Advancing Galactic Foreground Modeling for CMB Studies

Kenny Lau
Caltech

mm Universe 2025
2025-06-24

Python Sky Model (PySM)

- Old models: d1/2/3/4, s1/2/3, a1/2, f1 (B. Thorne *et al.* 2017)
- New models from Pan-Ex GS Group:
  - Dust: d9, d10, d11, d12
  - Synchrotron: s4, s5, s6, s7
  - CO: co1, co2, co3
- The latest multiple-component, high-resolution models by a public python module `pysm3`
- Finalized in 2023, widely used
- Paper online recently: arXiv:2502.20452

Full-sky Models of Galactic Microwave Emission and Polarization at Sub-arcminute Scales for the Python Sky Model

The Pan-Experiment Galactic Science Group

Julian Borrill[1,2,3], Susan E. Clark[4,5], Jacques Delabrouille[6,7], Andrei V. Frolov[8], Shamik Ghosh[1,6], Brandon S. Hensley[9], Monica D. Hicks,[4,5,10] Nicoletta Krachmalnicoff[11,12,13], King Lau[14], Myra M. Norton[15], Clement Pryke[16,17], Giuseppe Puglisi[18,19,20], Mathieu Remazeilles[21], Elisa Russier[7,6], Benjamin Thorne[7,22], Jian Yao[11], Andrea Zonca[23]

[1] *Computational Cosmology Center & Physics Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA*
[2] *Space Sciences Laboratory, University of California at Berkeley, 7 Gauss Way, Berkeley, CA 94720, USA*
[3] *Department of Physics and Astronomy, University of Pennsylvania, 209 South 33rd Street, Philadelphia, PA 19104, USA*
[4] *Department of Physics, Stanford University, Stanford, CA 94305, USA*
[5] *Kavli Institute for Particle Astrophysics & Cosmology, P.O. Box 2450, Stanford University, Stanford, CA 94305, USA*
[6] *CNRS-UCB International Research Laboratory, Centre Pierre Binétruy, IRL 2007, CPB-IN2P3, Berkeley, CA 94720, USA*
[7] *Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA*
[8] *Department of Physics, Simon Fraser University, 8888 University Drive, Burnaby, V5A 1S6, BC, Canada*
[9] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*
[10] *Department of Computer Science, Stanford University, Stanford, CA 94305, USA*
[11] *International School for Advanced Studies (SISSA), Via Bonomea 265, 34136 Trieste, Italy*
[12] *Institute for Fundamental Physics of the Universe (IFPU), Via Beirut, 2, 34151 Grignano, Trieste, Italy*
[13] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy*
[14] *Department of Physics, California Institute of Technology, 1200 E. California Boulevard, Pasadena, CA 91125, USA*
[15] *Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA*
[16] *Minnesota Institute for Astrophysics, University of Minnesota, Minneapolis, Minnesota 55455, USA*
[17] *School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*
[18] *Dipartimento di Fisica e Astronomia, Università degli Studi di Catania, via S. Sofia, 64, 95123, Catania, Italy*
[19] *INFN - Sezione di Catania, Via S. Sofia 64, 95123 Catania, Italy*
[20] *INAF - Osservatorio Astrofisico di Catania, via S. Sofia 78, 95123 Catania, Italy*
[21] *Instituto de Física de Cantabria (CSIC-UC), Avda. de los Castros s/n, 39005 Santander, Spain*
[22] *Department of Physics and Astronomy, University of California, Davis, CA 95616, USA*
[23] *San Diego Supercomputer Center, University of California San Diego, La Jolla, CA 92093, USA*

(Dated: March 3, 2025)

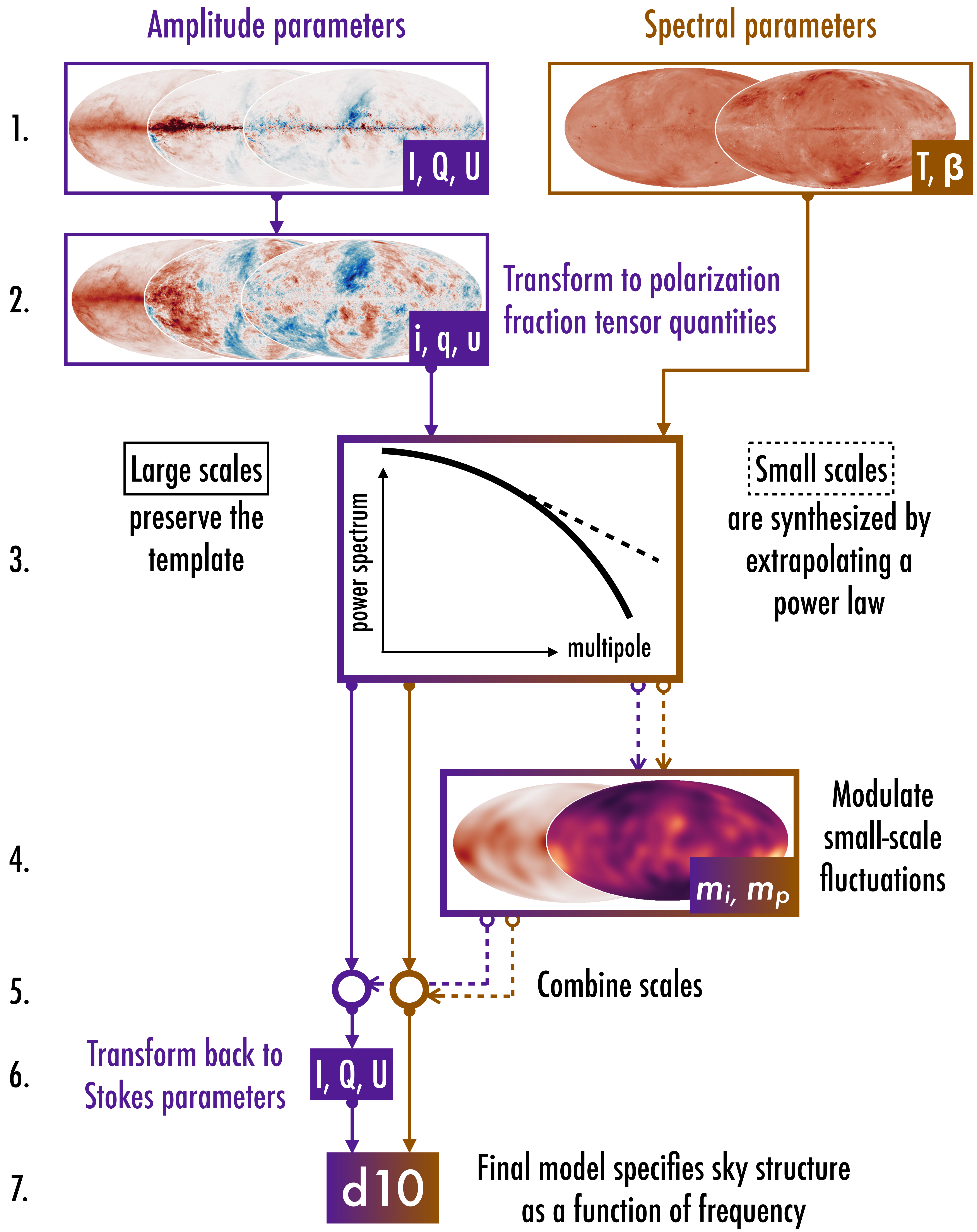
ABSTRACT

Polarized foreground emission from the Galaxy is one of the biggest challenges facing current and upcoming cosmic microwave background (CMB) polarization experiments. We develop new models

arXiv:2502.20452

Methodology

- Dust: $S_\nu = A_d^S \left(\nu/\nu_0\right)^{\beta_d} B_\nu(T_d)$
- Synchrotron: $S_\nu = A_s^S \left(\nu/\nu_0\right)^{\beta_s + c_s \ln(\nu/\nu_c)}$
- Amplitude parameters: A_d^S, A_s^S
- Spectral parameters: β_d, T_d, β_s, c_s
- Per-pixel frequency scaling from amplitude maps at $\nu_0 = 353, 23$ GHz
- Main idea:
  Preserve reliable large-scale modes from full-sky templates &
  Add stochastic small-scale fill-in



New PySM Dust Models

$(\beta_d, T_d) = (1.48, 19.6\,\mathrm{K})$

Low Complexity → High Complexity

Tag	Spectrum Model	Templates Large scale	Templates Small scale	Frequency scaling Large scale	Frequency scaling Small scale	Stochasticity
d9	Modified blackbody	GNILC PR2 I + GNILC PR3 Q/U 353 GHz	Modulated + polarization fraction tensor	Uniform β_d, T_d	Uniform β_d, T_d	—
d10	"	"	"	β_d, T_d from GNILC PR2	Modulated	—
d11	"	"	"	"	"	I, Q, U & β_d, T_d
d12	6 layers, each is a different modified blackbody	GNILC PR2 I + GNILC Q/U 353 GHz	Modulated + gaussian	Random realization for each layer	Random realization for each layer	—

GNILC dust:
less CIB contamination

New PySM Synchrotron Models

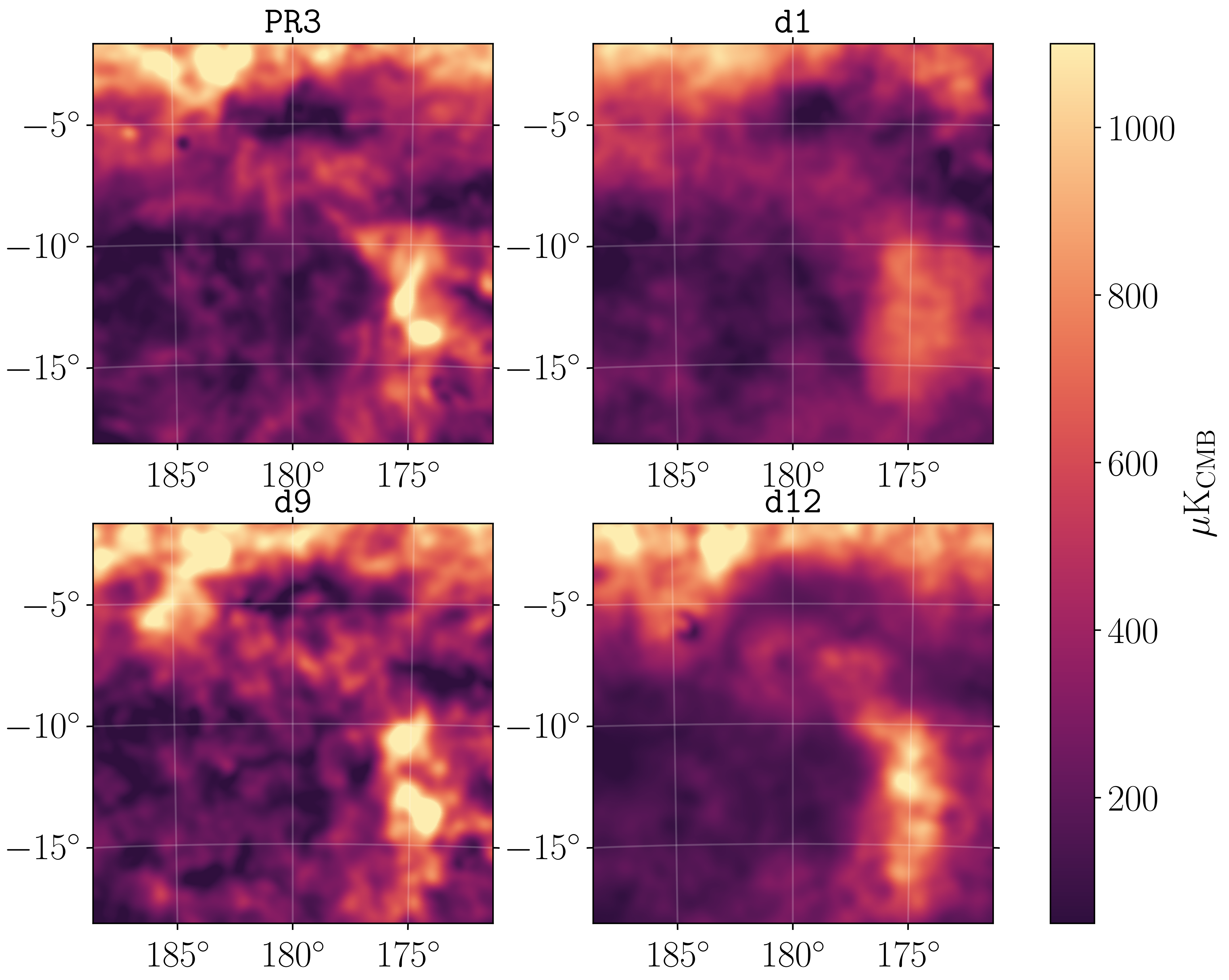
$\beta_s = -3.1$

Low Complexity → High Complexity

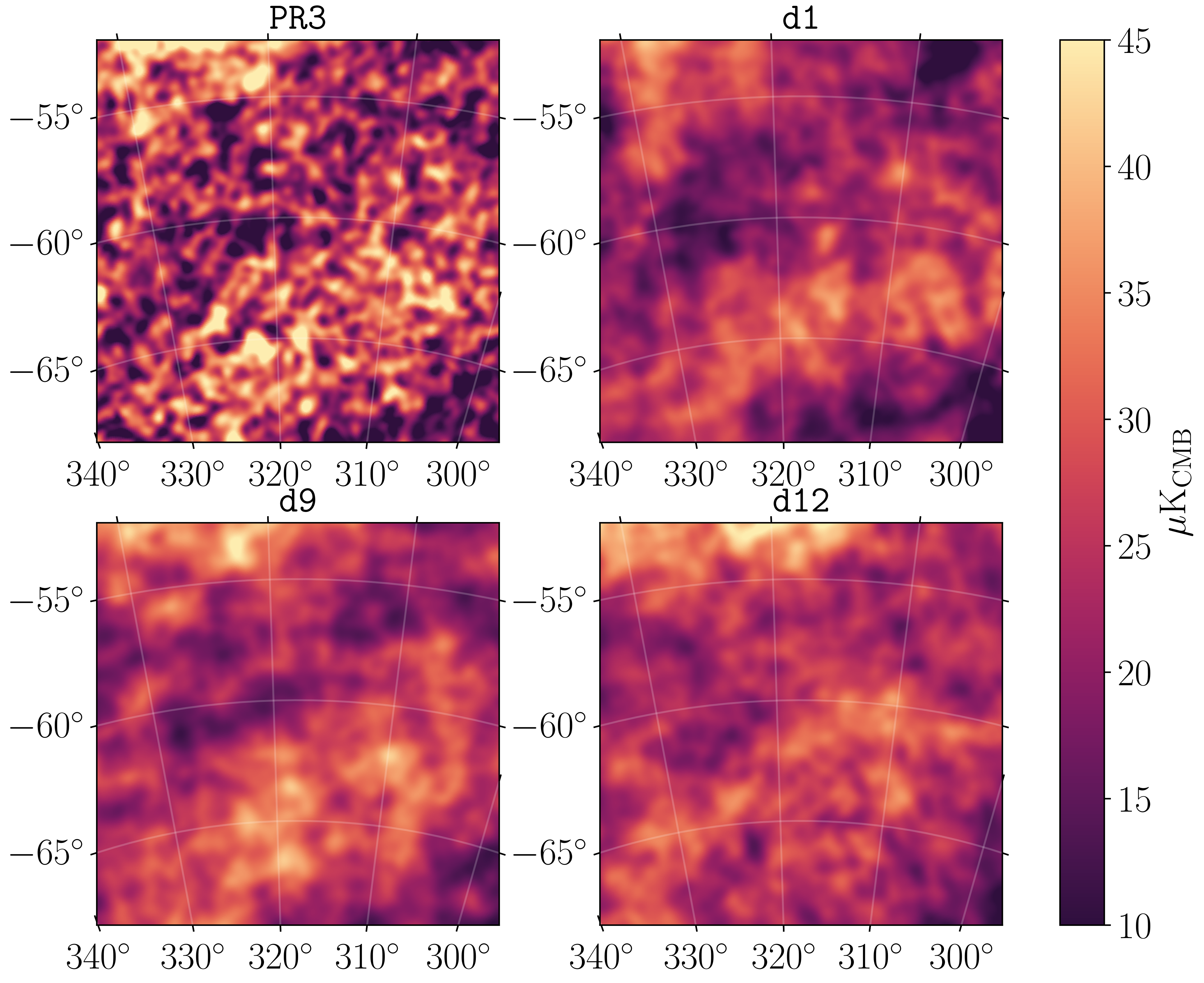
Tag	Spectrum Model	Templates Large scale	Templates Small scale	Frequency scaling Large scale	Frequency scaling Small scale	Stochasticity
s4	Power law	Haslam I 408 MHz + WMAP Q/U 23 GHz	Modulated + polarization fraction tensor	Uniform β_s	Uniform β_s	—
s5	"	"	"	β_s from Haslam, S-PASS, WMAP	Modulated	—
s6	"	"	"	"	"	I, Q, U & β_s
s7	Curved power law	"	"	"+ c_s from ARCADE	"+ c_s fluctuations	—

Haslam I scaled to $\nu_0 = 23$ GHz

PR3 vs. PySM P Maps (353 GHz)



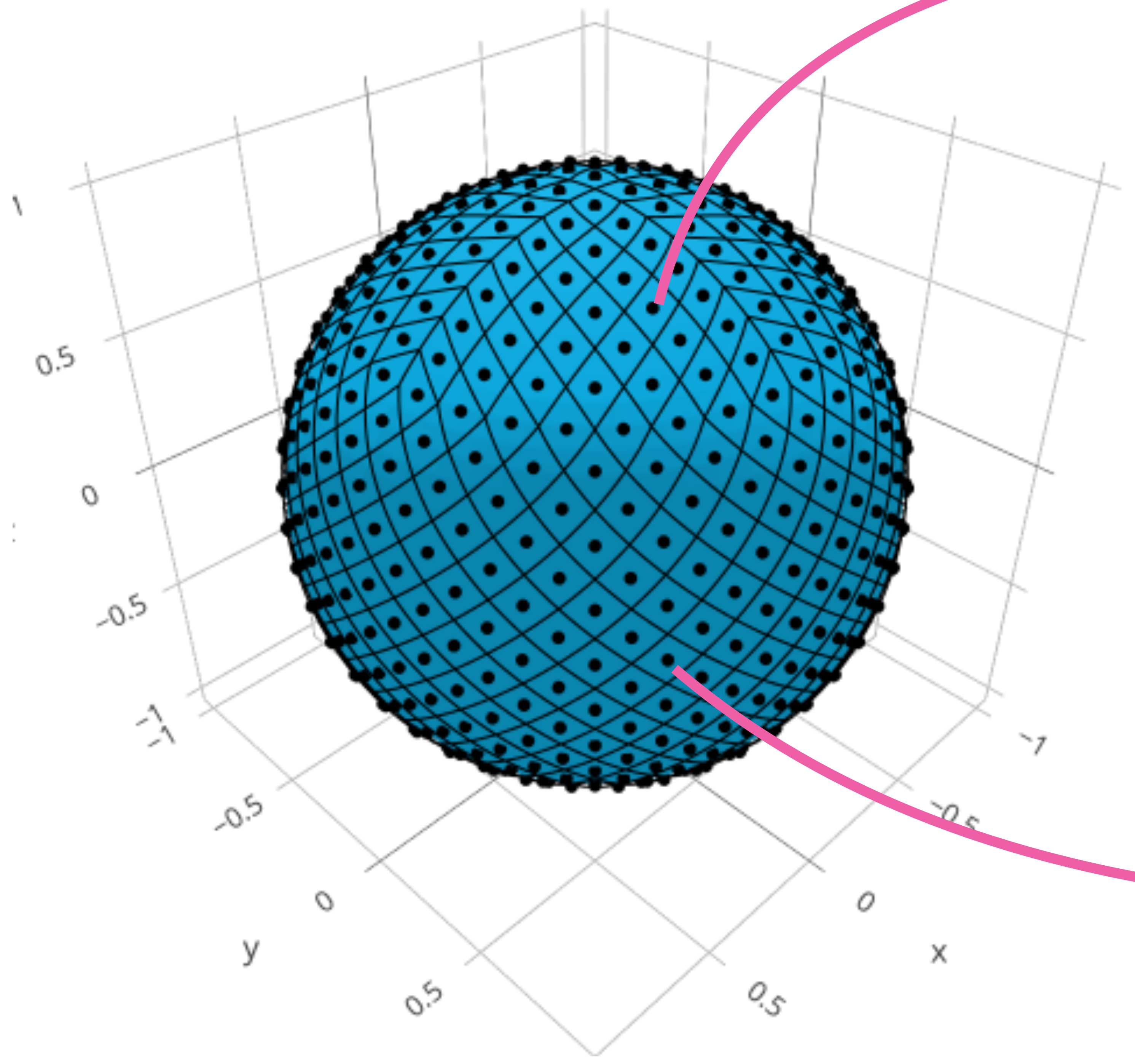
Galactic Plane: $(l, b) = (180^{\circ}, -10^{\circ})$

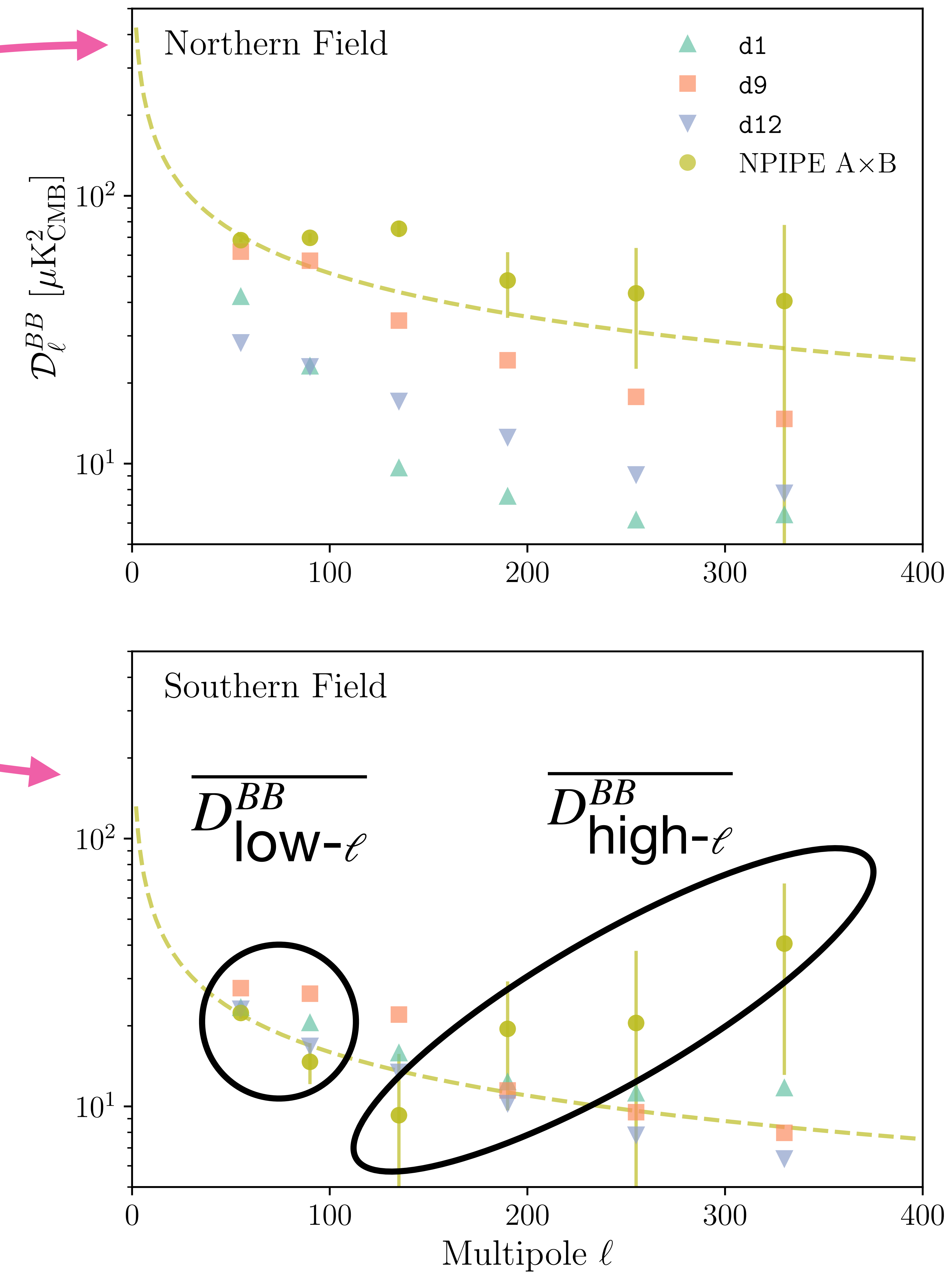


BICEP Field: $(l, b) = (318^{\circ}, -61^{\circ})$

Small-field Analysis

- Dust BB in small fields: full-sky PySM vs. NPIPE A/B maps at 353 GHz
- $N_{\rm side} = 8 \rightarrow$ 768 patches
- Gaussian-tapered circular masks ($f_{\rm sky} \approx 0.8\%$)
- Patch-wise BB spectra for $|b| > 30°$
- Model behavior vary over patches
  $\rightarrow$ averaging band powers to capture the overall trend amid NPIPE noise





Small-field Analysis

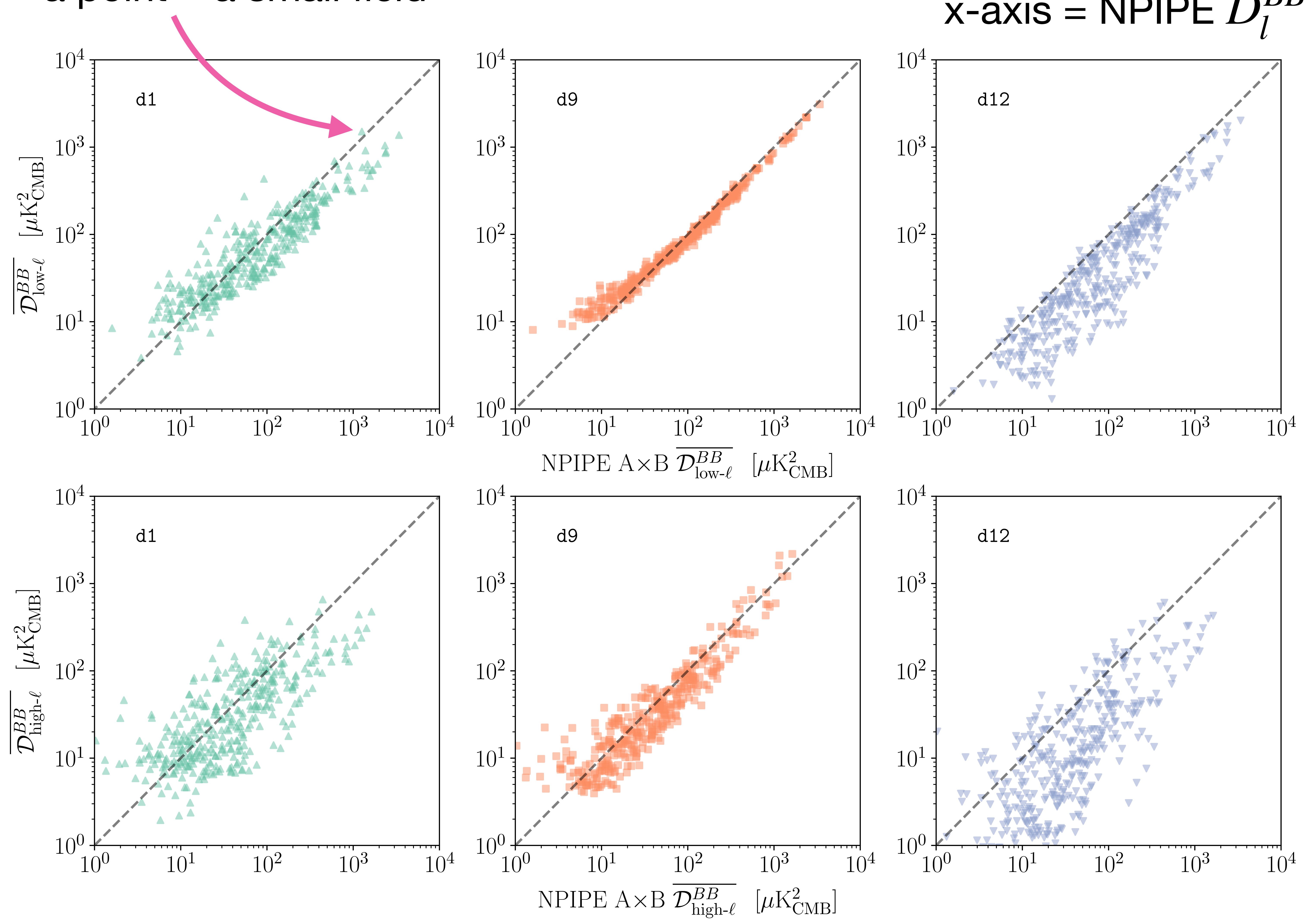
y-axis = PySM $\overline{D_l^{BB}}$

x-axis = NPIPE $\overline{D_l^{BB}}$

Patch-wise PySM vs. NPIPE $\overline{D_l^{BB}}$

- d12 underestimates dust level (e.g., SPIDER, BICEP field)
- d1/d9 generally agrees with data
- With high S/N, d9 vastly improves in low- and high-l
  → GNILC template + extrapolation
- Opposing trend: d9 overestimates when $\overline{D_l^{BB}} < 10^1\,\mu\mathrm{K}^2_{\mathrm{CMB}}$ (e.g., SPIDER, BICEP field)
- GNILC overestimates dust levels in that regime

a point = a small field



Small-field Analysis

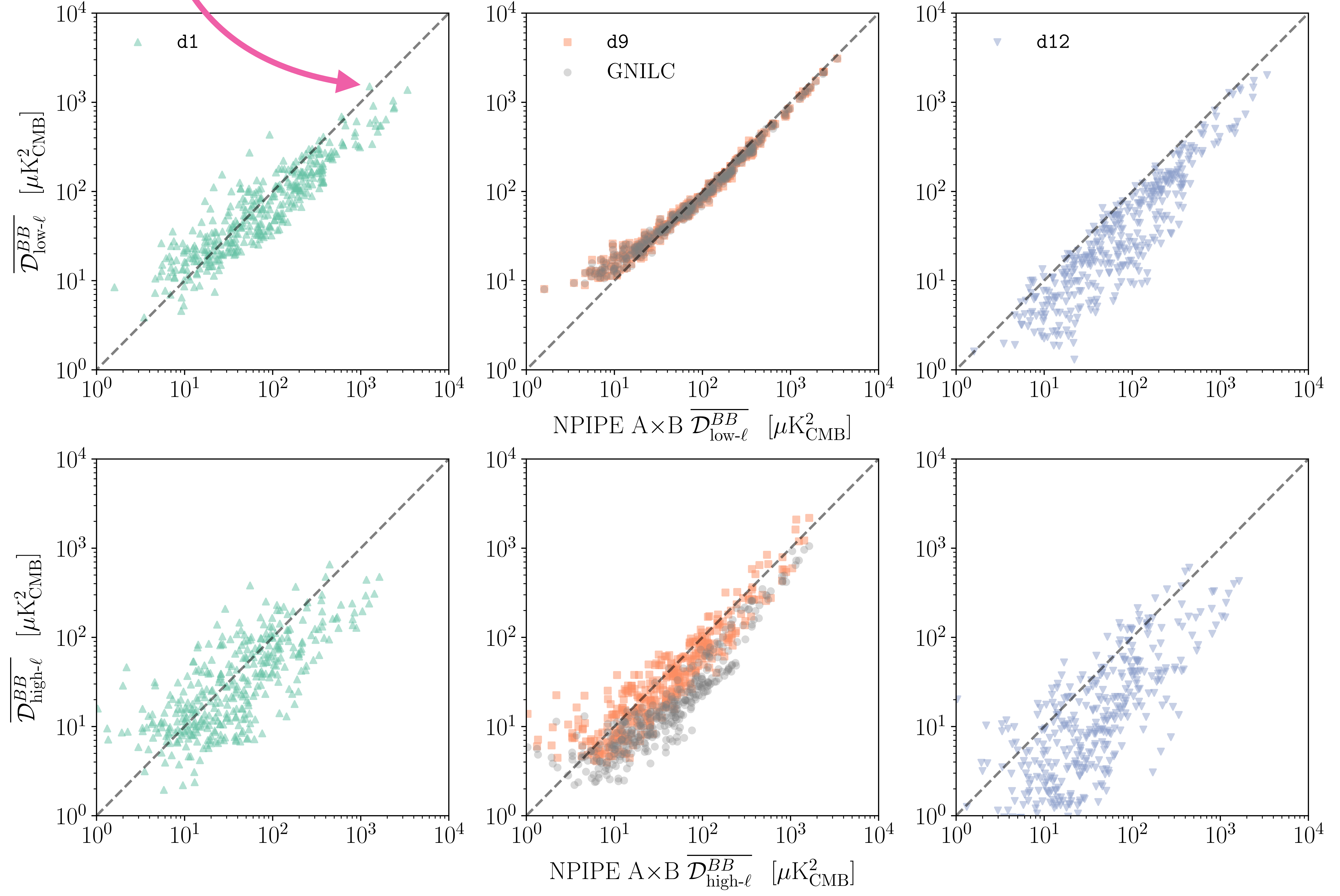
Patch-wise PySM vs. NPIPE $\overline{D_l^{BB}}$

- d12 underestimates dust level (e.g., SPIDER, BICEP field)
- d1/d9 generally agrees with data
- With high S/N, d9 vastly improves in low- and high-l
  → GNILC template + extrapolation
- Opposing trend: d9 overestimates when $\overline{D_l^{BB}} < 10^1\ \mu K^2_{CMB}$ (e.g., SPIDER, BICEP field)
- GNILC overestimates dust levels in that regime

a point = a small field

y-axis = PySM $\overline{D_l^{BB}}$

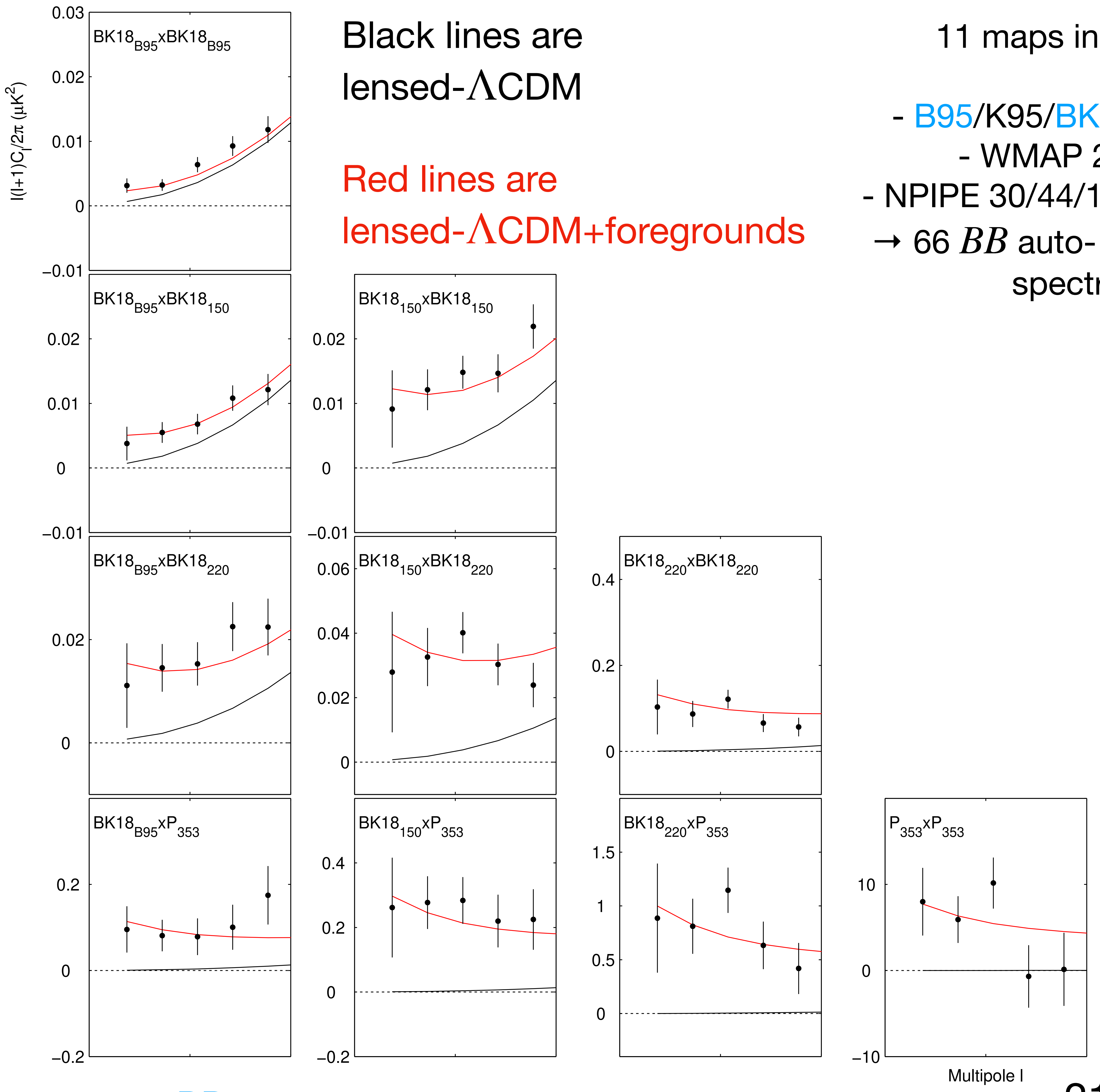
x-axis = NPIPE $\overline{D_l^{BB}}$



Specific Small-field Analysis: BK Field

BICEP/Keck field:

- 600 sq-deg, one of the cleanest patches in the Southern sky
- BK18: high S/N dust BB measurement via a parametric model
- MBB for dust: $A_{d,l=80} = 4.4\,\mu\mathrm{K}^2_{\mathrm{CMB}}$, $\beta_d = 1.5$, $\alpha_d = -0.66$, $T_d = 19.6\,\mathrm{K}$
- Sync amplitude upper limit
- Critical for ongoing/future B-mode searches: BA, SPT-3G+, SO, S4, …



Black lines are lensed-ΛCDM

Red lines are lensed-ΛCDM+foregrounds

11 maps in BK18:

- B95/K95/BK150/K220
- WMAP 23/33
- NPIPE 30/44/143/217/353

→ 66 BB auto- and cross-spectra

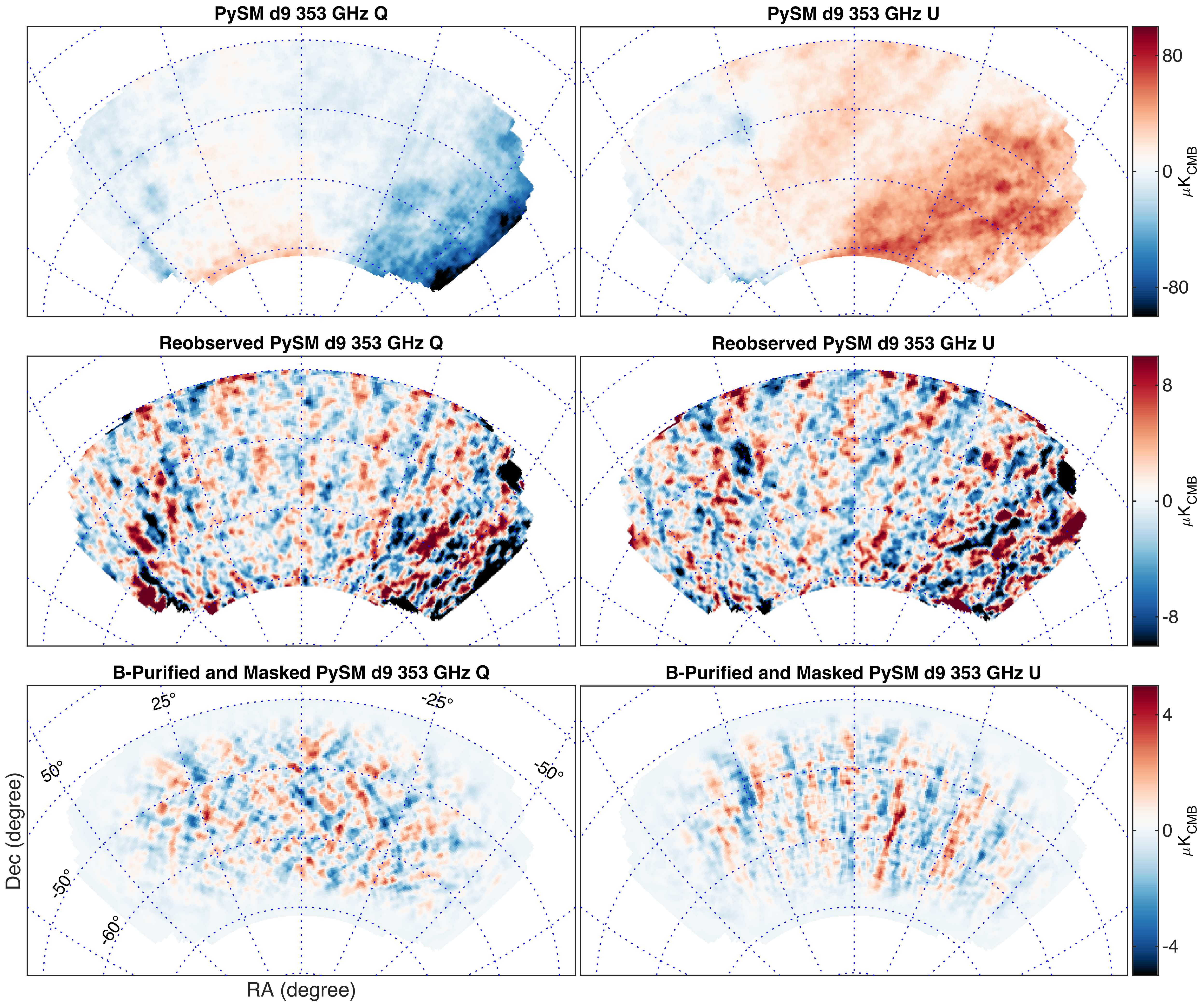
10 BB auto- and cross-spectra from a subset of 4 maps

arXiv: 2110.00483

Reanalyzing PySM Maps in BK Field

"Re-observing" PySM d/s (& NPIPE 353 GHz) maps in the BK field

- BK linear map-making process
  → BK observation matrix incorporating filtering and deprojection
- Step 1: B3 beam convolution + crop
- Step 2: B3 observation matrix
- Step 3: B3 purification matrix + apodization mask
- Replicate the impact of BK instrument & map-making pipeline for d1/d9/d10/d12 at 85/150/220/270/353 GHz & s1/s4/s5/s6/s7 at 23/30/40 GHz



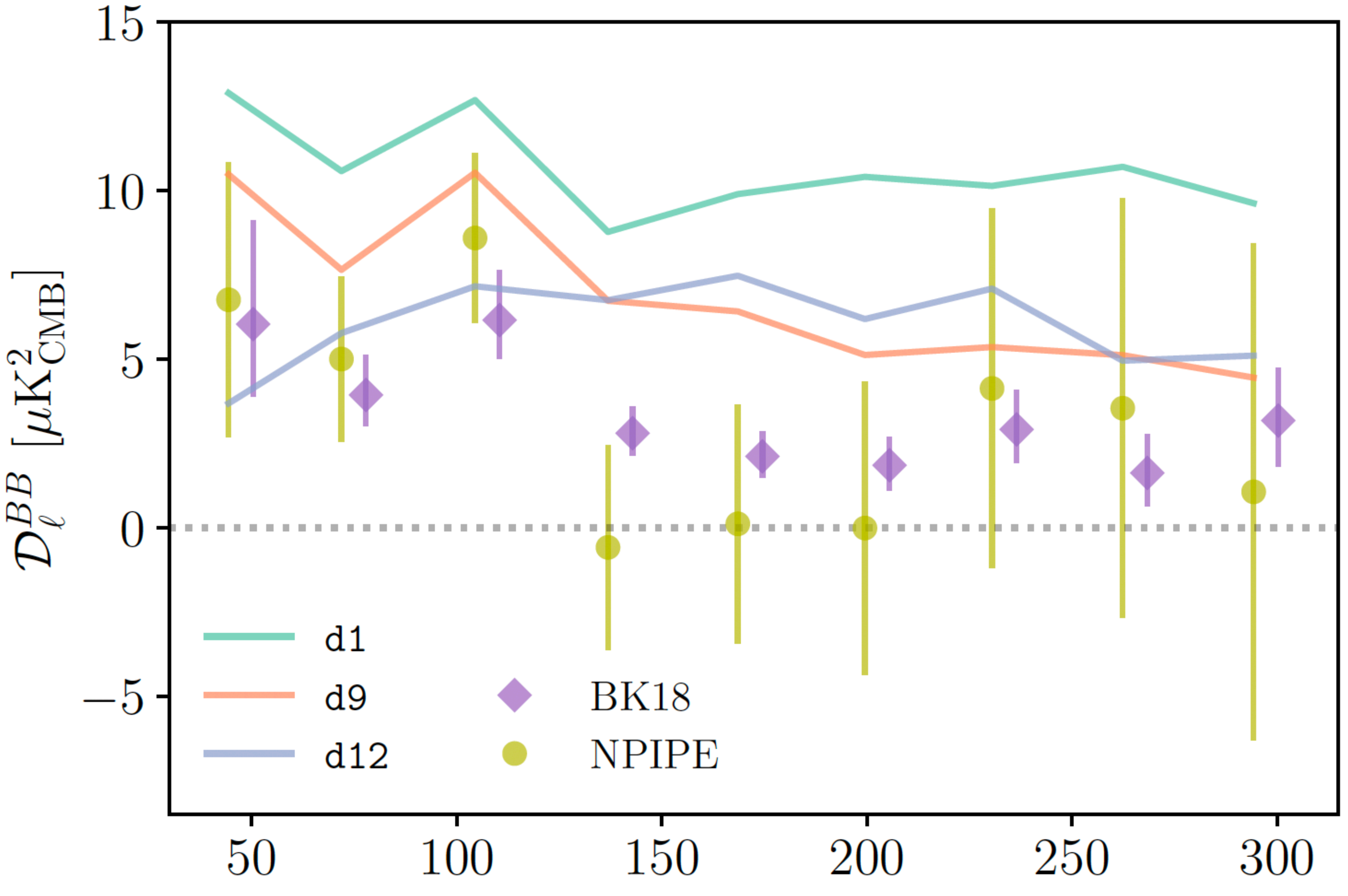
B3-processed d9 Q/U (353 GHz)

PySM vs. BK18 Dust

Full-sky dust D_l^{BB} with associated errors

- d1: 3 times higher, high-l power deviates more
- d9: high-$l \approx$ power law, 2 times higher overall
- d12: high-$l \approx$ power law, power drop at low l
- *Bonus:* NPIPE excess at $l \approx 100$, no clear high-l power decay amid noise

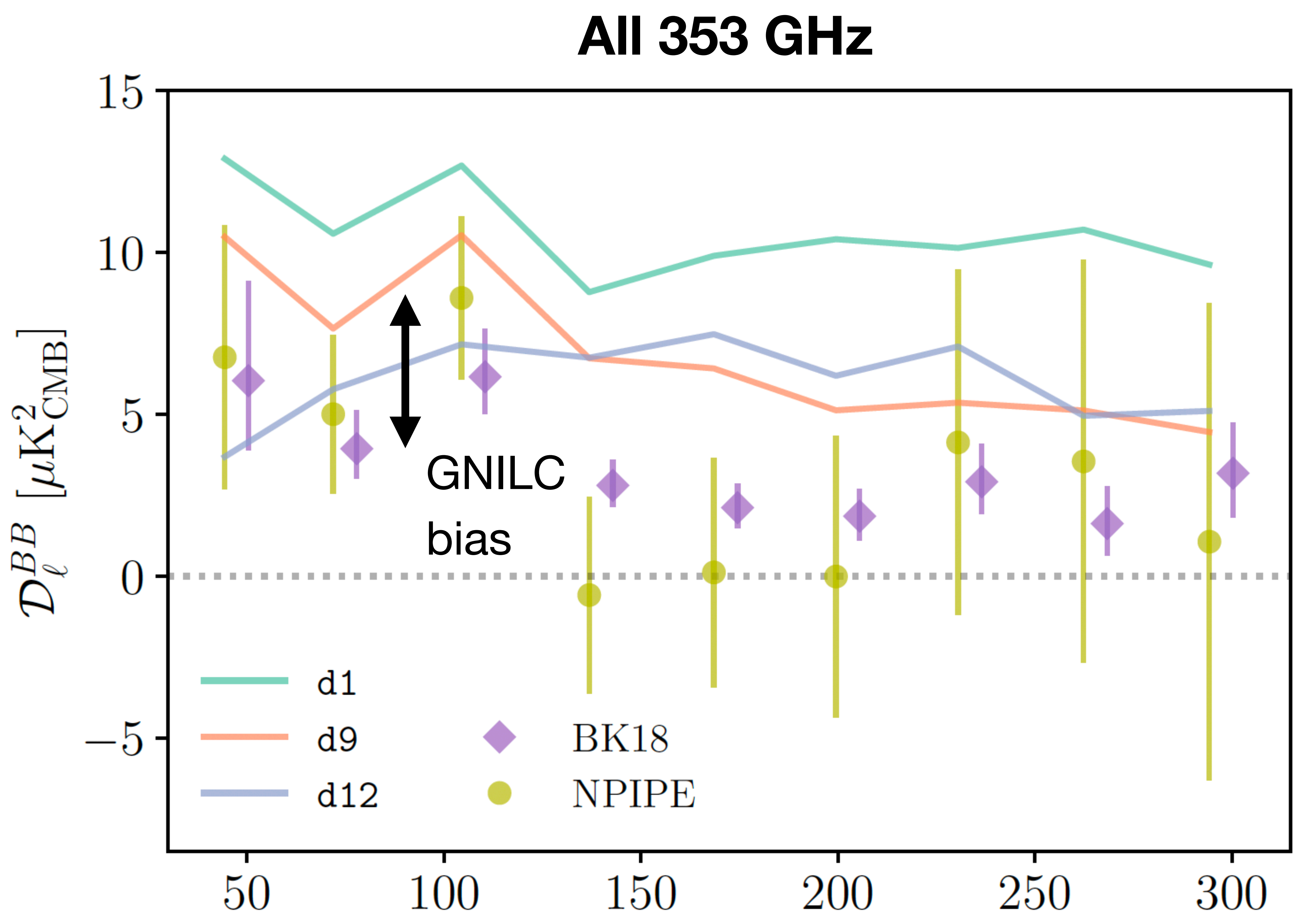
All 353 GHz



PySM vs. BK18 Dust

Full-sky dust D_l^{BB} with associated errors

- d1: 3 times higher, high-l power deviates more
- d9: high-l $\approx$ power law, 2 times higher overall
- d12: high-l $\approx$ power law, power drop at low l
- *Bonus:* NPIPE excess at $l \approx 100$, no clear high-l power decay amid noise



PySM vs. BK18 Dust

D_l^{BB} changes over frequencies

- Single-amplitude fit to BK18 dust ML model
- d9: $\approx$ 2, generally less than d1
- d10: decreasing → slightly larger β_d relative to BK18: $1.49^{+0.13}_{-0.12}$ (GNILC template: $\beta_d = 1.6$)
- d12: more complicated due to multiple-layer behavior

Ratio of PySM BB/BK18 dust BB

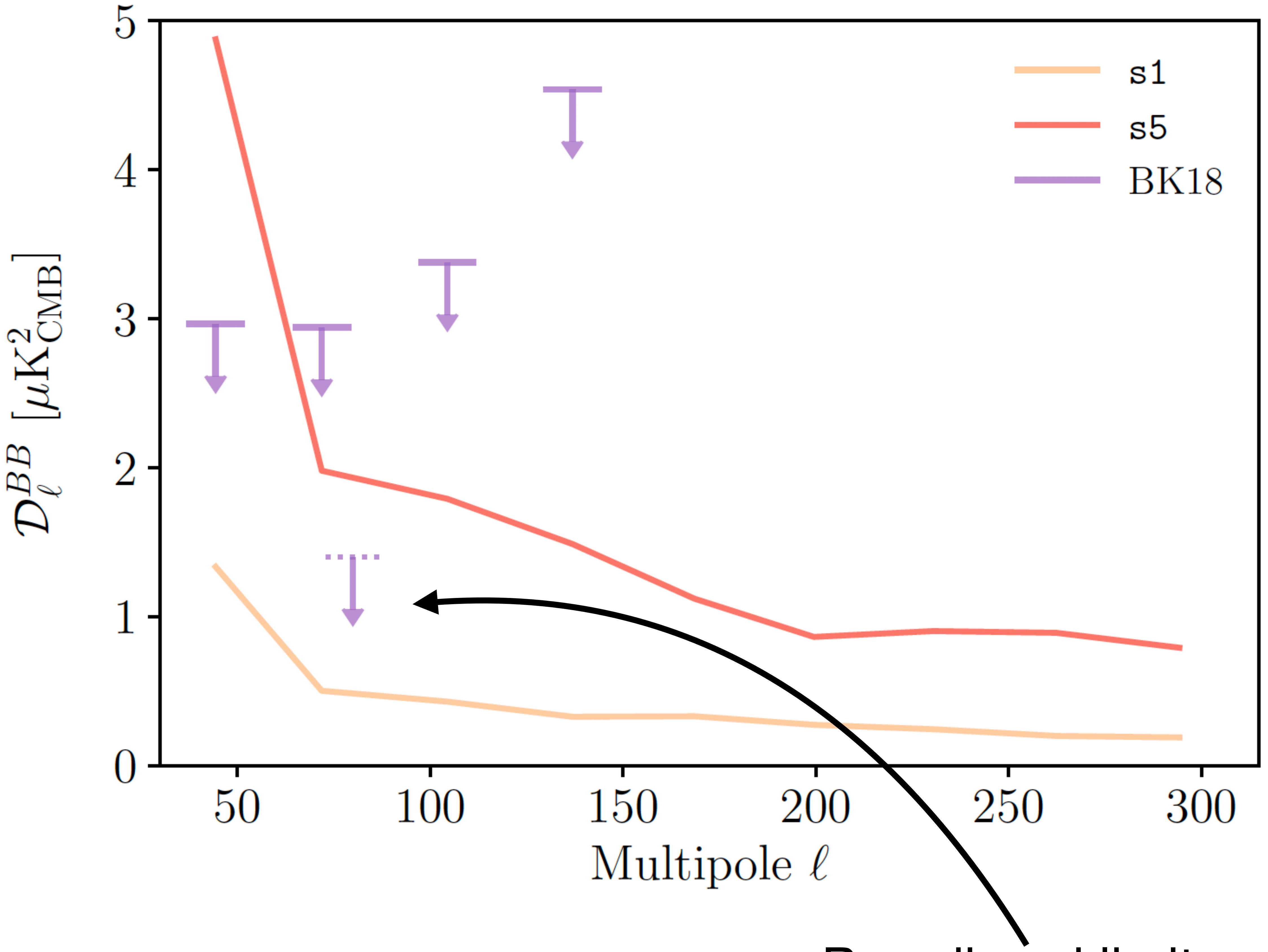
	85 GHz	150 GHz	220 GHz	270 GHz	353 GHz
d1	2.42	2.63	2.81	2.94	3.13
d9	2.17	2.12	2.08	2.06	2.03
d10	0.96	1.30	1.59	1.77	2.03
d12	2.76	2.27	2.08	2.02	1.96

PySM vs. BK18 Synchrotron

Full-sky synchrotron D_l^{BB} with associated upper limits

- s1: relatively flat, all below upper limits
- s5: excess power at $l \lesssim 50\ (70)$
- PySM WMAP 23 GHz templates vs. BK18 NPIPE 30/40 GHz prefers smaller A_s
- Similar results for s4/s6/s7 at 30/40 GHz
- Revisit with future BA 30/40 GHz results

All 23 GHz



Broadband limit

$A_{s,l=80} < 1.4\,\mu K^2_{CMB}$

Recommended Model Suite

Complexity	Model set	Short description
Low	`d9, s4, f1, a1, co1`	Small-scale emission fluctuations in amplitude only; no frequency decorrelation in dust or synchrotron. Unpolarized CO emission.
Medium	`d10, s5, f1, a1, co3`	Extrapolation to small scales for both amplitude and spectral parameters in dust and synchrotron. CO polarization at the 1% level.
High	`d12, s7, f1, a2, co3`	Dust layer model, spatially varying synchrotron curvature, polarized AME and CO.

- Three recommended model sets: low, medium, high complexity
- All $N_{\rm side} = 8192$ except free-free and CO ($N_{\rm side} = 2048$)
- Realistic over 1–1000 GHz
- d9, d10, d11: up to 3000 GHz
- Application and validation from the mm-wave community

Future Outlook

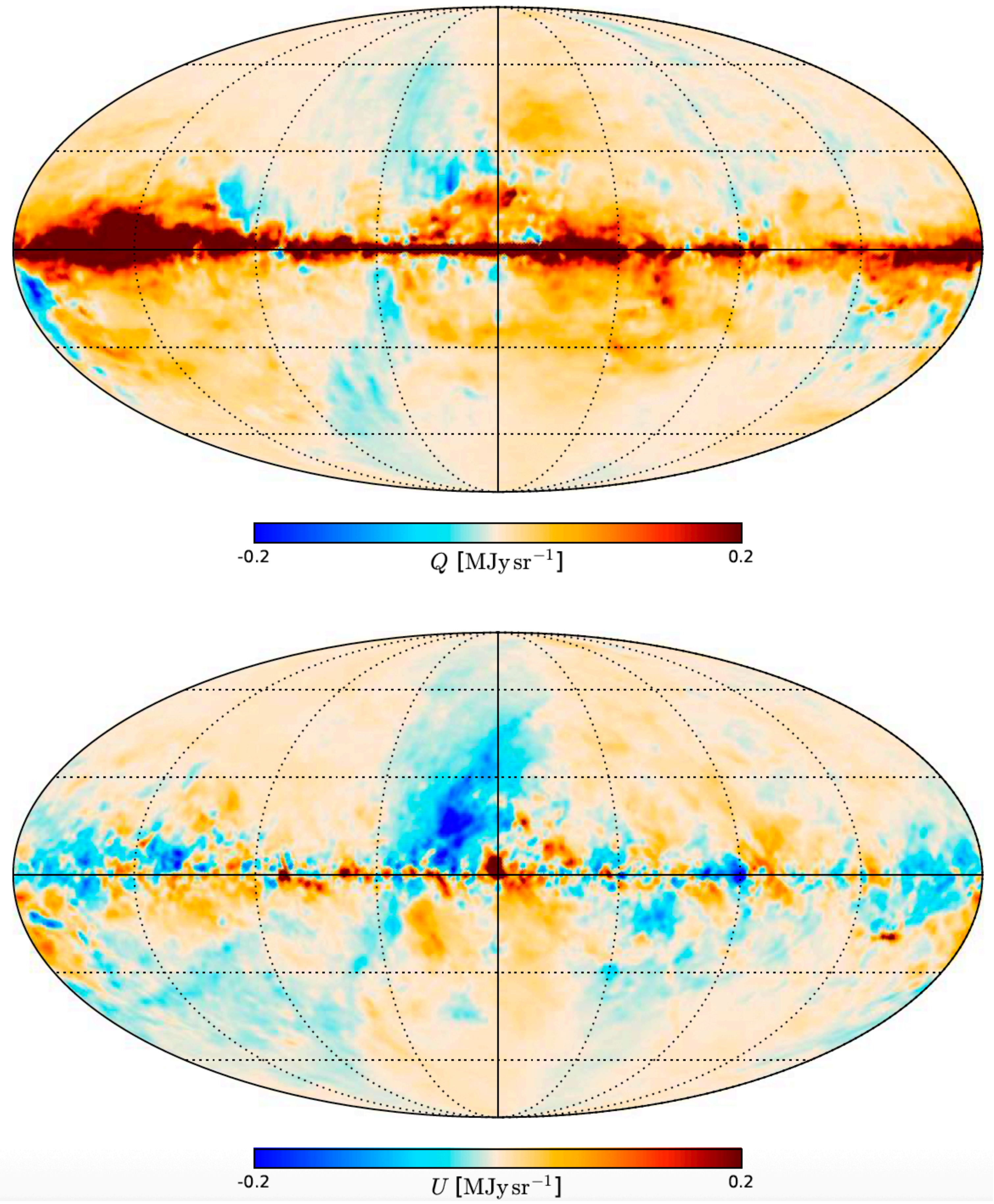
- We have demonstrated overall improvement of models. Moving forward:
  - New amplitude templates from improved algorithms
  - New spectral parameter templates from improved algorithms & high S/N data
  - Merging partial sky observations
  - Employing physical realism small-scale emission structure
- Improved internal workflow → new iterations of the iterative process

Backup Slides

Methodology

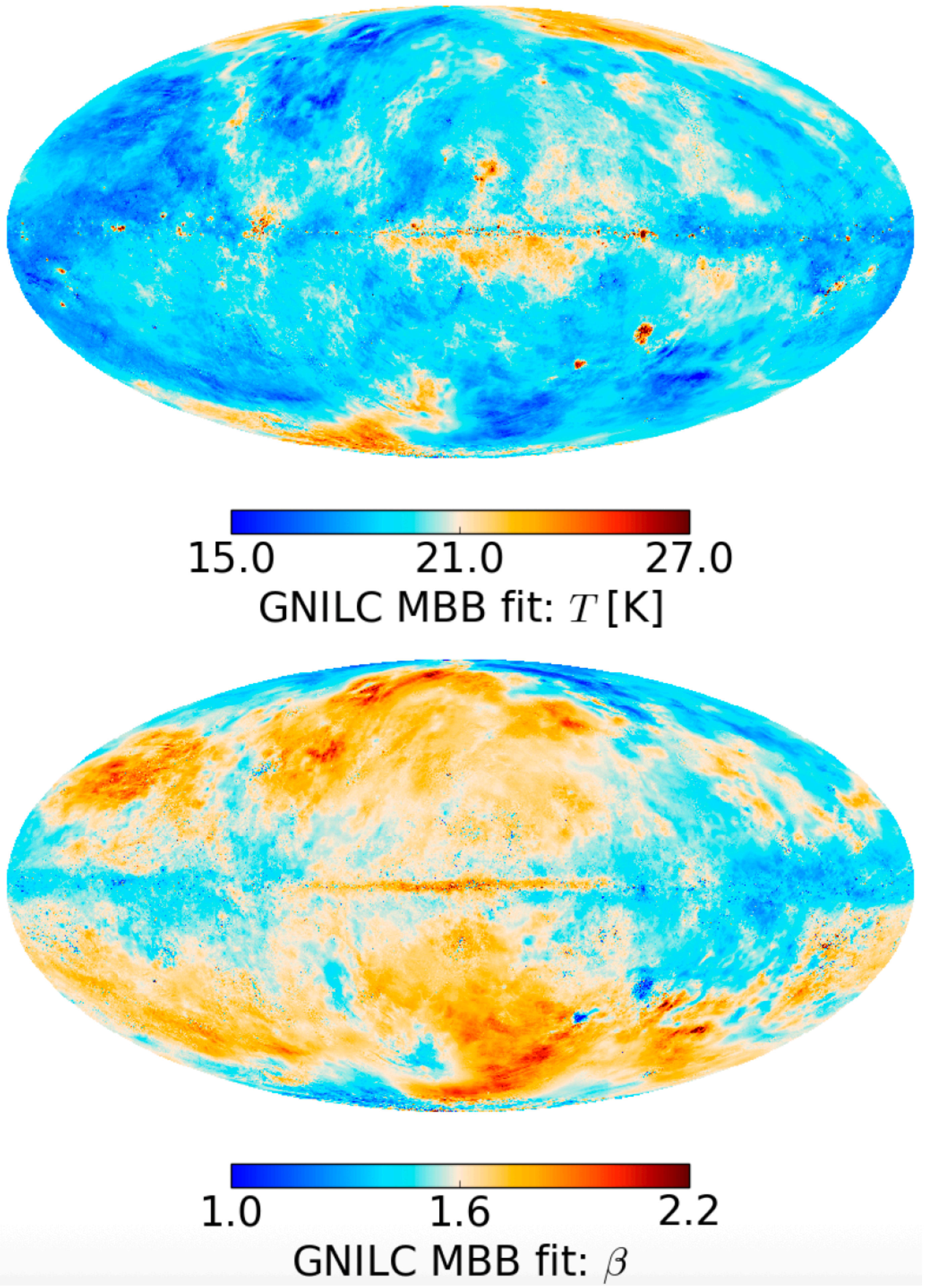
- Dust: $S_\nu = A_d^S \left(\nu/\nu_0\right)^{\beta_d} B_\nu(T_d)$
- Synchrotron:
  $S_\nu = A_s^S \left(\nu/\nu_0\right)^{\beta_s + c_s \ln(\nu/\nu_c)}$
- Amplitude parameters: A_d^S, A_s^S
- Spectral parameters: β_d, T_d, β_s, c_s
- Per-pixel frequency scaling from amplitude maps at $\nu_0 = 353, 23$ GHz
- Main idea: **preserve reliable large-scale modes, extrapolate them to small scales, and add stochastic small-scale fill-in**

GNILC PR3 Q/U (353 GHz)



arXiv:1807.06212

GNILC PR2 T_d/β_d



arXiv:1605.09387

Polarization Fraction Tensor Framework

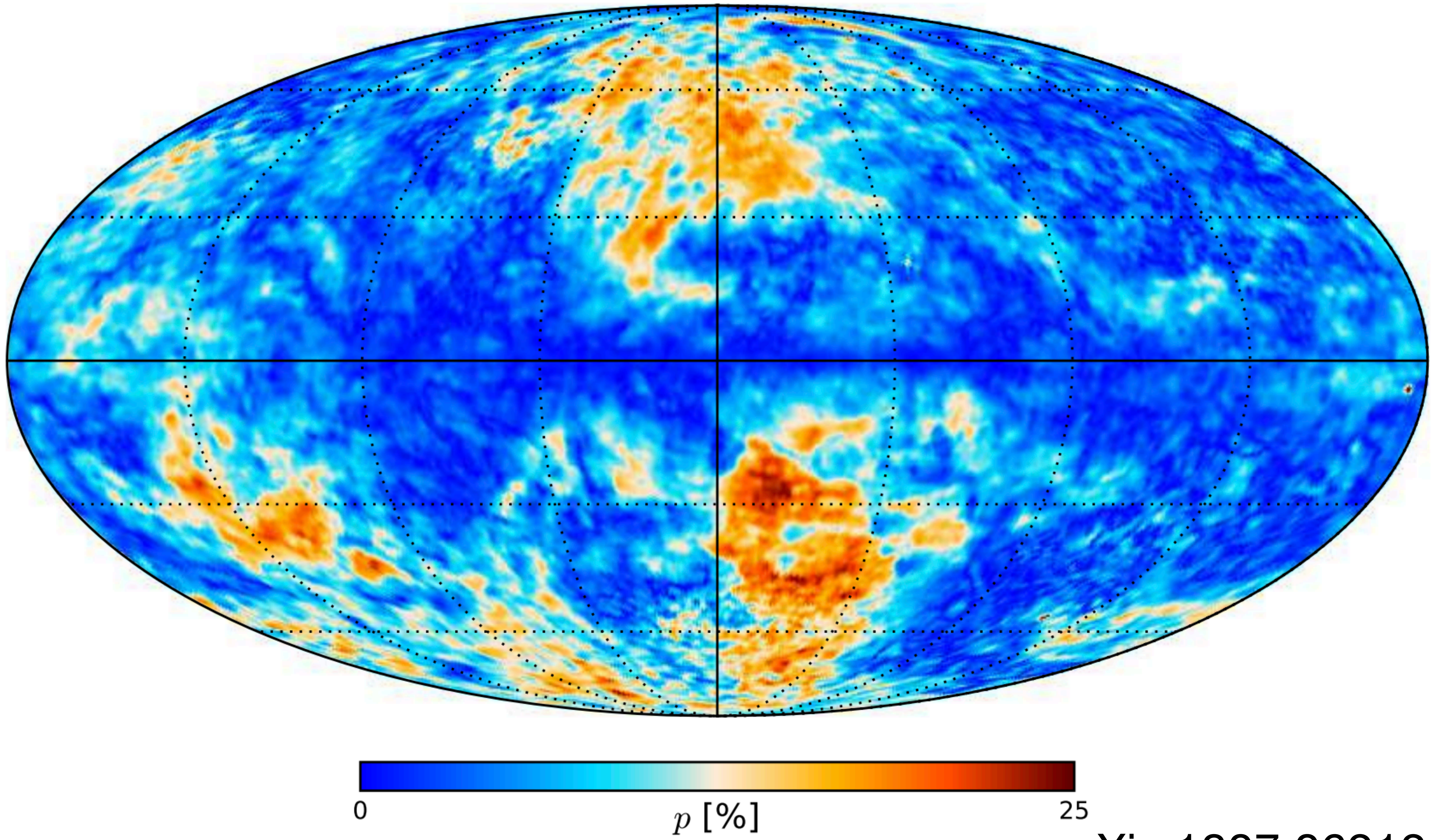
How to generate small-scale (filamentary) Galactic emissions?

A simplified picture:

- Dust I probes dust density structure (projection)
- Dust P modulated by large-scale Galactic magnetic fields
- $p \equiv P/I \approx$ isotropic + small fluctuations from magnetic field turbulent

Corresponding framework:

- $(I, Q, U)/I \rightarrow (x, y, z) \rightarrow D_l^{xy}$ for generating realizations
- Introduce non-Gaussianity during reverse transformation



arXiv:1807.06212

Polarization Fraction Tensor Framework

How to generate small-scale (filamentary) Galactic emissions?

A simplified picture:

- Dust I probes dust density structure (projection)
- Dust P modulated by large-scale Galactic magnetic fields
- $p \equiv P/I \approx$ isotropic + small fluctuations from magnetic field turbulent

Corresponding framework:

- $(I, Q, U)/I \to (x, y, z) \to D_l^{xy}$ for generating realizations
- Introduce non-Gaussianity during reverse transformation

$$(I, Q, U) \;\leftrightarrow\; (i, q, u)$$

$$i \equiv \frac{1}{2}\ln(I^2 - P^2) \qquad I = e^i \cosh\xi$$

$$q \equiv \frac{1}{2}\frac{Q}{P}\ln\frac{I+P}{I-P} \qquad Q = \frac{q}{\xi}e^i \sinh\xi$$

$$u \equiv \frac{1}{2}\frac{U}{P}\ln\frac{I+P}{I-P} \qquad U = \frac{u}{\xi}e^i \sinh\xi$$

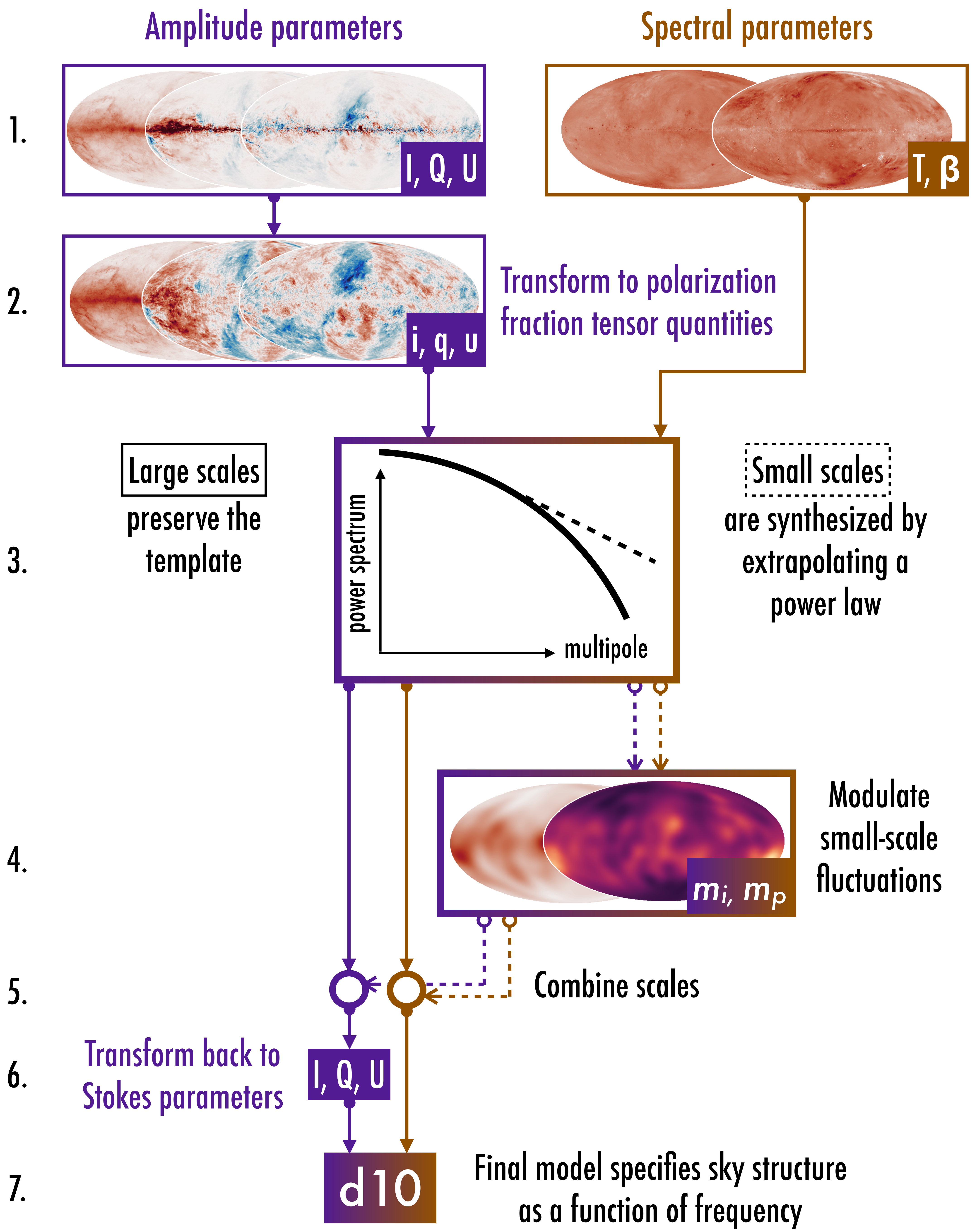
$$\xi \equiv (q^2 + u^2)^{1/2}$$

$I > 0$ and $0 \le p \le 1$ for all (i, q, u)

When $p \ll 1$:

$$i \simeq \ln I,\; q \simeq Q/I,\; u \simeq U/I$$

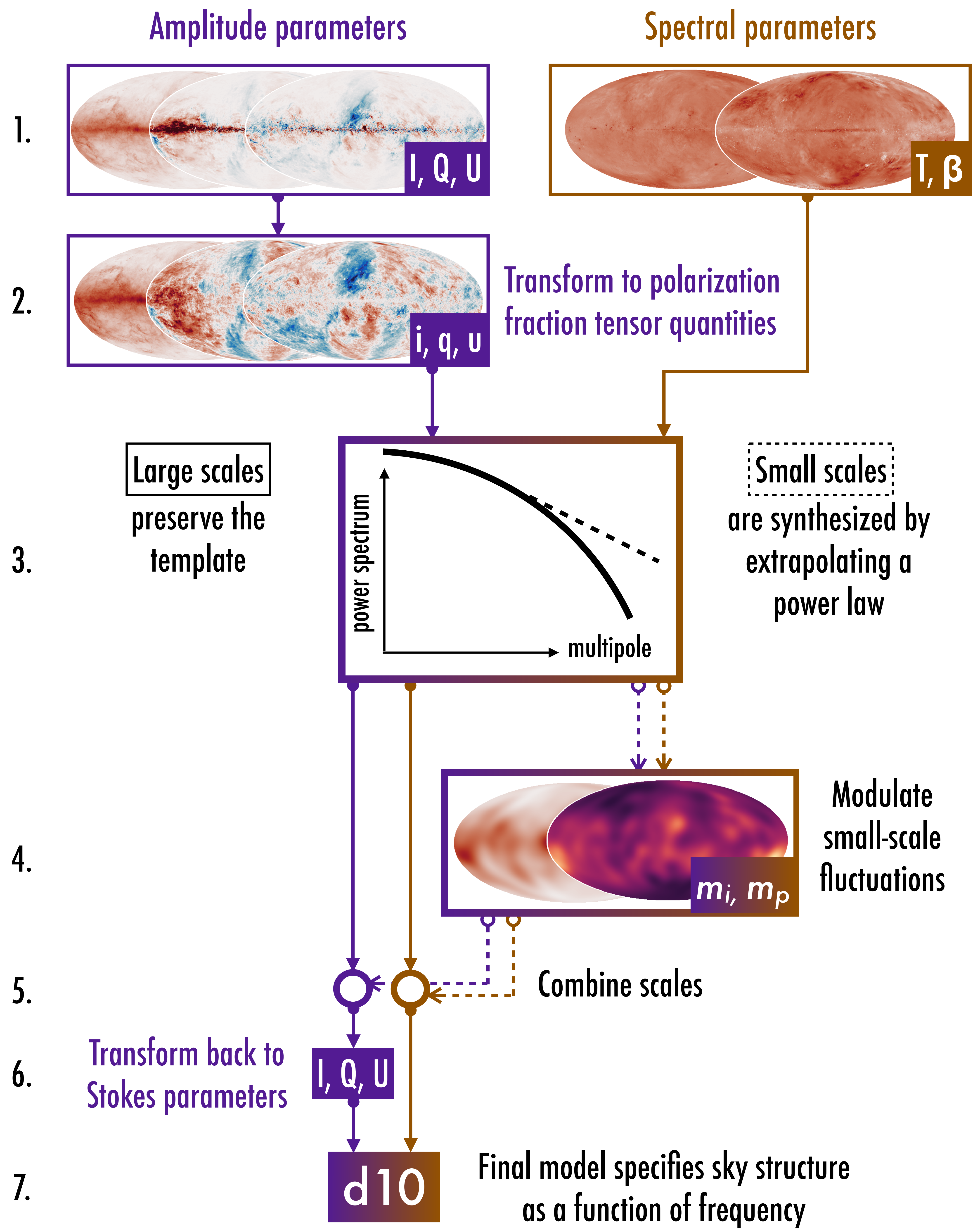
Model Construction Flowchart



1. Starting from amplitude template maps

New dust templates: Commander → GNILC

Low complexity models: uniform spectral parameters (d9/s4)



2. Performing polarization fraction tensor transformation

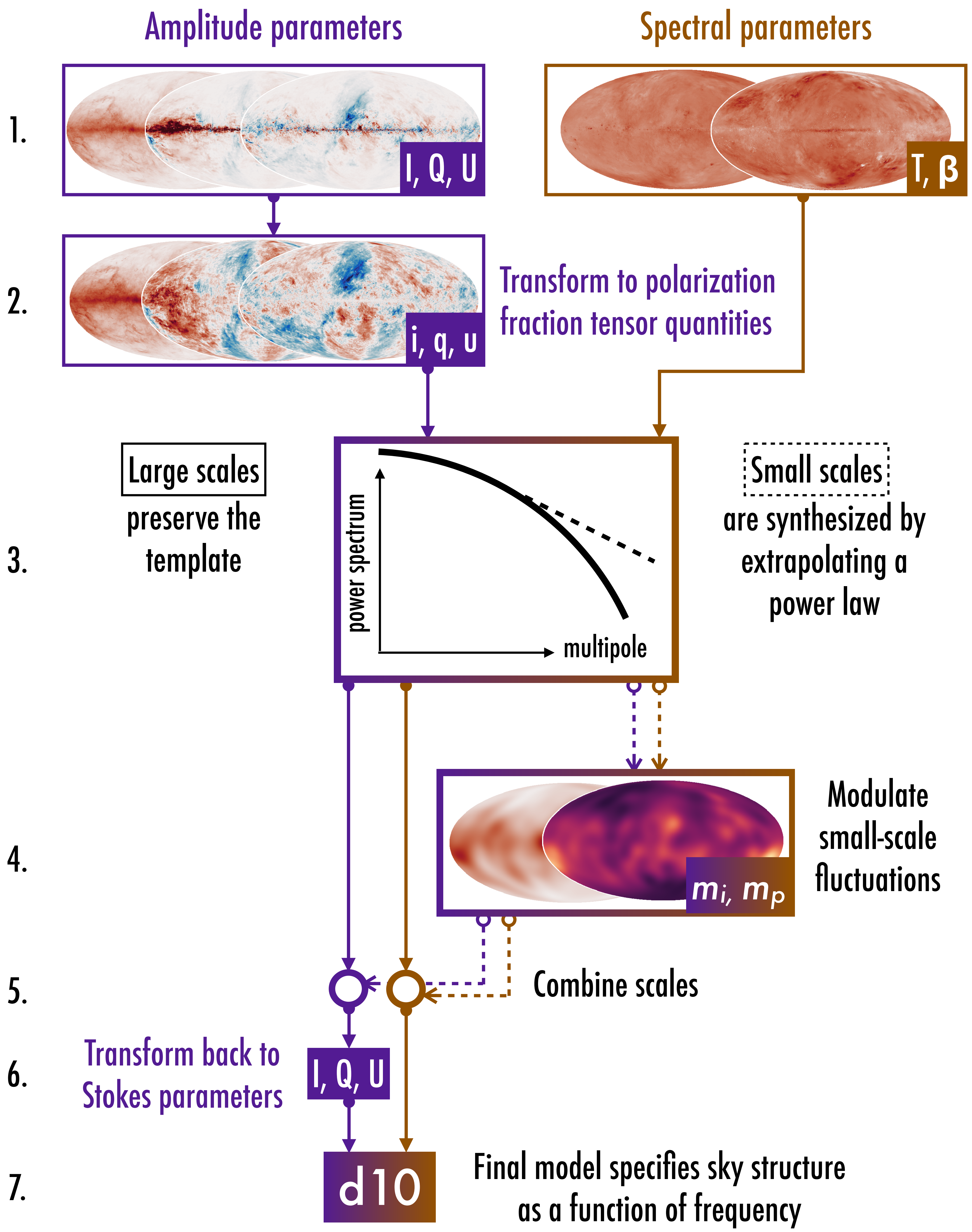
$(I, Q, U) \rightarrow (i, q, u)$

$(i, q, u) \rightarrow (t, e, b)$
same as $(I, Q, U) \rightarrow (T, E, B)$

Compute (tt, ee, bb) power spectra

Low-pass filter
(i, q, u) up to l_1

Preserved large-scale
(i, q, u) maps



3. Preserving large-scale modes and synthesizing small-scale modes

PR3 P 71/78%

	ℓ_0	ℓ_1	ℓ_2	ℓ_*	α_{tt}	α_{ee}	α_{te}	α_{bb}
Dust	50	100	2000	80	-0.80	-0.42	-0.50	-0.54
Synchrotron	10	38	400	36	-1.00	-0.84	-1.00	-0.76

Preserve (tt, ee, bb) spectra between $[l_0, l_1]$

↓

Perform $D_l^{xx} \propto l^{\alpha_{xx}}$ power-law fit with fixed index α_{xx}

↓

Extrapolate the spectra to fill $[l_1, l_2]$

↓

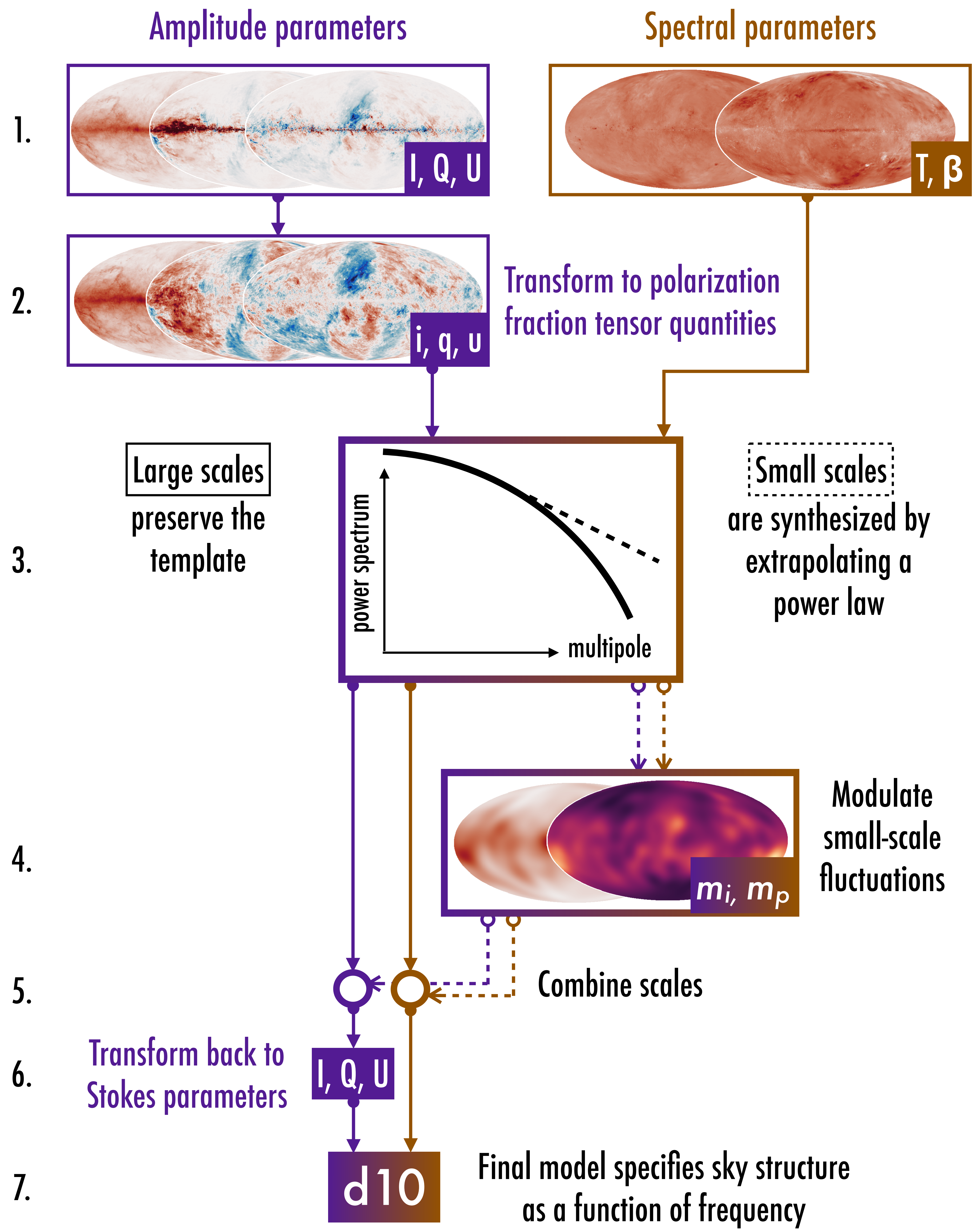
Synthesize (t, e, b) realizations (stochasticity!)

↓

High-pass filter (t, e, b) with cut-off l_1

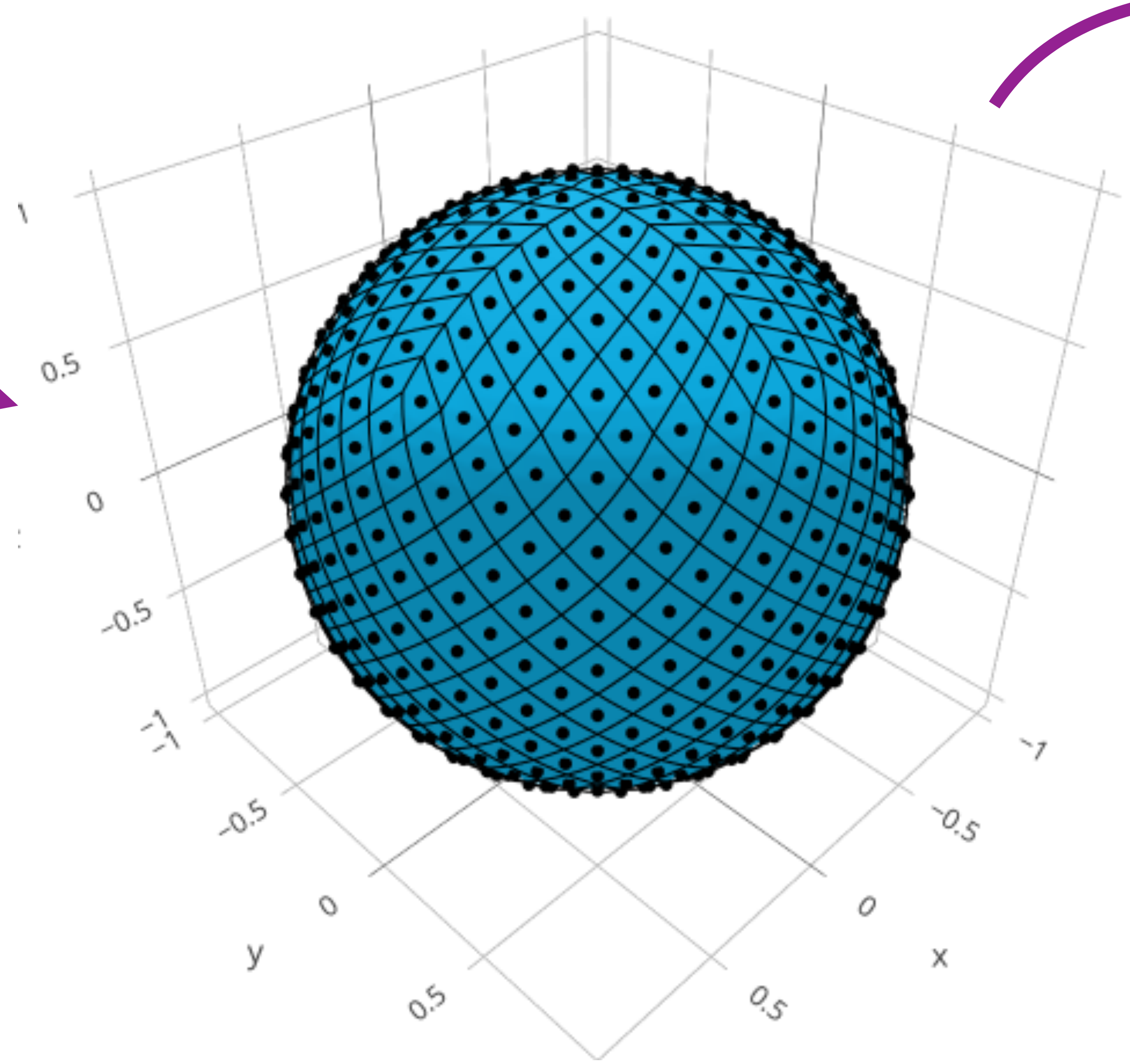
↓

Temporary small-scale realizations



4. Modulating small-scale fluctuations

(t, e, b) template maps



$N_{\text{side}} = 8$ & radius $11.3°$
→ higher-resolution overlapping circular masks

patch-wise (tt, ee, bb)

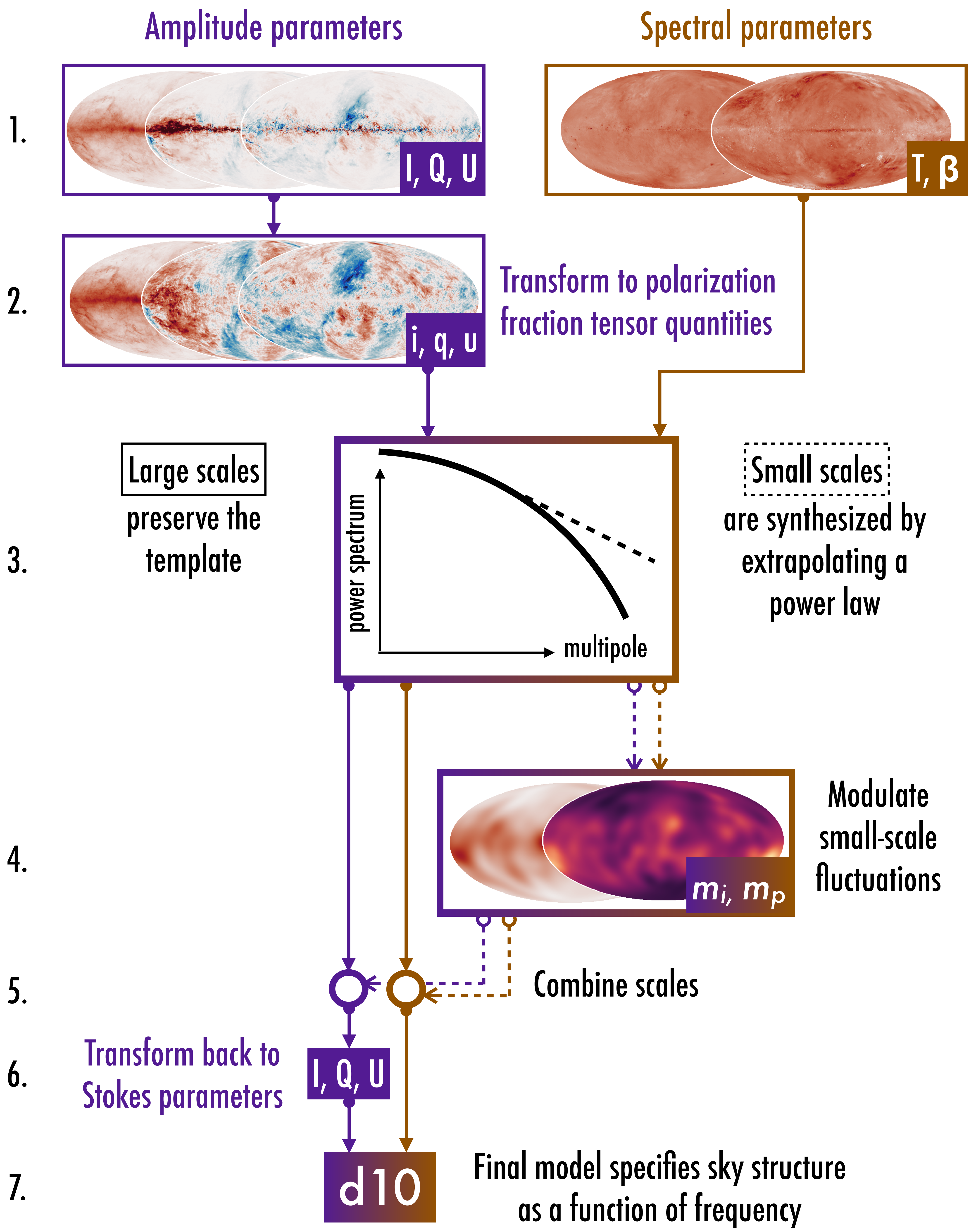
$$m_i\left(\hat{\theta}\right) = \left(\frac{C^{tt}_{l_*,circ}}{C^{tt}_{l_*,full}}\right)^{1/2}$$

$$m_p\left(\hat{\theta}\right) = \left(\frac{C^{ee}_{l_*,circ}}{C^{ee}_{l_*,full}}\right)^{1/2}$$

modulation maps

× temporary small-scale realizations

Final (t, e, b) small-scale realizations



5/6. Combining scales and transforming back

Preserved large-scale modes

Final small-scale modes

"Mode-stitching" $a_{lm}^{x,out} = a_{lm}^{x,ls}\left(1-\sigma_l\right)^{\gamma} + a_{lm}^{x,ss}\sigma_l$

$$\sigma_l = \left[1 + e^{-c_1(l/l_1 - c_2)}\right]^{-1}$$

Smoothing filter

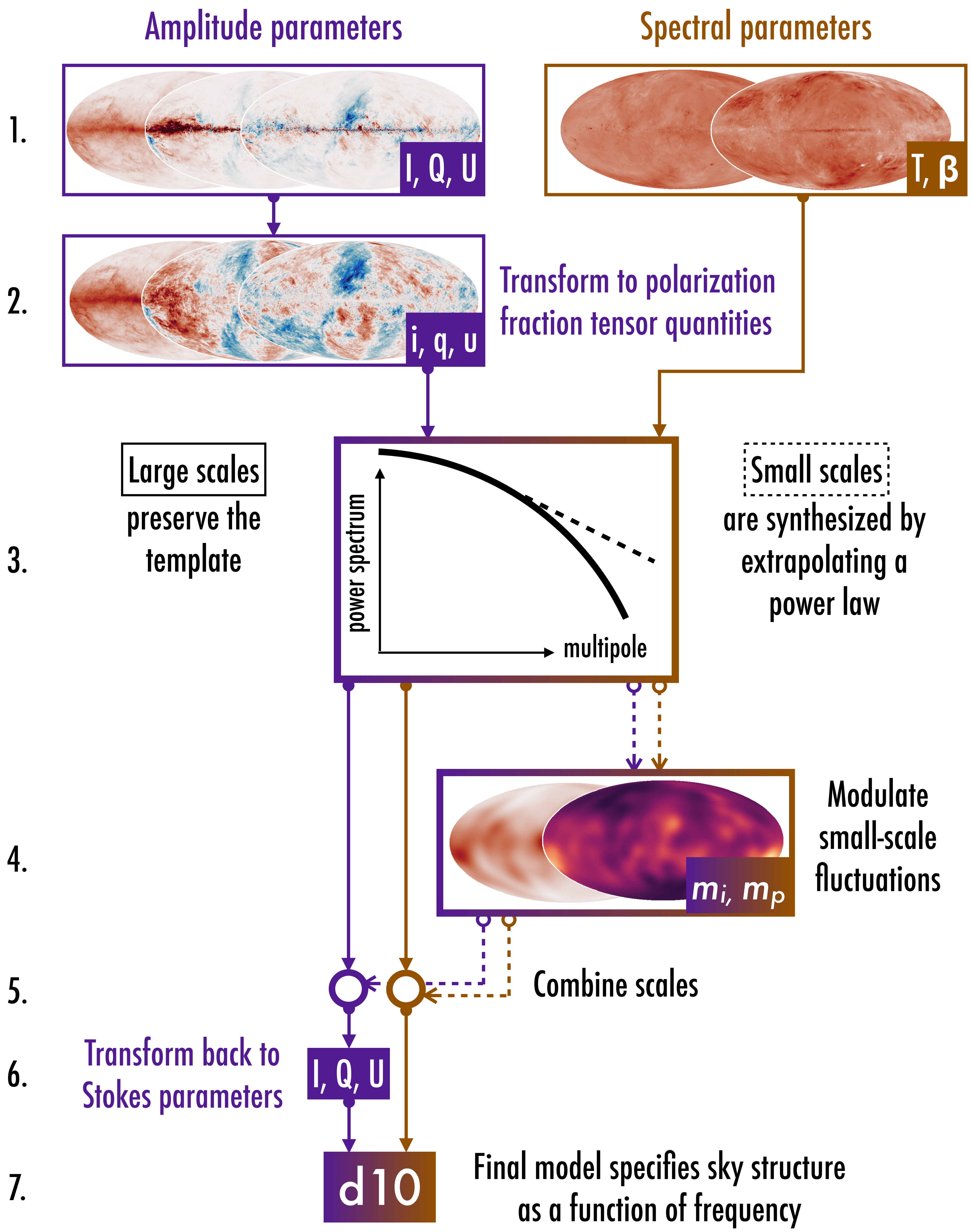
$$\gamma = 0.2,\ c_1 = 40,\ c_2 = 1.05$$

(A lot of tweaking…)

d9/s4 (t, e, b) maps

Reverse transformation

d9/s4 (I, Q, U) maps at ν_0



7. Similar process in parallel for spectral parameter template maps

No polarization fraction tensor transformation

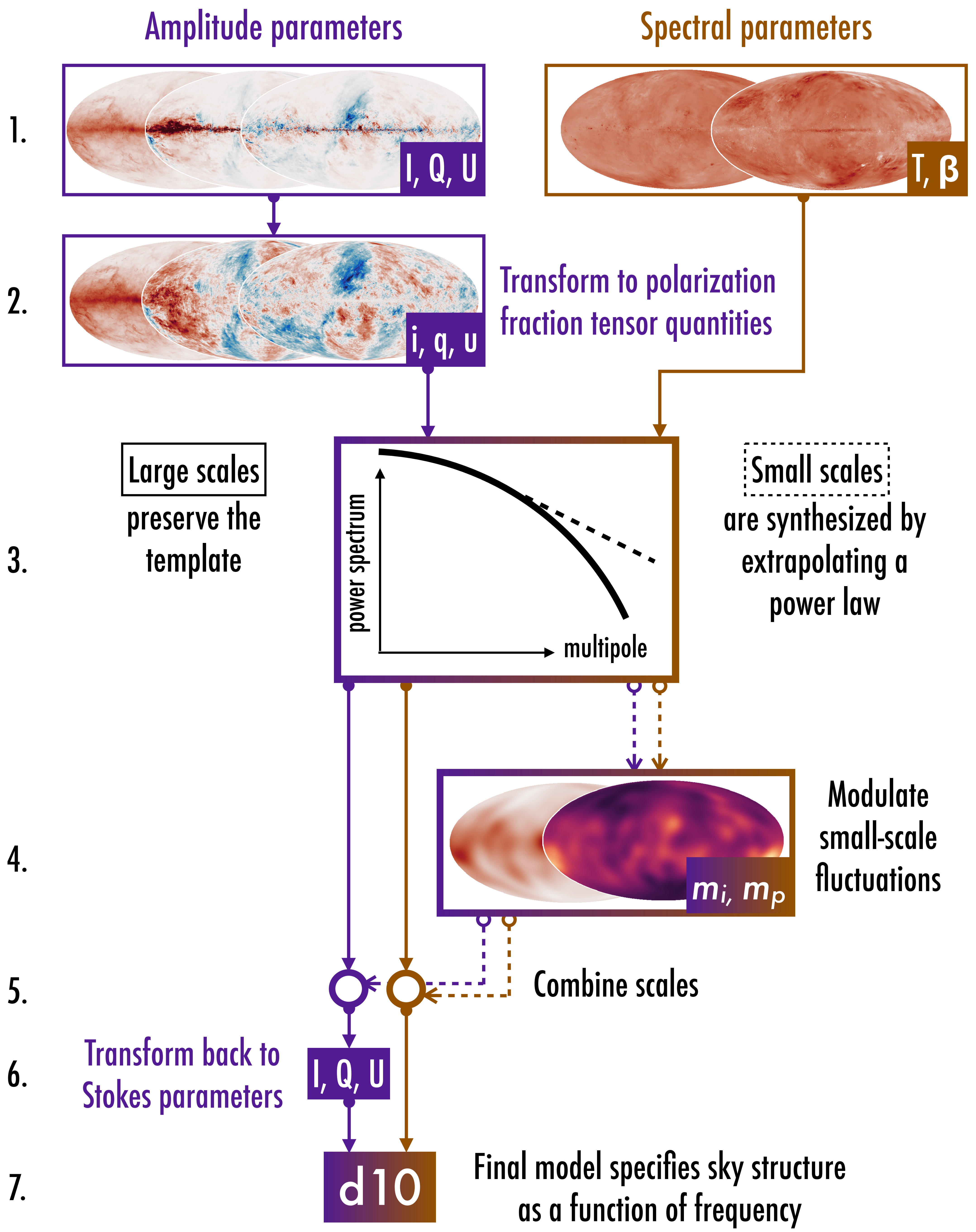
$D_l^{XX} \propto l^{\alpha_{XX}}$:

	ℓ_0	ℓ_1	α
β_d	200	400	0.04
T_d	100	400	-0.47
β_s	10	36	-0.61
c_s	10	36	-0.61

Synthesized + modulated small-scales

Mode stitching using the same method

d9/s4 at ν_0 + resultant spectral parameter maps = d10/s5



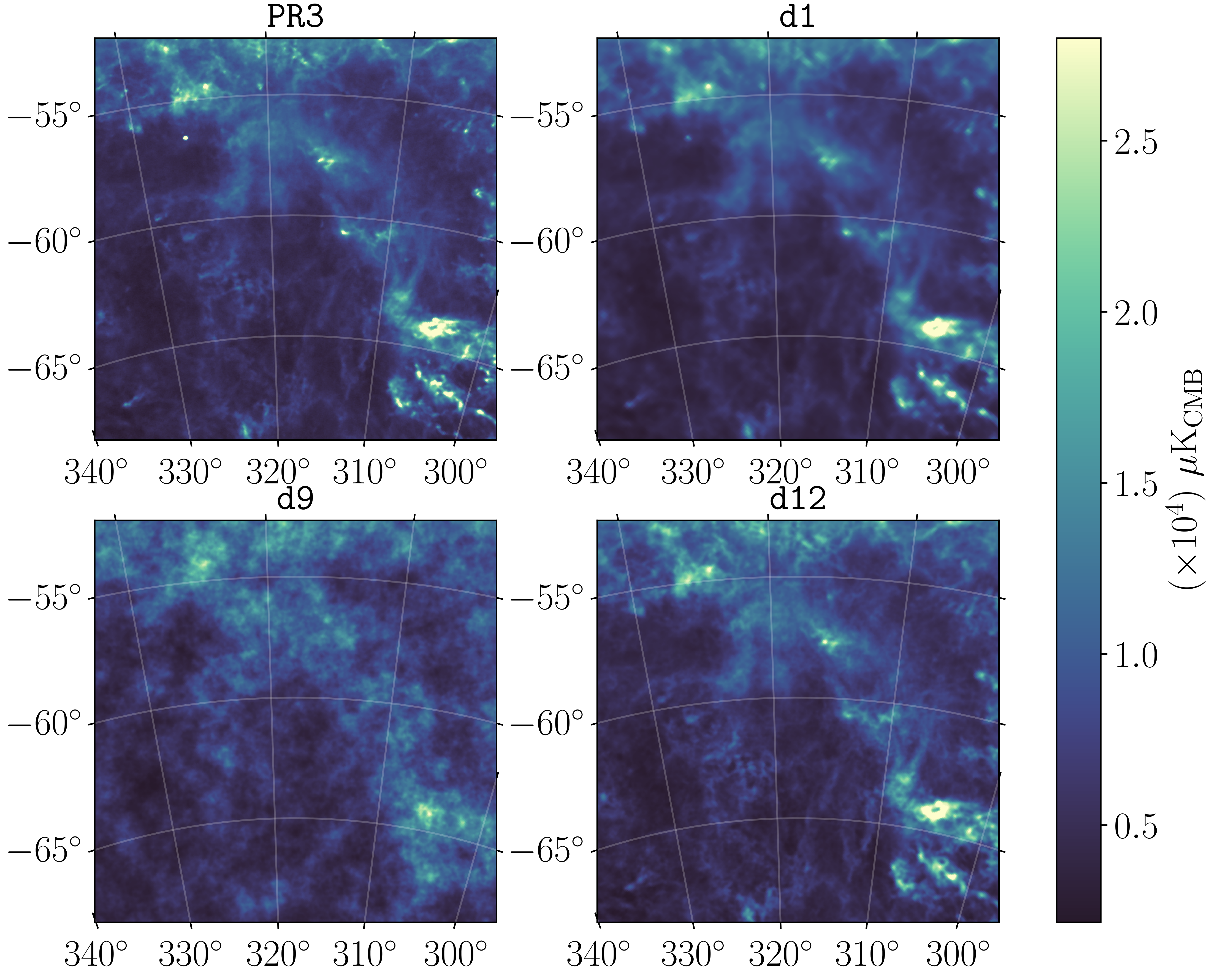
New PySM CO Models

Low Complexity → High Complexity

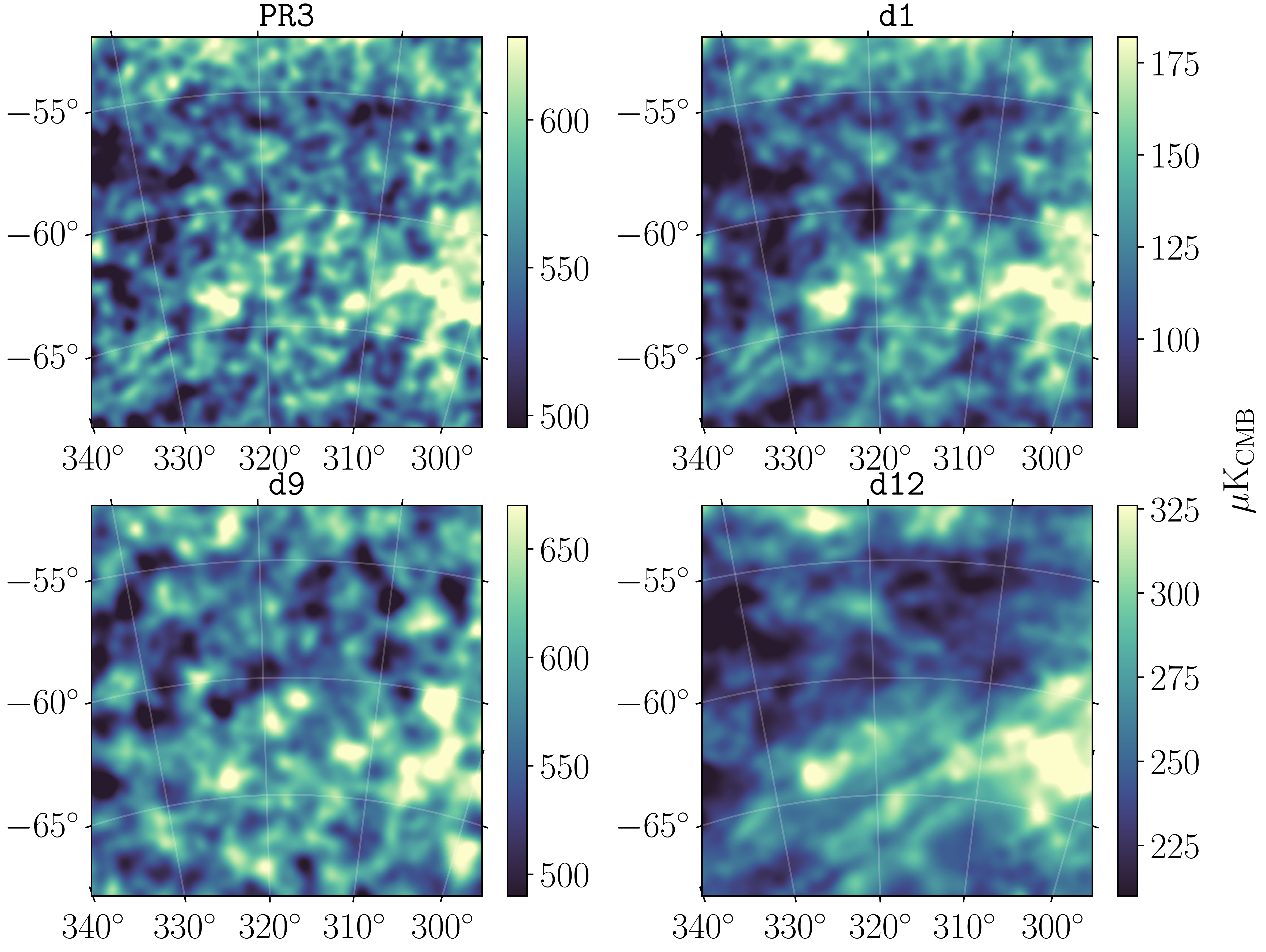
Tag	Spectrum Model	Templates Large scale	Templates Small scale	Stochasticity
`co1`	Single line emissions at 115, 230, 346 GHz	Planck PR2 `Type-1` maps smoothed to 1°	—	—
`co2`	"+ 0.1% polarized	"	—	—
`co3`	"	"	Simulated high galactic clouds	—

CO:
$$J = 1 \rightarrow 0$$
$$J = 2 \rightarrow 1$$
$$J = 3 \rightarrow 2$$

PR3 vs. PySM I Maps (353 GHz)



Galactic Plane: $(l, b) = (180°, -10°)$



BICEP Field: $(l, b) = (318°, -61°)$

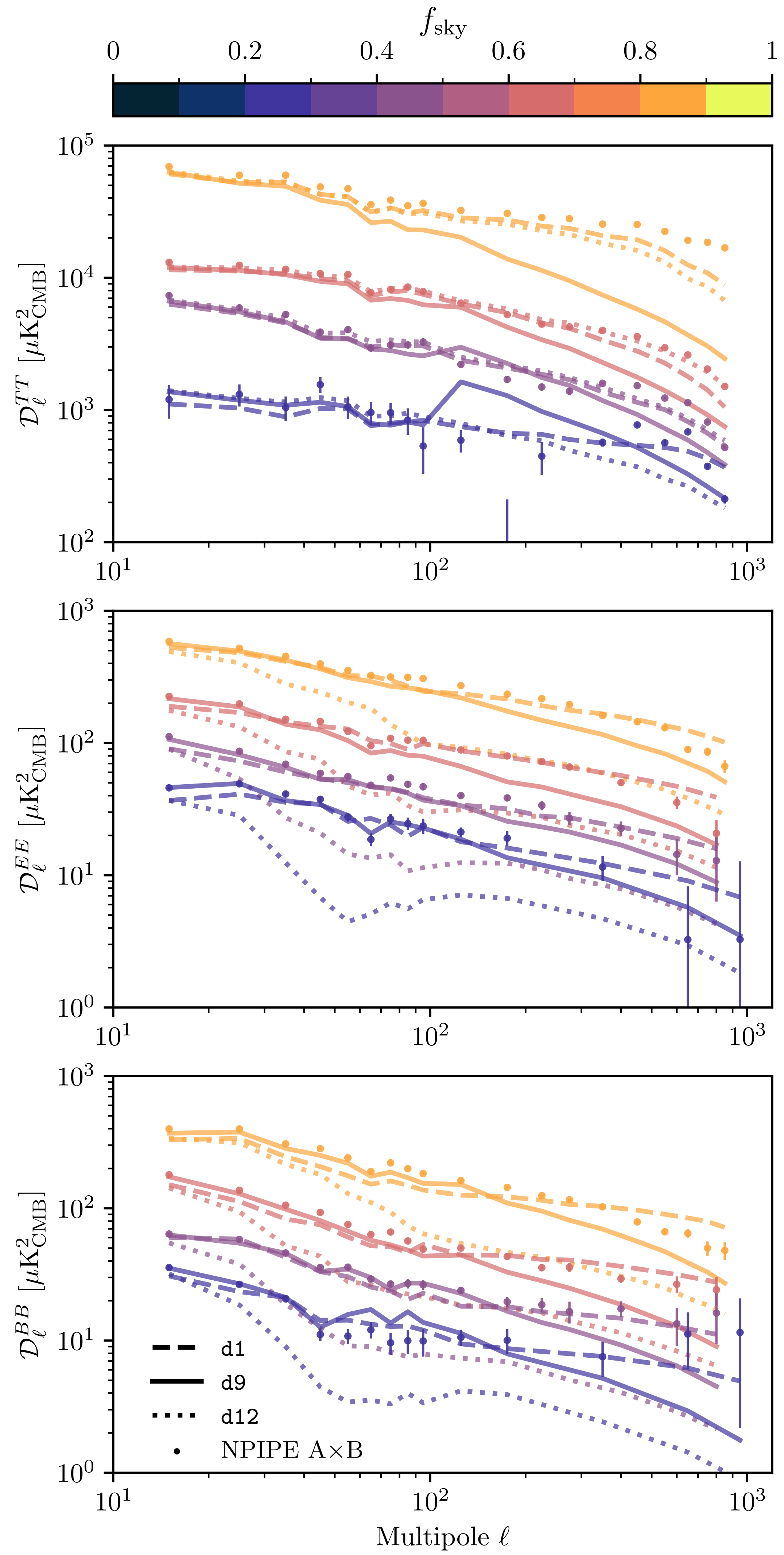
Large-field Analysis

TT, EE, BB overview:

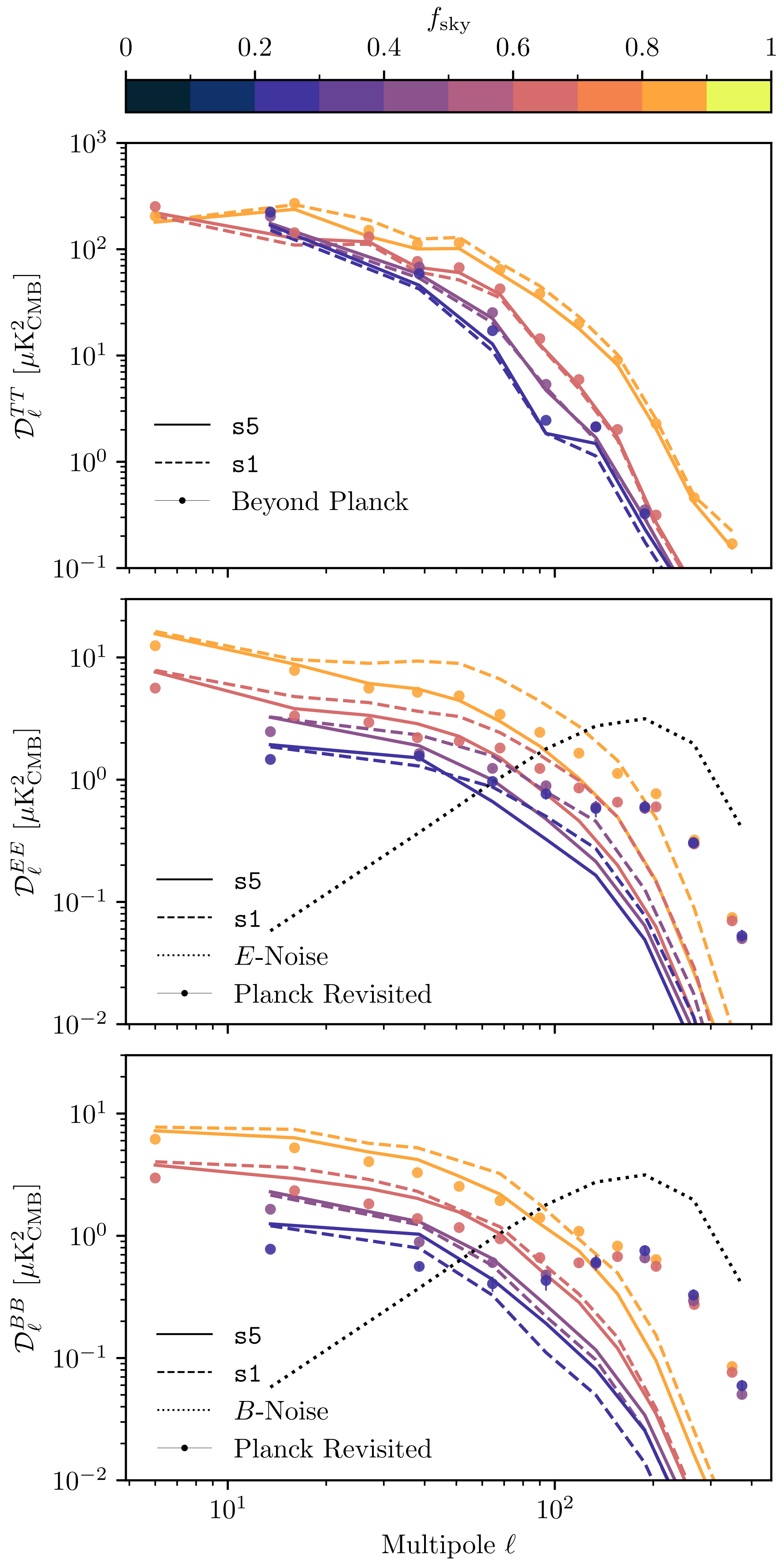
- Dust: NPIPE (PR4) A $\times$ B vs. PySM d1, d9, d12 at 353 GHz
- Sync: BeyondPlanck vs. PySM s1, s5 at 30 GHz
- Different galactic masks $\rightarrow f_{\text{sky}}$ variation

- General agreement in large-scales (except d12)
- Smooth transition, mitigated artifacts in stitching scales $l_* \approx 100, 40$
- Polarization: d9 OK, d12 underestimates
- s1, s5: excellent for TT $(l < 300)$; s5 better for EE $(l < 100)$

Dust

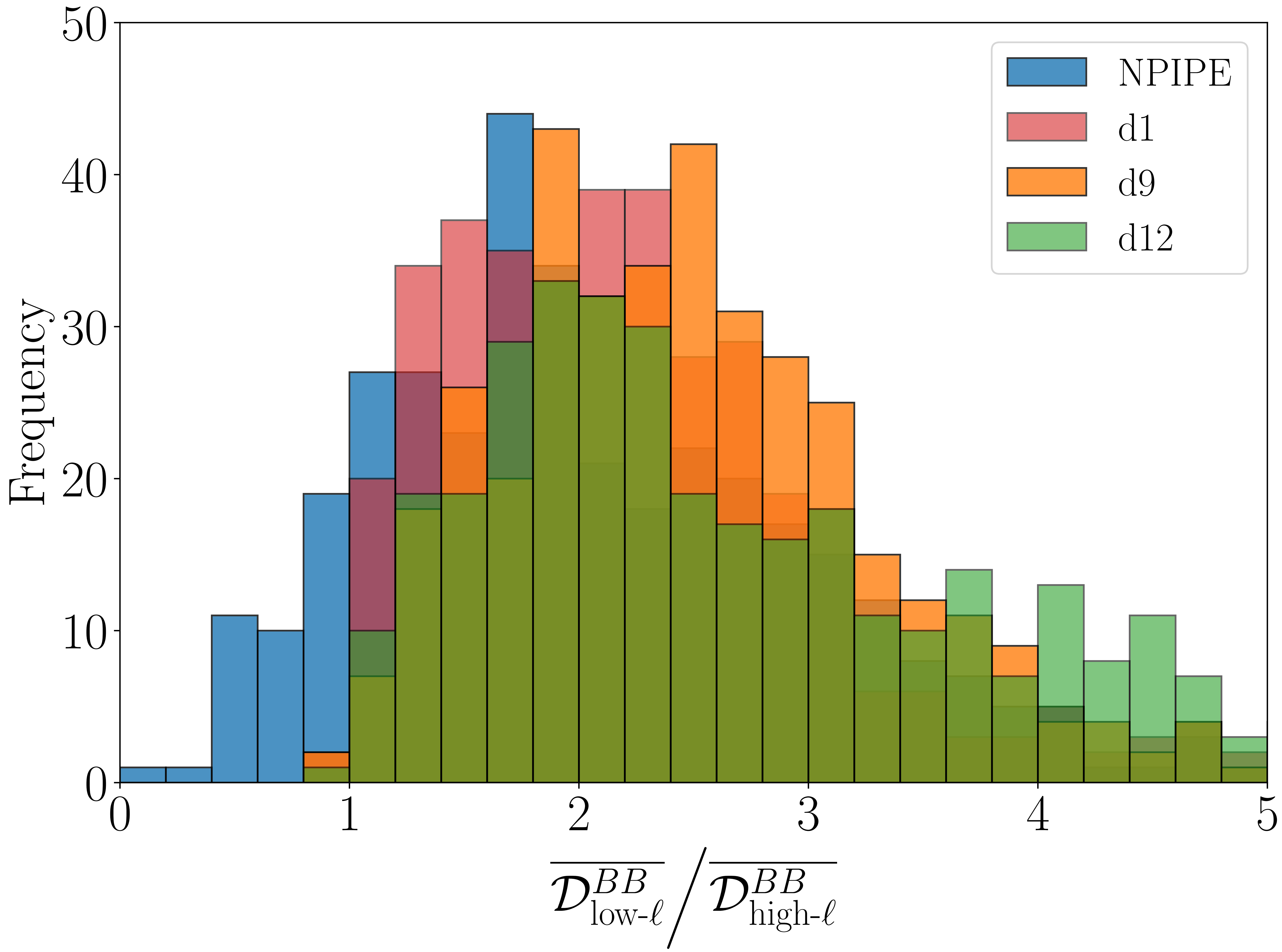


Synchrotron



Small-field Analysis

- Smoothing the "mode-stitching" connections
- $R \equiv \overline{D^{BB}_{\text{low-}\ell}} \Big/ \overline{D^{BB}_{\text{high-}\ell}}$
    - $D^{BB}_l \propto l^{-0.54} \rightarrow R = 1.83$
    - NPIPE: $R = 1.85 \pm 0.93$
- Back-and-forth efforts!
    - d1: $R = 2.03 \pm 0.72$
    - d9: $R = 2.35 \pm 0.77$
    - d12: $R = 2.26 \pm 0.91$
- Small deviations due to $\alpha_d = 0.54$ fit in bb



PySM BB Spectra in BK Field

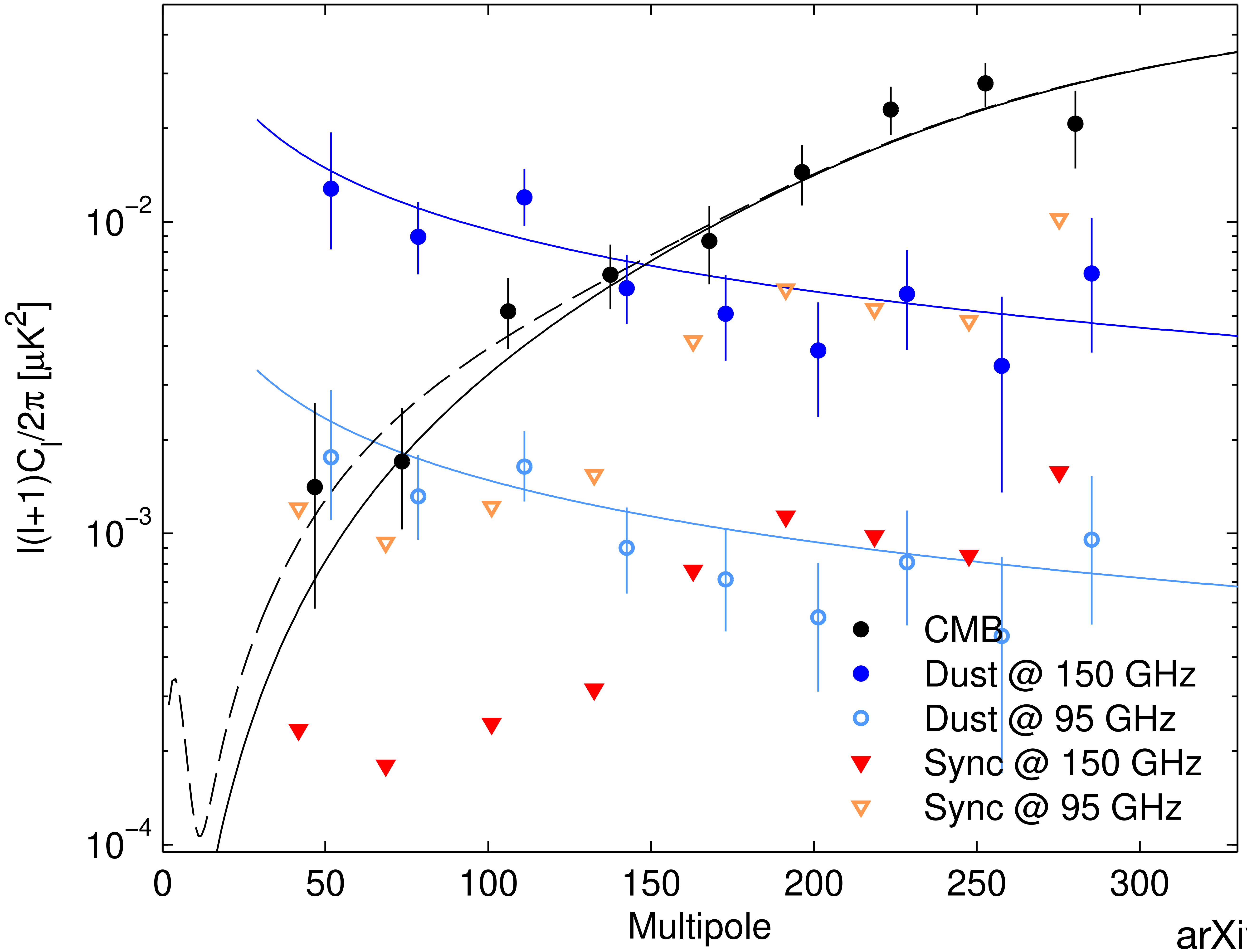
Recurring (and relentless) foreground questions from S4:

- “What are the changes of PySM model behavior in the BK field?”
- “How to compare the full-sky PySM dust models with BK measurements from heavily-filtered maps?”
- “Is the BK dust measurement consistent with the Planck measurement at 353 GHz? What are their errors?”
- “What about the synchrotron foreground?”
- …

Reanalyzing BK18 BB Spectra

BK18 spectral decomposition analysis

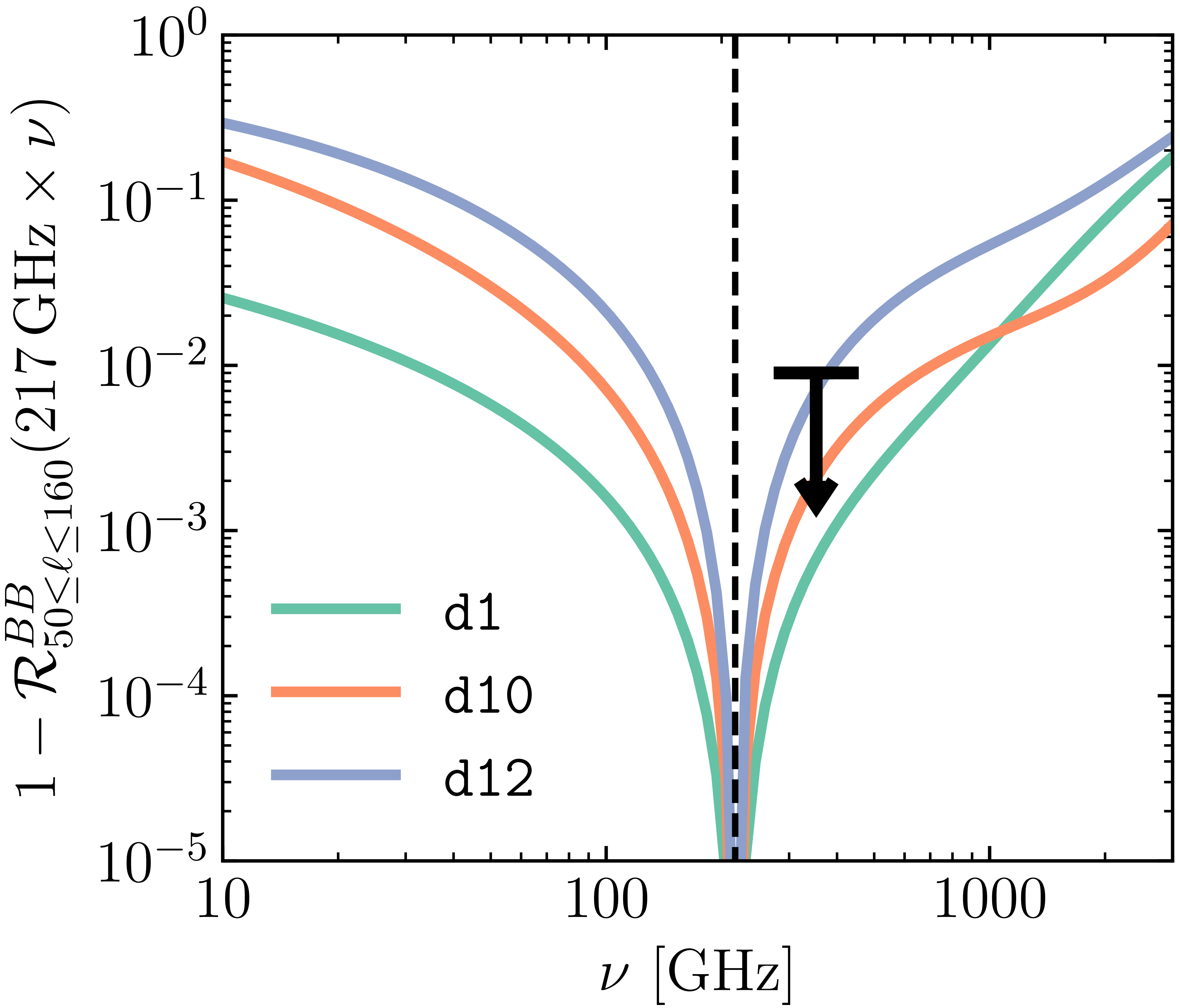
- BB bandpower component separation (lensed-ΛCDM+r+dust+synchrotron)
- MCMC per-bandpower
- Strong constraints on dust (consistency with ML model) & upper limit on sync band powers at 95 GHz and 150 GHz
- Reanalyzed at 23 GHz and 353 GHz



arXiv: 2110.00483

Dust Decorrelation

- $$R_l^{XY}(\nu_1 \times \nu_2) \equiv \frac{D_l^{XY}(\nu_1 \times \nu_2)}{\sqrt{D_l^{XY}(\nu_1 \times \nu_1)\, D_l^{XY}(\nu_2 \times \nu_2)}}$$
- LR71 and $50 \leq l \leq 160$
- PySM dust $R^{BB}(217 \times \nu)$ vs.
  PR3 $R^{BB}(217 \times 353) < 0.991$ (97.5% confid)
- d1/d10 below, d12 coming close
- Future high frequency observations to differentiate



Quantifying Extragalactic Contamination

- Cross-correlating the local fluctuations in PySM maps and galaxy density maps
- GLADE+ catalog: 90% complete at $z \sim 0.1$
- GLADE+ z-maps: stacked in HEALPix grid + redshift bins over $0 < z < 0.35$
- d10: less CIB contamination from GNILC templates