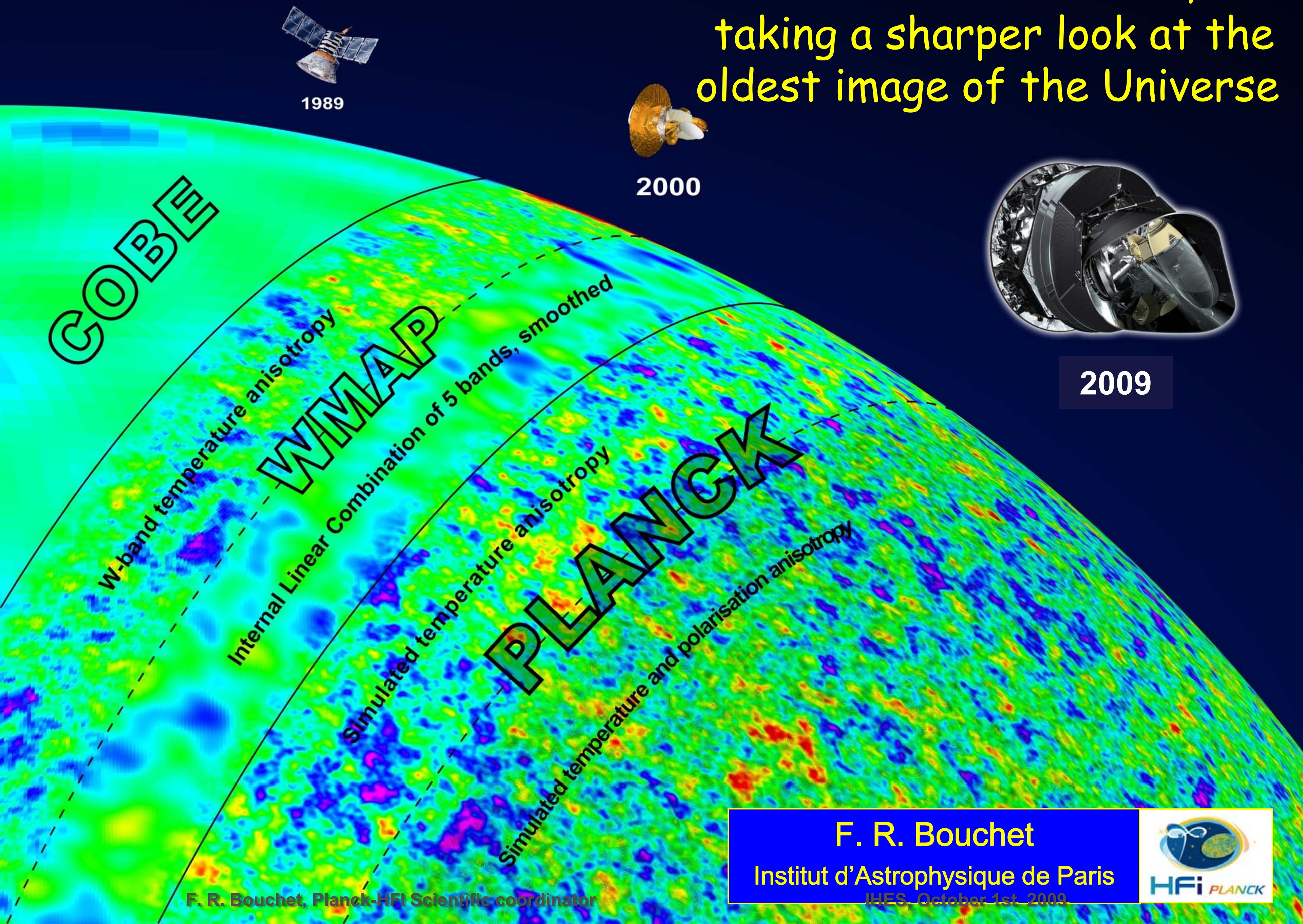
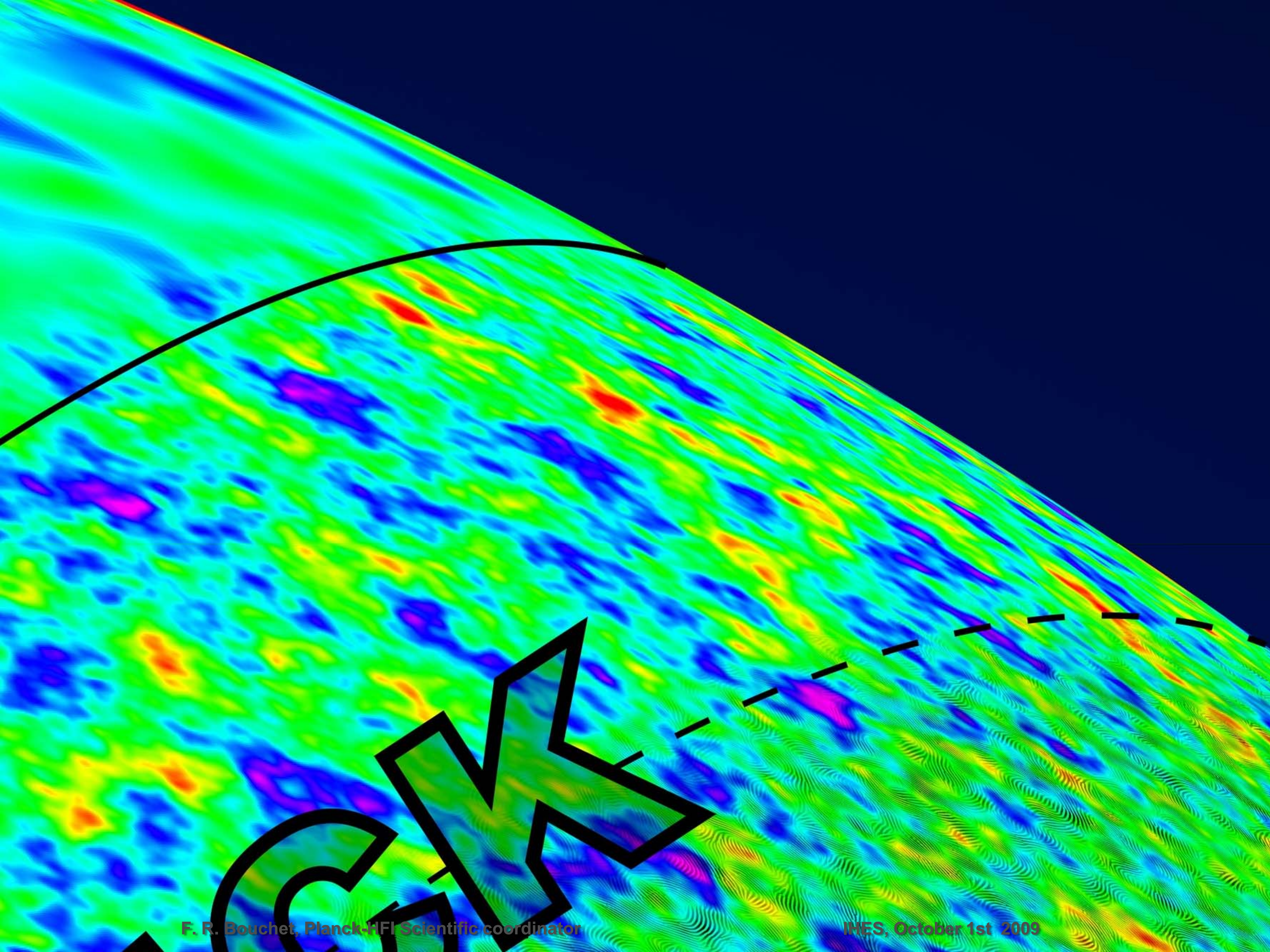
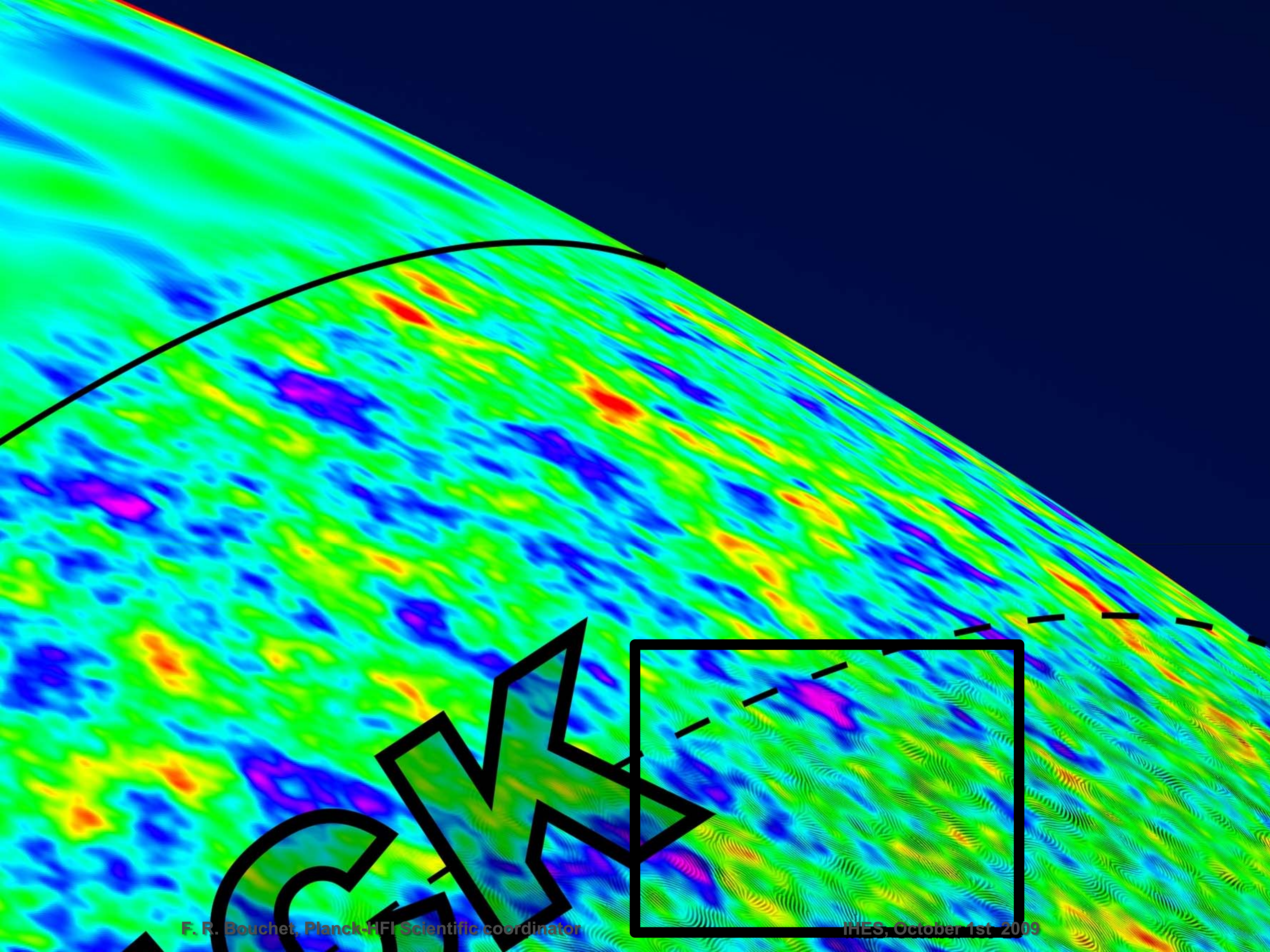
The Planck Satellite, taking a sharper look at the oldest image of the Universe

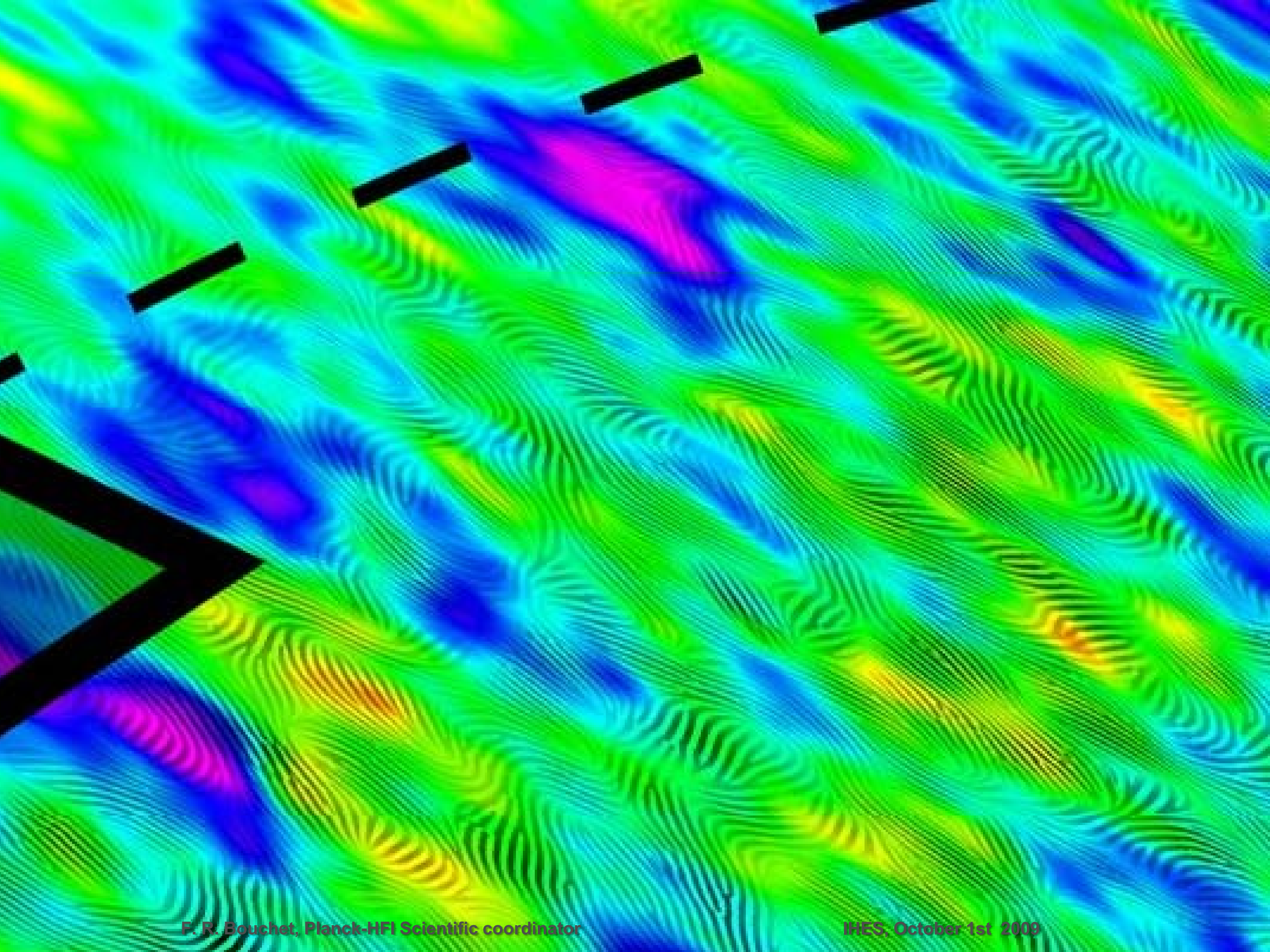


F. R. Bouchet
Institut d'Astrophysique de Paris

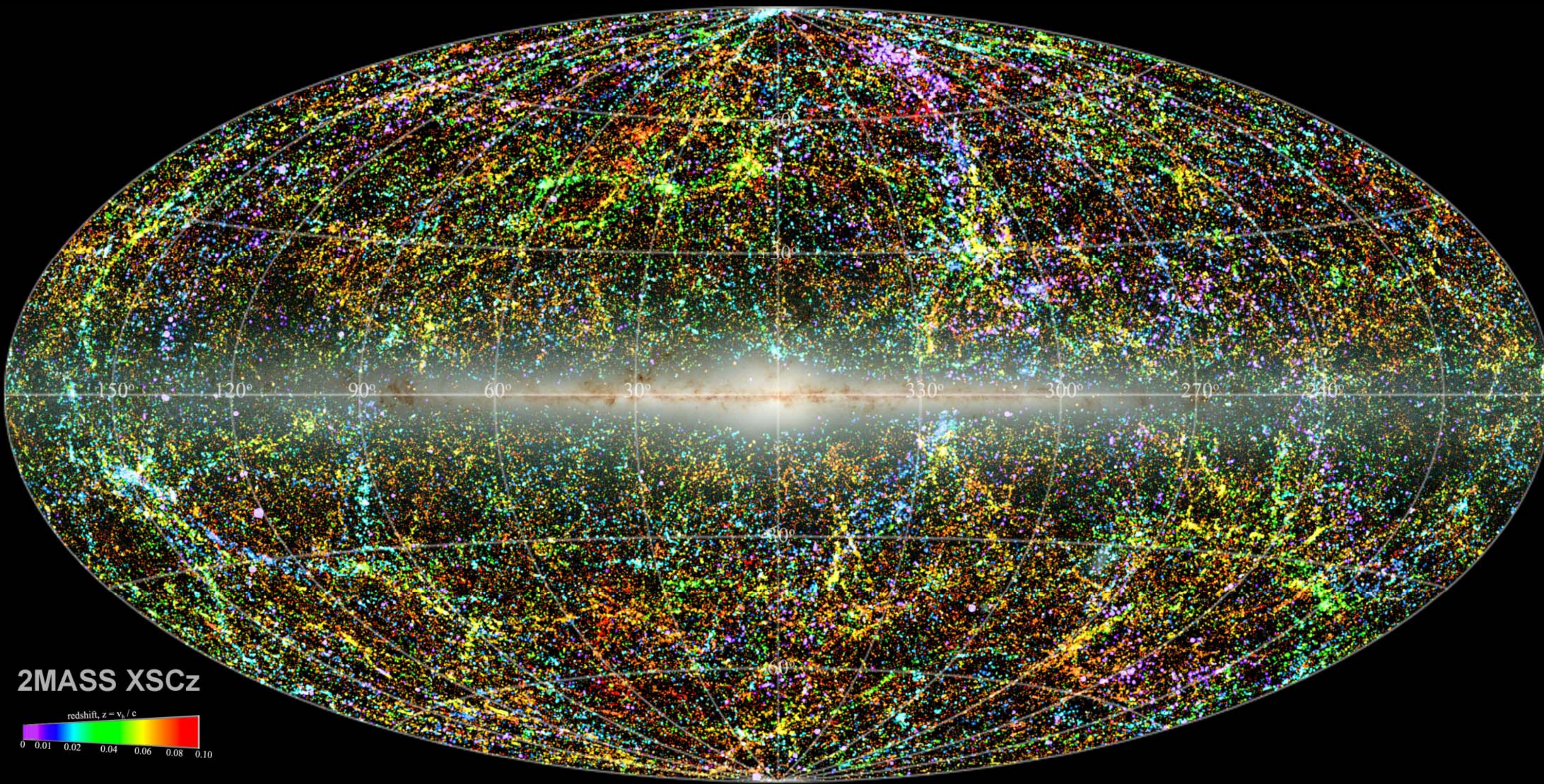
HFI PLANCK

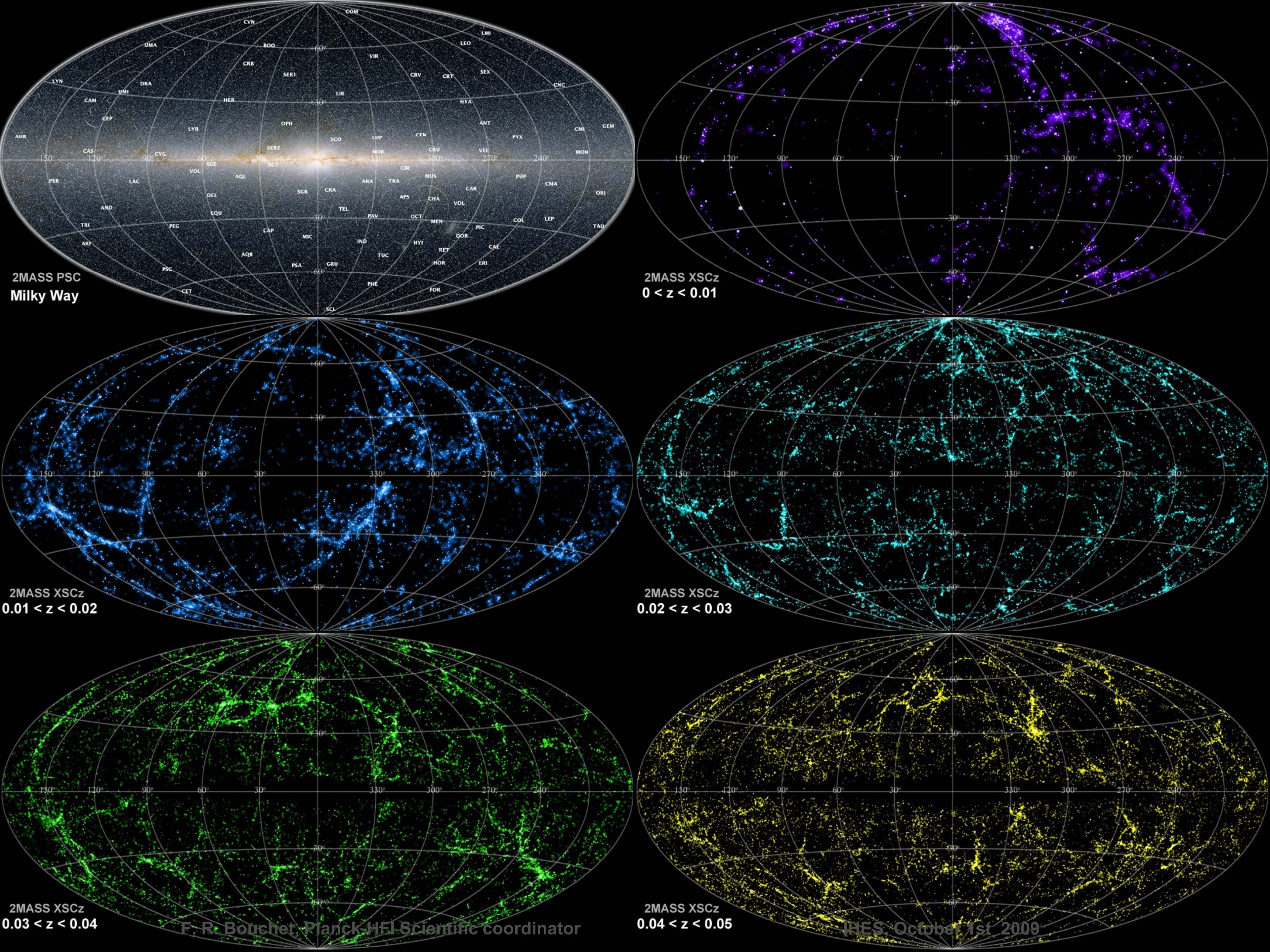






The sky of “nearby”galaxies

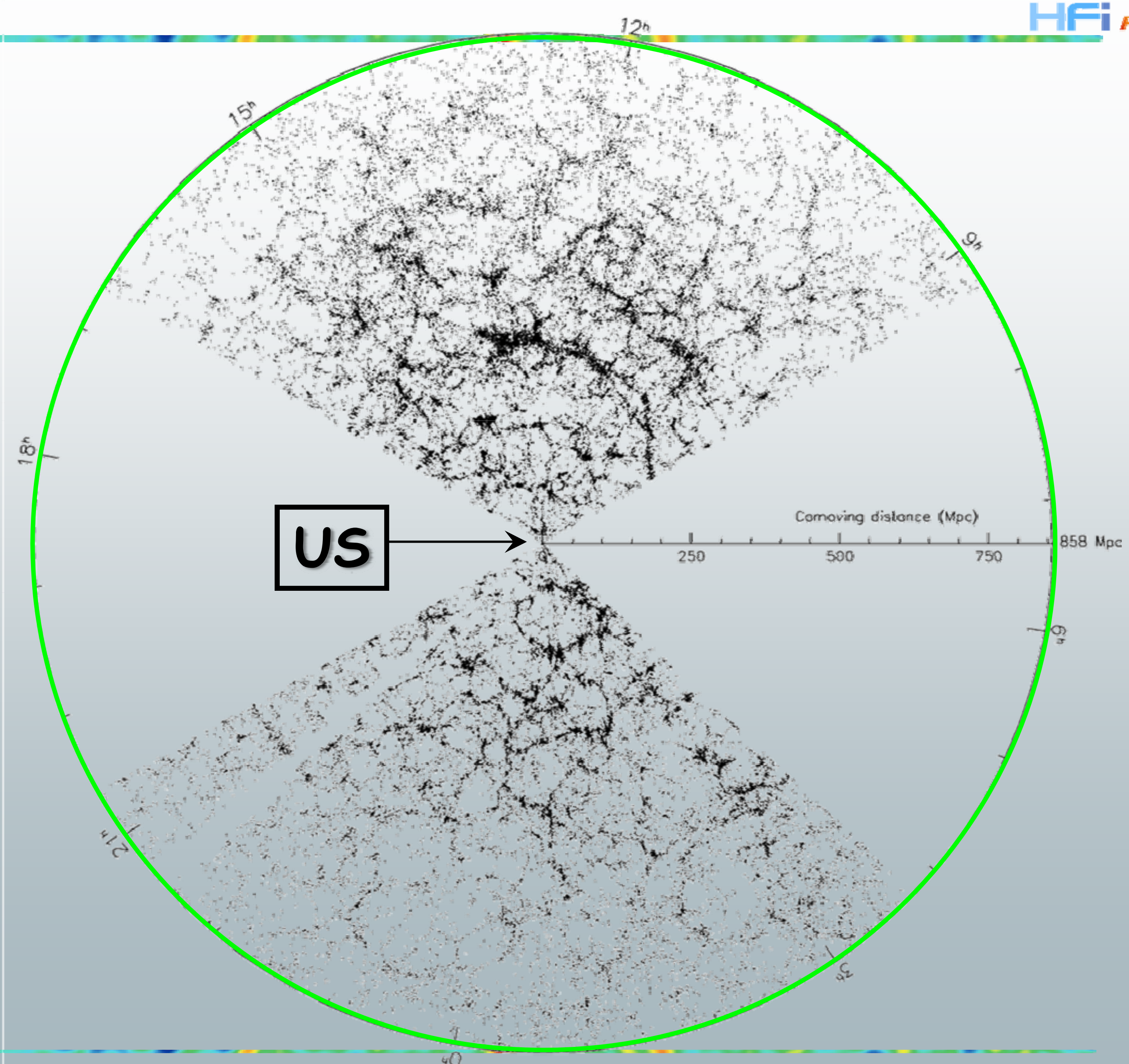


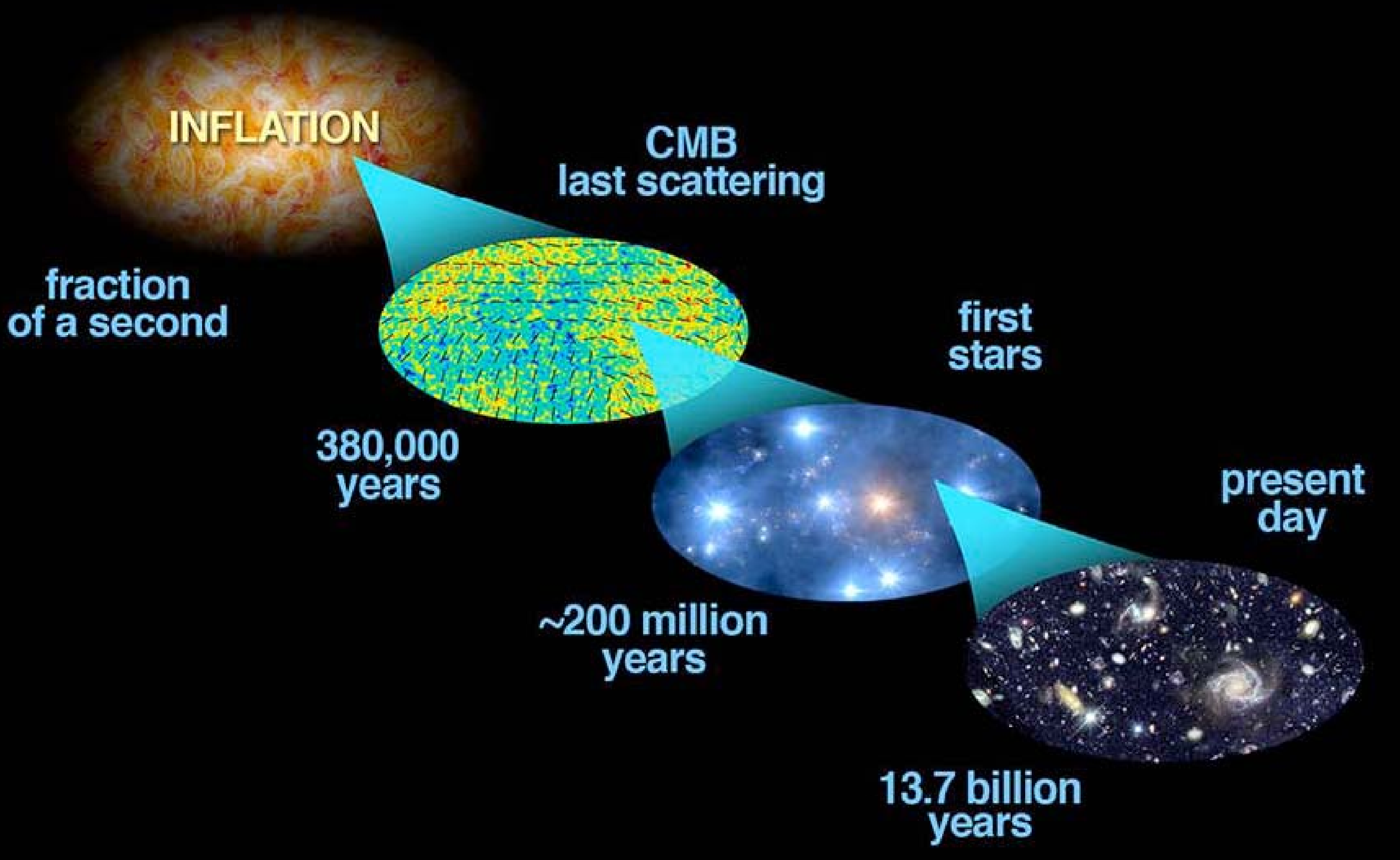

2MASS PSC
Milky Way
2MASS XSCz
0 < z < 0.01
2MASS XSCz
0.01 < z < 0.02
2MASS XSCz
0.02 < z < 0.03
2MASS XSCz
0.03 < z < 0.04
2MASS XSCz
0.04 < z < 0.05

Galaxies are not scattered at random!

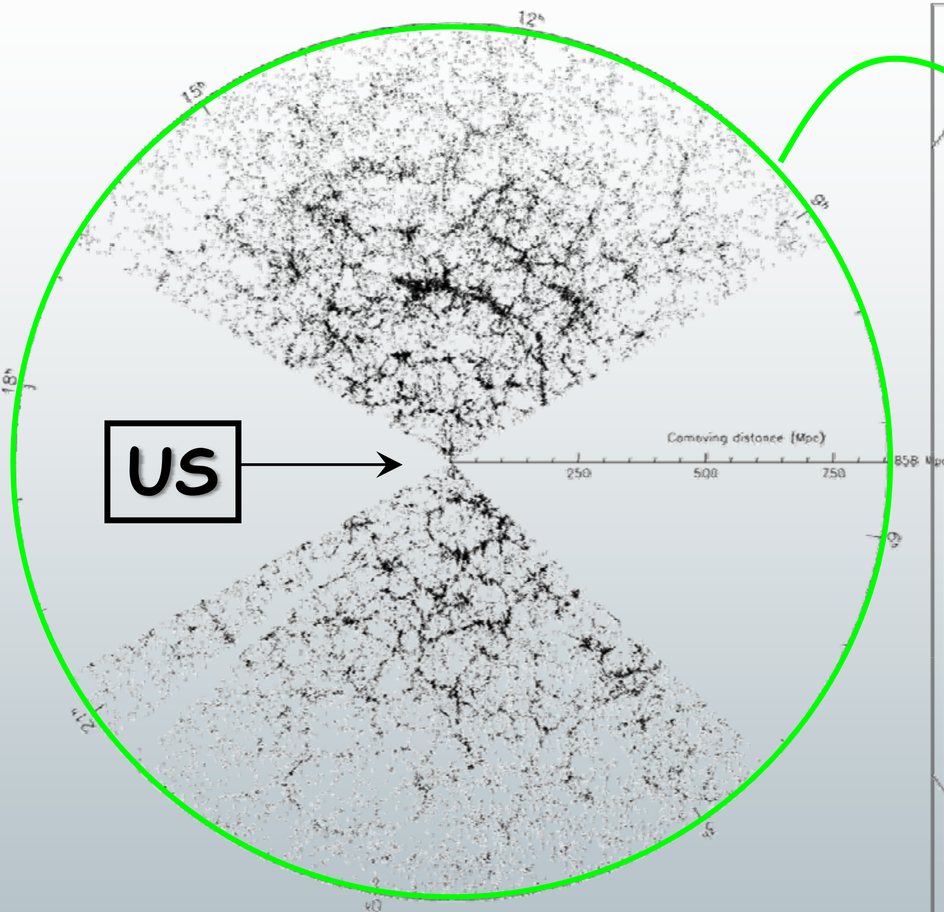
Each point is a galaxy like ours. The closest from us, M31, is at ~2,5 Mly.

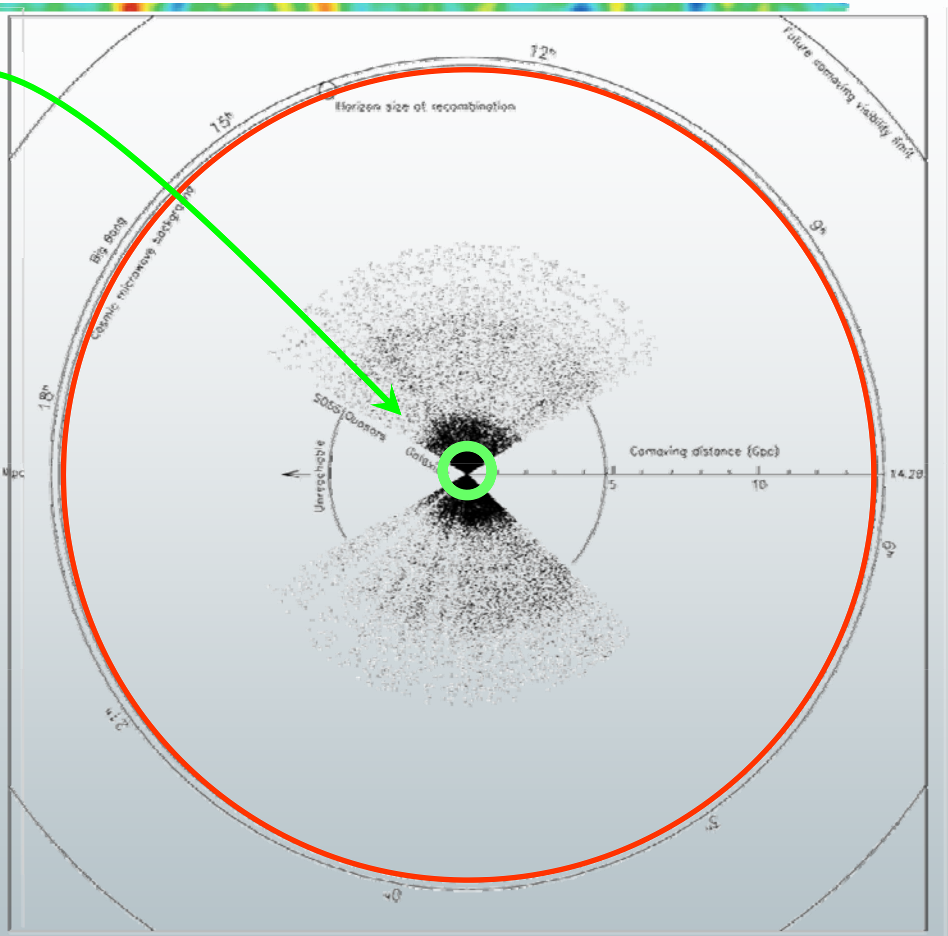
Light takes 2,7 billion years to travel to us from a galaxy on the green circle.



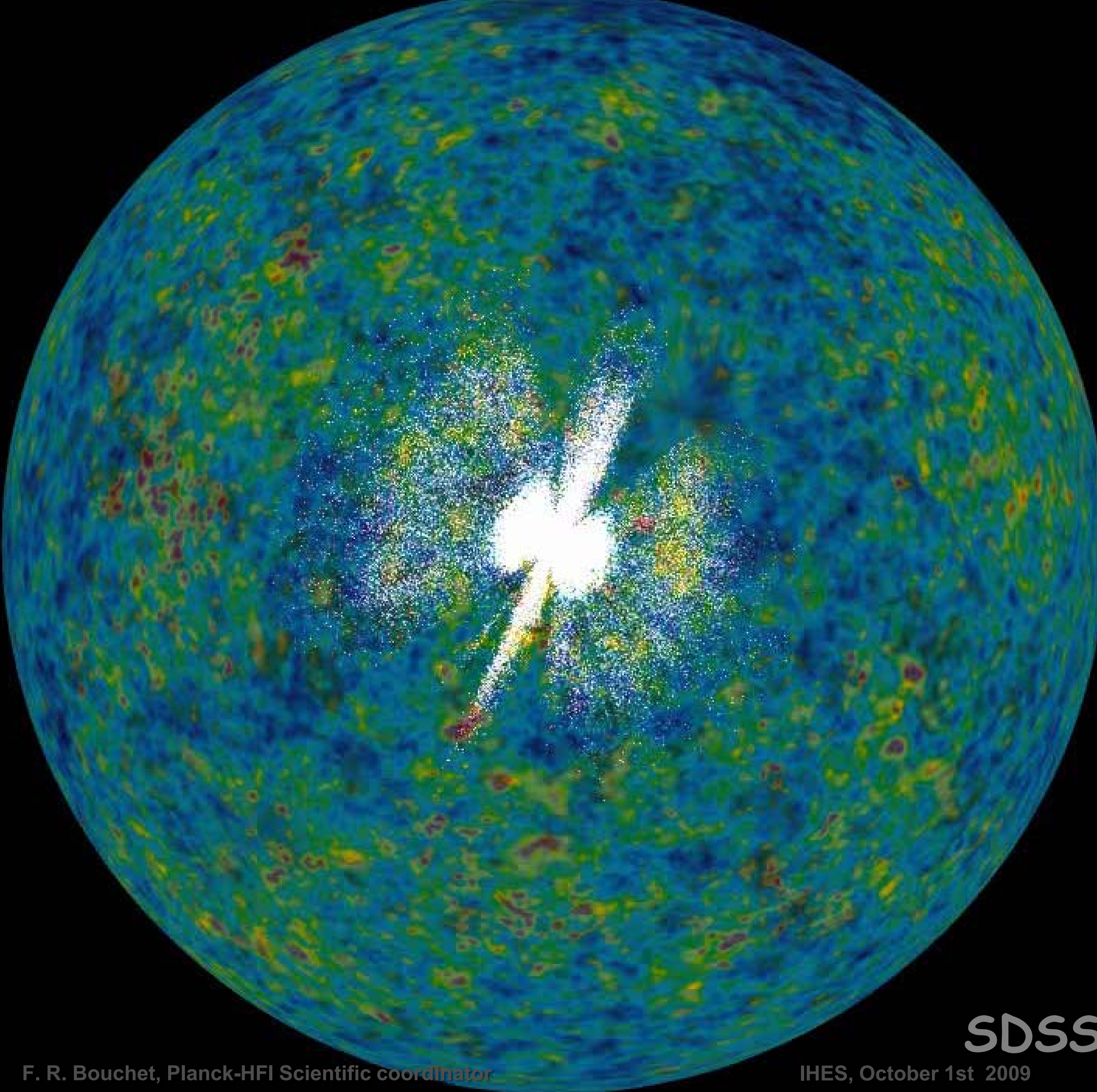

INFLATION
CMB
last scattering
fraction
of a second
first
stars
380,000
years
present
day
~200 million
years
13.7 billion
years

To look far away is watching a remote past!

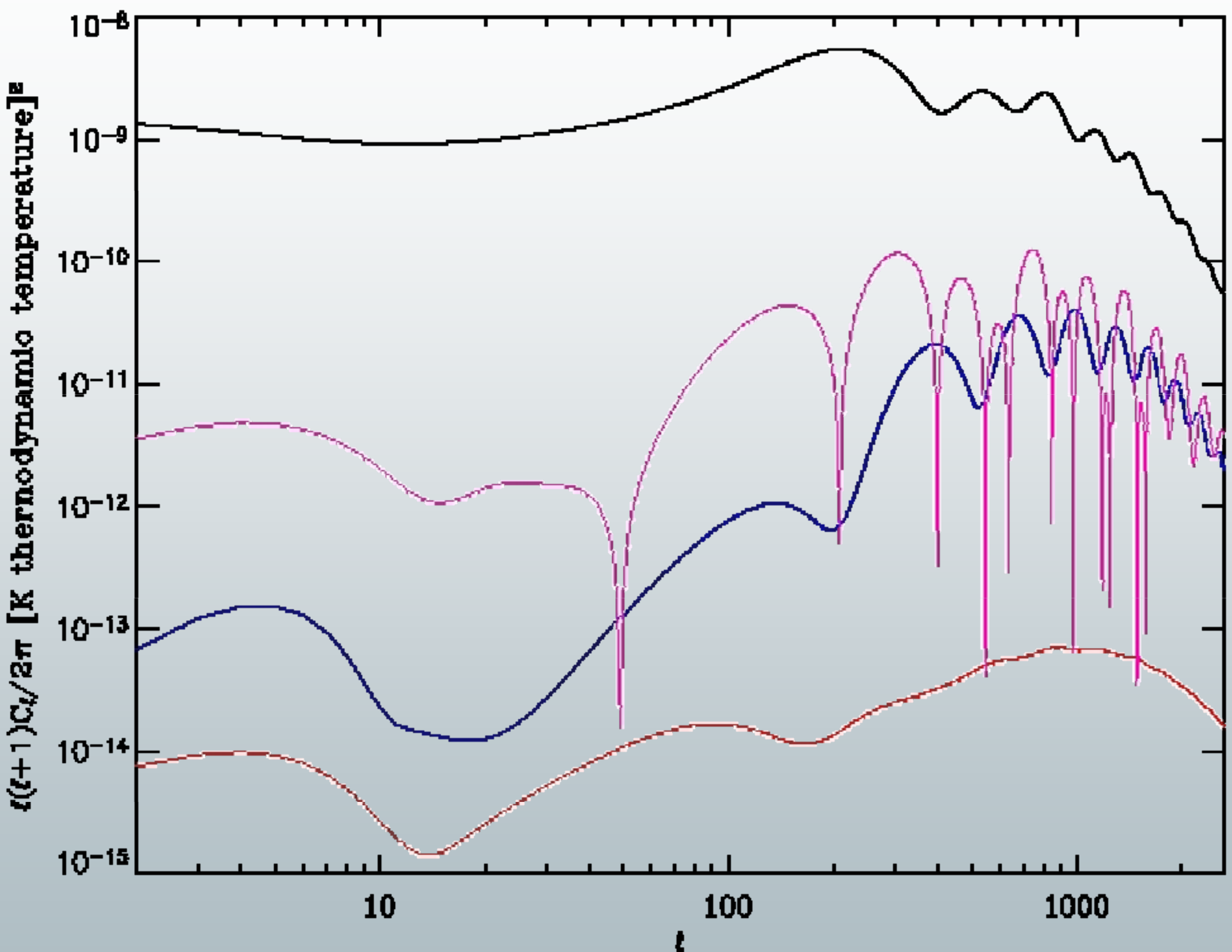




Light takes 2,7 billion years to travel to us from a galaxy on the green circle .
The millimetric light took ~13 billion years to travel to us from the LSS (red circle).
This is the fossil from the primordial furnace, 400 000 years after the Bang, when the universe became transparent.

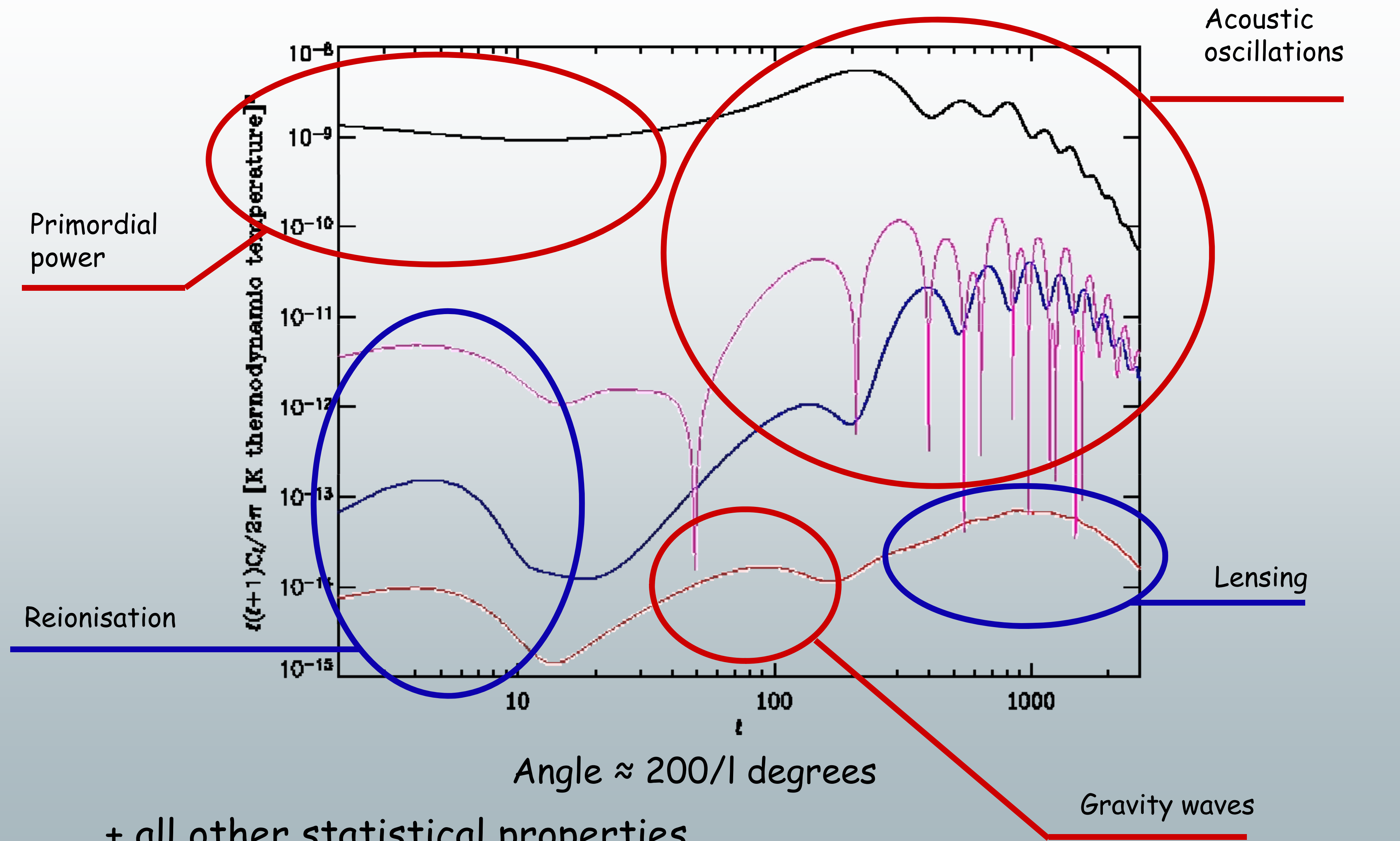

SDSS & WMA

CMB information mine



Angle ≈ 200/l degrees

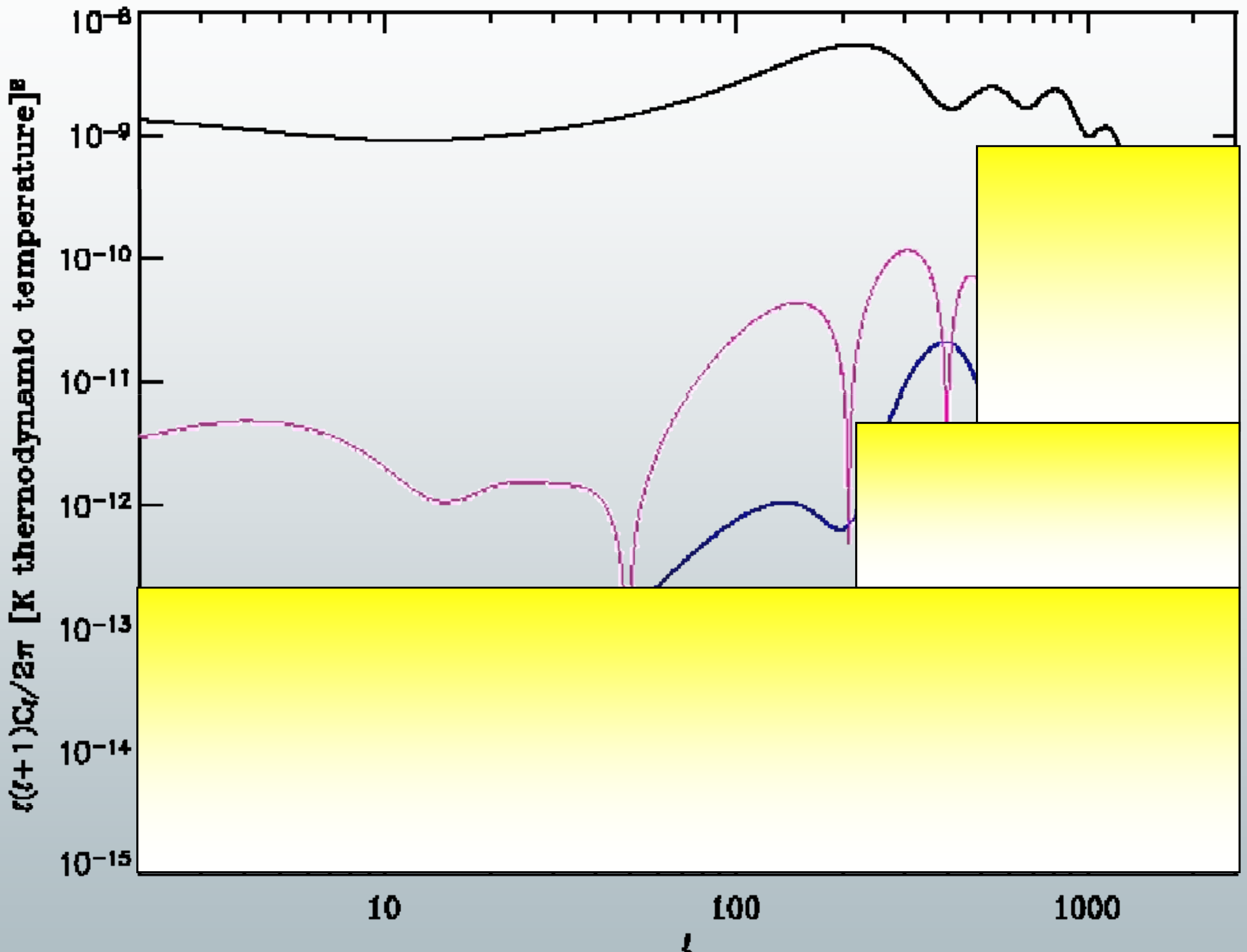
CMB information mine



Angle ≈ 200/l degrees

+ all other statistical properties

Known CMB angular power spectra



Angle ≈ 200/l degrees

⇨ **Blessed with much more to extract**

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]*
- get the best performances possible on the polarization with the technology available

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

Sensitivity goals per channel

- Two instruments, covering a range of 30 in frequency
  - *LFI = Low Frequency instrument, using HEMTS*
  - *HFI = High Frequency instrument, using bolometers*

Instrument Characteristic	LFI			HFI					
Detector Technology	HEMT arrays			Bolometer arrays					
Center Frequency [GHz]	30	44	70	100	143	217	353	545	857
Bandwidth ($\Delta\nu/\nu$)	0.2	0.2	0.2	0.33	0.33	0.33	0.33	0.33	0.33
Angular Resolution (arcmin)	33	24	14	10	7.1	5.0	5.0	5.0	5.0
$\Delta T/T$ per pixel (Stokes I)[a]	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
$\Delta T/T$ per pixel (Stokes Q & U)[a]	2.8	3.9	6.7	4.0	4.2	9.8	29.8	...	...

[a] Goal (μK/K, 1σ), 14 months integration, square pixels whose sides are given in the row "Angular Resolution".

Planck Bluebook

- *Robustness of design for T Component Separation*

Goals in perspective

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)

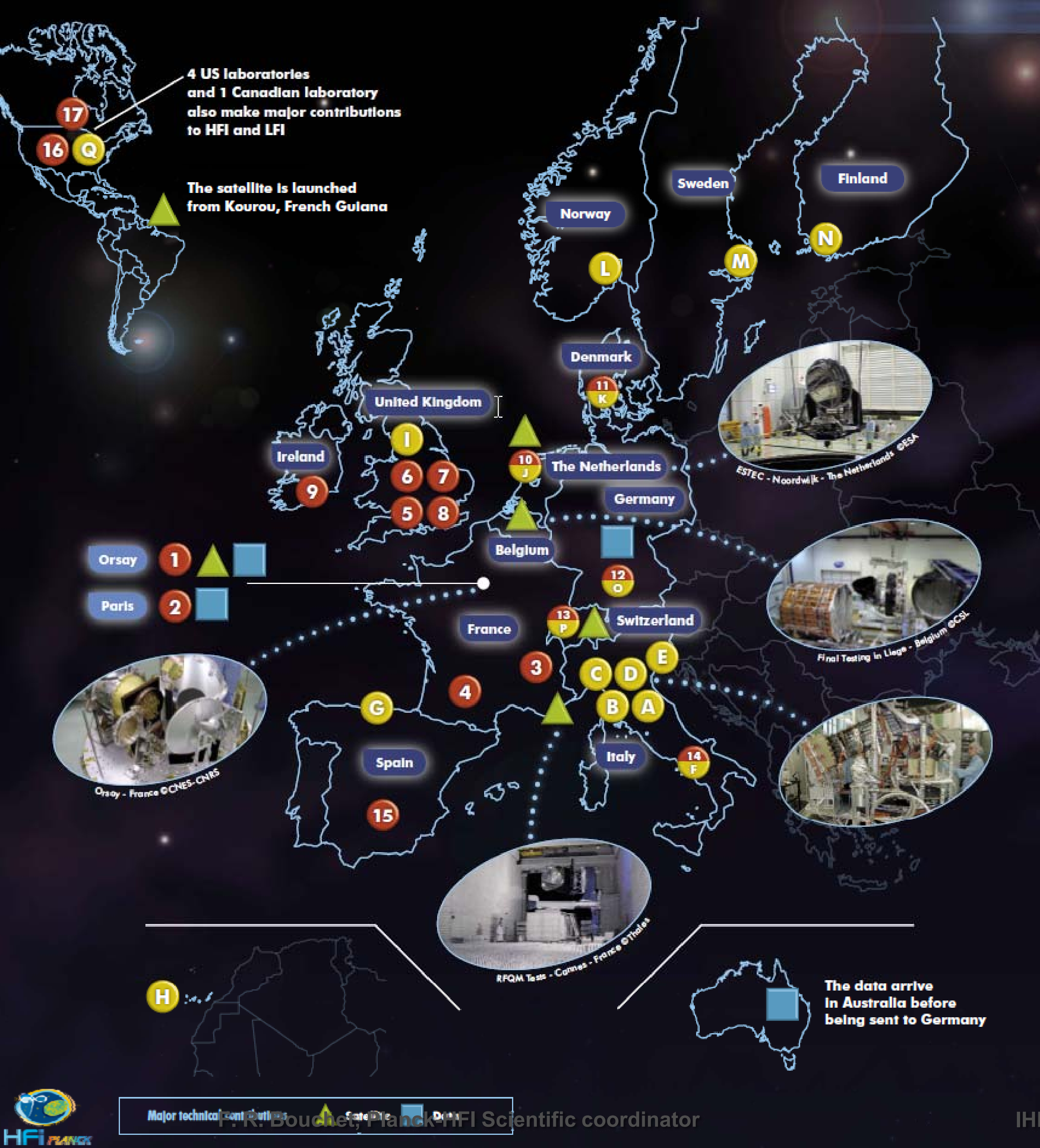
The aggregated sensitivity of Planck core CMB channels is ~0.5μK.deg in T, 1 μK.deg QU (nominal mission – 14months)

Planck needed breakthroughs

- The sensitivity goals of Planck requires several technological performance never achieved in space before
  - *Sensitive & fast bolometers with*
    - NEP< 2 10^{-17} W/$Hz^{1/2}$ & 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/$Hz^{1/2}$ from 10 mHz to 100 Hz
  - *Excellent temperature stability, from 10 mHz (1 rpm) to 100 Hz (cf. Lamarre et al. 04)*
    - < 10 μK/$Hz^{1/2}$ for 4K box (30% emissivity)
    - < 30 μK/$Hz^{1/2}$ on 1.6K filter plate (20% emissivity)
    - < 20 nK/$Hz^{1/2}$ 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*



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)

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

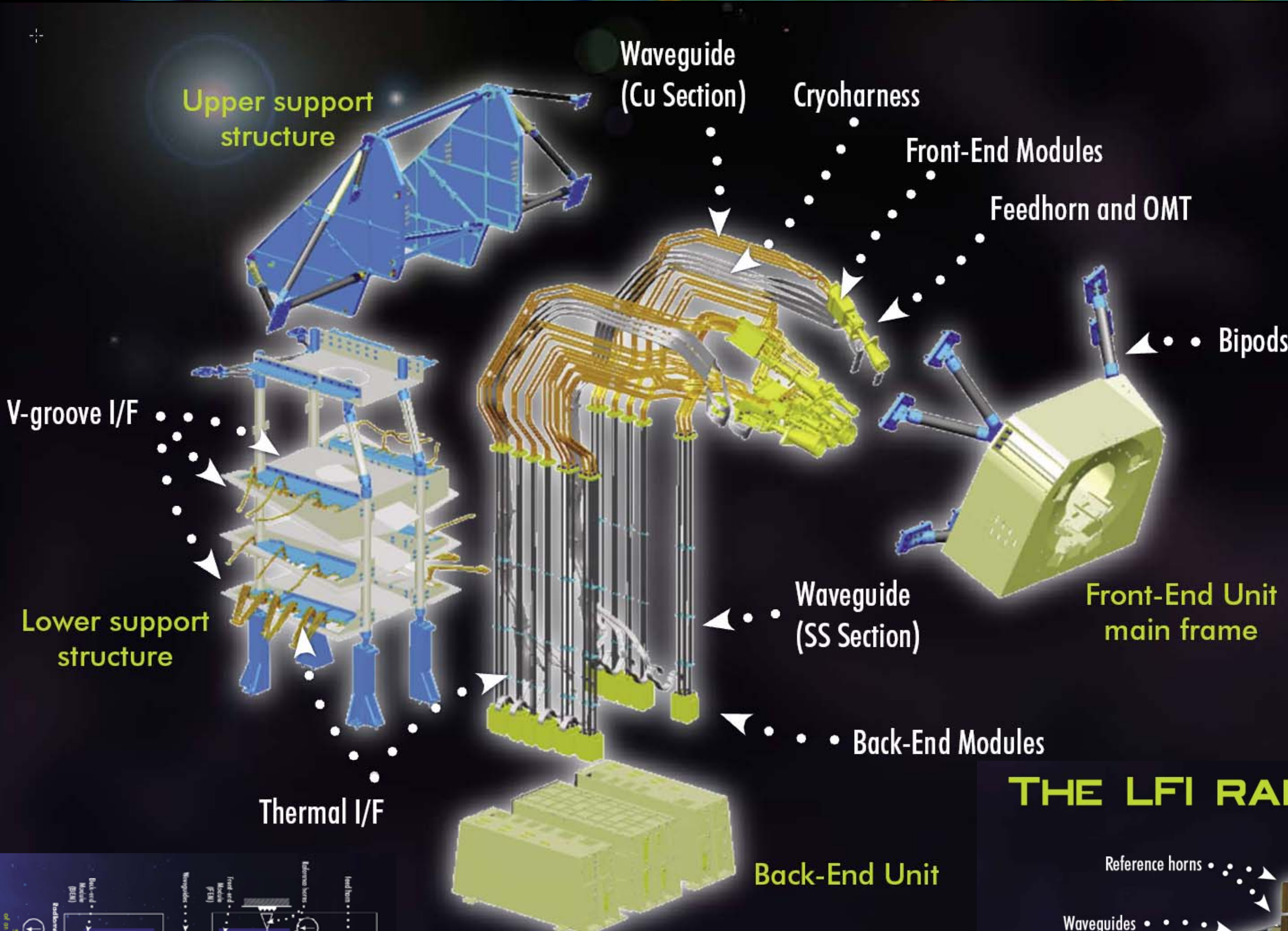
4,2 m

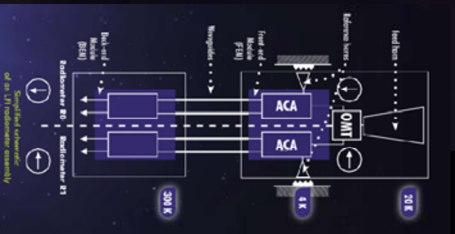
4,2 m

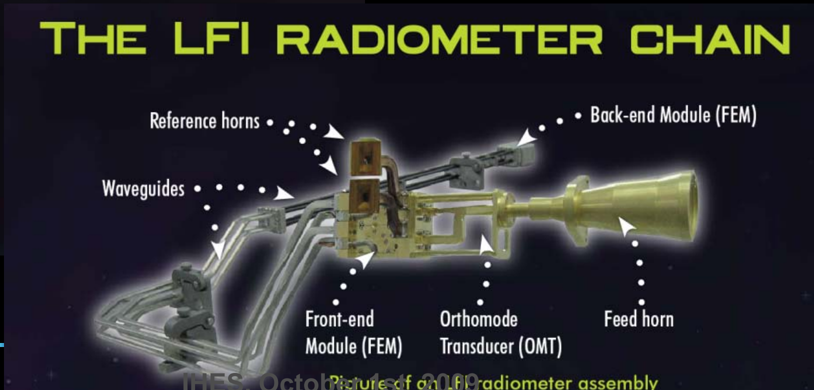
50 000 electronic components
36 000 l ^{4}He
12 000 l ^{3}He
11 400 documents
20 years between the first project and first results (2013)

5c per European per year
16 countries
400 researchers among 1000

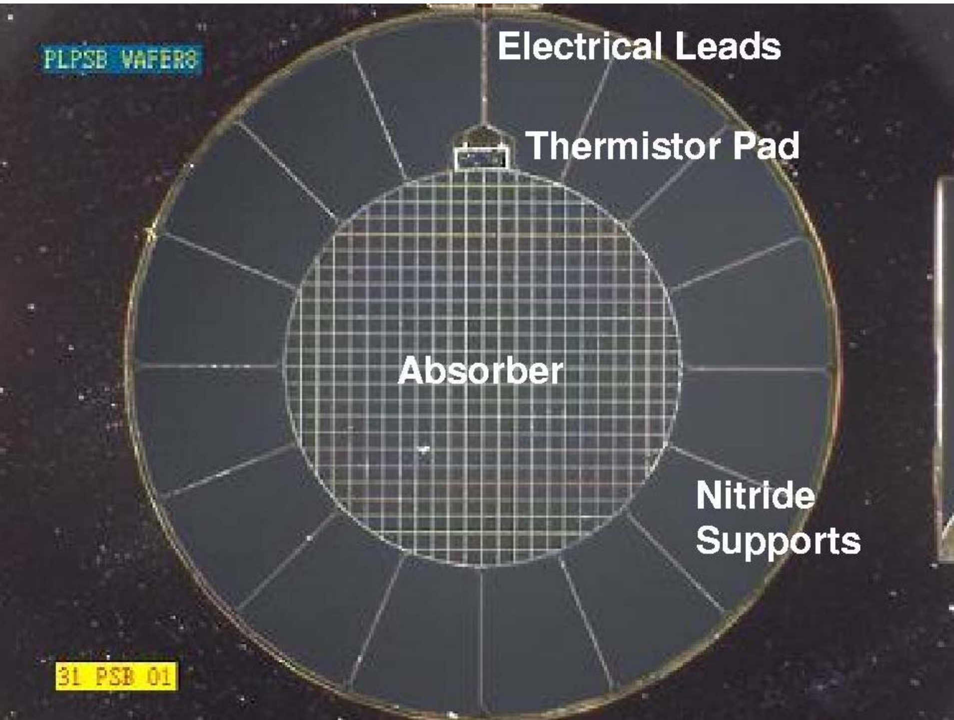
The Low Frequency Instrument LFI







HFI Spider Web Bolometers & PSBs

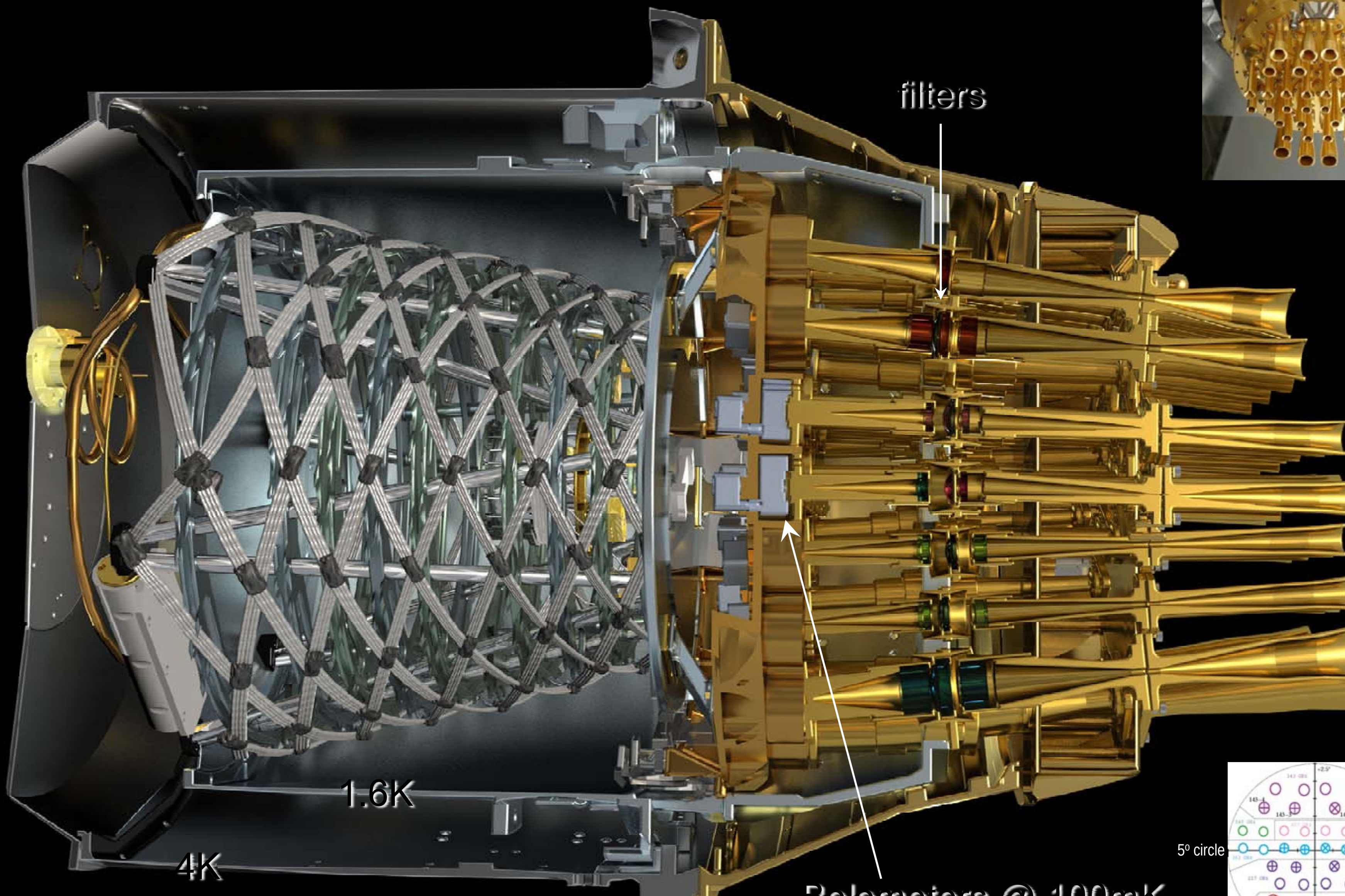


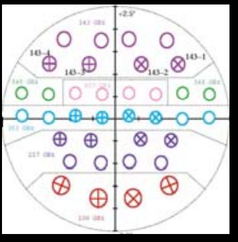
145 GHz PolarSensitiveBolometers | **857 GHz SpiderWeb Bolometer**

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





Planck Cooling chain

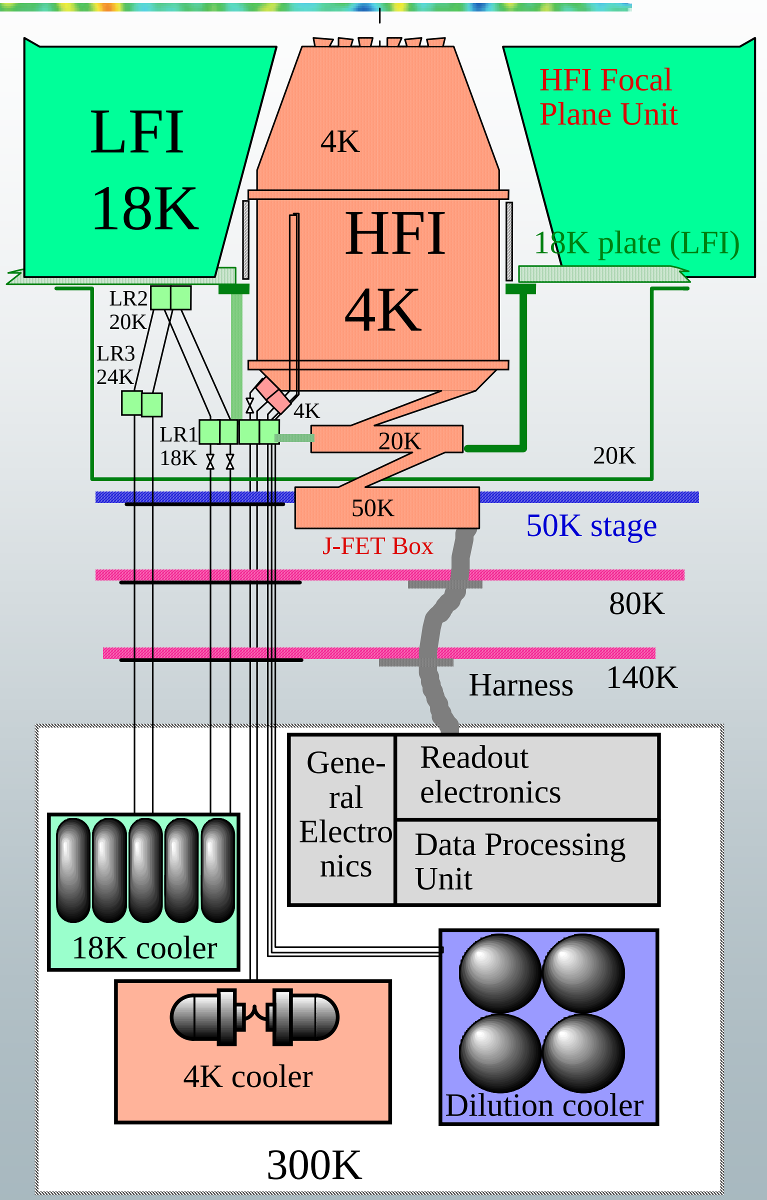
To Bring
- LFI HEMTS to 18K
- HFI Bolometers to 0.1K

40K: radiative cooling ≈2W

18K: H_2 J-T Sorption pumps (JPL, *USA*) ≈1W

4K: He J-T Mech. Pump (RAL, *UK*) ≈15mW

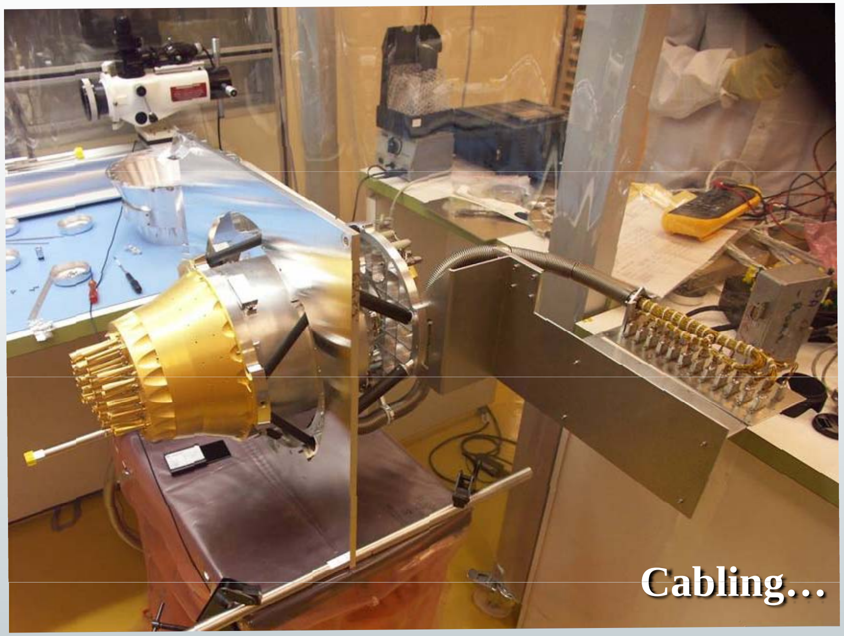
1.6K: J-T expansion 0.5mW
0.1K 3He/4He dilution 0.2μW
(AL, CRTBT, IAS, *France*)

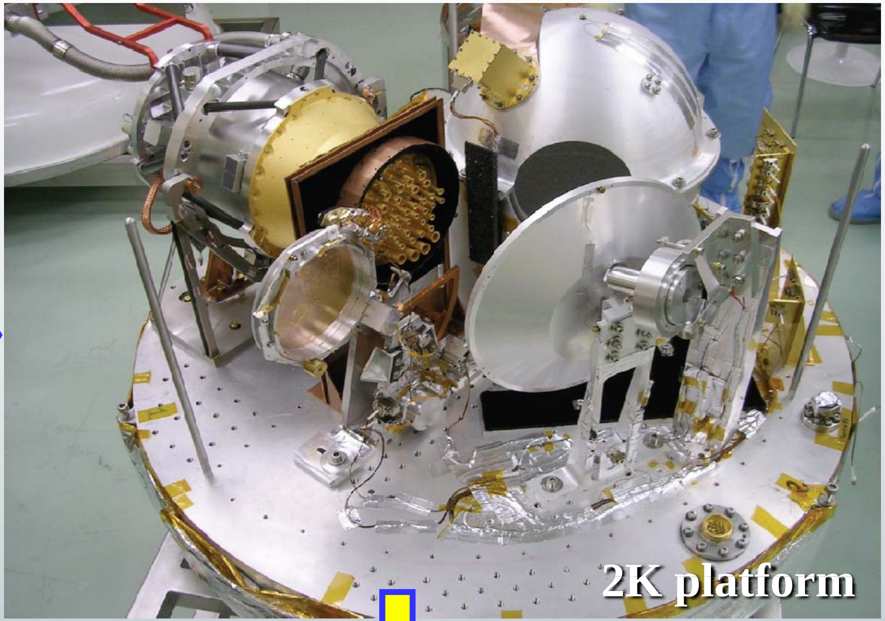


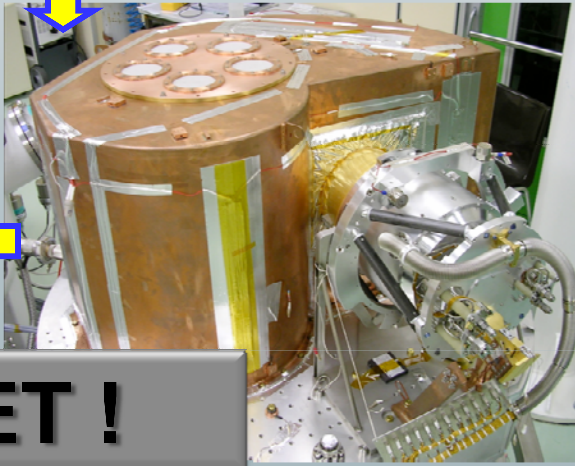
Birth of the Cool

HFI Integration & Calibration @ IAS

(reproduction of spatial and micro-wave environment)

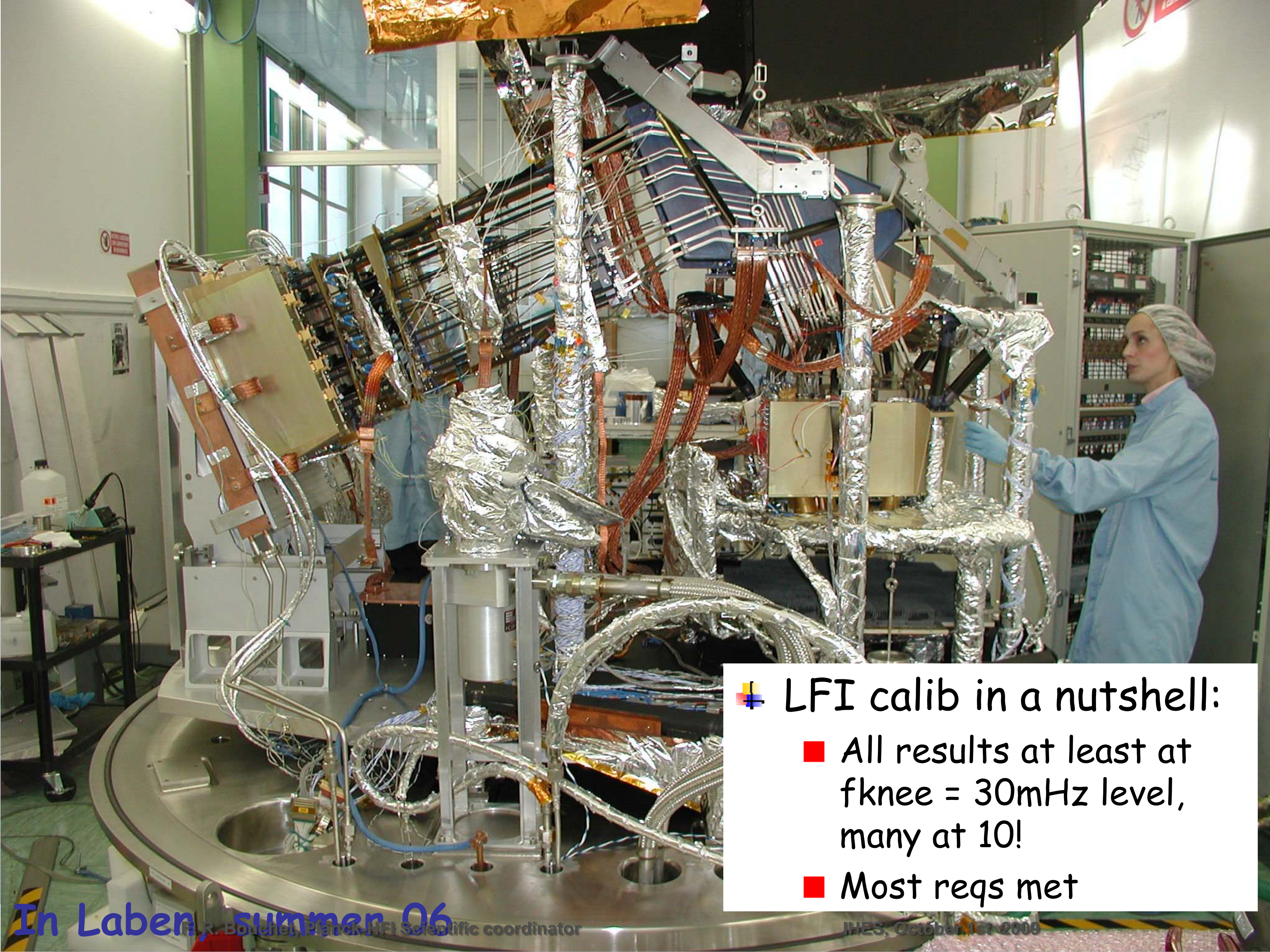






DESIGN GOALS MET !

WMAP would need ~500 years of survey time to reach HFI 1yr sensitivity



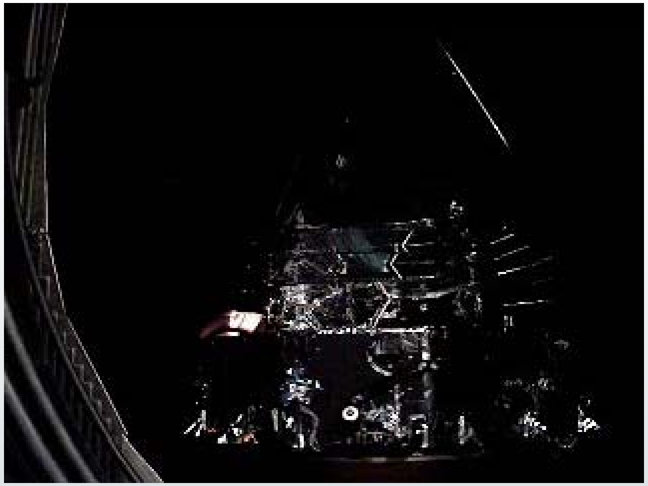
- LFI calib in a nutshell:
  - All results at least at fknee = 30mHz level, many at 10!
  - Most reqs met

In Laben, summer 06

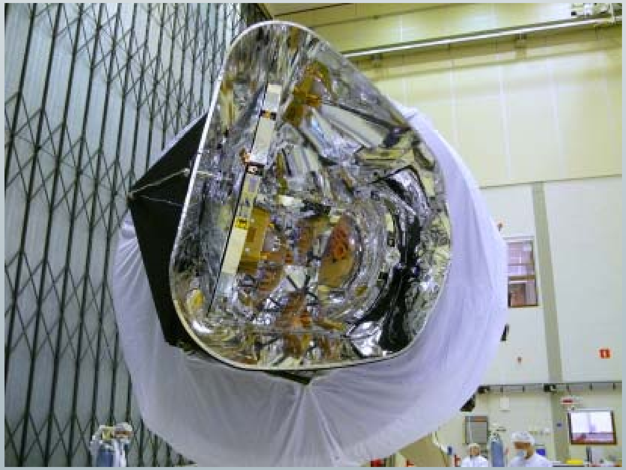
Integration at Thales-Cannes

Nov 2006,
HFI + LFI
integration

Dec 9th 2007, Ready
for vibration testing



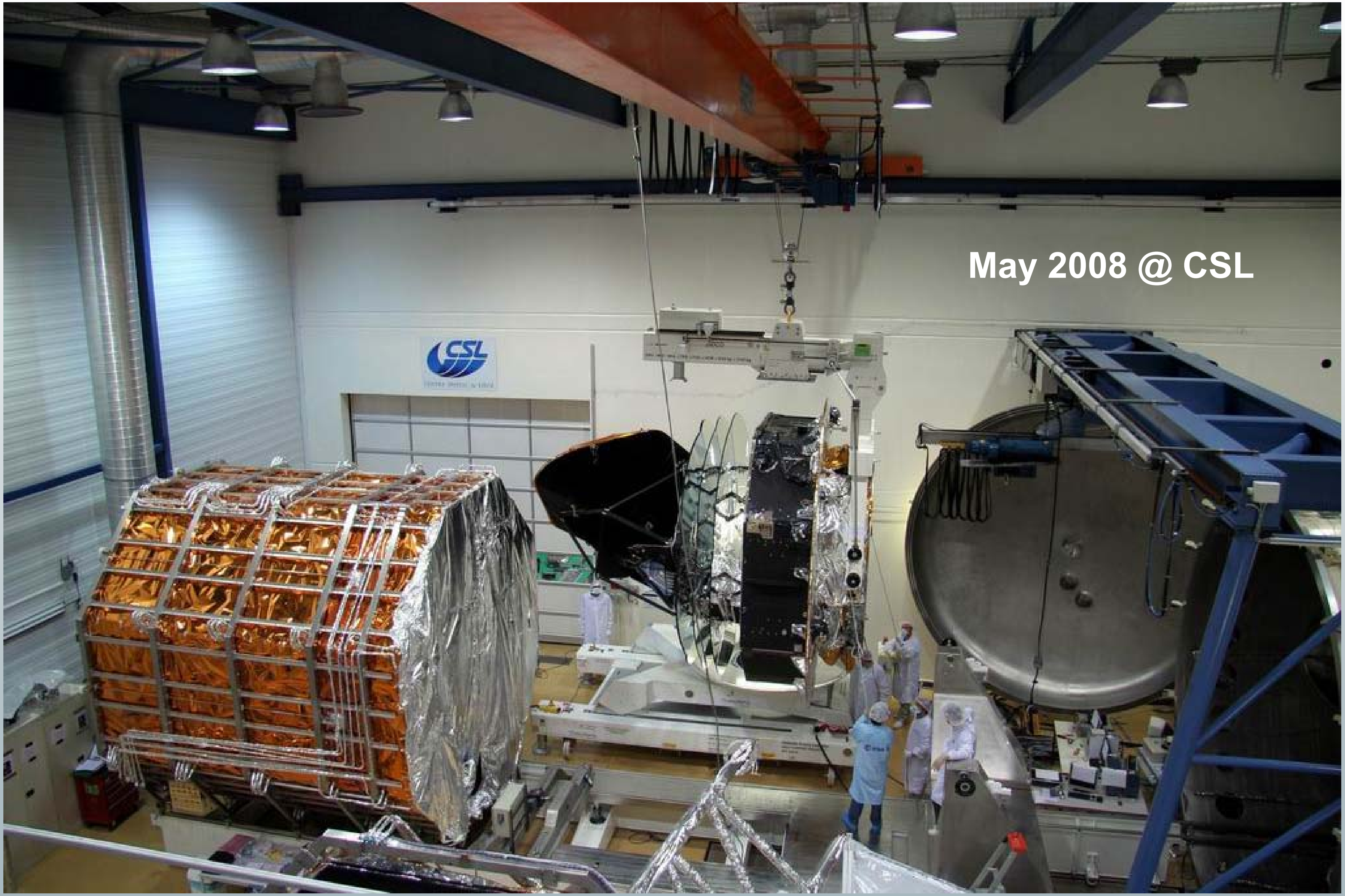
April 7th 08: load balancing



April 18th 2008: preparing
ESTEC → CSL

03/08: Antonov Nice → ESTEC

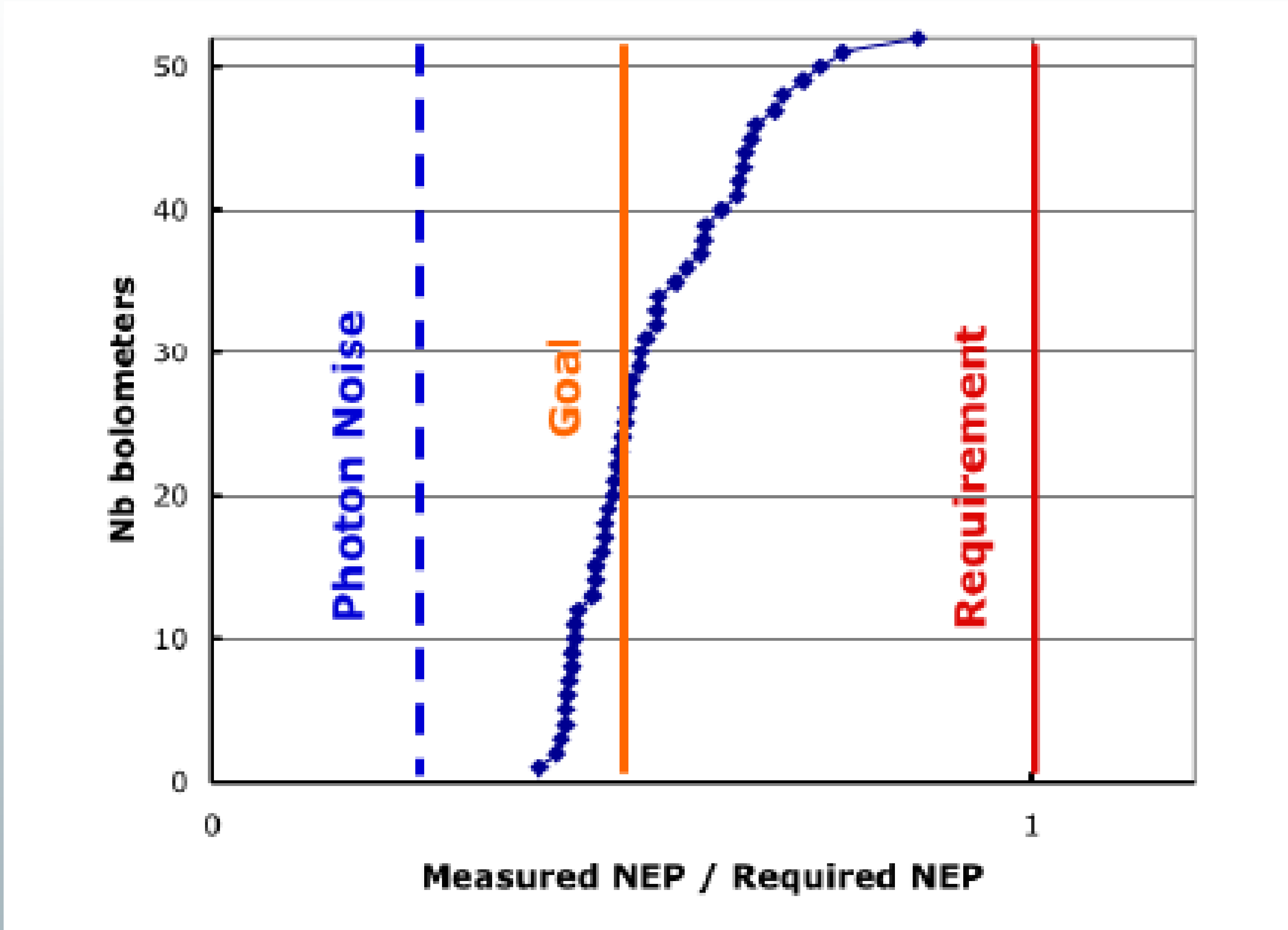
1st & last full thermal vacuum test @ CSL



CSL results in a nutshell

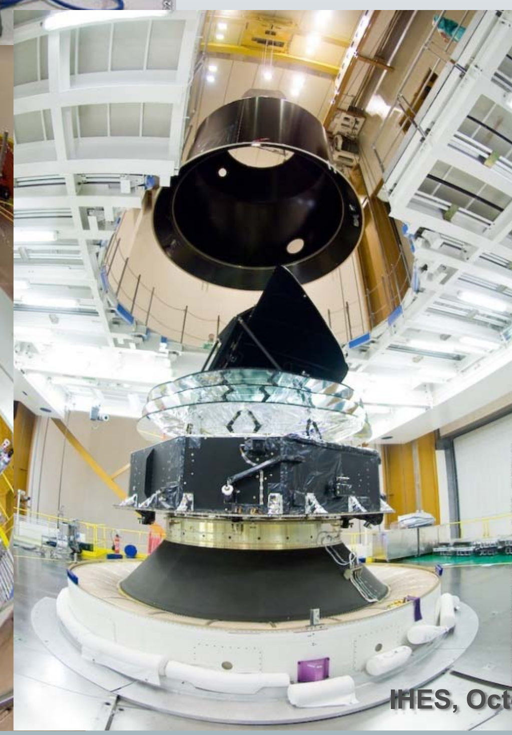
- The test has shown that the dilution can work with the *minimal* helium 3 and 4 flux, which should allow 30 months of survey duration (nominal 14)
- The required temperature stability (at 1/5 of the detection noise) was extremely demanding but has been verified
  - *20 nK/rt Hz on the bolometer plate at 100mK over the needed range [10mHz, 100Hz]*
  - *10µK/rt Hz on the 4K horns and filters*
- Bolometers expected sensitivities in flight conditions (see next)

HFI bolometers at CSL



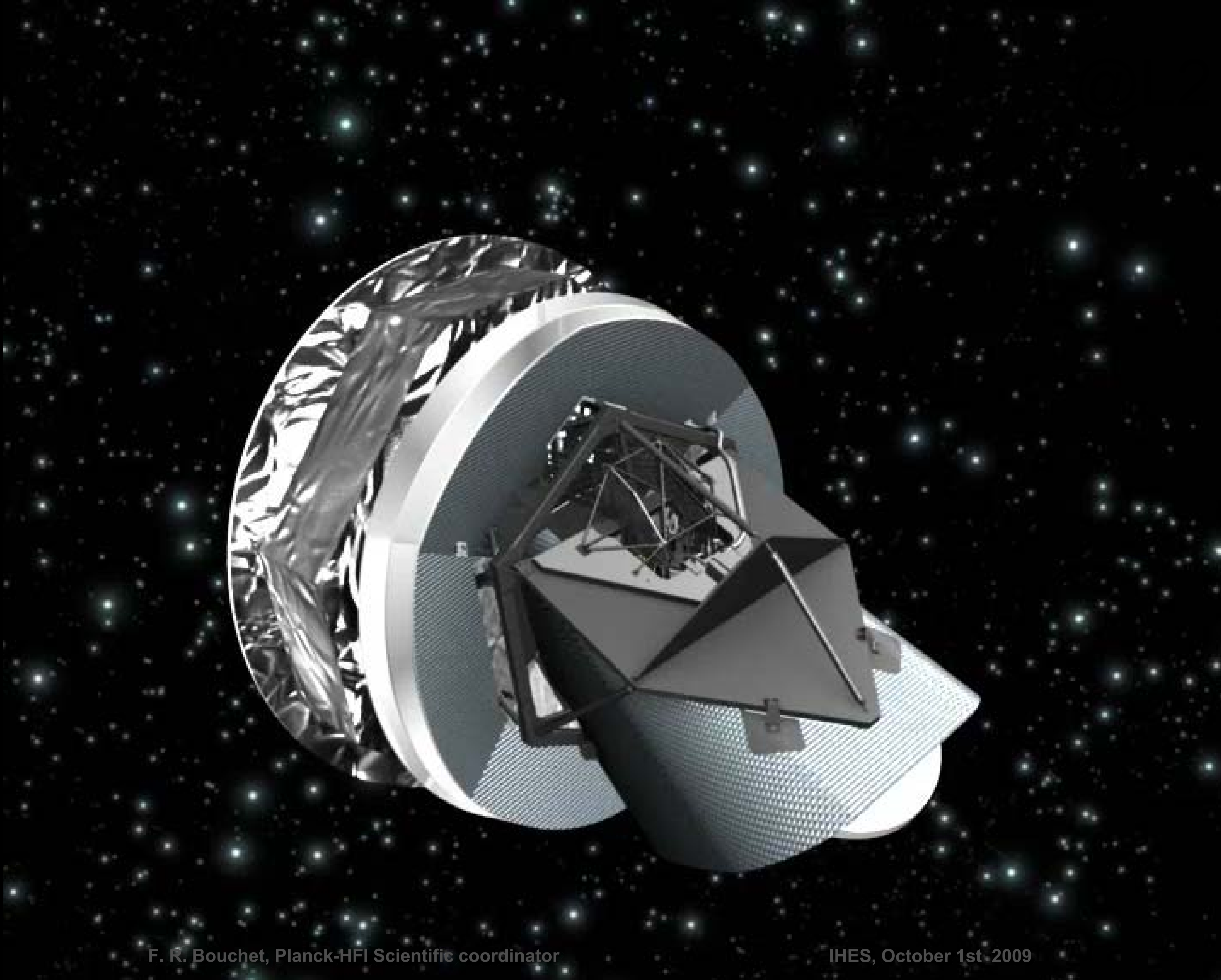
Kourou

After a few more nerve – wracking delays, we finally lost sight of Planck for ever



May 14th 2009: 15 yrs on 440t of powder

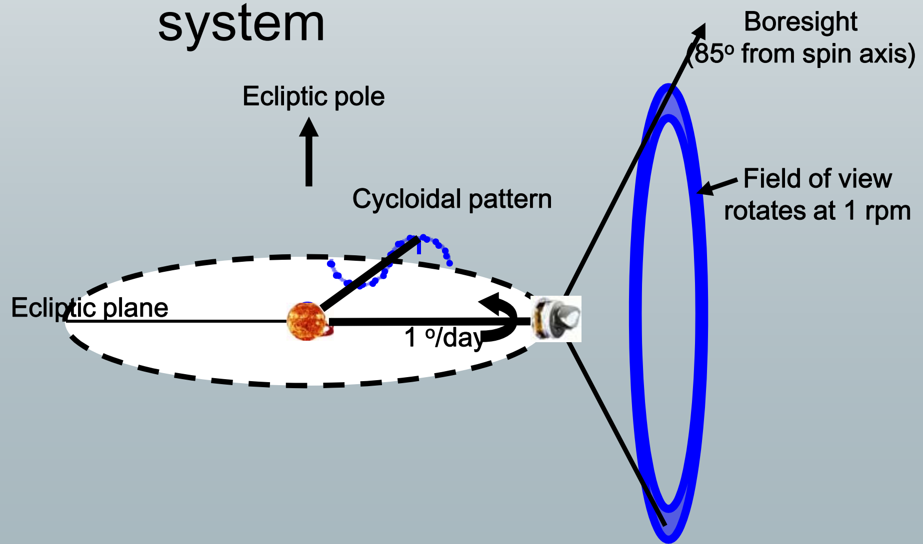
Observational site: halo orbit @ L2



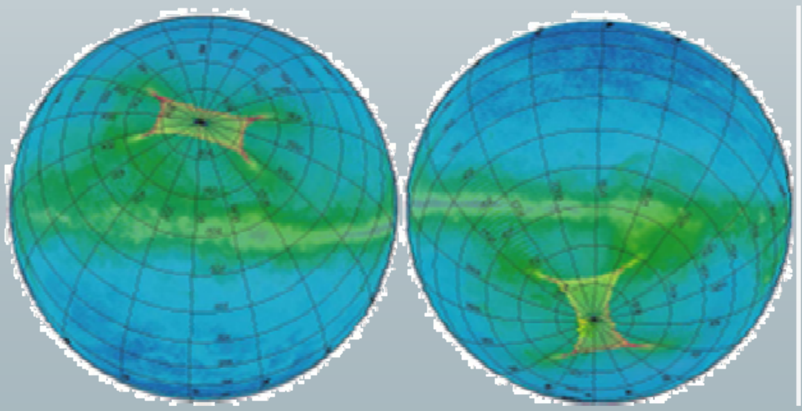
Baseline scanning strategy

1 rpm middle-ground
Constraints:

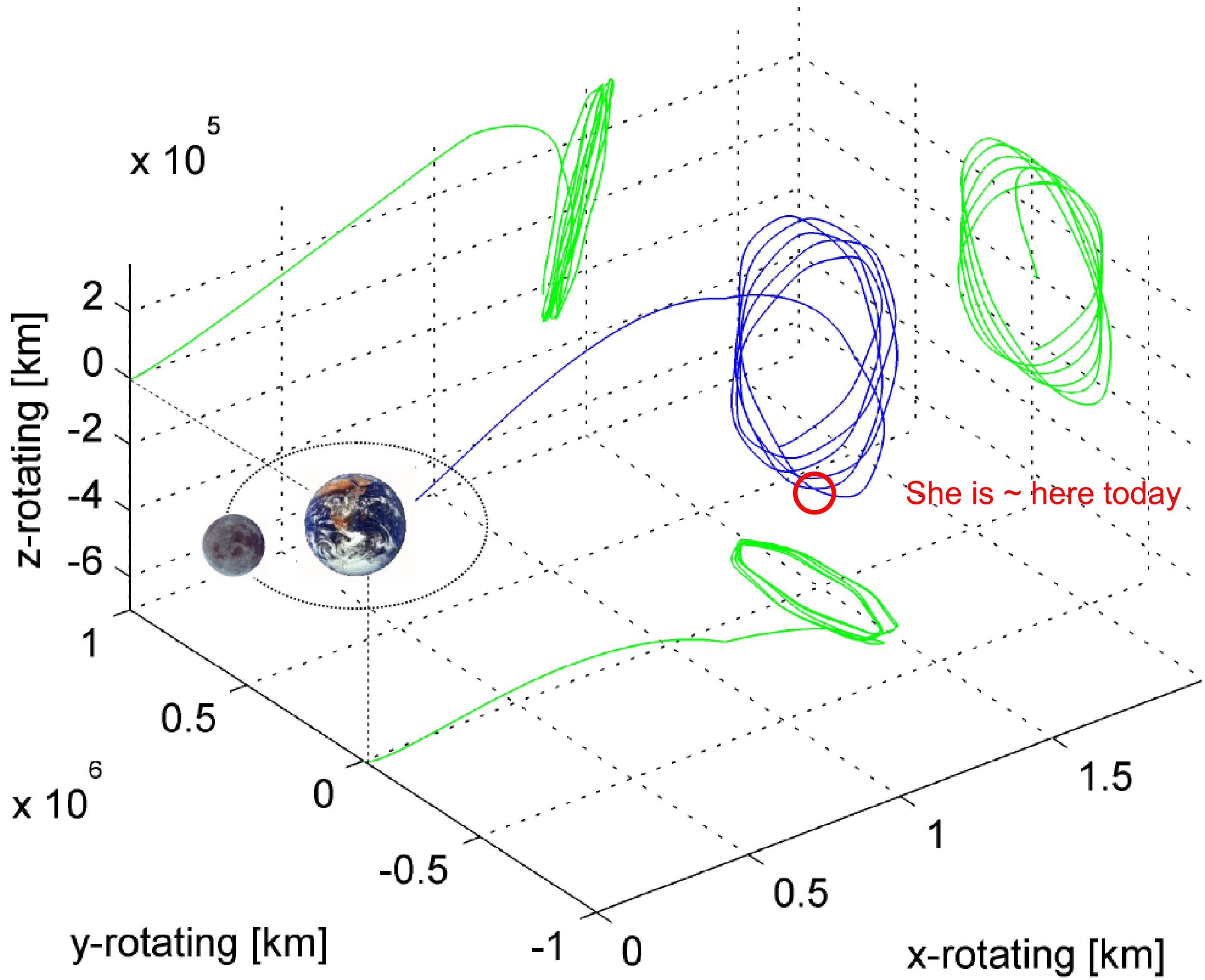
- High data rate & fixed antenna → spin axis must remain within ~10^0 of earth
- Excellent radiative cooling & coolers → no warm surface can be seen by telescope, baffle or any part of FP
- Spin stabilised attitude control system



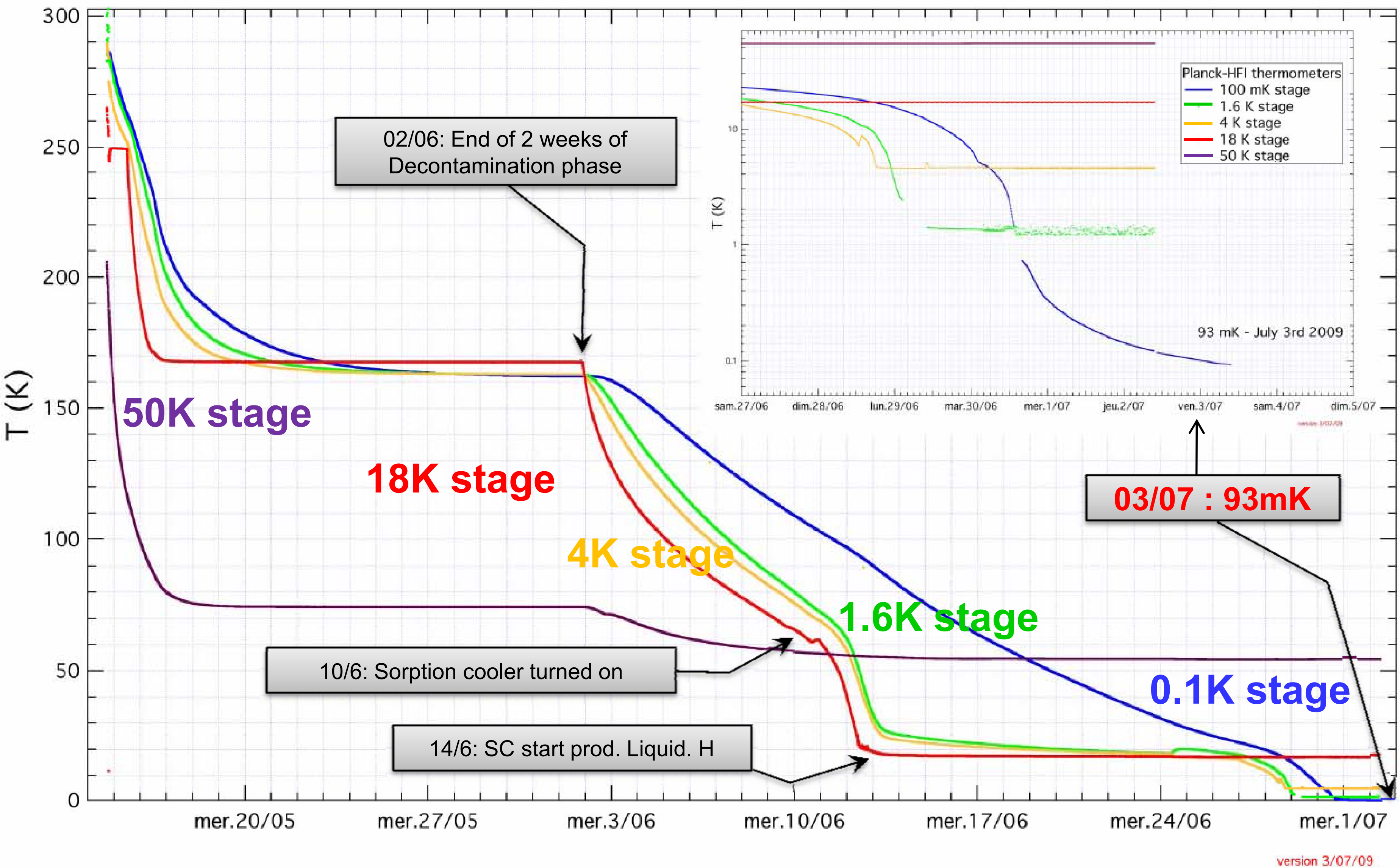
- Slow Precession: circular motion of the spin axis around anti-Sun direction, inclination of the solar array remains fixed
  - *precession circle 7.5 degrees*
  - *period of 6 months*
  - *phase depends on launch date, determines the position of the deep b, as well as the alignment w.r.t. the dipole*
- Baseline parameters :
  - *step size = 2 arcmin*
  - *dwell time = 45 min*



Planck is in L2 orbit since July



Planck is cool...



Calibration & Perf. Verification phase

- Detector found to behave exactly 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, ie close to 5 sky surveys

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

➔The first All-sky Planck survey is ongoing!

WHAT, WHEN

- Launch from Kourou was on May 14th – PERFECT!
- Travel to L2 and cool till end of June 2009, Verifications & tuning till mid August

NOW

15 days of First Light Survey as ultimate test,
14 months of operations to complete 2 surveys (12/10)

- End 2010 : "Early Release Point Source Catalogue" (Herschel followup)
- End 2012 : First public data release by ESA of 14 month of data + ~50 papers
  - *Clean calibrated time-ordered data*
  - *Full sky maps in (HFI 6+ LFI 3) frequencies*
  - *Maps of identified astrophysical components (1st Generation)*
    - CMB
    - Galactic Emissions (sync. Free-free, dust)
    - Extragalactic sources catalogue
  - *CMB characterisation (C(l), likelihood…)*

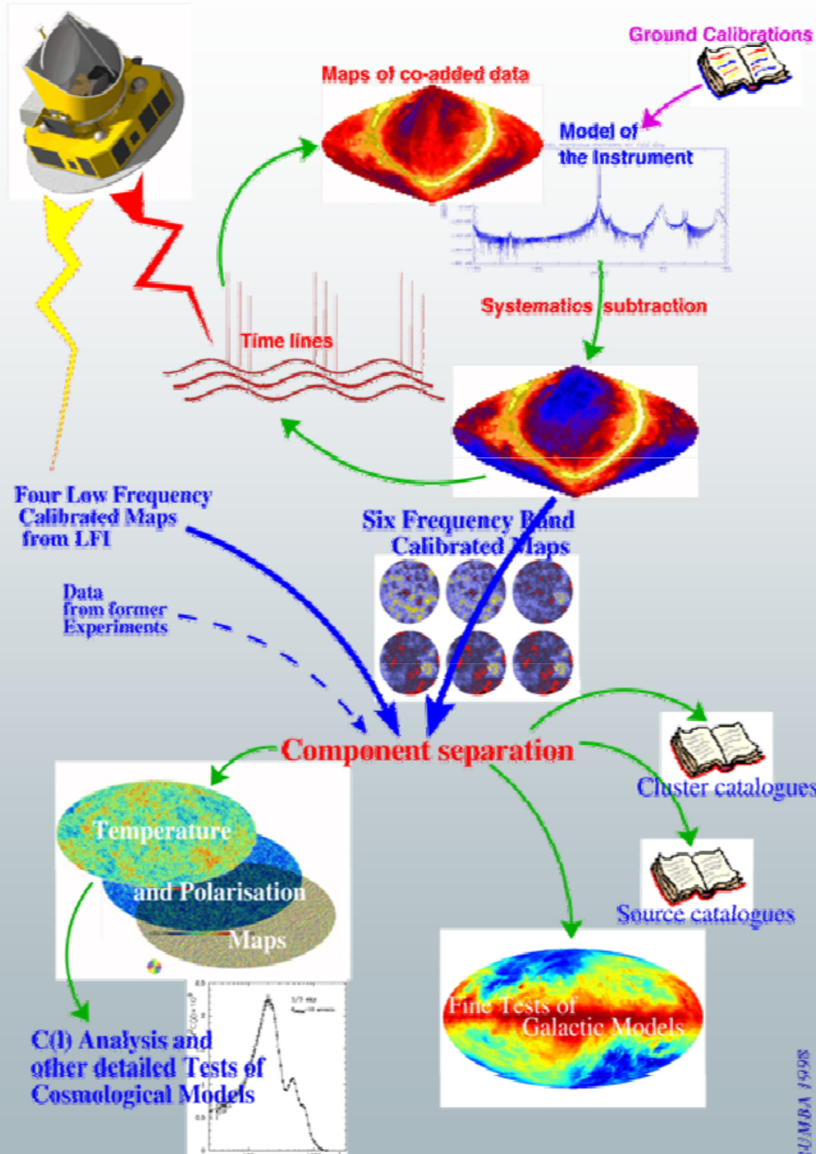
- ≥ 2013 : Potential second data release (helium permitting)
- Intermediate products, ~ every 6 months, for scientific exploitation/preparation by the Planck collaboration during the operations (1.2 yr) and the analysis (1yr) and proprietary time (1 year).

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

Data reduction



Measurements (HFI)
~10 000 /s ~3 x 10^{11}/an (~2 TB/an w. aux)

Measurement Model including systematics

ERCSC

57 Clean calibrated TOIs (57 x 30GB)
14 maps (~ 14 x 50 x 10^6 pixels) &
Statistical characterization

3 x 3 maps from LFI (lower res.)

> 10^4 sources

6 x 3 component maps
(CMB+SZ+CIRB+Sync+Free+Dust)

4 angular power spectra (~4x200) + Cov.Matrices

~ 20 cosmological parameters ?

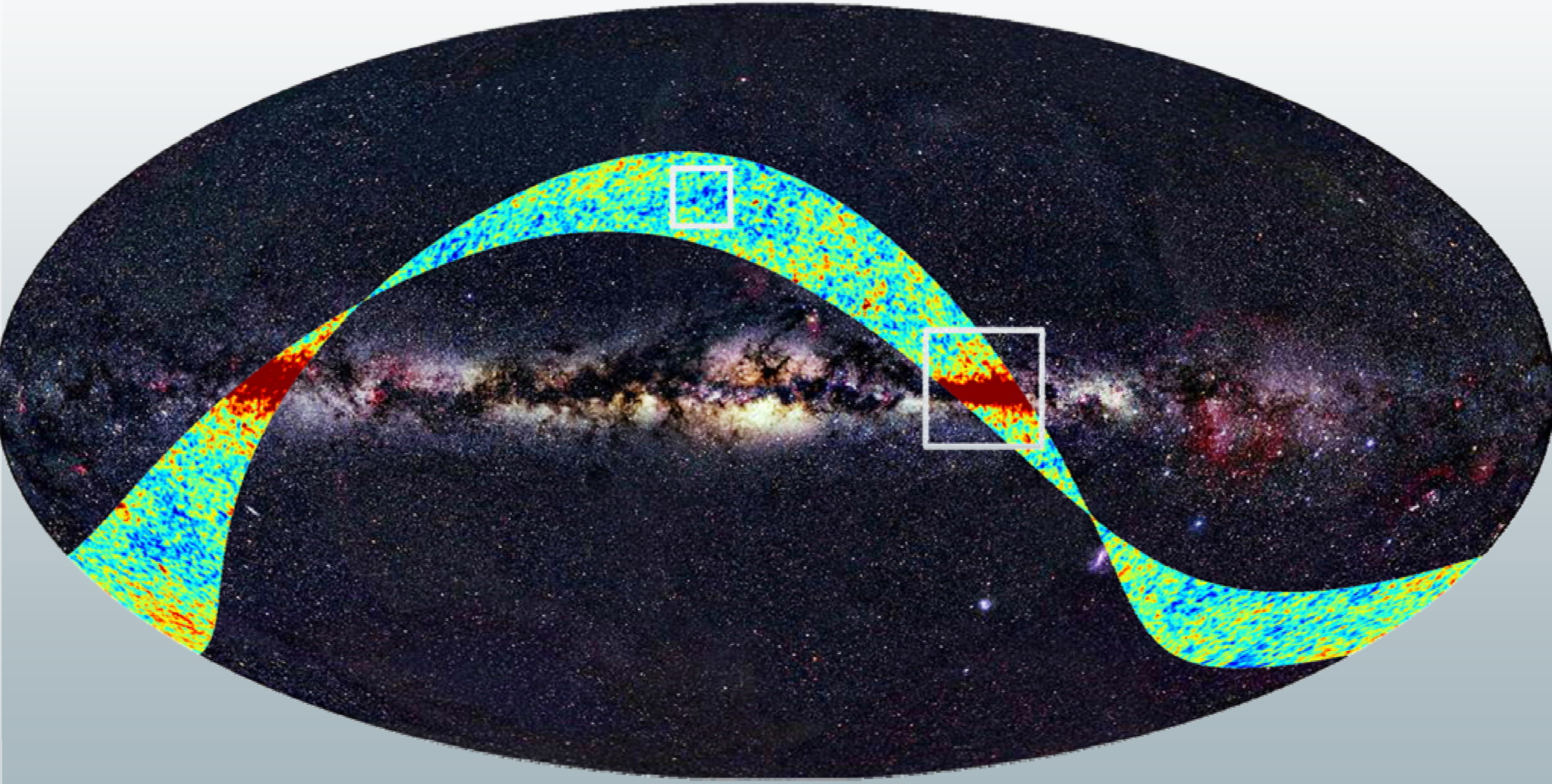
Data Processing Center preparation

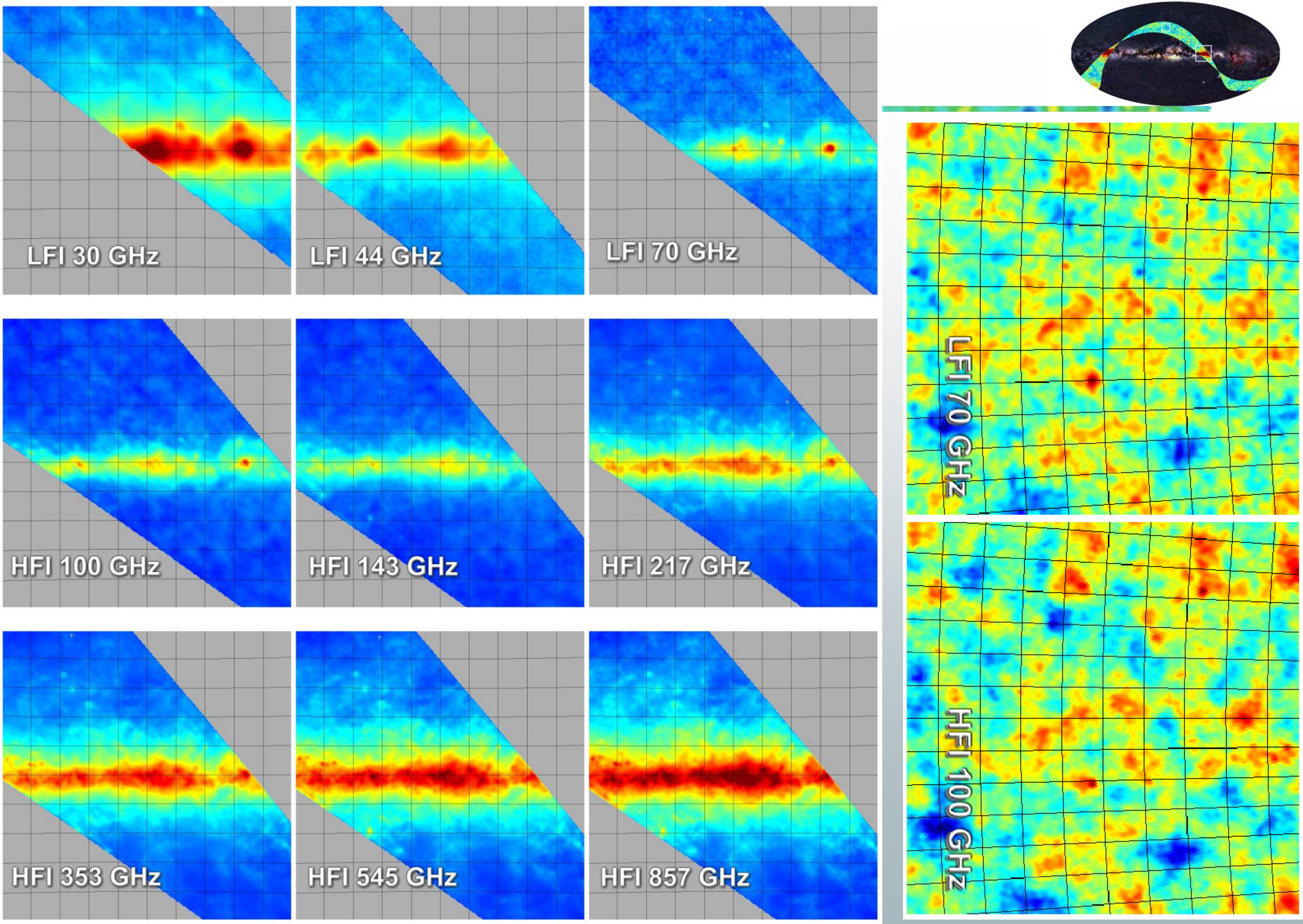
- One for each instrument,
  - *with exchange at the level of clean calibrated timelines for cross-checks& validation*
- Developed an ad-hoc **information management infrastructure**
  - *with requirement of traceability and efficiency*
- Developed a **simulation pipeline to** produce a realistic rendering of data
  - *plausible sky + all known instrumental non-idealities*
- Established a pre-flight **minimal processing pipeline;**
  - *will indubitably need be upgraded, but only where/when necessary.*
- Very active (mostly) internal **R&D** continuously improves
  - *processing steps (methods/codes challenges on speed, accuracy, robustness on benchmark data, including blind tests)*
  - *Assessment of magnitude of residual systematic effects and various ways to minimize them*
    - (e.g. asymmetric beams, cross-polar leakage, finite knowledge of polariser angles, limited accuracy of calibration sources, etc)

➔ pipelines churned out maps only hours after data ingested in the reference database

First light survey

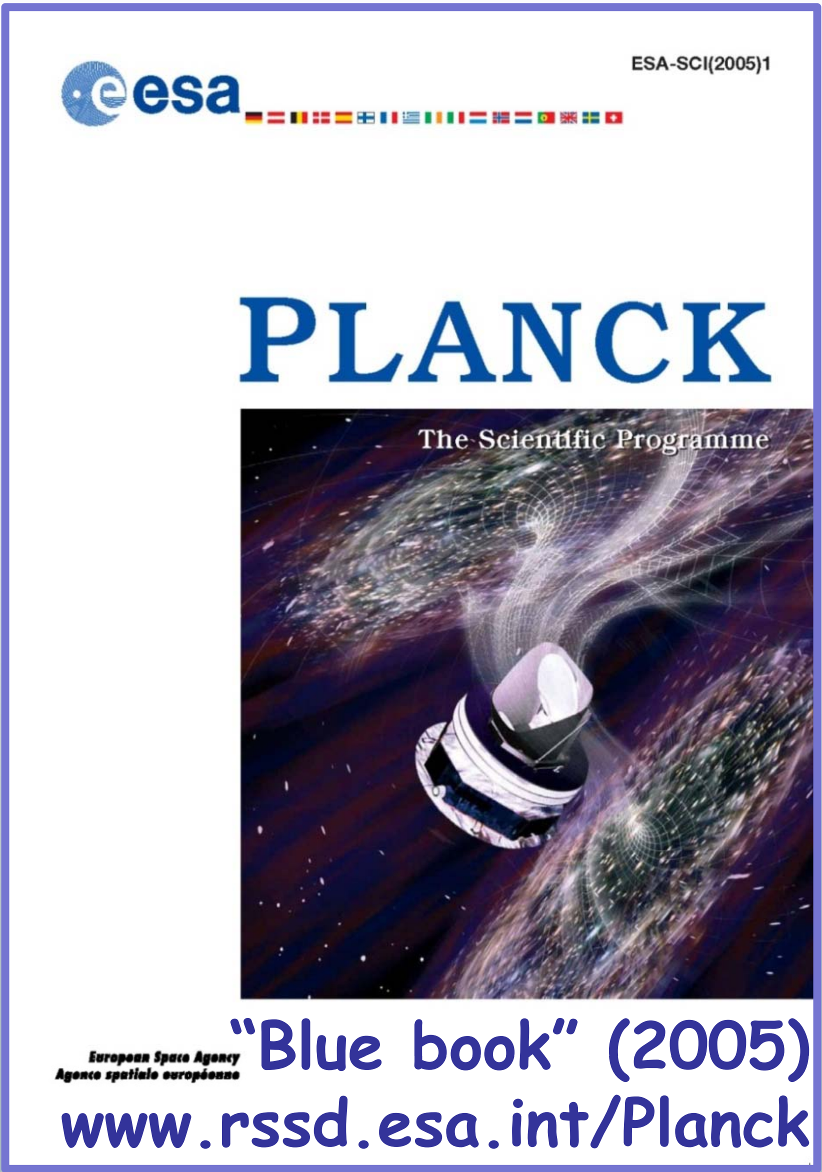
15 days of normal operations covering a ~15^{o} strip like this




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

Broad science

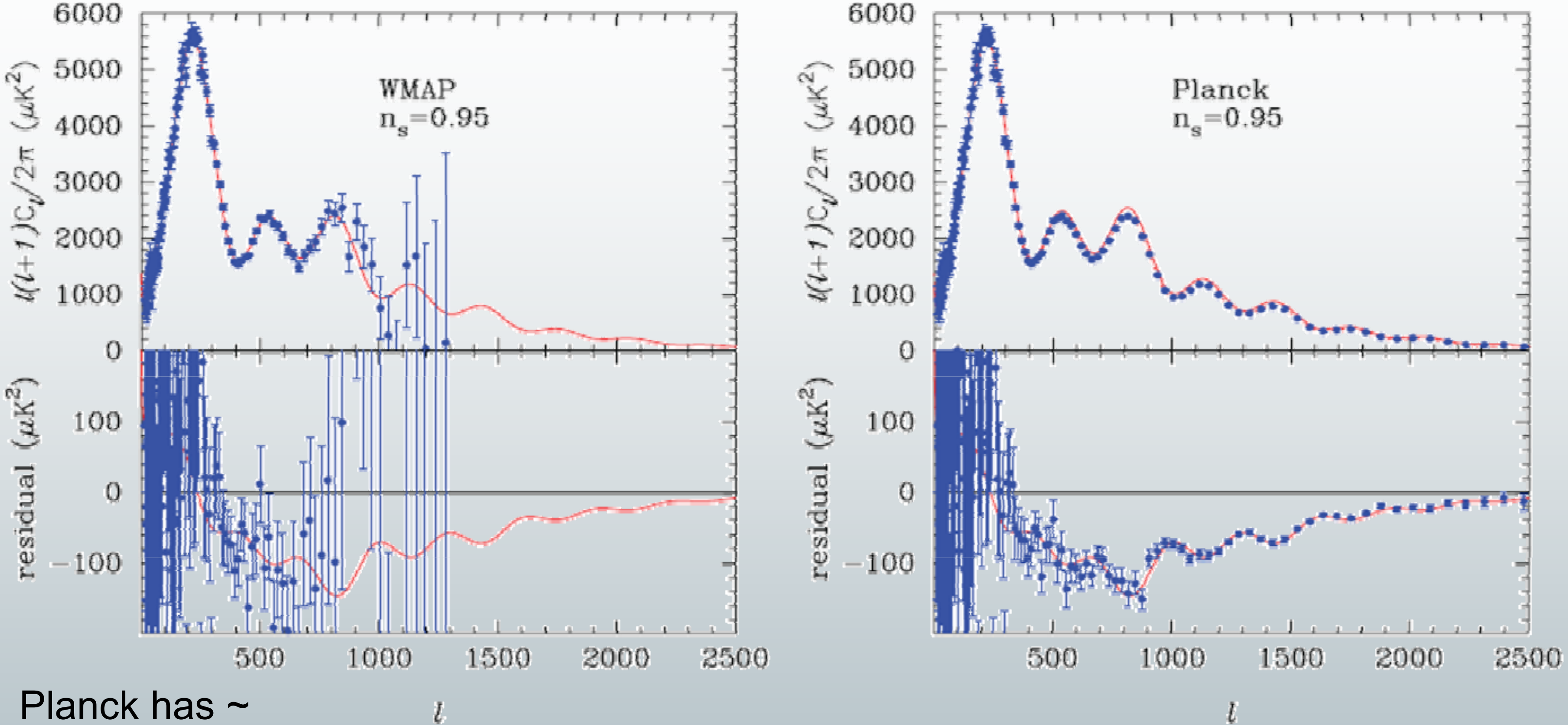
- Primary anisotropies
  - *Cosmological parameters, fundamental physics probes, non-Gaussianity*
- Secondary anisotropies
  - *ISW, Gravitational lensing, reionisation, galaxy clusters*
- Extragalactic sources
  - *Radio-sources, dusty galaxies and their background*
- Galactic & solar system



Some non-CMB science with Planck

- Sunyaev-Zeldovich selected sources
  - *Measurement of y in > 10^3 galaxy clusters*
  - *Cosmological evolution of clusters to z ~1*
  - *H_0 and X-ray measurements, gas properties*
  - *Bulk velocities on scales > 300*
- Extragalactic sources and background
  - *SEDs of IR *& radio-galaxies*
  - *SEDs of AGN's QSO's, blazars*
  - *Evolution of galaxy counts to z > 1*
  - *Far Mpc-IR backfround fluctuatiuons*
- Maps of Milky Way from 30 to 1000 GHz
  - *|Dust properties, Cloud & cirrus morphology*
  - *Star forming regions, cold molecular clouds*
  - *Galaxy-scale distribution of gas and dust*
  - *Polarisation based science, eg Galactic magnetic field*

TT Forecast



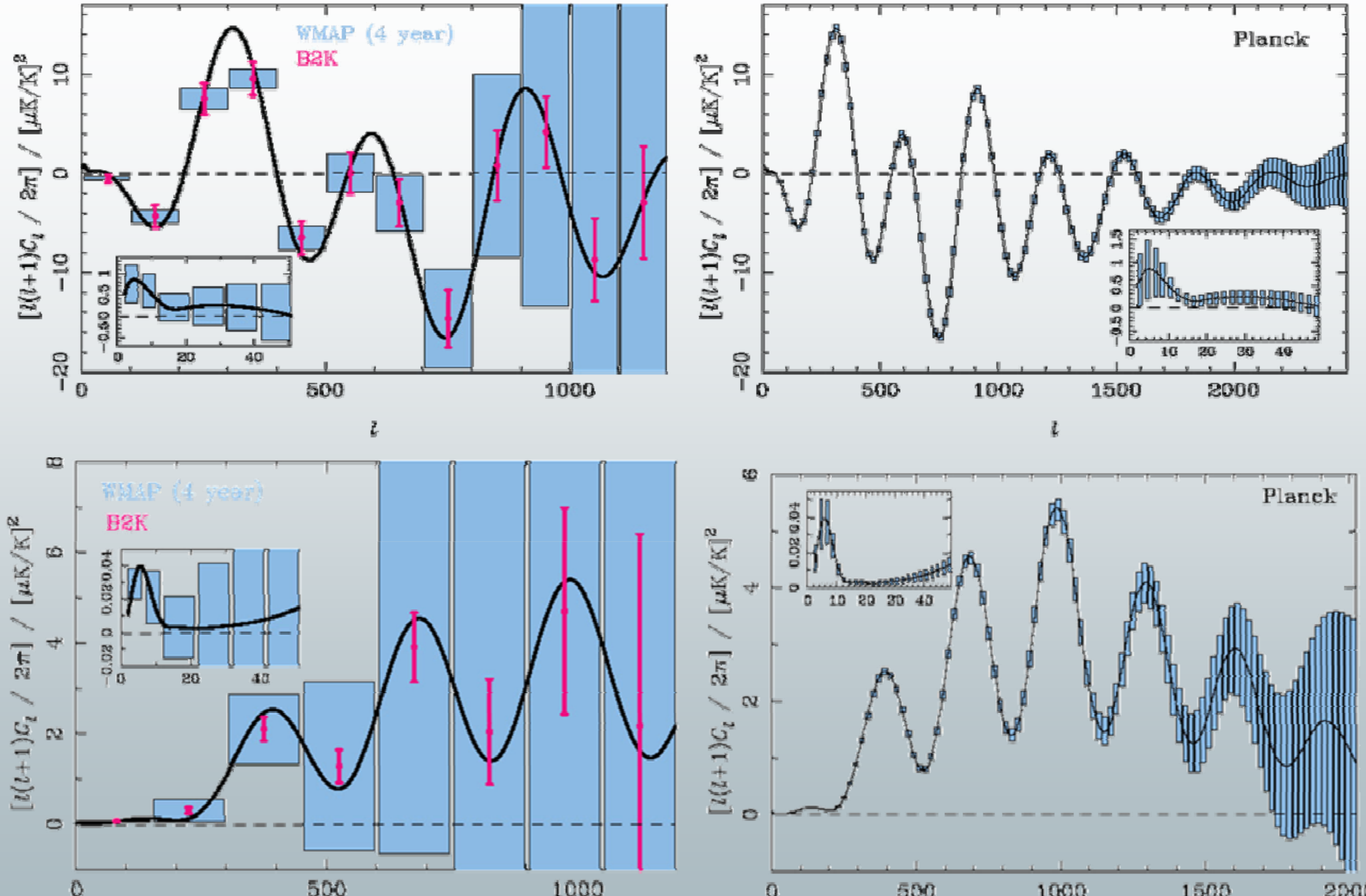
Planck has ~
- *25 × the sensitivity of WMAP*
- 3 × *the angular resolution*

→ Planck limited by cosmic variance only well into the damping tail.

WMAP measures ~10% of the modes with SNR ≥ 1. Planck will get them all.

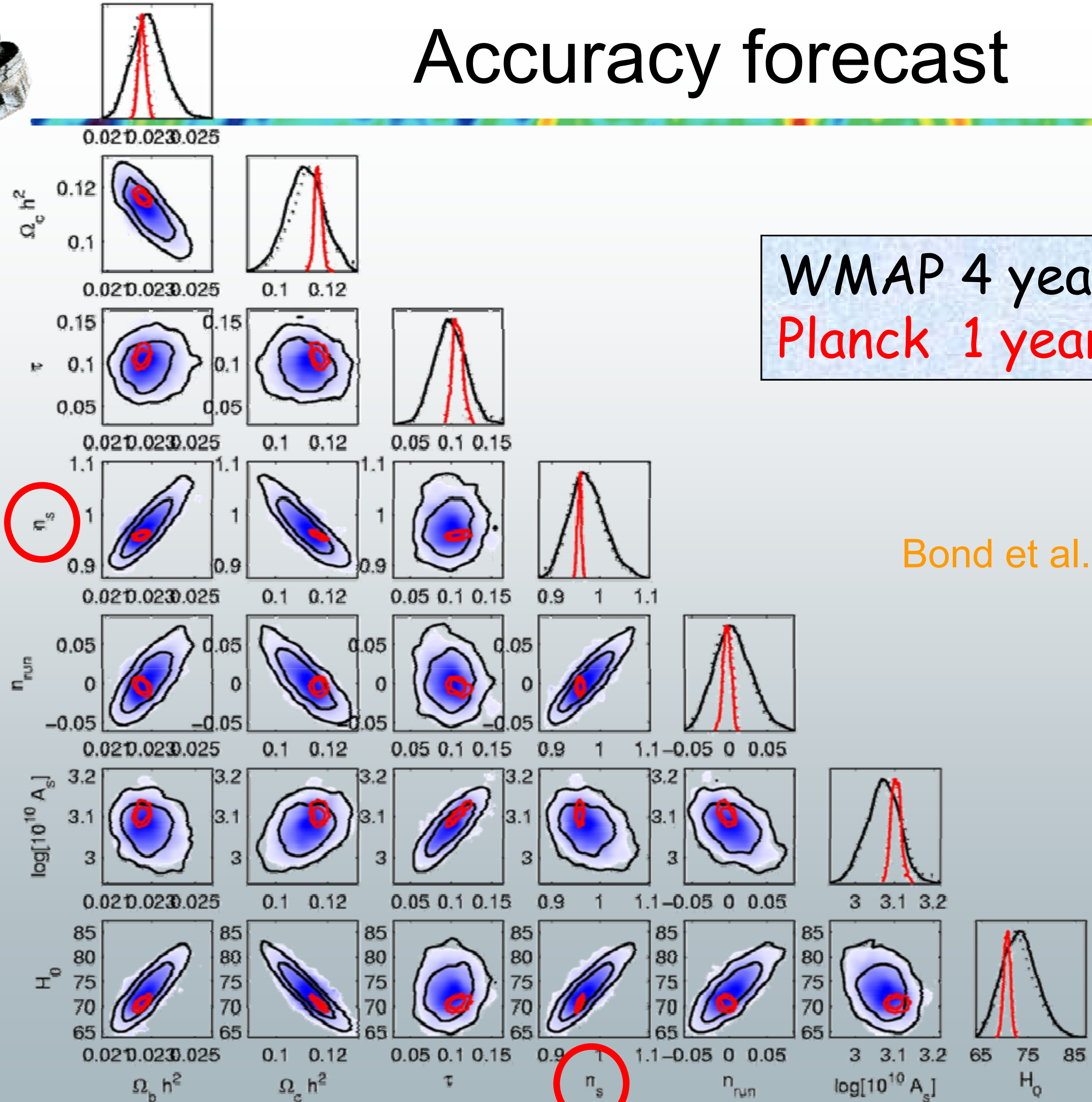
Top: samples drawn from a LCDM model w. n_s=0.95 versus an n_s=1 (red line) one.
Bottom: residuals (red is now expectation)

TE & EE forecasts



Planck will measure polarisation about as well as WMAP measure temperature

Accuracy forecast



WMAP 4 years (94 GHz)
Planck 1 year (143 GHz)

Bond et al.astroph/0406195

Inflation

- **Solves the flatness/horizon problems if the early universe inflates by factor ~10^{30}.**
- **Cosmological perturbations arise from quantum fluctuations, evolve classically.**

$$P_\phi(k) \simeq \hbar \left(\frac{H}{2\pi}\right)^2$$

$$\rightarrow \quad P_\mathcal{R} \simeq \frac{\hbar}{4\pi^2}\left(\frac{H^4}{\dot\phi^2}\right)^2_{k=aH} \qquad \text{scalar}$$

$$\rightarrow \quad P_h \simeq \frac{2\hbar}{\pi^2}\left(\frac{H}{m_\mathrm{Pl}}\right)^2_{k=aH} \qquad \text{tensor}$$

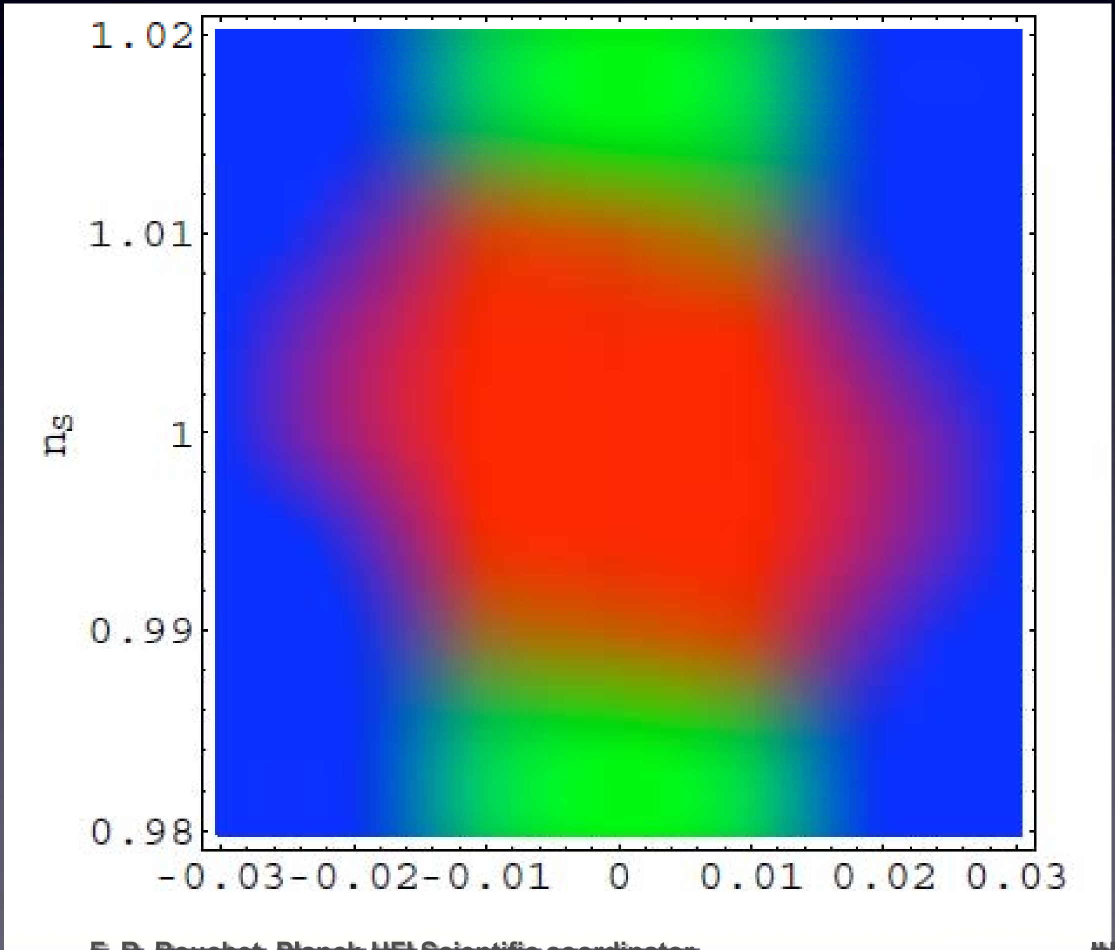
- **Don't know the dynamics of inflation: parameterize weakly scale-dependent functions with a few numbers to pin down observationally.**

$$P_\mathcal{R}(k) \simeq A_s\left(\frac{k}{k_0}\right)^{n_s-1} \qquad P_h(k) \simeq A_t\left(\frac{k}{k_0}\right)^{n_t} \qquad r = \frac{P_h(k_0)}{P_\mathcal{R}(k_0)}$$

Model selection forecasts for Planck

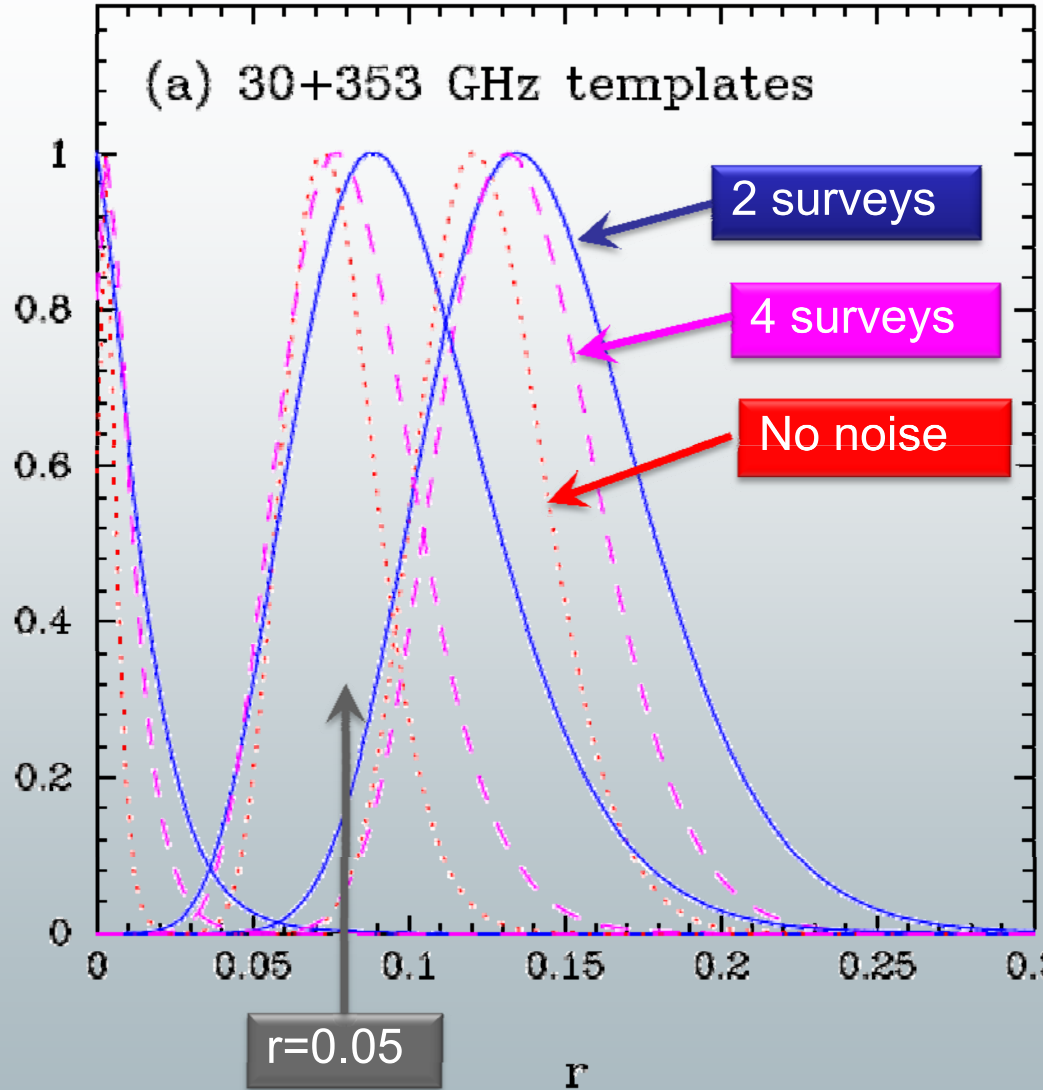
Pahud, Liddle, Mukherjee, and Parkinson, MNRAS, astro-ph/0701481

Zones of certainty/uncertainty for *n* and α=dn/dlnk.



With 4 surveys...

- A simplified analysis
  - *using for CMB the 70+100+143+217GHz (goal is .5μK.deg)*
  - *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 r values
- Interesting for high field inflation models (e.g. r~0.13 for n_s=.97)



0903.0904 GPE & Gratton

ISOCURVATURE MODES

∏ $=8.10^{-11}$ ∏ $=7.10^{-24}$

	MAP T adia only	MAP TP adia only	MAP T all modes	MAP TP all modes	PLANCK T adia only	PLANCK TP adia only	PLANCK T all modes	PLANCK T+P all modes	PLANCK TP all modes
$\delta h/h$	12.37	7.42	175.84	20.40	9.93	3.69	40.13	7.31	4.36
$\delta\Omega_b/\Omega_b$	27.76	13.34	325.38	28.57	19.37	7.26	68.85	14.42	8.61
$\delta\Omega_k$	9.79	2.72	75.32	4.55	4.92	1.83	20.56	3.59	2.18
$\delta\Omega_\Lambda/\Omega_\Lambda$	12.92	5.02	123.63	18.53	2.74	1.21	5.93	2.45	1.49
$\delta n_s/n_s$	7.02	1.62	89.89	6.53	0.73	0.37	3.92	0.90	0.70
τ_{reion}	37.39	1.81	104.81	2.23	8.25	0.41	35.35	0.74	0.56
$\langle NIV, NIV\rangle$	..	..	114.34	11.47	..	..	43.45	1.36	1.14
$\langle BI, BI\rangle$	..	..	573.46	29.71	..	..	53.29	6.16	4.23
$\langle NID, NID\rangle$	..	..	351.79	29.87	..	..	19.18	4.77	2.37
$\langle NIV, AD\rangle$	..	..	434.70	44.06	..	..	121.59	8.21	4.69
$\langle BI, AD\rangle$	..	..	1035.02	59.25	..	..	58.75	15.03	8.97
$\langle NID, AD\rangle$	..	..	1287.60	67.49	..	..	114.39	13.87	5.77
$\langle NIV, BI\rangle$	..	..	601.70	32.29	..	..	46.91	7.72	3.67
$\langle NIV, NID\rangle$	..	..	744.00	46.46	..	..	80.01	7.55	2.97
$\langle BI, NID\rangle$	..	..	534.32	39.11	..	..	100.97	7.56	4.60

TABLE I. This table indicates the one sigma percentage errors on cosmological parameters and isocurvature mode amplitudes anticipated for the MAP and PLANCK satellite experiments. In the column headers, T denotes constraints inferred from temperature measurements alone, TP those from the complete temperature and polarisation measurements, and T+P those inferred if temperature and polarisation information is used separately without including the cross-correlation.

Bucher, Moodley, Turok, astroph/0012141

NB: Still assuming simple scale-invariant (initial) P(k)…

(Can add LSS, or HST+SN1A to improve Ω_k, cf. Dunkley et al. astroph/0507473, but reliance on external data)

CMB core (2pt) Science with Planck

- Of course Planck will improve on standard constraints
  - *Census (Omega's)*
  - A_s, n_s *(amplitude and log. slope of scalar fluct. Spectrum)*
- And less minimally:
  - r *(~A_T/A_s, and also n_T, $dn_s/dlnk$, slow-roll consistency check)*
  - *Isocurvature modes*
  - $\Sigma\, m_\nu$
  - N_{eff}
  - *w1, w2...*
  - $G\mu$
- Planck lesser reliance on external dataset (often with complicated astrophysical processing) will allowing cross-checks of parameters and assumptions and provide a foundation for future dedicated project (e.g. 4 on w)

Departures from Isotropic Gaussian...

- A broad topics...
- Will indubitably be found owing to processing weaknesses, since the observed sky is NG
  - *Well known astrophysical sources (point sources, Galaxy)*
  - *Secondary effect (kinetic effect, Lensing)*
  - *Inhomogeneous/correlated noise, systematic effects...*
- We will search for the signature of
  - *non-trivial topologies*
  - *primordial magnetic field*
  - f_{NL} *(see next)*
  - *topological defects, eg cosmic strings*
  - *New physics*

f_{NL}

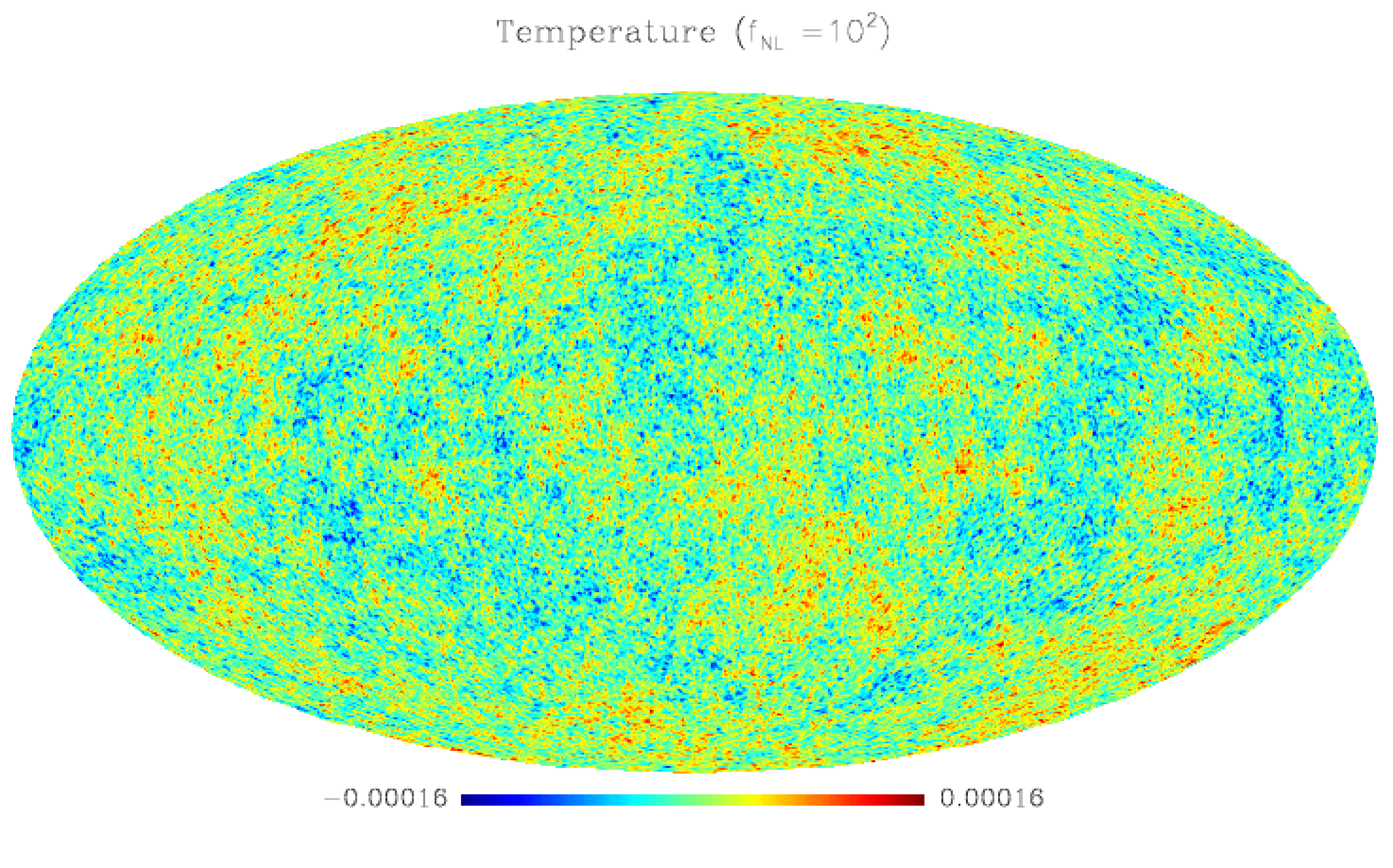
- Parameterize non-Gaussianity as $\Phi=\Phi_L+\mathbf{f_{NL}\Phi_L^2}$ as in (*Salopek & Bond 1990)*
  - *Φ_L~10^{-5} is a Gaussian, linear curvature perturbation in the matter era*
  - *Therefore, f_{NL}<100 means that the distribution of Φ is consistent with a Gaussian distribution to ~100×$(10^{-5})^2/(10^{-5})$=**0.1% accuracy** at 95% CL.*

- Non-Gaussianity from Inflation
  - *f_{NL}~ 0.05 canonical inflation (single field, couple of derivatives) (Maldacena 2003, Acquaviva etal 2003)*
  - *f_{NL}~ 0.1--100 → higher order derivatives*
    - ~100: DBI inflation (Alishahiha, Silverstein and Tong 2004)
    - ~0.1 : UV cutoff (Creminelli and Cosmol, 2003)
  - *f_{NL} >10 curvaton models (Lyth, Ungarelli and Wands, 2003)*
  - *f_{NL} ~100 ghost inflation (Arkani-Hamed et al., Cosmol, 2004)*
  - *...   Your name here*

- Of course, oversimplified, propagation corrections...

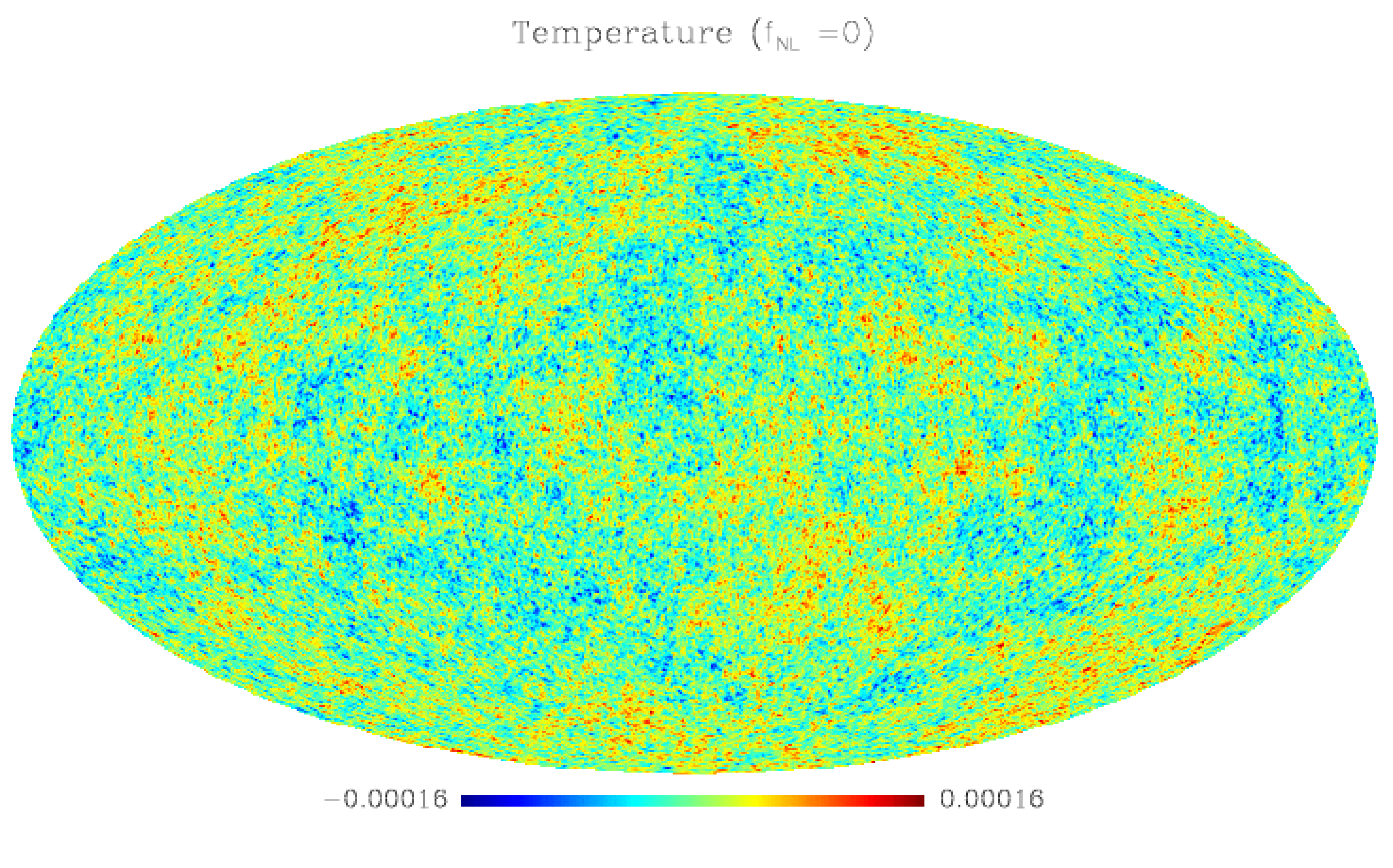
f_{NL}= 100

Positive f_{NL} = More Cold Spots



Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

$f_{NL} = 0$



Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

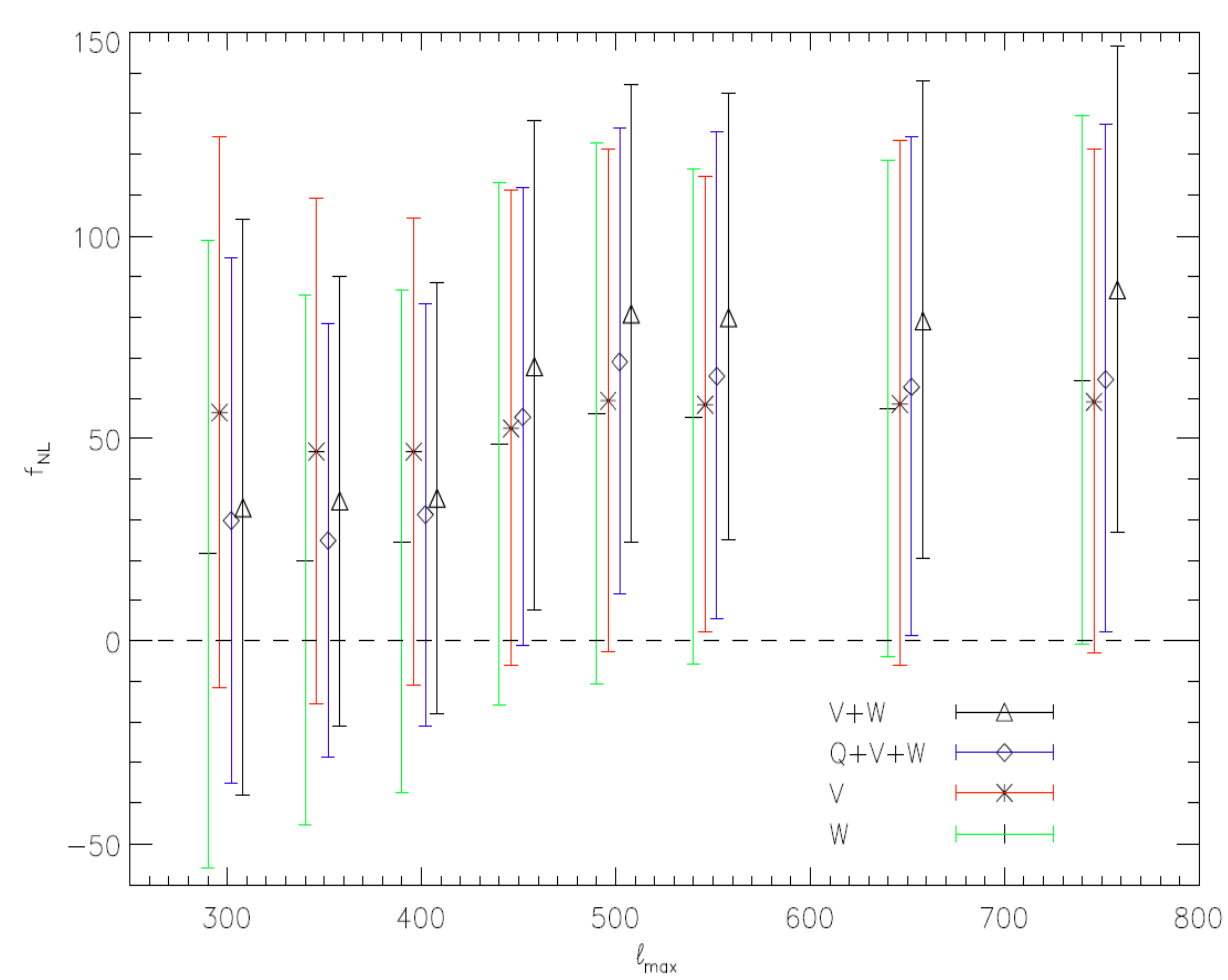
f_{NL} Bi-spectrum

- Natural probe
  - $\langle T^3 \rangle \propto 0 + f_{NL}\Phi_L^{\,3}$, $\langle T^4 \rangle \propto \langle T^2 \rangle^2 + f_{NL}\Phi_L^{\,4}$ +HOT
  - *Nearly all the f_{nl} information (Babich 2005)*

- Polishing (& using) the estimator
  - *Komatsu & Spergel 2001 – CMB bispectrum from fNL*
  - *Komatsu, Wandelt, Spergel, Banday, Gorski 2001 – fNL from COBE*
  - *Komatsu Spergel & Wandelt 2003 – fast fNL estimator*
  - *Komatsu et al (WMAP team) 2003 – WMAP1 analysis using KSW*
  - *Babich and Zaldarriaga 2004 – temperature + polarization*
  - *Creminelli, Nicolis, Senatore, Tegmark, Zaldarriaga 2006 – introduce linear term to improve KSW estimator*
  - *Spergel et al (WMAP team) 2006 – WMAP3 analysis using KSW*
  - *Creminelli, Senatore, Tegmark, Zaldarriaga 2006 – apply cubic + linear term to WMAP3 data*
  - *Yadav Komatsu & Wandelt 2007 – KSW generalized to T+P*
  - *Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007 – calibrate YKW estimator against non-Gaussian simulations*
  - *Yadav, Komatsu, Wandelt, Liguori, Hansen, Matarrese 2007 – Creminelli et al. corrected and generalized to T+P*

- Till recently only upper limits
  - $-58 < f_{NL} < 137$ *(95%) WMAP 1 yr*
  - $-54 < f_{NL} < 114$ *(95%) WMAP 3 yr refined to* $-36 < f_{NL} < 100$ *(95%) by Creminelli etal 06*
  - *NB: this is for the local form (ekpyrotic, curvaton), weaker constraints exist for equilateral configuration (Ghost condensation, DBI, low speed of sound models)*

Tantalising evidence ?



Is it:

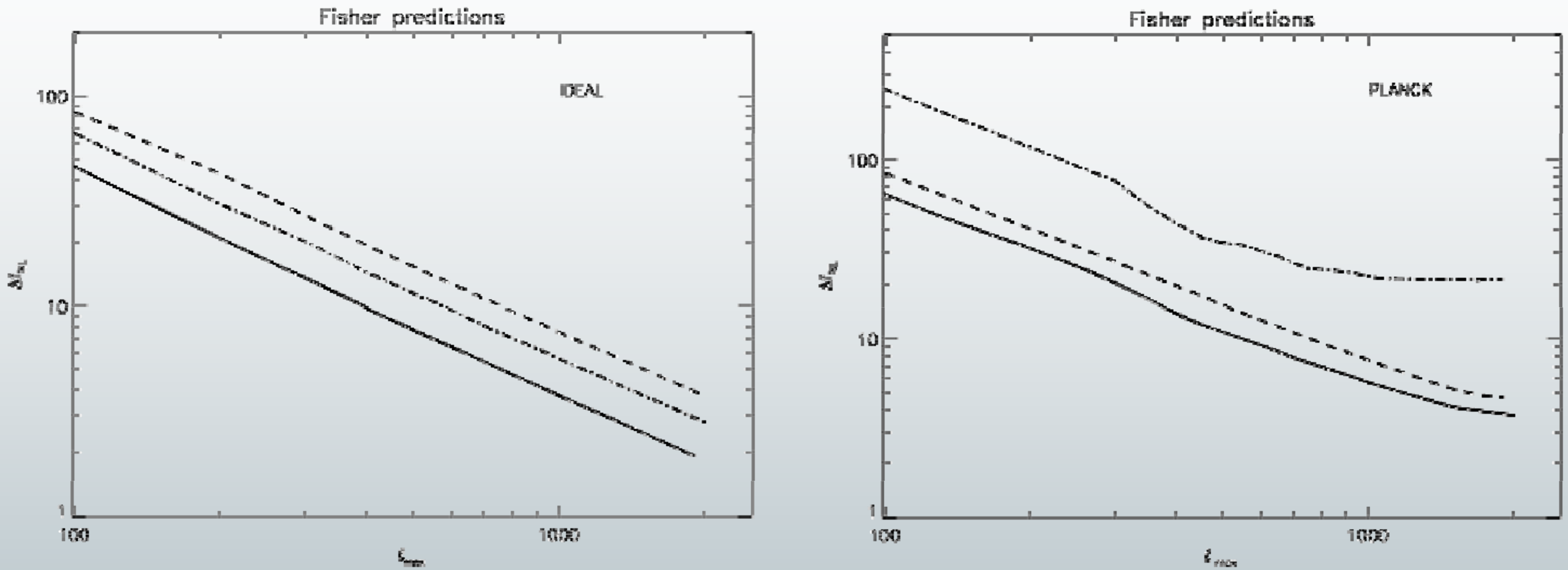
- Instrument systematics?
- Foregrounds?
- Secondary anisotropies?
- Rediscovery of other non Gaussian signals?
- Noise fluctuation?
- Primordial?

$27 < f_{NL}^{(local)} < 147$ (95%CL, a 2.5σ result)

Yadav & Wandelt Phys. Rev. Lett. 100, 181301 (2008)

Komatsu et al. have more generous error bars...

f_{NL} quest



- Ideal CMB experiment, using temperature & polarization could reach $\Delta f_{NL} \sim 1$
- For Planck, the Cramer-Rao limit is $\Delta f_{NL} \sim 3$.

Yadav, Komatsu and Wandelt, astro-ph/0701921

NB: WMAP-8yr could reach ~21 (/30 w. 3yr data)

Inflation...

- S-dimensional assisted inflation
- assisted brane inflation
- anomaly-induced inflation
- assisted inflation
- assisted chaotic 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
- 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
- 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
- Hagedorn inflation
- higher-curvature inflation
- hybrid inflation
- hyperextended inflation
- induced gravity inflation
- intermediate inflation
- inverted hybrid inflation
- isocurvature inflation.....................

Conclusions

Planck is in routine operations

Performances are as expected or better

Yes we can! (detect deviations from minimal model)