Future CMB polarization observatories in the presence of foregrounds and gravitational lensing: POLARBEAR-2 and the SIMONS ARRAY
Polarbear-1 ➔ Polarbear-2 ➔ Simons Array

It is happening NOW!

( = 3x Polarbear-2)

Josquin Errard (ILP) — Moriond 2016
there is now growing evidence that there are no regions of the sky in which B-mode emission from dust can be neglected when attempting to extract inflationary B-modes at frequencies above \(\sim100\) GHz
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CMB-S4 Science Book ➤ there is now growing evidence that there are no regions of the sky in which B-mode emission from dust can be neglected when attempting to extract inflationary B-modes at frequencies above \(\sim 100 \text{ GHz}\).
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CMB-S4 Science Book ➤ there is now growing evidence that there are no regions of the sky in which B-mode emission from dust can be neglected when attempting to extract inflationary B-modes at frequencies above ~100 GHz.
Errard, Feeney, Peiris and Jaffe (arXiv:1509.06770, JCAP, 2016)
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<table>
<thead>
<tr>
<th>Instrument specification</th>
<th>Observation strategy</th>
<th>Astrophysical foreground maps and power spectra</th>
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<td>frequencies, number of detectors, FWHM, Tobs</td>
<td>fsky, patch location</td>
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Errard, Feeney, Peiris and Jaffe (arXiv:1509.06770, JCAP, 2016)

- Instrument specification
  frequencies, number of detectors, FWHM, Tobs
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  fsky, patch location
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Astrophysical foreground rejection
Errard, Feeney, Peiris and Jaffe (arXiv:1509.06770, JCAP, 2016)

Instrument specification
- frequencies, number of detectors, FWHM, Tobs

Observation strategy
- fsky, patch location

Astrophysical foreground rejection
- foregrounds residuals, degraded noise variance, degraded resolution

Josquin Errard (ILP) — Moriond 2016
Errard, Feeney, Peiris and Jaffe (arXiv:1509.06770, JCAP, 2016)

- Instrument specification: frequencies, number of detectors, FWHM, Tobs
- Observation strategy: fsky, patch location
- Astrophysical foreground maps and power spectra
  - Astrophysical foreground rejection: foregrounds residuals, degraded noise variance, degraded resolution
  - Delensing
  - Fisher forecasts on cosmological parameters
Instrument specification
frequencies, number of detectors,
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foregrounds residuals, degraded noise variance, degraded resolution

Delensing

Fisher forecasts on cosmological parameters

optimization!
Errard, Feeney, Peiris and Jaffe (arXiv:1509.06770, JCAP, 2016)

Instrument specification
frequencies, number of detectors, FWHM, Tobs

Observation strategy
fsky, patch location

Astrophysical foregrounds and power spectra

Astrophysical foreground rejection
foregrounds residuals, degraded noise variance, degraded resolution

Delensing

Fisher forecasts on cosmological parameters

being constantly updated!

optimization!
Rendition of parametric max-L component separation

\[ d_i(p) = A_{ij} s_j(p) + n_i(p) \]

data modeling
for each sky pixel:
Rendition of parametric max-L component separation

\[ d_i(p) = A_{ij} s_j(p) + n_i(p) \]

Data modeling for each sky pixel:

1. estimation of the mixing matrix \( A \)

\[ A_{\text{sync}}^{\text{raw}}(\nu, \nu_{\text{ref}}) = \left( \frac{\nu}{\nu_{\text{ref}}} \right)^{\beta_s} \]
\[ A_{\text{dust}}^{\text{raw}}(\nu, \nu_{\text{ref}}) = \left( \frac{\nu}{\nu_{\text{ref}}} \right)^{\beta_d+1} \frac{e^{\frac{h\nu_{\text{ref}}}{kT_d}} - 1}{e^{\frac{h\nu}{kT_d}} - 1} \]
\[ A \equiv A(\beta = \beta_d, \beta_s, ...) \rightarrow \text{max} \left( \mathcal{L}(\beta) \right) \]

Not perfect recovery of input spectral parameters ➤ foregrounds residuals
Rendition of parametric max-L component separation

\[ d_i(p) = A_{ij} s_j(p) + n_i(p) \]

**data modeling**

for each sky pixel:

\[ d = A s + n \]

---

1. estimation of the mixing matrix \(A\)

\[
A_{\text{sync}}(\nu, \nu_{\text{ref}}) \equiv \left( \frac{\nu}{\nu_{\text{ref}}} \right)^{\beta_d} \\
A_{\text{dust}}(\nu, \nu_{\text{ref}}) \equiv \left( \frac{\nu}{\nu_{\text{ref}}} \right)^{\beta_d+1} e^{\frac{\hbar \nu_{\text{ref}}}{\kappa T_d}} - 1 \left( e^{\frac{\hbar \nu}{\kappa T_d}} - 1 \right)
\]

\[ A \equiv A(\beta = \beta_d, \beta_s, \ldots) \rightarrow \max (\mathcal{L}(\beta)) \]

---

2. solve for \(s\) [rather general to any comp sep method]

\[ s = (A^T N^{-1} A)^{-1} A^T N^{-1} d \]

---

not perfect recovery of input spectral parameters ➤ foregrounds residuals

linear combination of various frequency maps ➤ boosted noise

Josquin Errard (ILP) — Moriond 2016
Rendition of parametric max-L component separation

Brandt et al. (1994), Ericksen et al. (2006), Stompor et al. (2009)

\[-2 \log \mathcal{L}(s, \beta) = \text{constant} + \sum_p (d_p - A_p s_p)^T N_p^{-1} (d_p - A_p s_p)\]

\[-2 \log \mathcal{L}_{\text{marg}}(\beta) = -2 \log \int ds \exp \left[ -\frac{1}{2} (d - A s)^T N^{-1} (d - A s) \right] \]

\[= \text{constant} - (A^T N^{-1} d)^T (A^T N^{-1} A)^{-1} (A^T N^{-1} d) + \log |(A^T N^{-1} A)^{-1}|\]

\[-2 \log \mathcal{L}_{\text{spec}}(\beta)\]
Rendition of parametric max-L component separation

Brandt et al. (1994), Ericksen et al. (2006), Stompor et al. (2009)

\[-2 \log \mathcal{L}(s, \beta) = \text{constant} + \sum_p (d_p - A_p s_p)^T \mathbf{N}_p^{-1} (d_p - A_p s_p)\]

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\[= \text{constant} - (A^T \mathbf{N}^{-1} d)^T (A^T \mathbf{N}^{-1} A)^{-1} (A^T \mathbf{N}^{-1} d) + \log |(A^T \mathbf{N}^{-1} A)^{-1}|\]

\[-2 \log \mathcal{L}_{\text{spec}}(\beta)\]

Errard, Stivoli and Stompor (2011)

\[-2 \log \mathcal{L}_{\text{spec}}(\beta) \text{ turns out to be often well-approximated by a Gaussian at its peak}\]
Rendition of parametric max-L component separation

Statistical error bars on spectral parameters:

\[
\Sigma^{-1} \simeq - \left\langle \frac{\partial^2 \mathcal{L}}{\partial \beta \partial \beta'} \right\rangle_{\text{noise}} \bigg|_{\text{true } \beta}
\]

Errard, Stivoli and Stompor (PRD, 2011)

\[
= - \text{tr} \left\{ \left[ \frac{\partial \mathbf{A}^T}{\partial \beta} \mathbf{N}^{-1} \mathbf{A} \left( \mathbf{A}^T \mathbf{N}^{-1} \mathbf{A} \right)^{-1} \mathbf{A}^T \mathbf{N}^{-1} \frac{\partial \mathbf{A}}{\partial \beta'} - \frac{\partial \mathbf{A}^T}{\partial \beta} \mathbf{N}^{-1} \frac{\partial \mathbf{A}}{\partial \beta'} \right] \sum_p \mathbf{s}(p) \mathbf{s}^T(p) \right\}
\]

\[\downarrow\] prediction of error bars for parametric methods like COMMANDER
Rendition of parametric max-L component separation

Statistical error bars on spectral parameters:

\[
\Sigma^{-1} \simeq - \left( \frac{\partial^2 \mathcal{L}}{\partial \beta \partial \beta'} \right)_{\text{noise}} \bigg|_{\text{true } \beta} 
= - \text{tr} \left\{ \left[ \frac{\partial A^T}{\partial \beta} \right] N^{-1} A \left( A^T N^{-1} A \right)^{-1} A^T N^{-1} \frac{\partial A}{\partial \beta'} - \frac{\partial A^T}{\partial \beta} N^{-1} \frac{\partial A}{\partial \beta'} \right\} \sum_p s(p) s^T(p)
\]

Errard, Stivoli and Stompor (PRD, 2011)

\( \rightarrow \) prediction of error bars for parametric methods like COMMANDER

noise in the reconstructed maps

information about sky components
Rendition of parametric max-L component separation

**Statistical error bars on spectral parameters:**

$$\Sigma^{-1} \simeq - \left\langle \frac{\partial^2 L}{\partial \beta \partial \beta'} \right\rangle_{\text{noise}} \bigg|_{\text{true } \beta}$$

$$= - \text{tr} \left\{ \frac{\partial A^T}{\partial \beta} N^{-1} A \left( A^T N^{-1} A \right)^{-1} A^T N^{-1} \frac{\partial A}{\partial \beta'} - \frac{\partial A^T}{\partial \beta} N^{-1} \frac{\partial A}{\partial \beta'} \right\} \sum_p s(p) s^T(p)$$

Errard, Stivoli and Stompor (PRD, 2011)

| noise in the reconstructed maps |
| information about sky components |

\(\downarrow\) prediction of error bars for parametric methods like COMMANDER

**Statistical amplitude of foregrounds residuals:**

$$C_{\ell}^{fg \ res} \equiv \sum_{k,k'} \sum_{j,j'} \sum_{kk'} \kappa_{kk'}^{jj'} C_{\ell}^{jj'}$$

Stivoli, Grain, Leach, Tristram, Baccigalupi, Stompor (MNRAS, 2010)

Josquin Errard (ILP) — Moriond 2016
Errard, Feeney, Peiris and Jaffe (arXiv:1509.06770, JCAP, 2016)
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- ✓ sky + frequency coverage
- ✗ angular resolution

- ✓ high frequency sensitivity
- ✗ observing time

- ✓ angular resolution
- ✓ observing time
- ✗ frequency coverage

Josquin Errard (ILP) — Moriond 2016
Errard, Feeney, Peiris and Jaffe (arXiv:1509.06770, JCAP, 2016)

- Broad frequency-coverage + balanced sensitivities leads to low noise boost and low foregrounds residuals.

- Spatial variation of spectral indices requires sensitive foregrounds monitors (e.g. C-BASS, QUIJOTE, sensitive frequencies above 300GHz)

✓ high frequency sensitivity
✗ observing time
✓ angular resolution
✓ observing time
✗ frequency coverage

✓ sky + frequency coverage
✗ angular resolution

✓ angular resolution
✓ observing time
✗ frequency coverage

!/\ inter-calibration, band-mismatch, mis-modeling, etc.
Errard, Feeney, Peiris and Jaffe (arXiv:1509.06770, JCAP, 2016)

➤ user-friendly web interface — currently moving to NERSC “Science Gateways”

<table>
<thead>
<tr>
<th>Arg-Name</th>
<th>Type</th>
<th>Element Range</th>
<th>Input w/ Default</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>fsky</td>
<td>float</td>
<td>[0.01, 1]</td>
<td>0.1</td>
<td>[Fraction of the sky to be observed. We consider galactic polar caps patches and assume the latest Planck polarized foregrounds maps.]</td>
</tr>
<tr>
<td>freqs</td>
<td>list-float</td>
<td>[1.0, 1000.0]</td>
<td>[95, 150, 220]</td>
<td>[Frequency channels in GHz]</td>
</tr>
<tr>
<td>uKCMBarcmin</td>
<td>list-float</td>
<td>[1.0, 1000.0]</td>
<td>[10.0, 10.0, 10.0]</td>
<td>[Polarized sensitivity, in uK_CMB.arcmin, for each frequency channel]</td>
</tr>
<tr>
<td>FWHM</td>
<td>list-float</td>
<td>[1.0, 100.0]</td>
<td>[5.0, 3.0, 2.0]</td>
<td>[FWHM in arcmin for each frequency channel]</td>
</tr>
<tr>
<td>ell_max</td>
<td>int</td>
<td>[300, 4000]</td>
<td>2000</td>
<td>[Maximum multipole to be considered in the analysis]</td>
</tr>
<tr>
<td>ell_min</td>
<td>int</td>
<td>[2, 500]</td>
<td>20</td>
<td>[Minimum multipole to be considered in the analysis]</td>
</tr>
<tr>
<td>Bd</td>
<td>float</td>
<td>[0.1, 10.0]</td>
<td>1.59</td>
<td>[Dust spectral index, assuming a grey body spectral emission]</td>
</tr>
<tr>
<td>prior_dust</td>
<td>float</td>
<td>[0.0, 10.0]</td>
<td>0.0</td>
<td>[Prior on dust spectral index]</td>
</tr>
<tr>
<td>Td</td>
<td>float</td>
<td>[0.1, 100.0]</td>
<td>18.0</td>
<td>[Dust temperature, assuming a grey body spectral emission]</td>
</tr>
<tr>
<td>Bs</td>
<td>float</td>
<td>[-10.0, -0.1]</td>
<td>-3.1</td>
<td>[Synchrotron spectral index, assuming a power law spectral emission]</td>
</tr>
<tr>
<td>prior_sync</td>
<td>float</td>
<td>[0.0, 10.0]</td>
<td>0.0</td>
<td>[Prior on synchrotron spectral index]</td>
</tr>
<tr>
<td>components_v</td>
<td></td>
<td></td>
<td></td>
<td>[Pick the assumed sky components (there is always CMB by default)]</td>
</tr>
<tr>
<td>delensing_option_v</td>
<td></td>
<td></td>
<td></td>
<td>[Pick the delensing method]</td>
</tr>
<tr>
<td>params_dev_v</td>
<td></td>
<td></td>
<td></td>
<td>[Pick the cosmological parameters to be estimated (the code will give you marginalized errors over cosmological parameters, but also over foregrounds residuals if components != cmb-only)]</td>
</tr>
<tr>
<td>informations_channels_v</td>
<td></td>
<td></td>
<td></td>
<td>[Pick the relevant observables of your survey]</td>
</tr>
<tr>
<td>planck_combination</td>
<td></td>
<td></td>
<td></td>
<td>[This adds frequencies/sensitivities from Planck on the overlapping sky, as well as it could add low-ell information as explained in paragraph 2.5 of 1509.06770]</td>
</tr>
</tbody>
</table>

➤ code can be run on NERSC machines

```python
forecast_wrapper.forecast( fsky=0.1, freqs=[95, 150, 220], uKCMBarcmin=[10.0, 10.0, 10.0], FWHM=[5.0, 3.0, 2.0], ell_max=2000, ell_min=20, Bd=1.59, prior_dust=0.0, Td=19.6, Bs=-3.1, prior_sync=0.0, components_v=[0,1,0,0], delensing_option_v=[0,1,0,0], params_dev_v=[1,1,1,1,1,1,1,1,1,1,1,1,1], information_channels_v=[1,1,1,1], planck_combination=[0] )
```
Example of an application for CMB-S4 study

Constraints on $r$: fixed-aperture, 8-band CMB-S4, +Planck, CMB delensing

Marginalized constraint on $r$

$\sigma(r)$

Cost (arbitrary units)

USD ($)

Optimum cost scale and aperture depend on telescope model, in this case
Example of an application for SIMONS ARRAY study

\[ \ell_{\text{min}} \geq 20 \]

\[ T_{\text{obs}} \text{ [yrs]} \]

\[ \sigma_r = 0.0 \]

\[ 5\% < f_{\text{sky}} < 25\% \]

Simons Array = 95, 150, 220 and 280GHz

Josquin Errard (ILP) — Moriond 2016
• Offset Gregorian telescope, high polarization fidelity and small side lobe
• 3 meter diameter primary, 3.5 arcmin @ 150 GHz
• Telescope sized for B-mode lensing and inflationary science
• POLARBEAR-2 will use three plates of birefringent sapphire to achieve broadband polarization modulation performance
POLARBEAR-2 Receiver

Pulse tube coolers

2 meters

Optics tube

Receiver backend

Focal plane

Alumina lenses (4 K)

Alumina IR Filter (50 K)

Zotefoam Window (300 K)

Josquin Errard (ILP) — Moriond 2016
- **POLARBEAR-1**
  - 1,274 Bolometers
  - 150 GHz
  - 22 cm diameter
  - 4” wafers

- **POLARBEAR-2**
  - 7,588 Bolometers
  - 95/150 GHz pixels
  - 36.5 cm diameter
  - 6” wafers
1. Anti-reflection coated silicon lenslet focuses beam to antenna
2. Sinuous antenna collects photon over wide frequency range
3. On chip RF filter (diplexer) splits signal into frequency bands
4. Superconducting TES bolometers detect signal
Simons Array = 3 x Polarbear-2

two extra telescopes being assembled now!
Simons Array = 3 x Polarbear-2

two extra telescopes being assembled now!
Simons Array = 3 x POLARBEAR-2

two extra telescopes being assembled now!

22,764 detectors
4 bands: 95, 150, 220 and 280 GHz
fsky ~ 65 %

The Simons Array: expanding POLARBEAR to three multi-chroic telescopes
Arnold et al., SPIE proceedings (2014)
**Conclusions**

- We developed a tool forecasting scientific performance for CMB instruments, in the presence of astrophysical foregrounds and gravitational lensing.

- Upcoming CMB projects will need sensitive foregrounds monitors, covering both large and small angular scales.

- The instrumental designs should be robust in front of the “unknown” — now working on a generalized formalism to incorporate systematics due to modeling assumptions.

- POLARBEAR-2 is being installed (first light this year!) and the Simons Array will start observing in 4 frequency bands in 2018!
Stay tuned!