Largest Angular Scale CMB E-mode Polarization Measurement with CLASS

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mm Universe, Chicago, 2025

Johns Hopkins University

NSF

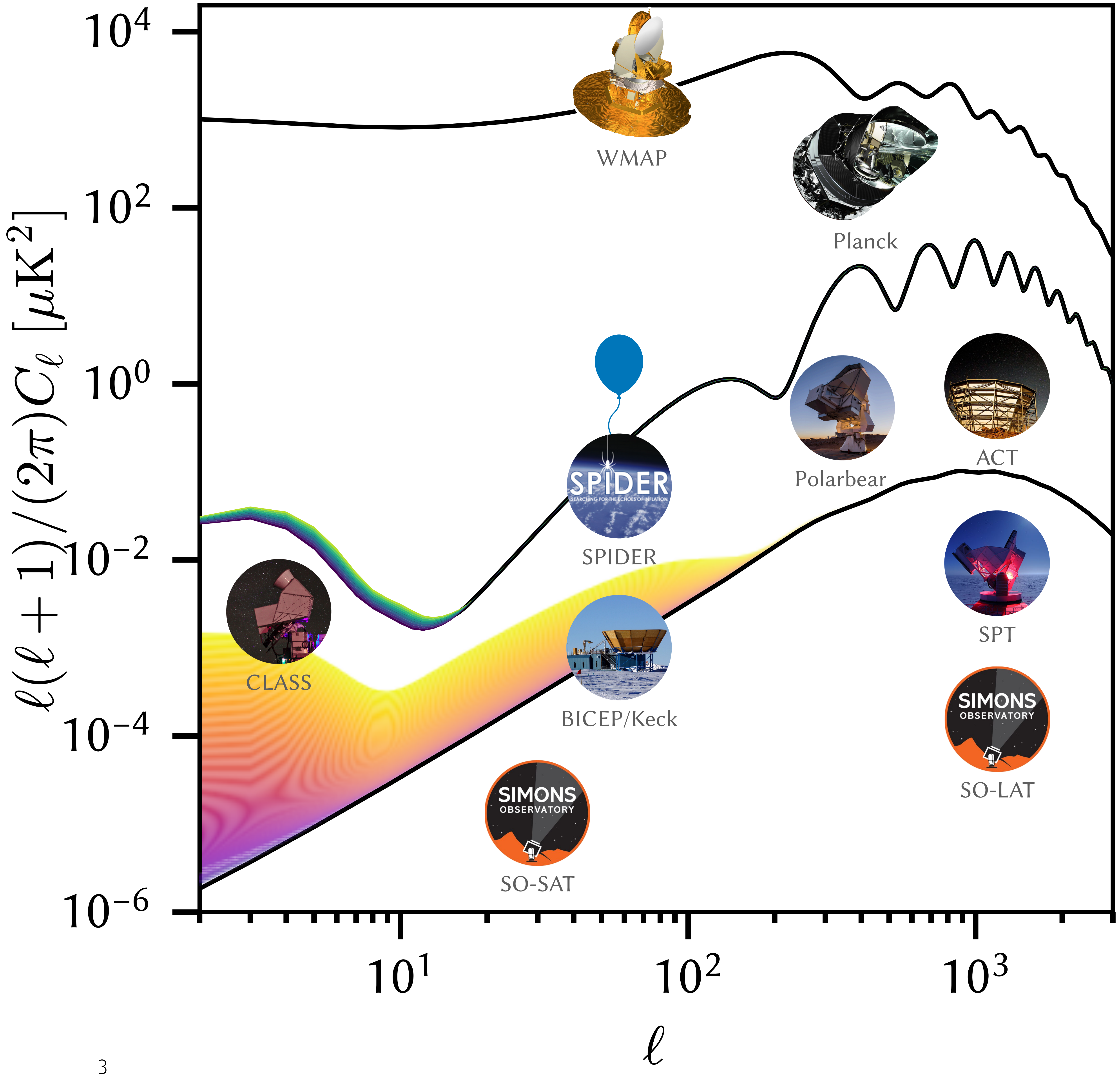
NASA

NIST

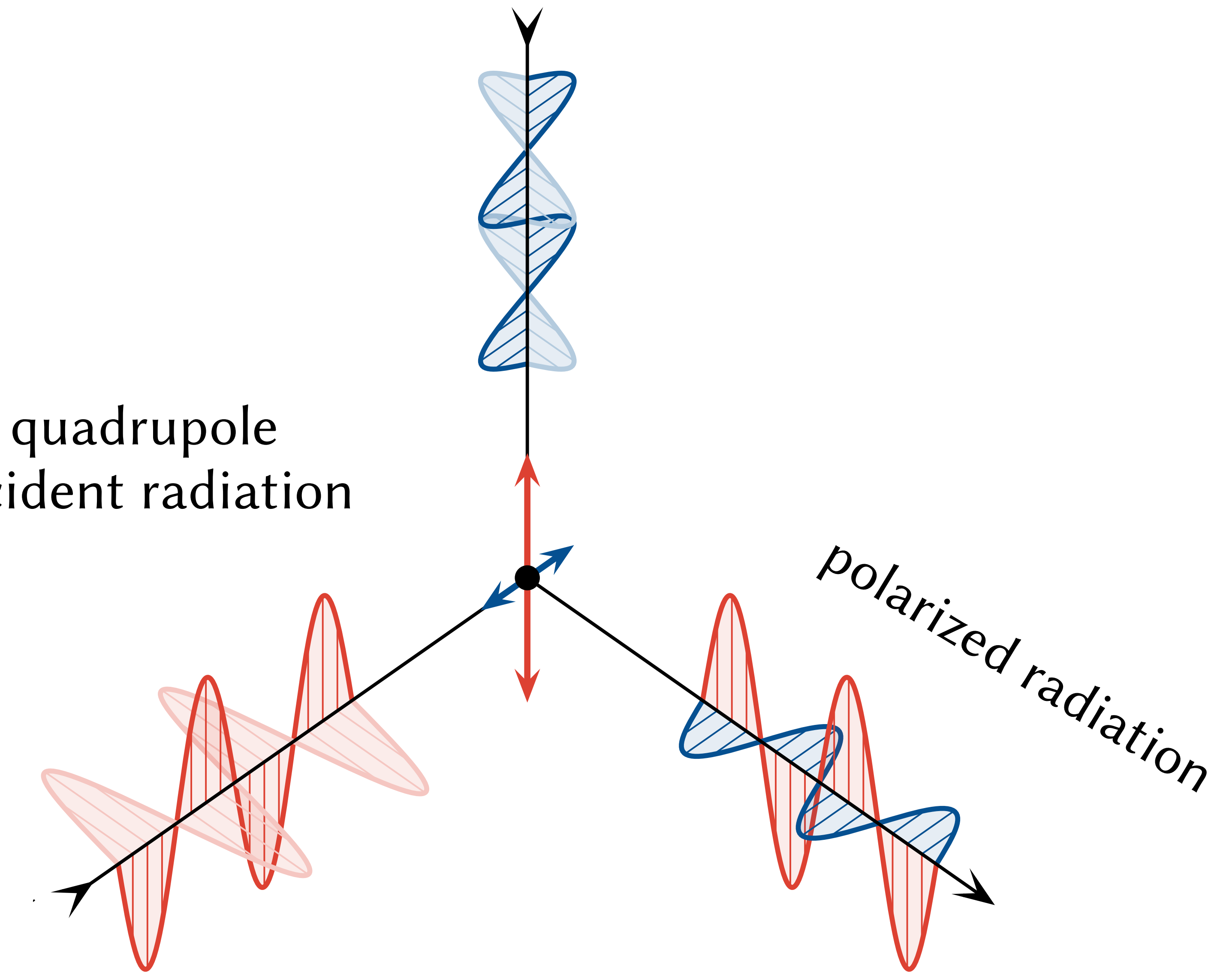
Cerro Toco as of 2021. M.Petroff

Status of the Field

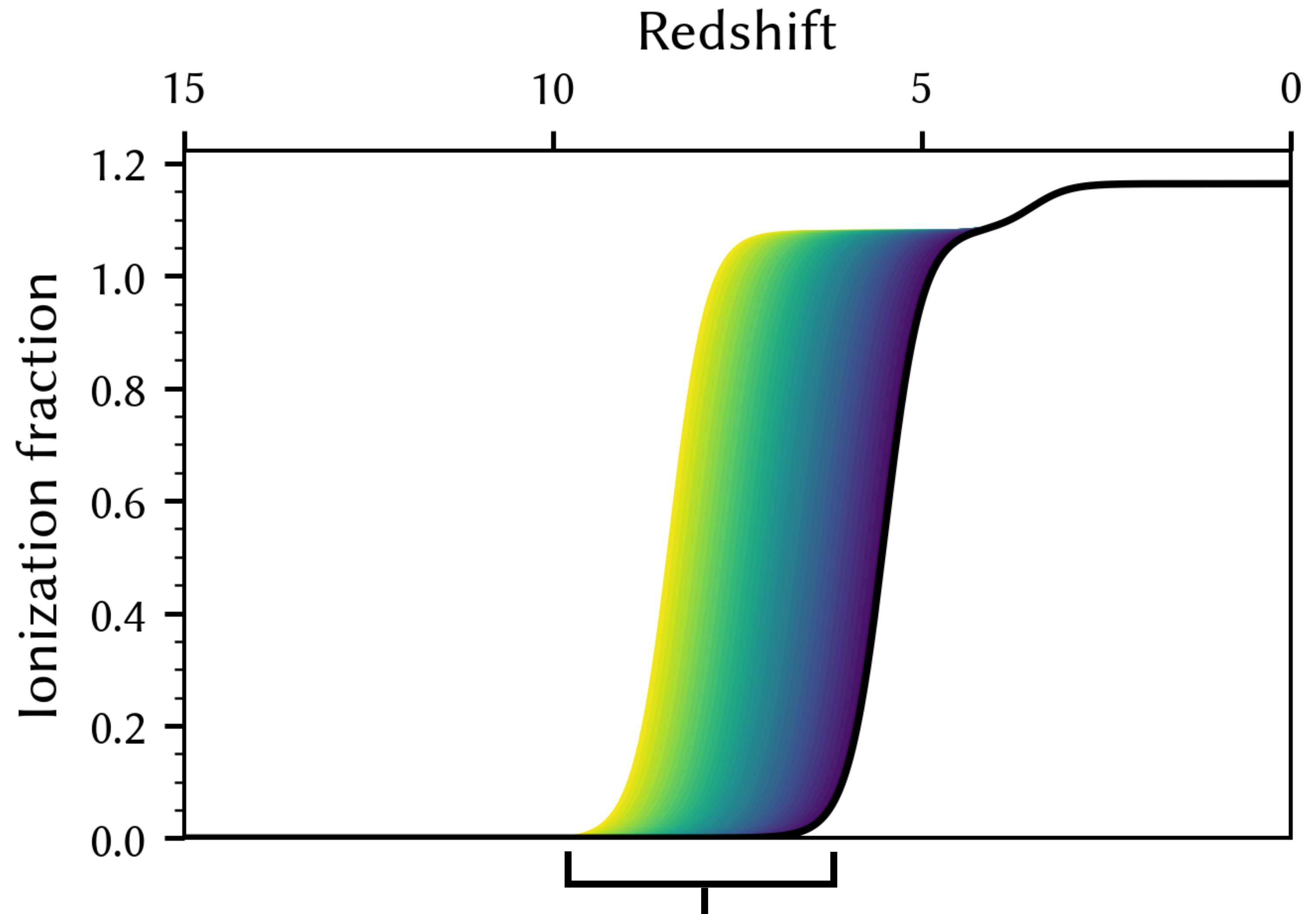
- Space missions achieved exquisite sensitivity in CMB *temperature anisotropy* but lack sensitivity in polarization.
- Ground-based experiments excel in polarization measurement at intermediate to small angular scales.
- CLASS targets the largest scale ($\ell \leq 30$) polarization to study *reionization* and probe *inflation* signals.
- On the horizon: *Taurus, LiteBird, CMB-S4...*



Reionization optical depth

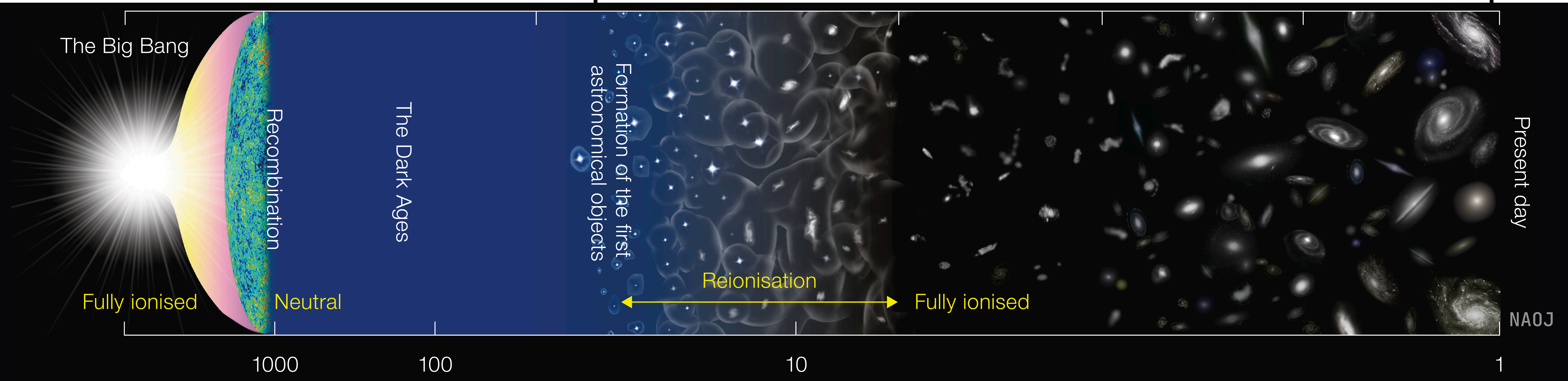


Thomson scattering



Thomson scattering of free electrons leaves an imprint on the large scale CMB E-mode polarization.

The amplitude of this signal is determined by the *reionization optical depth*: $\tau = \int \sigma_T n_e(t) c \mathrm{d}t$



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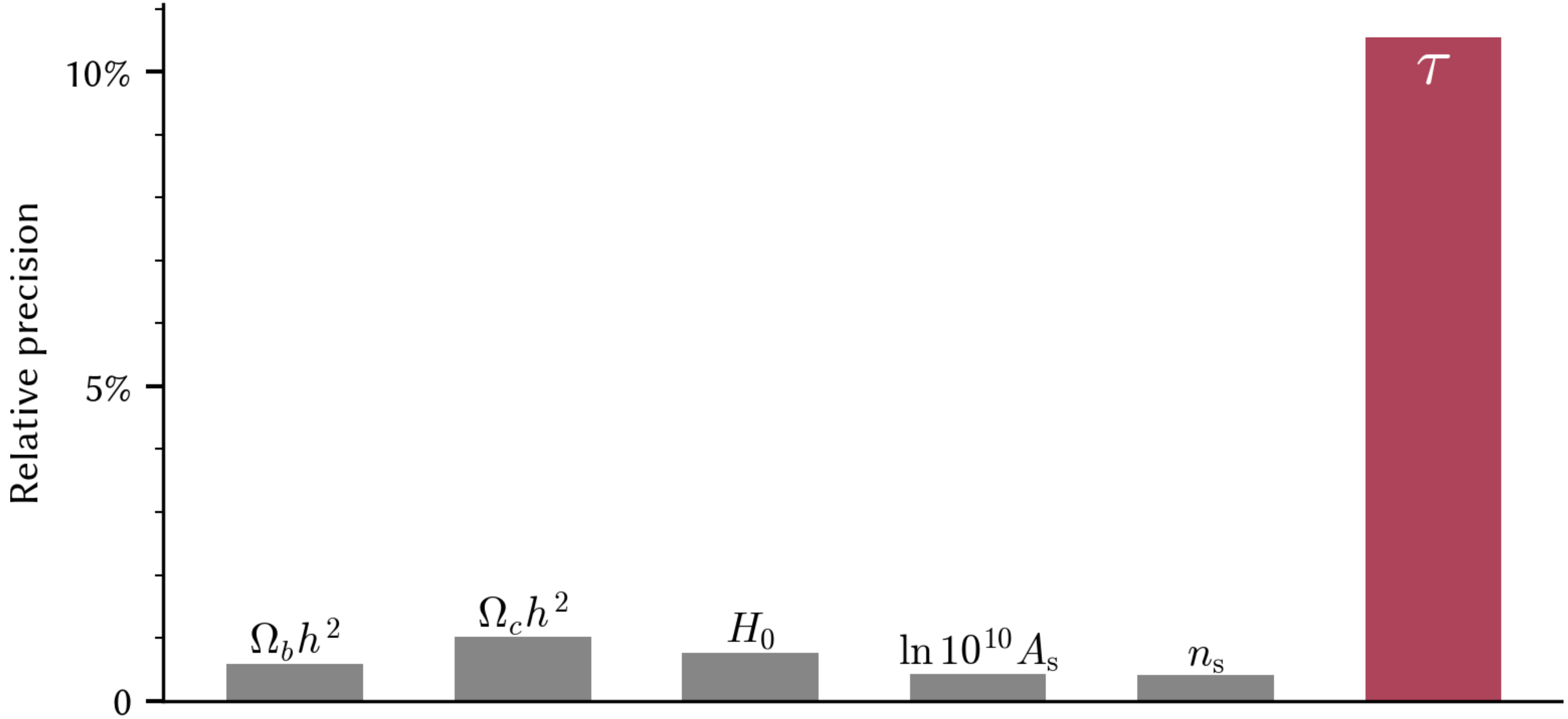

Planck (PR4) constraints on ΛCDM parameters
a.k.a. the state-of-the-art of *"precision cosmology"*

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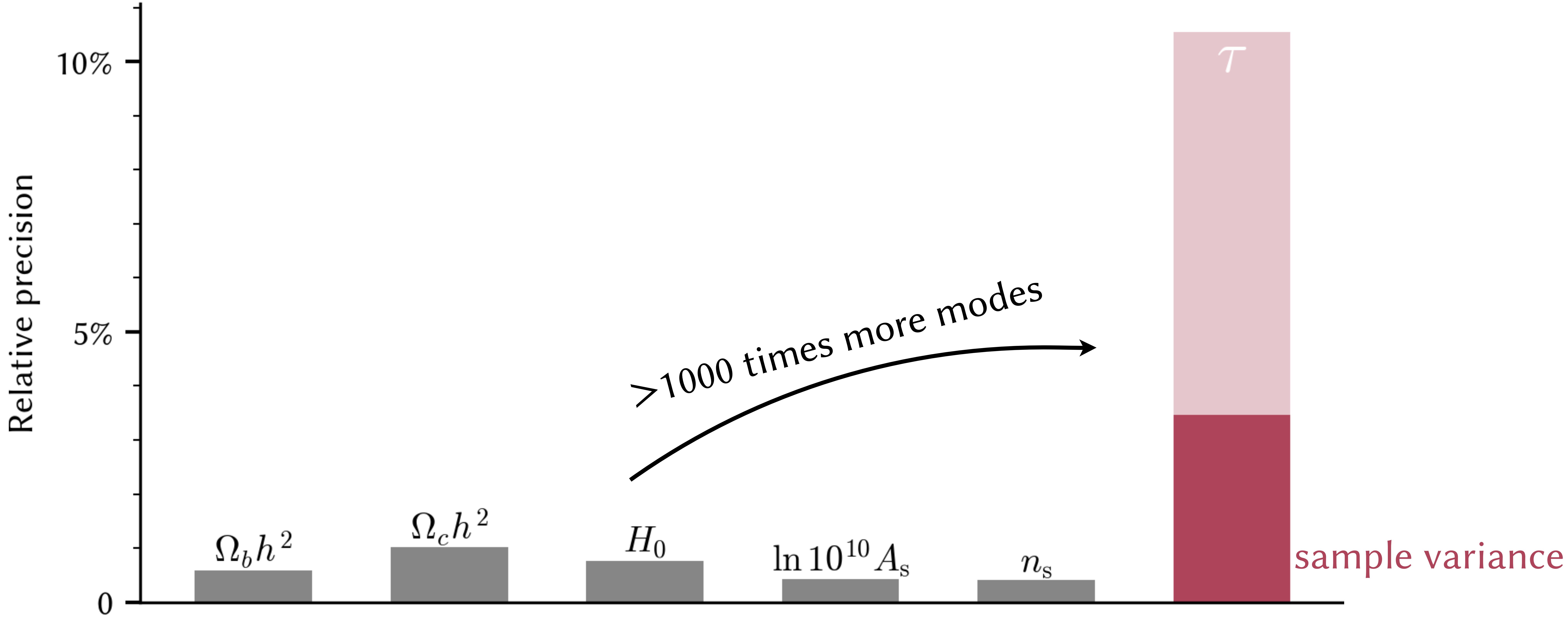

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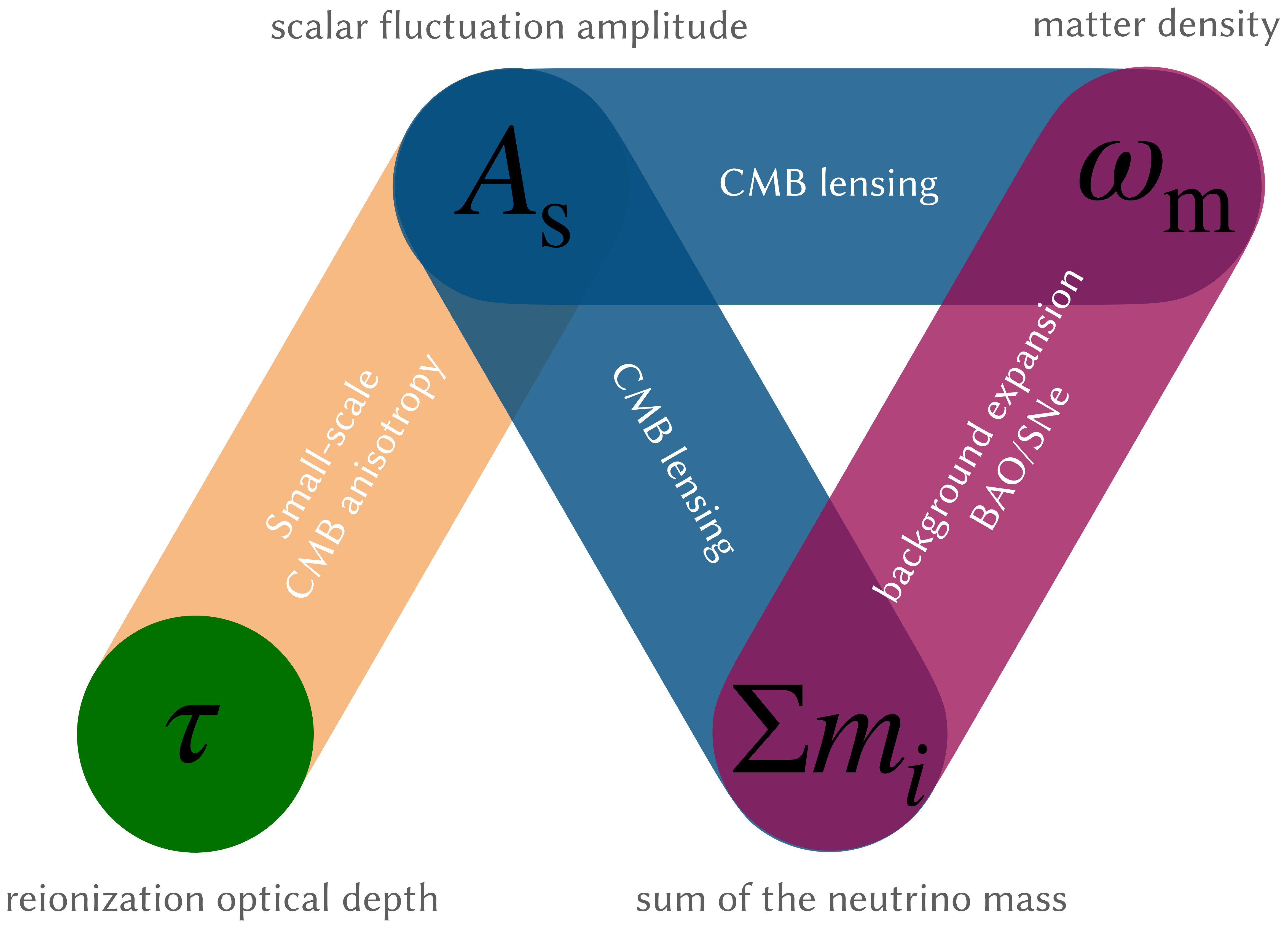

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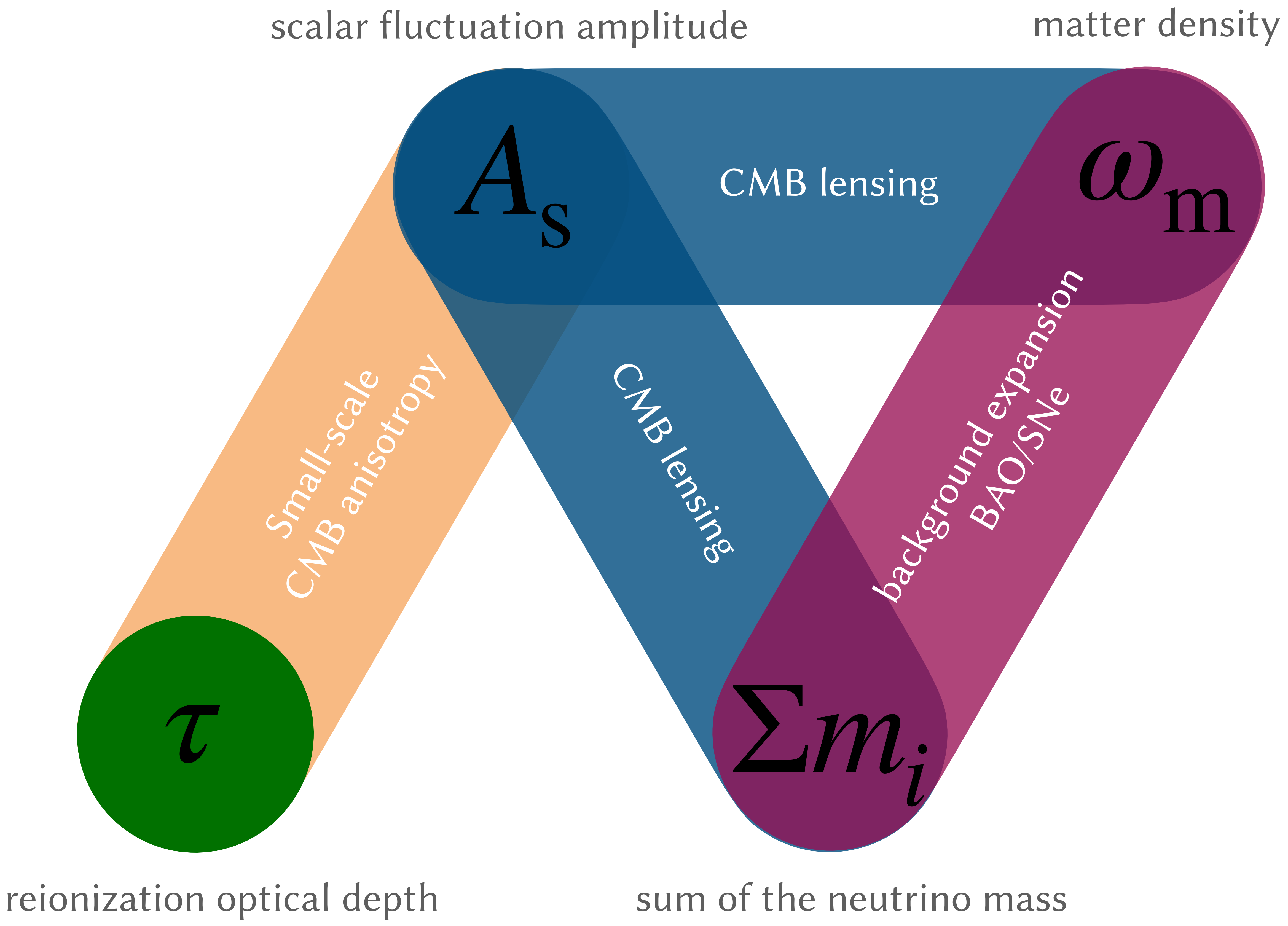

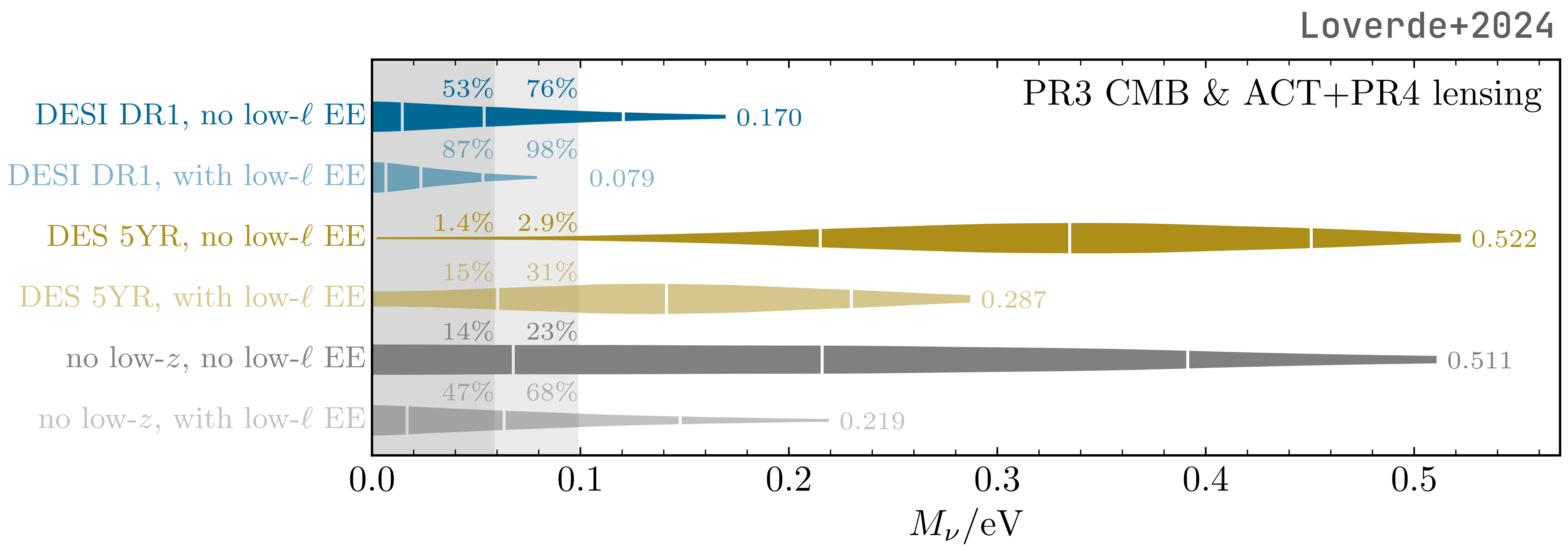

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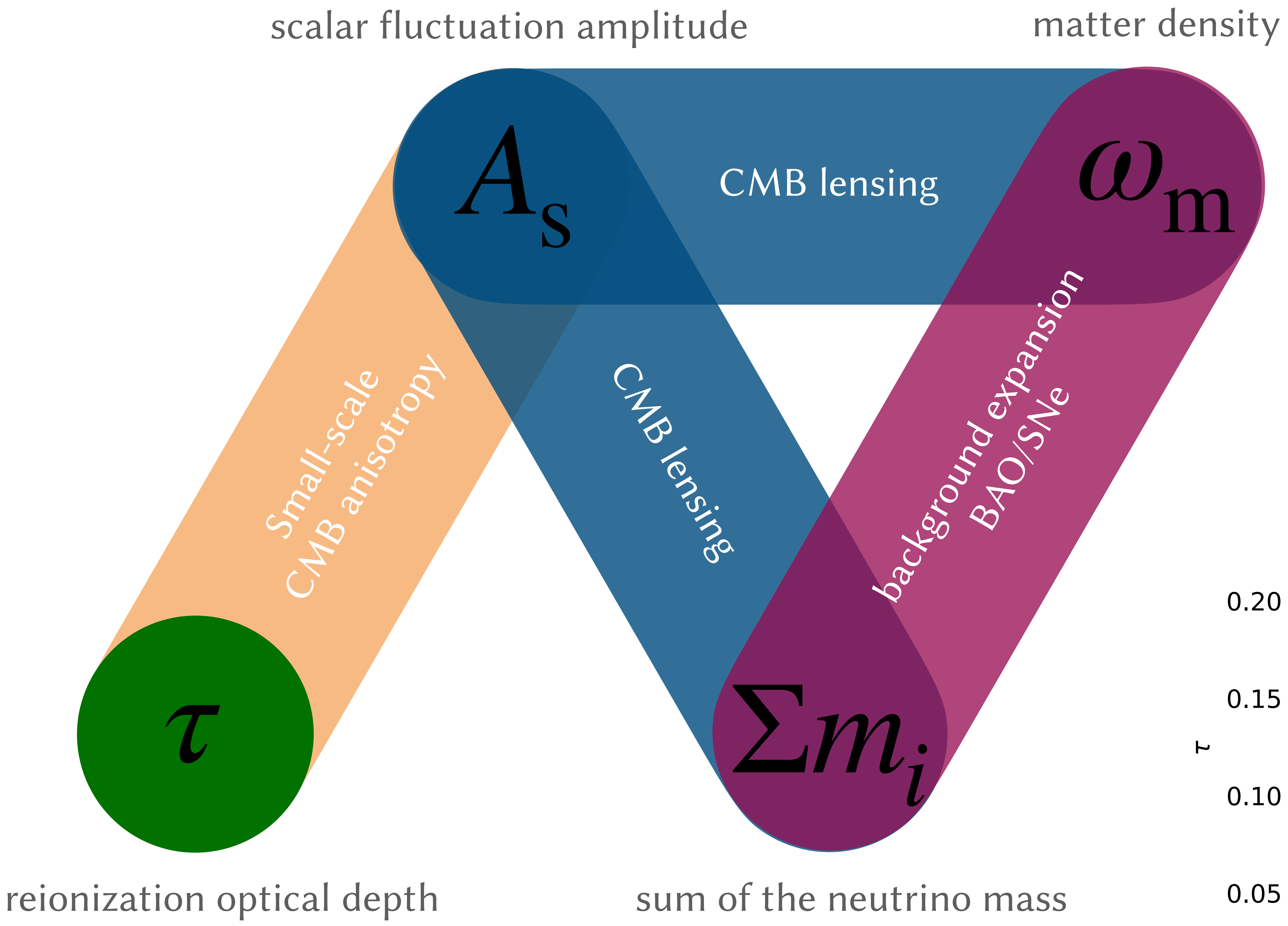
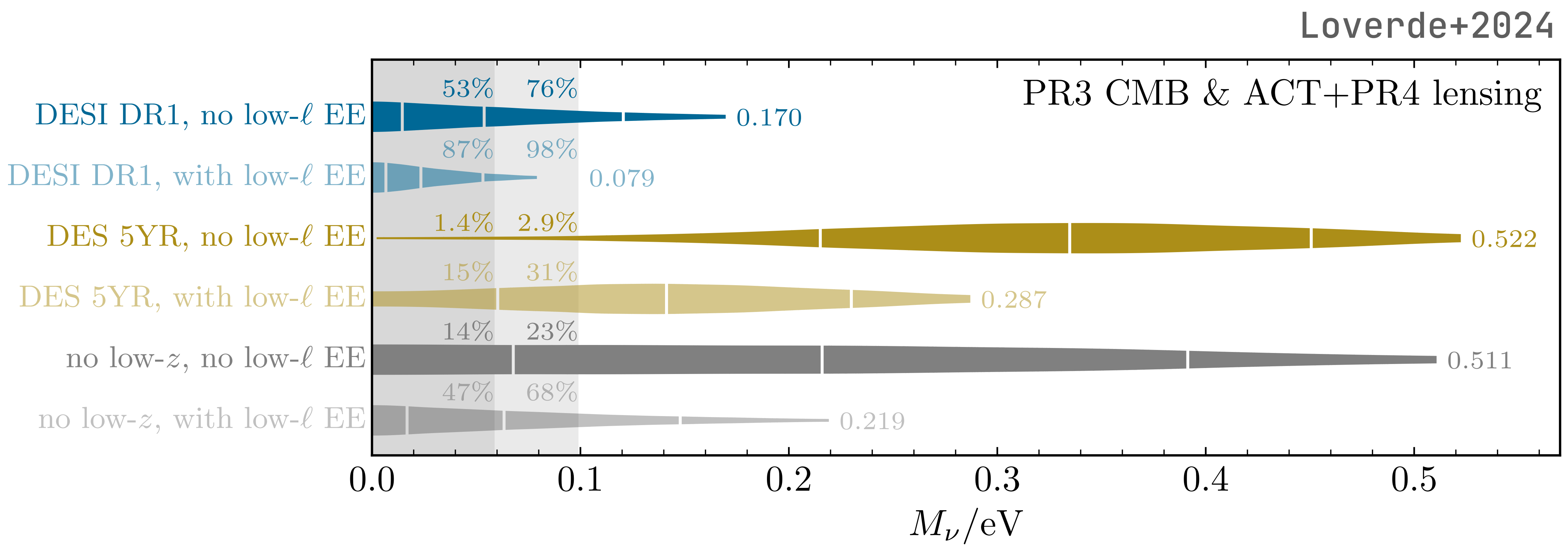
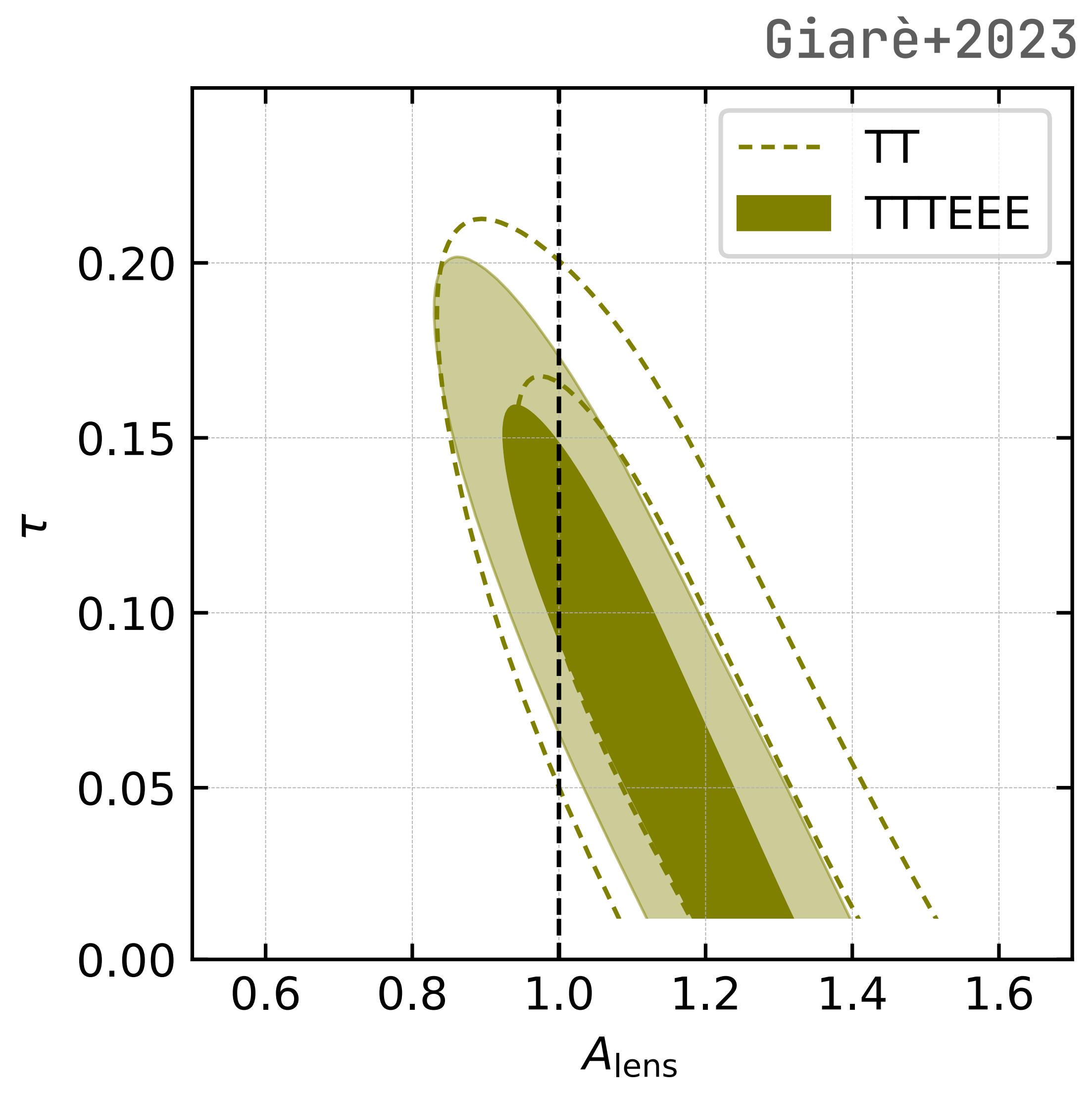




Planck Pre-DESI
$\tau = 0.08 \pm 0.012$



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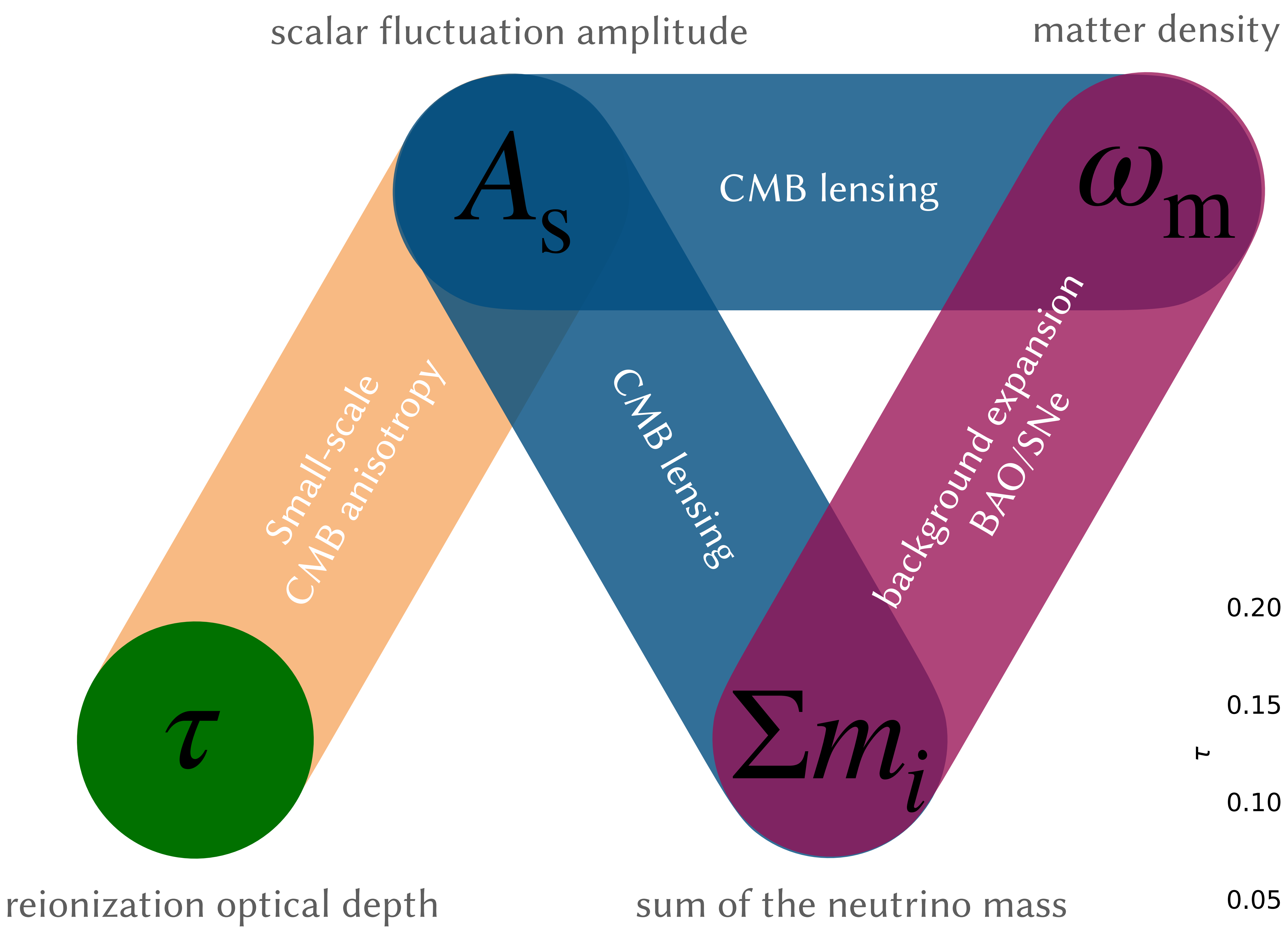
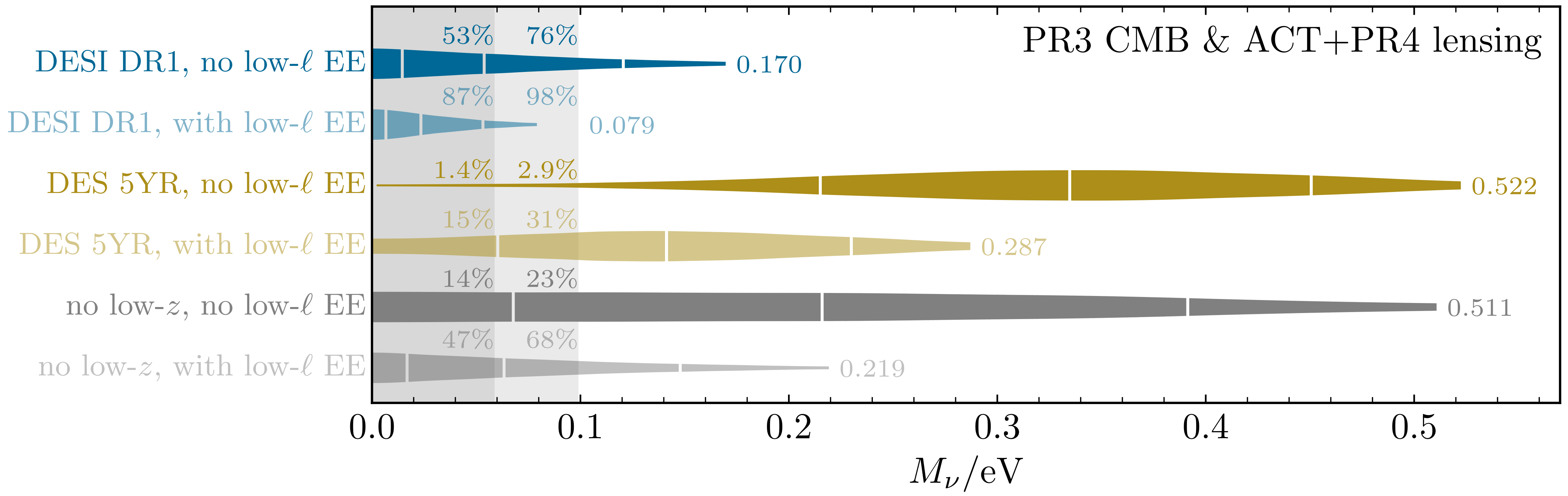


Loverde+2024



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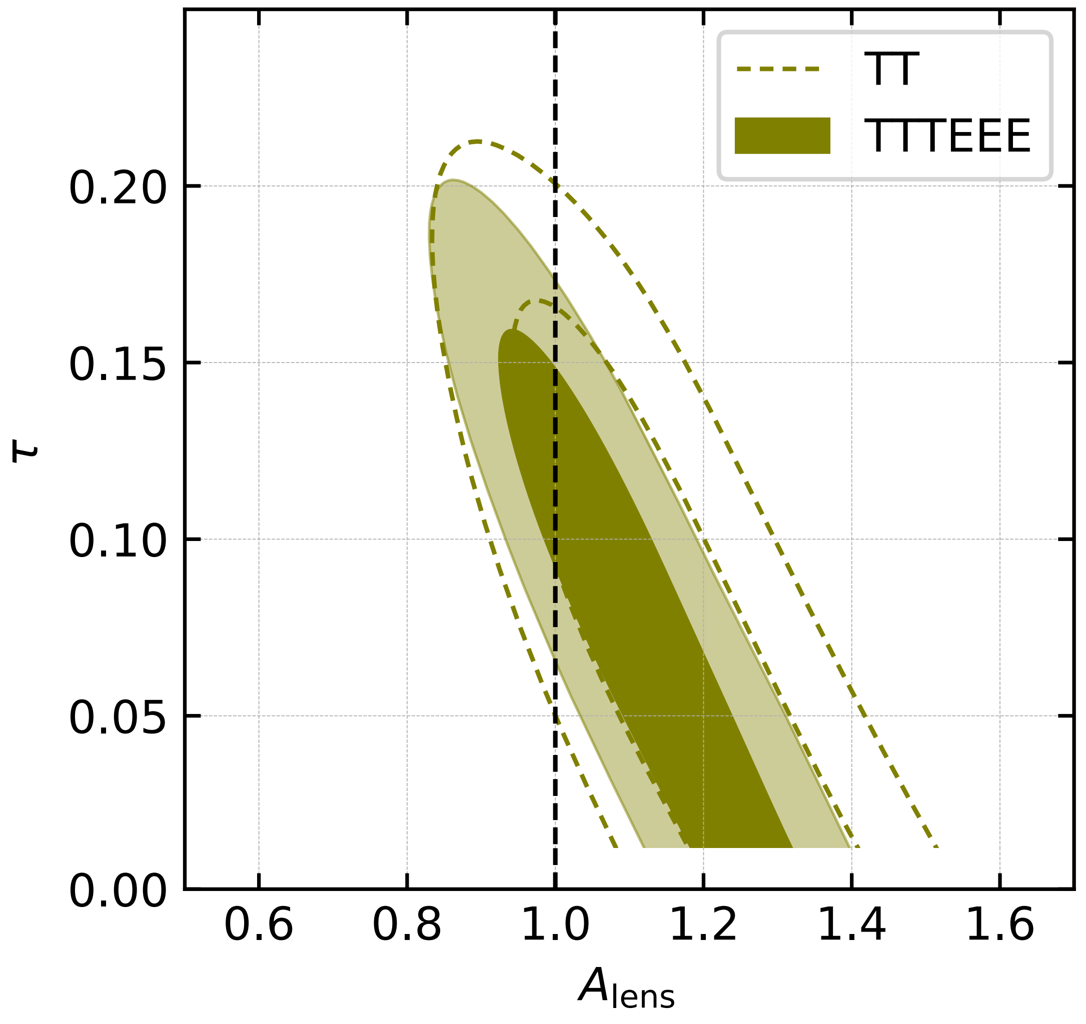
Giarè+2023



Planck+DESI
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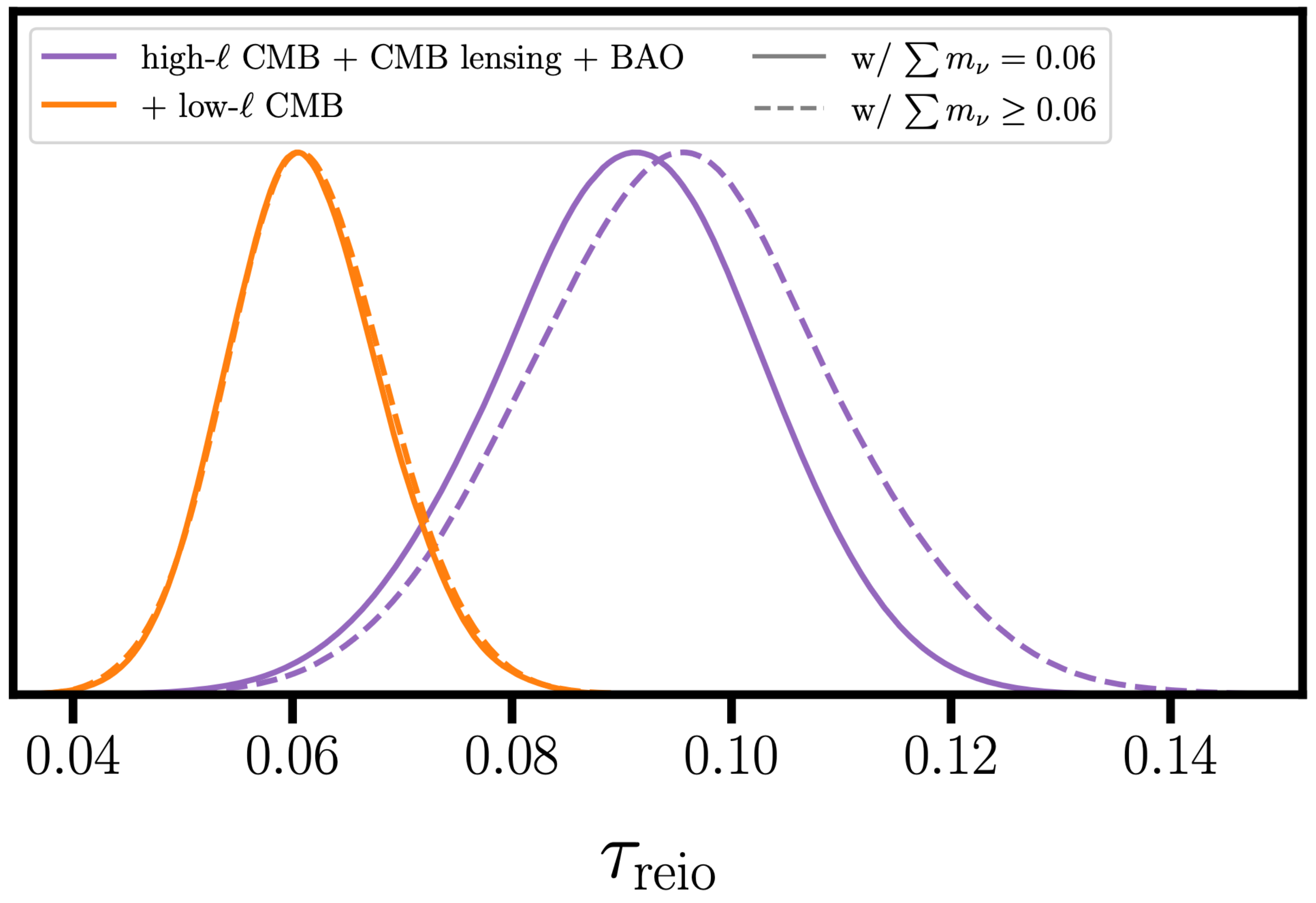
Sailer+2025/Jhaveri+2025



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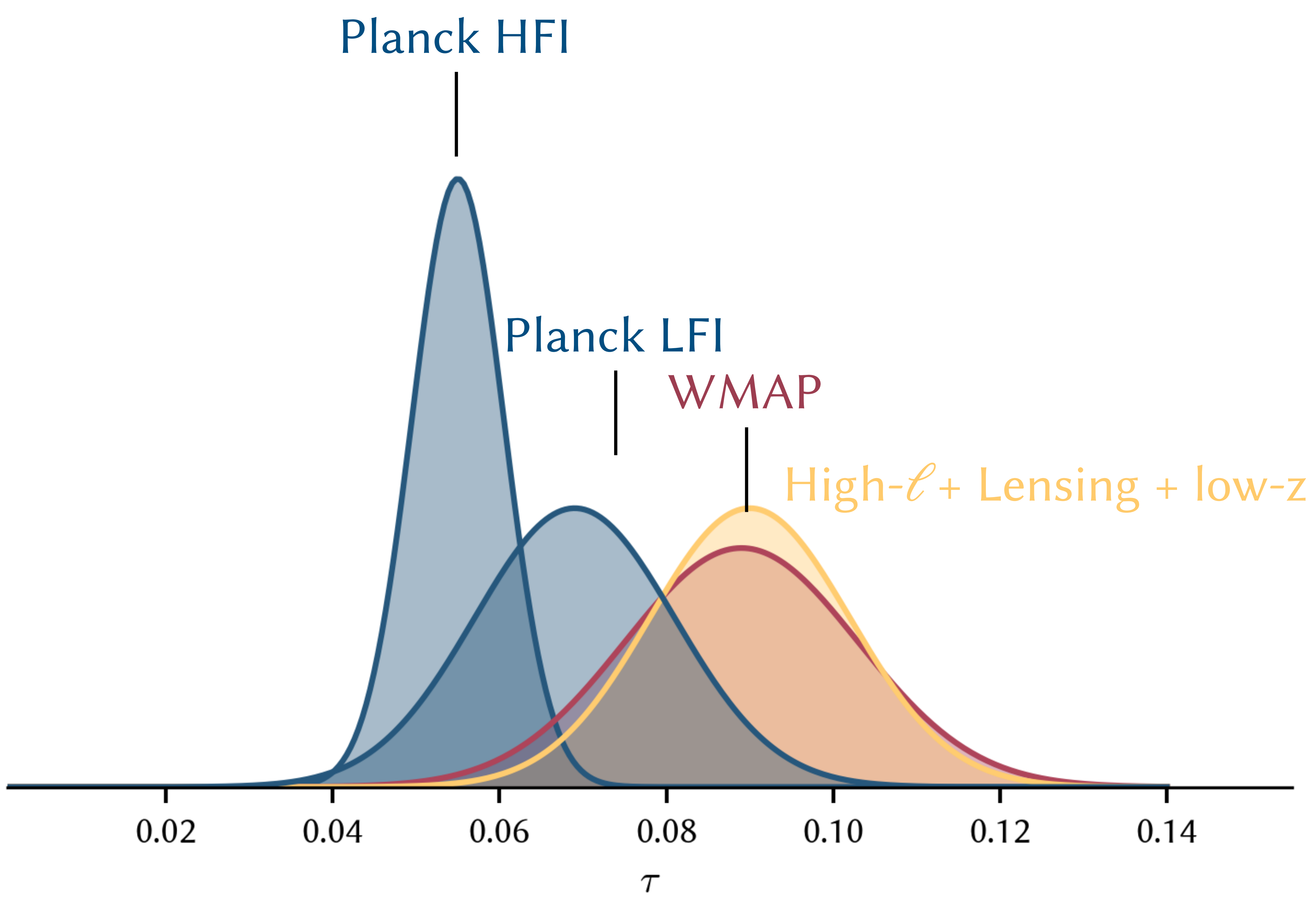

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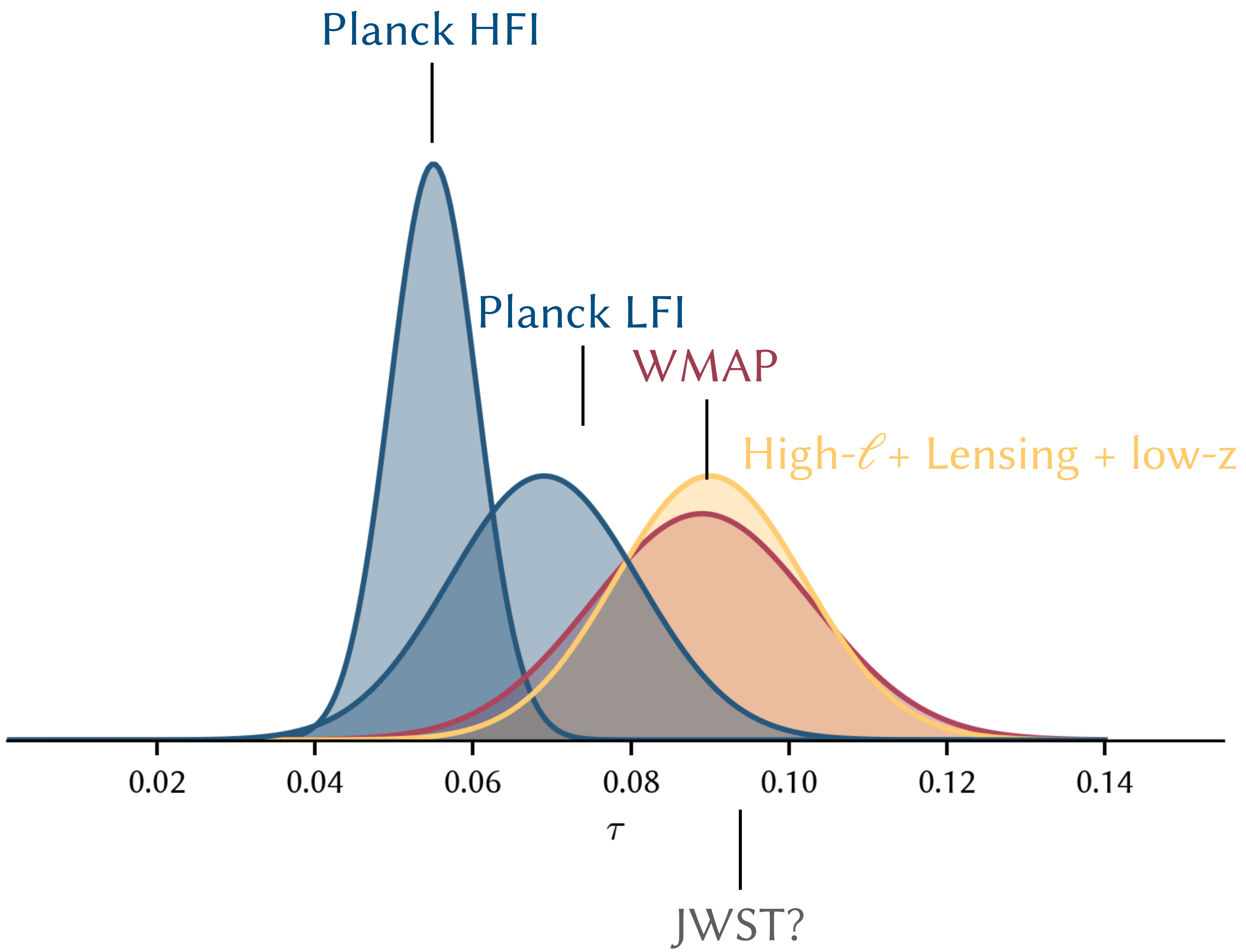
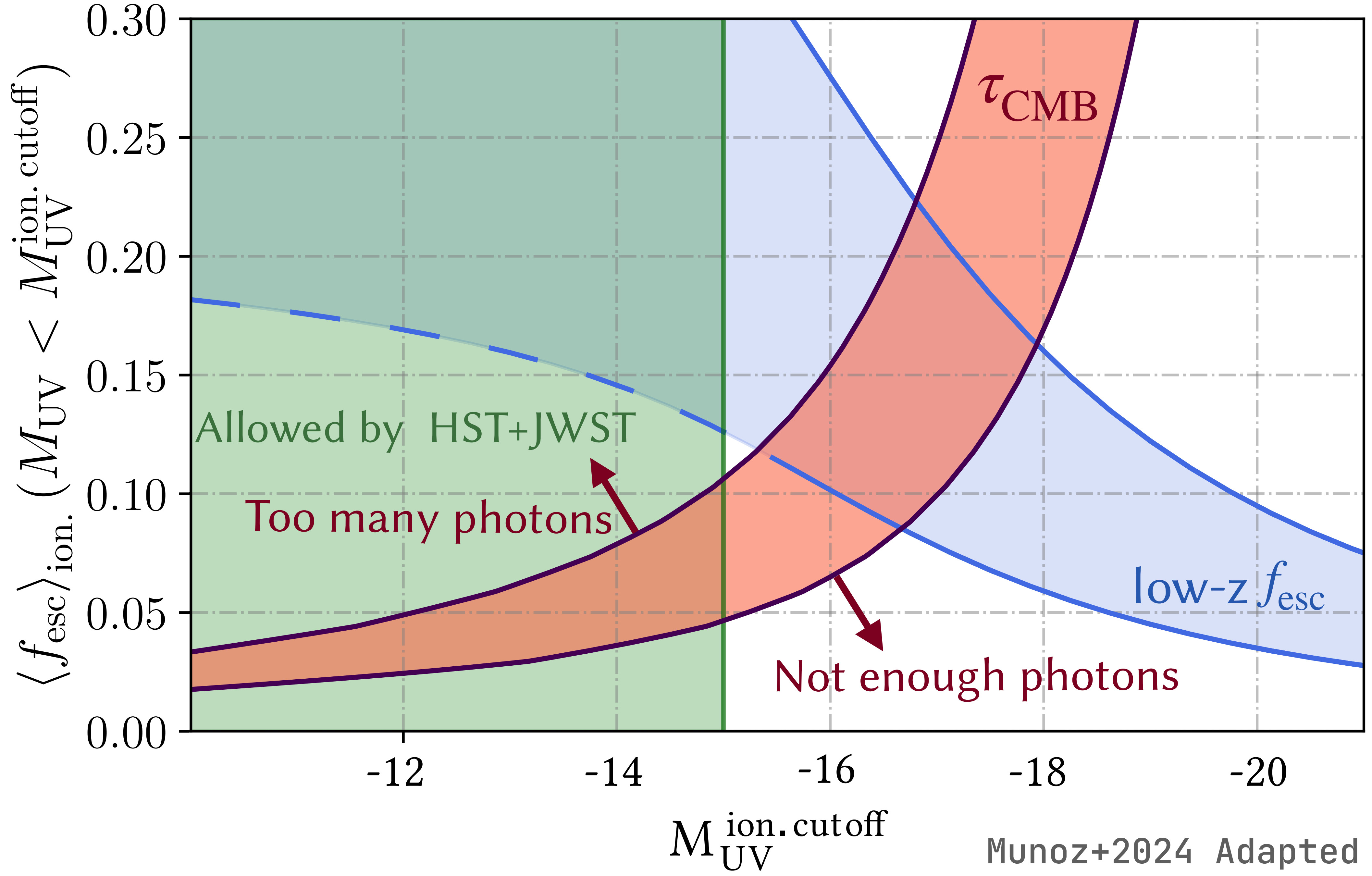
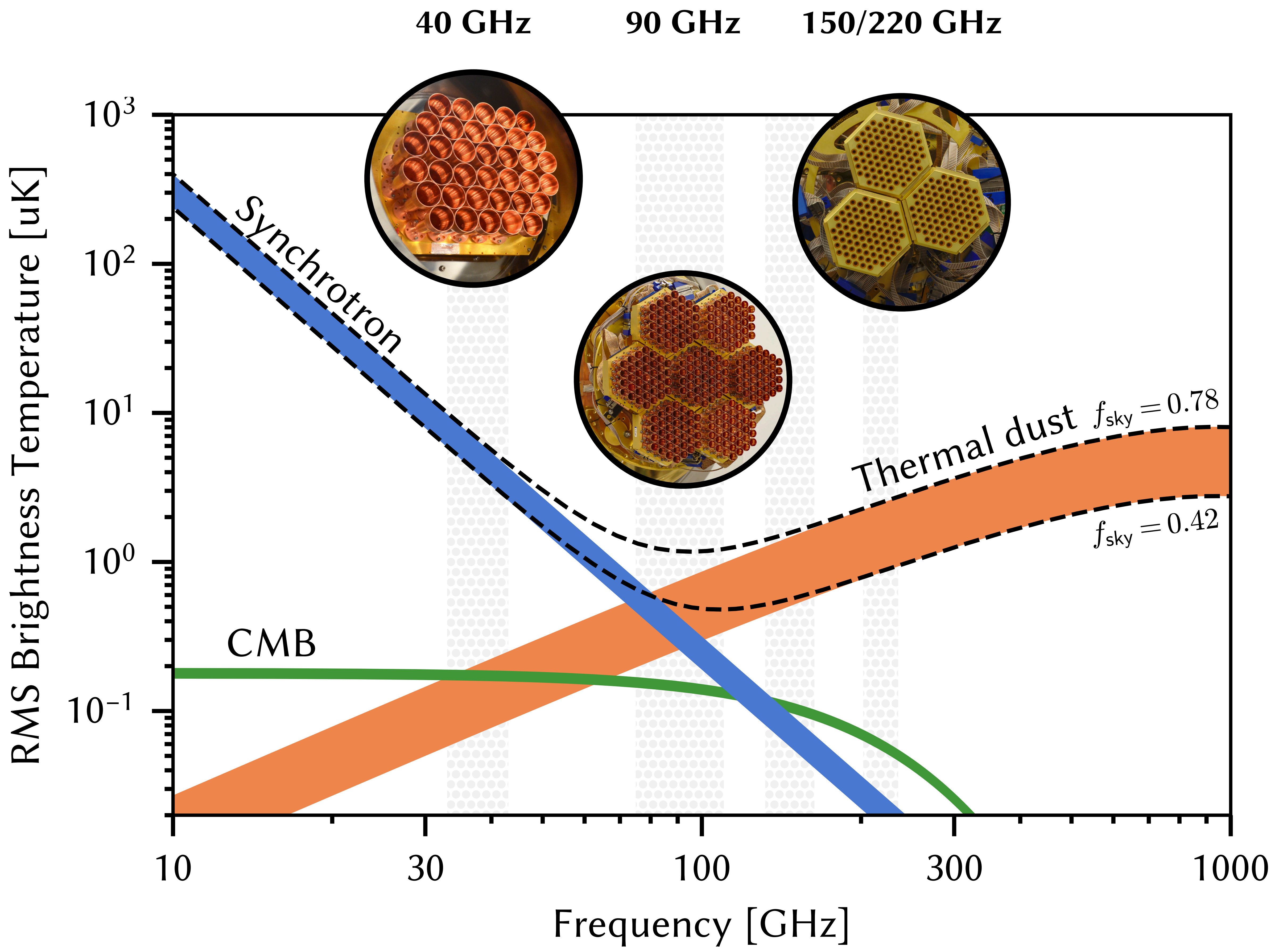




Large-scale challenge and CLASS's strategy

- Access to large fraction (75%) of the sky.
- Multiple frequencies for Galactic foreground mitigation.



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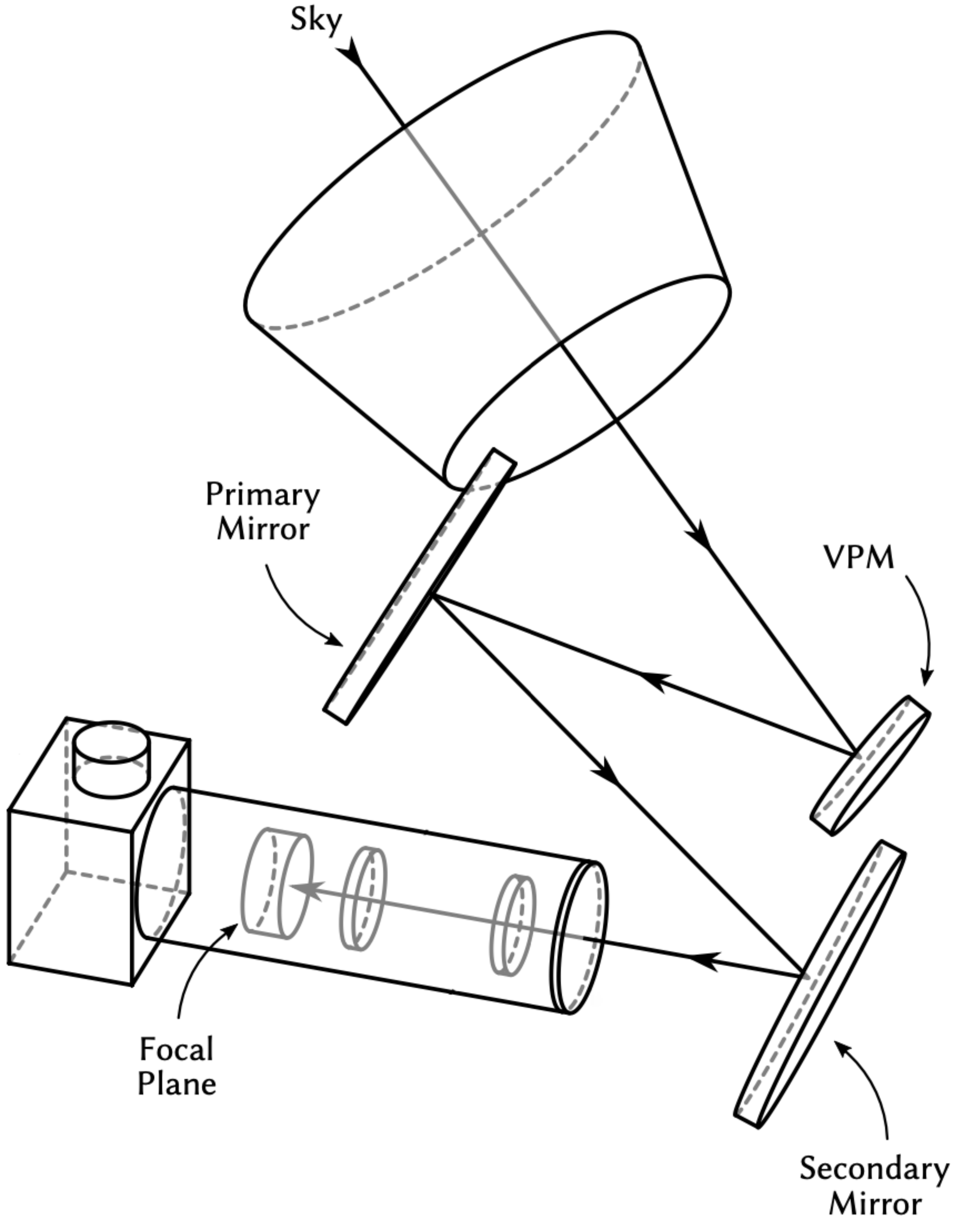
  - Suppress of unpolarized atmospheric noise.
  - Reduce systematics from detector pairings.
  - Unique sensitivity to circular polarizations.



M. Petroff

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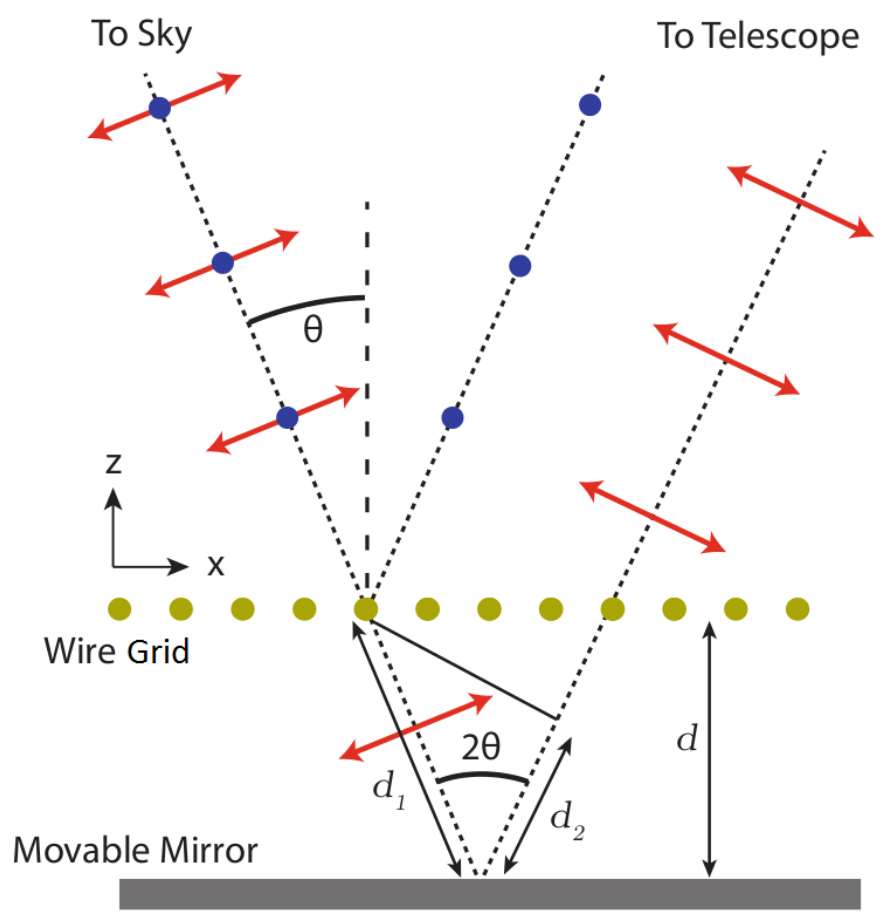

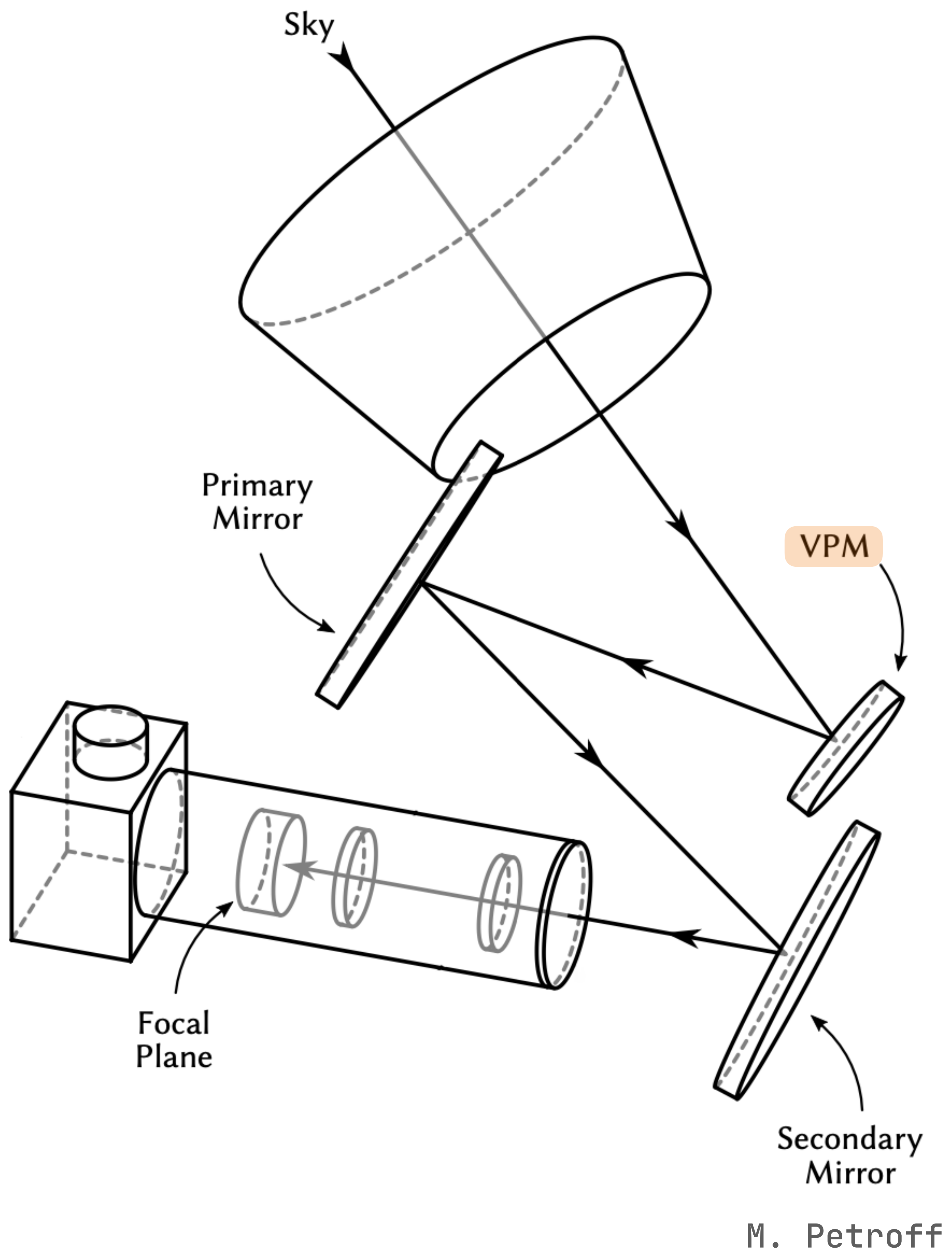

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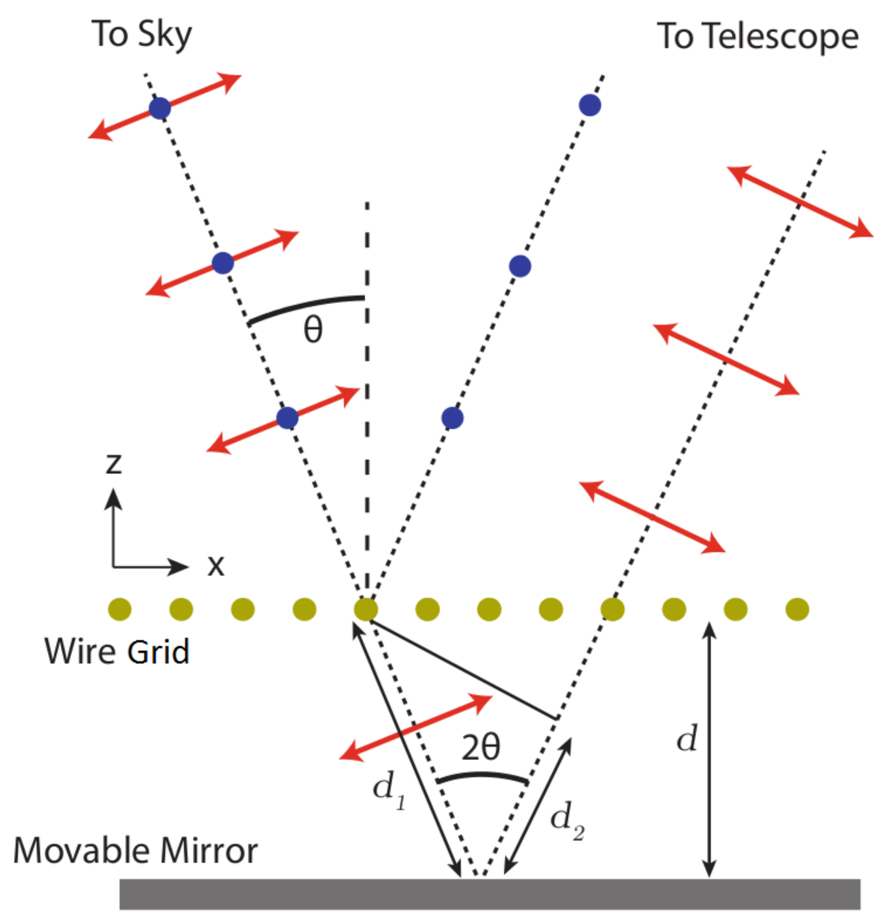
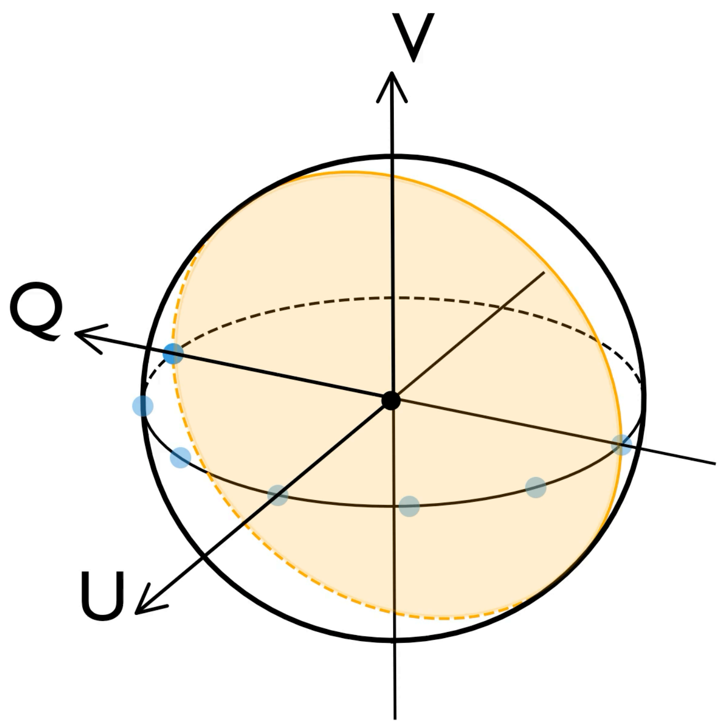
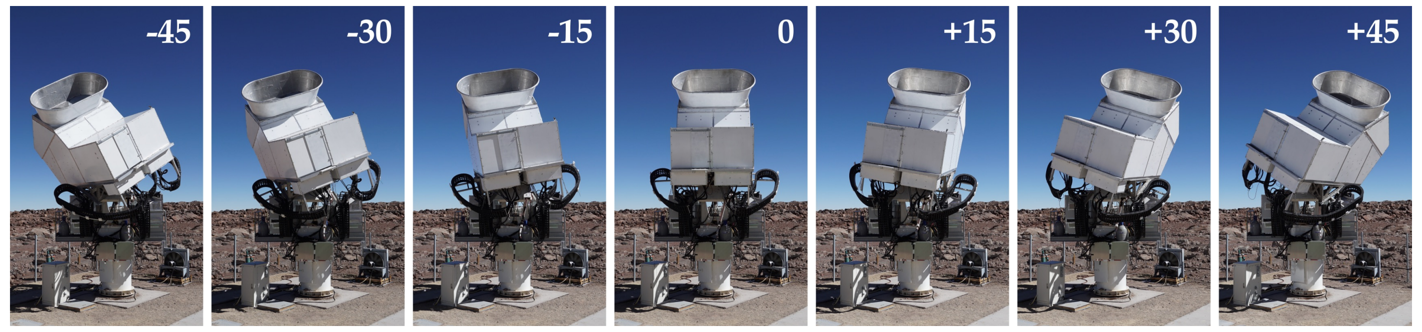
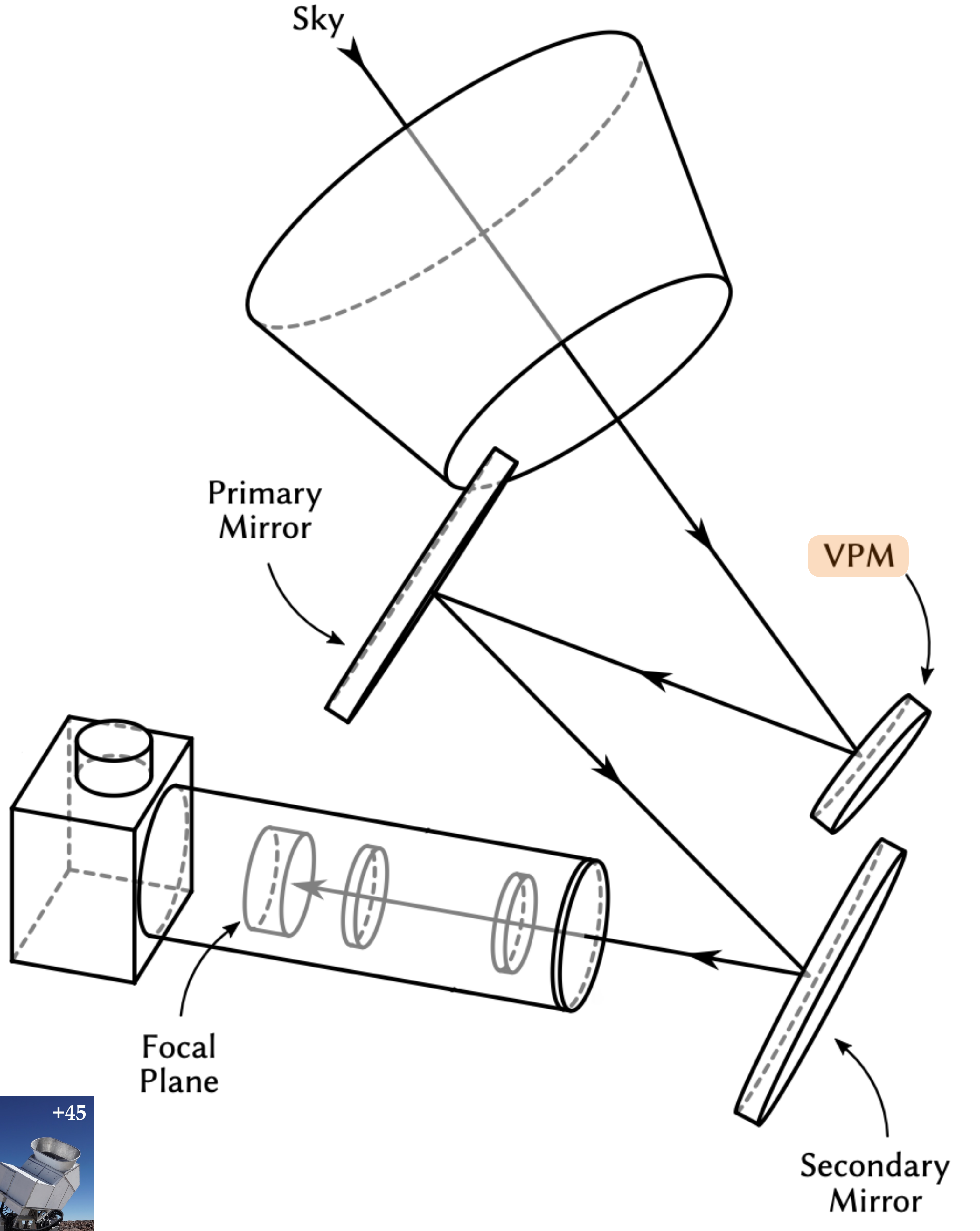




Datta+2023





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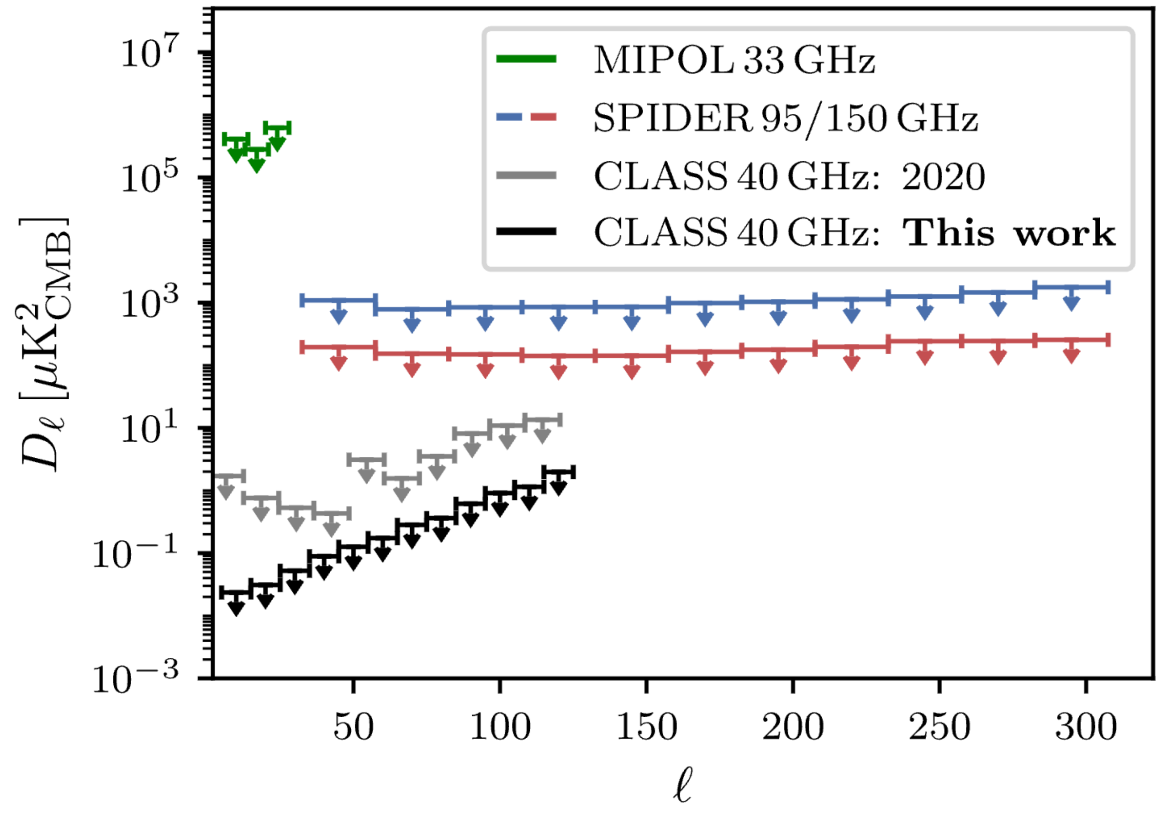
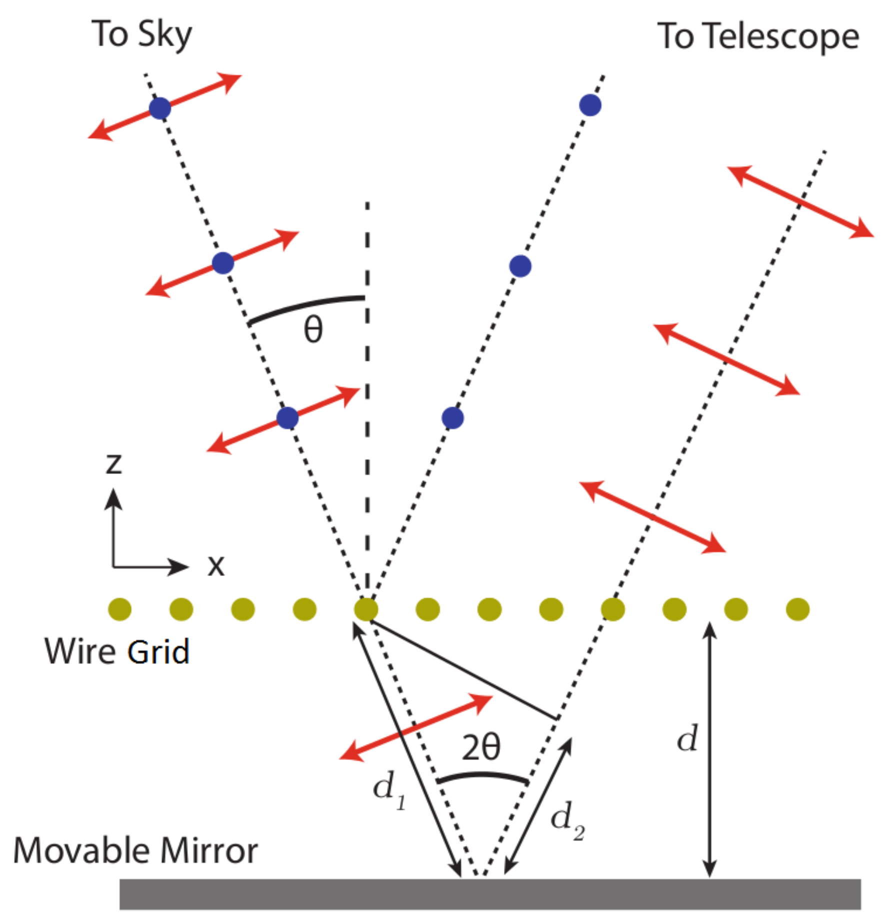
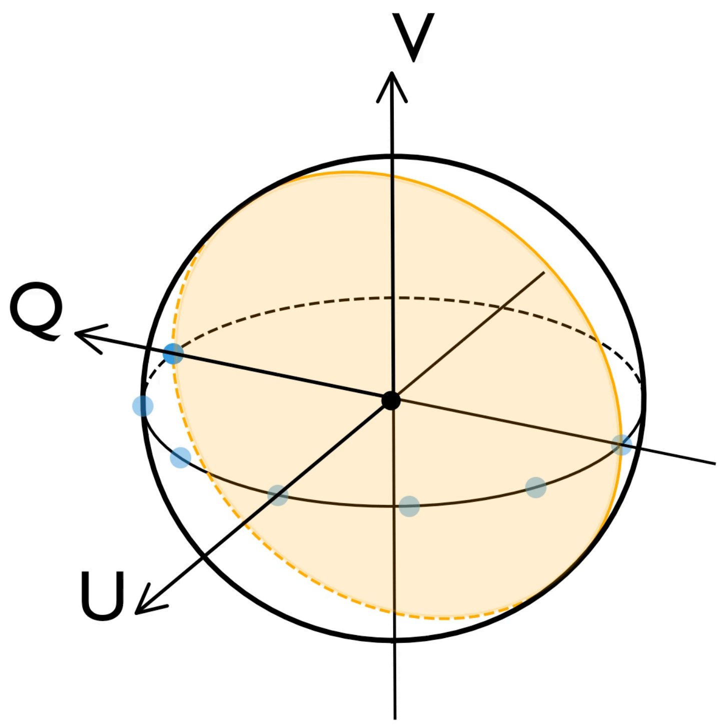
Circular polarization science

- First measurement of atmospheric circular polarization. (Petroff+2020)
- Best constraints on astrophysical circular polarization background. (Padilla+2020/Eimer+2024)

Eimer+2024







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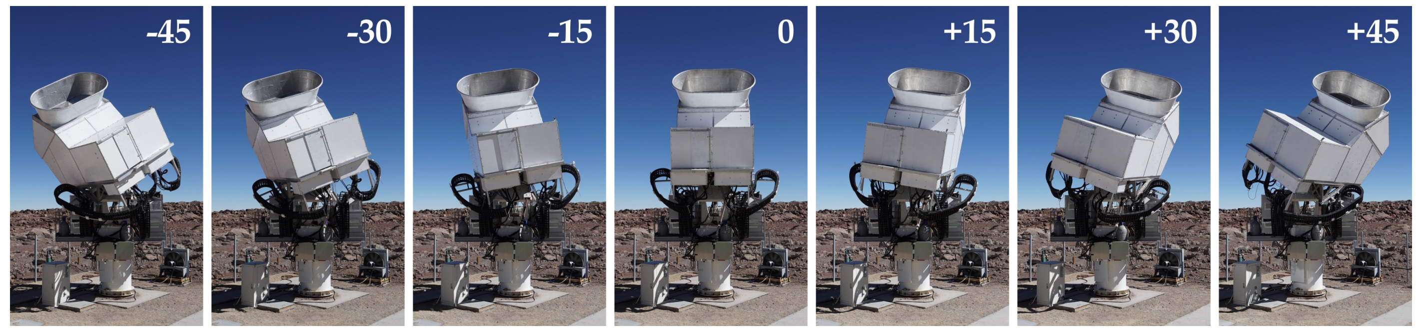

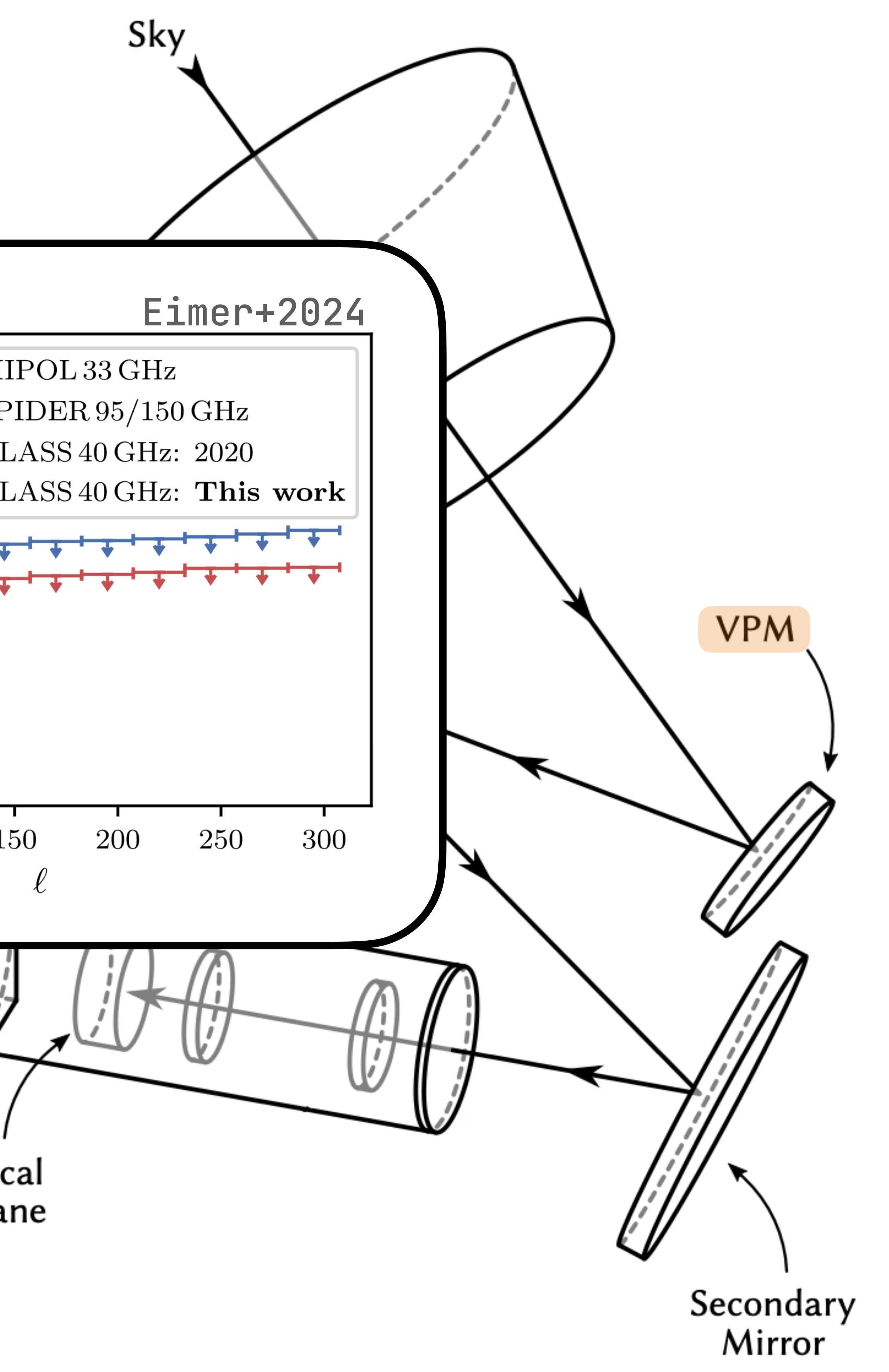

M. Petroff

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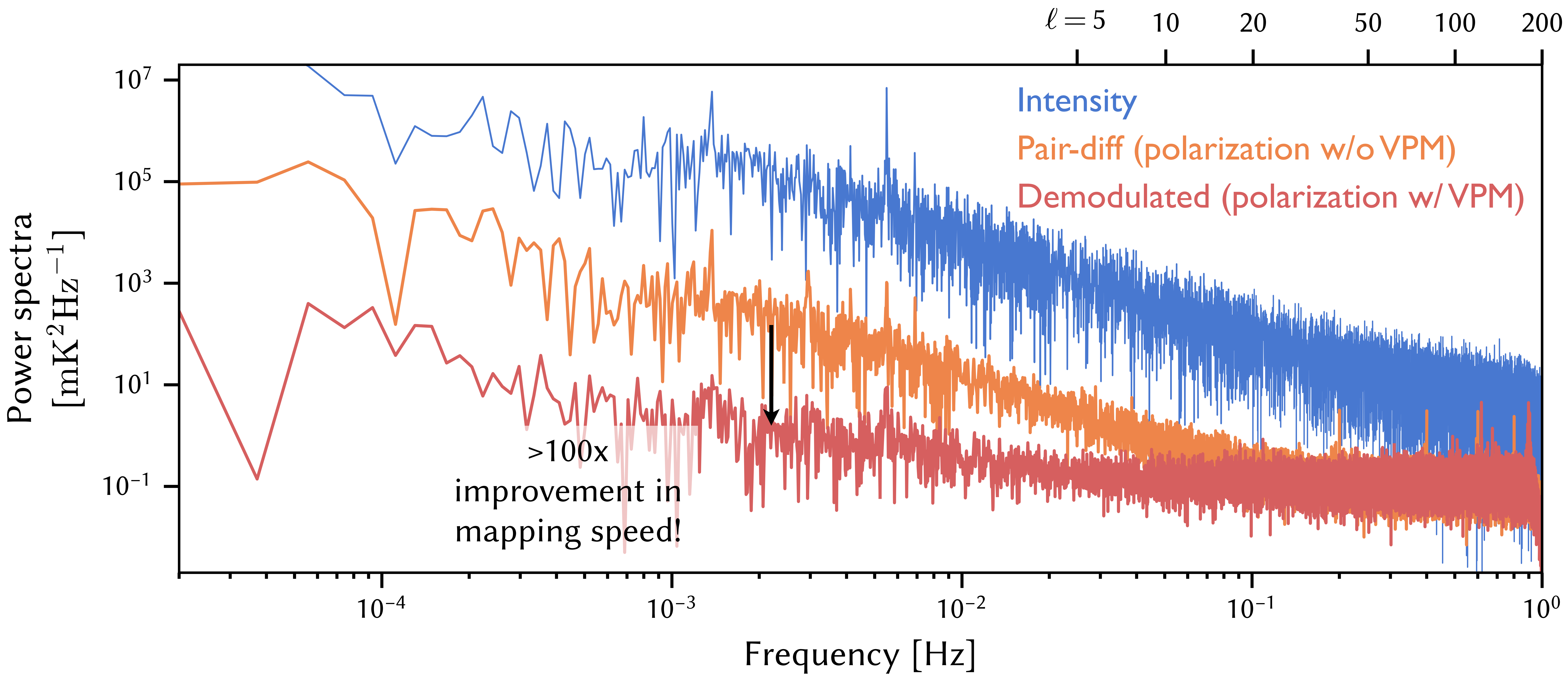

Harrington+(2021) Adapted

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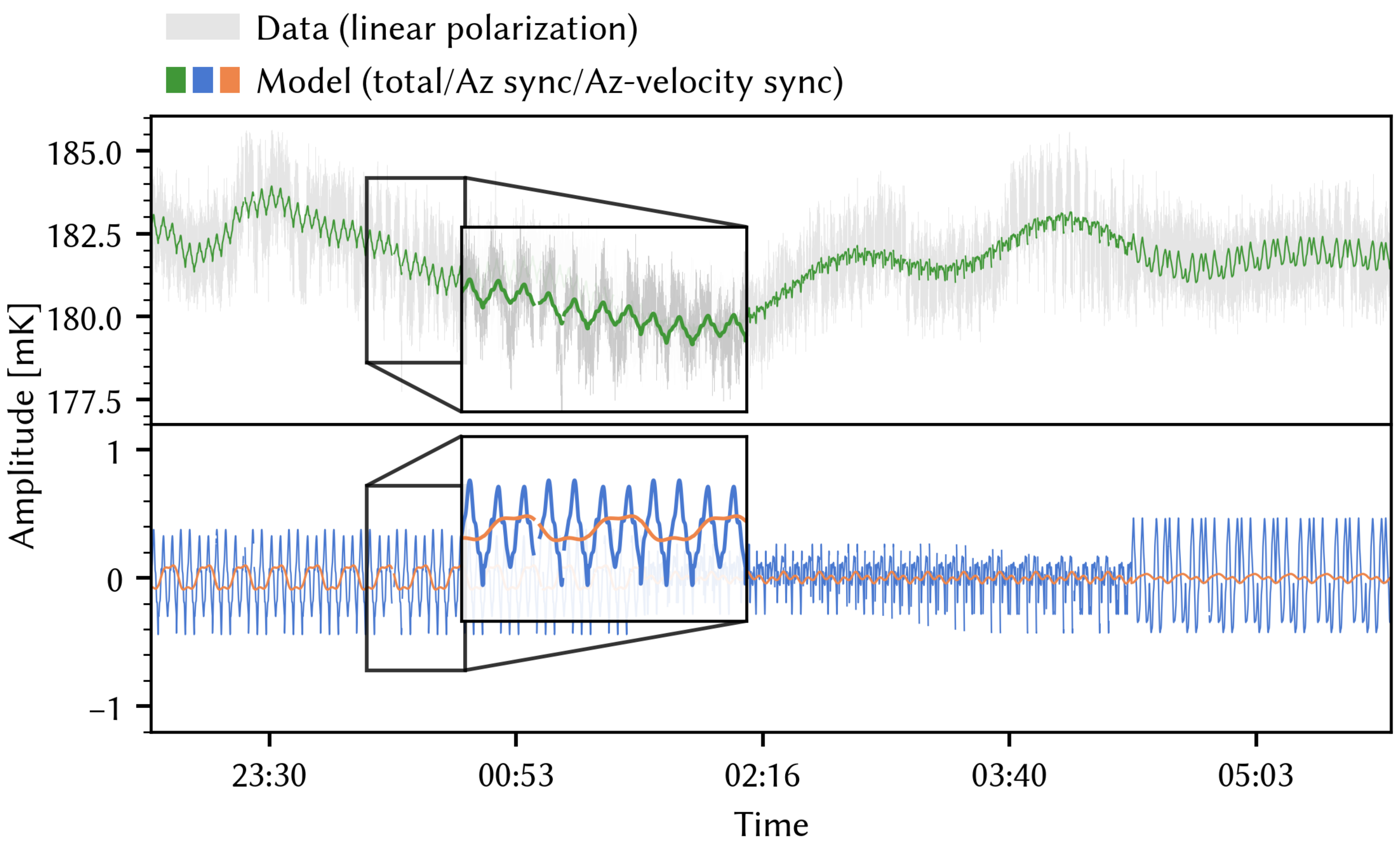

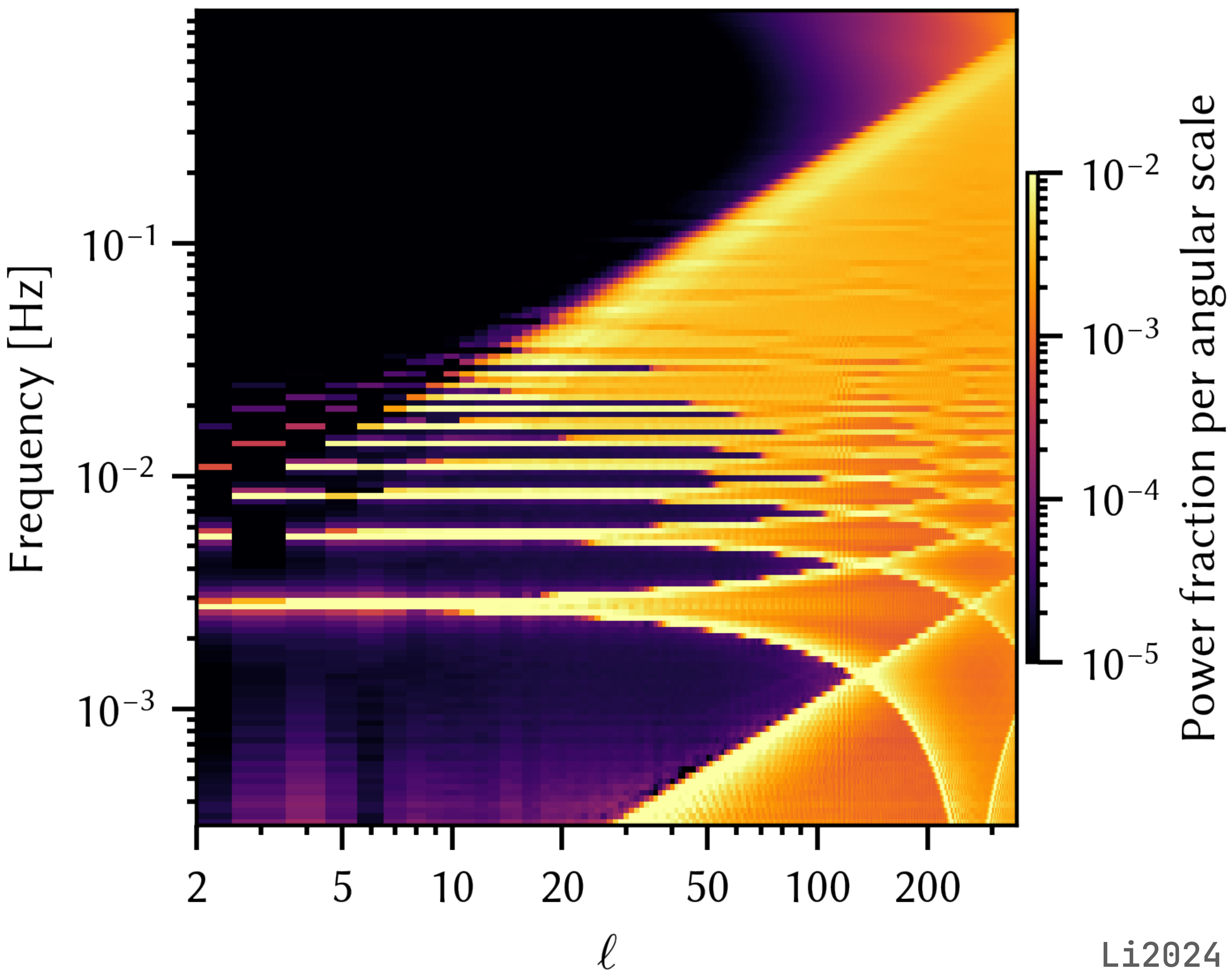

Li2024

Very large-scale signals are modulated within a very narrow band around the telescope scanning frequency — these modes are highly degenerate with the systematics correlated with the scanning motion.

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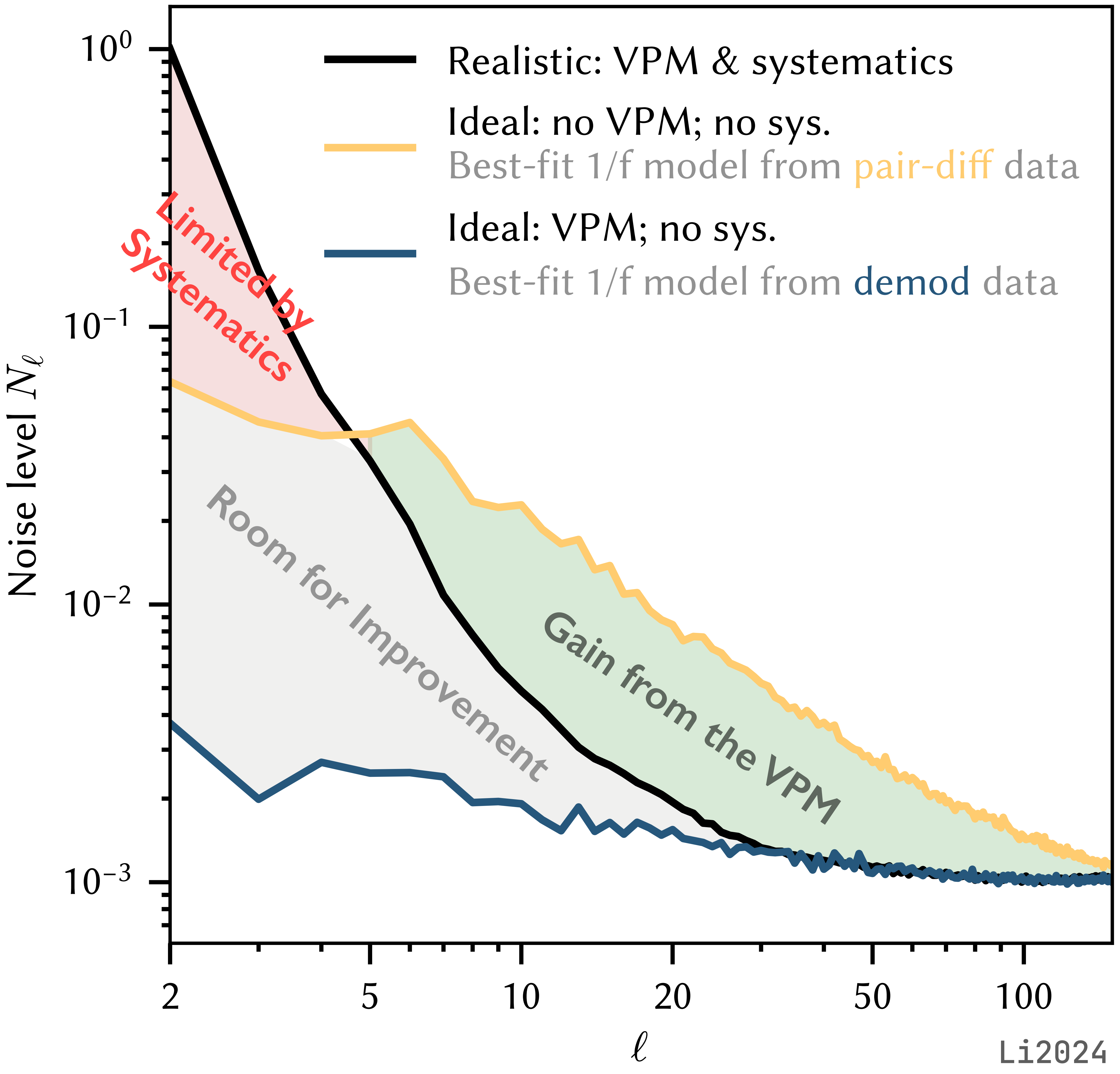
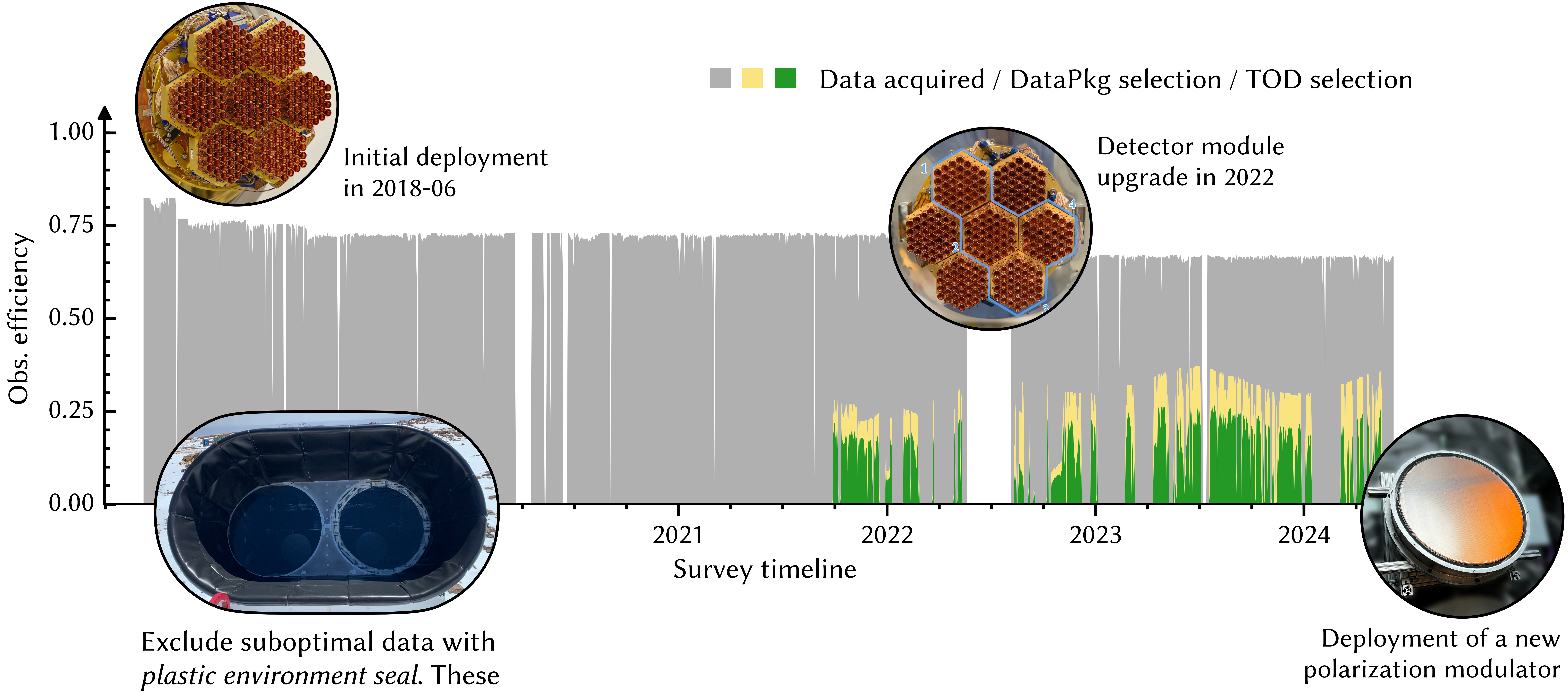
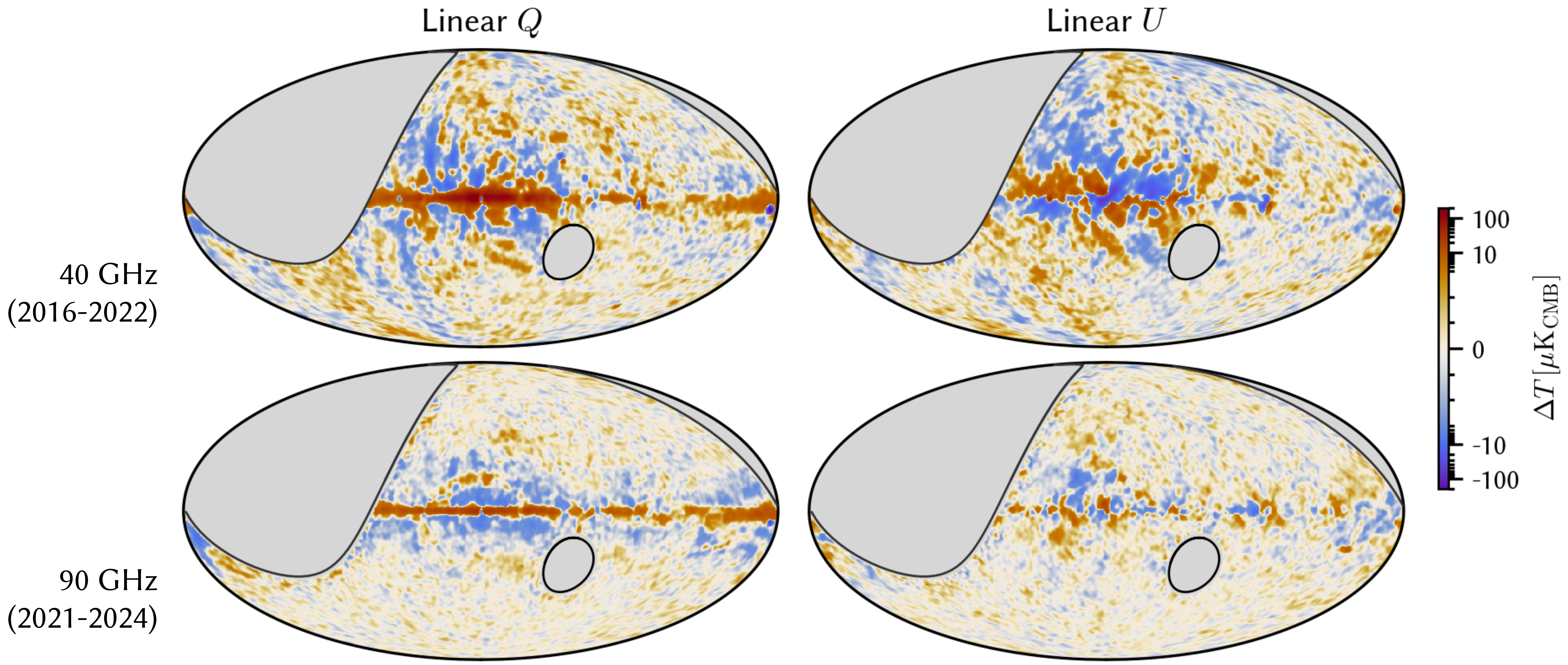


The 90 GHz survey Li, Eimer+2025 (arXiv: 2501.11904)



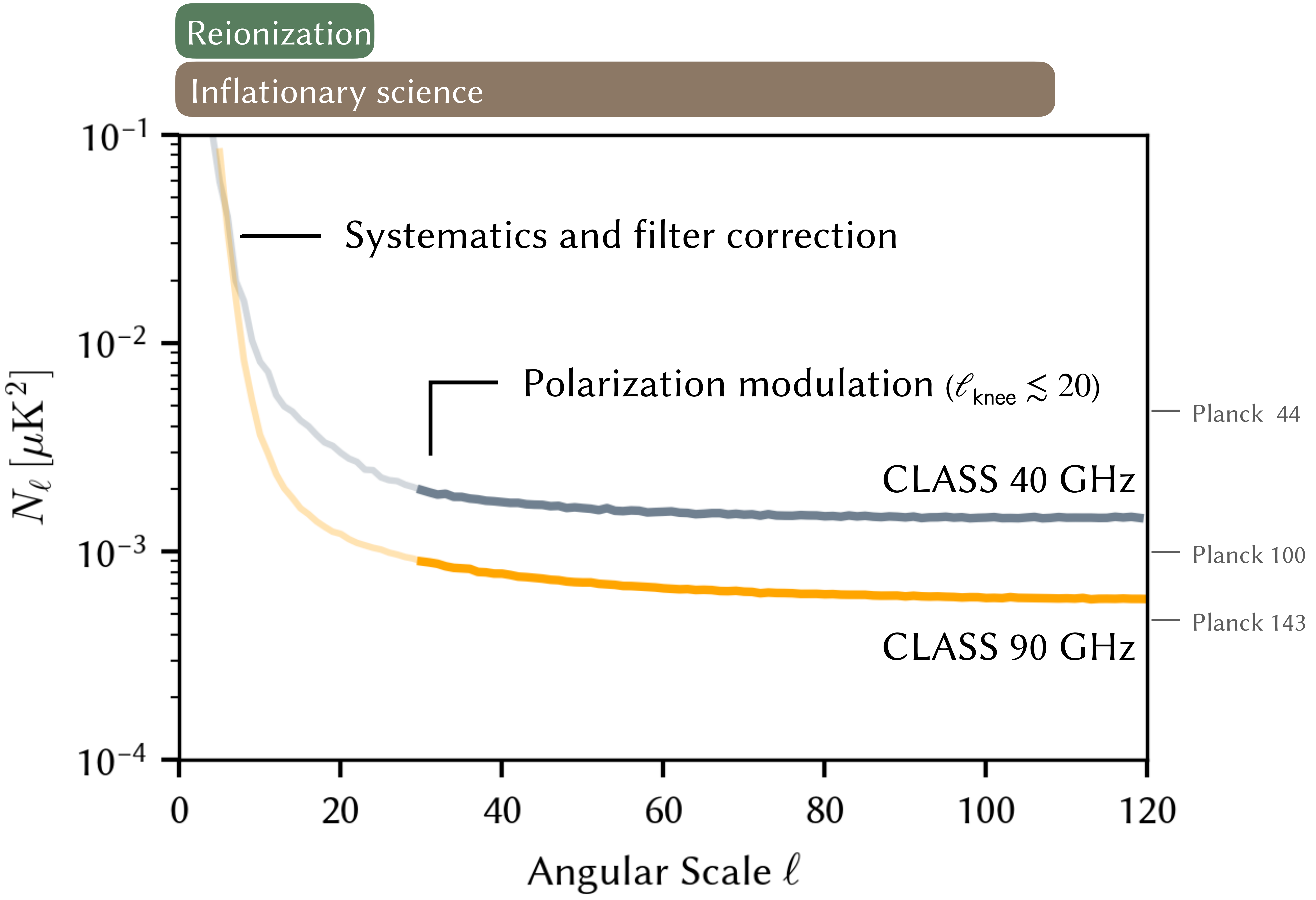
Exclude suboptimal data with *plastic environment seal*. These data are recoverable with improved analysis techniques.

The 90 GHz survey Li, Eimer+2025 (arXiv: 2501.11904)



Eimer,Li+2024
Li,Eimer+2025

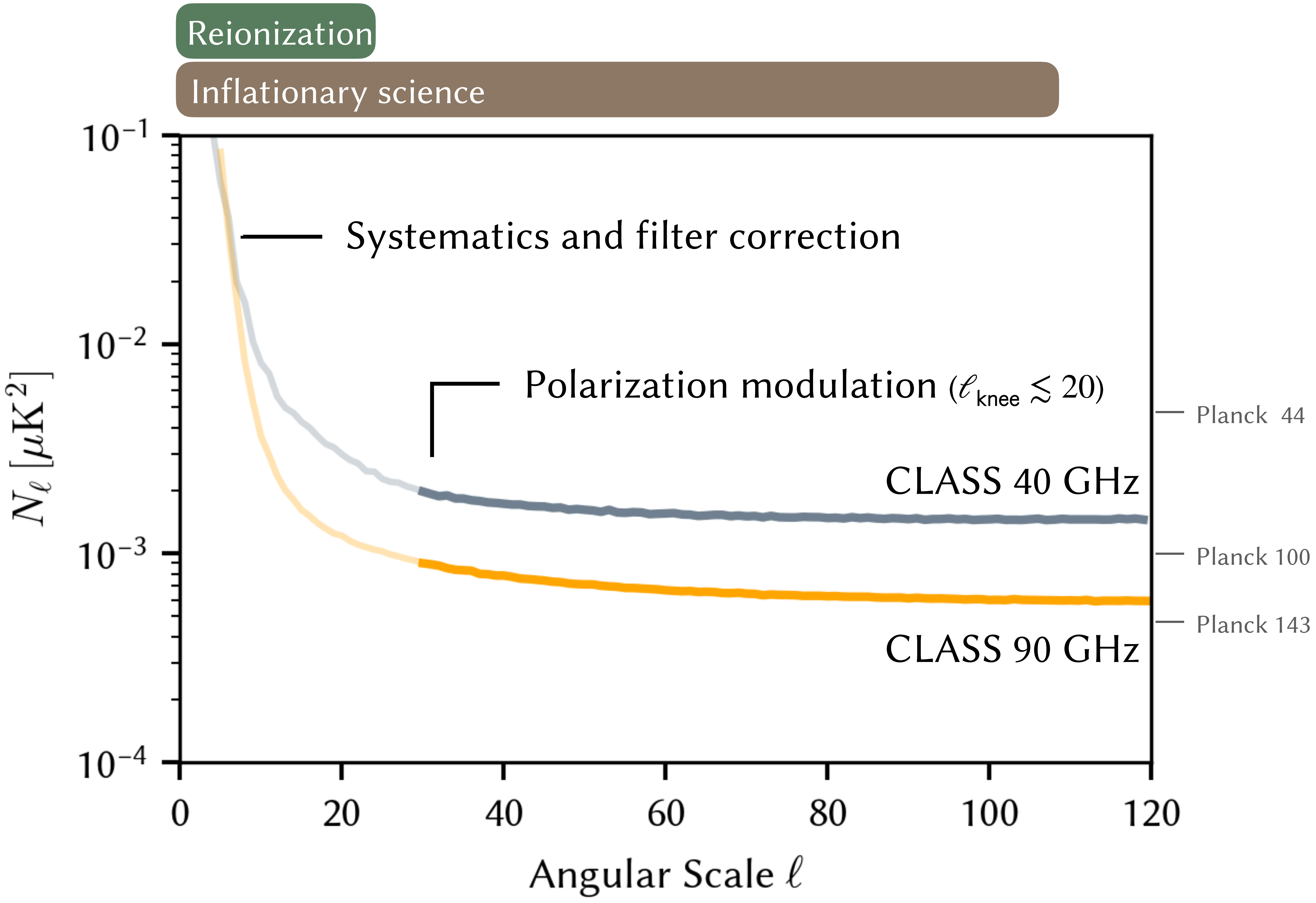
The 90 GHz survey Li, Eimer+2025 (arXiv: 2501.11904)



CLASS Noise Spectra

Best demonstrated low-ℓ performance from the ground.

The 90 GHz survey Li, Eimer+2025 (arXiv: 2501.11904)



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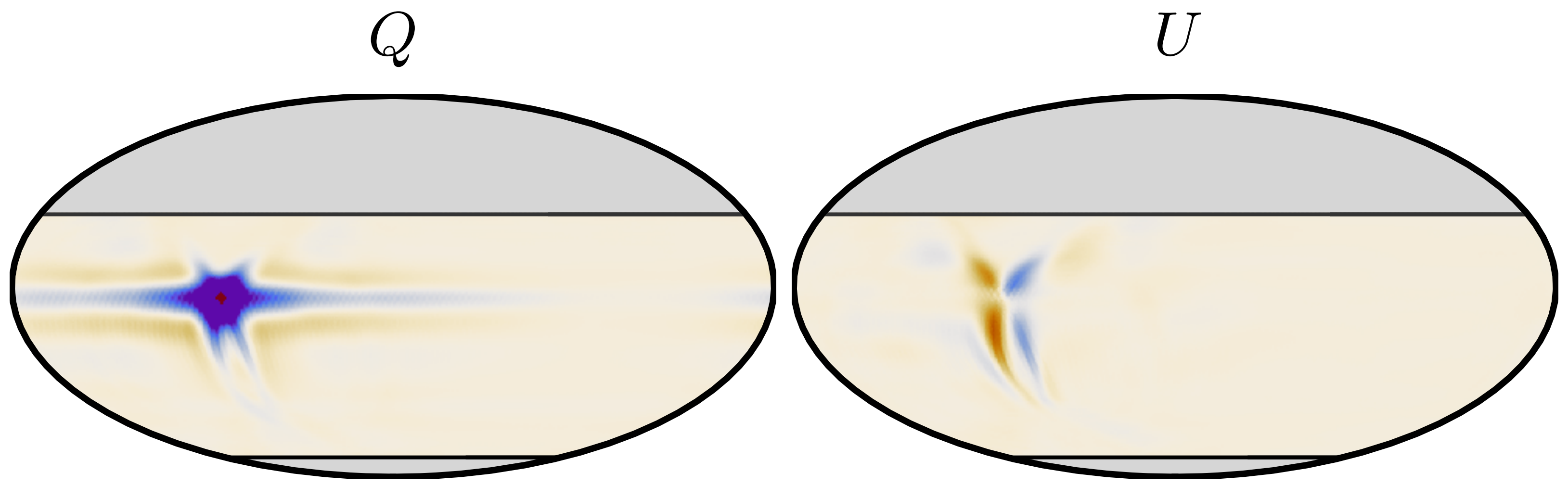
The recovery of the *largest-scale* modes is limited by scan-correlated systematics, and its mitigation strategy is an active field of research:

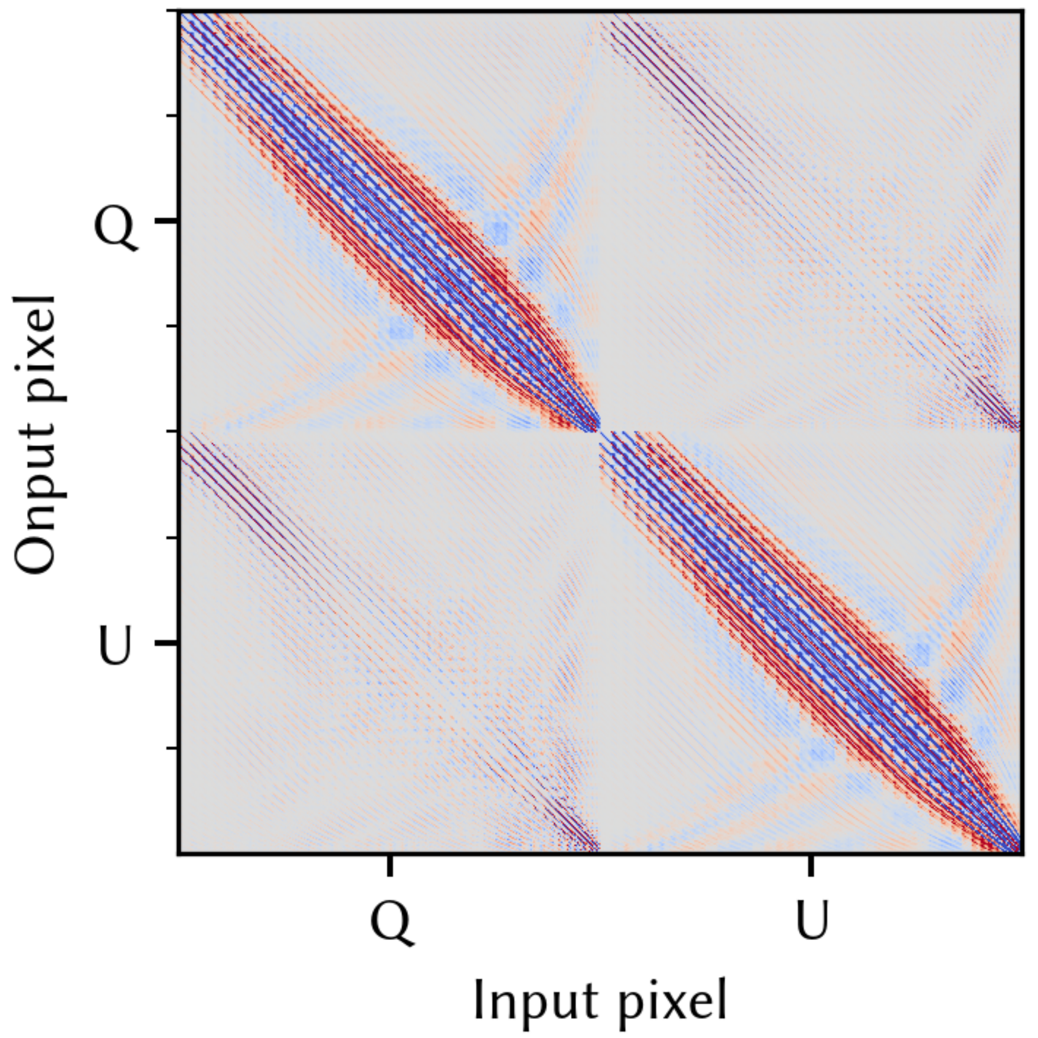
- Improving filtering strategy that leverages correlated nature of various systematic modes. (Chan+ in prep.)
- Robust characterization of the transfer function and reliable signal recovery despite missing modes.
- Multiple hardware improvements.

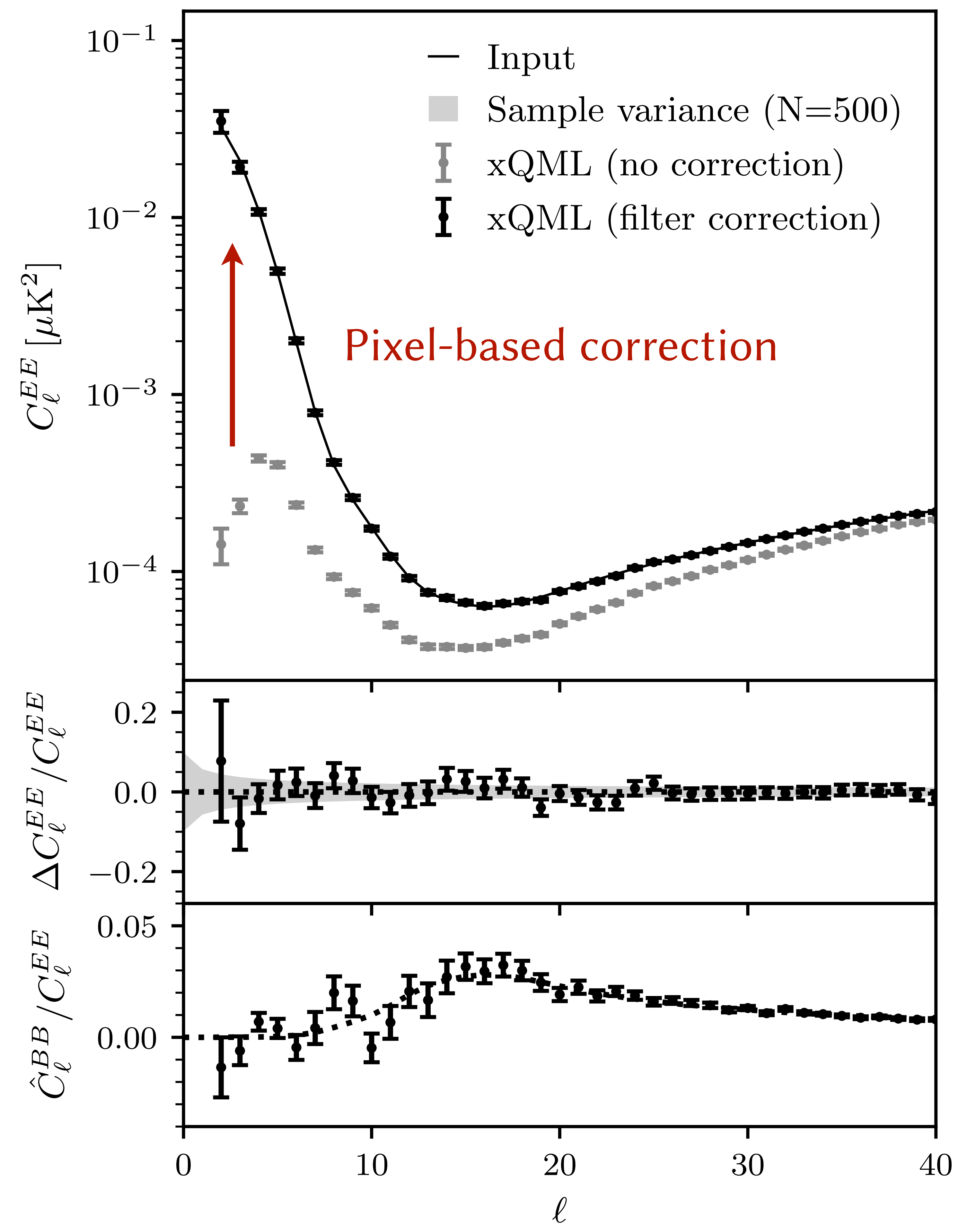
The 90 GHz survey Li, Eimer+2025 (arXiv: 2501.11904)

- Pixel-based transfer function built from map-making for every pixel.
- *Near-optimal* power spectra correction with quadratic estimator.



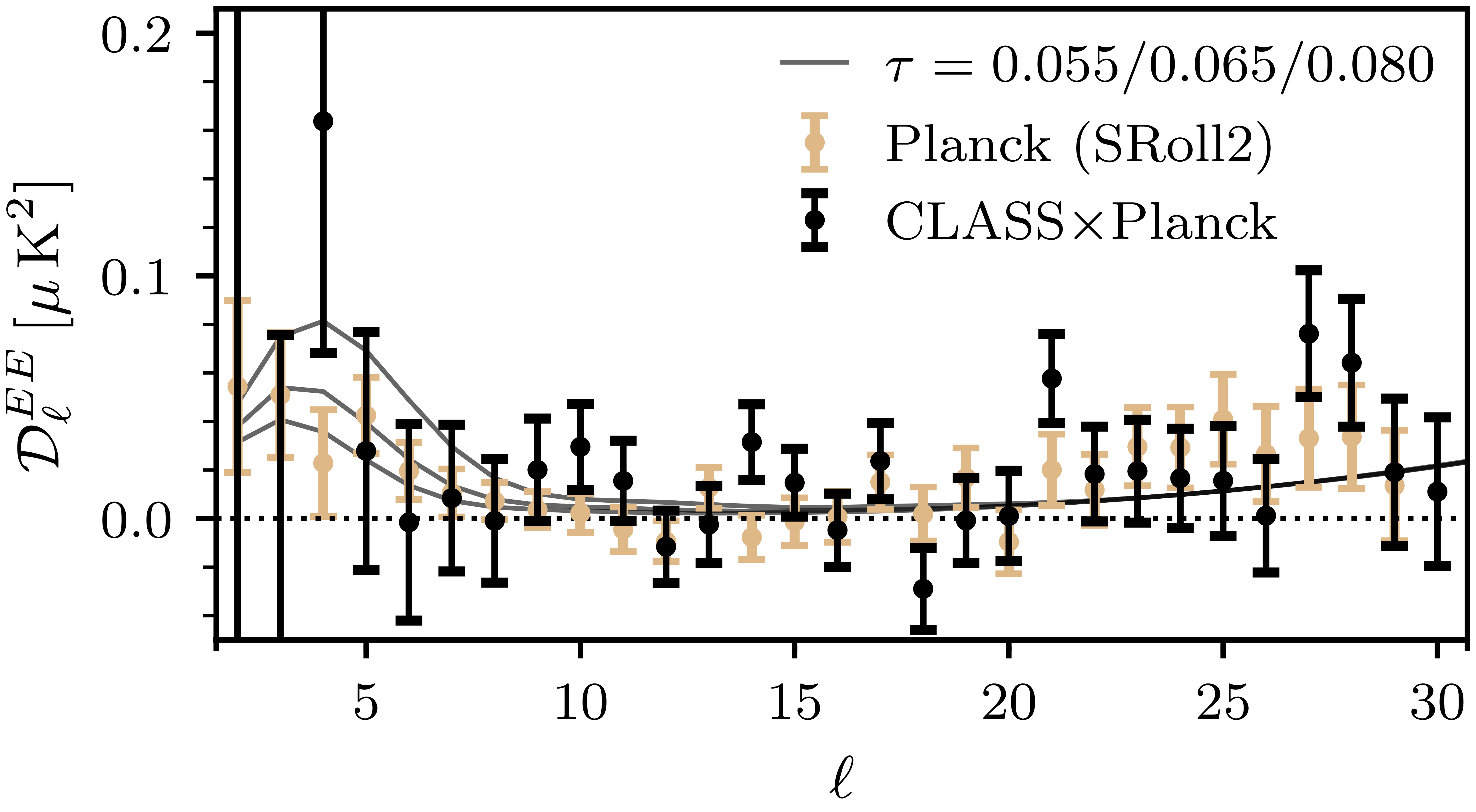
Filter response of a single pixel





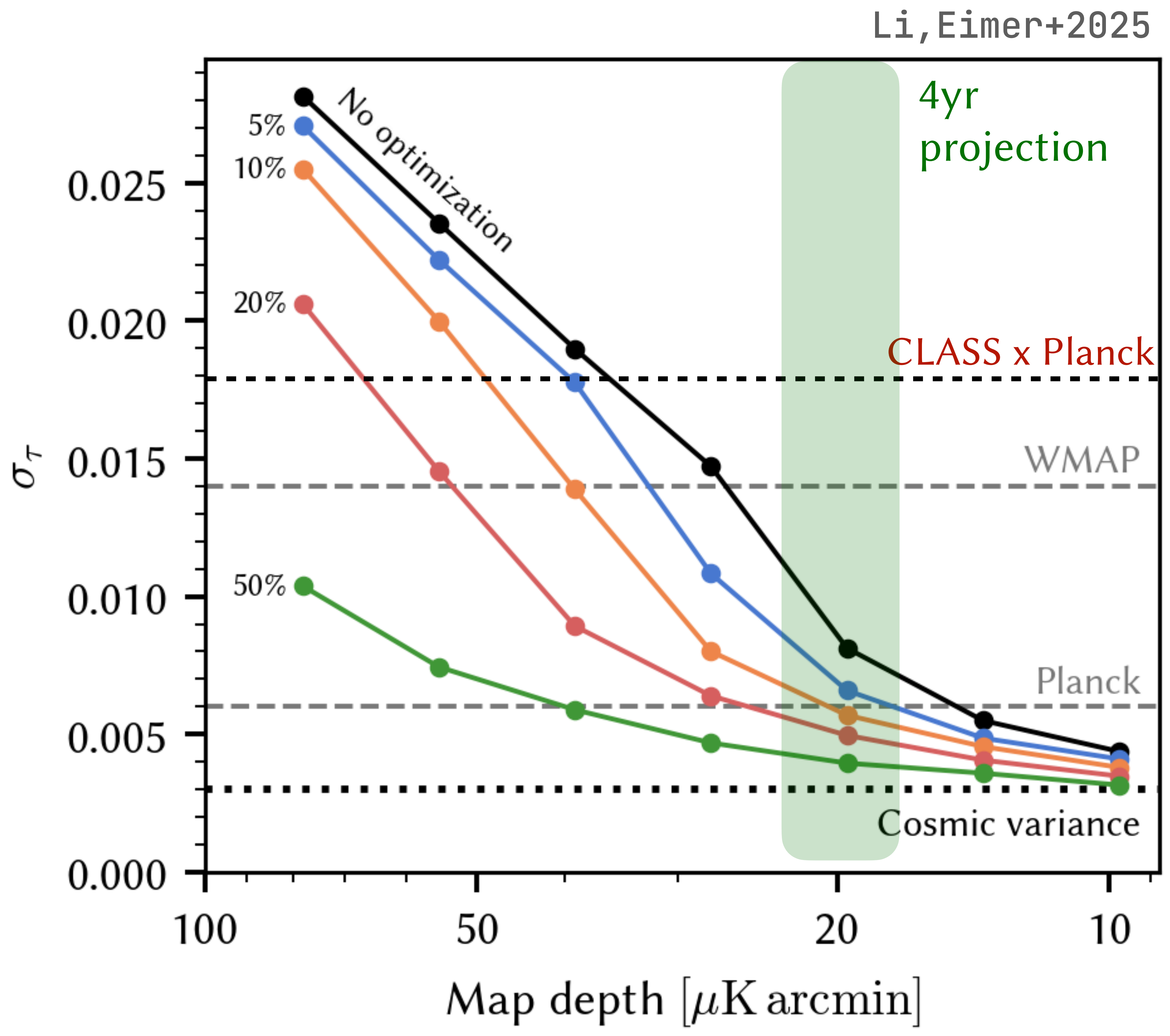
https://github.com/class-telescope/xQML

The 90 GHz survey Li, Eimer+2025 (arXiv: 2501.11904)



- Baseline result: $\tau = 0.053^{+0.018}_{-0.019}$; a detection of reionization at 99.4% confidence through cross-correlation with Planck.
- The result is robust against multiple analysis choices.

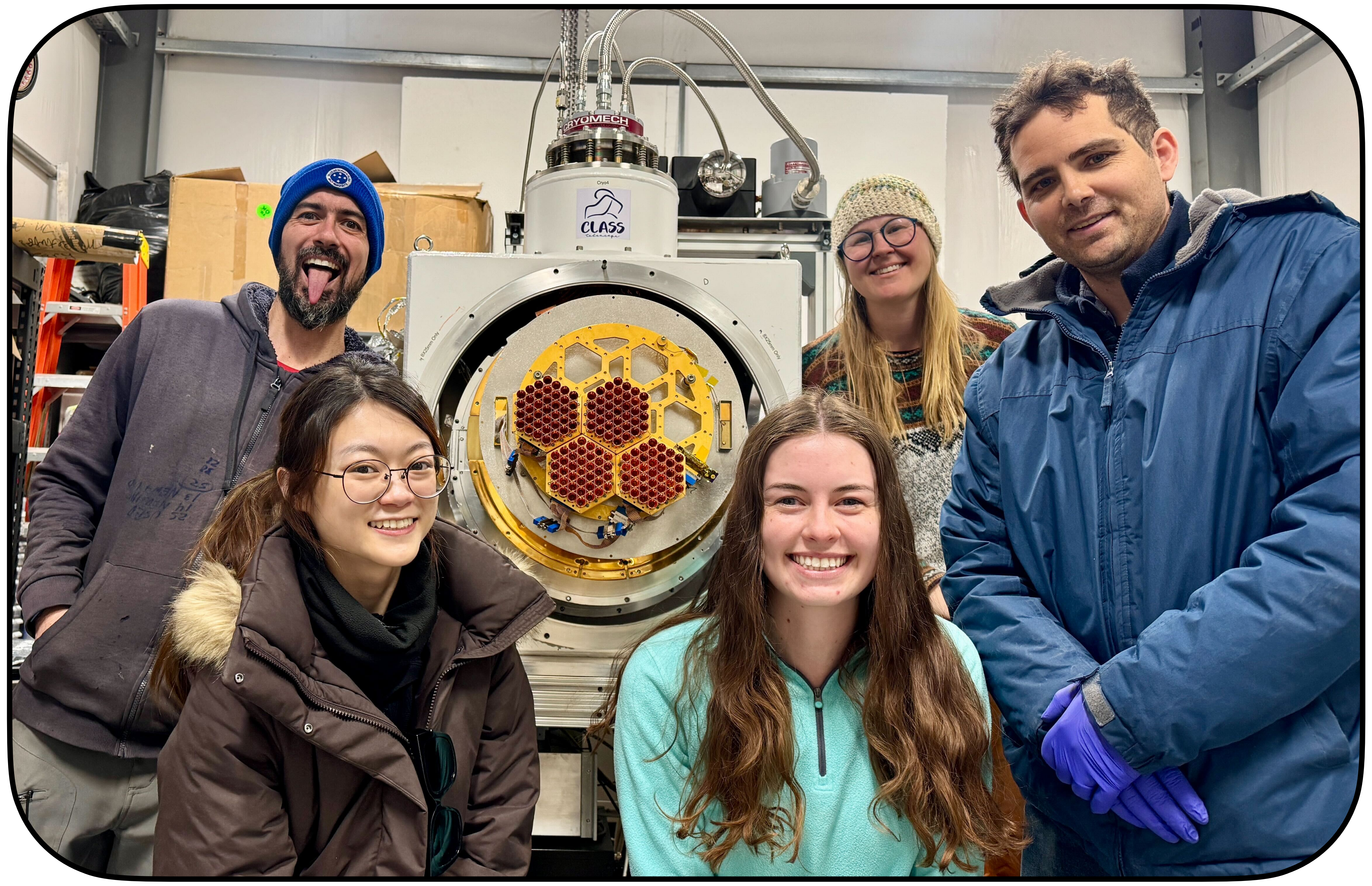
The 90 GHz survey Li, Eimer+2025 (arXiv: 2501.11904)



τ constraints from CLASS data alone

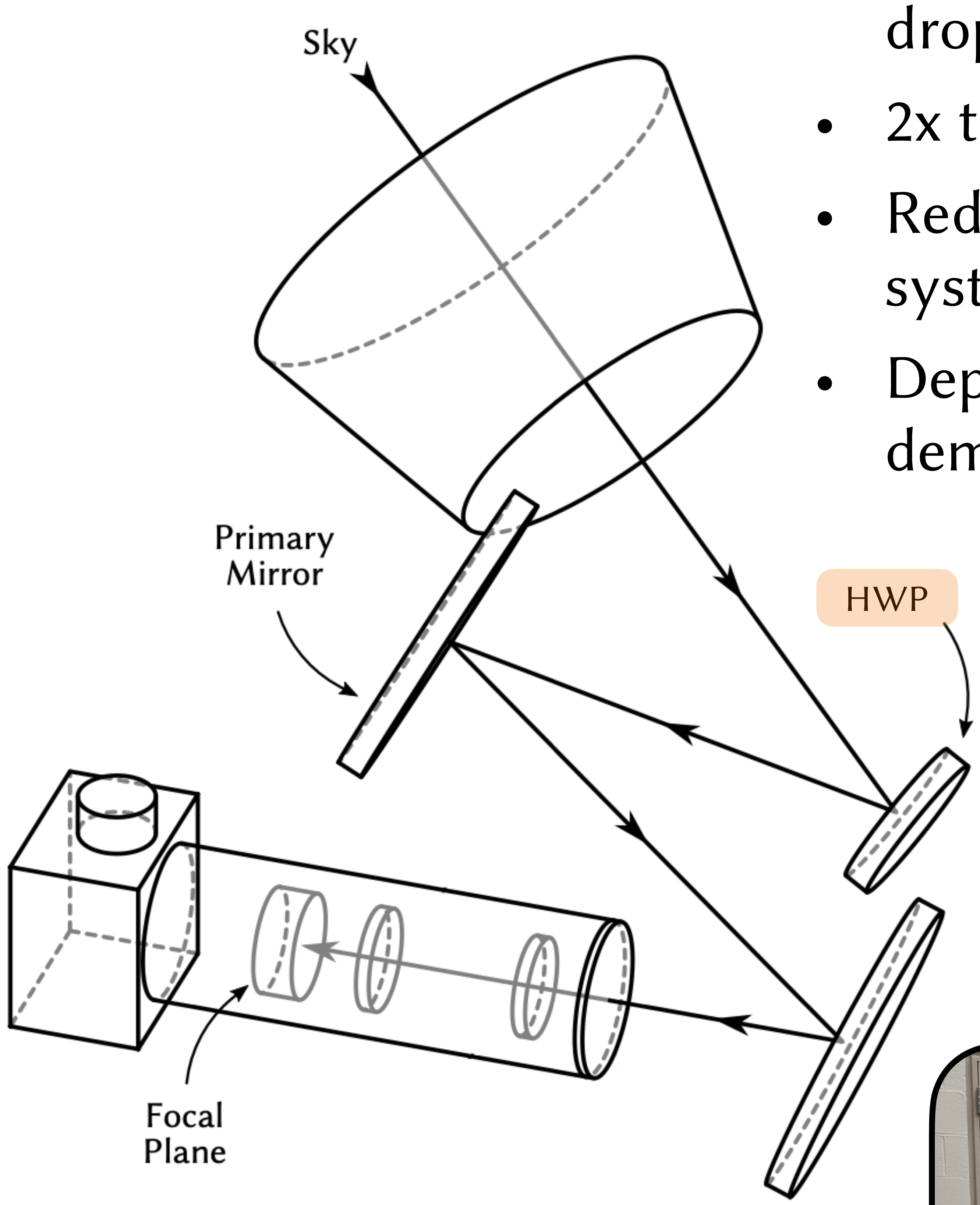
- Continuous integration is essential for surpassing the current limit set by Planck.
  - More detectors being deployed right now.
  - Alternative modulation strategy
  - Funding for extended project operations.
- The aggressive filtering is a limiting factor, and any small improvement there makes a big difference in the effective low-ell sensitivity.
  - Optimization of the filtering strategy given better understanding of the systematics.

Hardware development



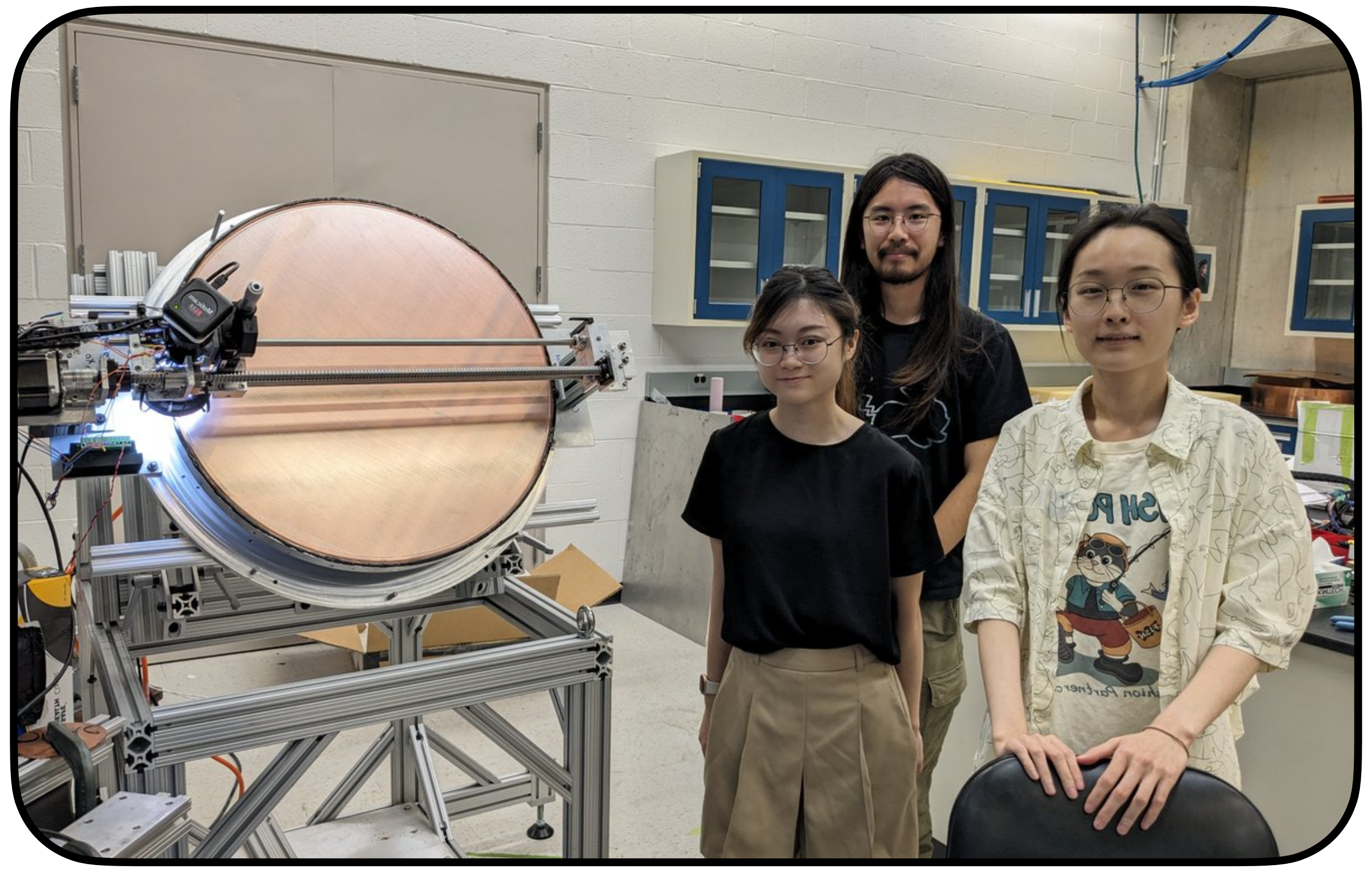
Second 90 GHz telescope deployment Happening right now!

- Half-populated high-yield NIST detectors.
- Starting with a VPM, with future upgrade plan for a HWP.

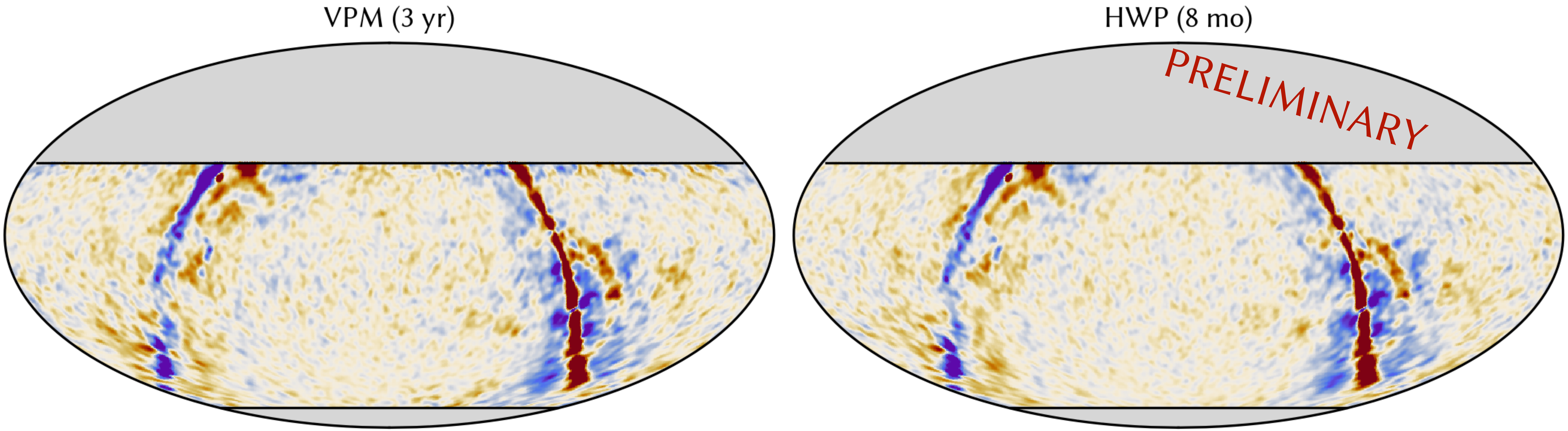


New Reflective HWP

- Rotating HWP with similar design for a drop-in replacement of the VPM.
- 2x the polarization mapping speed.
- Reduced modulator emission-related systematics.
- Deployed since 2024-07, with demonstrated on-sky performance!



Hardware development: New RHWP data



With 8 months of data, the HWP map is already deeper than as the 3-yr VPM data.
With preliminary indication of improved low-ell performance!

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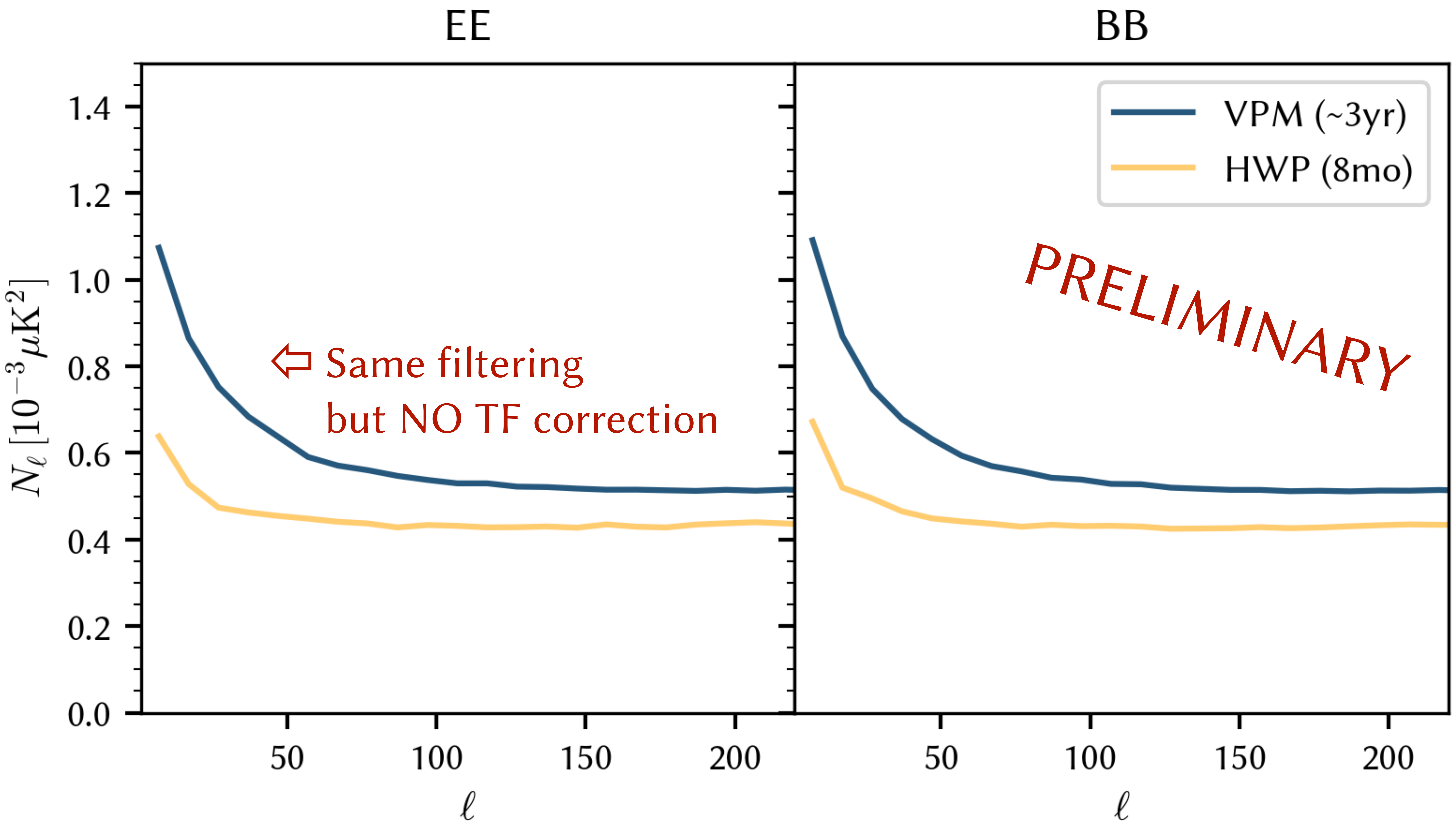

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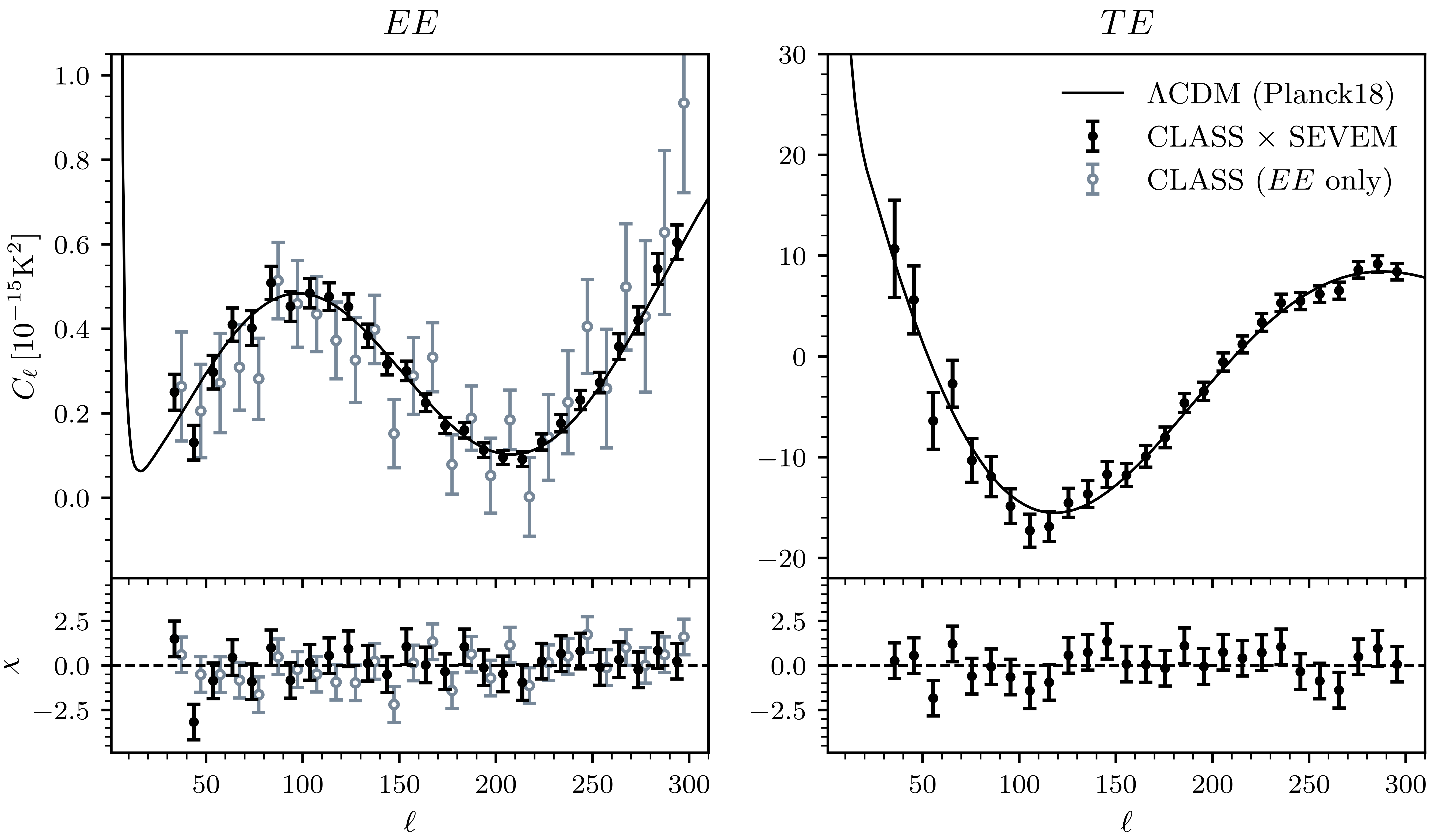
Summary

- CLASS 40 and 90 GHz surveys demonstrate the efficacy of the polarization modulation in improving the stability of ground-based CMB polarization measurements.
- CLASS measured consistent CMB E-mode spectrum in the range $2 \leq \ell \leq 300$ as Planck, and obtained the first ground-based reionization optical depth constraint $\tau = 0.053^{+0.018}_{-0.019}$ through cross correlation.
- The next phase of CLASS will drastically improve the sensitivity at 90GHz through instrument upgrades and deliver independent constraints on reionization τ.

backup slides

Linear polarization maps



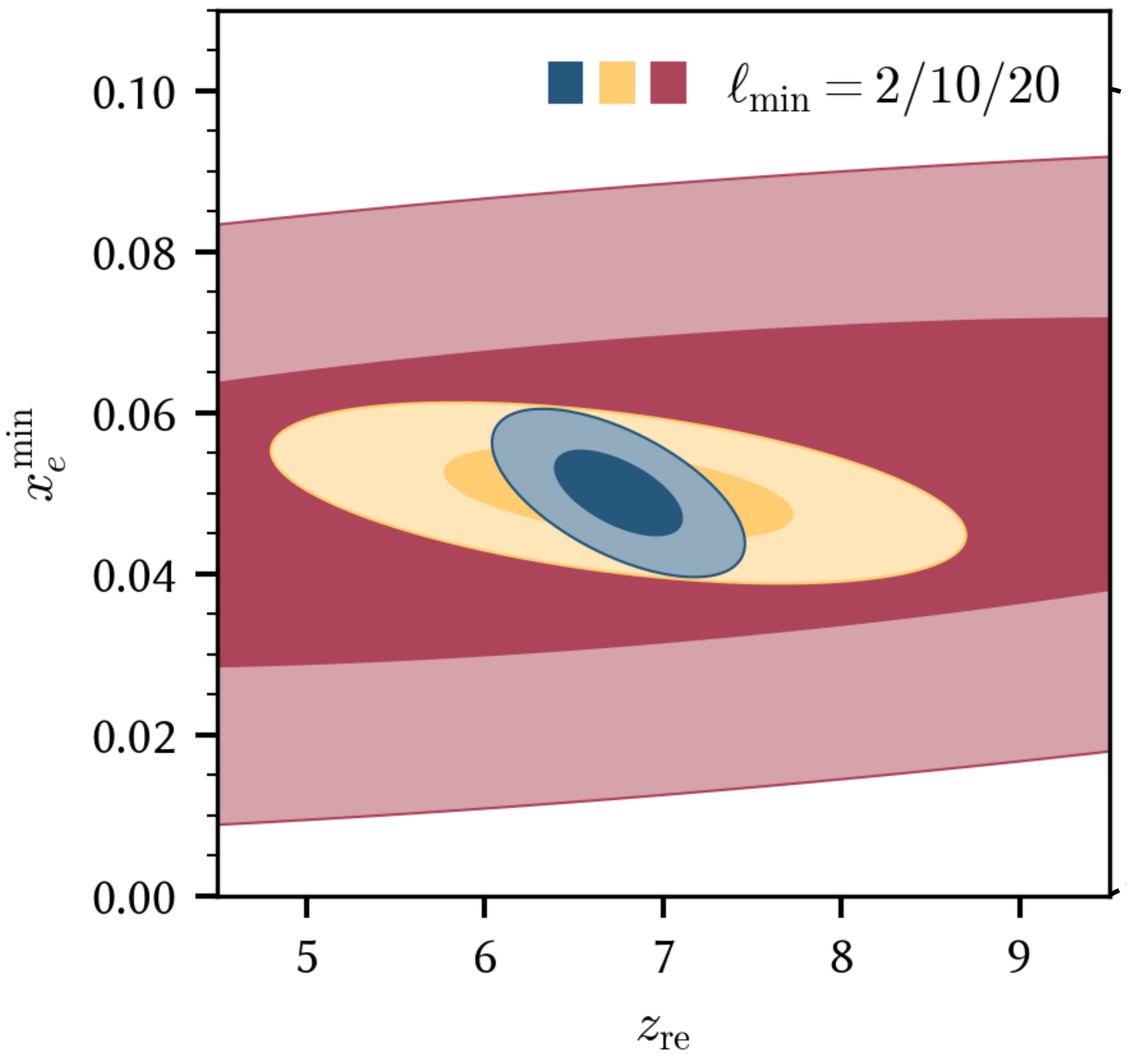
E-mode CMB Spectra

Li,Eimer+2025

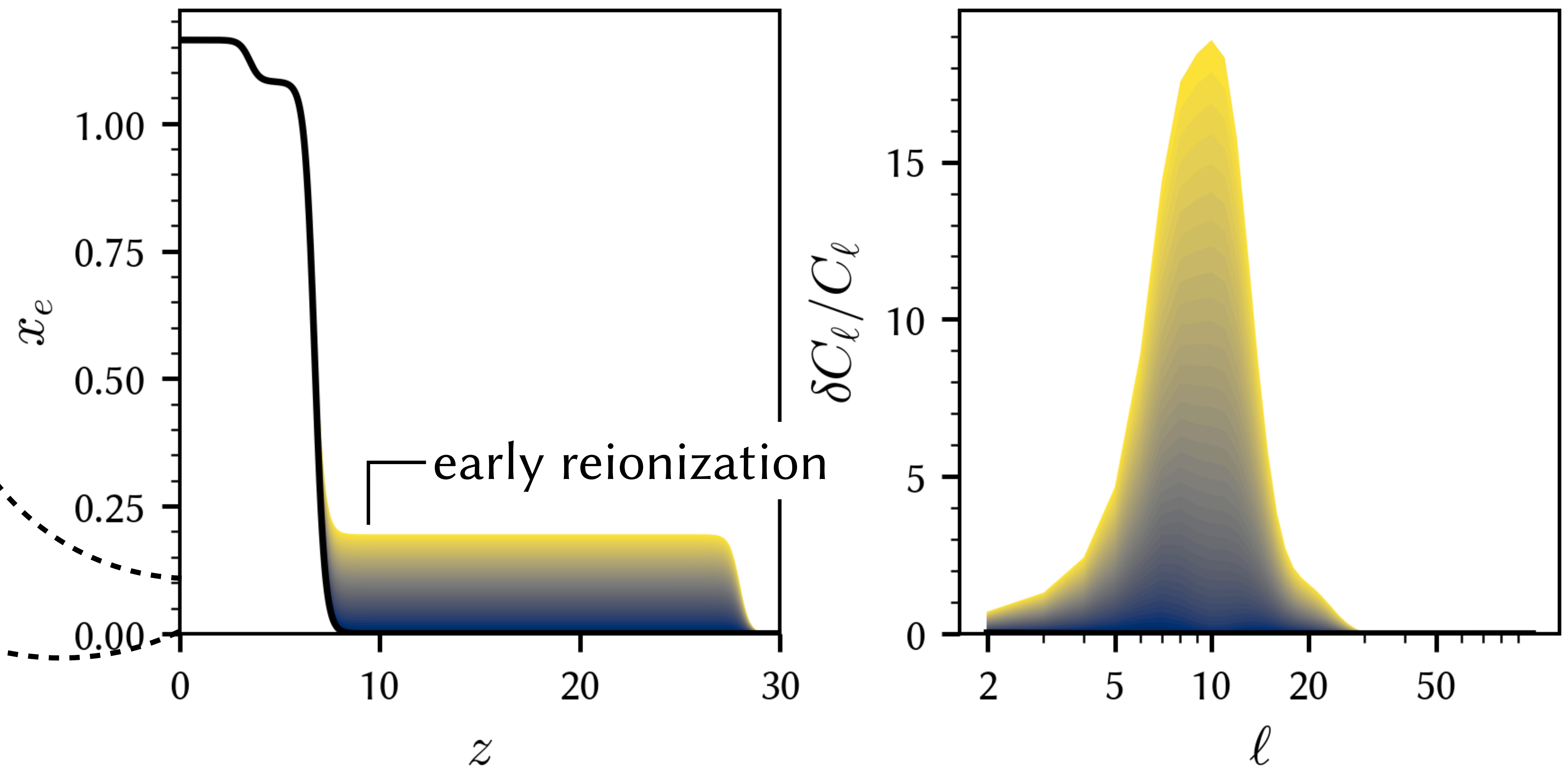
CLASS's first detection of the CMB!

Fully consistent with Planck2018 in the intermediate scales $30 < \ell \leq 300$

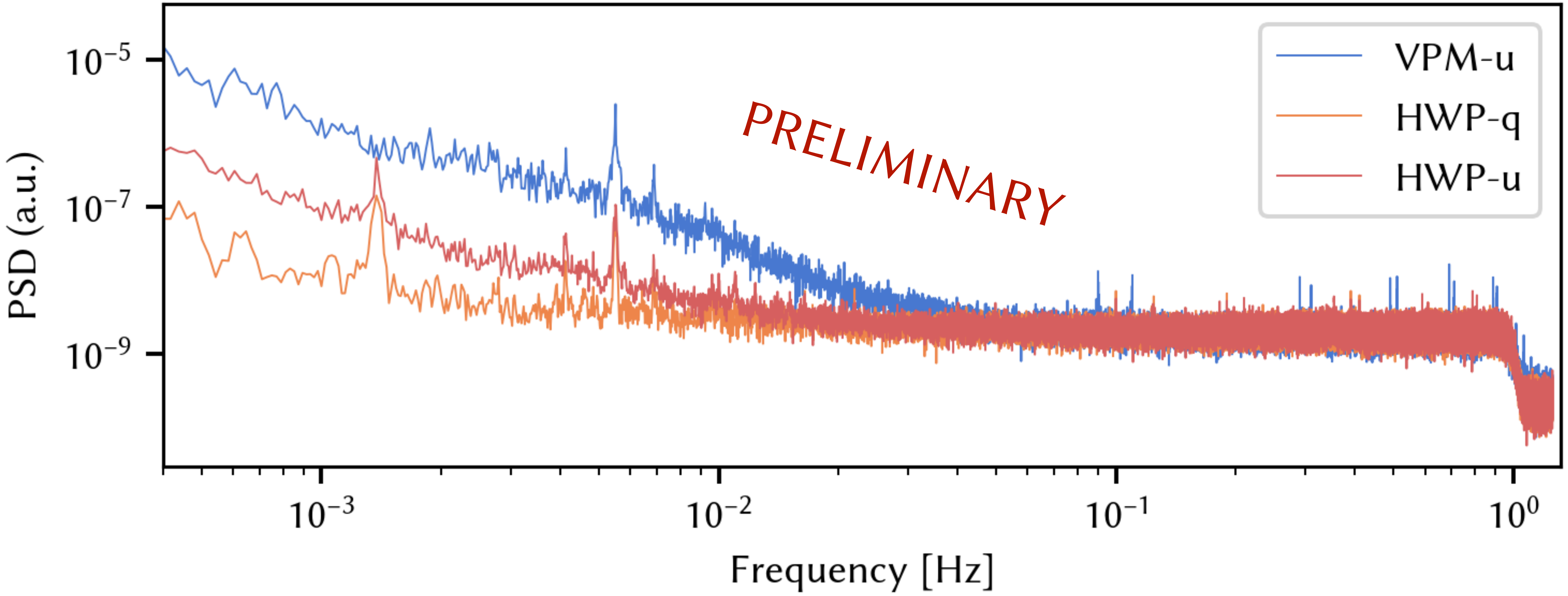
Reionization optical-depth and beyond



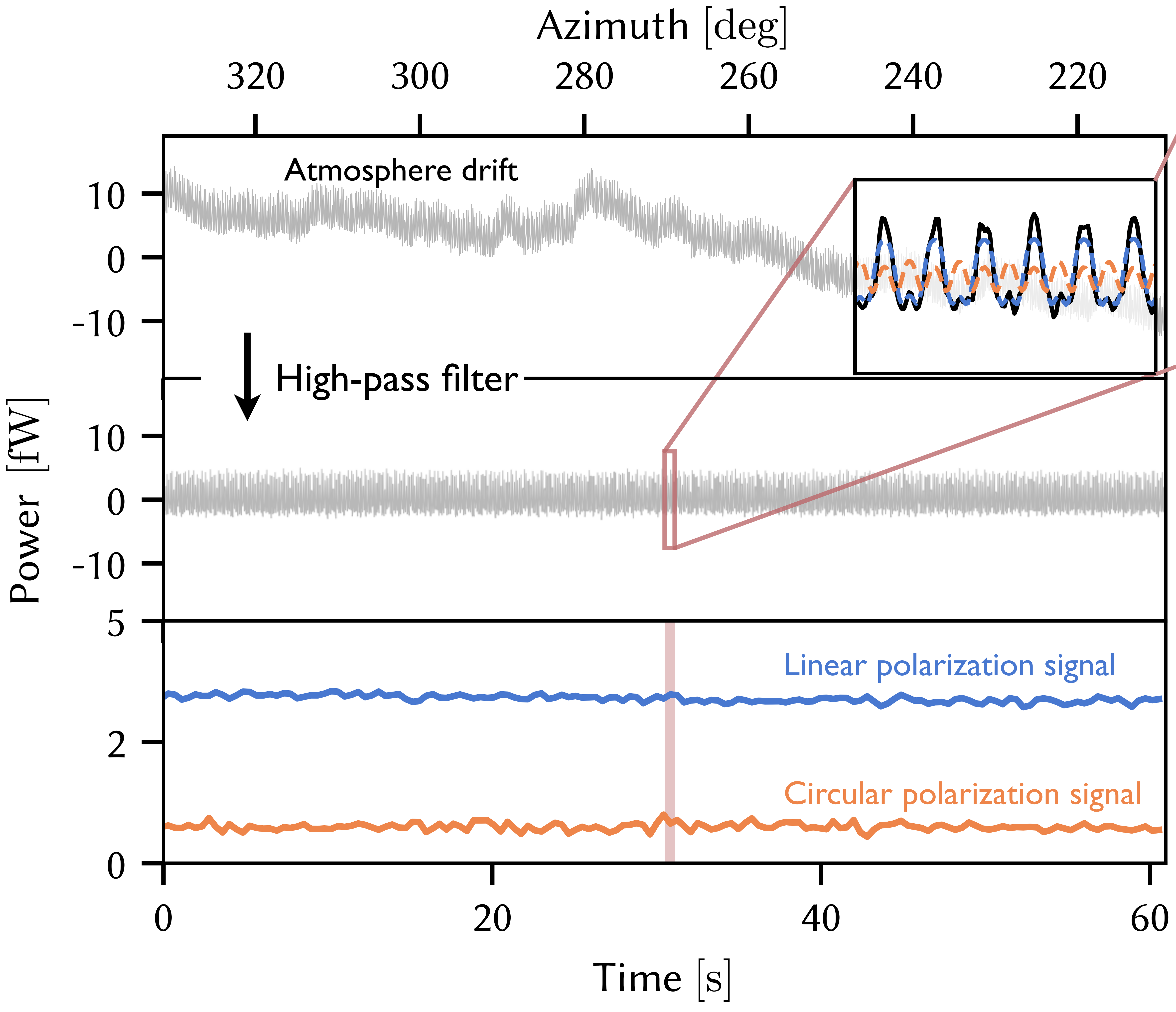
The **high-redshift reionization** physics is most sensitive to scales $\ell \geqslant 10$, where the dependence on the transfer function correction is less critical.



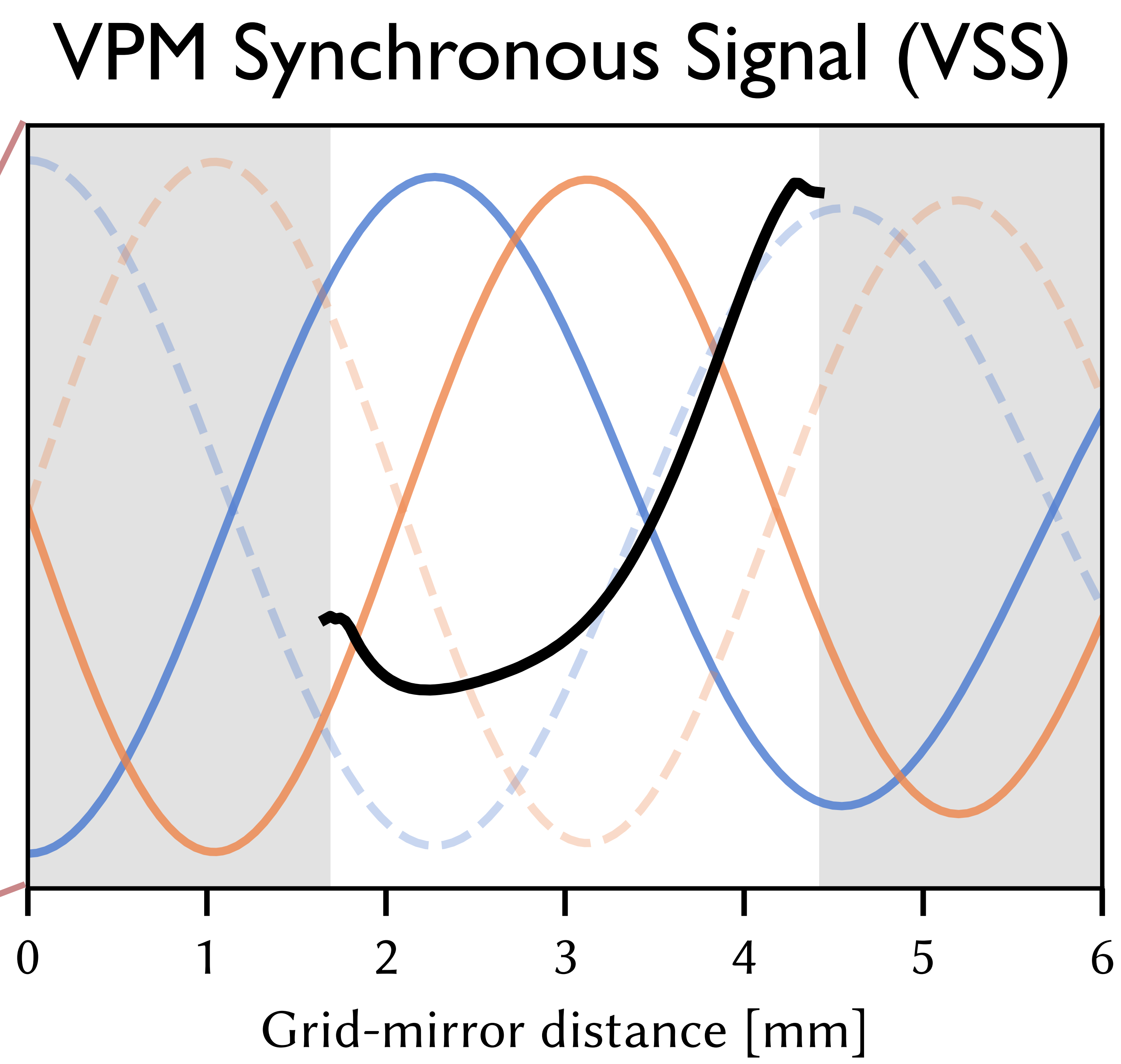
Watts+2020 Adapted


PRELIMINARY
VPM-u
HWP-q
HWP-u
PSD (a.u.)
10^{-5}
10^{-7}
10^{-9}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Frequency [Hz]

VPM: Demodulation and Emission



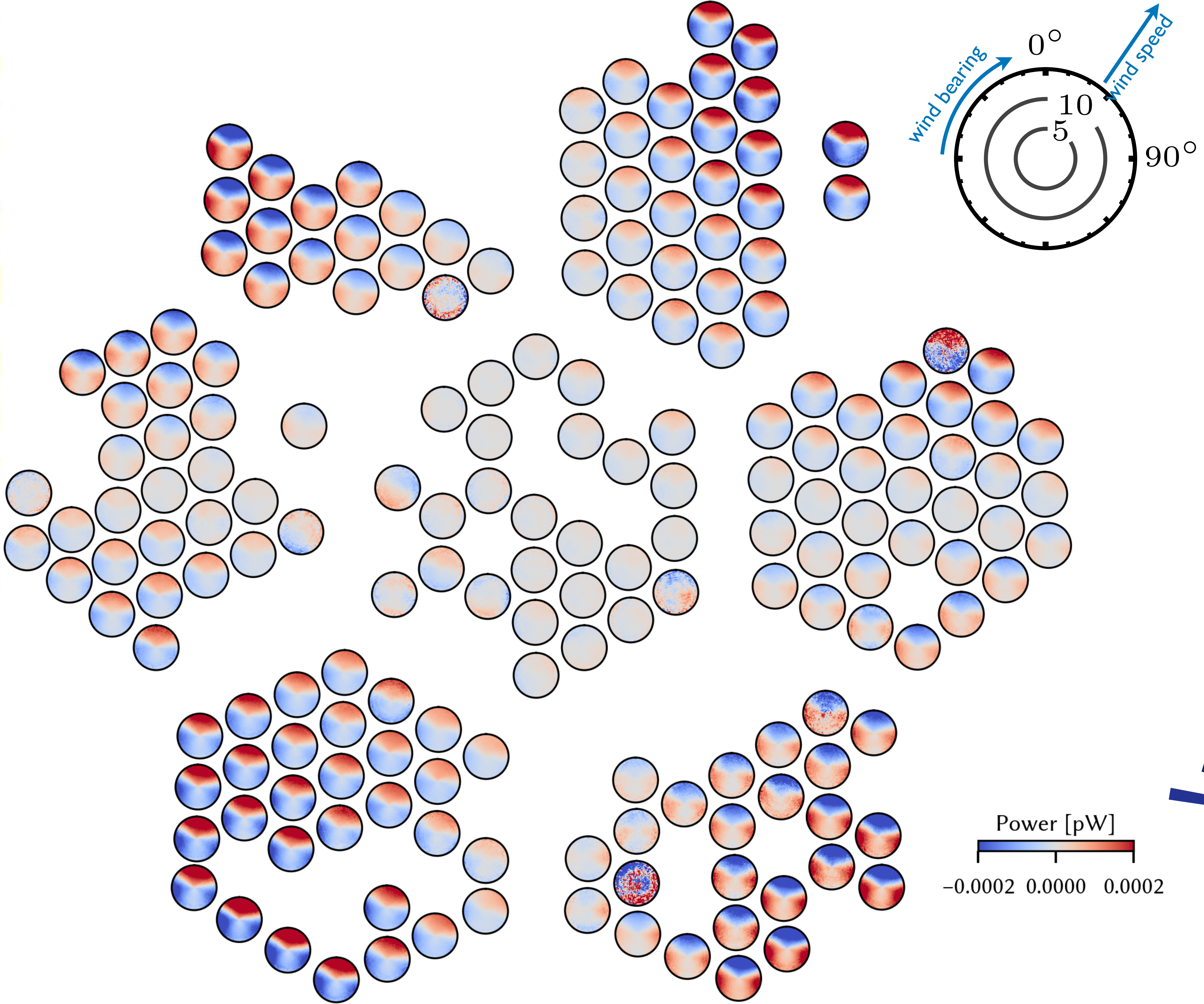
Li+(2023a) Adapted

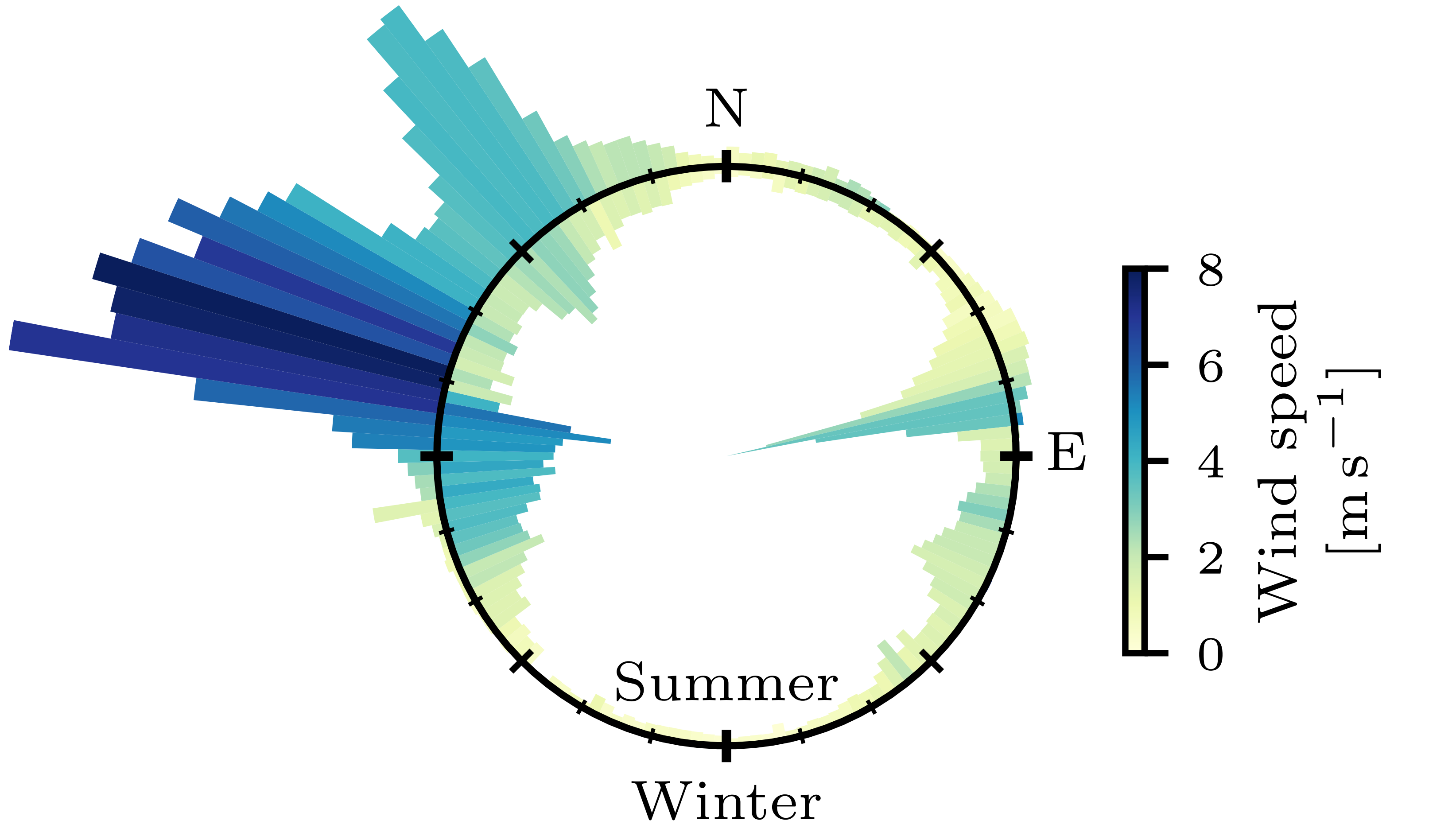


VPM emits *at same frequency* **as polarization modulation.**

Demodulation *does not account* **for the VSS, therefore, VSS → DC levels in demodulated polarization data.**

- *Stable*: **does not significantly impact 1/f.**
- **Contribute to the** *scan synchronous noise*.
- **Intensity-like:** *cancels upon pair-diff*.


wind bearing
wind speed
0°
90°
10
5
Power [pW]
−0.0002
0.0000
0.0002


N
E
Summer
Winter
Wind speed [m s−1]
0
2
4
6
8

	$2 \leq \ell \leq 30$			$31 \leq \ell < 301$		
Splits	*EE*	*BB*	*EB*	*EE*	*BB*	*EB*
top/bot	0.11	0.16	0.39	0.07	0.06	0.77
left/right	0.29	0.76	0.27	0.19	0.94	0.57
radial	0.34	0.67	0.44	0.88	0.93	0.05
horizontal	0.63	0.21	0.65	0.59	0.40	0.81
vertical	0.41	0.97	0.73	0.60	0.52	0.22
quadrupole	0.97	0.98	0.47	0.54	0.09	0.25
MUX halves	0.17	0.44	0.75	0.86	0.82	0.91
MUX parity	0.08	0.88	0.36	0.58	0.67	0.06
VPM sync.	0.00_0	0.45	0.11	0.73	0.01	0.84
bs in/out	0.97	0.72	0.86	0.68	0.96	0.31
bs pos/neg	0.13	0.29	0.73	0.88	0.12	0.01
az-east/west	0.23	0.00_2	0.64	0.03	0.33	0.92
az-2π	0.83	0.97	0.99	0.44	0.40	0.93
az-4π	0.74	0.53	0.99	0.07	0.68	0.88
az-velocity	0.43	0.84	0.99_7	0.39	0.16	0.62
6h in/out	0.57	0.22	0.34	0.98	0.34	0.03
moon	0.46	0.24	0.35	0.93	0.88	0.58
midnight	0.75	0.15	0.30	0.10	0.17	0.02
survey	0.17	0.02	0.42	0.77	0.87	0.67
KS test	0.29	0.47	0.84	0.61	0.39	0.19