Map-based delensing with realistic noise and foregrounds for the Probe of Inflation and Cosmic Origins (PICO)

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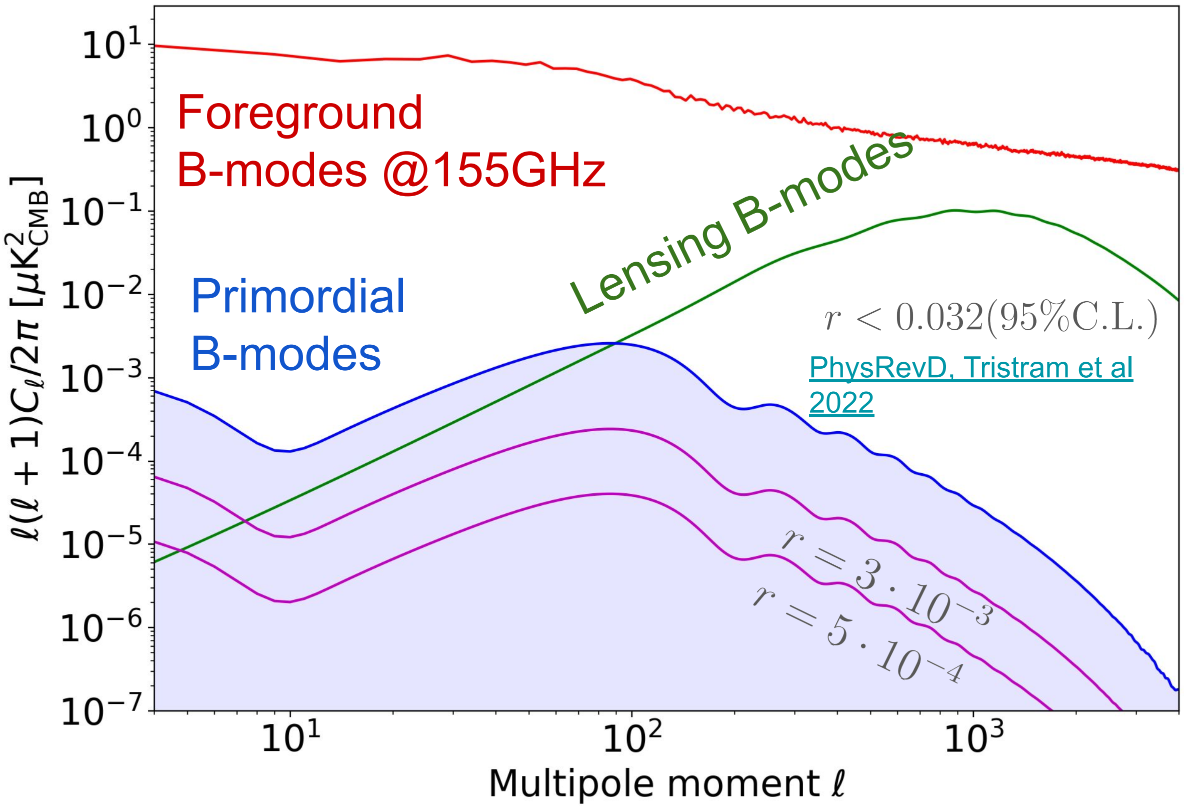
PICO: r science (PICO Report, Hanany et al)



PICO's requirement is to

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

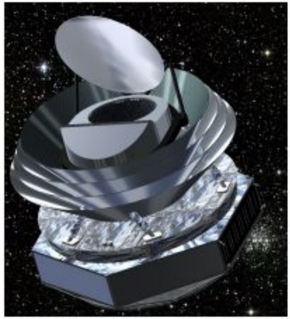
or

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

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

…among other science goals

PICO Concept (from PICO study report)



- 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 → **internal delensing,** high sensitivity

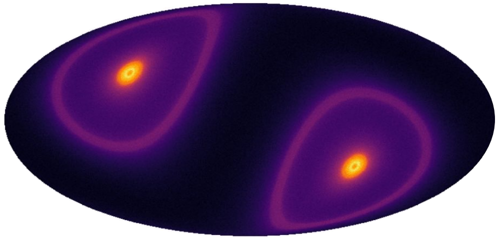
Previous results (JCAP 06 (2023) 034, Aurlien et al) and current exercise

Previous paper:

- White noise, uniform full sky coverage
- 5 foreground models :
  - Delensing with “Planck baseline foreground model” : pysm d1s1, small spatial variation of the dust SED.
- 4 out of the 5 models achieved or nearly achieved the requirements.

Current project:

- Realistic noise (50mHz, 100mHz 1/f noise) and as-designed scan strategy
- Planck baseline and medium complexity foreground model : pysm d10s5, larger spatial variation of the dust SED.
- Masked sky, for better component separation



Inhomogeneous scan strategy

What is the impact of foreground and noise complexities on the delensing performance?

Summary of the different configurations

Foreground complexity

Noise complexity

	No foregrounds	Planck baseline	Medium complexity
White homogeneous	✅	✅	✅
"White" inhomogeneous	✅		✅
50 mHz inhomogeneous	✅	✅	✅

- Planck baseline : d1s1, small SED variation for dust.
- Mid complexity : d10s5, larger SED variation for dust.

“White” : in TOD space

Data simulation and analysis pipeline

TOAST

Simulated Data

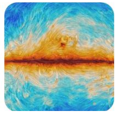
Realistic noise maps

CMB maps

- Lensing B modes
- Primordial B modes

Foregrounds maps

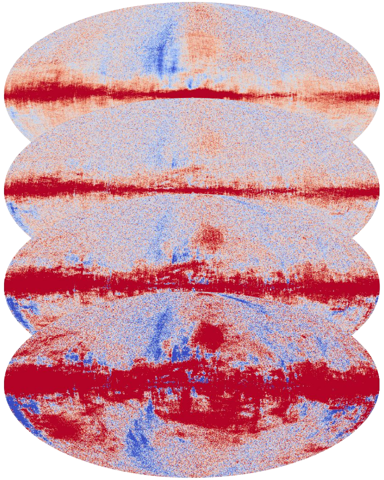
galsci/**pysm**



[Pan-Ex galactic science group, https://github.com/galsci/pysm]

NERSC

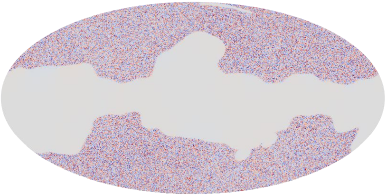
Frequency maps



Estimated CMB map separated from foregrounds

Component separation

Elisa's talk



My presentation today!

Map-Based Delensing

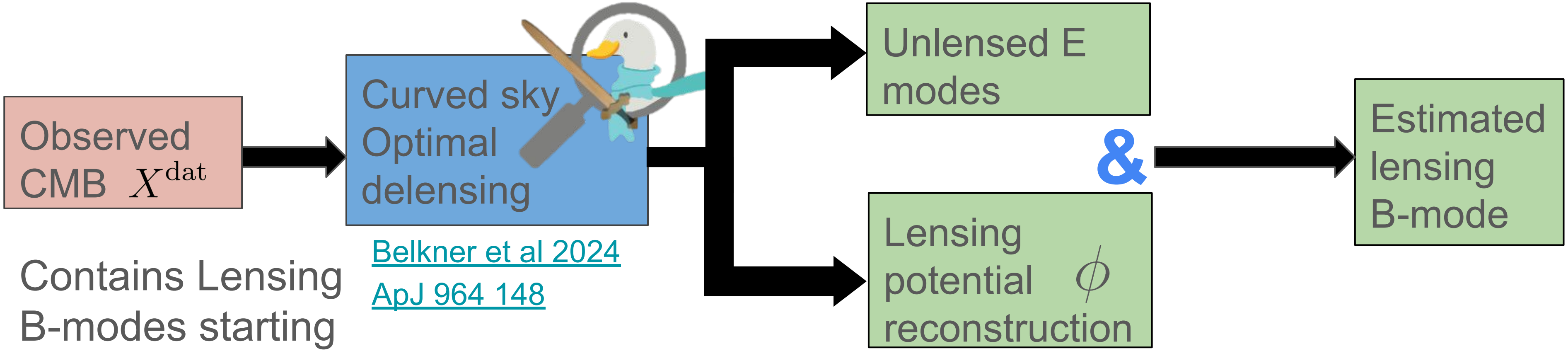
Minnesota Supercomputing Institute
University of Minnesota
Driven to Discover®

Elisa's talk

r forecast

Delensing

- Bayesian (Optimal) method: maximum a posteriori lensing potential reconstruction [PhysRevD, Carron, Lewis]
- Map-based method
- Internal: using information from the data to reconstruct lensing

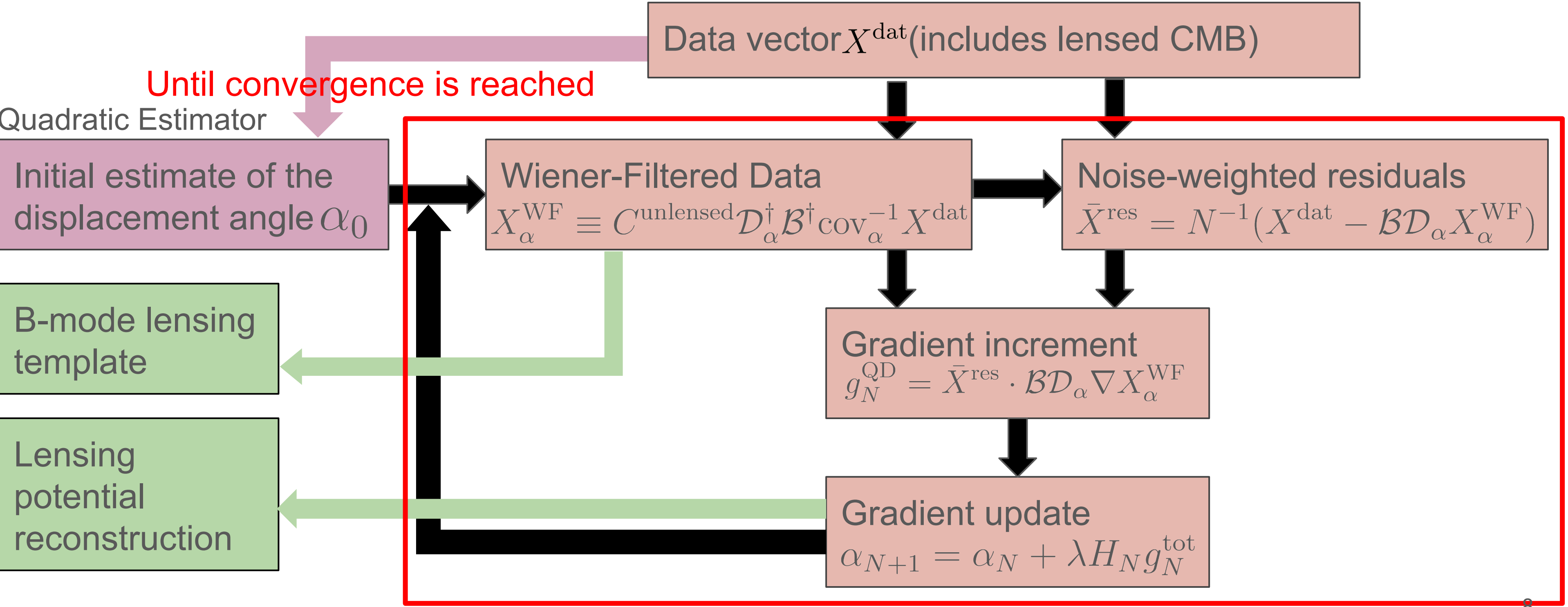


Contains Lensing B-modes starting at $\ell_{\rm min} \sim 300$

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

Iterative Internal Delensing with Delensalot

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

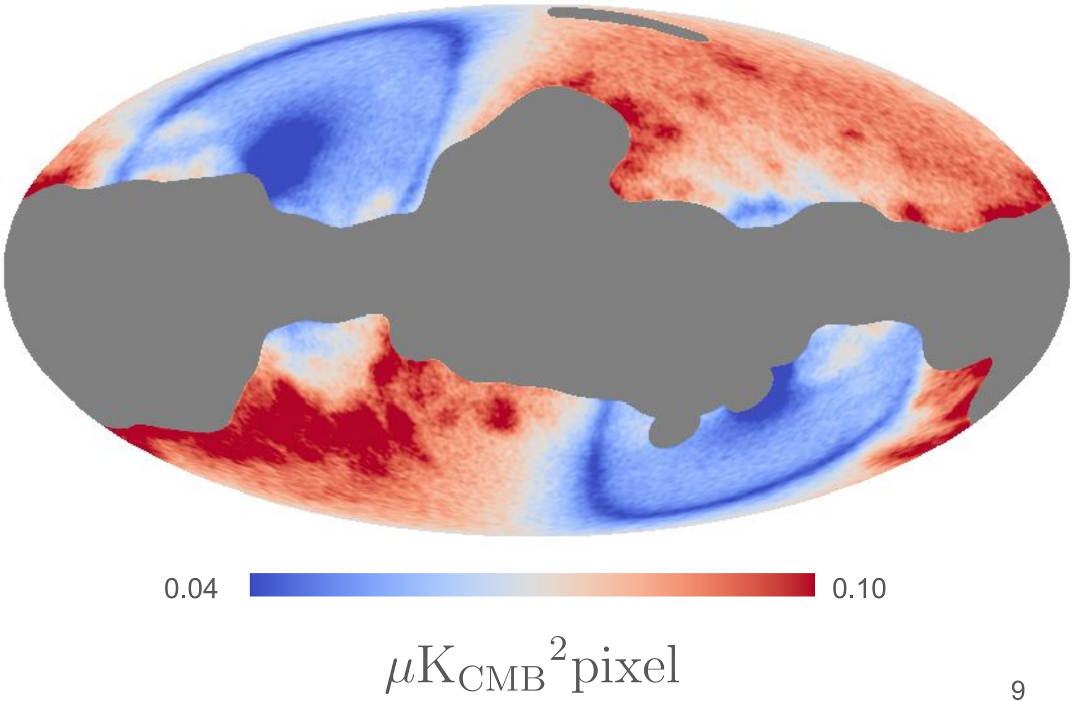


Noise model for inhomogeneous noise case

- Galactic mask applied before component separation

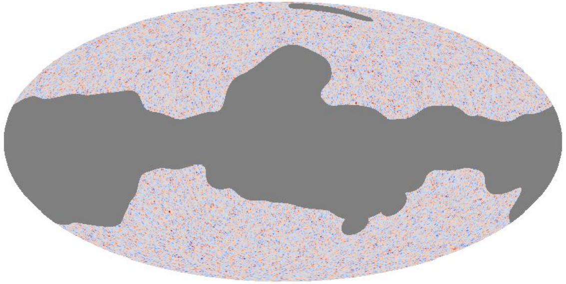
- Construct noise variance map from NILC noise residuals maps (mostly looks like survey depth).

Component separation noise residuals variance



Lensing analysis

Lensing B input (before adding noise and foregrounds)



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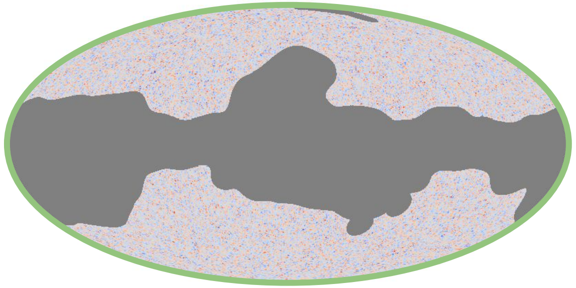
Inferred lensing B map



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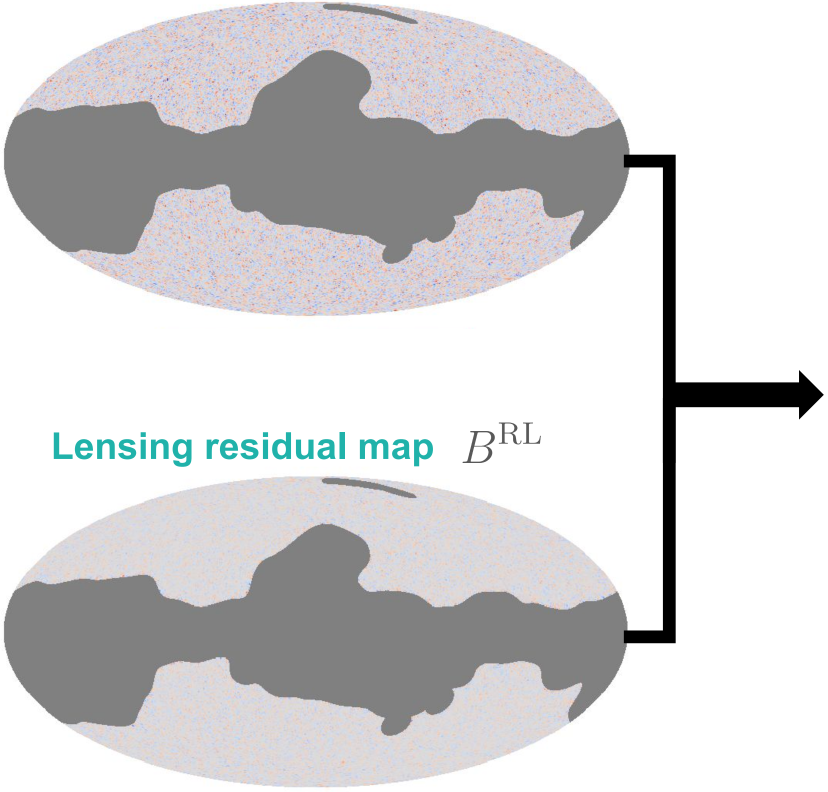
$$B^{\mathrm{RL}} \equiv B^{\mathrm{lens}} - B^{\mathrm{MAP}}$$

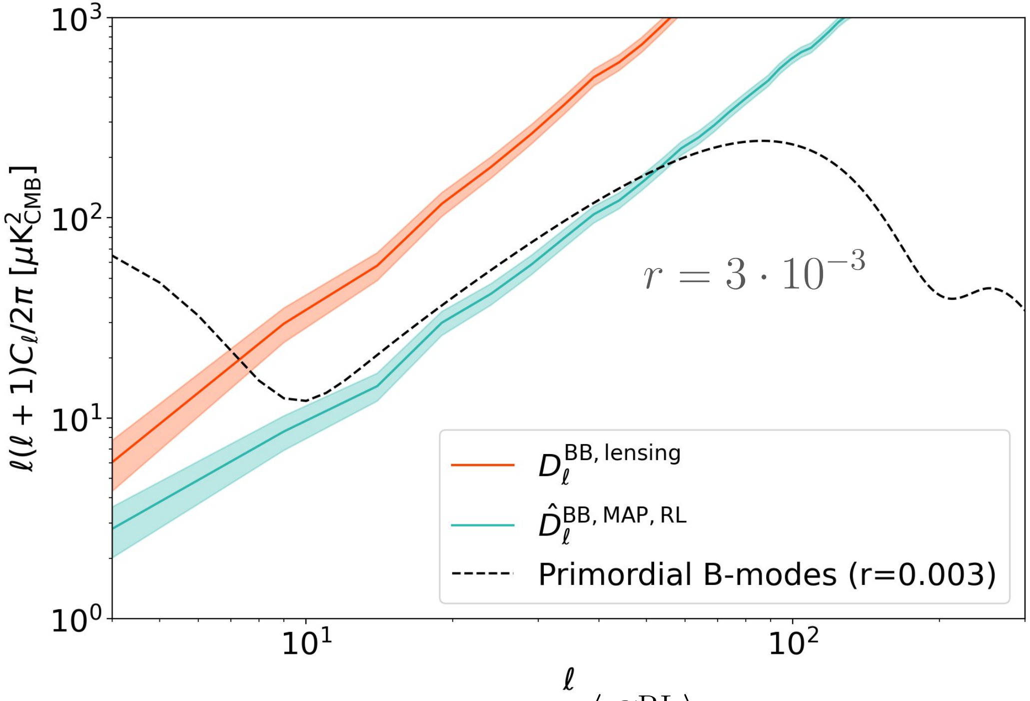
Lensing residual map

Lensing analysis (example with 50mHz, mid complexity)

Lensing B input B^{lens}



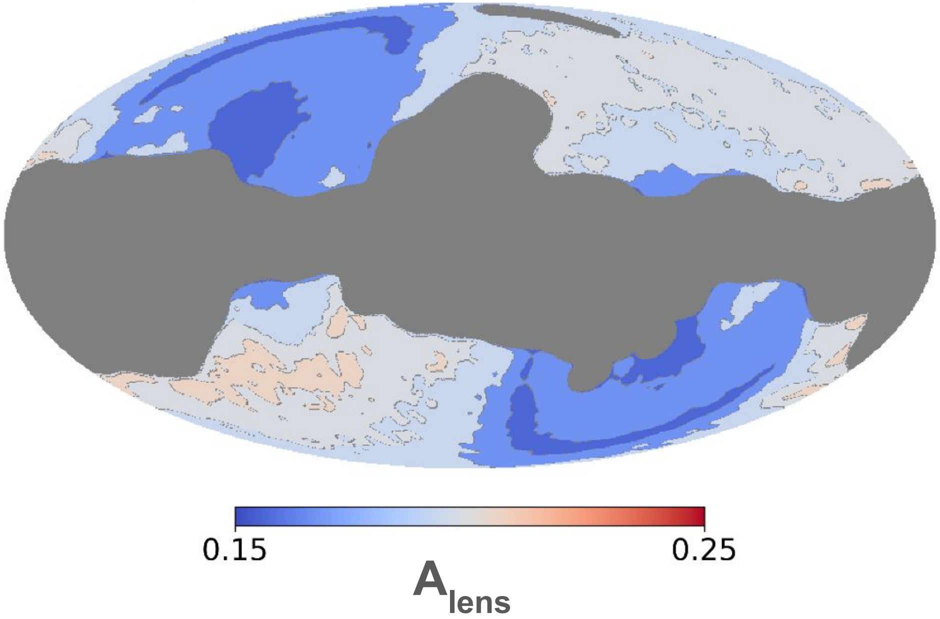
Shaded region for cosmic variance: $\frac{\Delta C_{\bar{\ell}}}{C_{\bar{\ell}}} = \sqrt{\frac{2}{(2\bar{\ell}+1)\Delta\ell f_{\mathrm{sky}}}}$



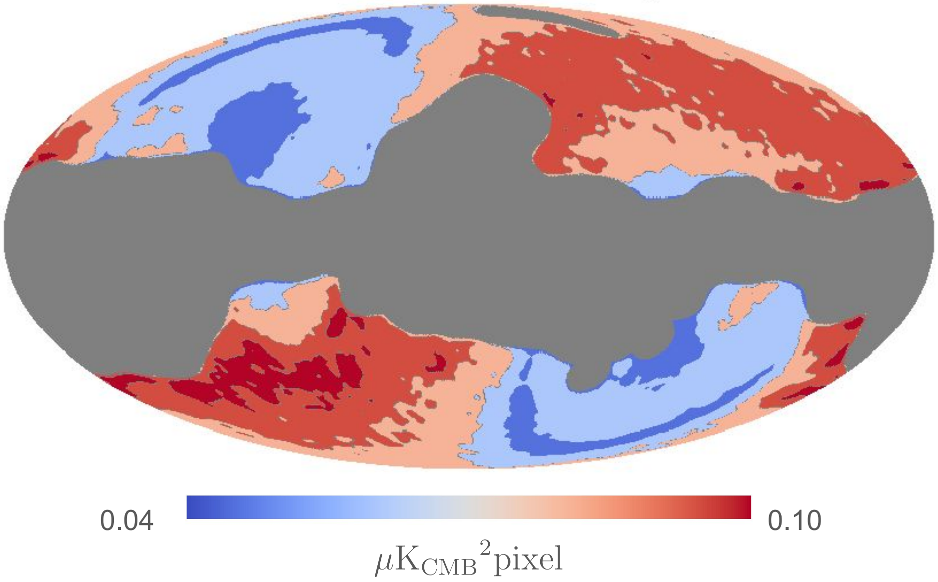
Residual lensing amplitude : $A_\ell^{\mathrm{lens}} \equiv \frac{\left\langle C_\ell^{\mathrm{RL}} \right\rangle}{\left\langle C_\ell^{\mathrm{lensing}} \right\rangle}$

Spatial variation of lensing residual

Residual lensing (50mHz, mid complexity)



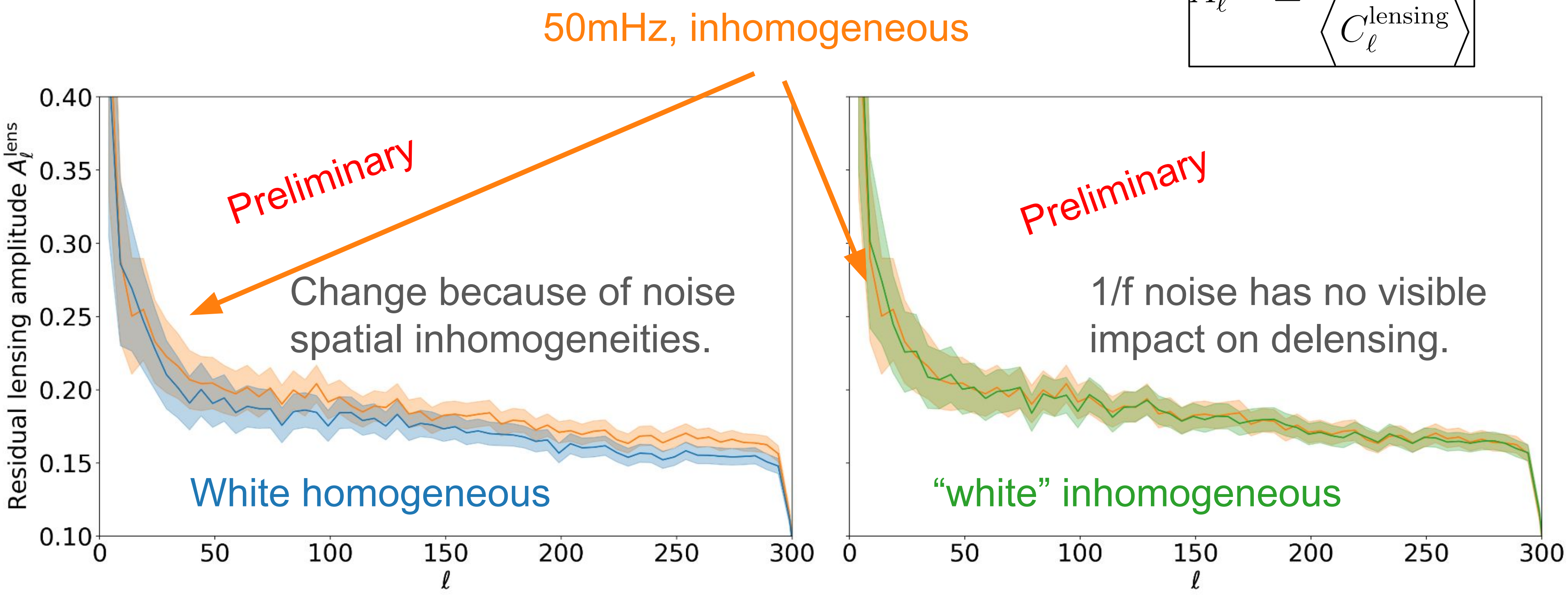
Component separation noise residuals variance



The delensing performance is strongly correlated with the noise variance across the sky.

Mid complexity foreground : Comparison with noise structure (global)

$$A_\ell^{\rm lens} \equiv \frac{\langle C_\ell^{\rm RL} \rangle}{\langle C_\ell^{\rm lensing} \rangle}$$



Mid complexity foreground : Comparison with noise structure (global)

$$A^{\rm lens} \equiv \left\langle A_\ell^{\rm lens} \right\rangle_{\ell \in [2,300]}$$

	No foreground	Planck baseline	Medium complexity
White homogeneous			0.181 ± 0.004
"White" inhomogeneous			0.191 ± 0.004
50 mHz inhomogeneous			0.191 ± 0.004

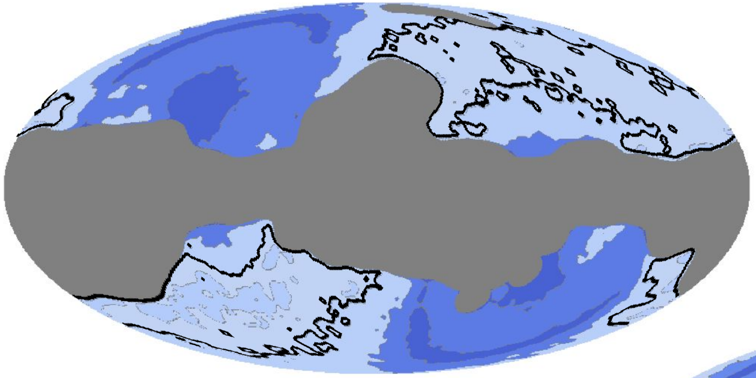
5.4%

1/f does not impact the delensing performance, contrarily to noise spatial inhomogeneities.

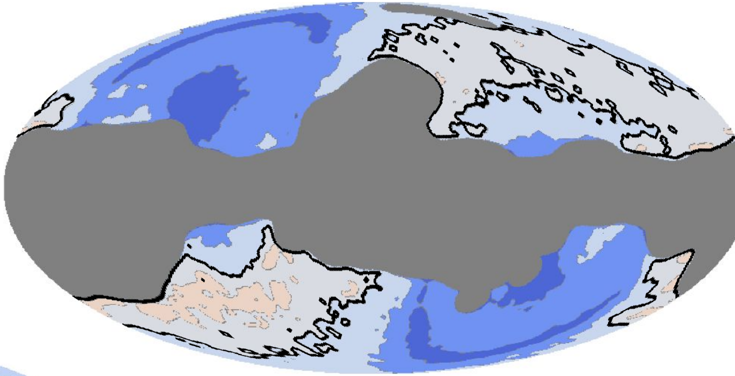
Impact of foreground complexity (inhomogeneous noise case)

Foreground complexity →

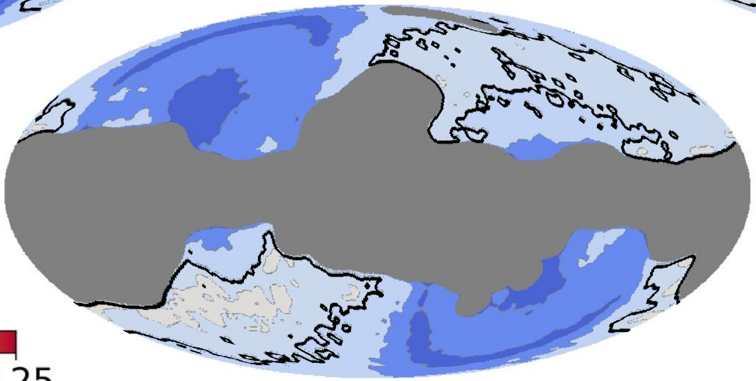
No foregrounds



Mid complexity



Planck Baseline



Impact of foreground complexity only in the noisy regions.

Impact of foreground complexity

$$A^{\text{lens}} \equiv \langle A_\ell^{\text{lens}} \rangle_{\ell \in [2,300]}$$

	No foreground	Planck baseline	Medium complexity
White homogeneous	0.169 ± 0.004	0.177 ± 0.004	0.181 ± 0.004
"White" inhomogeneous			
50 mHz inhomogeneous	0.184 ± 0.004	0.187 ± 0.004	0.191 ± 0.004

Stronger reduction than .27 predicted in the PICO report.

Foreground complexity impacts delensing performance in the least observed regions, but global performance is very similar.

Conclusion

- **The proposed PICO design features high sensitivity, high angular resolution, and broad frequency coverage, and will do internal delensing.**
- The first implementation of integrated pipeline with component separation and map-level delensing was for PICO (JCAP 06 (2023) 034, Aurlien et al).
- Current exercise includes realistic noise and inhomogeneous scan strategy. Delensing pipeline successfully reduces the lensing signal on simulations.
- Stronger reduction of lensing B-modes than conservatively estimated in **PICO Report**.

Spatial variation of effective noise and **high multipoles noise properties** information are the main drivers on the delensing performance.

- 1/f has small impact on the delensing performance, the main difference is between inhomogeneous and homogeneous scan strategy.
- Global delensing performance marginally impacted by foreground complexity.

Thank you for your attention

Please ask me questions!