

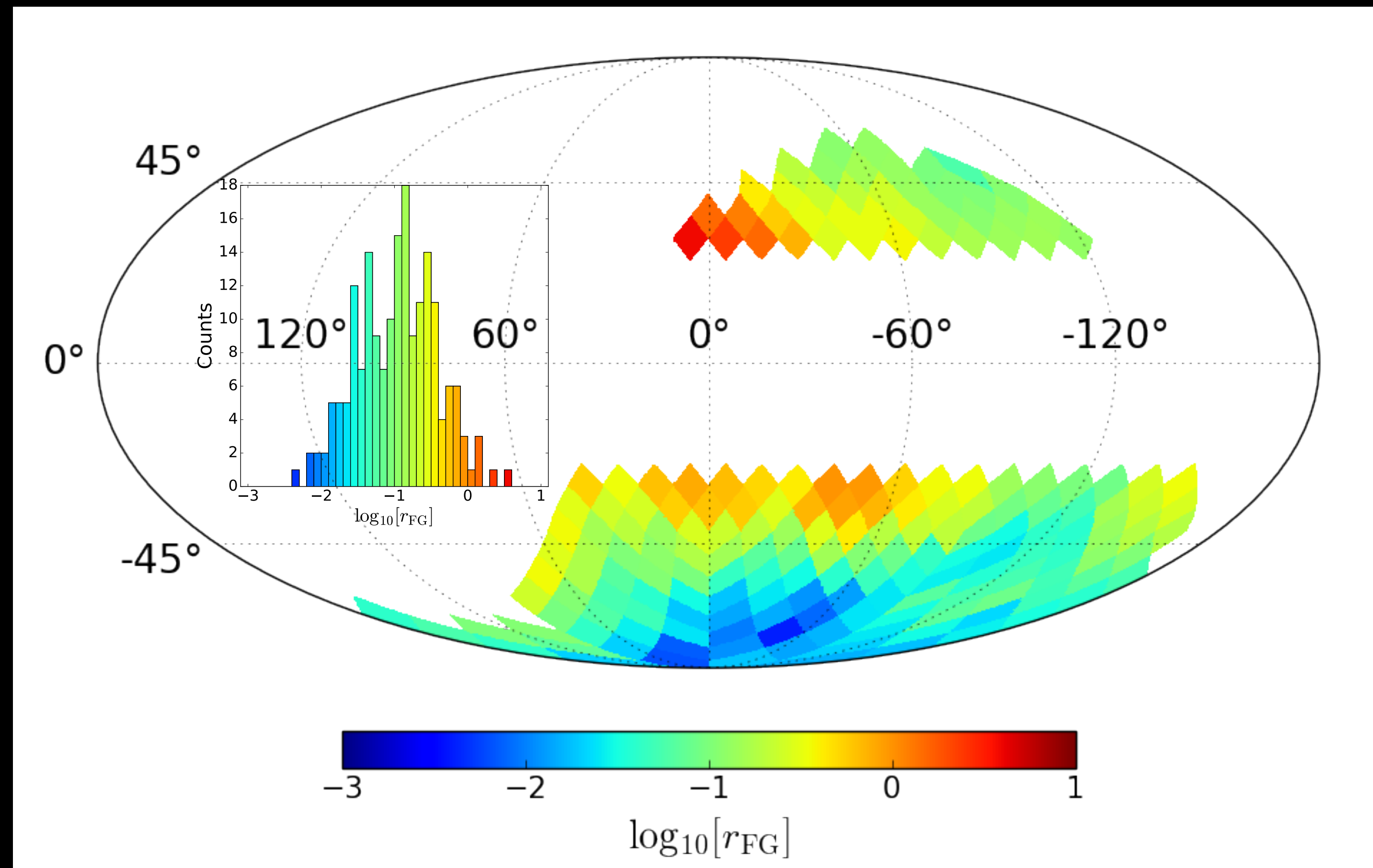
Getting ready for the unknown:
**Galactic Foreground Modeling for
CMB Polarization**



*Nicoletta
Krachmalnicoff*

What we know about Galactic foregrounds

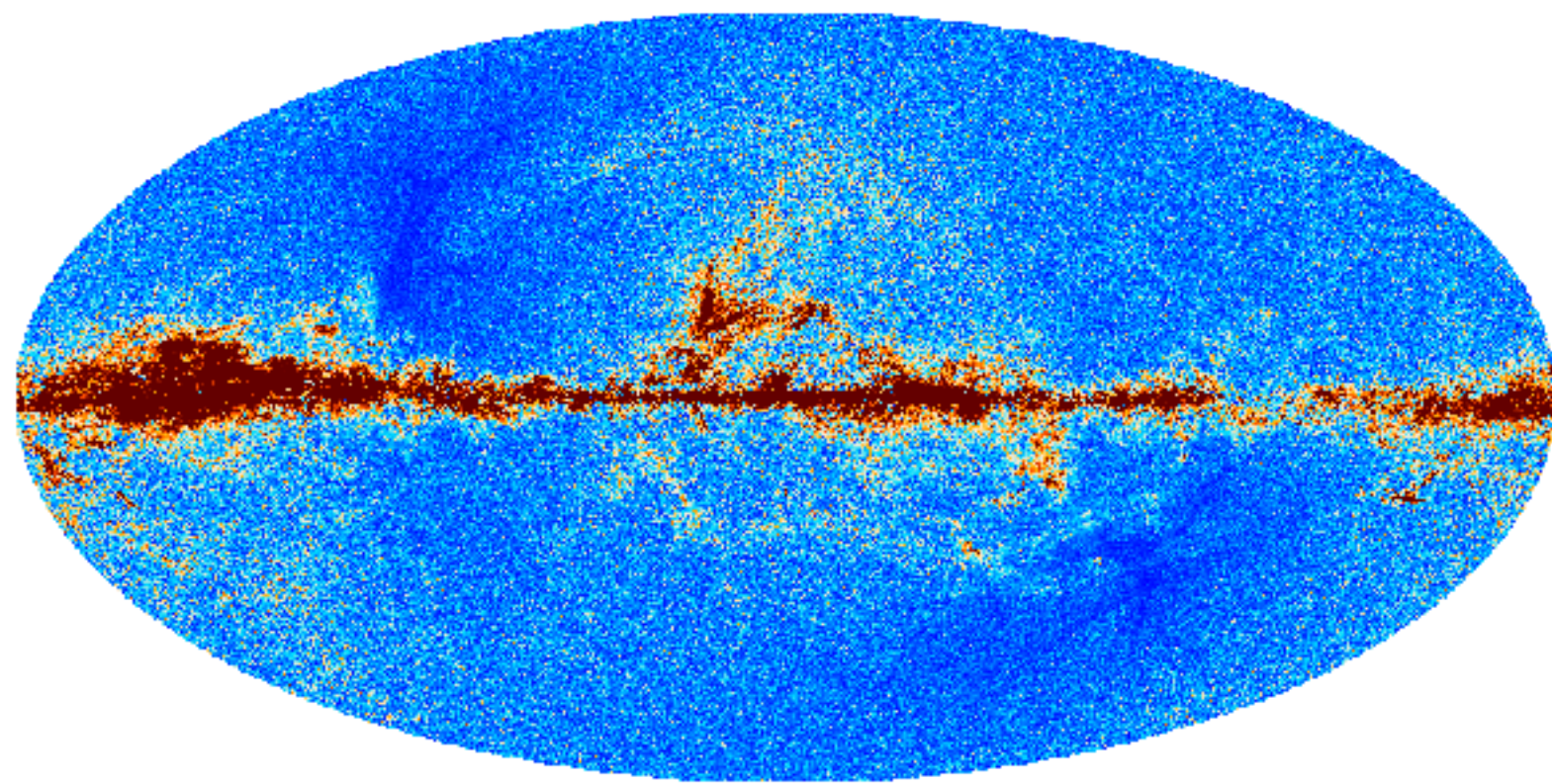
In polarization foregrounds dominate the full sky and the full microwave band



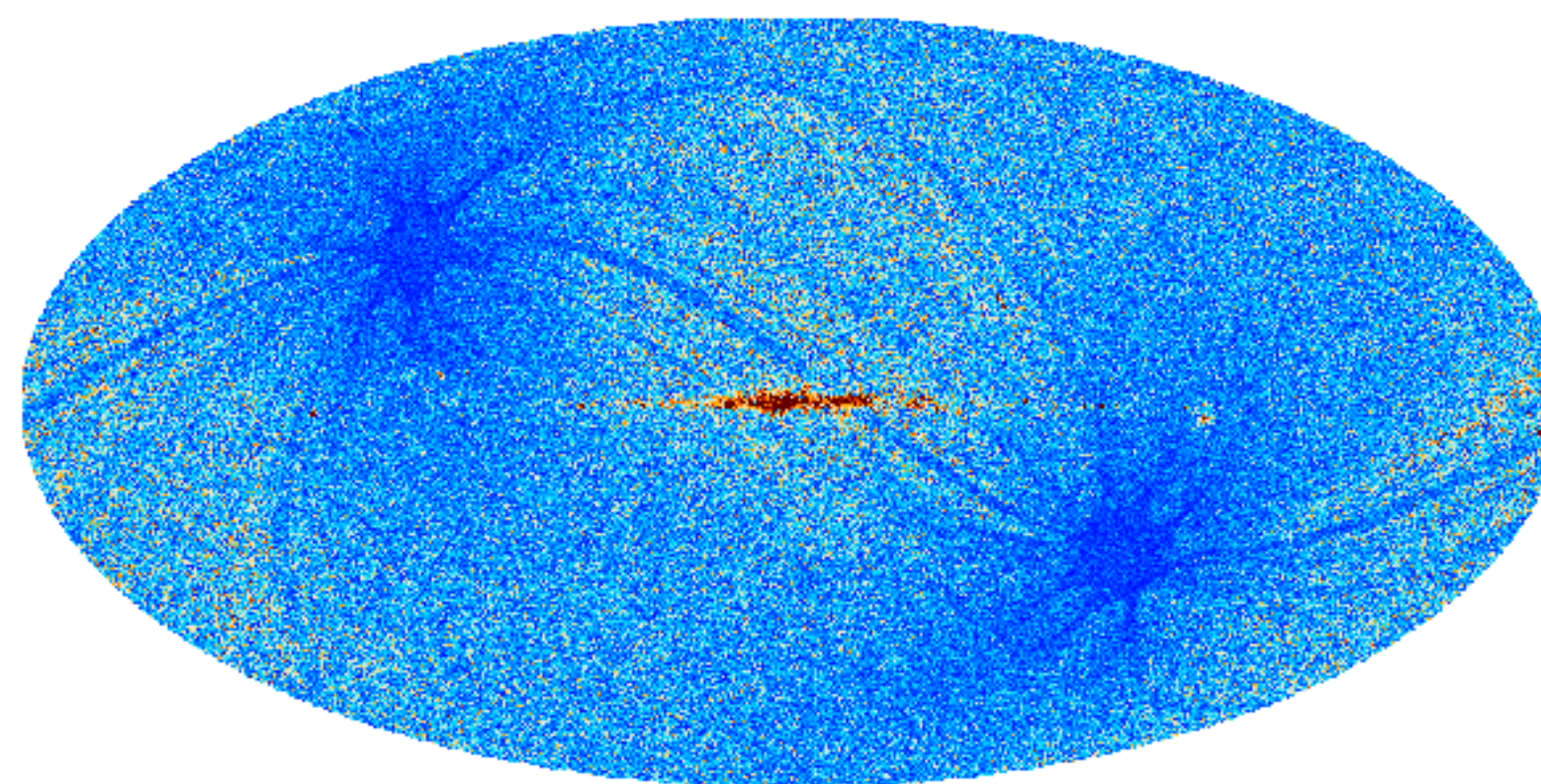
What we know about Galactic foregrounds

The most complete dataset we have (on full sky and large angular scales) is still coming from WMAP and Planck

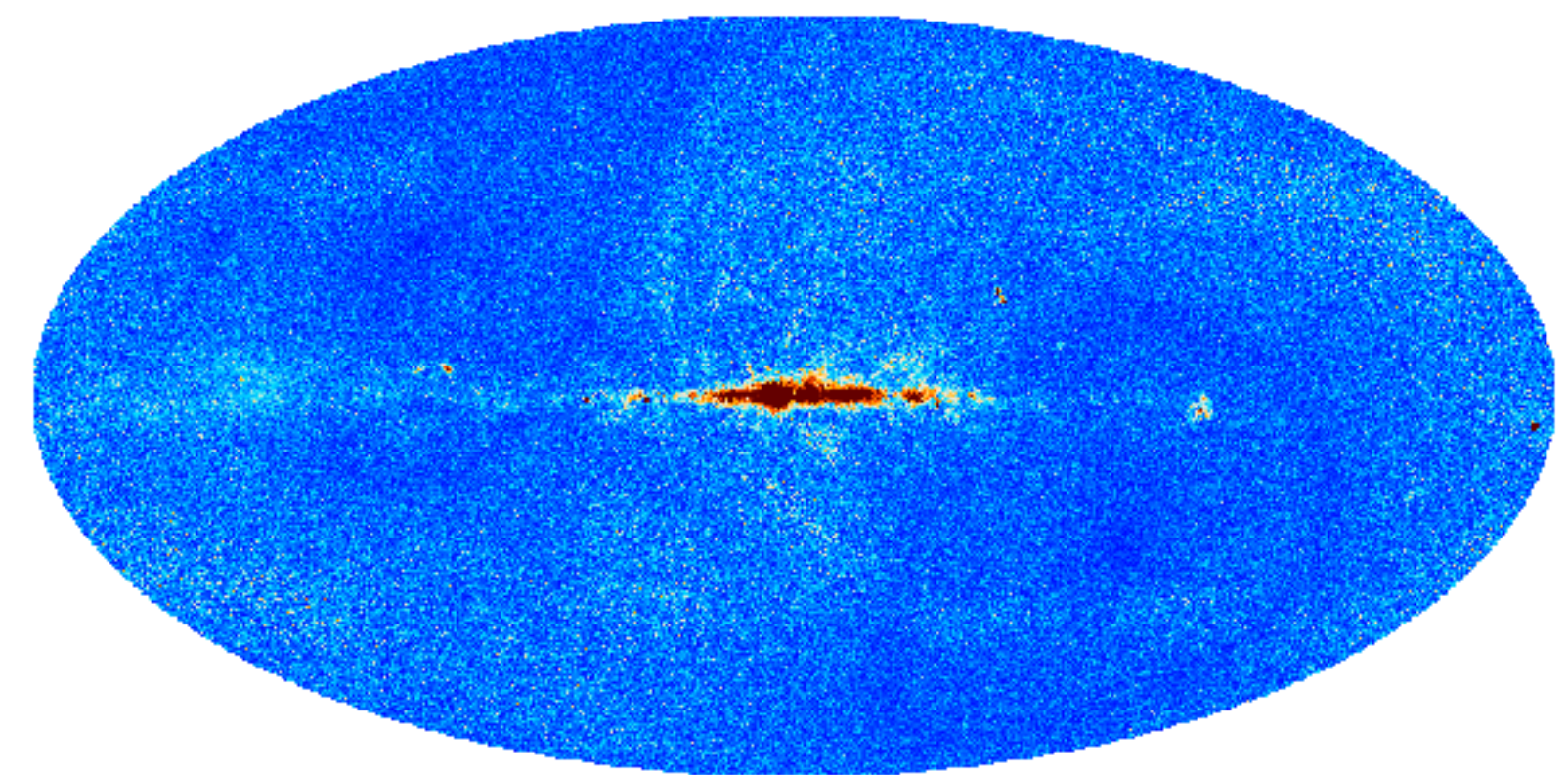
HFI 353 GHz



LFI 30 GHz



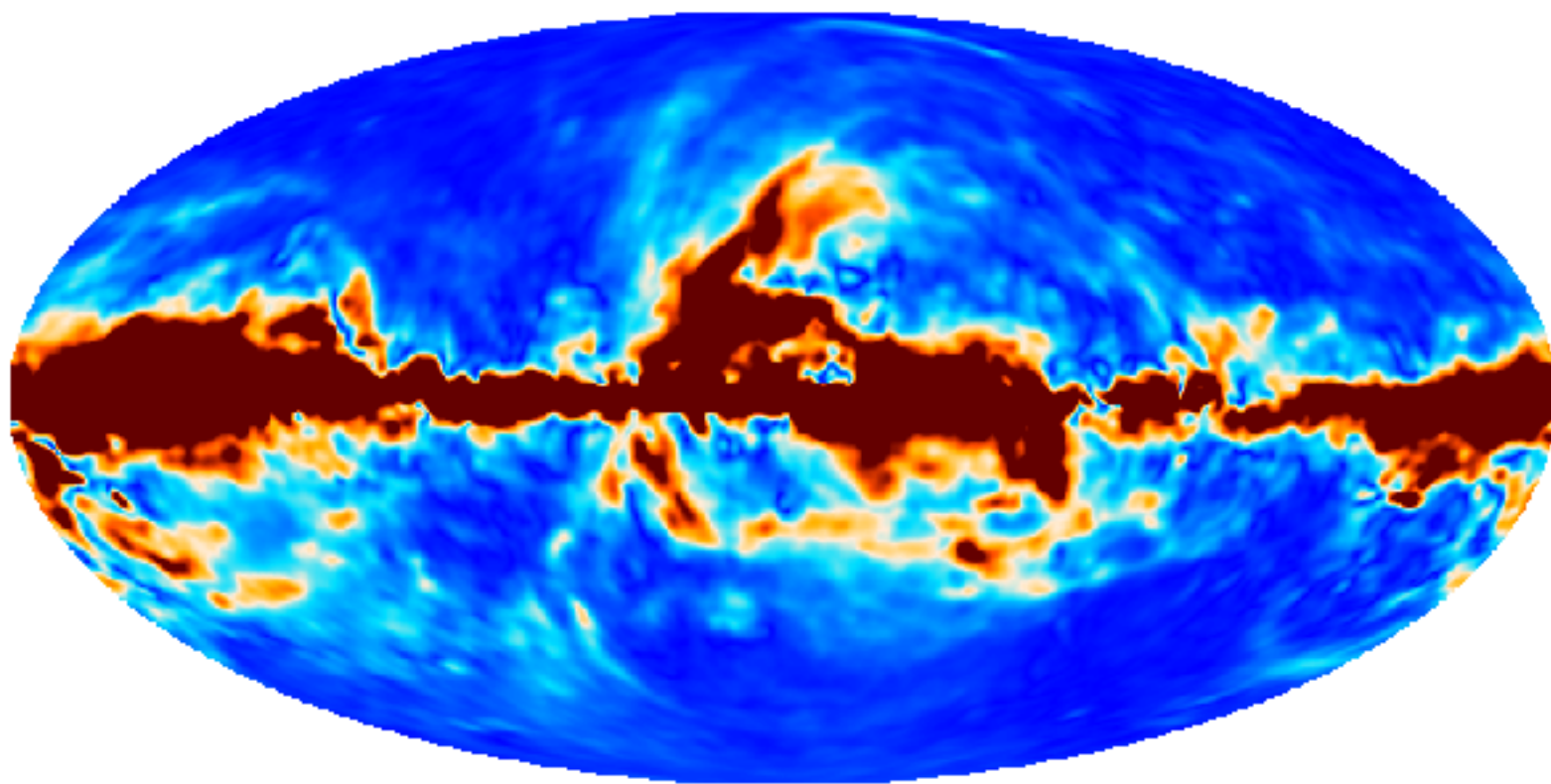
WMAP-K



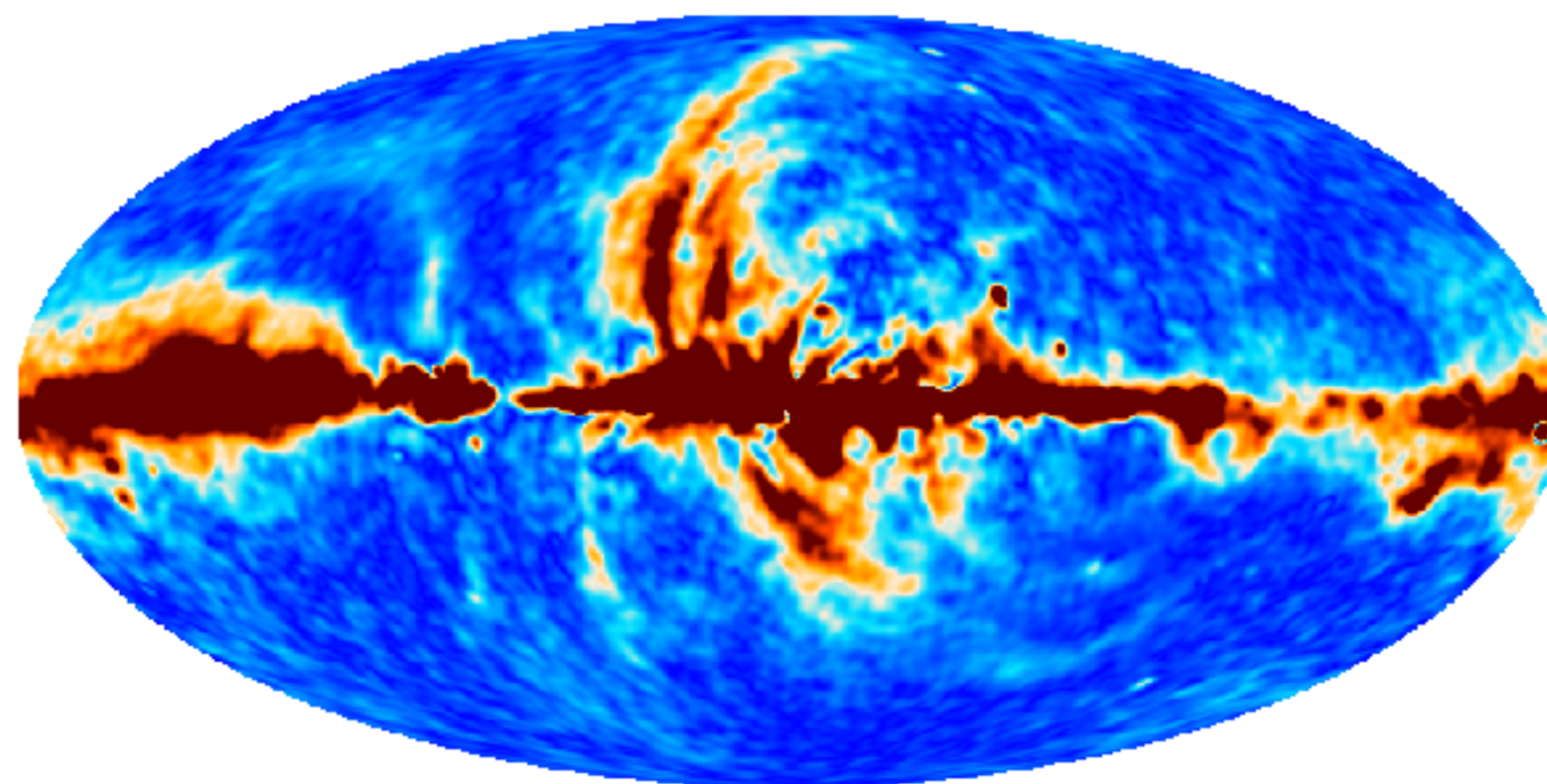
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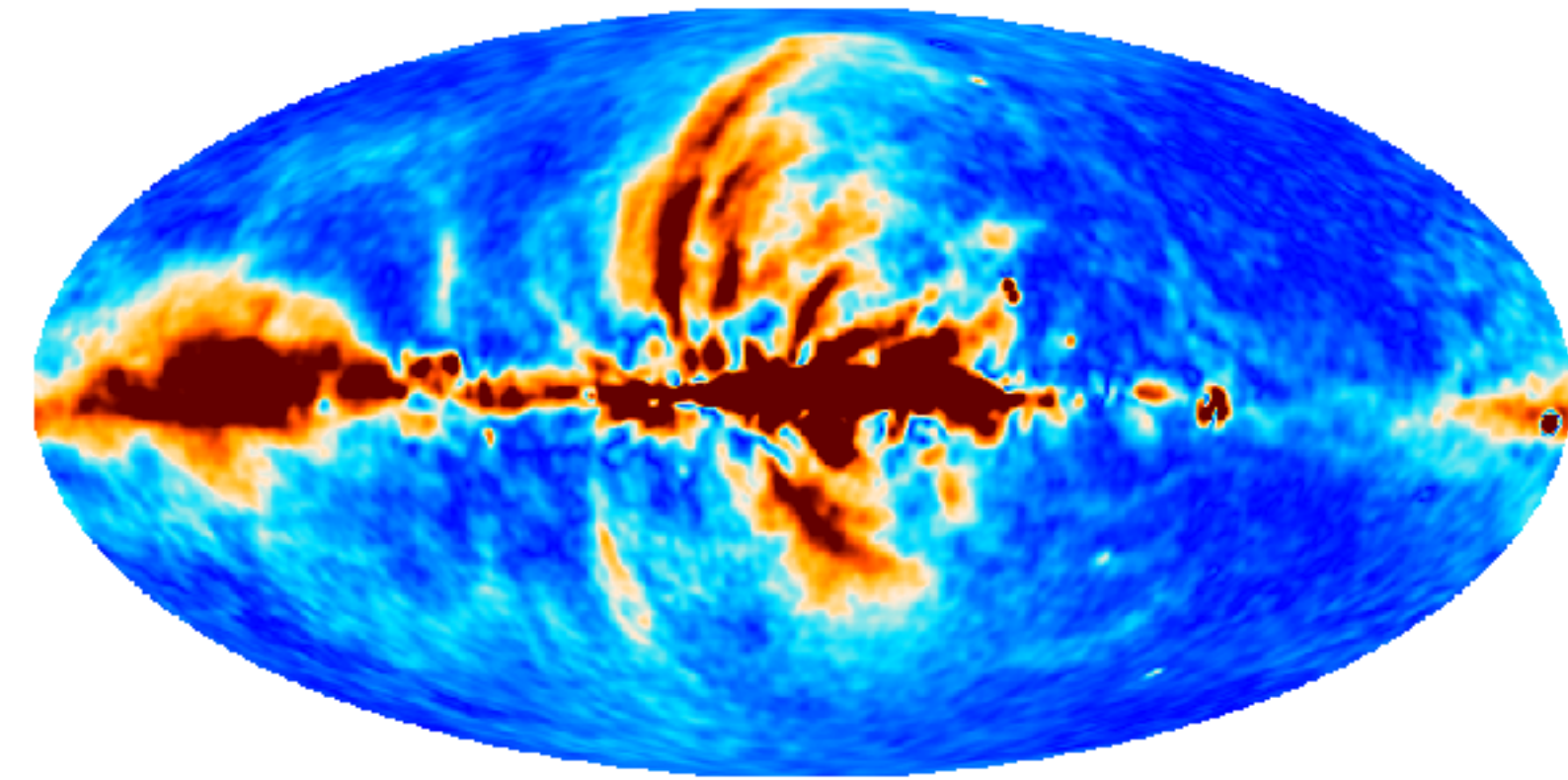
HFI 353 GHz
2deg



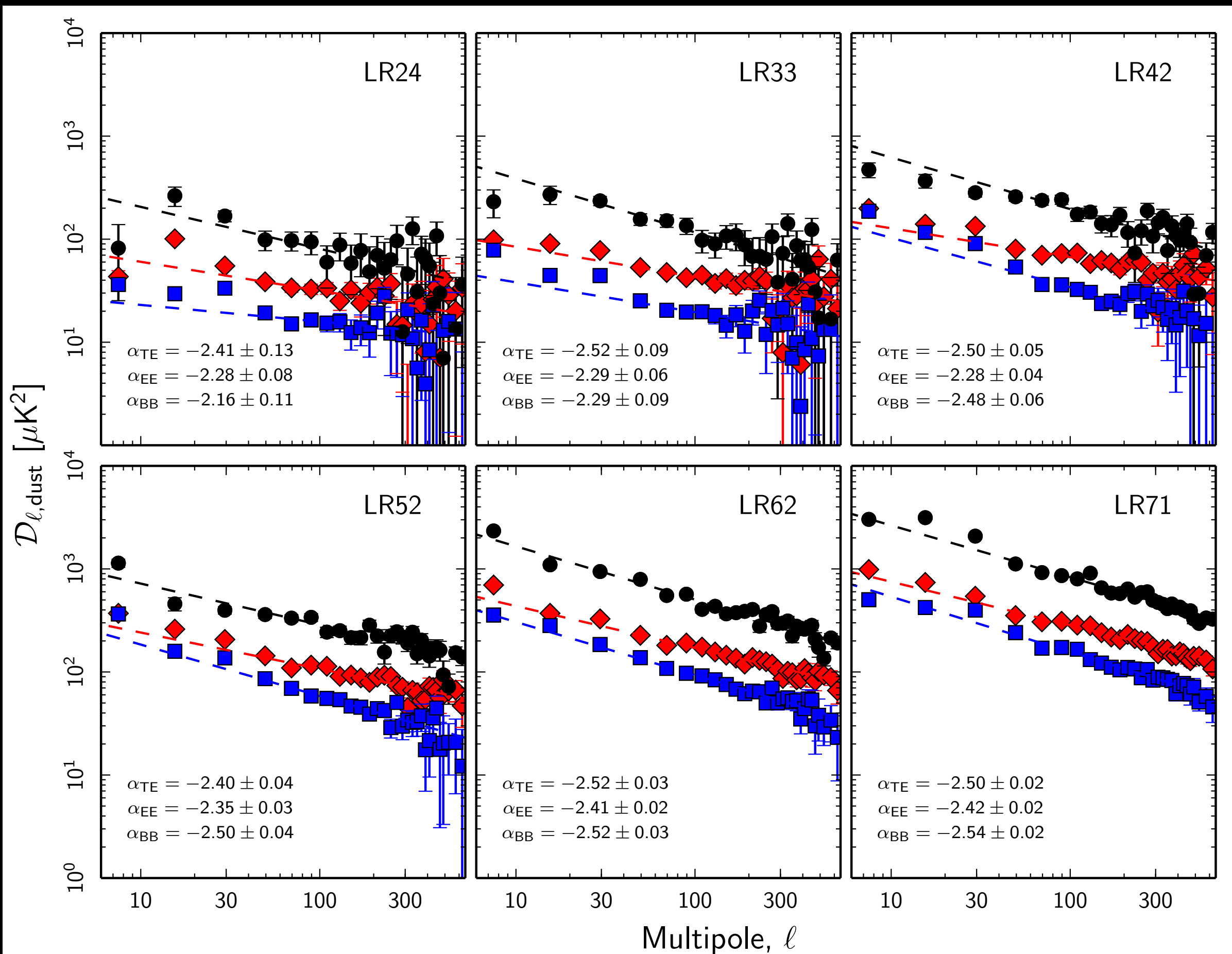
LFI 30 GHz
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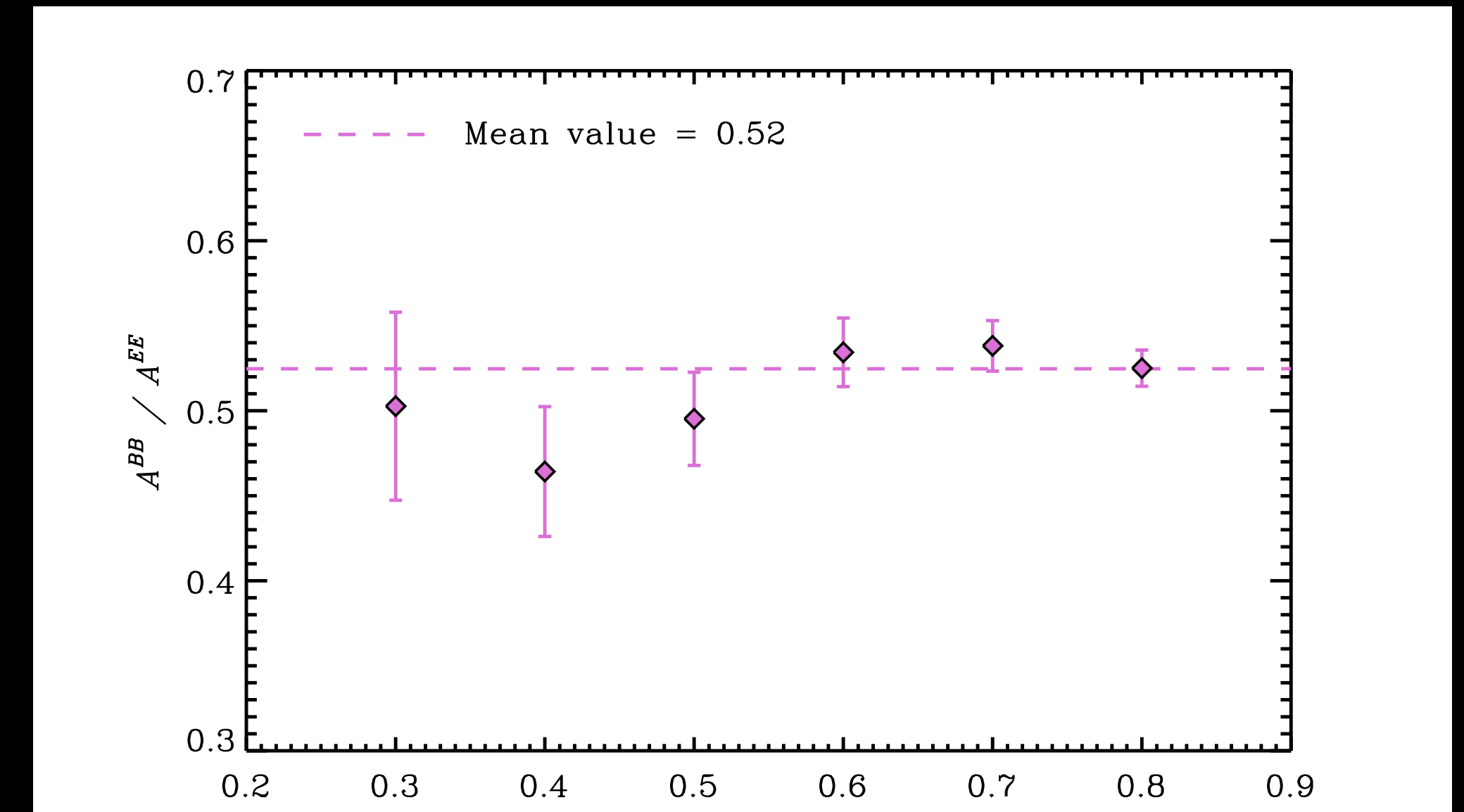
WMAP-K
2deg



What we know about Galactic foregrounds

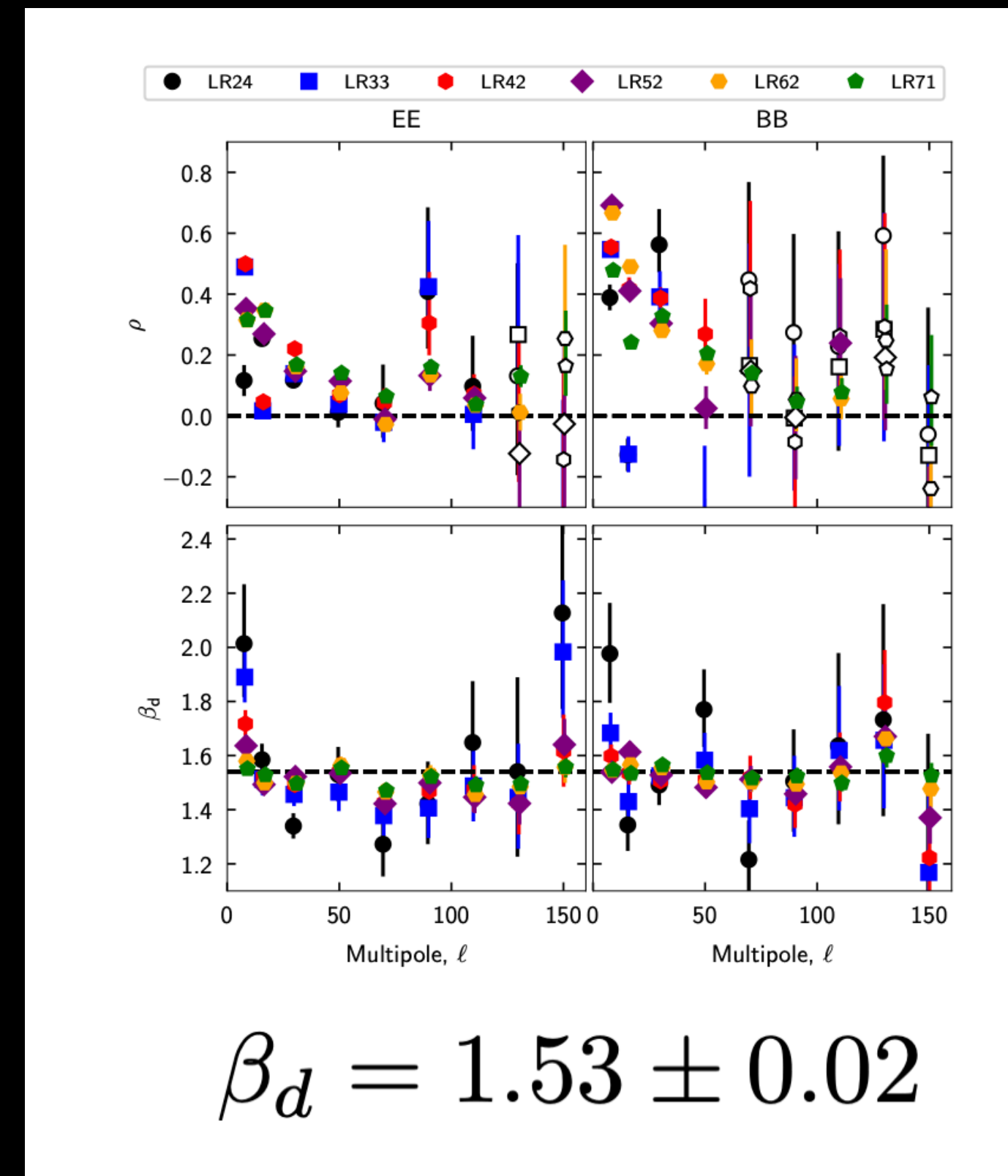
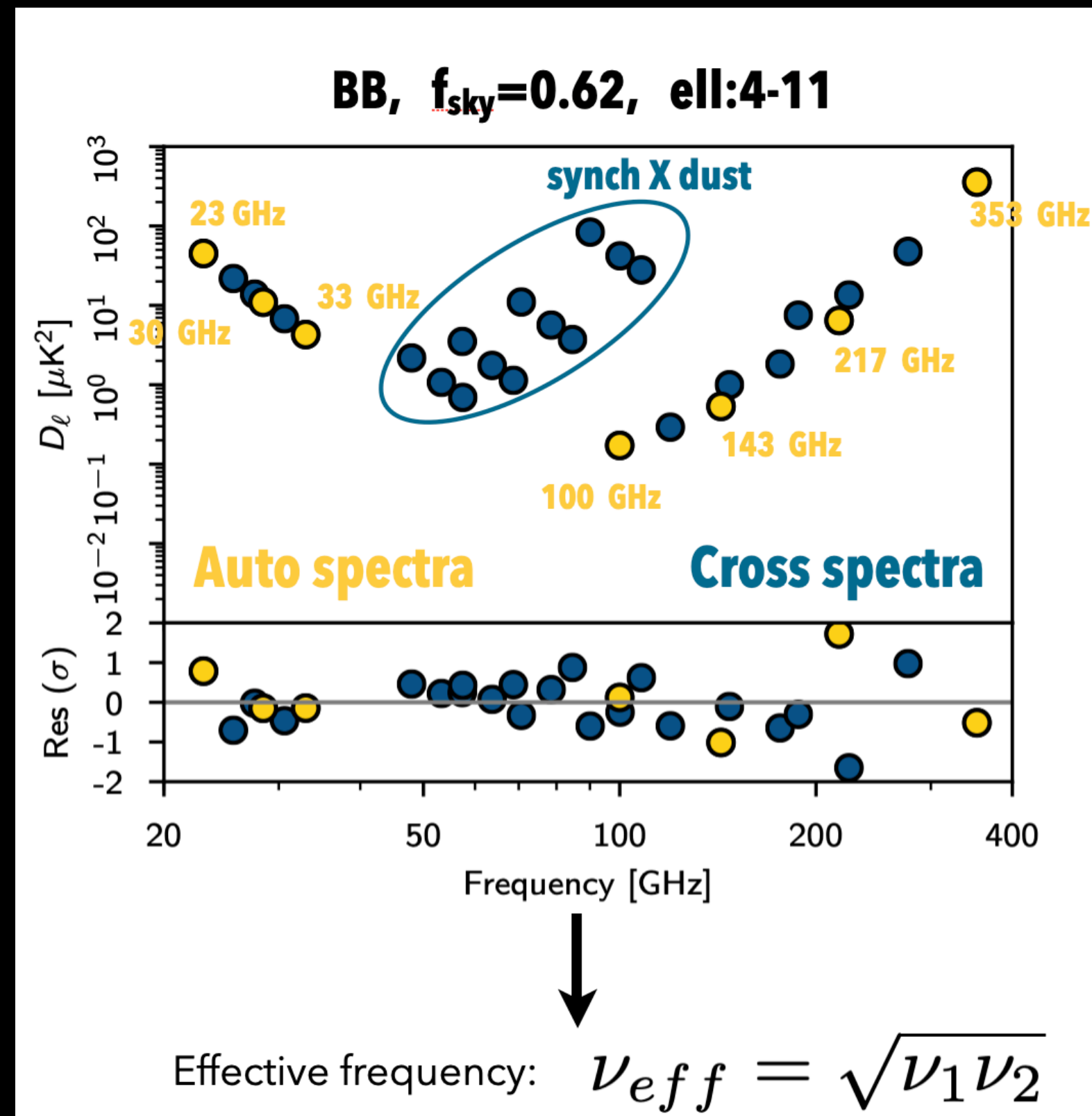


Thermal dust power spectra are well measured by Planck 353 GHz



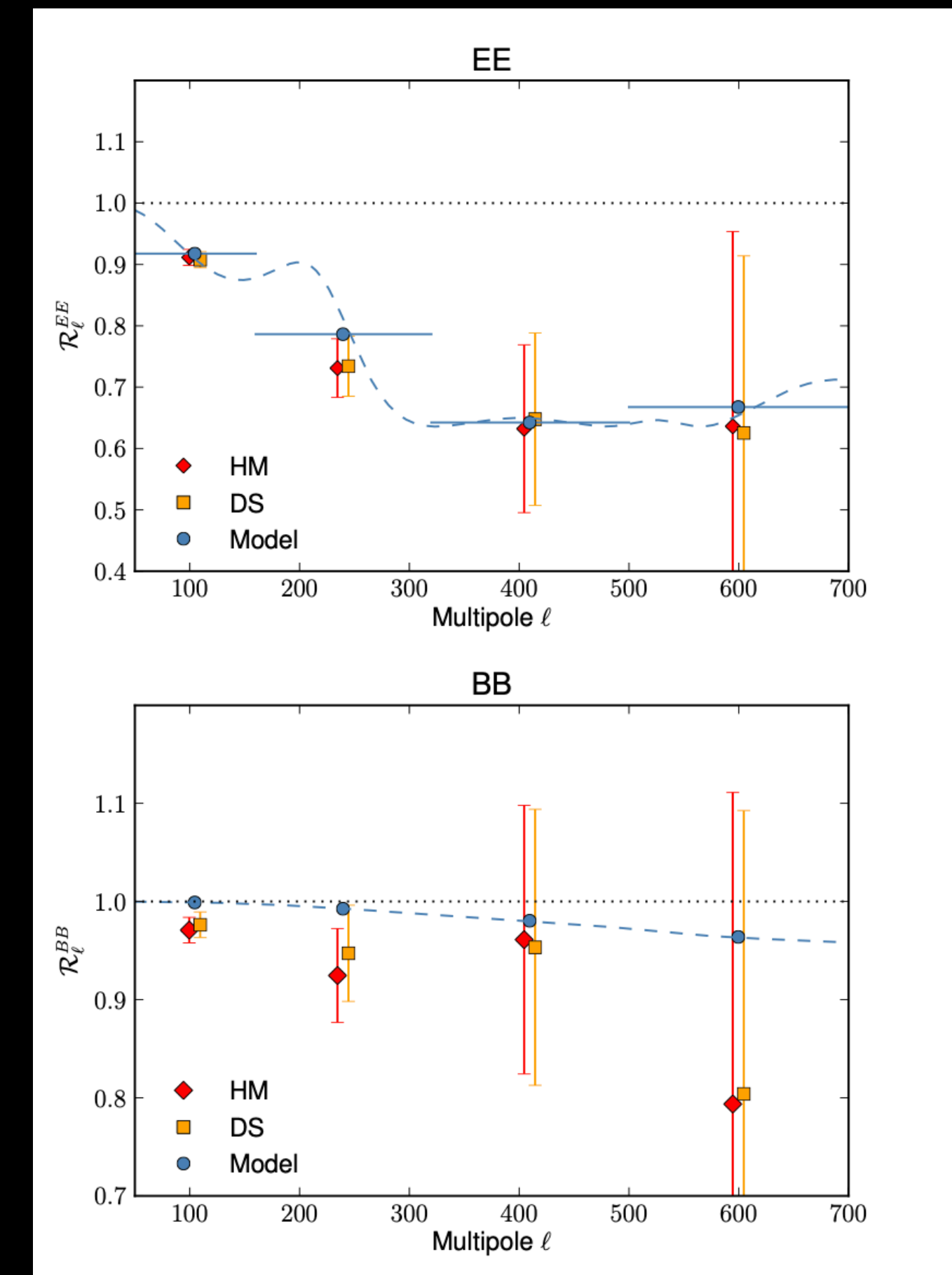
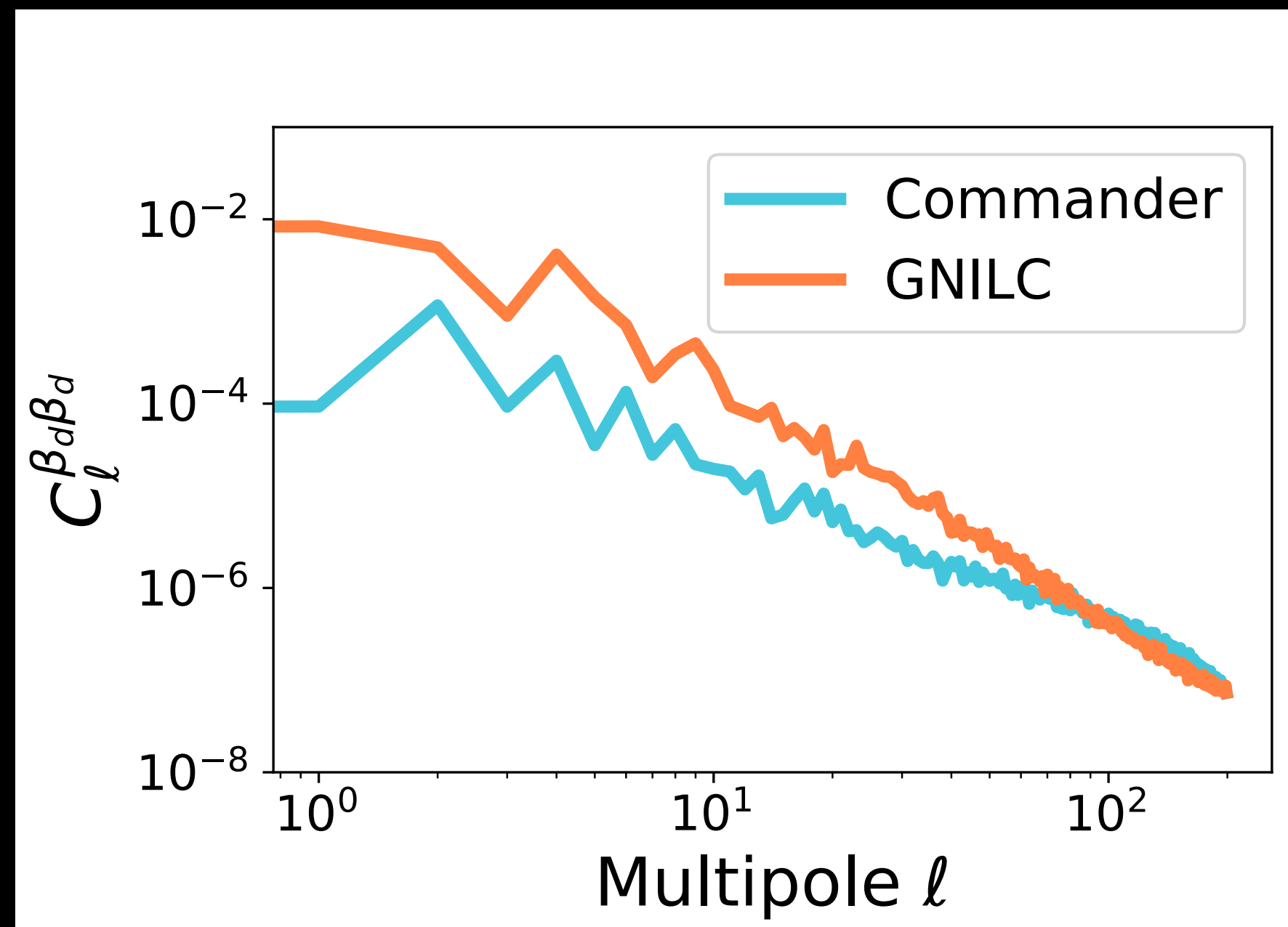
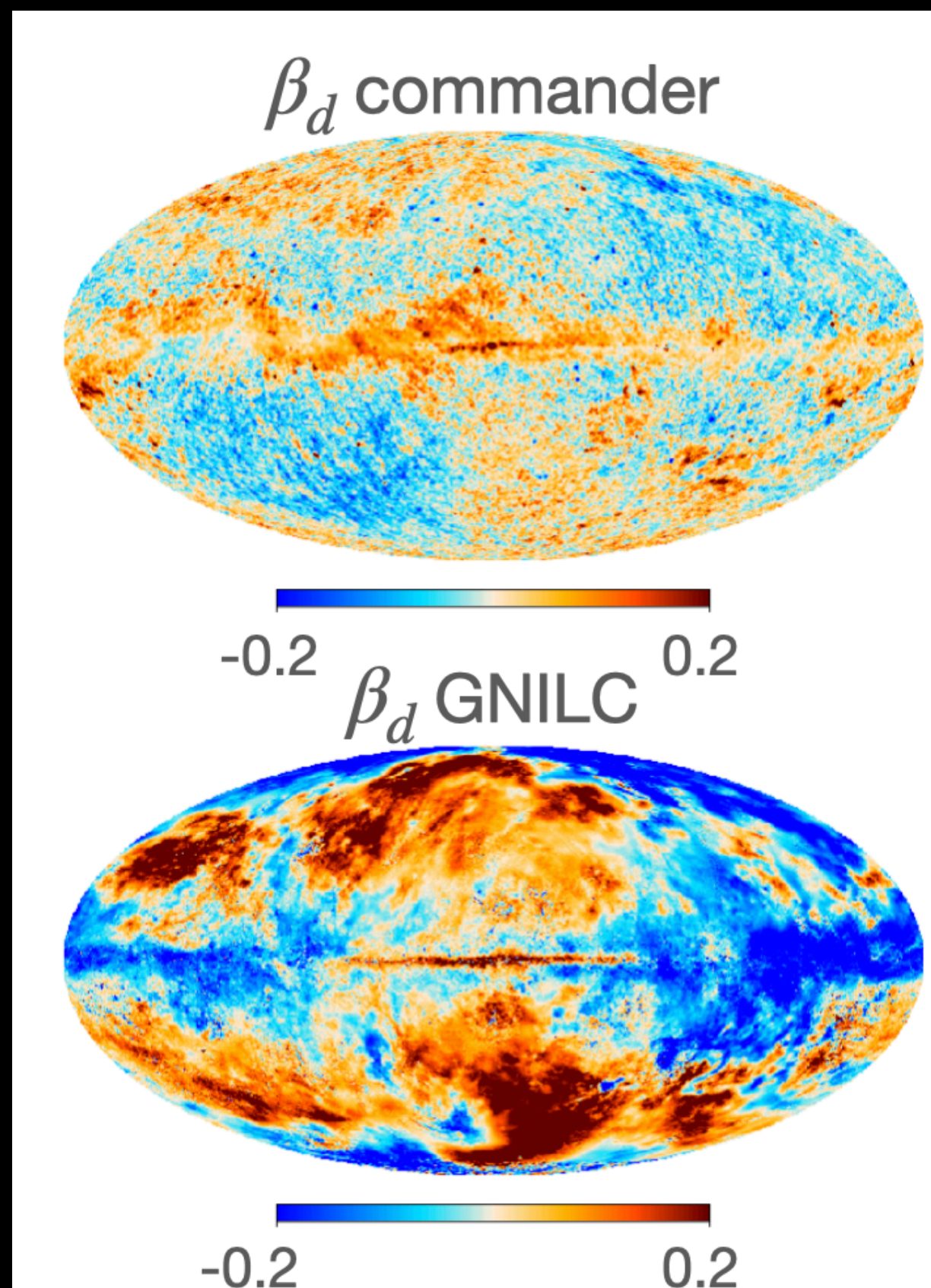
What we know about Galactic foregrounds

Dust-Synch cross correlation is well measured (at large scales), and average β_d is well constrained from data



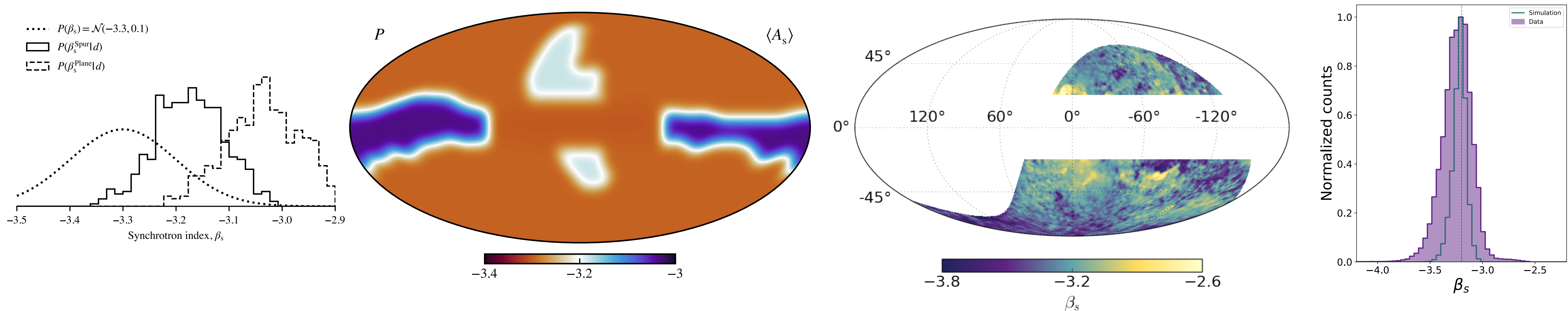
What we know about Galactic foregrounds

Amplitude of β_d spatial variation and dust frequency decorrelation remains uncertain

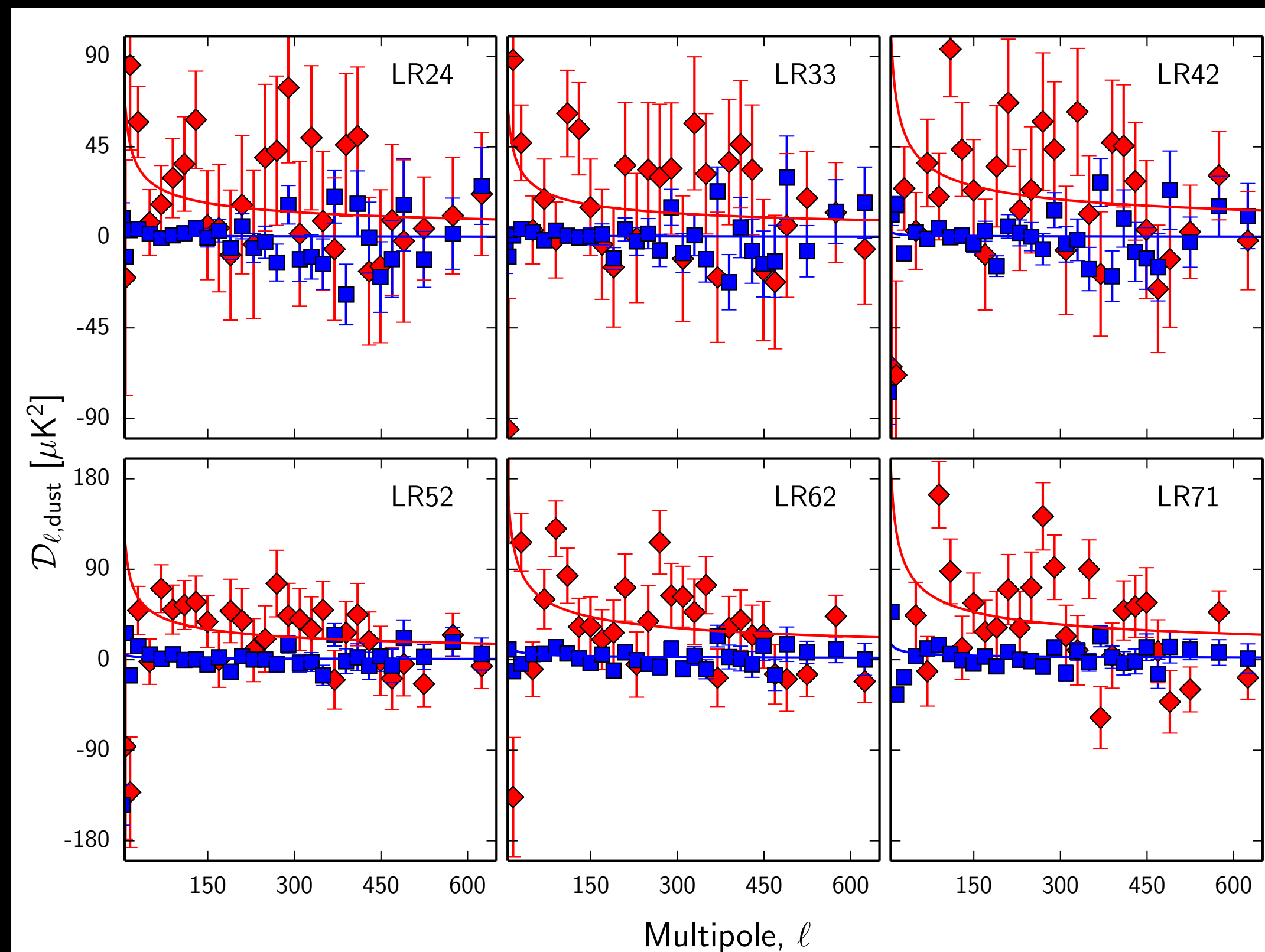


What we know about Galactic foregrounds

β_s spatial variation is poorly constrained from Planck and WMAP data, but low frequency data can provide additional information (on partial sky)



What we know about Galactic foregrounds



From Planck data we have a robust detection of positive TB correlation with

$$r^{TB} = \frac{C_{\ell}^{TB}}{\sqrt{C_{\ell}^{TT} \times C_{\ell}^{BB}}} \sim 0.05$$

while C_{ℓ}^{EB} is consistent with zero

Current available models

PySM is the current most up-to-date library of FG models, used by all CMB collaborations for validation/testing of pipelines and forecasts

Table 7. Recommended Model Suite

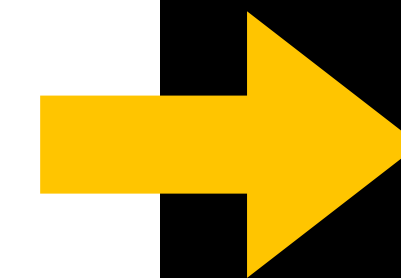
Complexity	Model set	Short description
Low	d9, s4, f1, a1, co1	Small-scale emission fluctuations in amplitude only; no frequency decorrelation in dust or synchrotron. Unpolarized CO emission.
Medium	d10, s5, f1, a1, co3	Extrapolation to small scales for both amplitude and spectral parameters in dust 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.

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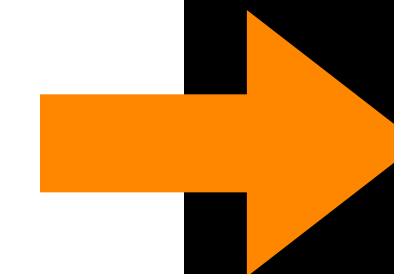
Simplified model, already ruled out by data, useful to validate pipelines (similar to d0s0)

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Model based on our current knowledge and constraints from observations (similar to *d1s1*)

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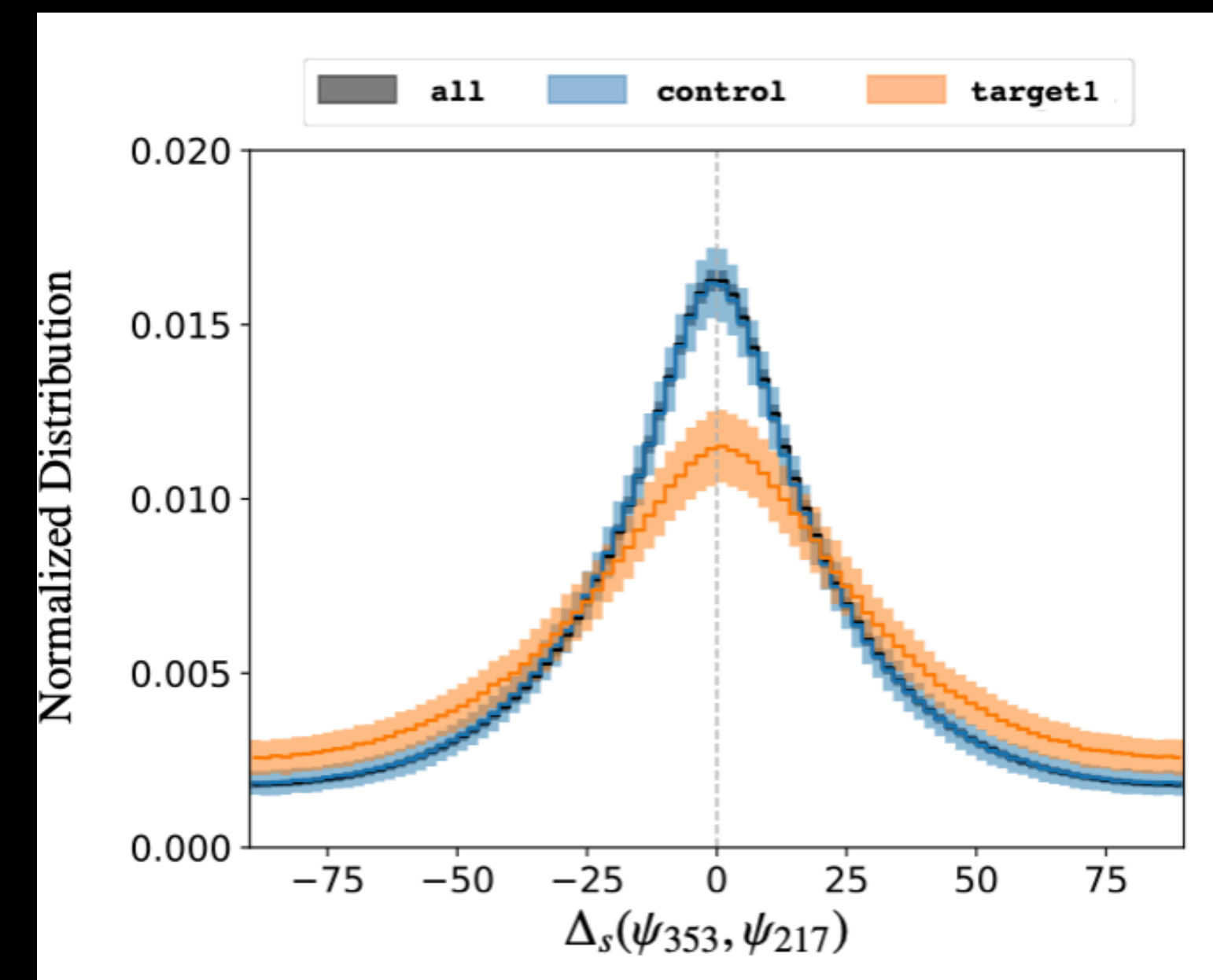
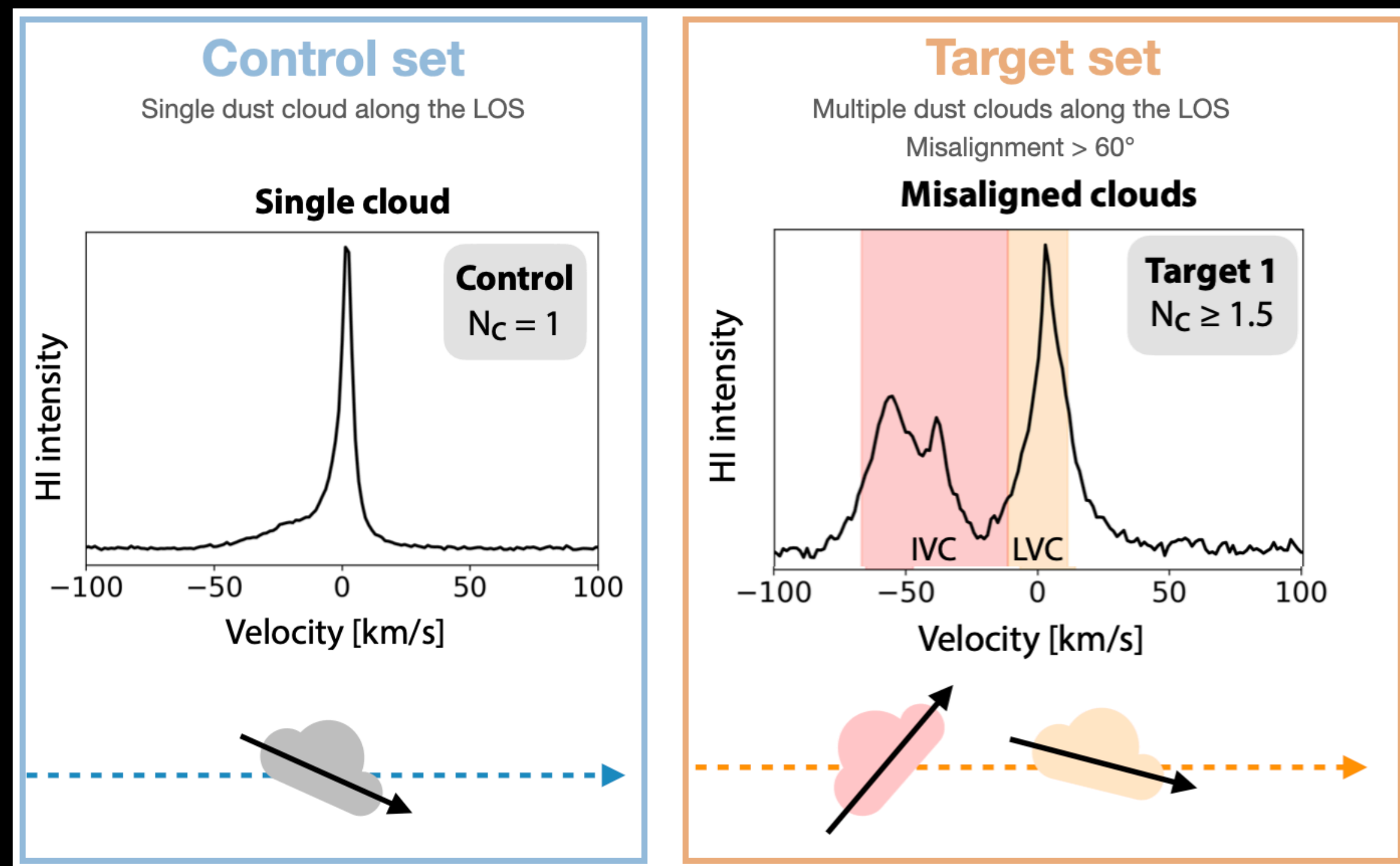
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More complex model,
representing one of
the possible scenarios,
but currently not
sustained by data

Are these models sufficient?

Line-of-sight dust complexity

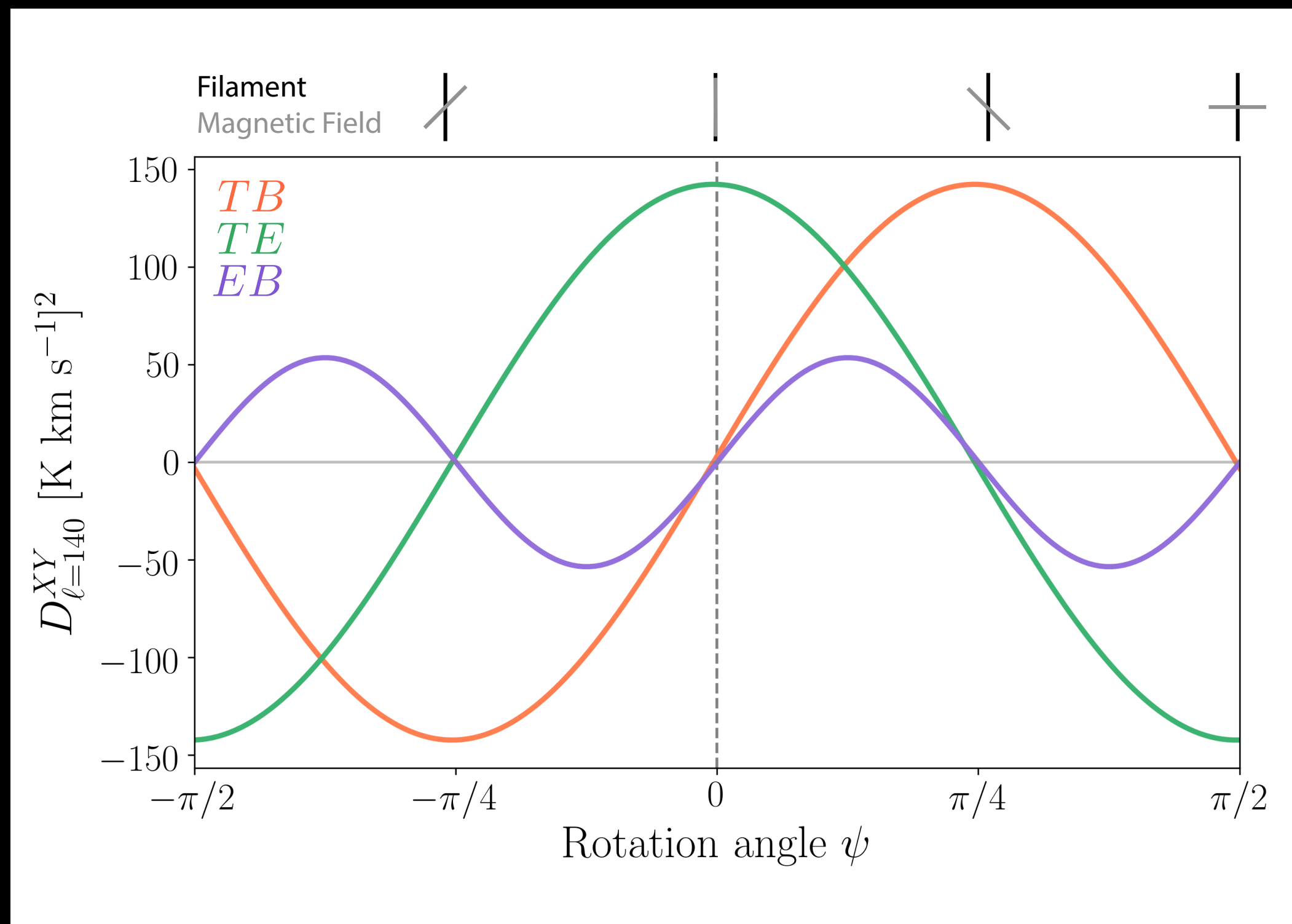
- If multiple dust clouds are present along the line-of-sight with different SED and orientation de-correlation is expected, as Q and U have different frequency scaling
- Hints of detection in Planck 353 GHz map



impact on component separation

Are these models sufficient?

Dust EB correlation



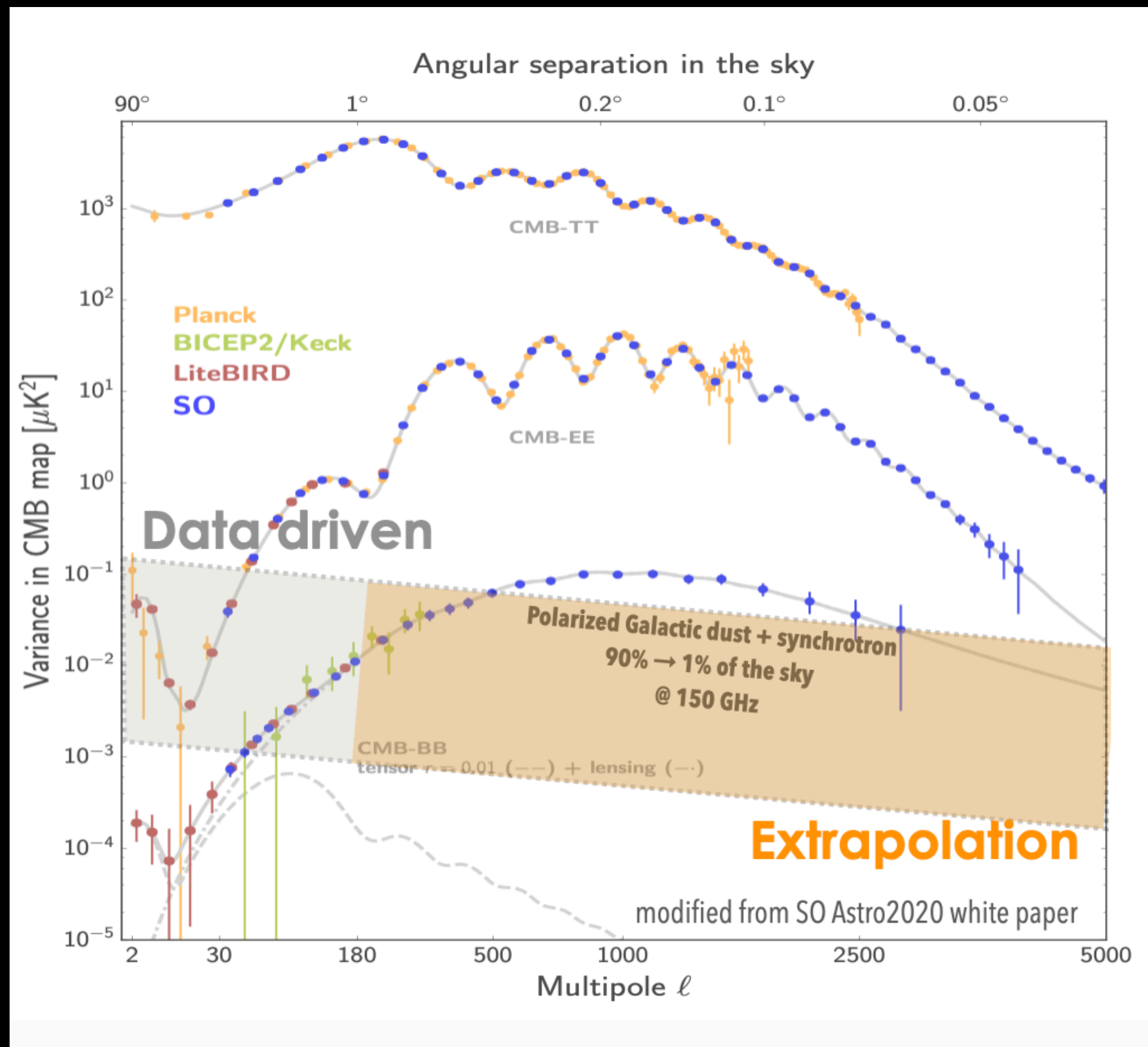
Clark et al. 2021

- The TB dust correlation observed in Planck data can be explained by misalignment between filamentary dust structure and the plane-of-sky magnetic field
- The same mechanism would similarly give rise to EB correlation, although not detected yet

impact on cosmic birefringence

Are these models sufficient?

Small scale non-Gaussianity



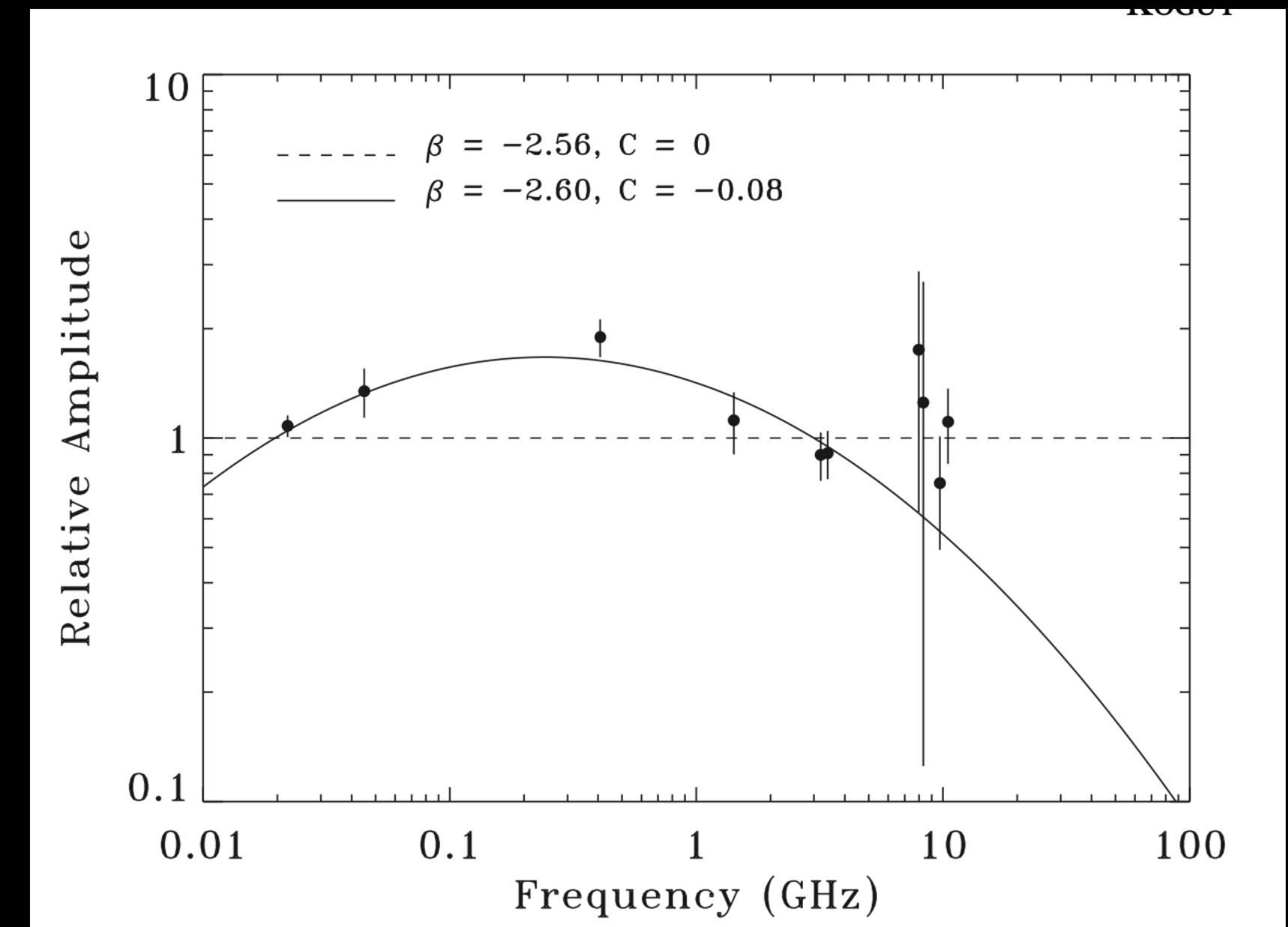
impact on lensing reconstruction

Synchrotron curvature

Changes in the cosmic-ray electron spectrum and line-of-sight mixing can produce an effective curved SED

Observed in total intensity, not clear detection yet in polarization

Kogut 2010

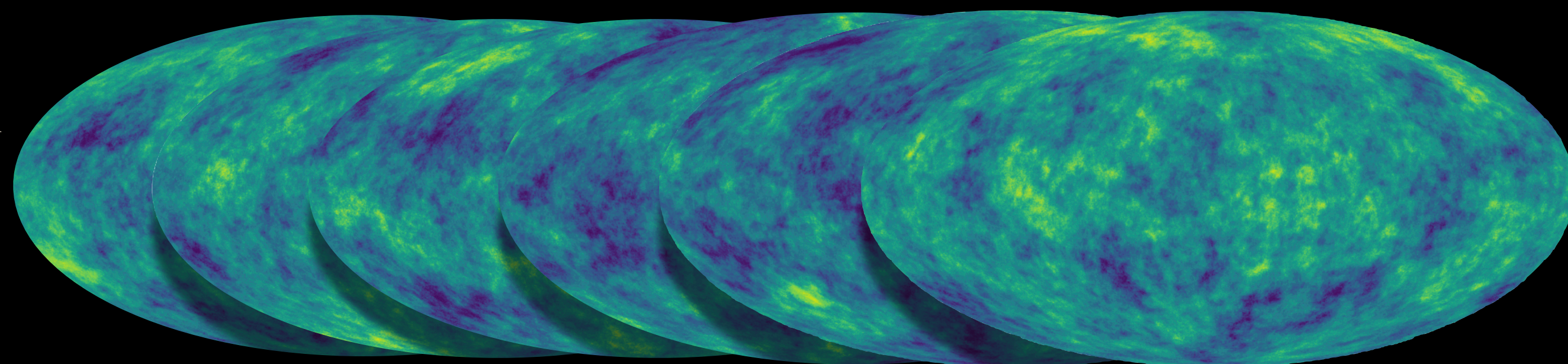
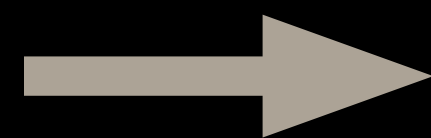


impact on component separation

Are these models sufficient?

Some of these physically motivated, but not yet observed, foreground features are already included in current simulation templates.

Line-of-sight dust complexity

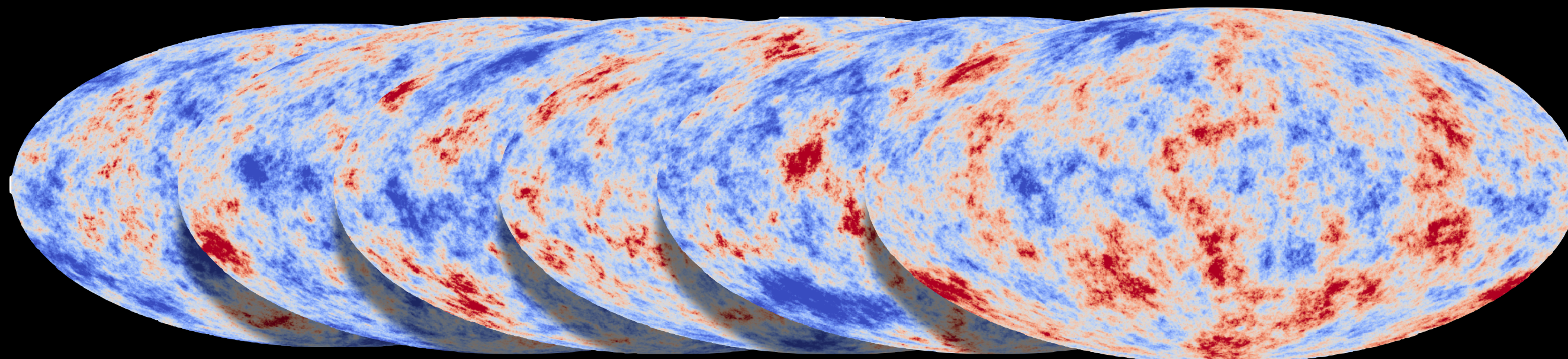


0.9

β_d

2.5

d12 PySM model implements a six-layer dust model, with Gaussian realization of β_d and T_d for each layer



15

$T_d(K)$

25

Are these models sufficient?

Some of these physically motivated, but not yet observed, foreground features are already included in current simulation templates.

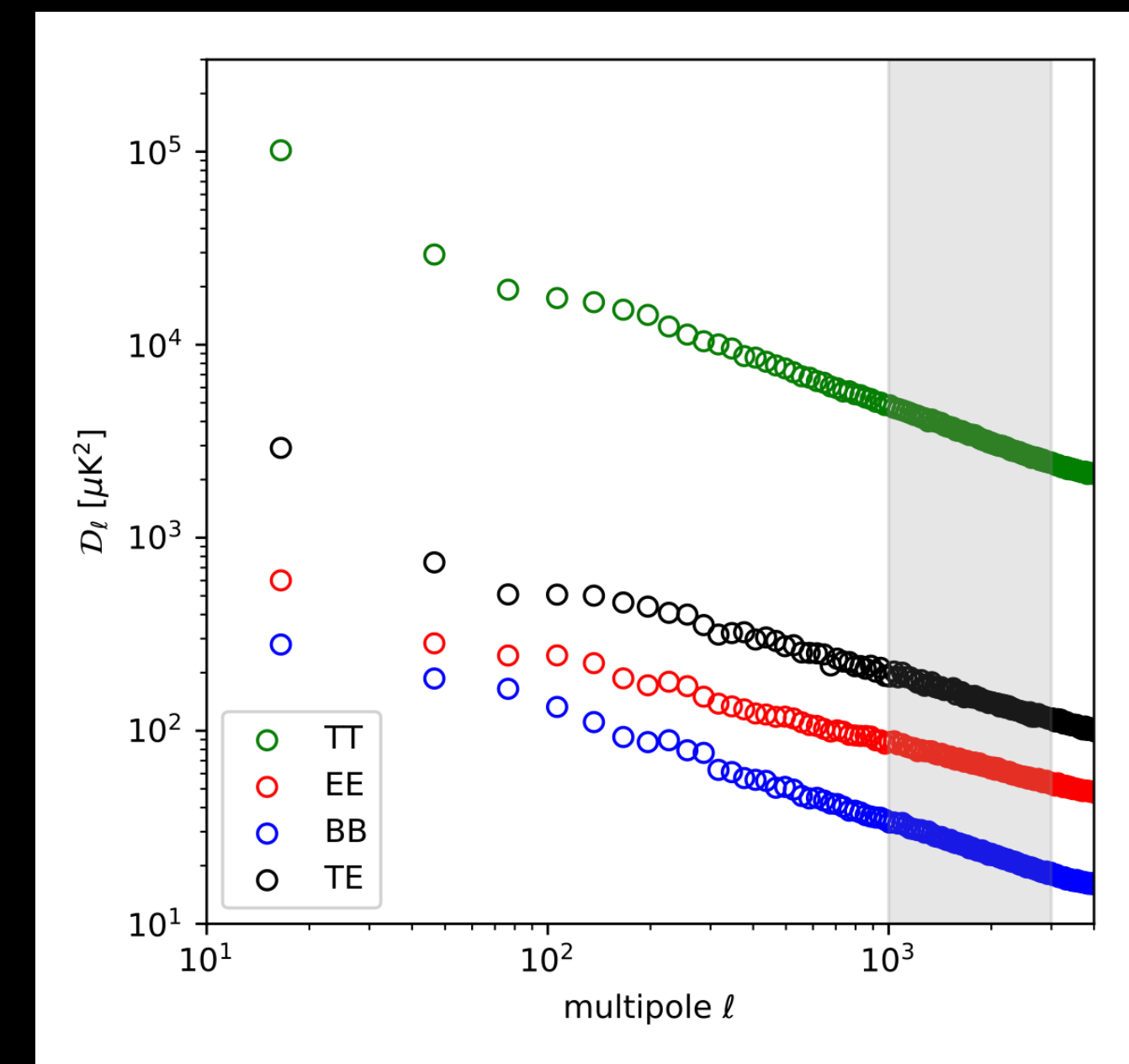
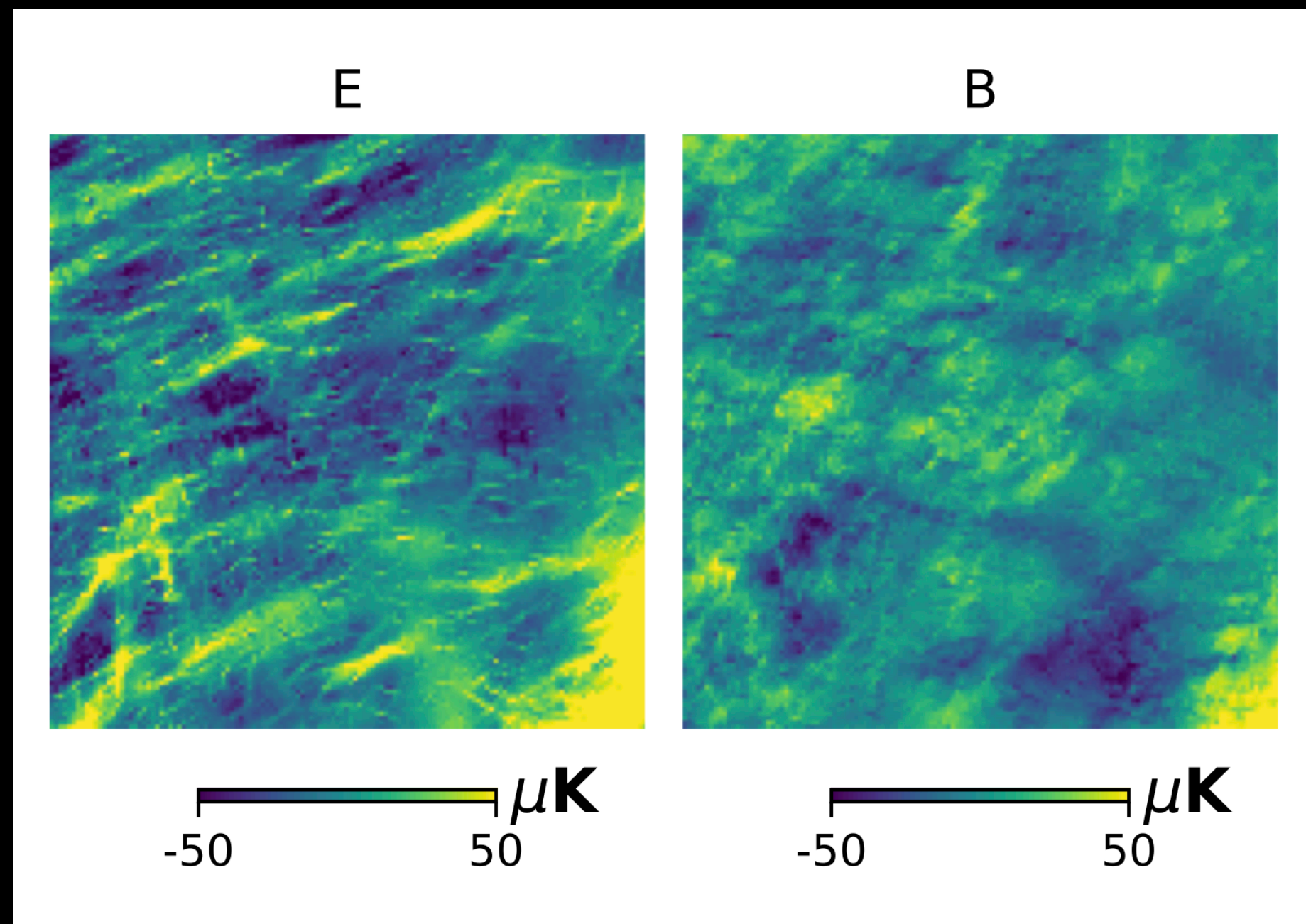
Line-of-sight dust complexity

Dust EB correlation



PySM models do not have a “coherent” EB correlation.

Filament model at 353 GHz



Are these models sufficient?

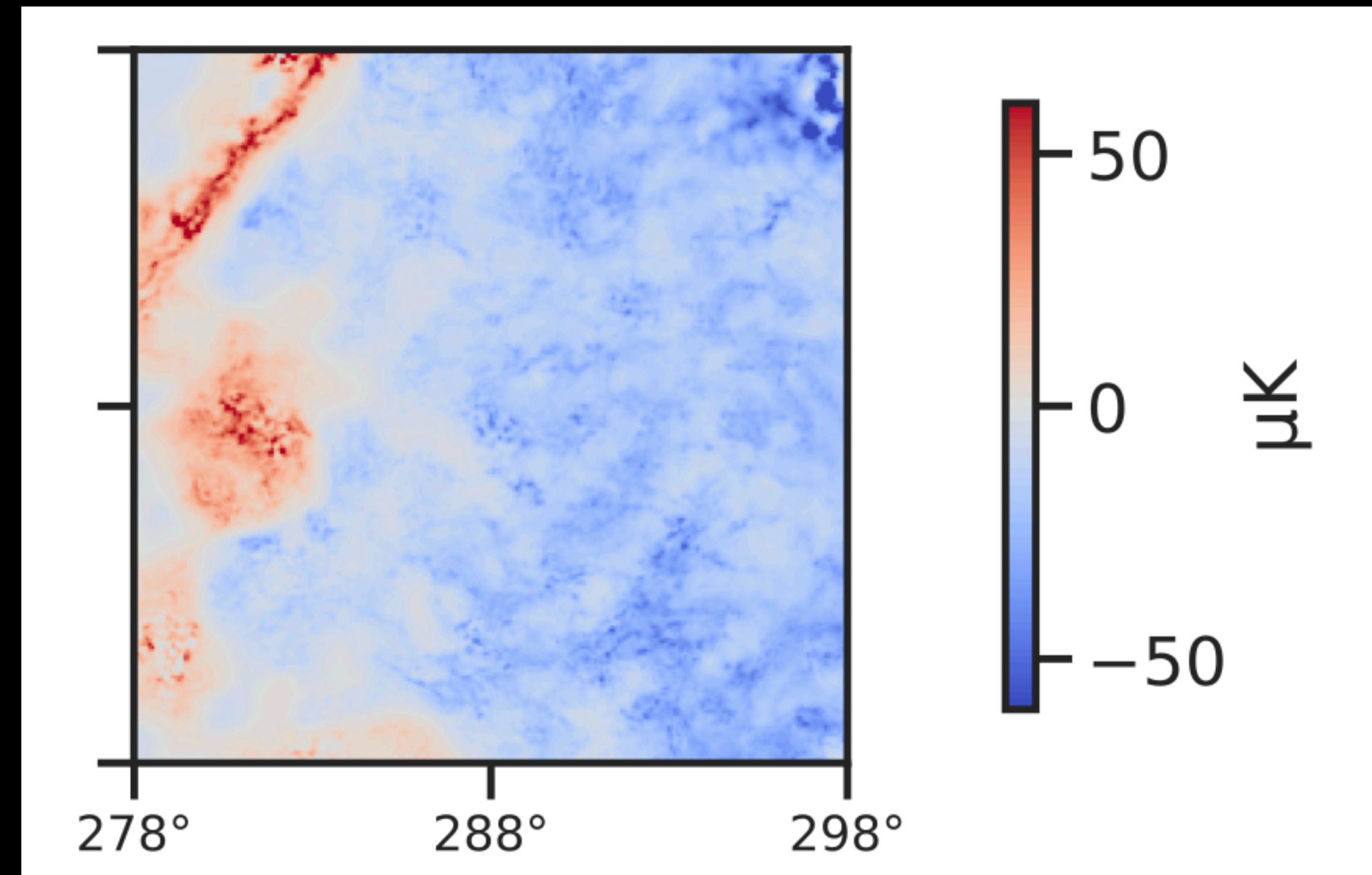
Some of these physically motivated, but not yet observed, foreground features are already included in current simulation templates.

Jian et al. 2025

Line-of-sight dust complexity

Dust EB correlation

Small scale non-Gaussianity



NN based model with non-Gaussian small features up to 3 arcmins

Are these models sufficient?

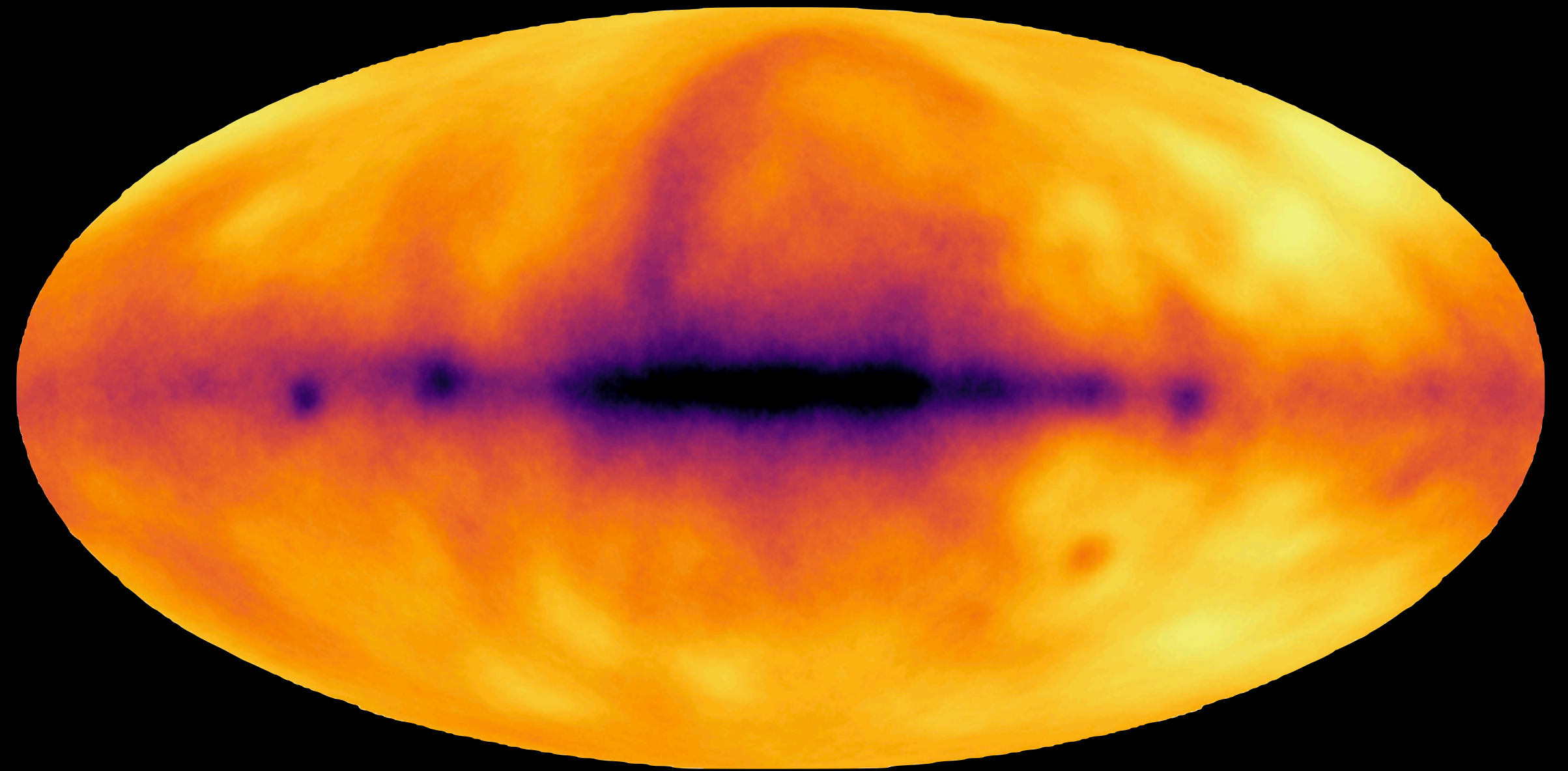
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Line-of-sight dust complexity

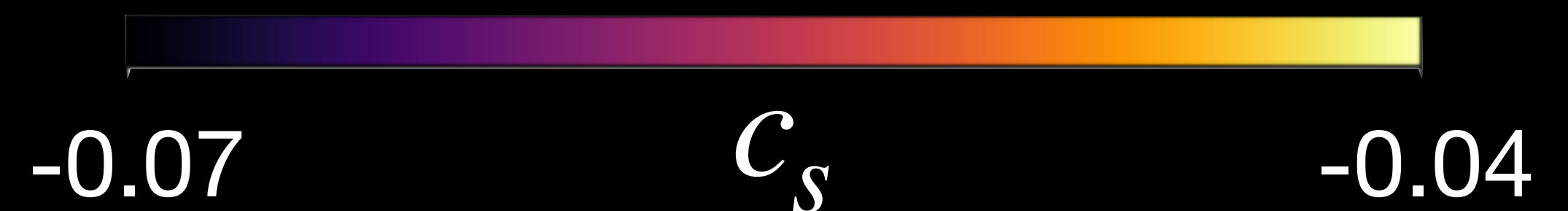
Dust EB correlation

Small scale non-Gaussianity

Synchrotron curvature



PySM s7 model implements synchrotron curvature by modulating it with large scale total intensity features



Are these models sufficient?

Some of these physically motivated, but not yet observed, foreground features are already included in current simulation templates.

Line-of-sight dust complexity	→	d12 PySM model implements a 6 -ayers dust model
Dust EB correlation	→	Current PySM models do not include a coherent EB correlation. A filament-based model has been proposed at 353 GHz.
Small scale non-Gaussianity	→	NN based model with non-Gaussian small features up to 3 arcmins
Synchrotron curvature	→	s7 PySM model implements a full sky variable synchrotron curvature

These models are useful for stress testing pipelines, but they should not be mistaken for realistic representations of the microwave sky.

What to do next

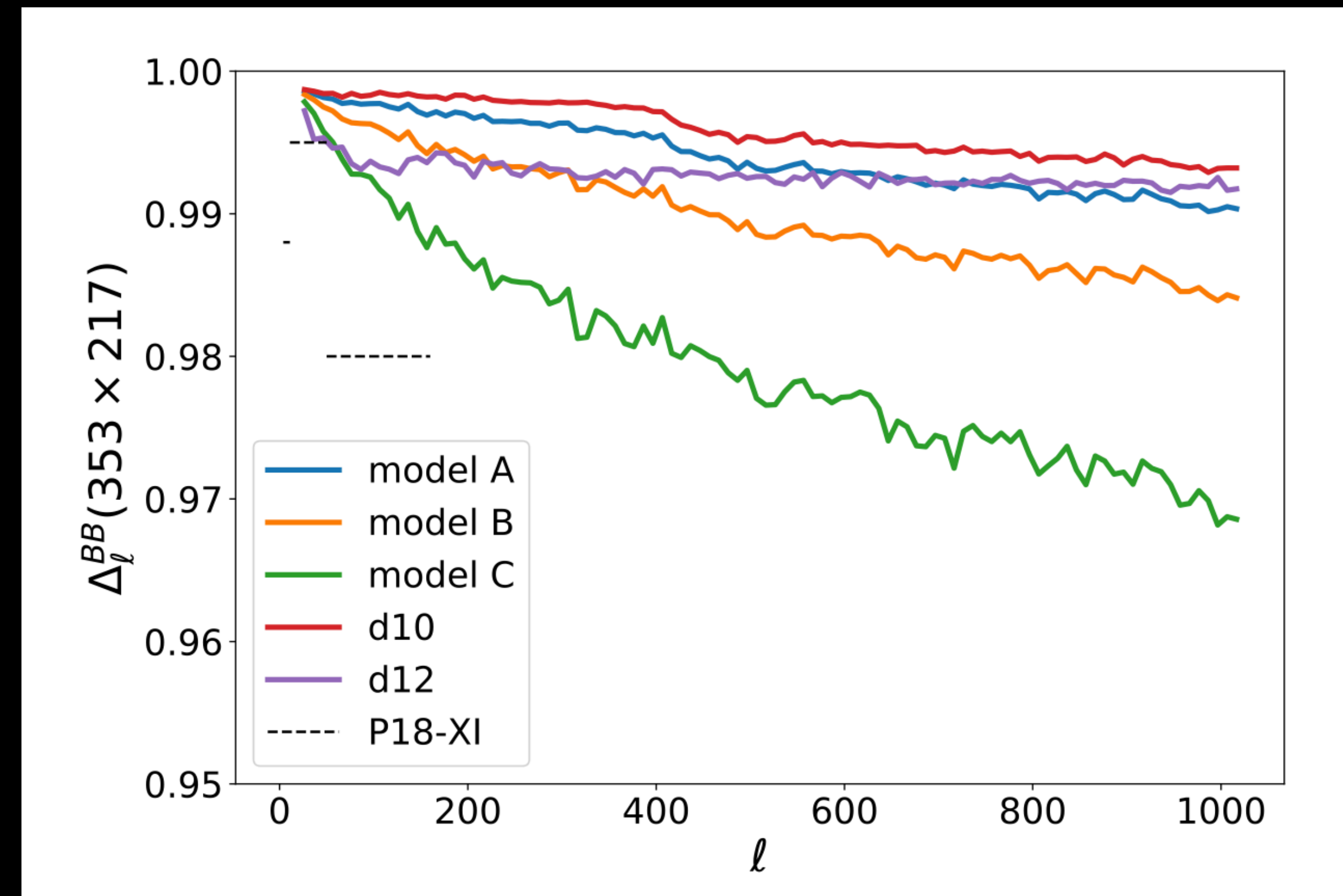
- **We must accept that our knowledge of foregrounds is fundamentally incomplete.**
- Partial improvements will come in the near to mid term from low-frequency observations (e.g. QUIJOTE, CBASS) and ongoing CMB experiments (Simons Observatory, BICEP, SPT), but on partial sky.
- New complete full-sky foreground models, including large angular scales, will most likely only become available with LiteBIRD's multi-frequency space observations.

The way forward is to tackle the problem from multiple directions!

What to do next

Tunable models

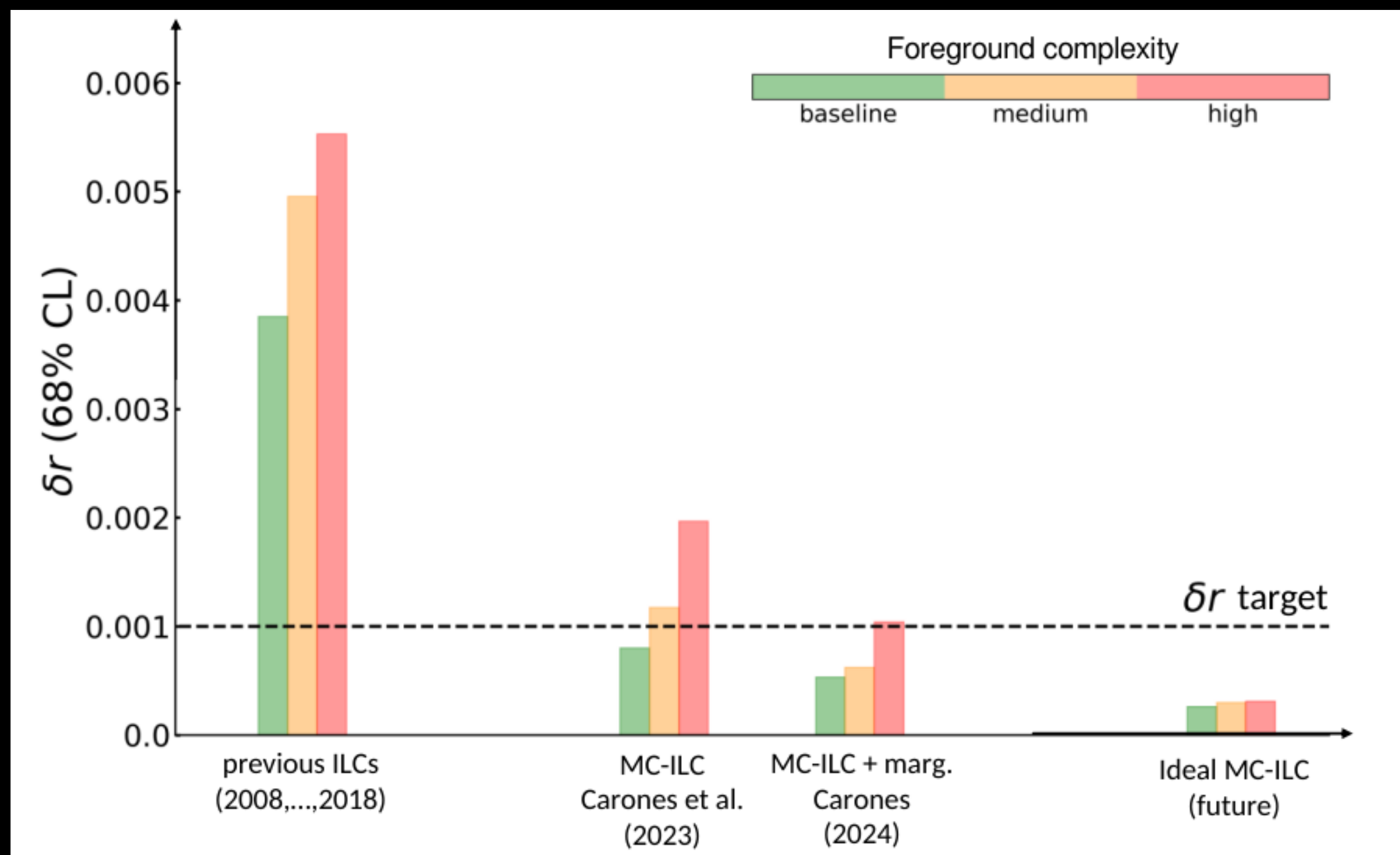
- There will be no single sky model that can serve as the baseline for pipeline development and validation.
- A possible approach is to build a set of tunable models, parameterizing the physical features we expect but whose amplitudes remain uncertain.
- Varying these parameters would enable systematic testing and optimization of component separation methods
- The moment expansion framework provides one way to achieve this flexibility



What to do next

Component separation and blind application

- Component separation algorithms have advanced significantly since the *Planck* era.
- There is still substantial room for improvement, but developing and validating new methods takes time.



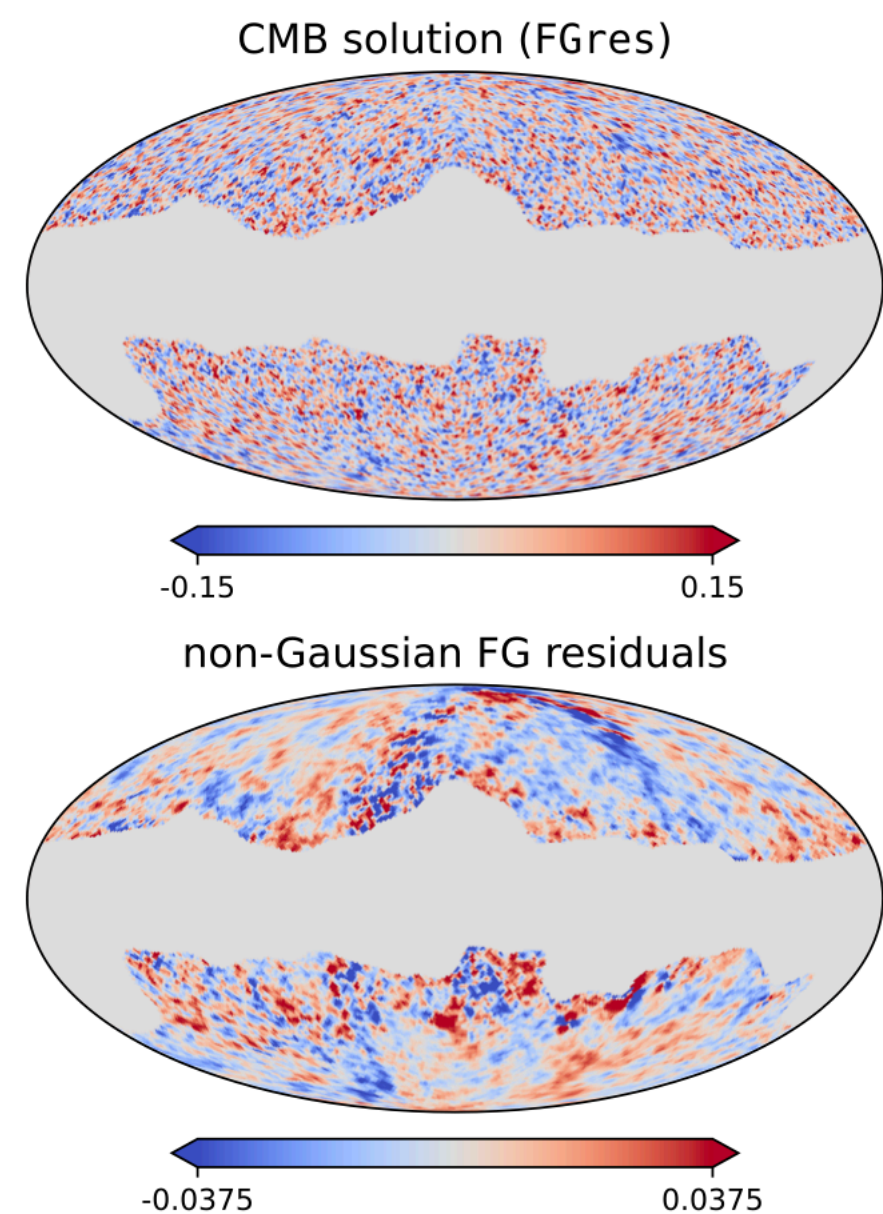
- At the same time, we should avoid unnecessarily overcomplicated component-separation models if the data do not justify them
- Blind analyses can provide a rigorous way to validate our methods: recover the CMB without knowing the complexity of the simulated foregrounds or the input cosmological parameters.

What to do next

Robustness tests

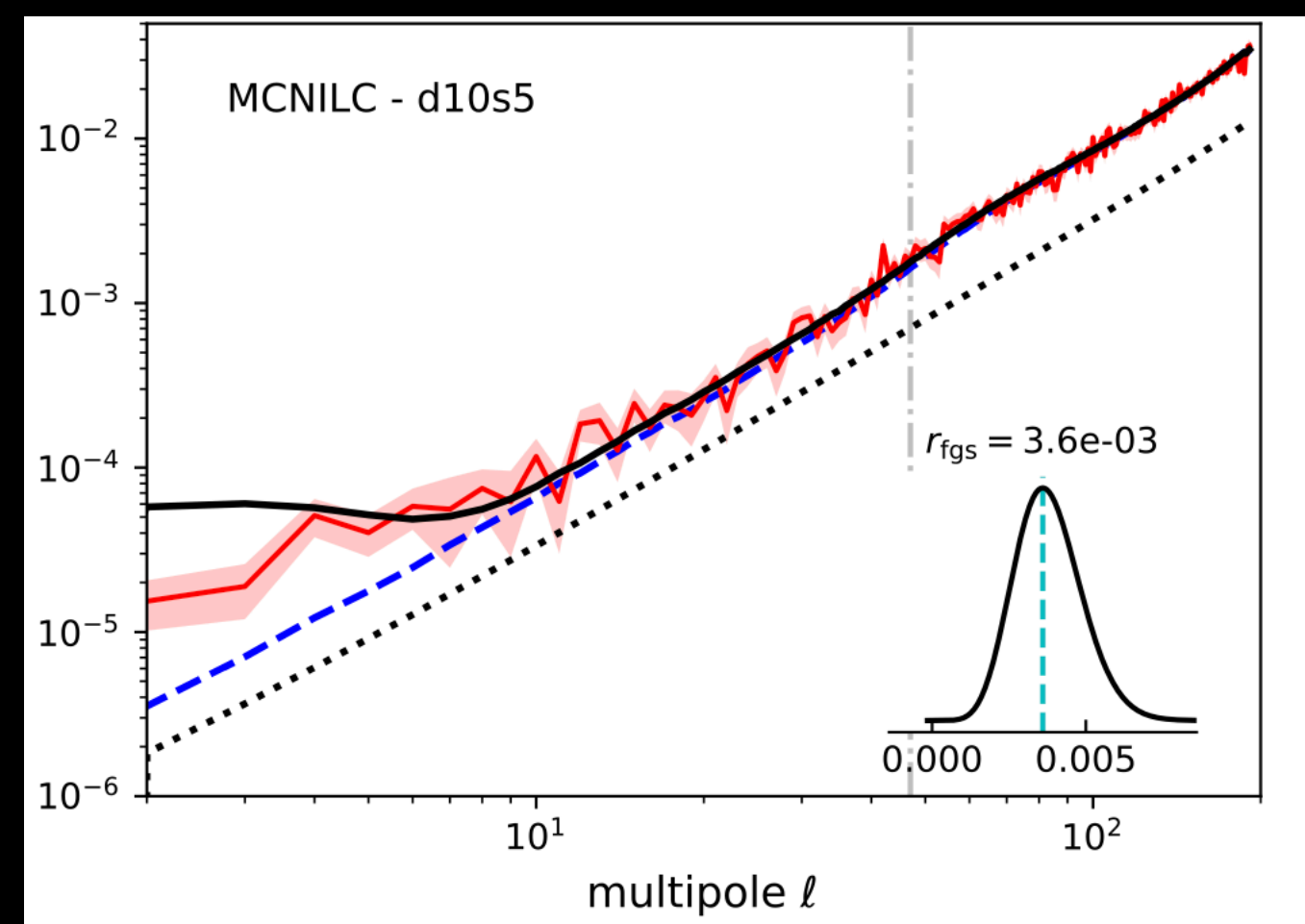
- In parallel we should develop robustness tests able to confirm/reject the cosmological origin of any possible r detection

CMB solution
(CMB+noise+FG residuals)

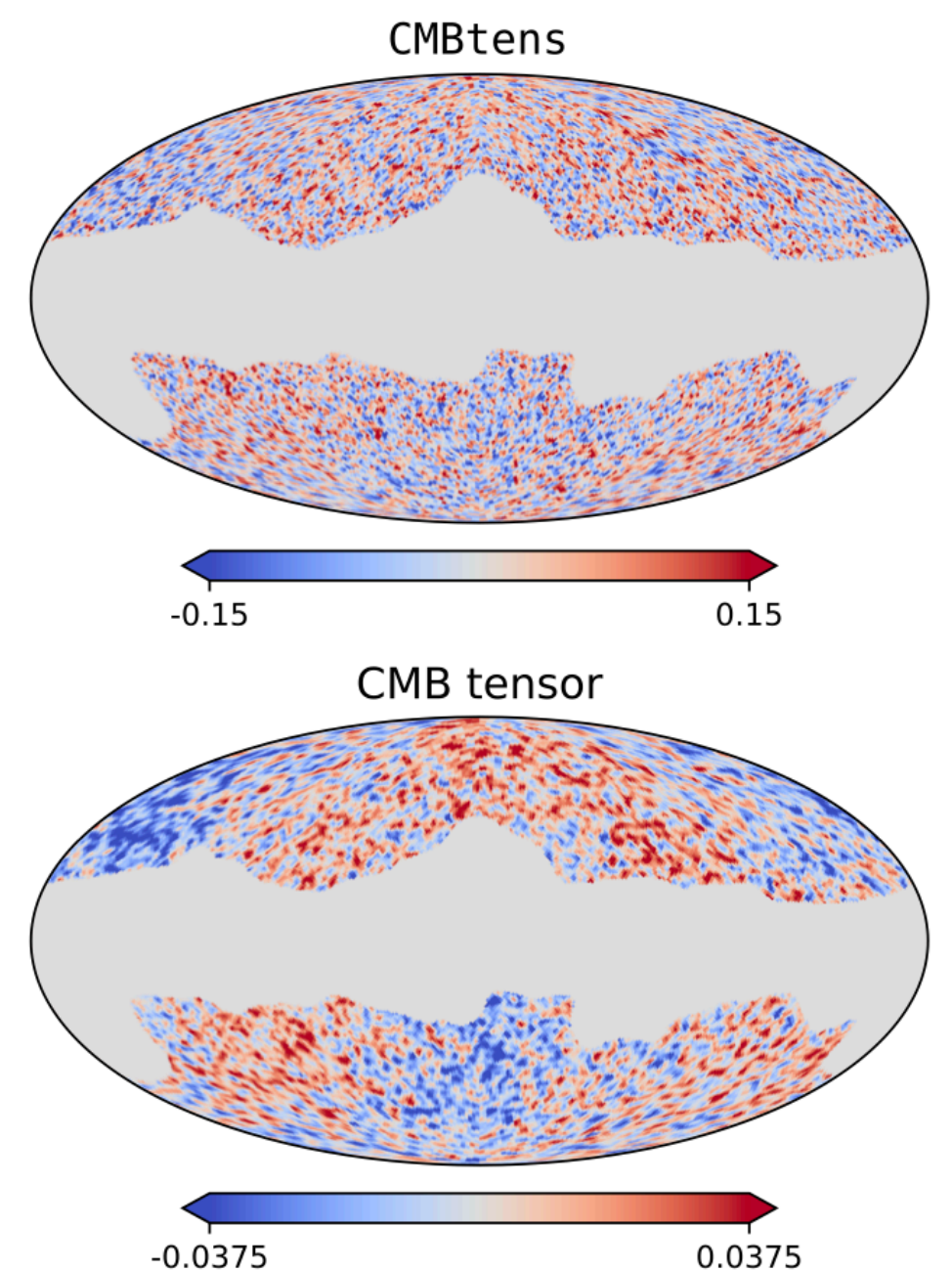


Statistical comparison

Biased r



Simulations with
noise + CMB with r
inferred from data



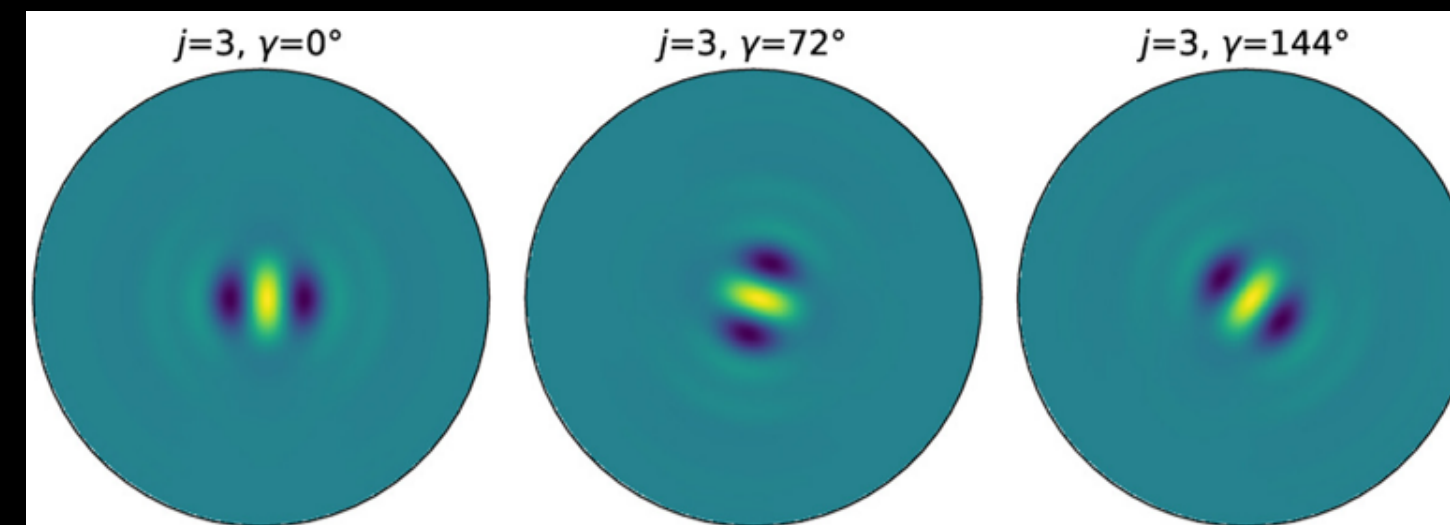
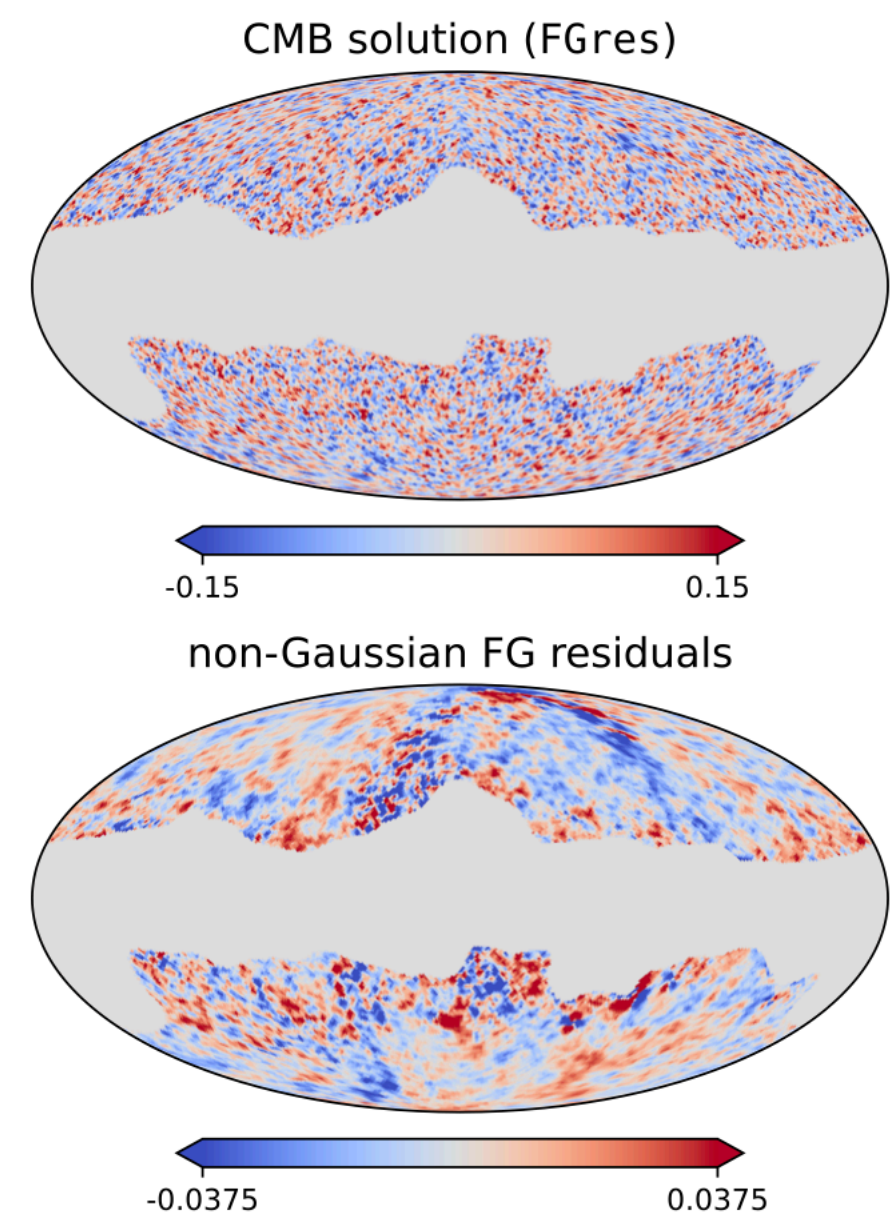
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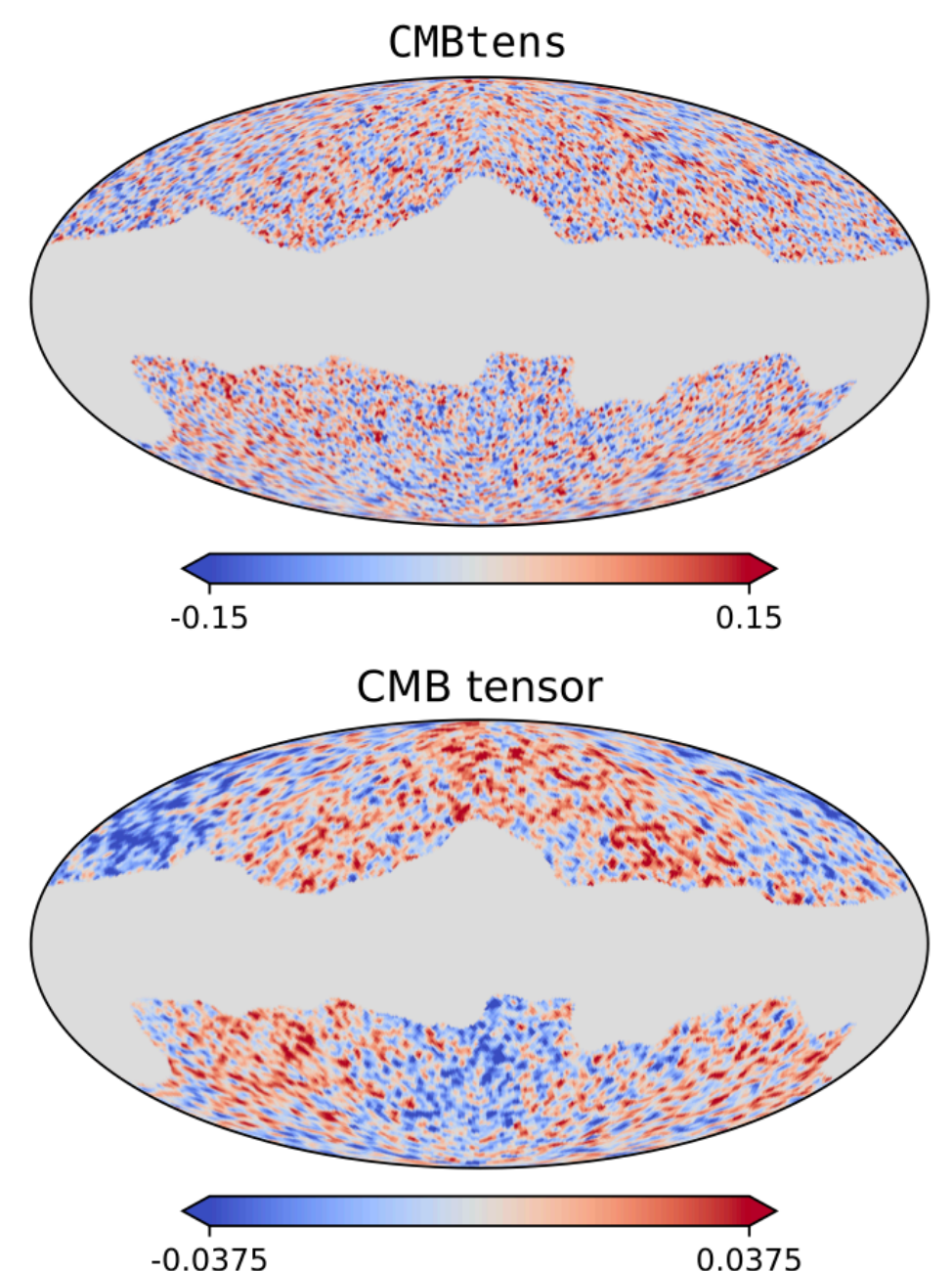
CMB solution
(CMB+noise+FG residuals)



Statistics based on **wavelet transform**,
convolving maps with oriented filters

For a LB-like experiment we can identify
false r detections at the level of $r_{FG} \sim 0.001$

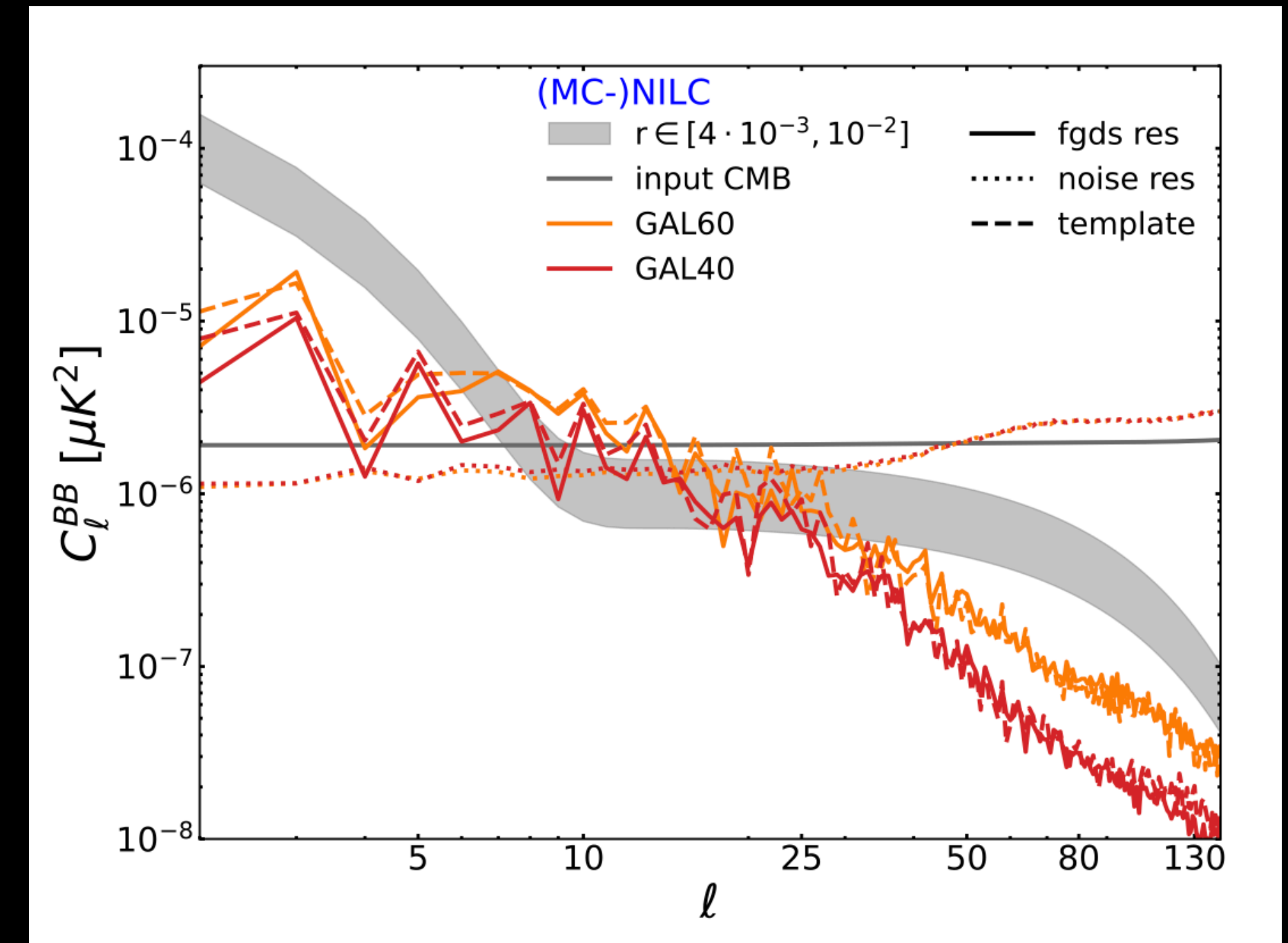
Simulations with
noise + CMB with r
inferred from data



What to do next

Likelihood

- Likelihood models can also be extended to account for uncertainties in foreground properties.
- This requires an appropriate parameterization/ data driven templates
- The data — not our assumptions — should determine how much model complexity is needed



Personal conclusions

- We must accept that **our knowledge of Galactic foregrounds is fundamentally incomplete** and will likely remain so in the near to medium term.
- Foreground models will continue to improve, but **we should not expect a complete, reliable full-sky baseline model** before the next generation of CMB observations.
- Our knowledge of foregrounds will evolve at the same time as the arrival of new high-sensitivity CMB data.
- This inevitably is challenging and introduces risk for CMB experiments, and that **risk must be explicitly acknowledged**.
- We can mitigate this risk by tackling the problem from multiple directions: developing **tunable foreground models**, improving **component-separation** methods, performing robust **validation tests**, and extending the **likelihood** framework.
- **We should also trust our ability to adapt**: unforeseen challenges will arise with the next generation of high-sensitivity data, but they can be addressed as they emerge.