Treatment of less-known CMB instrumental systematics

CosmoForward 2026/02/09

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Lead, SO LAT PS pipeline AWG

The End

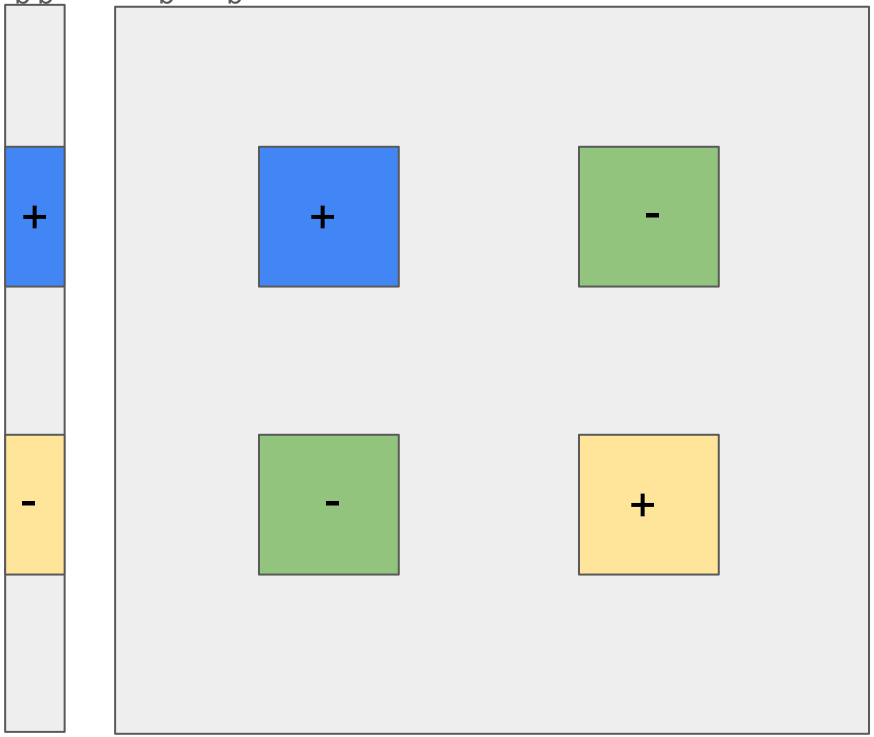
Treatment of ~~less~~ unknown CMB instrumental systematics

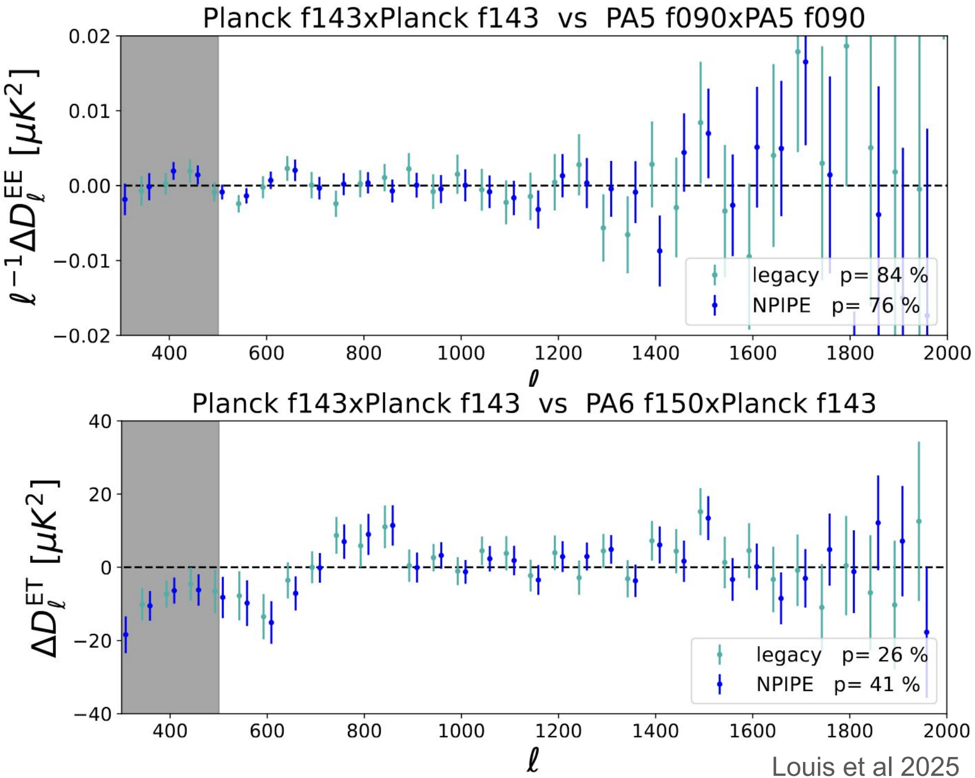
~~Treatment of less- unknown CMB instrumental systematics~~
What/how/why of null tests?

- Comparison of 2+ measurements of the same thing
- How example: (ps1_ell - ps2_ell) / cov -> □^{2}
- Measure systematics (or don’t)
- Internal consistency of dataset
- Validate software pipeline
- …
- (~)Independent of cosmology/sky model

Quick example of classic null tests (1)

$d_b, d_{b'}$ $C_{bb}, C_{bb'}, C_{b'b}, C_{b'b'}$ $□^2 = (d_b - d_{b'})^T*(C_{bb} - C_{bb'} - C_{b'b} + C_{b'b'})^{-1}*(d_b - d_{b'})$





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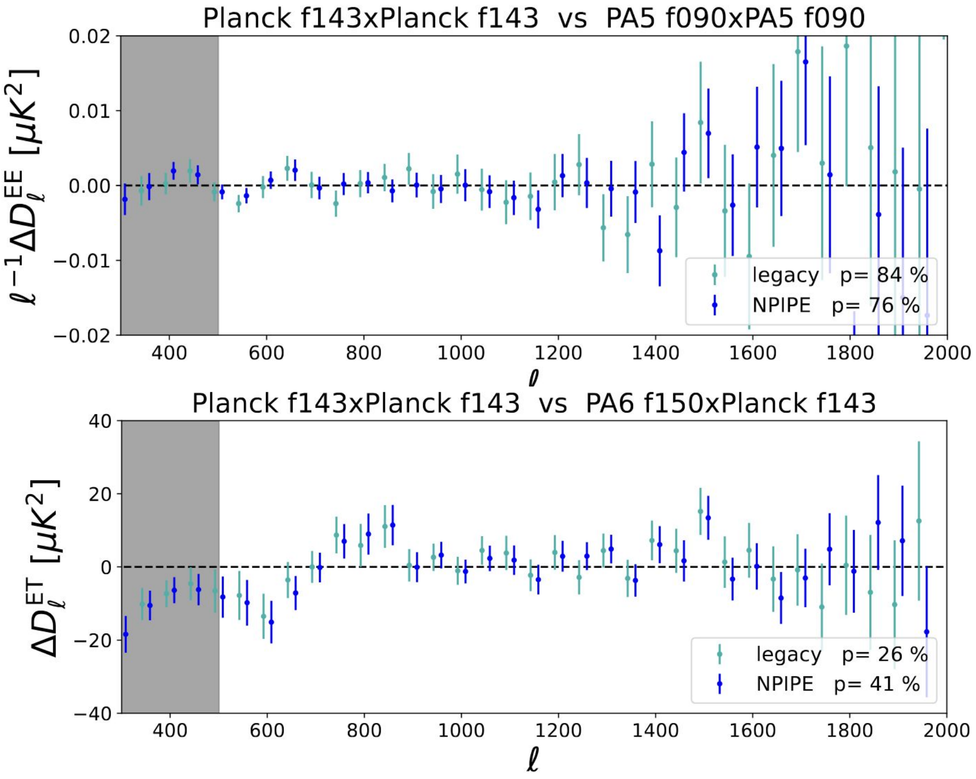
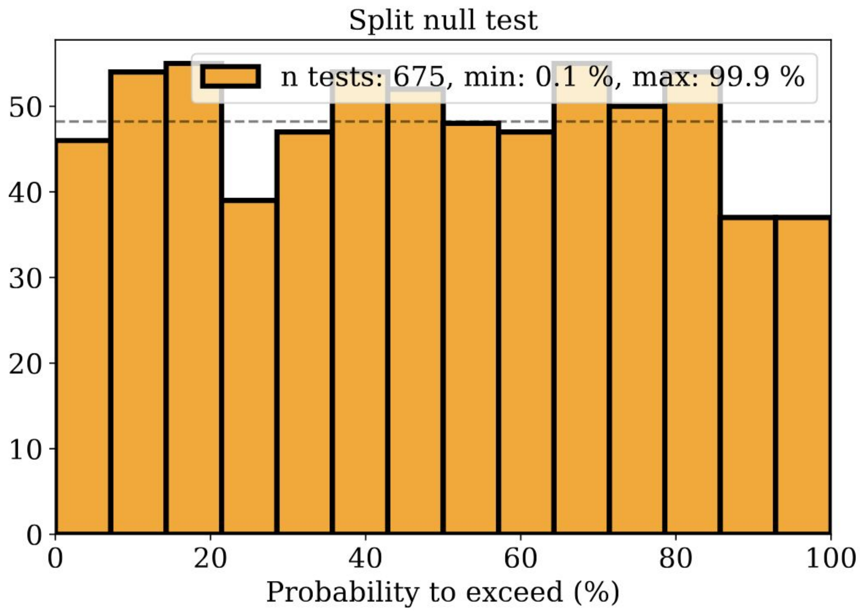
Quick example of classic null tests (2)

$\square^2 = (d_b - d_{b'})^T * (C_{bb} - C_{bb'} - C_{b'b} + C_{b'b'})^{-1} * (d_b - d_{b'})$

Uniform?





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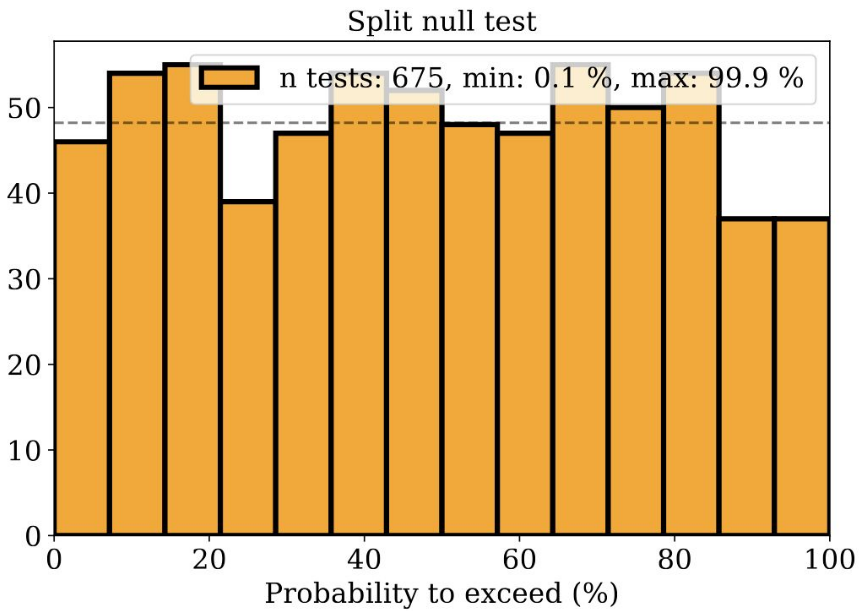
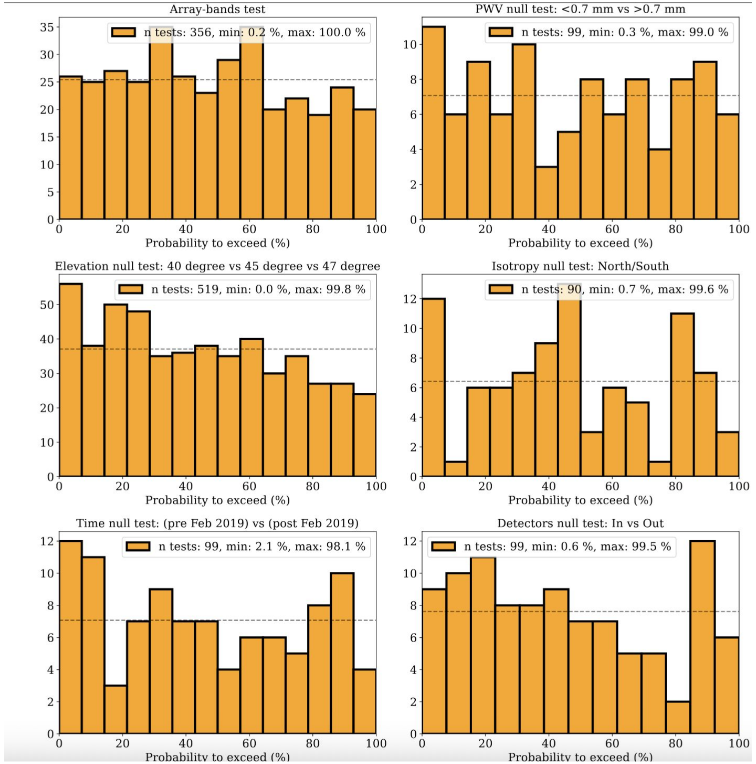
Quick example of classic null tests (3)

Uniform?



All uniform?



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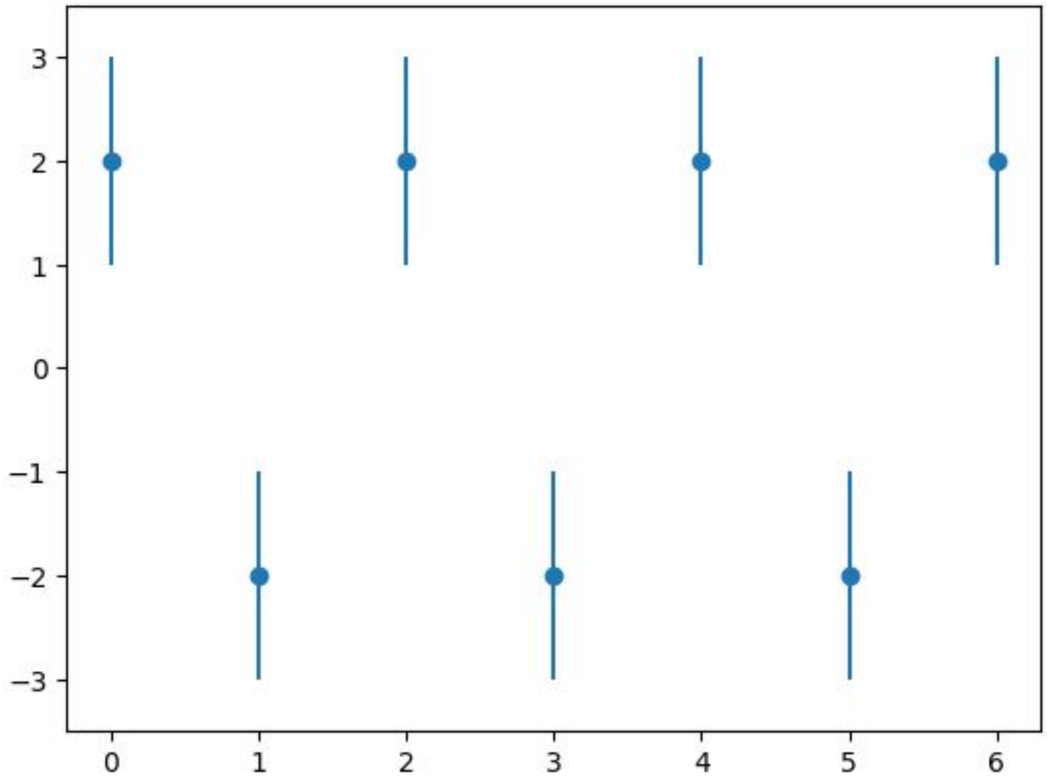
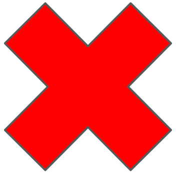
Null tests in the literature

Experiment	Type of null	Summary of null	Summary of summaries	Joint summaries of null	Joint summaries of summaries
ACT DR6	Spectrum	PTE(□^{2})	Rank statistics		
SPT DR1	Spectrum, Conditional	PTE(□^{2})	Rank statistics		
Planck 2018	Spectrum, Conditional	PTE(□^{2})			
BICEP/Keck 2021	Map	PTE(□^{2}), PTE(□)	Rank statistics, KS, Σ(□^{2})	~100s map sims	
POLARBEAR 2022	Map	PTE(□^{2}), PTE(□)	5 (incl. summary of summary of summaries)	~100s maps sims	~100s maps sims
SPIDER 2021	Map	PTE(□^{2})	Rank statistics, KS	~100s maps sims, ~1000s spectra sims	

Choice of summary of null

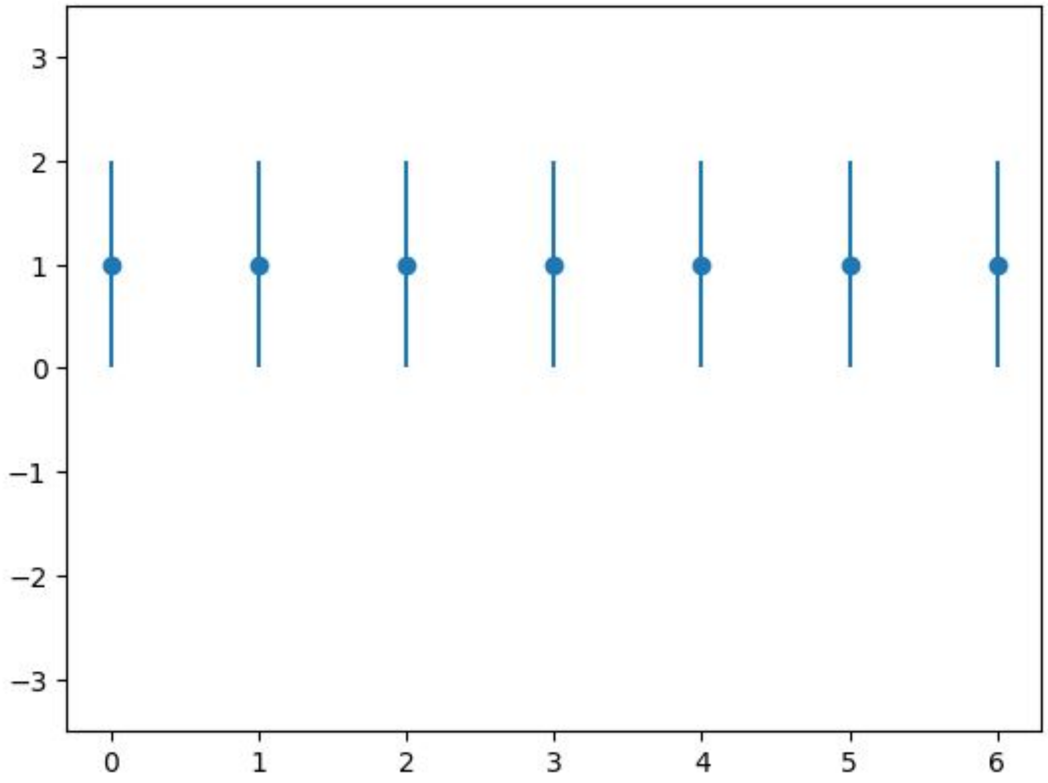


$$\chi^2 = \vec{d}^T \mathbf{C}^{-1} \vec{d}$$



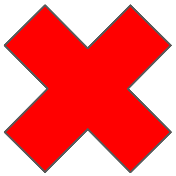
$$\chi = \vec{1}^T \mathbf{C}^{-\frac{1}{2}} \vec{d}$$

Choice of summary of null

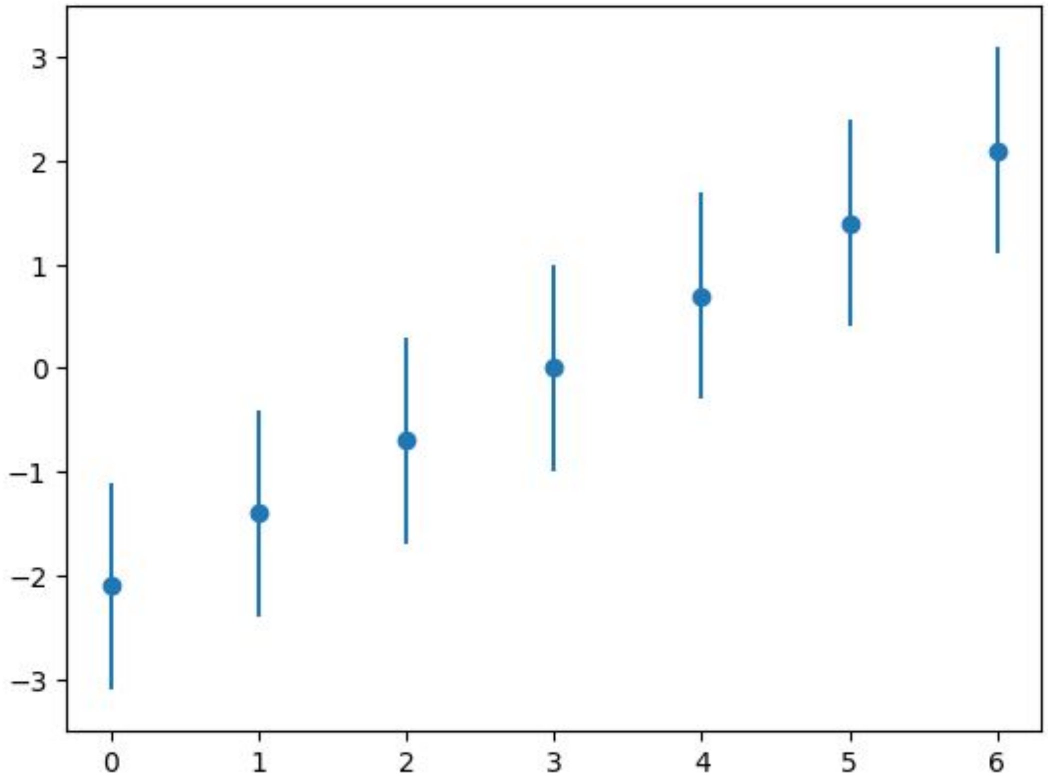


$$\chi^2 = \vec{d}^T \mathbf{C}^{-1} \vec{d}$$

$$\chi = \vec{1}^T \mathbf{C}^{-\frac{1}{2}} \vec{d}$$



Choice of summary of null



$$\chi^2 = \vec{d}^T \mathbf{C}^{-1} \vec{d}$$

$$\chi = \vec{1}^T \mathbf{C}^{-\frac{1}{2}} \vec{d}$$

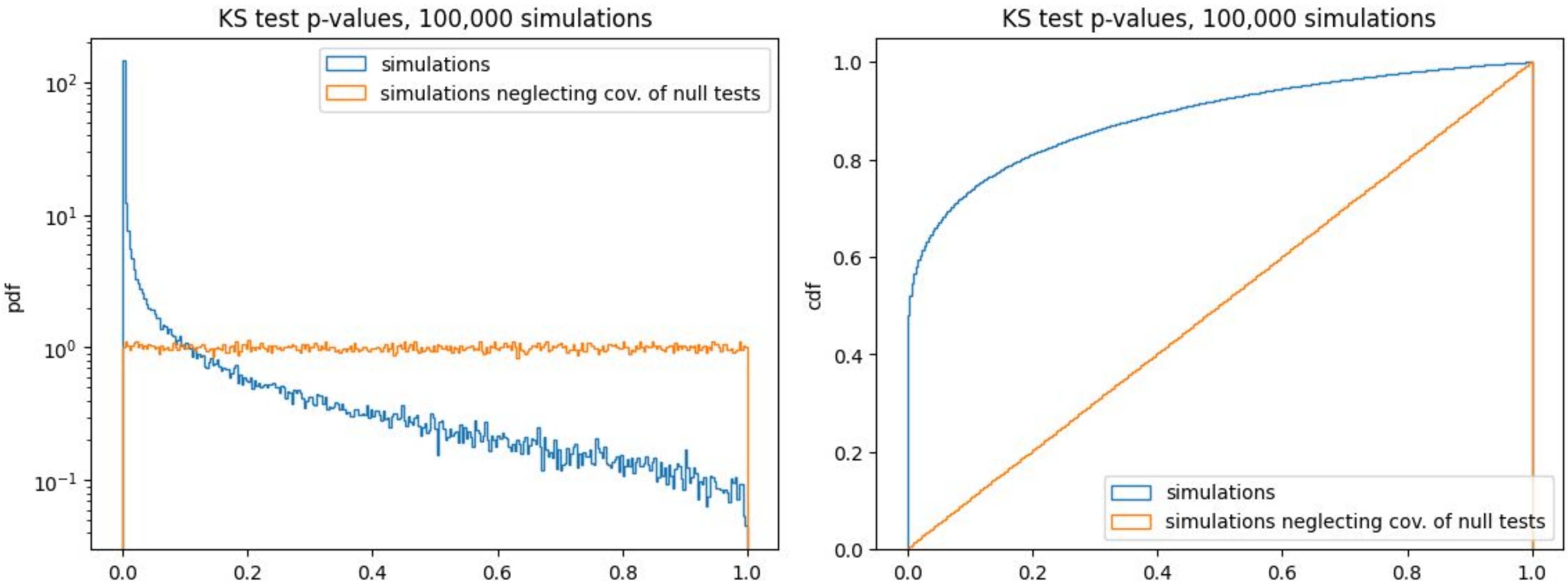
Choice of summary of summaries + joint distributions

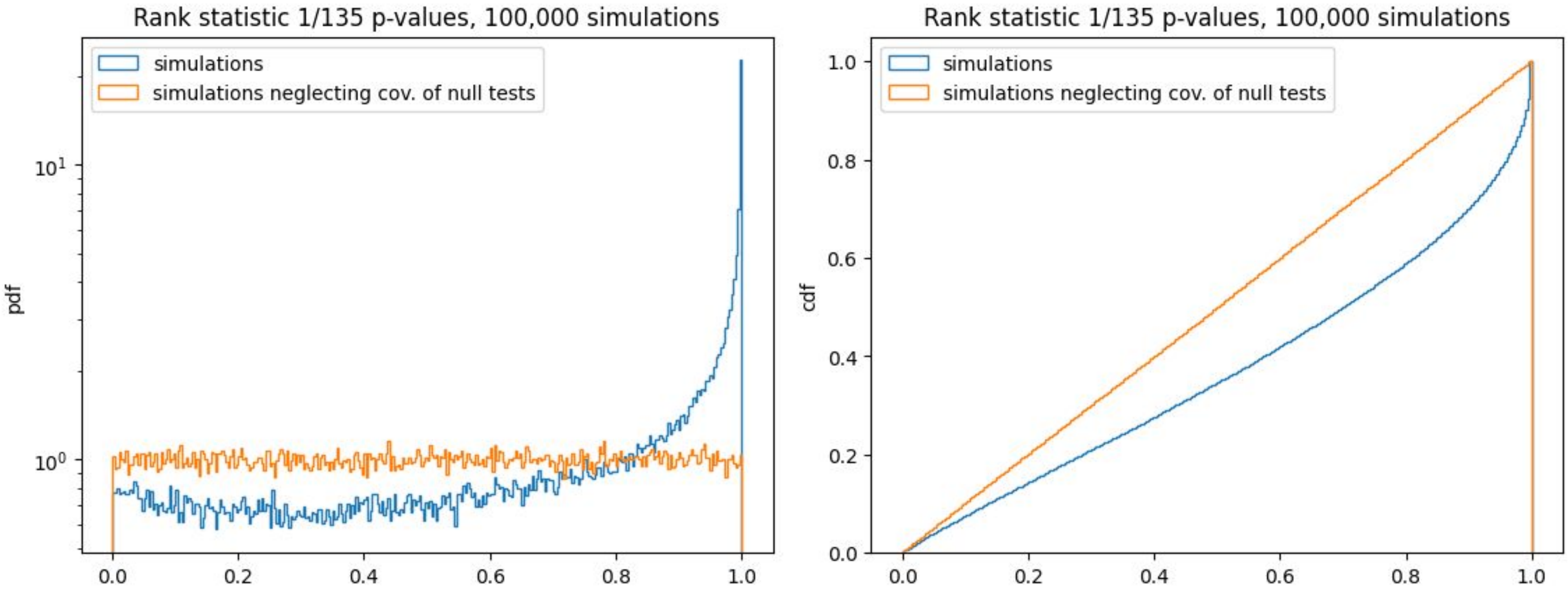
Setup mock PS covariance matrix (slices of ACT DR6 cov):

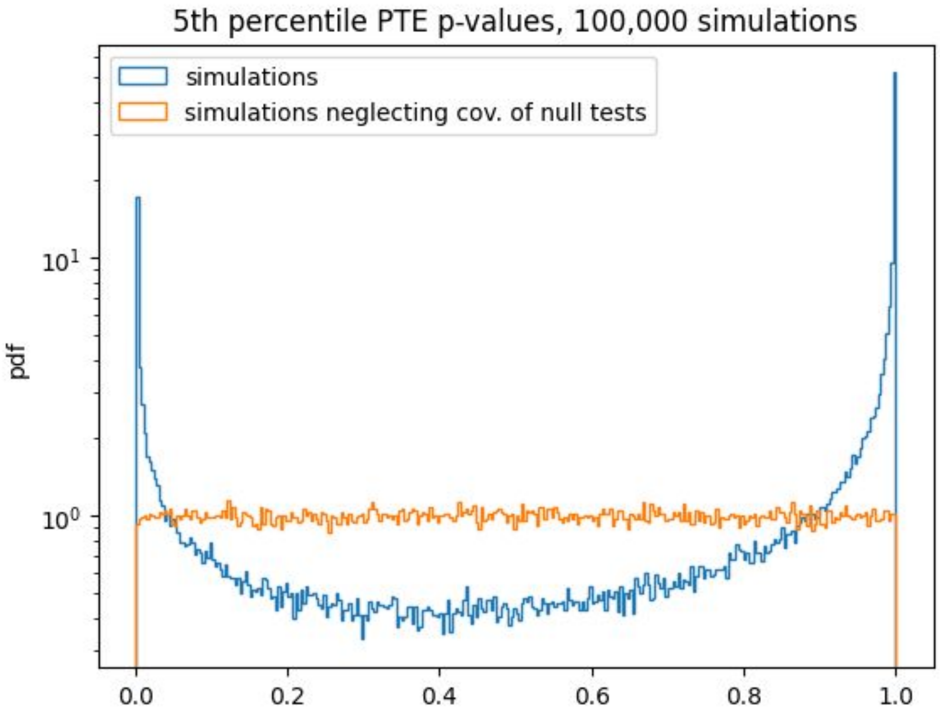
- Only TT TE EE + assume each spectrum shares sky model
- Tile this for 10 blocks

Draw 100,000 realizations from covariance:

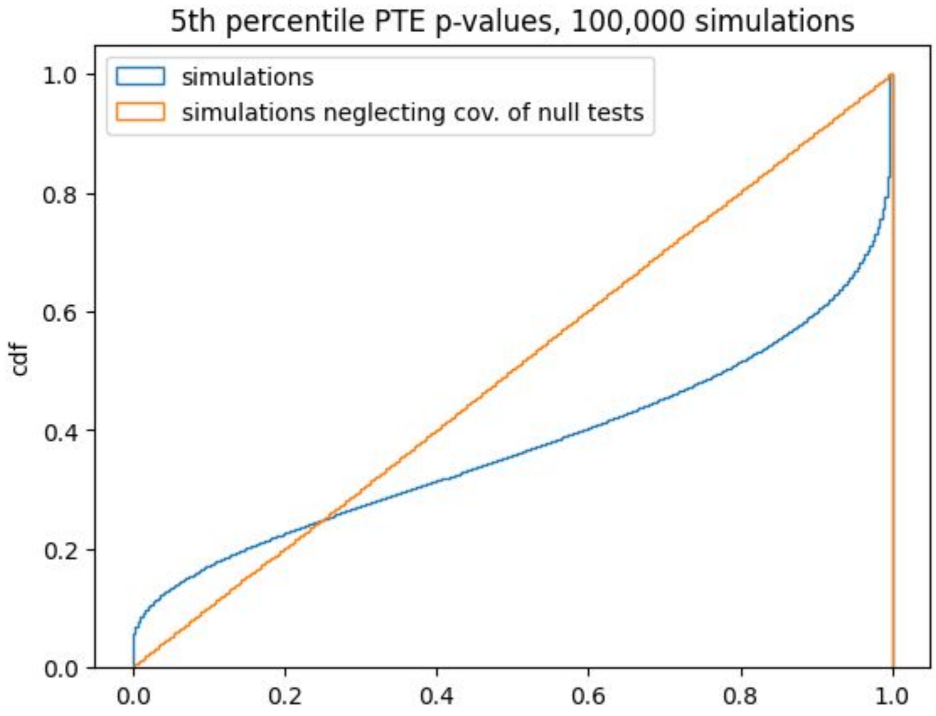
- Form all spectrum null tests (for 10 blocks, 135 tests), calculate PTE(χ^2) for each (135 x 100,000 χ^2 values)
- For each simulation, calculate : KS test p-value, rank statistic 1/135, rank statistic 7/135 (~5th percentile)


KS test p-values, 100,000 simulations
simulations
simulations neglecting cov. of null tests
pdf
10^2
10^1
10^0
10^{-1}
0.0
0.2
0.4
0.6
0.8
1.0
KS test p-values, 100,000 simulations
cdf
simulations
simulations neglecting cov. of null tests

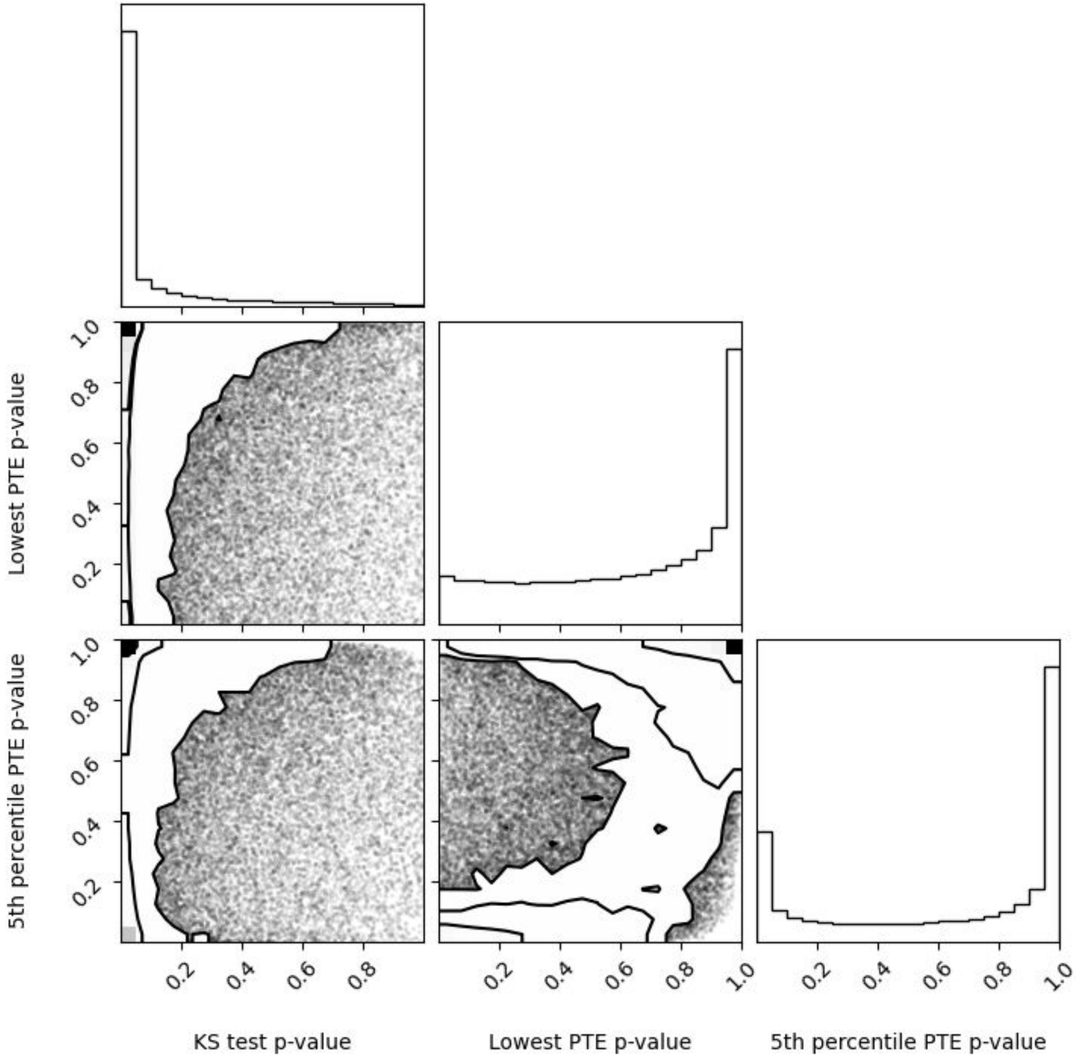

Rank statistic 1/135 p-values, 100,000 simulations
simulations
simulations neglecting cov. of null tests
pdf
10^1
10^0
0.0
0.2
0.4
0.6
0.8
1.0
Rank statistic 1/135 p-values, 100,000 simulations
simulations
simulations neglecting cov. of null tests
cdf
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0



5th percentile PTE p-values, 100,000 simulations
simulations
simulations neglecting cov. of null tests
pdf
10^1
10^0
0.0
0.2
0.4
0.6
0.8
1.0



5th percentile PTE p-values, 100,000 simulations
simulations
simulations neglecting cov. of null tests
cdf
0.0
0.2
0.4
0.6
0.8
1.0



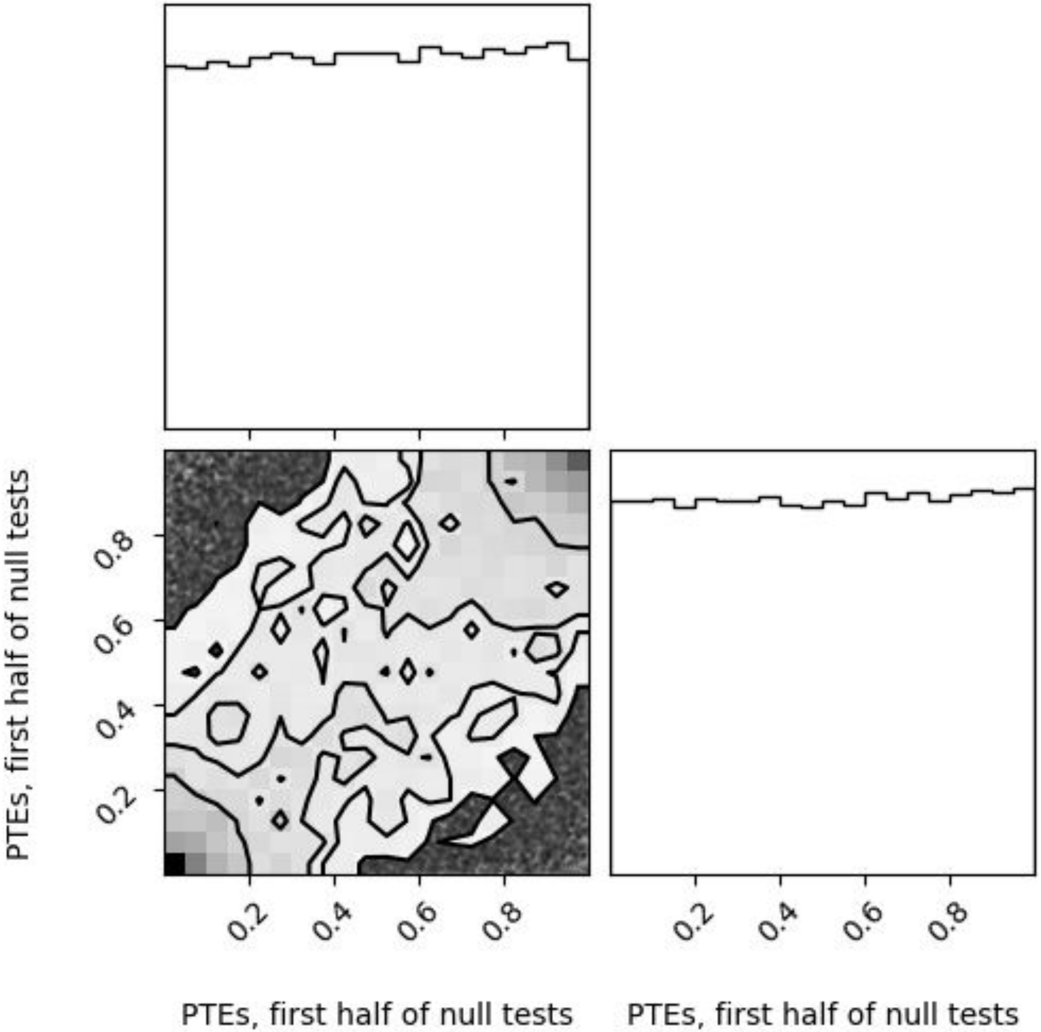
Lowest PTE p-value
5th percentile PTE p-value
0.2
0.4
0.6
0.8
1.0
KS test p-value
Lowest PTE p-value
5th percentile PTE p-value

Choice of summary of summaries + joint distributions

Same setup as before except:

- Tile cov template for 20 blocks
- Form all spectrum null tests for first 10 blocks and second 10 blocks separately for 1,000 simulations
- For each null test in each half of null tests, calculate PTE(χ^2) (2 x 135 x 1,000)
- (Don't push through to summary of summaries, just plot raw PTE(χ^2))

Simulates a pair of "systematics-targeting" null tests (e.g., PWV and Elevation)



PTEs, first half of null tests
0.2
0.4
0.6
0.8
0.2
0.4
0.6
0.8
PTEs, first half of null tests
0.2
0.4
0.6
0.8
PTEs, first half of null tests

Null test design choices...summary

Choice of summary of null: throw kitchen sink at problem?

Choice of summary of summaries: throw kitchen sink at problem?

Modeling joint distributions of summaries (of summaries) important

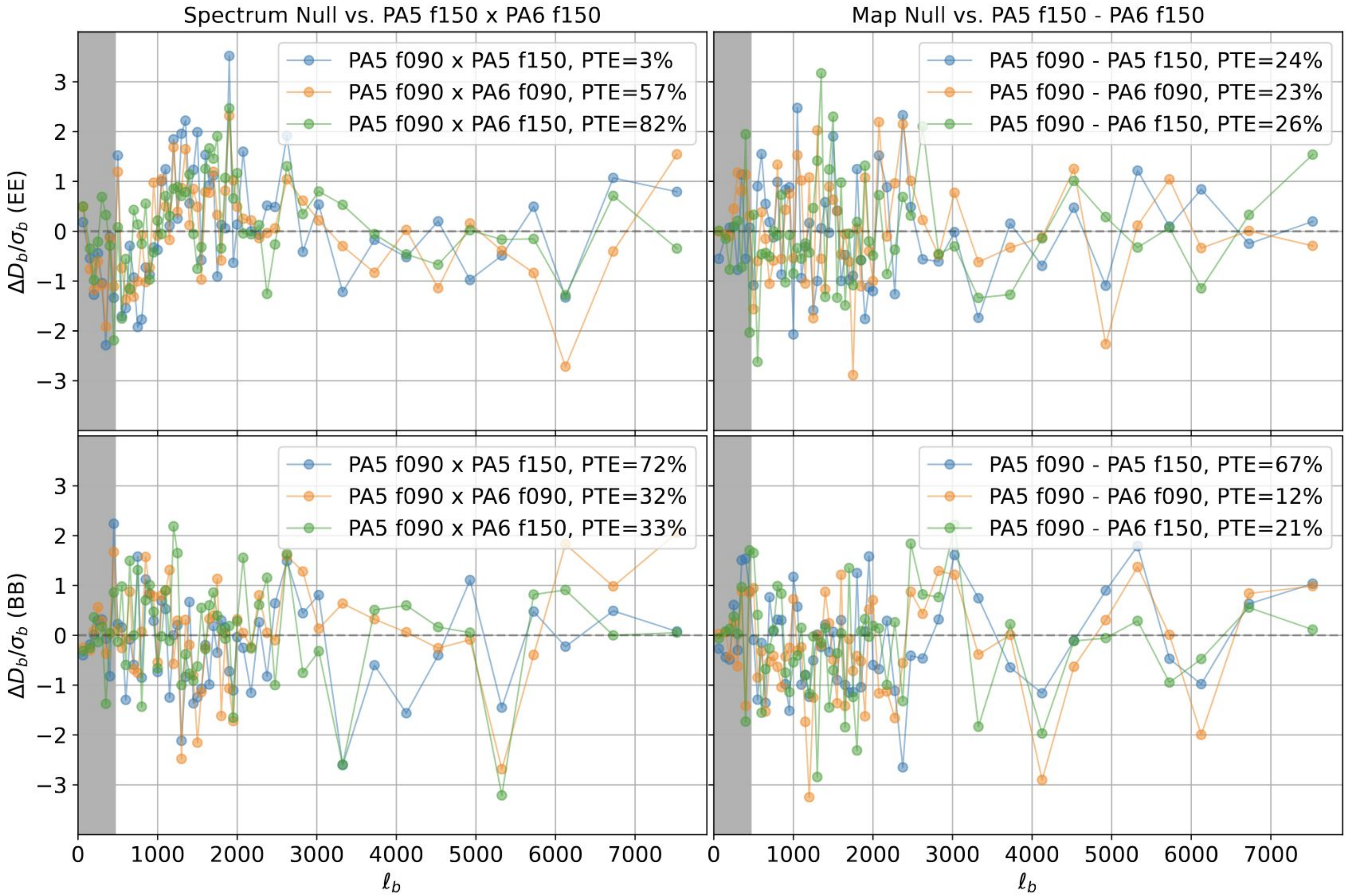
Why do test → summaries → summaries of summaries → etc. in the first place?

Ultimately, we want:

→ Evaluate likelihood P(d|Model excl. cosmology)

→ Provide feedback to instrumentalists etc. before unblinding

A complementary null test: motivation from ACT DR6



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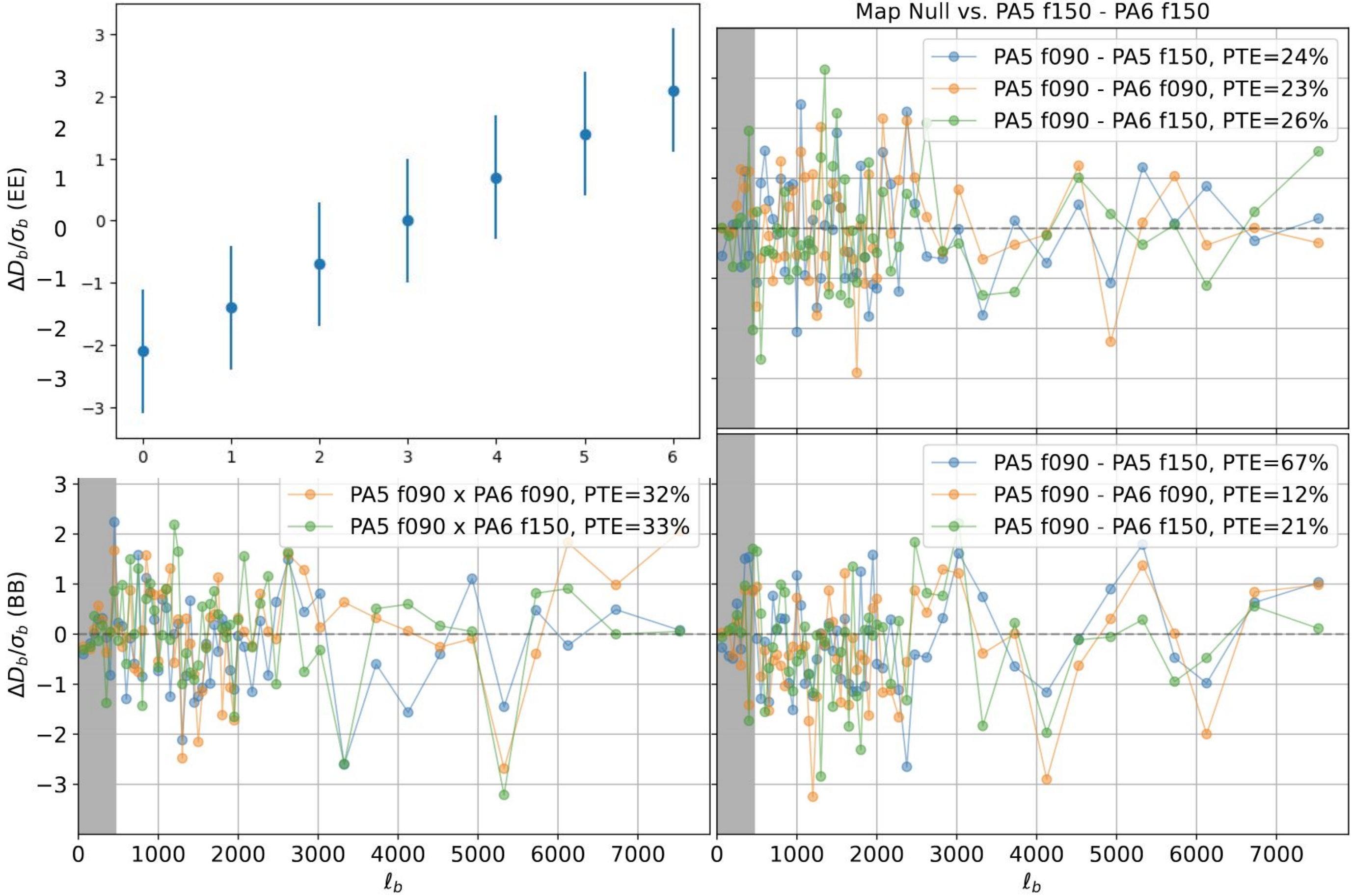
A complementary null test: motivation from ACT DR6



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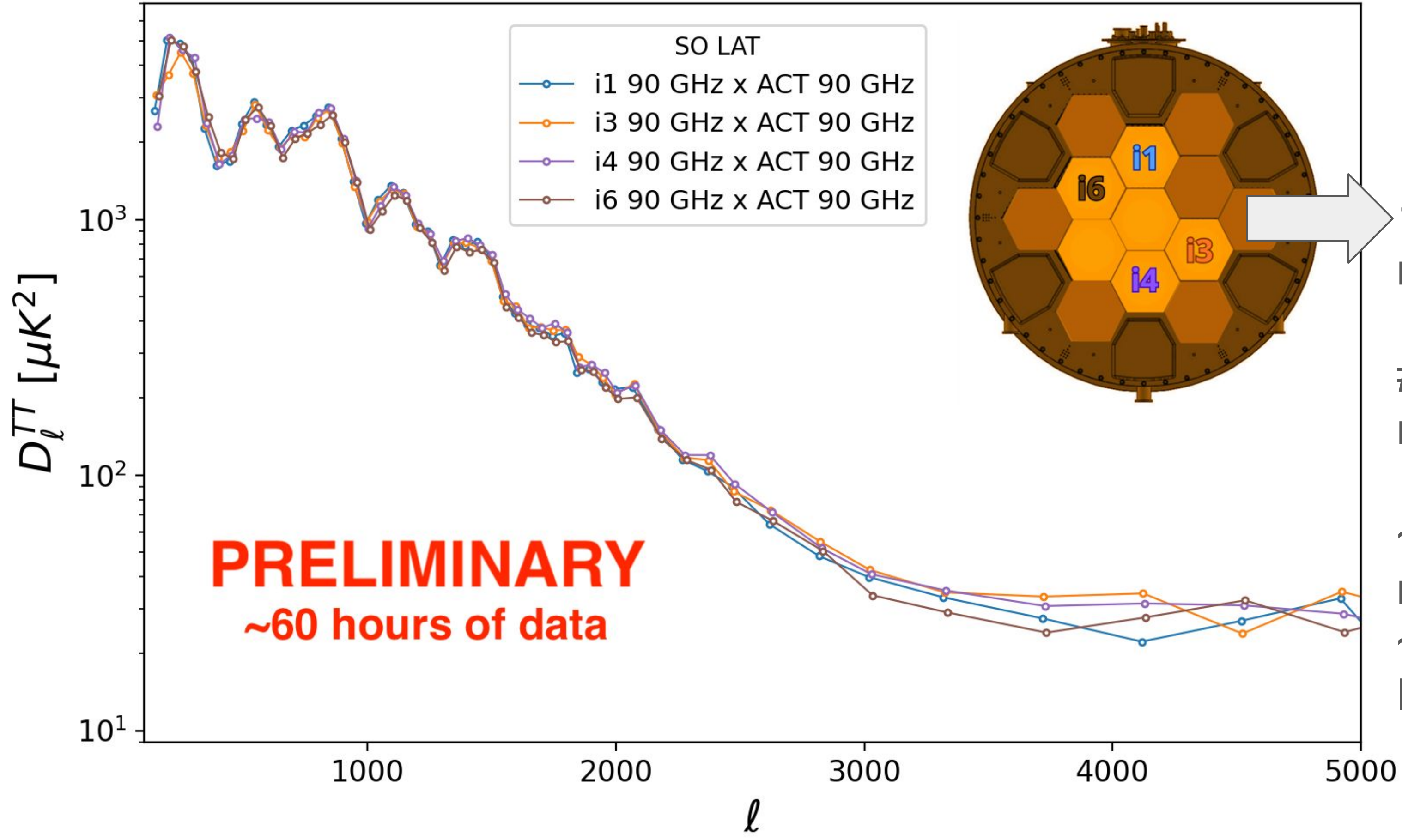
A complementary null test: motivation from SO



13 tubes → 26 maps (DR6: 4)

Null tests ~ maps^4

~100s DR6 null tests → ~100,000s SO LAT null tests

pc: Merry Duparc and SO

A map-level, linear summary statistic

Assume some baseline sky model, model map-level perturbations:

$$\begin{pmatrix} \tilde{T^{\alpha}_{\ell m}} \\ \tilde{E^{\alpha}_{\ell m}} \end{pmatrix} = \begin{pmatrix} 1+\delta_\ell^{T_\alpha} & \gamma_\ell^\alpha \\ \gamma_\ell^\alpha & 1+\delta_\ell^{E_\alpha} \end{pmatrix} \begin{pmatrix} T^{\alpha}_{\ell m} \\ E^{\alpha}_{\ell m} \end{pmatrix}$$

Effect on spectra:

$$\begin{pmatrix} \tilde{C}_\ell^{T_\alpha,T_\beta} \\ \tilde{C}_\ell^{T_\alpha,E_\beta} \\ \tilde{C}_\ell^{E_\alpha,T_\beta} \\ \tilde{C}_\ell^{E_\alpha,E_\beta} \end{pmatrix} = \begin{pmatrix} (1+\delta_\ell^{T_\alpha})(1+\delta_\ell^{T_\beta}) & (1+\delta_\ell^{T_\alpha})\gamma_\ell^\beta & \gamma_\ell^\alpha(1+\delta_\ell^{T_\beta}) & \gamma_\ell^\alpha\gamma_\ell^\beta \\ (1+\delta_\ell^{T_\alpha})\gamma_\ell^\beta & (1+\delta_\ell^{T_\alpha})(1+\delta_\ell^{E_\beta}) & \gamma_\ell^\alpha\gamma_\ell^\beta & \gamma_\ell^\alpha(1+\delta_\ell^{E_\beta}) \\ \gamma_\ell^\alpha(1+\delta_\ell^{T_\beta}) & \gamma_\ell^\alpha\gamma_\ell^\beta & (1+\delta_\ell^{E_\alpha})(1+\delta_\ell^{T_\beta}) & (1+\delta_\ell^{E_\alpha})\gamma_\ell^\beta \\ \gamma_\ell^\alpha\gamma_\ell^\beta & \gamma_\ell^\alpha(1+\delta_\ell^{E_\beta}) & (1+\delta_\ell^{E_\alpha})\gamma_\ell^\beta & (1+\delta_\ell^{E_\alpha})(1+\delta_\ell^{E_\beta}) \end{pmatrix} \begin{pmatrix} C_\ell^{T_\alpha,T_\beta} \\ C_\ell^{T_\alpha,E_\beta} \\ C_\ell^{E_\alpha,T_\beta} \\ C_\ell^{E_\alpha,E_\beta} \end{pmatrix}$$

Linearize:

$$\begin{pmatrix} \tilde{C}_\ell^{T_\alpha,T_\beta} \\ \tilde{C}_\ell^{T_\alpha,E_\beta} \\ \tilde{C}_\ell^{E_\alpha,T_\beta} \\ \tilde{C}_\ell^{E_\alpha,E_\beta} \end{pmatrix} = \begin{pmatrix} 1+\delta_\ell^{T_\alpha}+\delta_\ell^{T_\beta} & \gamma_\ell^\beta & \gamma_\ell^\alpha & 0 \\ \gamma_\ell^\beta & 1+\delta_\ell^{T_\alpha}+\delta_\ell^{E_\beta} & 0 & \gamma_\ell^\alpha \\ \gamma_\ell^\alpha & 0 & 1+\delta_\ell^{E_\alpha}+\delta_\ell^{T_\beta} & \gamma_\ell^\beta \\ 0 & \gamma_\ell^\alpha & \gamma_\ell^\beta & 1+\delta_\ell^{E_\alpha}+\delta_\ell^{E_\beta} \end{pmatrix} \begin{pmatrix} C_\ell^{T_\alpha,T_\beta} \\ C_\ell^{T_\alpha,E_\beta} \\ C_\ell^{E_\alpha,T_\beta} \\ C_\ell^{E_\alpha,E_\beta} \end{pmatrix}$$

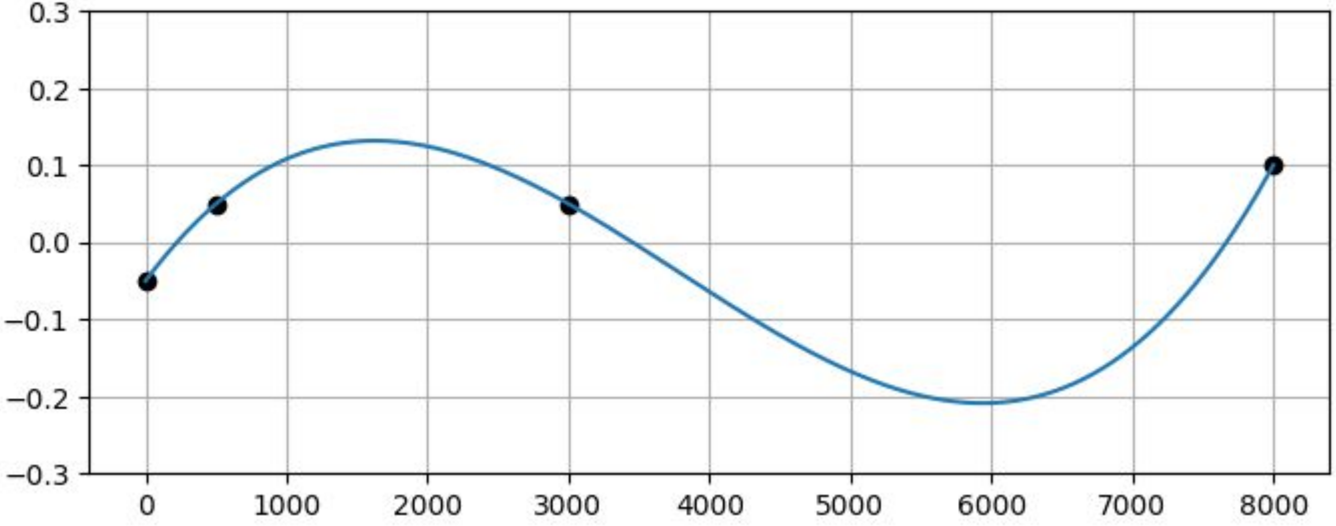
Choose parameterization for $\delta_\ell^T, \gamma_\ell, \delta_\ell^E$

Want model that is (1) linear, (2) expressive, (3) robust

Cubic spline: (1) and (2)

Linear spline: (1) and (3)

Pick cubic spline:



Make model parameters indep. of cosmology template

Setup:

- 3 kinds of systematics: $\delta_\ell^T, \gamma_\ell, \delta_\ell^E$
- Each map gets one of each (Nmaps): $\delta_\ell^{T_\alpha}, \gamma_\ell^\alpha, \delta_\ell^{E_\alpha}$
- For fixed spline x-values, fit the y-values (Nknots): $\boxed{\delta_{\{i\}}^{T_\alpha}, \gamma_{\{i\}}^\alpha, \delta_{\{i\}}^{E_\alpha}}$

Independent from cosmology (to 1st order) if (e.g.): $\Sigma_\alpha \delta_{\{i\}}^{T_\alpha} = 0$

- Enforce with Nmaps x (Nmaps - 1) matrix
- Nmaps - 1 latent parameters ~ “linearly indep. differences vs. the mean”

Total params = 3 * (Nmaps - 1) * Knots

Distribution of Model

Total model = Linear → Just a matrix! → **knts2spec** (d.size x # total params)

Model distribution:

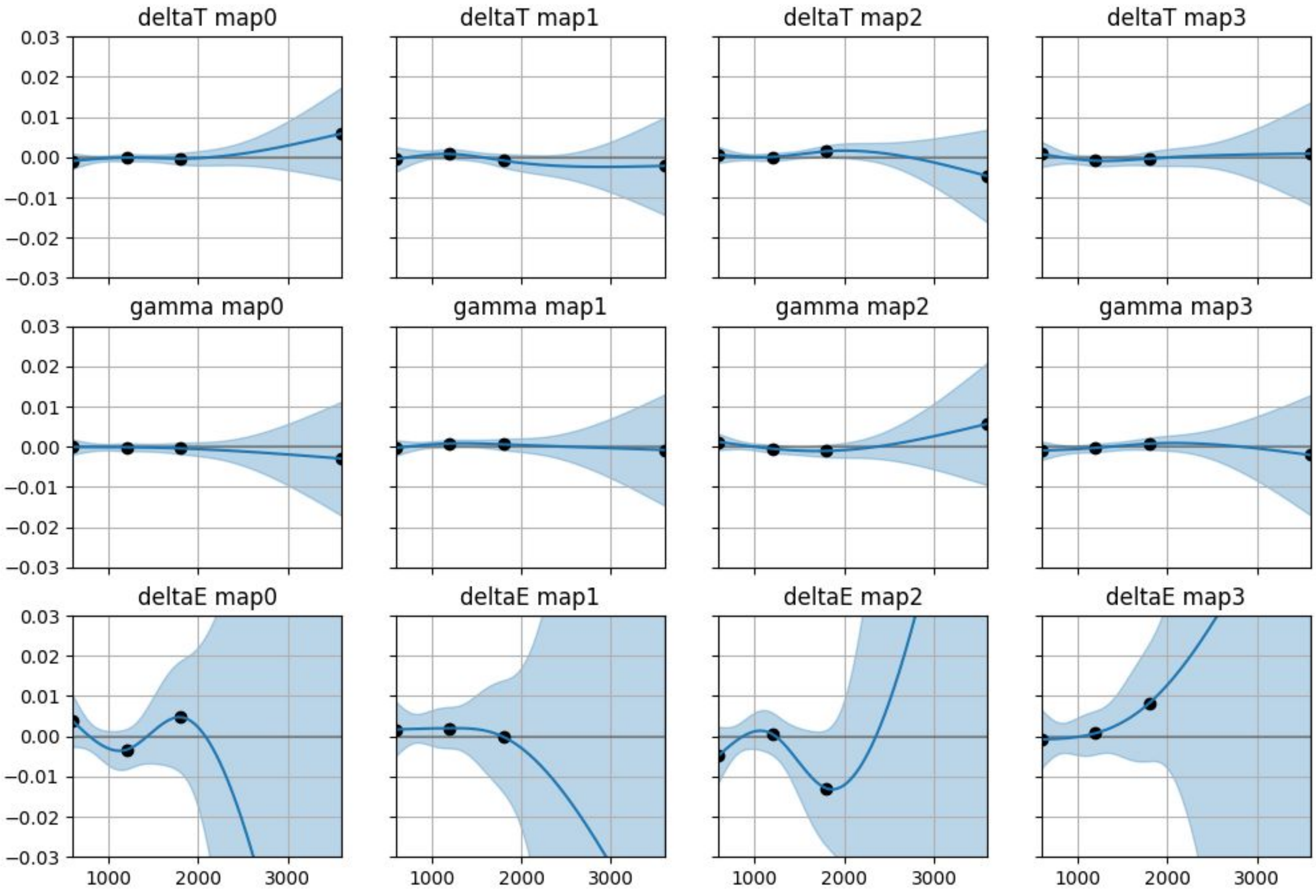
- mean: **(knts2spec * cov^{-1} * knts2spec.T)$^{-1}$ * knts2spec.T * cov^{-1} * d**
- covariance: **(knts2spec * cov^{-1} * knts2spec.T)$^{-1}$**

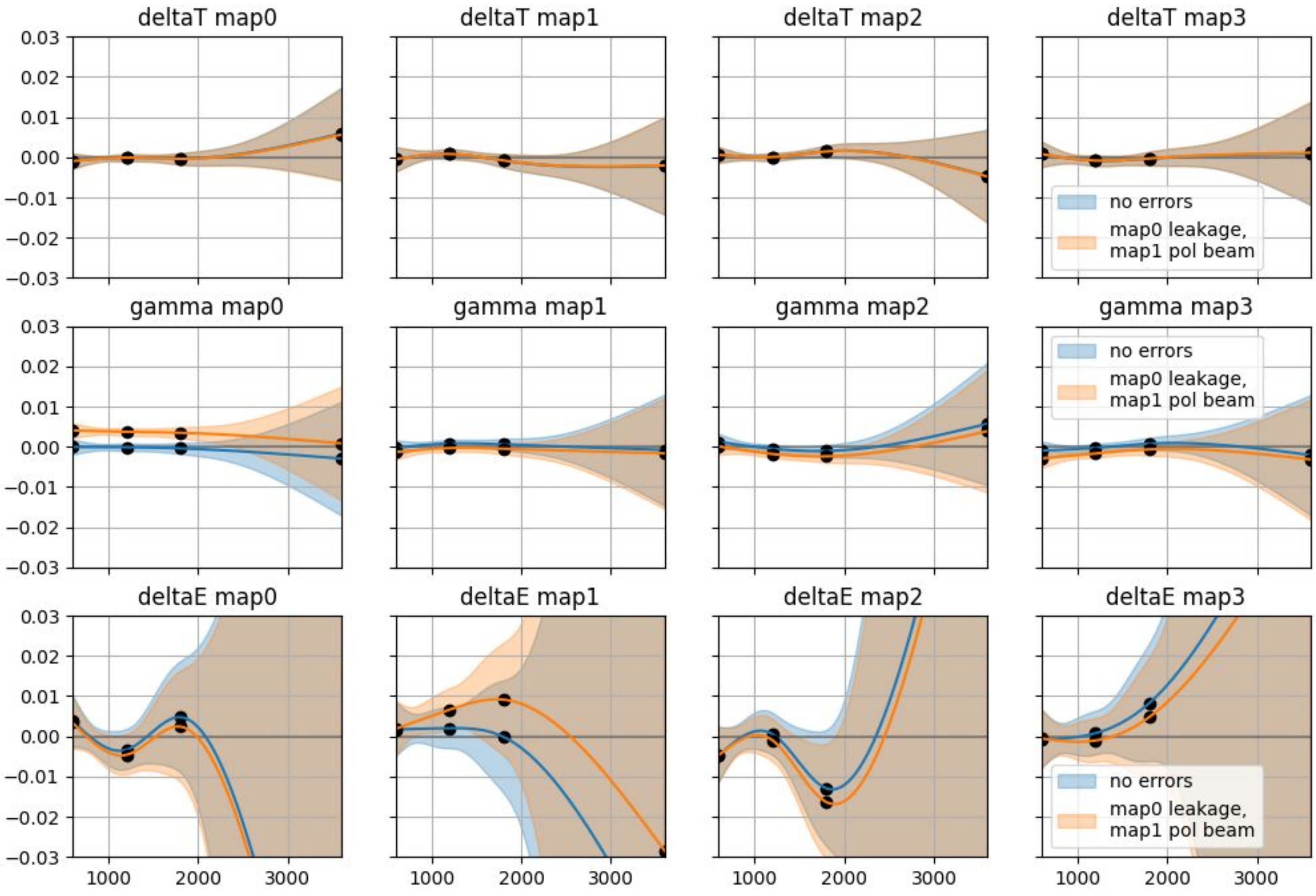
Fast, interpretable, low-dimensional!

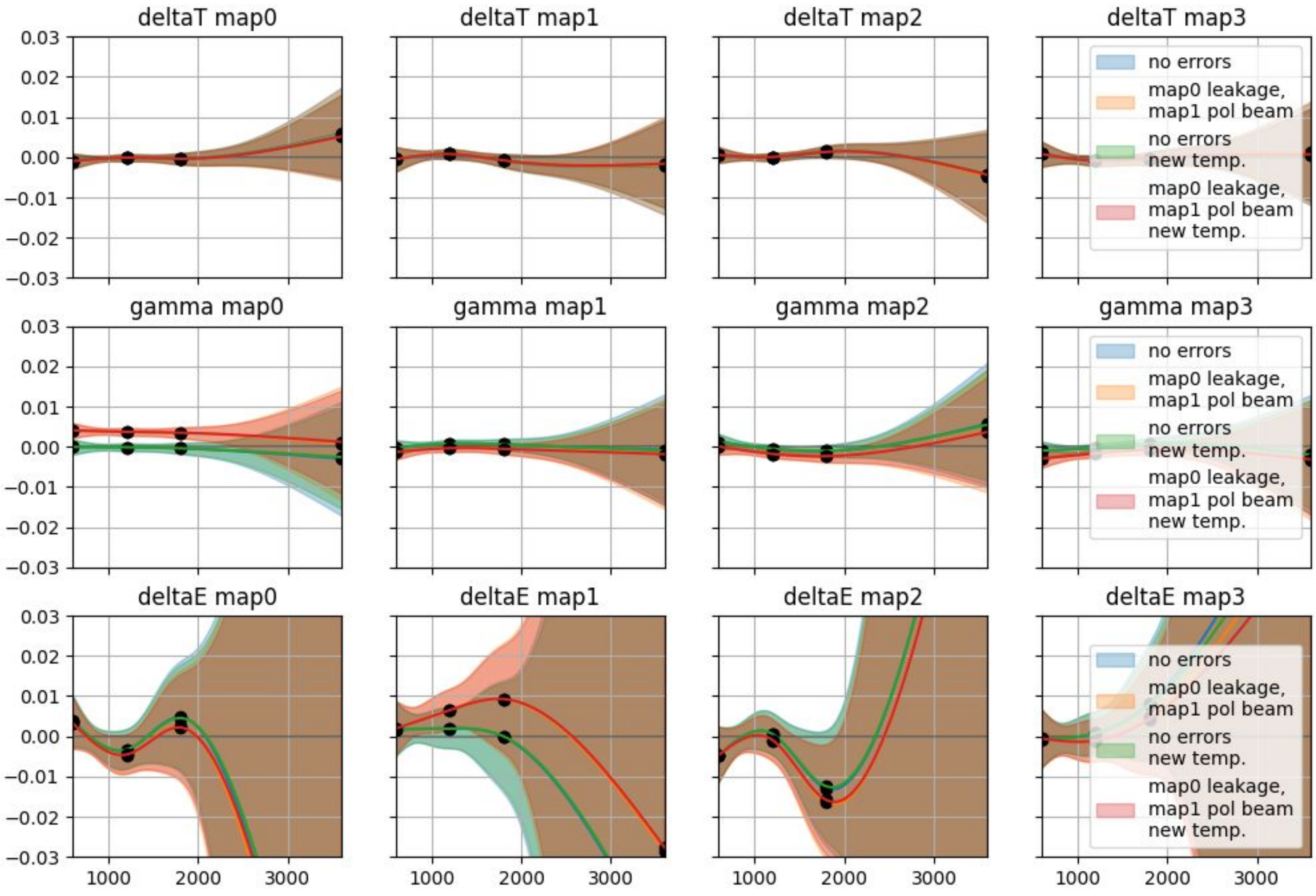
Let’s try it out

Setup:

- Borrow the ACT DR6 covariance matrix*
- Draw 10,000 simulations with no errors and a “correct” cosmology template
- Repeat, add 0.5% leakage to one map and 1%/1000 ell pol beam error to another map in each simulation
- Repeat both with a “very wrong” cosmology template (Cl += 5%/1000 ell)


deltaT map0
deltaT map1
deltaT map2
deltaT map3
gamma map0
gamma map1
gamma map2
gamma map3
deltaE map0
deltaE map1
deltaE map2
deltaE map3
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
1000
2000
3000


deltaT map0
deltaT map1
deltaT map2
deltaT map3
gamma map0
gamma map1
gamma map2
gamma map3
deltaE map0
deltaE map1
deltaE map2
deltaE map3
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
1000
2000
3000
no errors
map0 leakage, map1 pol beam

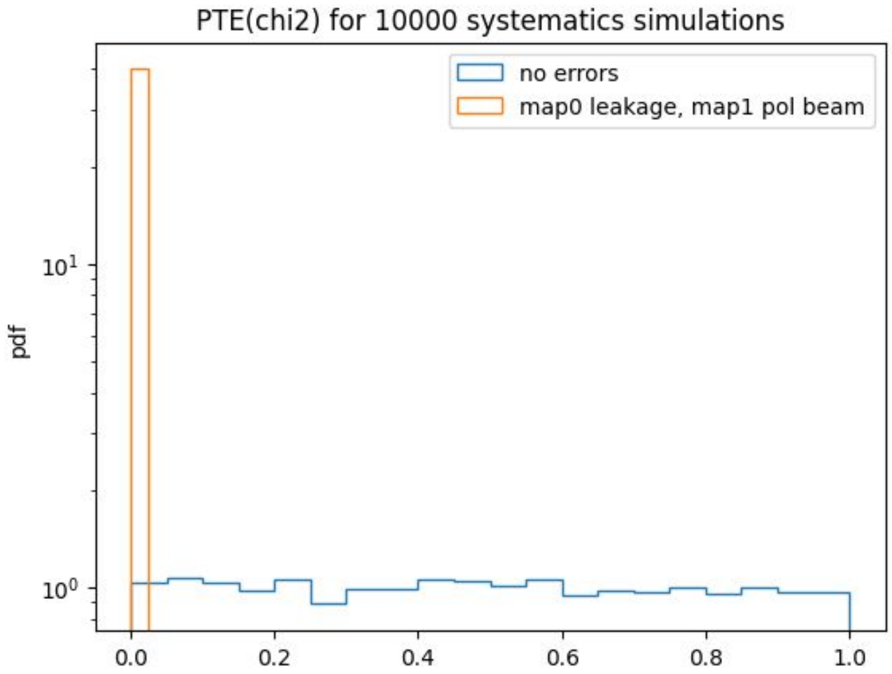


deltaT map0
deltaT map1
deltaT map2
deltaT map3
gamma map0
gamma map1
gamma map2
gamma map3
deltaE map0
deltaE map1
deltaE map2
deltaE map3
no errors
map0 leakage, map1 pol beam
no errors new temp.
map0 leakage, map1 pol beam new temp.
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
1000
2000
3000

Last note on this

Need to be careful with look-elsewhere effect when inspecting specific parameters!

“Global” PTE of the parameter vector still sensible though:



Summary to end all summaries…

1. Current null test “paradigm” a bit contrived in my opinion, “best practices” not well studied
2. More work needed on modeling joint distribution of summary statistics
3. Interesting new pathways for null tests (map-level)

Null tests independent of cosmology/shared sky model

= Null tests **cannot** measure or rule-out systematics common to observation channels

Three important ways around this:

1. Calibration
2. Calibration
3. Calibration

Backup

A lot to discuss

Topic is open-ended (and under-studied)

Can’t put all my thoughts in one talk, not sure what all my thoughts are

Excited to discuss more with anyone!

Cubic splines as a matrix

This link https://www.math.ntnu.no/emner/TMA4215/2008h/cubicsplines.pdf

Combine slides 16 and 19

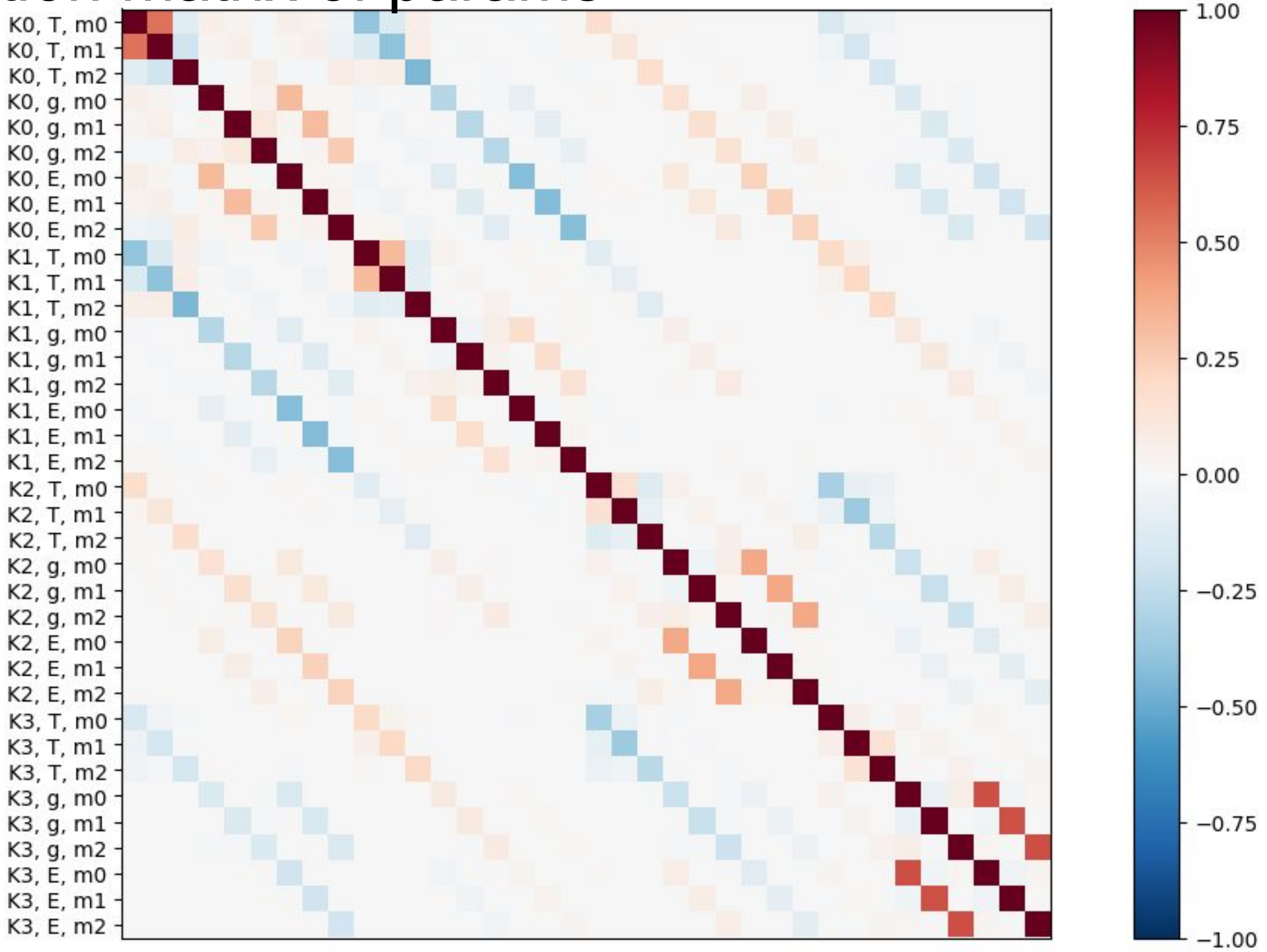
The magic Nmaps x Nmaps - 1 matrix

$\mathbf{C}_n \equiv \mathbf{I}_n - (1/n)\mathbf{J}_n$, where J_n is the $n \times n$ matrix full of ones.

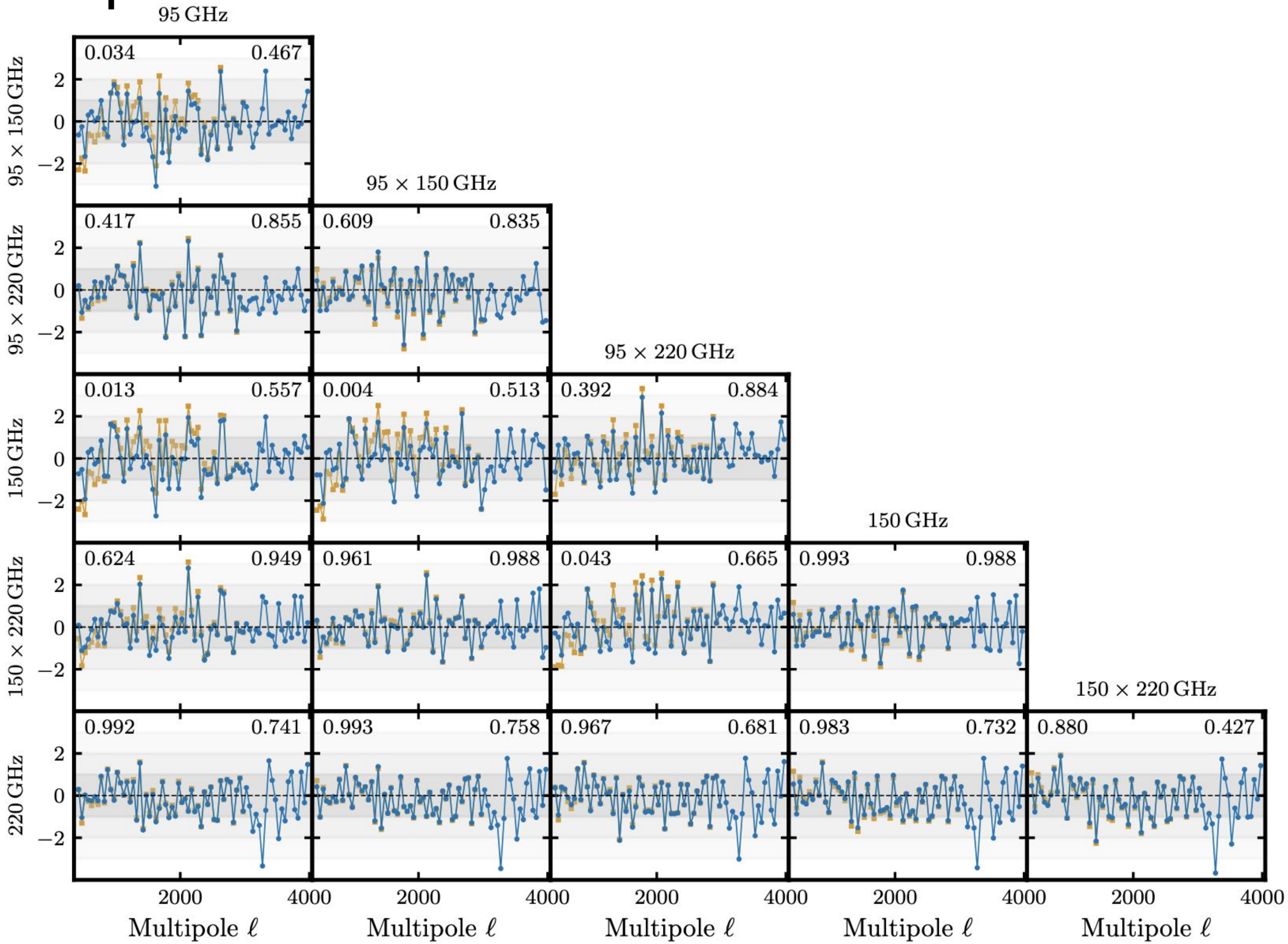
$\mathbf{C}_n \equiv \mathbf{P}_n \mathbf{E}_n \mathbf{P}_n^T$: singular value corresponds to the null space of $\mathbf{C}_n$, $\vec{1}_n$

define $\mathbf{Z}_n$ instead: the matrix composed of the $n-1$ non-singular column vectors of $\mathbf{P}_n$

Correlation matrix of params



SPT D1 equivalent to ACT DR6 null tests



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