arXiv:2103.13334

B-mode constraint from SPIDER's first flight

with SMICA: a spectral based component separation pipeline

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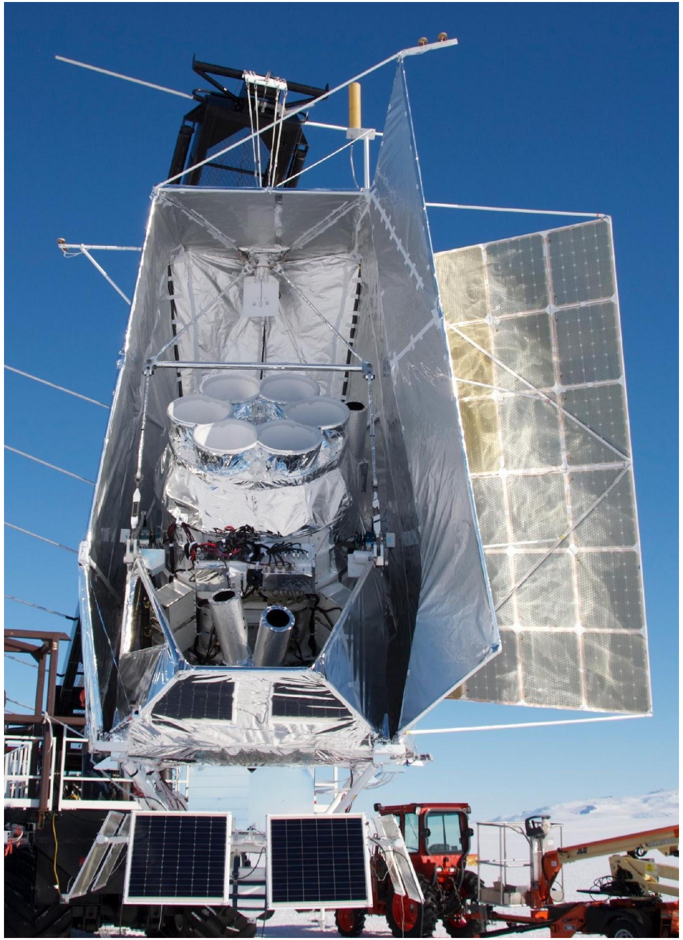
on behalf of the SPIDER Collaboration

2021 Aug 13 CMB S4 Workshop

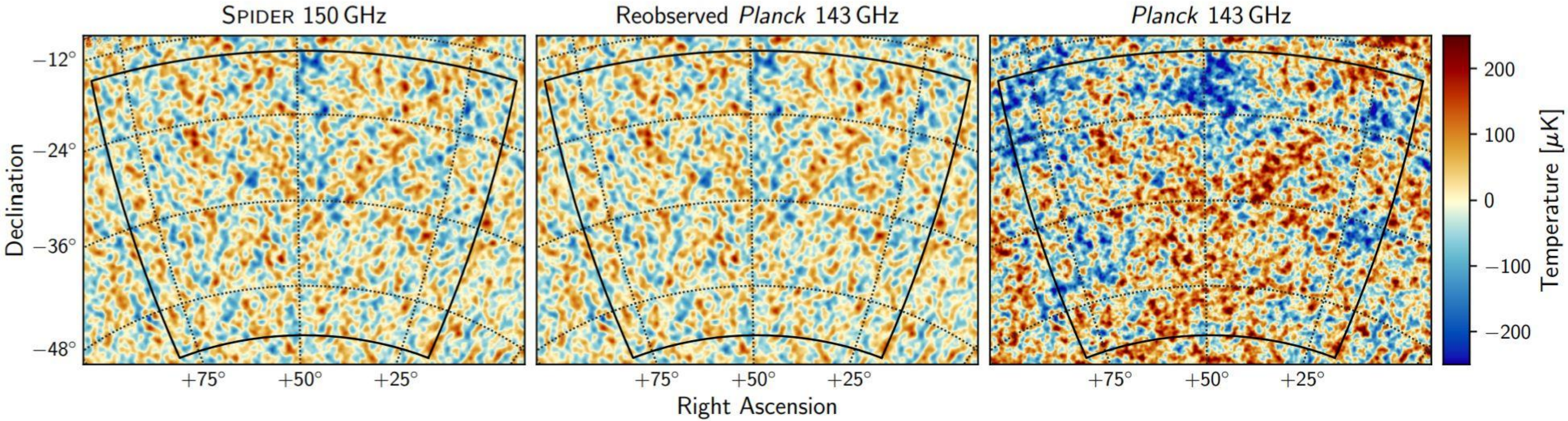
Intro to SPIDER

- Balloon-borne CMB polarimeter with the goal of measuring r
- 6 telescopes (3 at 95 and 3 at 150 GHz) with 2400 antenna-coupled TESs
- Half-degree beams
- Flew for 16 days above Antarctica in January 2015, with **12 LST days** scientific data.
- **4.8%** of the sky used in first analysis
- A second flight with 280 GHz detectors…(someday)



Intensity Maps

*reobservation:
Using SPIDER scan strategy and filtering to observe planck maps

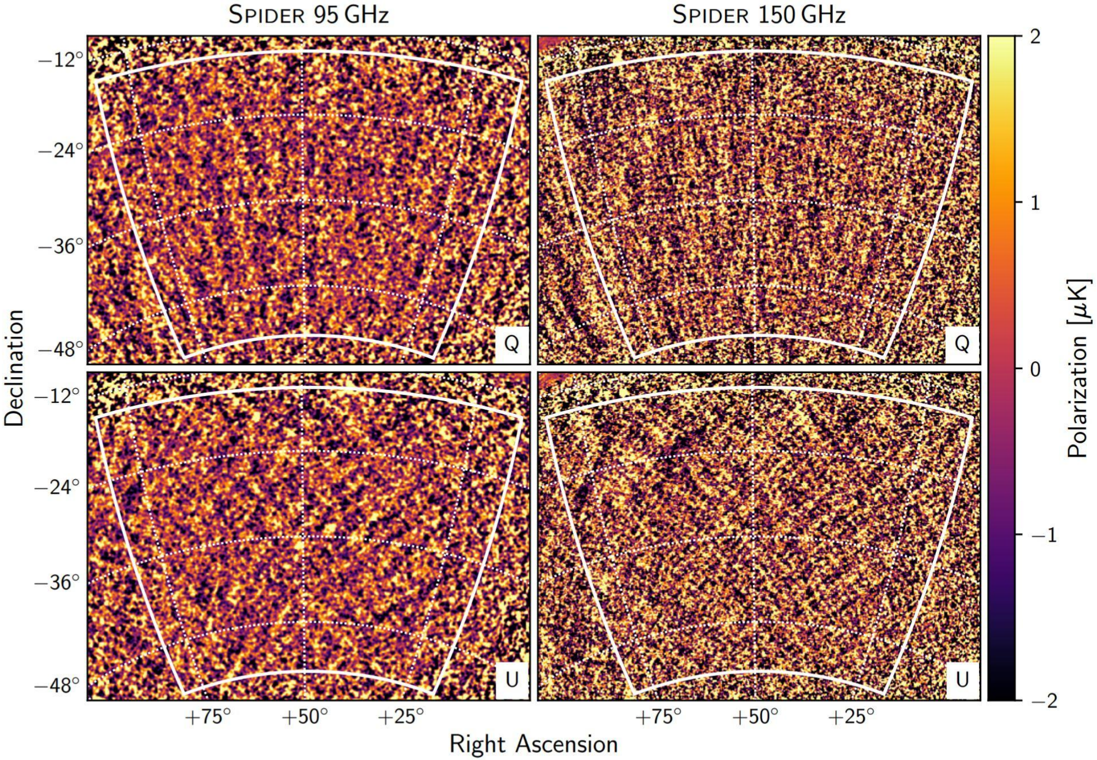


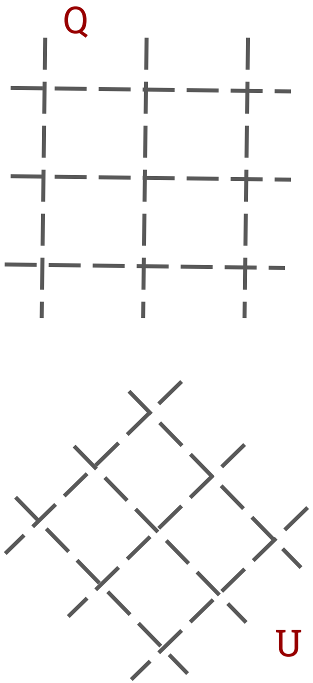
The comparison between re-observed planck map and raw planck map illustrates the impact of SPIDER'S scan strategy and filtering that suppresses power at large angular scales

Polarization Maps

The dominant E-mode pattern of the cosmological signature is evident in the maps, *and is diluted by the Galactic signal.*

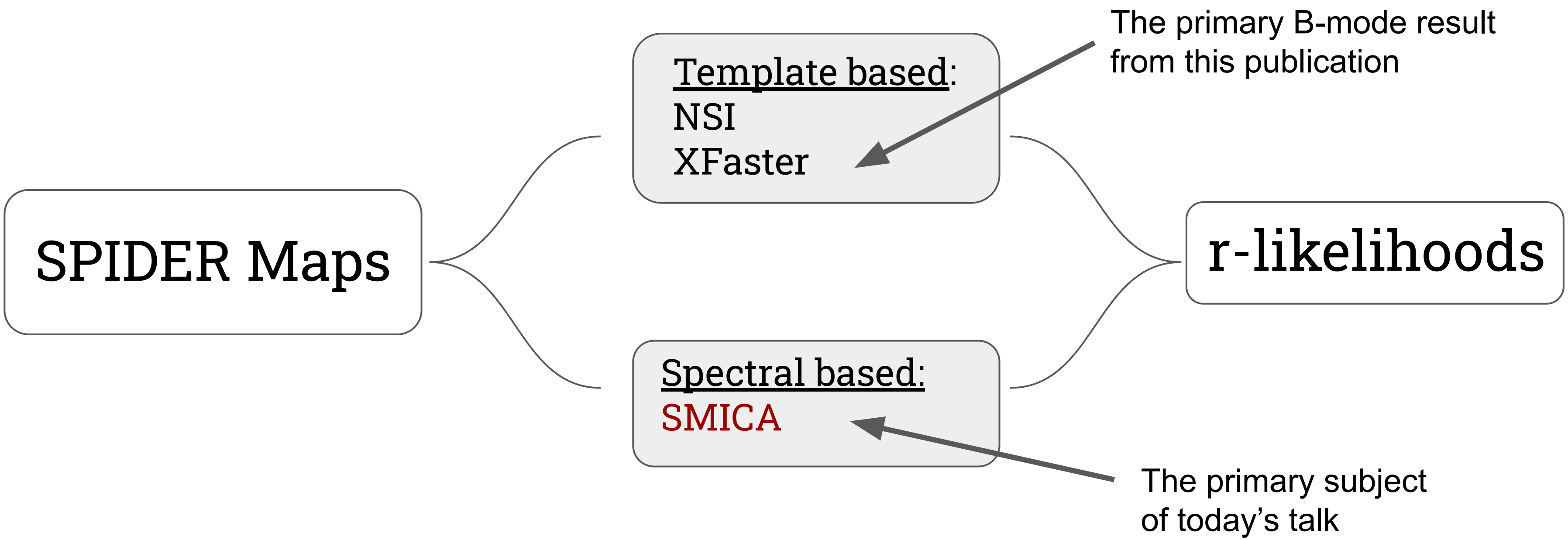
There are more structure in the 150GHz maps. (evidence of foreground power)





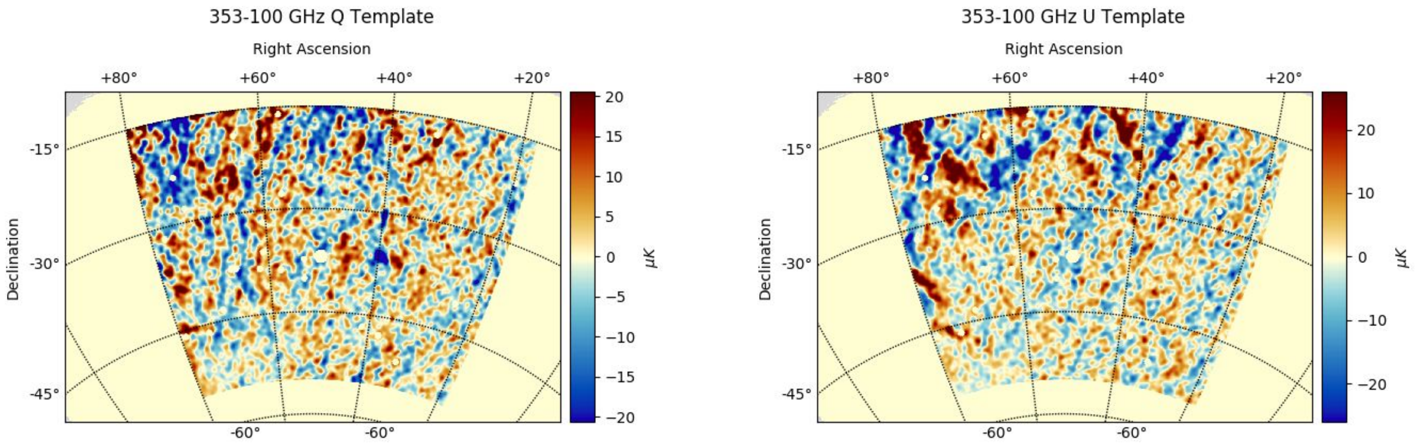
High level Analysis Outline

Foreground Cleaning methods



Template removal methods: XFaster and NSI

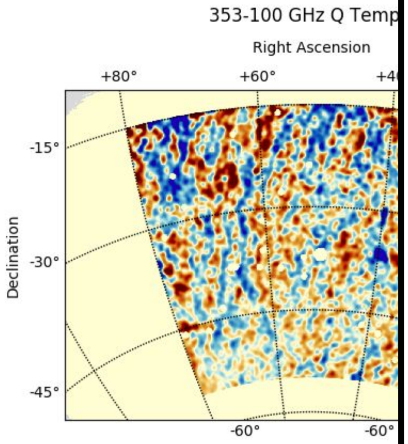
Construct foreground templates from Planck maps (353-100 or 217-100)

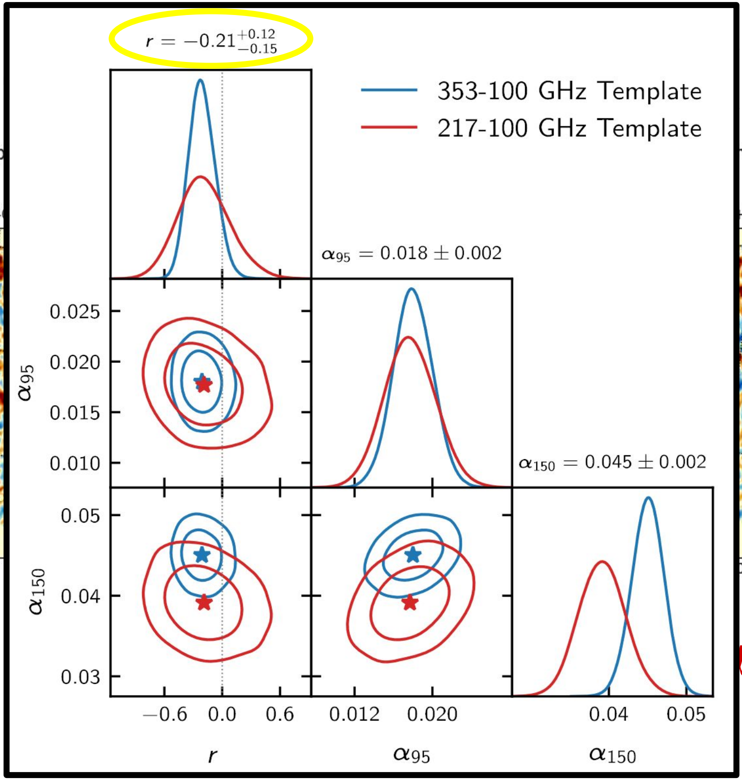


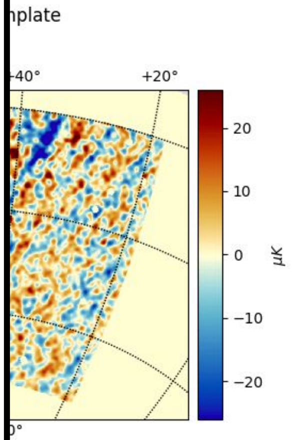
Minimize CMB power by fitting a scale parameter α.

Template removal methods: XFaster and NSI

Construct foreground t… 353-100 or 217-100)







Minimize CMB power … α.

XFaster jointly fits for α and *r* and provides the primary result

SMICA for SPIDER

Data covariance $\hat{R}_b$

- (2N x 2N) matrix where N = number of maps.
- Consisting of all auto and cross spectra
- Computed with PolSpice

Model Equation

Transfer matrix   fb = frequency scaling

$$\tilde{R}_b(\theta) = \tilde{N}_b + \sum_{b'} J_{b,b'} \left[f_{b'} P_{b'} f_{b'}^T + C_{b'} \right]$$

Noise   Dust   CMB

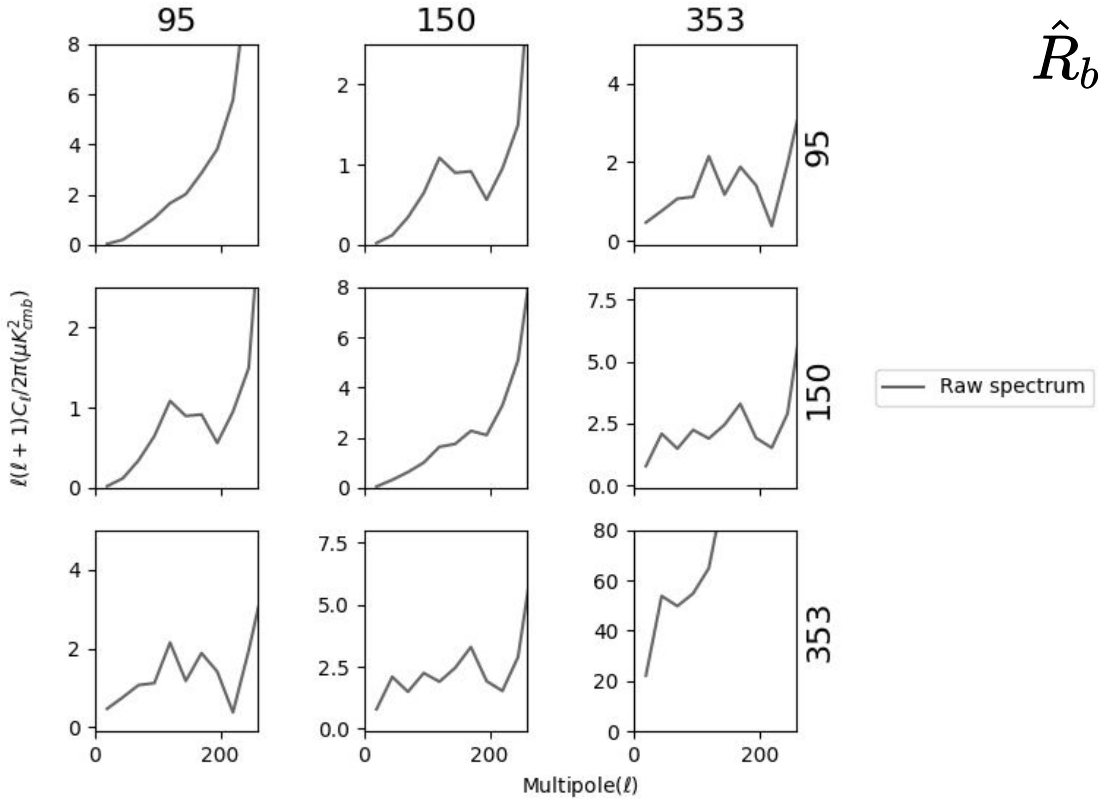
Likelihood (Kullback-Leibler divergence)

$$-2\log L = \sum_b w_b Tr\left[\hat{R}_b \tilde{R}_b^{-1}(\theta) - \ln\left(\hat{R}_b \tilde{R}_b^{-1}(\theta)\right)\right]$$

$$w_b = \sum_{\ell \in b} (2\ell + 1) f_{sky}$$

SMICA for SPIDER

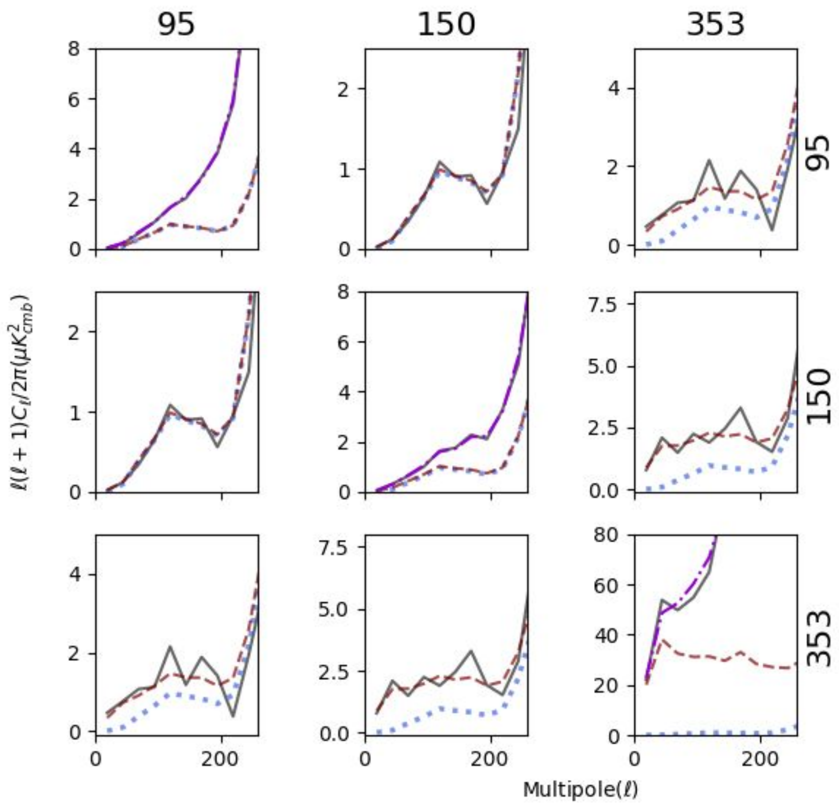
Pared down example EE only (95, 150, 353)



$\hat{R}_b$ Auto and cross spectra of inputs: spider (95, 150), planck 353

SMICA for SPIDER

Pared down example EE only (95, 150, 353)

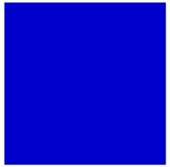


$\hat{R}_b$ Auto and cross spectra of inputs: spider (95, 150), planck 353

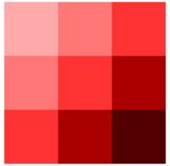
$\tilde{R}_b(\theta)$ Model fitted

Components are partitioned by spectral shape

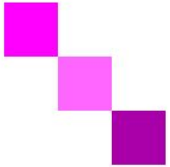
Uniform CMB



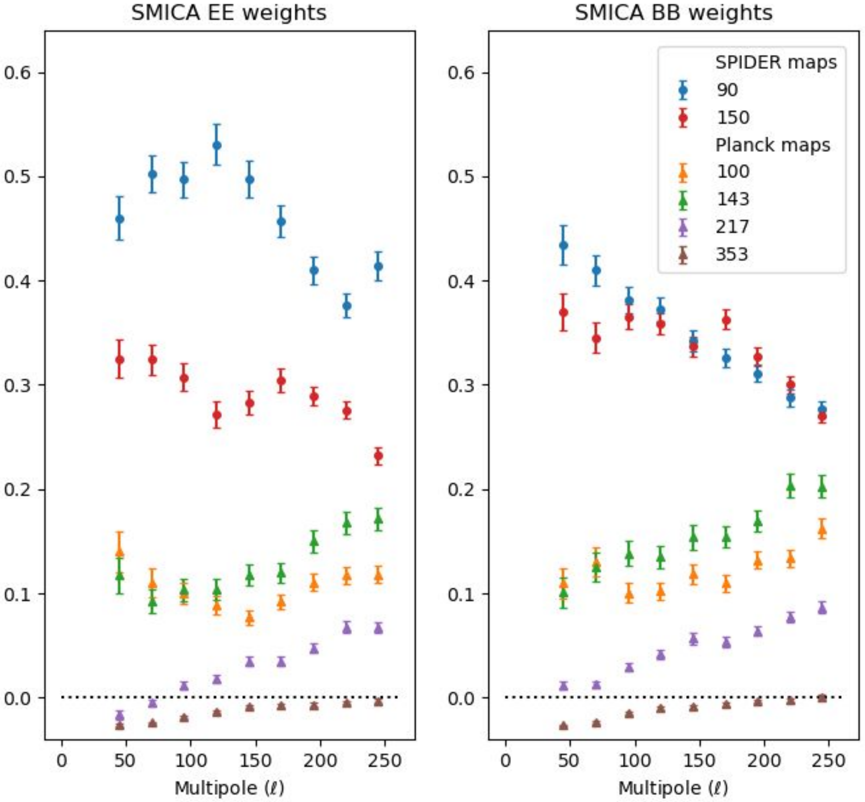
Dust scales with frequency



Diagonal Noise



SMICA, Component recovered CMB

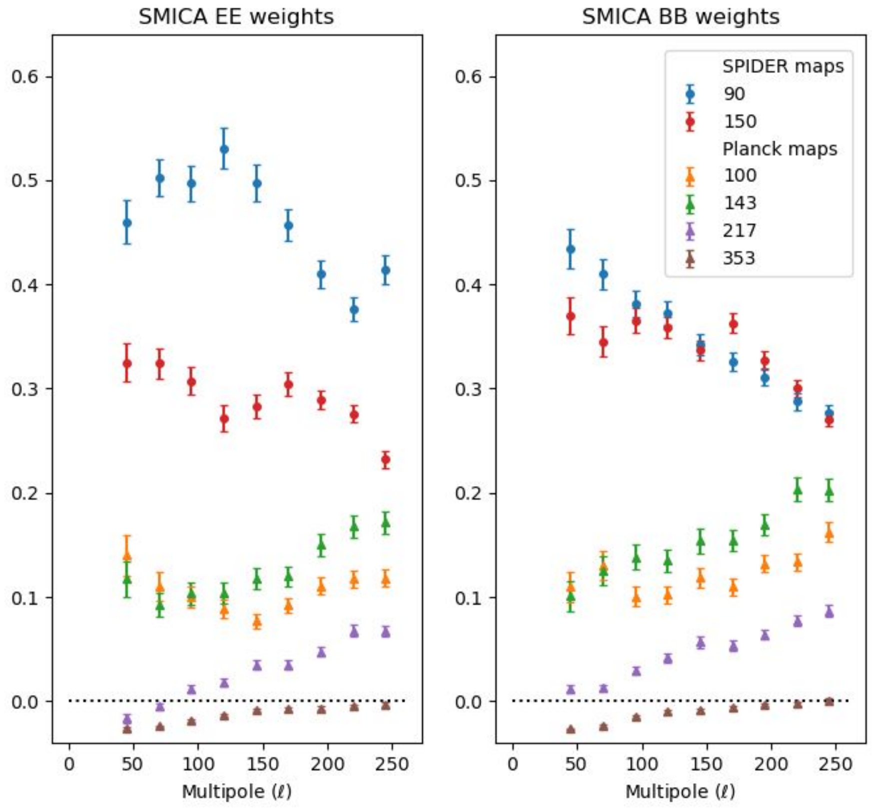


$$W_\ell = (A^T R_\ell^{-1} A)^{-1} R_\ell^{-1} A$$

R*l* = Model of the spectral covariance
A = spectral scaling of the desired component

The weights applied to each map to construct a component cleaned map

SMICA, Component recovered CMB

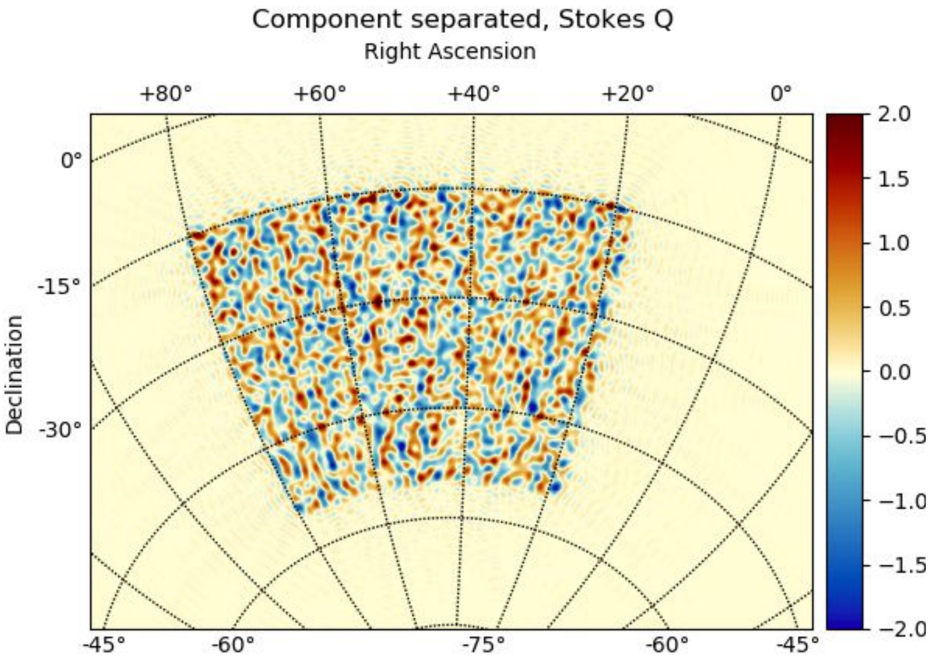


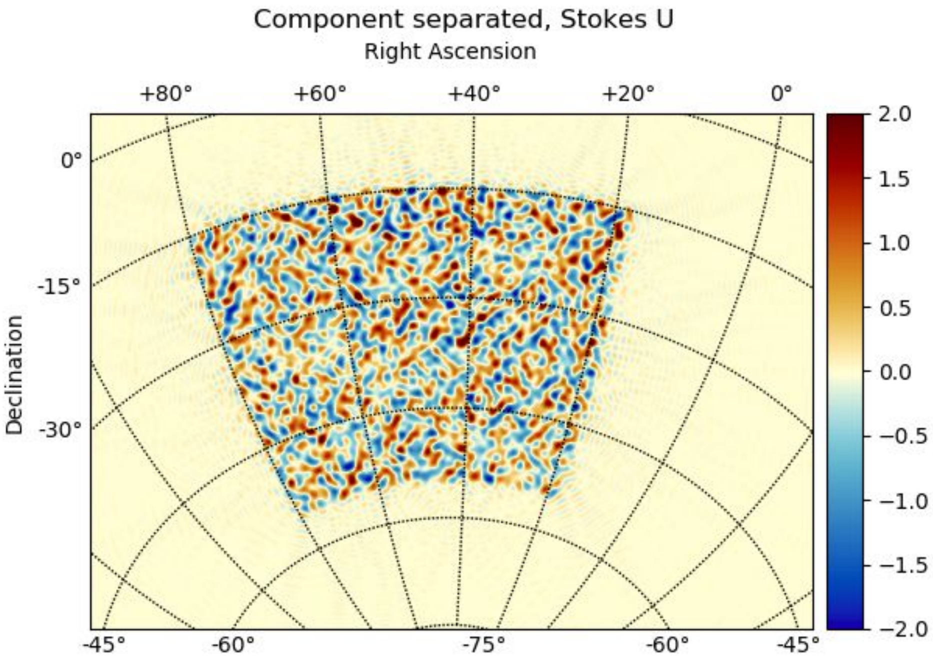
$$W_\ell = (A^T R_\ell^{-1} A)^{-1} R_\ell^{-1} A$$

SPIDER 90/150 has substantially higher weight than Planck equivalents

353 has a negative weight indicating it acts as a template (in preference over 217)

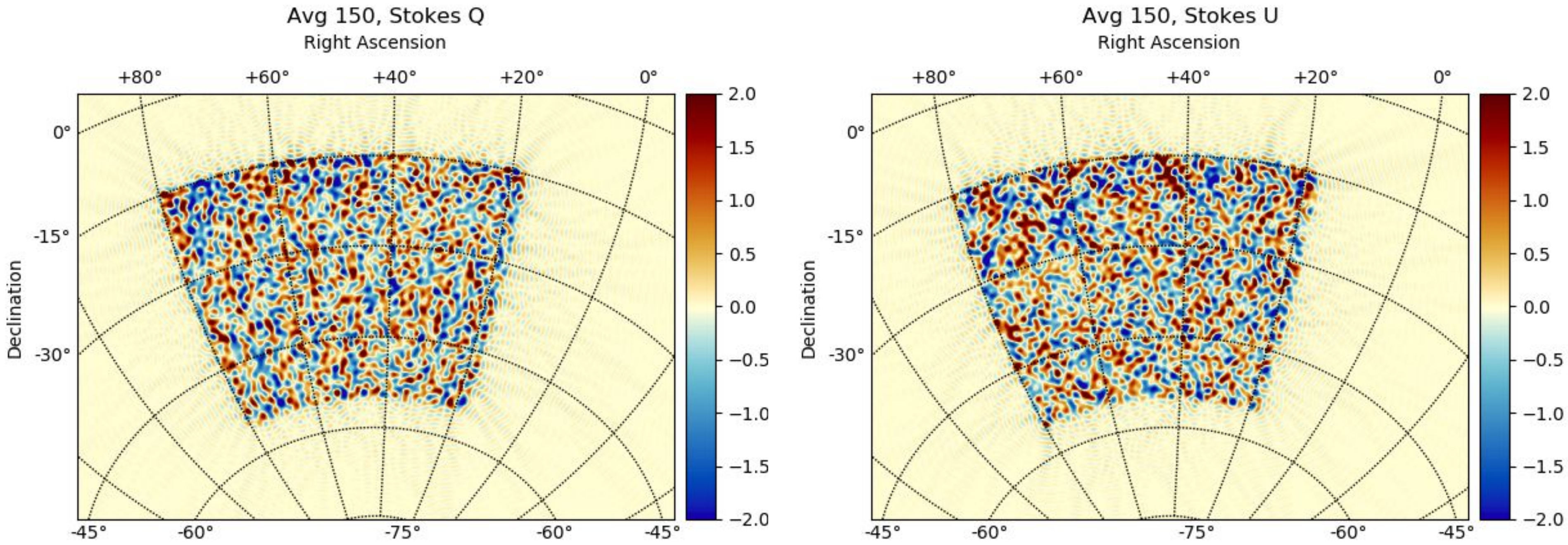
SMICA, Component recovered CMB





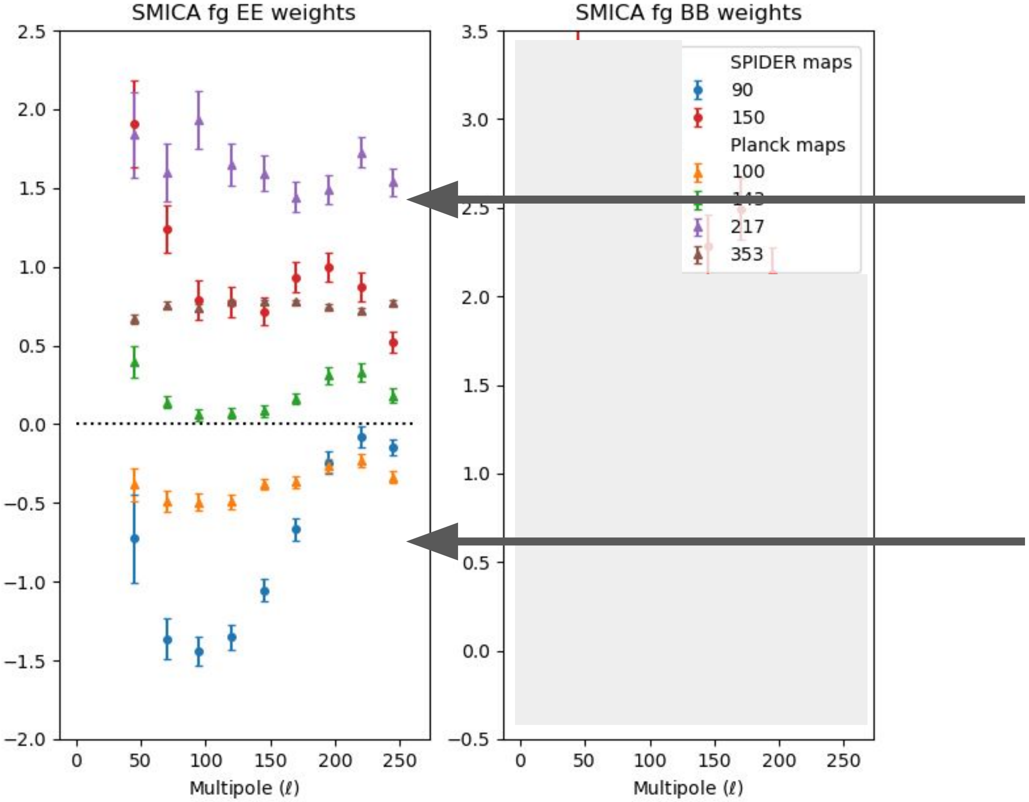
SMICA component cleaned map

SMICA, Component recovered CMB



Raw SPIDER map

SMICA, Component recovered fg

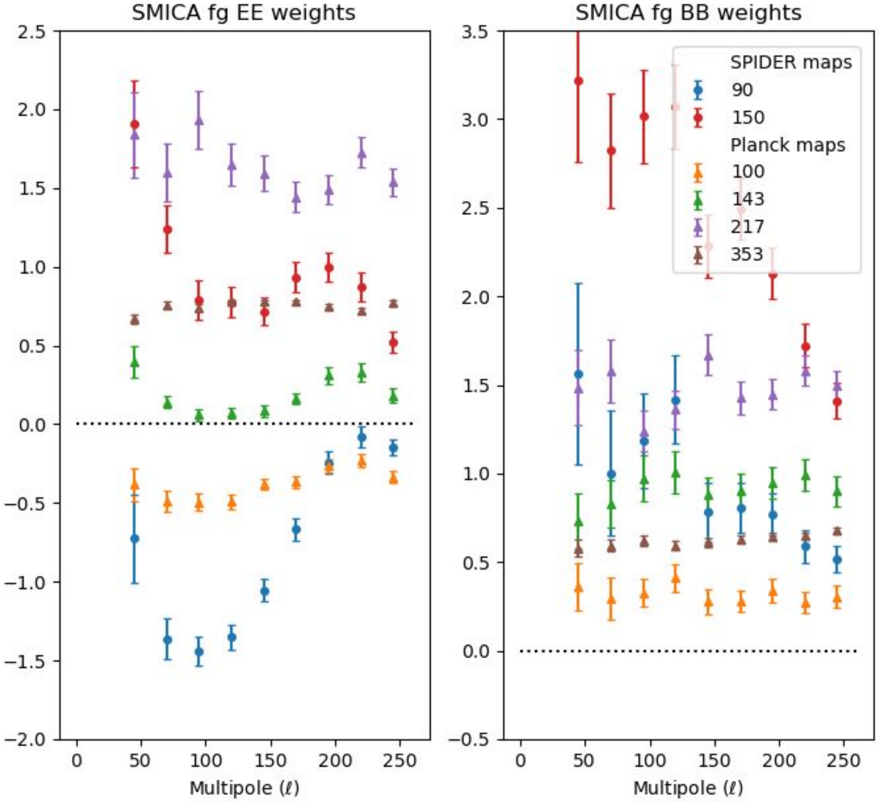


$$W_\ell = (A^T R_\ell^{-1} A)^{-1} R_\ell^{-1} A$$

Planck 217 appear to have the largest contribution (over 353) but remember that *weights act on alms* and Planck 353 has 4-5x more dust power

CMB must be cleaned from the foreground map so SPIDER 90 / Planck 100 have negative weights

SMICA, Component recovered fg

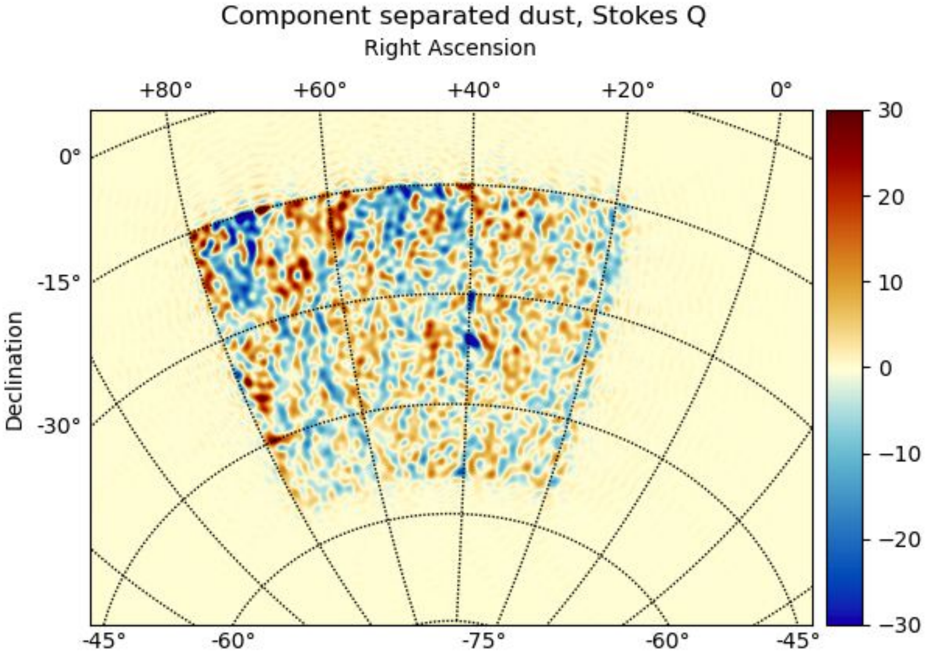


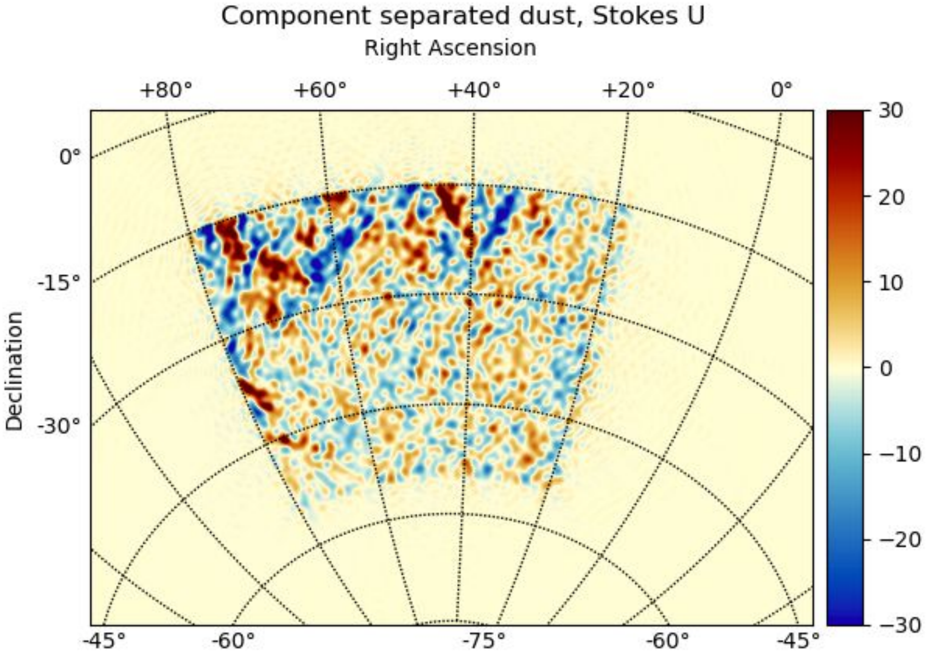
$$W_\ell = (A^T R_\ell^{-1} A)^{-1} R_\ell^{-1} A$$

Maps are weighted according to signal-to-noise on the only (fg) component.

No negative maps = SMICA believes there is no CMB power to subtract in BB

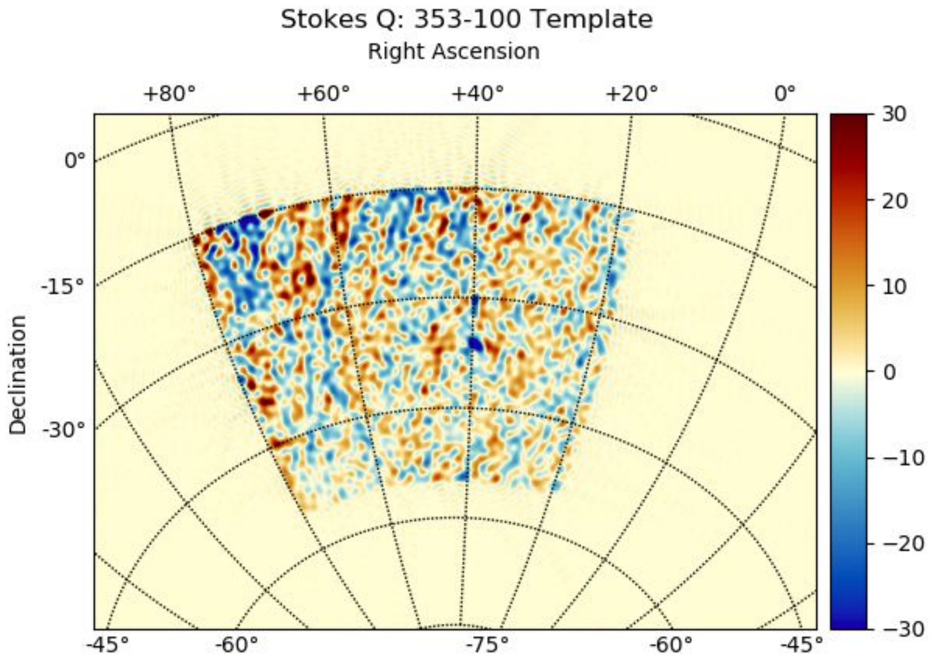
SMICA, Component recovered fg

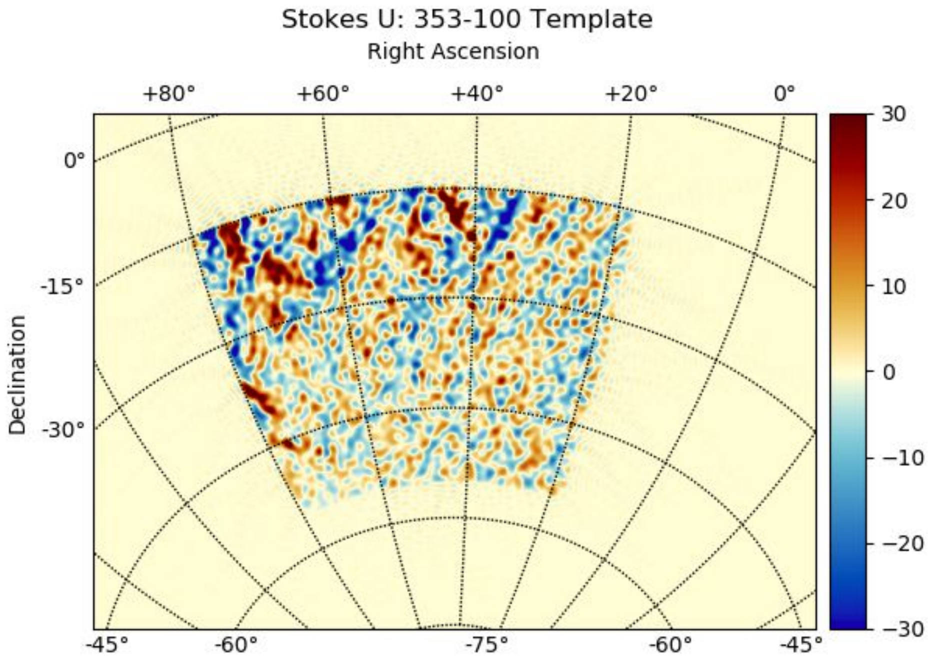




SMICA component map

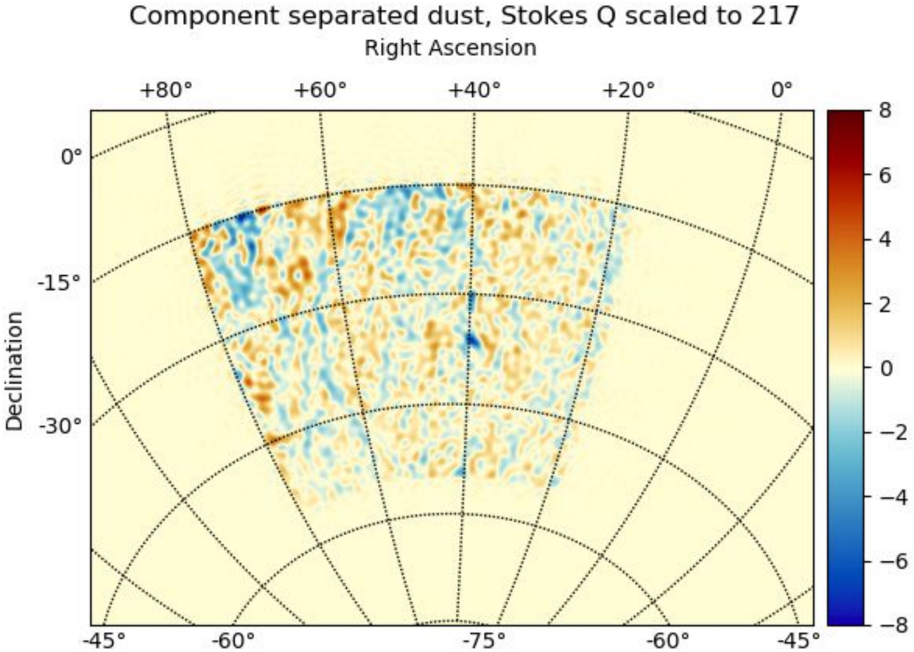
SMICA, Component recovered fg

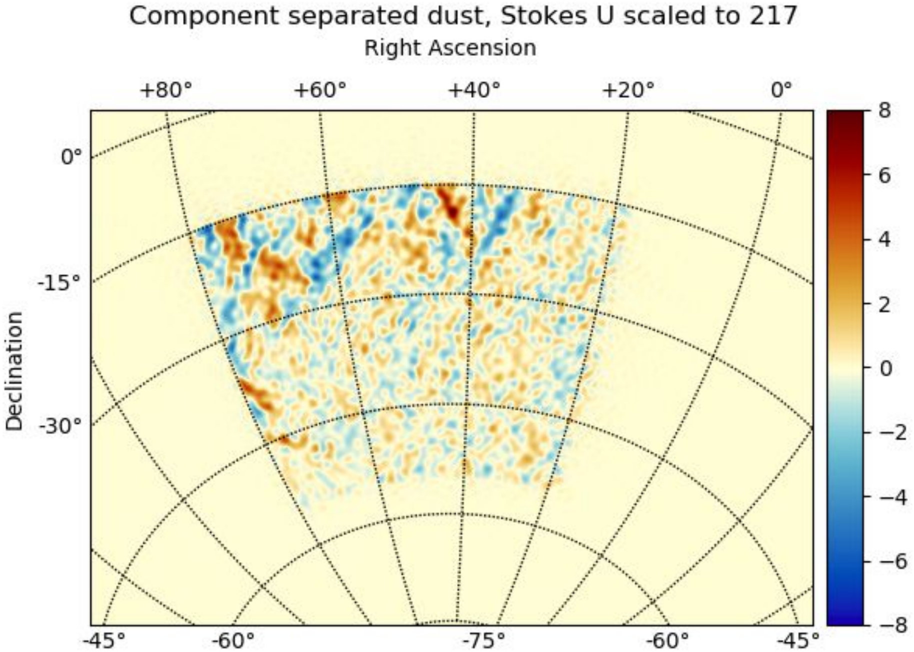




Reobserved **Planck 353-100** map

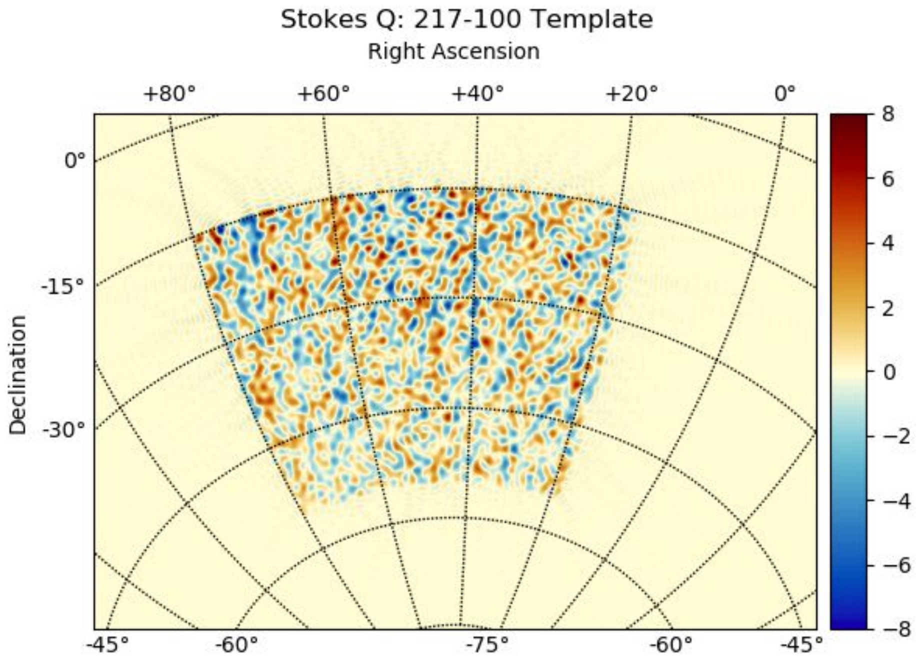
SMICA, Component recovered fg

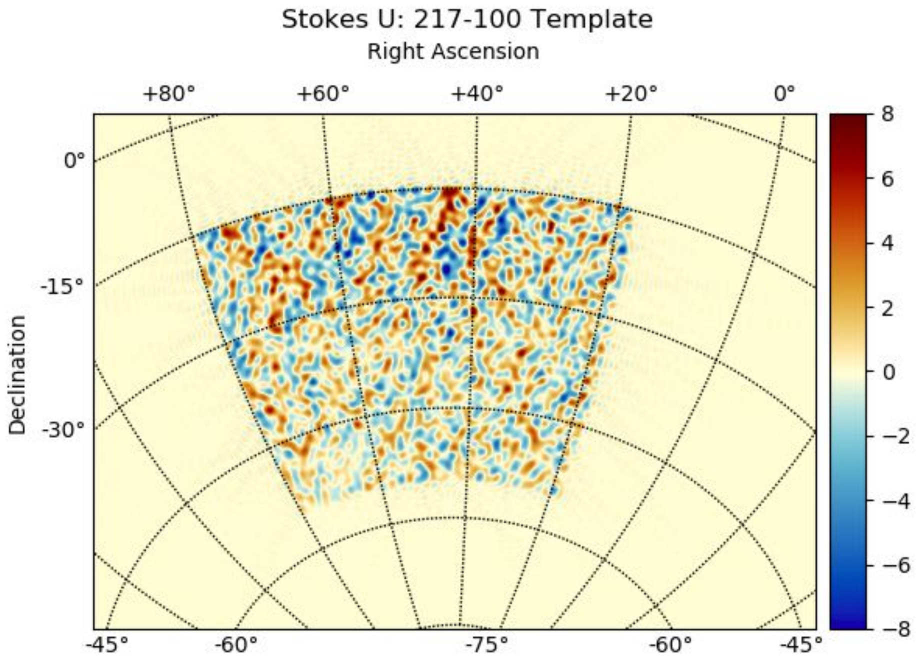




SMICA component map

SMICA, Component recovered fg



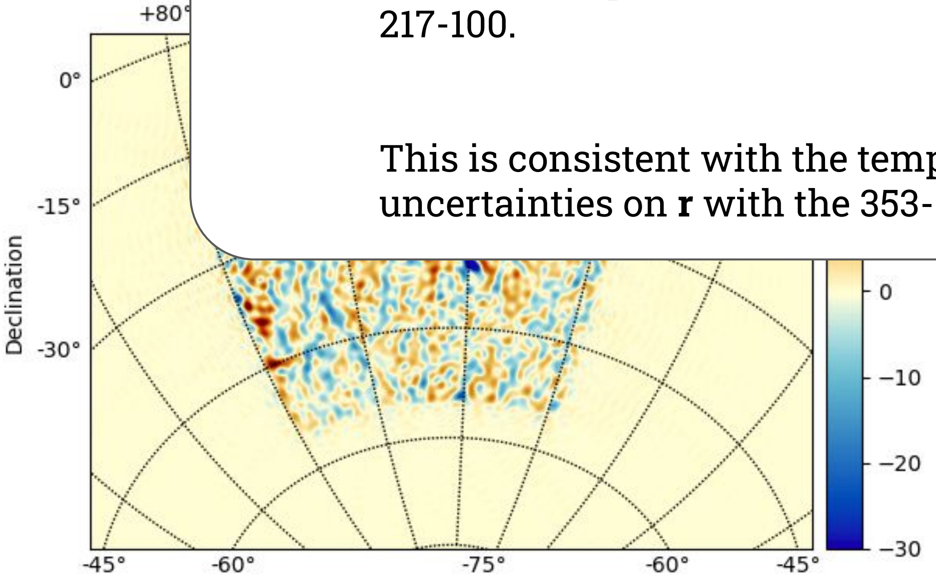


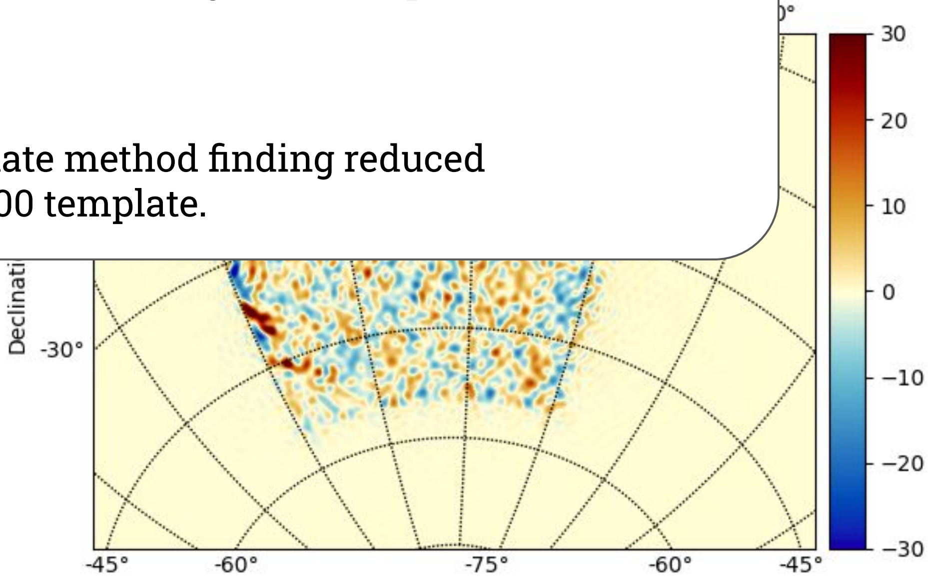
Reobserved **Planck 217-100** map

SMICA, Component recovered fg

SMICA’s foreground component map can weigh in on the template method, and prefers Planck 353-100 as a foreground template over 217-100.

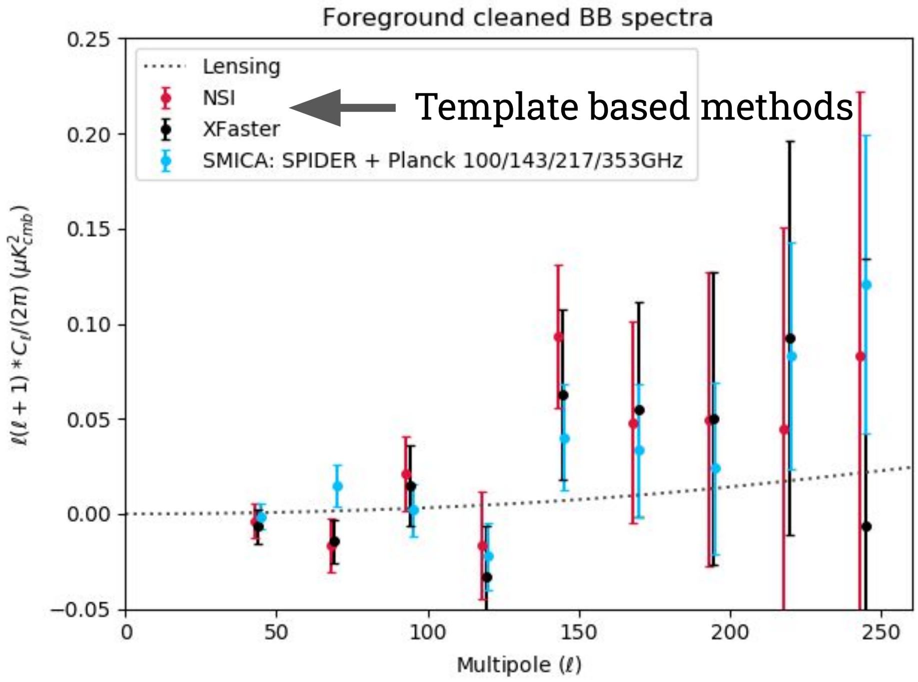
This is consistent with the template method finding reduced uncertainties on **r** with the 353-100 template.

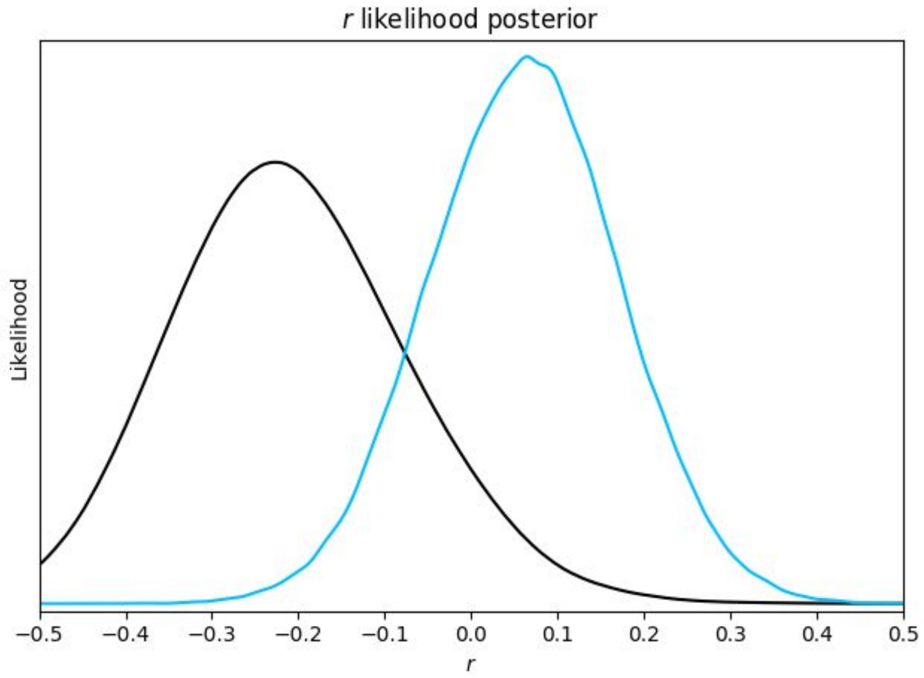




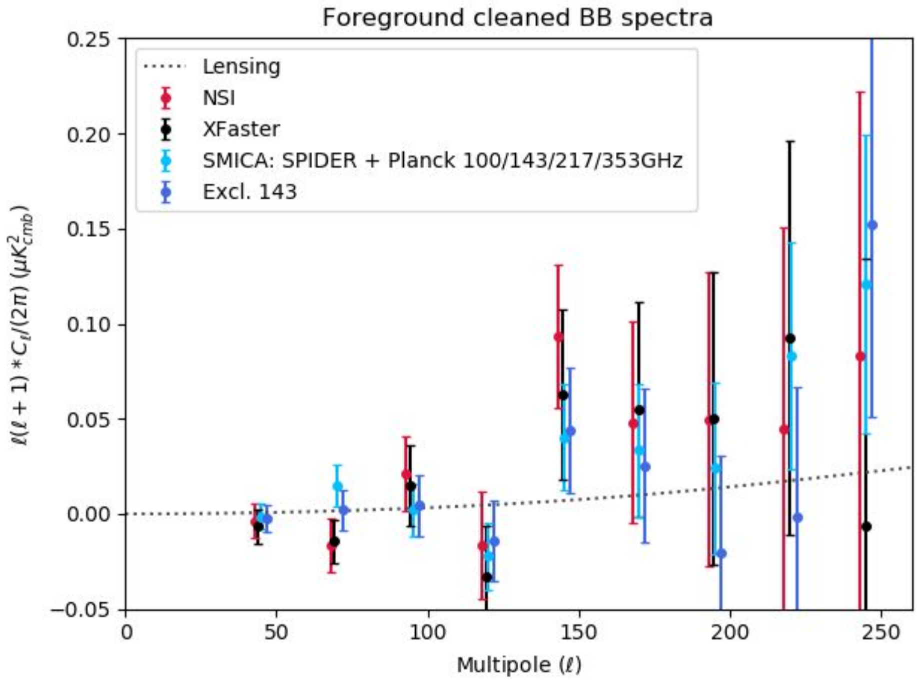
SMICA component map

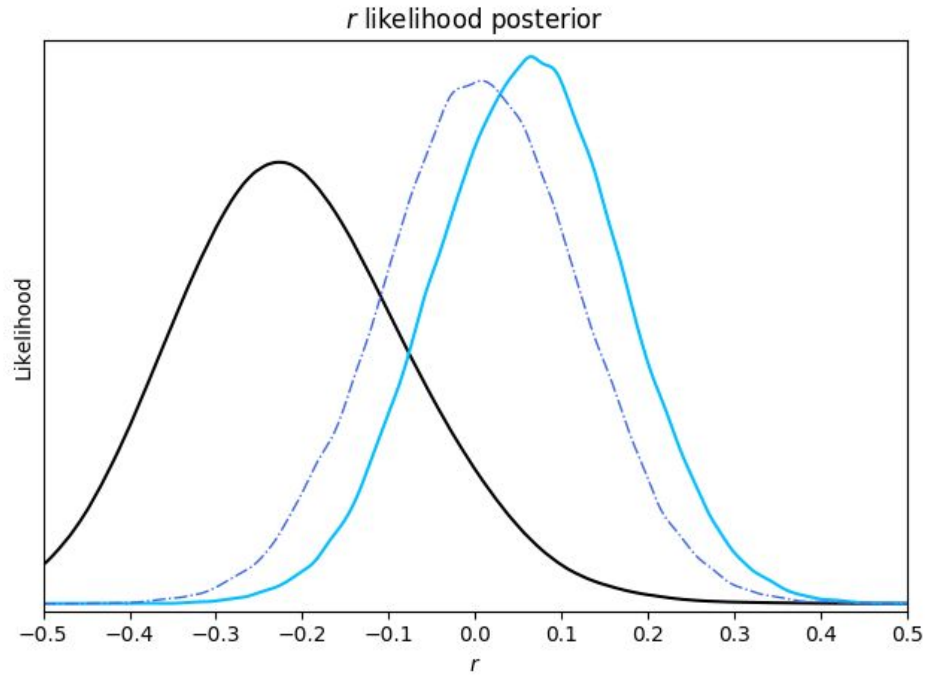
Cleaned BB bandpowers and r likelihood





Cleaned BB bandpowers and r likelihood





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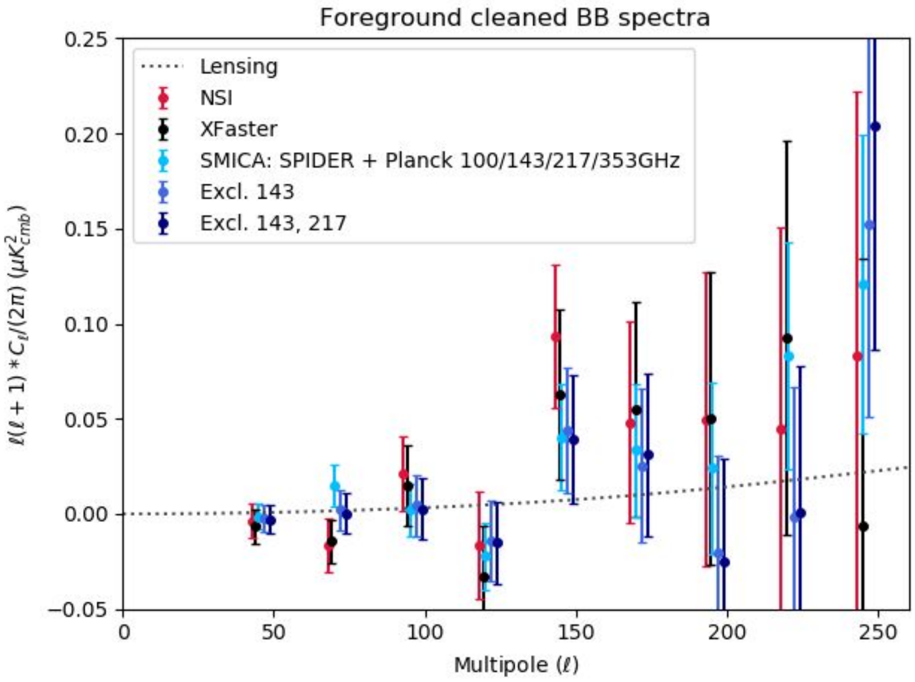

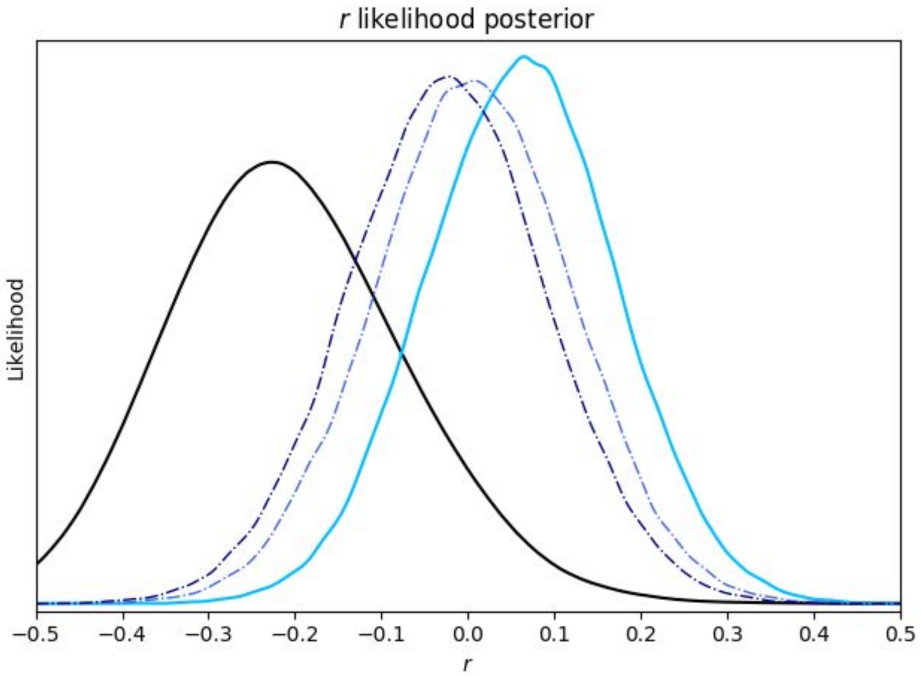

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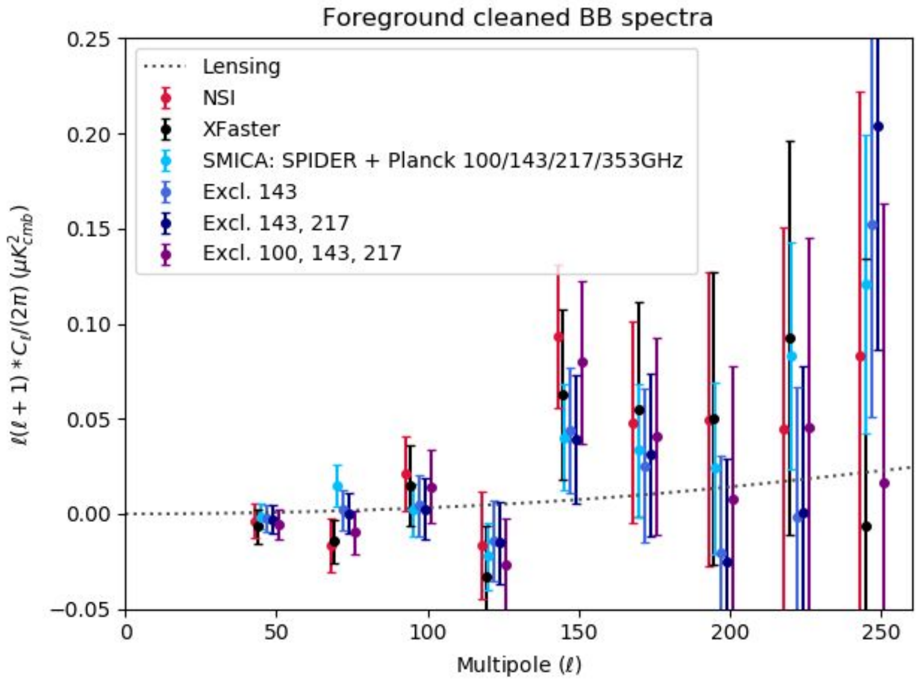
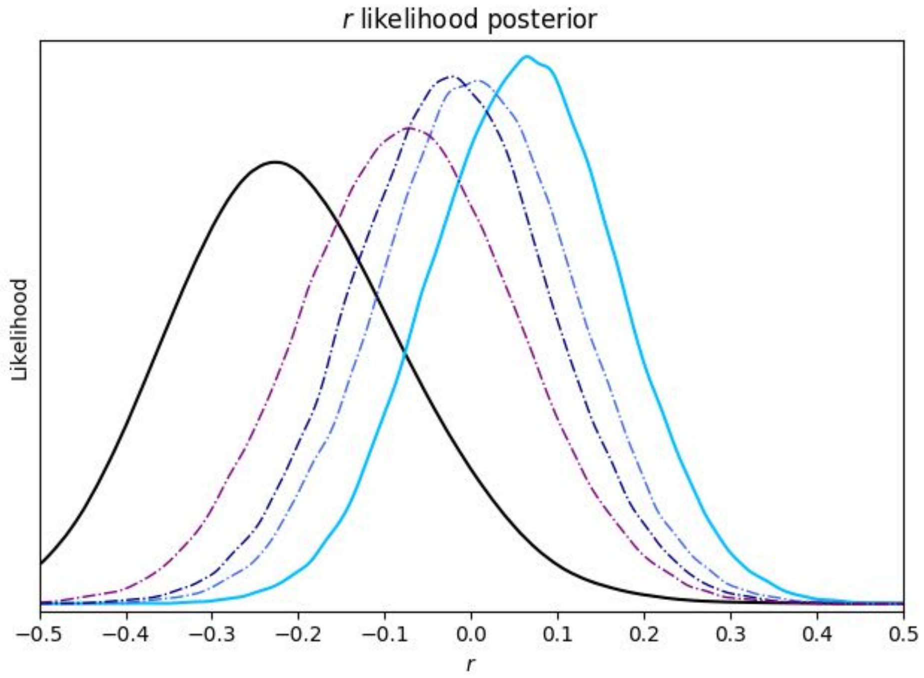




Summary

Spider had a successful first flight!

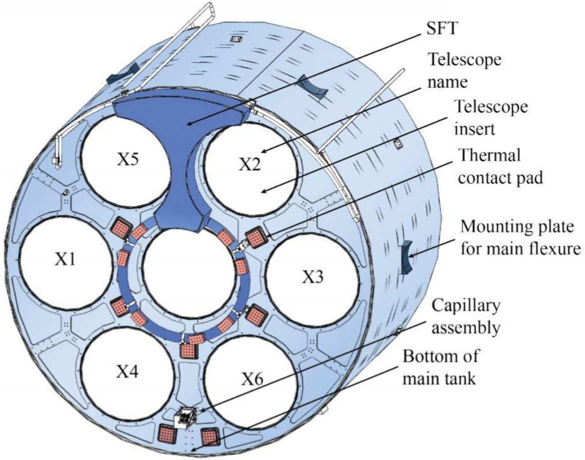
- B-mode results out now.
- $r < 0.19$ (95% Bayesian) or $r < 0.11$ (95% frequentist)
- More to come.
- Second flight in ~~2019~~, ~~2020~~, ~~2021~~, … *first chance we get*

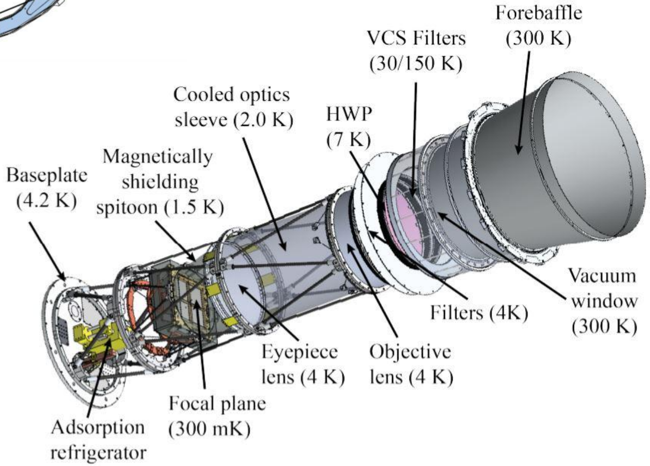
Taurus coming ~2026. E-modes over 70% of sky 150 to 350 GHz

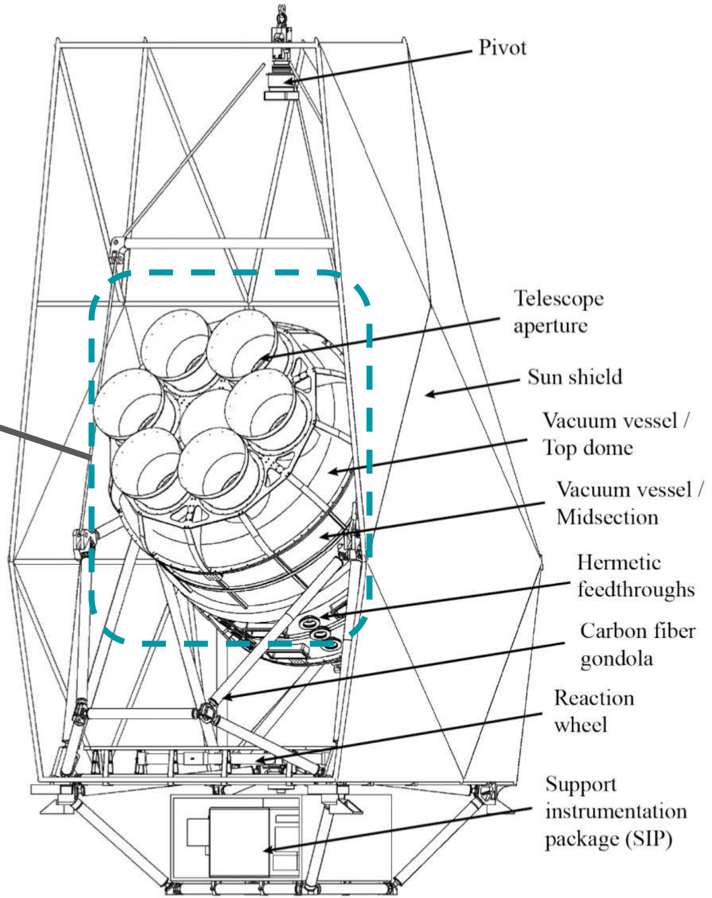
Thank You!

Extra Slides

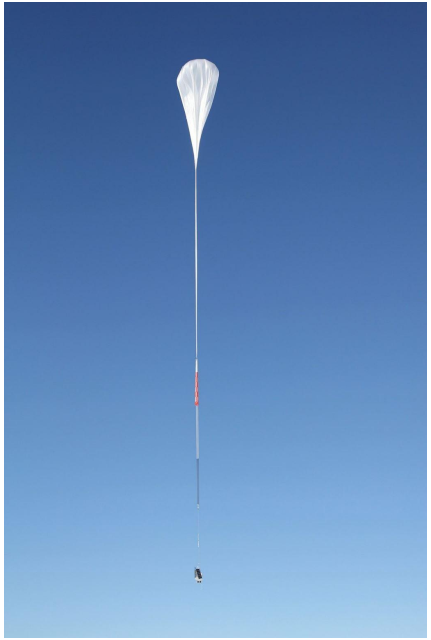
The payload - a brief introduction







Credit: **Steve Benton**



Credit:
Steve Benton

Low-level Data Processing: From TOD to map

Time-Ordered Data

Divide only at turn-arounds of the scan

... 10 minute data chunks ...

Correlated noises are flagged or filtered out

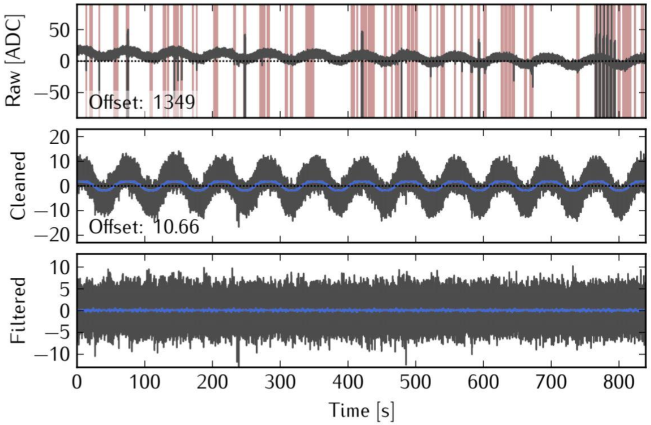
Cleaned Data

Apply calibration (beam estimation)

using cross spectra with PLANCK

Combine with reconstructed pointing and observed polarization angles

Maps!



Simulated TOD (Signal/Noise)

Apply same flagging, filtering, beams, pointing, and polarization angles as SPIDER

Noise model: stationary and uncorrelated

Maps from other experiment

SPIDER scan strategy and filtering

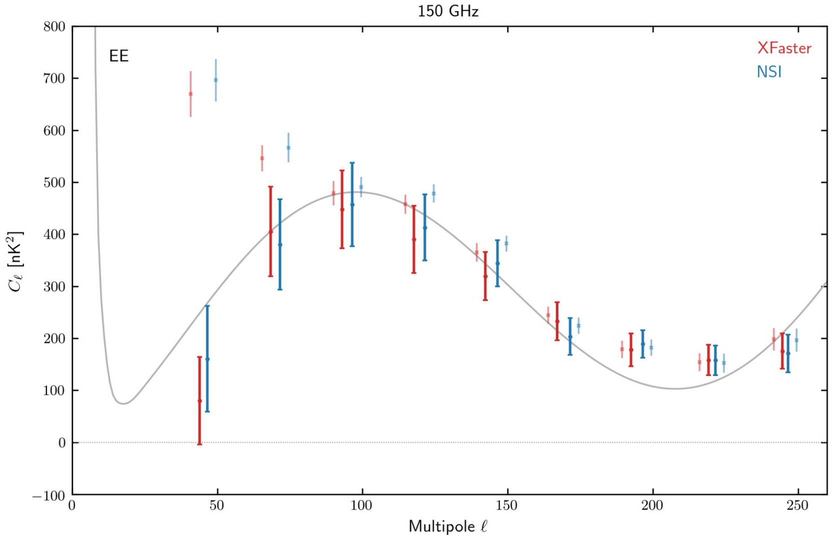
Simulated/reobserved Maps

Template Removal

We use the template removal method with both the NSI and XFaster pipelines

Dust is big

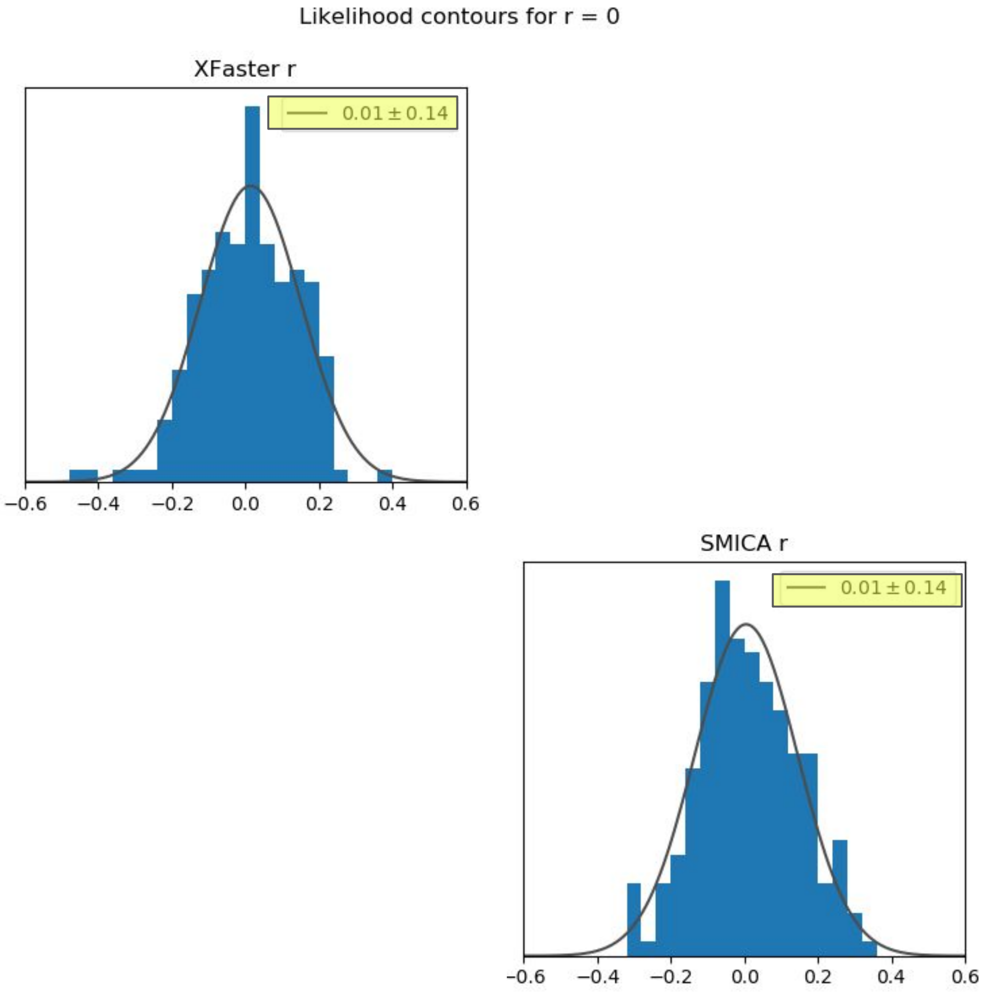
Results are highly consistent between NSI and XFaster, especially in the "nominal" 353-100 case



	$10^3\,\alpha_{95}$	$10^3\,\alpha_{150}$	β_d^{95}	β_d^{150}
Template: $\nu_0 = 353\,\mathrm{GHz}$				
Planck	16.8 ± 0.5	44.4 ± 0.8	1.53 ± 0.02	
XFaster	18 ± 2	45 ± 2	$1.49^{+0.07}_{-0.09}$	1.52 ± 0.05
NSI	19 ± 5	45 ± 4	$1.44^{+0.22}_{-0.17}$	1.51 ± 0.10
Template: $\nu_0 = 217\,\mathrm{GHz}$				
Planck	153 ± 3	404 ± 4	1.53 ± 0.02	
XFaster	159 ± 17	377 ± 16	$1.51^{+0.10}_{-0.12}$	$1.68^{+0.08}_{-0.09}$
NSI	140 ± 50	350 ± 58	$1.63^{+0.46}_{-0.31}$	$1.81^{+0.38}_{-0.31}$

Statistical consistency of XFaster and SMICA

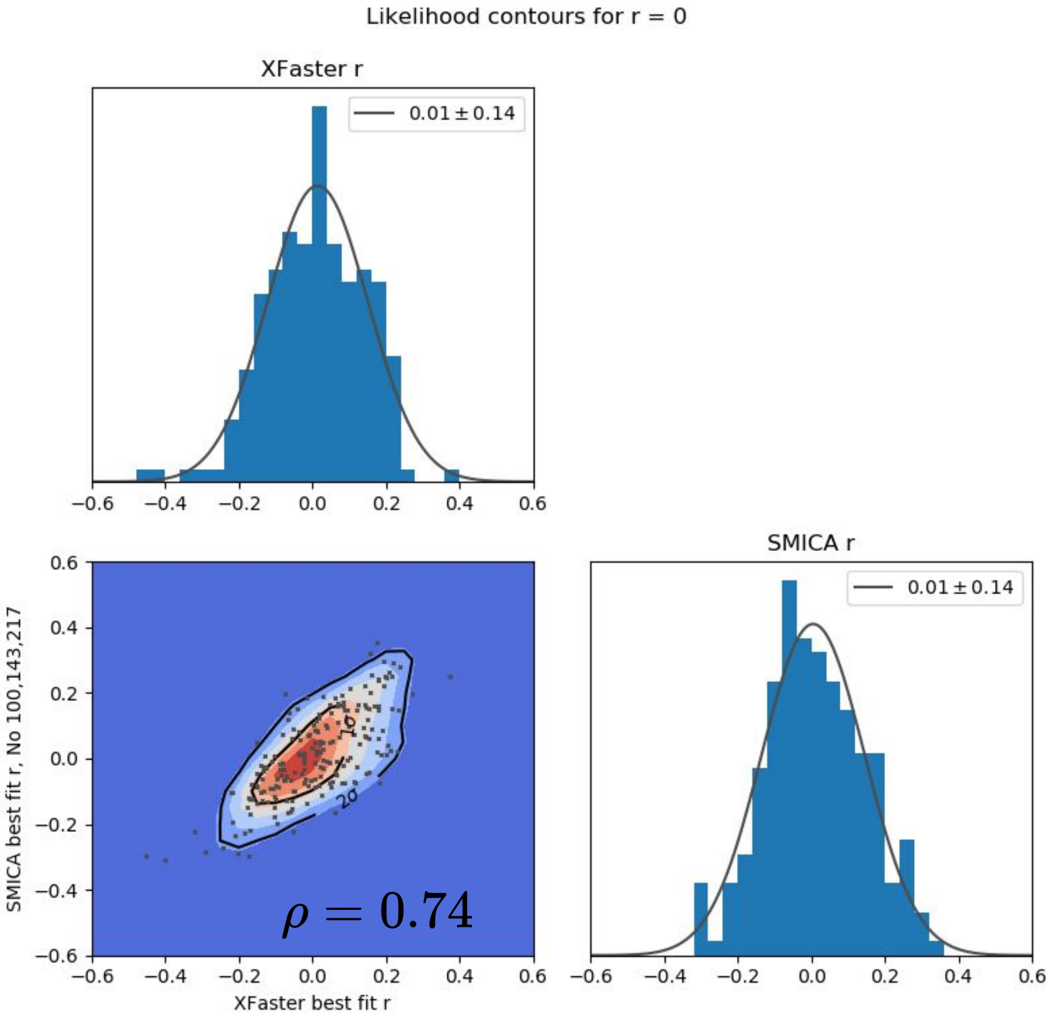
- Both XFaster and SMICA give <u>unbiased estimates</u> of r and are similarly optimal estimators



Statistical consistency of XFaster and SMICA

- Both XFaster and SMICA give unbiased estimates of r and are similarly optimal estimators

- When run on as identical simulation inputs, the estimators have substantial scatter
    - Different estimators project noise differently



Statistical consistency of XFaster and SMICA

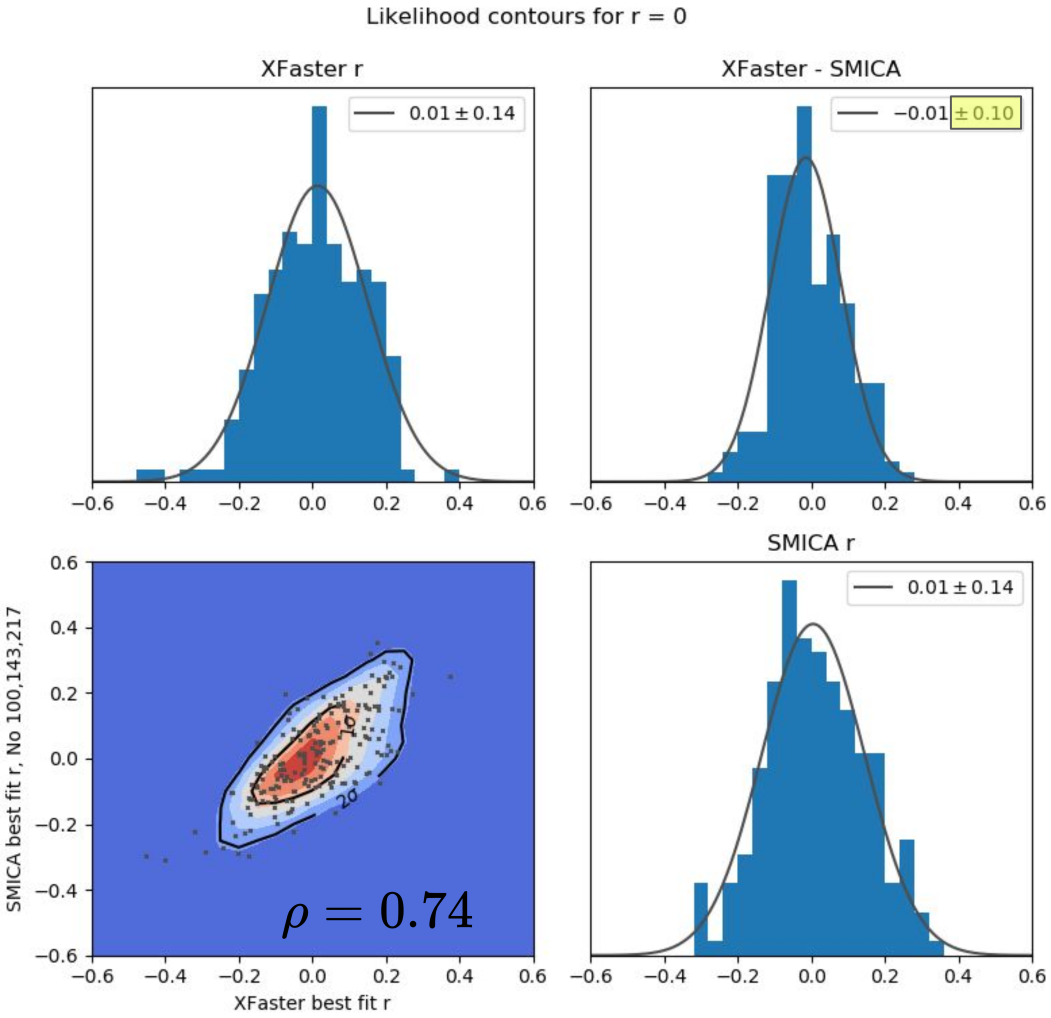
- Both XFaster and SMICA give <u>unbiased estimates</u> of r and are similarly optimal estimators

- When run on as identical simulation inputs, the estimators have substantial scatter

    - Different estimators project noise differently

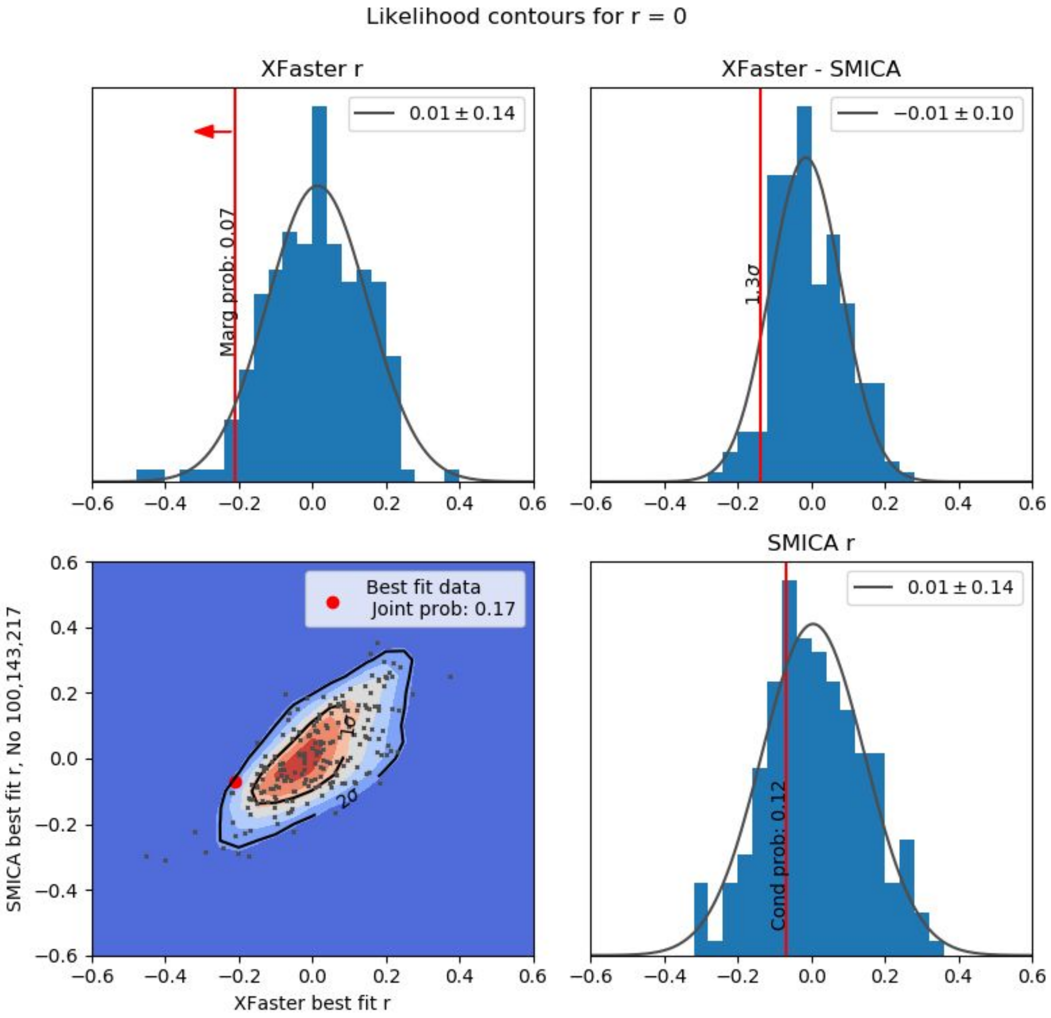
- Put another way,

$$\sigma(\Delta r) \gg \text{Bias}$$

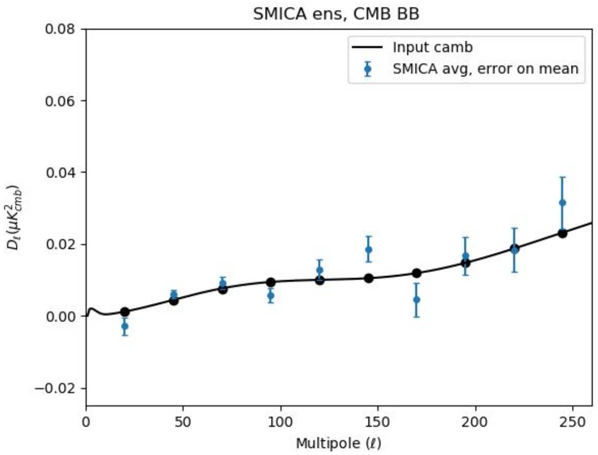


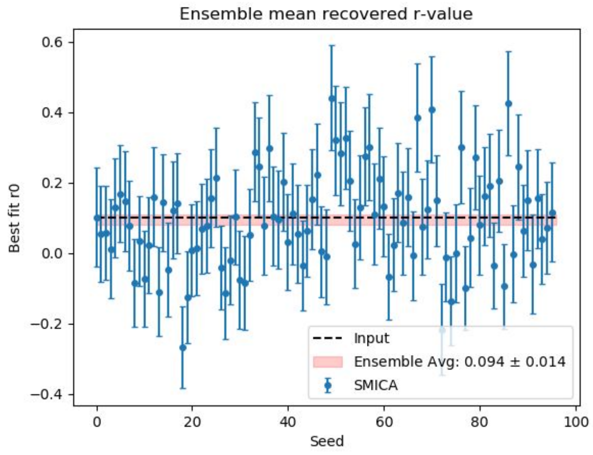
Statistical consistency of XFaster and SMICA

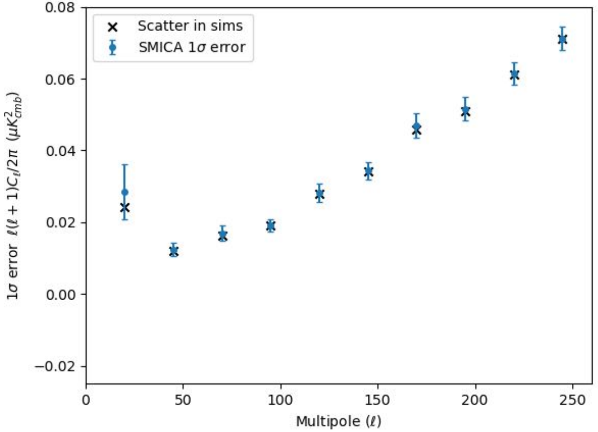
- The XFaster result is consistent with sims with input r = 0
- At first glance XFaster and SMICA have very different results
  - Half the differences are due to data inputs
  - Other half is due to different estimators
- The data result is statistically consistent between the two pipelines

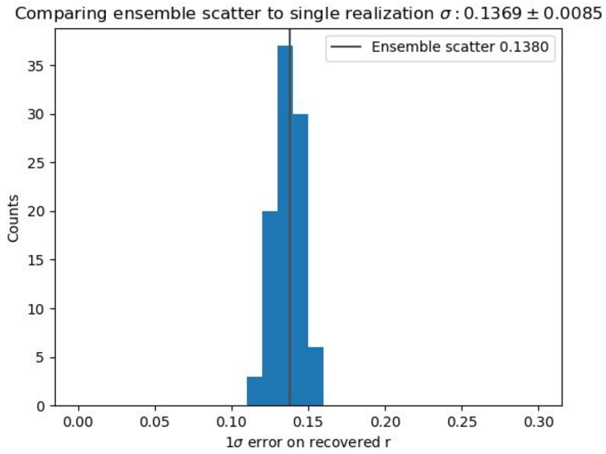


Backup Slides: SMICA Validation on Sims









XFaster Estimator (Gambrel+ 2021 arxiv:2104.01172)

https://annegambrel.github.io/xfaster/

Hybrid: quadratic and Monte Carlo pseudo-C_ℓ

Flexible: solve for bandpower deviations *or*
solve for parameterized power spectrum model.
Filter transfer function, foregrounds, etc

Marginalizes over nuisance parameters:
noise model residuals, beam model uncertainty

Mode Counting — Data pseudo-spectra

$$\mathcal{L} \equiv \ln L = -\frac{1}{2}\sum_{\ell k} \overbrace{(2\ell+1) g_\ell^k}^{\text{Mode Counting}} \left[\widetilde{\boldsymbol{C}}_\ell^{-1} \cdot \widehat{\boldsymbol{C}}_\ell + \ln \widetilde{\boldsymbol{C}}_\ell \right]_{kk}$$

Model pseudo-spectra