SPIDER: B-mode Results and Status

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From Planck to the Future of CMB Conference
26 May 2022

The SPIDER Program

Instrument

First Flight

SPIDER-1 Results

Maps,
Power Spectra,
Foregrounds,
r-likelihoods

Upcoming Flight

SPIDER-2

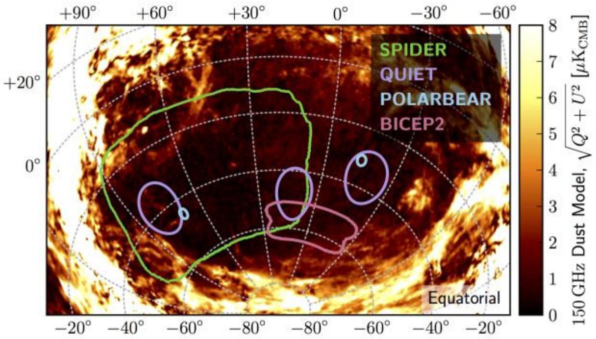
Taurus

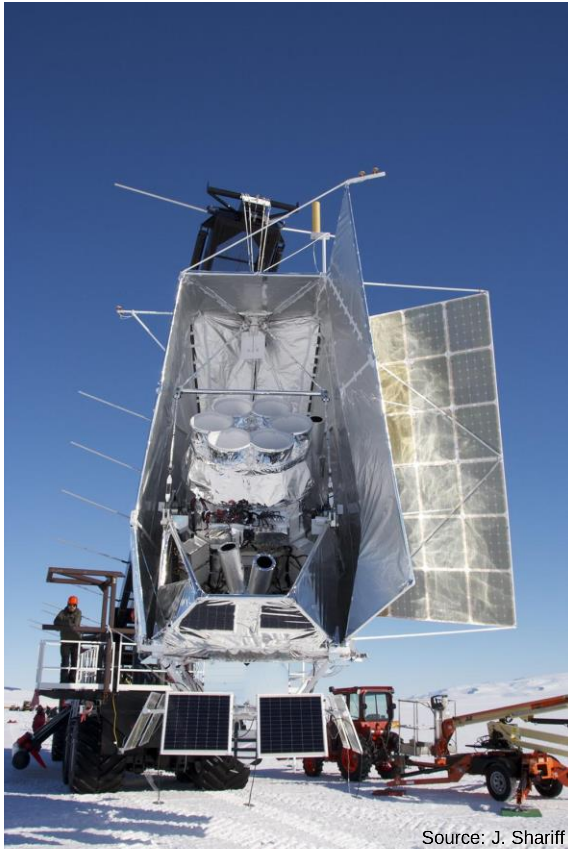
The SPIDER Program

Balloon-borne Polarimeter targeting *r* in the presence of foregrounds.

- Measure the B-mode **angular power spectrum**
  - Multipole range $33 \leq \ell \leq 257$ (bin width $\triangle\ell = 25$)
- Verify statistical **isotropy**
  - Cover large sky area ~10%
- Verify **frequency spectrum**
  - 95, 150, 280 GHz

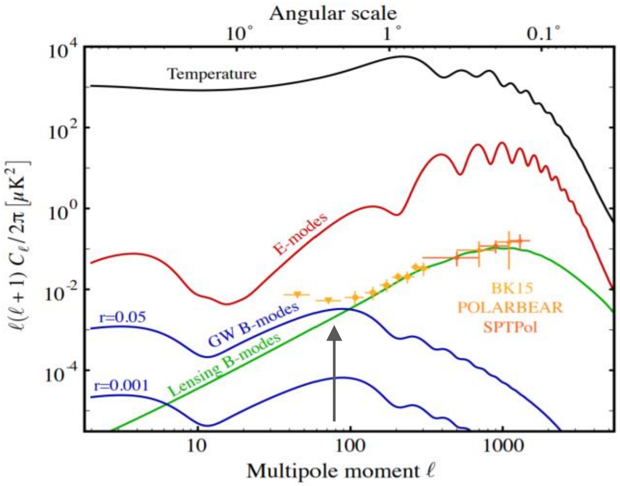
Two Antarctic flights suspended from NASA Long Duration Balloon





B-modes: Goals and Challenges

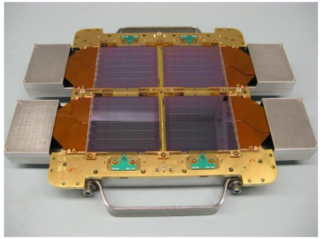
Target: B-mode polarization in the CMB at degree angular scales



Source: CMB-S4 Science Book, First Edition, 2016

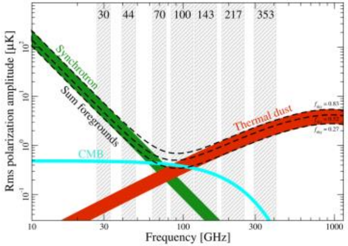
Measurement challenges:

SPIDER

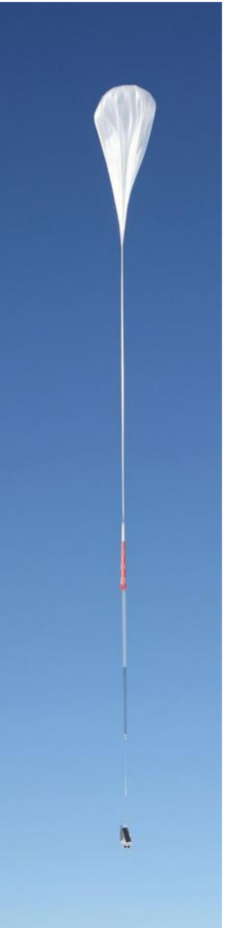


- Sensitivity
  - *Approach photon noise limit*
- Systematics
  - *Control of polarized systematics*
- Foregrounds
  - *Isolate CMB from polarized foregrounds (synchrotron, dust, …)*

Planck Collab. iv (2018)



Ballooning Approach



The Good

- Access to frequencies obscured from the ground
- Detector sensitivity - ability to approach photon noise limit
- Technology tryouts for orbital missions

The Bad

- Strict mass and power constraints
- Short observation times (~ weeks)
- Limited bandwidth for communications -- nearly autonomous during flight

Observing the CMB from the stratosphere

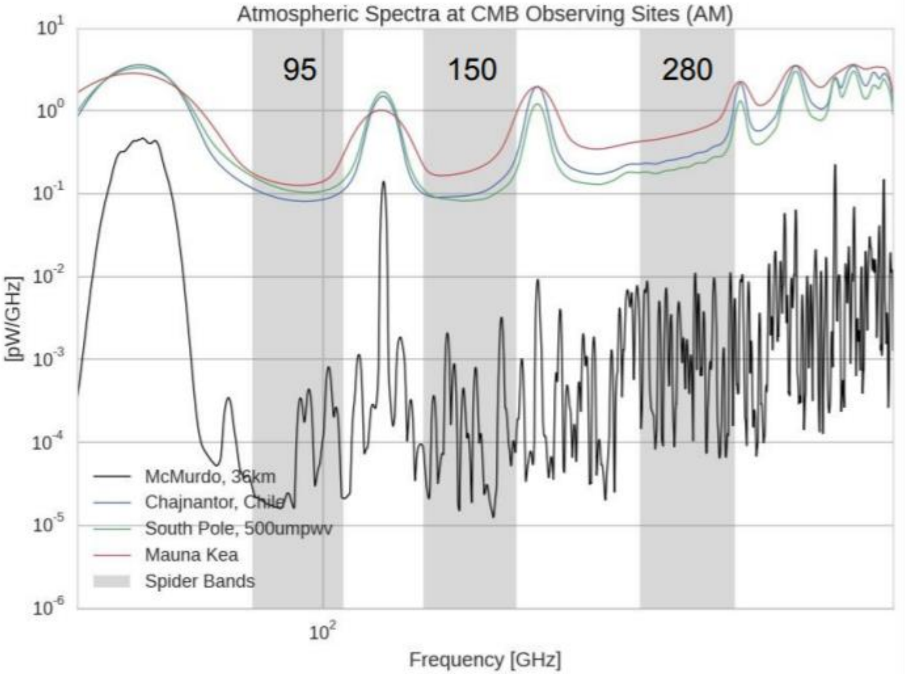
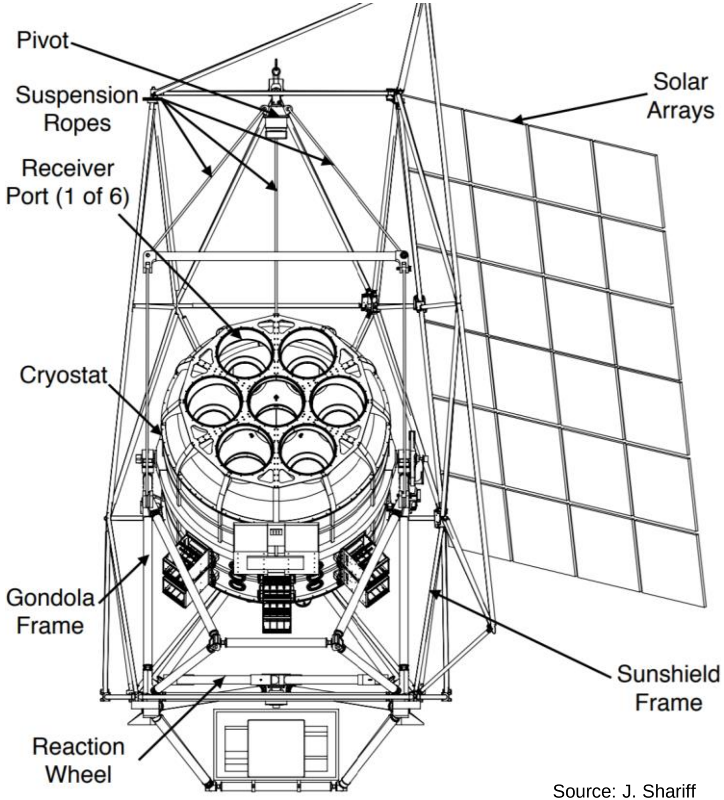


Figure from A.S. Bergman, using am model

SPIDER Payload (2015)

- Large 1300 L shared liquid helium cryostat
- Lightweight carbon fiber gondola
    - *Az/el drives, pointing controls*
    - *Baffling and Sunshields*
- 3000 kg launch mass
- 6 on-axis monochromatic refractors
    - *4K HDPE Lenses, 270 mm stop*
    - *stepped Sapphire **half-wave plate***
- Emphasis on **low internal loading**
    - *Thin (2.4 mm) window*
    - *Reflective filter stack*
    - *2K Optical baffling between lenses*
- Antenna-coupled TES bolometer arrays (JPL)
    - *Low-G, low-noise design, dual-TES for calibration*
- Time-division SQUID multiplexer (NIST, UBC)
    - *Extensive magnetic shielding*



Source: J. Shariff

SPIDER Payload (2015)

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- 3000 kg launch mass
- 6 on-axis monochromatic refractors
  - *4K HDPE Lenses, 270 mm stop*
  - *stepped Sapphire **half-wave plate***
- Emphasis on **low internal loading**
  - *Thin (~3 mm) window*
  - *Reflective filter stack*
  - *2K Optical baffling between lenses*
- Antenna-coupled TES bolometer arrays (JPL)
  - *Low-G, low-noise design, dual-TES for calibration*
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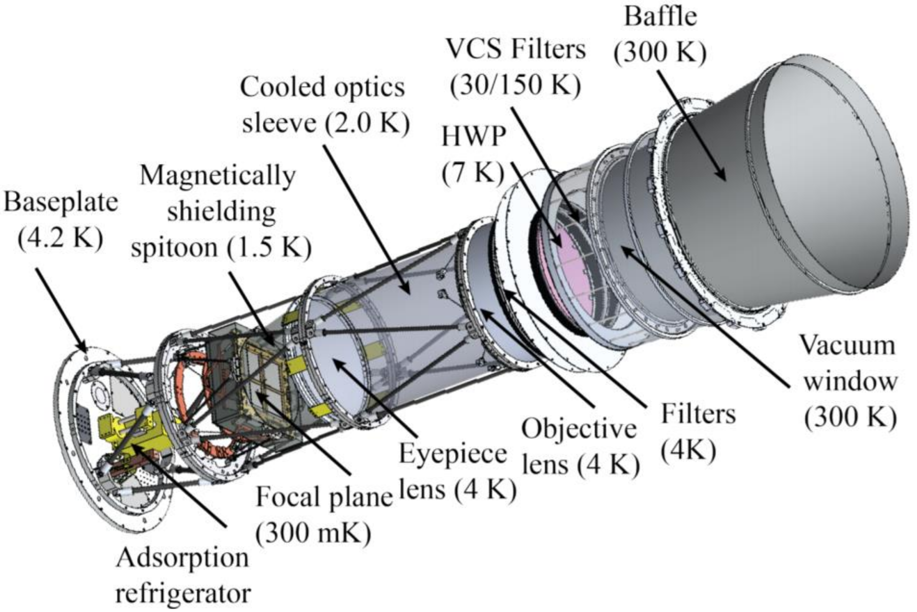

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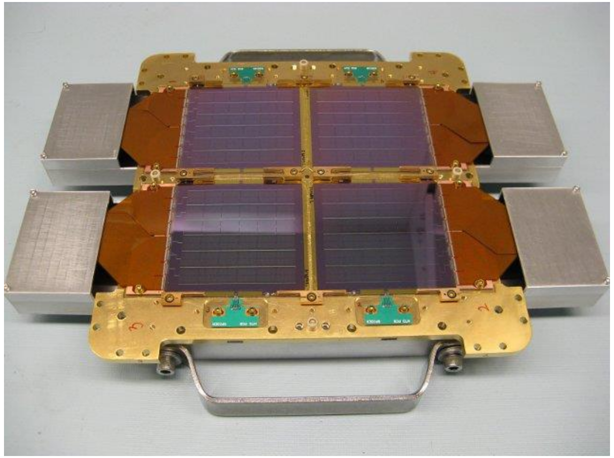
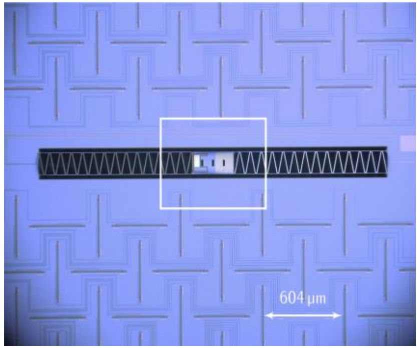
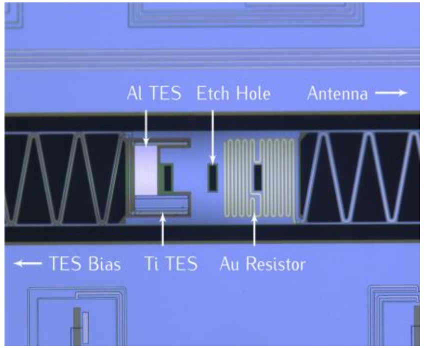
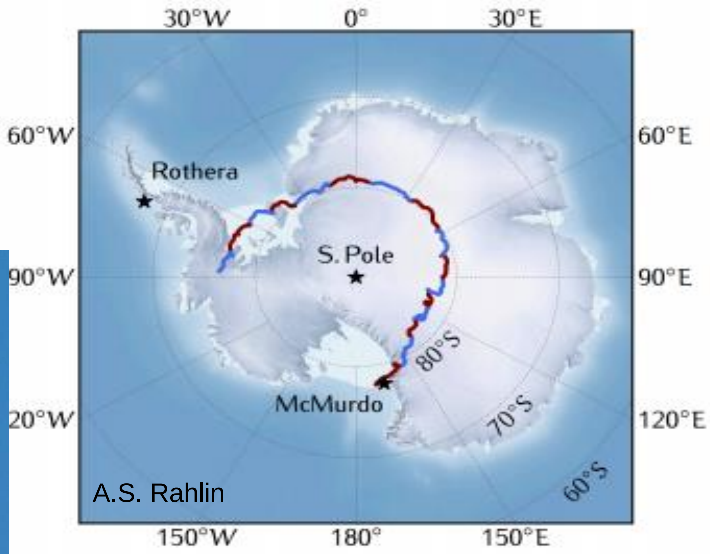


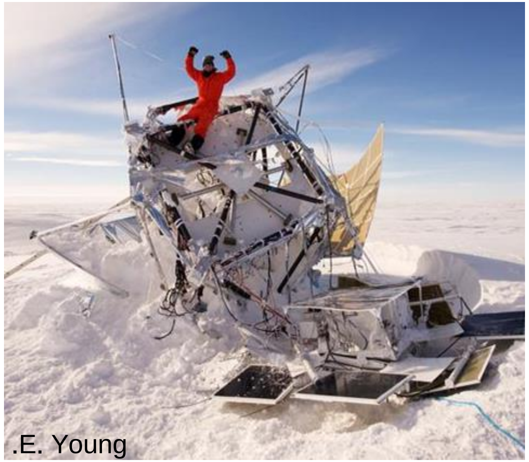




First Flight 2015

- January 1-18, 2015
- Flew three 95 GHz and three 150 GHz receivers
- All critical payload systems operational!
- Data drives recovered in February 2015
- Full hardware recovery in December 2015 with help from British Antarctic Survey





Publications
Filippini *et al* JLTP (2022)
Leung *et al* 2022 ApJ **928** 109
Ade *et al* (SPIDER) 2022 *ApJ* **927** 174
Gambrel *et al* 2021 ApJ **922** 132
Osherson *et al* JLTP (2020)
Gualtieri *et al* JLTP (2018)
Nagy *et al* ApJ **844** 151 (2017)

In-Flight Performance

Exceptionally low internal loading

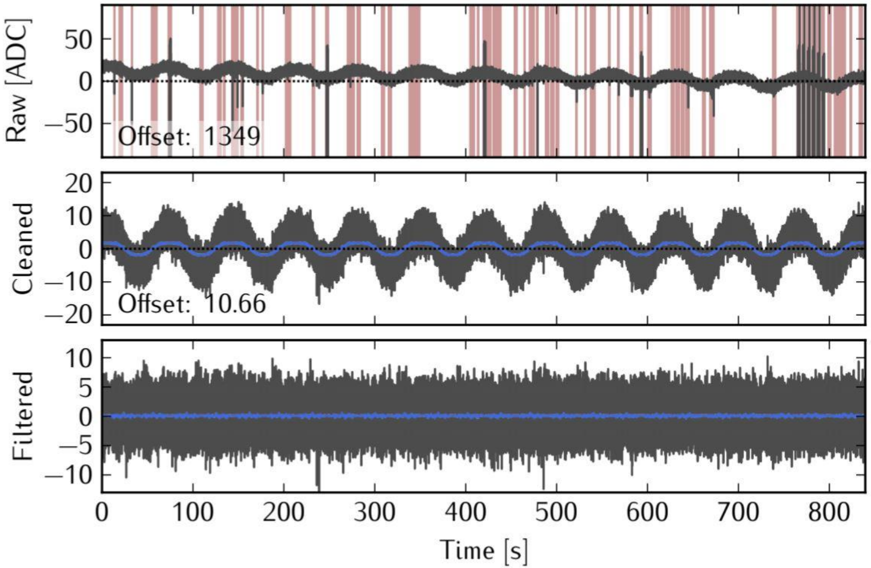
- 95 GHz: ≤0.25 pW total absorbed power
- 150 GHz: ≤0.35 pW total absorbed power

Low Level Processing

- RFI data loss is significant
  - *On board antennas (5.6%)*
  - *Iridium transmitters (7.7%)*
- Fridge cycles (11.1%)
- Scan turnarounds *(~¼ time outside sky mask)*
- One 150 GHz receiver excluded (~10%)
- Negligible impact from cosmic rays (<1%)
- Scan-synchronous pickup (filtered)
  - *loss of ell = 20 bin*

Time Ordered Data Sample

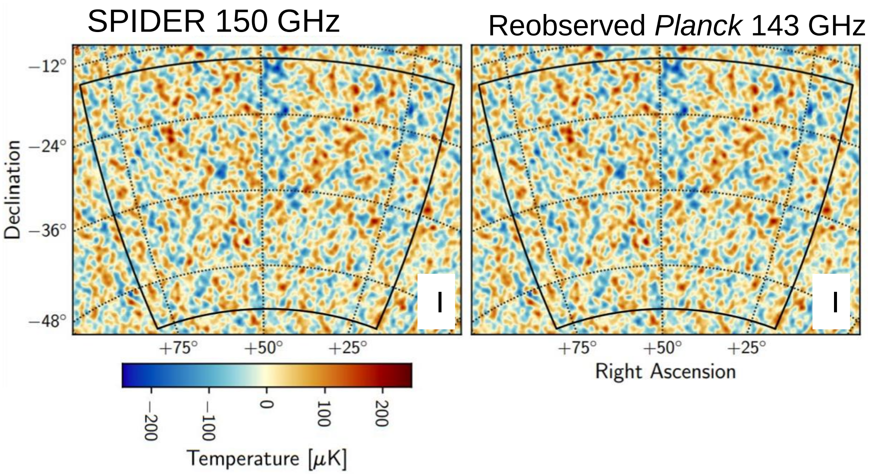
A.S. Rahlin Thesis

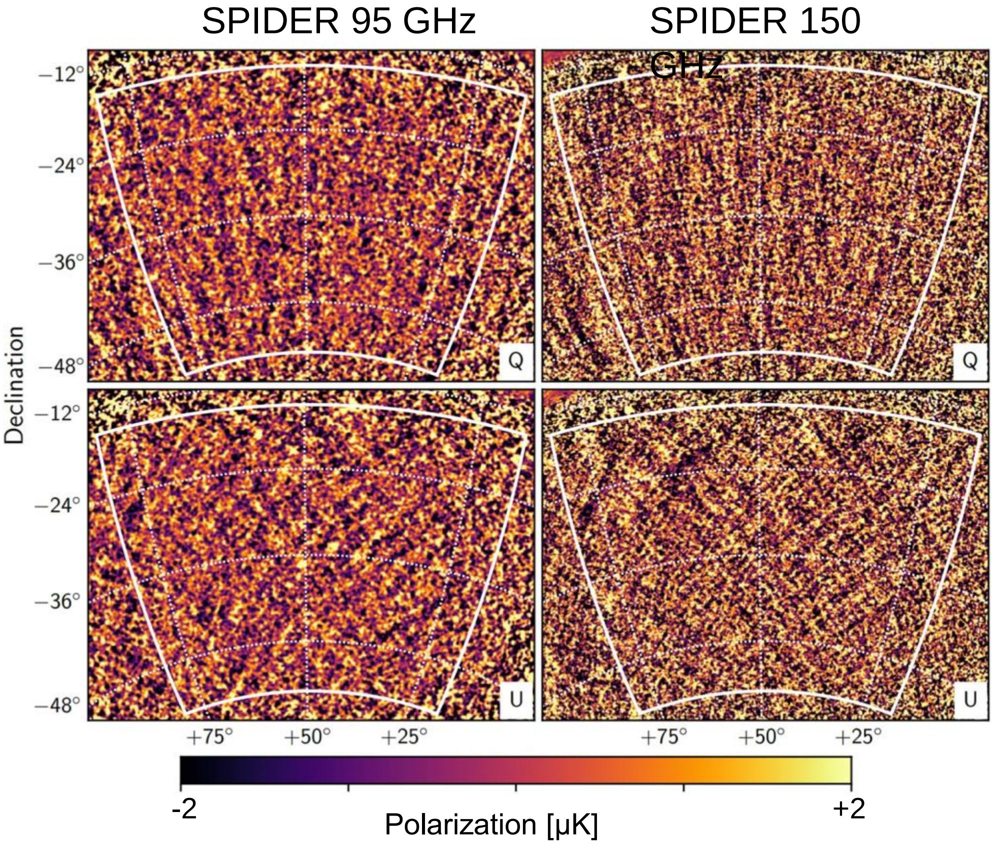


Band	Center [GHz]	Width [%]	FWHM [arcmin]	# Det. Used	NET_{tot} [$\mu K\sqrt{s}$]	Data Used [days]	Map Depth [$\mu K \cdot$ arcmin]
95 GHz	94.7	26.4	41.4	675	7.1	6.5	22.5
150 GHz	151.0	25.7	28.8	815	6.0	5.6	20.4

Maps I, Q, U

Ade *et al* (SPIDER)
2022 *ApJ* **927** 174

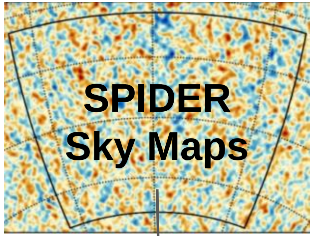


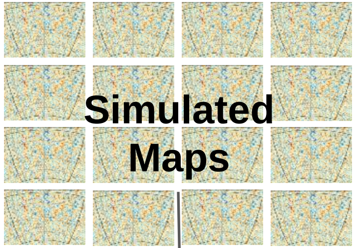


4.8% of sky used for polarization analysis.

Time Ordered Data → **Maps** → Raw Power Spectra → Cleaned Power Spectra → r-likelihoods

Power Spectrum Estimation





Maps ➞ Power Spectra

XFaster **NSI**

Data Split Null Tests

Are the data and pipelines consistent?

Time-domain Simulations

Do known systematics affect *r* constraint?

(beam ellipticity, detector cross-talk …)

XFaster - Maximum Likelihood Estimator

- Hybrid of Monte Carlo and iterative quadratic estimators.
- Solves for binned bandpower deviations, adapting signal and noise simulation libraries to the data
- 10 minute data chunks; 4 data subsets
- Code is publicly available spider-cmb.github.io/xfaster/
- *A.E. Gambrel, A.S. Rahlin, C. Contaldi… (2021 ApJ **922** 132)*

NSI (Noise Simulation Independent)

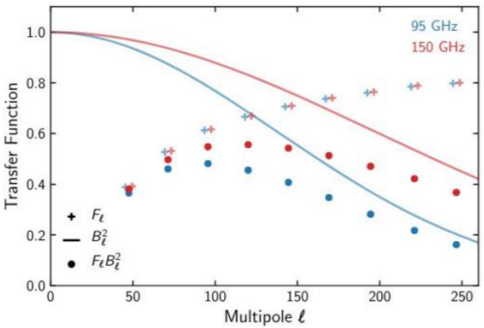
- PolSPICE based Pseudo-Cl Monte Carlo estimator.
- Signal-only simulation library built “transfer-matrix” for mode mixing and filtering effects
- Bandpowers estimated from noise-weighted mean of 378 cross-spectra
- Error bars derived from distribtion
- 3 minute time chunks; 14 data subsets
- *J. Nagy, J. Hartley, S. Benton, J. Leung, …*

Time Ordered Data → **Maps** ➞ Raw Power Spectra → Cleaned Power Spectra → r-likelihoods

Raw Power Spectra

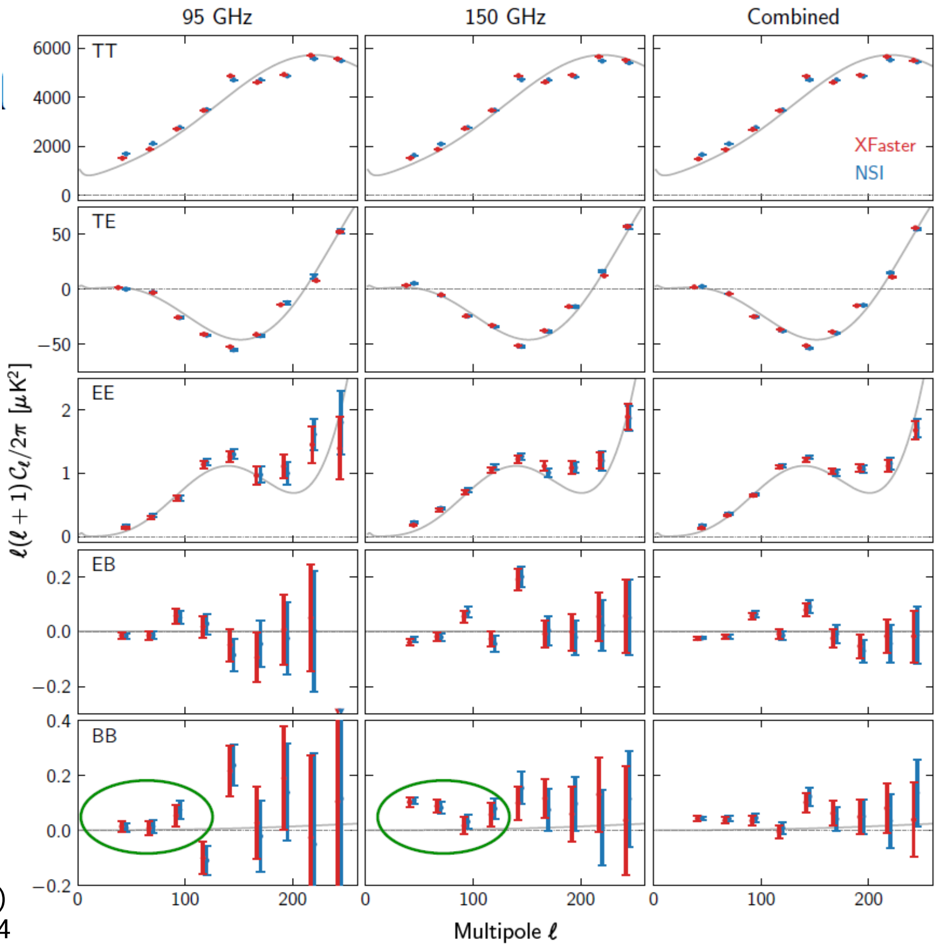
- Use a common sky mask:
  - 1992 square degree rectangle with point sources removed
  - Multipole range used for science results is cut to 33⩽ ℓ ⩽ 257, in bins with width 25
- Estimators include correction for beams and filtering
- Sample variance omitted from error bars
- Good agreement between estimators
- Extra power from foregrounds

SPIDER Transfer Function



Ade *et al* (SPIDER)
2022 *ApJ* **927** 174

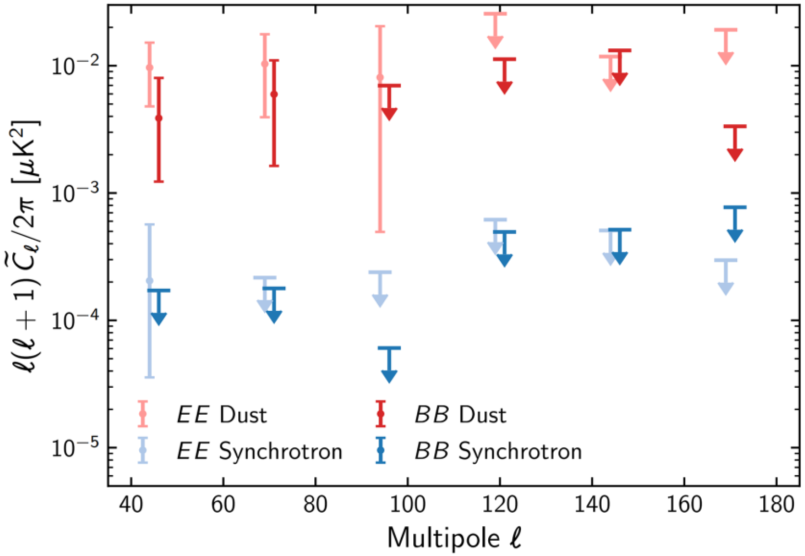
Raw Power Spectra Comparison



Time Ordered Data → Maps → Raw Power Spectra → Cleaned Power Spectra → r-likelihoods

Foreground Subtraction

95 GHz Foreground Constraints (95% CL)



Work by J. van der List in Ade et al (SPIDER) 2022 ApJ **927** 174

Which foregrounds matter?

- Harmonic SED fitting with *WMAP*, *Planck* HFI, and SPIDER maps to probe foreground power
- Synchrotron emission is negligible for SPIDER

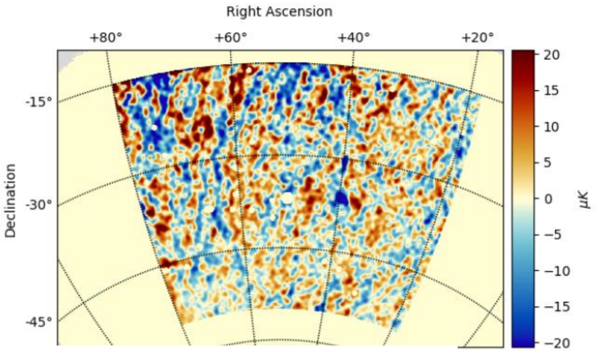
Component Separation Methods in paper:

- Map-based Template Subtraction
  (XFaster, NSI)
- Harmonic-domain joint analysis with Planck
  (SMICA)

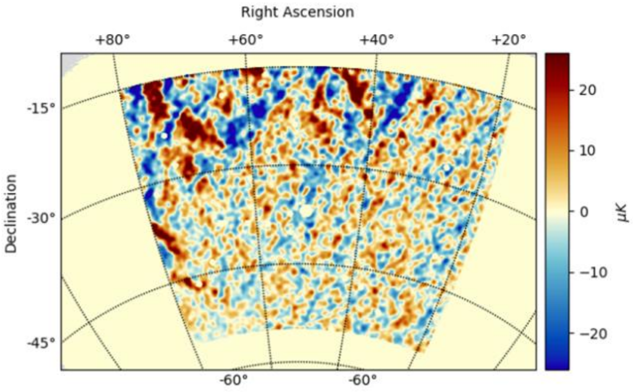
Assume Galactic dust is the dominant source of polarized foregrounds in our sky patch.

Template Subtraction

353-100 GHz Q Template



353-100 GHz U Template



1. Construct two dust templates from Planck maps

(**353-100** & **217-100**)

$$S_\nu^{Clean} = S_\nu^{Raw} - \alpha S_{\nu_0}^{template}$$

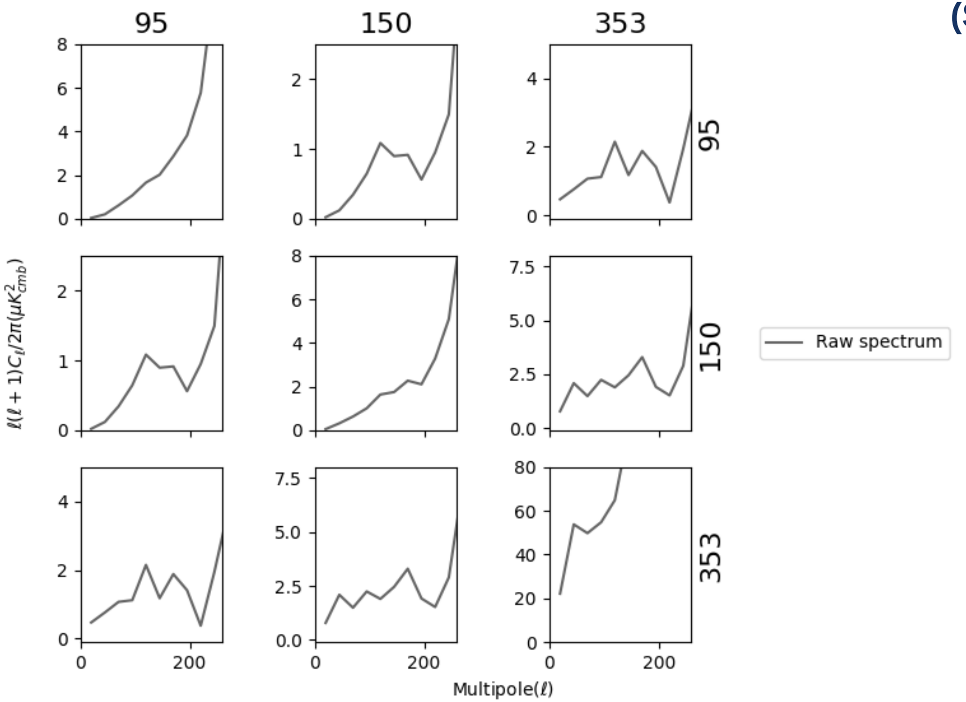
2. Find template scaling factor, alpha, that minimizes CMB power to get clean maps

NSI fits for alpha using lowest three bins in EE and then fits for r

XFaster fits for r and alpha simultaneously with EE and BB

SMICA for SPIDER

Pared down example, EE only

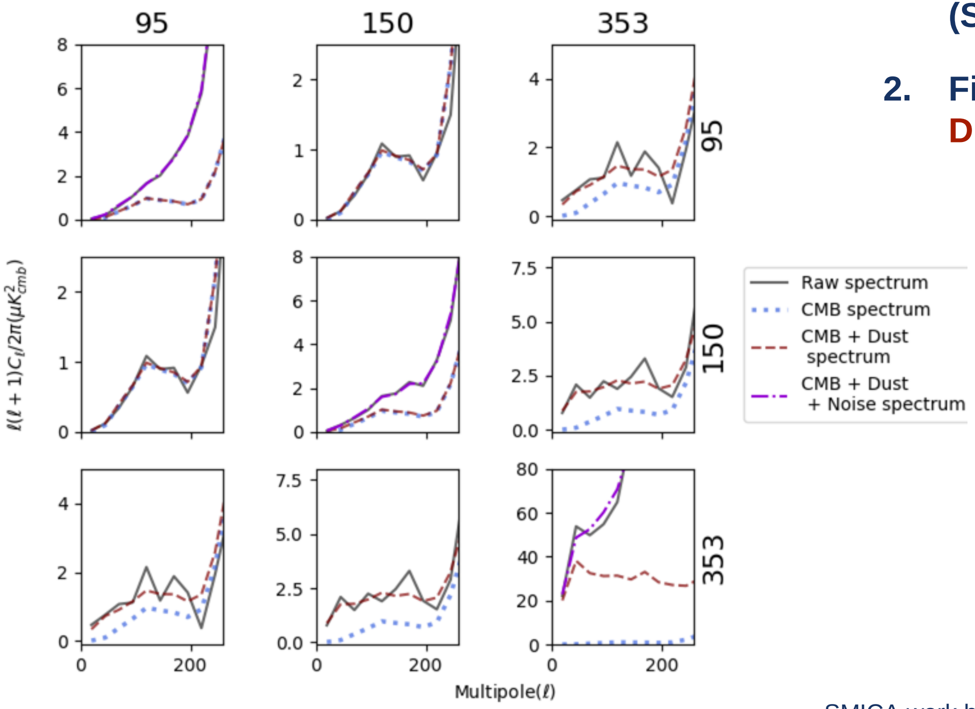


Source: Corwin Shiu

1. **Compute all EE and BB cross spectra (SPIDER 95 &150, *Planck* 100, 143, 217 & 353)**

SMICA for SPIDER

Pared down example, EE only



1. **Compute all EE and BB cross spectra (SPIDER 95 &150, *Planck* 100, 143, 217 & 353)**

2. **Fit to a flexible, parameterized model of CMB, Dust, and Noise.**

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

Noise — Transfer matrix — Dust — CMB

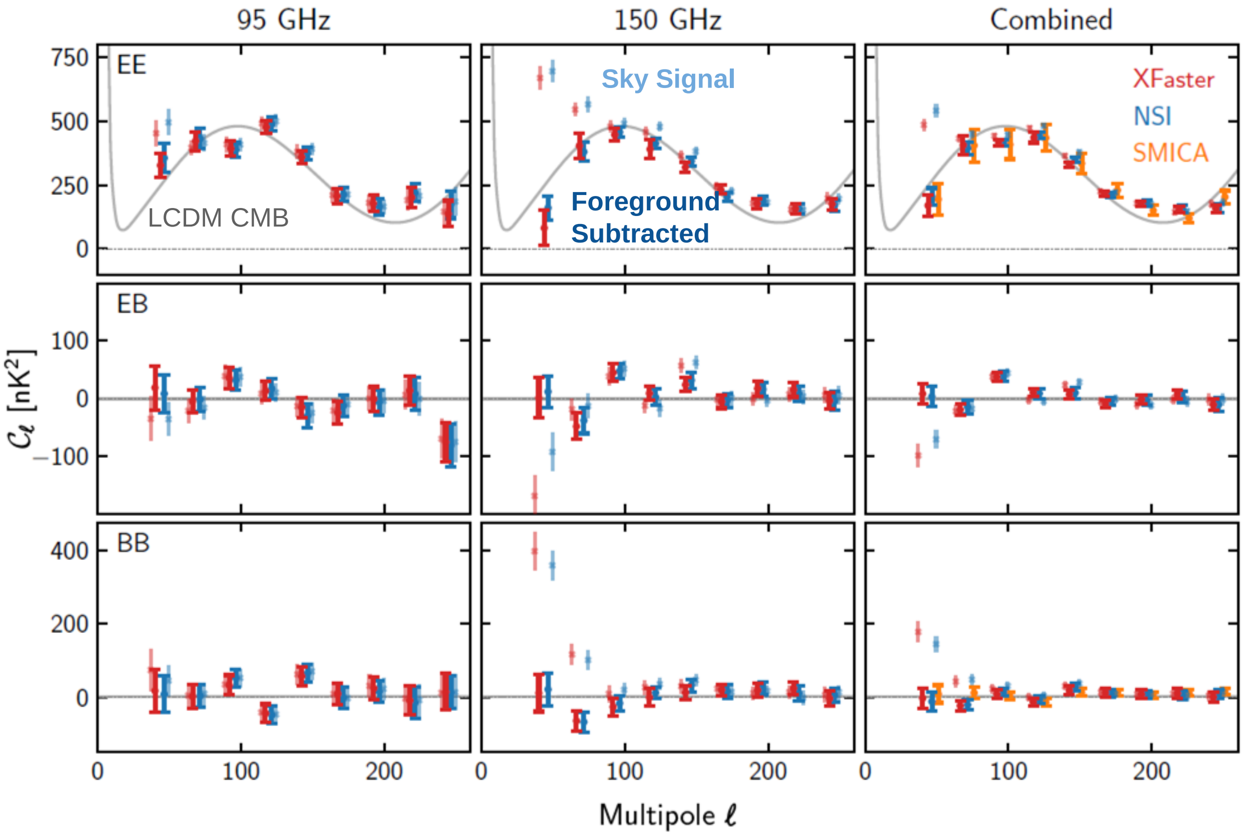
Dust modeled as a modified black body

$$f_b \sim \left(\frac{\nu}{\nu_0}\right)^{\beta_d} \left(\frac{B(\nu,T)}{B(\nu_0,T)}\right)$$

SMICA work headed by C. Shiu in Ade et al (SPIDER) 2022 ApJ **927** 174

Time Ordered Data → Maps → **Raw Power Spectra** → Cleaned Power Spectra → r-likelihoods

Template Cleaned CMB Power Spectra



Ade *et al* (SPIDER)
2022 *ApJ* **927** 174

Time Ordered Data → Maps → Raw Power Spectra → Cleaned Power Spectra → r-likelihoods

Comparing Results from Different Templates

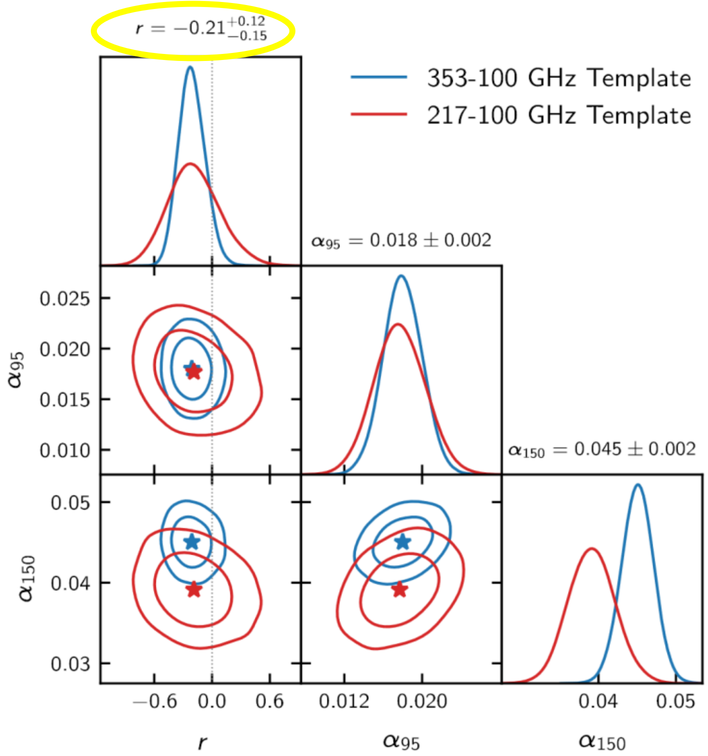
- Results from both templates are consistent with each other.
- 353 - 100 GHz Template provides tighter constraint.

Published results from XFaster:

r_{mle} = **-0.21** with 95% CL limits at:

r ≤ 0.19 (Bayesian)

r ≤ 0.11 (Feldman-Cousins)



SPIDER Collab, ApJ 2021

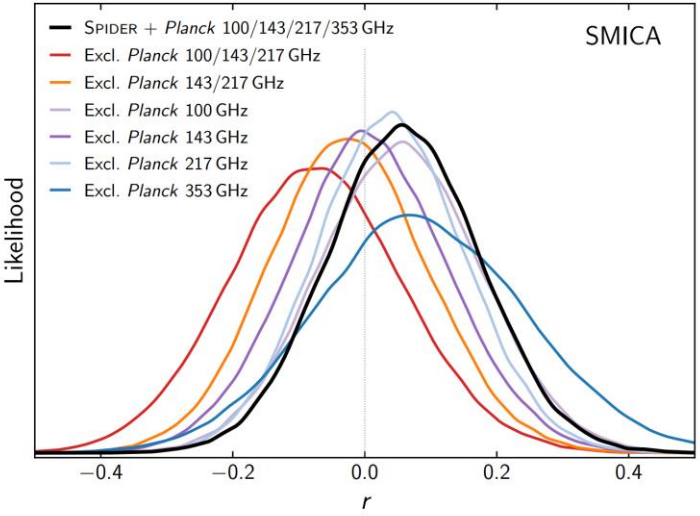
Time Ordered Data → Maps → Raw Power Spectra → Cleaned Power Spectra → r-likelihoods

Comparing Foreground Cleaning Methods

- Nominal result from SMICA, r_{mle} = 0.06
- Nominal result from XFaster, r_{mle} = -0.21

- Different choices of *Planck* input data moves r_{mle} by $O(0.1)$ (about a sigma)
- All pipelines produce unbiased estimates on r
- Discrepancy in r_{mle} between pipelines is consistent with simulation ensembles ran on identical data sets.

Varying Planck data used in SMICA



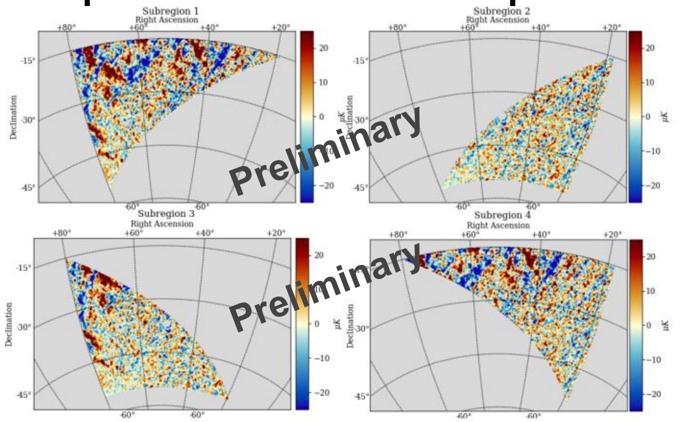
Work by C. Shiu in Ade et al (SPIDER) 2022 ApJ **927** 174

Time Ordered Data → Maps → Raw Power Spectra → Cleaned Power Spectra → **r-likelihoods**

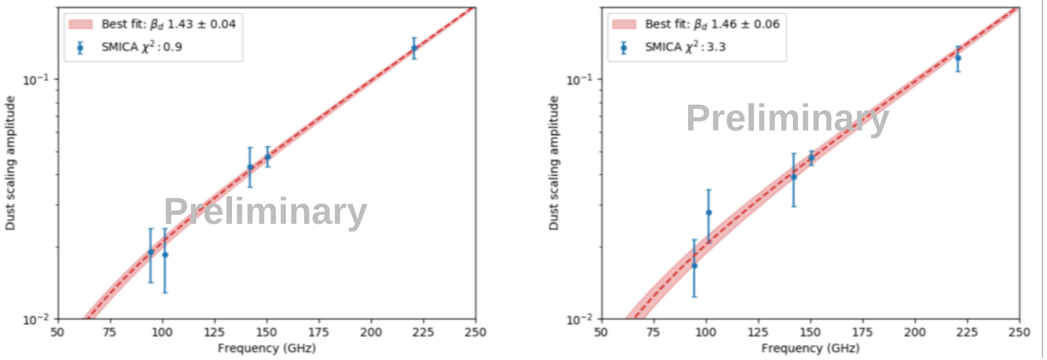
Ongoing Foreground Analysis

Foregrounds Paper in Preparation

Spatial variations in dust parameters



Consistency of MBB model



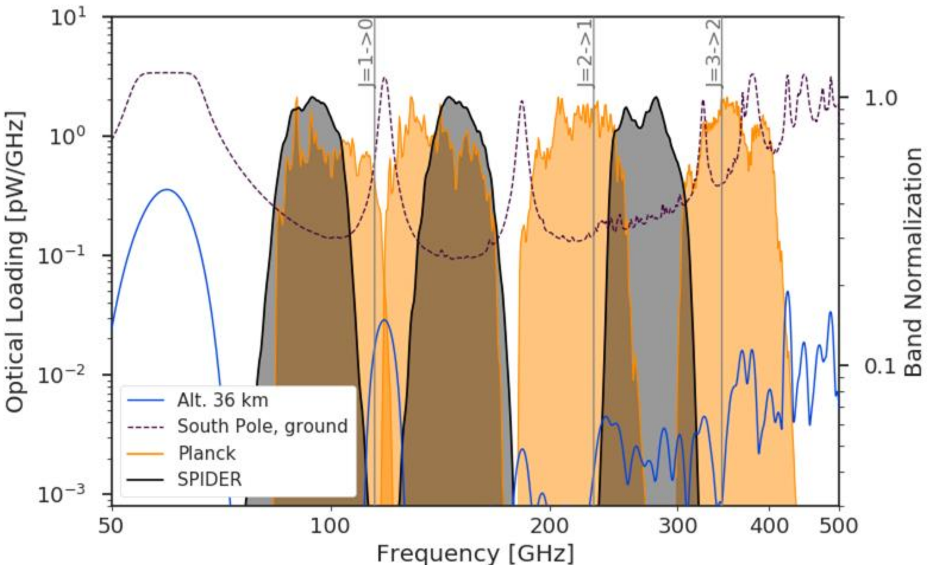
Searching for evidence of multiple dust populations

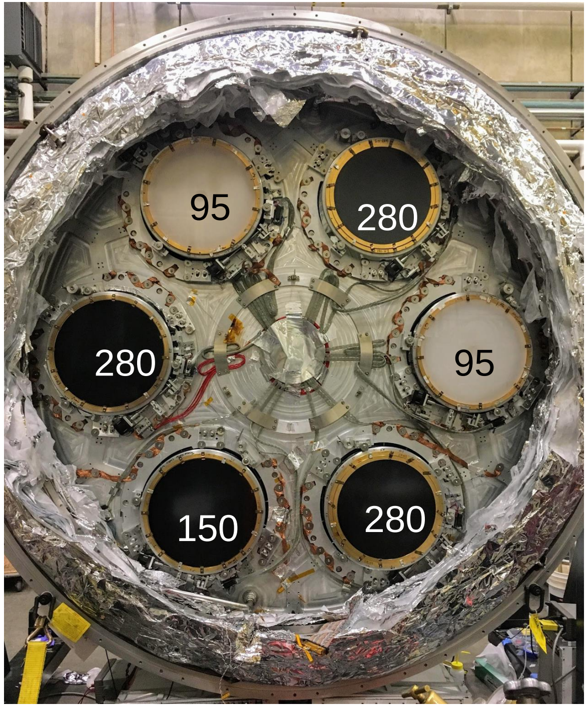
Handling of EB within SMICA

β_d vs ell

SPIDER's Second Flight

- **Three new 280 GHz receivers,** for polarized dust sensitivity
- Deeper maps for foreground sensitivity than Planck
- Redeploy best two 95 GHz, and one 150 GHz receivers
- New, upgraded cryostat and rebuilt gondola

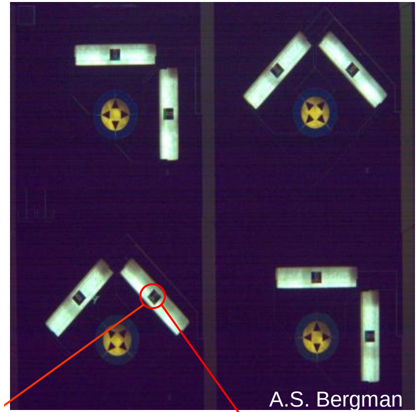


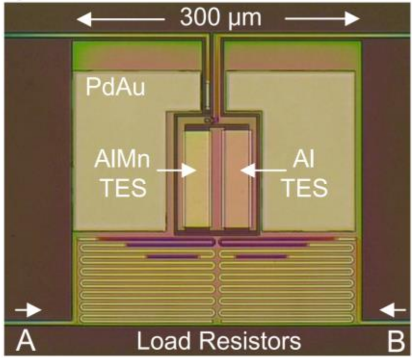


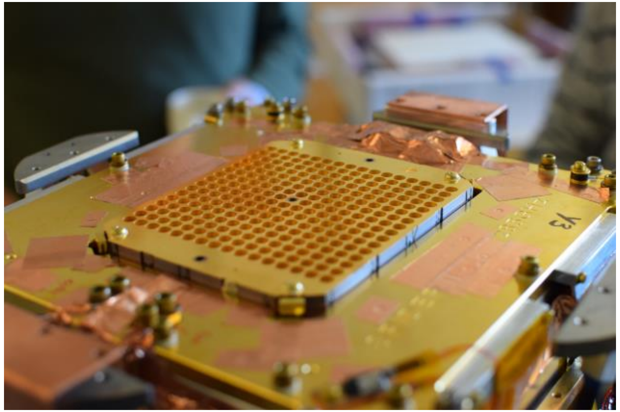
285 GHz Receivers

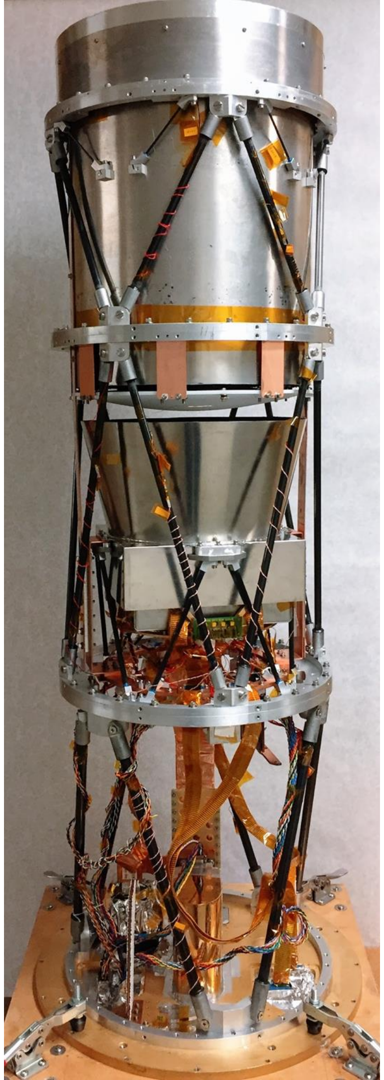
E. Shaw+ Proc. SPIE (2020)
Bergman+ JLTP (2018)
Hubmayr+ Proc. SPIE (2016)

- Focal Planes have 512 feedhorn-OMT coupled TESs (NIST design and fab)
- Simultaneous coverage of Stokes Q and U polarization
- 280 GHz receivers were built and tested at UIUC

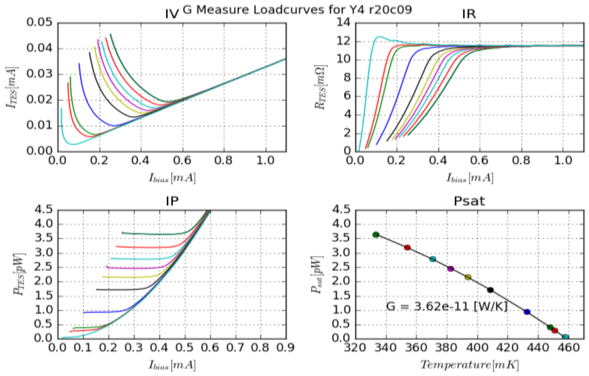








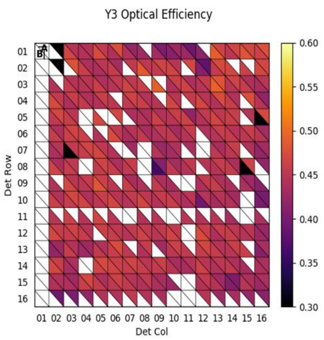
280 GHz Receiver Characterization at UIUC

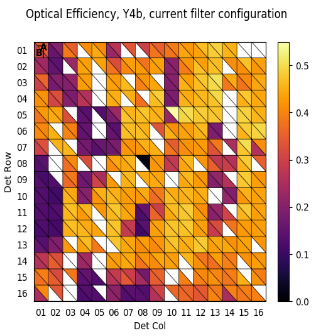


Dark Testing: Electrical and thermal detector properties

Light (Optical) Testing: Detector response to optical input

- Near-field beam mapping
- Optical efficiency
- Optical Loading
- Characterizing radiative emission within telescopes





SPIDER-2 2022 Launch Opportunity

After a long, long wait we are packing for Antarctica!

Summary

SPIDER-1

First flight 2015, 3 @ 95 and 3 @ 150 GHz observations went well
Details of analyis published this year (Ade *et al* 2022 ApJ **927** 174)
Pipelines developed and are unbiased and we report $r \leq 0.11$
Foregrounds paper in progress

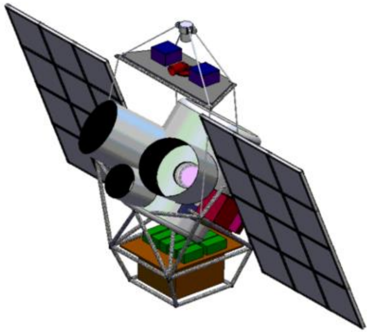
SPIDER-2

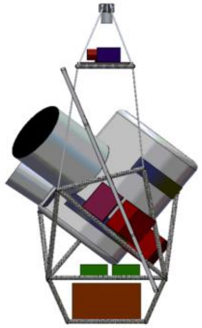
3 @ 280 GHz, 1@ 150 GHz, 2 @ 95 GHz
On our way to get better foreground characterization with 280 GHz band

Upcoming Project: Taurus

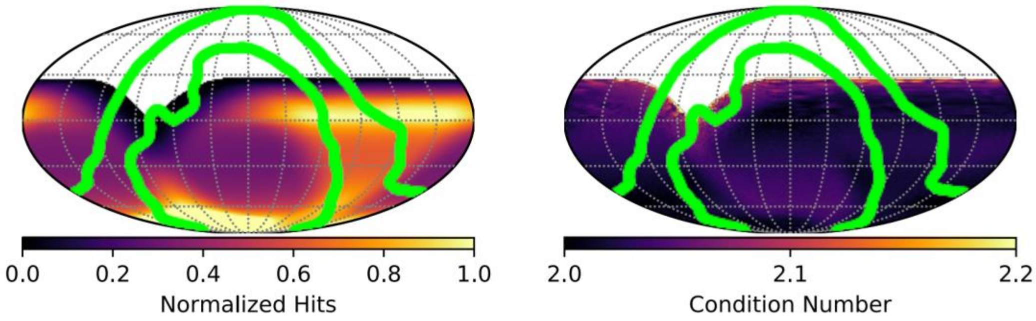
Target: Optical depth to reionization, tau, and Galactic dust characterization

- Observation at: 150, 220, 280, 350 GHz
- ~10,000 detectors @ 100 mK
- Flight from Wanaka, NZ on a Super Pressure Balloon
- Offset pointing for reduced sensitivity to scan-synchronous noise





Simulated scan strategy for Taurus flight



Acknowledgements

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SPIDER Collaboration

Image courtesy of S.J. Benton

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