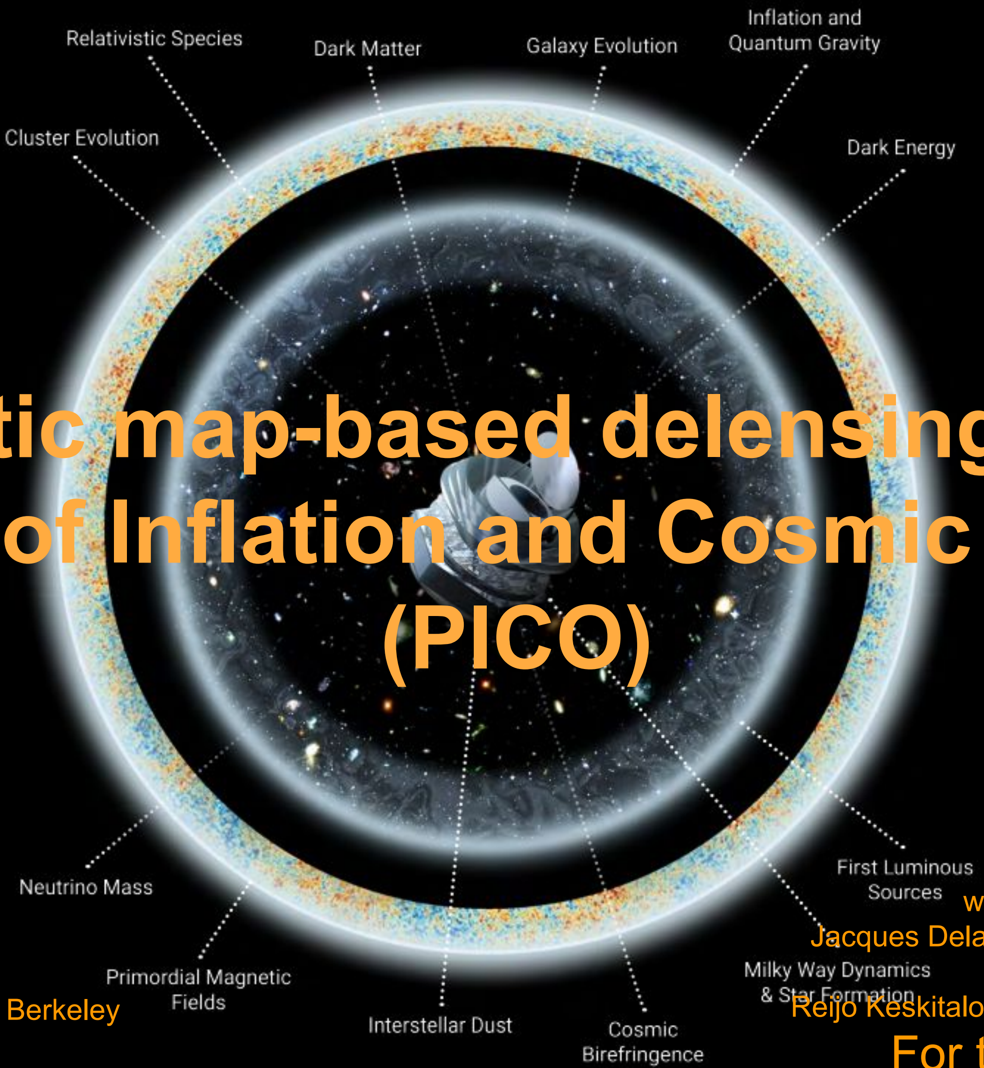
Realistic map-based delensing for the Probe of Inflation and Cosmic Origins (PICO)



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For the PICO collaboration

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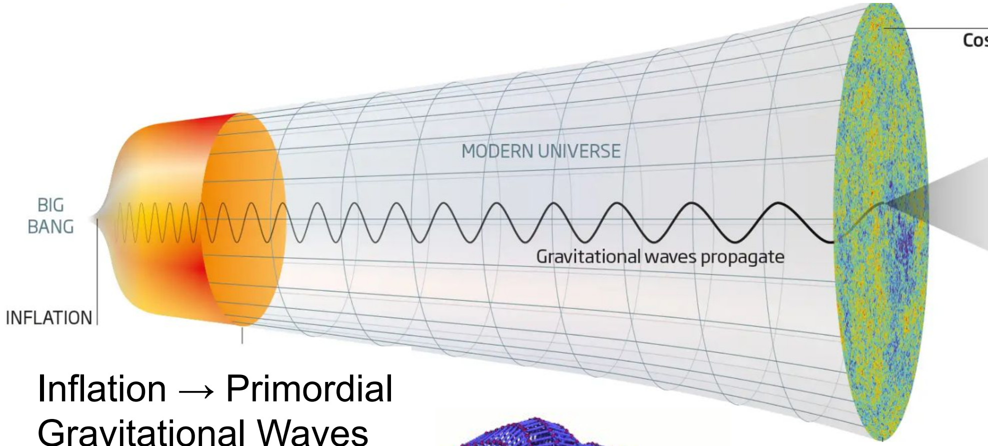
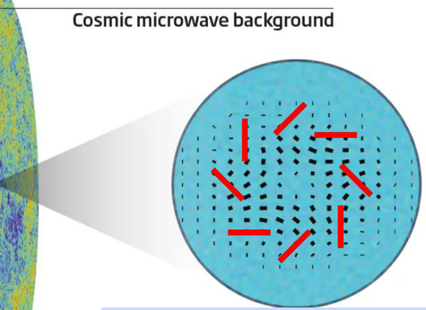
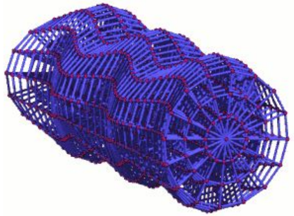
[2]APC

Searching for inflation with CMB B-Modes



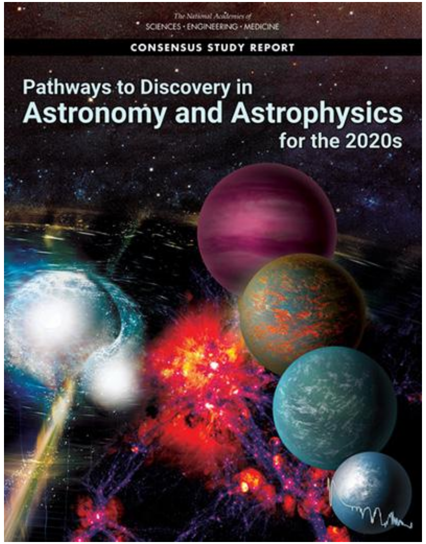


Inflation → Primordial Gravitational Waves



Credit: the New Scientist, Einstein-online

Primordial Gravitational waves → B-mode (parity-odd) polarization pattern



CMB B-modes identified as high priority in the Astro2020 Decadal Survey report

Primordial Gravitational Waves are a smoking gun for inflation!

Defined by the tensor-to-scalar ratio r (“Amplitude of the PGW”)

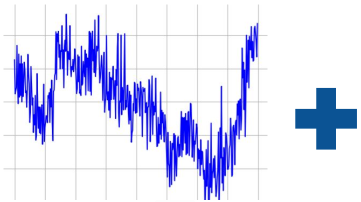
Energy scale: 10^{12} LHC!!!

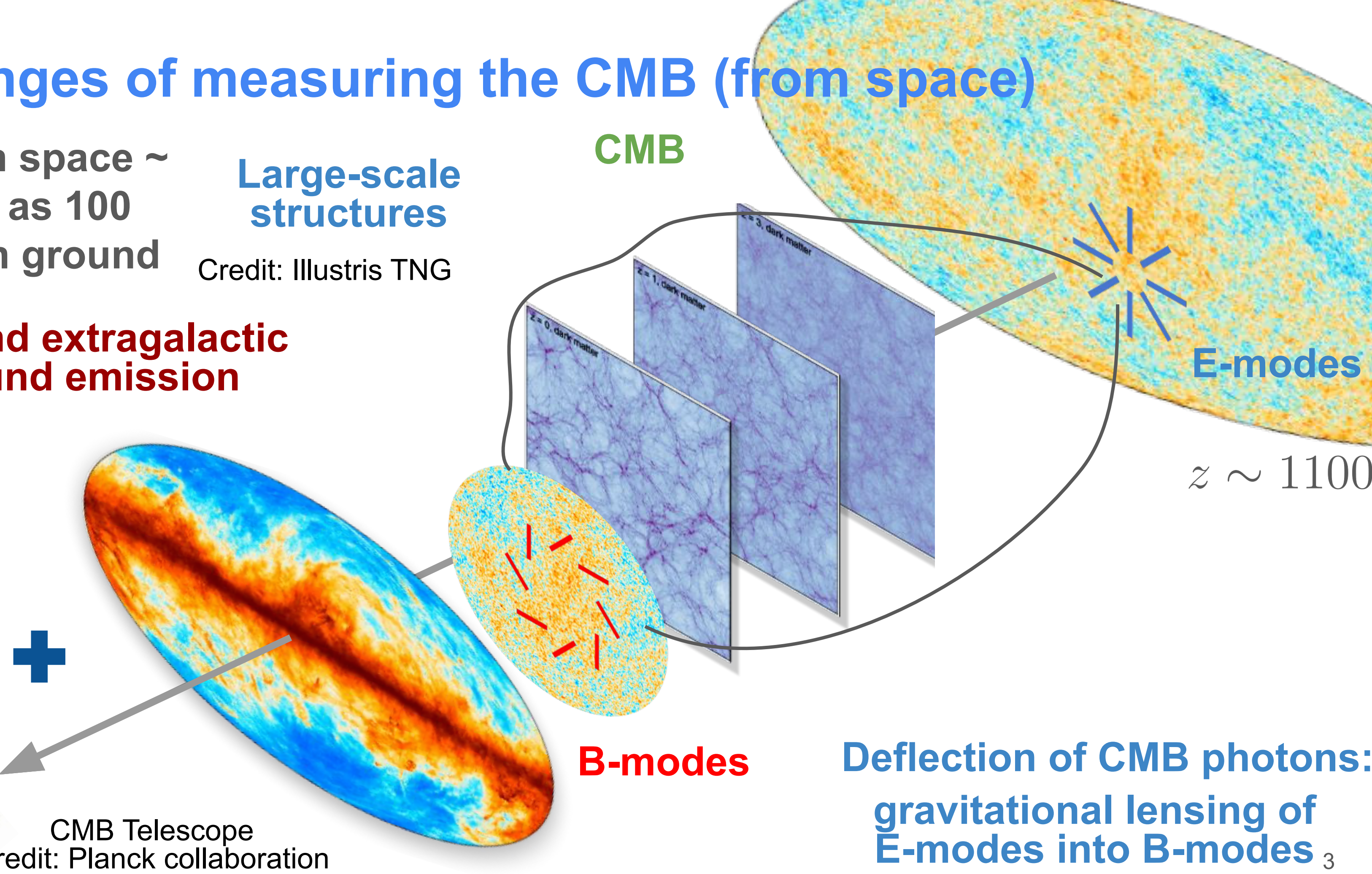
Challenges of measuring the CMB (from space)

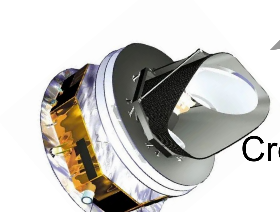
1 detector in space ~ as sensitive as 100 detectors on ground

Galactic and extragalactic foreground emission

Instrumental noise

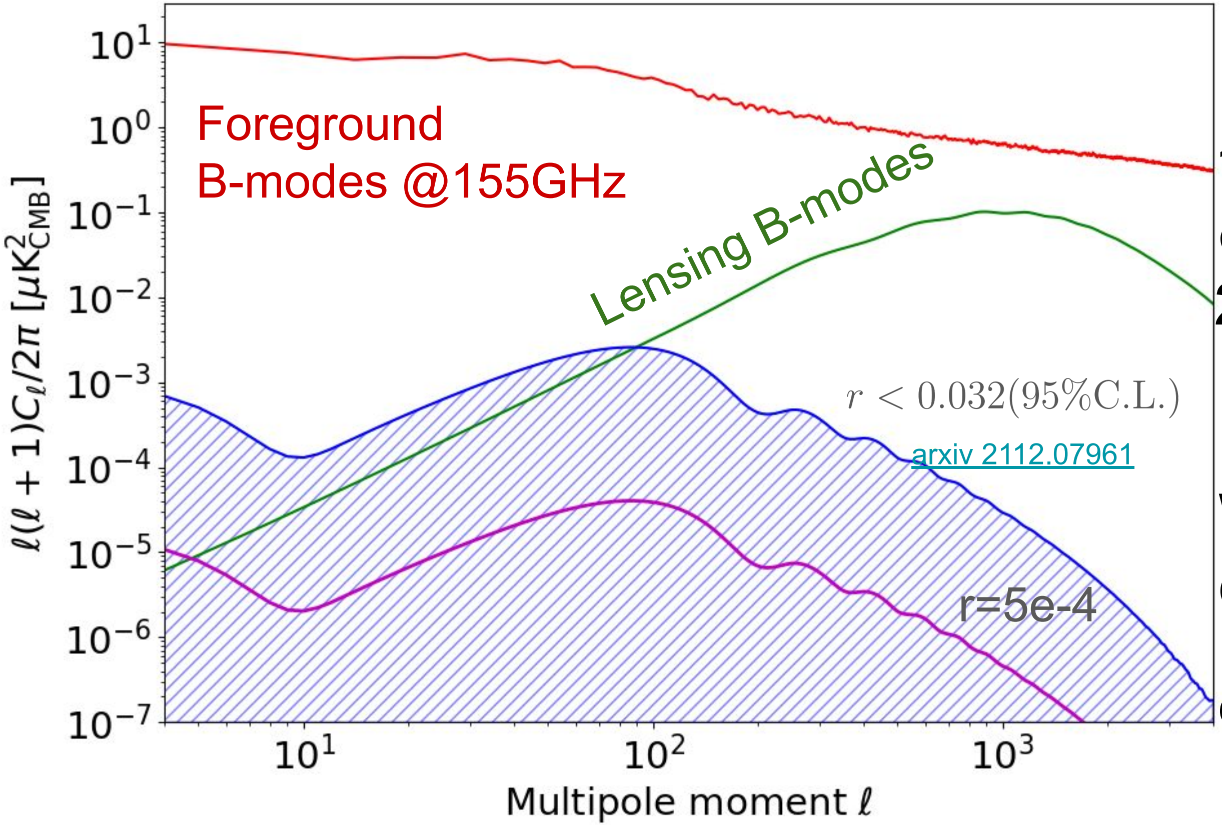






PICO: r science (arXiv 1902.10541)

Primordial
B-modes



PICO is designed to

1) Detect $r \sim 5 \cdot 10^{-4}$

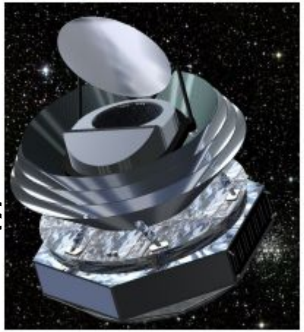
or

2) Rule out inflation models which predict $r \gtrsim 5 \cdot 10^{-4}$

With **5 years** and at **5σ** confidence level

CMB S4: $r \gtrsim 3 \cdot 10^{-3}$ **in 10 years**

PICO Concept



- Endorsed for implementation by the US Astro2020 Decadal Panel
- Lowest noise, all-sky instrument among next generation experiments

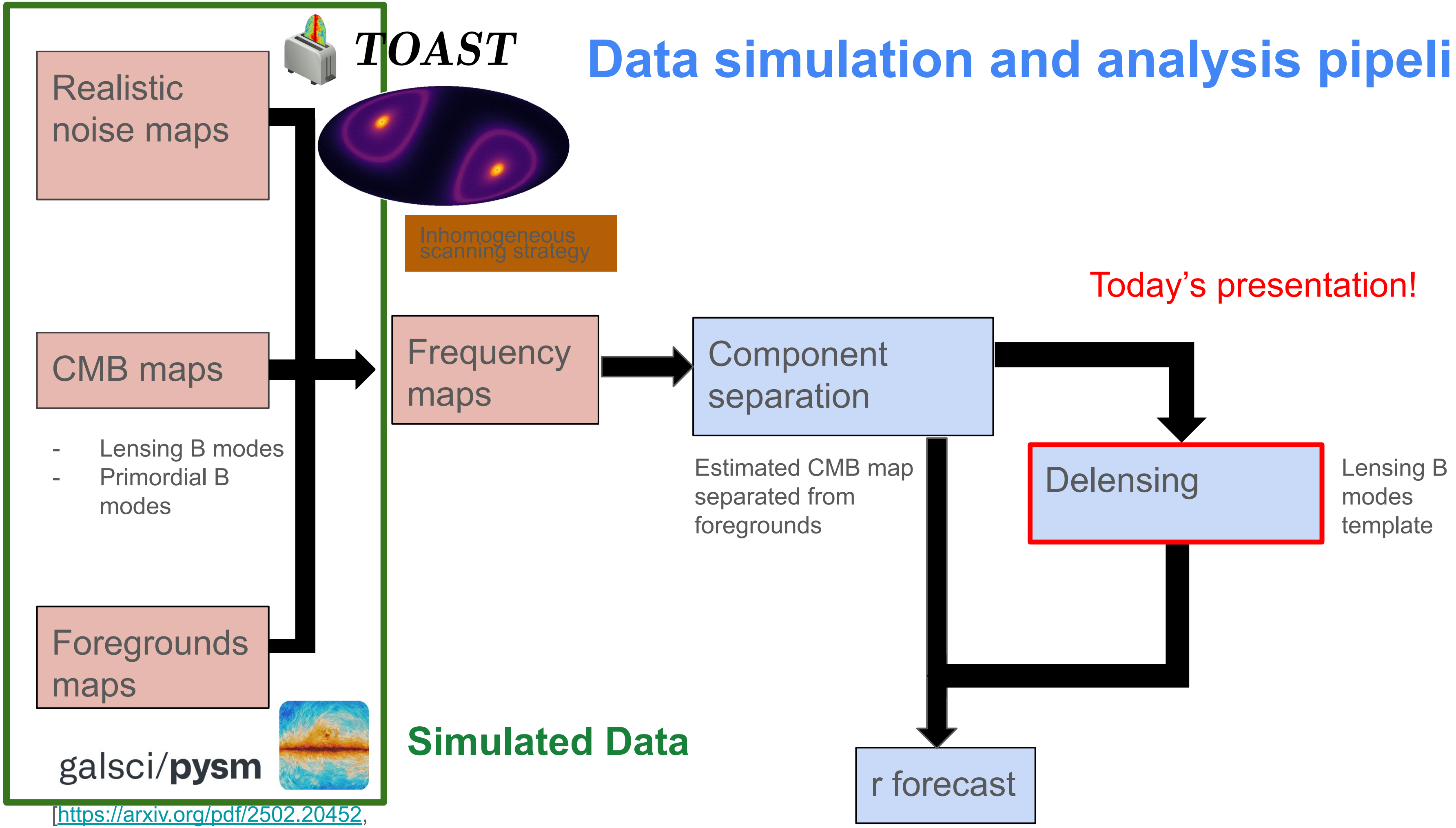
  (e.g. ~10000 Planck years to reach PICO's sensitivity)

- Large frequency range with a single 13,000 detector focal plane

Sky coverage	**Full sky**
Duration [years]	**5**
Frequency range [GHz]	**21 — 799 GHz (21 bands)**
Angular resolution [arcmin]	**38.4 — 1.1**
Noise sensitivity (CBE) [μK.arcmin]	**0.61**

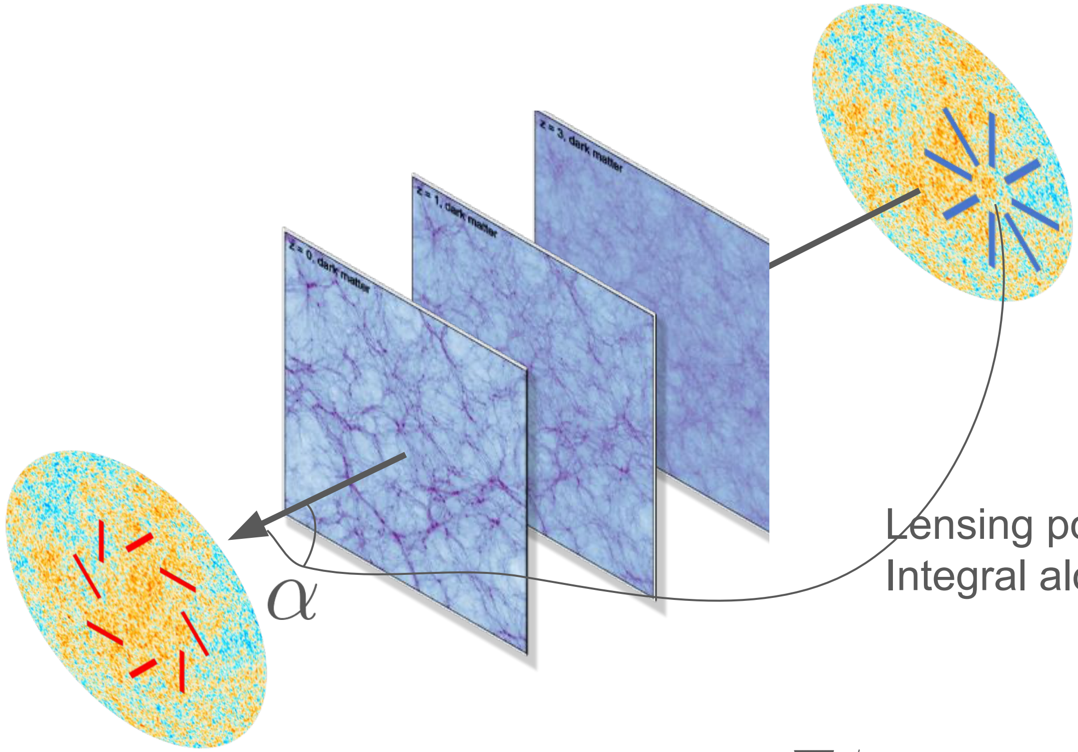
Large frequency range, high resolution, high sensitivity

Data simulation and analysis pipeline



[https://arxiv.org/pdf/2502.20452, https://github.com/galsci/pysm]

Model for weak lensing of the CMB



Unlensed E-modes

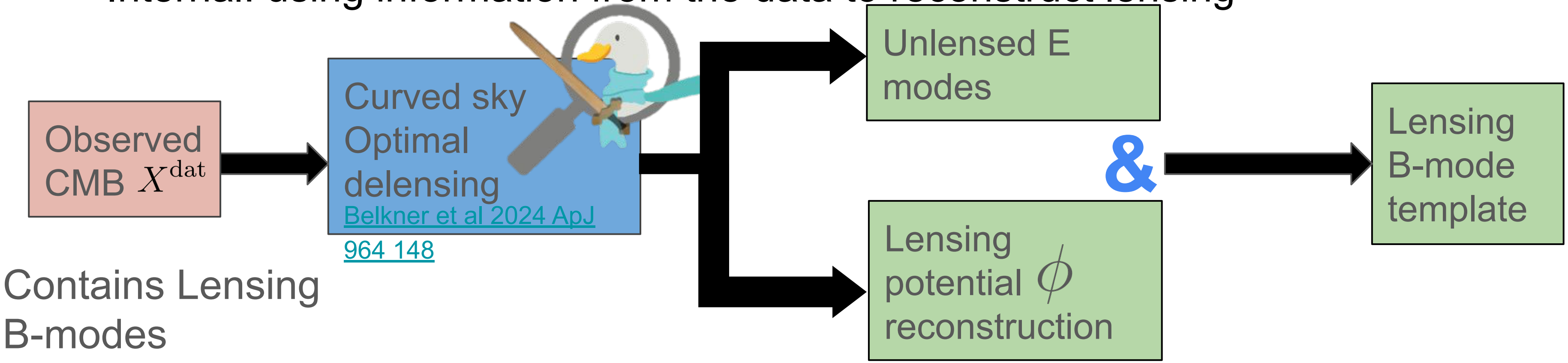
Lensing potential ϕ :
Integral along the line-of-sight

Deflection angle: $\alpha = \nabla\phi$

Lensing B-modes

Delensing

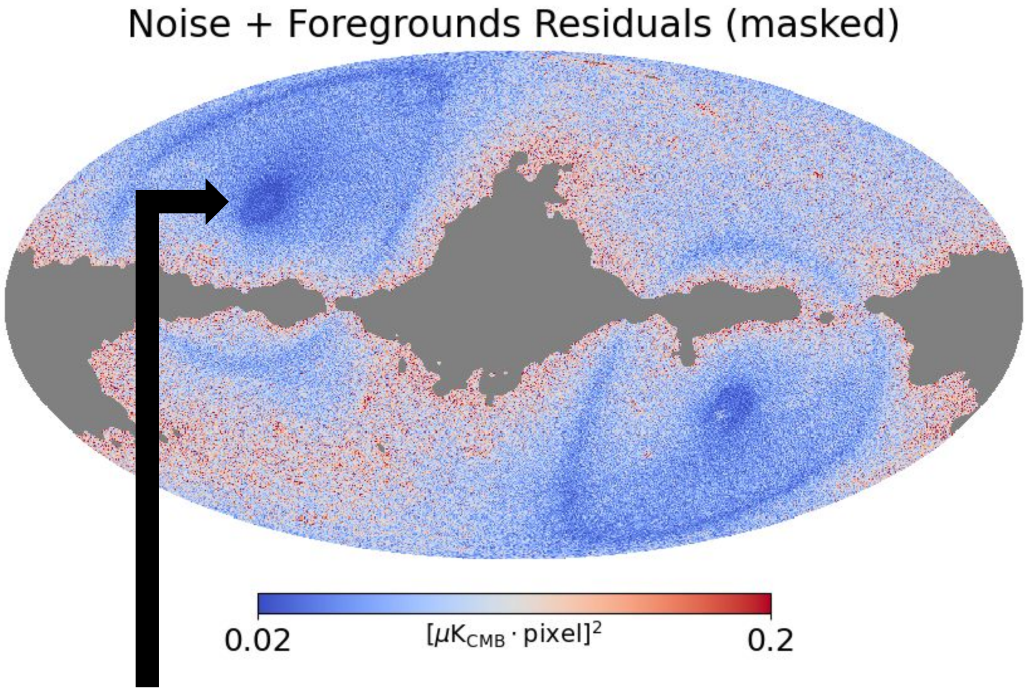
- Bayesian (Optimal) method: maximum a posteriori lensing potential reconstruction Carron, Lewis arxiv.org/1704.08230
- Map-based method
- Internal: using information from the data to reconstruct lensing



Deflection angle: $\alpha = \nabla\phi$

Data and noise model

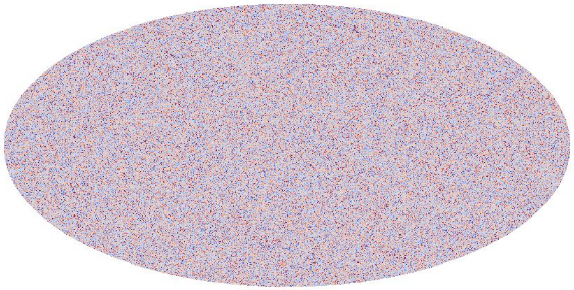
- Foregrounds contaminate the signal in the galactic plane, which impacts the delensing.
- Minimal galactic mask
- variance inversely proportional to the survey depth $\sigma_p^2 \propto \frac{1}{\text{hits}_p}$



More depth, less noise

Results: residual lensing

Lensing B input (before adding noise and foregrounds)



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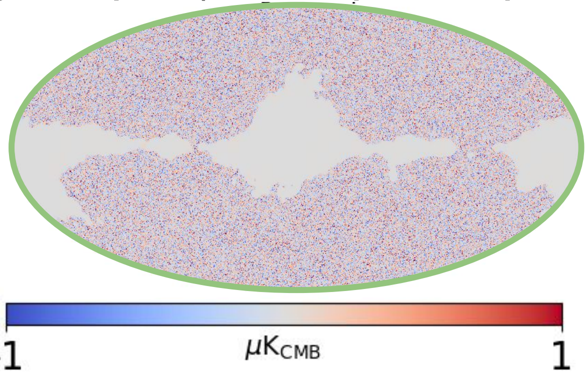
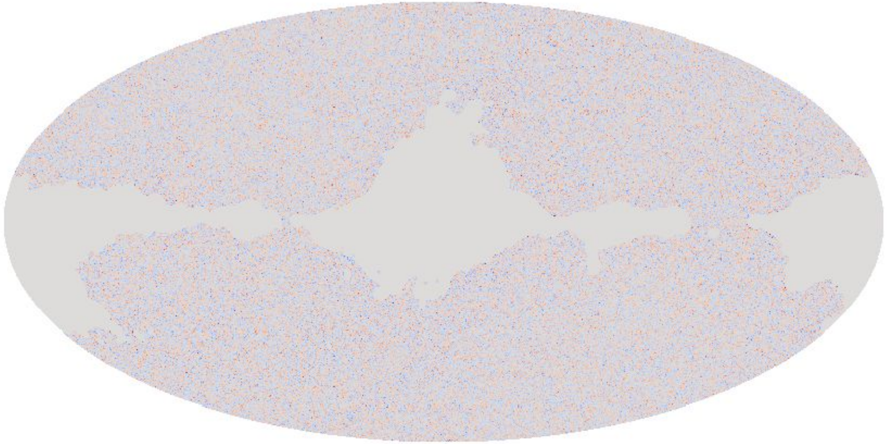
Lensing B Template (from component separation product)



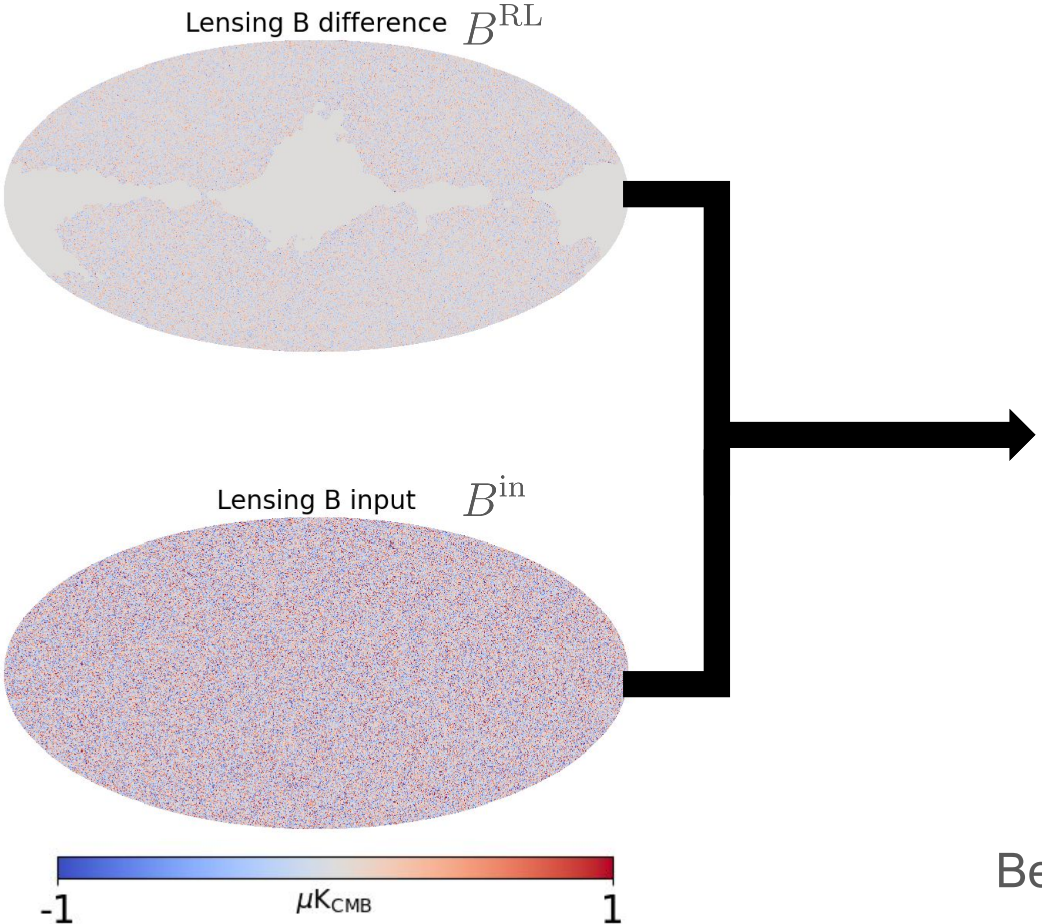
$$B^{\mathrm{RL}} \equiv B^{\mathrm{in}} - B^{\mathrm{LT}}$$

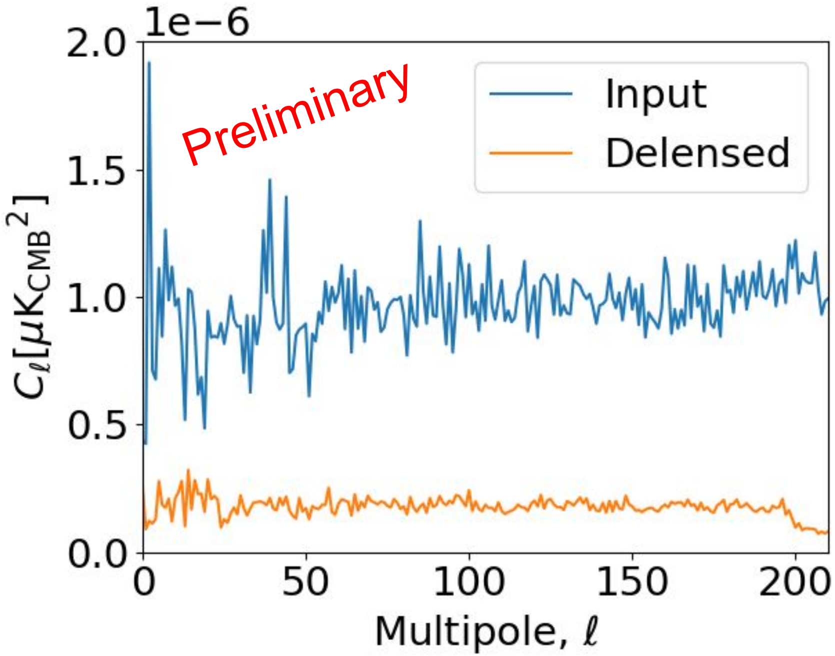
Lensing B difference



Results: Delensing performance

$$A_{\rm lens} \equiv \left\langle \frac{C_\ell^{\rm RL}}{C_\ell^{\rm in}} \right\rangle_{\ell \in [\ell_{min}, \ell_{max}]}$$

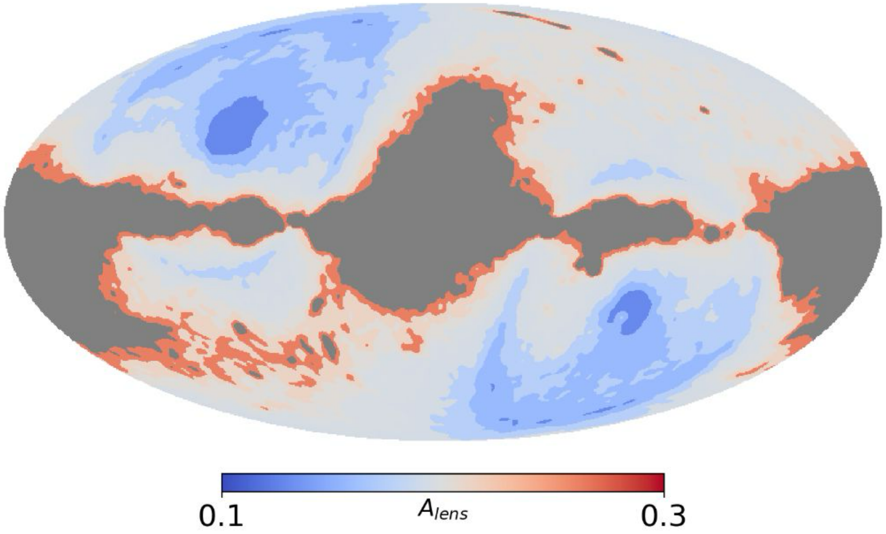




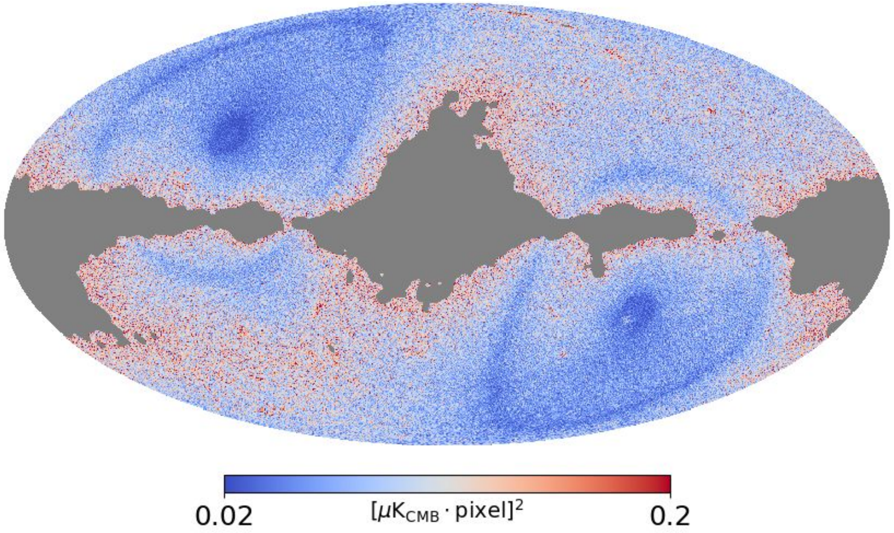
Between 2 and 190: $A_{\rm lens} = 0.19$

Consistency check: Local delensing performance

Residual Lensing

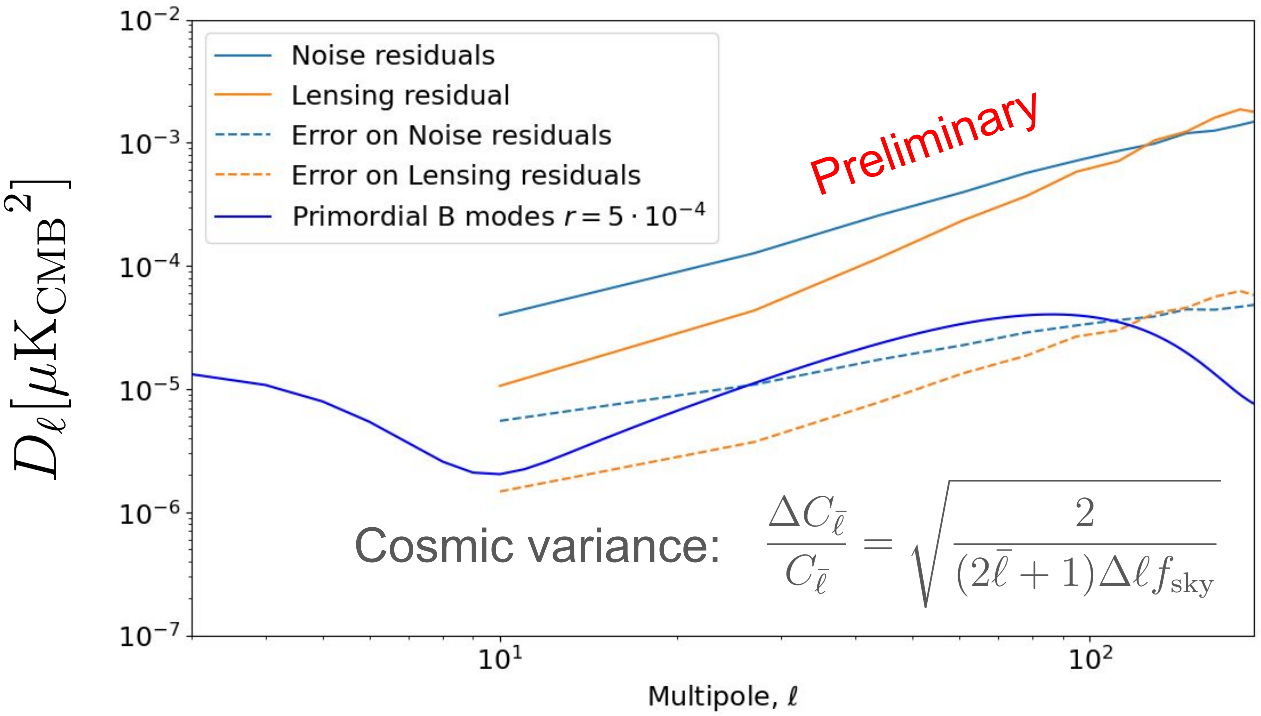


Noise and foreground variance



The delensing performance traces the noise and foreground variance.

Total error on the power spectra



Cosmic variance: $$\frac{\Delta C_{\bar\ell}}{C_{\bar\ell}} = \sqrt{\frac{2}{(2\bar\ell + 1)\Delta\ell f_{\rm sky}}}$$

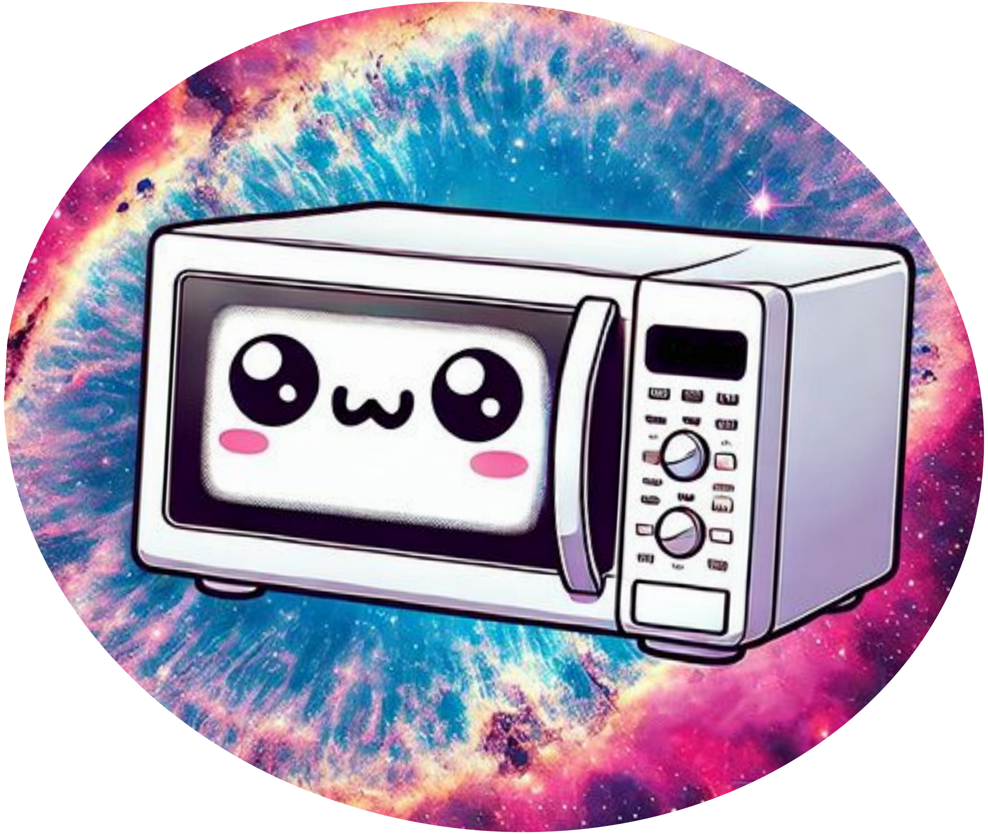
- **Cosmic variance** limits ultimate sensitivity on primordial GW with r
- For this simulation, contributions of noise and residual lensing to sensitivity on r roughly similar
- **Next step**: run multiple realizations and propagate to **cosmological likelihood**

$f_{\rm sky} = 46\%$

Conclusion

- Detection of inflation remains one of the most compelling science goals in cosmology today.
- The CMB offers an extraordinary window into this early epoch.
- Efficient delensing is crucial for detection of primordial B-modes.
- The proposed PICO design features high sensitivity, high angular resolution, and broad frequency coverage.
- We developed and validated a delensing pipeline that successfully reduces the lensing signal.
- Next step: scale up with many simulations to produce robust forecasts on Primordial Gravitational Waves (with r) .
- Get started on curved-sky optimal delensing with https://github.com/NextGenCMB/delensalot

Please ask me questions!



Backup

Weak Lensing of the CMB

- Gravitational pull by structures deflect CMB photons, with lensing potential ϕ
- In temperature, this corresponds to a remapping $\tilde{\Theta}(\mathbf{x}) = \Theta\left(\mathbf{x} + \nabla\phi\right)$
- In polarization, this converts E-modes into B-modes

$$X^{\rm dat} \equiv \begin{pmatrix} Q^{\rm dat} \\ U^{\rm dat} \end{pmatrix} = \mathcal{B}\mathcal{D}_\alpha X^{\rm unlensed} + \text{noise}$$

- $\mathcal{B}$ describes the instrument beam and transfer functions
- $\mathcal{D}_\alpha$ is the deflection operator with $\alpha = \nabla\phi$

- What is the most probable (Maximum A-posteriori) lensing potential given the observed data? i.e. maximize the log-posterior probability

$$-2\ln\mathbb{P}\left(\alpha|X^{\rm dat}\right) = \underbrace{X^{\rm dat,\dagger}{\rm cov}_\alpha^{-1}X^{\rm dat}}_{\text{Quadratic}} + \underbrace{\ln\det{\rm cov}_\alpha}_{\text{Mean-Field}} + \underbrace{\sum_{LM}\frac{\phi_{LM}^2}{C_L^{\phi\phi,{\rm fid}}}}_{\text{Priors}}$$

Pixel-Pixel covariance matrix: ${\rm cov}_\alpha \equiv \langle X^{\rm dat} X^{\rm dat,\dagger}\rangle = \mathcal{B}\mathcal{D}_\alpha C^{\rm unlensed}\mathcal{D}_\alpha^\dagger\mathcal{B}^\dagger + N$

Deflection of unlensed E-modes

Iterative Internal Delensing with Delensalot

[CMB-S4: Iterative Internal Delensing and r Constraints]