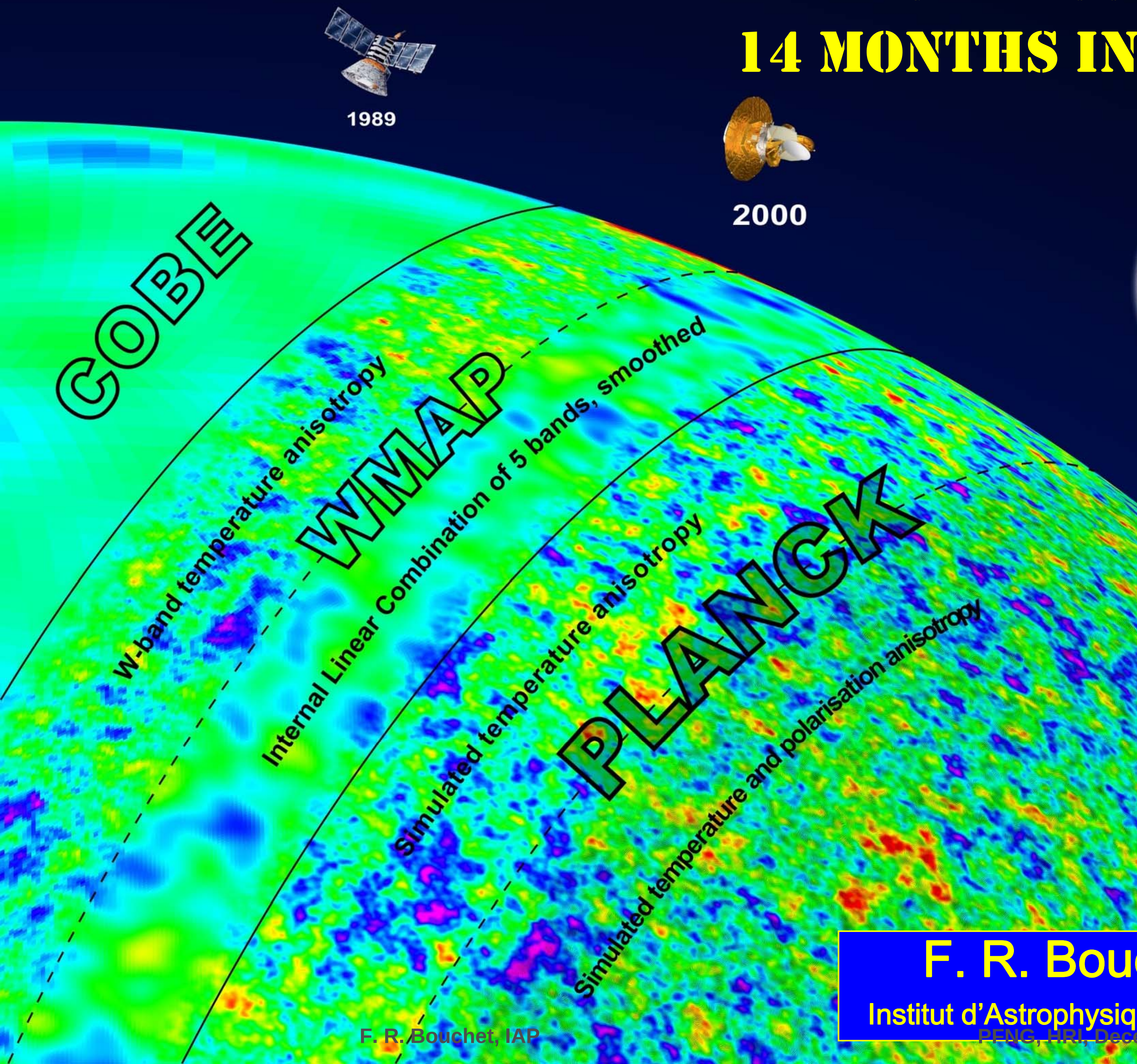
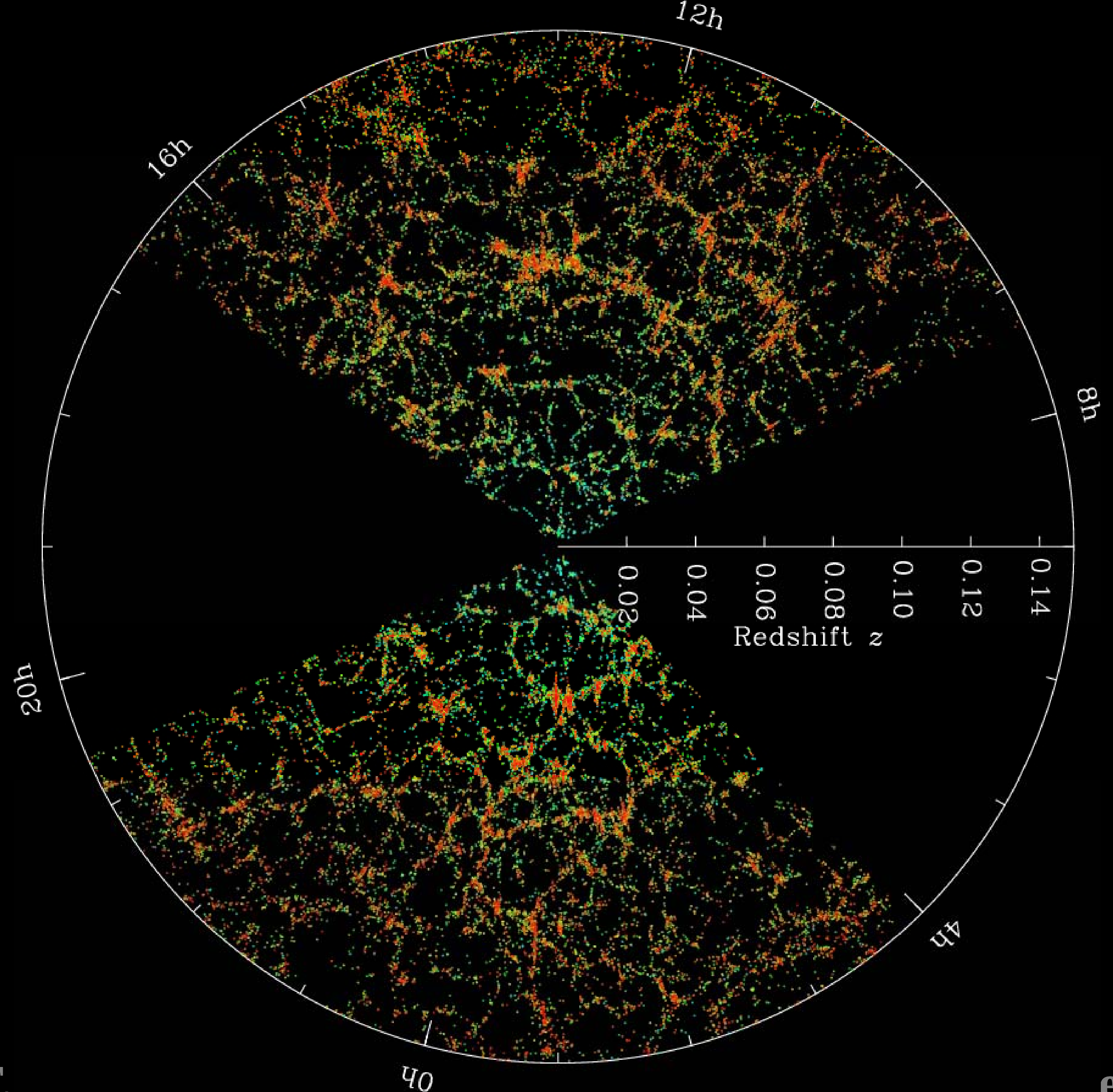
THE PLANCK MISSION – AFTER 14 MONTHS IN OPERATION



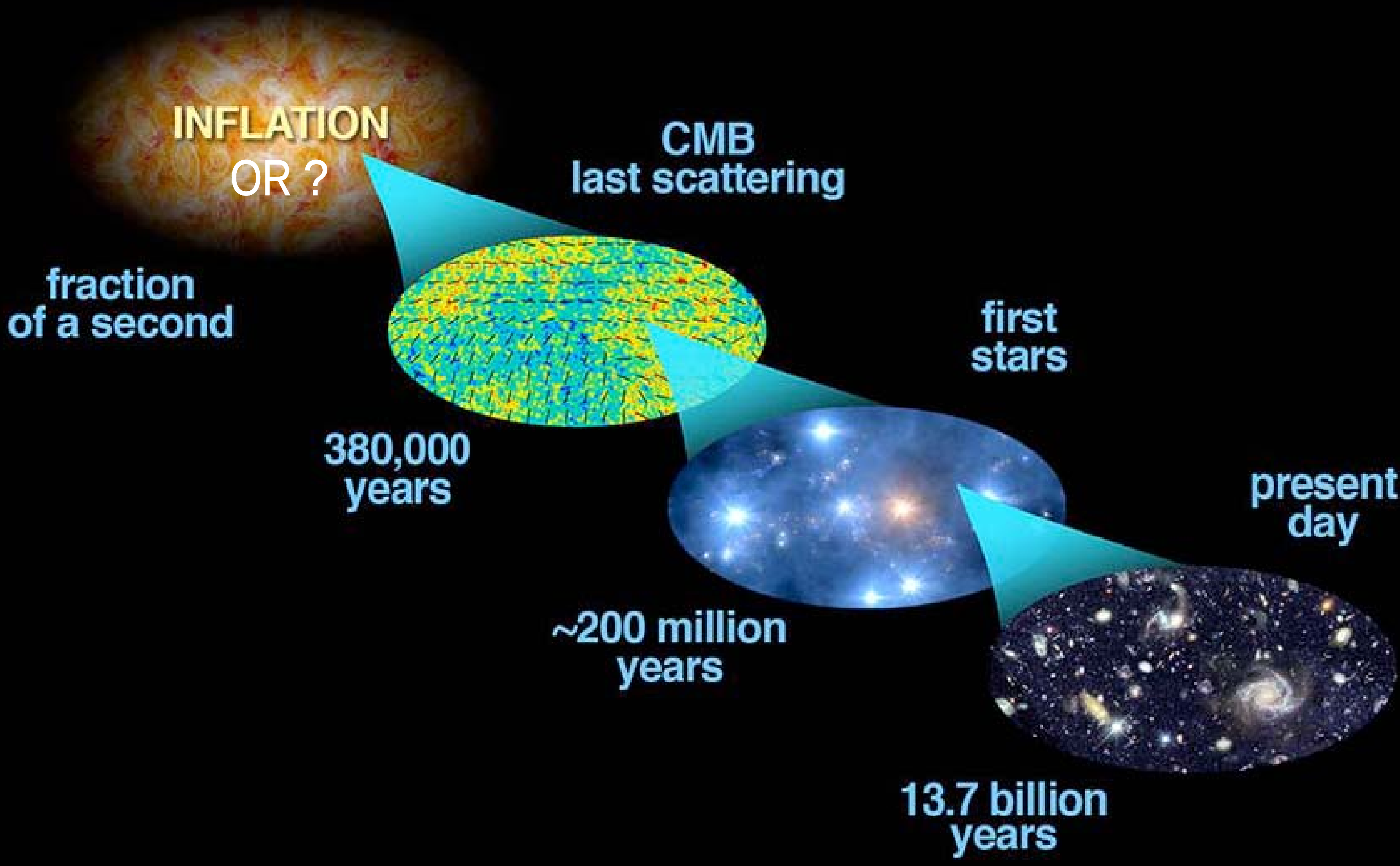
2009

14 May

F. R. Bouchet
Institut d'Astrophysique de Paris



SDSS


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

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

NB: Cosmic strings Maps, Bouchet et al. , nature (1989)

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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

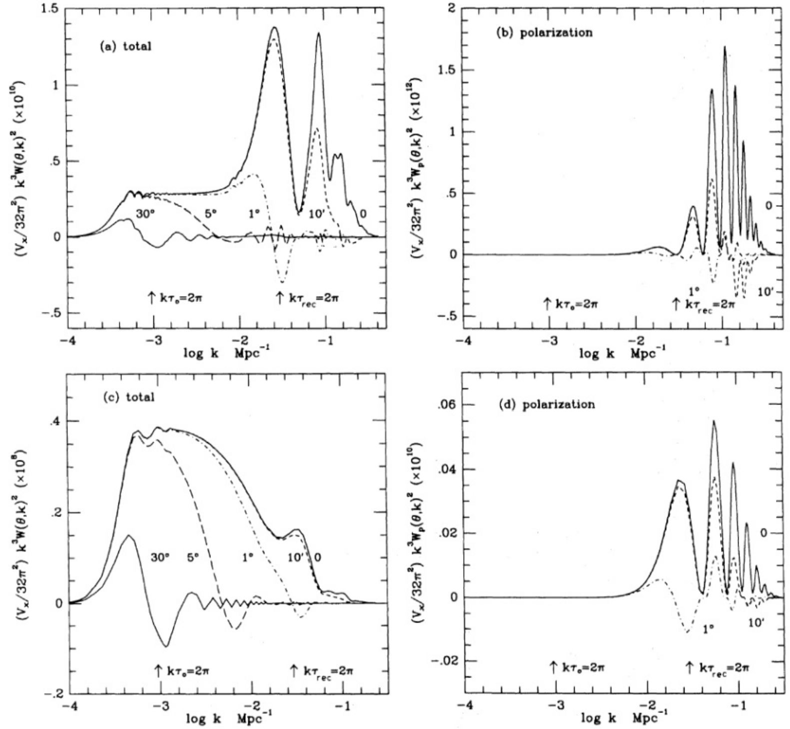


Figure 4. Integrands of the radiation autocorrelation function $k^3W_T^2(\theta, k)$ plotted against log k for various θ. (a, b) Show the integrands for the total and polarization correlation functions, respectively for a scale-invariant adiabatic CDM model with $\Omega=1$, $\Omega_B=0.03$, $h=0.75$. (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 $b=1$.

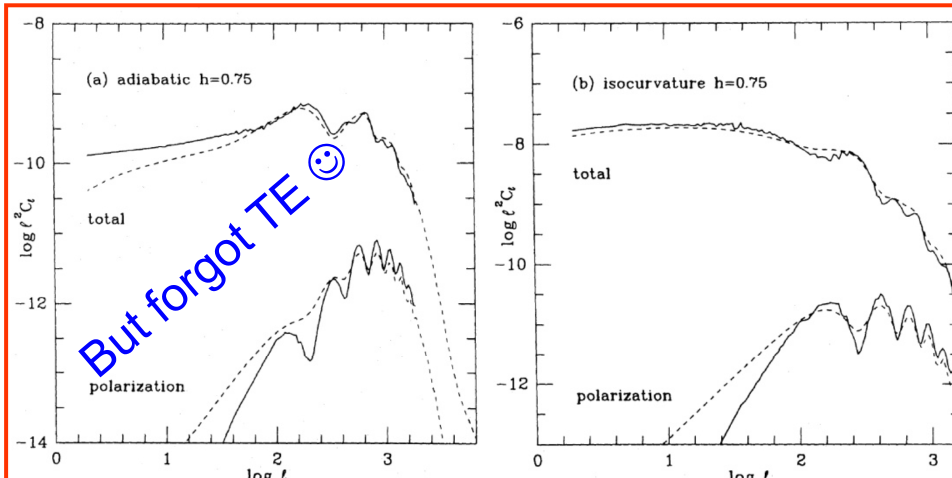
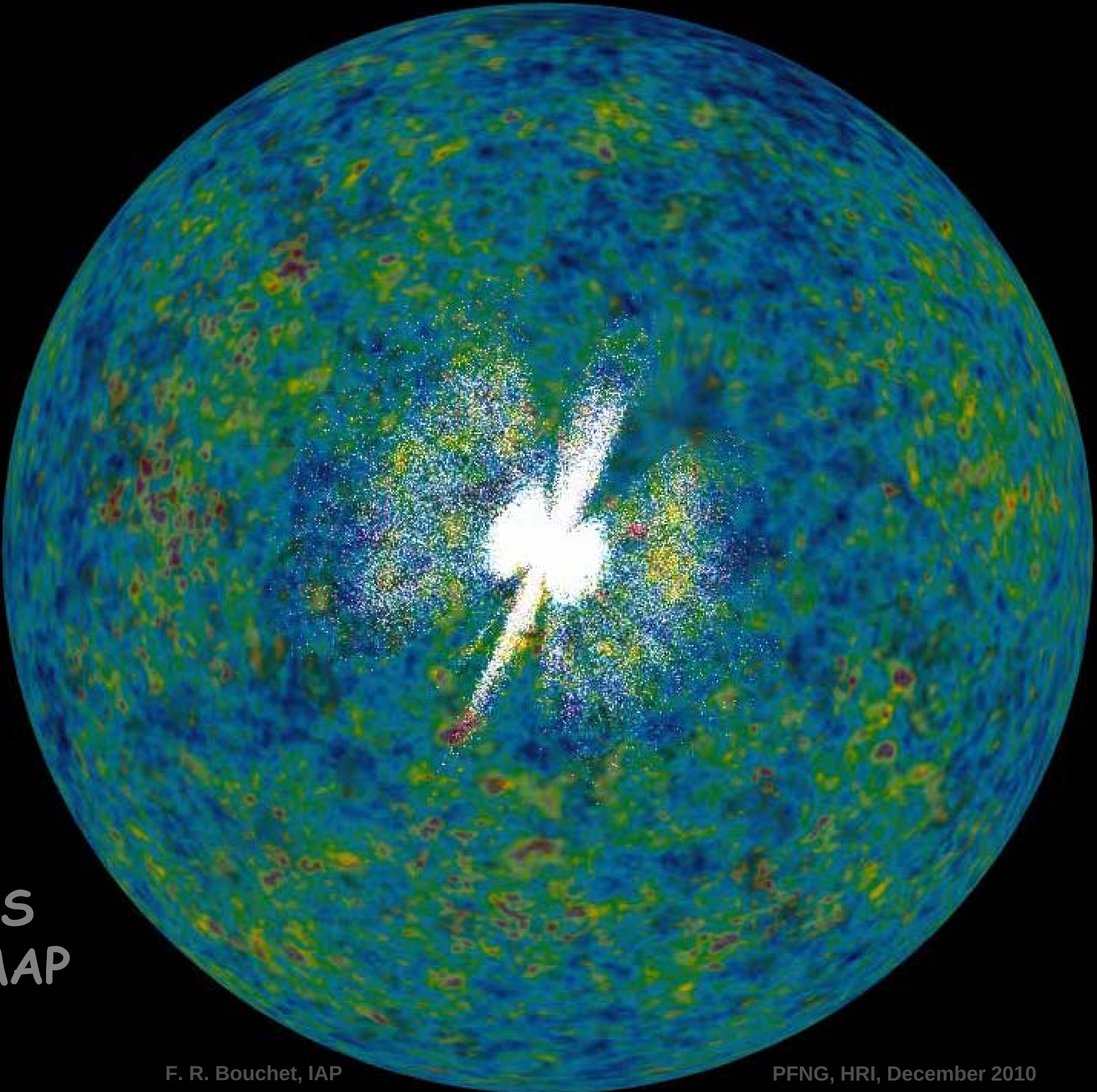


Figure 7. Power spectra for the two $h=0.75$ scale-invariant CDM models. The solid lines show results from equation (4.17) and the dotted lines show approximate results derived from equation (4.19).



SDSS
& WMAP

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] [$\sigma_{pix}\ \Omega_{pix}^{1/2}$]	3.0	3.0	3.0	1.1	0.7	1.1	3.3	33	1500
Sensitivity in Q or U [μK.deg] [$\sigma_{pix}\ \Omega_{pix}^{1/2}$]	4.3	4.3	4.3	1.8	1.4	2.4	6.8		

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)

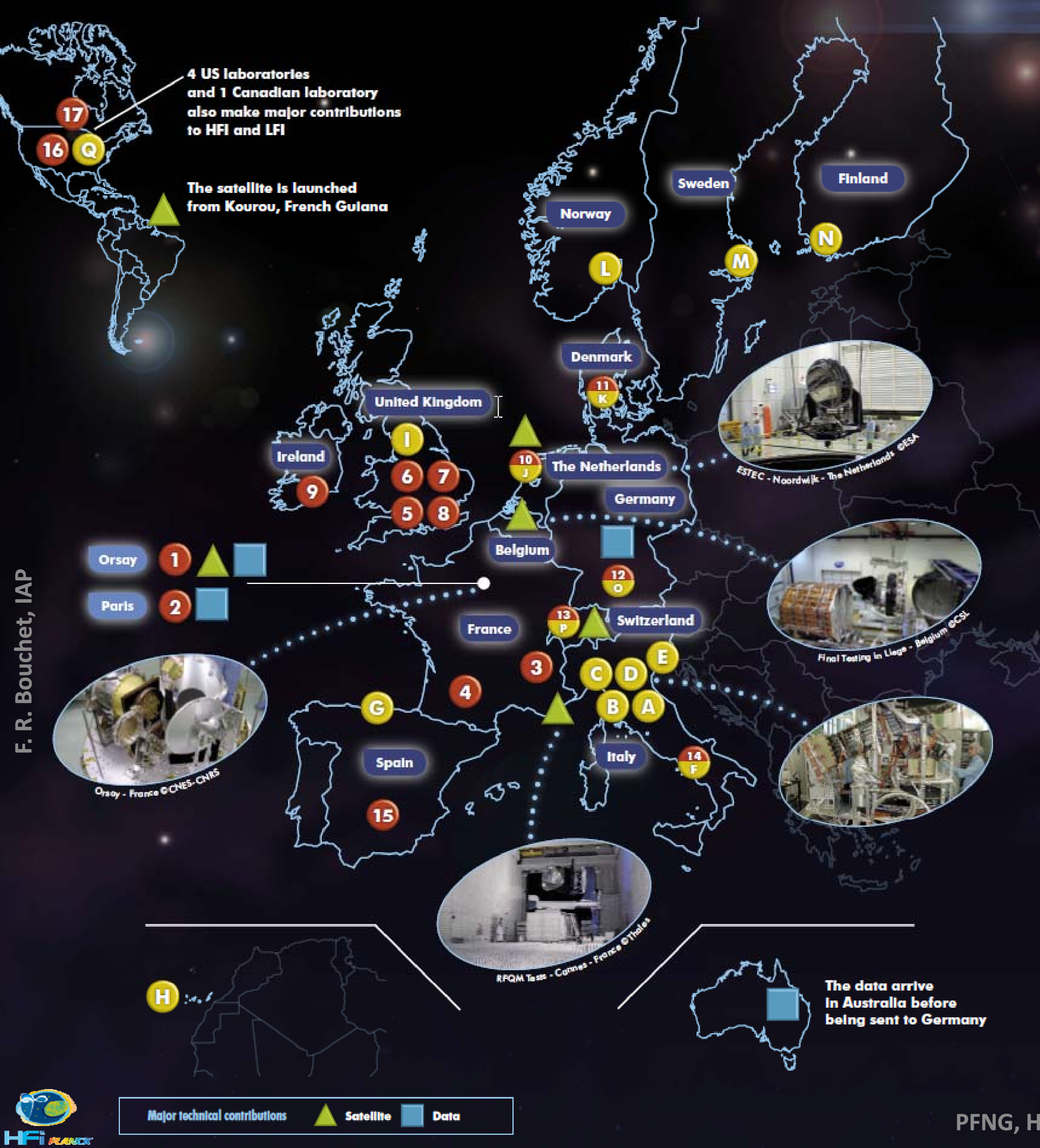
NB: Anticipated survey duration is now ~30 months, so final sensitivity ~0.33 μK.deg in T (approx 1000 years of WMAP 60+90GHz aggregated sensitivity of 10.8 μK.deg in1yr)

Planck needed breakthroughs

- The 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

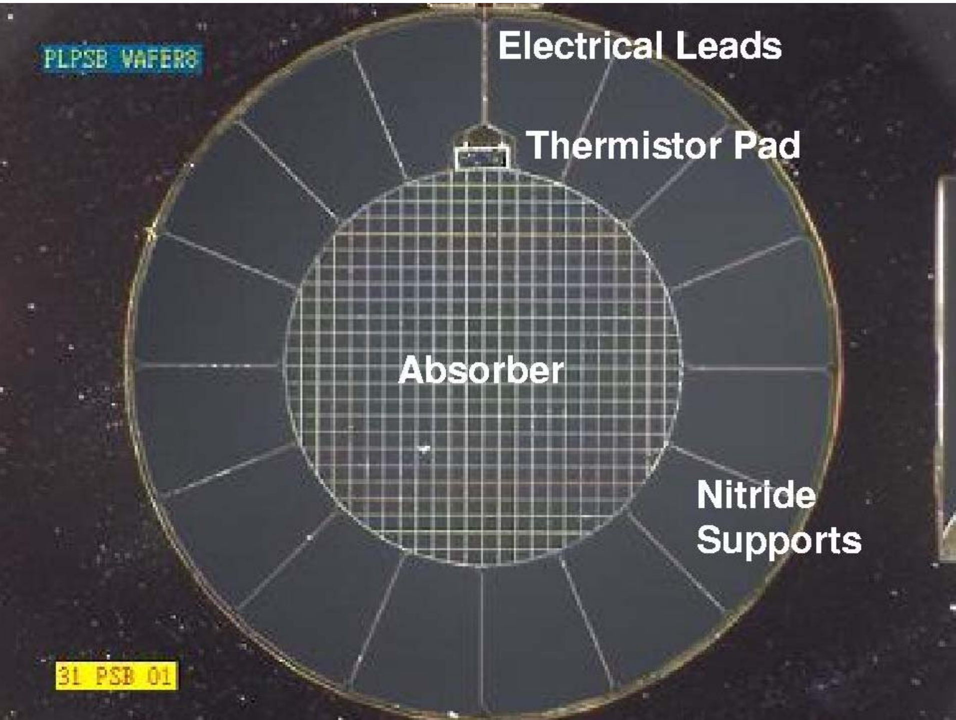
4,2 m

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

4,2 m

HFI Spider Web Bolometers & PSBs



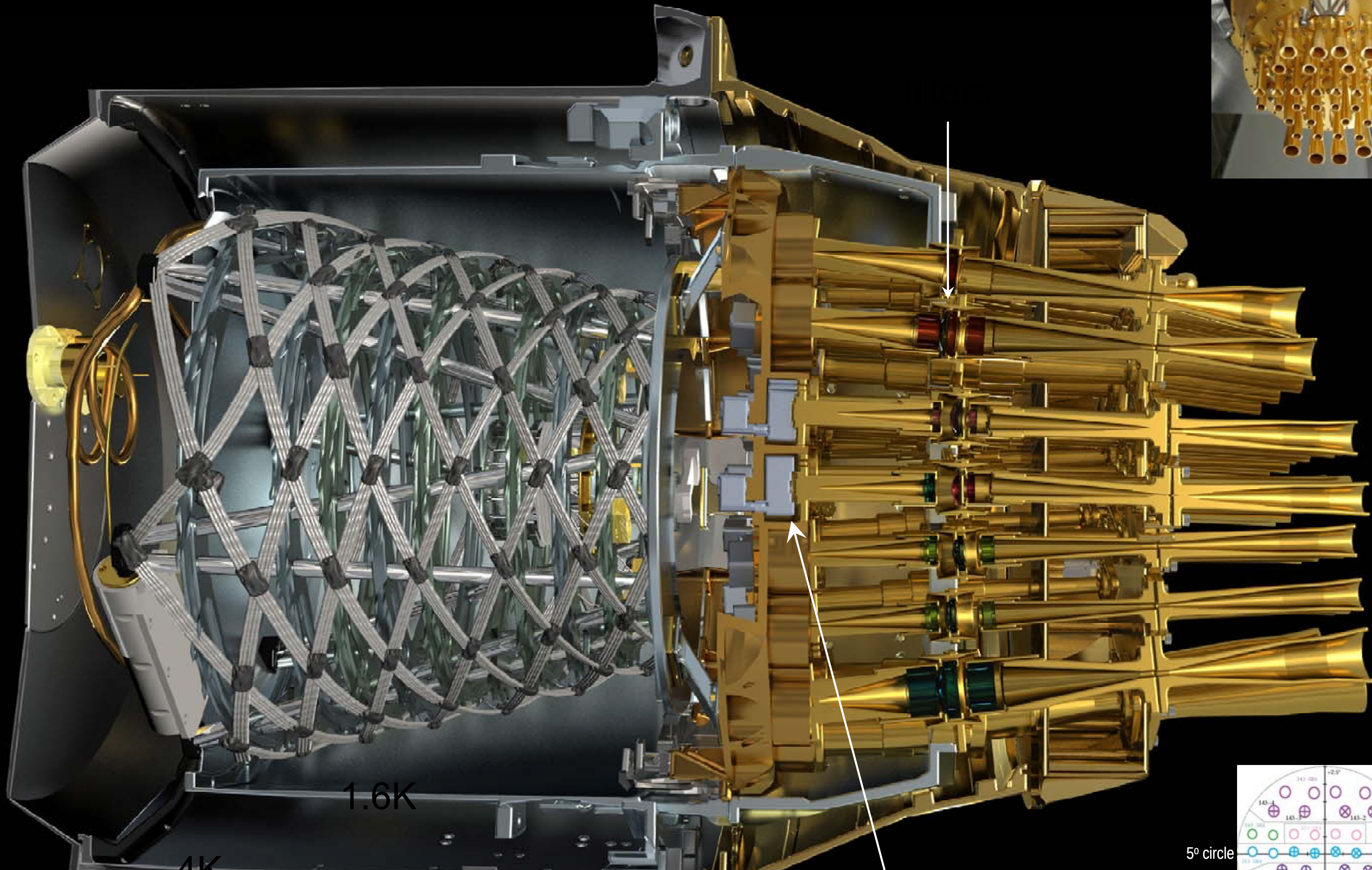
145 GHz PolarSensitiveBolometers

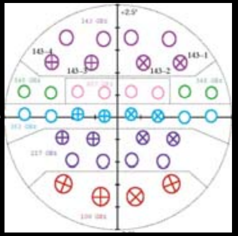
857 GHz SpiderWeb Bolometer

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.

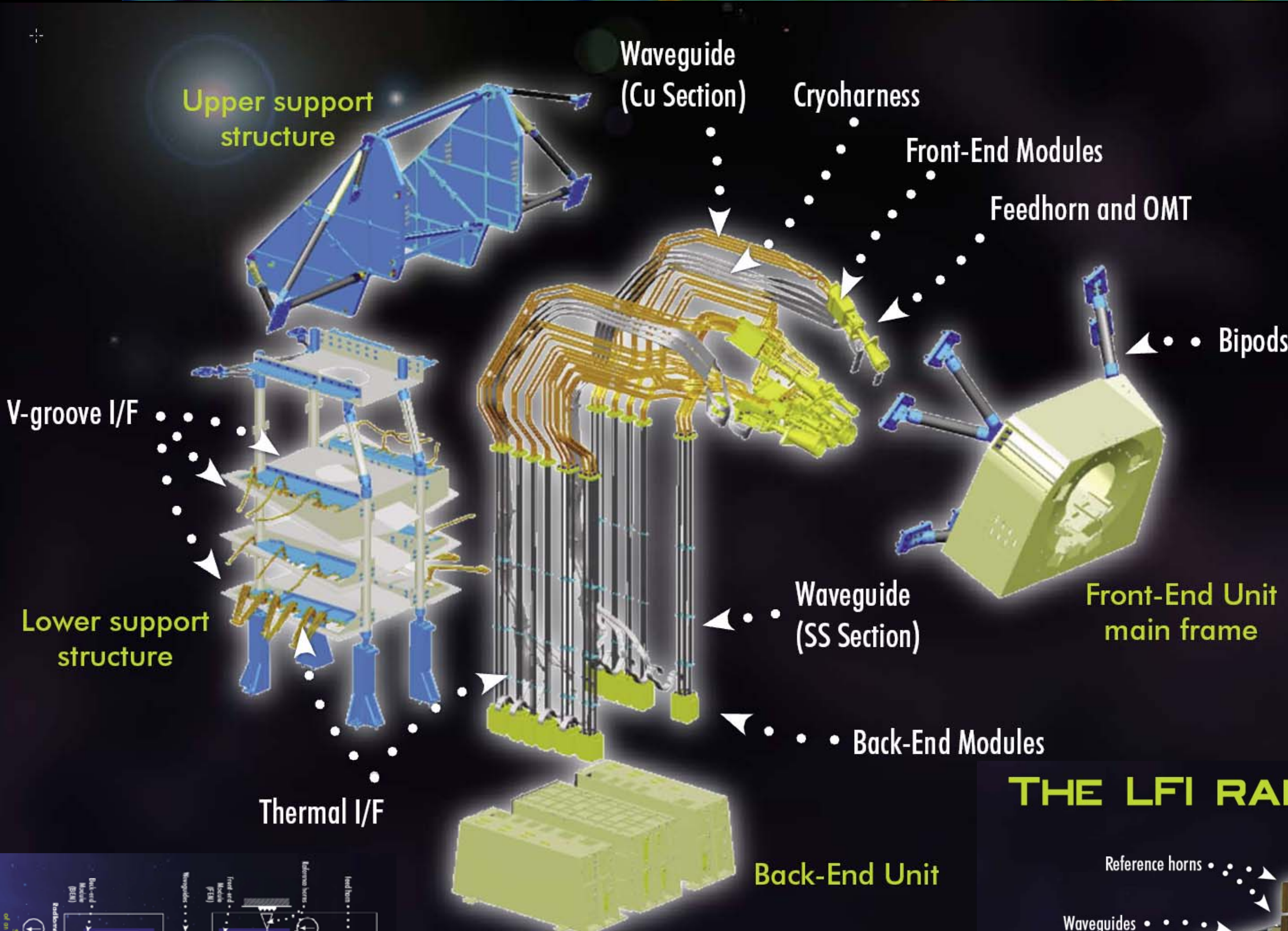
NB: Flight Model includes 4 PSB pairs @ 100 GHz (following the descoping of the 100 GHz receivers from the LFI)

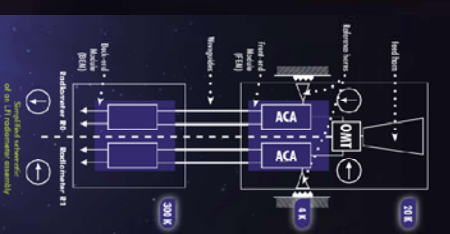
HFI cut-away

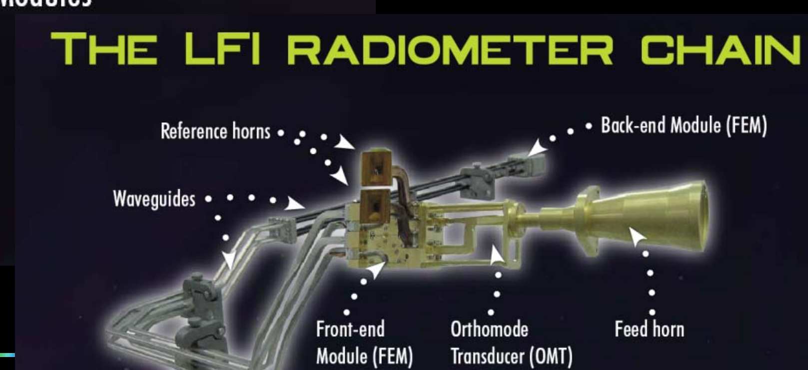




The Low Frequency Instrument LFI



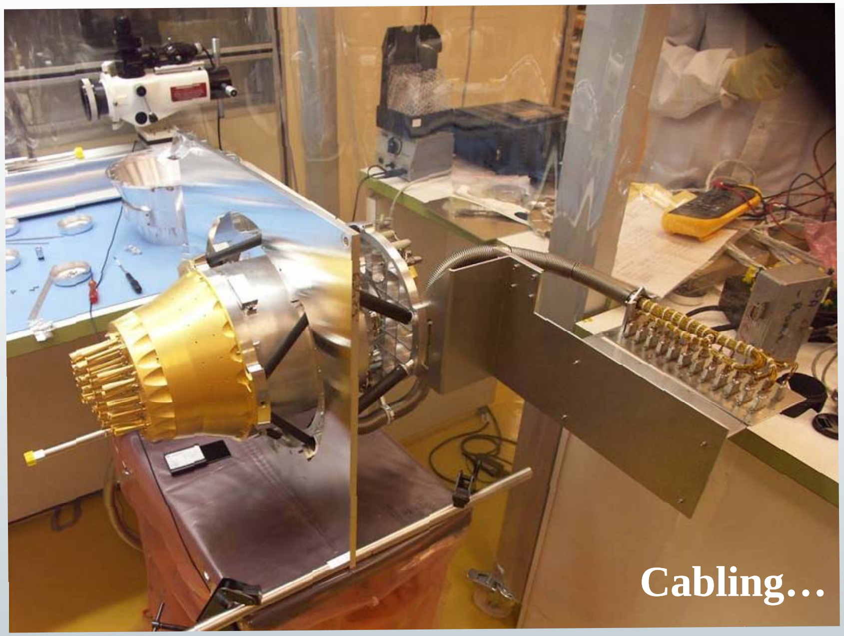


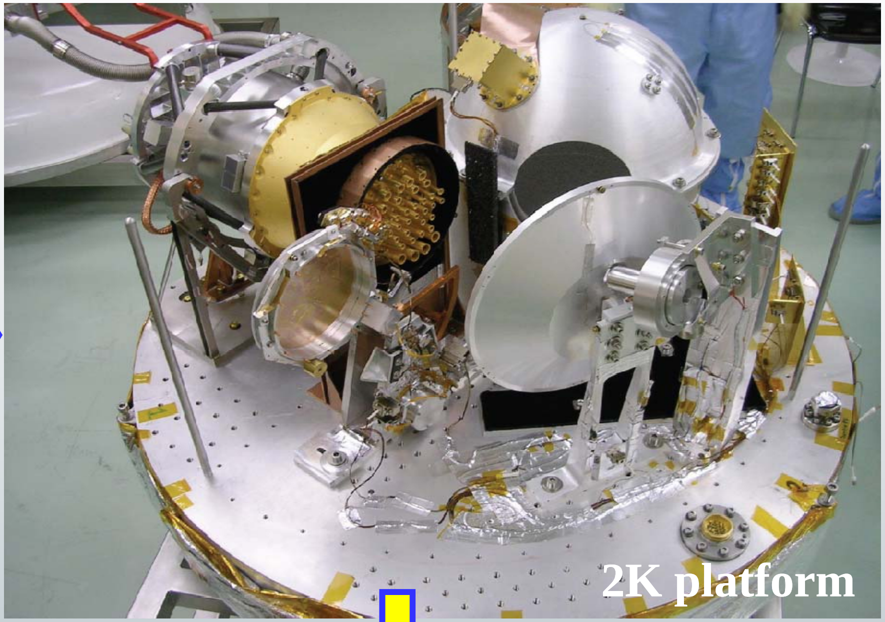


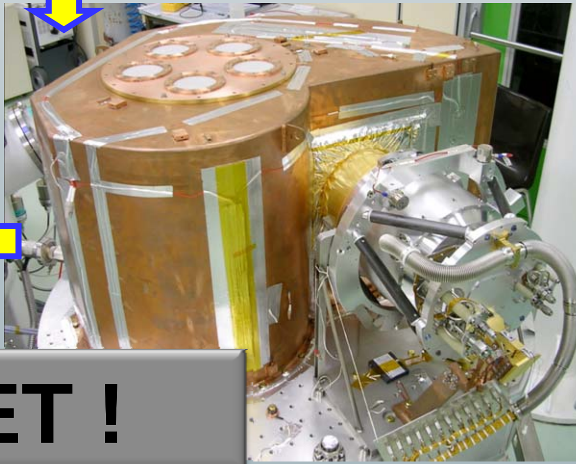
Birth of the Cool

HFI Integration & Calibration @ IAS

(reproduction of spatial and micro-wave environment)







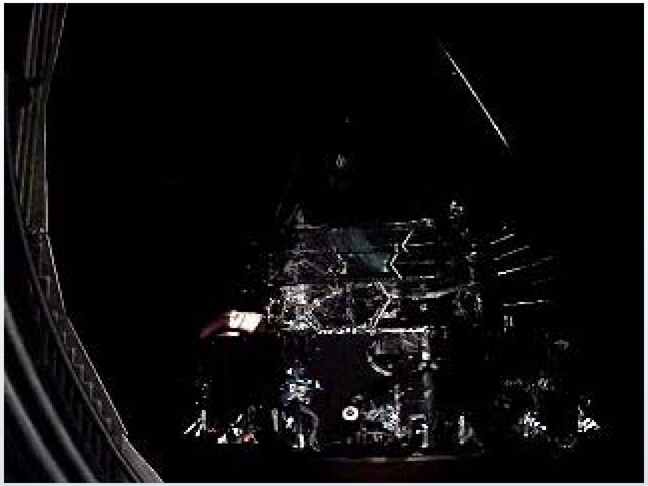
DESIGN GOALS MET !

WMAP would need ~500 years of survey time to reach HFI 14m sensitivity

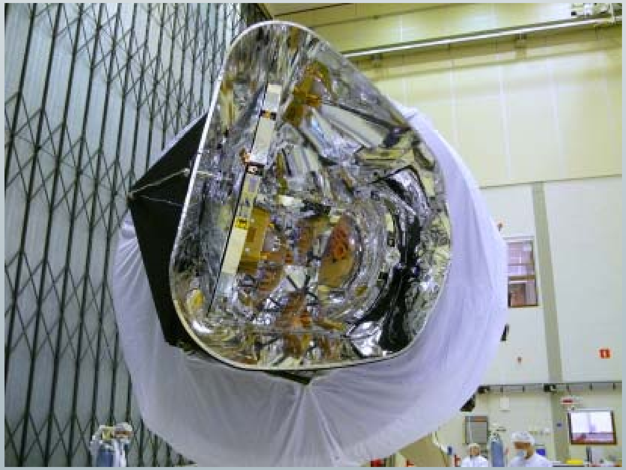
Integration at Thales-Cannes

Nov 2006, HFI + LFI integration

Dec 9th 2007, Ready for vibration testing



April 7th 08: load balancing



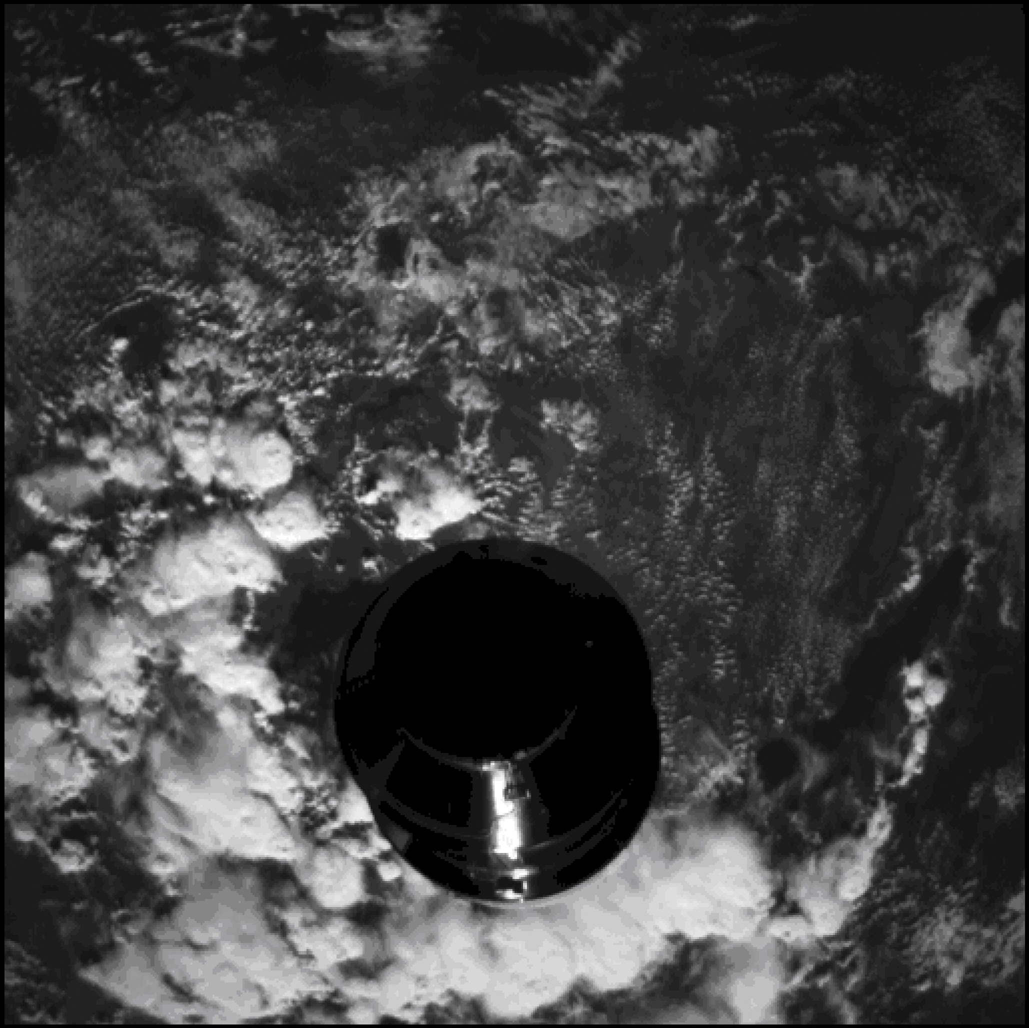
April 18th 2008: preparing ESTEC → CSL

03/08: Antonov Nice → ESTEC

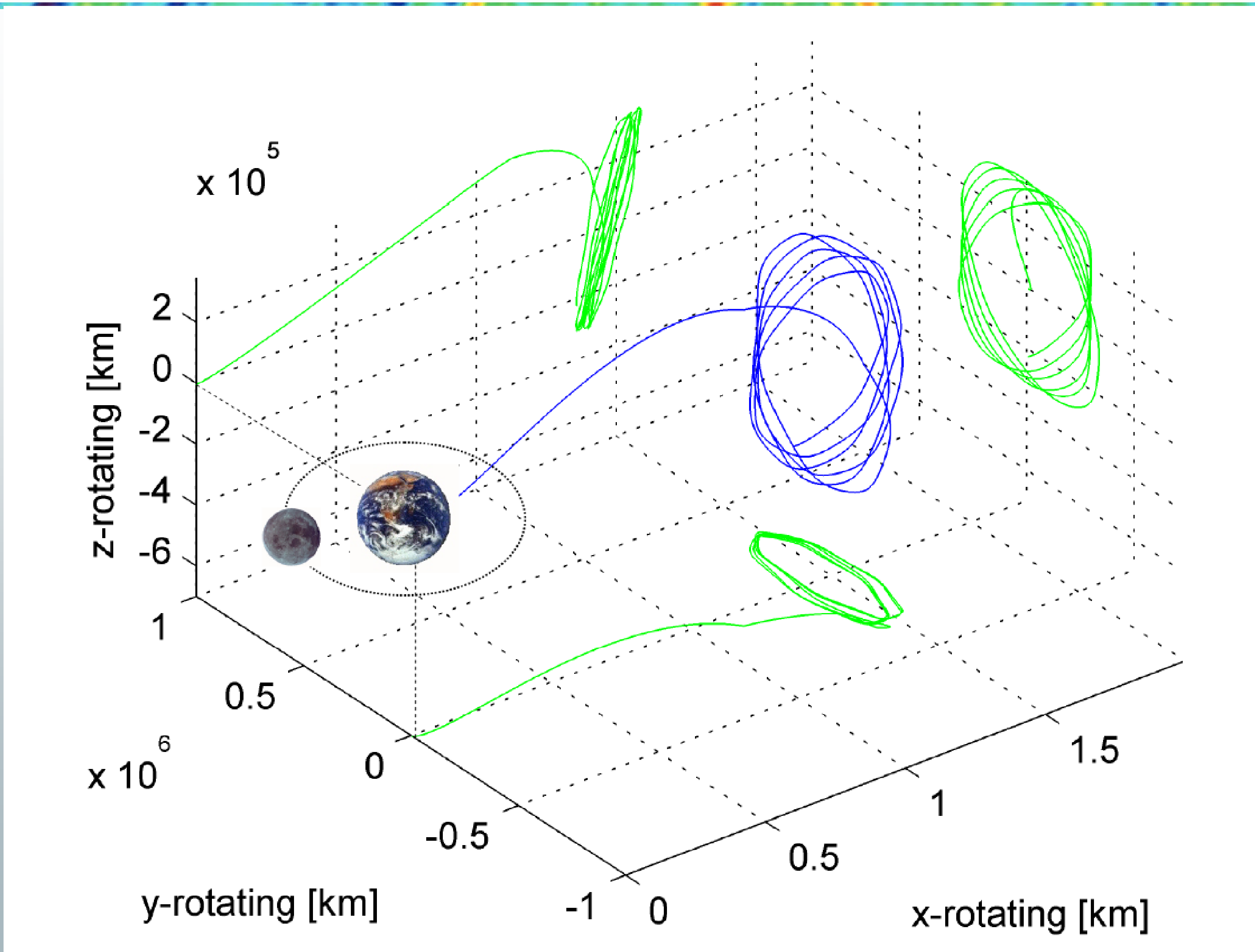

DUSTING IT OFF...
AFTER 16 YEARS
OF HOPES & WORK

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

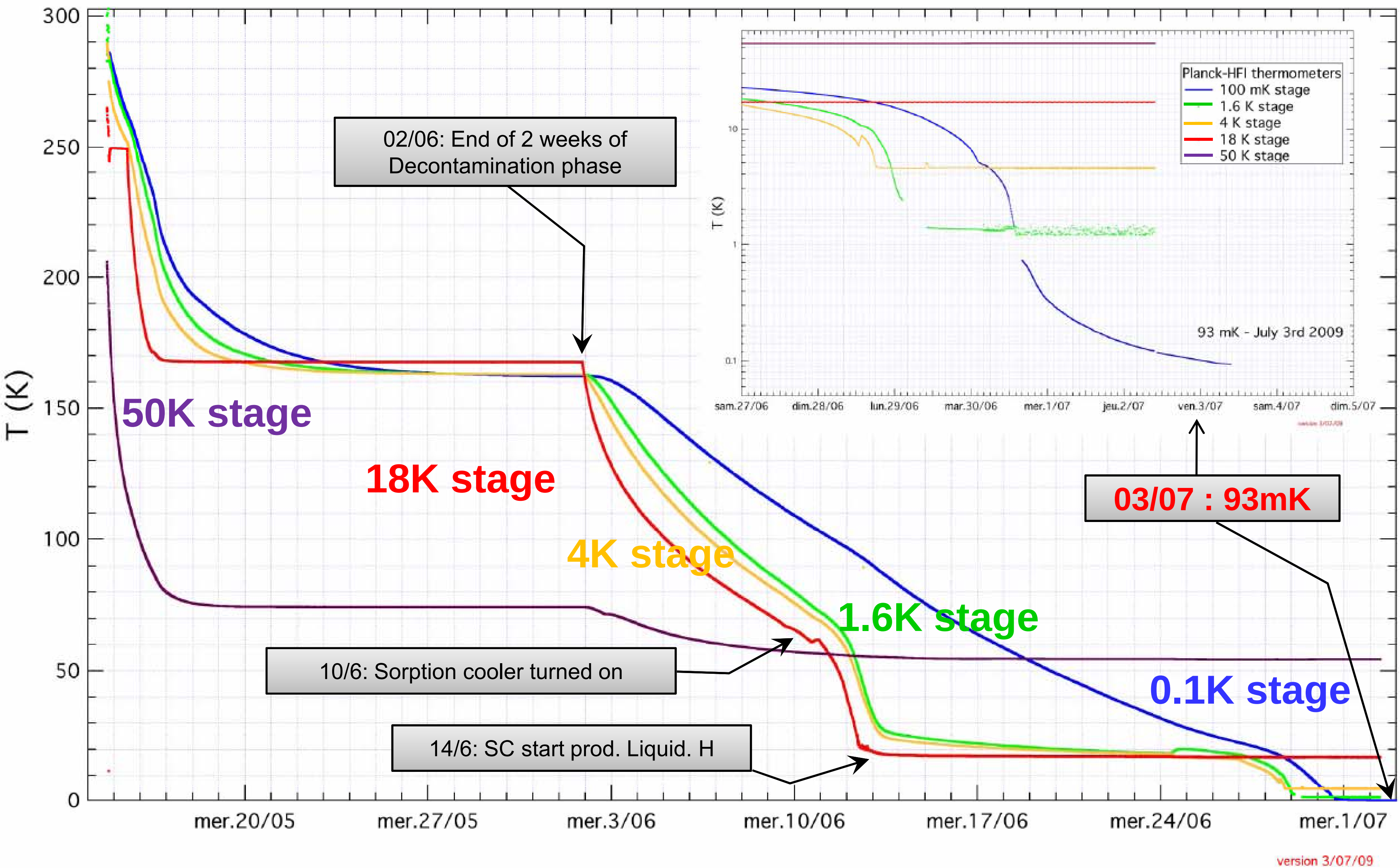
Planck by Herschel webcam ☺



Planck is in L2 orbit since July 2009



Planck is cool...



Planck scans the sky, at 1 rpm

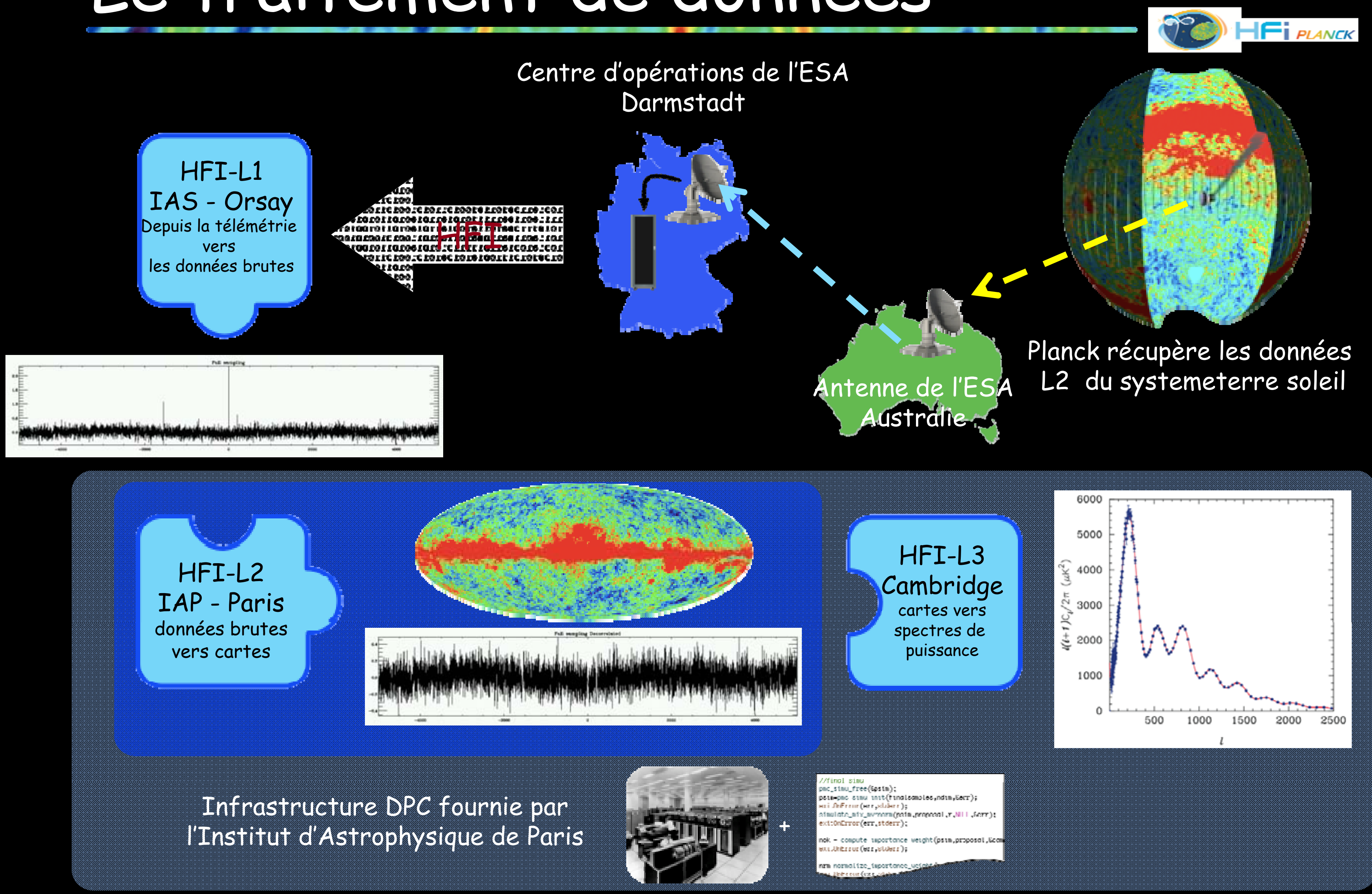
WHAT, WHEN

- May 14th 2009 - Launch from Kourou
- 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,
- Nov 2010: End of nominal 15 months of operations
  to complete 2 surveys

NOW

- 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 15 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…)*
- ~Jan 2014: Final data release with all data acquired (ie till ~mid-Jan 12?)

Un défi technologique :
Le traitement de données



Data Processing

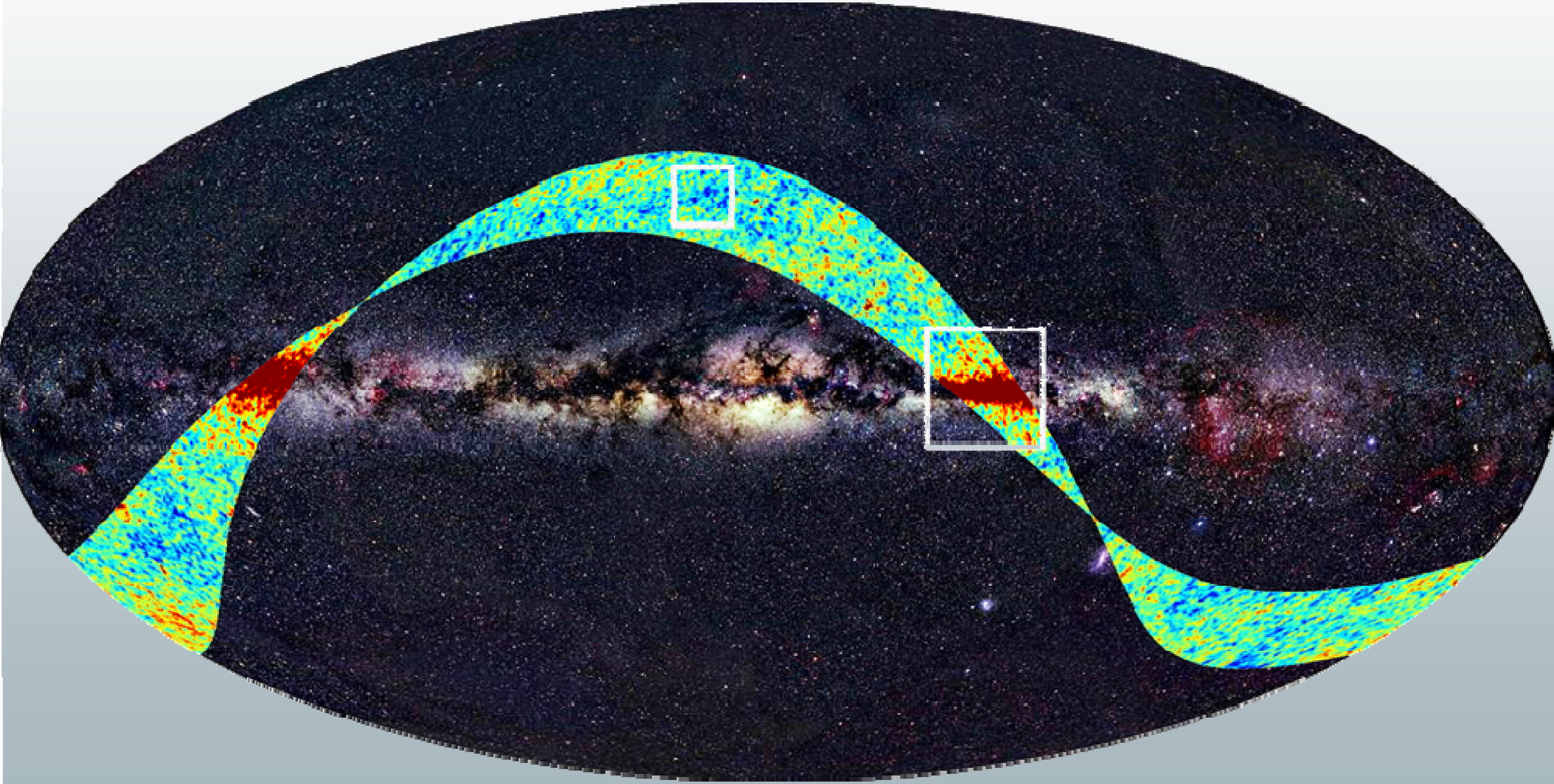
- Physics → CMB sky → Frequency sky → TOI
- TOI → frequency maps → CMB map → Physics

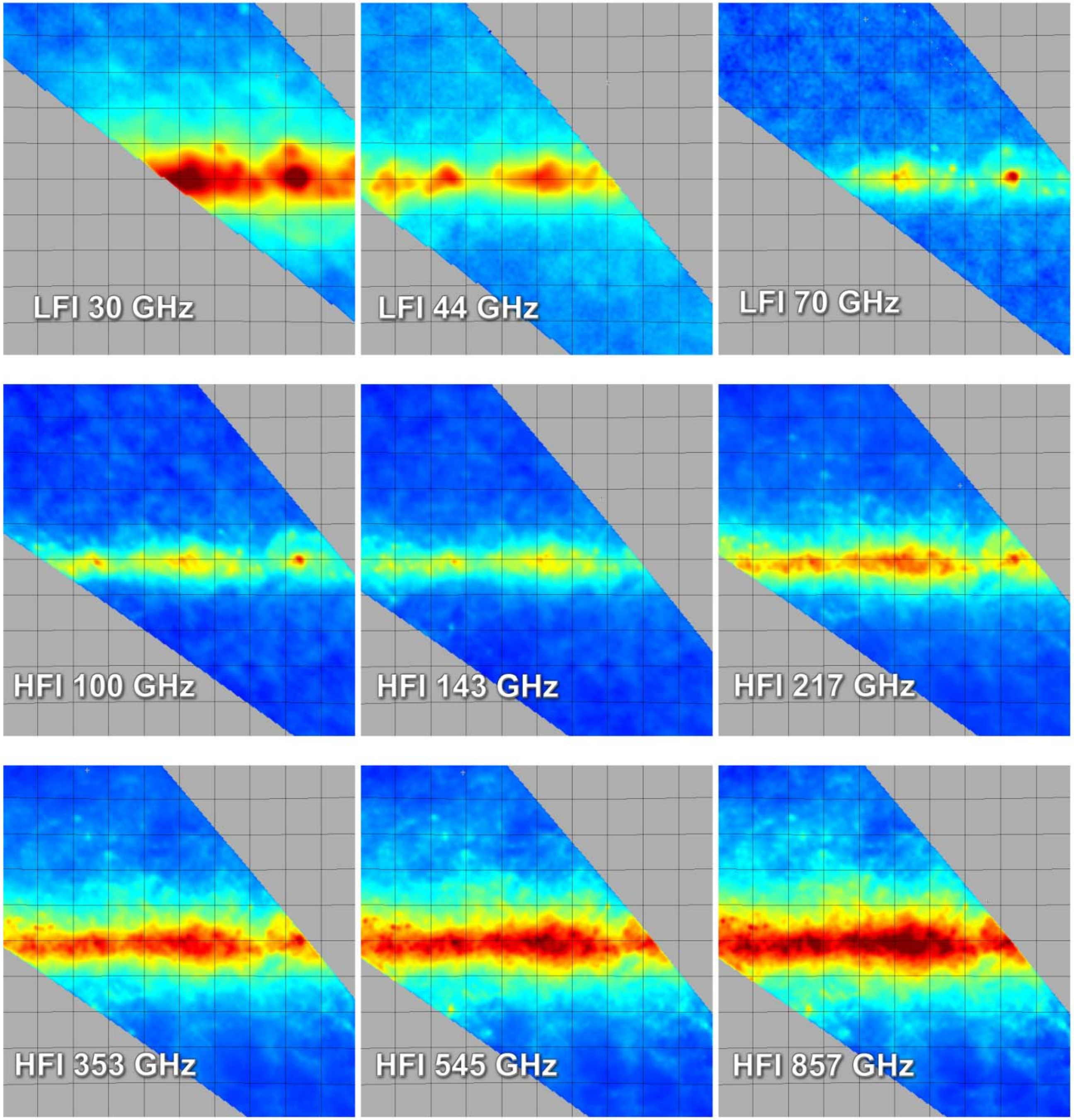
- One needs to write and verify a model of TOI = f(Physics) and to "invert" it and to assess errors.
  - *The frequency response is measured on the ground.*
  - *The optical response is measured on the ground, modelled, and partially verified on planets, Crab, etc.*
  - *The detector chain response is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

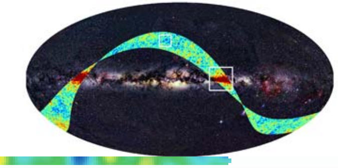
- Many Interesting challenges: *optimality/speed, propagation of separation errors, exploration of large dimensionality spaces... in addition to herding a large cat population, and surprises in the data*

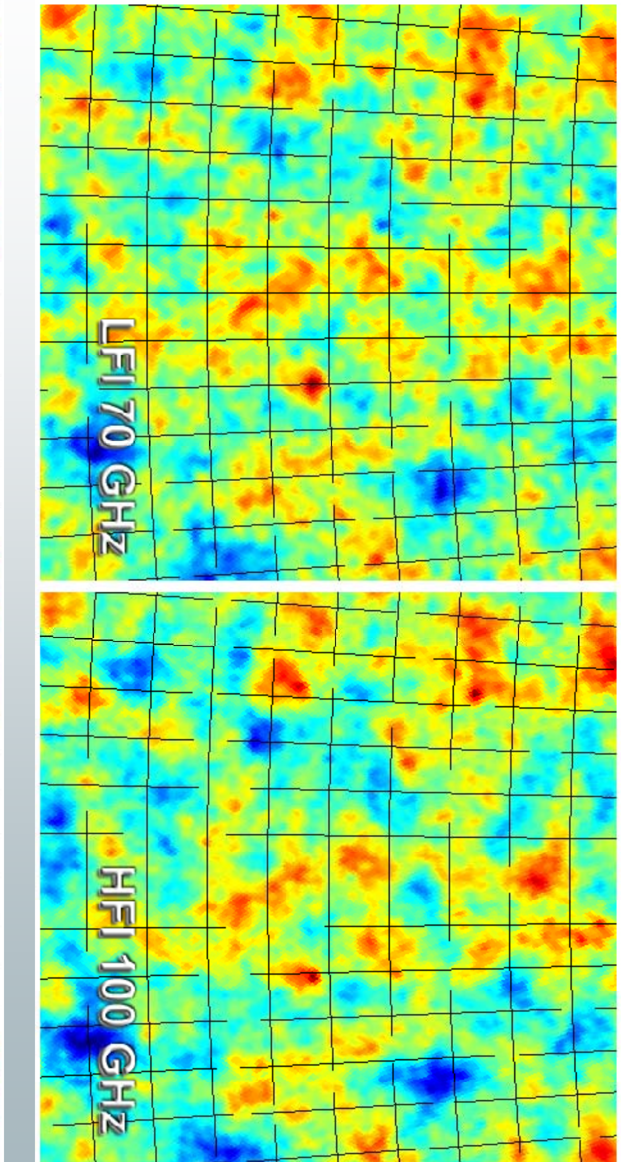
First light survey

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



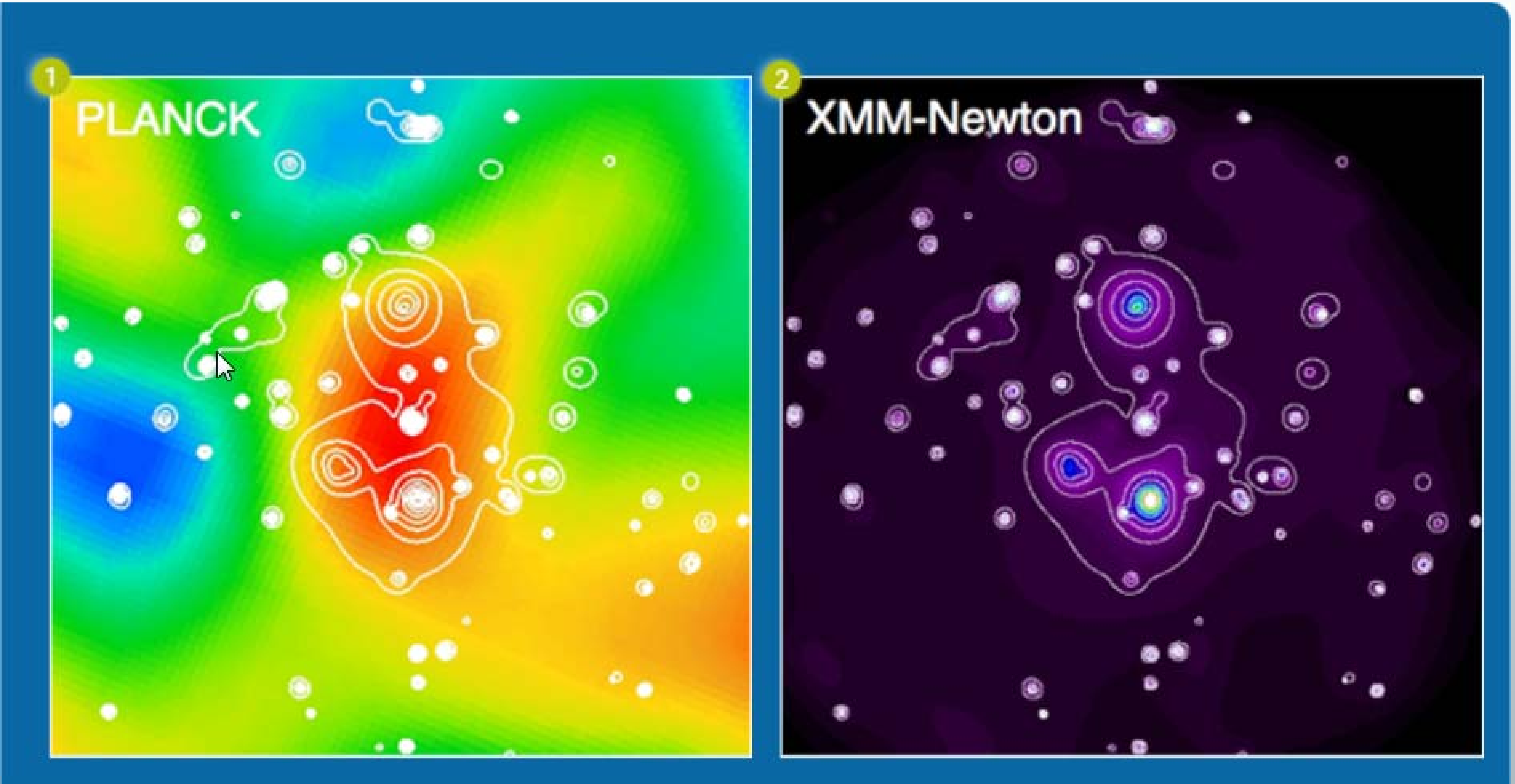

LFI 70 GHz
HFI 100 GHz

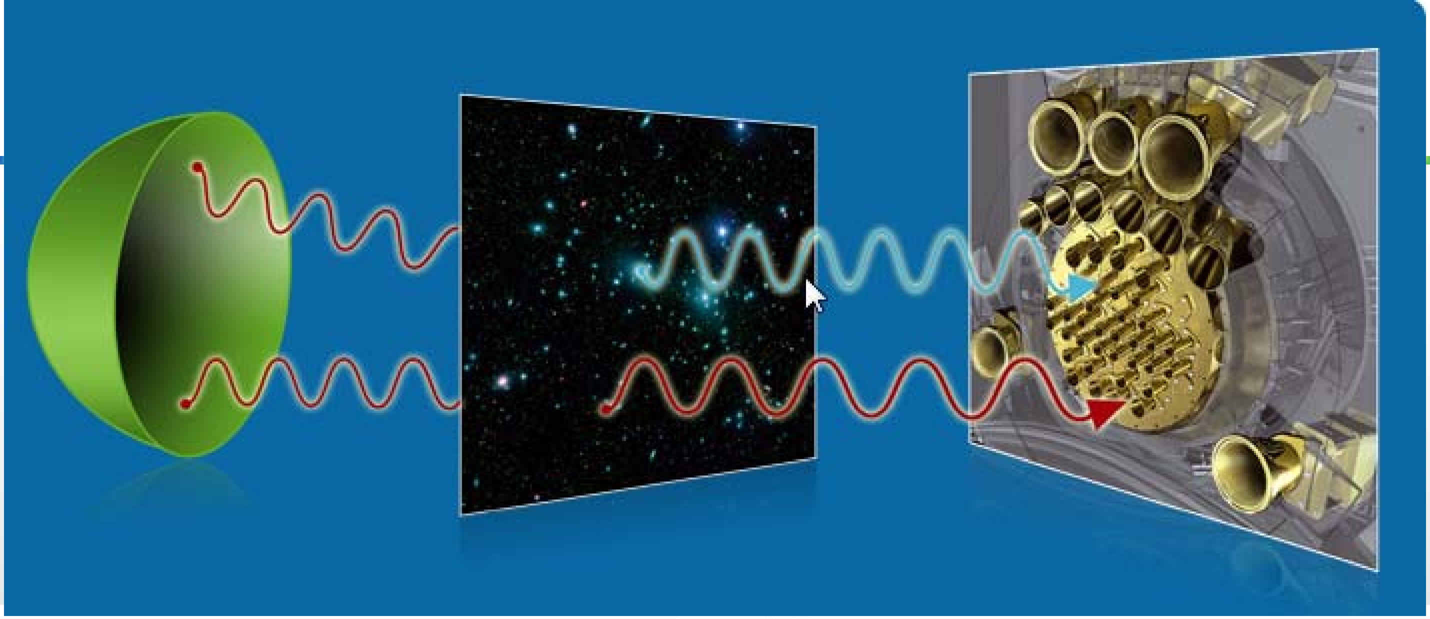
4th Press Release (05/07/2010)

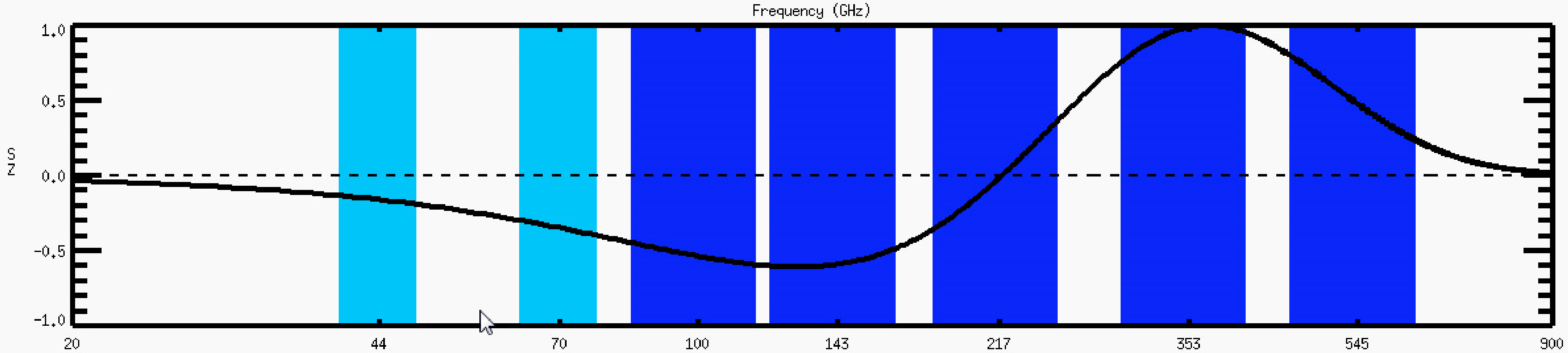
The Planck one-year all-sky survey

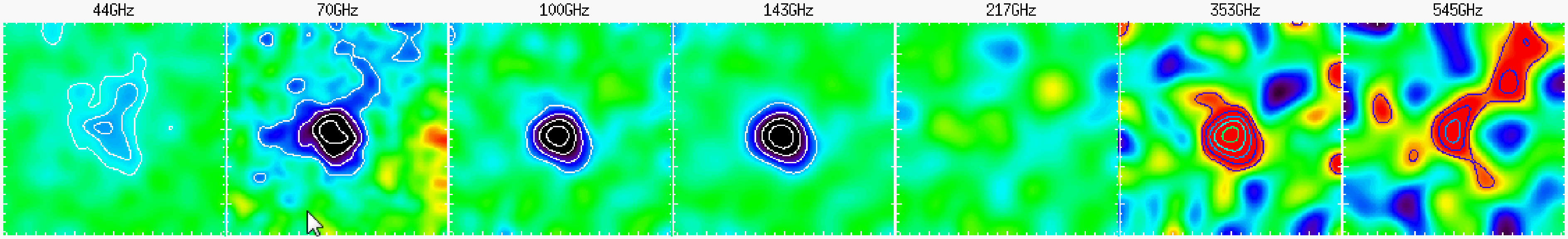
esa

5th Press Release (05/07/2010)



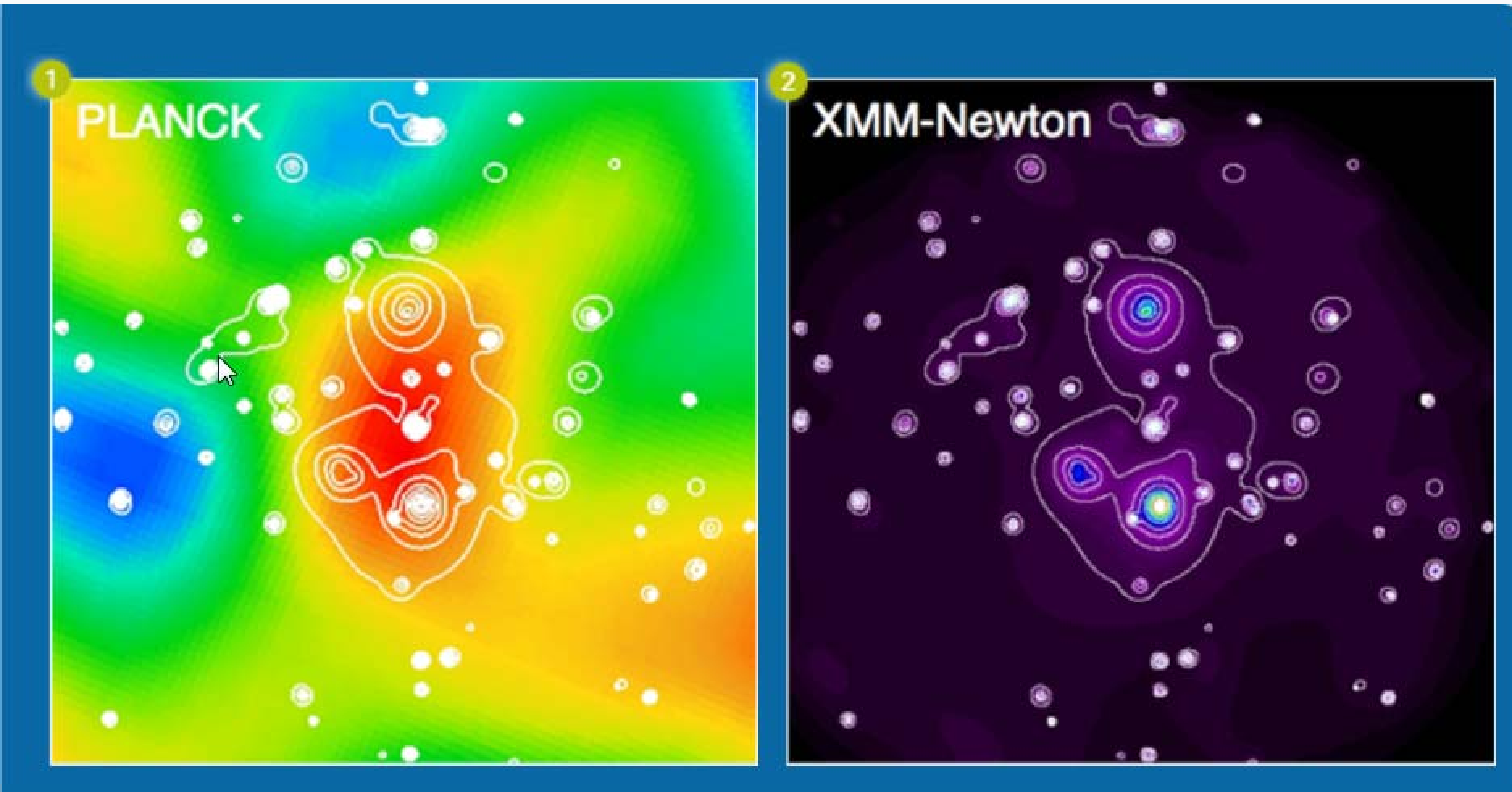



Frequency (GHz)
SZ
1.0
0.5
0.0
-0.5
-1.0
20
44
70
100
143
217
353
545
900


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

Abell2319

5th Press Release (05/07/2010)



Home | Programme | Registration | Participants | Venue

The Millimeter and Submillimeter Sky in the Planck Mission Era

Paris, France

January 10-14 2011

Cité des Sciences

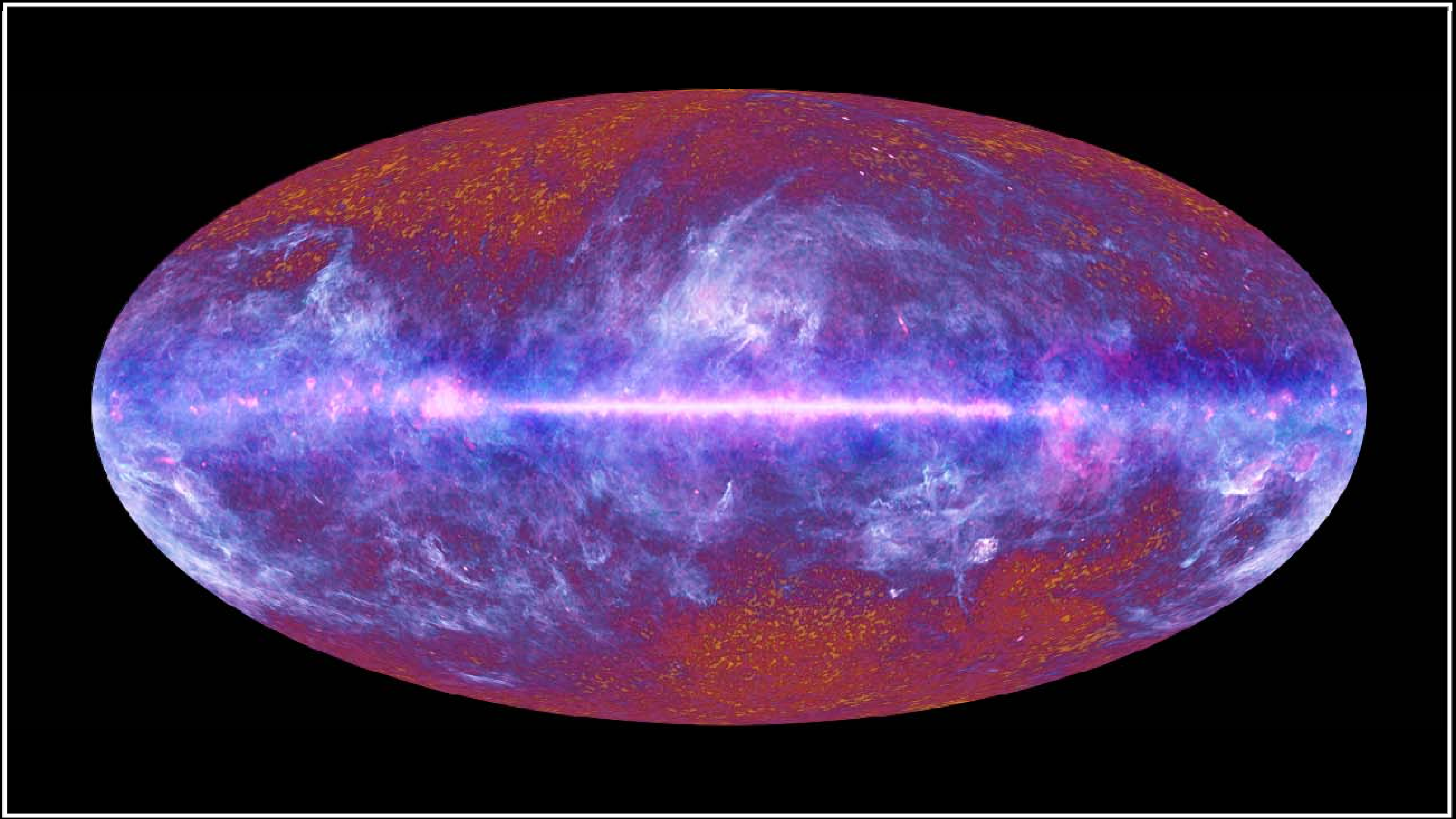
http://www.planck2011.fr/

Conference menu

- ~ ½ about Planck stuff drawing on
  - *Mission paper, Thermal chain*
  - *HFI & LFI in flight performance*
  - *HFI & LFI Data processing*
  - *ERCSC + supplement*
  - *~20 early science papers on (unpolarised) emission of foregrounds:*
    - ~ 5 on SZ & relation to Opt & X
    - ~ 8 on Compact sources (radio, IR), CIB
    - ~ 7 Galactic components (NB: Anomalous dust, Cold cores)

- ~ + ½ from other sources of knowledge, e.g. ACT, SPT, WISE, including CO (Nanten, Dame,...), polarised foreground surveys, component separation methods, etc.

4th Press Release (05/07/2010)

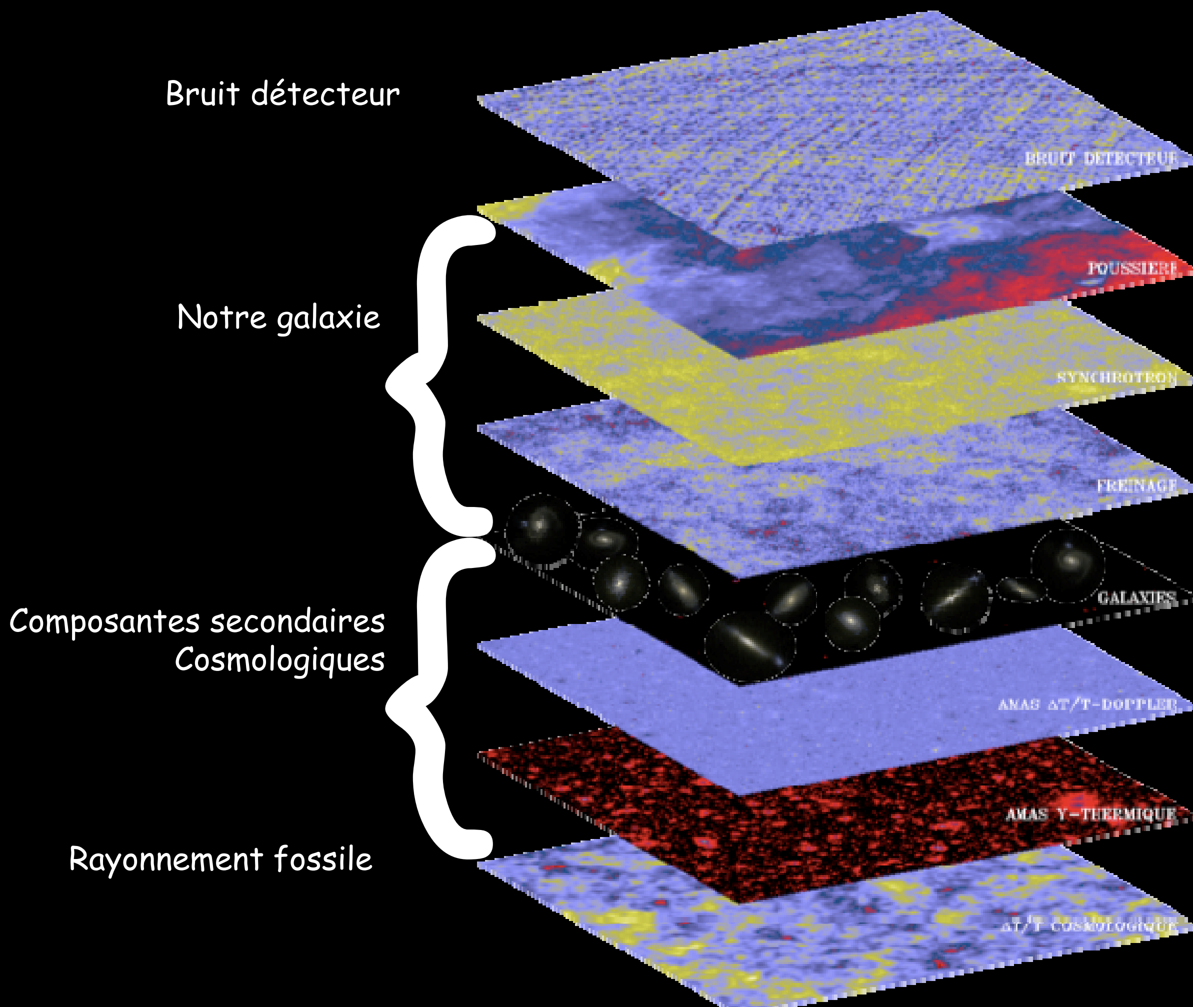


The Planck one-year all-sky survey

esa

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

Défis toujours…
Séparer les différentes composantes



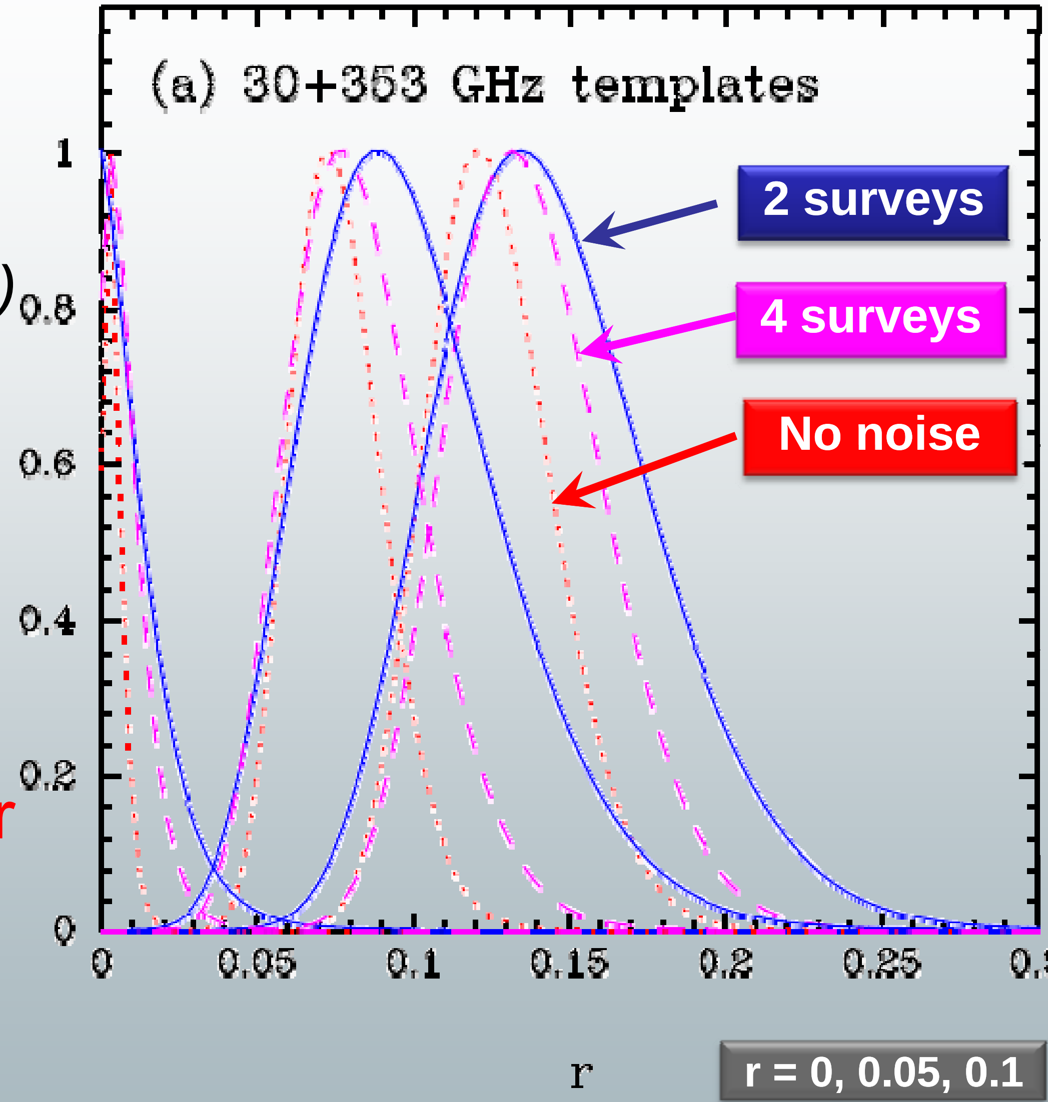
Le rayonnement fossile n'est pas la seule émission micro-onde…

Il faut la séparer des autres émissions (qui forment aussi des données astrophysiques très intéressantes !).

On utilise pour cela des algorithmes issus de la recherche en mathématiques appliquées.

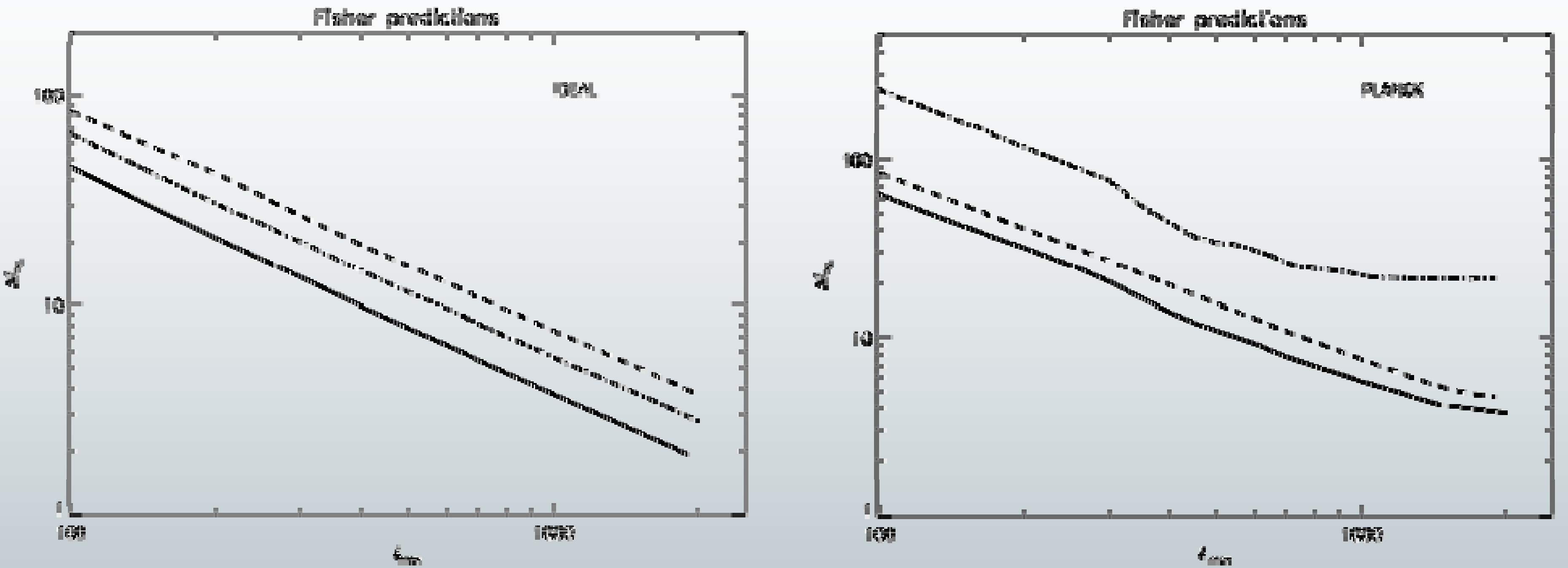
With 4 surveys...

- 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 r = 0.05 & 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)
- (*not a Planck claim*)



0903.0904 GPE & Gratton

f_{NL} quest

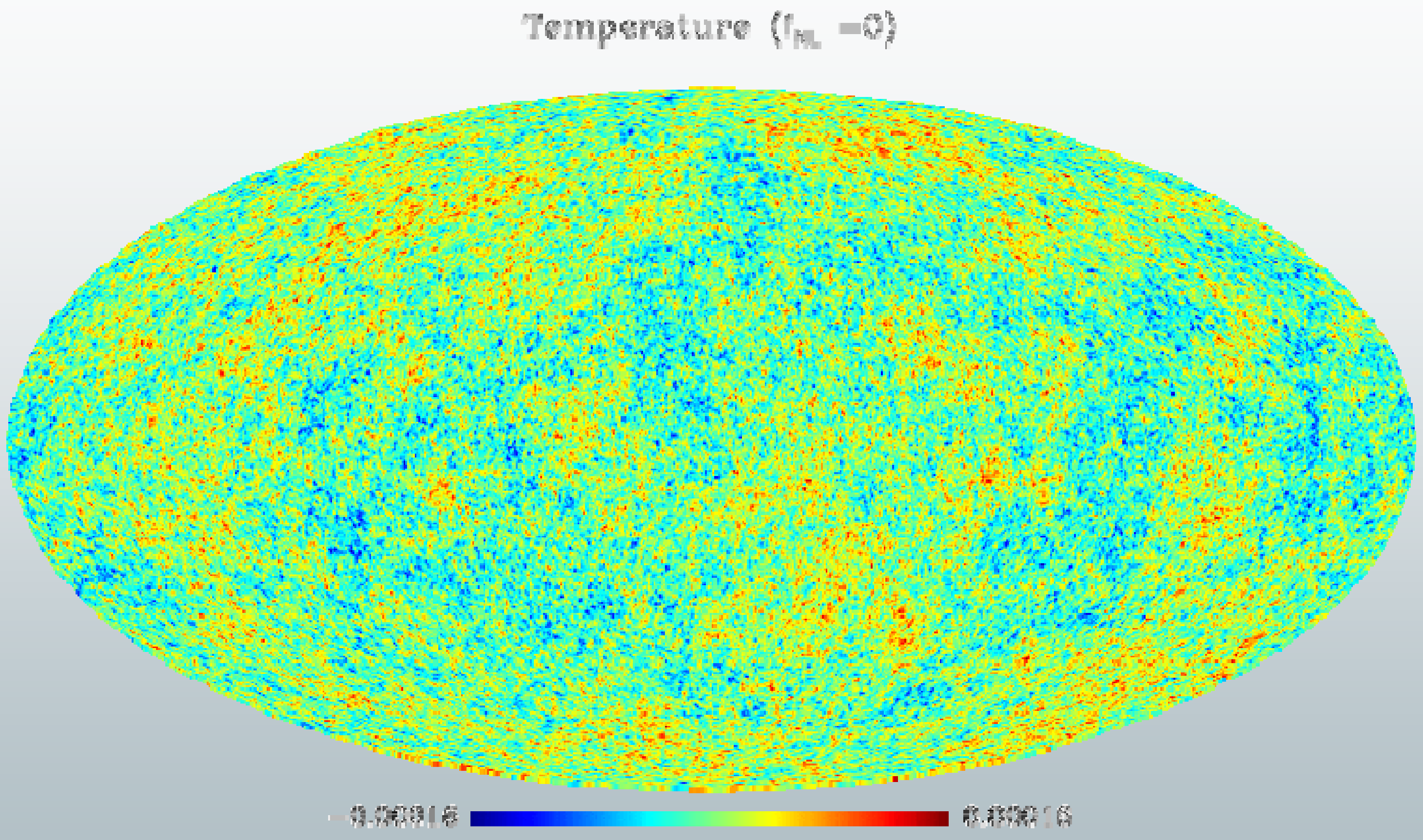


- Ideal CMB experiment, using temperature & polarization could reach $\Delta f_{NL} \sim 1$
- For Planck, the Cramer-Rao limit is $\Delta f_{NL} \sim 3$.

Yadav, Komatsu and Wandelt, astro-ph/0701921

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

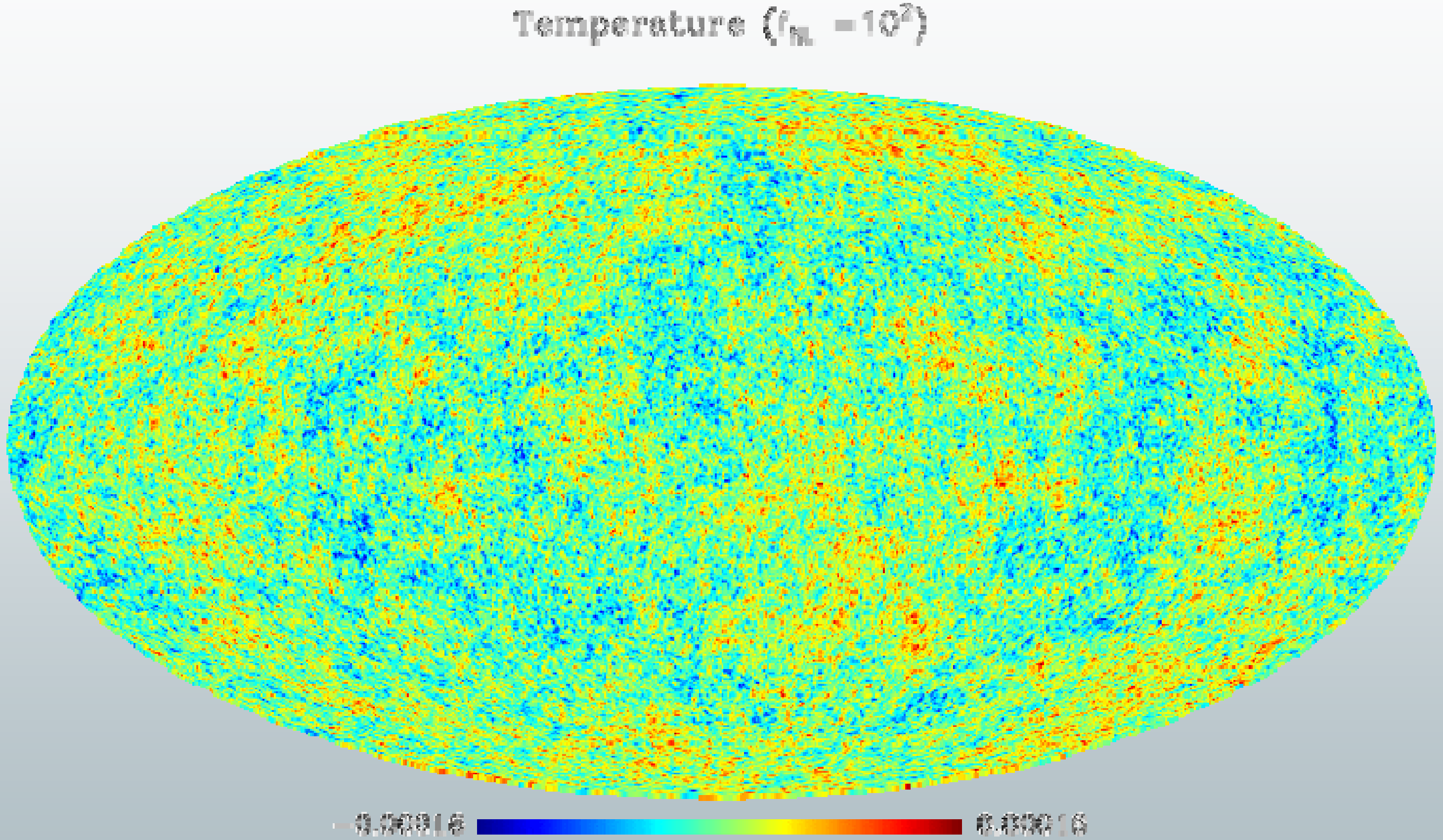
$f_{NL} = 0$



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

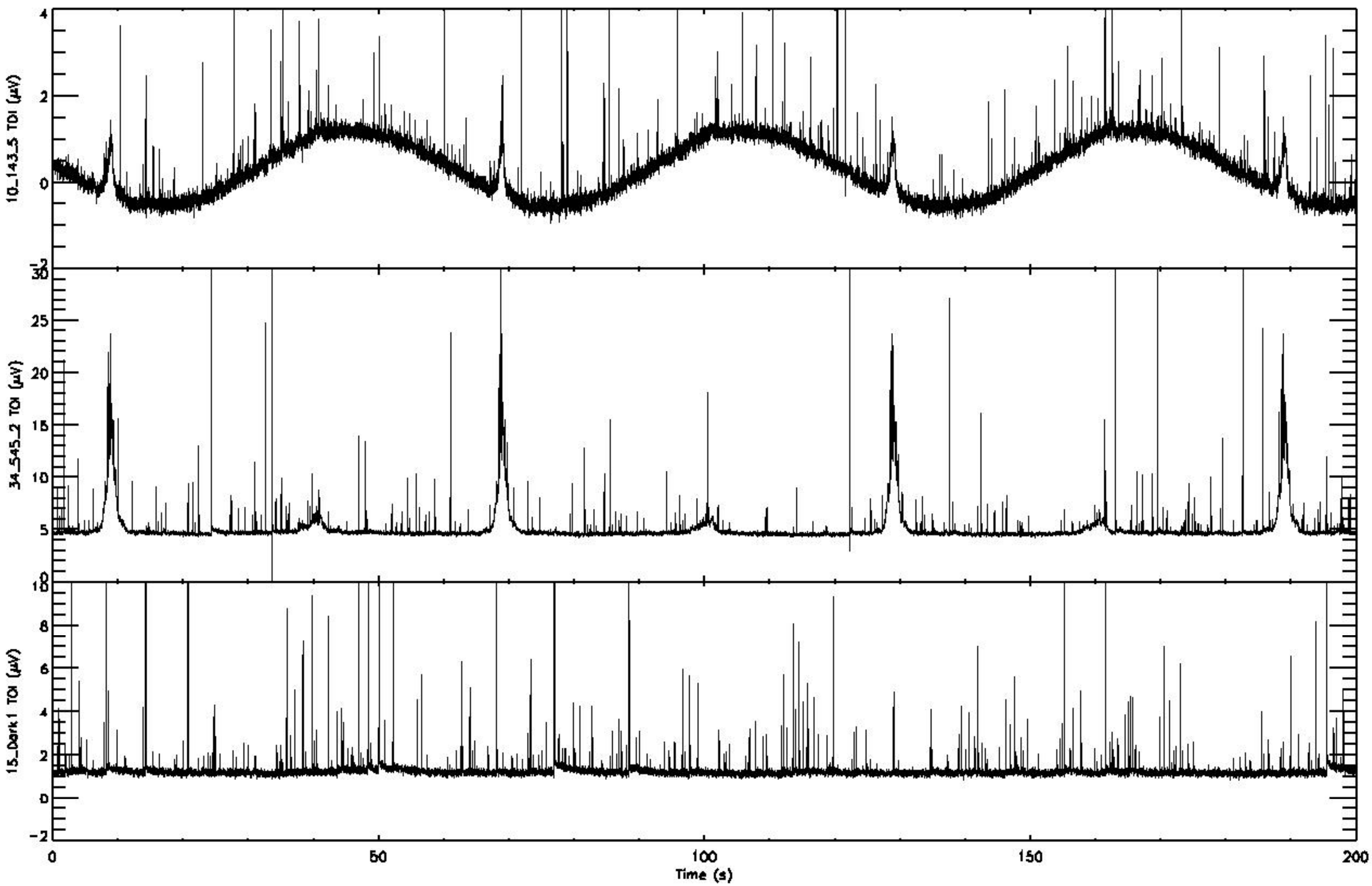
f_{NL}= 100

Positive f_{NL} = More Cold Spots

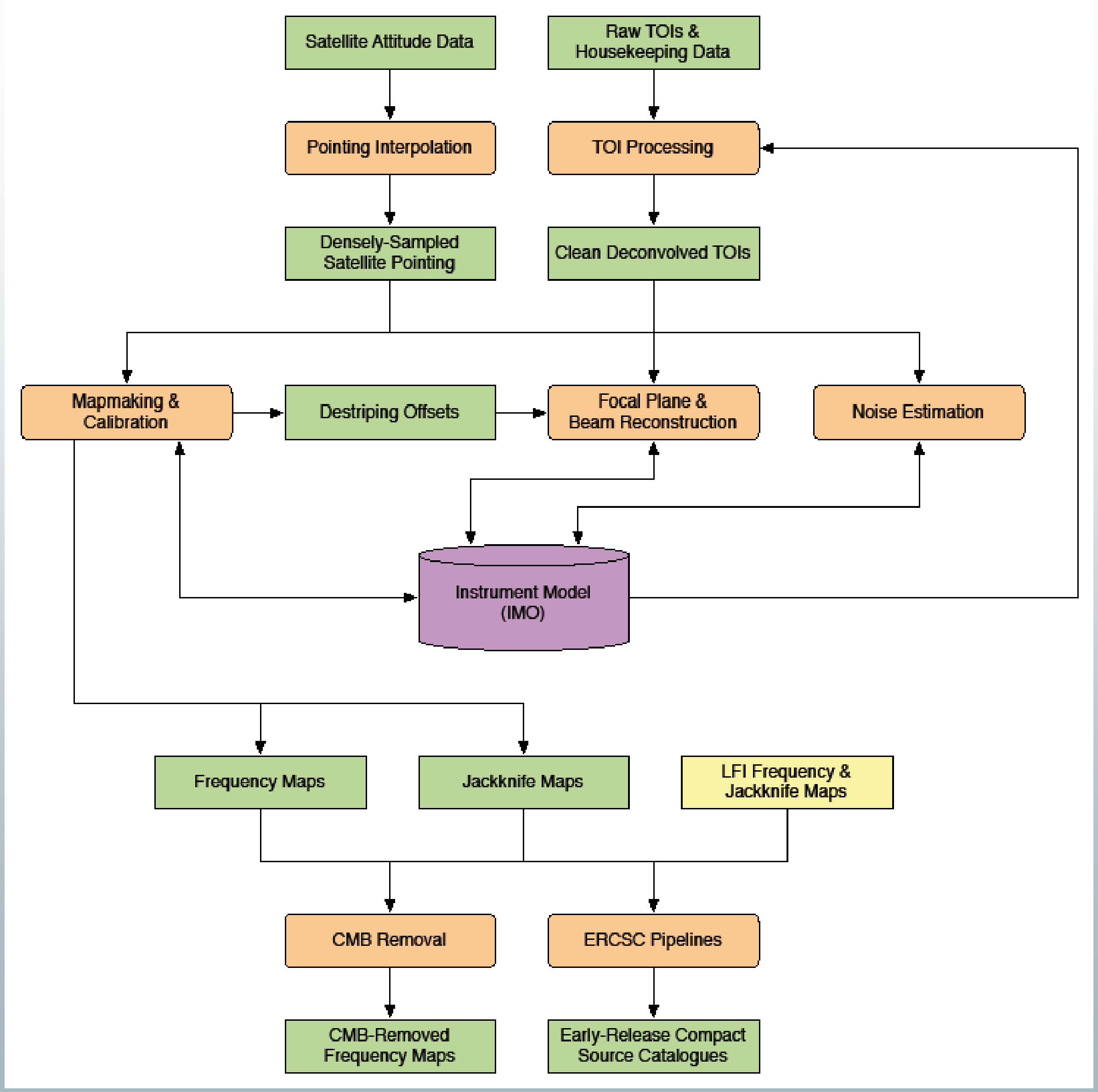


Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

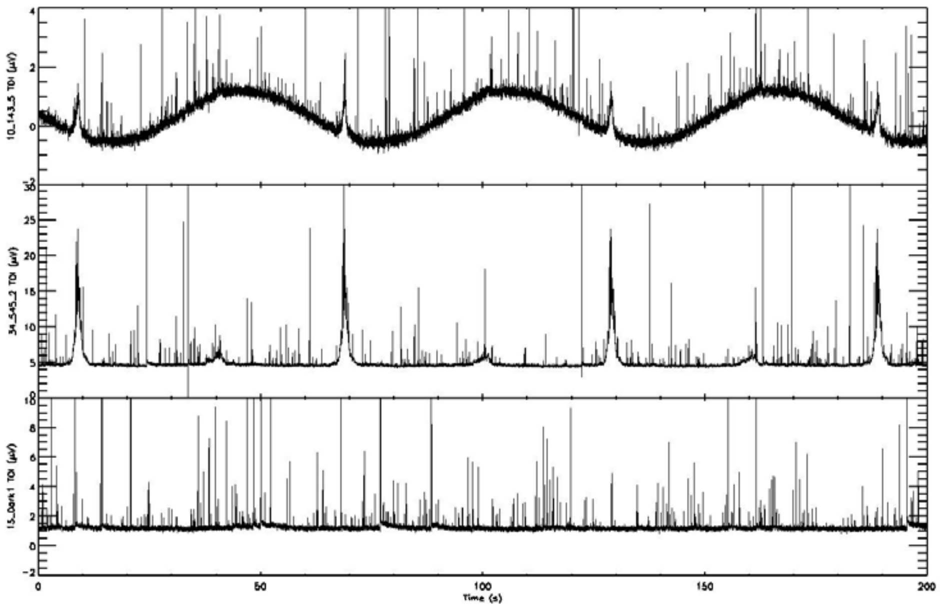
RAW TOIs (demodulated)

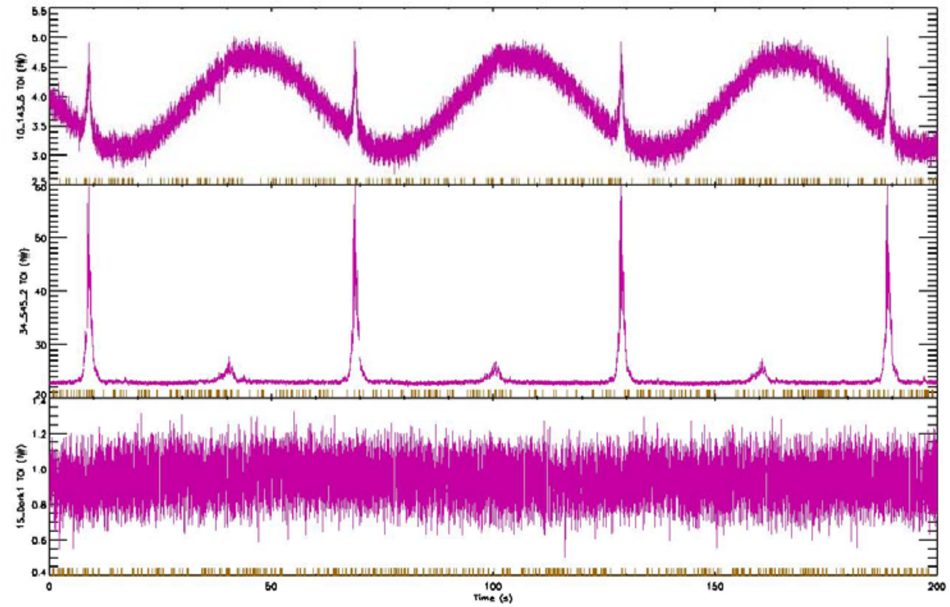


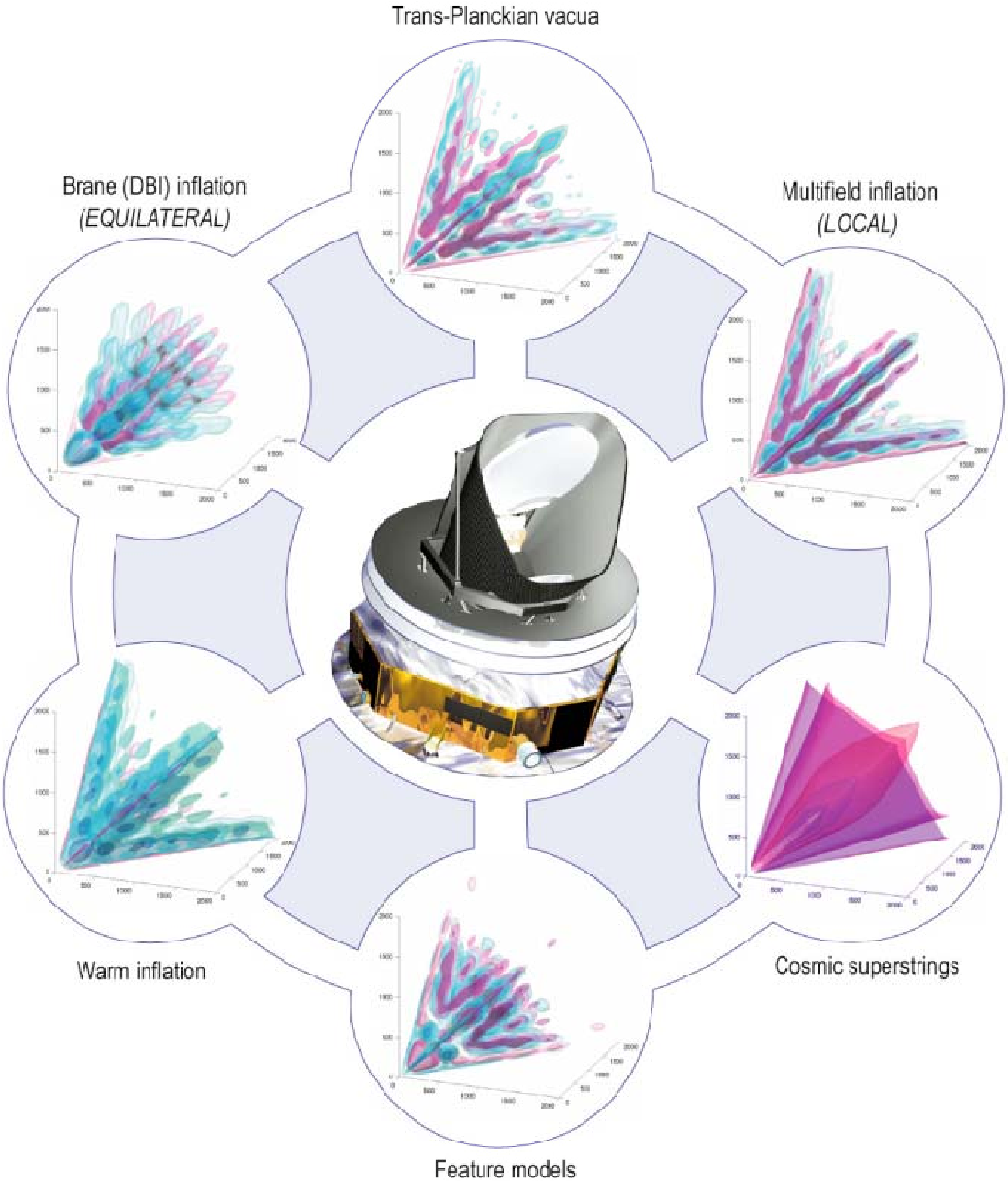
HFI Data flow overview



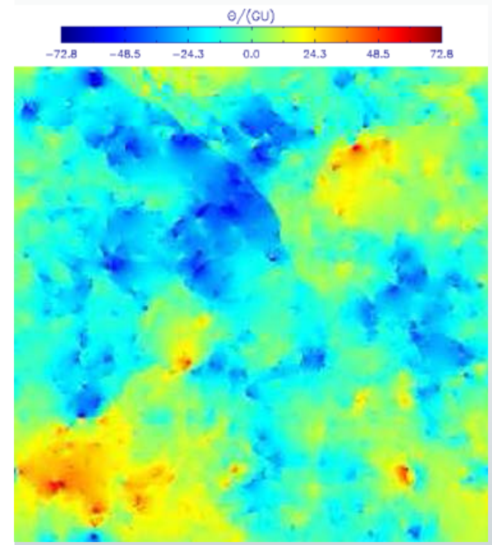
Cleaning TOIs...



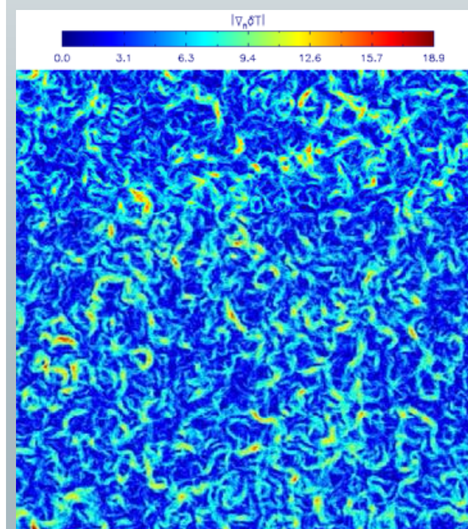




Trans-Planckian vacua
Brane (DBI) inflation
(EQUILATERAL)
Multifield inflation
(LOCAL)
Warm inflation
Cosmic superstrings
Feature models



−72.8 −48.5 −24.3 0.0 24.3 48.5 72.8



0.0 3.1 6.3 9.4 12.6 15.7 18.9

f, g, t and all that

- T only, analysis by Smidt et al in astroph1004.1409v2:
- WMAP-7 (@95CL)
  - $-10 < f_{NL} < 74$
  - $-7.4 < g_{NL}/10^5 < 8.2$
  - $-6 < \tau_{NL}/10^3 < 33$
- Planck: based on 143GHz, they suggest (@95%CL)
  - $\Delta f_{NL} \sim 15$
  - $\Delta g_{NL} \sim 2.5\ 10^5$
  - $\Delta \tau_{NL} \sim 3\ \ 10^3$
- EPIC: 200 times better sens.

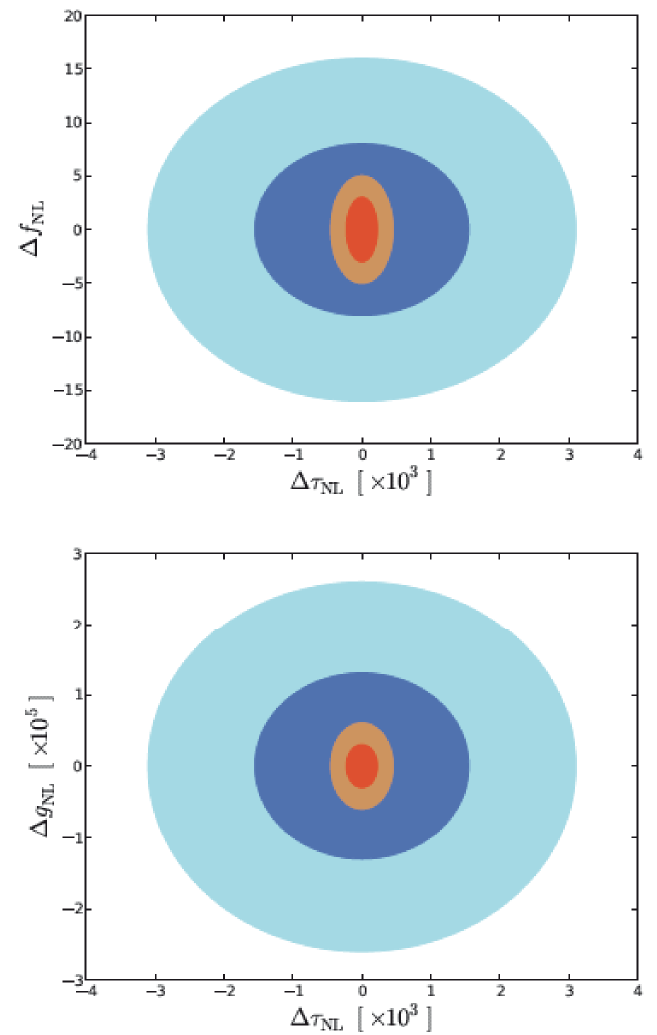
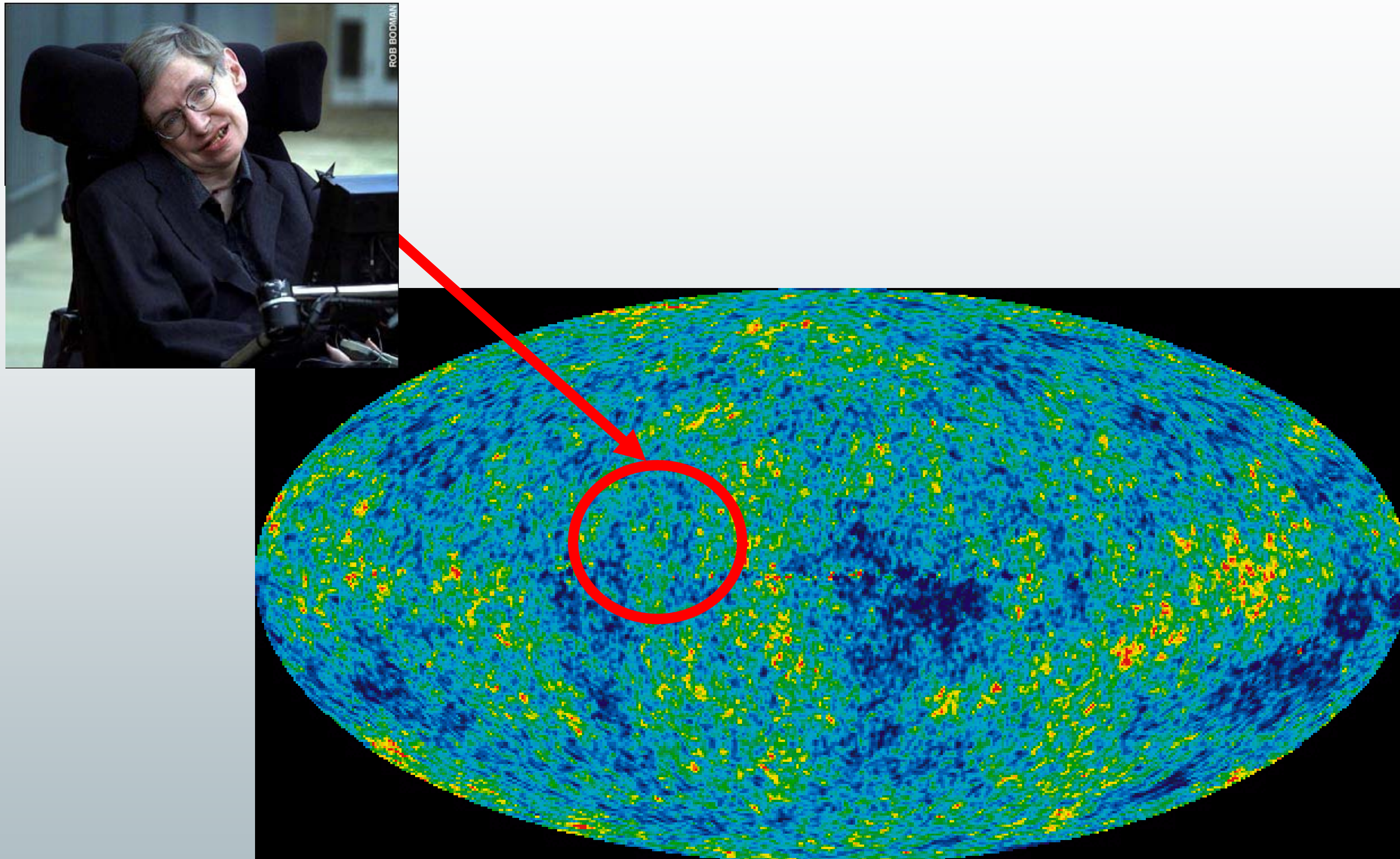
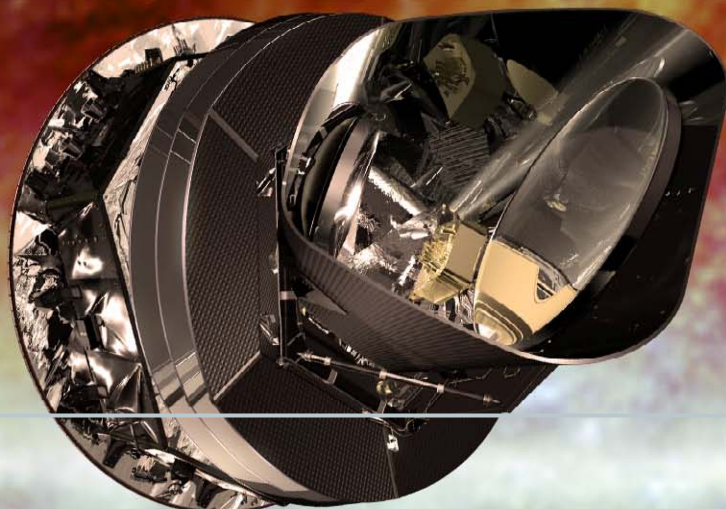


FIG. 12: Fisher confidence intervals for $f_{\rm NL}$, $g_{\rm NL}$ and $\tau_{\rm NL}$. The dark and light blue represent the 68% and 95% intervals respectively for Planck. The red and orange represent the 68% and 95% intervals respectively for EPIC.

SH in the sky?



Conclusions



Planck is in routine operations
Performances are as expected or better

On the horizon

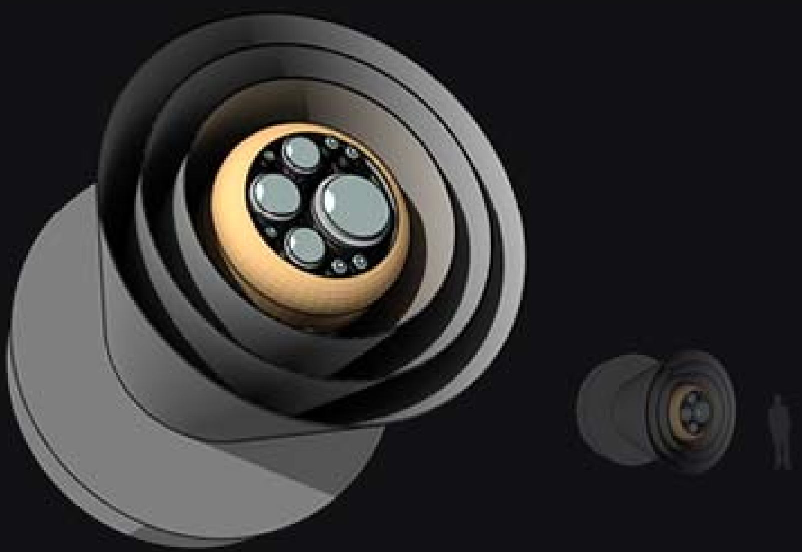
- Jan 2011: T foregrounds
- Jan 2012: P foregrounds?
- Jan 2013: T+P on 14 m data
- Jan 2014: all data collected (30months)
- Feb 2012: M3 pre-select.
- Nov 2012: M3 down sel
- Nov 2014: M3 selection
- Jan 2022: M3 launch
- Jan 2028: Core Final data del.?

B-Pol

A B-Polarization Satellite
Proposal for Detecting Primordial
Gravitational Waves from Inflation

- Intro
- Latest
- B-Pol Science
- Instrument
- People
- Institutions
- Supporters
- Documents

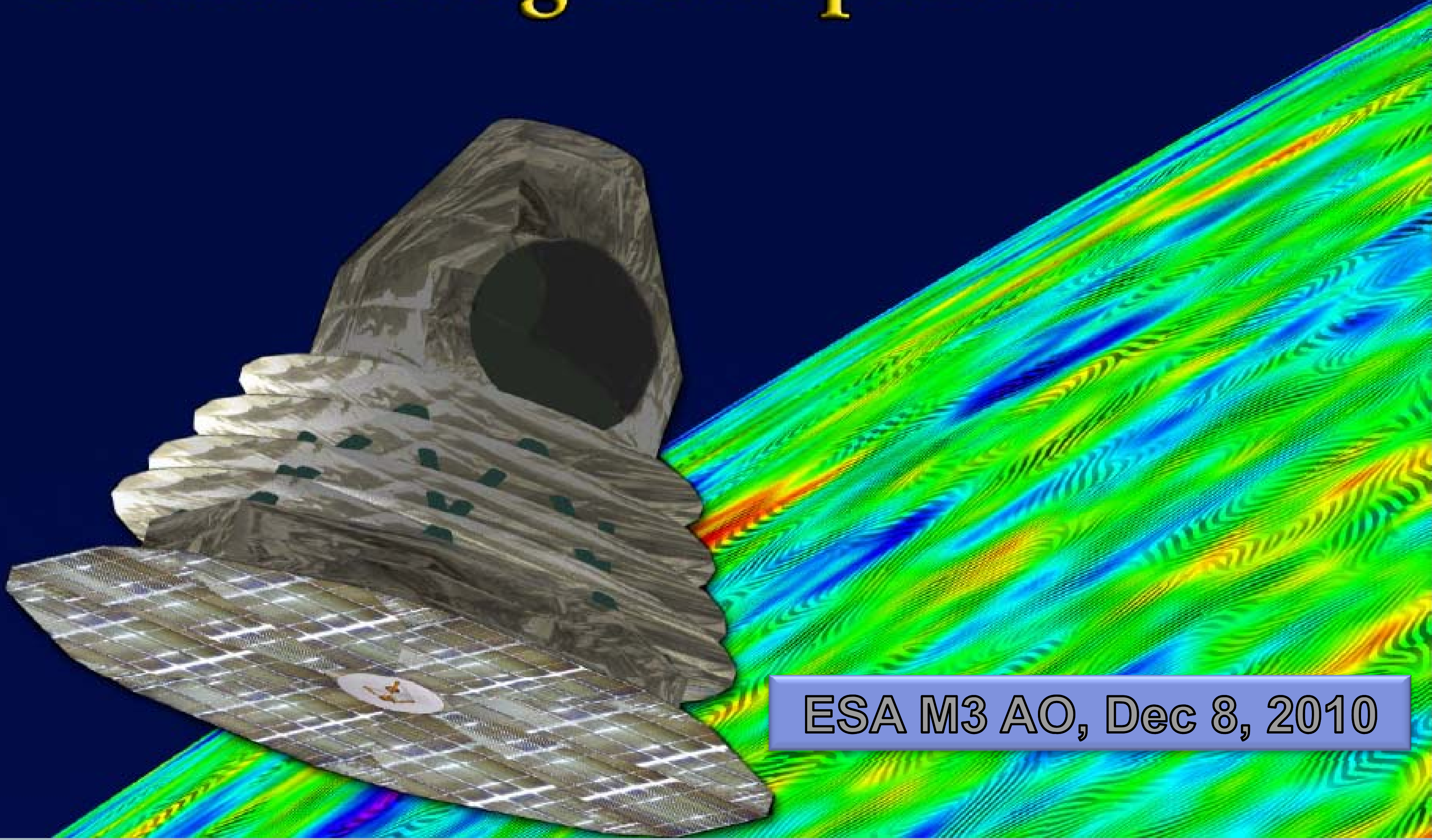
Introduction



We propose a Class M space mission aimed at detecting the primordial gravitational waves generated during inflation, in response to the Call for Proposals of ESA Cosmic Vision 2015-2025.

CORE

Cosmic ORigins Explorer



ESA M3 AO, Dec 8, 2010

Executive Summary

We propose *COrE*, the Cosmic Origins Explorer, a Class M space mission whose aim is to deliver high precision, reference-quality, full-sky maps of the polarized microwave and sub-mm sky in 15 bands ranging from 45 GHz to 795 GHz. Polarization maps in this frequency range will enable an unprecedented exploration of *Cosmic Origins*—from the origins of stars and the origin of cosmic structure to the origin of the Universe itself.

Owing to *COrE*'s exquisite polarization sensitivity, systematics control, and foreground separation capabilities, *COrE* will: improve sensitivity to the **B-mode signal of primordial gravitational waves** by two orders of magnitude; vastly increase the number of resolved modes available to probe the **cosmological initial conditions**, allow an unprecedented probe of **non-Gaussianity** and thus either detect or rule out the presence of non-linear physics during inflation or in a pre-Big Bang epoch; and measure **neutrino masses** to sufficient precision to distinguish the direct from the inverted neutrino hierarchies.

At the higher frequencies *COrE* will observe all-sky polarization maps for the first time. These maps will uncover the role played by magnetic fields in **star formation**; revolutionize our picture of the three-dimensional **galactic magnetic field** and of the properties of interstellar dust; determine directly the initial conditions for star formation in the **diffuse ISM**; and discover, characterize and time-resolve a large number of new **polarized galactic and extragalactic point sources**.

Sigma_{T/S}=5 10^{-4} after marginalising over other parameters

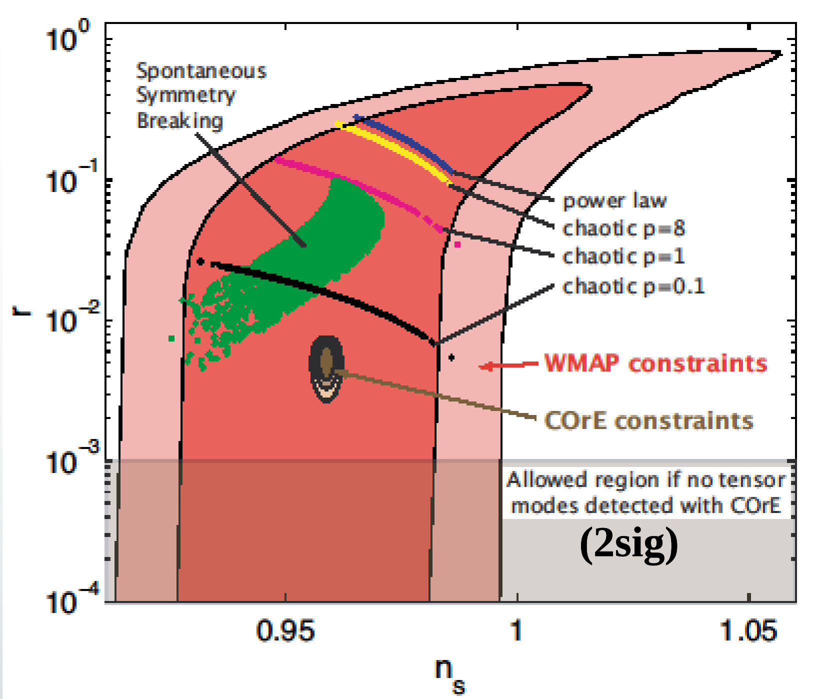
Improve to delta f_{NL} ~2, ie by 2.5 wrt Planck

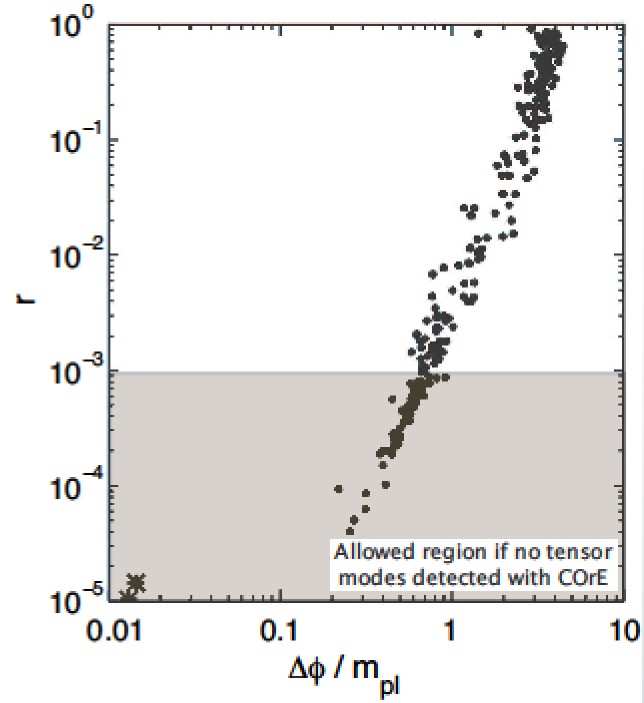
FOM on joint local, equilateral & flattened improved by ~20 /Planck

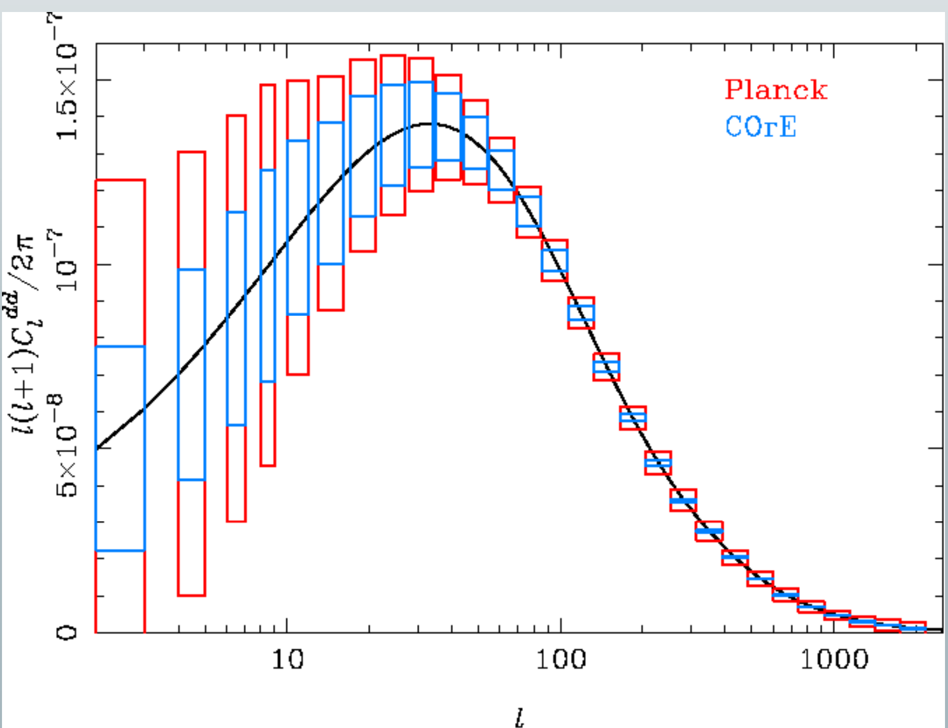
Performances Goals

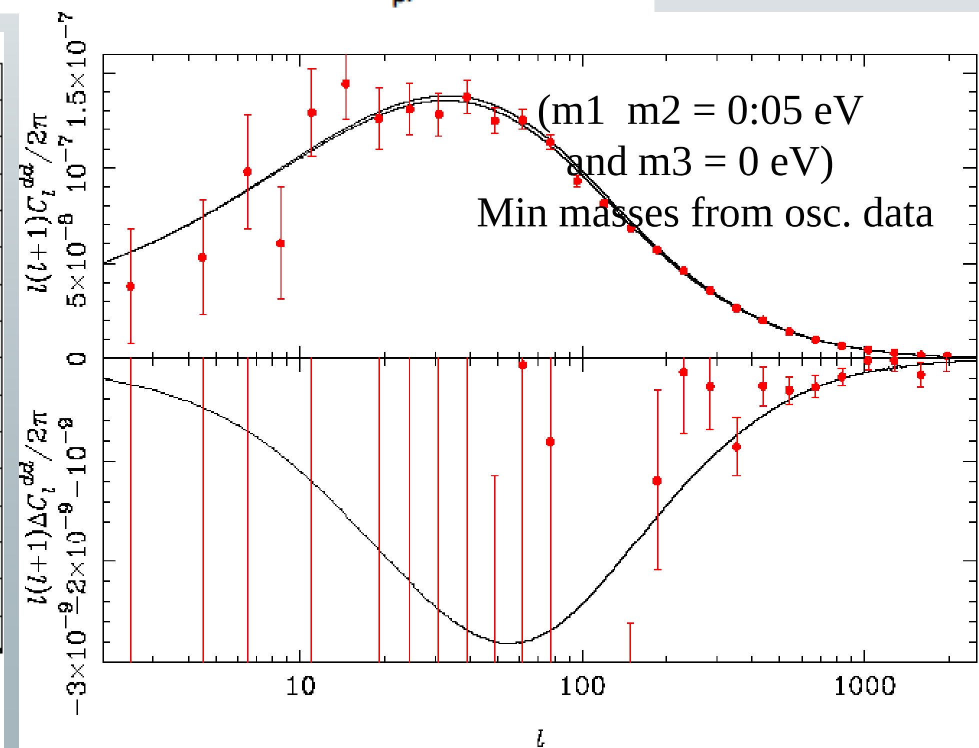
Central Freq. (GHz)	$\Delta\nu$ (GHz)	$N_{detectors}$	FWHM (arcmin)	Unpol. sensitivity (μK.arcmin)	Q & U sensitivity (μK.arcmin)
45	15	64	23.3	5.2	9.0
75	15	300	14	2.7	4.7
105	15	400	10	2.7	4.6
135	15	550	7.8	2.6	4.5
165	15	750	6.4	2.6	4.6
195	15	1150	5.4	2.6	4.5
225	15	1800	4.7	2.6	4.5
255	15	575	4.1	6.0	10.4
285	15	375	3.7	10.0	17
315	15	100	3.3	26.6	46
375	15	64	2.8	67.8	117
435	15	64	2.4	147.6	255
555	195	64	1.9	218	589
675	195	64	1.6	1268	3420
795	195	64	1.3	7744	20881

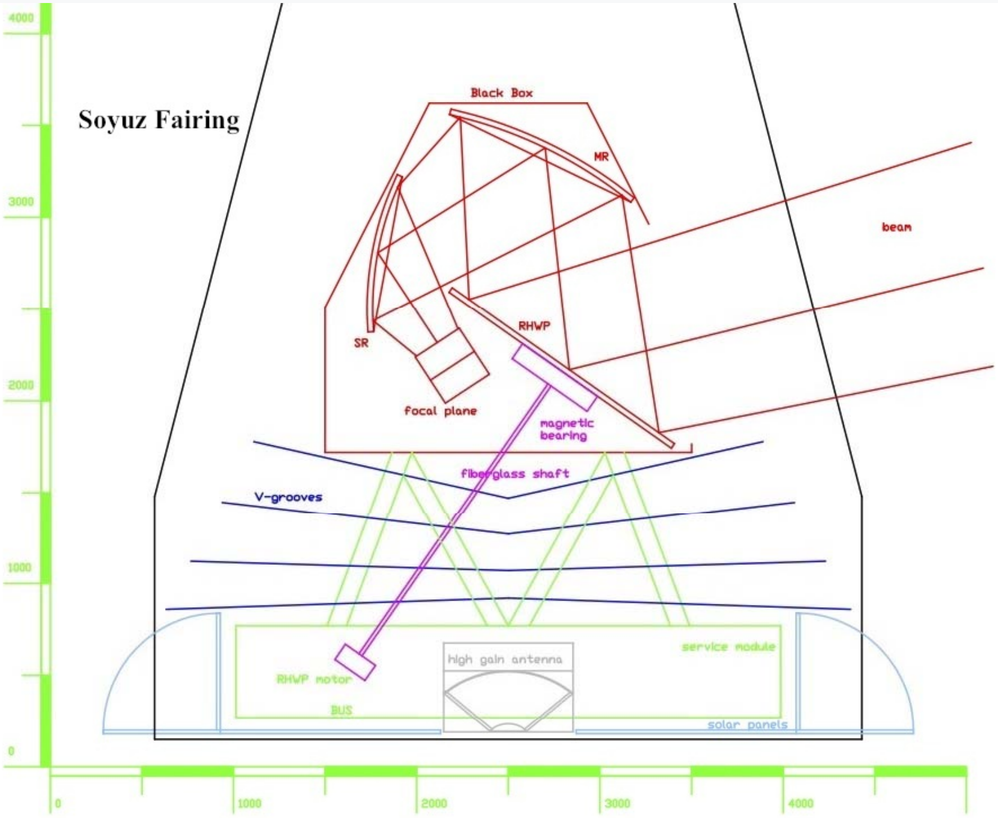
15 bands with dnu=15GHz (but for 3)
Diffraction limit, ie till 4.7' at 225GHz
CMB sensitivity better than 5μK.arcmin (B lensing lev.)
in ALL CMB channel (~1μk.arcmin aggregated)

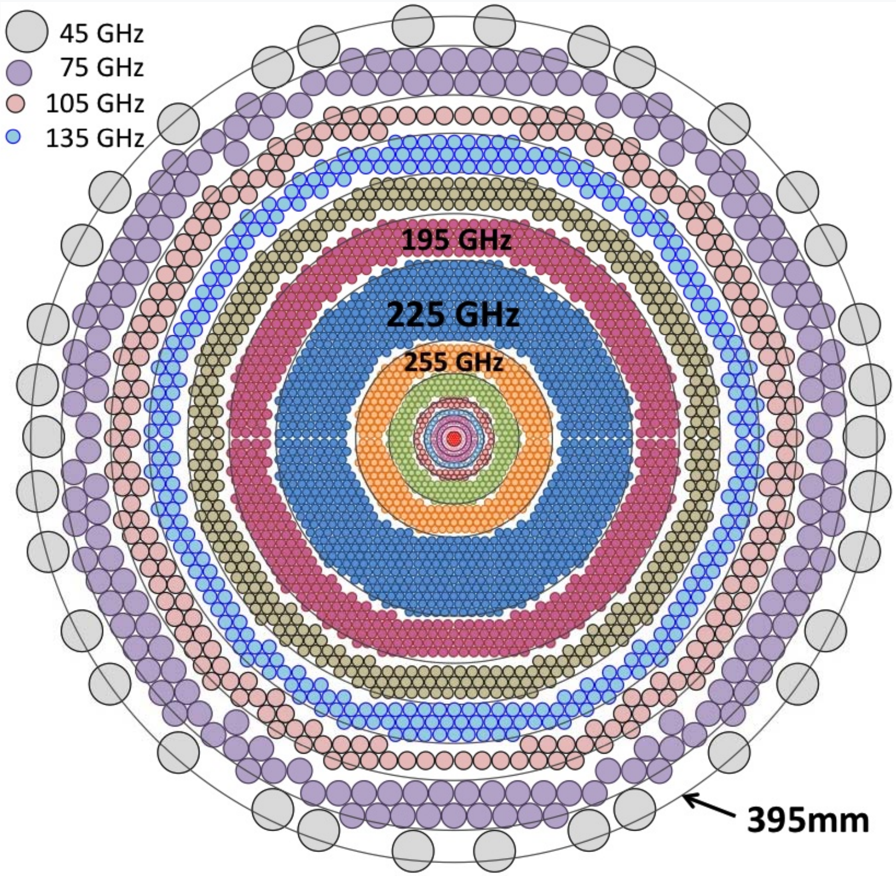

Spontaneous
Symmetry
Breaking
power law
chaotic p=8
chaotic p=1
chaotic p=0.1
WMAP constraints
COrE constraints
Allowed region if no tensor
modes detected with COrE
(2sig)
r
n_s


Allowed region if no tensor
modes detected with COrE
r
Δφ / m_pl


Planck
COrE
l(l+1)C_l^dd/2π
l


(m1 m2 = 0:05 eV
and m3 = 0 eV)
Min masses from osc. data
l(l+1)C_l^dd/2π
l(l+1)ΔC_l^dd/2π
l


Soyuz Fairing
Black Box
MR
SR
RHWP
focal plane
magnetic bearing
fiberglass shaft
beam
V-grooves
service module
high gain antenna
RHWP motor
BUS
solar panels
0
1000
2000
3000
4000


45 GHz
75 GHz
105 GHz
135 GHz
195 GHz
225 GHz
255 GHz
395mm

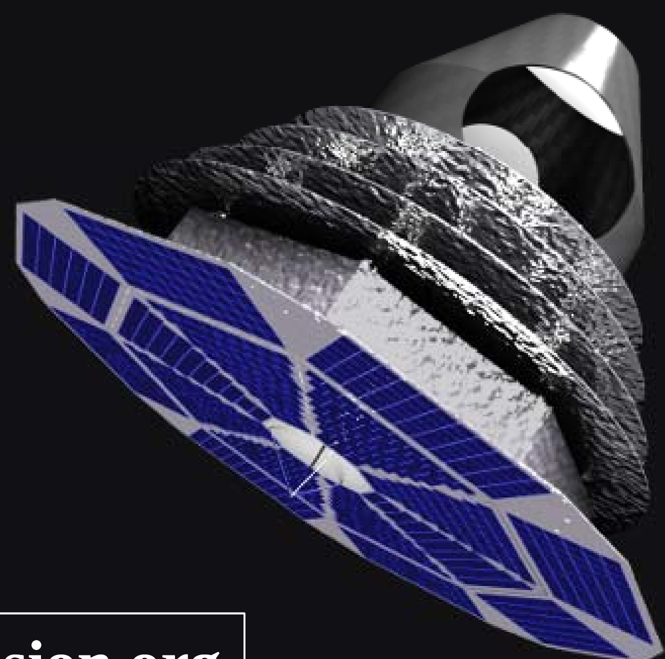
COrE

Cosmic Origins Explorer

- Intro
- COrE Science
- Instrument
- Mission
- People
- Institutions
- Documents

A proposal in response to the European Space Agency Cosmic Vision 2015-2025 Call

A satellite mission for probing cosmic origins, neutrino masses and the origin of stars and magnetic fields through a high sensitivity survey of the microwave polarization of the entire sky



http://www.core-mission.org