SPIDER: Examining Deviations in Dust Modeling

Suren Gourapura
Princeton University

What’s Inside

- What and Why
- SPIDER-1
- Foregrounds
- SPIDER-2

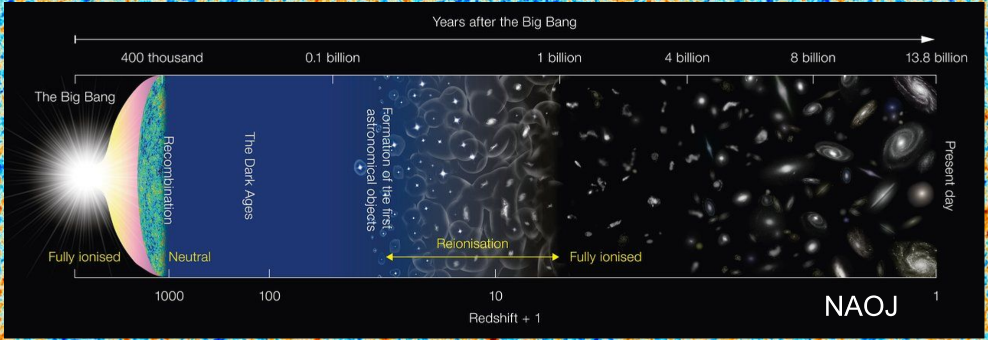

by Vy Luu

The CMB is a Goldmine

Temperature

Polarization

Primary Anisotropies



Secondary Anisotropies

Cosmological Parameters (Ωb, Ωc, Ωm, θMC, τ, As, ns,→ H0, $\sigma 8$, r, …)

Inflation

Reionization History

Sum of Neutrino Masses

Dark Matter

Non-Gaussianity

and more!

Courtesy NASA/JPL-Caltech

Search for Primordial B-modes

- ***r*** : tensor-to-scalar energy ratio

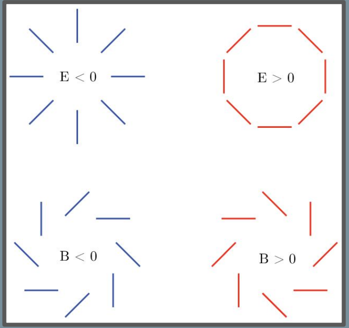
$$r = \frac{A_t}{A_s}$$

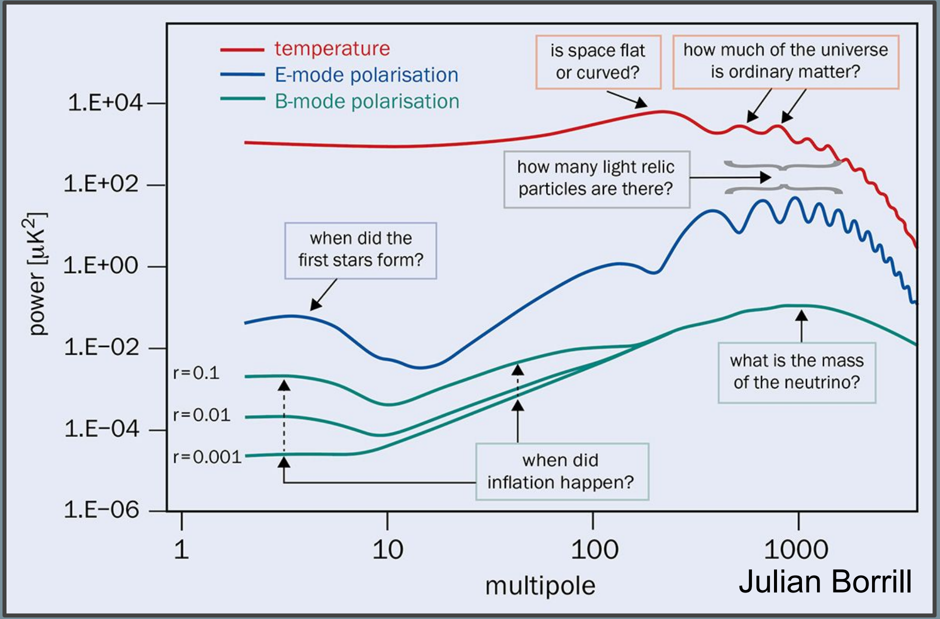
- Tensor perturbations affect temperature and polarization

Thomson Scattering

Gravitational Waves

Gravitational Waves

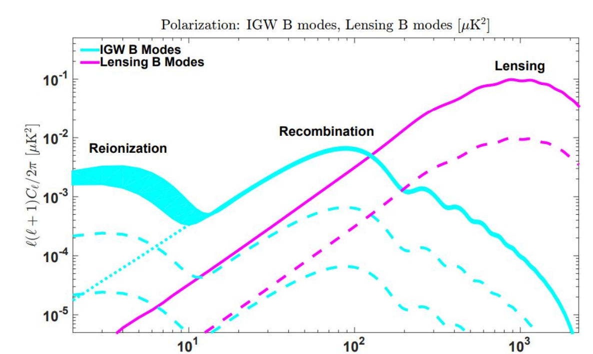




- Want to measure B-mode polarization as the *clean* signature of ***r***

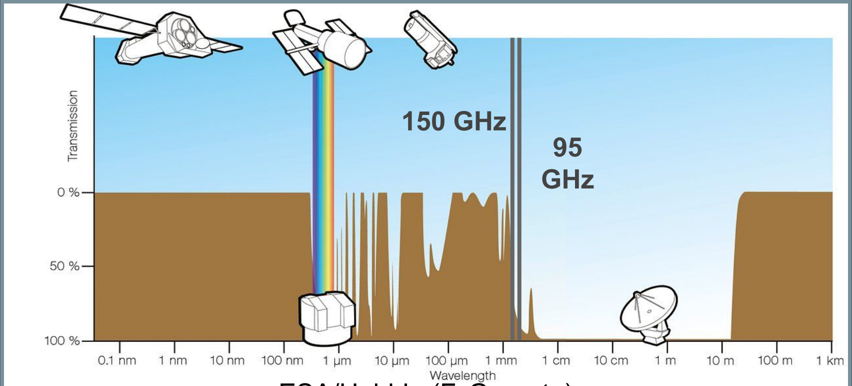
Measurement Challenges

Primordial vs. Lensed B modes



M. Kamionkowski 2015

Atmospheric Loading



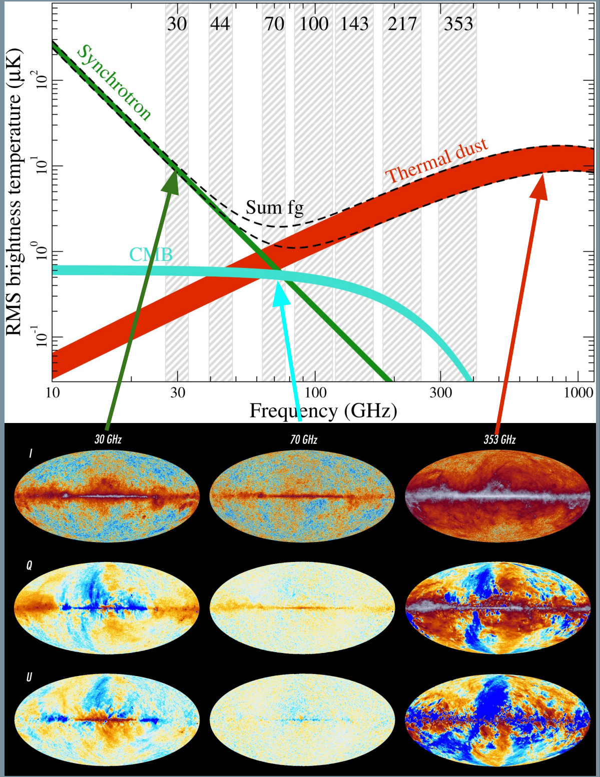
ESA/Hubble (F. Granato)

Very faint signal

Polarization ≪ Temperature

B-modes ≪ E-modes

Galactic Foregrounds



Planck/ESA 2015

What and Why

Why


by Joe, CSBF staff

Analysis:

- Aiming to measure B-mode signal, constrain *r* (2103.13334)
- Better understand diffuse dust emission (coming soon!)
- Create near-orbital quality 280 GHz map for future exps (future work)

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Hardware:

- Develop and implement robust detectors; heritage for future exps (1606.09396, 1711.04169, 2002.05771, 2012.12407…)
- Develop and implement cryostat hardware, gondola, pointing, thermal performance, etc. (1506.06953, 1407.2906, 1407.1881, 1407.1880, 1106.2507)

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by Joe, CSBF staff

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People:

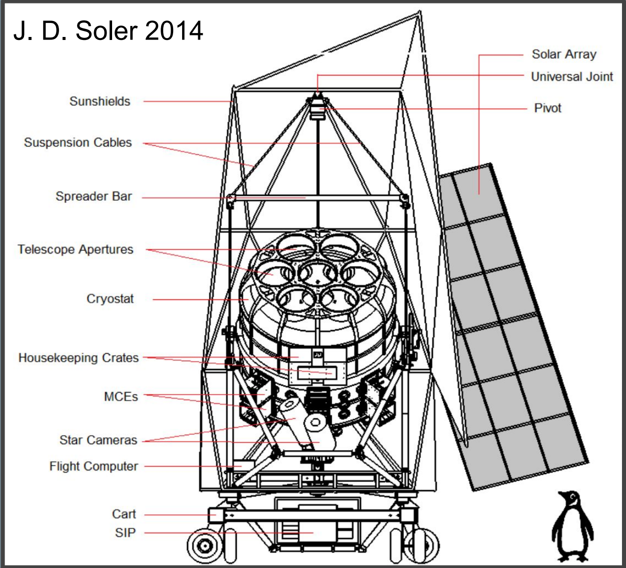
- Train young scientists for earth, balloon, and space observational experiments
- Vast skill set: computer design, cryogenics, data analysis, electronics, machining, rigging, supercomputing, vacuum work

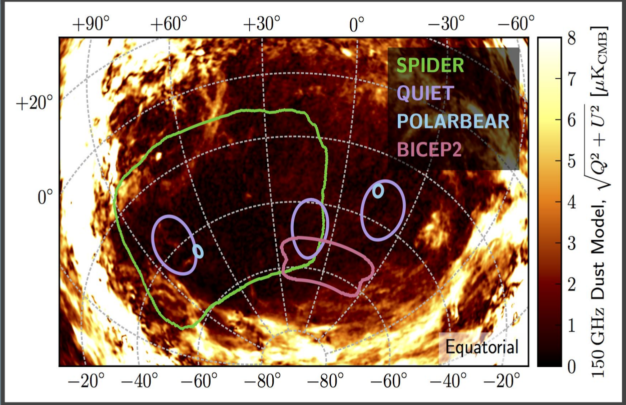
What is SPIDER

CMB polarimeter flying on a NASA Long Duration Balloon from McMurdo Antarctica

SPIDER 1: 2014-15

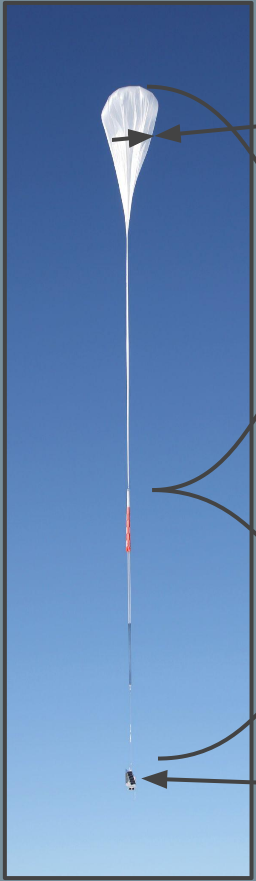
- 6 telescopes, half degree beams
  3 x 95, 3 x 150 GHz
- Flew for 16 days
- As much sky as possible given constraints (Galactic equator, sun, earth's limb, balloon)
- 4.8% of sky used in analysis
- High fidelity polarization measurement at ℓ ~(33, 260)





SPIDER-1

Long Duration Ballooning Platform



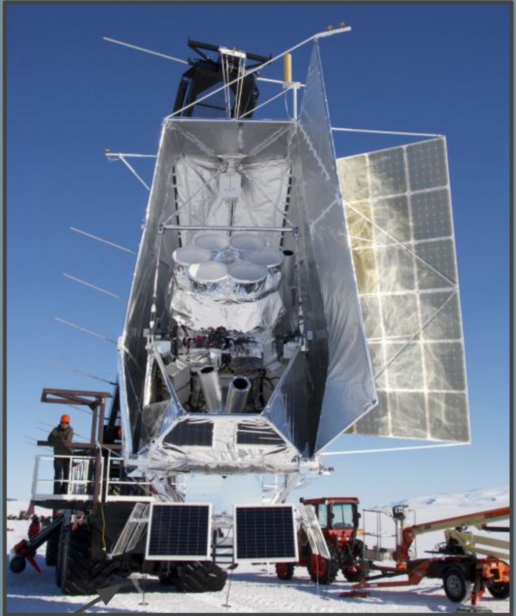
2 millimeters thick

1 million cubic meters
(195 Goodyear Blimps)

Altitude: ~36 km
Payload: 3000 kg
Duration: >50 days

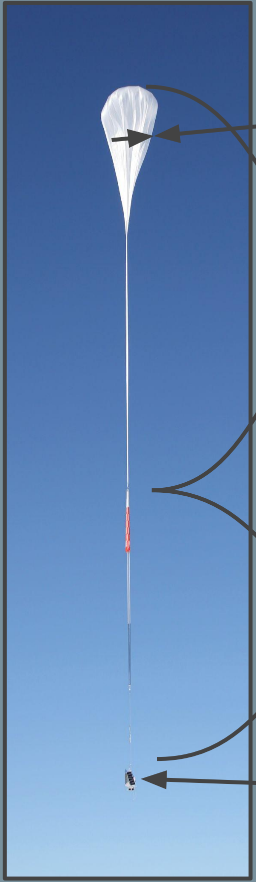
Parachute and Flight
Train

SPIDER-2 Gondola



SPIDER-1

Long Duration Ballooning Platform



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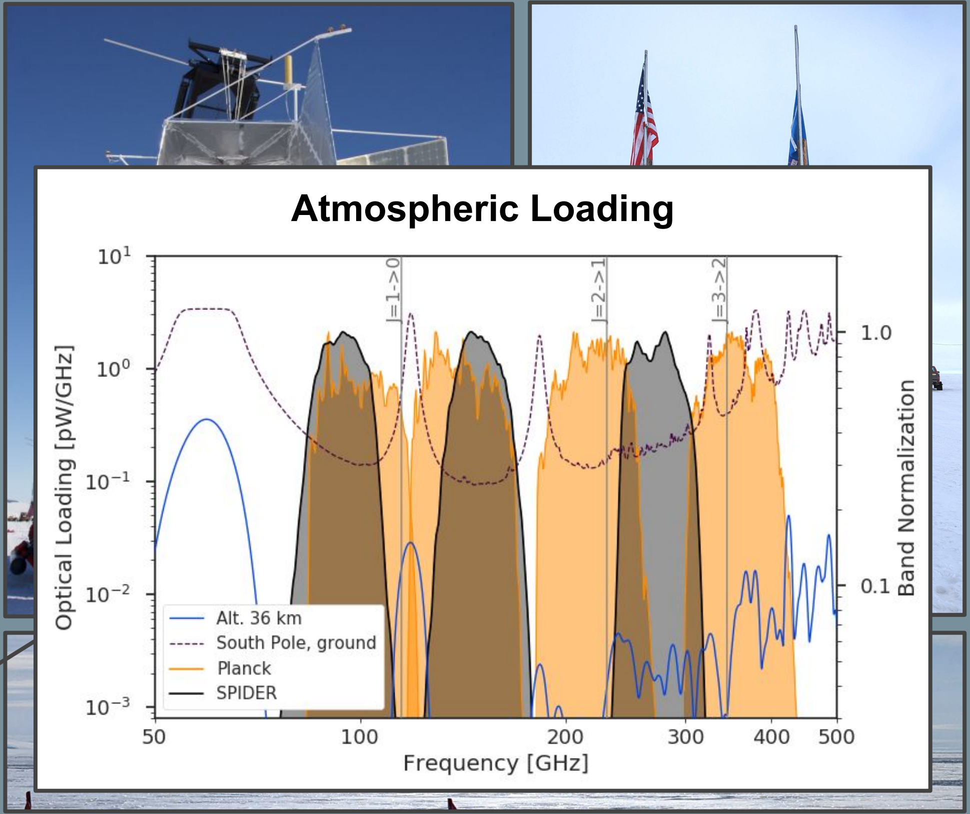
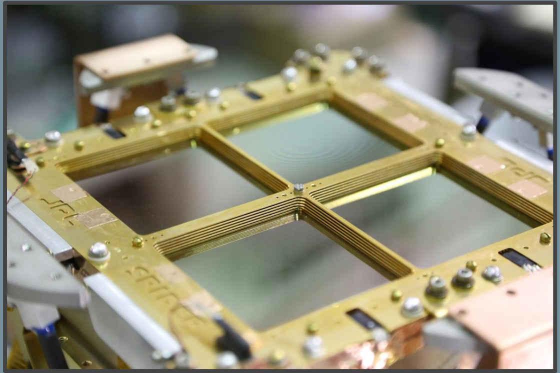


Tackling Measurement Challenges

Very faint signal

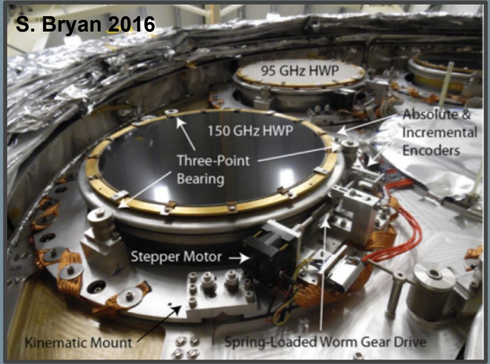
Sensitive detectors
- 2300 sensors at 0.3K
- Reduced stray loading with absorptive filters at many temperature stages



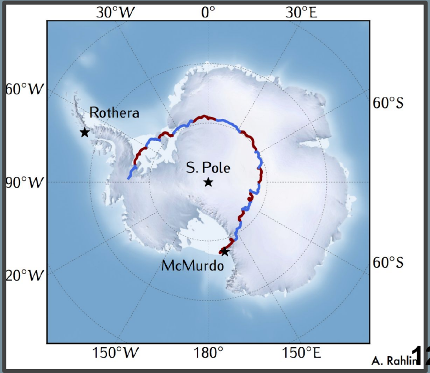
Long Duration
- 1300 L liquid helium tank
- 16 L superfluid tank
- Multi-week capacity


Meyer Tool & Manufacturing

Controlling Systematics
- half-wave plates to modulate signal polarization
- Stepped twice a day throughout flight to reduce polarization systematics


S. Bryan 2016

- Longest overland flight possible
- Low radio/comm interference
- 24h sun for solar panels

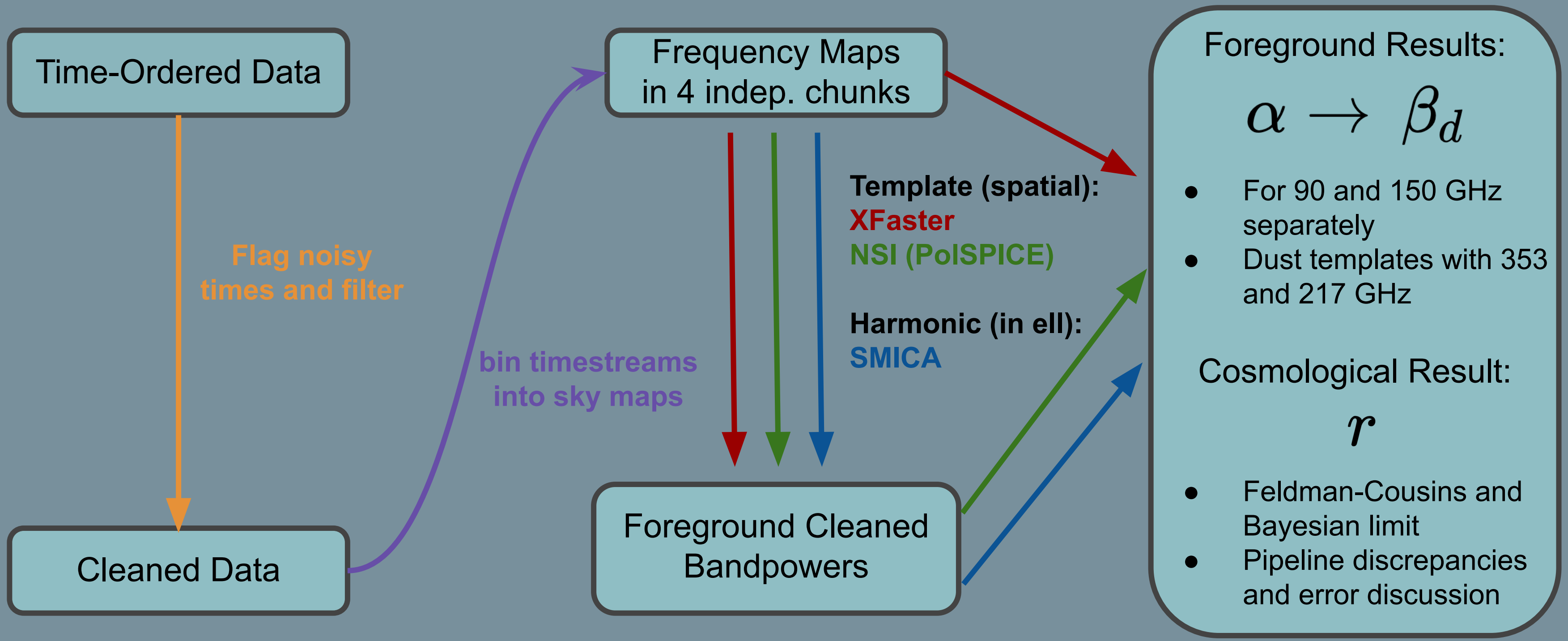


A. Rahlin

SPIDER-1

Analysis Pipeline

2103.13334



2103.13334

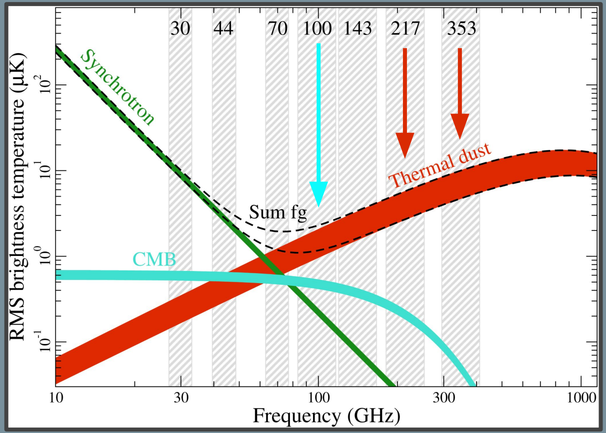
Modeling Foregrounds with Template Subtraction

Construct a dust template using Planck difference maps

$$S^t_{\nu_0} = S_{\nu_0} - S_{100\,GHz}$$

Where ν_0 refers to a map at a high dust frequency. We use both 353 and 217 GHz

$$S^{cleaned}_{\nu} = S_{\nu} - \alpha S^t_{\nu_0}$$



Assumes fixed dust morphology, only amplitude variation

SPIDER-1

2103.13334

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Planck 2018 cosmological parameters into CAMB to generate a theory shape spectrum

For XFaster

$$C^{(S)}_{\ell}(r) = C_{\ell}(r=0) + r\,C^{tens}_{\ell}(r=1)$$

Maximum likelihood parameter estimates are calculated for $r,\ \alpha_{95},\ \alpha_{150}$ simultaneously

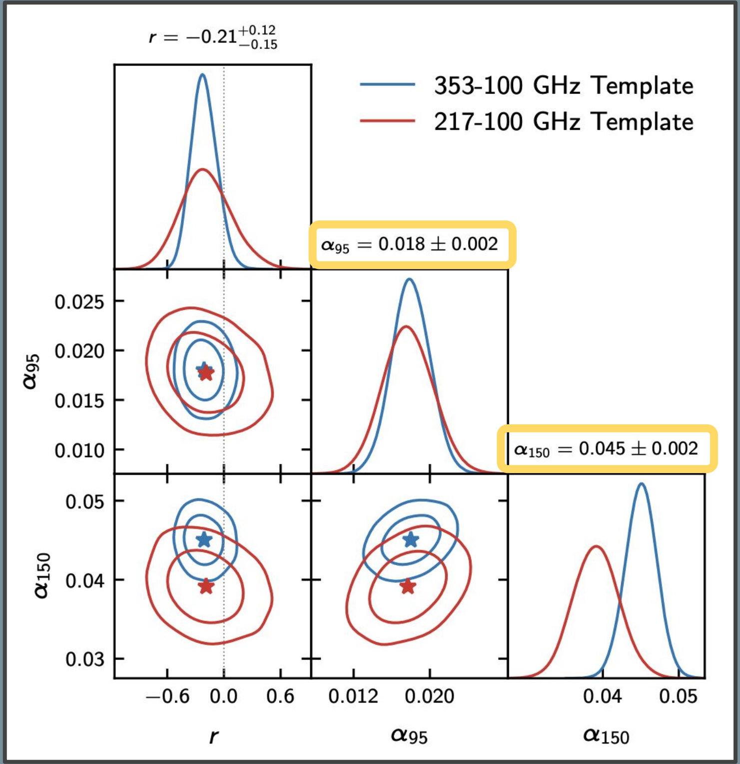
SPIDER-1

SPIDER-1 Results

2103.13334

Table 5. Summary of r-likelihood values from various pipelines, with nominal upper limits in bold.

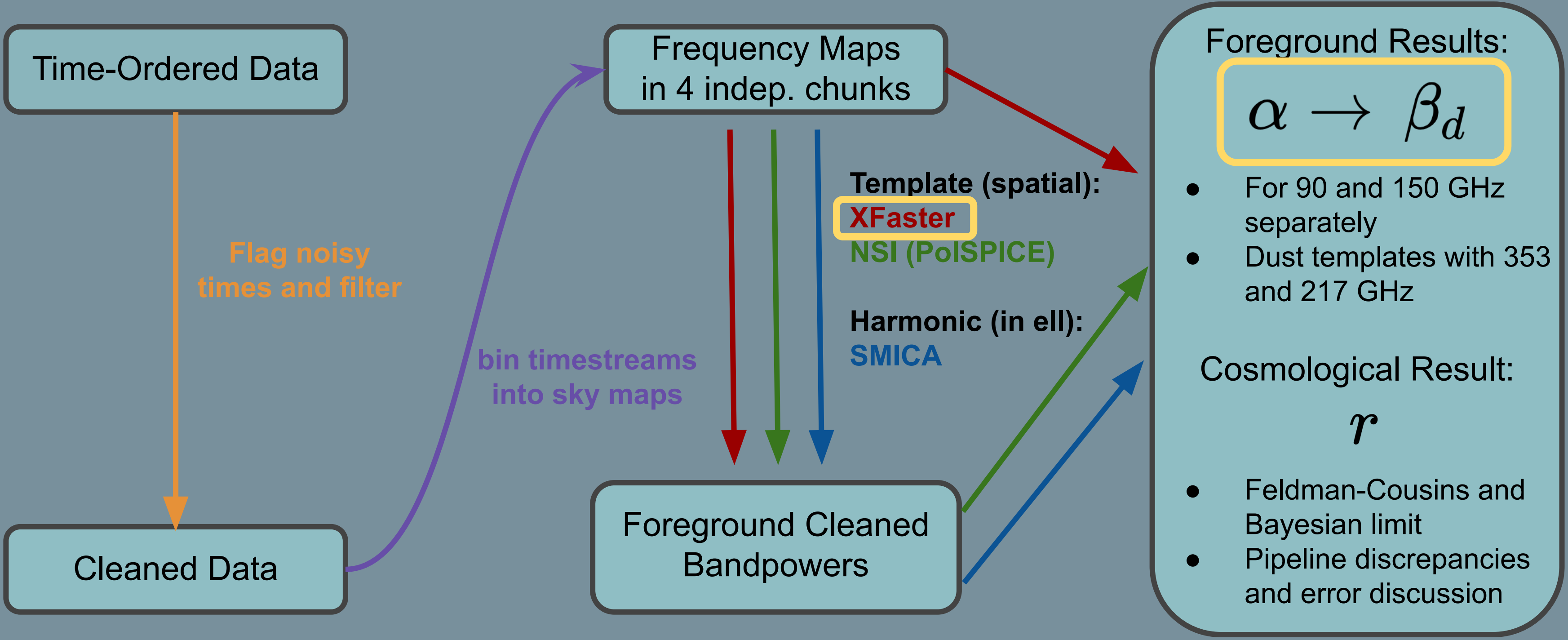
Pipeline	Description	r_{mle}	$r \leq 95\%$
XFaster	Nominal, Feldman–Cousins	-0.21	**0.11**
	Nominal, Bayesian	-0.21	**0.19**
	NSI-like:		
	(a) r from BB only	-0.19	–
	(b) Independent EE & BB noise	-0.19	–
	(a) + (b)	-0.15	–
NSI	Nominal, Feldman–Cousins	-0.09	0.23
	Nominal, Bayesian	-0.09	0.27
SMICA	Nominal, Bayesian	0.06	0.24
	Template-like:		
	Excl. *Planck* inputs < 353 GHz	-0.07	–



Foregrounds

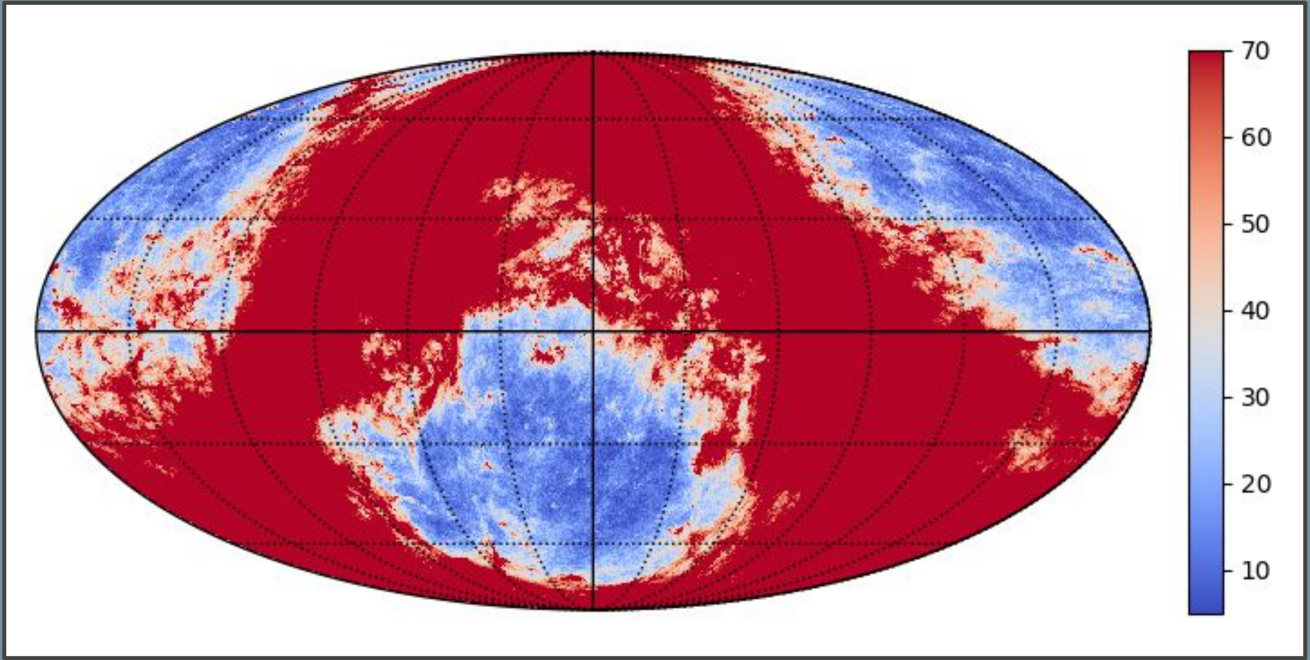
Analysis Pipeline

2103.13334



Foregrounds

Spatial Variation from PLANCK

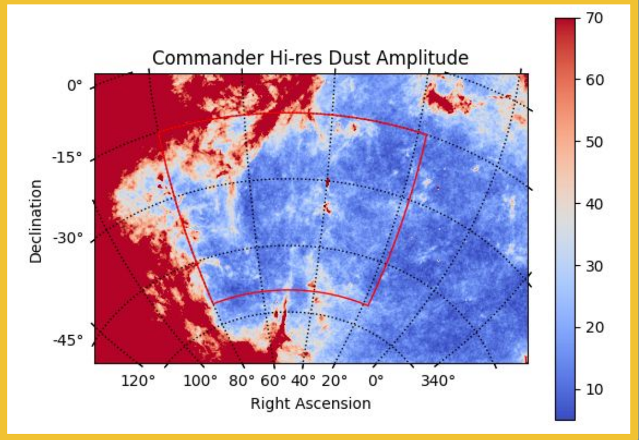


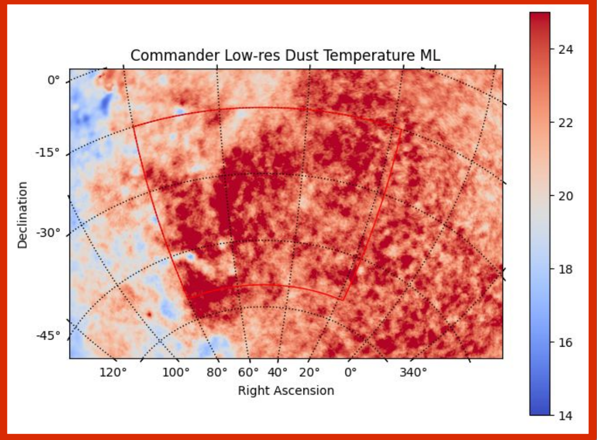
Commander High-Res Dust Amplitude (Celestial Projection)

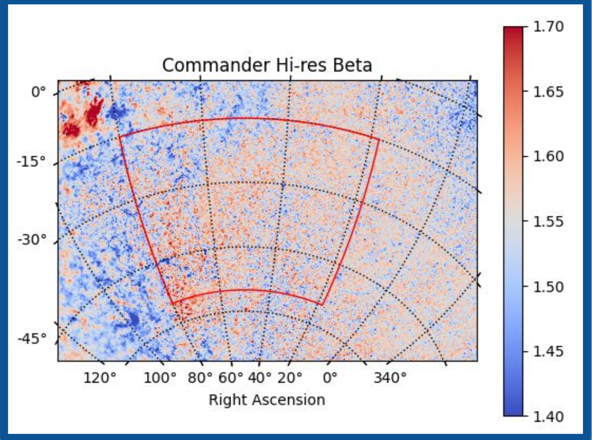
Foregrounds

Spatial Variation from PLANCK

Graybody Model, in ΔTcmb units



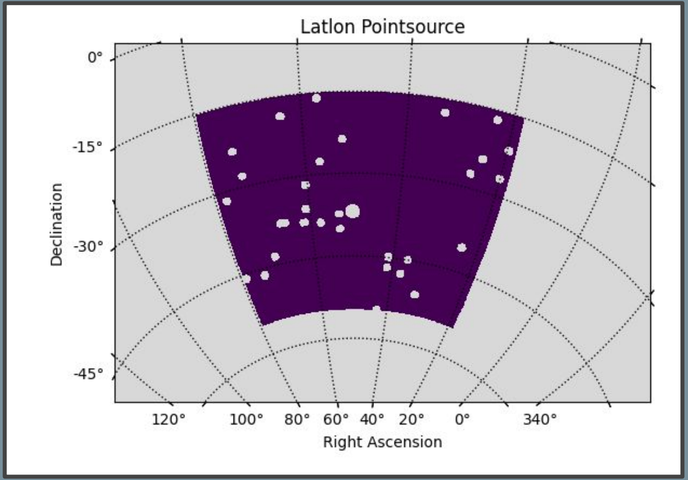




$$S_\nu = cc(\boxed{T_d}, \boxed{\beta})\, \boxed{A_d} \left(\frac{\nu}{\nu_0}\right)^{\boxed{\beta}} B_\nu(\boxed{T_d}, \nu)$$

Foregrounds

Probing Spatial Variation



Make subregions that better capture spatial variation

Must be:

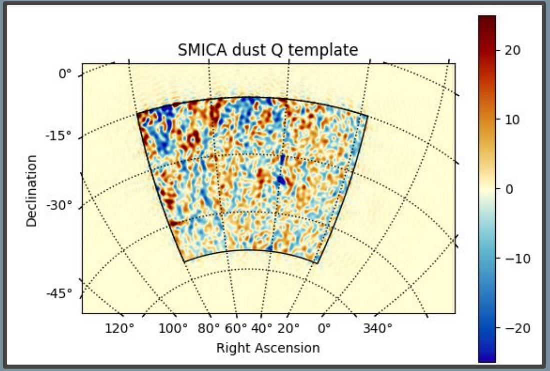
- Smooth
- Simply connected
- ~50/50 area

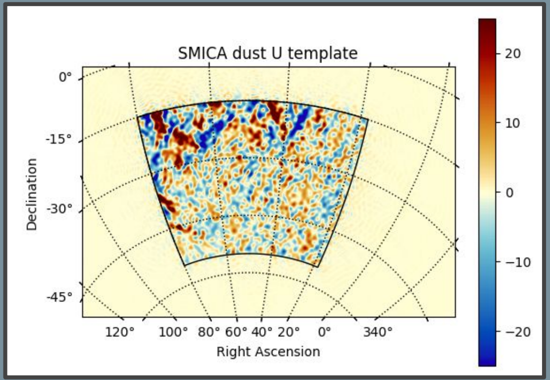
Procedure to generate masks

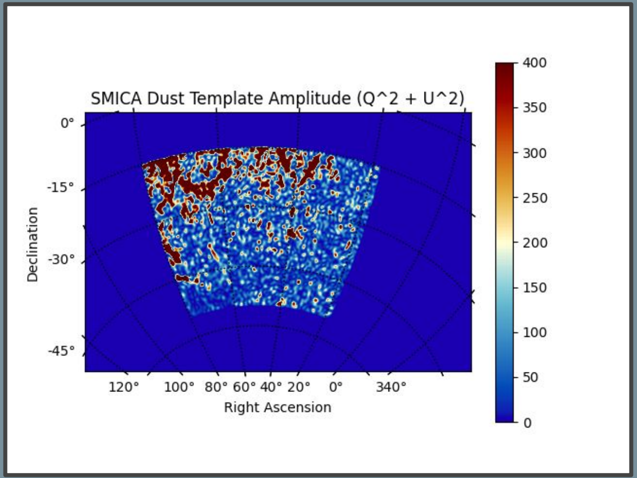
- Find foreground-informative map
- Make map strictly positive
- Smooth with gaussian
- Threshold

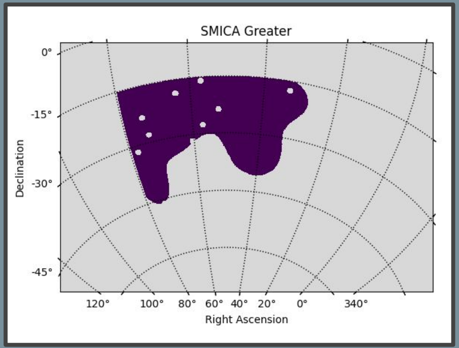
Foregrounds

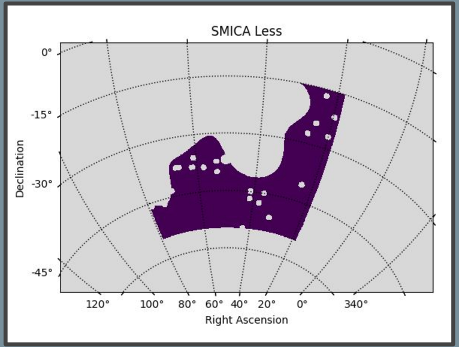
SMICA informed Subregions





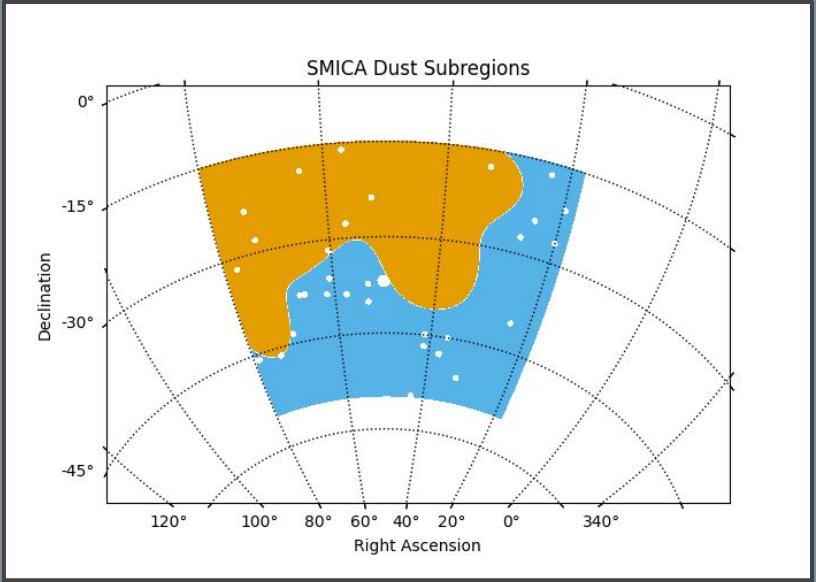


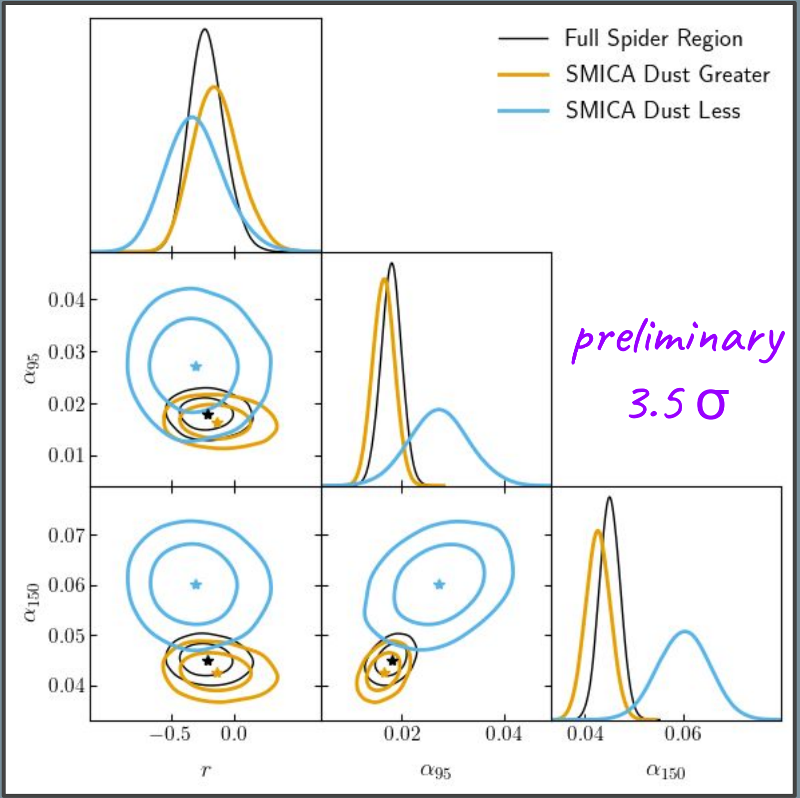




Foregrounds

SPIDER-1 Sees Spatial Variation



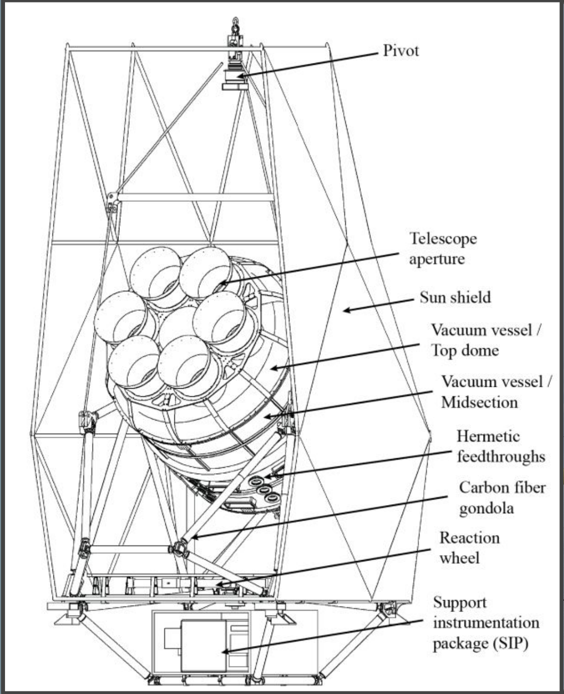


Foregrounds and Intensity papers coming soon!

SPIDER-2

SPIDER 2: 2022-23

- 6 telescopes
  2 x 95, 1 x 150, **3 x 280 GHz**
- About 8 days of data
- Data recovered and low-level work starting now

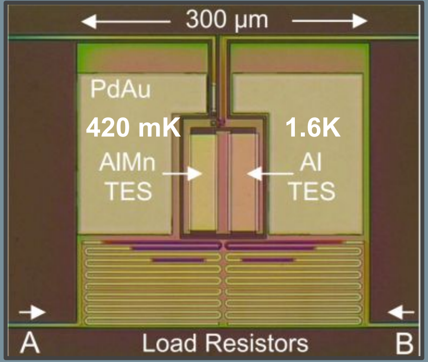


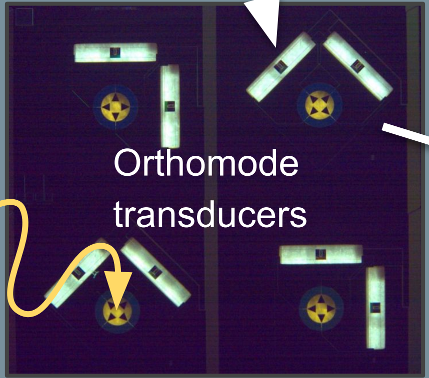
SPIDER-2

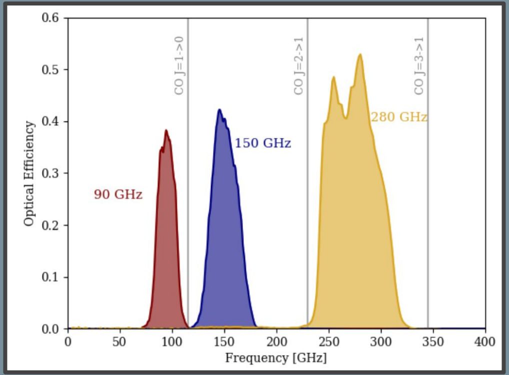
2012.12407, 1711.04169, 1606.09396

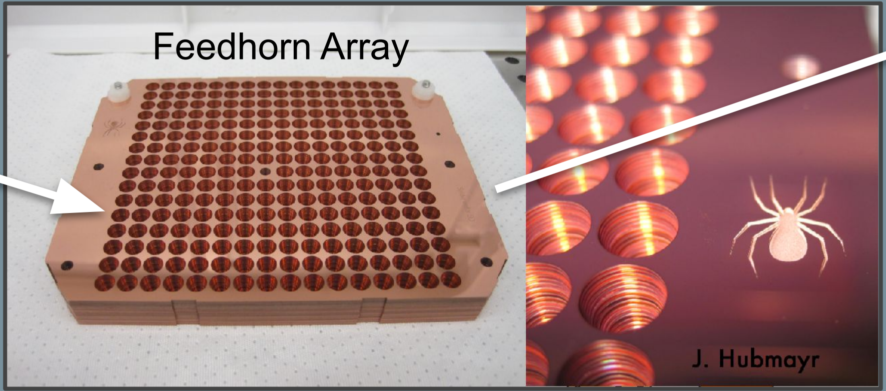
280 GHz Telescopes

Transition Edge Sensor island

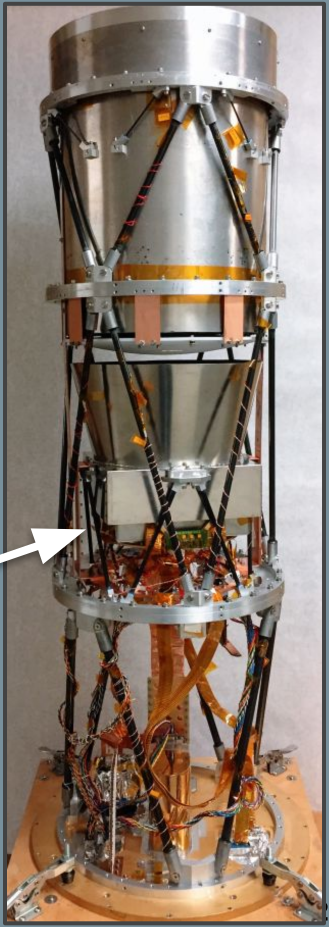








focal plane of
280 telescope

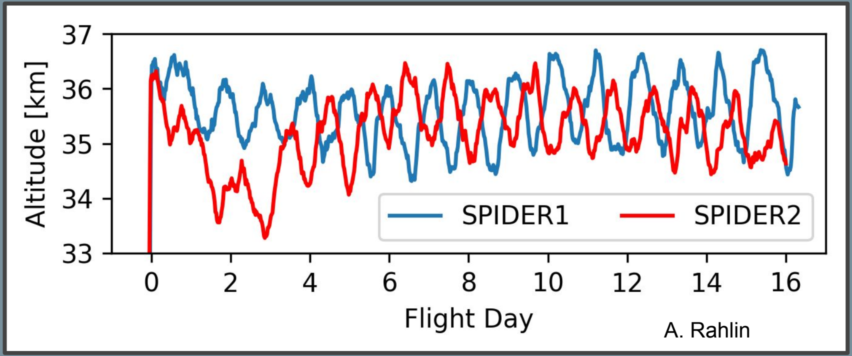


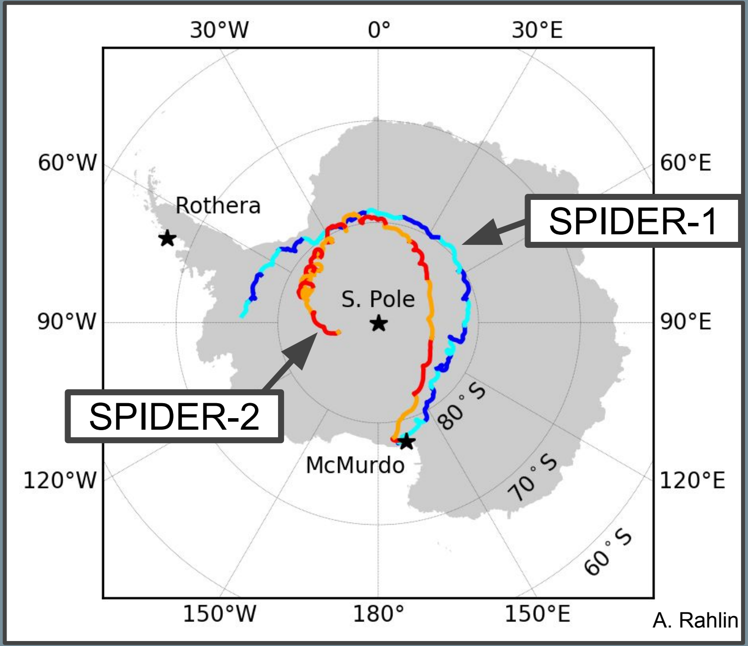
Flight! Dec 22-Jan 7 2023

SPIDER-2

In-Flight Statistics

- 8 days of data
- Similar sky region and area to SPIDER-1
- All 280 GHz receivers fully on science transition
- Nearly half the photons seen by detectors are CMB





Summary

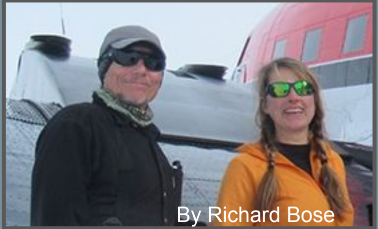
- Ballooning is a challenging but rewarding platform

- Foregrounds are hard
  - Future polarization measurements need better dust models
  - Foregrounds and Intensity papers coming out soon

- Second flight a success!
  - More integration time, better handle of systematics → better constraints
  - Unparalleled 280 GHz maps for better foreground modeling in future experiments

Thank You!

1. Suren Gourapura (Princeton)
2. Riccardo Gualtieri (Argonne National Lab)
3. Elle Shaw (UIUC)
4. Johanna Nagy (WUSTL)
5. Vy Luu (Princeton)
6. Steven Benton (Princeton)
7. Jason Leung ( )
8. Sho Gibbs (UIUC)
9. Steven Li (Princeton)
10. Corwin Shiu (Princeton)
11. Susan Redmond (Princeton)
12. Sasha Rahlin (U. Chicago)
13. Simon Tartakovsky (Princeton)
14, Joseph van der List (Princeton)
15. Jared May (WUSTL)
16. Jeff Filippini (UIUC)
17. Bill Jones (Princeton)

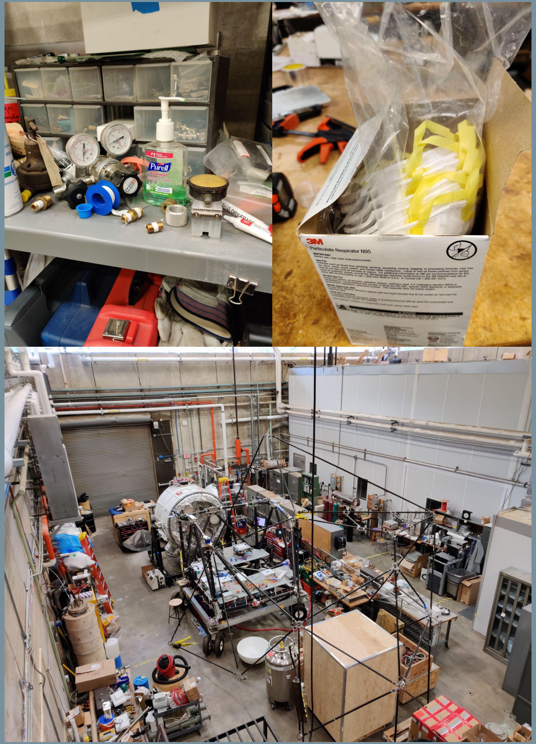


Scott Battaion, Kaija Webster, Pam Melroy (Nasa Deputy Administrator), Rose McAdoo

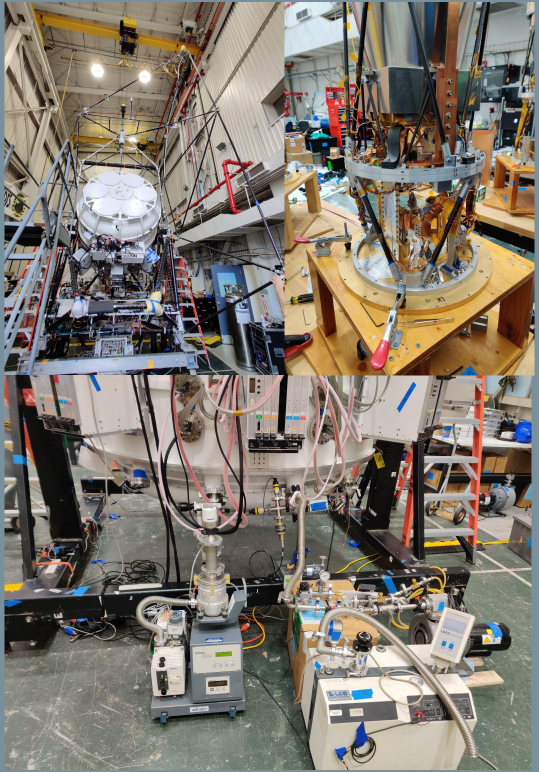

Backup Slides

Second Flight Hardware: Cryo Runs

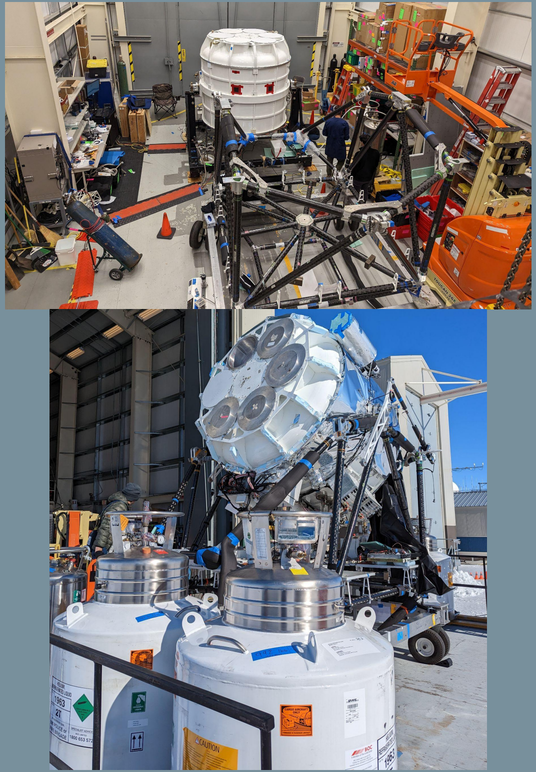
Spring 2020 (Princeton)



Summer 2022 (Palestine)



Winter 2022 (McMurdo)



Foregrounds

XFaster Algorithm

2104.01172

Uses a fiducial full-sky model and iteratively solves for bandpower deviations

$$\tilde{\boldsymbol{C}}(\theta) = \tilde{\boldsymbol{S}}(\theta) + \tilde{\boldsymbol{N}}$$

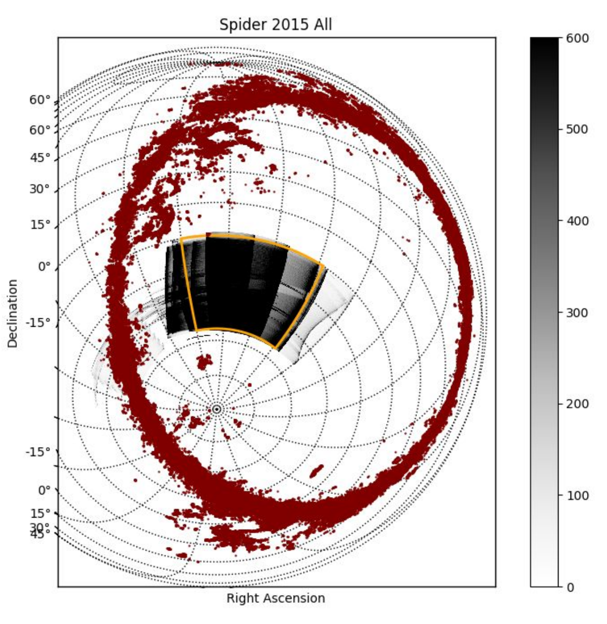
$$\tilde{S}_\ell^{XY,ij} = \sum_b q_b^{XY}\, \tilde{C}_{b\ell}^{XY,ij}$$

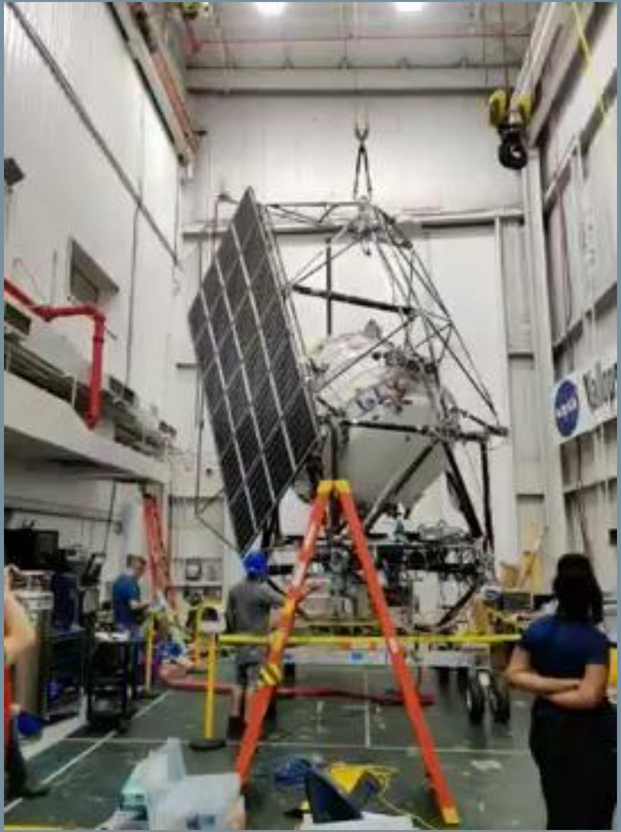
$$\tilde{N}_\ell^{XY,ij} = \delta^{ij} \sum_b \chi_{b\ell} \left(1 + n_b^i\right) \langle \tilde{N}_\ell^i \rangle$$

$$\tilde{C}_{b\ell}^{XY,ij} = \sum_{\ell'} \chi_{b\ell'}\, K_{\ell\ell'}^{ij} F_{\ell'}^{XY,ij} \left(B_{\ell'}^{XY,ij}\right)^2 C_{\ell'}^{XY\,(S)}$$

$\tilde{\boldsymbol{C}}(\theta)$	Generalized covariance matrix
$\tilde{S}_\ell^{XY,ij}$ $\tilde{N}_\ell^{XY,ij}$	Signal and Noise covariance
q_b^{XY}	Bandpower deviation of bin b
$\chi_{b\ell}$	Binning operator
n_b^i	Noise scaling parameter
$\langle \tilde{N}_\ell^i \rangle$	Mean spectrum of noise sim ensemble
$\tilde{C}_{b\ell}^{XY,ij}$	Bandpower kernel
$K_{\ell\ell'}^{ij}$	Mode coupling matrix
$F_{\ell'}^{XY,ij}$	Linear filter function
$B_{\ell'}^{XY,ij}$	Beam function
$C_{\ell'}^{XY\,(S)}$	Shape spectrum (fiducial)

Second Flight Scan Strategy: Pointing Hardware





Pointing in AZ

- Reaction wheel
- Pivot motor

Pointing in EL

- 2 EL drives
- Inline strain gauges
- 2 EL sensors

Other sensors

- 2 Star cameras
- Inner and outer frame gyros
- Sun sensor
- Magnetometer
- NASA GPS

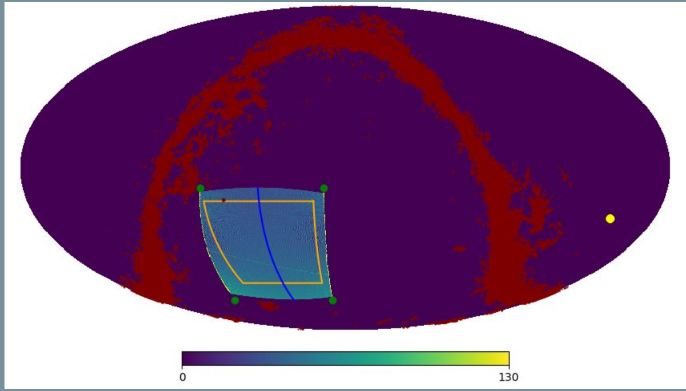
Second Flight Scan Strategy: Scan Simulation

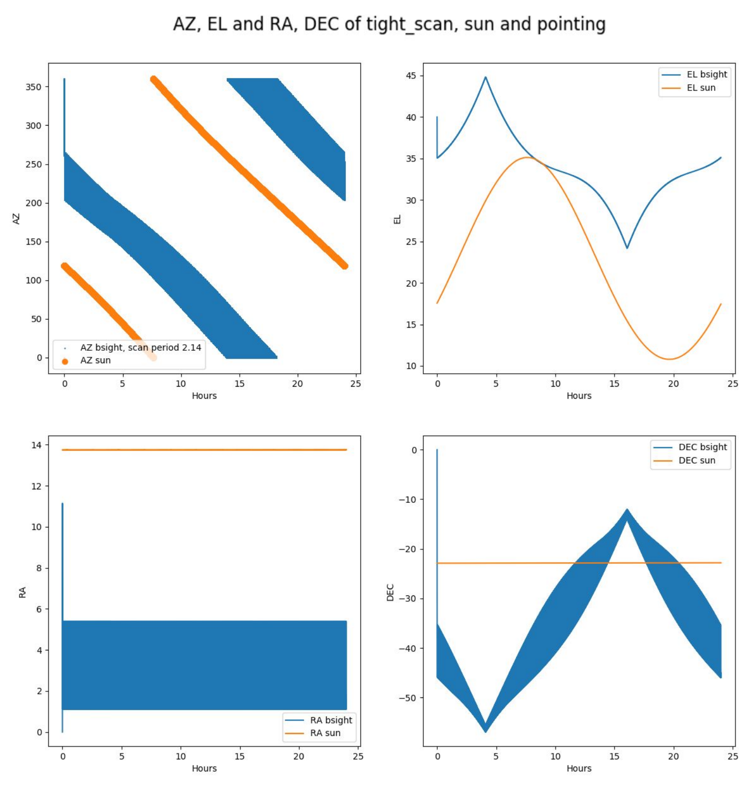
We control:

- Quad box
- Scan track pt.
- Half scans per EL step
- Scan velocity

We don't control:

- Date (sun)
- Min and max EL
- Balloon Latitude
- Galaxy





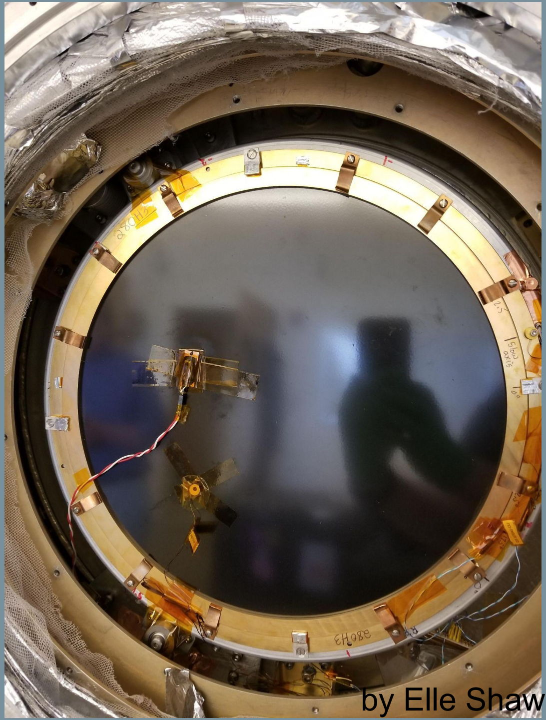
Second Flight Scan Strategy: Pointing in SPIDER-2

Three latitude pointings

- -78 degrees (McMurdo)
- -82 degrees
- -85 degrees

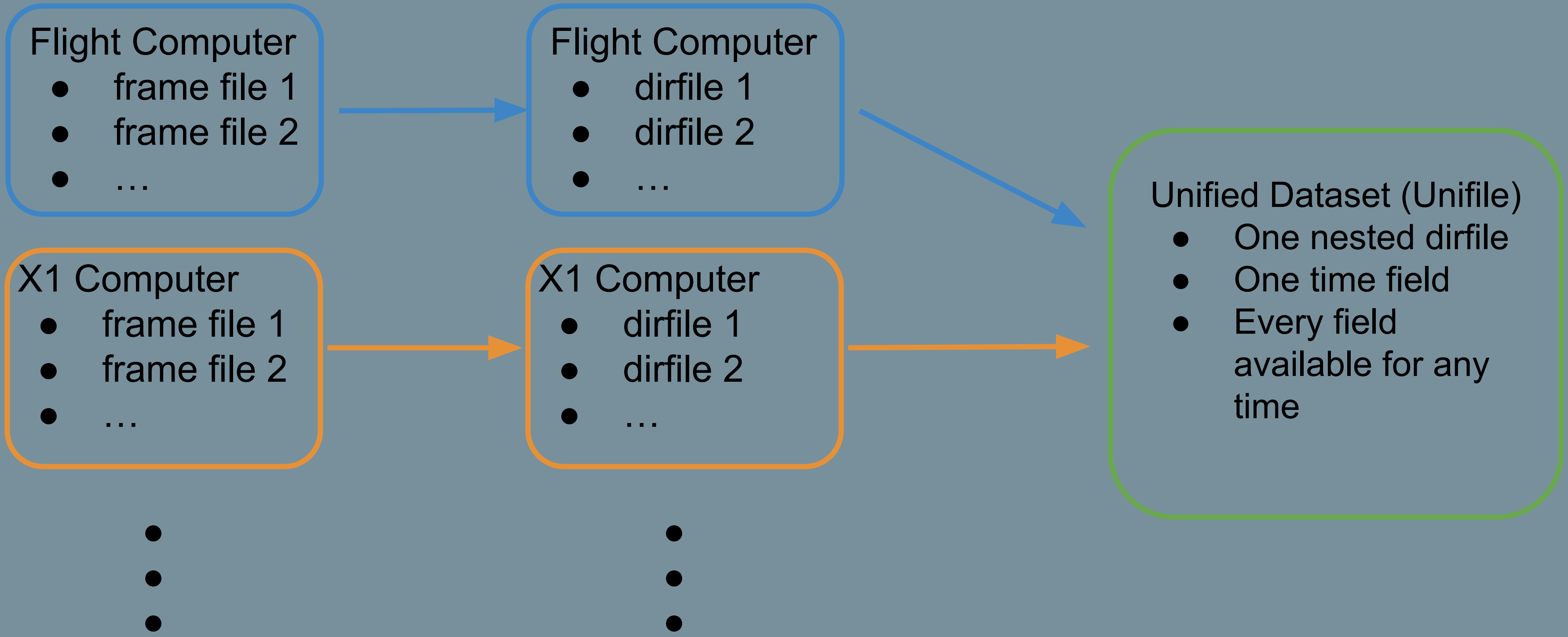
Schedule of Commands

- Half-wave plate rotation
  2x a day
- Fridge cycle
  1x a day
- Scanning

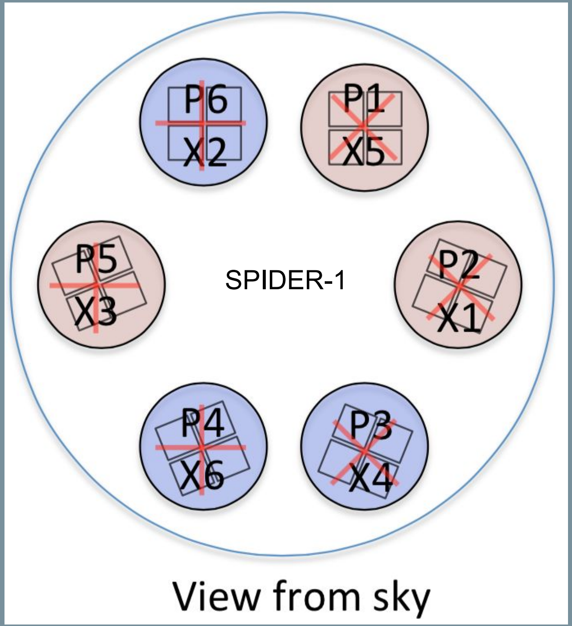


by Elle Shaw

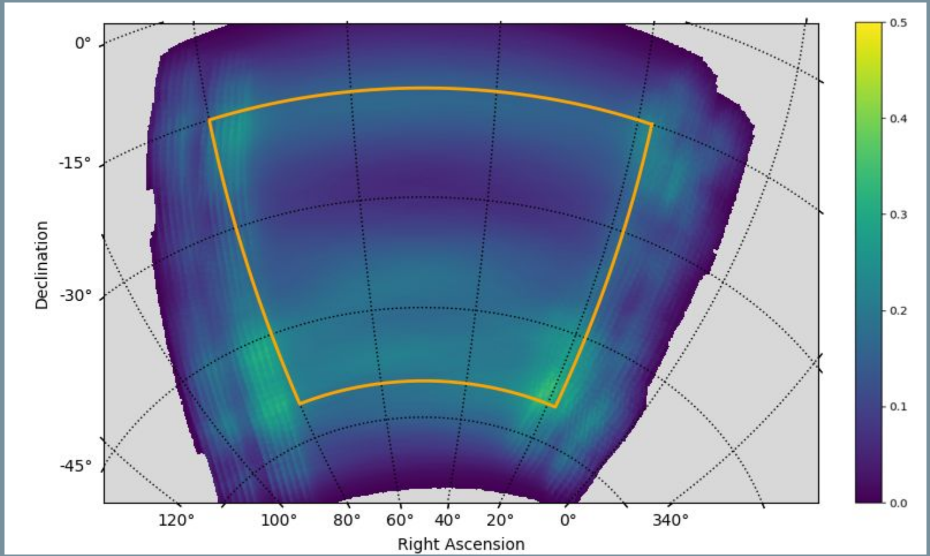
Second Flight Low-Level Analysis: Getting a Unified Dataset



Second Flight Scan Strategy: Integrating with Unimap



by John Ruhl



B-Mode Tabled Results

	$10^3\,\alpha_{95}$	$10^3\,\alpha_{150}$	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	$1.63^{+0.46}_{-0.31}$	$1.81^{+0.38}_{-0.31}$
SMICA				
FFP10	—	—	1.43 ± 0.04	
Auto-Cross	—	—	1.50 ± 0.04	

Table 5. Summary of r-likelihood values from various pipelines, with nominal upper limits in bold.

Pipeline	Description	r_{mle}	$r \leq 95\%$
XFaster	Nominal, Feldman–Cousins	-0.21	**0.11**
	Nominal, Bayesian	-0.21	**0.19**
	NSI-like:		
	(a) r from BB only	-0.19	–
	(b) Independent EE & BB noise	-0.19	–
	(a) + (b)	-0.15	–
NSI	Nominal, Feldman–Cousins	-0.09	0.23
	Nominal, Bayesian	-0.09	0.27
SMICA	Nominal, Bayesian	0.06	0.24
	Template-like:		
	Excl. *Planck* inputs $< 353\,\mathrm{GHz}$	-0.07	–

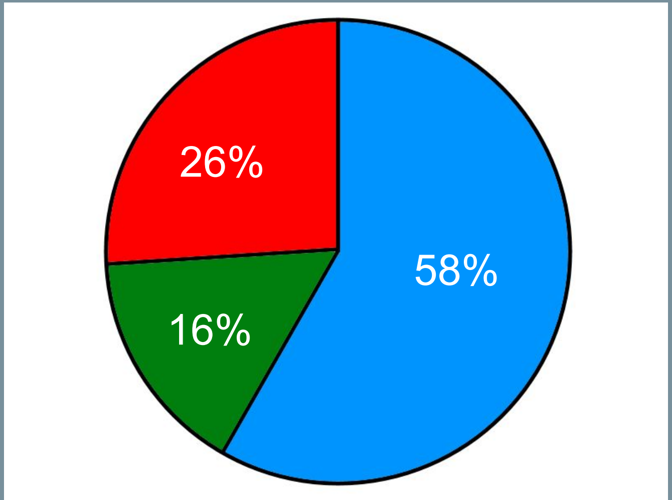
Band details: NET, Map Depth

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

Finding Sigma *r* Budget: Varying one Ensemble

Vary **SIGNAL**, Spider **Noise**, and **Template Noise** individually and calculate the contribution

$$x\% = \frac{\sigma_X^2}{\sigma_{Signal}^2 + \sigma_{Noise}^2 + \sigma_{T.Noise}^2}$$



Commander Map Info

Data Sources and Structure

For Commander 2015, we are provided two sets of data. A Low-res (nside=256) that contains maximum likelihood, mean, and rms for intensity, temperature, and beta. And, a Hi-res (nside=2048) that just has posterior maximum values for intensity and beta for different data splits (full, hm1, hh2, hr1, hr2, yr1, yr2). The high-resolution products are derived from the same algorithm as for the low-resolution analyses, but only including frequency channels including and above 143 GHz. The dust temperature for the high-resolution fit is fixed, and derived from the low-resolution fit converted to alm space.

For GNILC, everything is nside=2048 and we have amplitude, beta plus beta error, and temperature plus temperature error.

Analysis Pipeline	Nside	Ref. Frequency	Intensity Data	Intensity Units	Temperature Data	Temperature Units	Beta Data
Commander 2015 (Hi-res)	2048	545 GHz	I_ML (different splits)	uK_RJ	N/A	N/A	BETA_ML (different splits)
Commander 2015 (Low-res)	256	545 GHz	I_ML, I_MEAN, I_RMS	uK_RJ	TEMP_ML, TEMP_MEAN, TEMP_RMS	K	BETA_ML, BETA_MEAN, BETA_RMS
GNILC 2016	2048	353 GHz	AMP	MJy/sr	TEMP, TEMP_ERROR	K	BETA, BETA_ERROR

The dataset is in Galactic 'G' coordinates and have been rotated to Celestial 'C' (also known as eQuatorial 'Q') coordinates.

CAMB: Code for Anisotropies in the Microwave Background