

NILC results for PICO

Mathieu Remazeilles

15 July 2021

A variety of realistic foreground skies

NERSC: /project/projectdirs/pico/data_xx.yy/

- ❖ **Model 91 (d1s1):** *Planck dust MBB* with β , T variations, synchrotron power-law with β variations
- ❖ **Model 92 (d4s3a2):** *Two dust MBBs* with uniform β_1 , β_2 but T_1 , T_2 variations, synchrotron curvature, AME 2% polarization
- ❖ **Model 93 (d7s3a2):** *Physical dust model (not MBB)*, synchrotron curvature, AME 2% polarization
- ❖ **Model 96 (MHD):** *dust and synchrotron derived from MHD*, multiple MBBs along the line-of-sight
- ❖ **Model 98 (Multi-layer):** *3D dust model* (decorrelation), MBB layers along the line-of-sight

A variety of realistic foreground skies

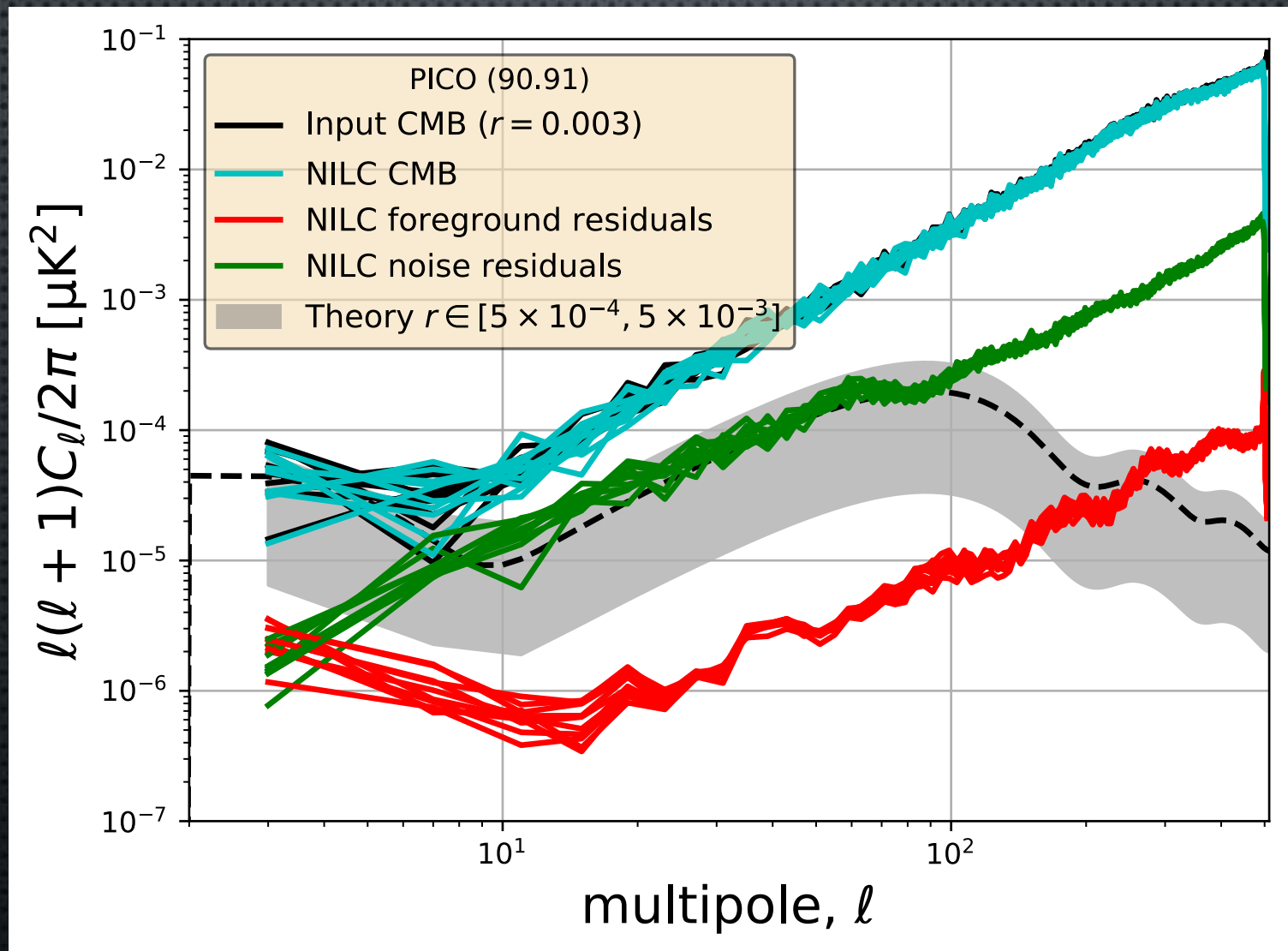
NERSC: /project/projectdirs/pico/data_xx.yy/

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$$r = 0.003$$

Model 91, $r = 0.003$

NILC



10 realizations

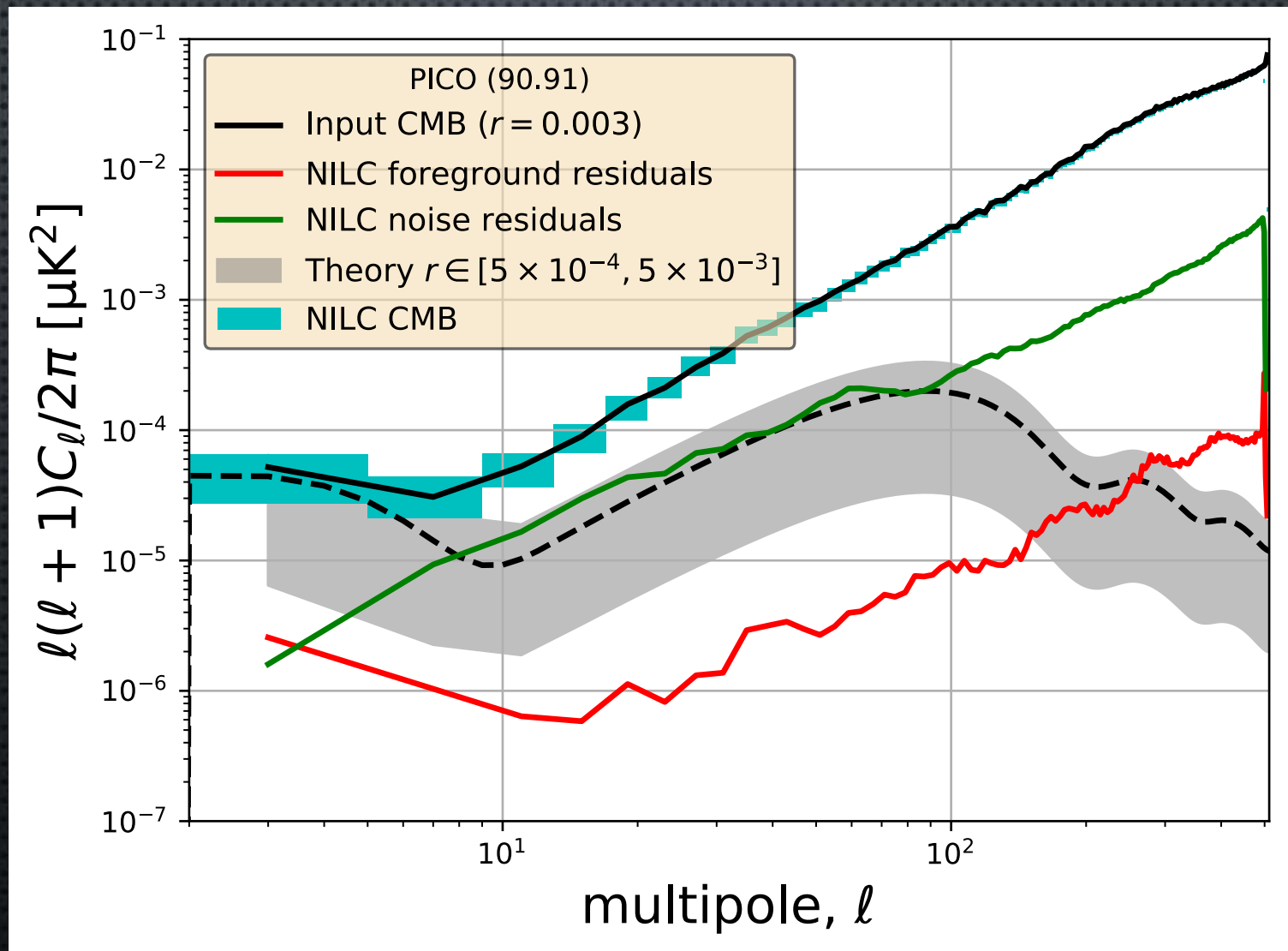
MASTER

$f_{\text{sky}} = 50\%$

Binning: $\Delta l = 4$

Model 91, $r = 0.003$

NILC



Foreground residuals
10 times lower
than $r = 0.003$

10 realizations

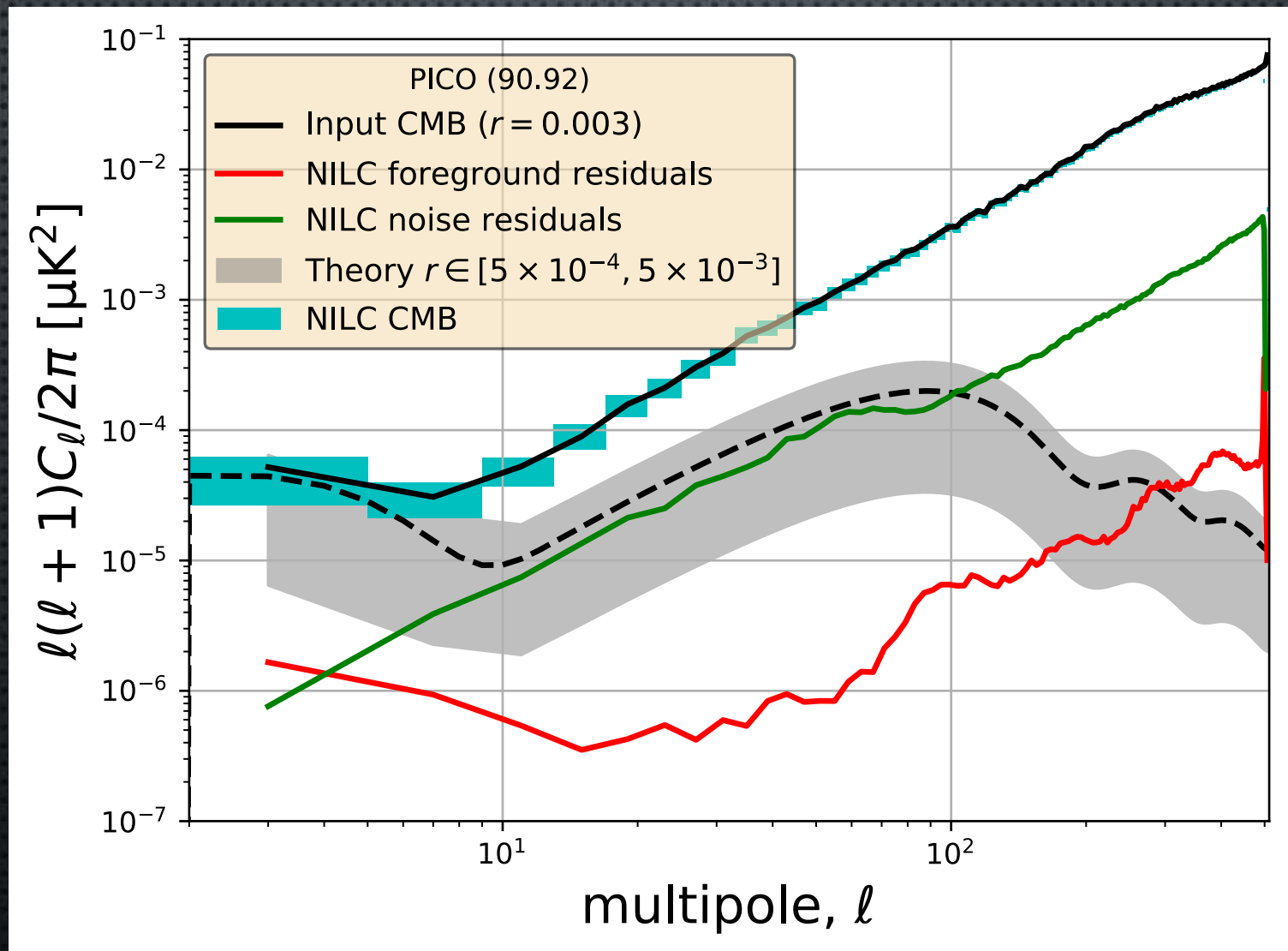
MASTER

$f_{\text{sky}} = 50\%$

Binning: $\Delta\ell = 4$

Model 92, $r = 0.003$

NILC



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10 realizations

MASTER

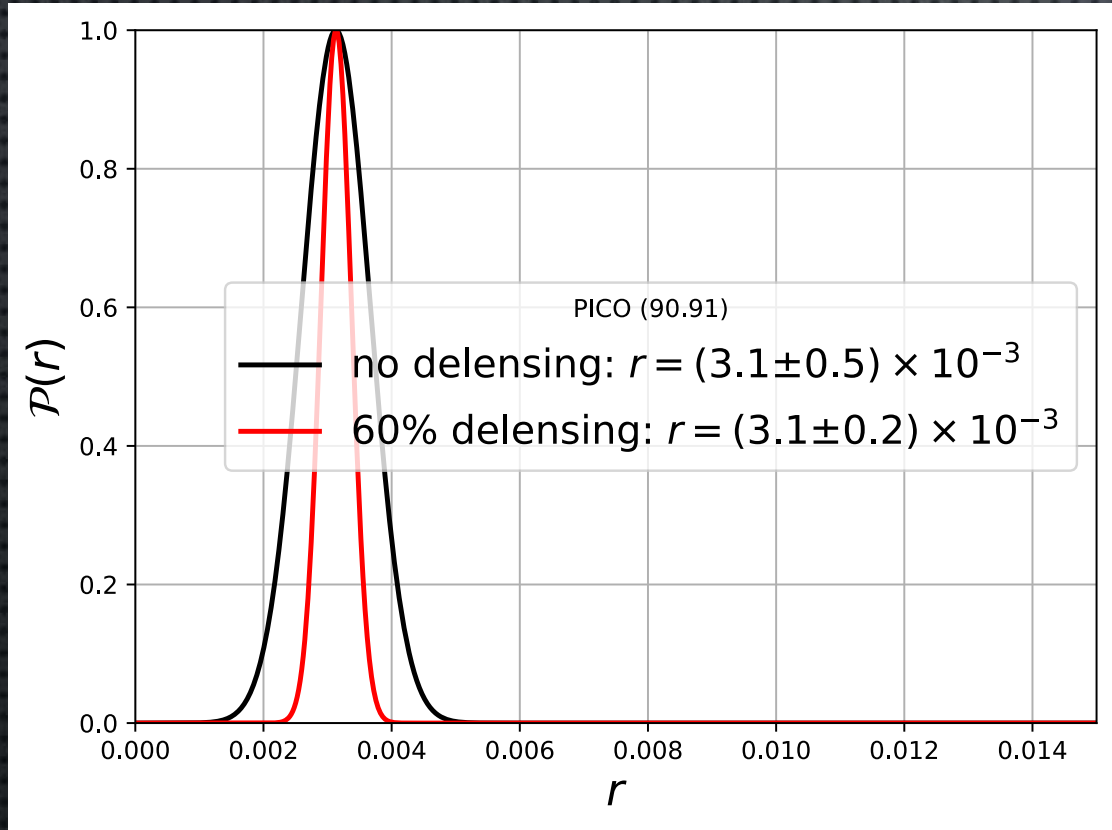
$f_{\text{sky}} = 50\%$

Binning: $\Delta l = 4$

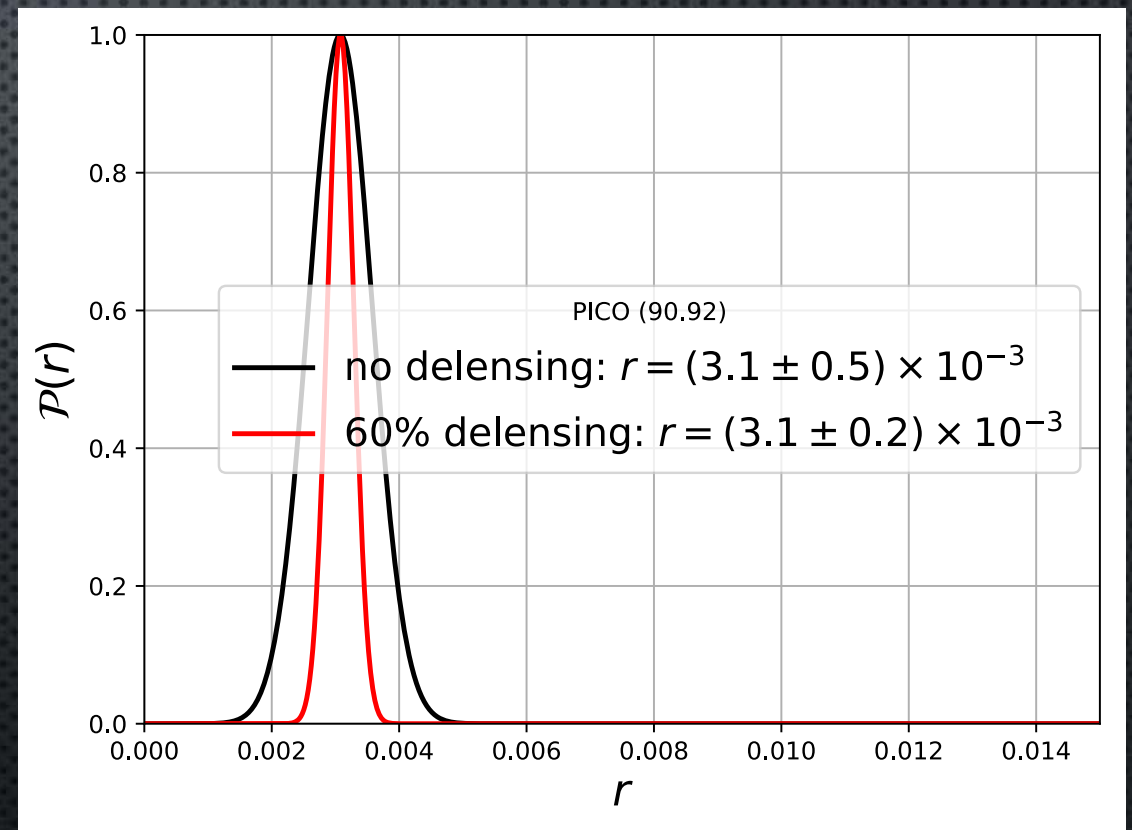
$$r = 0.003$$

NILC

Model 91



Model 92

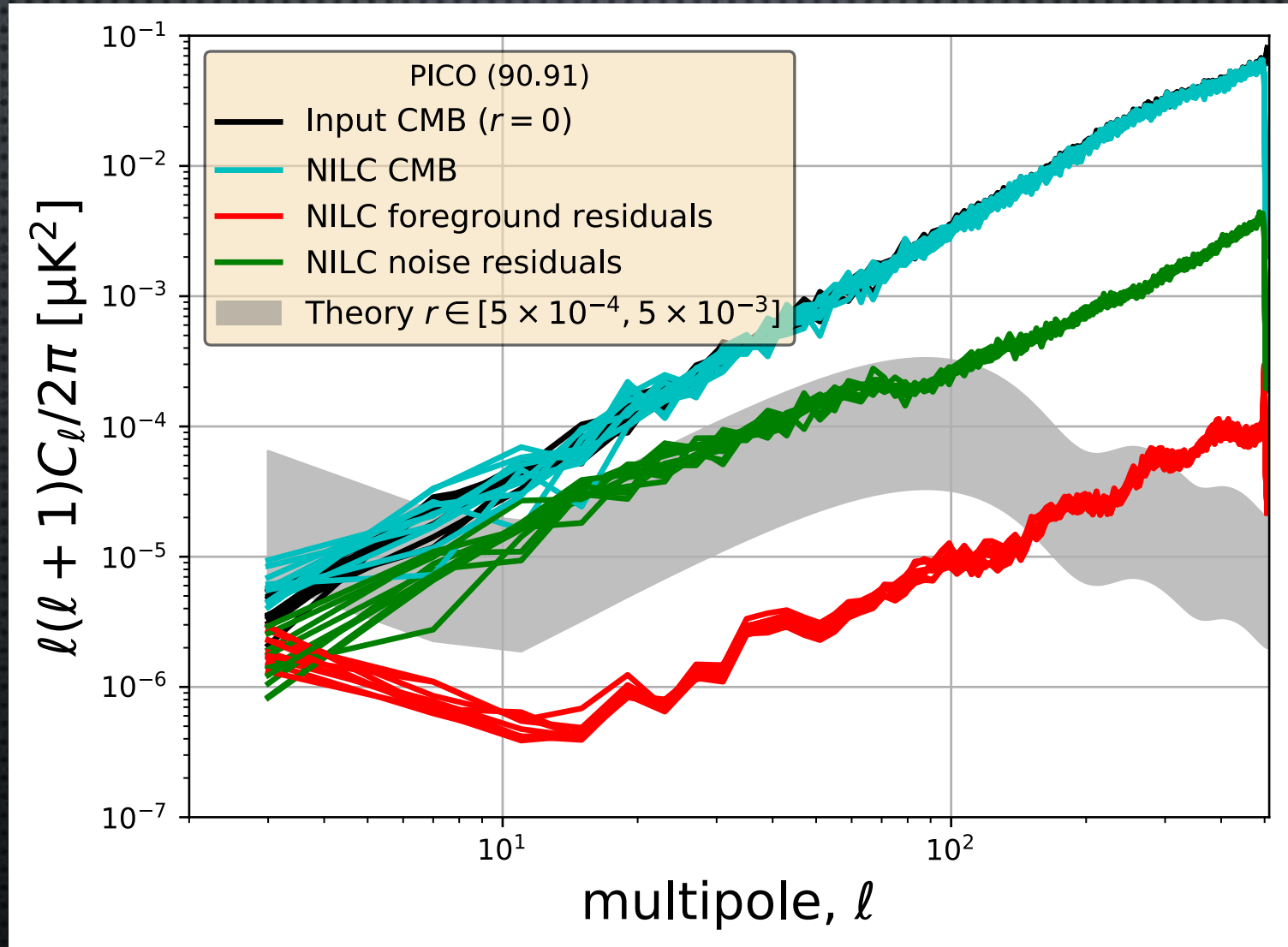


Robust recovery of the tensor-to-scalar ratio:
10 sigma detection for both sky models

$$r = 0$$

Model 91, $r = 0$

NILC



10 realizations

MASTER

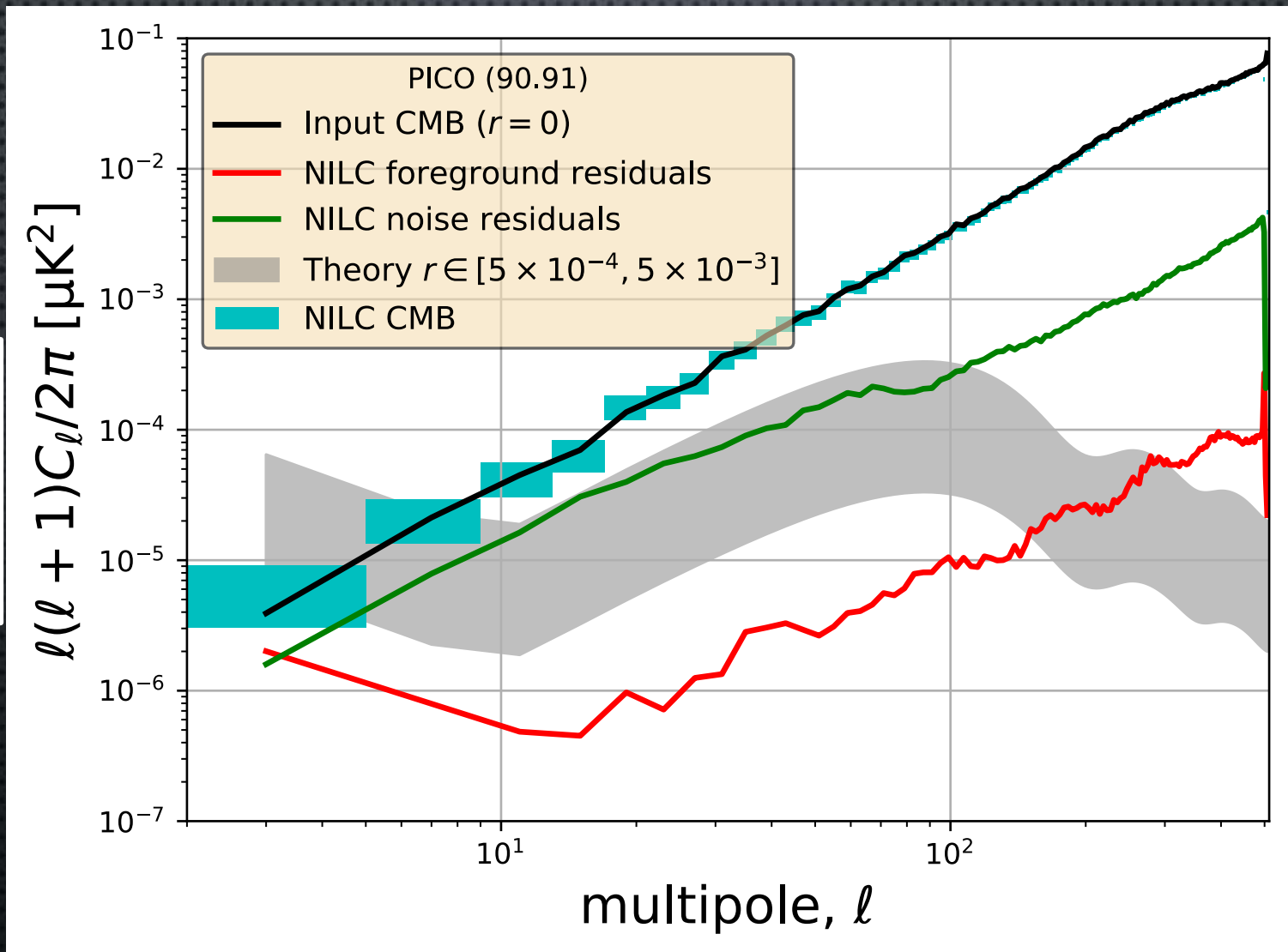
$f_{\text{sky}} = 50\%$

Binning: $\Delta l = 4$

10

Model 91, $r = 0$

NILC



Foreground residuals
3 times lower
than $r = 5 \times 10^{-4}$

10 realizations

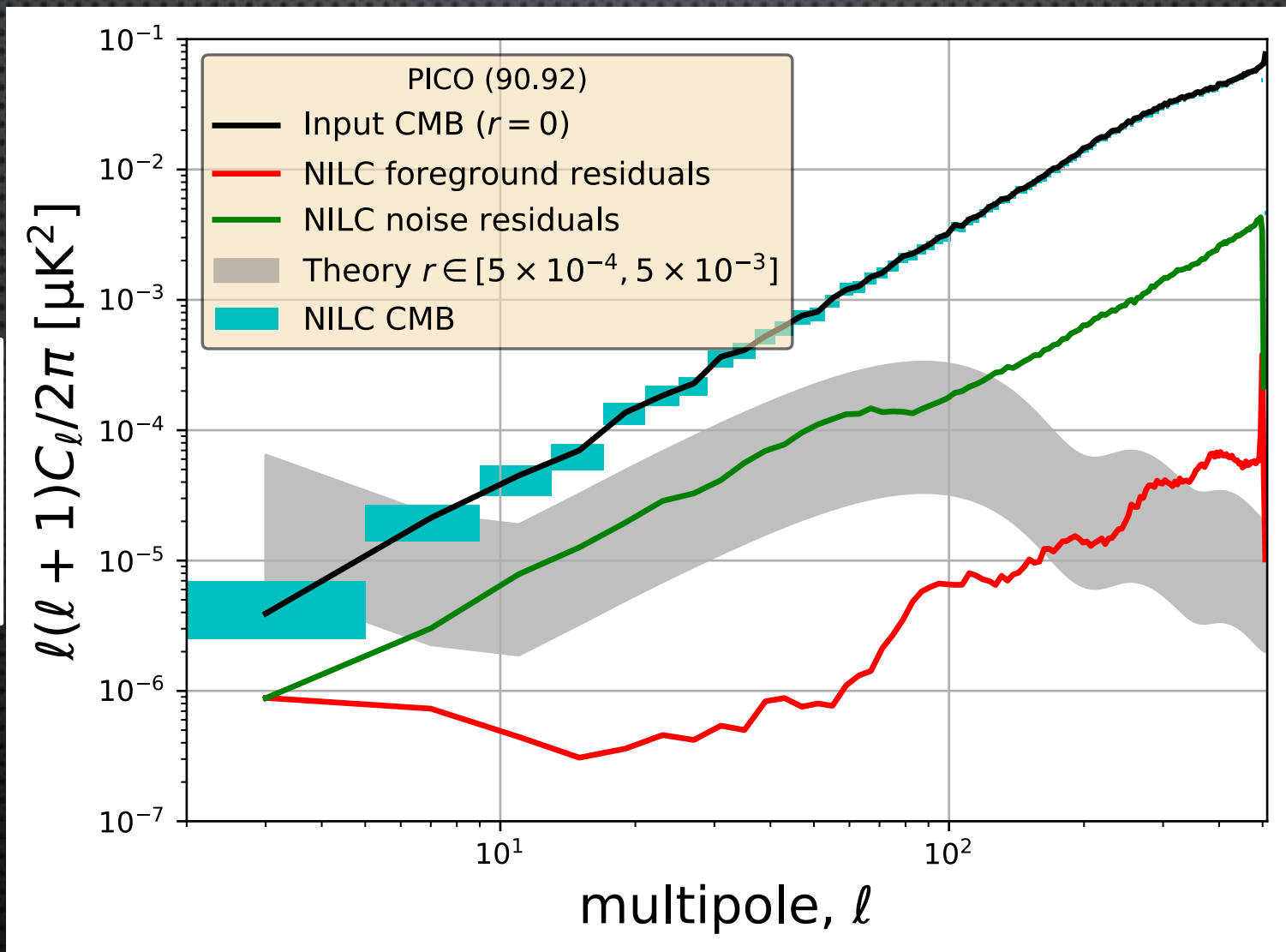
MASTER

$f_{\text{sky}} = 50\%$

Binning: $\Delta\ell = 4$

Model 92, $r = 0$

NILC



10 realizations

MASTER

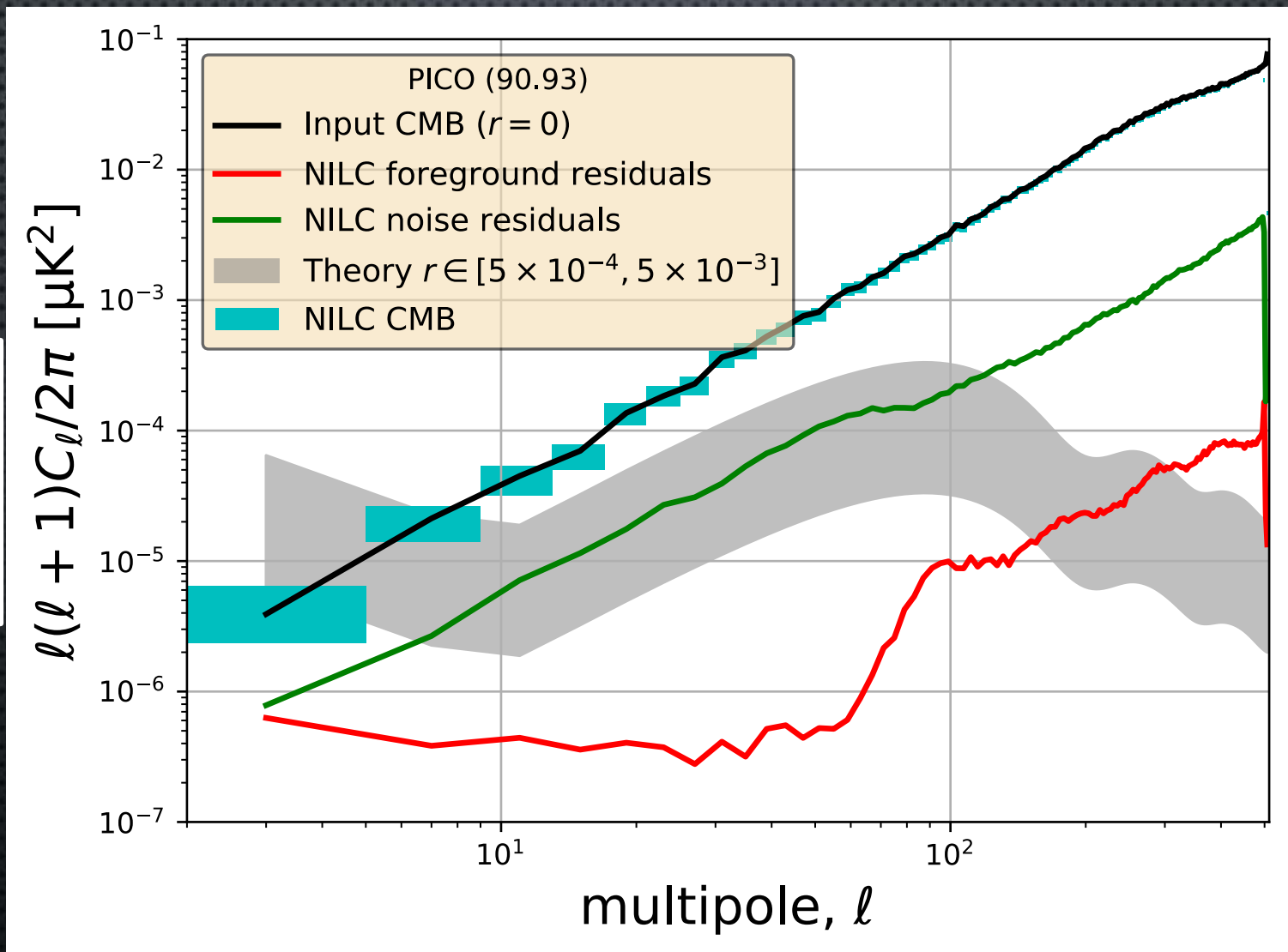
$f_{\text{sky}} = 50\%$

Binning: $\Delta\ell = 4$

Foreground residuals
3 times lower
than $r = 5 \times 10^{-4}$

Model 93, $r = 0$

NILC



10 realizations

MASTER

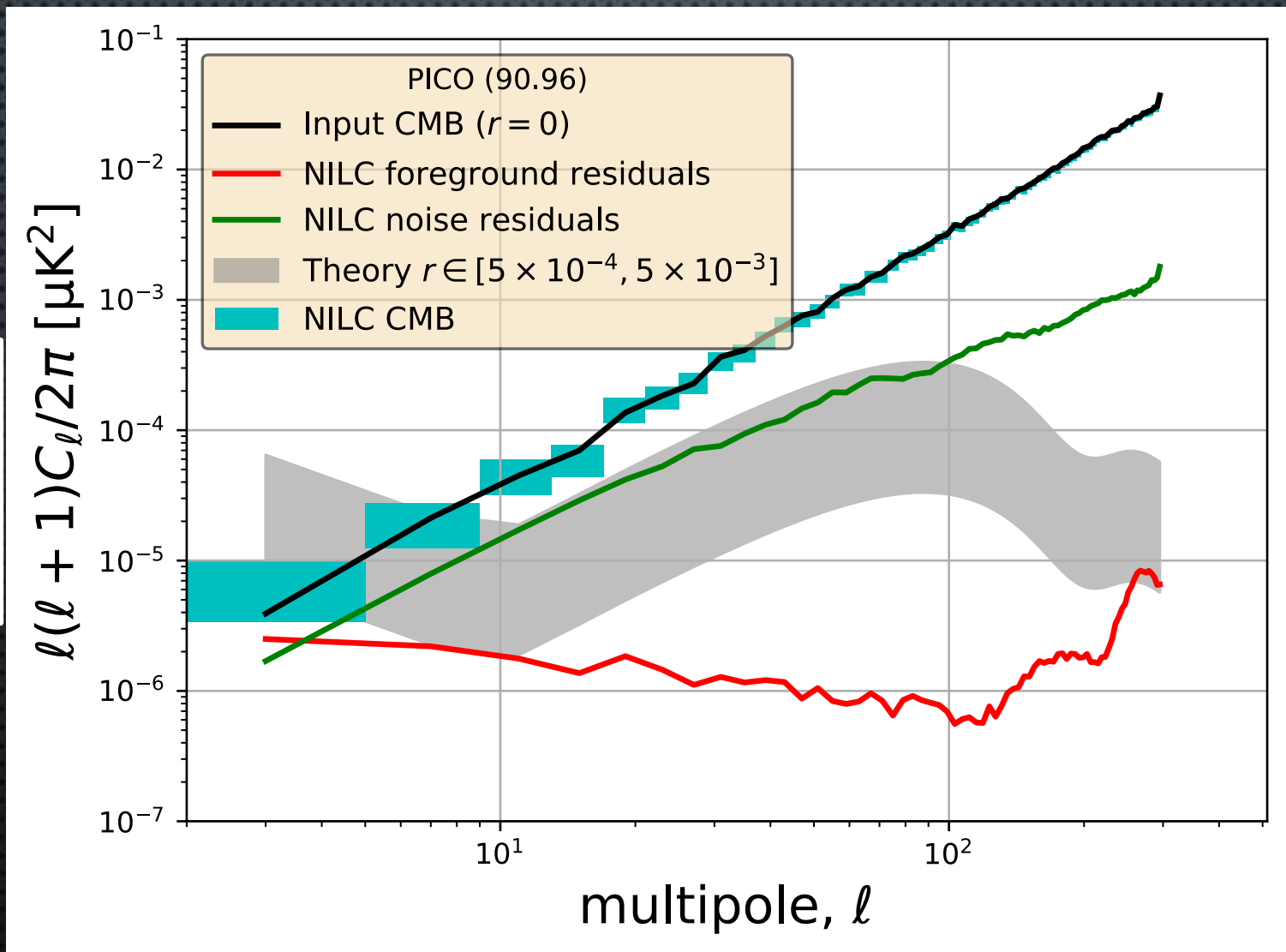
$f_{\text{sky}} = 50\%$

Binning: $\Delta\ell = 4$

Foreground residuals
3 times lower
than $r = 5 \times 10^{-4}$

Model 96, $r = 0$

NILC



Foreground residuals just lower than $r = 5 \times 10^{-4}$

10 realizations

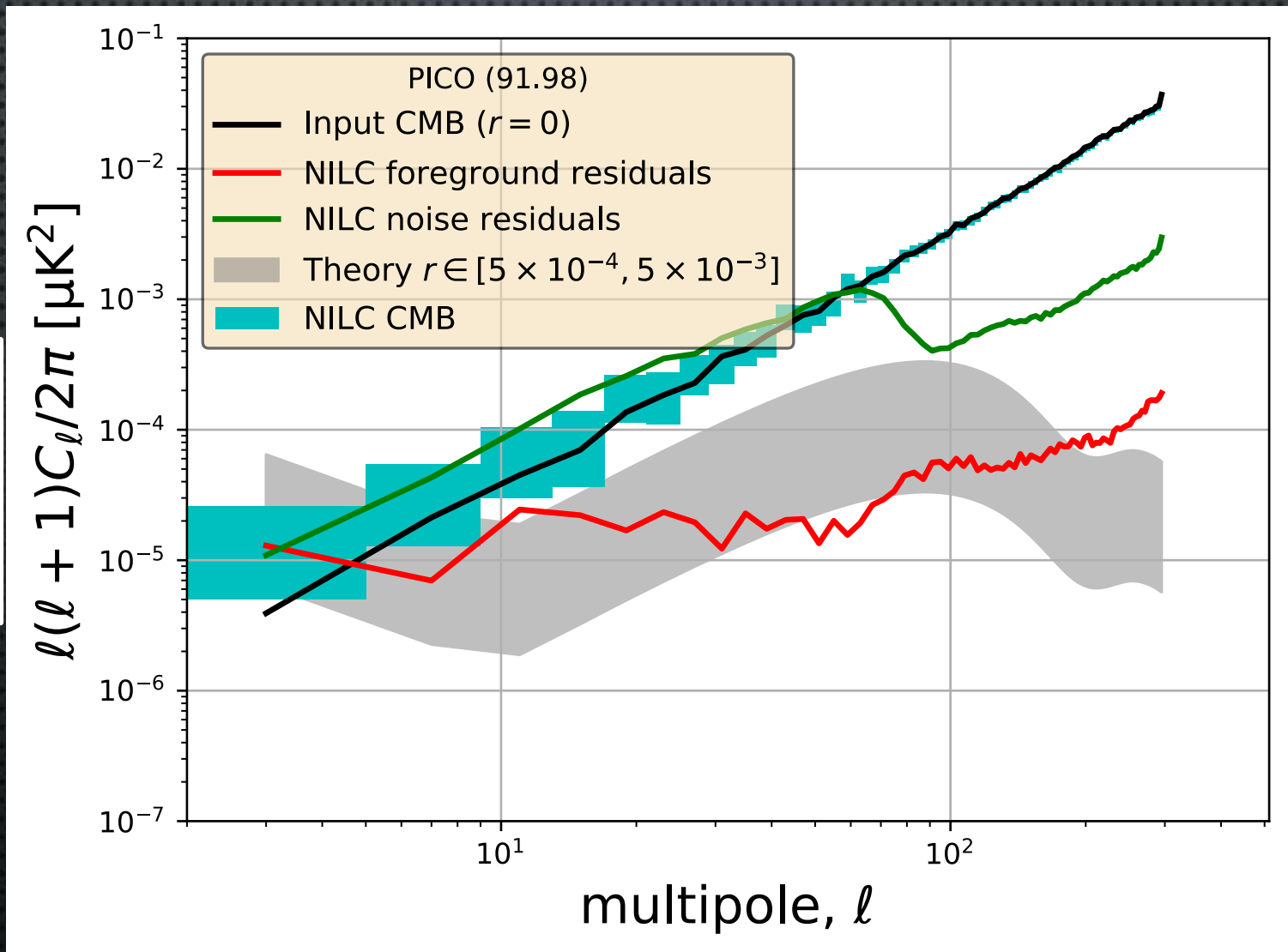
MASTER

$f_{\text{sky}} = 50\%$

Binning: $\Delta\ell = 4$

Model 98, $r = 0$

NILC



10 realizations

MASTER

$f_{\text{sky}} = 50\%$

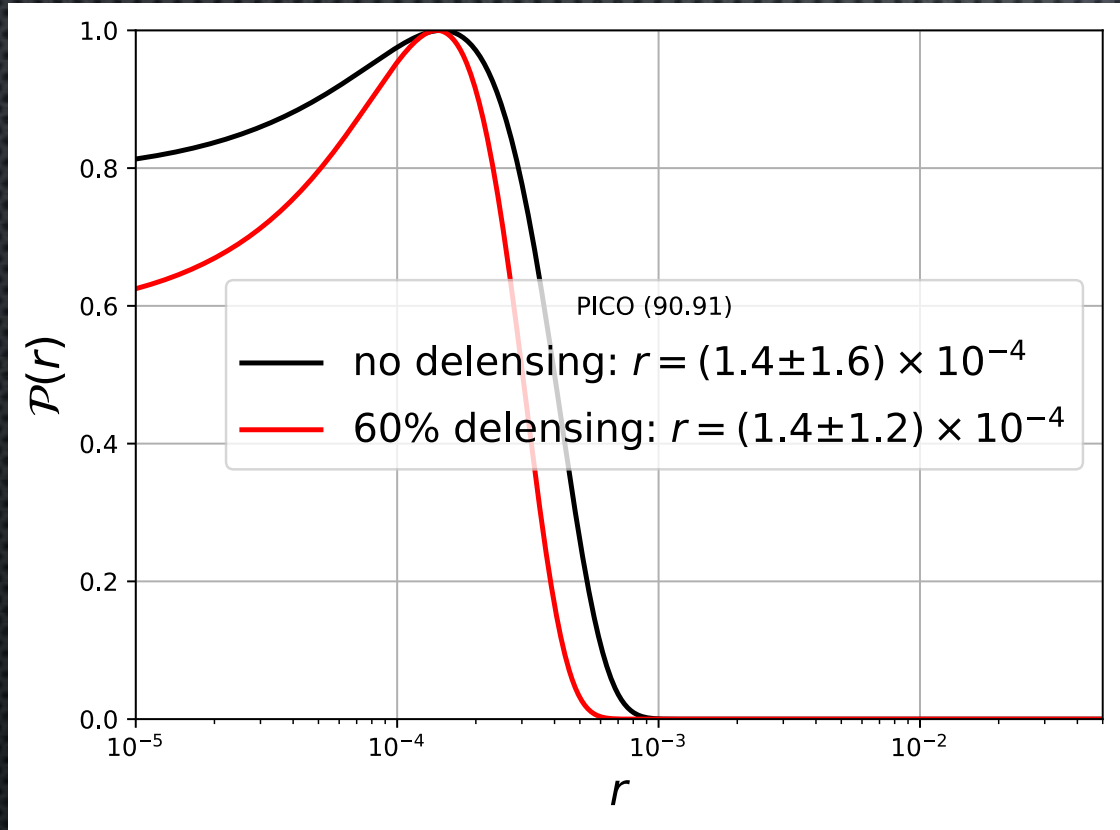
Binning: $\Delta l = 4$

Significant foreground residuals above $r = 5 \times 10^{-4}$

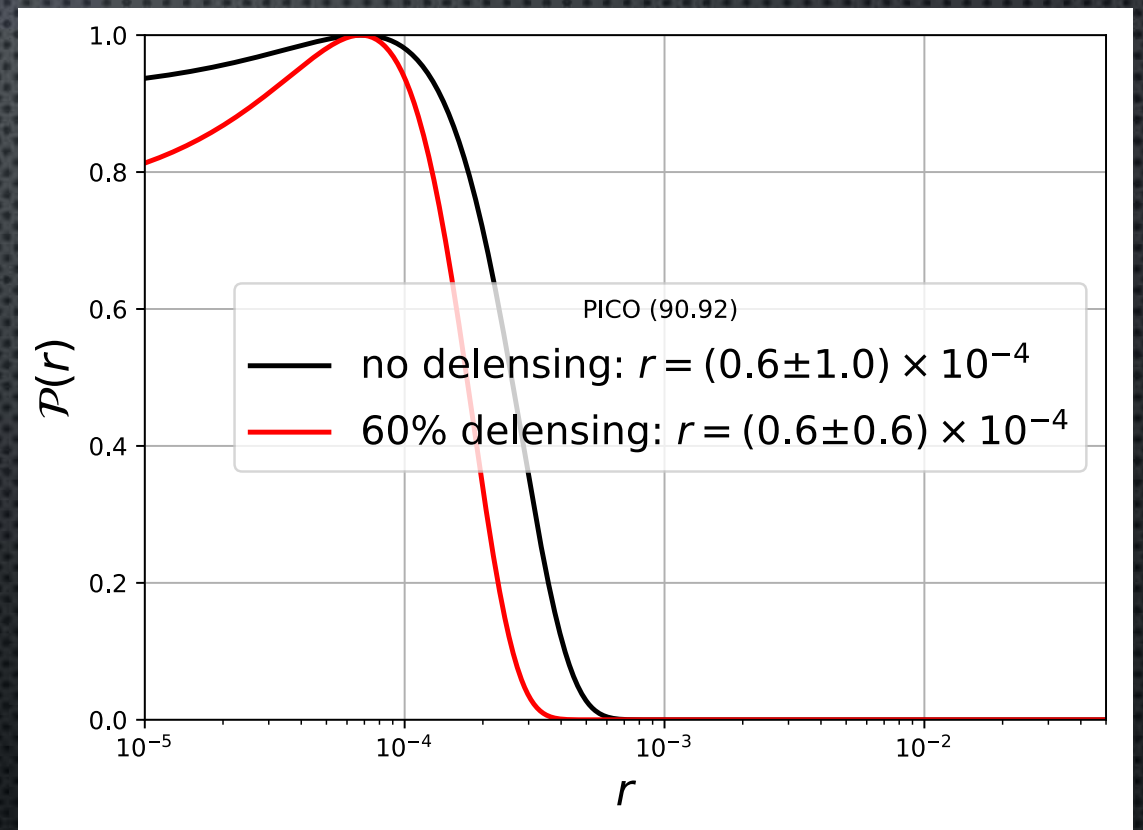
$$r = 0$$

NILC

Model 91



Model 92

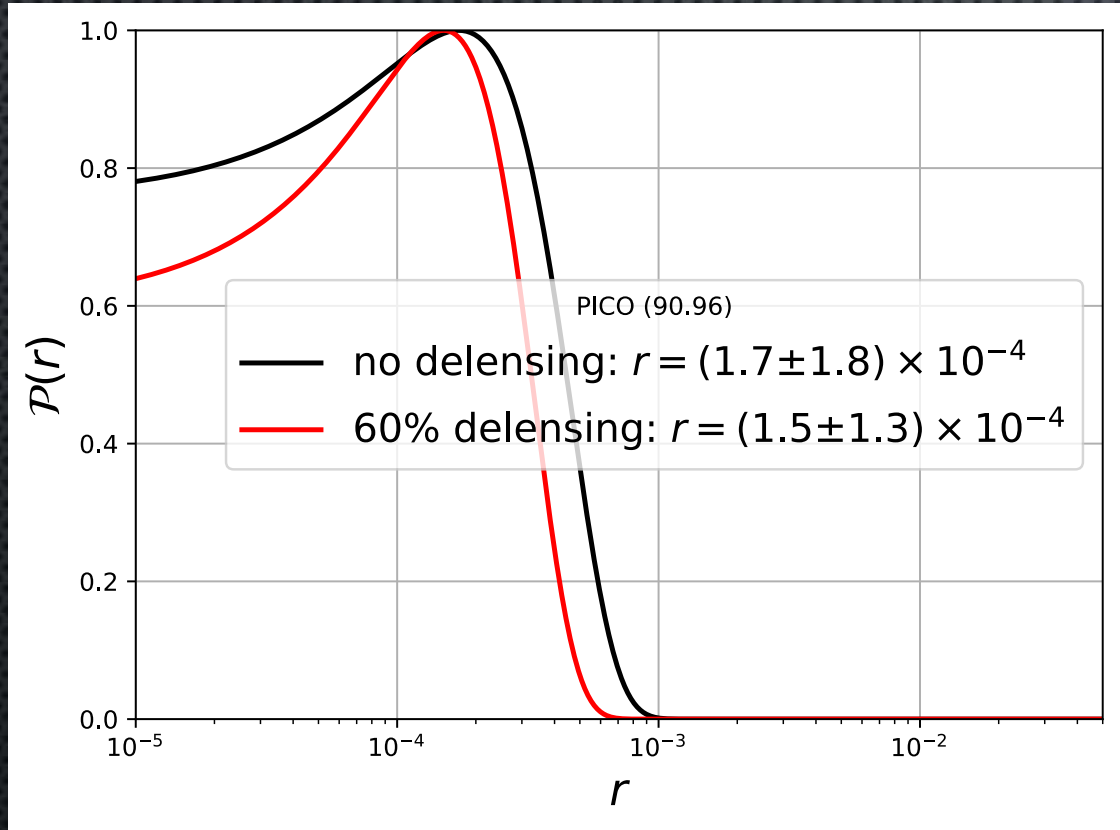


Robust recovery of the tensor-to-scalar ratio:
 $\sigma(r) \simeq 10^{-4}$ for both sky models

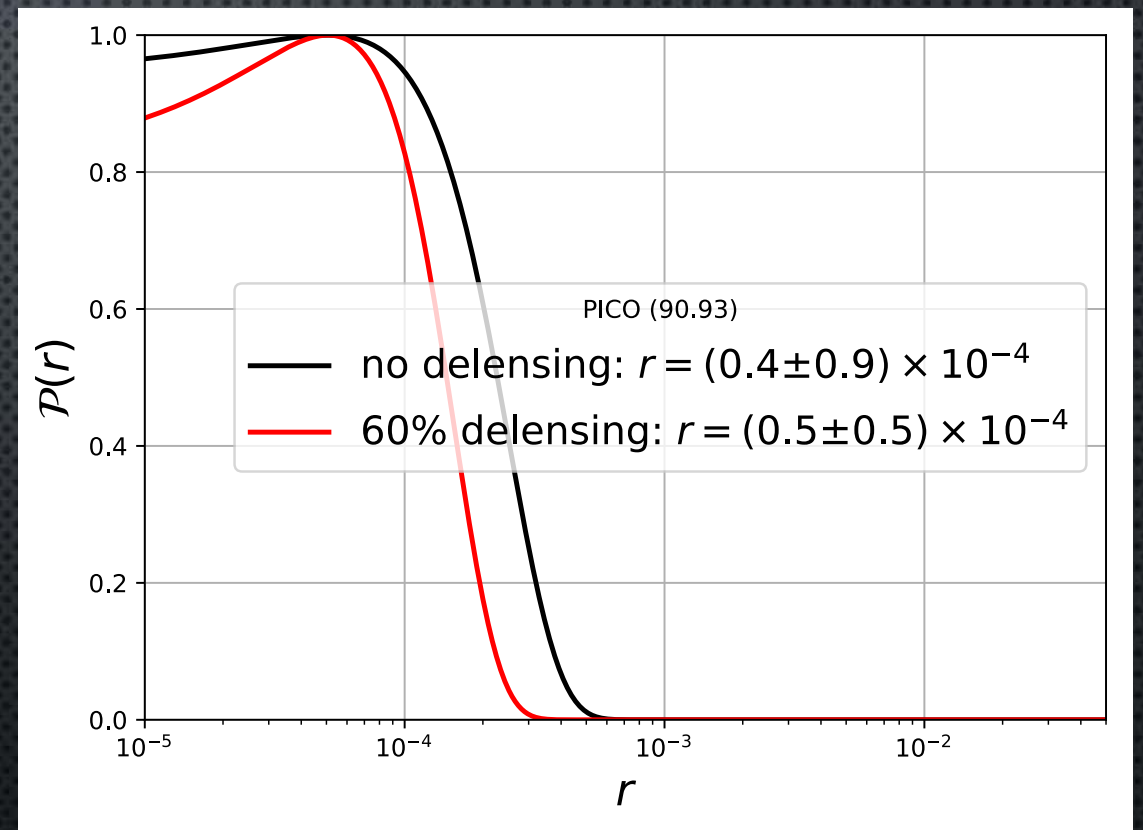
$$r = 0$$

NILC

Model 96



Model 93

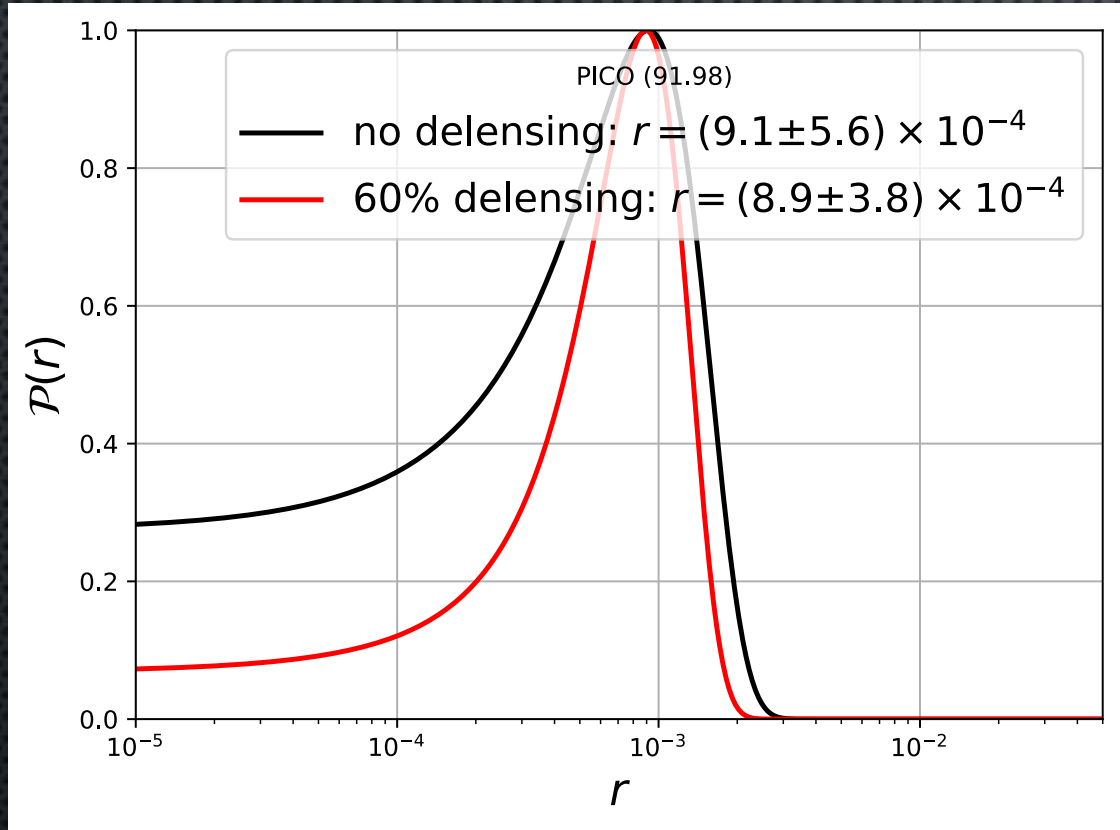


Robust recovery of the tensor-to-scalar ratio:
 $\sigma(r) \simeq 10^{-4}$ for both sky models

$$r = 0$$

NILC

Model 98



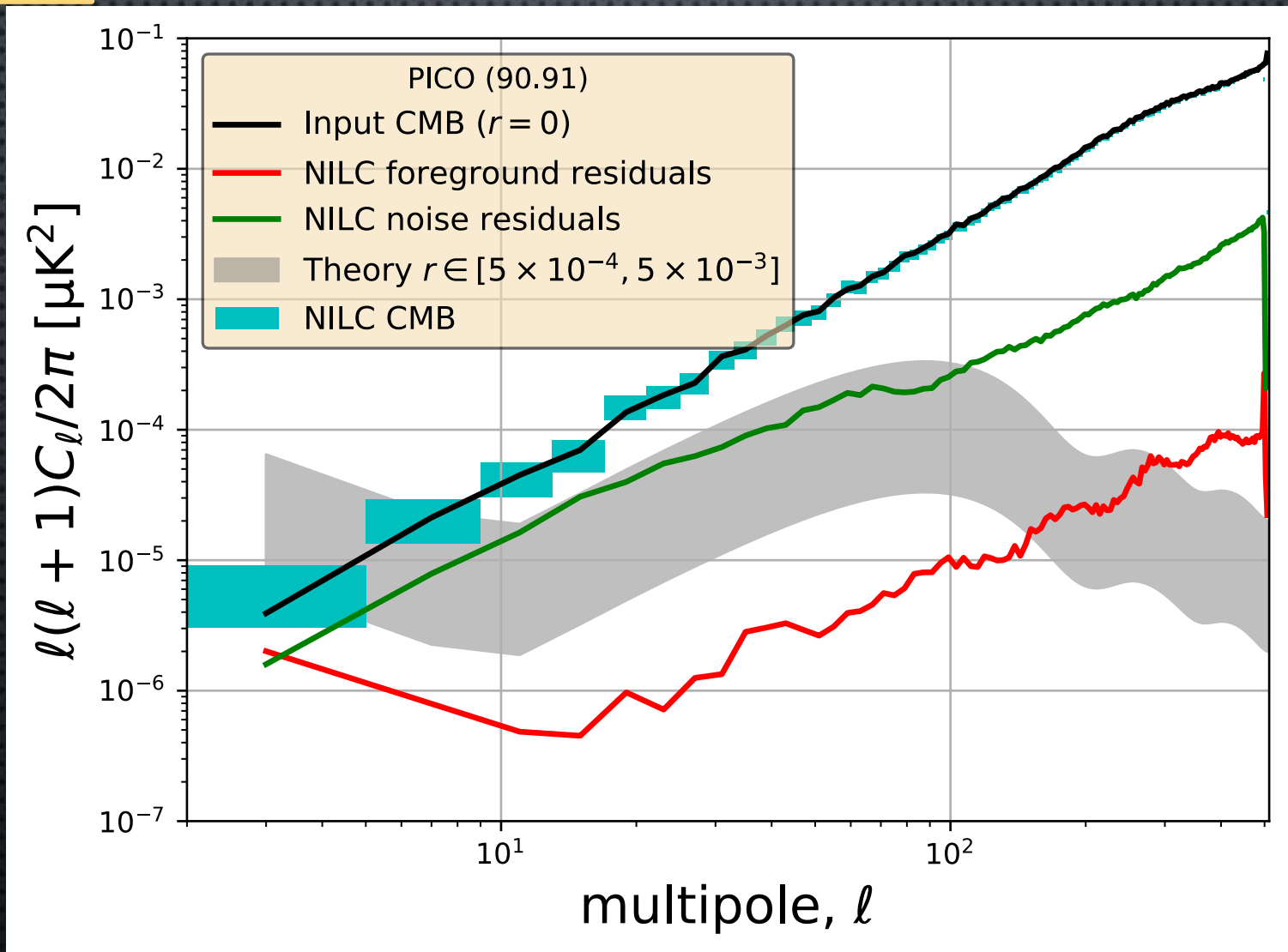
More than one sigma bias on the recovered tensor-to-scalar ratio¹⁸

Importance of high/low frequency channels

Baseline
21 - 800 GHz

Model 91, $r = 0$

NILC



10 realizations

MASTER

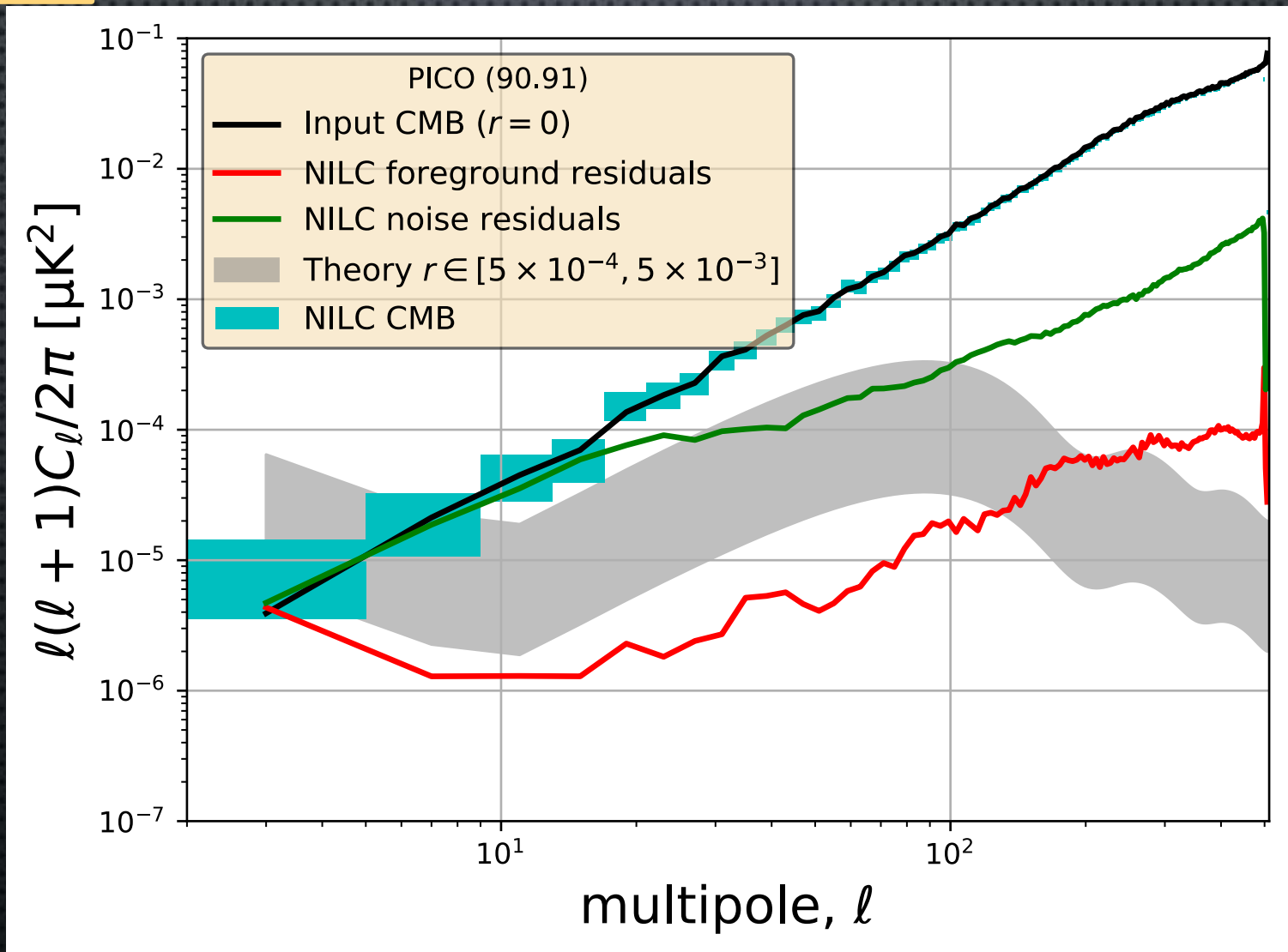
$f_{\text{sky}} = 50\%$

Binning: $\Delta\ell = 4$

Without LF
43 - 800 GHz

Model 91, $r = 0$

NILC



10 realizations

MASTER

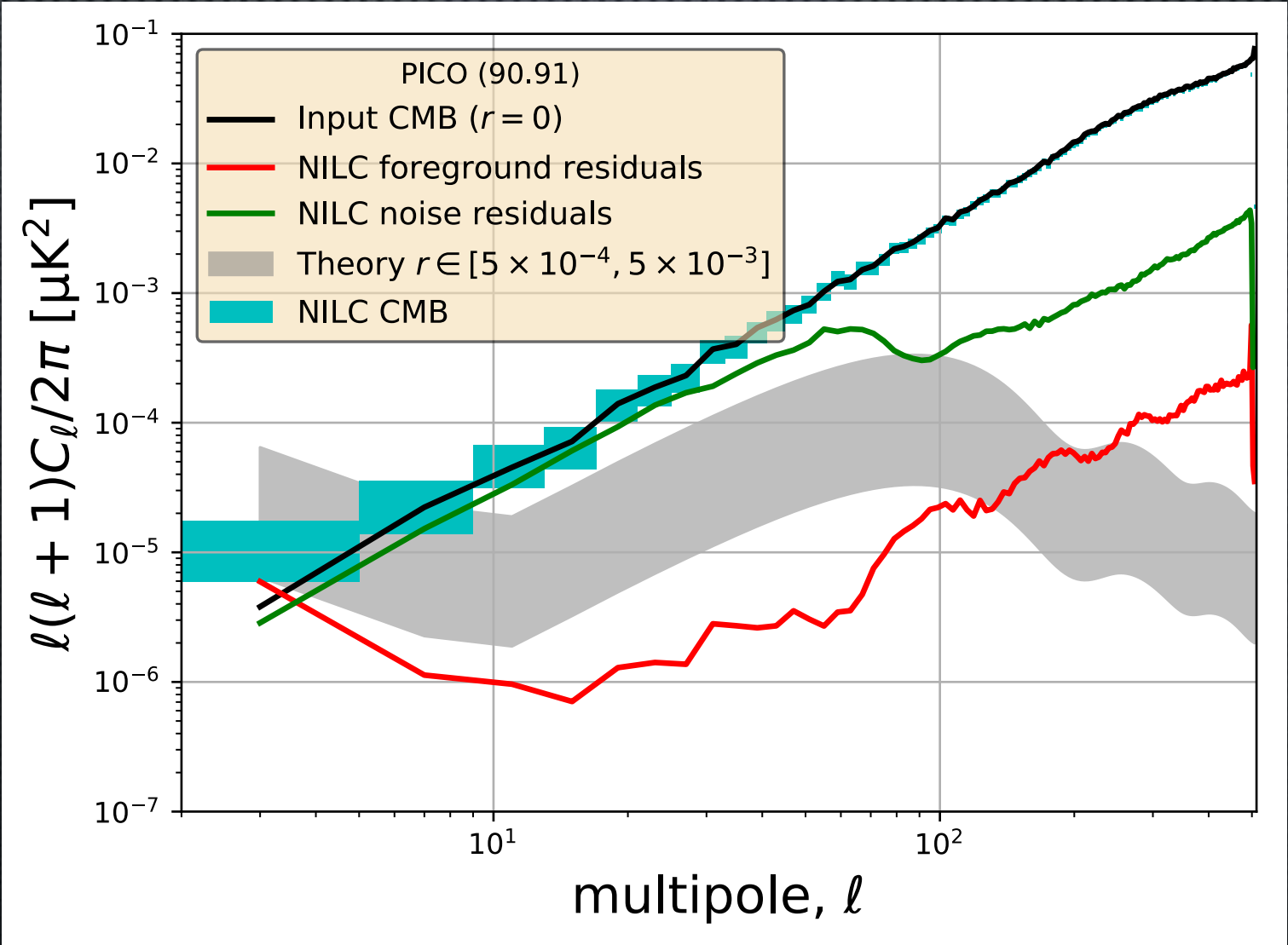
$f_{\text{sky}} = 50\%$

Binning: $\Delta\ell = 4$

Without HF
21 - 462 GHz

Model 91, $r = 0$

NILC



10 realizations

MASTER

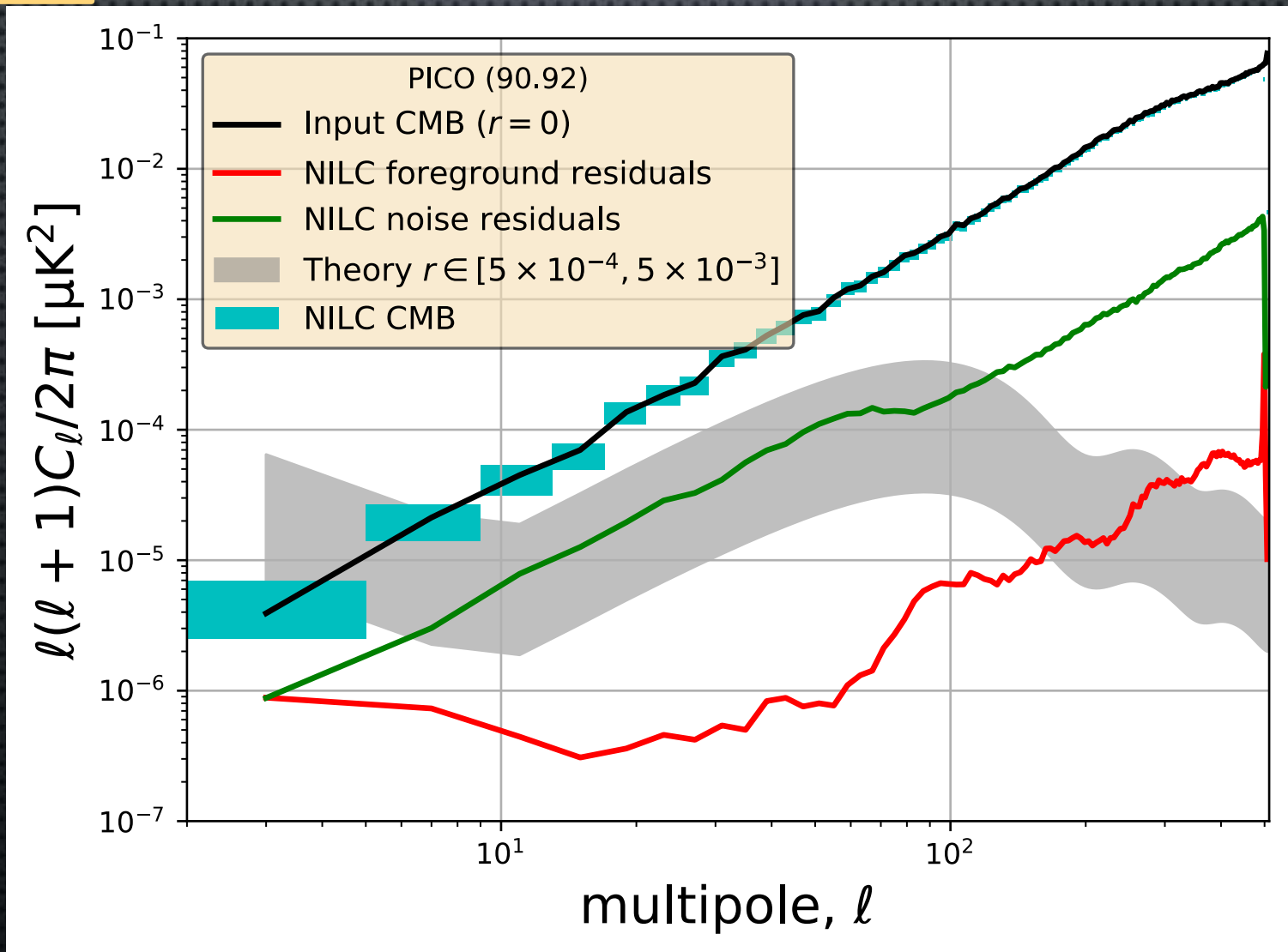
$f_{\text{sky}} = 50\%$

Binning: $\Delta l = 4$

Baseline
21 - 800 GHz

Model 92, $r = 0$

NILC



10 realizations

MASTER

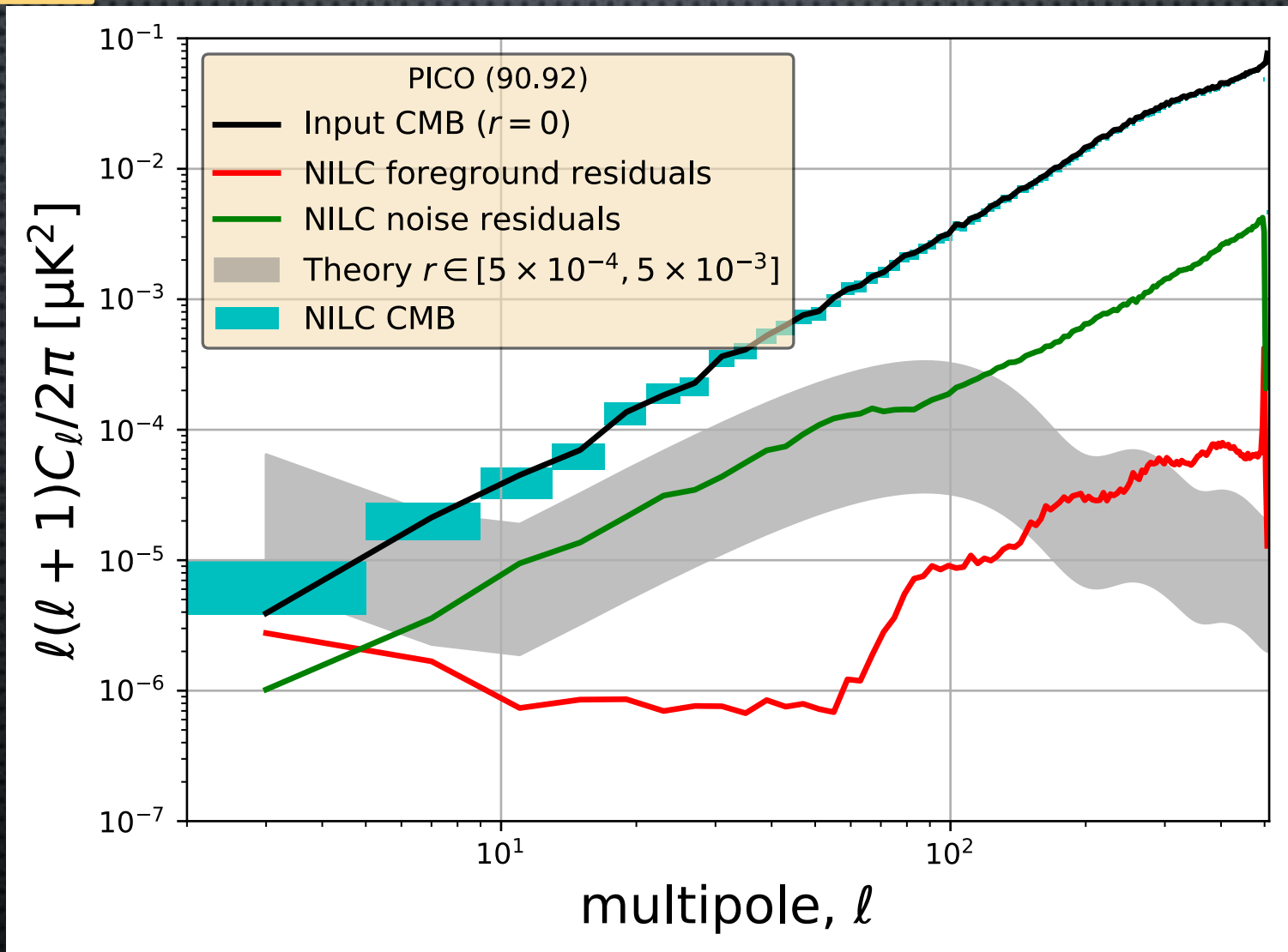
$f_{\text{sky}} = 50\%$

Binning: $\Delta l = 4$

Without LF
43 - 800 GHz

Model 92, $r = 0$

NILC



10 realizations

MASTER

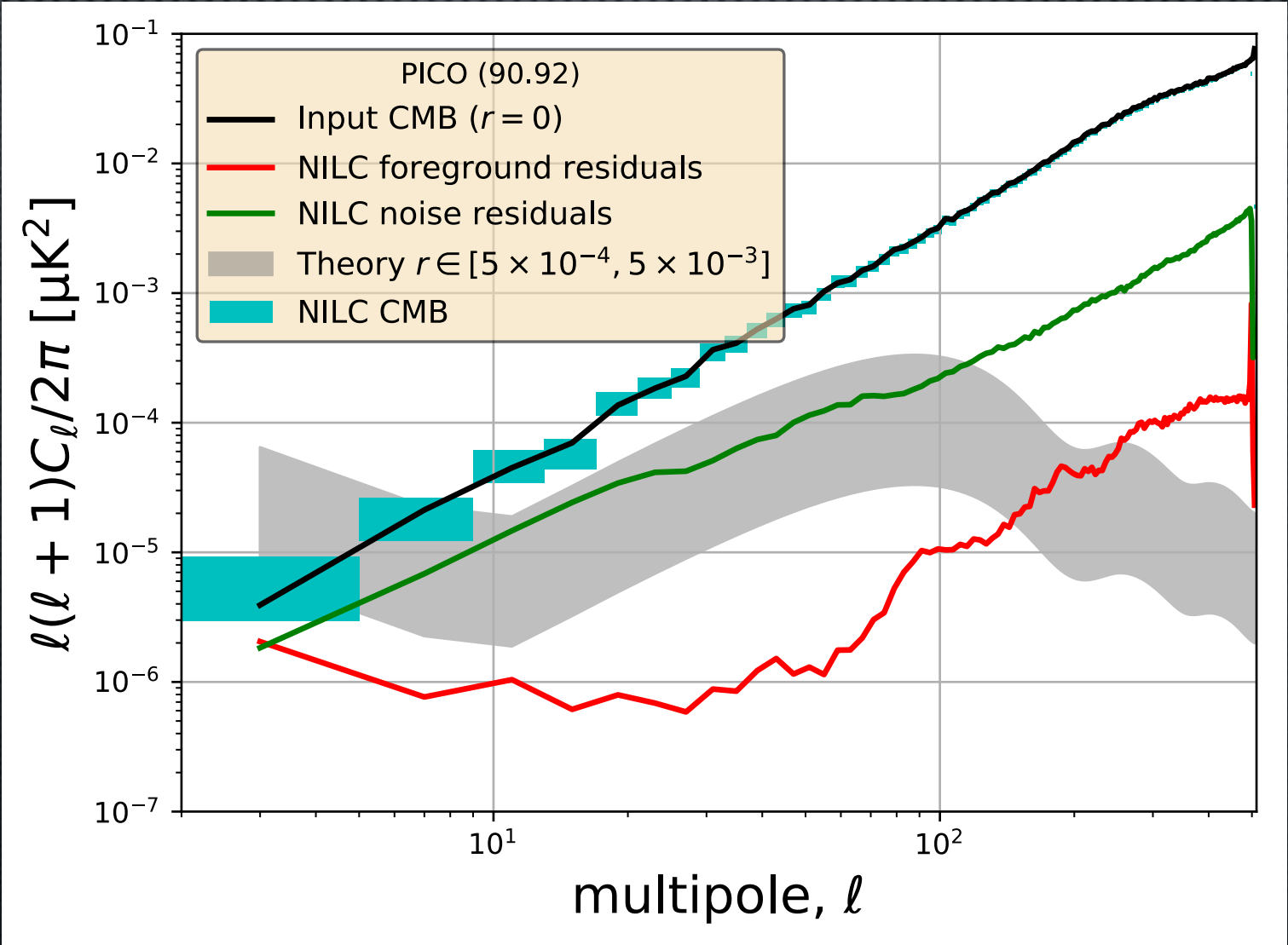
$f_{\text{sky}} = 50\%$

Binning: $\Delta\ell = 4$

Without HF
21 - 462 GHz

Model 92, $r = 0$

NILC



10 realizations

MASTER

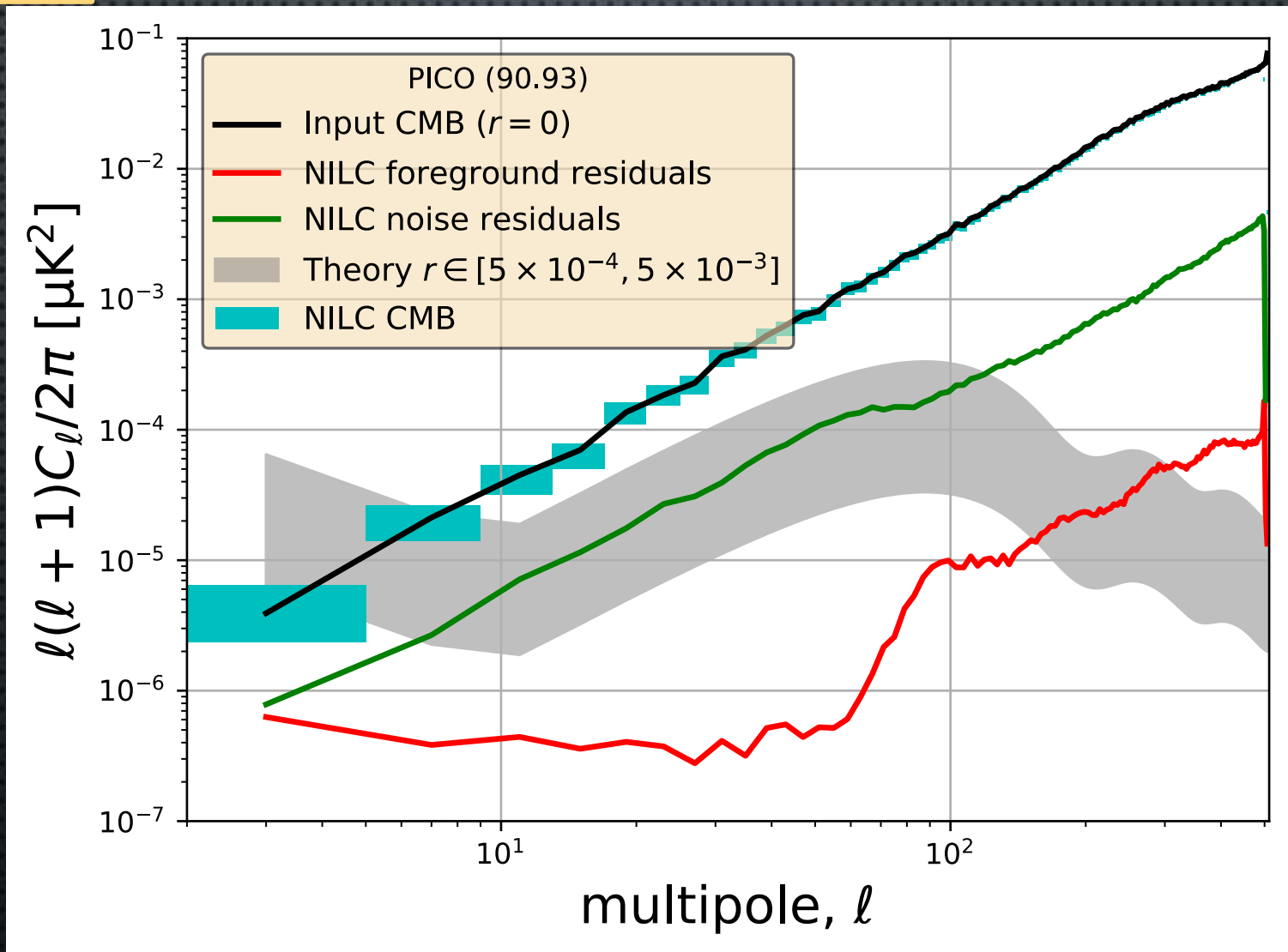
$f_{\text{sky}} = 50\%$

Binning: $\Delta\ell = 4$

Baseline
21 - 800 GHz

Model 93, $r = 0$

NILC



10 realizations

MASTER

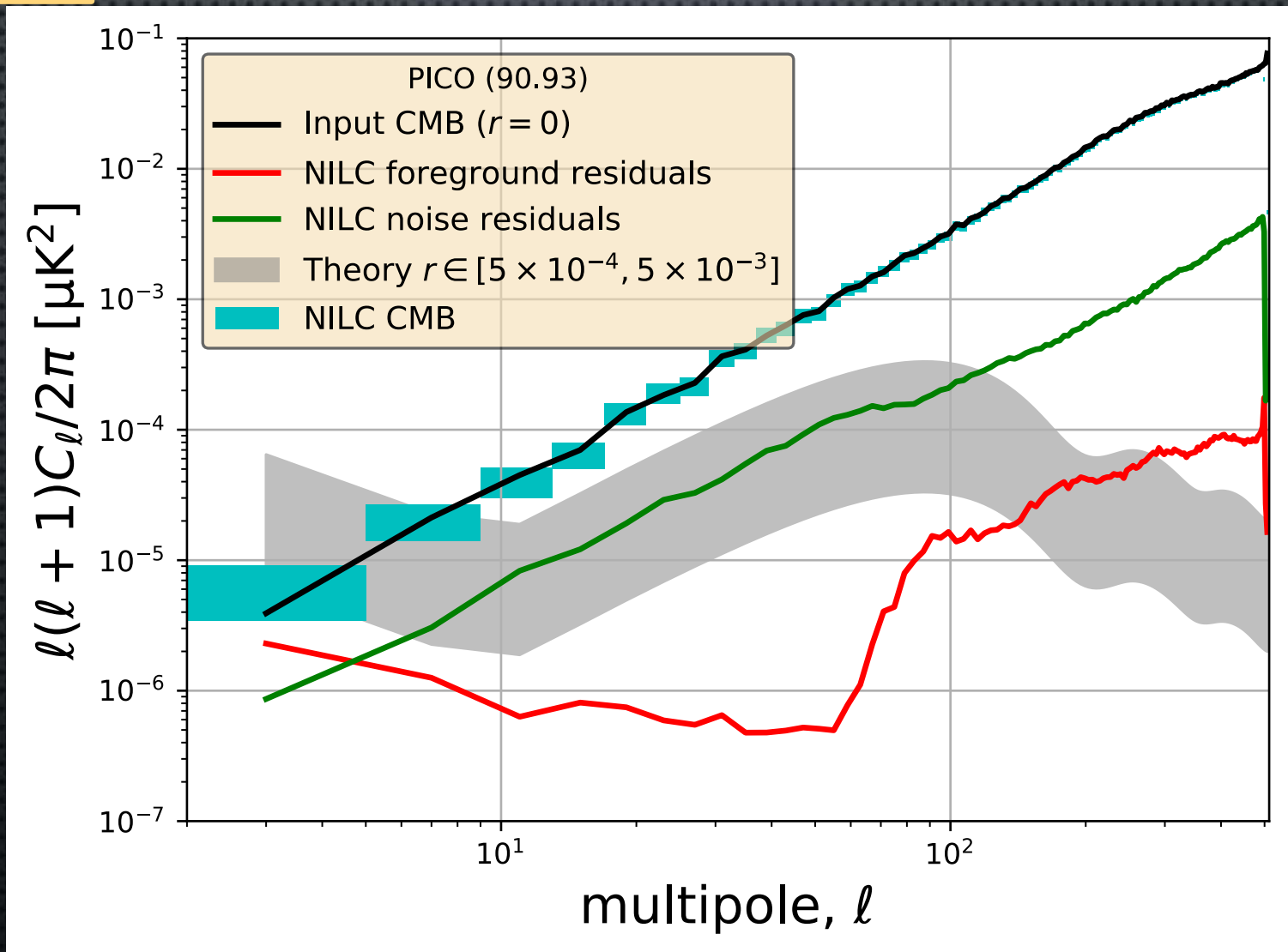
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Without LF
43 - 800 GHz

Model 93, $r = 0$

NILC



10 realizations

MASTER

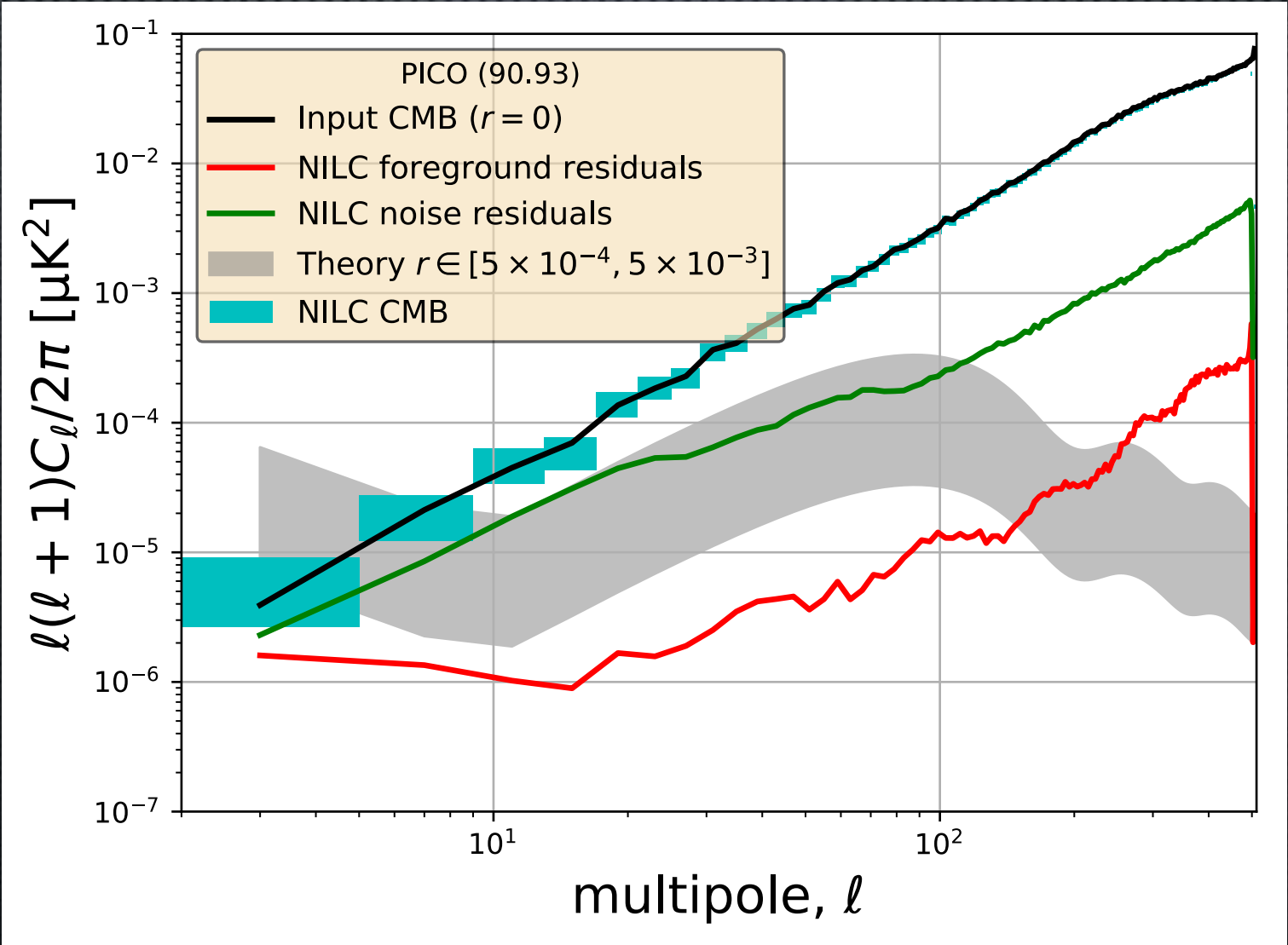
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Without HF
21 - 462 GHz

Model 93, $r = 0$

NILC



10 realizations

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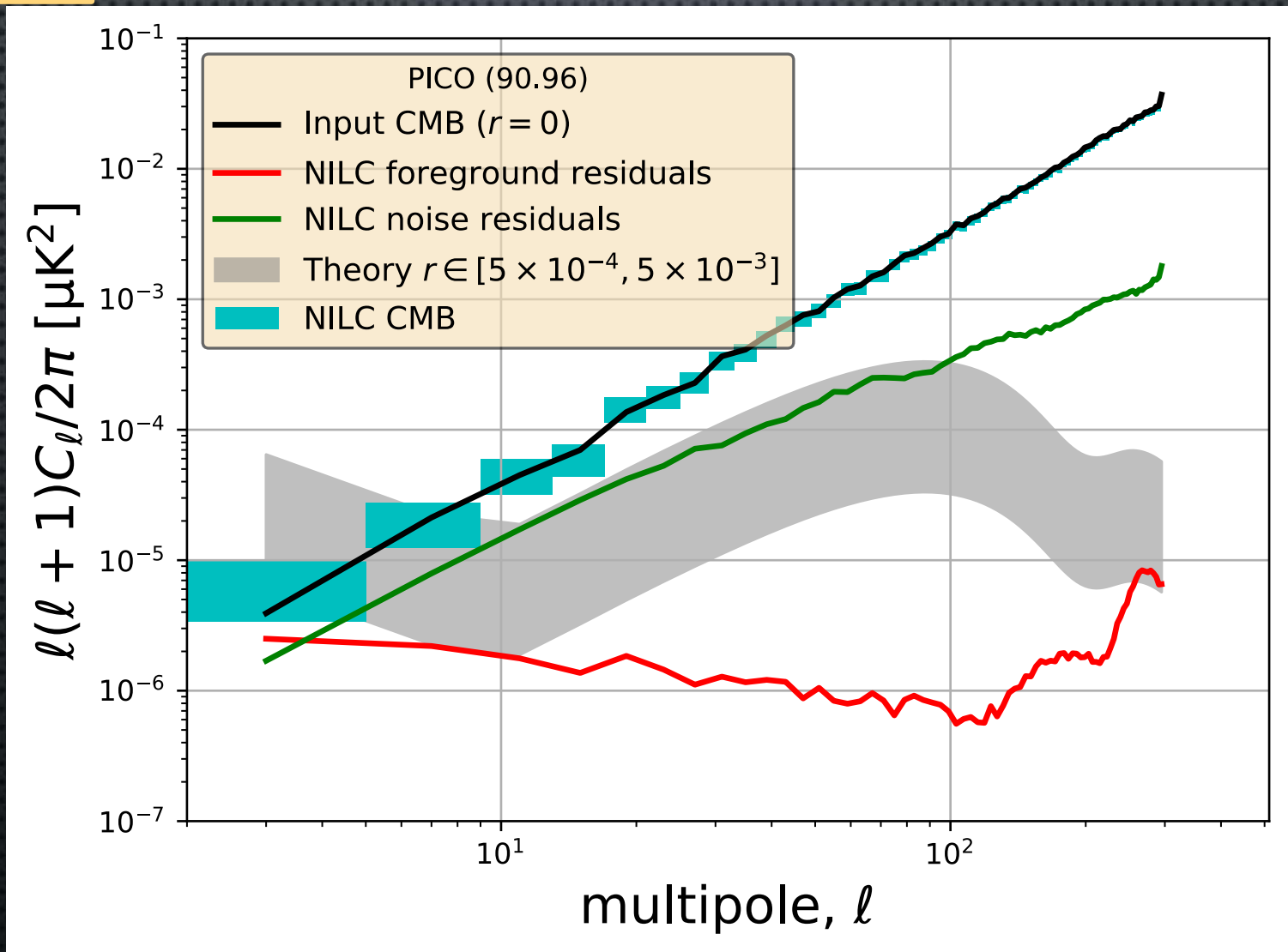
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Baseline
21 - 800 GHz

Model 96, $r = 0$

NILC



10 realizations

MASTER

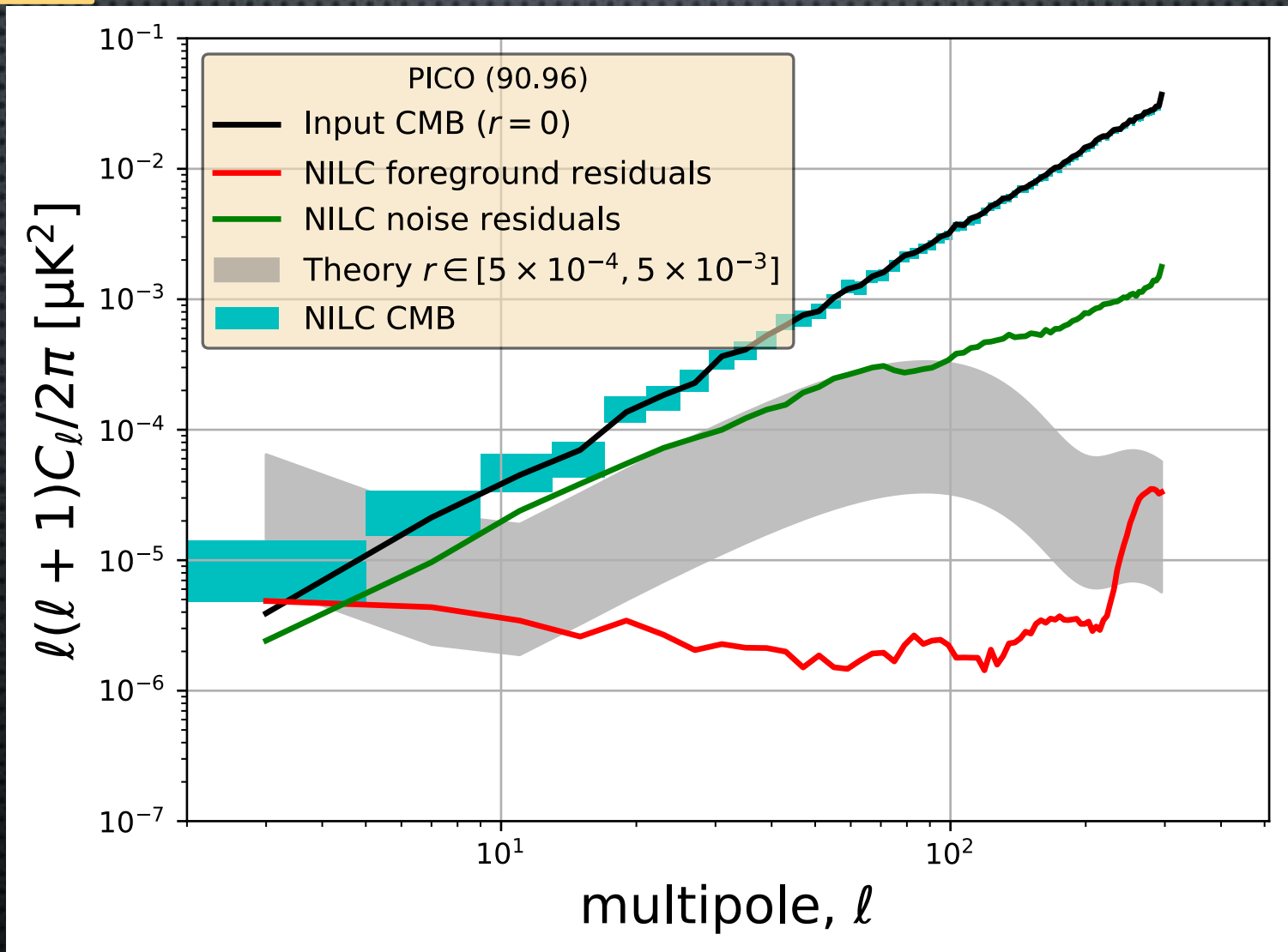
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Without LF
43 - 800 GHz

Model 96, $r = 0$

NILC



10 realizations

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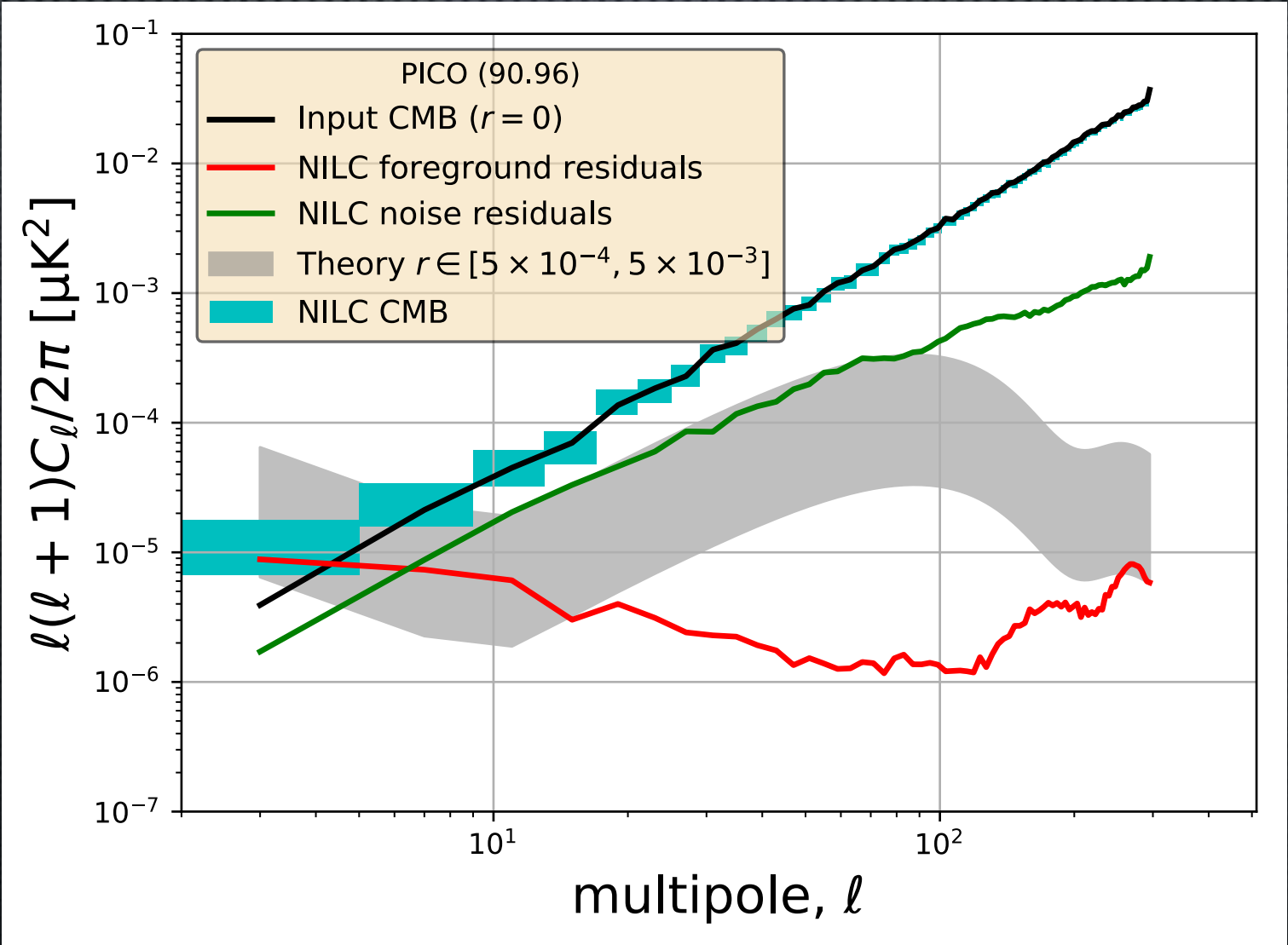
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Without HF
21 - 462 GHz

Model 96, $r = 0$

NILC



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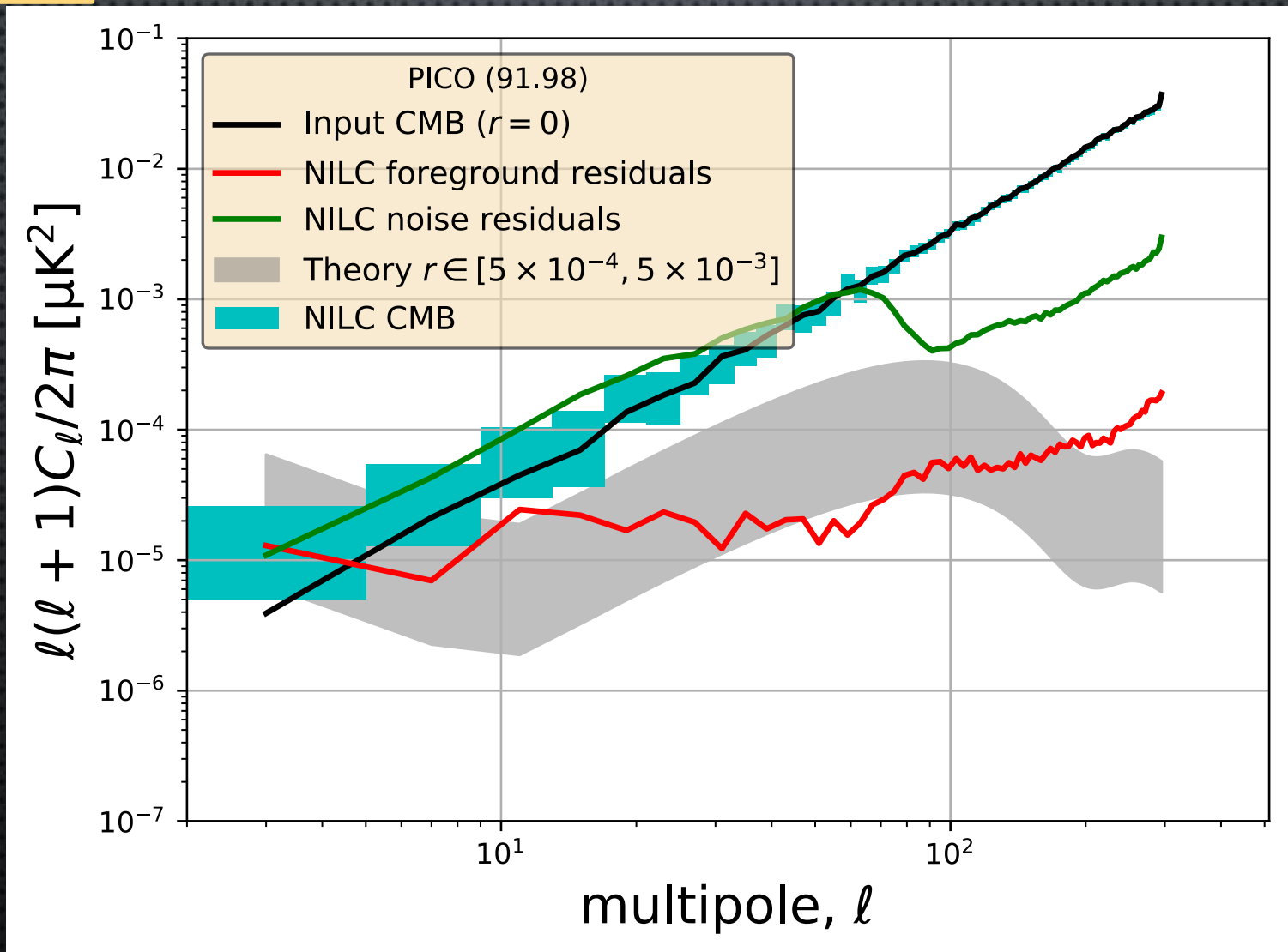
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NILC



10 realizations

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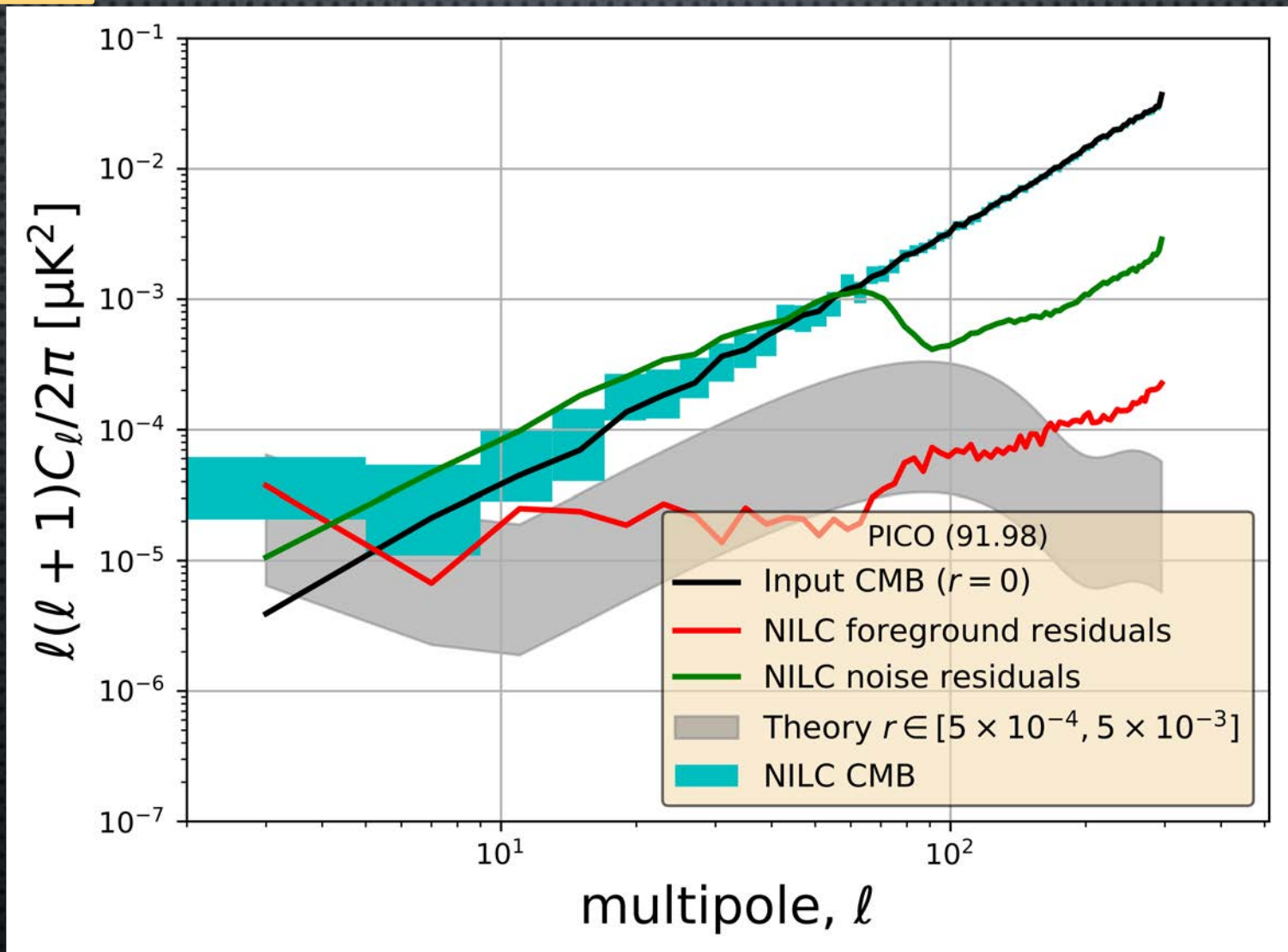
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NILC



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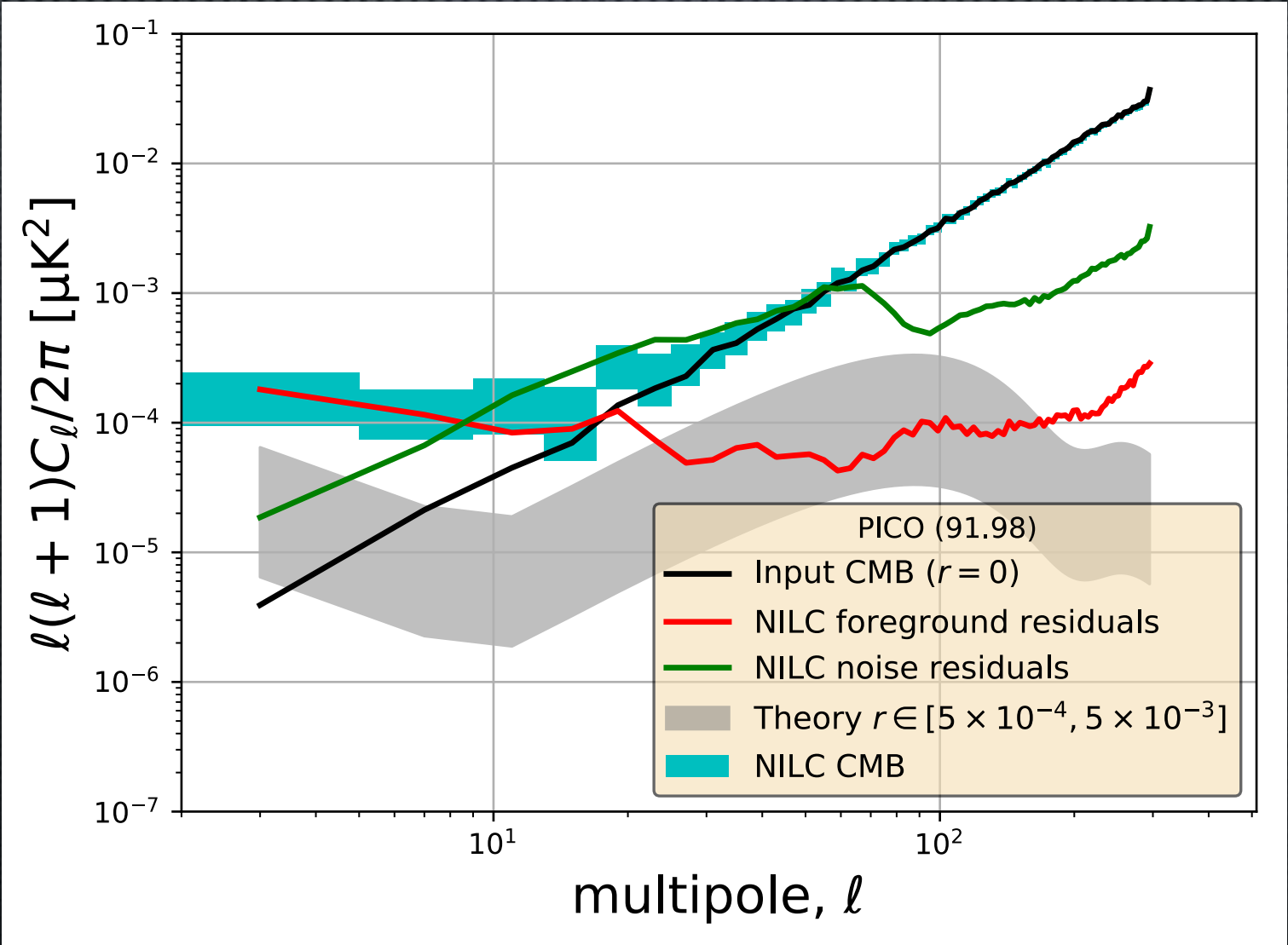
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Without HF
21 - 462 GHz

Model 98, $r = 0$

NILC



10 realizations

MASTER

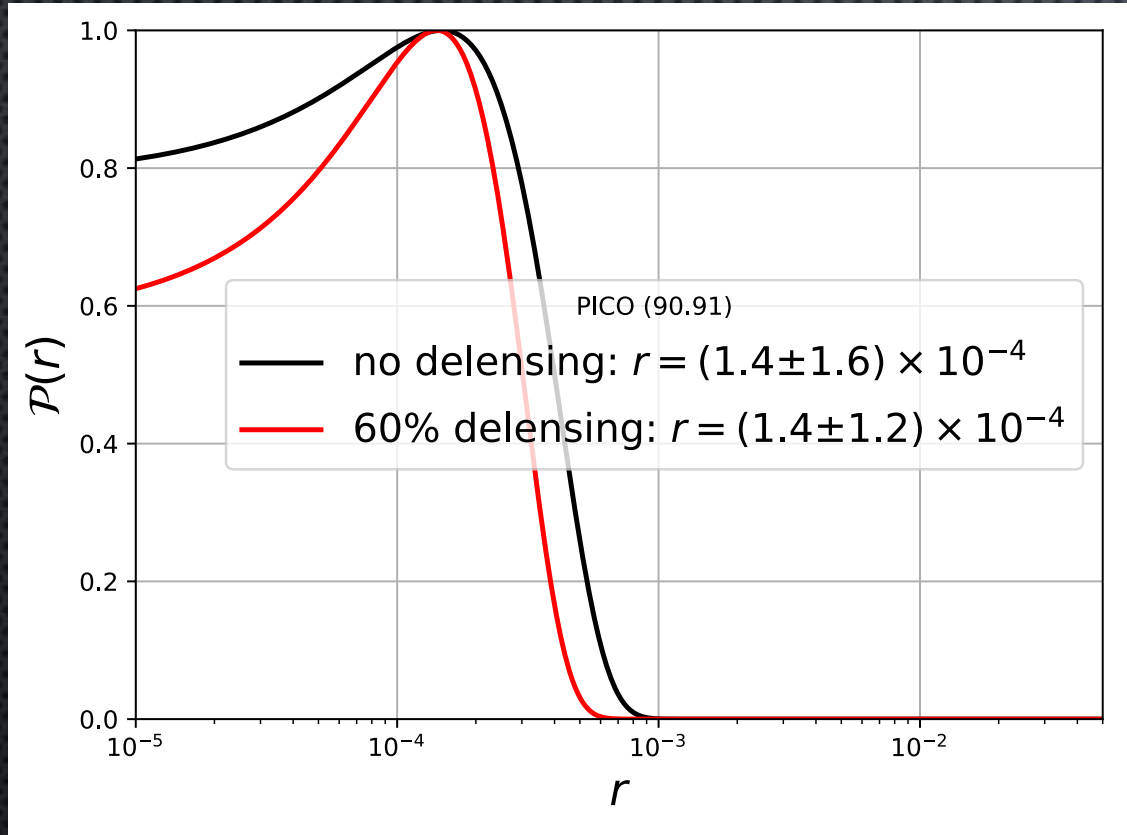
$f_{\text{sky}} = 50\%$

Binning: $\Delta\ell = 4$

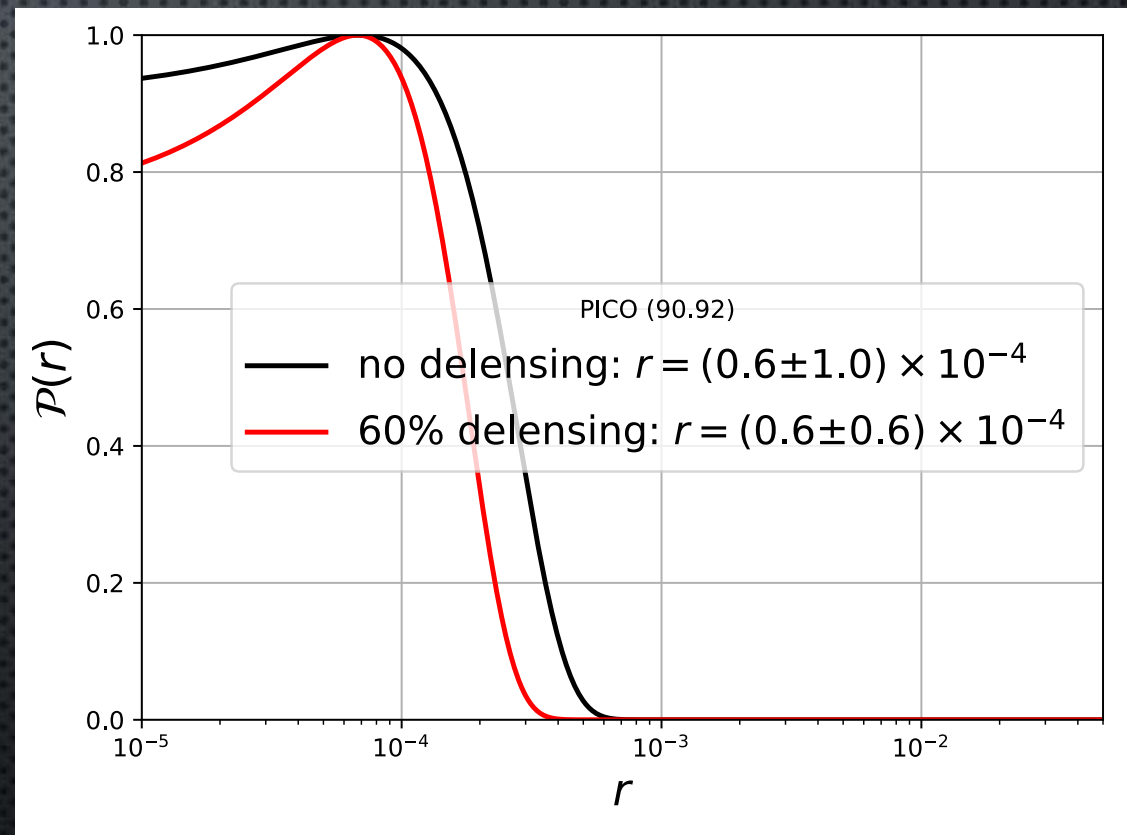
Baseline
21 - 800 GHz

$r = 0$
NILC

Model 91



Model 92



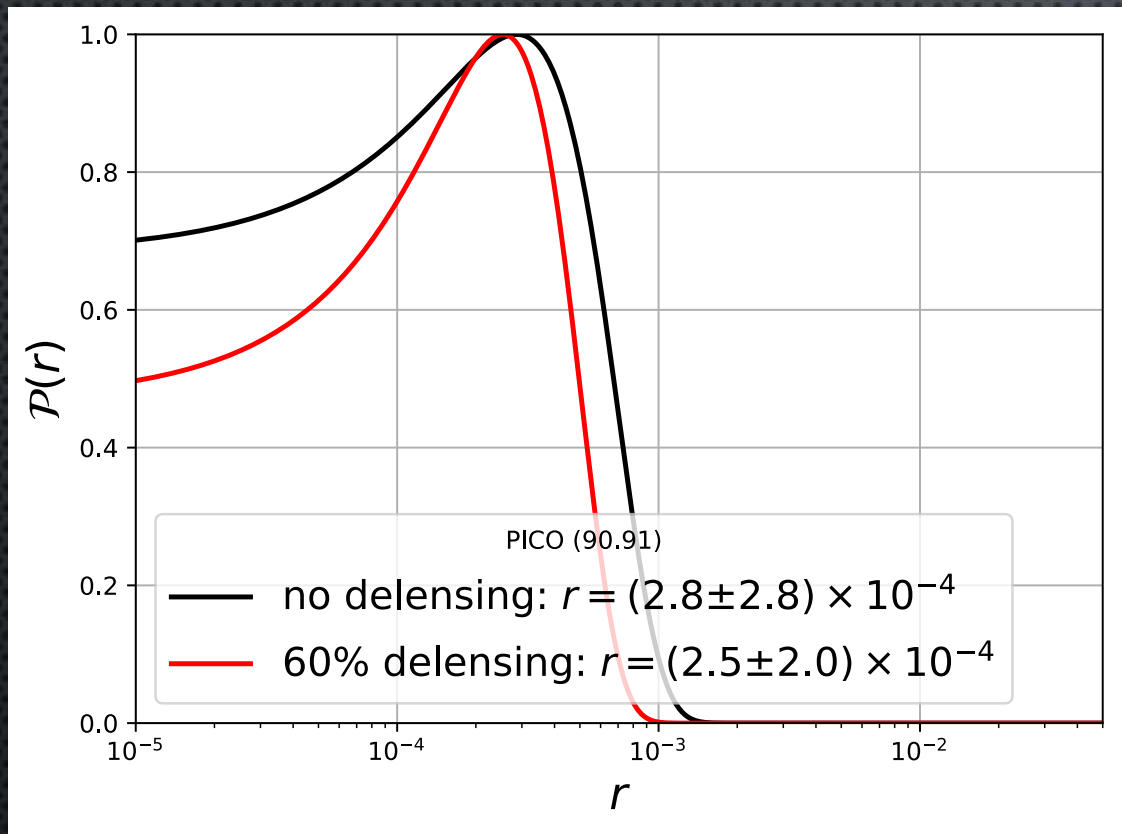
Unbiased recovery of the tensor-to-scalar ratio
Consistent with $r = 0$, $\sigma(r) \simeq 10^{-4}$

Without LF
43 - 800 GHz

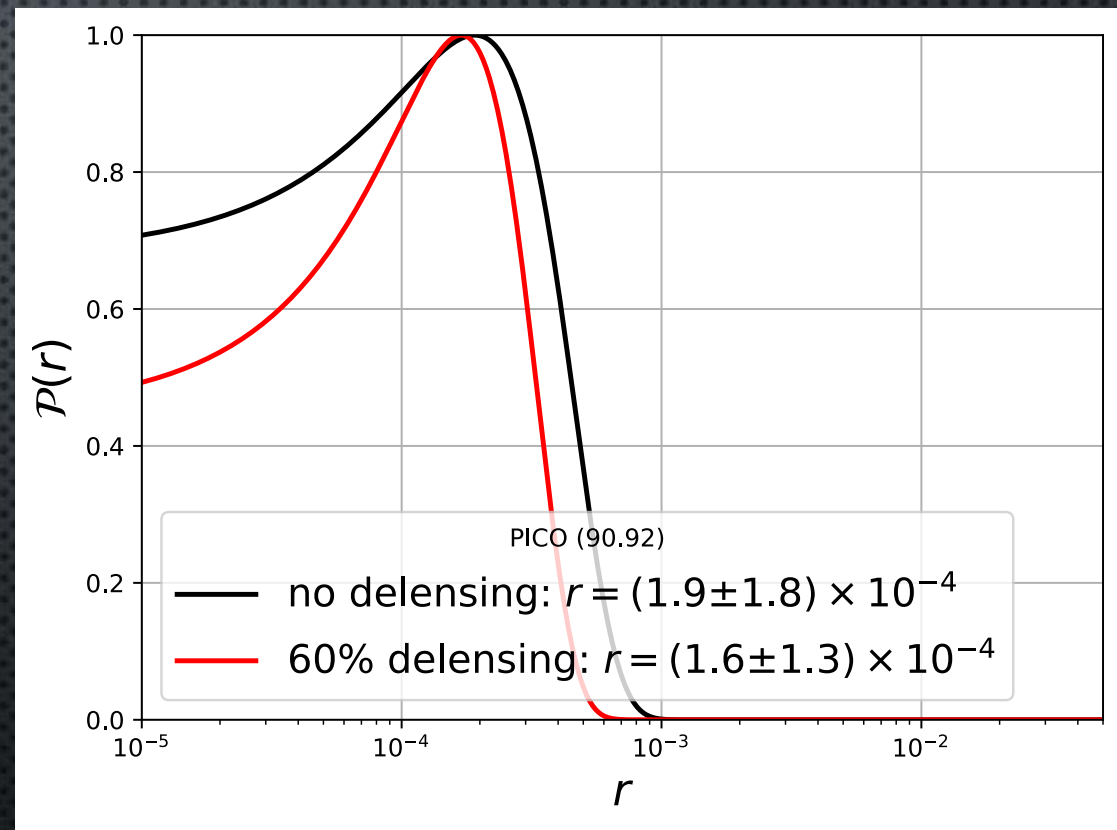
$$r = 0$$

NILC

Model 91



Model 92

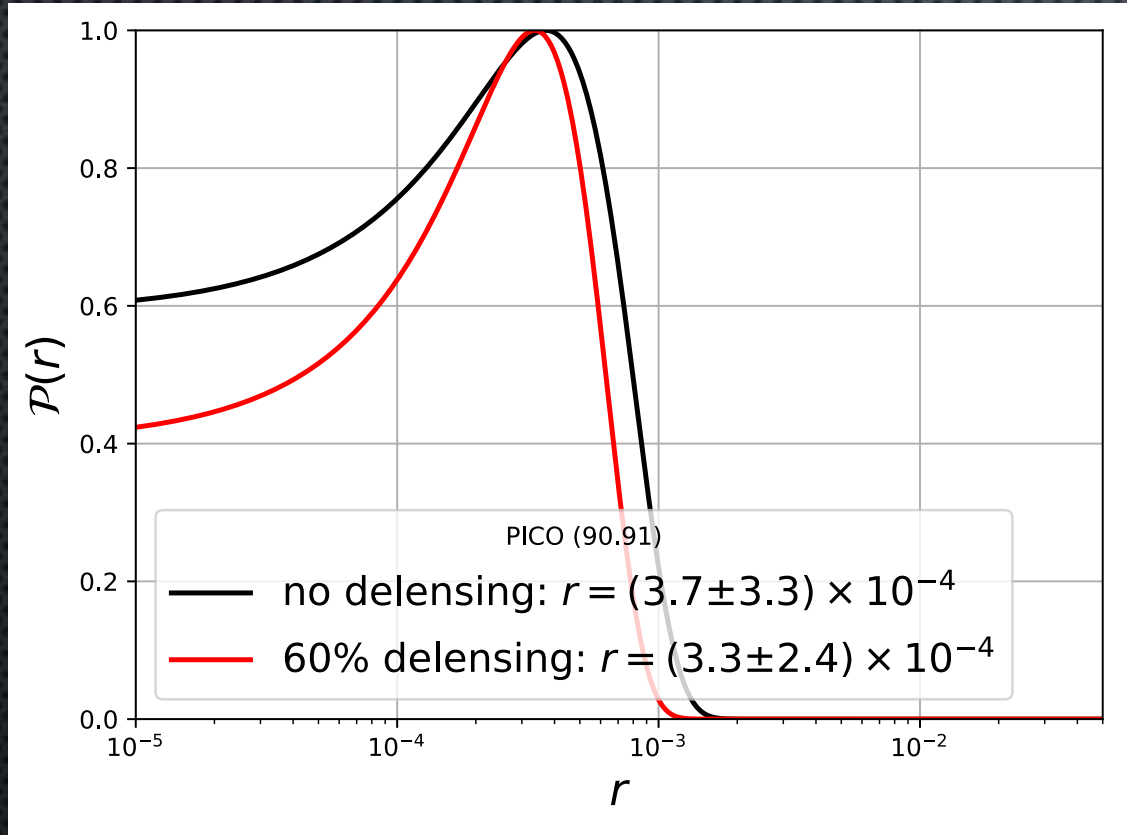


One-sigma bias without low frequencies
exceeding the required performance

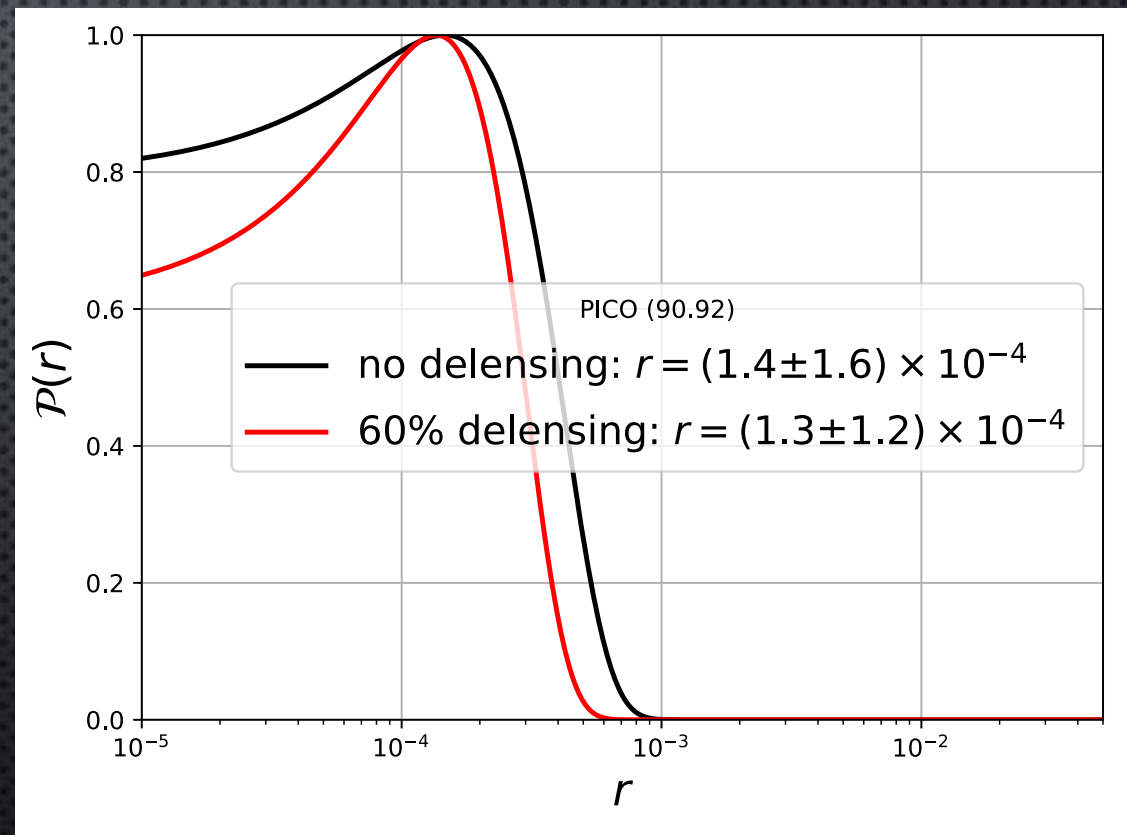
Without HF
21 - 462 GHz

$r = 0$
NILC

Model 91



Model 92

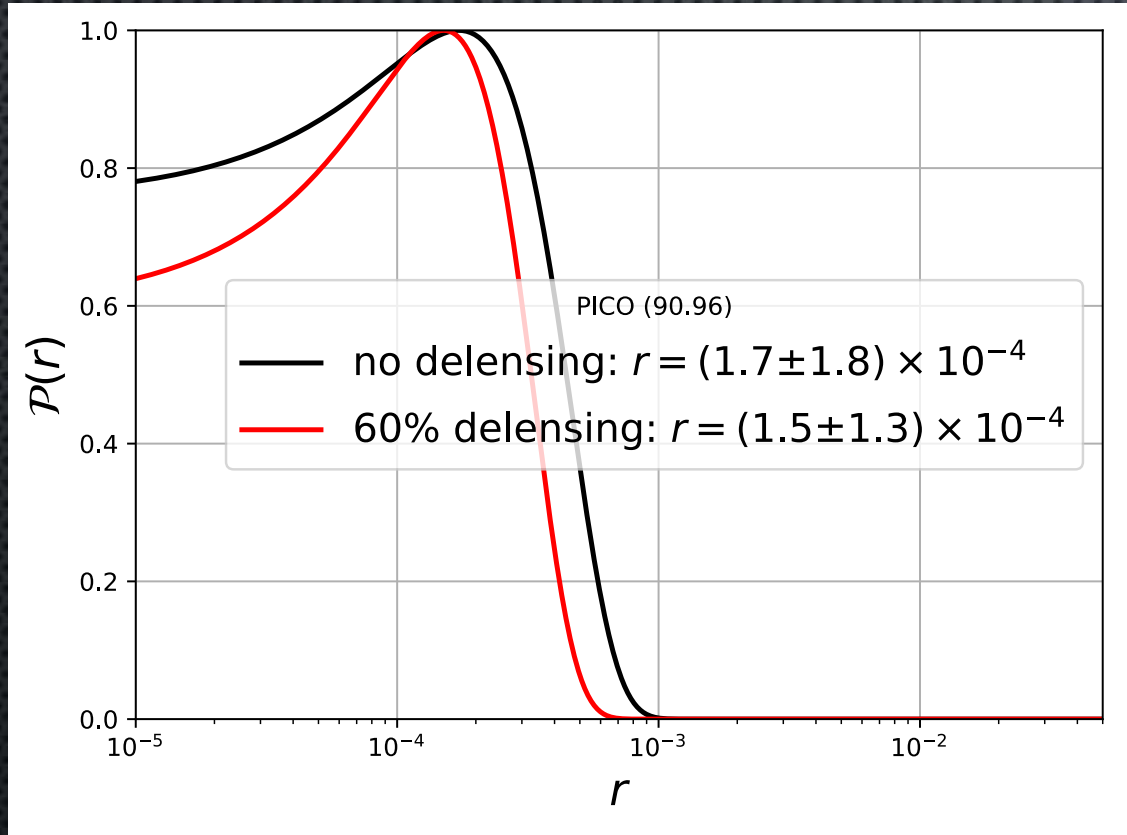


One-sigma bias without high frequencies
exceeding the required performance

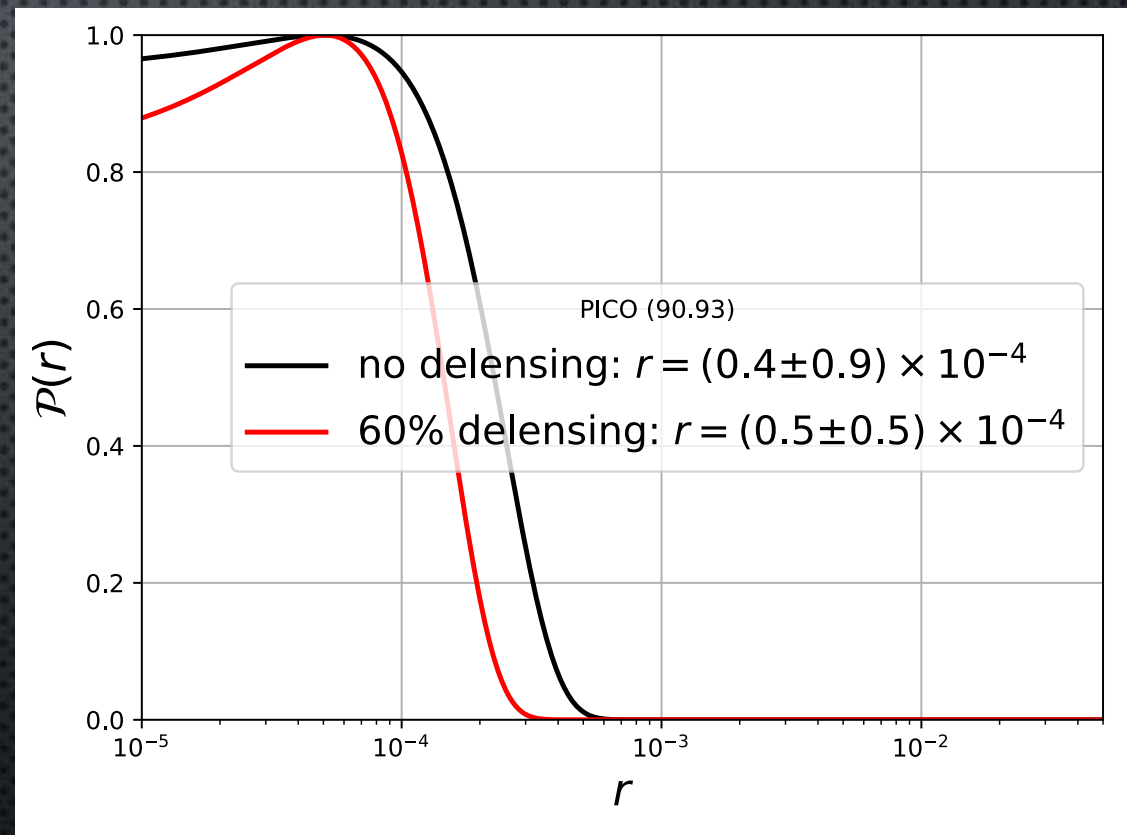
Baseline
21 - 800 GHz

$r = 0$
NILC

Model 96



Model 93

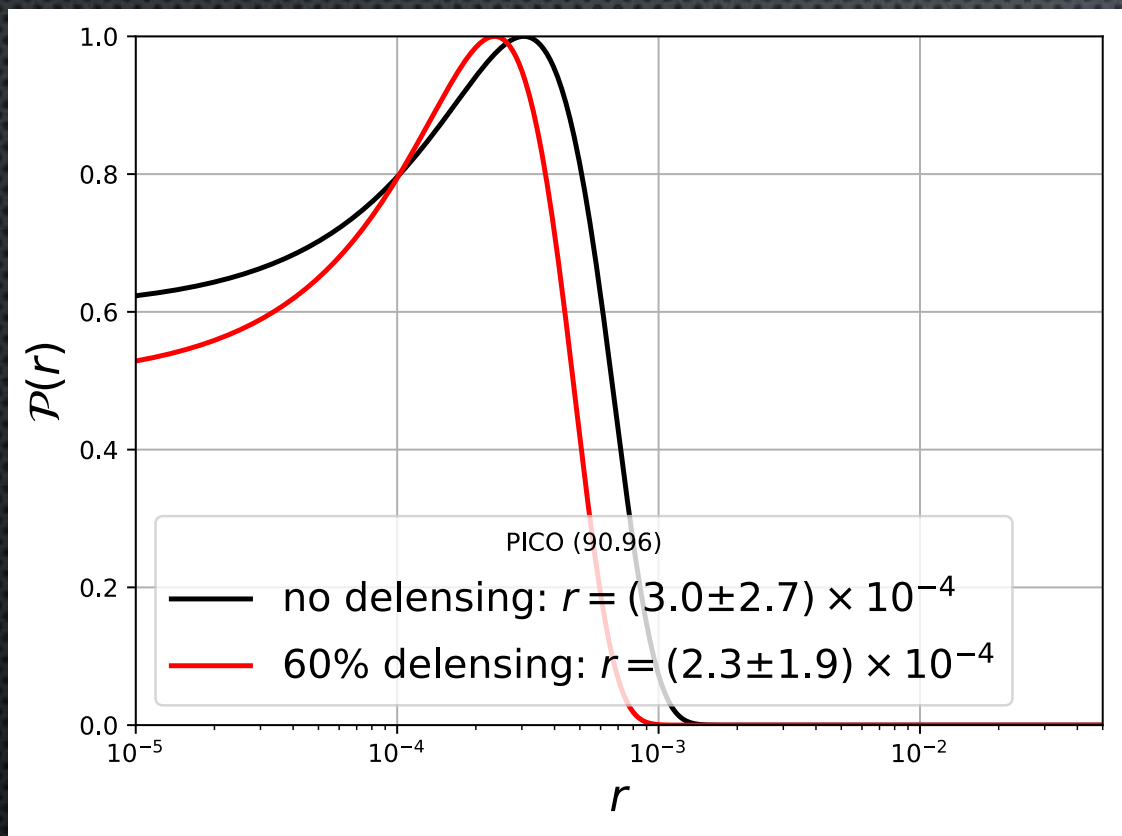


Unbiased recovery of the tensor-to-scalar ratio
Consistent with $r = 0$, $\sigma(r) \simeq 10^{-4}$

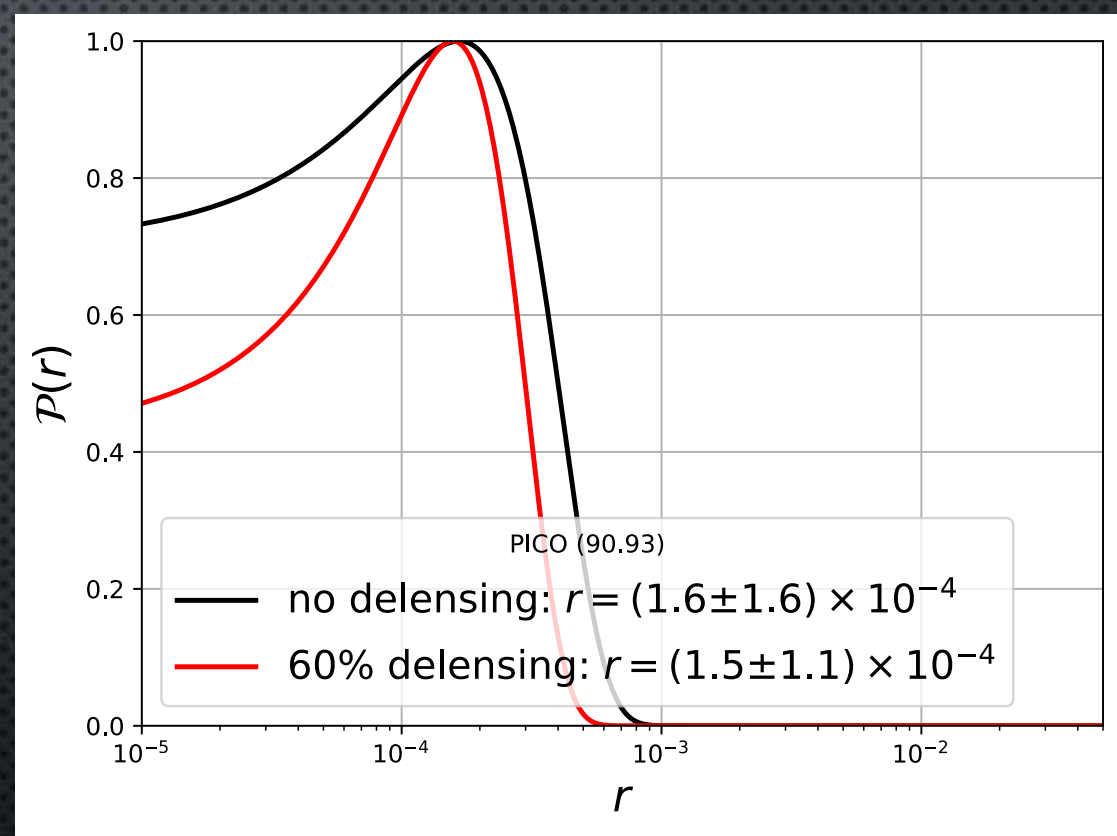
Without LF
43 - 800 GHz

$r = 0$
NILC

Model 96



Model 93

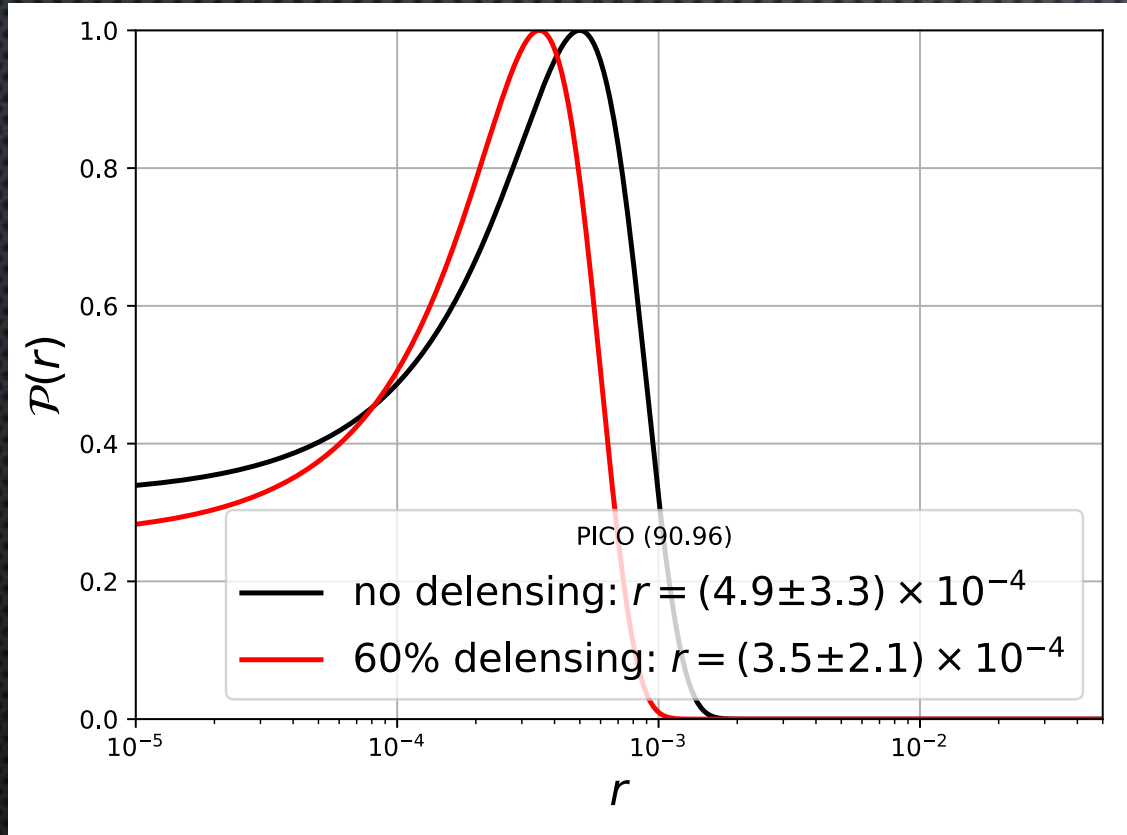


One-sigma bias without high frequencies
exceeding the required performance

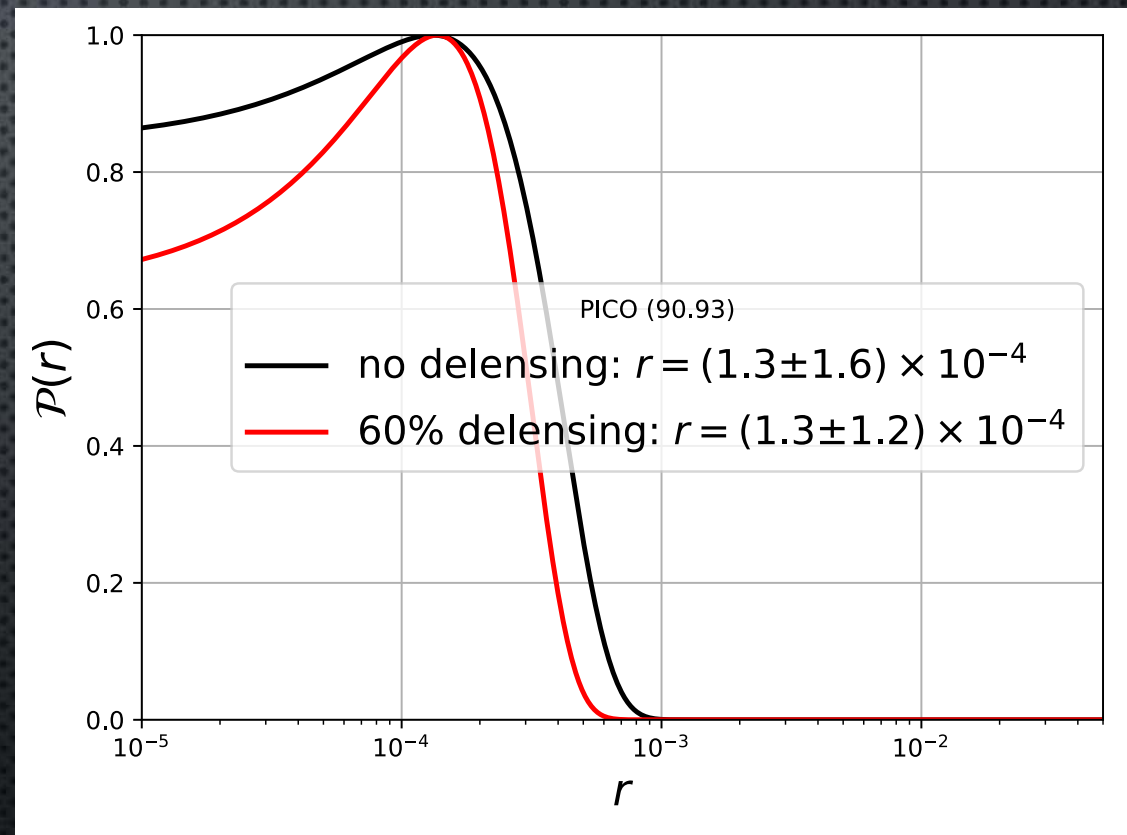
Without HF
21 - 462 GHz

$r = 0$
NILC

Model 96



Model 93

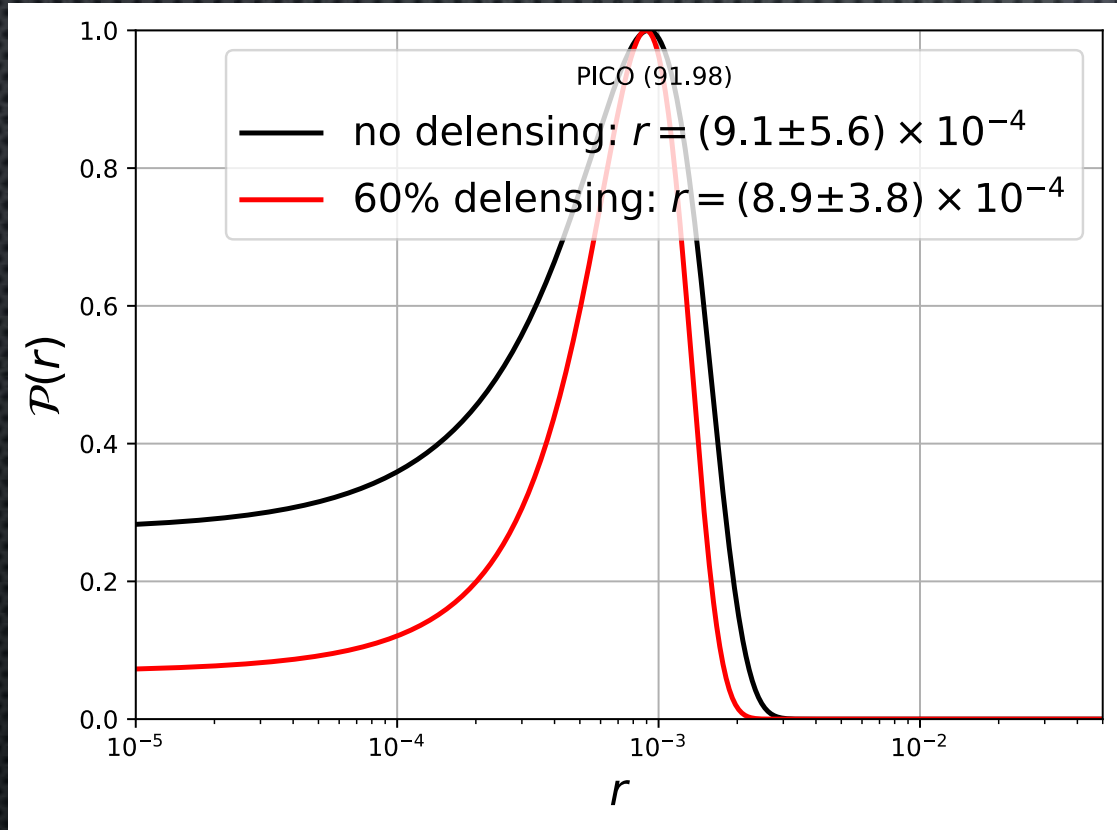


More than one-sigma bias without high frequencies
exceeding the required performance

Baseline
21 - 800 GHz

$r = 0$
NILC

Model 98

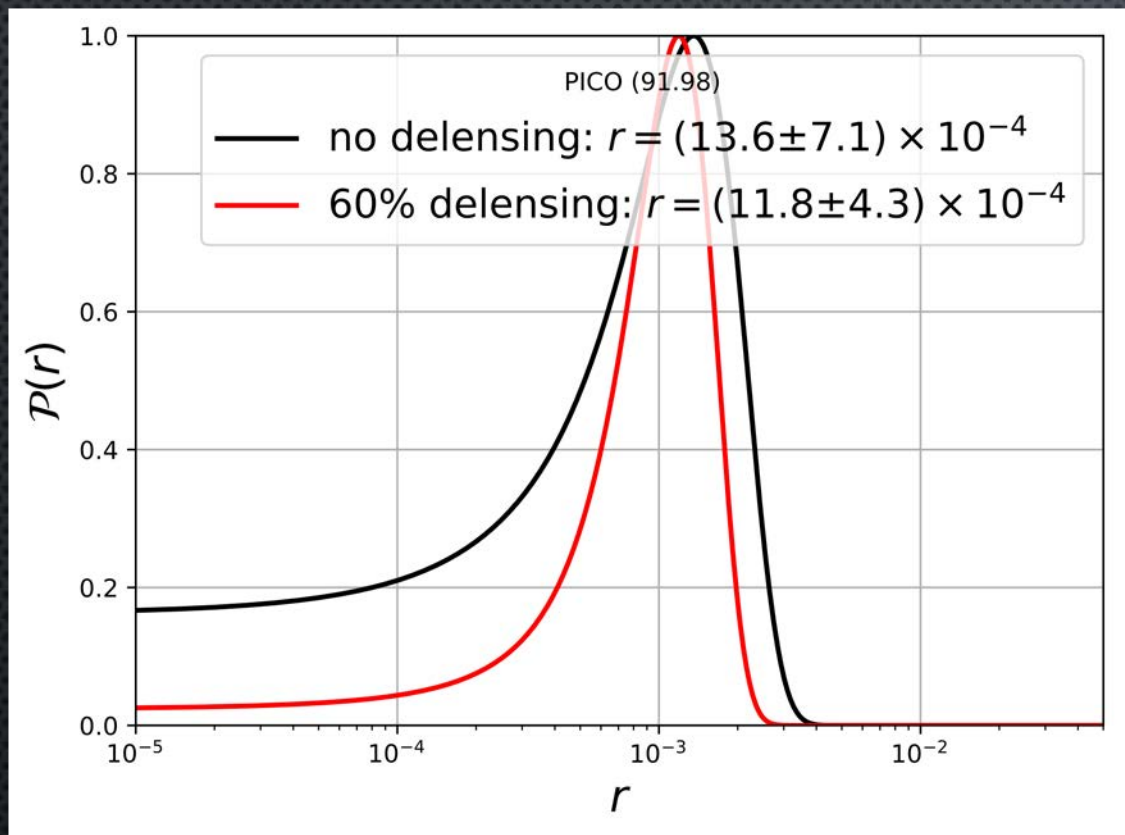


More than one-sigma bias for the MKD sky!
exceeding the required performance

Without LF
43 - 800 GHz

$r = 0$
NILC

Model 98

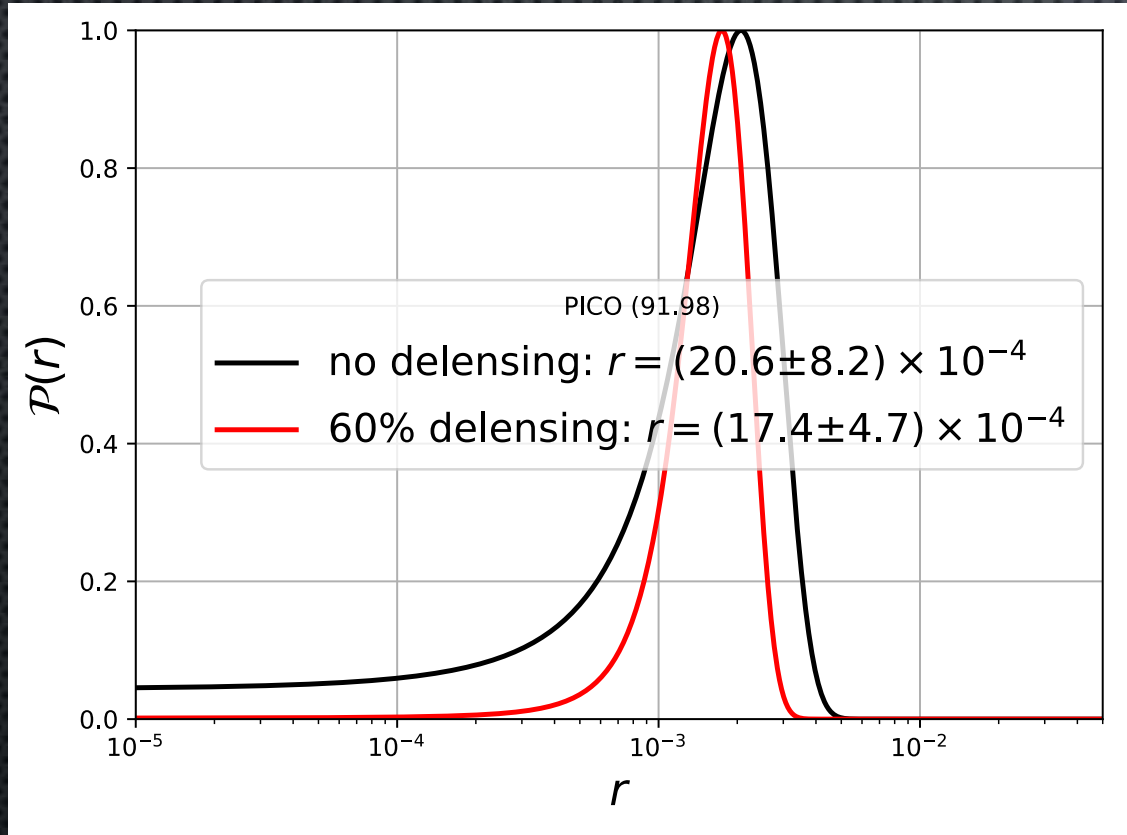


More than two-sigma bias for MKD sky without low frequencies!⁴²
exceeding the required performance

Without HF
21 - 462 GHz

$r = 0$
NILC

Model 98



About three-sigma bias for MKD sky without high frequencies!
exceeding the required performance

Summary

- ❖ PICO allows to control foreground contamination below $r = 5 \times 10^{-4}$
(except for model 98 / MKD)
- ❖ Robustness of NILC results irrespective of foreground sky complexity
(except for model 98 / MKD)
- ❖ Importance of PICO's high/low frequencies to mitigate residual foregrounds

Next steps (ongoing activities)

- ❖ Importance of high frequencies to inform on false detections of r ?
 - *Break spectral degeneracies over different dust models*
 - *Provide chi-square evidence for incorrect dust models*
- ❖ Importance of low frequencies? Do we need high-resolution at low frequency ?
 - *Non-gaussian small scales of synchrotron emission may distort baseline SED models at larger angular scale (higher-order moments / effective curvatures)*
- ❖ Which of increased number of detectors or extended frequency coverage provides more leverage ?
- ❖ Parametric results forthcoming from Commander (Ragnhild Aurlien / Oslo team)

Why PICO, Why Now

- Further progress with CMB requires leaps in sensitivity, foreground characterization, and systematic control.
- PICO is the only instrument with the combination of sky coverage, resolution, frequency bands, and sensitivity to achieve these leaps with one platform.
Figure: R. Flauger
- Analysis of foreground removal efficacy ongoing.

Dark Matter

Evo

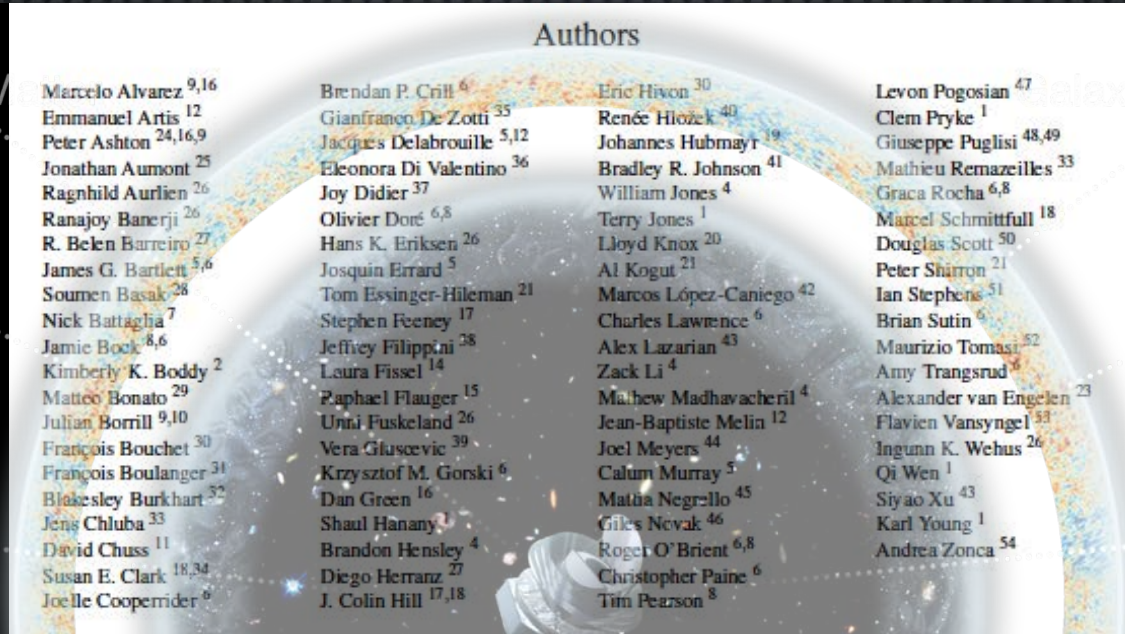
213 Authors and Endorsers

Relativistic Species

Quantum Gravity

Cluster Evolution

Dark Energy



Endorsers

Maximilian Abitbol	Colin Bischoff	Andrei V. Prolov	Chang-Goo Kim	Alessandro Melchiorri	Marco Peloso	Neelima Sehgal	Caterina Umiltà
Zeeshan Ahmed	Sebastian Bocquet	Nicholas Galitzki	Theodore Kisner	Marius Millea	Francesco Piacentini	Sarah Shandera	Rien van de Weygaert
David Alonso	J. Richard Bond	Silvia Galli	Arthur Kosowsky	Amber Miller	Michel Piat	Erik Shirokoff	Vincent Vennin
Mustafa A. Amin	Ken Ganga	Ken Ganga	Ely Koveč	Joseph Mohr	Giampaolo Pisano	Anže Slosar	Licia Verde
Adam Anderson	Sean Bryan	Tuhin Ghosh	Kerstin Kunze	Lorenzo Moncelsi	Nicolas Ponthieu	Tarun Souradeep	Patricio Vielva
James Annis	Carlo Burigana	Sunil Golwala	Guilaine Lagache	Pavel Motloch	Giuseppe Puglisi	Suzanne Staggs	Abigail Vieregg
Jason Austermann	Giovanni Cabass	Riccardo Gualtieri	Daniel Lenz	Tony Mroczkowski	Benjamin Racine	George Stein	Jan Vrtilek
Carlo Baccigalupi	Robert Caldwell	Jon E. Gudmundsson	François Levrier	Suvodip Mukherjee	Christian Reichardt	Radek Stompom	Benjamin Wallisch
Darcy Barron	John Carlstrom	Nikhel Gupta	Marilena Loverde	Philip Lubin	Christophe Ringeval	Rashid Sunyaev	Benjamin Wandelt
Ritoban Basu Thakur	Xingang Chen	Nils Halverson	Juan Macias-Perez	Johanna Nagy	Karwan Rostem	Aritoki Suzuki	Gensheng Wang
Elia Battistelli	Francis-Yan Cyr-Racine	Kyle Helson	Nazareno Mandolese	Federico Nati	Anirban Roy	Eric Switzer	Scott Watson
Daniel Baumann	Paolo de Bernardis	Sophie Henrot-Versille	Enrique Martínez-González	Paolo Natoli	Jose-Alberto Rubino-Martin	Andrea Tartari	Edward J. Wollack
Karim Benabed	Tijmen de Haan	Thiem Hoang	Carlos Martins	Michael Niemack	Matarrese Sabino	Grant Teply	Zhilei Xu
Bradford Benson	C. Darren Dowell	Kevin M. Huffenberger	Silvia Masi	Elena Orlando	Maria Salatino	Peter Timbie	Siavash Yasini
Paolo de Bernardis	Cora Dvorkin	Kent Irwin	Tomotake Matsumura	Bruce Partridge	Benjamin Saliwanchik	Matthieu Tristram	
Marco Bersanelli	Chang Feng	Marc Kamionkowski	Darragh McCarthy				
Federico Bianchini	Ivan Soares Ferreira	Reijo Keskkitalo	P. Daniel Meerburg				
Daniel Bilbao-Ahedo	Aurelien Fraisse	Rishi Khatri					

Interstellar Dust

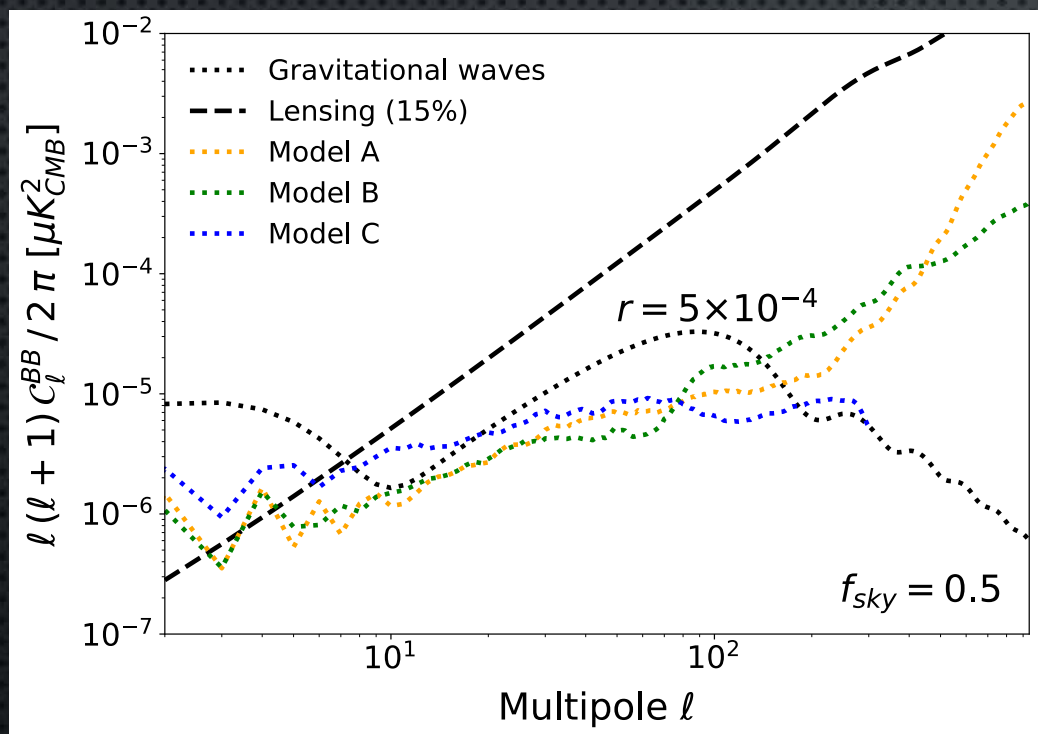
Cosmic Birefringence

Backup

Two years ago...

Probe class mission study submitted to
NASA and Astro2020 Decadal Panel

[arXiv:1902.10541](https://arxiv.org/abs/1902.10541)



GNILC

- Foreground residuals controlled below $r = 5 \times 10^{-4}$ over the whole range of multipoles $2 \leq \ell \leq 200$

- Irrespective of the complexity of the foregrounds:

Two dust MBBs (model A/92) ; Non-MBB physical dust (model B/93) ; MHD with line-of-sight MBBs (model C/96)