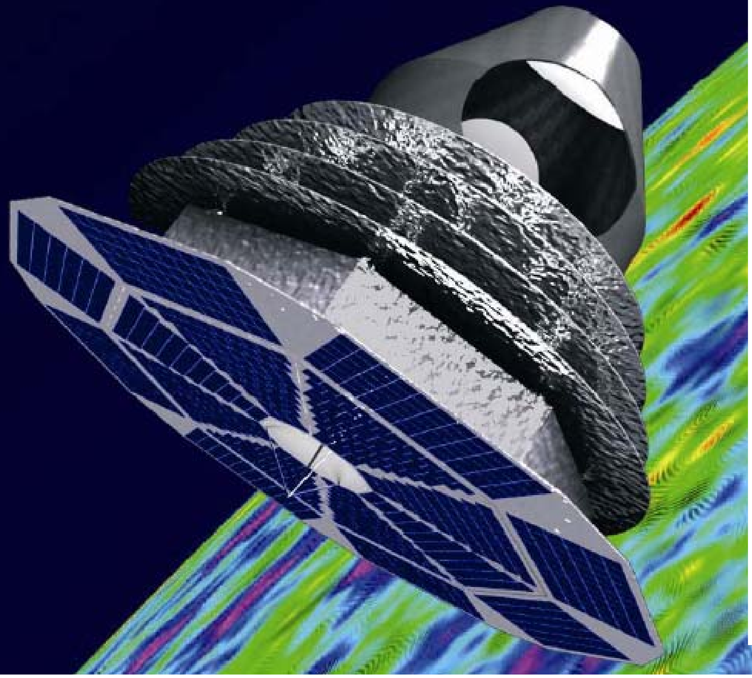
COrE

Cosmic ORigins Explorer

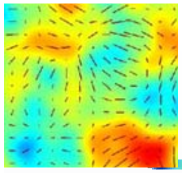


A satellite mission for probing
cosmic origins, neutrinos masses and
the origin of stars and magnetic fields

through a high sensitivity survey of
the microwave polarization of the entire sky

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

Paolo de Bernardis (Physics, Sapienza Univ. of Rome)
for the COrE collaboration : see astro-ph/1102.2181
15-August-2012 - virtually at the **IPSAG** meeting



What is *COrE*

- an extremely sensitive *and accurate* polarimeter
- exploring the whole sky with few arcmin FWHM resolution
- covering the mm - sub-mm λ range in 15 bands
- using arrays of thousands of bolometers
- based on
  - *a polarization modulator as the first optical element*
  - *a 2m-class telescope*
  - *a large array of bolometers (about 6000)*
  - *in L2 orbit*
- Proposed to ESA in 2010 by a large community (Europe + USA + Japan)

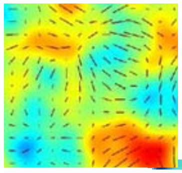
The COrE ollaboration

The consortium is composed of more than 300 researchers from the following European institutions (to be finalized): **Canada** Dept. of Physics and Astronomy, Univ. of British Columbia, Vancouver; Canadian Institute for Theoretical Astrophysics (CITA), University of Toronto **Denmark:** Neils Bohr Institute **France:** Laboratoire Astroparticules et Cosmologie (APC), Univ. Paris VII , Institut d'Astrophysique Spatiale (IAS), Univ. Paris-Sud, Orsay , Centre d'Etude Spatiale des Rayonnements (CESR), Toulouse . Commissariat à l'Energie Atomique (CEA), Saclay , Institut d'Astrophysique de Paris (IAP) , Institut Néel - Matière Condensée et Basses Températures (IN-MCBT), Grenoble , Laboratoire de l'Accélérateur Linéaire (LAL), Univ. Paris-Sud, Orsay , Laboratoire d'Astrophysique de l'Observatoire de Grenoble (LAOG), Laboratoire de Physique Théorique (LPT), Univ. Paris-Sud, Orsay, Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Grenoble, **Germany:** Argelander-Institut füur Astronomie (AIfA), Bonn Univ. , Institut für Photonische Technologien (IPHT), Jena , Max-Planck-Institut für Astrophysik (MPA), Garching , Max-Planck-Institut für Radioastronomie (MPIfR), Bonn , **Ireland:** Maynooth. , **Italy:** Istituto di Elettronica e di Ingegneria , dell'Informazione e delle Telecomunicazioni (CNR-IEIIT), Torino , Istituto di Astrofisica Spaziale e Fisica cosmica (INAF-IASF), Bologna , Osservatorio Astronomico di Padova (INAF-OAPd) Padova , Osservatorio Astronomico di Trieste (INAF-OATs) Padova , INAF-OAC Cagliari, Istituto di RadioAstronomia (INAF-IRA), Bologna , Istituto Nazionale di Fisica Nucleare (INFN) - Sezioni di Genova, Perugia, Roma1 , Scuola Internazionale Superiore di Studi Avanzati (SISSA), Trieste , Univ. di Firenze, Dip. di Fisica , Univ. di Genova, Dip. di Fisica , Univ. di Milano Bicocca, Dip. di Fisica , Univ. di Milano, Dip. di Fisica , Univ. di Padova, Dip. di Fisica , Univ. di Perugia, Dip. di Fisica , Univ. di Roma La Sapienza, Dip. di Fisica , Univ. di Roma Tor Vergata, Dip. di Fisica , **Netherlands:** Institute for Theoretical Physics, Amsterdam , **Norway:** , Institute of Theoretical Astrophysics, University of Oslo , **Portugal:** Instituto de Telecomunicações (IT), Lisbon , Instituto de Telecomunicações (IT), Aveiro , Instituto Superior Té:cnico (IST), Lisbon , **Romania:** Institute for Space Sciences (ISS), Bucharest , **Spain:** Instituto de Astrofisica de Canarias (IAC), La Laguna , Instituto de Física de Cantabria (IFCA), Santander , Instituto de Ciencias del Espacio (ICE), Barcelona , Universidad Autonoma de Madrid (UAM), Madrid , Universidad de Oviedo (UNIOVI), Oviedo, Spain , **Sweden:** Chalmers Univ.of Technology, Dept. of Microtechnology and Nanoscience. , **Switzerland:** U. Genève , **United Kingdom:** Univ. of Manchester, Physics Dept. , Jodrell Bank , Univ. of Cardiff, Physics and Astronomy Dept. , Univ. of Oxford, Physics and Astronomy Dept. , Univ. of Cambridge, Physics and Astronomy Dept. , Imperial College, London , Univ. of Edinburgh. , **United States:** Caltech , NASA Goddard Space Flight Center (GSFC) , NASA Jet Propulsion Laboratory (JPL) , Univ. of Wisconsin, Madison, Dept. of Physics .

History of *COrE*

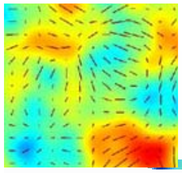
- B-Pol was proposed to ESA for M1 & M2 (2007) targeting squarely only B-modes to improve TRL (Technology Readiness Level) & minimize costs
- The high scientific interest of the mission was recognized, but we were recommended to further develop the detection system.
- Positive Evolution since then:
  - *Planck / HFI works as expected or better (reaching so far goals @ ~ twice requirements)*
  - *Improvements in detector technology (bolometer arrays & readout electronics) progressing as expected*
  - *Understanding of polarisation Systematic ahead of plans (Bicep, EBEX, beams)*
  - *Study in US for "EPIC-IM" (after EPIC-LC/CS)*

→ Increase target sensitivity and angular resolution w.r.t. B-Pol to allow most of CMB polarisation science in a moderate package, becoming *COrE*



5 Science targets for *COrE* (1/2)

1. The “*physics of beginning*”: study of **B-modes** in the linear polarization of the CMB, and of the **Gaussianity** of the CMB anisotropy. A comprehensive way to test the inflation scenario, limited only by cosmic variance.
2. The *mass of neutrino*: Perform a precision full sky CMB **lensing survey**, constraining the sum of neutrino masses to *0.05 eV* and thus mass hierarchies, and constraining the gravitation theory via the measurement of the equation of state of the dark energy and of the growth of structures.
3. Challenge the cosmology paradigm by estimating the *cosmological parameters* with unprecedented precision, using all **CMB anisotropy and polarization power spectra and cross spectra** limited only by cosmic variance up to very high multipoles. In particular, constrain the *reionization process* and *primordial magnetic fields* with unprecedented sensitivity and accuracy.

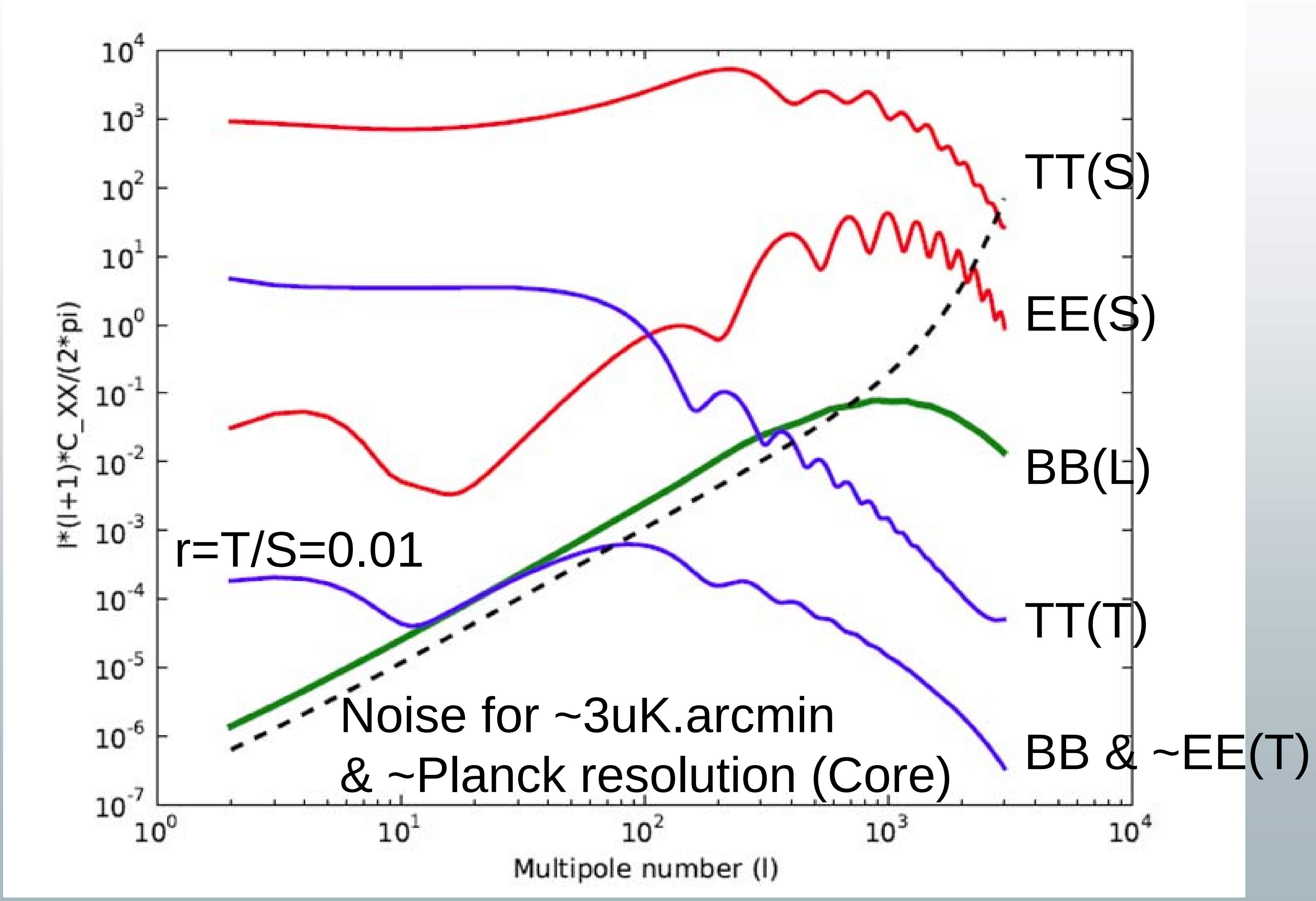


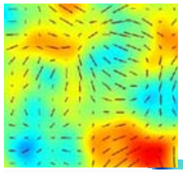
5 Science targets for *COrE* (2/2)

4. Performing a *tomography of our Galaxy* through the measurement of polarization of its mm-wave emission. This will test the initial conditions of star formation, unveiling *the role of magnetic fields in the interstellar medium* at small-medium angular scales.
5. Characterizing *Extragalactic Sources* providing a multi-wavelenght (mm and submm) catalog of *flux and polarization* for thousands of sources. This will allow to investigate the origin of magnetic fields on the sources, and their physical properties.

- ➢ All these targets require a full-sky survey with good angular resolution, exquisite stability, and control of systematic errors of both instrumental and astrophysical origin –
- ➢ (hence the need to go to space)

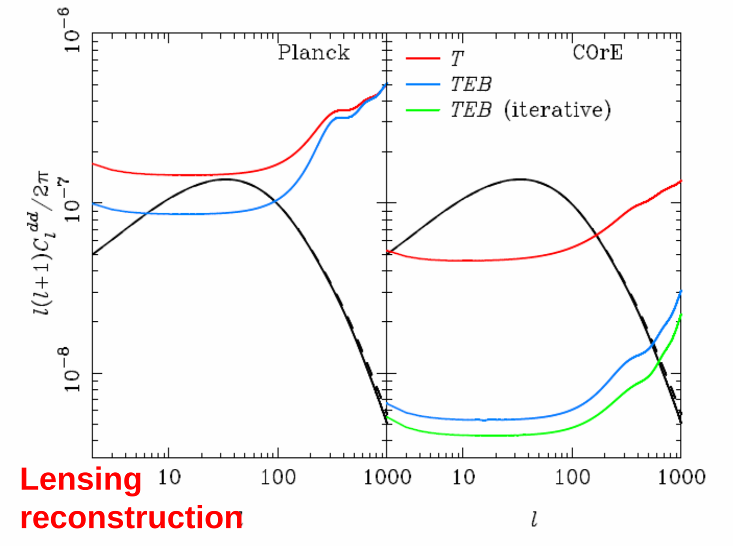
Requirements from science and possible implementation





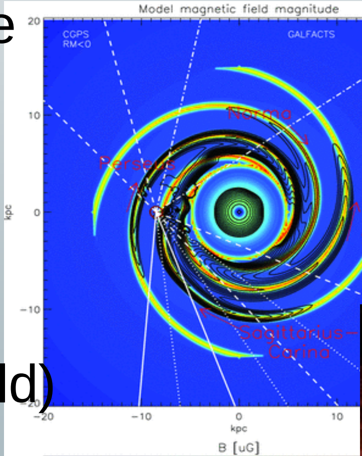
Requirements from science and possible implementation

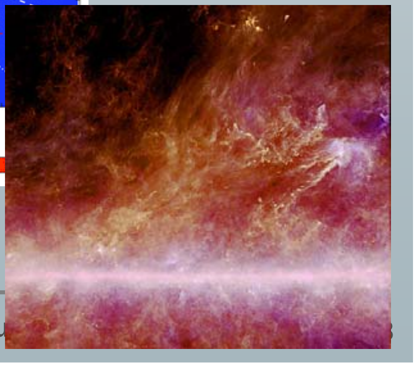
- The *3 μK arcmin* sensitivity must be achieved by means of a wide sky and frequency coverage.
- This level of sensitivity allows a measurement of the sum of neutrino masses at the 0.05 eV level, thus allowing to investigate their hierearchy.



Lensing reconstruction

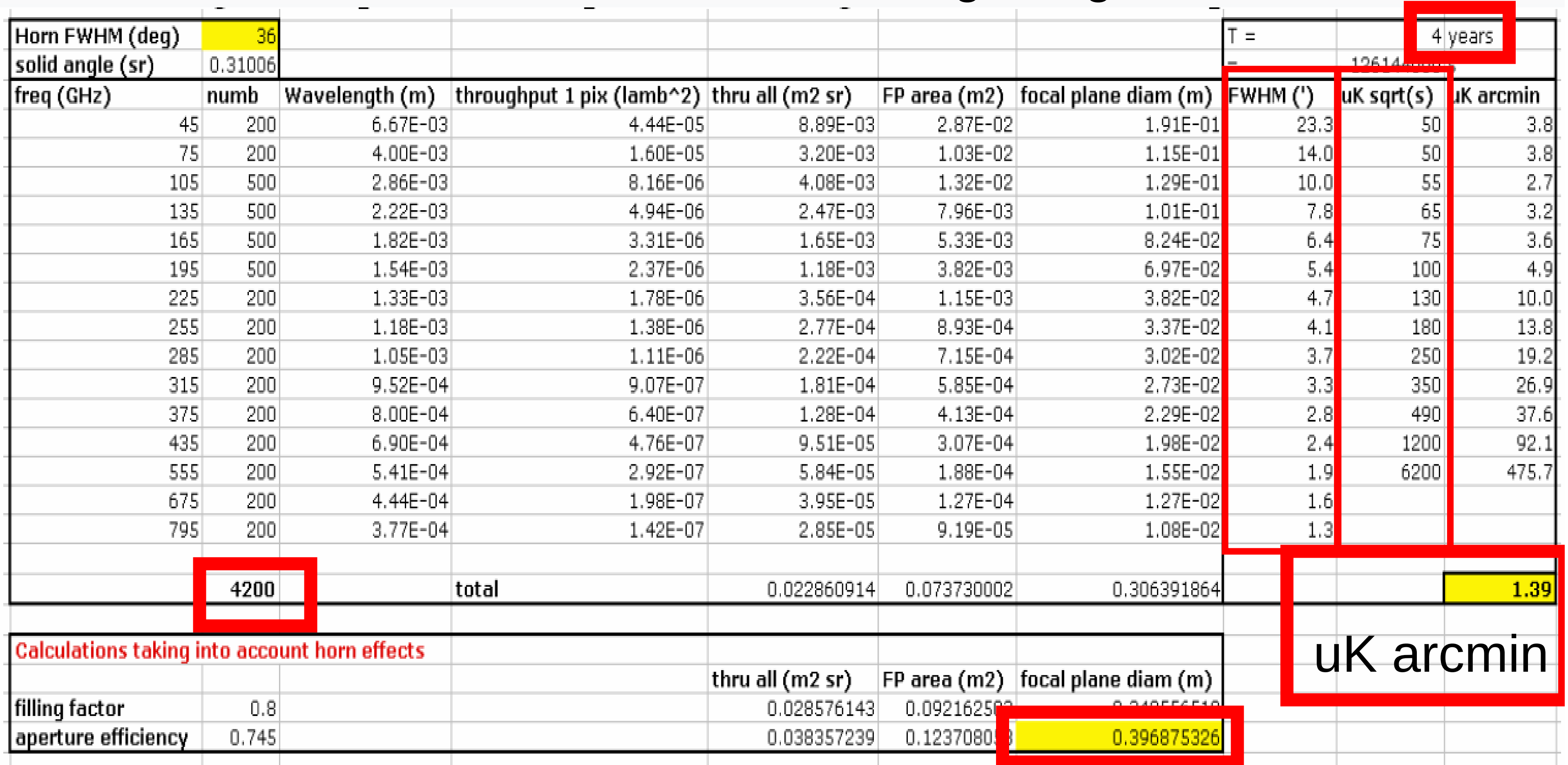
- Frequency coverage is essential because polarized foregrounds are overwhelming, and sufficient leverage is needed to separate them and extract a clean cosmological signal
- In addition, polarimetry of ISD (and the related study of the Galactic magnetic field) at high frequencies is one of the main targets of COrE.





Requirements from science and possible implementation

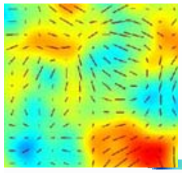
- To achieve about 3 uK arcmin and high angular resolution:



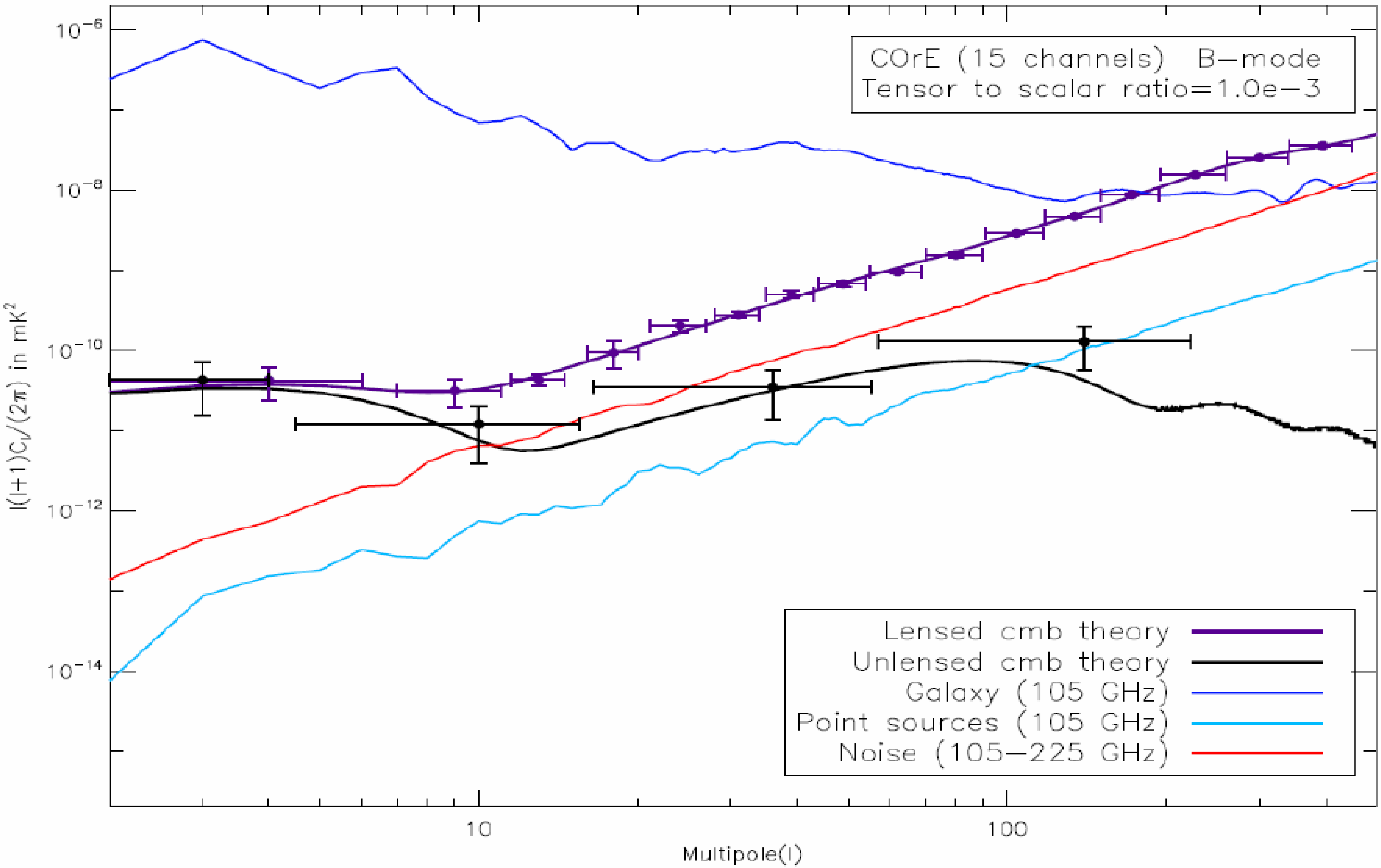
Horn FWHM (deg)	36						T =		4 years
solid angle (sr)	0.31006						=	12614[illegible] s	
freq (GHz)	numb	Wavelength (m)	throughput 1 pix (lamb^2)	thru all (m2 sr)	FP area (m2)	focal plane diam (m)	FWHM (')	uK sqrt(s)	uK arcmin
45	200	6.67E-03	4.44E-05	8.89E-03	2.87E-02	1.91E-01	23.3	50	3.8
75	200	4.00E-03	1.60E-05	3.20E-03	1.03E-02	1.15E-01	14.0	50	3.8
105	500	2.86E-03	8.16E-06	4.08E-03	1.32E-02	1.29E-01	10.0	55	2.7
135	500	2.22E-03	4.94E-06	2.47E-03	7.96E-03	1.01E-01	7.8	65	3.2
165	500	1.82E-03	3.31E-06	1.65E-03	5.33E-03	8.24E-02	6.4	75	3.6
195	500	1.54E-03	2.37E-06	1.18E-03	3.82E-03	6.97E-02	5.4	100	4.9
225	200	1.33E-03	1.78E-06	3.56E-04	1.15E-03	3.82E-02	4.7	130	10.0
255	200	1.18E-03	1.38E-06	2.77E-04	8.93E-04	3.37E-02	4.1	180	13.8
285	200	1.05E-03	1.11E-06	2.22E-04	7.15E-04	3.02E-02	3.7	250	19.2
315	200	9.52E-04	9.07E-07	1.81E-04	5.85E-04	2.73E-02	3.3	350	26.9
375	200	8.00E-04	6.40E-07	1.28E-04	4.13E-04	2.29E-02	2.8	490	37.6
435	200	6.90E-04	4.76E-07	9.51E-05	3.07E-04	1.98E-02	2.4	1200	92.1
555	200	5.41E-04	2.92E-07	5.84E-05	1.88E-04	1.55E-02	1.9	6200	475.7
675	200	4.44E-04	1.98E-07	3.95E-05	1.27E-04	1.27E-02	1.6		
795	200	3.77E-04	1.42E-07	2.85E-05	9.19E-05	1.08E-02	1.3		
	4200		total	0.022860914	0.073730002	0.306391864			1.39
Calculations taking into account horn effects									
				thru all (m2 sr)	FP area (m2)	focal plane diam (m)			
filling factor	0.8			0.028576143	0.0921625[illegible]	[illegible]			
aperture efficiency	0.745			0.038357239	0.12370805[illegible]	0.396875326			

uK arcmin

- To achieve polarimetric accuracy at the same level:
- introduce a polarization modulator.

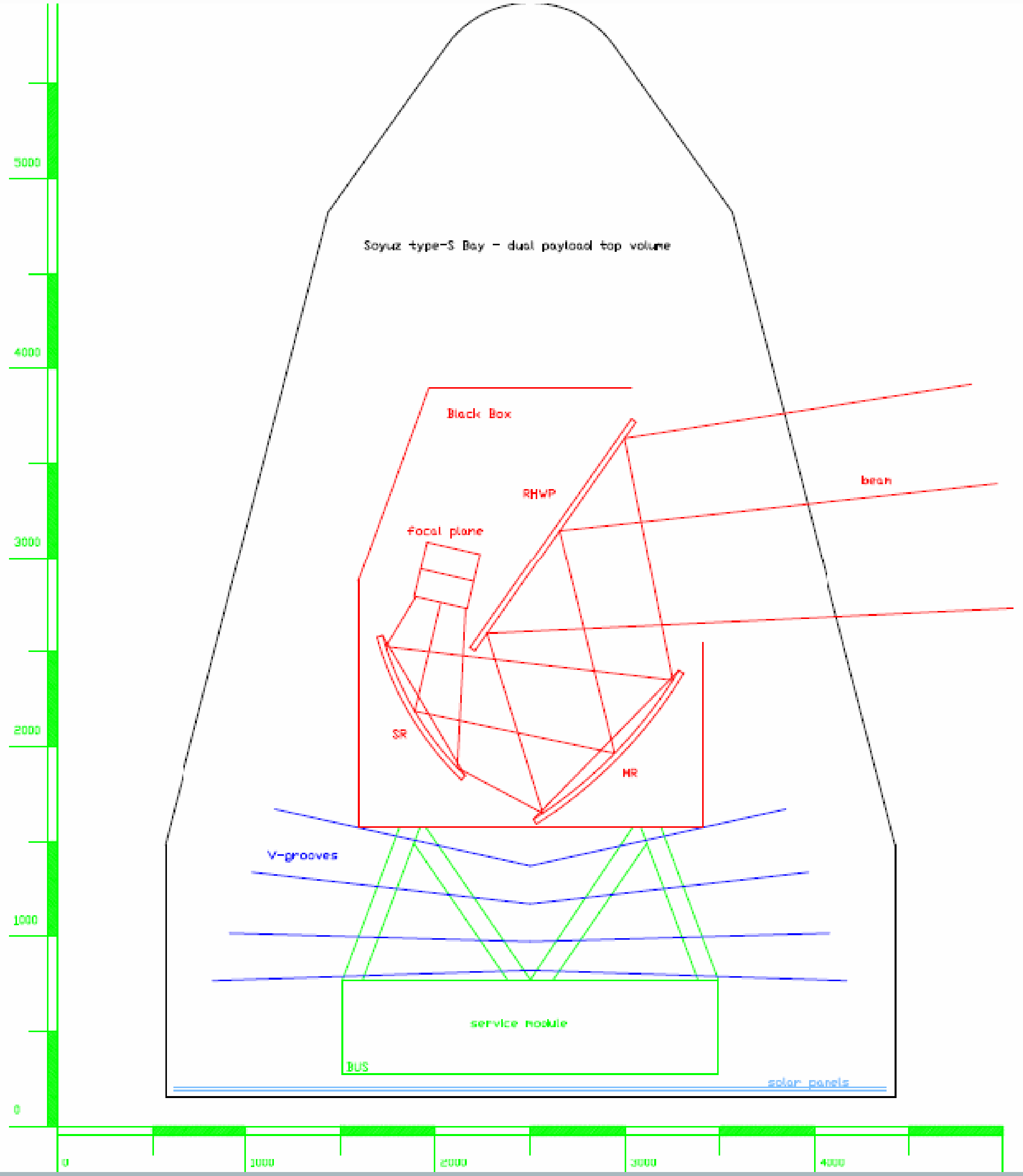


- Simulated performance of COrE
- with realistic foreground removal.



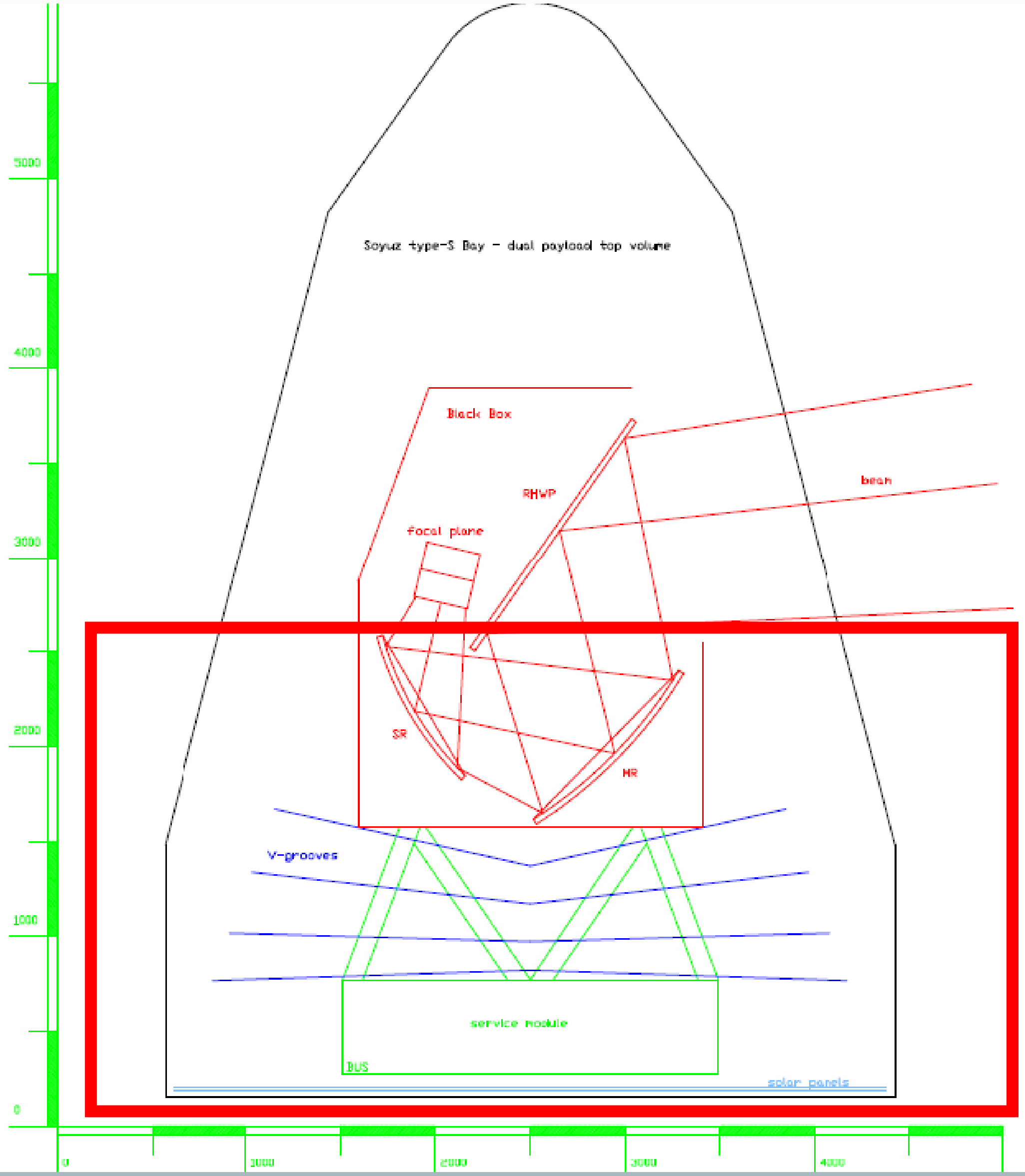
- To achieve polarimetric accuracy at the same level:
- introduce a cold polarization modulator.

Payload Concept



The COrE payload inside the Soyuz launcher bay (dual payload configuration, top volume), with the the main subsystems of the instrument labeled. The dimensions are in mm.

Payload Concept

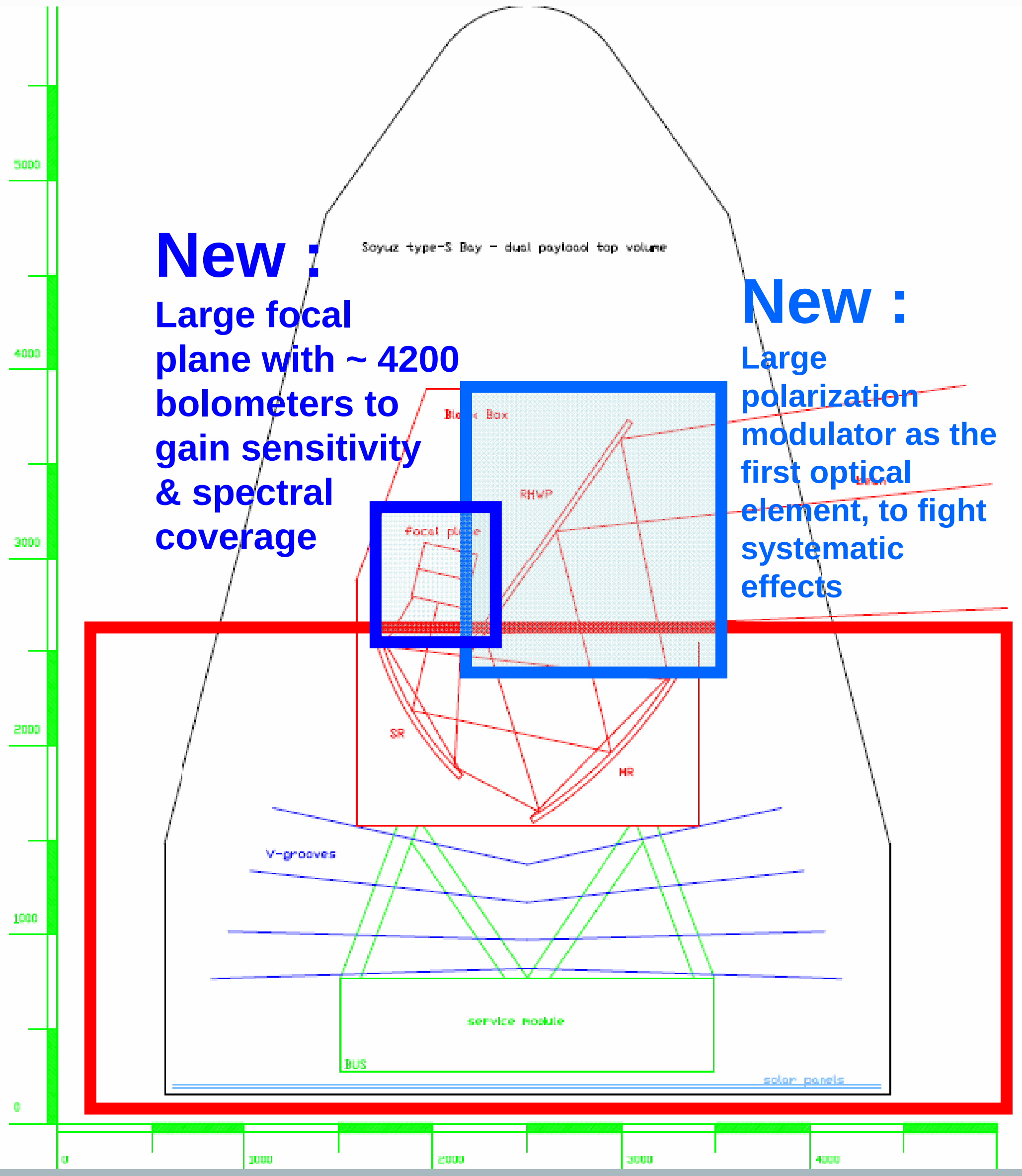


The COrE payload inside the Soyuz launcher bay (dual payload configuration, top volume), with the the main subsystems of the instrument labeled. The dimensions are in mm.

~ Planck

re-use successful Solutions: V-grooves, cryosystem, off-axis 2m-class Dragone telescope

Payload Concept



New :

Large focal plane with ~ 4200 bolometers to gain sensitivity & spectral coverage

New :

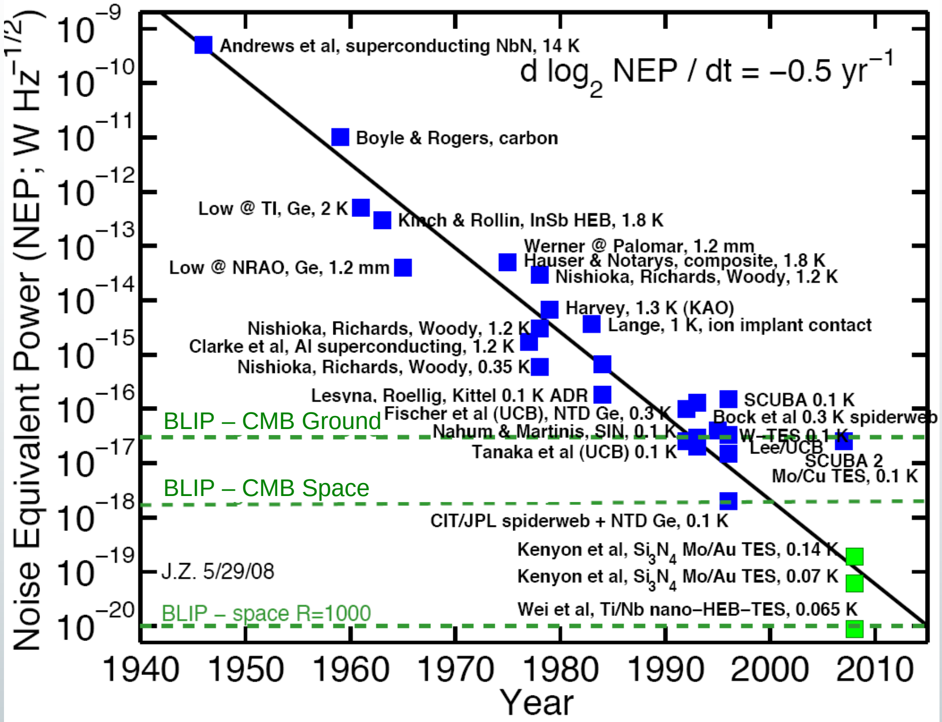
Large polarization modulator as the first optical element, to fight systematic effects

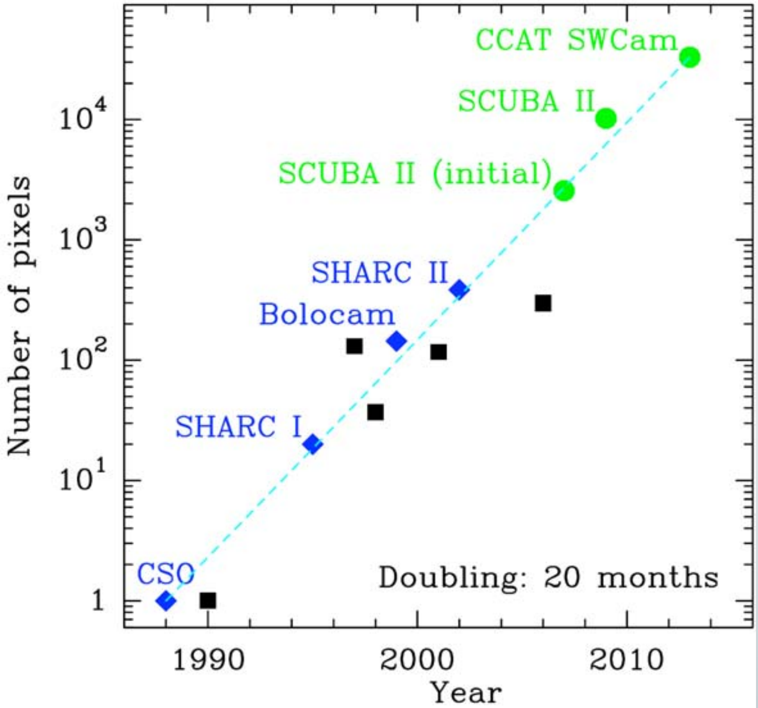
~ Planck

re-use successful solutions: V-grooves, 0.1K cryosystem, off-axis 2m-class telescope

The COrE payload inside the Soyuz launcher bay (dual payload configuration, top volume), with the the main subsystems of the instrument labeled. The dimensions are in mm.

Exponential Progress in Detector Development

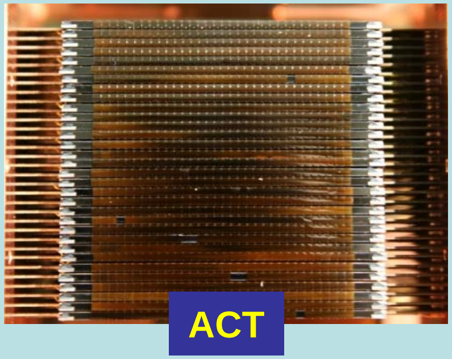




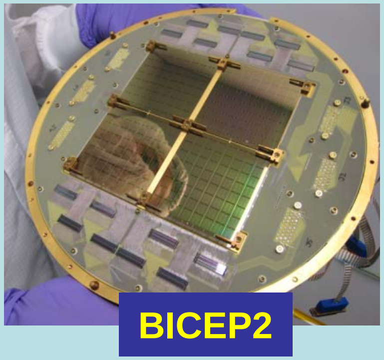
EPIC slide

Rapid progress in **arrays** (development synergy with far-IR and X-ray astronomy)

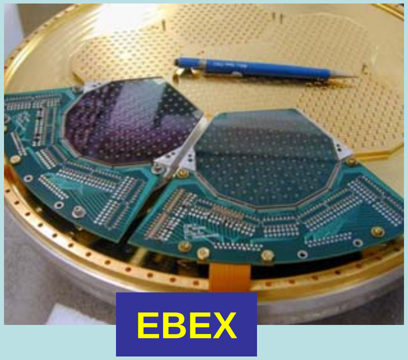
Technology & Sub-Orbital Program



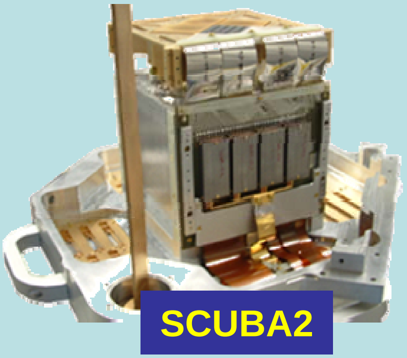
ACT



BICEP2

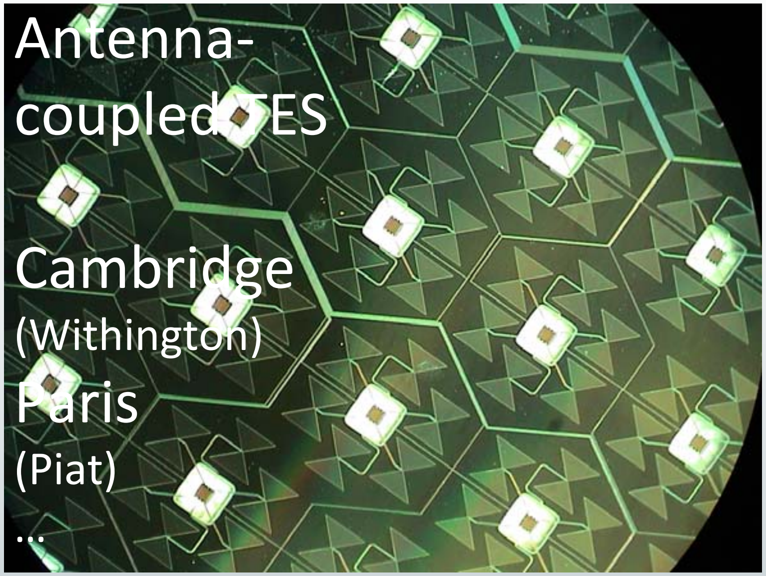


EBEX



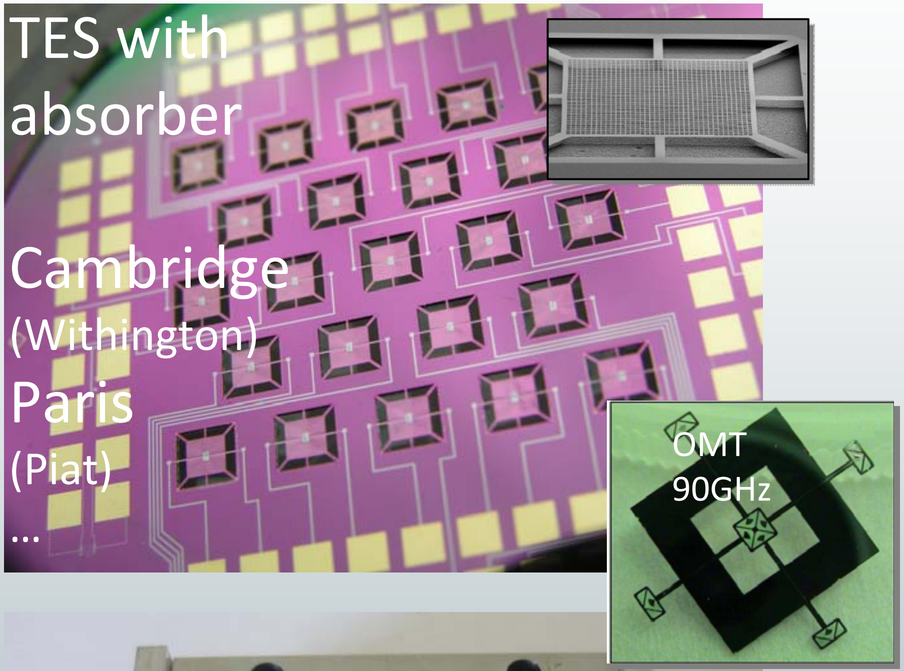
SCUBA2

Ongoing R&D also in Europe



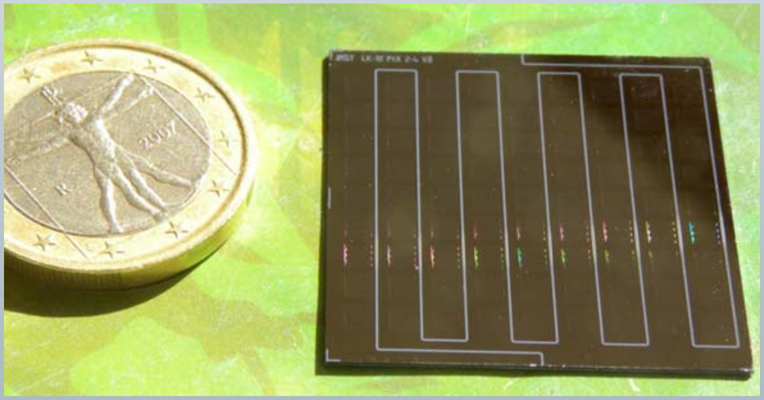
Antenna-coupled TES

Cambridge
(Withington)
Paris
(Piat)
…



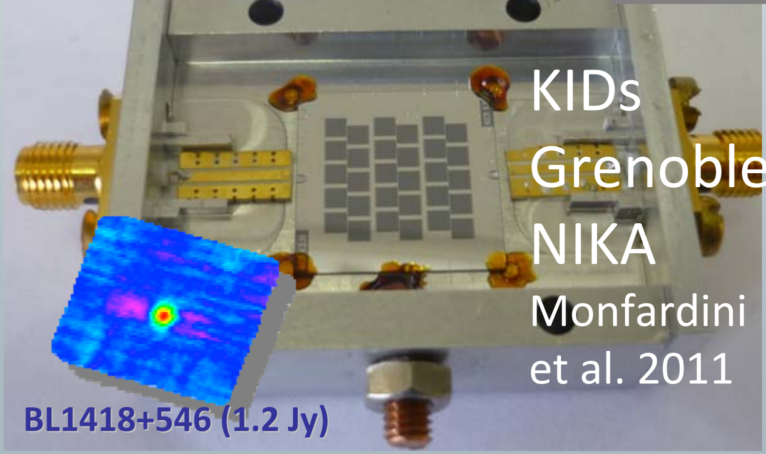
TES with absorber

Cambridge
(Withington)
Paris
(Piat)
…



KIDs : Roma1-TN-FBK

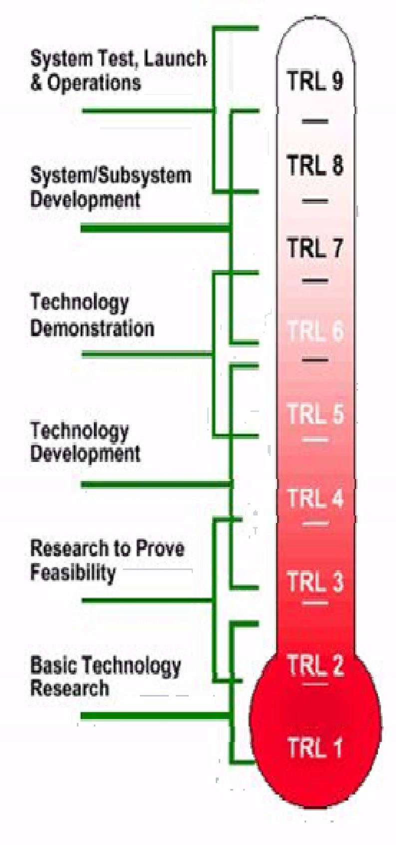
Calvo et al. 2010



KIDs
Grenoble
NIKA
Monfardini
et al. 2011

Detection Chain - TRL Evolution

Sub-system	2010	2014	Experiments
Supercondcting bolometer arrays + multiplixed RE electronics using SQUIDs	5	6	SPT, APEX, GISMO…
Antennas	4	6	Polar Bear, SPIDER
Quasi-optical filters	9	9	Planck
Planar Filters	4	6	Polar Bear
Horns	9	9	Planck
Quasi-optical Phase Modulator	4	6	EBEX



COrE Pointing strategy

- Same scan strategy as Planck …
  - *Simple, reliable, demonstrated in L2*
  - *Cheap: spinner spacecraft, with small spin axis correction every hour.*

- … complemented by a polarization modulator
  - *First element in optical chain*
  - *Relaxed requirements on the cross-polarization quality of all the optical components*
  - *Cheaper optical components*
  - *Better packing of detectors in focal plane, increased sensitivity*

Pointing strategy to mitigate systematic effects (EPIC)

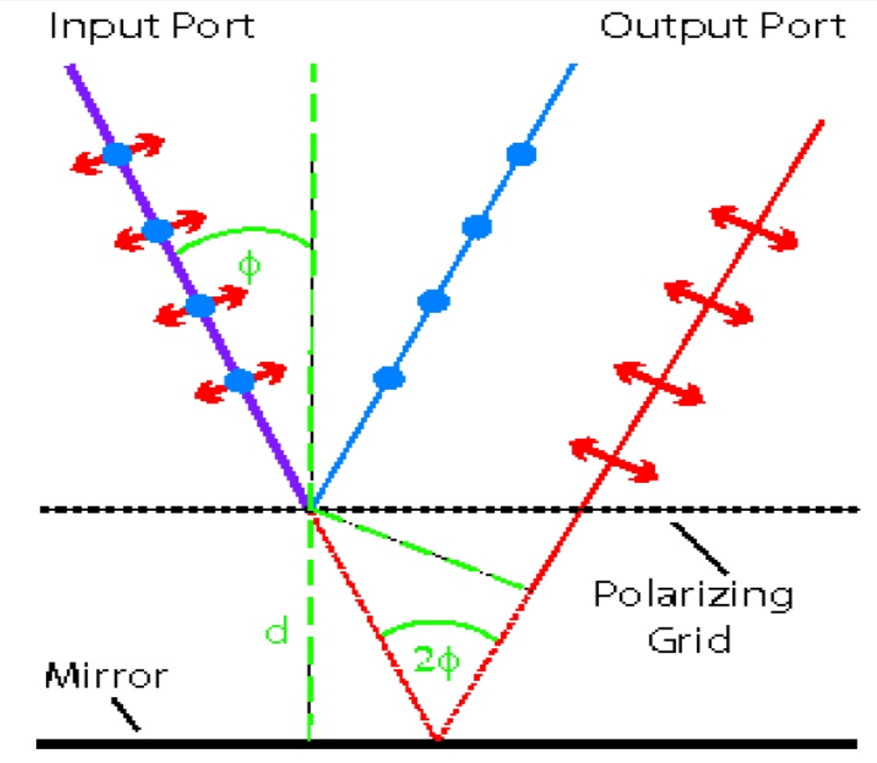
Without a polarization modulator,
it is extremely difficult
to separate
beam-induced errors
from
polarimetry-induced errors.

Very stringent requirements
on beam shape knowledge

COrE wide band polarization modulator

- Reflective HWP.
- See Siringo et al. 2004 for a description
- Works as a HWP at all frequencies
- For a given incidence, one can adjust *d*

$$\nu_n = \frac{2n+1}{4\cos\varphi}\frac{c}{d}$$

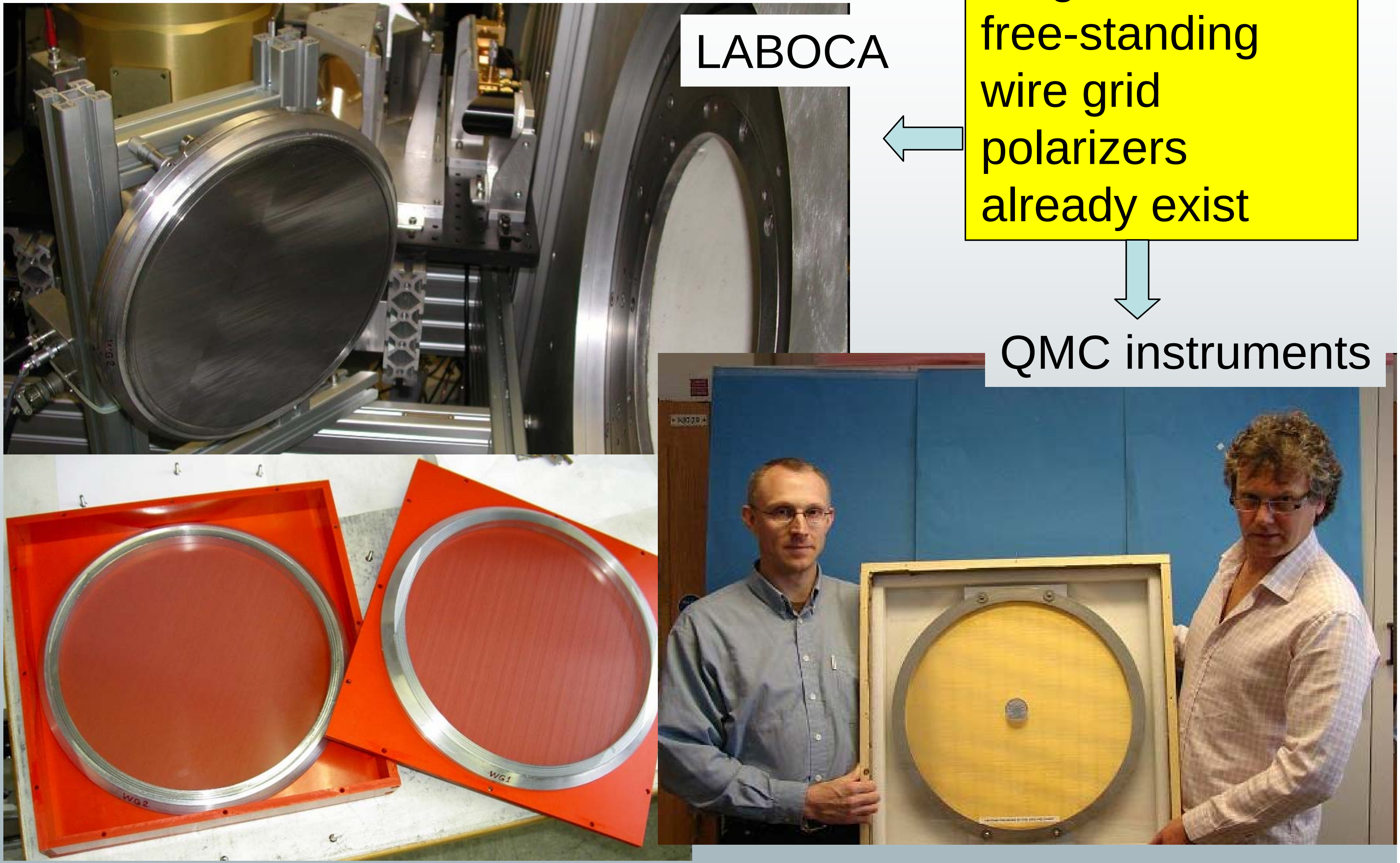


n	$\nu_n(GHz)$
1	60
2	100
3	140
4	180
5	220
6	260
7	300
8	340

n	$\nu_n(GHz)$
1	45
2	75
3	105
4	135
5	165
6	195
7	225
8	255
9	285
10	315
12	375
14	435
18	555
22	675
26	795

- Usable bandwidth = ν_o

RHWP



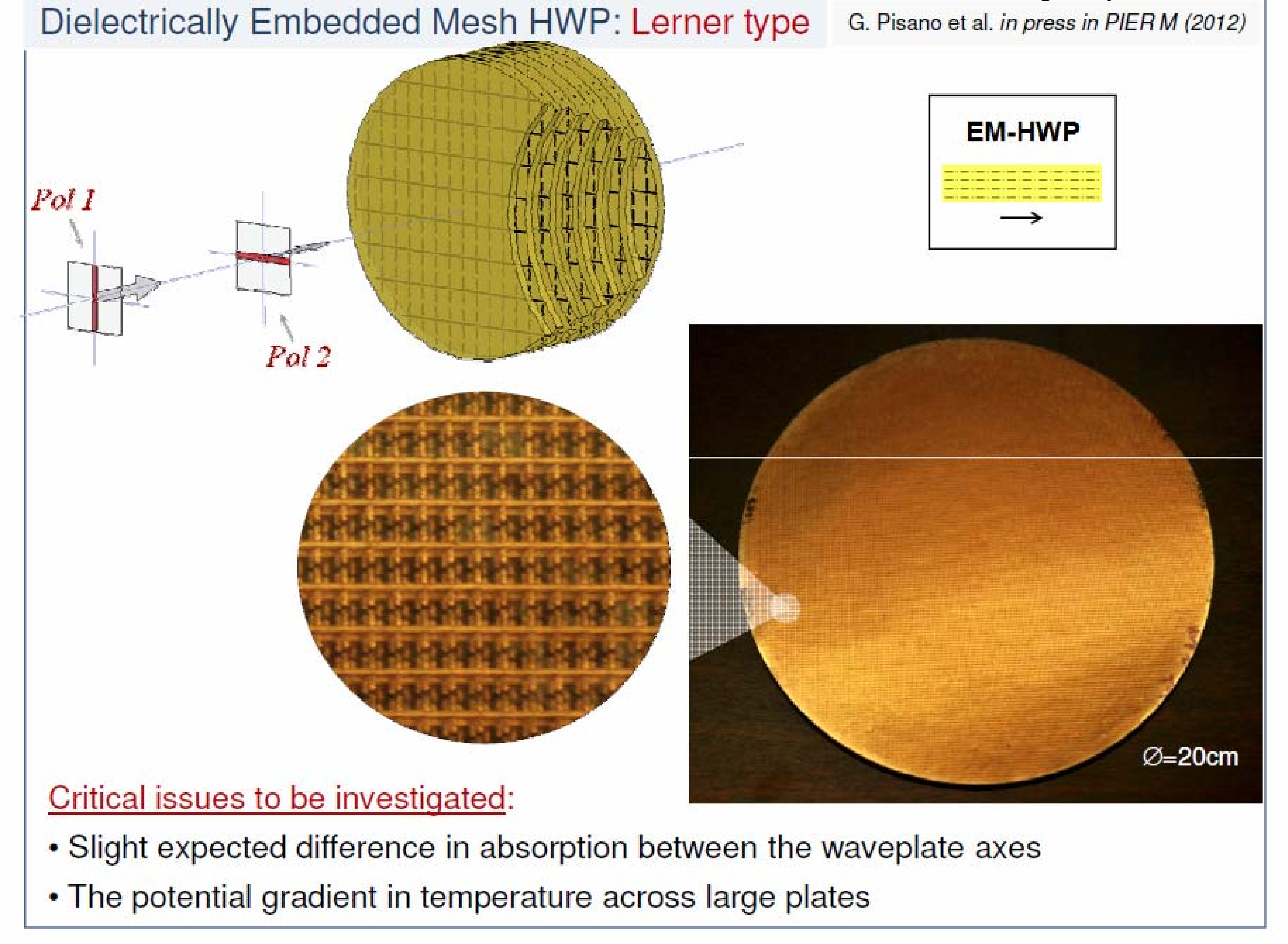
LABOCA

Large free-standing wire grid polarizers already exist

QMC instruments

Progress in dielectric-embedded mesh THWP

Manchester group: Pisano, Maffei



Dielectrically Embedded Mesh HWP: Lerner type

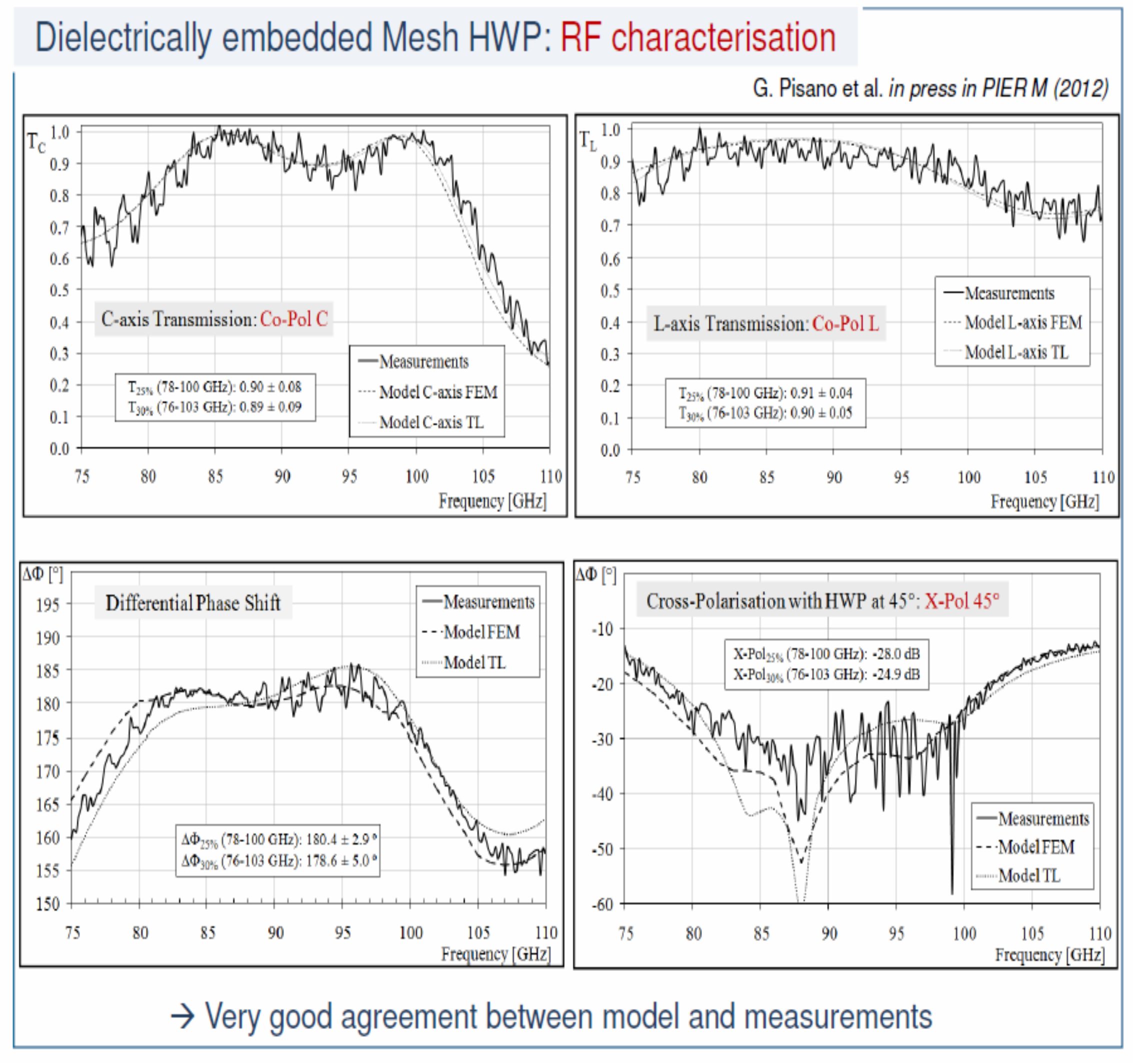
G. Pisano et al. *in press in PIER M (2012)*

Critical issues to be investigated:

- Slight expected difference in absorption between the waveplate axes
- The potential gradient in temperature across large plates

Progress in dielectric-embedded mesh THWP

- This technology has excellent performance
- Can be modeled accurately
- Can be modified to produce RHWP
- See also astro-ph/1206.2284 for a translational polarization modulator



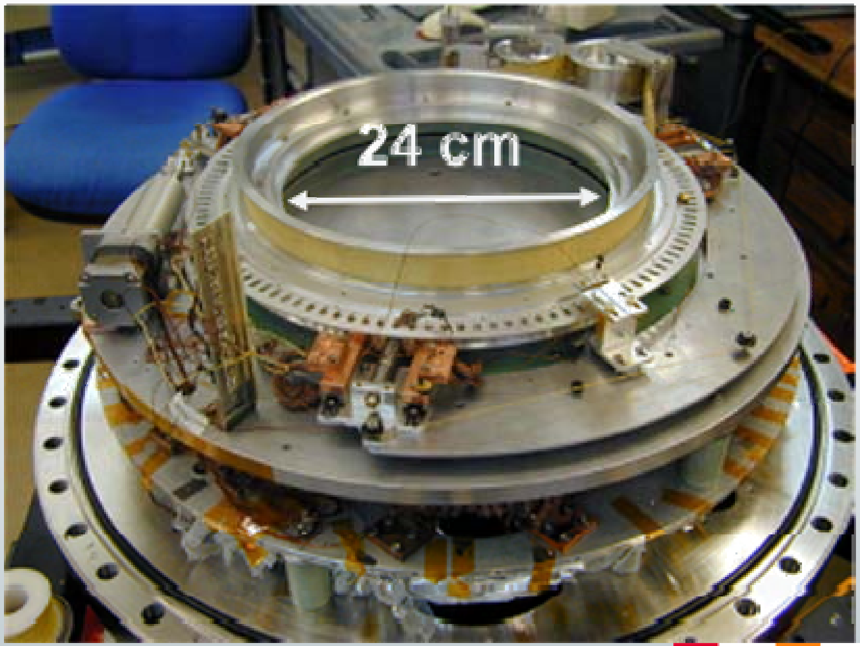
Dielectrically embedded Mesh HWP: RF characterisation

G. Pisano et al. *in press in PIER M (2012)*

→ Very good agreement between model and measurements

RHWP bearing

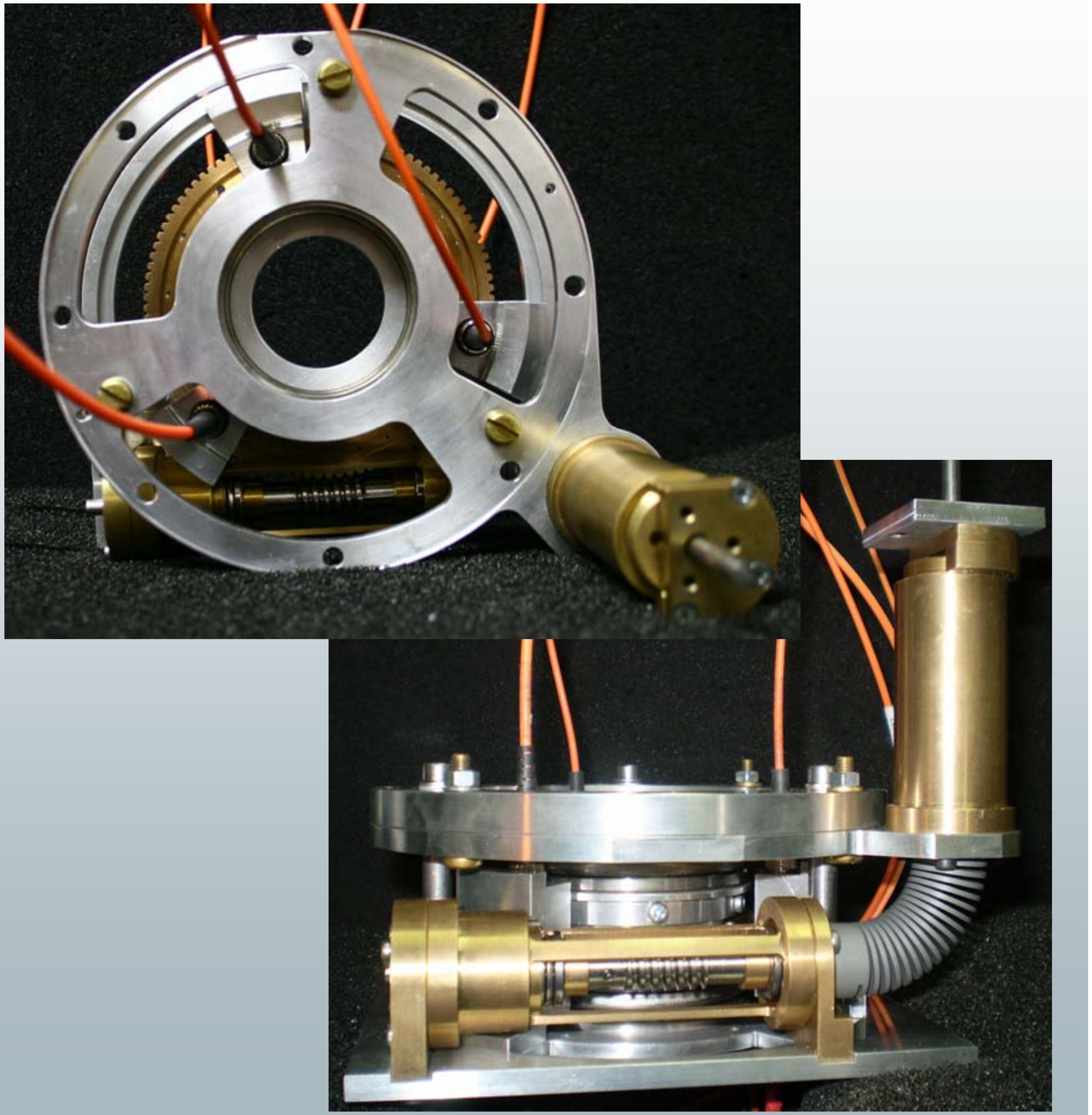
- One option is to use superconducting magnetic sustentation for continuously rotating modulation (reflecting) plate
- Negligible vibrations
- Balloon Experience with EBEX
  - *Technical flight: June 2009, rotation OK !*
  - *Antarctic flight: 2012*



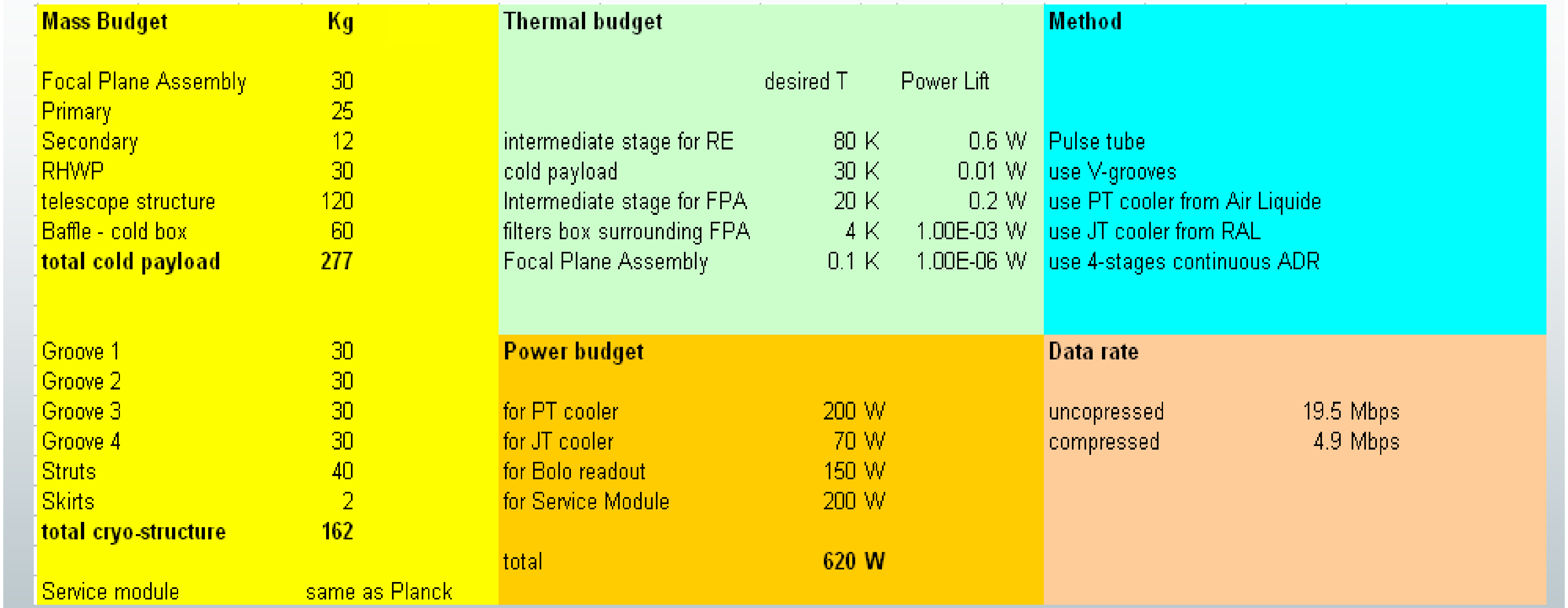
Continuous, magnetic bearing EBEX

Rotating plate bearing

- A simpler option is to use normal thrust bearings with belleville washers to compensate for thermal contractions.
- Proven bearing and readout technology (Salatino et al. 2010), part of ASI technology program, used @2K in the PILOT balloon experiment.



Budgets



Mass Budget	**Kg**
Focal Plane Assembly	30
Primary	25
Secondary	12
RHWP	30
telescope structure	120
Baffle - cold box	60
total cold payload	**277**
Groove 1	30
Groove 2	30
Groove 3	30
Groove 4	30
Struts	40
Skirts	2
total cryo-structure	**162**
Service module	same as Planck

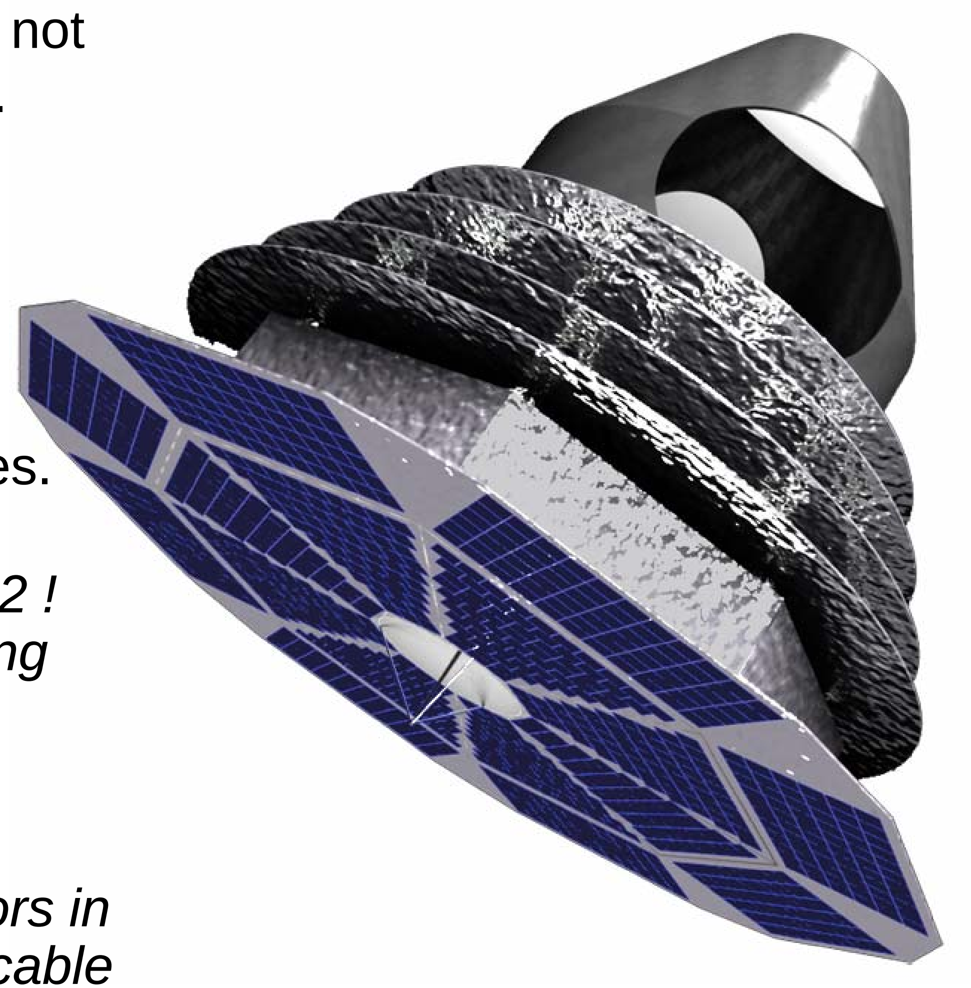
Thermal budget	desired T	Power Lift	**Method**
intermediate stage for RE	80 K	0.6 W	Pulse tube
cold payload	30 K	0.01 W	use V-grooves
Intermediate stage for FPA	20 K	0.2 W	use PT cooler from Air Liquide
filters box surrounding FPA	4 K	1.00E-03 W	use JT cooler from RAL
Focal Plane Assembly	0.1 K	1.00E-06 W	use 4-stages continuous ADR

Power budget	
for PT cooler	200 W
for JT cooler	70 W
for Bolo readout	150 W
for Service Module	200 W
total	**620 W**

Data rate	
uncopressed	19.5 Mbps
compressed	4.9 Mbps

- ➢Very similar to Planck
- ➢Thermally simpler than Planck, since we do not have any significant heat load on the 20K stage
- ➢Data rate higher than Planck, but new phased array technology ready to be used.

Conclusions



- After being shortlisted, COrE was not selected for the M3 study in 2010.
- The scientific importance was recognized, and a technology development program has been supported (by ESA and national agencies)
- Meanwhile, many other progresses. in particular
  - *Planck HFI operating well in L2 ! Telescope, detector and cooling chains validated*
  - *control of systematic effects (Bicep, BicepII, EBEX, ..);*
  - *work on SPICA/BLISS detectors in Europe, a lot of which is applicable to CMB polarisation measurement*
- We look forward to the next occasion (in a 1-2 years timescale) to submit an updated proposal.