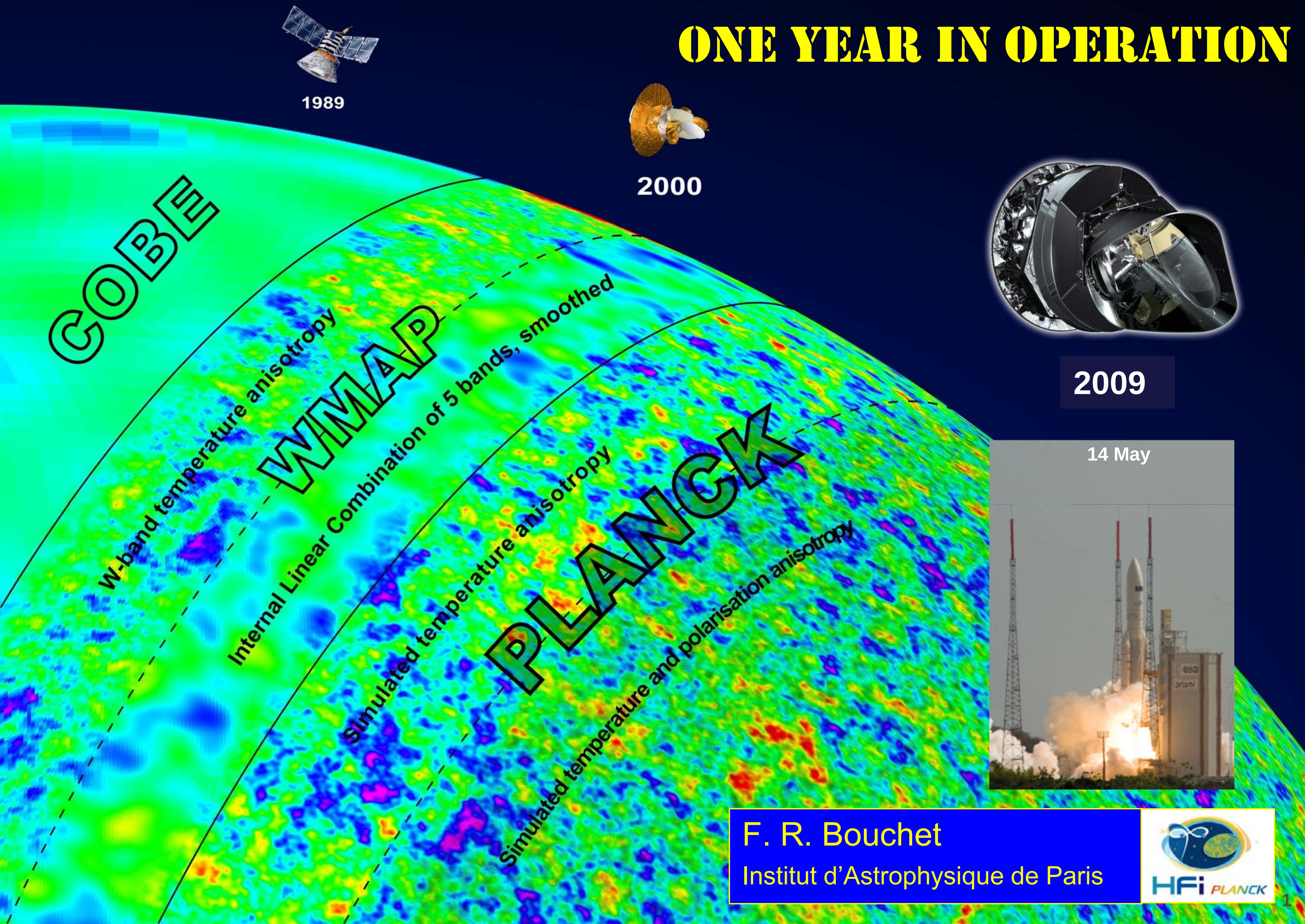
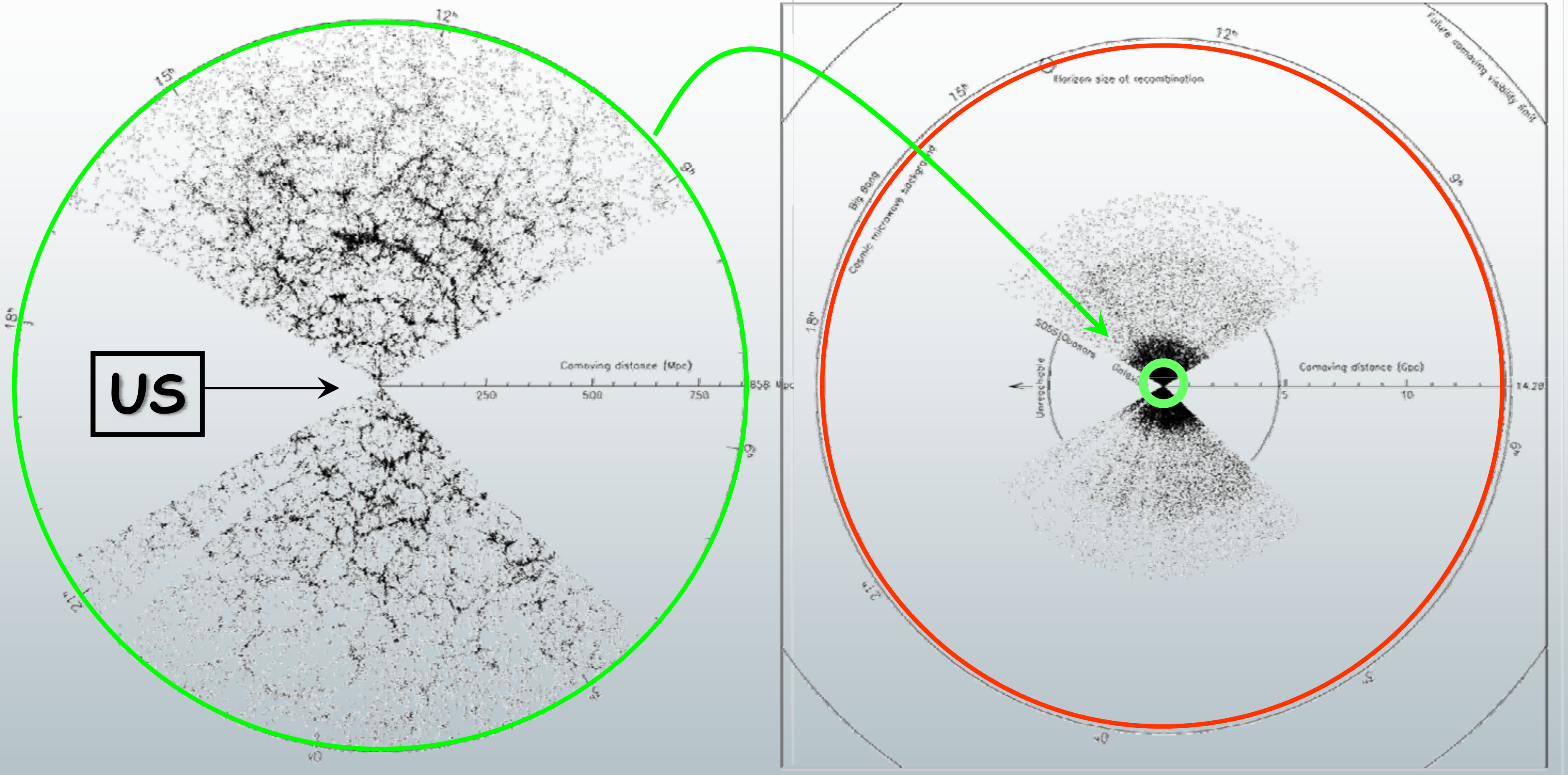
THE PLANCK MISSION
ONE YEAR IN OPERATION

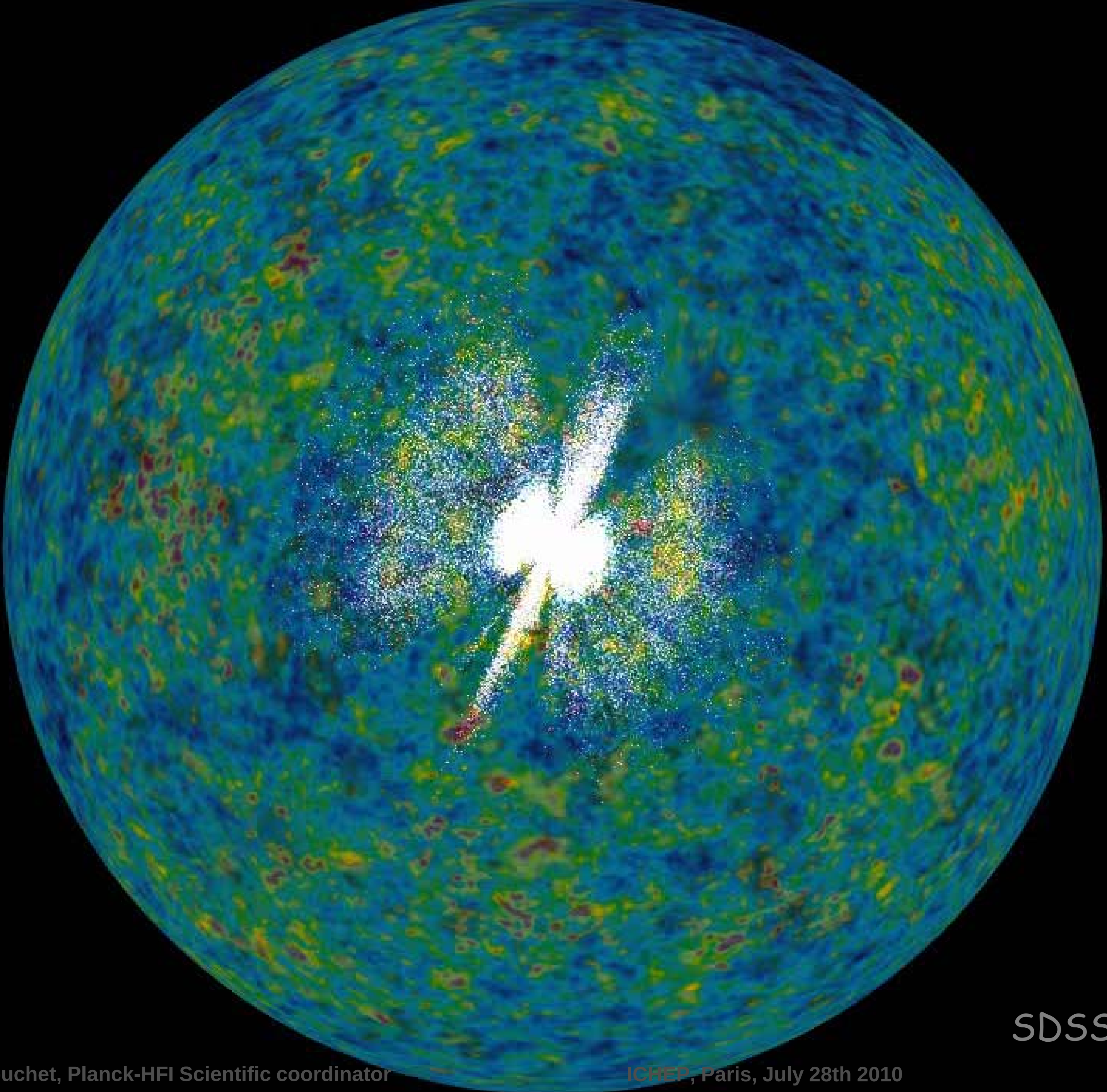


F. R. Bouchet
Institut d’Astrophysique de Paris

To look far away is to watch a remote past



Light takes 2,7 billion years to travel to us from a galaxy on the green circle .
The millimetric light took ~13.7 billion years to travel to us from the LSS (red circle). This is the fossil from the primordial furnace, ~370 000 years after the Bang, when the universe became transparent.



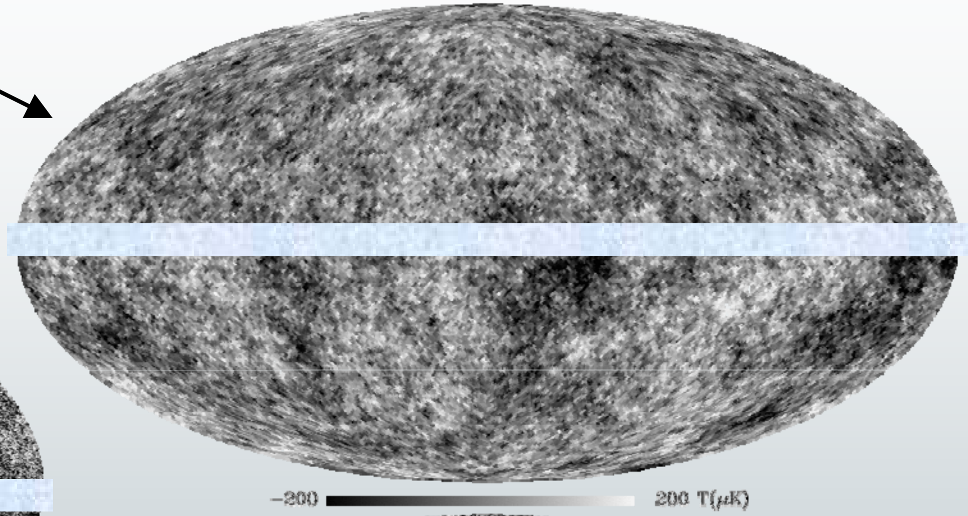
SDSS & WMAP

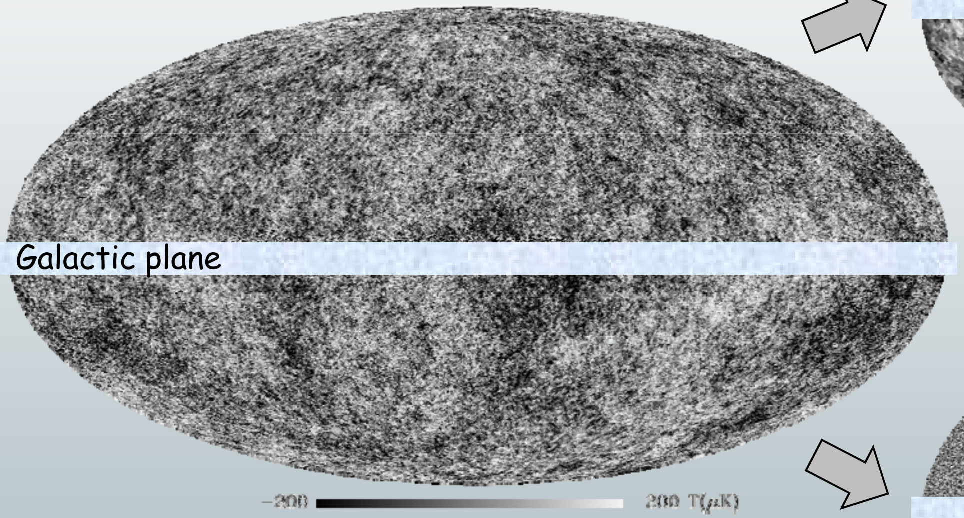
What is there to be seen?

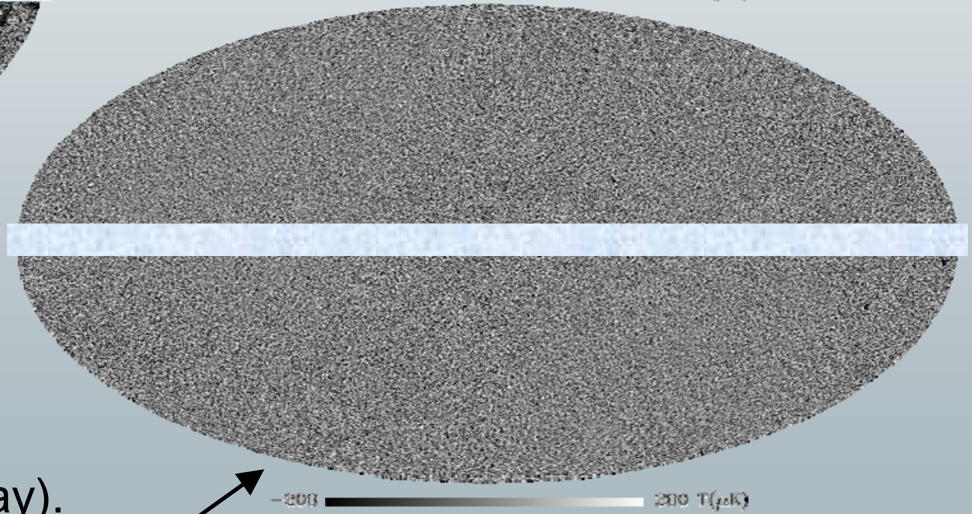
Smoothed map (suppressing scales θ < 1 deg) :

Quantum Fluctuations imprinted

When the age of the Universe was in the interval [10^{-43}, 10^{-12}] seconds







Difference map (scales θ < 1 deg) :

Acoustic oscillations at small scales

< ct when t=370 000 years (~150Mpc today).

Which allows to take a census of the Universe content

±200μK scale

Mon. Not. R. astr. Soc. (1987) **226,** 655–687

1987: 1st detection is still 5 years away!
(Pionneering calculations 20 yrs earlier)

The statistics of cosmic background radiation fluctuations

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Accepted 1987 January 9. Received 1986 November 25

Summary. We present computations of the radiation correlation functions and angular power spectra for microwave background anisotropies expected in $\Omega=1$ cold dark matter dominated universes with scale-invariant adiabatic or isocurvature initial conditions. The results are valid on all angular scales. We describe the statistical properties of the radiation pattern and develop the theory of two-dimensional Gaussian random fields. A large number of properties of such fields may be derived analytically or semi-analytically, such as the number densities of hotspots and coldspots, the eccentricities of peaks and peak correlation properties. The formulae presented here provide valuable insight into the textural characteristics of the microwave background anisotropies and must be satisfied if the primordial fluctuations are Gaussian. The assumption of Gaussian initial conditions allow us to make highly specific predictions for the pattern of the temperature anisotropies. This is demonstrated by the construction of maps of the fluctuations predicted for the total intensity and the polarization.

1 Introduction

The origin of density irregularities in the Universe represents one of the most important problems in cosmology which, until recently, was largely considered intractable. The inflationary model of the early Universe has, however, led to a potentially viable mechanism for the origin of primordial density fluctuations (e.g. Starobinskii 1982; Guth & Pi 1982; Bardeen, Steinhardt & Turner 1983). Although these calculations are hardly definitive, they have succeeded in drawing attention to a particular set of initial conditions, namely scale-invariant, Gaussian fluctuations superimposed on an $\Omega=1$ Friedman background.

In this paper, we investigate the statistical properties of the cosmic microwave background radiation (CMB), assuming that the initial fluctuations are Gaussian. The background radiation will then form a 2D Gaussian random field and should provide a clean and direct test of the statistics of the initial conditions. Given a particular cosmological model, we can compute all statistical aspects of the radiation pattern. It is unfortunate, then, that CMB anisotropies have yet

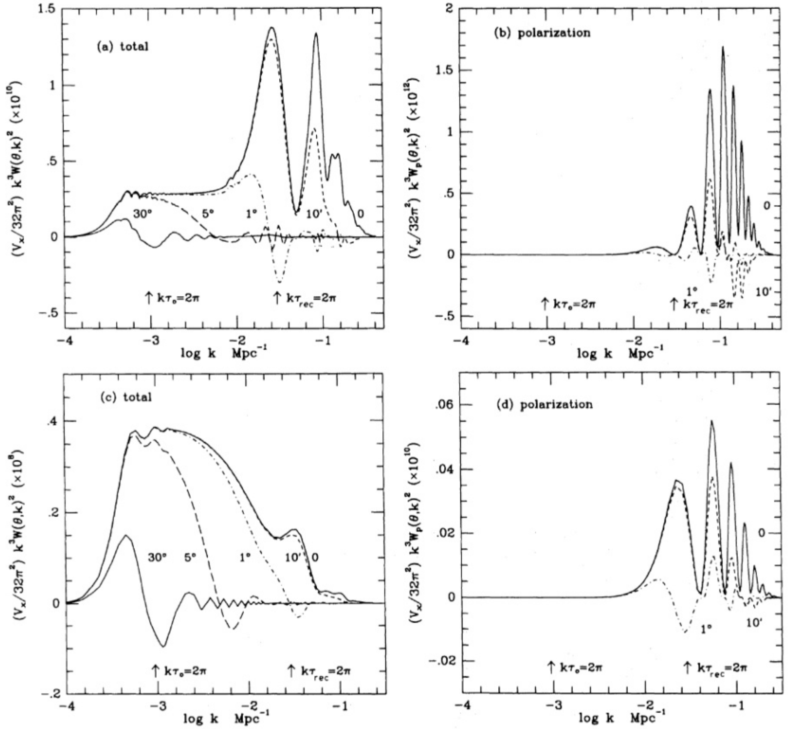
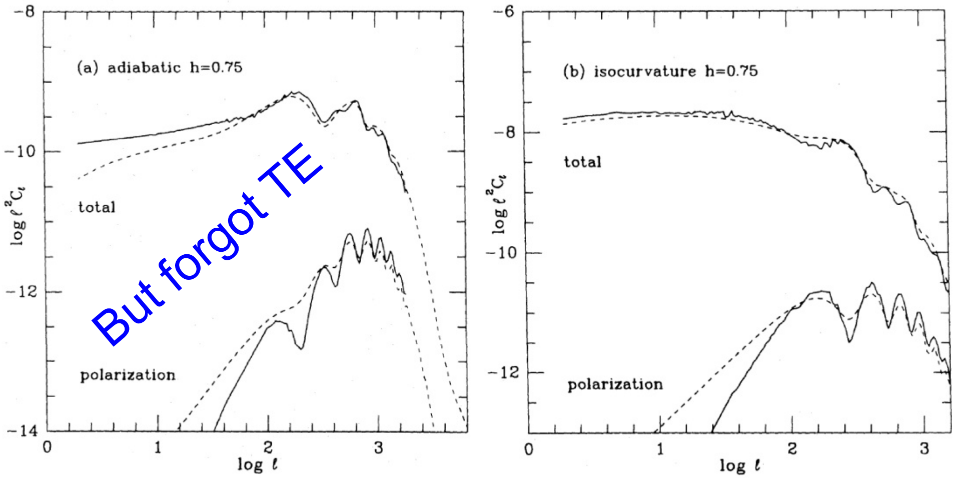


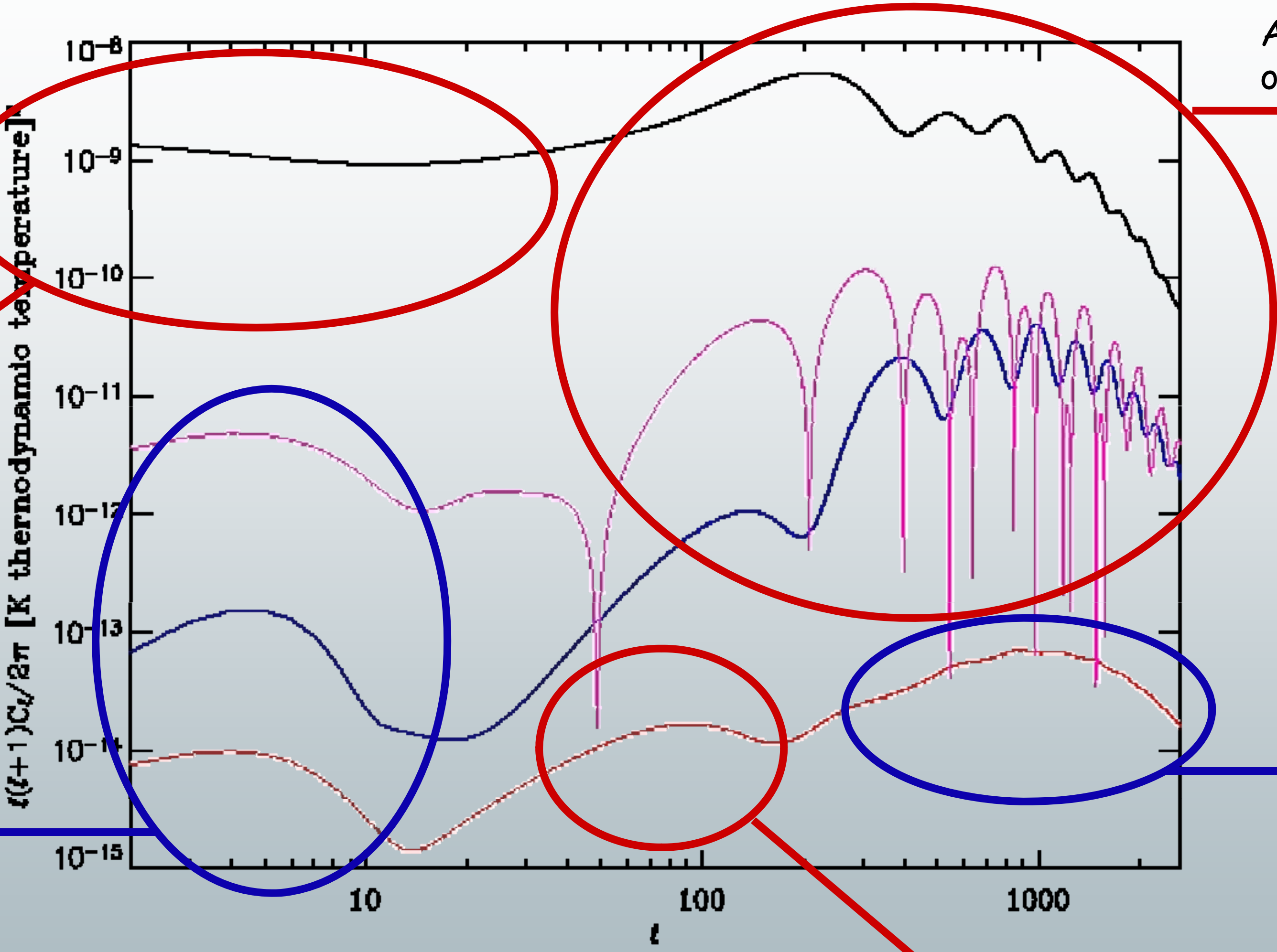
Figure 4. Integrands of the radiation autocorrelation function $k^3W_T^2(\theta,k)$ plotted against log k for various θ. (a, b) Show the integrands for the total and polarization correlation functions, respectively for a scale-invariant adiabatic CDM model with $\Omega=1$, $\Omega_B=0.03$, $h=0.75$. (c, d) Show the equivalent plots for a scale-invariant isocurvature CDM model with identical cosmological parameters. The area under each curve gives $C(\theta)$ thus it is easy to assess how fluctuations on various scales would contribute to experiments probing any particular angle. These curves have been normalized according to the prescription given in Section 4.2 with the biasing parameter $b=1$.



But forgot TE

Figure 7. Power spectra for the two $h=0.75$ scale-invariant CDM models. The solid lines show results from equation (4.17) and the dotted lines show approximate results derived from equation (4.19).

CMB information mine



Acoustic oscillations

Primordial power

Reionisation

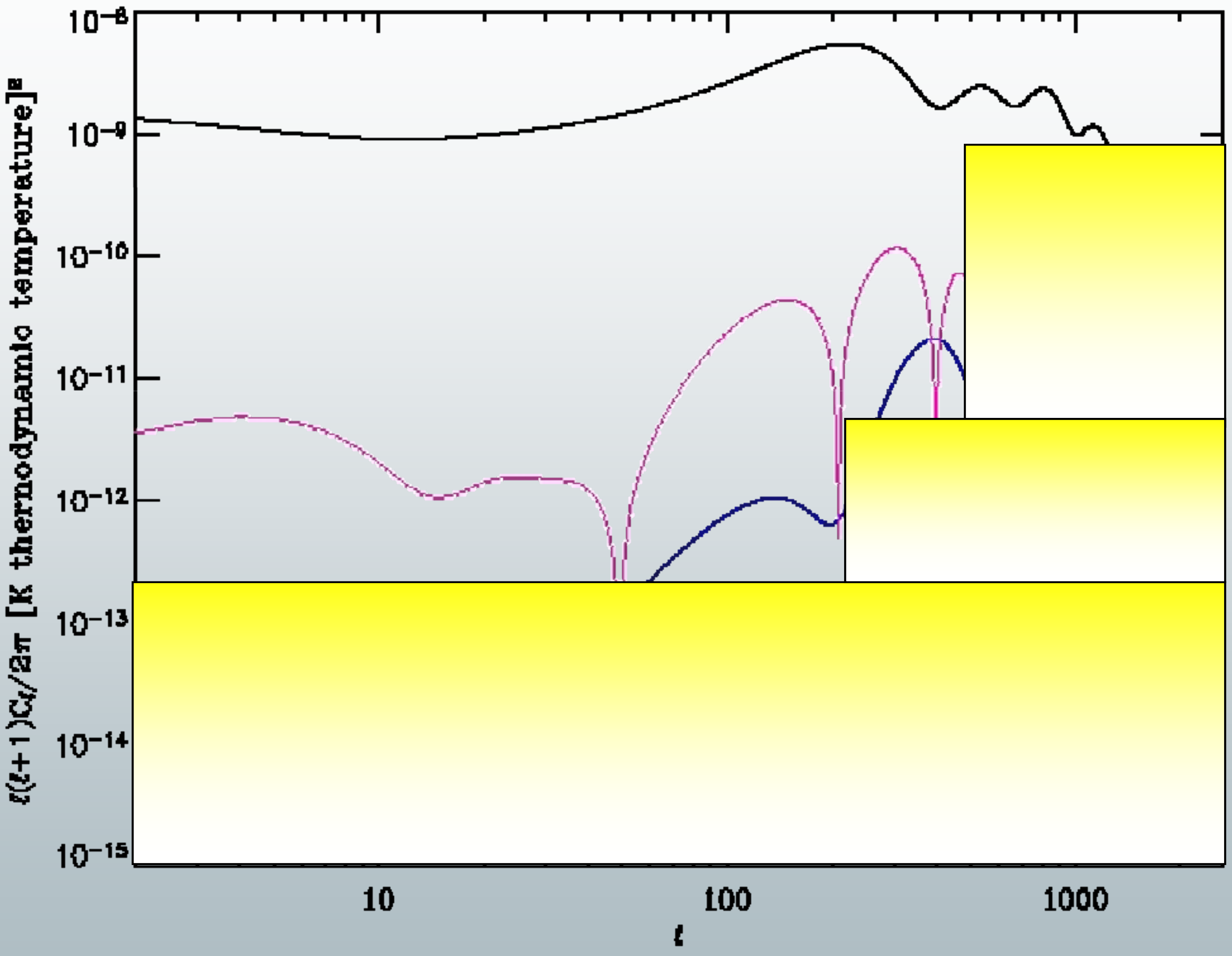
Lensing

Gravity waves

Angle ≈ 200/l degrees

+ all other statistical properties (NG)

CMB angular power spectra: 2010 knowledge



Angle ≈ 200/l degrees

Blessed with much more to extract (eg ~10% only of T modes known)

The Planck concept

- ➢ to perform the “ultimate” measurement of the Cosmic Microwave Background (CMB) temperature anisotropies:
  - – *full sky coverage & angular resolution / to survey all scales at which the CMB primary anisotropies contain information (~5’)*
  - – *sensitivity / essentially limited by ability to remove the astrophysical foregrounds*
  - ⇒ *enough sensitivity within large frequency range [30 GHz, 1 THz] (~CMB photon noise limited for ~1yr in CMB primary window)*

- ➢ get the best performances possible on the polarization with the technology available

⇒ ESA selection in 1996 (after ~ 3 year study)

NB: with the Ariane 501 failure delaying us by several years (03 → 07) and WMAP then flying well before us, polarization measurements became more and more a major goal

Goals in perspective

("Blue Book", twice better than requirements)

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

WMAP Center Freq.	23	33	41	61	94
Angular resolution (FWHM arcmin)	49	37	29	20	12,6
Sensitivity in I [μK.deg], 1 yr (8 yr)	12.6 (4.5)	12.9 (4.6)	13.3 (4.7)	15.6 (5.5)	15.0 (5.3)

The aggregated sensitivity of Planck core CMB channels is ~0.5μK.deg in T, 1 μK.deg Q&U (nominal mission – 14months)

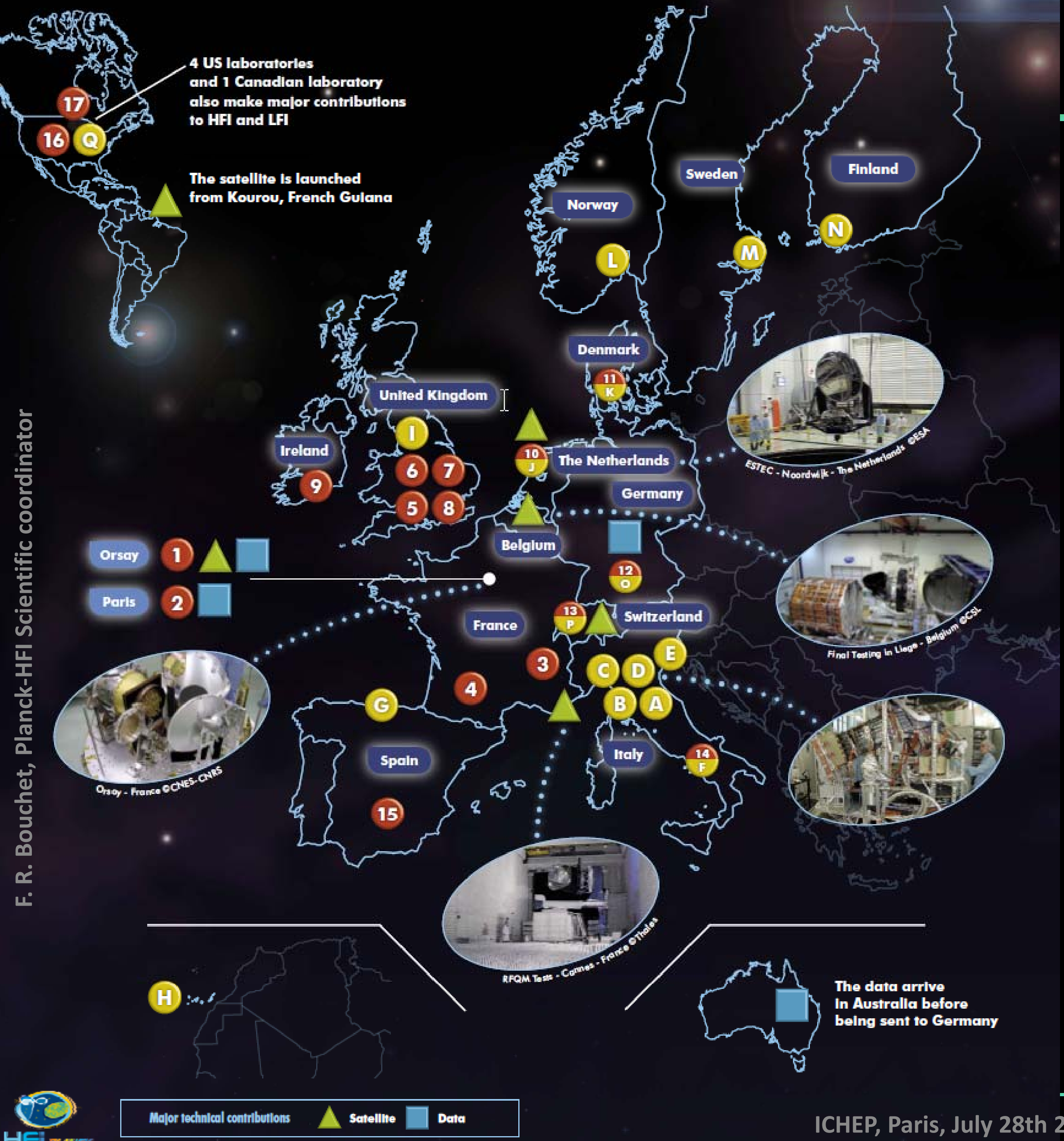
NB: Anticipated survey duration is now ~30 months, so final sensitivity ~0.33 μK.deg in T (approx 1000 years of WMAP 60+90GHz aggregated sensitivity of 10.8 μK.deg in1yr)

Planck needed breakthroughs

- The performance goals of Planck require several technological performances never achieved in space before
  - *Sensitive & fast bolometers with*
    - NEP< 2 10^{-17} W/$\text{Hz}^{1/2}$ & time constants typically < 5 msec

    (thus cooling them to 100 mK, very low heat capacity & charged particles sensitivity)
  - *total power read out electronics with very low noise*
    - < 6nV/$\text{Hz}^{1/2}$ from 10 mHz to 100 Hz
  - *Excellent temperature stability, from 10 mHz (1 rpm) to 100 Hz (cf. Lamarre et al. 04)*
    - < 10 μK/$\text{Hz}^{1/2}$ for 4K box (30% emissivity)
    - < 30 μK/$\text{Hz}^{1/2}$ on 1.6K filter plate (20% emissivity)
    - < 20 nK/$\text{Hz}^{1/2}$ for detector plate (~5000 damping factor needed)
  - *low noise HEMT amplifiers (⇒ cooled to 20K) & very stable cold reference loads (4K)*
- Additionally:
  - *low emissivity, very low side lobes, telescope (strongly under-illuminated)*
  - *no windows, minimum warm surfaces between detectors and telescope*
  - *Complex cryogenic cooling chain: 50K (passive)+20K+4K+0.1K active coolers*
    - 20K for LFI with large cooling power K (0.7W)
    - 4K, 1.6K and 100mK for HFI
    - Thermal architecture optimised to damp thermal fluctuations (active+passive)
  - *NB: 100mK cooling by dilution cooler does not tolerate micro-vibrations at sub-mg level or 7.10^{10} He atoms accumulated on dilution heat exchanger (typically He pressure 1.10^{-10} mb)*

⇒ *Integration of 3 intertwined complex chains - optical, electronic, cryogenic*



4 US laboratories and 1 Canadian laboratory also make major contributions to HFI and LFI

The satellite is launched from Kourou, French Guiana

The data arrive in Australia before being sent to Germany

F. R. Bouchet, Planck-HFI Scientific coordinator

Research Laboratories in the HFI Collaboration

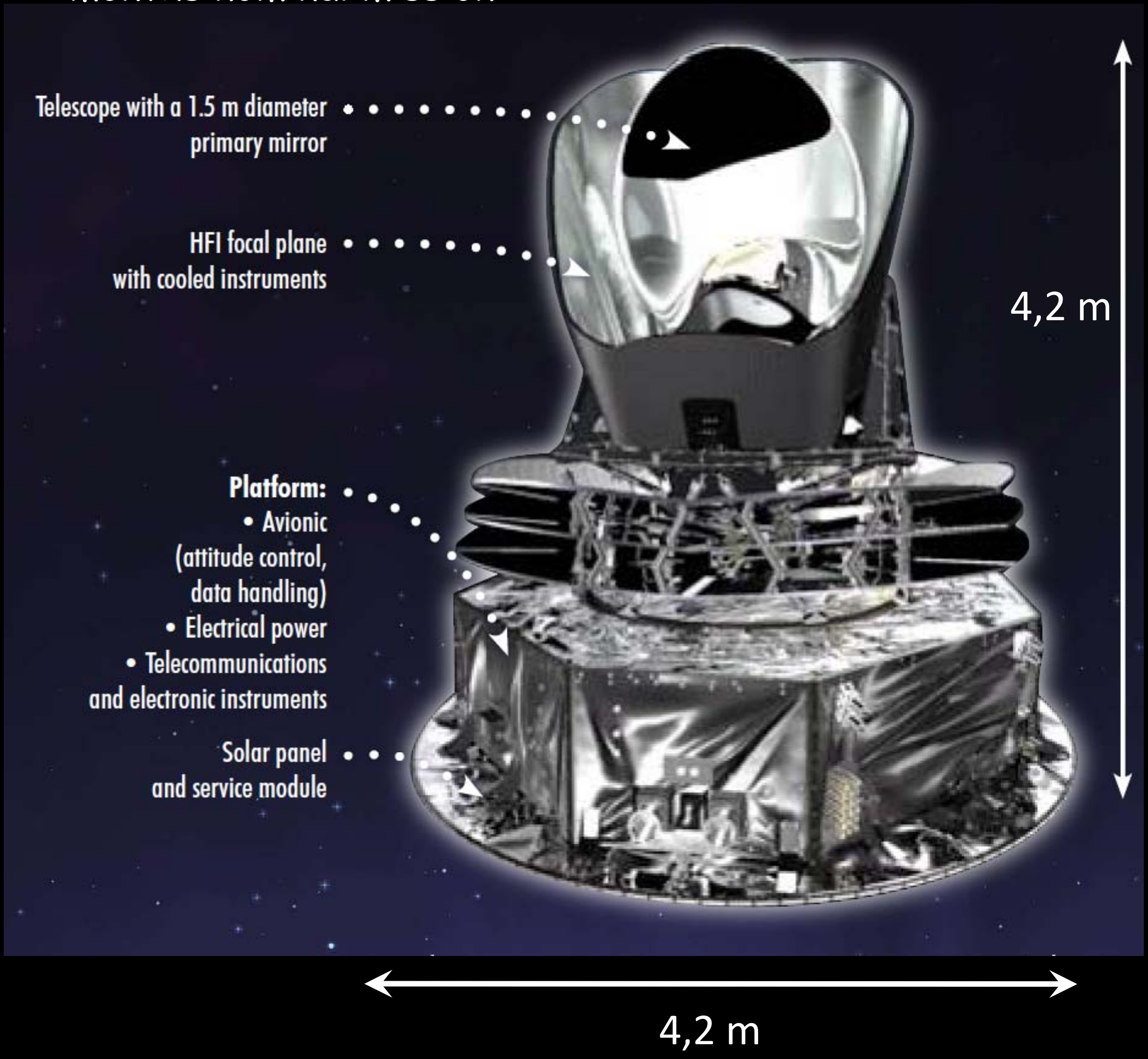
1	Institut d'Astrophysique Spatiale, Orsay (F)
1	Laboratoire de l'Accélérateur Linéaire, Orsay (F)
1	Commissariat à l'Énergie Atomique, Gif-sur-Yvette (F)
2	Institut d'Astrophysique de Paris, Paris (F)
2	Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique, Paris, (F)
2	AstroParticule et Cosmologie, Paris (F)
3	Laboratoire de Physique Subatomique et de Cosmologie, Grenoble (F)
3	Institut Louis Néel, Grenoble (F)
4	Centre d'Études Spatiales des Rayonnements, Toulouse (F)
5	Cardiff University, Cardiff (UK)
6	Rutherford Appleton Laboratory, Chilton (UK)
7	Institute of Astronomy, Cambridge (UK)
7	Mullard Radio Astronomy Observatory, Cambridge (UK)
8	Imperial College, London (UK)
9	National University of Ireland, Maynooth (IR)
10	Space Science Dpt of ESA, Noordwijk (NL)
11	Danish Space Research Institute, Copenhagen (DK)
12	Max-Planck-Institut fuer Astrophysik, Garching (D)
13	Université de Genève , Geneva (CH)
14	University La Sapienza, Rome (I)
15	Universidad de Granada, Granada (E)
16	California Institute of Technology, Pasadena (USA)
16	Jet Propulsion Laboratory, Pasadena (USA)
16	Stanford University, Stanford (USA)
17	Canadian Institute for Theoretical Astrophysics, Toronto (Canada)

Research Laboratories in the LFI Collaboration

A	Istituto Nazionale di Astrofisica Spaziale et Fisica Cosmica, Bologna (I)
B	Istituto CAISMI, Firenze (I)
C	Istituto IASF (CNR), Milano (I)
C	Istituto di Fisica del Plasma IFP (CNR), Milano (I)
D	Osservatorio Astronomico di Padova, Padova (I)
E	Osservatorio Astronomico di Trieste, Trieste (I)
E	SISSA, Trieste (I)
F	Istituto IFSI, Roma (I)
F	Universita Tor Vergata, Roma (I)
G	Instituto de Fisica de Cantabria, Santander (E)
H	Instituto de Astrofisica de Canarias, La Laguna (E)
I	Jodrell Bank Observatory, Macclesfield (UK)
J	Space Science Dpt of ESA , Noordwijk (NL)
K	Danish Space Research Institute , Copenhagen (DK)
K	Theoretical Astrophysics Center, Copenhagen (DK)
L	University of Oslo, Oslo (N)
M	Chalmers University of Technology, Goteborg (S)
N	Millimetre Wave Laboratory, Espoo (FI)
O	Max-Planck-Institut fuer Astrophysik, Garching (D)
P	Université de Genève, Geneva (CH)
Q	University of California (Berkeley), Berkeley (USA)
Q	University of California (Santa Barbara), Santa Barbara (USA)
Q	Jet Propulsion Laboratory, Pasadena (USA)

ICHEP, Paris, July 28th 2010

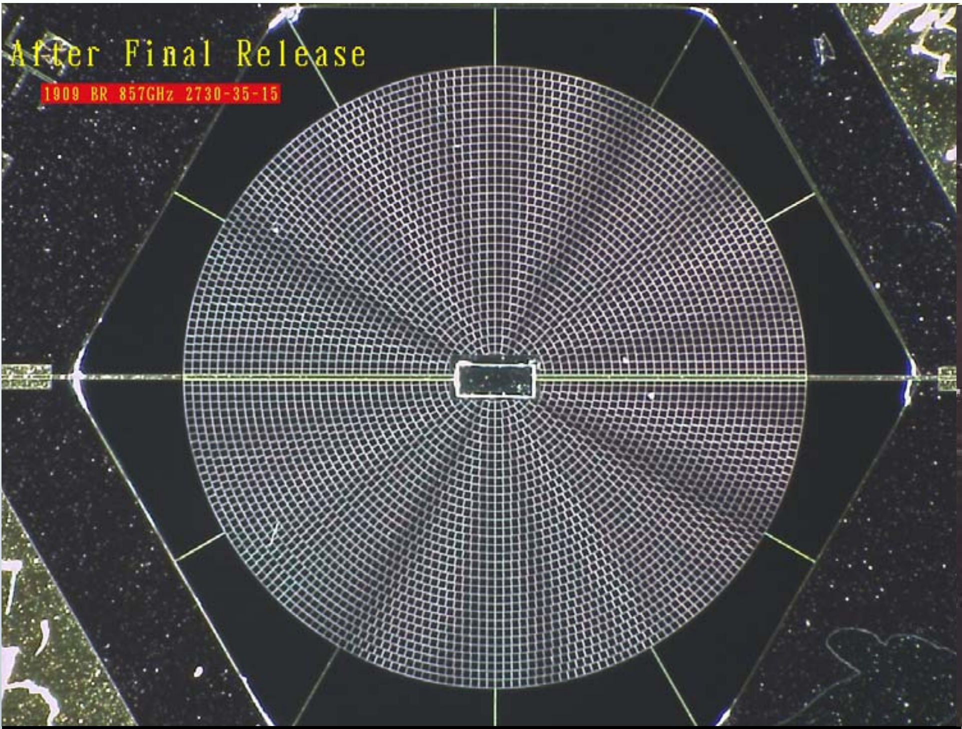
2000 Kg
1600 W consumption
2 instruments - HFI & LFI
21 months nominal mission



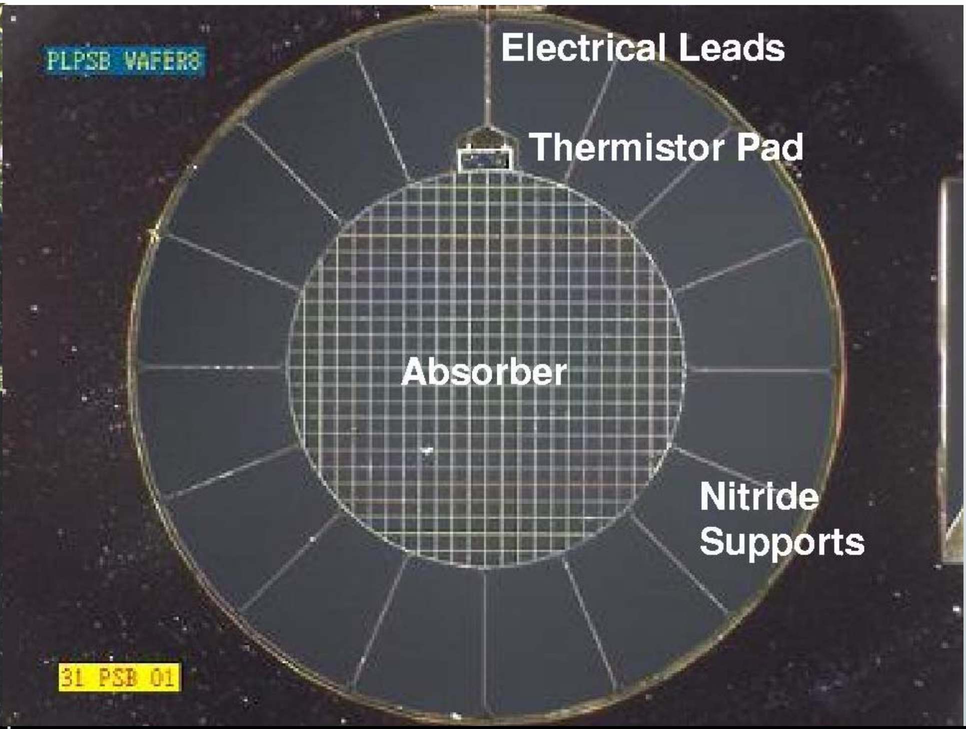
50 000 electronic components
36 000 l ^{4}He
12 000 l ^{3}He
11 400 documents
20 years between the first project and first results (2013)

6c per European per year
16 countries
400 researchers among 1000

HFI Spider Web Bolometers & PSBs



857 GHz SpiderWeb Bolometer

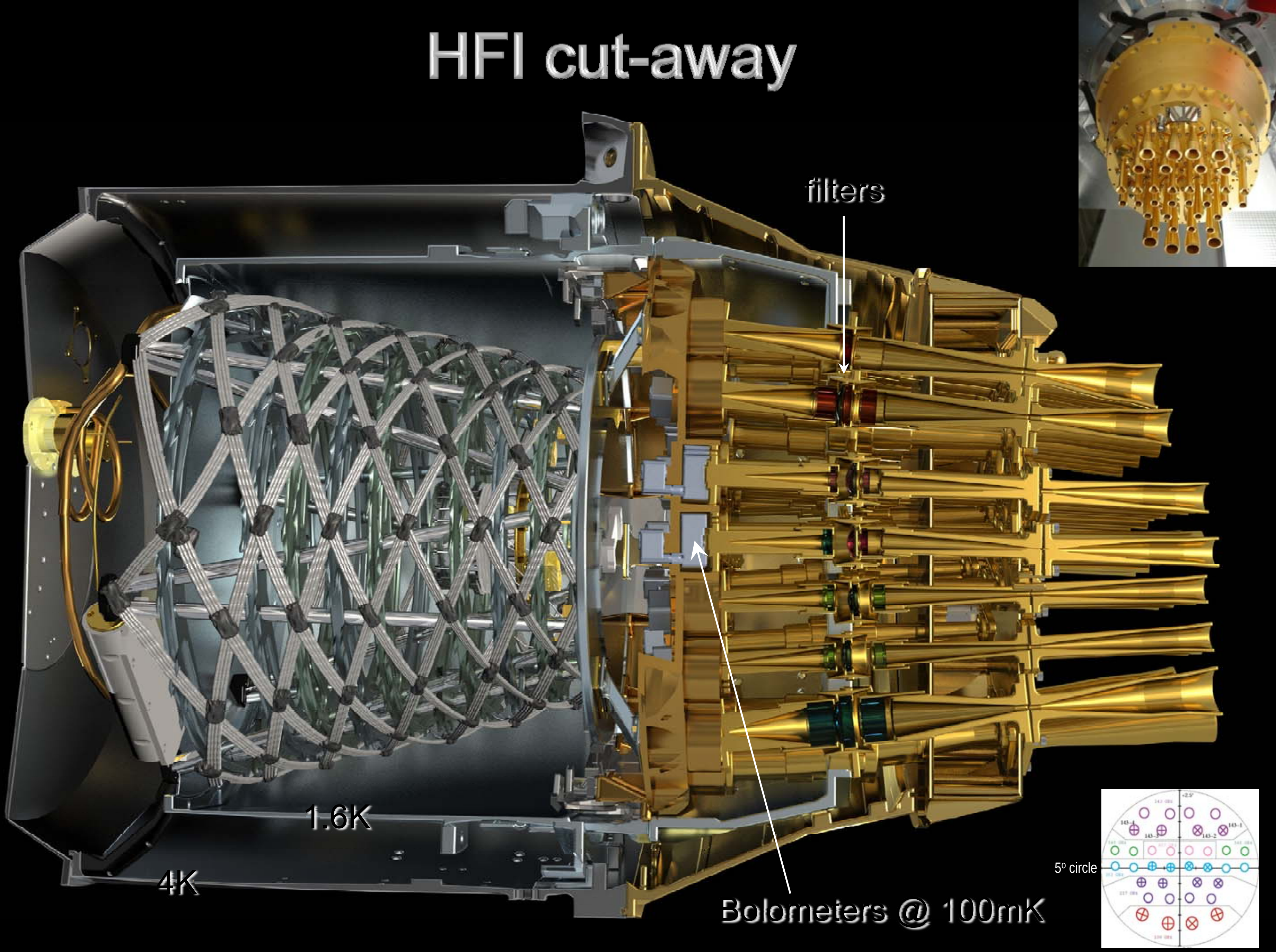


145 GHz PolarSensitiveBolometers

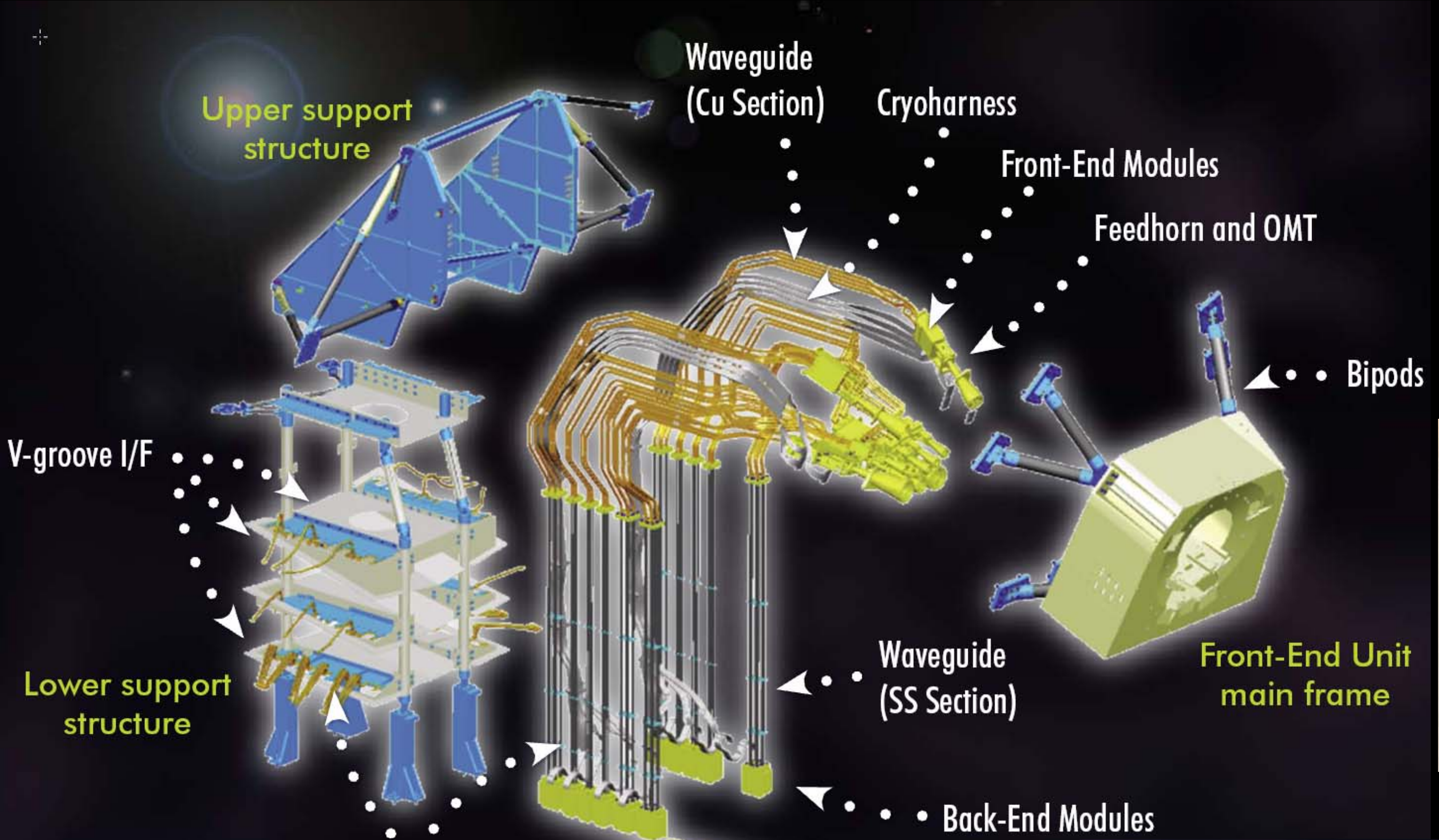
All HFI flight bolometers have been built by Caltech/JPL, integrated into pixels and tested in Cardiff, integrated into HFI – notably. JFET (Rome) + REU (CESR) and then tested at instrument level @ IAS, Orsay.

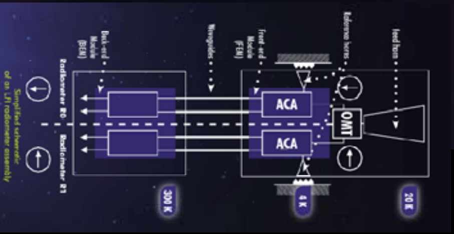
NB: Flight Model includes 4 PSB pairs @ 100 GHz (following the descoping of the 100 GHz receivers from the LFI)

HFI cut-away



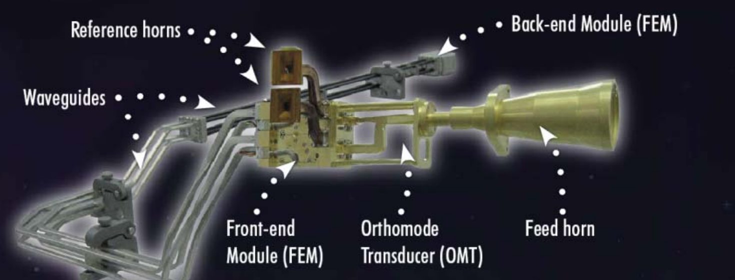
The Low Frequency Instrument LFI





Simplified schematic of an LFI radiometer assembly

THE LFI RADIOMETER CHAIN



Picture of an LFI radiometer assembly

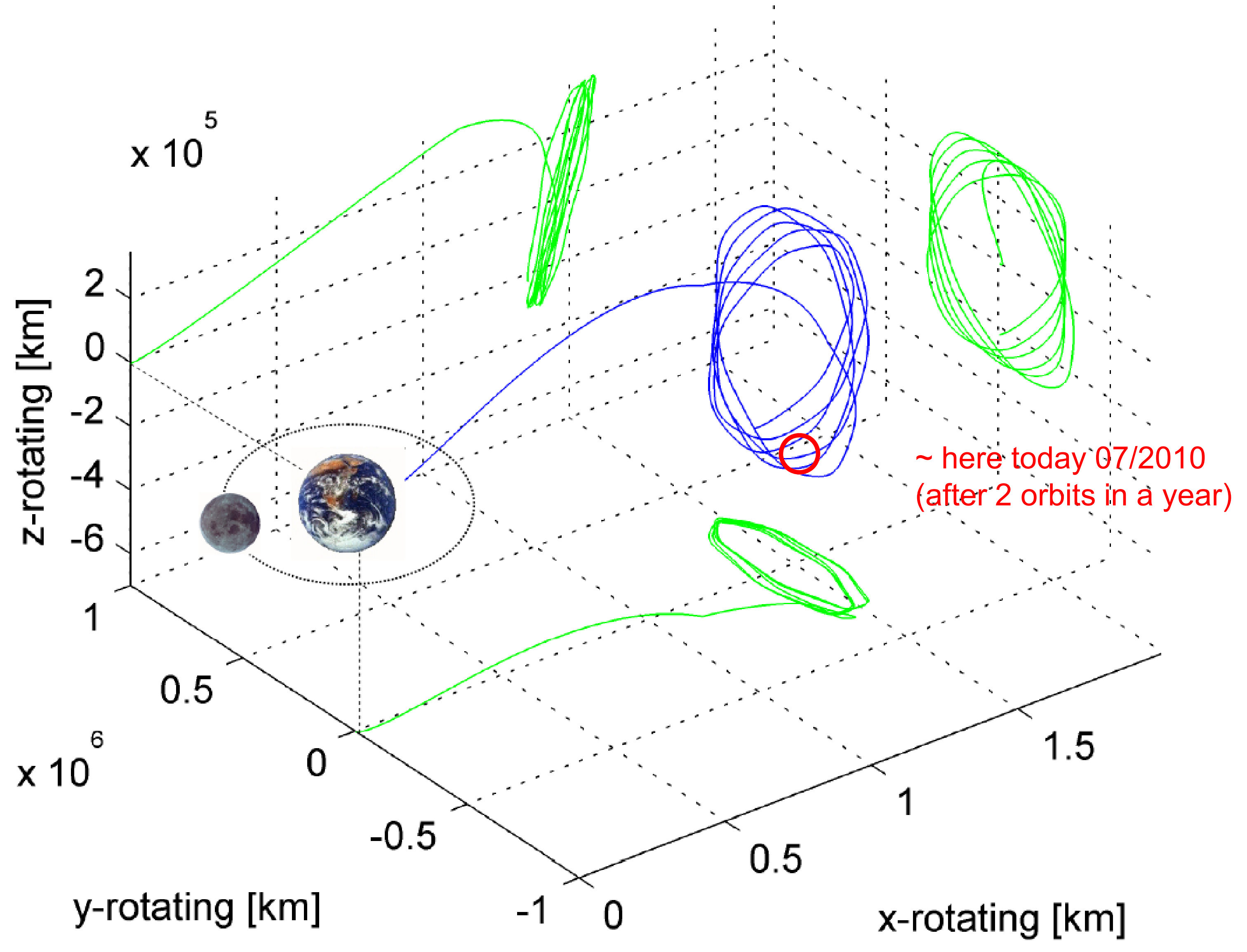
Birth of the Cool

DUSTING IT OFF…

AFTER 16 YEARS OF HOPES & WORK

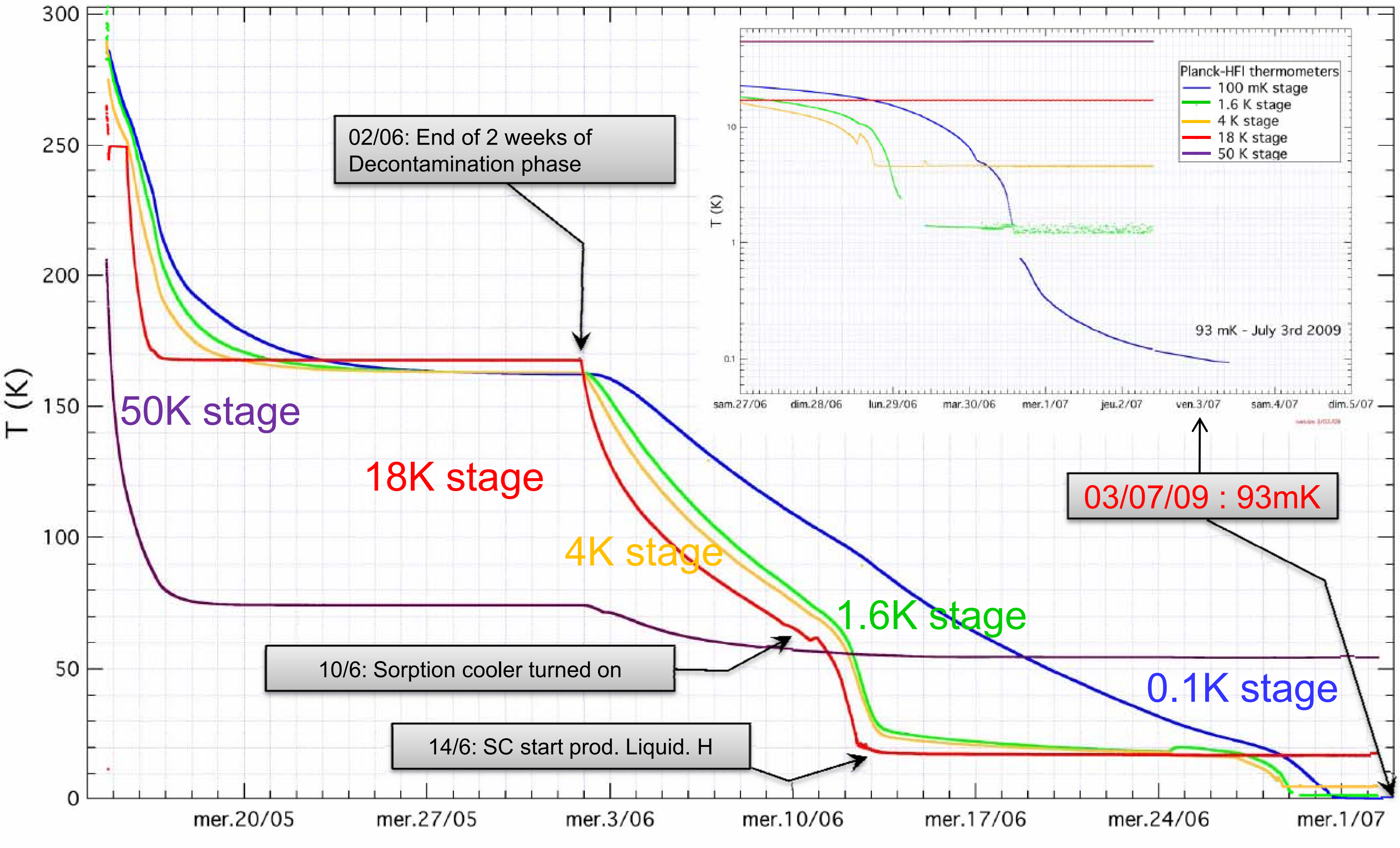
14 May 2009

Planck is in L2 orbit since July 2009



~ here today 07/2010
(after 2 orbits in a year)

Planck is cool...



02/06: End of 2 weeks of Decontamination phase

10/6: Sorption cooler turned on

14/6: SC start prod. Liquid. H

03/07/09 : 93mK

version 3/07/09

Planck declared fit for service

Calibration & Performance Verification phase:

- Detectors found to behave precisely as in ground tests
- Cooling chain fully functional
  - *4K stage at 4.68 K with vibration control system working nominally*
  - *1.6 K stage at 1.38K*
  - *Bolometers at 101.5 mK*
  - *Dilution to be operated with the lowest flow of isotopes, which should provide*

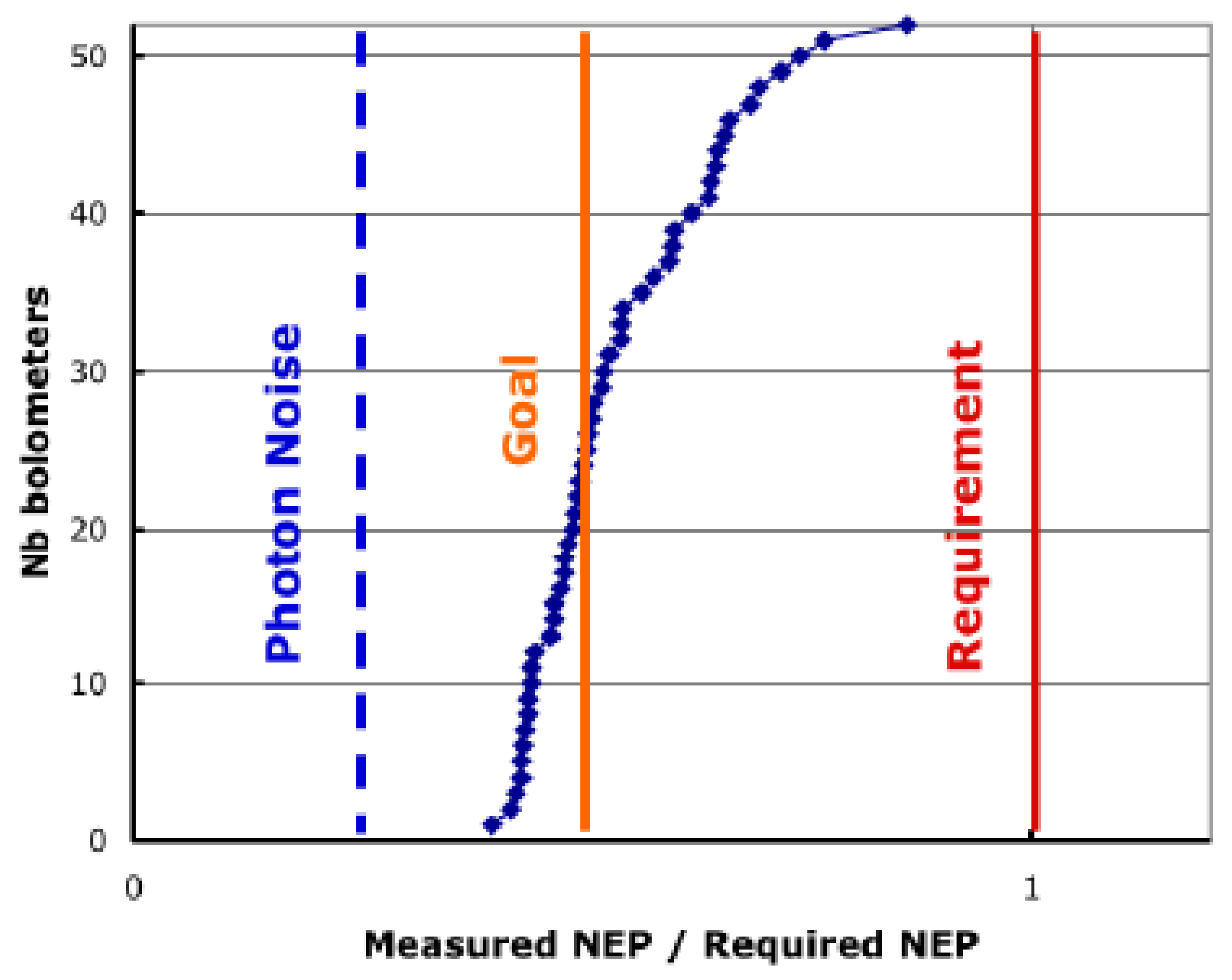
➔30 months of survey expected, ie close to **5** sky surveys

- First Light Survey final test started mid August
  - *15 days of normal operations*
  - *covering a ~15° strip*
  - *declared successful Thursday Sep 3rd*
  - *Preparing PR with first maps*
  - *Confirming instruments' scientific potential*

➔The All-sky Planck survey is ongoing since Aug 13th!

Planck is sensitive

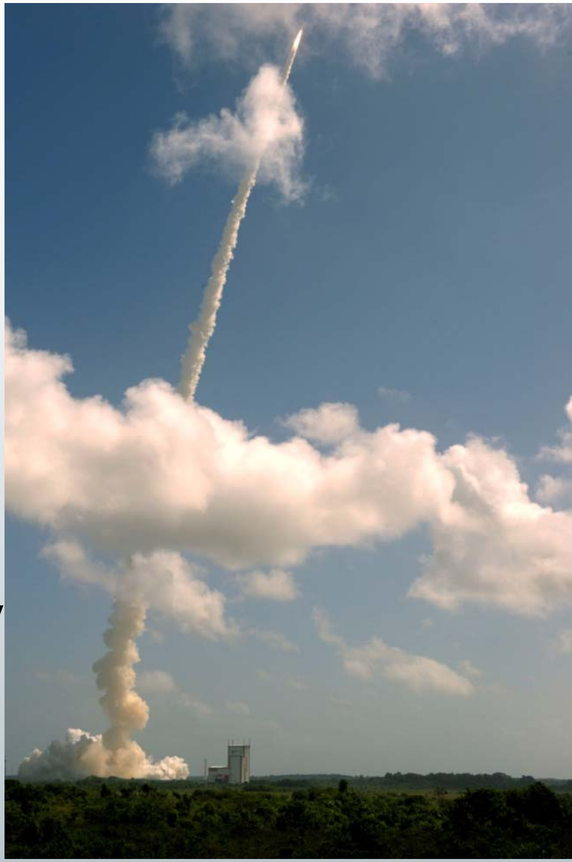
HFI bolometers at CSL



No significant difference found in flight

Planck scans the sky, at 1 rpm

WHAT, WHEN



- May 14th 2009 - Launch from Kourou, Guyana
- Travel to L2 and cool till end of June 2009,
  Verifications & tuning till August 13th 2009
  15 days of First Light Survey as ultimate test,

NOW

- *13 Oct 2010: End of nominal 14 months of operations*
  to complete 2 surveys

- 12 Jan 2011 : “Early Release Point Source Catalogue”
  for follow-ups (Herschel)
  + early science papers on foregrounds Intensity

- Jan 2013 : First public data release by ESA
  of 14 month of data & science papers
  - *Clean calibrated time-ordered data*
  - *Full sky maps in (HFI 6+ LFI 3) frequencies*
  - *Maps of identified astrophysical components (including source catalogues)*
  - *CMB characterisation (C(l), likelihood, NG…)*

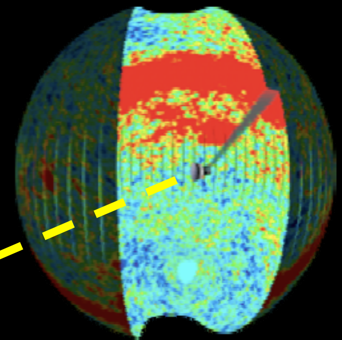
- Early 2014 (TBC): Final data release with all data acquired (till end-Jan 12?)

Ground segment data flow: from sky bits to cosmology

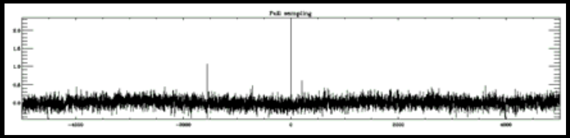
Mission Operations Center
ESA, Darmstadt

HFI-L1
IAS - Orsay
From telemetry
to raw data

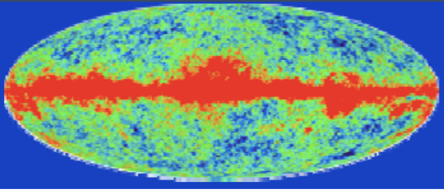
ESA Antenna
Australia

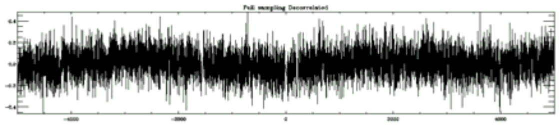


L2 of sun-earth system
Planck acquires data

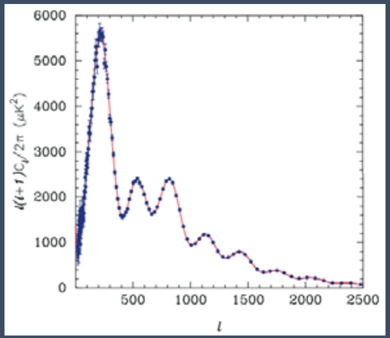


HFI-L2
IAP - Paris
Raw data to maps

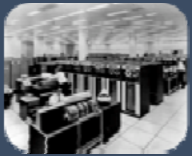




HFI-L3
Cambridge
maps to
power spectra



HFI DPC infrastructure provided by
the Institut d'Astrophysique de Paris



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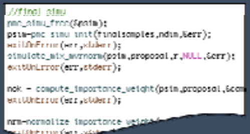


```
//final simu
pmc_simu_free(&psim);
psim=pmc_simu_init(finalsamples,ndim,&err);
exitOnError(err,stderr);
simulate_mix_mvnorm(psim,proposal,r,NULL,&err);
exitOnError(err,stderr);

nok = compute_importance_weight(psim,proposal,&com
exitOnError(err,stderr);

nrm=normalize_importance_weight(
```

Data Processing

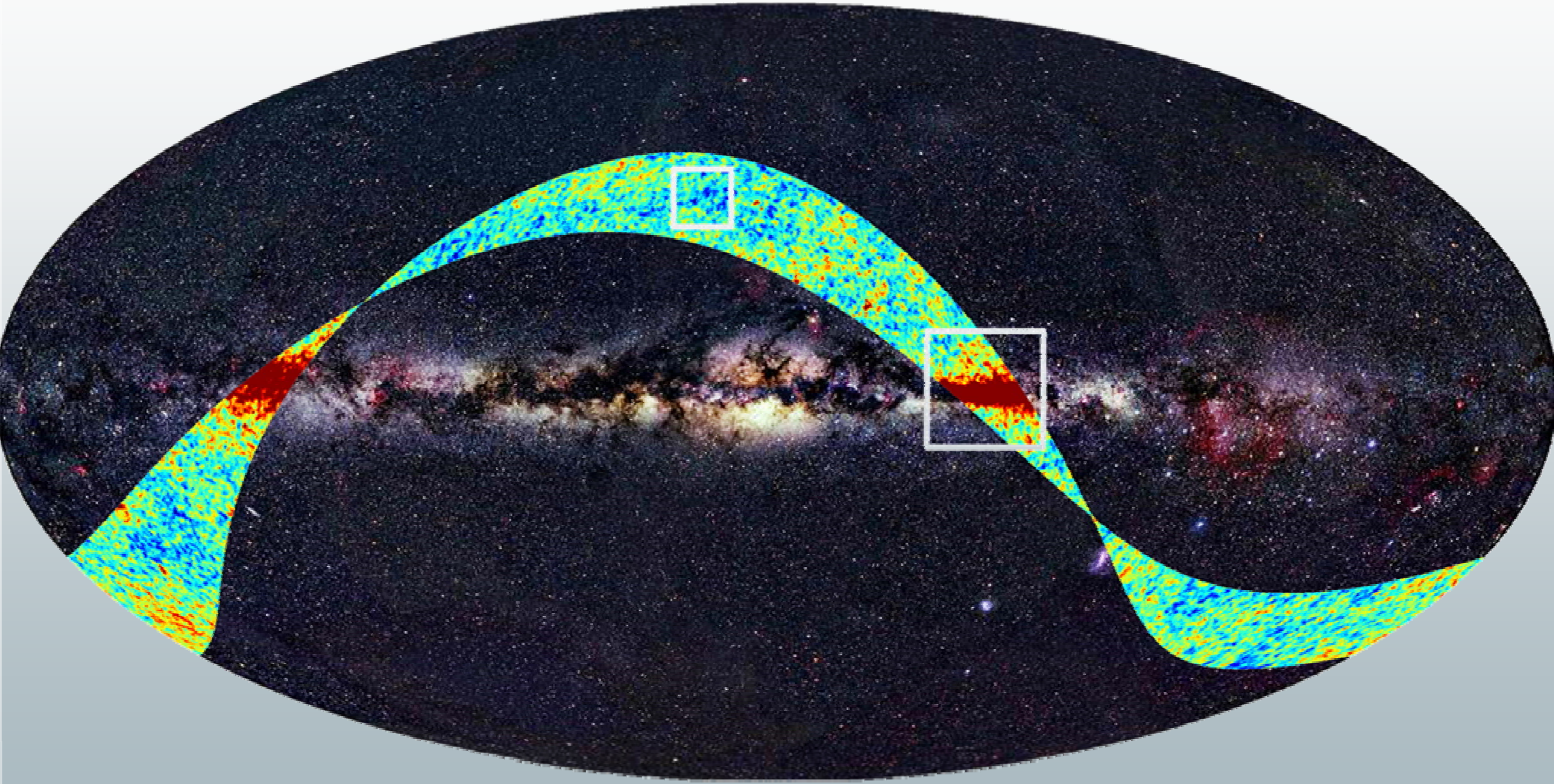
- Physics → CMB sky → Frequency sky → TOI
- TOI → frequency maps → CMB map → Physics

- One needs to write and verify a model of TOI = f(Physics) and to "invert" it and to assess errors.
  - *The frequency response is measured on the ground.*
  - *The optical response is measured on the ground, modelled, and partially verified on planets, Crab, etc.*
  - *The detector chain response is measured on ground*
  - *A full simulation phase was built (MC)...*
- One uses templates (Thermometers, foreground tracers) and redundancy

- Many Interesting challenges: *optimality/speed, propagation of separation errors, exploration of large dimensionality spaces... in addition to herding a large cat population, and surprises in the data*

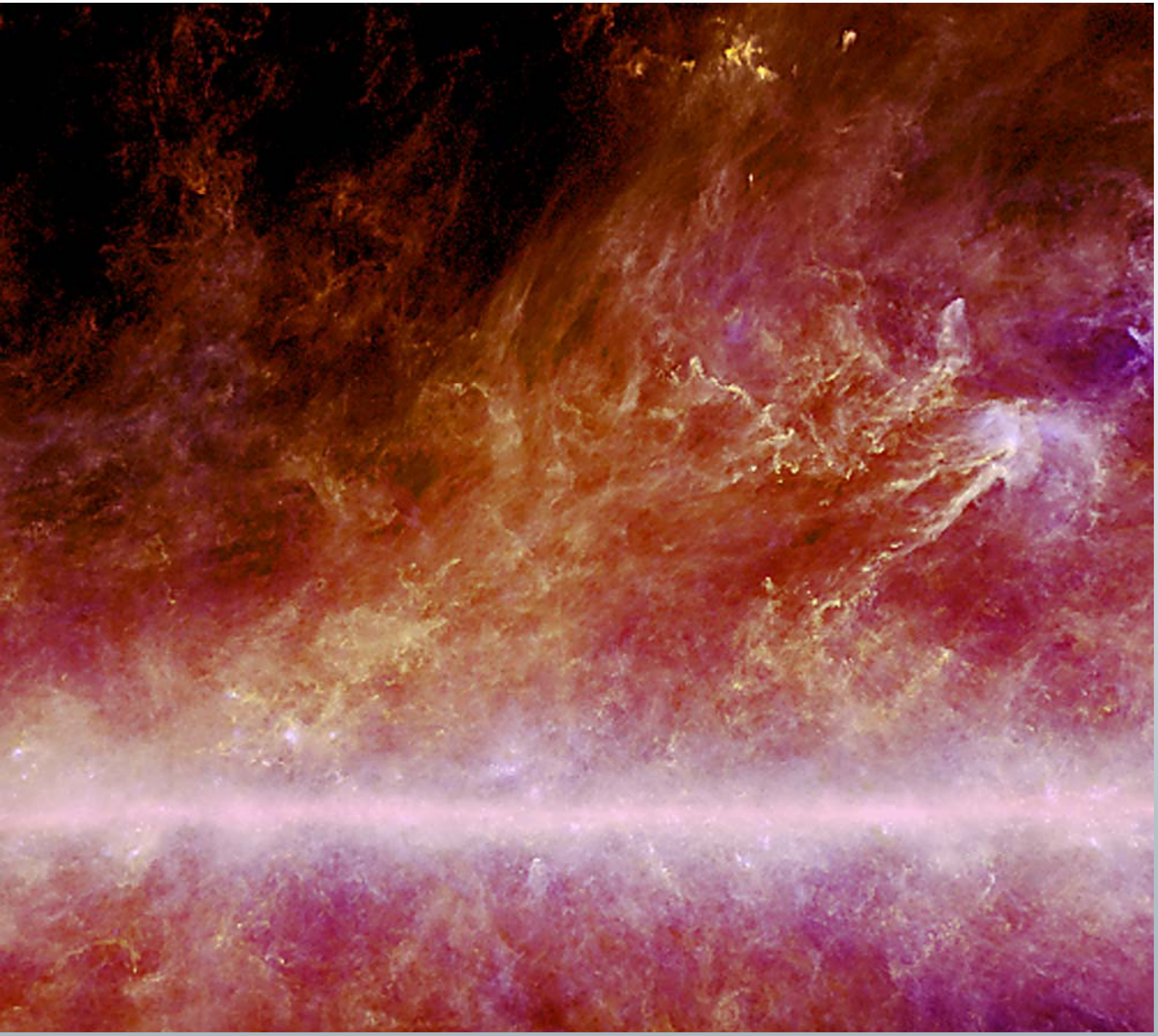
First light survey/1st Press release

15 days of normal operations covering a ~15° strip

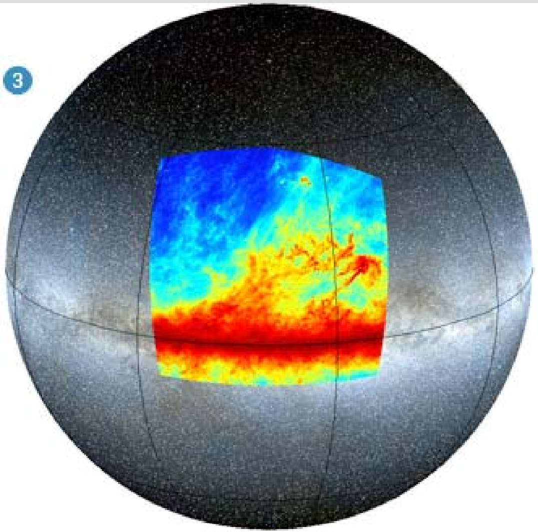


Map obtained within days of data taking (PR1=17/09/09)

2nd Press Release (17/03/10)

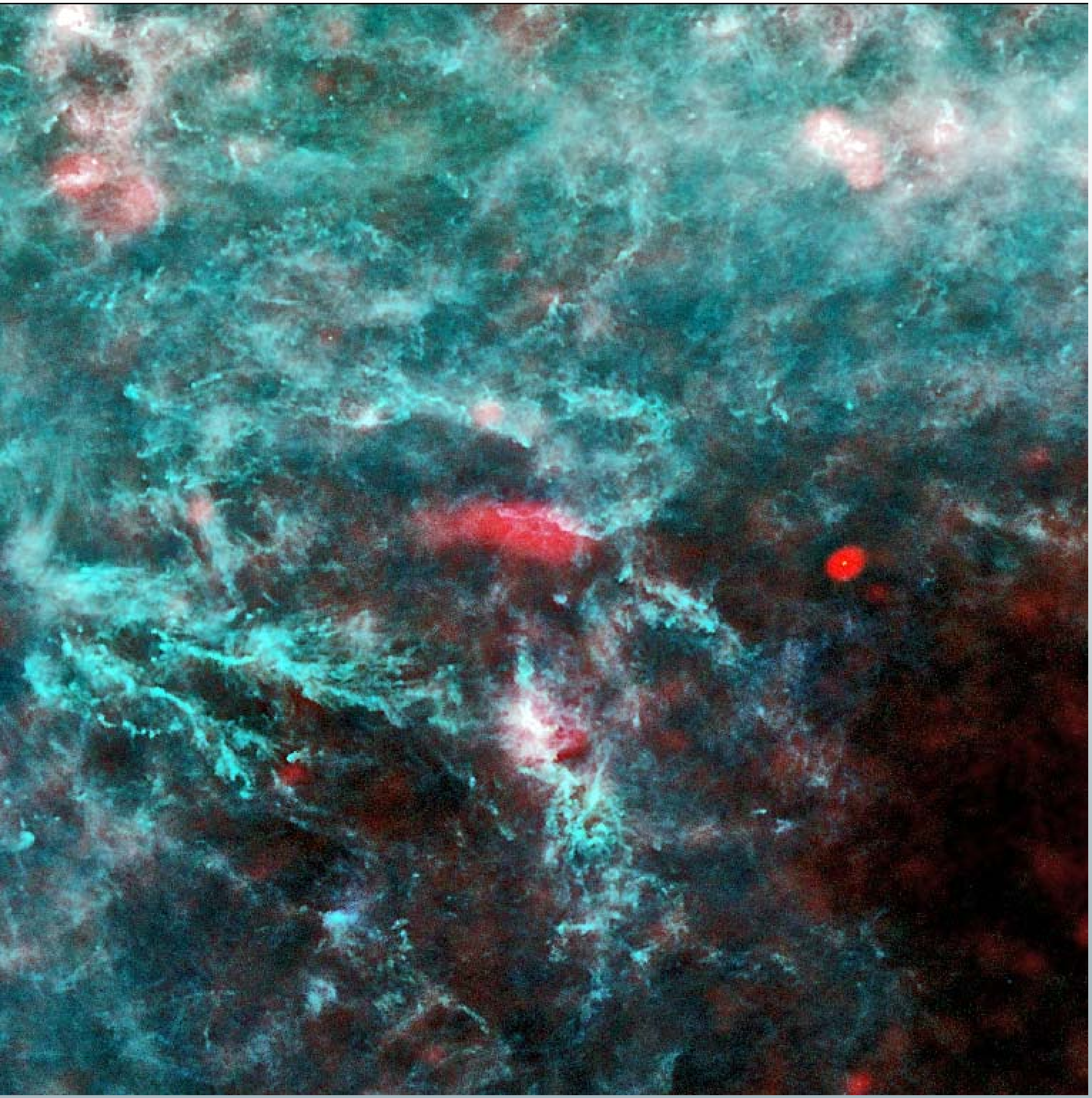


Composite image from the emission observed with the IRAS satellite at a wavelength of 100 microns (purple) and Planck data at 350 microns (or 857 GHz, oriange) and at 550 microns (543 GHz, red). Redish glows as col as ~12K



50 degrees of the sky at 857 GHz
superimposed to the optical sky

3rd Press Release (15/04/10)



A region of low star formation in the Perseus constellation as seen with Planck (left) and in visible light with the Digitised Sky Survey (right)
The Planck image covers a region of 30x30 degrees in total extent. It is a three colour combination constructed from three of Planck's nine frequency channels: 30, 353 and 857 GHz.

4th Press Release (05/07/2010)

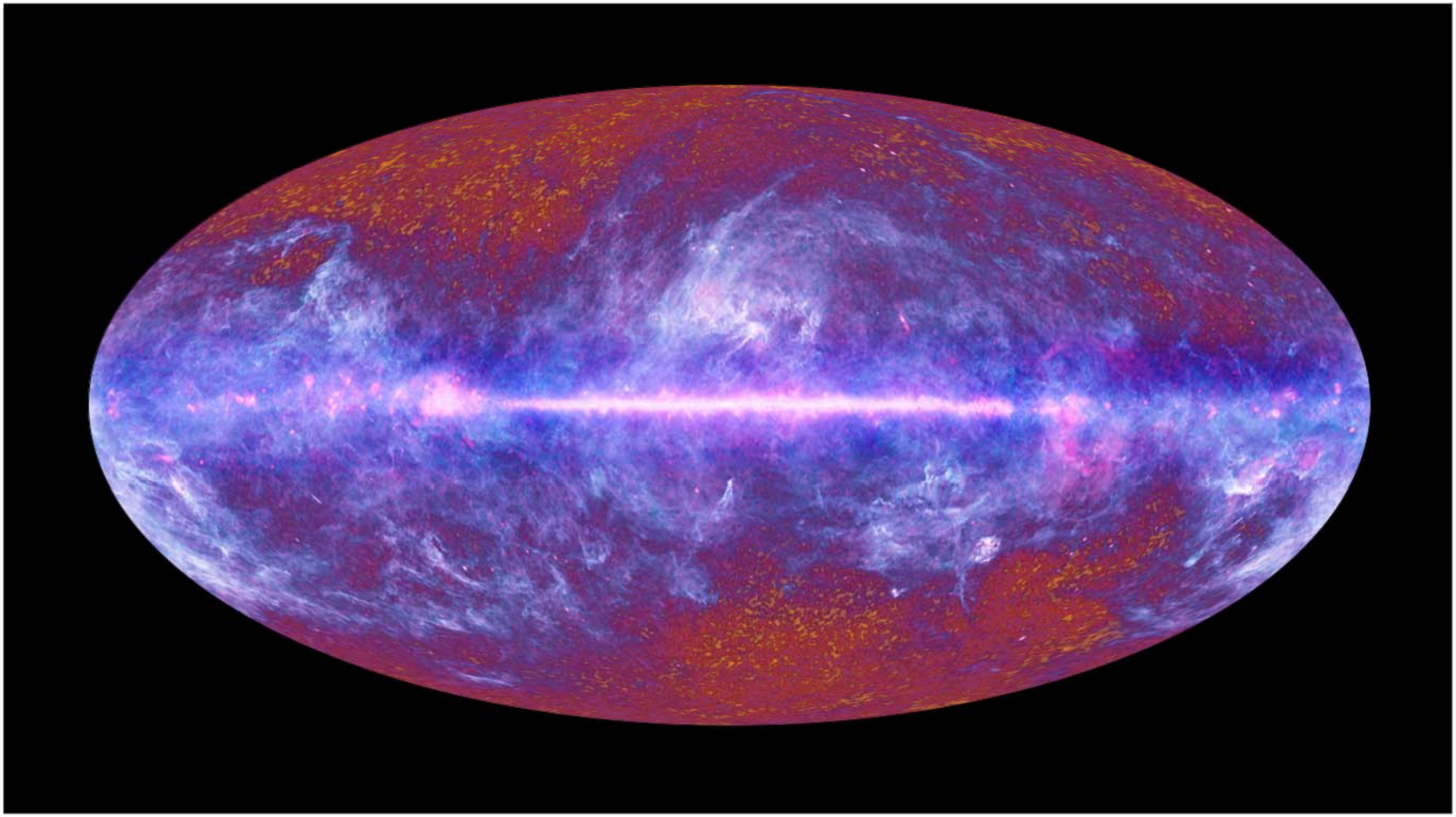
After 16 years gestation

The Planck one-year all-sky survey

esa

(c) ESA, HFI and LFI consortia, July 2010

4th Press Release (05/07/2010)

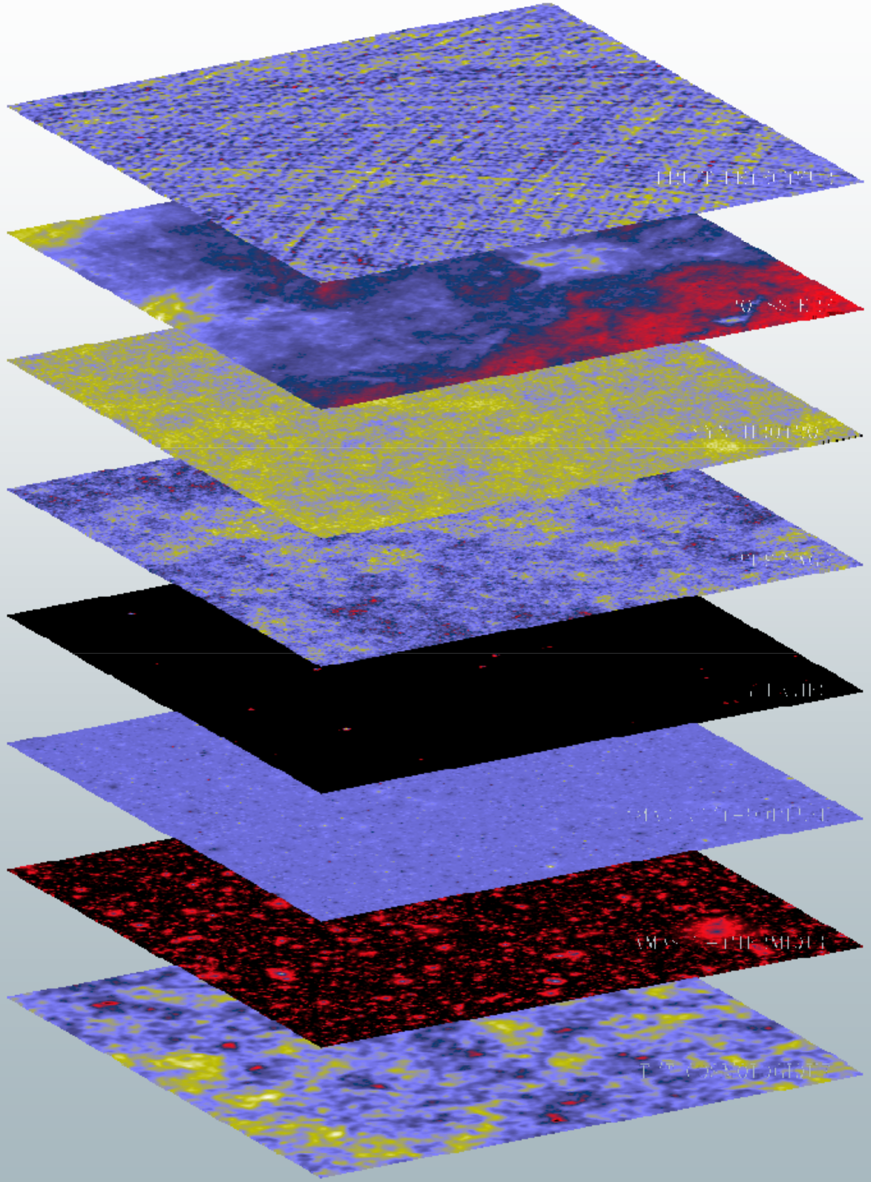


The Planck one-year all-sky survey

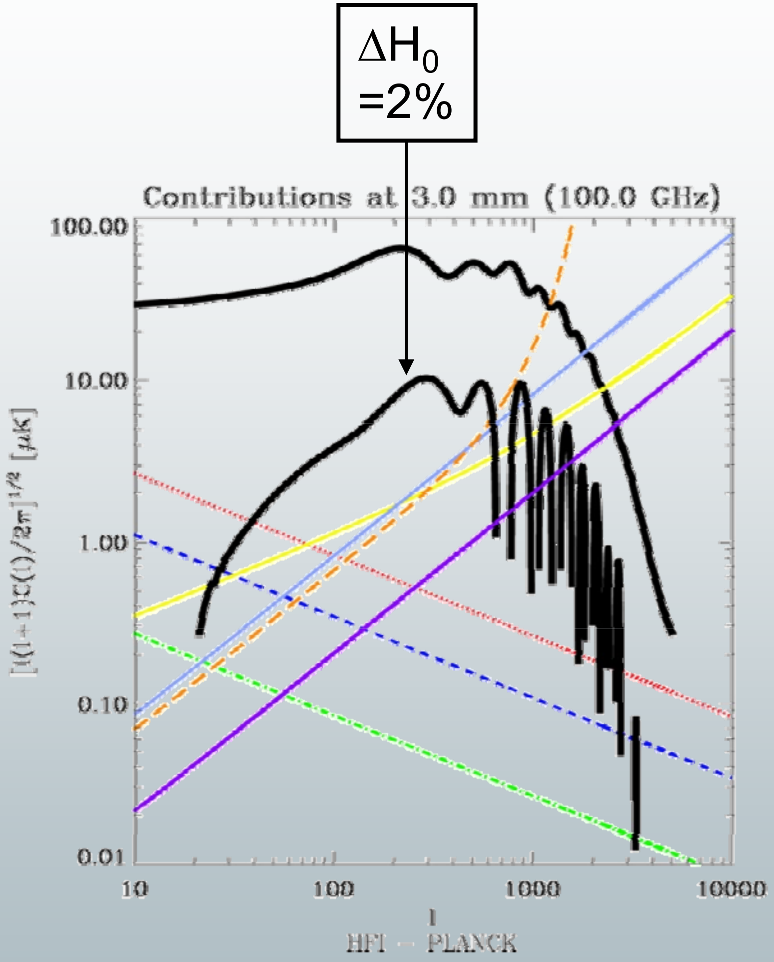
esa

(c) ESA, HFI and LFI consortia, July 2010

Foregrounds !!



F.R. BOUCHET & R. GISPERT 1996

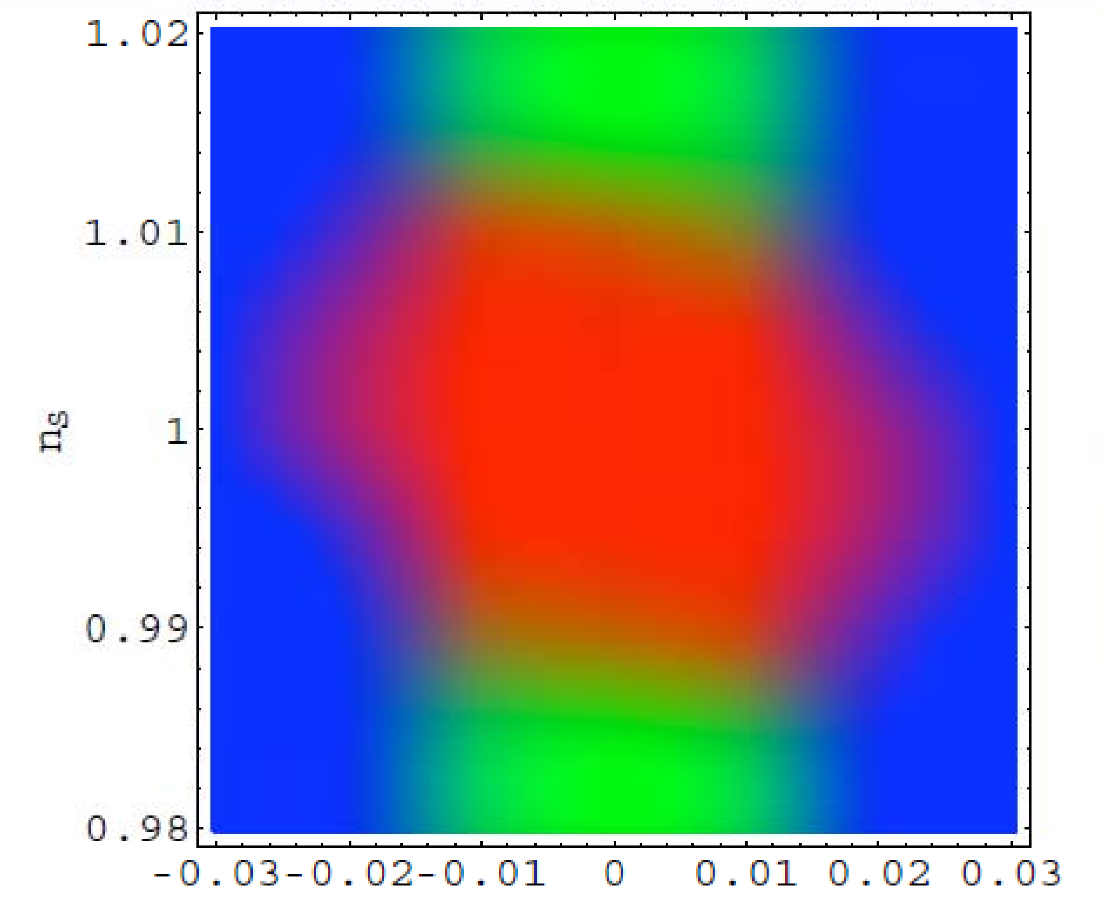


ΔH_0 =2%

Model selection forecasts for Planck

Pahud, Liddle, Mukherjee, and Parkinson, MNRAS, astro-ph/0701481

Zones of certainty/uncertainty for *n* and $\alpha = dn/d\ln k$.



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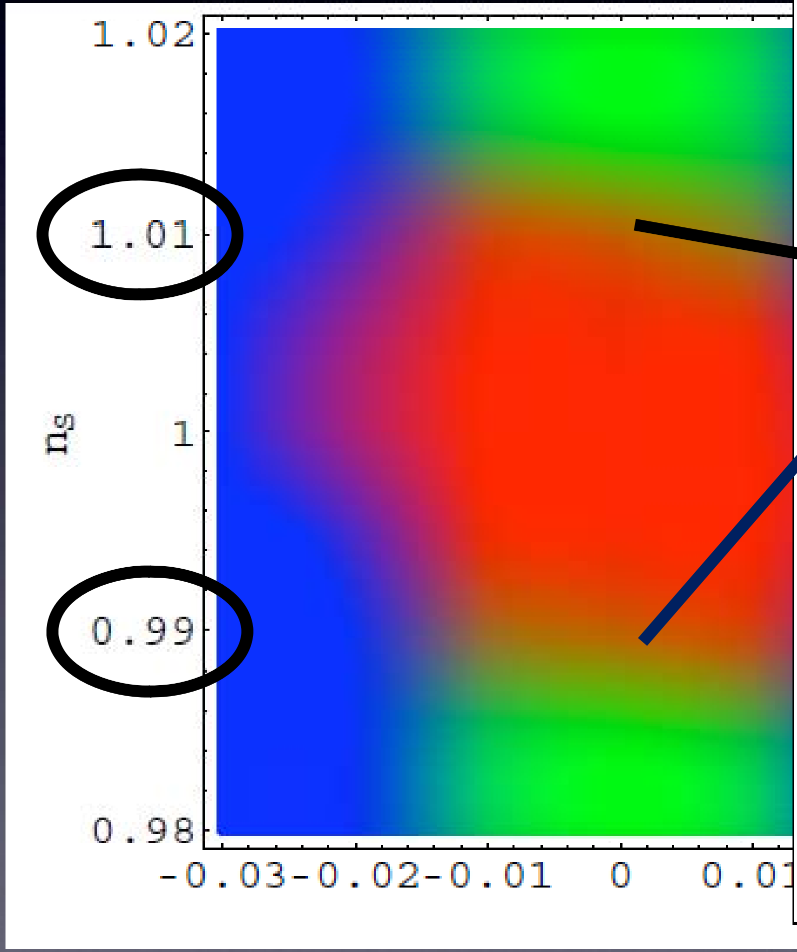
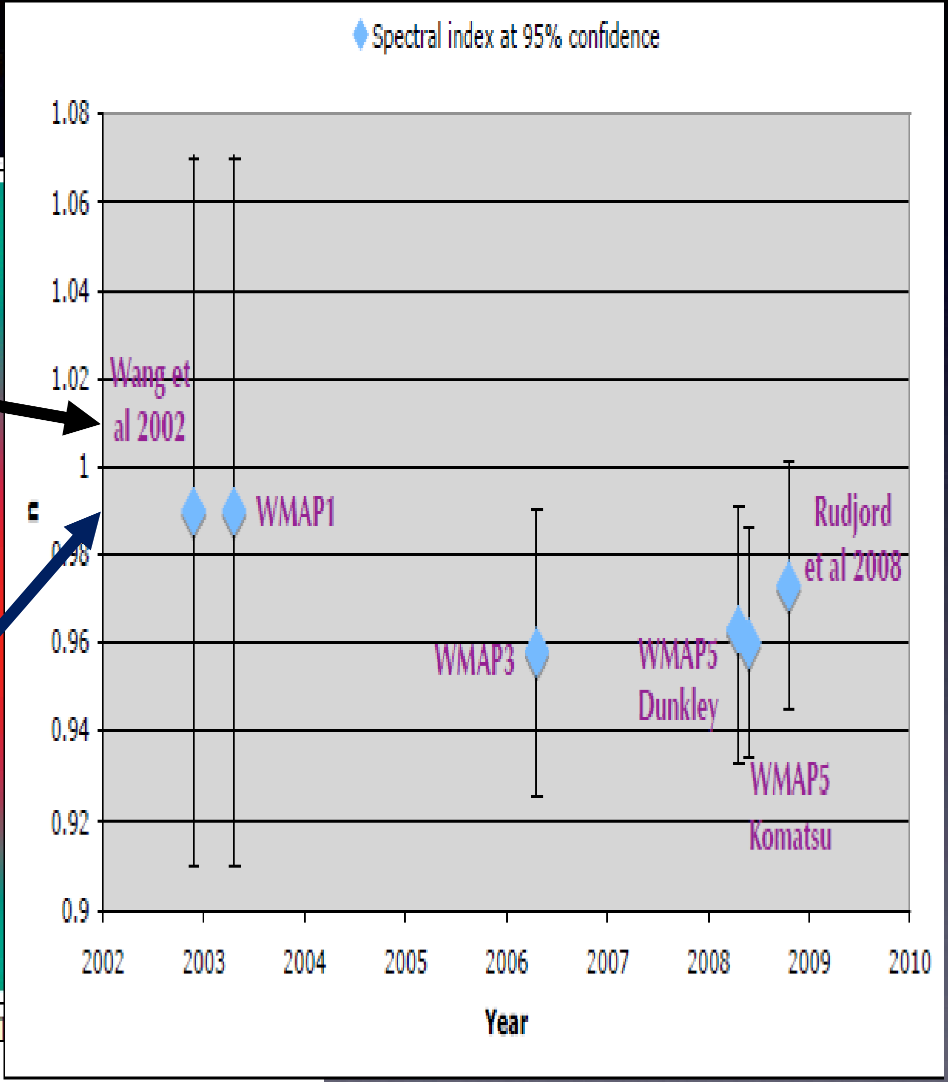
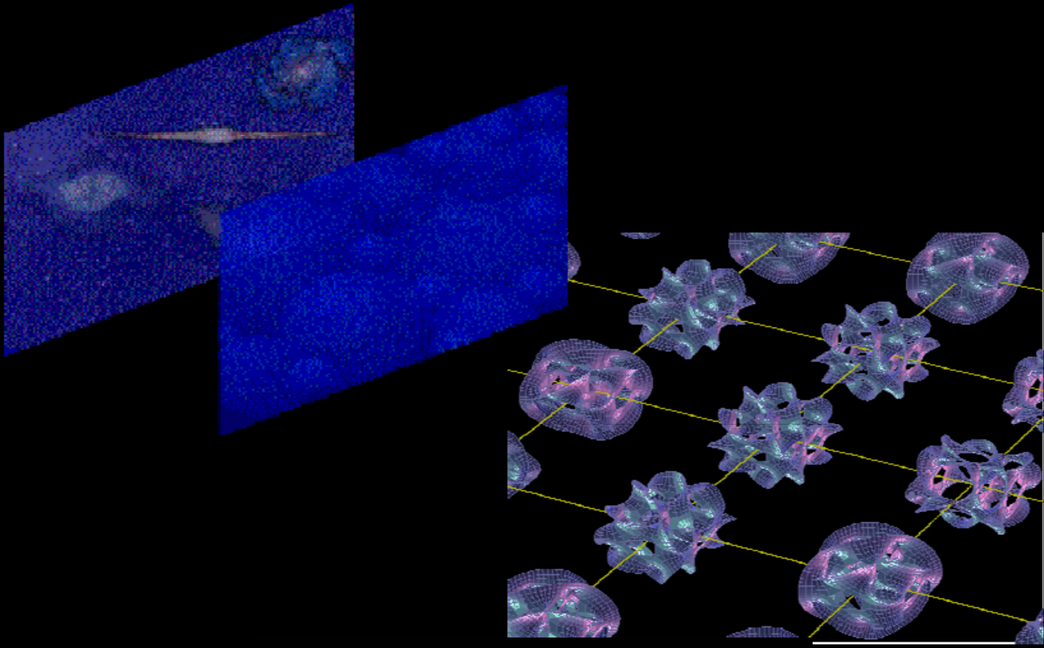
Zones of certainty/uncertainty for *n*

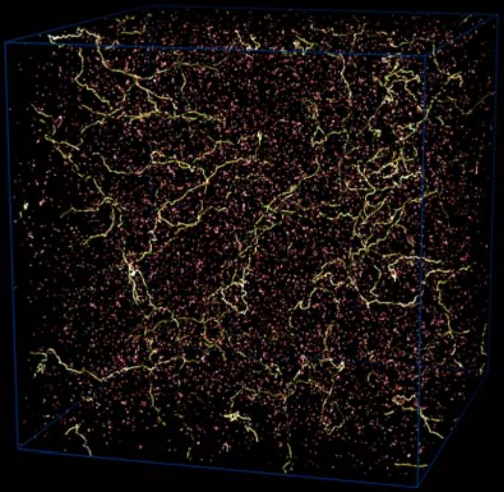




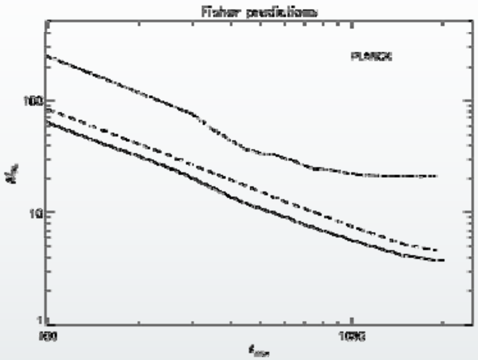
Beyond the standard BB model

1. Branes – signatures of extra dimensions
2. Signatures of Pre-big bang
3. Cosmic defects, superstrings
4. Non-Gaussianity (ies)
5. Indication of a curved / non trivial geometry
6. Isocurvature perturbations
7. Deviations from Einstein Relativity
8. Neutrinos masses
9. Interacting dark matter
10. ....





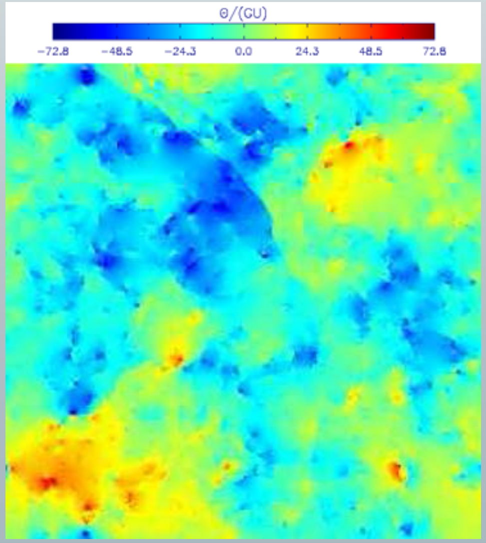
Gaussian statistics is an approximation

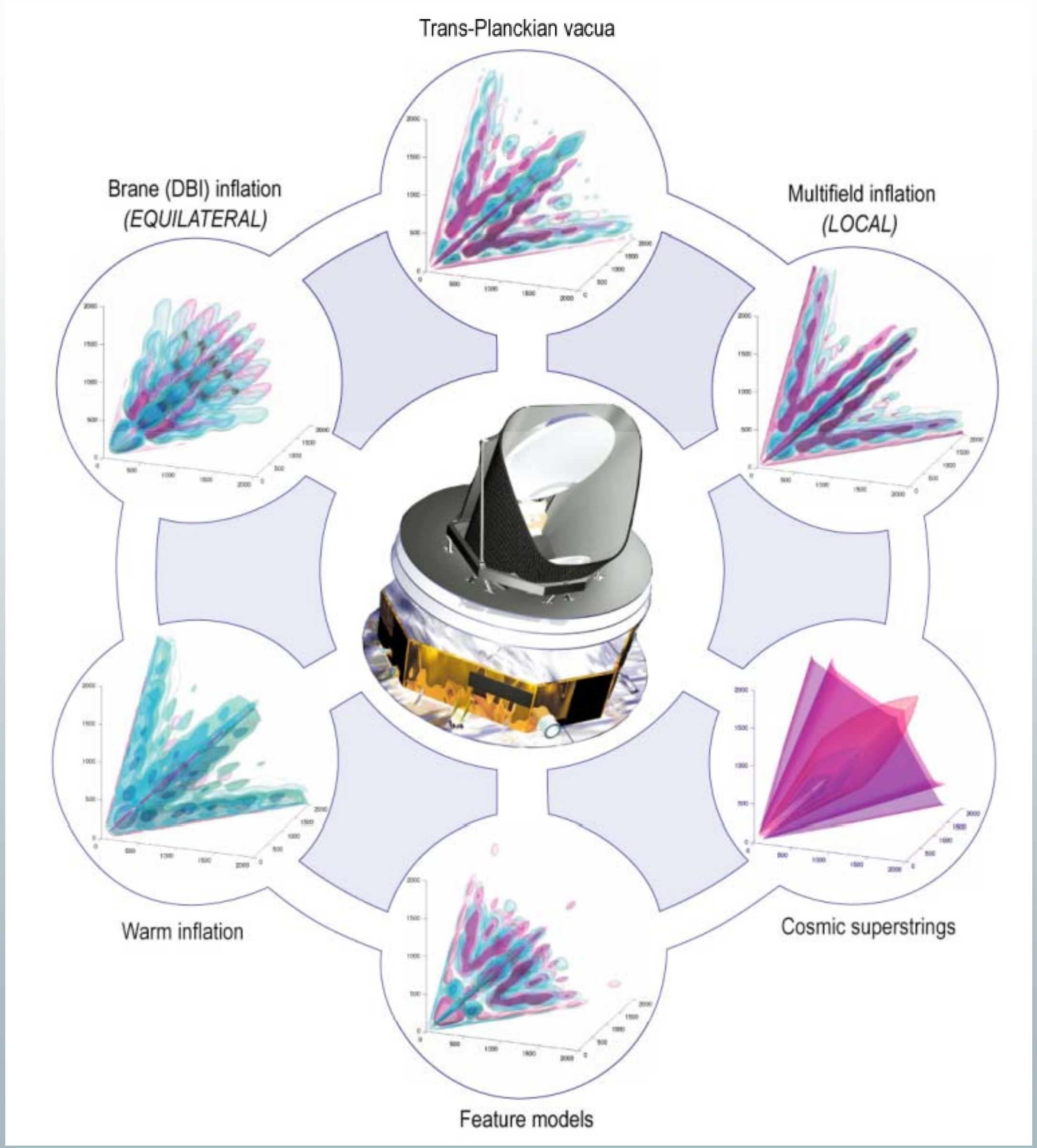


- Ideal CMB experiment, using temperature & polarization could reach Δf_{NL} ~ 1
- For Planck, the Cramer-Rao limit is Δf_{NL} ~3.

Yadav etal, astro-ph/0701921

NB: WMAP-8yr could reach ~21





What can we learn from polarisation?

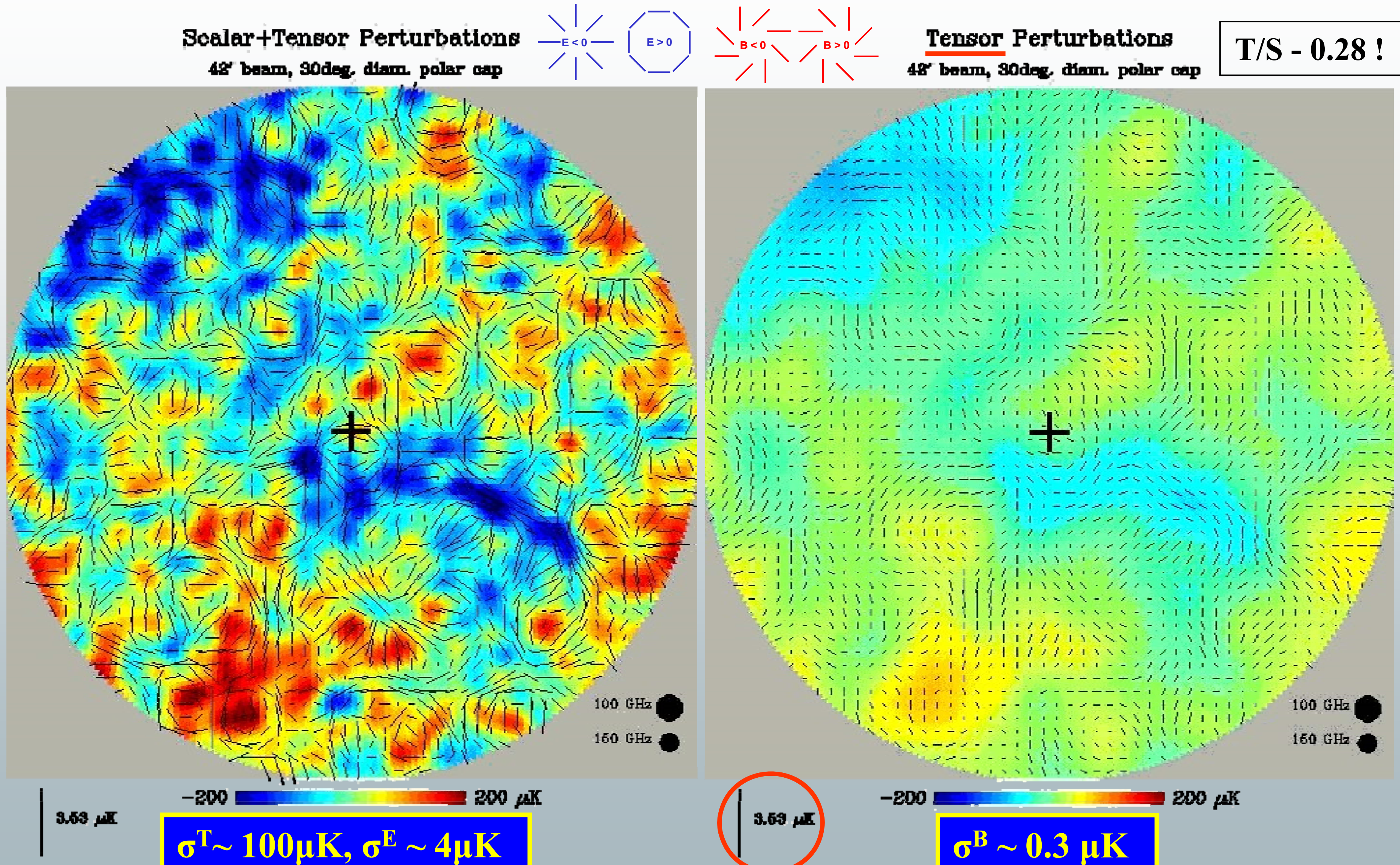
- Consistency check of the paradigm (may also include evolution –or lack of- of physical constants)
- Detailling super-horizon perturbations
- Improvement in parameter constraints (lifting degeneracies, e.g. n_s versus optical depth) and on features in the primordial spectrum
- Isocurvature perturbations

- Reionization history
- Help with lensing reconstruction of los-projected matter density properties (P_{kk})

- Gravitation wave from inflation – existence, maybe n_T

  (and indirectly on inflaton potential)

Expected polarisation patterns



T/S - 0.28 !

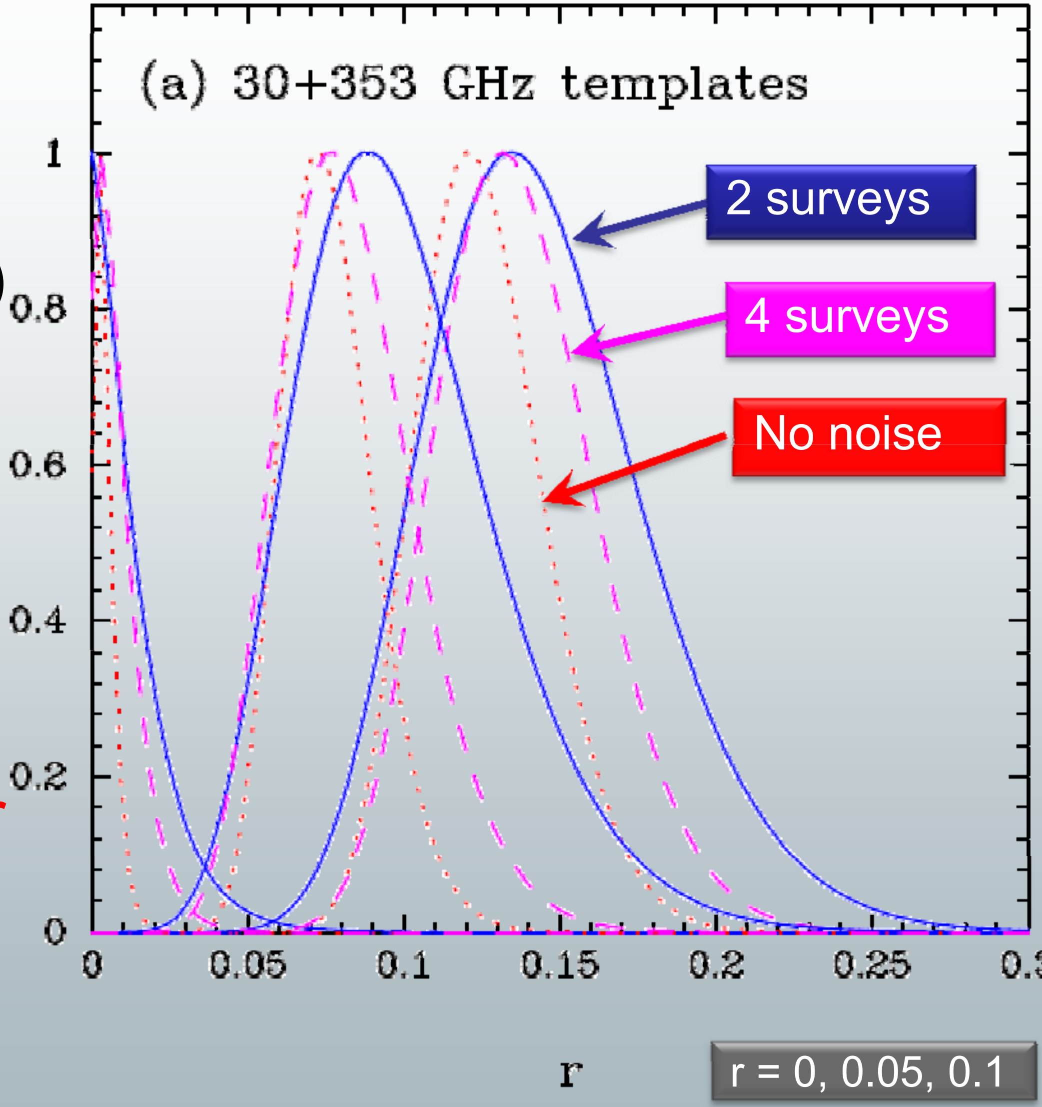
$\sigma^T \sim 100\mu K$, $\sigma^E \sim 4\mu K$

$\sigma^B \sim 0.3\ \mu K$

www.astro.caltech.edu/~lgg/bicep_front.htm

With 4 surveys...

- A simple forecast
  - *using all CMB channels 70+100+143+217GHz (goal is 0.5 µK.deg in 1yr)*
  - *and using 30 & 353 GHz as template channels,*
  - *assuming isotropic noise*
- Suggests possibility of detecting <u>r = 0.05</u> & put a 95% limit of r=0.03 for much smaller values of r
- Interesting for high field inflation models (e.g. r~0.13 for n_s=.97)



2 surveys

4 surveys

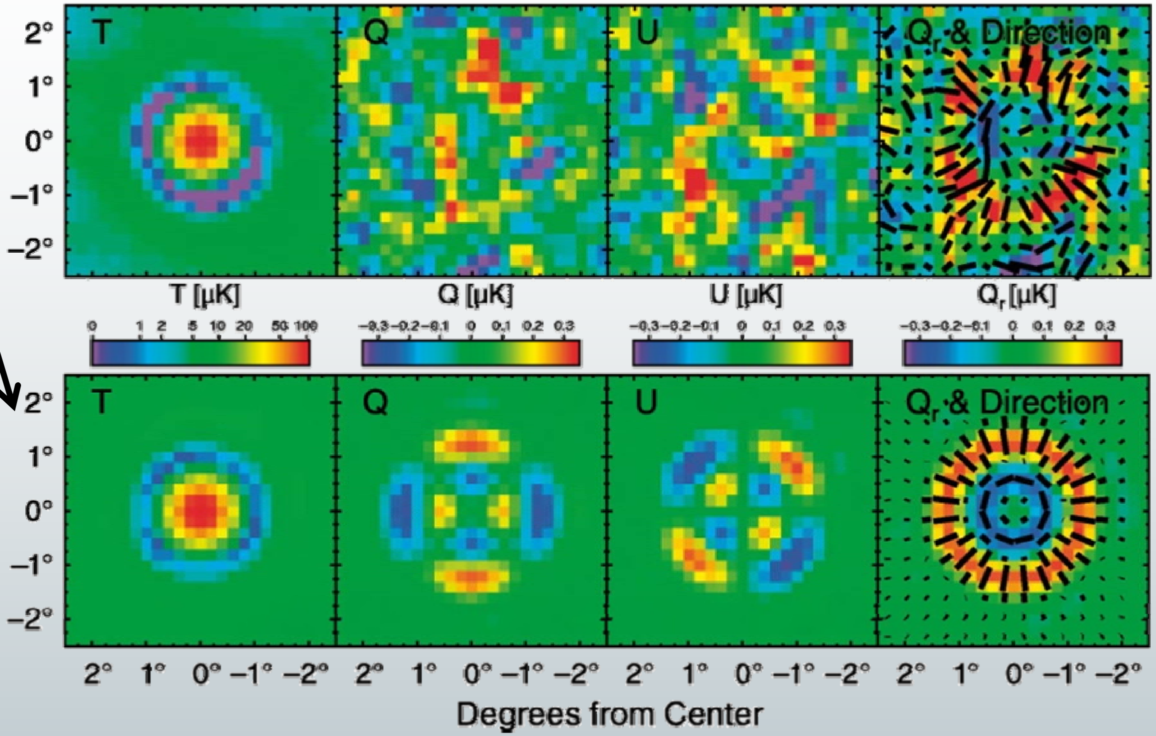
No noise

r = 0, 0.05, 0.1

0903.0904 GPE & Gratton

"A typical CMB Hot spot"
Illustration of polarization sensitivity

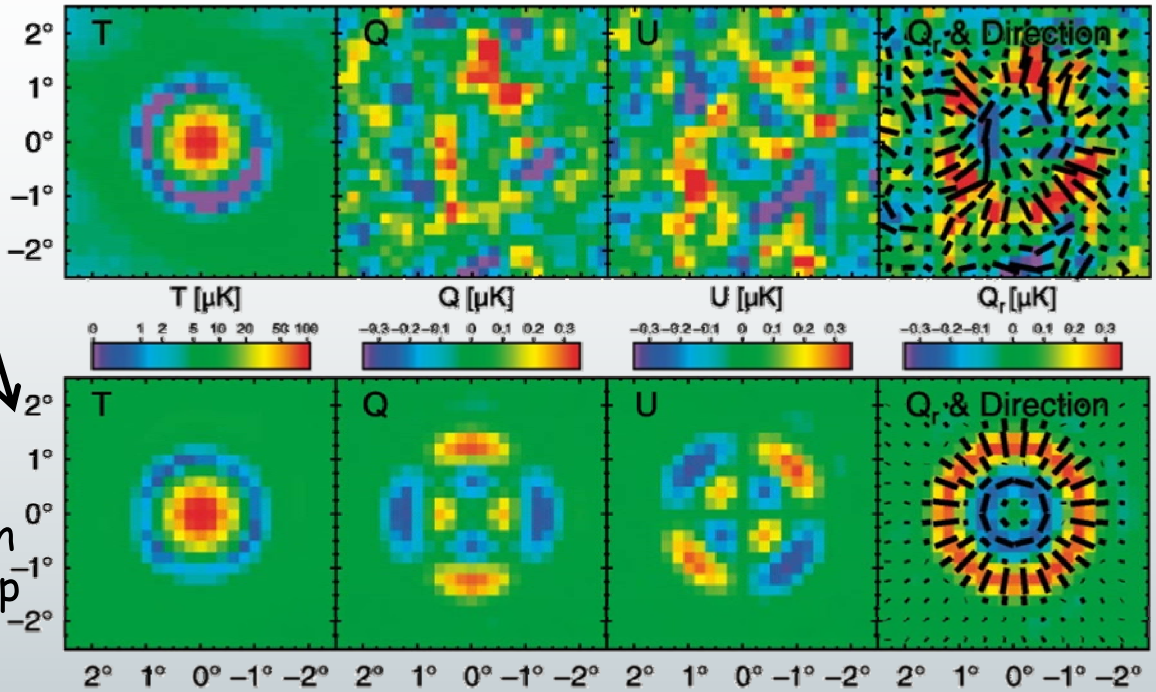
WMAP 7years
(Komatsu et al.
preprint 2010)
& simulations



"A typical CMB Hot spot" Illustration of polarization sensitivity

WMAP 7years (Komatsu et al. preprint 2010) & simulations

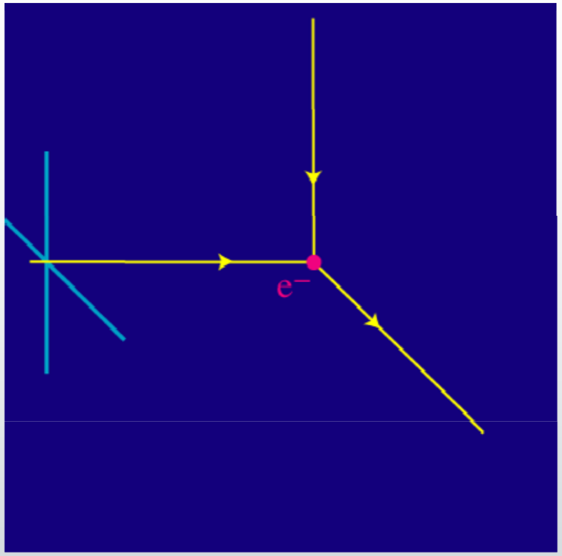
HFI – first look in quasi-raw DPC map

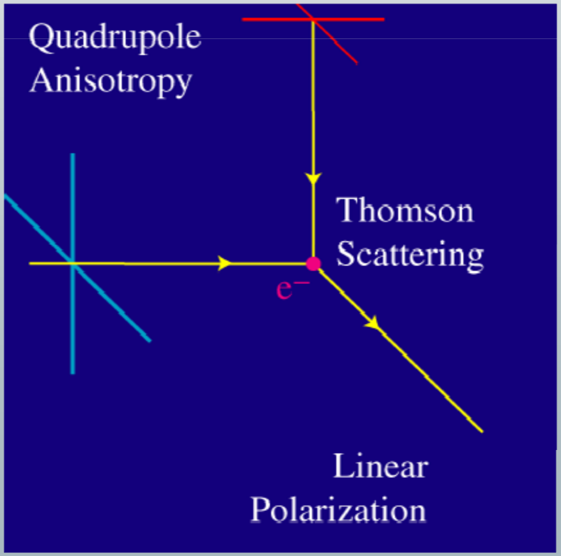


Health Warning: not assured yet whether systematic effects are controlled for "precision cosmology"

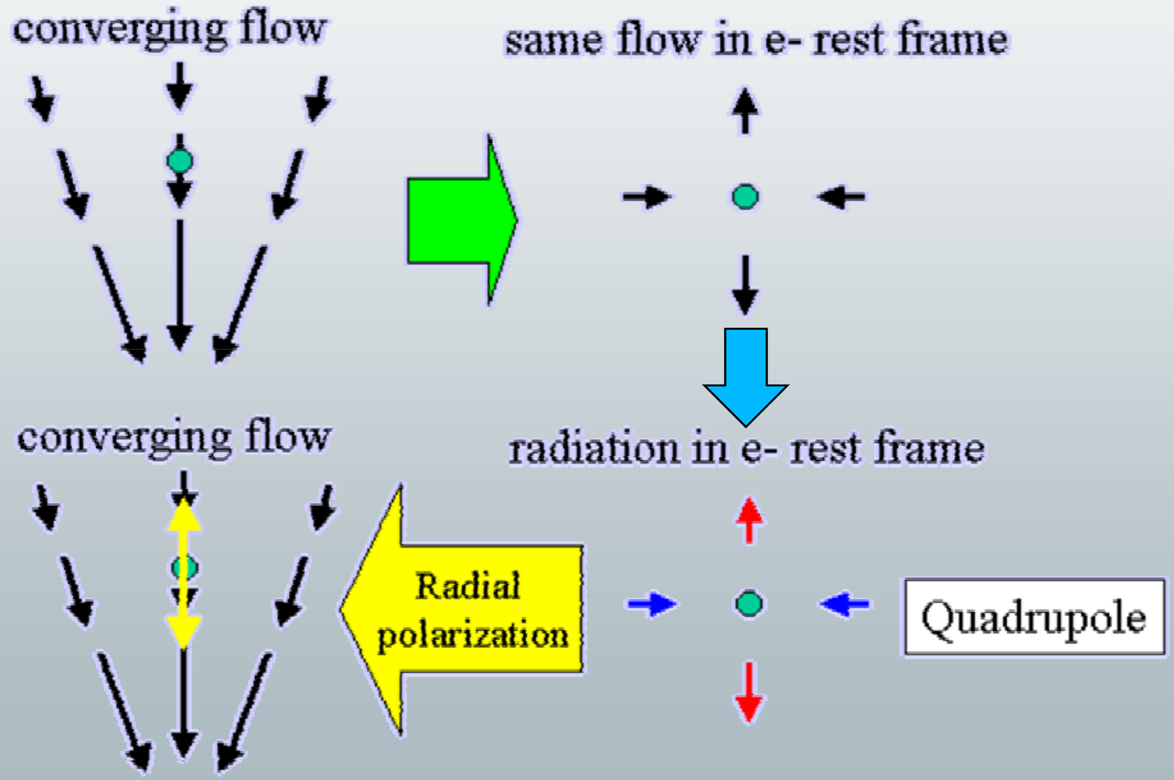
ILLUSTRATIVE PLANCK PLOTS REMOVED FOR DISTRIBUTION

Thomson scatterings are polarised



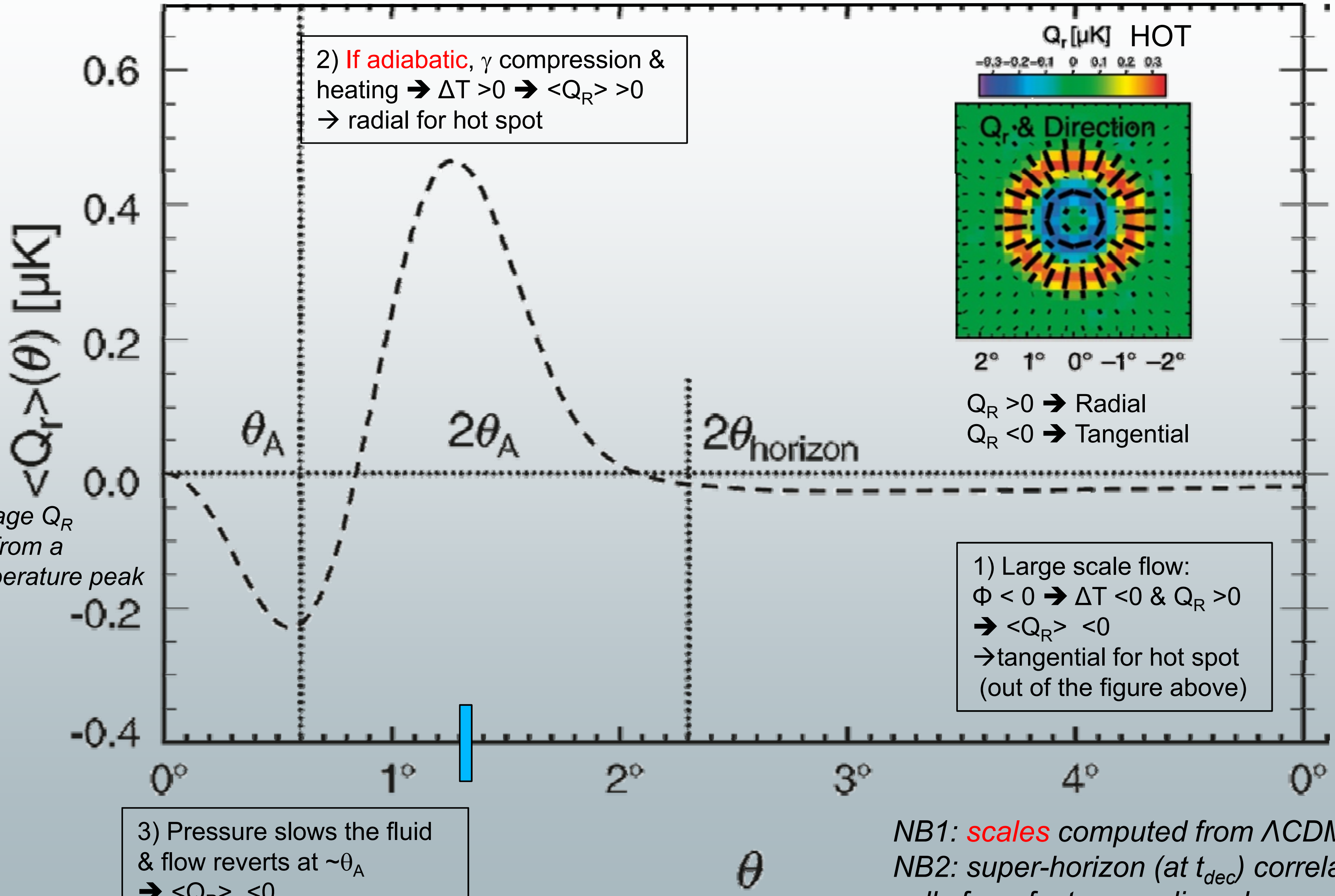


- Before recombination, successive scatterings destroy polarization and the radiation arrives at recombination unpolarized
- During recombination, Gradients in the velocity field can produce a quadrupole in the rest frame of the scattering electron



- A *diverging* flow leads to a *tangential* pattern of polarisation

Temperature and polarisation link



Average Q_R
At θ from a
Temperature peak

2) If adiabatic, γ compression & heating ➔ $\Delta T > 0$ ➔ $\langle Q_R \rangle > 0$
→ radial for hot spot

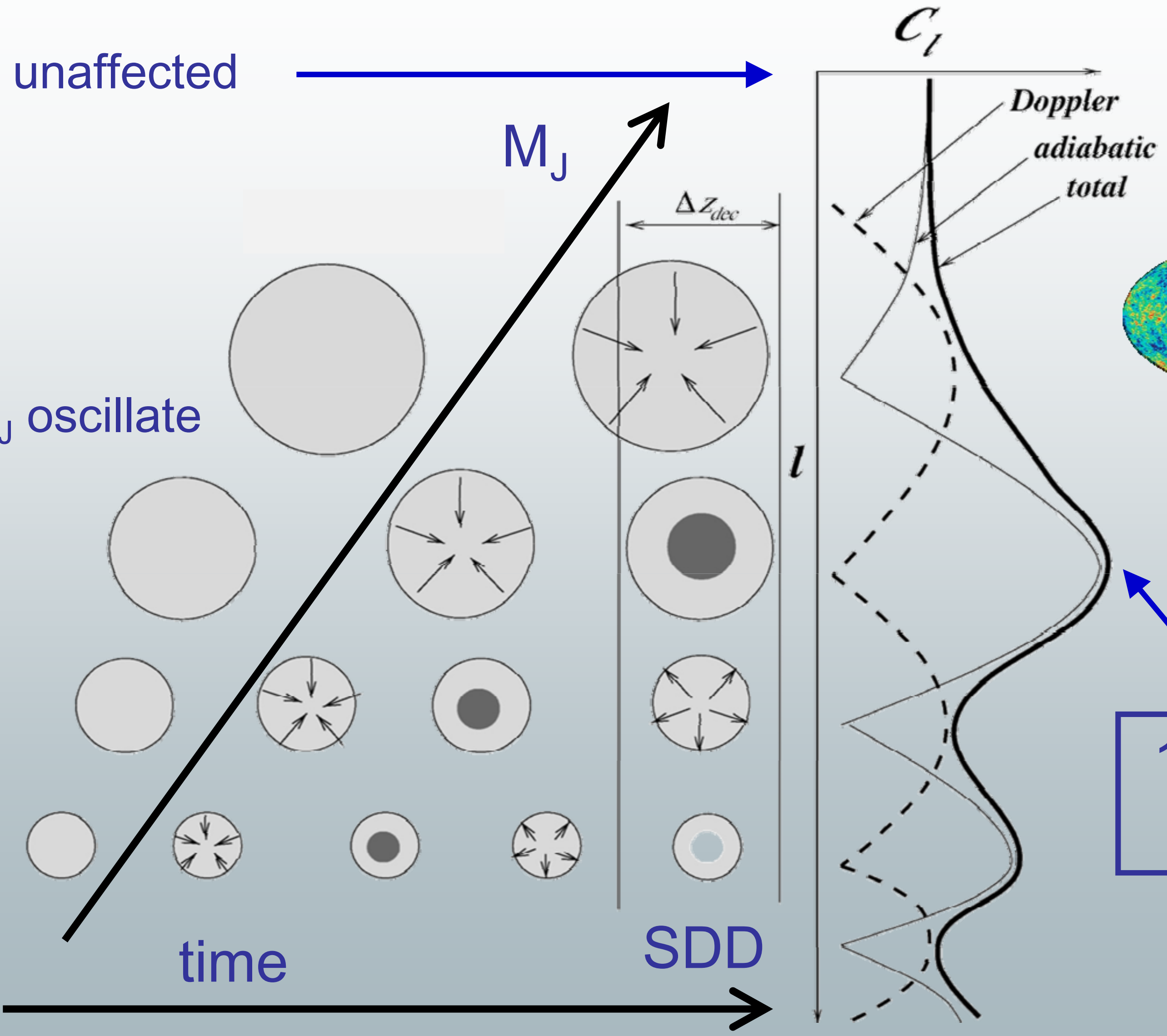
$Q_R > 0$ ➔ Radial
$Q_R < 0$ ➔ Tangential

1) Large scale flow:
$\Phi < 0$ ➔ $\Delta T < 0$ & $Q_R > 0$
➔ $\langle Q_R \rangle < 0$
→tangential for hot spot
(out of the figure above)

3) Pressure slows the fluid & flow reverts at $\sim\theta_A$
➔ $\langle Q_R \rangle < 0$

NB1: scales computed from ΛCDM
NB2: super-horizon (at t_{dec}) correlation calls for a fast expanding phase

Acoustic Oscillations



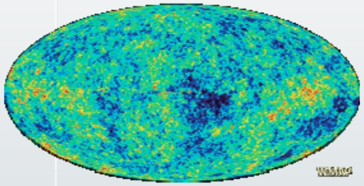
$M > M_J$ unaffected

M_J

$M < M_J$ oscillate

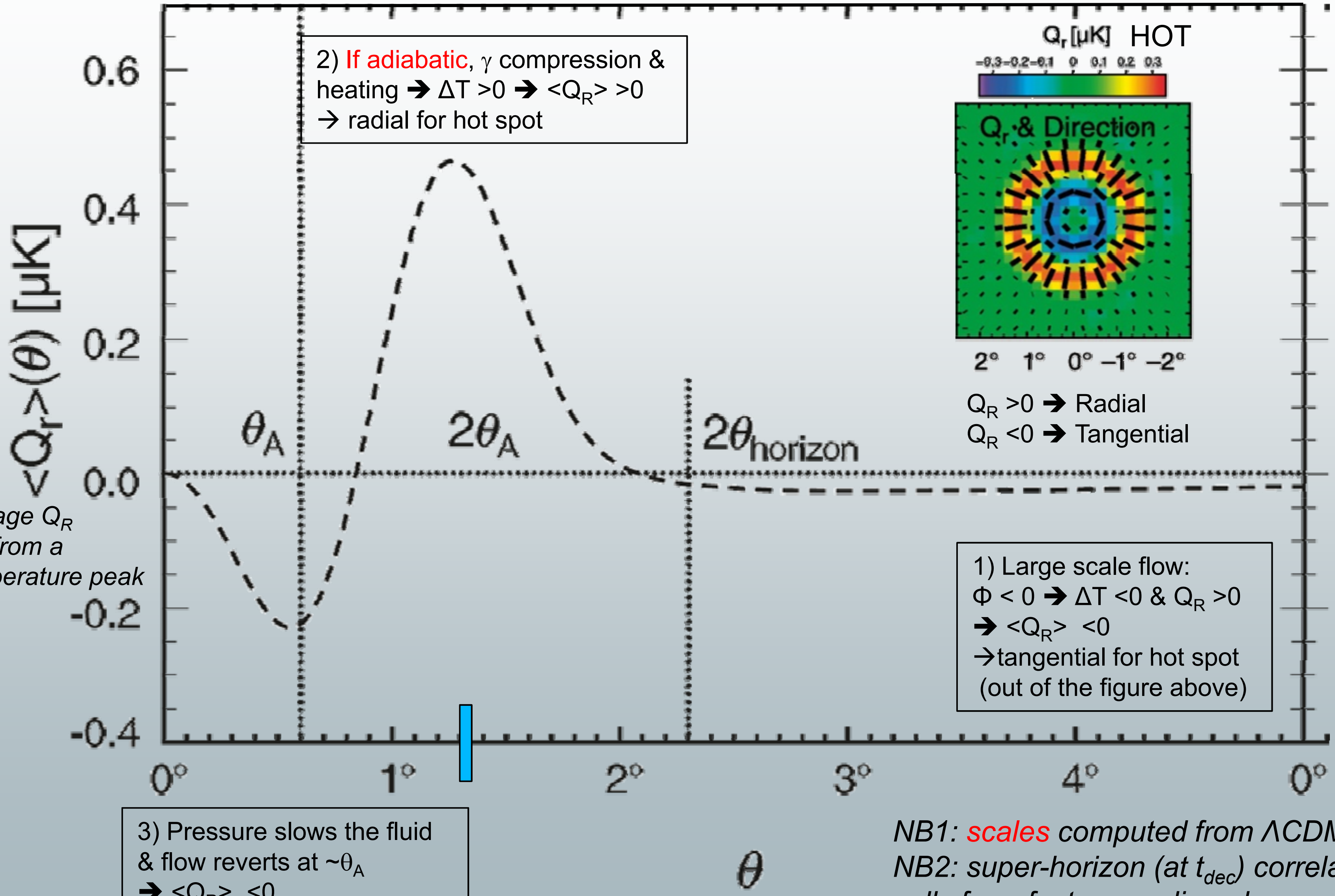
time

SDD



1 degree scale

Temperature and polarisation link



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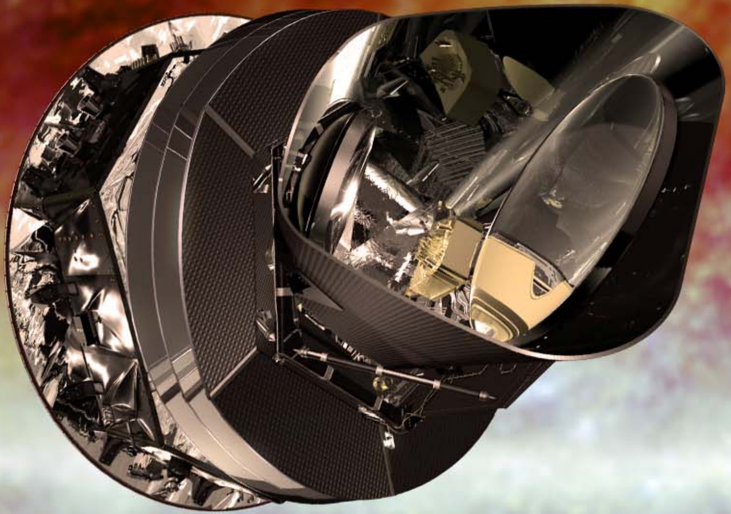
Conclusions



Planck is in routine operations

Performances are as expected or better