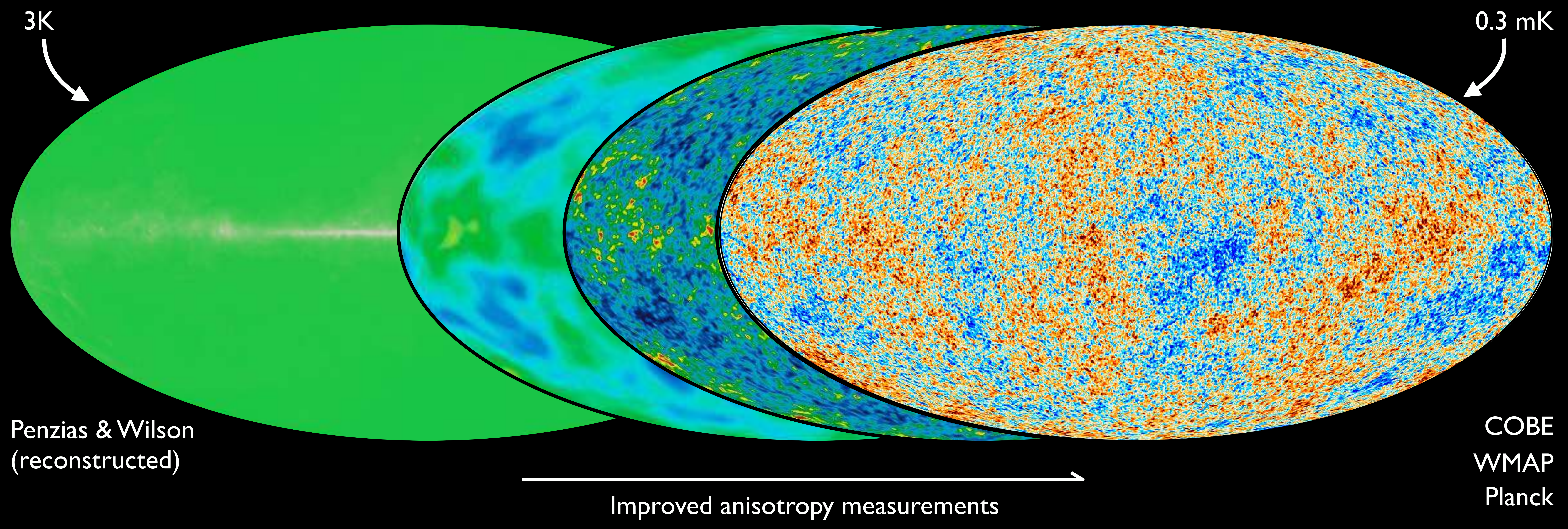
Cosmology Large Angular Scale Surveyor

Recent progress and the 40 GHz results

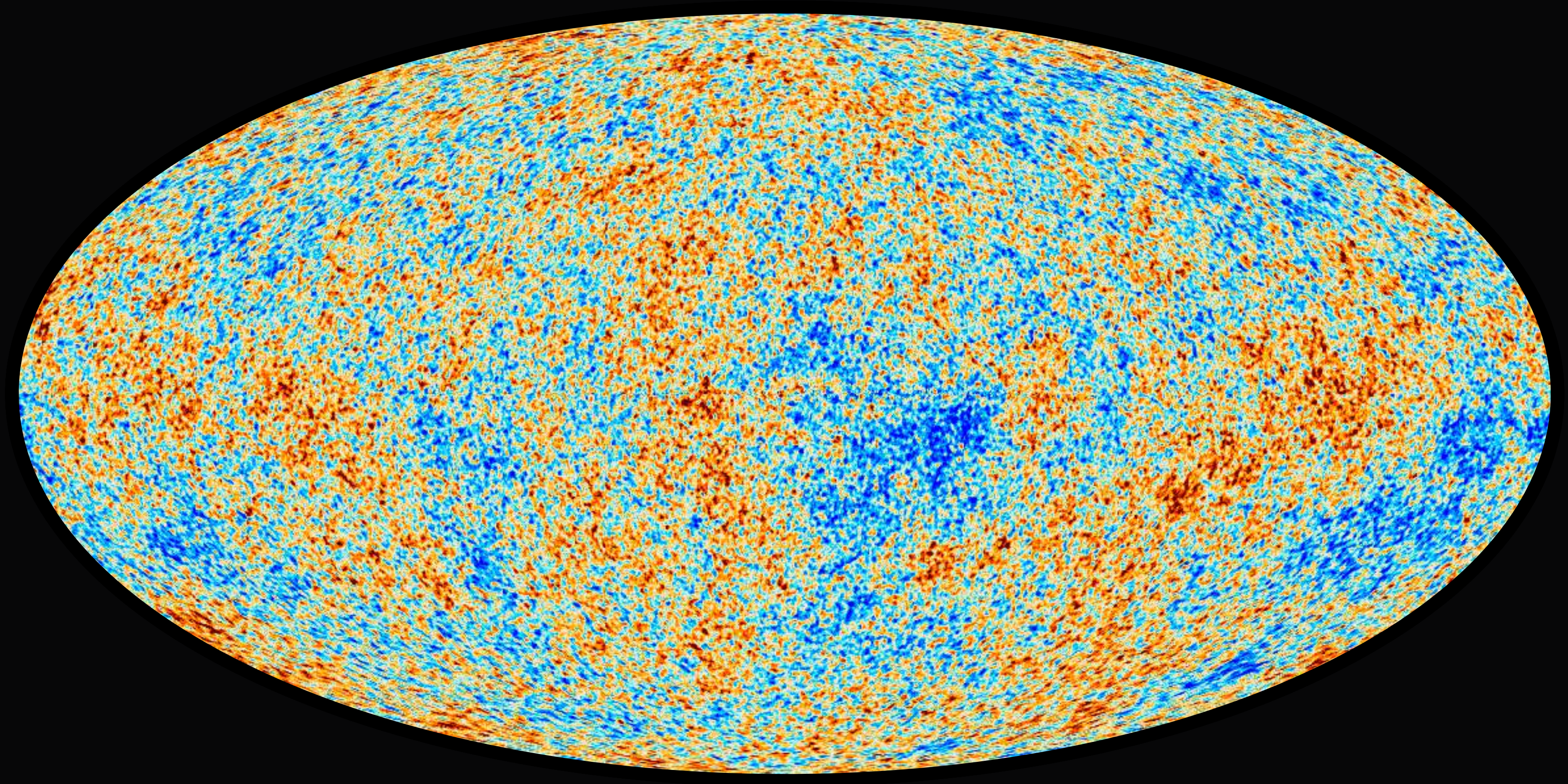
Yunyang Li | Johns Hopkins University | SLAC FPD Seminar 2023


Simons Array
ACT
CLASS
Simons Observatory
M. Petroff

Cosmology learned from the Cosmic Microwave Background



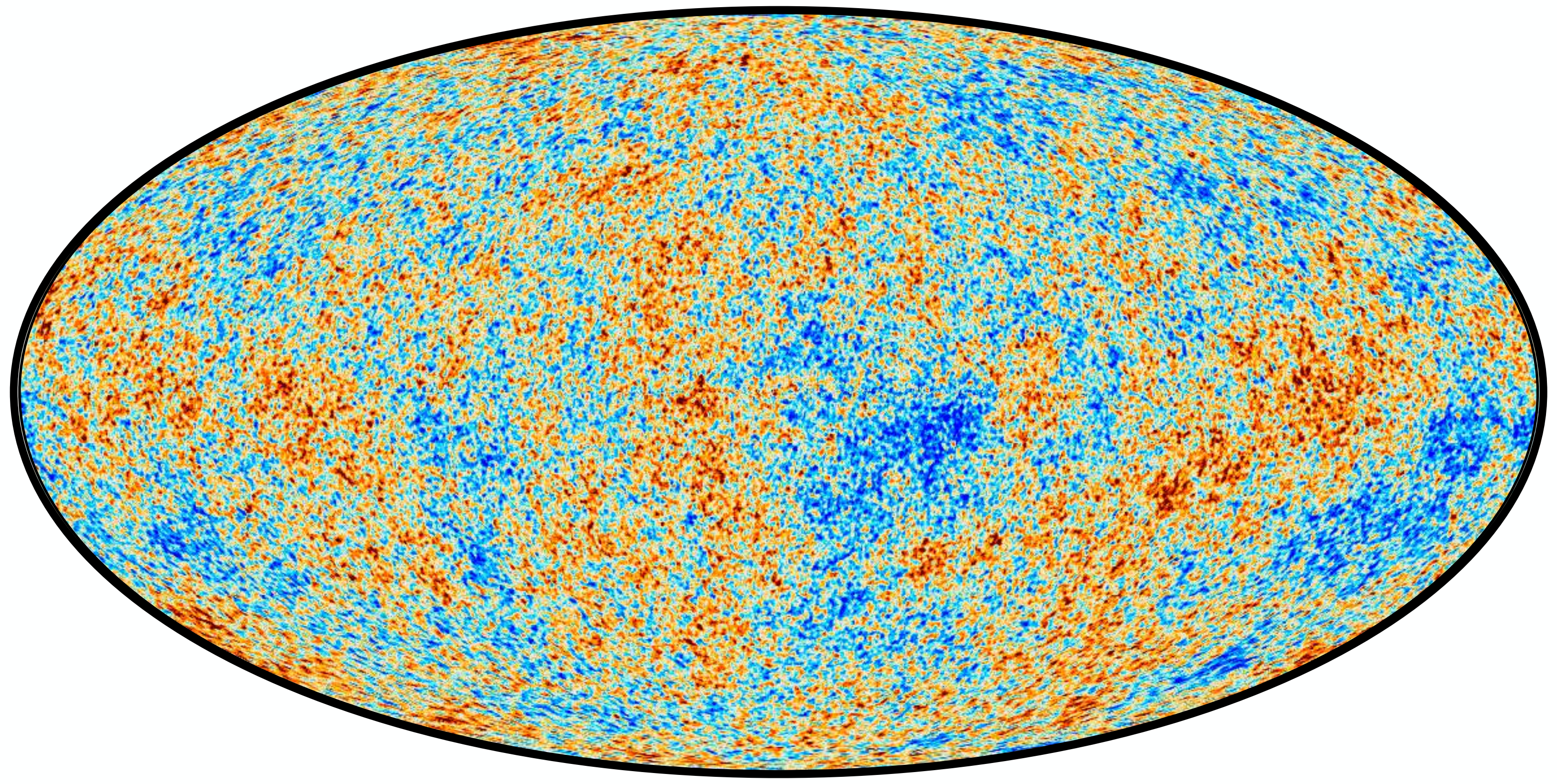
Cosmology learned from the Cosmic Microwave Background



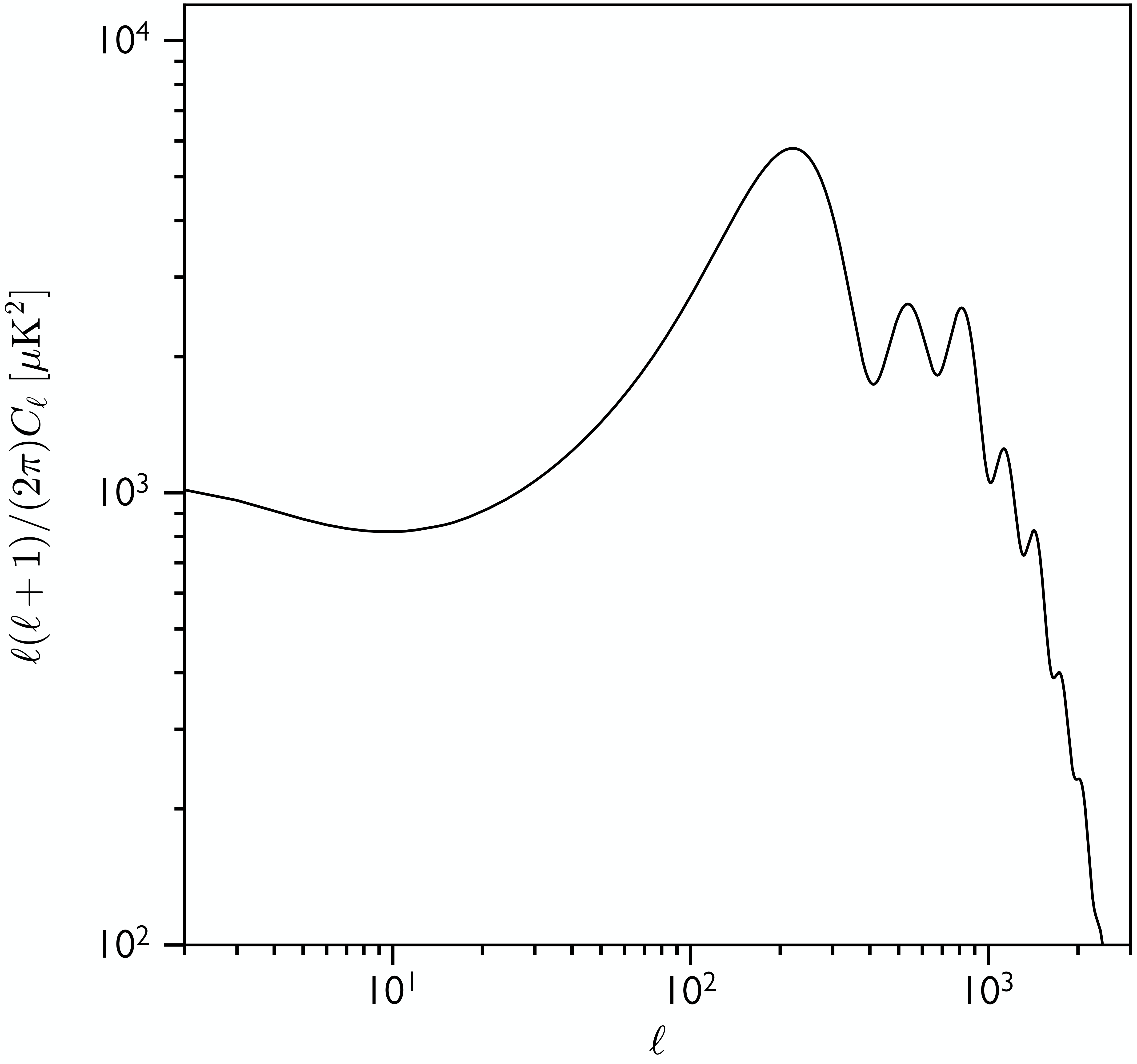
Condordance model of cosmology

- Dark matter and dark energy, in addition to ordinary matter.
- Geometry (flat) and age of the universe (13.8b yr).
- Initial Gaussian fluctuation set up during inflation.
- CMB released at recombination, before the universe was reionized.

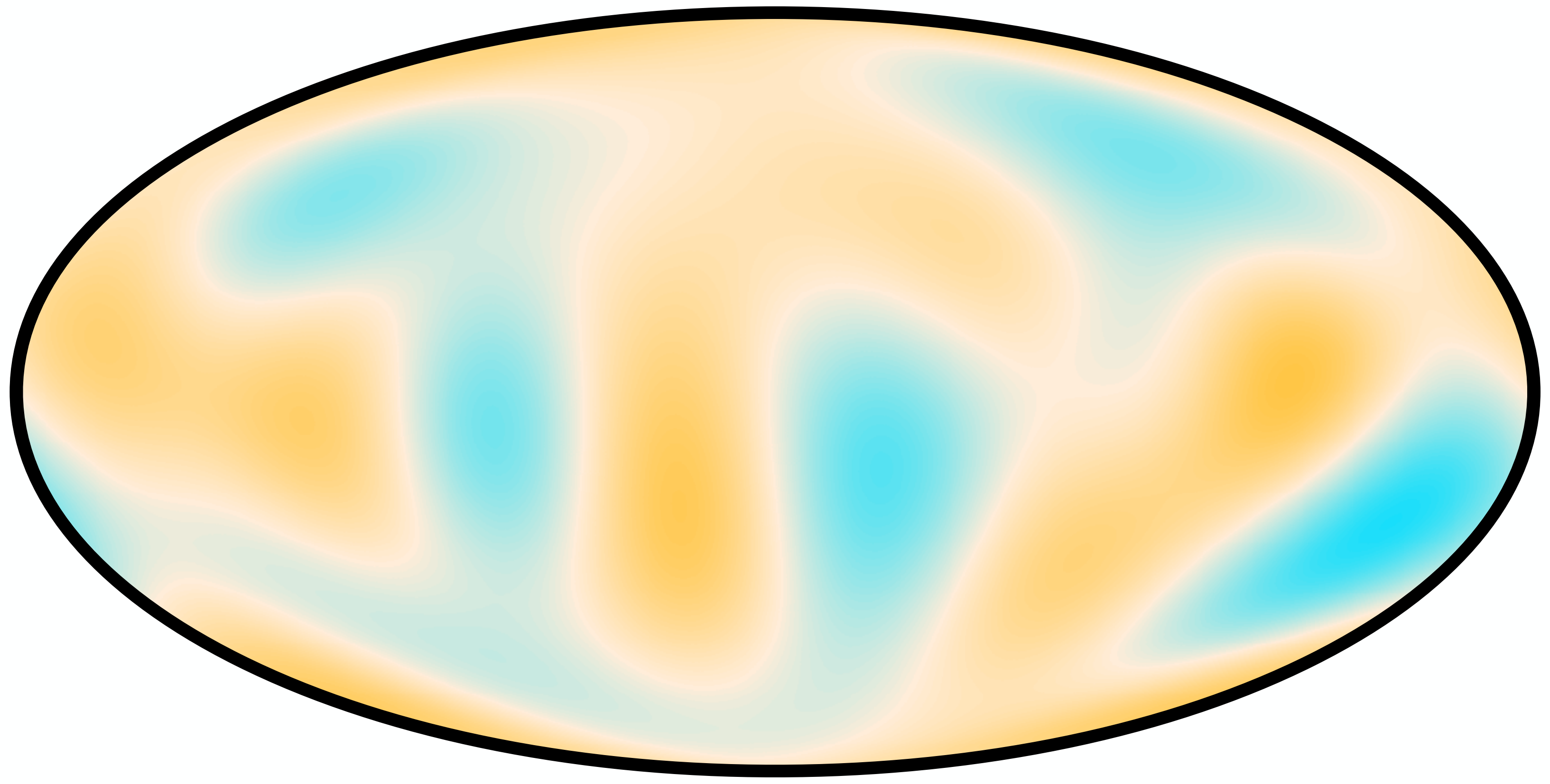
CMB angular spectra



- Angular power spectra describe the amount of power in each spherical harmonic mode.



CMB angular spectra



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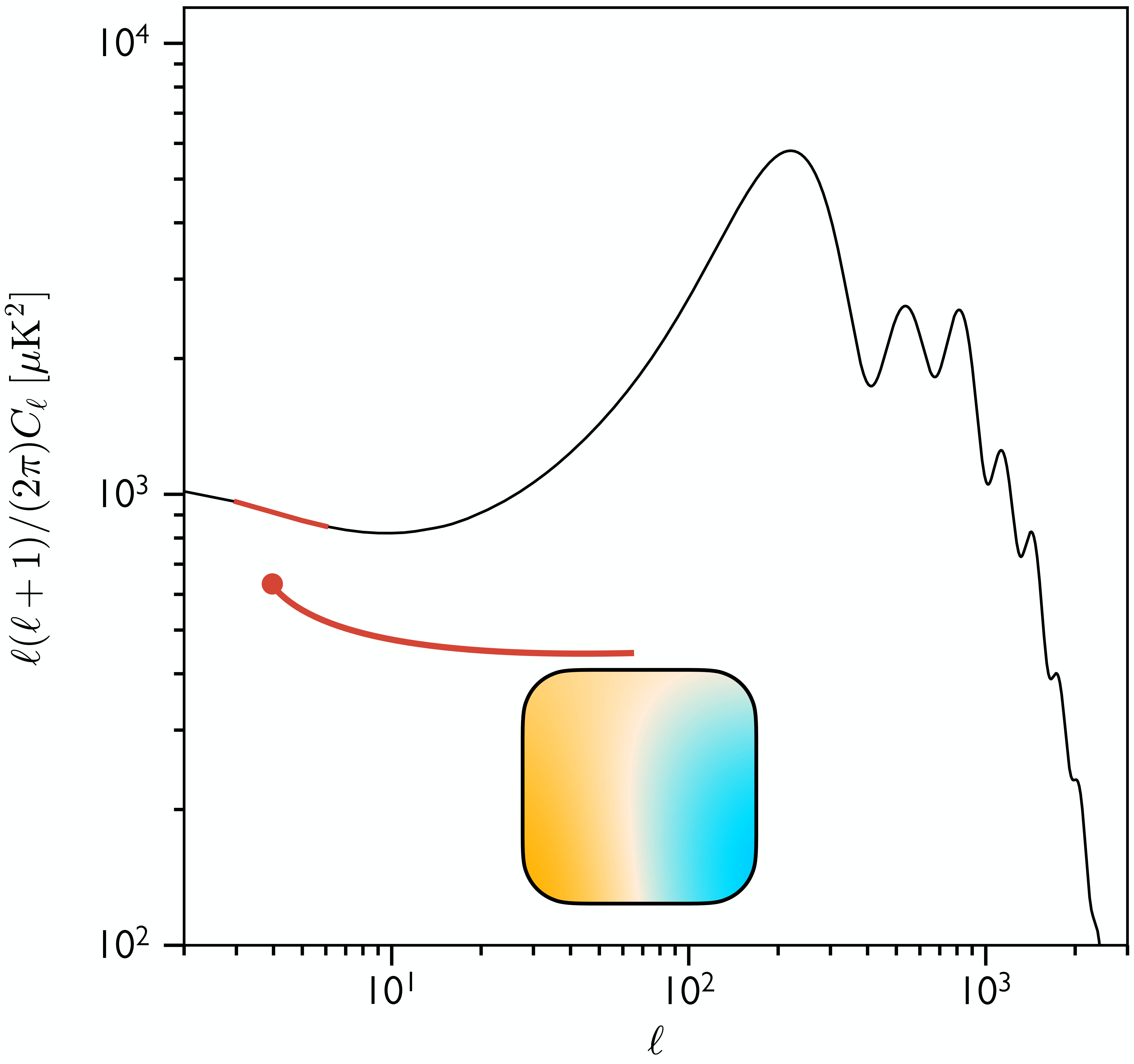
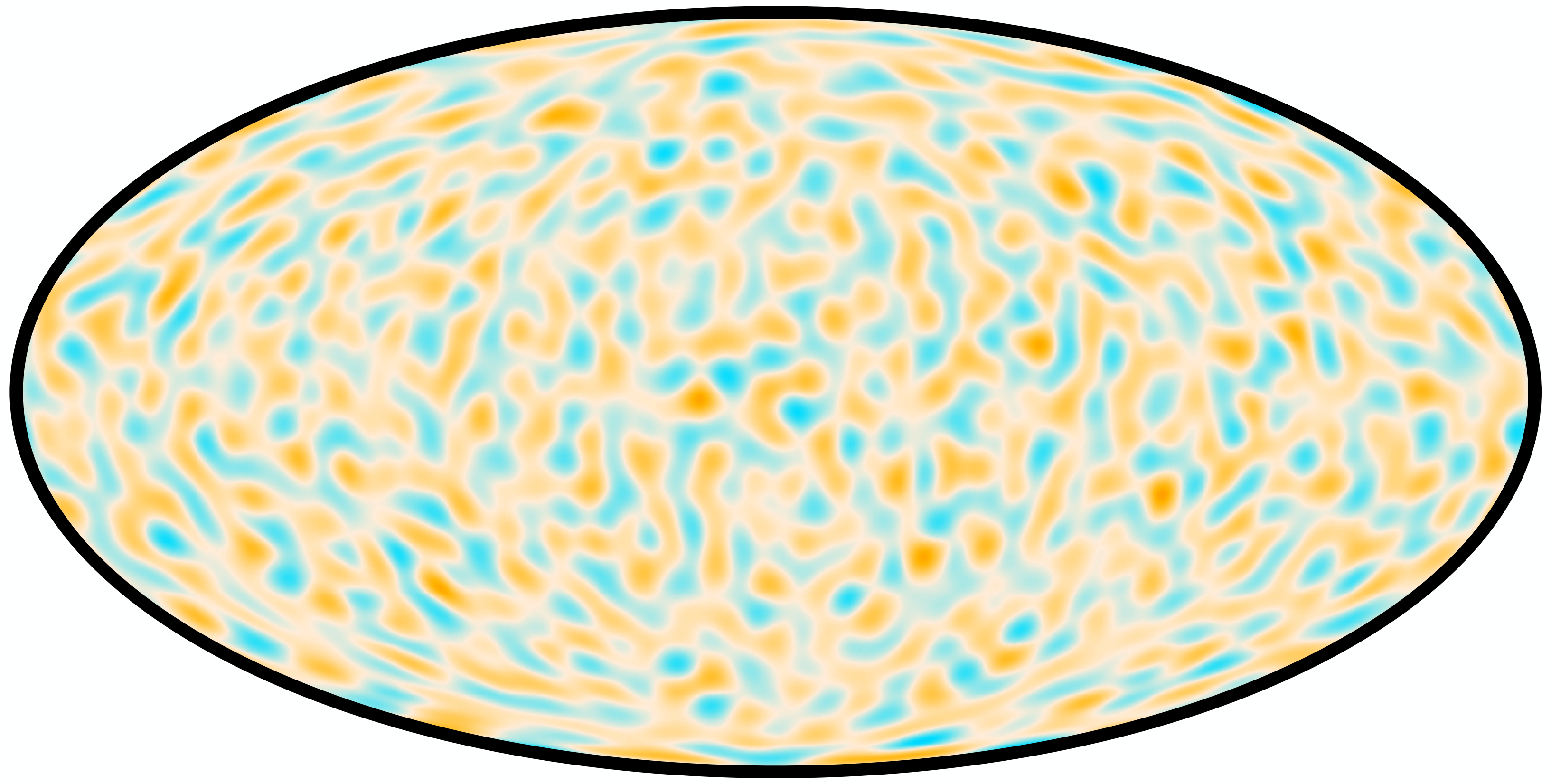


CMB angular spectra



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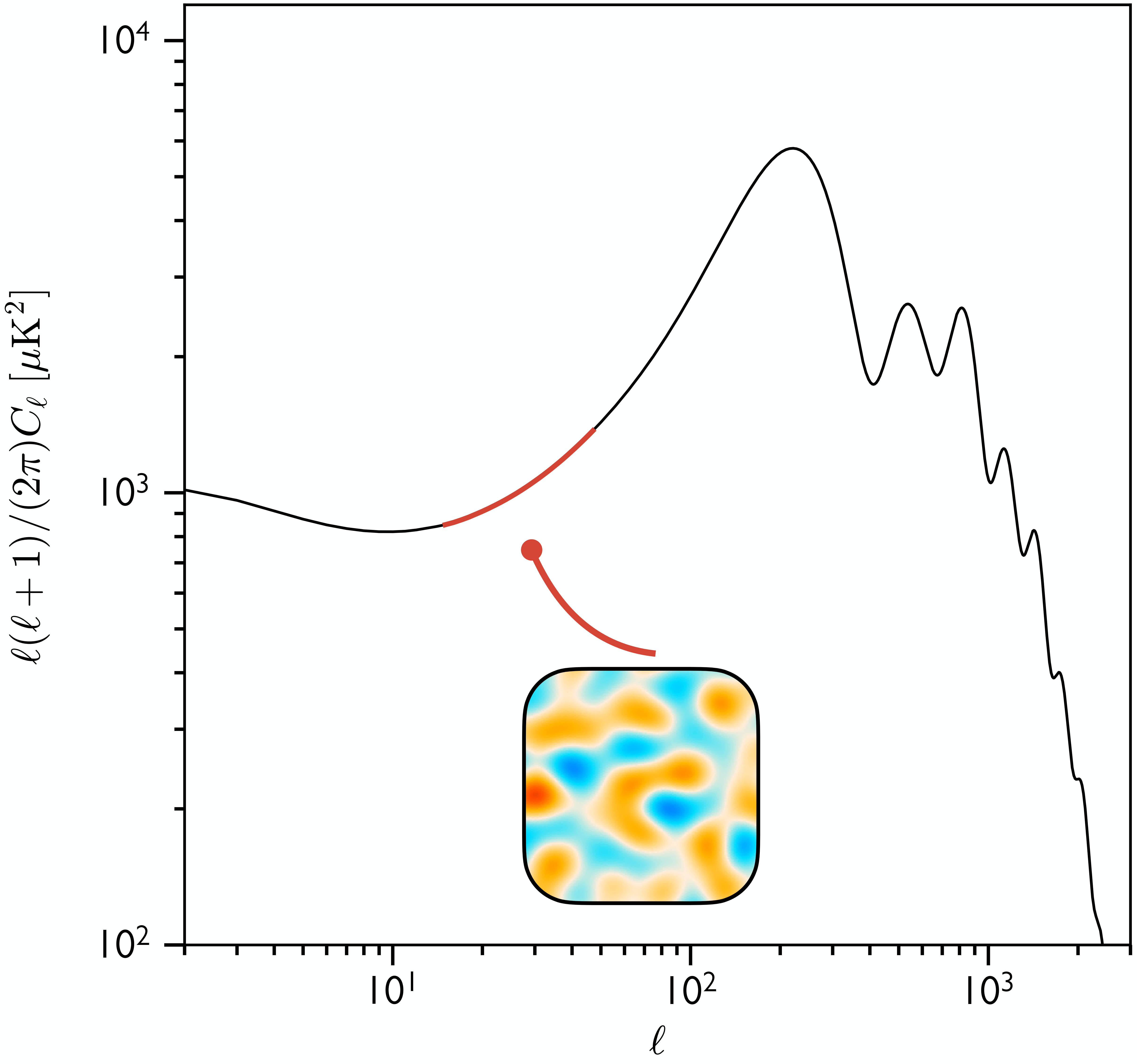
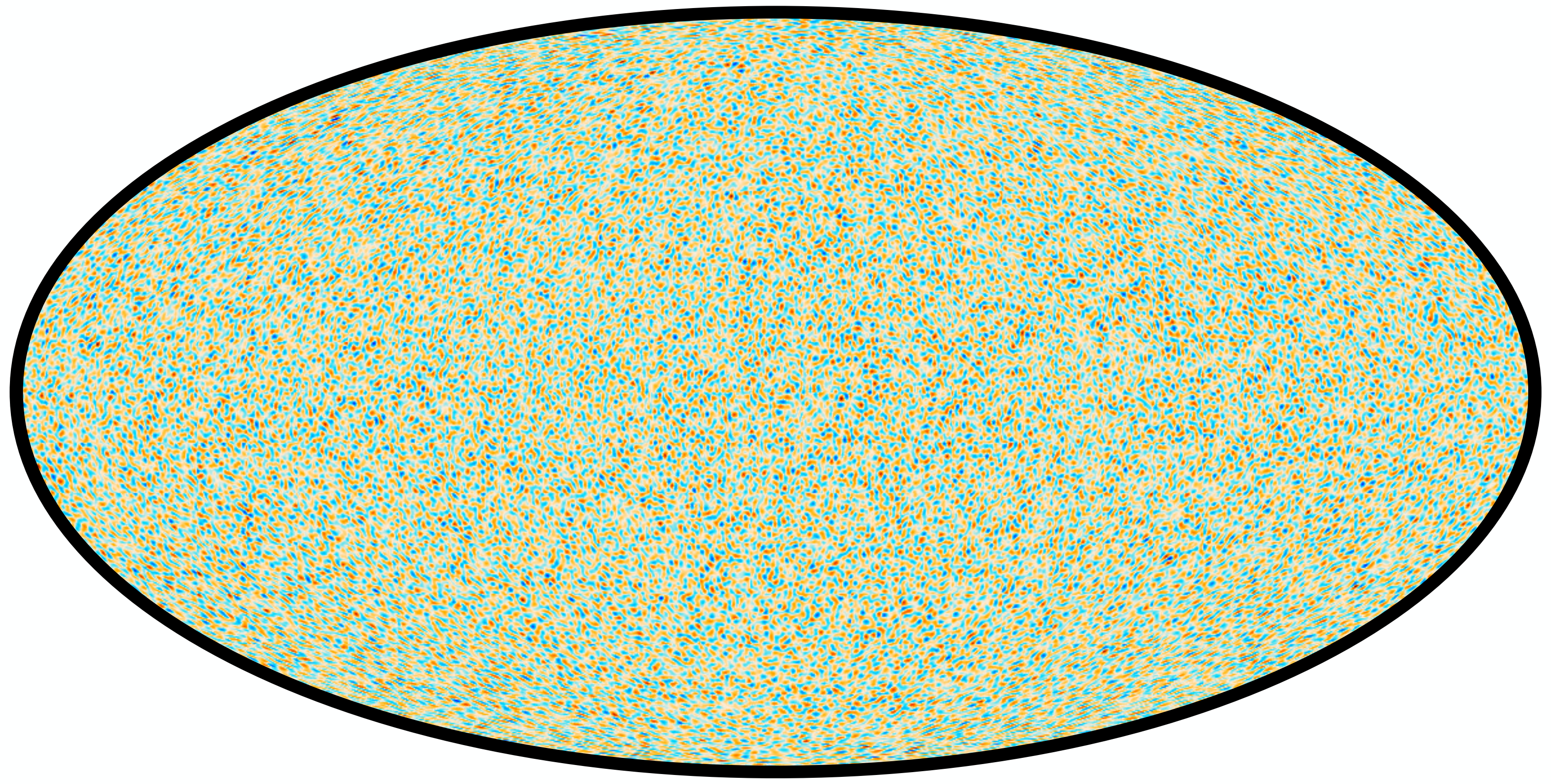
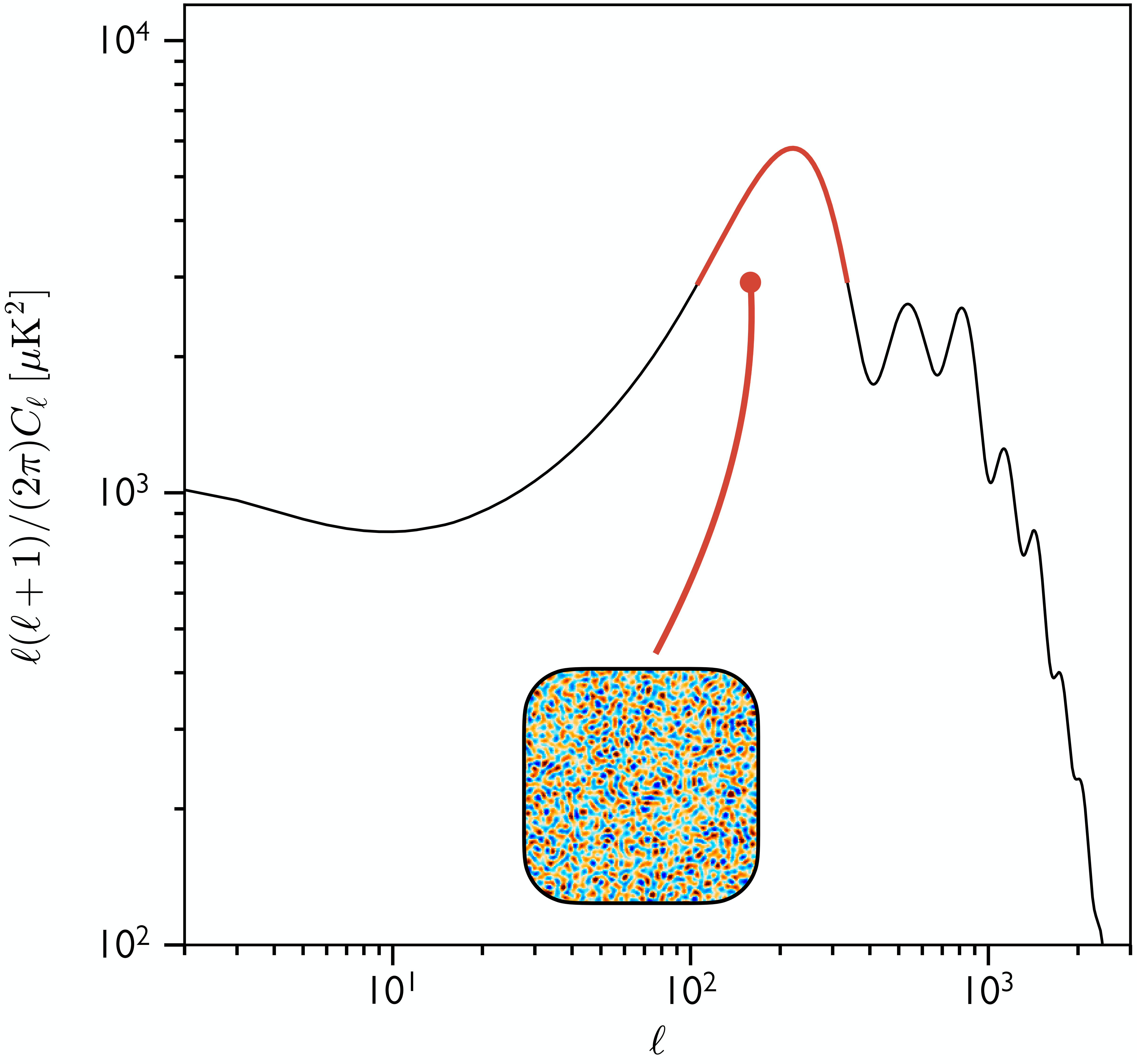


CMB angular spectra



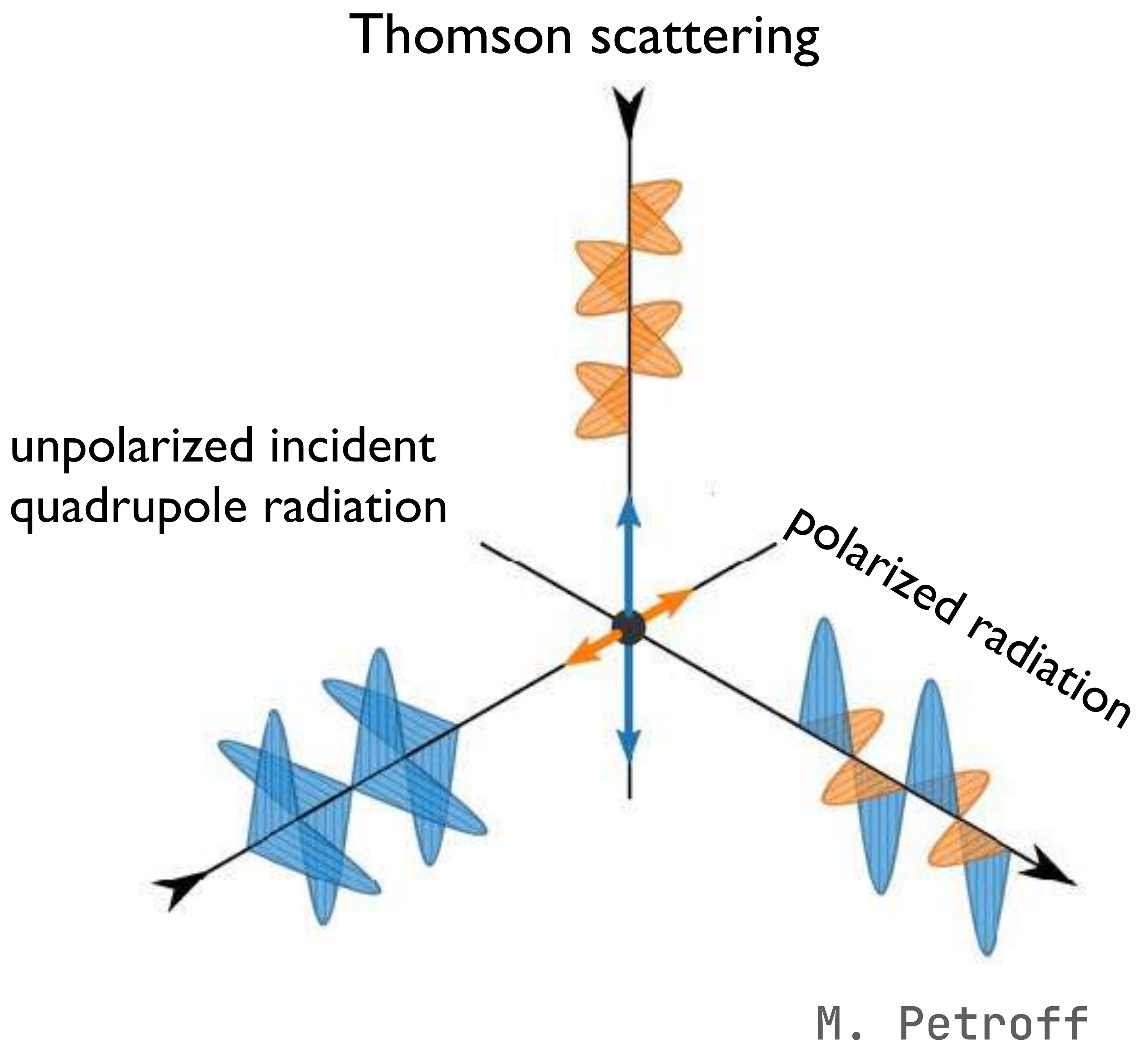
- Angular power spectra describe the amount of power in each spherical harmonic mode.
- Physical processes operate on different scales.
- The overall shape/amplitude of the spectrum tells us cosmology!

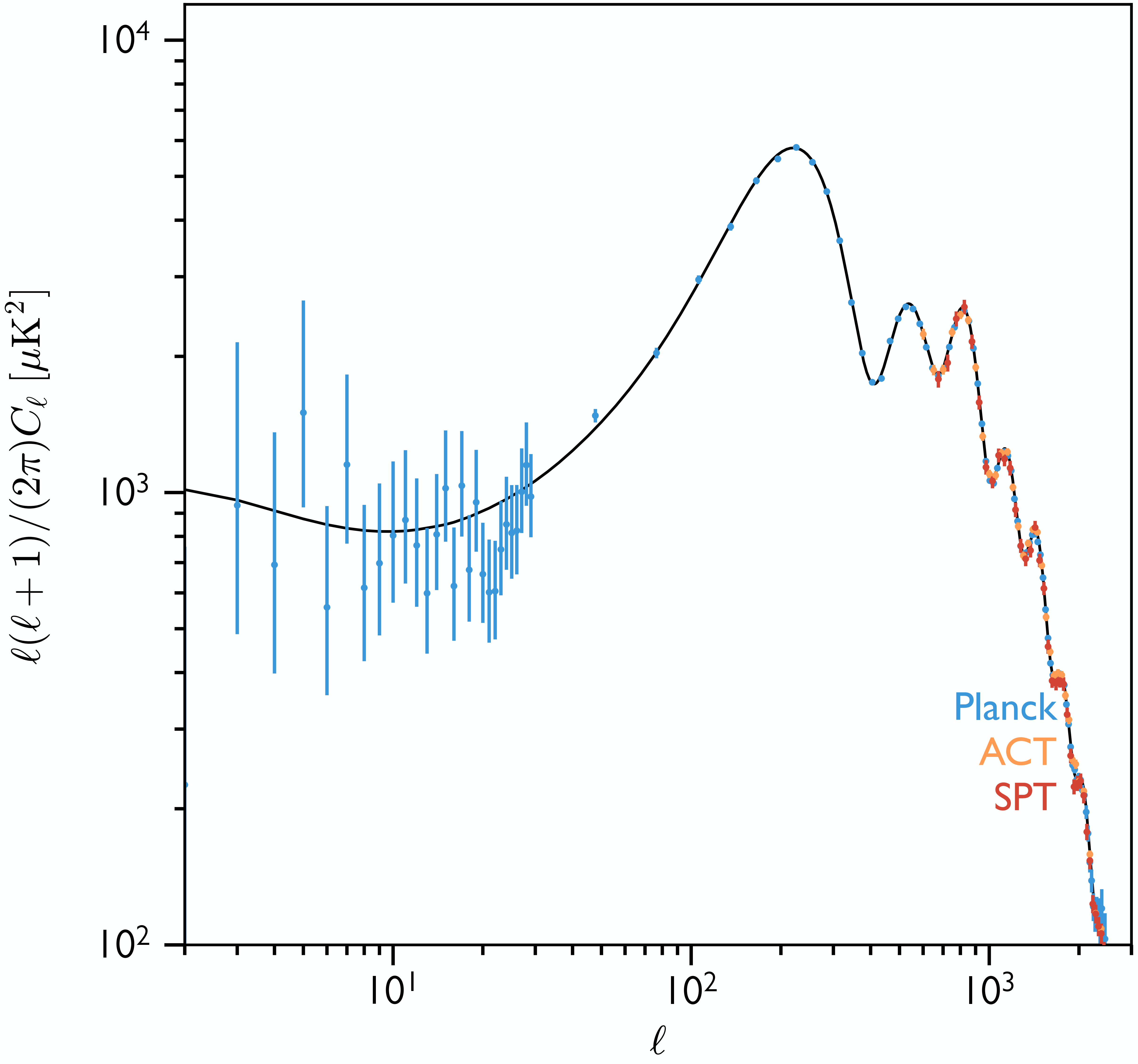


CMB angular spectra

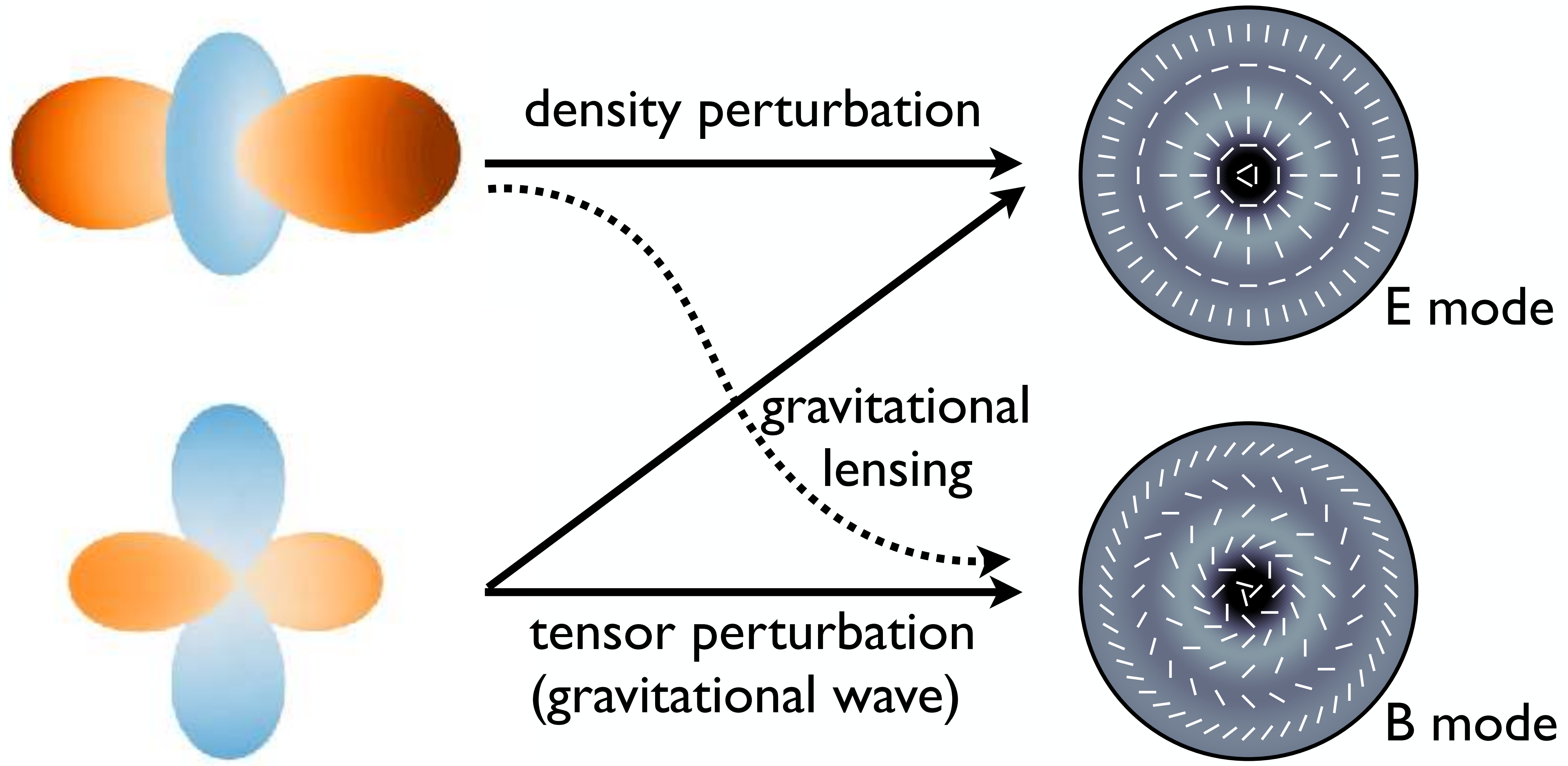
Ground-base experiments have pushed the frontier in CMB measurements in *small angular scales*

and in *polarization*

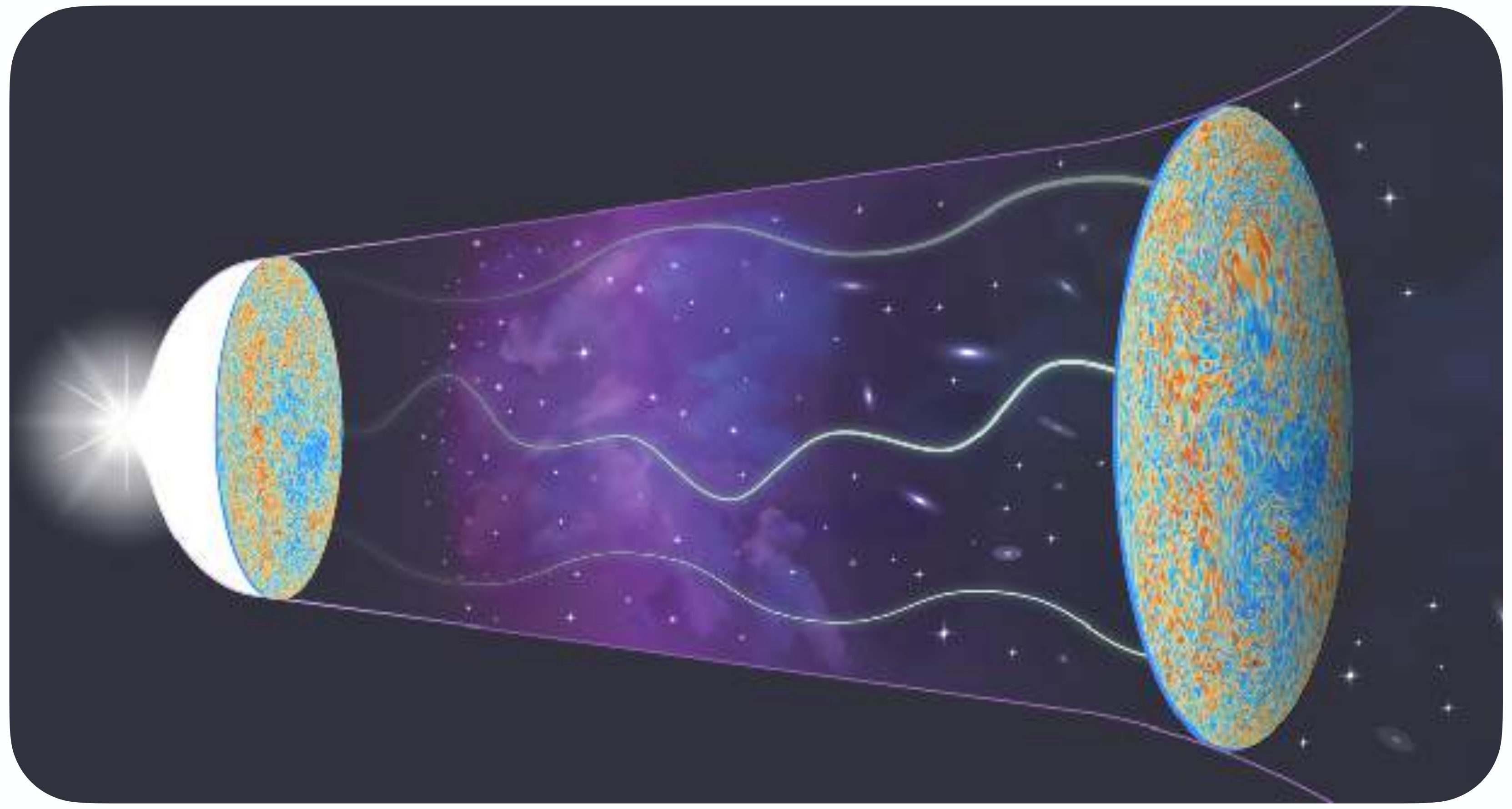


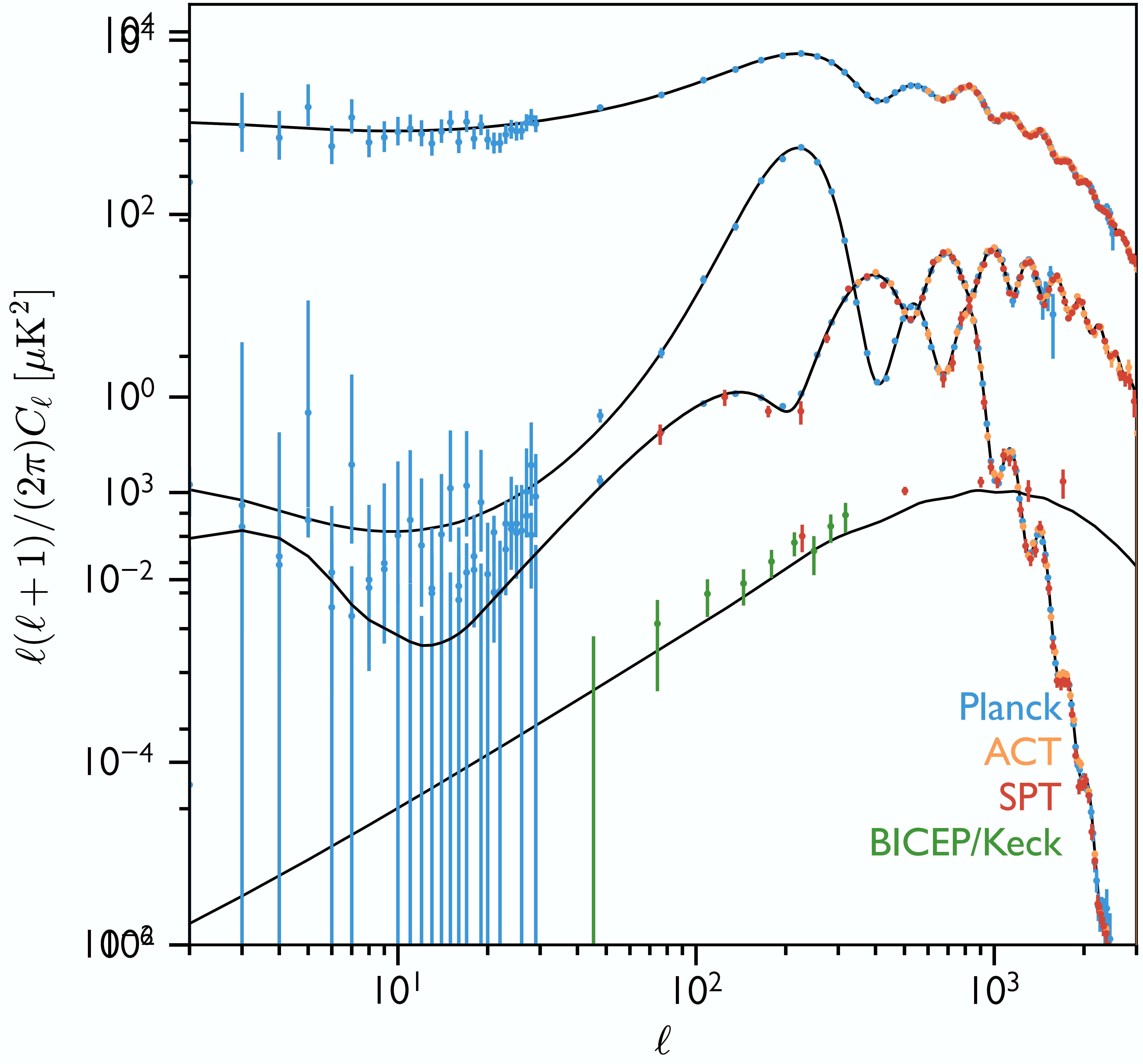


CMB angular spectra: polarization



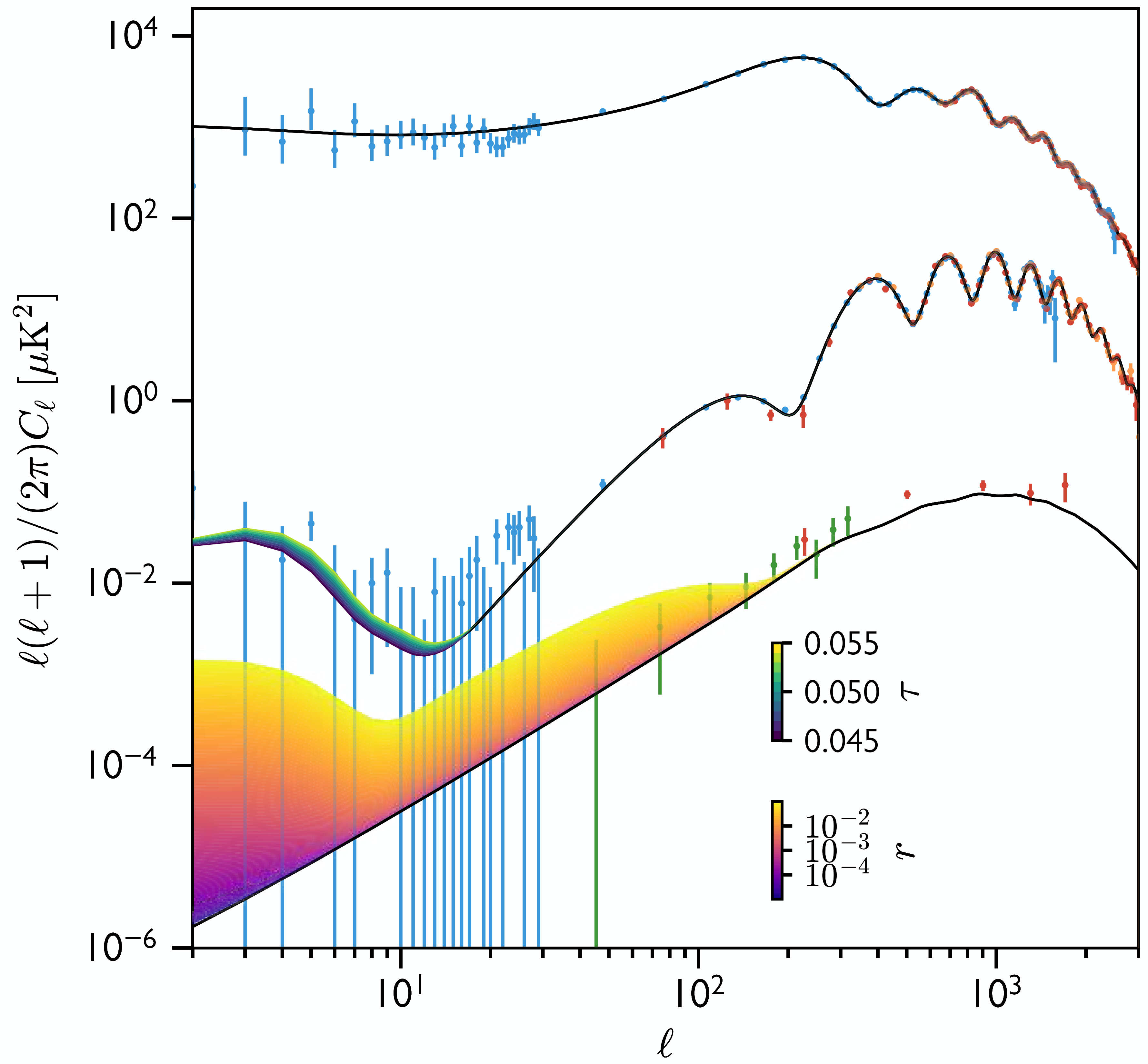
Simons Foundation

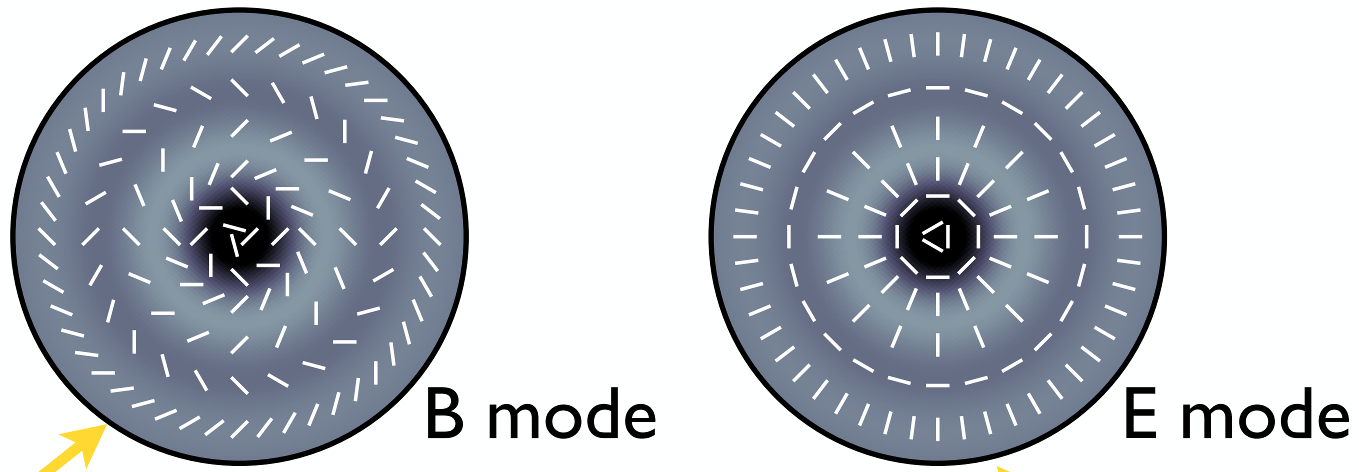


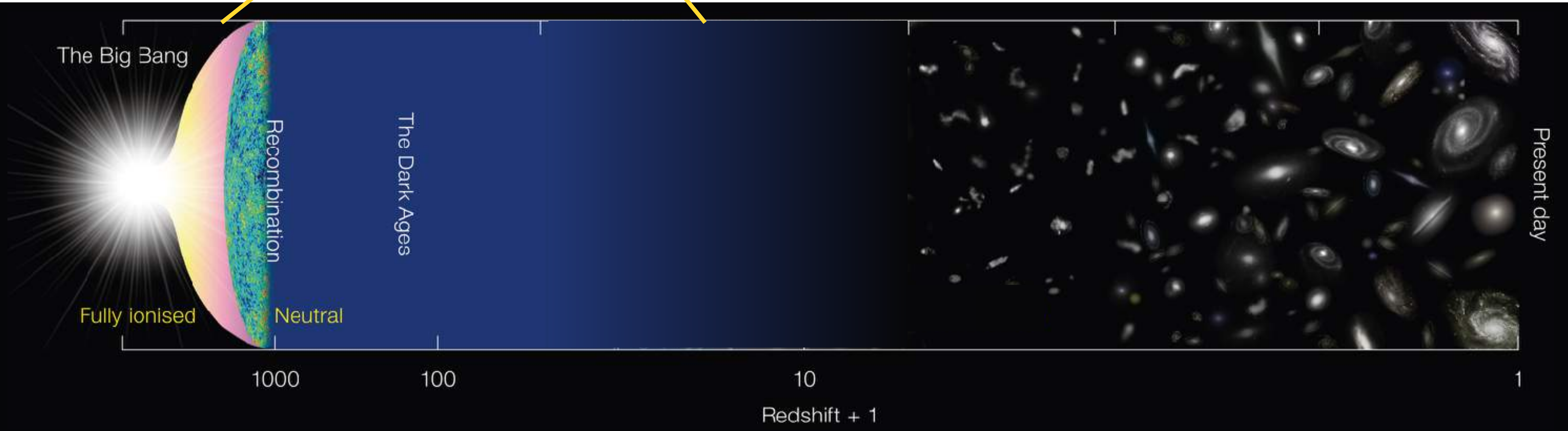


CMB angular spectra: polarization

- Primordial B mode from inflation is most separable from lensing effect at large scale.
- The Thomson scattering from reionization only appears on large-scale E mode.







CMB angular spectra: polarization

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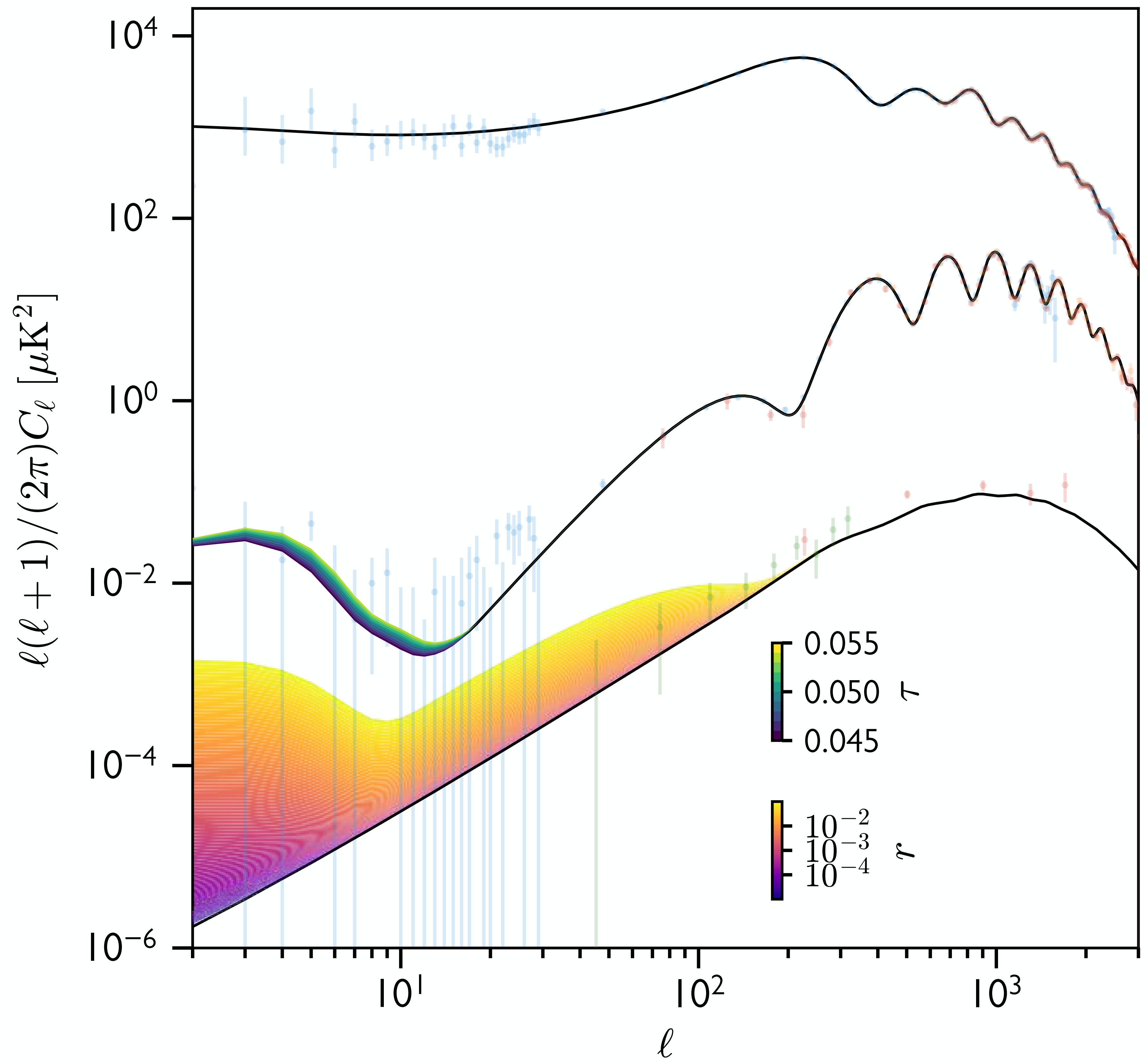
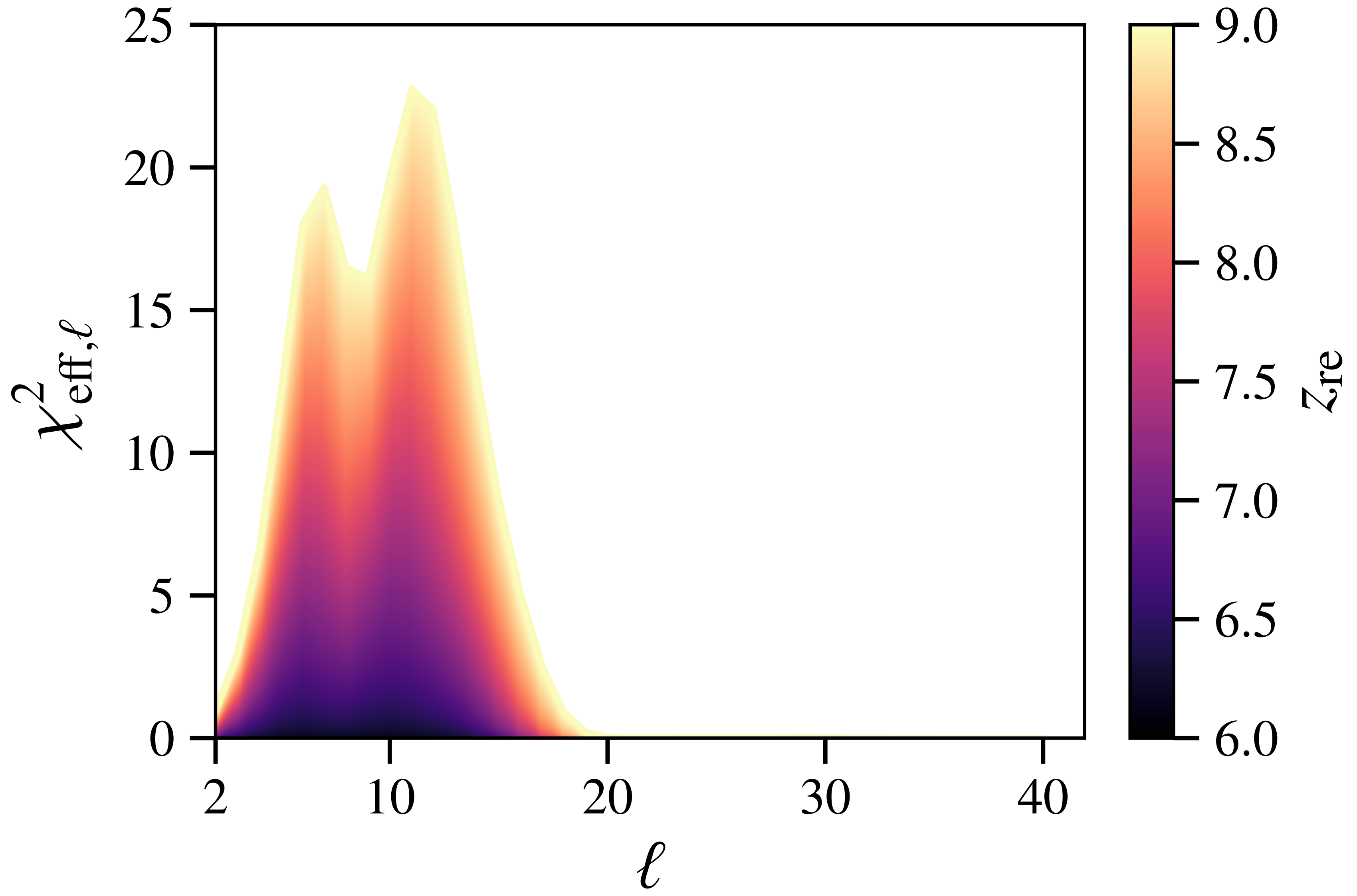
- The low-ℓ shape of the E mode spectra informs the reionization history.





Watts et al. (2020)

CMB Angular Spectra: polarization

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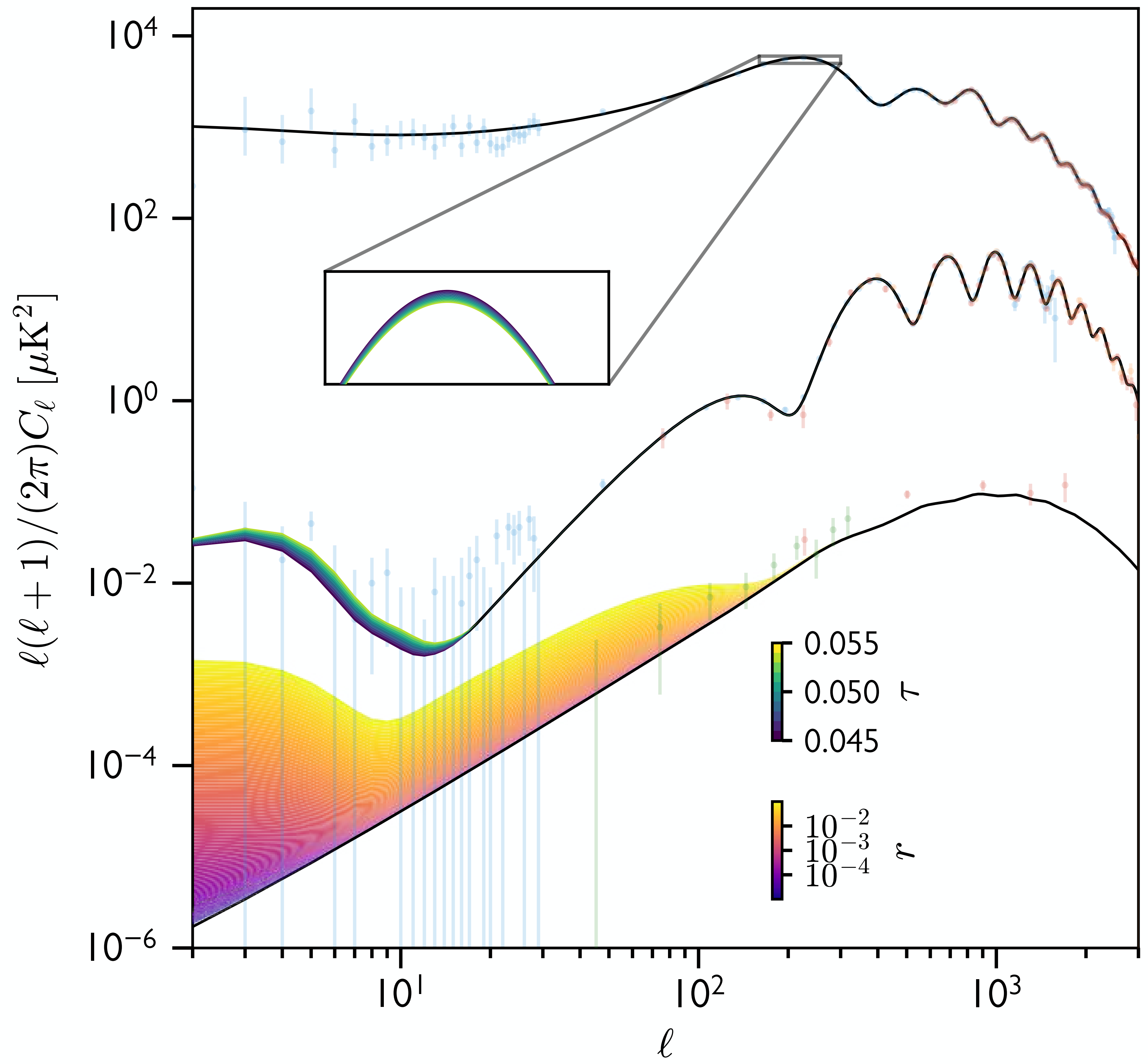
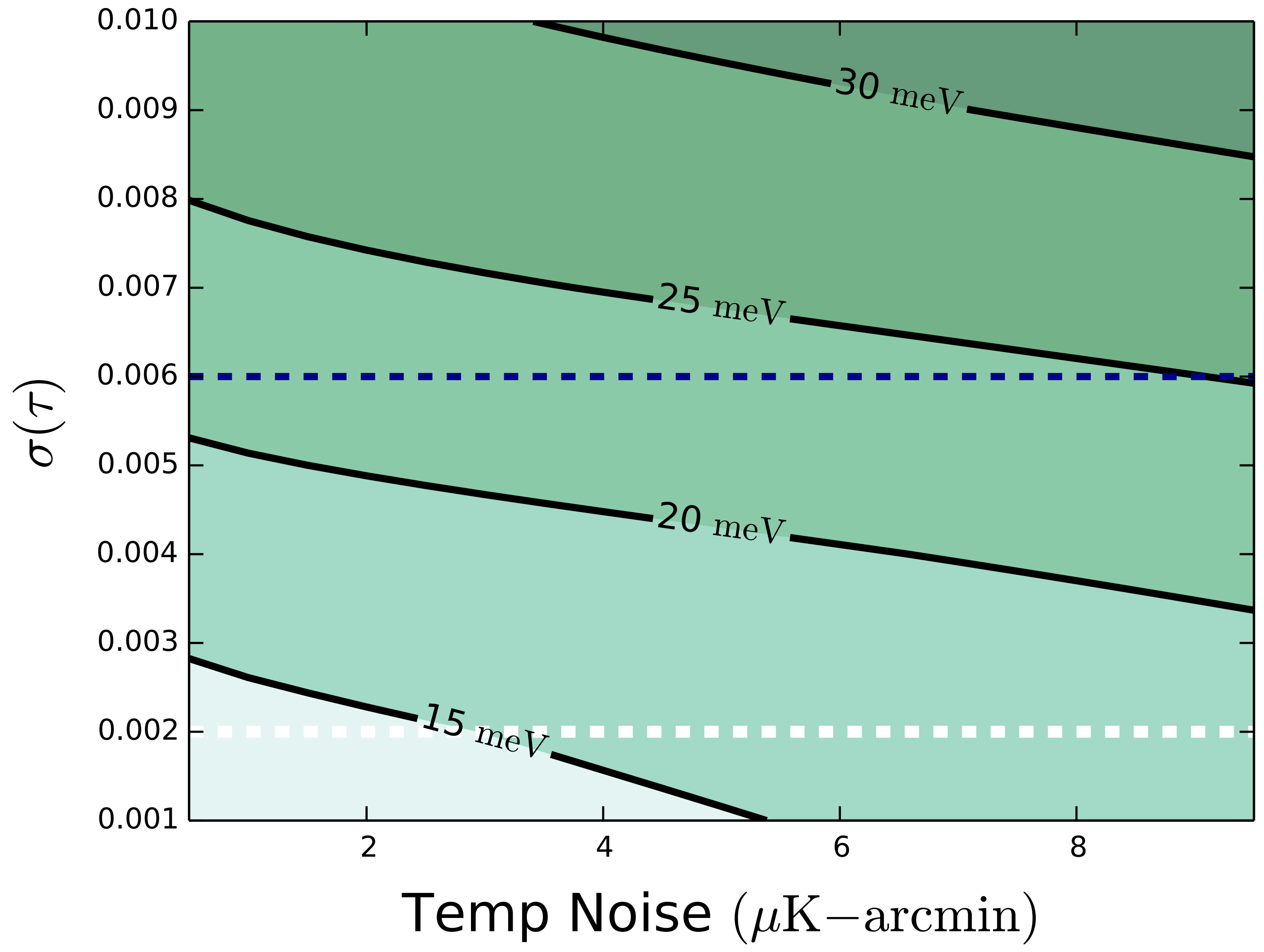
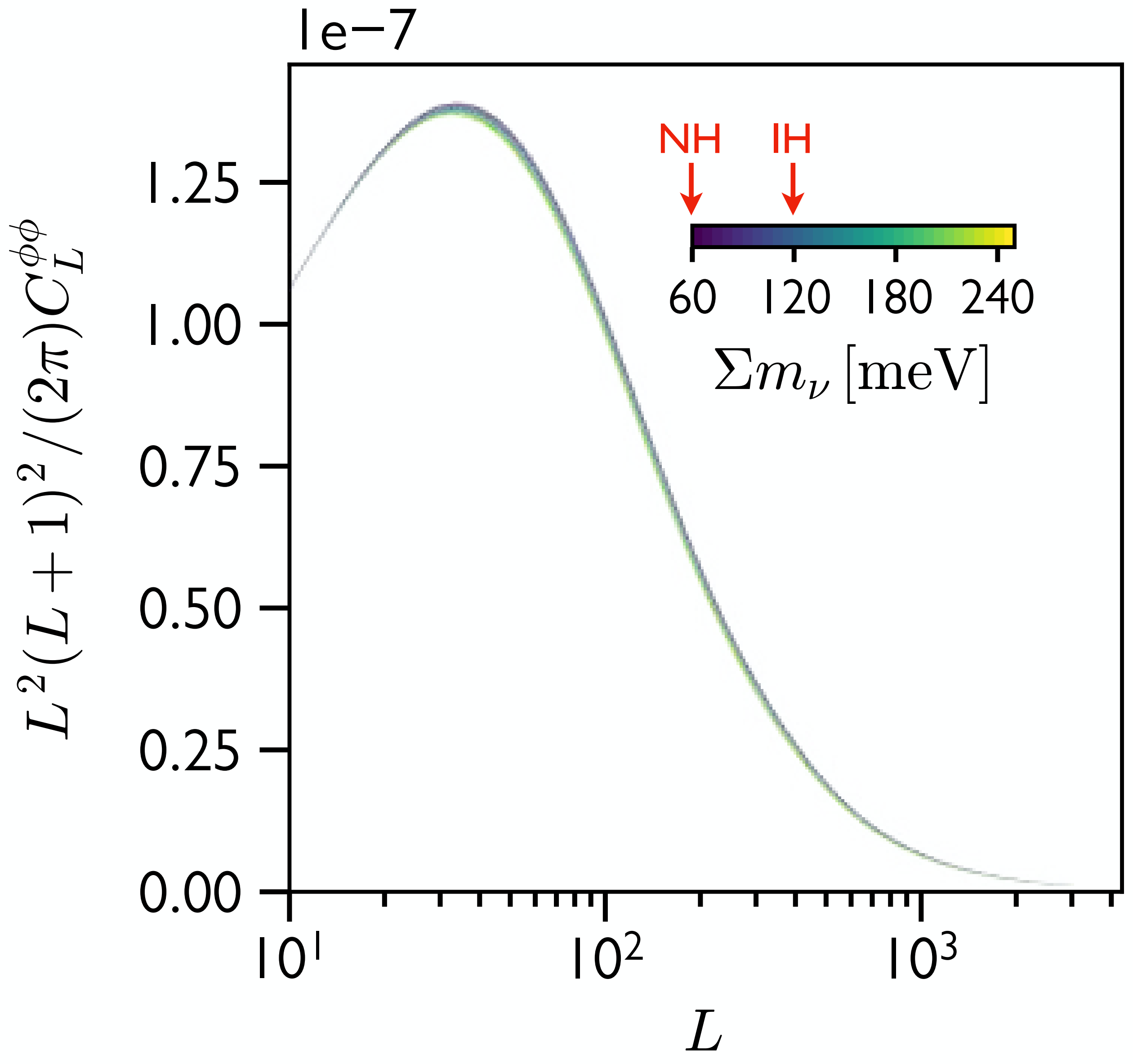


CMB.S4 Science book



CMB lensing (or other LSS tracers)



- Measurement of τ breaks the degeneracy between scalar perturbation amplitude A_s and lead to accurate neutrino mass measurement!

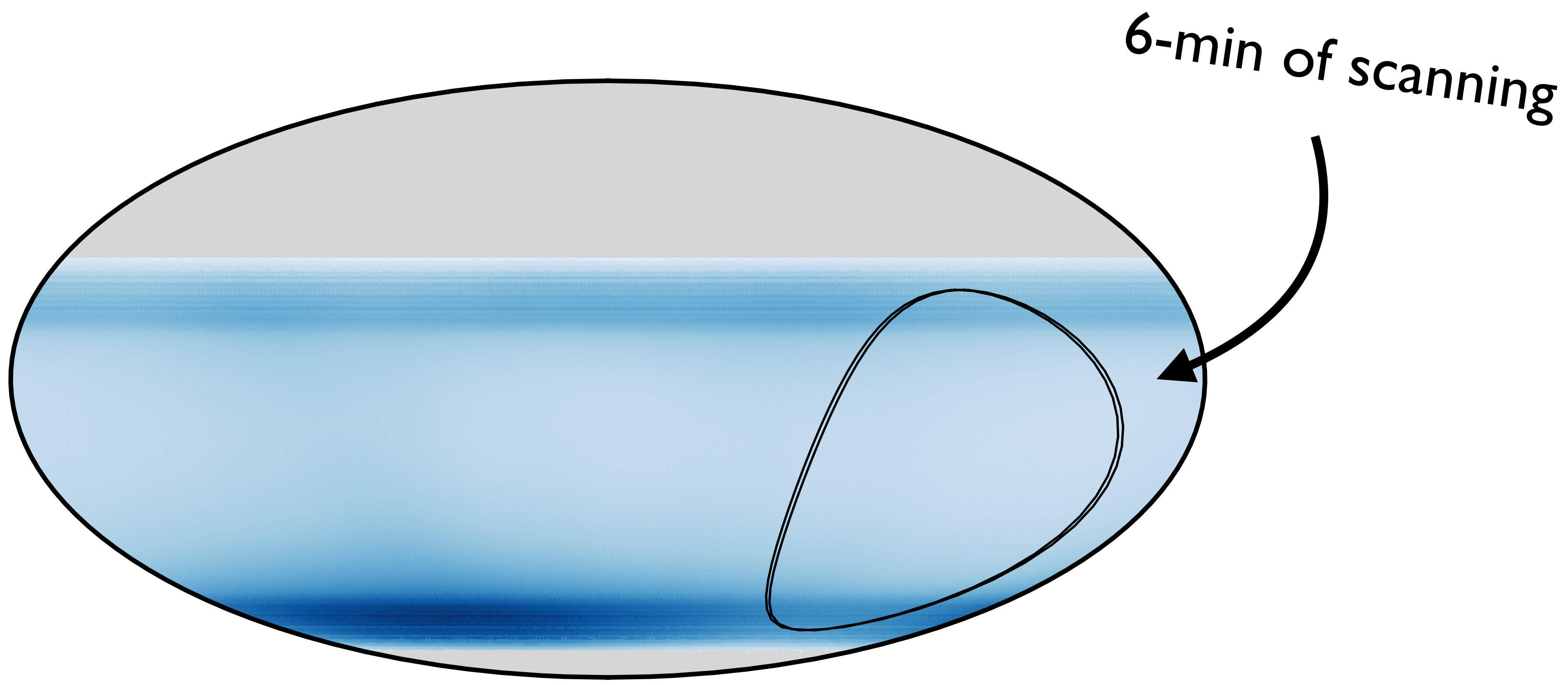
The CLASS Experiment

J. Denes Couto

Site and scan strategy

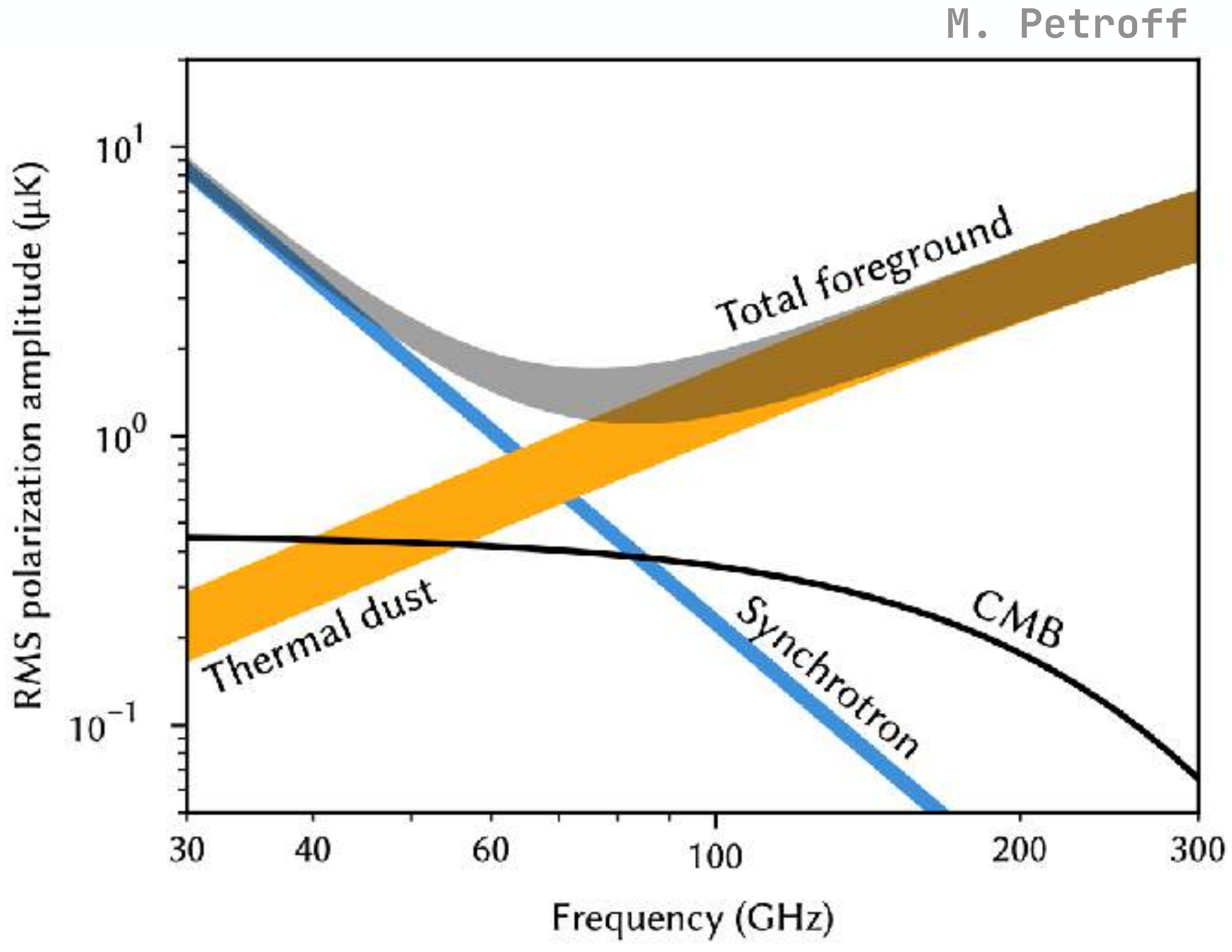
D. Valle

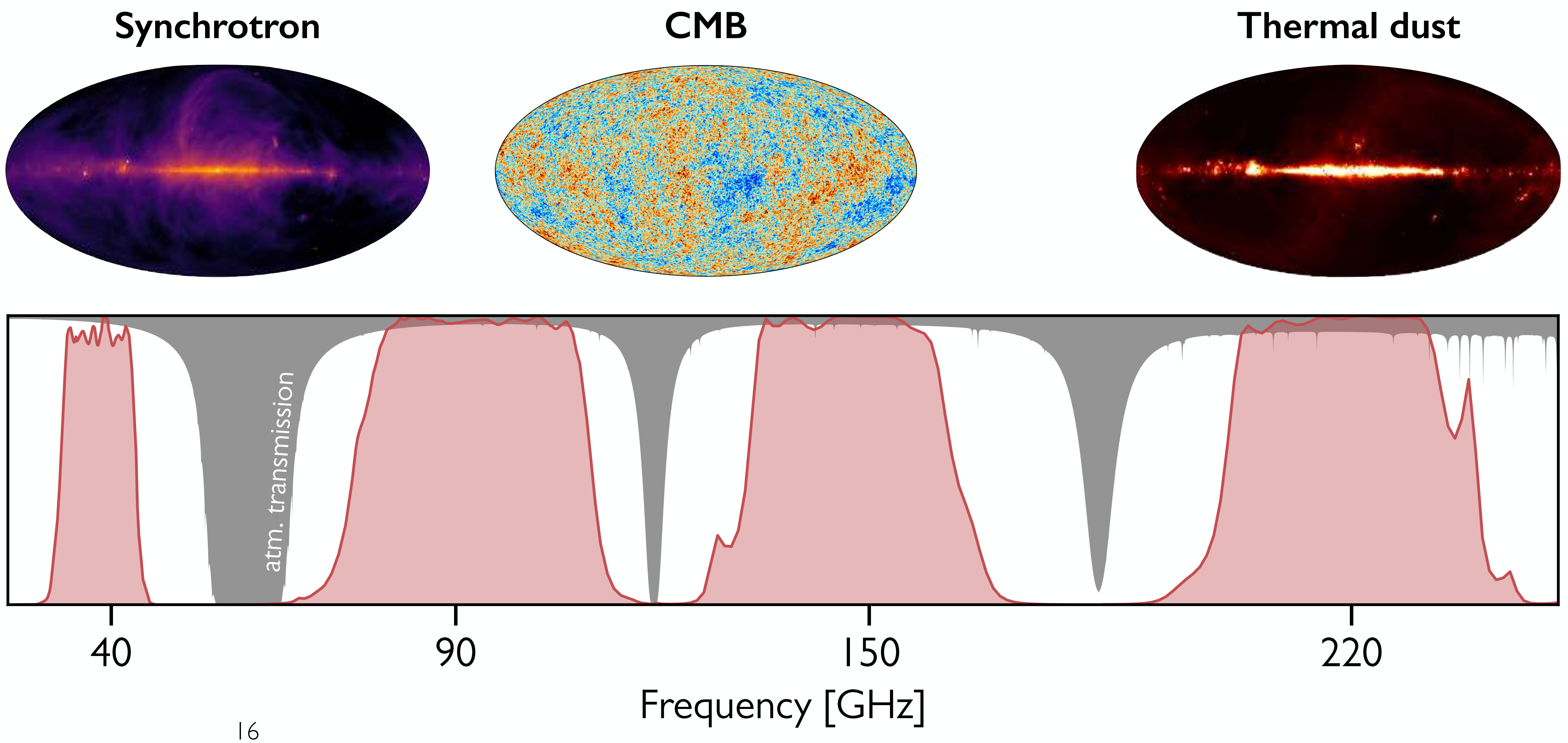
- Access to large fraction of the sky.
- Constant elevation scanning → observe 75% of the sky (minus sun avoidance) daily.



Multifrequency design

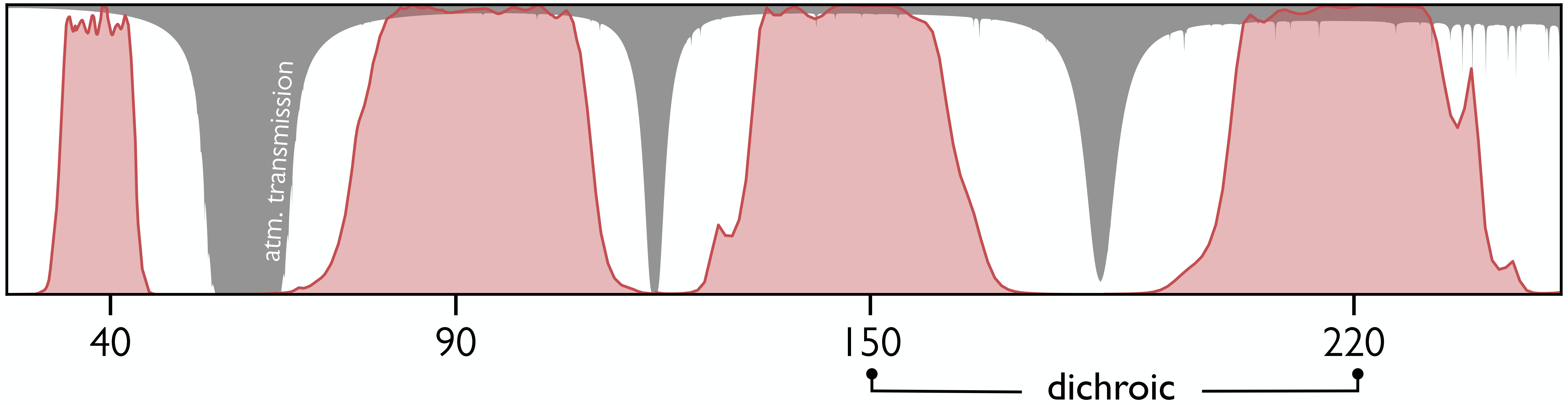
- *Four-frequency* **designed to avoid atmospheric transmission bands while maintaining wide sampling around CMB minimum to handle foregrounds.**

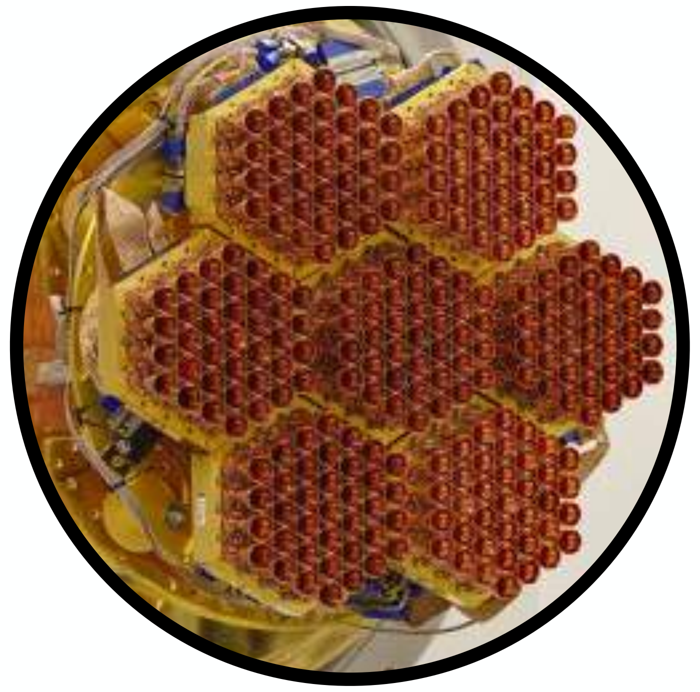




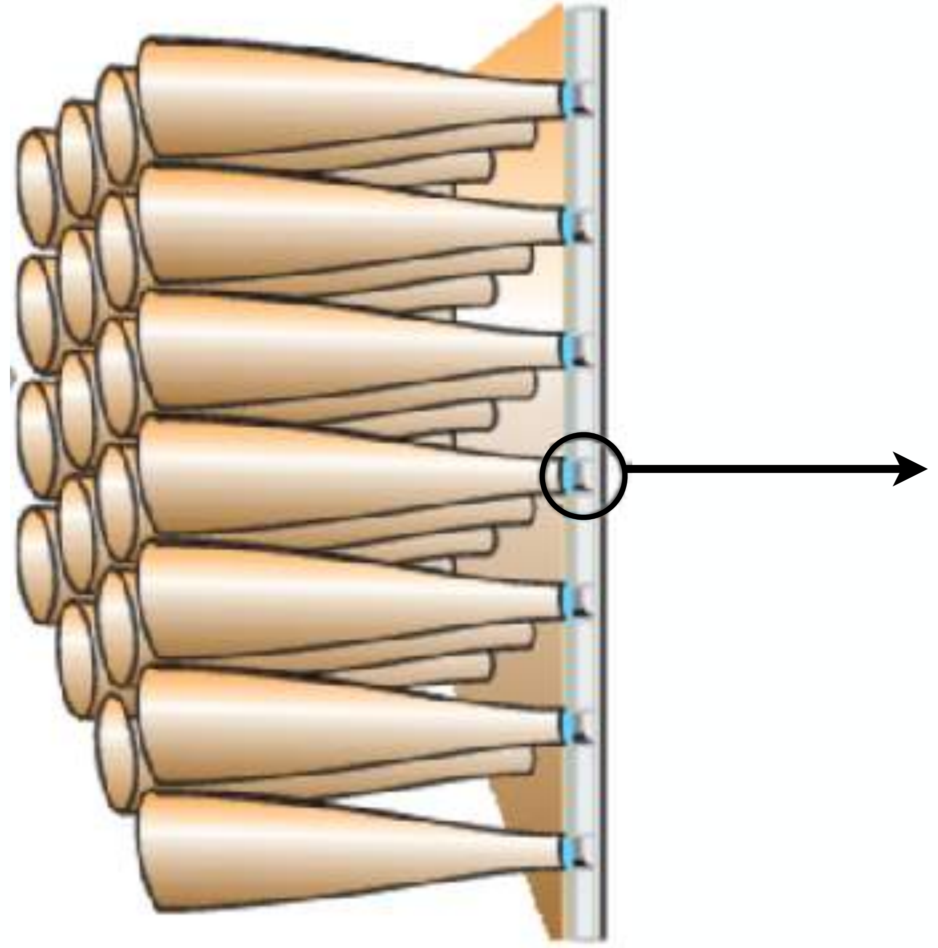
Detector technology

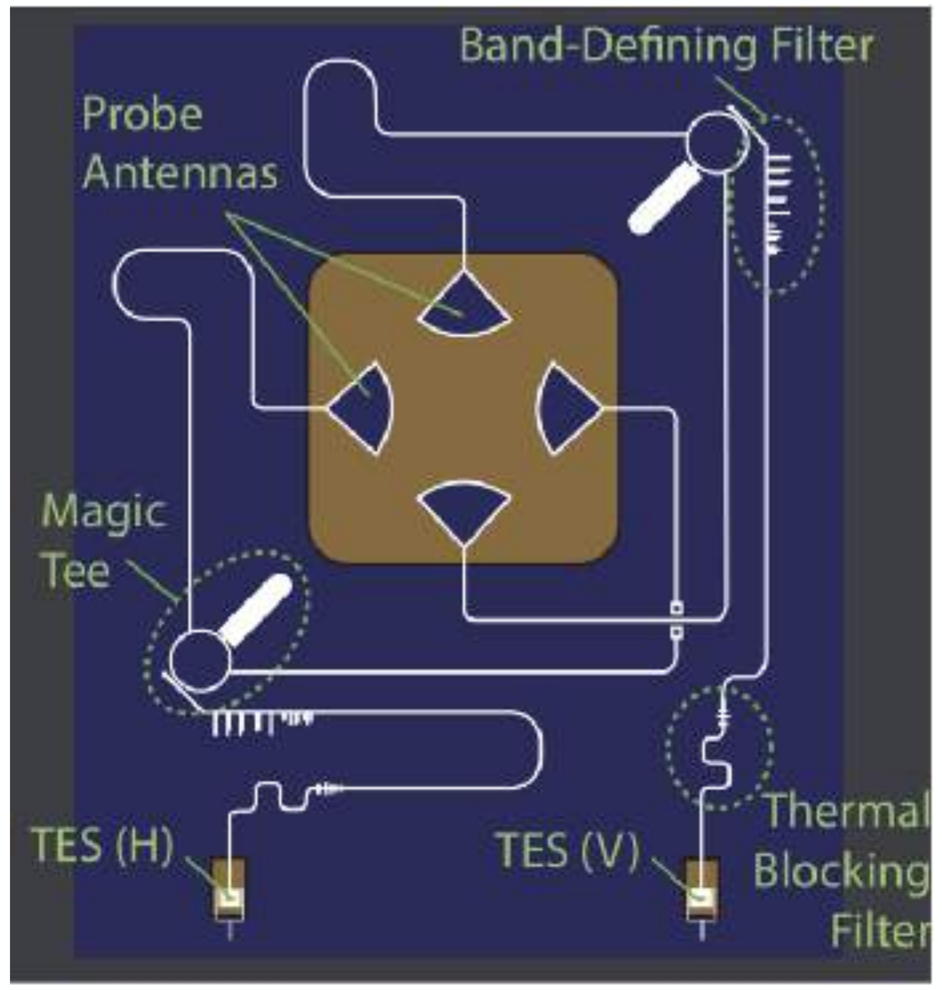
- CLASS uses smooth-walled feedhorn to couple radiation onto orthogonal pairs of transition-edge sensor (TES) bolometers (T_c = 150 mK).
- Data are readout with SQUID-based time-division multiplexing.





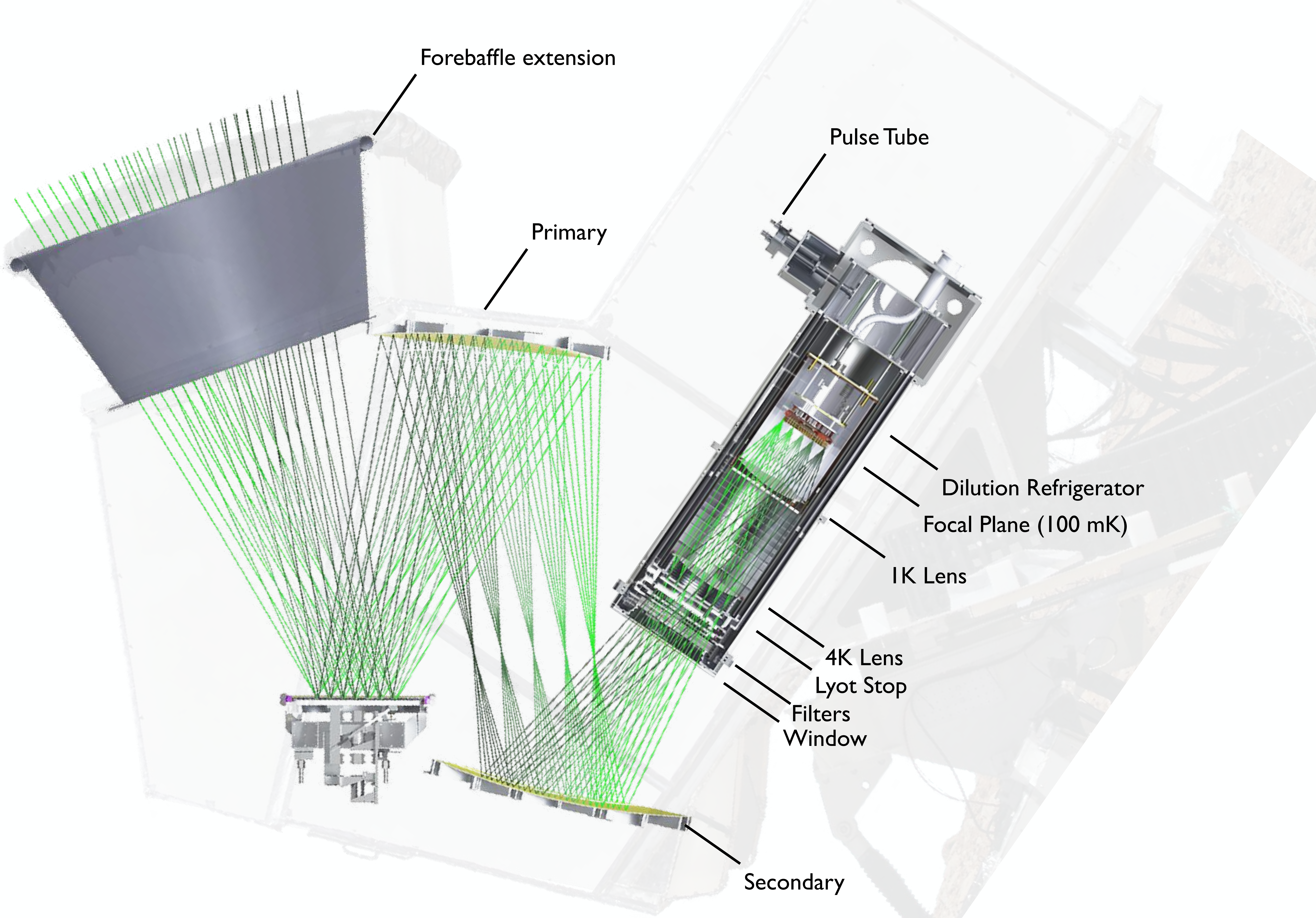
Radiation →

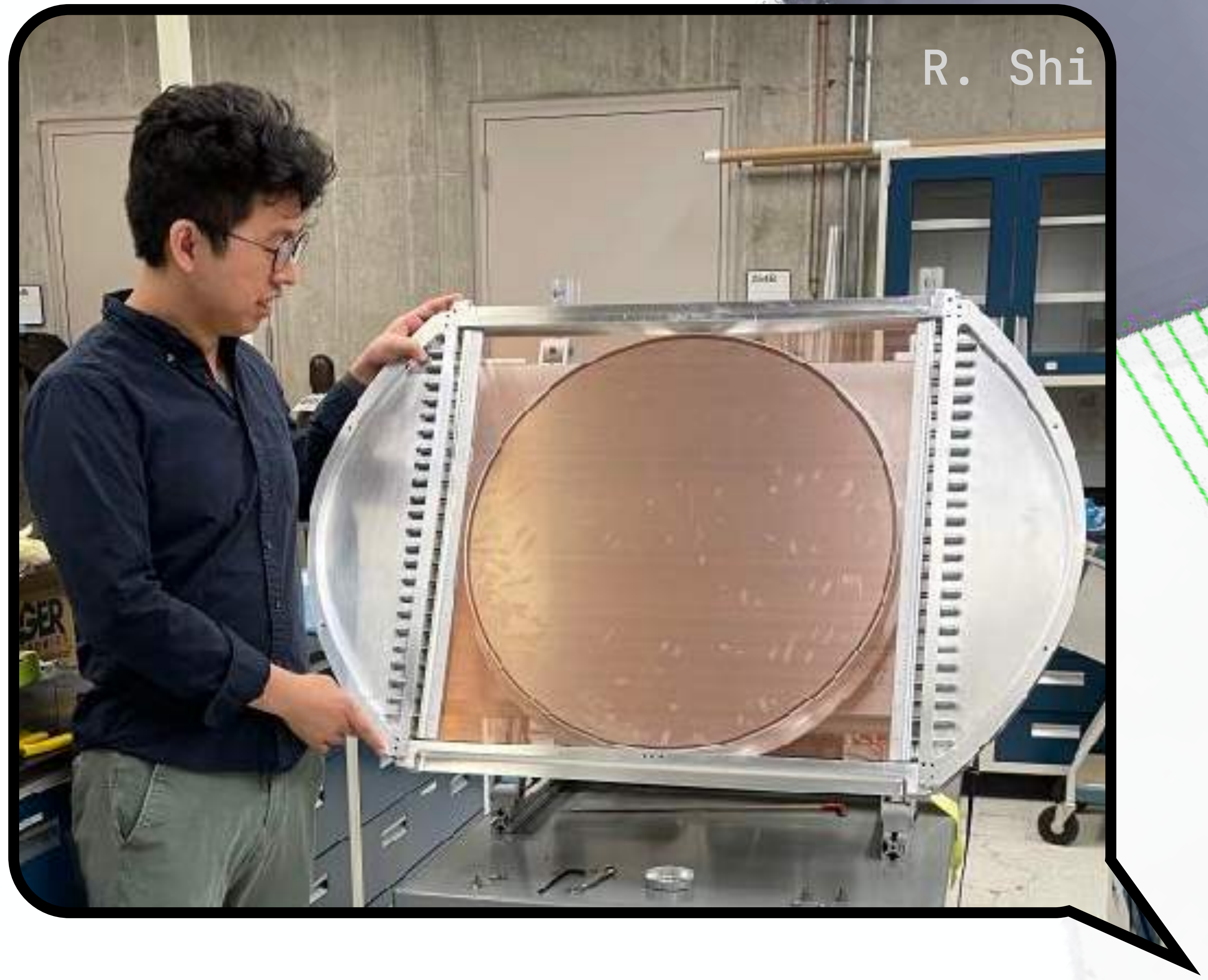


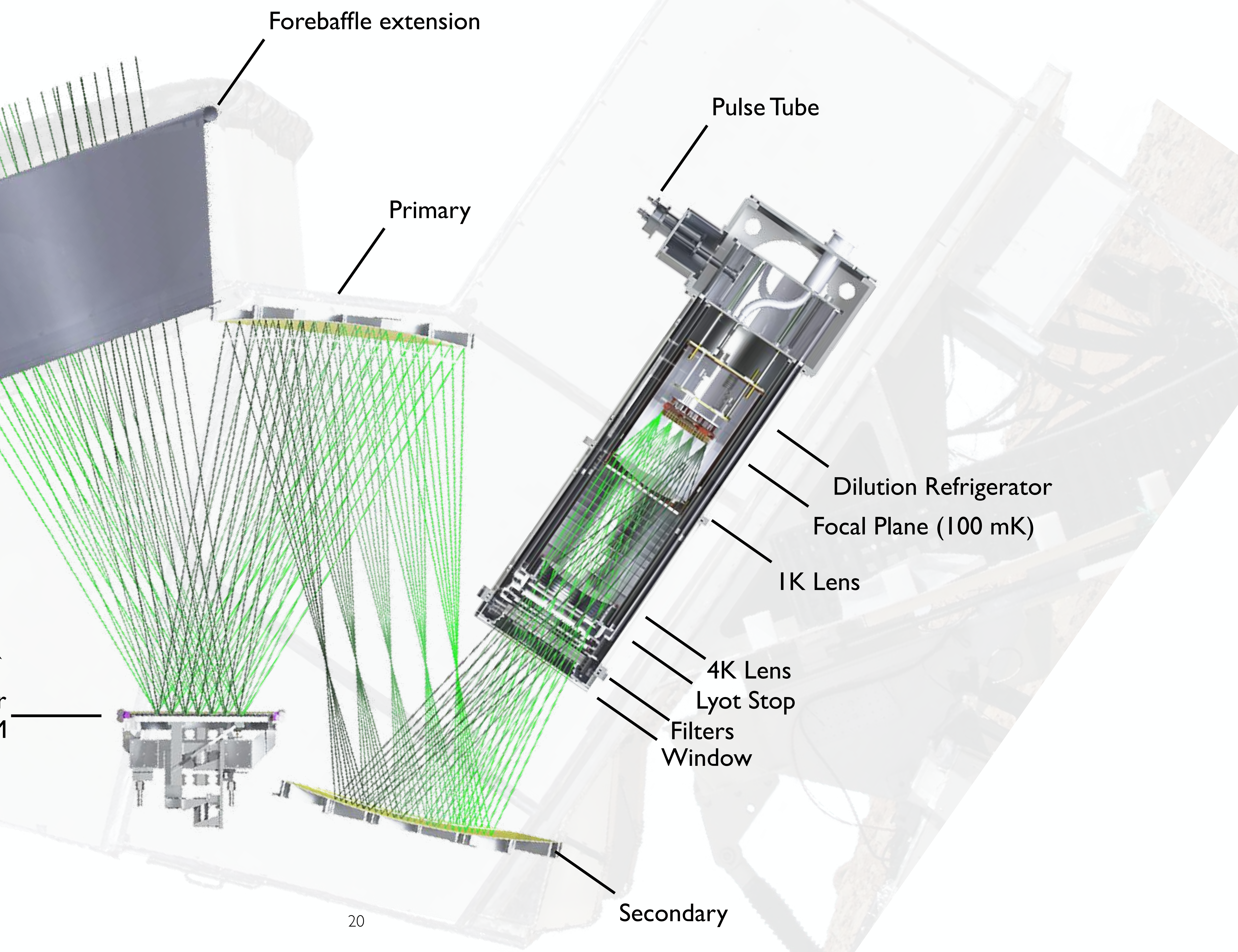


S. Dahal

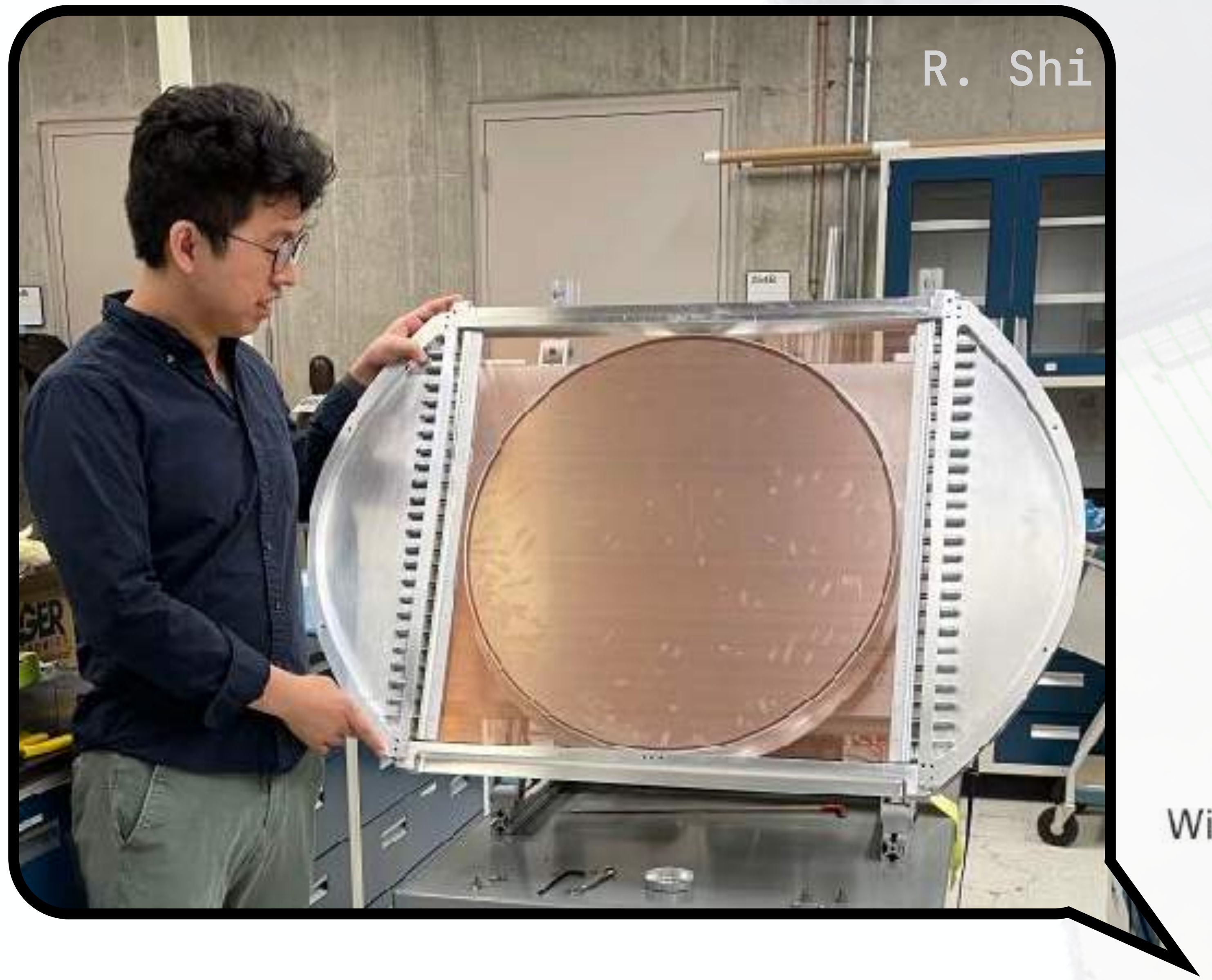
CLASS Instruments


Forebaffle extension
Pulse Tube
Primary
Dilution Refrigerator
Focal Plane (100 mK)
1K Lens
4K Lens
Lyot Stop
Filters
Window
Secondary

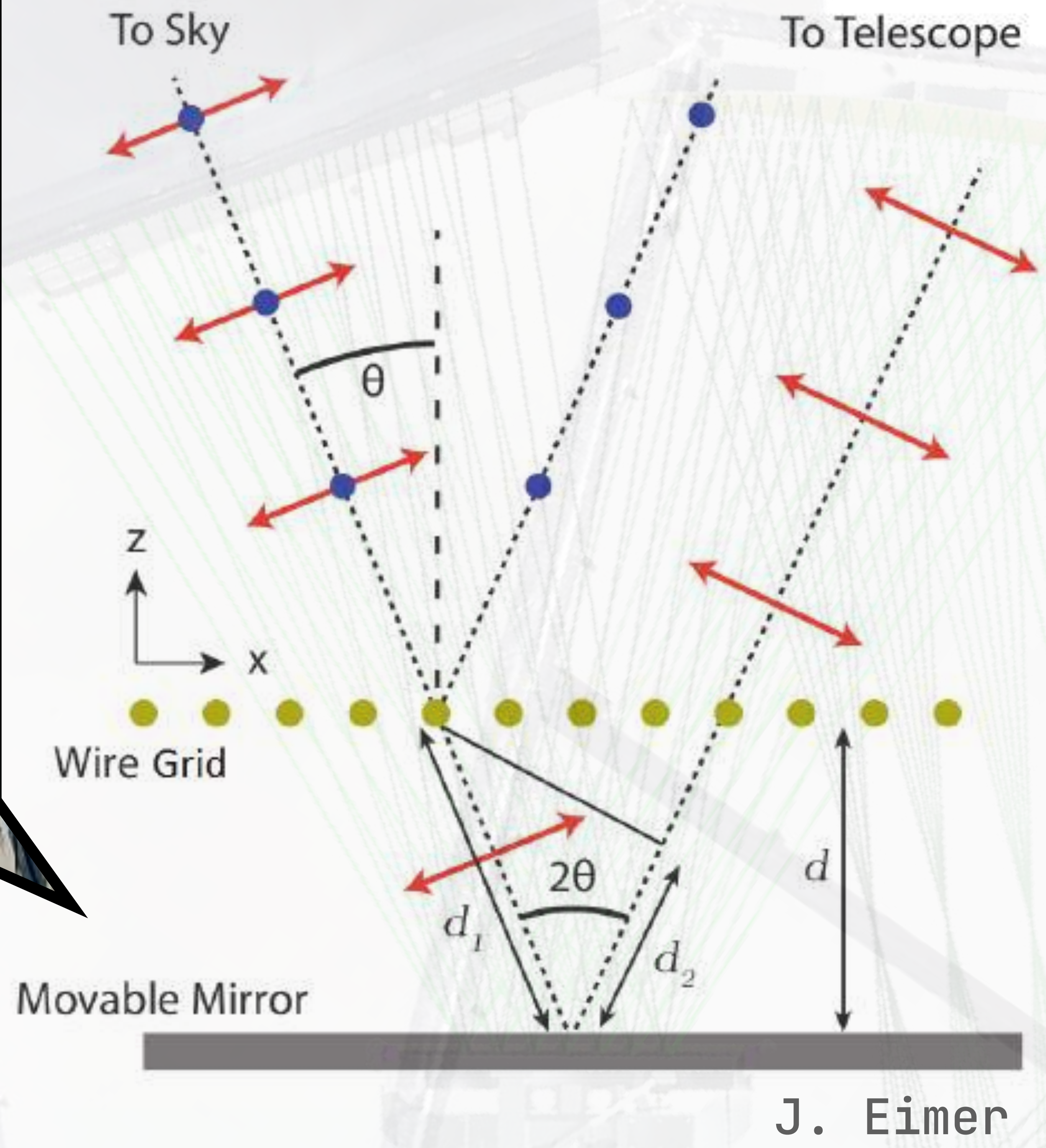

R. Shi


Forebaffle extension
Pulse Tube
Primary
Dilution Refrigerator
Focal Plane (100 mK)
1K Lens
4K Lens
Lyot Stop
Filters
Window
Variable-delay Polarization Modulator
VPM
Secondary

Polarization modulation: VPM

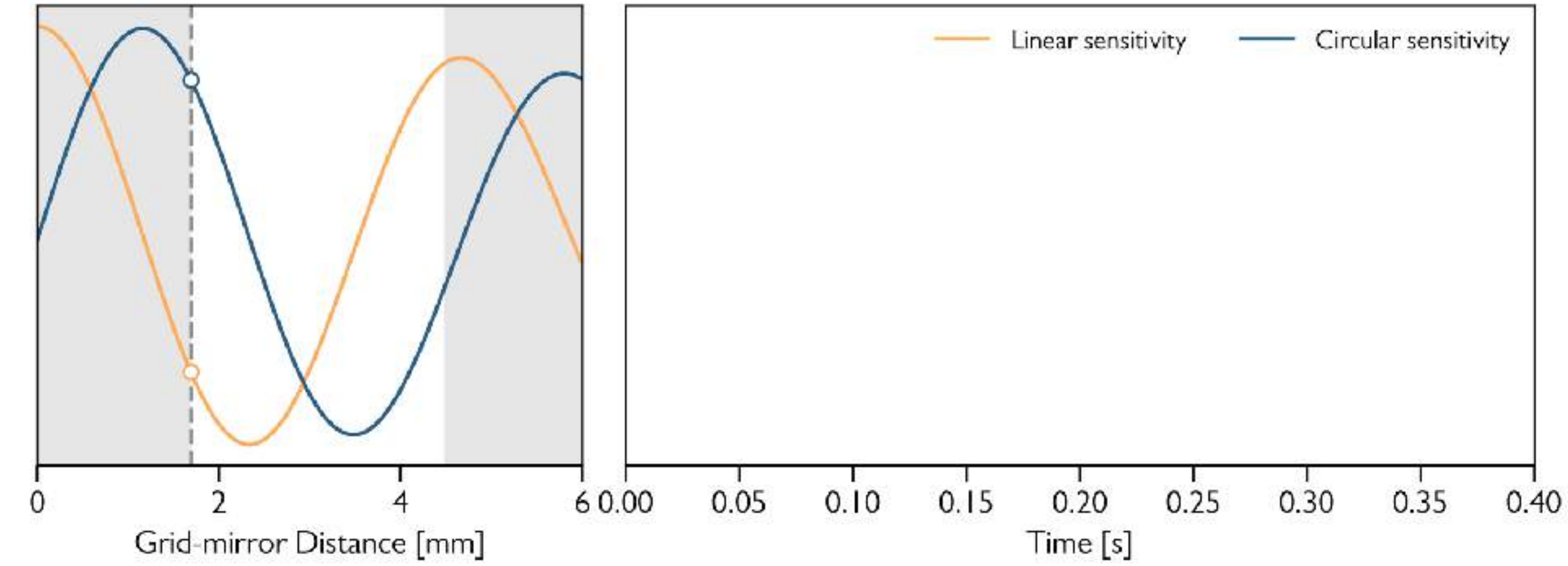


Linear pol. phase delay: $\phi = \dfrac{4\pi d \cos\theta}{\lambda}$



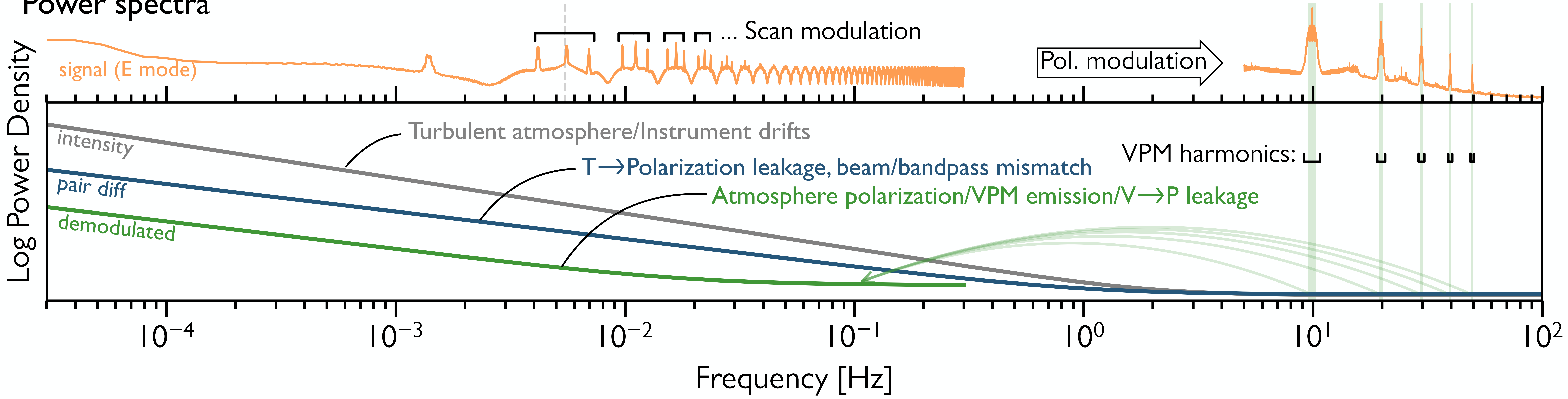
Polarization modulation: VPM

Amplitude modulation



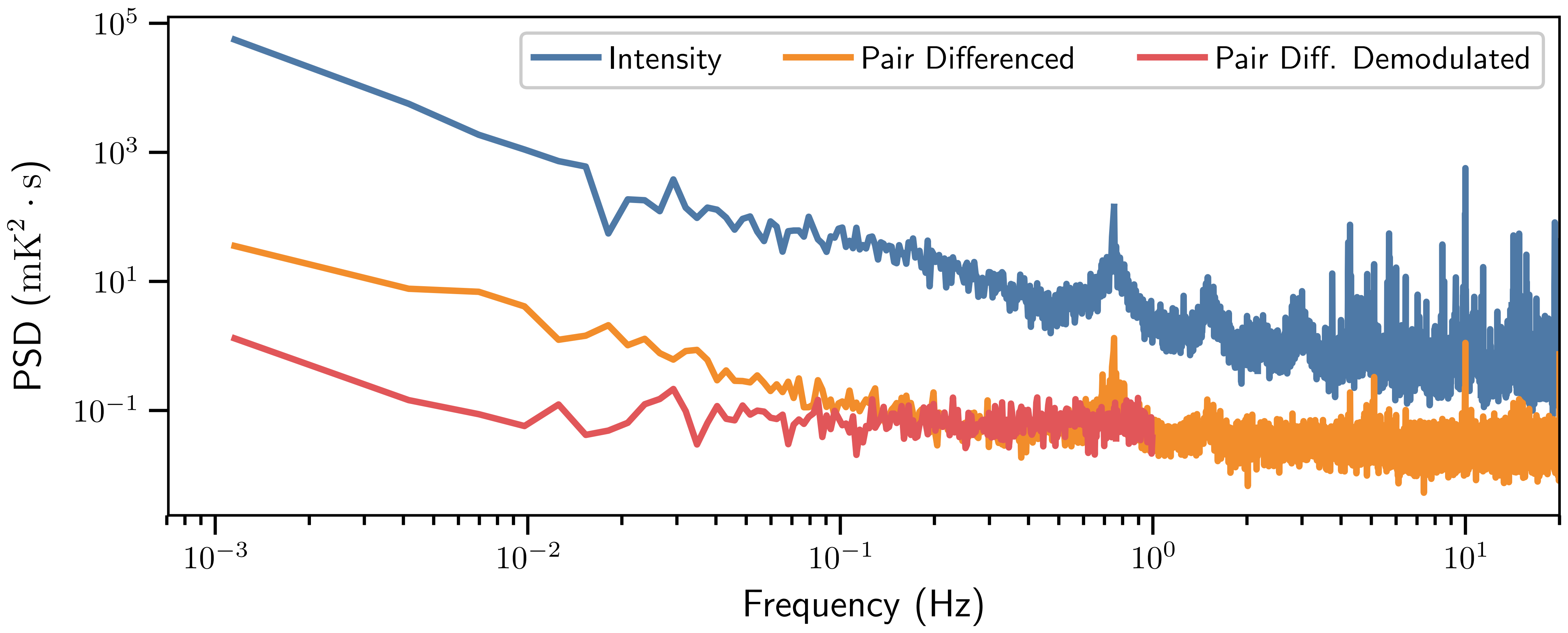
- Move away the signal band from low-frequency (mostly atmospheric) noise.
- Front-end modulation result in *superior noise performance* and *systematics rejection* compared to pair-differencing.
- Sensitive to *circular polarization* as well!

Power spectra

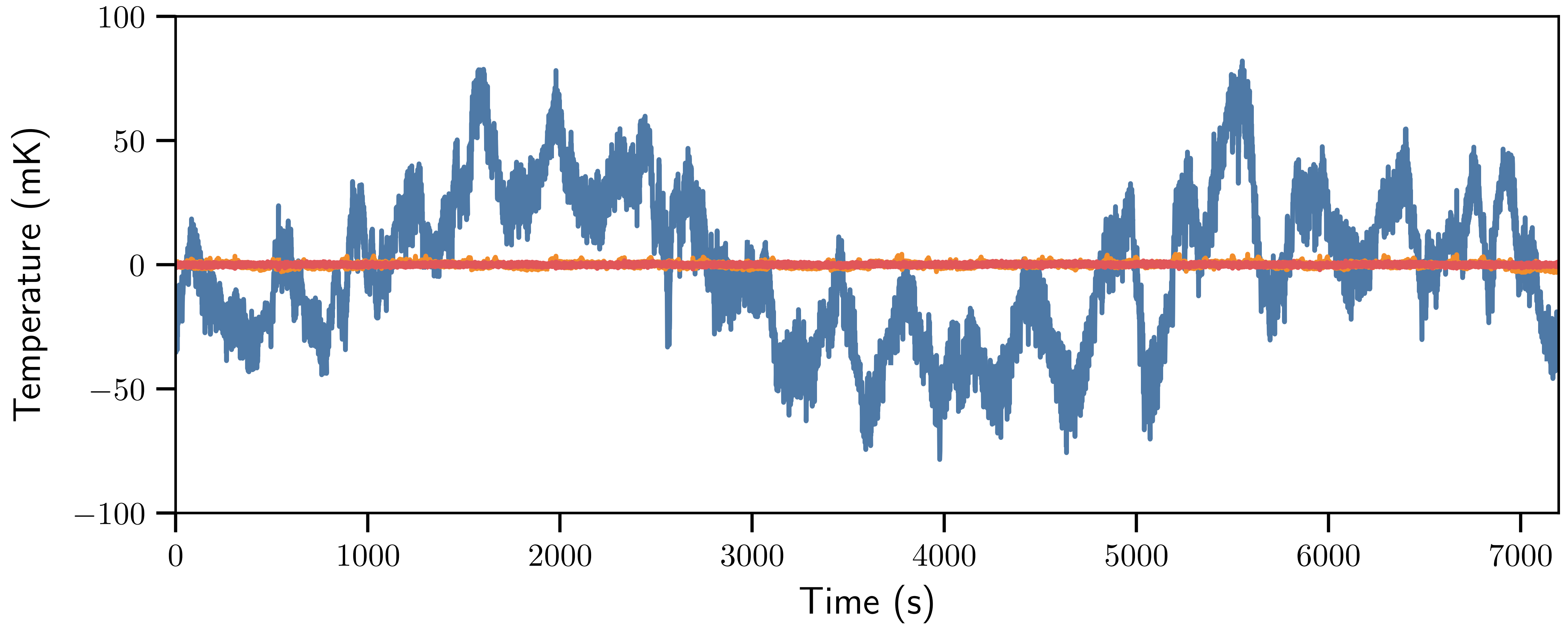


Polarization modulation: 40 GHz data

Frequency spectrum



Time-ordered data



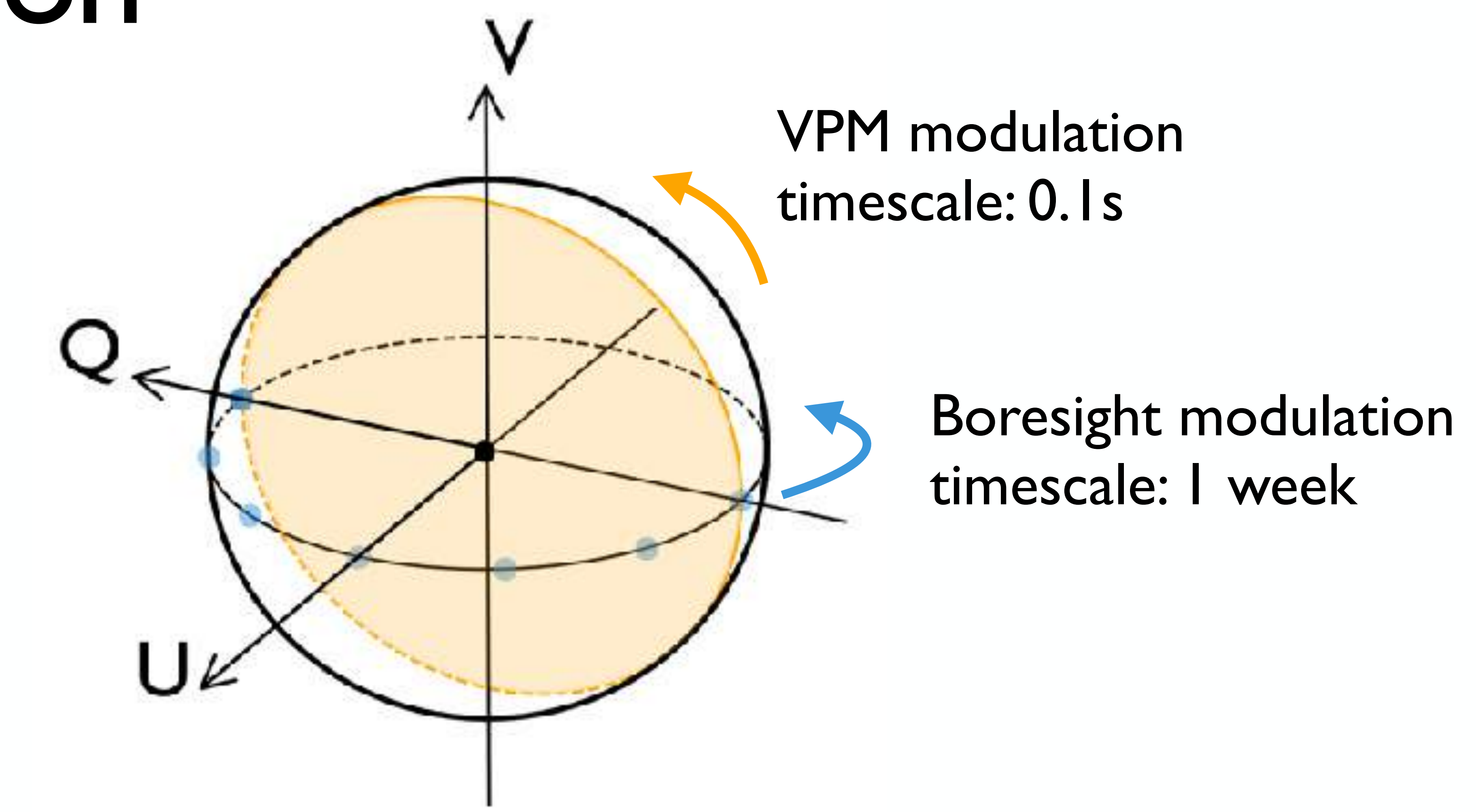
Harrington+2021

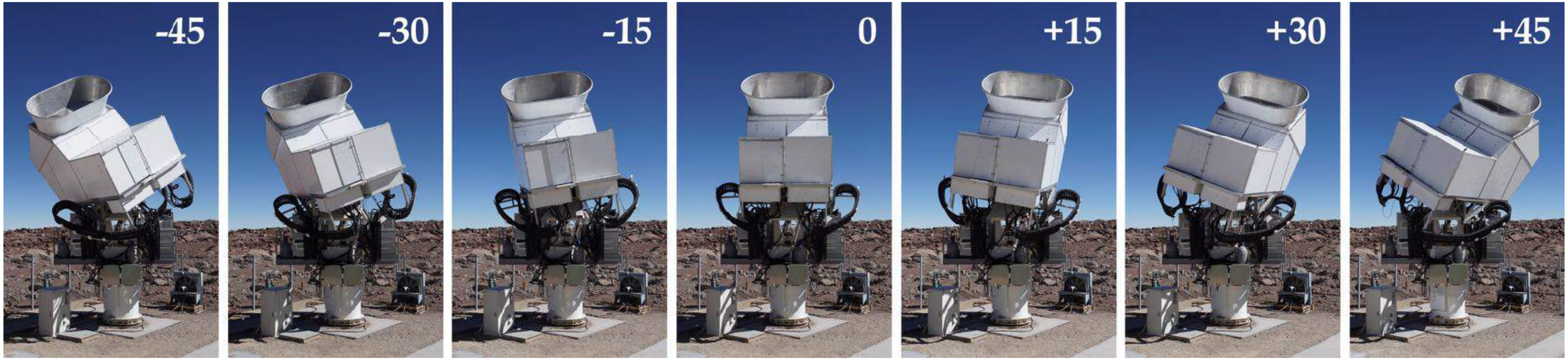
Further reading

- **CLASS 40 GHz Stability:** *Harrington+2021 (ApJ 929 212)*
- **Multifrequency Stability:** *Cleary+ in prep.*

Polarization modulation: Boresight rotation

- 3-axis mount supports boresight rotation.
- Boresight rotation enables better angle coverage.
- Daily boresight rotation assignment (15 degree increment)



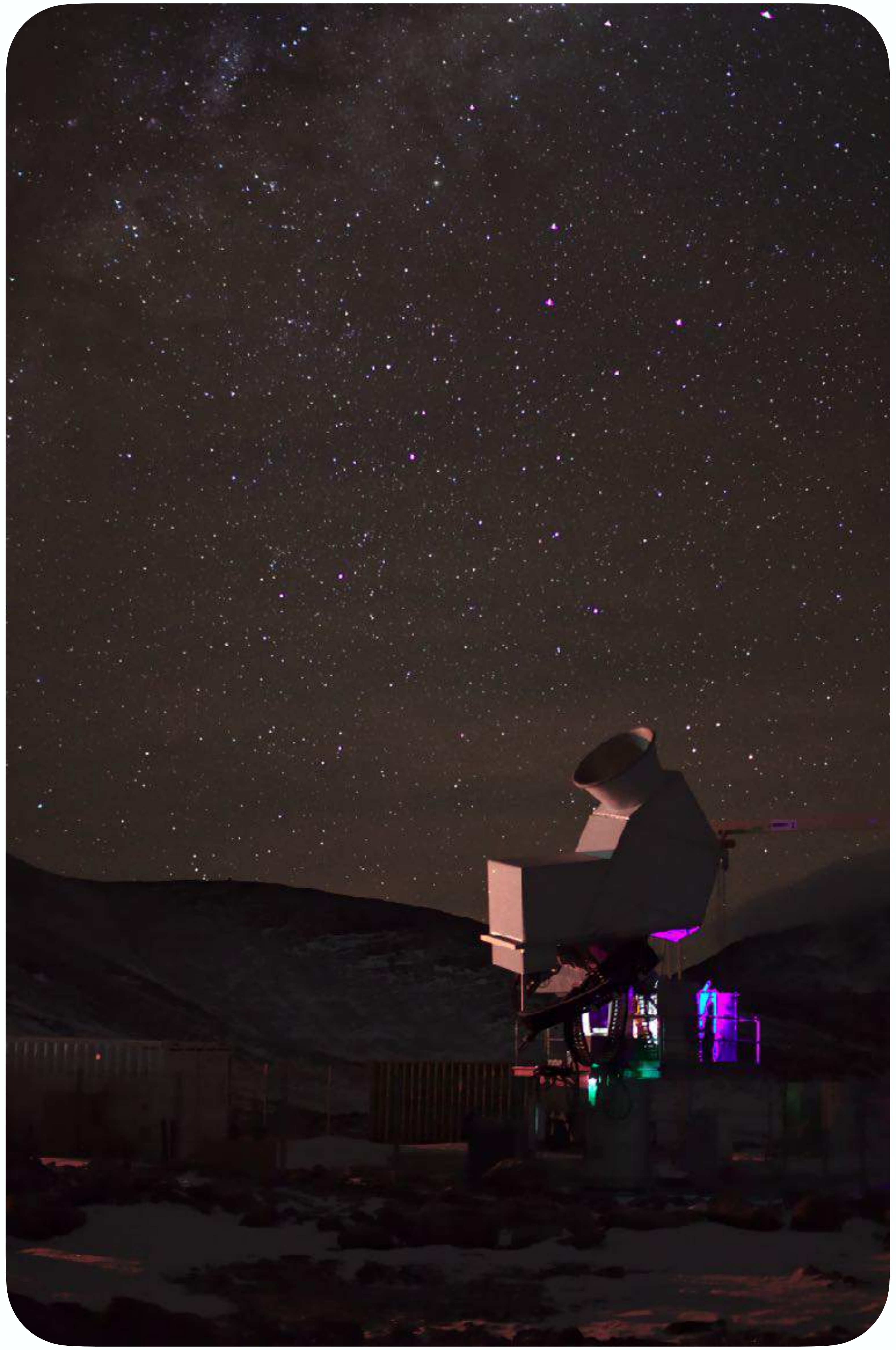


Datta+2023

The 40 GHz Survey

Scientific results: *Eimer, Li, Brewer, Shi+2023 (arXiv:2309.07221)*

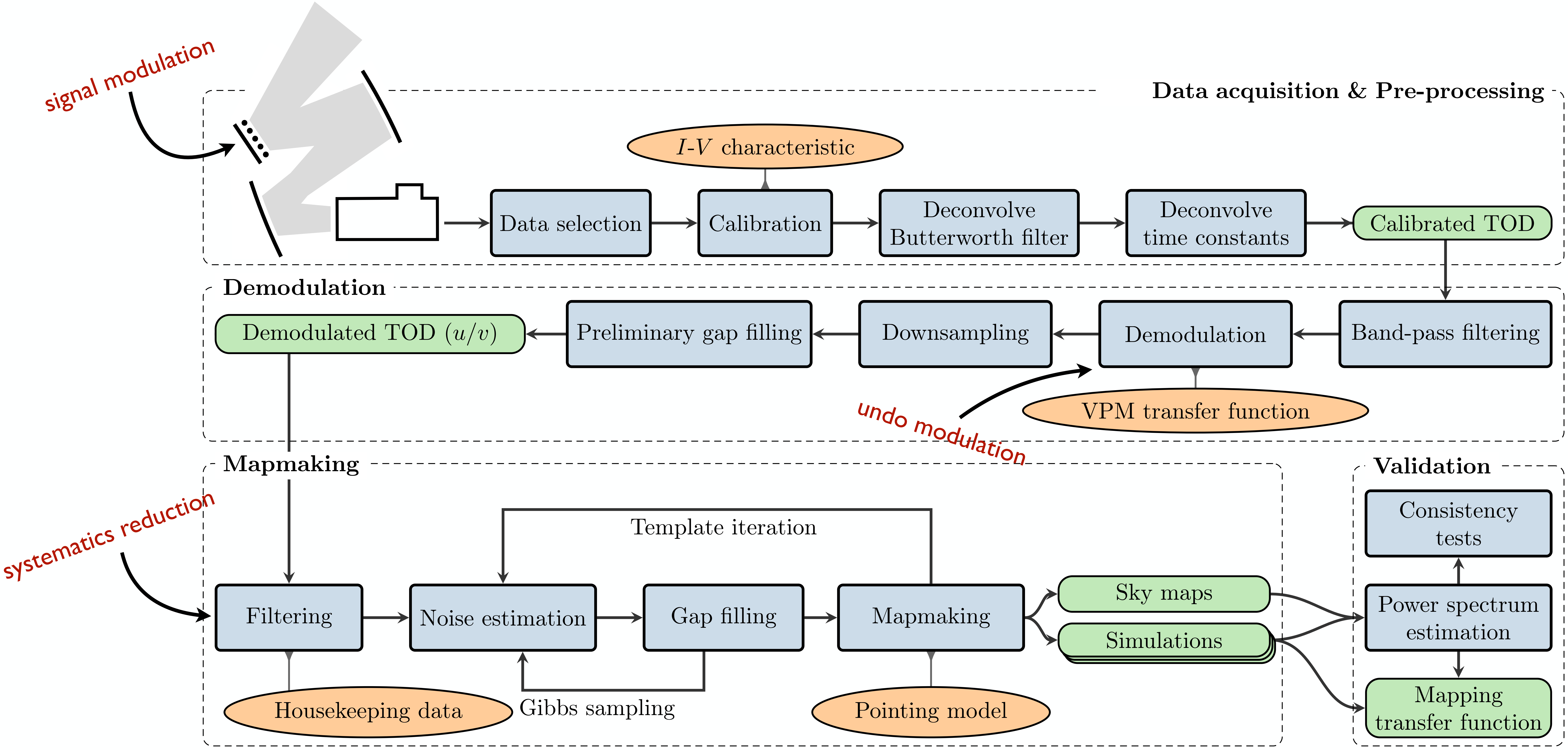
Data pipeline: *Li, Eimer, Osumi+2023 (ApJ 956 77)*



Survey timeline

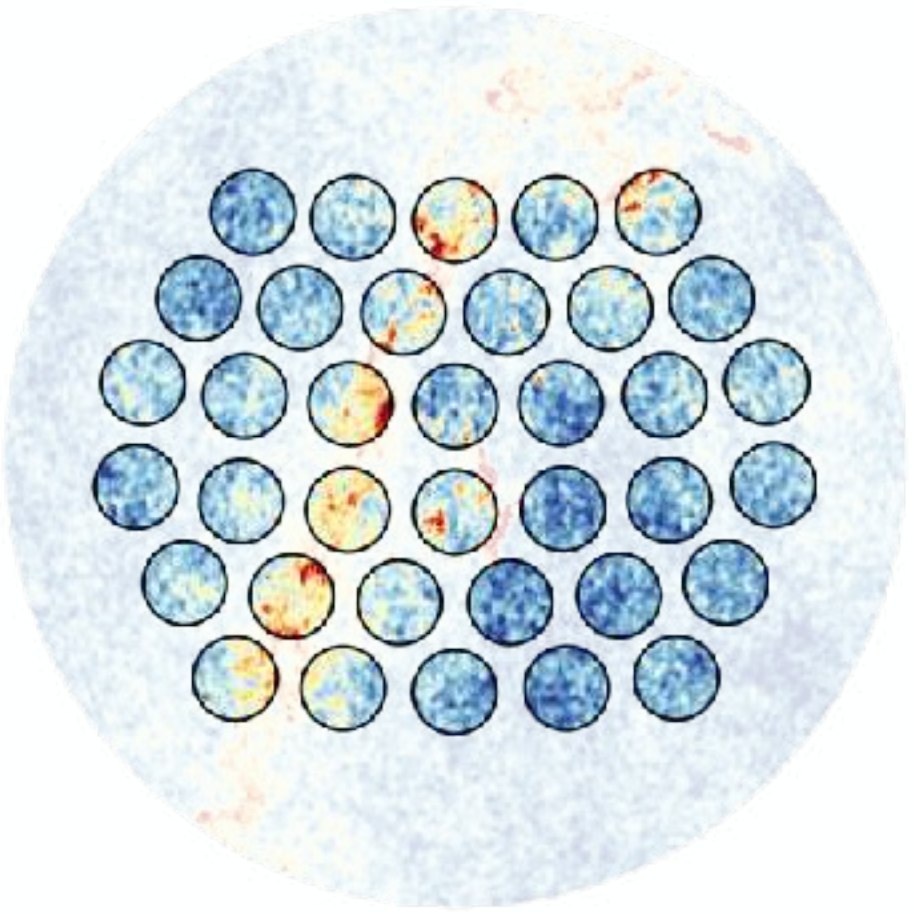
Li+2023a Adapted

Data reduction pipeline



Li+2023a Adapted

Maximum-likelihood map-making



40 GHz Detector Array

Covariance estimates
- temporal correlations
- detector correlations

$\mathbf{d} - A \cdot \hat{\mathbf{m}}$

template iteration

pointing matrix

noise

$$\mathbf{d}(t) = A \cdot \mathbf{m}(\hat{p}) + \mathbf{n}(t)$$

time-ordered data

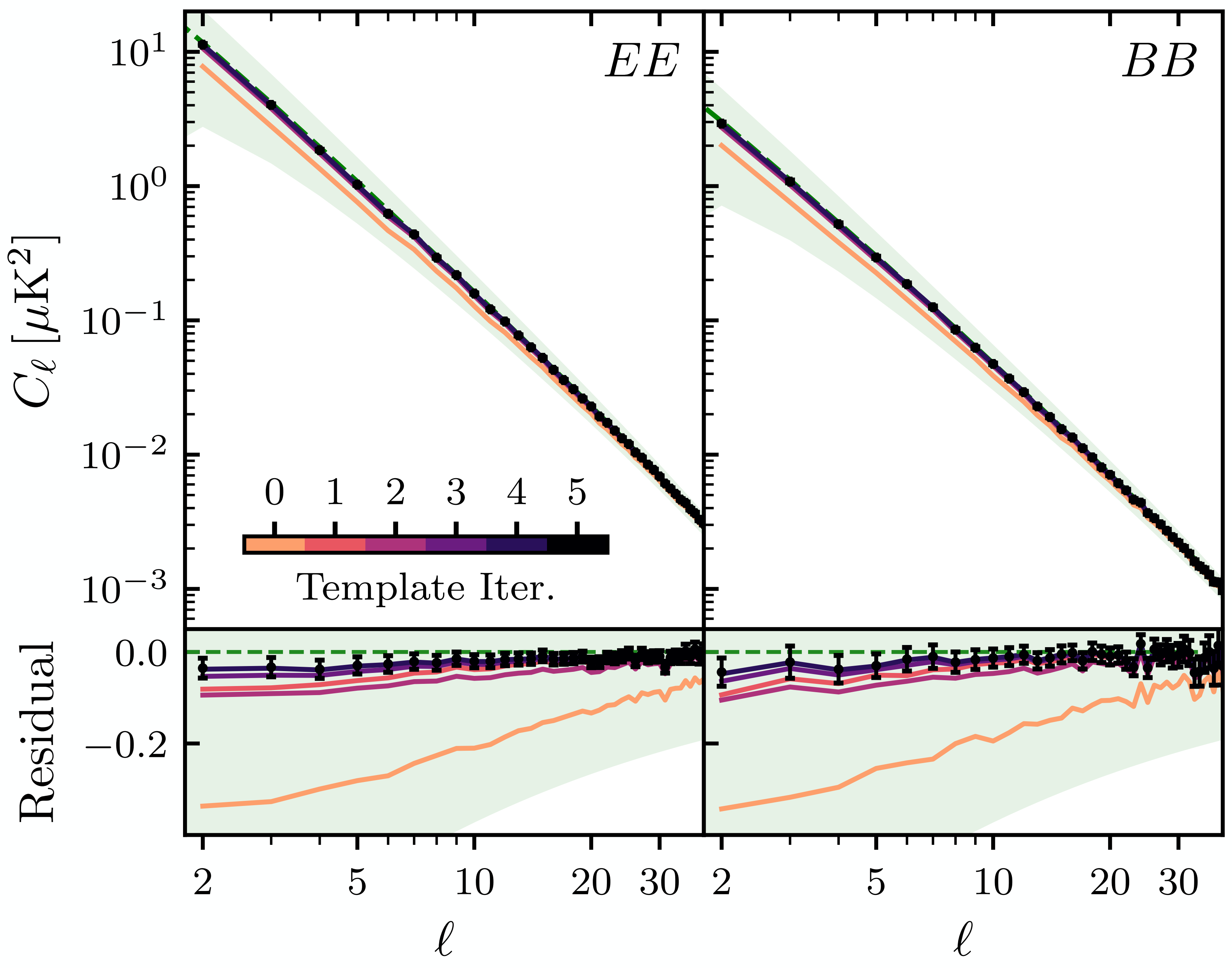
sky map

General least-square solution

$\hat{m} = (A^{\mathrm{T}}\mathbf{N}^{-1}A)^{-1}A^{\mathrm{T}}\mathbf{N}^{-1}\mathbf{d}$

pre-condition conjugate gradient iterations

Template iteration recovery



Li+2023a

Iterative correction for an optimal and *unbiased (<2.5% at $\ell \lesssim 5$)* noise weighting.

Systematic issues

Real data are more complicated than the sky signal + gaussian noise scheme…,
the extras are systematics.

VPM modeling and demodulation

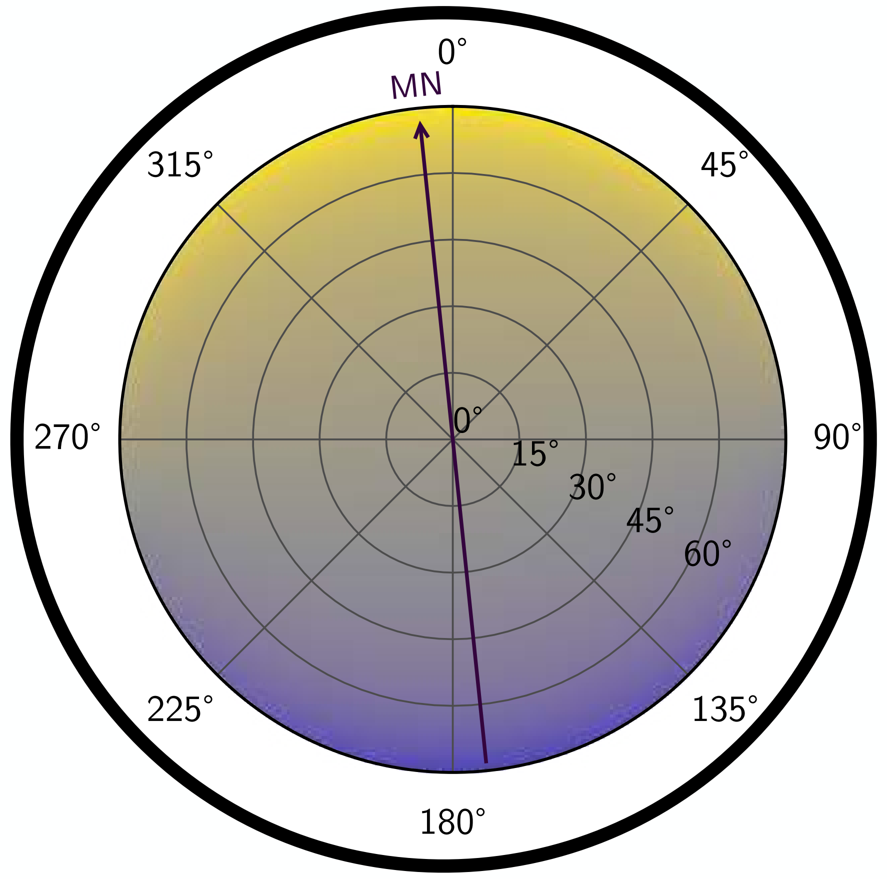
↑

Mitigation (calibration) through analysis

Plastic closeout and "wind signal"

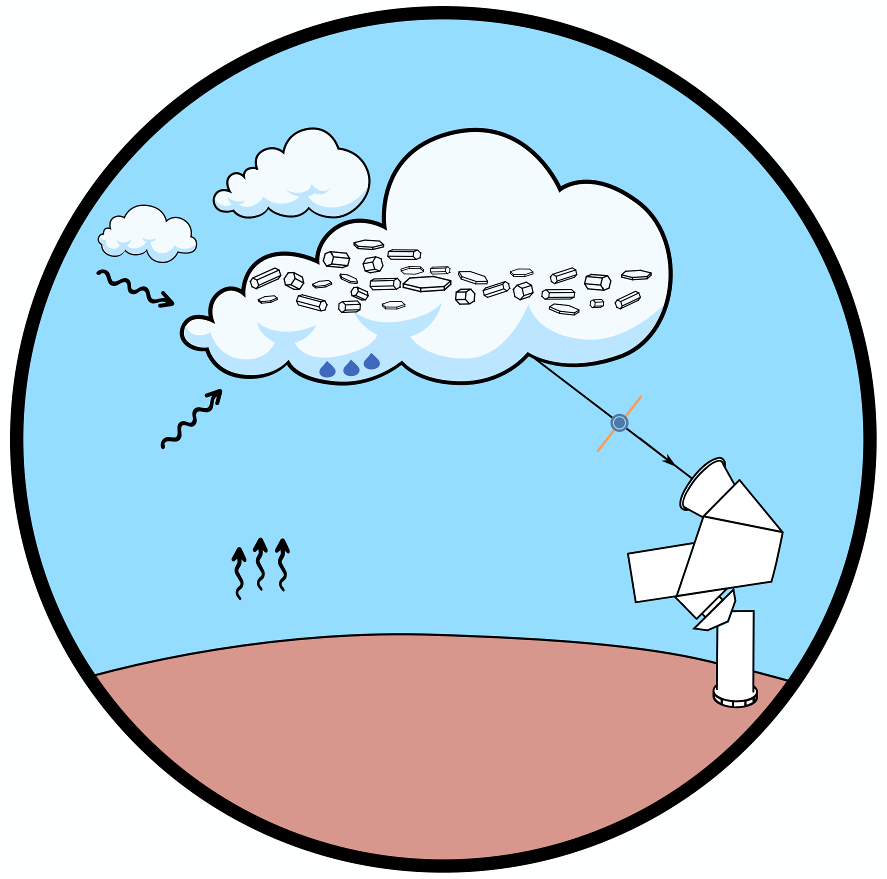
↑

Fixed since 2021



Atmospheric circular polarization

`Petroff+2020`



Atmospheric cloud polarization

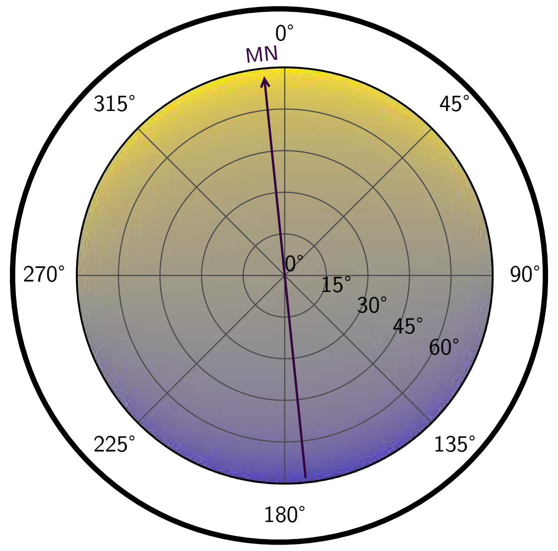
`Li+2023b`

Azimuthal synchronous signals

`Chan+ in prep.`

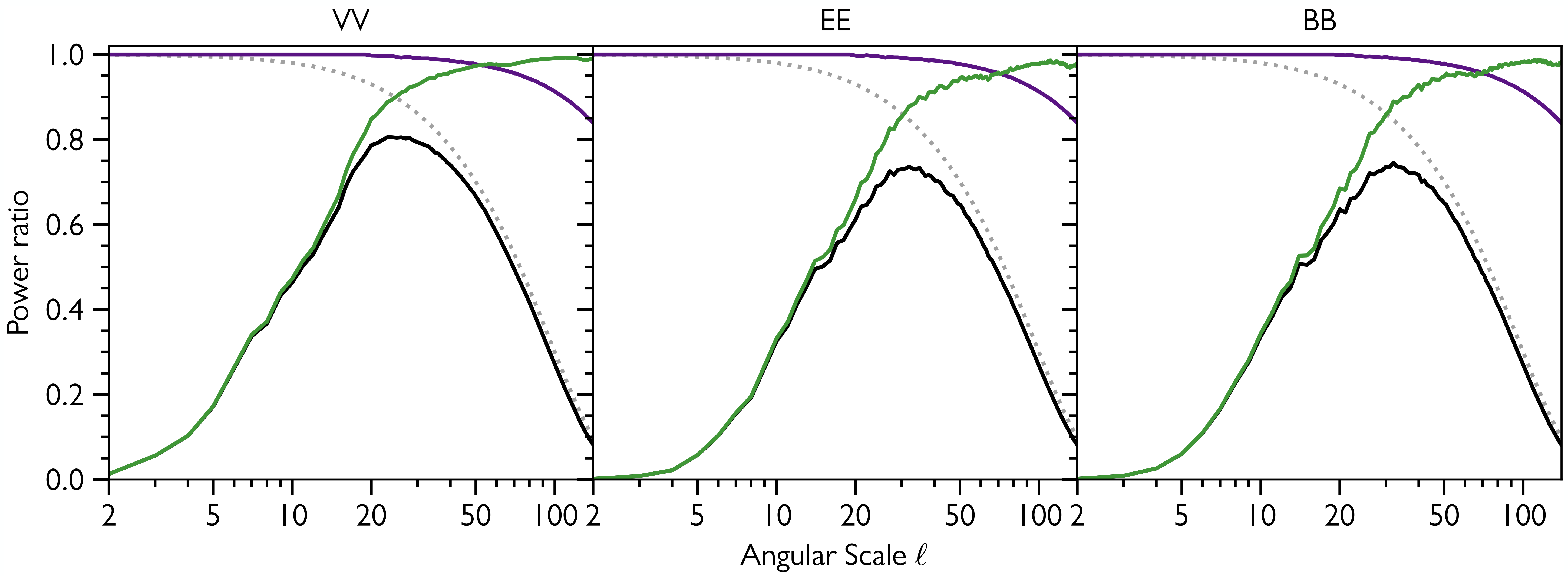
and others …

Systematic issues: filtering and transfer function



- Systematic signals that are quasi-covariance with the sky needs to be filtered. These includes signals from *wind/ground-pickup/electric-coupling/atmospheric circular emission* etc…
- The temporal variance of the signal necessitate short time-scale filters (~3h)
- Filters degrade the signal recovery at large angular scales.

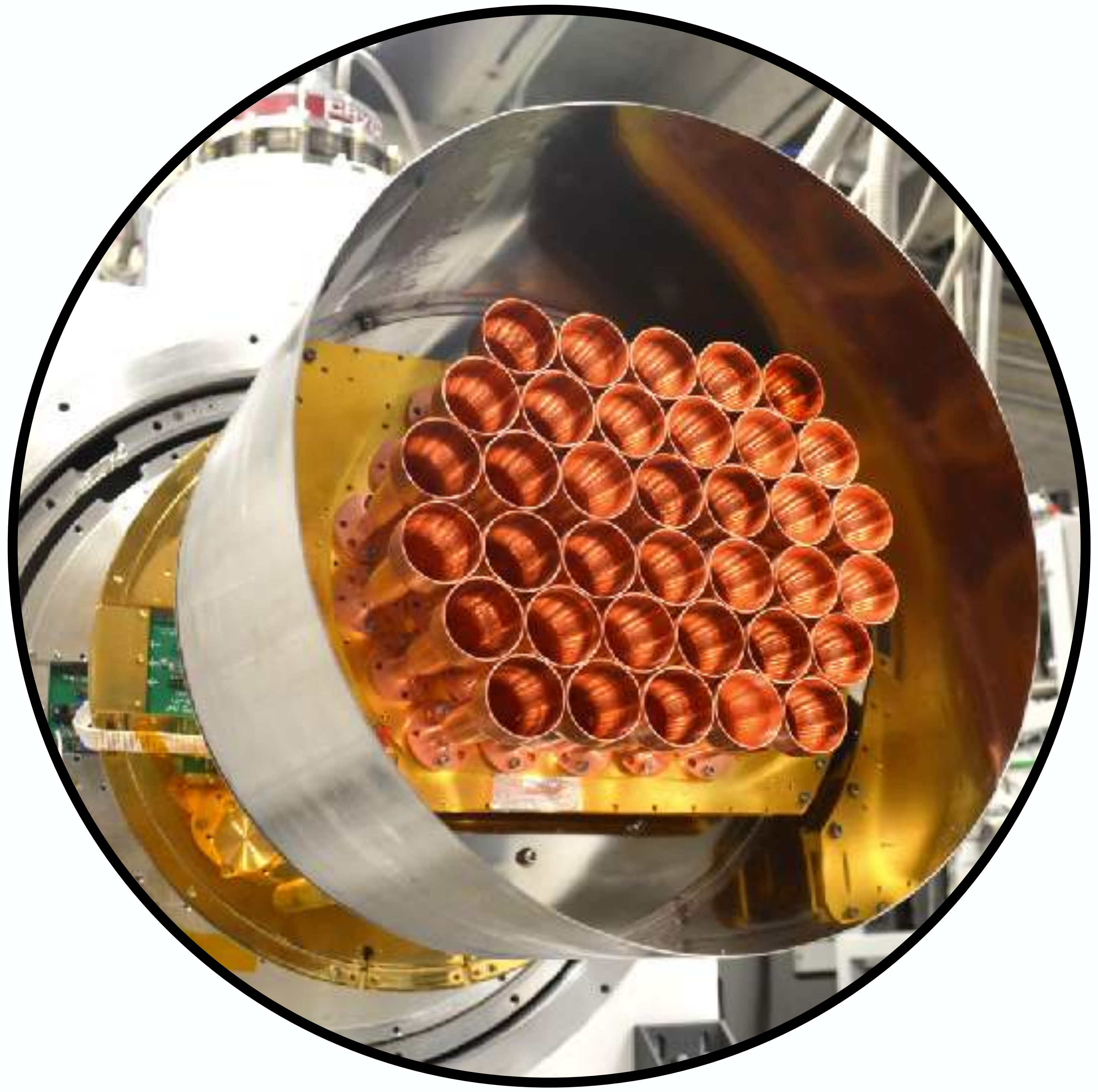
Transfer functions



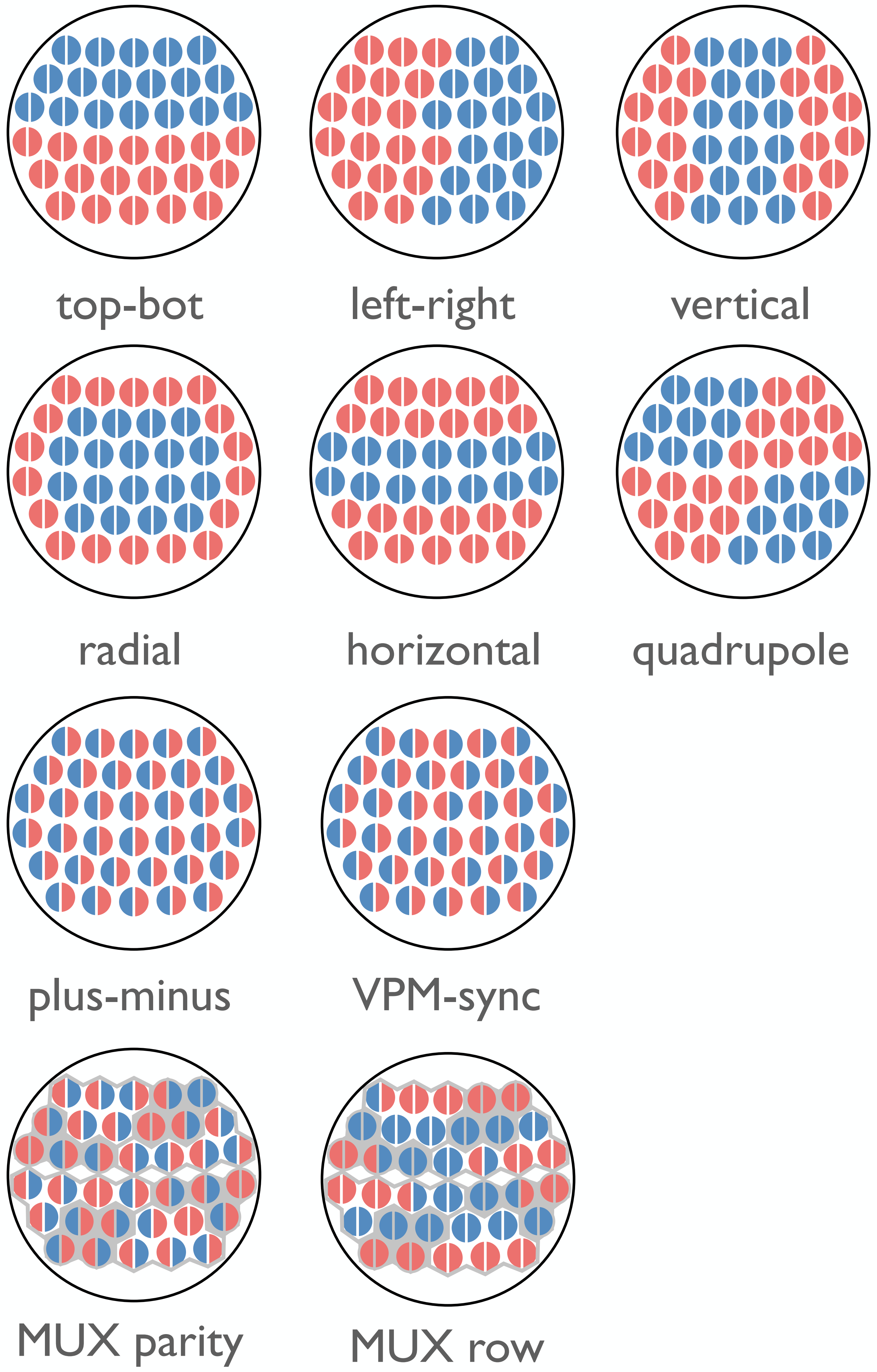
combined= TOD filtering
beam
demodulation

Li+2023a Adapted

Systematic issues: null test



Q-band Focal Plane

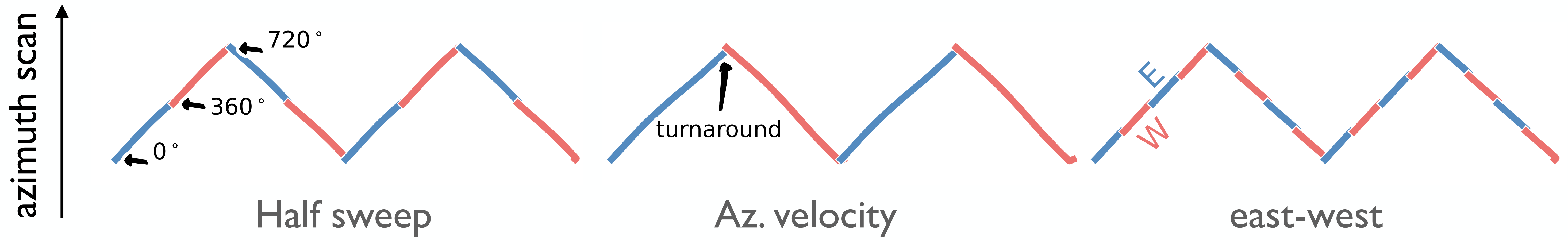


Geometric splits
Atmospheric loading; circular polarization; optics symmetry; Wind-induced polarization signal; VPM modeling.

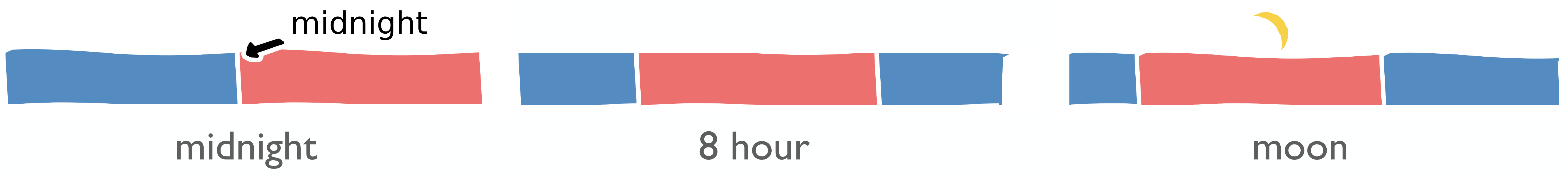
Polarization sensitivity/ VPM related
VPM modeling, VPM related "polarization leakage"

Detector readout

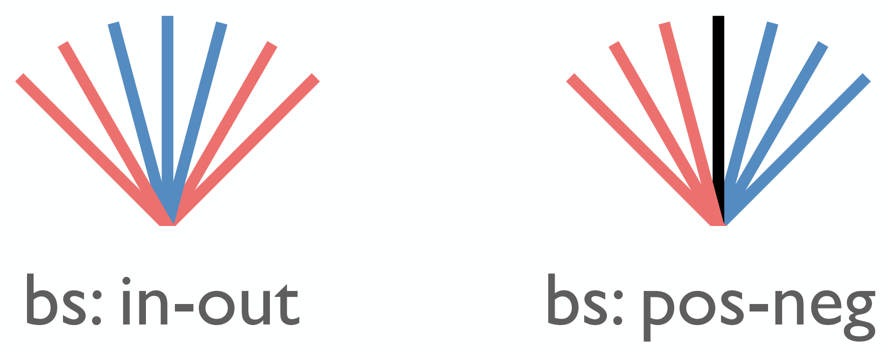
Systematic issues: null test



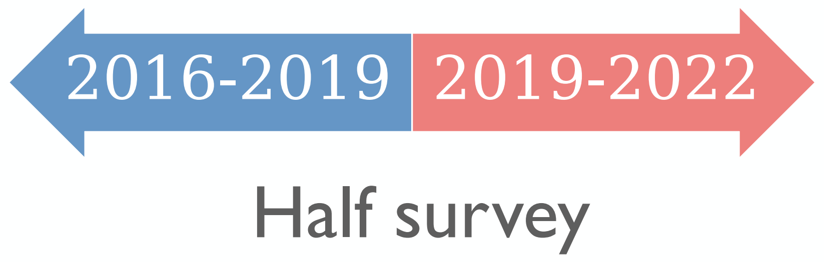
Scan related
Az-servo motor motion; ground pickups
Timescale: 10 minutes.



Diurnal evolution
Far-side lobes; instrument. temperatures; environment factors.
Timescale: few hours



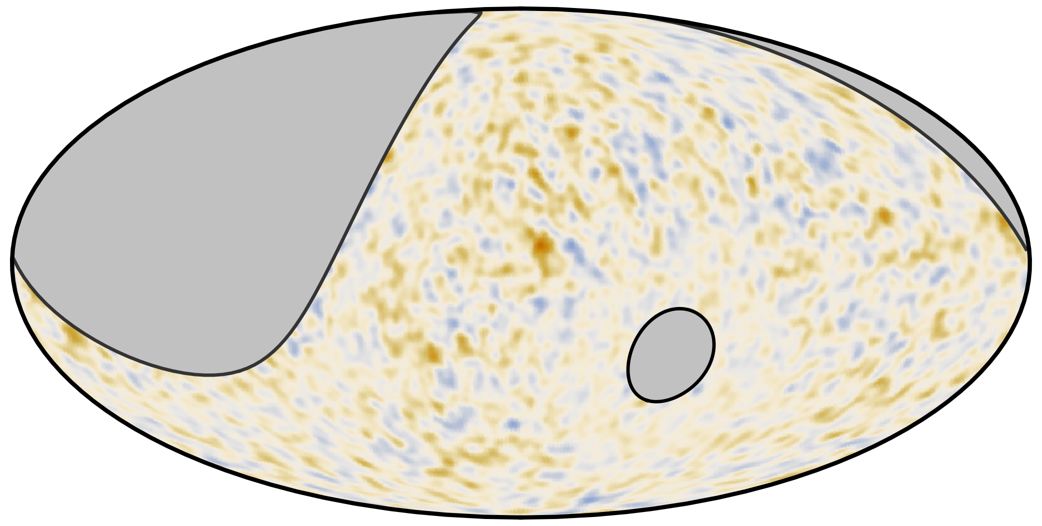
Telescope boresight
polarization angle calibration; detector pointing offsets; cryogenic receiver position etc.
Timescale: few days.



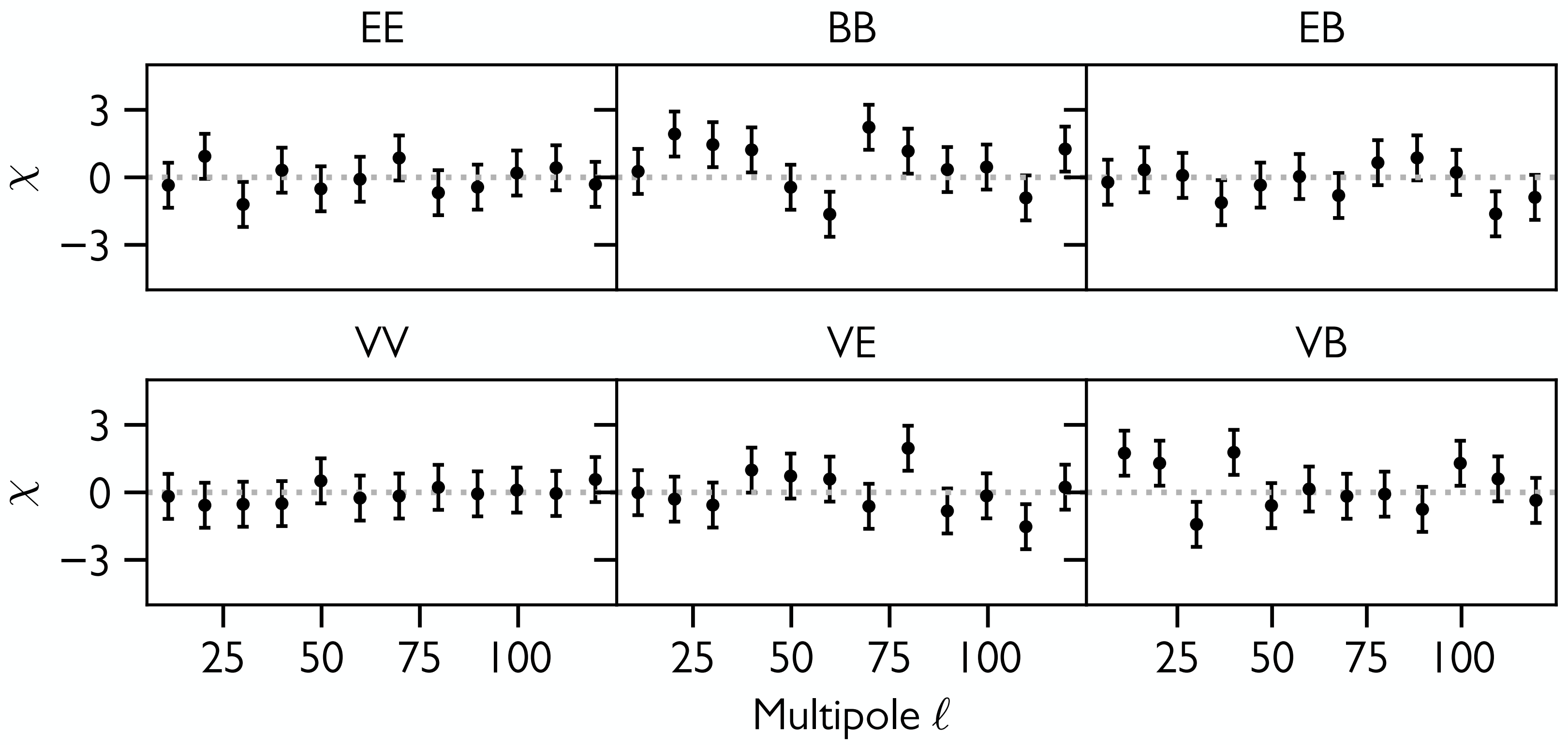
Half survey
Instrumental upgrades, and other secular evolution of the telescope
Timescale: few years

Systematic issues: null test

Null maps

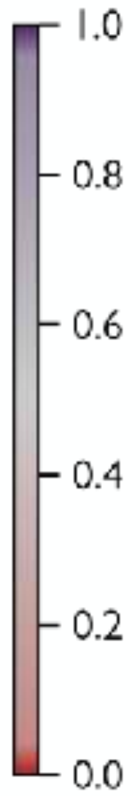


Null spectra

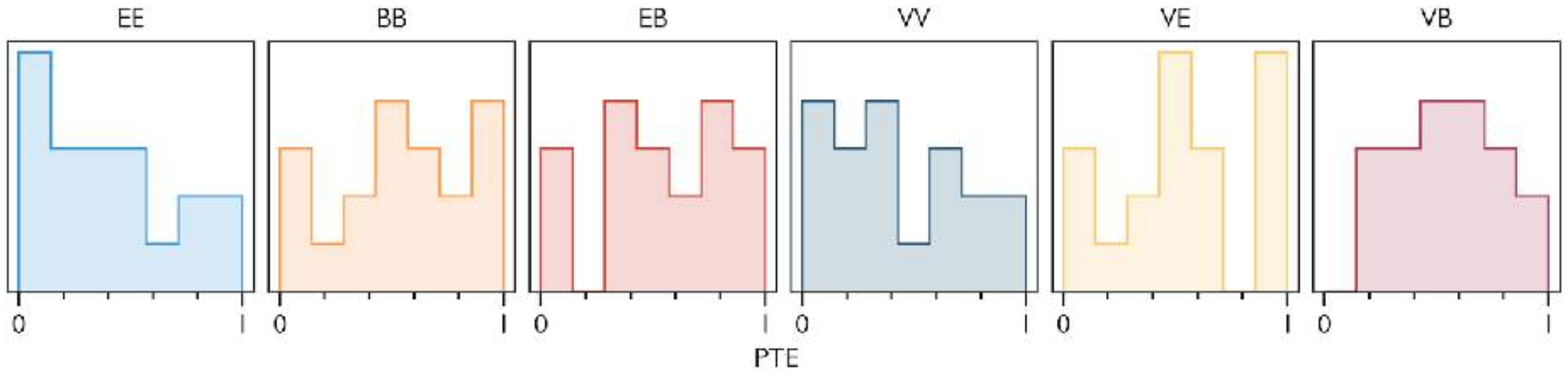


Probability-to-exceed (PTE)

Split	EE	BB	EB	VV	VE	VB
top/bot	0.11	0.14	0.42	0.08	0.50	0.53
left/right	0.31	0.13	0.14	0.40	0.50	0.74
radial	0.84	0.55	0.43	0.84	0.91	0.27
horizontal	0.17	0.29	0.50	0.23	0.60	0.86
vertical	0.87	0.43	0.91	0.16	0.98	0.24
quadrupole	0.98	0.09	0.85	0.99_9	0.65	0.40
MUX halves	0.23	0.97	0.92	0.12	0.50	0.70
MUX parity	0.29	0.93	0.91	0.36	0.94	0.86
plus/minus	0.62	0.69	0.53	0.29	0.54	0.73
VPM syn.	0.49	0.67	0.75	0.66	0.94	0.67
bs in/out	0.02	0.81	0.43	0.58	0.11	0.23
bs pos/neg	0.22	0.02	0.30	0.24	0.09	0.65
east/west	0.04	0.99	0.74	0.86	0.57	0.46
az velocity	0.76	0.99_9	0.67	0.04	0.89	0.75
half sweep	0.12	0.81	0.52	0.61	0.36	0.29
midnight	0.53	0.43	0.11	0.78	0.01	0.42
8h in/out	0.43	0.45	0.74	0.48	0.44	0.61
Moon	0.11	0.41	0.67	0.38	0.29	0.44
survey	0.43	0.69	0.04	0.13	0.20	0.56



PTE distribution (among the splits)



Eimer+2023 Adapted

Sky maps

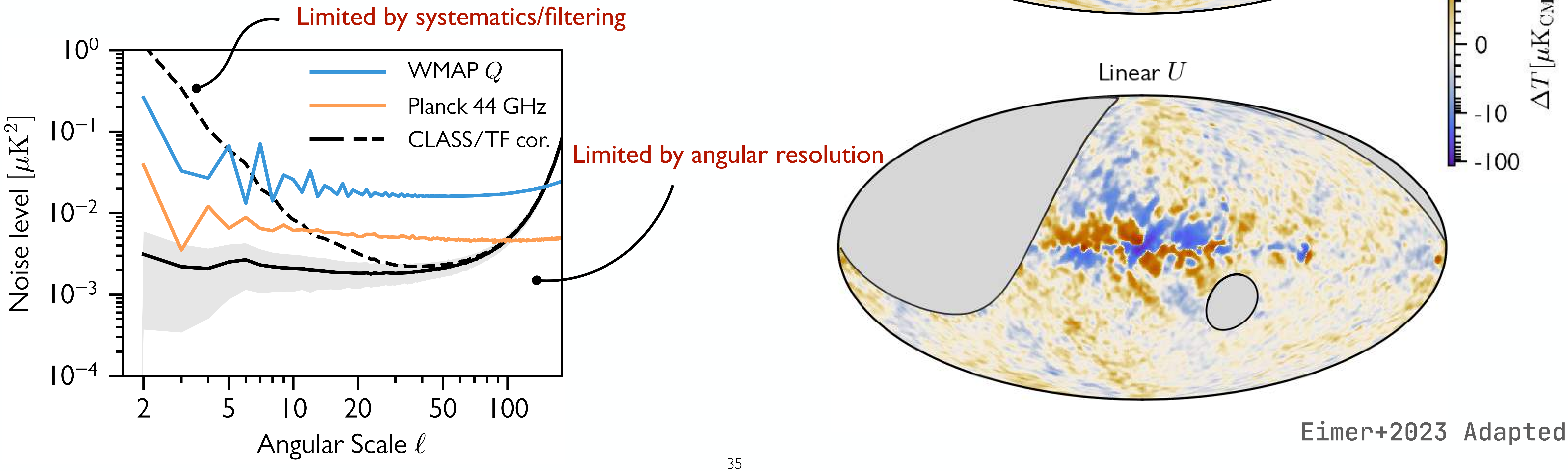
Li+2023a Adapted

* Maps are smoothed to 2 degree FWHM for visualization

Maps and other auxiliary data are available on LAMBDA

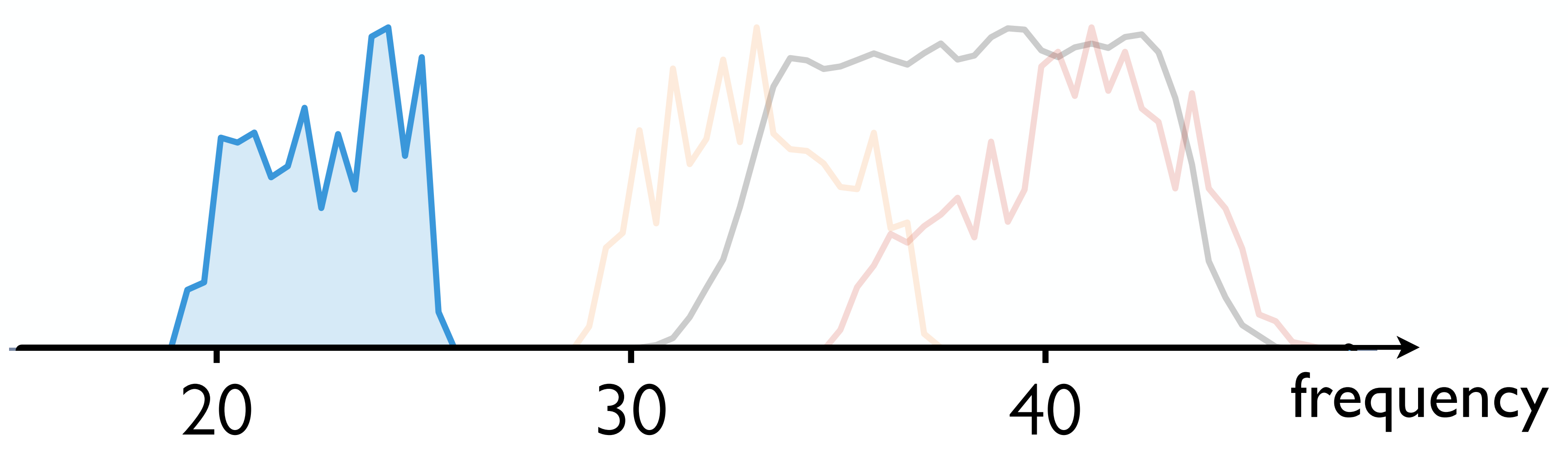
Linear polarization: maps

- 75% Sky maps from the ground.
- Dominated by synchrotron emission at 40 GHz
- Significant improvement over satellite measurements in the critical $10 < \ell < 100$ range.

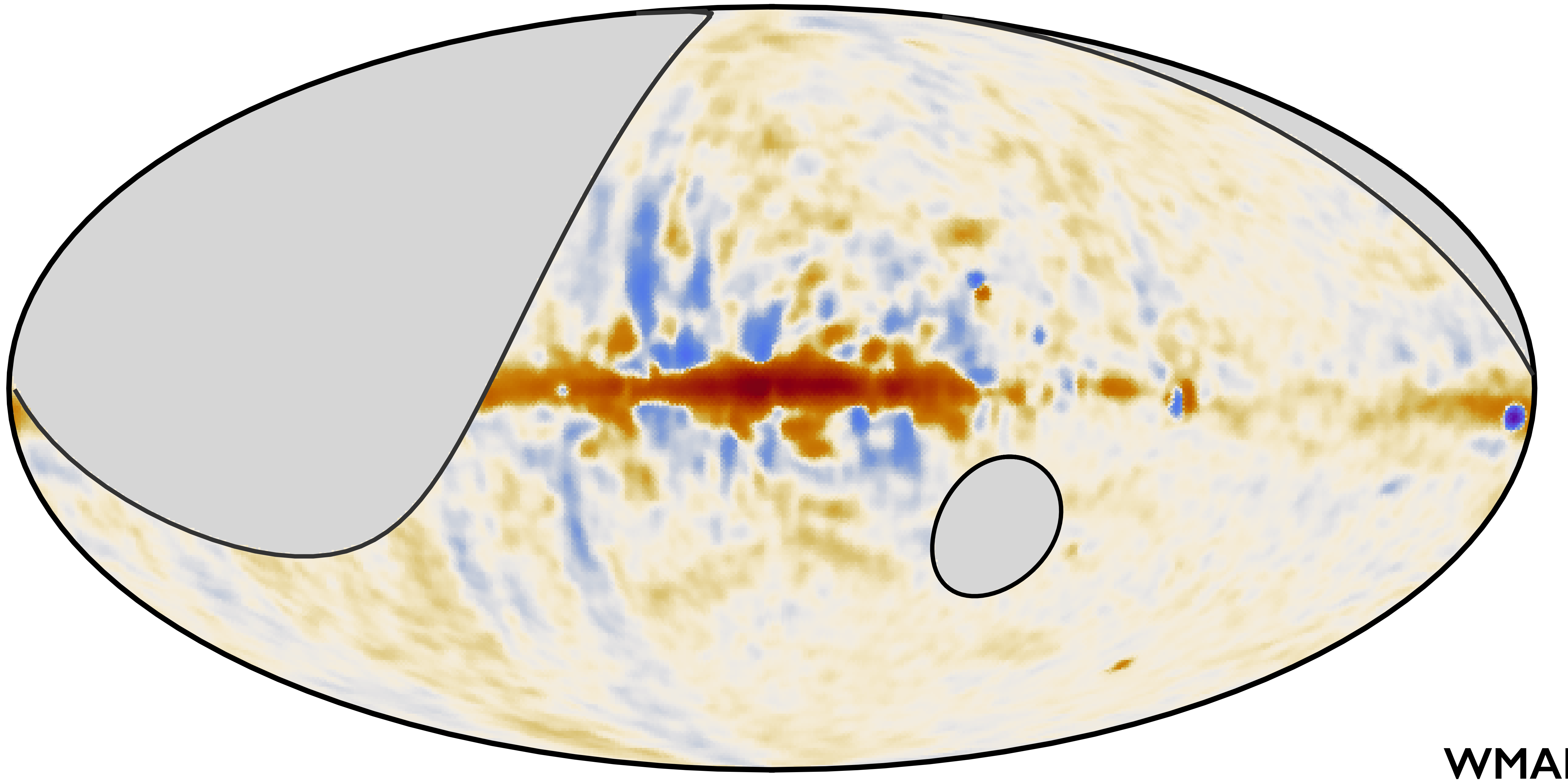


Eimer+2023 Adapted

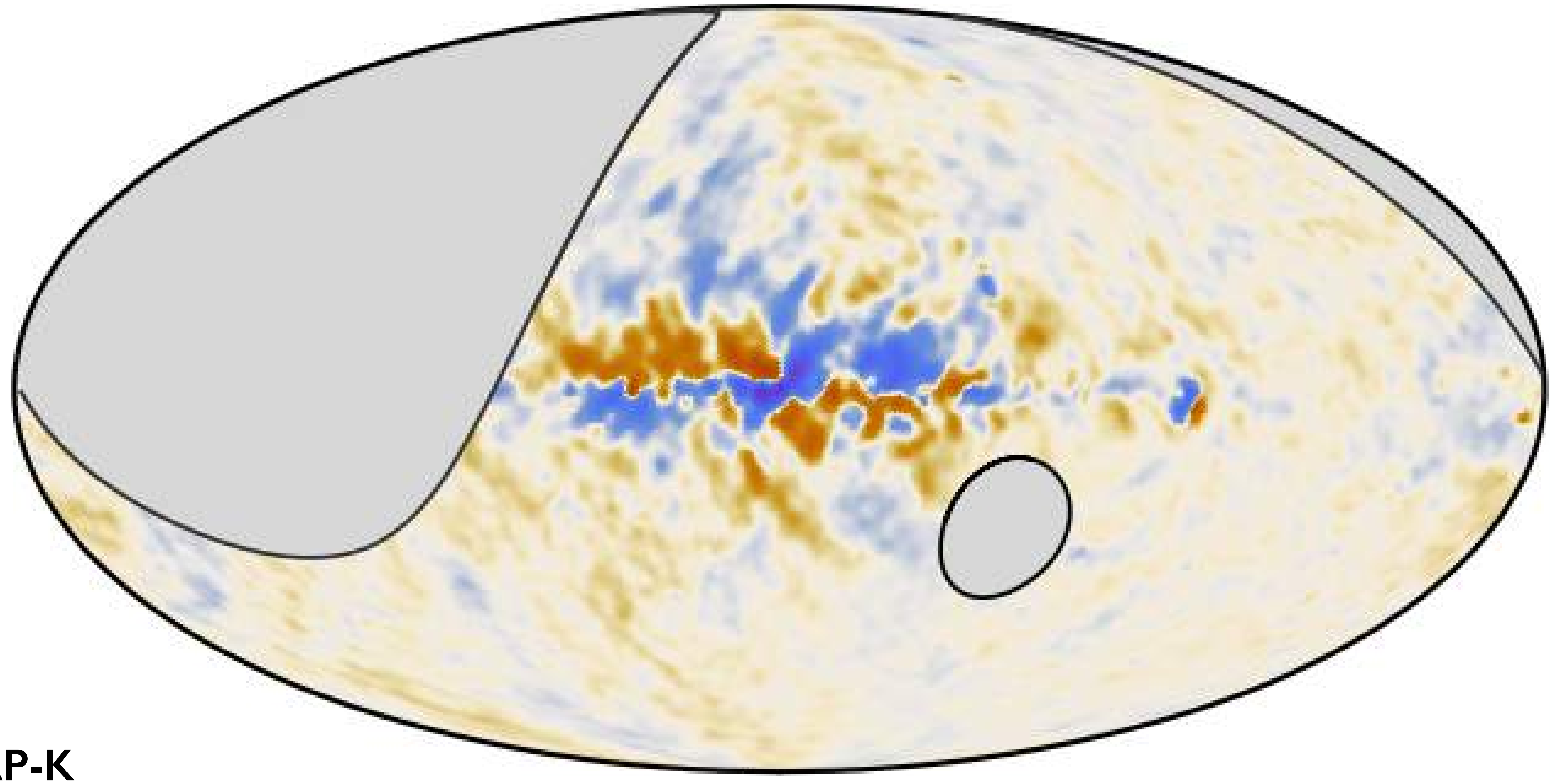
Linear polarization: comparison



Linear Q

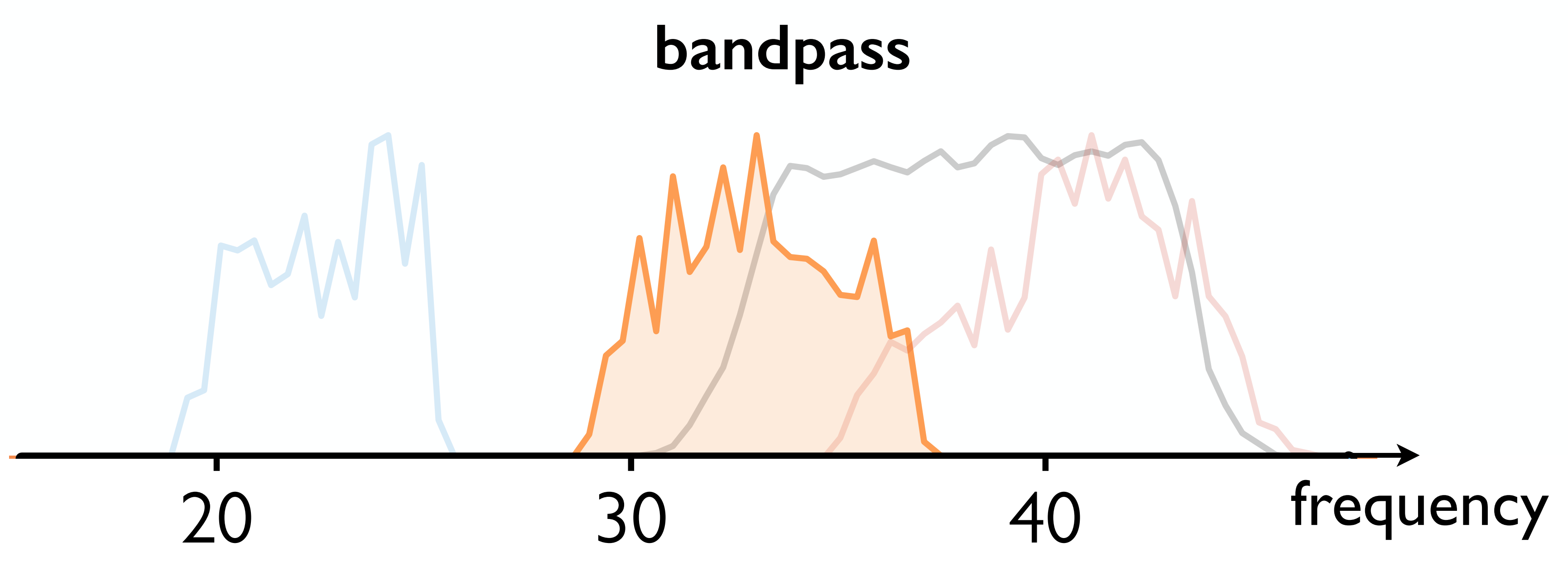


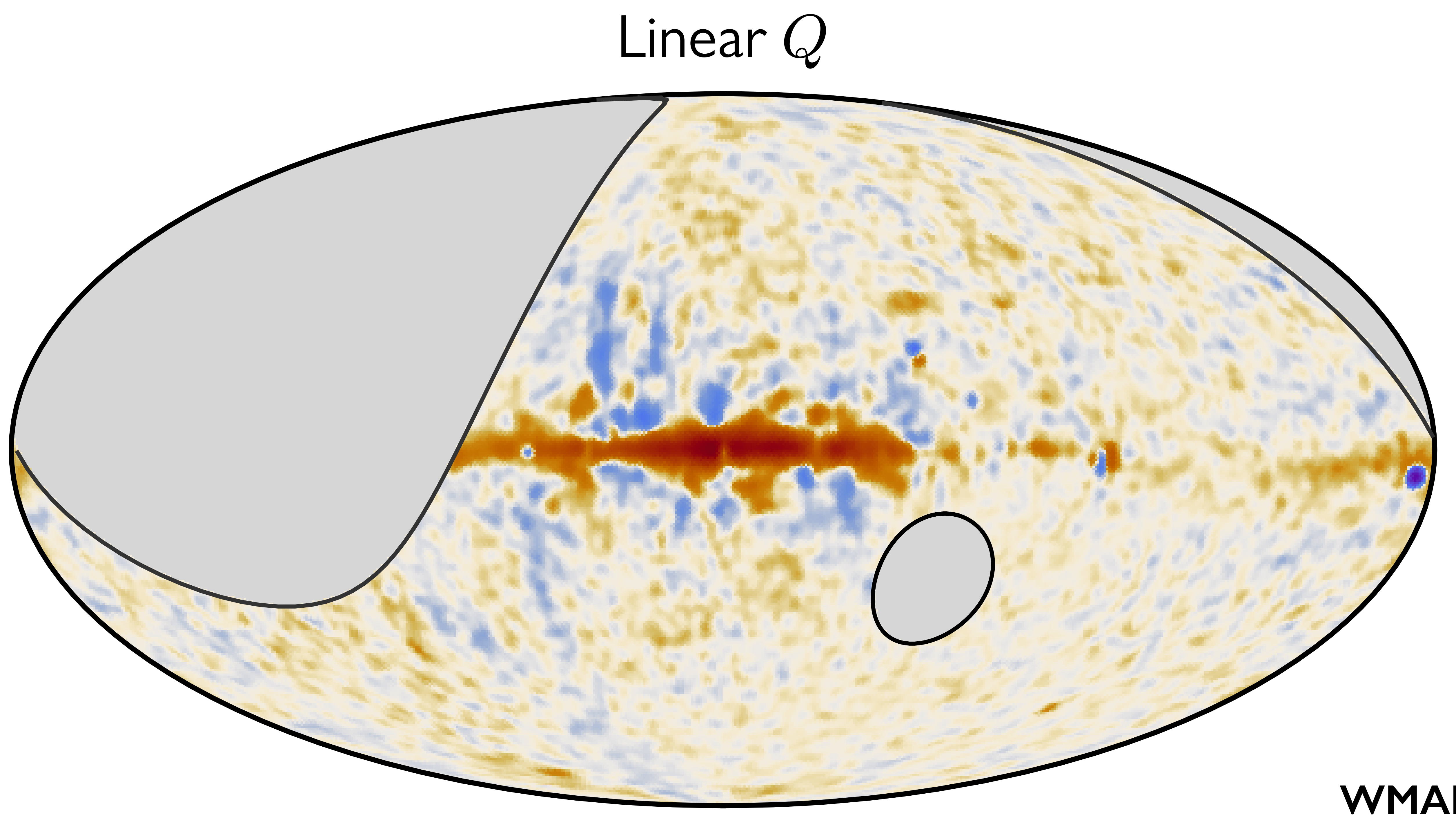
Linear U

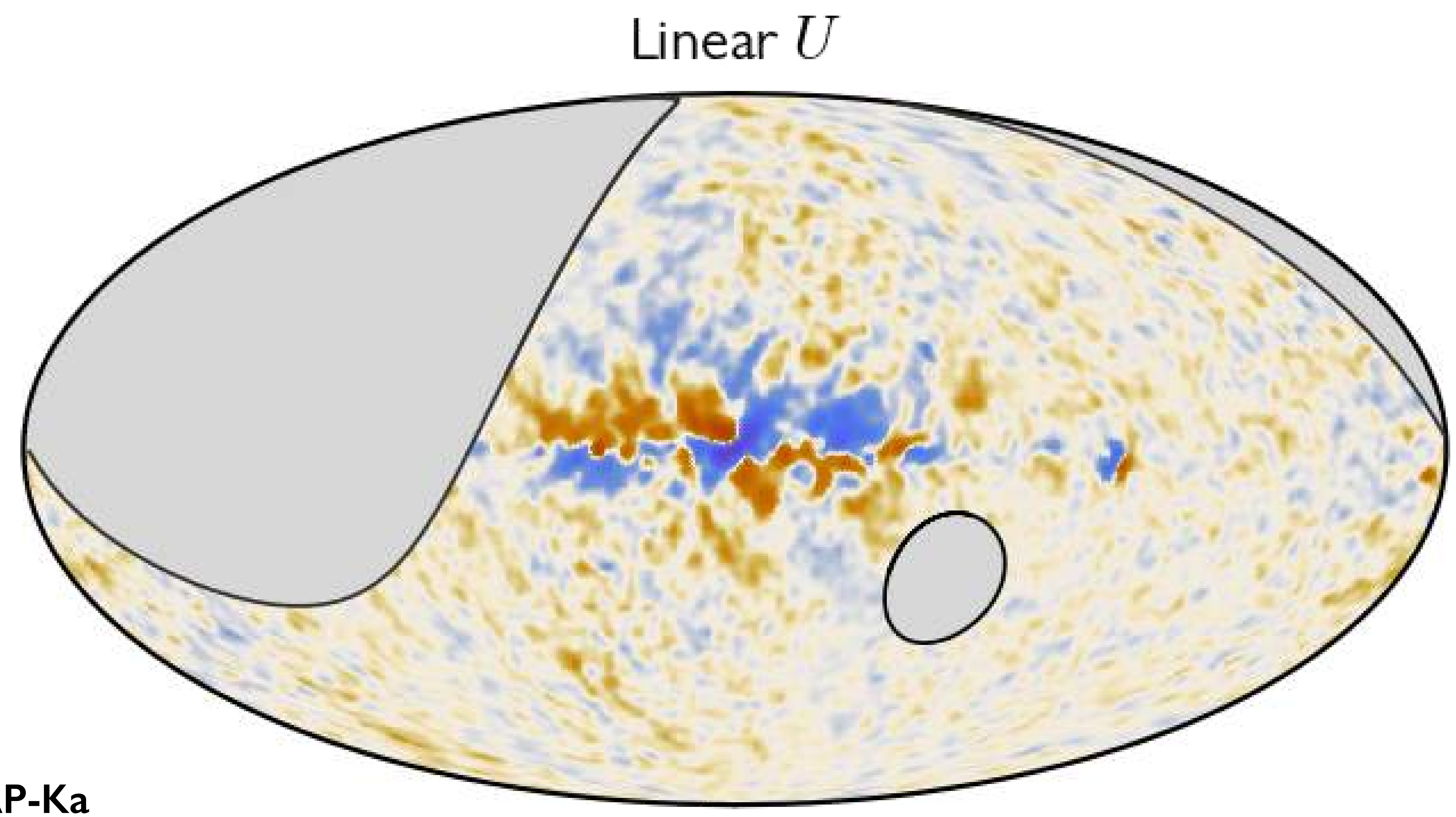


WMAP-K
(filtered/scaled)

Linear polarization: comparison

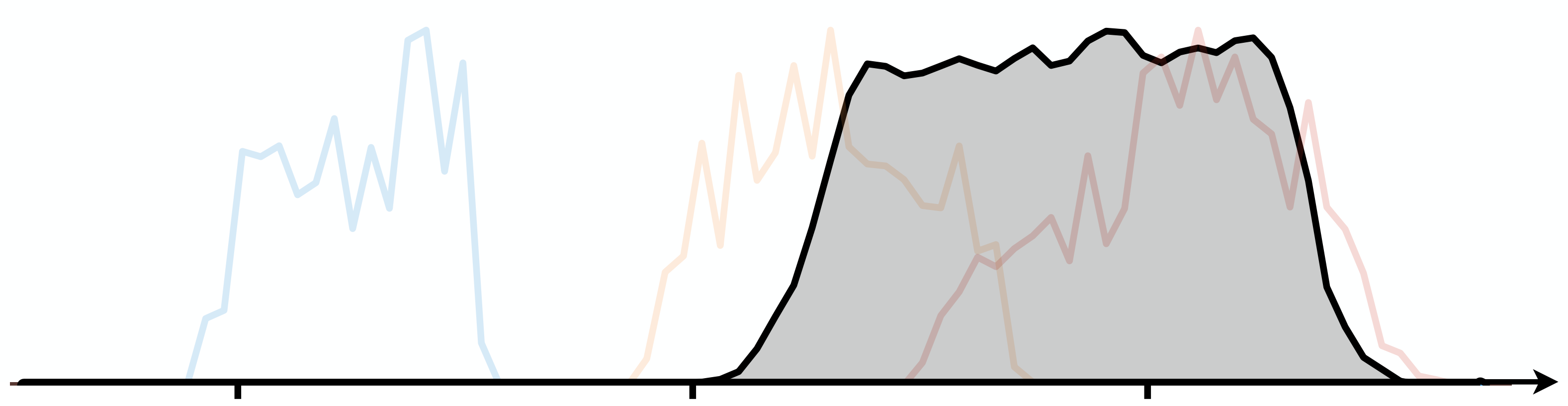




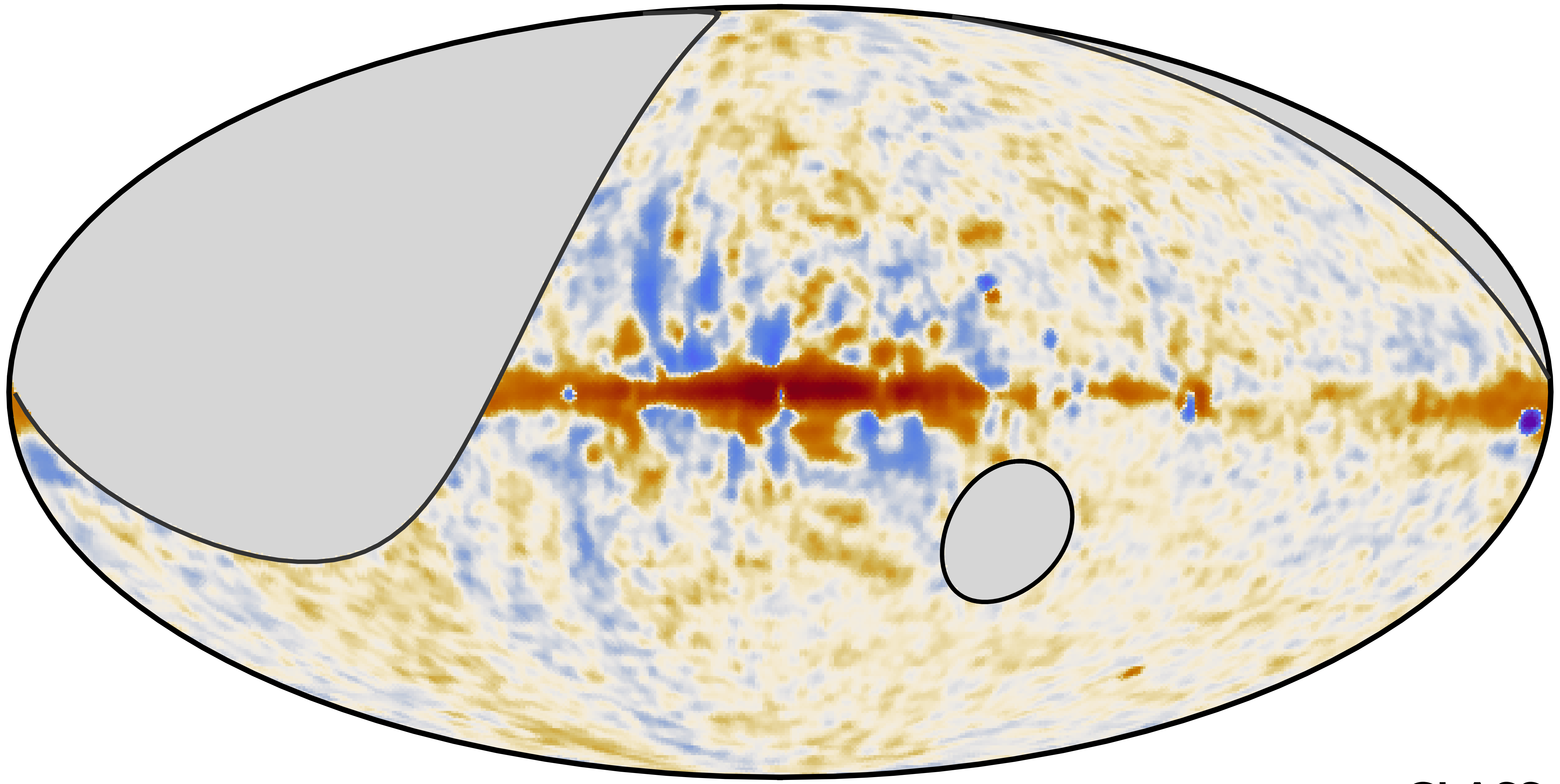


WMAP-Ka (filtered/scaled)

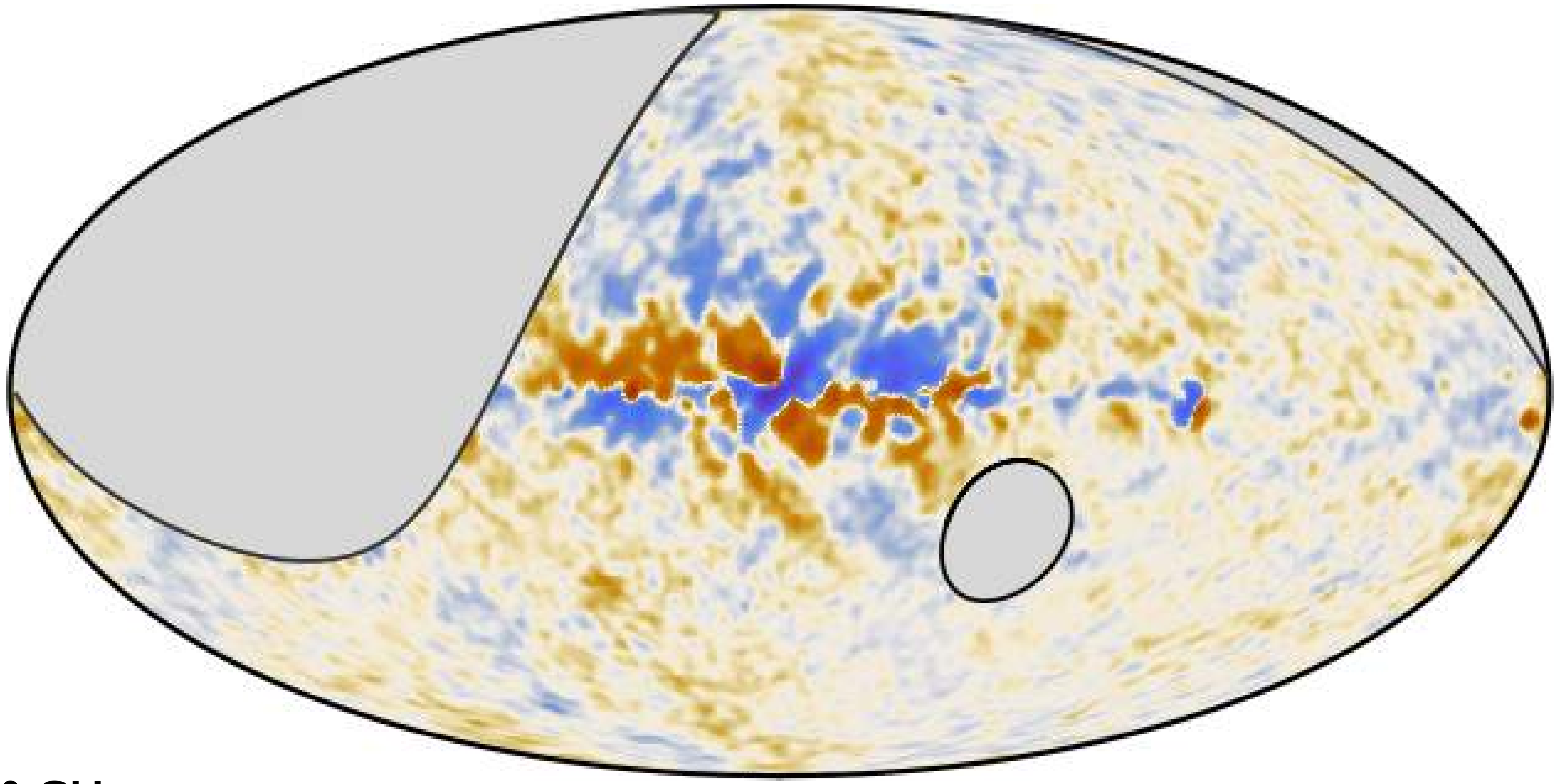
Linear polarization: comparison



Linear Q

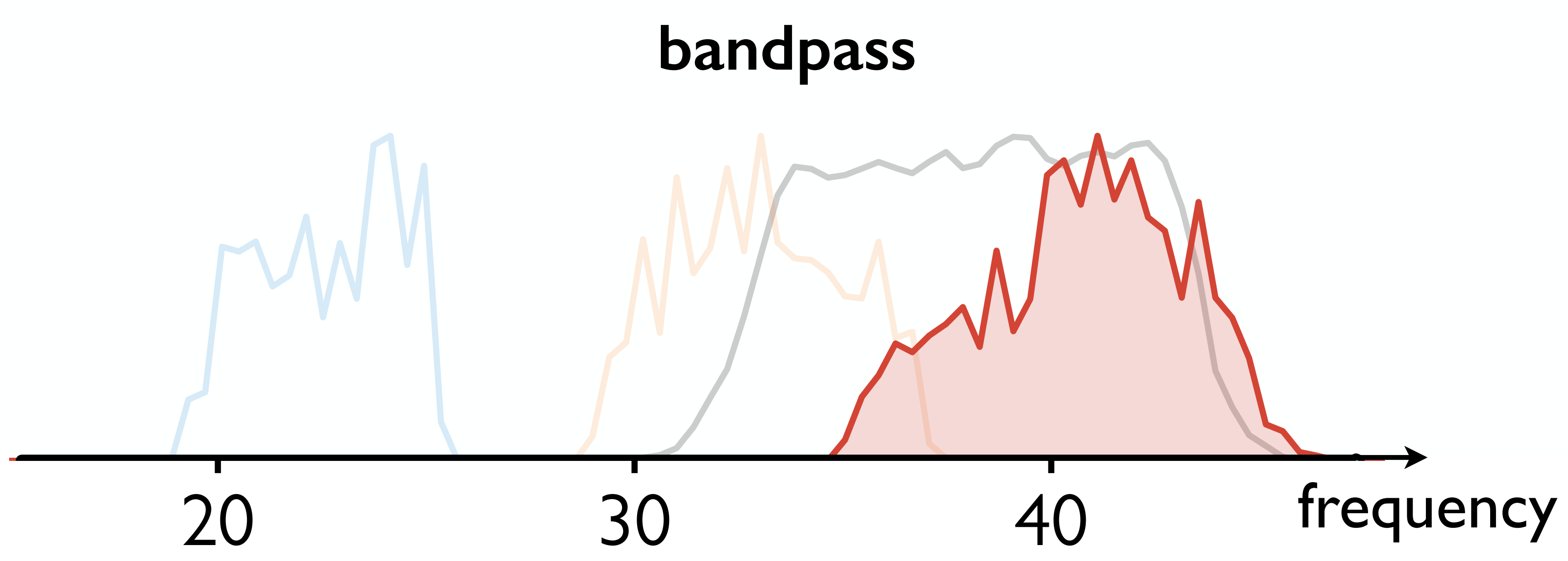


Linear U



CLASS 40 GHz

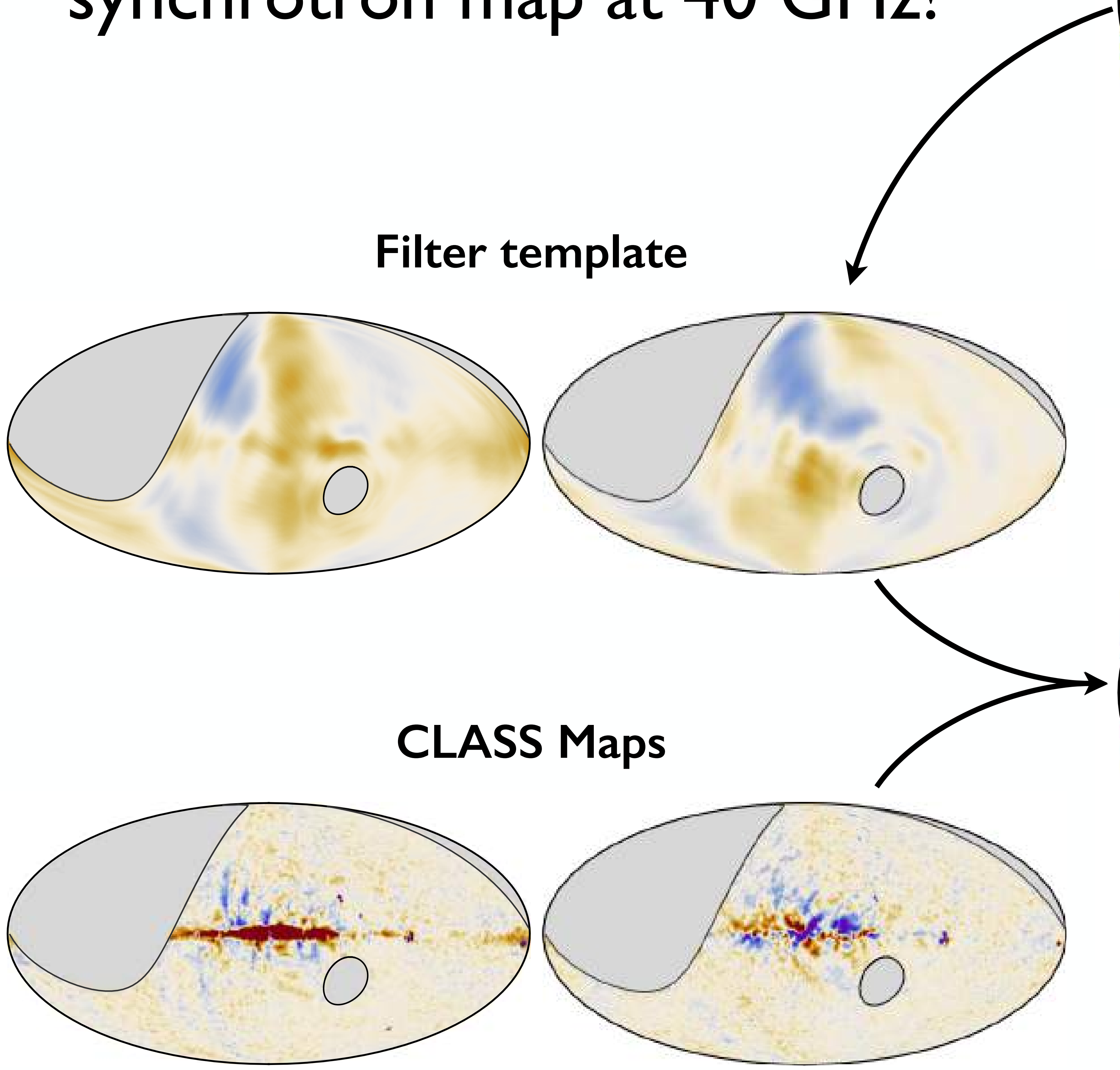
Linear polarization: comparison

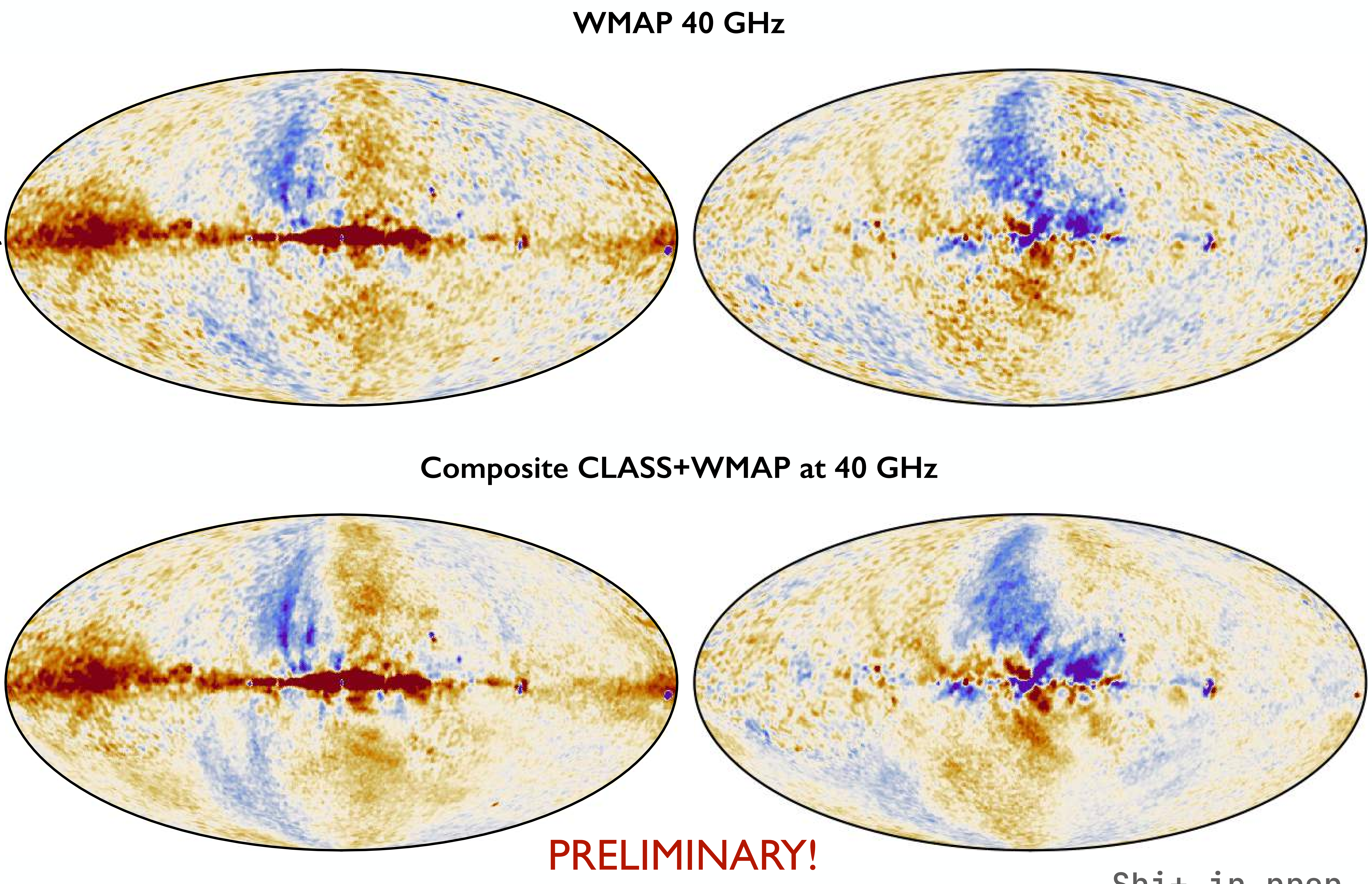


WMAP-Q
(filtered/scaled)

Linear polarization: comparison

- Linear mapper: map-domain filter template.
- Composite with WMAP: *unbiased* synchrotron map at 40 GHz!

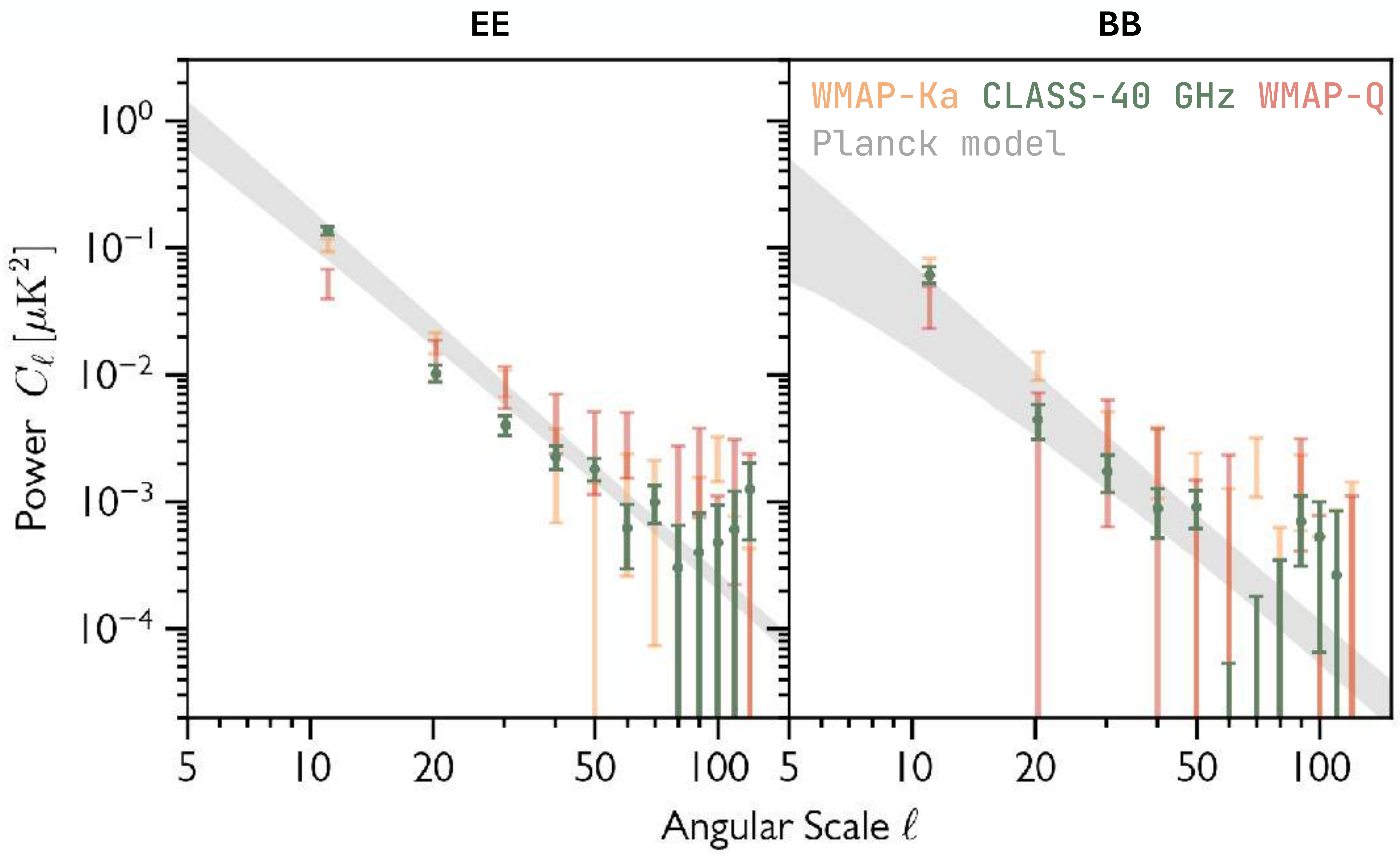




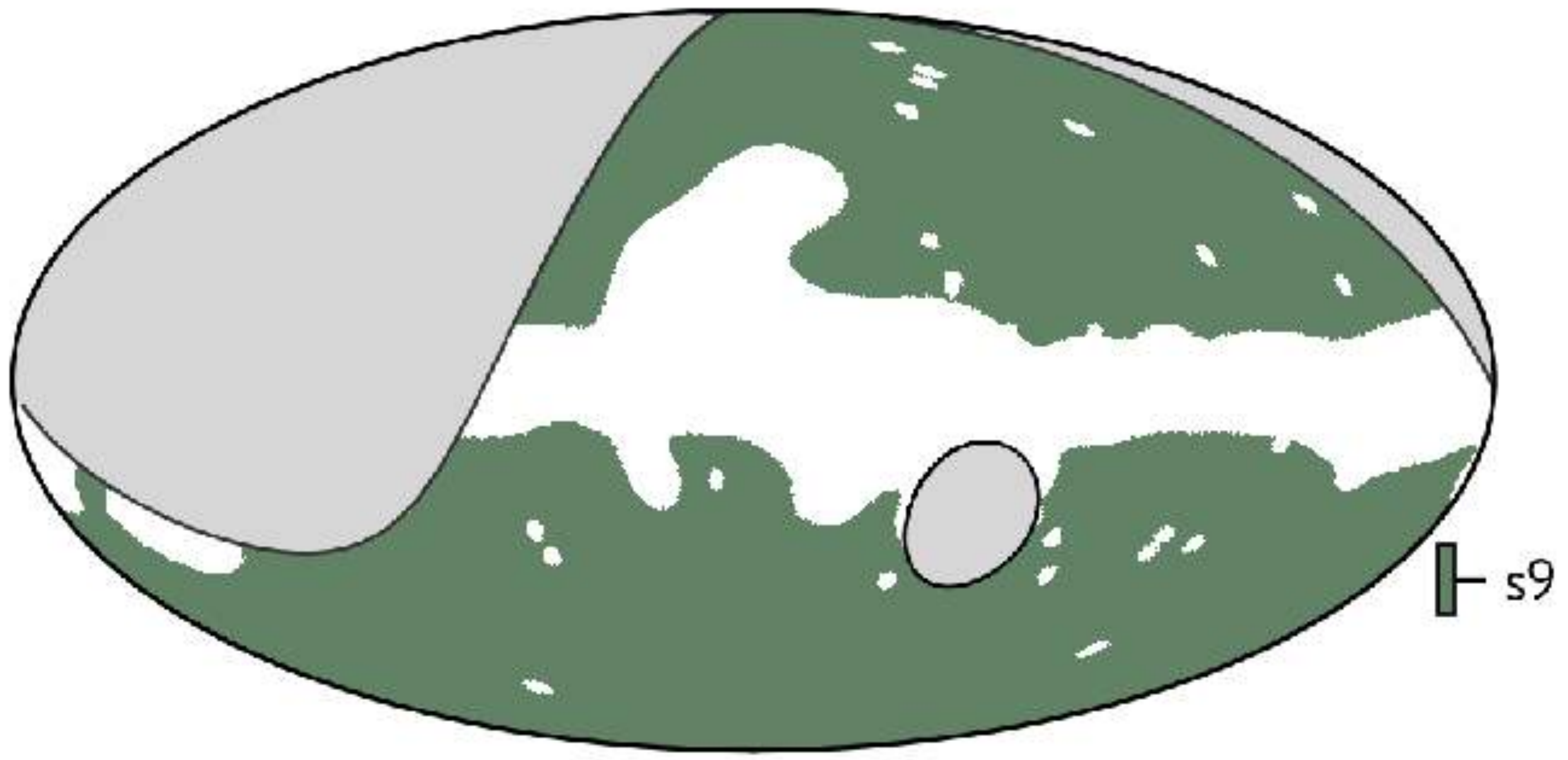
Shi+ in prep.

Synchrotron: angular power spectra

Synchrotron Angular Spectra



Galactic Avoidance

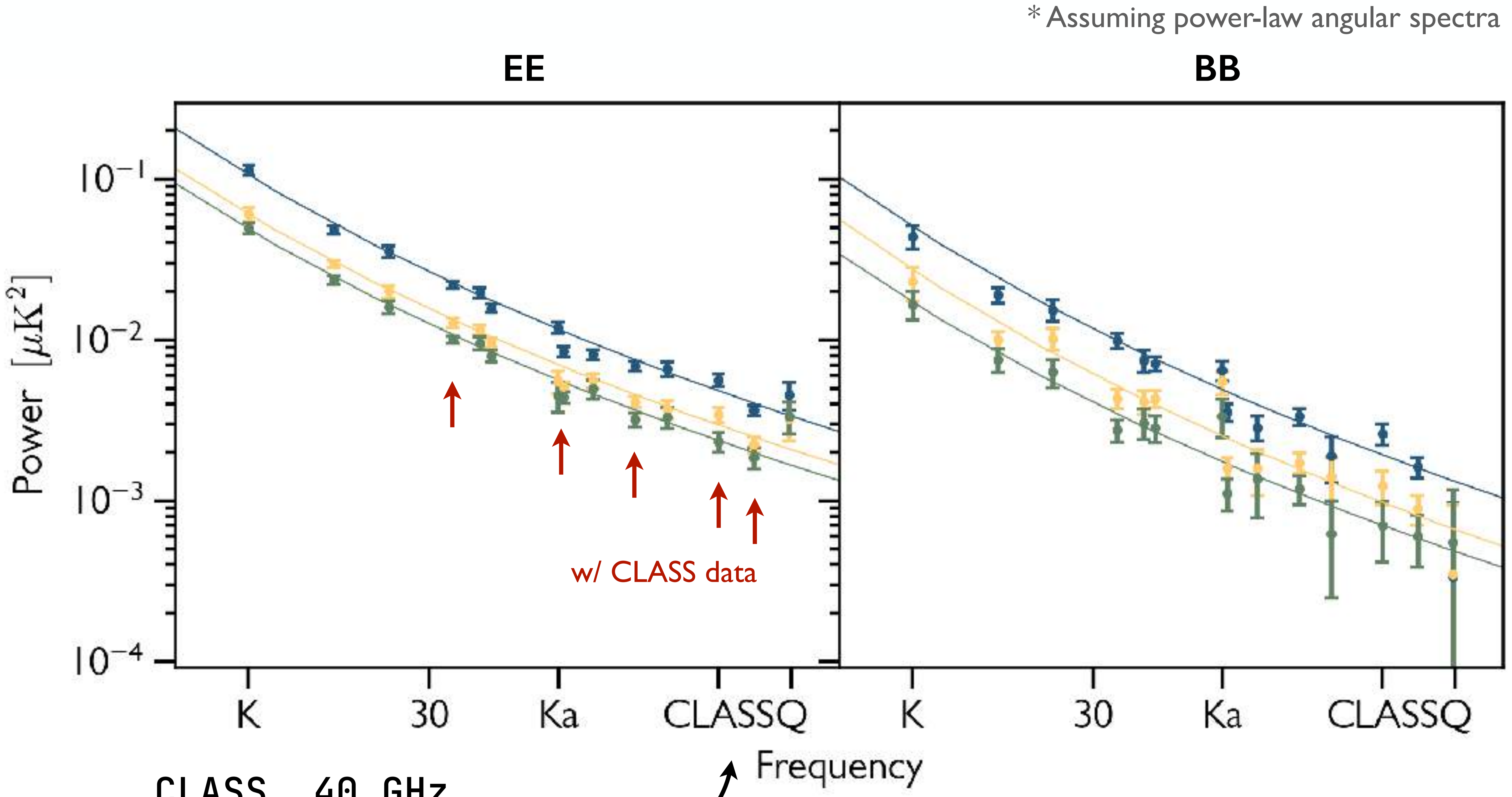


- Recovery of large angular scale synchrotron (with filter correction)
- Consistent spectral shape (approx. power-law) with satellite measurements
- E/B asymmetry: BB/EE $\approx$ 0.3-0.4

Eimer+2023 Adapted

Synchrotron: spectral energy distribution

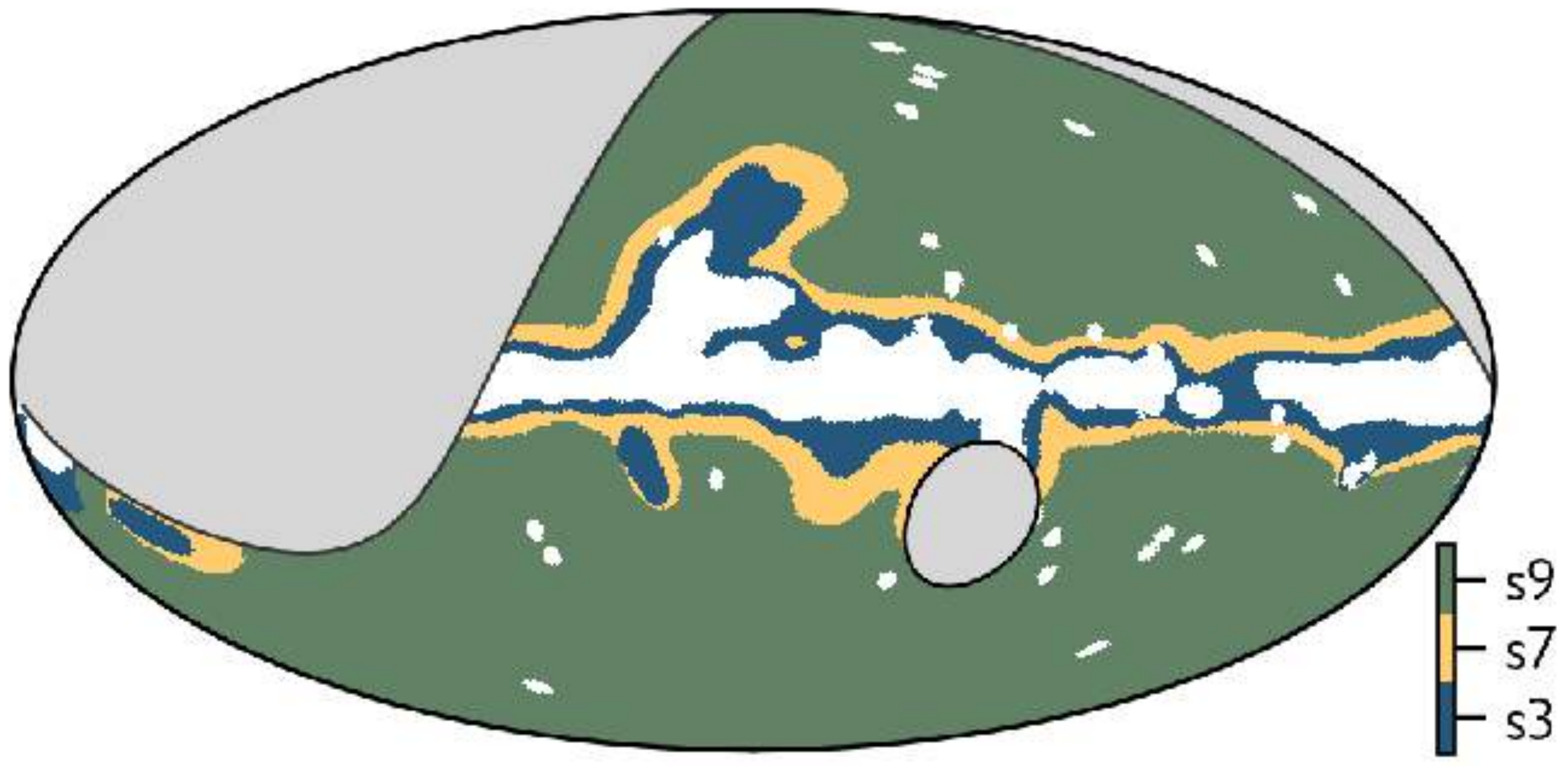
Synchrotron spectral energy distribution




```
CLASS  40 GHz
WMAP   22/33/40 GHz
Planck 30 GHz
```

All combination of inter-frequency crossing

Galactic Avoidance



$$C^{1\times 2}(\ell) = A\left(\frac{\nu_1\nu_2}{\nu_c^2}\right)^{\beta_s}\left(\frac{\ell}{40}\right)^{\alpha}$$

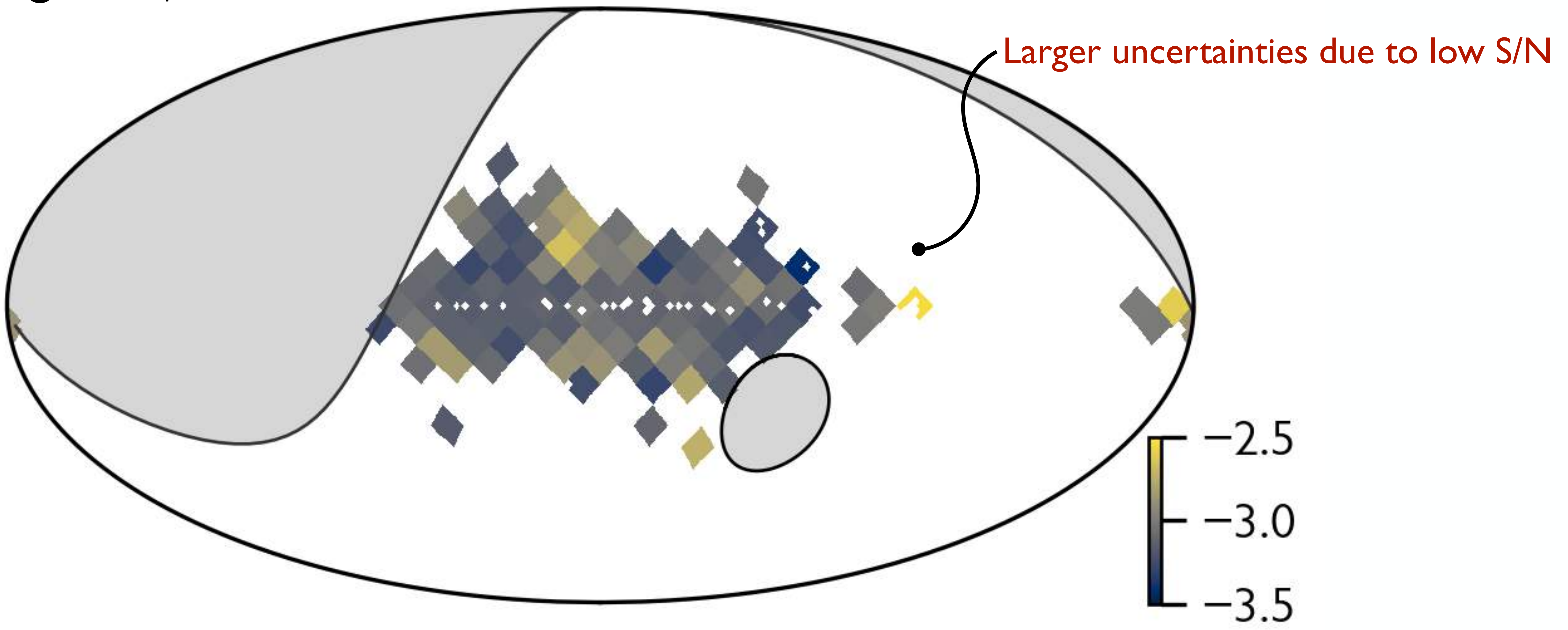
- Diffuse synchrotron shows consistent $\beta_s \approx -3.0 \pm 0.1$ in polarization within the $20 \sim 40$ GHz range.

Eimer+2023 Adapted

Synchrotron: spectral energy distribution spatial variation

- Combining WMAP K/Q and CLASS
- The brightest Galactic region show significant synchrotron index variation.
- Variation of order 0.3 is robust against *filter effects/Galactic dust*

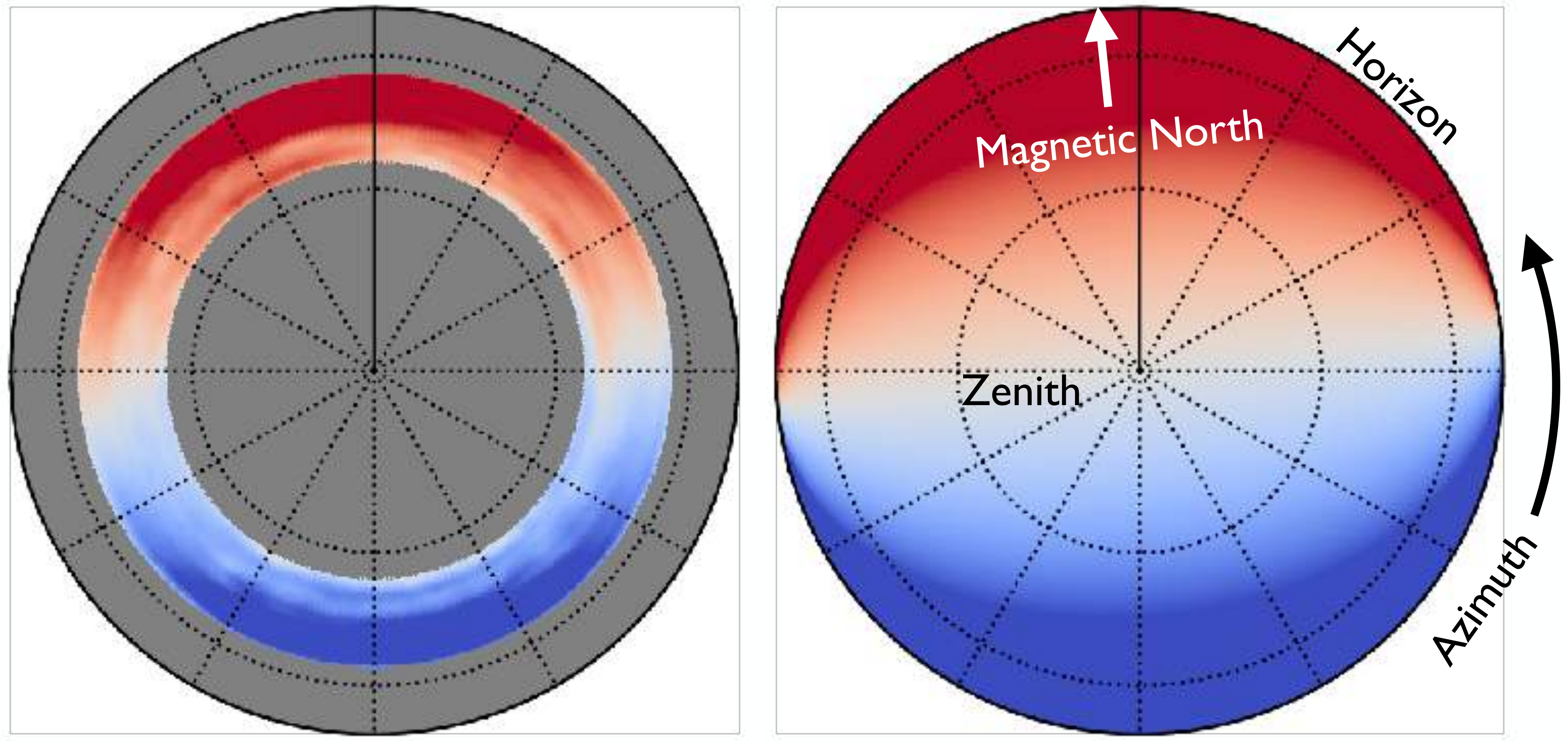
β_s **spatial variation**



Eimer+2023 Adapted

Circular science: atmospheric

Atmospheric Emission



data model

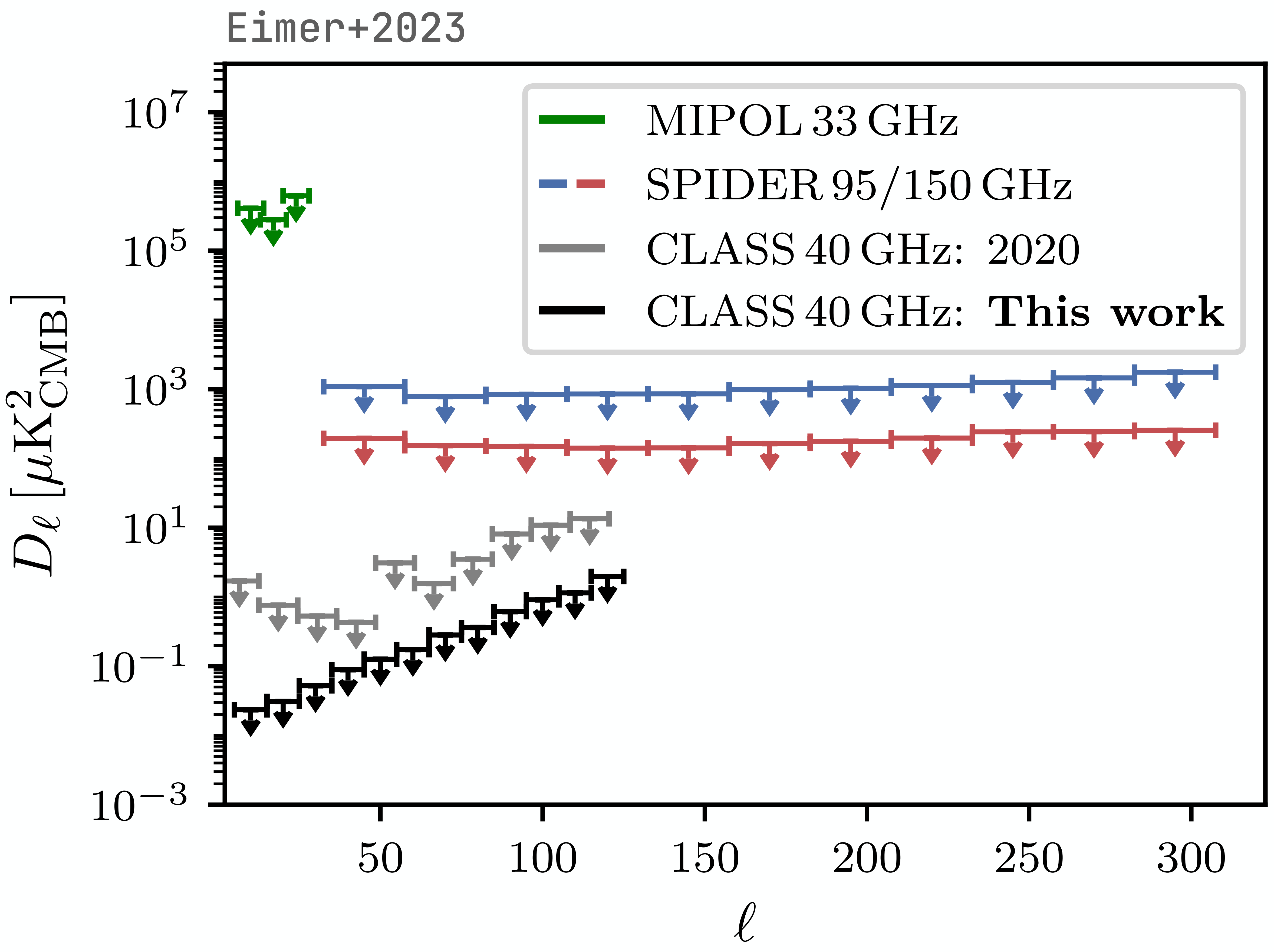
circular polarization maps in horizontal coordinates (az, el)

- Zeeman splitting of the molecular Oxygen in the Earth magnetic field.
- Earth magnetic field defines the spatial pattern of the signal (dipole)
- This signal is treated as systematics and filtered out for the cosmological products

Further reading

- Theory and 40 GHz observation *Petroff+2020 (ApJ 889 120)*
- Multifrequency observation *Essinger-Hileman+ in prep.*

Circular science: astrophysical

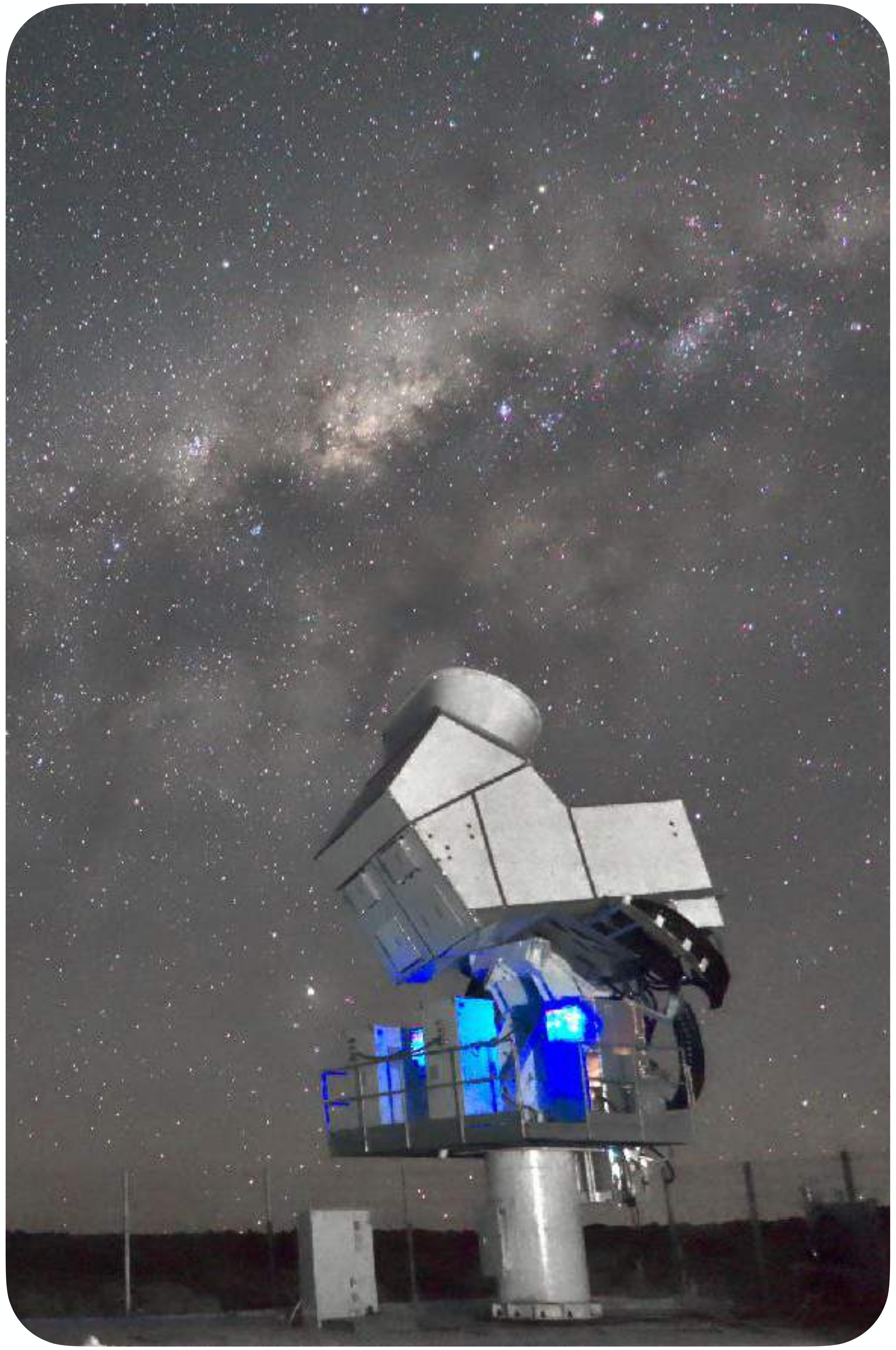


- Circular polarizations are expected from *primordial magnetic fields/Faraday conversion* mechanisms. The most prominent one is expected from the Galactic synchrotron, of order $10^{-6}\,\mu K^2$.
- All mechanisms predict *steep and negative frequency scaling*, making 40 GHz most sensitive to these mechanisms.
- CLASS places *best upper limit* at 40 GHz at $10^{-1}\mu K^2$

Further reading

- Circular polarization physics and 40 GHz constrains *Padilla+2020 (ApJ 889 105)*
- Multifrequency observation *Essinger-Hileman+ in prep.*

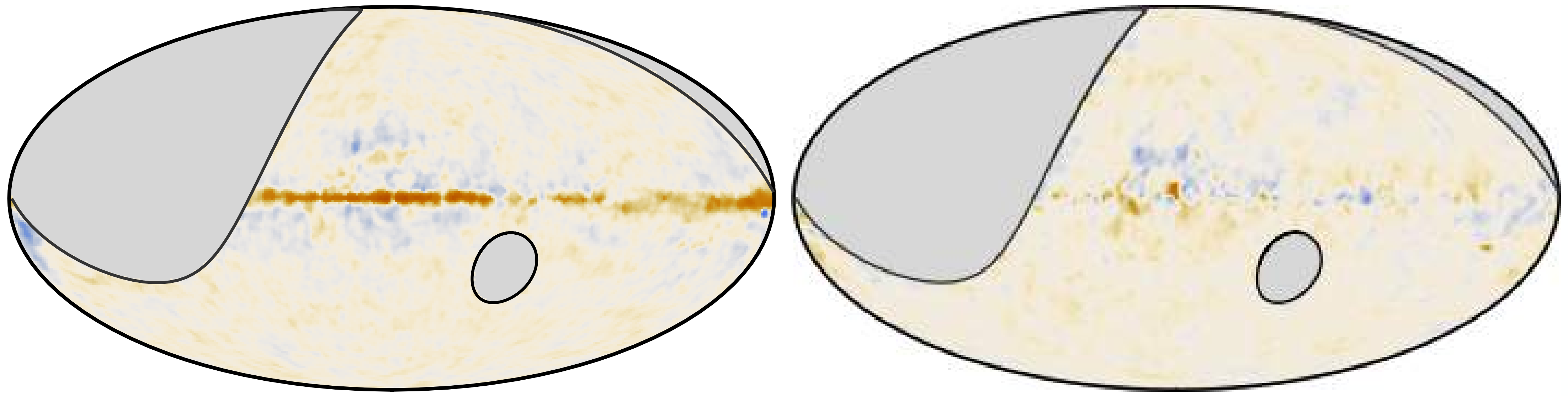
Future Prospects



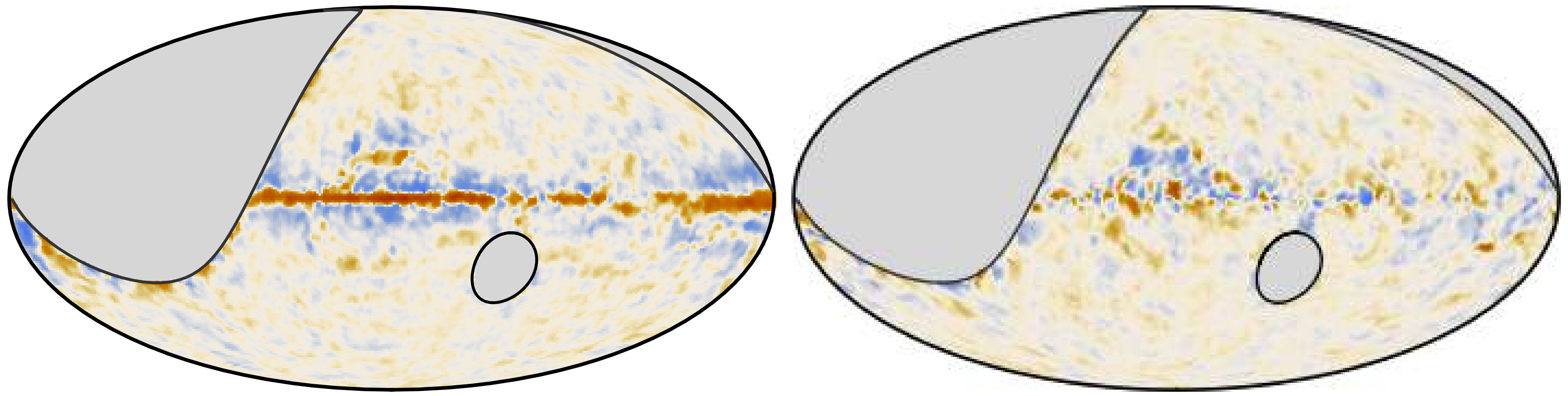
Multifrequency data

PRELIMINARY!

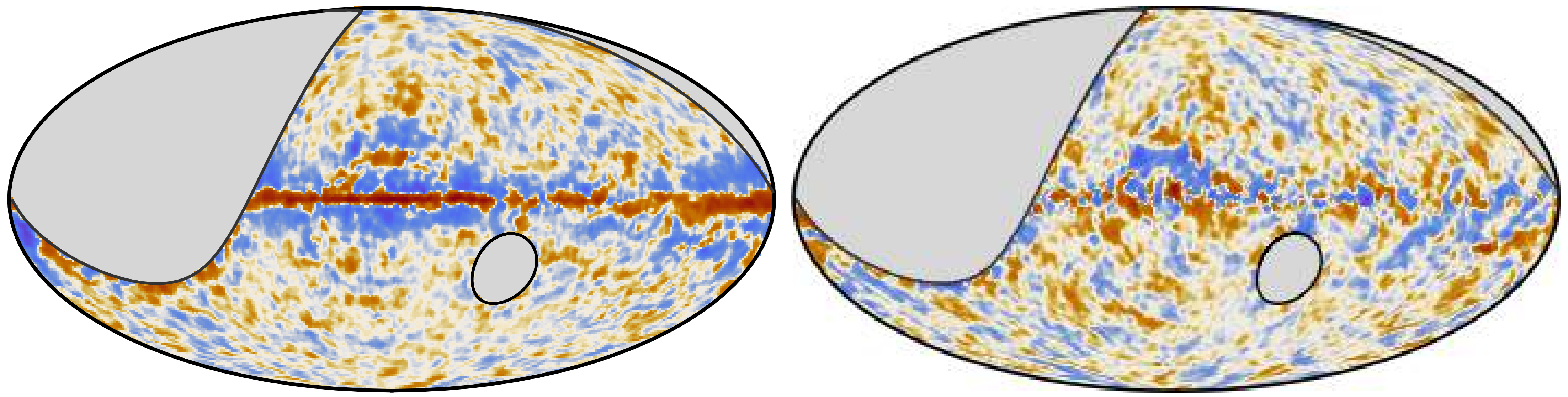
90 GHz



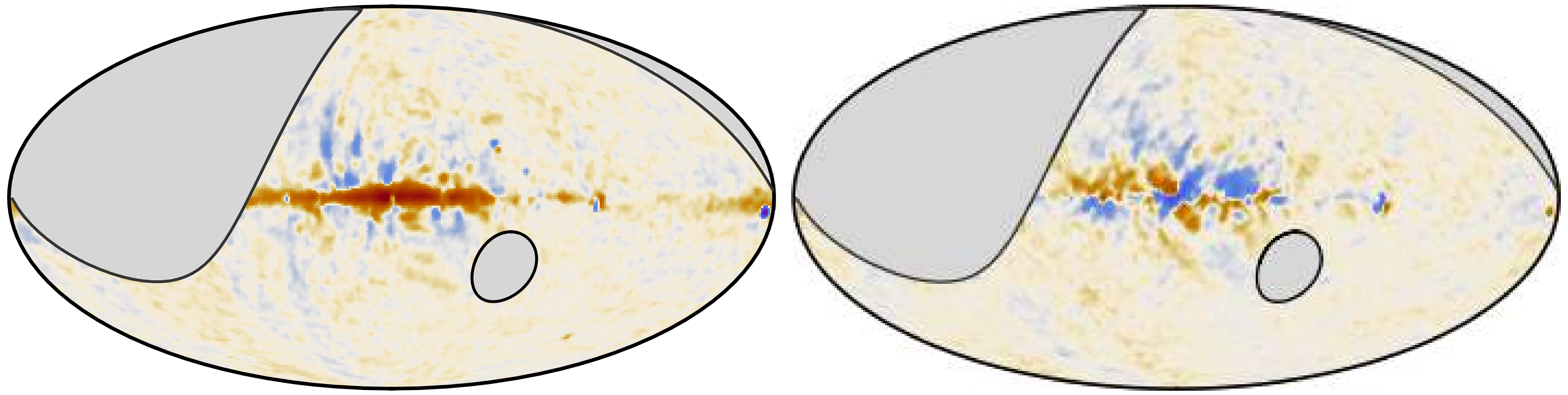
150 GHz



220 GHz



40 GHz

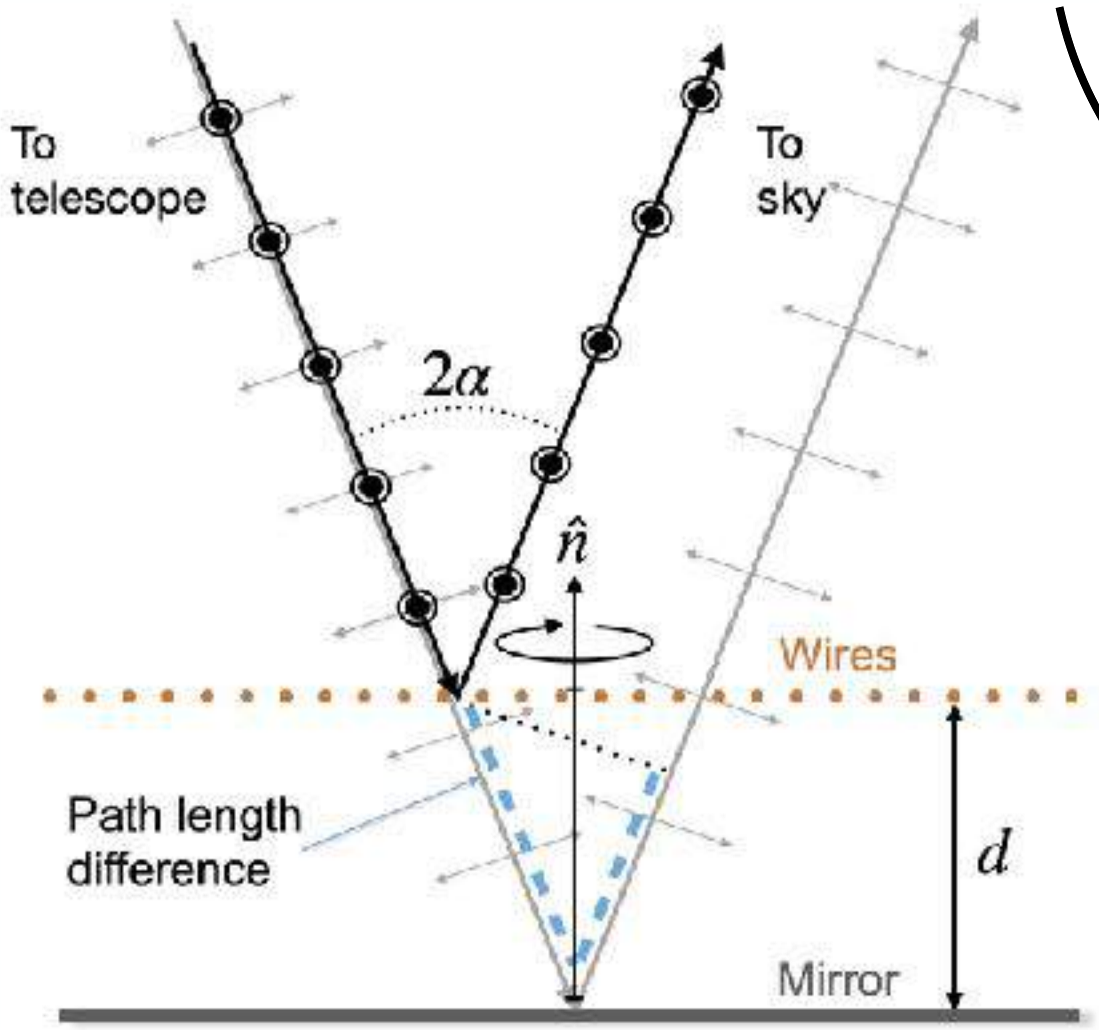


40 GHz has the longest survey and most extensively studied data.

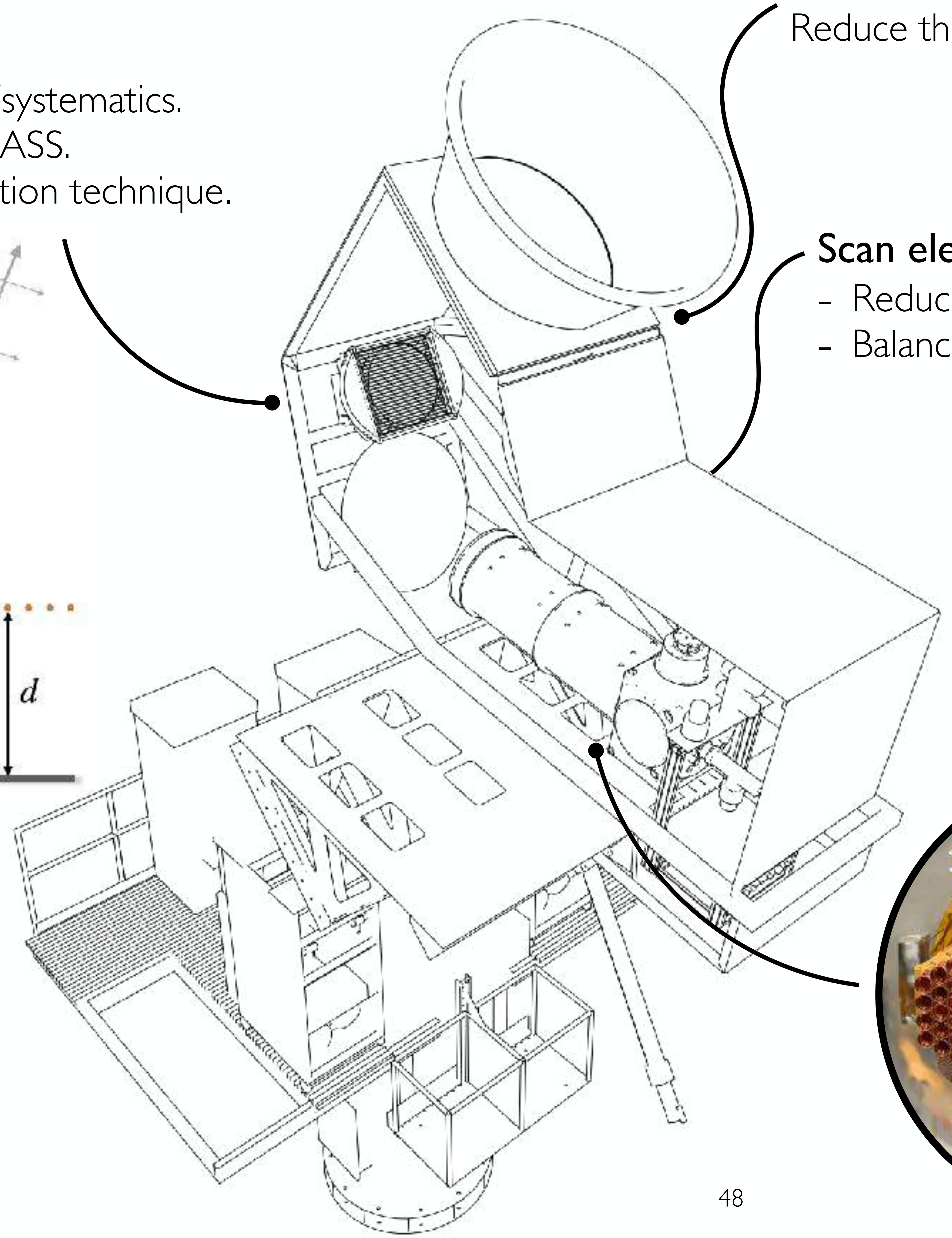
But, the processing and lessons learned are highly transferable to other frequencies.

Hardware upgrades

Reflective half-wave plate
- Reduce modulation emission/systematics.
- "drop-in" replacement for CLASS.
- New investigation on modulation technique.



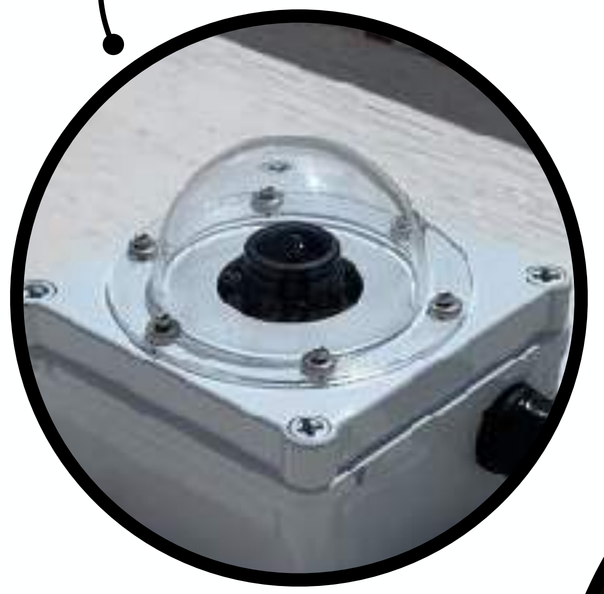
Eimer+2022

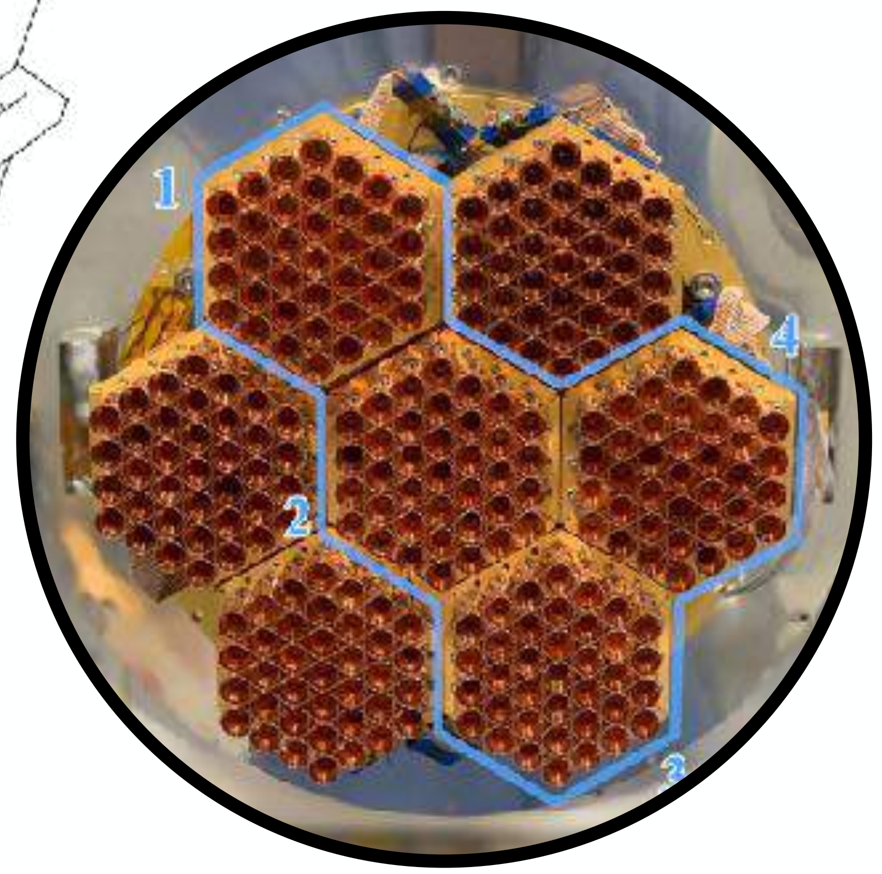


Remove environmental closeout
Reduce the varying azimuth-covariant signals

Scan elevation 45° → 55°
- Reduce ground pick-ups
- Balancing the sky coverage.

All-sky camera for cloud monitor
Improve data selection



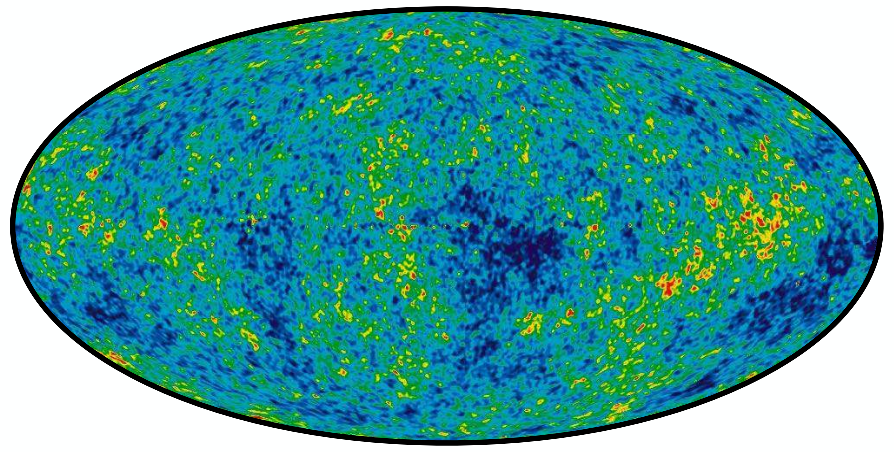


90 GHz upgrades & new 90 GHz array
- New designs improves stability and optical efficiency
- Get more detectors on sky!

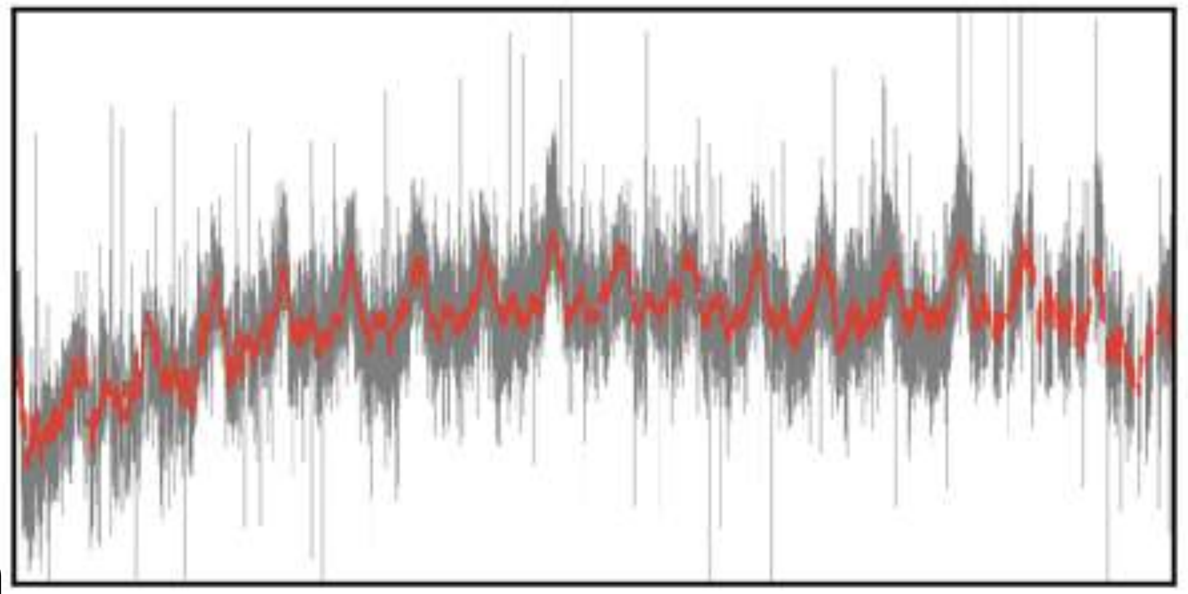
Núñez+ in prep.

Software upgrades

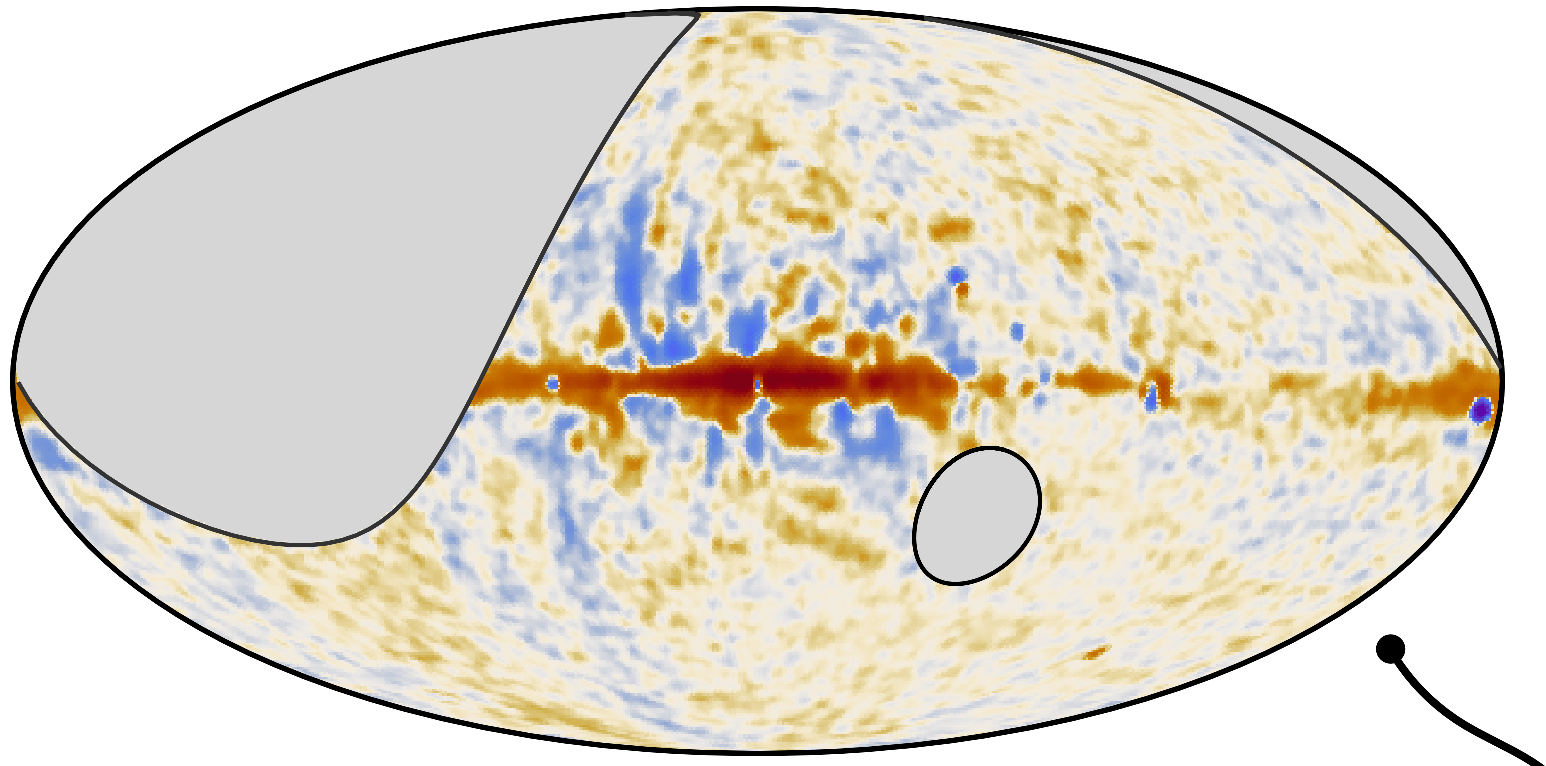
sky

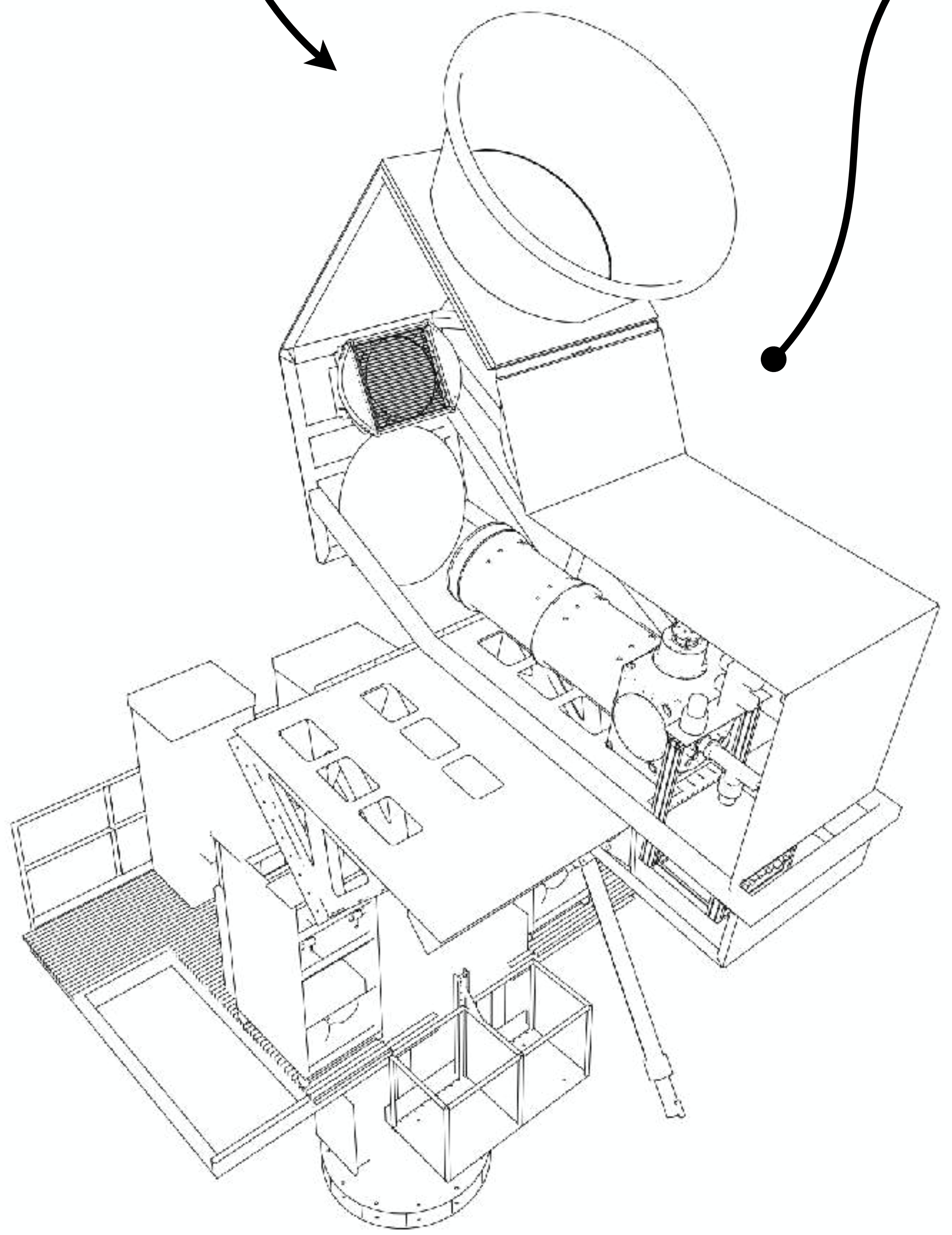


time-ordered data



multifrequency maps

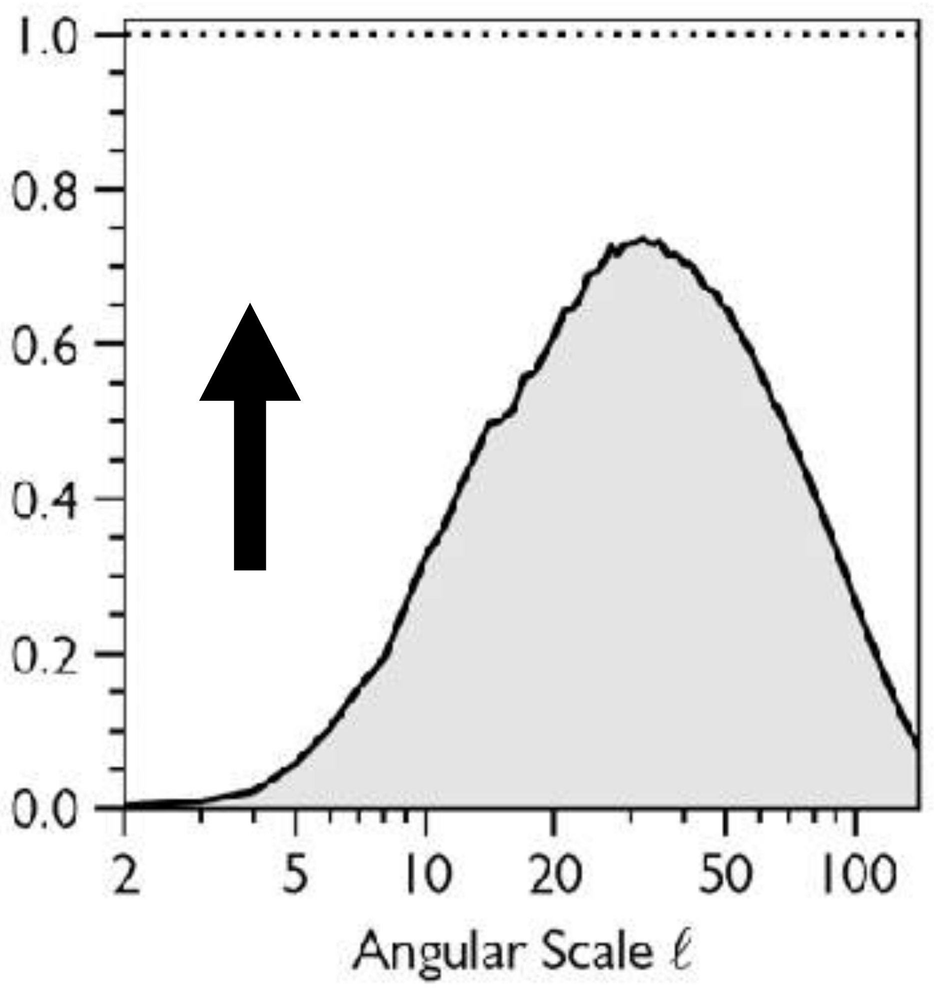




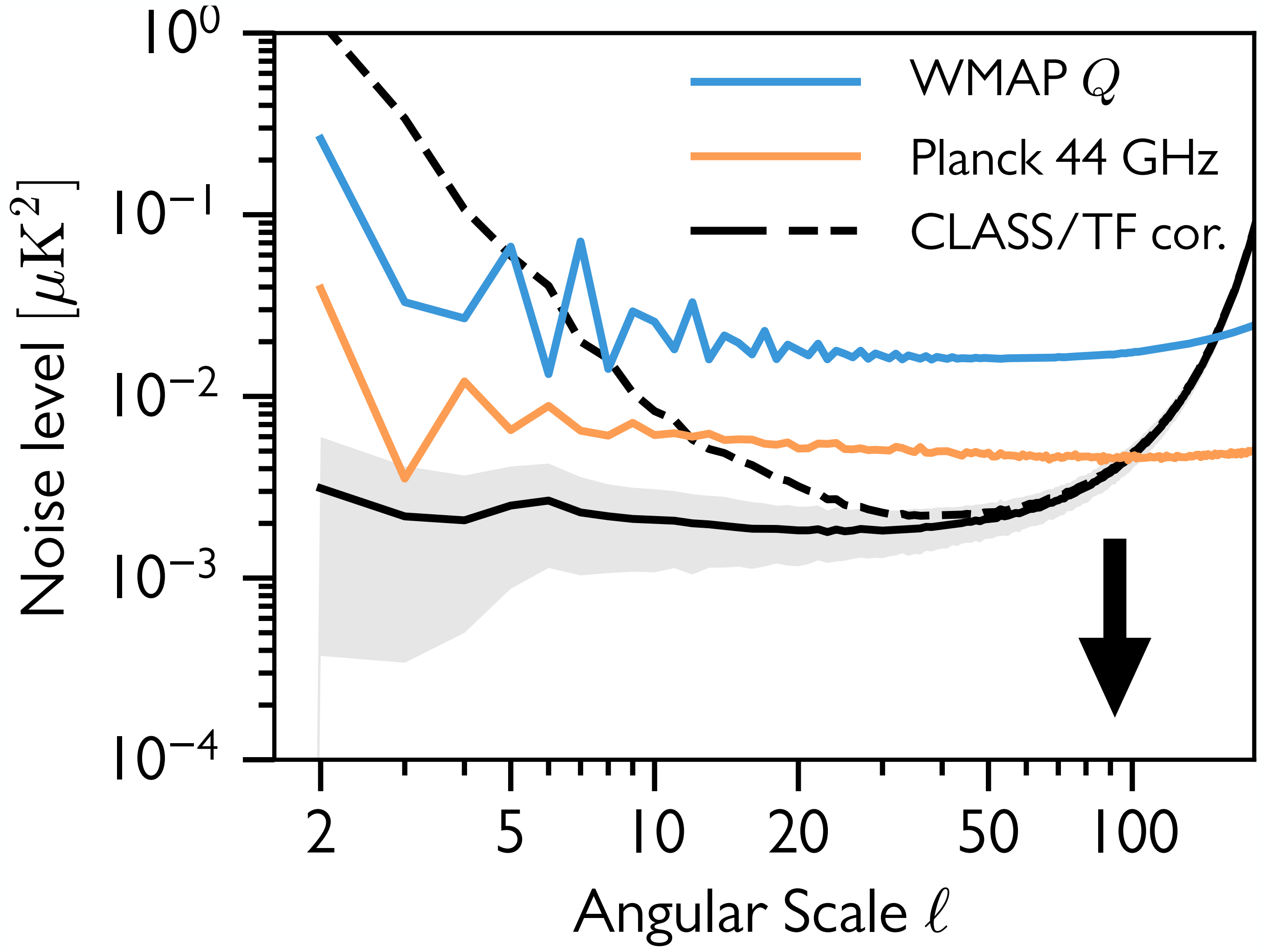
systematics reduction

- Less aggressive filtering
- Strategic filtering with improved data selection

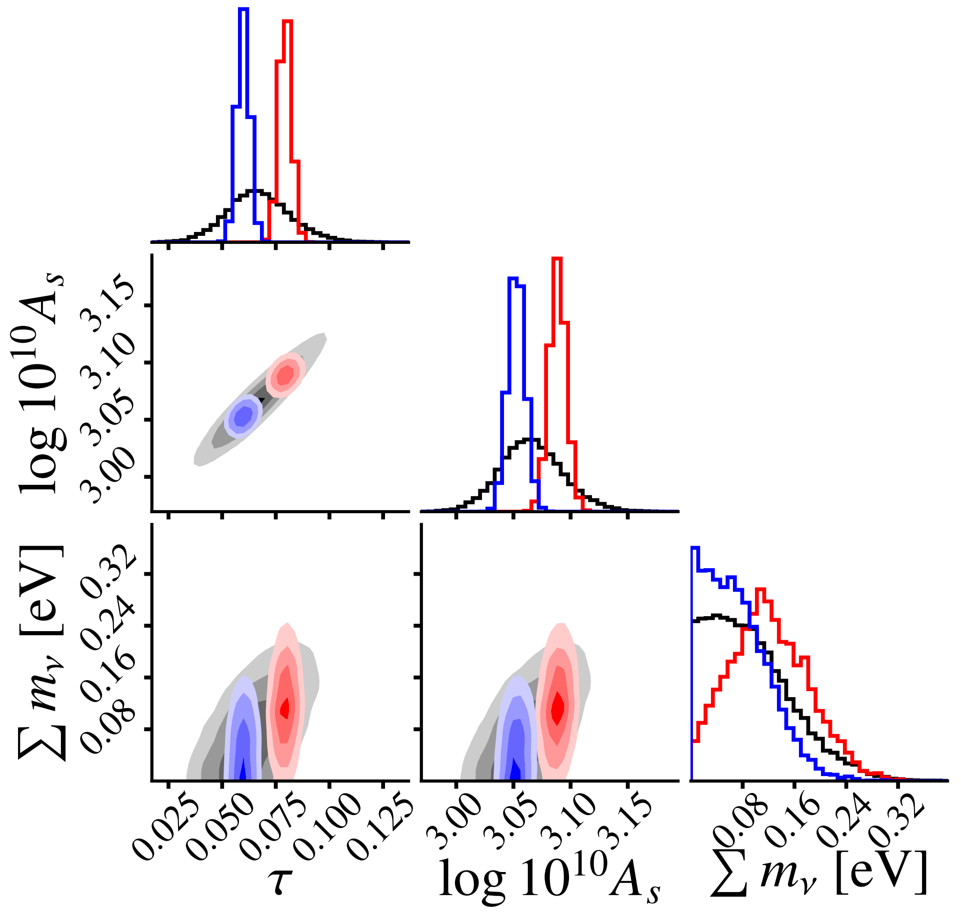
Improve large scale recovery



Improve sensitivity



Cosmology



Watts+18

CLASS

JOHNS HOPKINS UNIVERSITY

NSF

UBC

NASA

NIST

CONICYT
COMISIÓN NACIONAL DE INVESTIGACIÓN CIENTÍFICA Y TECNOLÓGICA

Thank you!

Summary

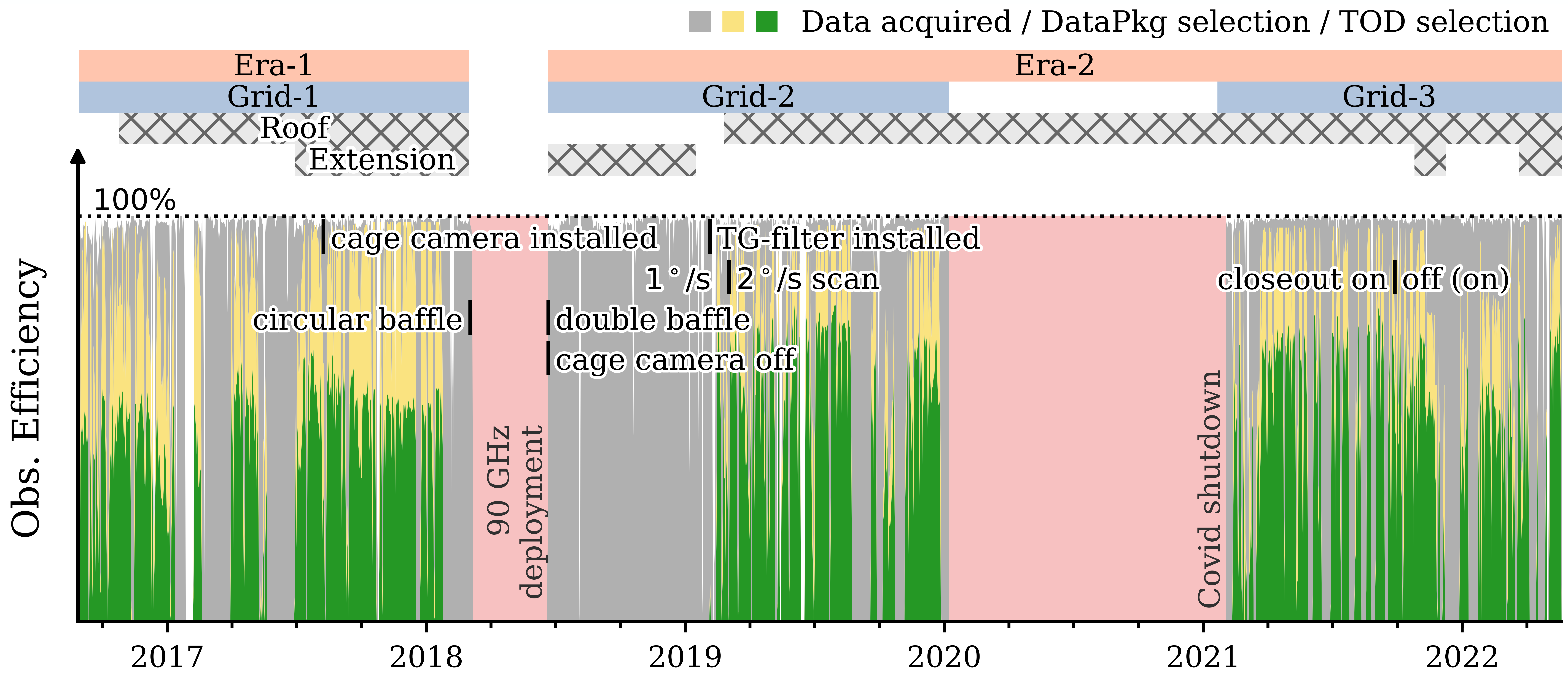
- CLASS delivers linear and circular polarization maps covering 75% of the sky.
- First end-to-end demonstration of the recovery of large angular scale polarization from the ground with the VPM technology.
- The initial processing recovers 75% (45%) of power at angular scales $\ell = 20\ (10)$.
- At 40 GHz, CLASS observe the synchrotron radiation that is consistent with previous result but with superior sensitivities in angular range $10 < \ell < 100$.
- Established solid understanding of the related systematic issues, and their mitigation strategies. Software and hardware solutions are both on the way.
- Multifrequency maps and more cosmological science are underway. Stay tuned!

40 GHz Results
Eimer+2023

40 GHz Data Pipeline
Li+2023a

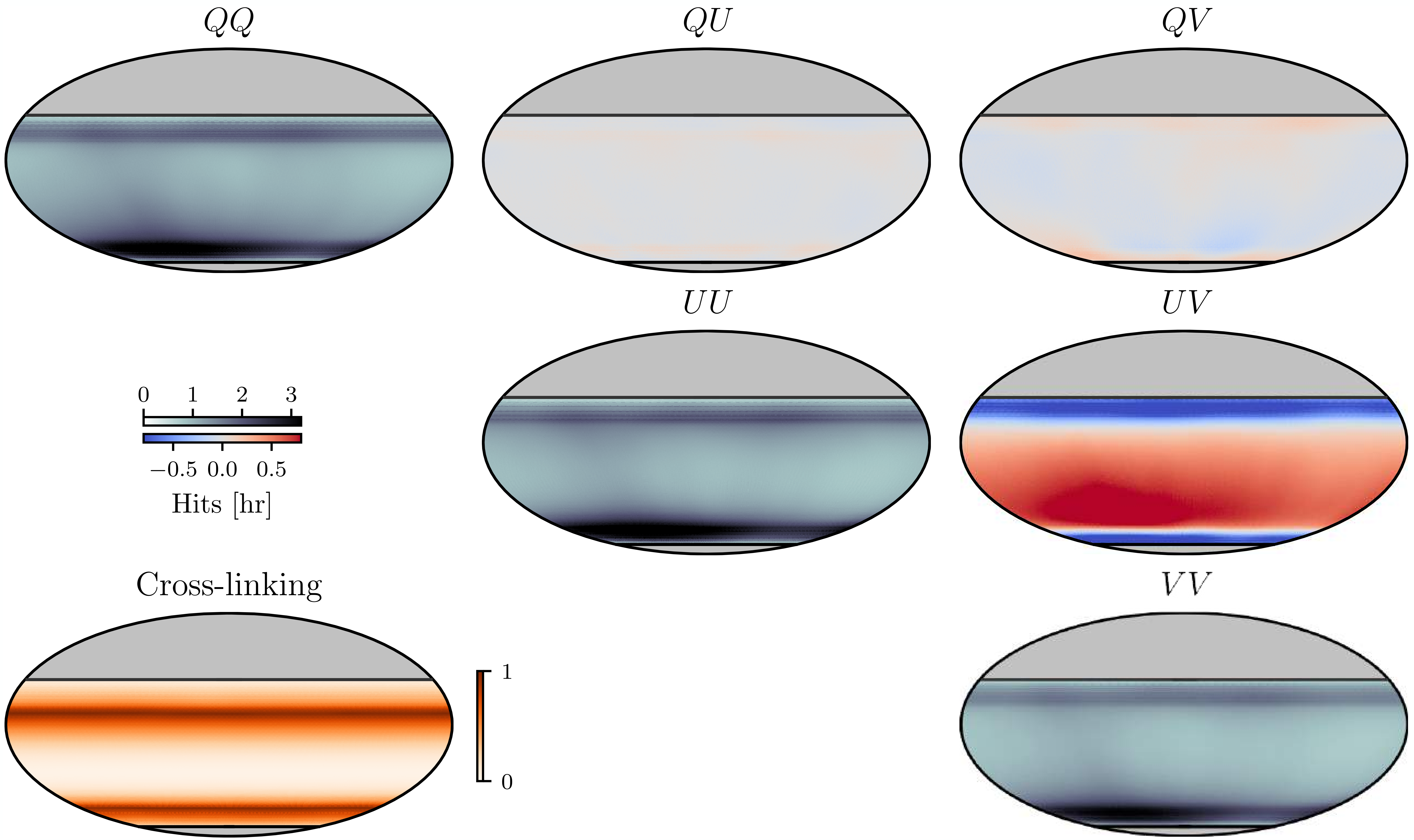
backup slides

40 GHz survey timeline



Li+2023a

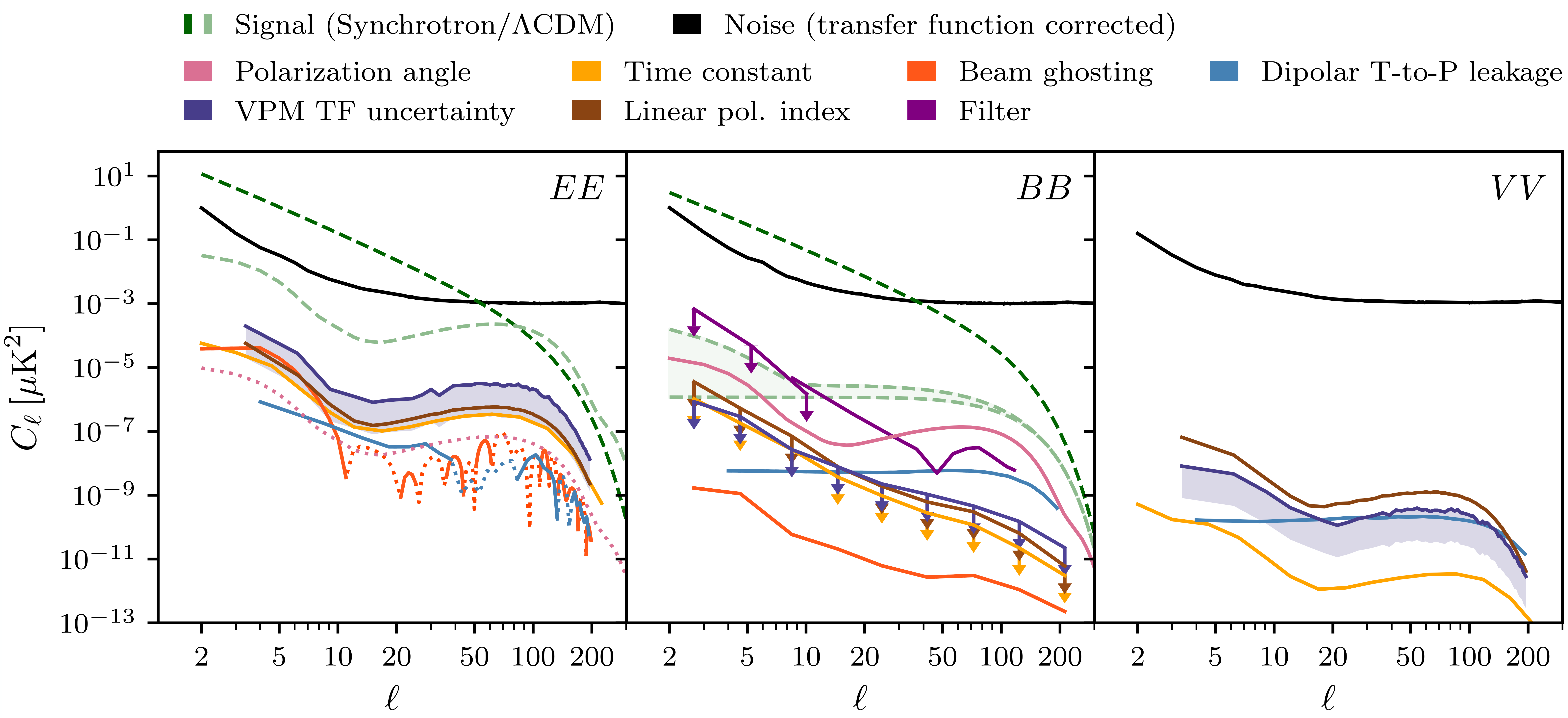
Hits maps



Li+2023a

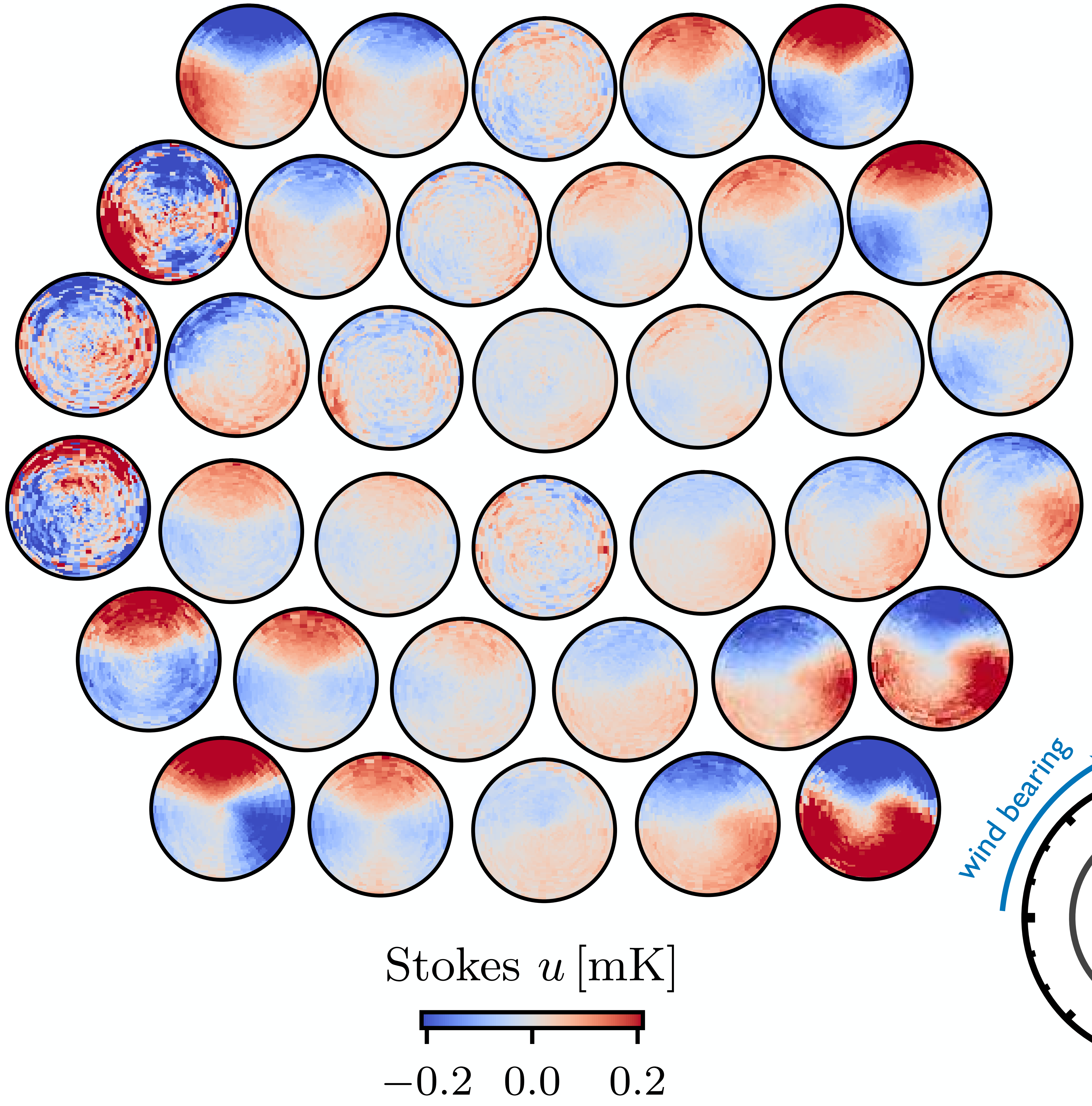
Systematic issues: impacts

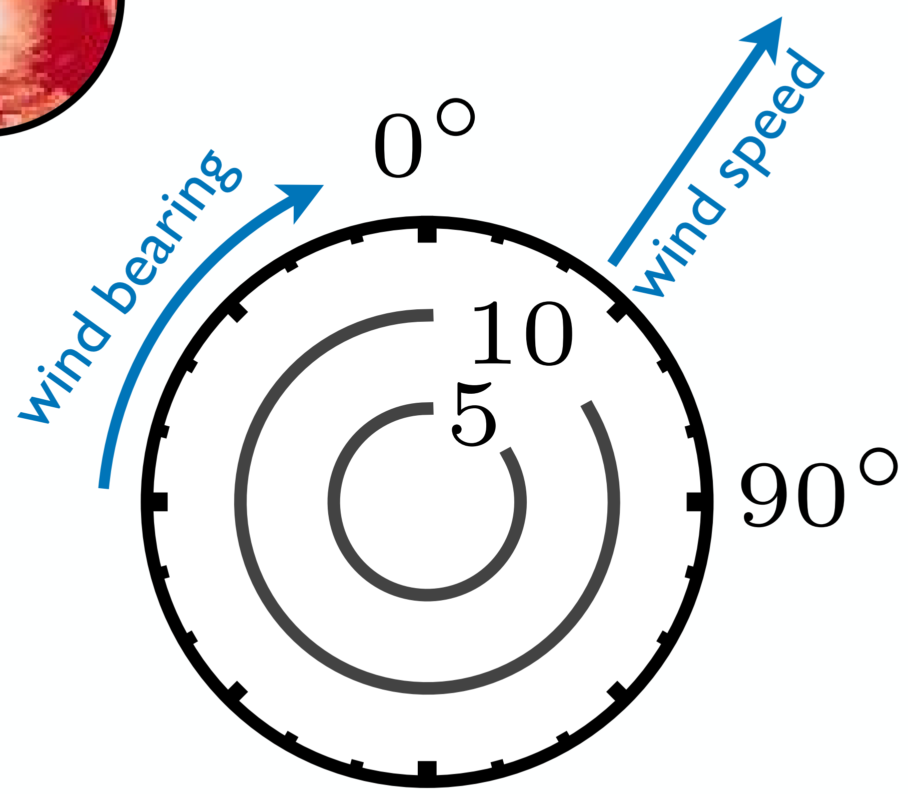
Known systematics exist beneath the noise level, but they are irrelevant for the targeted **signals**



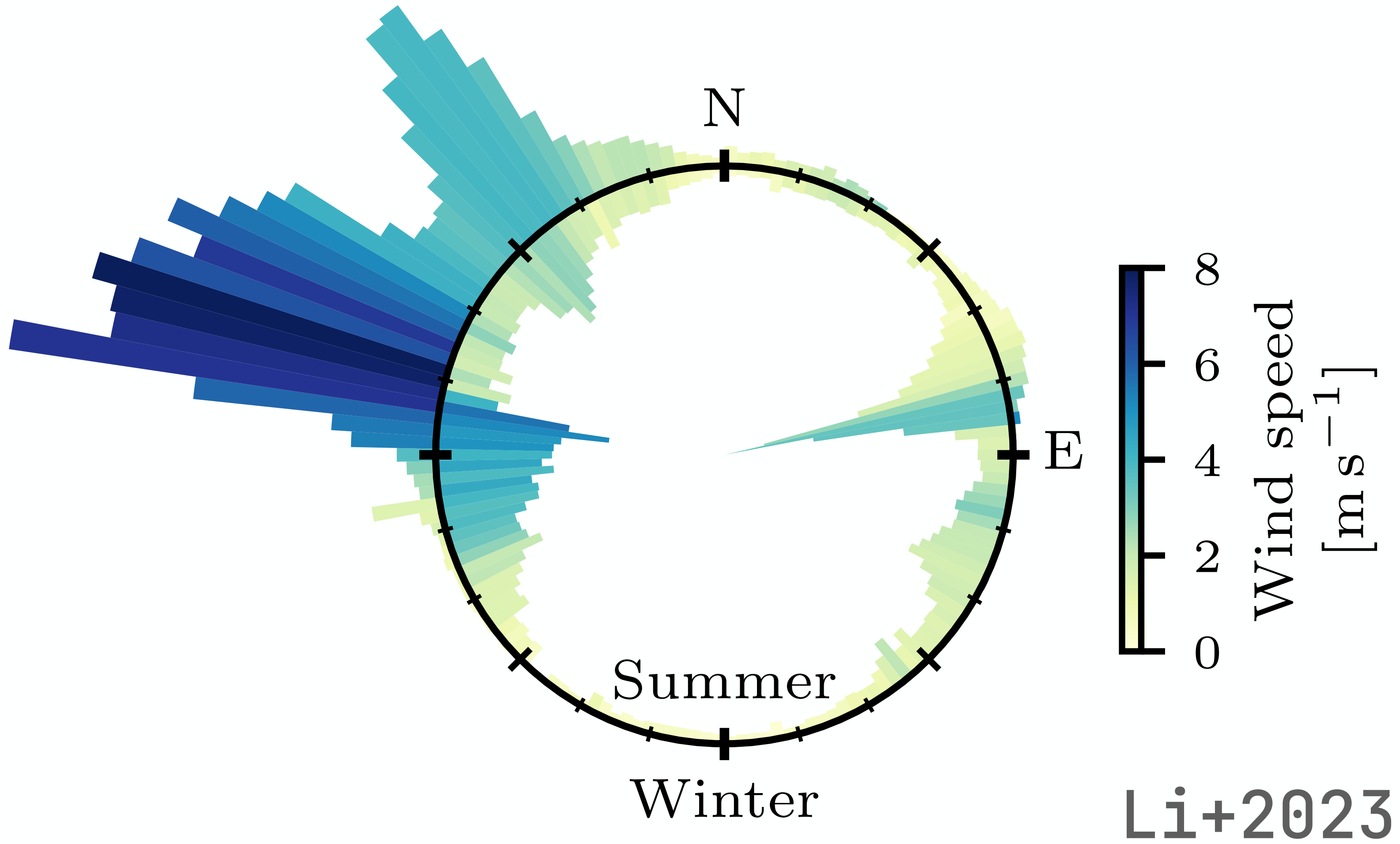
Li+2023a

The “wind” signal





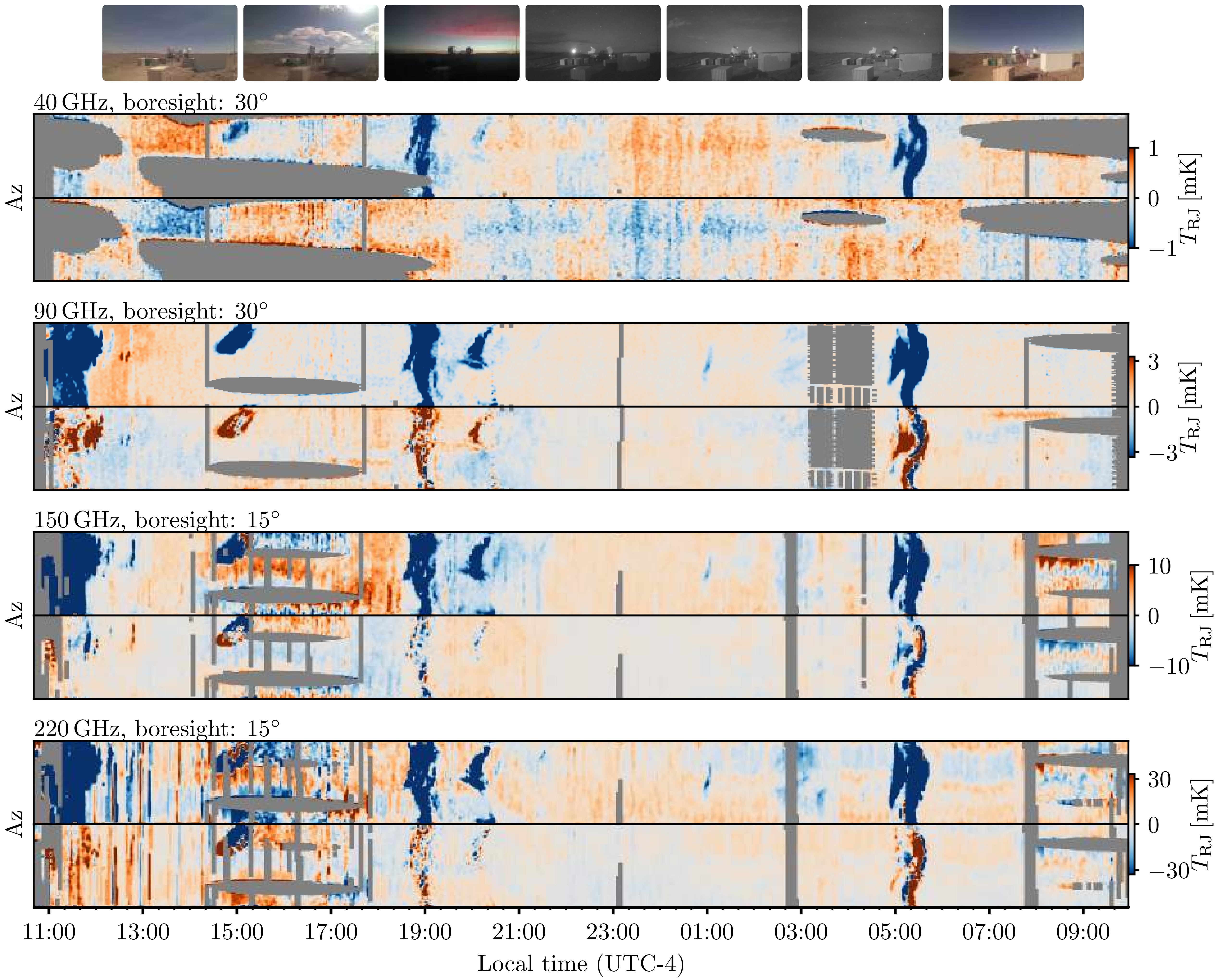
- Deformation of the plastic closeout produces a quadrupole pattern across the focal plane.
- The signal is a function of wind bearing angle and the wind speed.
- The is a particular problem in Atacama, because the wind almost come from a single direction — making it highly covariant with the sky.



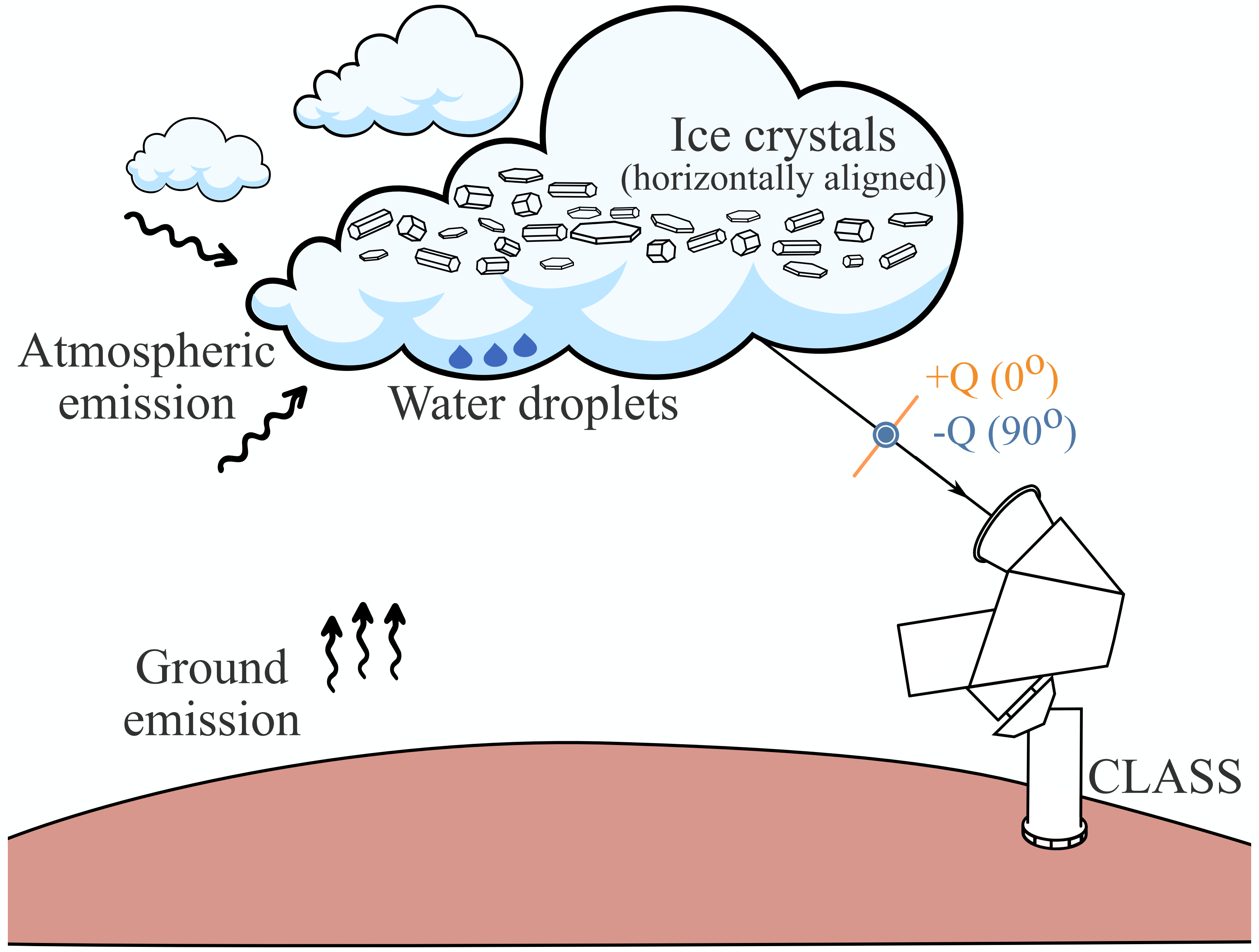
Li+2023a

Polarized atmospheric clouds

Cloud time-ordered maps



- Horizontal alignment of the ice crystal enhance its polarization through the Rayleigh scattering of the thermal radiation.
- This one factor of polarized low-frequency noise ground-based observation.



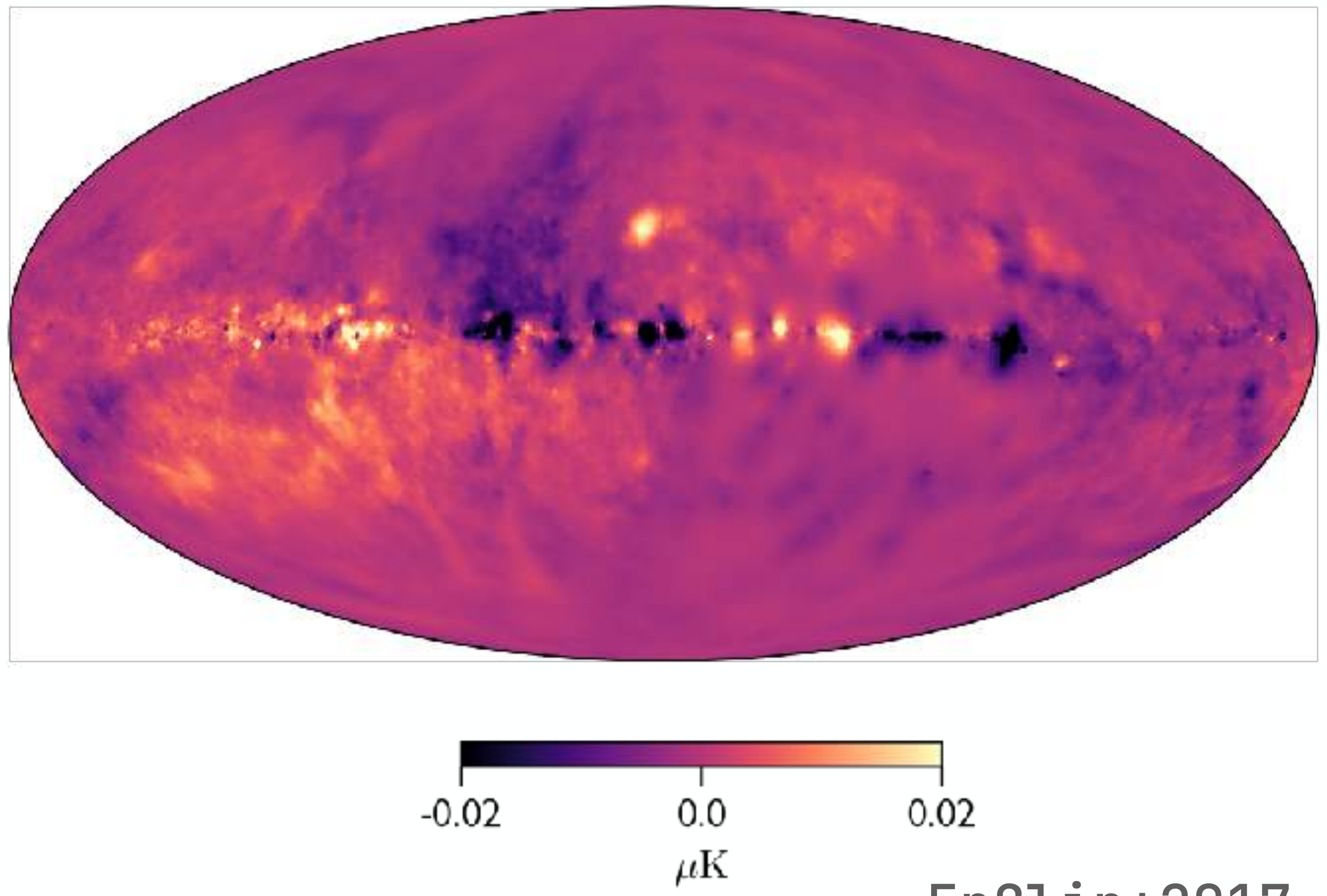
Li+2023b

circular polarization mechanisms

Source	Mechanism for CP	Frequency dependence	B dependence	Predicted CP signal in δV (K) at $\nu = 10$ GHz
Primordial	Primordial $B+$ Compton scattering [24]	ν^{-3}	B	10^{-9}
Primordial	Lorentz invariance violations [28]	ν^{-3}	Not applicable	10^{-12}
Primordial	Noncommutivity [25,26]	ν^{-1}	Not applicable	10^{-12}
Primordial	$B+$ Thomson scattering [23]	ν^{-3}	B^2	10^{-12}
Cosmic neutrino background ($C\nu B$)	Scattering with left-handed neutrinos [27]	ν^{-1}	Not applicable	10^{-8}
Pop III stars	FC [20,31]	ν^{-3}	B^2	few $\times 10^{-6}$ ($\ell \sim 1000$, $t_{\rm age} = 10^4$ yr, $N_p = 100$) few $\times 10^{-5}$ ($\ell \sim 1000$, $t_{\rm age} = 10^4$ yr, $N_p = 1000$) few $\times 10^{-7}$ ($\ell \sim 100$, $t_{\rm age} = 10^4$ yr, $N_p = 100$)
Galaxy clusters	FC	ν^{-3}	B^2	10^{-10} ($\ell \sim 1000$ [39])
Galactic synchrotron	Intrinsic emission [21]	$\nu^{(-2-\alpha_{\rm sync}/2)}$	$B^{3/2}$	10^{-8} ($\ell \sim 100$) $< 10^{-9}$ ($\ell \sim 500$)

King&Lubin2016

Galactic synchrotron V model



Enßlin+2017