The First Flight of SPIDER

Hunting B-Modes from the Edge of Space

Jeff Filippini

ILLINOIS

B-Mode From Space

18Dec2019

Outline

Instrument Overview

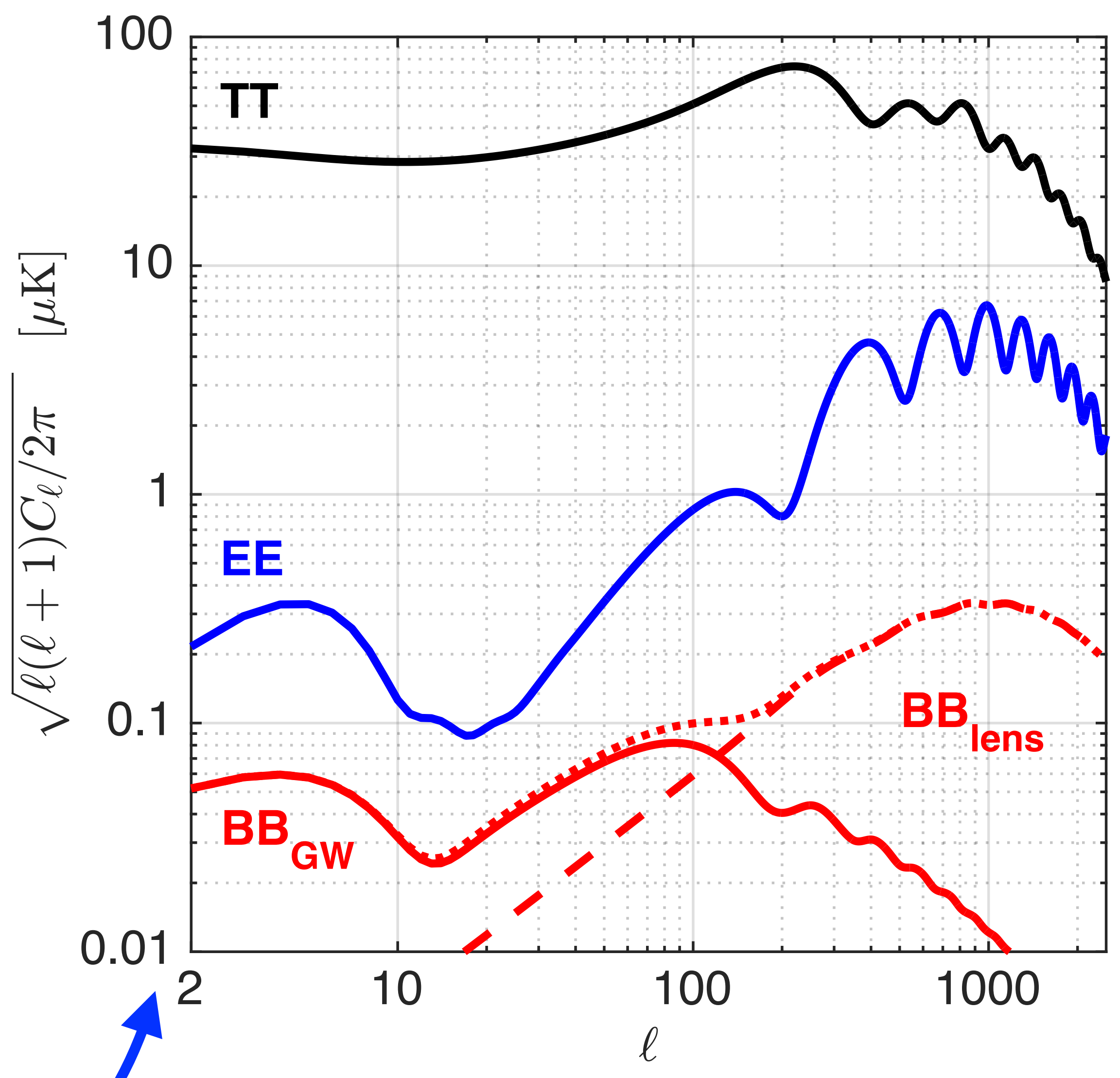
2015 In-Flight Performance
Data, Calibration, Systematics

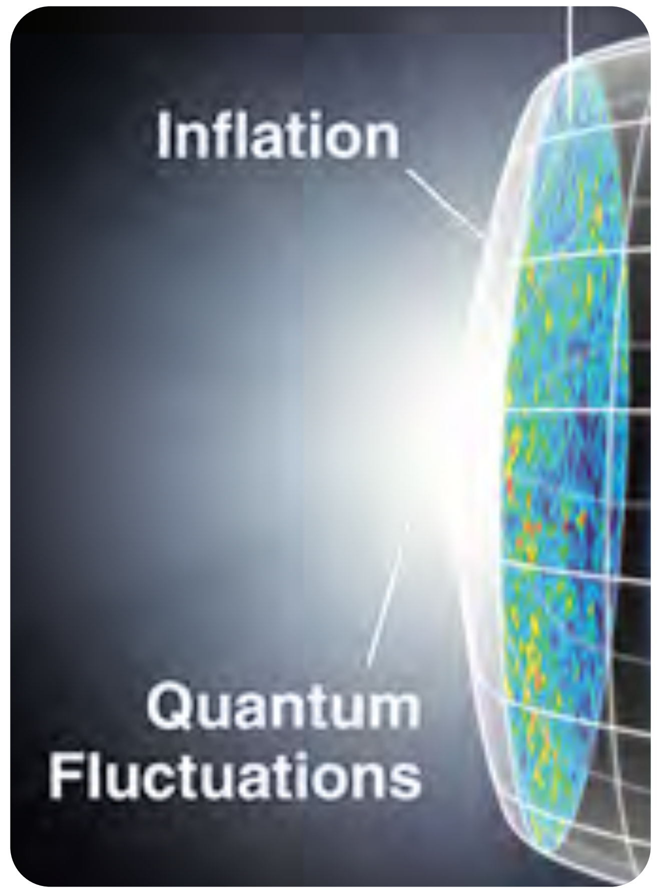
The View From Above
Sky maps and current status

Up Next: Spider-2

B-modes: Goals and Challenges

Primordial gravitational waves





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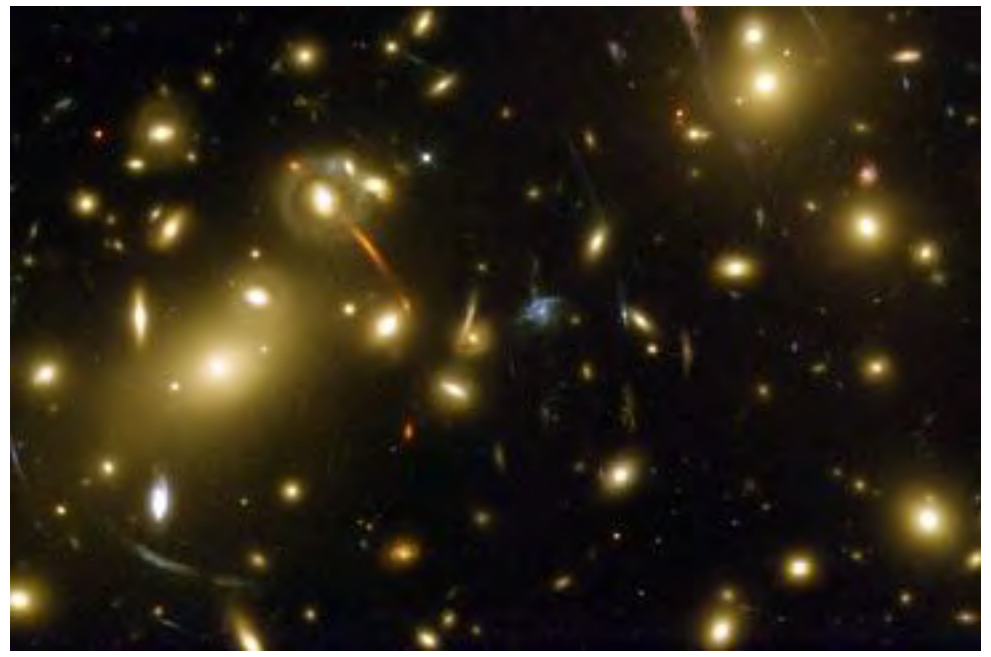
Tensor-to-Scalar Ratio

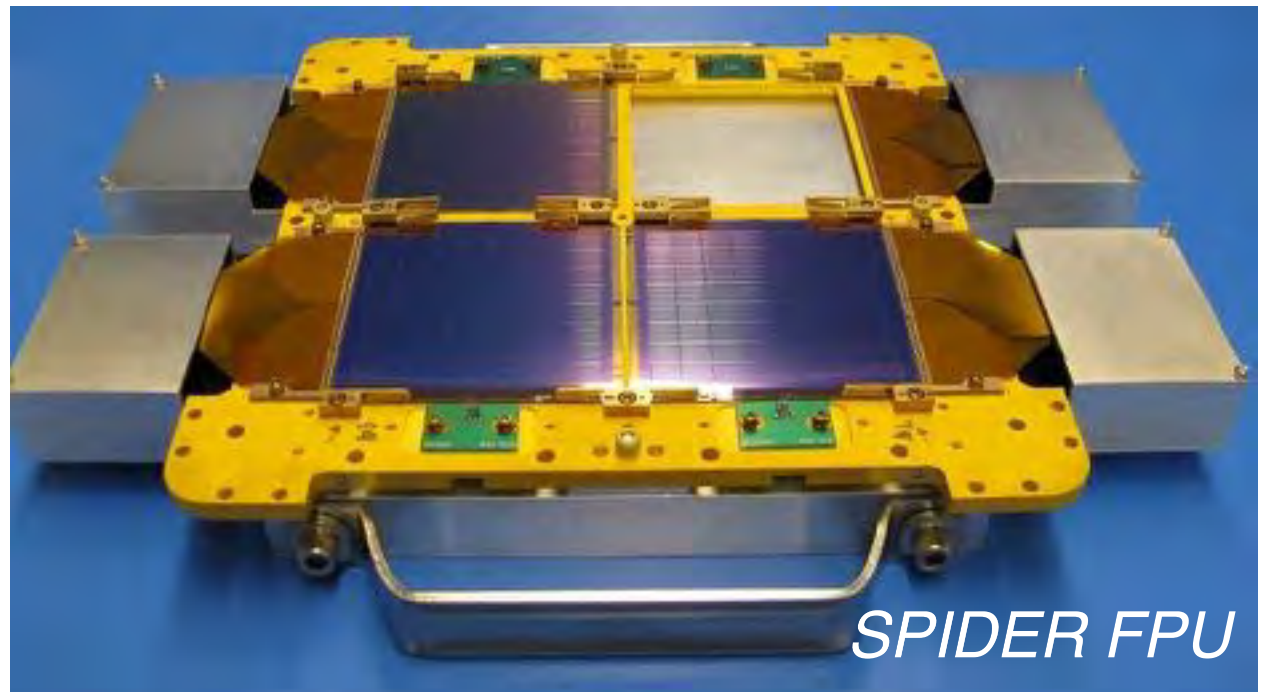
Density perturbations



PRECISION

Approach photon noise limit

Few photons, many detectors

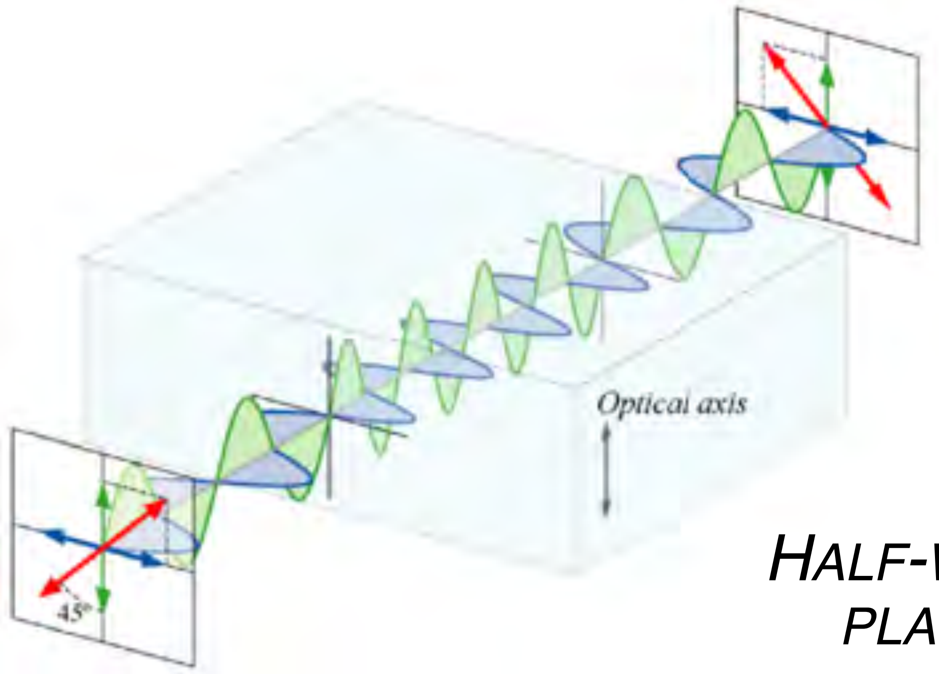


SPIDER FPU

ACCURACY

Rigid control of polarized systematics

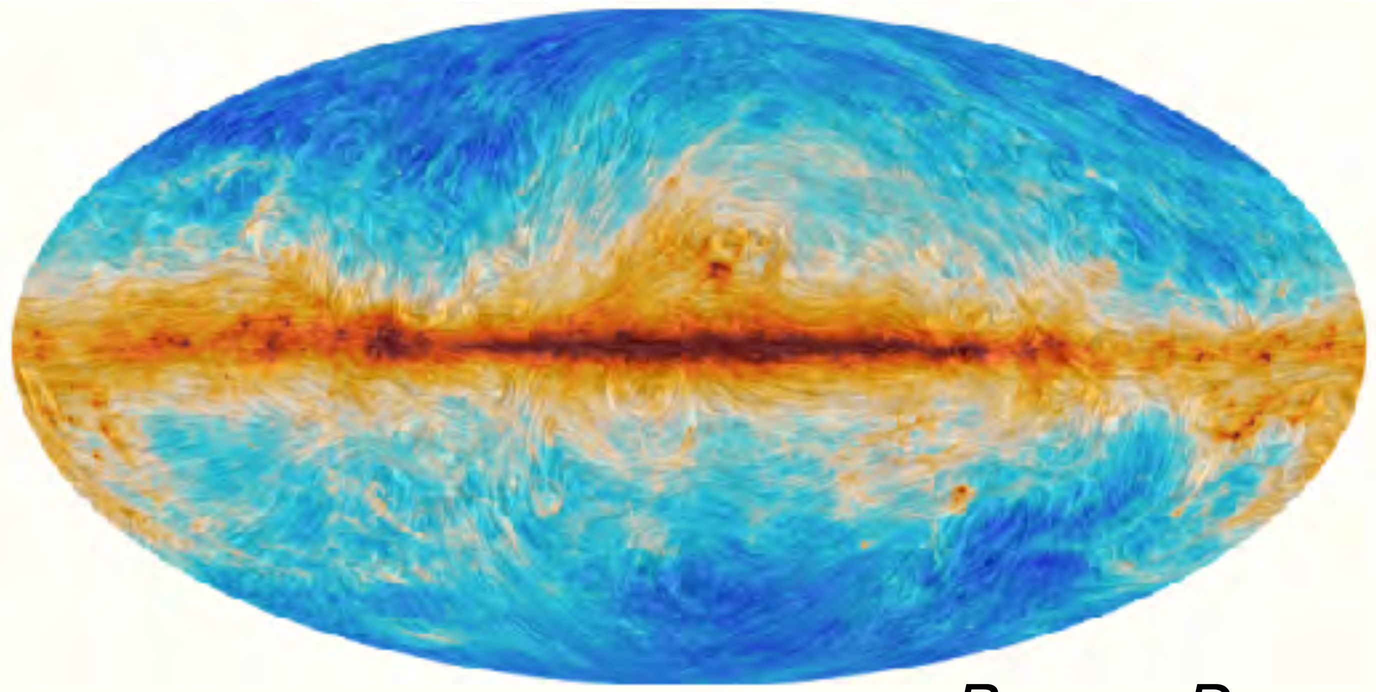
Instrument symmetry



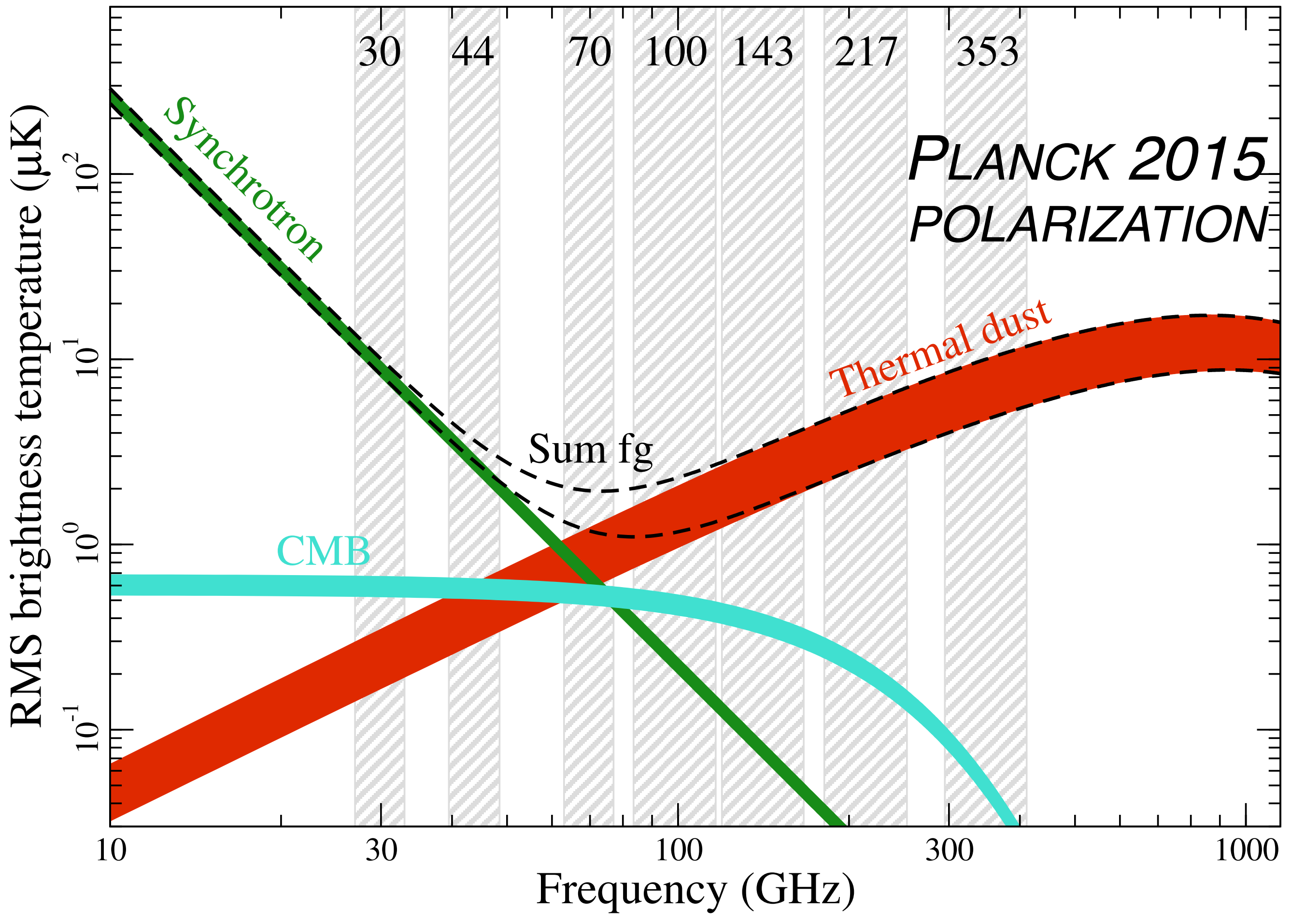
HALF-WAVE PLATE

CLARITY

Isolation of CMB from polarized foregrounds (dust, synchrotron…)



PLANCK DUST POLARIZATION



The SPIDER Program

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

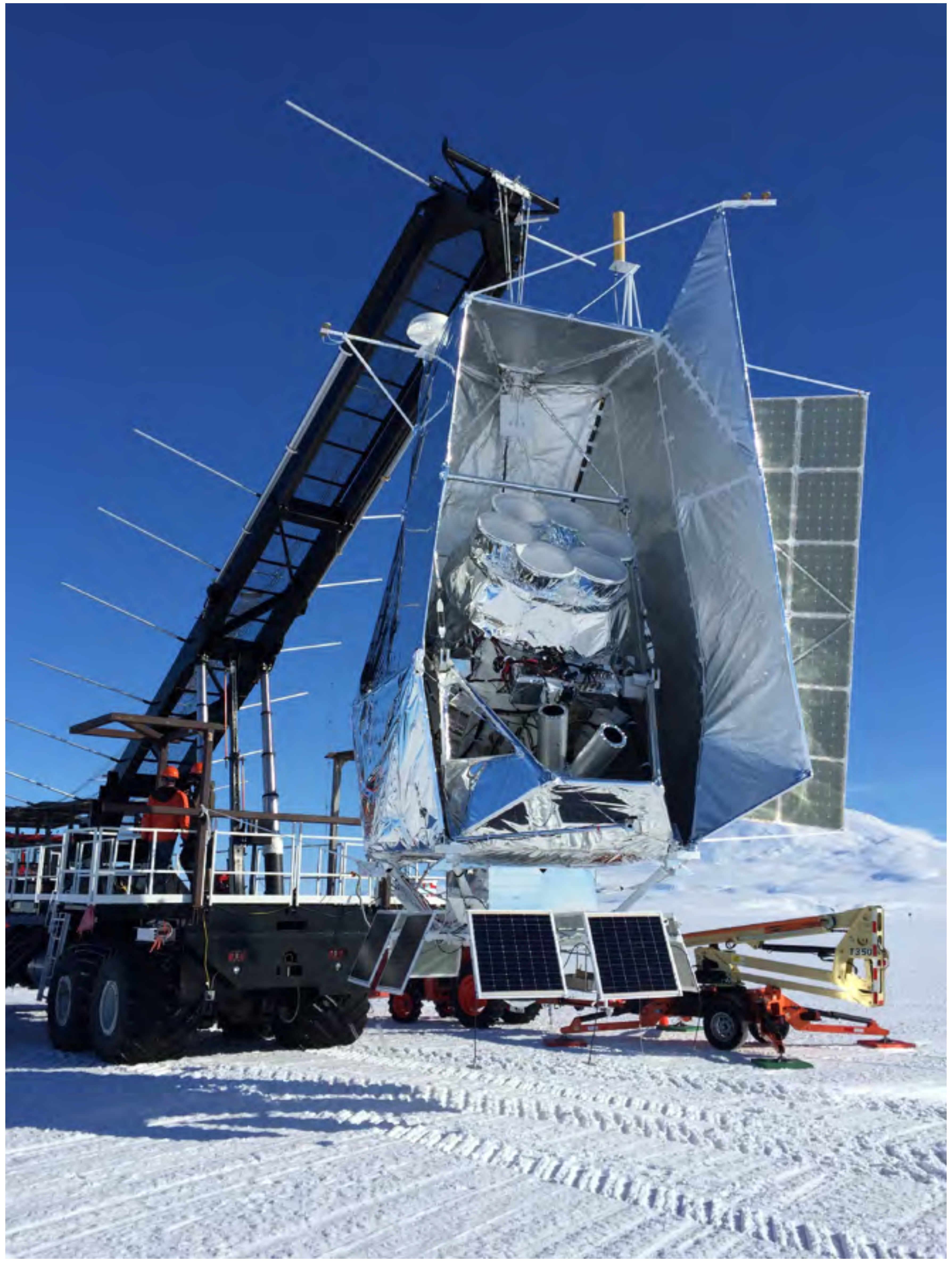
1. Verify **angular power spectrum**
   Observe many modes
   High fidelity from ~10 < l < 300

2. Verify statistical **isotropy**
   Large (~10%) sky coverage

3. Verify **frequency spectrum**
   Multiple colors, (esp. 200+ GHz)

Nagy+ ApJ 844, 151 (2017)
Rahlin+ Proc. SPIE (2014)
Fraisse+ JCAP 04 (2013) 047

O'Dea+ ApJ 738, 63 (2011)
Filippini+ Proc. SPIE (2010)
… and more …



Balloonatics

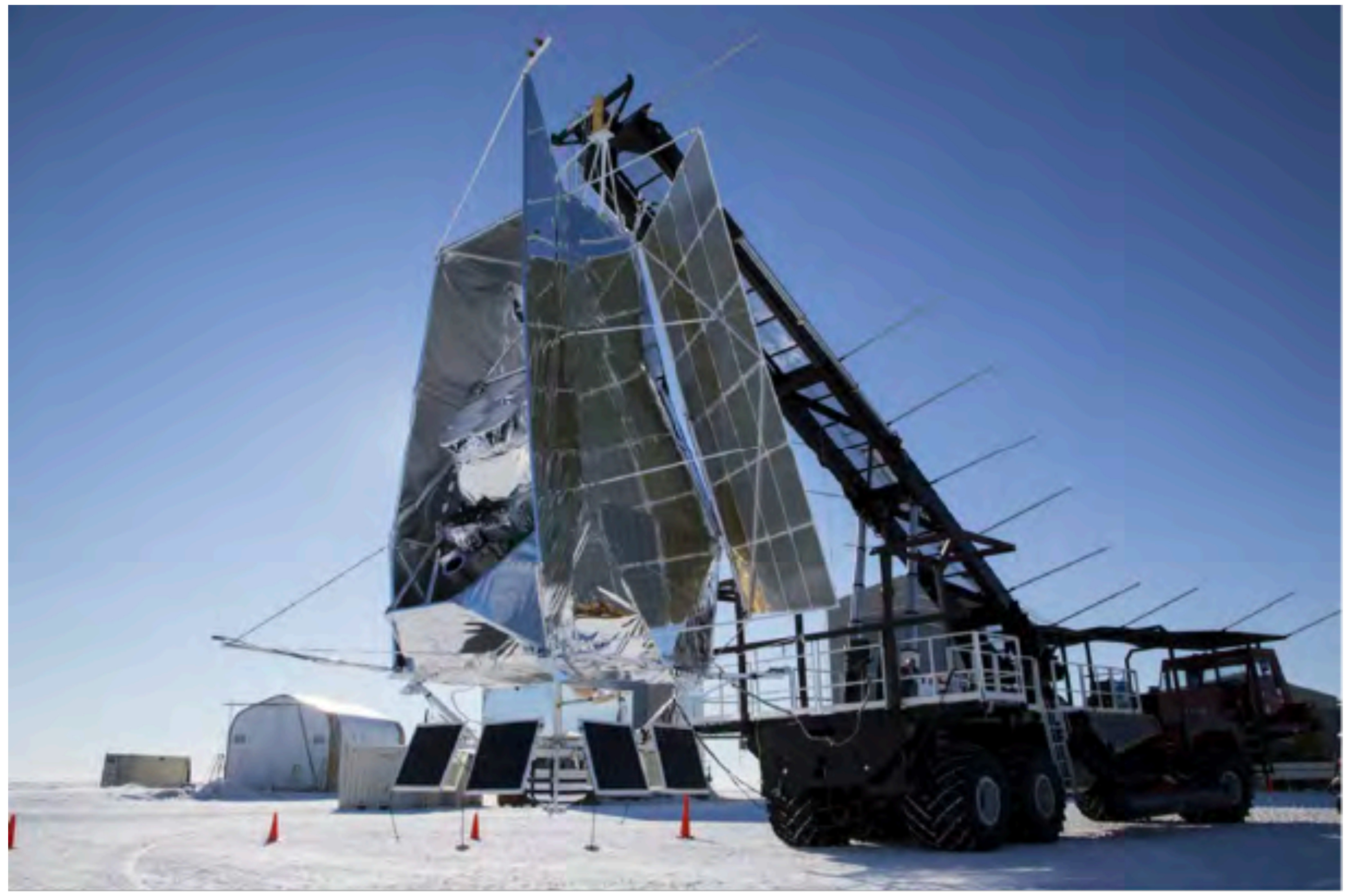
SPIDER
SEARCHING FOR THE ECHOES OF INFLATION

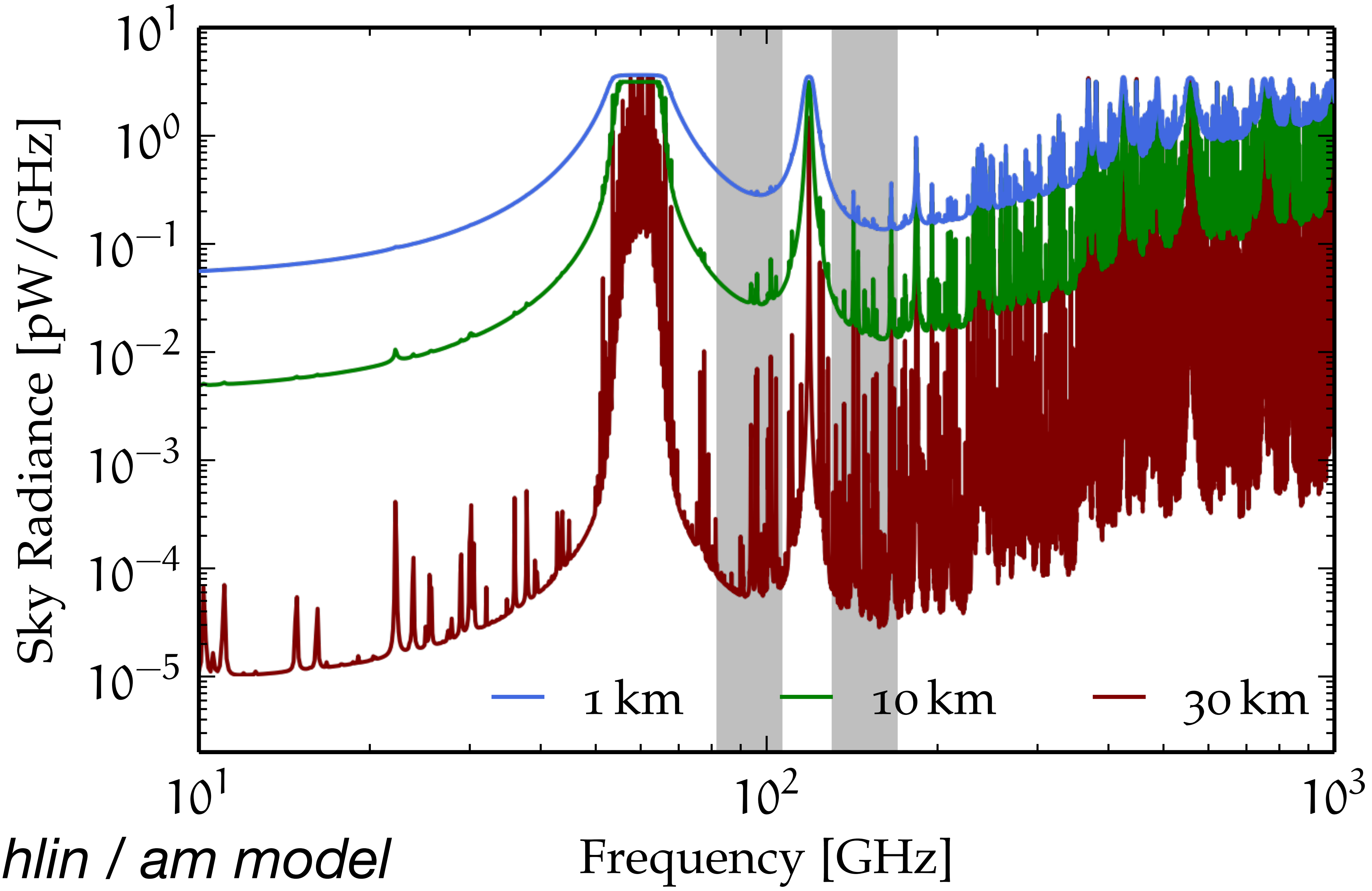
NASA
NSF
CSA ASC
C.S.B.F.
PALESTINE, TEXAS
JPL
NSERC CRSNG
the David & Lucile Packard FOUNDATION
UNIVERSITY OF TORONTO
CASE WESTERN RESERVE UNIVERSITY
CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD
UBC
NIST
PRINCETON UNIVERSITY
CITA ICAT
Imperial College London
UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI
ILLINOIS

Antarctic Ballooning

The Good

- **High sensitivity** to approach CMB photon noise limit
- Access to **higher frequencies** obscured from the ground
- Retain **larger angular scales** due to reduced atmospheric fluctuations (*less aggressive filtering*)
- **Technology pathfinder** for orbital missions





A.S. Rahlin / am model

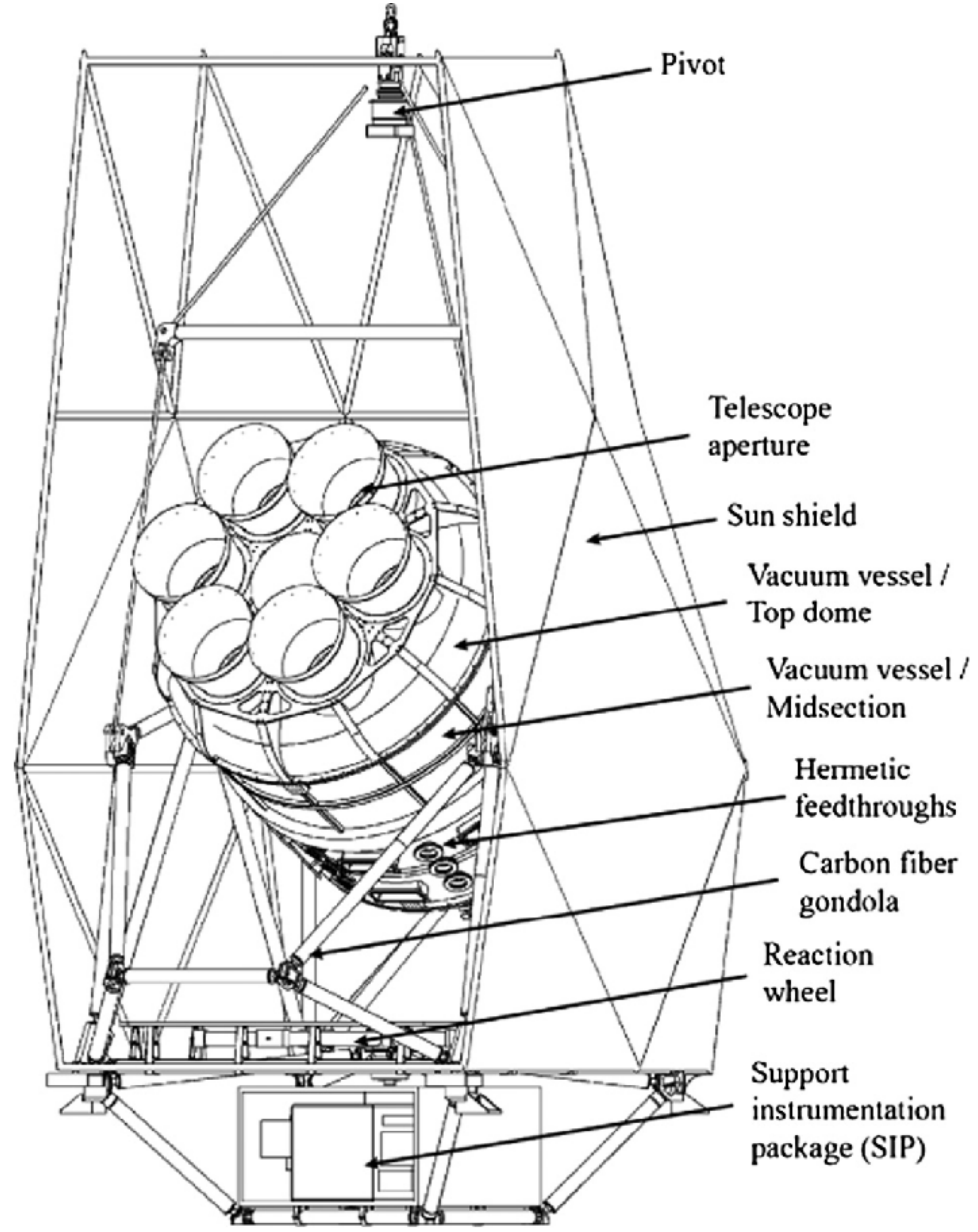
The Bad

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

Excellent proxy for space operations!

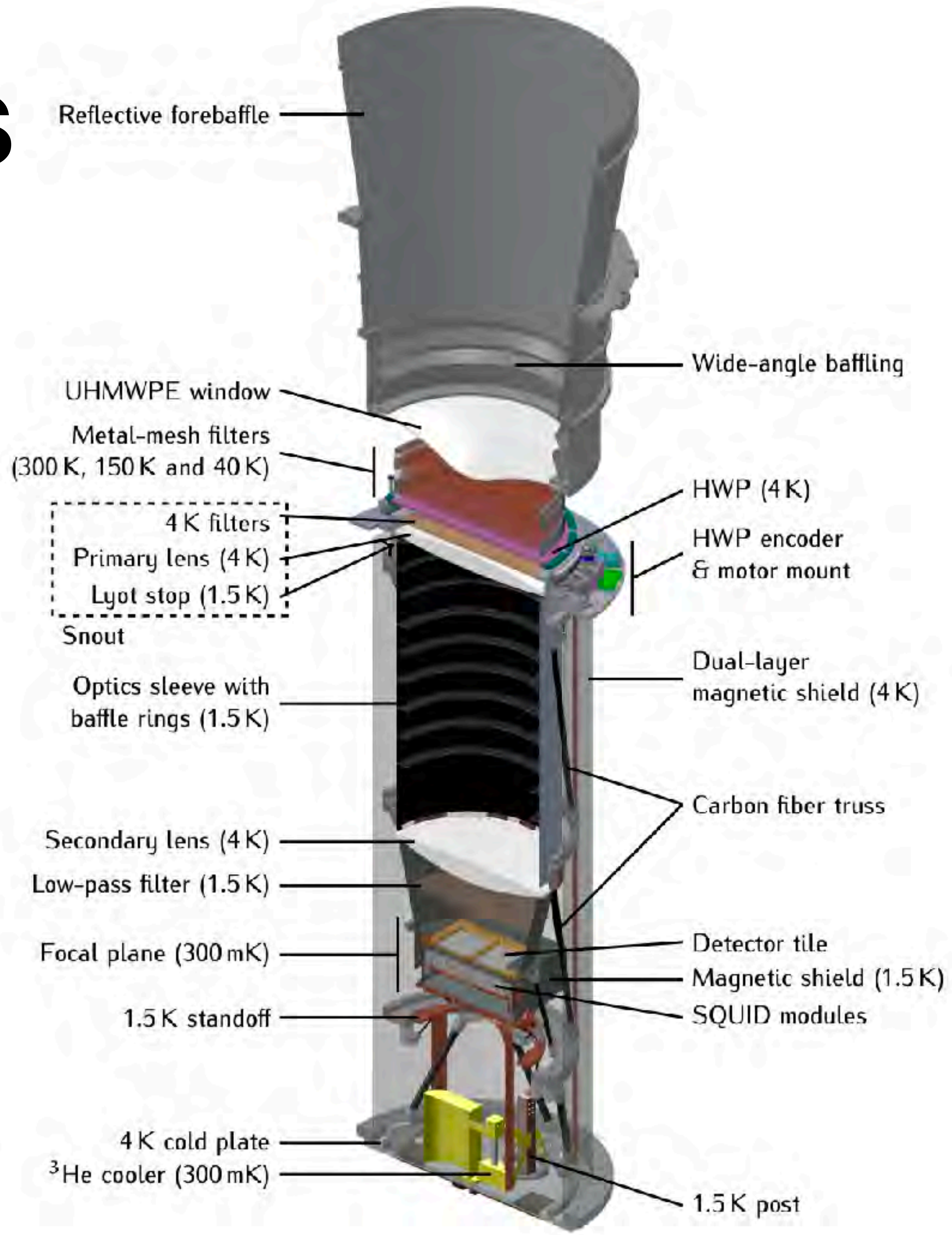
Payload Overview

- Large **shared LHe cryostat**
  - 1284L main tank (4K)
  - 16L vented, capillary-fed superfluid tank (1.6K)
- 6 **monochromatic refractors**
  - **SPIDER 2015**: 3x95 GHz, 3x150 GHz
- Lightweight **carbon fiber gondola**
  - Azimuthal scanning: reaction wheel
  - Stepped elevation: linear drives
- 24h solar power: 2200/1440W peak/avg
- Launch mass: ~6500 lbs (3000 kg)

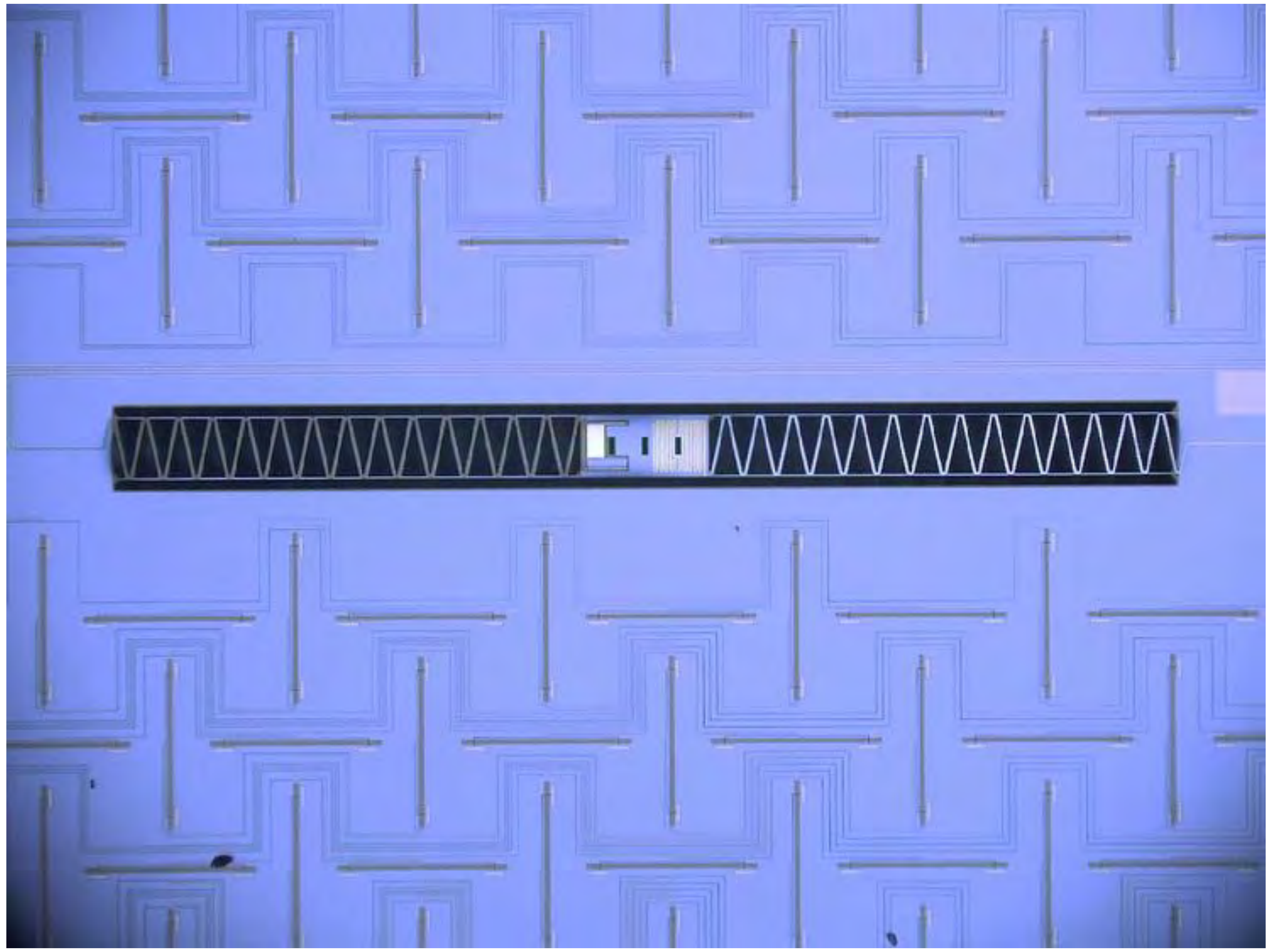


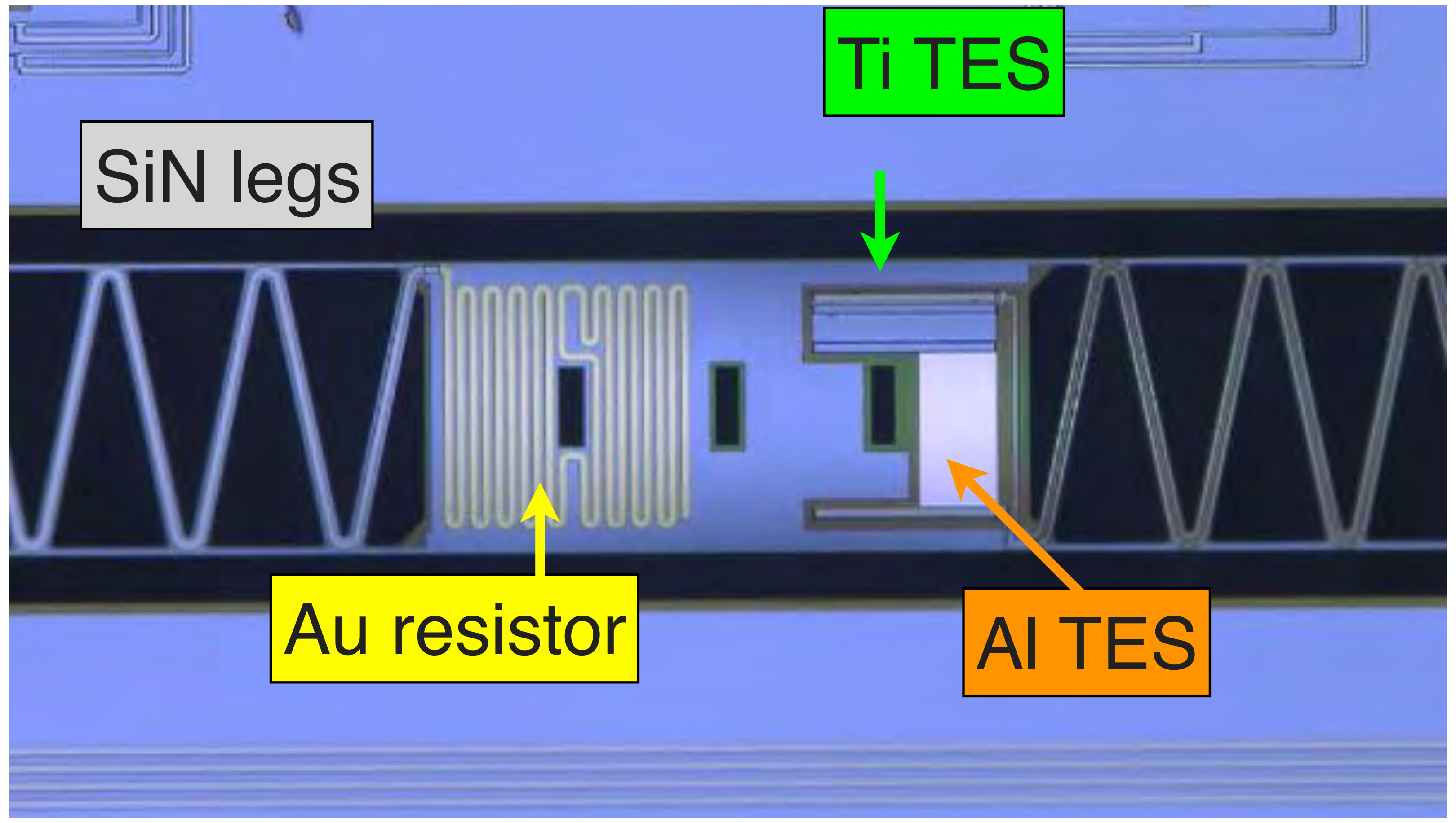
SPIDER Receivers

- Monochromatic 2-lens refractors
  Cold HDPE lenses, 264mm stop
- Emphasis on **low internal loading**
  - Predominantly reflective filter stack
    Metal-mesh + one 4K nylon
  - Inter-lens 1.6K absorptive baffling
  - Thin vacuum window (*3/32” UHMWPE*)
  - Reflective wide-angle fore baffle
- Polarization modulation with **stepped cryogenic HWP** *(AR-coated sapphire)*
- Dedicated **^{3}He sorption** coolers (0.3K)



Bolometer Arrays



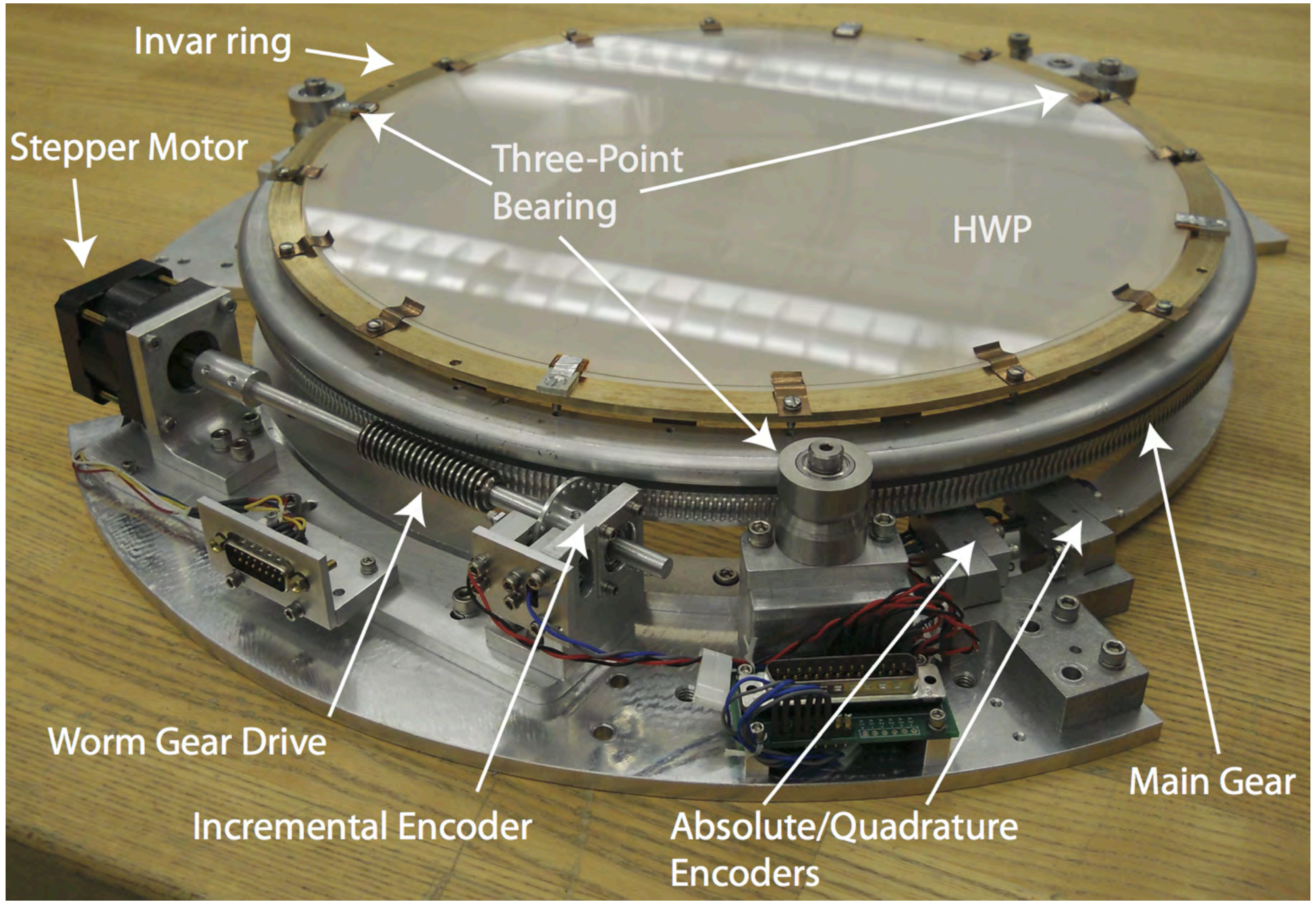


- **JPL antenna-coupled TES arrays**
  Also used in BICEP2 / 3 / Keck Array
  SPIDER-2: NIST platelet horn arrays
- Planar antenna synthesized via microstrip network
- Lumped element band-defining filter
- Meandered isolation legs (G~12-20 pW/K)
- Dual TES: science (Ti, 0.5K) and lab (Al, 1.3K)
- Time-division SQUID multiplexer
  NIST cold electronics, warm UBC MCE

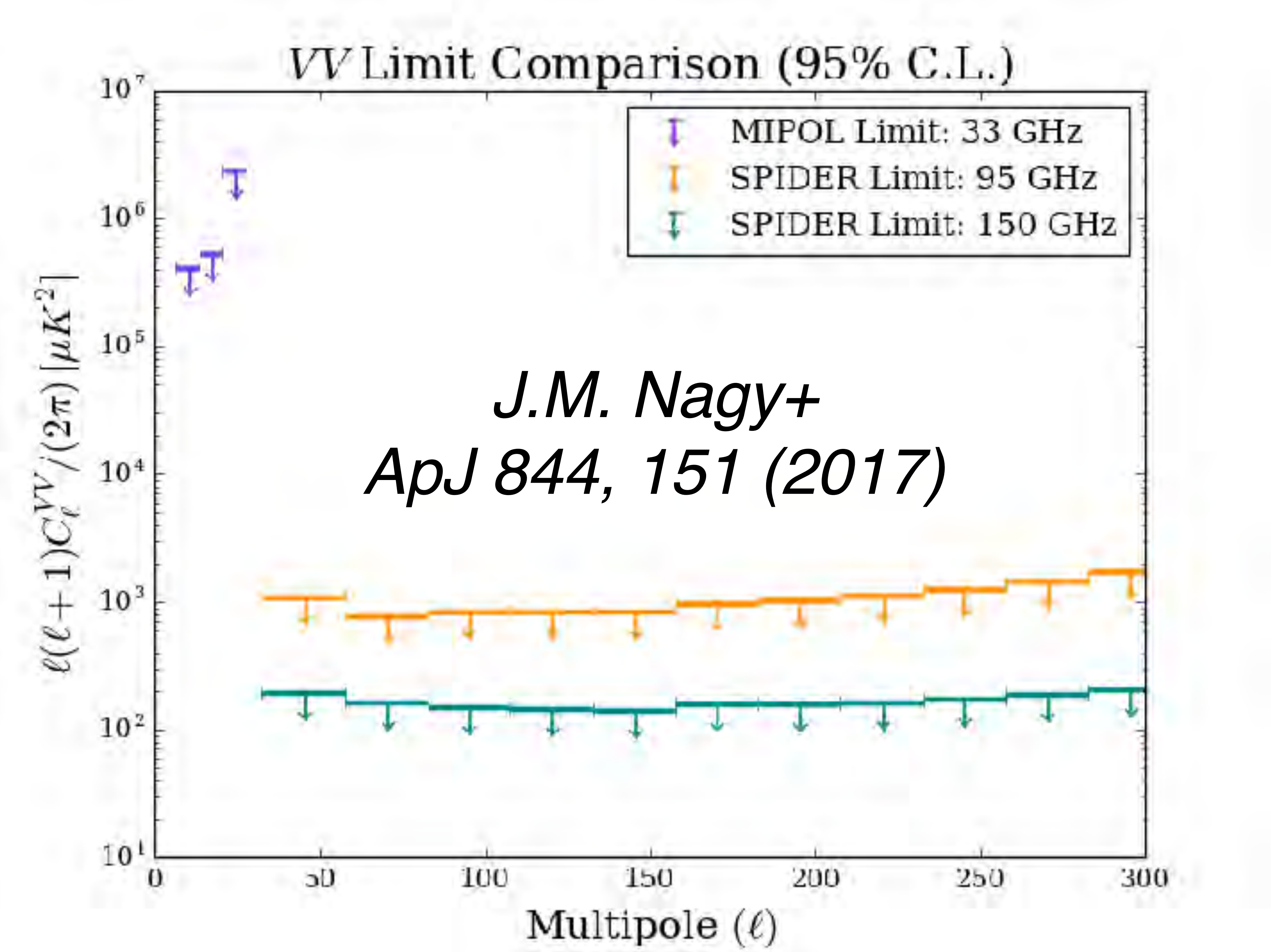
Band center	Optical eff.	N_{TES}
94 GHz	30-45%	864
150 GHz	30-45%	1536

2400 TESs

Half-Wave Plate

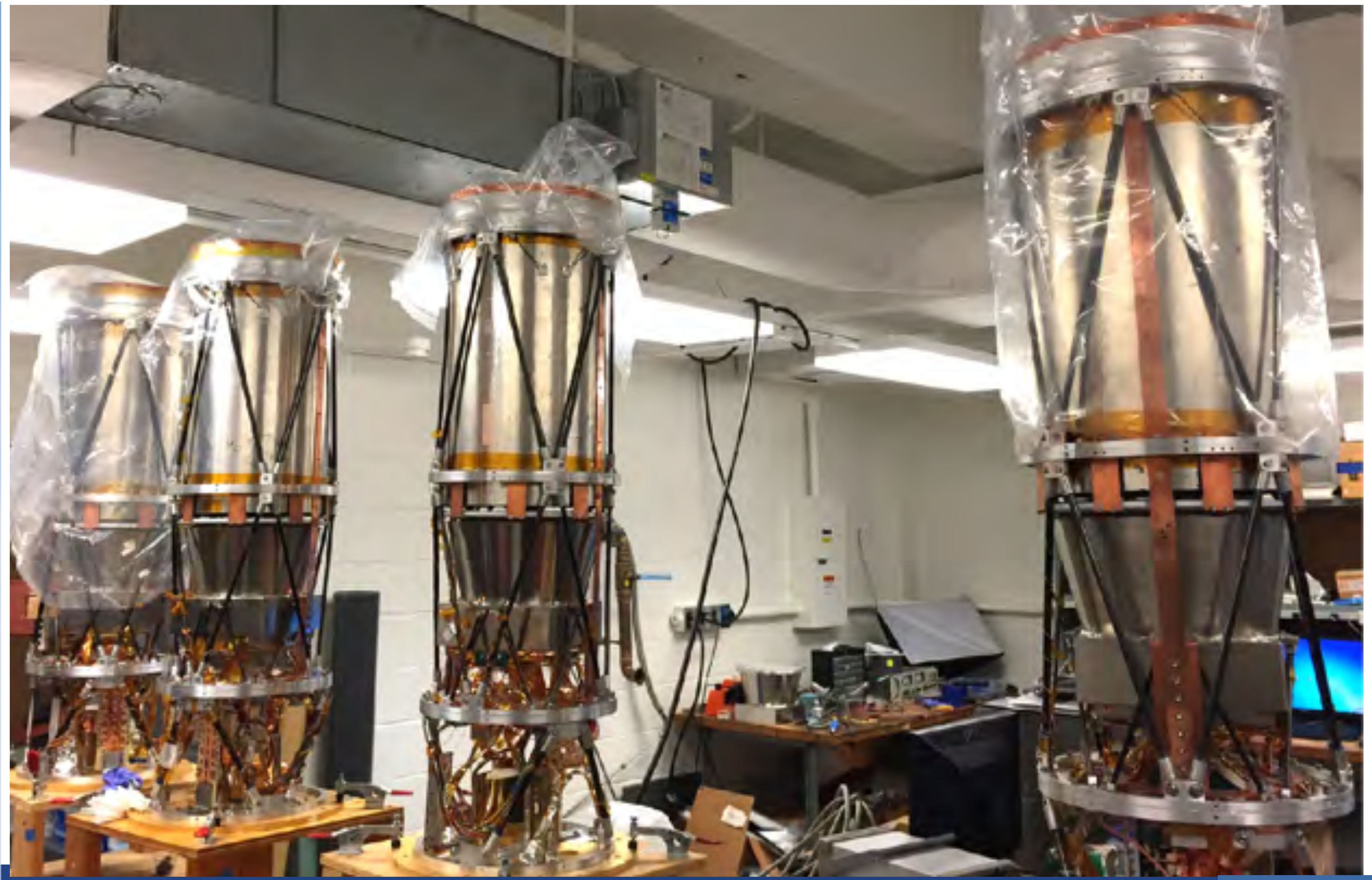


- Birefringent single-crystal sapphire, anti-reflection coated at 4K in each receiver
- **Stepped** by 22.5° twice daily
  Full Q/U coverage every 2 days
- Inevitable non-idealities yield sensitivity to **circular** (V) polarization

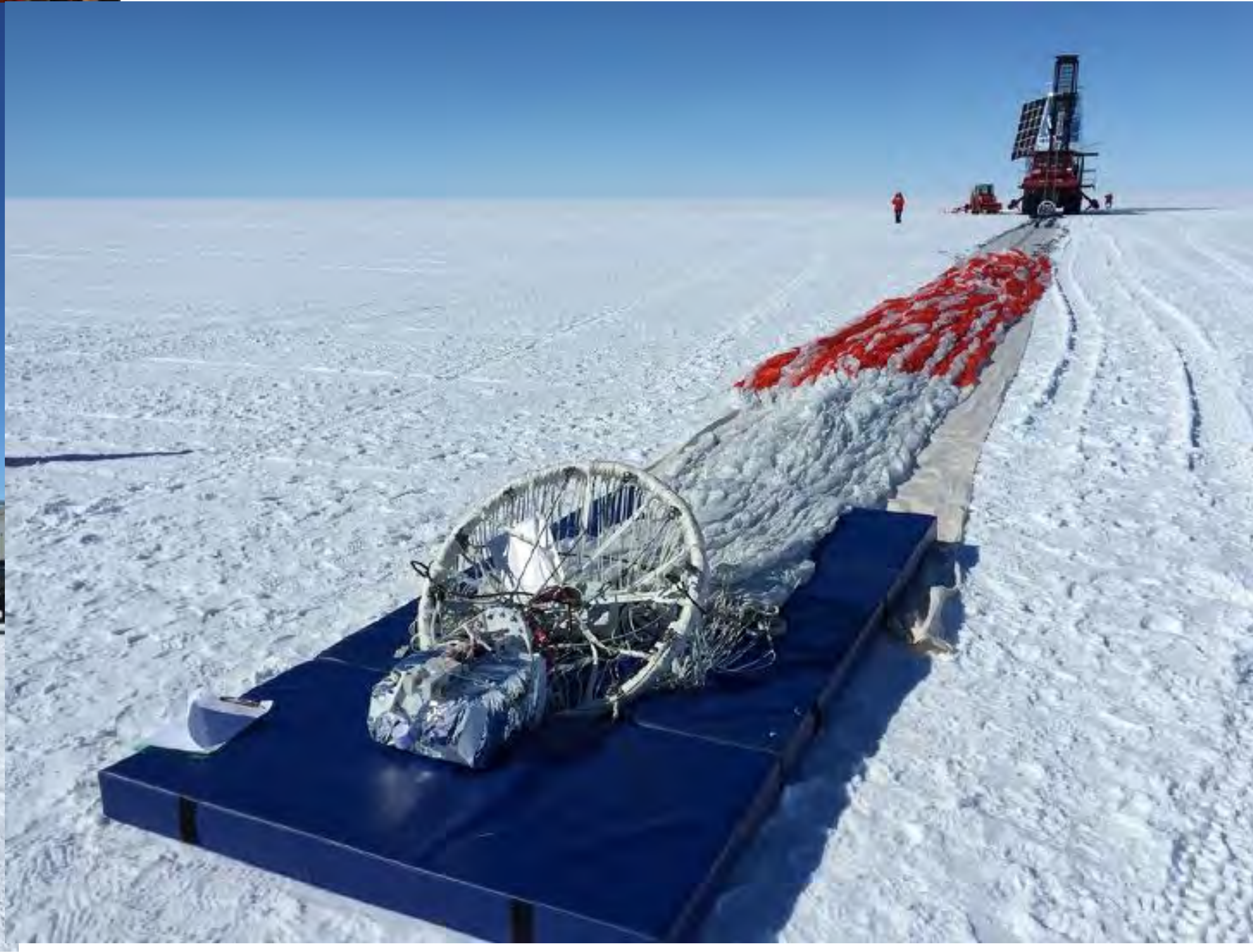


J.M. Nagy+
ApJ 844, 151 (2017)

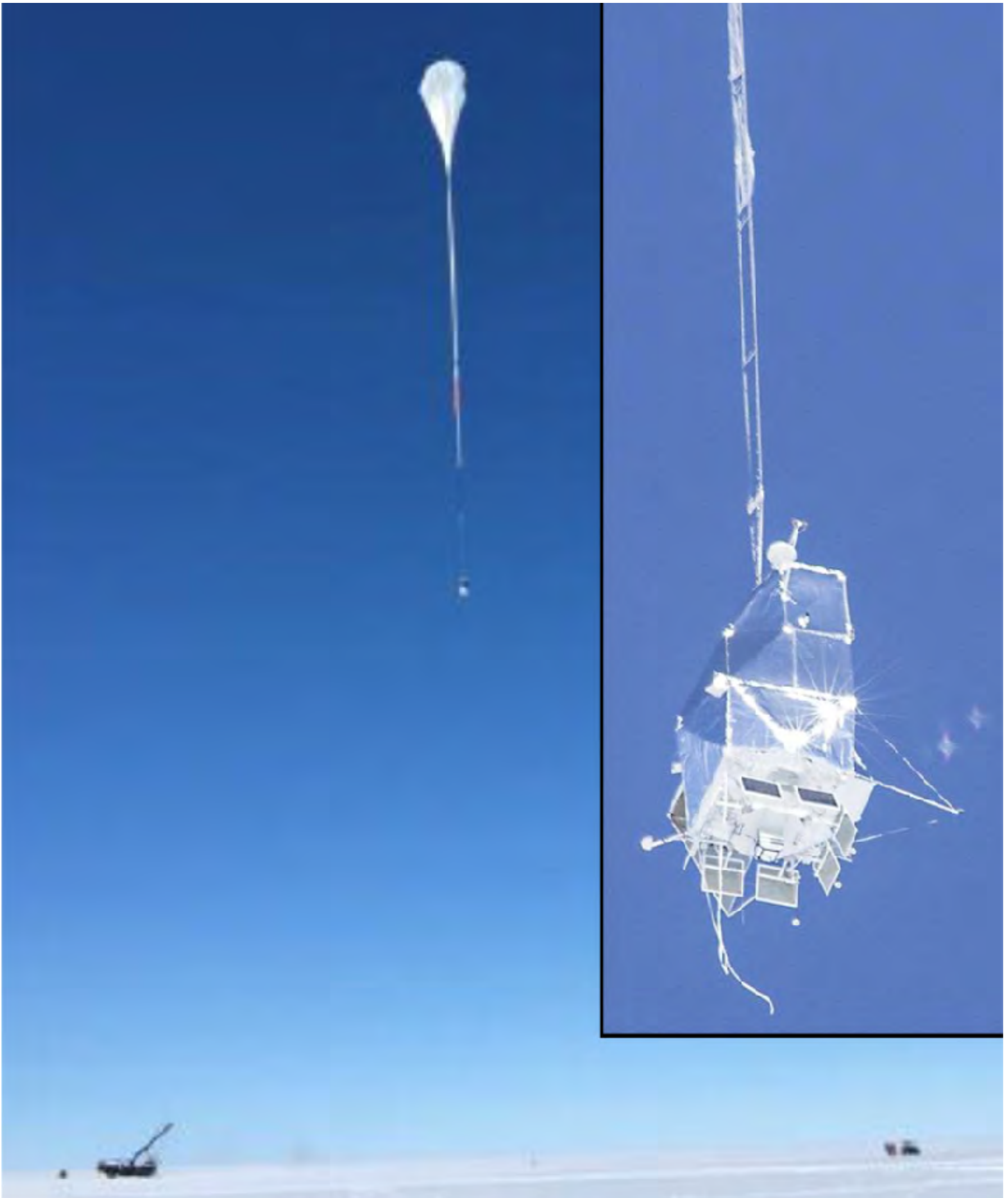
Antarctica 2014-15

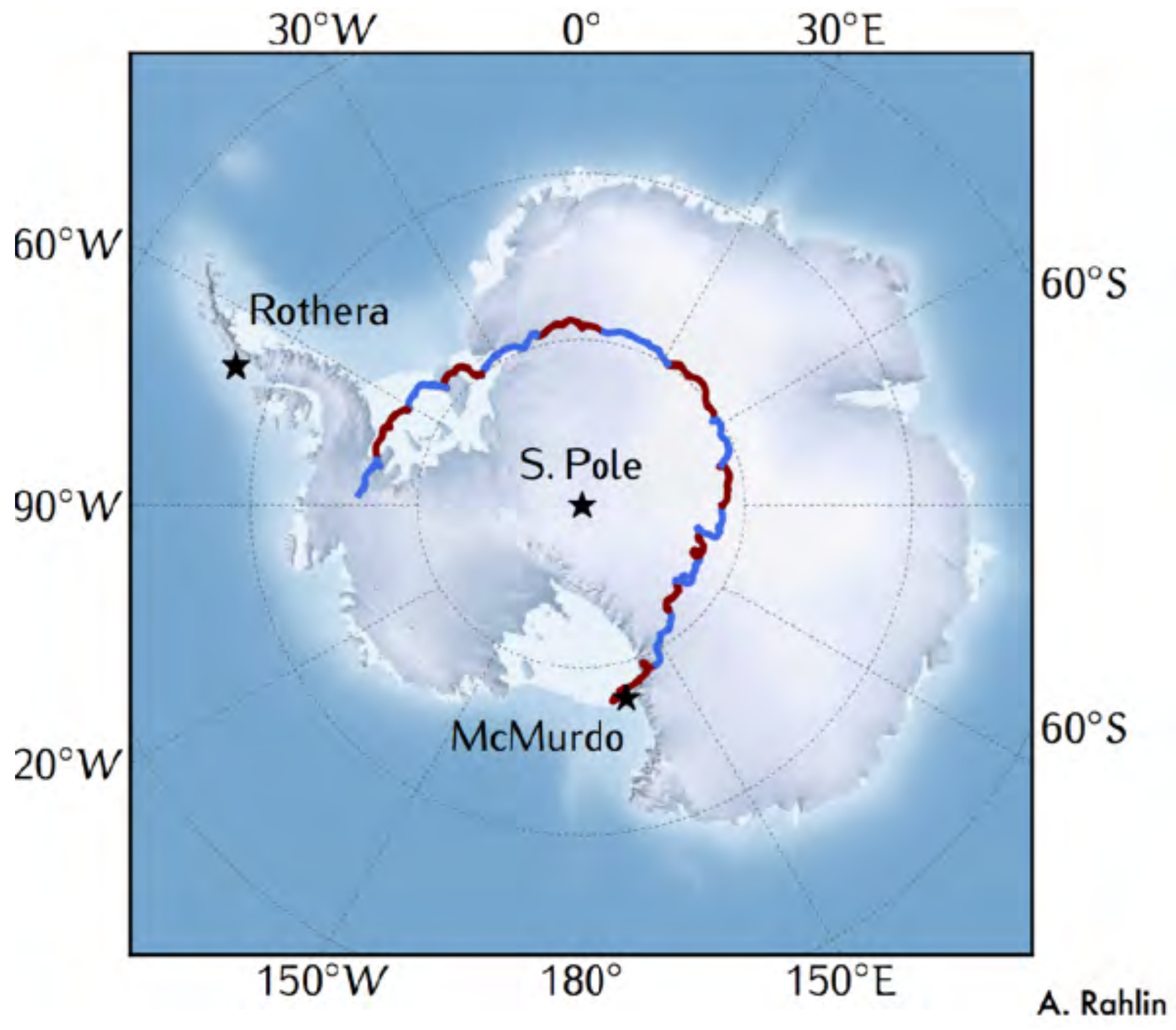


S. Benton



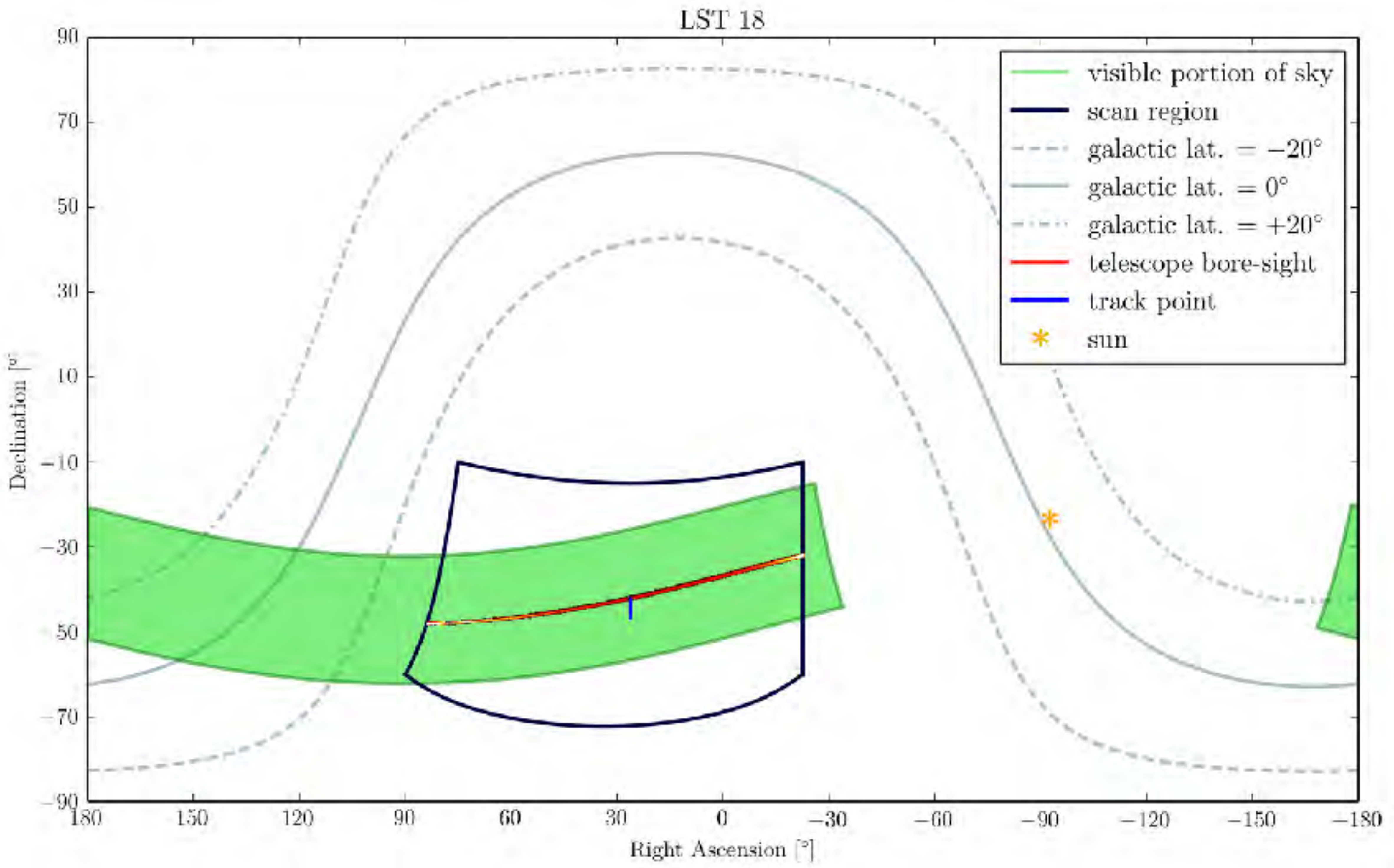
SPIDER Aloft





- **January 1-18, 2015**
- ~36 km altitude
- All systems functional (except dGPS, no science impact)
- All HWPs turned reliably
- Full hardware and data recovery with help of British Antarctic Survey personnel

Scanning the Sky



- **Sky coverage**: ~12% (geometric), 6.3% hit-weighted
- Full map each sidereal day
- Complete Q/U map for each bolometer every **2 days**

- Back-and-forth **sinusoidal** azimuth scan (max **~3.6 dps**) stepped in elevation
- Scan tracks map center, width limited by sun/galaxy, elevation by balloon/earth
- HWPs stepped by 22.5° every 0.5 sidereal day (timed to minimum sky rotation)

Pointing reconstruction

In-flight (**~1' accuracy**)
- Magnetometer
- Pinhole sun sensors

Post-flight (**~6" accuracy**)
- 3-axis gyroscopes
- Orthogonal star cameras on deck
- Fixed boresight star camera


+90°
+60°
+30°
0°
−30°
−60°
+20°
0°
SPIDER
QUIET
POLARBEAR
BICEP2
Equatorial
−20°
−40°
−60°
−80°
−80°
−60°
−40°
−20°
150 GHz Dust Model, $\sqrt{Q^2 + U^2}$ [μK_{CMB}]
0
1
2
3
4
5
6
7
8

Autonomous Detector Operations

SQUID tuning

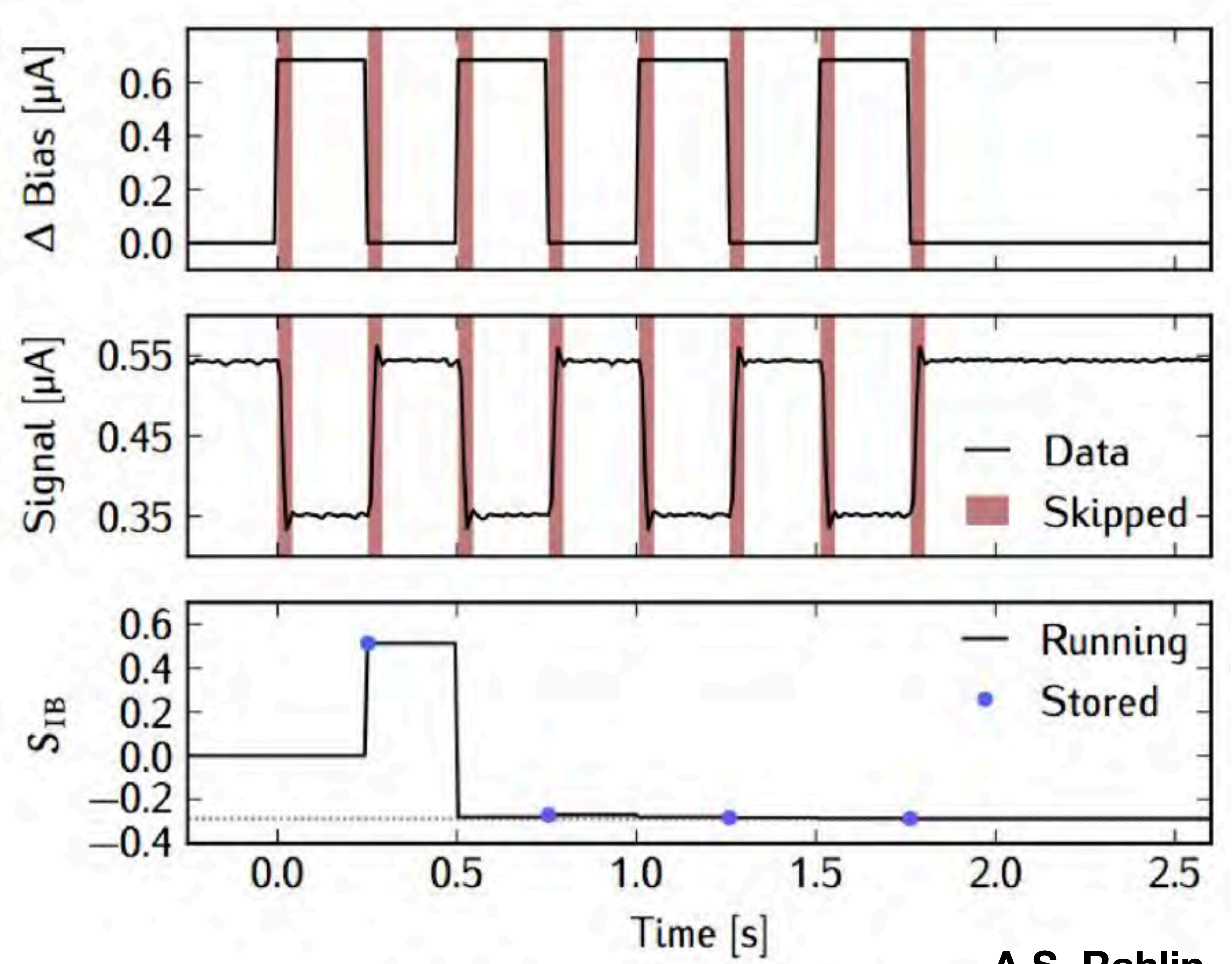
- Retuned (~5 min) after every fridge cycle
- Compares to pre-flight examples, adjusts parameters as needed

Detector responsivity

- Electrical bias step response used as proxy for optical gain variation
- 2s bias step every few turnarounds gives ~0.1% uncertainty
- Monitor loop adjusts TES biases occasionally if needed

Fully automated

- Downlinks minimal statistics to verify functionality

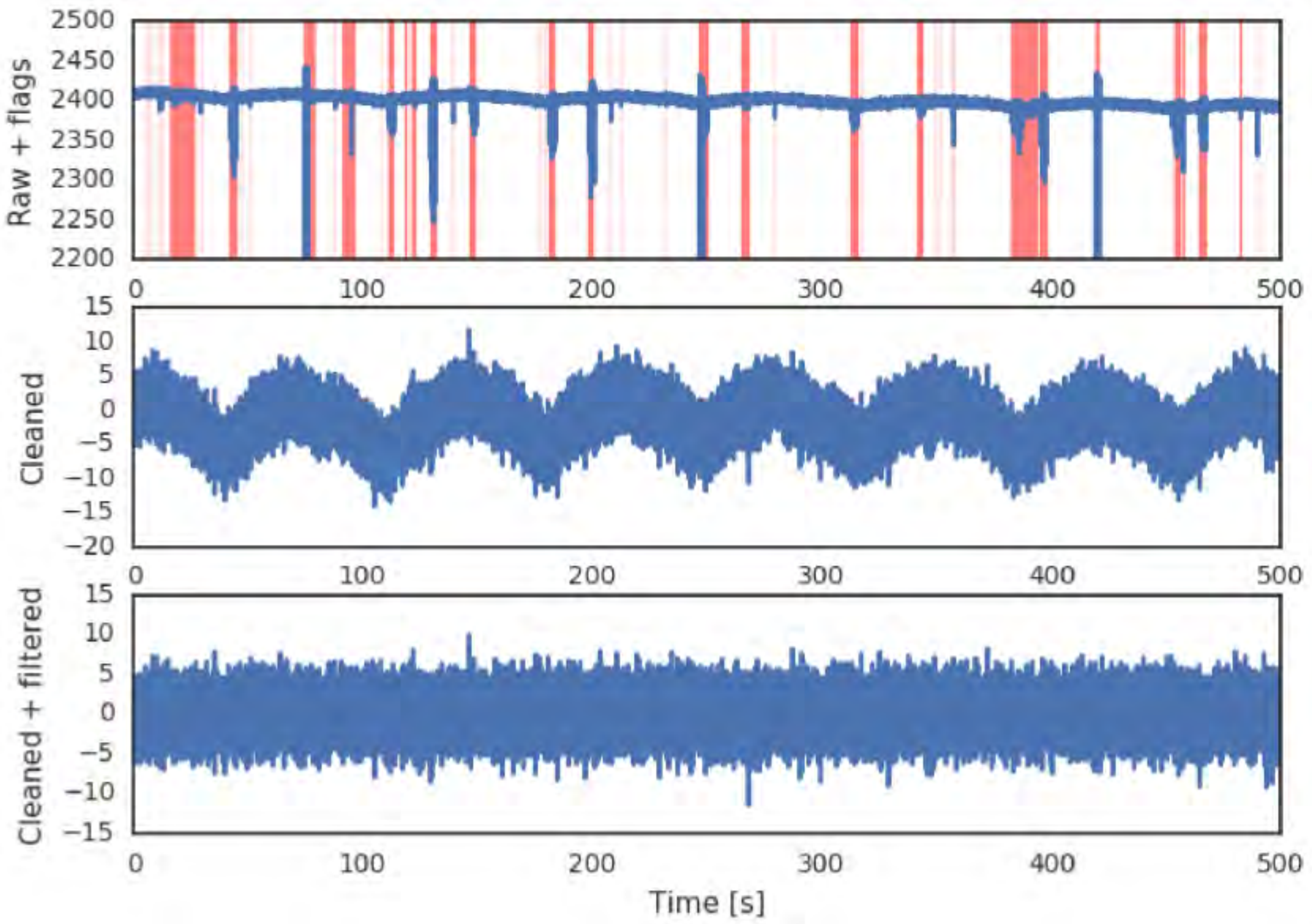


A.S. Rahlin

Detector Performance

- 1.56 TB data set
- Very low **internal loading**!
- Substantial flagging due to **RFI**
  - Transmitter handshake every ~1 minute
  - ~10% data loss in good channels
- Negligible flagging due to **cosmic rays**

See poster for more on cosmic rays in SPIDER!



Band center	Absorbed power	Optical eff.	N_{TES}	N_{TES} (w/cuts)	NET
94 GHz	≲0.25 pW	30-45%	864	675	~7.1 μK-√s
150 GHz	≲0.35 pW	30-50%	1536	1184	~5.3 μK-√s

Gain Stability Revisited

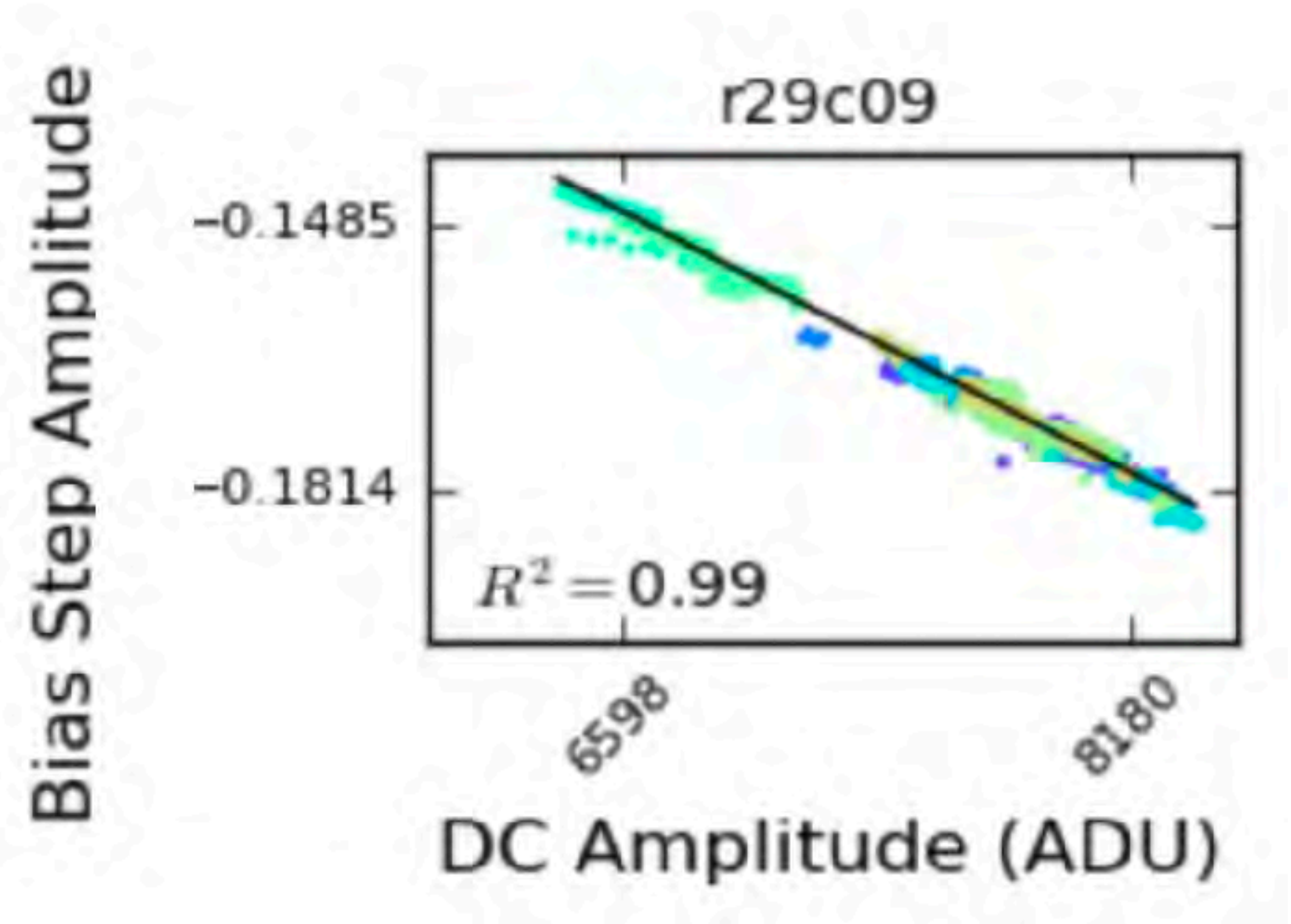
Problem: bias steps stopped on some receivers about halfway through flight!

TES bias adjustments not performed

Bias step results were not downlinked during flight, so we didn't notice

Careful use of DC signal level as an alternate proxy for TES bias state

Conclusion: No evidence that we needed to re-bias so often after all!



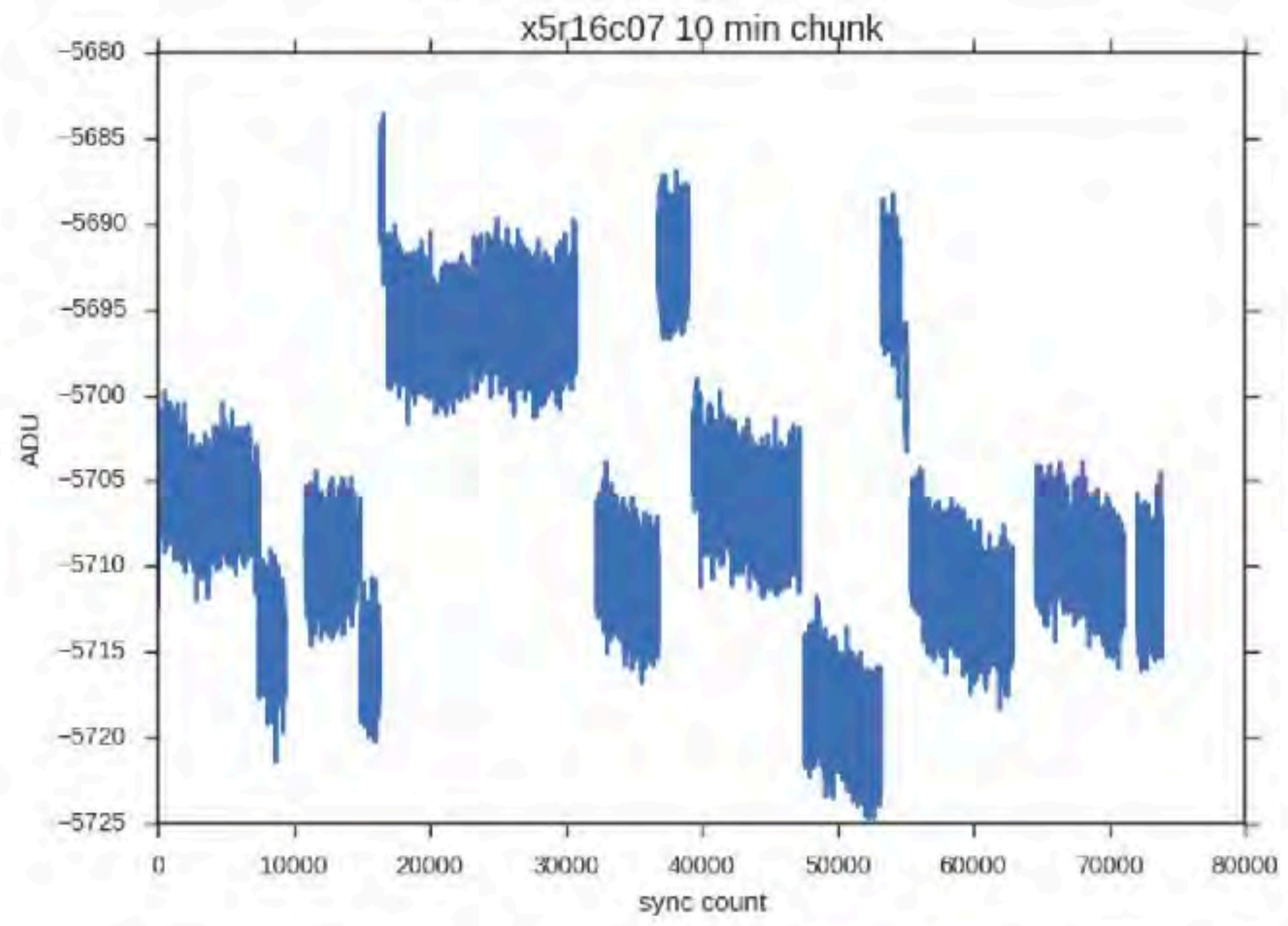
Anne Gambrel

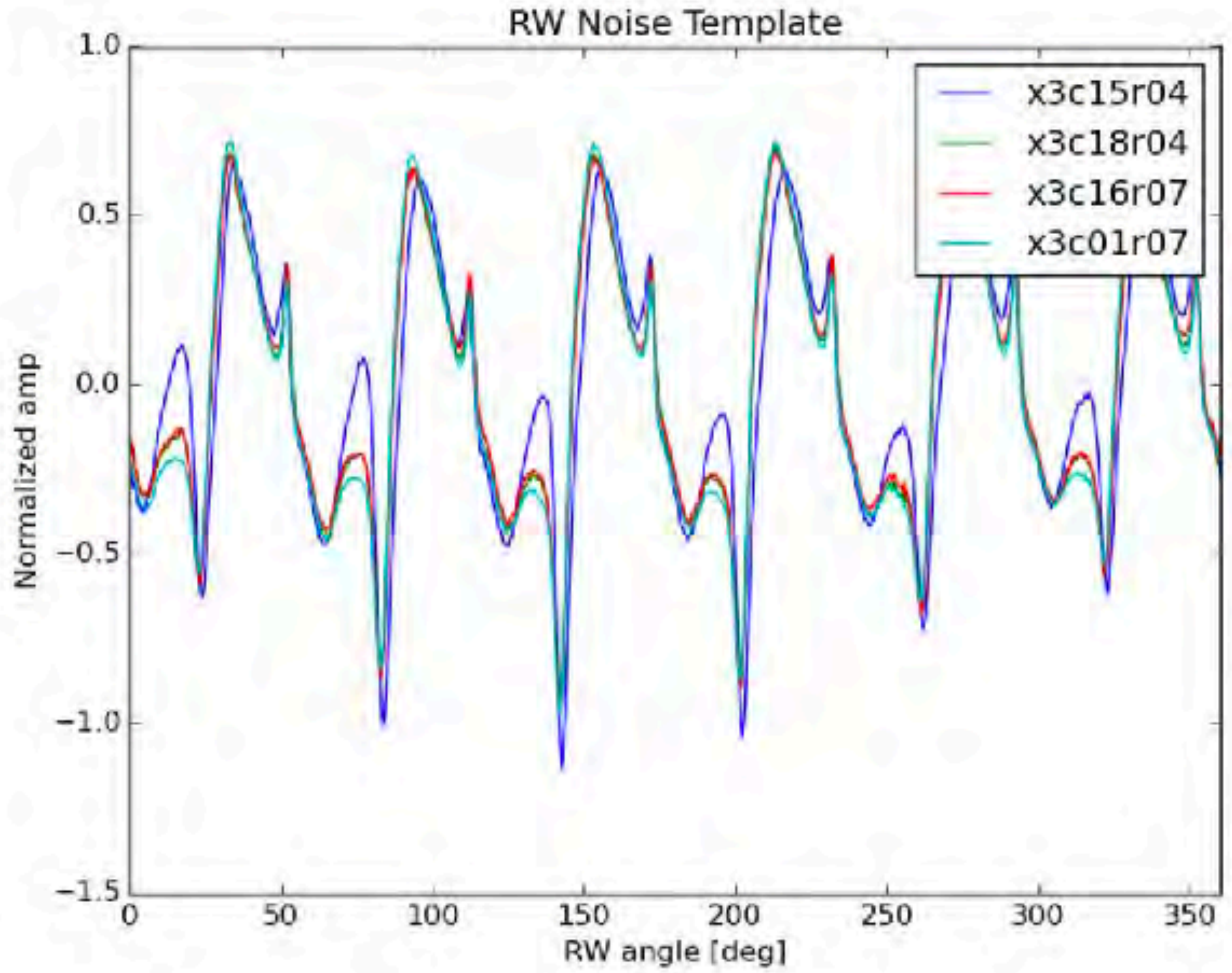
RFI Challenges

DC level losses (“flux slips”) during RFI glitches as SQUID loses lock

Difficult to recover, may include small crosstalk to other channels

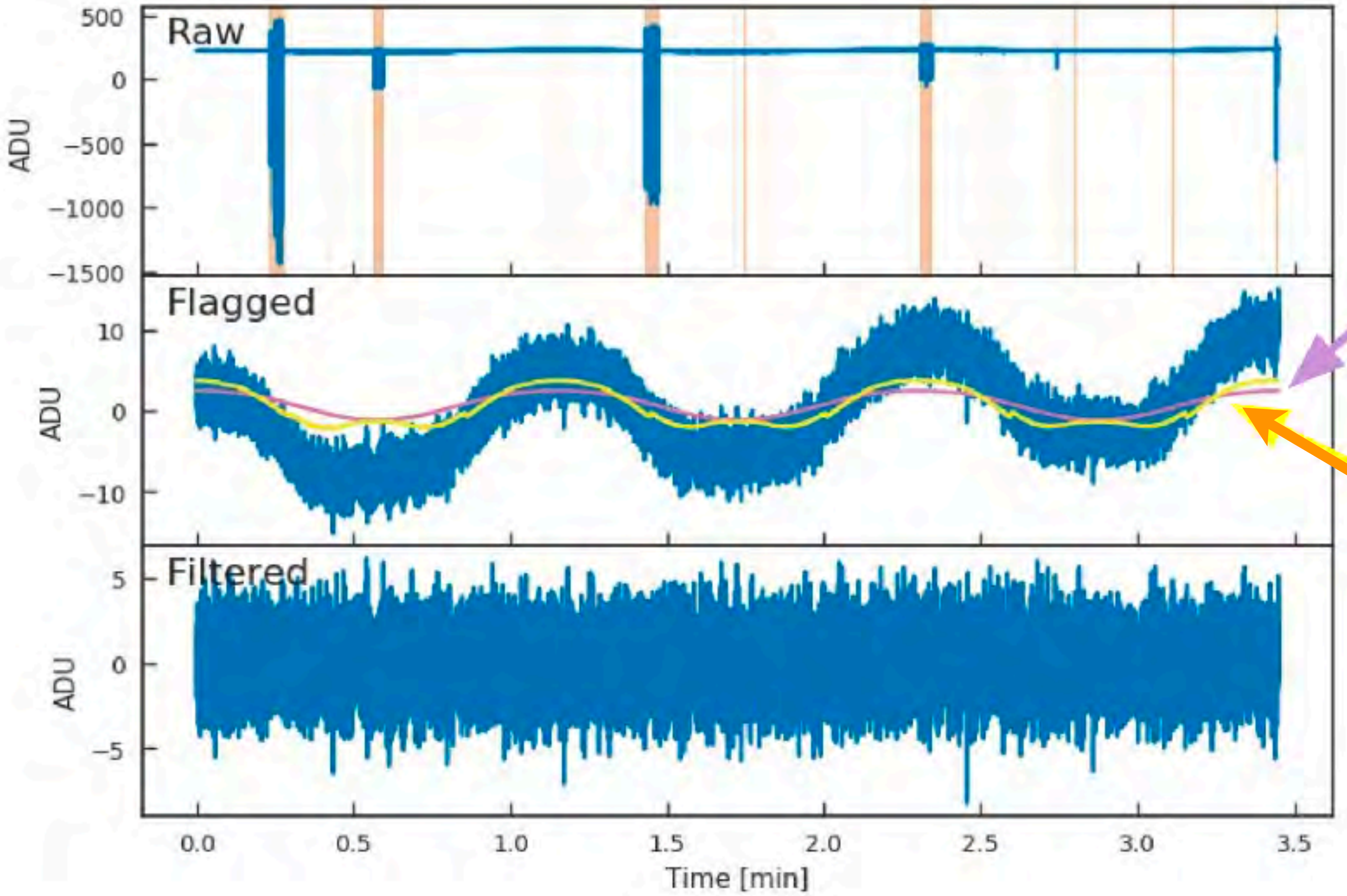
“Reaction wheel noise”: signal seen in some detectors synchronized with reaction wheel angle (*not* payload orientation)





Reaction Wheel

Scan-Synchronous Noise

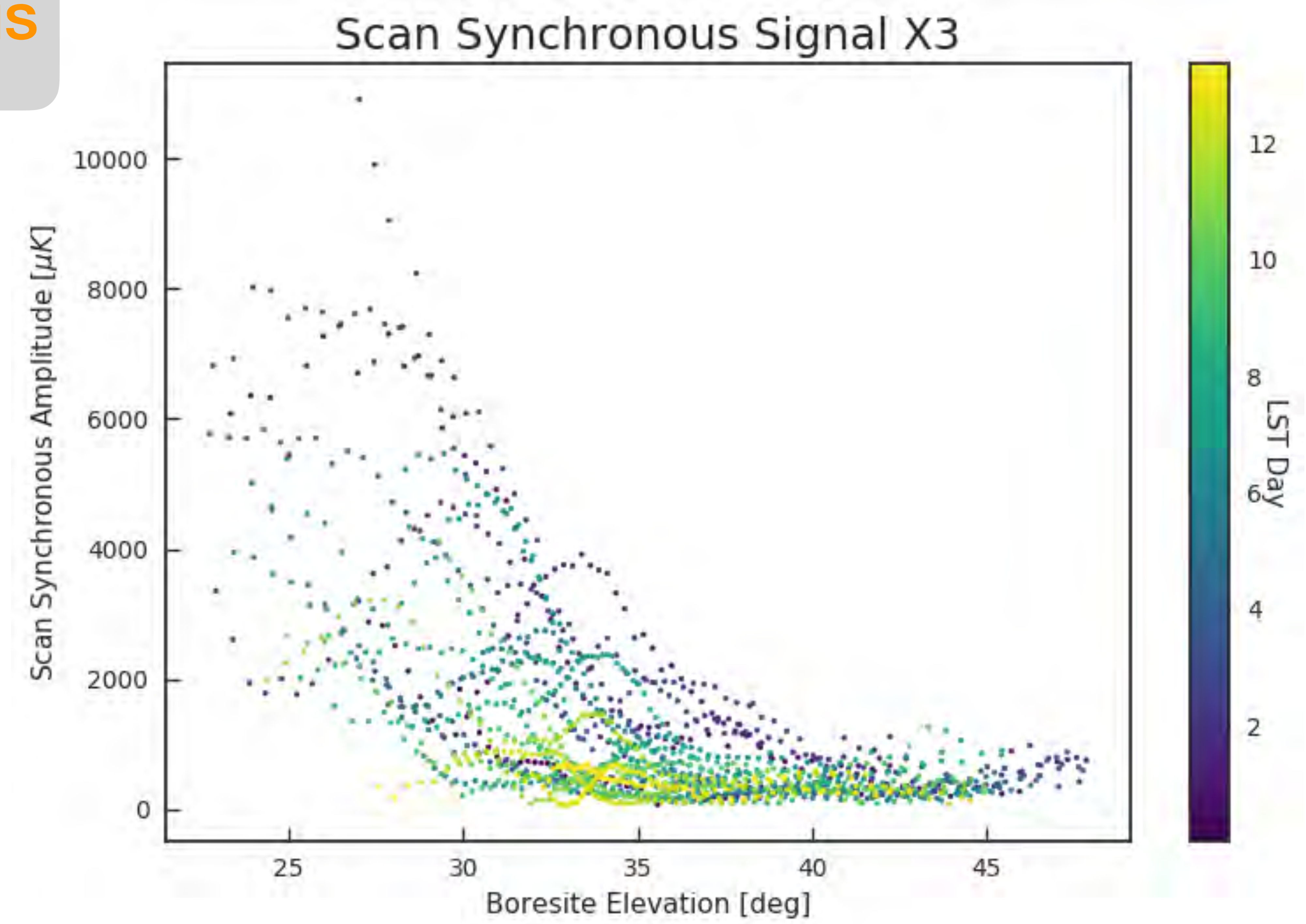


Dipole

Scan-Synchronous

Comparable to CMB dipole

Complex dependence on detector, boresight elevation, time, …



For now, impose **aggressive filtering** (5th order polynomial per half scan), exploring better options

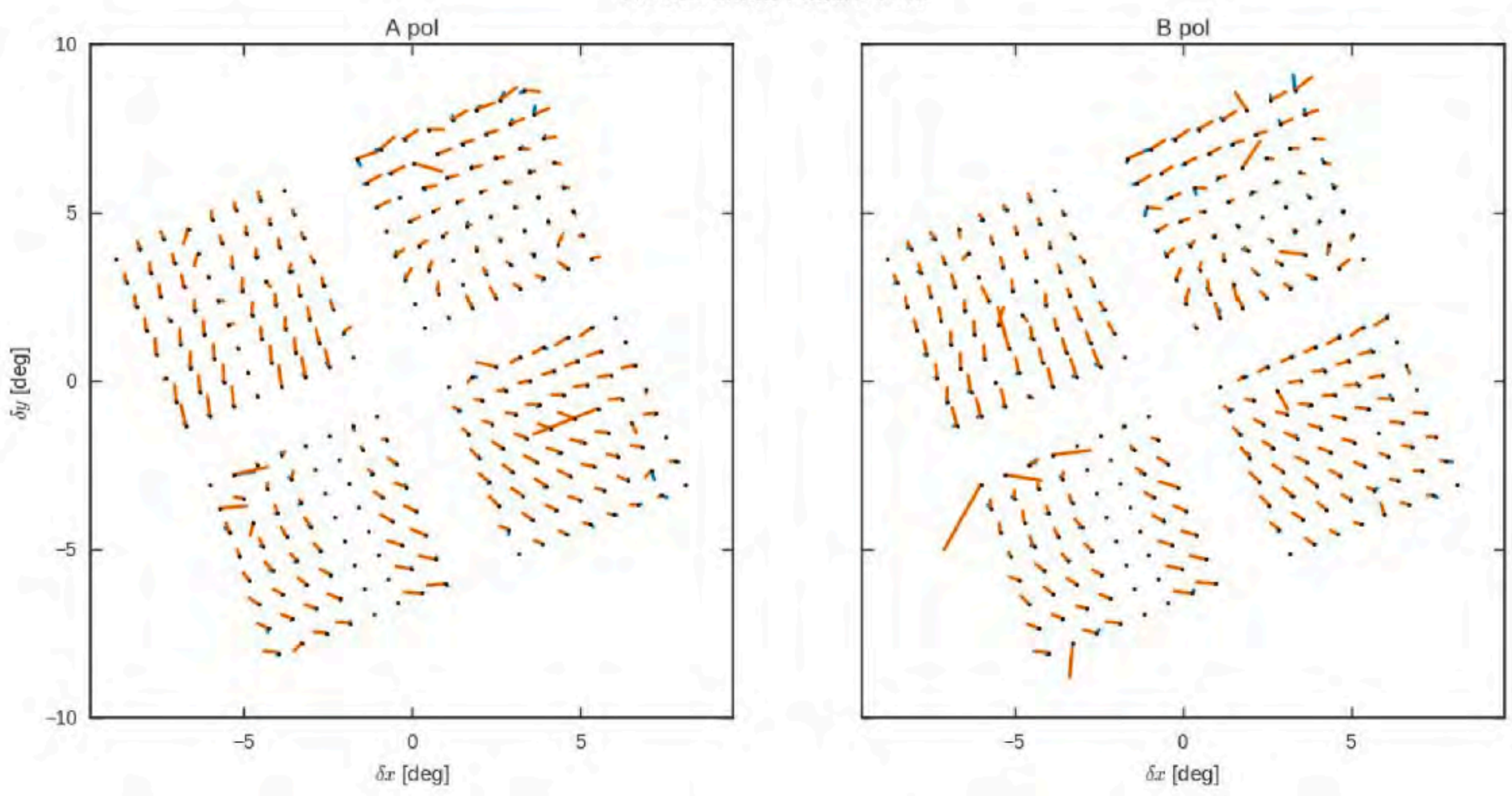
Optical Characterization

Pre-flight measurements of passband (FTS) and mid-field beams

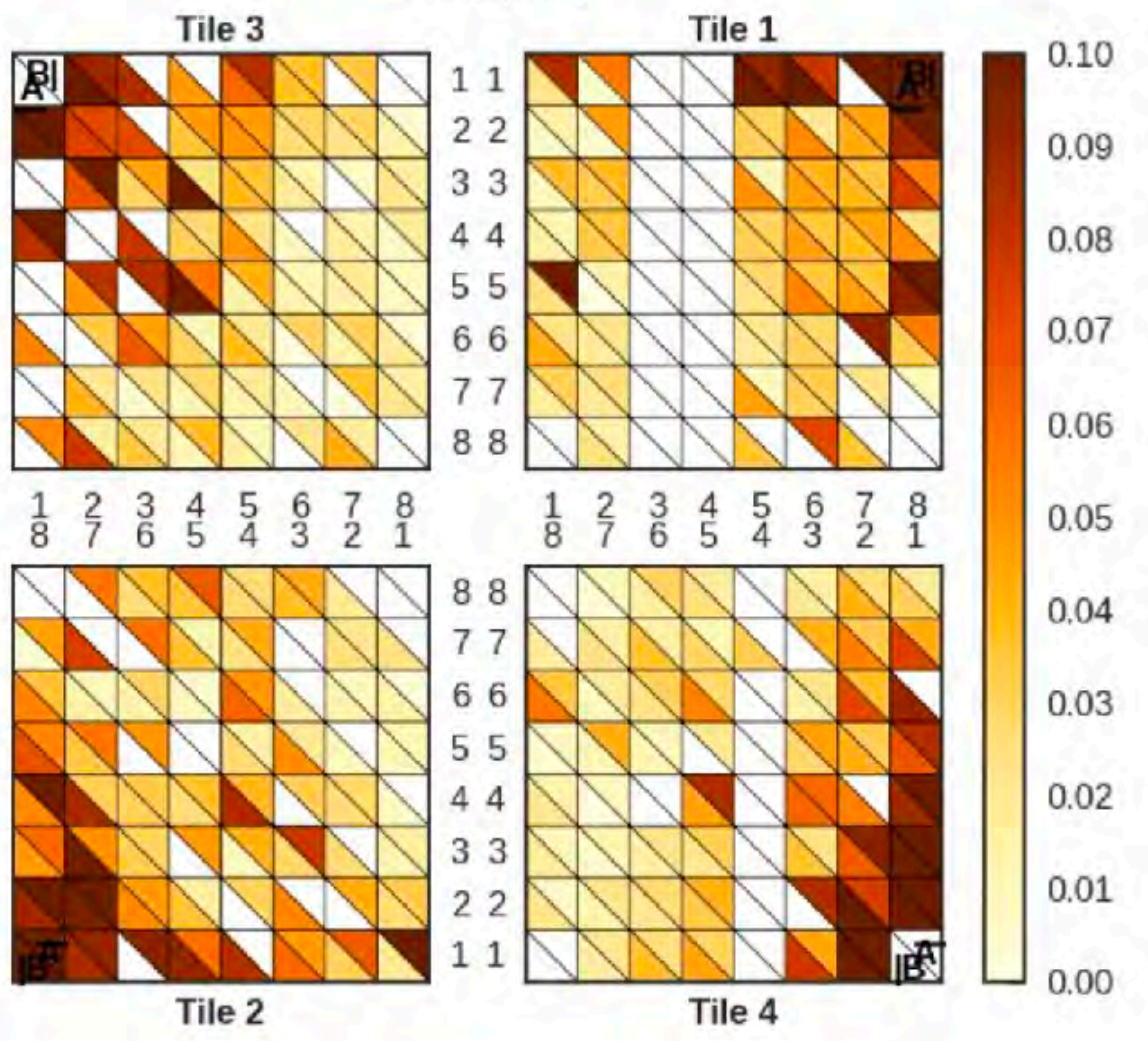
Characterize beams in-flight by fits to Planck maps (analog of BICEP2 “deprojection”)

Adjust beam centroids; other fitted beam anomalies are inputs to systematic studies

X1 det offset : scale 10.0



X1 ellipticity

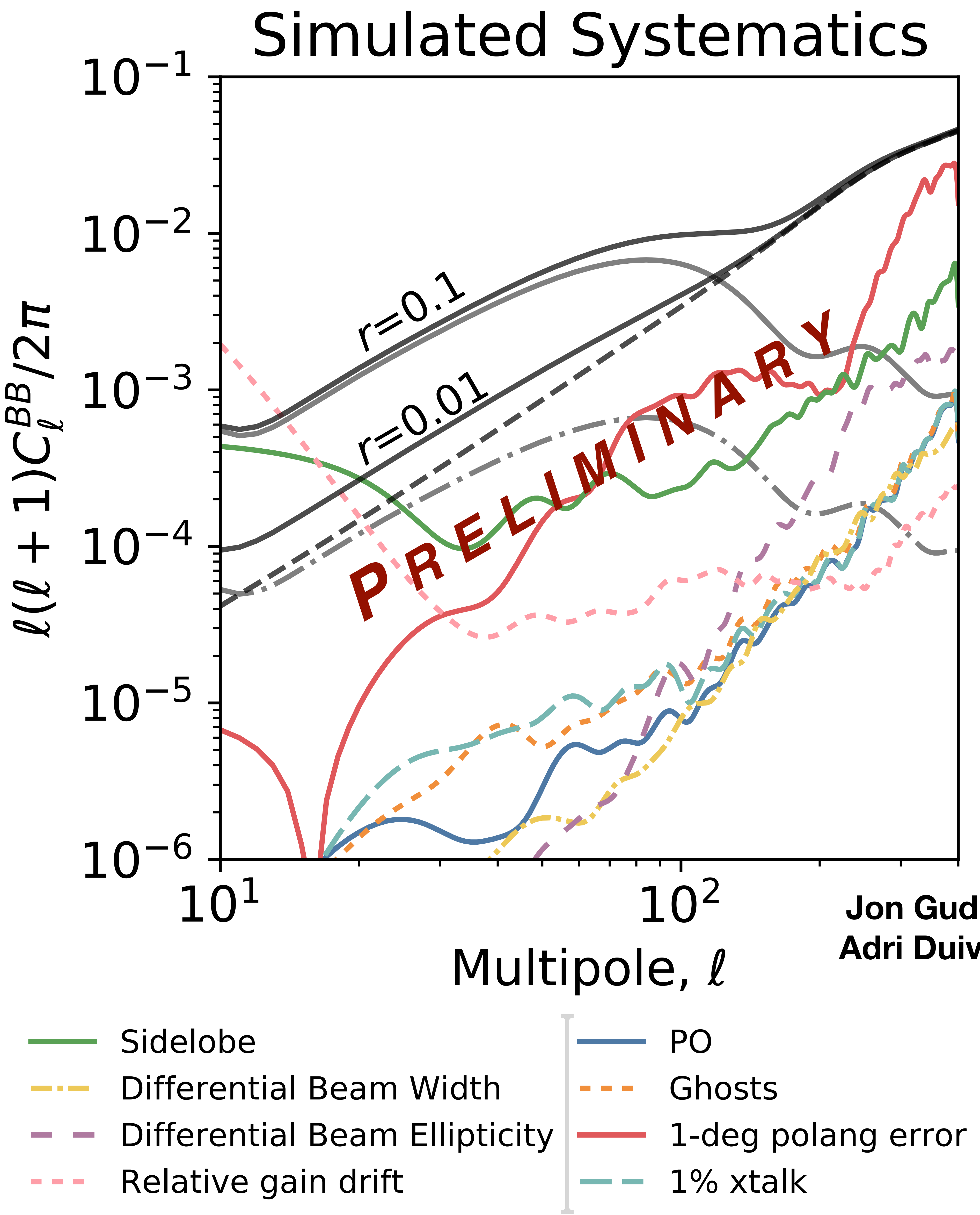


Optical Systematics Budget

Simulate effects of known non-idealities

- Differential beams, gain drift (*deprojected*)
- Full physical optics beam convolution
- Beam ghosts, crosstalk above known levels

Known beam and readout systematics should have negligible effect at current sensitivities.



Jon Gudmundsson
Adri Duivenvoorden


Right Ascension
Right Ascension
Right Ascension
+80°
+60°
+40°
+20°
0°
0°
−15°
−30°
Declination
SPIDER 95 GHz
Planck 100 GHz
S95 − P100
200
100
0
−100
−200
20
15
10
5
0
−5
−10
−15
−20
Temperature [μK]
1
0
−1
Q Polarization [μK]
U Polarization [μK]
−45°
−60°
−75°
−60°
−45°


Right Ascension
Right Ascension
Right Ascension
+80°
+60°
+40°
+20°
0°
Declination
0°
−15°
−30°
−45°
−60°
−75°
−60°
−45°
SPIDER 150 GHz
Planck 143 GHz
S150 − P143
200
100
0
−100
−200
20
15
10
5
0
−5
−10
−15
−20
Temperature [μK]
1
0
−1
Q Polarization [μK]
U Polarization [μK]

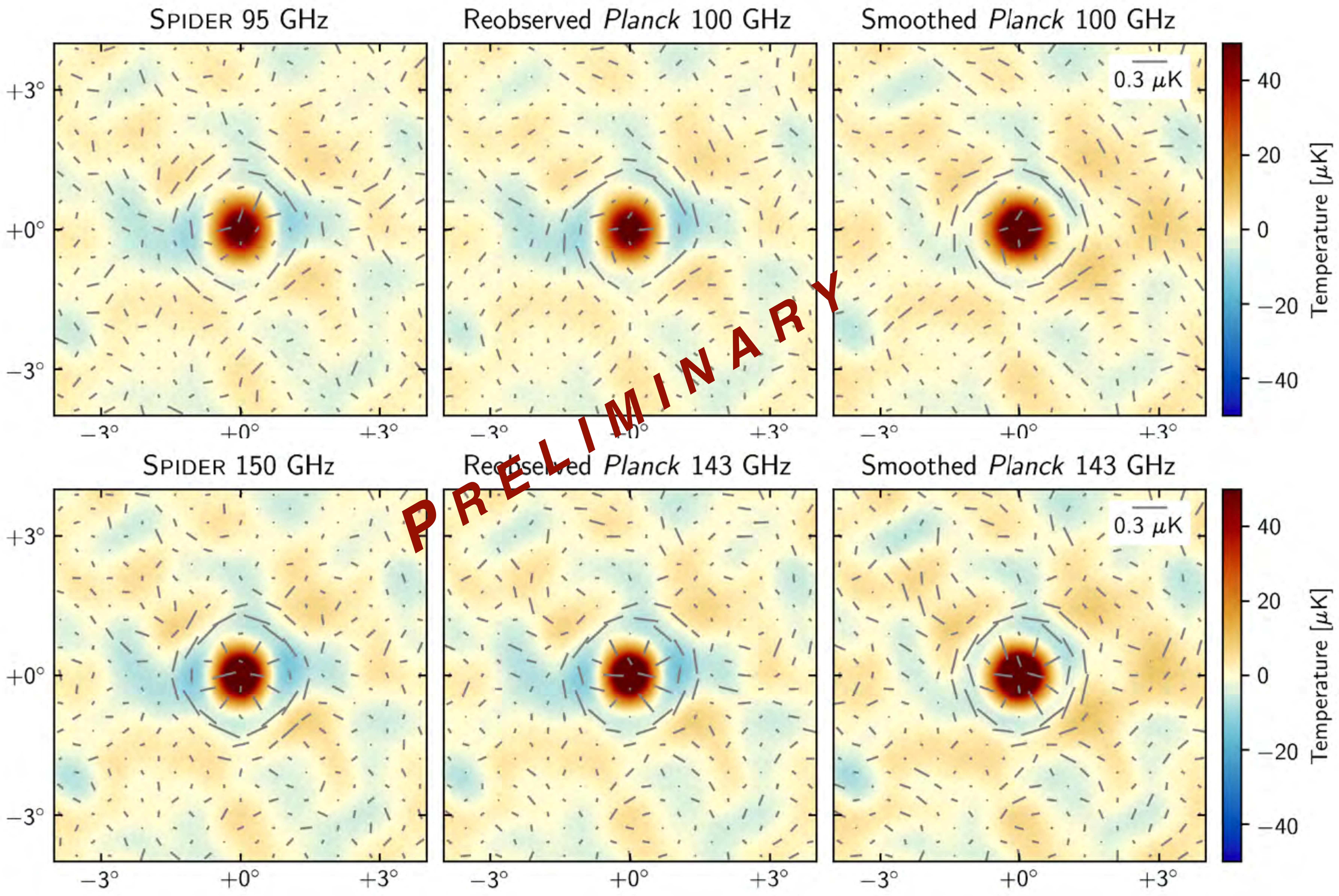
Seeking LCDM

Reobservation: Simulate SPIDER's beam, scan, filtering on external map for fair comparison to SPIDER

Close agreement with reobserved Planck maps

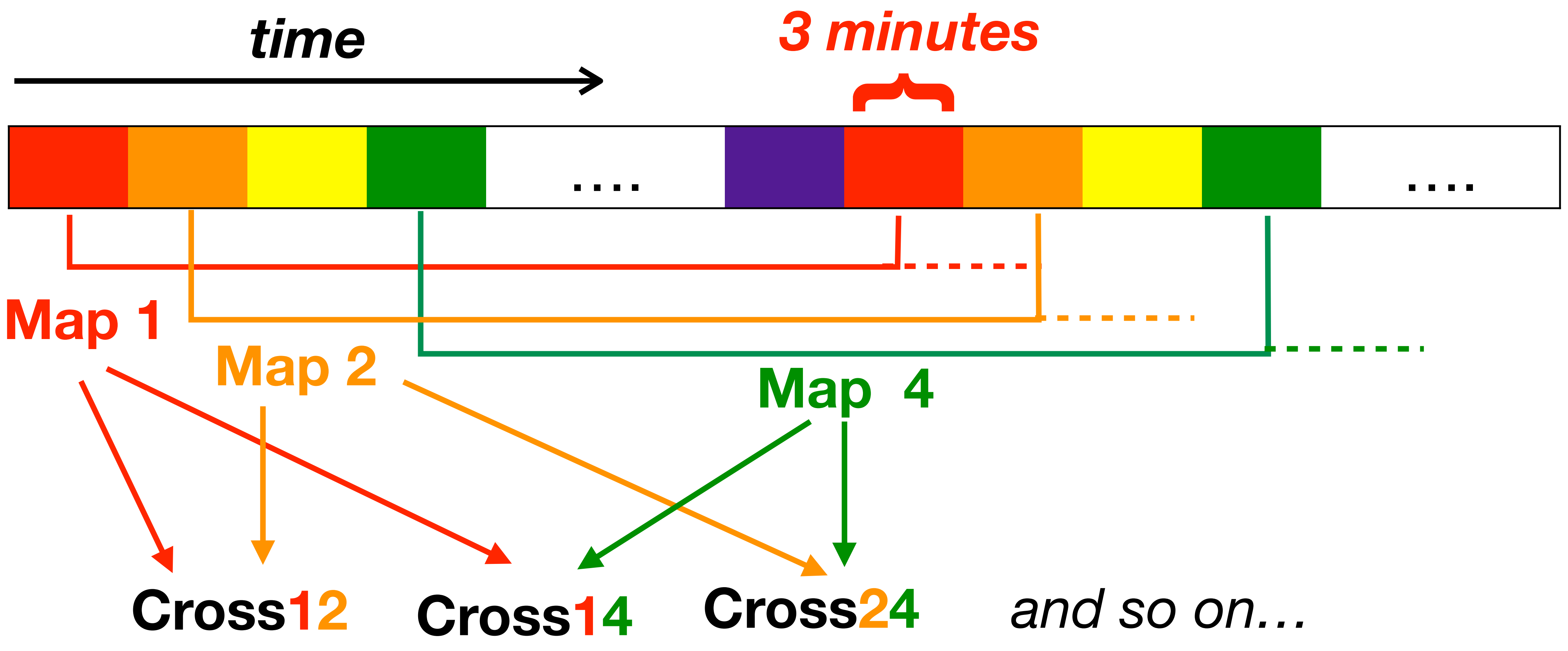
LCDM E-mode structure dominates polarization maps, clearly visible in stacked (**hot**-**cold**) spots in temperature map

… but also plenty of dust!



Power Spectrum Estimators

Empirical **noise modeling is hard**: data redundancy is limited relative to Pole instruments (though high relative to Planck!)



time

3 minutes

....

....

Map 1

Map 2

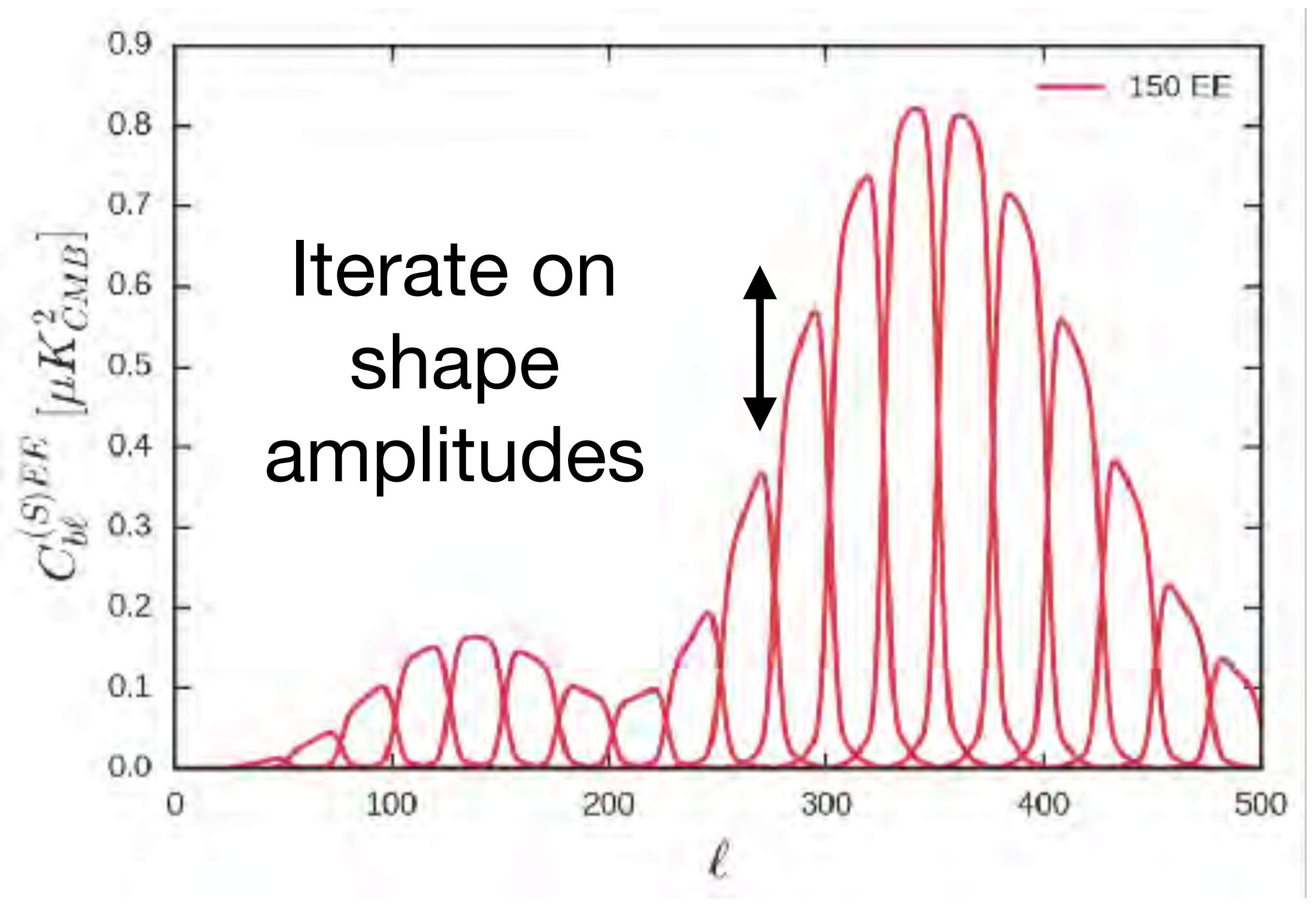
Map 4

Cross12

Cross14

Cross24

and so on…



Iterate on shape amplitudes

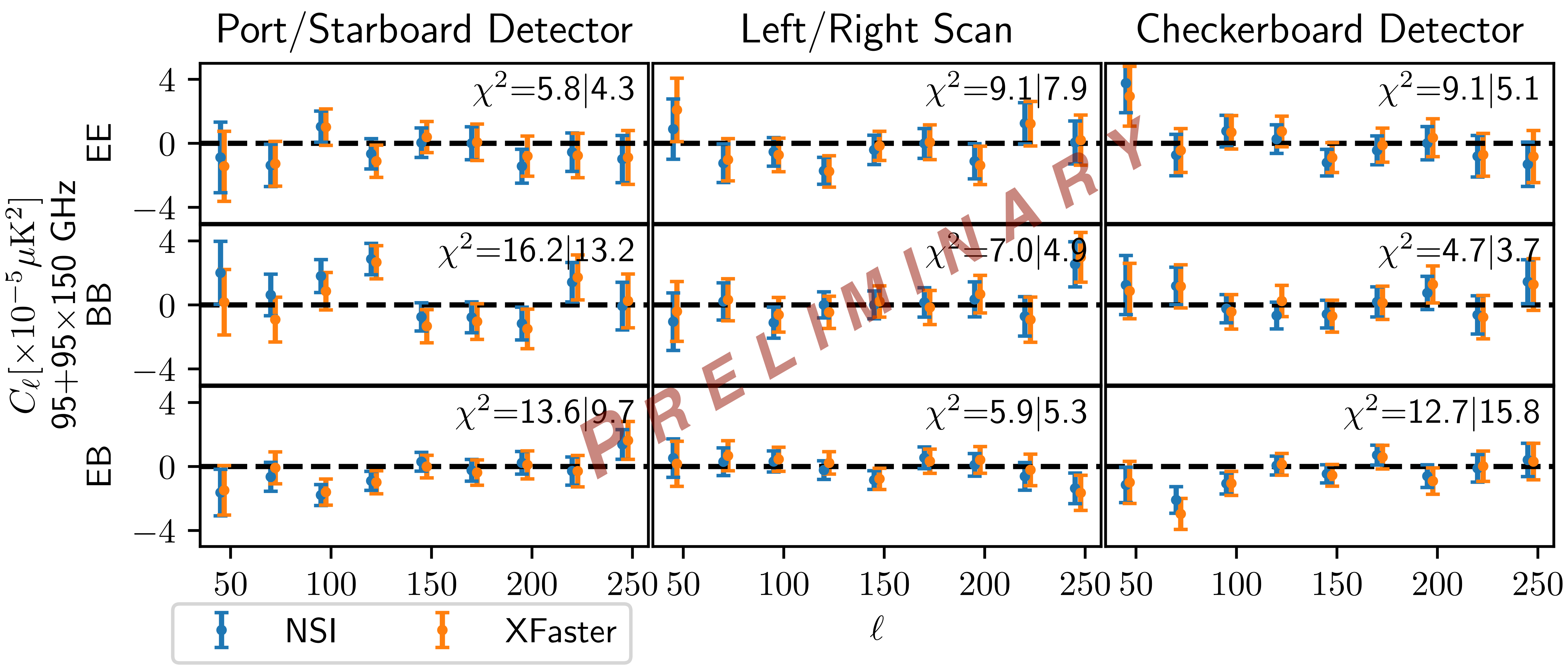
Noise Spectrum Independent (NSI):

- PolSPICE pseudo-Cl Monte Carlo
- Signal-only simulation library
- Covariances from cross spectra among 14 data subsets (interleaved 3-min chunks)
  91 crosses/band, 378 total crosses
- *J.M. Nagy, J. Hartley, …*

XFaster: Hybrid maximum-likelihood

- Iterative quadratic estimator in the isotropic, diagonal approximation used by MASTER
- Solves for binned bandpowers using signal and noise simulation library
- Adapted for null tests, foreground sep in progress
- *C. Contaldi, D. Mak, A.E. Gambrel, A.S. Rahlin, …*

Null Tests



Present status: Most null tests look good
but some work ongoing on stats, 150 GHz

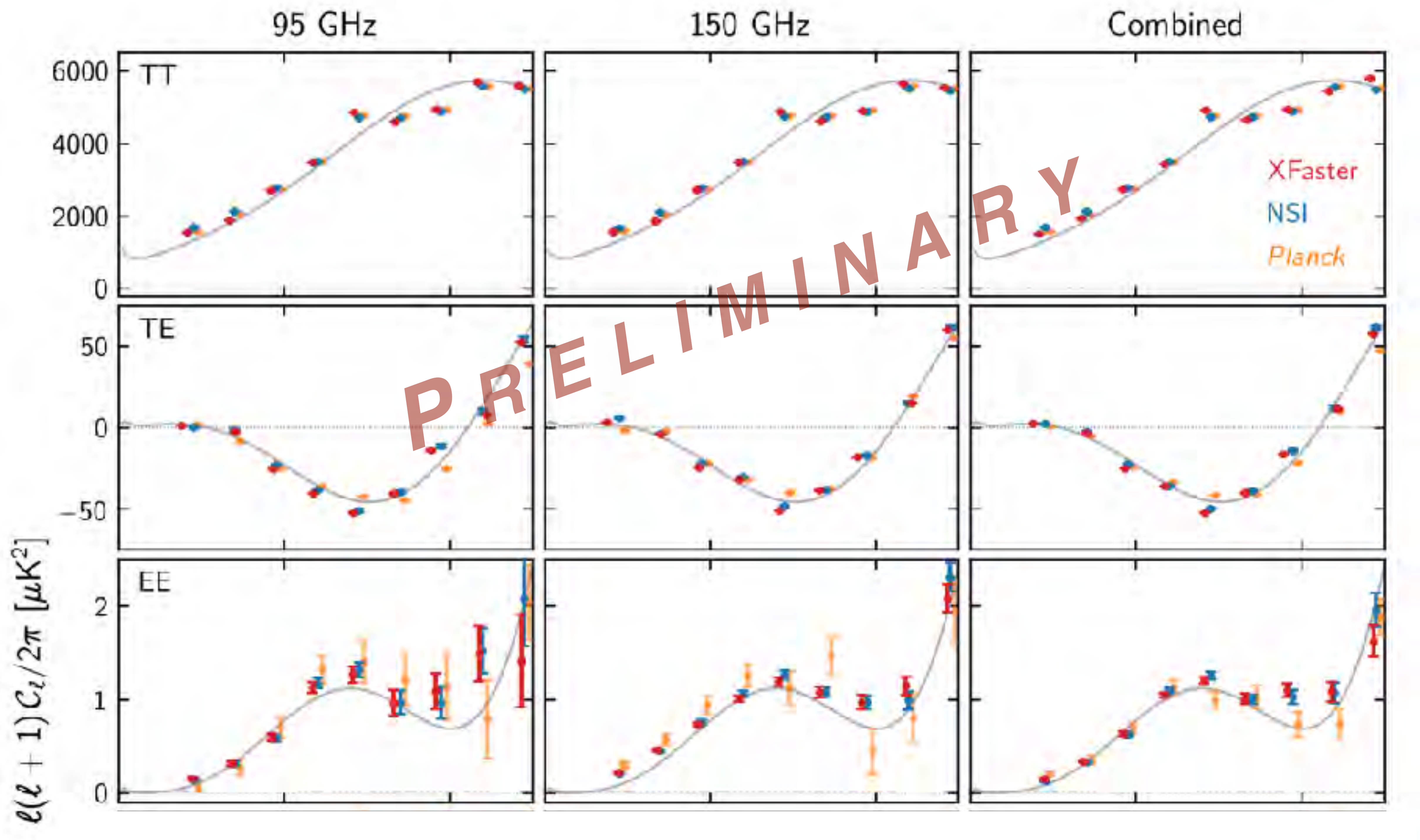
Construct difference maps between (near-) equal data halves

10 data splits, 3 spectra considered
- Left / right-going scans
- 2 mission time splits
- 7 detector splits
  6 spatial, hi/lo band center

Estimate power spectra of difference maps

Subtract simulated signal residual

Raw Power Spectra



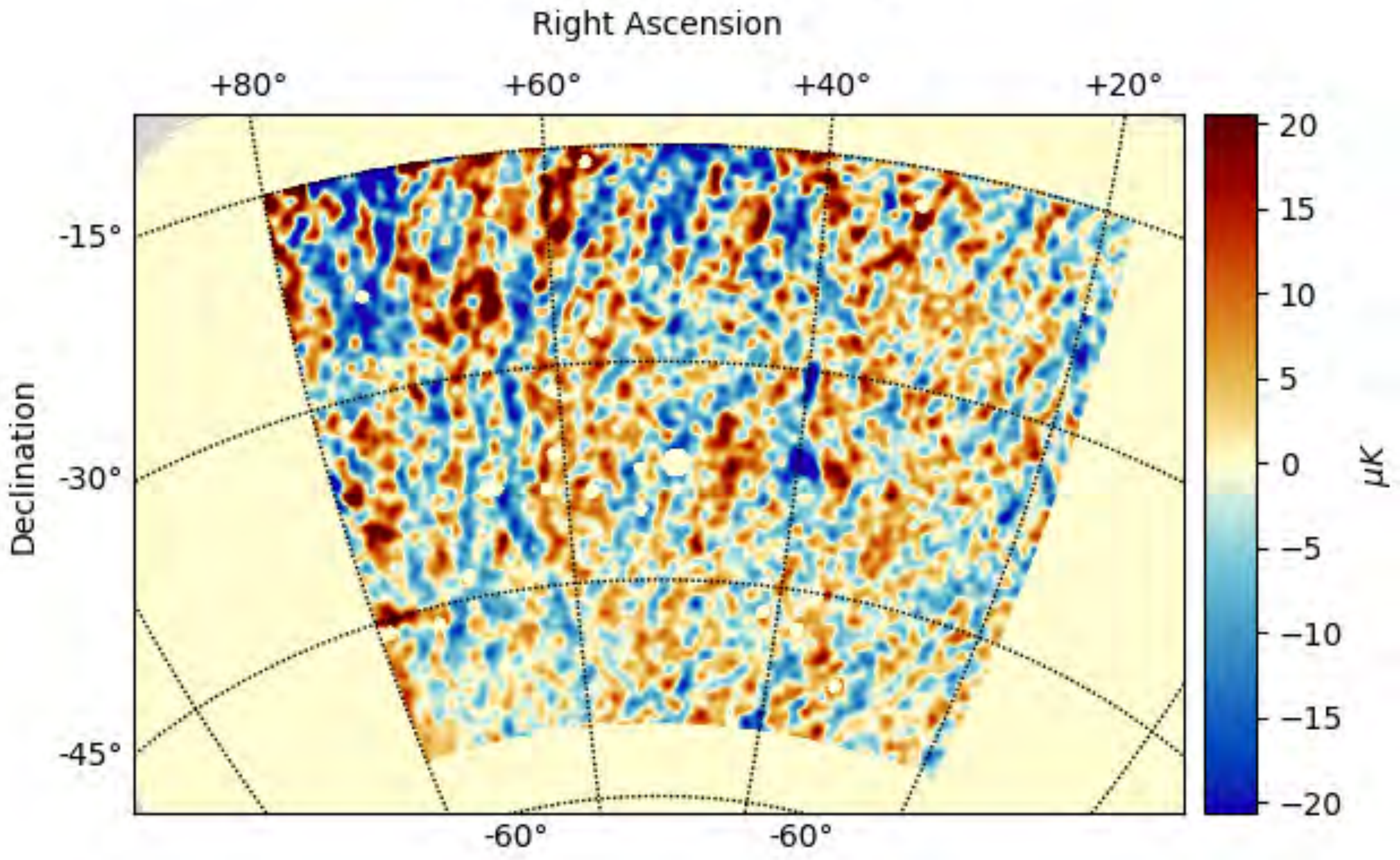
PRELIMINARY

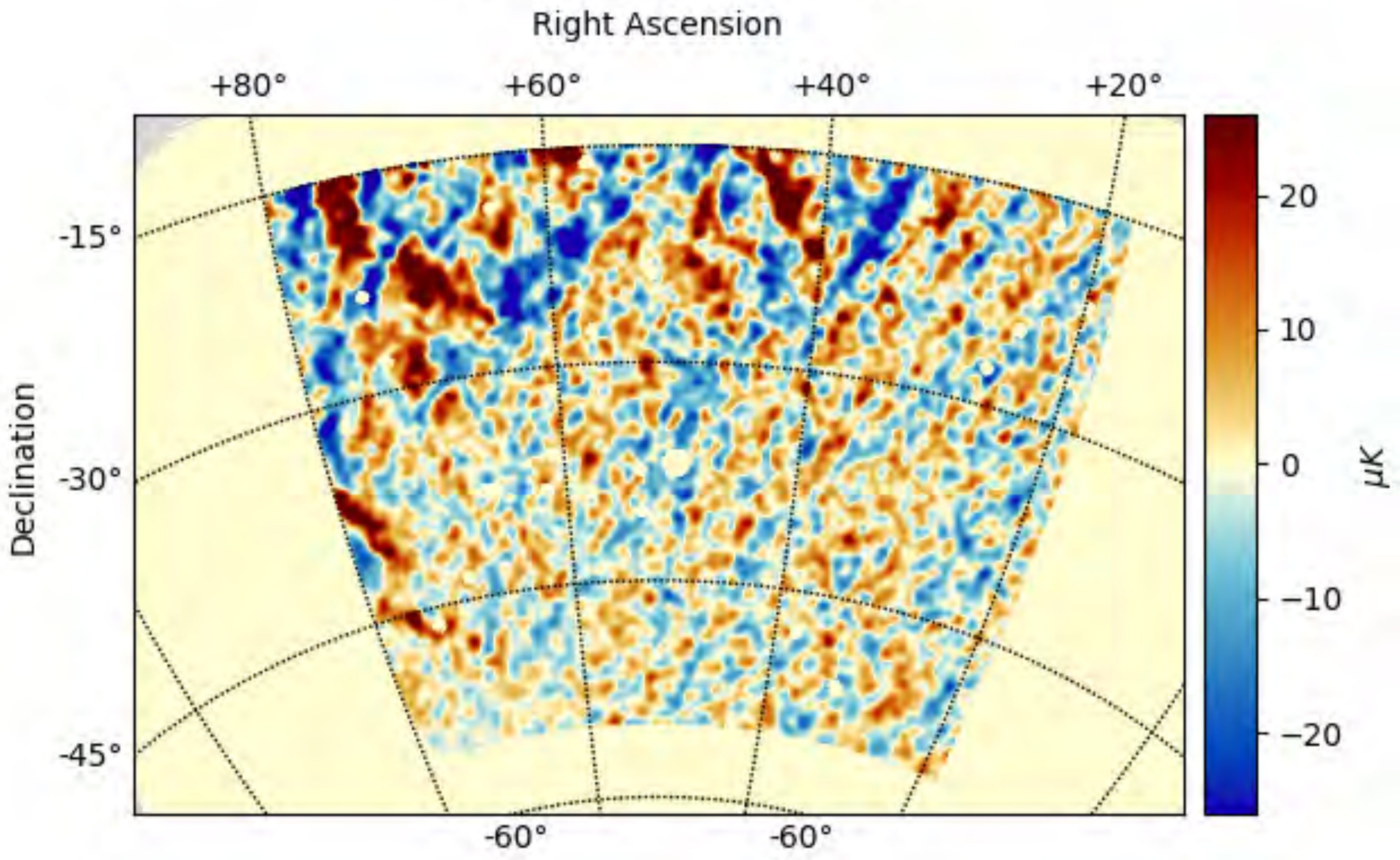
- Good consistency between distinct power spectrum pipelines
- Good consistency with Planck 100/143 when restricted to common sky patch (with higher S/N!)
- Clear frequency-dependent excess above LCDM -> ***Dust***

Foreground Strategies

How can we effectively **clean** foregrounds from our data while **quantifying the error** on what we're doing?

- **Spatial template subtraction**
  Decorrelation across frequencies?
  Chance correlations?
- **Harmonic domain** - per-bandpower or multipole model
  Non-gaussian sample variance
  Spatial variation of SED?
- **Spatial / harmonic variants** - SMICA, NILC
- **Per-pixel** joint component estimation - Commander

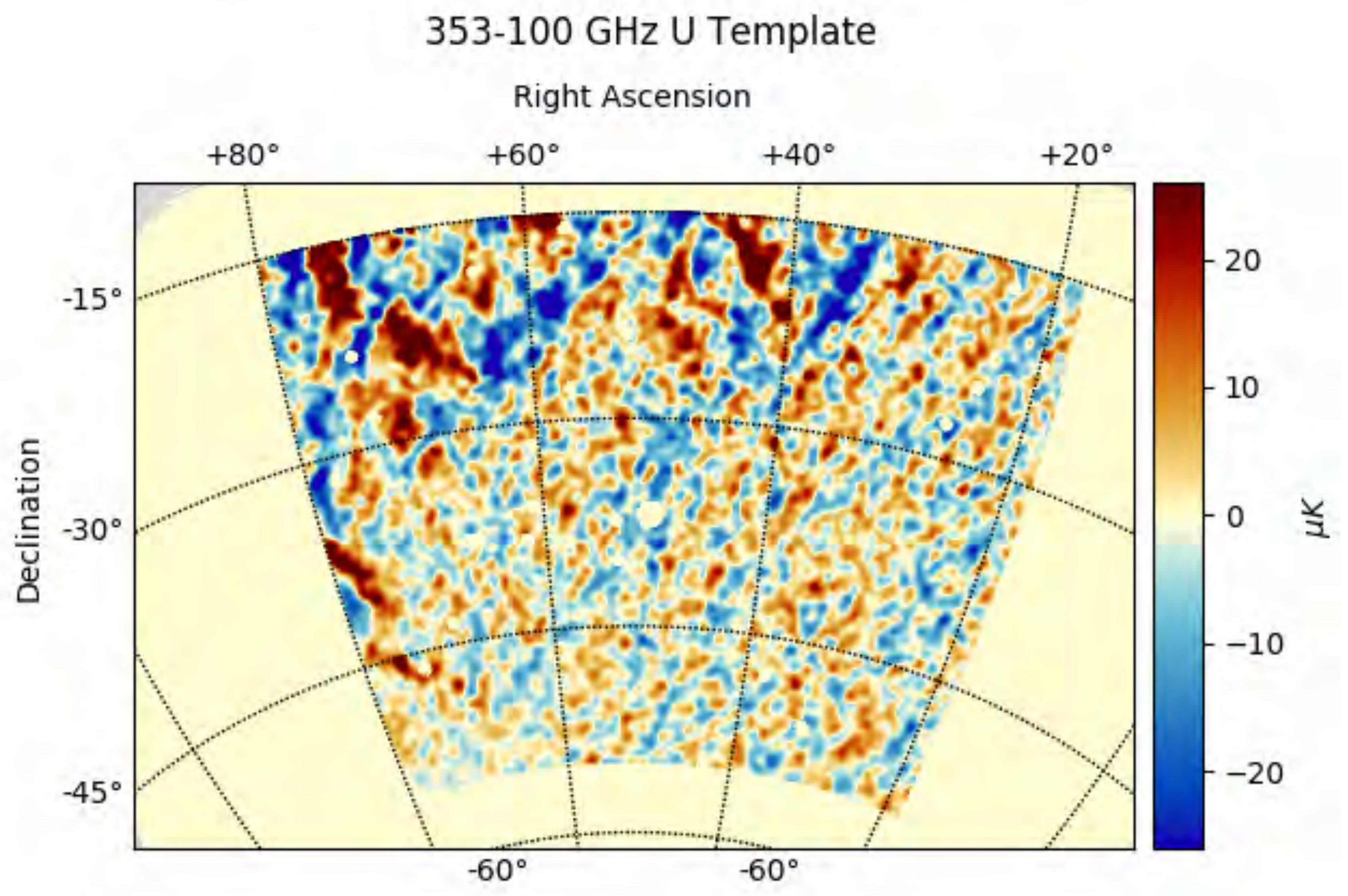

353-100 GHz Q Template

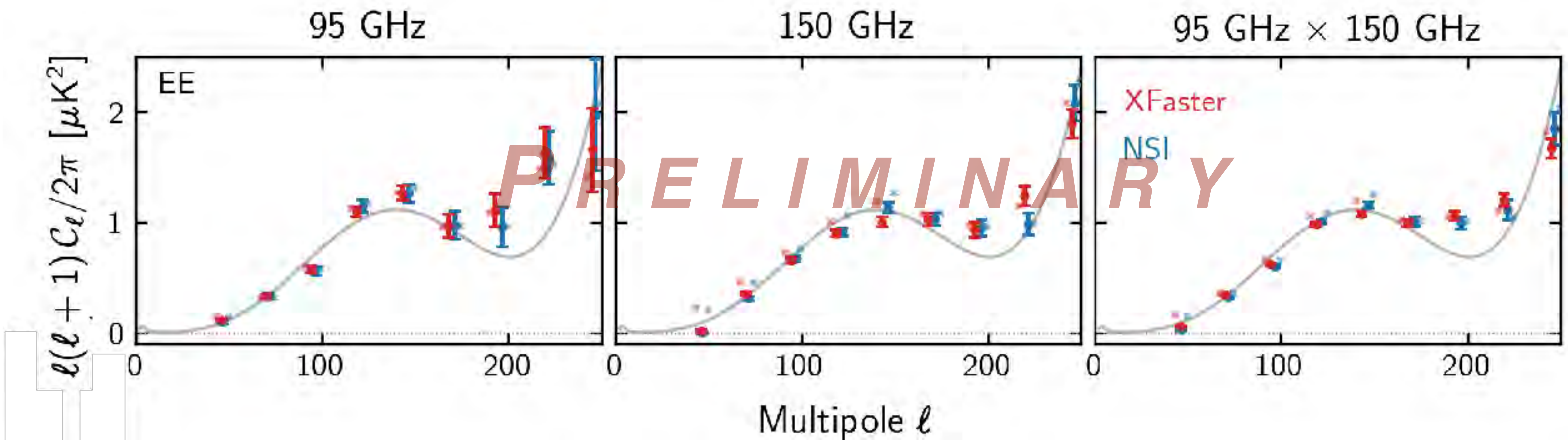

353-100 GHz U Template

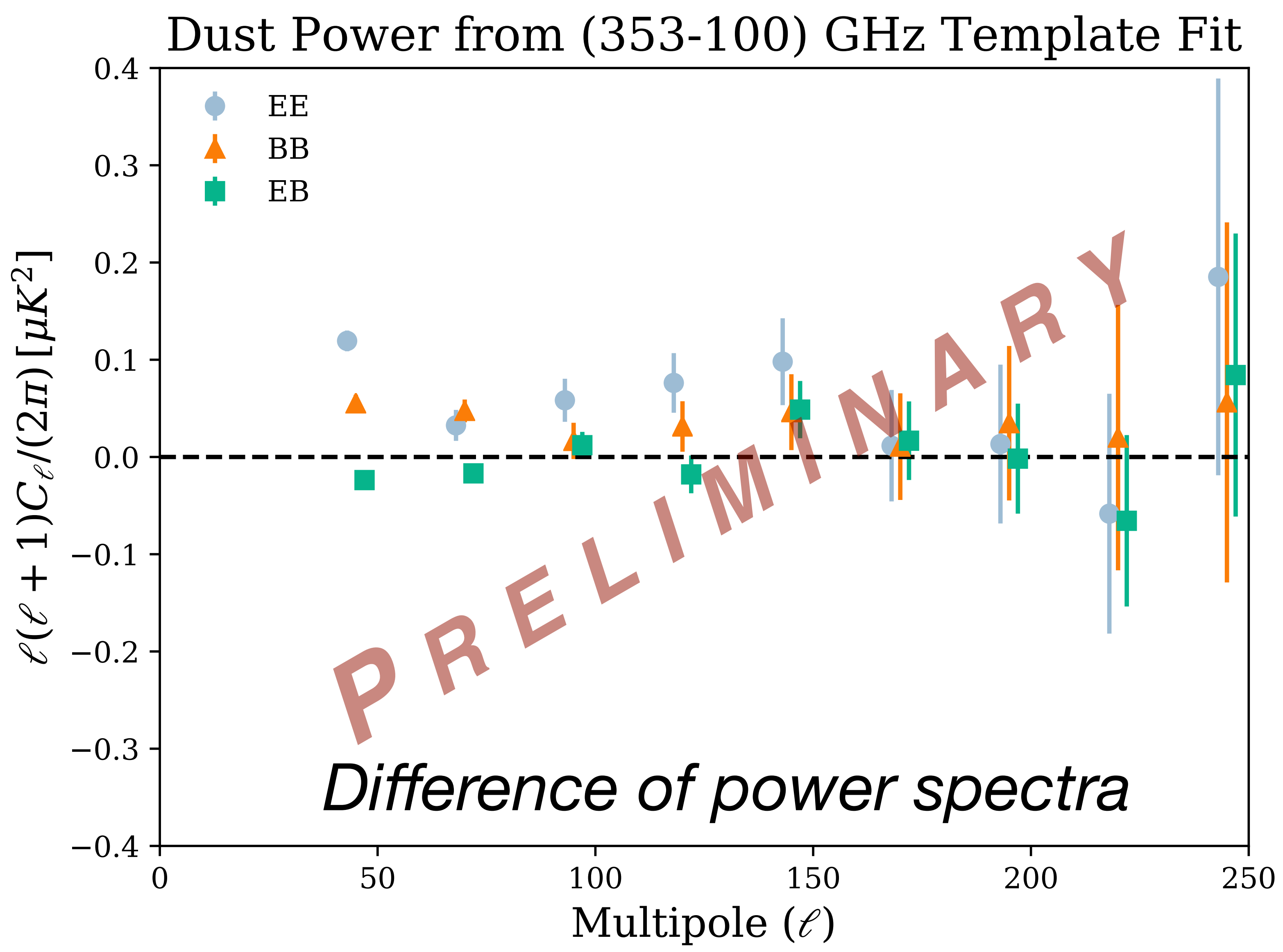
Spatial Template Removal

- Regress Planck-derived dust templates (P353-P100, P217-P100) out of SPIDER maps
  (*can also be done for synchrotron, S/N low for now*)

- 353 GHz: α =0.043±0.004 (0.015±0.004) at 150 (95) GHz
  Additional work on 217 GHz template







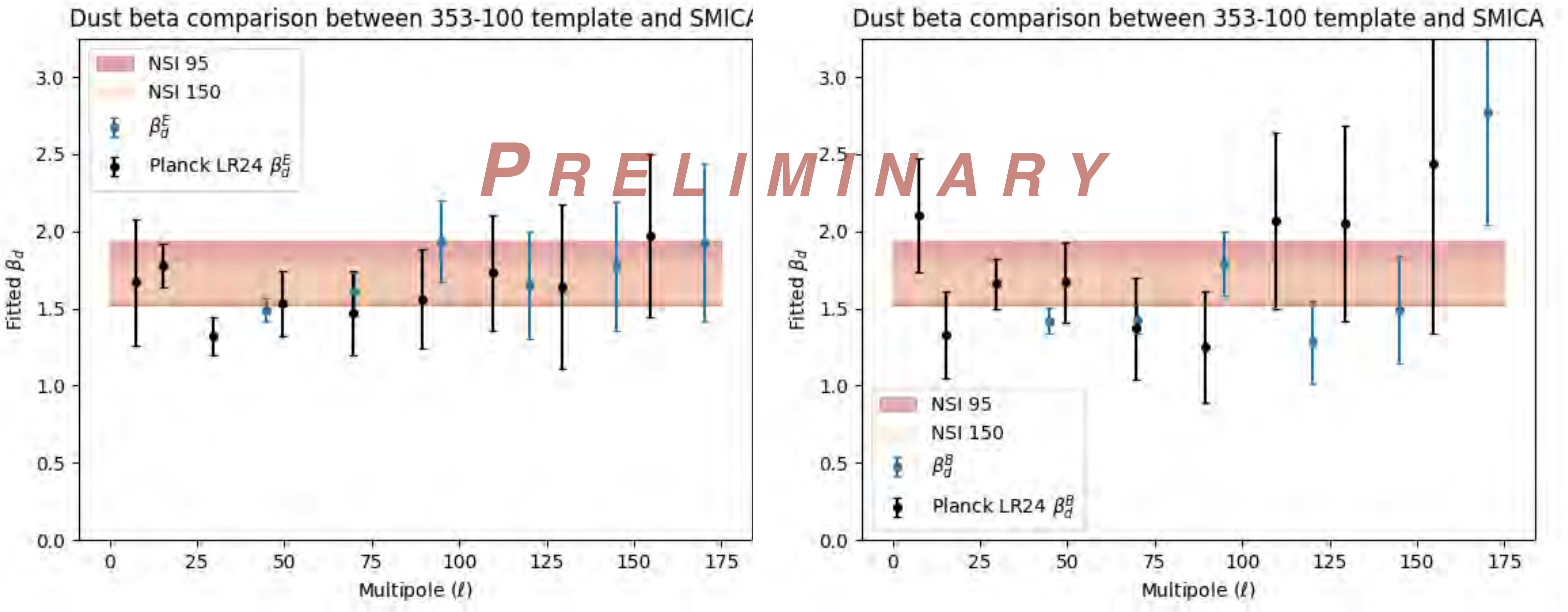
Difference of power spectra

Harmonic Domain

- **SMICA**: fit components to map auto/crosses
  - No multipole model required: fit each band power separately
  - Optional SED model: modified blackbody dust
  - SPIDER (95/150), Planck pol HFI (100/143/217/353)

Good agreement in SMICA β_D between 95 and 150, and E and B

(E/B constrained to match in NSI template work)

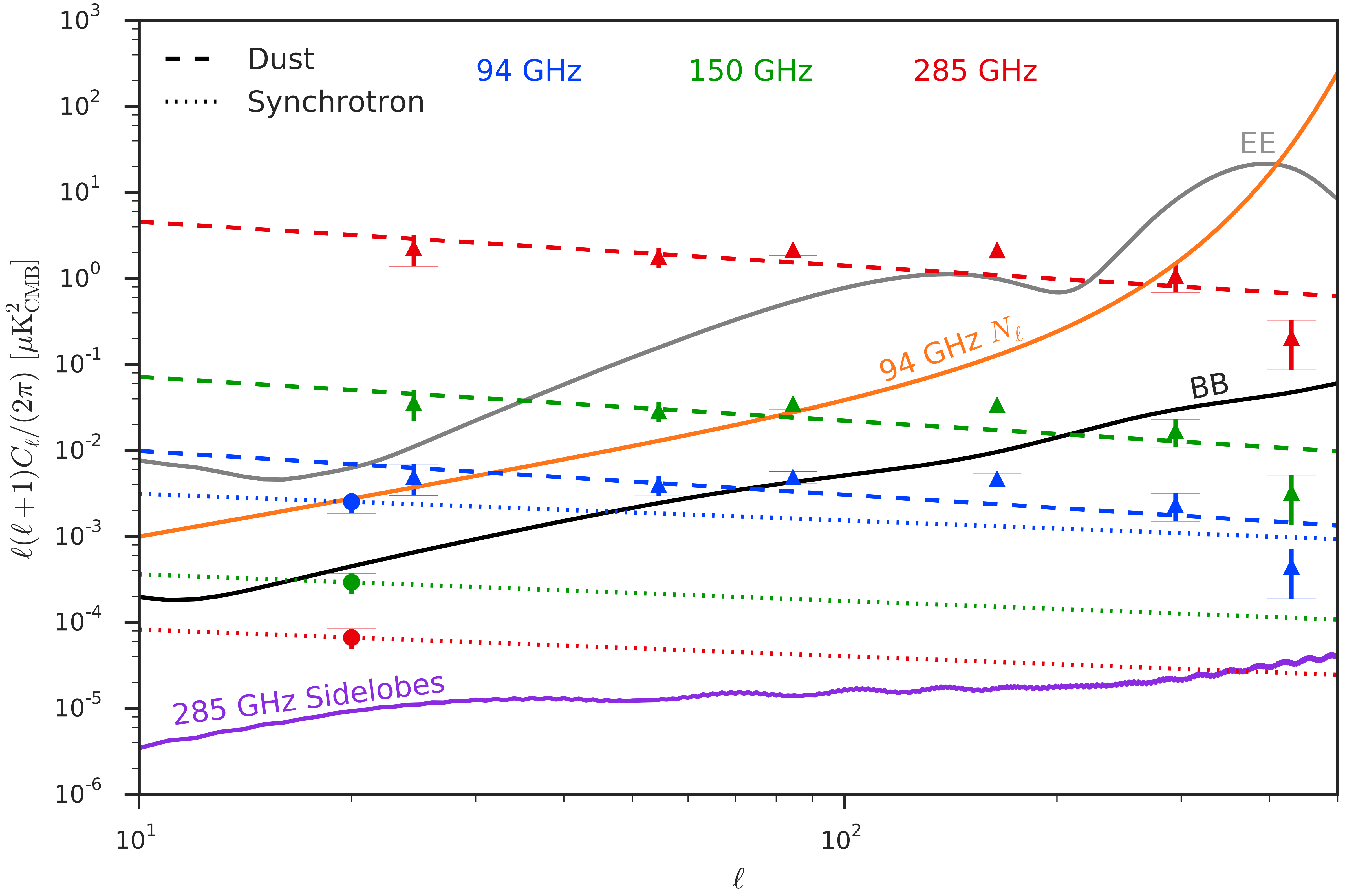


NSI spatial template subtraction
SMICA all bands, unconstrained bin-to-bin
SMICA all bands, grey body (“beta”) model

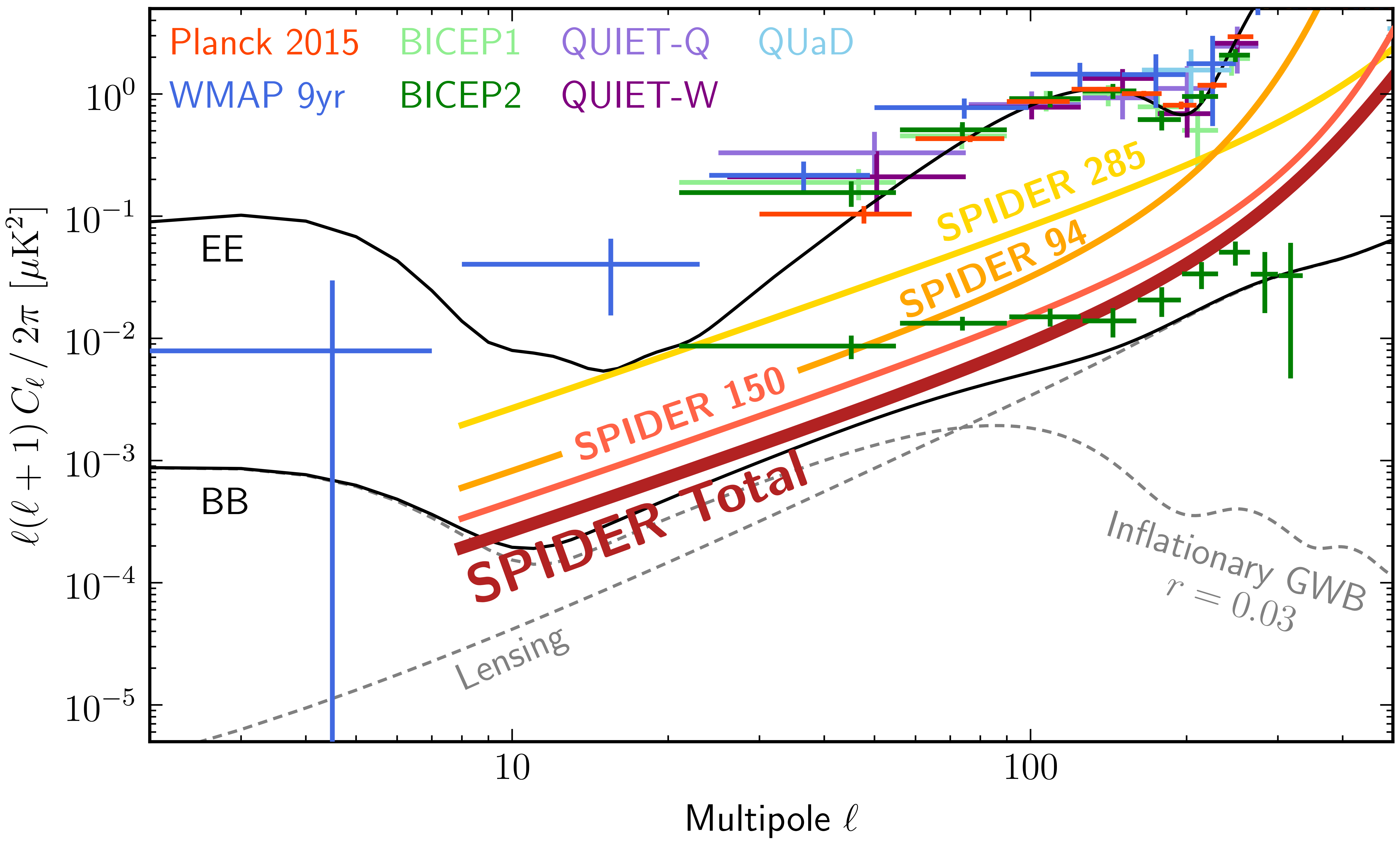
SPIDER Mission Goals

TARGET: r<0.03 (95% CL) in the presence of foregrounds

Commander foreground estimate



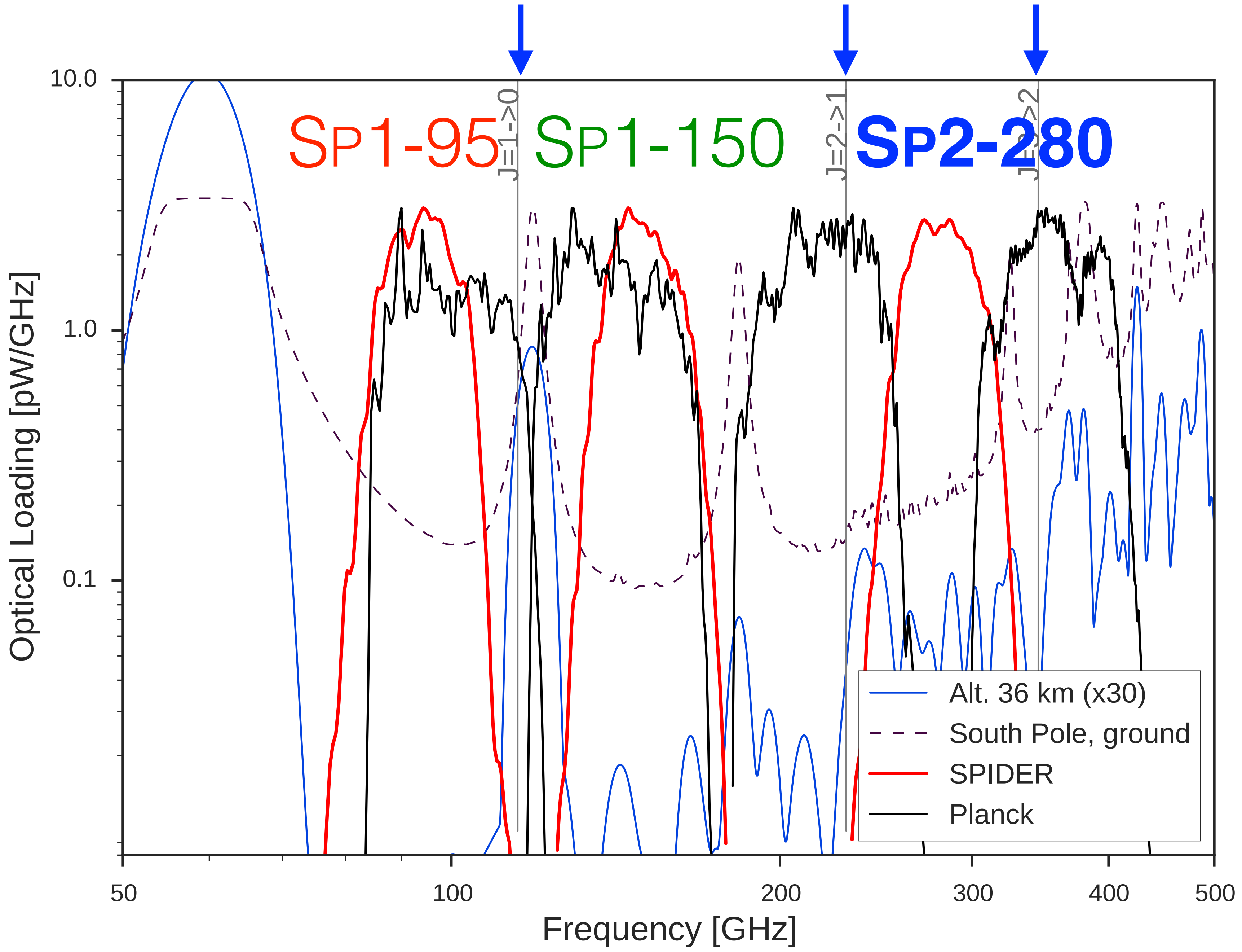
Proposal sensitivity - 2 flights

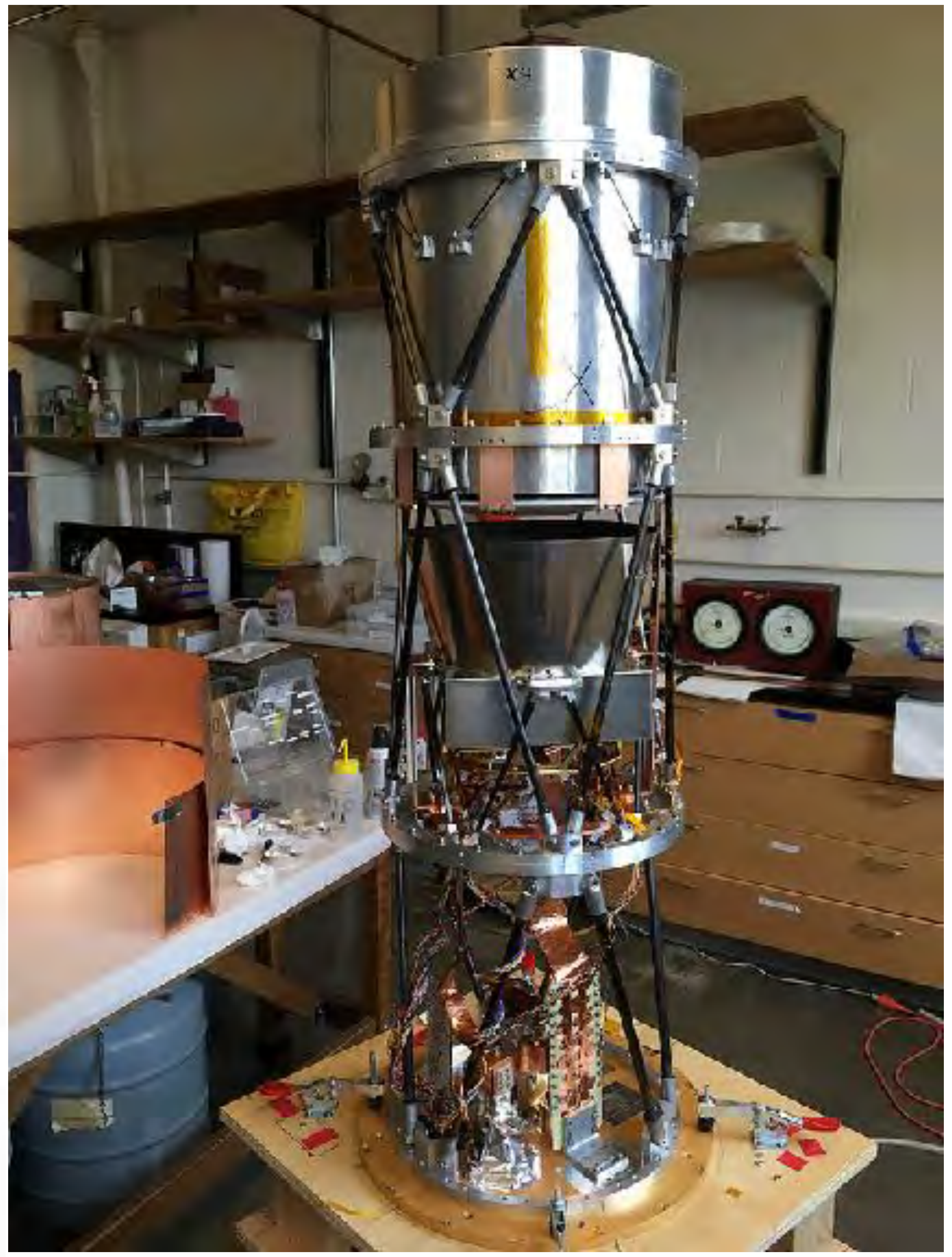


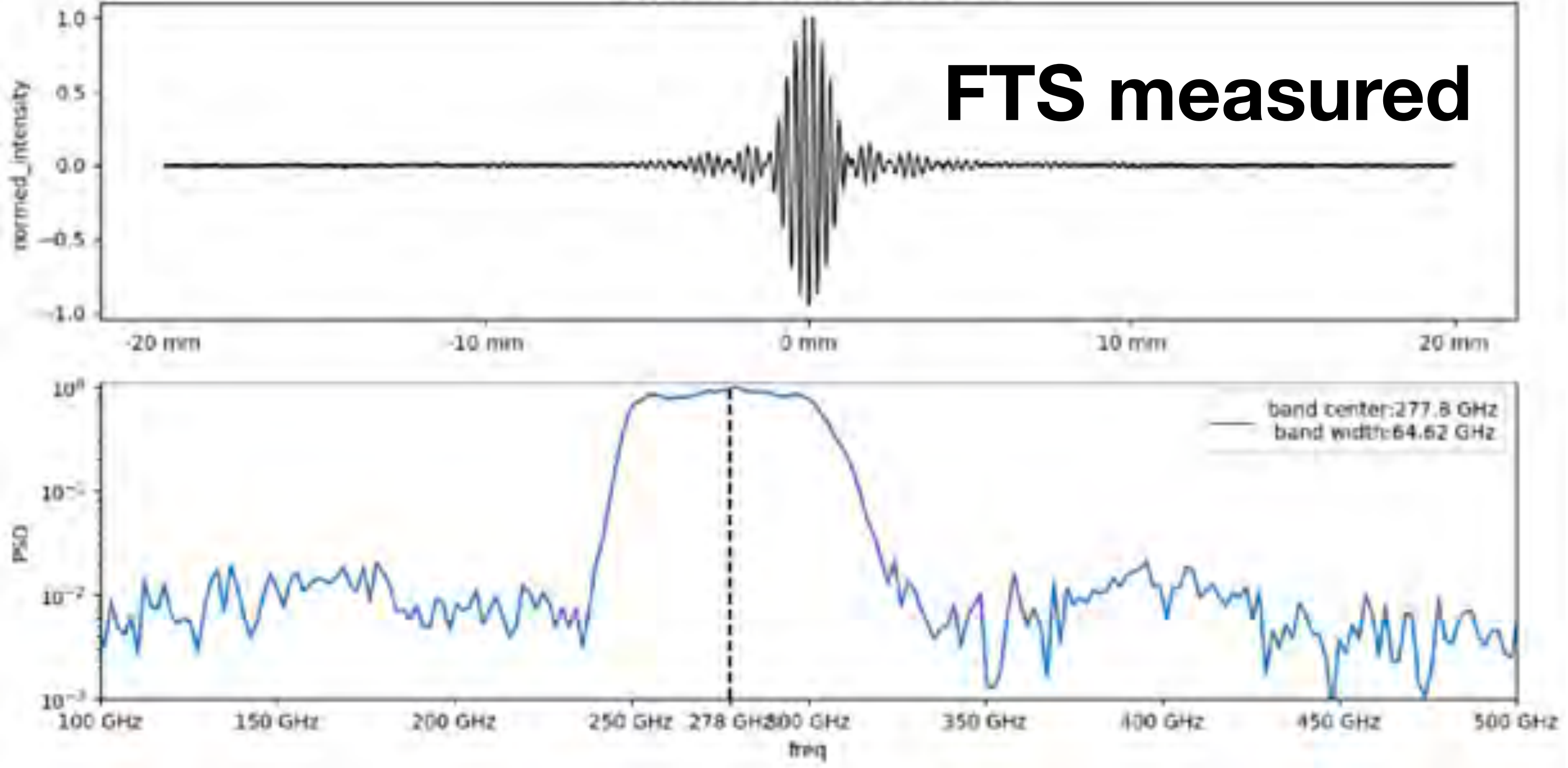
SPIDER-2

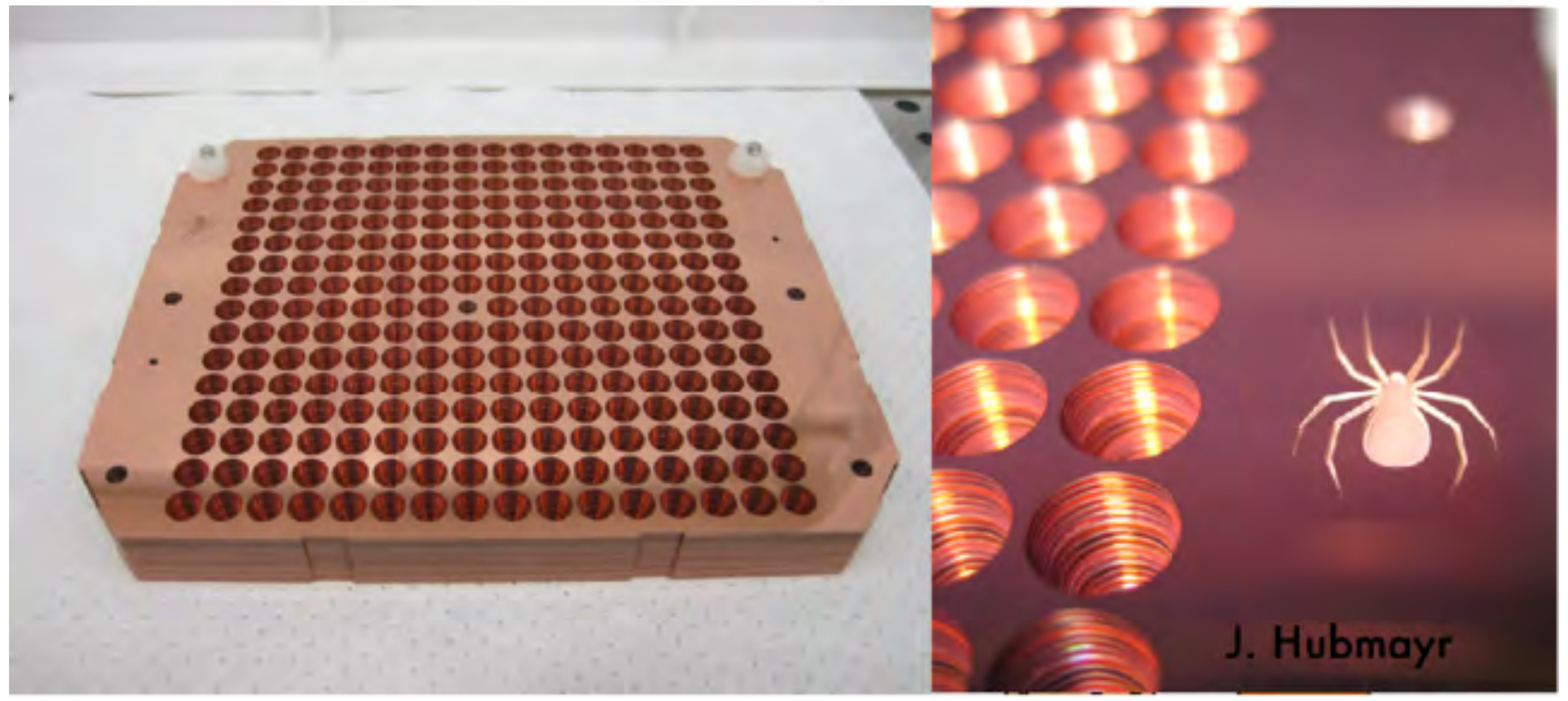
- Second flight targeting ~~2018/19~~ ~~2019/20~~ **2020/21** austral summer
- Expanded frequency coverage to resolve foregrounds with post-Planck sensitivities
  *3x **280 GHz** receivers, new optical design*
  *Best **95**/**150** receivers from first flight*

Avoid galactic CO lines









NIST platelet horn array
AlMn science TES

Hubmayr+ SPIE 2016
Bergman+ LTD 2017

Conclusions

- SPIDER performed well during its first flight
  - Successful automation, pointing, detector operations
  - Minimal impact from cosmic rays, RFI more significant
- 95/150 polarization analysis nearing completion
  - Ongoing work on foregrounds: rich and interesting!
- SPIDER-2 will soon map the sky at 280 GHz