CMB polarization measurements and the Planck Mission

Paolo de Bernardis

Dipartimento di Fisica, Universita' La Sapienza, Roma

Rencontres de Blois

19/July/2010

CMB Polarization – Why ?

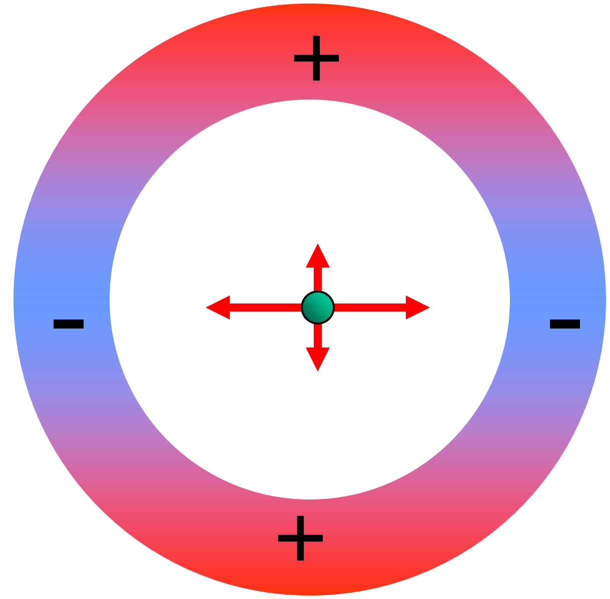
- An **inflation** phase at **$E=10^{16}$–10^{15} GeV** ($t=10^{-36}$-10^{-33} s) is currently the most popular scenario to explain
  - The origin of our universe
  - The geometry of our universe
  - The origin and morphology of structures in our universe
  - The lack of defects, and the smoothness of the CMB at super-horizon scales.
- Inflation is a **predictive** theory:
  1. Any initial curvature is flattened by the huge expansion: we expect an Euclidean universe.
  2. Adiabatic, gaussian density perturbations are produced from quantum fluctuations. This is the physical origin for structures in the Universe.
  3. The power spectrum of scalar perturbations is approximately scale invariant, $P(k)=Ak^{n-1}$ with n slightly less than 1.
  4. Tensor perturbations produce a background of primordial gravitational waves (PGW)
- 1.,2.,3. have been confirmed already by measurements of CMB anisotropy
- 4. can be tested measuring CMB polarization

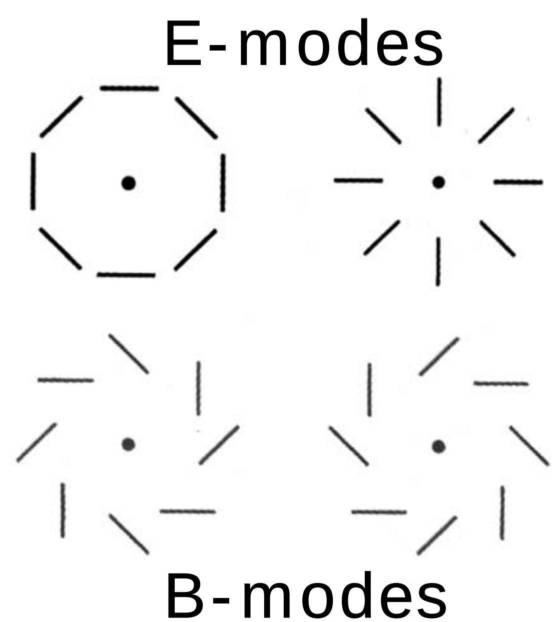
CMB Polarization – Why ?

- Linear Polarization of CMB photons is induced via Thomson scattering by quadrupole anisotropy at recombination ($z=1100$, $t=1.2\times10^{13}$s).

- In turn, quadrupole anisotropy is induced by
  - Density perturbations (*scalar* relics of inflation) producing a curl-free polarization vectors field (**E-modes**)
  - Gravitational waves (*tensor* relics of inflation) producing both curl-free and curl polarization fields (**B-modes**)

- No other sources for a curl polarization field of the CMB at large angular scales:
- **B-modes are a clear signature of inflation**.





E-modes & B-modes

Spin-2 quantity

Spin-2 basis

$$(Q \pm iU)(\vec{n}) = \sum_{\ell,m} \left(a^{E}_{\ell m} \pm i a^{B}_{\ell m} \right) {}_{\pm 2}Y_{\ell m}(\vec{n})$$

- From the measurements of the Stokes Parameters $\boldsymbol{Q}$ and $\boldsymbol{U}$ of the linear polarization field we can recover both irrotational and rotational a_{lm} by means of modified Legendre transforms:

E-modes produced by scalar and tensor perturbations

$$a^{E}_{\ell m} = \frac{1}{2} \int d\Omega W(\vec{n}) \left[(Q + iU)(\vec{n}) {}_{+2}Y_{\ell m}(\vec{n}) + (Q - iU)(\vec{n}) {}_{-2}Y_{\ell m}(\vec{n}) \right]$$

B-modes produced **only** by tensor perturbations

$$a^{B}_{\ell m} = \frac{1}{2i} \int d\Omega W(\vec{n}) \left[(Q + iU)(\vec{n}) {}_{+2}Y_{\ell m}(\vec{n}) - (Q - iU)(\vec{n}) {}_{-2}Y_{\ell m}(\vec{n}) \right]$$

B-modes from P.G.W.

- The amplitude of this effect is very small, but depends on the Energy scale of inflation. In fact the amplitude of tensor modes normalized to the scalar ones is:

$$R = \left(\frac{T}{S}\right)^{1/4} \equiv \left(\frac{C_2^{GW}}{C_2^{Scalar}}\right)^{1/4} \cong \frac{V^{1/4}}{3.7\times 10^{16}\,\mathrm{GeV}}$$

Inflation potential

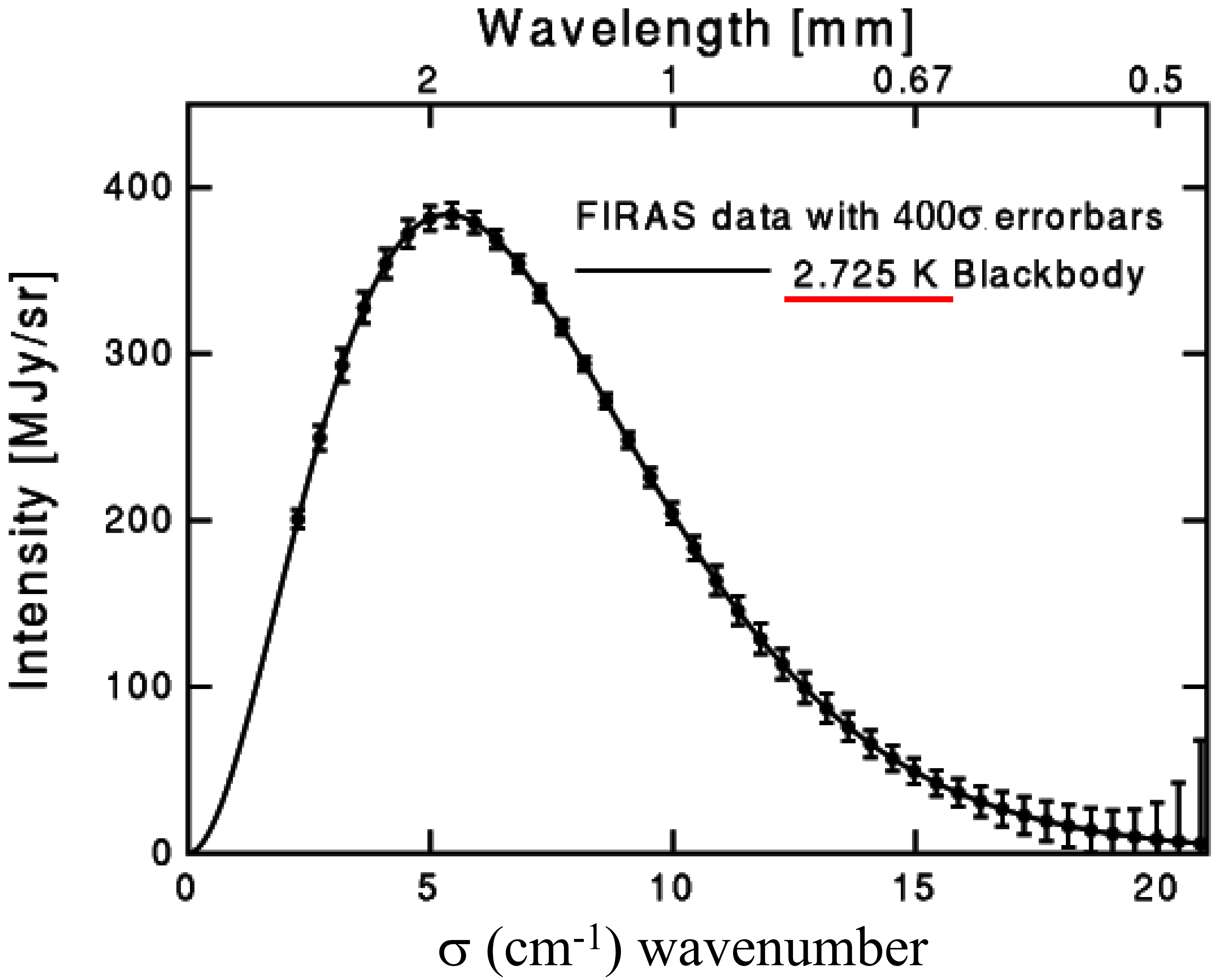
- and

$$\sqrt{\frac{\ell(\ell+1)}{2\pi}c^B_{\ell\,\mathrm{max}}} \cong 0.1\mu K\left[\frac{V^{1/4}}{2\times 10^{16}\,\mathrm{GeV}}\right]$$

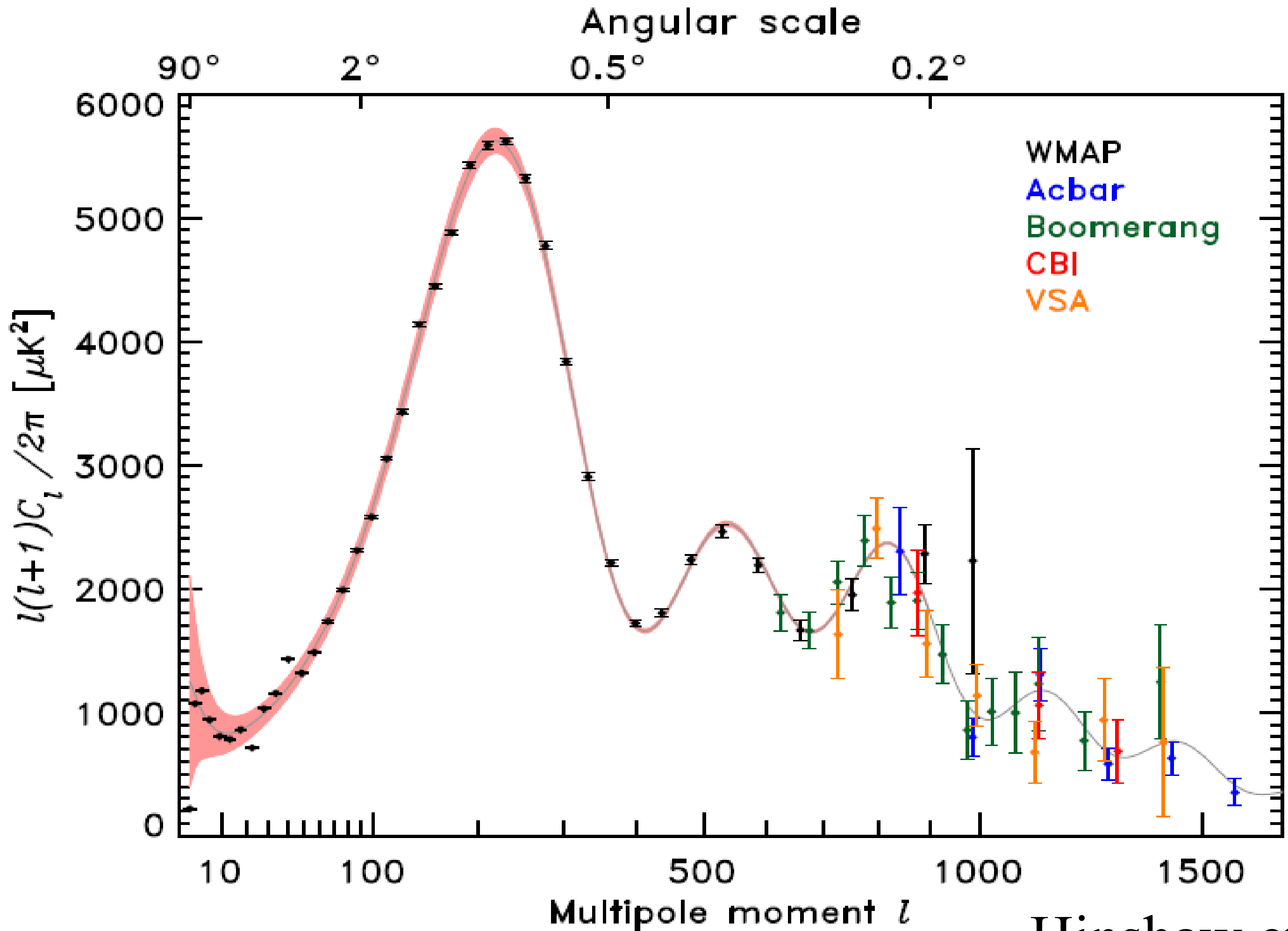
- There are theoretical arguments to expect that the energy scale of inflation is close to the scale of GUT i.e. around 10^{16} GeV.
- The measurement of B-modes is a good way to investigate fundamental physics at extremely high energies.

The signal is extremely weak

- The current upper limit on anisotropy at large scales gives R<0.5 (at 2σ)
- A competing effect is lensing of E-modes, which is important at large multipoles.
- Nobody really knows how to detect this.
  - Pathfinder experiments are needed
- Whatever smart, ambitious experiment we design to detect the B-modes:
  - It needs to be extremely sensitive
  - It needs an extremely careful control of systematic effects
  - It needs careful control of foregrounds
  - It will need independent experiments with orthogonal systematic effects.
- A lot has been done, but there is still a long way to go: ...



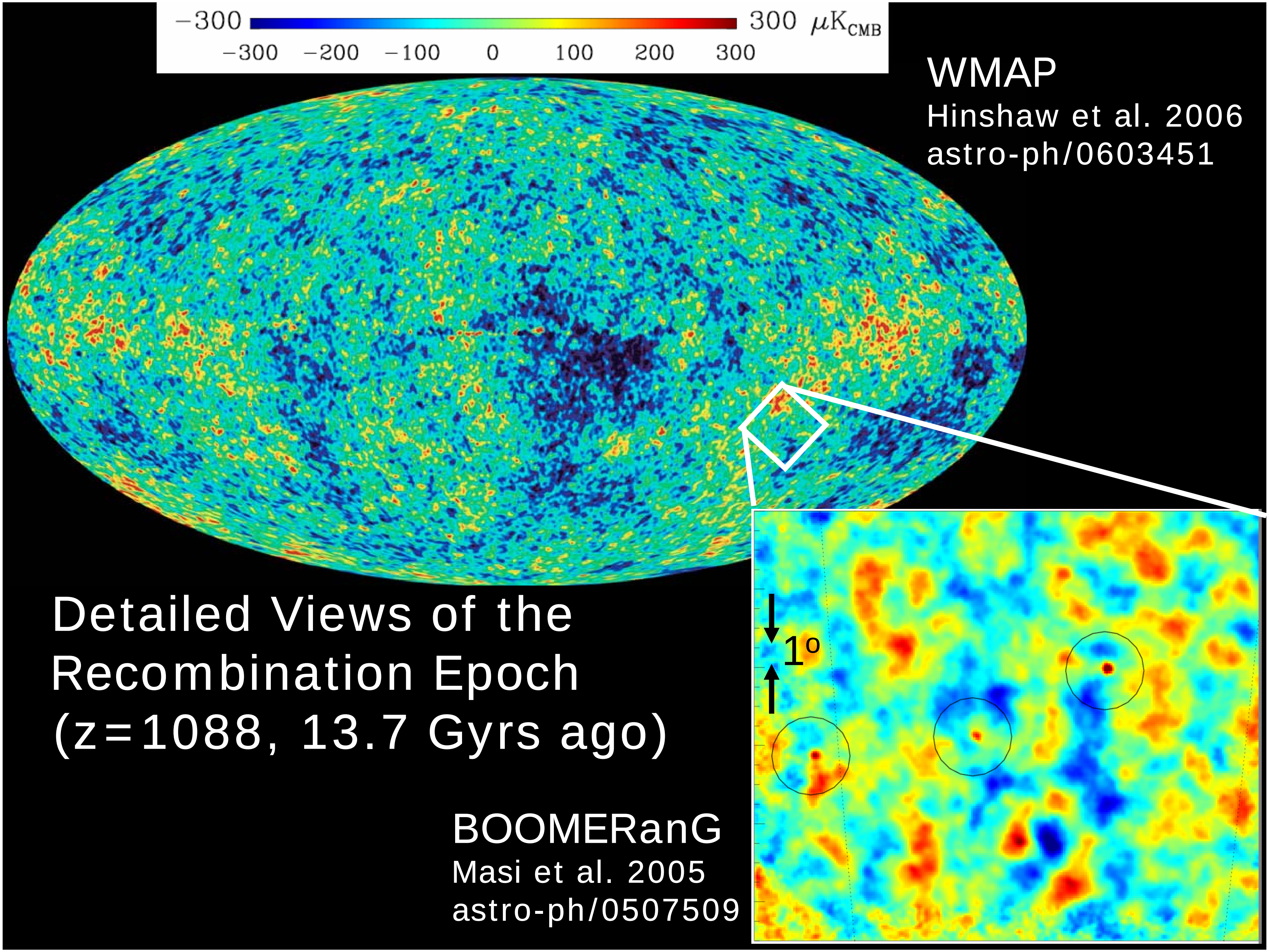
CMB Temperature (1992): 3K



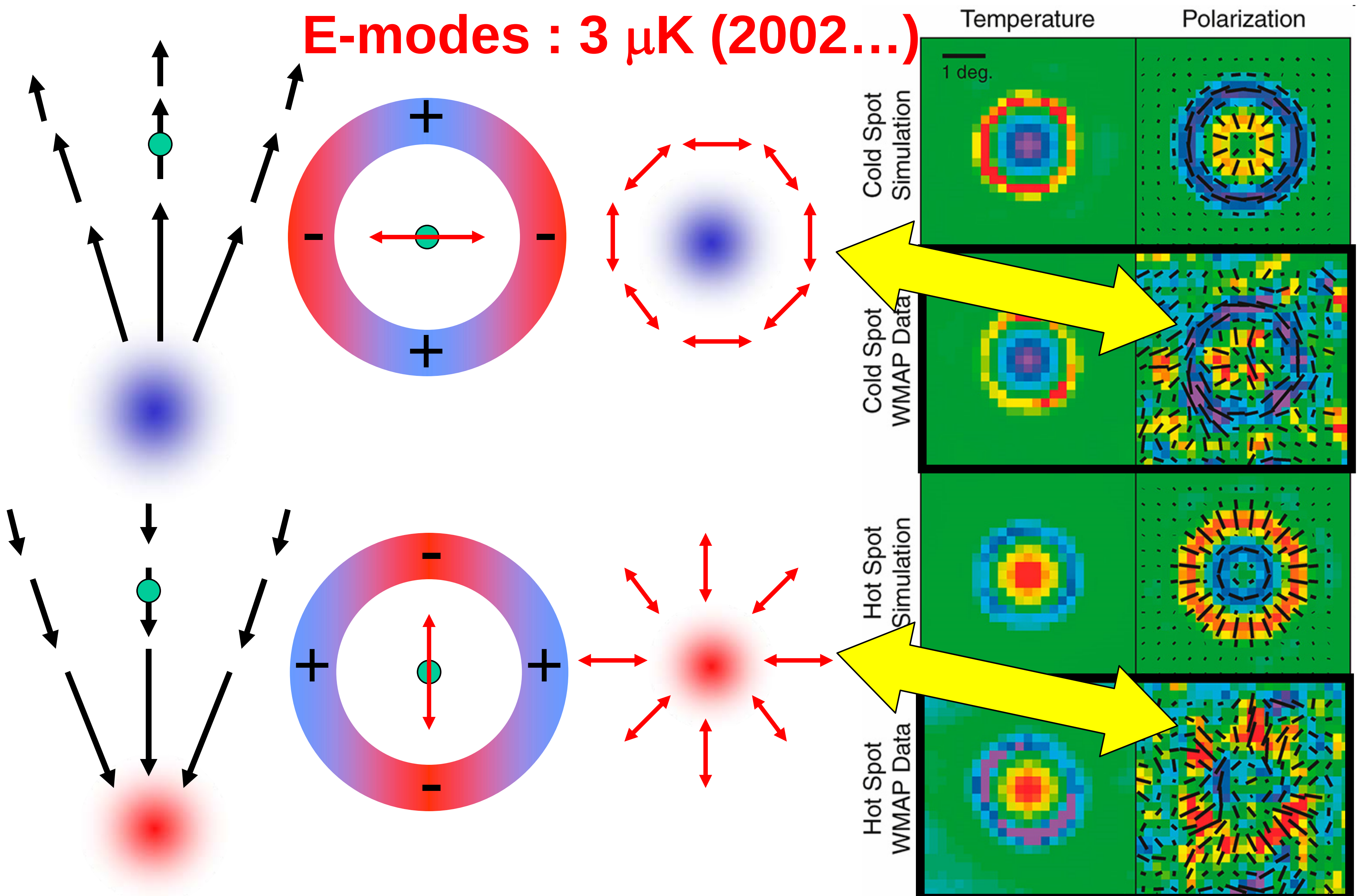
Hinshaw et al. 2006

Fig. 18.— The *WMAP* three-year power spectrum (in black) compared to other recent measurements of the CMB angular power spectrum, including Boomerang (Jones et al. 2005), Acbar (Kuo et al. 2004), CBI (Readhead et al. 2004), and VSA (Dickinson et al. 2004). For clarity, the $l < 600$ data from Boomerang and VSA are omitted; as the measurements are consistent with *WMAP*, but with lower weight. These data impressively confirm the turnover in the 3rd acoustic peak and probe the onset of Silk damping. With improved sensitivity on sub-degree scales, the *WMAP* data are becoming an increasingly important calibration source for high-resolution experiments.

CMB Temperature Anisotropy (1998 …): 100 μK


−300 300 μK_CMB
−300 −200 −100 0 100 200 300
WMAP
Hinshaw et al. 2006
astro-ph/0603451
Detailed Views of the
Recombination Epoch
(z=1088, 13.7 Gyrs ago)
1°
BOOMERanG
Masi et al. 2005
astro-ph/0507509

E-modes : 3 μK (2002…)



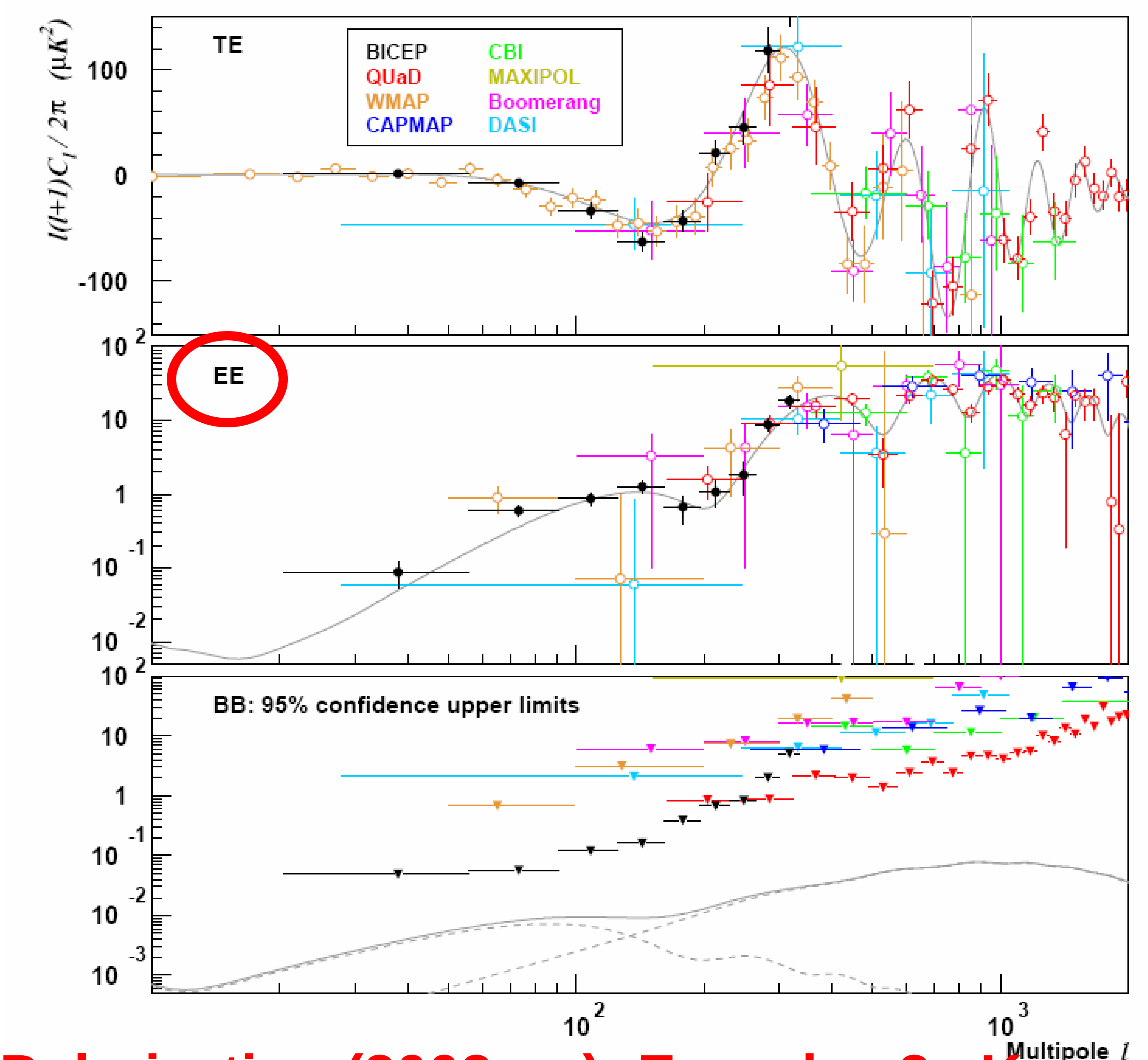
Velocity field near density fluctuation

Resulting anisotropy seen by e-

Resulting polarization pattern

Komatsu et al. 2010 – astro-ph/1001.4538

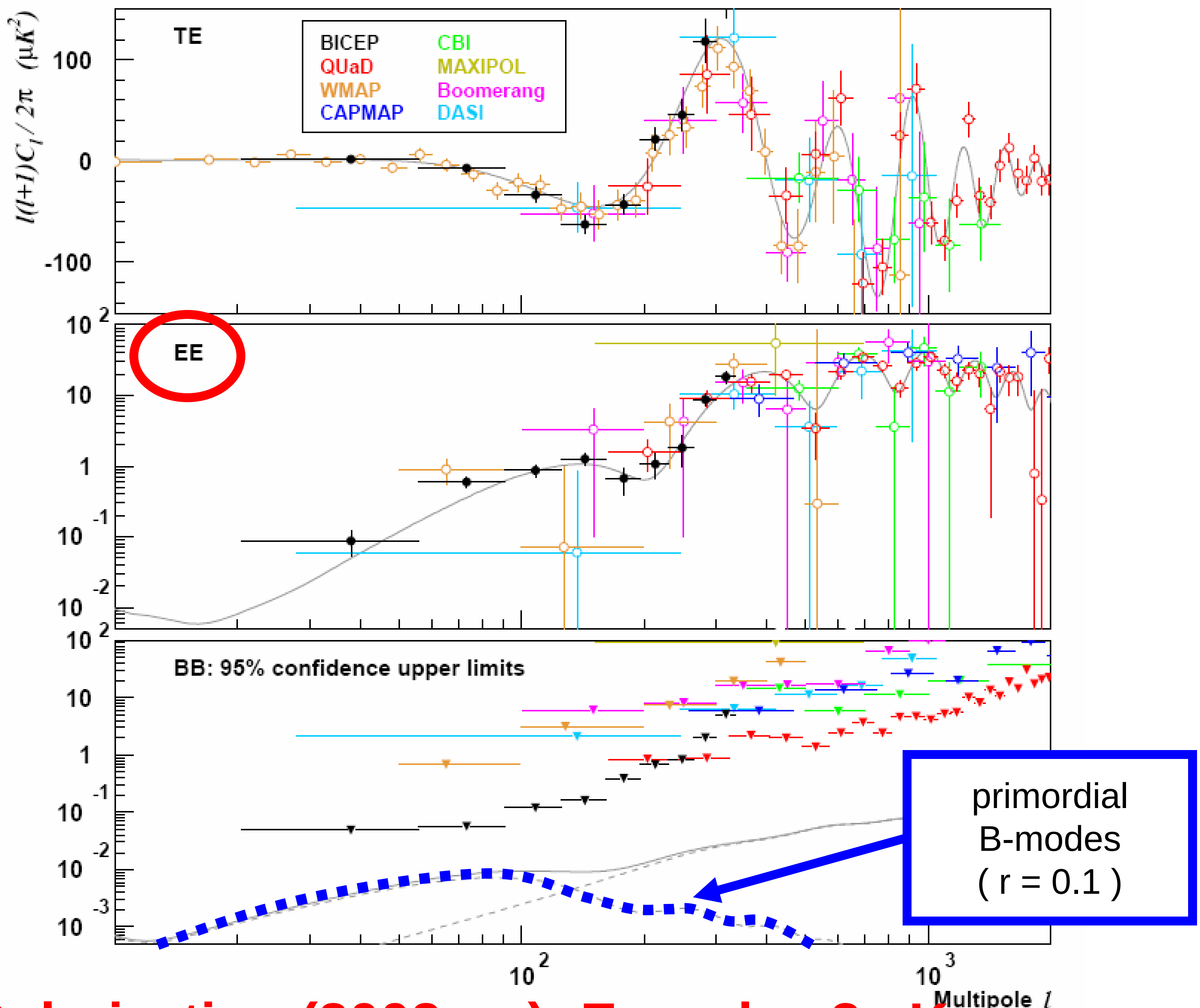
WMAP7 measured data (stacked)



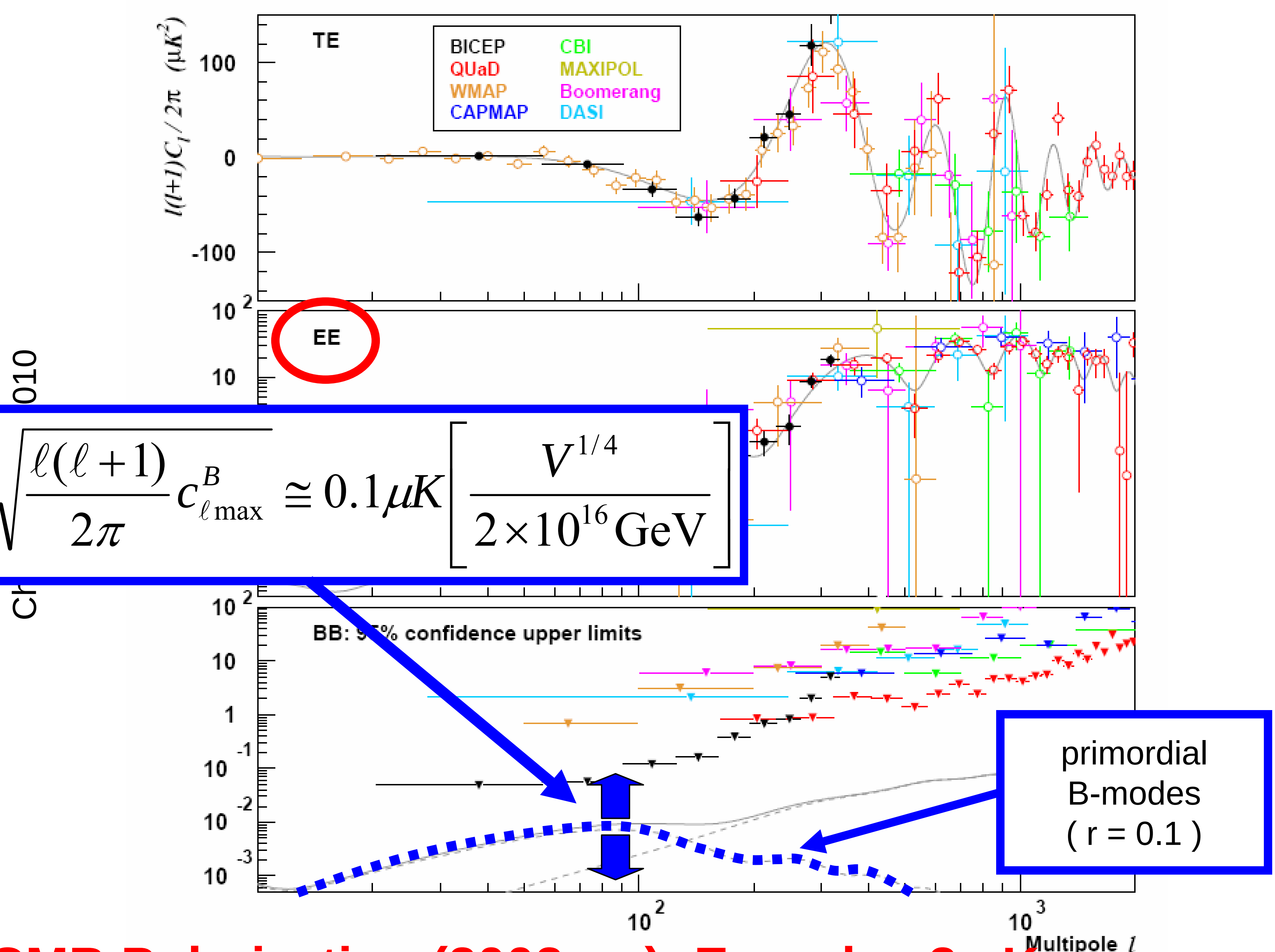
Chiang et al. 2010

CMB Polarization (2002 …): E-modes 3 μK

Chiang et al. 2010

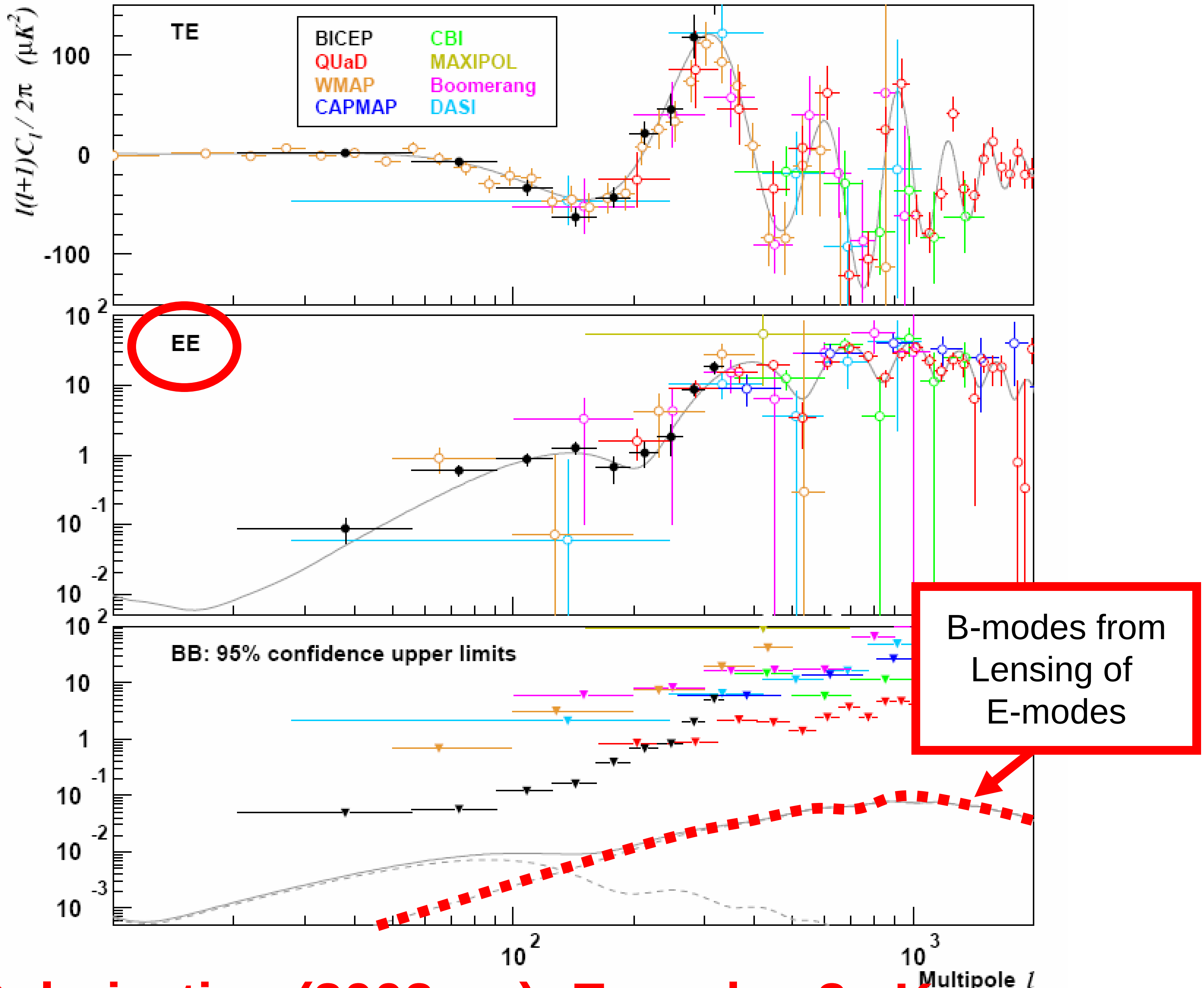


CMB Polarization (2002 …): E-modes 3 μK



$$\sqrt{\frac{\ell(\ell+1)}{2\pi}c^{B}_{\ell\max}} \cong 0.1\mu K\left[\frac{V^{1/4}}{2\times10^{16}\,\mathrm{GeV}}\right]$$

CMB Polarization (2002 …): E-modes 3 μK

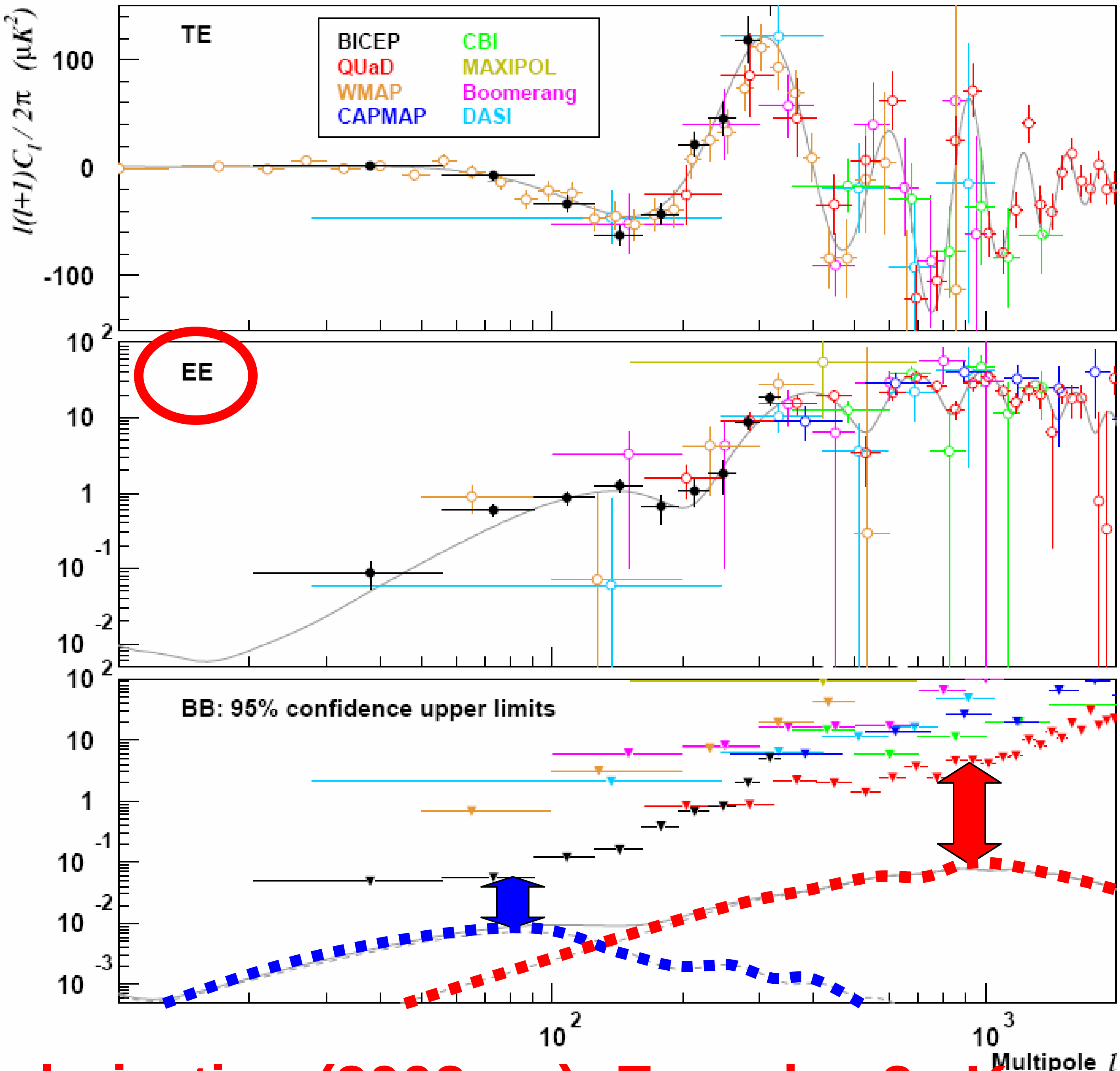


CMB Polarization (2002 …): E-modes 3 μK

Lensing of E-modes

- E-modes have been measured already with good accuracy, and will be measured with exquisite accuracy by Planck and other experiments.
- They depend on the distribution of mass (mainly dark matter) so their study can shed light on the nature of dark matter (including massive neutrinos).
- While the primordial B-mode is maximum at multipoles around 100 ($\theta=2°$), the lensed B-mode is maximum at multipoles around 1000 ($\theta=0.2°$), requiring high angular resolution polarization experiments

Chiang et al. 2010



CMB Polarization (2002 …): E-modes 3 μK

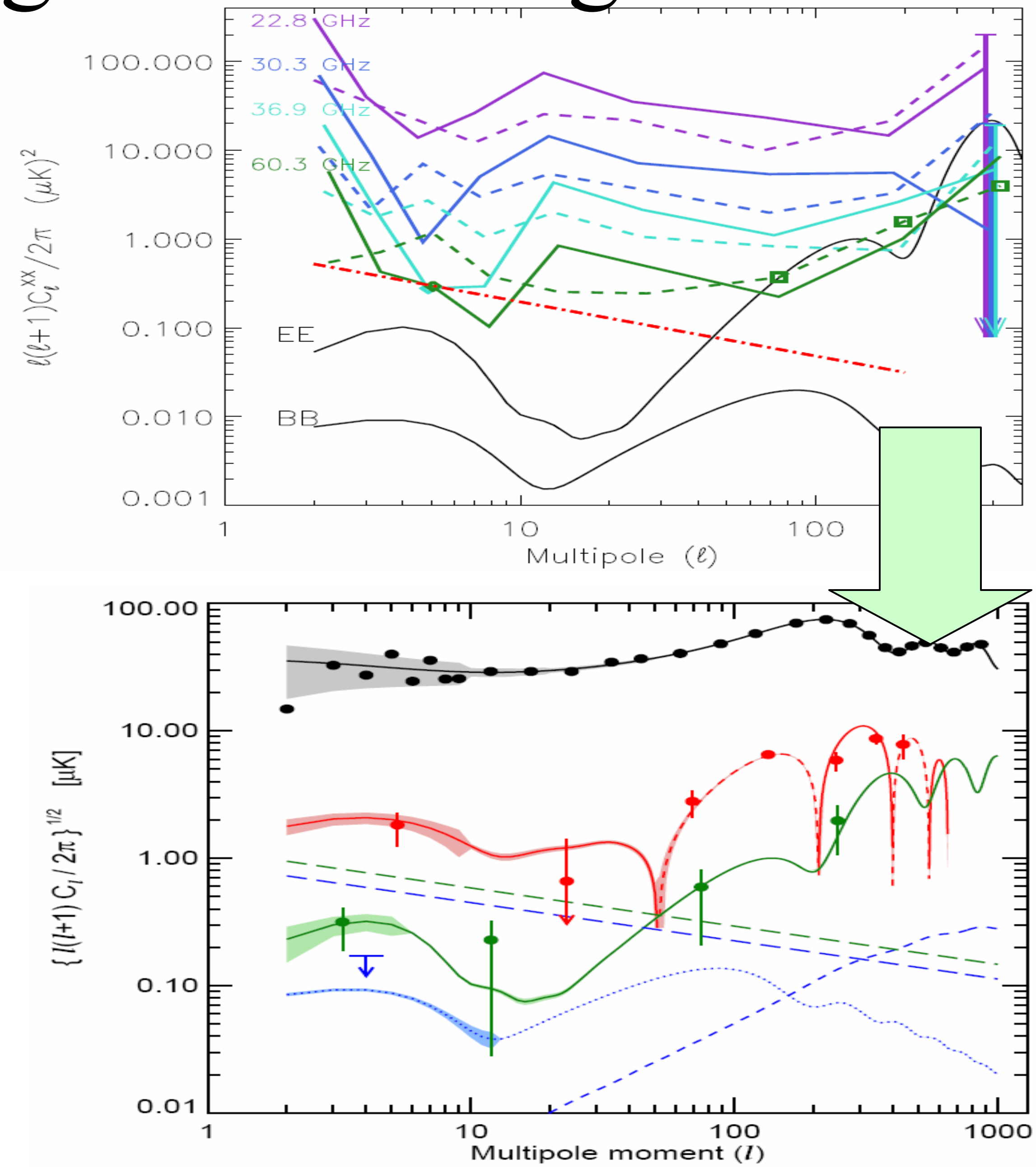
How to improve ?

1. Knowledge of Foregrounds
   (Planck)
2. Sensitivity
3. Control of Systematic Effects

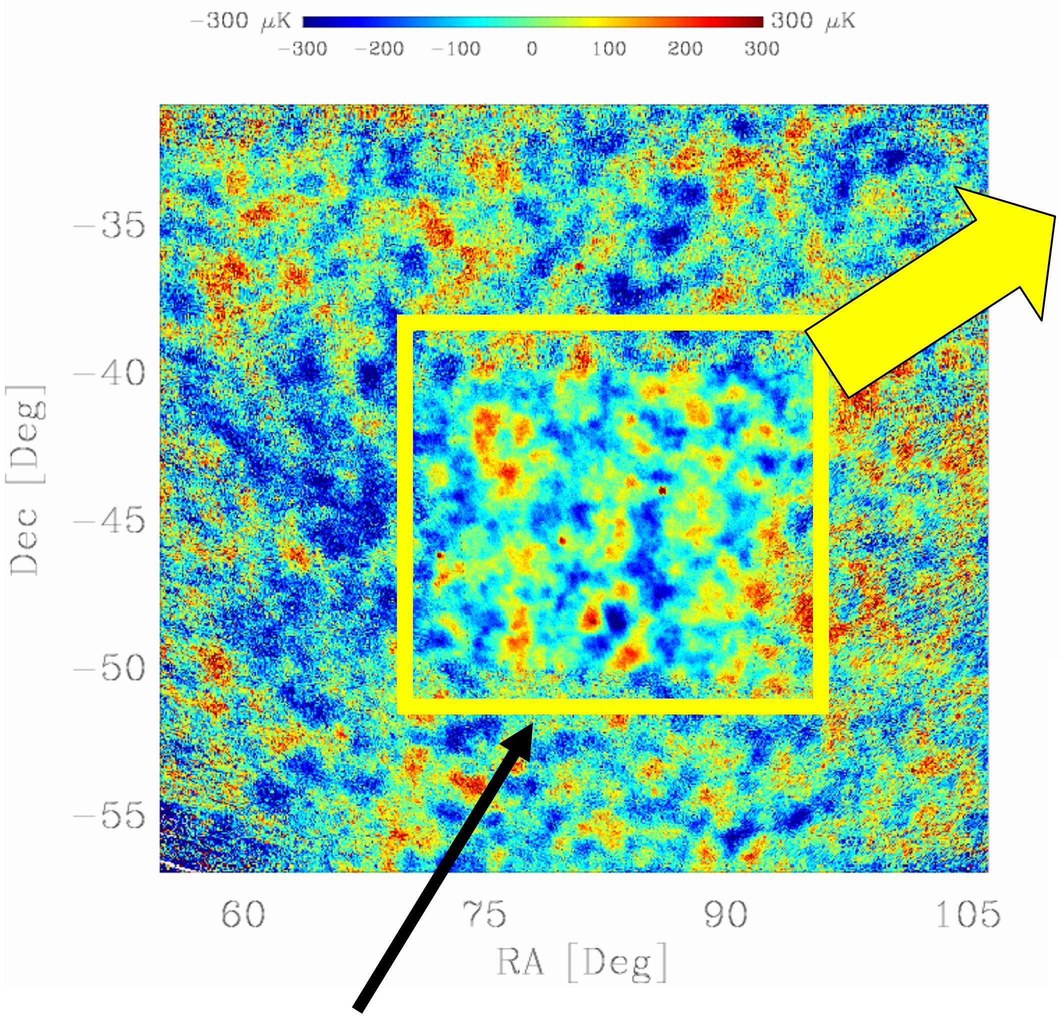
1. Knowledge of the foregrounds

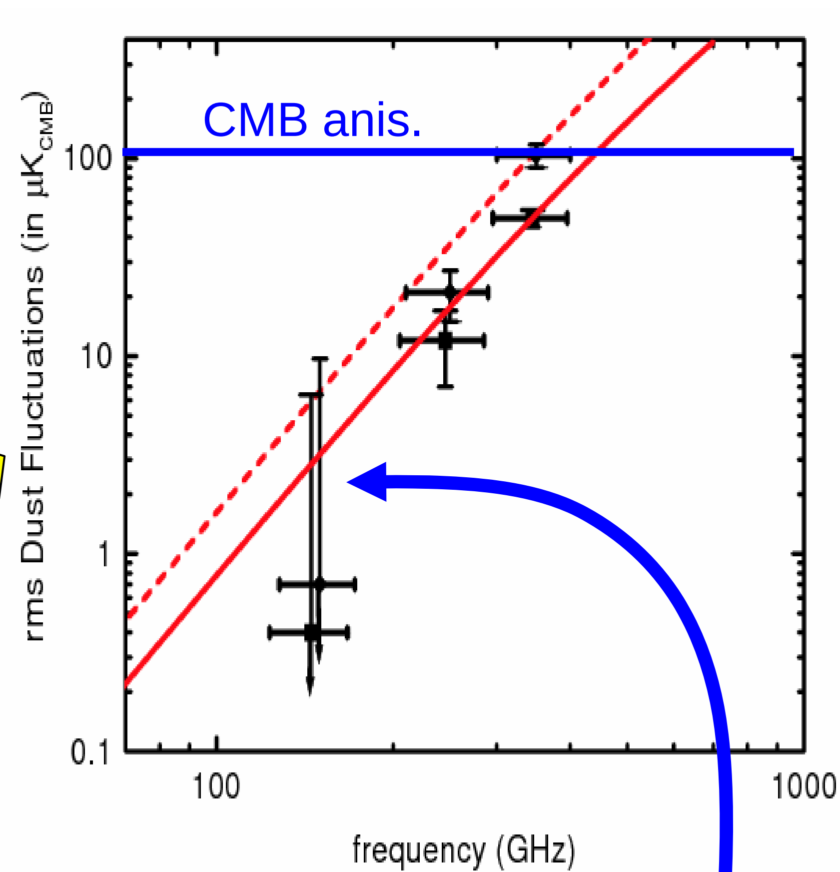
- WMAP results: Page et al. 2006. Hear Gary Hinshaw tomorrow for more.

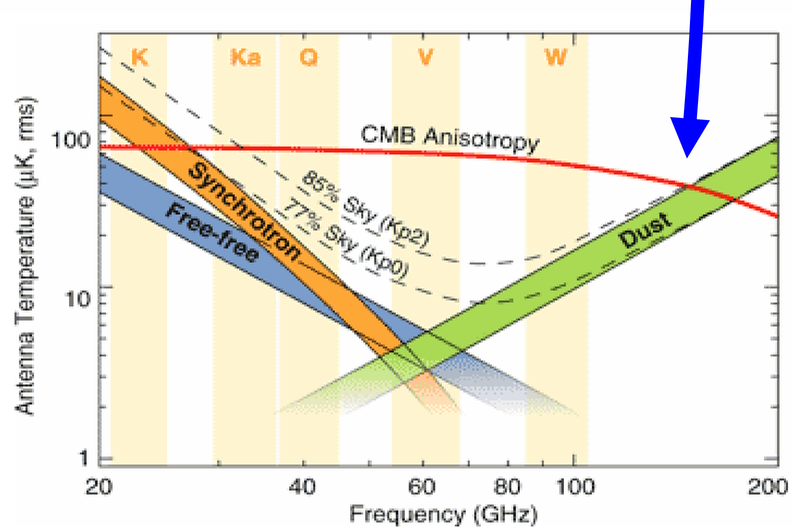
- Main message: primordial B-modes are extremely difficult to detect, because Galactic contamination is higher than E-modes **at these wavelengths and in the average high-latitude sky.**



Sweet spots (anisotropy)







BOOMERanG deep region (Masi et al. 2006):
dust anisotropy << CMB anisotropy @ 150 GHz

Chiang et al. 2010

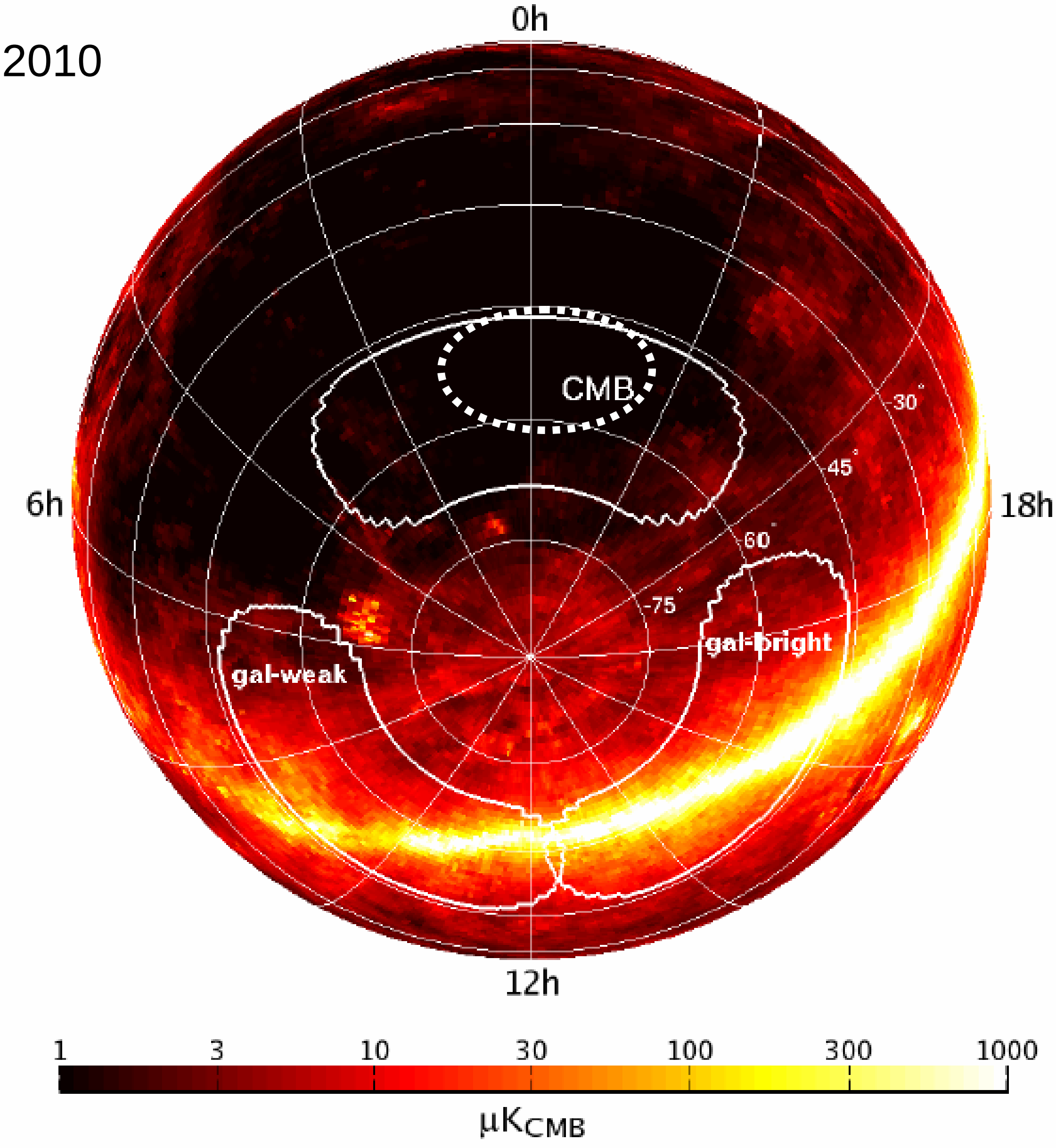
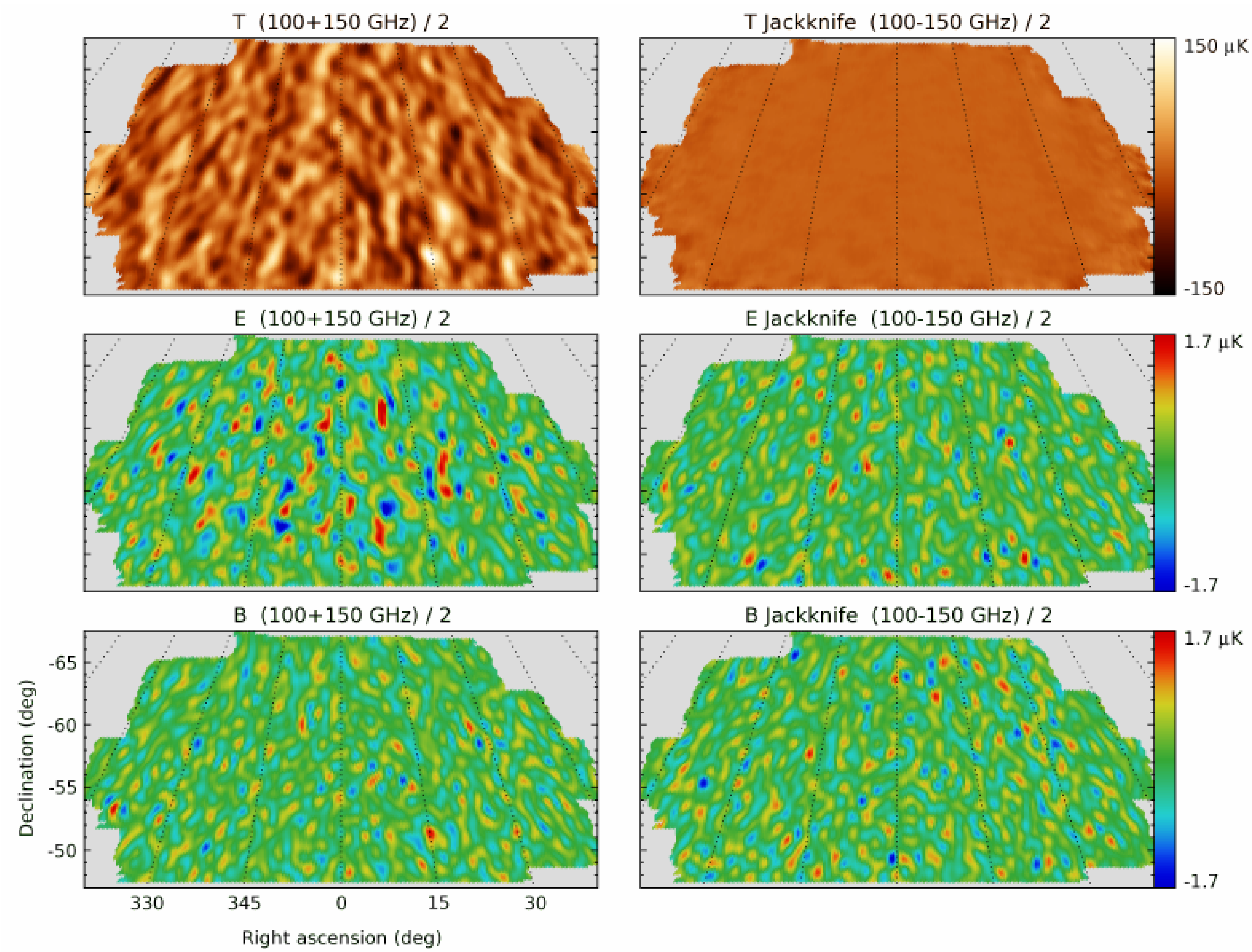


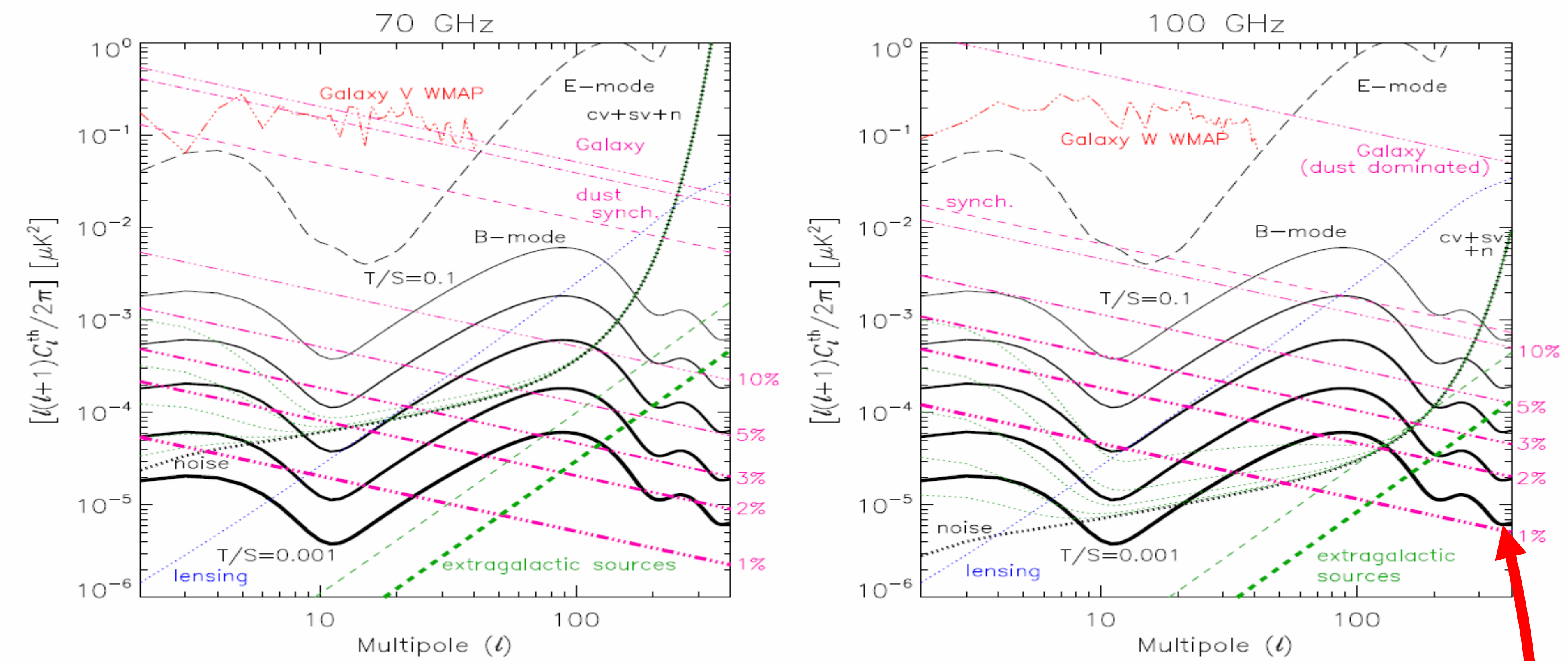
FIG. 1.— BICEP's CMB and Galactic fields are outlined on the 150-GHz FDS Model 8 prediction of dust emission (Finkbeiner et al. 1999), plotted here in equatorial coordinates.

Chiang et al. 2010
BICEP

Sweet Spots



2. Knowledge of the foregrounds



- This is the most difficult part of the path towards B-modes.
  - We need wide multiband observations
  - We need a detailed (3-D) model of galactic emission, able to predict the local polarized signal with <1% accuracy

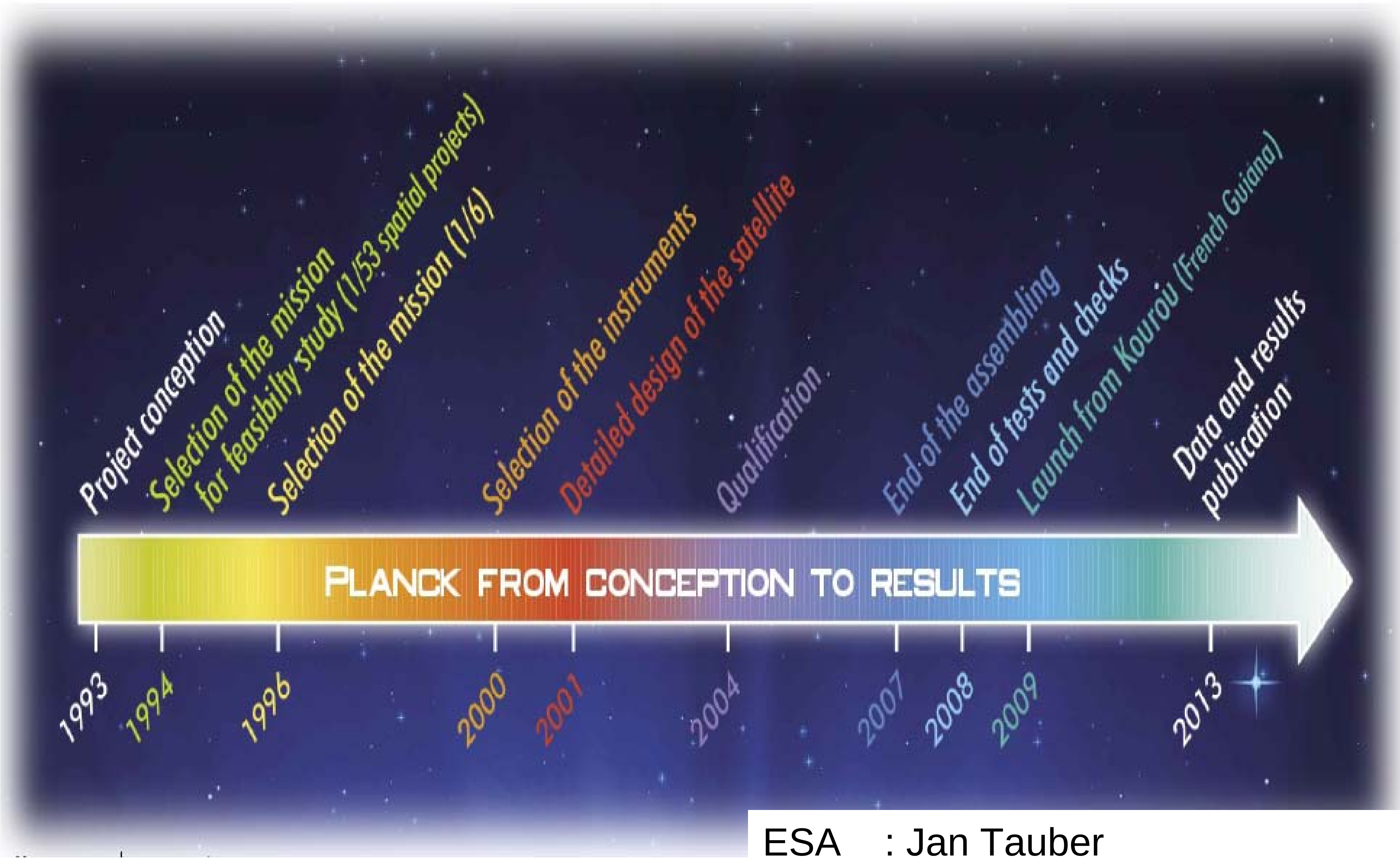
PdB et al., Exp.Astron. 23, 5-16 (2009), astro-ph/0808.1881. www.b-pol.org

Planck is a very ambitious experiment.

It carries a complex CMB experiment (the state of the art, a few years ago) all the way to L2,

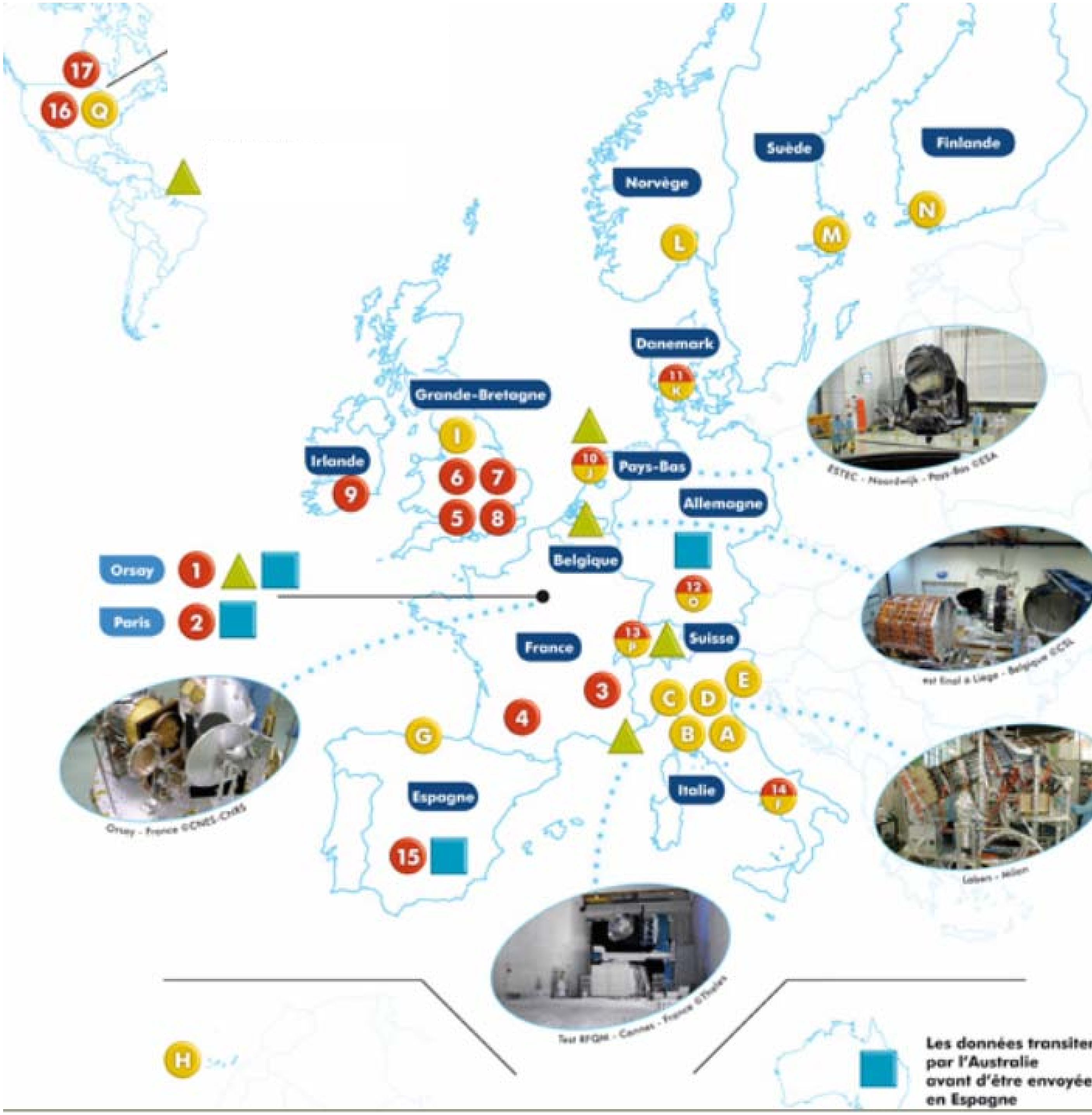
improving the sensitivity wrt WMAP by at least a factor 10,

extending the frequency coverage towards high frequencies by a factor about 10



Almost 20 years of hard work of a very large team, coordinated by:

ESA : Jan Tauber
HFI PI : Jean Loup Puget (Paris)
HFI IS : Jean Michel Lamarre (Paris)
LFI PI : Reno Mandolesi (Bologna)
LFI IS : Marco Bersanelli (Milano)



esa

National Agencies

cnes — asi agenzia spaziale italiana — NASA

Scientific Laboratories

HFI PI Puget

LFI PI Mandolesi

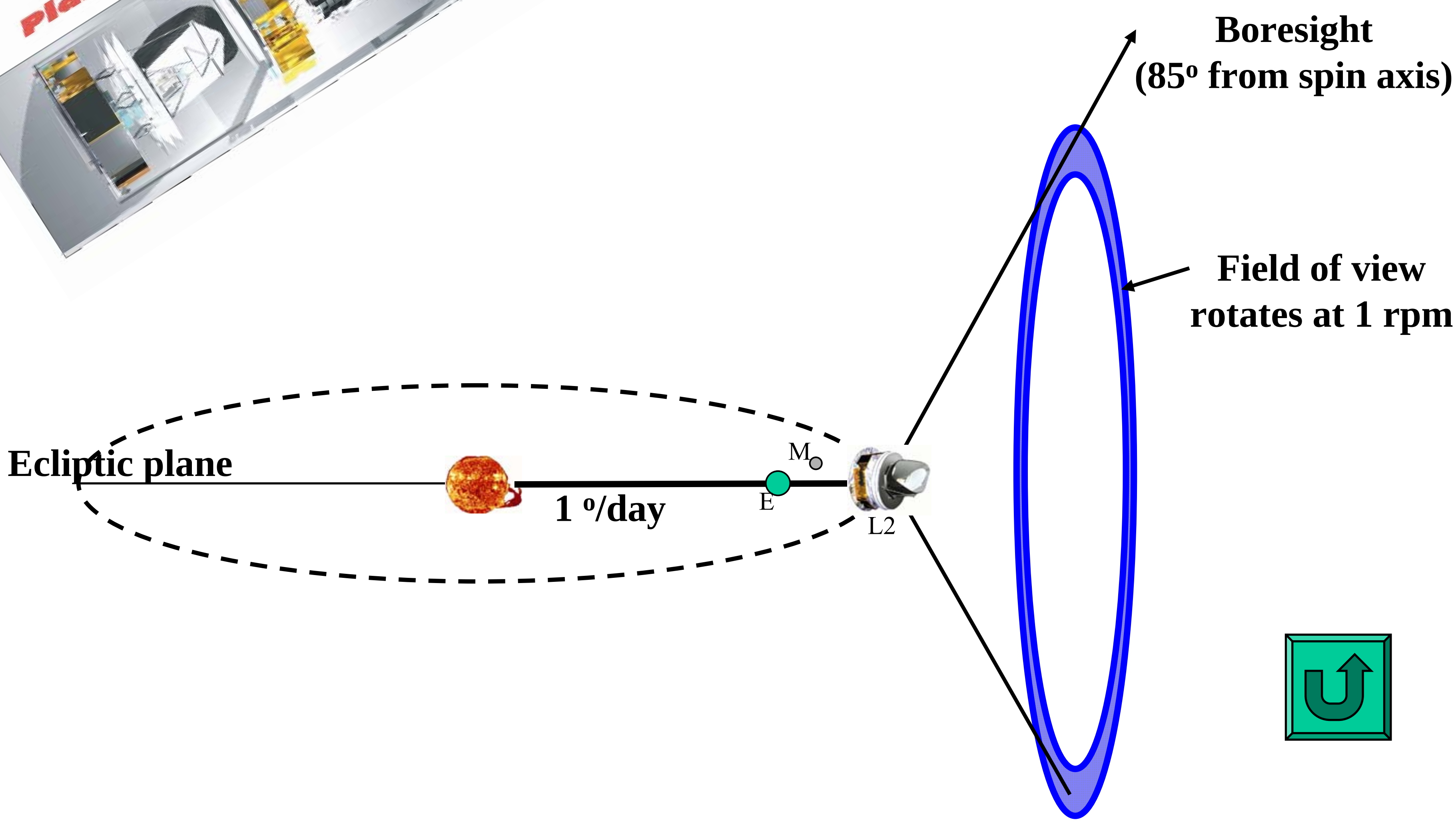
Satellite

ThalesAlenia Space

+ subcontractors

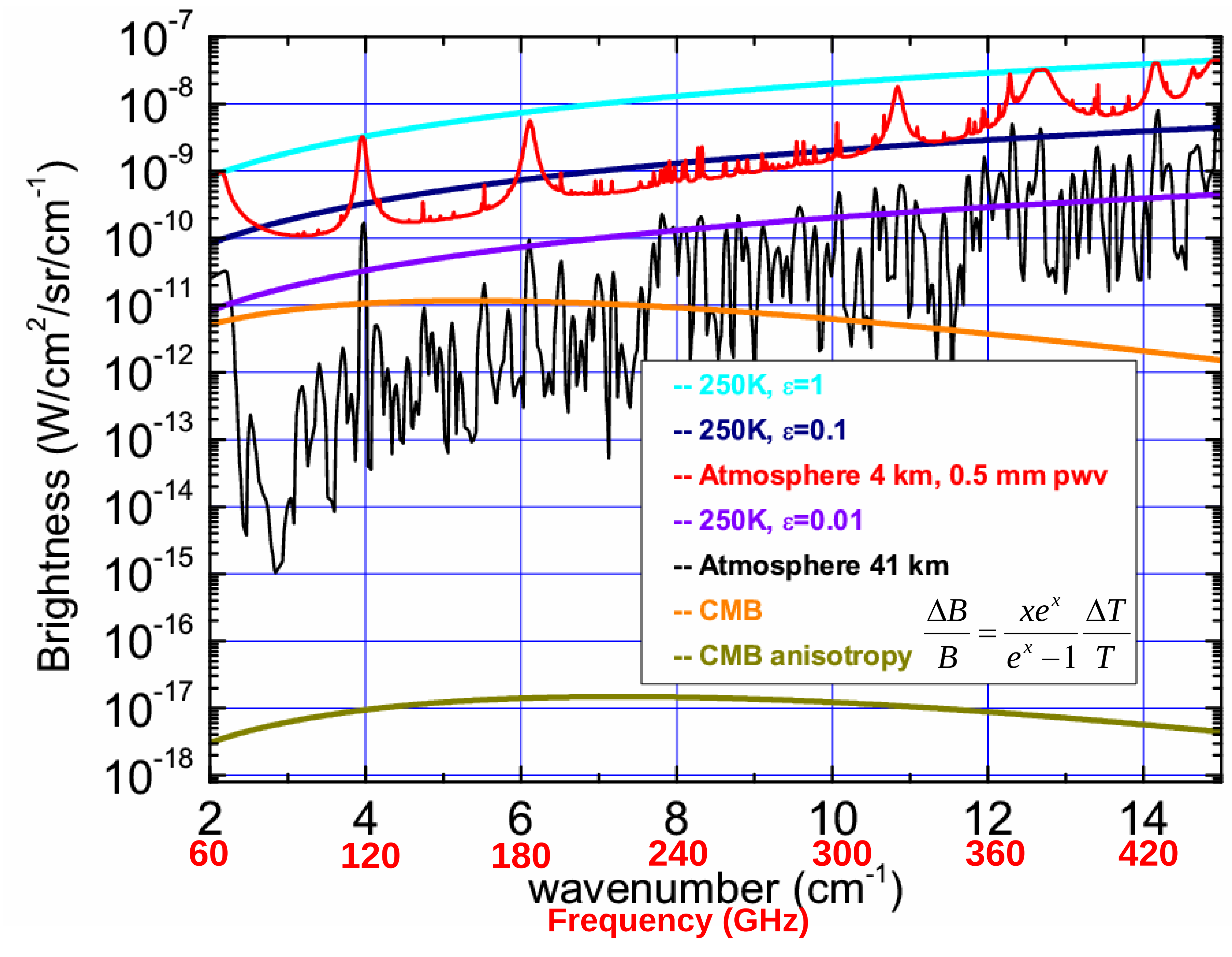
Observing strategy

The payload will work from L2, to avoid the emission of the Earth, of the Moon, of the Sun



Why so far ?

- Good reasons to go in deep space:
  - Atmosphere
  - Sidelobes
  - Stability



Brightness (W/cm²/sr/cm⁻¹)
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
-- 250K, ε=1
-- 250K, ε=0.1
-- Atmosphere 4 km, 0.5 mm pwv
-- 250K, ε=0.01
-- Atmosphere 41 km
-- CMB
-- CMB anisotropy
$\frac{\Delta B}{B} = \frac{xe^x}{e^x - 1}\frac{\Delta T}{T}$
2 4 6 8 10 12 14
60 120 180 240 300 360 420
wavenumber (cm⁻¹)
Frequency (GHz)

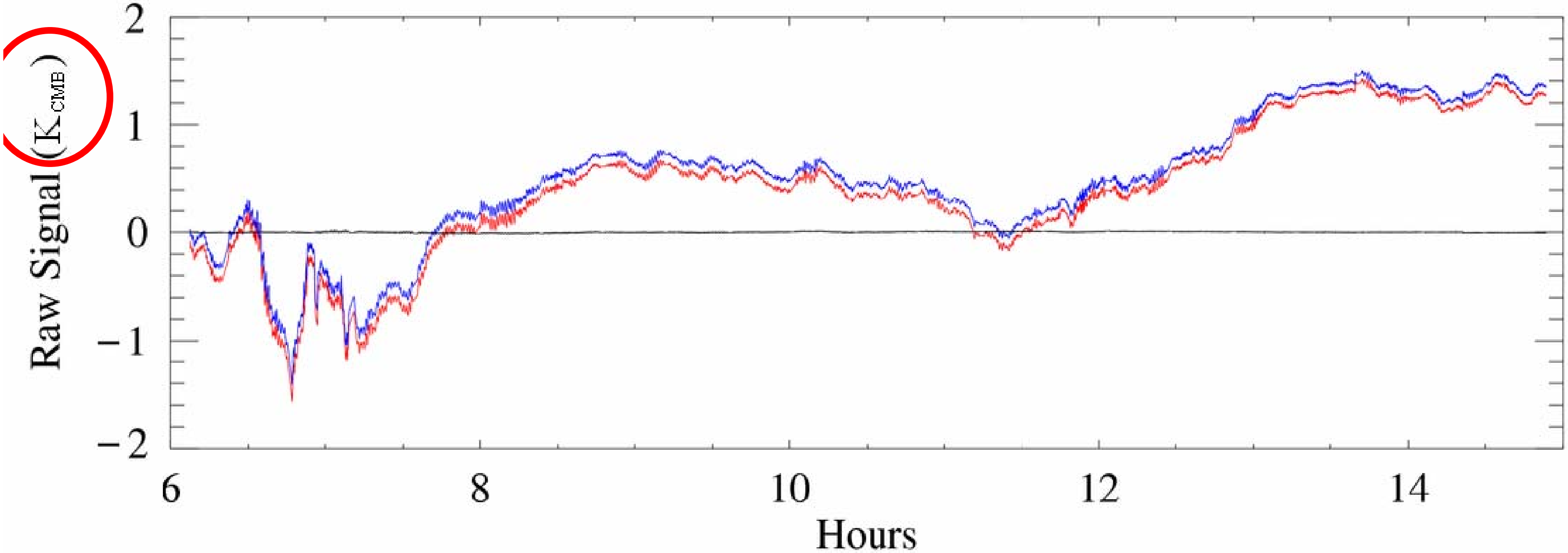
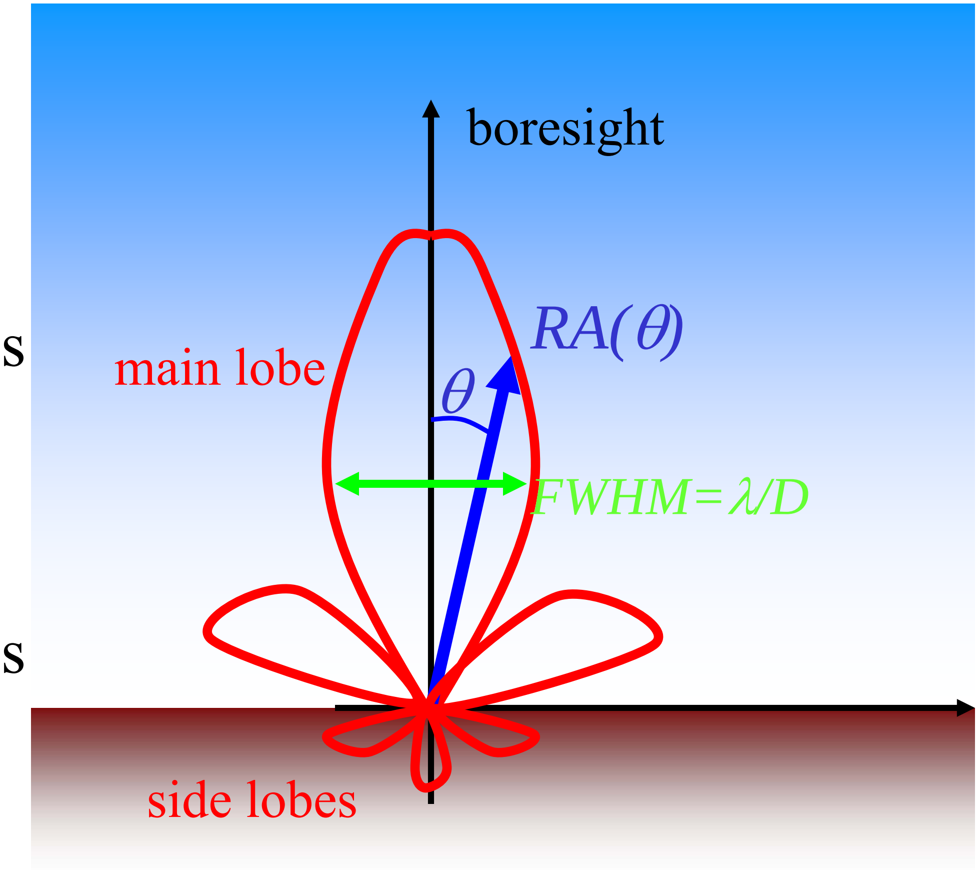


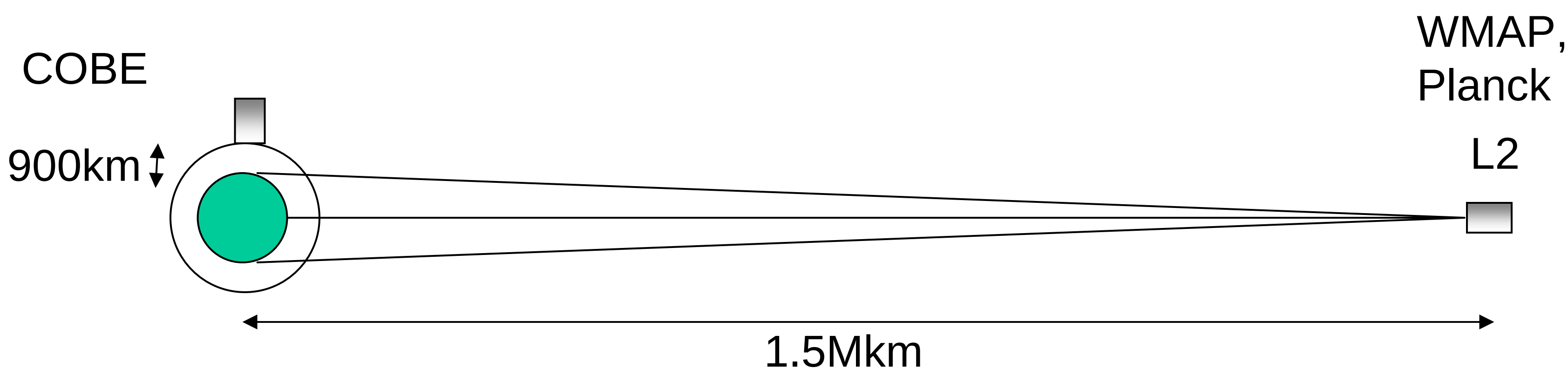
FIG. 6.— The individual 150 GHz timestreams within a PSB pair (red and blue) are differenced (black) in this plot using a single relative gain fit over the plotted 9-hour period. For the actual CMB analysis, relative gains are updated for every one-hour scan set.

- In the case of CMB observations, the detected brightness is the sum of the brightness from the sky (dominant for the solid angles directed towards the sky, in the main lobe) and the Brightness from ground (dominant for the solid angles directed towards ground, in the sidelobes).



$$W = A\left[\int_{\substack{main\\lobe}} B_{sky}(\theta,\varphi)RA(\theta,\varphi)d\Omega + \int_{\substack{side\\lobes}} B_{Ground}(\theta,\varphi)RA(\theta,\varphi)d\Omega\right]$$

- The angular response (beam pattern) $RA(\theta,\phi)$ is usually polarization-dependent



Going to L2 reduces the solid angle occupied by the Earth by a factor $2\pi/2x10^{-4}$=31000, thus relaxing by the same factor the required off-axis rejection.

FWHM	$\Omega_{mainlobe}$	$<RA_{sidelobes}>$
10^o	$2x10^{-2}$ srad	<<1
1^o	$2x10^{-4}$ srad	<<0.01
10’	$7x10^{-6}$ srad	$<<3x10^{-4}$
1’	$7x10^{-8}$ srad	$<<3x10^{-6}$

No day-night changes up there … extreme stability

PLANCK

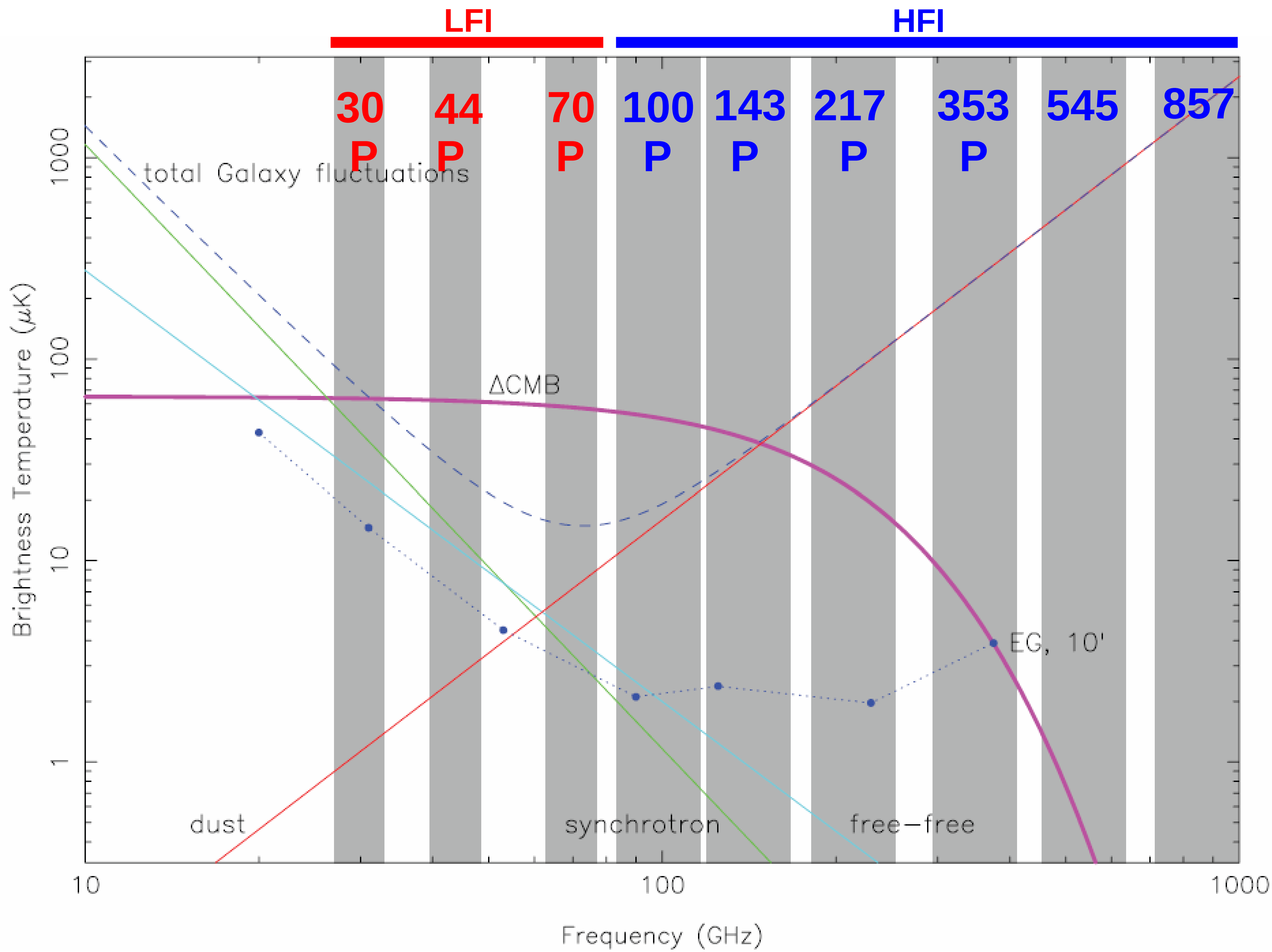
ESA's mission to map the Cosmic Microwave Background

Image of the whole sky at wavelengths near the intensity peak of the CMB radiation, with

- high instrument sensitivity ($\Delta T/T \sim 10^{-6}$)
- high resolution (≈5 arcmin)
- wide frequency coverage (25 GHz-950 GHz)
- high control of systematics
- Sensitivity to polarization

Launch: 14/May/2009; payload module: 2 instruments + telescope

- Low Frequency Instrument (LFI, uses HEMTs)
- High Frequency Instrument (HFI, uses bolometers)
- Telescope: primary (1.50x1.89 m ellipsoid)



LFI
HFI
30 P
44 P
70 P
100 P
143 P
217 P
353 P
545
857
total Galaxy fluctuations
ΔCMB
EG, 10'
dust
synchrotron
free−free
Brightness Temperature (μK)
Frequency (GHz)
1
10
100
1000
10
100
1000

HFI

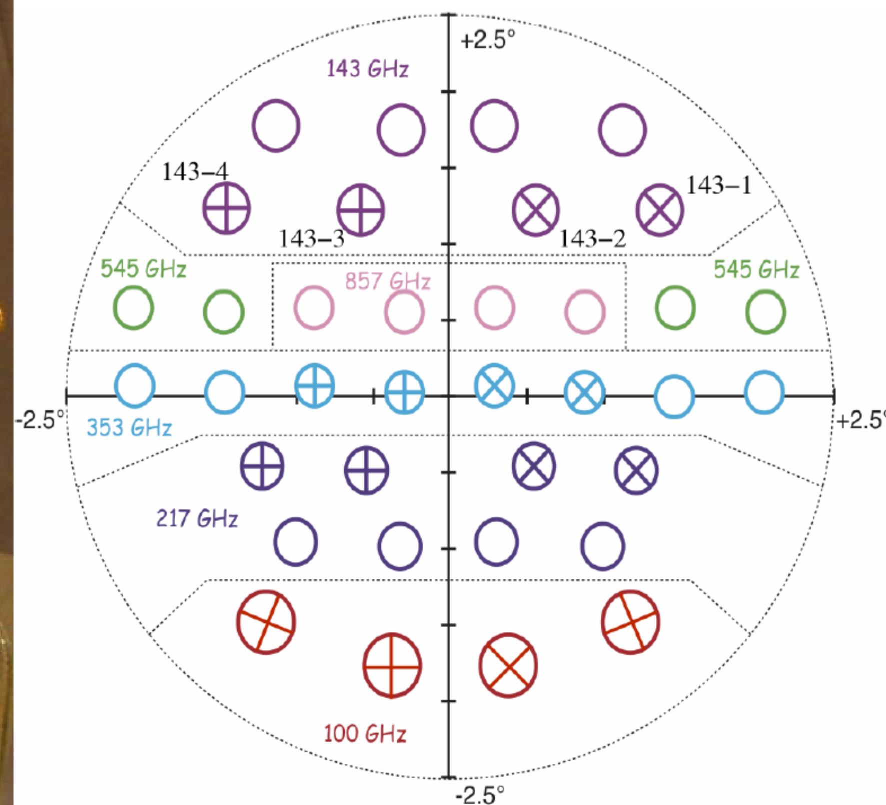
Spider-web bolometers

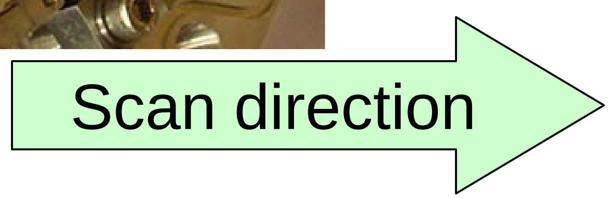
Made in JPL

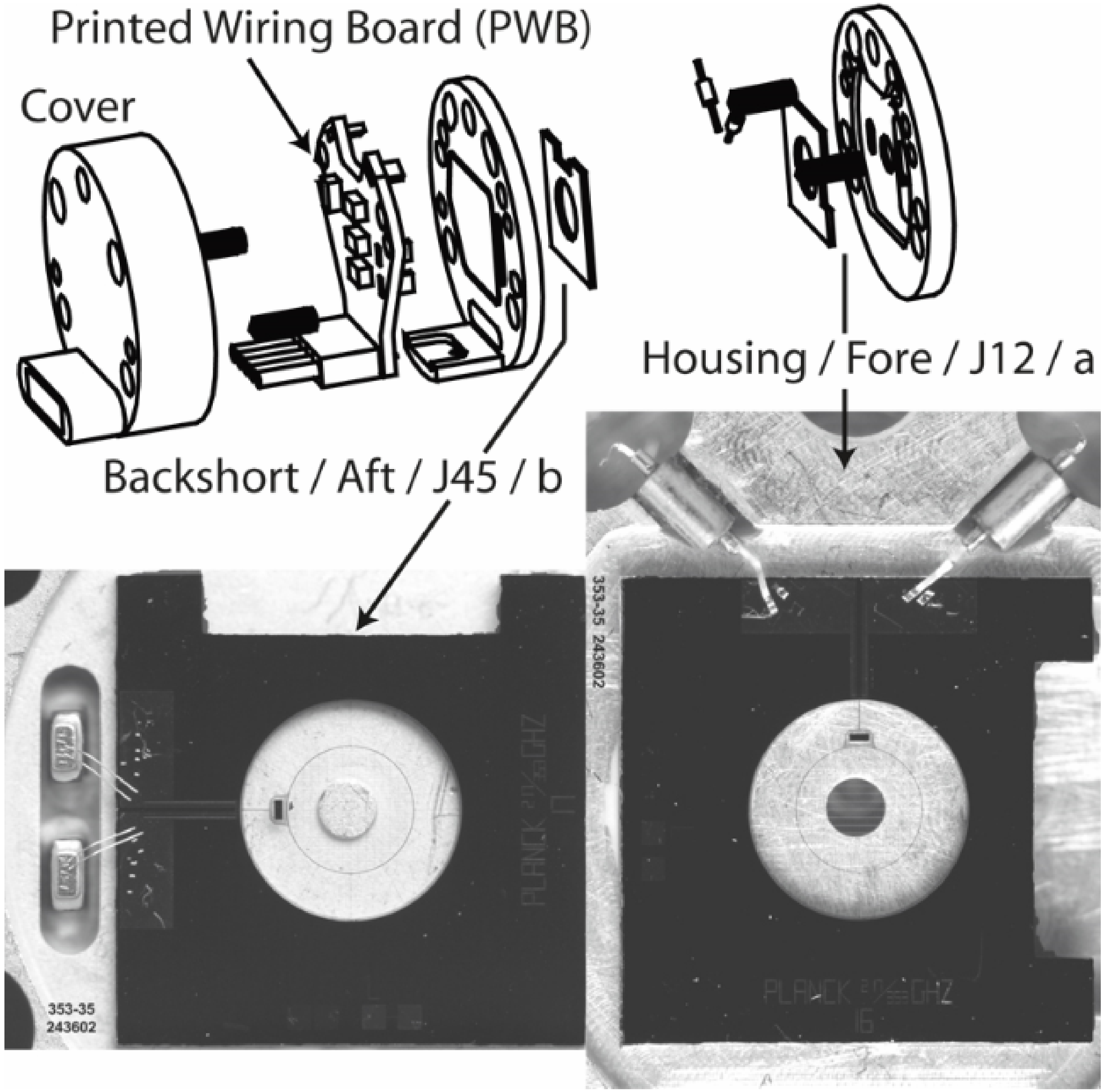
BOOMERanG 1998 (0.3K),
Archeops 2001 (0.1K),
….

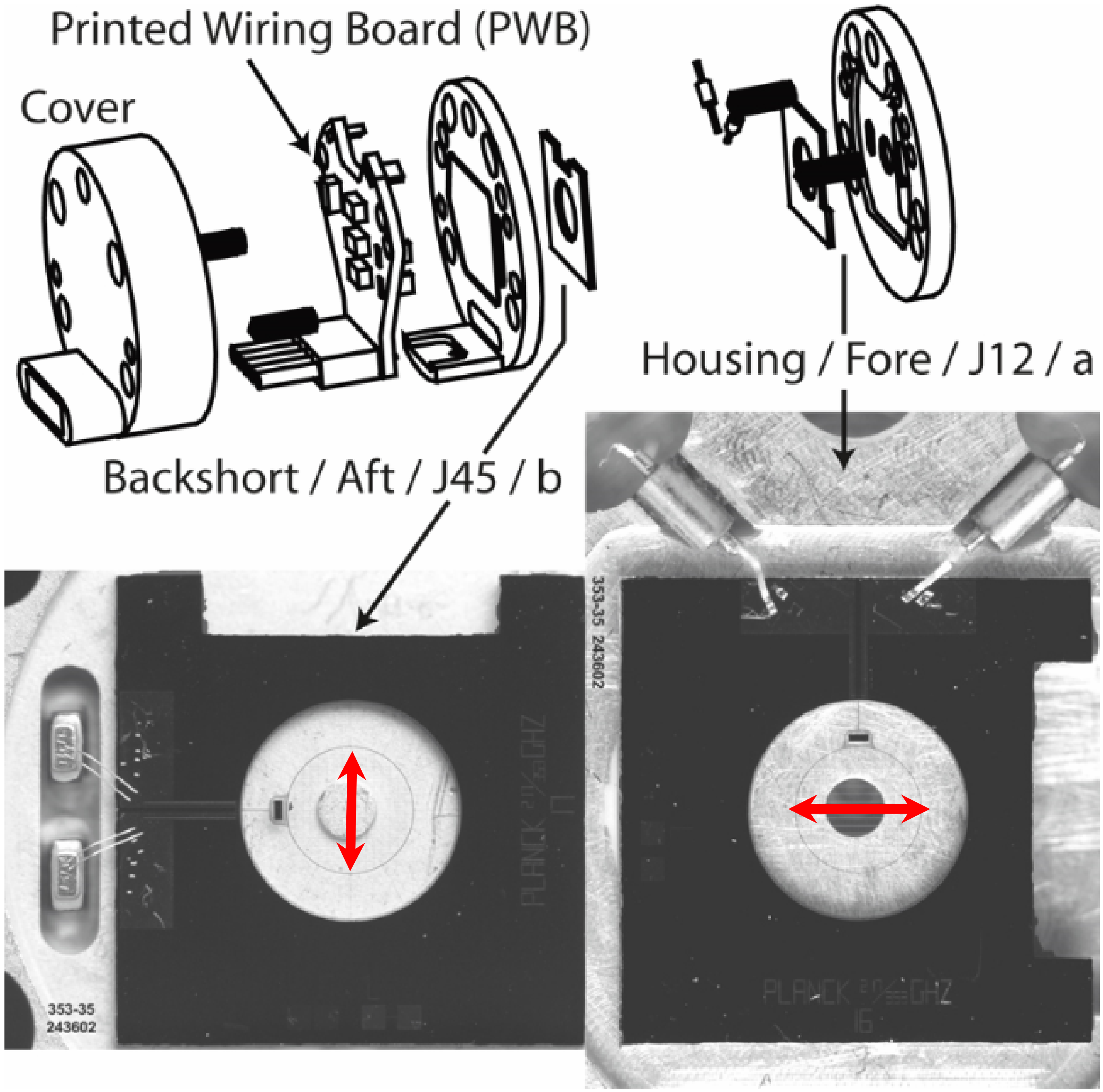
Planck – HFI polarization sensitive focal plane

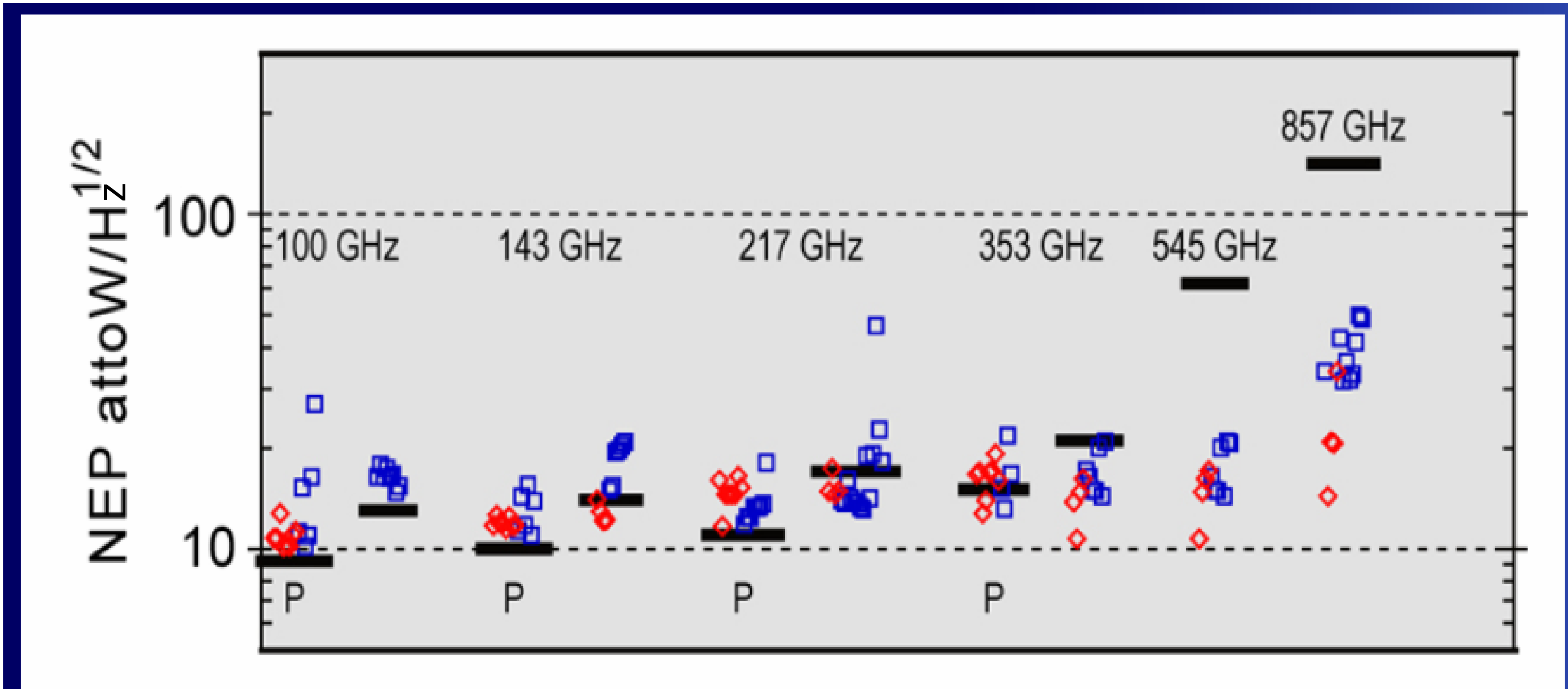
Ponthieu et al. 2010






Printed Wiring Board (PWB)
Cover
Housing / Fore / J12 / a
Backshort / Aft / J45 / b
353-35
243602
353-35 243602

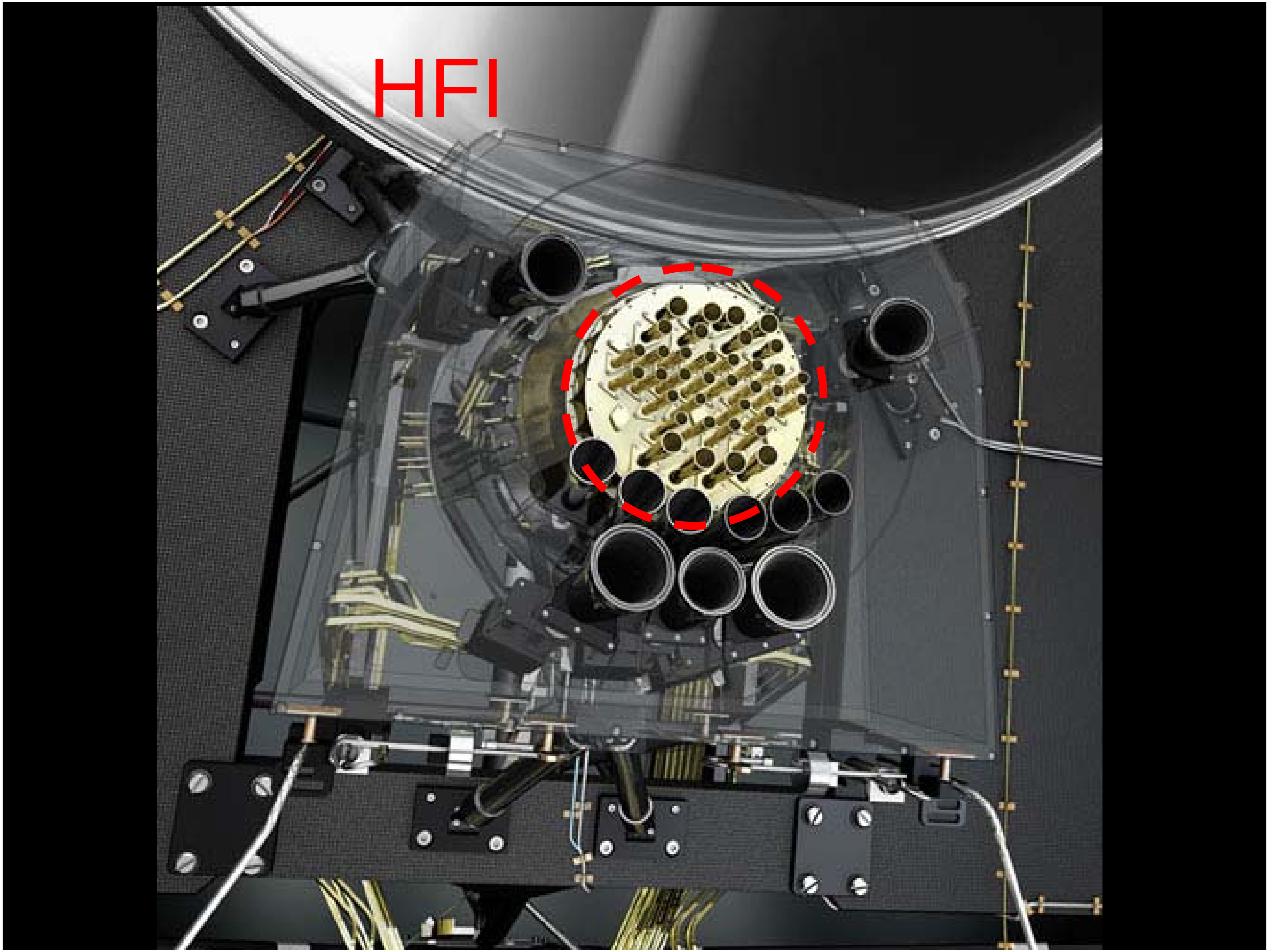

Printed Wiring Board (PWB)
Cover
Housing / Fore / J12 / a
Backshort / Aft / J45 / b
353-35
243602
PLANCK
GHZ
353-35 243602
PLANCK
GHZ
16

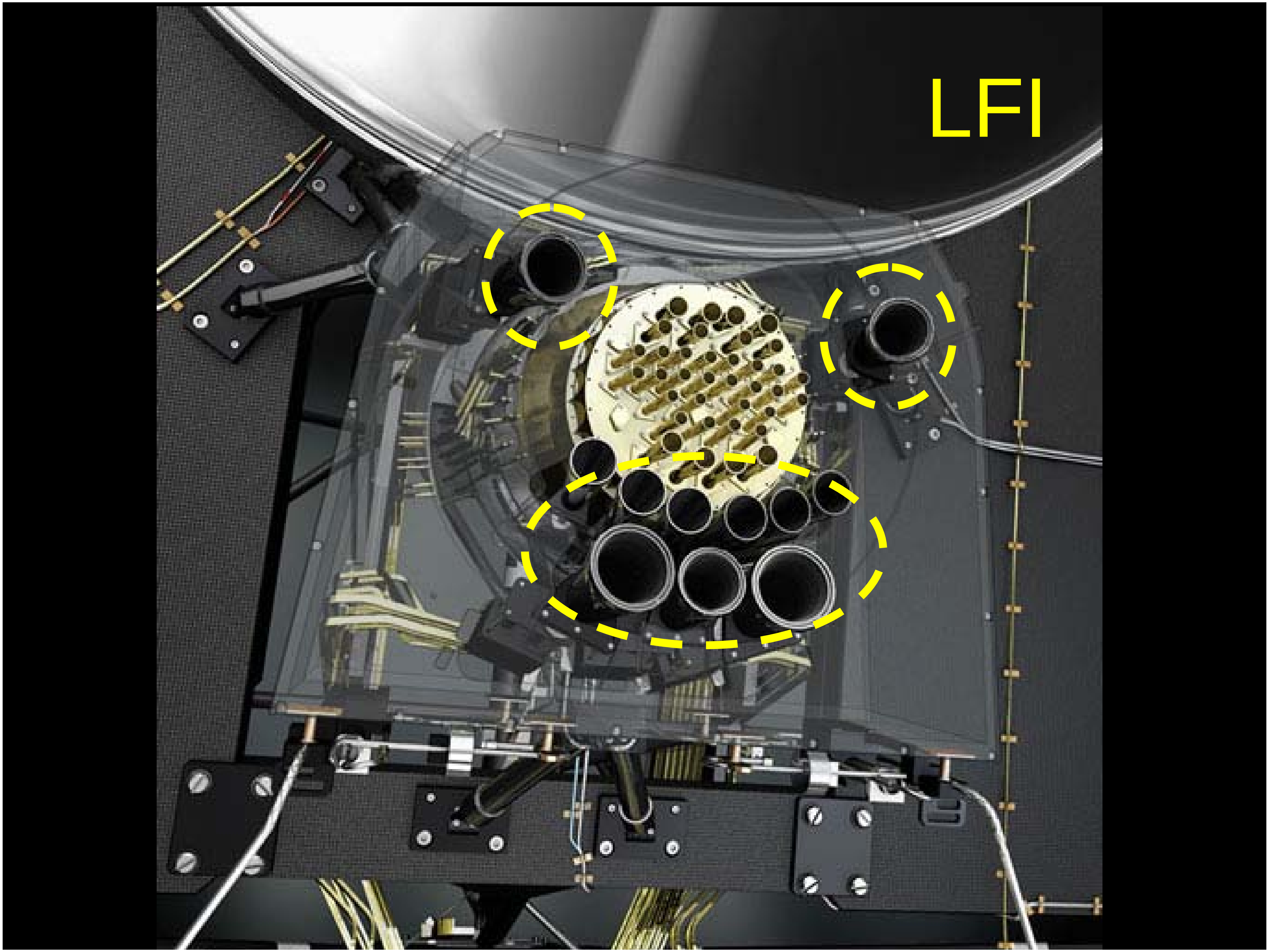


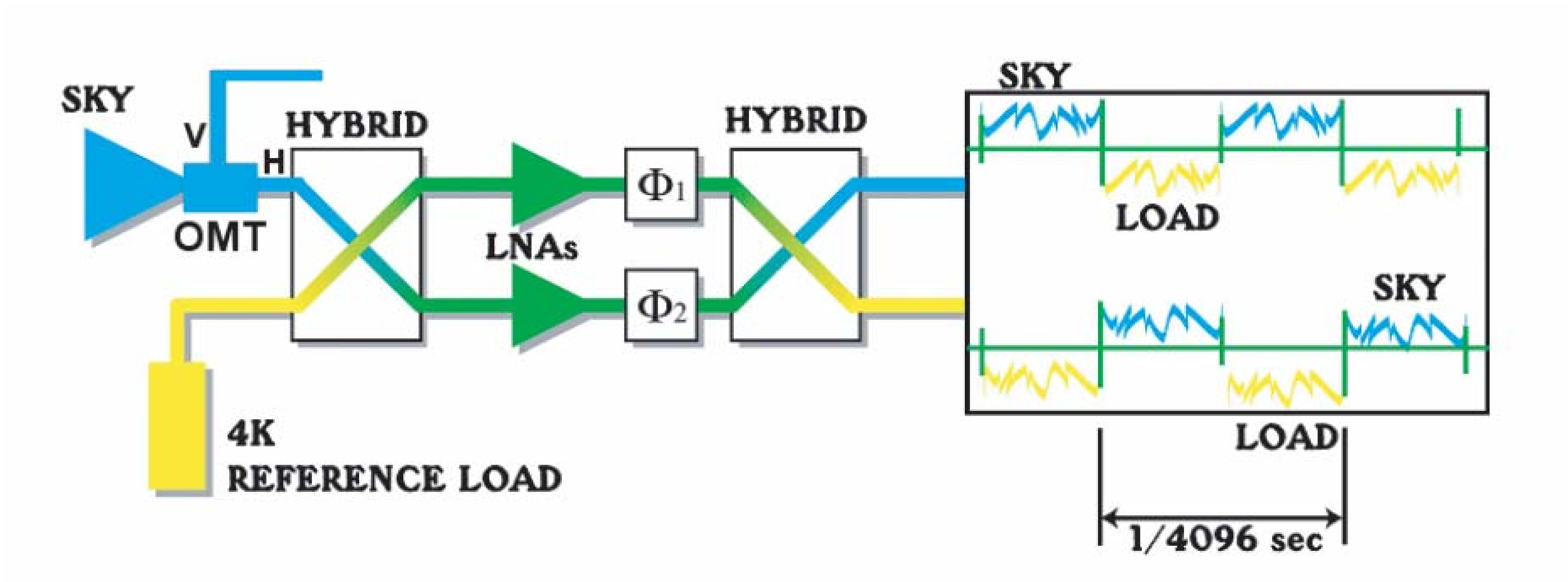
Measured dark noise equivalent power (NEP) of the focal plane detectors, including 6.5 nV / sqrt(Hz) amplifier noise at nominal bias. The open diamond symbols are the NEP for detectors installed in the focal plane. The open square symbols are the NEP of spare bolometers. The thick solid line segments indicate the photon background limit from a 35 K telescope and astrophysical sources in each band for a 30% bandwidth and 30% in band optical efficiency. Unpolarized detectors at 100 GHz were made and delivered but were replaced by polarized detectors. (from Holmes et al. (2008))

$NEP_b = 15\ aW/Hz^{1/2}$ -> $70\ \mu K/Hz^{1/2}$

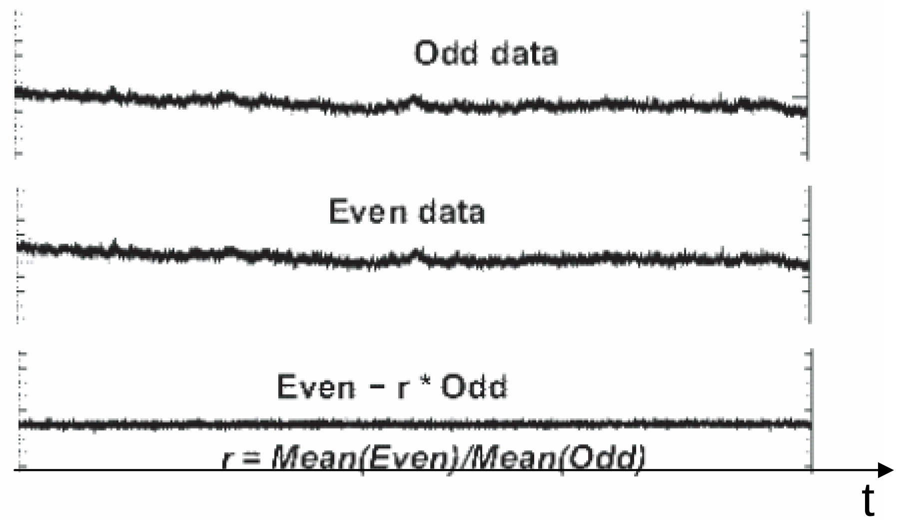
Total NET (bolo+photon) = $85\ \mu K/Hz^{1/2}$

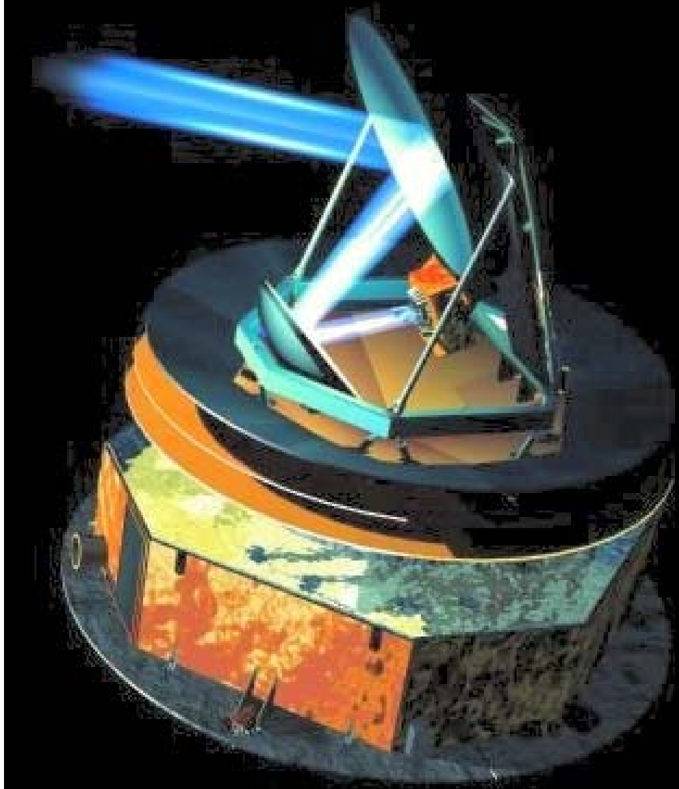

HFI


LFI

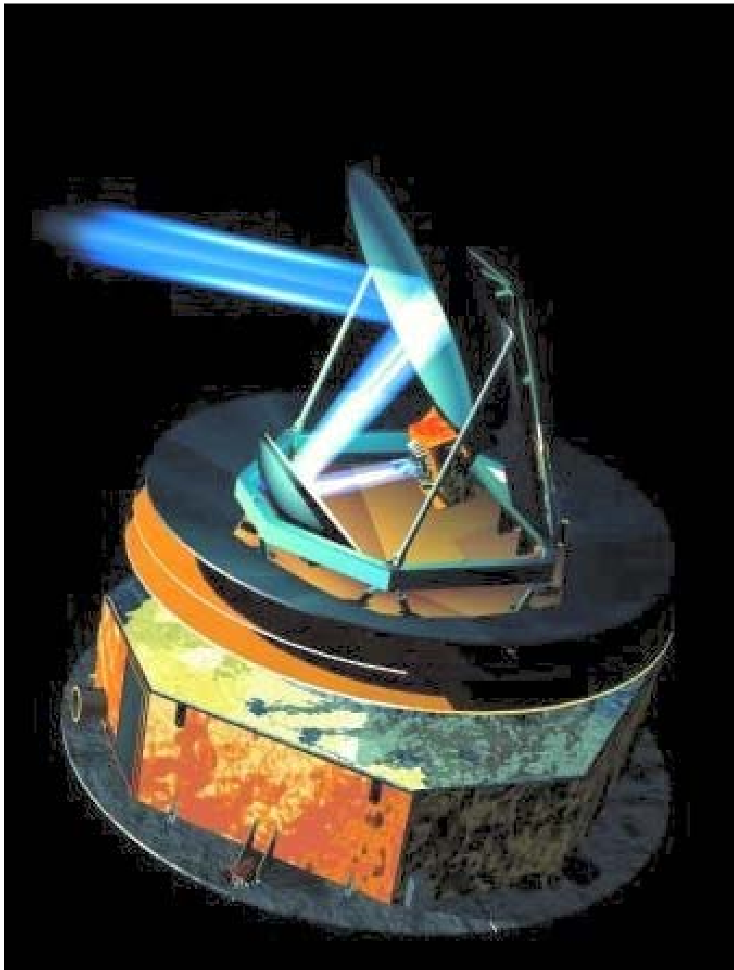


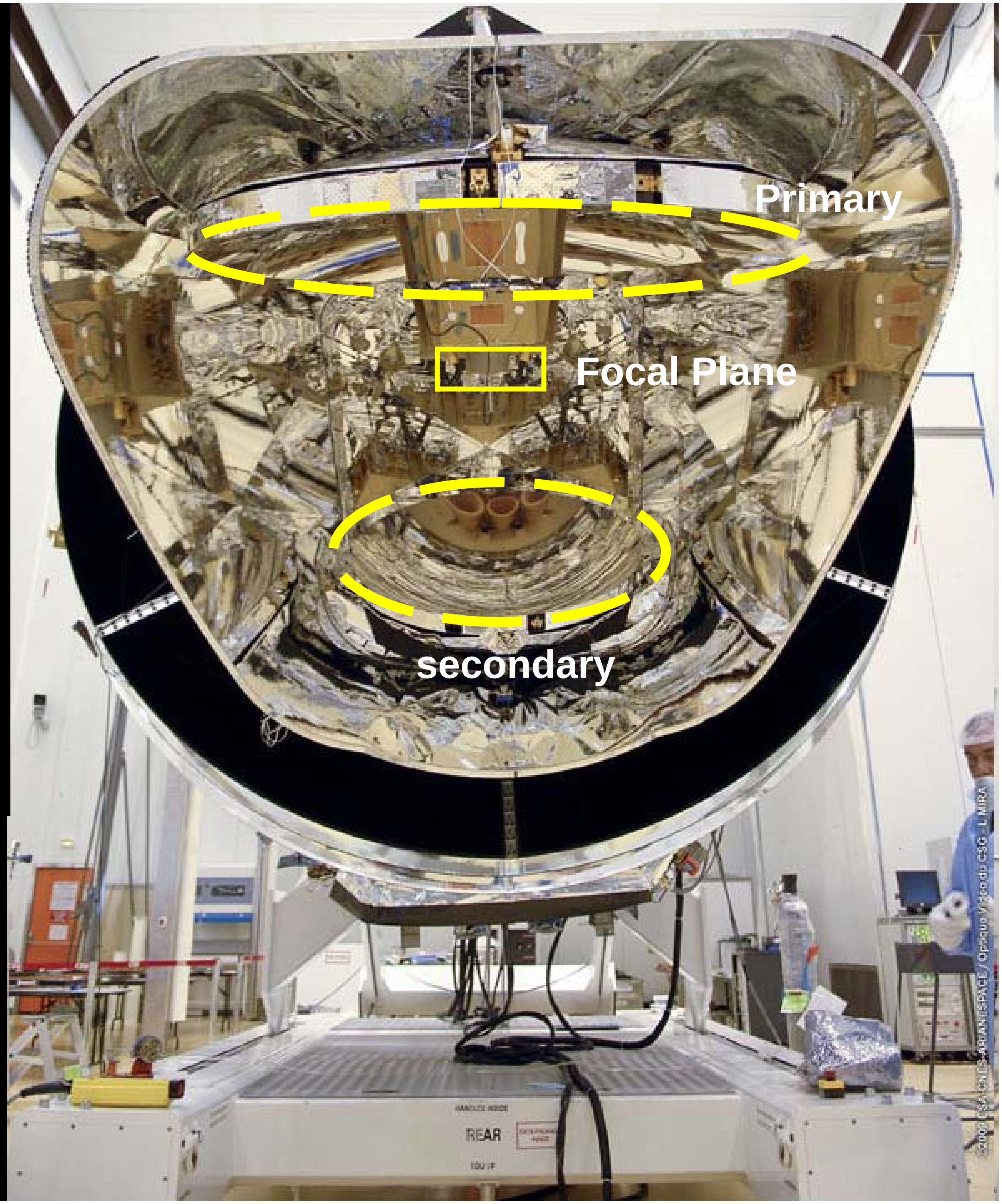
LFI
Pseudo-correlation
Differential radiometer
Measures I,Q,U
30, 44, 70 GHz





Off-axis Dragone Telescope, wide field, good polarization properties, 1.89mx1.50m aperture





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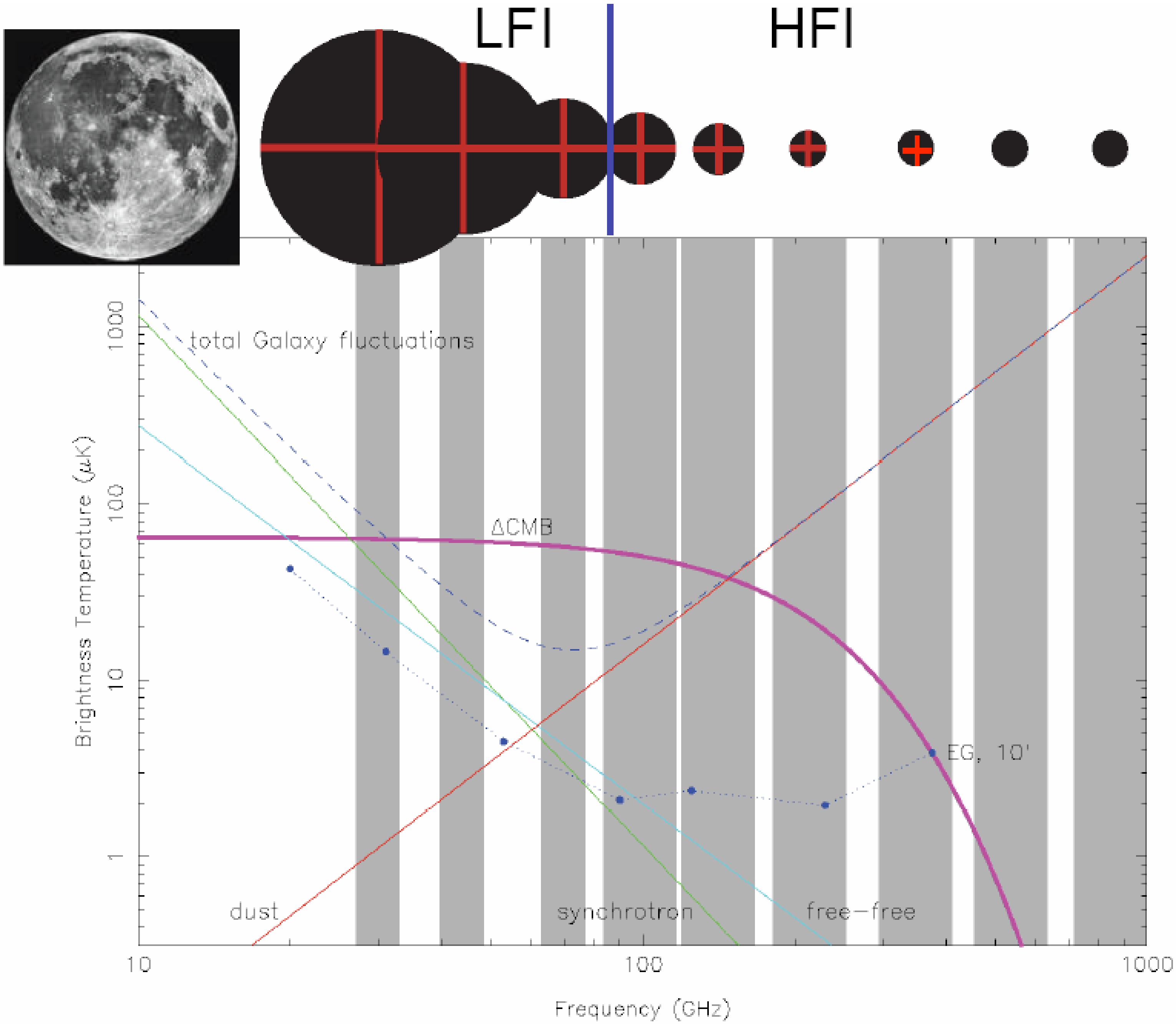
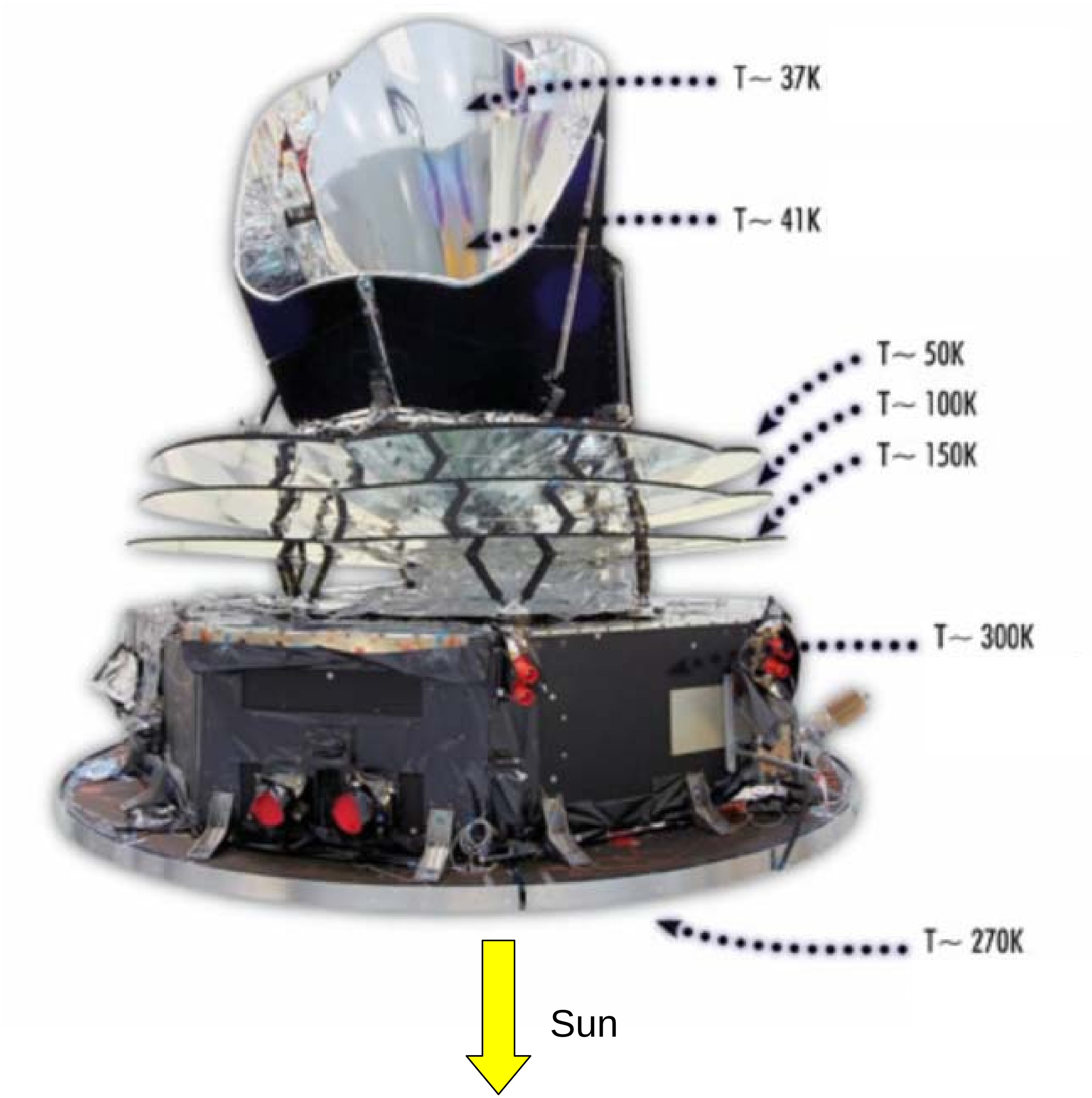
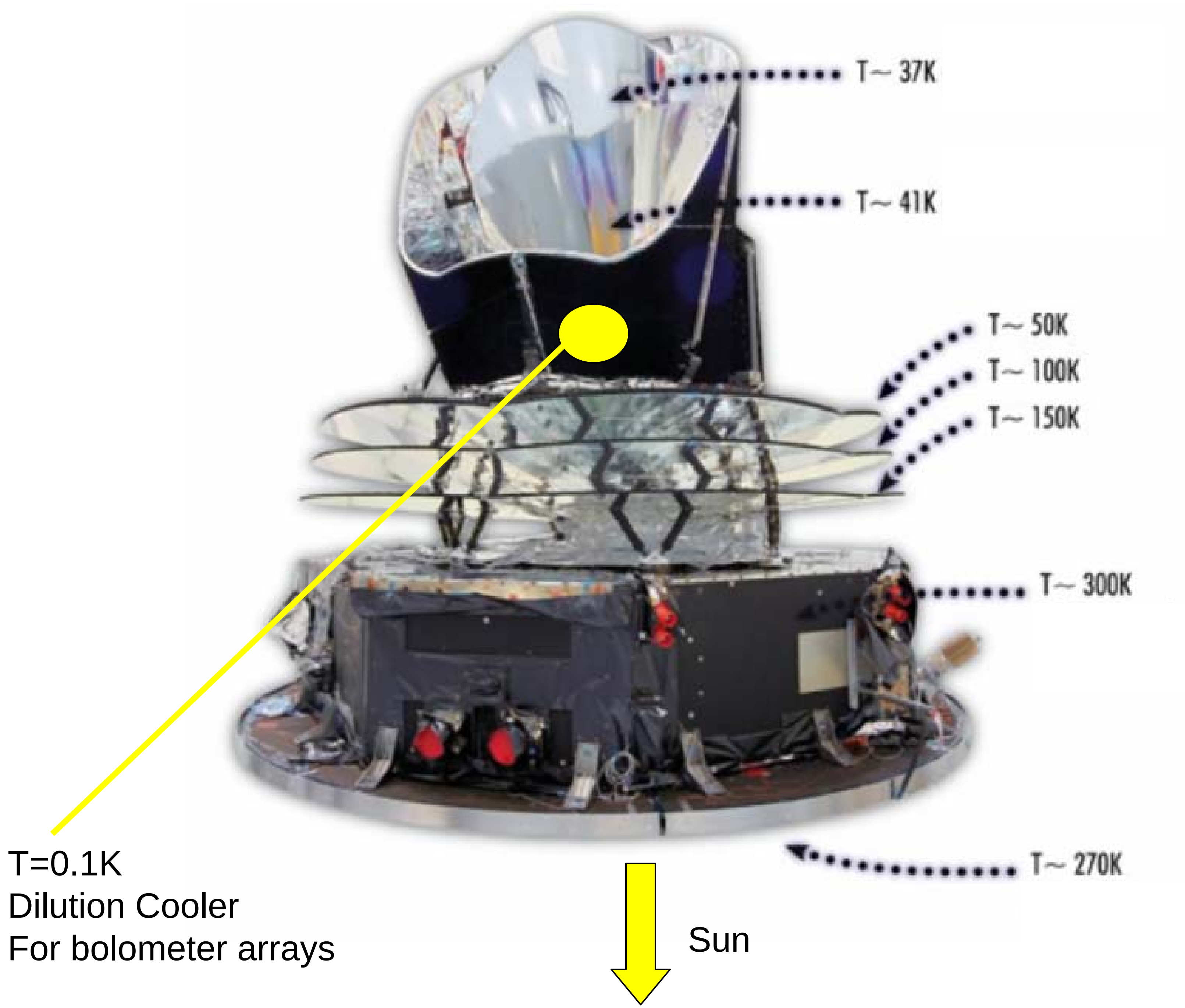

LFI
HFI
total Galaxy fluctuations
ΔCMB
EG, 10'
dust
synchrotron
free−free
Brightness Temperature (μK)
1000
100
10
1
10
100
1000
Frequency (GHz)


T~ 37K
T~ 41K
T~ 50K
T~ 100K
T~ 150K
T~ 300K
T~ 270K
Sun


T~ 37K
T~ 41K
T~ 50K
T~ 100K
T~ 150K
T~ 300K
T~ 270K
T=0.1K
Dilution Cooler
For bolometer arrays
Sun

Cooling system

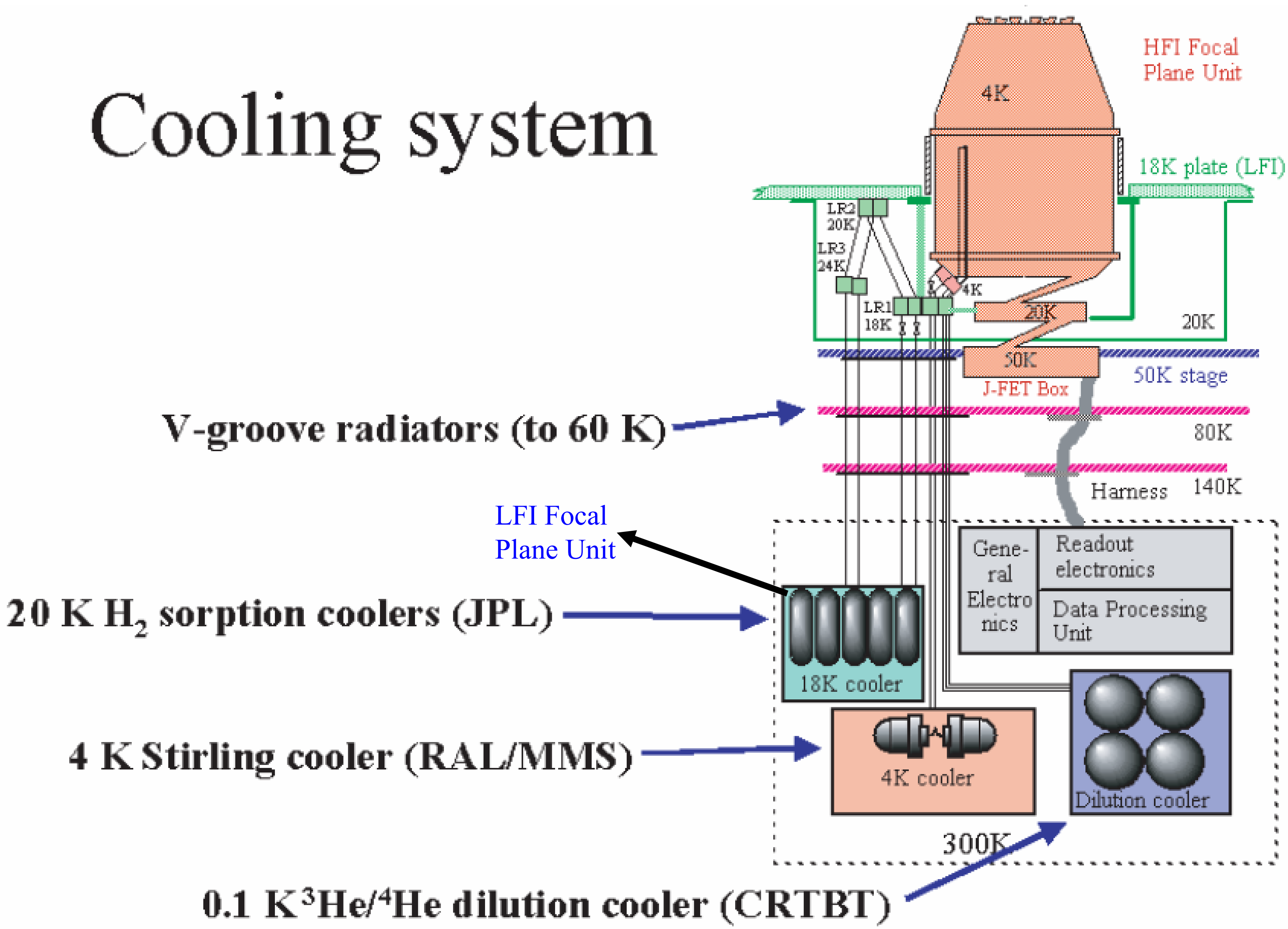


TABLE 1.1

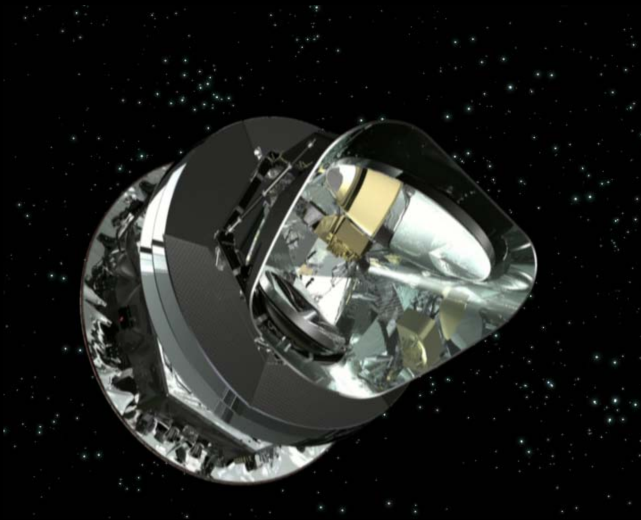
SUMMARY OF PLANCK INSTRUMENT CHARACTERISTICS

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	...	...

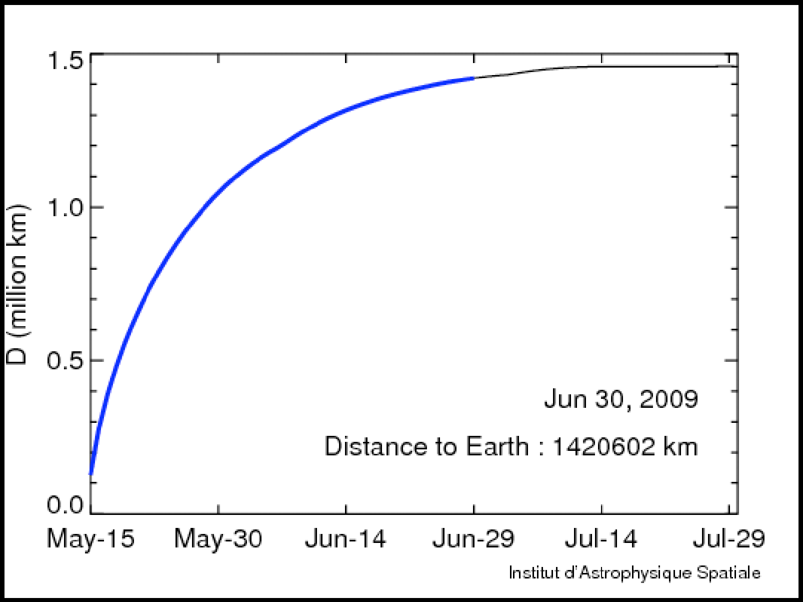
[a] Goal (in μK/K) for 14 months integration, 1σ, for square pixels whose sides are given in the row "Angular Resolution".

From the Blue Book (2005)

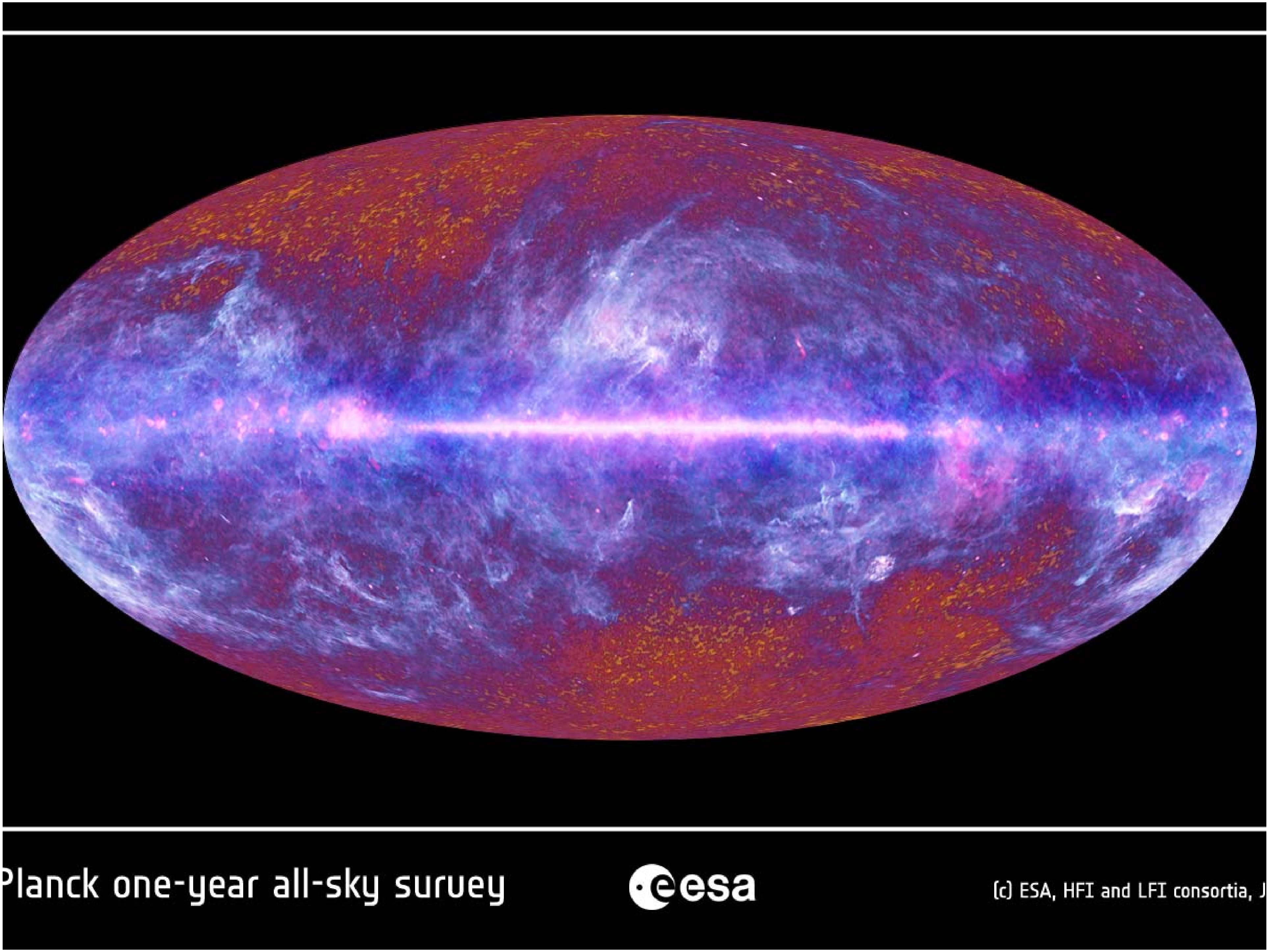
Launch
May 14th, 2009

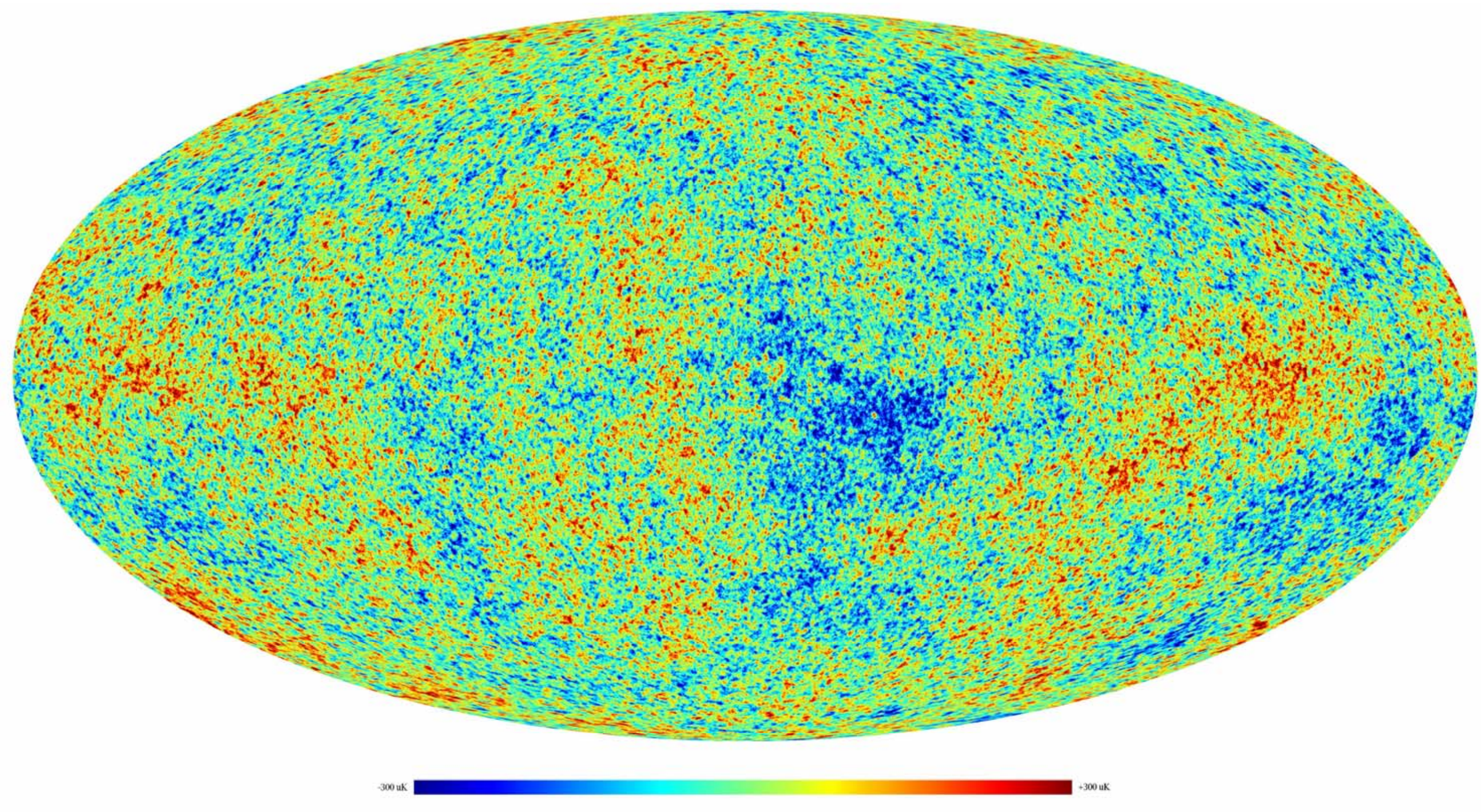


Cruise
May-June 2009

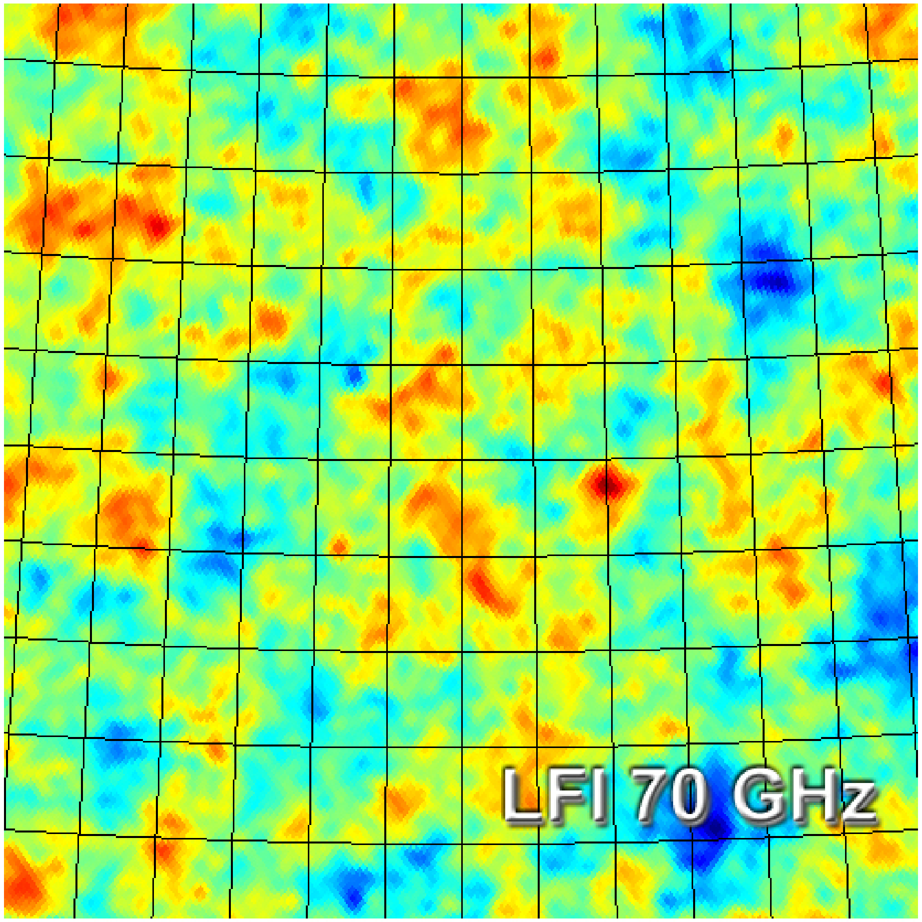


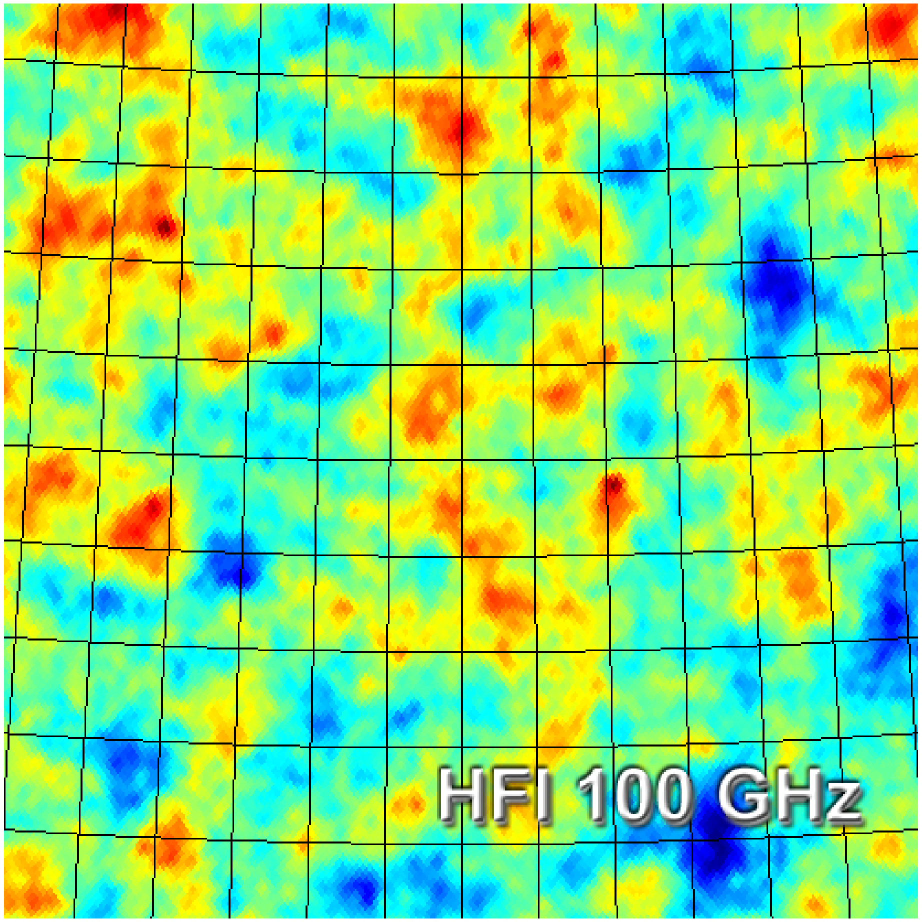
First All-sky survey
Completed May 2010


Planck one-year all-sky survey
esa
(c) ESA, HFI and LFI consortia, J



This is a simulation





Real data (from just 15 days of operation)

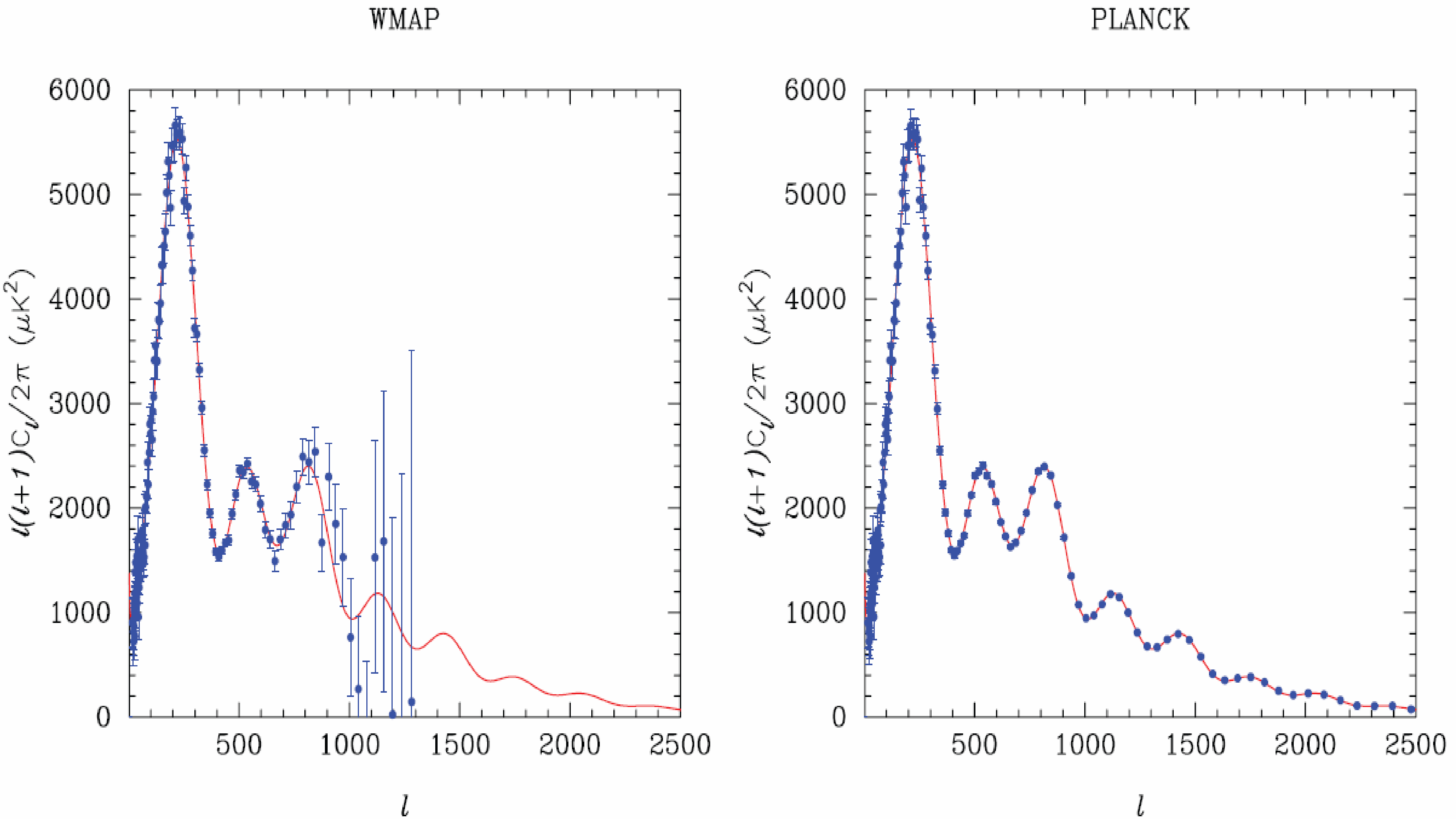


FIG 2.8.—The left panel shows a realisation of the CMB power spectrum of the concordance ΛCDM model (red line) after 4 years of *WMAP* observations. The right panel shows the same realisation observed with the sensitivity and angular resolution of *Planck*.

ESA-SCI(2005)1

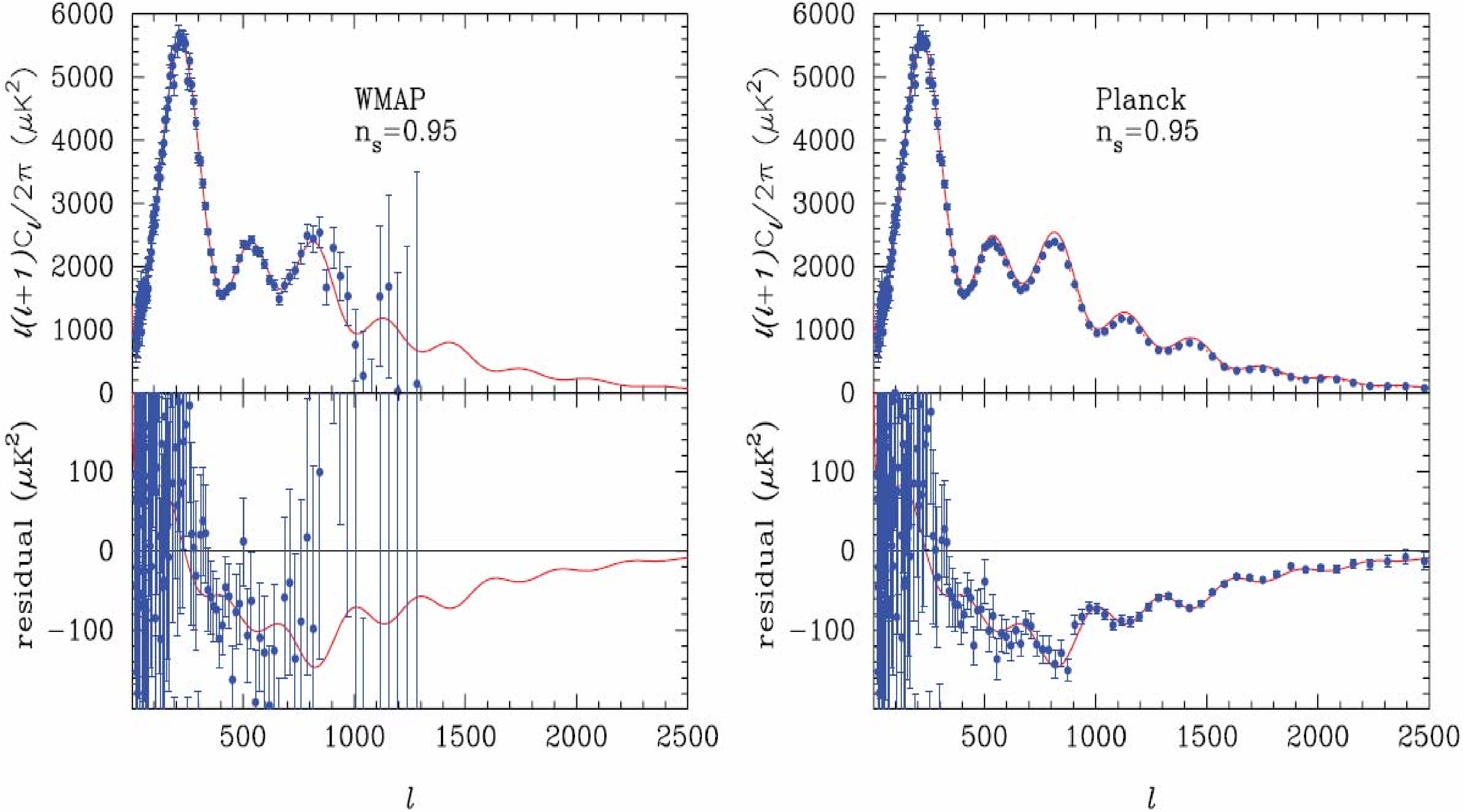


FIG 2.11.—The solid lines in the upper panels of these figures show the power spectrum of the concordance ΛCDM model with an exactly scale invariant power spectrum, $n_S = 1$. The points, on the other hand, have been generated from a model with $n_S = 0.95$ but otherwise identical parameters. The lower panels show the residuals between the points and the $n_S = 1$ model, and the solid lines show the theoretical expectation for these residuals. The left and right plots show simulations for *WMAP* and *Planck*, respectively.

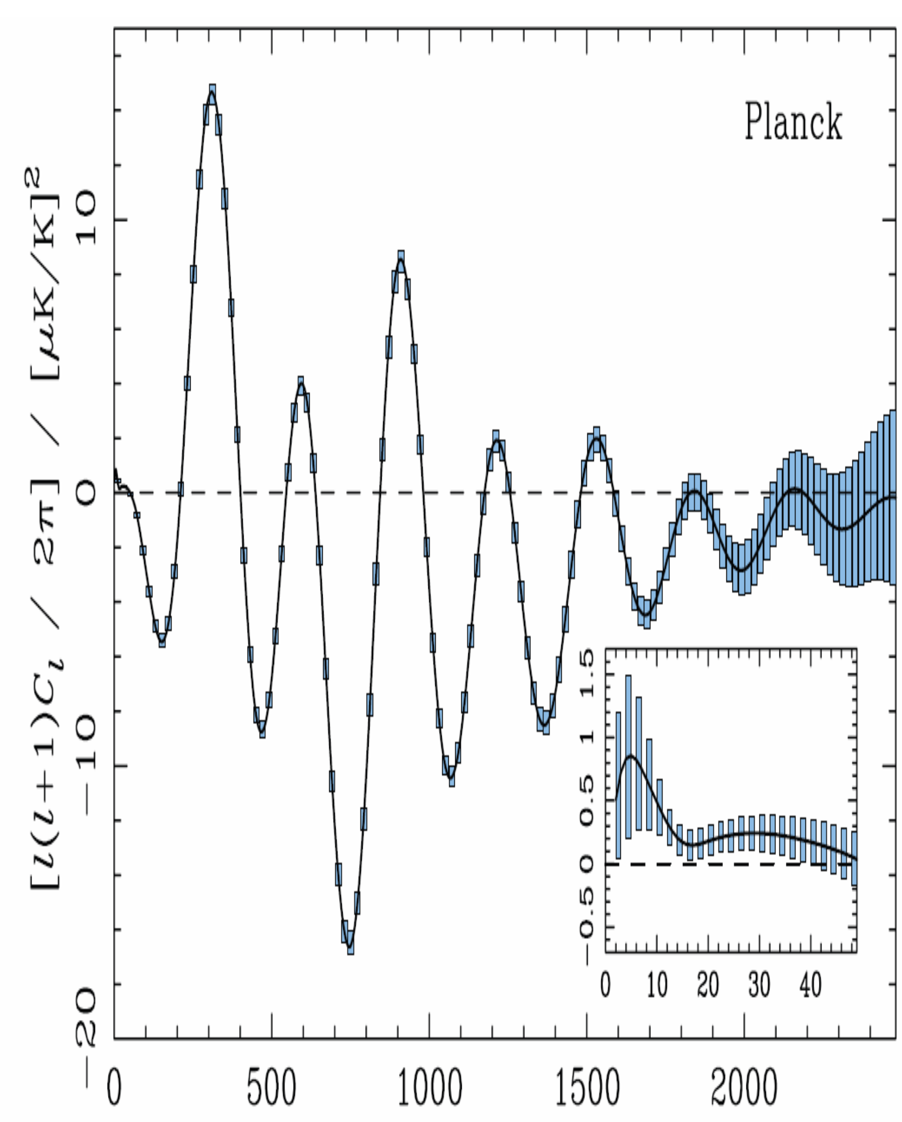
TABLE II: Representative cosmological data sets and corresponding 2σ (95% C.L.) constraints on the sum of ν masses Σ.

Case	Cosmological data set	Σ (at 2σ)
1	CMB	< 1.19 eV
2	CMB + LSS	< 0.71 eV
3	CMB + HST + SN-Ia	< 0.75 eV
4	CMB + HST + SN-Ia + BAO	< 0.60 eV
5	CMB + HST + SN-Ia + BAO + Lyα	< 0.19 eV

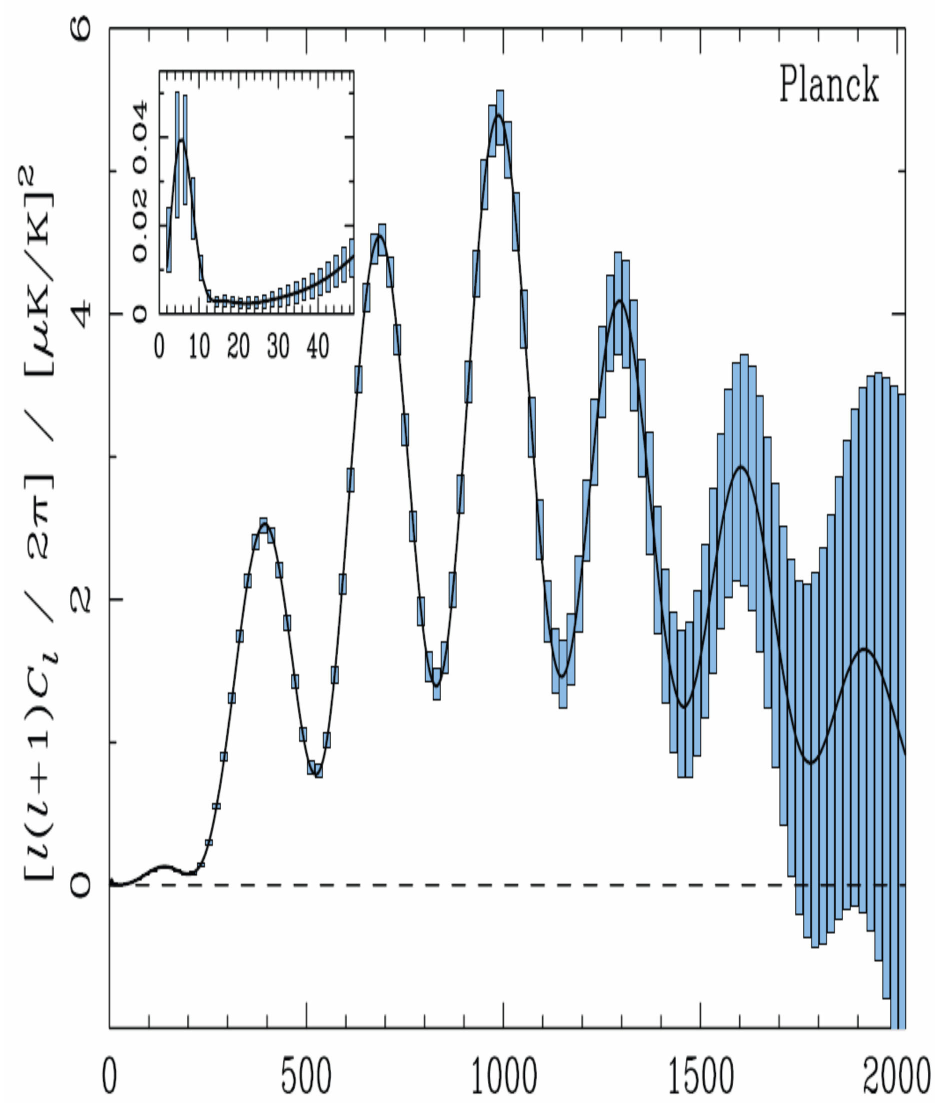
From Fogli et al. 2008, Astro-ph/0805.2517

With Planck : < 0.2 eV

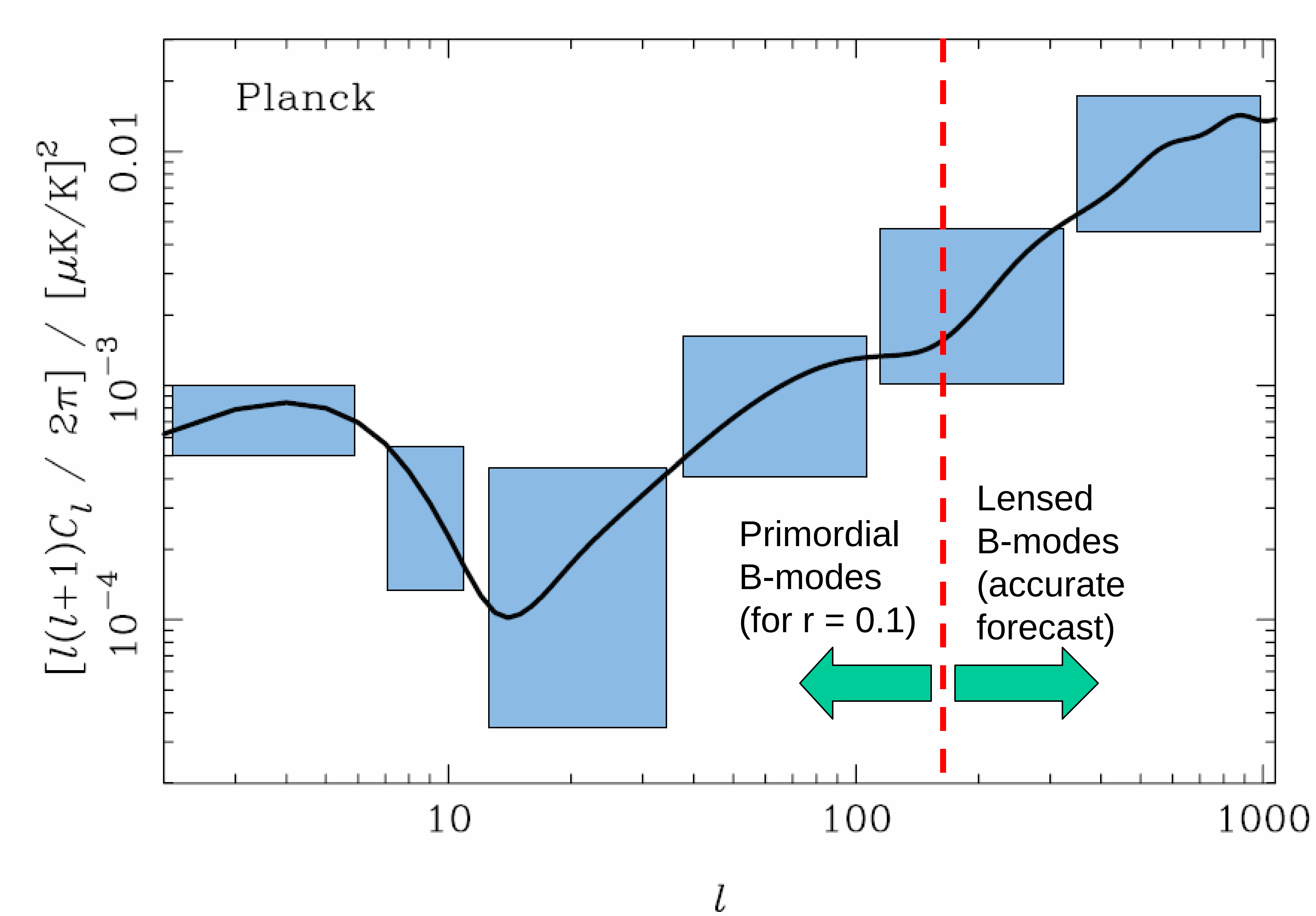
EE

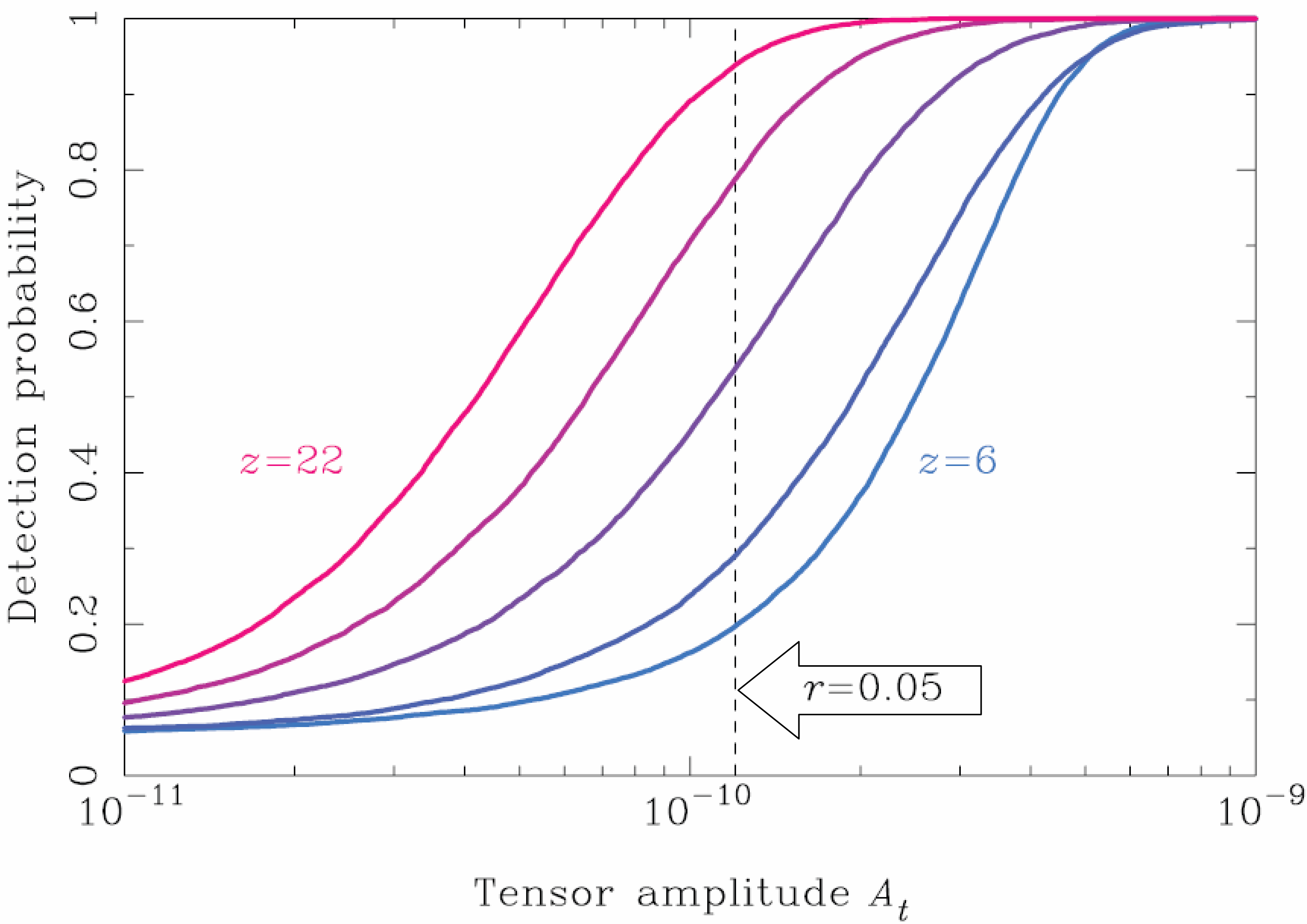


TE



ESA-SCI(2005)1


Planck
Primordial
B-modes
(for r = 0.1)
Lensed
B-modes
(accurate
forecast)
0.01
10^{-3}
10^{-4}
10
100
1000
l
$[l(l+1)C_l \ / \ 2\pi] \ / \ [\mu K/K]^2$



Detection probability
0
0.2
0.4
0.6
0.8
1
z=22
z=6
r=0.05
10^-11
10^-10
10^-9
Tensor amplitude A_t

From Efsthathiou & Gratton '09

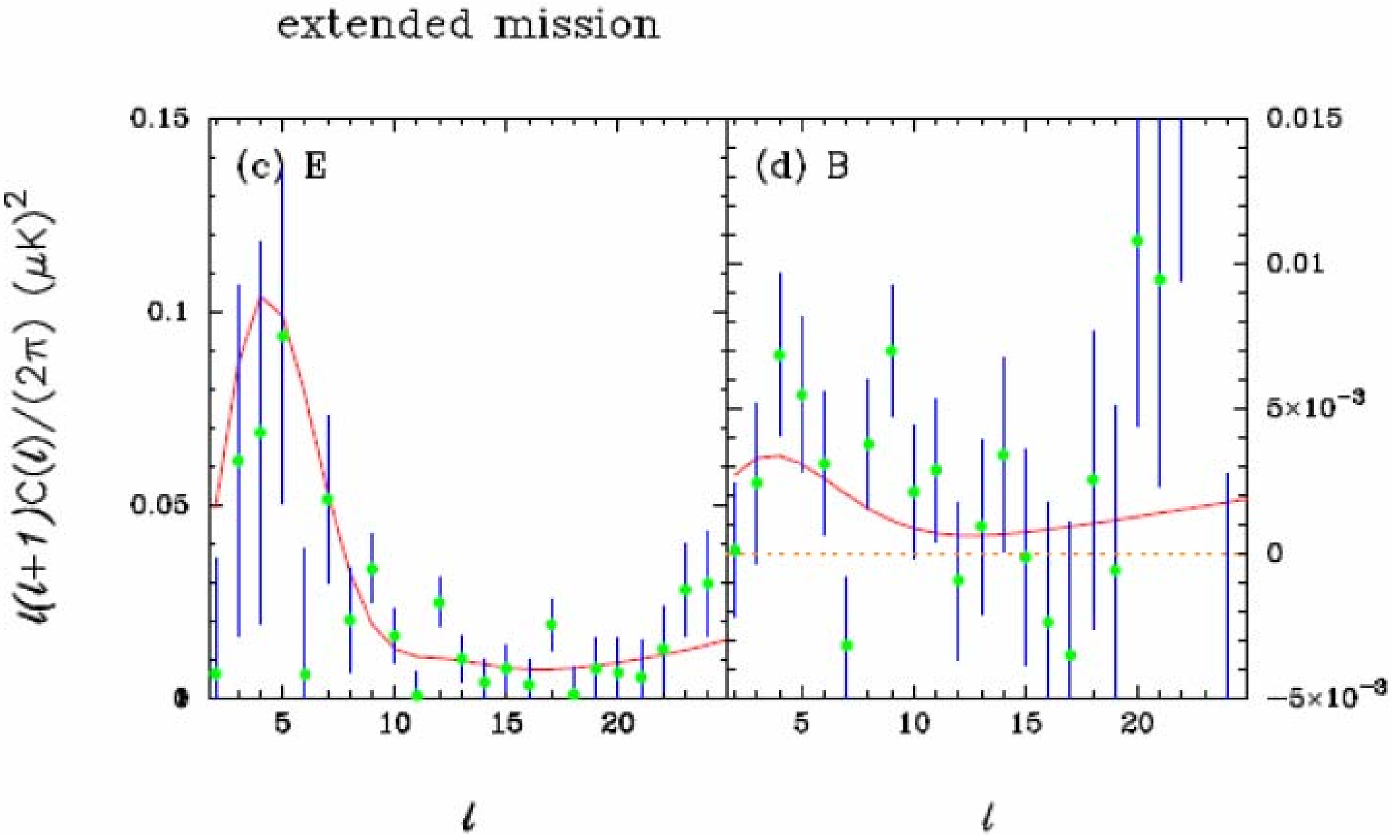
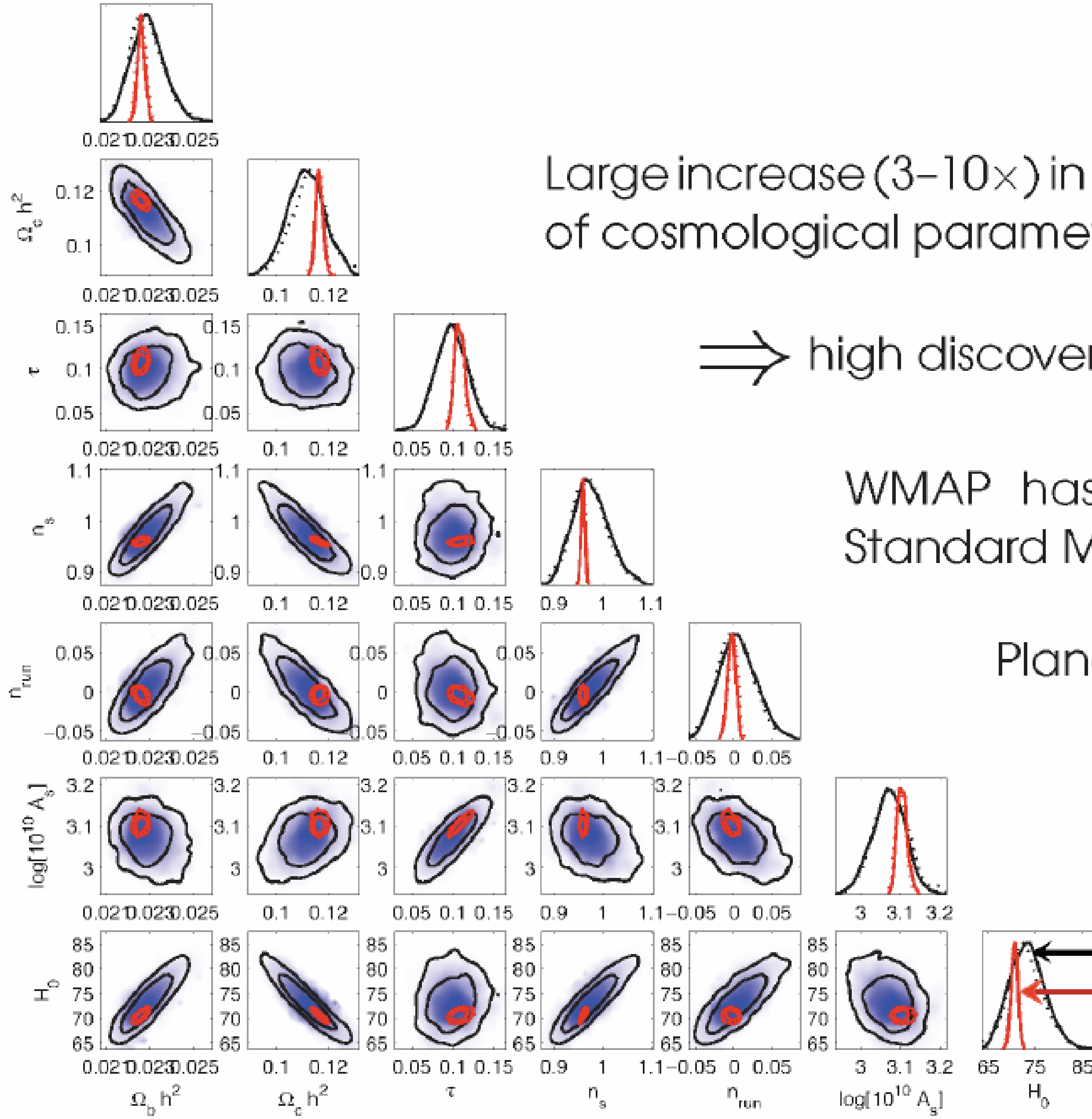


Figure 3. QML estimates of the E and B-mode polarization spectra for the simulations with $r = 0.05$. Figures 3a and 3b show power spectra for the nominal *Planck* mission. Figures 3c and 3d show power spectra for an extended *Planck* mission. The error bars are computed from the diagonal components of the inverse of the QML Fisher matrix using the theoretical input spectra for $r = 0.05$ (shown by the red lines).



Large increase (3–10×) in precision of cosmological parameters

⟹ high discovery potential

WMAP has confirmed the Standard Model

Planck will challenge it

Planck Bluebook

After Planck

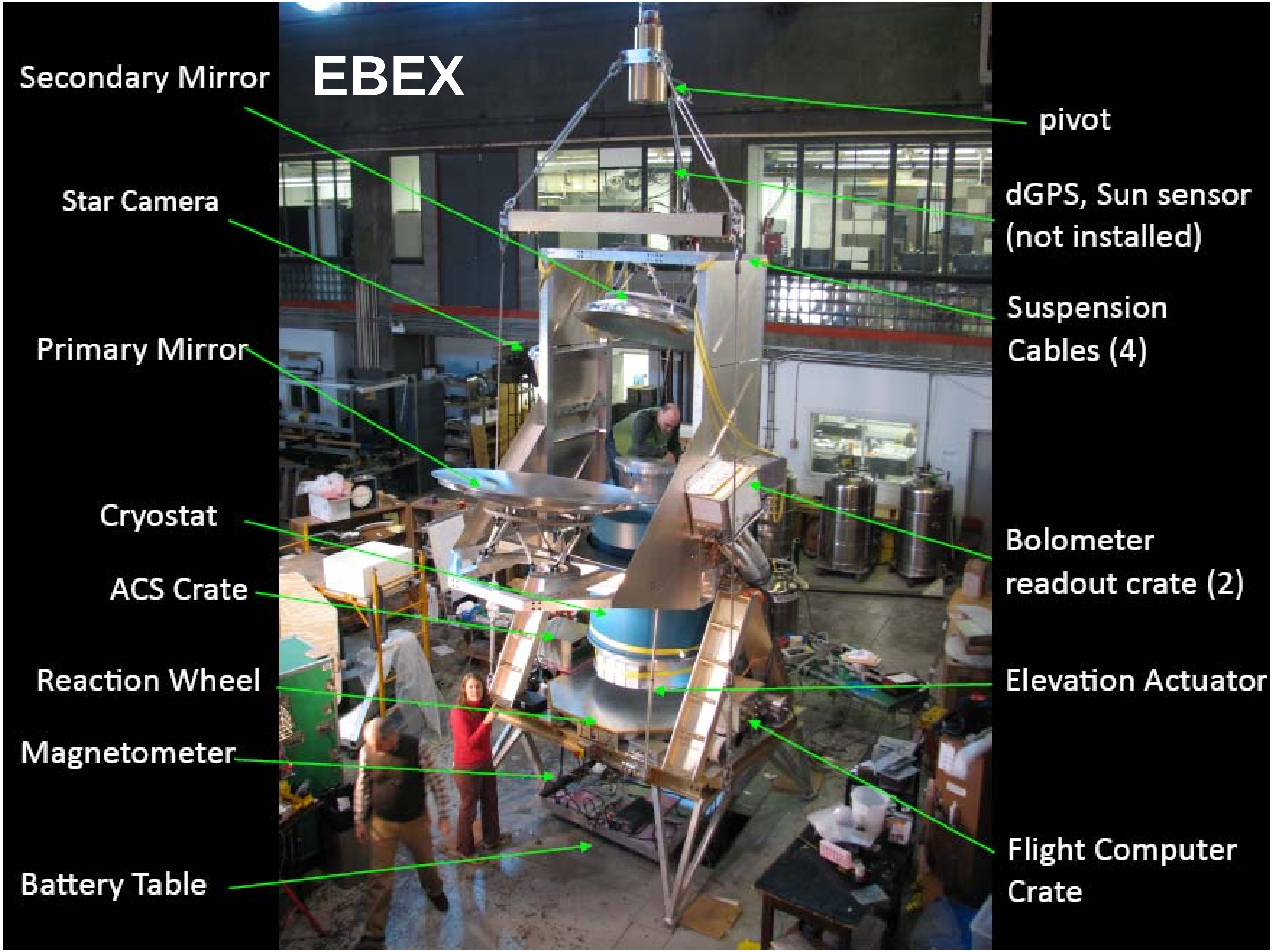
- New experiments have many more detectors than Planck (Sensitivity issue 2.)
- However,
  - it is difficult to obtain the same wide sky and frequency coverage if you are not working from space.
  - Sidelobes rejection is a big issue for large-scale surveys
- So I believe that the final word for primordial B-modes will come from a new space-based experiment
- Current and planned experiments are extremley useful to invent and test new configurations, to minimize and/or fully control systematic effects.

2. Sensitivity

- Reduce noise from the environment
  - Radiation noise from instrument, window, telescope, atmosphere
  - Get to astrophysical background limited conditions
  - Thermal noise in the detector
- Increase the number of detectors to boost the mapping speed.

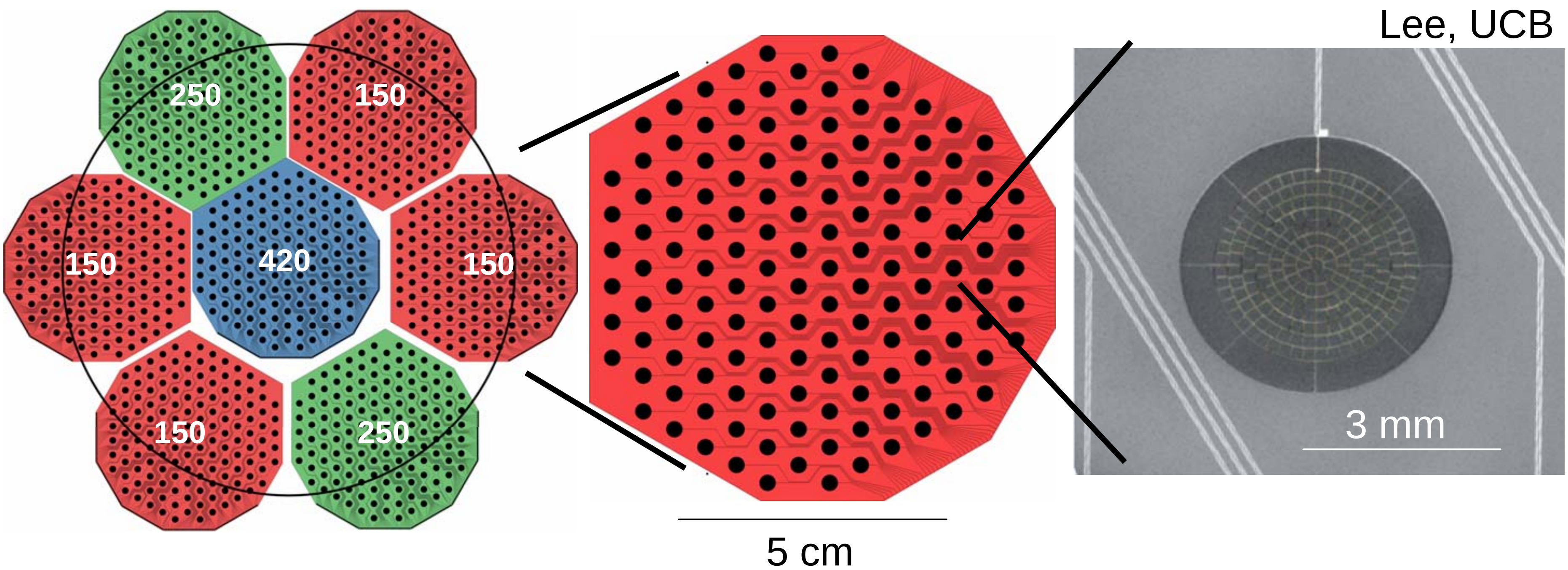
→ Space + Cryogenics

→ Large Arrays of mm-wave detectors


EBEX
Secondary Mirror
Star Camera
Primary Mirror
Cryostat
ACS Crate
Reaction Wheel
Magnetometer
Battery Table
pivot
dGPS, Sun sensor
(not installed)
Suspension
Cables (4)
Bolometer
readout crate (2)
Elevation Actuator
Flight Computer
Crate

EBEX Focal Plane

738 element array | 141 element hexagon | Single TES



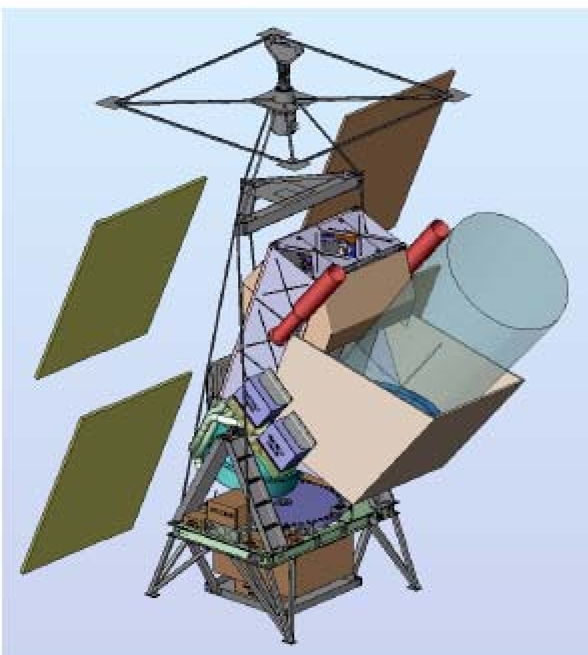
- Total of 1476 detectors
- Maintained at 0.27 K
- 3 frequency bands/focal plane

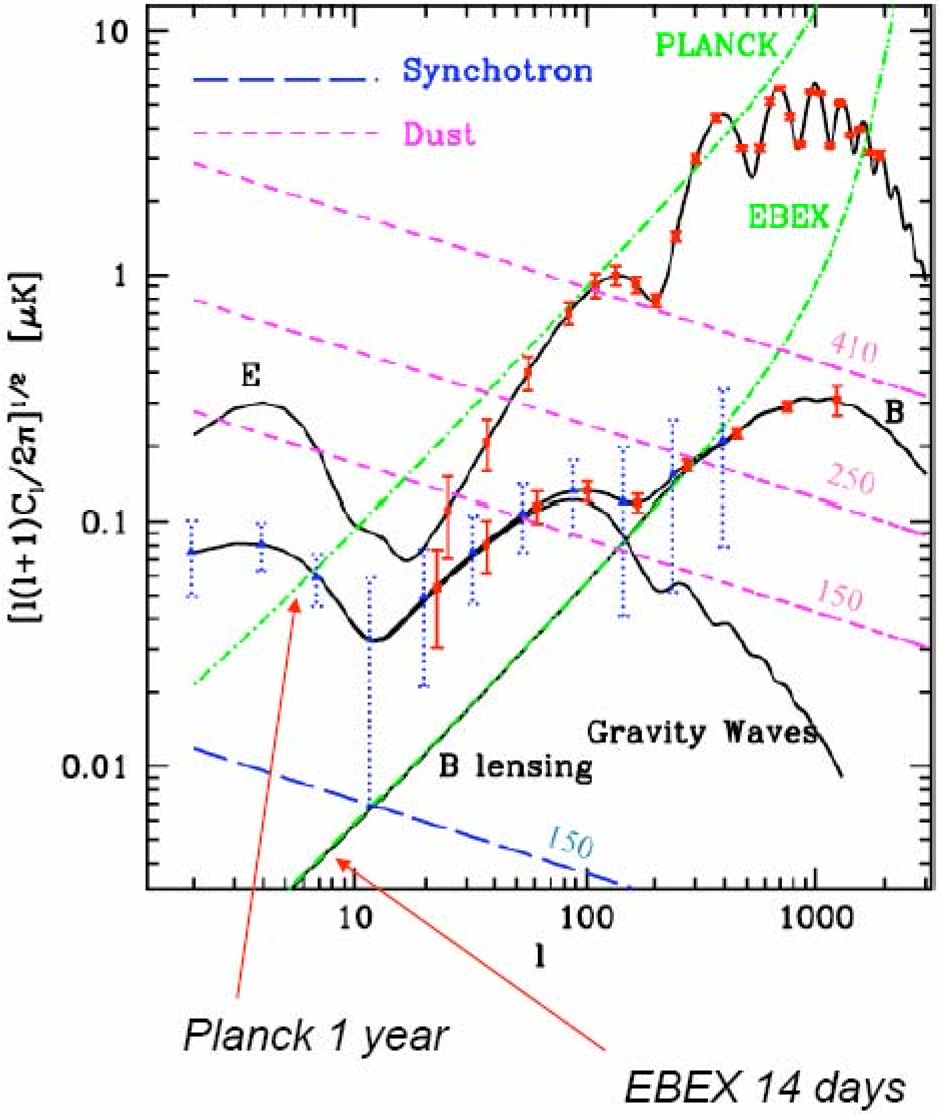
- G=15-30 pWatt/K
- NEP = 1.4e-17 (150 GHz)
- NEQ = 156 μK*rt(sec) (150 GHz)
- $\tau = 3$ msec,

Slide: Hanany

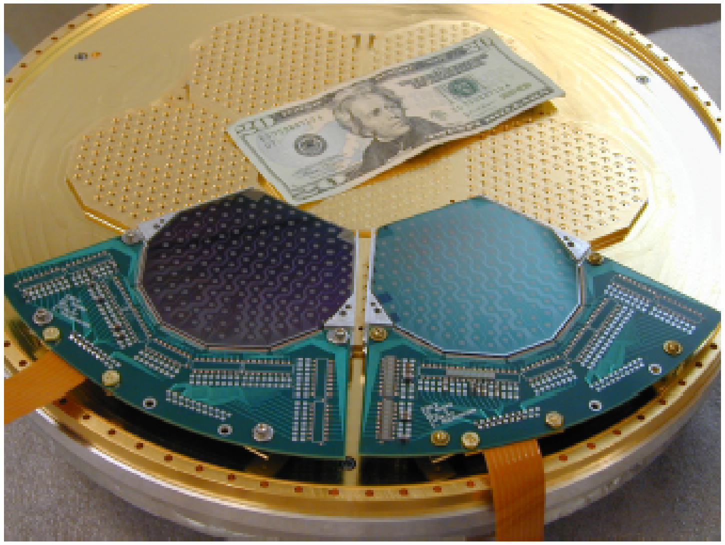
Science Goals

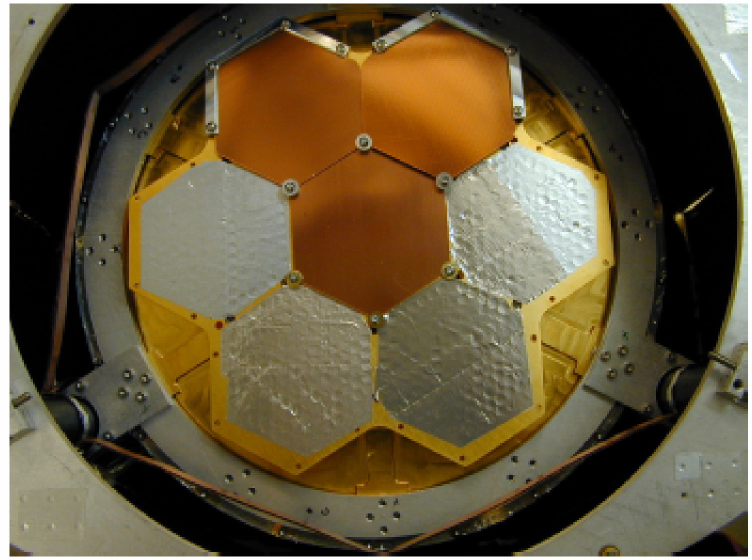
- Detect or set upper bound on inflation B-mode
- Measure lensing B-mode
- Understand Polarized Dust
- Improve estimation of cosmological parameters

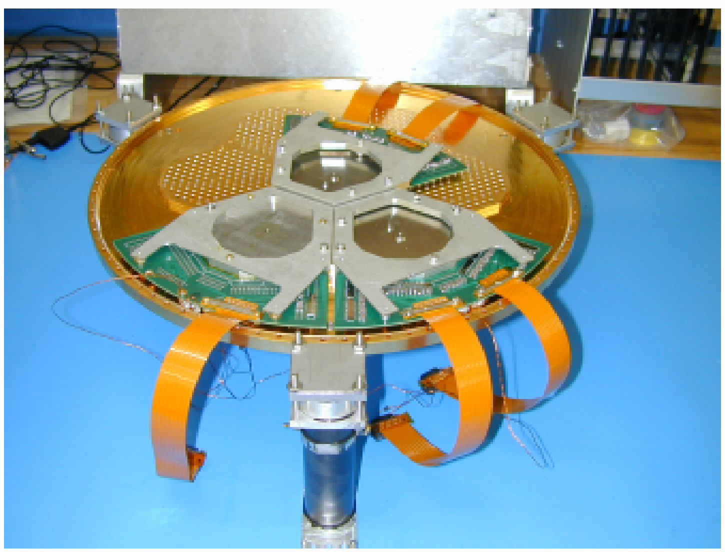


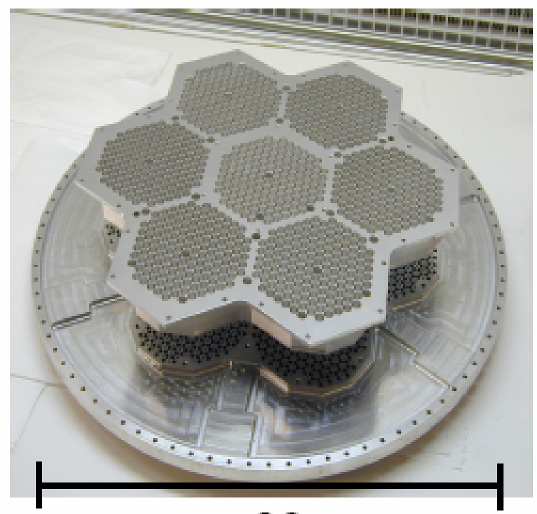


Focal Plane Hardware









SPIDER

Suborbital Polarimeter for Inflation Dust and the Epoch of Reionization

William Jones
Princeton University
for the
Spider Collaboration

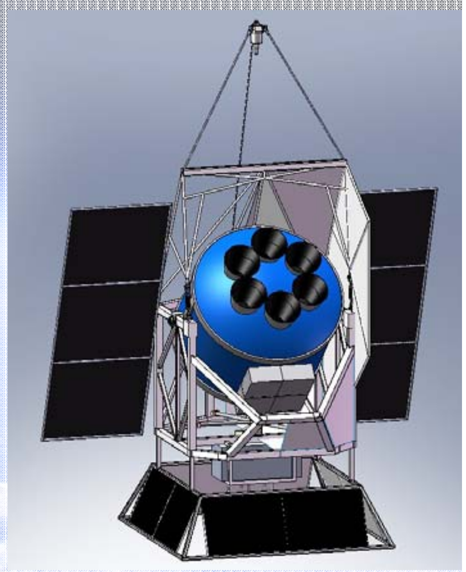
The Path to CMBpol
June 31, 2009

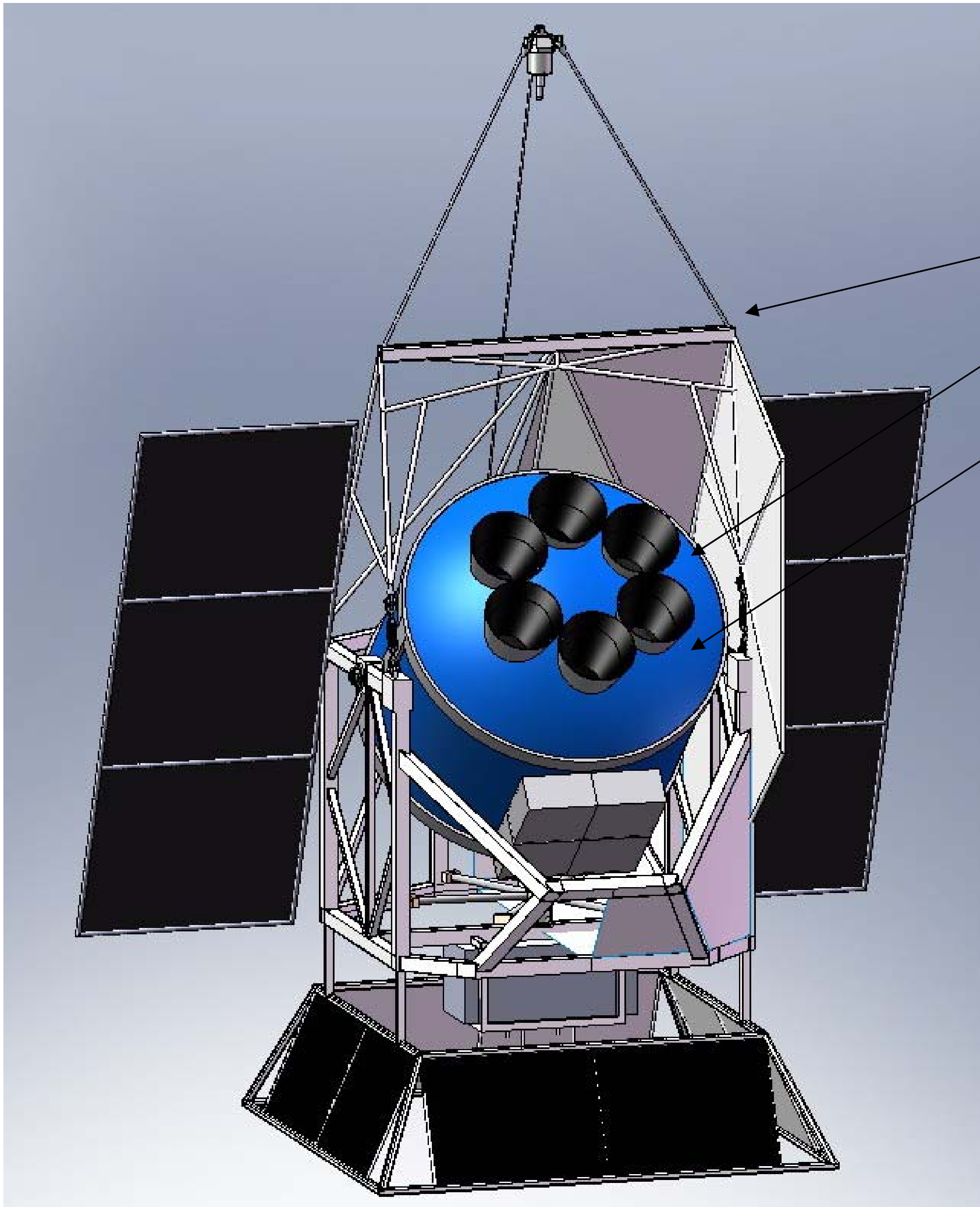
NASA · CSA ASC · C.S.B.F. Palestine, Texas · NSERC CRSNG · JPL · California Institute of Technology · University of Toronto · Case Western Reserve University · Cardiff University Prifysgol Caerdydd · UBC · NIST · Princeton University · CITA ICAT · Imperial College London

Spider: A Balloon Borne CMB Polarimeter

Suborbital Polarimeter for Inflation Dust and the Epoch of Reionization

- Long duration (~30 day cryogenic hold time) balloon borne polarimeter
- Surveys 60% of the sky each day of the flight, with ~0.5 degree resolution
- Broad frequency coverage to aid in foreground separation
- Will extract nearly all the information from the CMB E-modes
- Will probe B-modes on scales where lensing does not dominate
- Technical Pathfinder: solutions appropriate for a space mission





Carbon Fiber Gondola

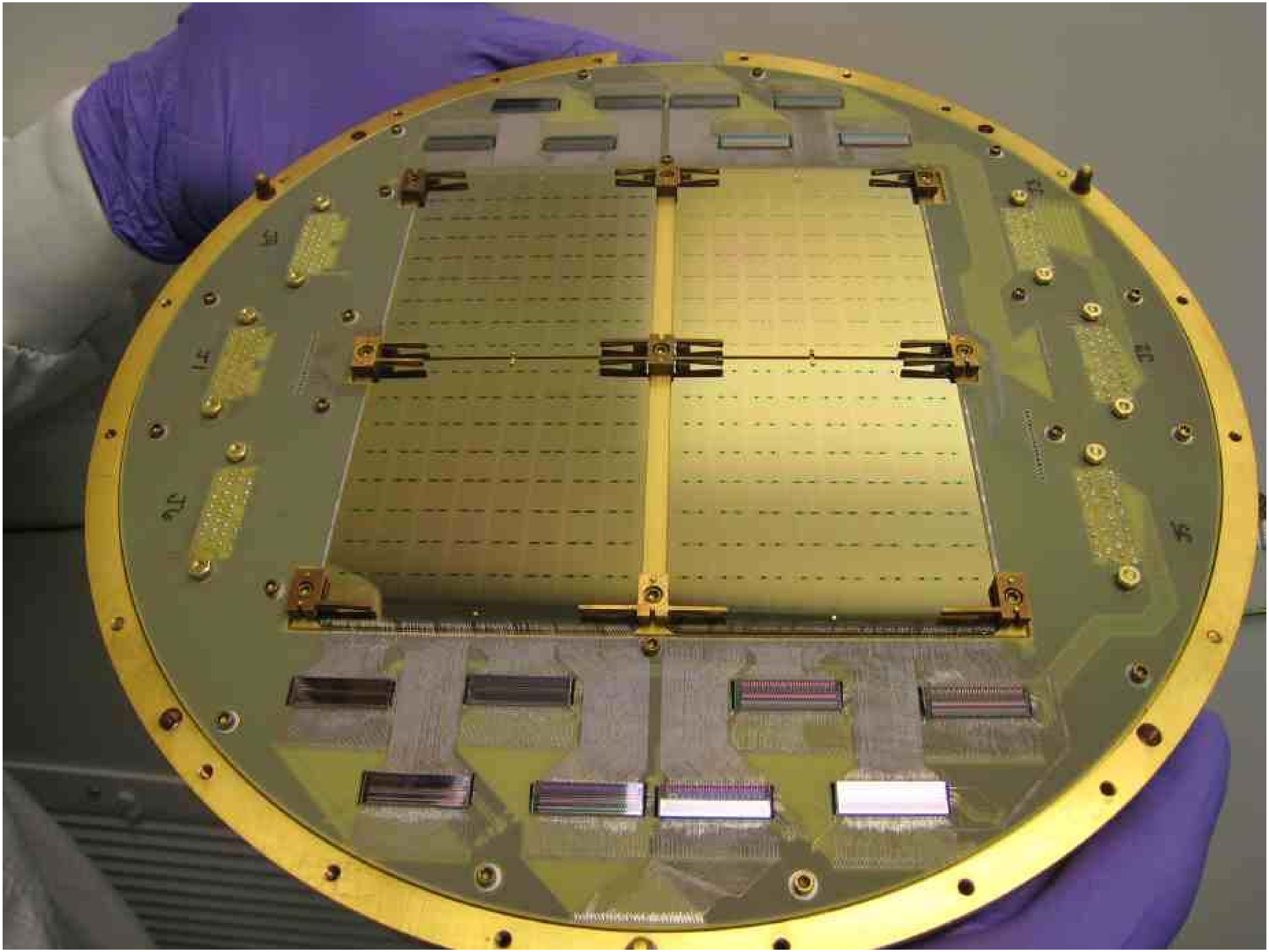
Six single freq. telescopes

30 day, 1850 lb, 4K / 1.4 K cryostat

Attitude Control
- flywheel
- magnetometer
- rate gyros
- sun sensor

Pointing Reconstruction
- 2 pointed cameras
- boresight camera
- rate gyros

Flight Computers/ACS
- 1 TB for turnaround
- 5 TB for LDB



3. Control of systematic effects

- Polarized sidelobes (large baffles, space)
- Polarization modulators (many different methods)
- Orthogonal measurement methods:
  - Coherent imagers (QUIET, ..)
  - Bolometric imagers (BOOMERanG, MAXIPOL, Planck, BICEP, EBEX, SPIDER, PIPER, LSPE, …
  - Coherent interferometers (DASI, CBI, …)
  - Bolometric interferometers (MBI, QUBIC)

Astro-ph/0906.4069 Takahashi et al.

BICEP instrument characterization

TABLE 3
SYSTEMATIC ERRORS POTENTIALLY PRODUCING FALSE B-MODE POLARIZATION

	Benchmark[a]	Measured	Measurement notes	Reference
Relative gain uncertainty: $\Delta(g_1/g_2)/(g_1/g_2)$	0.9%	$<$ 1.1%	Upper limit, rms error over the array.[b]	§3.1
Differential pointing: $(\mathbf{r}_1 - \mathbf{r}_2)/\sigma$ [c]	1.9%	1.3%	Average, each repeatedly characterized to 0.4% precision.[d]	§3.2
Differential beam size: $(\sigma_1 - \sigma_2)/\sigma$	3.6%	$<$ 0.3%	Upper limit, rms over the array.	§3.2
Differential ellipticity: $(e_1 - e_2)/2$	1.5%	$<$ 0.2%	Upper limit, rms over the array.	§3.2
Polarization orientation uncertainty: $\Delta\psi$	2.3°	$<$ 0.7°	Upper limit, rms absolute orientation error over the array.	§3.3
Telescope pointing uncertainty: $\Delta\mathbf{b}$	5′	0.2′	Fit residual rms in optical star pointing calibration.	§3.4
Polarized sidelobes (100, 150 GHz)	-9, -4 dBi	-26, -17 dBi	Response at 30° from the beam center.	§3.5
Focal plane temperature stability: $\Delta T_{\rm FP}$	3 nK	1 nK	Scan-synchronous rms fluctuation on $\ell \sim 100$ time scale.	§3.6
Optics temperature stability: $\Delta T_{\rm RJ}$	4 μK	0.7 μK	Scan-synchronous rms fluctuation on $\ell \sim 100$ time scale.	§3.6

[a] Benchmarks correspond to values that result in a false B-mode signal of at most $r = 0.1$. For $r = 0.01$, all benchmarks would be lower by $\sqrt{10}$.

[b] If relative gain errors are detected, we anticipate removing their effects in future analyses using a CMB temperature template map.

[c] $\sigma = FWHM/\sqrt{8\ln(2)} = \{0.39°, 0.26°\}$ at $\{100, 150\}$ GHz.

[d] This measurement of differential pointing could be used in future analyses to remove the small predicted leakage of CMB temperature into polarization maps.

	Measured	max false B, equiv. r
1. Relative gain uncertainty: $\Delta(g_1/g_2)/(g_1/g_2)$	$< 1.1\%$	< 0.15
2. Differential pointing: $(\mathbf{r_1} - \mathbf{r_2})/\sigma$	1.3%	0.05
3. Focal plane temperature stability: ΔT_{FP}	1 nK	0.011
4. Polarization orientation uncertainty: $\Delta\psi$	$< 0.7^\circ$	< 0.009
5. Optics temperature stability: ΔT_{RJ}	0.7 μK	0.003
6. Differential ellipticity: $(e_1 - e_2)/2$	$< 0.2\%$	< 0.002
7. Differential beam size: $(\sigma_1 - \sigma_2)/\sigma$	$< 0.3\%$	< 0.0007
8. Polarized sidelobes (100, 150 GHz)	-26, -17 dBi	0.0002
9. Telescope pointing uncertainty: $\Delta\mathbf{b}$	$0.2'$	0.0002

The result from BICEP 2 years is a 95% upper limit r < 0.73

Enitrely dominated by receiver noise and relative gain uncertainty .

	Measured	max false B, equiv. r
1. Relative gain uncertainty: $\Delta(g_1/g_2)/(g_1/g_2)$	$< 1.1\%$	< 0.15
2. Differential pointing: $(\mathbf{r}_1 - \mathbf{r}_2)/\sigma$	1.3%	0.05
3. Focal plane temperature stability: ΔT_{FP}	1 nK	0.011
4. Polarization orientation uncertainty: $\Delta\psi$	$< 0.7°$	< 0.009
5. Optics temperature stability: ΔT_{RJ}	0.7 μK	0.003
6. Differential ellipticity: $(e_1 - e_2)/2$	$< 0.2\%$	< 0.002
7. Differential beam size: $(\sigma_1 - \sigma_2)/\sigma$	$< 0.3\%$	< 0.0007
8. Polarized sidelobes (100, 150 GHz)	-26, -17 dBi	0.0002
9. Telescope pointing uncertainty: $\Delta\mathbf{b}$	0.2′	0.0002

A 10x improvement is possible:

- The best way to remove relative gain uncertainty is to use the same bolometer for both polarizations i.e. insert a polarization modulator.
- Then, to improve the sensitivity, boost the number of bolometers and reduce the background. EBEX, SPIDER, PIPER, LSPE are balloon borne instruments doing exactly this.

3. Control of systematic effects

- Polarized sidelobes (large baffles, space)
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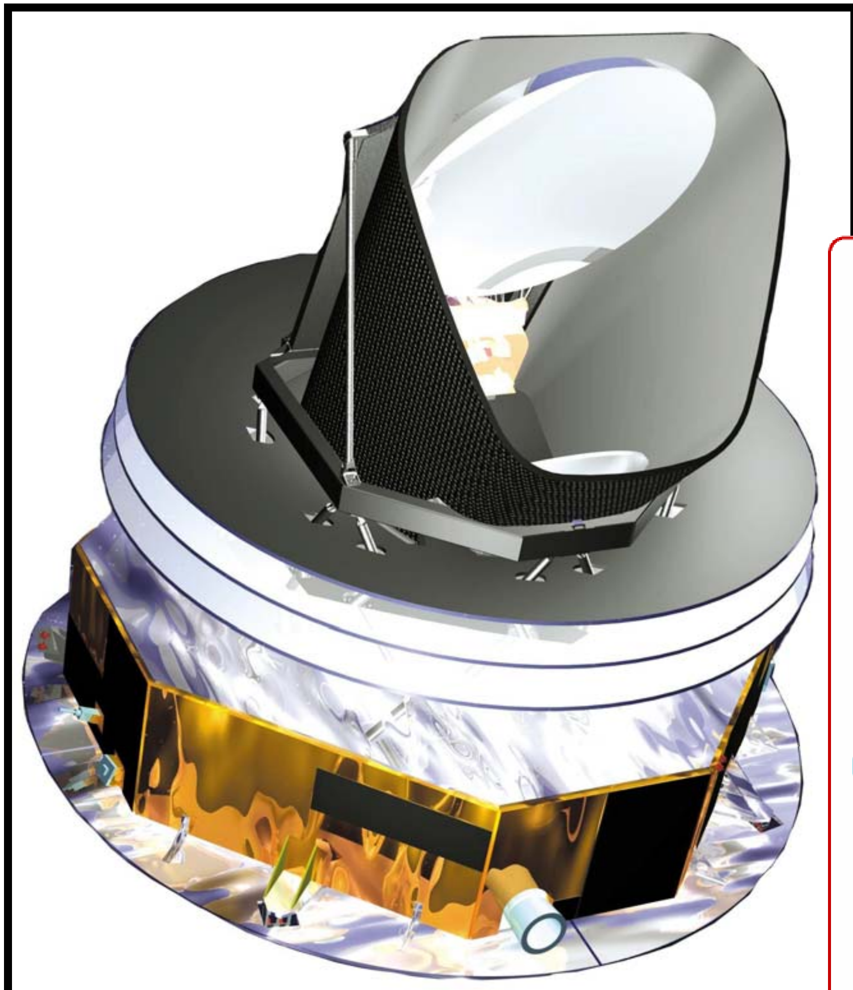
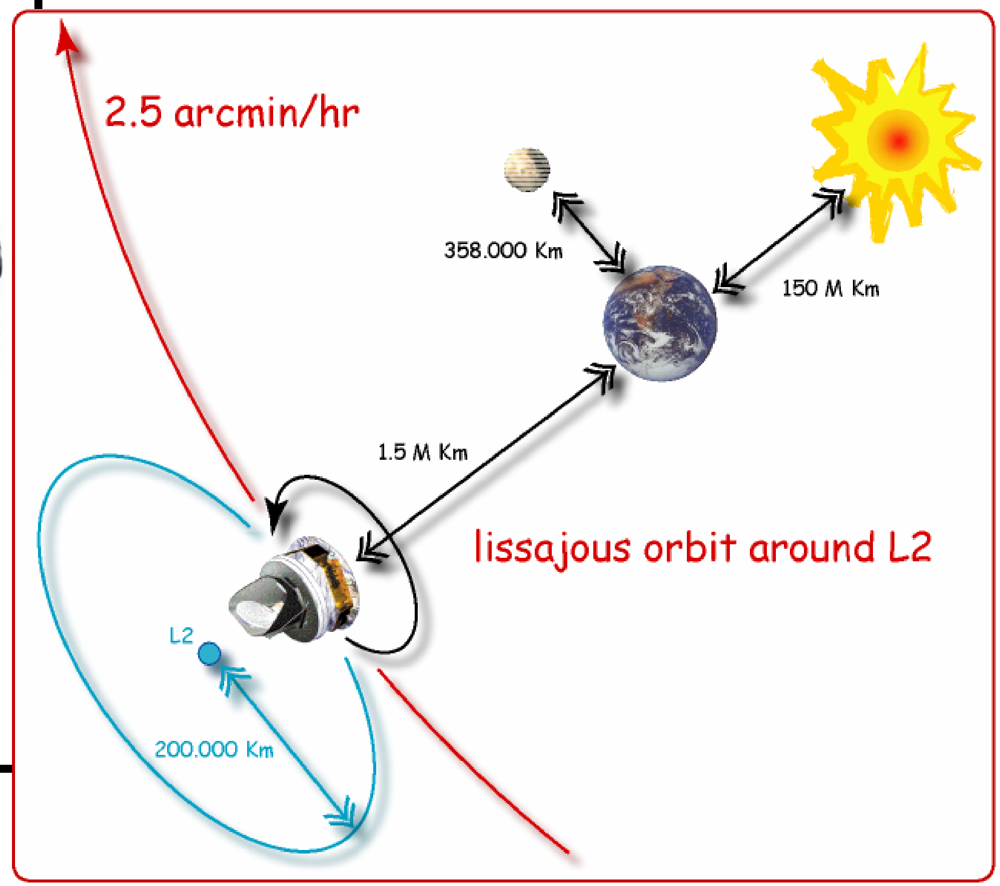
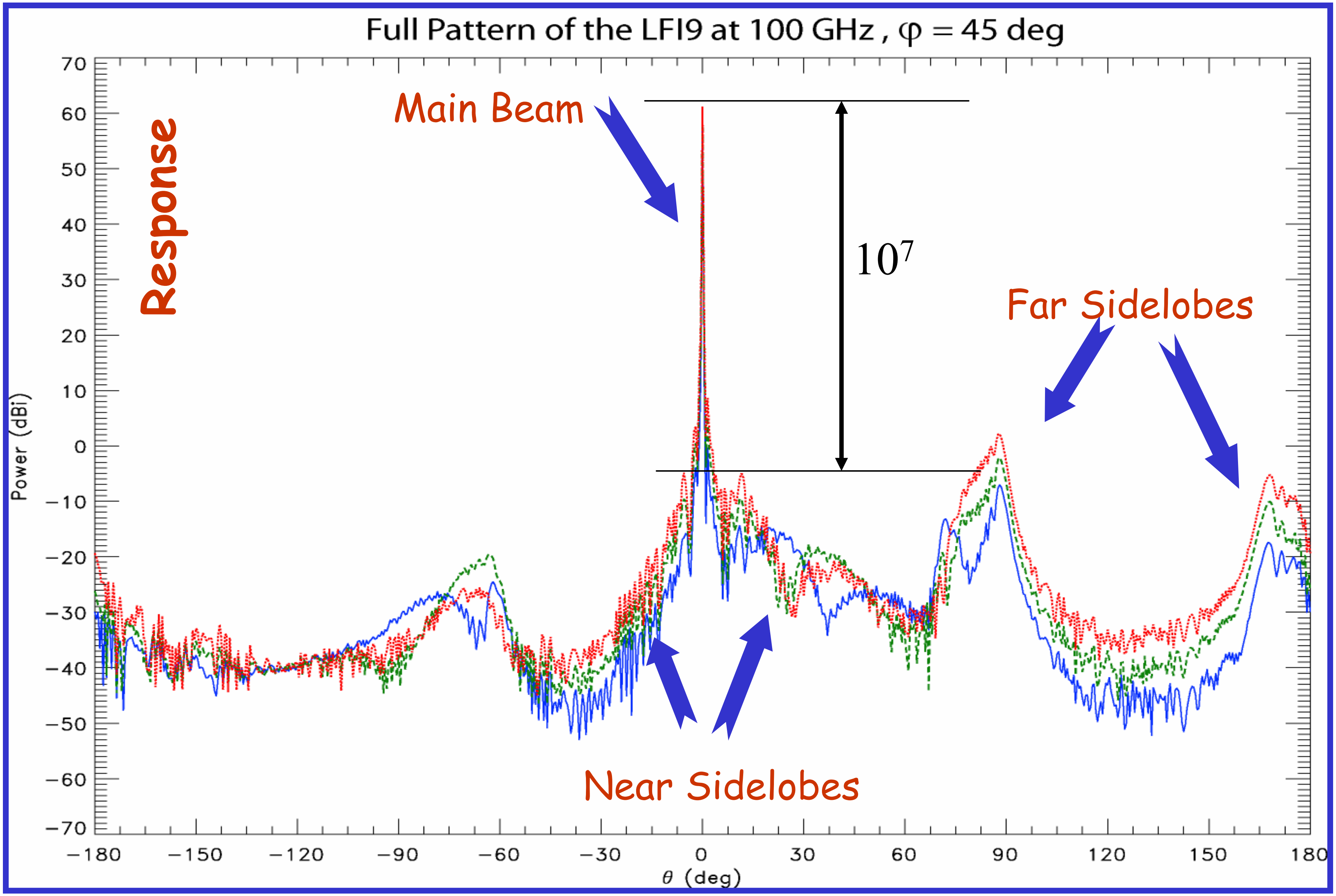
- Orthogonal measurement methods:
  - Coherent imagers (QUIET, ..)
  - Bolometric imagers (BOOMERanG, MAXIPOL, Planck, BICEP, EBEX, SPIDER, PIPER, LSPE, …
  - Coherent interferometers (DASI, CBI, …)
  - Bolometric interferometers (MBI, QUBIC)

low sidelobes & reduced solid angle: Planck







Angle from boresight

F. Villa, LFI

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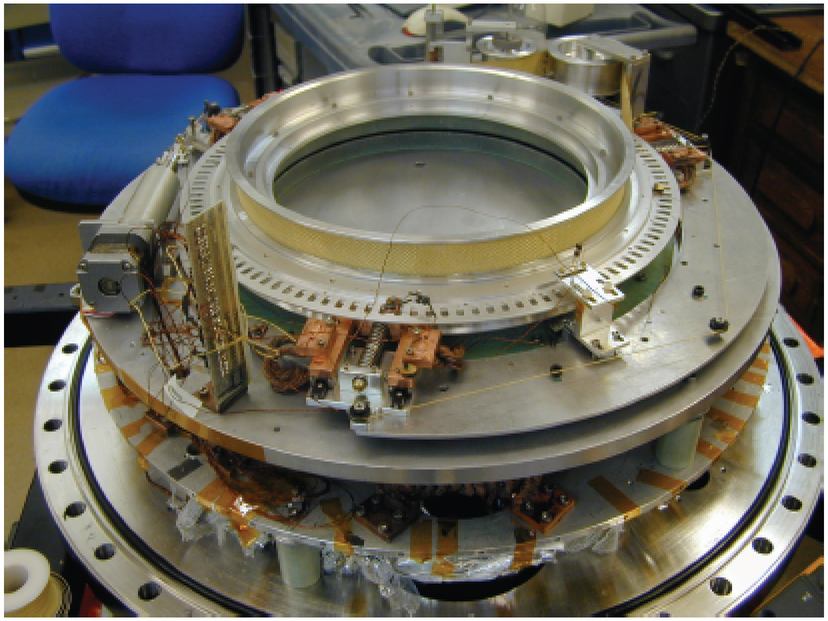
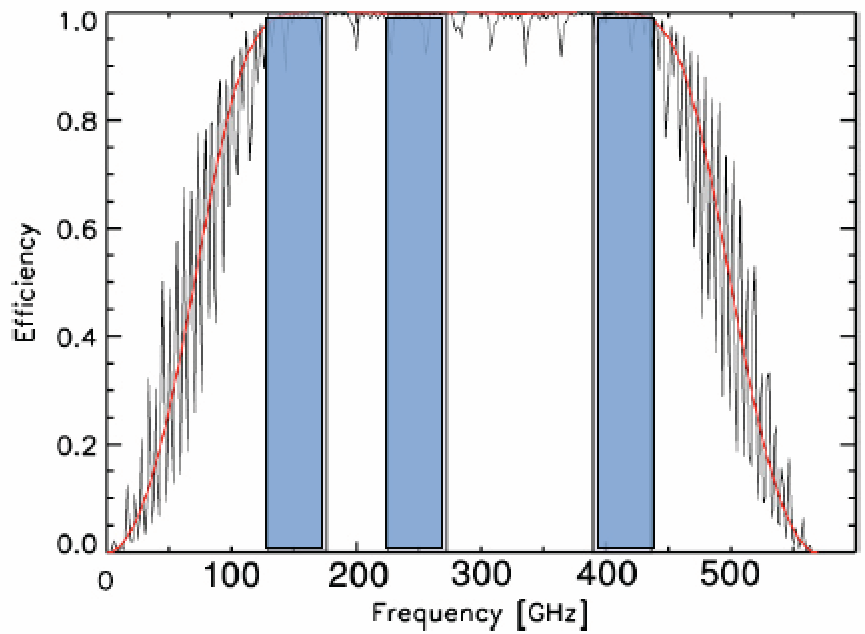
  - Bolometric interferometers (MBI, QUBIC)

Polarization modulators (quasi-optical mode)

- Throughput advantage wrt coherent systems
- HWP + Polarizer (Stokes polarimetry)
  - Dielectric waveplates with ARC (EBEX, SPIDER, KECK…) Savini, Pisano, Hanany, Bryan
  - Metal mesh waveplates (LSPE …) Pisano
- Reflecting HWP (PolKA) Siringo
- VPM (Variable delay polarization modulator, PIPER) Kogut

Polarimetery with an achromatic Half Wave Plate





Rotates on a superconducting magnetic bearing

6 Hz rotation (2 Hz North American Flight)

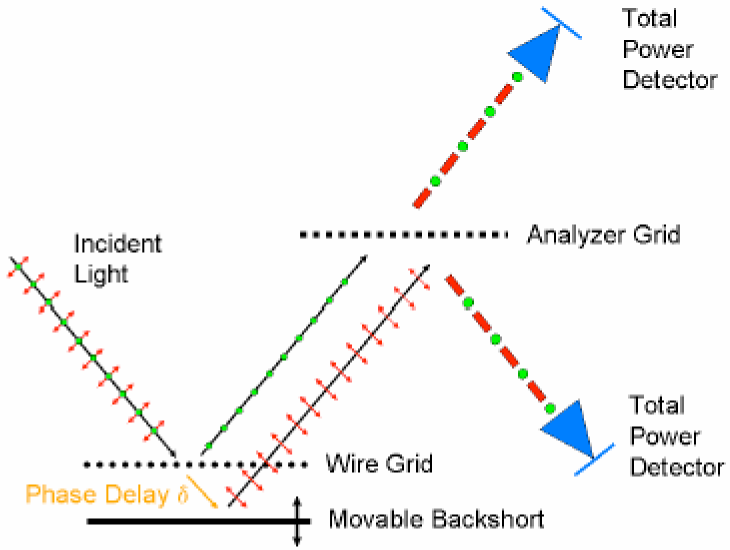
0.25 degree angular encoding limited by sampling

< 10% attenuation from 3 msec time constant

5 stack achromatic HWP (sapphire)

0.98 efficiency for 120< ν < 420 Ghz

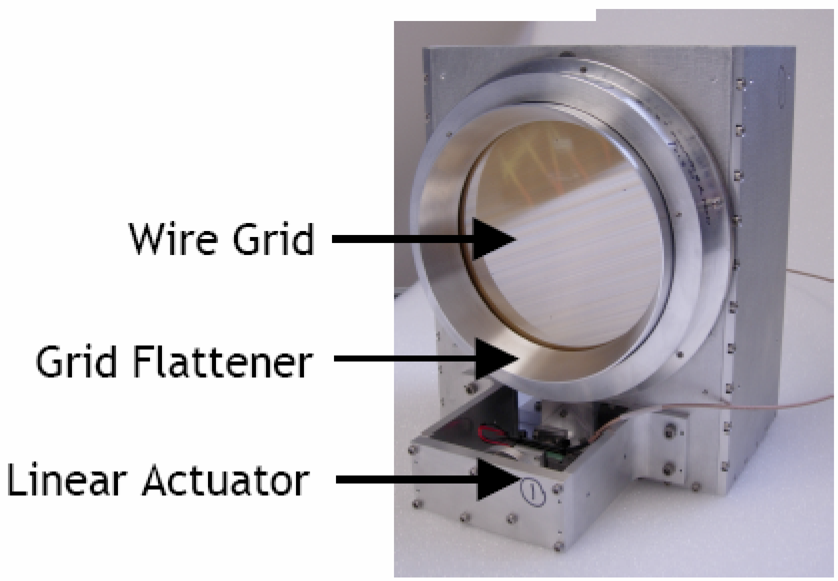
Polarization Modulator

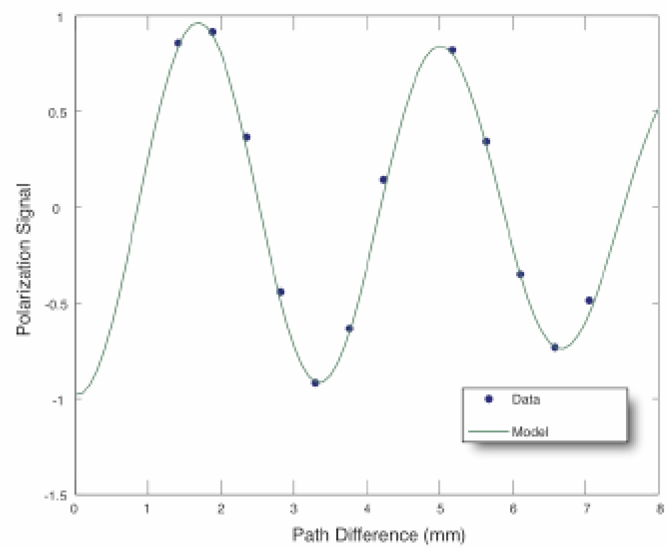


$$P_x = \frac{1}{2}\left(I + Q\cos\delta - V\sin\delta\right)$$

Measure linear and circular polarization!

$$P_y = \frac{1}{2}\left(I - Q\cos\delta + V\sin\delta\right)$$





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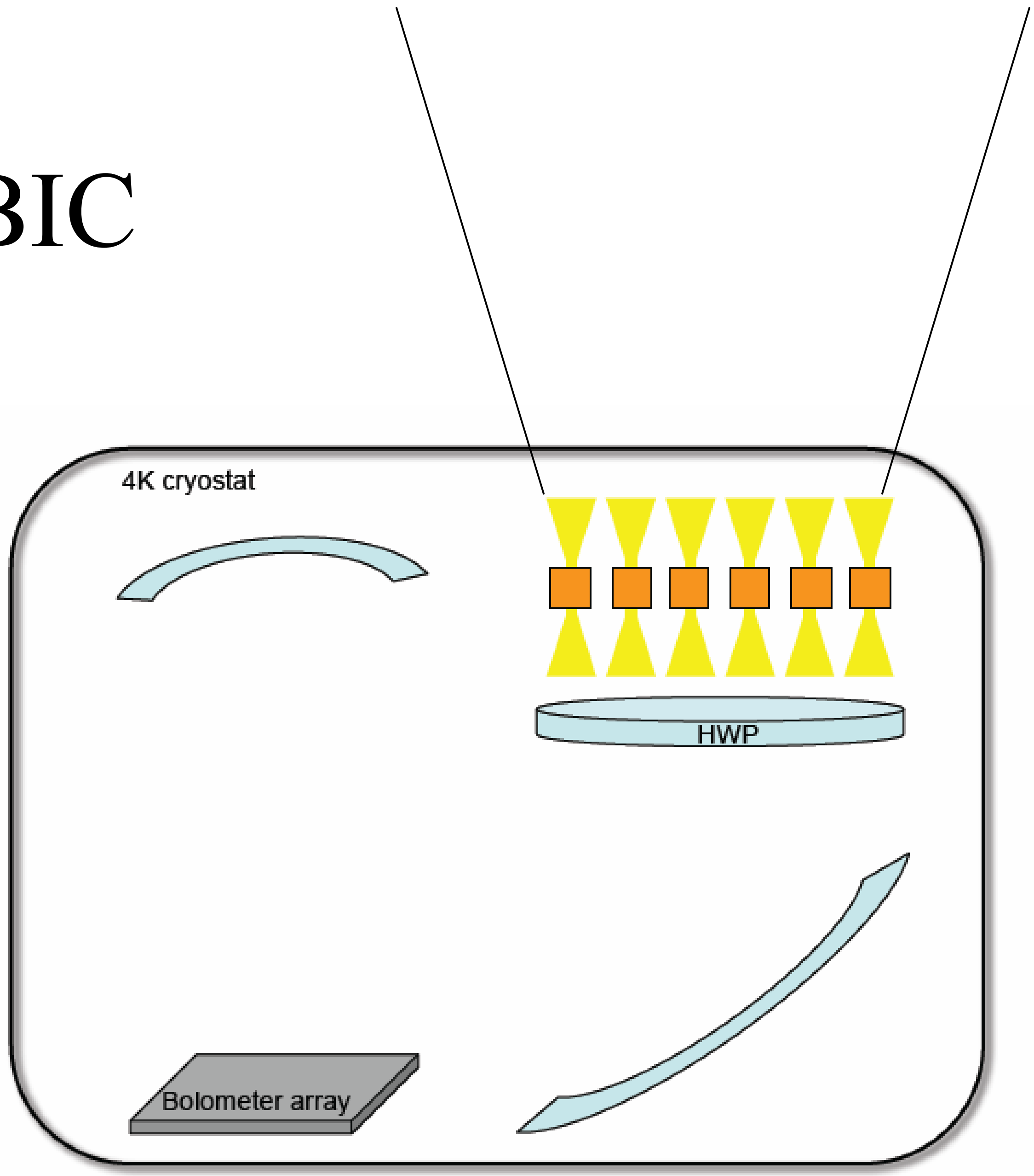
  - Coherent interferometers (DASI, CBI, …)
  - Bolometric interferometers (MBI, QUBIC)

QUBIC



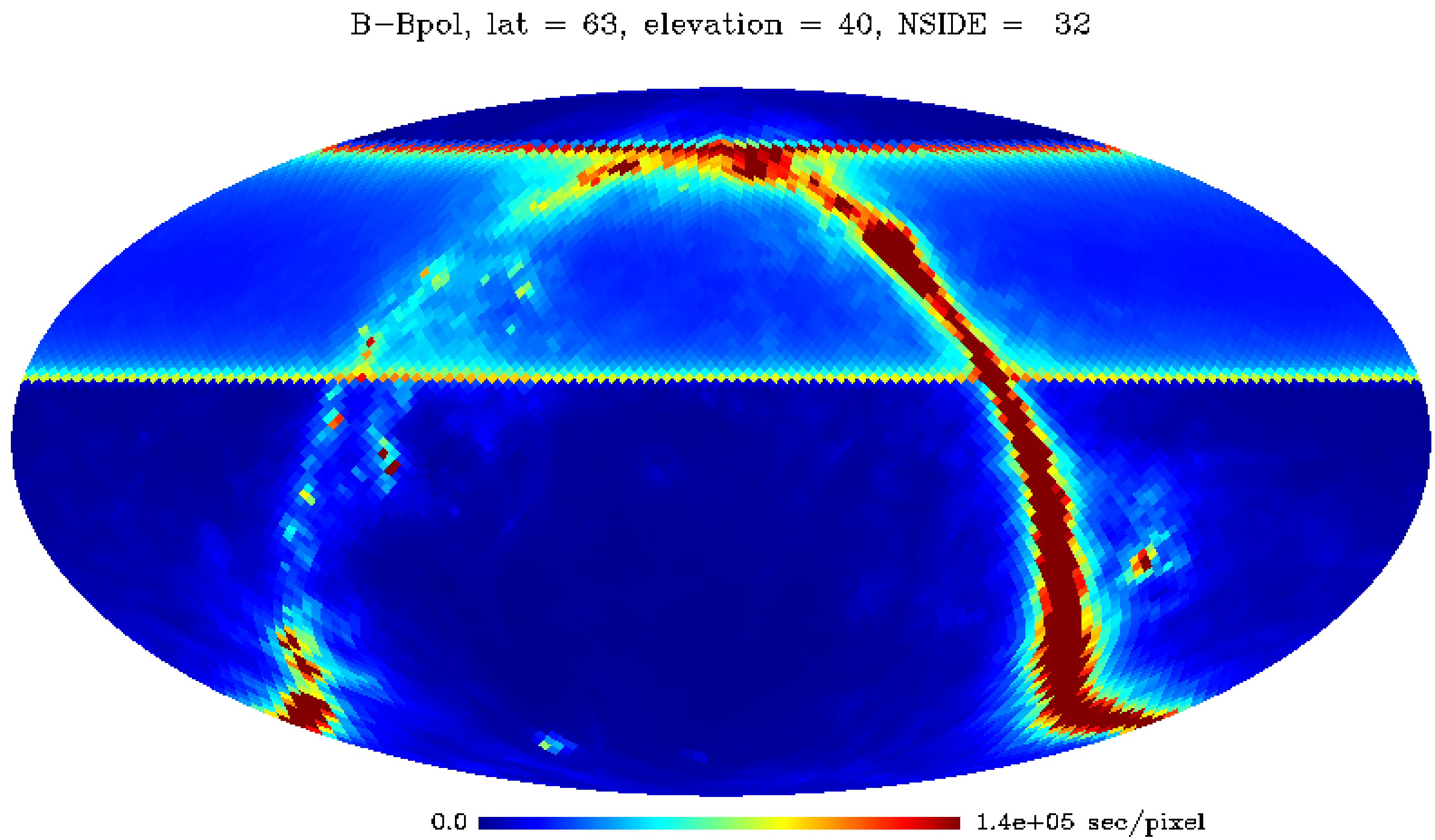
Large Scale Polarization Explorer

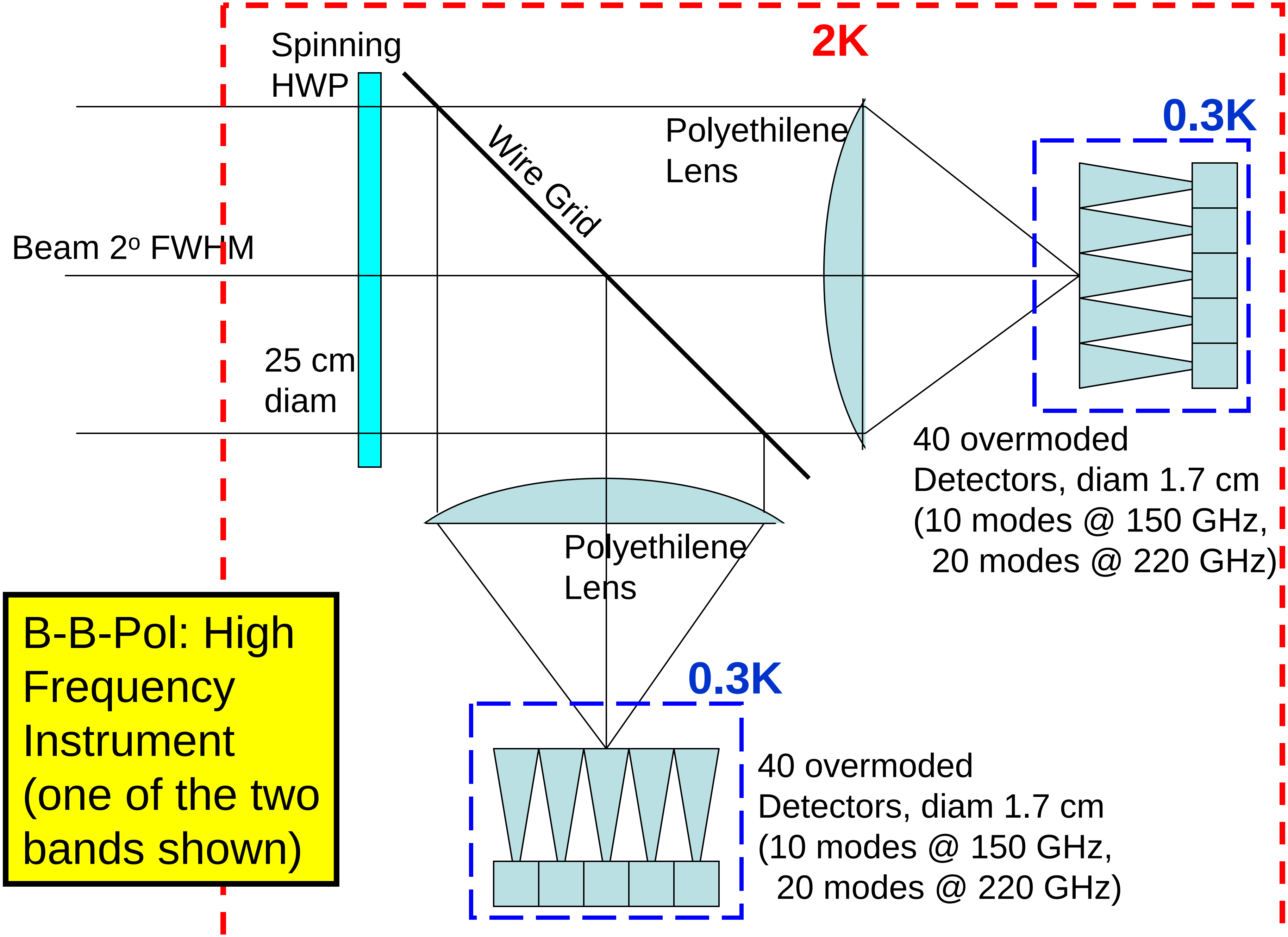
WHY ?

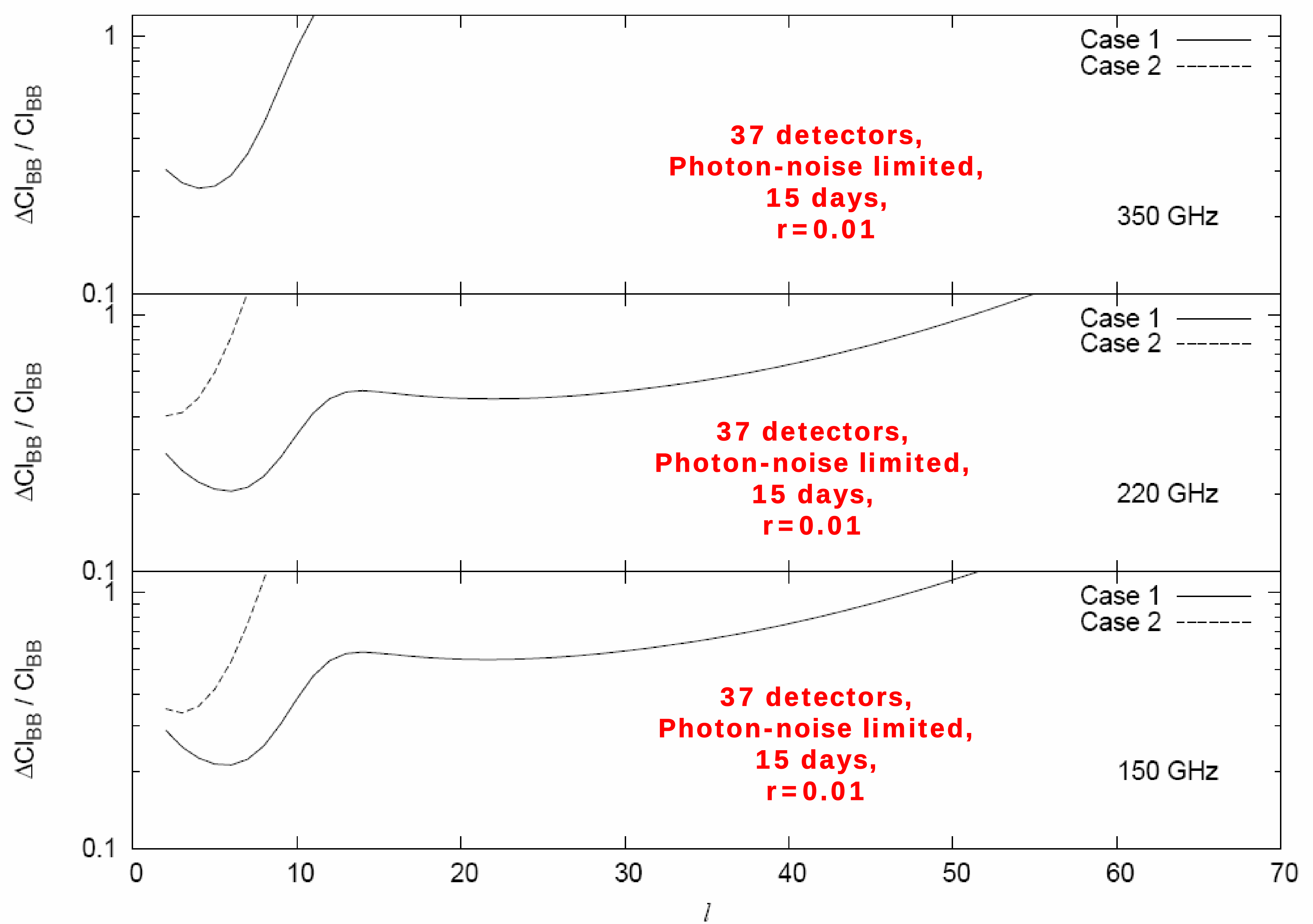
- Get important science (complementary to SPIDER, EBEX, etc.)
- Validate needed technology, for next round of ESA cosmic vision

HOW ?

- **ASI** polar-night flight -> large sky coverage
- Two instruments to cover from 40 to 220 GHz
- Low angular resolution – large scales
- High-Throughput Channels – High sensitivity
- Single-mode channels – Foregrounds
- Large ground shields
- No optics – no spurious polarization


B−Bpol, lat = 63, elevation = 40, NSIDE = 32
0.0
1.4e+05 sec/pixel


2K
Spinning HWP
Wire Grid
Polyethilene Lens
0.3K
Beam 2o FWHM
25 cm diam
40 overmoded Detectors, diam 1.7 cm (10 modes @ 150 GHz, 20 modes @ 220 GHz)
Polyethilene Lens
0.3K
40 overmoded Detectors, diam 1.7 cm (10 modes @ 150 GHz, 20 modes @ 220 GHz)
B-B-Pol: High Frequency Instrument (one of the two bands shown)


ΔCl_BB / Cl_BB
Case 1
Case 2
37 detectors,
Photon-noise limited,
15 days,
r=0.01
350 GHz
220 GHz
150 GHz
1
0.1
0
10
20
30
40
50
60
70
l

And now let’s dream …

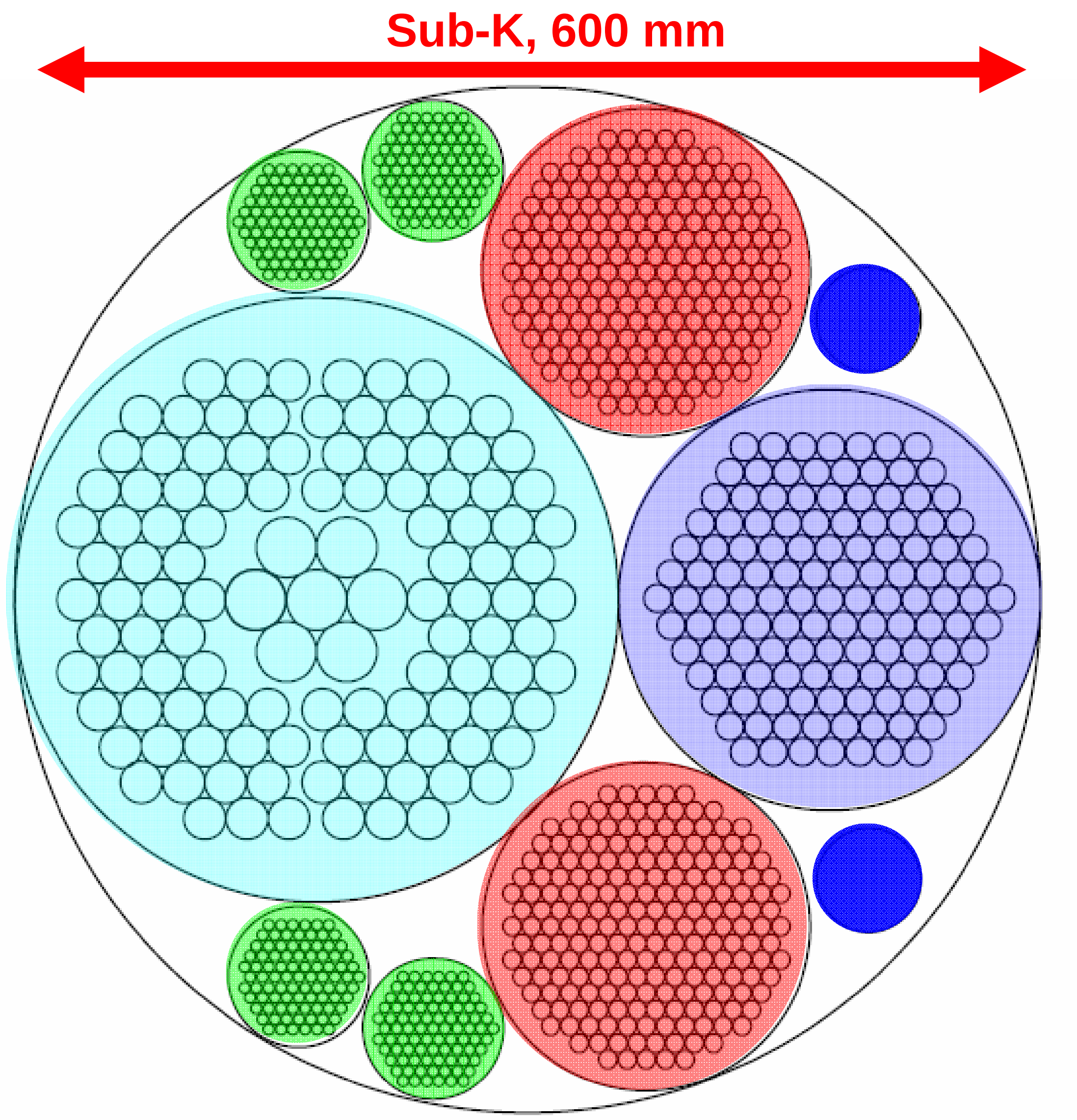
B-Pol
(www.b-pol.org)

- European proposal recently submitted to ESA (Cosmic Vision).
- ESA encourages the development of technology and resubmission for next round
- Detector Arrays development activities (KIDs in Rome, TES in Oxford, Genova etc.)
- A balloon-borne payload being developed with ASI (LSPE).

Sensitivity and frequency coverage: the focal plane

- Baseline technology: TES bolometers arrays

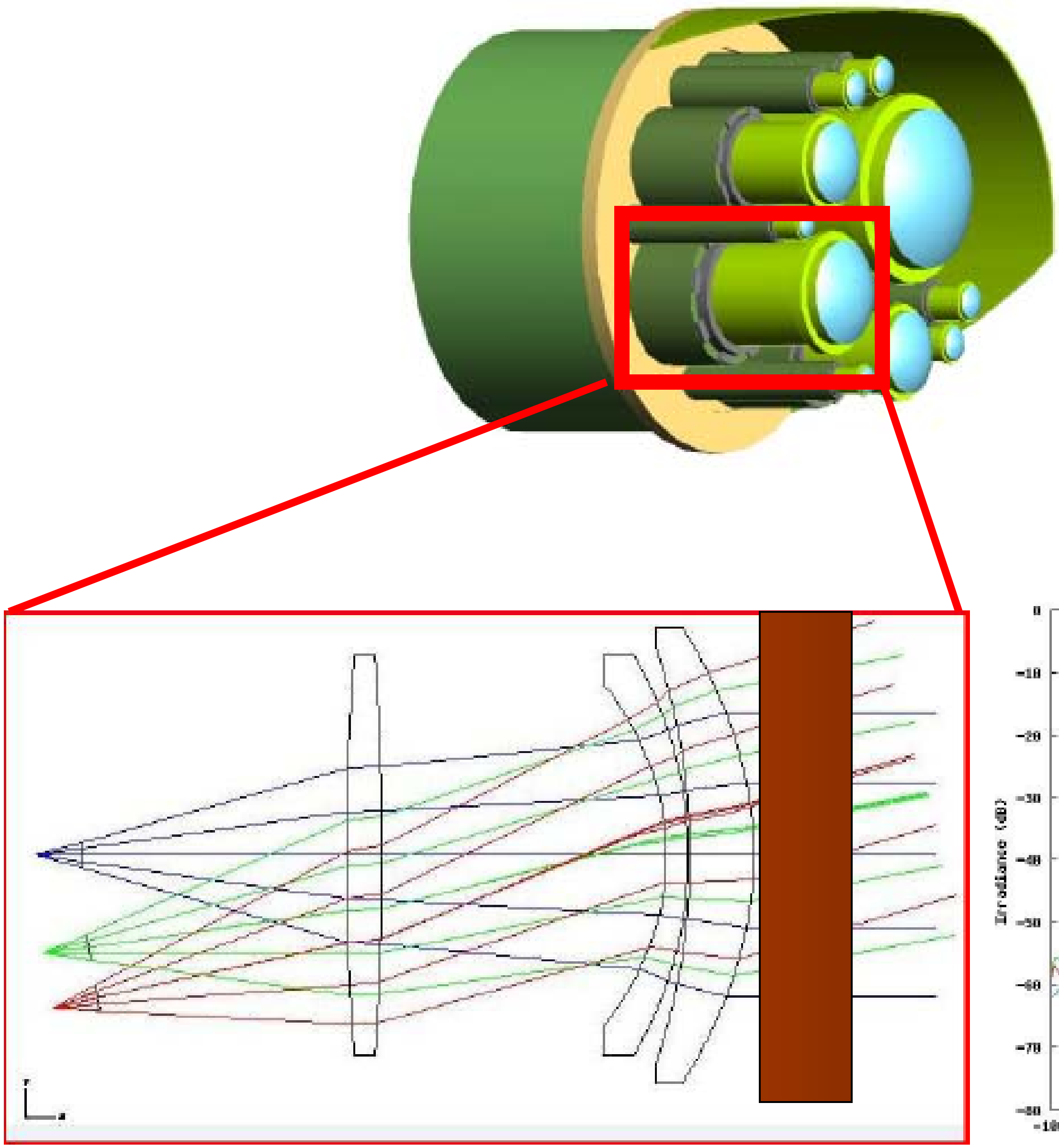
Corrugated feedhorns
for polarization purity and
beam symmetry



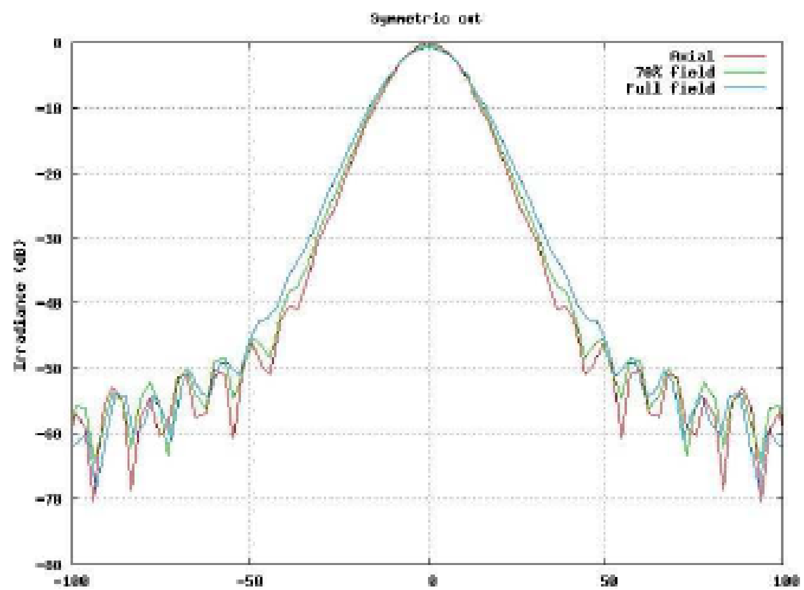
Optical system:

- **Wide field,**
- **low cross-pol,**
- **low emissivity**

Possible solution: modified telecentric telescope



HWP



For more information visit www.b-pol.org

And read the paper (astro-ph/0808-1881)

B-Pol: Detecting Primordial Gravitational Waves Generated During Inflation

Paolo de Bernardis, Martin Bucher,
Carlo Burigana and Lucio Piccirillo
(for the B-Pol Collaboration)*

Received: date / Accepted: date

Abstract B-Pol is a medium-class space mission aimed at detecting the primordial gravitational waves generated during inflation through high accuracy measurements of the Cosmic Microwave Background (CMB) polarization. We discuss the scientific background, feasibility of the experiment, and implementation developed in response to the ESA Cosmic Vision 2015-2025 Call for Proposals.

Keywords Cosmology · Cosmic Microwave Background · Satellite

Space-Borne Measurements of CMB Polarization

The Experimental Probe of Inflationary Cosmology – Intermediate Mission

Jamie Bock (JPL/Caltech)

Representing the EPIC-IM Mission Study Team

Abdullah Aljabri	JPL	Darren Dowell	JPL/Caltech	Elena Pierpaoli	USC
Alex Amblard	UC Irvine	Mark Dragovan	JPL	Nicolas Ponthieu	IAS, France
Daniel Bauman	Harvard U.	Sunil Golwala	Caltech	Jean-Loup Puget	IAS, France
Marc Betoule	IAS, France	Krzysztof Gorski	JPL/Caltech	Jeff Raab	NGAS
Talso Chui	JPL	Shaul Hanany	U. Minnesota	Paul Richards	UC Berkeley
Loris Colombo	USC	Warren Holmes	JPL	Celeste Satter	JPL
Asantha Cooray	UC Irvine	Kent Irwin	NIST	Mike Seiffert	JPL
Dustin Crumb	ATK Space	Brad Johnson	UC Berkeley	Meir Shimon	UCSD
Peter Day	JPL	Steve Meyer	U. Chicago	Huan Tran	UC Berkeley/SSL
Clive Dickenson	JPL	Nate Miller	UC San Diego	Brett Williams	JPL
Darren Dowell	JPL/Caltech	Hien Nguyen	JPL	Jonas Zmuidzinas	Caltech/JPL

The Path to CMBPOL: Upcoming Measurements of CMB Polarization
University of Chicago, 1-3 July 2009

Unprecedented CMB Community Organization!

CMB Inflation Probe ASMCS

Jamie Bock	JPL/Caltech
Asantha Cooray	UC Irvine
Scott Dodelson	FNAL
Joanna Dunkley	Princeton U.
Krzysztof Gorski	JPL/Caltech
Shaul Hanany	U. Minnesota
Gary Hinshaw	GSFC
Kent Irwin	NIST
Adrian Lee	UC Berkeley
Charles Lawrence	JPL
Steve Meyer (PI)	U. Chicago
Lyman Page	Princeton U.
John Ruhl	Case Western
Mike Seiffert	JPL
Matias Zaldarriaga	Harvard U.

+ 175 participants

PPPDT

Charles Bennett	JHU
Jamie Bock	JPL
Julian Borril	LBNL
Joshua Gundersen	U. Miami
Shaul Hanany, chair	U. Minnesota
Gary Hinshaw	GSFC
Alan Kogut	GSFC
Lawrence Krauss	Case Western
Adrian Lee	UC Berkeley
Amber Miller	Columbia U.
Samuel H. Moseley	GSFC
Lyman Page	Princeton U.
Charles Lawrence	JPL
Tony Readhead	Caltech
Peter Timbie	U. Wisconsin

EPIC-IM / Chicago

Decadal White Papers

The Origin of the Universe as Revealed Through the Polarization of the CMB, Dodelson et al. and **211** Co-signers

Observing the Evolution of the Universe, Page et al. and **168** Co-signers

A Program of Technology Development and Sub-Orbital Observations of CMB Polarization Leading to and Including a Satellite Mission Meyer et al. and **141** Co-signers

CMB Community Reports

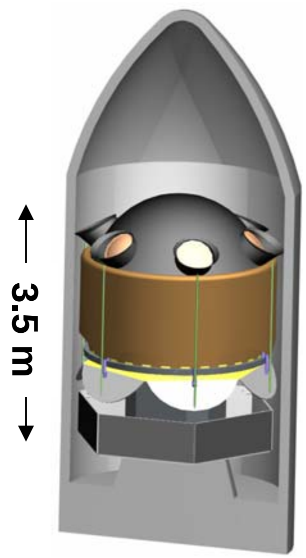
Theory and Foregrounds: 5 Papers with **135** Authors and Co-Authors
Probing Inflation with CMB Polarization, Baumann et al. 2008, ArXiv 0811.3919
Gravitational Lensing, Smith et al. 2008, ArXiv 0811.3916
Reionization Science with the CMB, Zaldarriaga et al. 2008, ArXiv 0811.3918
Prospects for Polarized Foreground Removal, Dunkley et al. 2008, ArXiv 0811.3915
Foreground Science Knowledge and Prospects, Fraisse et al. 2008, ArXiv 0811.3920
Systematic Error Control: 10 Papers with **68** Authors and Co-Authors
CMB Technology Development: 22 Papers with **37** Authors and Co-Authors
Path to CMBPol: Conference on CMBPol mission in July with **85** participants

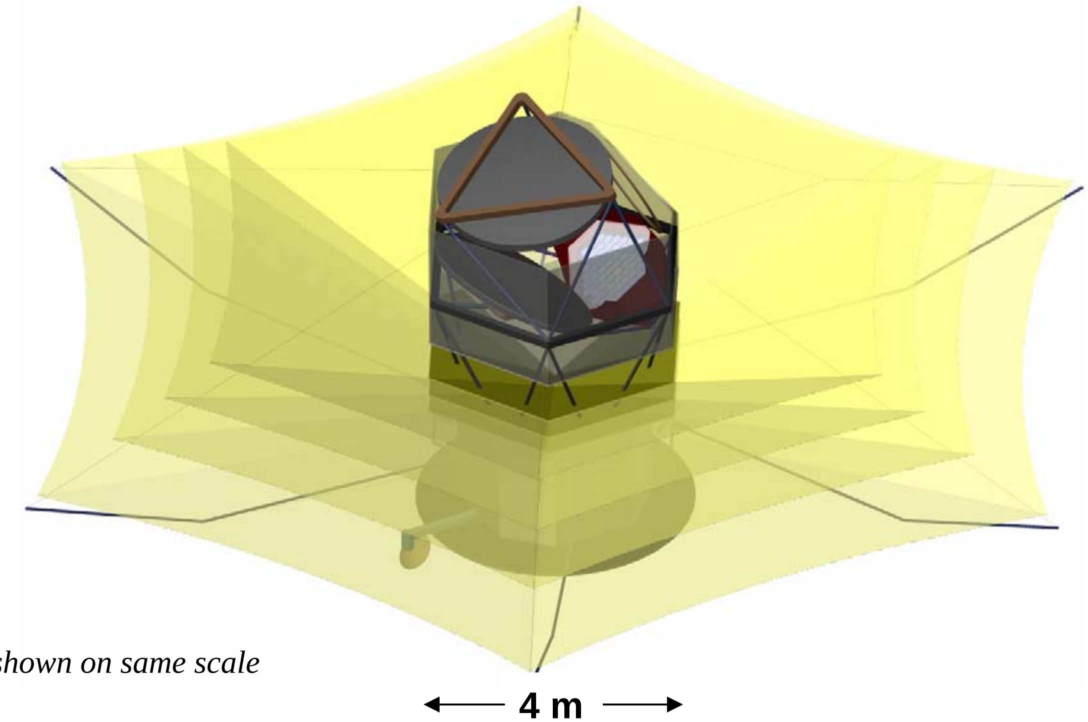
Mission Study Reports

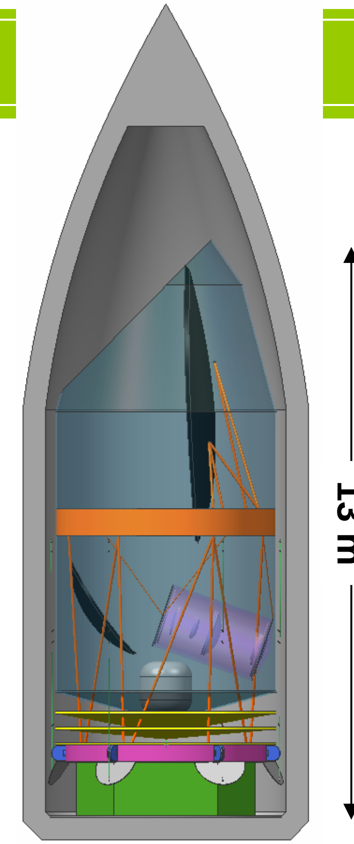
Study of the EPIC-Intermediate Mission, ArXiv 0906.1188
The Experimental Probe of Inflationary Cosmology, ArXiv 0805.4207

See http://cmbpol.uchicago.edu for a full compilation

The Role of the EPIC-IM Design







Note: Configurations not shown on same scale

EPIC-	*Low Cost*	*Intermediate Mission 4 K Option*	*Comprehensive Science*
Science	Inflationary B-mode polarization only	Inflationary B-modes, E-modes to cosmic variance, gravitational lensing to cosmic limits, neutrino mass, dark energy, Galactic astronomy	Inflationary B-modes, E-modes to cosmic variance, gravitational lensing, neutrino mass, dark energy, Galactic astronomy
Speed	500 Plancks	3600 Plancks	250 Plancks
Detectors	2400	11,000 (TES bolometer or MKID)	1500
Aperture	Six 30 cm refractors	1.4 m Crossed Dragone telescope	3 m Gregorian Dragone
Bands	30 – 300 GHz	30 – 300 GHz + 500 & 850 GHz	30 – 300 GHz
Cooling	LHe cryostat + ADR	4 K Cryo-cooler + ADR	TBD
Mass	1320 kg CBE	1670 kg CBE	3500 kg CBE
Publication	ArXiv 0805.4207 (192 pages)	ArXiv 0906.1188 (157 pages)	ArXiv 0805.4207 (192 pages)
Cost	$660M (FY07)	$920M (FY09)	No cost assessed

Stay tuned !