Polarization of the CMB and foregrounds: the "QUIJOTE" experiment

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Outline

- Inflation, Gravitational Waves and Polarization of the CMB
- CMB Polarization measurements
- The QUIJOTE CMB experiment
    - Science: B-modes and Galactic foregrounds
    - Basic Features: Telescopes and instruments

INFLATION

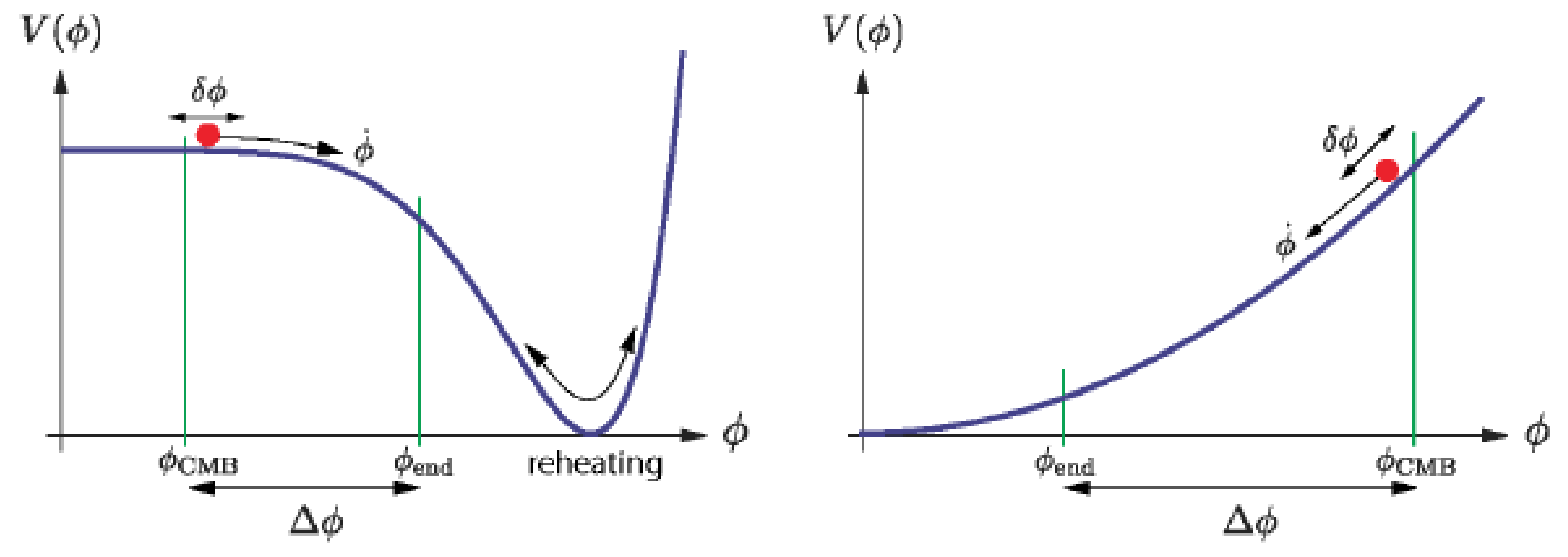
Guth 1981, Linde, Albrecht et al.

- Inflation reflects our present best understanding for the Physics of the very early universe and the generation of the primordial cosmological perturbations

- Inflation unifies physics just a few orders below the Planck scales with the cosmological fluctuations up to the largest observable scales. Physical processes underlying inflation reach the scale of Grand Unified Theories (GUTs) or 10^{15} GeV

- Understanding Inflation may lead to a major change in our conceptions of spacetime, particles and their interactions (see e.g. Baumann et al. 2009)

Examples of Inflaton Potentials



Accelerated expansion only if $V \gg \dot{\phi}^2$

Quantitatively, inflation requires smallness of the slow-roll parameters

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{M_{\rm pl}^2}{2}\frac{\dot{\phi}^2}{H^2} \approx \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2 , \qquad |\eta| \approx M_{\rm pl}^2\left|\frac{V''}{V}\right| .$$

Models of single field slow-roll inflation predict the power spectra

$$P_s(k) = \frac{1}{24\pi^2 M_{\rm pl}^4}\frac{V}{\epsilon}\bigg|_{k=aH} , \qquad n_s - 1 = 2\eta - 6\epsilon ,$$

$$P_t(k) = \frac{2}{3\pi^2}\frac{V}{M_{\rm pl}^4}\bigg|_{k=aH} , \qquad n_t = -2\epsilon , \qquad r = 16\epsilon .$$

$$r \equiv \frac{P_t}{P_s} .$$

The tensor to scalar ratio depends on the time evolution of the inflaton field

$$r = 16\epsilon = \frac{8}{M_{\rm pl}^2}\left(\frac{\dot{\phi}}{H}\right)^2$$

$$r = -8n_t$$

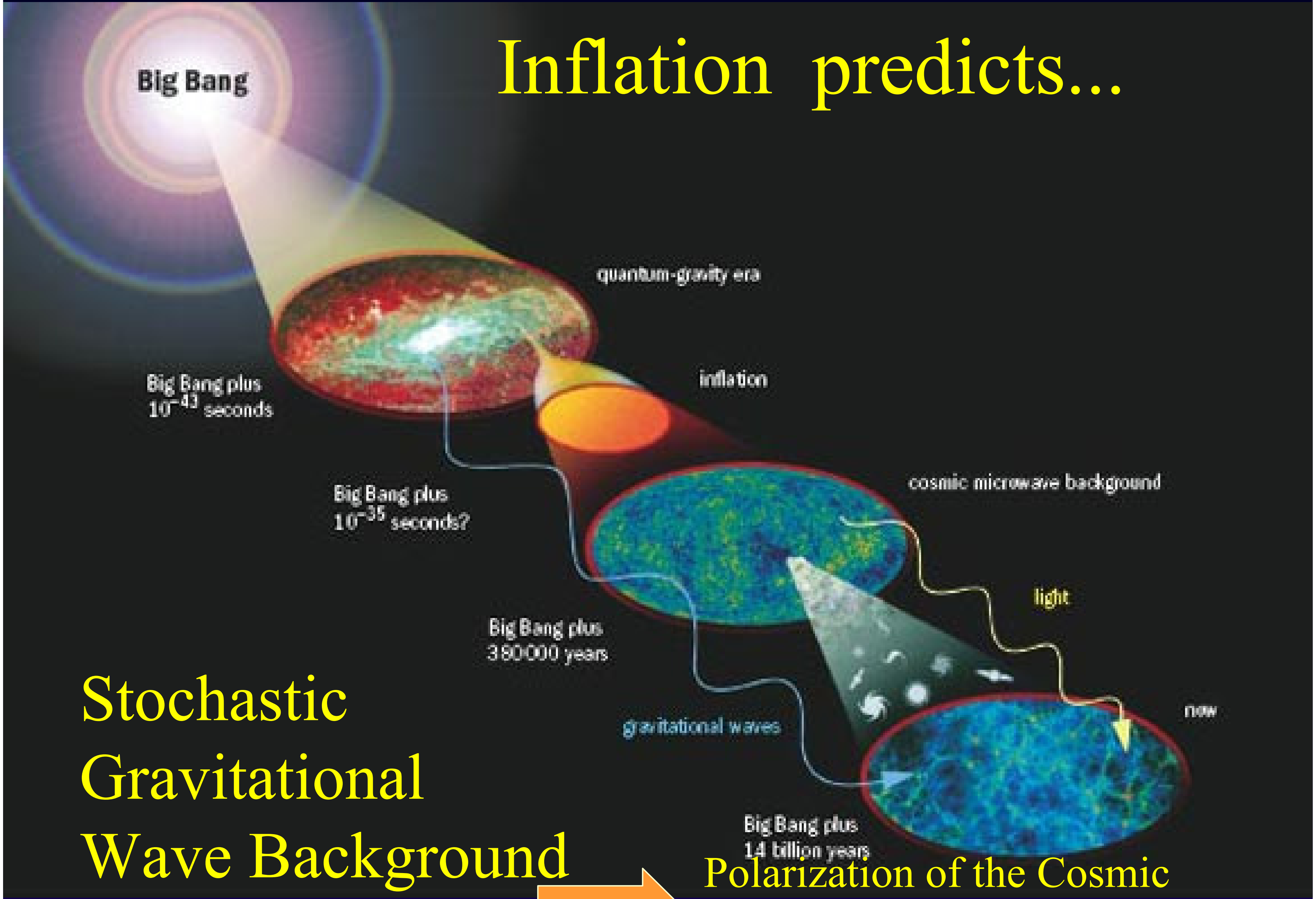
Reconstruction of the inflaton potential from observables

- $P_t \rightarrow V$
- $P_s \rightarrow V'$
- $n_s \rightarrow V''$
- $\alpha_s \rightarrow V'''$

$$V(\phi) = V|_\star + V'|_\star (\phi - \phi_\star) + \frac{1}{2} V''|_\star (\phi - \phi_\star)^2 + \frac{1}{3!} V'''|_\star (\phi - \phi_\star)^3 + \cdots ,$$

Taylor expansion around the time when fluctuations on CMB scales exited the horizon

Inflation predicts...



Stochastic Gravitational Wave Background

(see e.g. Dodelson 2003)

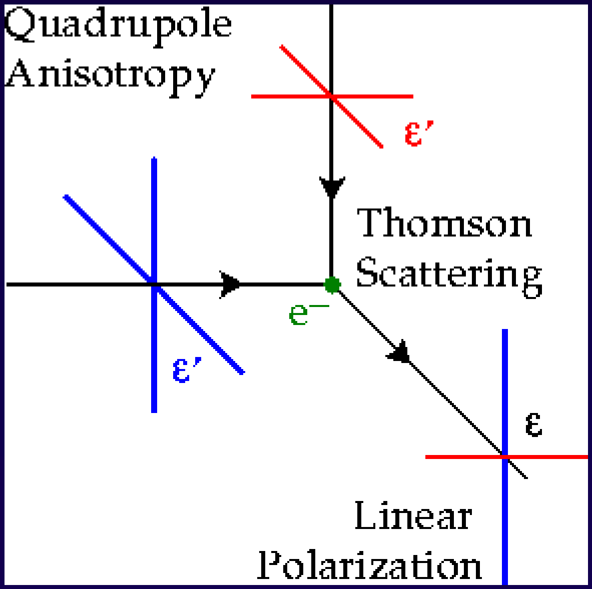
→ Polarization of the Cosmic Microwave Background

The polarization of the CMB

- **Anisotropies in the CMB are caused by primordial density fluctuations.**
- **Differential cross section for Thomson scattering depends on polarization → scattering generates polarization**
- A net polarization is generated during recombination if there is a quadrupole anisotropy in the radiation field. For a multipole decomposition of the radiation field into spherical harmonics,

  the five quadrupole moments are represented by l=2, m=0,±1, ±2.

  Orthogonality of spherical harmonics → only quadrupole moment can generate polarization from Thomson scattering.
- The net polarization generated via scattering is **linear** (i.e. the CMB will have non-zero Stokes parameters Q and U, but V=0).

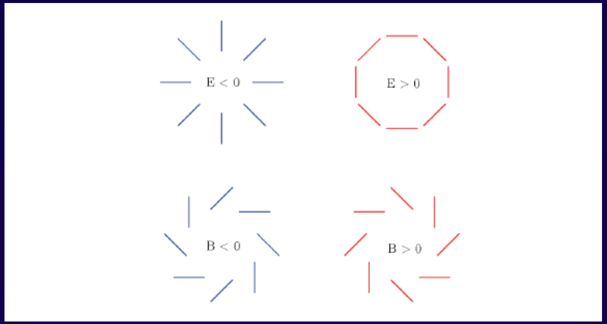


The polarization of the CMB(II)

- Primordial tensor perturbations make a small contribution to the CMB temperature perturbations but a significant contribution to the polarization of the CMB which is particularly sensitive to the ratio of tensor power to scalar power

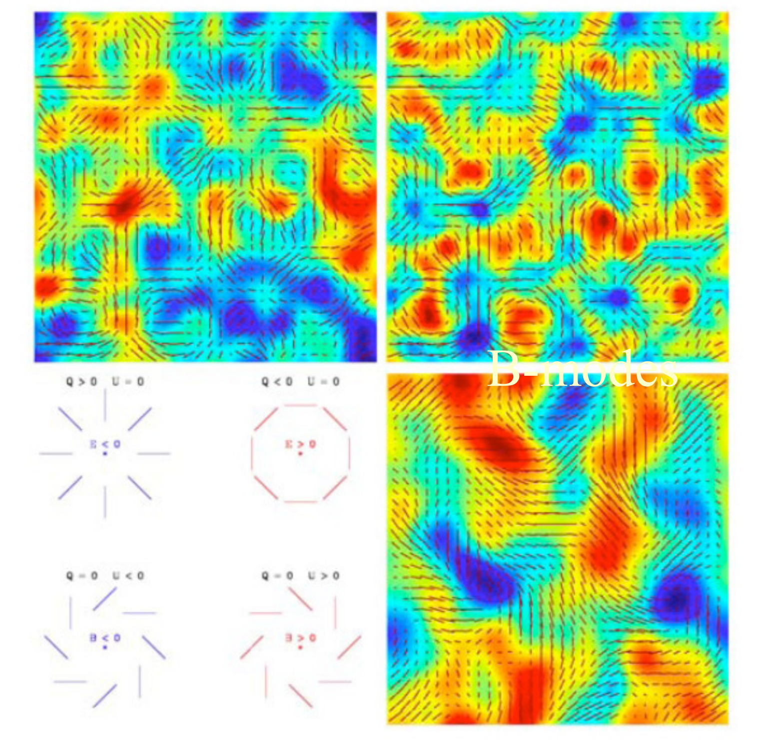
$$r \equiv \frac{P_t}{P_s}\,.$$

- Polarization of the CMB divides into two orthogonal components :
  - a curl-free E-mode giving polarization vectors that are radial around cold spots and tangential around hot spots on the sky
  - a divergence-free B-mode giving polarization vectors with vorticity around any point on the sky.



The polarization of the CMB (III)

- Polarization maps can be decomposed into two scalar fields usually called **E-modes** (analog of the gradient component) and **B-modes** (analog of the curl component). Kamionkowski et al. 1997; Seljak & Zaldarriaga 1997.
- These modes are independent of how the coordinate system is oriented and are related to the Q and U (Stokes parameters) by a non-local transformation



- **Physics of generation of the Polarization.** Different sources of anisotropies generate different types of modes:

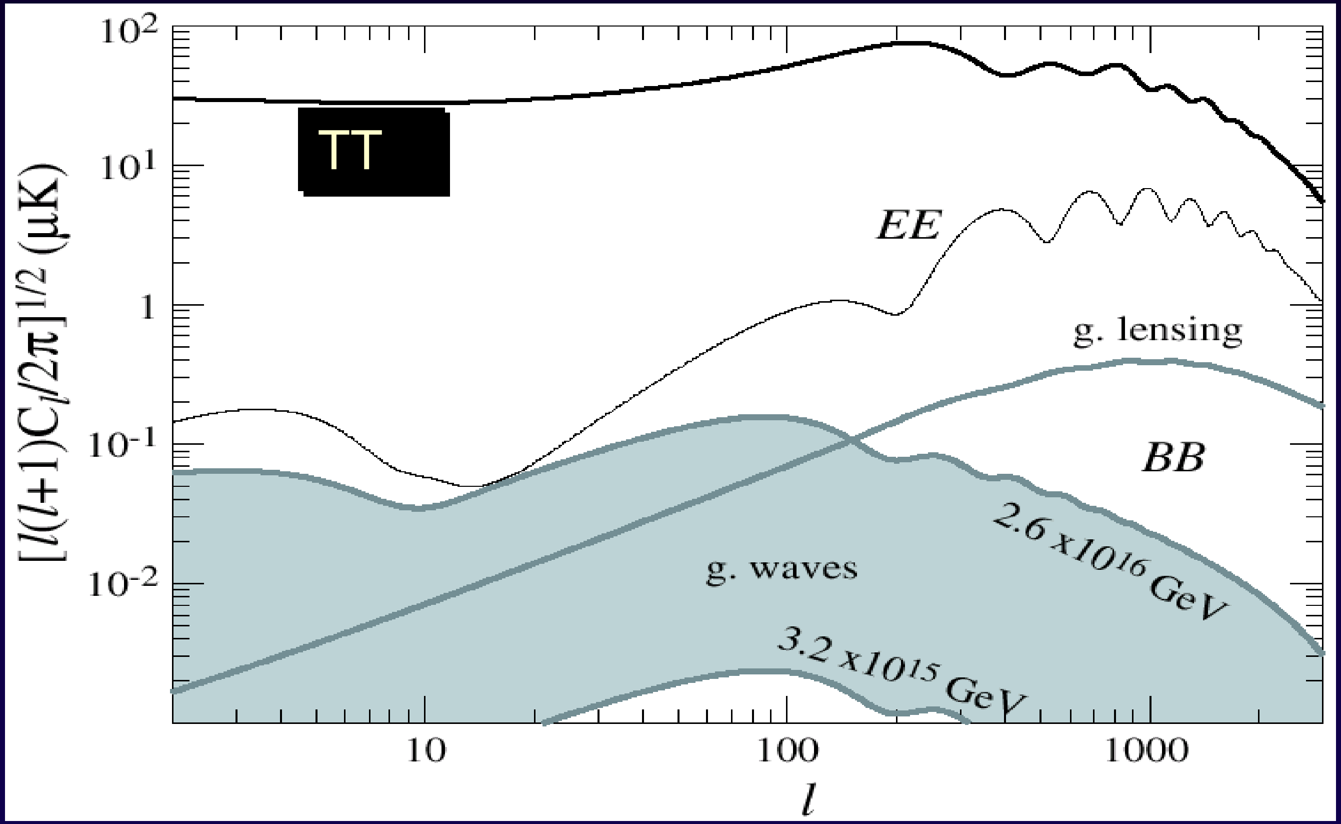
	E-modes	B-modes
Scalar (density perturbations)	Yes	No
Tensor (gravity waves)	Yes	Yes

E-mode

- Detected at a high level of significance
- Generated by density perturbations at recombination is tightly correlated with the temperature anisotropies in the CMB.

B-mode

Caused by the differential stretching of spacetime associated with a background of primordial GWs



- **r=T/S** is proportional to (the square of) the energy scale of inflation, which is proportional to the density of primordial gravitational waves.
- r=0.1 corresponds to an energy scale of inflation around the expected GUT scale.

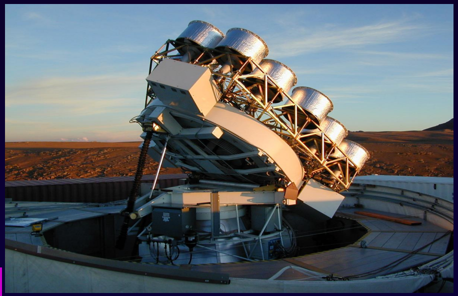
Main reasons to measure CMB polarization

a) break degeneracy between cosmological parameters and improve accuracy of constraints

b) provide an independent test of the basic assumptions that underlay the standard cosmological model

c) the detection of primordial gravitational waves

CMB Polarization experiments



Ground-based:

- CAPMAP
- DASI
- Polatron
- BICEP
- QUAD
- QUIET
- ACT
- QUIJOTE

- CBI
- KuPID
- AMiBA

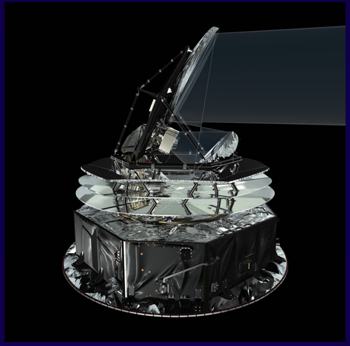
- PolarBear
- ClOVER

Balloon:

- Archeops
- BOOMERanG
- MAXIPOL
- EBEX
- SPIDER
- SPUD

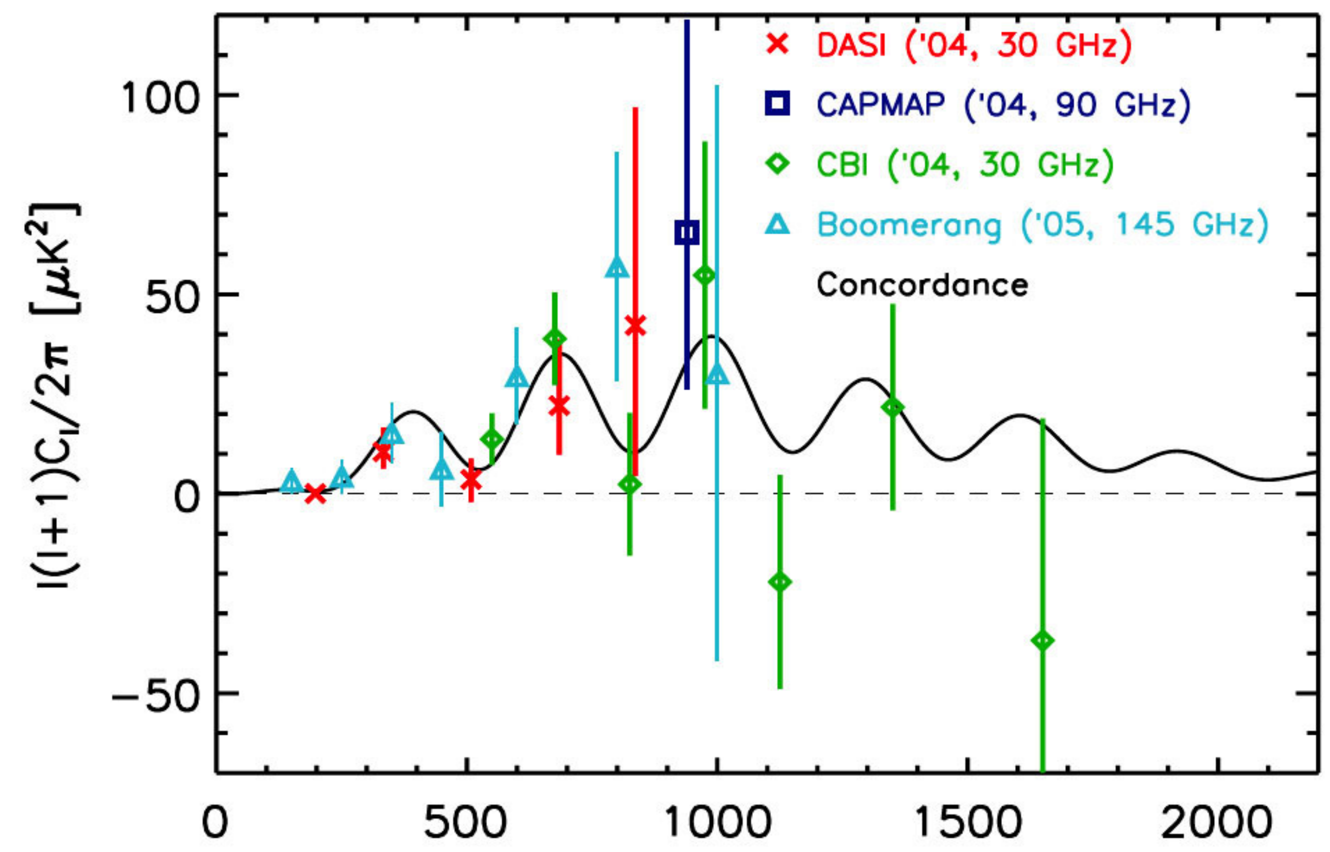
Space:

- WMAP
- Planck
- SPOrt
- B-Pol
- CMB-Pol

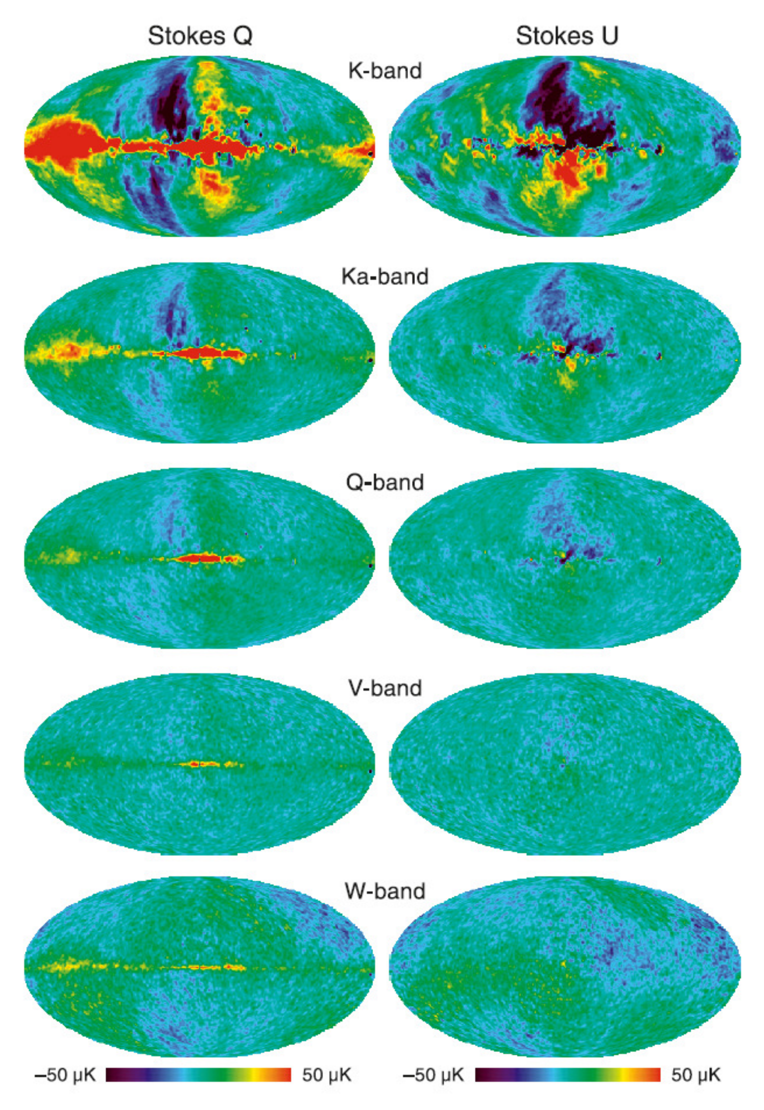


First Observations of CMB polarization

- *E-mode detections: DASI (Kovac et al. 2002, Nature) WMAP, CAPMAP, CBI, Boomerang,*

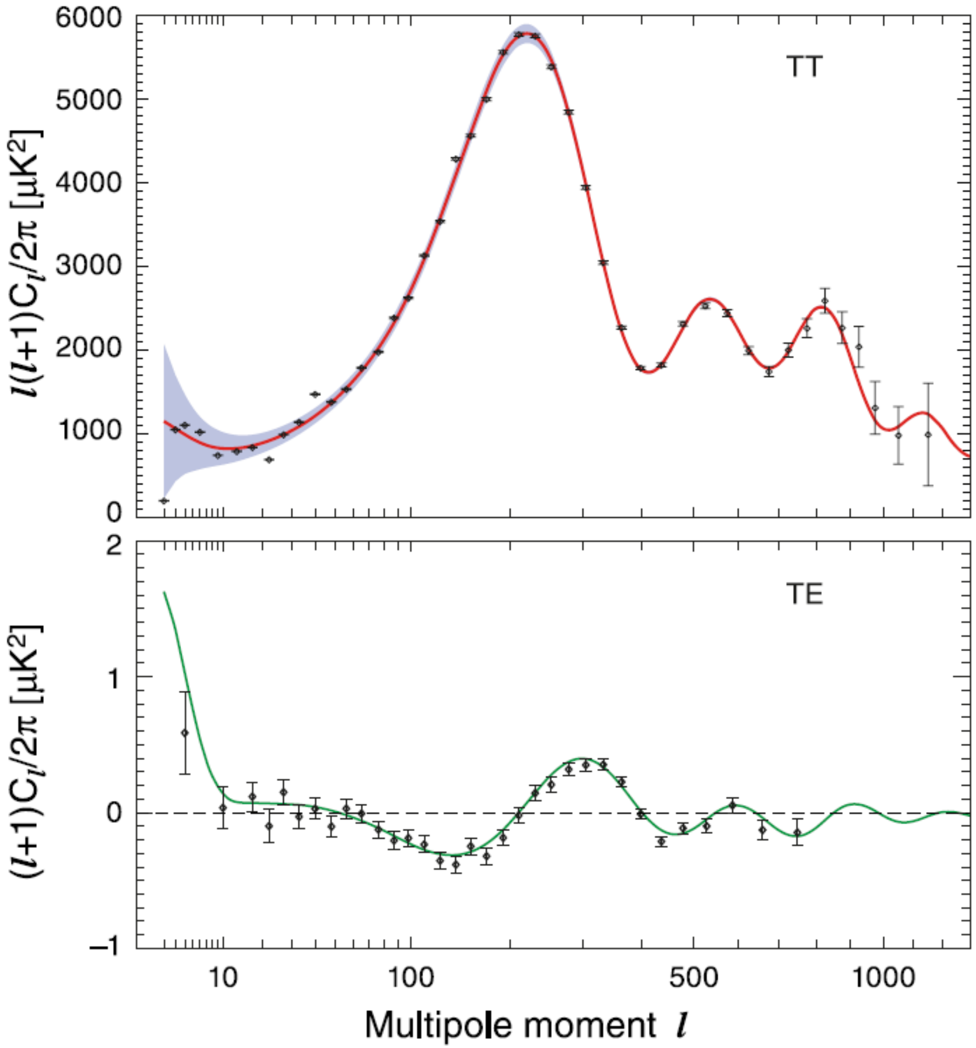


Results from WMAP 7yr

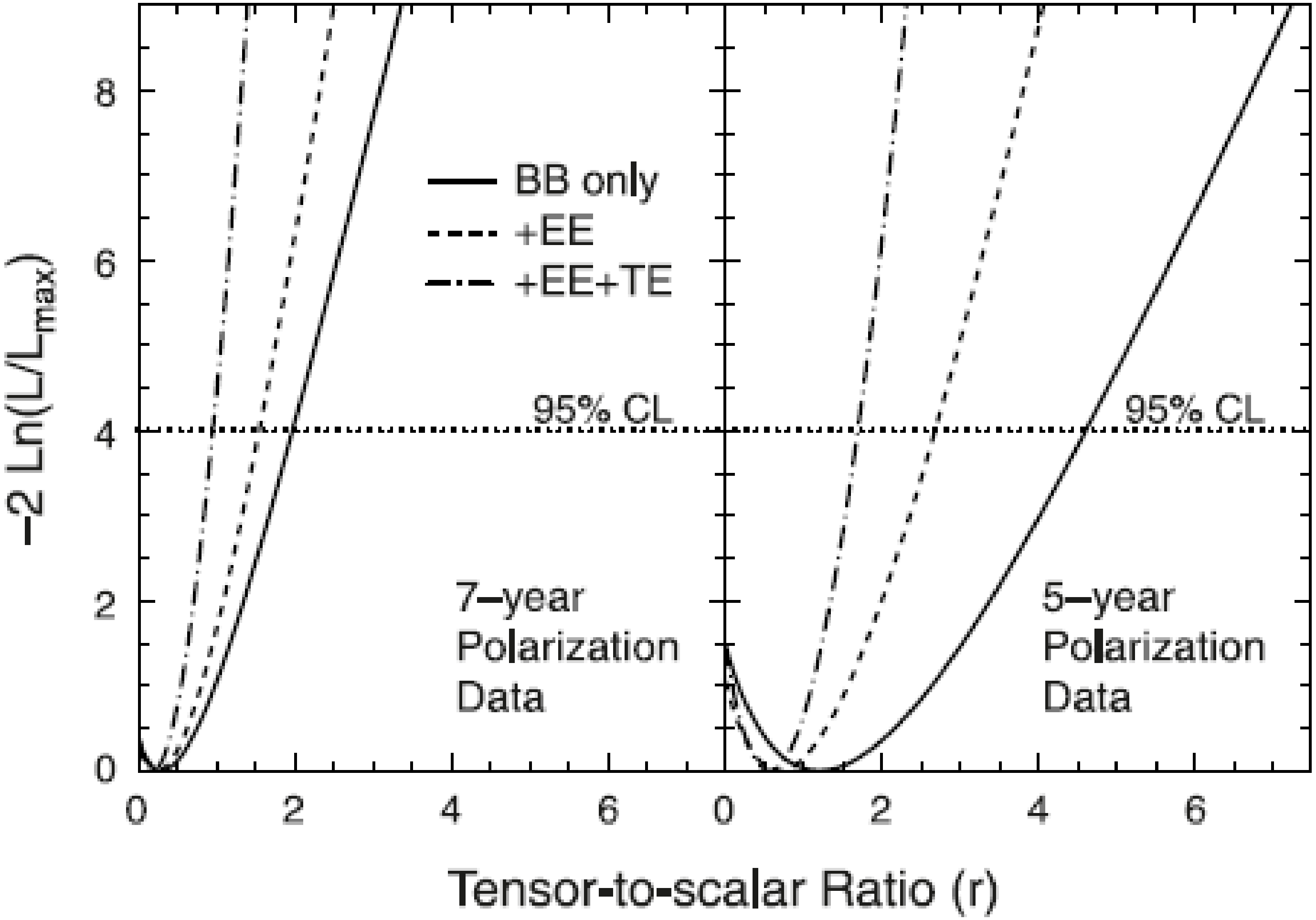


Jarosik et al .2010

WMAP 7-yr

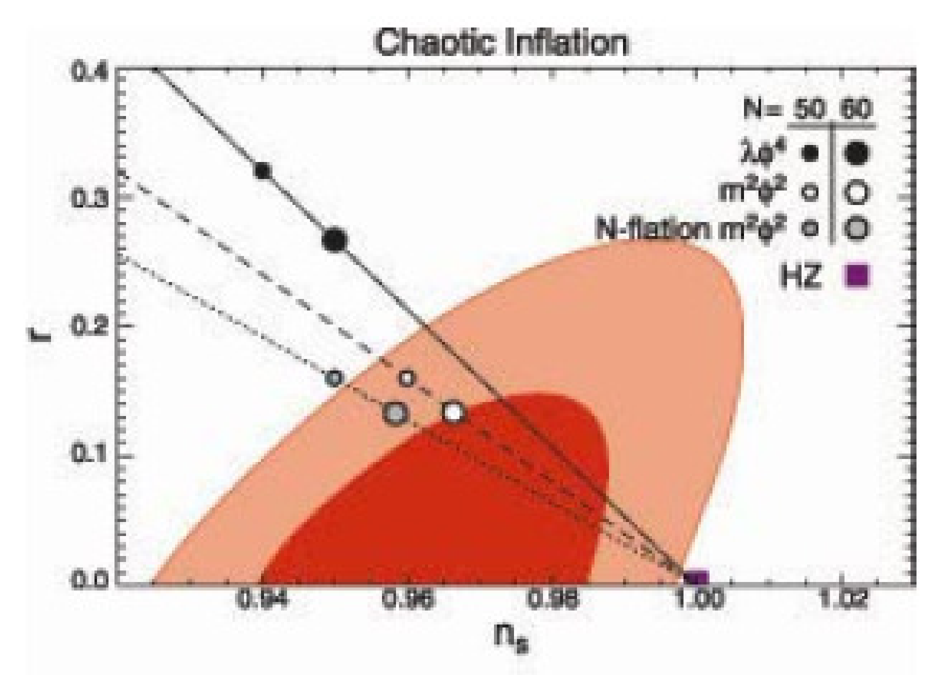

6000
5000
4000
3000
2000
1000
0
TT
$l(l+1)C_l/2\pi$ [μK²]
2
1
0
–1
TE
$(l+1)C_l/2\pi$ [μK²]
10
100
500
1000
Multipole moment l

Constraints on r from WMAP 7-yr



Komatsu et al. 2010

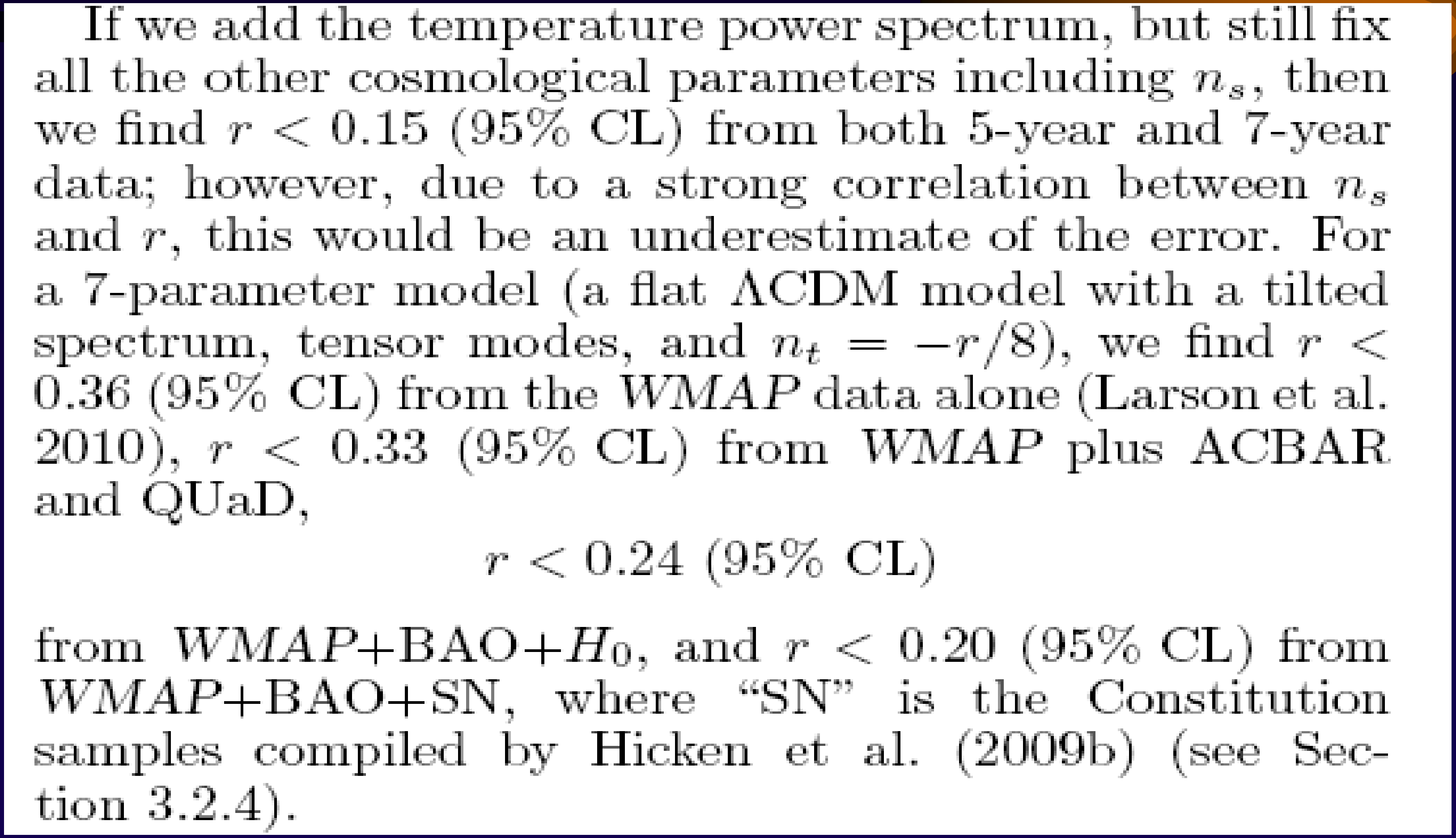
Chaotic single field Inflation with Φ^4 is ruled out



Constraints from WMAP+ Acoustic Baryon Oscillations + SNe

Komatsu et al. 2010 → r <0.2 ,, 95% C.L.

Constraints on r: WMAP 7-yr + others

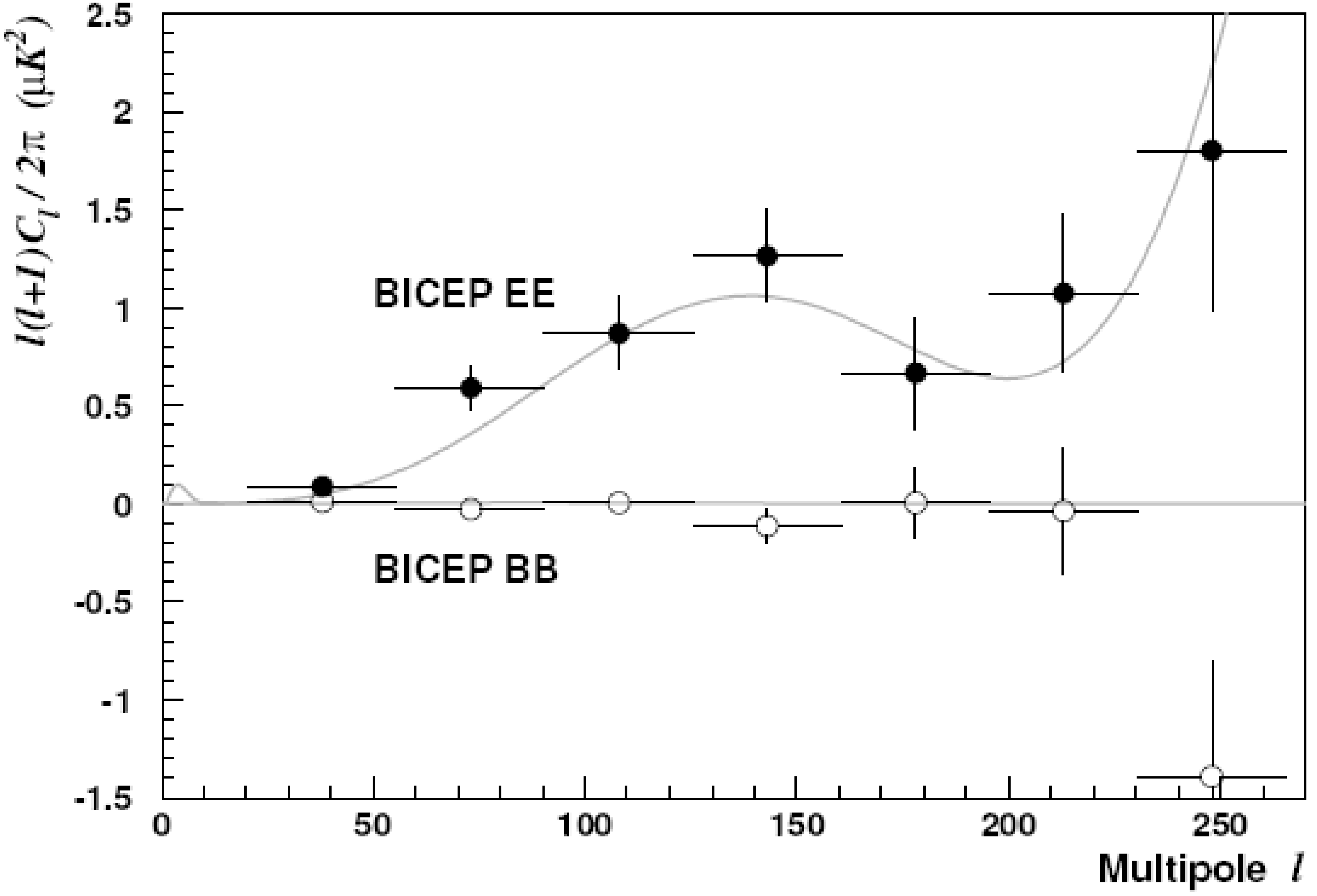


If we add the temperature power spectrum, but still fix all the other cosmological parameters including n_s, then we find $r < 0.15$ (95% CL) from both 5-year and 7-year data; however, due to a strong correlation between n_s and r, this would be an underestimate of the error. For a 7-parameter model (a flat ΛCDM model with a tilted spectrum, tensor modes, and $n_t = -r/8$), we find $r < 0.36$ (95% CL) from the *WMAP* data alone (Larson et al. 2010), $r < 0.33$ (95% CL) from *WMAP* plus ACBAR and QUaD,

$$r < 0.24 \text{ (95\% CL)}$$

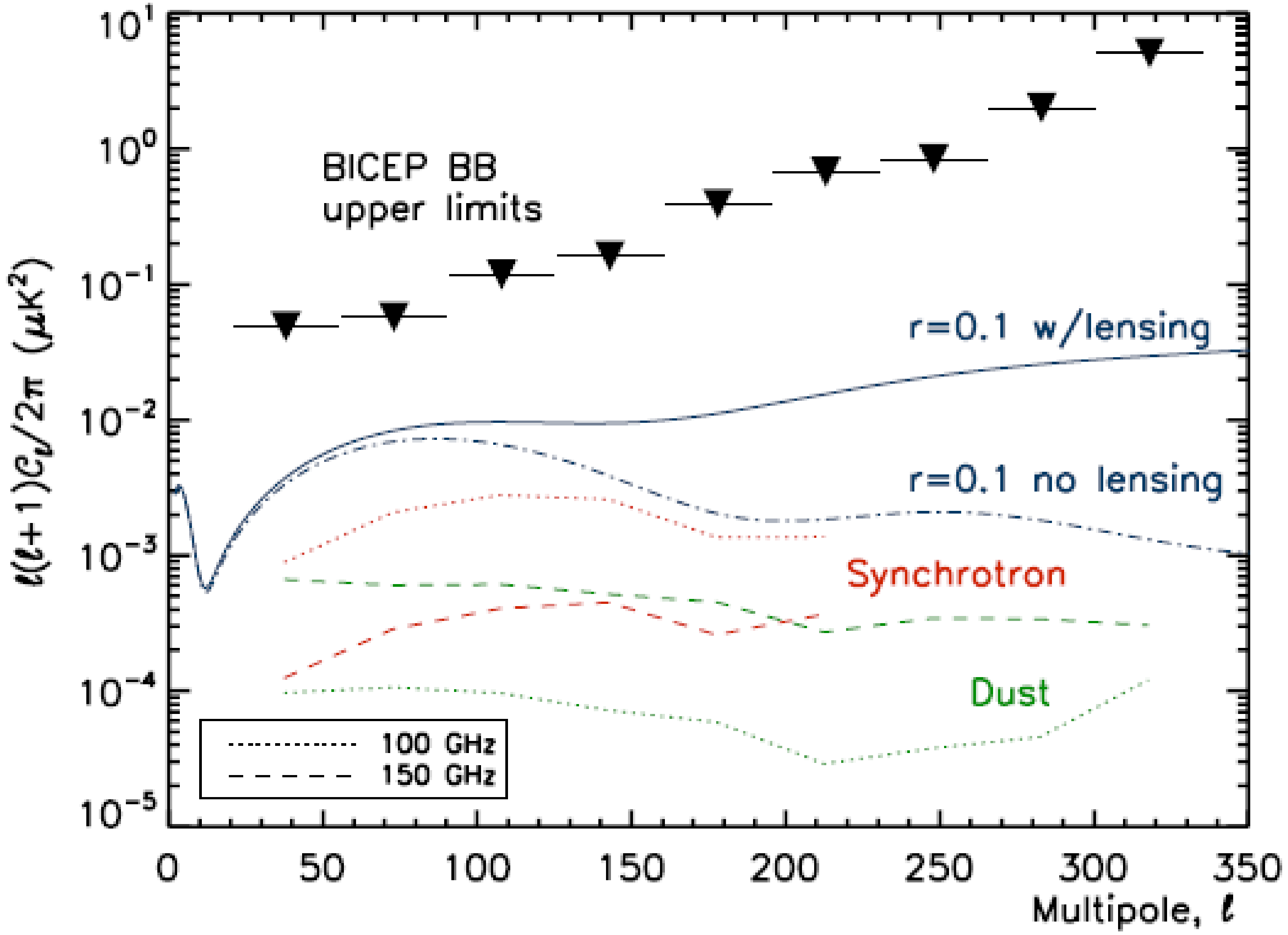
from *WMAP*+BAO+H_0, and $r < 0.20$ (95% CL) from *WMAP*+BAO+SN, where "SN" is the Constitution samples compiled by Hicken et al. (2009b) (see Section 3.2.4).

Komatsu et al. 2010

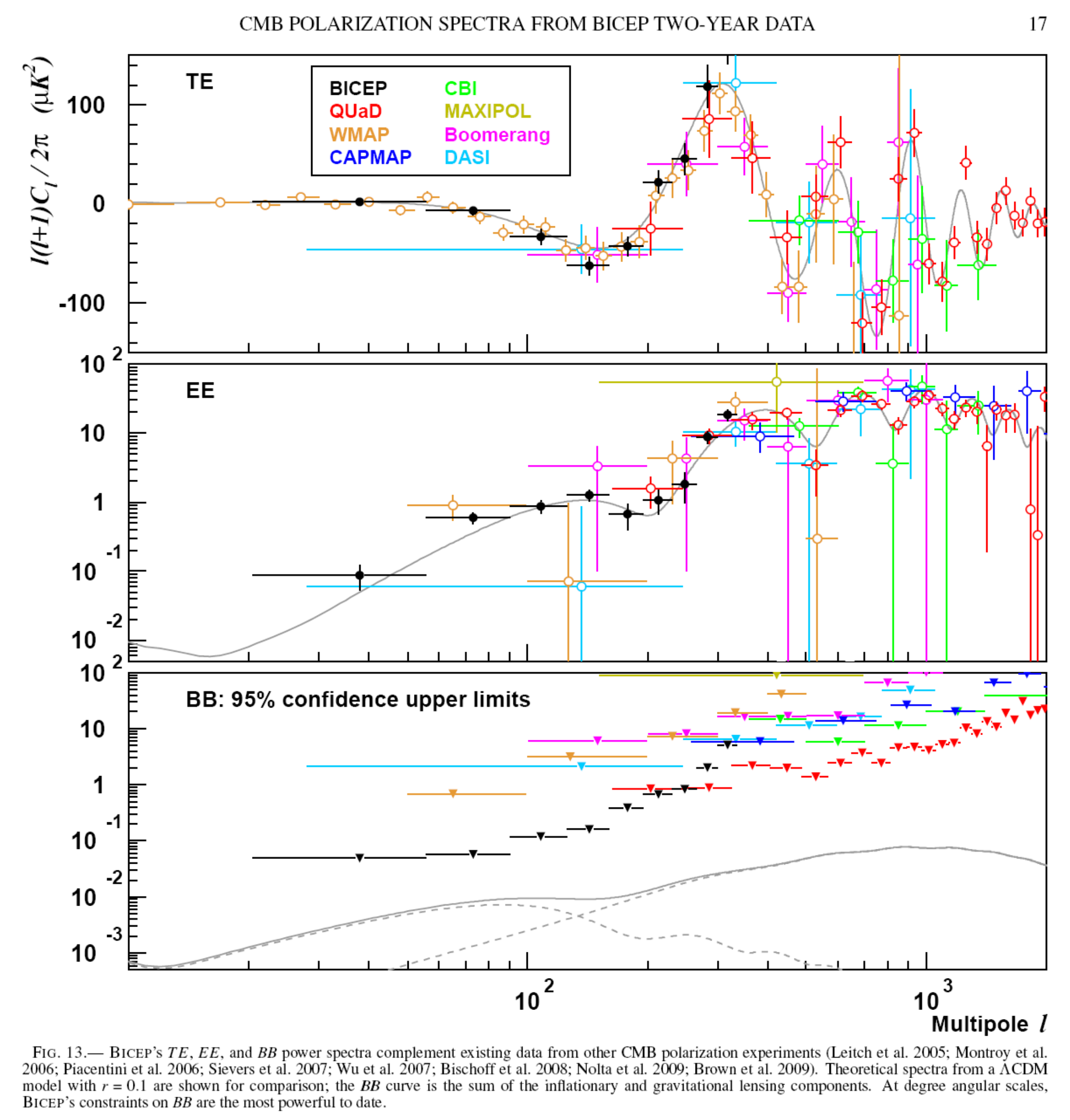


Chiang et al. 2010

BICEP (Chiang et al.)



Recent observations of CMB polarization



CMB POLARIZATION SPECTRA FROM BICEP TWO-YEAR DATA 17

FIG. 13.— BICEP's *TE*, *EE*, and *BB* power spectra complement existing data from other CMB polarization experiments (Leitch et al. 2005; Montroy et al. 2006; Piacentini et al. 2006; Sievers et al. 2007; Wu et al. 2007; Bischoff et al. 2008; Nolta et al. 2009; Brown et al. 2009). Theoretical spectra from a ΛCDM model with $r = 0.1$ are shown for comparison; the *BB* curve is the sum of the inflationary and gravitational lensing components. At degree angular scales, BICEP's constraints on *BB* are the most powerful to date.

Chiang et al. 2010

Primordial B modes and High energy physics

A large tensor amplitude (r=0.1) would imply a very high energy scale comparable to that of GUTs. From the amplitude of the scalar power spectrum A_s= 2.4 x 10^{-9}

$$\boxed{V^{1/4} = 1.06 \times 10^{16}\,\mathrm{GeV}\left(\frac{r_\star}{0.01}\right)^{1/4}}\,.$$

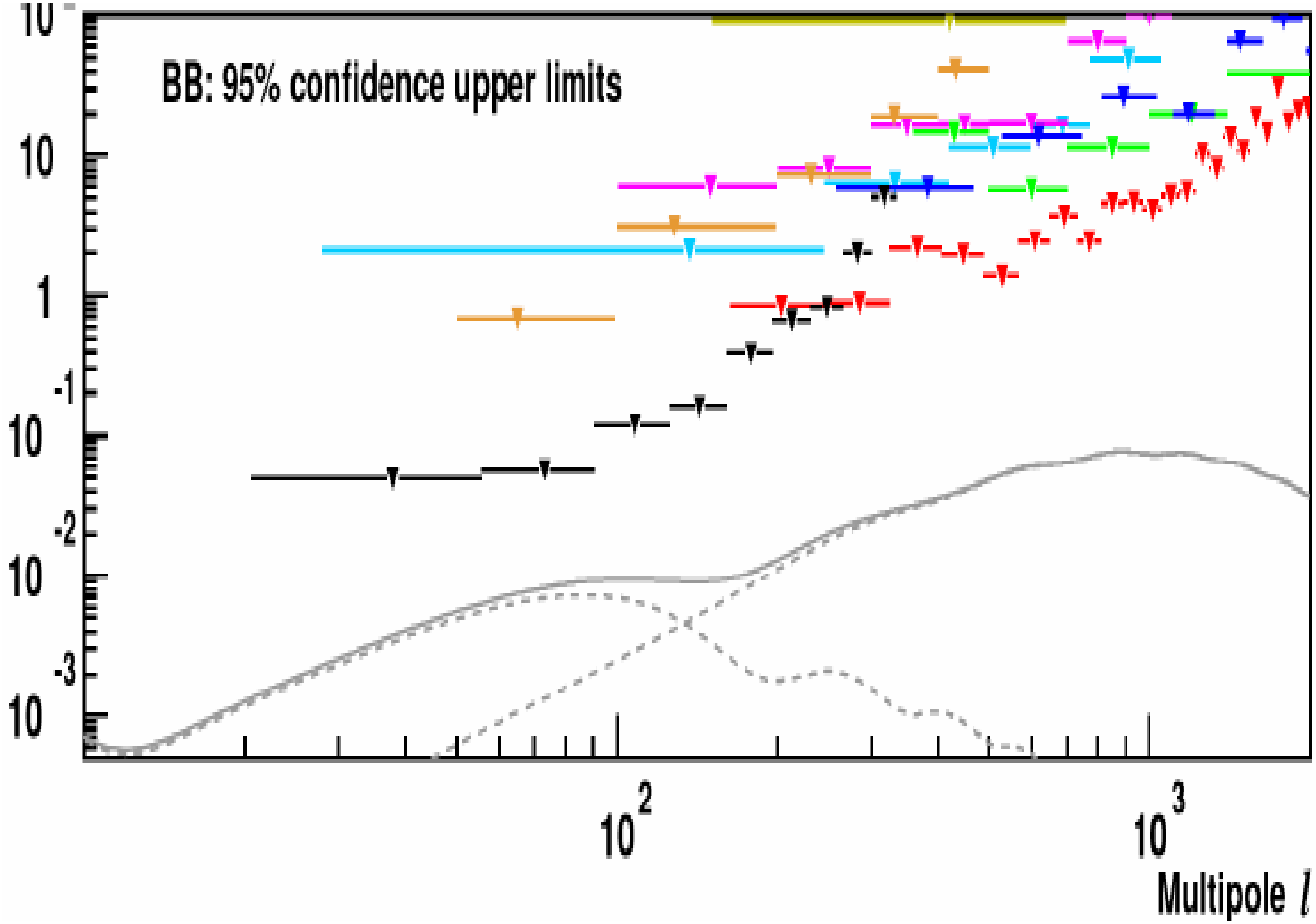
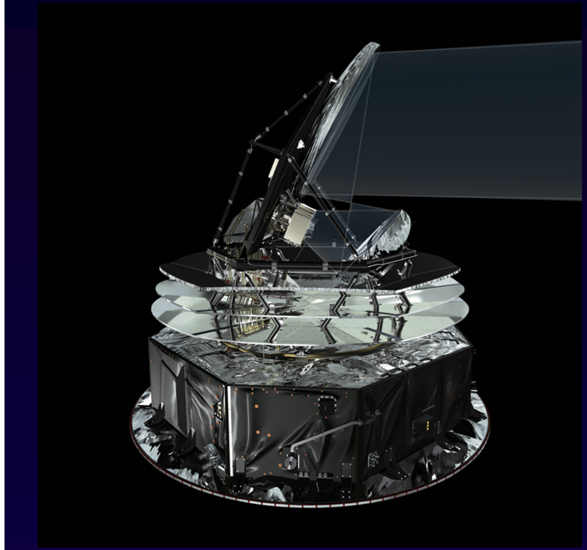


Figure 2: Current constraints on the CMB B-mode of polarization: QUAD (red), BICEP (black), Boomerang (magenta), DASI (cyan), WMAP (orange), CBI (green), CAPMAP (blue), MAXIPOL (dark green). The solid grey line corresponds to a theoretical LambdaCDM spectrum with r=0.1 (the grey dashed lines indicate the contribution from the primordial mode and from lensing). Figure reproduced from [Chi09].

Planck



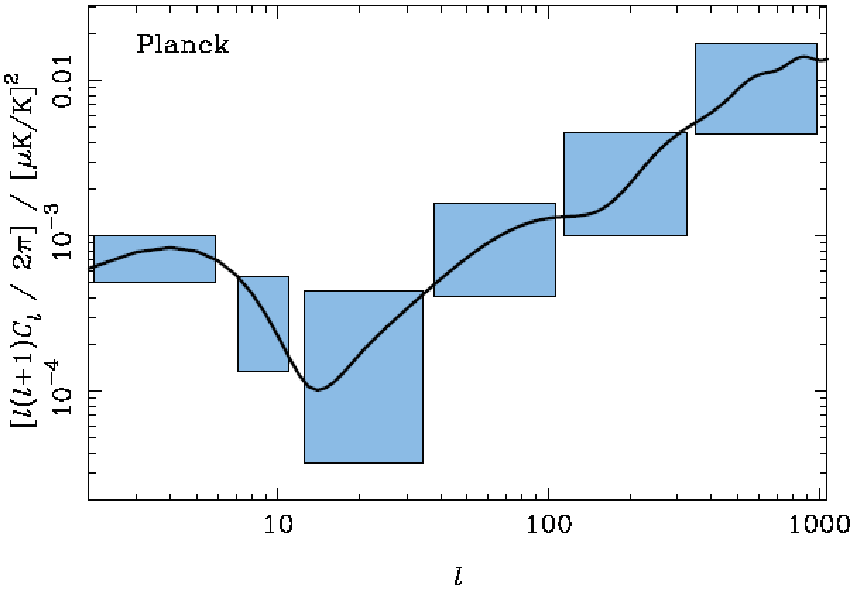


FIG 2.17.—Forecasts for the $\pm 1\sigma$ errors on the B-mode polarization power spectrum C_ℓ^B from *Planck* (for $r = 0.1$ and $\tau = 0.17$). Above $\ell \sim 150$ the primary spectrum is swamped by weak gravitational lensing of the E-polarization produced by the dominant scalar perturbations. The cosmological model, and the assumptions about instrument characteristics, are the same as in Figure 2.13.

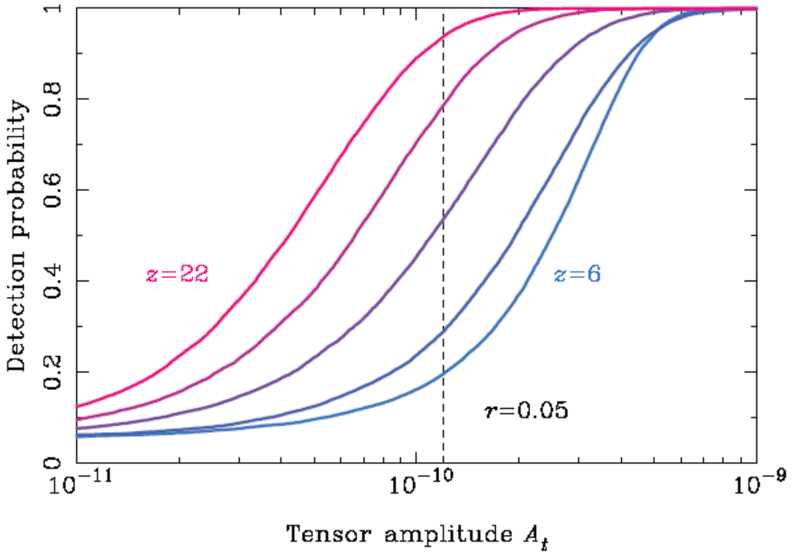
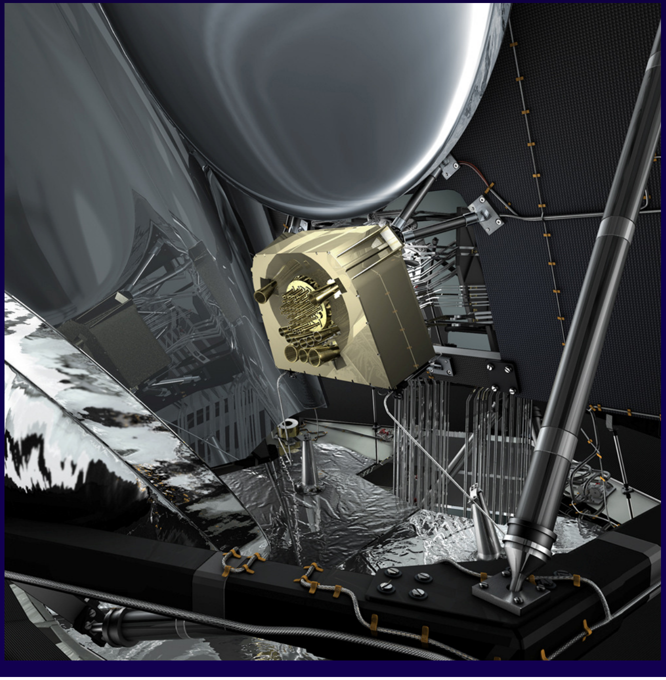


FIG 2.16.—The probability of detecting B-mode polarization at 95% confidence as a function of A_T, the amplitude of the primordial tensor power spectrum (assumed scale-invariant), for *Planck* observations using 65% of the sky. The curves correspond to different assumed epochs of (instantaneous) reionization: $z = 6$, 10, 14, 18 and 22. The dashed line corresponds to a tensor-to-scalar ratio $r = 0.05$ for the best-fit scalar normalisation, $A_S = 2.7\times10^{-9}$, from the one-year *WMAP* observations.



Observability of B-modes

- **Critical issues**:
  - Signals are extremely small. Large number of receivers. Large bandwidths.
  - Control on systematics (spillover, cross-pol, etc).
  - Foregrounds. B-modes are never dominant over galactic foregrounds.
- **Planck** (launched 2009; frequency range 30-800GHz) will reach r~0.05.
- Next generation missions: **EPIC** (NASA Beyond Einstein Program), **BPOL** (ESA Cosmic Visions). 2015-2020. Planned sensitivities between r=0.01-0.001.

Observability of B-modes (II)

- **Systematic program to study polarized astrophysical foreground signals is needed** (see NASA-NSF report "Task Force on CMB research" and ESA-ESO report on "Fundamental cosmology").

- **Exploration/development of modulation techniques to measure polarization needed.**

- Ground-based polarization experiments: (mainly small scales and high frequencies)
  - Correlation receivers (QUIET)
  - Bolometers (B2K, SPTpol, ACT, QUAD).

The QUIJOTE CMB Experiment

(Q-U-I JOint TEnerife Cosmic Microwave Background Experiment)

(http://www.iac.es/project/cmb/quijote)

- **Aim**: To perform high sensitivity observations of the polarization of the CMB, Galactic and extragalactic foregrounds in the frequency range 10-30 GHz at large angular scales (one degree resolution).

The QUIJOTE CMB consortium

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The QUIJOTE CMB Experiment

(Q-U-I JOint TEnerife Cosmic Microwave Background Experiment)

- QUIJOTE is a collaborative project between IAC, IFCA (CSIC-UC), DICOM (UC), IDOM, Jodrell-Bank Observatory (Univ. of Manchester, UK) and Cavendish Laboratory (Univ. Cambridge, UK) .
- **Aim**: To perform high sensitivity observations of the polarization of the CMB and Galactic emissions in the frequency range 10-33 GHz at large angular scales (one degree resolution).

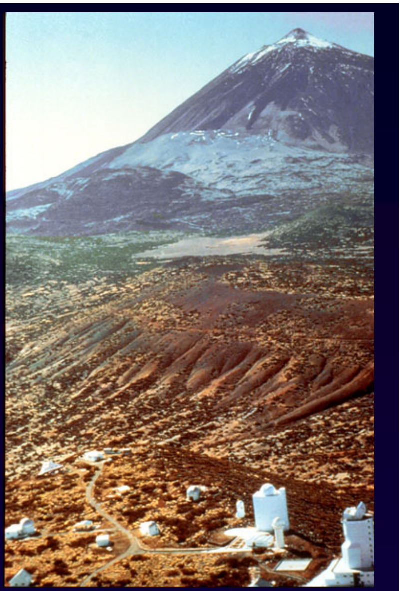
Quijote Science goals

- Search for a signature of gravitational B-modes (amplitude r >0.05)
    - In combination with Planck push limits beyond r=0.05

- Characterize foregrounds with unprecedented sensitivity in the 10-30 GHz range (needed to correct future space missions aiming to reach r=0.001)

- Cosmological parameters from E-mode polarization

QUIJOTE: Project baseline



- **Site**: Teide Observatory
- **Frequencies**: 11, 13, 17, 19 and 30 GHz.
- **Angular resolution**: ~1 degree

- **Telescopes and instruments: three phases.**
  - **Phase I (funded) .** First telescope with a multichannel instrument providing 11-30 GHz (starts operation next October), and a second instrument with 16 polarimeters @ 30 GHz (shall be completed at the end of 2011) . A polarised source subtractor will also start operation in 2010.
  - **Phase II.** Second telescope and third instrument at 40 (90GHz?).
  - **Phase III.** New concepts (30GHz-90GHz) /replicate at Southern Hemisphere?

- **Polarization detection**: modulation (similar to half-wave plate).
- **Observing strategy**: each set of antennae mounted on a fast spinning system (0.25-0.1 Hz) . Earth rotation provides daily sky coverage of several thousand sq degrees. Each antenna system operates with an independent cryo-cooled multi-channel receiver.

The Izaña Site

Observatorio del Teide
(http://www.iac.es)

Altitude: 2400 m

Longitude: 16º 30’ W

Latitude: 28º 17’ N

Typical PWV: 1-3 mm

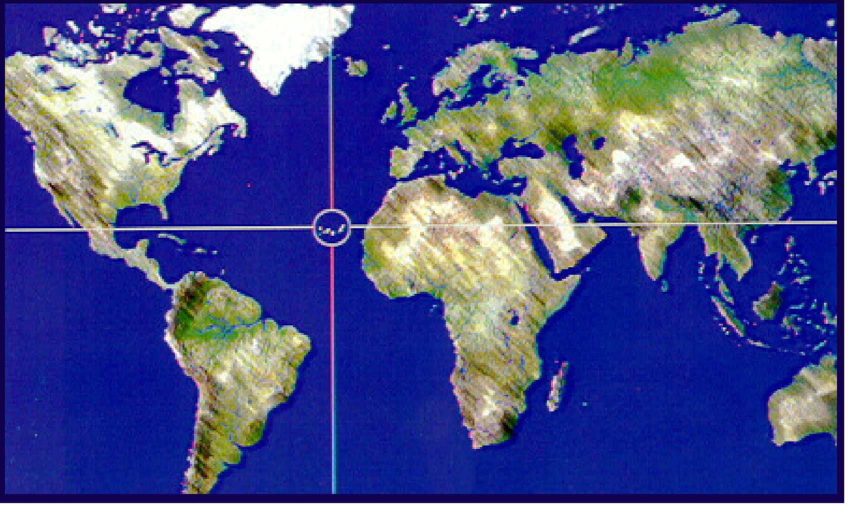
Transmissivity: 98%
$\equiv \; T_{sky} \approx 5$ K

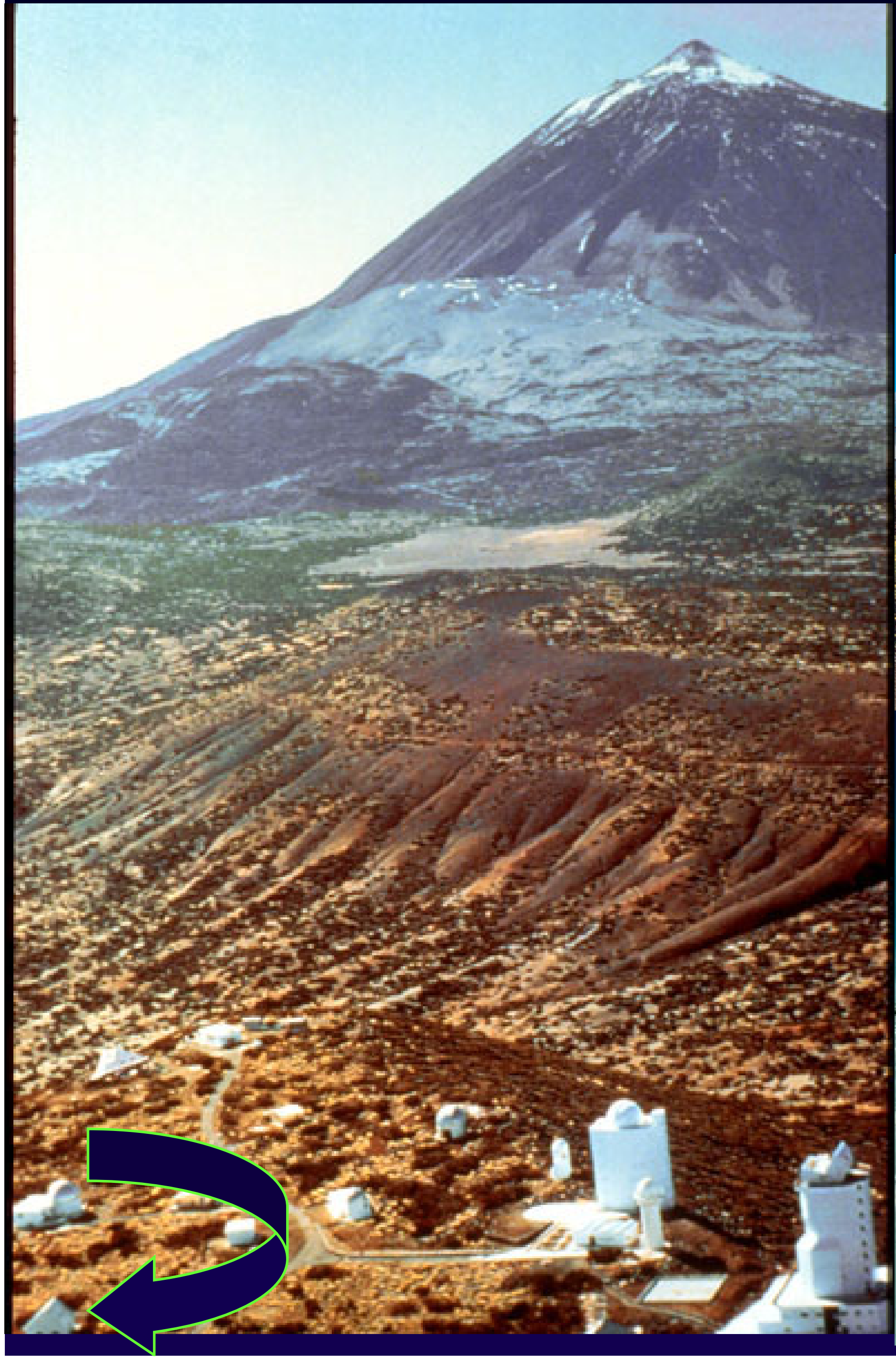
Good weather: 80%

Easy access: 40 km road journey from IAC

The Teide Observatory site run by the Instituto de Astrofisica de Canarias (IAC) and is above much of the atmospheric water vapour with a stable dry climate.

Our previous experience with CMB experiments (Tenerife, VSA, COSMOSOMAS) shows that 80% of the time the data is just system noise limited.





First CMB Experiments

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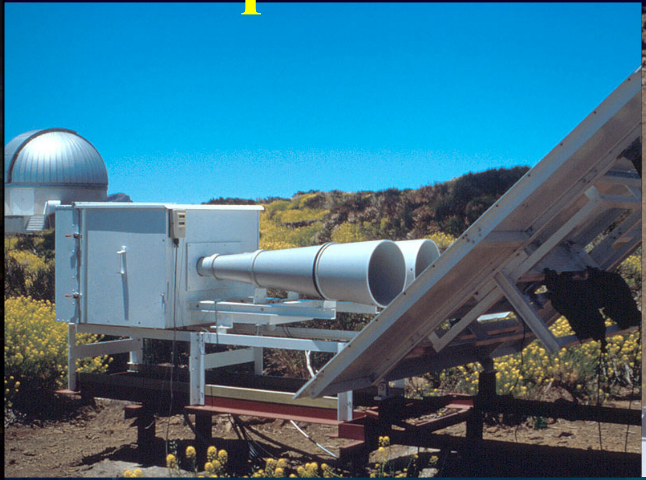
IAC



CMB experiments at Tenerife

The *Very Small Array*

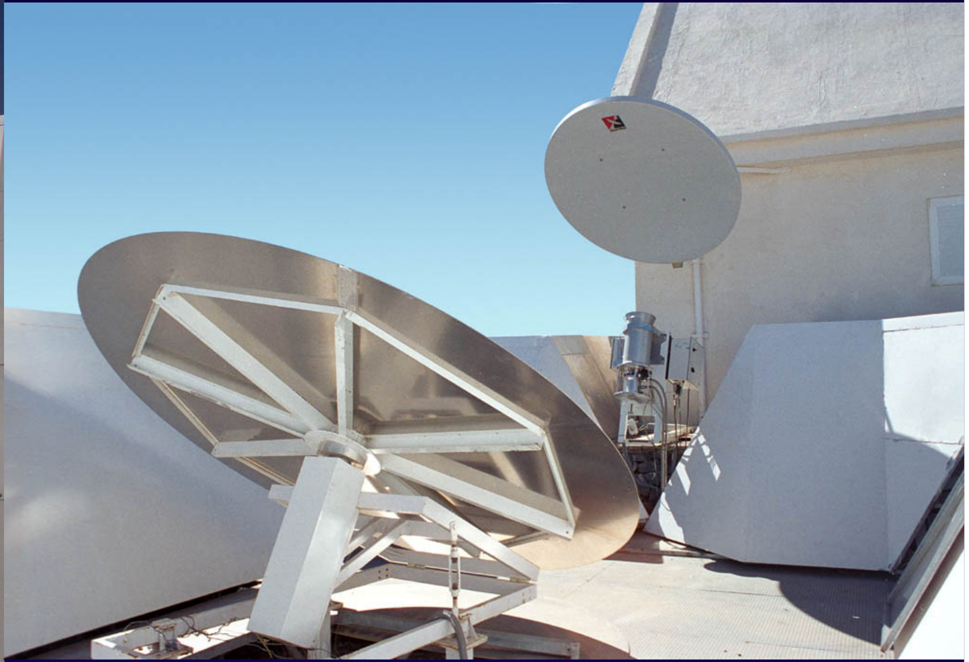
Cavendish Astrophysics Group
Jodrell Bank Observatory
Instituto de Astrofisica de Canarias

COSMOSOMAS

Instituto de Astrofísica
de
Canarias


VSA Extended configuration

33 GHz


11, 13, 15, 17 GHz

Cavendish Astrophysics

Jodrell Bank Observatory


QU

QUIJOTE telescope and enclosure

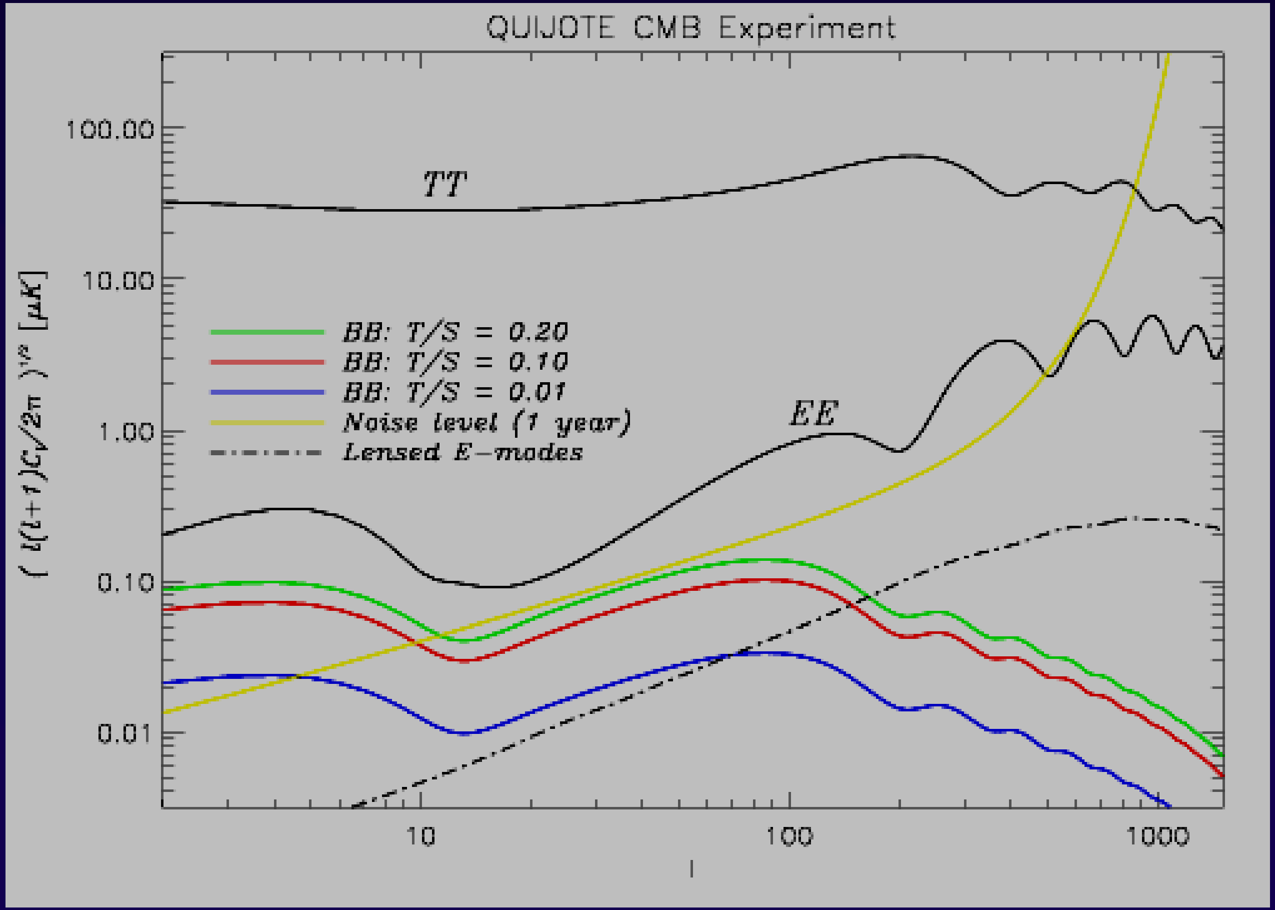
- Alt-azimuthal mount
- Maximum rotation speed around AZ axis: 0.25 Hz
- Maximum zenith angle: 60º
- Cross-Dragonian design
- Aperture: 3 m (primary) and 2.6 m (secondary)

QUIJOTE enclosure at Teide Obs

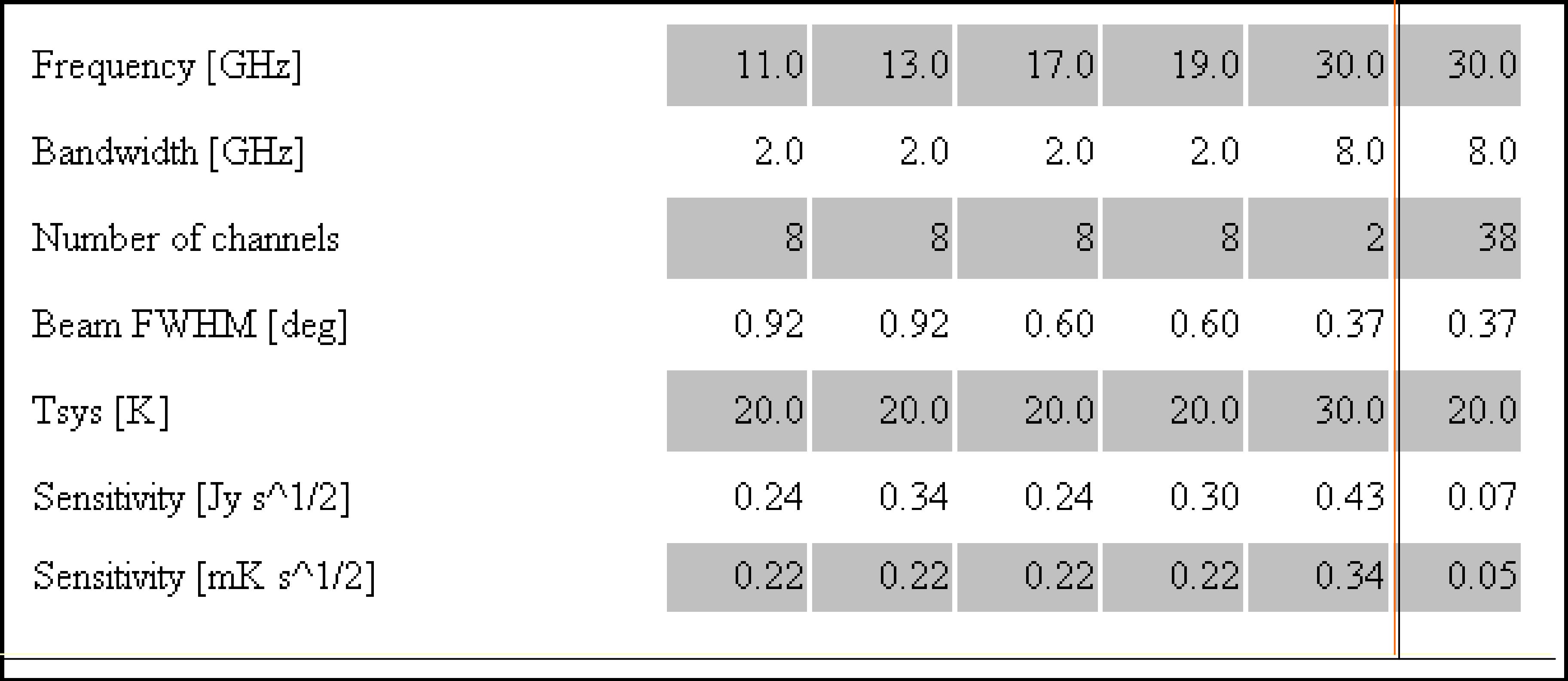
QUIJOTE first telescope at the IAC workshops

SCIENCE

The goal for QUIJOTE (Phase I) is to obtain five polarization maps in the frequency range 10-30 GHz with sufficient sensitivity to correct the 30 GHz map from foreground emission and detect the imprint of B modes with r=0.05



QUIJOTE Experiment-Phase I. Basic facts



	Instrument I					Instr. II
Frequency [GHz]	11.0	13.0	17.0	19.0	30.0	30.0
Bandwidth [GHz]	2.0	2.0	2.0	2.0	8.0	8.0
Number of channels	8	8	8	8	2	38
Beam FWHM [deg]	0.92	0.92	0.60	0.60	0.37	0.37
Tsys [K]	20.0	20.0	20.0	20.0	30.0	20.0
Sensitivity [Jy s^1/2]	0.24	0.34	0.24	0.30	0.43	0.07
Sensitivity [mK s^1/2]	0.22	0.22	0.22	0.22	0.34	0.05

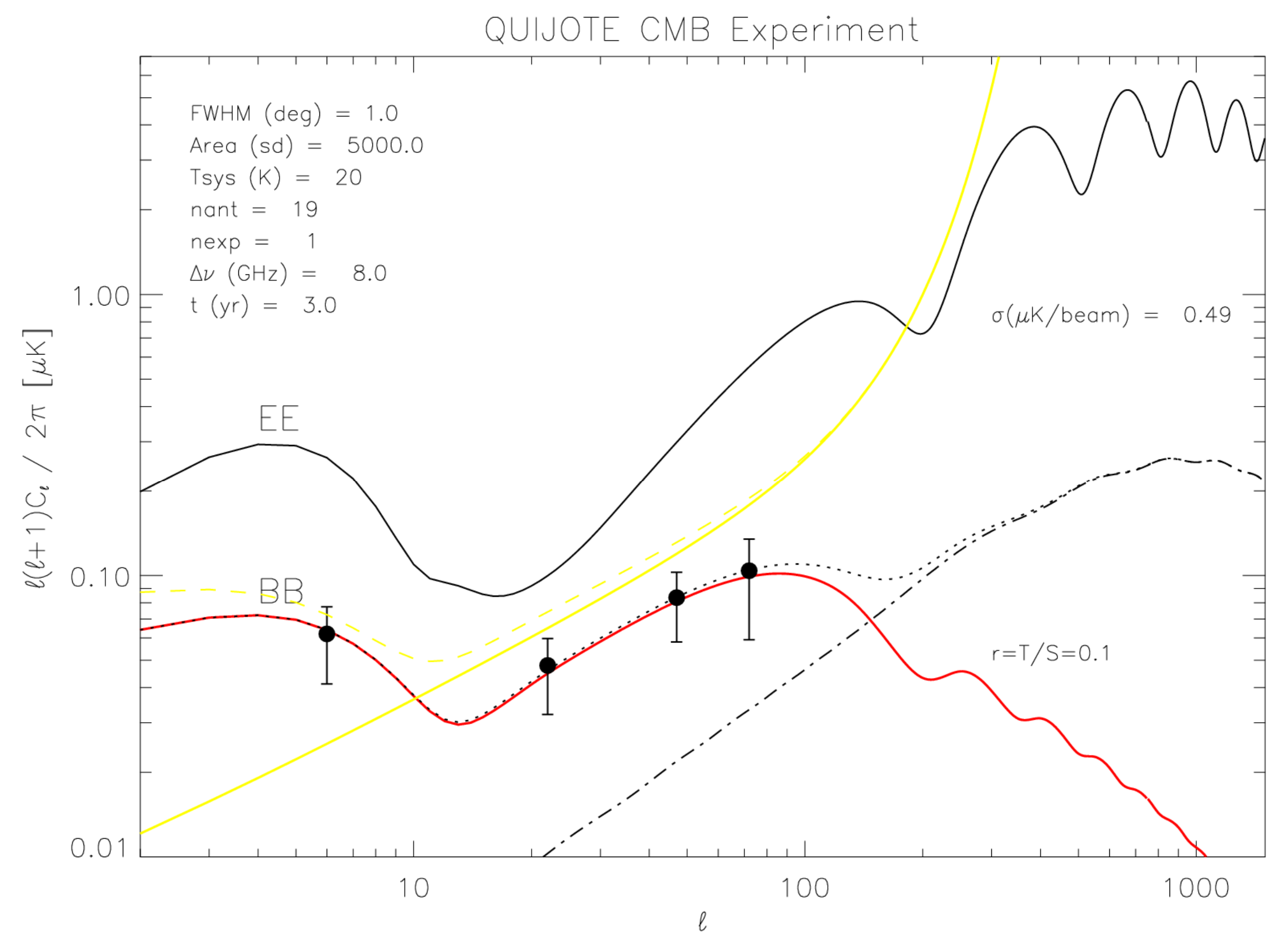
- Temperature sensitivity per beam, given by

$$\Delta Q = \Delta U = \sqrt{2}\frac{T_{sys}}{\sqrt{\Delta \nu \times t_{\mathrm{int}} \times N_{chan}}}$$

- Our definition of Q is given by Q = Tx – Ty.

QUIJOTE: Science

QUIJOTE will achieve at 10-30 GHz a sensitivity 1-2 μK per 1º beam over 10000 square degrees after one year of operation.



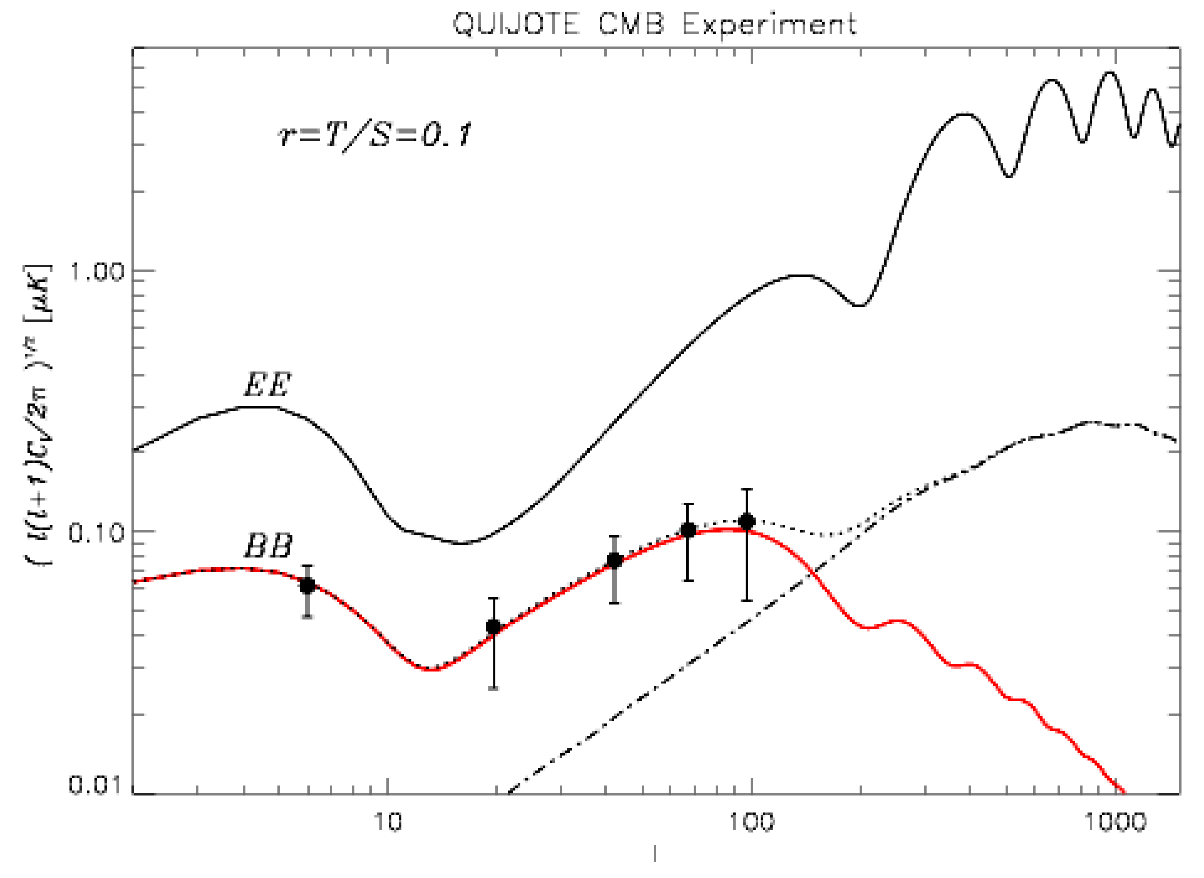
Area = 5000 sq deg

Time = 3 years

QUIJOTE: Science

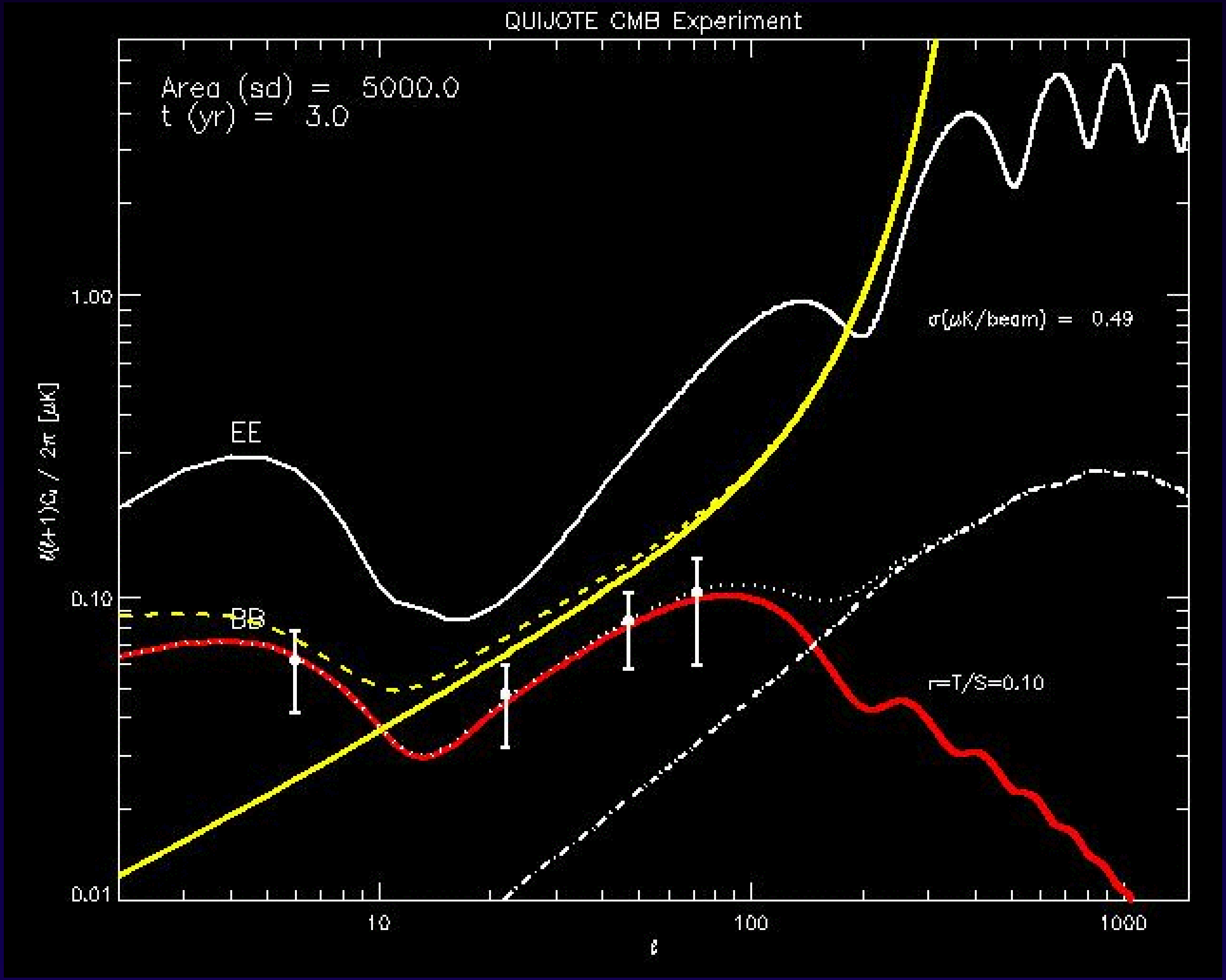
30 GHz
Δν = 8 GHz
15 polarim.
N_tel= 1
T_sys= 15 K
FWHM= 1 deg
2 yr
(eff. Integration)

0.5μK/beam
Over 5000 sq deg



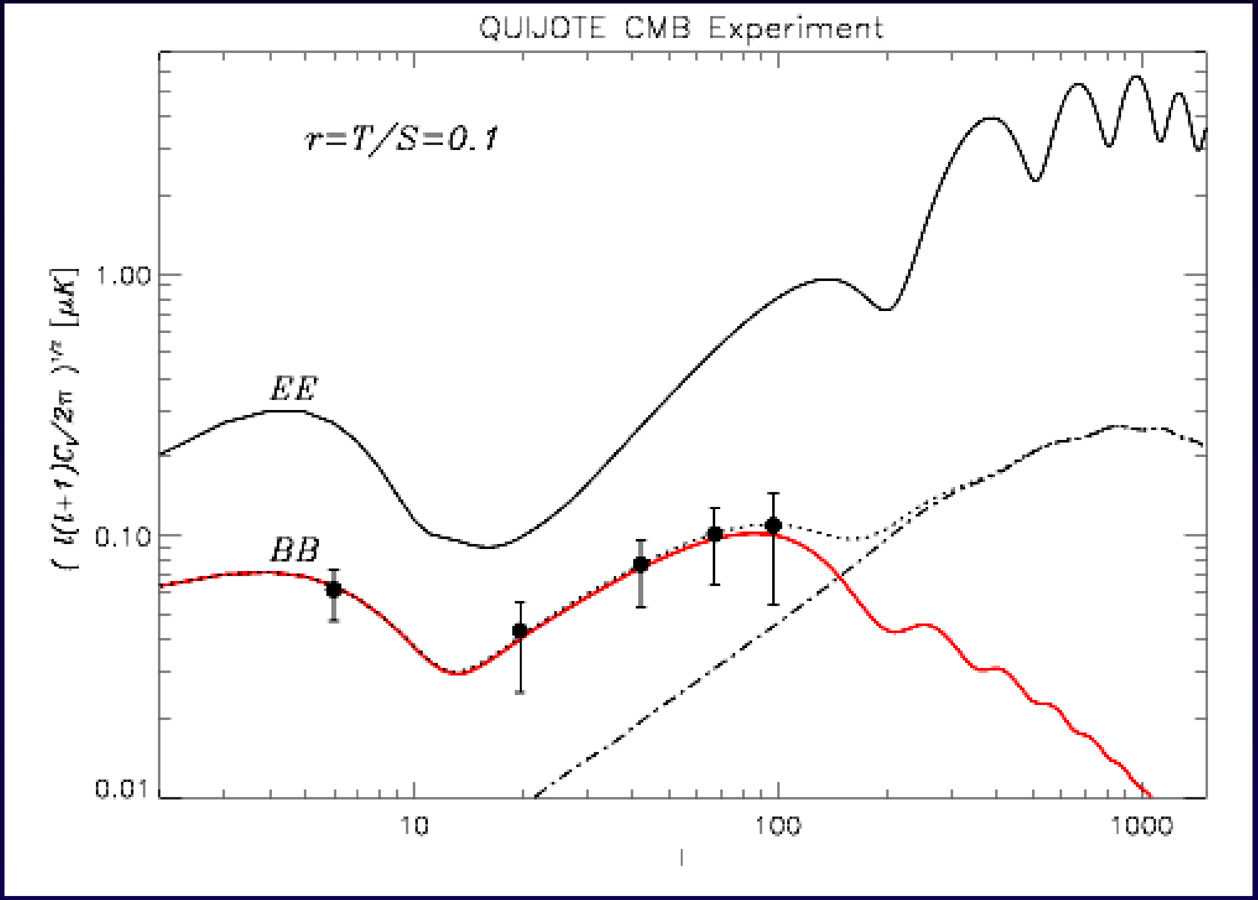
4 sigma detection r=0.1

QUIJOTE: Science



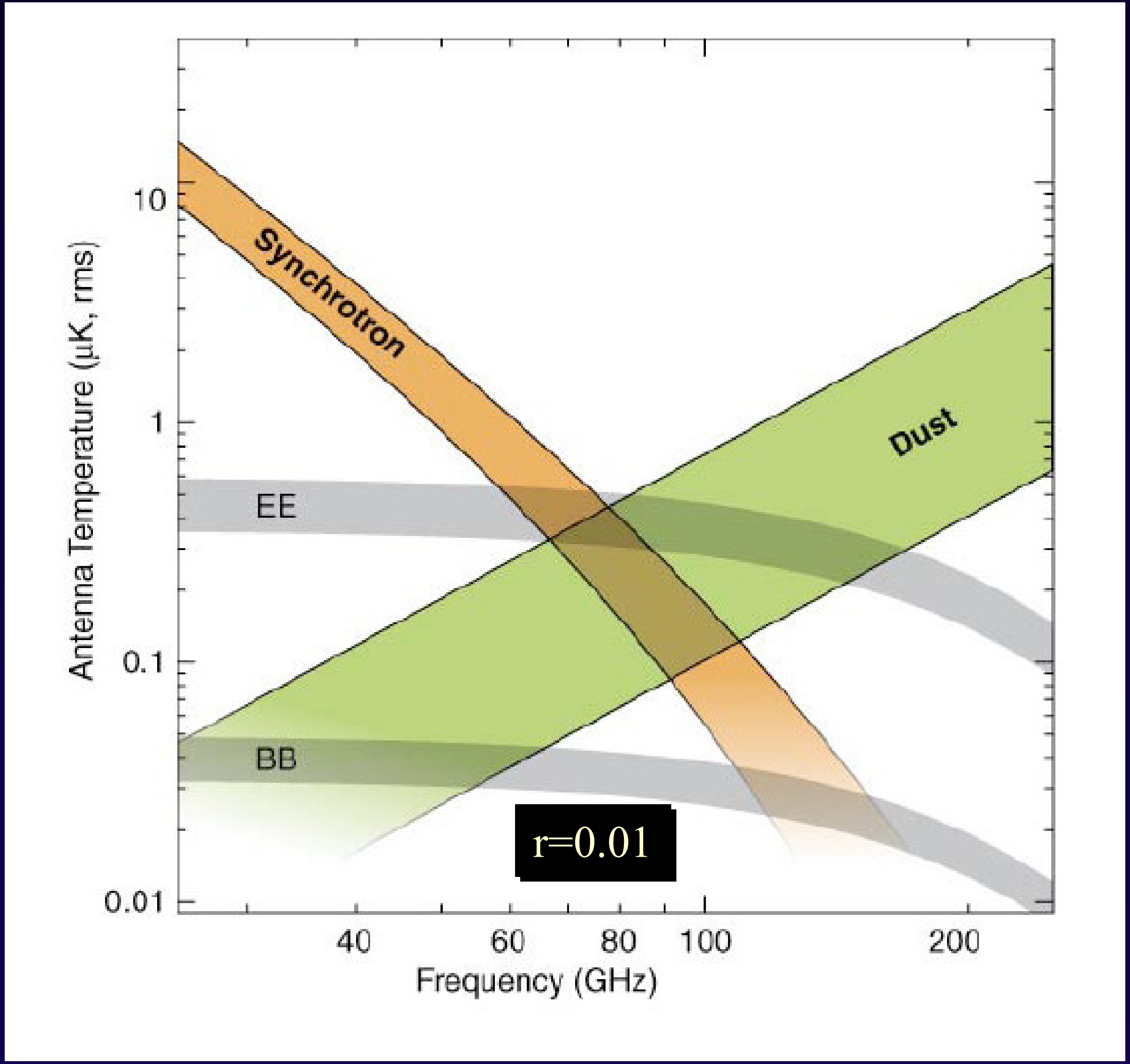
30 GHz
$\Delta\nu$ = 8 GHz
20 polarim.
N_tel= 1
T_sys= 15 K
FWHM= 1 deg
1.5 yr
(eff. Integration)

0.5μK/beam
Over 5000 sq deg



4 sigma detection r=0.1

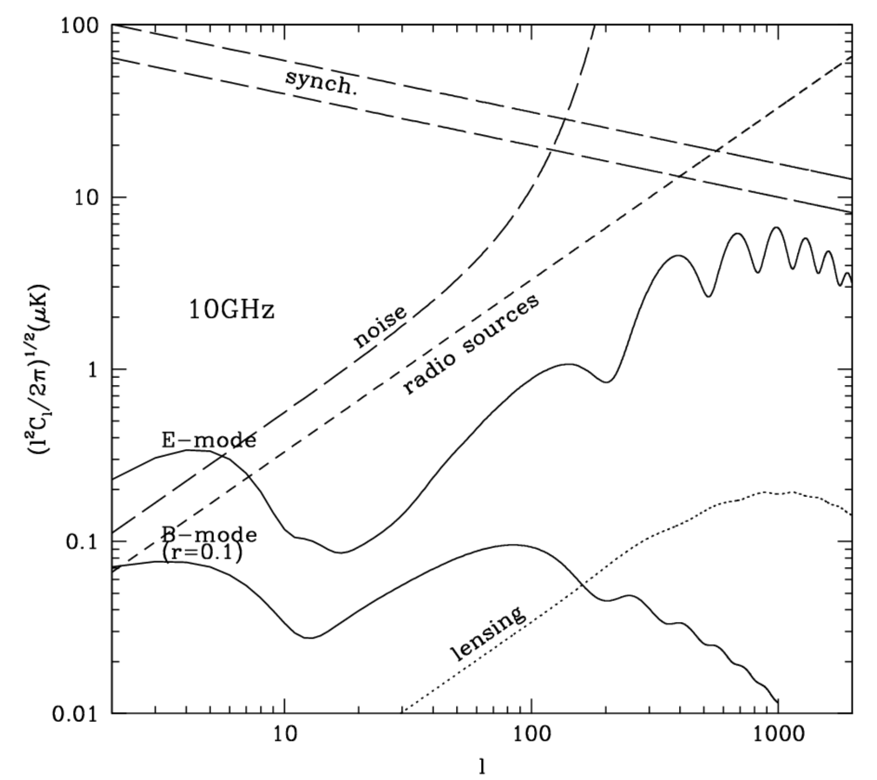
CMB foregrounds in the polarized microwave sky

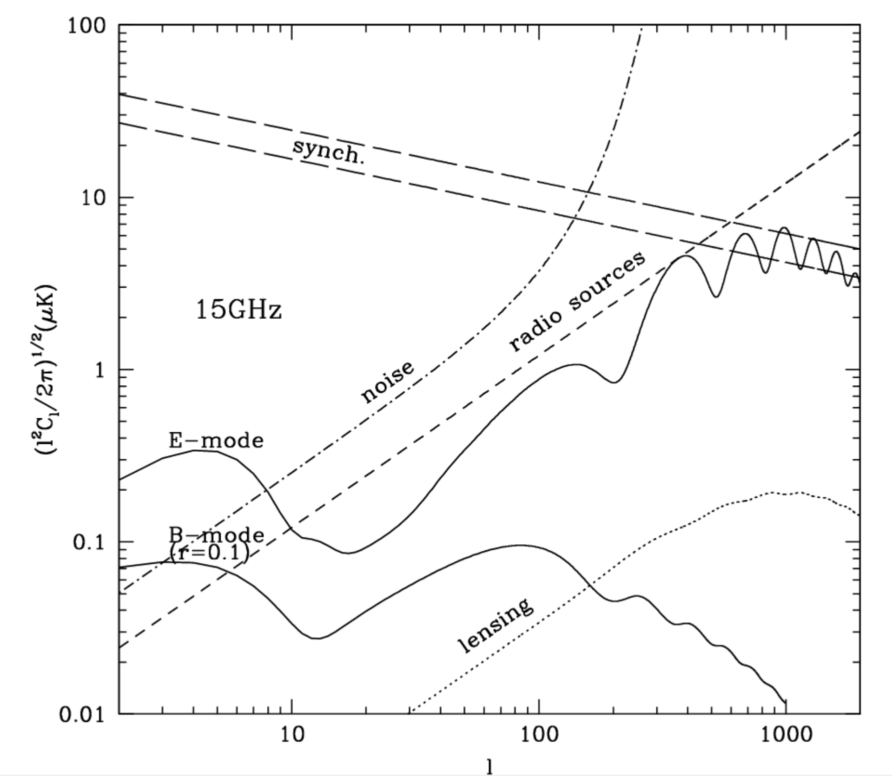


- A detailed study of the polarized large-scale emission from our galaxy in the microwave band is needed.
- Extrapolations from low frequency surveys (e.g. Wolleben et al. 2005) or high frequency studies (dust emission) show that the polarized CMB signal is never dominant.

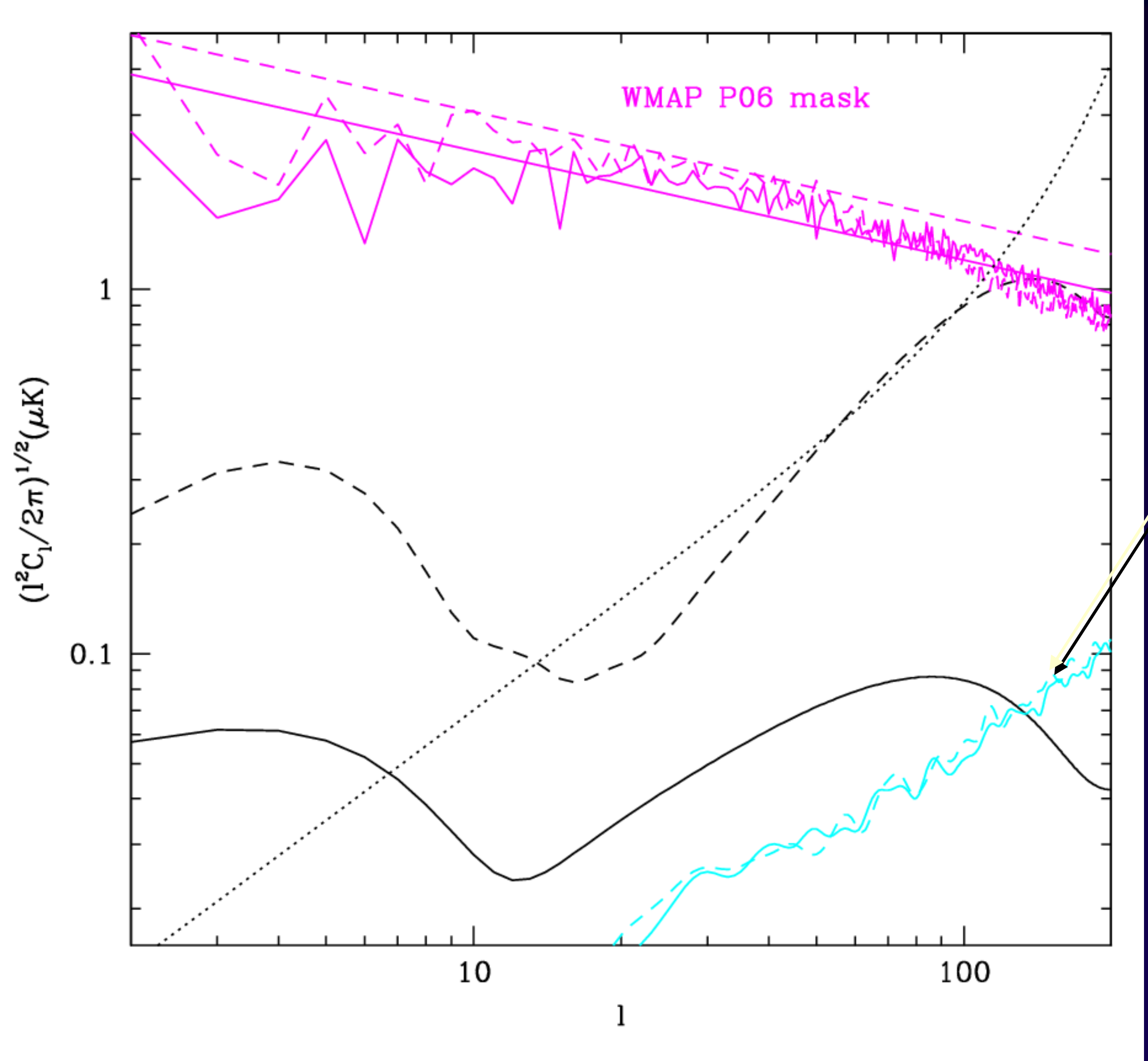
1. Correction of synchrotron emission at 30GHz

- We will obtain 4 frequency maps of the synchrotron polarization between 10 and 20 GHz, each with a sensitivity around 1-2μK per beam.
- Synchrotron frequency dependence scales approx. as ν^{-3}
- This will allow to predict the synchrotron contribution at 30 GHz with a precision better than 0.02 μK per sq. deg.





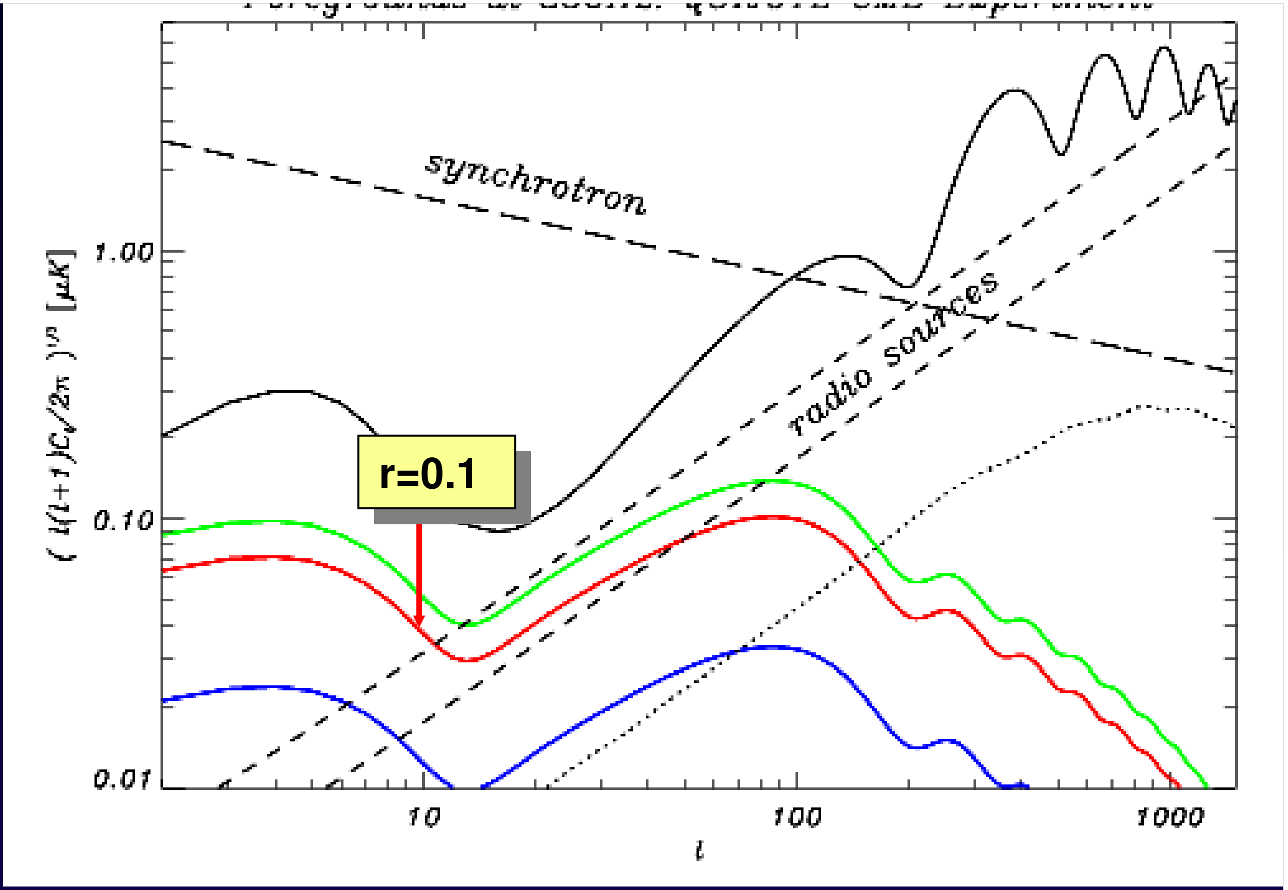
Correction of synchrotron emission at 30GHz



Synchrotron residual, assuming a pure power-law dependence in the 10-30 GHz frequency range, and 2μK per beam in the lower-frequency channels, and performing a pixel-by-pixel correction.

Foregrounds

contamination at 30 GHz as compared with BB modes.



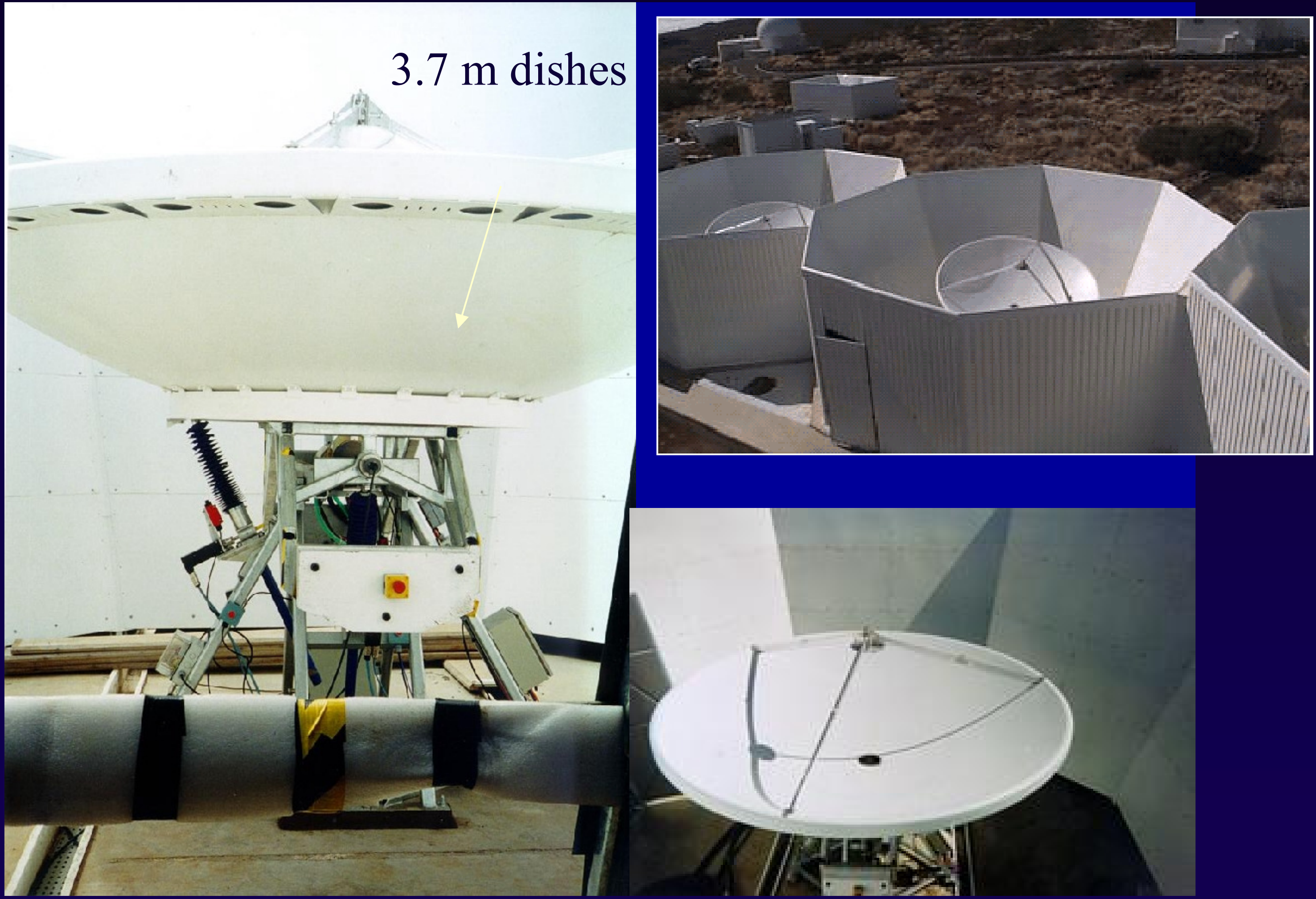
2. Extragalactic radio sources contribution (short dashed line) for the case of subtracting sources down to 1 Jy in total intensity (upper line) and 300 mJy (lower line) Tucci et al.

Extragalactic Radiosource correction

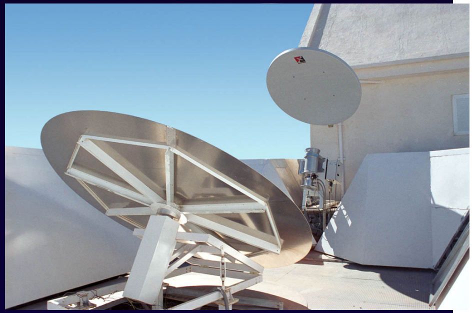
A dedicated instrument at 33 GHz

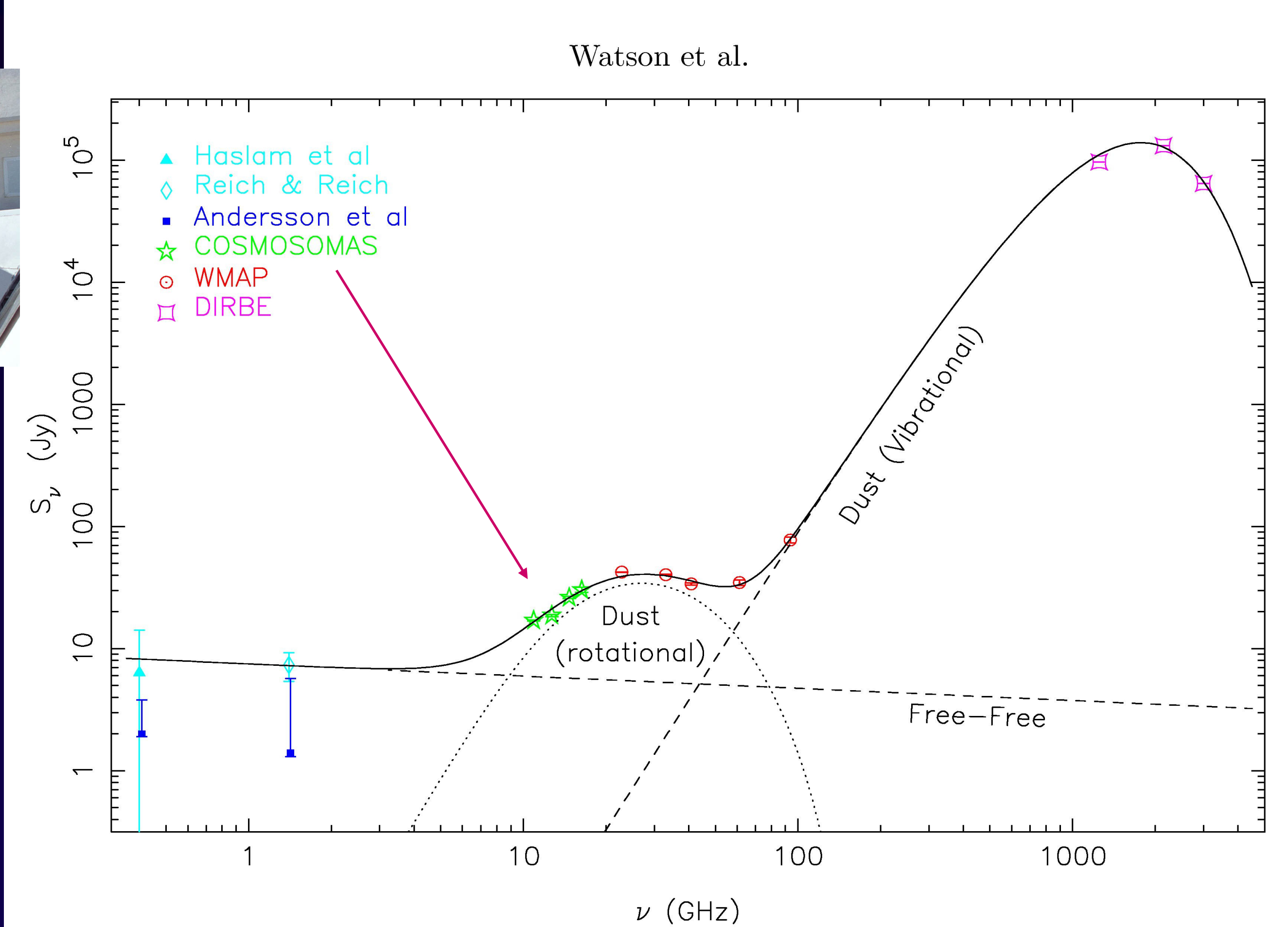
VSA subtractor converted to a polarimeter.

We estimate less than 500 sources below 300 mJy



3. Anomalous microwave emission: polarization



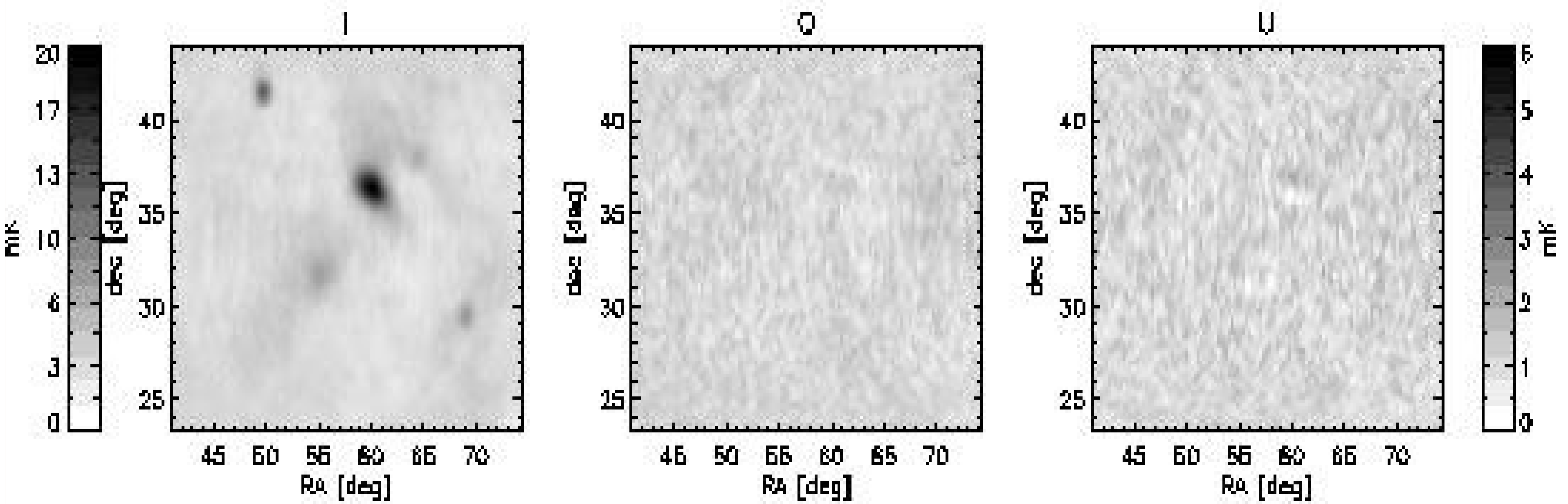


Watson, Rebolo, Rubiño et al. 2005, ApJ 624 L89

3. Polarization of Anomalous dust emission

Polarization observations of anomalous microwave emission at 11 GHz in the Perseus molecular complex

Battistelli, Rebolo, Rubiño et al. 2006 ApJ



Q: difference between the radiation intensity collected by COSMOSOMAS in the 0º plane (North-South) and the 90º one. Q= **- 0.2** ±1.0 % (95% c.l.)

U : difference between the orientation –45º and +45º. **U=-3.4±2% (95% c.l.)**

Overall polarization parameter Π=3.4 ± 2%.

The maps are calibrated to the nearby California Nebula (free-free dominated) which is assumed unpolarized (systematic error of less than 1%).

Possible carrier for the emission?

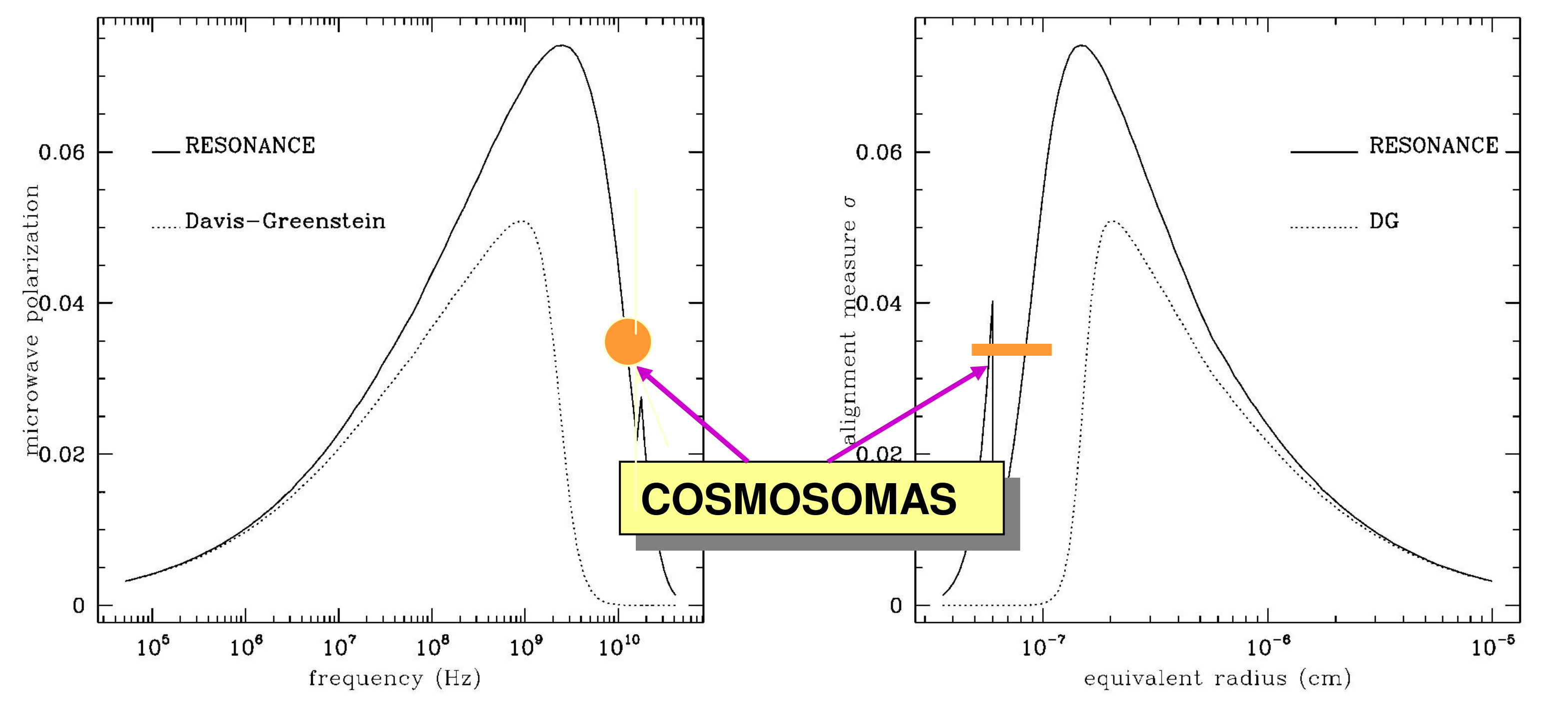
Carbon based molecules with permanent electric dipole

Polarization of rotational electric dipole radiation

Lazarian and Draine 2000 ApJ

Are the molecules aligned and their emission polarized?

The energy level splitting arising from grain rotation ensures maximum efficiency of paramagnetic dissipation : time dependent magnetization, energy dissipation and torque causing the molecules to rotate with the axis parallel to the magnetic field



Status of the QUIJOTE project

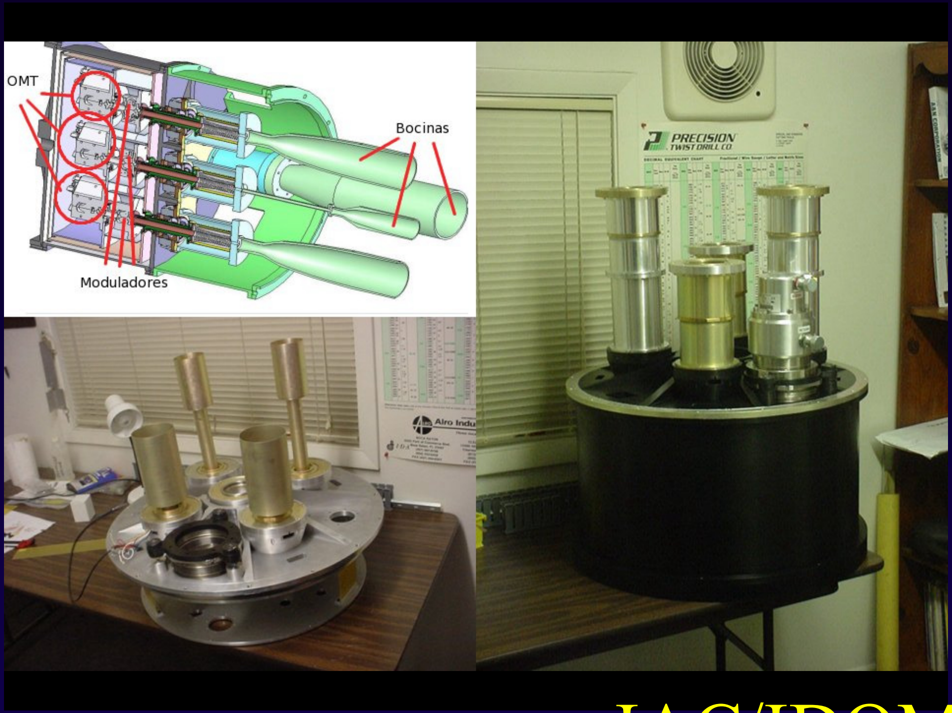
First QUIJOTE telescope and Interferometer for Polarized Radiosource Substraction

QUIJOTE
Subtractor de fuentes polarizadas
Obs. del Teide

Telescopio IAC/IDOM

QUIJOTE building at Observatorio del Teide Instituto de Astrofísica de Canarias 2400 m altitud

QUIJOTE Multi-frequency instrument

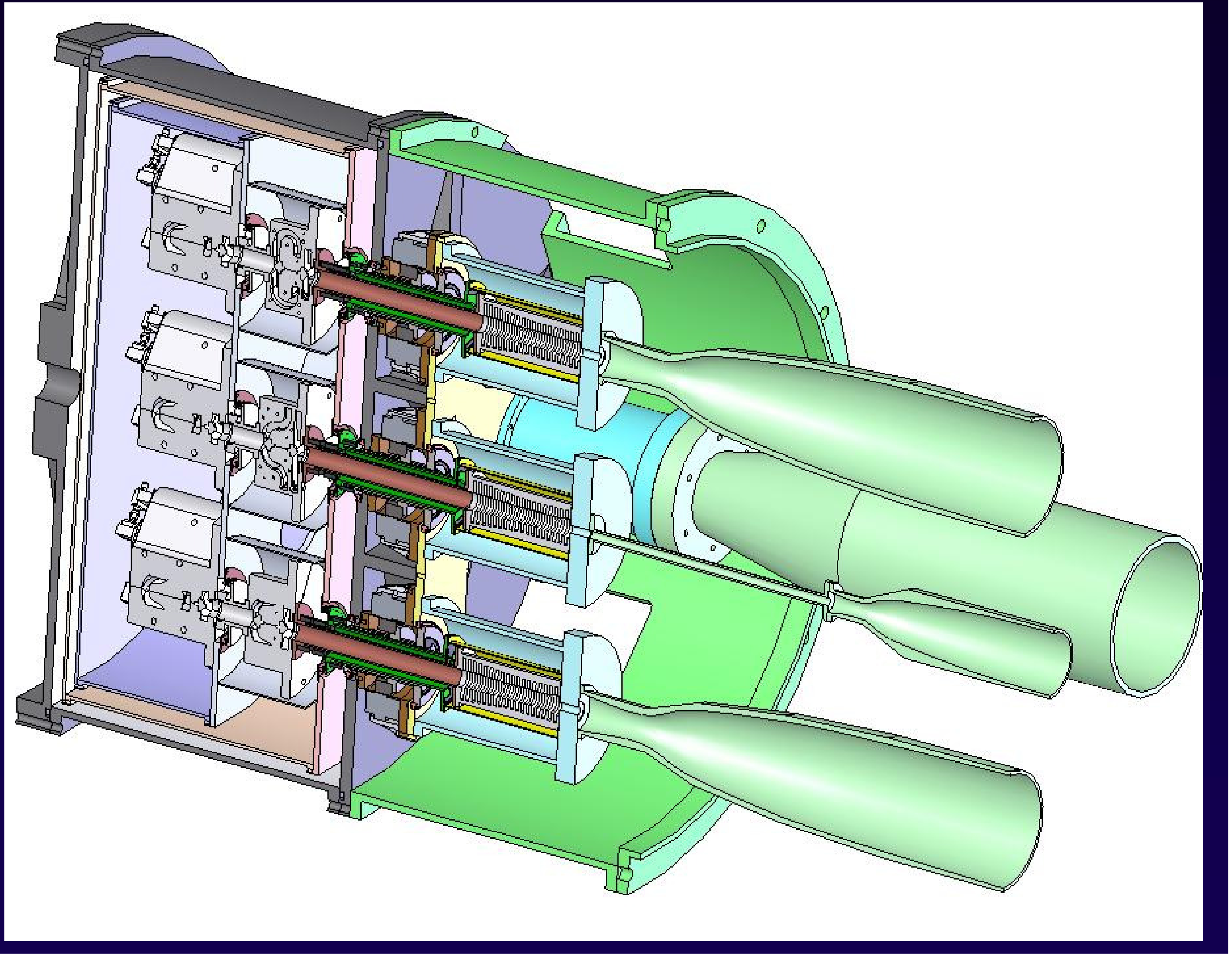


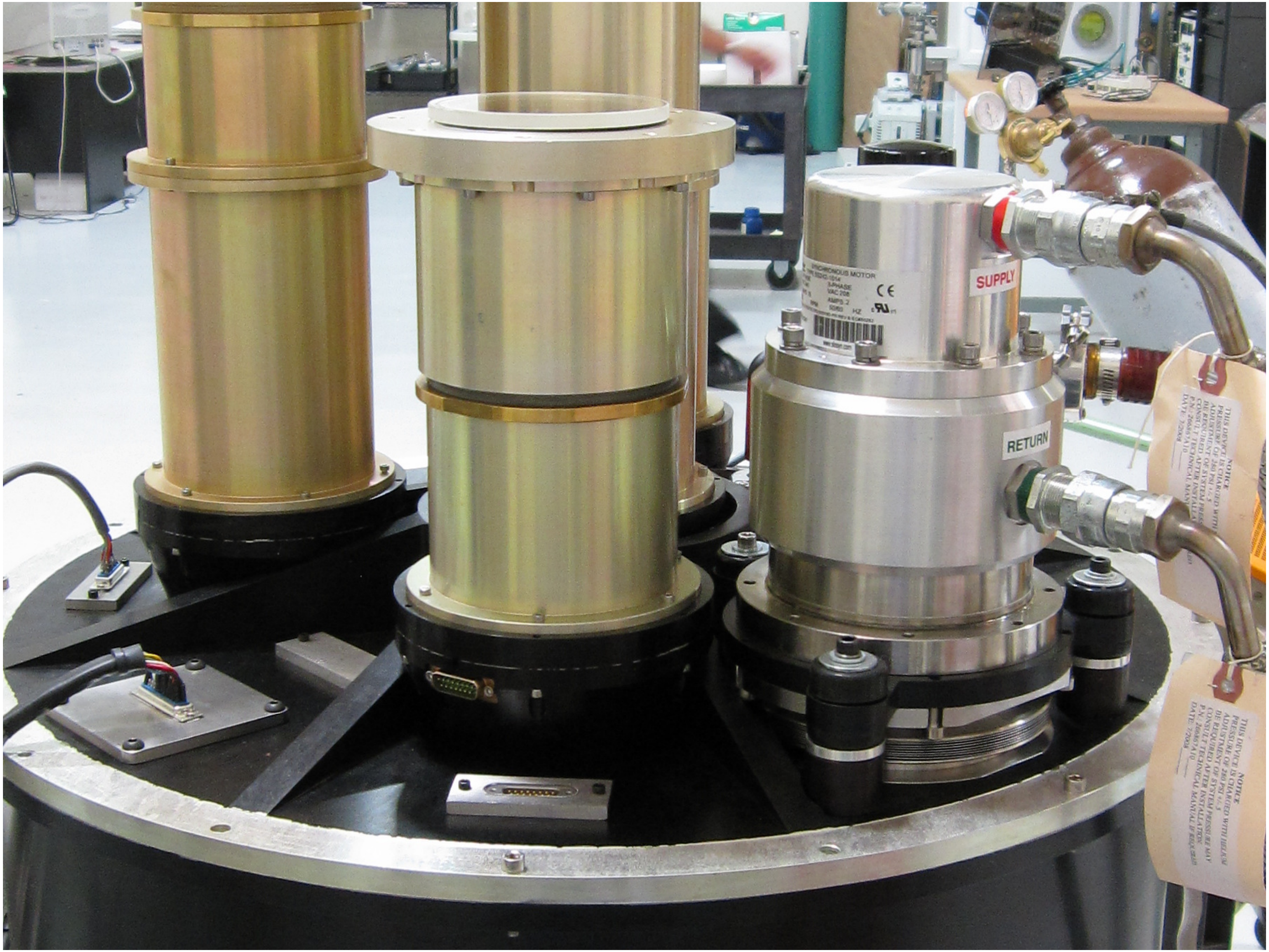
IAC/IDOM/IFCA

Complementarity

QUIJOTE MFI	from 10 to 30 GHz
Planck LFI	from 30 to 70 GHz
Planck HFI	from 100 to 300 GHz

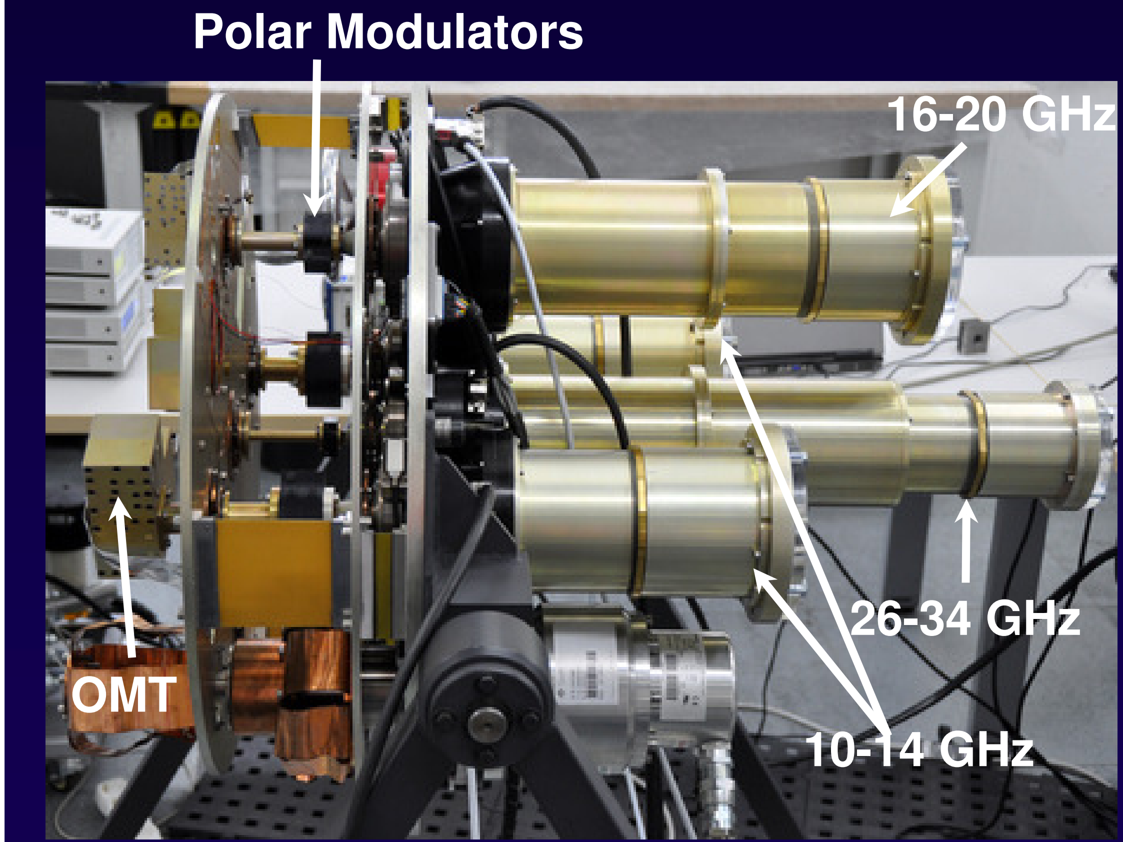
QUIJOTE First instrument



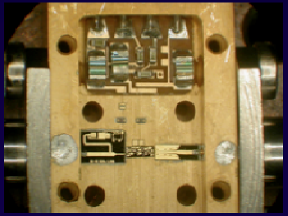

SUPPLY
RETURN

QUIJOTE first instrument

- 2 horns providing 8 channels at 11 and 13 GHz
- 2 horns providing 8 channels at 17 and 19 GHz
- 1 horn providing 2 channels at 30 GHz



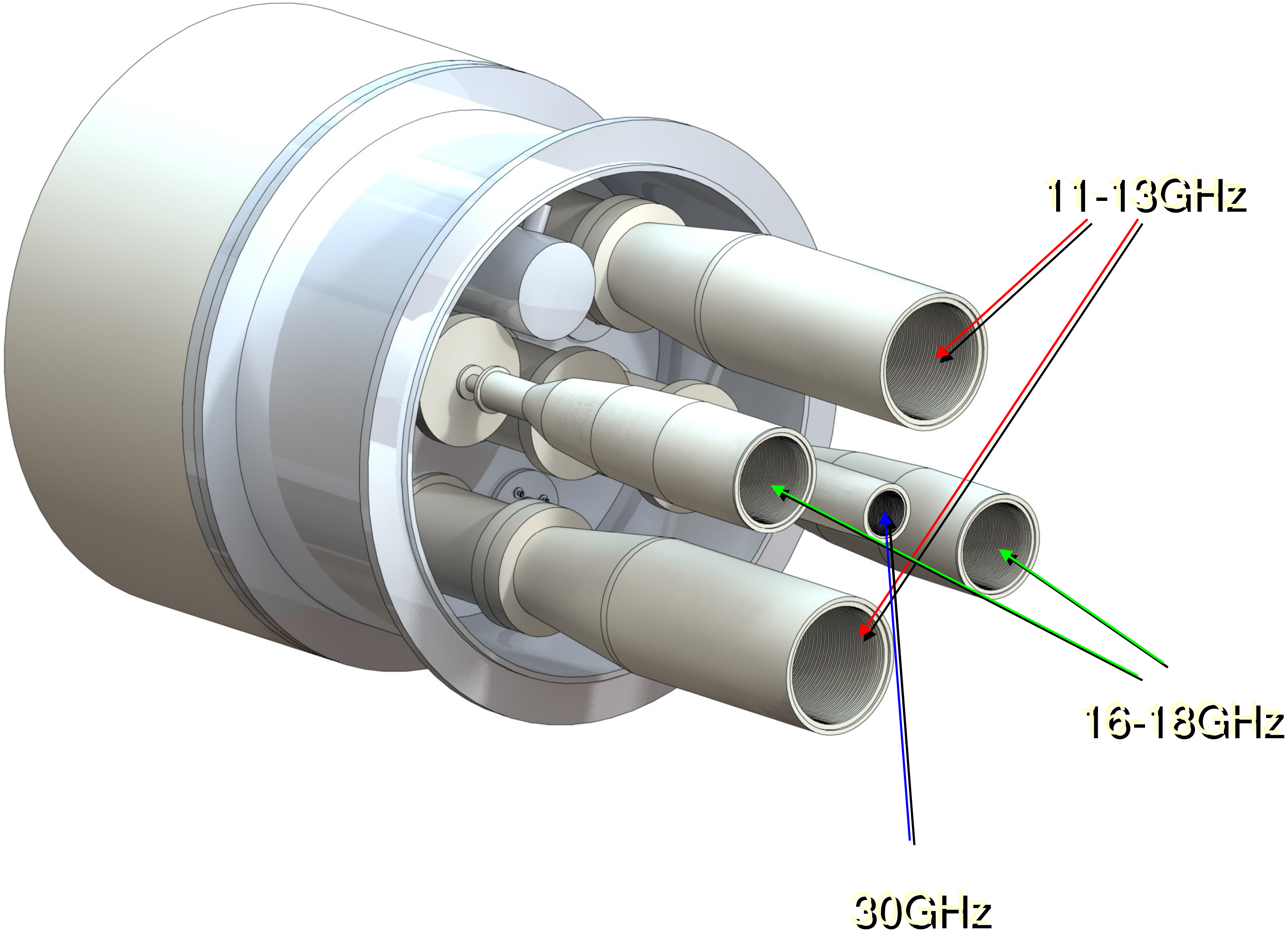
Spinning polar modulators


LNA

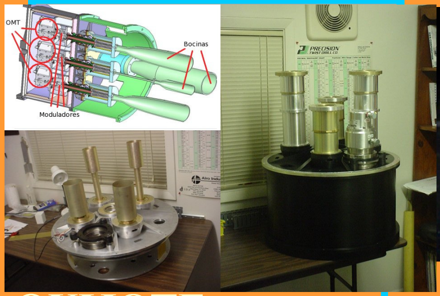

OMT and motor


Horns

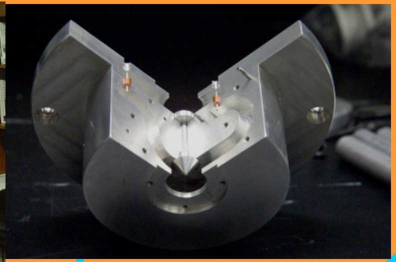
QUIJOTE First instrument



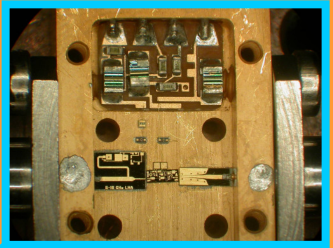
QUIJOTE INSTRUMENTATION



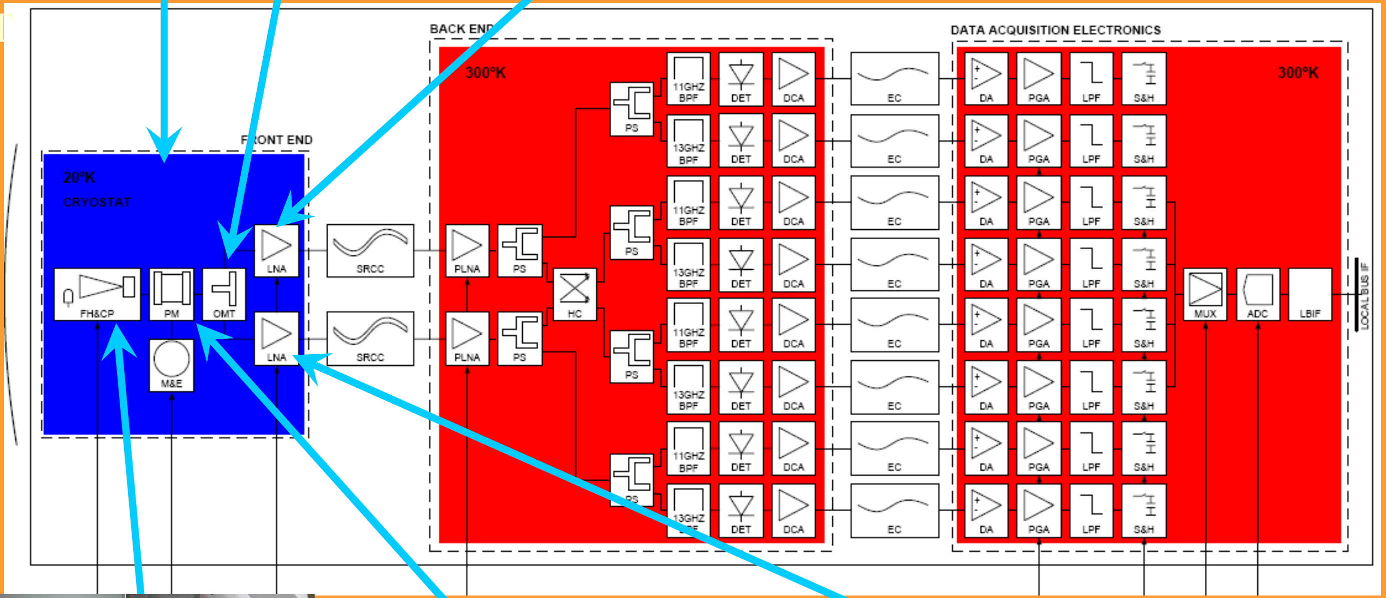
QUIJOTE CRYOSTAT



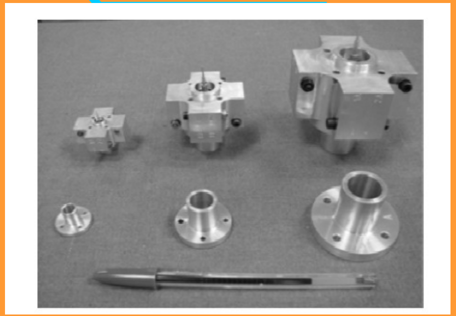
OMT



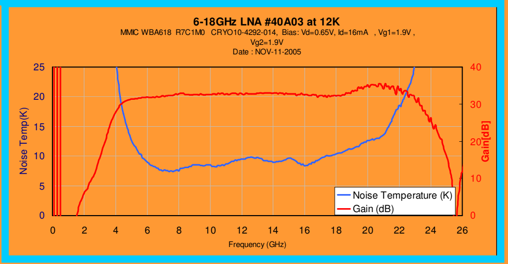
LNAs 6-18GHz



HORN



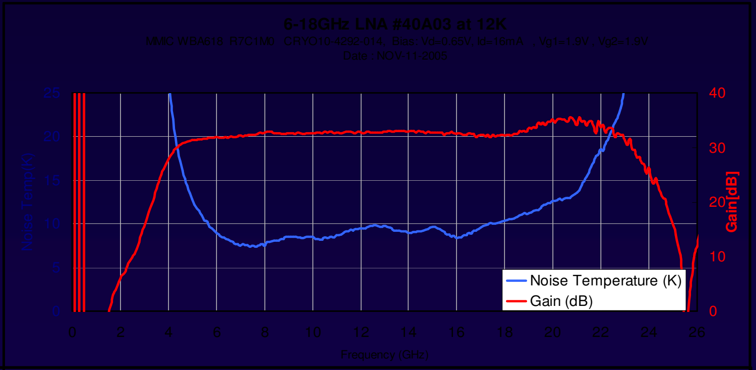
POLAR MODULATOR

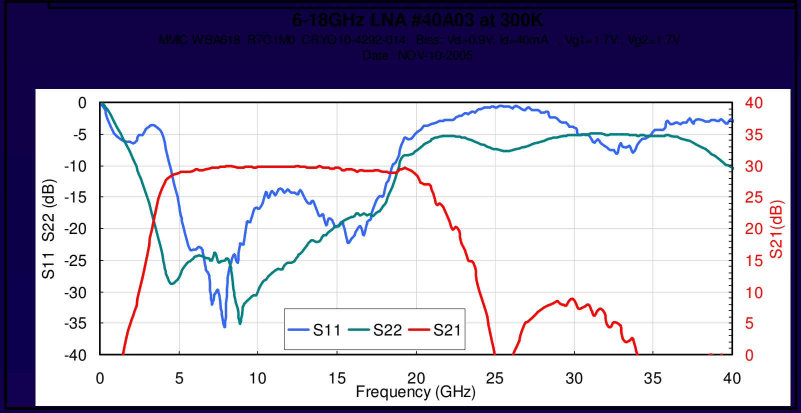


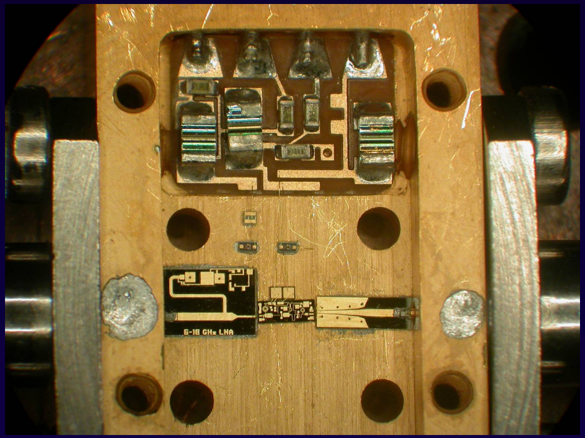
LOW NOISE AMPS

MMIC 6-18GHz LNA (Caltech)

(S. Weinreb)







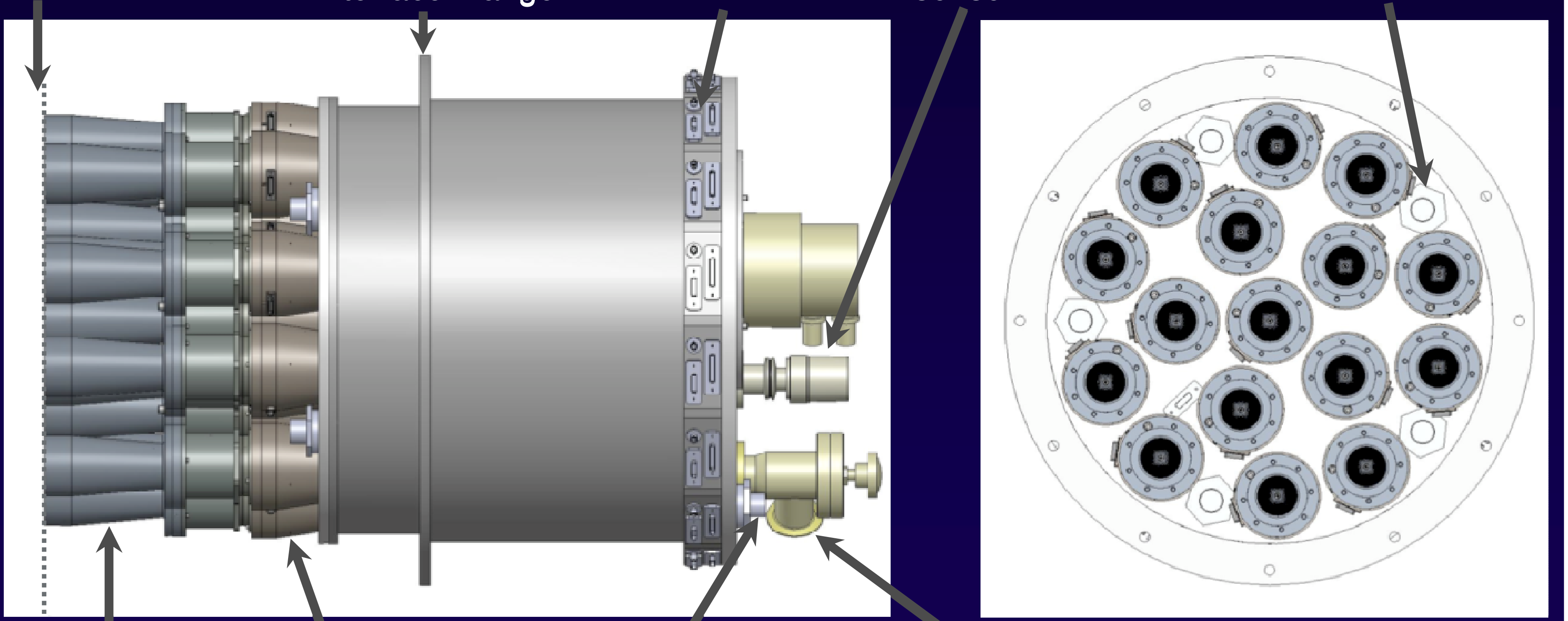
Gain = approx. 30dB

NT < 9K

For the second instrument (19 polarimeters at 30GHz) , we will use HEMTs produced at Jodrell Bank, Caltech and Chalmer Univ.

QUIJOTE Second Instrument

- 15 polarimeters operating at 30 GHz
- Conceptual design re-scaled version of the First Instrument



Focal plane

Telescope Mounting Interface Flange

Connectors for 26-36 GHz receivers

Pressure sensor

Hermetic feedthroughs for encoder signals

26-36 GHz feedhorn

Motor mount

Connectors for temperature sensors and heaters

Vacuum valve

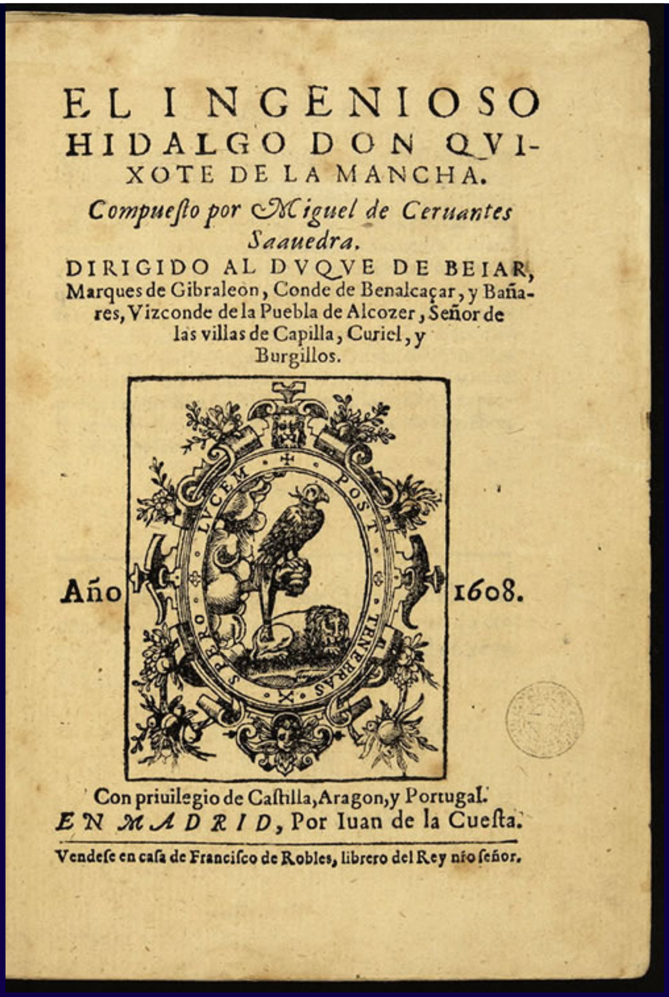
QUIJOTE & PLANCK

- QUIIJOTE will complement at low frequencies the information obtained by PLANCK. Improved constraint on r from the combination of the two experiments
- Improved determination of the synchrotron component at large angular scales.
- Determination of the anomalous component to correct PLANCK maps at 30 and 44 GHz.
- Better determination of the Galactic magnetic field model. Impact on the constraints on primordial magnetic fields

Summary

- QUIJOTE-CMB will provide unique information about the polarization emission (synchrotron and anomalous) from our Galaxy at low frequencies. This will be a valuable information for future B-mode experiments.
- It will reach the sensitivity level to detect the B-mode signal due to primordial gravity waves if r=0.05.

Dalí 1945



EL INGENIOSO
HIDALGO DON QVI-
XOTE DE LA MANCHA.
Compueſto por Miguel de Ceruantes
Saauedra.
DIRIGIDO AL DVQVE DE BEIAR,
Marques de Gibraleon, Conde de Benalcaçar, y Baña-
res, Vizconde de la Puebla de Alcozer, Señor de
las villas de Capilla, Curiel, y
Burgillos.

Año 1608.

Con priuilegio de Caſtilla, Aragon, y Portugal.
EN MADRID, Por Iuan de la Cueſta.
Vendeſe en caſa de Franciſco de Robles, librero del Rey nro ſeñor.

We are close to ride…

SUMMARY

Detection of B-modes in the CMB polarization signal may:

1. confirm that an epoch of inflationary expansion with a density near the Planck scale did in fact take place

2.Establish the energy scale of inflation

3.Provide constraints on physics near the Planck scale where quantum gravity is expected to unify with the other fundamental interactions.

Thanks for your attention!