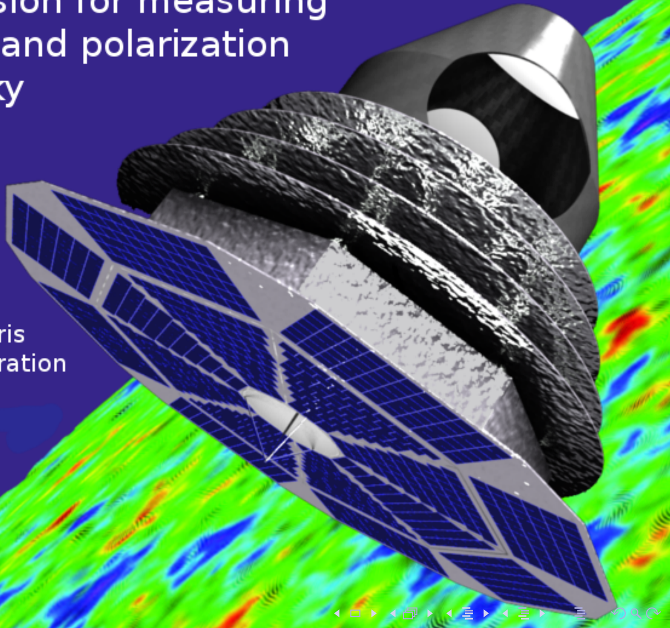
COrE : Cosmic Origins Explorer

A space mission for measuring microwave band polarization on the full sky

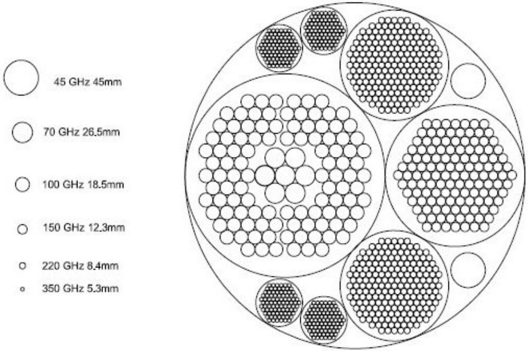


Martin Bucher, APC Paris
for the COrE Collaboration

History–European polarization satellites

- (circa 2006) CNES SAMPAN study - a refracting telescope - Conclusion : too expensive for France to do it alone, should explore mission in a European context
- (2006 - 2007) B-Pol defined (main partners : France, Germany, Italy, Spain, United Kingdom with a expression of interest from several US groups) proposal submitted in 2007 to ESA as a class M mission. Judged not technologically not ready, bets too much on a single and uncertain scientific objective, (i.e., B modes). Design : several telescopes for the various frequencies)
- (Jun 2010) Announcement of an M3 slot in the framework of ESA Cosmic Vision, remobilization of European collaboration, attempt to improve performance within the budget, to expand the science case, documents available at (www.core-mission.net). COrE was not selected but ranked 4th by the AWG, 3 projects were forwarded by the AWG to the SSAC. Disappointing but not bad ! !

B-Pol (2007)


45 GHz 45mm
70 GHz 26.5mm
100 GHz 18.5mm
150 GHz 12.3mm
220 GHz 8.4mm
350 GHz 5.3mm

COrE : Cosmic Origins Explorer

Proposed to ESA in December 2012 as a Cosmic Vision M3 Mission for ≈ 2020
http ://www.core-mission.org
White paper available (90 pages) (astro-ph/1102.2181)
Answers to AWG Questions (available on website)

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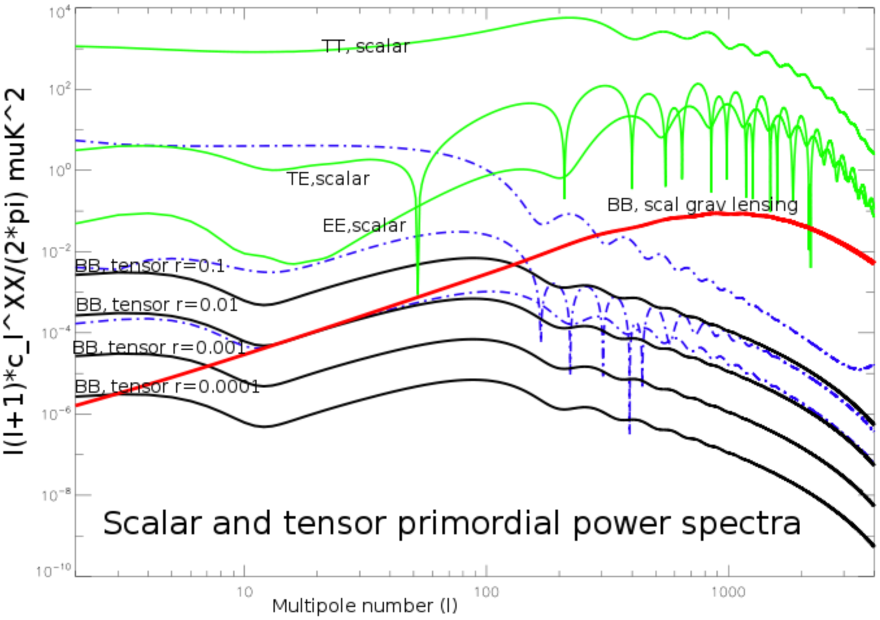
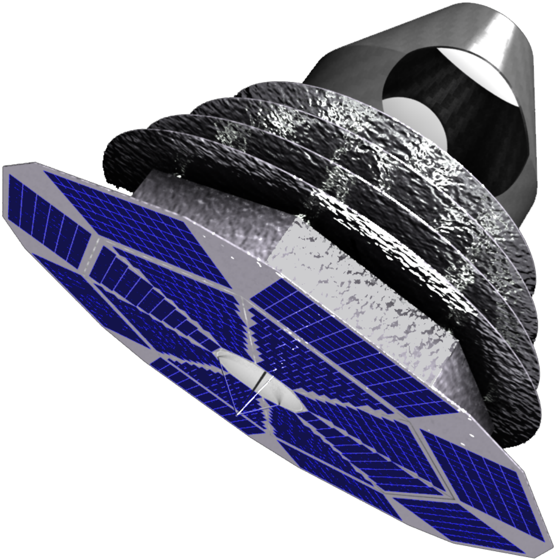
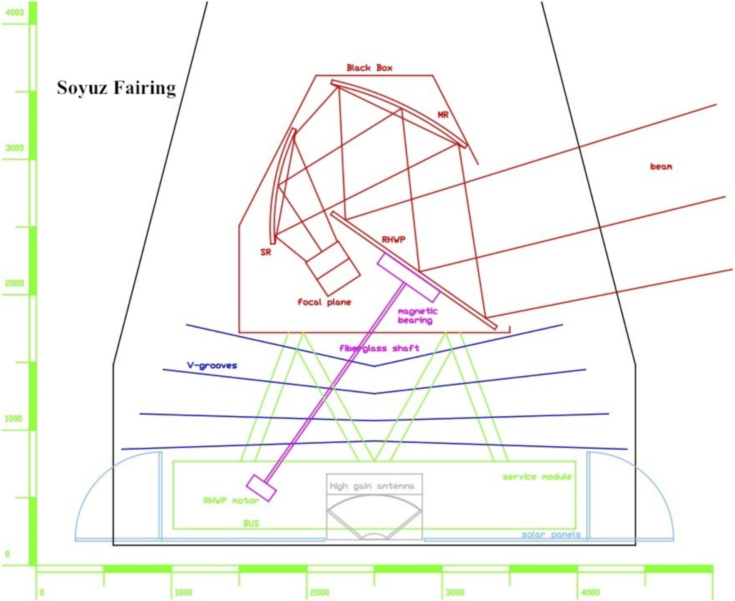


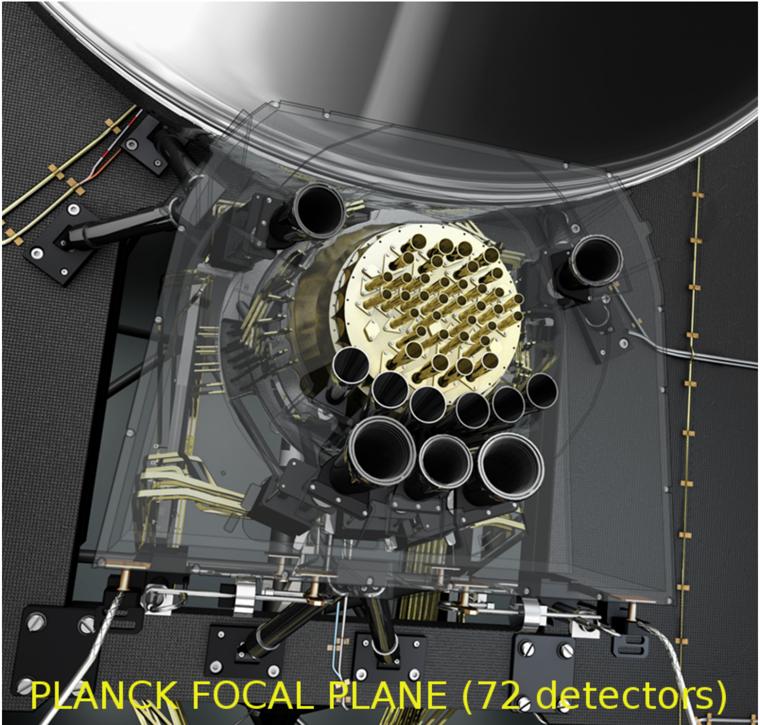
l(l+1)*c_l^XX/(2*pi) muK^2
TT, scalar
TE,scalar
EE,scalar
BB, scal grav lensing
BB, tensor r=0.1
BB, tensor r=0.01
BB, tensor r=0.001
BB, tensor r=0.0001
Scalar and tensor primordial power spectra
10
100
1000
Multipole number (l)

CAD realization of COrE design

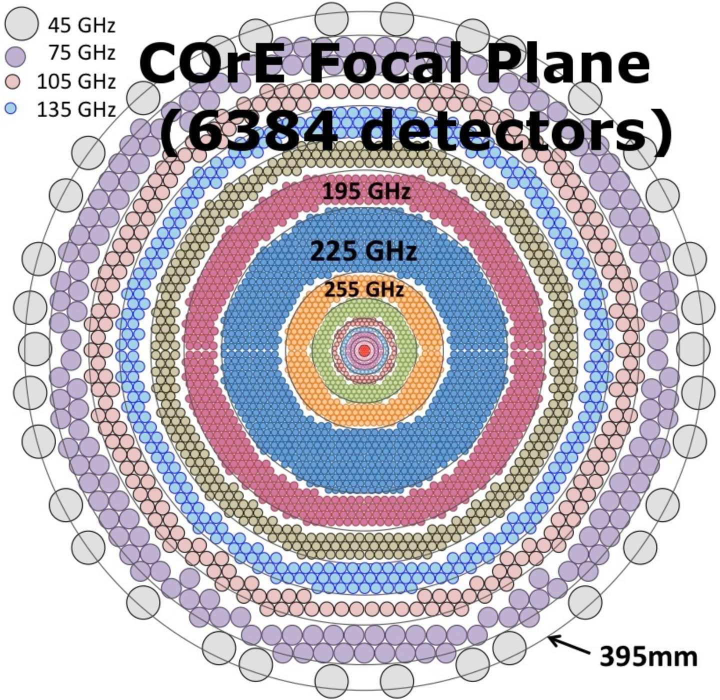


COrE schematic




PLANCK FOCAL PLANE (72 detectors)

COrE Focal Plane (6384 detectors)



Photon shot noise

For a single mode :

$$\langle N \rangle = \Big(\exp(x) - 1\Big)^{-1}, \qquad x = \left(\frac{h\nu}{k_B T_{CMB}}\right) = \left(\frac{\nu}{57\ GHz}\right)$$

$$\langle N^2 \rangle = 2\langle N \rangle^2 + \langle N \rangle, \qquad \langle (\delta N)^2 \rangle = \langle N \rangle^2 + \langle N \rangle = N^2 + N$$

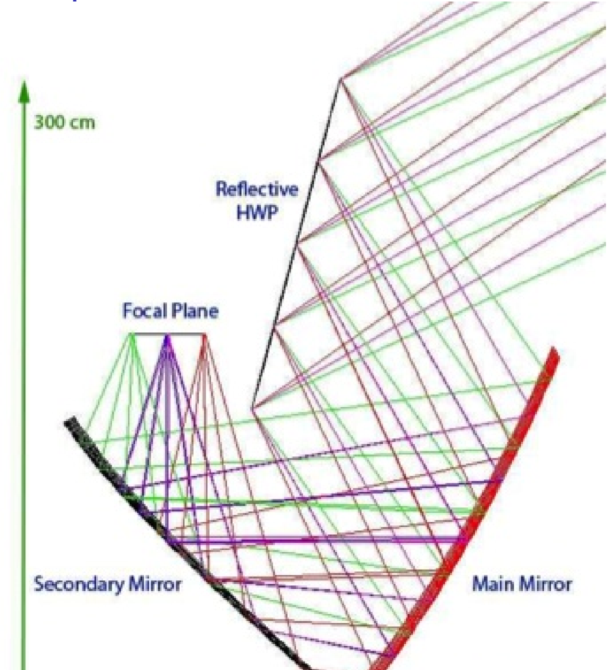
$$\left(\frac{\delta N}{N}\right) = \sqrt{1 + N^{-1}}$$

For $x \gg 1$, pure Poissonian noise, almost. For $x \ll 1$, photon bunching (Hanbury Brown and Twiss) photons arrive roughly in bunches of N, these correlations augment noise relative to Poisson distribution.
Radio astronomers' formula (quantum corrected)

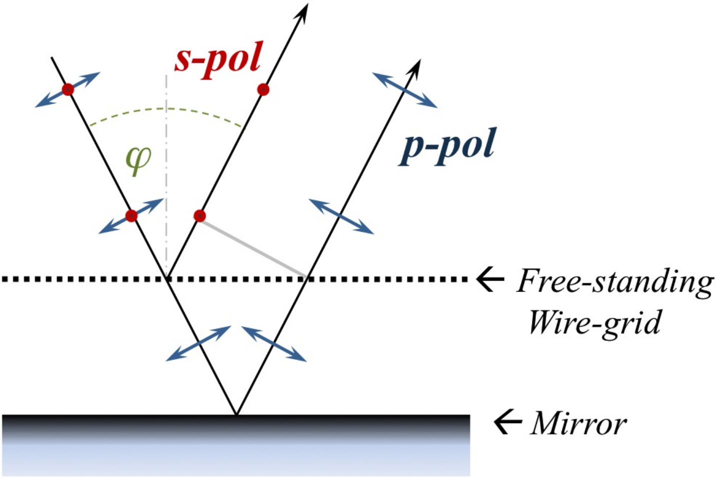
$$\left(\frac{\delta I}{I}\right) = \frac{1}{\sqrt{N_{det}}} \left(\frac{T_{sky} + \epsilon_{tel} T_{tel}}{T_{sky}}\right) \frac{1}{\sqrt{(\Delta\nu) t_{obs}}} \sqrt{e^{-1} + n_{occ}^{-1}}$$

$e =$ (quantum efficiency) $=$ (prob. γ is absorbed), $\qquad T_{sky} \approx T_{CMB}$
$\epsilon_{tel} =$ (telescope emissivity)

Core Optics


300 cm
Reflective HWP
Focal Plane
Secondary Mirror
Main Mirror

Polarization Modulation—Rotating Half-Wave Plate



Polarization modulation with a rotating half-wave plate

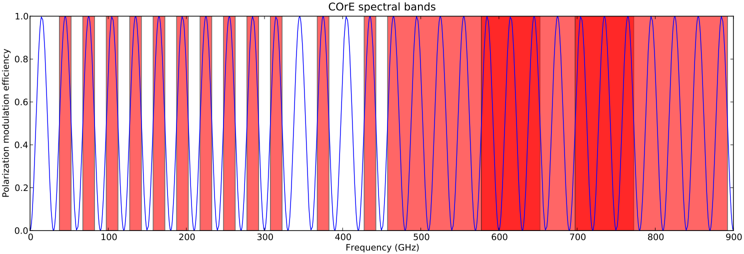
$$\begin{pmatrix} E_x^{(tel)} \\ E_y^{(tel)} \end{pmatrix} = \begin{pmatrix} \cos \Omega t & \sin \Omega t \\ -\sin \Omega t & \cos \Omega t \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} \cos \Omega t & -\sin \Omega t \\ \sin \Omega t & \cos \Omega t \end{pmatrix} \begin{pmatrix} E_x^{(sky)} \\ E_y^{(sky)} \end{pmatrix}$$

$$\left\langle (E_x^{tel})^2 \right\rangle = I + Q \cos 4\Omega + U \sin 4\Omega t$$

$$\left\langle (E_x^{tel})^2 \right\rangle = I - Q \cos 4\Omega - U \sin 4\Omega t$$

- For measuring polarization, all harmonics —in particular those at $0\Omega t$, $2\Omega t$—are rejected except those at $4\Omega t$ are rejected.
- Stray light that becomes polarized from within telescope is thus rejected. $T_{tel} \rightarrow B\ mode$
- One is not subtracting two measurements with different beamsizes, aliasing T anisotropy into B mode
- Still has to know detector and telescope geometry very accurate ; otherwise, E mode masquerades as B mode

COrE's 15 Spectral Bands



Note that 3 highest bands overlap

- In order to carry out foreground subtraction and provide redundancy for cross-checks 15 bands are required, minus a few. [3 synchrotron-amp.+spect-ind+running, 1 CMB, 2 free-free, 6 dust (2 BBs A+temp+emmis. index)+1 th.sz=13+2(safety)]

ν GHz	n_{unpol}	n_{pol}	θ_{fwhm} arcmin	Temp (I) $\mu K\cdot$arcmin RJ	CMB	Pol (Q,U) $\mu K\cdot$arcmin RJ	CMB
30	4	4	32.7	198.5	203.2	280.7	287.4
44	6	6	27.9	228.0	239.6	322.4	338.9
70	12	12	13.0	186.5	211.2	263.7	298.7
100	8	8	9.9	23.9	31.3	33.9	44.2
143	11	8	7.2	11.9	20.1	19.7	33.3
217	12	8	4.9	9.4	28.5	16.3	49.4
353	12	8	4.7	7.6	107.0	13.2	185.3
545	3	0	4.7	6.8	1.1×10^3	—	—
857	3	0	4.4	2.9	8.3×10^4	—	—

PLANCK (30 month mission)

ν *GHz*	$(\Delta\nu)$ *GHz*	n_{det}	θ_{fwhm} arcmin	Temp (I) $\mu K\cdot$arcmin RJ	CMB	Pol (Q,U) $\mu K\cdot$arcmin 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
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)

TABLE: **COrE performance compared to WMAP and PLANCK.**

Broadening HF Bands

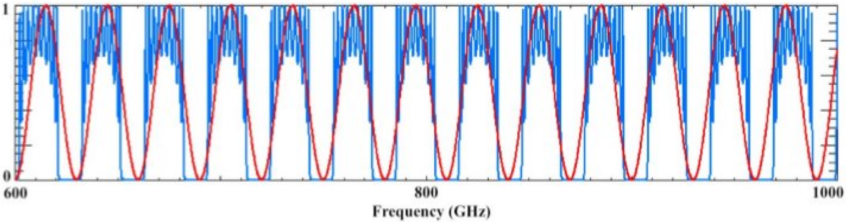
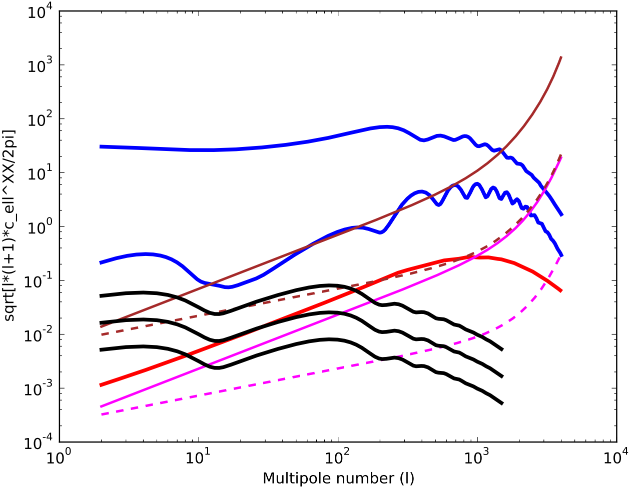


Figure 30: Sub-band filtering: Filter transmission (blue) and RHWP efficiency (red).

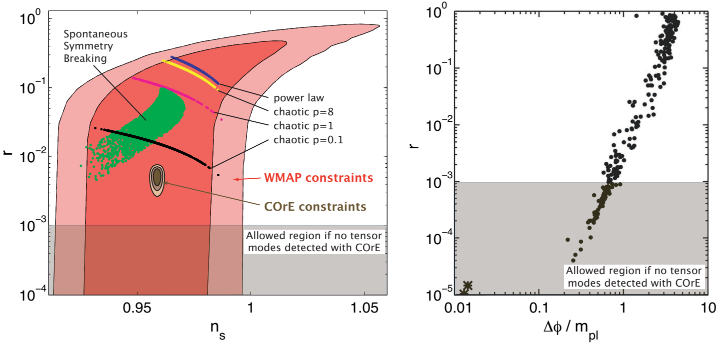
Science with COrE

COrE Planck Sensitivities vs. Expected signal



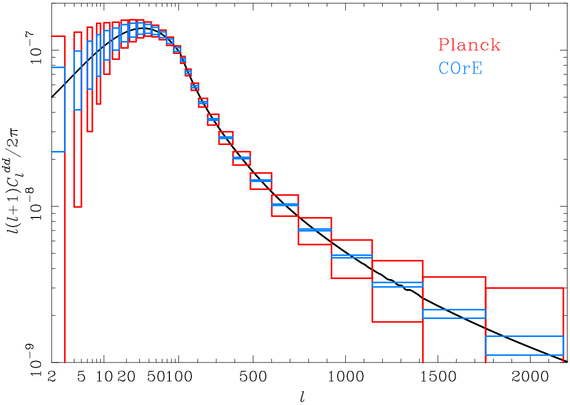
brown=planck ; magenta=COrE ; dashed = broad binning $\Delta\ell \approx \ell$, black=BB, ten for $r = 10^{-1}$, $r = 10^{-2}$, and $r = 10^{-3}$

Constraining inflation with COrE

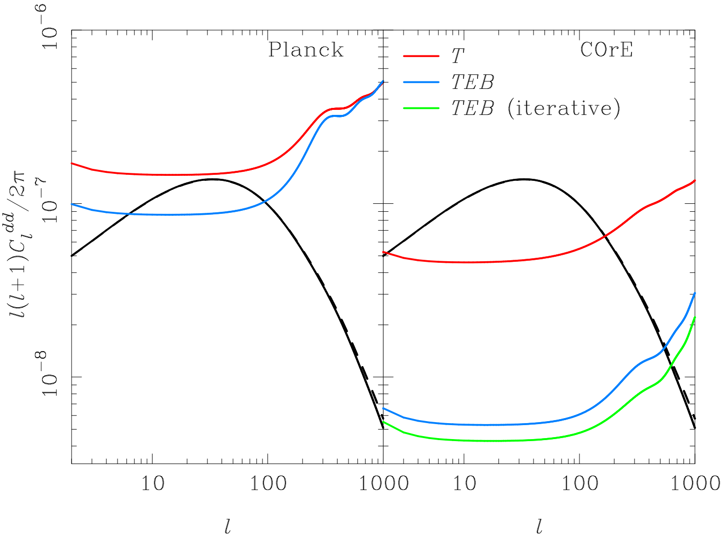


$r = 10^{-3}$ at 3σ at least.

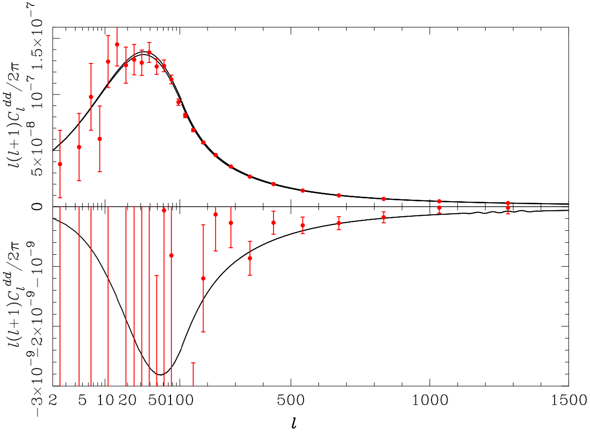
Lensing science with COrE—Measuring the Lensing Deflection Power Spectrum



Lensing reconstruction noise : PLANCK vs COrE



Detecting inverted absolute neutrino mass hierarchy



Here we plot $m_\nu^i = 0$ vs. $m_1 = m_2 = 0.05$ eV, $m_3 = 0$

$\sigma(\sum m_\nu^i)$=0.03 eV (COrE with all parameters other parameters determined by COrE), 0.012 eV (with other parameters fixed)
For comparison, KATRIN projection is $\sigma \approx 0.1eV$ on electron neutrino mass.

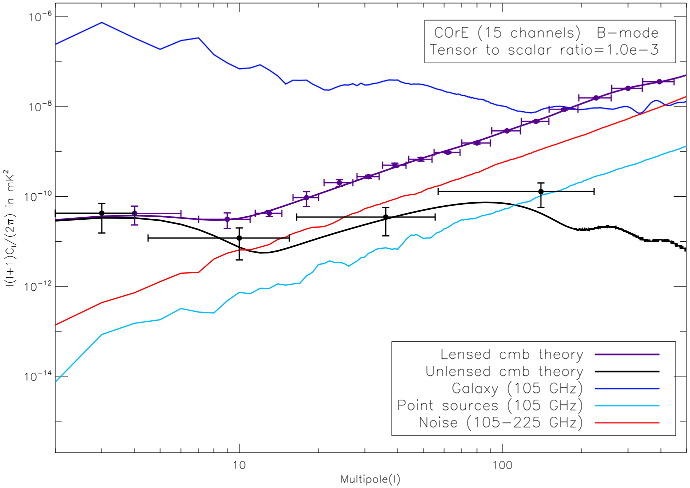
Galactic science with COrE

- The low-frequency data (especially the 45 GHz map) will be 30 times more sensitive than PLANCK LFI and will provide a full-sky view of the synchrotron polarization virtually free of Faraday rotation, which in conjunction with lower frequency data from the ground (eg QUIJOTE ....) can be used to map the galactic magnetic field.
- Above 353 GHz PLANCK has no polarization sensitive bolometers and the resolution is not diffraction limited (4.4 arcmin vs 1.3 arcmin) in highest frequency channel. This will allow high-resolution mapping of the polarized dust emission in diffuse regions not accessible and allow mapping the magnetic field in regions of star formation.
- Numerous new point sources (both polarized and unpolarized) will be discovered across the full sky.

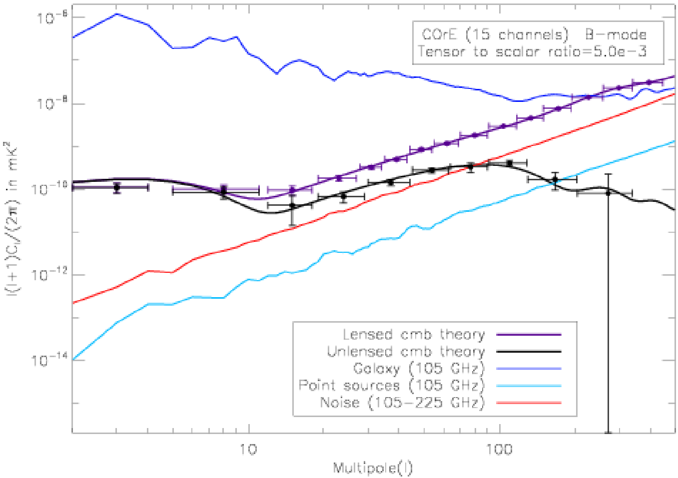
Foregrounds and component separation

- **Synchrotron emission** (cosmic rays spiralling in galactic magnetic field) $T_{sync,RJ} \propto \nu^{\alpha}$ where $\alpha \approx 3$ but varies spatially. Spectrum smooth in ν. Observed by WMAP to be highly polarized.
- **Free-free emission** bremsstrahlung of electrons in HI regions, For I H_{α} maps serve as faithful tracer. At most slightly polarized.
- **Spinning dust** (aka anomalous dust emission) regions of low frequency emission correlated with dust emission at high-frequencies. Attributed to rapidly (supra-thermally) spinning dust grains. Polarization properties uncertain.
- **Thermal dust emission.** At present best model has two components with separate amplitudes, emissivity indices, and temperatures. Model could become more complicated as data improves.
- **Zodiacal light.** Hotter dust from our solar system. Thermal emission and scattering. Most visible in 25μ maps, does not lend itself well to traditional component separation methods.
- **Sunyaev-Zeldovich (thermal and kinetic).**
- **Radio and infrared point sources.** Each have a different spectrum. Mask brightest and model unresolved.

Linear component separation model.
$T_f^{sky}(\Omega) = M_{fc} X_c(\Omega)$
Simulations and forecasts for COrE : Basak, Bonaldi, Delabrouille, Peiris, Ricciardi, Verde



Basak & Delabrouille ; similar results from Bonaldi & Ricciardi



Basak & Delabrouille ; similar results from Bonaldi & Ricciardi

ν	$\Delta\nu$	n_{det}	θ_{fwhm}^{arcmin}	(ΔP)/arcmin			Pixel sensitivity		$(\Delta P)_{A(V)=1}^{forecast}$	$(S/N)_{pol}^{pix}$
				$(\mu K)_{thermo}$	$(\mu K)_{RJ}$	MJy/st	$(\mu K)_{RJ}$	MJy/st	MJy/st	
255	15	575	4.10	1.05×10^1	2.43	4.85×10^{-3}	0.59	1.18×10^{-3}	6.30×10^{-3}	5.33
285	15	375	3.70	1.74×10^1	2.94	7.33×10^{-3}	0.79	1.98×10^{-3}	8.20×10^{-3}	4.13
315	15	100	3.30	4.66×10^1	5.62	1.71×10^{-2}	1.70	5.19×10^{-3}	1.13×10^{-2}	2.20
375	15	64	2.80	1.19×10^2	7.01	3.03×10^{-2}	2.50	1.08×10^{-2}	2.12×10^{-2}	2.00
435	15	64	2.40	2.58×10^2	7.12	4.14×10^{-2}	2.97	1.72×10^{-2}	3.82×10^{-2}	2.20
555	185	64	1.90	6.26×10^2	3.39	3.21×10^{-2}	1.78	1.69×10^{-2}	7.53×10^{-2}	4.47
675	185	64	1.60	3.64×10^3	3.52	4.92×10^{-2}	2.20	3.08×10^{-2}	1.28×10^{-1}	4.13
795	185	64	1.30	2.22×10^4	3.60	6.99×10^{-2}	2.77	5.38×10^{-2}	1.65×10^{-1}	3.07
795**	185	64	1.30	1.00×10^4	1.61	3.13×10^{-2}	1.24	2.41×10^{-2}	1.65×10^{-1}	6.86

** represents the new modified baseline with the number of detectors in the 795 GHz channel increased by a factor of five as discussed in the main text.

Table 4: ***COrE* performance for mapping polarized dust in the highest frequency channels.** For the eight highest frequency channels for the baseline defined in Table 1, we indicate in three different ways the sensitivities scaled to an arcmin square pixel for the polarization (Q, U) anisotropies, first as a thermodynamic temperature fluctuation relative to $T_{CMB} = 2.73K$—that is, as a fluctuation in ΔT_{CMB}, then as a Rayleigh-Jeans temperature fluctuation, and finally in terms of radiance units—that is, megaJansky per steradian. The polarization sensitivity is then given for a square pixel of dimension θ_{fwhm} on a side, as well as the prediction of the rms signal in Q and U in a pixel expected in a region with $A_V = 1$. Finally the resulting signal-to-noise within a pixel with unit magnitude visual extinction is indicated.

COrE

Answers to questions from the AWG

10 February 2011

Question 1

Full assessment of the COrE scientific potential will need knowledge of Planck results. While Planck seems to be performing well, its CMB results will not be known until 2013. In that situation, the proposers should provide a clear description of the potential and specific role of COrE assuming main branches of possible Planck outcome, in particular for the two cases of a detection or nondetection of polarization B modes by Planck.

Question 2

Making COrE a reality on the M3 timescale implies filling a large focal plane with complex sensitive TES detector systems. The AWG would like to get a status of the preparatory activities within the proposing consortium, and of the performances reached.

Question 3

The proposal (section 2.1) refers to a baseline design based on 6 frequency channels (75-225 GHz). The actual instrument design is based on 15 frequency channels (40-800 GHz), with a significant increase in size and complexity (overall frequency range to be covered by the optics, focal plane dimensions, number of pixels, heat load. etc.). What is the minimum number of frequency channels (and the corresponding frequency range) compatible with the COrE science objectives? A reduction in frequency range would enable a considerable simplification, potentially allowing to consider a smaller size, transmissive HWP.