Complementing future CMB ground-based data sets with balloon observations

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Sub-orbital synergies

Ground-based CMB experiments:

✦ long survey durations reach high sensitivity

✦ access to very small scale CMB fluctuations

✦ no large angular scale fluctuations ($\ell < 30$) or high frequencies (ν > 280 GHz) due to atmospheric emission

Balloon-borne CMB experiments:

✦ shorter duration survey

✦ access to large angular scale CMB fluctuations

✦ access to high frequencies as they are not as impacted by the atmosphere

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Large-scale E-modes with balloon

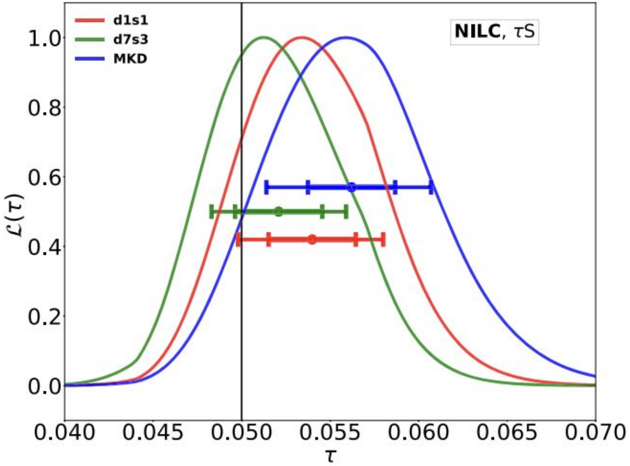
- TauSurveyor concept: Balloon-borne CMB experiment can measure large-angular scale E-mode polarization
- Can constrain the optical depth to reionization (**τ**)

TauSurveyor forecast: $\sigma(\tau)$ = 0.0034

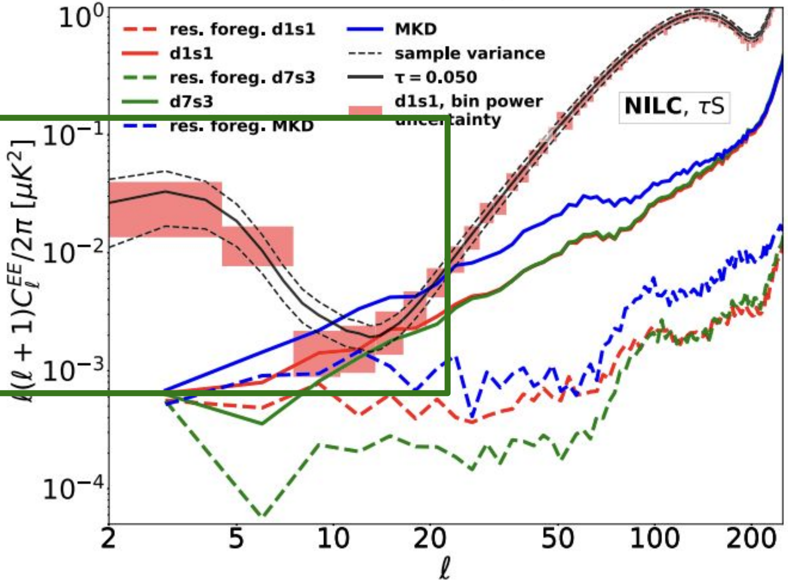
Achieving $\sigma(\tau)$ < 0.003 from realistic sub-orbital experiments, for realistic sky is very challenging!

(*Errard, J. et. al. ApJ 940:68 2022*)

What can balloons do in CMB B-mode polarization?



Access to the largest scales



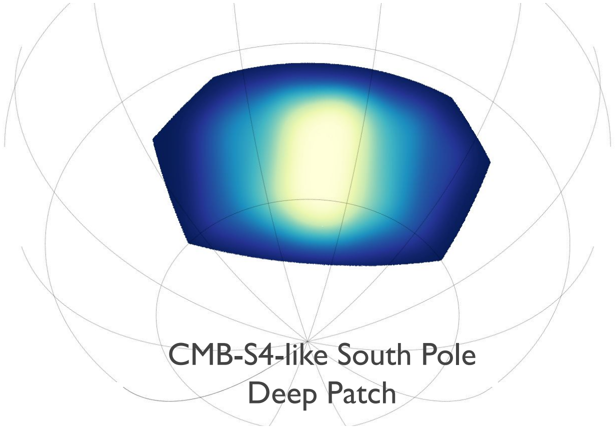
Constraining PGW with CMB-S4

CMB-S4 PGW Science Goal:

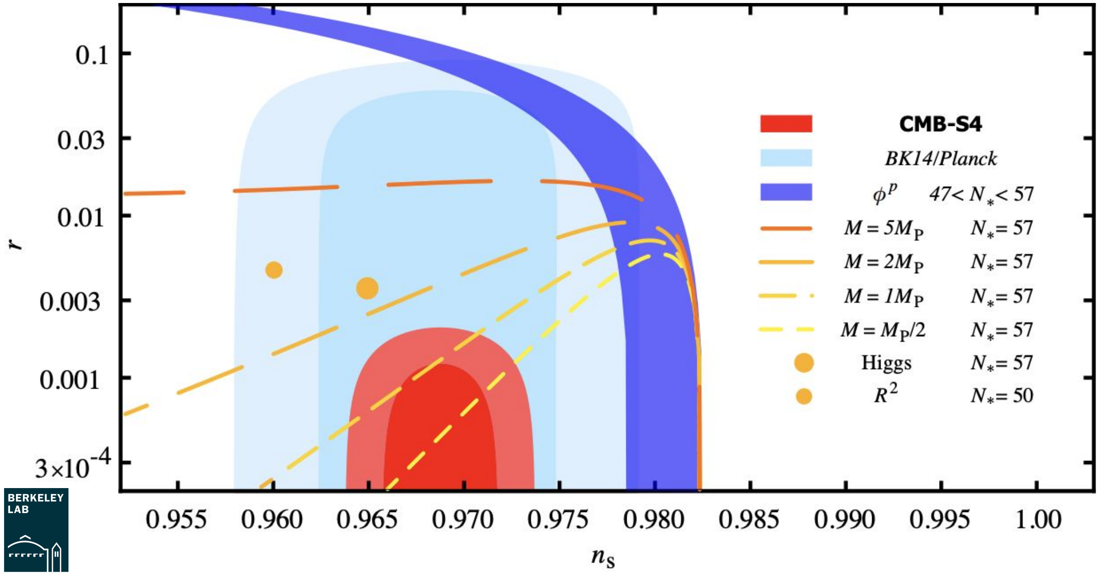
If $r \geq 0.003$, achieve a 5σ detection.

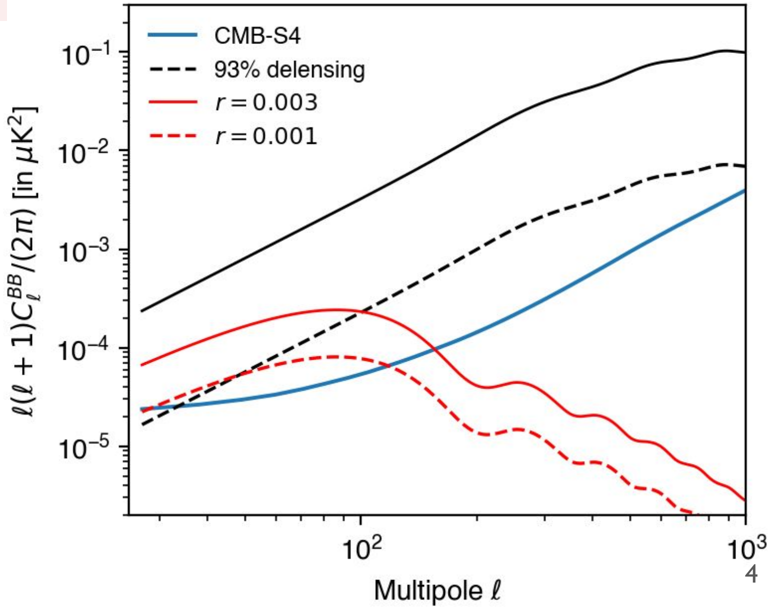
If $r = 0$, achieve a 95% confidence upper limit of $r \leq 0.001$.

Target $\sigma(r)$ = **5×10^{-4}** achieved after approx. 10 years of survey



CMB-S4-like South Pole Deep Patch





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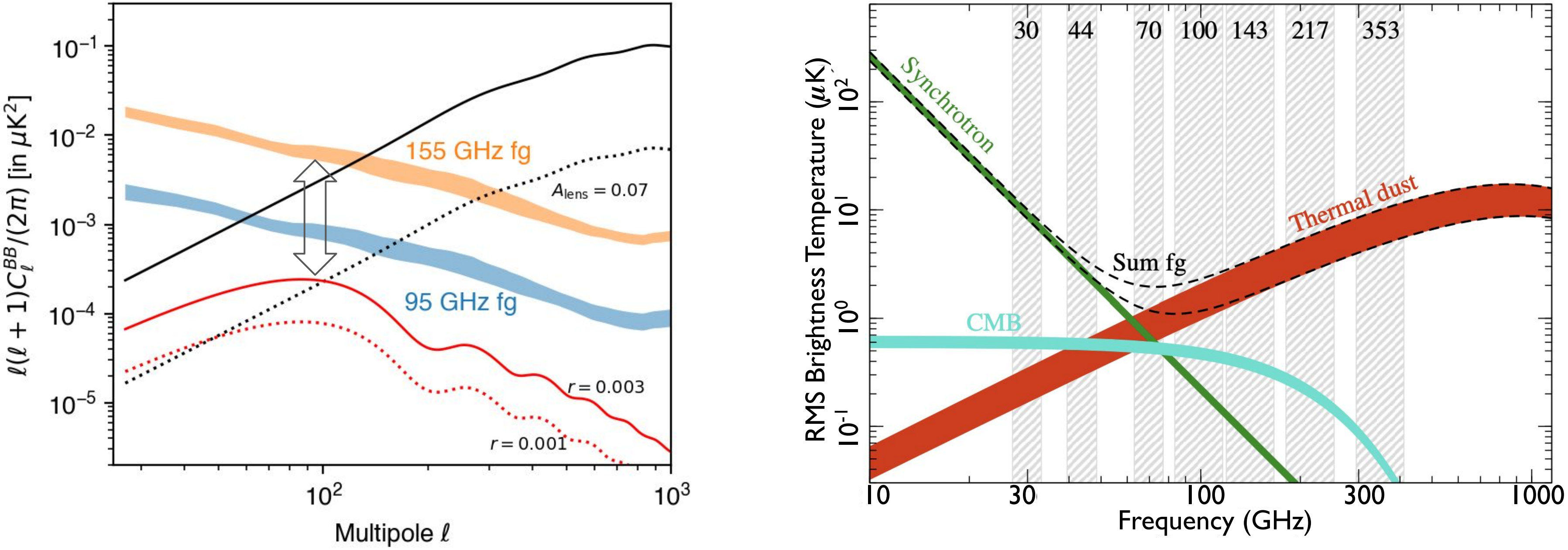
Foregrounds and the component separation challenge



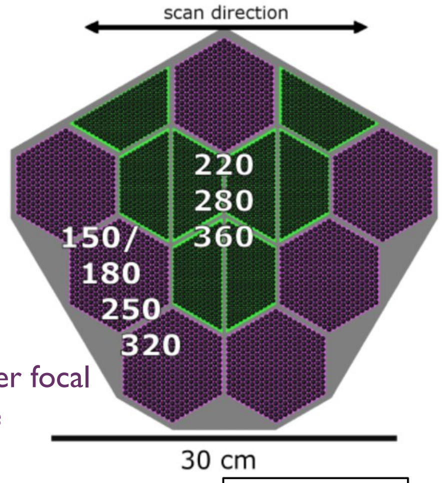
Component separation is vital for achieving PGW detection target.

- Primary polarized foregrounds: Dust and synchrotron
- Foreground modelling uncertainty in how frequency scaling changes across sky and decorrelation.
- PySM models: **Low**, **Medium** and **High** complexity

Balloon-borne mission: imager vs spectrometer

Realistic configurations for Imager:

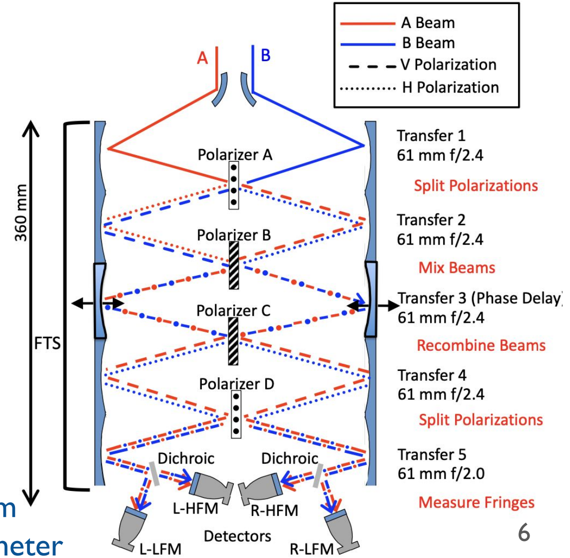
- Two types of pixels: low frequency pixels (2316 pixels), frequencies - **150, 180, 250, 320 GHz** and high frequency pixels (1680 pixels), frequencies - **220, 280, 360 GHz**.
- Resolution: 7.2 arcmin at 150 GHz and 3.2 arcmin at 360 GHz.
- Total 20562 TES bolometers.



Imager focal plane

Realistic configurations for Spectrometer:

- Single spectrometric pixel with 33 arcmin resolution.
- Two beams (one each for Q and U polarization).
- FTS has dichroic split to high and low frequency detector.
- Low frequency module: 7 frequencies 150-400 GHz with 50 GHz bandwidth each
- High frequency module: 9 frequencies 400-800 GHz with 50 GHz bandwidth each



Fourier Transform Spectrometer

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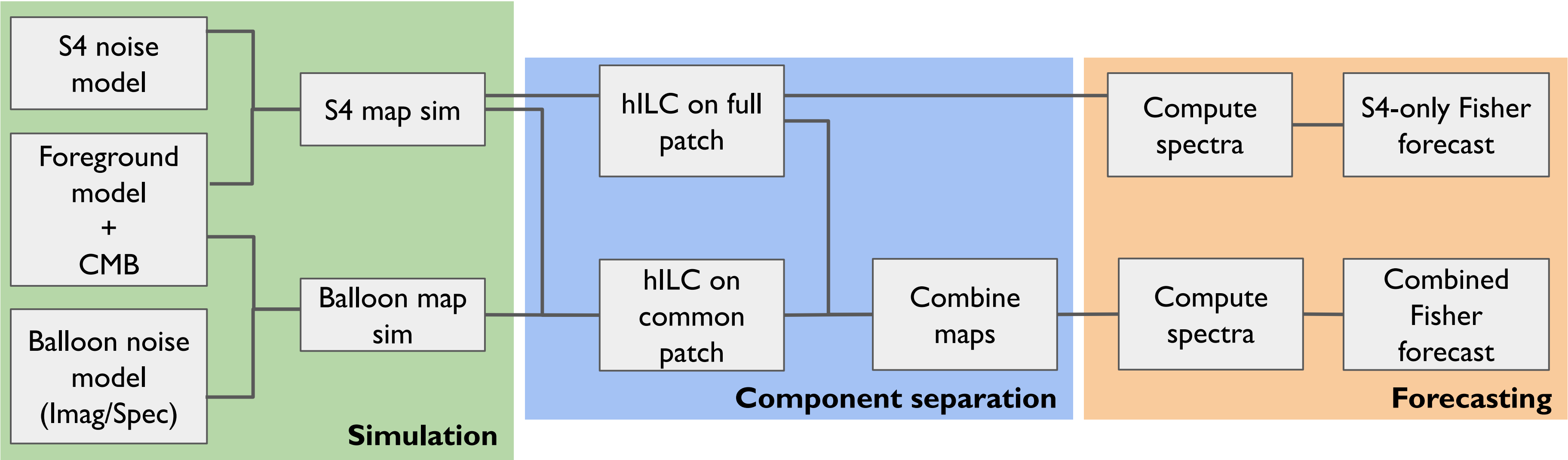
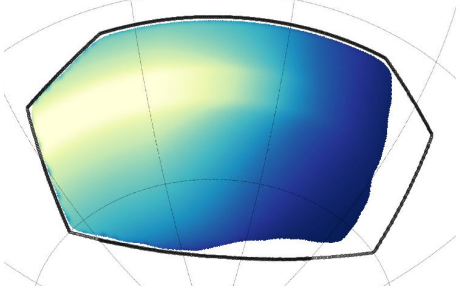
Component separation and *r* forecasting



- ✦ S4 noise model, delensing level based on *Belkner et. al. 2024 ApJ.*
- ✦ Foregrounds: medium and high complexity from PySM.
- ✦ Balloon noise model constructed from patch visibility only, for 30 day observation. *(preliminary)*

Realistic S4 patch visibility for a balloon flight from Antartica



- ✦ Bias on *r* is estimated by fitting the foreground residuals.
- ✦ The uncertainty estimates come from a Fisher estimate assuming a Gaussian likelihood:

$$\sigma(r) = r_0 \left[\sum_{\ell_{\min}}^{\ell_{\max}} \left(\frac{\sigma(C_\ell)}{C_{\ell,r_0}} \right)^{-2} \right]^{-1/2}$$

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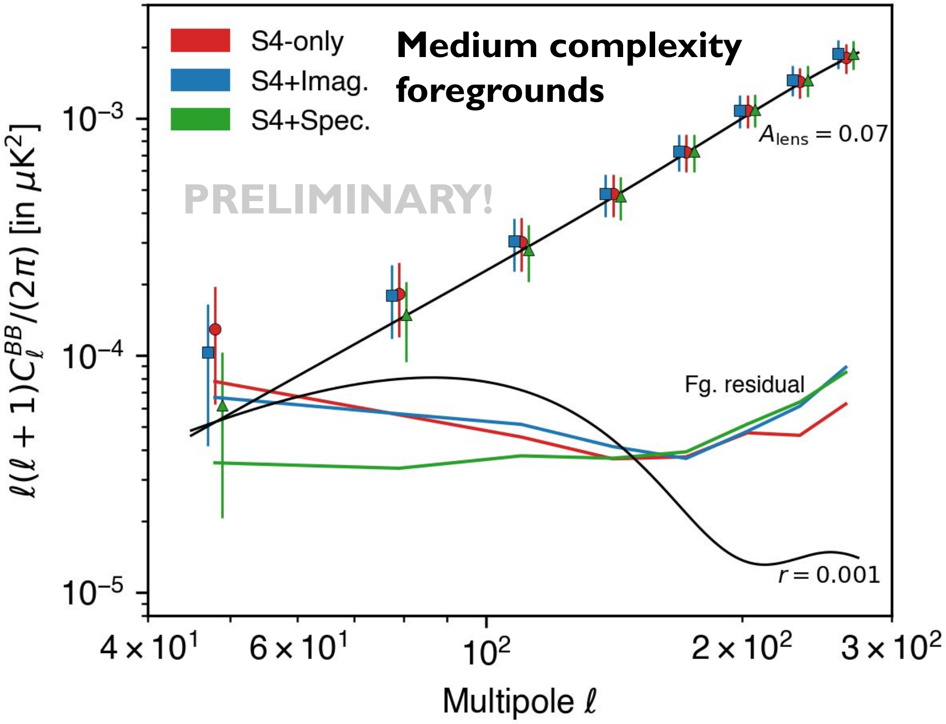
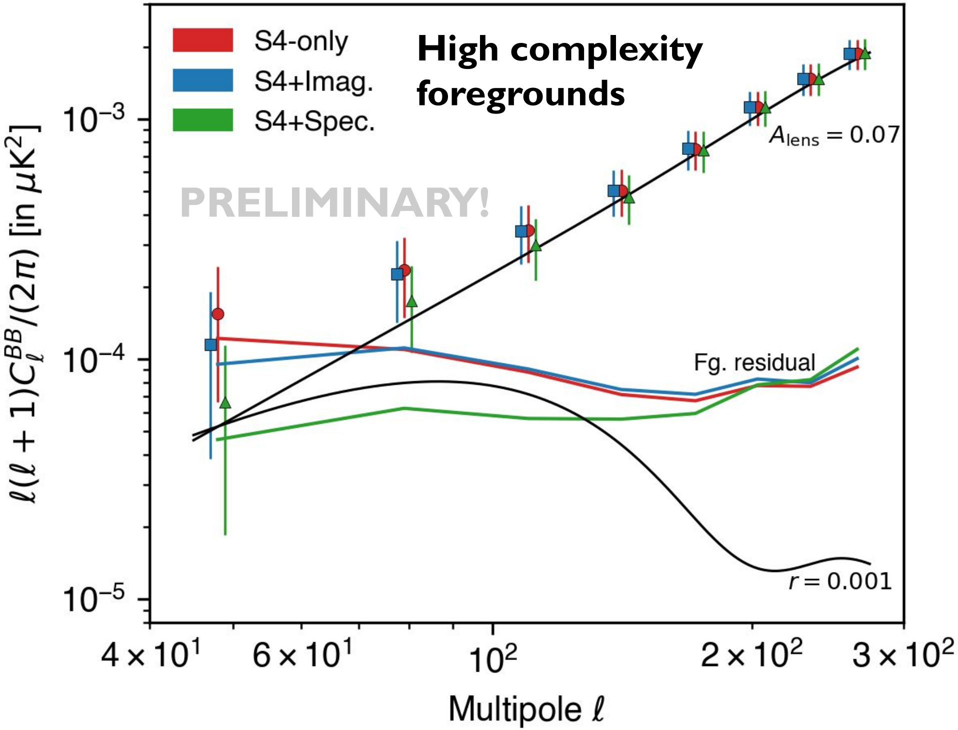
Recovered spectra, uncertainties and residuals





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Forecast for PGW

Foreground residual after component separation:

- Adding observations from a balloon-based spectrometer can reduce residual foreground level by 35% for medium complexity and 45% for high complexity foregrounds.

Uncertainty:

- The spectrometer option achieves a significant reduction in $\sigma(r)$.
- Reduction in $\sigma(r)$ varies 4% to 16% for medium complexity.
- For high complexity foregrounds $\sigma(r)$ reduces by 4% to 20%.

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Summary

- Balloon-based CMB observations complement ground-based CMB experiment with access to large angular scale fluctuations and higher frequencies.
- We are studying how balloon-based measurements can help foreground cleaning for CMB-S4 in context of detection of PGW.
- Increasing foreground complexity gives increased foreground residual and uncertainty after component separation stage.
- We find significant improvement in foreground residual when adding high frequency observations from the balloon-based spectrometer.
- We also find reduction of uncertainty $\sigma(r)$ with both instruments. The spectrometer option outperforms the imager.

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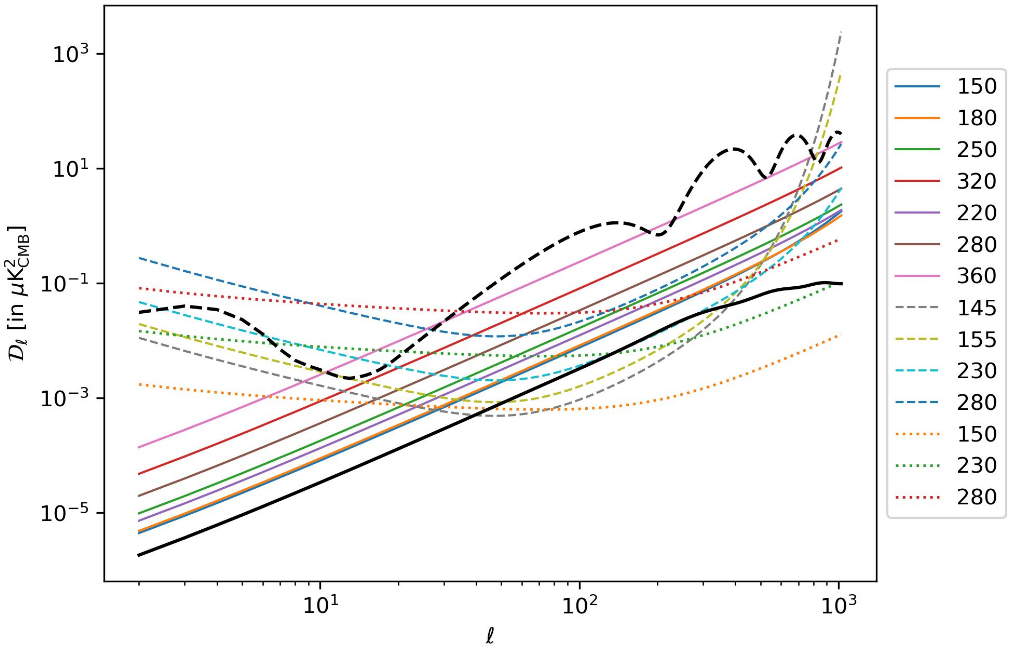
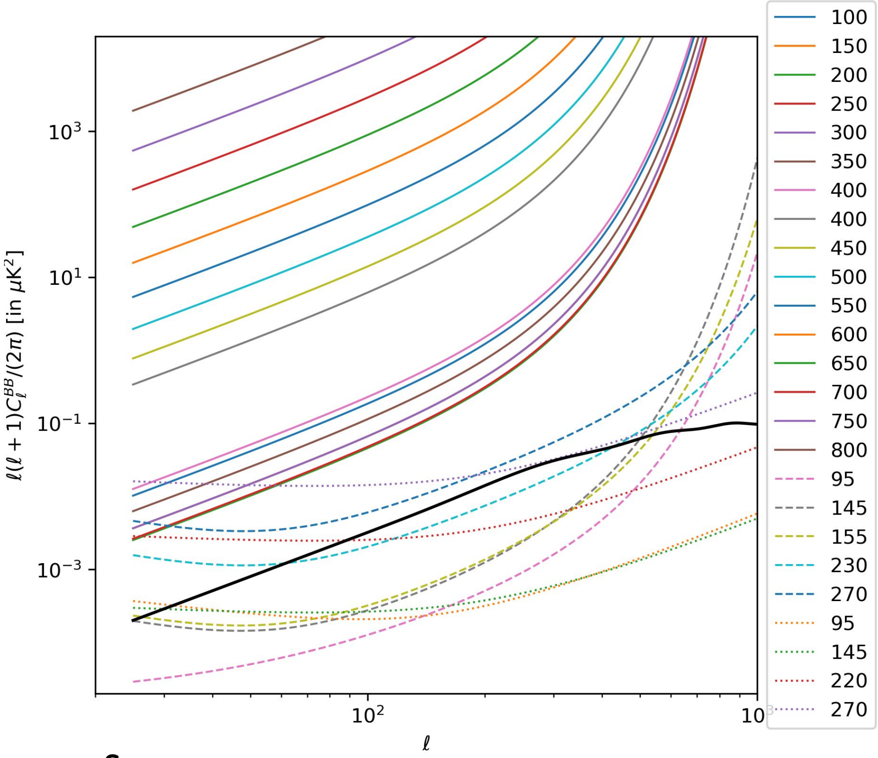
Backup slides

Noise comparison

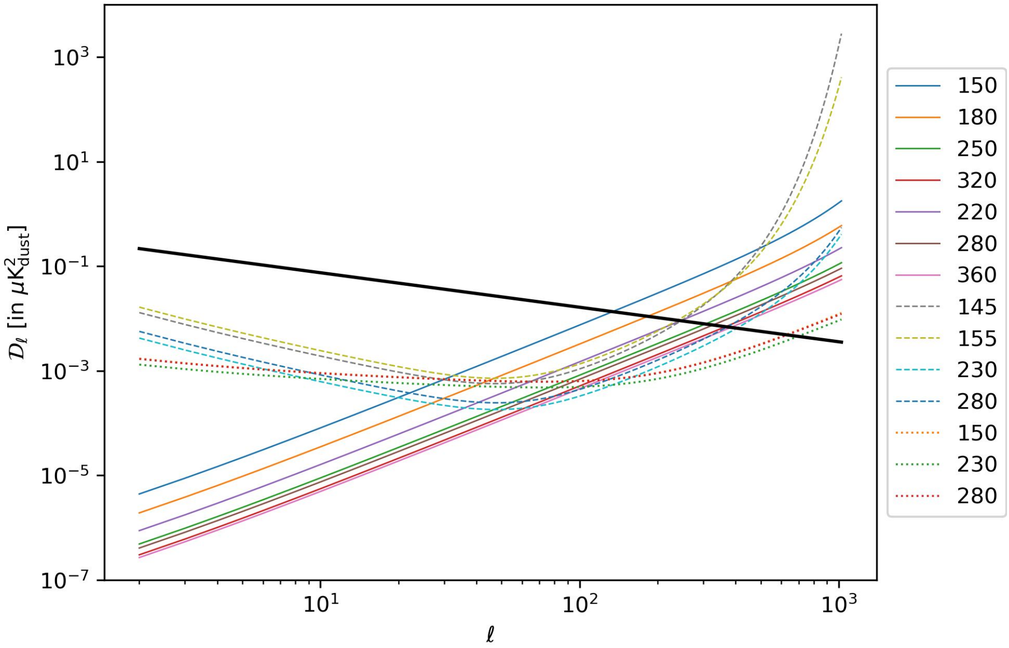


Imager

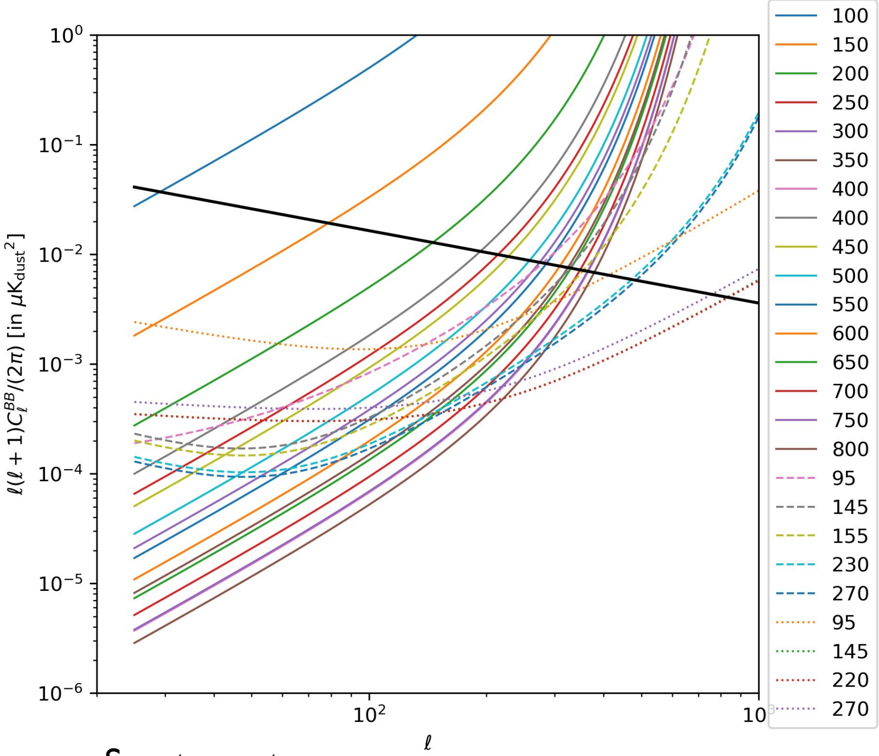


Spectrometer

Dust sensitivity



Imager



Spectrometer

PGW detection forecast

	CMB-S4 only		CMB-S4 + Imager		CMB-S4 + Spectrometer	
	$\sigma(r)$ x 10^{-4}	equiv. *r* bias* x 10^{-4}	$\sigma(r)$ x 10^{-4}	equiv. *r* bias* x 10^{-4}	$\sigma(r)$ x 10^{-4}	equiv. *r* bias* x 10^{-4}
Medium complexity	5.6	8.7	5.4	8.7	4.6	5.6
High complexity	7.2	16	6.9	15	5.5	8.7

PRELIMINARY!

*Equivalent *r* bias: Equivalent value of *r* for the ILC residual foreground power spectrum.

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