COrE+
Mapping our Cosmic Origins

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On behalf of the COrE+ Collaboration
(with thanks to J. Delabrouille & P. de Bernardis)
Open questions

Everything fits beautifully with a 6-parameter model. So far so good!

however...

no answer yet to some fundamental questions

What is the physics behind inflation?
Did inflation really occur?
What are dark matter and dark energy?
Many proposed Post-Planck CMB missions

- SAMPAN (CNES 2006)
- BPOL (ESA 2007)
- NASA 2008 EPIC-IM
- JAXA 2008 LiteBIRD
- NASA PIXIE
- PRISM (ESA 2013)
- COrE (ESA 2010)
- COrE+ (ESA 2015)

**Low resolution**
- Limited frequency coverage
- Primary CMB B-modes

**High resolution**
- Many frequency bands
- More comprehensive science cases (spectroscopy, sub-mm astronomy, astrophysical cosmology)
Explore our cosmic origins, from the origin of stars and large-scale structures to that of the Universe itself

...through high-sensitivity full-sky observations of the polarized microwave and sub-mm sky, between 60 and 600 GHz

This dataset will enable the following primary science goals

Mapping inflation
Mapping the entire mass of the Universe
Mapping all the hot gas in the Universe
Mapping star formation
Mapping the Milky Way
Very Early Universe Physics at $\approx 10^{16}$ GeV

$E_{\text{CORE}^+} > 10^{12} \times E_{\text{LHC}}$
Initial perturbations
- scalar (density)
- tensor (gravity waves)
depend on the potential $V(\phi)$ and derivatives:

- scalar spectral index $n_S - 1$
- running $\frac{dn_S}{d\ln k}$
- tensor/scalar ratio $r = T/S$
- tensor spectral index $n_T$

Tensors produce B-mode polarization.
Current upper limit on $r$ is $\sim 0.1$
Target of COrE+ : 0.001 (close to cosmic variance)
Roughly two classes of $r$ models

- Large field, $r \approx 0.1$
  (Already disfavored by Planck)

  Precision contraints on the shape
  Of the B-mode power spectrum,
  Exquisite test of near scale-invariance
  of primordial tensor modes

- Small field, $r \approx \text{few} \times 10^{-3}$
  $r > 10^{-3}$ detectable, even with complex
  polarized foregrounds

Evaluation of PRISM L-scale mission proposed science (early 2014):
"The SSC was fully convinced of the great importance of the core CMB science and encourages
the CMB community to consider proposing this science for a future M-class mission."
Fundamental limitations

Figure 2: Statistical error $\sigma_0(r)$ on the tensor-to-scalar ratio for varying noise level, assuming no delensing has been done. The forecast is strongly dependent on whether the reionization B-mode signal at $\ell \lesssim 10$ is assumed measurable in the presence of sky cuts and Galactic foregrounds. The value of $\sigma_0(r)$ levels off for noise levels $\lesssim \SI{4.4}{\mu K\text{-arcmin}}$ since the observations have become lensing-limited.
Fundamental limitations

Figure 3: Forecasted improvement $\alpha = \sigma_0(\nu)/\sigma(\nu)$ in the statistical error on $\nu$ due to polarization delensing, for varying noise level and beam. In the limit of low noise and high resolution, we find no limit (from delensing residuals alone) to how well $\nu$ can be measured.
Figure 1: Expected sensitivity of COrE+ to the B mode power spectrum. The blue lines show the theoretical B mode power spectra from tensor modes with $r = 0.1$, 0.01, and 0.001. The left and right panels show the expected error bars on the B mode power spectrum for the fiducial amplitudes of tensor modes with $r = 0.01$ and 0.001,
Very Early Universe Physics at $\approx 10^{16}$ GeV

$E_{\text{COR+E}} > 10^{12} \times E_{\text{LHC}}$

$z \approx 1-3$

Gravitational Lensing Mass Distribution

COrE+ : target 2 : gravitational lensing
T (unlensed) and lensing potential

Unlensed Temperature

Lensing Potential

Figures by Ata Karakci
T (lensed) and lensing potential

Lensed Temperature

Lensing Potential

Figures by Ata Karakci
E, B (unlensed) r=0.01

Figures by Ata Karakci
E, B (lensed) $r=0.01$
• **COrE+**: High-fidelity reconstruction of the integral of the gravitational potential all the way to recombination.
• 3 unknowns ($\Phi, T_{LSS}, E_{LSS}$), 3 observables ($T_{OBS}, E_{OBS}, B_{OBS}$)
• Correlation with other mass tracers (galaxies, clusters, quasars) to obtain a tomography of dark matter in the whole Hubble volume.
Case Study: Neutrino Physics

Lensing of EE

\[ \Sigma m_{\nu} = 0 \text{ eV} \]

\[ \Sigma m_{\nu} = 1.5 \text{ eV} \]

\[ C^T_T \]

\[ C^E_E \]

\[ C^B_B \]
Constraining the neutrino sector

A mission such as COrE+ could measure the neutrino hierarchy!

- Normal
  - $m_3$
  - Total mass $> 60$ meV

- Inverted
  - $m_3$
  - Total mass $> 100$ meV
Foreground emission

- Virgo A (M87) and Virgo cluster
- Coma cluster
- Virgo A (M87) and Virgo cluster
- Cen A
- Galactic Dust
- Andromeda M 31
- Tau A (Crab)
- Brehmsstrahlung (free-free) (Gum nebula)
- Anisotropies of the CMB and of the cosmic infrared background
- Magellanic clouds
Foreground complexity

Other dust component?

### Need more bands than components

<table>
<thead>
<tr>
<th>Count components (or parameters)</th>
<th>I</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Thermal SZ</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>2-component thermal dust</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>2-component synchrotron</td>
<td>4-6</td>
<td>4-6</td>
</tr>
<tr>
<td>Free-free</td>
<td>1-2</td>
<td>0 ?</td>
</tr>
<tr>
<td>Spinning dust</td>
<td>a few</td>
<td>?</td>
</tr>
<tr>
<td>CIB</td>
<td>many</td>
<td>0 ?</td>
</tr>
<tr>
<td>Zodiacal light</td>
<td>1-3</td>
<td>0 ?</td>
</tr>
<tr>
<td>Radio source background</td>
<td>a few</td>
<td>a few</td>
</tr>
<tr>
<td>Surprises</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

**TOTAL**

15-20 +

11-13 +

*In cleaner regions of the sky, fewer parameters may be needed, but this depends on the sensitivity of the survey.*
Why go to space?

• Sensitivity (in particular at high frequency)
  – The more sensitive the mission, the more channels are needed

• Frequency coverage
  – additional science (CIB, clusters, ISM and more...)
  – foreground cleaning reliability

• Sky coverage
  – cosmic variance
  – statistics (cross correlations)
  – large scale anomalies?

• Legacy value
What space mission?

Solid scientific incentive to reach $r \approx 2-3 \times 10^{-3}$ at 5σ

Achievable with a reasonably-sized space mission, with large sky coverage and some de-lensing

Sensitivity 1.5-2.5 μK.arcmin (2000-6000 detectors in space); CMB angular resolution between 4' et 6' (~1.5 m telescope)

Need enough channels to separate CMB from foregrounds

Clear science driver ($r$), but exceptional ancilliary science (mapping structures with lensing, and the hot gas with SZ)

(Near-) ultimate CMB polarisation mission (No spectral distortions of the continuum)
Proposition leader: Paolo de Bernardis
Co-leaders: François Bouchet & Jacques Delabrouille
# TLRs

<table>
<thead>
<tr>
<th><strong>Quantity</strong></th>
<th><strong>Requirement</strong></th>
<th><strong>Driver</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>1) frequency coverage</td>
<td>60-600 GHz</td>
<td>Component separation</td>
</tr>
<tr>
<td>2) number of bands</td>
<td>19</td>
<td>Component separation</td>
</tr>
<tr>
<td>3) angular resolution (FWHM)</td>
<td>6’ @ 145 GHz, 4’ @ 200 GHz</td>
<td>CMB polarization, Lensing science</td>
</tr>
<tr>
<td></td>
<td>1.5’ or better @ highest frequency</td>
<td>Galactic science</td>
</tr>
<tr>
<td>4) beam asymmetry</td>
<td>&lt;3% @ CMB channels</td>
<td>CMB polarization</td>
</tr>
<tr>
<td>5) sensitivity</td>
<td>2.5 μK arcmin @ CMB channels</td>
<td>CMB polarization</td>
</tr>
<tr>
<td>6) sky coverage</td>
<td>100%</td>
<td>CMB cosmic variance; legacy</td>
</tr>
<tr>
<td>7) polarization axis directions coverage</td>
<td>wide for all sky pixels, see text</td>
<td>CMB polarization</td>
</tr>
<tr>
<td>a) telescope aperture</td>
<td>1.5 m</td>
<td>3)</td>
</tr>
<tr>
<td>b) # of detectors</td>
<td>2410 (see table 3)</td>
<td>1), 2), 4)</td>
</tr>
<tr>
<td>c) detectors temperature</td>
<td>0.1K</td>
<td>5)</td>
</tr>
<tr>
<td>d) telescope temperature</td>
<td>60K</td>
<td>5)</td>
</tr>
<tr>
<td>e) orbit</td>
<td>Lissajous around L2</td>
<td>5), systematic effects</td>
</tr>
<tr>
<td>f) scan</td>
<td>spin (1 rpm) + precession (0.25 rpd)</td>
<td>6), 7), systematic effects</td>
</tr>
<tr>
<td>g) continuous data rate</td>
<td>2.4 Mbps</td>
<td>b), f), 0.25× compression</td>
</tr>
<tr>
<td>h) mission duration</td>
<td>3 years</td>
<td>5), systematic effects</td>
</tr>
<tr>
<td>i) launcher</td>
<td>Soyuz or Ariane 6</td>
<td>e) + payload volume and mass</td>
</tr>
</tbody>
</table>
Primordial Universe
Physics at $\approx 10^{16}$ GeV
$E_{\text{CorE}^+} > 10^{12} \times E_{\text{LHC}}$

1st Stars

Quantum Fluctuations

Inflation

CMB

Extragalactic Astrophysics

Interstellar medium
(magnetic field)

$z \approx 1-3$
Gravitational lensing
Dark matter distribution

$z \approx 0-2$
Sunyaev-Zeldovich effect:
Distribution of the hot gas and velocity field
Observation of >100,000 Galaxy clusters

SZ map reconstruction
Needlet ILC (Mathieu Remazeilles)
on PSM simulations (Ata Karakci)

Limit mass as a function of redshift (Jean-Baptiste Melin)
A space mission is the only way to extract all the essential information from the CMB polarization.

This is true both for primordial gravitational waves and for the exploitation of CMB lensing.

COrE+ is optimized for these objectives, which can’t be reached by any means short of it (ie, regardless of any progress from the ground or from modest space missions, a COrE+like mission is a scientific necessity).

Doing this will automatically bring along a vast amount of extra science that will serve a broad community.
Conclusion

Let’s do it!