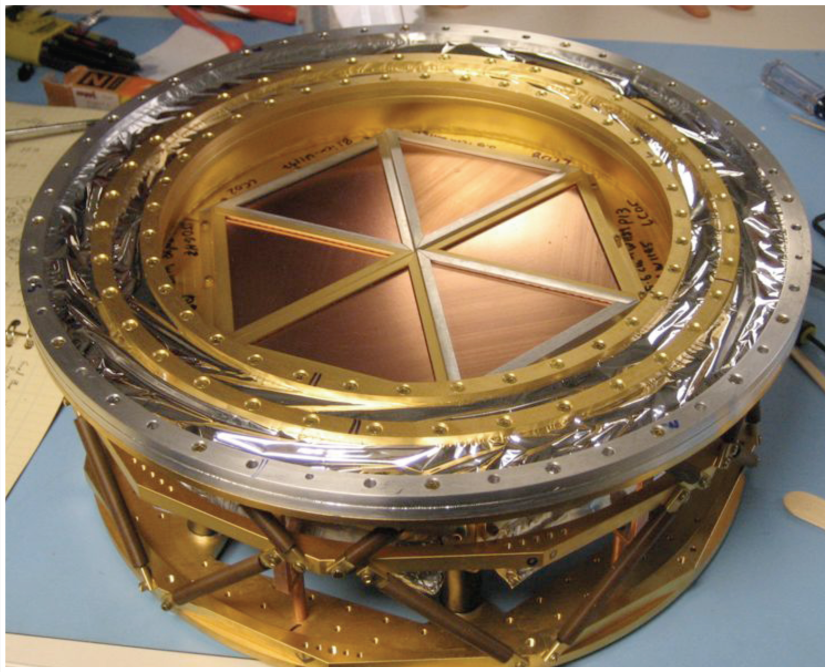
Simulations in CMB and SPT Analyses

Adam Anderson
8 March 2023

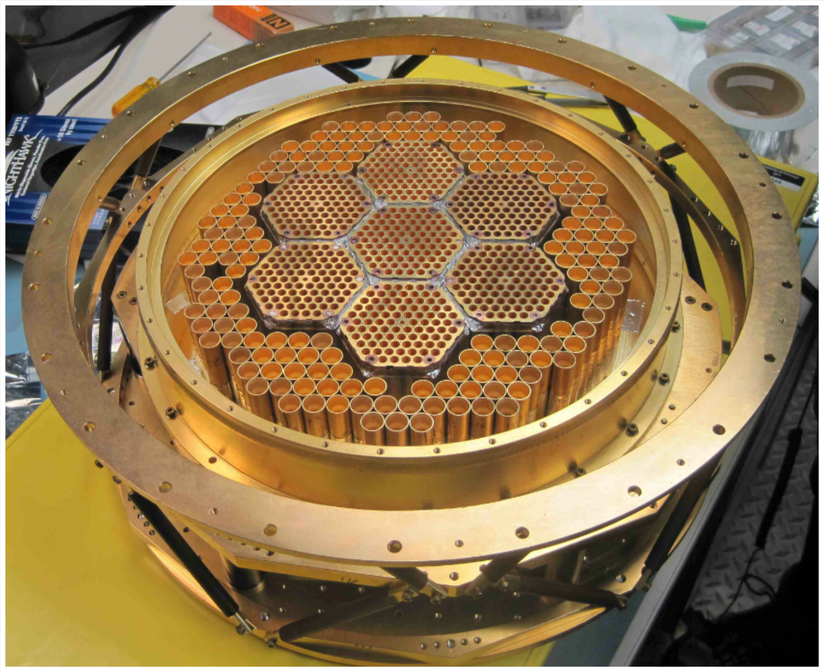
The 10-meter South Pole Telescope (SPT)

SPT-SZ (2007-2012)



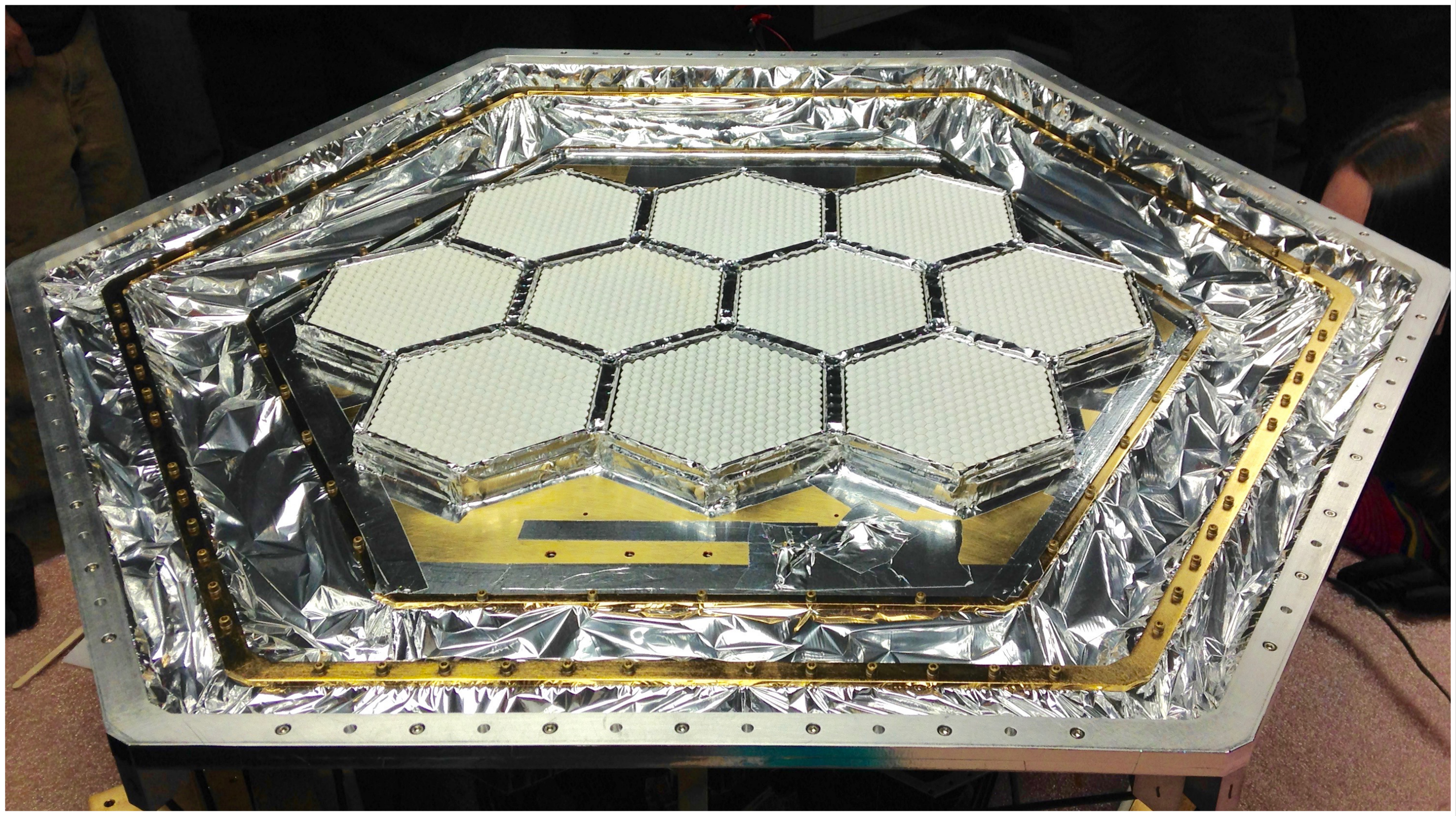
960 detectors at 95, 150, 220 GHz

SPTpol (2012-2017)



1500 detectors at 95, 150 GHz w/polarization

SPT-3G (2017-2024)



15,000 detectors at 95, 150, 220 GHz w/polarization

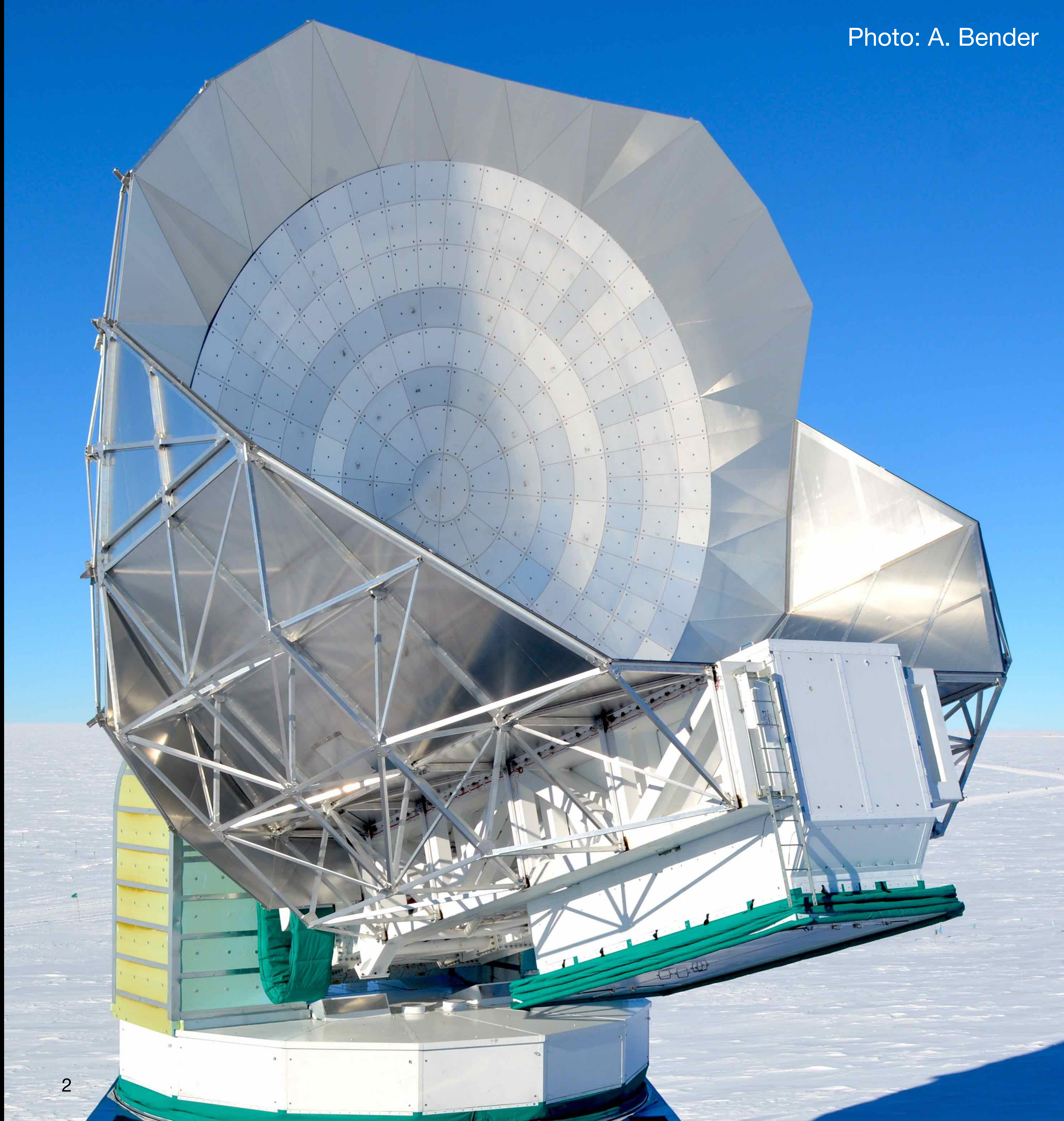
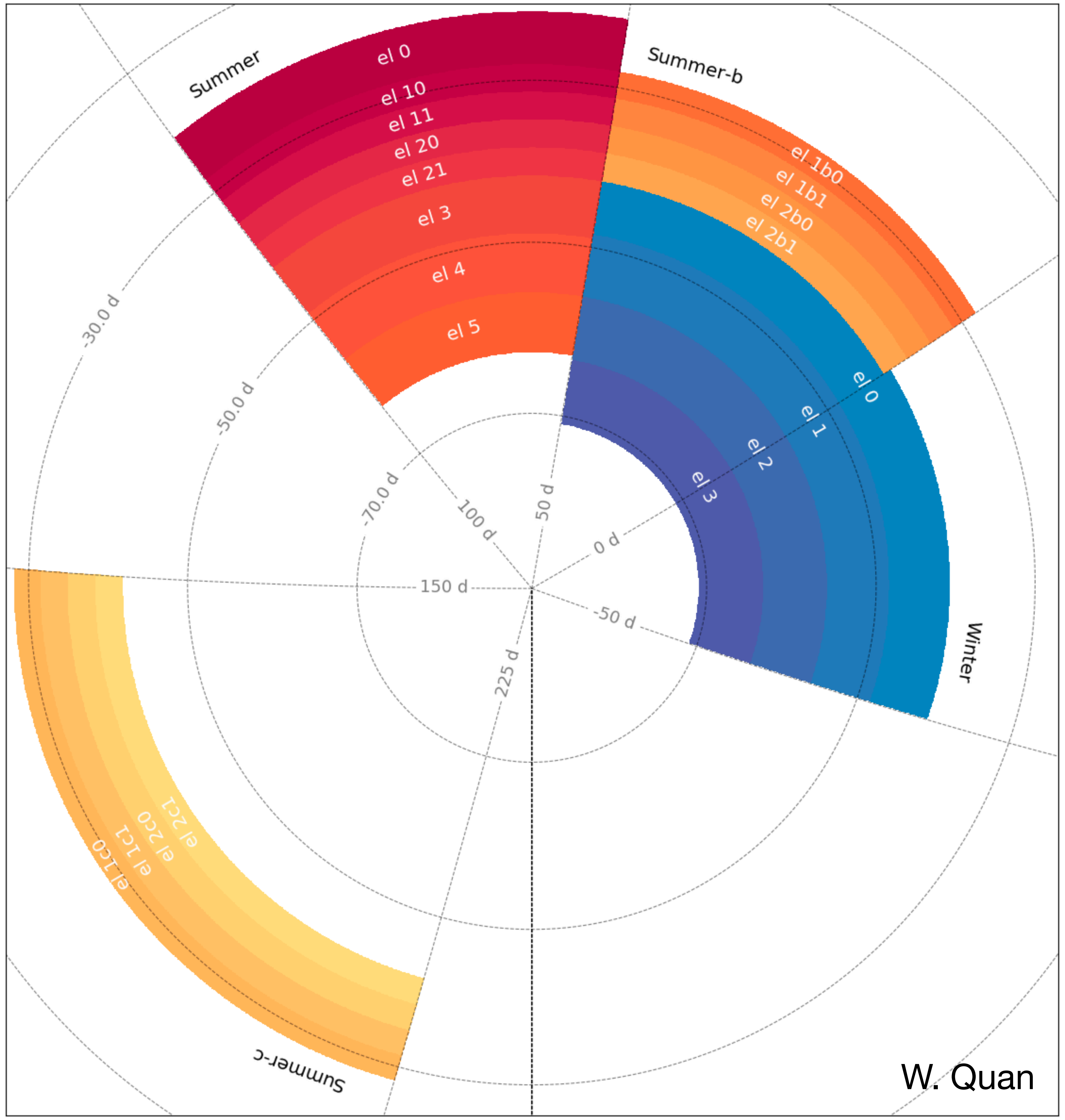


Photo: A. Bender

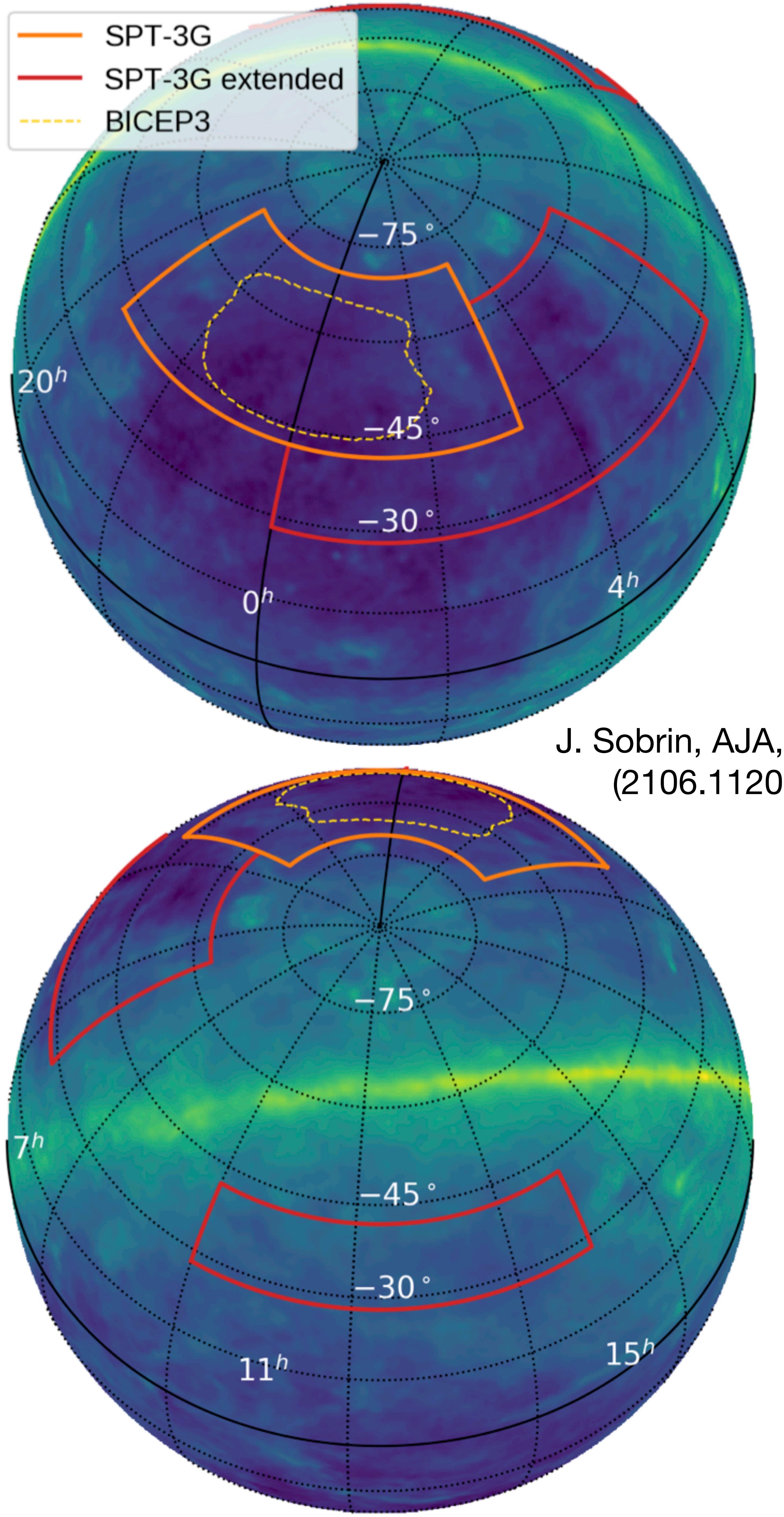
Observing Cadence

- “Fields” chosen to observe based on a mix of scientific and technical/practical factors, then split into “subfields” with narrow range of elevation
- Raster scan at constant elevation, then step in elevation until subfield is covered.
- Observing one subfield takes ~2 hours. Repeat for other subfields 24/7 for 9-11 months per year, integrating down coadded noise level.

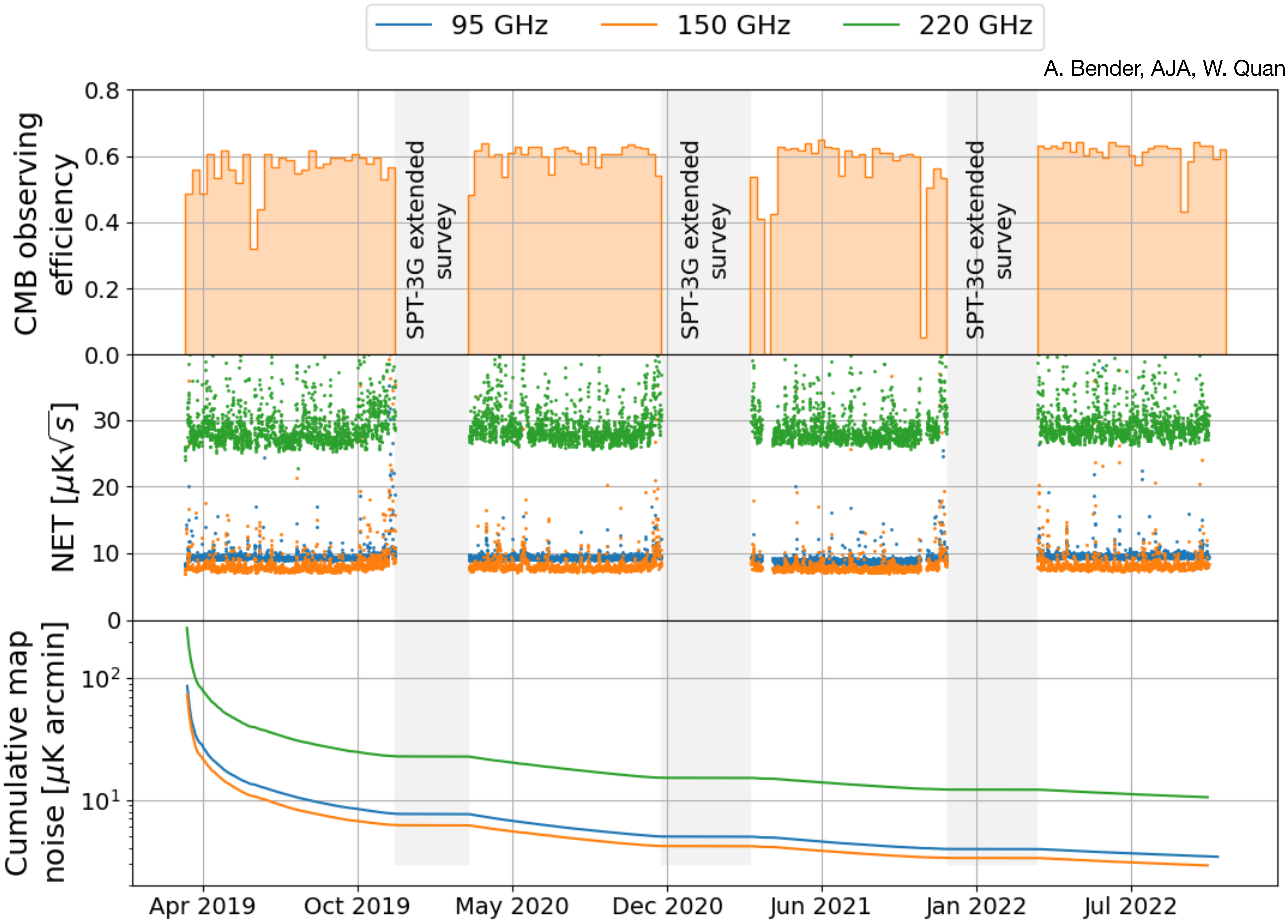
1500d winter, 1500d summer, 600d summer-b, and 900d summer-c field



W. Quan



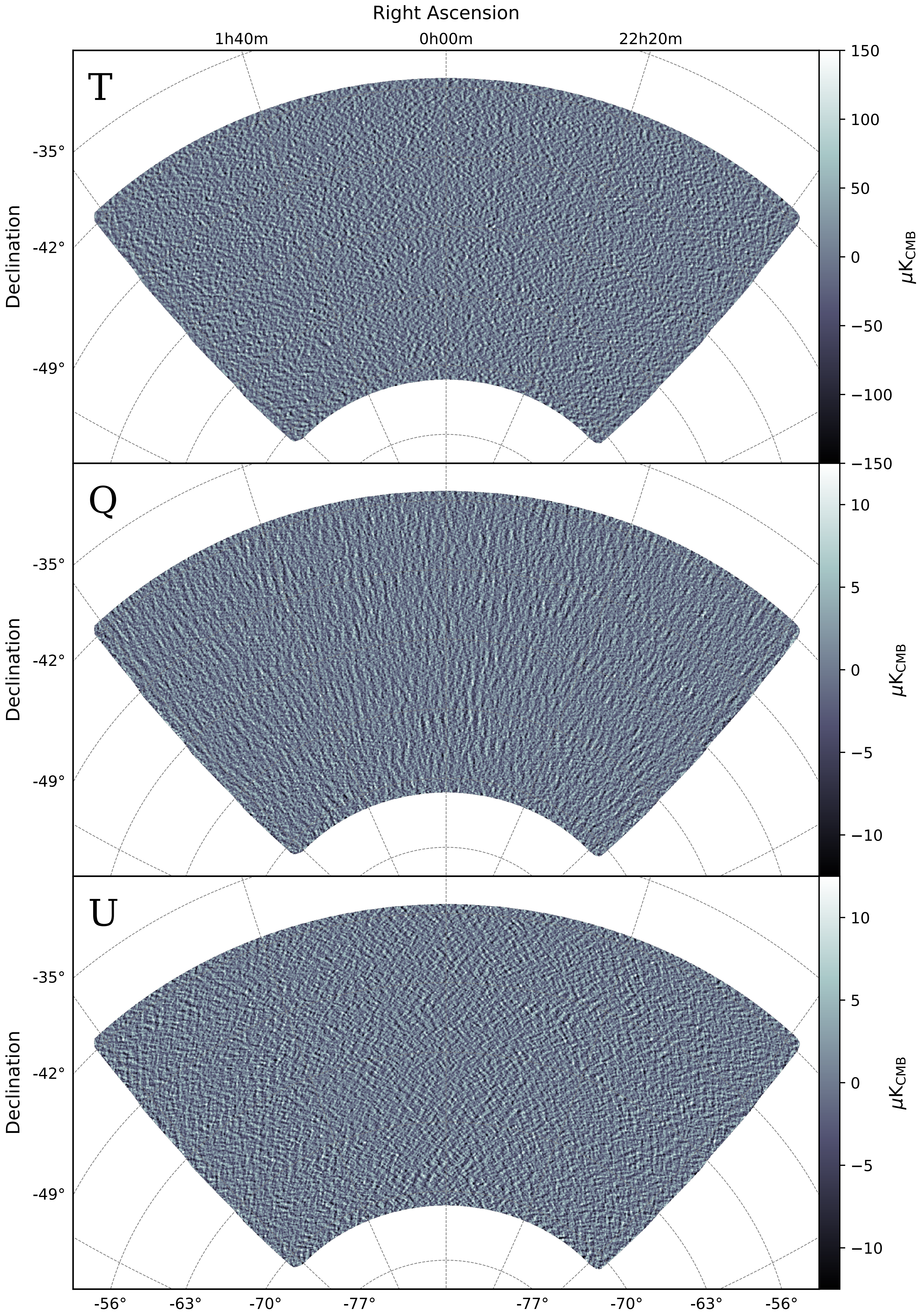
J. Sobrin, AJA, et al.
(2106.11202)



A. Bender, AJA, W. Quan

SPT-3G Science

- Core SPT-3G science is the CMB, but full range of topics is extremely broad. *Heterogeneous analyses require different suites of simulations*:
  - Primary CMB power spectra (2101.01684, 2212.05642, updates coming soon…)
  - Kinematic Sunyaev-Zeldovich effect (2207.11937)
  - Survey of mm-wave astrophysical transients (2103.06166)
  - Mm-wave measurements of asteroids (2202.01406)
  - Constraints on axion dark matter (2203.16567)
  - Gravitational lensing of the CMB (coming soon…)
  - SZ-selected galaxy cluster catalog (coming soon…)
  - Constraints on inflationary B-modes (coming soon…)
  - Polarization properties of South Pole atmosphere (coming soon…)
  - Many more analyses in progress!



Dutcher, et al., (2101.01684)

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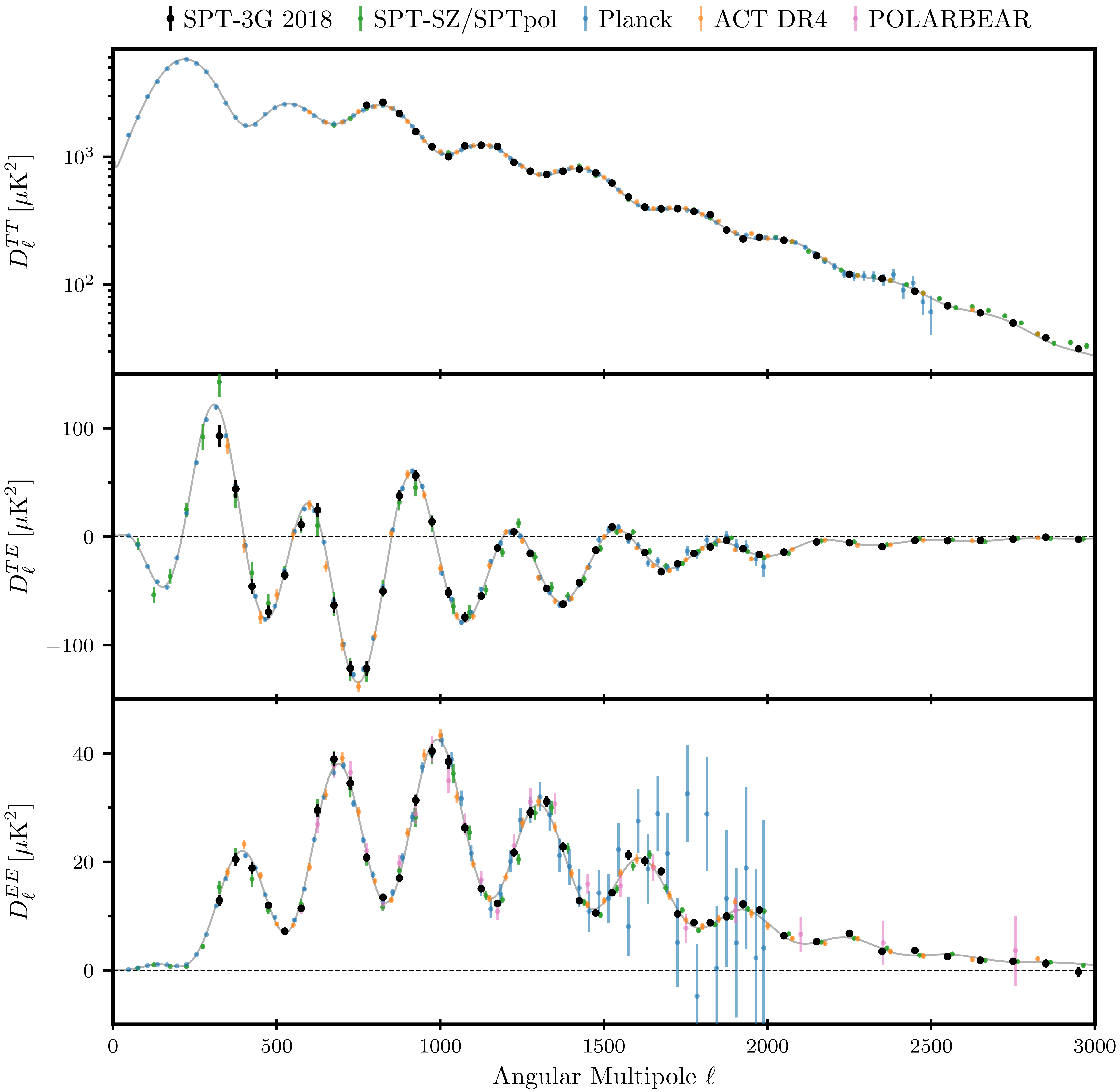

Balkenhol, et al., (2212.05642)

General Remarks

- SPT does not use a single suite of end-to-end simulations for all analyses. E.g. Filtering settings will be different for different analyses, so this does not make sense.
- Full-scale simulations usually only really make sense up to map-level. Parameter constraints can be calculated directly using power spectrum information without reference to maps or their simulations.
- Auxiliary measurements (e.g. beams) incorporated into bandpower covariance matrix.
- Instrumental systematics that are small in magnitude or difficult to model are checked with null tests and ignored.
- Simulation frameworks and tools are standardized and fairly easy to use. People make their own simulations, but they do so with a common framework for mock observation, noise realizations, etc.

Software Notes

- Analysis and simulations software framework, `spt3g_software`, written in mix of python (interface) and C++ (for bits that need to be efficient).
- Software written specifically for SPT-3G, based core pieces of IceTray, the IceCube analysis software. “Events” are replaced by “scans”.
- Subset of spt3g_software is publicly available on GitHub, targeted for CMB-S4 and future CMB experiments:
    - https://github.com/CMB-S4/spt3g_software
- HEP-style stupidly parallel jobs for simulations and mapmaking run on OSG / MWT2 (memory requirement ~ 2-4 GB / job).

Highly Simplified Power Spectrum Analysis Flow

1. Compress raw data into a map (several different ways to do this, e.g. MASTER (astro-ph/0105302) vs. maximum likelihood):
    1. Observe the sky: 15,000 timestreams (“TOD”).
    2. Filter each TOD until noise is approximately white in time-domain.
    3. Bin timestream samples into map, using telescope pointing information, with inverse-variance weighting based on TOD noise spectrum, rough temperature calibration
2. Estimate power spectra:
    1. TOD filtering removes power, biases power spectrum in a non-isotropic way (i.e. scan strategy means that atmospheric noise is primarily at low k_x). Estimate as Fourier-space “transfer function” from simulations.
    2. Incomplete sky coverage acts as window function, smears out power between independent modes. Map projection also induces small bias. Calculate analytically or simulate by brute force.
    3. Beam calibration using observations of planets (large scales) and point sources (small scales).
    4. Calculate debiased power spectra (“bandpowers”):

$$\underbrace{\langle \tilde{C}_\ell \rangle}_{\text{Biased observed spectra}} = \sum_{\ell'} \overbrace{M_{\ell\ell'}}^{\text{Mode-coupling kernel}} \underbrace{F_{\ell'}}_{\text{Filter transfer function}} \overbrace{B^2_{\ell'}}^{\text{Beam}} \underbrace{\langle C_{\ell'} \rangle}_{\text{True spectra}}$$

Highly Simplified Power Spectrum Analysis Flow

3. Estimate combined bandpower covariance matrix.
    - A. Noise covariance matrix.
    - B. Signal covariance matrix.
4. Jackknife tests for instrumental systematics:
    - A. Difference subsets of the data that have identical CMB signal and check that result is compatible with noise. Estimate noise “expectation spectra” from simulations.
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“Mock observations”

Mode-coupling kernel

Beam

$$\langle \tilde{C}_\ell \rangle = \sum_{\ell'} M_{\ell\ell'} F_{\ell'} B^2_{\ell'} \langle C_{\ell'} \rangle$$

Biased observed spectra

Filter transfer function

True spectra

Mock Observations

- Generate fake realizations of CMB skies based Planck cosmology, possibly including point sources and foregrounds.
- “Mock observe” these fake skies by using the real pointing information of every detector during the observing season to generate a fake TOD for every detector.
- Apply the same filtering procedure used on the real data to the mock observations, bin into maps per observation. Coadd maps if desired.
- Result is noise-free coadded maps of the entire experiment but for different CMB realizations. Comparison of real CMB power spectra to mock spectra provides estimate of the “transfer function”.

$$F_\ell^{(0)} = \frac{\langle \tilde{C}_\ell^{\rm sim} \rangle}{w_2 B_\ell^2 C_\ell^{\rm th}} \ ,$$

$$F_\ell^{(i+1)} = F_\ell^{(i)} + \frac{\langle \tilde{C}_\ell^{\rm sim} \rangle - M_{\ell\ell'} F_\ell^{(i)} B_\ell^2 C_\ell^{\rm th}}{w_2 B_\ell^2 C_\ell^{\rm th}} \ ,$$

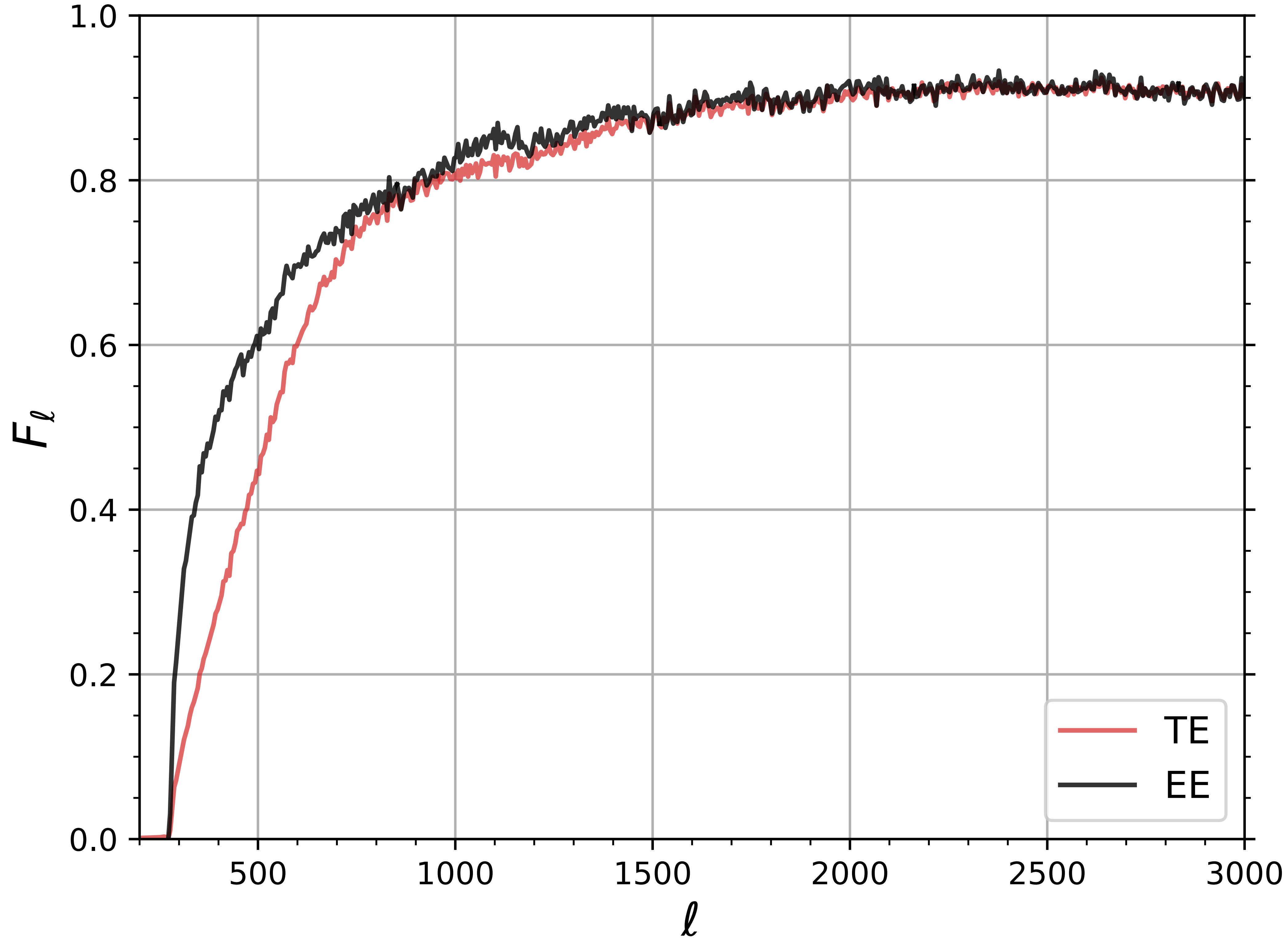

FIG. 5. Filter transfer functions for 150 GHz *TE* and *EE* power spectra, computed using 250 TOD simulations of the full SPT-3G 2018 dataset. The difference between the *TE* and *EE* transfer functions is caused by the common-mode filter.

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Beam Estimation

- Beam is estimated from planet observations (e.g. Mars in 2101.01684) for large scales, and many point sources for small scales. Maps are stitched together in real space.
- The beam is estimated by the square root of the azimuthal average of the 2D power spectrum of the composite map.
- Uncertainty is estimated by jackknife resampling to construct a beam covariance matrix, which is added with the main bandpower covariance.

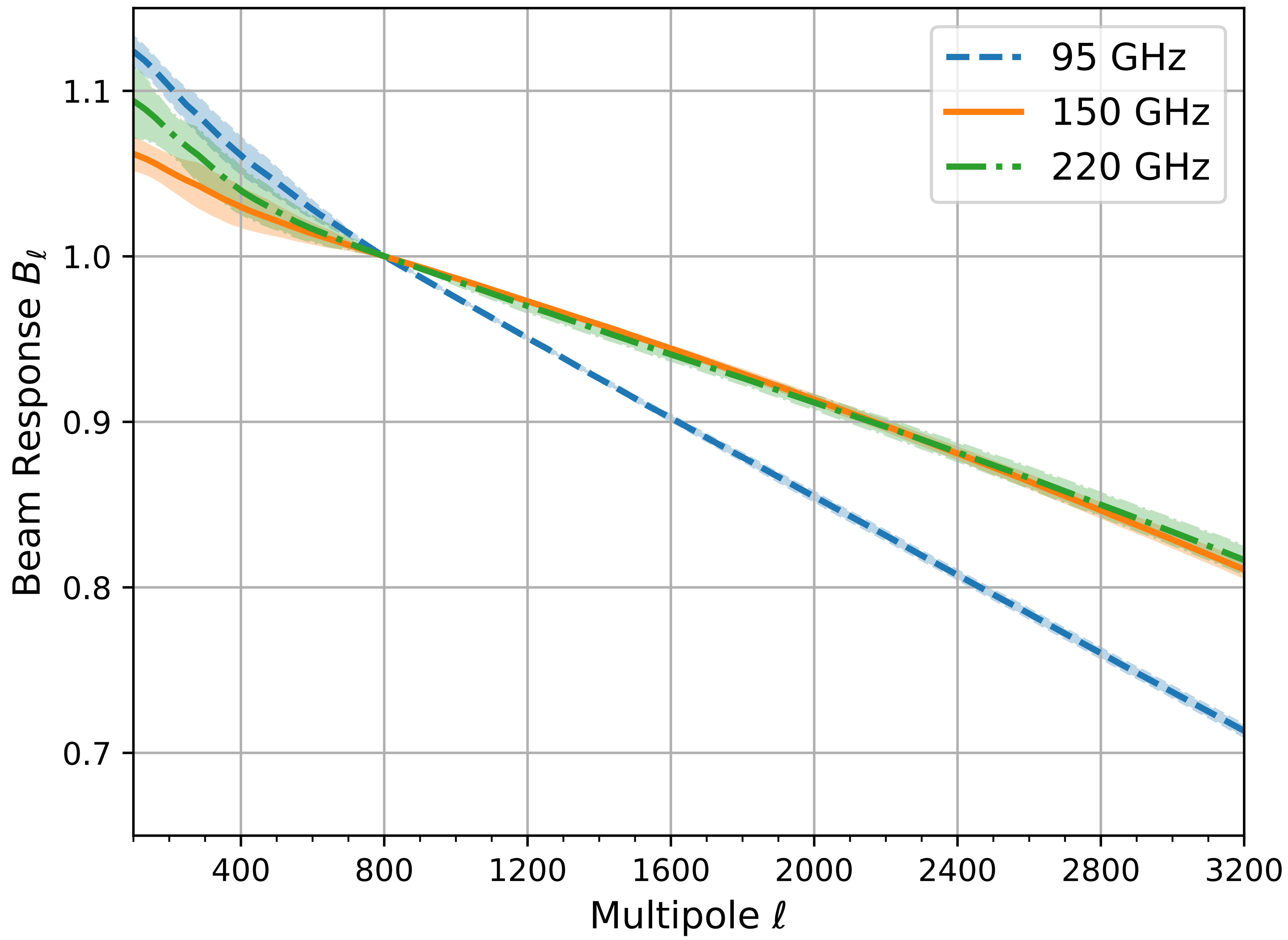

FIG. 6. One-dimensional multipole-space representation of the measured instrument beam, B_ℓ, with uncertainties indicated by the shaded regions. The data are normalized to unity at $\ell = 800$.

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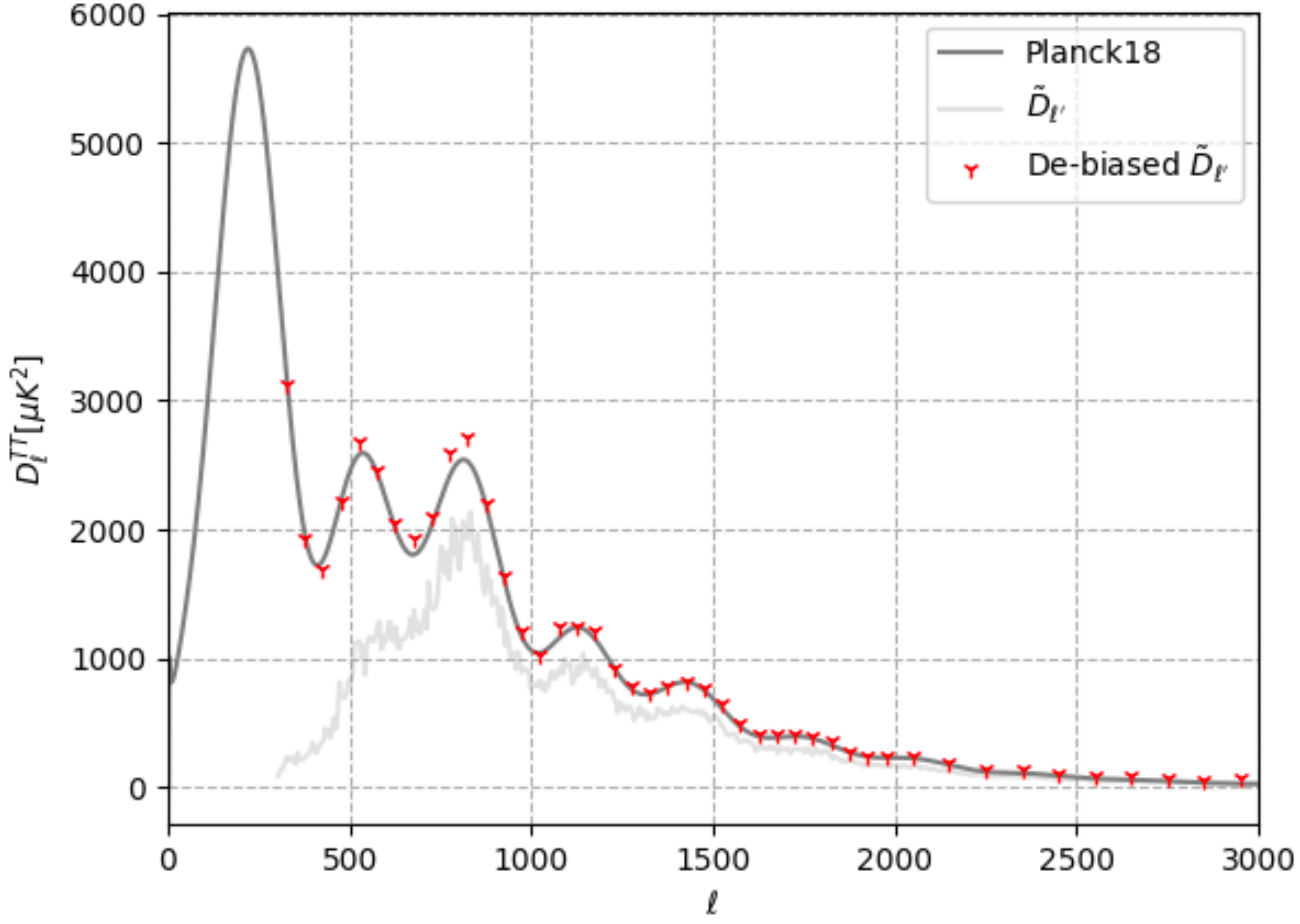
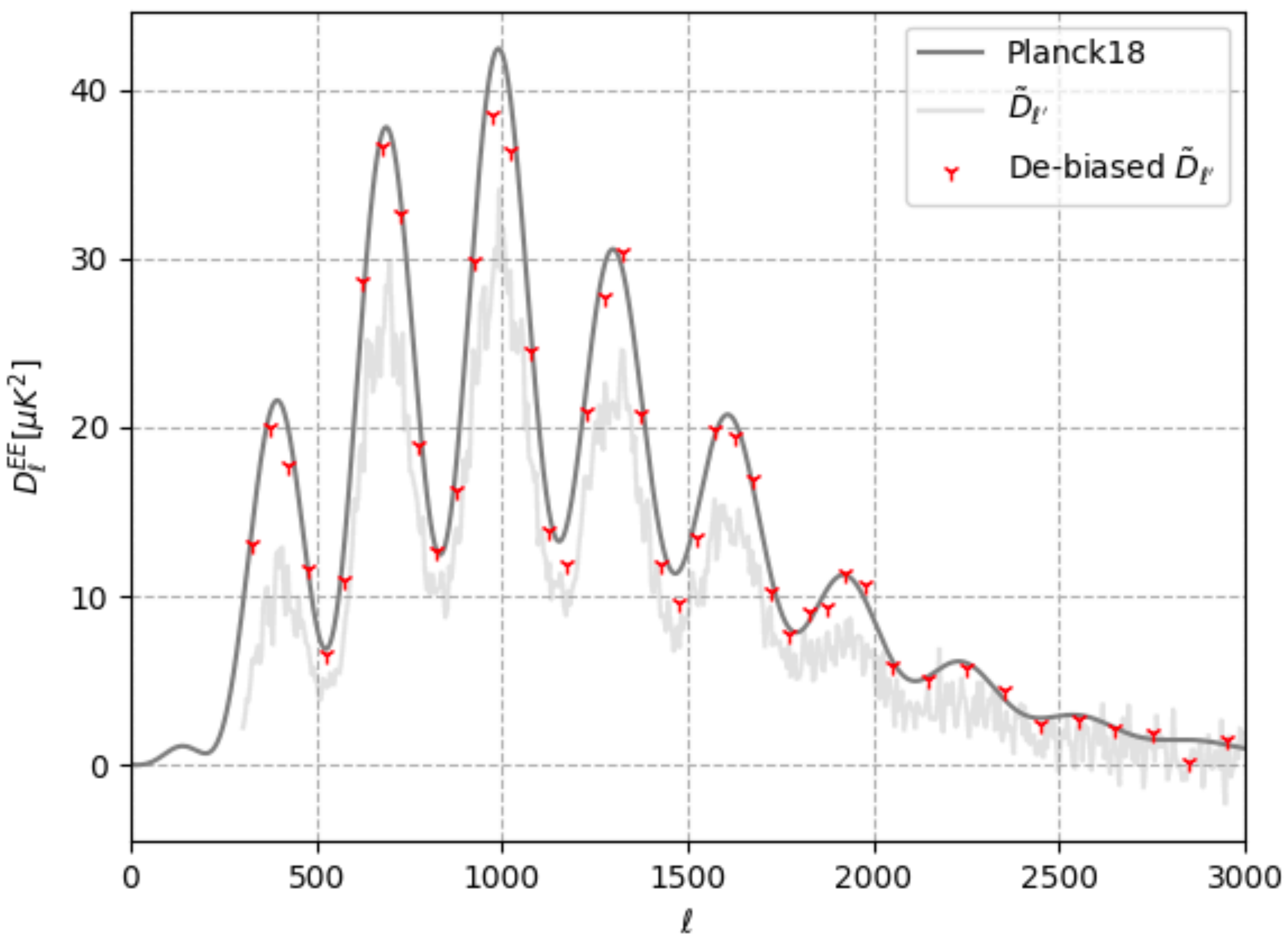
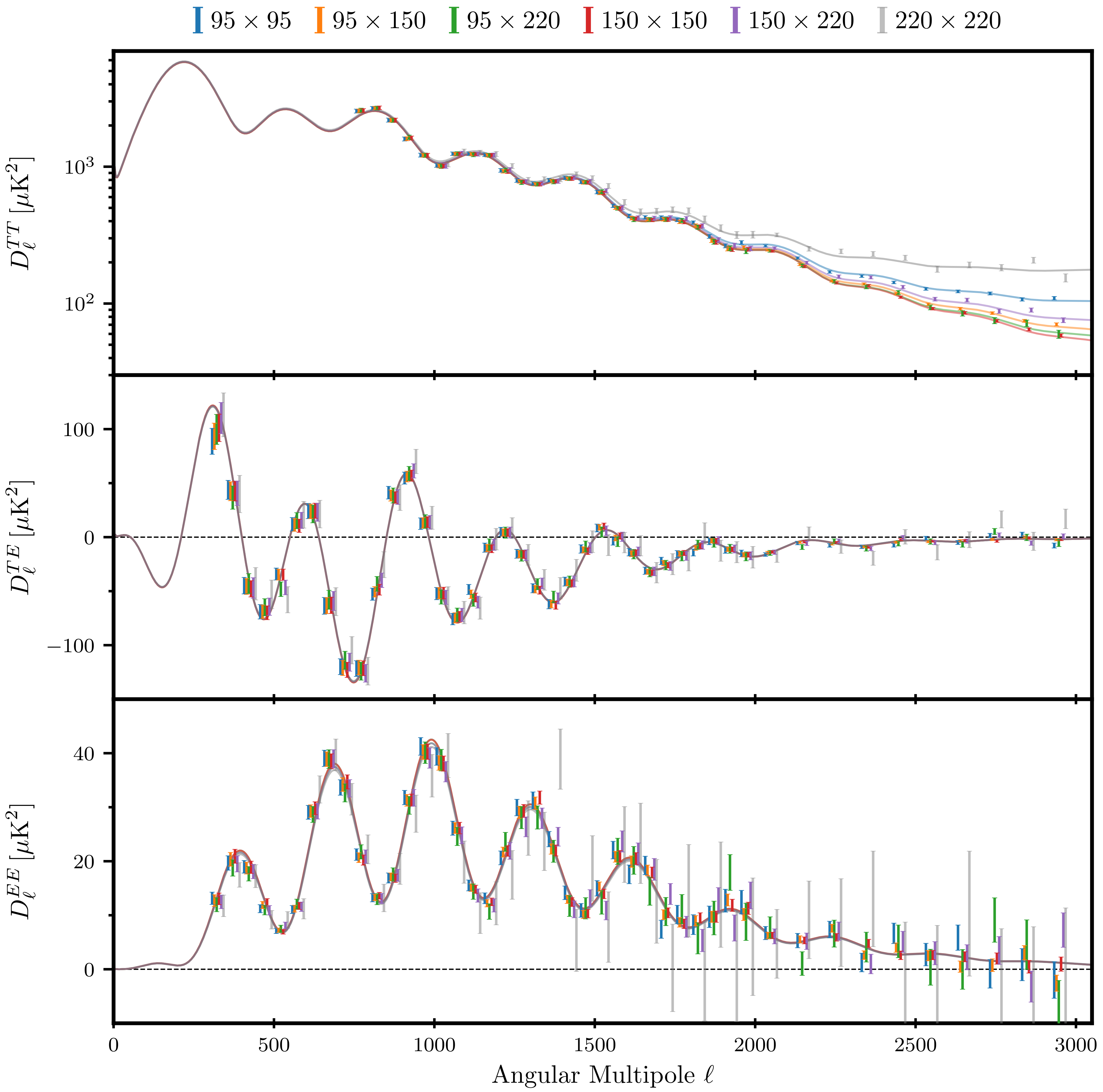
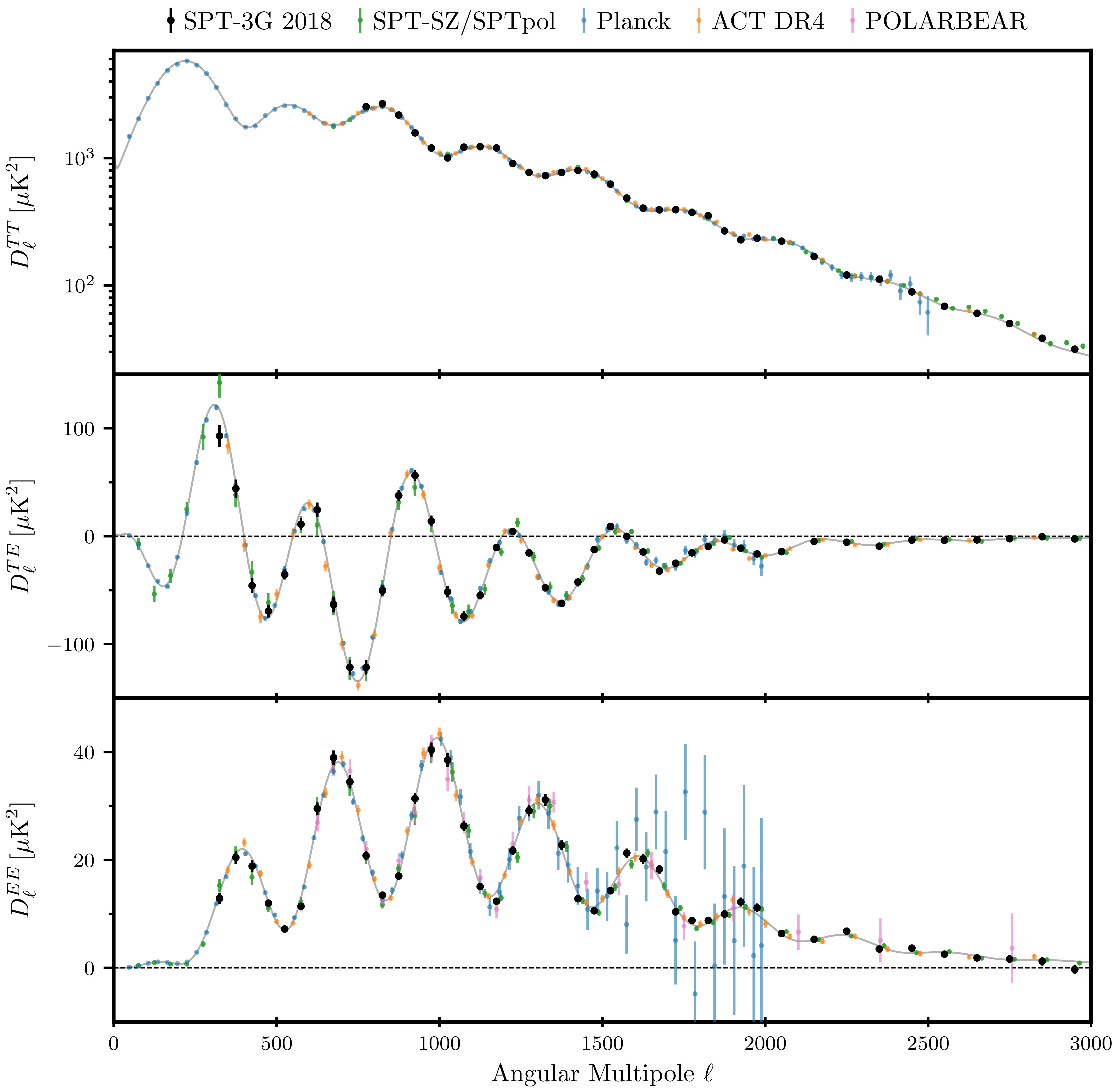
Examples of Debiasing





Bandpowers


95 × 95
95 × 150
95 × 220
150 × 150
150 × 220
220 × 220
D_ℓ^{TT} [μK^2]
10^3
10^2
D_ℓ^{TE} [μK^2]
100
0
−100
D_ℓ^{EE} [μK^2]
40
20
0
0
500
1000
1500
2000
2500
3000
Angular Multipole ℓ


SPT-3G 2018
SPT-SZ/SPTpol
Planck
ACT DR4
POLARBEAR
D_ℓ^{TT} [μK^2]
10^3
10^2
D_ℓ^{TE} [μK^2]
100
0
−100
D_ℓ^{EE} [μK^2]
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20
0
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1000
1500
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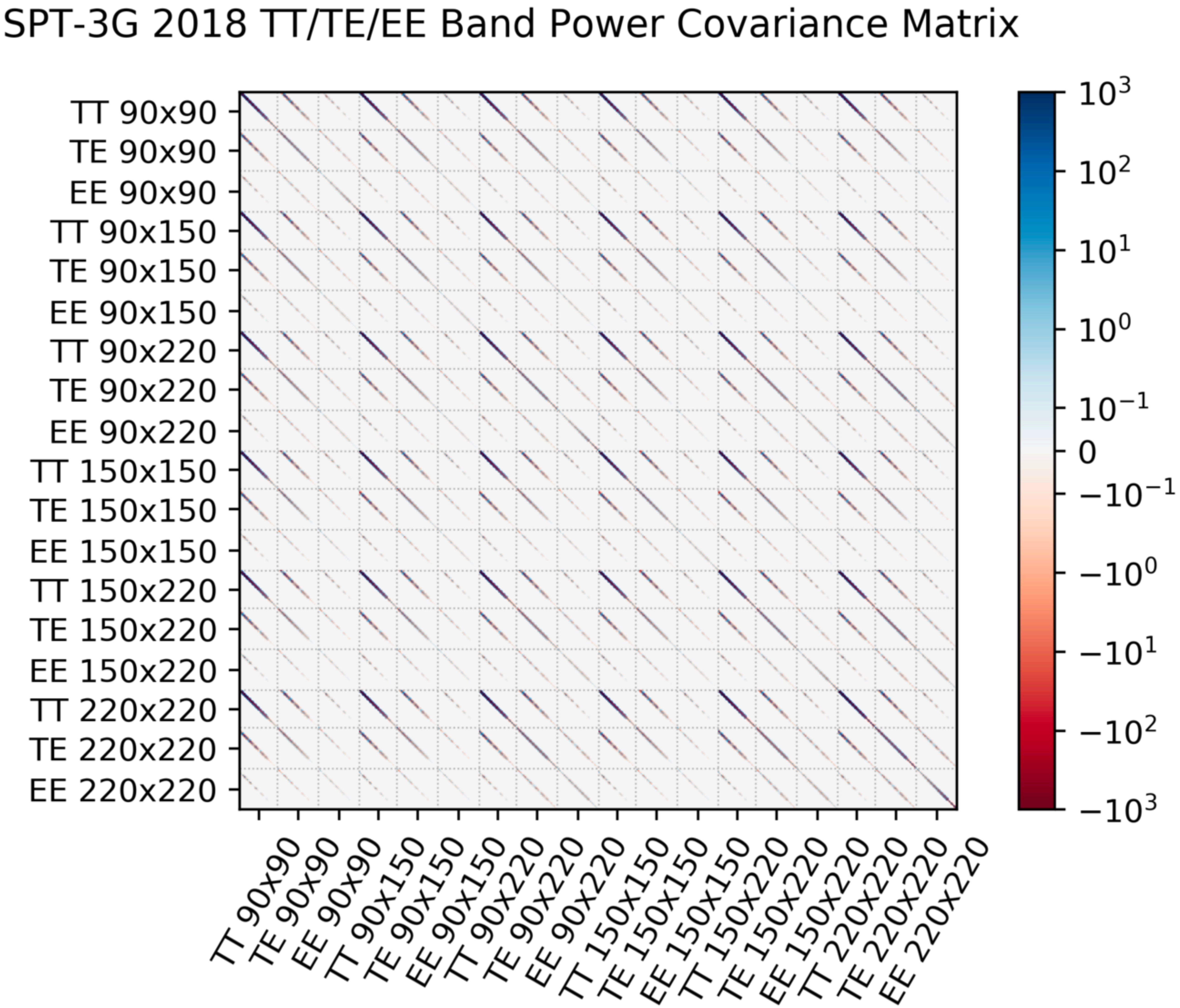
Bandpower Covariance Matrix

- Captures correlations between all band powers in 90, 150, 220 GHz maps in TT, TE, EE, with 1 block per combination.

- Rather complicated estimator for covariance based on:

  - Signal component estimated using mock observations.

  - Noise component is estimated empirically from the data. Several techniques are possible, but very large number of noise-only maps can be constructed from coadds in which ~half of the single observation maps are multiplied by -1.


SPT-3G 2018 TT/TE/EE Band Power Covariance Matrix

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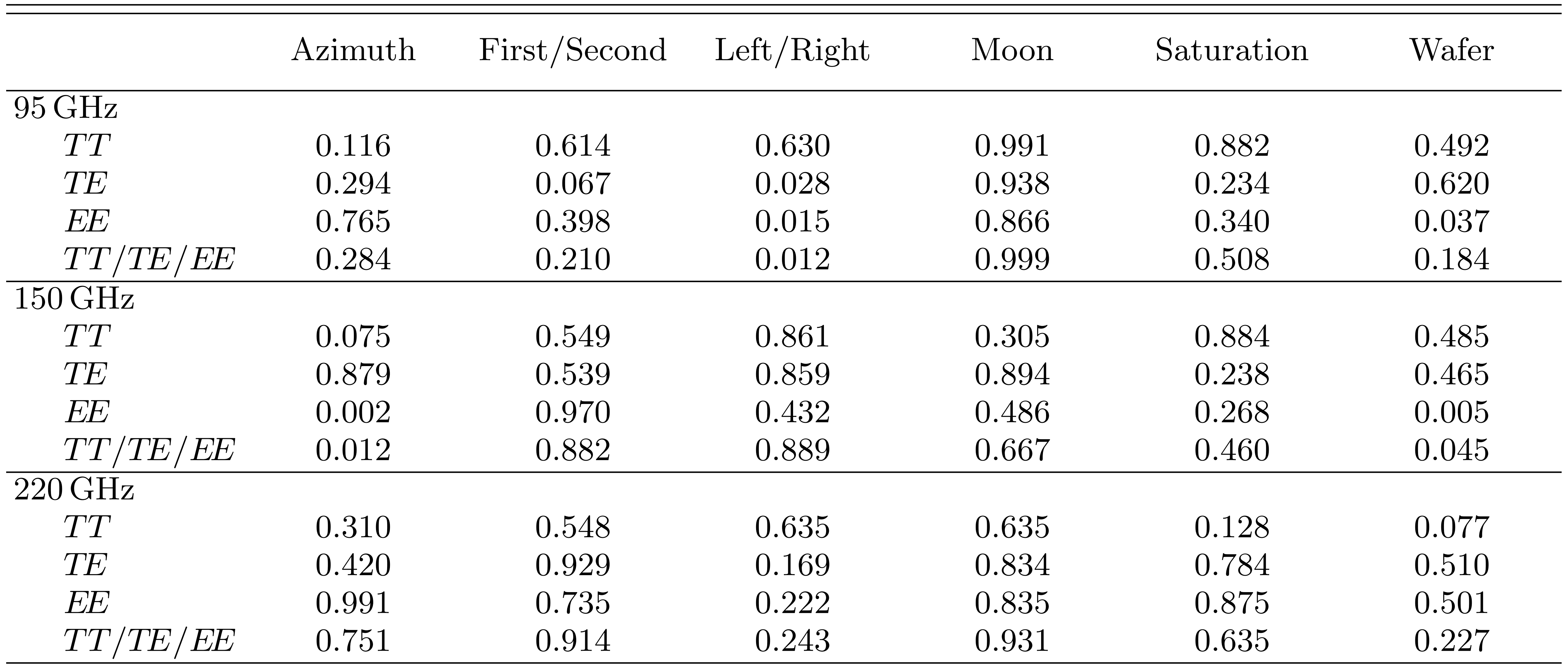
“Null Tests” for Systematics

- Split data into two maps according to possible systematics, and difference maps so that the CMB signal nearly vanishes.
- Calculated expected residual from mock observation simulations.
- Compute chi-square of data relative to null expectation and evaluate p-value.
- Use distribution of p-values as criteria for unblinding (i.e. looking at cosmological parameters).
- Several other internal consistency tests are used, using the band power covariance matrix, but not explicitly using simulations.



	Azimuth	First/Second	Left/Right	Moon	Saturation	Wafer
95 GHz						
TT	0.116	0.614	0.630	0.991	0.882	0.492
TE	0.294	0.067	0.028	0.938	0.234	0.620
EE	0.765	0.398	0.015	0.866	0.340	0.037
$TT/TE/EE$	0.284	0.210	0.012	0.999	0.508	0.184
150 GHz						
TT	0.075	0.549	0.861	0.305	0.884	0.485
TE	0.879	0.539	0.859	0.894	0.238	0.465
EE	0.002	0.970	0.432	0.486	0.268	0.005
$TT/TE/EE$	0.012	0.882	0.889	0.667	0.460	0.045
220 GHz						
TT	0.310	0.548	0.635	0.635	0.128	0.077
TE	0.420	0.929	0.169	0.834	0.784	0.510
EE	0.991	0.735	0.222	0.835	0.875	0.501
$TT/TE/EE$	0.751	0.914	0.243	0.931	0.635	0.227

TABLE I. Individual null test PTE values for 95, 150, and 220 GHz and TT, TE, and EE spectra. Additionally, we show the combined $TT/TE/EE$ null test PTE values. All PTE values lie above the required threshold of $0.05/(9 \times 6) \approx 0.001$.

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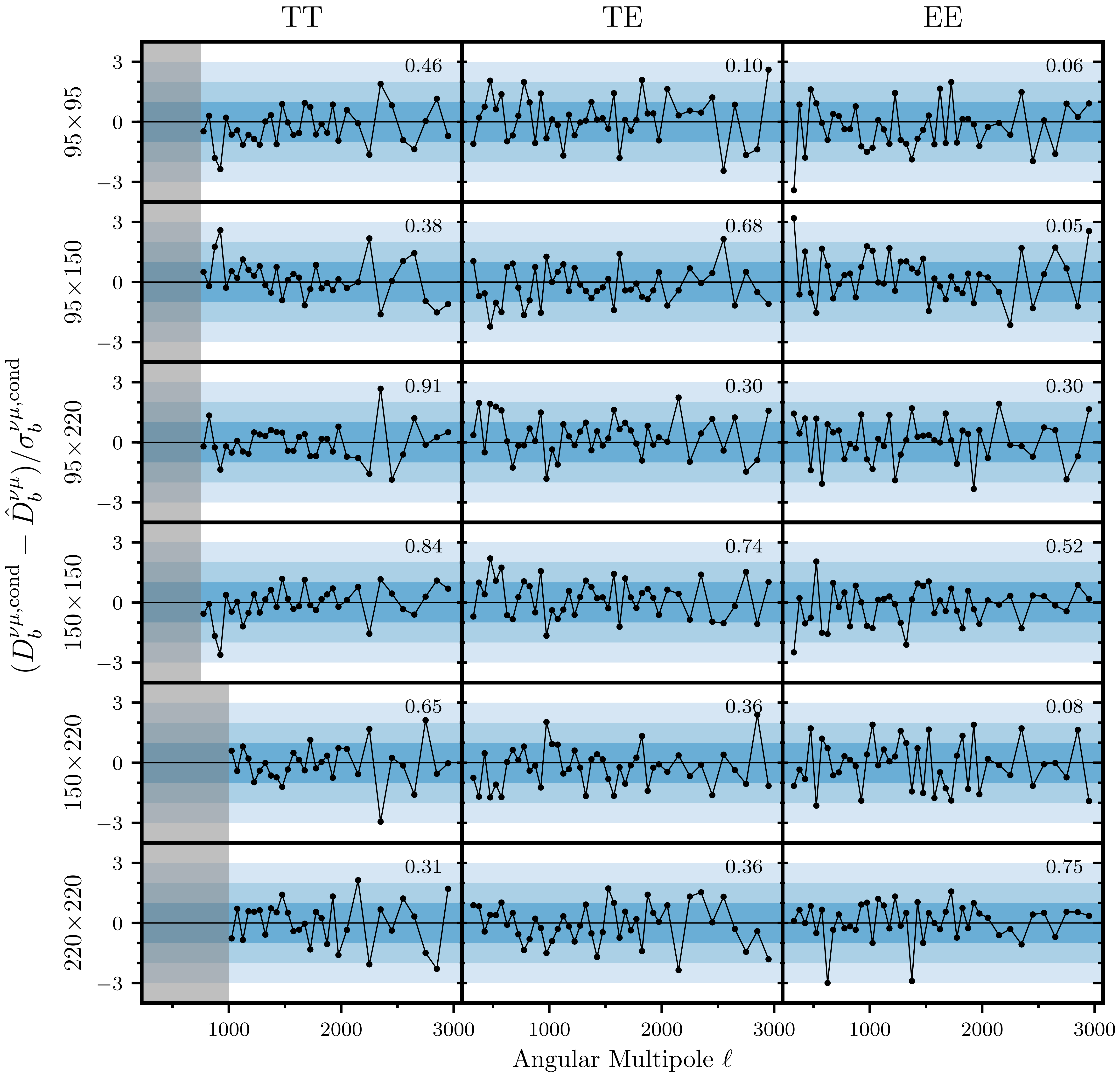

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Parameter Constraints

- Likelihood function incorporates:
    - Debiased bandpowers
    - Bandpower covariance
    - Model of CMB band powers as a function of cosmological parameters
    - Models of foregrounds with priors on parameters (simple analytic models good enough for SPT patch + polarized data)
- MCMC to extract cosmological parameters in Bayesian framework, which facilitates combination of data from different probes (e.g. Planck, BAO, etc.).