The Next Generation CMB Space Mission

COrE
Cosmic Origins Explorer

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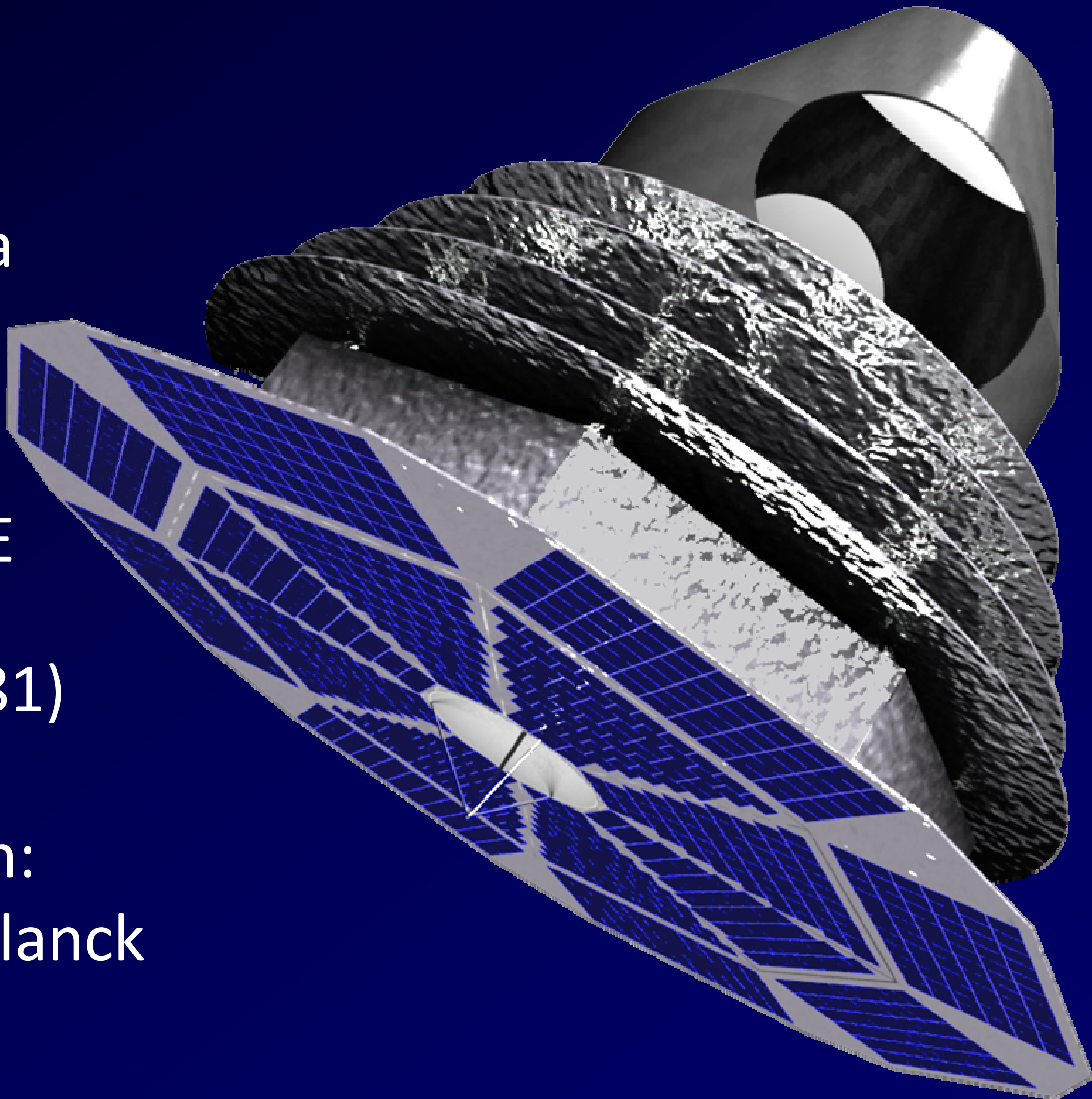
“La Sapienza”

On behalf of the COrE collaboration
(see astro-ph/1102.2181)



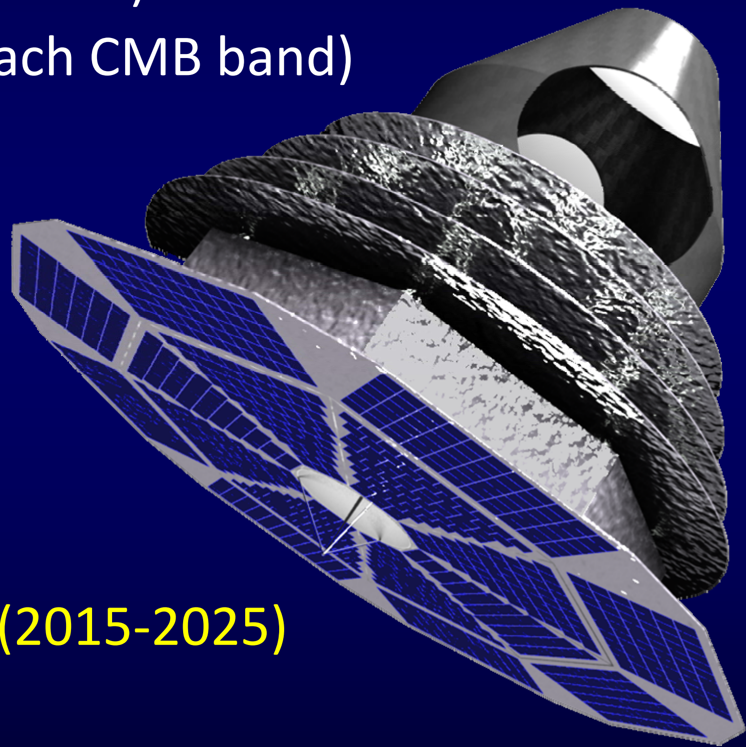
47th ESLAB Symposium:
The Universe as seen by Planck
ESTEC, 05/04/2013

The COrE collaboration

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 Astrofísica 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 .

COrE
Cosmic Origins Explorer

- A space mission to measure the **polarization** of the mm/sub-mm sky , with
  - High purity (instrumental polarization < 0.1% of polarized signal)
  - Wide spectral coverage (15 bands centered at 45-795 GHz)
  - Unprecedented angular resolution (23' – 1.3' fwhm)
  - Unprecedented sensitivity (< 5 μK arcmin in each CMB band)
- Science Targets of the mission:
  - Inflation (CMB B-modes)
  - Neutrino masses (CMB, E-modes + lensing)
  - CMB non-Gaussianity
  - Origin of magnetic fields (Faraday rotation …)
  - Origin of stars (ISM polarimetry …) ……. …
- Proposal submitted to ESA Cosmic Vision (2015-2025)
- White paper : astro-ph/1102.2181
- Web page: www.core-mission.org



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B-modes
($r > 0.001$)

Polarized
foregrounds

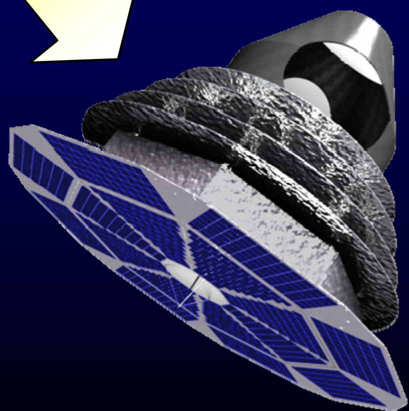
ISM

νs +
N.G.

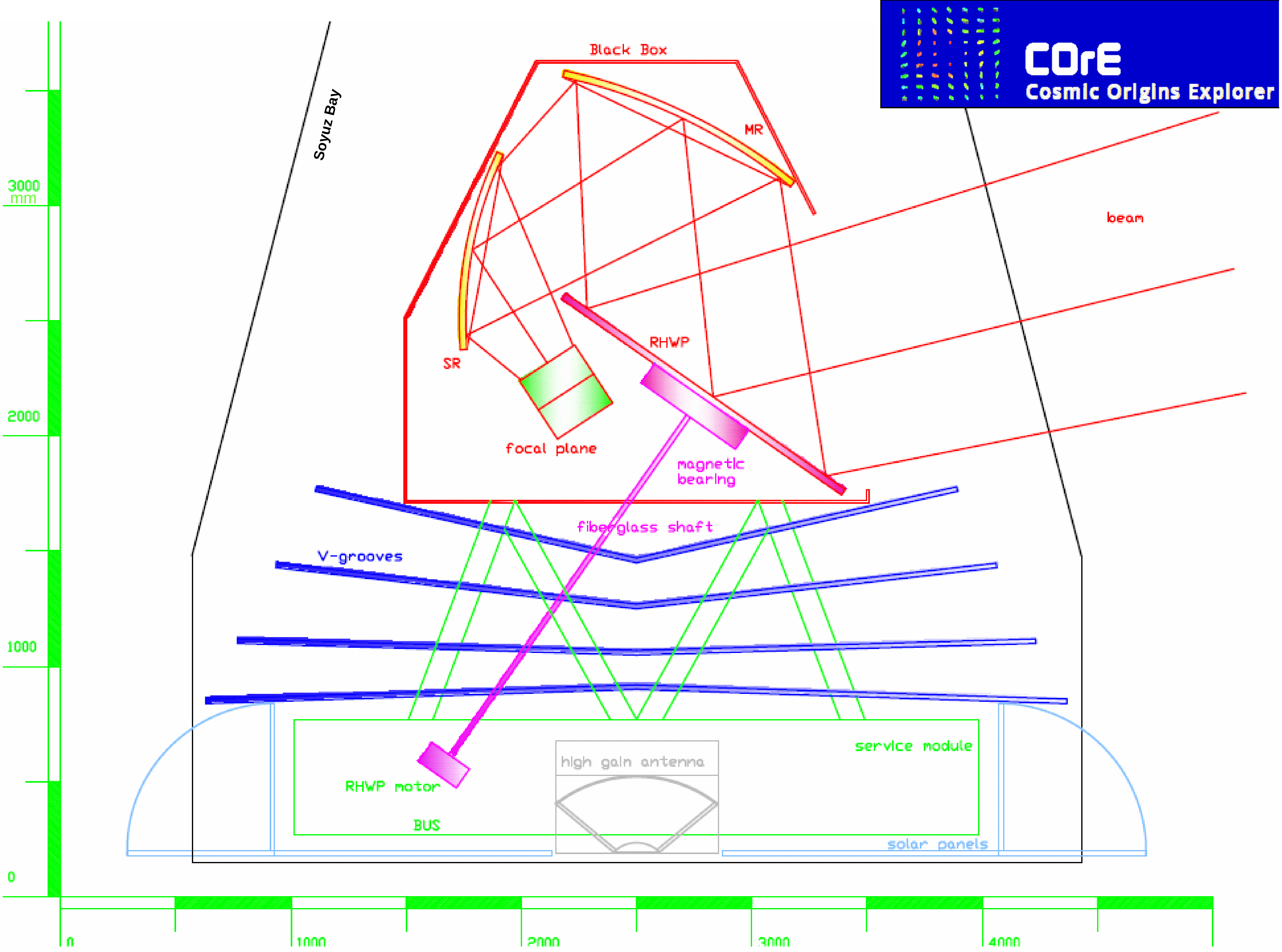
2) Sensitivity !
Large Array

3) Wide
Frequency
Coverage !
Many bands

1) Polarimetric
purity !
Polarization
Modulator first;
Single-mode
beams



4) High
angular
Resolution !
Large telescope +
high frequency



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

1)

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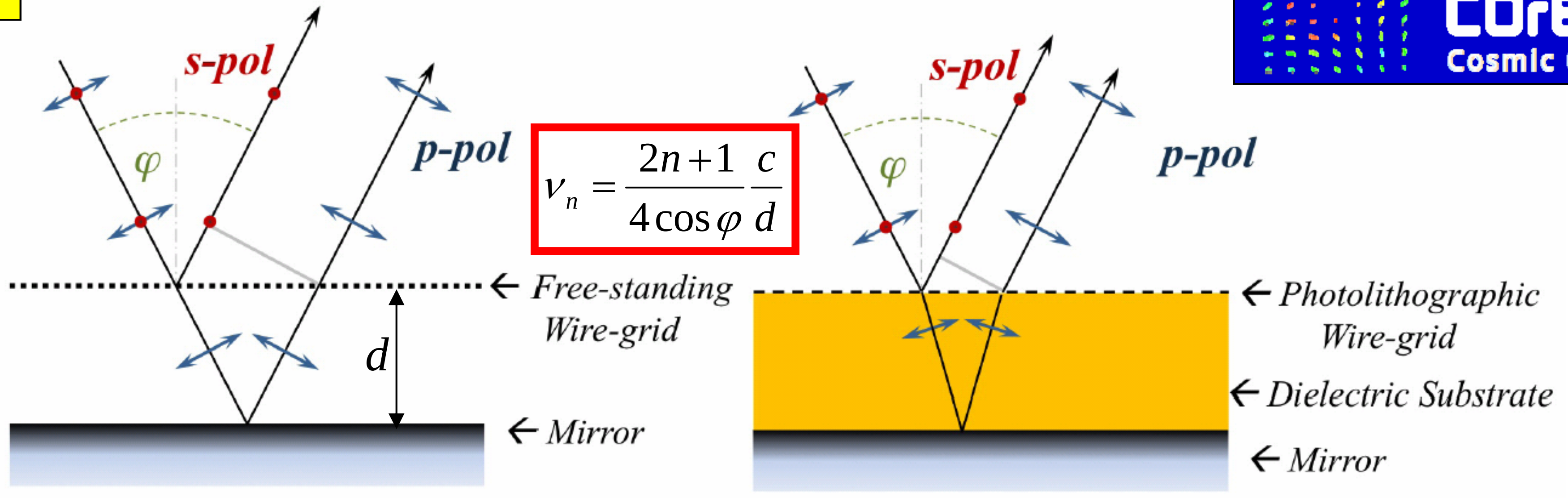

Figure 27: Left: Free-standing RHWP. Right: Dielectric substrate RHWP

- Rotating Reflecting-Half-Wave-Plate (RWHP)
  - \+ Modulator = first optical element – polarization purity of following elements not critical
  - \+ Must be rotated for modulation – simple mechanical system
  - \+ Many bands (many orders) – wide frequency coverage
  - \+ Can be made large diameter (embedded wire-grid technology)
  - \+ Can be deposited on a support structure – good flatness

1)

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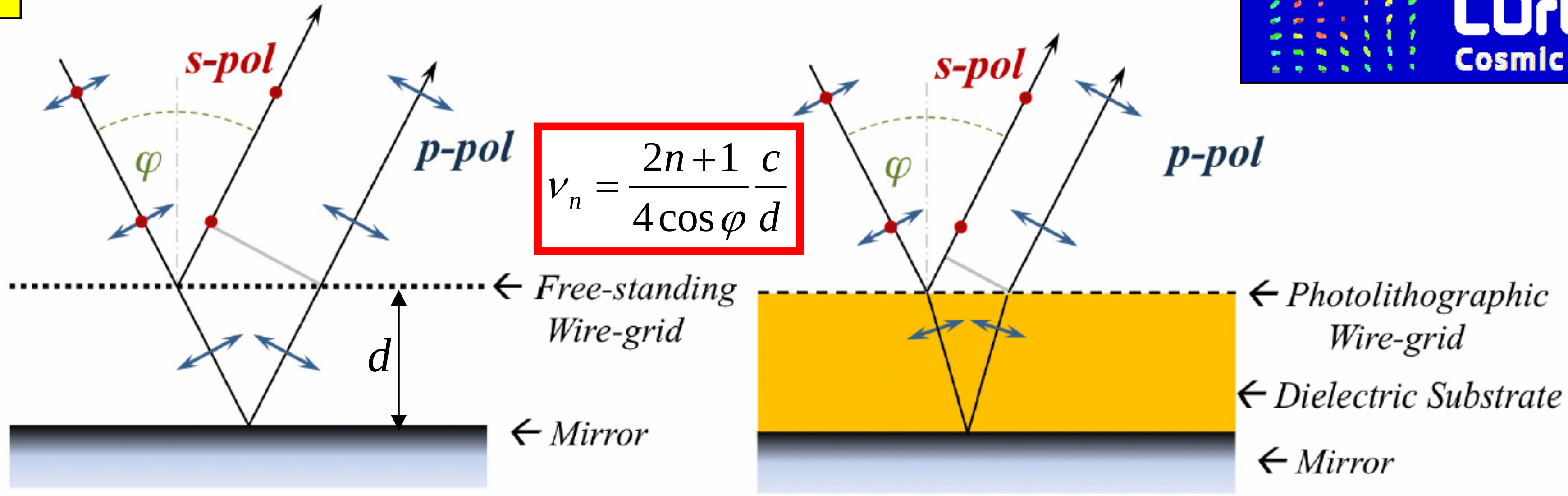

Figure 27: Left: Free-standing RHWP. Right: Dielectric substrate RHWP

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  - \+ Many bands (many orders) – wide frequency coverage
  - \+ Can be made large diameter (embedded wire-grid technology)
  - \+ Can be deposited on a support structure – good flatness
  - \- Narrow bands at high orders (high frequencies: $\Delta\nu_n = \Delta\nu_o$)
  - \- Equalization of s-pol and p-pol efficiency not trivial (0.1% ?)

1)

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

ν GHz	$(\Delta\nu)$ GHz	n_{det}	θ_{fwhm} arcmin	Temp (I) $\mu K\cdot$arcmin RJ	Temp (I) $\mu K\cdot$arcmin CMB	Pol (Q,U) $\mu K\cdot$arcmin RJ	Pol (Q,U) $\mu K\cdot$arcmin CMB
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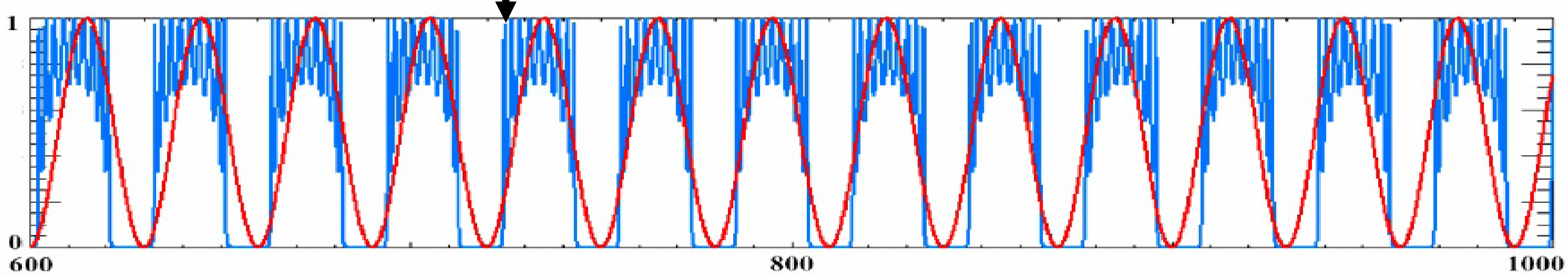
105	15	400	10.0	2.03	2.68	3.50	4.63
135	15	550	7.8	1.68	2.63	2.90	4.55
165	15	750	6.4	1.38	2.67	2.38	4.61
195	15	1150	5.4	1.07	2.63	1.84	4.54
225	15	1800	4.7	0.82	2.64	1.42	4.57
255	15	575	4.1	1.40	6.08	2.43	10.5
285	15	375	3.7	1.70	10.1	2.94	17.4
315	15	100	3.3	3.25	26.9	5.62	46.6
375	15	64	2.8	4.05	68.6	7.01	119
435	15	64	2.4	4.12	149	7.12	258
555	195	64	1.9	1.23	227	3.39	626
675	195	64	1.6	1.28	1320	3.52	3640
795	195	64	1.3	1.31	8070	3.60	22200

COrE summary (4 year mission)



1)

RHWP feasibility

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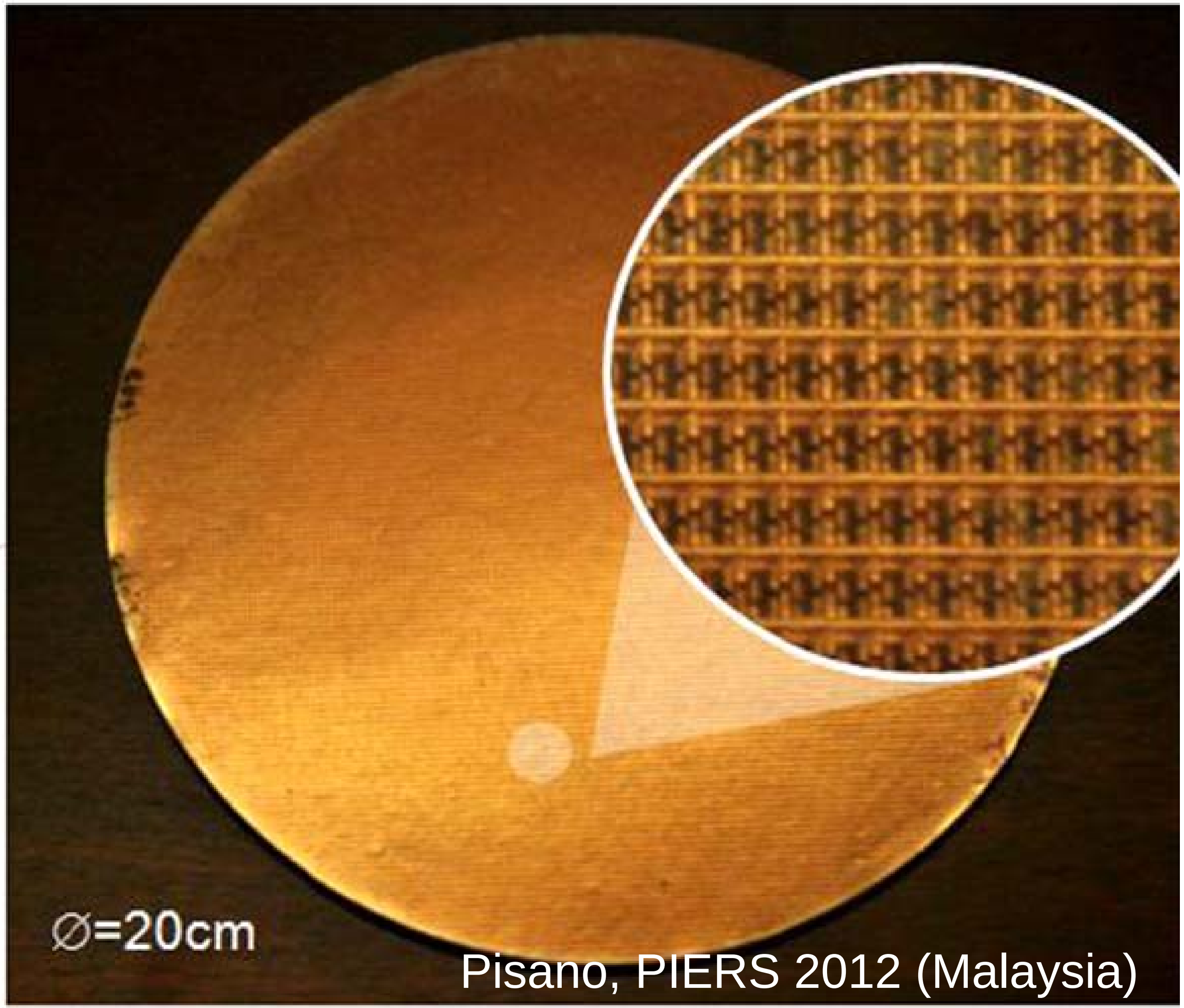
- Embedded-mesh design flexible and effective
- Small (20 cm) prototypes already exist and perform
- ESA ITT issued for larger prototypes, target 1.5 m (Manchester)



1)

Rotator & flatness

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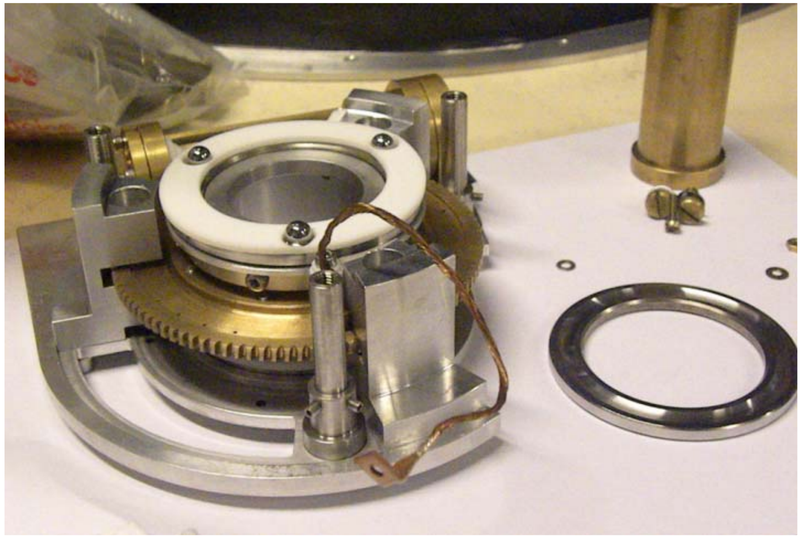
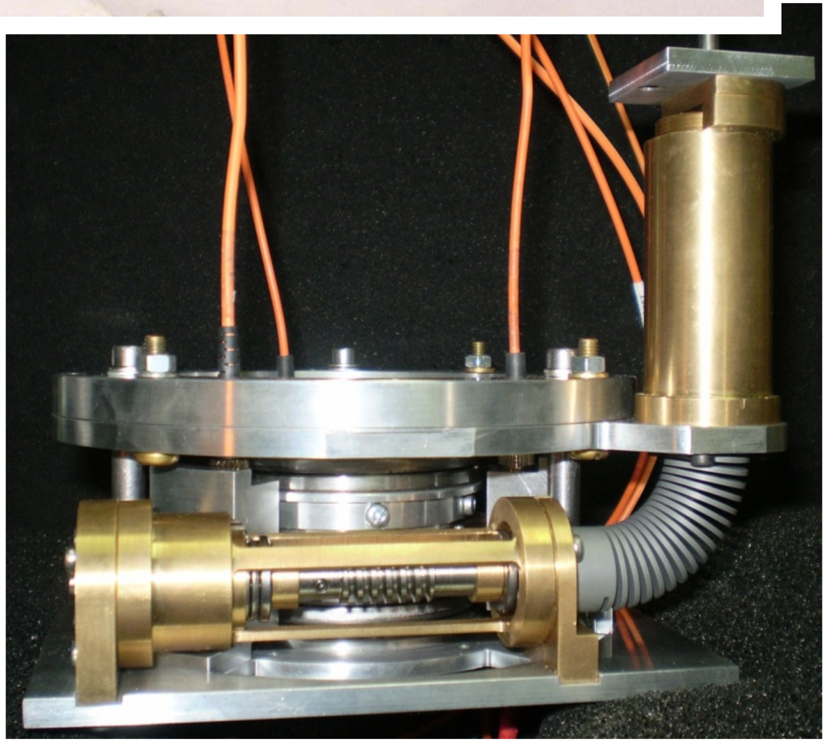
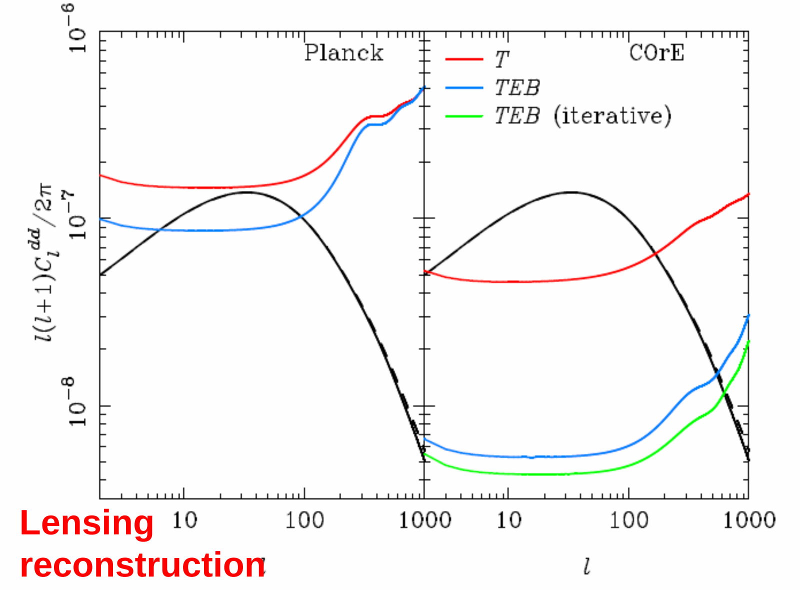
- Multilayer:
  - CFRP honeycomb plate
  - Al/Au skin
  - RHWP
- Very light, very flat, low inertia
- Step and integrate
- Motor @ room temperature
- Long insulating shaft
- Low-T thermal contact via copper braids (see e.g. Salatino et al. A&A 528 A138, 2011)





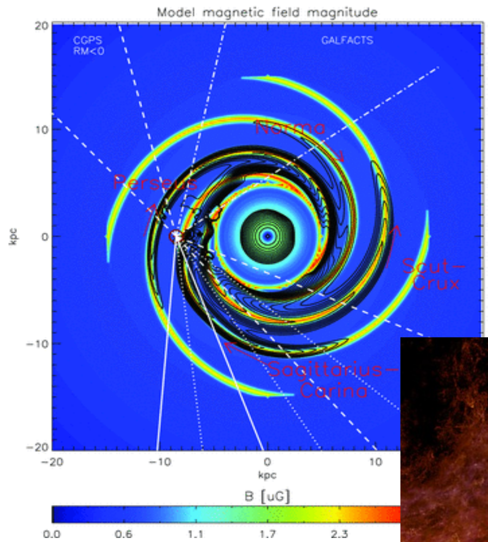
2) Requirements from science and possible implementation

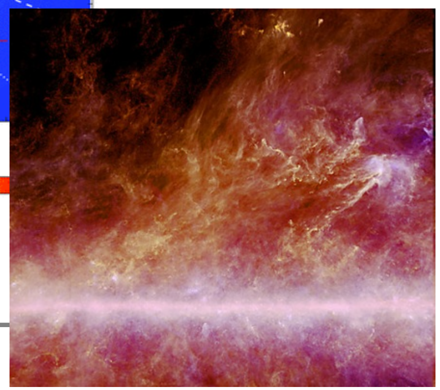
- The *5 μK arcmin* sensitivity must be achieved by means of a wide sky and frequency coverage.
- This level of sensitivity allows a measurement of the sum of neutrino masses at the 0.05 eV level, thus allowing to investigate their hierearchy.



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.





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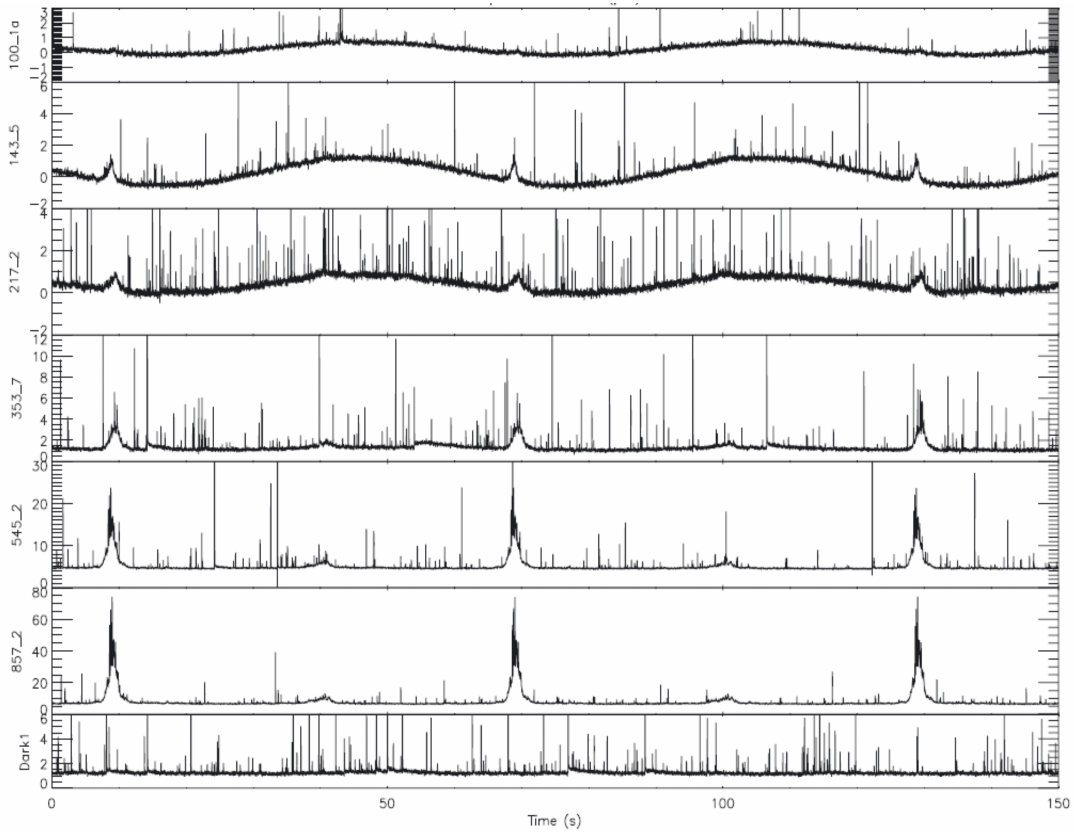
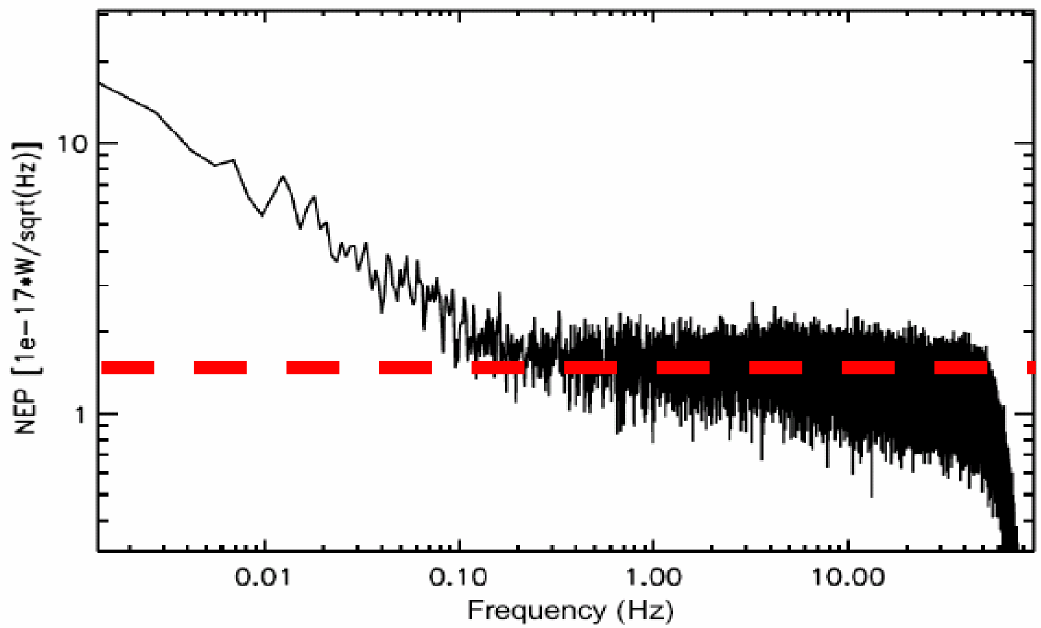
2)

Detectors Count & Focal-plane real-estate

- 5 uK arcmin target (after removal of foregorunds): extremely high total sensitivity required.
- Bolometric detectors
- Sensitivity achieved by multiplication of number of detectors, not through reduction of NEP (<T & < background).
- Planck experience with 40K telescope + CMB background: photon noise limit, with cosmic rays hits close to be important





Planck HFI Core Team: *Planck* early results. IV. A&A 536, A4 (2011)

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Requirements from science and possible implementation

- To achieve about 5 uK arcmin and high angular resolution:

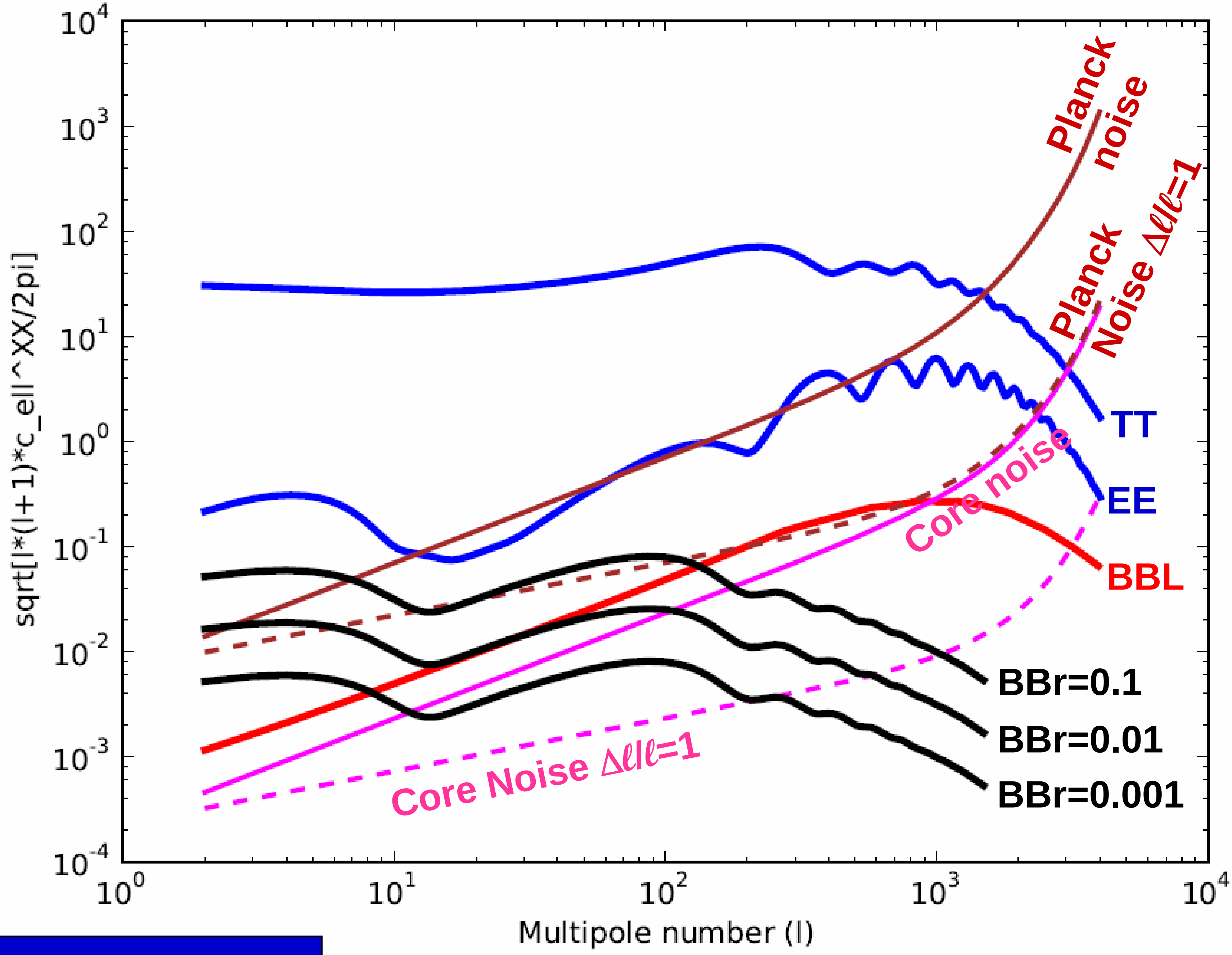
Horn FWHM (deg)	36						T =	4	years
solid angle (sr)	0.31006						=	12614[illegible]	
freq (GHz)	numb	Wavelength (m)	throughput 1 pix (lamb^2)	thru all (m2 sr)	FP area (m2)	focal plane diam (m)	FWHM (')	uK sqrt(s)	uK arcmin
45	200	6.67E-03	4.44E-05	8.89E-03	2.87E-02	1.91E-01	23.3	50	3.8
75	200	4.00E-03	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

uK arcmin

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

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

2) Target Sensitivity: 5 μK arcmin after foreground subtraction



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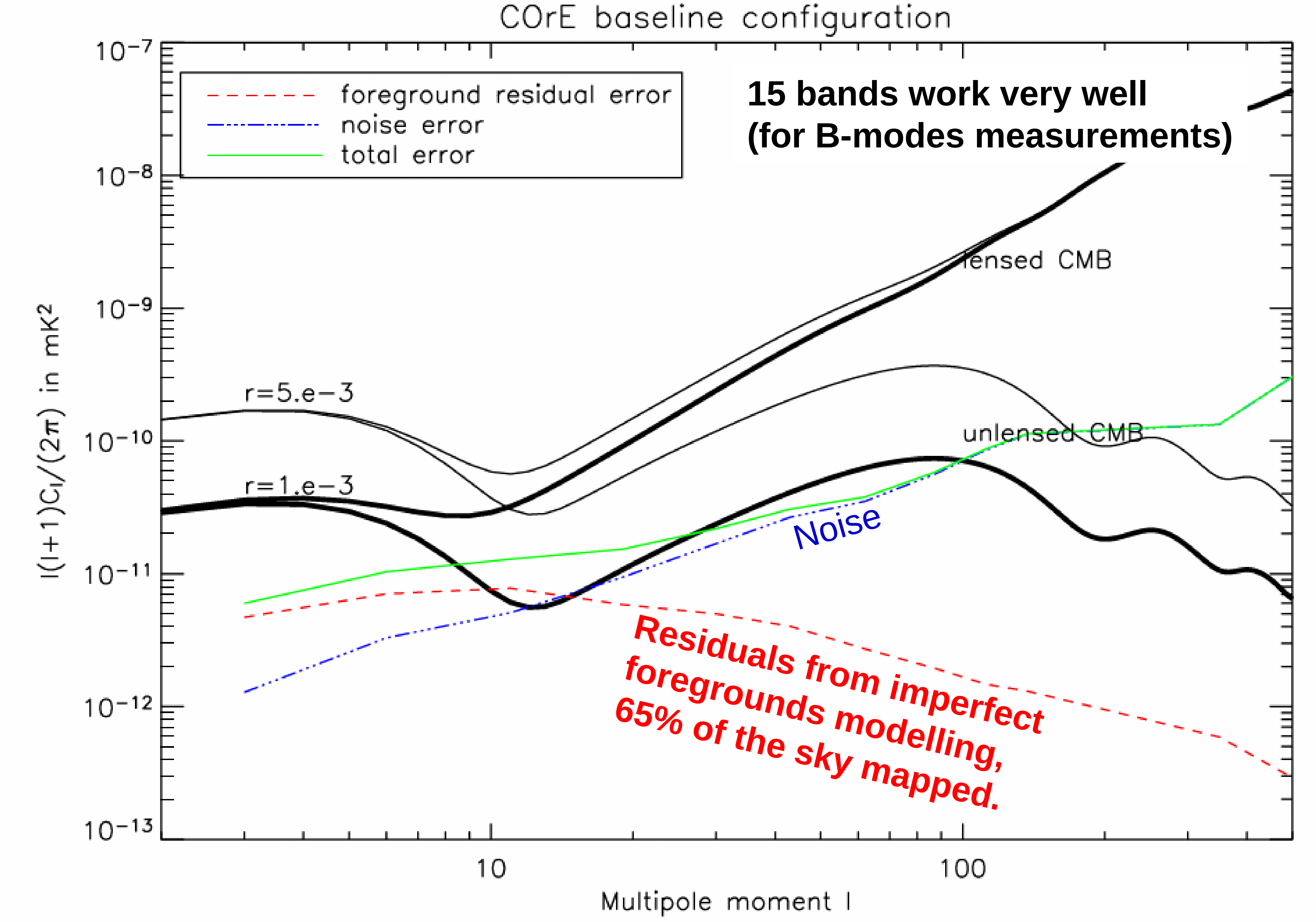
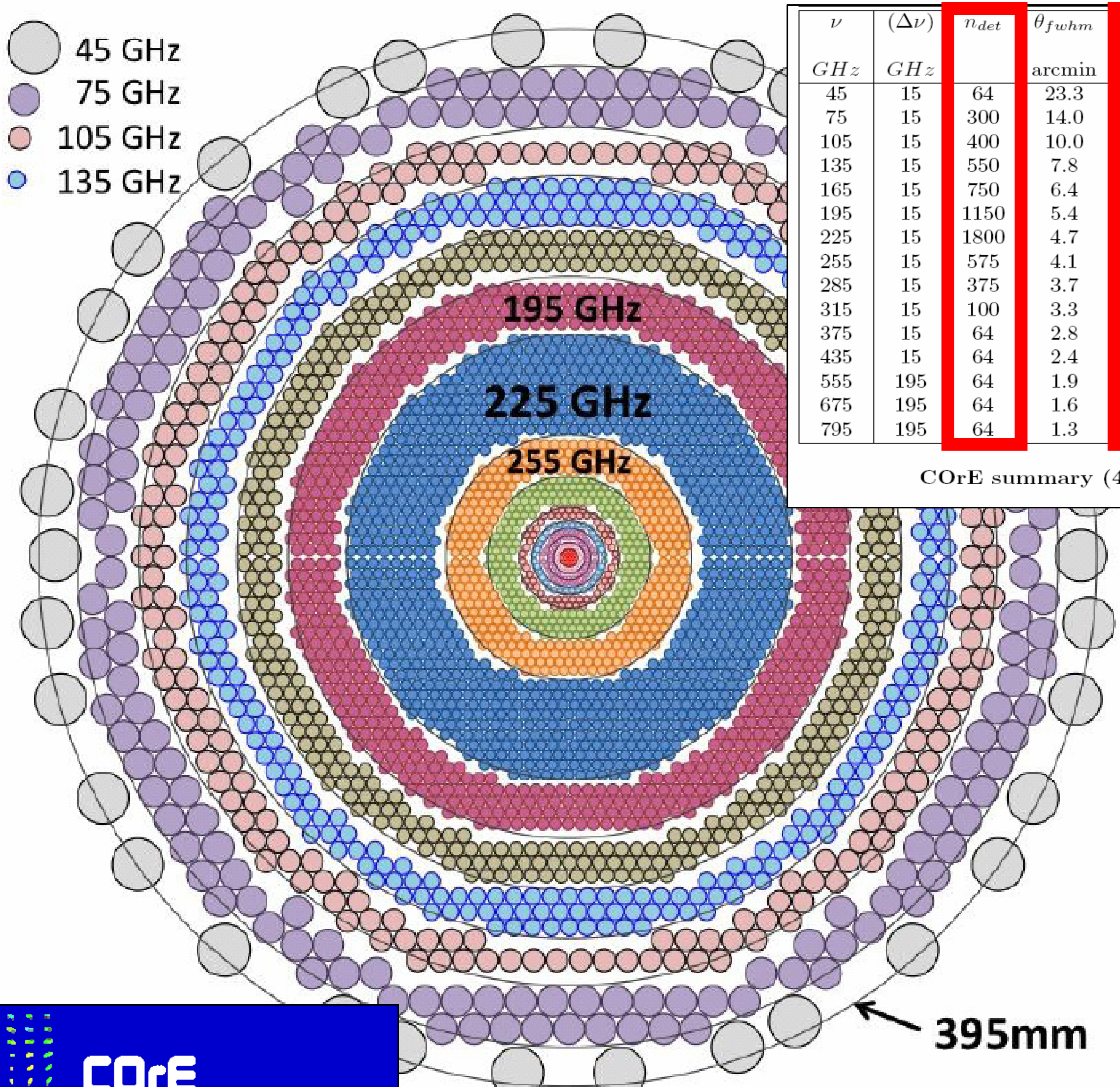
3)

Wide frequency coverage



2)



ν	$(\Delta\nu)$	n_{det}	θ_{fwhm}	Temp (I) μK·arcmin		Pol (Q,U) μK·arcmin	
GHz	GHz		arcmin	RJ	CMB	RJ	CMB
45	15	64	23.3	4.98	5.25	8.61	9.07
75	15	300	14.0	2.36	2.73	4.09	4.72
105	15	400	10.0	2.03	2.68	3.50	4.63
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795	195	64	1.3	1.31	8070	3.60	22200

COrE summary (4 year mission)

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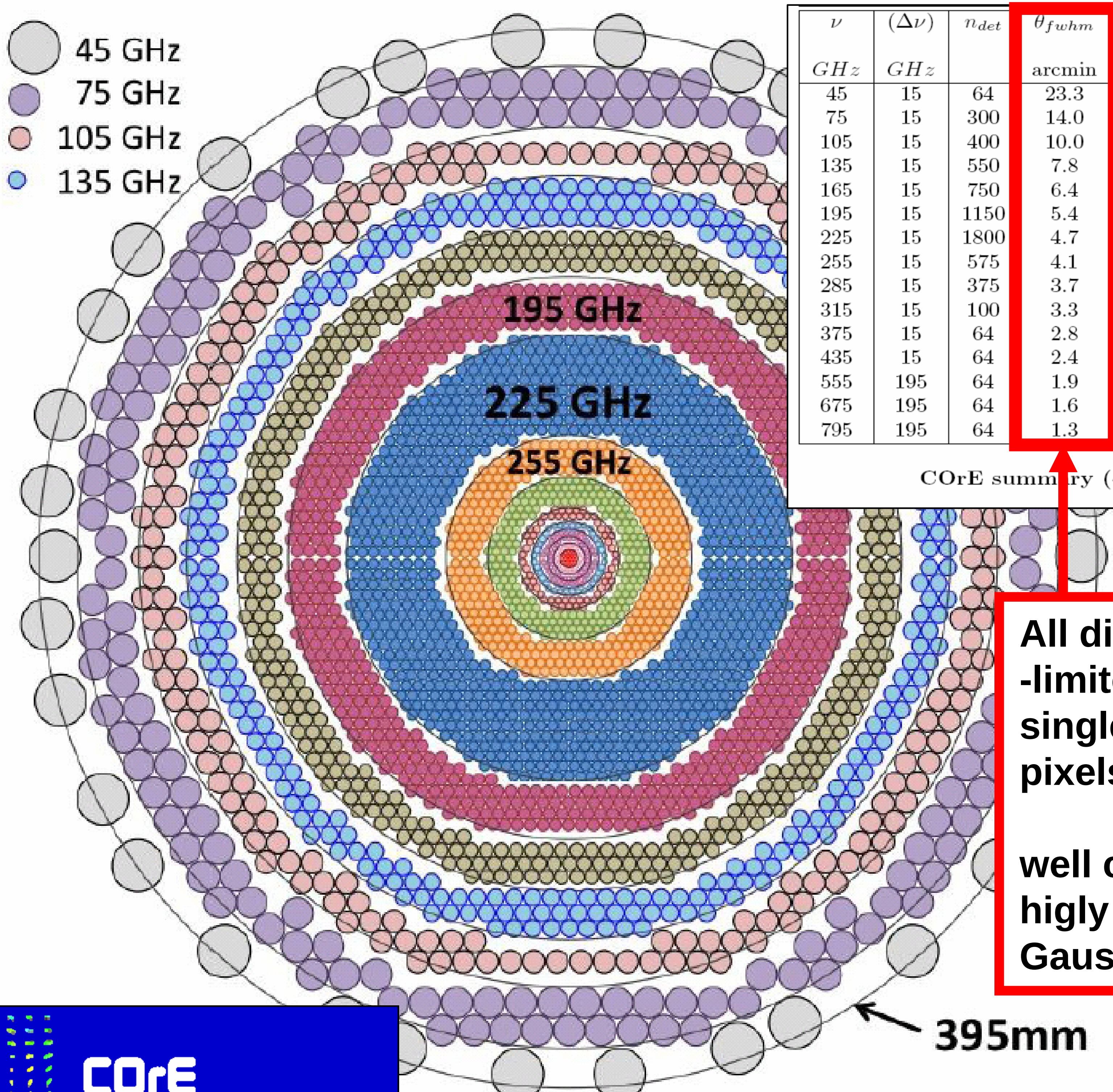
2)



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COrE summary (4 year mission)

All diffraction-
-limited,
single-mode
pixels:

well controlled,
higly circular
Gaussian beams !

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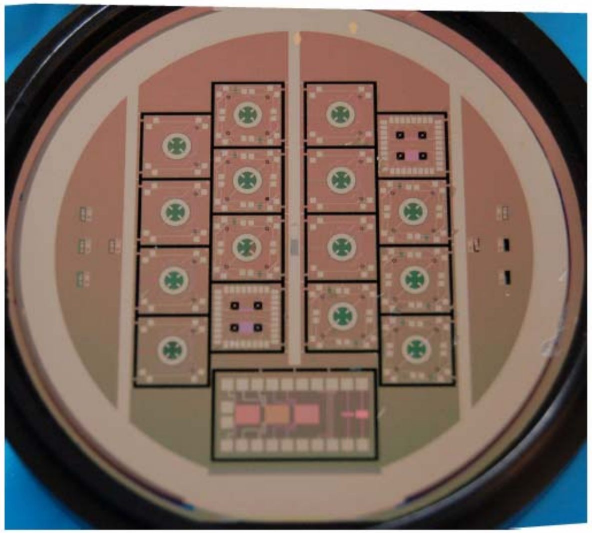
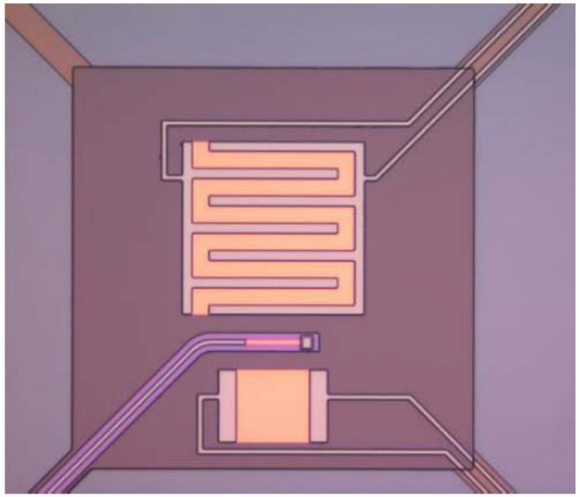
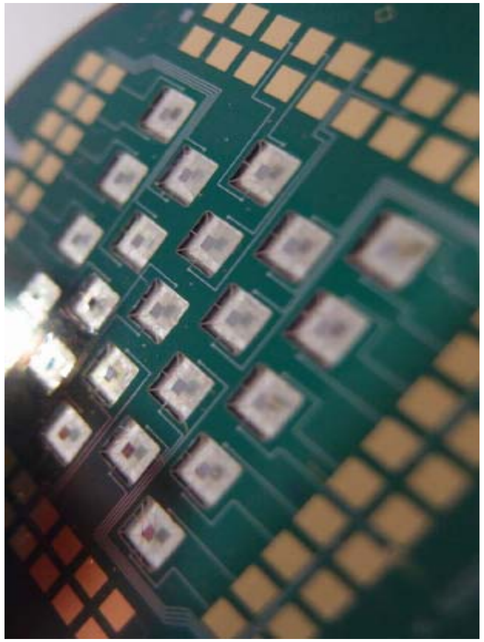
TES bolometer technology :

- Well established, and performing well (at the telescope: SPT, ACT & on balloons EBEX, SPIDER …)
- Idem for MUX readout
- European technology also well advanced.
- We need >4000 of them.
  - MUX readout
  - Horns
- Can we avoid CR hits ?





S. Withington et al., Cambridge



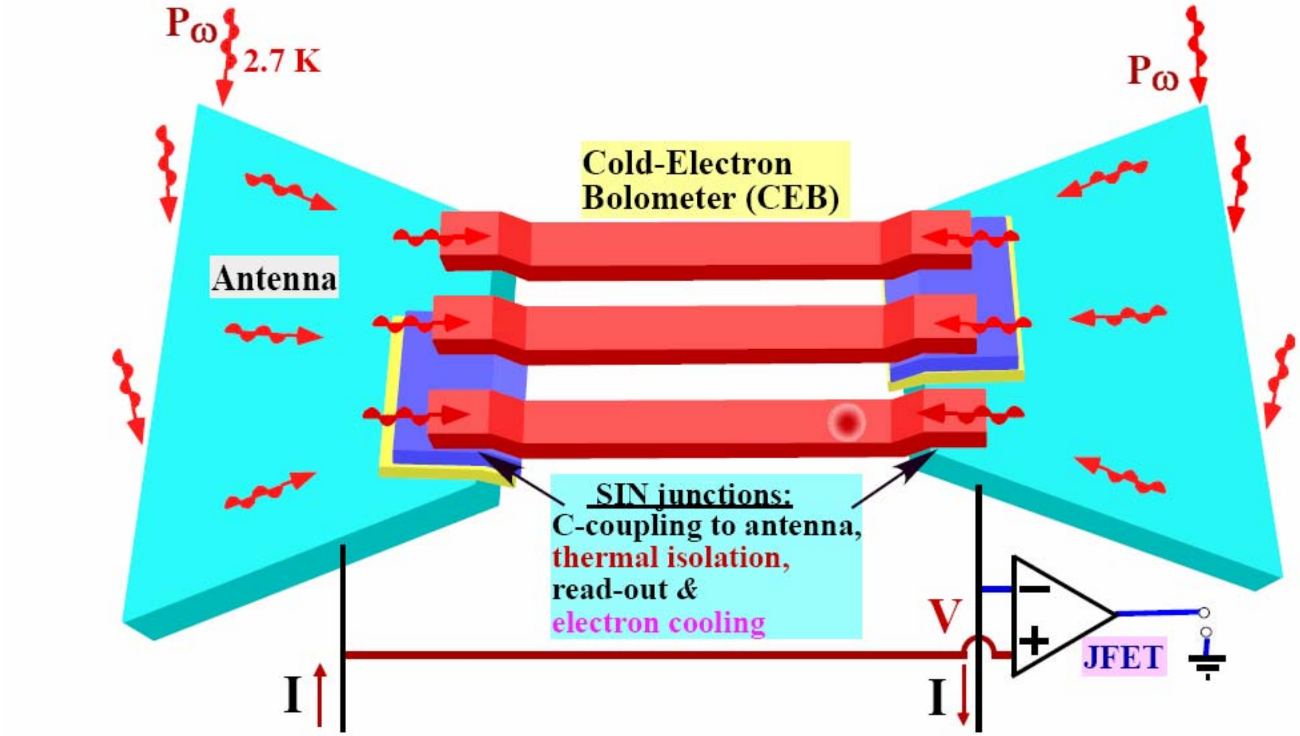
M. Piat et al. Paris

F. Gatti et al. Genova
multi-moded spider webs

2)

Improving over TES bolometers ?

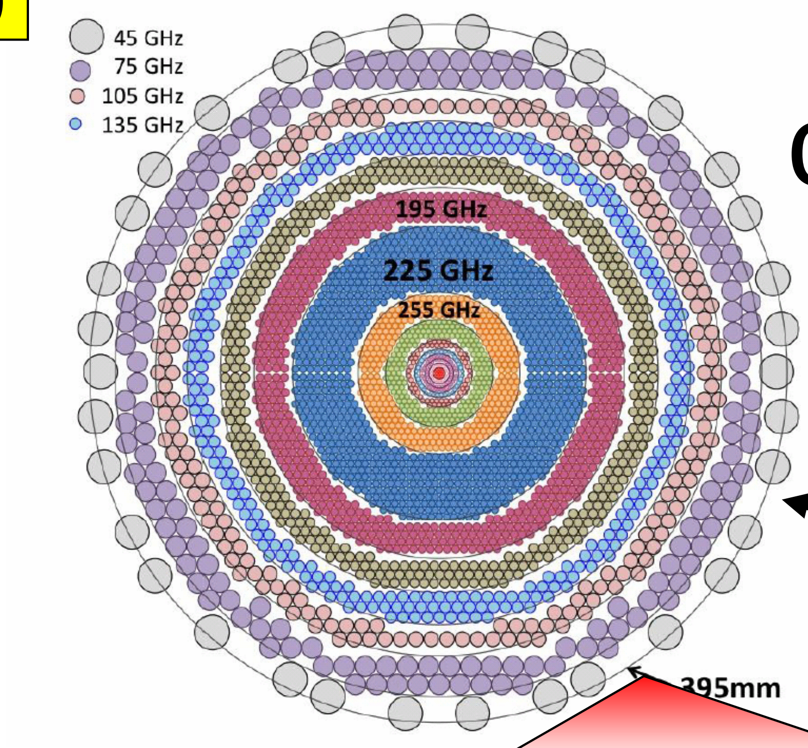
- KIDs & CEBs !
- KIDs made in Cardiff, Grenoble, Rome/TN etc.
- CEBs made in Chalmers

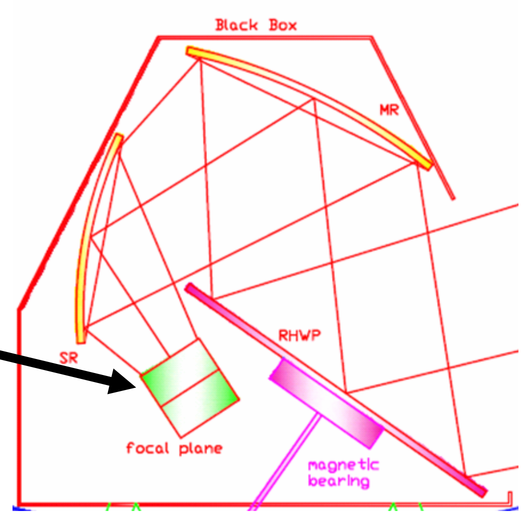


Very insensitive to CR hits (sensing electrons are confined in a sub-μm sized junction, and effectively decoupled from the lattice) Kuzmin et al. 2010

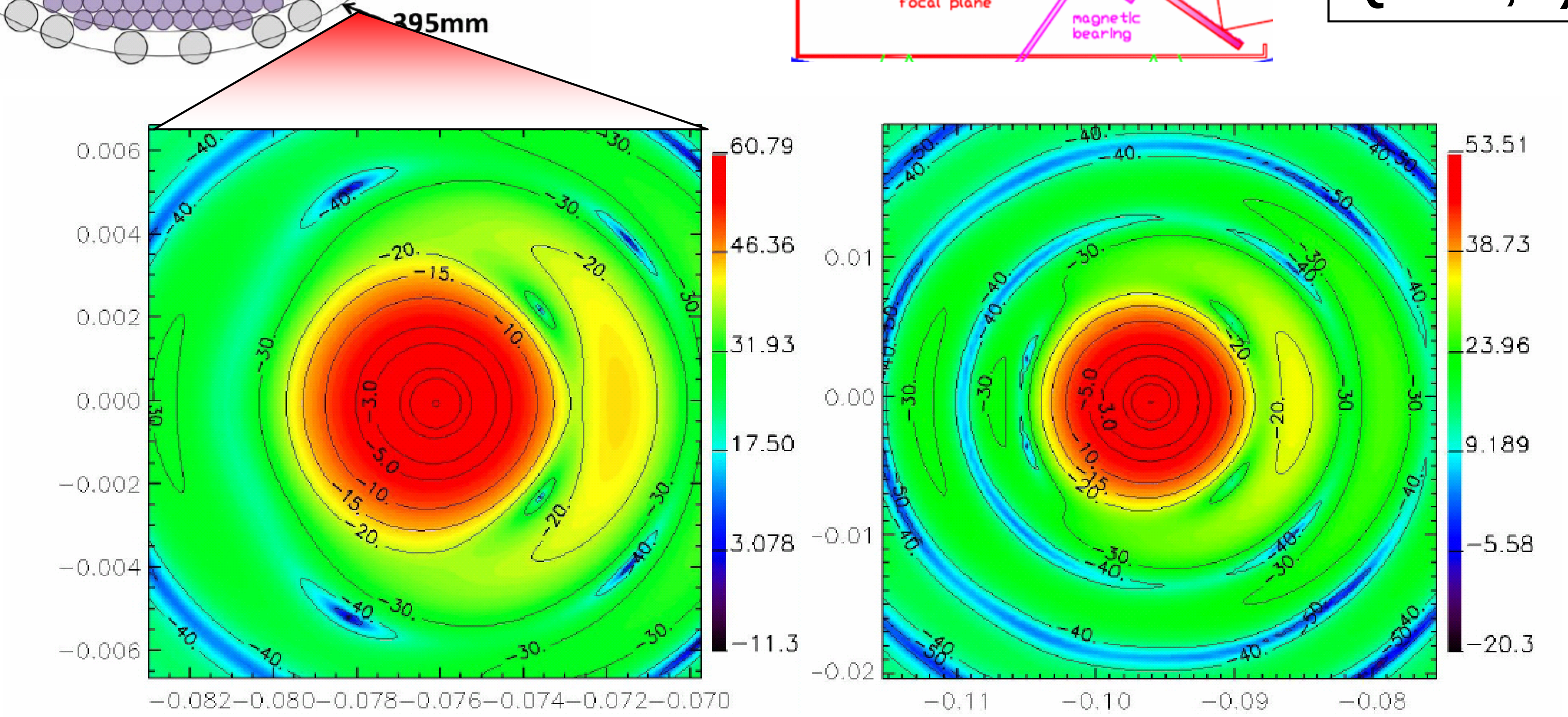
4)

Large Telescope & clean, wide focal plane





Compact test-range Mitsugushi -Dragone design (Clover, QUIET, ..)



Very wide focal plane, with < 5% ellipticity even at the edges (400 mm diam)

4)

Large Telescope & clean, wide focal plane

- The real-estate problem can be relaxed if each pixel is sensitive to both polarizations and to several frequencies
- OMTs required – good quality prototypes existing already at 100 GHz; more difficult at high frequency end.
- Multichroic pixels (as in LiteBIRD at al.) are an option
- ESA has issued an ITT for developing high detector density focal plane architectures for COrE &.

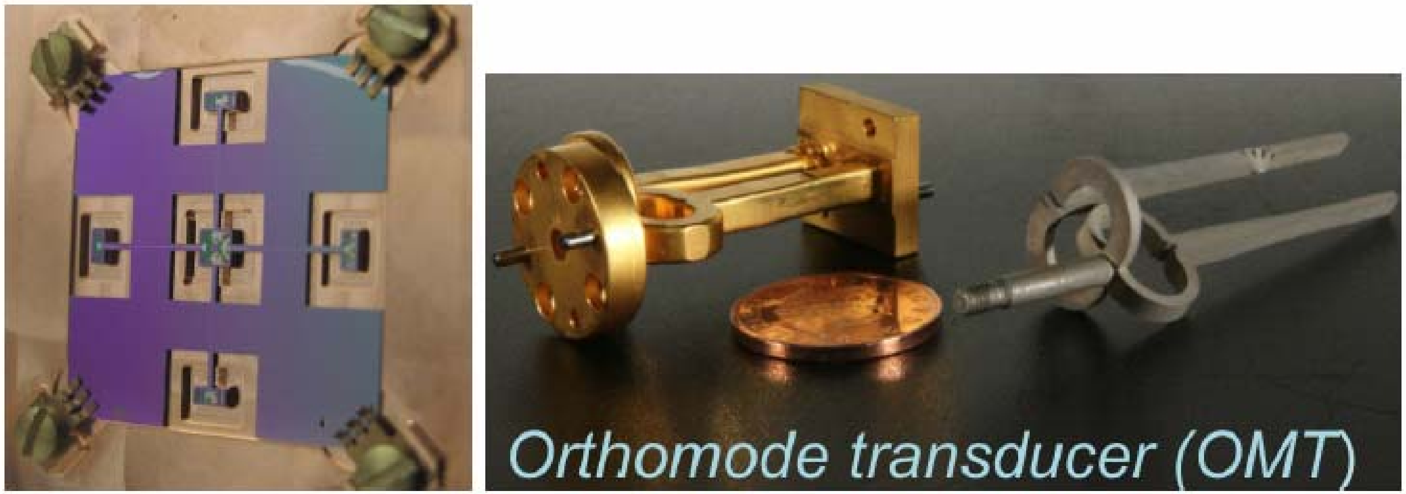
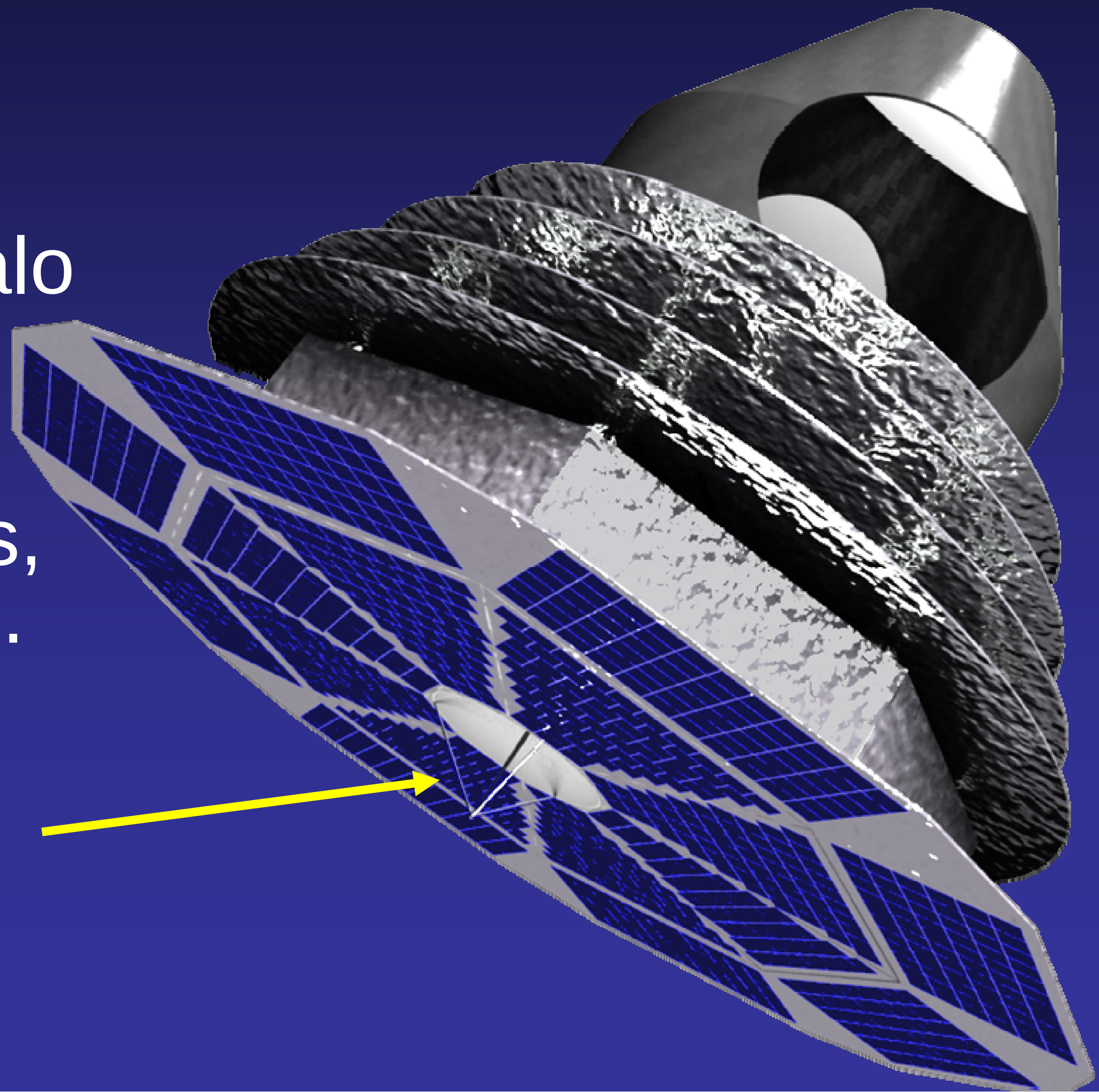


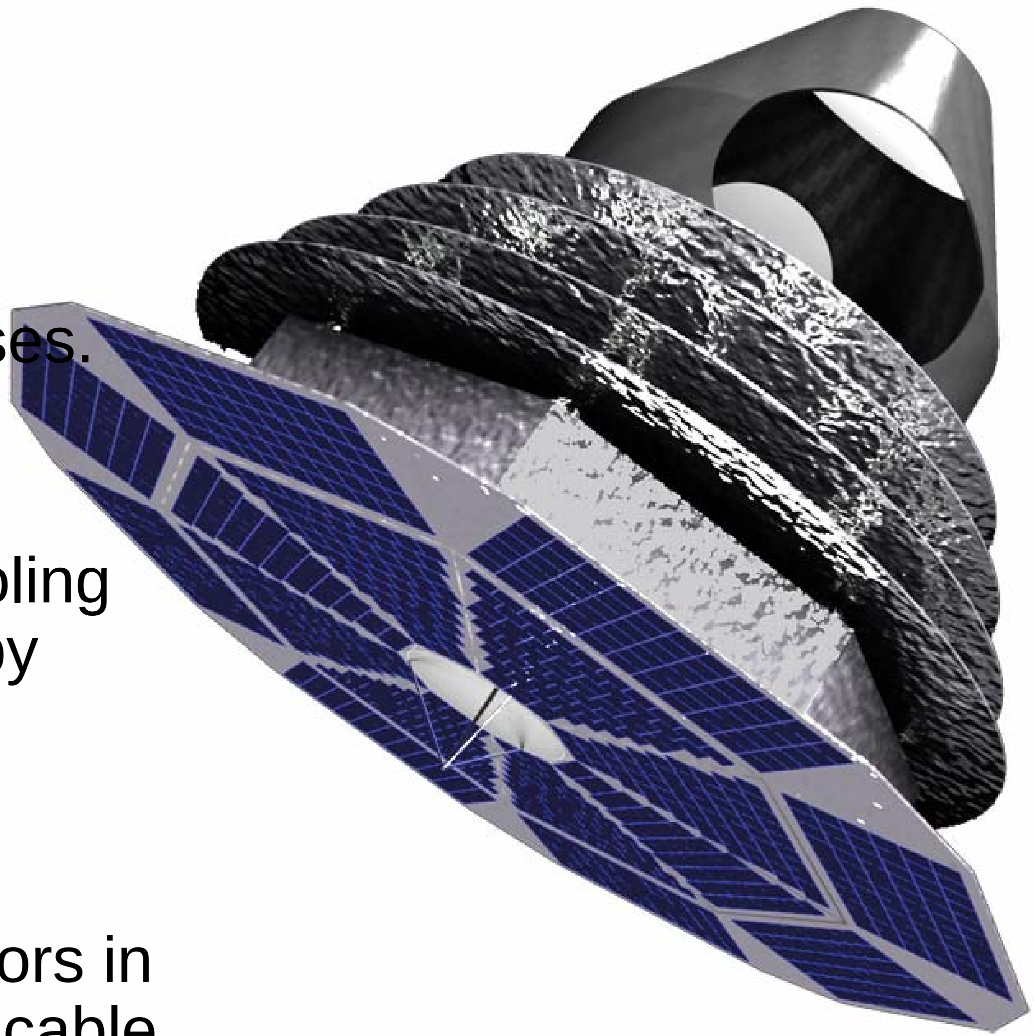
Figure 26: Left: prototype of 100 GHz planar OMT (Fr). Right: Clover 97 GHz waveguide OMT (UK).

COrE : the mission

- No atmosphere, Full-sky coverage, thermal stability, sidelobes
  -> L2 mission
- Mass: 1800 kg
- 500000/800000 km halo orbit (Herschel)
- Launcher : Soyuz
- Raw data rate 18Mbps, compressed 4.5 Mbps.
- Spin axis : sun-earth
- High gain Ka antenna
  2 h/day download.



- 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 results
  - Telescope, detectors and cooling chains completely validated by Planck
  - control of systematic effects (Bicep, BicepII, EBEX, ..);
  - work on SPICA/BLISS detectors in Europe, a lot of which is applicable to CMB polarisation measurement
- **Next opportunity: M4 in 2014**



Meanwhile ….

- Call for white papers for the definition of the “L2” and “L3” missions in the ESA science programme
- **“… the science themes and questions** that will be addressed by the next two L-class missions in the Cosmic Vision 2015-2025 plan, currently planned for a launch in 2028 and 2034, respectively.“

Meanwhile ….

- Call for white papers for the definition of the “L2” and “L3” missions in the ESA science programme
- **“… the science themes and questions** that will be addressed by the next two L-class missions in the Cosmic Vision 2015-2025 plan, currently planned for a launch in 2028 and 2034, respectively.“
- We have a dream !
- This call offers the opportunity to define the dream in view of a **very ambitious mission**, which cannot fit the “M” size.
- Following informal meetings, we plan to submit a white paper stressing the following science themes and questions :

The dream …

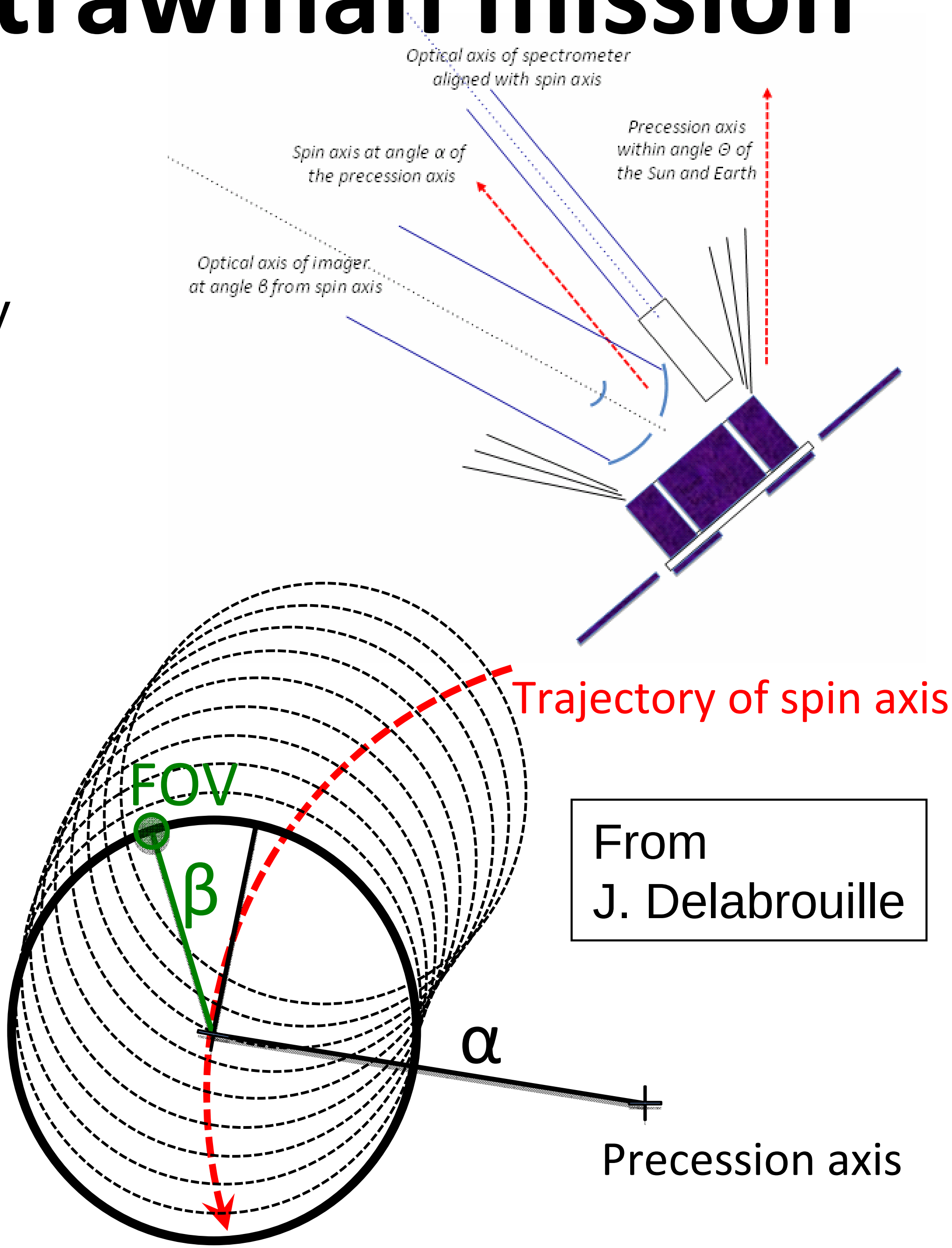
- Full sky, astrophysical background limited, *high resolution, mm to FIR* polarization measurements AND high accuracy *absolute spectral measurements,* with inter-calibration capabilities
- A killer combination to
  - Measure B-modes / non gaussianity -> inflation
  - Measure neutrino masses / hierarchy
  - Distributions of DM and BM, via lensing, SZ clusters (> 10^6 up to z > 3 !) and the CIB
  - Measure Y, atoms and molecules during the reionization epoch
  - Enter in the primeval fireball, studying recombination lines, He/He+ recombination, energy dissipation / chemical potential distortions
  - Measure ISM turbulence and magnetic fields, detailing star formation

… and a sample strawman mission

- Based on heritage from :
  - **Planck**
  - the **COrE** study (but notice, this is a larger telescope, and a different polarization modulation approach)
  - the **PIXIE** proposal
  - the **SAGACE** phase-A study
  - the **Millimetron** Low Resolution Spectrometer phase-A study
  - …

… and a sample strawman mission

- In the framework of an L mission envelope:
  - Polarimetry: from 30 GHz to 3 THz, 3.5m mirror, limited only by the astrophysical background. Cycloid scan.
  - Absolute Spectroscopy: from 30 GHz to 3 THz, accuracy of 10^{-8} of the peak CMB brightness, angular resolution <1° TBD
  - TBD: L2 observatory satellite + calibrator & communications relay satellite, formation flight.
- White paper due: May 24th, 2013 (!)
- Collaboration very welcome ! Invitation mail to be circulated soon



From J. Delabrouille