planck

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IN2P3 - CNRS

esa

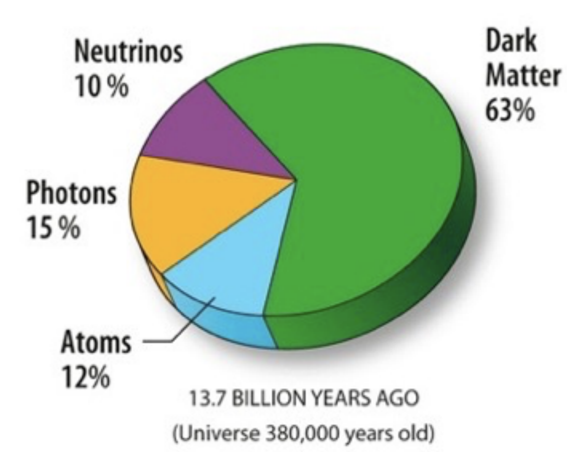
Cosmology

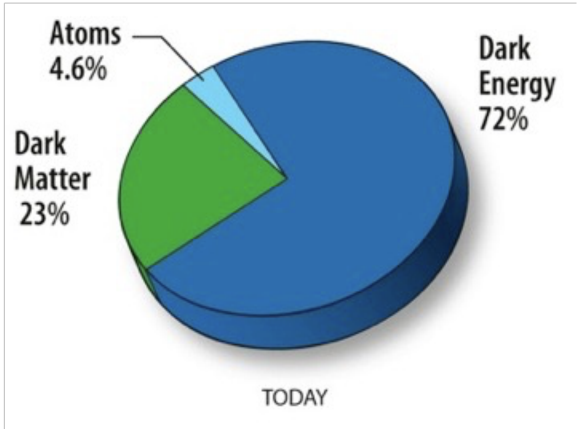
- **"Cosmology": the branch of philosophy dealing with the origin, evolution and general structure of the universe, with its parts, elements, and laws, and especially with such of its characteristics as space, time, causality, and freedom.**

- **Questions :**
  - How old is the Universe ?
  - What's its composition ?
  - How could we describe its evolution ?

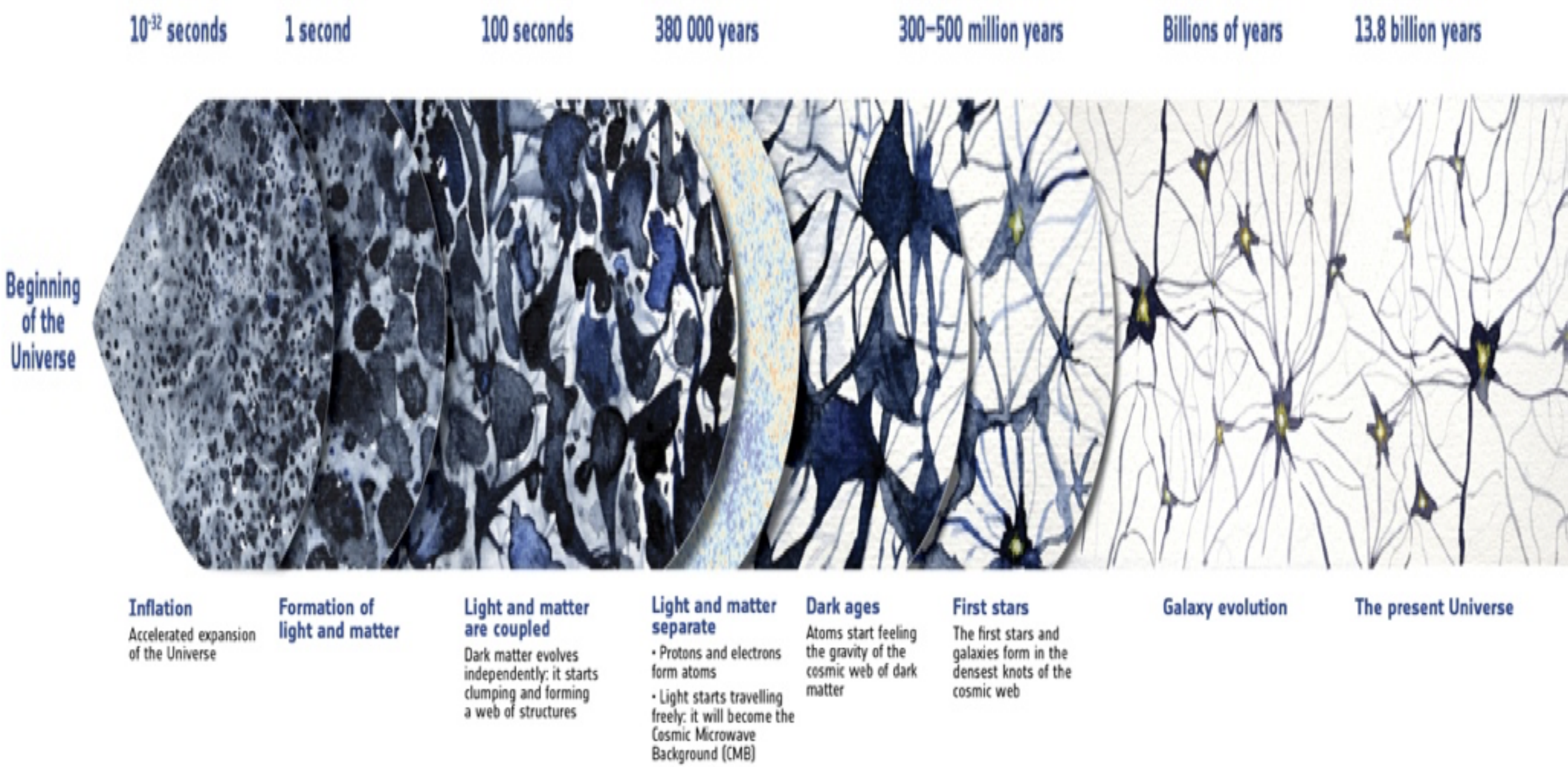
- **that leads to more questions :**
  - What is dark matter ?
  - What is Dark Energy ?
  - …

- **In practice:**
  - CMB anisotropies trace the matter distribution at the decoupling (very early in the age of the Universe) allowing to put strong constraints on the cosmological model

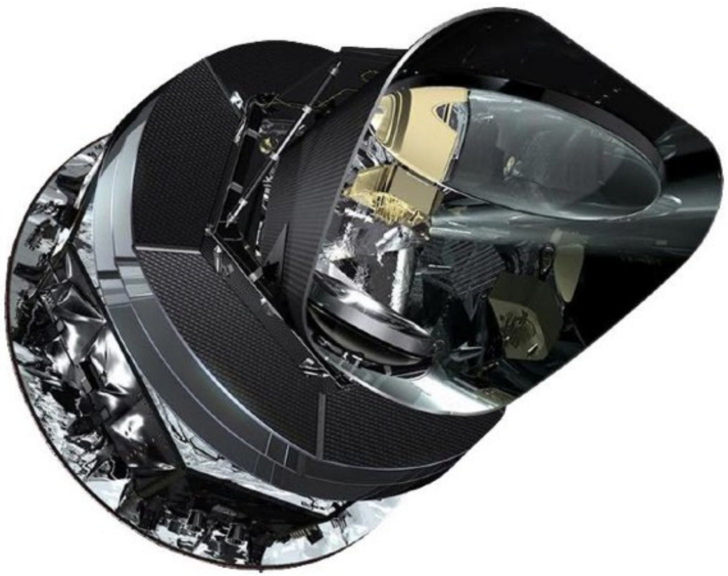




Big-Bang model



Planck
time schedule



- **1992:** studies of the HFI-Samba concept (M3 call)
- **1994:** M3 selection phase A (COBRAS & SAMBA)
- **1996:** ESA approval (name: Planck)
- **1997:** project accepted at IN2P3
- **2004 & 2006 & 2008:** calibrations
- **14 may 2009:** launch
- **2011:** **early results**
- **13 January 2012:** end of mission HFI
- **2013:** **first release (PR1)**
- **mid-2013:** end of mission LFI
- **23 oct. 2013:** spacecraft turned off
- **2015:** **second release (PR2)**
- **2018:** **third release (PR3)**

Planck @ IN2P3
labs

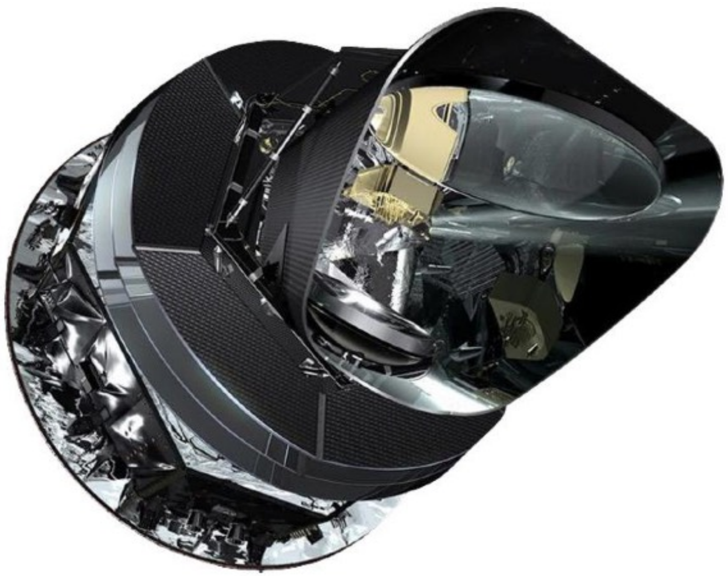
- **HFI with French PI lead (CNES, INSU, CEA, IN2P3)**
  IN2P3 = 50% French contribution
  large involvement in terms of IT
- **LPSC (ex ISN)**
  - date: 1999
  - up to 11 researchers / 25 IT
- **LAL**
  - date: 1996
  - MOU LAL/IAS (april 2004)
  - up to 8 researchers / 14 IT
- **APC (ex PCC Collège de France)**
  - date: 1996
  - up to 16 researchers / 28 IT

Planck
Science case

- **The primary science goals of Planck**
  - Mapping the **Cosmic Microwave Background** anisotropies with improved sensitivity and angular resolution
  - Testing **inflationary** models of the early Universe
  - Measuring the amplitude of structures in the Cosmic Microwave Background
  - Measurement of the **ΛCDM** cosmological parameters at percent level
  - Perform measurements of Sunyaev-Zel'dovich effect

- **Extra**
  - Galactic emissions and interstellar medium
    (Synchrotron, Dust, Free-free, molecular lines)
  - Extra-galactic objects
    (clusters, diffuse emission from galaxies with the Cosmic Infrared Background, radio sources, AGN, ...)
  - studies of the Solar System, including planets, asteroids, comets and the zodiacal light

Planck
in a nutshell



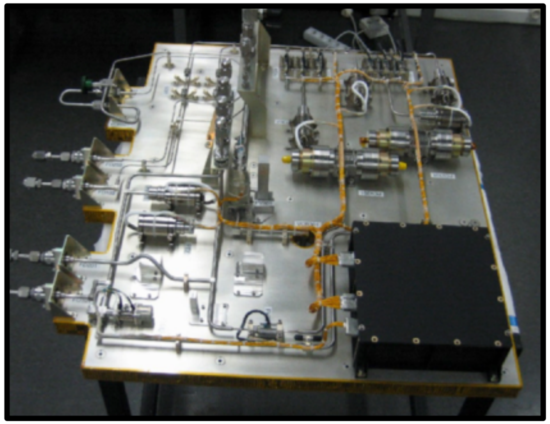
- **ESA M3 mission to observe the first light in the Universe with all-sky measurements in 9 frequencies in the mm domain**
- **Third generation of CMB space mission**
  - COBE (1993)
  - WMAP (2003)
- **Launch 2009**
  - for 15 months nominal + extended to 30 months
- **Orbit:** Lissajous around the L2 Lagrangian point
- **Instruments:**
  - LFI (22 radio receivers, 27 - 77 GHz, operated at 20K)
  - HFI (52 bolometric detectors, 83 GHz - 1 THz, operated at 0.1K)
- **Consortia**
  - LFI: PI Mandolesi (Bologna), deputy Bersanelli (Milan)
  - HFI: PI Puget (IAS), deputy Bouchet (IAP)
  - telescope: PI H.U. Norgaard-Nielsen (Dan)

Archeops

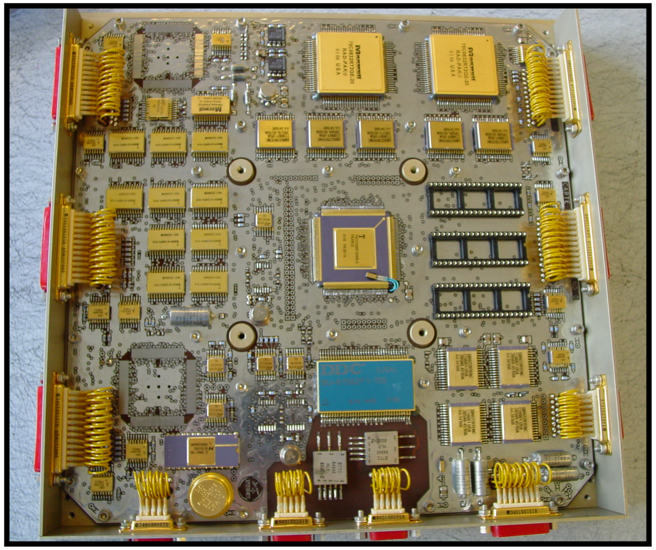
- **balloon-borne experiment for CMB measurements**
- **test-bench for Planck-HFI instrument**
  - increase TRL of hardware (e.g. cryogenic dilution)
  - validation of instrumental concept
  - experience for instrument people
  - experience in data treatment
- **science**
  - Measurement of CMB TT power spectrum (first link with COBE data)
  - First measurement of dust emission in polarisation
  - Point sources and SZ diffuse
- **large implication of IN2P3**
  - hardware (essentially in Grenoble)
  - launches (1 flight from Trapani, 3 from Kiruna)
  - data analysis (7 collaboration papers)

Planck @ IN2P3
inflight hardware

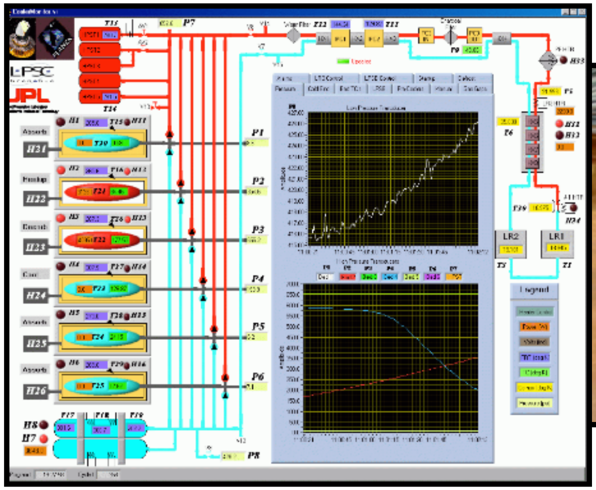
- **Data Processing Unit (DPU)**
  - development and construction of the Planck-HFI DPU
- **Electronics for cryogeny**
  - electronic for the sorption cooler (SCE-20K)
  - electronic for 100mK dilution valve control (DCE)
  - control command (SCE-20K) (soft & validation tests)
  - cryo-harness (SCE-50K)



DCE (LPSC)



DPU (LAL)



SCE

SCE FM2 (LPSC)

Planck @ IN2P3
ground segment hardware

- **Participation to the ground pre-flight HFI calibration**
  - construction of the polarisation wheel and source
  - calibration sources
  - control command of the calibration setup cryogenics
  - measurement of time constants, non-linearity, cross-talk
  - FTS measurements
  - impact of cosmic rays on detector (using particle beam)

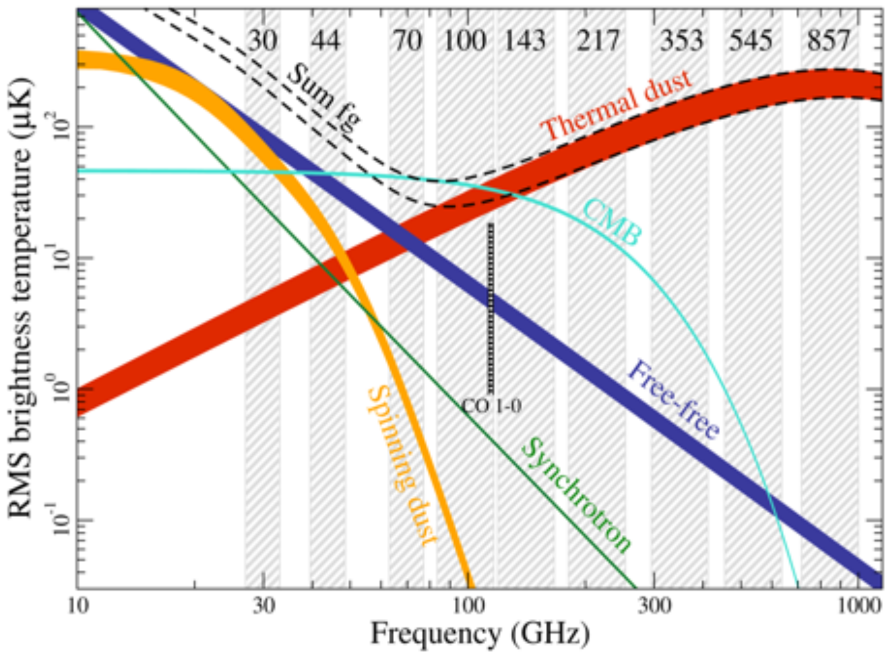
- **Data taking**
  - participation to calibration phases (2004 & 2006 & 2008)
  - participation to the Daily Tele-Communication Period


HFI focal plane & calibration sources

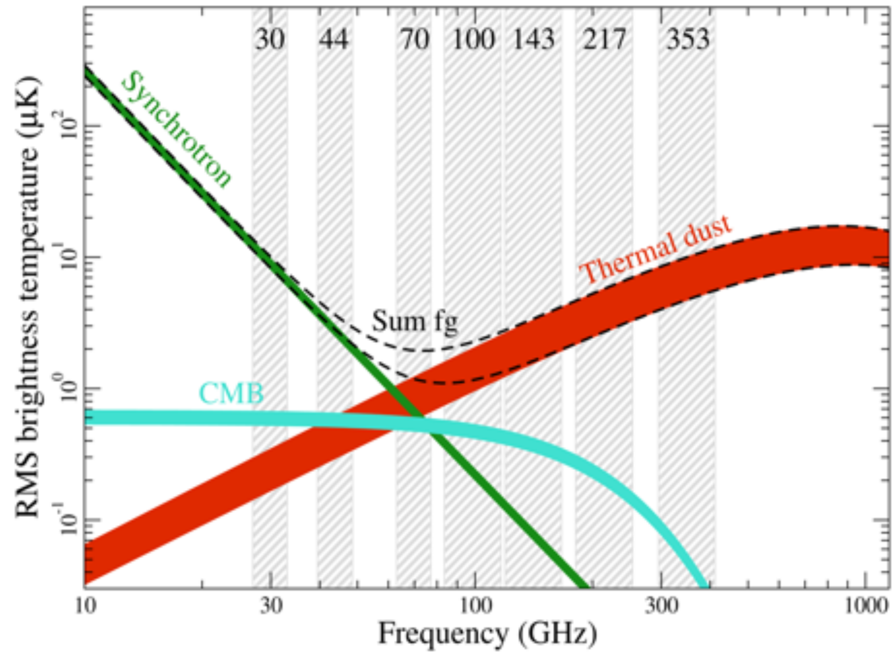

LAL team & calibration setup

frequency coverage and foregrounds

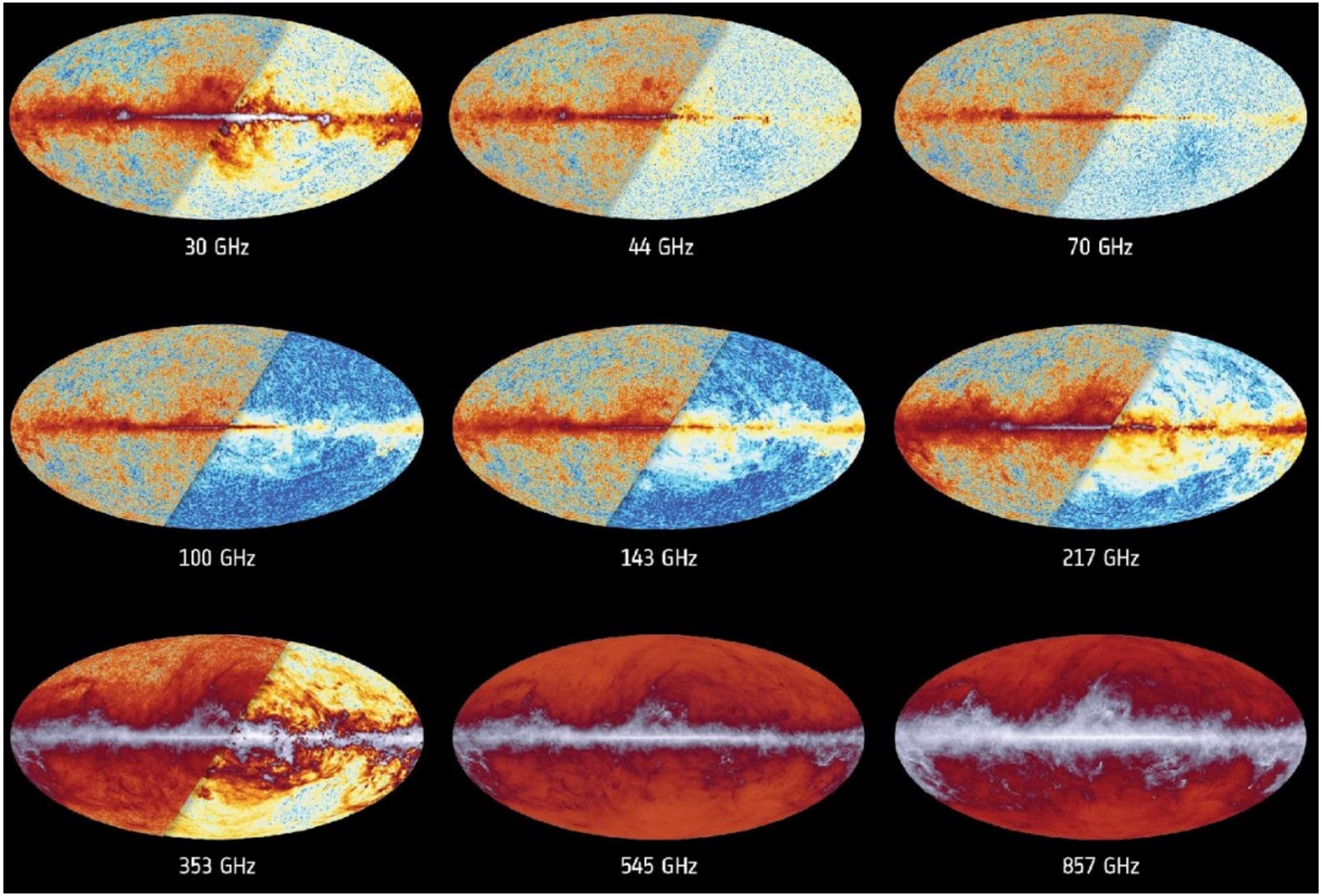
TEMPERATURE



POLARIZATION

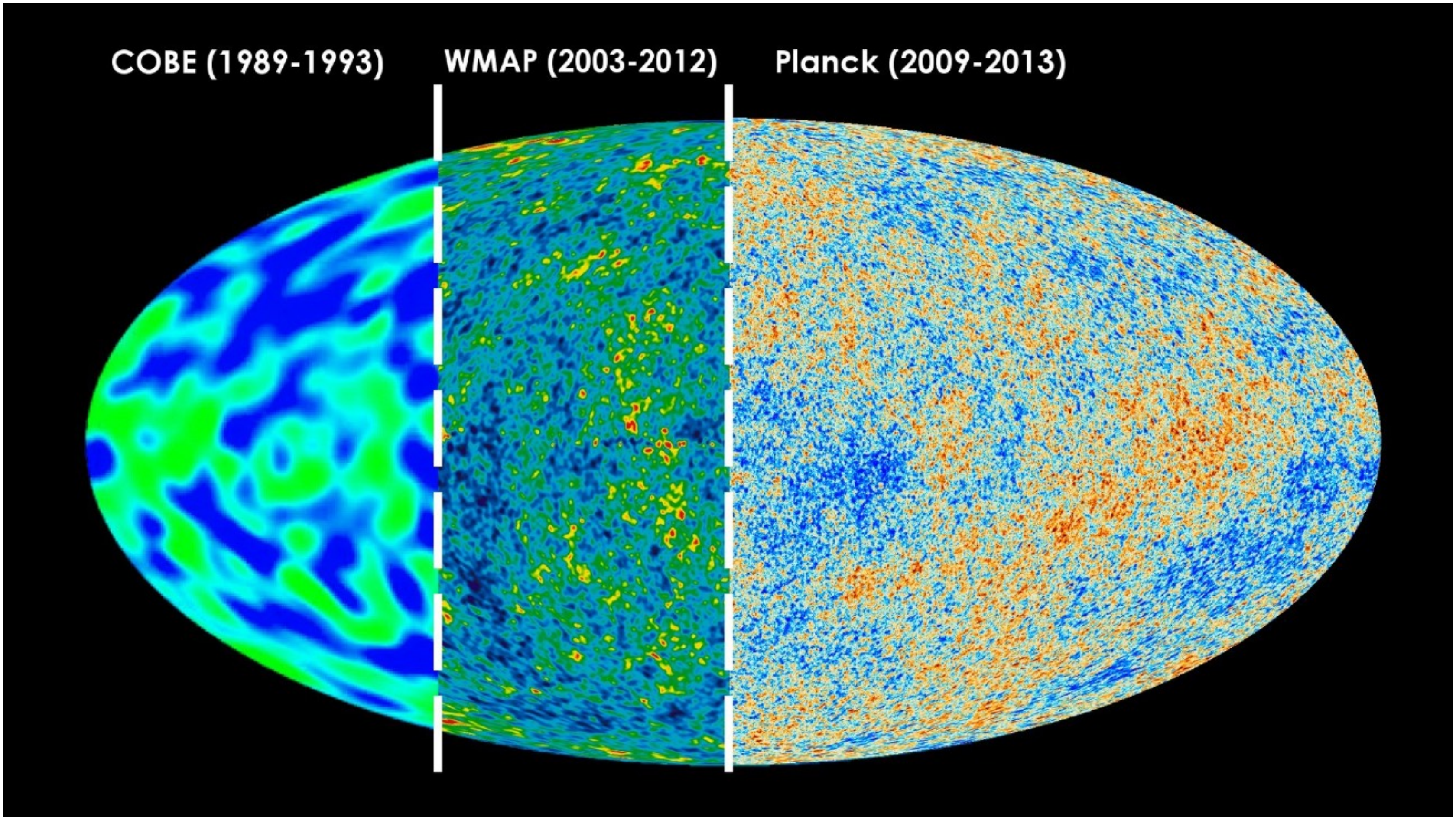


Sky maps

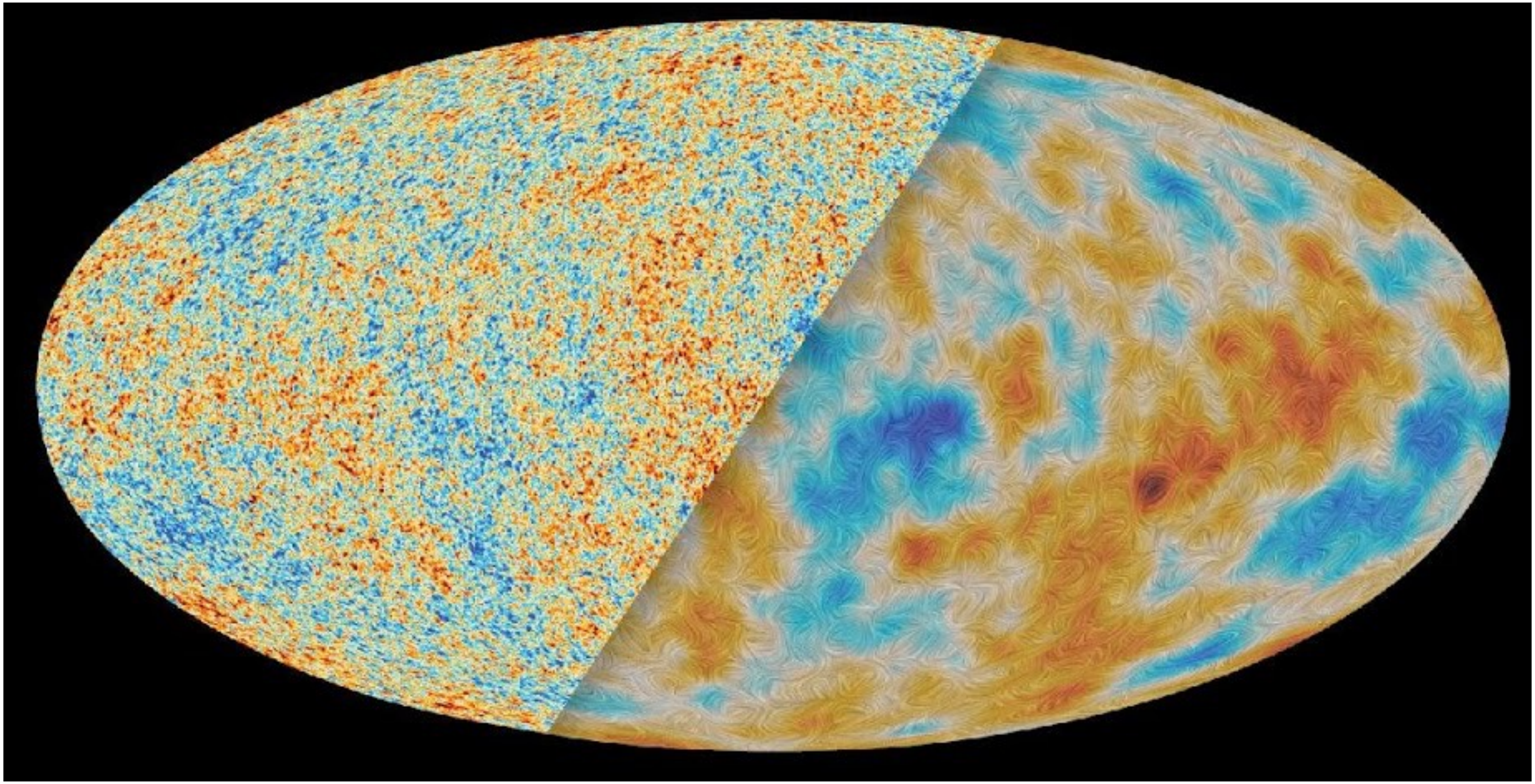


30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz

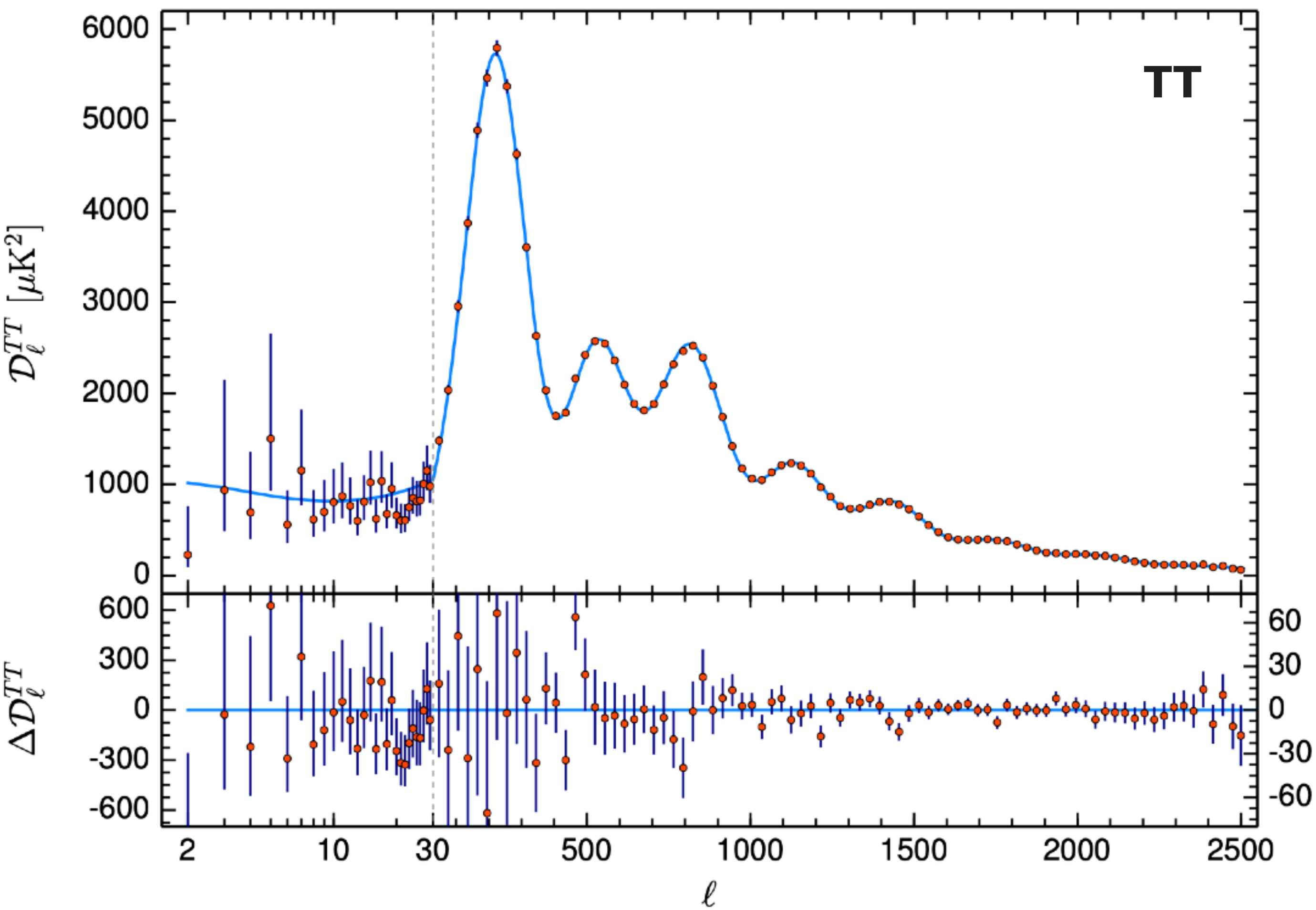
Sky maps



Sky maps



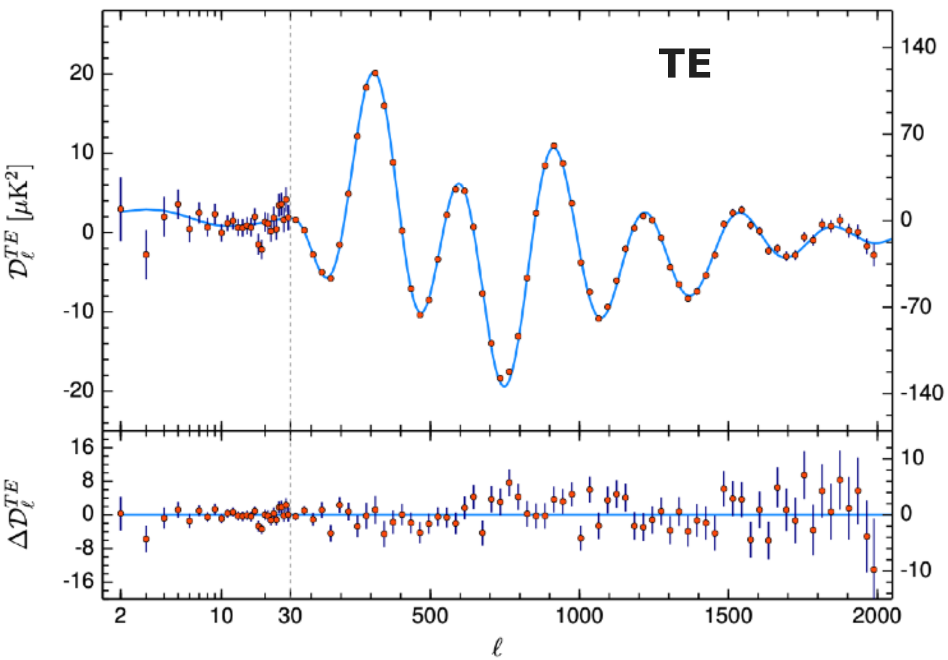
CMB power spectra
temperature anisotropies

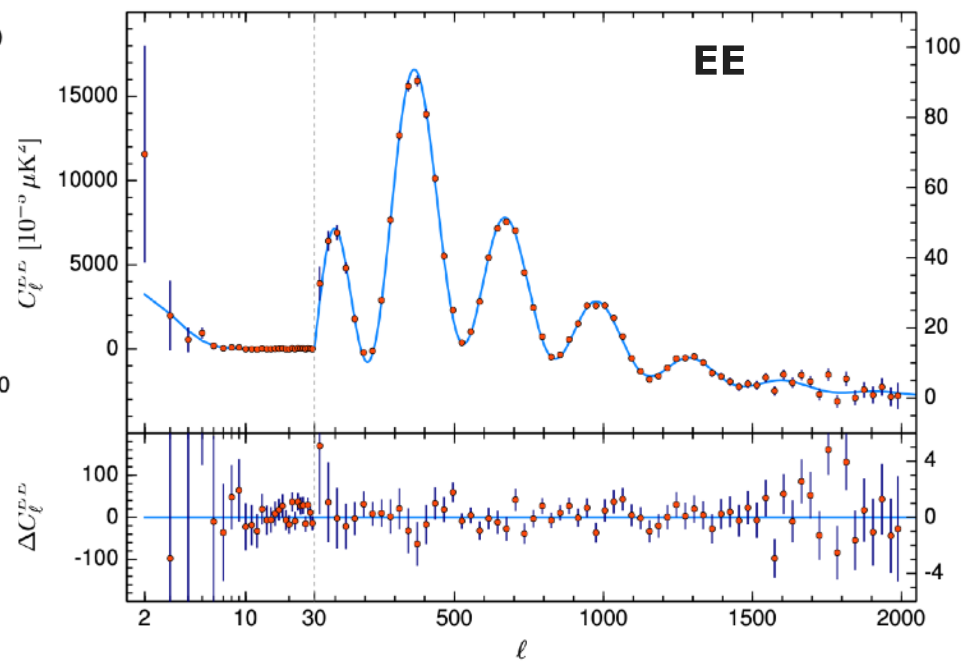


[Planck 2018 results. VI]

CMB power spectra

polarisation anisotropies

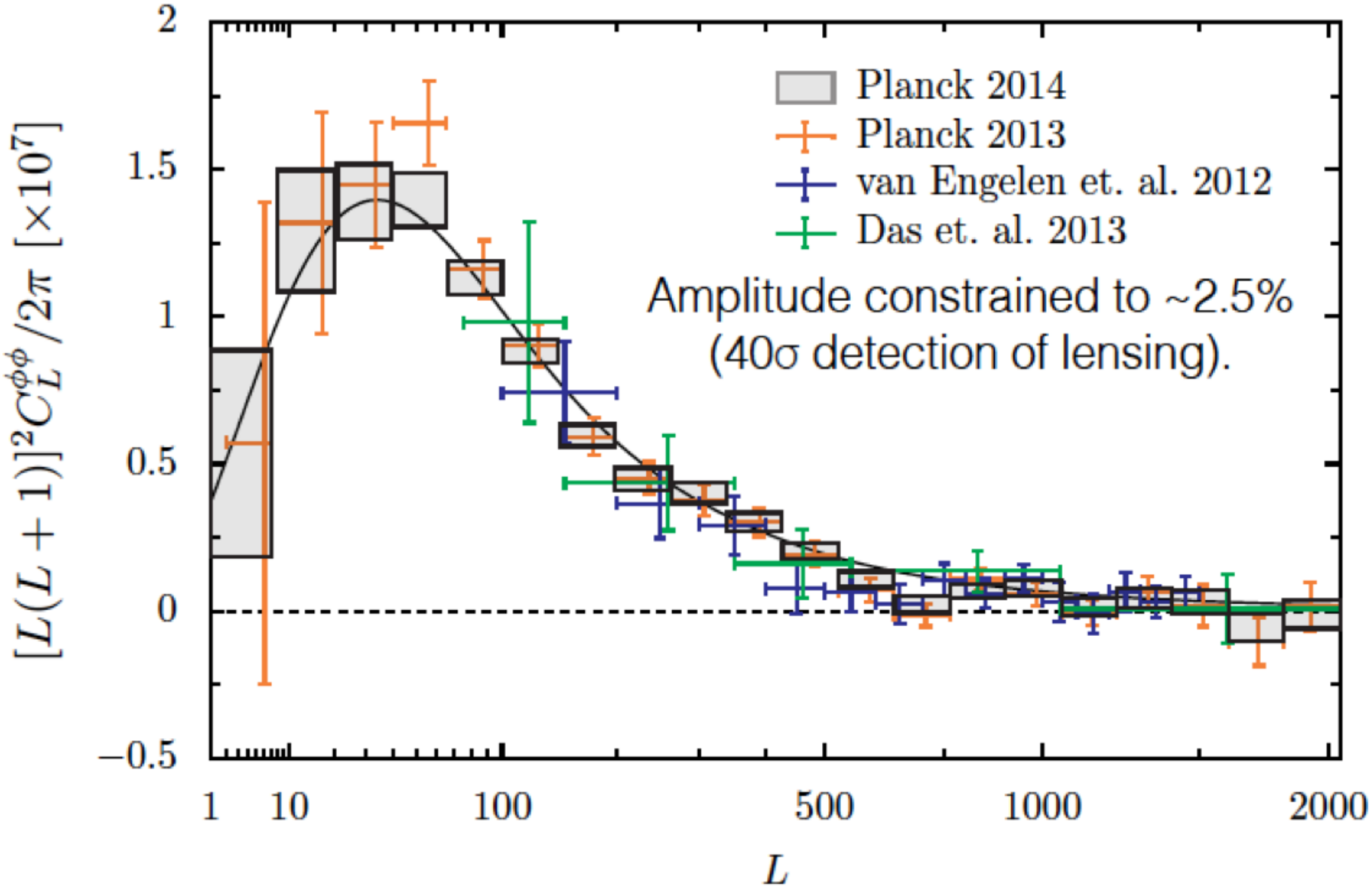




- almost as sensitive as TT for ΛCDM parameters
- can break degeneracies between cosmological parameters

- more noisy than TT
- can break degeneracies between cosmological parameters
  (in particular the reionization optical depth τ)

CMB measurements
lensing



[Planck 2018 results. VIII]

ΛCDM results
with time

	WMAP	Planck 2013	Planck 2015	Planck 2018
$\Omega_b h^2$	0.02264 ± 0.00050	0.02205 ± 0.00028	0.02225 ± 0.00016	0.02236 ± 0.00015
$\Omega_c h^2$	0.1138 ± 0.0045	0.1199 ± 0.0027	0.1198 ± 0.0015	0.1202 ± 0.0014
H_0	70.0 ± 2.2	67.3 ± 1.2	67.27 ± 0.66	67.27 ± 0.60
n_s	0.972 ± 0.013	0.960 ± 0.007	0.964 ± 0.005	0.965 ± 0.004
$10^9 A_s$	2.189 ± 0.090	2.196 ± 0.060	2.207 ± 0.074	2.101 ± 0.033
τ	0.089 ± 0.014	0.089 ± 0.014	0.079 ± 0.017	0.054 ± 0.007
Ω_Λ	0.721 ± 0.025	0.685 ± 0.018	0.684 ± 0.009	0.685 ± 0.007
Ω_m	0.279 ± 0.023	0.315 ± 0.018	0.316 ± 0.009	0.315 ± 0.007

- **more than a factor 2 on errors for basic ΛCDM parameters wrt WMAP**
- **Very stable with time**
- **Precision cosmology (below 1% error bar for most of them)**

ΛCDM

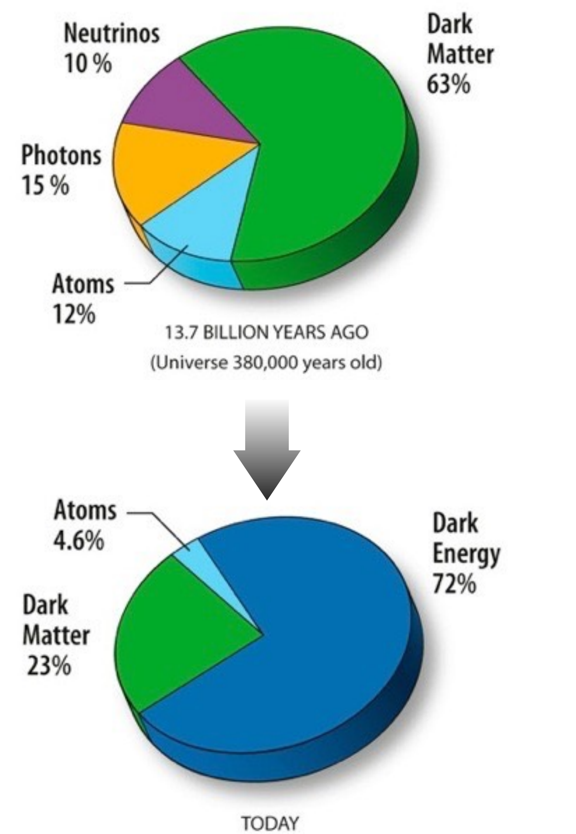
Parameter	TT,TE,EE+lowP+lensing+ext 68 % limits	
$\Omega_b h^2$	0.02230 ± 0.00014	0.6%
$\Omega_c h^2$	0.1188 ± 0.0010	0.8%
$100\theta_{MC}$	1.04093 ± 0.00030	0.03%
τ	0.066 ± 0.012	18%
$\ln(10^{10} A_s)$	3.064 ± 0.023	0.75%
n_s	0.9667 ± 0.0040	0.4%

- **Consistency**
  The **CMB anisotropies** in temperature and polarisation (TT, TE, EE), **CMB lensing** ΦΦ, as well as **BAO**, **BBN**, and **SNIa** measurements are all consistent, among themselves and across experiments, within ΛCDM

- **Robustness**
  many different checks of the robustness for the **ΛCDM** model including **non-gaussianity** constraints and **isotropie**

- **beyond ΛCDM**
  Constraints on **ΛCDM** model extensions, including **flatness** at 5 x 10–3 level, sum of **neutrinos masses** and **effective number**, **DM annihilation** limits, **dark energy** equation of state w(z), details of the **recombination** history ($A_{2s\rightarrow1}$, T_0, and also fundamental constants variation, or any energy input...)

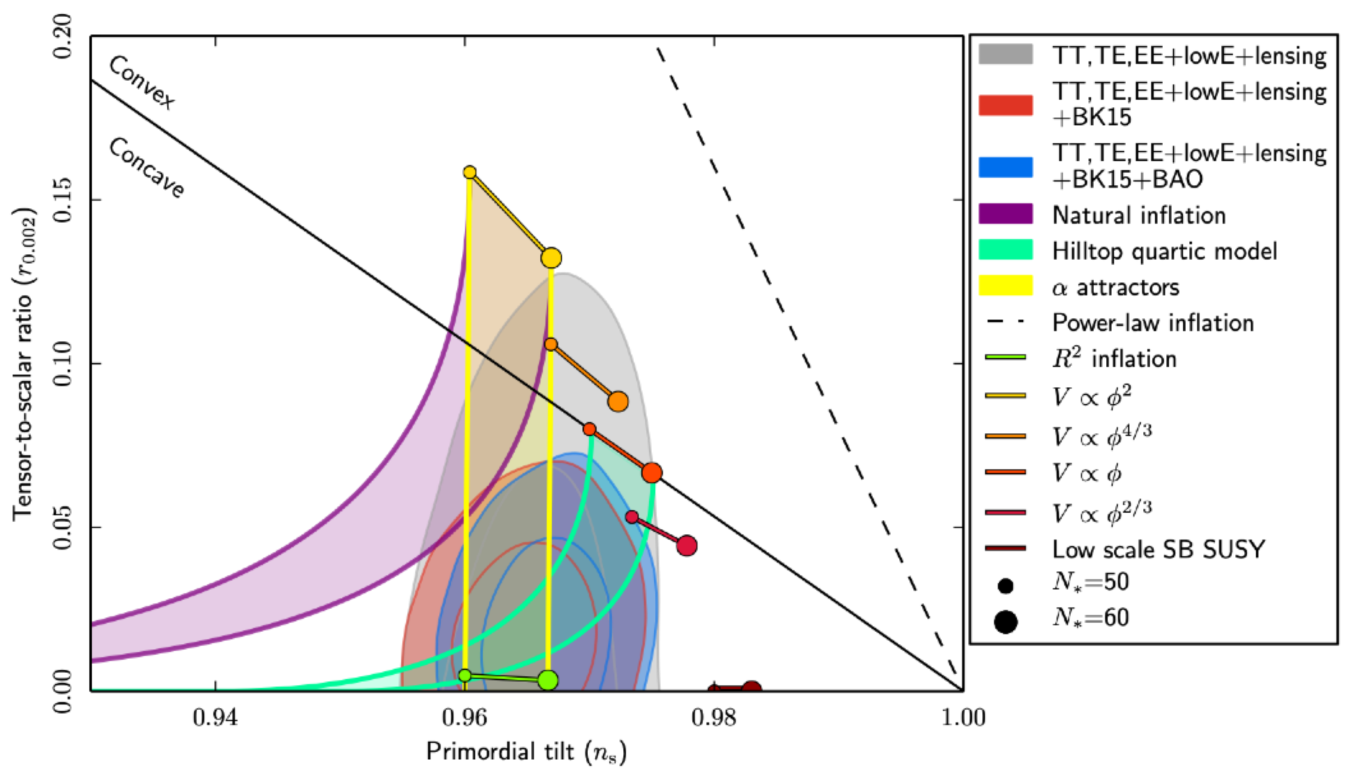
- **Precision**
  This network of consistency tests is passed with **per cent** level precision



ΛCDM and inflation

- $n_S = 0.965 \pm 0.006$
  $f_{NL} < 10$ (95% CL)
  $\Omega_K = 0.000 \pm 0.005$

- potential in Φ^2 and natural **inflation** are now disfavoured compared to models predicting a smaller tensor-to-scalar ratio, such as R^2 inflation.

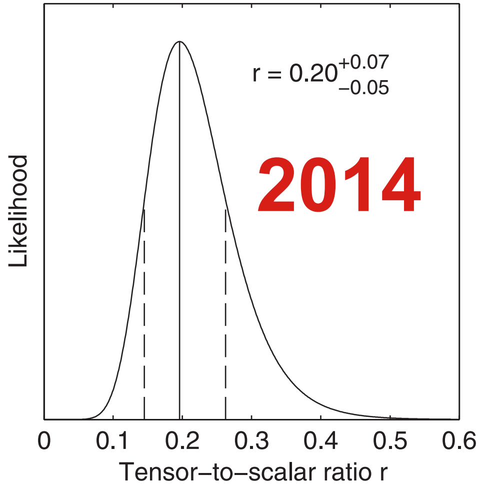


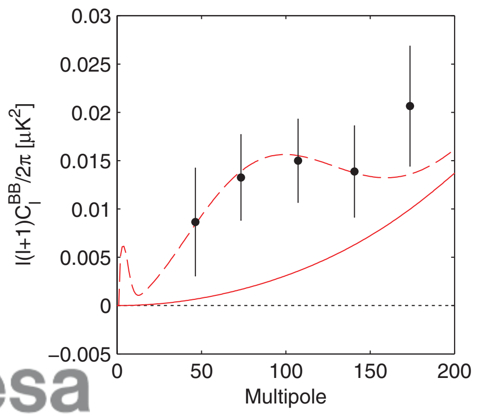
[Planck 2018 results. X]

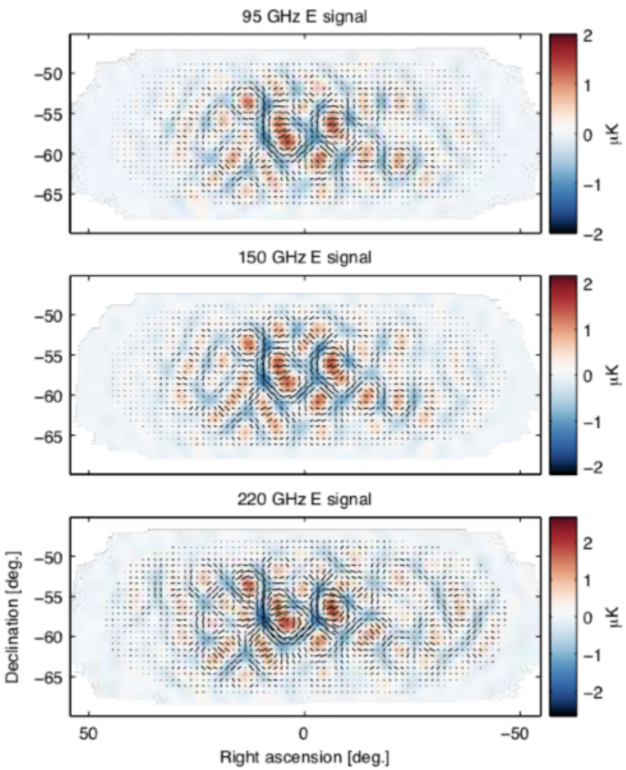
Early Universe

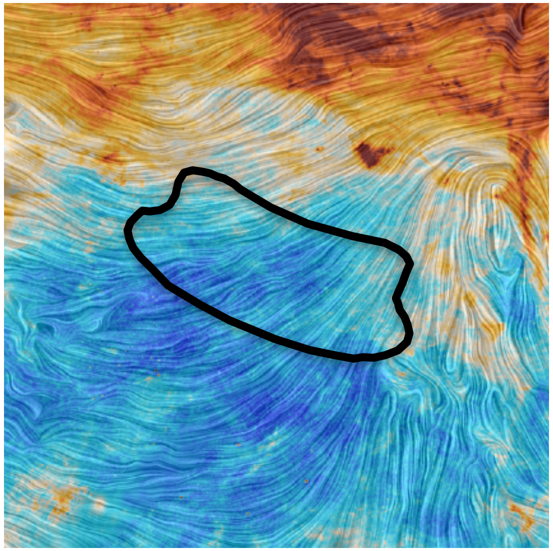
- **Planck ruled out the first detection claimed by BICEP2 (2014)**
  - need for different frequencies in order to separate sky components (easier in space)
- **the 353GHz channel was used to assess the level of foregrounds and set the current limit on tensor-to-scalar ratio**

r < 0.06 95%CL [BICEP2/Keck + Planck]





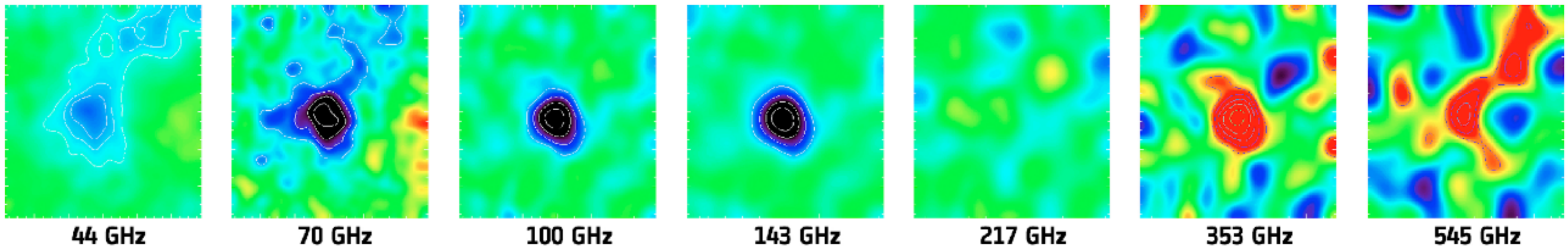




[BICEP2 PRL, 121, 221301 (2018)]

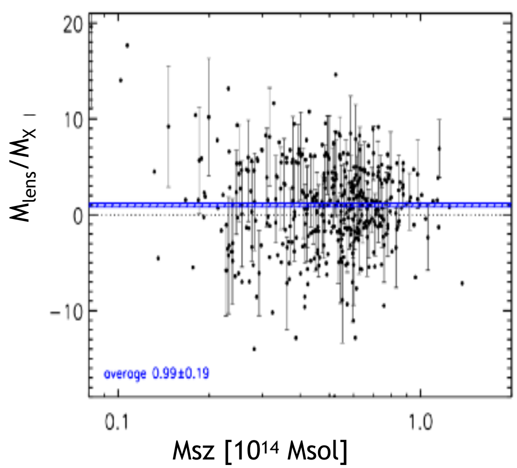
CMB measurements
clusters

- **Planck detect clusters via SZ effect**



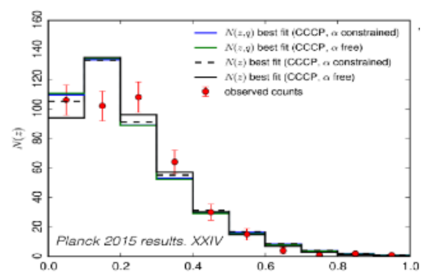
- **Cluster mass (through lensing)**

First ever cluster mass measurement with CMB lensing



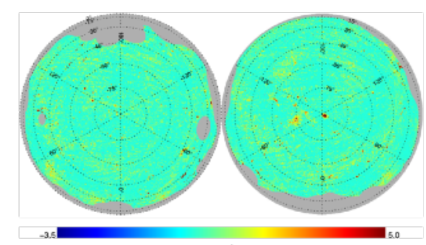
- **Cosmology (Cluster counts)**

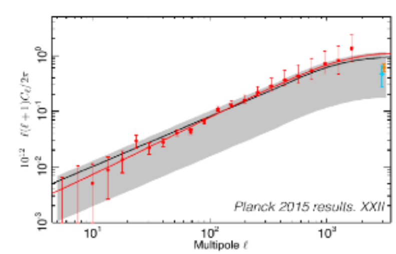
$$\frac{dN}{dz} = \int d\Omega \int dM_{500}\,\hat{\chi}(z, M_{500}, l, b)\,\frac{dN}{dz\,dM_{500}\,d\Omega}$$



- **Cosmology (y-map power spectra)**

$$C_\ell^{1\mathrm{halo}} = \int_0^{z_{\max}} dz \frac{dV_c}{dz d\Omega} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_\ell(M,z)|^2$$

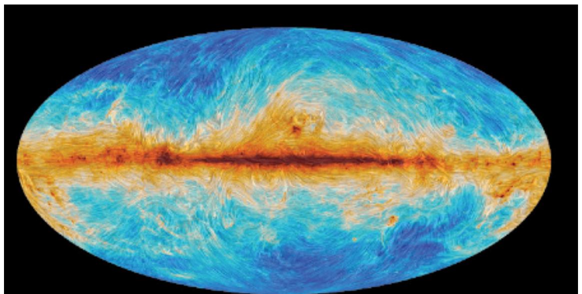




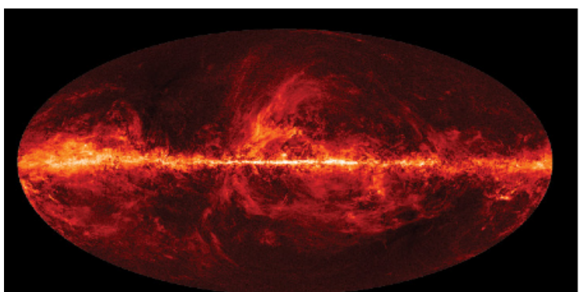
Galactic emissions

Thanks to its large frequency coverage, Planck provided all-sky maps for different components

- **Dust**

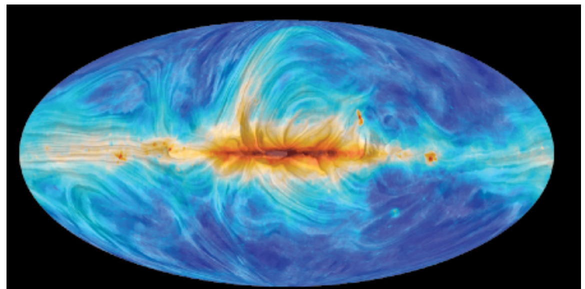


Magnetic field lines traced by dust emission at 353 GHz

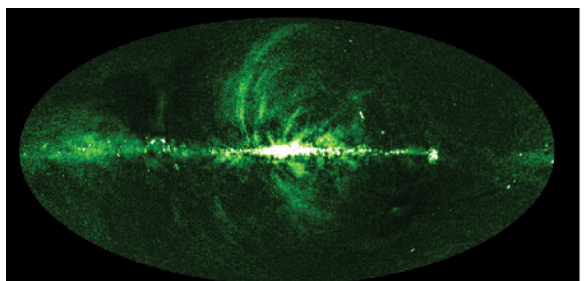


Polarised dust emission

- **Synchrotron**

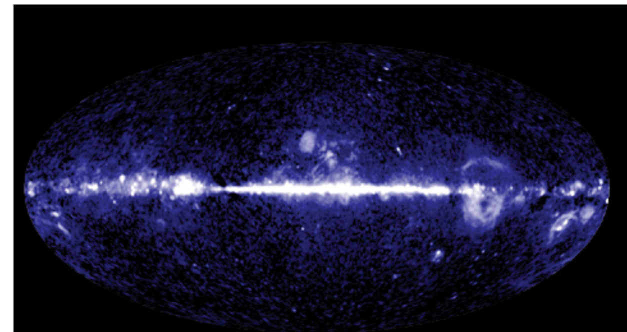


Magnetic field lines traced by synchrotron radiation at 30 GHz



Polarised synchrotron emission

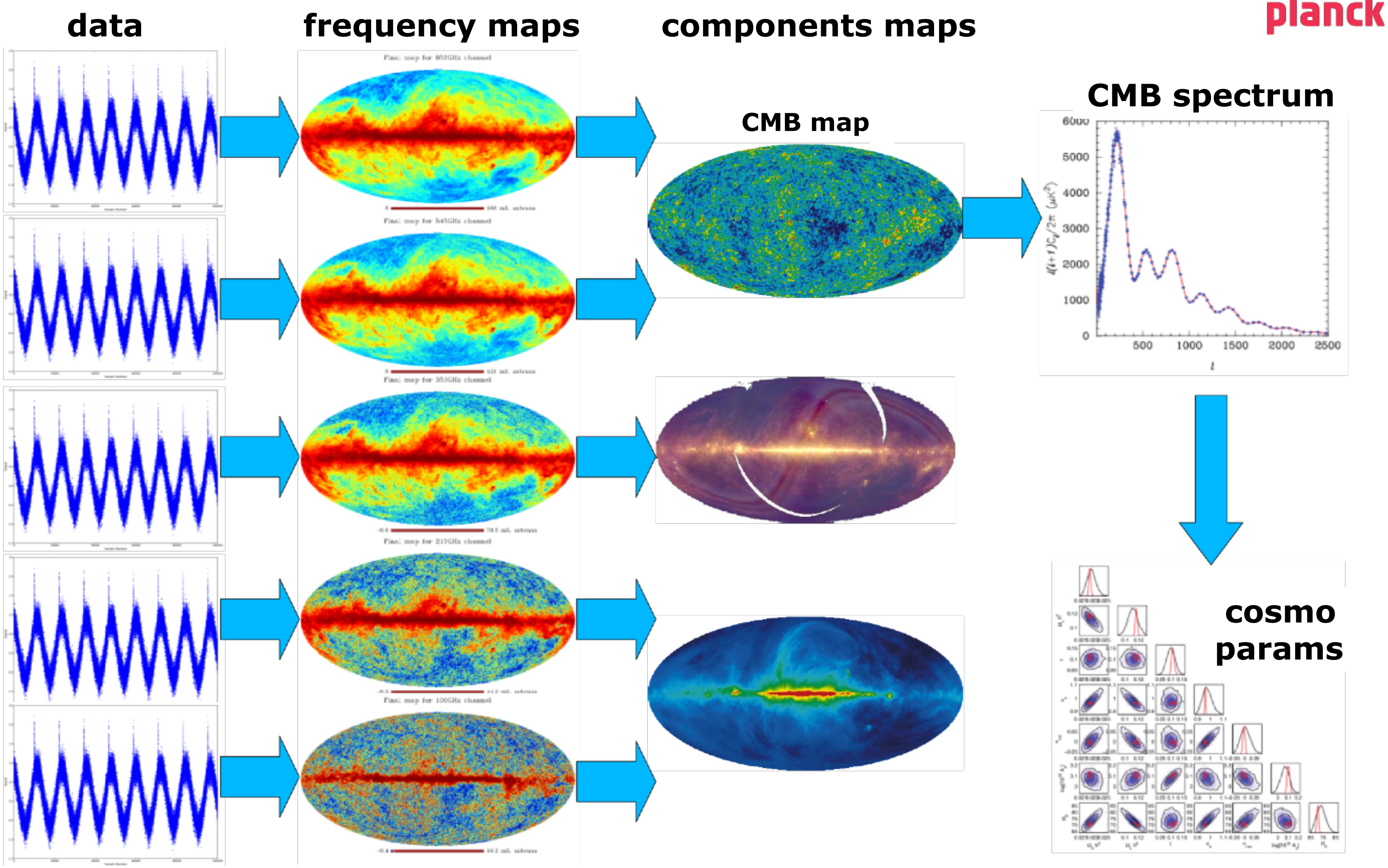
- **molecular lines (CO)**



Line radiation from carbon monoxide gas

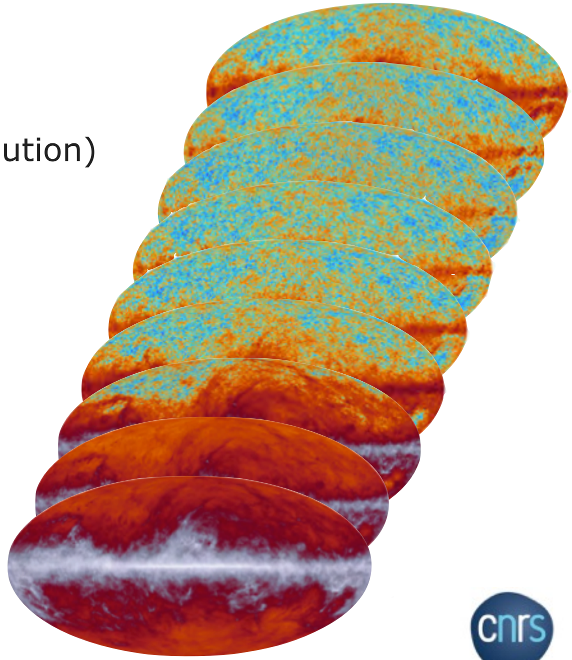
- **zodiacal light**

CMB data processing



Planck @ IN2P3
data analysis #1

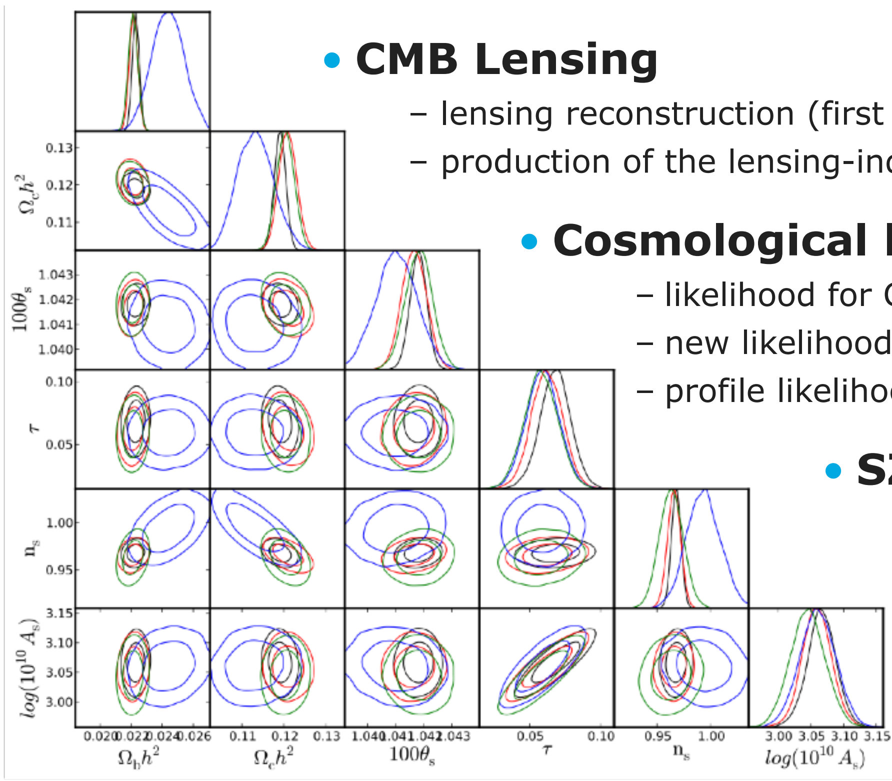
- **Simulations**
  - **pipeline** construction and support
  - development of simulation modules for instrumental effects
- **Data processing and systematics studies**
  - study of **glitch** impact on data and method for removal
  - model for **non-linearity** of the detector response (from ADC)
  - studies of systematics for polarisation (including impact of NL ADC)
  - time constant models
- **responsible for Timeline processing**
  - development of **time processing pipeline** and algorithms (demodulation, detector non-linearity, temperature variation deconvolution)
  - Data validation, cleaned timeline production
- **responsible for Map-Making and calibration**
  - development of **map-making** algorithm (destriping)
  - upgrades to include identified systematics (as templates)
  - inflight calibration in temperature and polarization
  - map production (for public releases 2013 & 2015, plus internal releases ~2 per year)



[Planck 2015 results. VIII]

Planck @ IN2P3
data analysis #2

- **Component separation**
  - code development (SMICA, NILC, GNILC, MILCA) and participation to the challenges
  - full-sky CO maps provided for the collaboration
- **Sky modeling**
  - development of Planck Sky Model (PSM) used for all simulations



- **CMB Lensing**
  - lensing reconstruction (first analysis using patches, full sky reconstruction)
  - production of the lensing-induced B-mode map
- **Cosmological likelihood analysis**
  - likelihood for CMB anisotropies temperature and polarisation
  - new likelihood dedicated to large-scale polarisation
  - profile likelihoods and adaptive sampling (CAMEL)
- **SZ science**
  - cluster catalog production
  - y-map, tSZ power-spectra
  - cluster cosmology
- **CMB-lensing cluster-mass measurements**

Planck @ IN2P3
publications

- **PLANCK scientific papers**
  - "early results": 26 papers (7 with >100 citations)
  - "2013 results": 32 papers (25 papers with >100 citations, ~6700 for cosmo)
  - "2015 results": 28 papers (19 papers with >100 citations, ~8500 for cosmo)
  - "2018 results": 12 papers (6 papers with >100 citations, ~3000 for cosmo)
  - "intermediate results" from 2011 to 2019: 57 papers (11 articles with >100 citations)
- **Lead**
  - High Frequency Instrument polarization calibration (Rosset 2010)
  - Cluster SZ optical scaling relations (J. Bartlett 2012)
  - glitch paper (G. Patanchon 2013)
  - CO paper (J.F. Macias-Perez 2013)
  - Zodiacal light paper (K. Ganga 2013)
  - Impact of particles on the Planck HFI detectors (A. Catalano 2014)
  - profile likelihood results (S. Plaszczynski in 2014)
  - map-making papers (O. Perdereau in 2013, M. Tristram in 2015)
  - reionisation paper (M. Tristram in 2015)
  - Inflation paper (M. Bucher in 2013 & 2015)
  - tSZ map (J.F. Macias-Perez 2013, B. Comis 2015)
  - Cosmology cluster count (M. Roman 2015)
  - lensing-induced B-modes (L. Perotto 2015)
  - Spectral energy distribution of dust in clusters (B. Comis 2016)

Planck @ IN2P3
hardware expertise

planck

- **New expertise at IN2P3**
  - expertise on TRL improvement (electronics)
  - integration and validation of sub-system for space missions
  - mechanics onboard (DPU, electronic sorption cooler)
  - onboard hardware and onboard soft for space missions
  - active participation to scientific calibration
- **Interactions in both ways**
  - Quality Engineer from IN2P3 for Planck + external contractors (then applied to IN2P3 projects)
  - support for Space procedures
- **Bring new partners**
  - ESA, CNES, NASA
  - recognition of the technical expertise at IN2P3

Planck @ IN2P3
data & calcul

- **CMB data analysis is highly HPC**
  - need for large memory and CPU requiring high level of parallelism
  - support from IN2P3 engineers for software computing

- **Machines**
  - Magique (2, 3, 4) at IAP (dedicated Planck machine)
  - NERSC (HPC super-computer at LBNL, Berkeley)
  - CC-IN2P3 (not fully adapted, used for specific studies and as an archive solution)

- **Simulations**
  - Planck effort on simulations have been under-estimated from the beginning (no real Monte Carlo available till 2020, only 1000 sims)
  - strong involvement of IN2P3 people with not enough support from the Planck management

- **Data releases**
  - ESA decided the schedule and organised the data releases
  - data are proprietary of PI after official releases (ESA rules)
  - Raw data not fully accessible (replication of analysis not feasible)
  - Community essentially make use of digested data (maps or likelihood)

Planck @ IN2P3
management

- **Planck Management**
  - very centralised decision process through the Planck Science Team (PST)
  - PST or PI in charge of membership, talks in conferences, paper leaders, hardware and software decisions, ...
  - The scientific activities of the Planck Collaboration within the proprietary period were organised in Working Groups
  - Despite its huge implication in both the instrument and the data-analysis, **IN2P3 was not represented** in Planck's decisional instances (no member at the Planck Science Team, no WG leader)
  - Major responsibilities (including PST positions and WG leaders) were decided at the beginning of the project (the few changes were directly agreed at the PST level), with no rotation of responsibilities over the years.
- **Visibility**
  - Paper leads were decided by the PST with only a few science papers being led by IN2P3 people (14/168) despite an important participation in the data analysis and the science interpretation
  - Talks in conferences have not been distributed (essentially concentrated on PI and first deputies, plus some specific person)
  - Post-doc and PhD students had very little visibility outside the project (PhD defence "huit-clos", membership procedure very heavy)

Conclusions

planck

- **Planck: a reference for cosmology**
  - more than 40000 citations (3-4 per day since the 2013 release)
  - provide the reference for cosmological parameters, neutrino masses and species, dark matter, …
  - full-sky maps will be the reference for the next decades
- **IN2P3 participated actively to all major steps of the Planck project**
  - fulfilled initial engagements (and even more !)
  - provided onboard hardware and onboard soft
  - hardware construction, raw data analysis, development of new analysis methods, astrophysical and cosmological interpretation, product delivery, public outreach…
- **Our work and expertise has been recognised**
  - both inside the collaboration and by the agencies (CNES, ESA, NASA)
  - responsibilities in data analysis, some paper lead, Planck scientists
  - integrated engineer-scientist IN2P3 teams allowed for a deep understanding of Planck-HFI instrumental systematics
  - International prices:
    - Group Achievement Award 2018 of the Royal Astronomy Society
    - Gruber Cosmology prize 2018

but visibility could have been more closely related to the huge work that IN2P3 scientists have accomplished

Conclusions

- **Planck acted as a huge stepping stone for IN2P3 in space missions and helped develop expertise in cosmology**
  - large community has been formed, recruited and trained
  - expertise in cosmology has been developed
  - support from IN2P3 with new recruitments (sections 01 and 47) and IT
  - Planck has allowed us to gain state-of-art expertise in cosmology, which we now use for new experiments and projects

- **Now**
  - IN2P3 increased its participation to space missions (Fermi, EUCLID, LISA, SVOM, EUSO…)
  - IN2P3 has the largest active CMB community (compared to other institutes)
  - Leader of the NIKA/NIKA2 project (for SZ cosmology)
  - Involvement in many future CMB projects (LiteBIRD, Simons-Observatory, CMB-S4)

Thèses et HDR (IN2P3)

- **Thèses (31)**
  - Benoît Revenu (PCC-CdF) - Planck - 2000
  - Alexandre Amblard (PCC-CdF) - Archeops - 2002
  - Philippe Filliatre (LPSC) - Archeops - 2002
  - Nicolas Ponthieu (LPSC) - Archeops - 2003
  - Guillaume Patanchon (PCC-CdF) - Archeops et Planck - 2003
  - Cyrille Rosset (PCC-CdF) - Archeops et Planck - 2003
  - Alexandre Bourrachot (LAL) - Archeops et Planck - 2004
  - Jean-Baptiste Melin (APC) - Planck - 2004
  - Matthieu Tristram (LPSC) - Archeops et Planck - 2005
  - Laurence Perotto (APC) - Planck - 2006
  - Stéphane Bargot (LAL) - Archeops et Planck - 2006
  - Lucien Larquère (APC) - Planck - 2006
  - Jonathan Aumont (LPSC) - Archeops et Planck - 2007
  - Antoine Chamballu (APC) - Planck - 2007
  - Marciella Veneziani (APC) - Planck - 2009
  - Marc Betoule (APC) - Planck - 2009
  - Damien Girard (LPSC) - Planck - 2010
  - Laurane Fauvet (LPSC) - Archeops et Planck - 2010
  - Sebastien Fromenteau (APC) - Planck - 2010
  - Gael Roudier (APC) - Planck - 2011
  - Alexis Lavabre (LAL) - Planck - 2011
  - Guillaume Castex (APC) - Planck - 2012
  - Lilien Sanselme (LPSC) - Planck - 2012
  - Guillaume Hurier (LPSC) - Planck - 2012
  - Clément Filliard (LAL) - Planck - 2012
  - Loic Maurin (APC) - Planck 2013
  - Benjamin Racine (APC) - Planck - 2014
  - Matthieu Roman (APC) - Planck - 2014
  - Marta Spinelli (LAL) - Planck - 2015
  - Antoine Miniussi (APC) - Planck - 2015
  - Rémi Adam (LPSC) - Planck - 2015

- **Habilitation à diriger des recherches**
  - Cécile Renault (LPSC) - Archeops - 2005
  - Sophie Henrot-Versillé (LAL) - Archeops et Planck - 2006
  - Michel Piat (APC) - Planck - 2008
  - Jacques Delabrouille - Planck - 2010
  - Juan-Francisco Macias-Perez - Archeops et Planck - 2011
  - Matthieu Tristram (LAL) - Planck - 2018