SPIDER

Cosmology and Galactic Dust from the Edge of Space

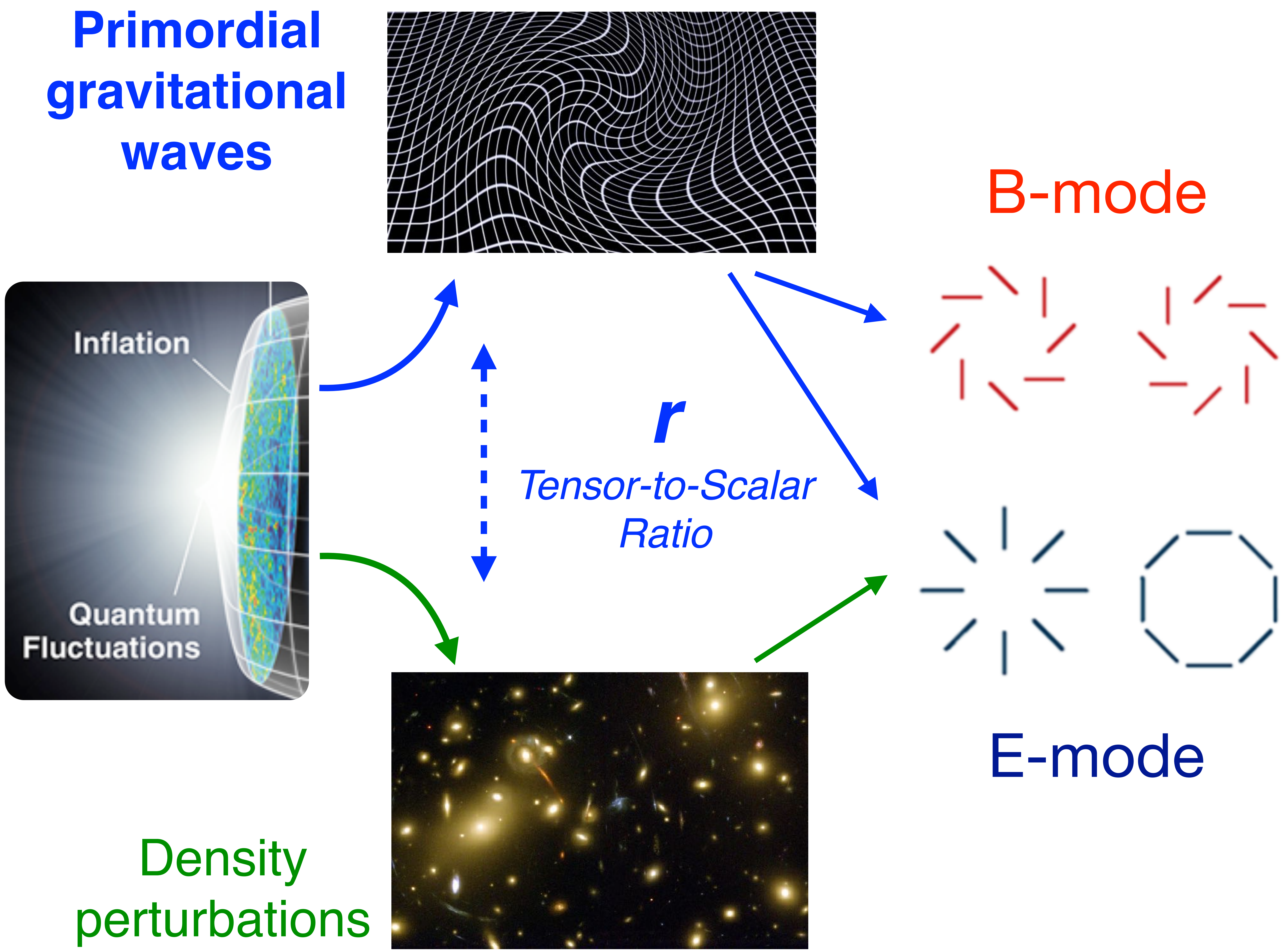
Jeff Filippini

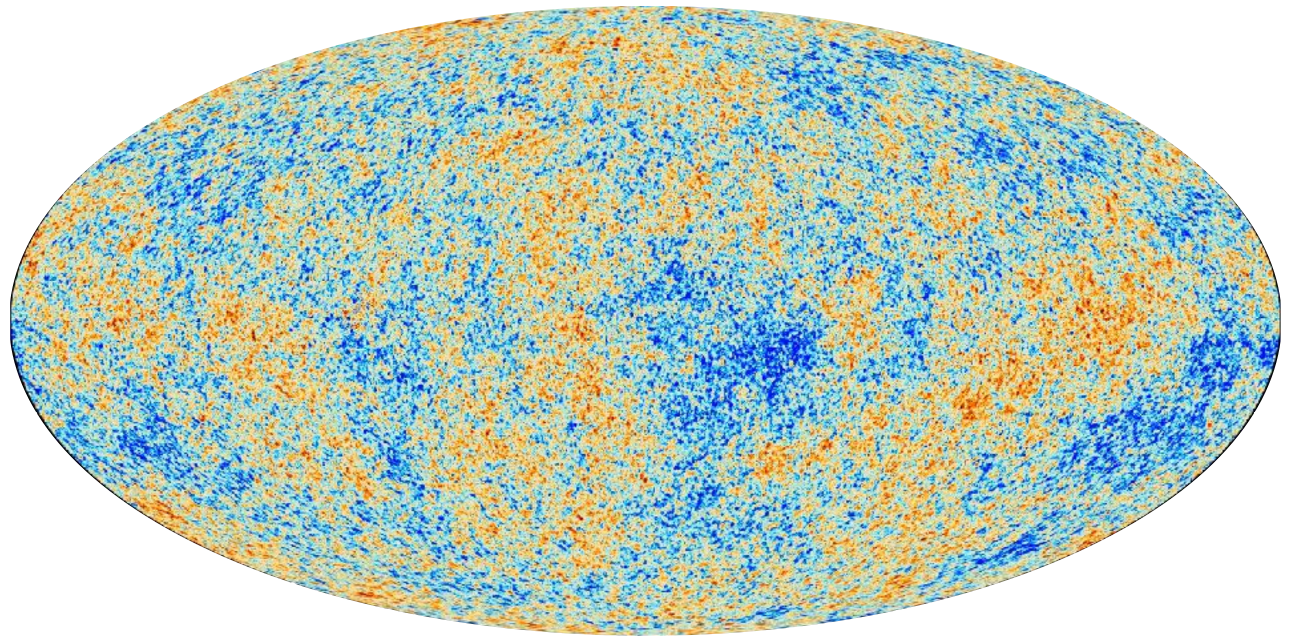
ILLINOIS

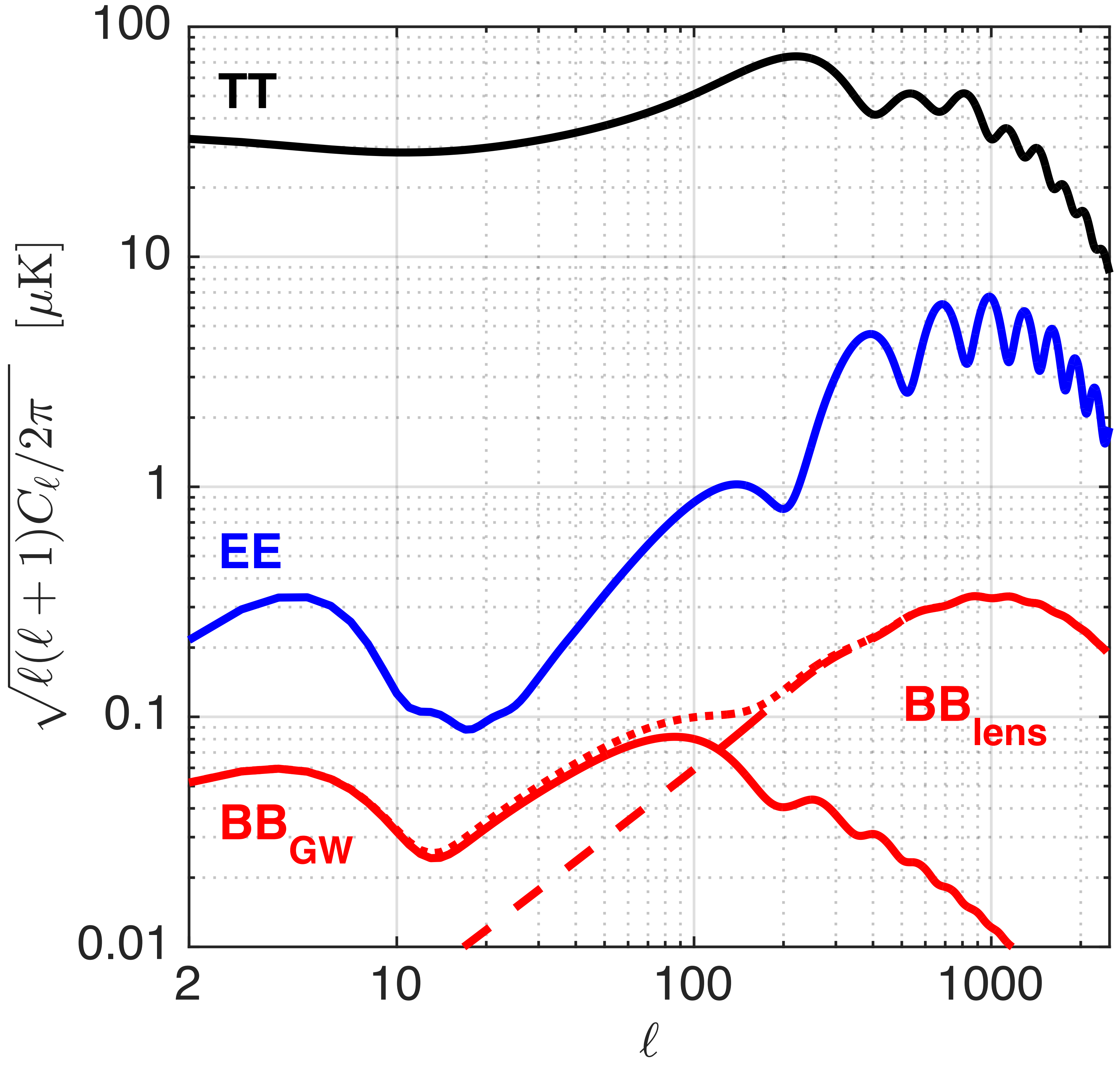
mm Universe 2025 - June 23, 2025


Big bang, inflation
Formation of CMB
Dark ages
Cosmic dawn
Reionization
Structure growth
Dark energy domination
z = 1100
150
50
20
10
2.5
0.5
Scalar (density) perturbations
Inflation
Tensor perturbations (gravitational waves)
H. Chiang

Echoes from the Early Universe





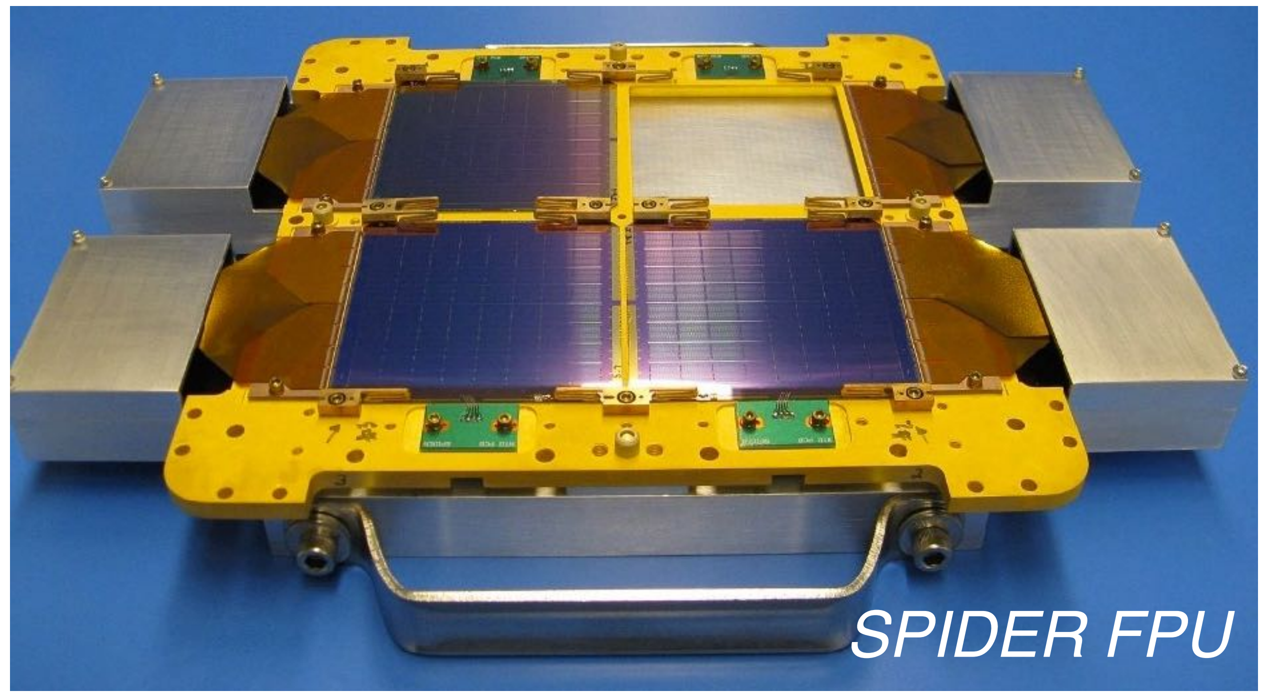


Challenges

Precision

Approach <u>photon noise limit</u>

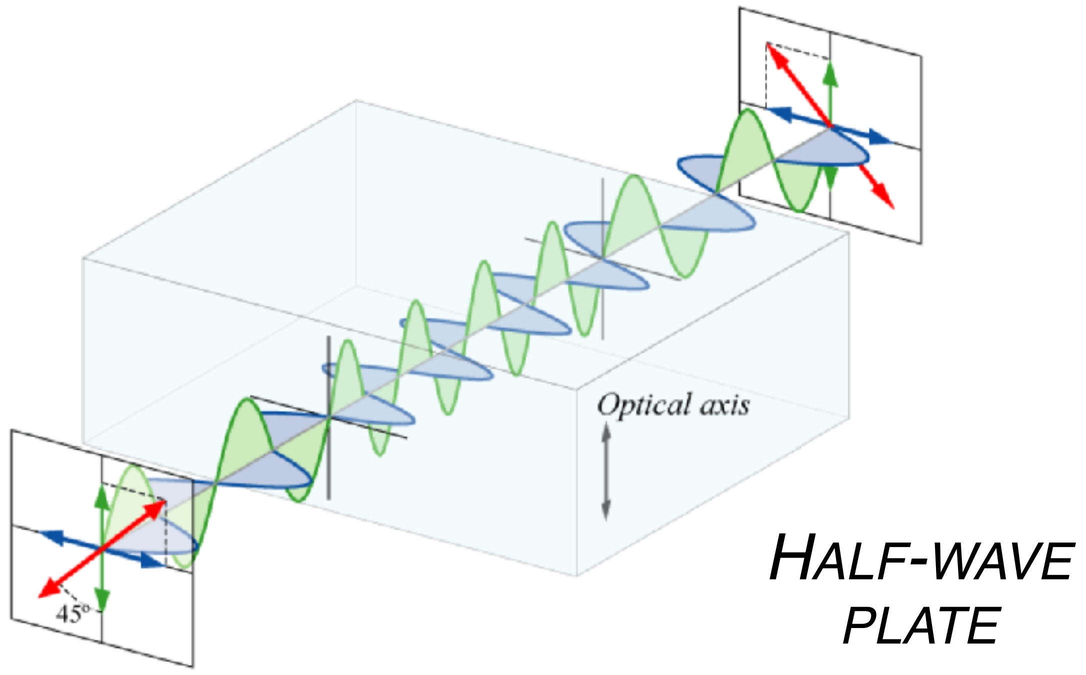
Few photons, many detectors



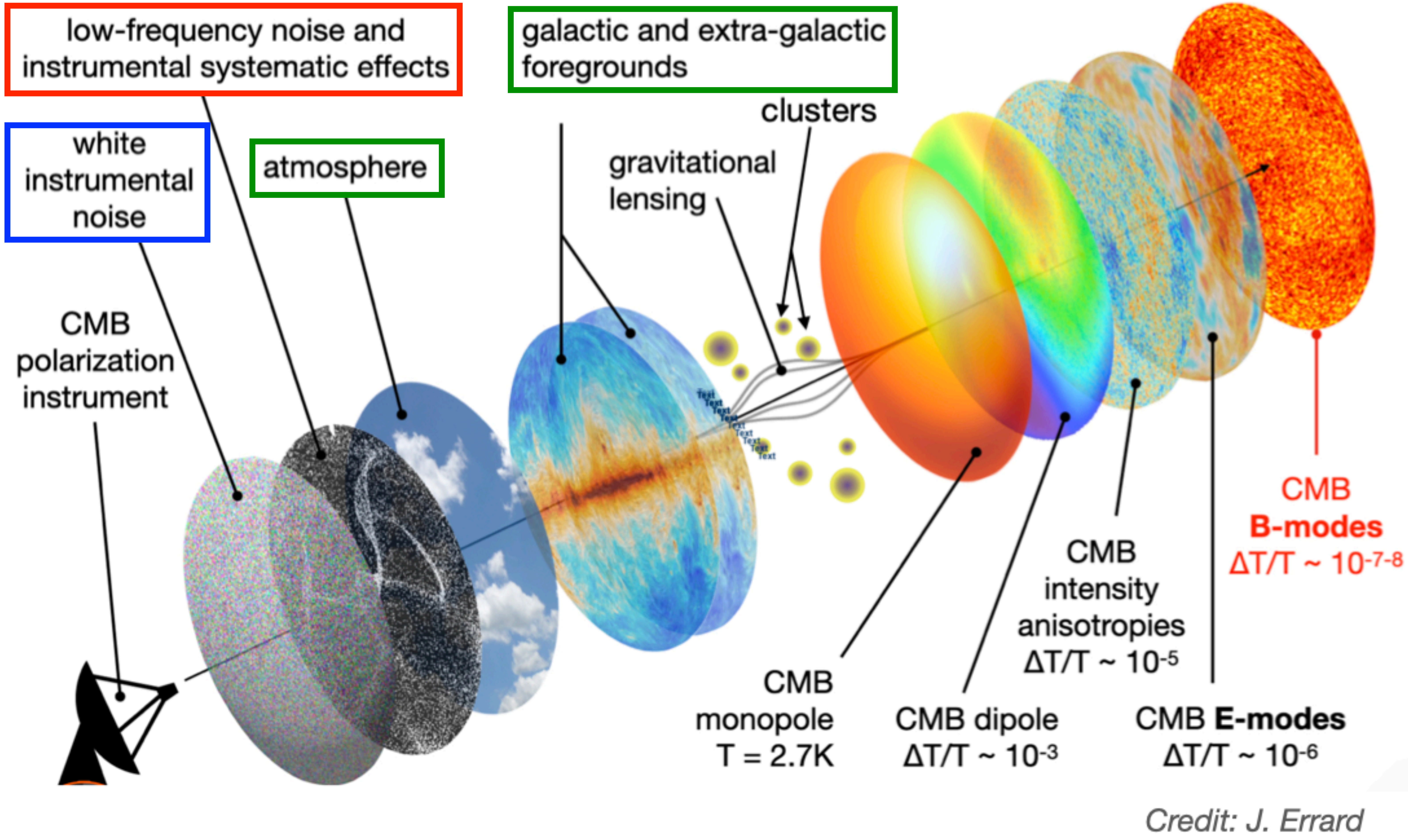
Accuracy

Rigid control of polarized <u>systematics</u>

Instrument symmetry



Clarity



The SPIDER Program

A **balloon-borne** payload to identify **primordial B-modes** on degree angular scales in the presence of **foregrounds**

Two flights with **broad frequency coverage** over a **large sky area** (~10%) to map (and distinguish) CMB polarization and Galactic emission

SPIDER-1 (2014-15): 95, 150 GHz

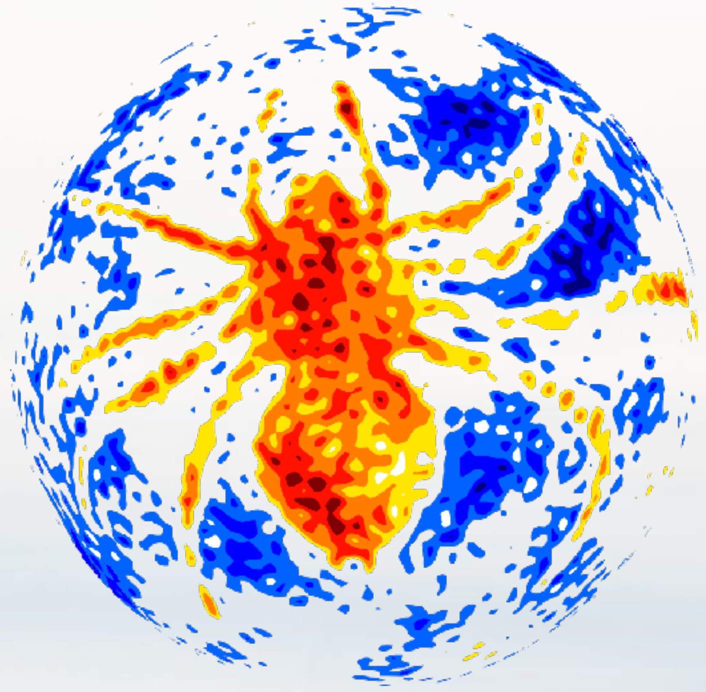
Description: Fraisse+ JCAP 04, 047 (2013)
B-modes: Ade+ ApJ 927, 174 (2022)
Foregrounds: Ade+ ApJ 978, 130 (2025)

SPIDER-2 (2022-23): 95, 150, 280 GHz

Instrument: Shaw+ JATIS 10, 044012 (2024)

*Support from **NASA SMD** (mission, science, detectors) and **NSF OPP** (Antarctic logistics)*

Balloonatics



NASA NSF CSA ASC C.S.B.F. PALESTINE, TEXAS JPL NSERC CRSNG the David & Lucile Packard FOUNDATION UNIVERSITY OF TORONTO CASE WESTERN RESERVE UNIVERSITY EST. 1826 CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD UBC NIST PRINCETON UNIVERSITY CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique théorique Imperial College London ILLINOIS

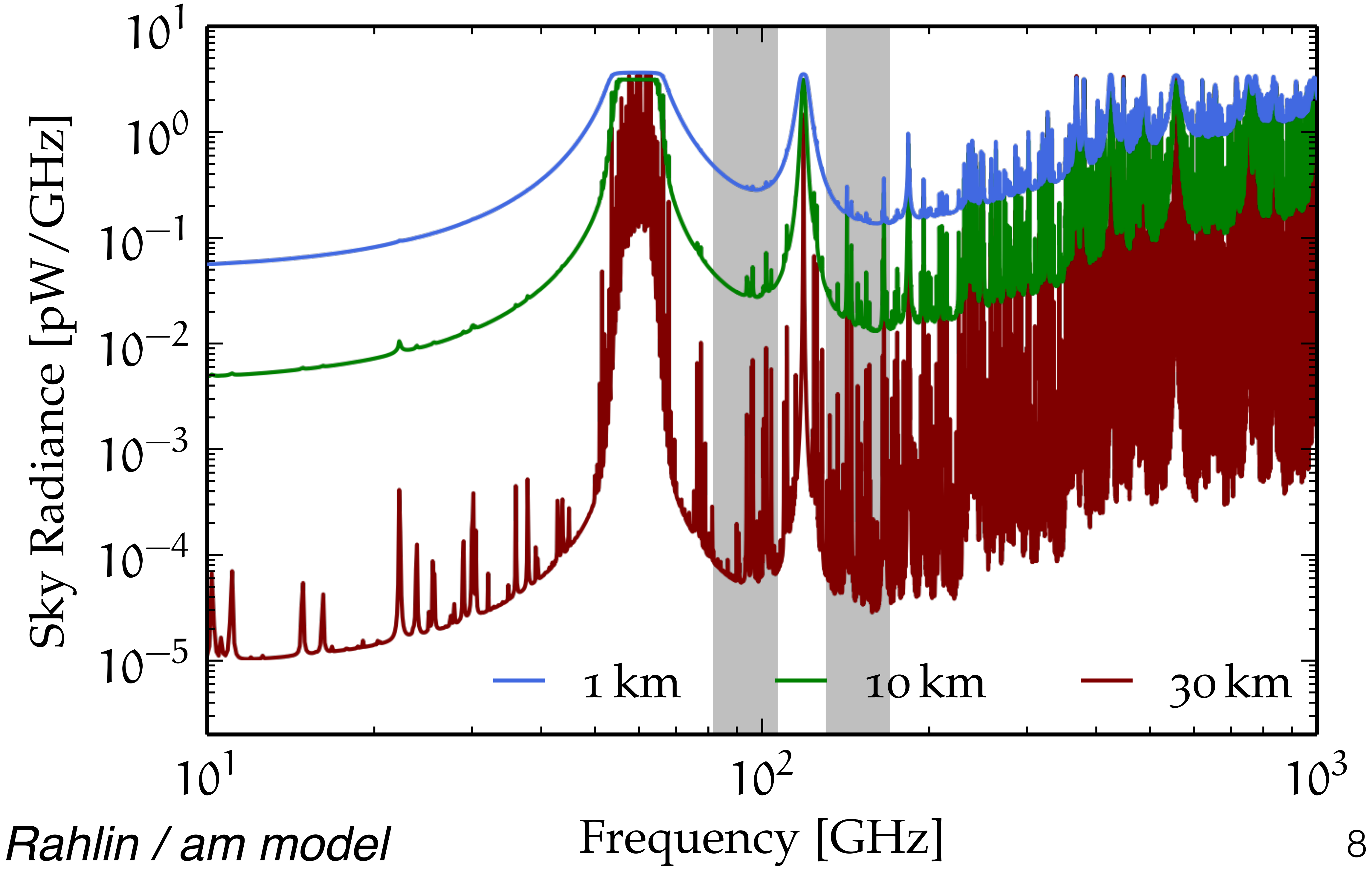
State Farm CENTER®

ILLINOIS BASKETBALL

Why Ballooning?

The Good

- **High sensitivity** to approach CMB photon noise limit
- Access to **higher frequencies** obscured from the ground
- **Technology pathfinder** for orbital missions



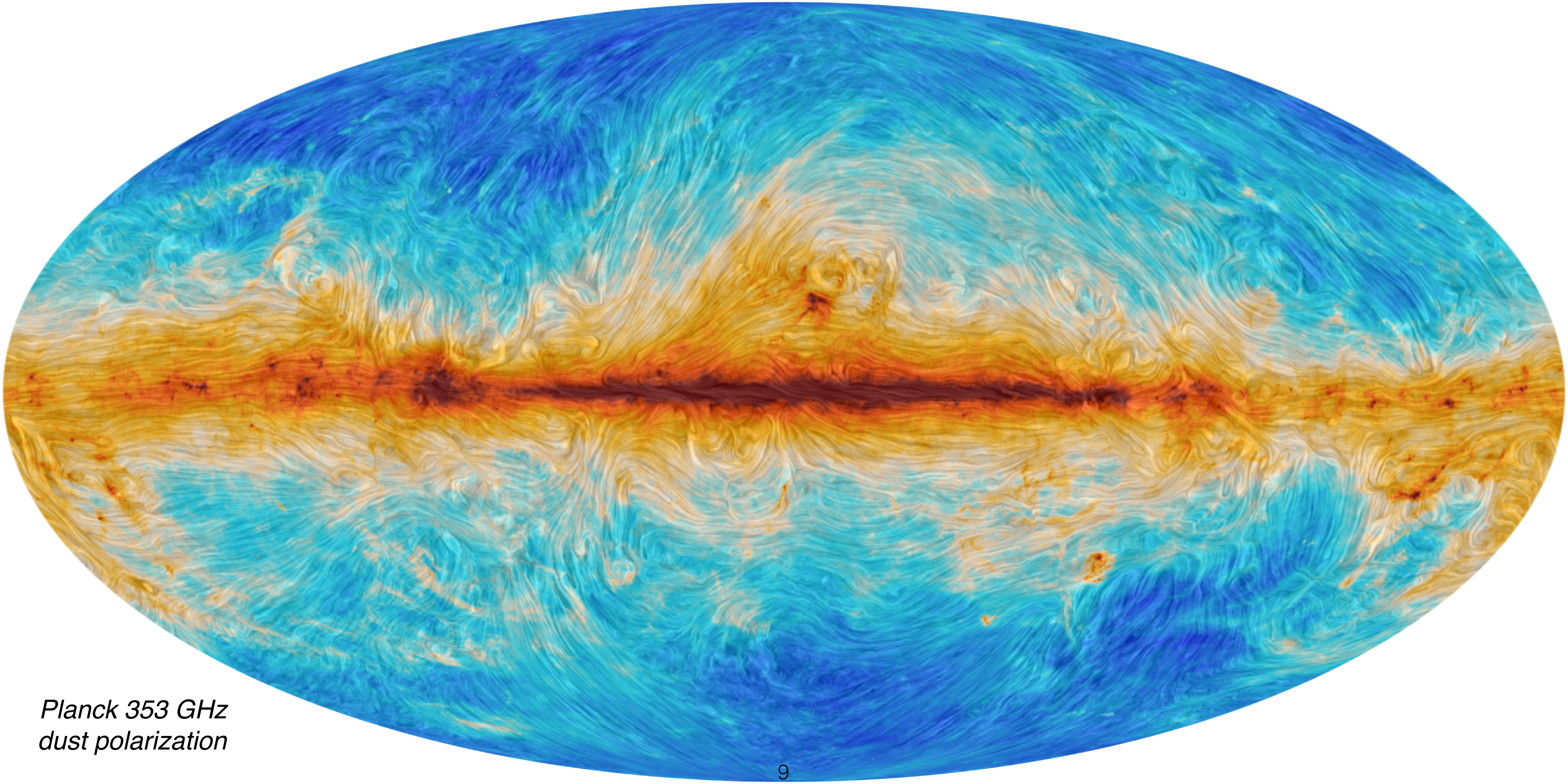
A.S. Rahlin / am model

The Bad

- Limited **integration time** (~weeks)
- Stringent **mass**, **power** constraints
- Very limited bandwidth demands ***nearly autonomous operations***

Excellent proxy for space operations!

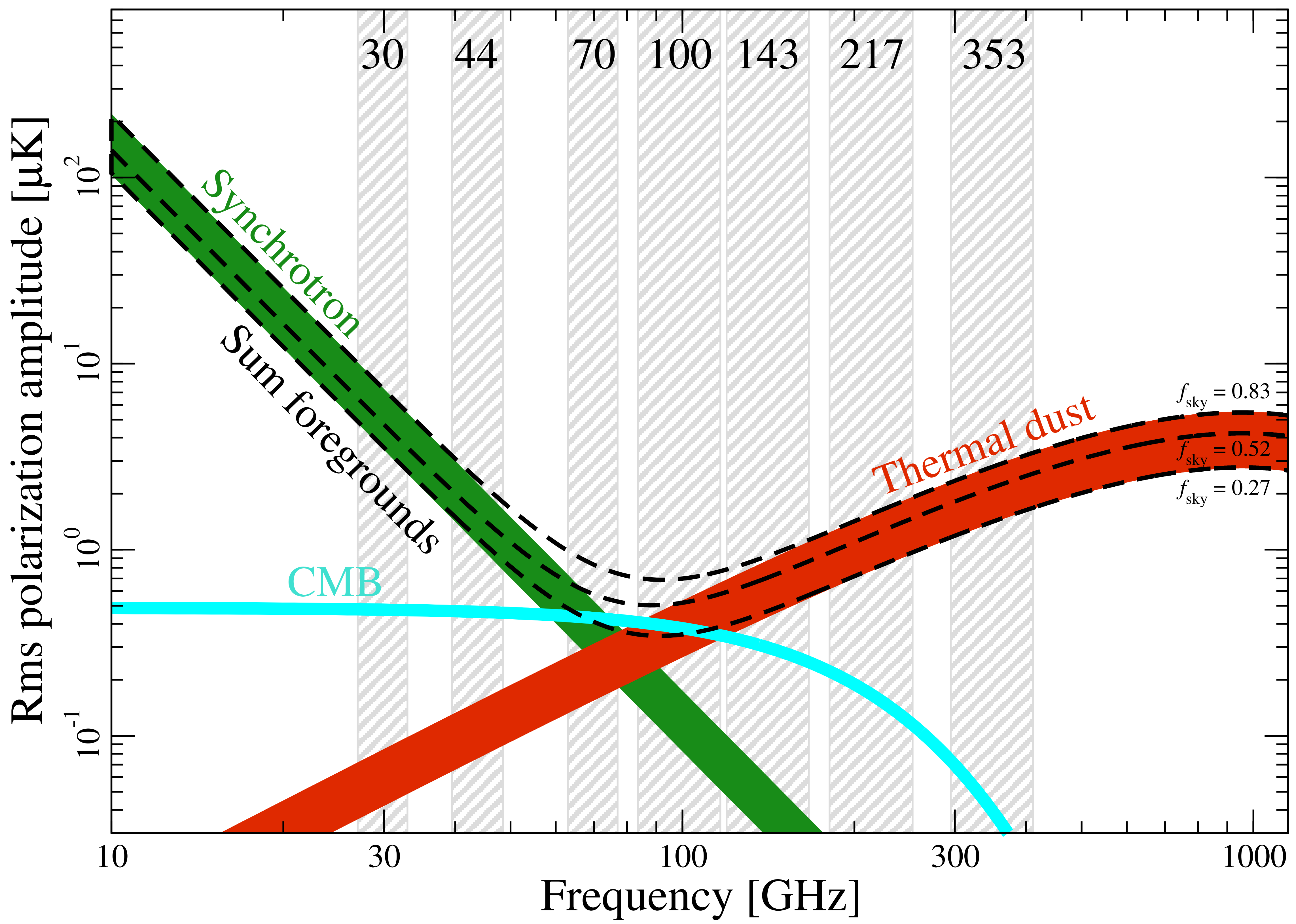
Galactic Foregrounds



Planck 353 GHz
dust polarization

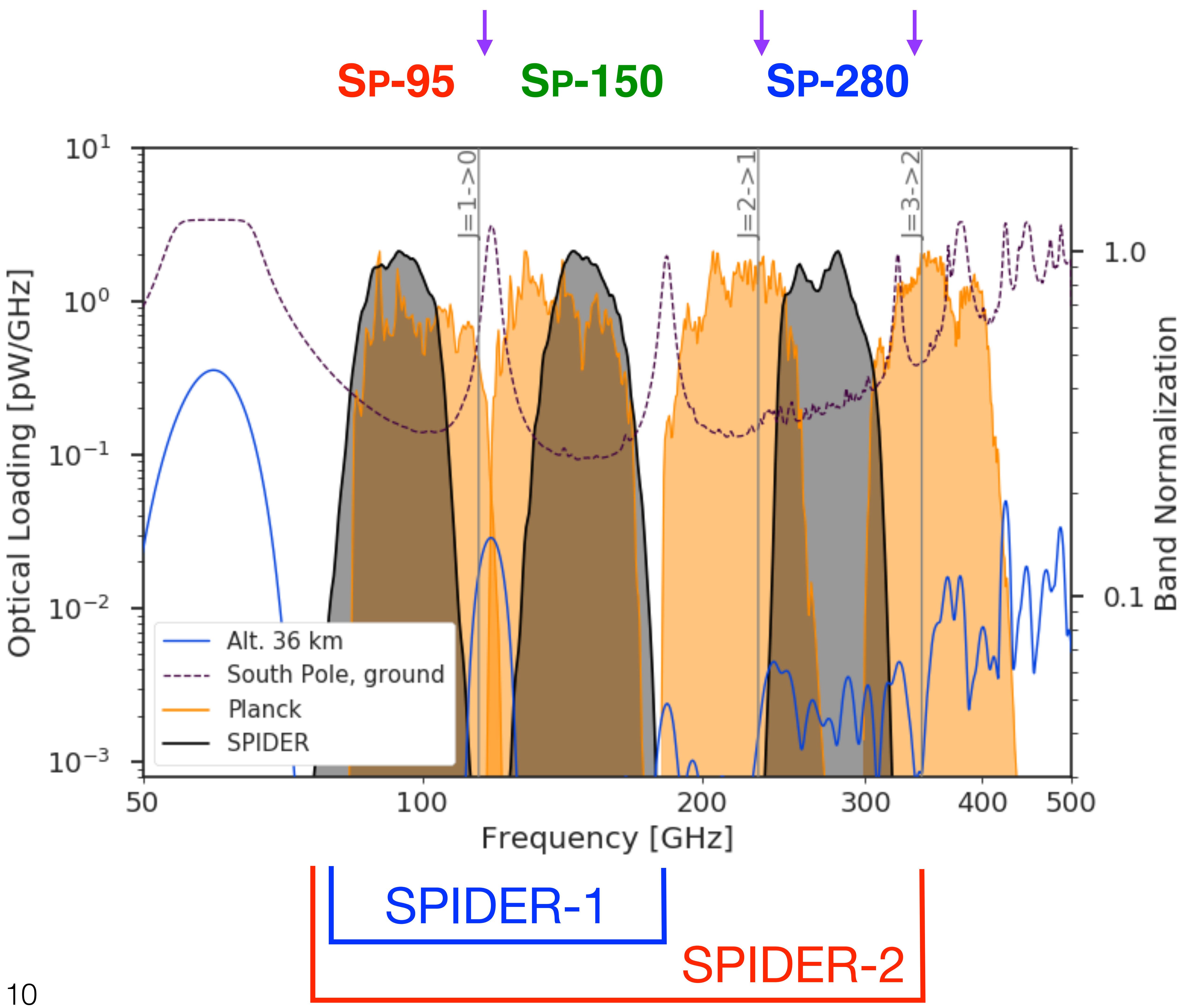
Observing Bands

Planck polarized observing bands



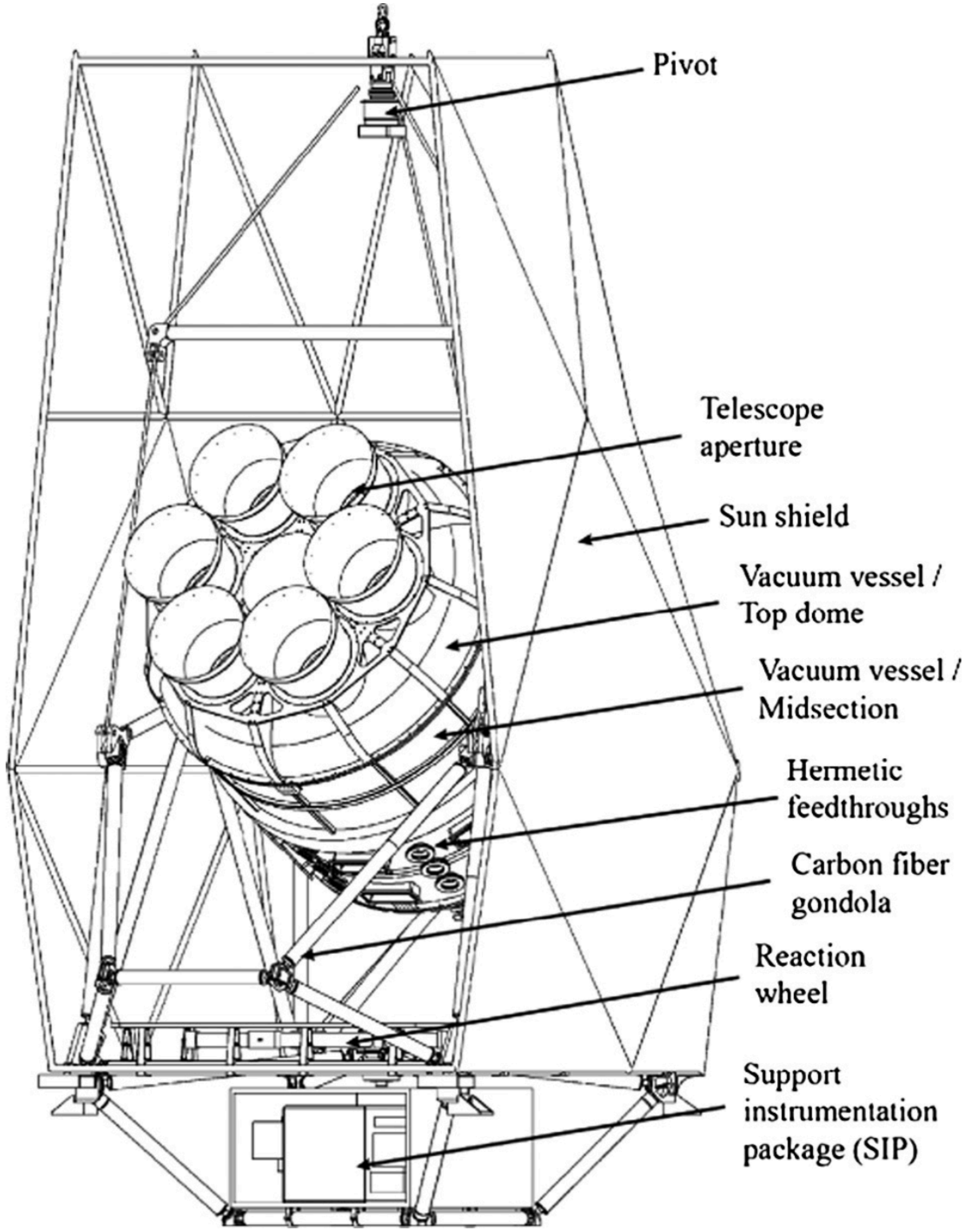
Planck 2018 (full sky, 40' smoothing)

Avoid galactic CO lines



The SPIDER Payload

- Lightweight **carbon fiber gondola**
  - *Az/el drives, redundant pointing sensor suite*
  - *Launch mass ~**3000kg***
- Large (*1300 L*) shared **LHe cryostat**
- Six **monochromatic refractors**
  - *Modular design for multiple frequencies*
  - *Cold optics (HDPE), 270mm stop*
  - *Stepped sapphire **half-wave plate***
  - *Superconducting bolometer arrays*
- Design emphasis on **low internal loading**
  - *1.6 K absorptive baffling, reflective fore baffle*
  - *Reflective filter stack, thin (3/32") window*



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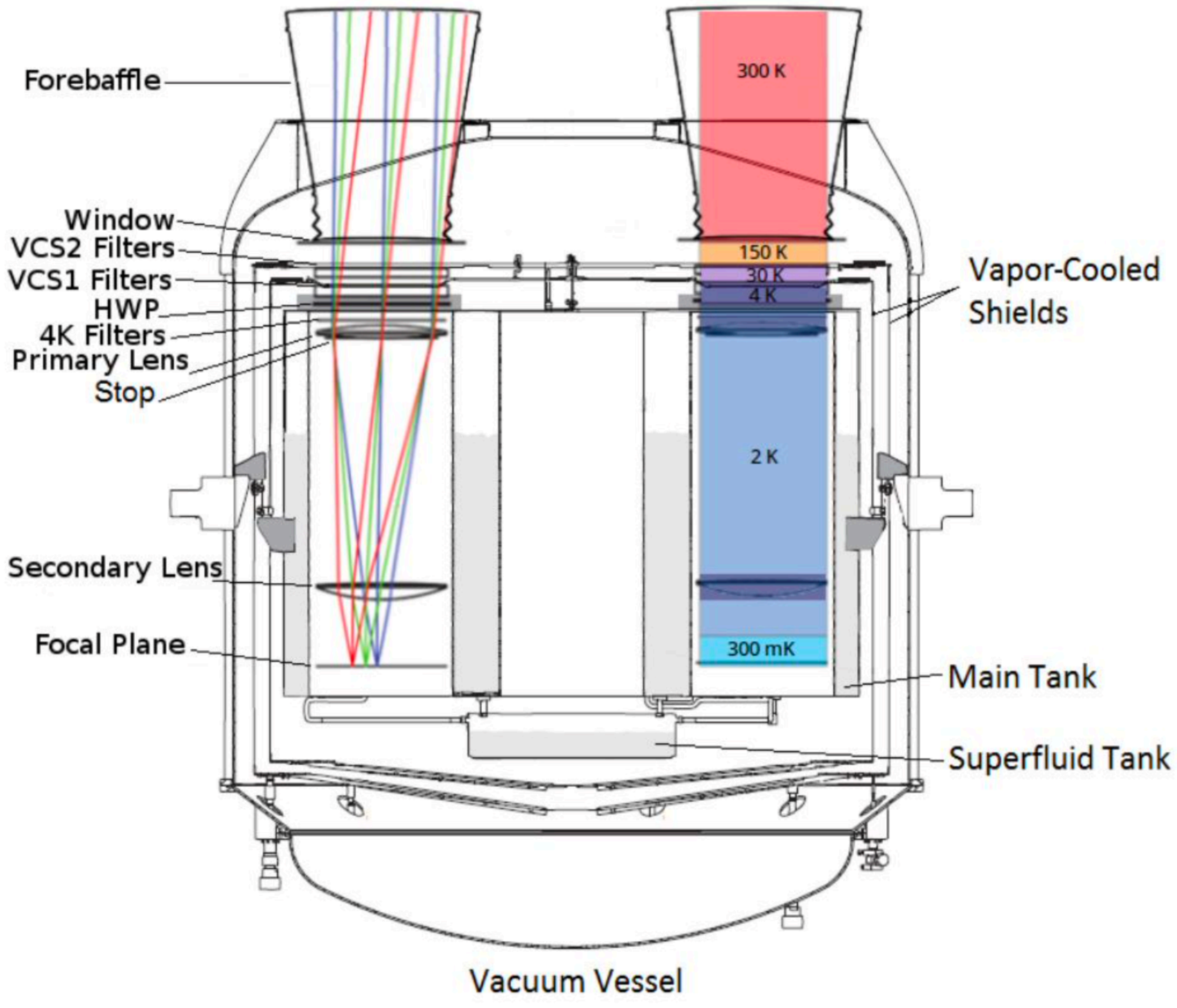

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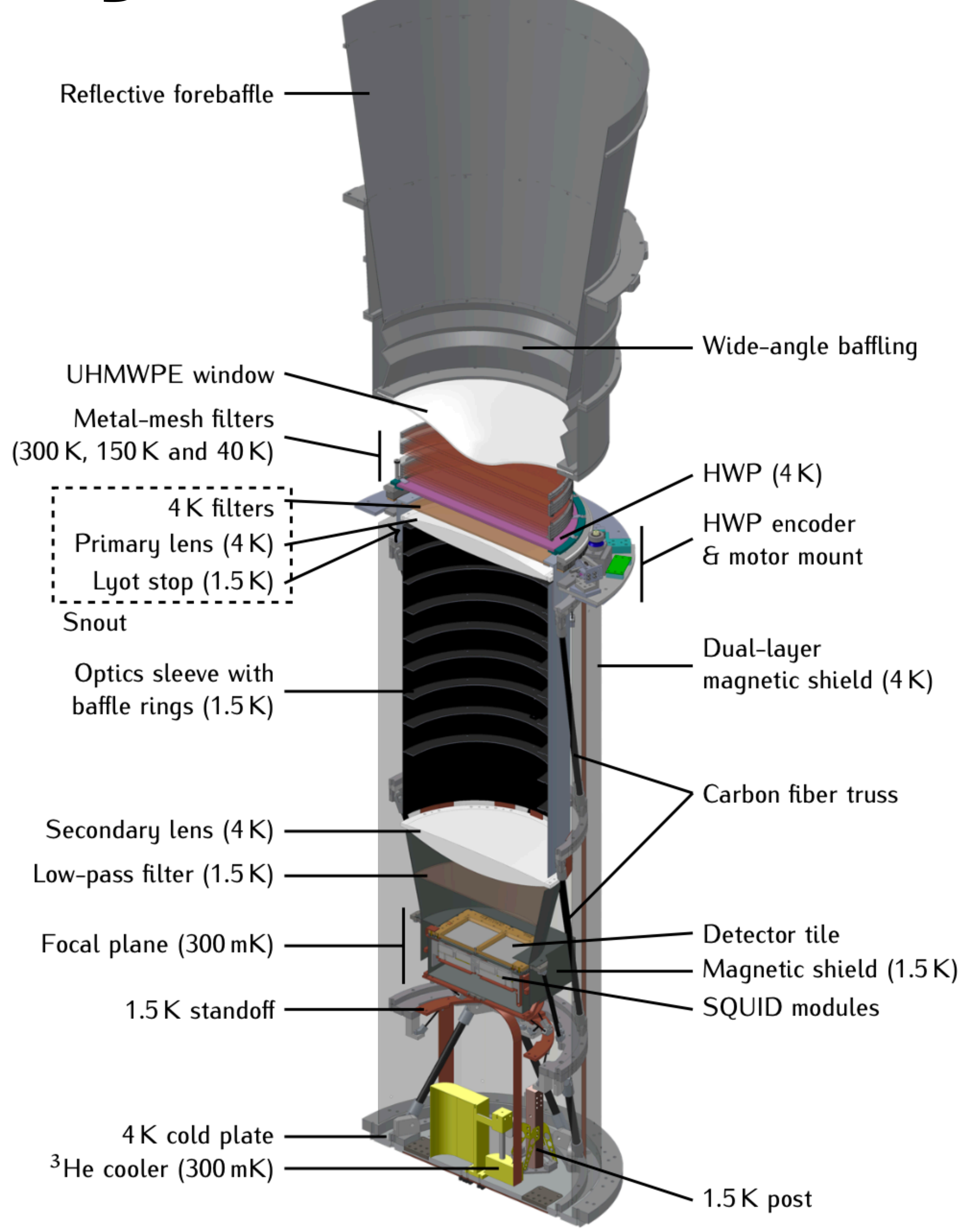


TES Bolometer Arrays

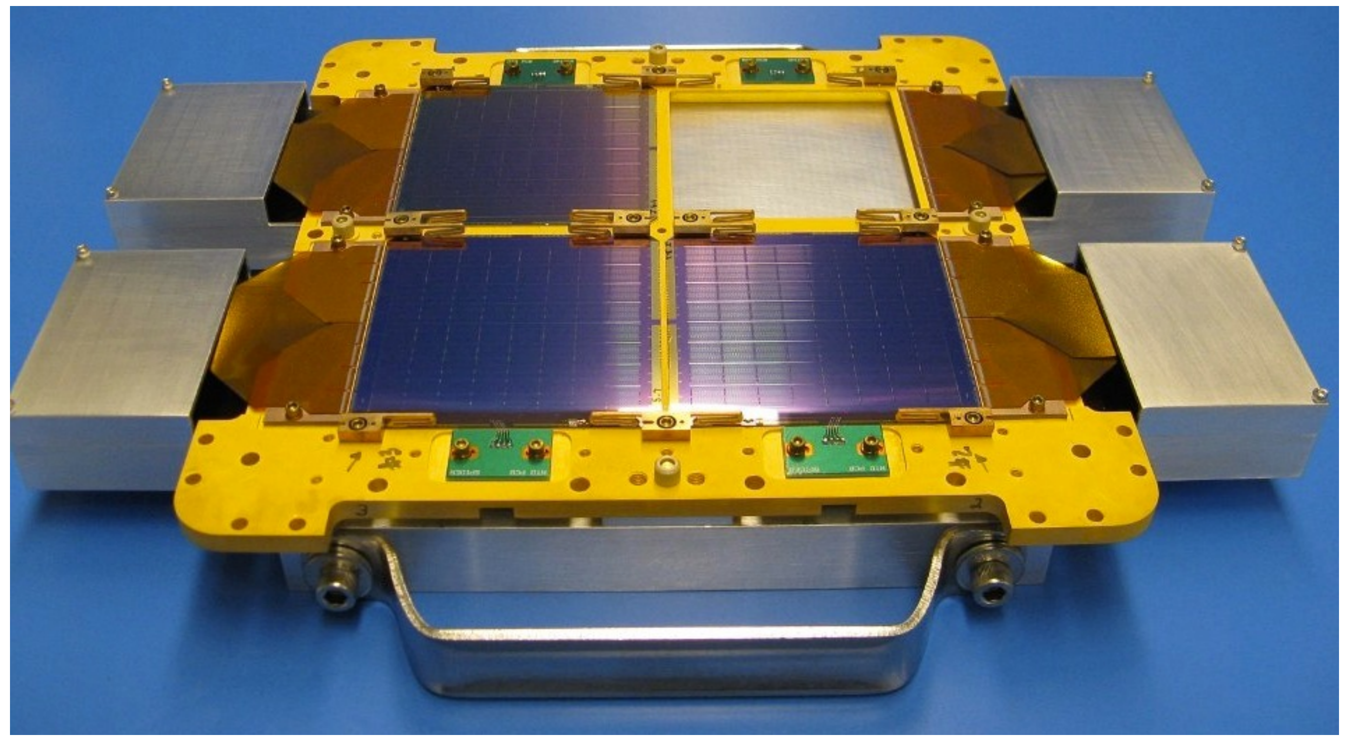
- Monolithic **Transition-edge sensor (TES) polarimeter arrays** (*~2500 channels total*)
- **Dual TES**: science (T_c~0.5K) and lab (T_c>1K); designed for **low loading / high sensitivity**
- **Time-division** SQUID multiplexer (TDM); *NIST cold electronics, UBC MCE warm electronics*

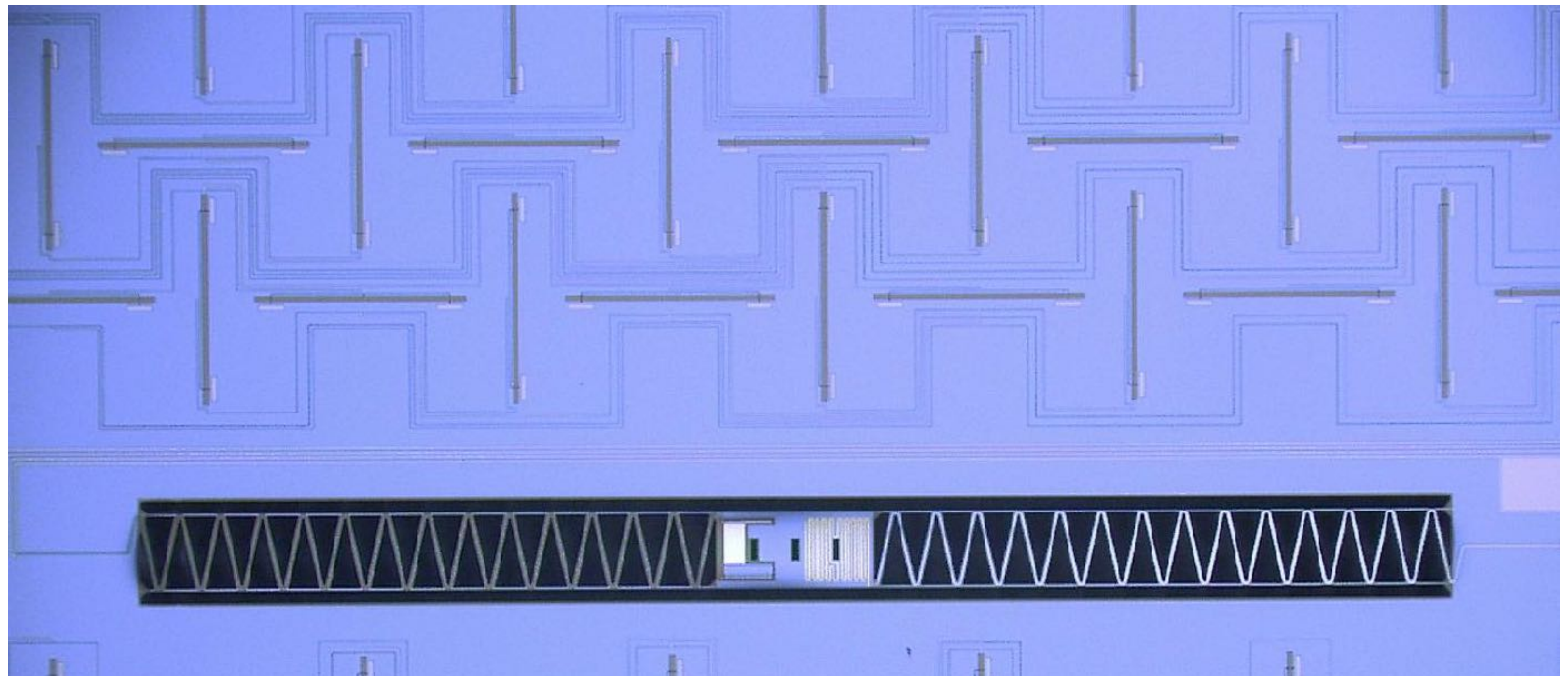
JPL

Planar phased-array antennas

95, **150** GHz

Ade+ ApJ 2015



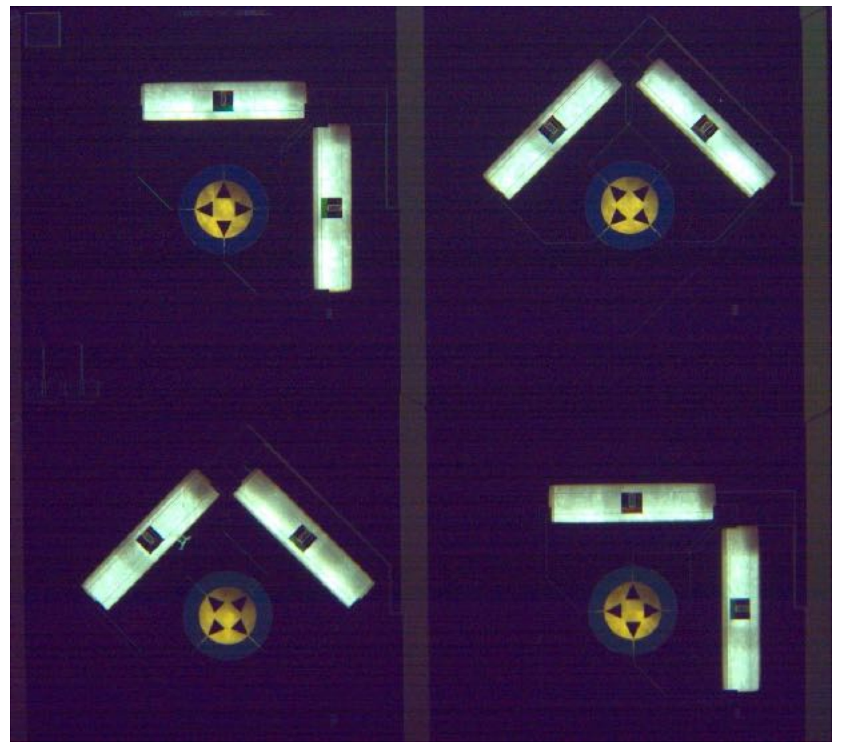


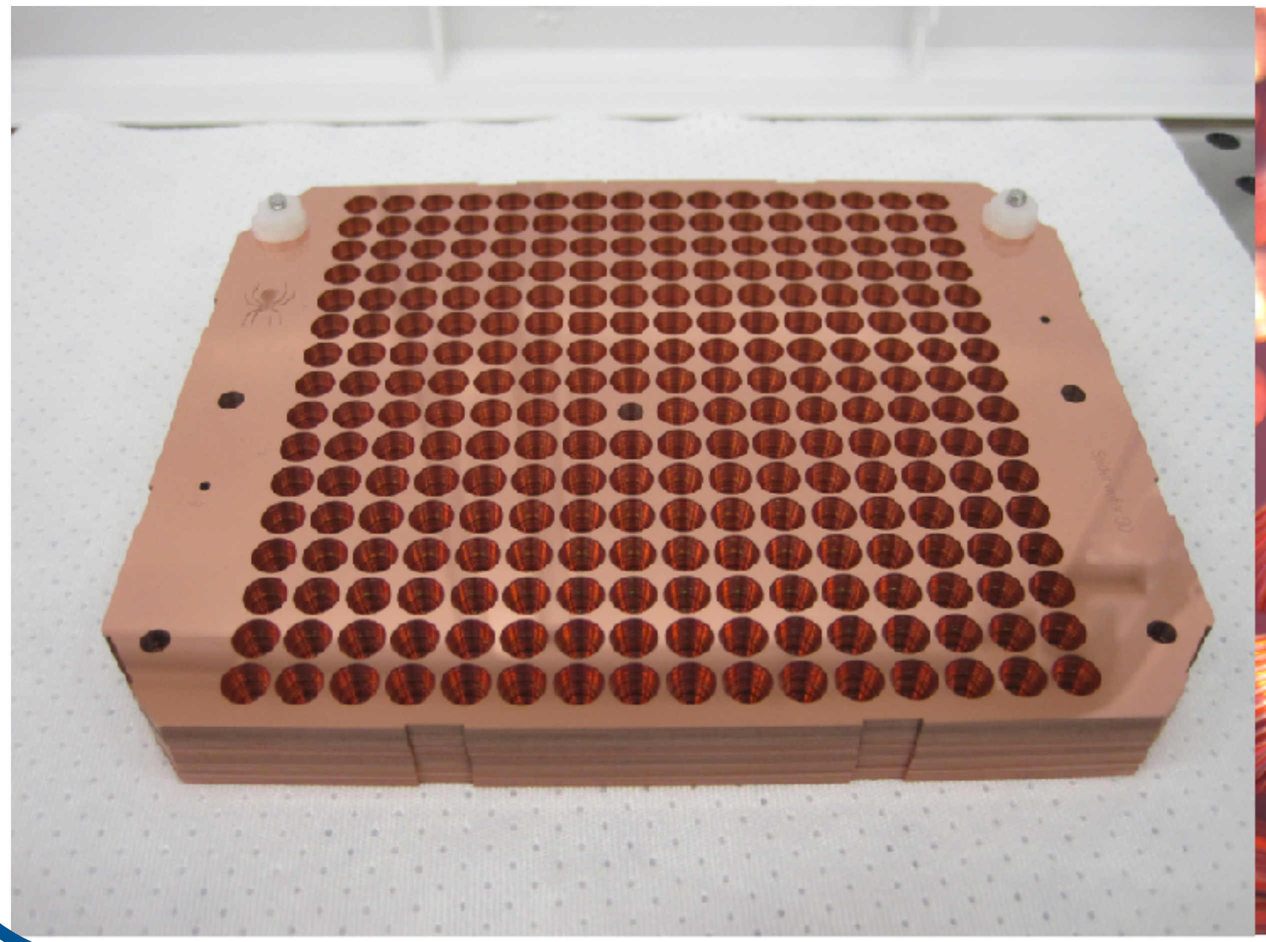
NIST

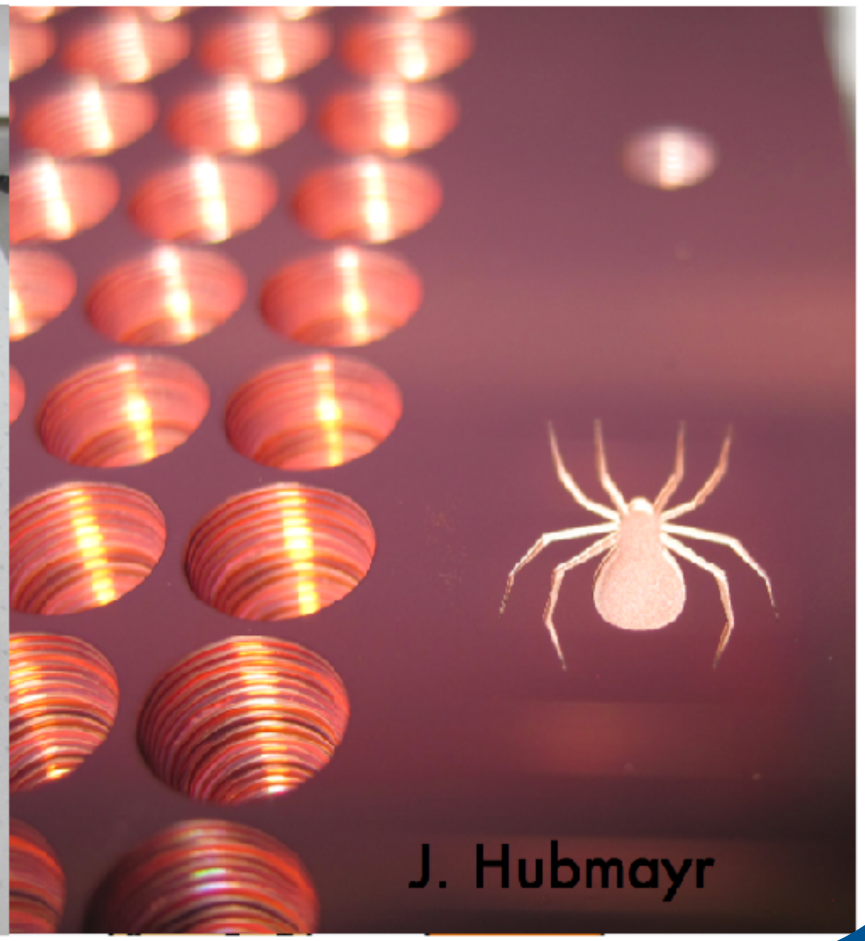
Platelet-stack horns

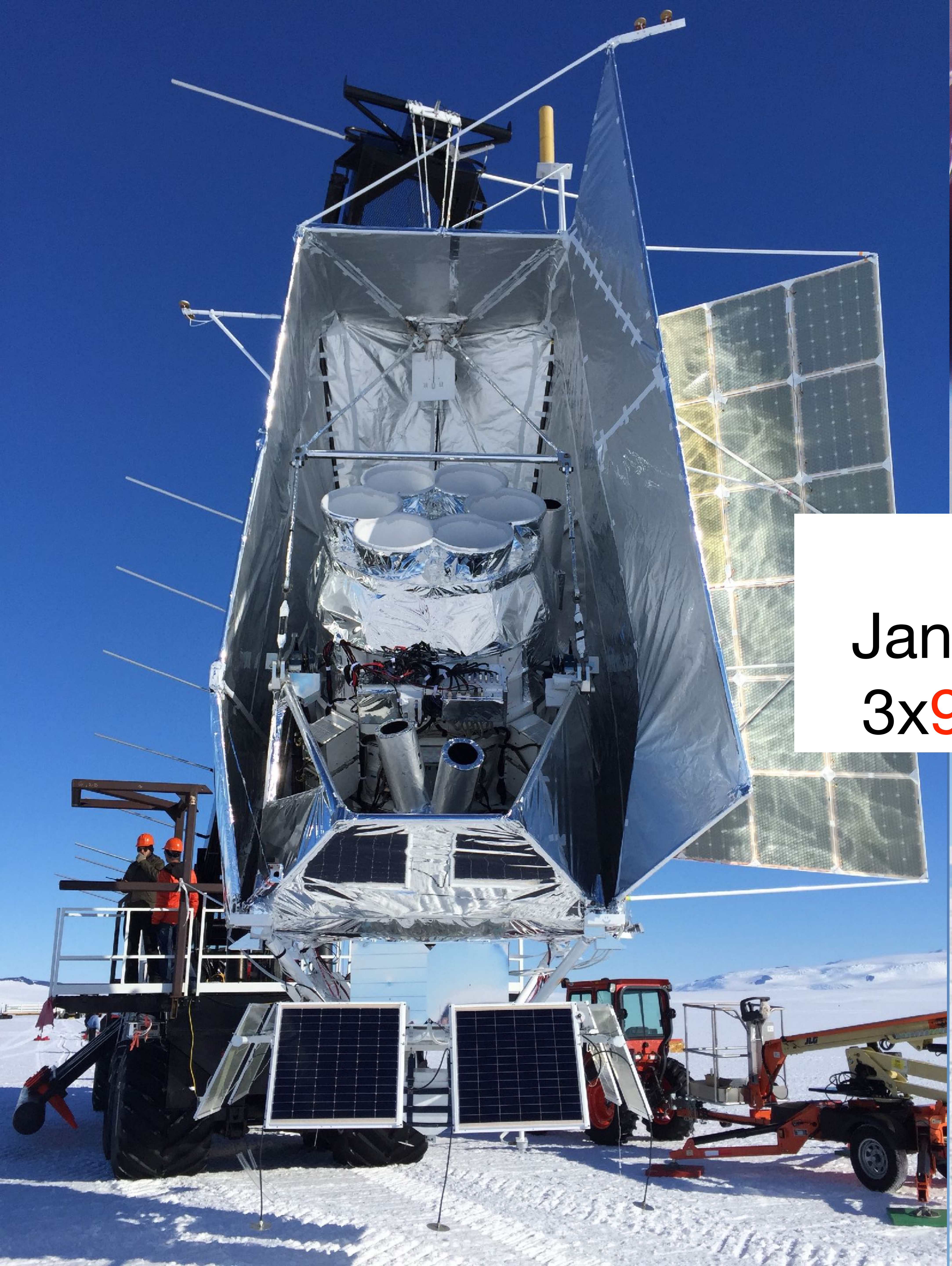
280 GHz

Hubmayr+ SPIE 2016
Bergman+ LTD 2017







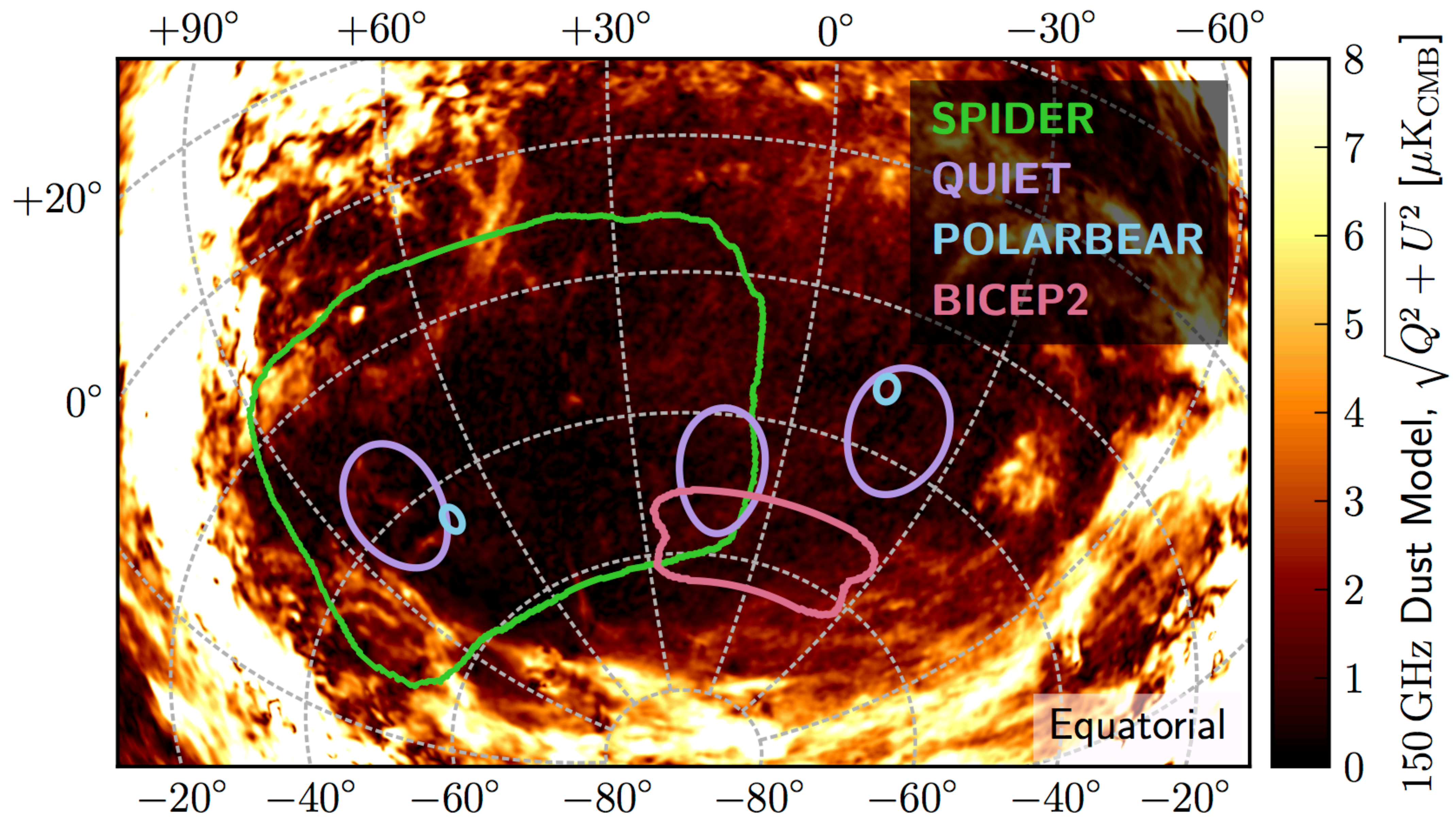


SPIDER-1

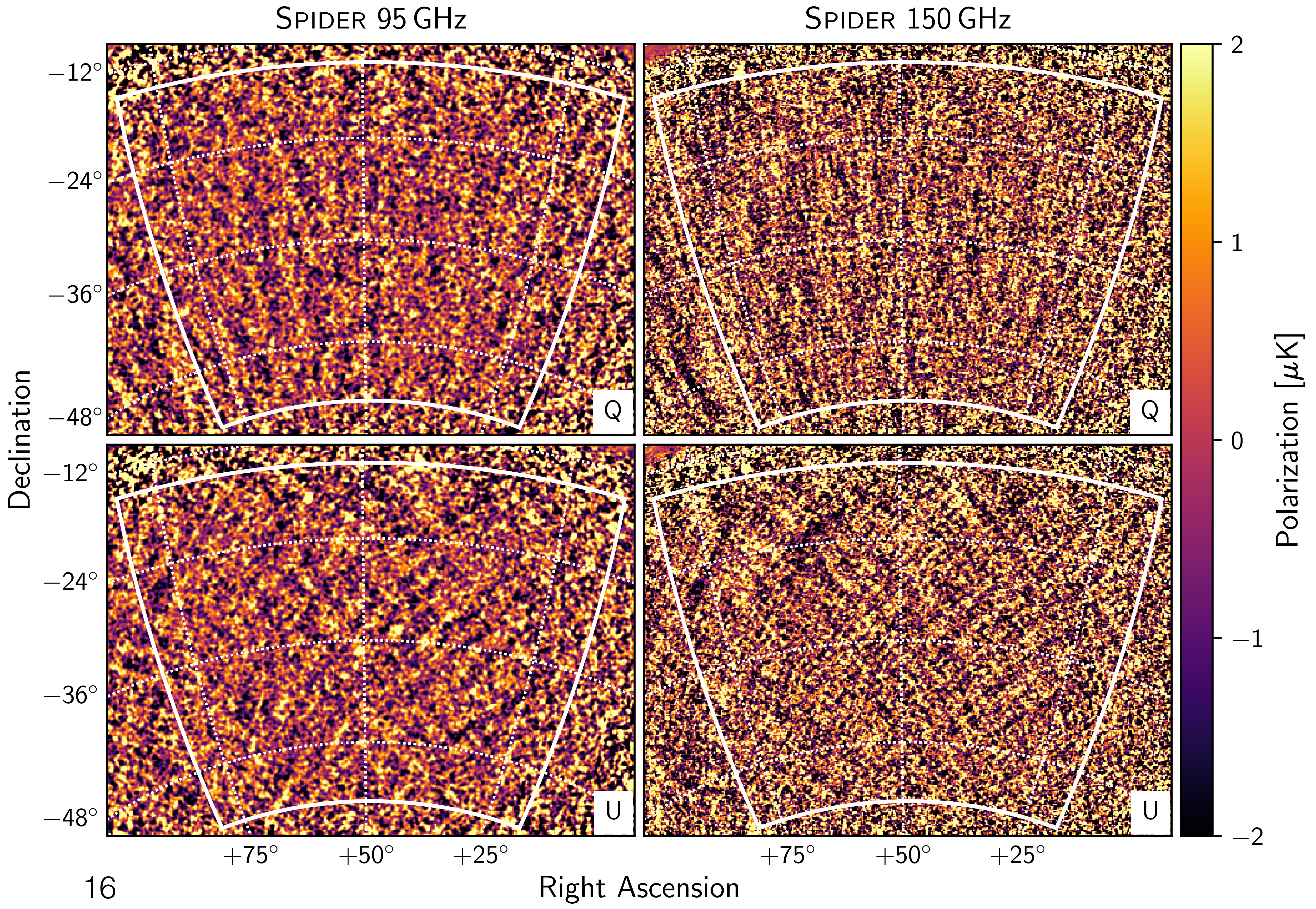
January 1-18, 2015

3x95 + 3x150 GHz

The View From Above



Band	Center [GHz]	Width [%]	FWHM [arcmin]	# Det. Used	NET_{tot} [$\mu K\sqrt{s}$]	Data Used [days]	Map Depth [$\mu K \cdot$ arcmin]
95 GHz	94.7	26.4	41.4	675	7.1	6.5	22.5
150 GHz	151.0	25.7	28.8	815	6.0	5.6	20.4



Observations cover **12.3%** of the sky

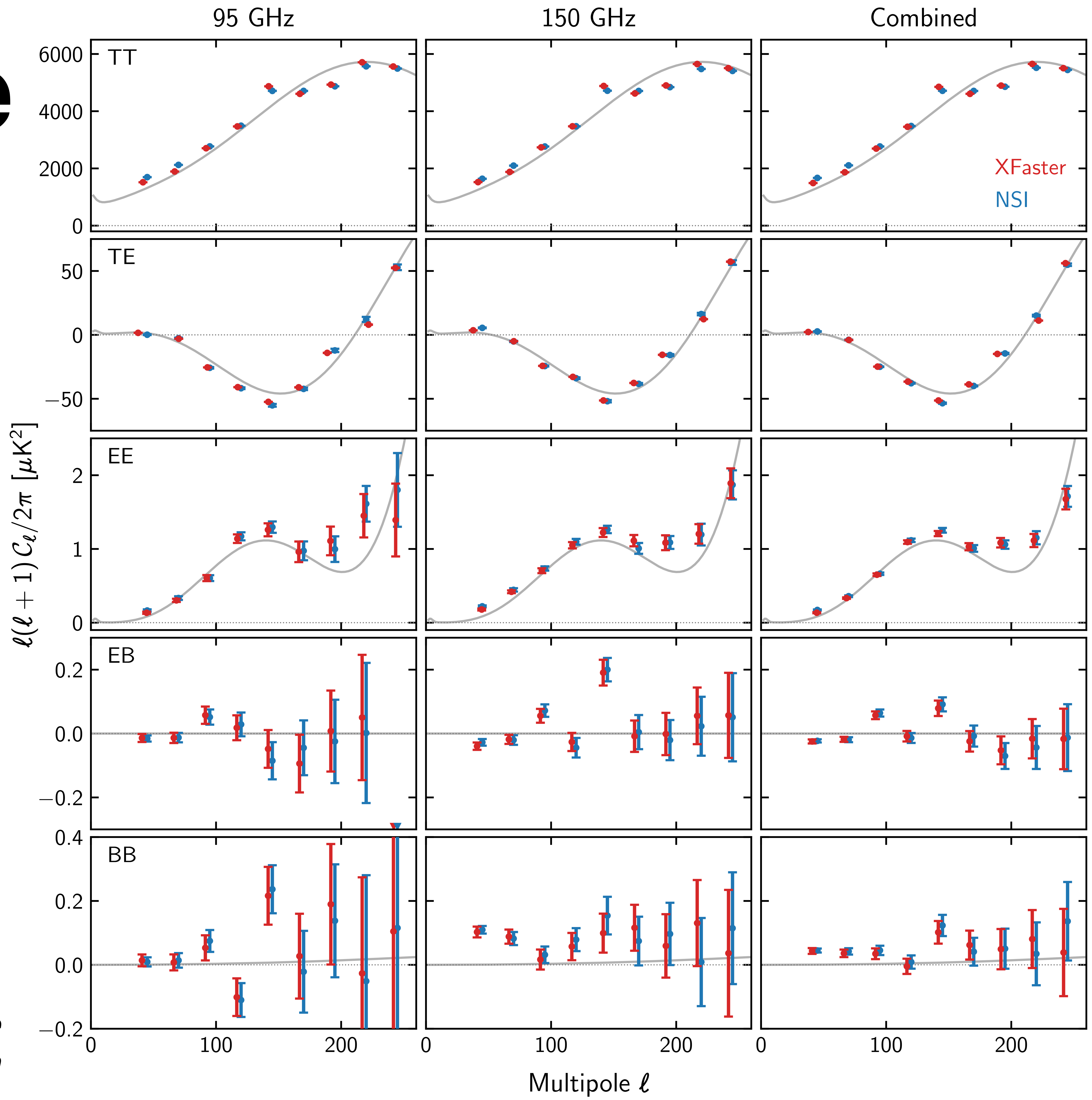
Hit-weighted 6.3%

Published analysis focuses on a reduced central sky mask: **4.8% sky**

1992 deg² rectangle, point sources cut

Analysis Pipeline

- Two independent **power spectrum** estimation pipelines
  - **XFaster**: Hybrid maximum likelihood
    Pseudo-Cl + iterative quadratic estimator
    A.E. Gambrel, A.S. Rahlin, C. Contaldi, …
    ApJ 922, 132 (2021)
  - **NSI**: "Noise-Simulation Independent"
    Empirical covariances among data subsets
    J. Nagy, J. Hartley, S. Benton, J. Leung, …
- Suite of **null tests** to confirm internal consistency in both pipelines
- Full time-domain **simulations** to calibrate methods, systematics

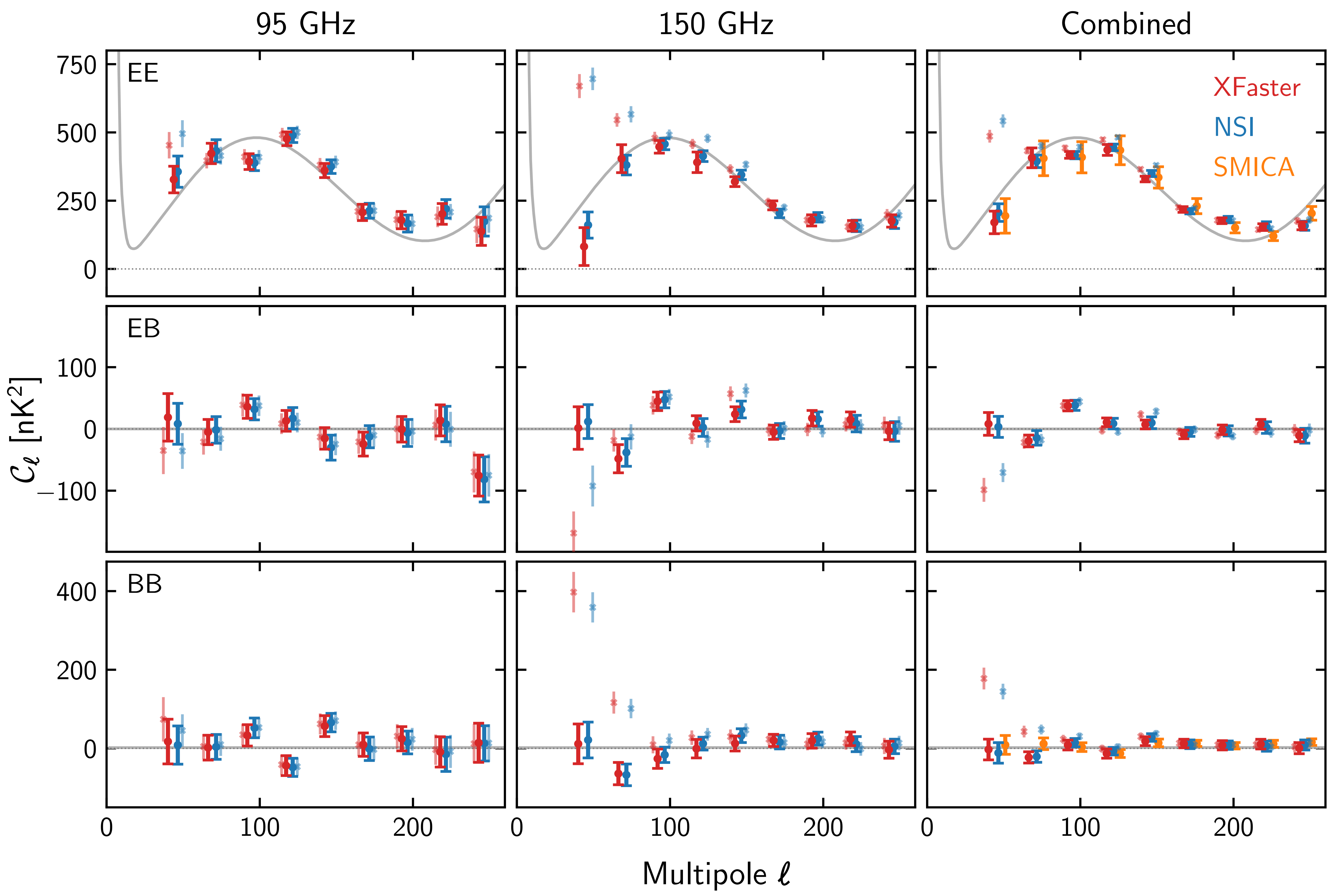


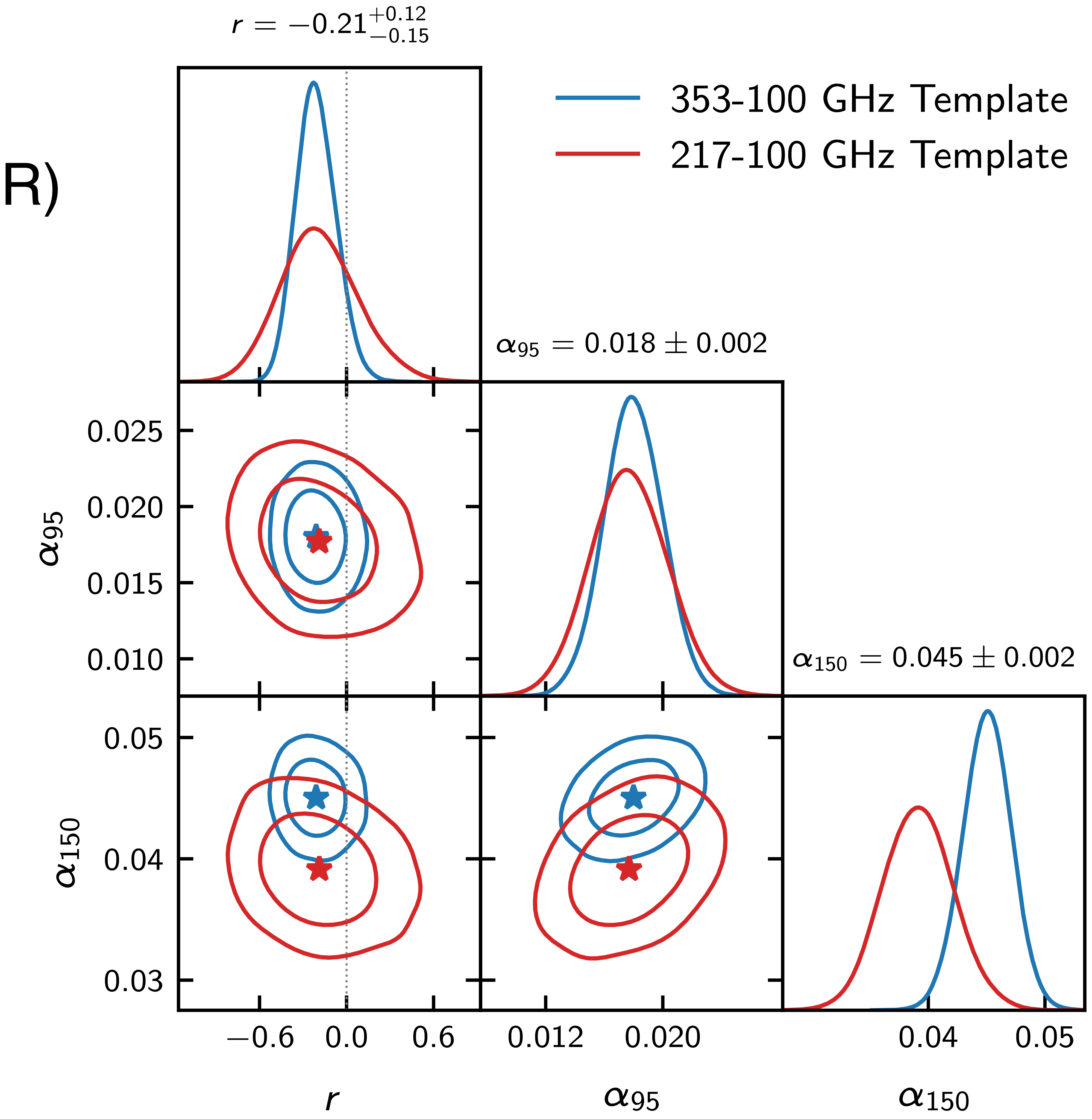
Error bars do not include sample variance, for ease of pipeline comparison

CMB Results

Multiple dust cleaning methods using Planck data

- Template based (P353-P100 or P217-P100)
- Harmonic domain (**SMICA**, polarized HFI + SPIDER)

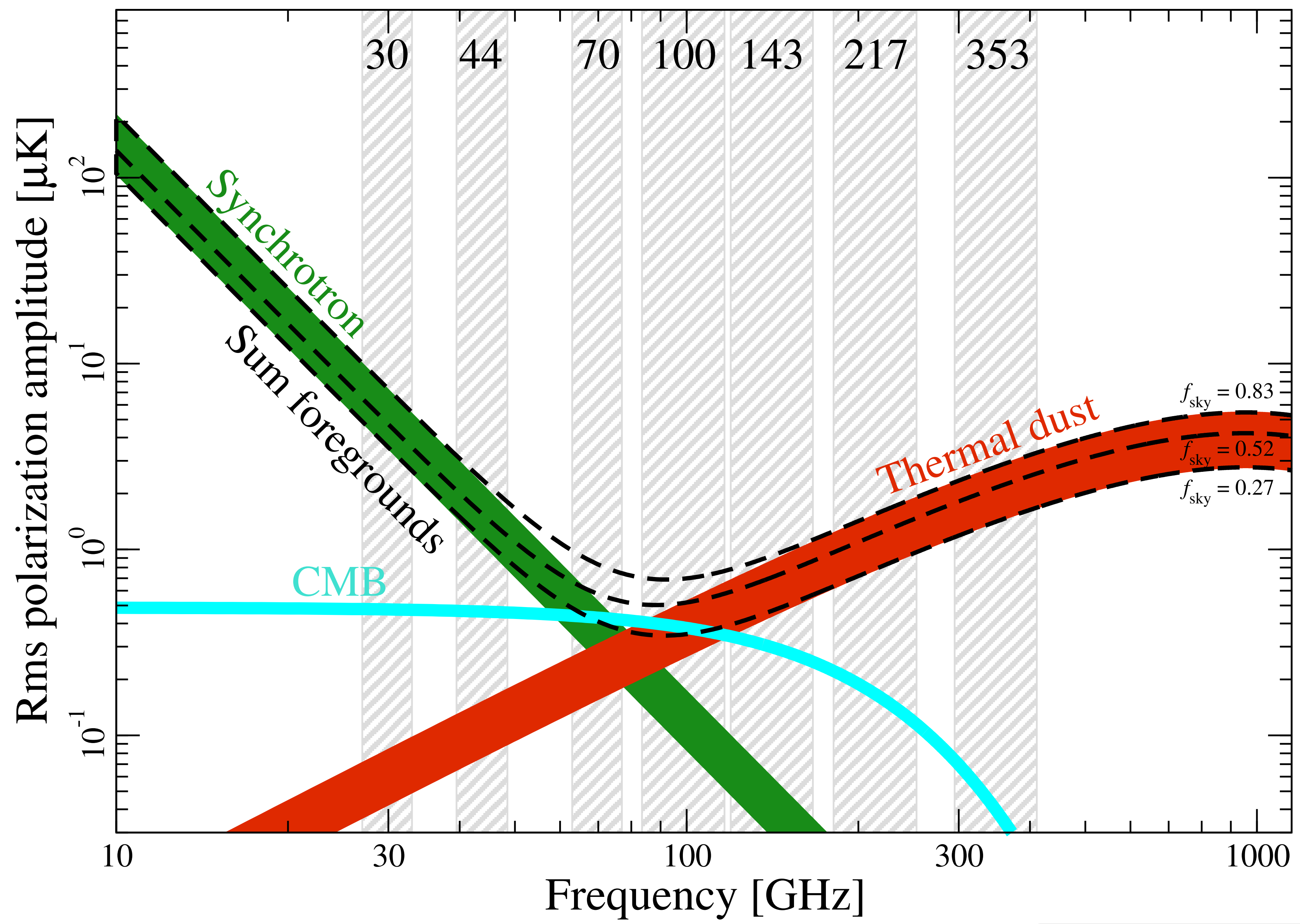




Sample variance included

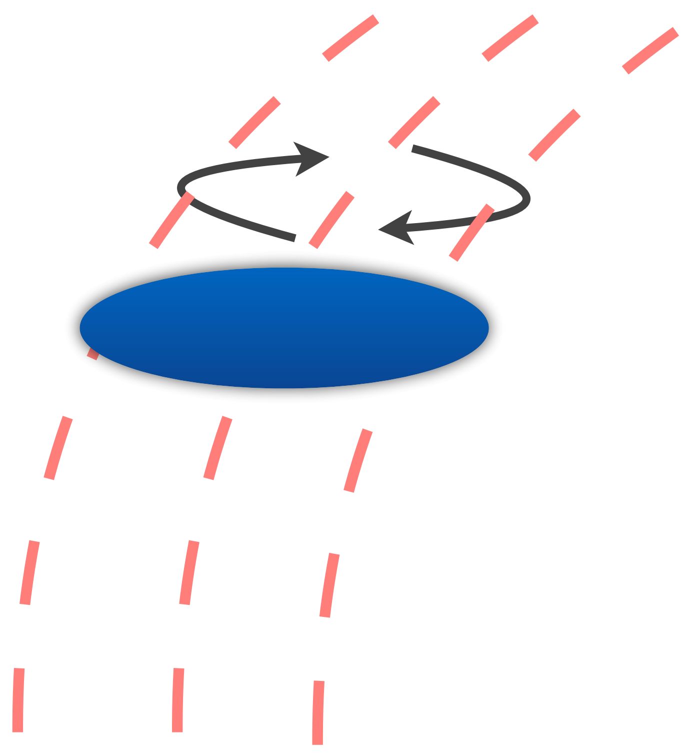
ApJ 927, 174 (2022)

Dust Foregrounds and CMB Analysis

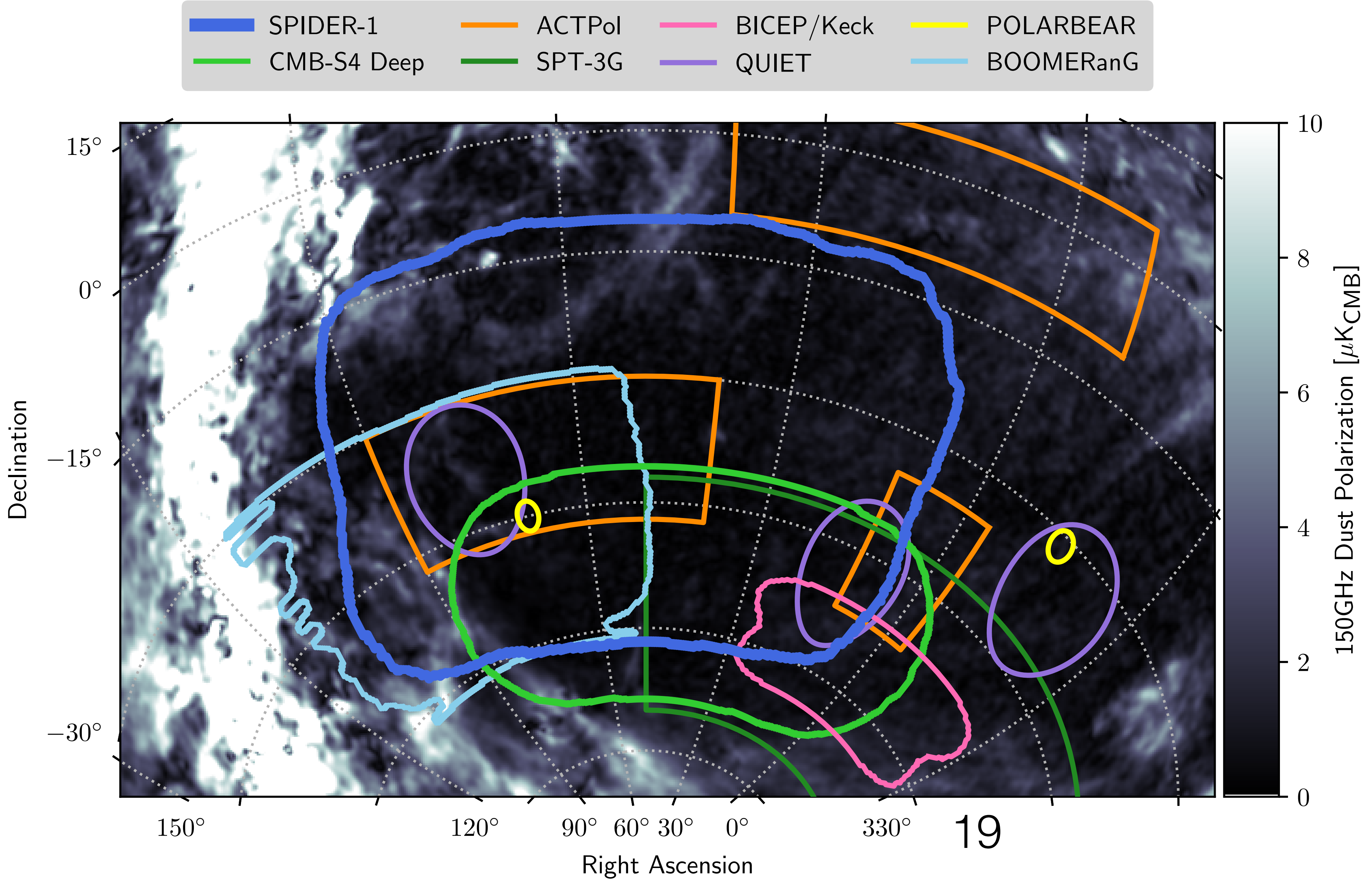


Planck 2018 full-sky spectra (40' smoothing)

Thermal Dust Emission



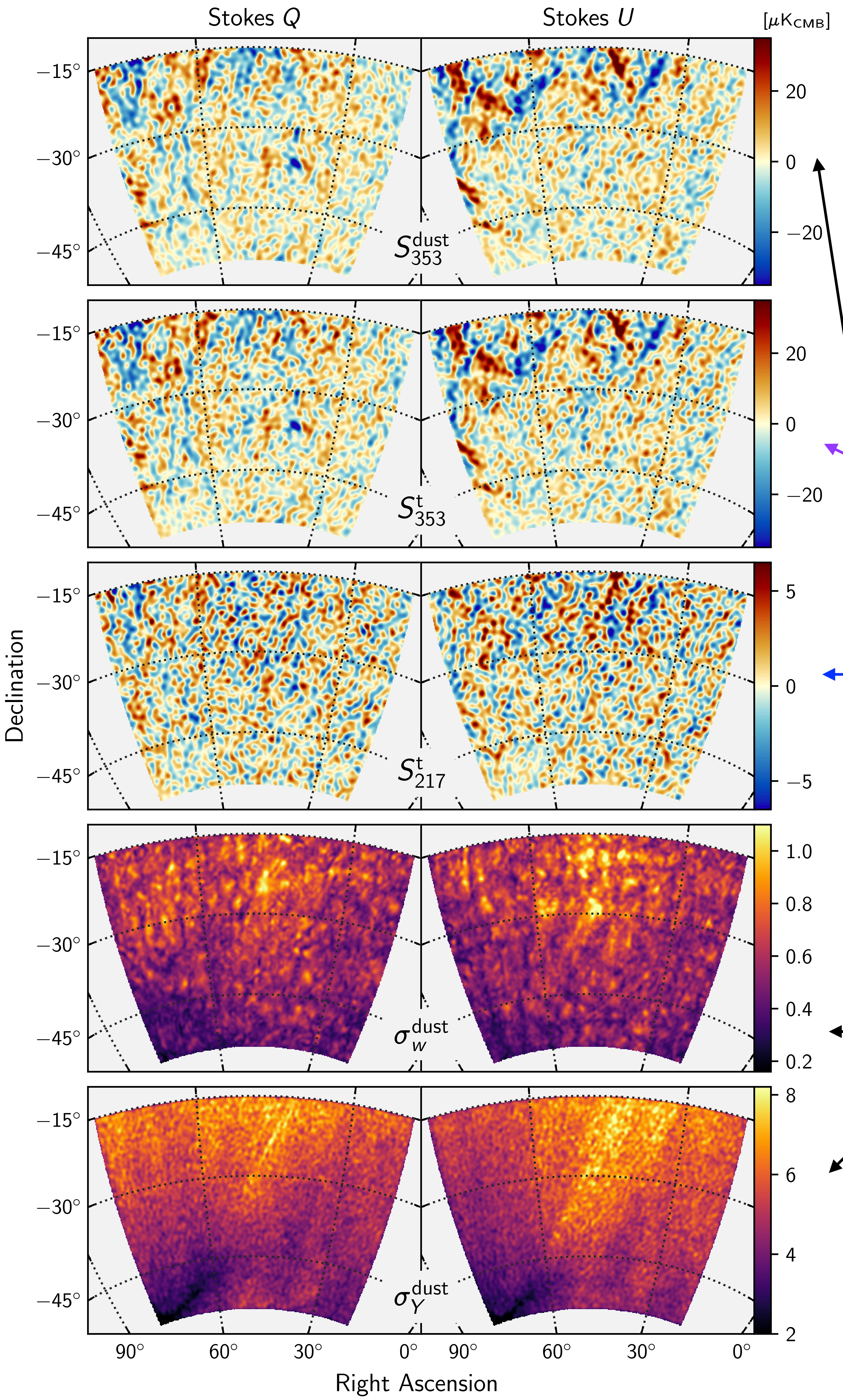
Weak torques statistically align asymmetric grains with B field



SPIDER observation area (~4.8% sky analyzed)

Of interest for current and future observations!

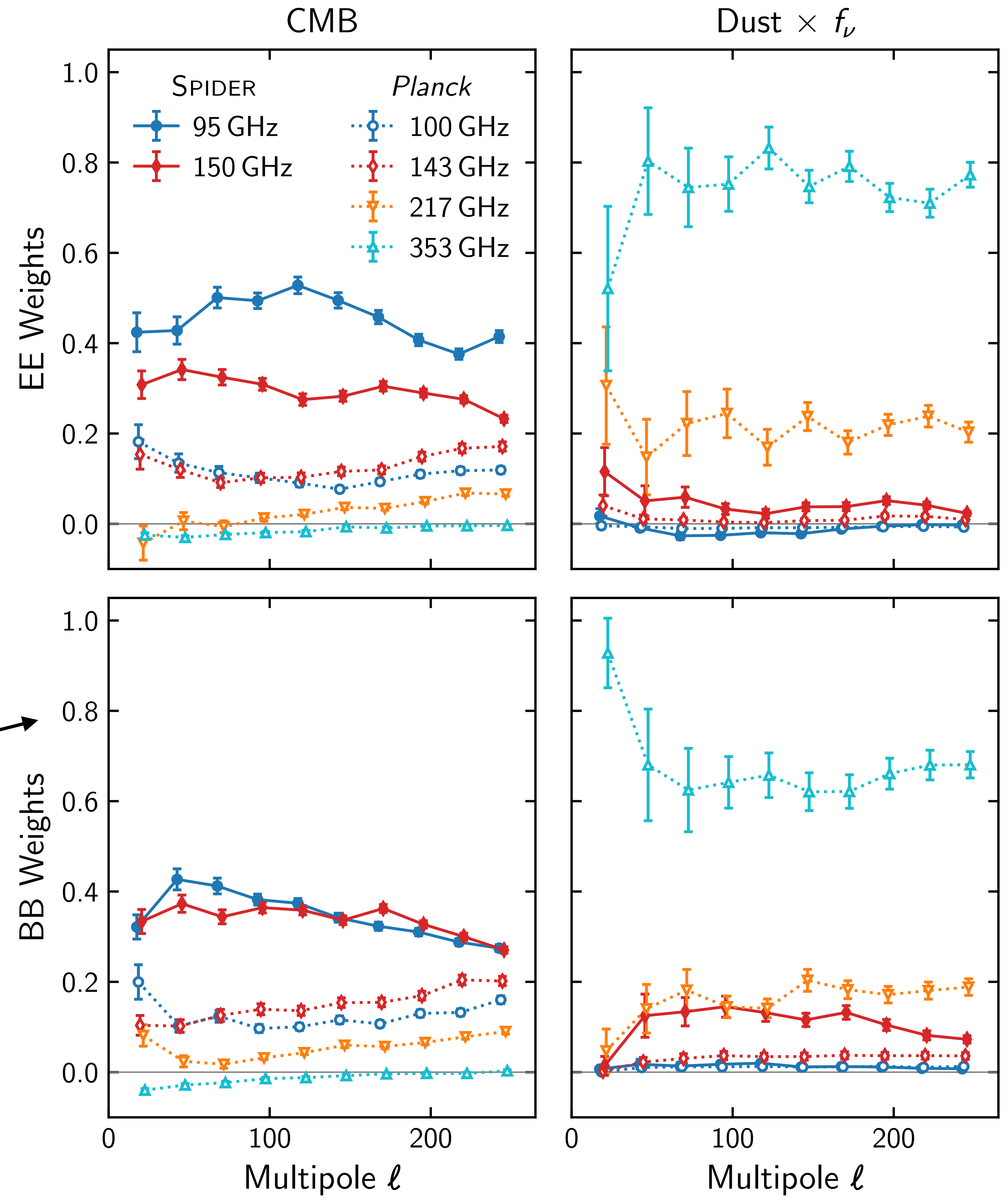
- Dust polarization physics is **complex** and incompletely understood
  - Dust grain compositions and shapes
  - Local radiative / magnetic environment
- CMB analysts make various **assumptions** to link multi-frequency observations
  - **Morphology** constant with frequency? *Uniform SED, template subtraction*
  - Simple **SED** form? *Modified blackbody:* $B_\nu^{(\mathrm{d})} \propto \nu^{\beta_\mathrm{d}} B_\nu(T_\mathrm{d})$
  - Simple **angular power spectrum**? *Power law:* $C_\ell^{(\mathrm{d})} \propto \ell^{-\alpha_\mathrm{d}}$
- **Goal**: Test common analysis assumptions with deep maps over a large sky area at high Galactic latitude



Foregrounds in SPIDER's Sky

Multiple estimates of polarized dust morphology

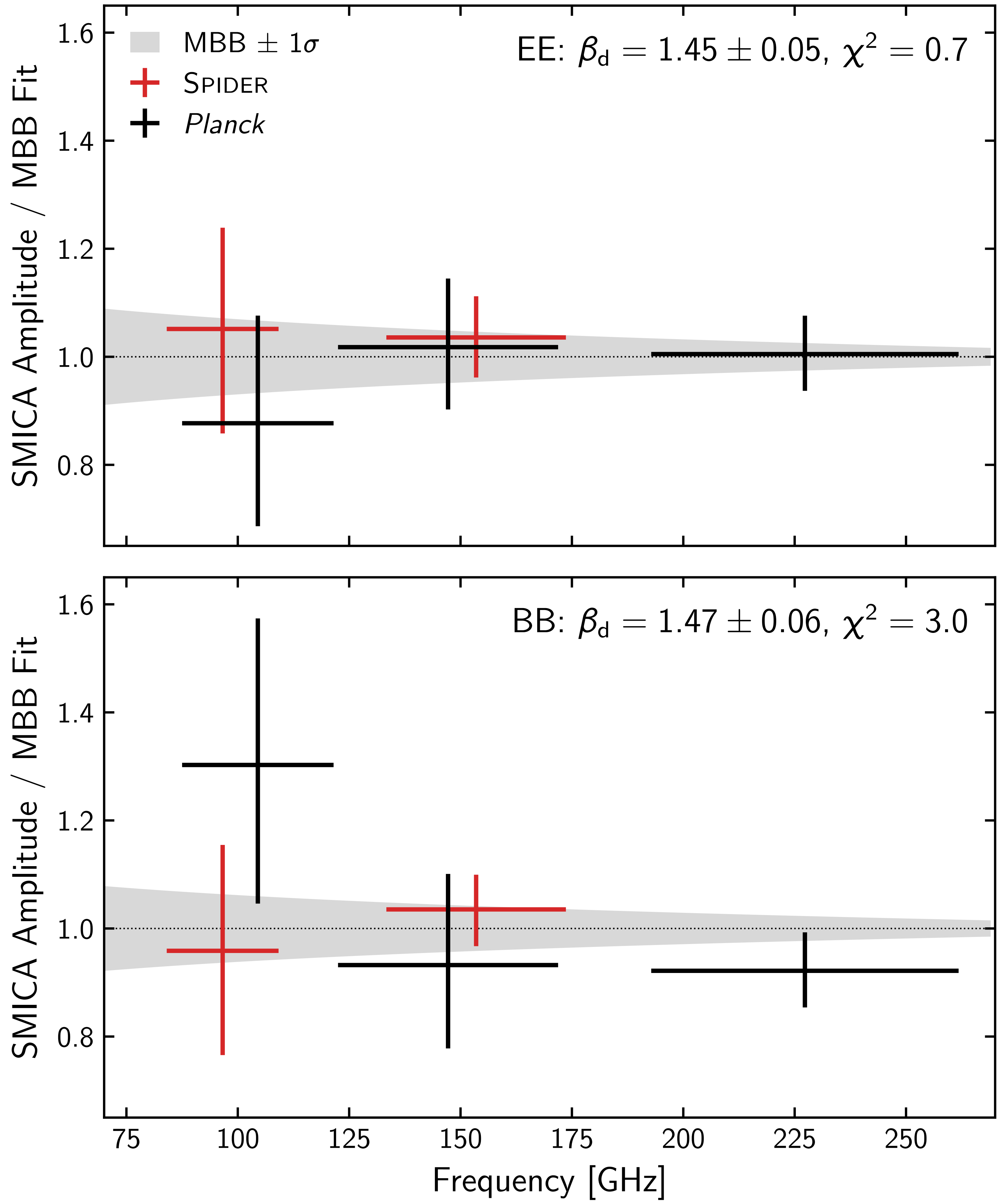
- **Templates** constructed from Planck-HFI data
  - Planck 353 GHz - 100 GHz
    primary for B-mode analysis
  - Planck 217 GHz - 100 GHz
    lower S/N
- **SMICA**: internal linear combination analysis
  - Planck 100, 143, 217, 353
  - **SPIDER 95, 150**



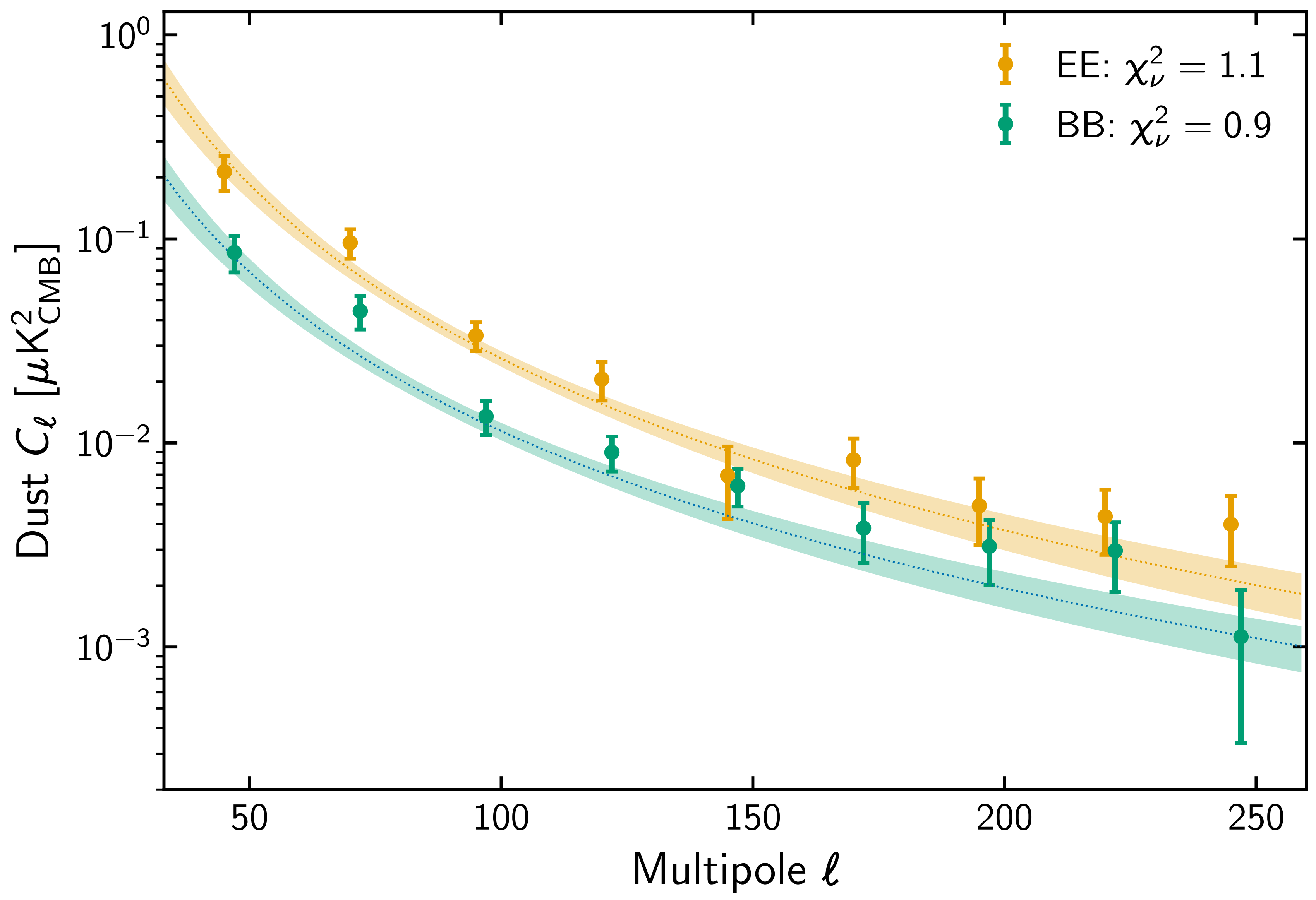
ApJ 978, 130 (2025)

Testing Common Assumptions

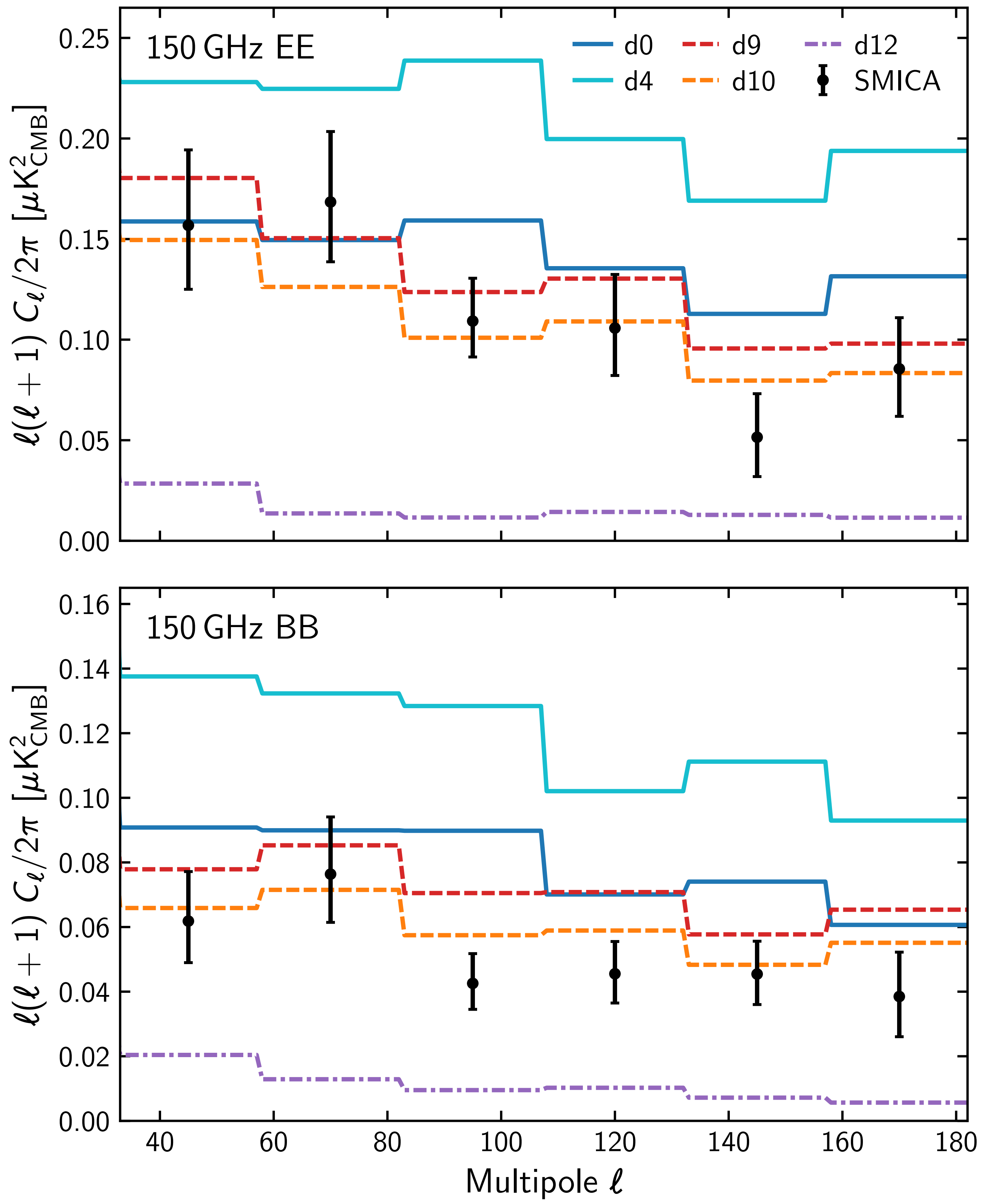
Frequency spectrum



Angular power spectrum



Reasonable agreement with MBB model, power law angular power spectrum, no evidence for line-of-sight decorrelation

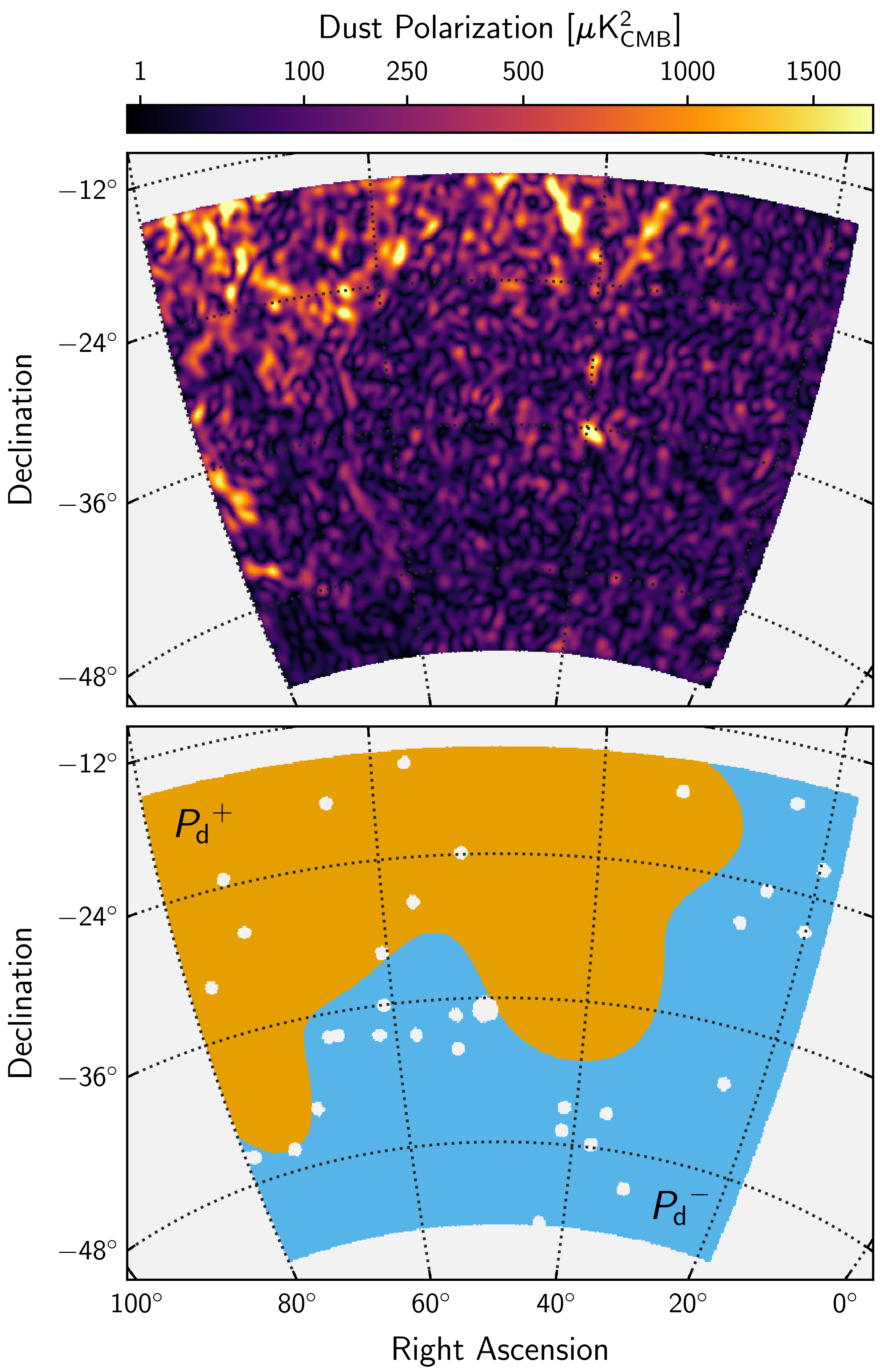


Comparisons to common forecasting models (PySM)

No significant evidence of deviations when considering *entire* SPIDER region

ApJ 978, 130 (2025)

Spatial Variation?



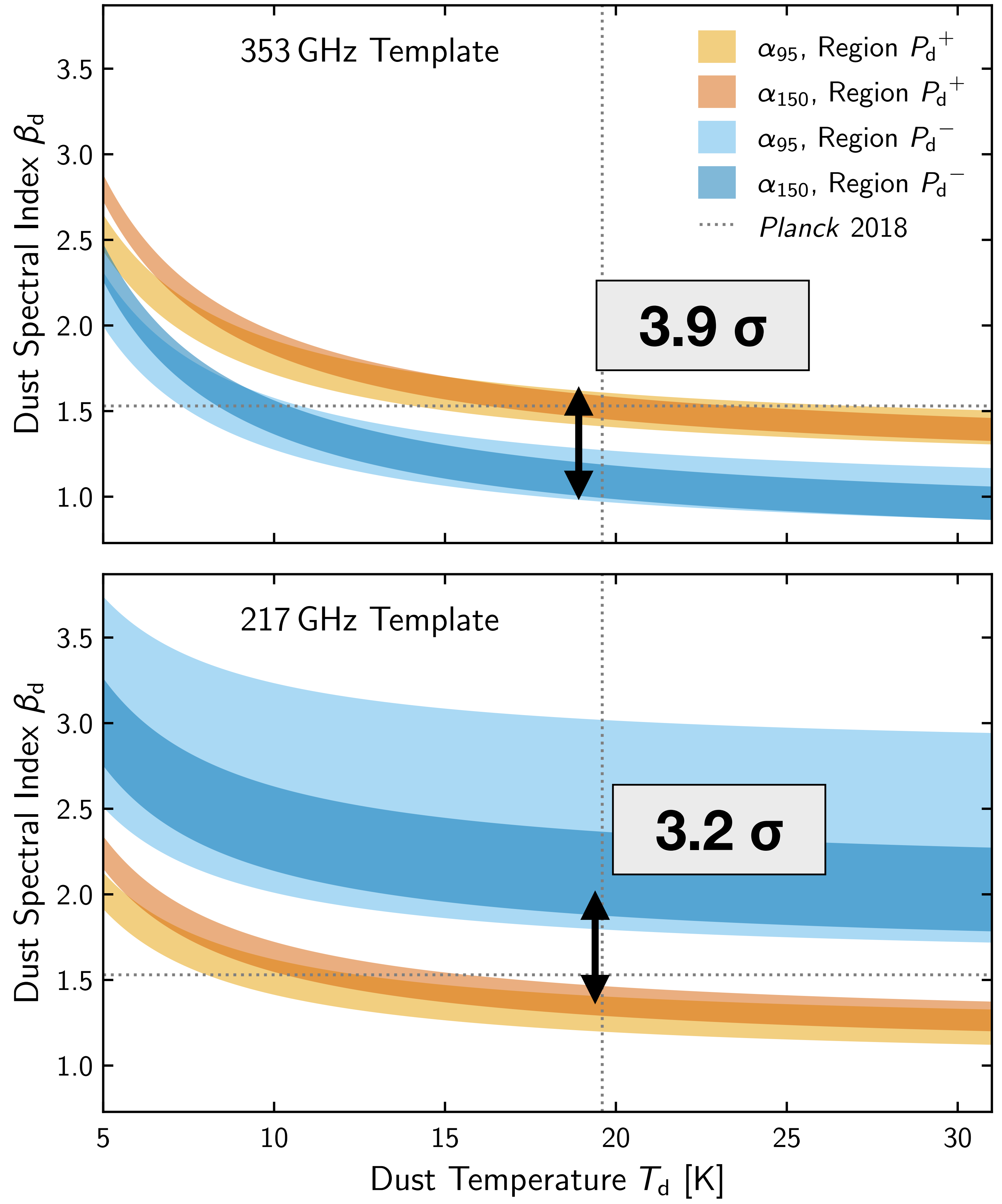
ApJ 978, 130 (2025)

Divide SPIDER sky patch into two regions: brighter dust (P_d^+), fainter dust (P_d^-)

Find correlation amplitudes between SPIDER 95/150 with 353/217 templates

- Good consistency among SPIDER bands
- P_d^+ largely consistent with MBB SED similar to Planck full-sky, using either template
- **Inconsistency** between P_d^+ and P_d^-
- **No good MBB fit** within P_d^-

More data needed!

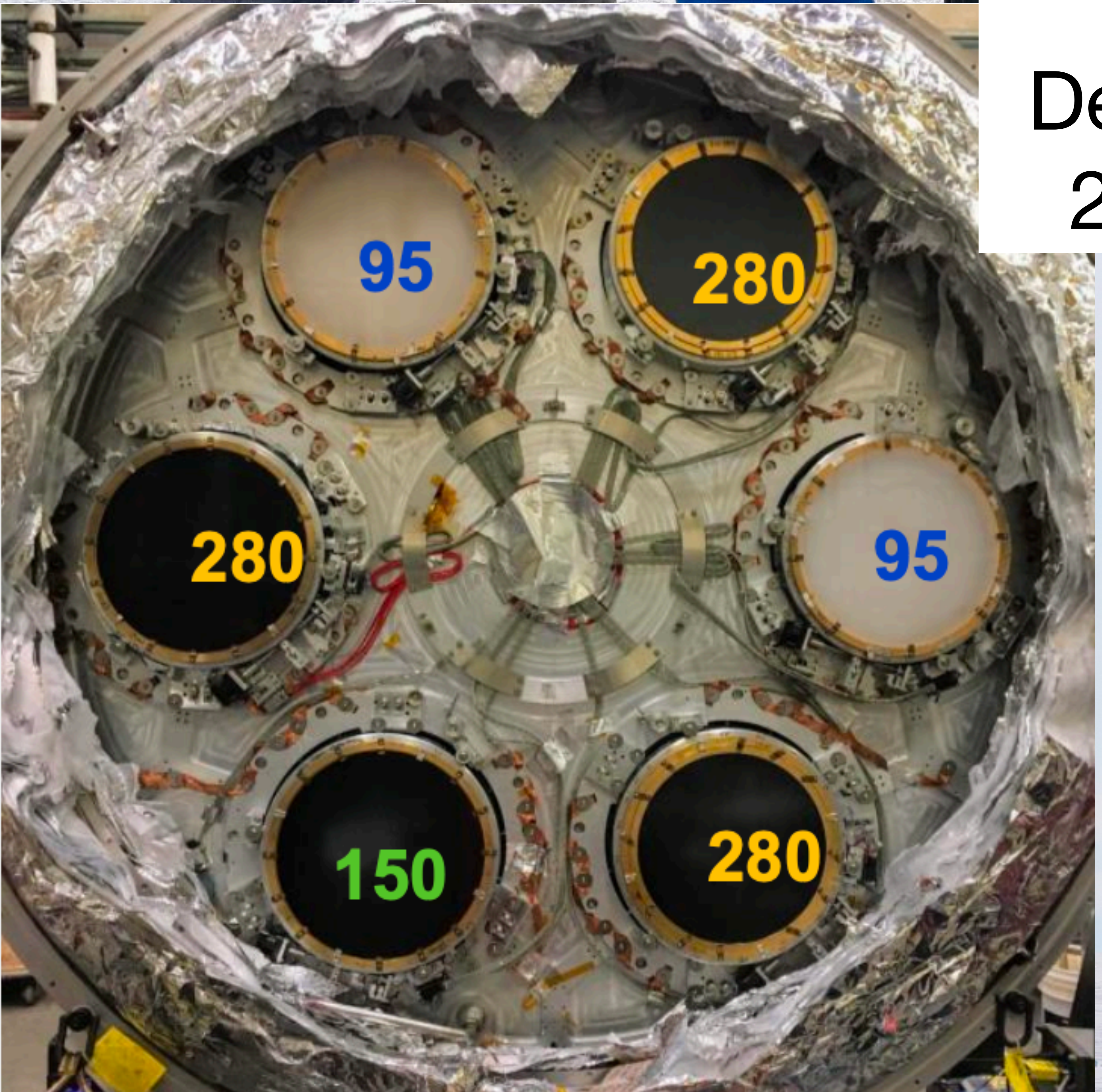


Modified blackbody SED fit parameters

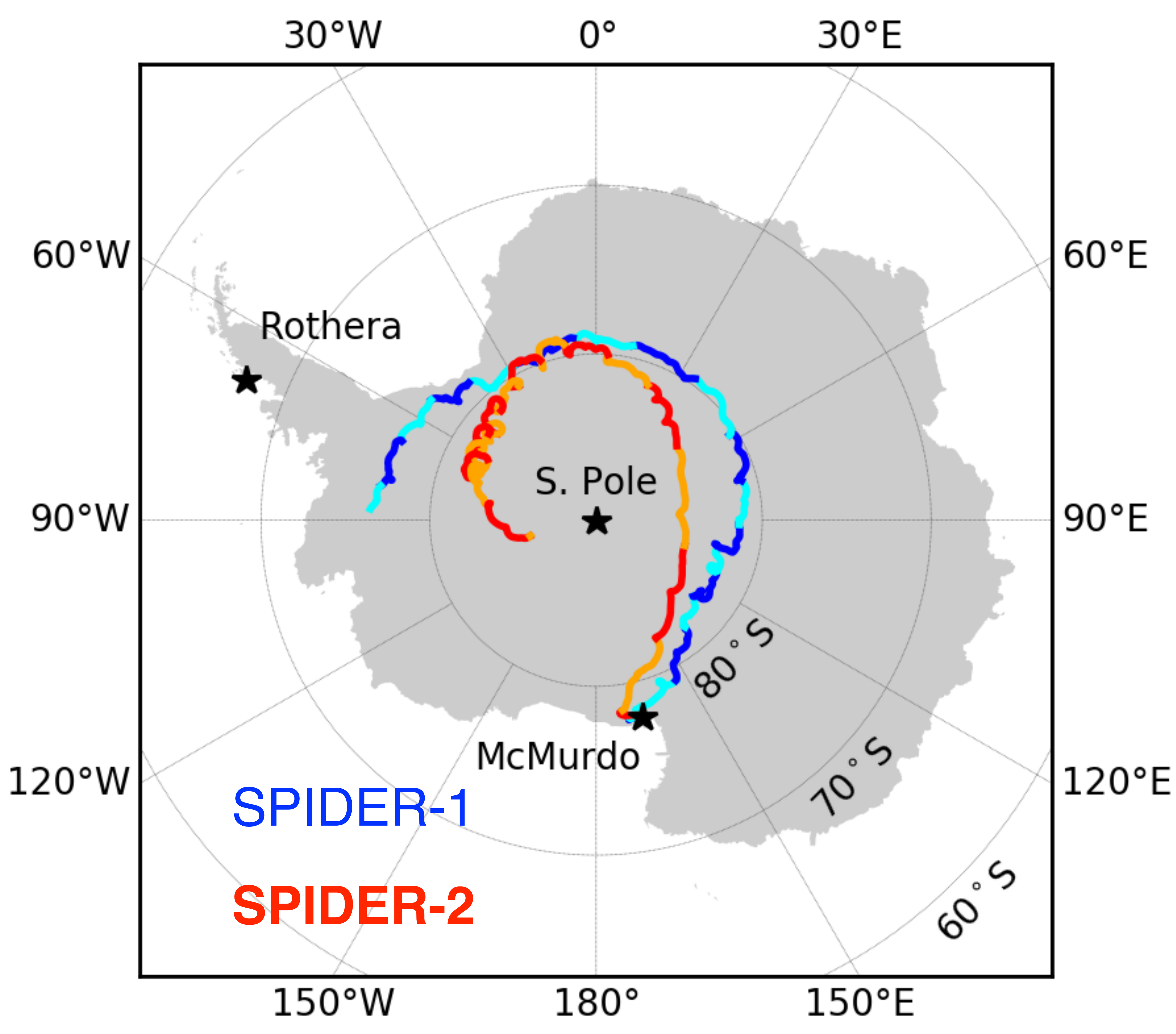
SPIDER-2

Dec. 22, 2022 - Jan. 16, 2023

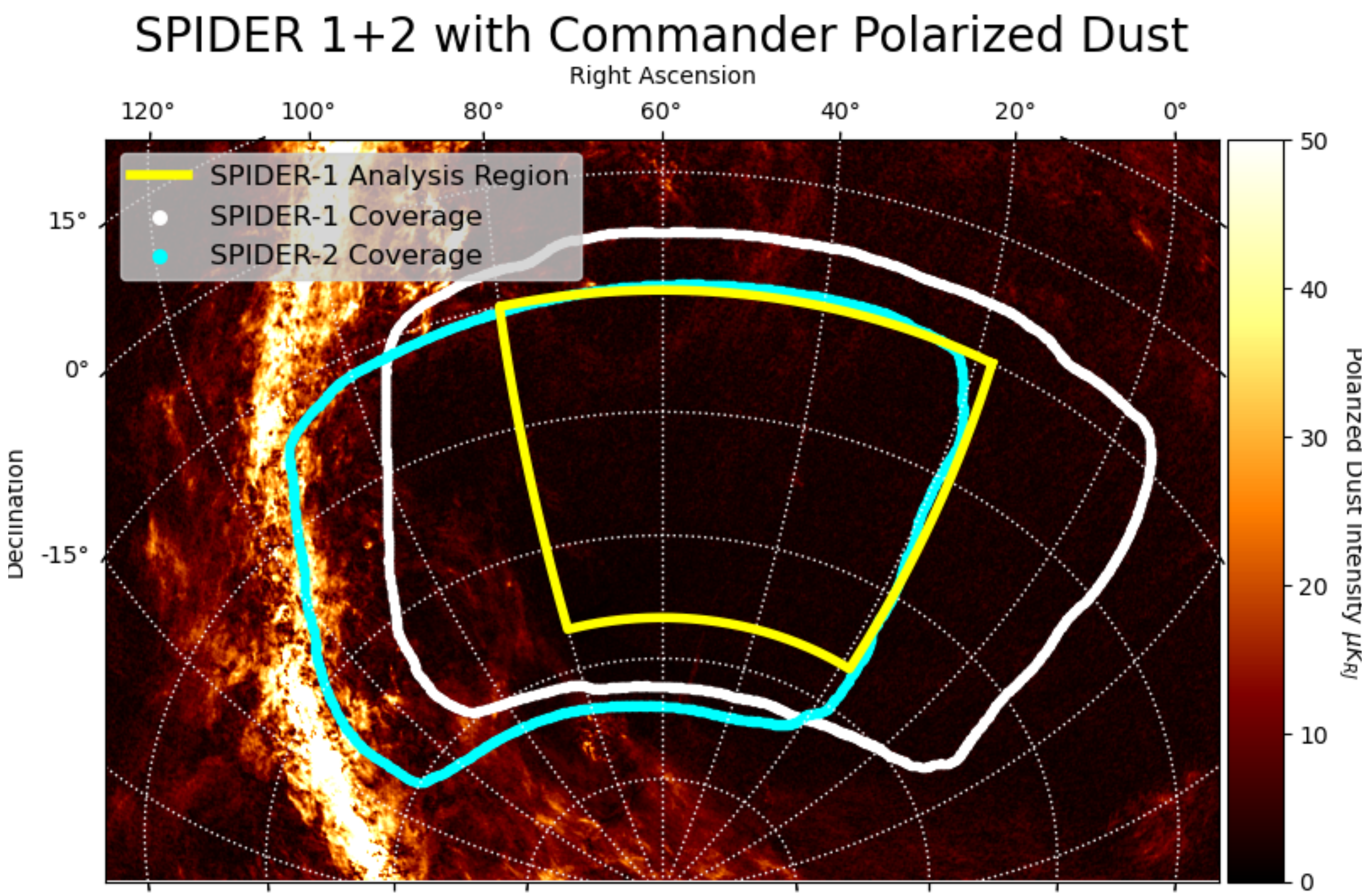
2x95 + 1x150 + 3x280 GHz



SPIDER Flights



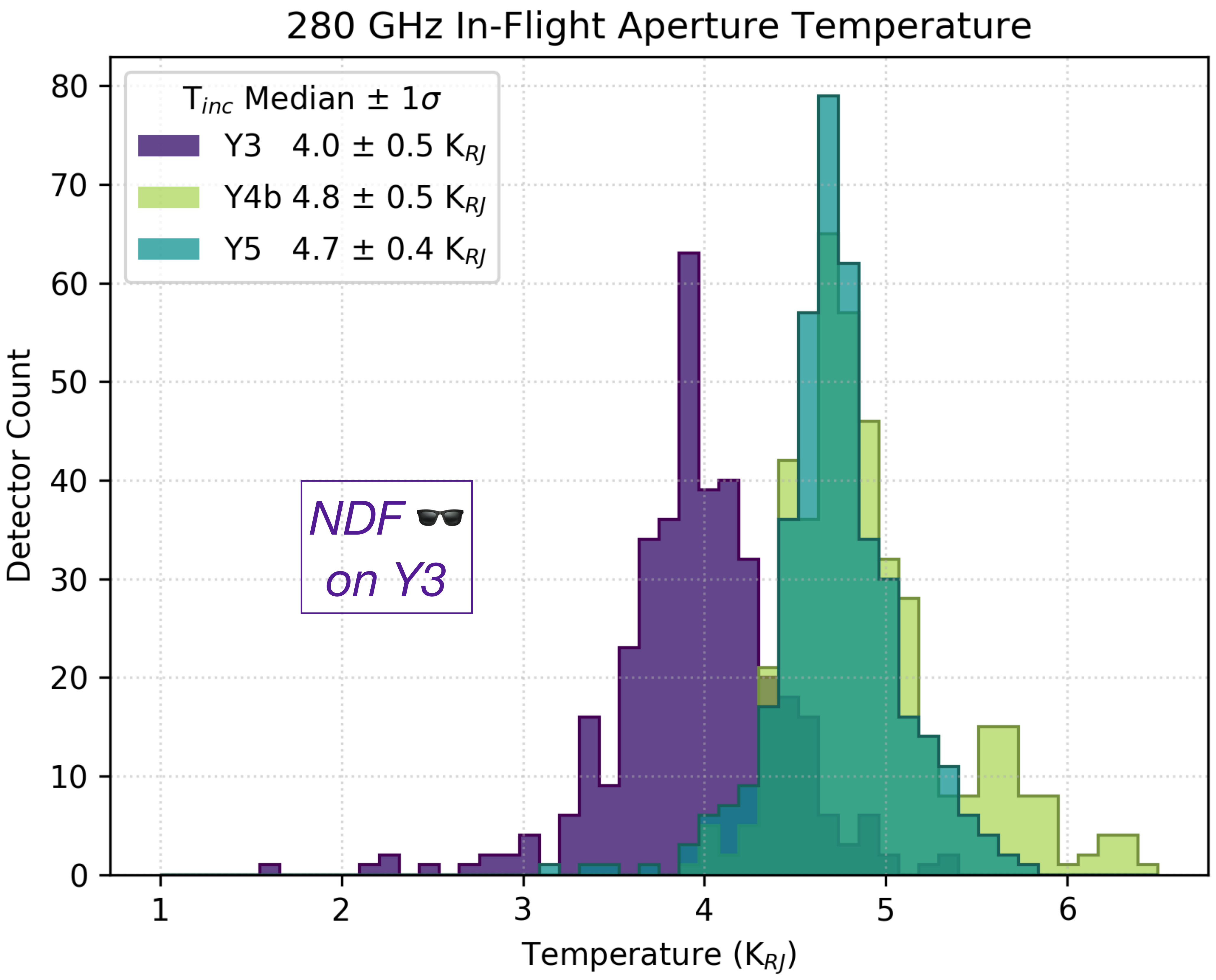
Sasha Rahlin



Observing region
shifted toward Galaxy

Suren Gourapura

280 GHz Receiver Performance



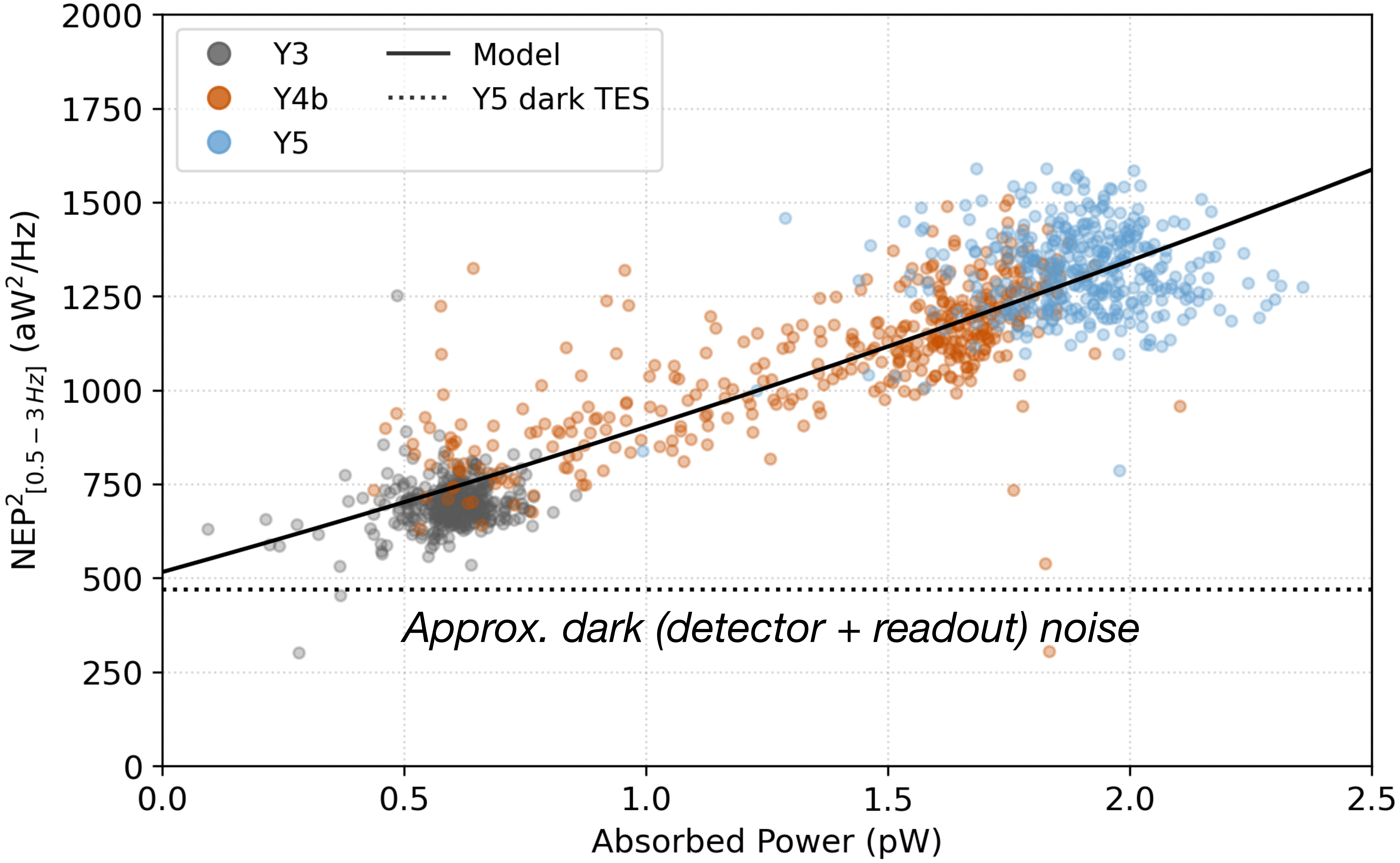
Low total photon loading

South Pole T_{atmo} ~ 24 K_{rj} (*ACBAR 280*)

SPIDER-1 90/150 ~ 2.5 K_{rj}

Photon noise-limited performance

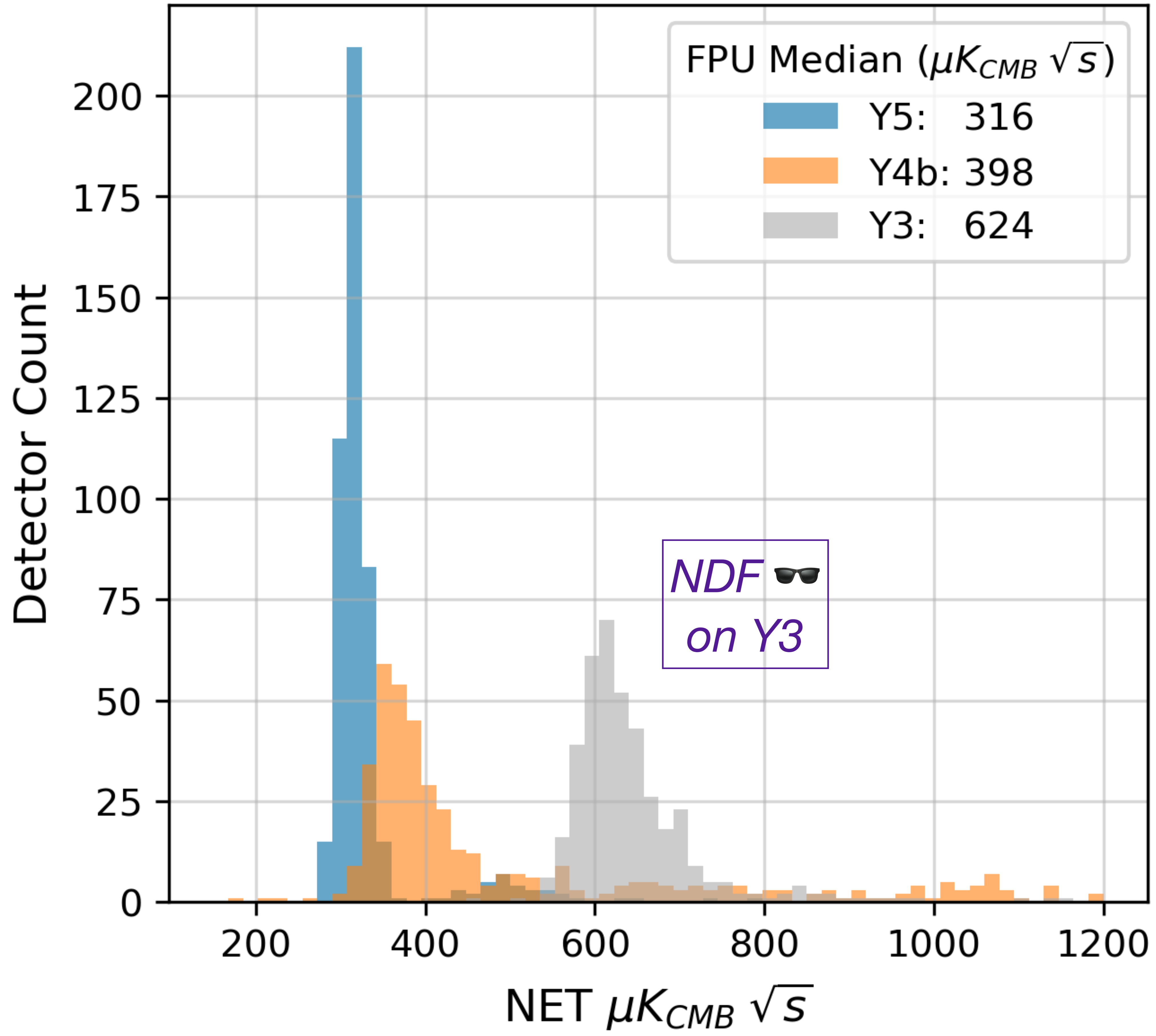
“Stare” noise (*no scanning*)



Plots by Elle Shaw (Shaw+ JATIS 2024)

280 GHz Receiver Performance

Preliminary "bottom-up" calibration (*<u>not</u> from sky)*



	GHz	uK·√s
Planck-HFI	*353*	*112*
BOOMERanG	*345*	*201*
ACBAR	280	800
SPIDER-2	**280**	**11**
BOOMERanG	245	158
Planck-HFI	*217*	*28*

Most instantaneously-sensitive 280 GHz receiver ever deployed

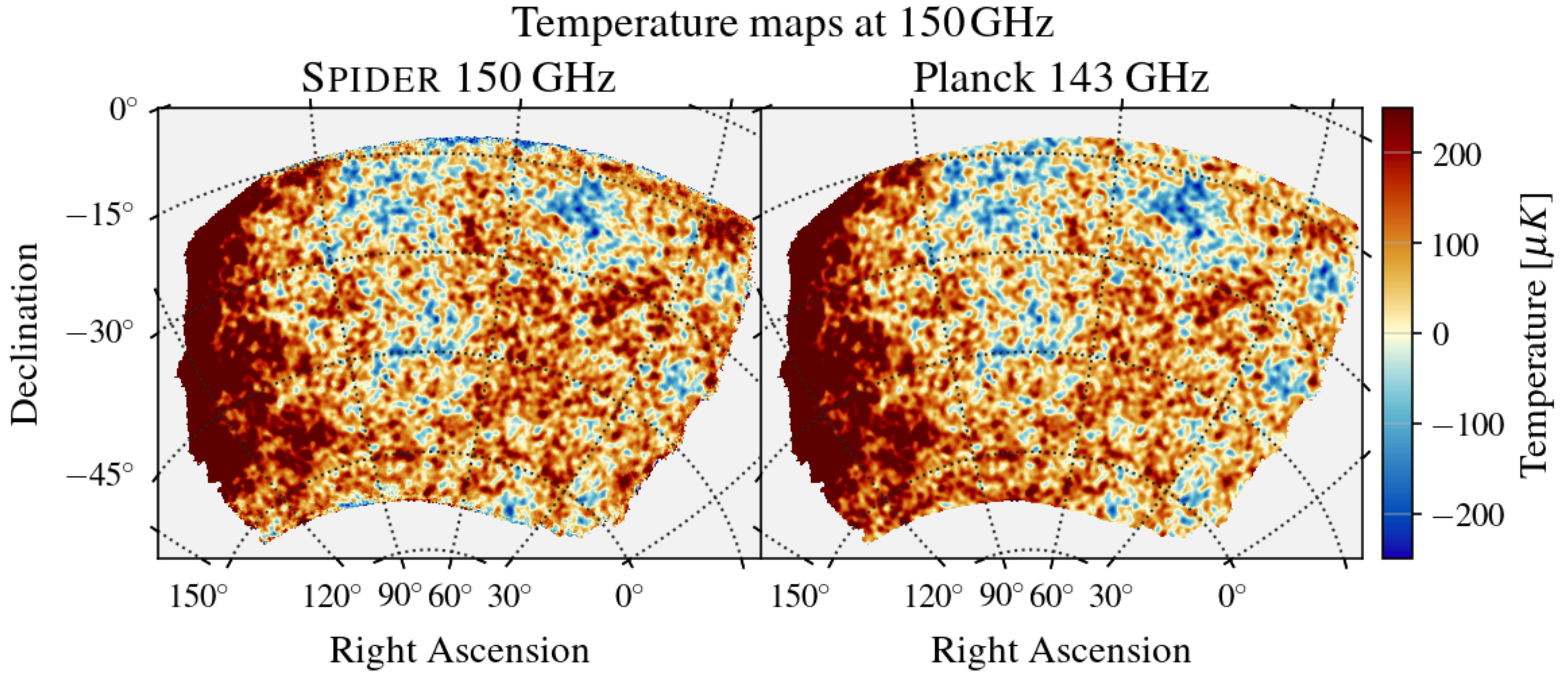
Plots by Elle Shaw (Shaw+ JATIS 2024)

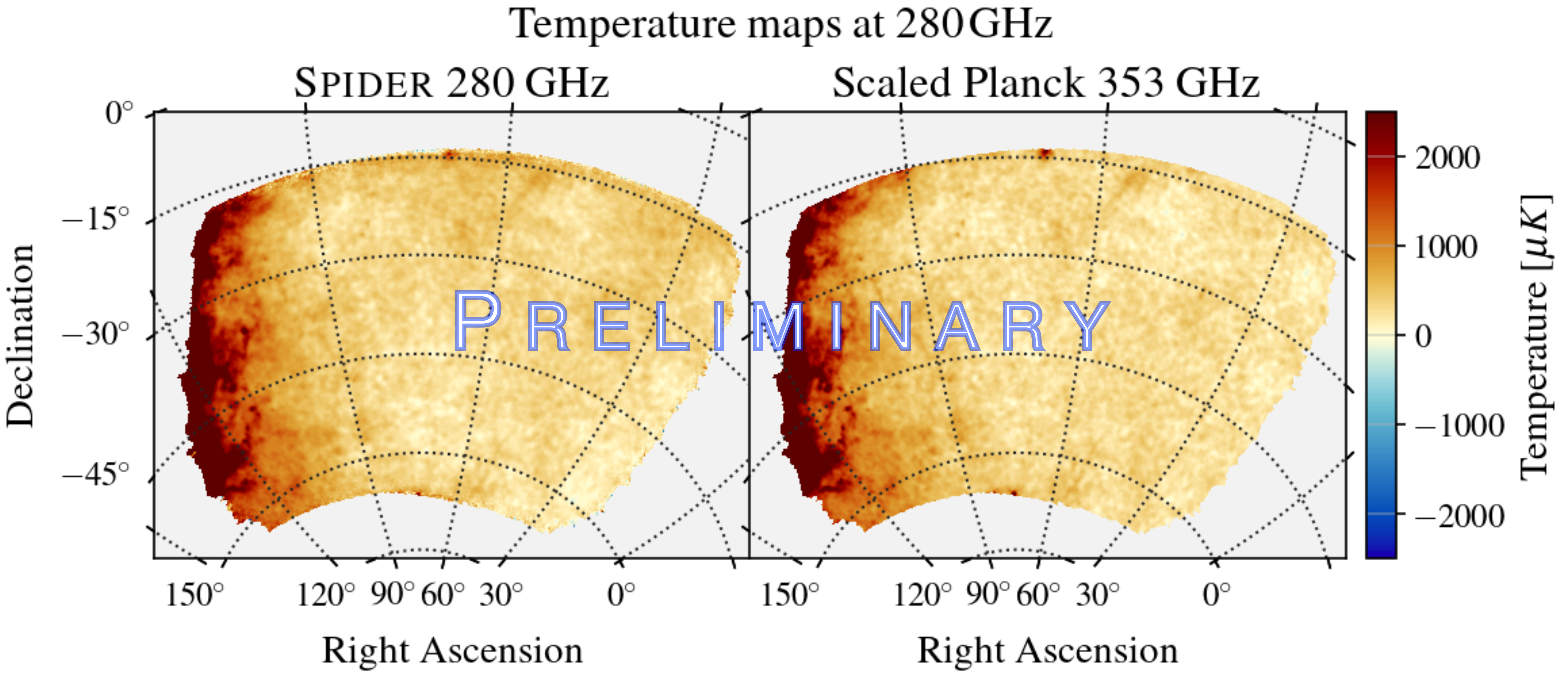
SPIDER-2 Mapmaking

Pointing solution undergoing iterative improvement from onboard sensors + sky regression

Flagging and low-level analysis (including sky calibration) ongoing

Preliminary temperature maps show good agreement with SPIDER-1 and with Planck





Calibration and filtering *<u>not</u>* *final!*

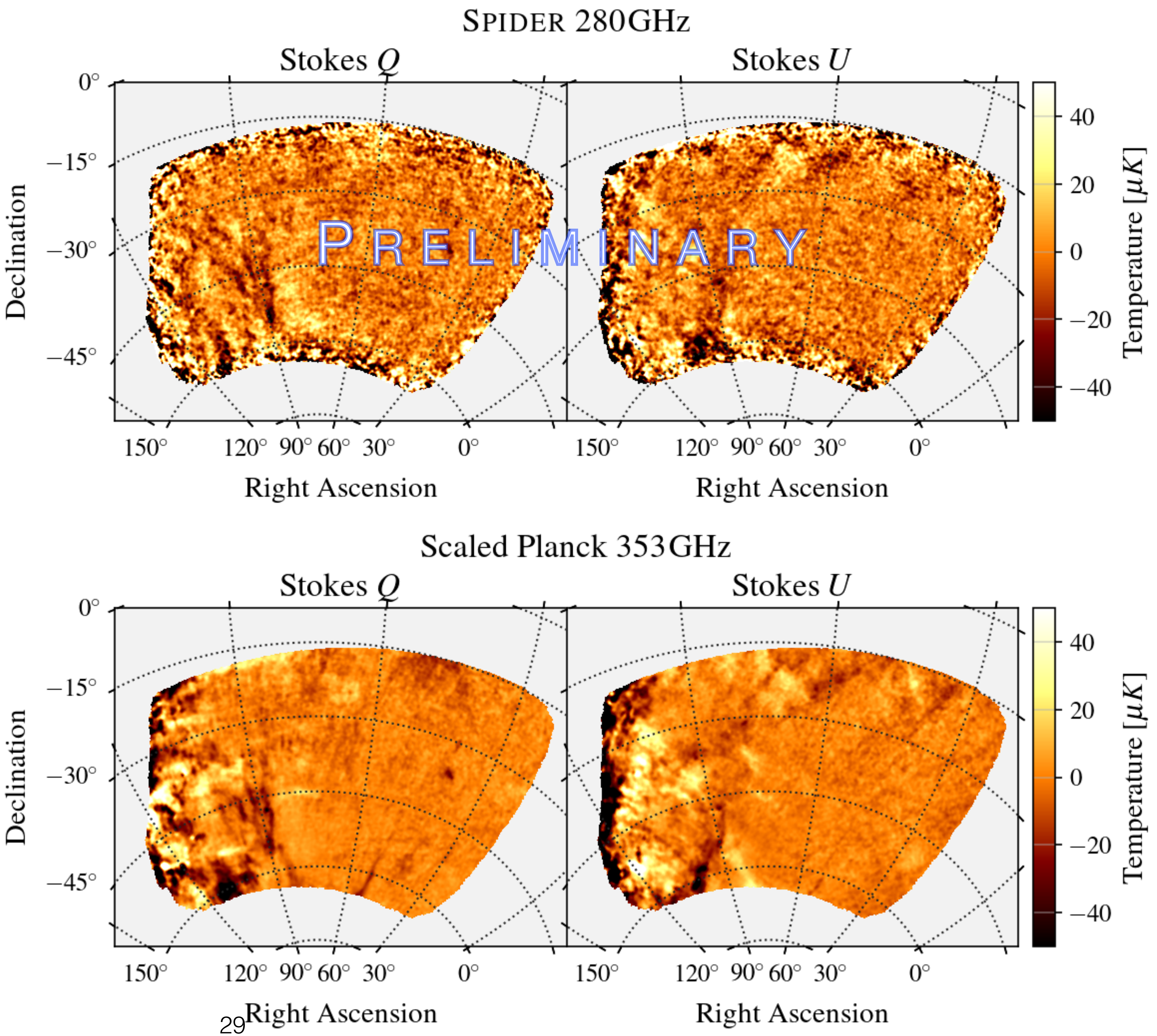
Plots by Ivan Padilla

SPIDER-2 Polarization

Early days, but signs are encouraging

Much more to come!

Maps shown use non-science filtering and calibration



Plots by Ivan Padilla

LAMBDA - Data Products

Data Hosted | Experiment Tables | Space-Based | Suborbital | Astrophysical | About Products

Overview

Products

Publications

SPIDER Data Products

SPIDER 1 CMB Results		
Product Download Page	Description	No. of Files/Size
General Products WGET DL CURL DL	beam, filter transfer function, bandpower window, functions, bandpowers, and covariance matrices. More...	50 files < 3.2 MB each
Map Products WGET DL CURL DL	mask, sample simulation map pairs, map pixel weights. More...	43 files , 10.6 MB each
Likelihood Products WGET DL CURL DL	r likelihood curve. More...	1 file 51 KB

Circular polarization data		
Product Download Page	Description	No. of Files/Size
Circular polarization data WGET DL CURL DL	CMB circular polarization results as discussed in Nagy et al. 2017 More...	3 files < 25.2 MB

Major science products released from SPIDER-1 papers

Full SPIDER-1 map release *almost* ready

SPIDER-2 maps and products will also be public

Conclusions

SPIDER-1 major analysis complete

- B-mode, foreground, technical papers published; public release in progress
- Possible evidence for complex foreground structure - needs more data!

SPIDER-2 analysis is well underway

- Most sensitive instrument to date at 280 GHz
- NASA funding to complete two-flight CMB / foreground analysis

Success is people

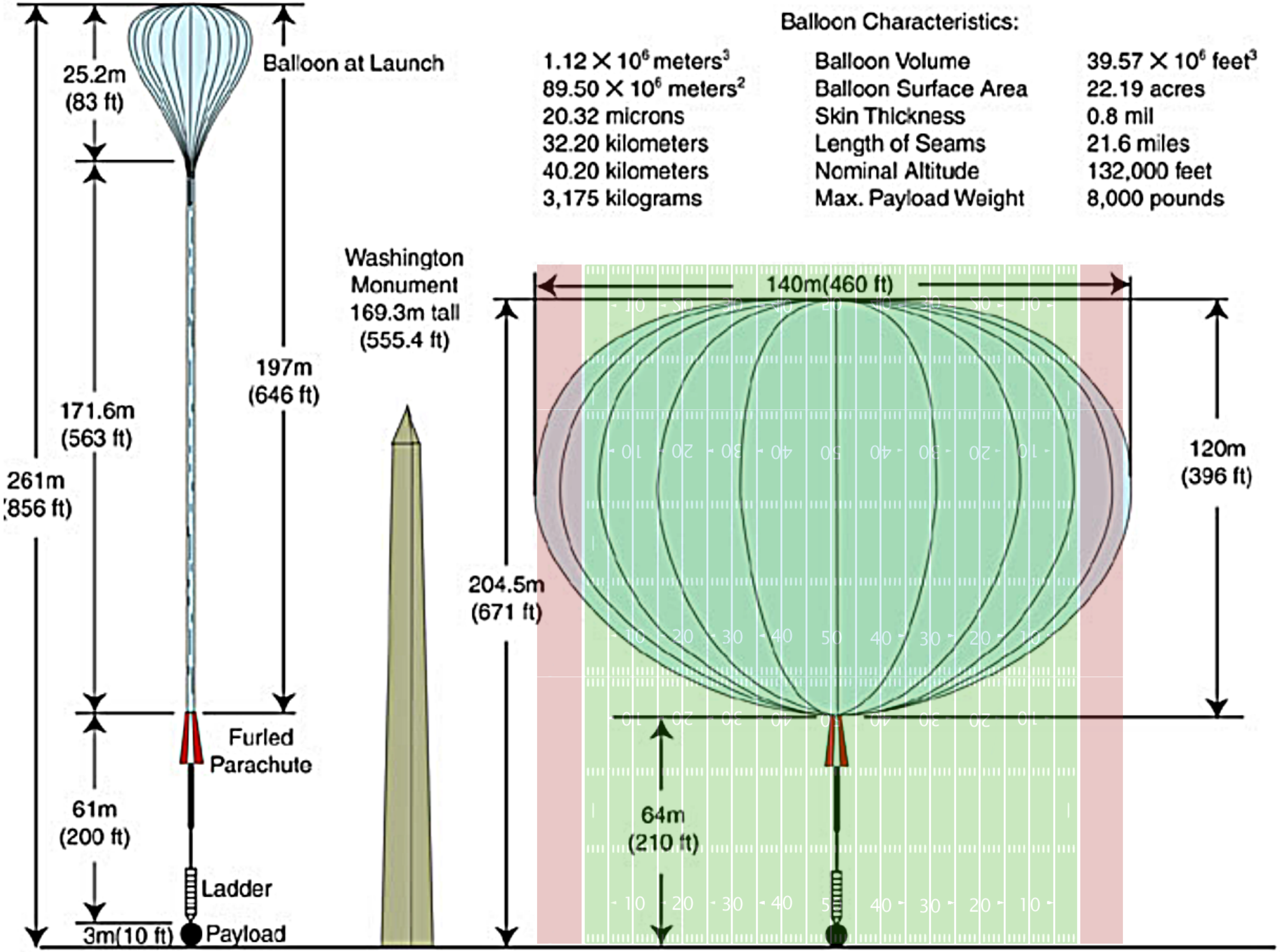
- SPIDER has trained 30+ Ph.D. students, 9 postdocs, numerous undergrads

ILLINOIS

Backup

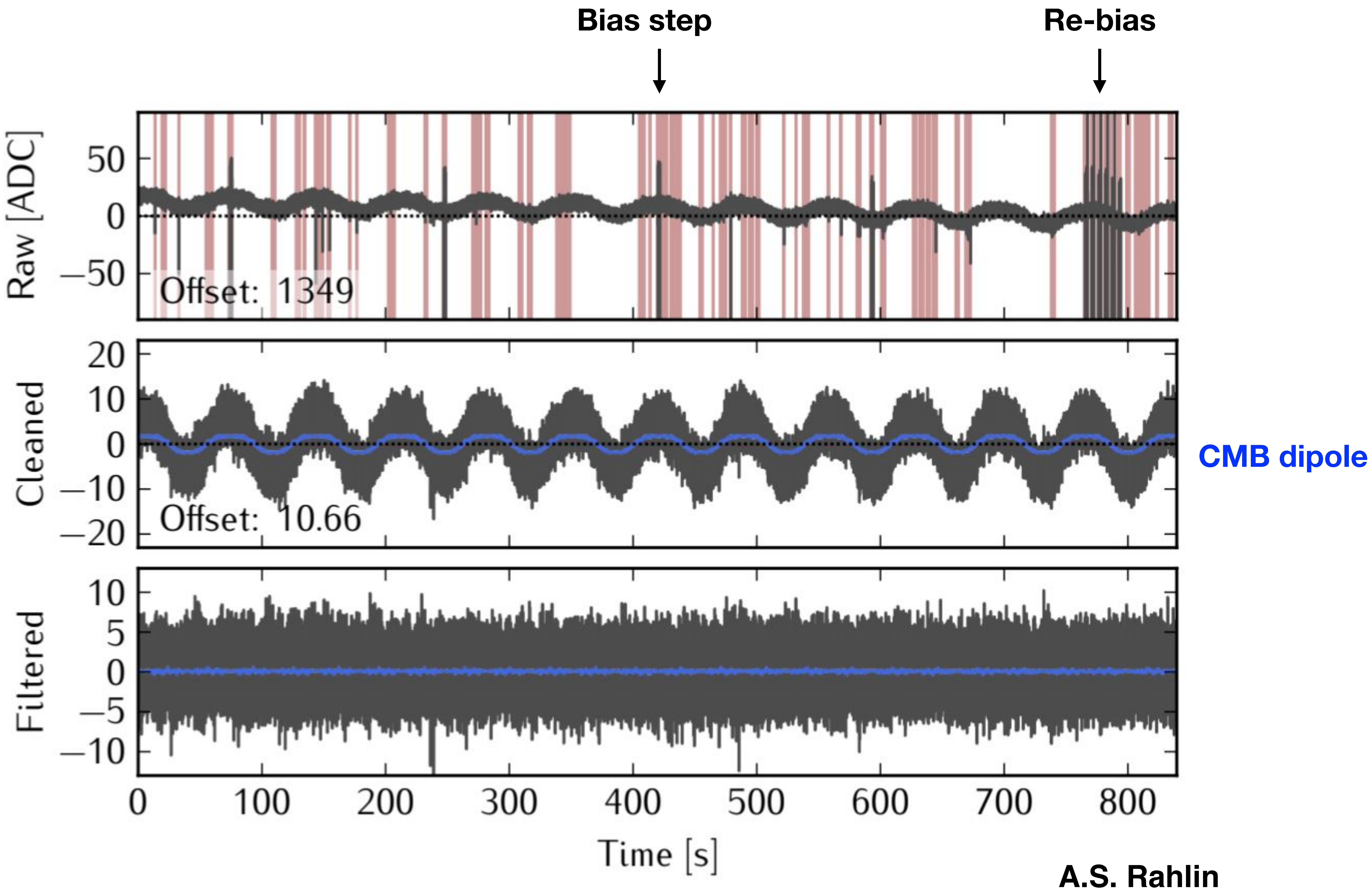
Balloon Characteristics:

1.12×10^6 meters^3	Balloon Volume	39.57×10^6 feet^3
89.50×10^6 meters^2	Balloon Surface Area	22.19 acres
20.32 microns	Skin Thickness	0.8 mil
32.20 kilometers	Length of Seams	21.6 miles
40.20 kilometers	Nominal Altitude	132,000 feet
3,175 kilograms	Max. Payload Weight	8,000 pounds



NASA Wallops

Low-Level Processing



Flagged samples
Mostly transmitter RFI
Occasional cosmic rays
Osherson+ JLTP 2020

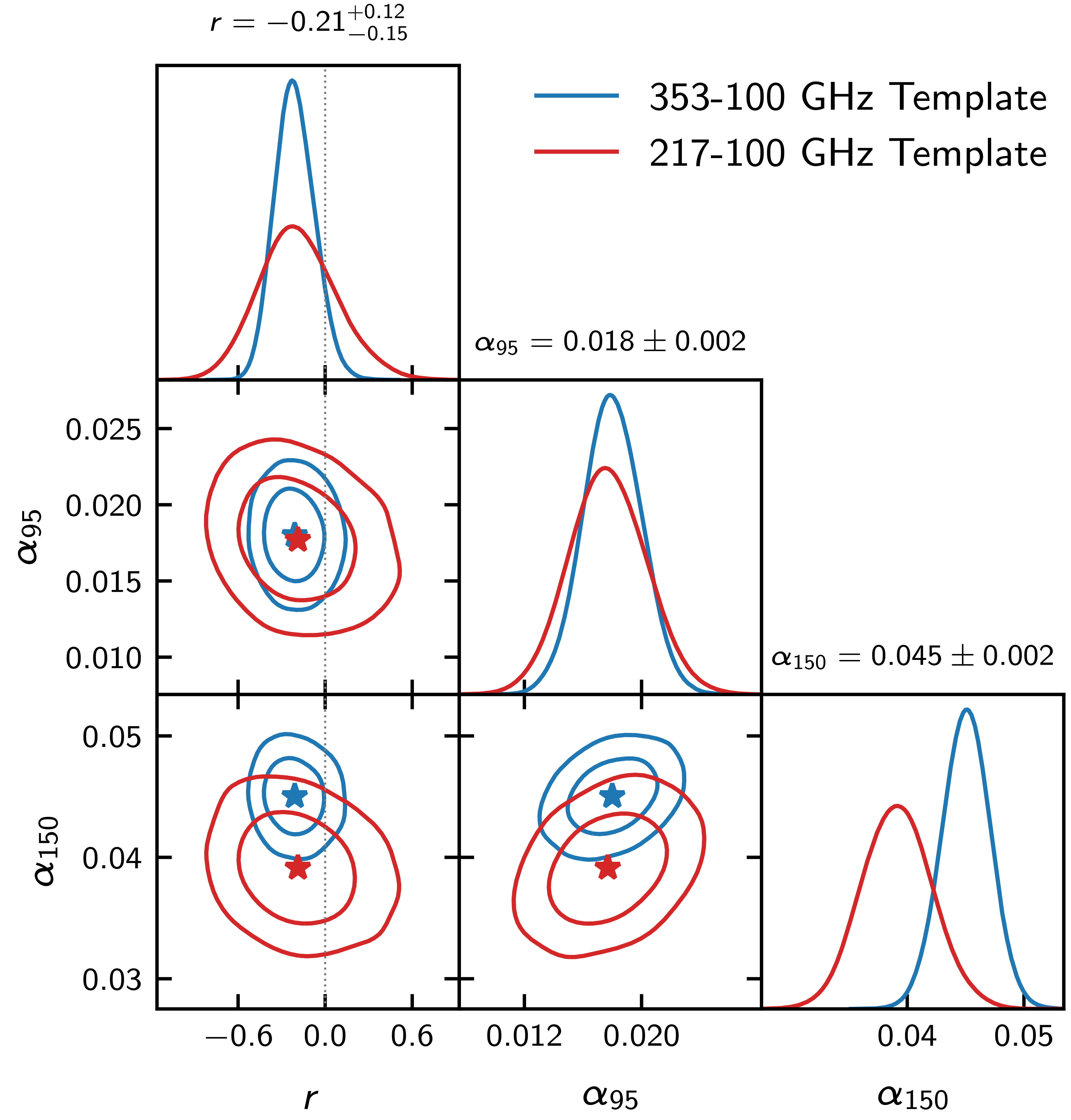
Automated bias monitor
TES bias square waves on turnaround to monitor (and correct) TES state
Filippini+ JLTP 2022

Scan-sync pickup
Managed for now with aggressive filtering

A.S. Rahlin

Constraining r

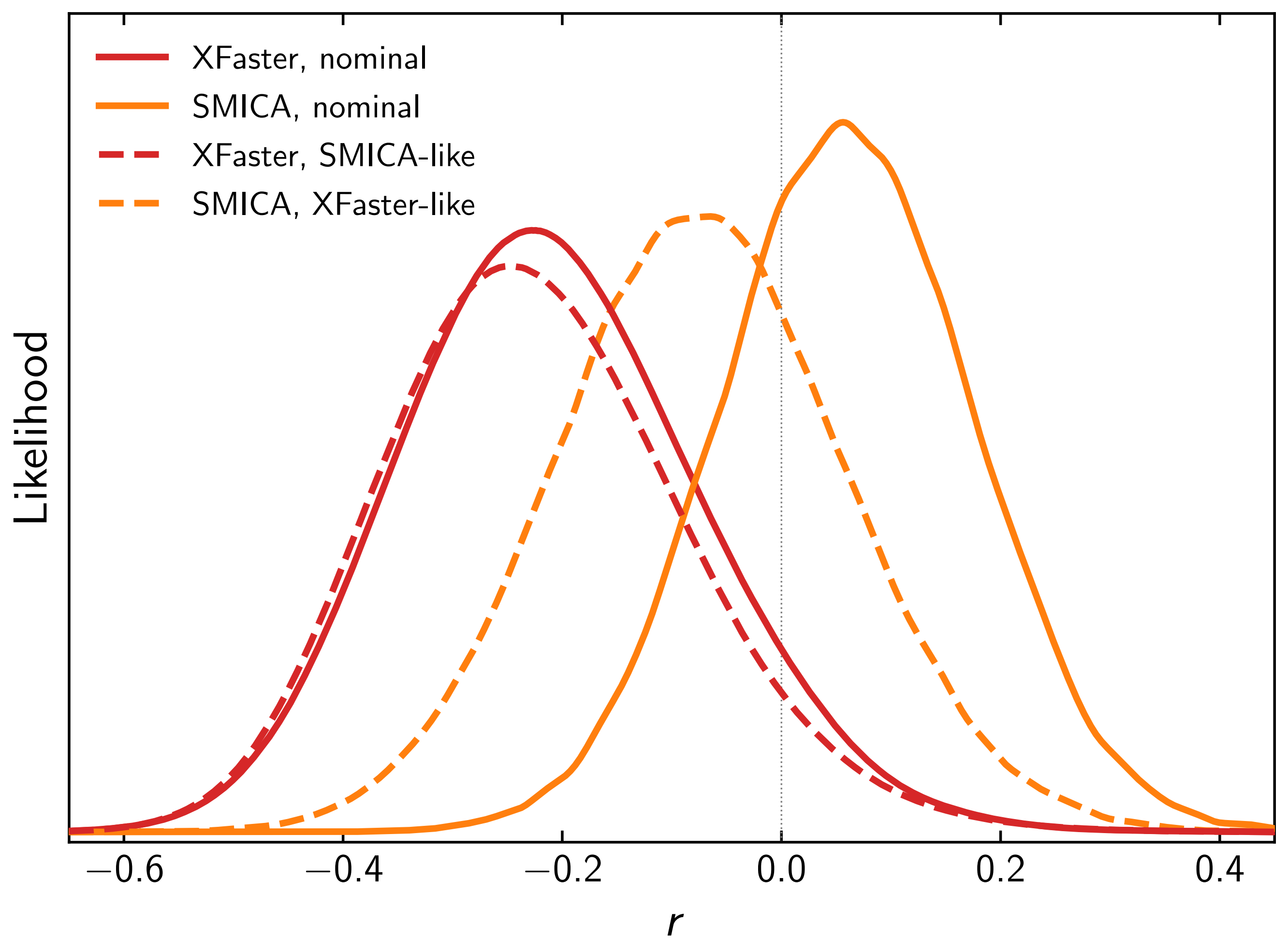
Focus on **XFaster** with **353-100 template subtraction** as primary result



Point estimate	$r = -0.21^{+0.12}_{-0.15}$
Feldman-Cousins (*frequentist*) constraint	$r < 0.11$
Bayesian constraint	$r < 0.19$

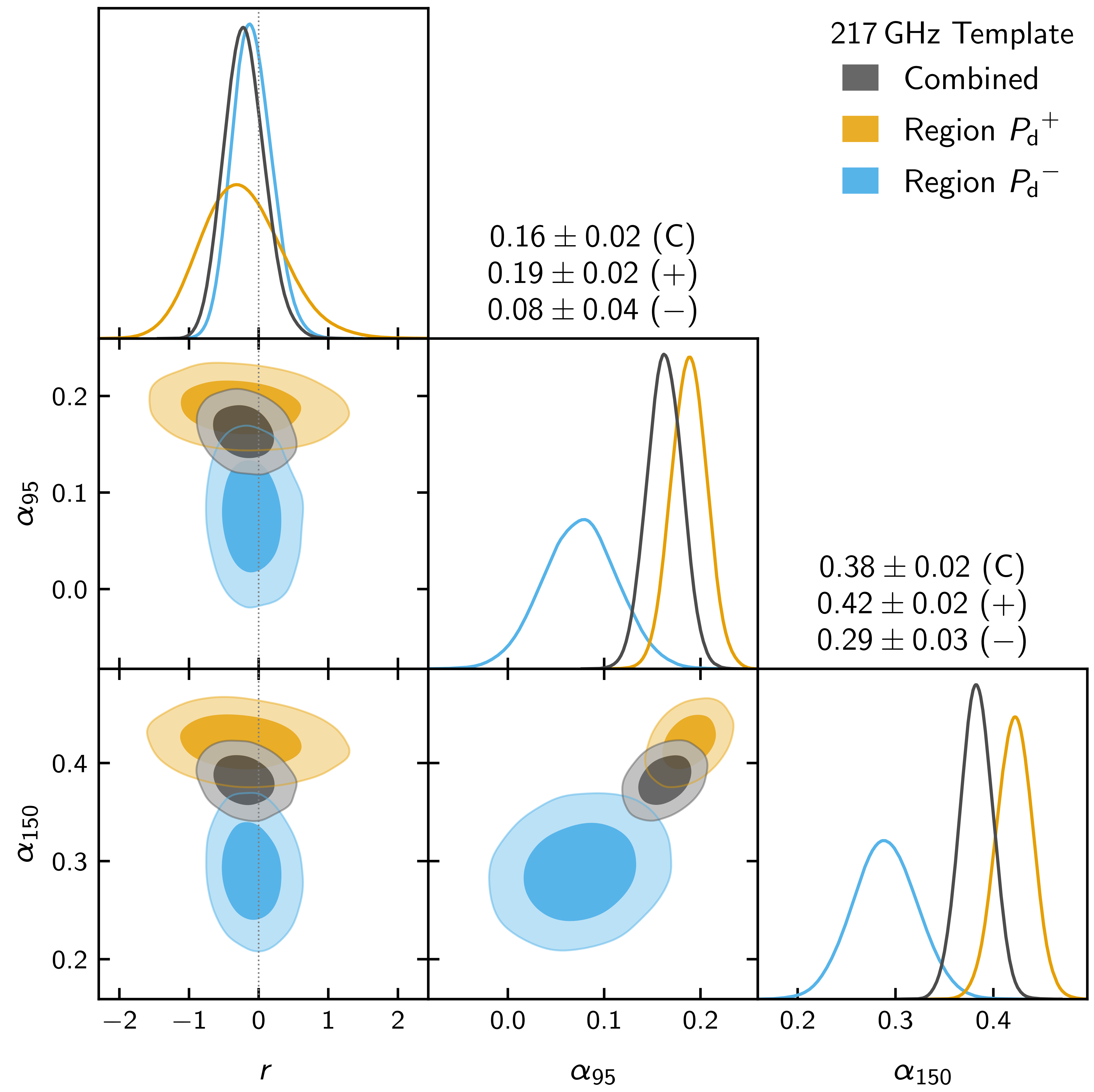
Rich and interesting effects from varying data, estimators *(all unbiased on sims)*

Reasonable agreement among various methods when applied to similar data selections

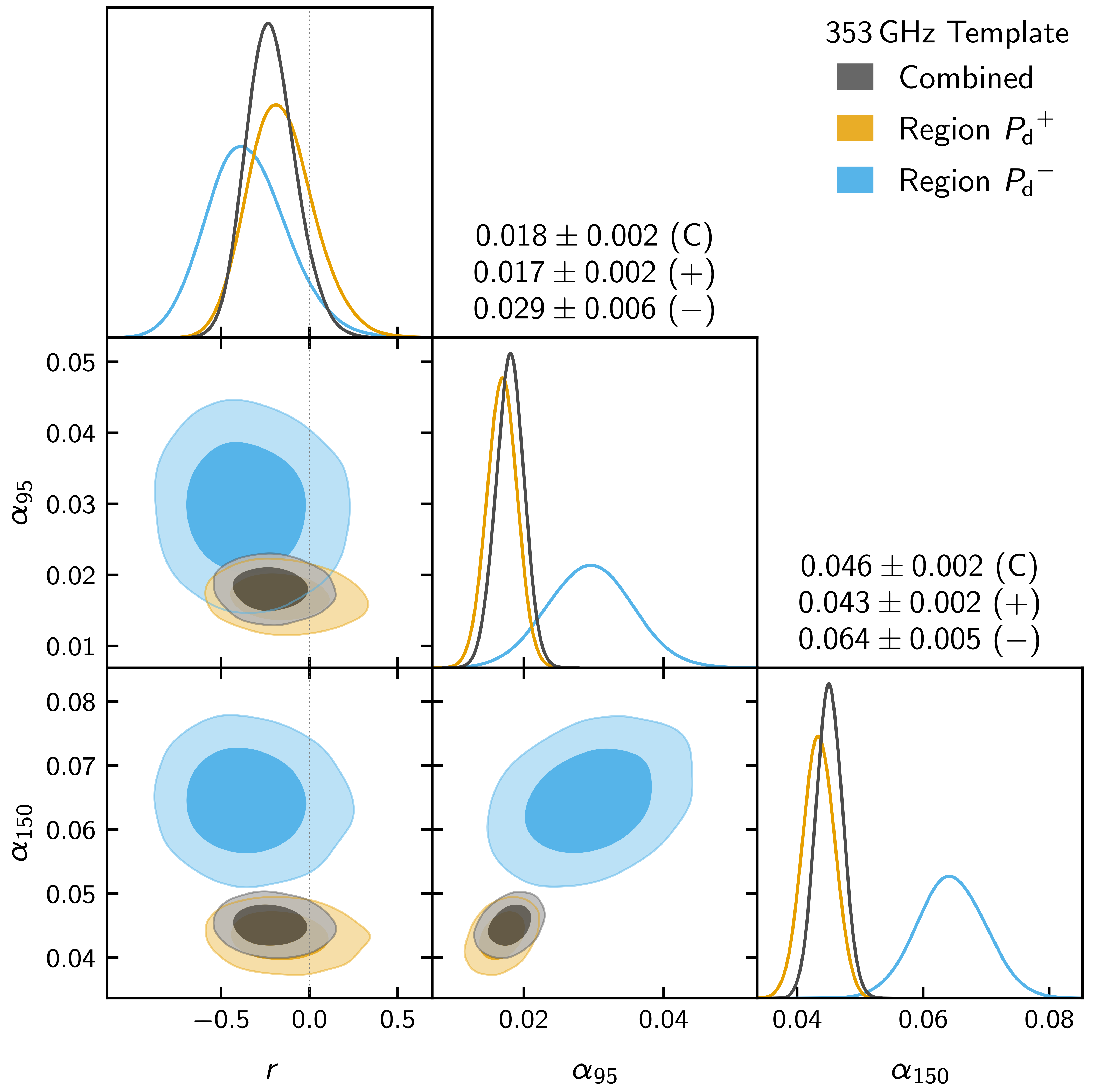


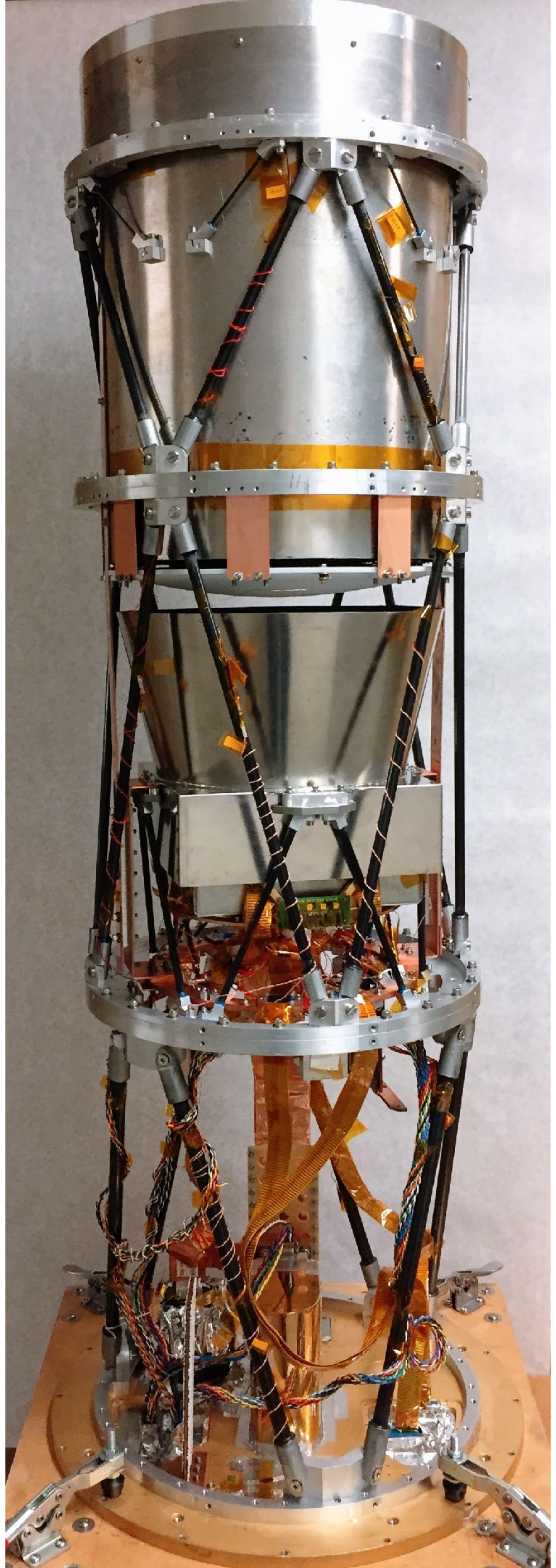
Foreground Scaling Constraints

217-100 GHz template

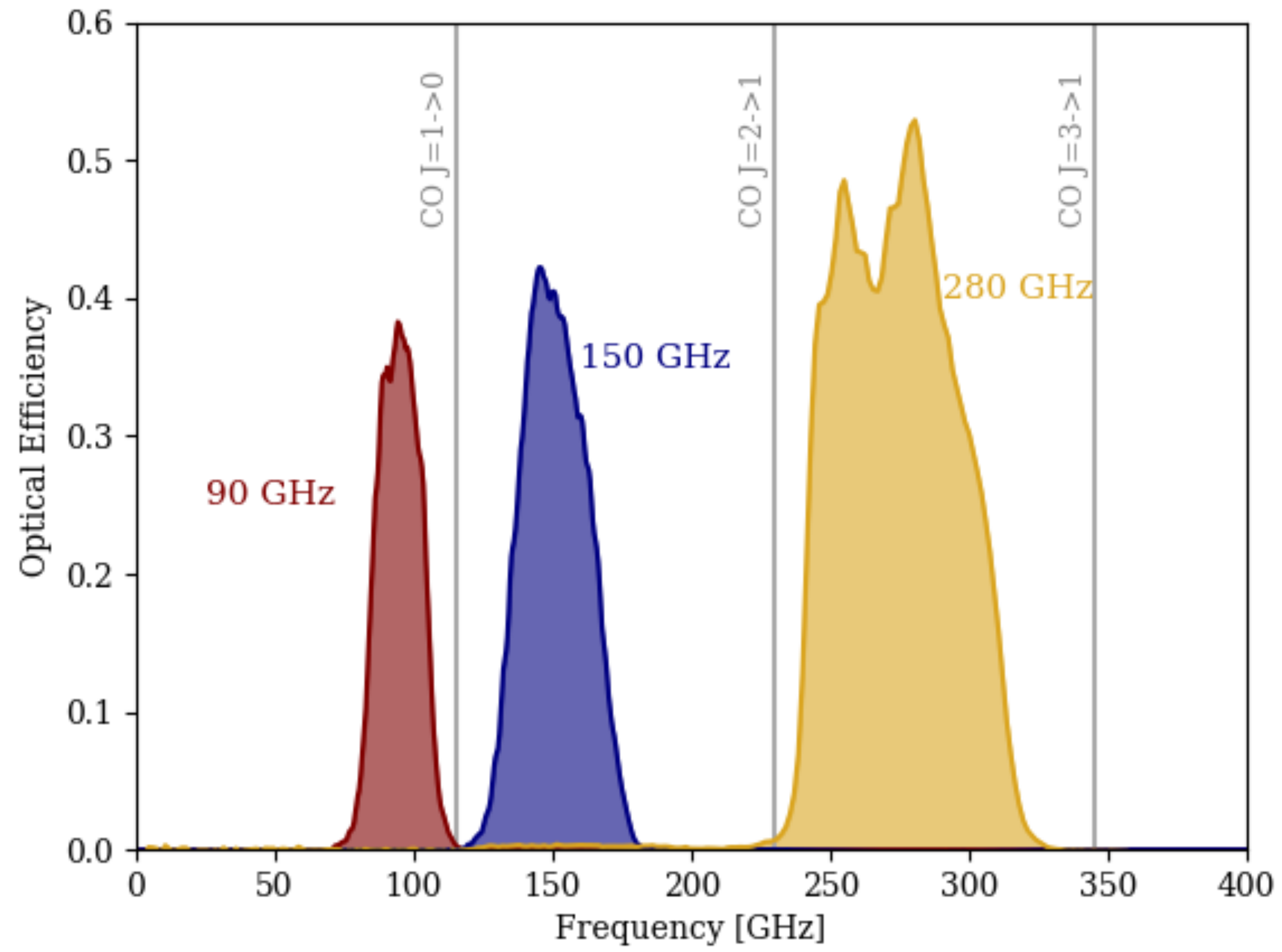


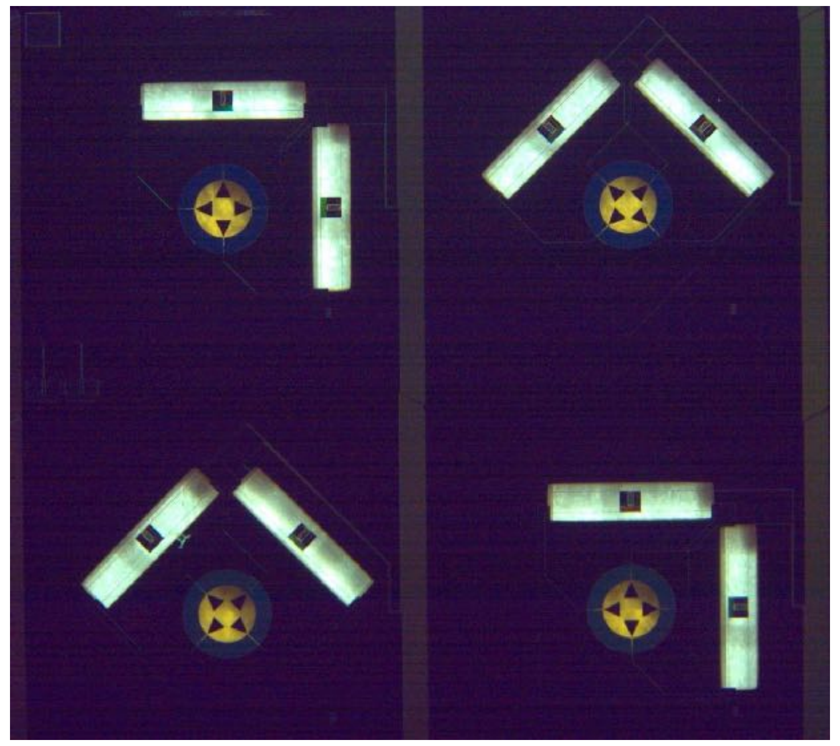
353-100 GHz template





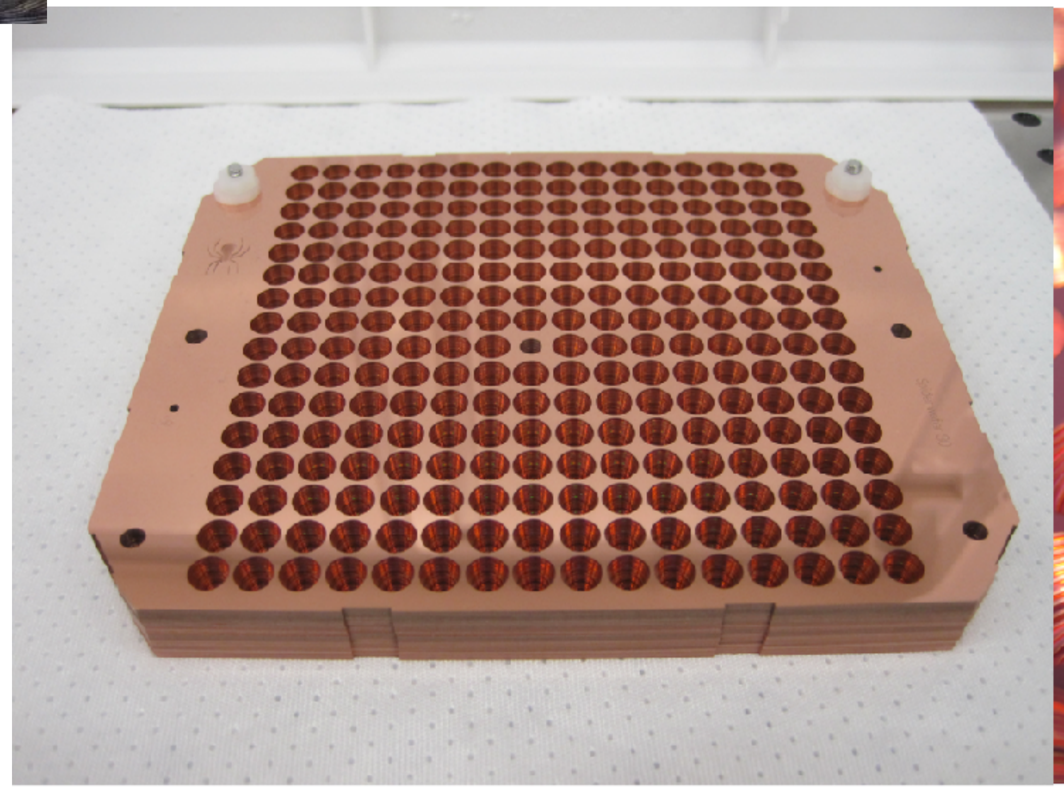
Dust Busters

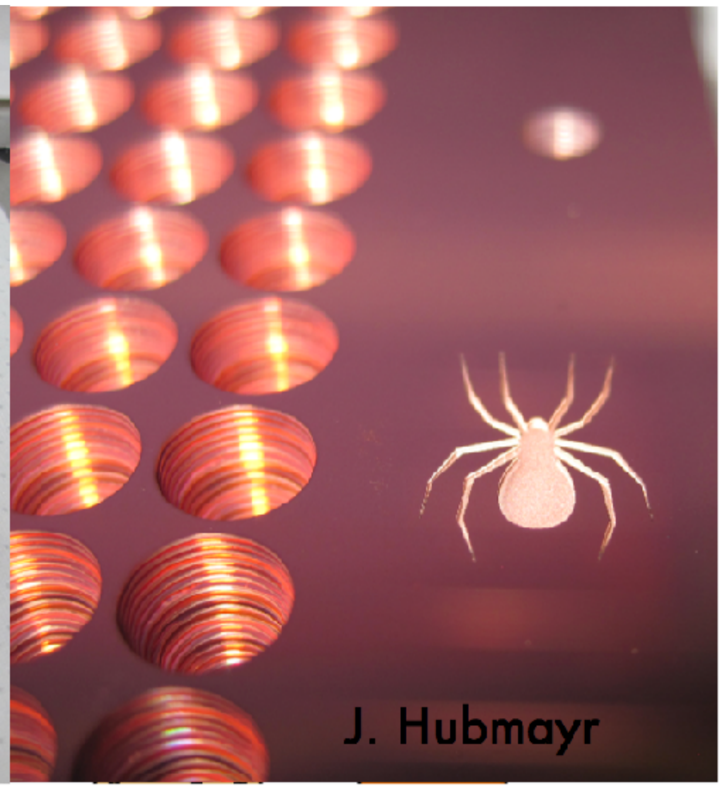




NIST platelet horn array
AlMn science TES

Hubmayr+ SPIE 2016
Bergman+ LTD 2017





*Details in **Shaw+, SPIE 2020**; arXiv:2012.12407*