L'inflation après BICEP2 (Partie II)

Martin Bucher (Université Paris-Diderot/CNRS)

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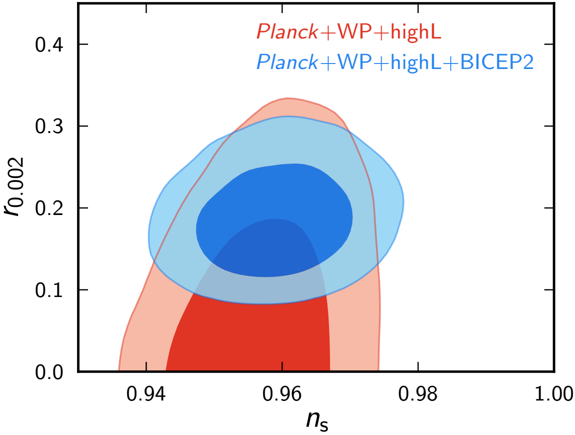
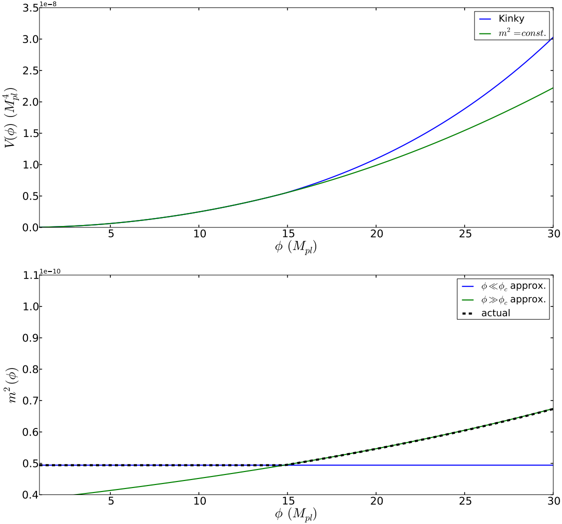
BICEP2 claim on Planck-like plot

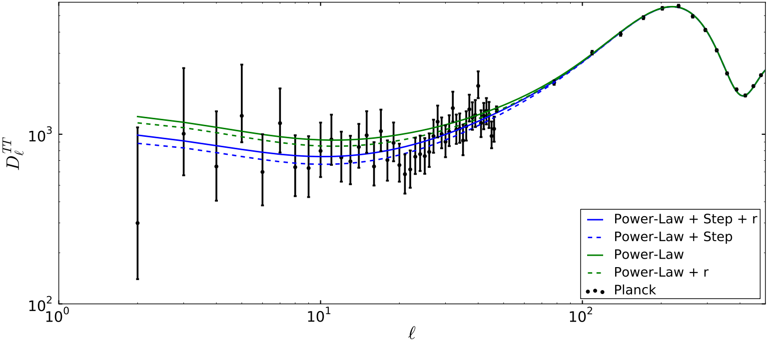


Hard art of power spectrum bending (I)

Work (with Chris Gauthier)



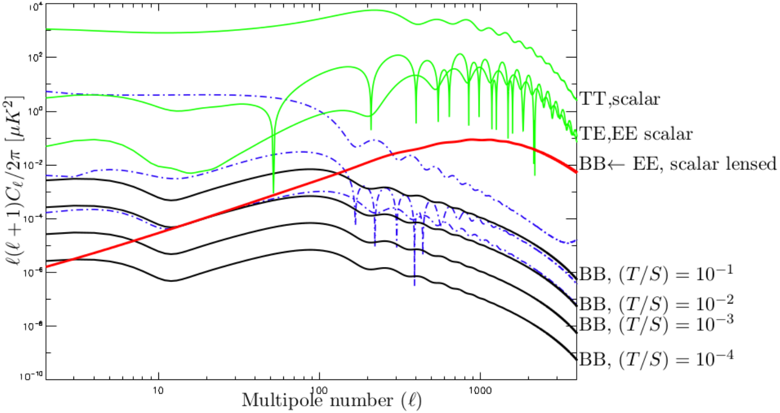
Hard art of power spectrum bending (II)



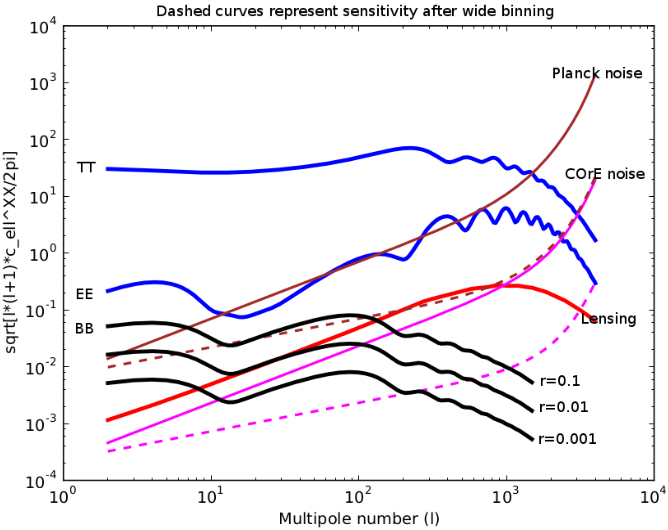
Many ways to bend low-ℓ power spectrum without messing up high-ℓ multipoles, but all seem to require extending the six-parameter concordance model of cosmology.

Scenario I : Targetting detection of $r \approx 10^{-3}$

B-mode predictions



Planck and COrE sensitivities



Planck and COrE sensitivities

ν	θ_{fwhm}	n_{det}	Temp (I) μK·arcmin		Pol (Q,U) μK·arcmin	
GHz	arcmin		RJ	CMB	RJ	CMB
23	52.8	2	413	418	584	592
33	39.6	2	413	424	584	600
41	30.6	4	365	381	516	539
61	21.0	4	438	481	619	681
94	13.2	8	413	516	584	729

WMAP (9 year mission)

ν	n_{unpol}	n_{pol}	θ_{fwhm}	Temp (I) μK·arcmin		Pol (Q,U) μK·arcmin	
GHz			arcmin	RJ	CMB	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	$(\Delta\nu)$	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
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 component separation

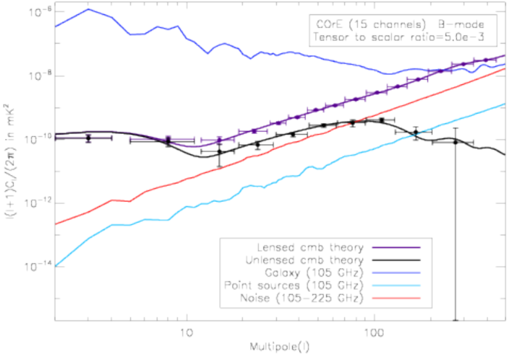


Figure 17: Component separation exercise for B mode detection assuming $(T/S) = 5 \times 10^{-3}$. The solid black curve shows the predicted blackbody B mode power spectrum, which is a combination of the tensor B modes (black curve) and a gravitational lensing background (not shown) making primordial E modes appear partially as B modes. The upper solid blue curve shows the contribution of diffuse galactic emission in one of the 'cleaner' channels (here 105 GHz) after masking. The red curve indicates the instrument noise that would be obtained by combining five CMB channels, and the light blue curve indicates contamination by point sources after the brightest ones ($S > 100$ mJy at 20 GHz and $S > 500$ mJy at 100 microns) have been cut out. The purple data points indicate the recovered raw primordial spectrum measurements, as compared to the theoretical spectrum (purple line). The black points result after the gravitational lensing contribution has been removed, leaving only the recovered tensor contribution. Here mask 2 (an apodised, galactic cut with $f_{sky} \simeq 0.70$) has been used.

Inflationary models

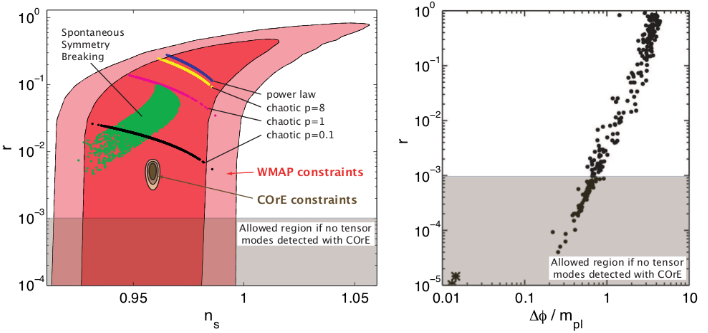


Figure 3: **Constraints on inflation from COrE.** For a broad range of inflationary models COrE can be expected to detect primordial gravitational waves from inflation. The large contours on the left panel show the present constraints from WMAP seven-year data in the r-n_S plane. A few parameterized families of inflationary models give an idea of representative model predictions. The small contours illustrate what a COrE detection would look like if $r > 5 \times 10^{-3}$. The part of parameter space still allowed at 2σ in the case of a non-detection is shown in grey. The right panel shows the 'main sequence' of inflationary models generated using a model independent approach.

Summary of low-r option : disovery of B modes from inflation

- This option assumes that the BICEP2 claimed detection is explaned by an underestimated contribution from galactic foregrounds or unaccounted systematic errors. Until a confirmation from another experiment is in hand, this option cannot be excluded.
- Under this option the mission design objective is to maximize the discovery potential. This means having exquisite raw sensitivity accompanied by corresponding control over systematic errors and observing over mutiple channels to allow accurate removal galactic and other foreground contaminants.

Scenario II : Precision characterization of $c_{BB,tensor}$ with $r \approx 0.1 - 0.2$

Probing consistency of inflationary paradigm

$$\epsilon \equiv \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 = \frac{1}{2}\left(\frac{d\ln V(\phi)}{d(\phi/M_{\rm Pl})}\right)^2 , \qquad \eta \equiv M_{\rm Pl}^2 \frac{V''}{V} = \frac{d^2 \ln V(\phi)}{d(\phi/M_{\rm Pl})^2} - 2\epsilon$$

$M_{\rm Pl} = (8\pi G)^{-1/2} = 2.4 \times 10^{18}$ GeV
Scalar perturbations cannot measure the height of the potential

$$A_S(k) = \frac{2}{5}\mathcal{P}_R^{1/2}(k) \approx \frac{\epsilon^{-1/2}}{5\pi\sqrt{3}} \left.\frac{V^{1/2}(\phi)}{M_{\rm Pl}^2}\right|_{k=a(\phi)H(\phi)} , \qquad n_S \equiv 1 + \frac{d\ln A_S^2(k)}{d\ln k} \approx 1 + 2\eta - 6\epsilon .$$

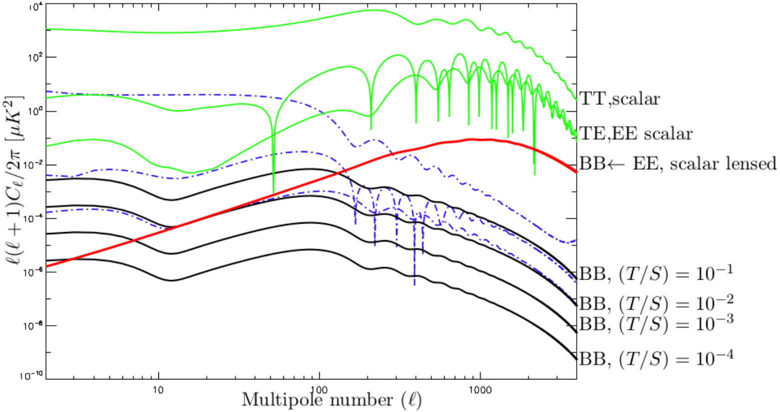
Tensor perturbations (i.e., gravitational wavesi generated during inflation) measure the height of the potential

$$A_T(k) \equiv \frac{1}{5\sqrt{2}}\mathcal{P}_{gw}^{1/2} \approx \frac{1}{5\pi\sqrt{3}} \left.\frac{V^{1/2}(\phi)}{M_{\rm Pl}^2}\right|_{k=a(\phi)H(\phi)} , \qquad n_T \equiv \frac{d\ln A_T^2(k)}{d\ln k} \approx -2\epsilon$$

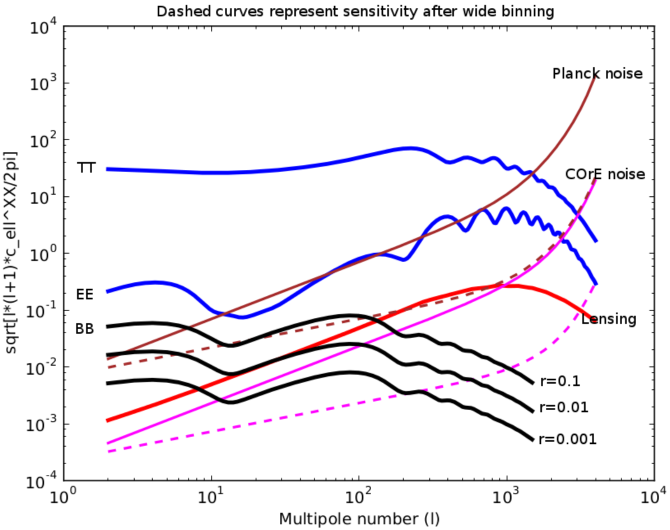
Consistency condition

$$r = T/S \equiv \frac{\mathcal{P}_{gw}}{\mathcal{P}_R} = 16\frac{A_T^2}{A_S^2} \approx 16\,\epsilon = -8\,n_T ,$$

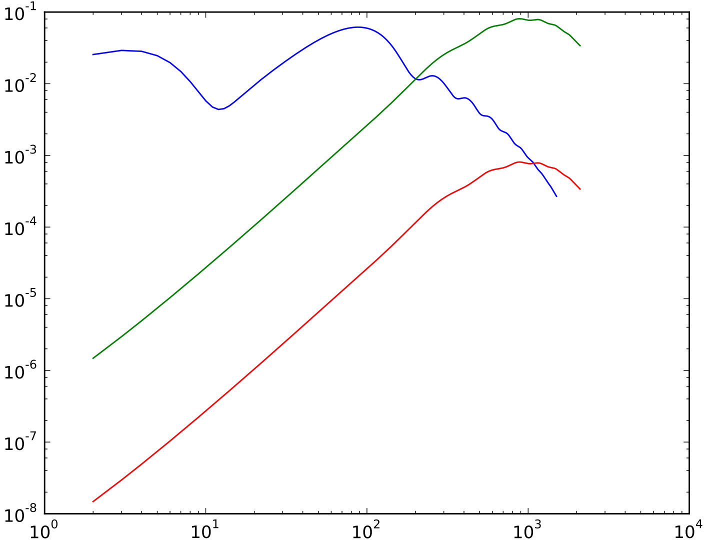
B-mode predictions



Planck and COrE sensitivities



What if we could clean 90% of the lensing noise?



Summary of high-r option : precision characterization of the B mode power spectrum

- While in this range of r detection from the ground is possible by looking through “holes between the clouds," a complete characterization requires full-sky coverage and wide, multiple-channel frequency coverage to remove foregrounds completely. Cosmic variance is the limiting factor.
- In single-field inflation the scalar perturbations determine the inflationary potential up to an integration constant, which is fixed by measuring r at one angular scale. Measurement of r at multiple scales provides a consistency check of single-field inflation.
- The first target is to fix n_T by measuring r at several angular scales as widely separated as possible. The reionization bump is an obvious target, but overcoming cosmic variance will require going to large ℓ where the primordial B mode signal becomes subdominant and delensing is needed.

Lensing science and delensing

Gravitational lensing spectrum : COrE vs Planck

From COrE White Paper (astro-ph/1102.2181

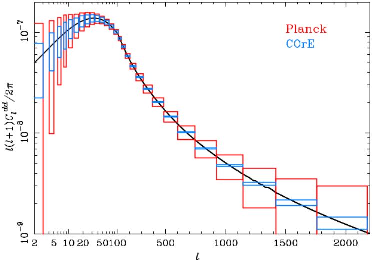


Figure 6: **COrE vs PLANCK for measuring the lensing power spectrum.** Bandpower errors are plotted (including cosmic variance) on the deflection power spectrum from PLANCK (24 months; red) and COrE (blue) using lens reconstruction with temperature and polarization (no iteration). With COrE, the power spectrum is cosmic-variance limited to $l \approx 500$.

Lensing reconstruction noise

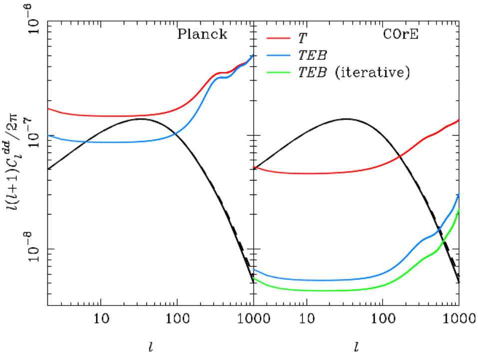


Figure 5: **Lensing reconstruction noise** on the deflection power spectrum for an extended PLANCK mission (24 months; left) and COrE (right) using temperature alone (red) and temperature and polarization (blue). For COrE, we also show the approximate noise level (green) for an improved iterative version of the reconstruction estimator following Ref. [30]. The deflection power spectrum is also plotted based on the linear matter power spectrum (black solid) and with non-linear corrections (black dashed). The maximum multipole used in the reconstruction is $l_{\max} = 2500$.

Measuring absolute neutrino masses with COrE

From COrE White Paper

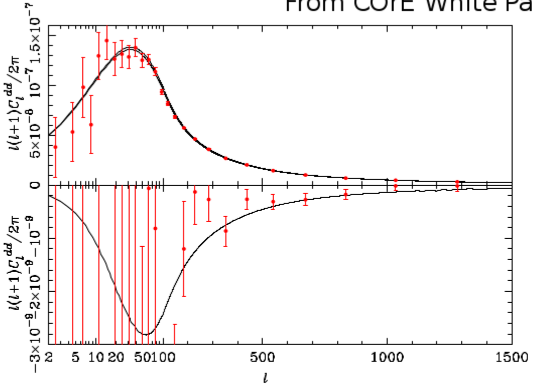


Figure 7: **Gravitational lensing deflection power spectrum.** The simulated deflection power spectrum from COrE is shown assuming an inverted hierarchy of neutrino masses with the minimum total mass allowed by oscillation data ($m_1 \approx m_2 = 0.05\,\mathrm{eV}$ and $m_3 = 0\,\mathrm{eV}$). In the upper panel, the solid lines are the theory power spectrum for this scenario (lower) and for three massless neutrinos (upper). The difference between these spectra is plotted in the lower panel illustrating how COrE can distinguish these scenarios from C_l^{dd} in the range $l > 200$. We have assumed 70% sky coverage after Galactic masking.

What it takes to measure neutrino masses

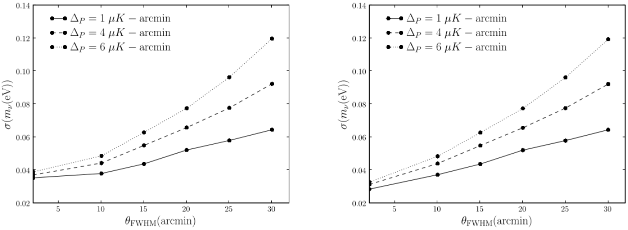


Figure 5: Uncertainty $\sigma(m_\nu)$ on the neutrino mass as a function of beam size and noise level for $\ell_{\max} = 2000$ (left panel) or $\ell_{\max} = 4000$ (right panel) using CMB lens reconstruction, assuming fixed w, Ω_K.

From: CMBPol Mission Concept Study: Gravitational Lensing

Cleaning out the lensing

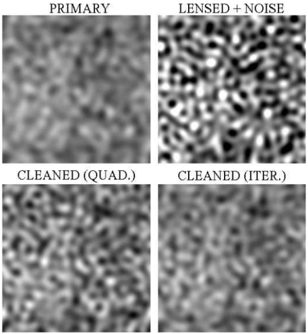


FIG. 1: Simulated extraction of a B mode from CMB data with noise $w_P^{-1/2} = 0.5\mu$K arcmin and beam FWHM 4 arcmin. In each panel we have plotted the scalar quantity $B = \sum_{\mathbf{l}} B_{\mathbf{l}} e^{i\mathbf{l}\cdot\hat{\mathbf{n}}}$. For clarity, only $l < 150$ modes are shown. The widths of the frames are 34 degrees, and the temperature scale runs from -0.136μK to $+0.136\mu$K. *Upper left*: The primary B mode. *Upper right*: The B mode after lensing and addition of 0.5 μK arcmin noise. *Lower left*: Recovered B mode after cleaning with the quadratic estimator. *Lower right*: Recovered B mode after cleaning with the iterative estimator.

Seljak & Hirata, (astro-ph/0310163) PRD 69 (2004) 043005

Cleaning out the lensing

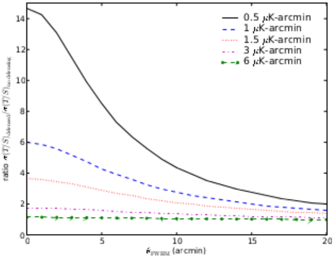


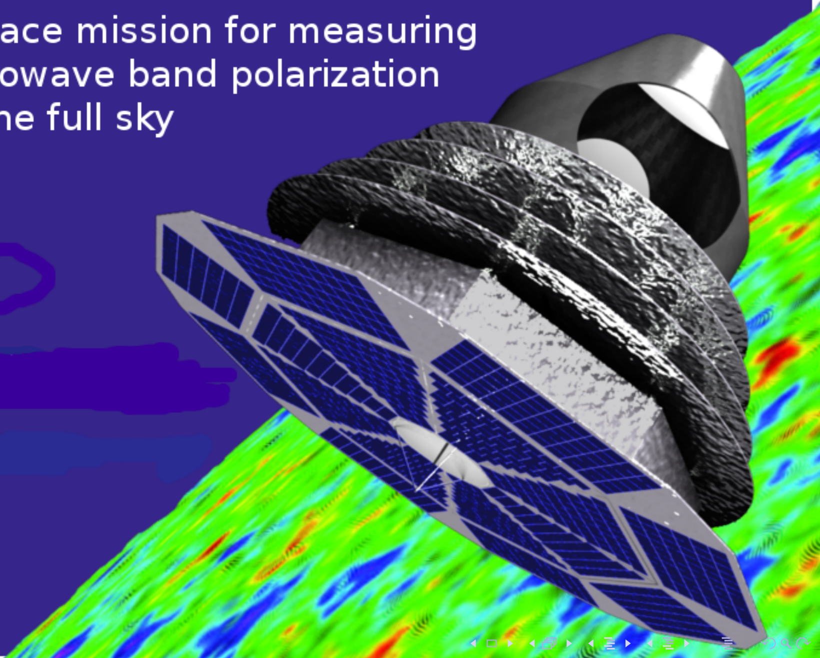
Figure 8: Ratio of $\sigma(T/S)$ with and without polarization delensing, forecasted using Eq. (12) for varying instrumental noise level and beam.

From: CMBPol Gravitational Lensing White Paper

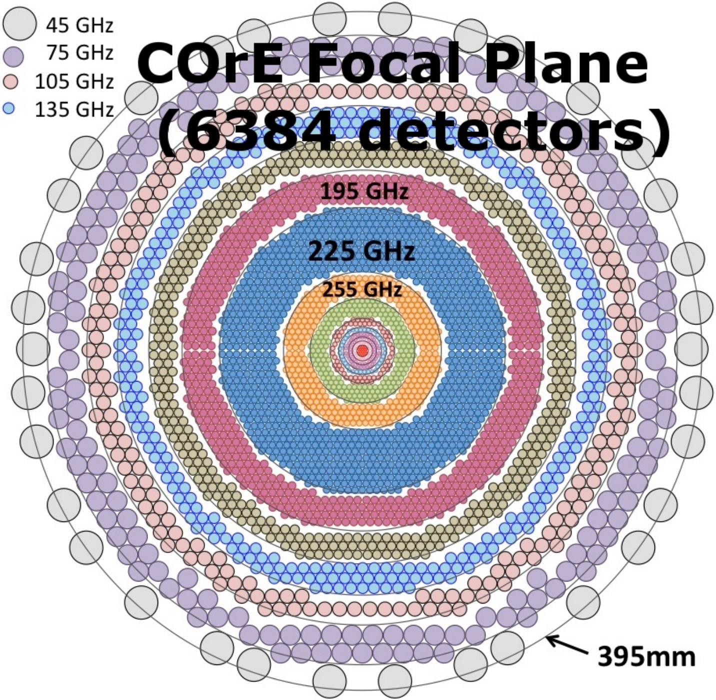
COrE : Cosmic Origins Explorer

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

[redacted]



COrE Focal Plane (6384 detectors)



Conclusions :

- COrE+ has an exciting primordial cosmology science case under both scenarios considered. While it would be more satisfying to make a first discovery, complete characterization of the B modes will require a mission from space.
- More study of the complete characterization of the primordial B mode spectrum with $r = 0.1$ is needed. In particular delensing must be better understood for large r.
- Besides primordial B modes COrE+ has exciting ancillary science such as measuring absolute neutrino masses, detecting clusters at large redshift, measuring cluster proper velocities, characterizing the CIB from early dusty galaxies to name a few examples.