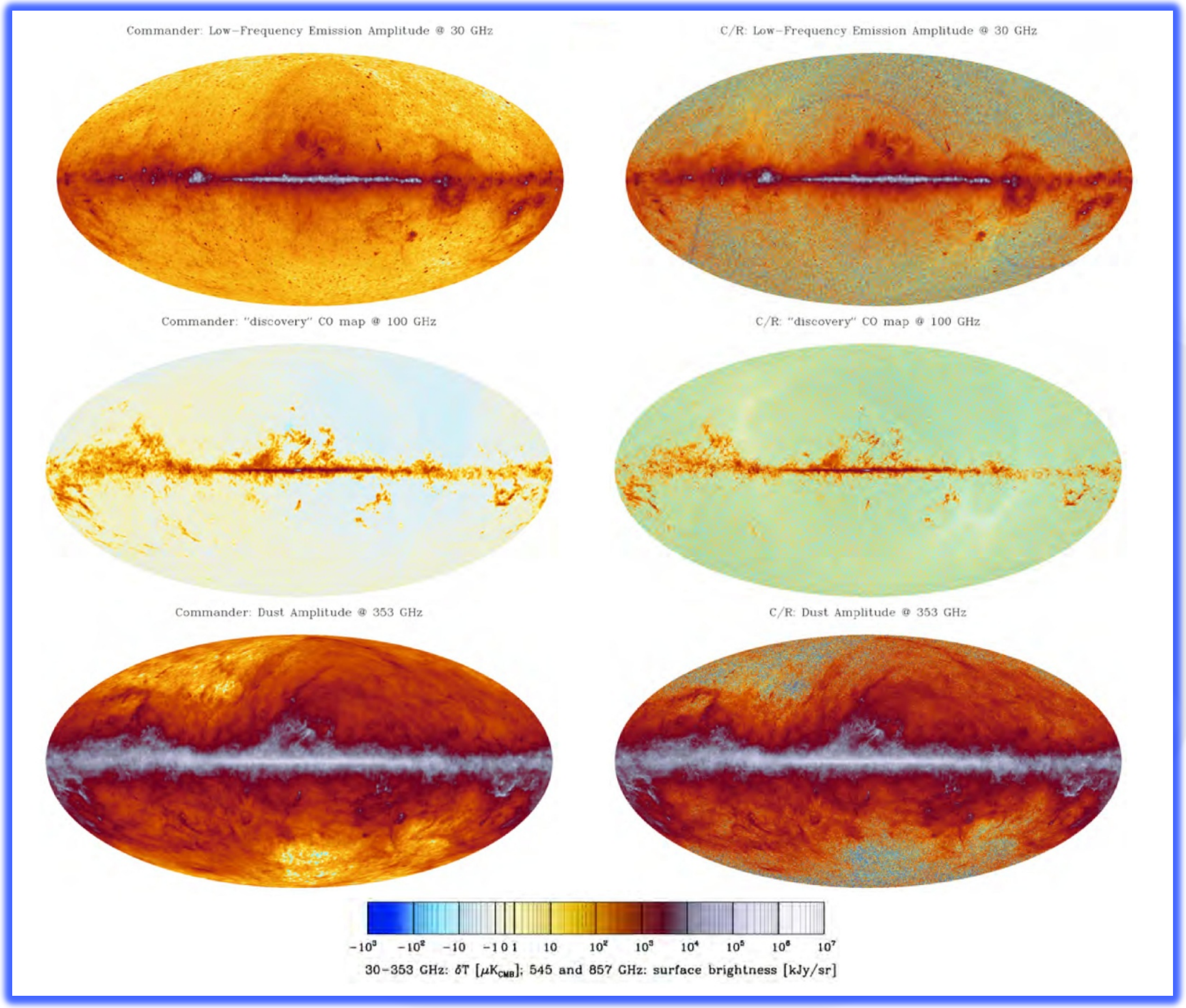


- Maps have been downgraded to N_{side} = 128 to show large scale features
- Large-scale features could be due to zodiacal light emission at high-frequencies
- Residuals at typically less than 5 μK at high Galactic latitude
- Discontinuity in SEVEM differences is due to two regions being used in the solution

Sky Maps

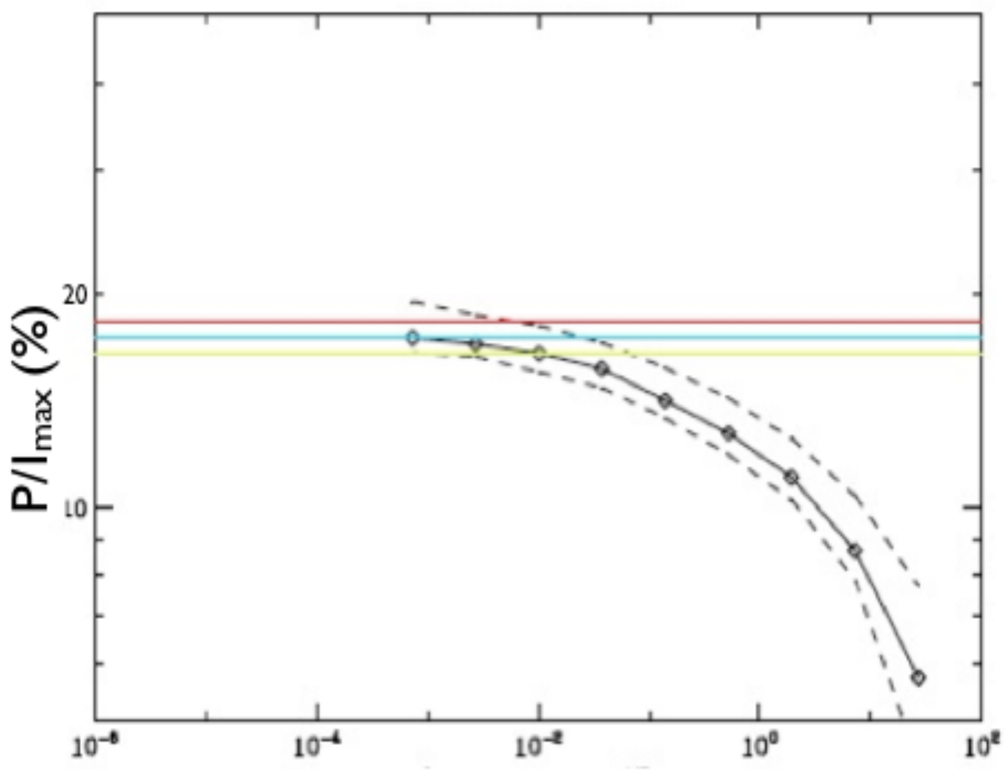
Sky Maps

ALIAS LINK	DESCRIPTION
MAIN CMB MAP	Map of the Cosmic Microwave Background fluctuations.
ALL NOMINAL FREQUENCY MAPS	Nine Main Frequency Maps.
NOMINAL FREQUENCY MAP - [30 GHZ]	All-sky maps at each of the nine Planck frequencies, based on the data acquired by Planck during its 'nominal' operations period, i.e. between 12 August 2009 and 27 November 2010.
NOMINAL FREQUENCY MAP - [44 GHZ]	All-sky maps at each of the nine Planck frequencies, based on the data acquired by Planck during its 'nominal' operations period, i.e. between 12 August 2009 and 27 November 2010.
NOMINAL FREQUENCY MAP - [70 GHZ]	All-sky maps at each of the nine Planck frequencies, based on the data acquired by Planck during its 'nominal' operations period, i.e. between 12 August 2009 and 27 November 2010.
NOMINAL FREQUENCY MAP - [100 GHZ]	All-sky maps at each of the nine Planck frequencies, based on the data acquired by Planck during its 'nominal' operations period, i.e. between 12 August 2009 and 27 November 2010.
NOMINAL FREQUENCY MAP - [143 GHZ]	All-sky maps at each of the nine Planck frequencies, based on the data acquired by Planck during its 'nominal' operations period, i.e. between 12 August 2009 and 27 November 2010.
NOMINAL FREQUENCY MAP - [217 GHZ]	All-sky maps at each of the nine Planck frequencies, based on the data acquired by Planck during its 'nominal' operations period, i.e. between 12 August 2009 and 27 November 2010.
NOMINAL FREQUENCY MAP - [353 GHZ]	All-sky maps at each of the nine Planck frequencies, based on the data acquired by Planck during its 'nominal' operations period, i.e. between 12 August 2009 and 27 November 2010.
NOMINAL FREQUENCY MAP - [545 GHZ]	All-sky maps at each of the nine Planck frequencies, based on the data acquired by Planck during its 'nominal' operations period, i.e. between 12 August 2009 and 27 November 2010.
NOMINAL FREQUENCY MAP - [857 GHZ]	All-sky maps at each of the nine Planck frequencies, based on the data acquired by Planck during its 'nominal' operations period, i.e. between 12 August 2009 and 27 November 2010.
COMPONENT MAP - CMB	Maps of the Cosmic Microwave Background fluctuations.
COMPONENT CO-TYPE1	Maps of the Galactic carbon monoxide emission.
COMPONENT CO-TYPE2	Maps of the Galactic carbon monoxide emission.
COMPONENT CO-TYPE3	Maps of the Galactic carbon monoxide emission.
COMPONENT DUST	Maps of the Galactic thermal dust emission.
COMPONENT DUSTOPACITY	Map of the Galactic thermal dust opacity.
COMPONENT LENSING	Map of the fiducial lensing potential.
COMPONENT LFREQFOR	Maps of the low-frequency Galactic emission.
COMPONENT MASK	Mask maps.


Commander: Low-Frequency Emission Amplitude @ 30 GHz
C/R: Low-Frequency Emission Amplitude @ 30 GHz
Commander: "discovery" CO map @ 100 GHz
C/R: "discovery" CO map @ 100 GHz
Commander: Dust Amplitude @ 353 GHz
C/R: Dust Amplitude @ 353 GHz
30-353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]

planck **Galactic dust emission** High polarization degree

Cumulative Histogram of P/I ratio
353 GHz and 1° resolution



- The observed degree of polarization $(P/I)_{obs}$ is up to 18%.

➡ **The intrinsic degree of dust polarization** $((P/I)_{dust} \geq (P/I)_{obs})$ **is high**

- This result is consistent with earlier results from the Archeops experiment (Benoit et al. 2004).

- $(P/I)_{dust}$ is likely to vary across the sky. Theory says alignment depends on the grain size distribution, the spectrum of the radiation field, and its orientation with respect to the B field. H_2 formation can also locally enhance $(P/I)_{dust}$ (Hoang & Lazarian 2008).

Cosmology Products

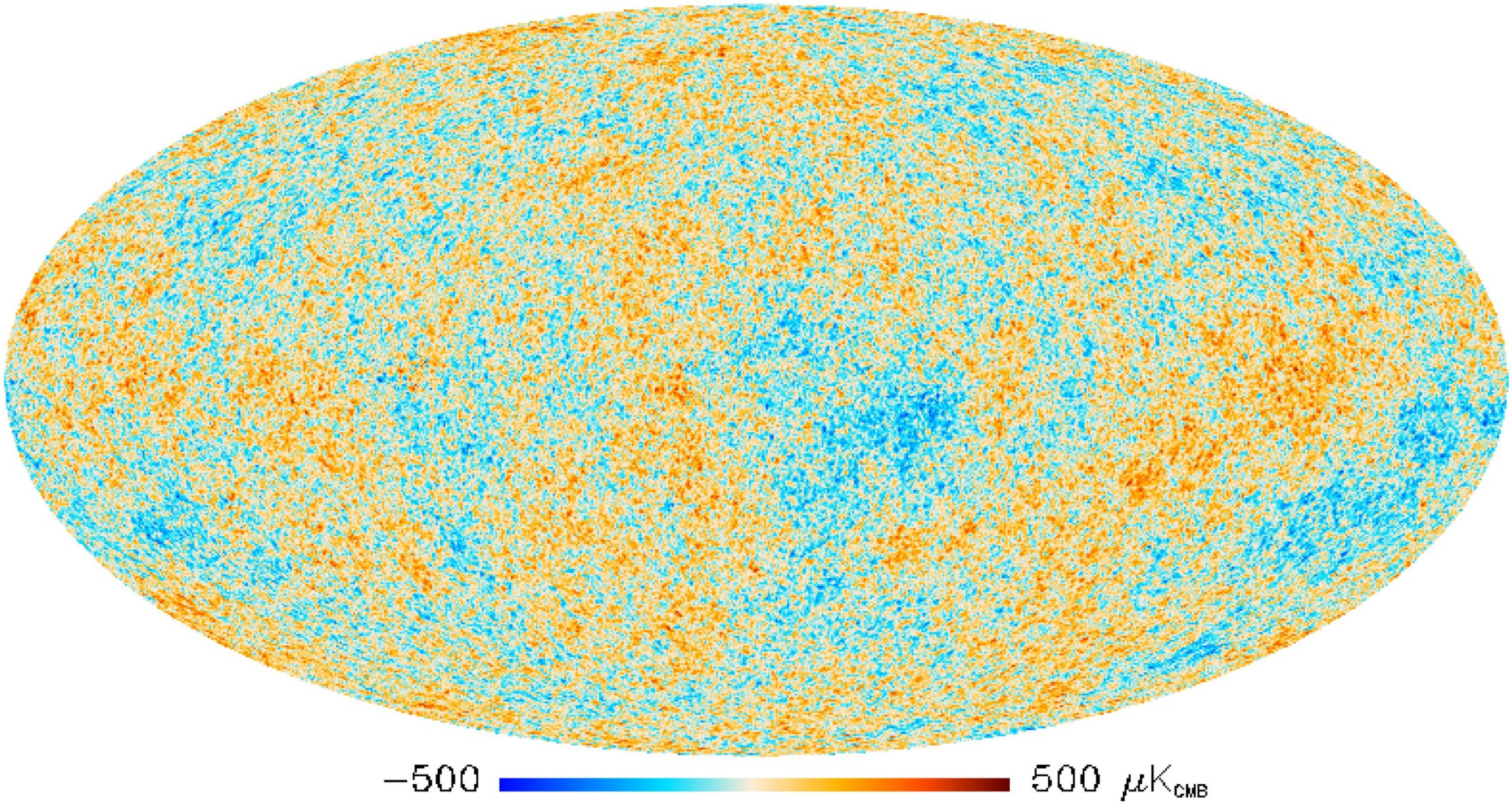
[–]

Cosmology Products

ALIAS LINK	DESCRIPTION
CMB ANGULAR POWER SPECTRA	Multi-frequency power spectra, and the best-fitting CMB power spectrum obtained from Planck data.
SKY ANGULAR POWER SPECTRA	Sky power spectra and covariance matrices.
COSMOLOGICAL PARAMETERS	Constraints on cosmological models and parameters arising from Planck data alone, plus a selection of other data sets.
LIKELIHOOD	A likelihood code adequate for testing cosmological models against the Planck data.

The CMB seen by *Planck* & its cosmological implications

(see also Anthony Lasenby's review)

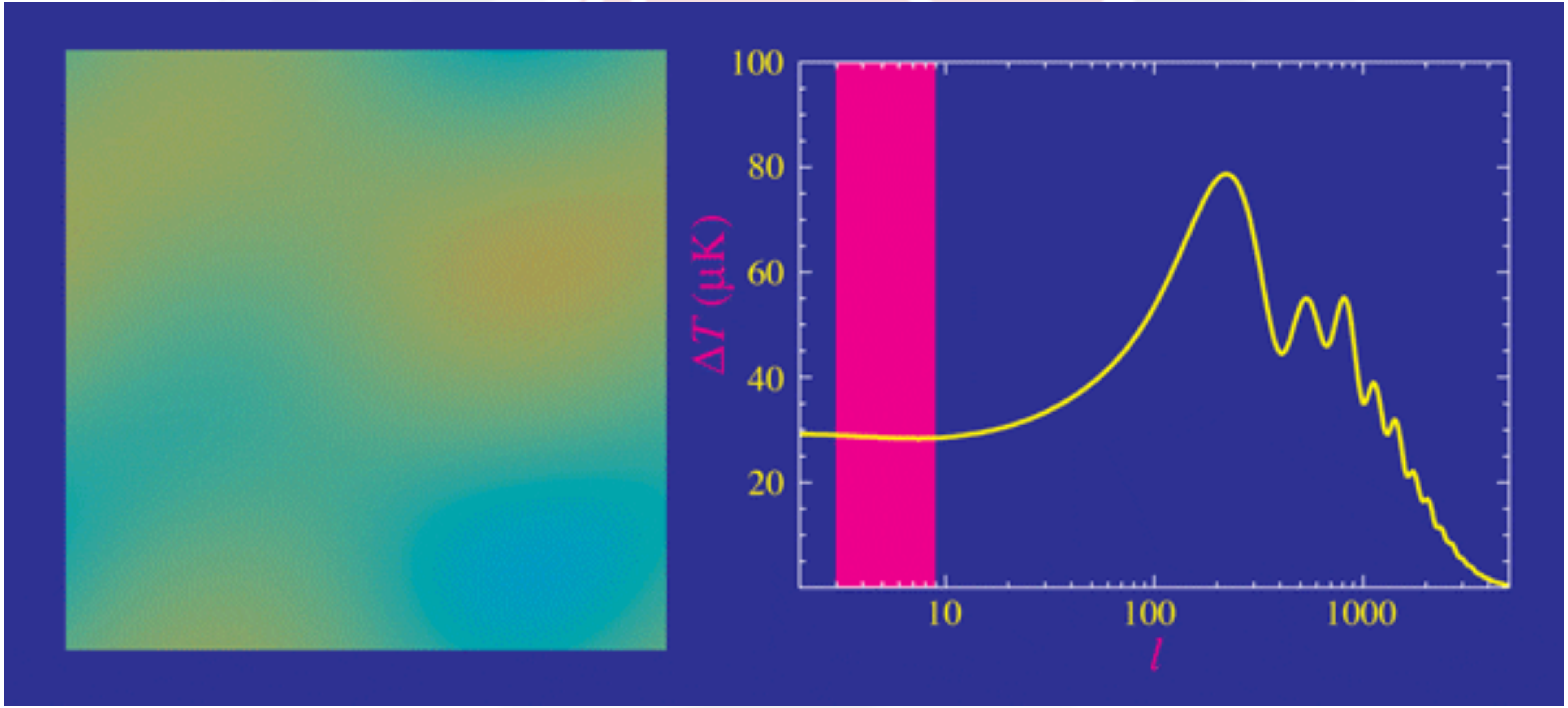


CMB ANISOTROPIES ARE ANALYZED IN A STATISTICAL WAY

$$\Delta T(\vec{x},\hat{n},\tau) = \Sigma_{l=1}^{\infty}\Sigma_{m=-l}^{l} a_{lm}(\vec{x},\tau) Y_{lm}(\hat{n})$$

THE ANGULAR POWER SPECTRUM

$$C_l = \frac{1}{2l+1}\Sigma_m \langle a_{lm}^* a_{lm}\rangle$$



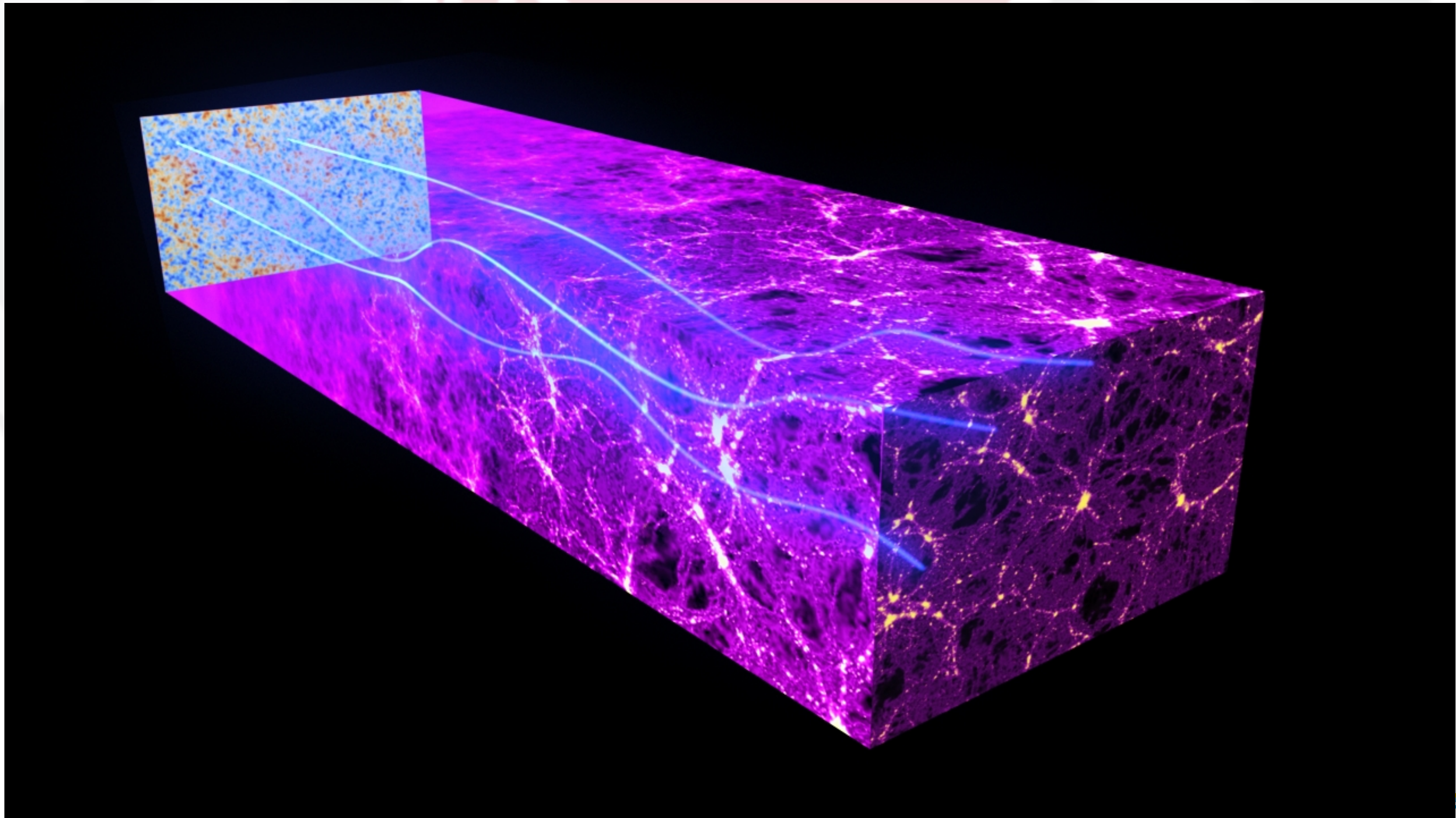
Waine Hu http://background.uchicago.edu/~whu/metaanim.html

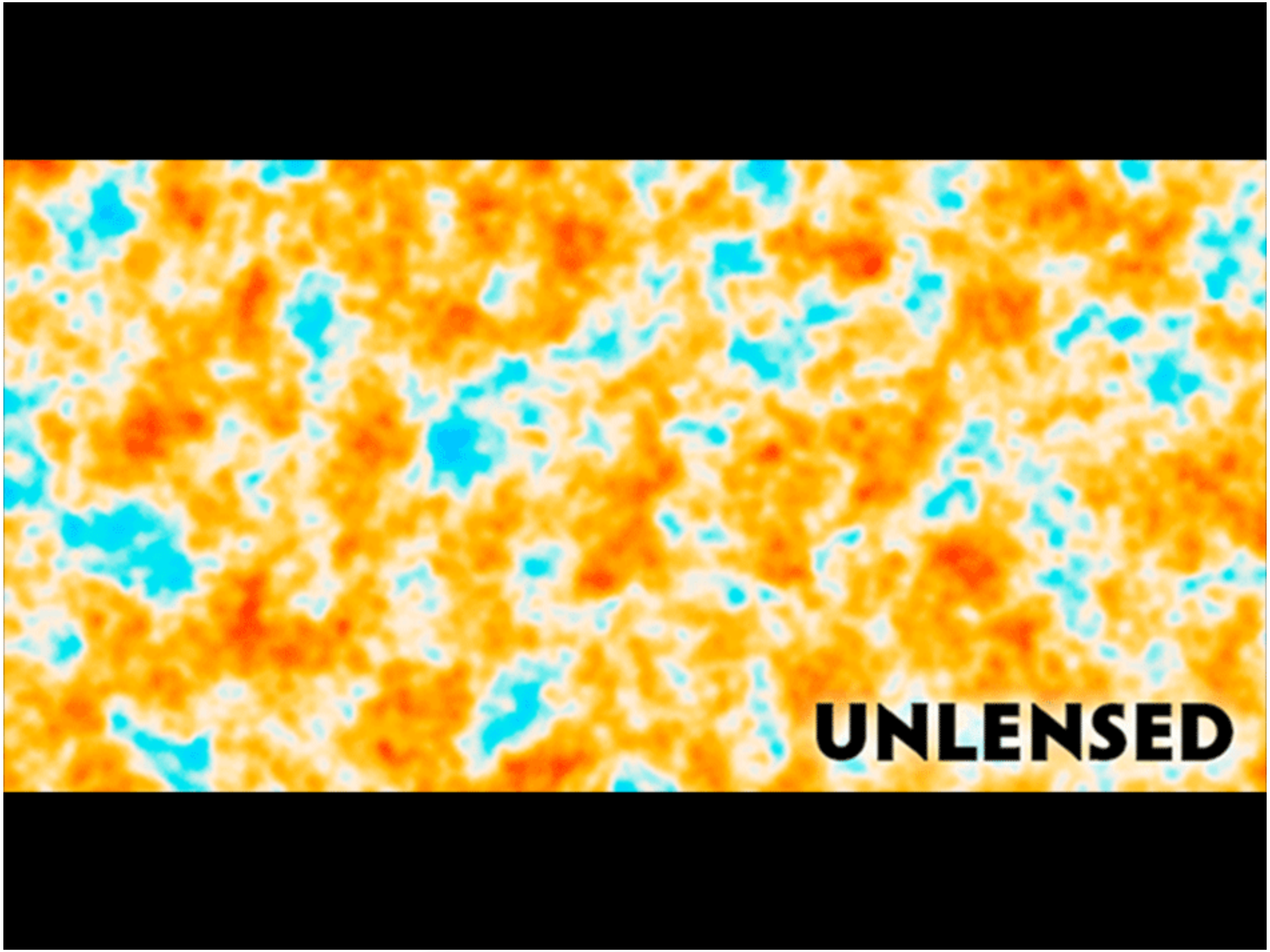
CMB photons are almost unperturbed in their journey from the last scattering surface …
but not completely … **LENSING EFFECT**

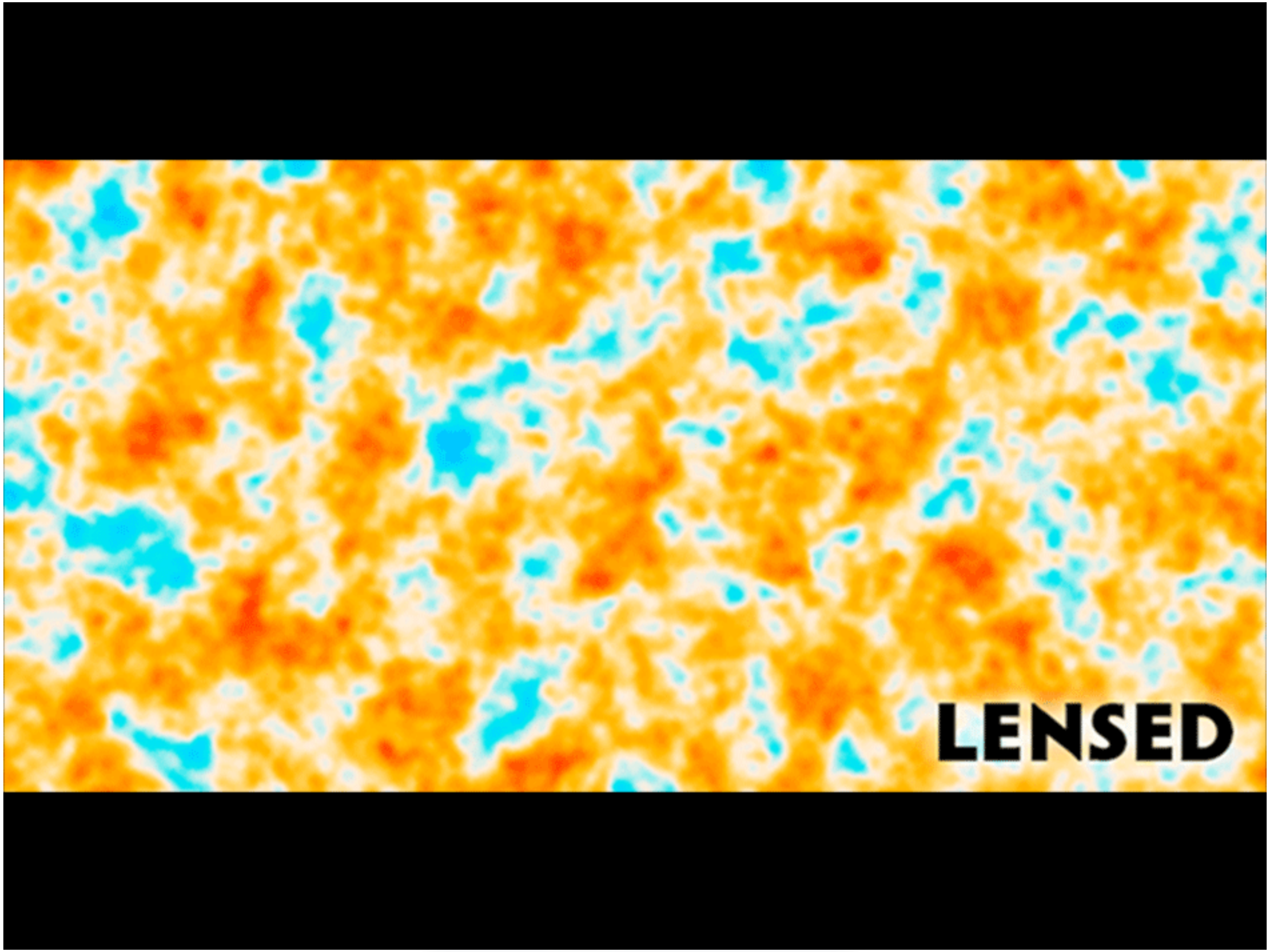
MATTER DISTRIBUTION DEFLECTS THE LIGHT PATH LENSING THE CMB PHOTONS

The effect is similar to a de-focusing of the maps

***PLANCK* HAS A 25 SIGMA DETECTION OF CMB LENSING!**




UNLENSED

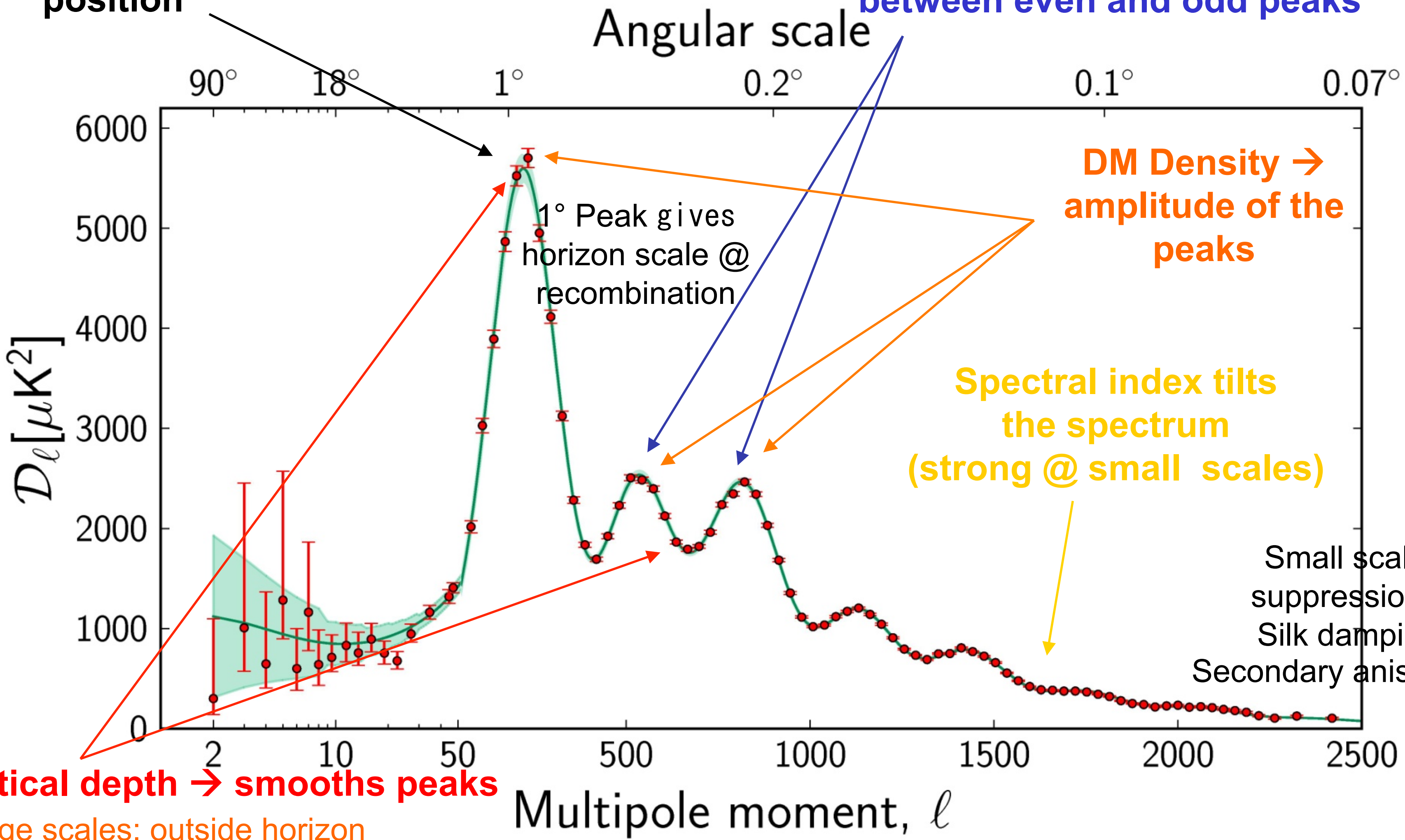

LENSED

APS DEPENDENCE ON COSMOLOGICAL PARAMETERS

Planck: a single experiment spanning a wide multipole range!

Theta → first peak position

Baryon Density → height difference between even and odd peaks



Optical depth → smooths peaks

Large scales: outside horizon @ recombination – only gravity

Intermediate scales: photon-baryon fluid acoustic oscillations - DM potential well vs radiation pressure

PLANCK COSMOLOGICAL PARAMETERS

The CMB anisotropy angular power spectrum shape and amplitude is strongly dependent on the underlying cosmological model.

Cosmological models are characterized by cosmological parameters

STANDARD VANILLA MODEL PARAMETERS

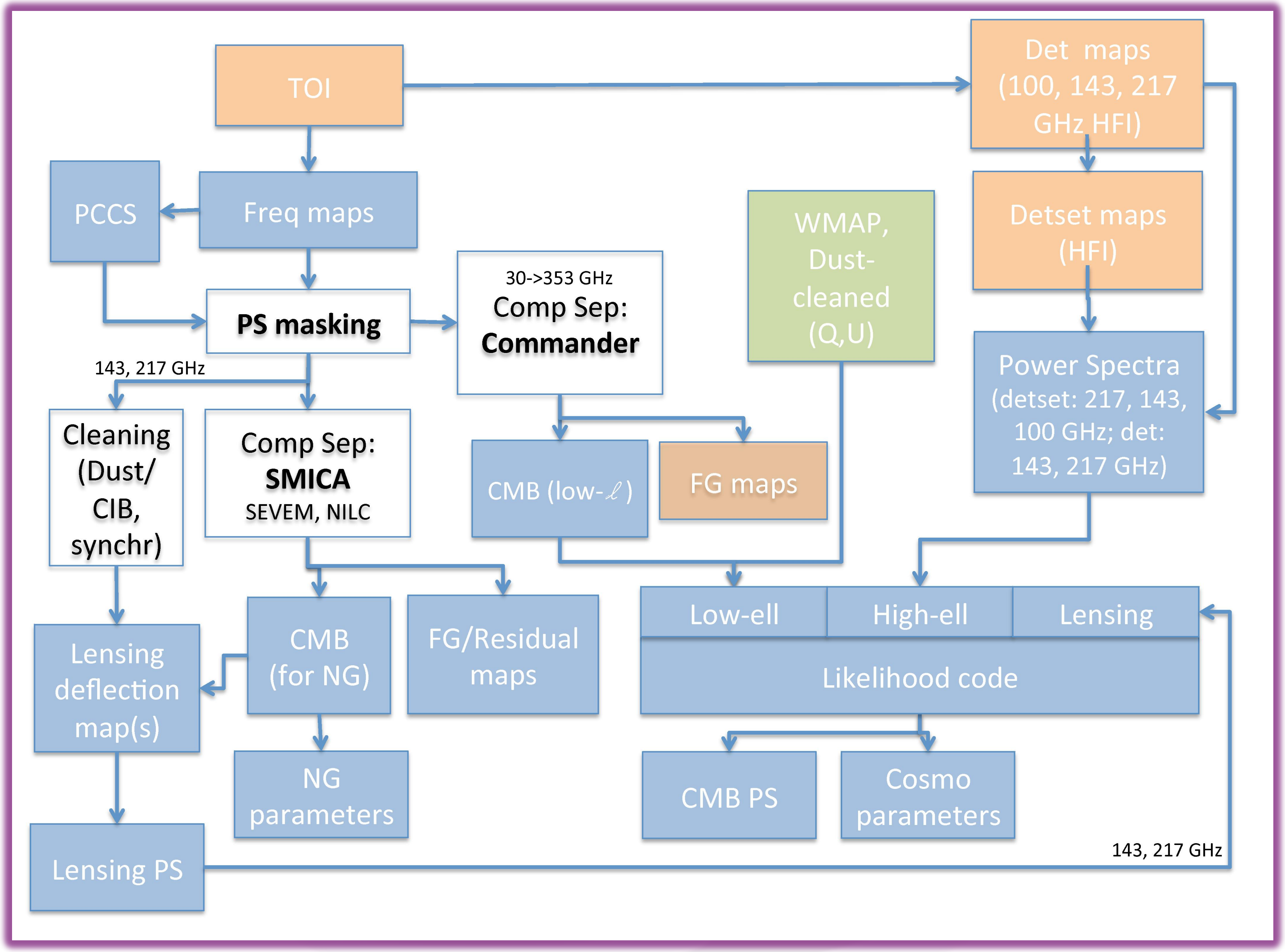
- Baryon Density today $\omega_b \equiv \Omega_b h^2$
- Dark Matter Density today $\omega_c \equiv \Omega_c h^2$
- Horizon @REC Angular Diameter Distance $100\theta_{MC}$
- Optical depth for reionization τ
- Cosmological perturbation tilt $P(k) = A_s k^n$ n_s
- Cosmological perturbation amplitude $\ln(10^{10} A_s)$

STANDARD EXTENSIONS TO VANILLA MODEL AND PRIORS

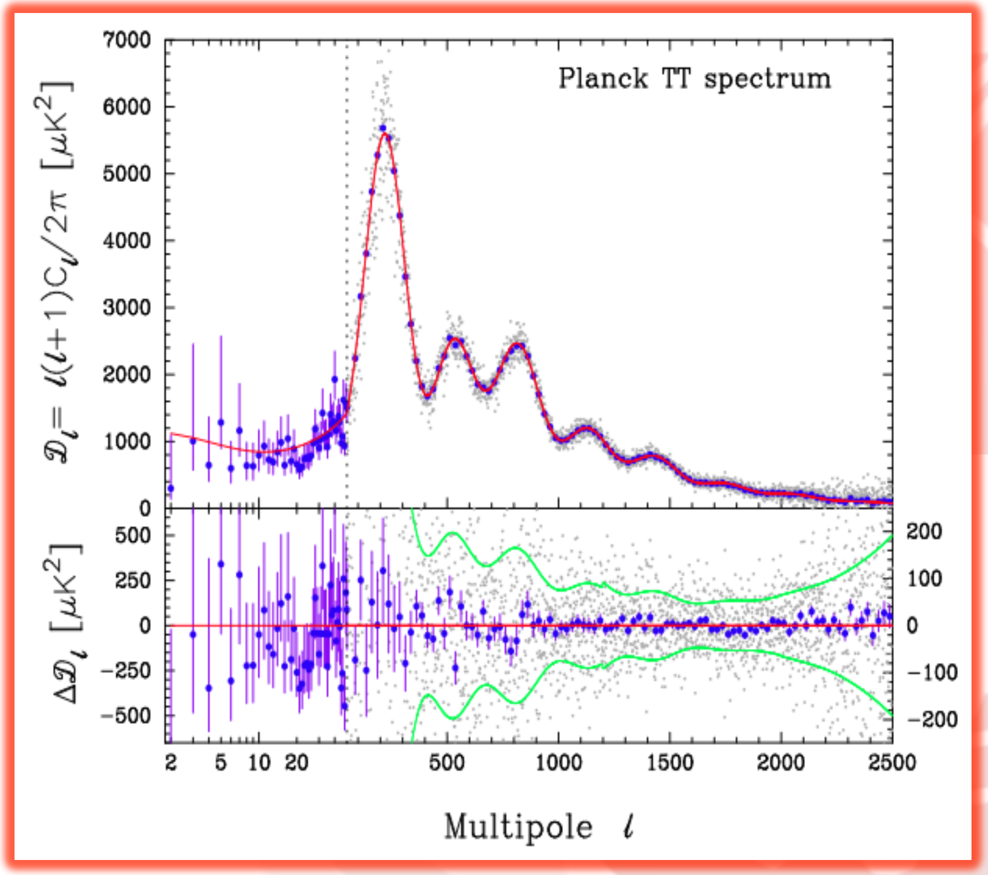
Parameter	Prior range	Baseline	Definition
$\omega_b \equiv \Omega_b h^2$	[0.005, 0.1]	. . .	Baryon density today
$\omega_c \equiv \Omega_c h^2$	[0.001, 0.99]	. . .	Cold dark matter density today
$100\theta_{MC}$	[0.5, 10.0]	. . .	$100 \times$ approximation to r_*/D_A (CosmoMC)
τ	[0.01, 0.8]	. . .	Thomson scattering optical depth due to reionization
Ω_K	[−0.3, 0.3]	0	Curvature parameter today with $\Omega_{tot} = 1 - \Omega_K$
$\sum m_\nu$	[0, 5]	0.06	The sum of neutrino masses in eV
$m^{eff}_{\nu,\,sterile}$	[0, 3]	0	Effective mass of sterile neutrino in eV
w_0	[−3.0, −0.3]	−1	Dark energy equation of state[a], $w(a) = w_0 + (1-a)w_a$
w_a	[−2, 2]	0	As above (perturbations modelled using PPF)
N_{eff}	[0.05, 10.0]	3.046	Effective number of neutrino-like relativistic degrees of freedom (see text)
Y_P	[0.1, 0.5]	BBN	Fraction of baryonic mass in helium
A_L	[0, 10]	1	Amplitude of the lensing power relative to the physical value
n_s	[0.9, 1.1]	. . .	Scalar spectrum power-law index ($k_0 = 0.05\text{Mpc}^{-1}$)
n_t	$n_t = -r_{0.05}/8$	Inflation	Tensor spectrum power-law index ($k_0 = 0.05\text{Mpc}^{-1}$)
$dn_s/d\ln k$	[−1, 1]	0	Running of the spectral index
$\ln(10^{10}A_s)$	[2.7, 4.0]	. . .	Log power of the primordial curvature perturbations ($k_0 = 0.05\,\text{Mpc}^{-1}$)
$r_{0.05}$	[0, 2]	0	Ratio of tensor primordial power to curvature power at $k_0 = 0.05\,\text{Mpc}^{-1}$

DERIVED PARAMETERS

Ω_Λ		. . .	Dark energy density divided by the critical density today
t_0		. . .	Age of the Universe today (in Gyr)
$\Omega_{\rm m}$		. . .	Matter density (inc. massive neutrinos) today divided by the critical density
σ_8		. . .	RMS matter fluctuations today in linear theory
$z_{\rm re}$		. . .	Redshift at which Universe is half reionized
H_0	[20,100]	. . .	Current expansion rate in $\mathrm{km\,s^{-1}Mpc^{-1}}$
$r_{0.002}$		0	Ratio of tensor primordial power to curvature power at $k_0 = 0.002\,\mathrm{Mpc}^{-1}$
$10^9 A_{\rm s}$		. . .	$10^9 \times$ dimensionless curvature power spectrum at $k_0 = 0.05\,\mathrm{Mpc}^{-1}$
$\omega_{\rm m} \equiv \Omega_{\rm m} h^2$		. . .	Total matter density today (inc. massive neutrinos)
z_*		. . .	Redshift for which the optical depth equals unity (see text)
$r_* = r_{\rm s}(z_*)$		. . .	Comoving size of the sound horizon at $z = z_*$
$100\theta_*$		. . .	$100 \times$ angular size of sound horizon at $z = z_*$ $(r_*/D_{\rm A})$
$z_{\rm drag}$		. . .	Redshift at which baryon-drag optical depth equals unity (see text)
$r_{\rm drag} = r_{\rm s}(z_{\rm drag})$		. . .	Comoving size of the sound horizon at $z = z_{\rm drag}$
$k_{\rm D}$		. . .	Characteristic damping comoving wavenumber (Mpc^{-1})
$100\theta_{\rm D}$		. . .	$100 \times$ angular extent of photon diffusion at last scattering (see text)
$z_{\rm eq}$		. . .	Redshift of matter-radiation equality (massless neutrinos)
$100\theta_{\rm eq}$		. . .	$100 \times$ angular size of the comoving horizon at matter-radiation equality
$r_{\rm drag}/D_{\rm V}(0.57)$		. . .	BAO distance ratio at $z = 0.57$ (see Sect. 5.2)



From $12*2048^2 \approx 5\times10^7$ pixels to ≈ 2500 C_l to 6 basic cosmological parameters + f_{NL}



Data:

Planck

maps & APS

\+ Additional

datasets

→ Cosmological parameters

LIKELIHOOD

$$\mathcal{L}(C_\ell) = P(\mathbf{m}|C_\ell) = \frac{1}{2\pi^{n/2}|\mathbf{M}|^{1/2}} \exp\left(-\frac{1}{2}\mathbf{m}^t\,\mathbf{M}^{-1}\mathbf{m}\right),$$

M= covariance matrix, m= data vector

The *Planck* CMB likelihood is based on a hybrid approach:

a. Gaussian likelihood approximation based on temperature pseudo cross-spectra

b. Map based temperature and polarization likelihood at low multipoles.

Low-l likelihood: Planck temperature data with the large angular scale 9-year WMAP polarization data.

Page et al. 2006: temperature and polarization likelihood can be separated assuming negligible noise in the temperature map.

Temperature likelihood: Gibbs approach, mapping out the distribution of the l < 50 CMB multipoles from a foreground-cleaned combination of 30-353 GHz maps.

Polarization likelihood: pixel-based approach using the WMAP 9-year polarization maps at 33, 41, and 61GHz , and including TE.

Angular range l <23 for TE, EE, and BB.

Small-scale Planck temperature likelihood: pseudo cross-spectra between detector pairs from maps at

100 GHz	$f_{sky} = 0.49$	$50 < \ell < 1200$
143 GHz	$f_{sky} = 0.31$	$50 < \ell < 2000$
217 GHz	$f_{sky} = 0.31$	$50 < \ell < 2500$ (for 143x217 as well)

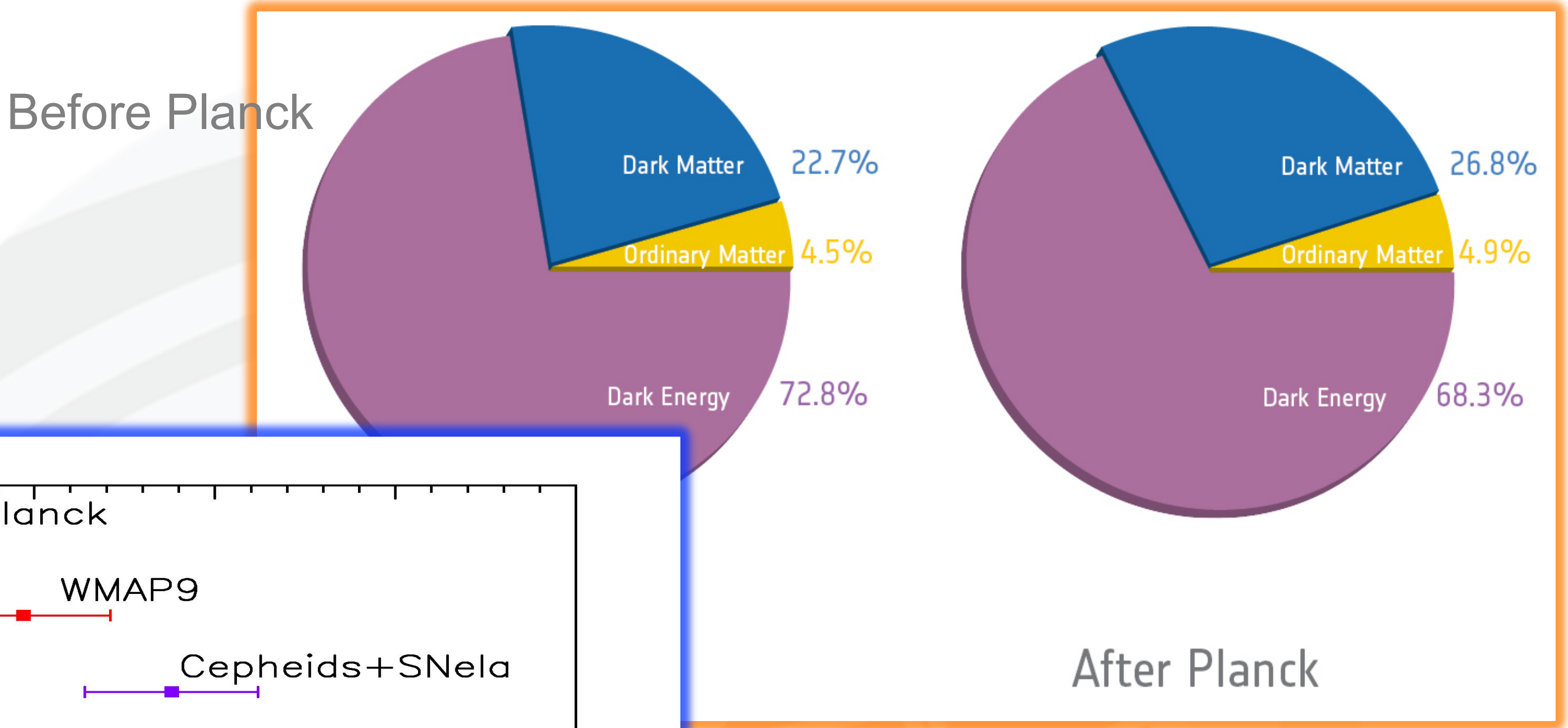
Foreground model includes: contributions to the auto and cross-frequency power spectra from unresolved radio point sources, CIB, tSZ and kSZ effects, for a total of 11 adjustable nuisance parameters.

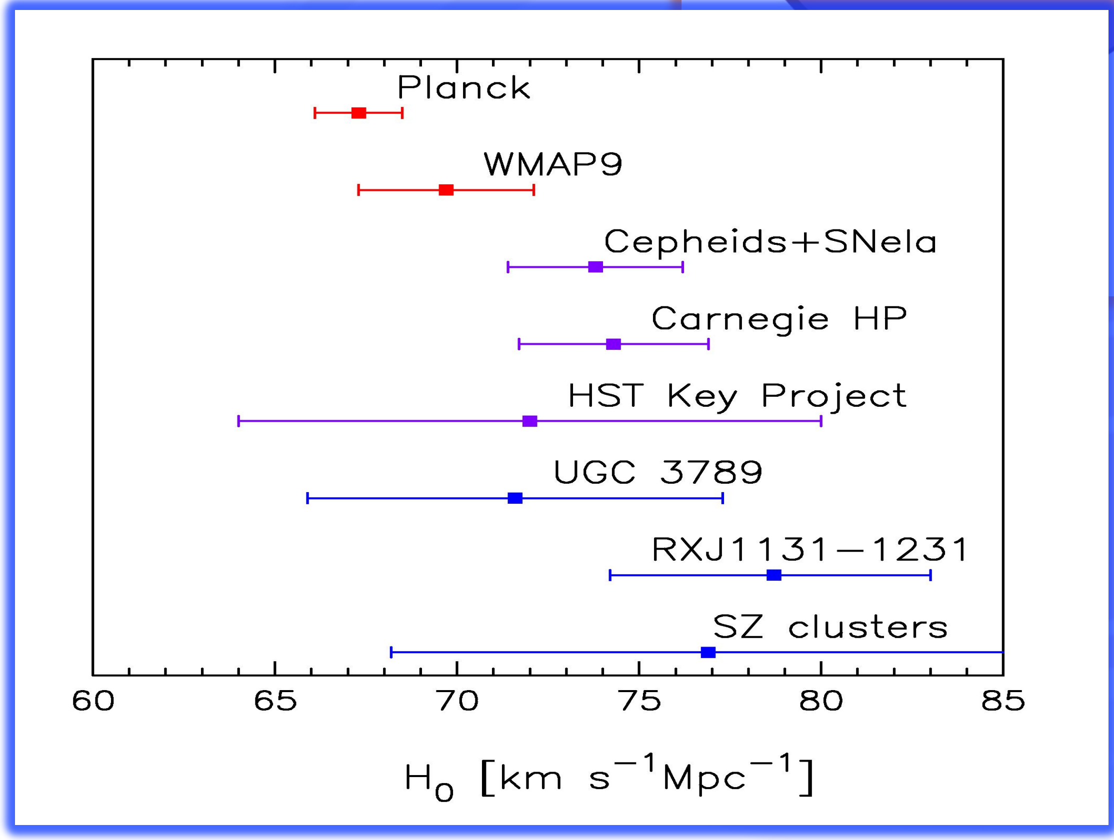
2 calibration parameters (for the 100 GHz and 217 GHz relative to the 143 GHz) and 1 amplitude for the dominant beam uncertainty are also left free to vary (other beam uncertainties are marginalized analytically).

The total sums to 14 parameters for the high-l likelihood.

PLANCK COSMOLOGICAL PARAMETERS: ΛCDM model

	Planck+WP		*Planck*+WP+highL		*Planck*+lensing+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013	0.6914	0.692 ± 0.010
σ_8	0.8347	0.829 ± 0.012	0.8322	0.828 ± 0.012	0.8271	0.8233 ± 0.0097	0.8288	0.826 ± 0.012
z_{re}	11.37	11.1 ± 1.1	11.38	11.1 ± 1.1	11.42	11.1 ± 1.1	11.52	11.3 ± 1.1
H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0	67.77	67.80 ± 0.77
Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044	13.7965	13.798 ± 0.037
$100\theta_*$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060	1.04163	1.04162 ± 0.00056
r_{drag}	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50	147.611	147.68 ± 0.45





Types of energy densities & Universe age

C. Burigana, Paris, 24-26/7/2013

Slide from Francois Bouchet

Inflation has a few variants...

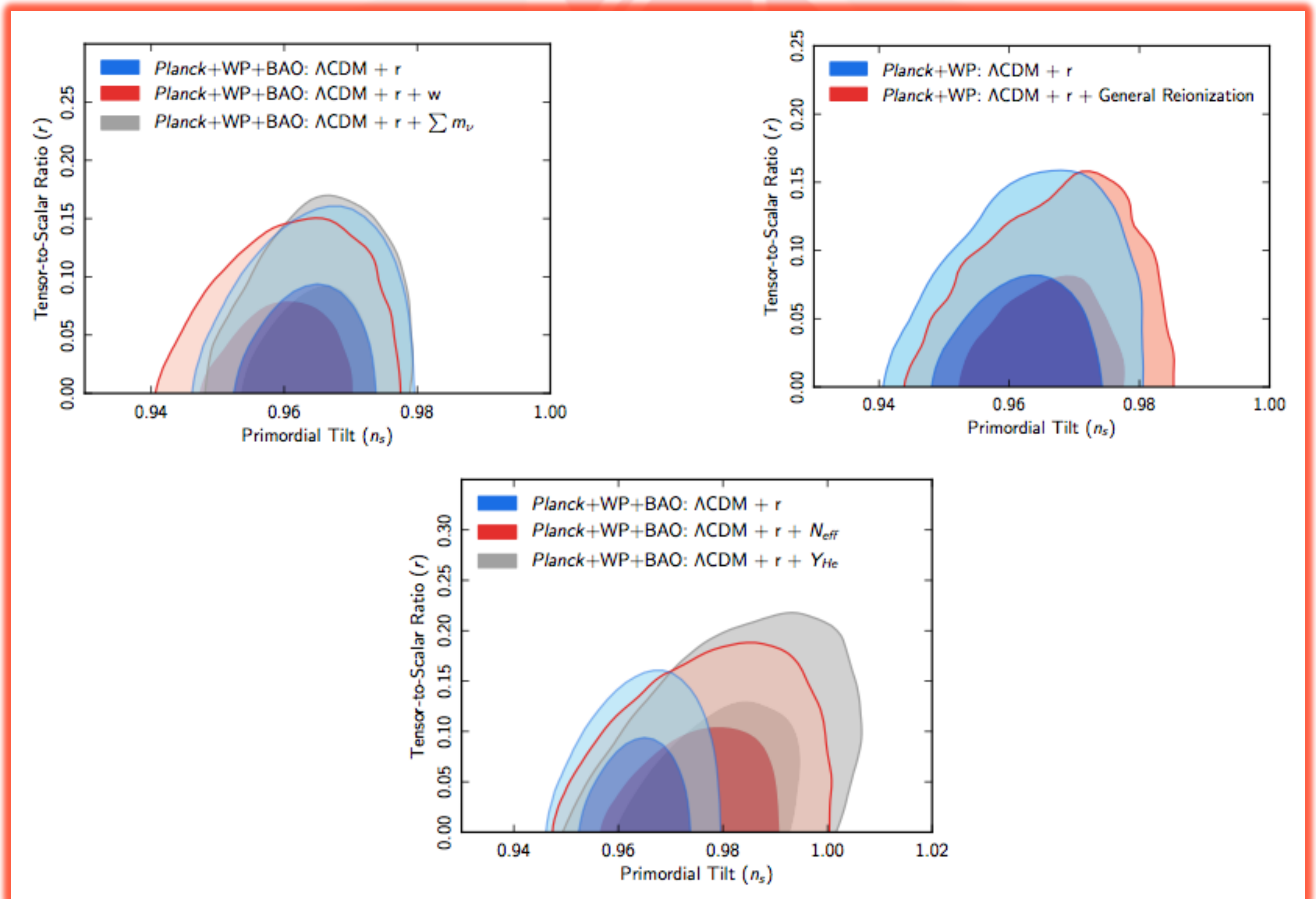
- assisted brane inflation
- anomaly-induced inflation
- assisted inflation
- assisted chaotic inflation
- B-inflation
- boundary inflation
- brane inflation
- brane-assisted inflation
- brane gas inflation
- brane-antibrane inflation
- braneworld inflation
- Brans-Dicke chaotic inflation
- Brans-Dicke inflation
- bulky brane inflation
- chaotic inflation
- chaotic hybrid inflation
- chaotic new inflation
- Chromo-Natural Inflation
- D-brane inflation
- D-term inflation
- dilaton-driven inflation
- dilaton-driven brane inflation
- double inflation
- double D-term inflation
- dual inflation
- dynamical inflation
- dynamical SUSY inflation
- S-dimensional assisted inflation
- eternal inflation
- extended inflation
- extended open inflation
- extended warm inflation
- extra dimensional inflation
- ...

- F-term inflation
- F-term hybrid inflation
- false-vacuum inflation
- false-vacuum chaotic inflation
- fast-roll inflation
- first-order inflation
- gauged inflation
- Ghost inflation
- Hagedorn inflation

- higher-curvature inflation
- hybrid inflation
- Hyper-extended inflation
- induced gravity inflation
- intermediate inflation
- inverted hybrid inflation
- Power-law inflation
- K-inflation
- Super symmetric inflation

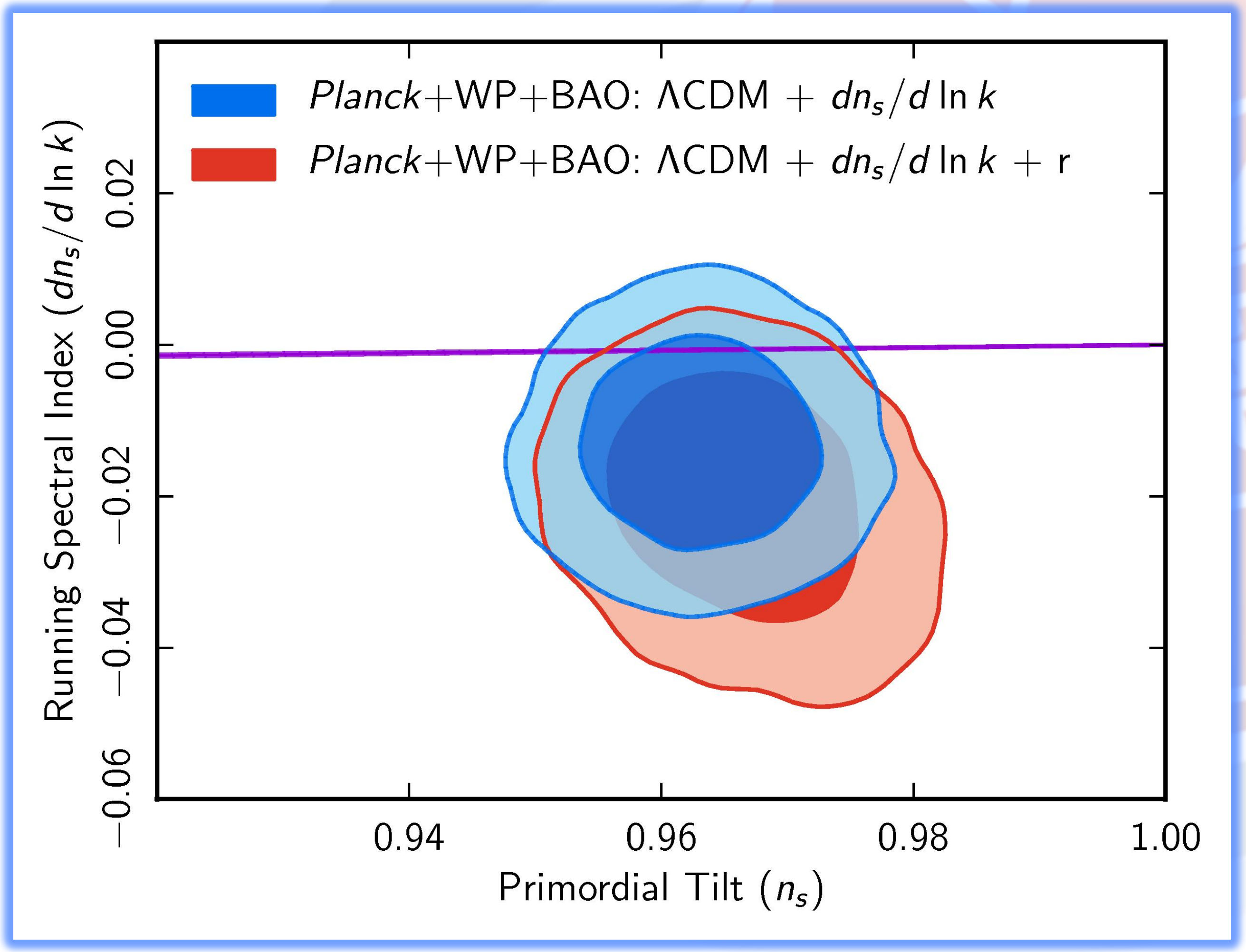
- Quintessential inflation
- Roulette inflation
- curvature inflation
- Natural inflation
- Warm natural inflation
- Super inflation
- Super natural inflation
- Thermal inflation
- Discrete inflation
- Polarcap inflation
- Open inflation
- Topological inflation
- Multiple inflation
- Warm inflation
- Stochastic inflation
- Generalised assisted inflation
- Self-sustained inflation
- Graduated inflation
- Local inflation
- Singular inflation
- Slinky inflation
- Locked inflation
- Elastic inflation
- Mixed inflation
- Phantom inflation
- Non-commutative inflation
- Tachyonic inflation
- Tsunami inflation
- Lambda inflation
- Steep inflation
- Oscillating inflation
- Mutated hybrid inflation
- Inhomogeneous inflation
- ...

Robustness n_s - r



RUNNING OF THE SPECTRAL INDEX

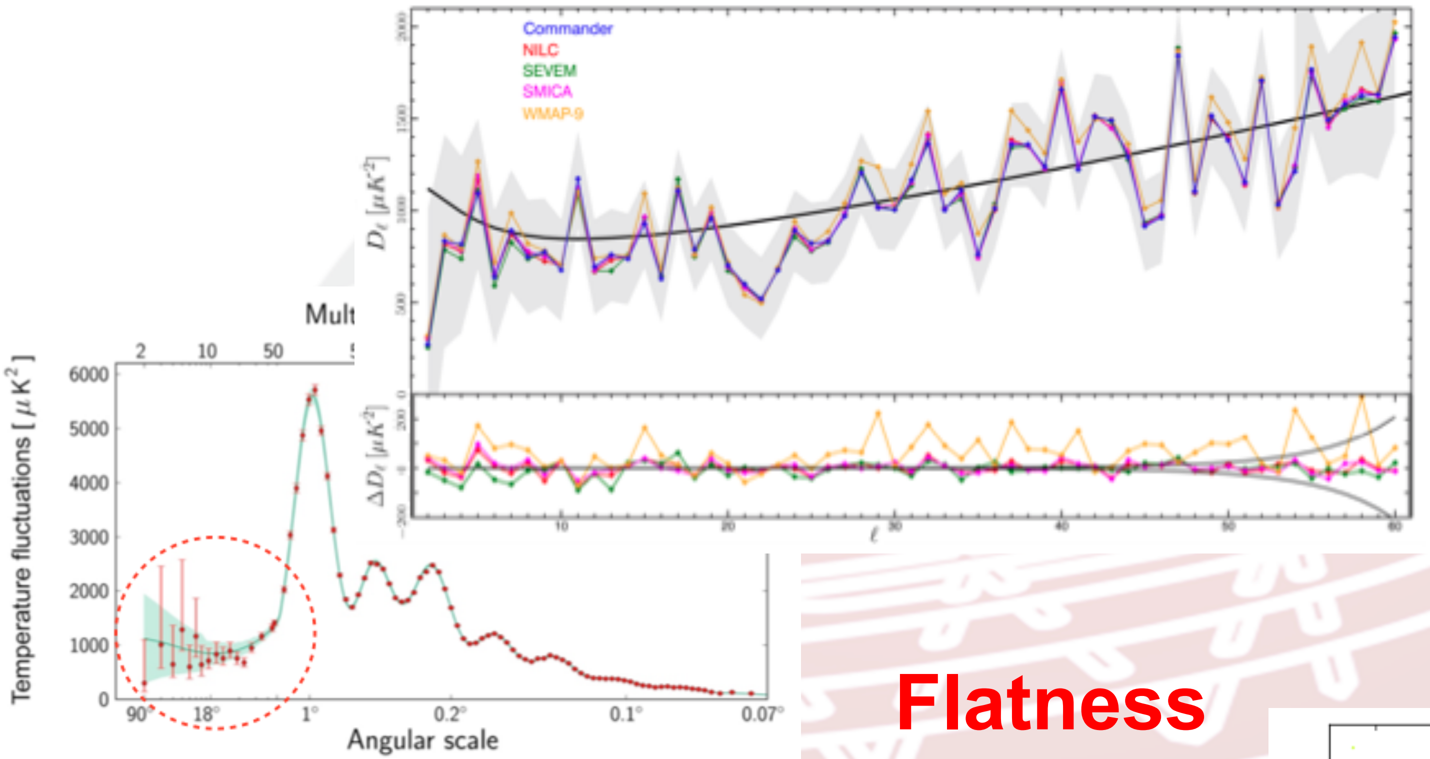
$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2}\, dn_s/d\ln k \ln(k/k_*) + \frac{1}{6}\, d^2 n_s/d\ln k^2 (\ln(k/k_*))^2}.$$



COMPATIBLE WITH ZERO RUNNING

(WITH A PREFERENCE FOR NEGATIVE VALUES)

Lack of power at low multipoles



+ tensors

Ω_K=-0.0006±0.0069
r < 0.13 *(95%; Planck+WP+BAO)*

+ running

(Ω_K + r + dn_s/dlnk)

Flatness

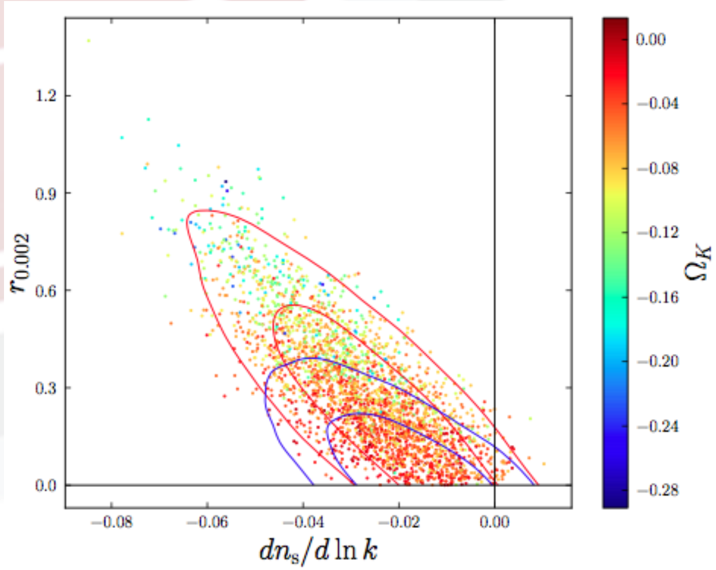
$$\Omega_K = -0.042^{+0.043}_{-0.048}$$ *(95%; Planck*+WP+highL)

$$\Omega_K = -0.007^{+0.018}_{-0.020}$$ *(95%; Planck*+lensing+WP)

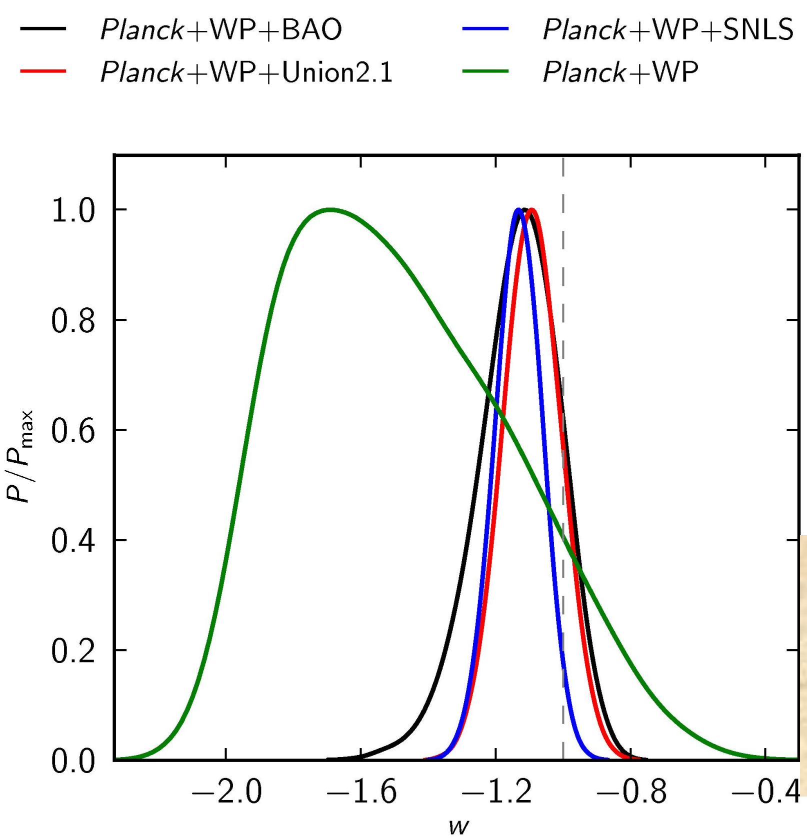
$$\Omega_K = -0.010^{+0.018}_{-0.019}$$ *(95%; Planck*+lensing+WP+highL)

$$\Omega_K = 0.000^{+0.0066}_{-0.0067}$$ *(95%; Planck*+WP+BAO)

$$\Omega_K = -0.0010^{+0.0062}_{-0.0065}$$ *(95%; Planck*+lensing+WP+highL+BAO)



DARK ENERGY

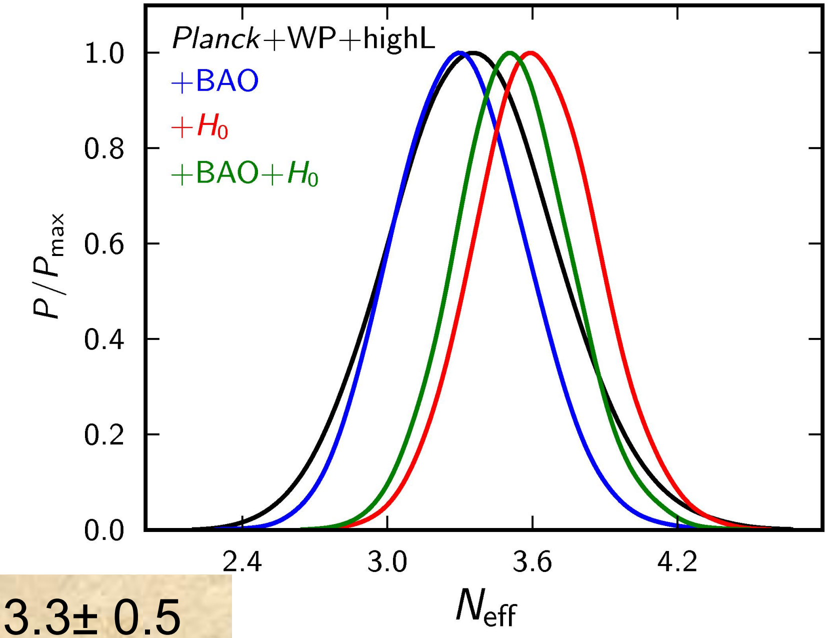


Compatible with a cosmological constant equation of state

$w = -1.13 \pm 0.24$

No need for dynamical DE

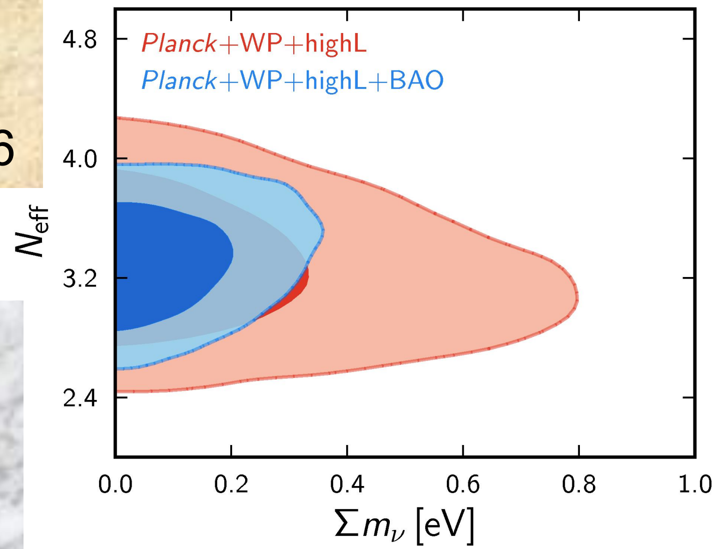
REL. NEUTRINOS



Neff = 3.3± 0.5

compatible with

? standard 3.046



Constraints on neutrino masses:

$\Sigma m_\nu < 0.23 eV$

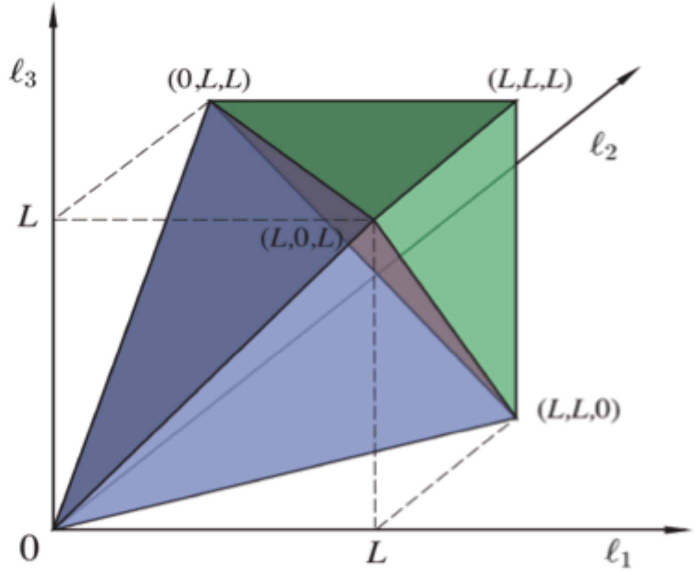
Non-Gaussianity … mainly through CMB bispectrum

$$B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3} \equiv \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle$$

$$= \mathcal{G}^{\ell_1 \ell_2 \ell_3}_{m_1 m_2 m_3} \, b_{\ell_1 \ell_2 \ell_3}$$

Gaunt integrals

$$\mathcal{G}^{\ell_1 \ell_2 \ell_3}_{m_1 m_2 m_3} \equiv \int Y_{\ell_1 m_1}(\hat{n}) \, Y_{\ell_2 m_2}(\hat{n}) \, Y_{\ell_3 m_3}(\hat{n}) \, d^2\hat{n}$$
$$= h_{\ell_1 \ell_2 \ell_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix},$$

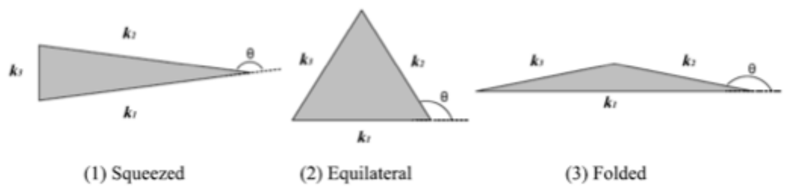


Triangle condition: $\ell_1 \leq \ell_2 + \ell_3$ for $\ell_1 \geq \ell_2, \ell_3$, +perms.

Parity condition: $\ell_1 + \ell_2 + \ell_3 = 2n\,, \quad n \in \mathbb{N}\,,$

Resolution: $\ell_1, \ell_2, \ell_3 \leq \ell_{\max}\,, \quad \ell_1, \ell_2, \ell_3 \in \mathbb{N}\,.$

(1) Multiple fields (local models, non-linearities develop outside horizon)
(2) Non-canonical kinetic term of quantum fields (higher derivative interactions; Dirac-Born-Infeld, K-inflation)
(3) Non-vacuum initial conditions



Optimal f_{NL} bispectrum estimator

$$\hat{f}_{NL} = \frac{1}{N}\sum B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3}\left[\left(C^{-1}a\right)^{m_1}_{\ell_1}\left(C^{-1}a\right)^{m_2}_{\ell_2}\left(C^{-1}a\right)^{m_3}_{\ell_3} - 3C^{-1}_{\ell_1 m_1 \ell_2 m_2}\left(C^{-1}a\right)^{m_3}_{\ell_3}\right]$$

The theoretical template needs to be written in separable form. This can be done in different ways and *alternative implementations differ basically in terms of the separation technique adopted and of the projection domain.*

- KSW (Komatsu, Spergel & Wandelt 2003) separable template fitting + Skew-C_l extension (Munshi & Heavens 2010)

Plus other two methods for f_{NL}

✧ **Binned bispectrum (Bucher, Van Tent & Carvalho2009)**
✧ **Modal expansion (Fergusson, Liguori & Shellard 2009)**

“Contaminants”:

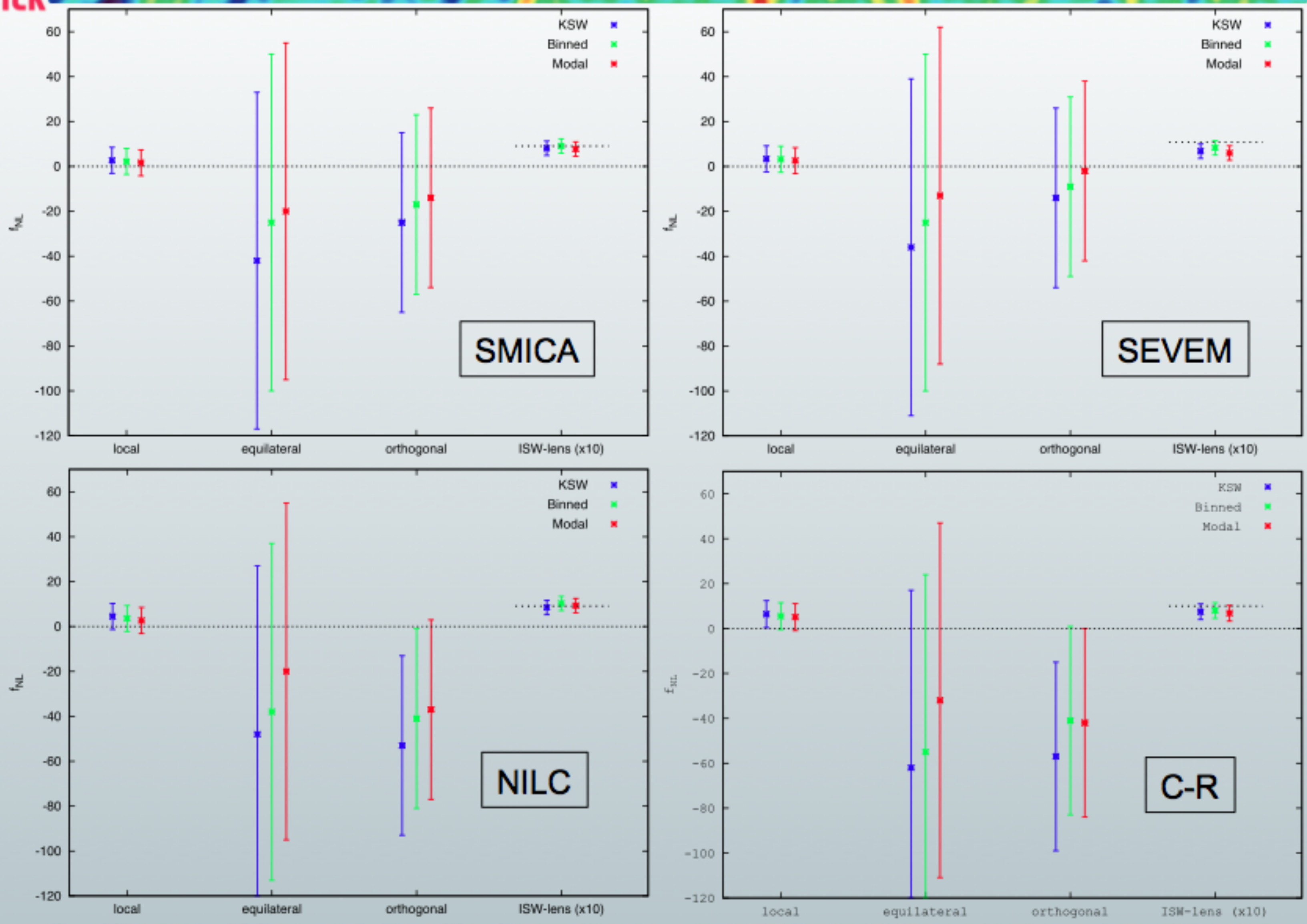
✧ Coupling between weak lensing and Integrated Sachs-Wolfe (ISW) effects: leading contamination to local NG.
✧ **We have detected the ISW lensing bispectrum with a significance of 2.6 σ**
✧ Point-source (Poisson) bispectrum from SMICA, NILC, SEVEM, & C-R foreground-cleaned maps, for KSW, binned and modal (polynomial) estimators

Results for 3 fundamental shapes

- Results for the f_{NL} parameters of the primordial local, equilateral, and orthogonal shapes, determined by the KSW, binned and modal estimators from the SMICA, NILC, SEVEM, and C-R foreground-cleaned maps. Both independent single-shape results and results marginalized over the point-source bispectrum and with the ISW-lensing bias subtracted are reported; error bars are 68% CL.

	Independent				ISW-lensing subtracted		
	KSW	Binned	Modal		KSW	Binned	Modal
SMICA							
Local	9.8 ± 5.8	9.2 ± 5.9	8.3 ± 5.9	. . . . .	**2.7 ± 5.8**	2.2 ± 5.9	1.6 ± 6.0
Equilateral	−37 ± 75	−20 ± 73	−20 ± 77	. . . . .	**−42 ± 75**	−25 ± 73	−20 ± 77
Orthogonal	−46 ± 39	−39 ± 41	−36 ± 41	. . . . .	**−25 ± 39**	−17 ± 41	−14 ± 42
NILC							
Local	11.6 ± 5.8	10.5 ± 5.8	9.4 ± 5.9	. . . . .	4.5 ± 5.8	3.6 ± 5.8	2.7 ± 6.0
Equilateral	−41 ± 76	−31 ± 73	−20 ± 76	. . . . .	−48 ± 76	−38 ± 73	−20 ± 78
Orthogonal	−74 ± 40	−62 ± 41	−60 ± 40	. . . . .	−53 ± 40	−41 ± 41	−37 ± 43
SEVEM							
Local	10.5 ± 5.9	10.1 ± 6.2	9.4 ± 6.0	. . . . .	3.4 ± 5.9	3.2 ± 6.2	2.6 ± 6.0
Equilateral	−32 ± 76	−21 ± 73	−13 ± 77	. . . . .	−36 ± 76	−25 ± 73	−13 ± 78
Orthogonal	−34 ± 40	−30 ± 42	−24 ± 42	. . . . .	−14 ± 40	−9 ± 42	−2 ± 42
C-R							
Local	12.4 ± 6.0	11.3 ± 5.9	10.9 ± 5.9	. . . . .	6.4 ± 6.0	5.5 ± 5.9	5.1 ± 5.9
Equilateral	−60 ± 79	−52 ± 74	−33 ± 78	. . . . .	−62 ± 79	−55 ± 74	−32 ± 78
Orthogonal	−76 ± 42	−60 ± 42	−63 ± 42	. . . . .	−57 ± 42	−41 ± 42	−42 ± 42

f_{NL} from *Planck* data



Non-Gaussianity summary

- We have **detected the ISW-lensing bispectrum**, as expected in ΛCDM scenario.
- We have derived **constraints on early-Universe scenarios that generate primordial NG**, including general single-field models of inflation, excited initial states (non-Bunch-Davies vacua), and directionally-dependent vector models.
- Initial survey of scale-dependent feature and resonance models.

These results bound both general single-field and multi-field model parameter ranges, such as the speed of sound,

$c_s \geq 0.02$ (95% CL), in an effective field theory parametrization ($c_s \geq 0.07$ for DBI inflation),

and the curvaton decay fraction $r_D \geq 0.15$ (95% CL).

- **The simplest inflation models (single-field slow-roll, standard kinetic term, BD initial vacuum state) are favoured by *Planck* data.**
- Multi-field models are not ruled out but also not detected.
- Ekpyrotic/cyclic models either ruled our or under severe pressure.
- Taken together, these constraints represent the **highest precision tests** to date of physical mechanisms for the origin of cosmic structure.

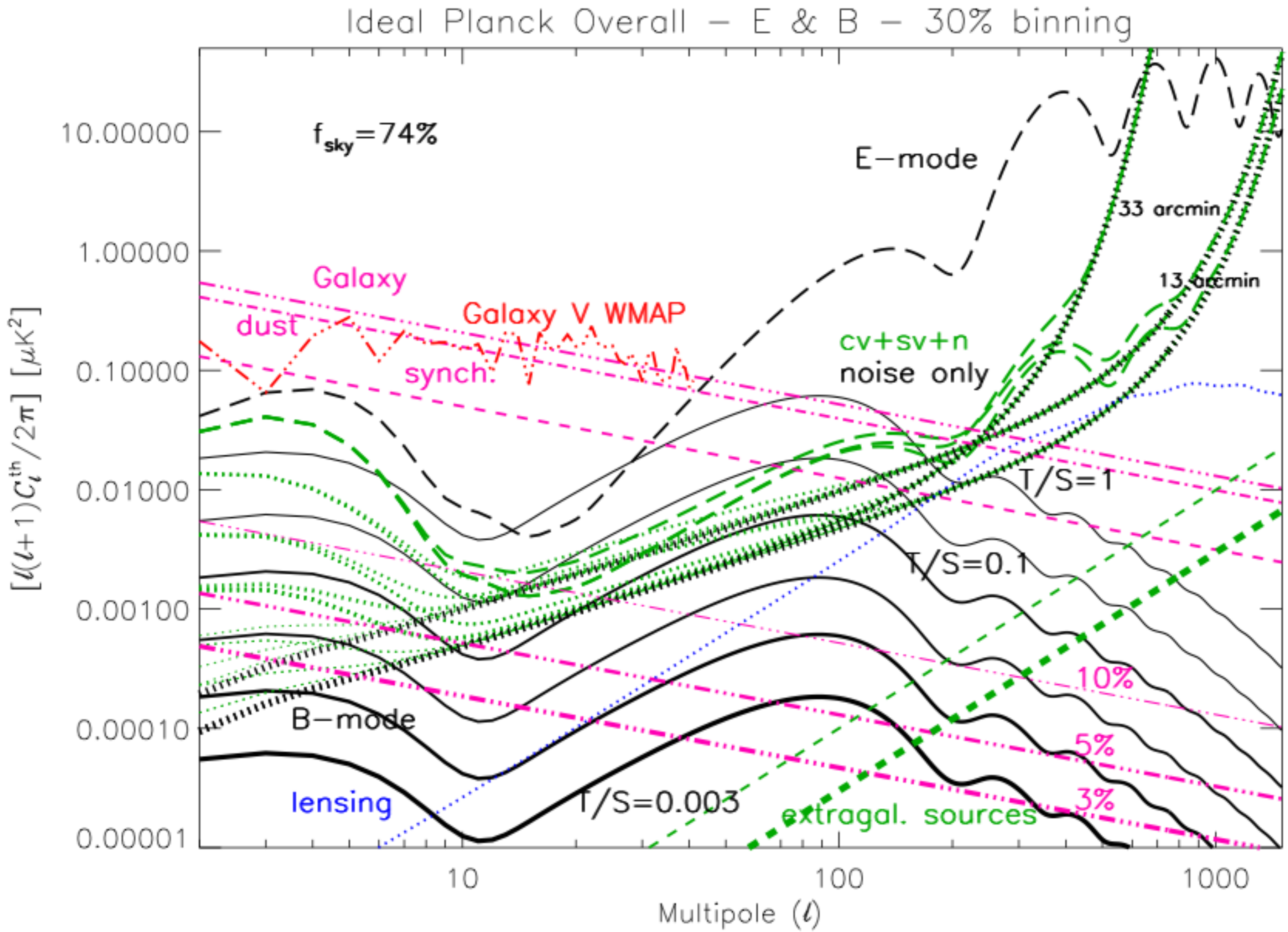
What next? *Planck* final performance & polarization

Average sensitivity, δT/T, per $FWHM^2$ resolution element (FWHM in arcmin) and white noise (per frequency channel for LFI and per detector for HFI) in 1 sec of integration (NET, in μK ·√s) in CMB temperature units. Acronyms: DT = detector technology, N of R (or B) = number of radiometers (or bolometers), EB = effective bandwidth (in GHz). At 100 GHz all bolometers are polarized, thus the temperature measure is derived combining data from polarized bolometers.

HFI	≃ 29.5 months	of integration	(≃ 5 surveys)	
Frequency (GHz)	100	143	217	353
FWHM in T (P)	9.6 (9.6)	7.1 (6.9)	4.6 (4.6)	4.7 (4.6)
N of B in T (P)	(8)	4 (8)	4 (8)	4 (8)
EB in T (P)	33 (33)	43 (46)	72 (63)	99 (102)
NET in T (P)	100 (100)	62 (82)	91 (132)	277 (404)
δT/T [μK/K] in T (P)	2.04 (3.31)	1.56 (2.83)	3.31 (6.24)	13.7 (26.2)

HFI		
Frequency (GHz)	545	857
FWHM in T	4.7	4.3
N of B in T	4	4
EB in T	169	257
NET in T	2000	91000
δT/T [μK/K] in T	103	4134

LFI	≃ 29.5 + 21 months	of integration	(≃ 8 surveys)
Frequency (GHz)	30	44	70
InP DT	MIC	MIC	MMIC
FWHM	33.34	26.81	13.03
N of R (or feeds)	4 (2)	6 (3)	12 (6)
EB	6	8.8	14
NET	159	197	158
δT/T [μK/K] (in T)	1.85	2.85	4.69
δT/T [μK/K] (in P)	2.61	4.02	6.64

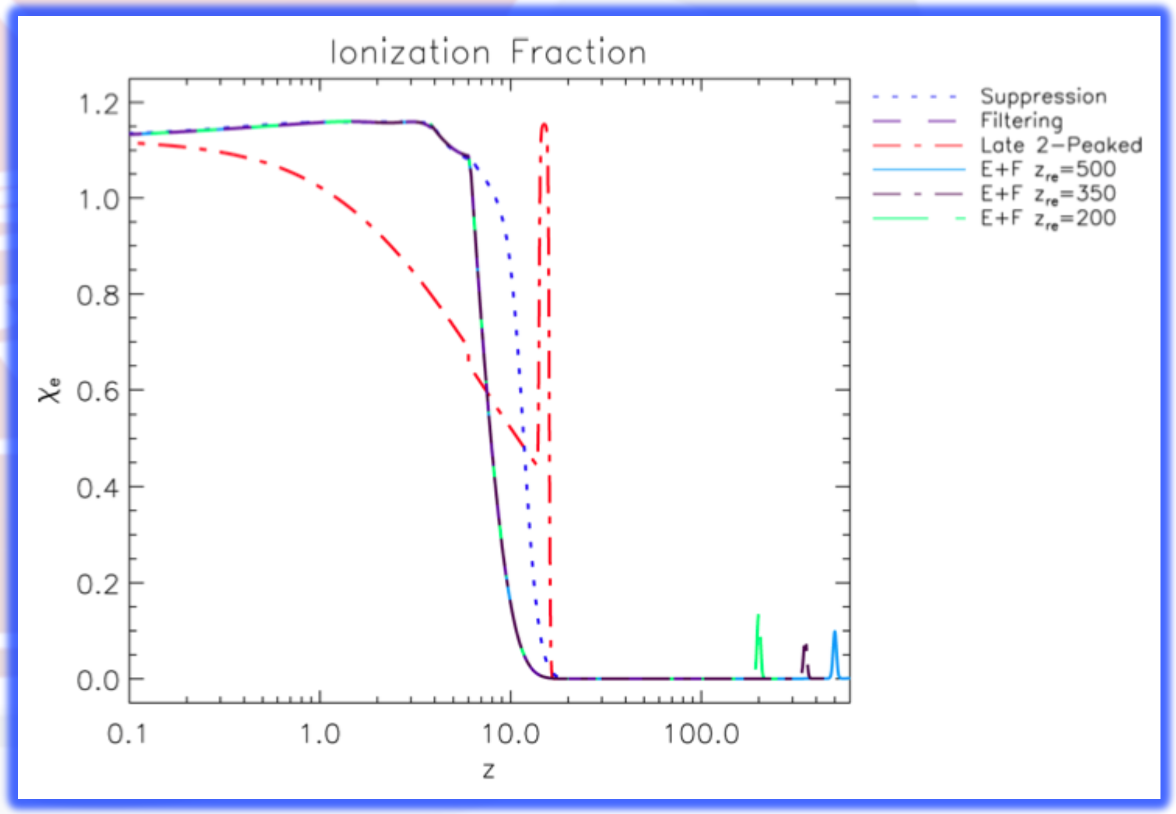


Ideal Planck Overall – E & B – 30% binning
f_sky=74%
E–mode
33 arcmin
13 arcmin
Galaxy
dust
Galaxy V WMAP
synch.
cv+sv+n
noise only
T/S=1
T/S=0.1
10%
5%
3%
B–mode
lensing
T/S=0.003
extragal. sources
10.00000
1.00000
0.10000
0.01000
0.00100
0.00010
0.00001
10
100
1000
Multipole (ℓ)
[ℓ(ℓ+1)C_ℓ^th/2π] [μK²]

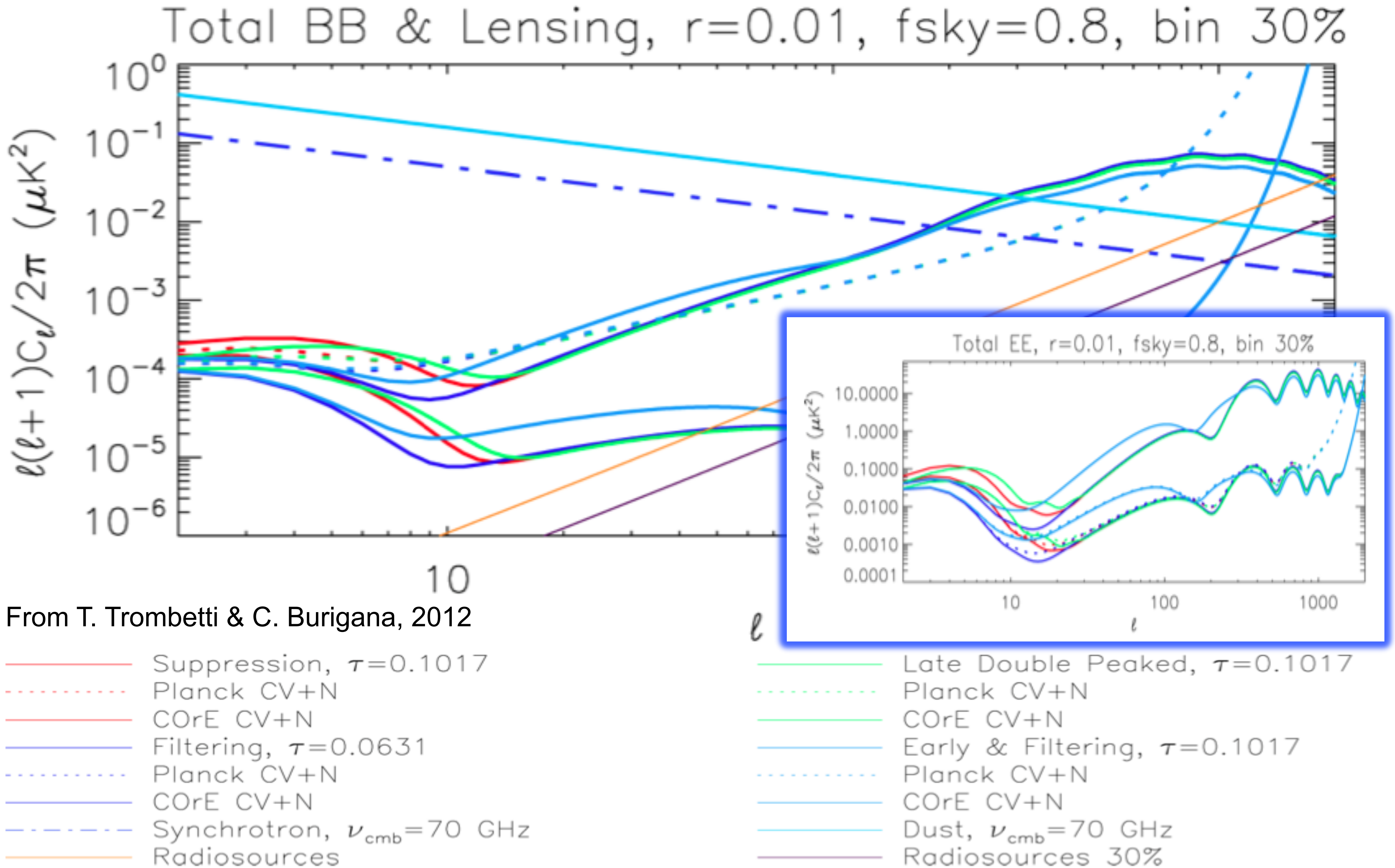
Extension to all modes
B-modes & reionization beyond simple tau-approximation

- Future of CMB polarization anisotropies:
  - towards B-modes & full exploitation of all modes
- Implementation of reionization models in CAMB code considering all modes & in particular B-modes (T. Trombetti & C. Burigana, 2012, JMP, 3, 1918)
- Inclusion of
  - Phenomenological models (high/low z)
  - Astrophysical models
  - Mix of models

Typical cases →

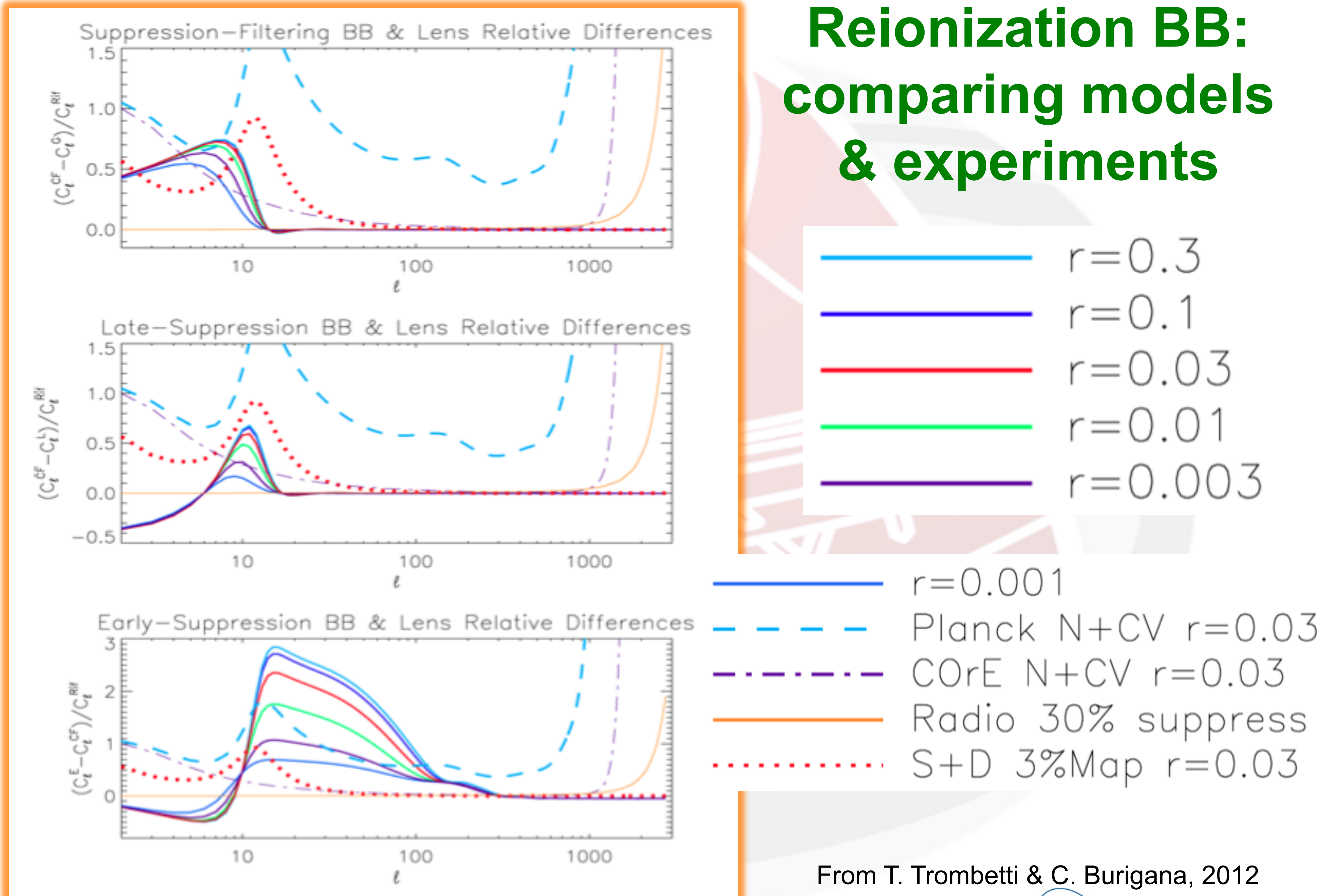


EE & BB predictions



From T. Trombetti & C. Burigana, 2012

Reionization BB: comparing models & experiments



From T. Trombetti & C. Burigana, 2012

Conclusions

- ✓ *Planck* worked & is working as expected
- ✓ DPCs, instruments, CTs, WGs worked & are working well & intensively to produce accurate TOD, frequency maps, component maps, source catalogs
- ✓ Production of the most accurate CMB all-sky temperature anisotropy maps in the range 30-857 GHz ☺ … working on polarization for next year release in 2014 ☺

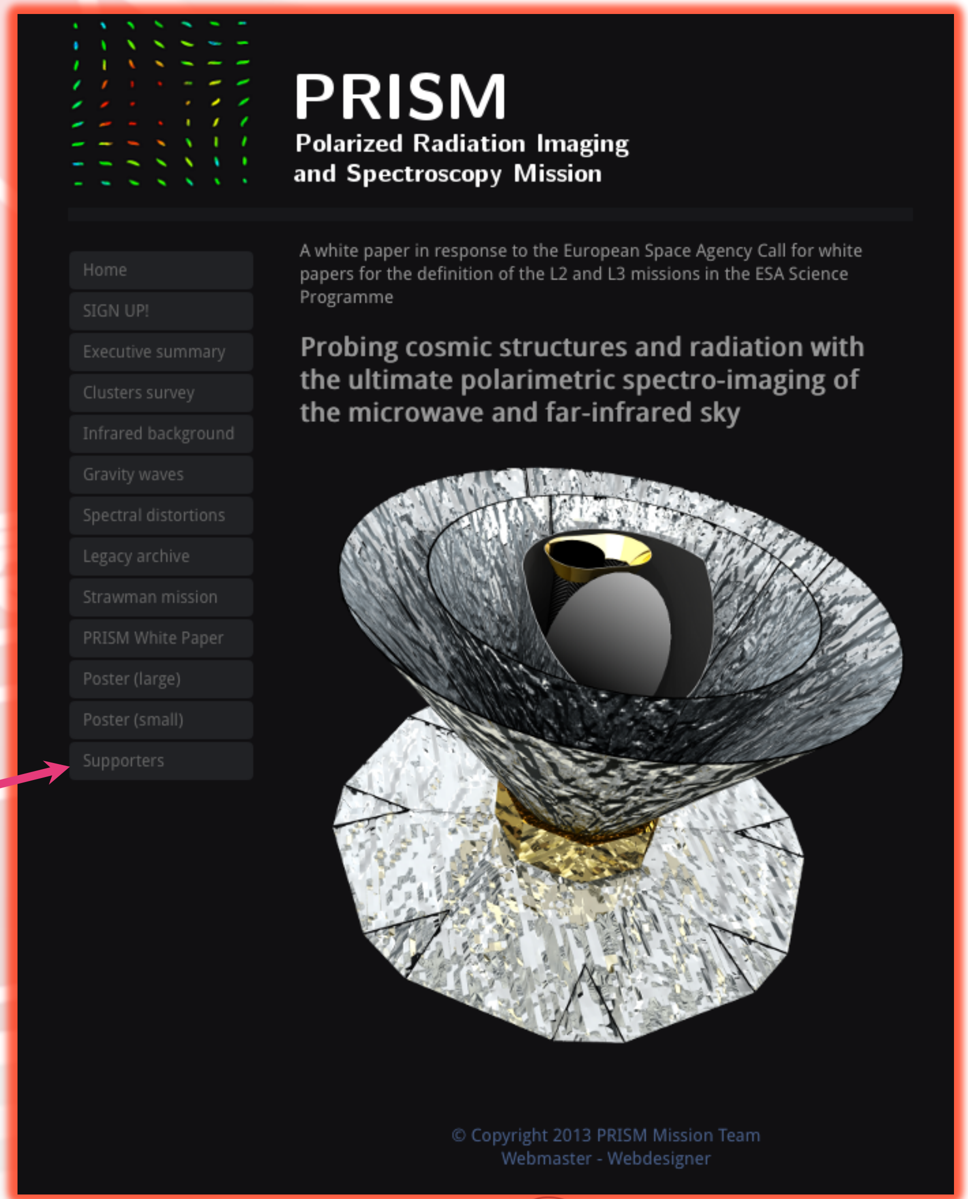
Implications for cosmology

- ❖ ΛCDM model OK, few parameters fit data
  - ✧ Almost flat Universe but with more baryons & DM and less DE
  - ✧ H_0 lower → Universe older, slower expansion
- ❖ Detection of ISW lensing bispectrum, strongest limits on primordial non-Gaussianity f_{NL}
- ❖ Inflation OK, n_s-r space constrained, simplest inflation models (single-field slow-roll, standard kinetic term, Bunch-Davies initial vacuum state) favoured
- ❑ No evidence for dynamical DE (w close to -1)
- ◆ Neutrinos species/thermodynamics: N_{eff} compatible with "standard 3.046", but between 3 and 4 ???
- ◆ Anomalies at large scales ???

(So far?) future: PRISM !

http://www.prism-mission.org/

Brief communication



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