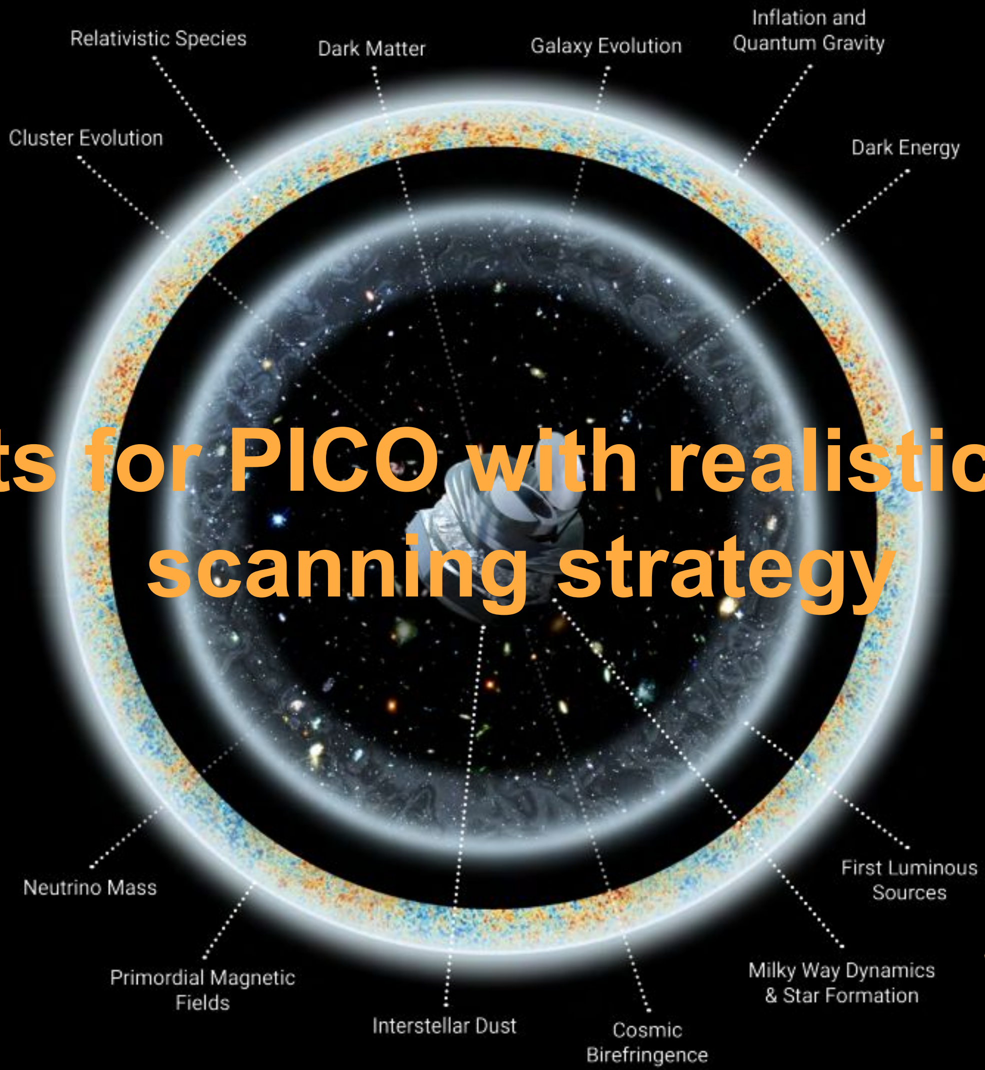
PICO report:
arXiv:1902.10541

r forecasts for PICO with realistic noise and scanning strategy



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Sebastian Belkner, Julien Carron, Jacques Delabrouille, Shamik Ghosh, Kris Gorski, Shaul Hanany, Brandon Hensley, Reijo Keskitalo, Mathieu Remazeilles, Julien Tang

PICO: r science

Decadal Panel Report requirements (Hanany et al, arXiv 1902.10541)

With 13000 detectors, **5 years** and **5σ** confidence level:

1) Reject inflation models $r \geq 5 \times 10^{-4}$
2) Detect $r \geq 5 \times 10^{-4}$

Goal: Assess whether PICO can achieve foreground cleaning such that the level of constraint on r can be attained

Previous Results (Aurlien, Remazeilles et al JCAP **06** (2023) 034) - white homogeneous noise, and 4 out of 5 foreground models:

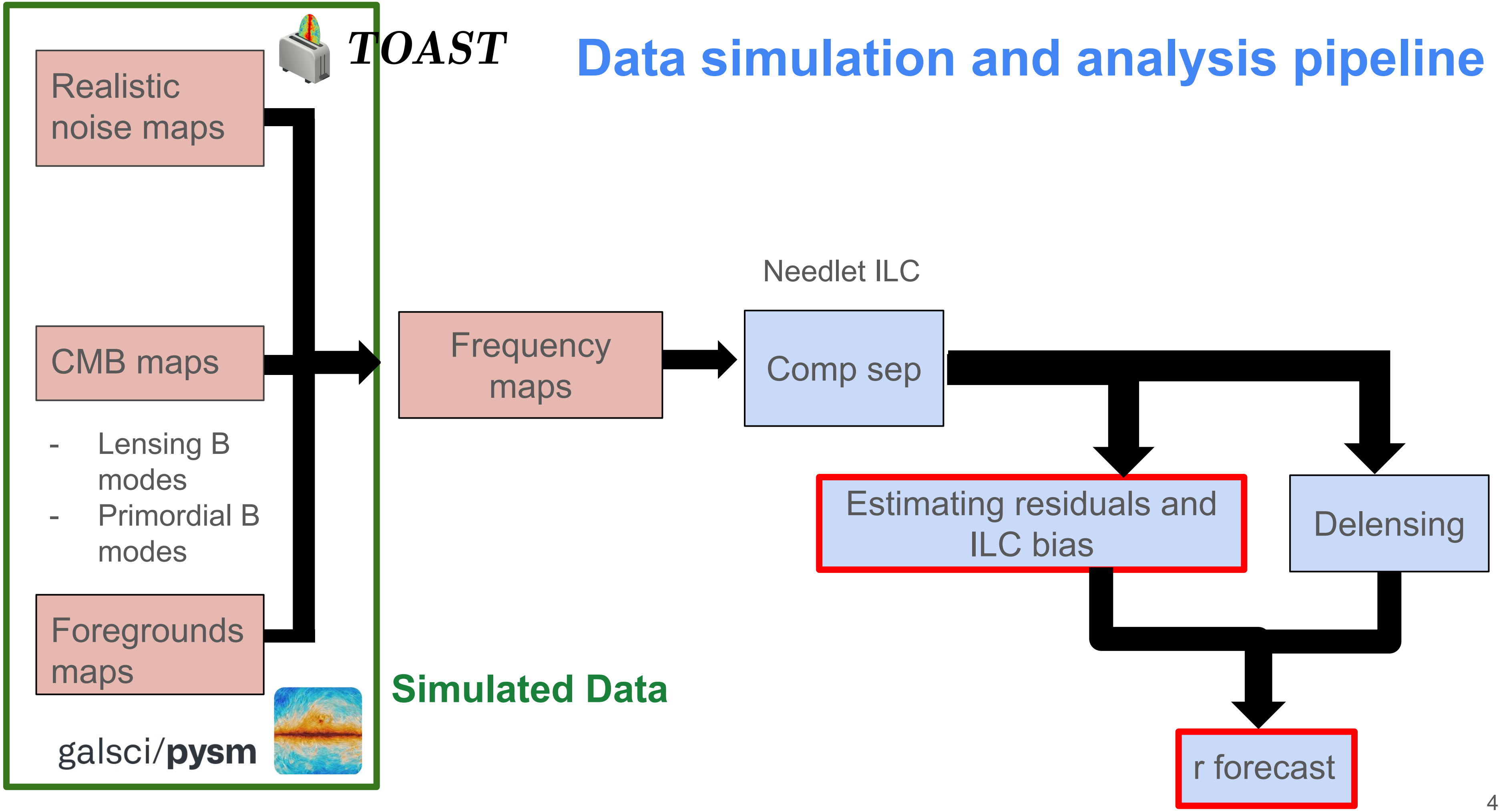
If r = 0.003, more than 15σ unbiased detection in **5 years**

If r = 0, unbiased 95% upper limits between 1 - 2 x 10^{-4} in **5 years**

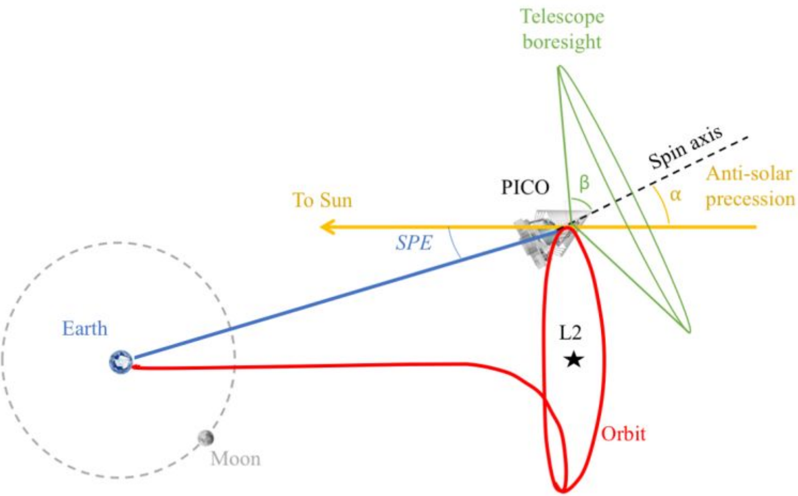
PICO: Our current study

Can we reach the requirements on r with more complex foreground models and more realistic noise (= scanning strategy + 1/f) without a half wave plate?

Data simulation and analysis pipeline



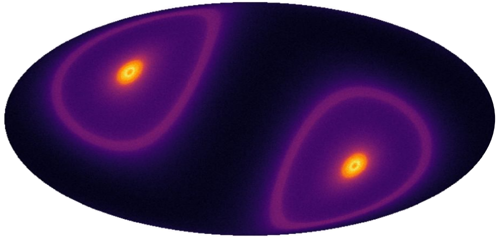
Modeling sources of contamination for PICO

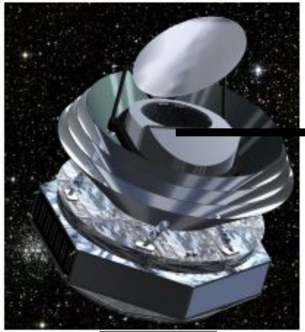


PICO scanning strategy

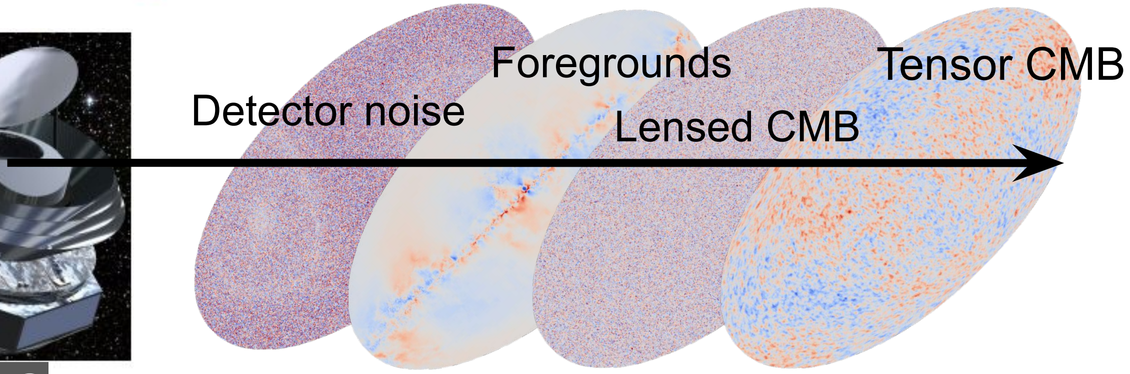
1 rpm and 10 hr anti-solar precession
The design of PICO is without a half wave plate.

Hits map





PICO



Summary of the different configurations

Foreground complexity →

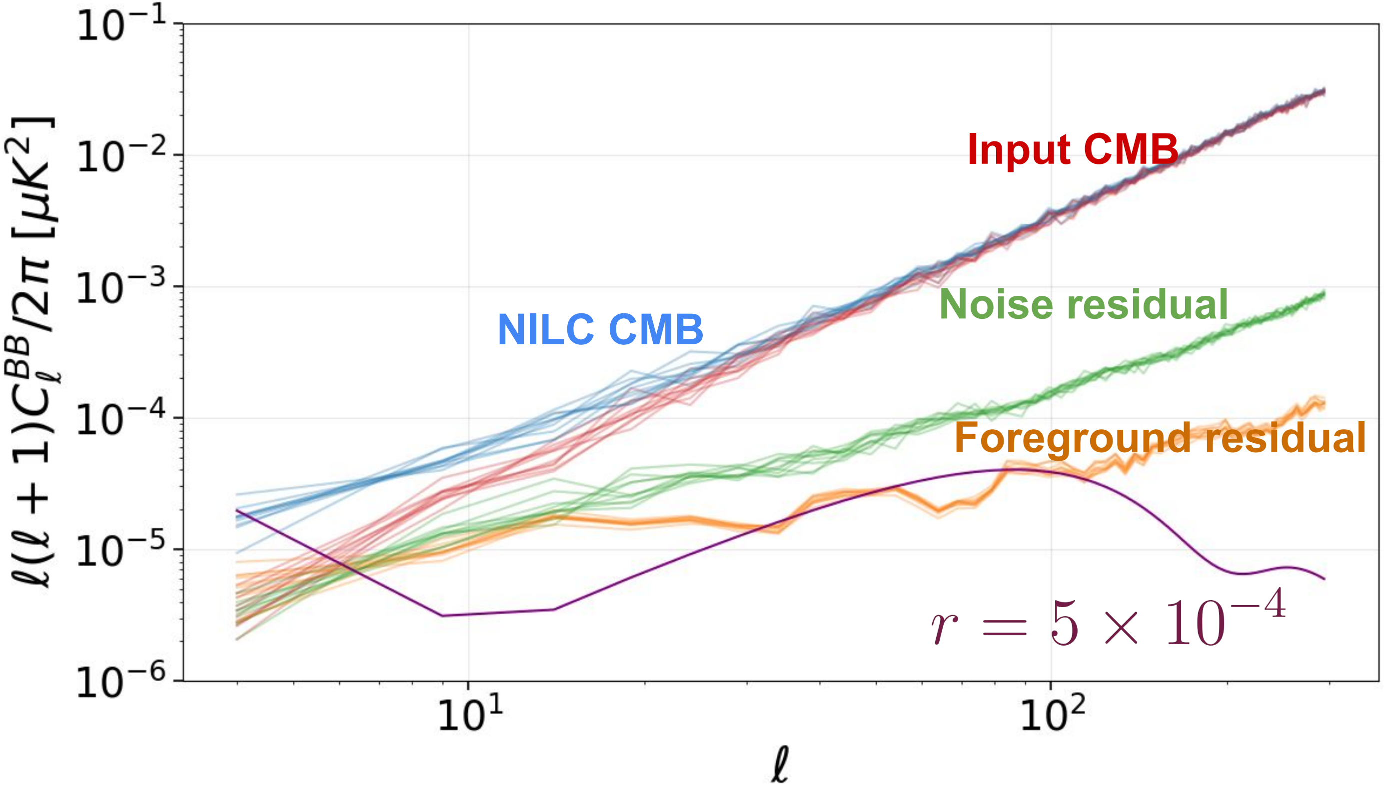
Noise complexity ↓

	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.

Estimating residuals

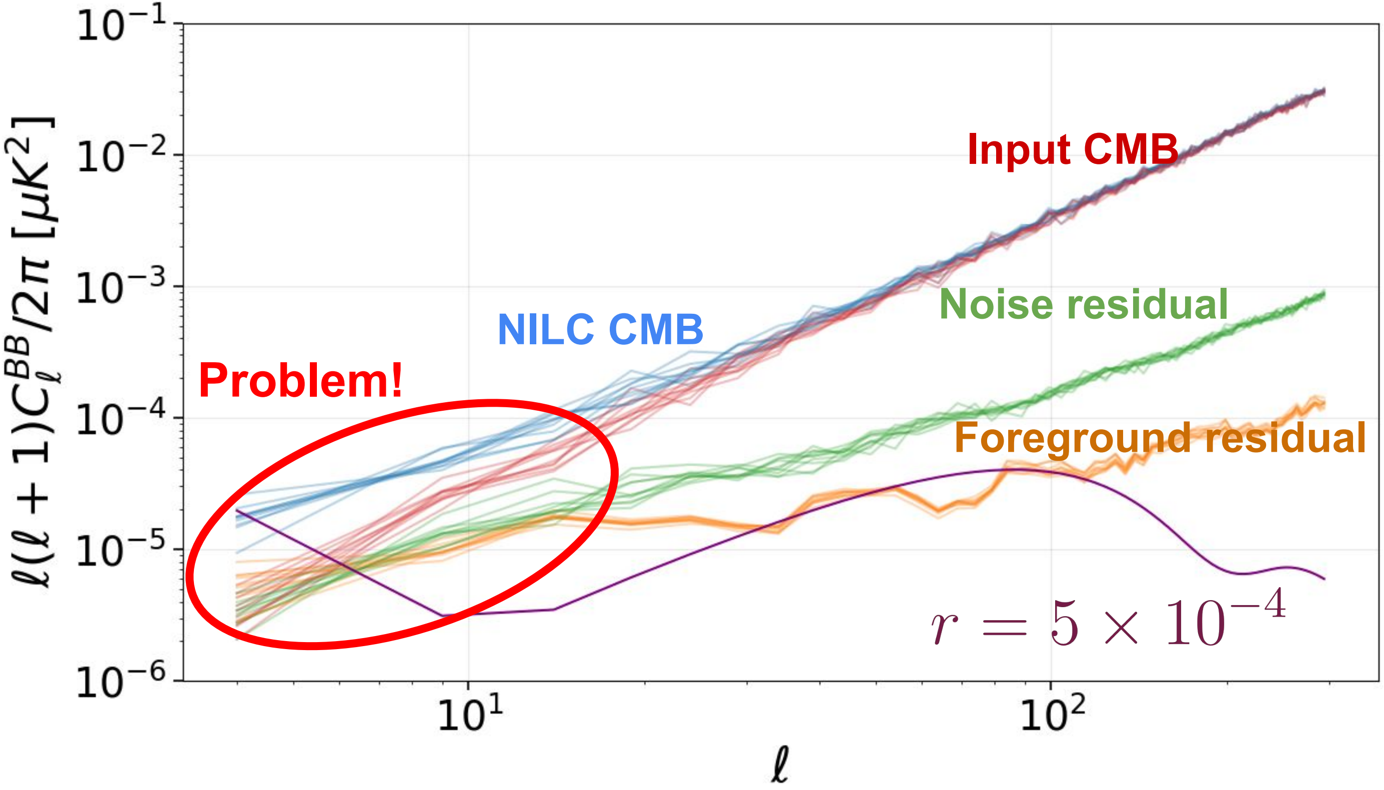
Reminder: After component separation, the estimated CMB map contains noise and foreground residuals. They are evaluated by applying the NILC weights to the inputs.



fknee = 50 mHz, medium complexity foregrounds, r = 0, 10 realizations of CMB and noise

Estimating residuals

Reminder: After component separation, the estimated CMB map contains noise and foreground residuals. They are evaluated by applying the NILC weights to the inputs.



fknee = 50 mHz, medium complexity foregrounds, r = 0

Residuals shown here are known because we are using simulations
⇒ **How would we estimate them on real data?**

Estimating residuals: Method

Noise residuals (estimated with 10 sims)

For each noise simulation i = 0, .., 9

Use NILC weights w_i

↓

Propagate the weights to the 9 noise simulations N_j where j ≠ i

↓

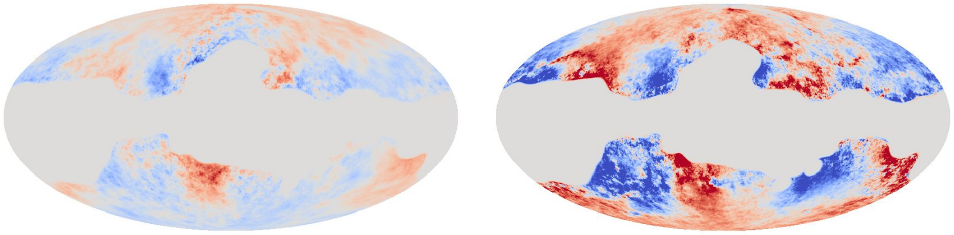
Compute the mean at the power spectrum level

$$n_{\mathrm{res}}^{(j)}(p) = \sum_{\nu=1}^{N_\nu} w_\nu^{(j)}(p) n_\nu^{(j)}(p)$$

Estimating residuals: Method

GNILC Galactic signal

21 GHz   799 GHz



$$f_{\mathrm{res}}^{(j)}(p) = \sum_{\nu=1}^{N_\nu} w_\nu^{(j)}(p) f_\nu^{(j)}(p)$$

Foreground residuals

Estimate foreground emission with GNILC

↓ For each NILC weights w_i, $i = 0, .., 9$

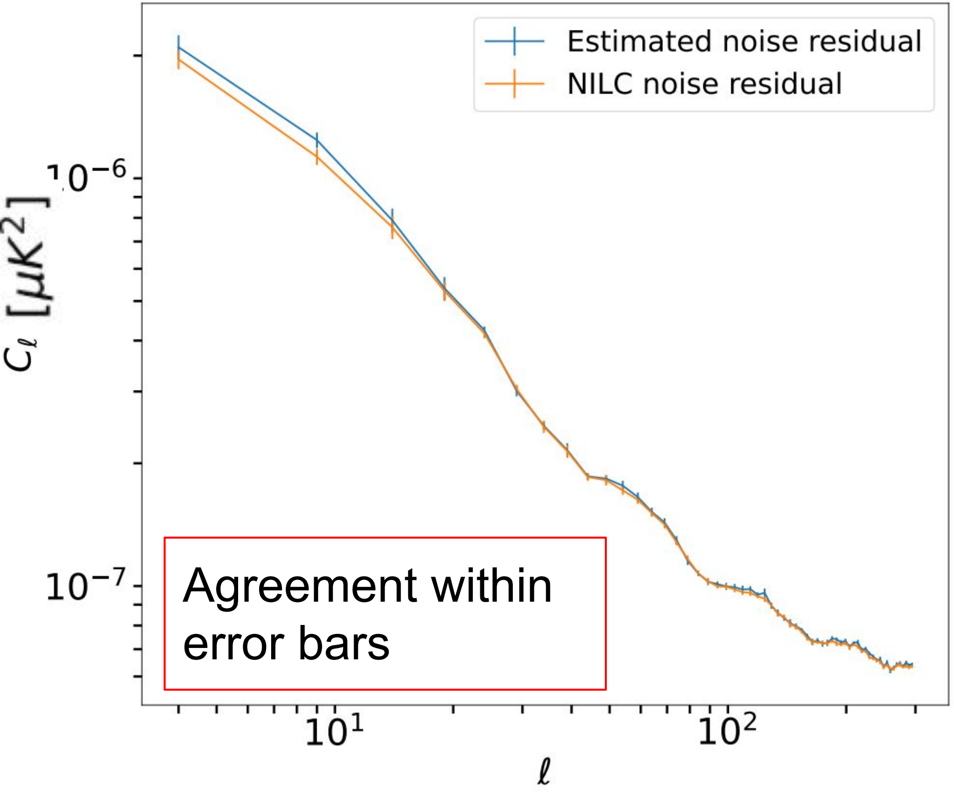
Use NILC weights w_i

↓

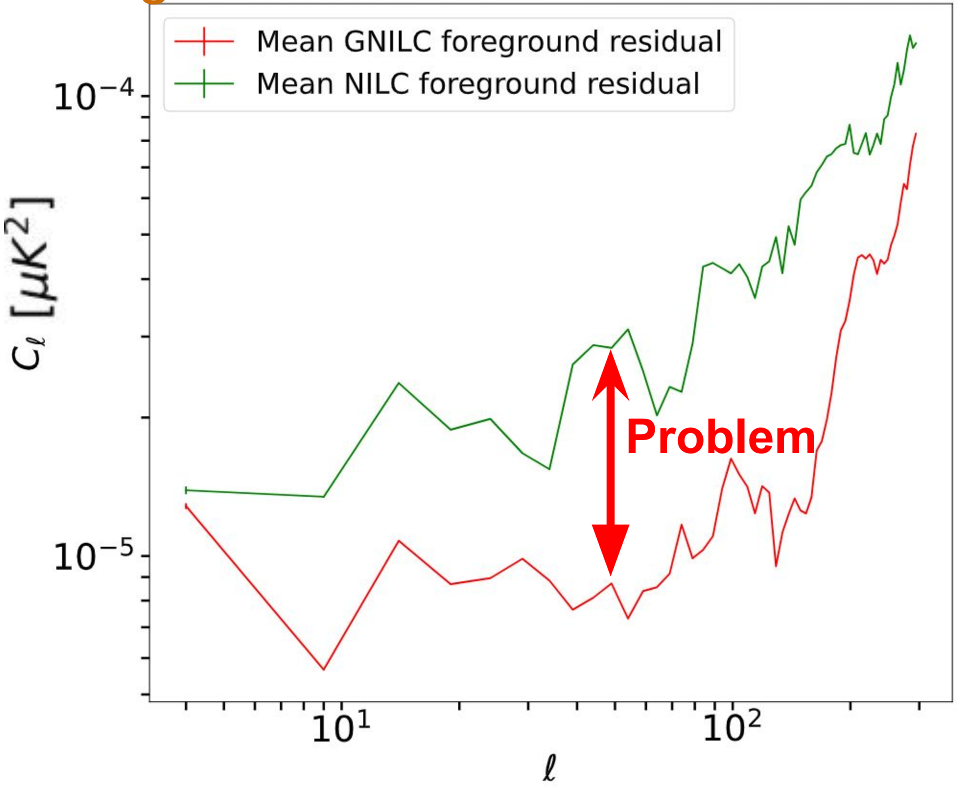
Propagate the weights to the estimated foreground emission

Estimating residuals: Estimated VS NILC

Noise residuals



Foreground residuals



⇒ Discrepancy in the foreground residuals: GNILC doesn't capture the foreground signal at or below the SNR

Estimating ILC bias: Origin

- ILC method: minimizes the total variance of the data and retain the CMB signal
- ILC weights are computed using the empirical covariance of the total data
- CMB contributes to the total covariance
- ILC bias is due to chance correlations between the CMB and the foreground and noise and shows as a loss of power in the estimated CMB signal
- At low multipoles: fewer modes → higher chance of correlation → more power suppression

Estimating ILC bias: Method

Generate the input maps

$$m = s_1 + f + n$$
$$m' = m + s_2$$

s_1, s_2 are two independent realizations of CMB

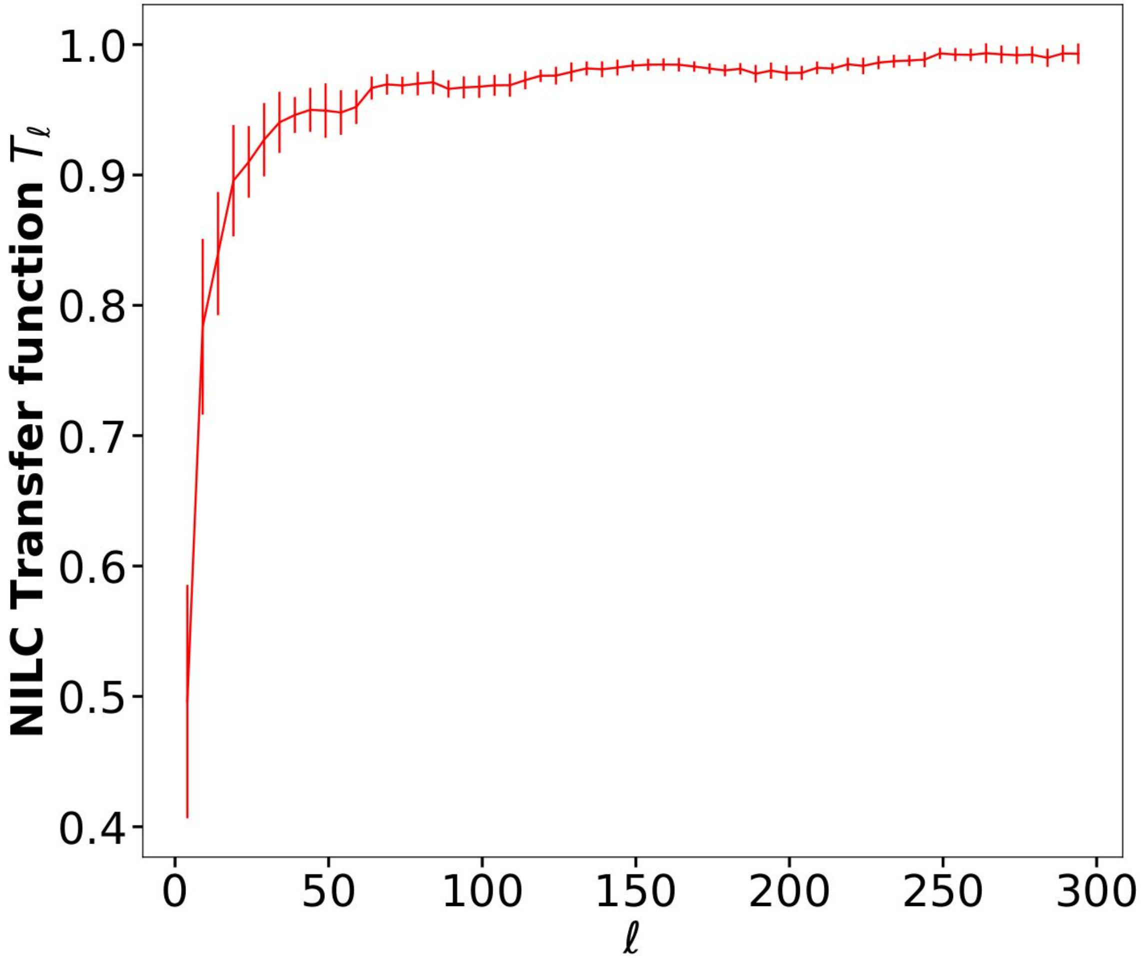
Run NILC

$$\tilde{s}_{1+2} = a s_1 + a s_2 + r_{1+2}$$

Compute the difference $\Delta = \tilde{s}_{1+2} - \tilde{s}_1 \simeq a s_2$

$$T_\ell = \frac{C_\ell^\Delta}{C_\ell^{s_2}}$$

Estimating ILC bias



⇒ Non negligible loss of power at low multipoles

Delensing for r forecasts

We use the Alens numbers predicted by Julien Tang, and subtract $(1 - \sqrt{A_{\mathrm{lens}}})$ from the input CMB map to "delens".

A_{lens}	Planck baseline	Medium complexity
White homogeneous		0.181 ± 0.004
White inhomogeneous		0.191 ± 0.004
50 mHz inhomogeneous	0.187 ± 0.004	0.191 ± 0.004

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

Likelihood model

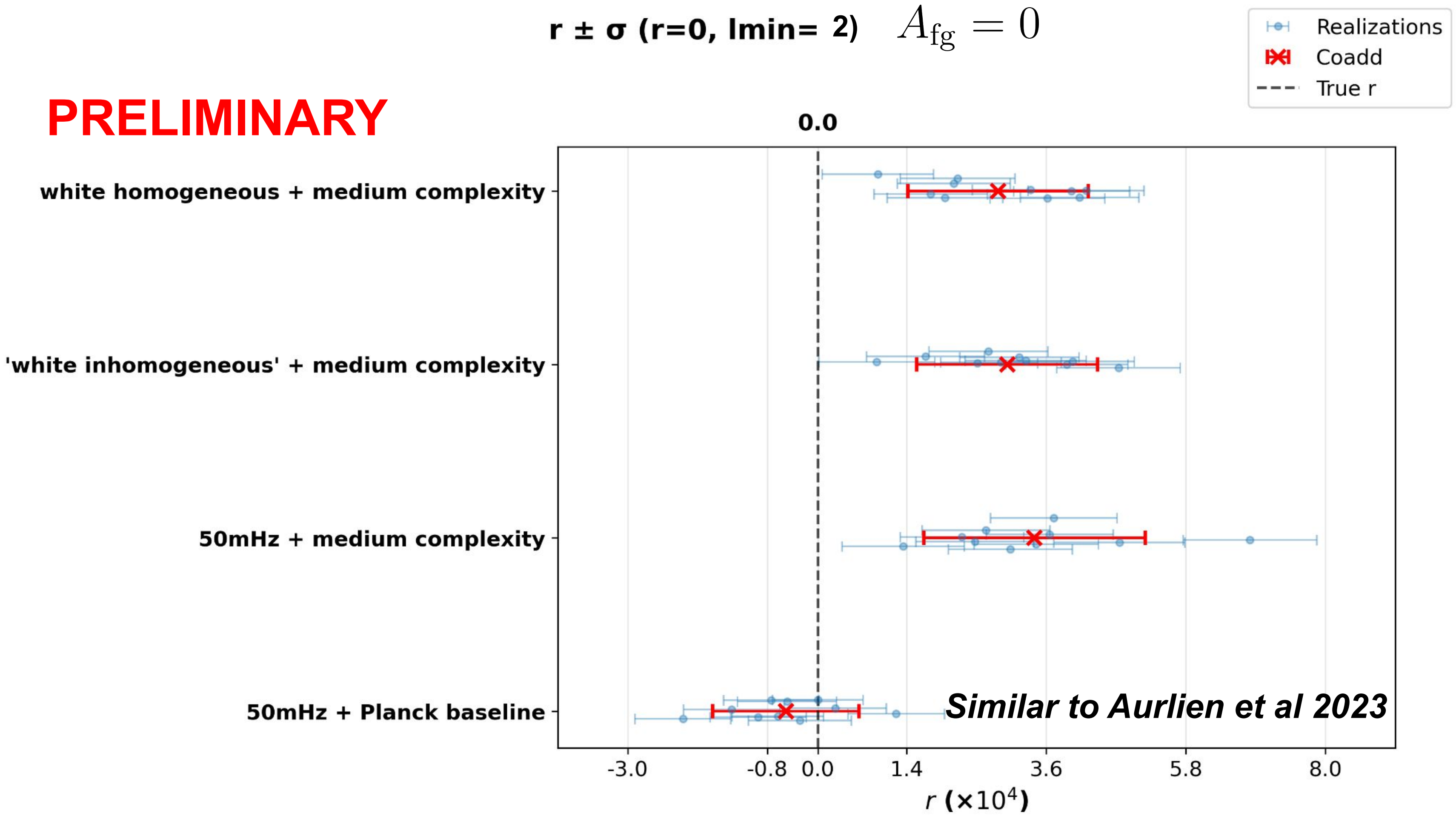
$$-2\log\mathcal{L}(r) = \frac{\frac{C_\ell^{\rm NILC}}{T_\ell} - \frac{C_\ell^{\rm NR}}{T_\ell} - A_{\rm fg}\frac{C_\ell^{\rm FR}}{T_\ell} - \left(A_{\rm lens}C_\ell^{\rm lens} + rC_\ell^{\rm tens}\right)}{{\rm Cov}_\ell}$$

where $${\rm Cov}_\ell = \left[\sqrt{\frac{2}{(2\ell+1)f_{\rm sky}\Delta_\ell}}C_\ell^{\rm NILC}\right]^2 + \left(\frac{C_\ell^{\rm NILC}\sigma_{T_\ell}}{T_\ell^2}\right)^2$$

We study three cases:
$A_{\rm fg}=0$, $A_{\rm fg}=1$, marginalization over $A_{\rm fg}$ → Today: $A_{\rm fg}=0$

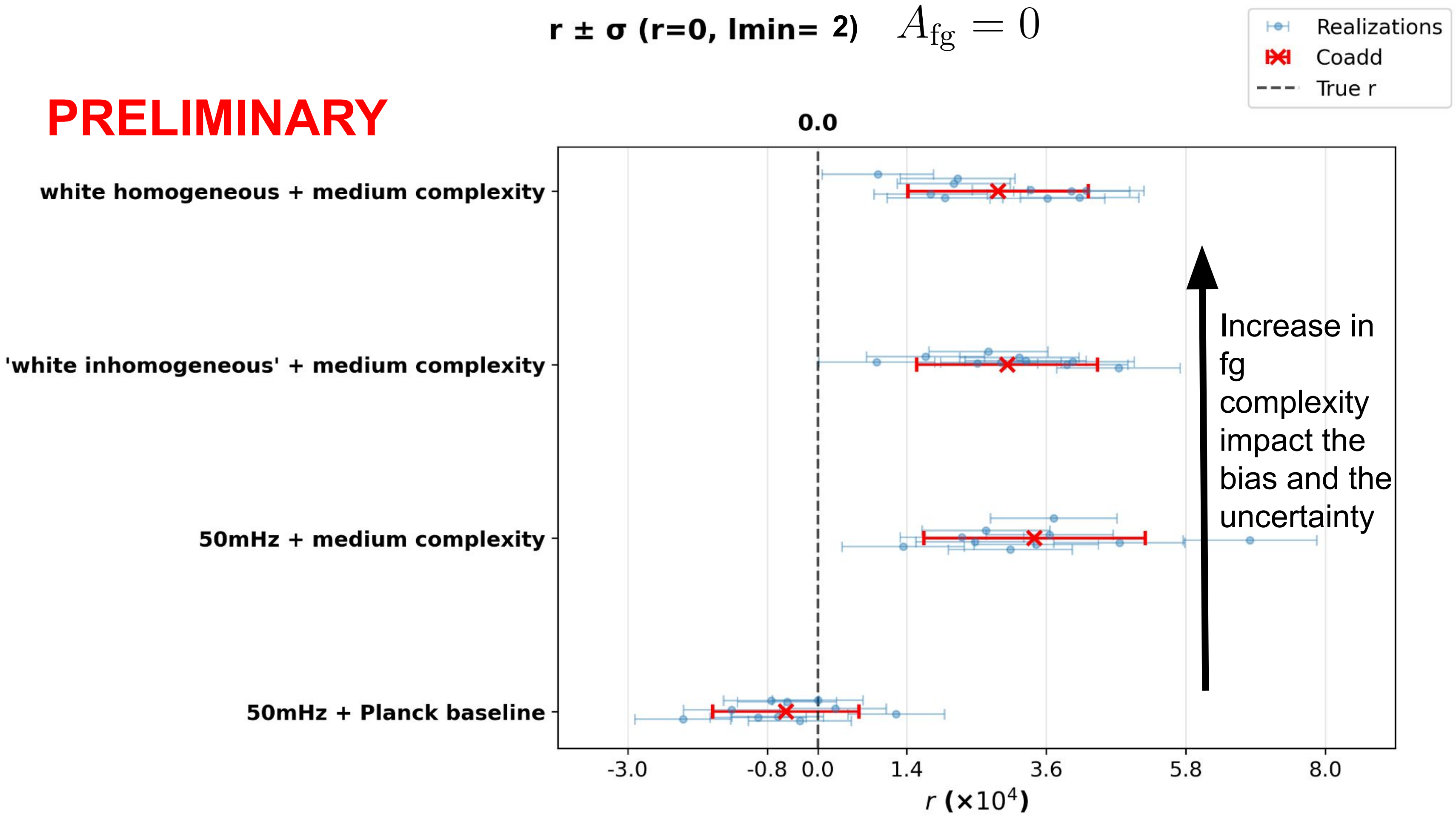
r forecasts

PRELIMINARY



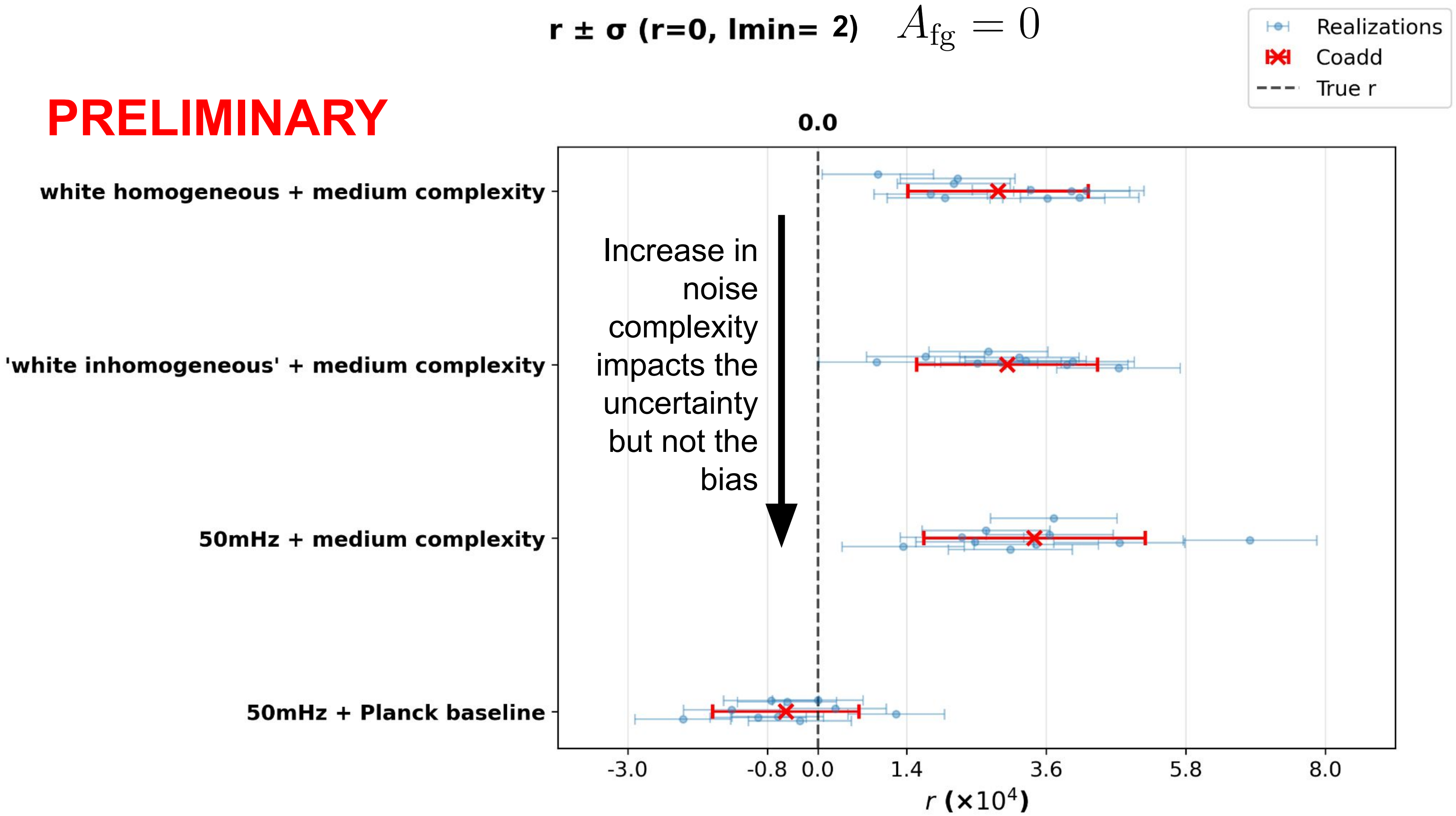
r forecasts

PRELIMINARY



r forecasts

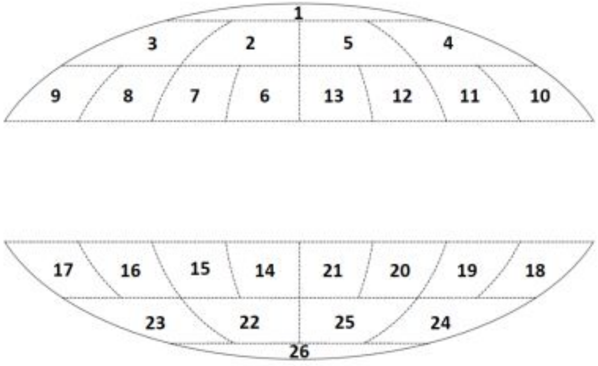
PRELIMINARY



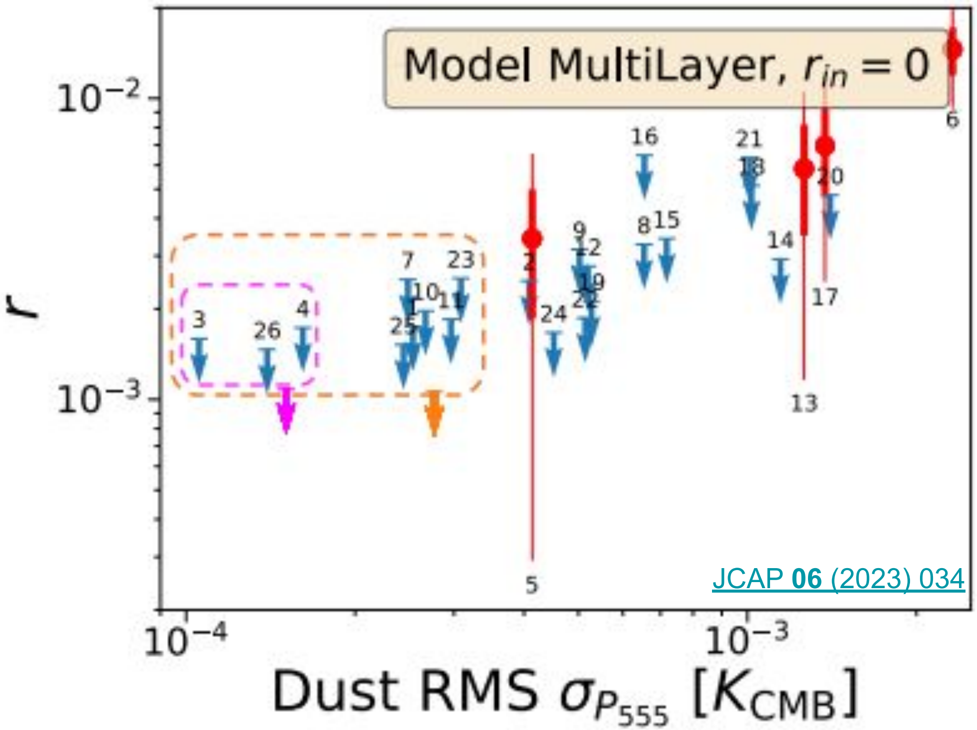
Multipatch analysis in previous work

- Biases with highest complexity foreground model (= d12 in PySM)
- Compare independent constraints on r from independent sections of the sky

Equal area sky sections with fsky = 2.5%



95% confidence limits for r = 0 per patch



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⇒ Advantage of a space mission with high sensitivity

Conclusion

- The PICO space mission aims for $\sigma(r) \sim 1 \times 10^{-4}$
- For white homogeneous noise, requirements are met for 4 fg models out of 5.

- We test an end-to-end pipeline with more complex noise and foregrounds
- With inhomogeneous and 1/f noise, for “Planck baseline”, similar results as before: 1/f at that level is not a major issue for PICO.
- Increase in noise complexity affects the uncertainty of ~ 20%.
- Increase in foreground complexity affects the bias on r (mostly due to dust) and the uncertainty.

- Studying the biases in independent patches of the sky mitigate the bias
- We are going to investigate with a different component separation method to reduce the low multipole bias: SMICA.