Review of previous M-class proposals

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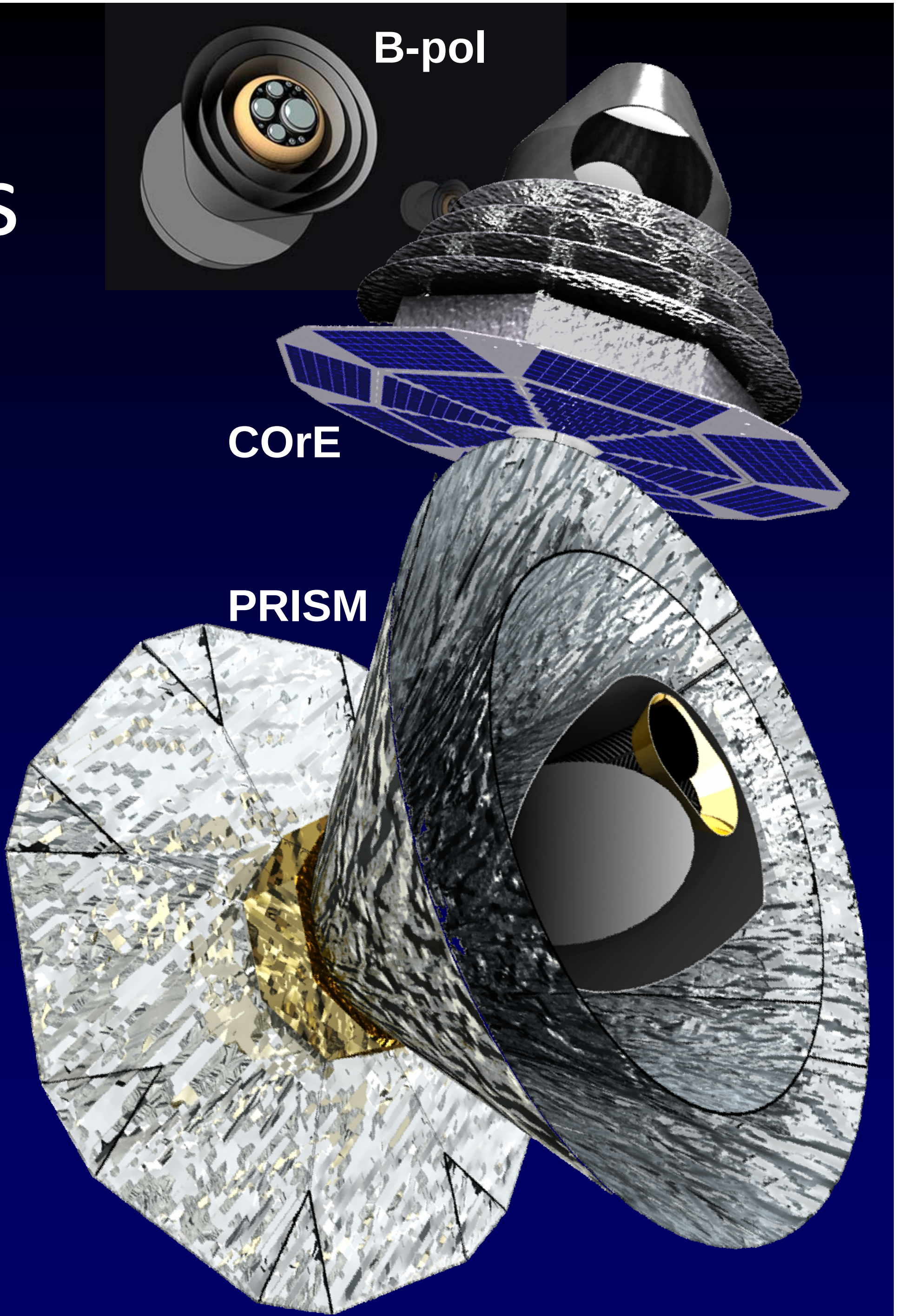


B-pol

- June 2007 - http://www.b-pol.org/index.php - astro-ph/0808.1881
- Target: CMB polarization – B-modes - large scales
- 5 μK arcmin sensitivity (set by lensing)
- Bolometers with lenses and rotating HWPs
- 1° FWHM angular resolution
- 45 to 350 GHz in 6 bands
- M-class
  - L2, Soyuz, satellite mass 1500 kg
  - Payload 590kg, 200W, cryogenic (V-grooves + liquids)
  - cost : ESA (launch, spacecraft, ground segment etc.) 304 M€ + Payload & DPC 154 M€ = **458 M€**

B-Pol

•A European mission to get a CMB polarization measurement limited only by natural foreground sources was proposed in response to the ESA Cosmic-Vision call.

•The mission is based on the availability of large format arrays of ultra-sensitive bolometric detectors, cooled at 0.1K, and fed by cold corrugated feedhorns and low polarization telecentric telescopes.

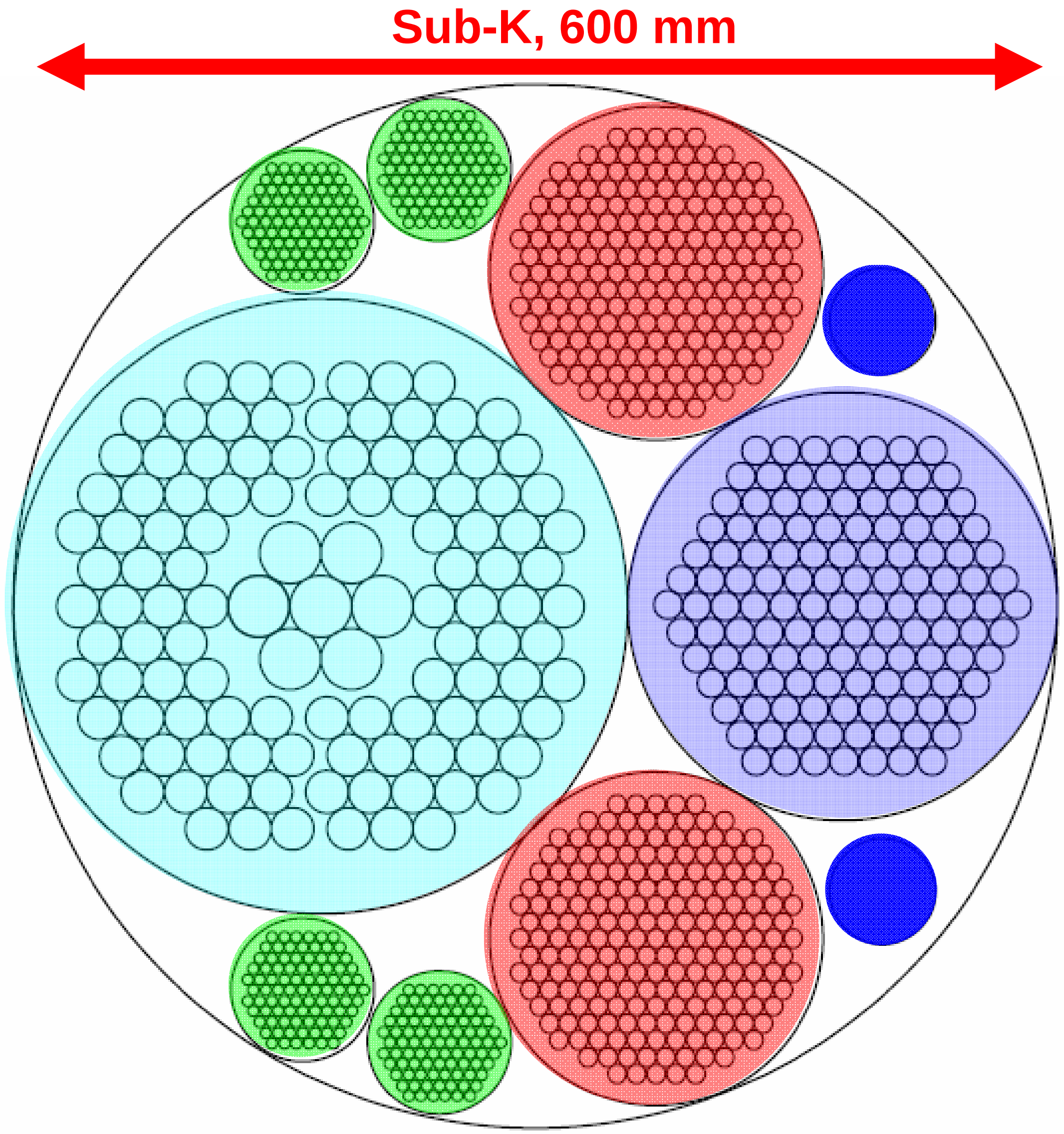
•Polarization modulation is obtained by means of rotating waveplates.

Sensitivity and frequency coverage: the focal plane

- Baseline technology: TES bolometers arrays

Corrugated feedhorns
for polarization purity and
beam symmetry

FWHM	
15°	45 GHz 45mm
68’	70 GHz 26.5mm
47’	100 GHz 18.5mm
47’	150 GHz 12.3mm
40’	220 GHz 8.4mm
59’	350 GHz 5.3mm



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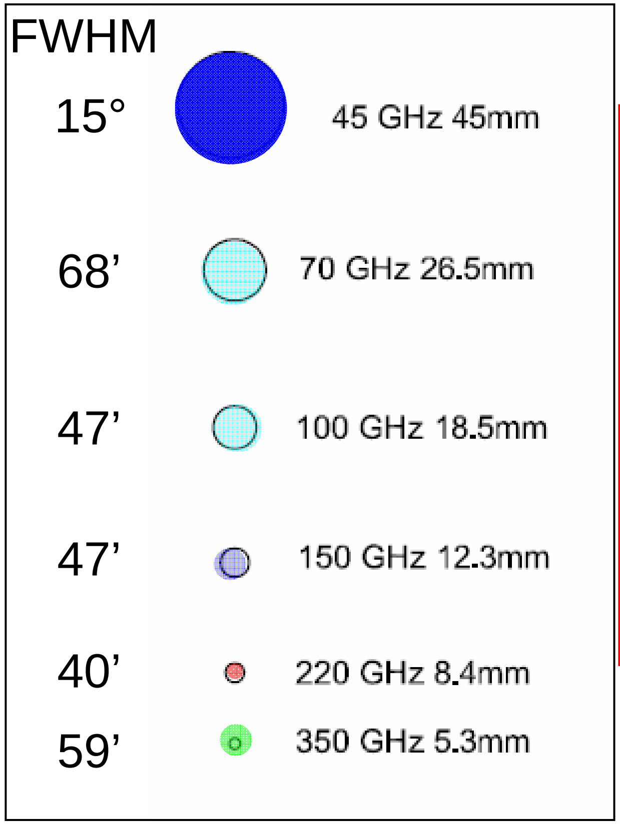
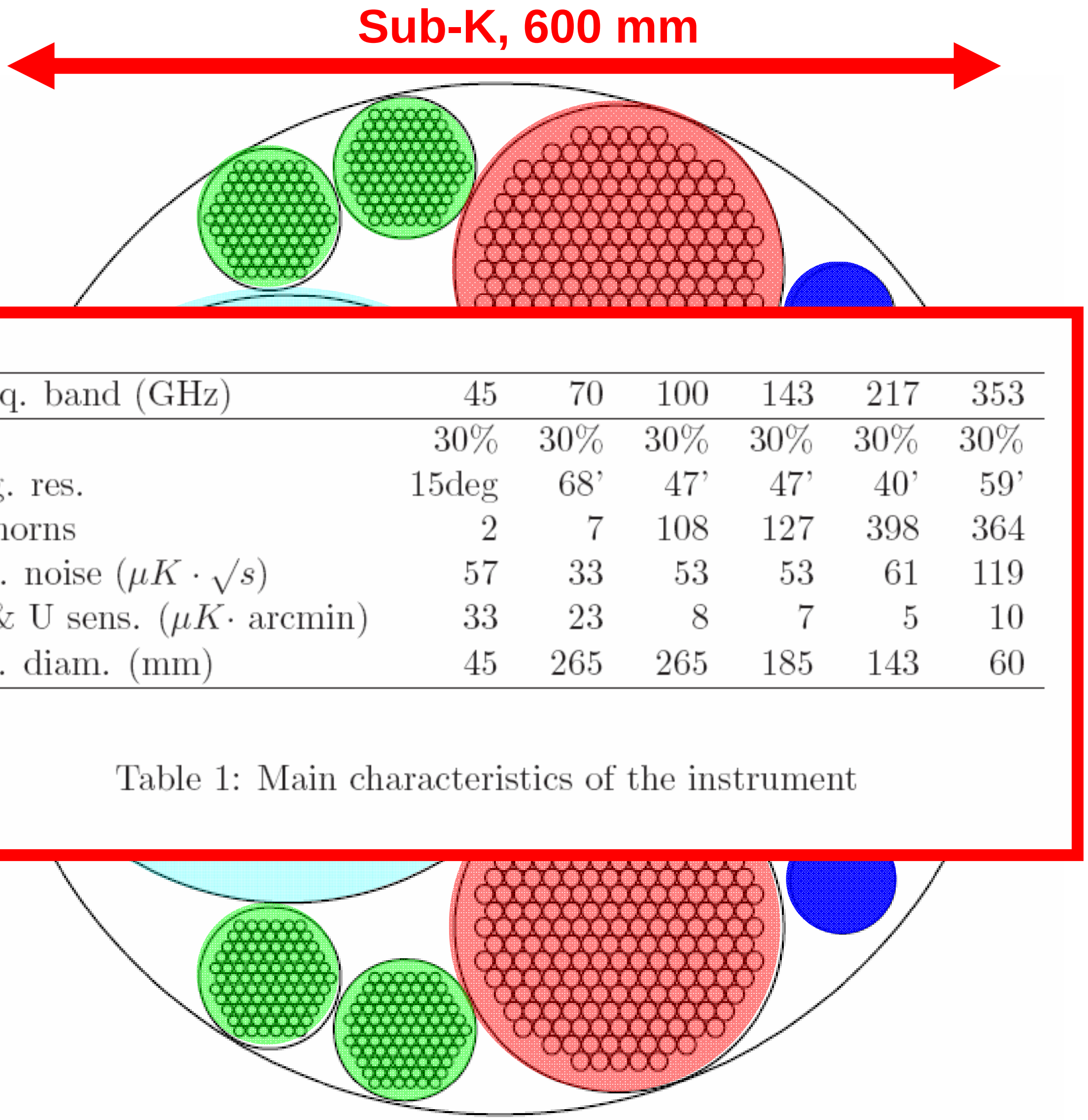
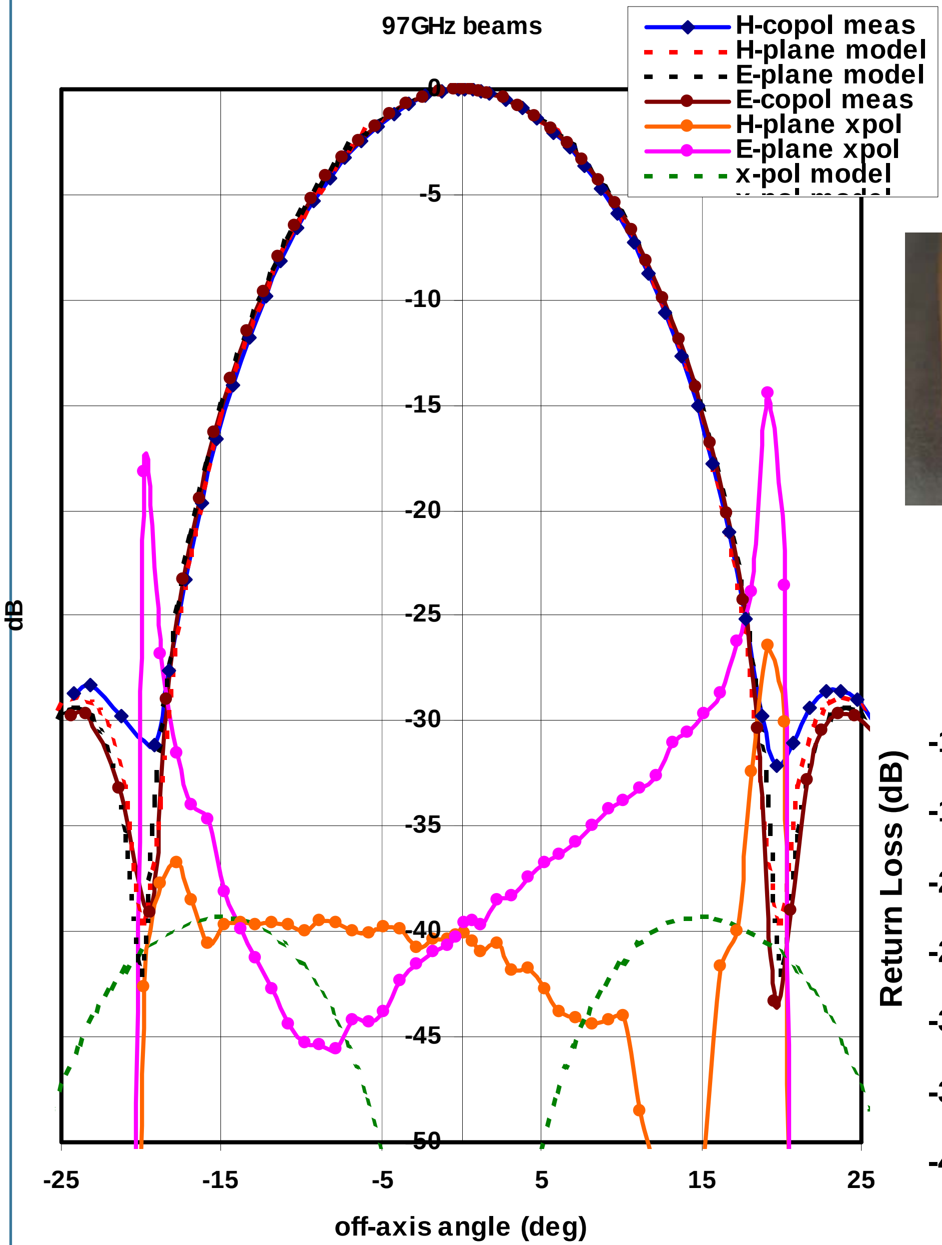




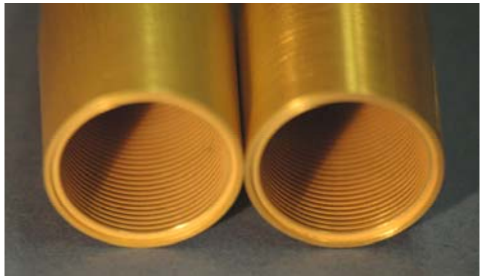
Freq. band (GHz)	45	70	100	143	217	353
$\Delta\nu$	30%	30%	30%	30%	30%	30%
ang. res.	15deg	68’	47’	47’	40’	59’
# horns	2	7	108	127	398	364
det. noise ($\mu K \cdot \sqrt{s}$)	57	33	53	53	61	119
Q & U sens. ($\mu K \cdot$ arcmin)	33	23	8	7	5	10
Tel. diam. (mm)	45	265	265	185	143	60

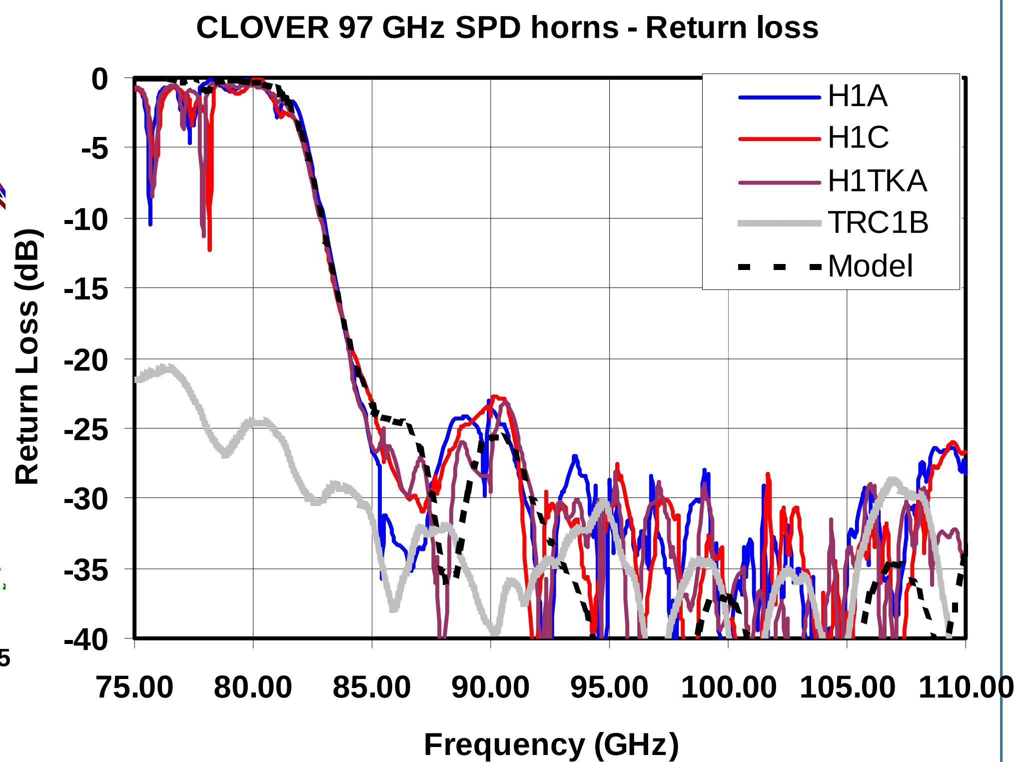
Table 1: Main characteristics of the instrument

97 GHz Horn development & tests

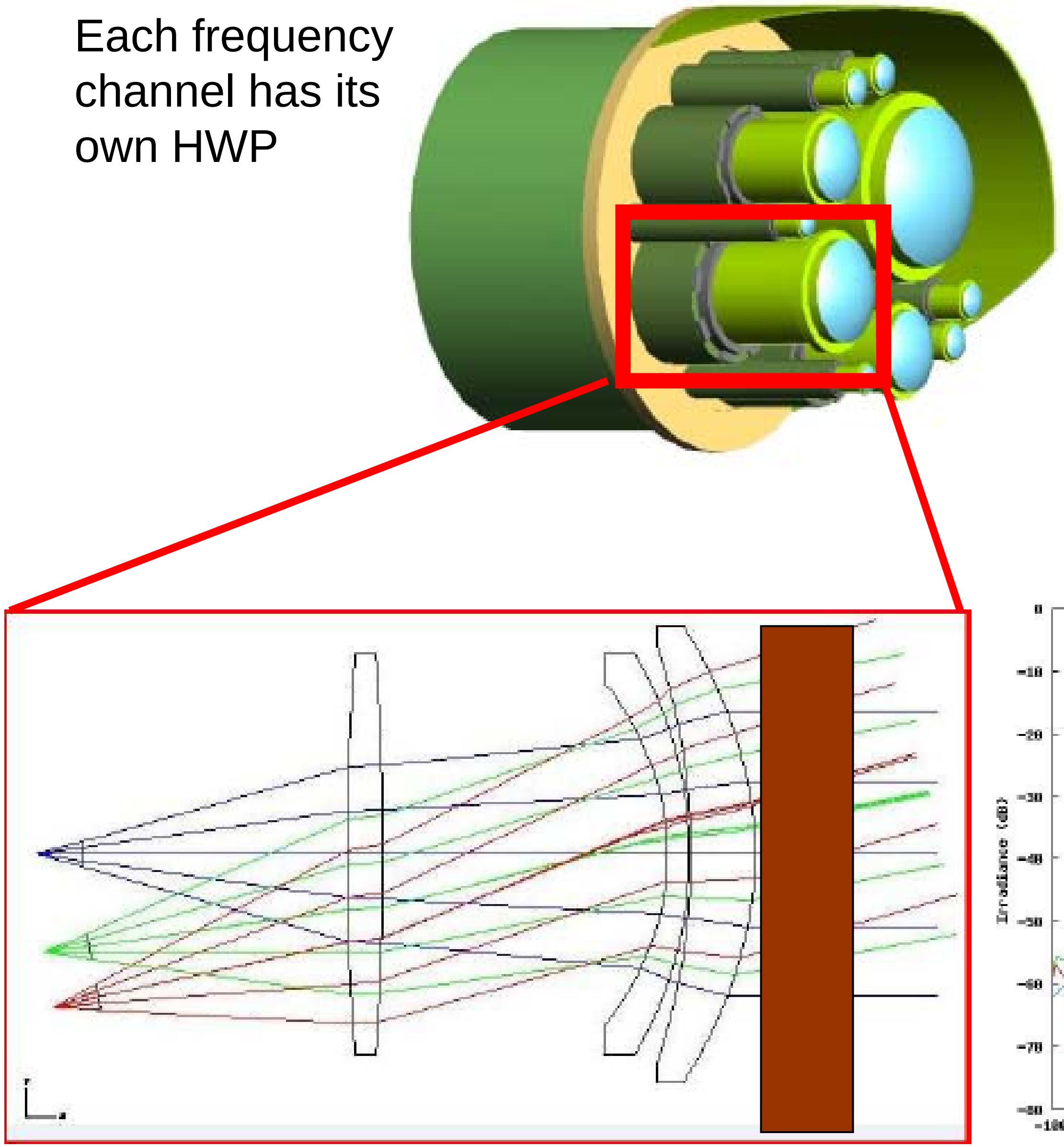


Horn prototypes





Each frequency channel has its own HWP

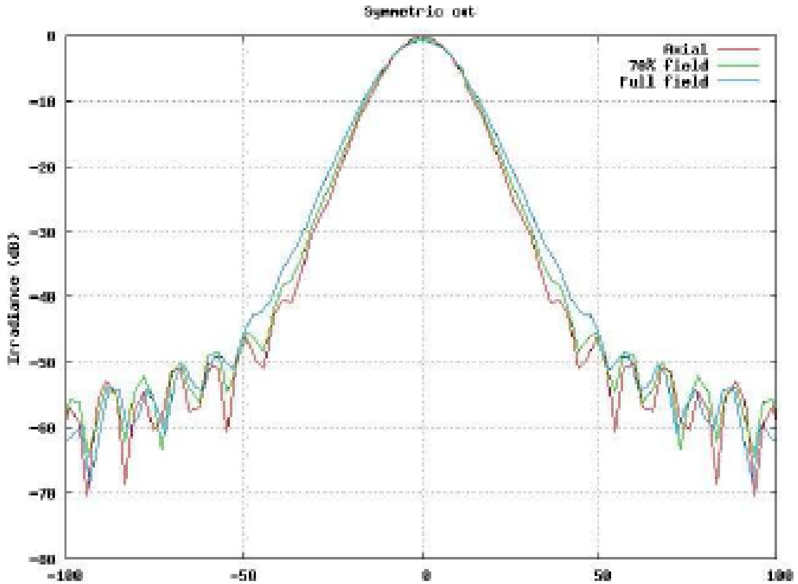


HWP

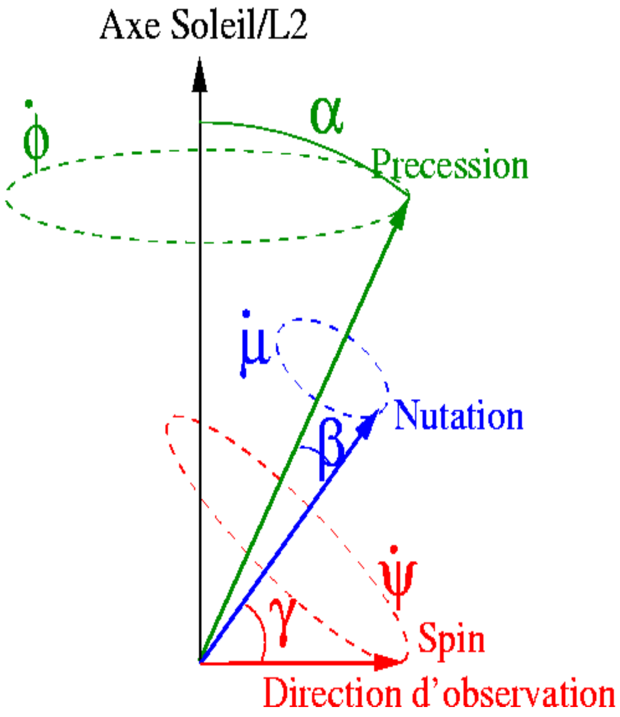
Optical system:

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

Possible solution: modified telecentric telescope



Sky Scan and Polarization Modulation (SAMPAN)



Example of set of parameters:

α = 45

β = 45

Tφ = 43200 sec

Tμ = 2400 sec

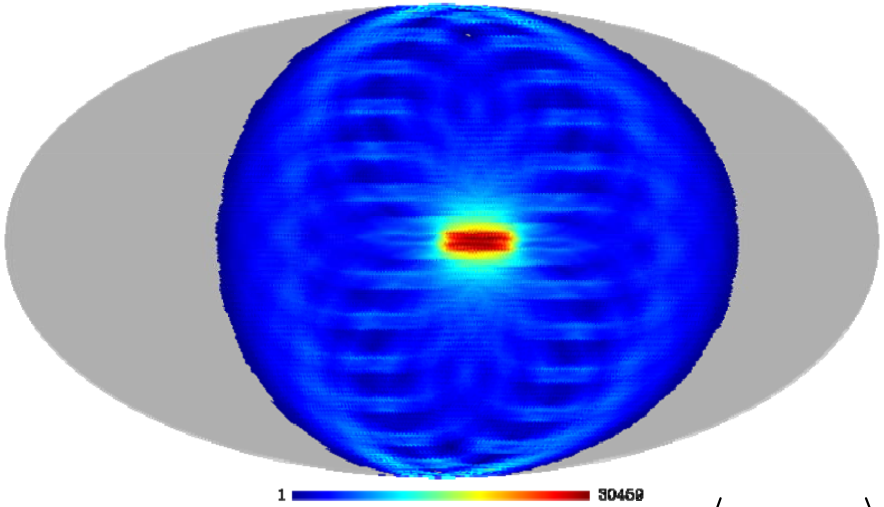
Tψ = 20 sec

- Parameters:
  - 3 angles
  - 3 rotation speeds
- Goal:
  - Short term redundancy on all angular scales
  - Large fraction of the sky covered in a few days
  - Good angular coverage
  - Jacknife possibilities
- some constraints
  - The scan speed of the line of sight must be compatible with the beam, the detector time constant
  - The sampling rate must be compatible with the telemetry (if no onboard aggressive data compression)
  - Cope with thermal effects, solar pannels orientation, SCAO etc…

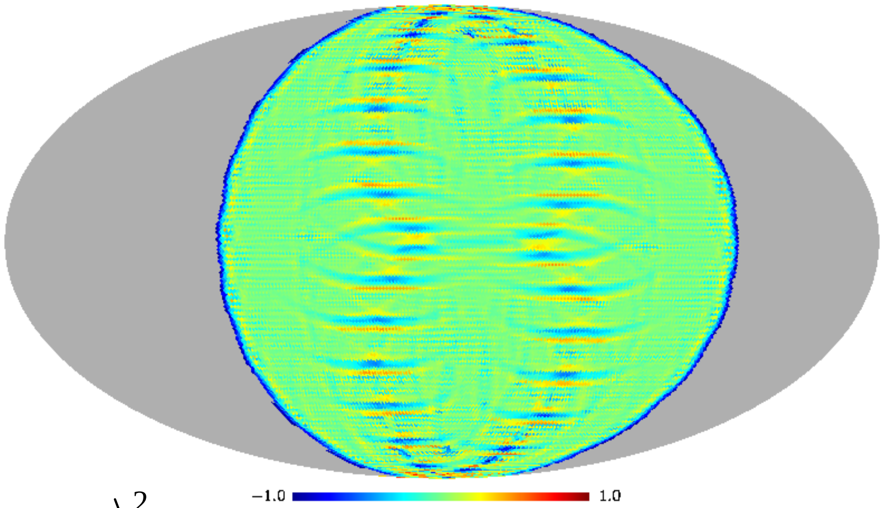
Sky Scan and Polarization Modulation (SAMPAN)

30 days, detector at r/3 (γ=2.5deg)

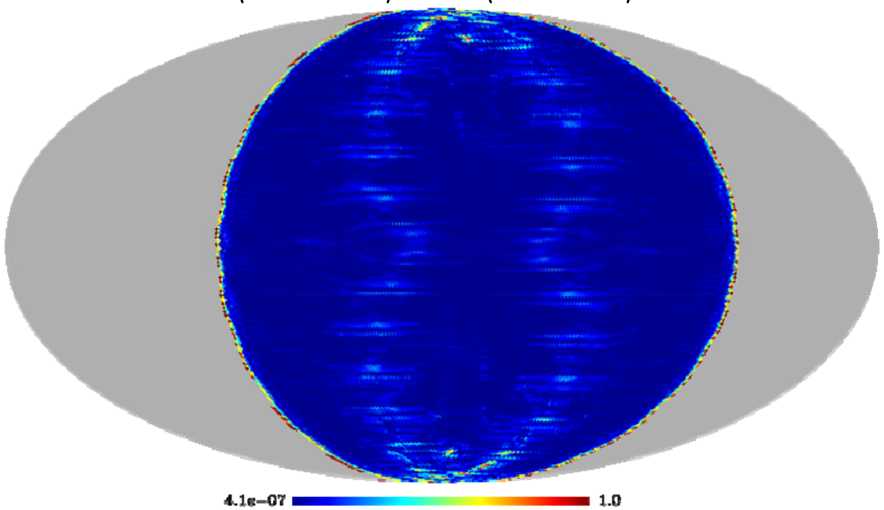
N_{hits}



$\cos 2\alpha$



$$\langle \cos 2\alpha \rangle^2 + \langle \sin 2\alpha \rangle^2$$



BPol Capabilities : Fisher matrix analysis

	Fiducial model	BPol 20′ fwhm, $(5\mu\mathrm{K}\cdot\mathrm{arcmin})^2$ (No reionization)					
		TT	TE	EE	BB	BB+EE	All
r	0.0	1.57×10^{-1}	7.19×10^{-2}	1.32×10^{-2}	1.58×10^{-3}	6.71×10^{-4}	6.60×10^{-4}
$\delta A_S/A_S$	1.00×10^{0}	3.14×10^{-1}	6.15×10^{-3}	3.81×10^{-3}	2.70×10^{0}	3.57×10^{-3}	1.27×10^{-3}
H	7.20×10^{1}	9.96×10^{-2}	6.62×10^{-2}	9.91×10^{-2}	5.94×10^{0}	8.06×10^{-2}	3.93×10^{-2}
Ω_b	5.00×10^{-2}	3.43×10^{-4}	2.68×10^{-4}	6.01×10^{-4}	3.91×10^{-2}	4.88×10^{-4}	1.39×10^{-4}
Ω_c	2.50×10^{-1}	3.73×10^{-5}	5.03×10^{-5}	1.34×10^{-4}	3.45×10^{-2}	1.28×10^{-4}	2.68×10^{-5}
n_s	1.00×10^{0}	3.47×10^{-3}	6.69×10^{-3}	3.98×10^{-3}	1.49×10^{-1}	3.74×10^{-3}	1.84×10^{-3}
Ω_k	0.0	5.53×10^{-4}	4.37×10^{-4}	3.08×10^{-4}	3.04×10^{-2}	3.01×10^{-4}	1.87×10^{-4}
τ	0.0	1.73×10^{-1}	8.00×10^{-4}	1.19×10^{-5}	1.60×10^{0}	5.96×10^{-6}	5.96×10^{-6}

TAB.: 1σ errors resulting from the fit of an eight parameter family of cosmological models for a detector rms white noise amplitude of $5\mu\mathrm{K}\cdot\mathrm{arcmin}$ and a resolution of 20 arc minute. (Note that $\delta A_S/A_S$ denotes the variation of the normalization of the scalar power spectrum as compared to that inferred from COBE data.) This table

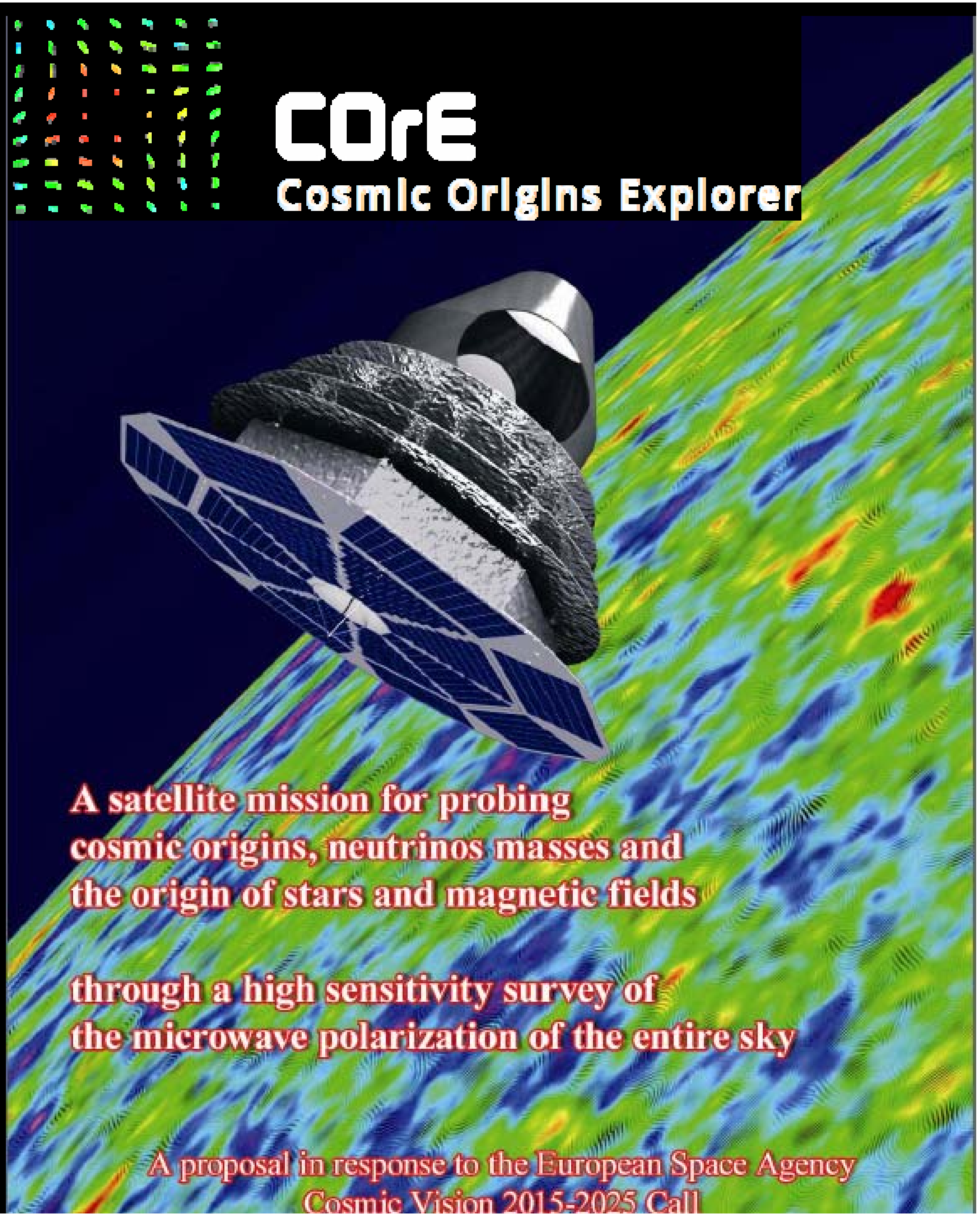
B-pol summary

- Focused on B-modes at large angular scales
- With today's technology certainly feasible
- Reasonably priced
- Concerns :
  - several rotators for waveplates, vs low heat load on the cryostat
  - Are 6 channels and 1° FWHM enough for careful polarized foregrounds removal ?
  - What if B-modes are below $r=10^{-4}$?

COrE

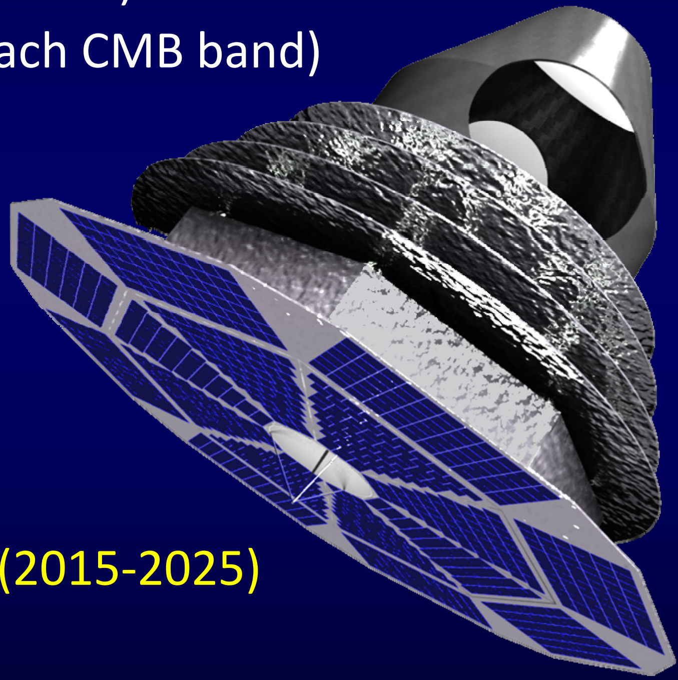
- Dec. 2010 - http://www.core-mission.org/ - astro-ph/1102.3181
- Still polarimetry, but more targets :
  - CMB polarization – B-modes, primordial and lensed
  - Non gaussianity
  - Neutrino masses
  - Galactic science (magnetic fields etc.)
- 1.5 μK arcmin sensitivity
- 6384 Bolometers, compact range telescope, large HWP
- angular resolution; 20’ to 1.3’ FWHM
- Coverage: 45 to 795 GHz in 12 narrow bands + 3 wide bands
- M-class
  - L2, Soyuz, satellite mass 1800 kg
  - Payload 750kg, 700W, cryogenic (Planck cryochain)
  - cost : ESA (launch, spacecraft, ground segment etc.) 434 M€
+ Payload & DPC 175 M€
= **619 M€**

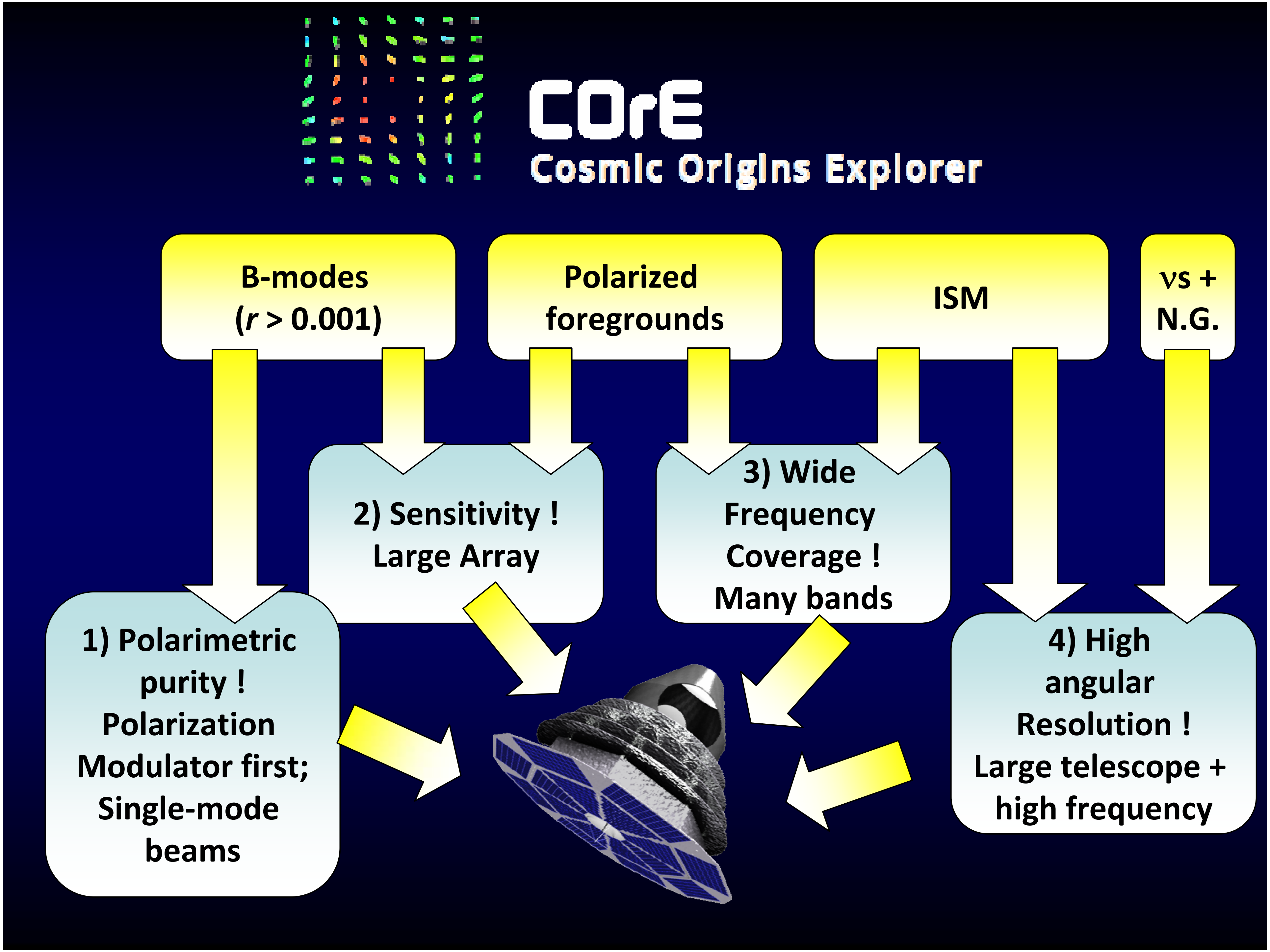
COrE white paper
astro-ph/1102.2181

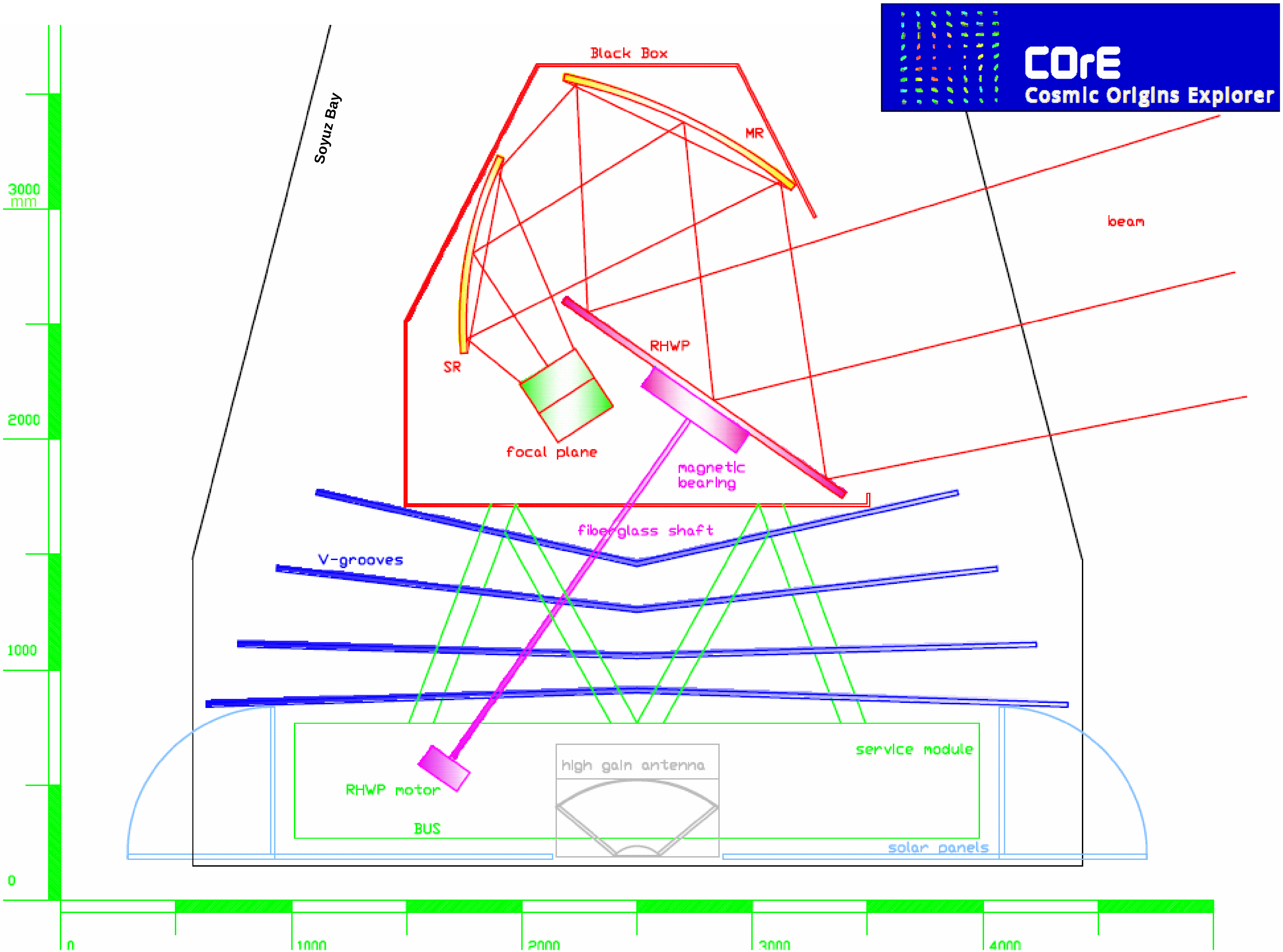


COrE
Cosmic Origins Explorer

- 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

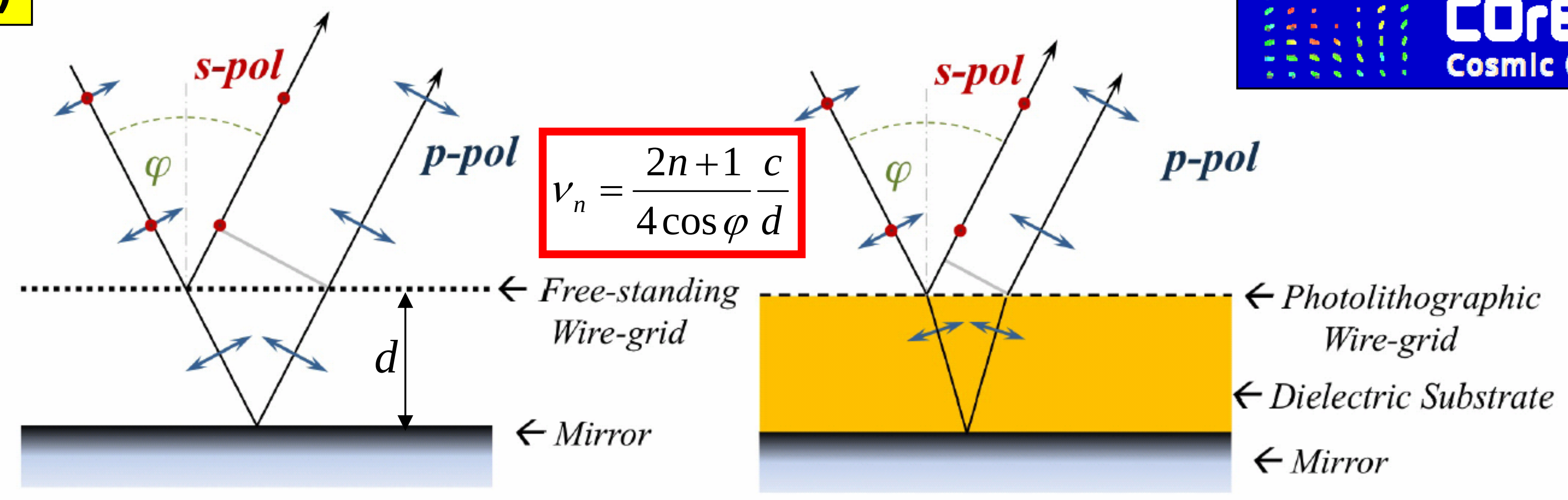



COrE
Cosmic Origins Explorer
B-modes
(r > 0.001)
Polarized
foregrounds
ISM
νs +
N.G.
2) Sensitivity !
Large Array
3) Wide
Frequency
Coverage !
Many bands
1) Polarimetric
purity !
Polarization
Modulator first;
Single-mode
beams
4) High
angular
Resolution !
Large telescope +
high frequency



COrE
Cosmic Origins Explorer
Black Box
MR
SR
RHWP
focal plane
magnetic bearing
beam
Soyuz Bay
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)



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

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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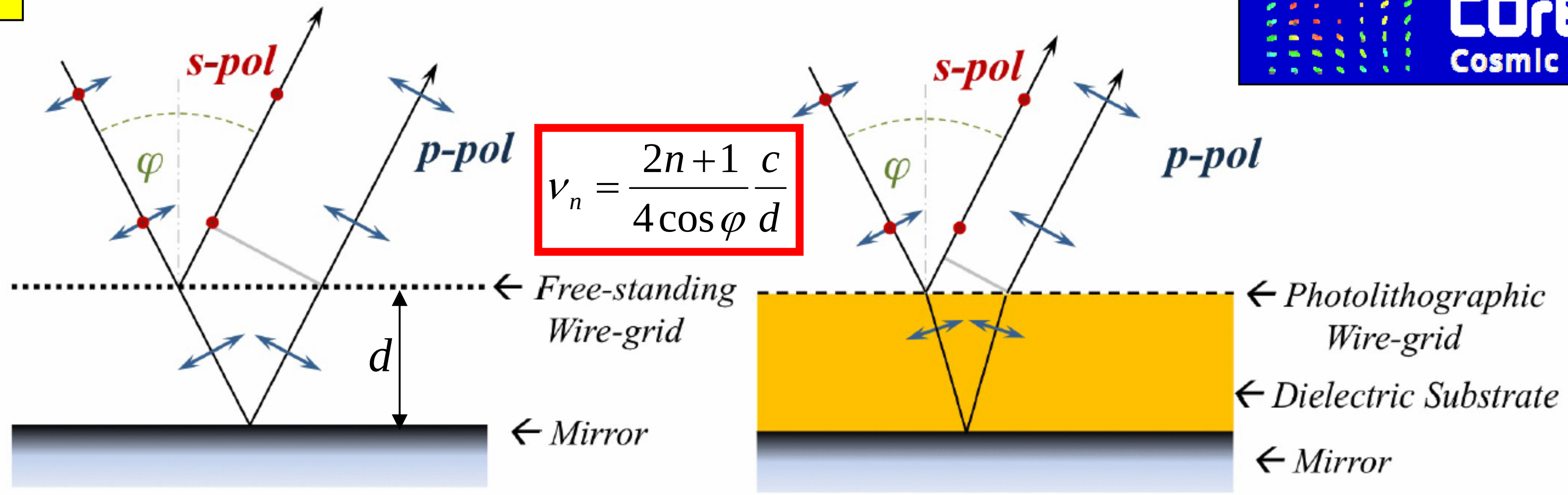

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- Rotating Reflecting-Half-Wave-Plate (RWHP)
  + Modulator = first optical element – polarization purity of following elements not critical
  + Must be rotated for modulation – simple mechanical system
  + Many bands (many orders) – wide frequency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

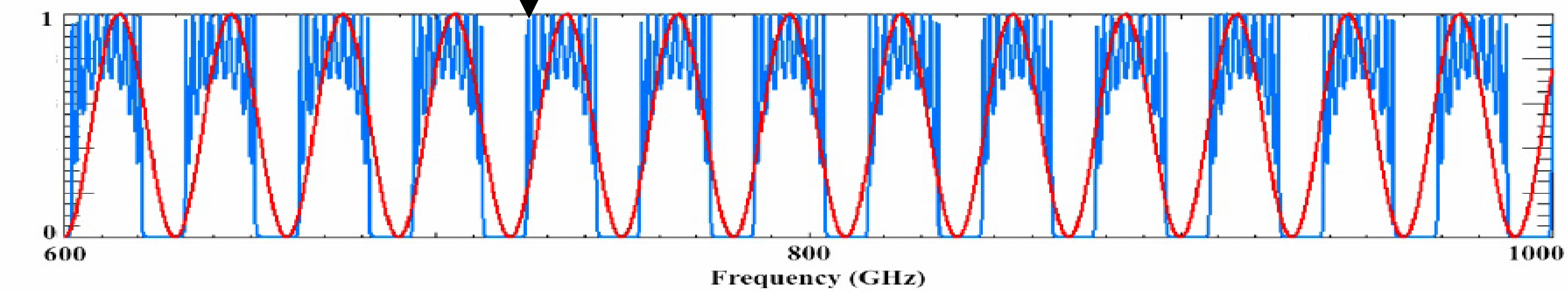
1)

COrE Cosmic Origins Explorer

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

ν GHz	$(\Delta\nu)$ GHz	n_{det}	θ_{fwhm} arcmin	Temp (I) μK·arcmin RJ	Temp (I) μK·arcmin CMB	Pol (Q,U) μK·arcmin RJ	Pol (Q,U) μK·arcmin 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
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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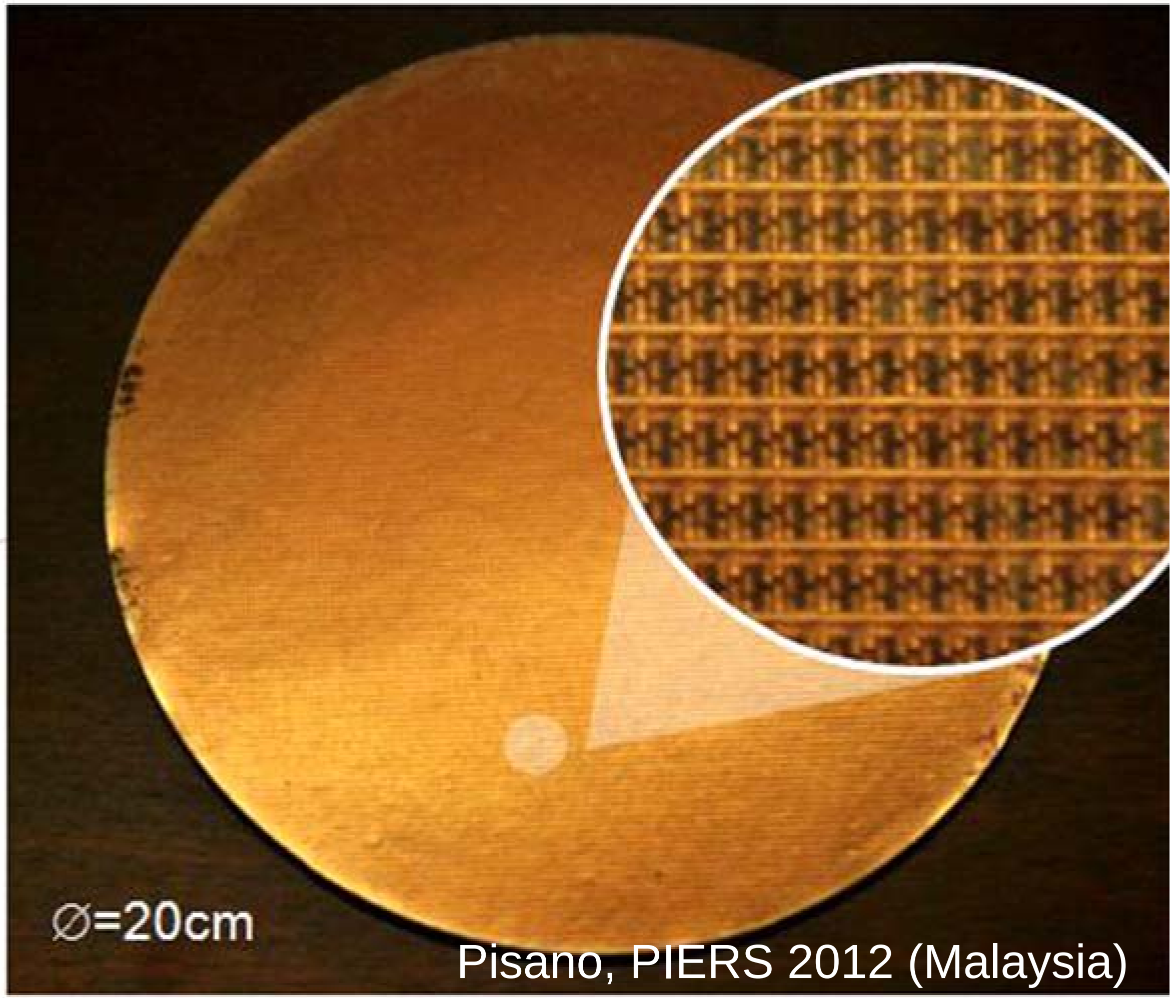
- Embedded-mesh design flexible and effective
- Small (20 cm) prototypes already exist and perform
- ESA ITT issued for larger prototypes, target 1.5 m (Manchester)



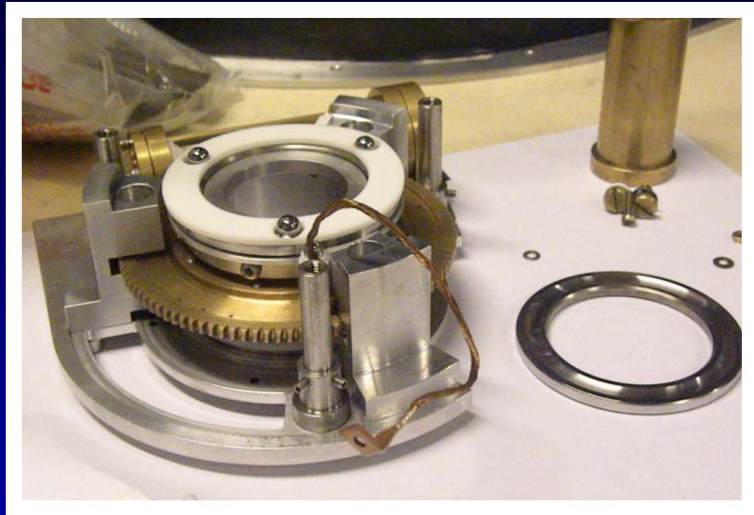
Pisano, PIERS 2012 (Malaysia)

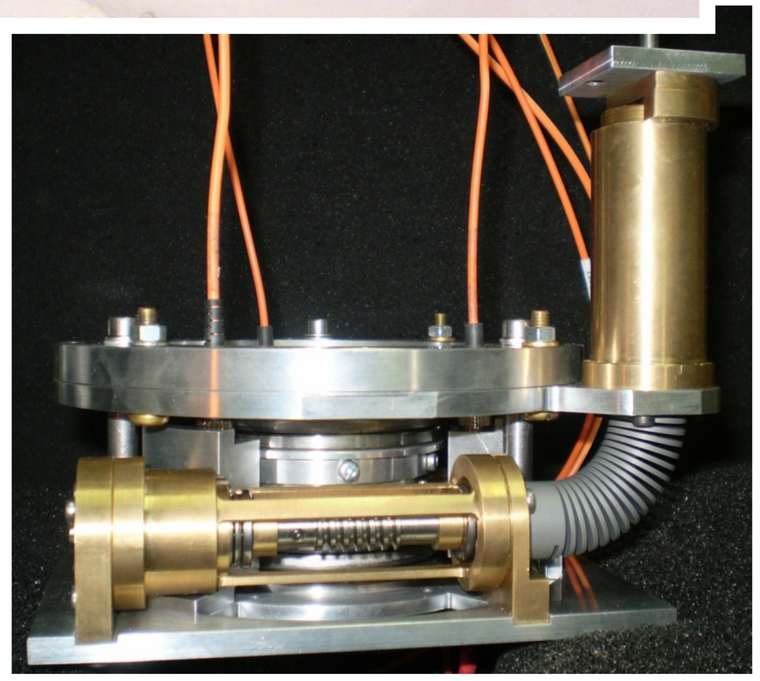
1)

Rotator & flatness

COrE
Cosmic Origins Explorer

- 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)

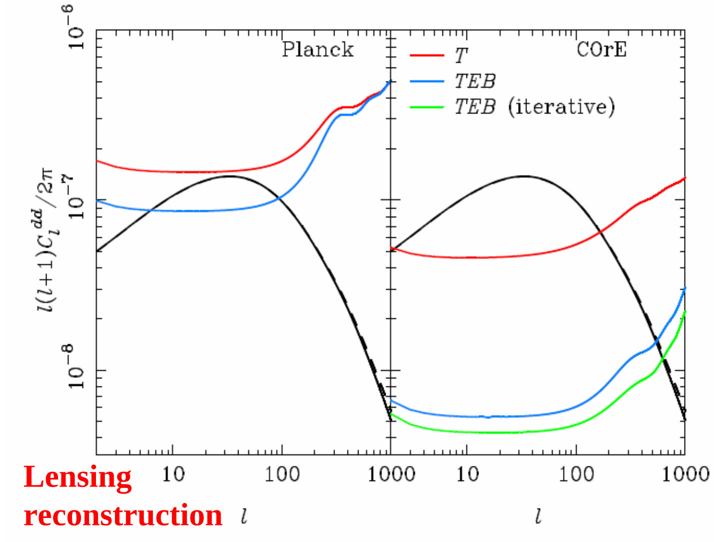




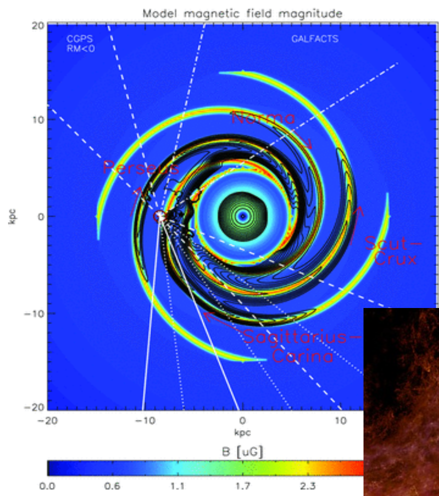
2)

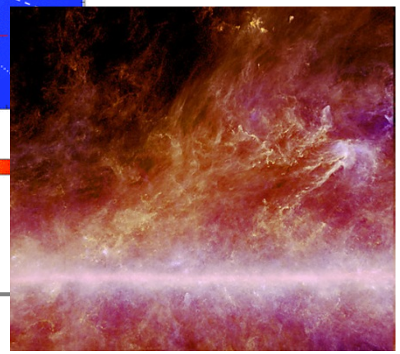
Requirements from science and possible implementation

- 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.



- 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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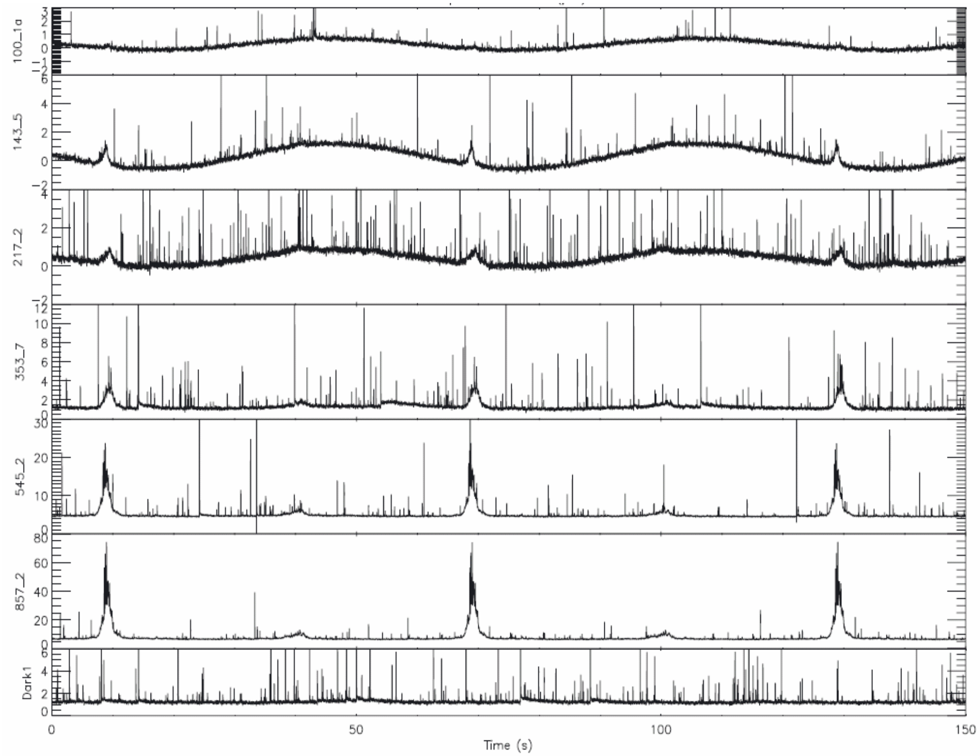
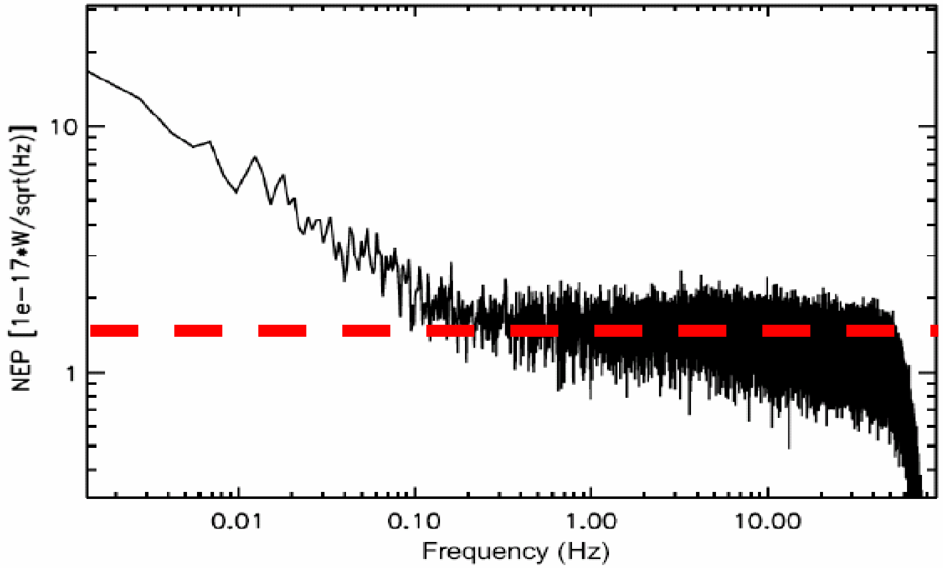
2) Detectors Count & Focal-plane real-estate

- 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)

COrE
Cosmic Origins Explorer

Requirements from science and possible implementation

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

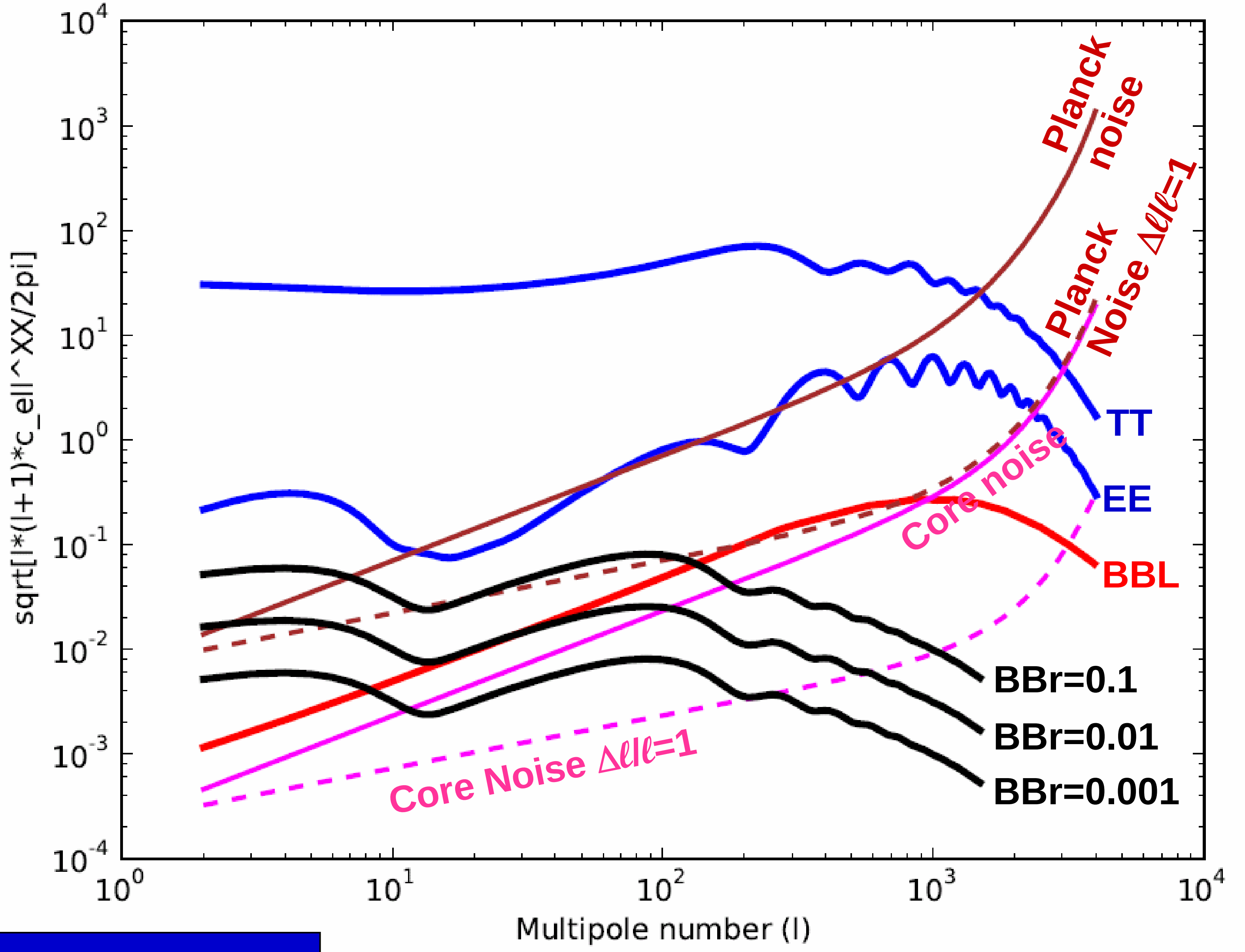
Horn FWHM (deg)	36						T =	4	years
solid angle (sr)	0.31006						=	12614[illegible]	
freq (GHz)	numb	Wavelength (m)	throughput 1 pix (lamb^2)	thru all (m2 sr)	FP area (m2)	focal plane diam (m)	FWHM (')	uK sqrt(s)	uK arcmin
45	200	6.67E-03	4.44E-05	8.89E-03	2.87E-02	1.91E-01	23.3	50	3.8
75	200	4.00E-03	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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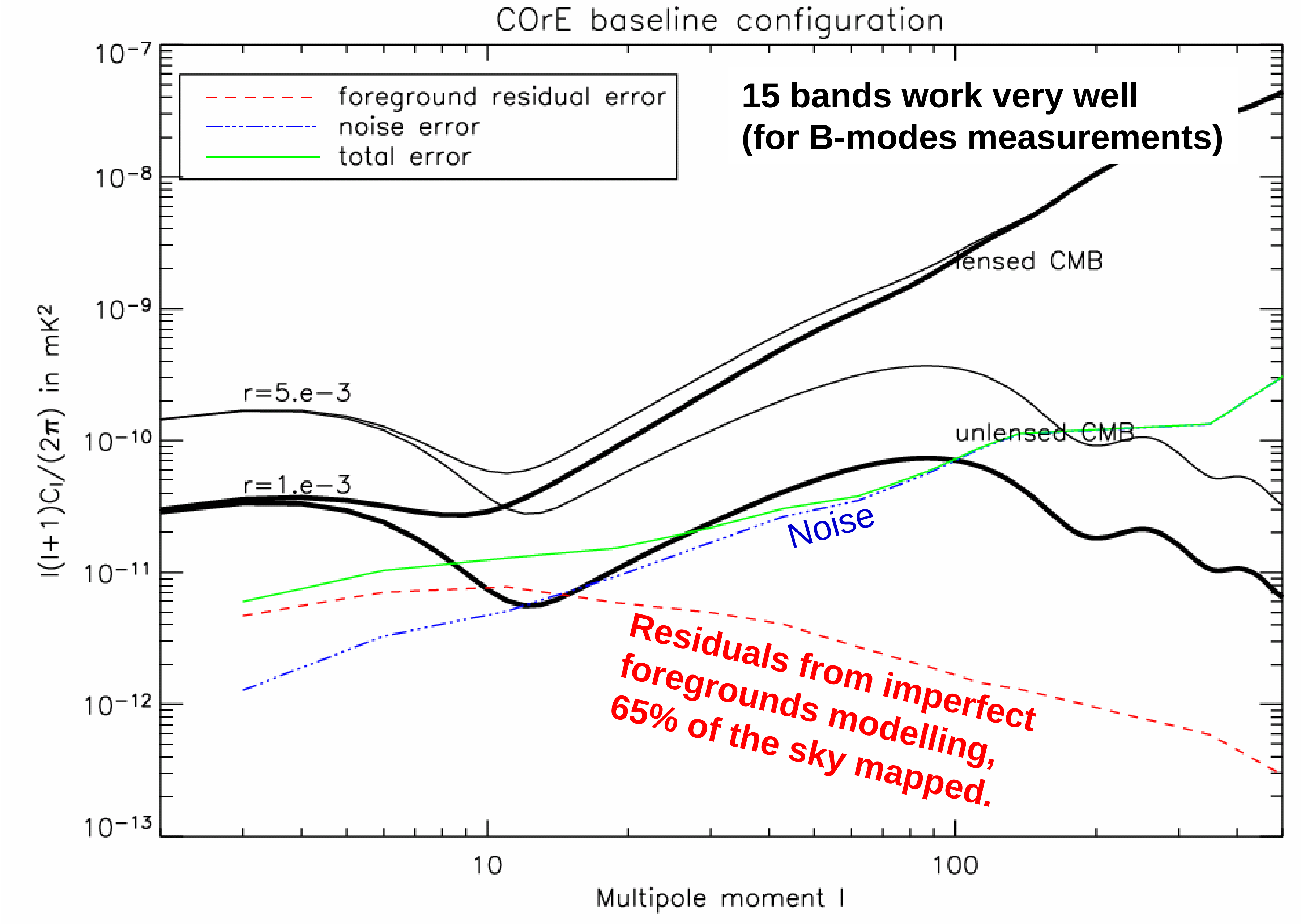
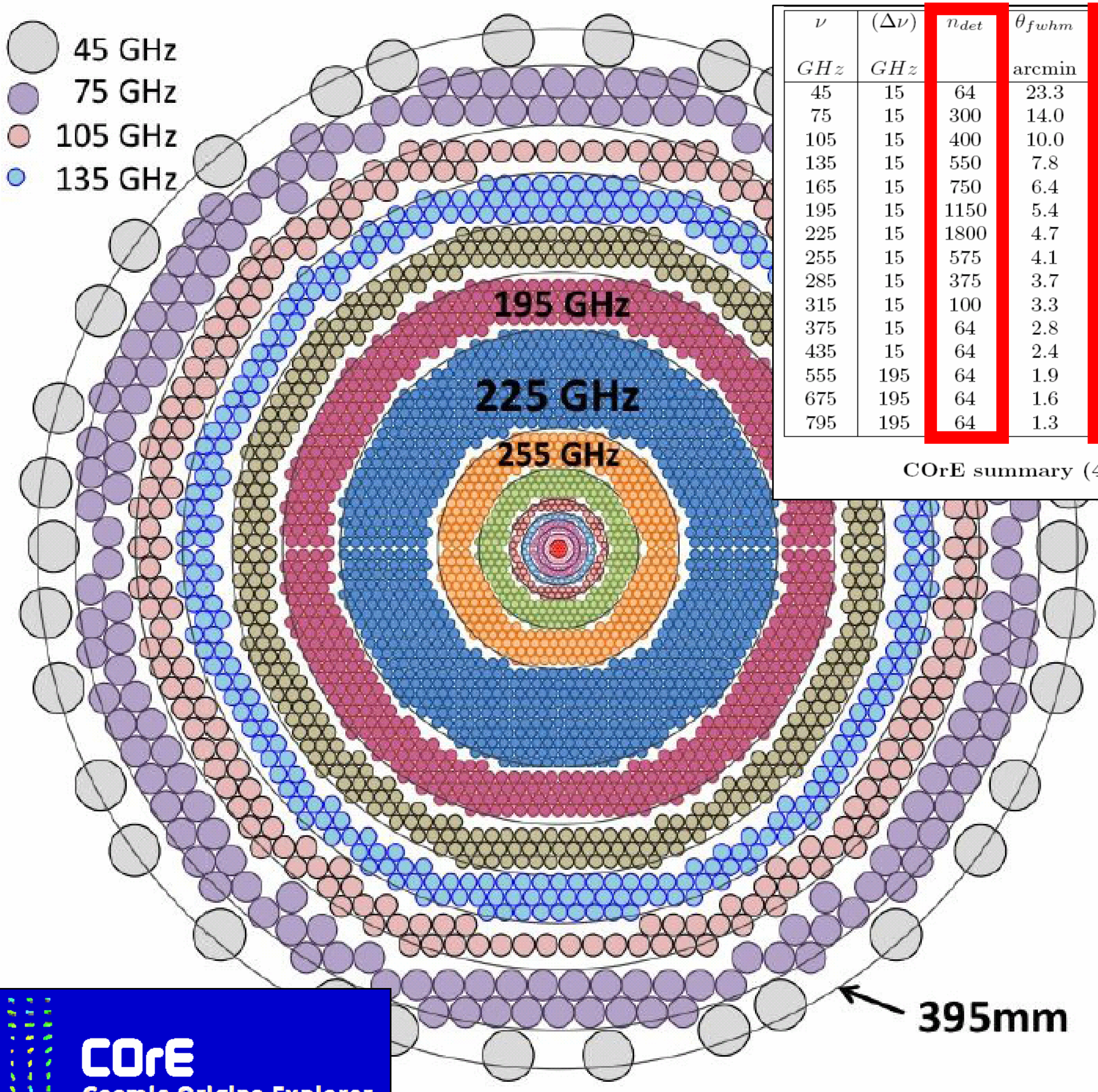
3)

Wide frequency coverage



2)

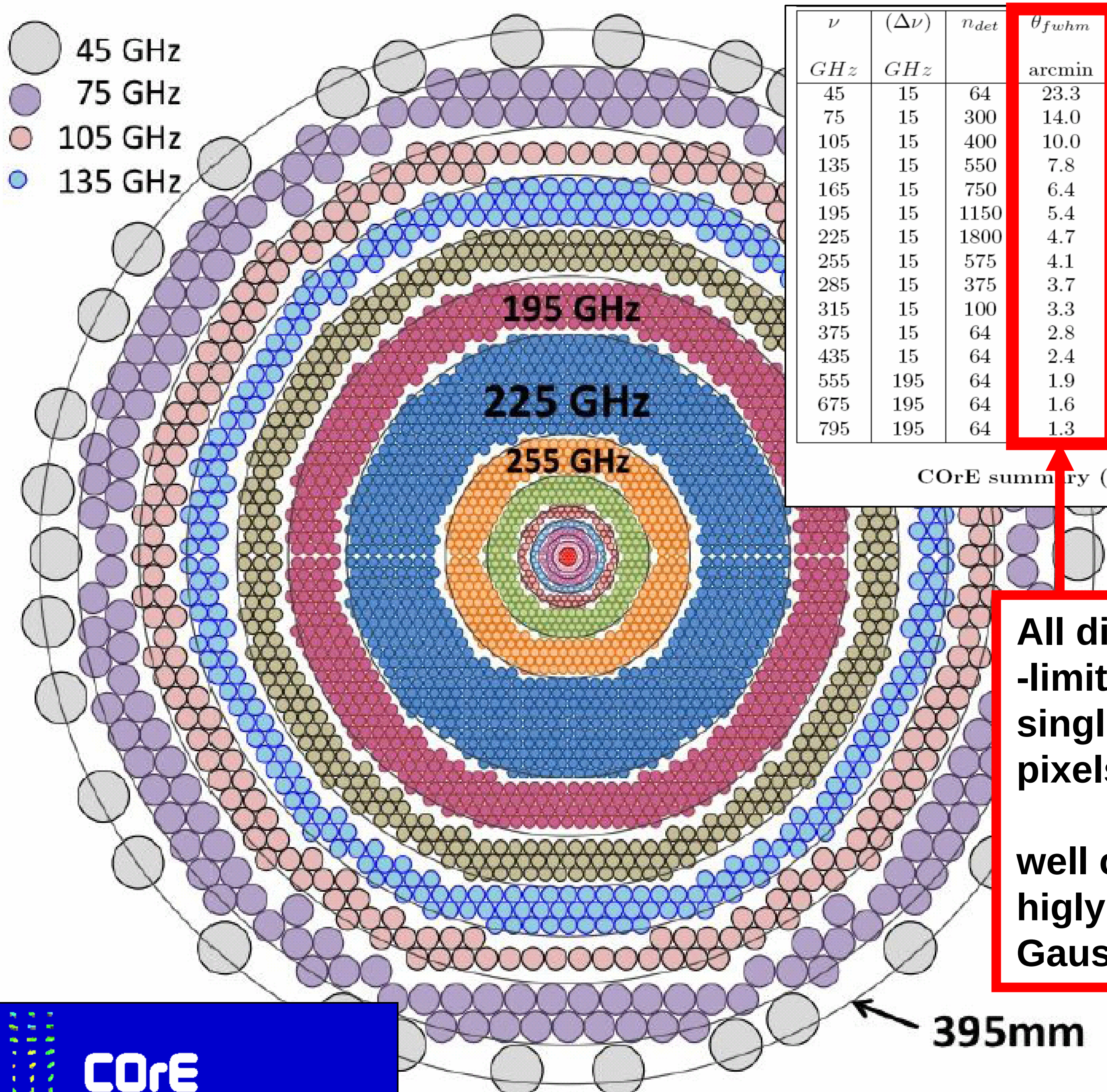


ν GHz	$(\Delta\nu)$ GHz	n_{det}	θ_{fwhm} arcmin	Temp (I) $\mu K\cdot$arcmin RJ	Temp (I) $\mu K\cdot$arcmin CMB	Pol (Q,U) $\mu K\cdot$arcmin RJ	Pol (Q,U) $\mu K\cdot$arcmin CMB
45	15	64	23.3	4.98	5.25	8.61	9.07
75	15	300	14.0	2.36	2.73	4.09	4.72
105	15	400	10.0	2.03	2.68	3.50	4.63
135	15	550	7.8	1.68	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)

COrE
Cosmic Origins Explorer

2)



ν	$(\Delta\nu)$	n_{det}	θ_{fwhm}	Temp (I) μK·arcmin		Pol (Q,U) μK·arcmin	
GHz	GHz		arcmin	RJ	CMB	RJ	CMB
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795	195	64	1.3	1.31	8070	3.60	22200

COrE summary (4 year mission)

All diffraction--limited, single-mode pixels:

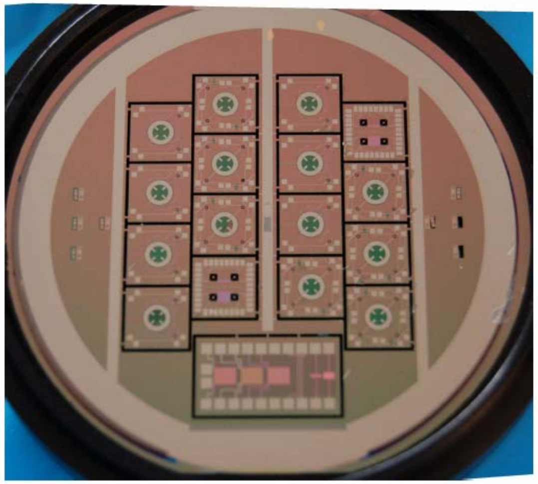
well controlled, higly circular Gaussian beams !

COrE
Cosmic Origins Explorer

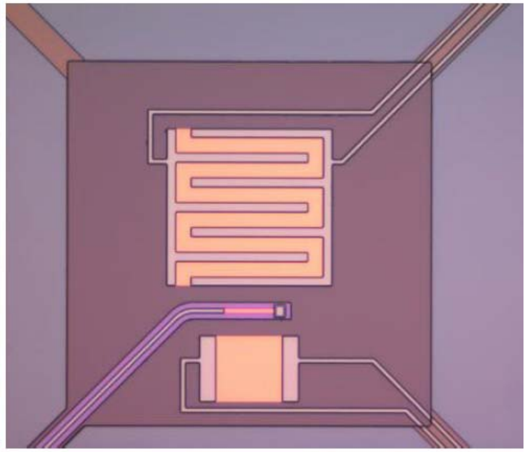
2)

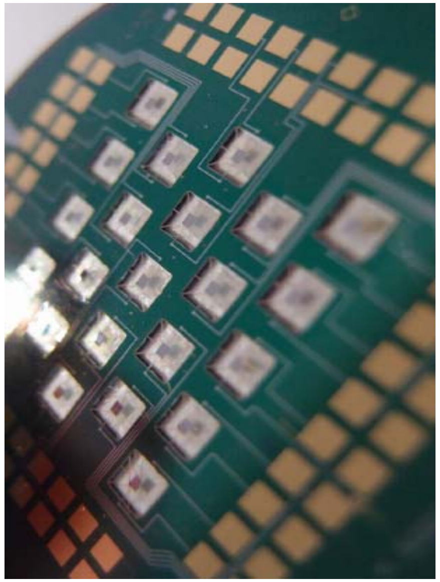
TES bolometer technology :

- 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



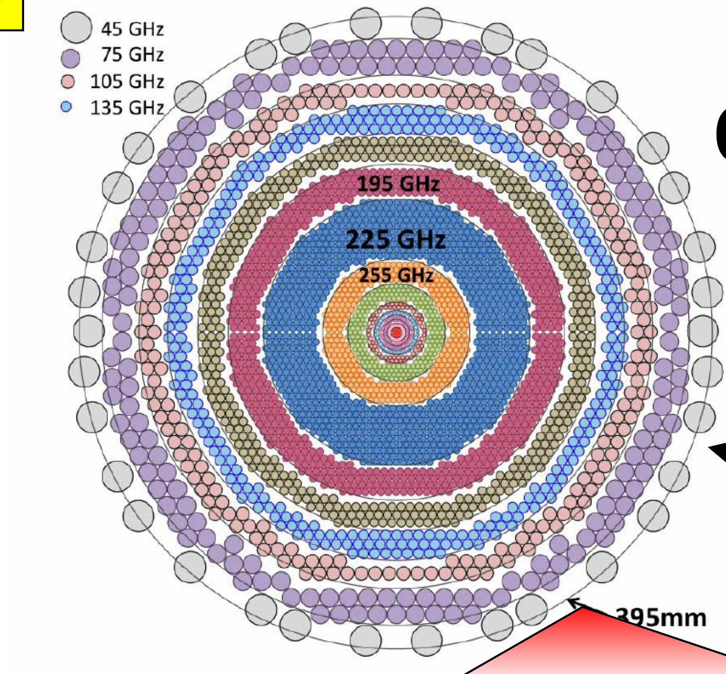


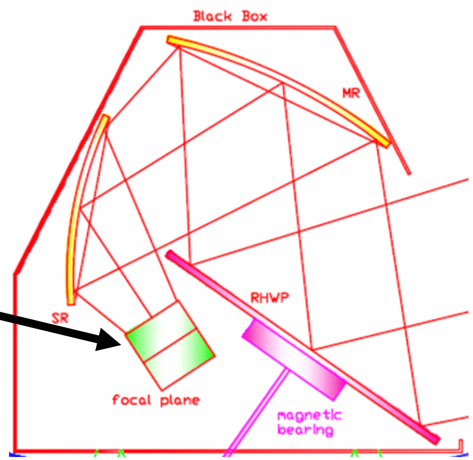
M. Piat et al. Paris

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

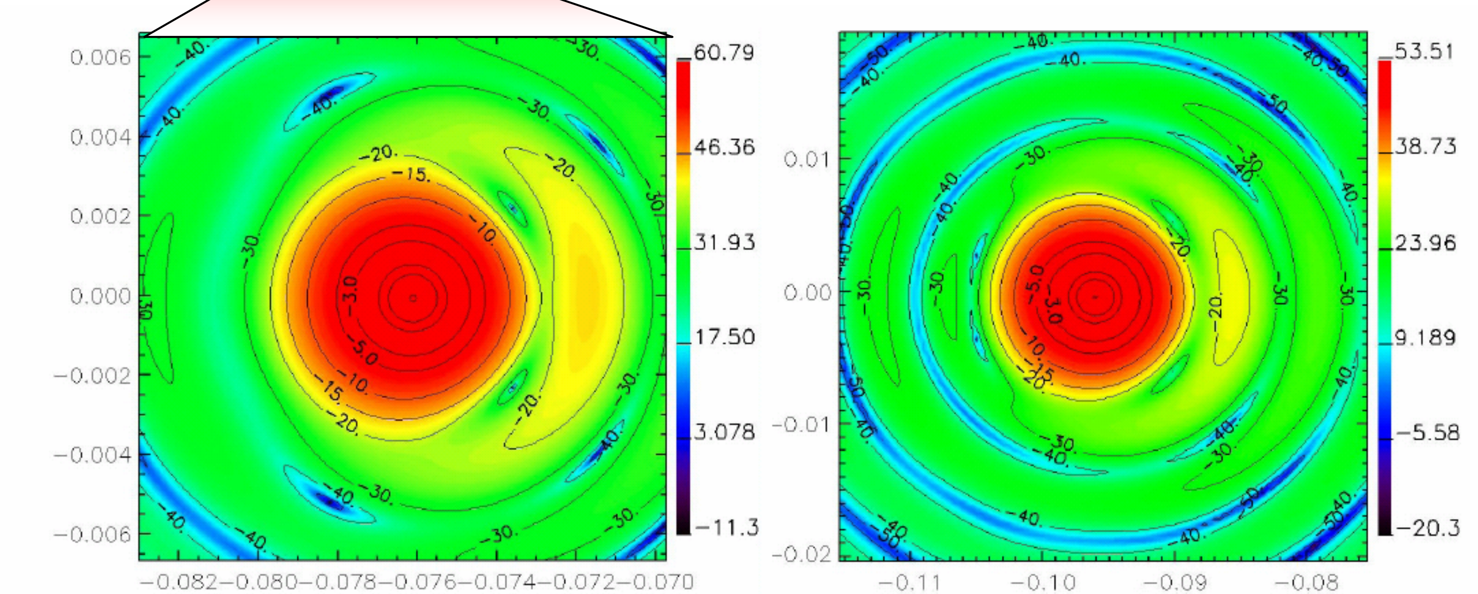
4)

Large Telescope & clean, wide focal plane





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

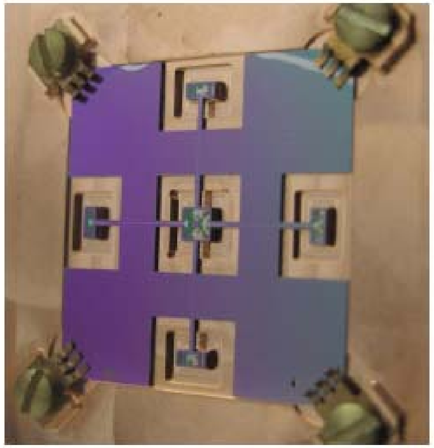


Very wide focal plane, with < 5% ellipticity even at the edges (400 mm diam)

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 & (Maynooth).



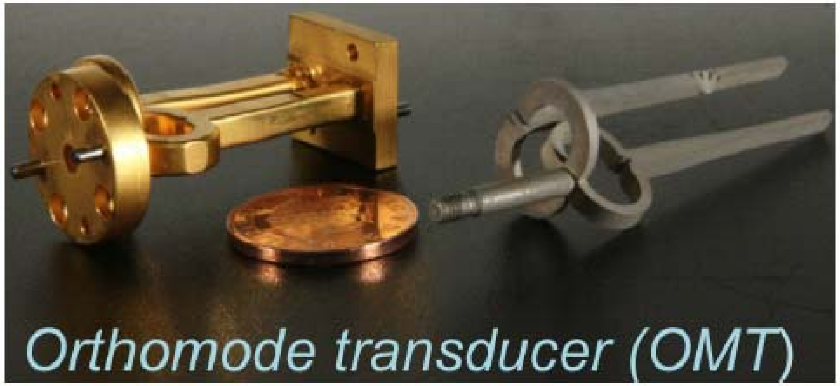
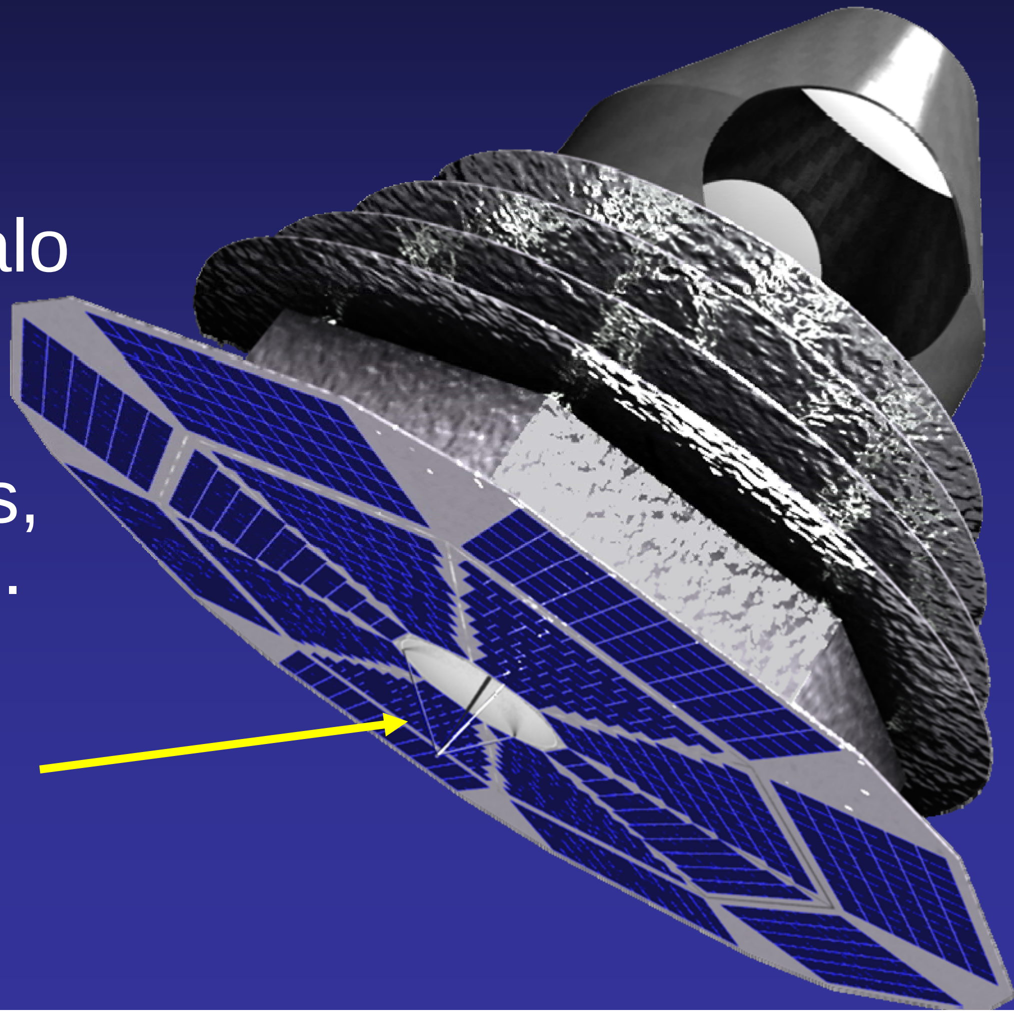


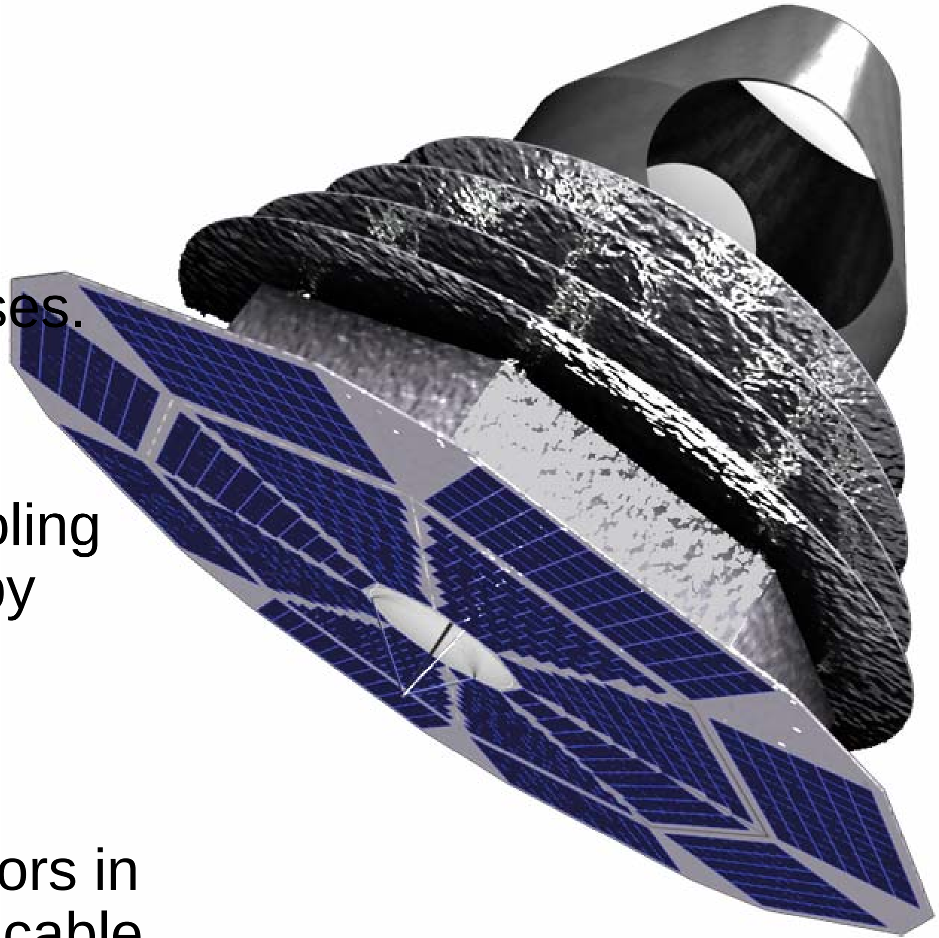
Figure 26: Left: prototype of 100 GHz planar OMT (Fr). Right: Clover 97 GHz waveguide OMT (UK).

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**



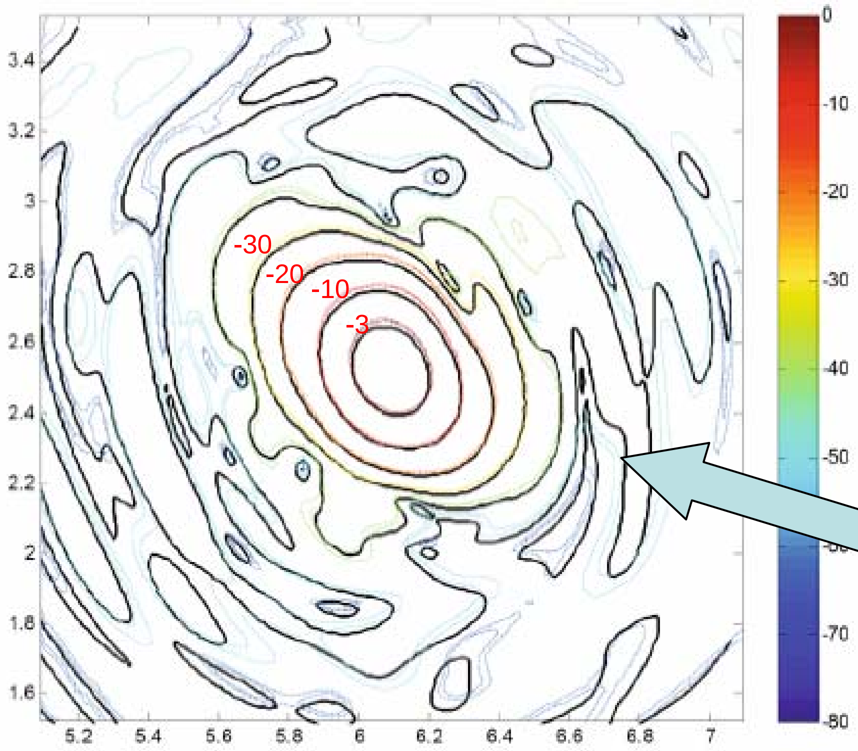
For both M missions:
Use of the HWP – why ?

- Wouldn’t be easier to rotate the whole instrument, with polarized detectors, or rotate a polarizer ?
- The added complexity of the HWP is well justified, because of beam – polarization coupling effects.
- Off-center, with large focal planes :
  - Polarization introduced by the telescope (a few %, so cannot use a rotating WG or HWP following the telescope)
  - Ellipticity of beams (so cannot rotate the entire telescope)

astro-ph/1101.2039 **PLANCK HFI**

Band	Expected FWHM [′]	Mars FWHM [′]	Mars σ_{FWHM} [′]	Expected ellipticity	Mars ellipticity	Mars σ_{ellip}
100P	9.58	9.37	0.06	1.17	1.18	0.006
143P	6.93	6.97	0.10	1.06	1.02	0.004
143	7.11	7.24	0.10	1.03	1.04	0.005
217P	4.63	4.70	0.06	1.12	1.13	0.006
217	4.62	4.63	0.06	1.10	1.15	0.010
353P	4.52	4.41	0.06	1.08	1.07	0.009
353	4.59	4.48	0.04	1.23	1.14	0.007
545	4.09	3.80	–	1.03	1.25	–
857	3.93	3.67	–	1.04	1.03	–

(b-a)/a >1% everywhere in the focal plane



Tauber et al. A&A 520, A2 (2010)

Significant ellipticity expected and measured for detectors in the outer focal plane. PLANCK LFI.

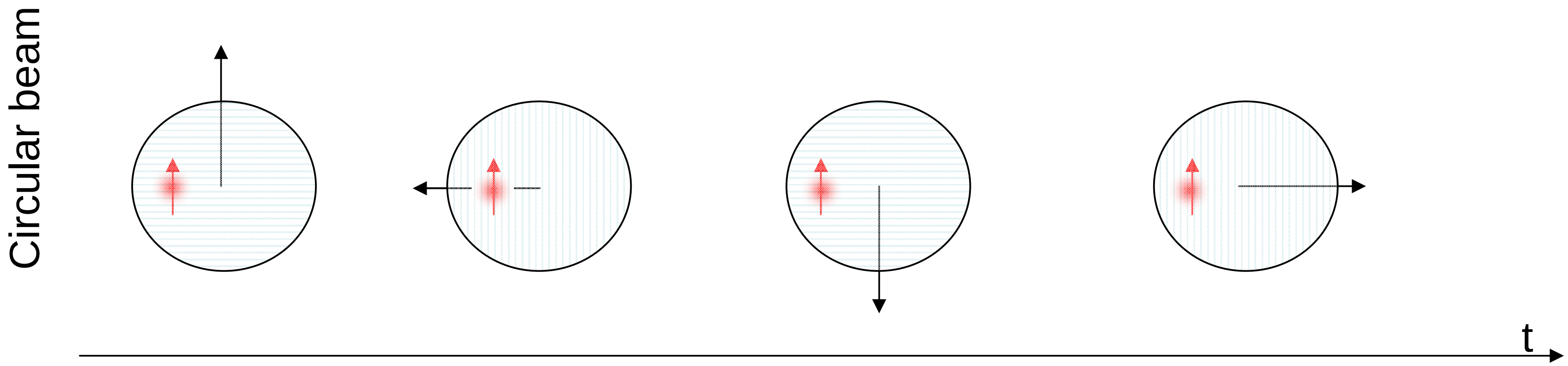
Increasing off-LOS (where it is more difficult to measure)

Planck LFI 70 GHz, main beam, copolar. *b/a*=1.26

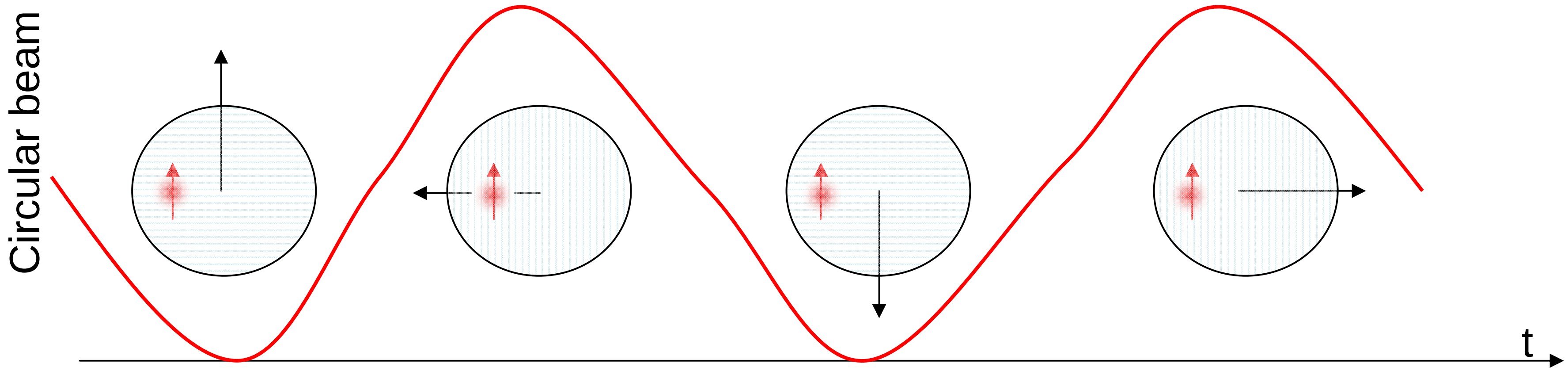
Measurement error = 0.13dB @ -3dB

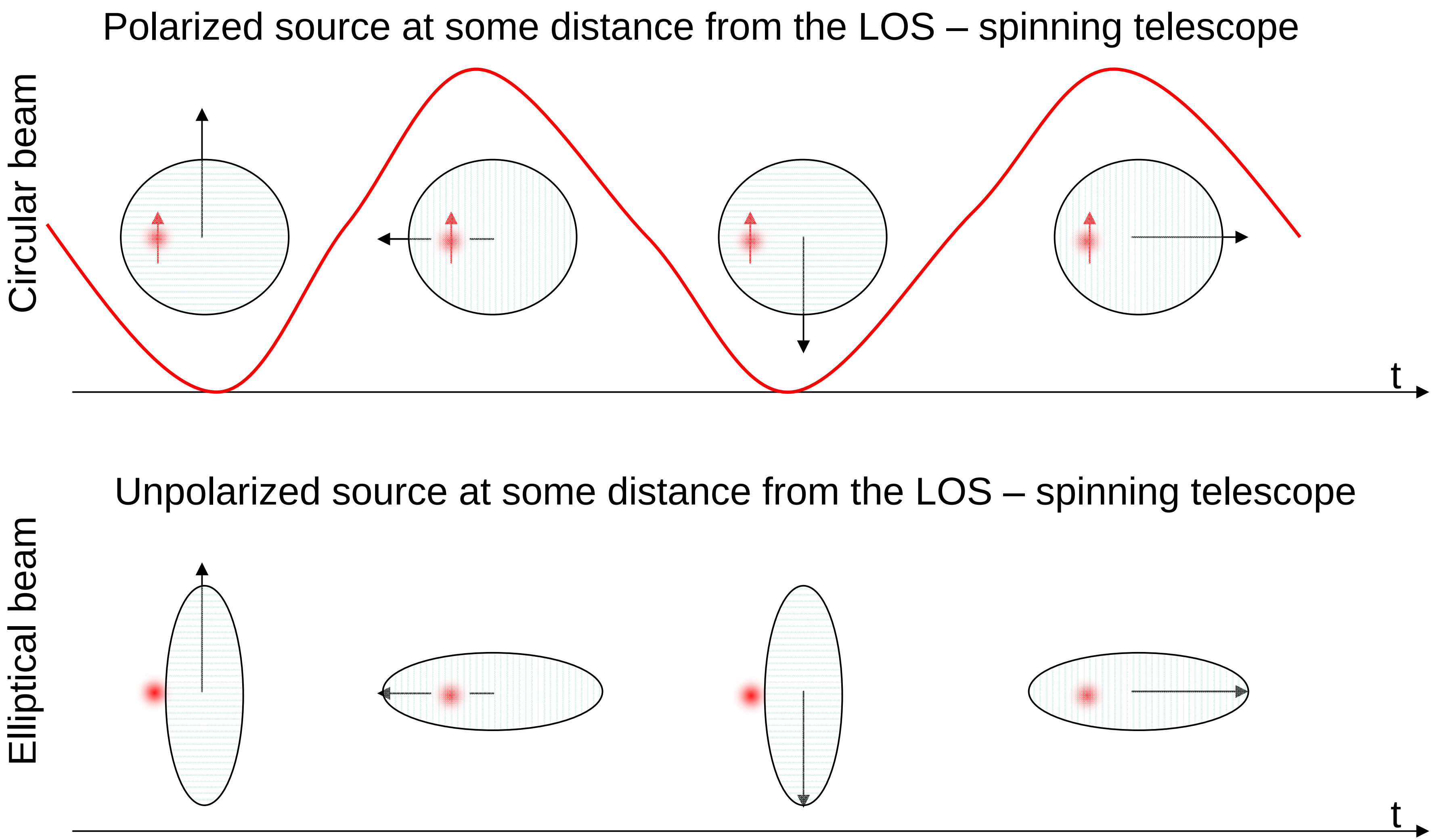
(3% at the FWHM)

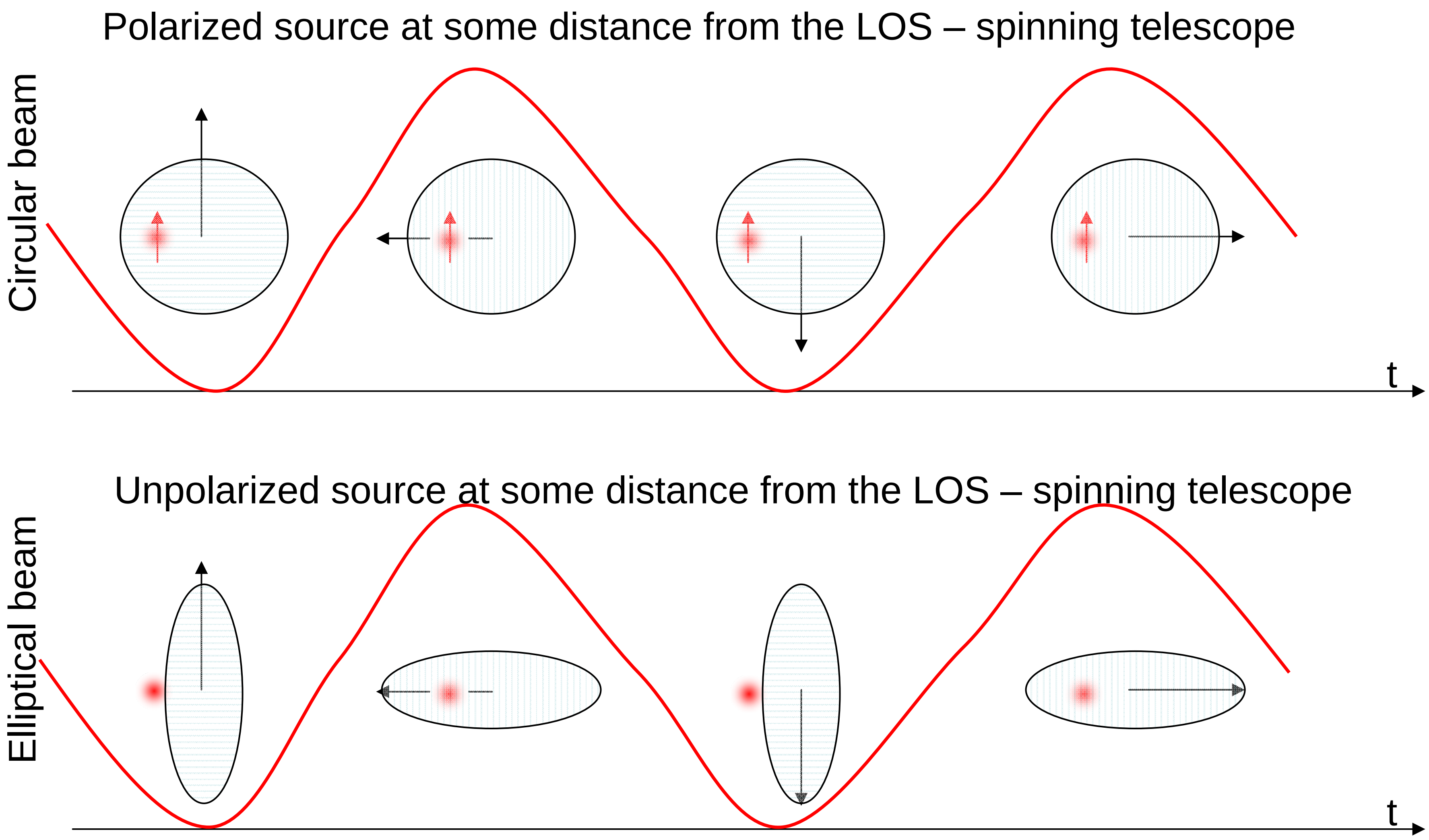
Polarized source at some distance from the LOS – spinning telescope



Polarized source at some distance from the LOS – spinning telescope




Polarized source at some distance from the LOS – spinning telescope
Circular beam
t
Unpolarized source at some distance from the LOS – spinning telescope
Elliptical beam
t



The shape of the signal vs spin angle is exactly the same.
Direct coupling T ➔ P

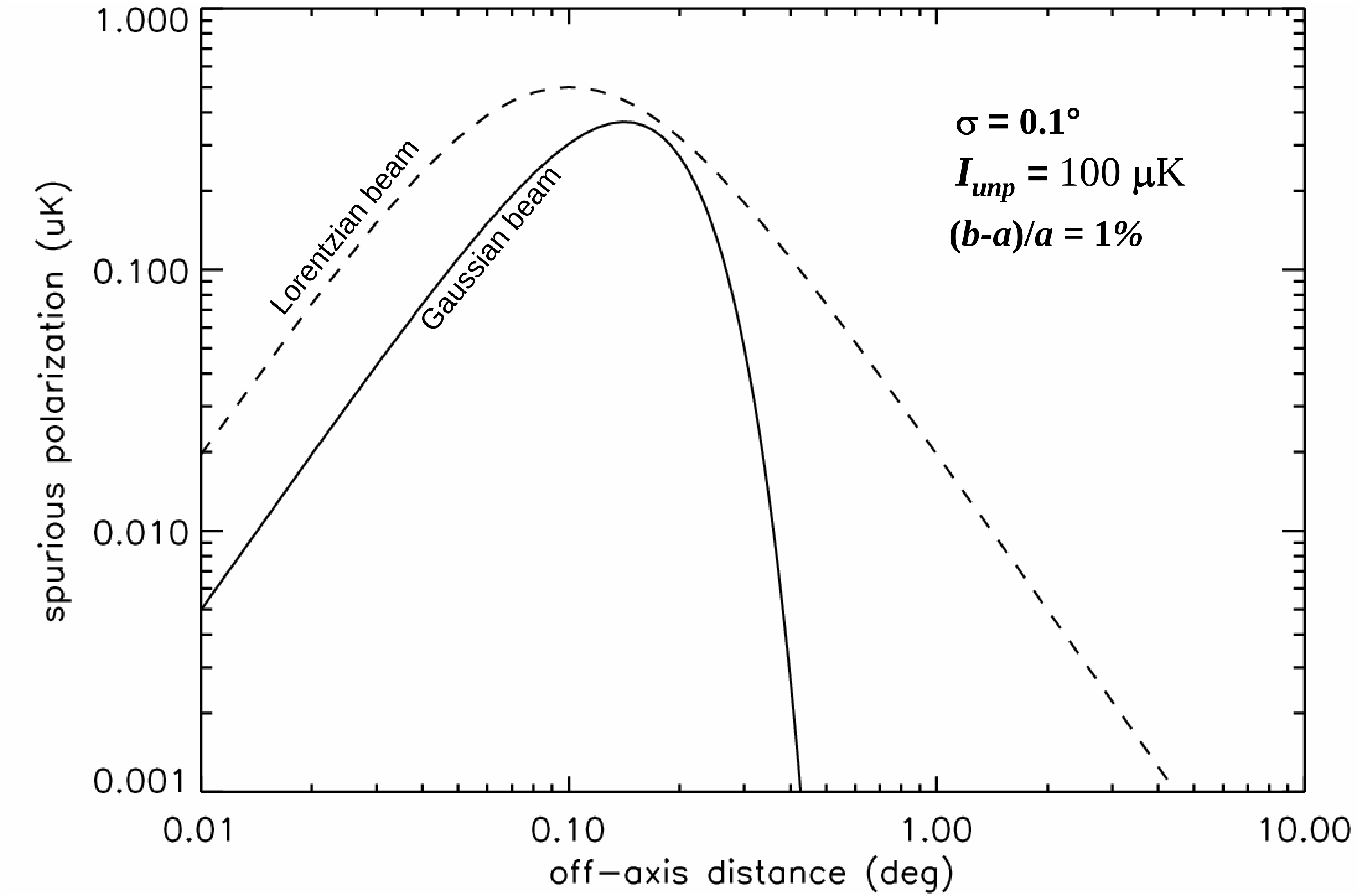
For an elliptical Gaussian beam

- Low Ellipticity $\varepsilon=(b\text{-}a)/a<<1$
- Unpolarized source signal I
- Detected polarized signal

$$\Delta T_{p,\max} \cong 0.3\mu K \left(\frac{\varepsilon}{1\%}\right)\left(\frac{I}{100\mu K}\right)$$

- for source distance $\theta_{\max} \cong \sqrt{2}a$

Spinning telescope - Main beam – ellipticity effects



Compact sources

- Are many, and produce spurious polarization signals with different amplitudes and phases. Effect somehow diluted, but number of sources at the most efficient distance is not large.

- Their spectrum is not the same as the CMB one. However, the beam is likely to be very different at different wavelengths, so the foregorund removal process becomes very complex.

Primary CMB anisotropy leakage

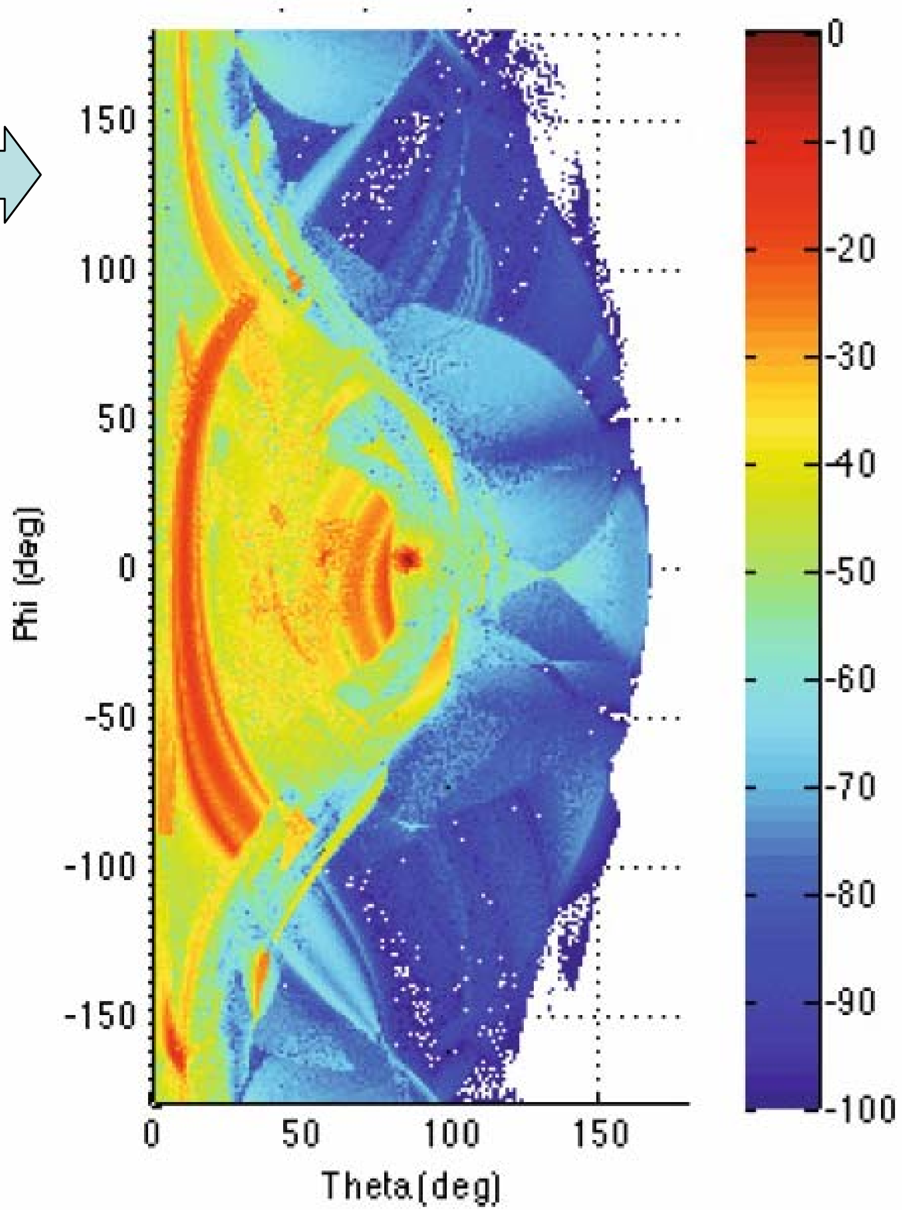
- CMB blobs have the same spectrum as CMB polarization – no spectral discrimination
- They are present for sure in every pointed direction.
- Smaller spurious polarization signal, order 0.1 μK (E *and* B) … still a concern for our target !

Diffuse sources

- Dangerous effect of large-scale gradients of diffuse galactic emission in the far sidelobes of the rotating beam.
- Structure of far sidelobes very complex and different for different frequency channels.
- Far sidelobes are polarized, thus adding complexity.

Diffuse sources

- Expected spillover in Planck 353GHz (Tauber et al. A&A 520, A2 (2010)).
- In a spinning telescope, the convolution of the rotating spillover/far-sidelobes pattern with large-scale sky signals (Galaxy, CMB dipole etc.) will produce a baseline variation, of few μK at 100 GHz.
- This signal is synchronous with rotation, and repeatable for repeated observations of the same sky pixel.
- The quadrupole component of this pattern will produce a polarization-like signal.
- **A fraction of a μK ?**



HWP

- All these spurious polarization effects are avoided with the use of a polarization modulator.
- Traditionally, a spinning or stepped HWP.
- Has to be the first element in the optical chain.
  - Its size limits the size of the telescope aperture.
  - Its spectral efficiency limits the spectral coverage of the entire instrument.
  - It is likely to reduce the sensitivity (narrow bands) …
- .. but reduces very significantly a number of important systematic effects.
- Hear later JD and FP talks.

Technical feasibility of large HWP

- Design concept:
  - Al honeycomb plate (for flatness mass & inertia) with deposited dielectric-embedded reflective HWP: < 20 kg, < 5 kg m^2 rotating assembly. Lower mass & I with CFRP, also possible.
  - Flexible Cu straps for temperature uniformity
  - Launch latches
  - Low conductivity (8 mW) shaft connecting HWP assembly to motor in service module (conductivity of shaft << conductivity of supports)
- ESA-ITT
  - At the moment, ϕ1.5m RHWP looks feasible
  - Hear Pisano later.