The First Flight of SPIDER

Probing Inflation from the Stratosphere

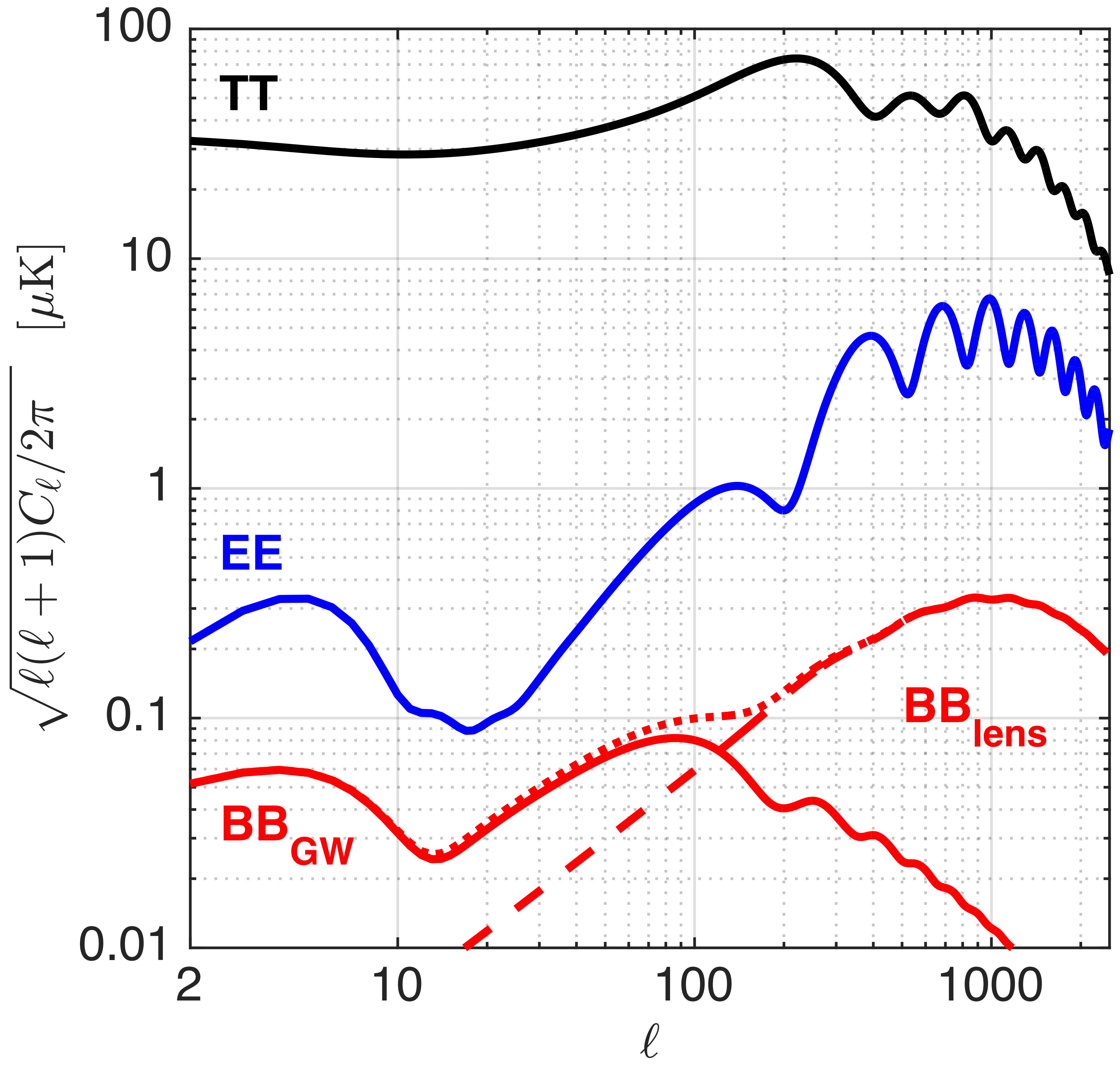
Jeff Filippini

ILLINOIS

APS April - Apr. 18, 2021

B-modes: Goals and Challenges

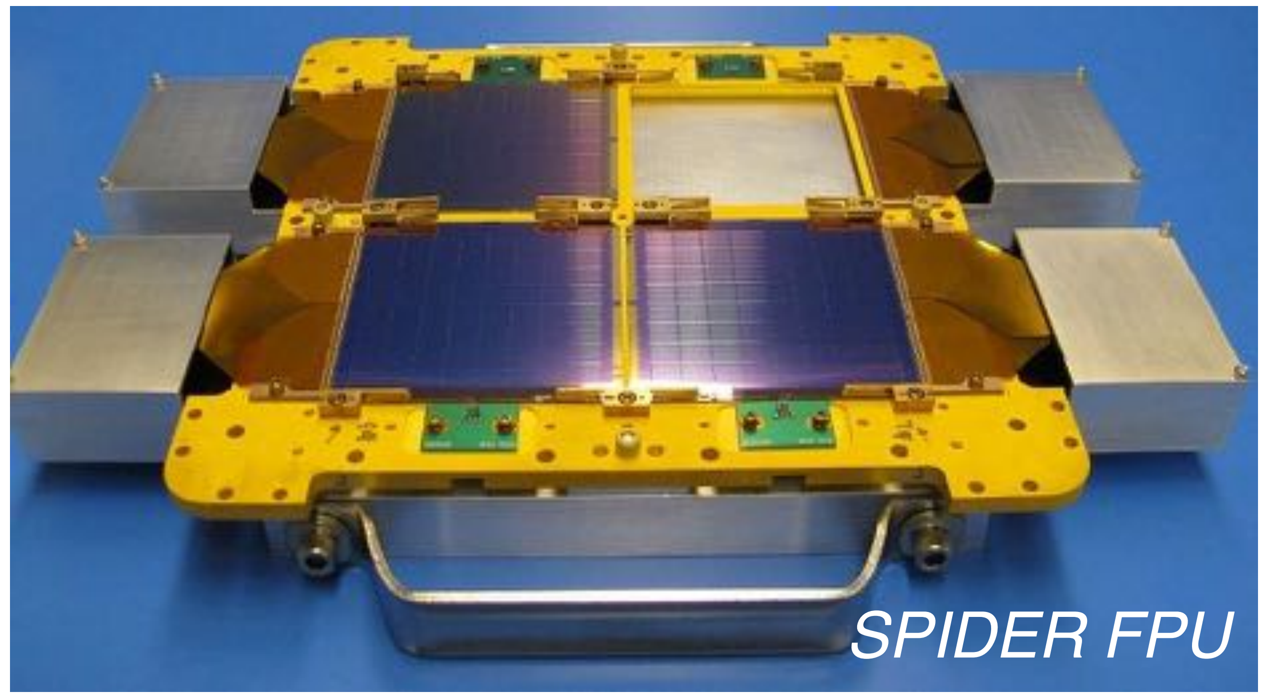
Target: B-mode polarization in the CMB at degree angular scales



Precision

Approach photon noise limit

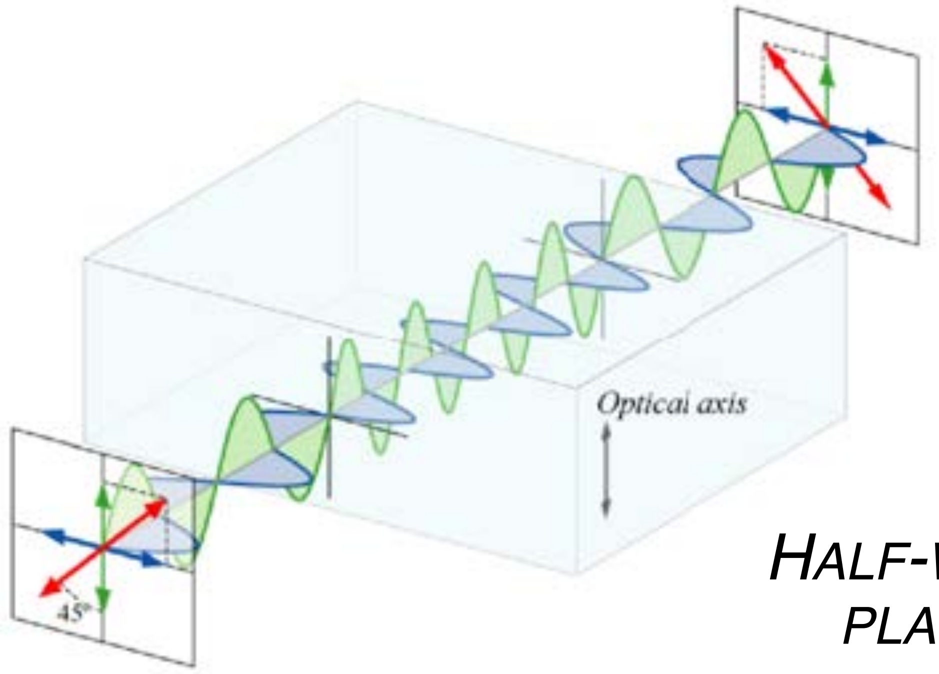
Few photons, many detectors



Accuracy

Rigid control of polarized systematics

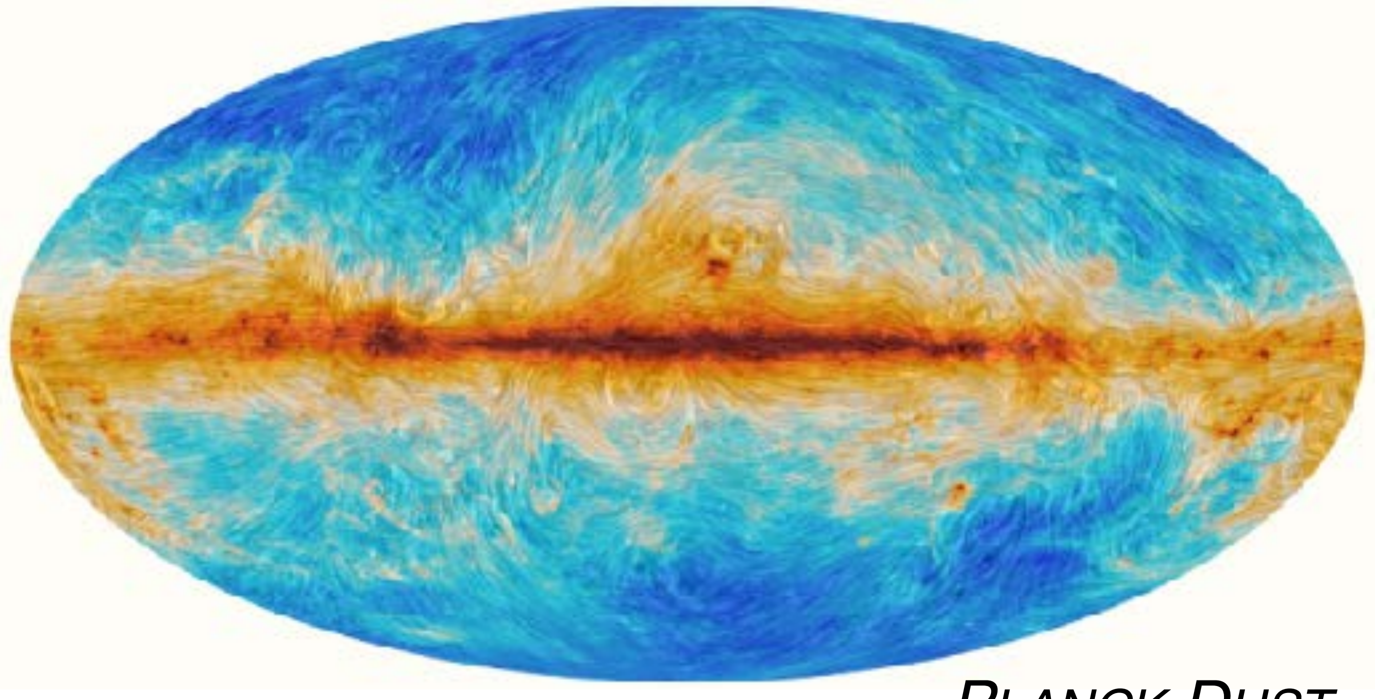
Instrument symmetry



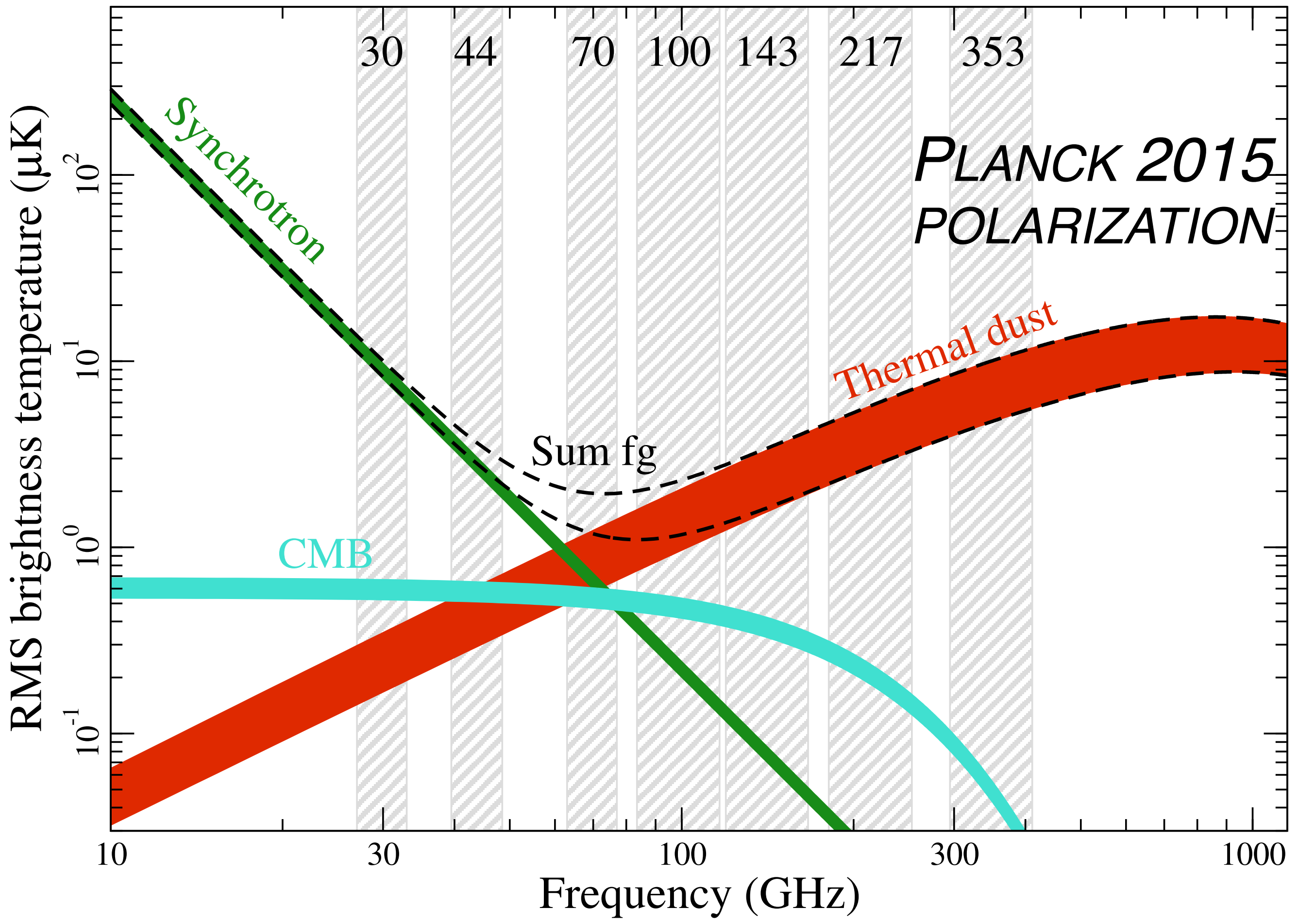
Half-wave plate

Clarity

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



Planck Dust polarization

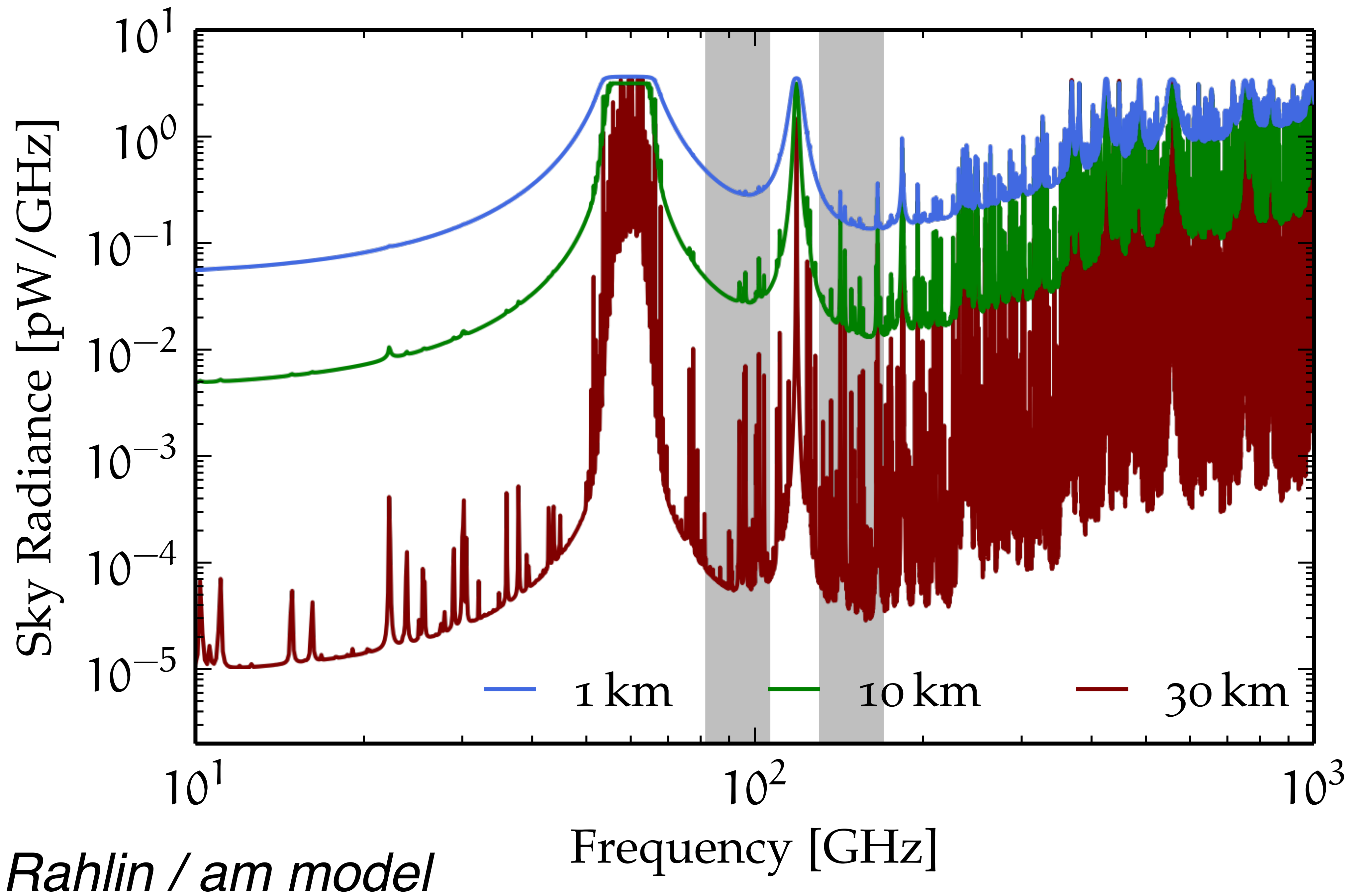


Planck 2015 polarization

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!

The SPIDER Program

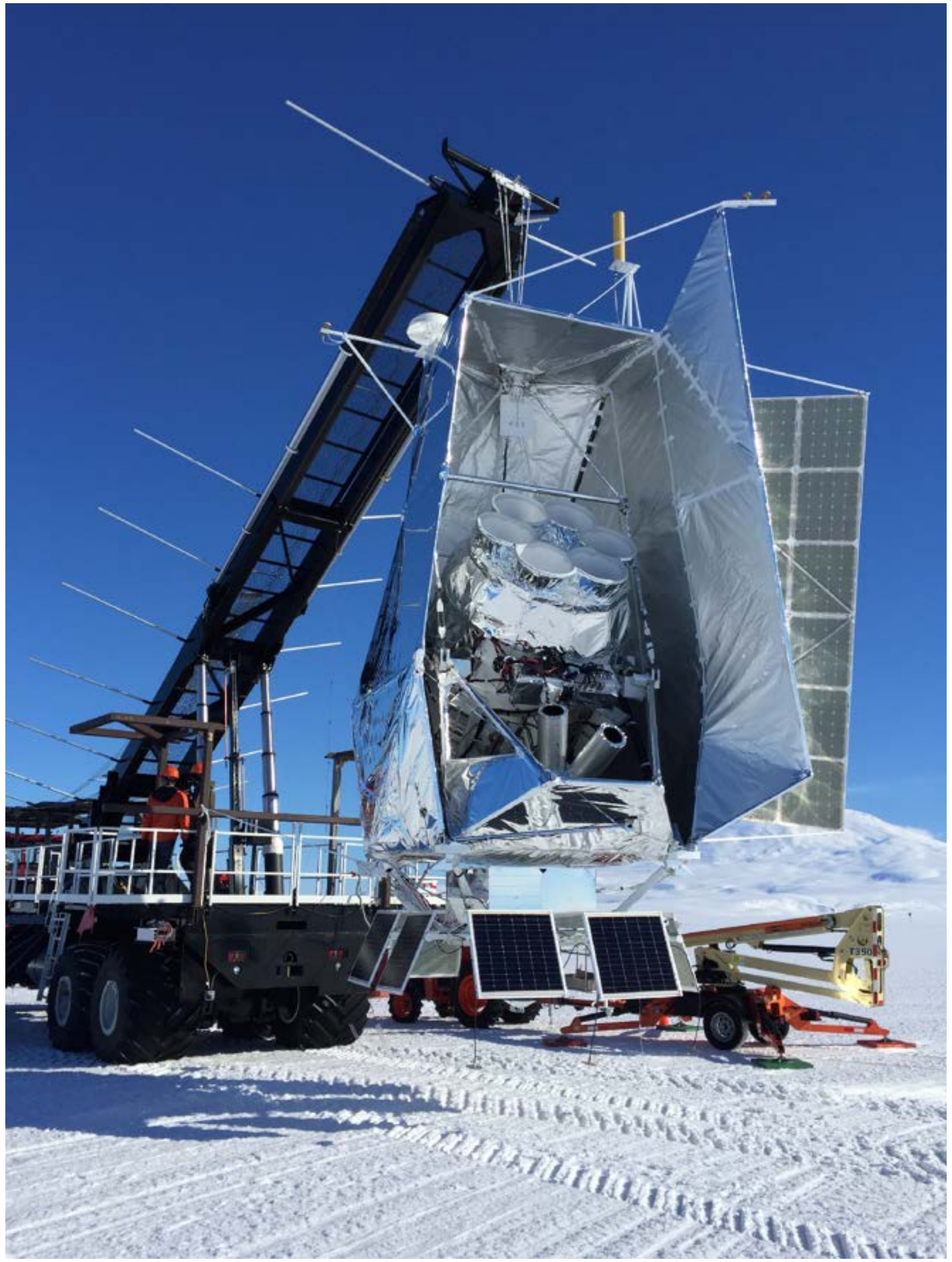
A **balloon-borne** payload to identify **primordial B-modes** on degree angular scales in the presence of **foregrounds**

1. Verify **angular power spectrum** and **isotropy**
   Large (~10%) sky coverage

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

Ade+ arXiv:2103.13334 (2021)
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 …

*Major support from **NASA APRA** (mission), **NASA SAT** (detectors), **NSF OPP** (Antarctic support)*



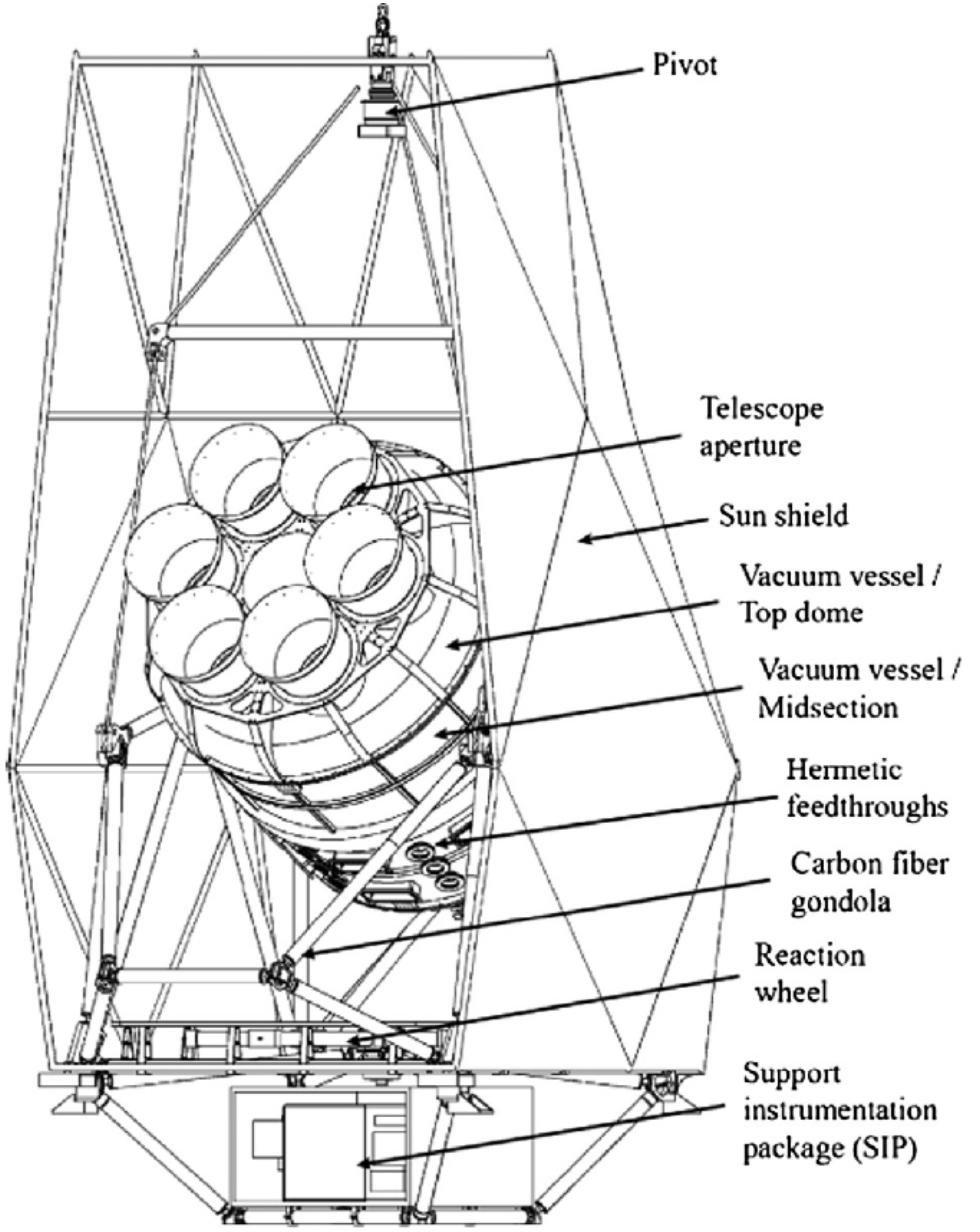
Balloonatics

SPIDER
SEARCHING FOR THE ECHOES OF INFLATION

NASA
NSERC CRSNG
JPL
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

The SPIDER 2015 Payload

- Large (*1300 L*) shared **LHe cryostat**
- Lightweight **carbon fiber gondola**
  - Az/el drives, redundant pointing sensor suite
  *- Launch mass **3000kg***
- Six **monochromatic refractors** (*3x95, 3x150 GHz*)
  - Cold HDPE lenses, 270mm stop
  *- Stepped sapphire **half-wave plate***
- Design emphasis on **low internal loading**
  - 1.6 K absorptive baffling, reflective fore baffle
  - Reflective filter stack, thin (3/32”) window
- JPL **antenna-coupled TES bolometer arrays**
  - Low-G, low-noise design; dual-TES for calibration
- Time-division SQUID multiplexer (*NIST, UBC*)
  - Extensive magnetic shielding



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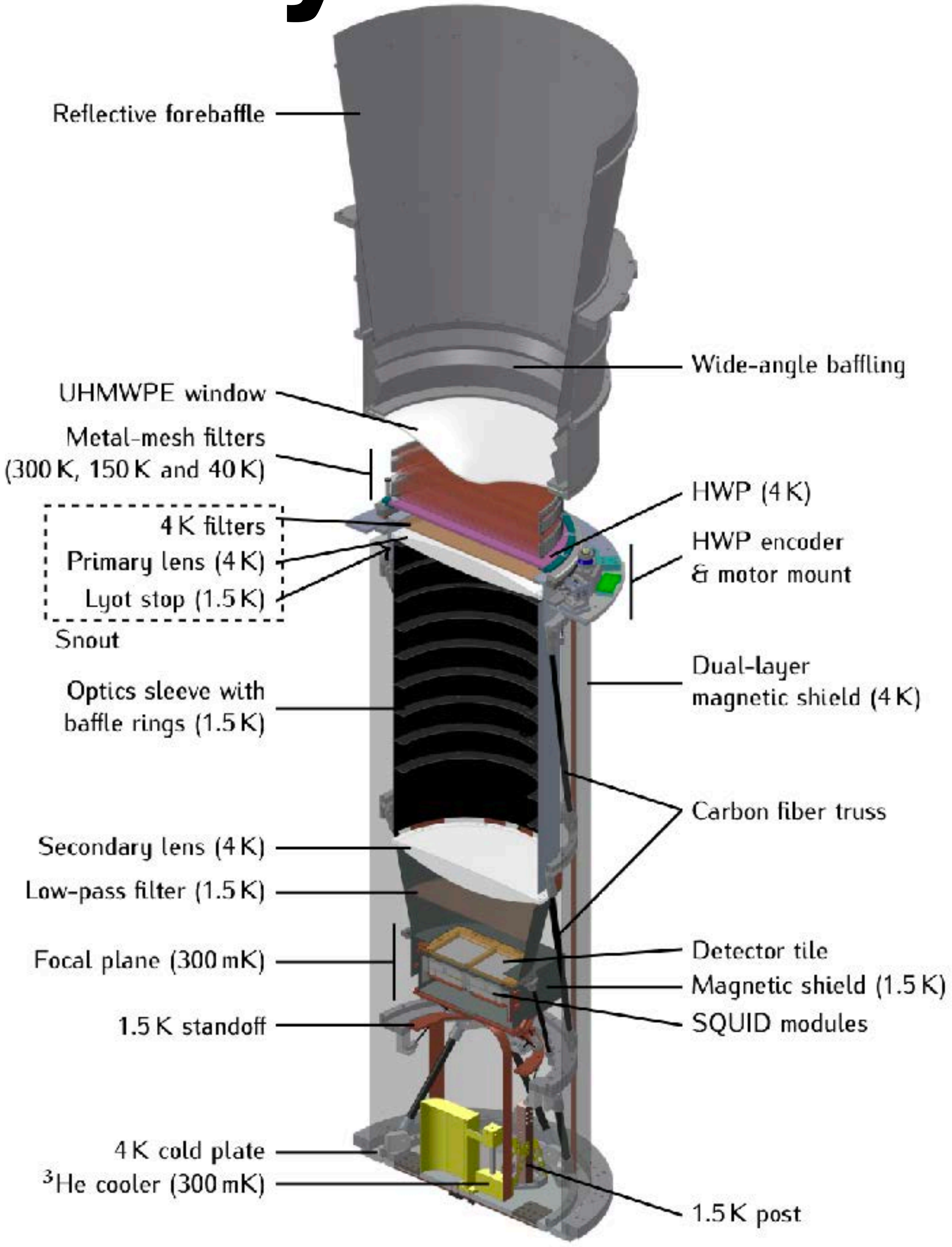

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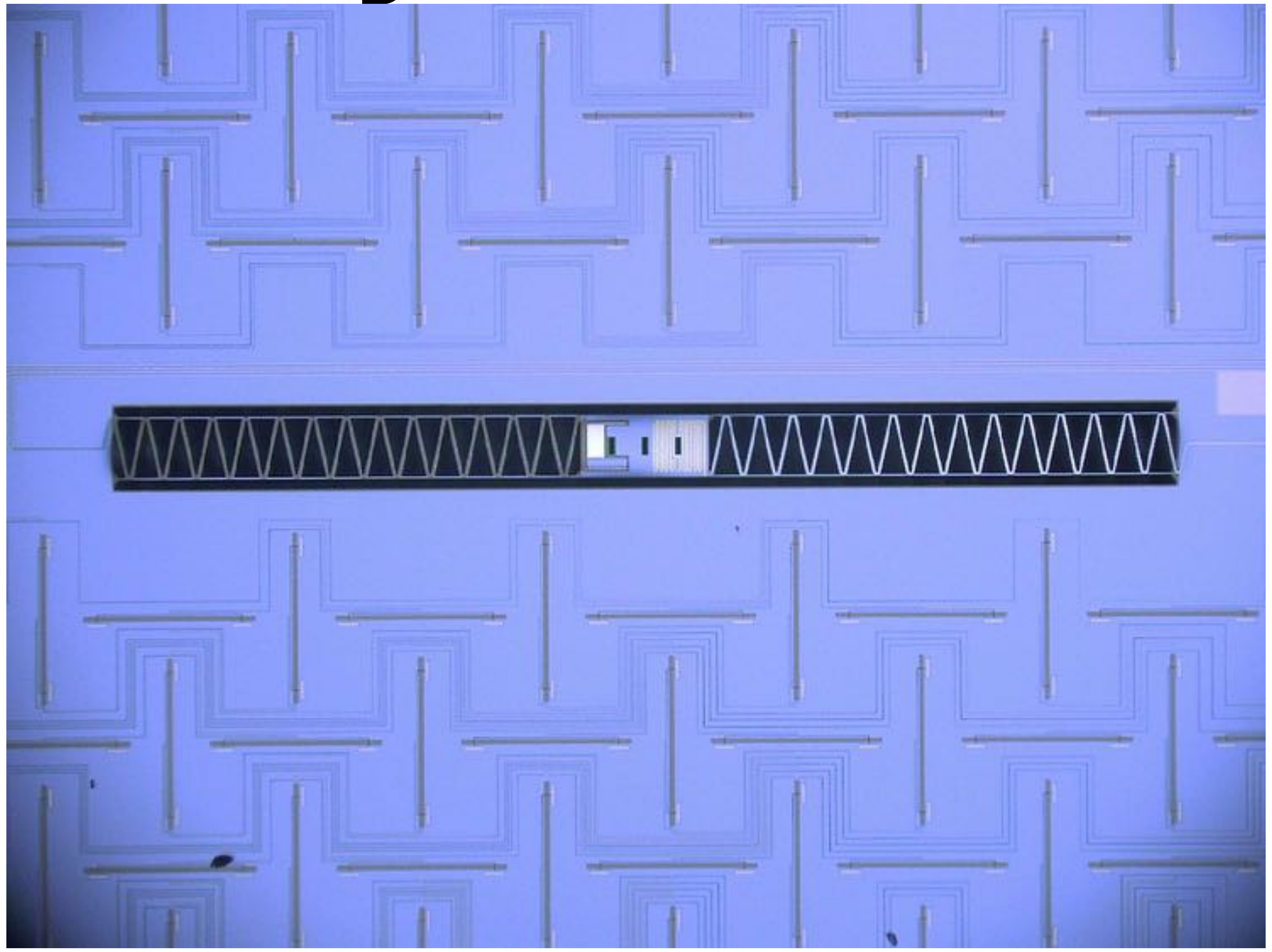
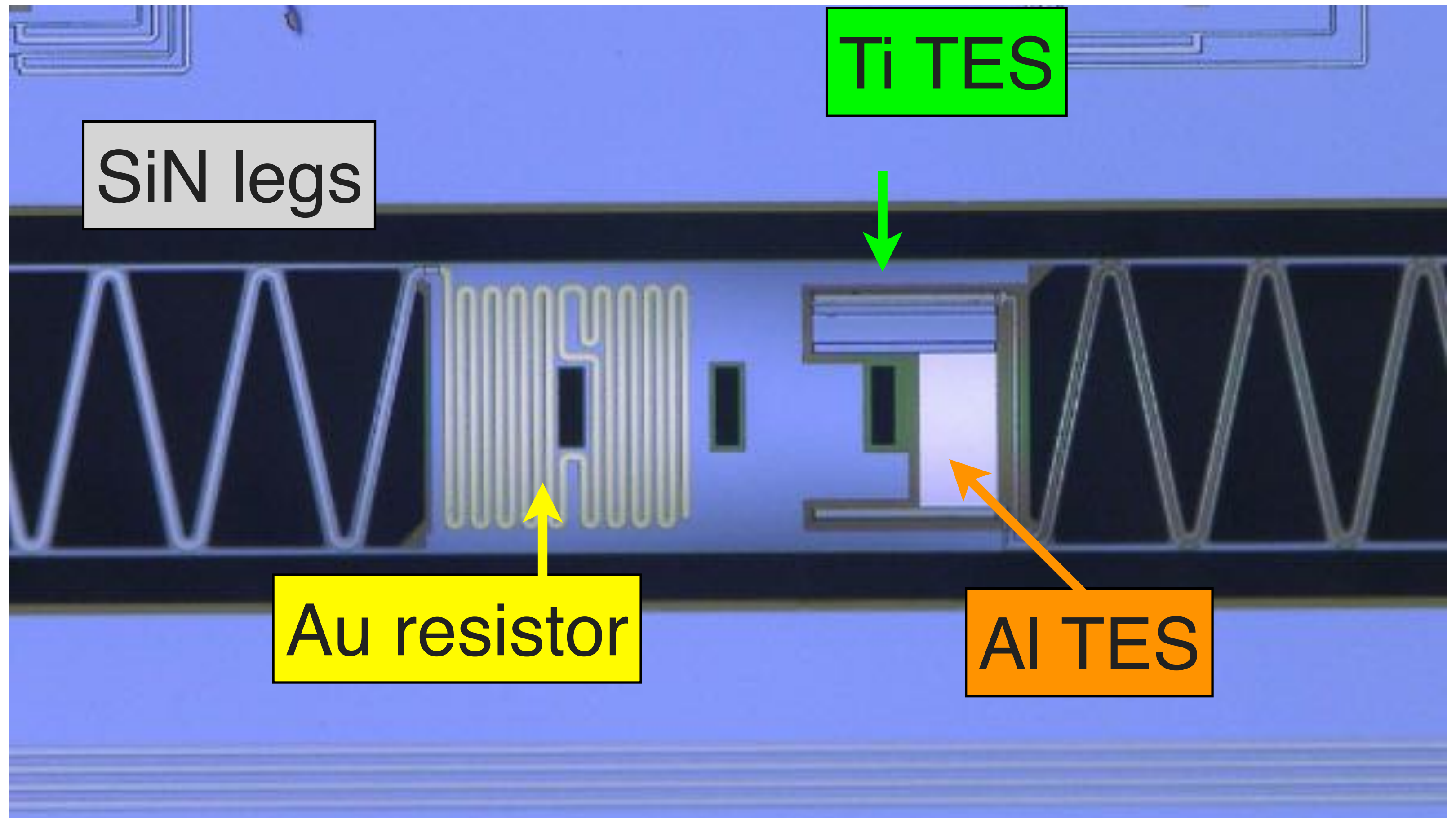
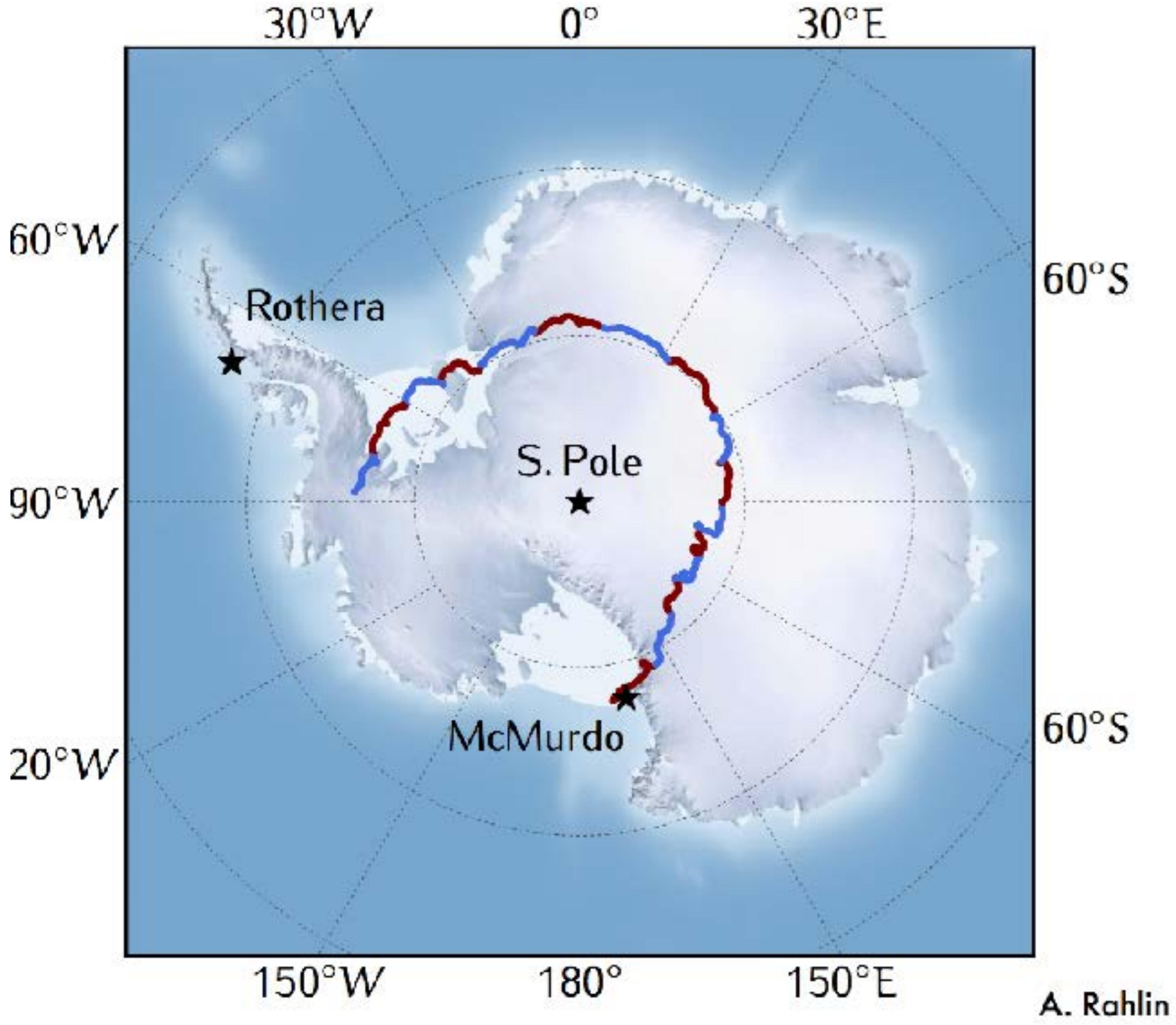




JPL

SPIDER Aloft!

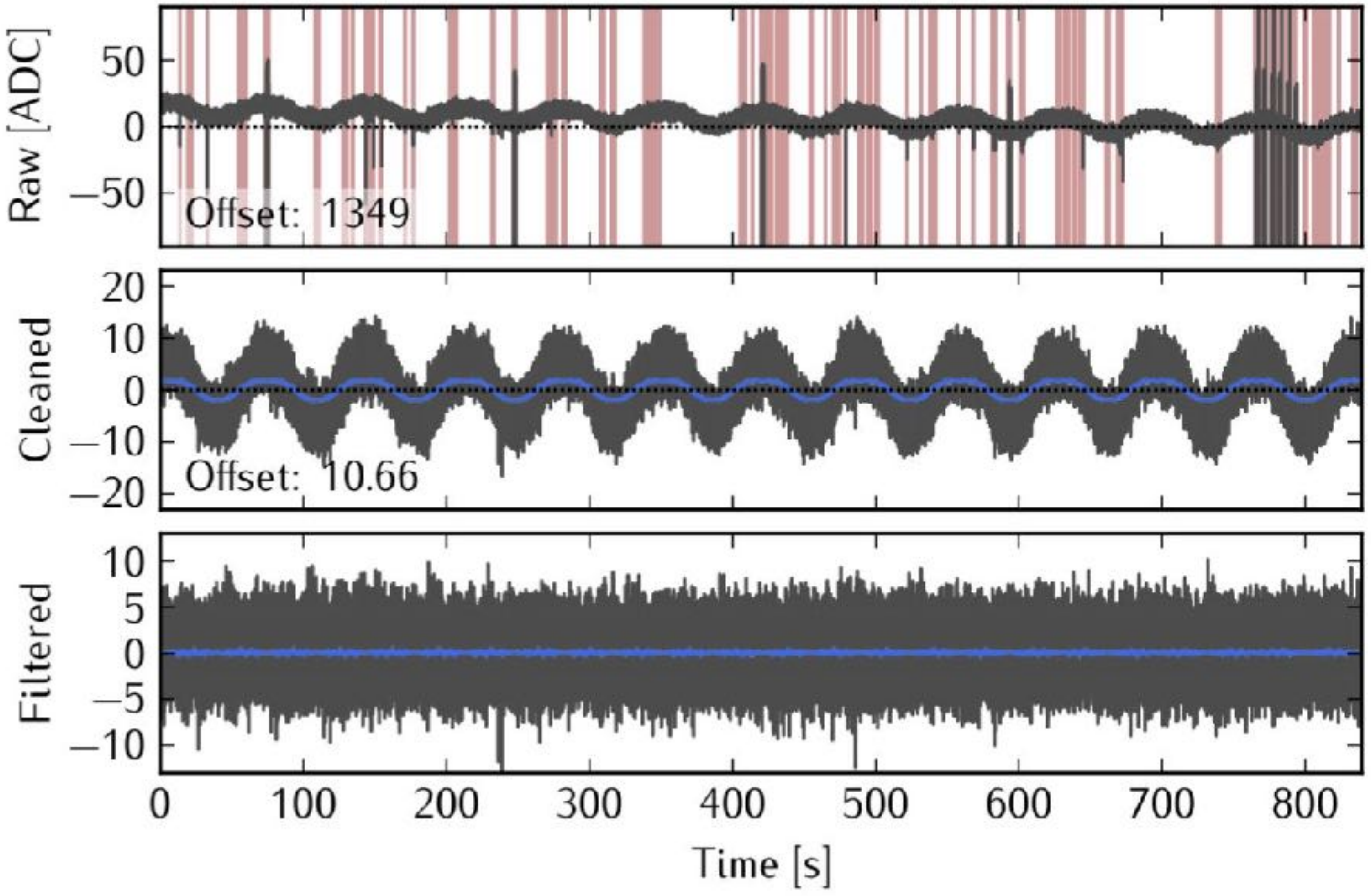
- January 1-18, 2015
  ~35 km altitude
- All* systems functional!
  **except dGPS, no science impact*
- Full hardware and data recovery in 2015 with help of **British Antarctic Survey**



In-Flight Performance

- Exceptionally **low internal loading**
  95 GHz: ≤ 0.25 pW total absorbed
  150 GHz: ≤ 0.35 pW total absorbed
- Flagging of samples and channels
  - Negligible from **cosmic rays**
    Osherson+, JLTP 199,1127–1136 (2020)
  - Significant from **RFI**
    Transmitter handshake every ~1 minute
  - Strict channel / sky cuts this analysis
    ~1/4 of scan time outside analysis region
    Wide exclusion around fridge cycles
    One 150 GHz receiver excluded
- Scan-synchronous pickup (*~CMB dipole*)
  Addressed for now with aggressive filtering

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



Monitoring and Calibration

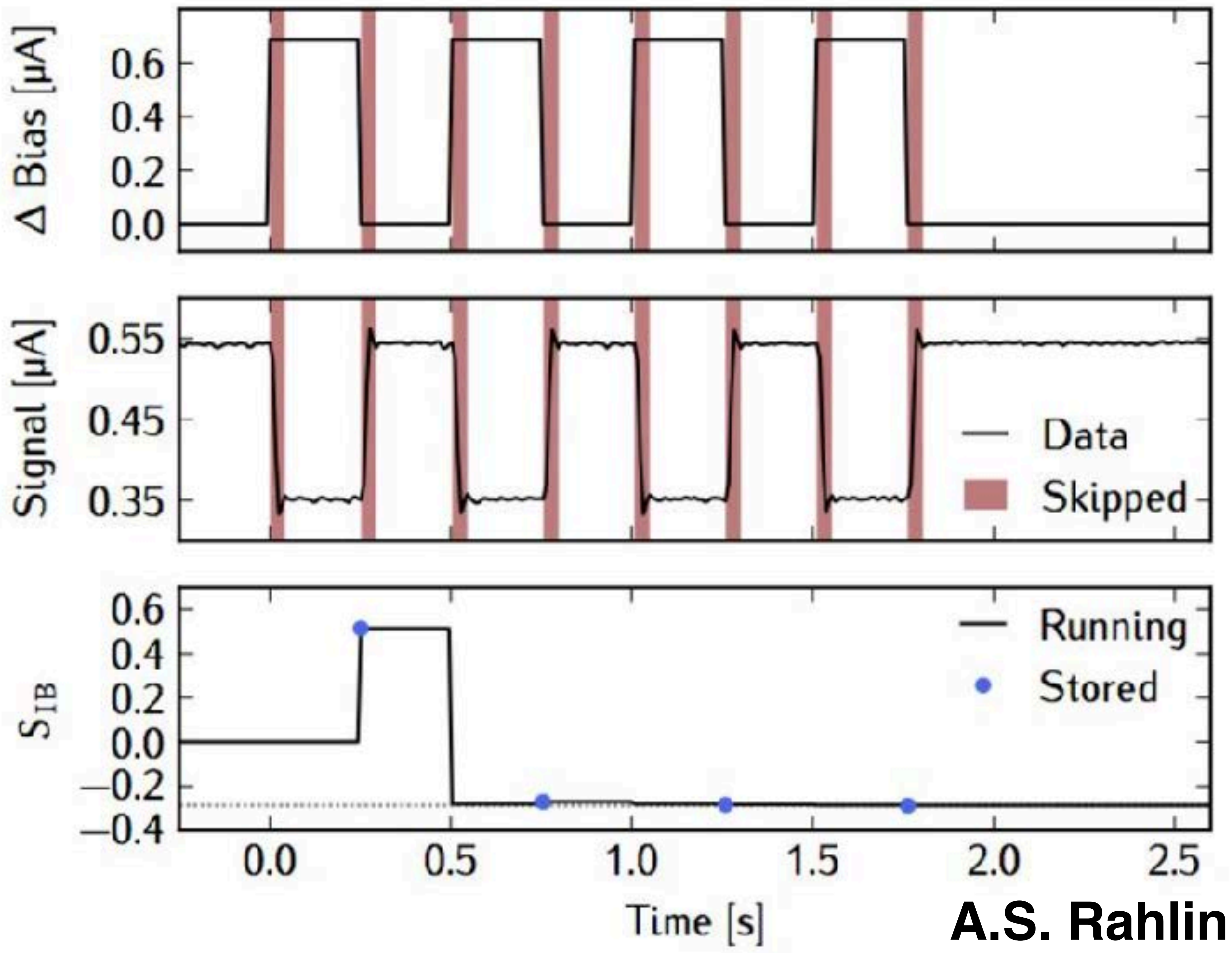
Pre-flight calibrations

TESs, pol angle, FTS spectra, near-field beams, …

Autonomous detector operations

Electrical bias step response during scan turnarounds used as proxy for CMB gain variation

Monitor loop adjusts TES biases (and SQUID tuning) as needed; downlinks minimal statistics



A.S. Rahlin

Post-flight

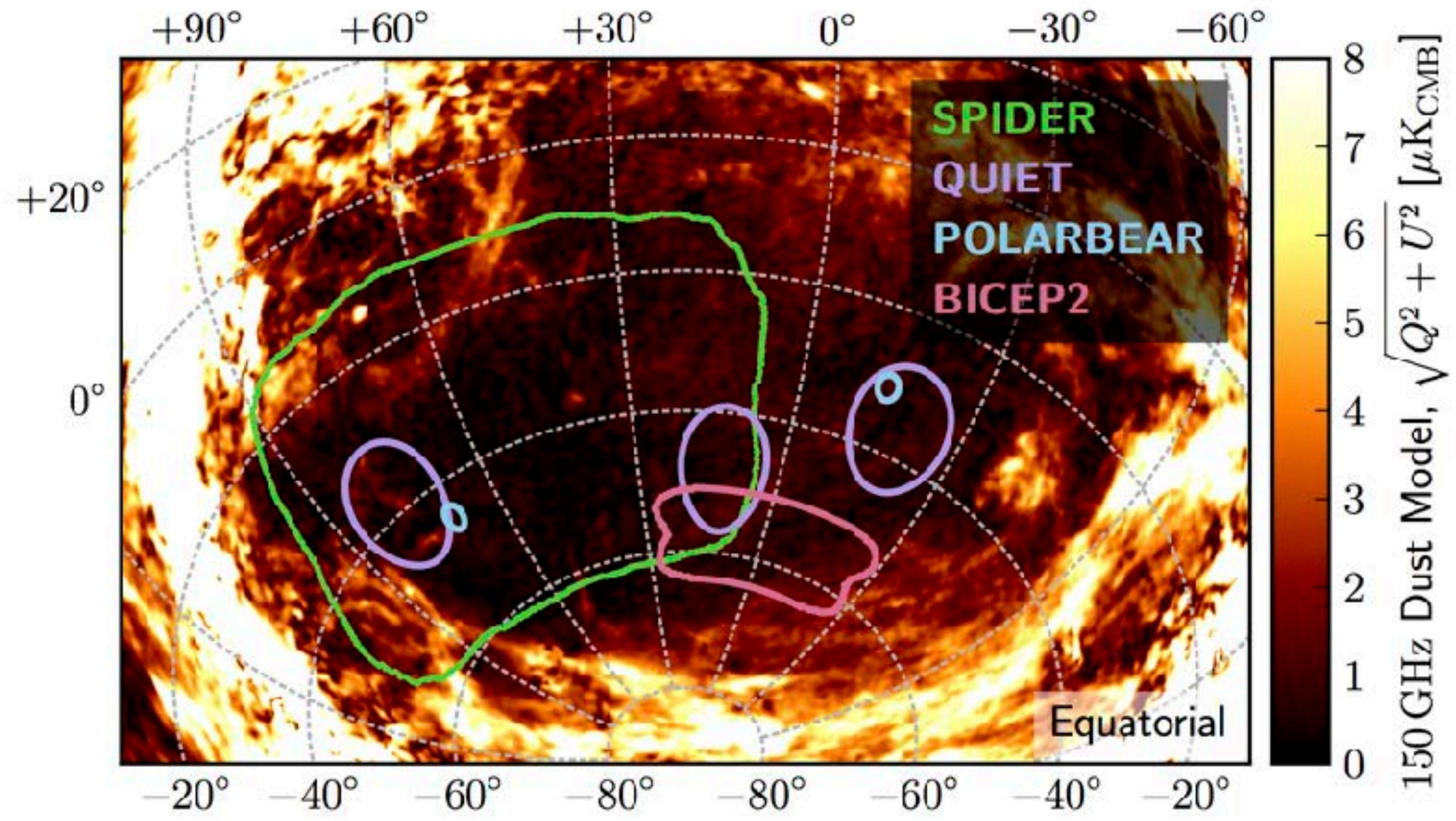
Beam, gain regression against *Planck* maps

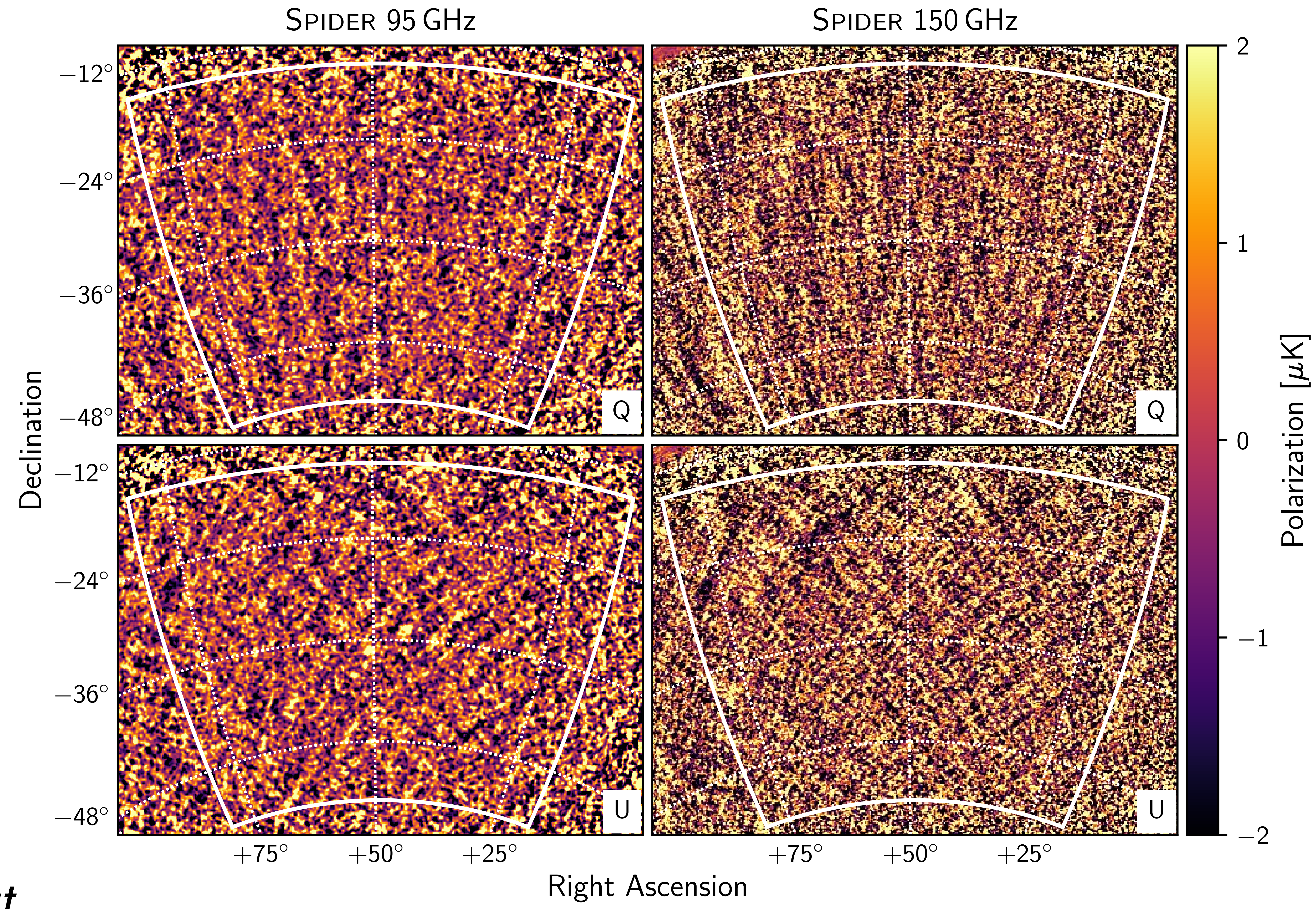
Simulations of effects of known systematics
Negligible at required sensitivity

Excellent **gain stability** in flight

Electrical calibration correlates well with in-flight gain estimates

The View From Above





Observations cover **12.3%** of the sky

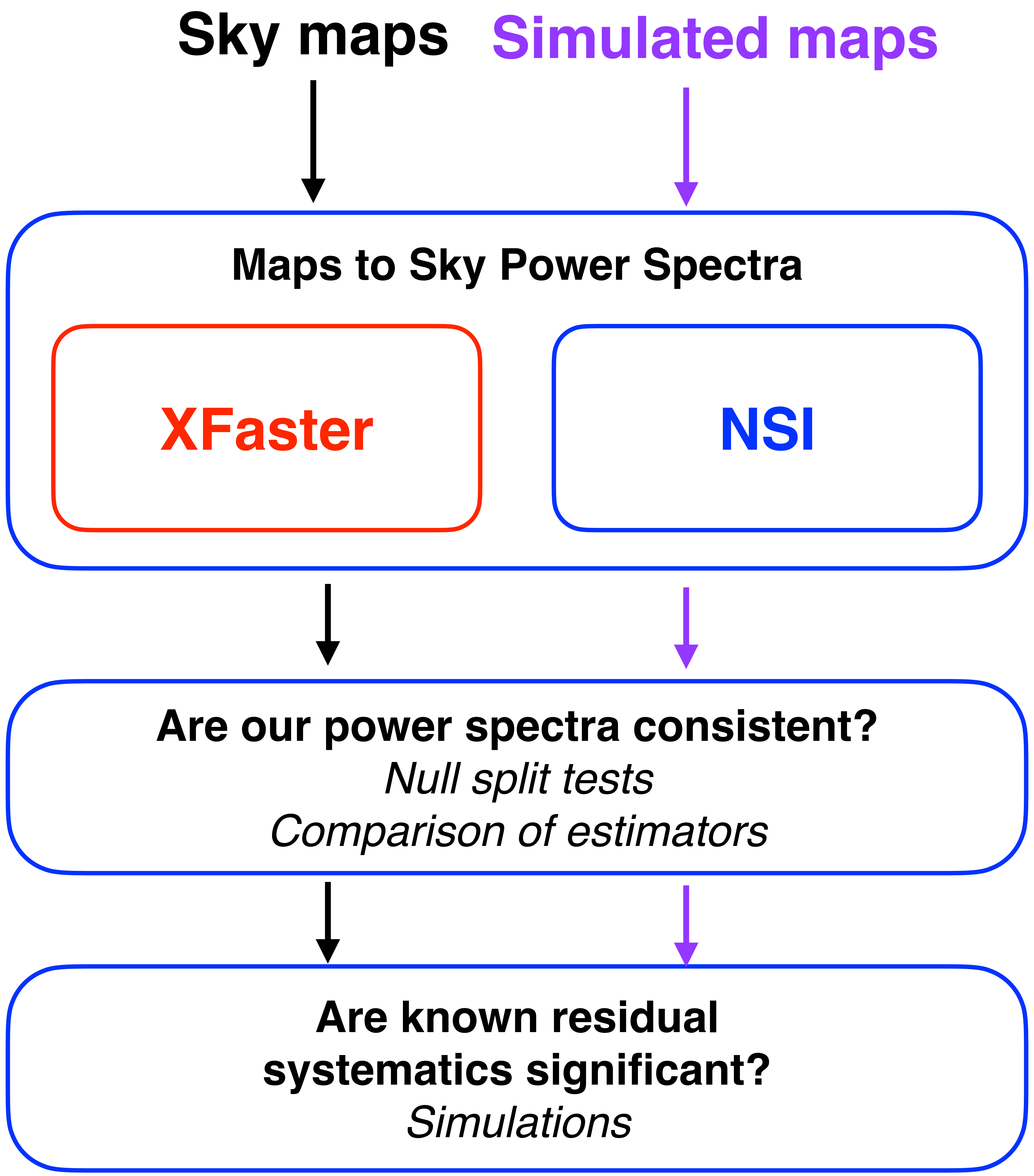
Hit-weighted 6.3%

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

1992 deg² rectangle, point sources cut

From Maps to Power Spectra

- Two independent **power spectrum** estimation pipelines
  - XFaster: Hybrid maximum likelihood
    Pseudo-Cl + iterative quadratic estimator
    A.E. Gambrel, A.S. Rahlin, C. Contaldi, …
    arXiv:2104.01172
  - NSI: "Noise Simulation Independent"
    Covariances among data subsets
    No noise simulations
    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 and estimate systematic effects



Raw Power Spectra

Power spectra over *9 "science" bins*

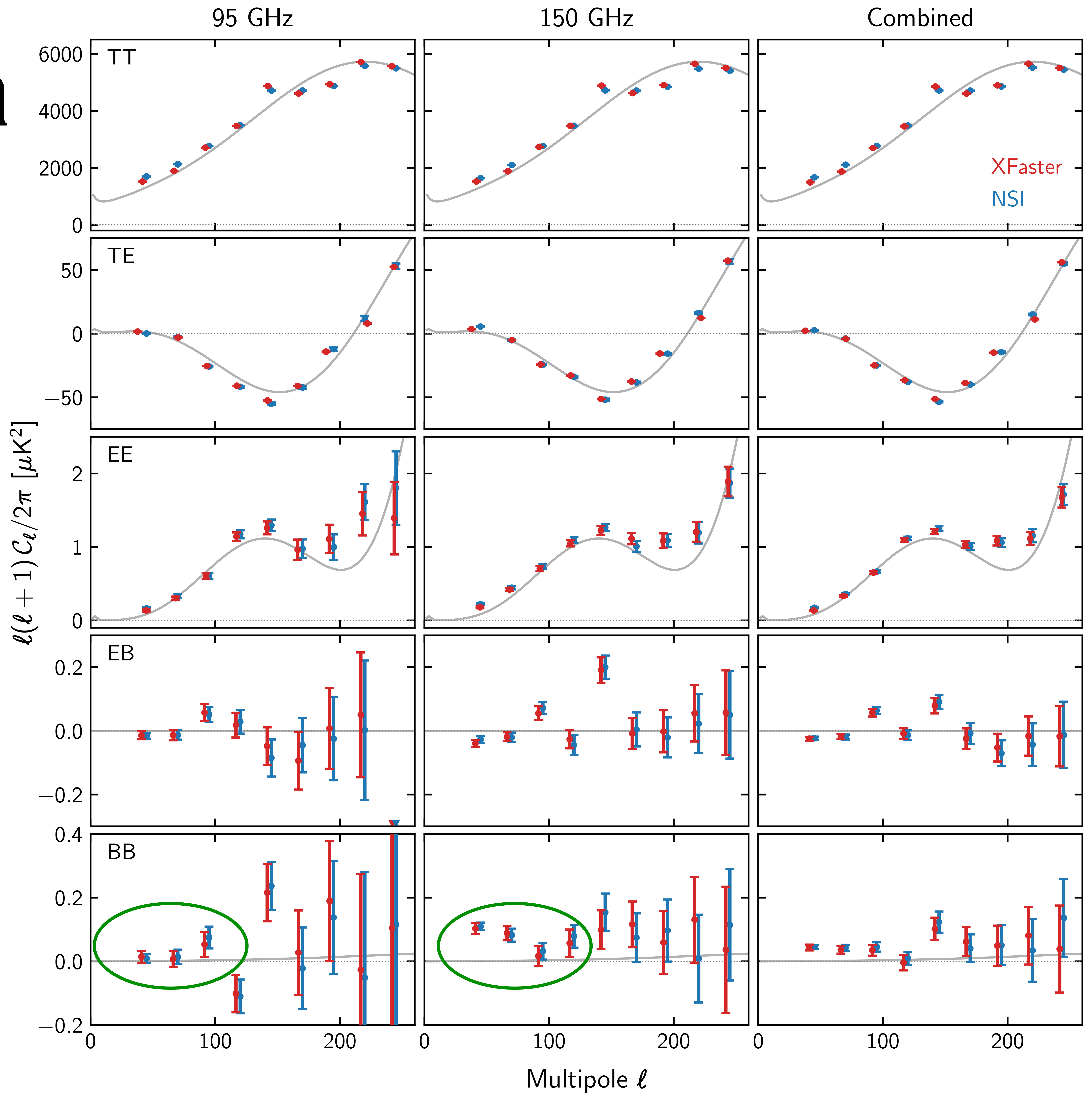
Multipoles $33 \leq \ell \leq 257$

Good agreement among estimators

Multiple **foreground cleaning** techniques

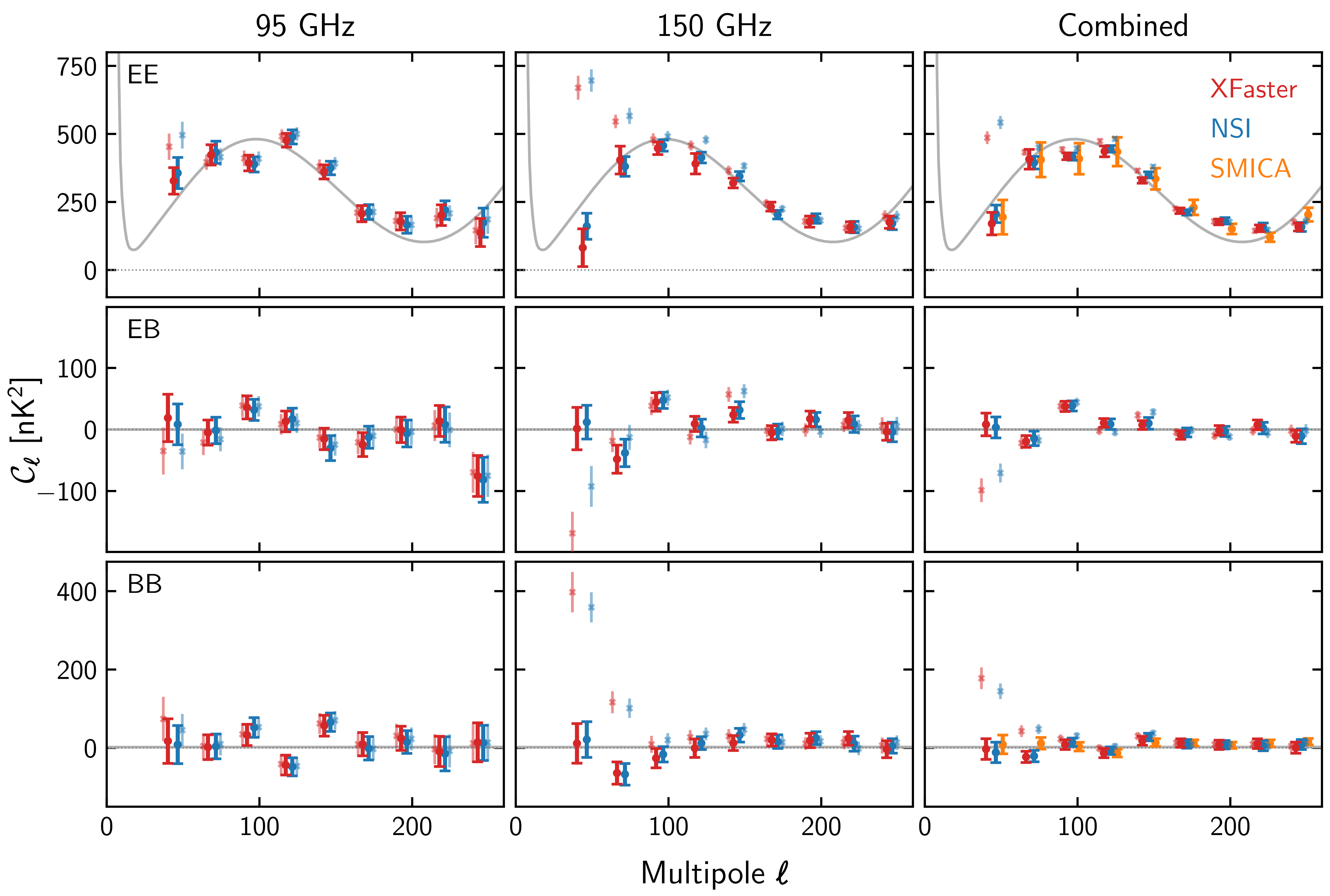
- Spatial template subtraction
  Planck 353-100 / 217-100 templates
- SMICA
  Harmonic domain model
- Harmonic SED fitting
  Multi-component synchrotron + dust

See talk by Johanna Nagy

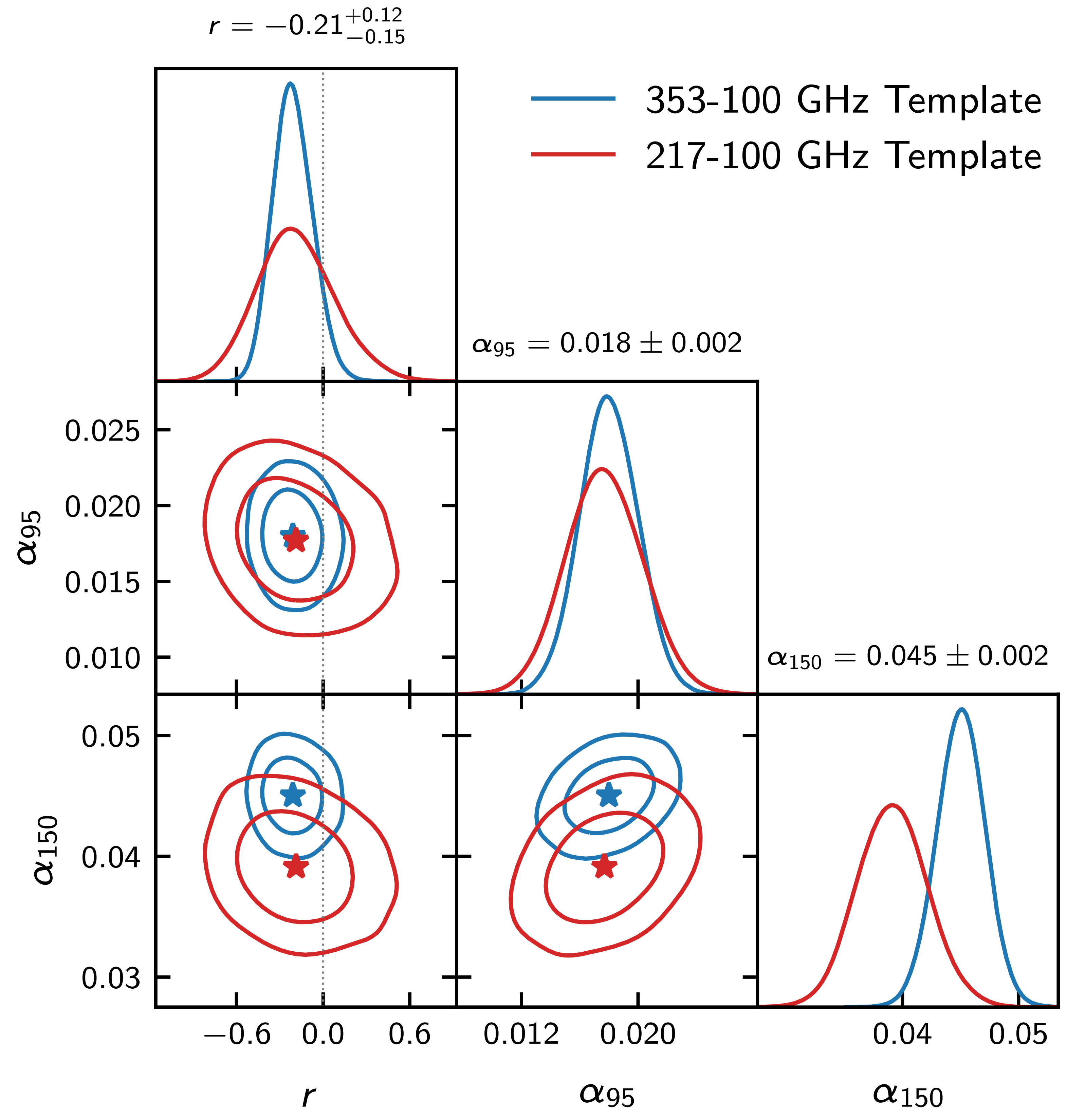


Error bars do not include sample variance, for ease of pipeline comparison

CMB and Constraining *r*



353GHz template subtraction; sample variance included



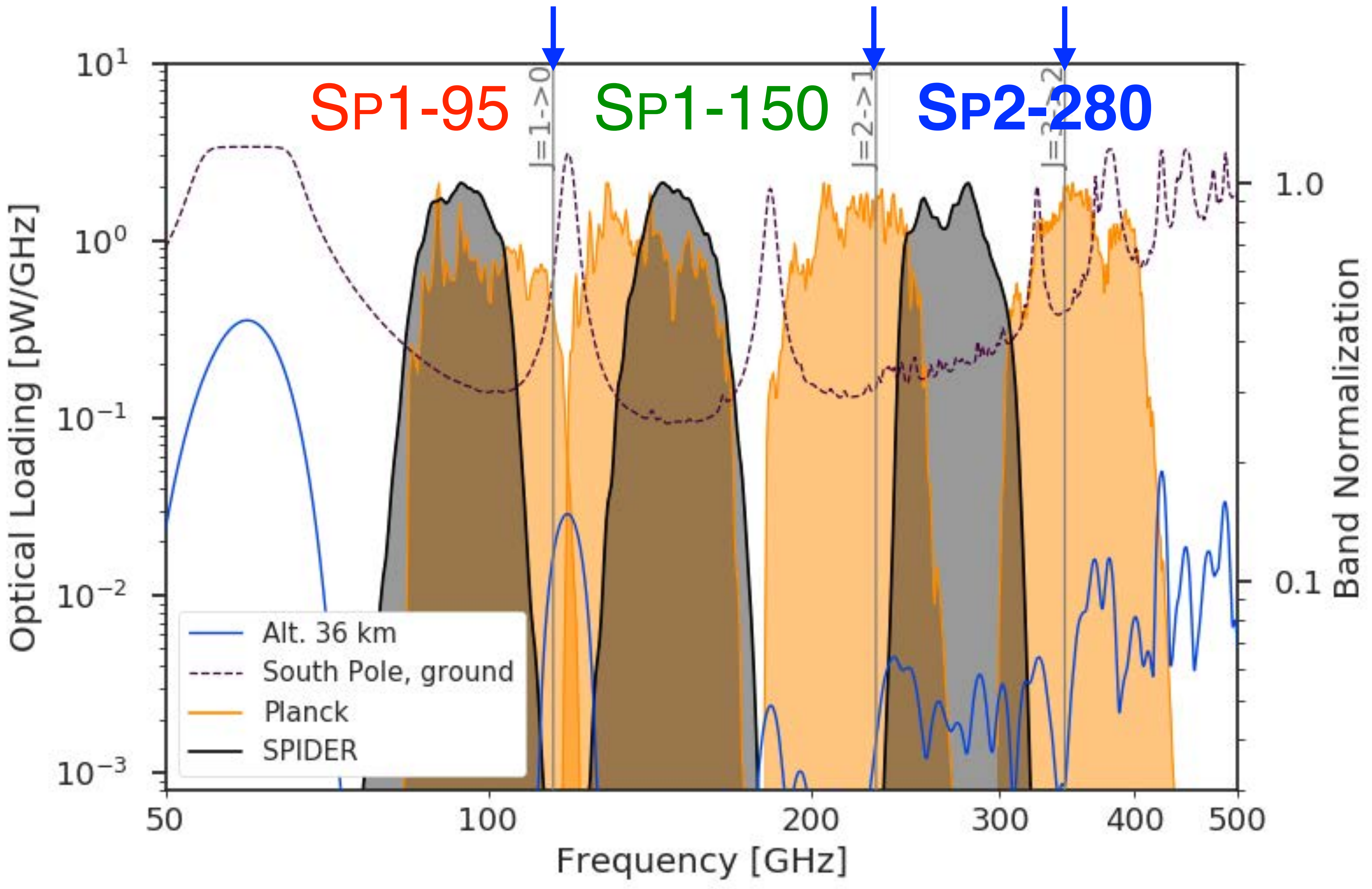
Primary results: XFaster, 353 GHz template

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

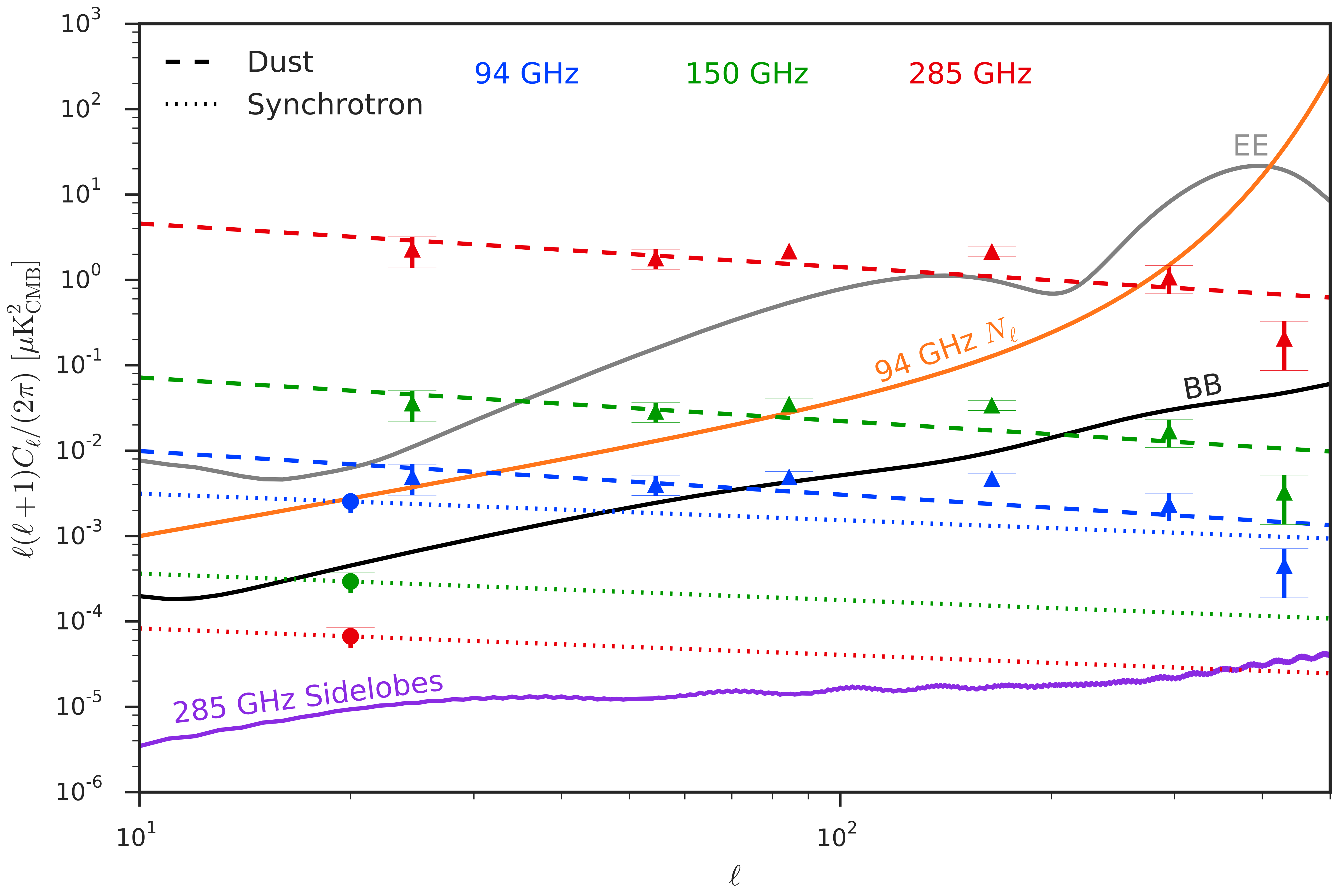
SPIDER-2

Expanded frequency coverage to resolve **Galactic dust** with **post-Planck sensitivities** over a **large sky area**

Avoid galactic CO lines



Commander foreground estimate

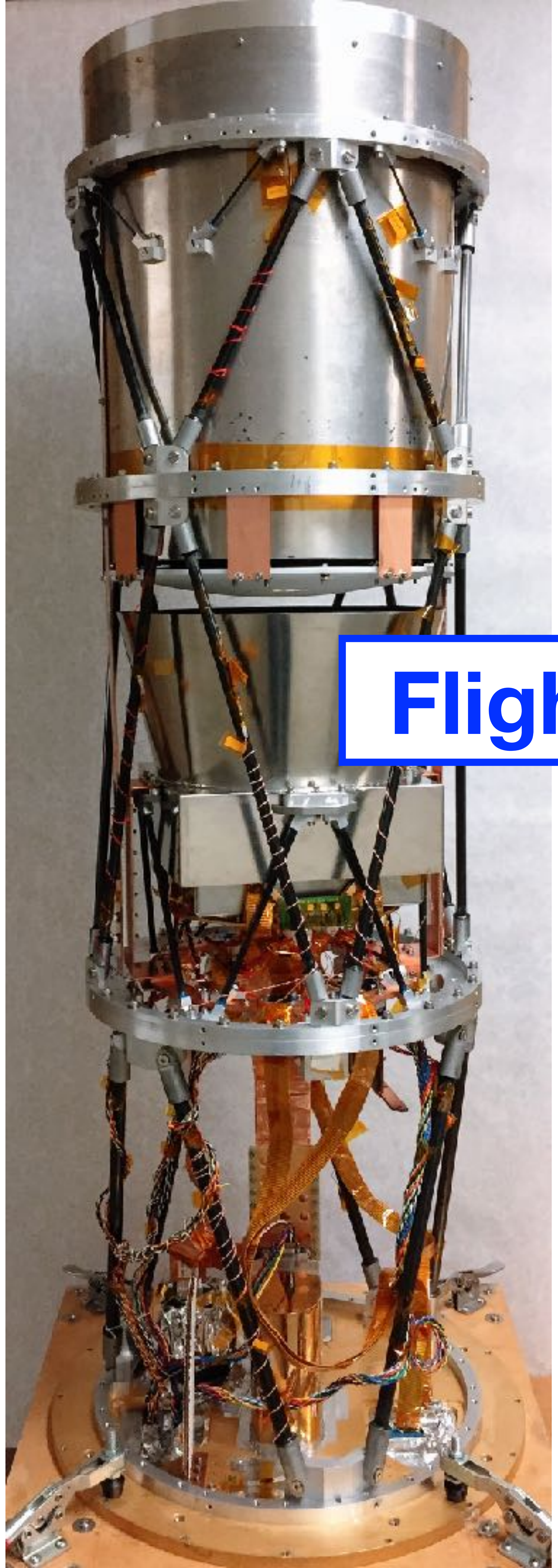


*3x **280 GHz** receivers, new optical design*

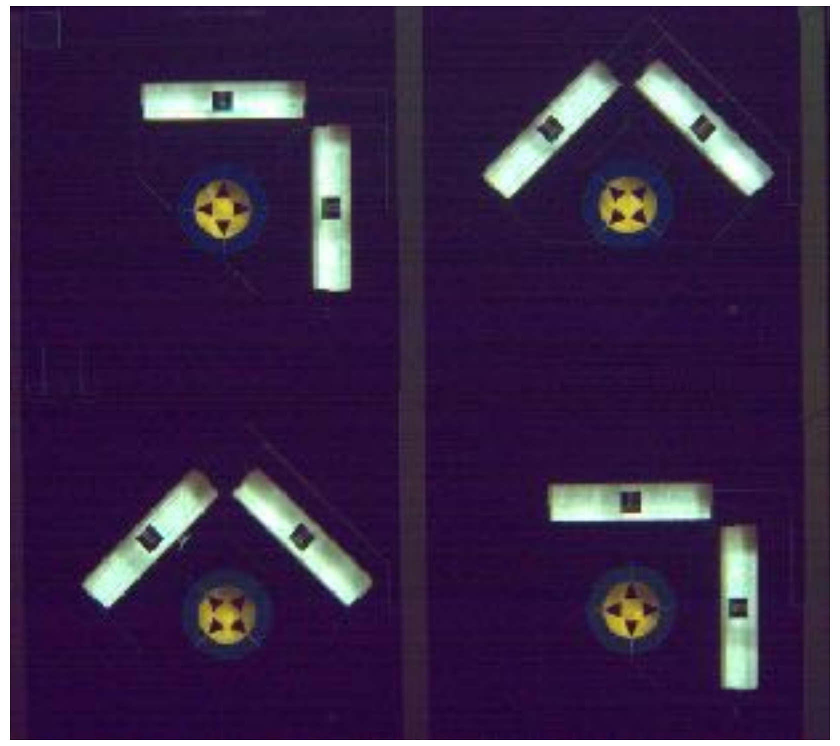
*Best **95**/**150** receivers from first flight*

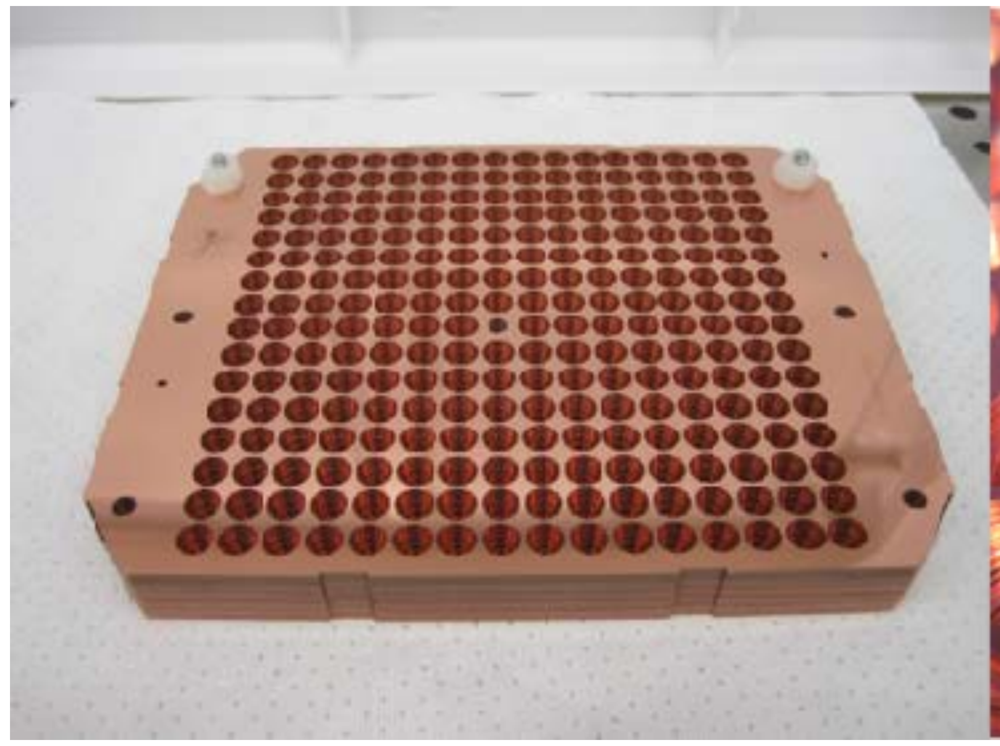
Rebuilt cryostat and gondola

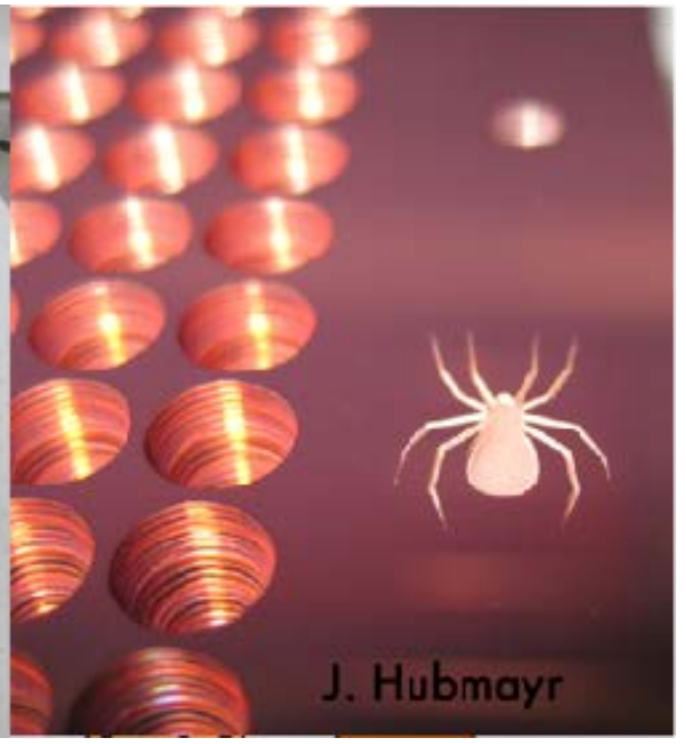
Dust Busters

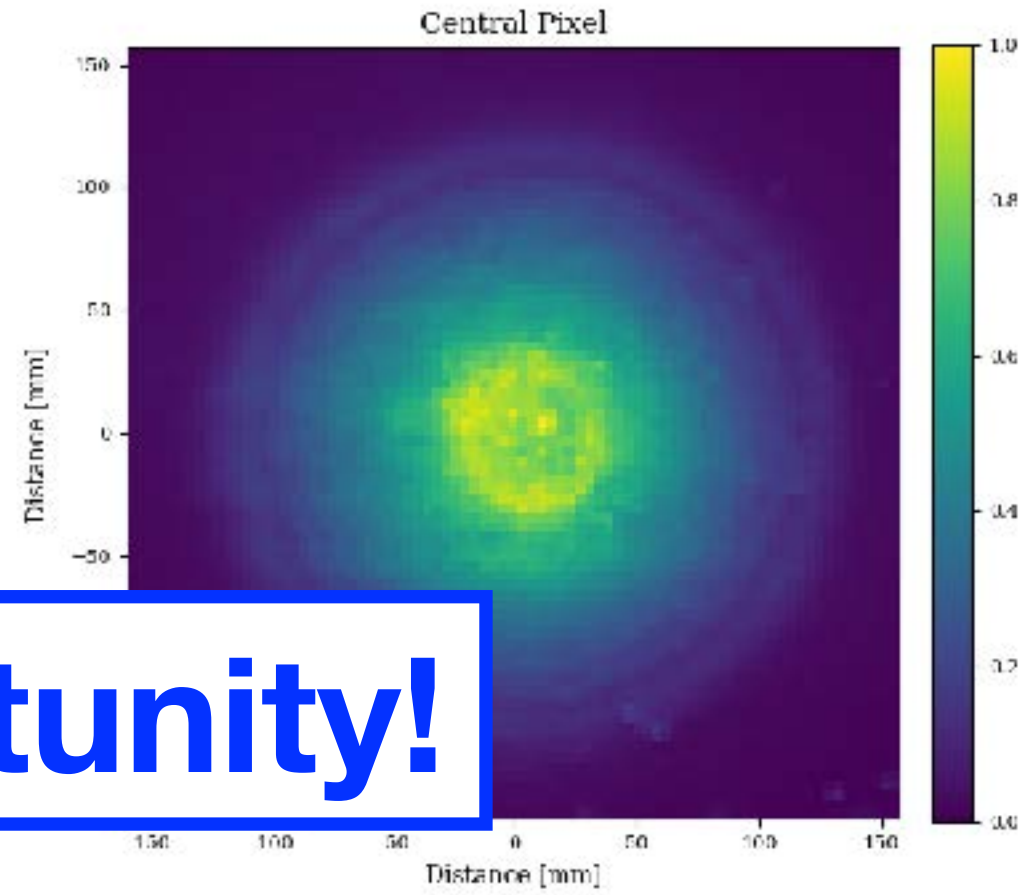


NIST platelet horn array
AlMn science TES

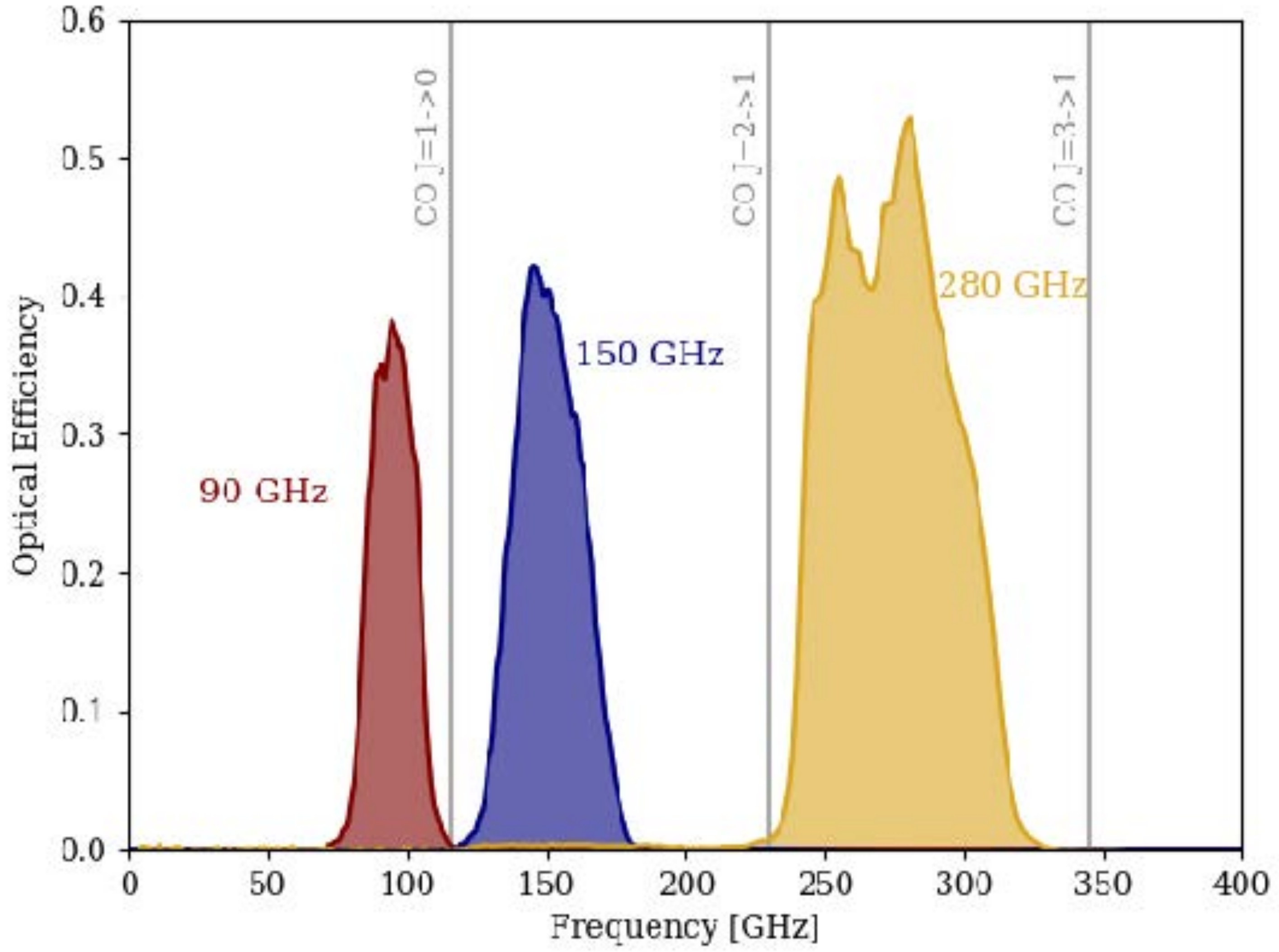






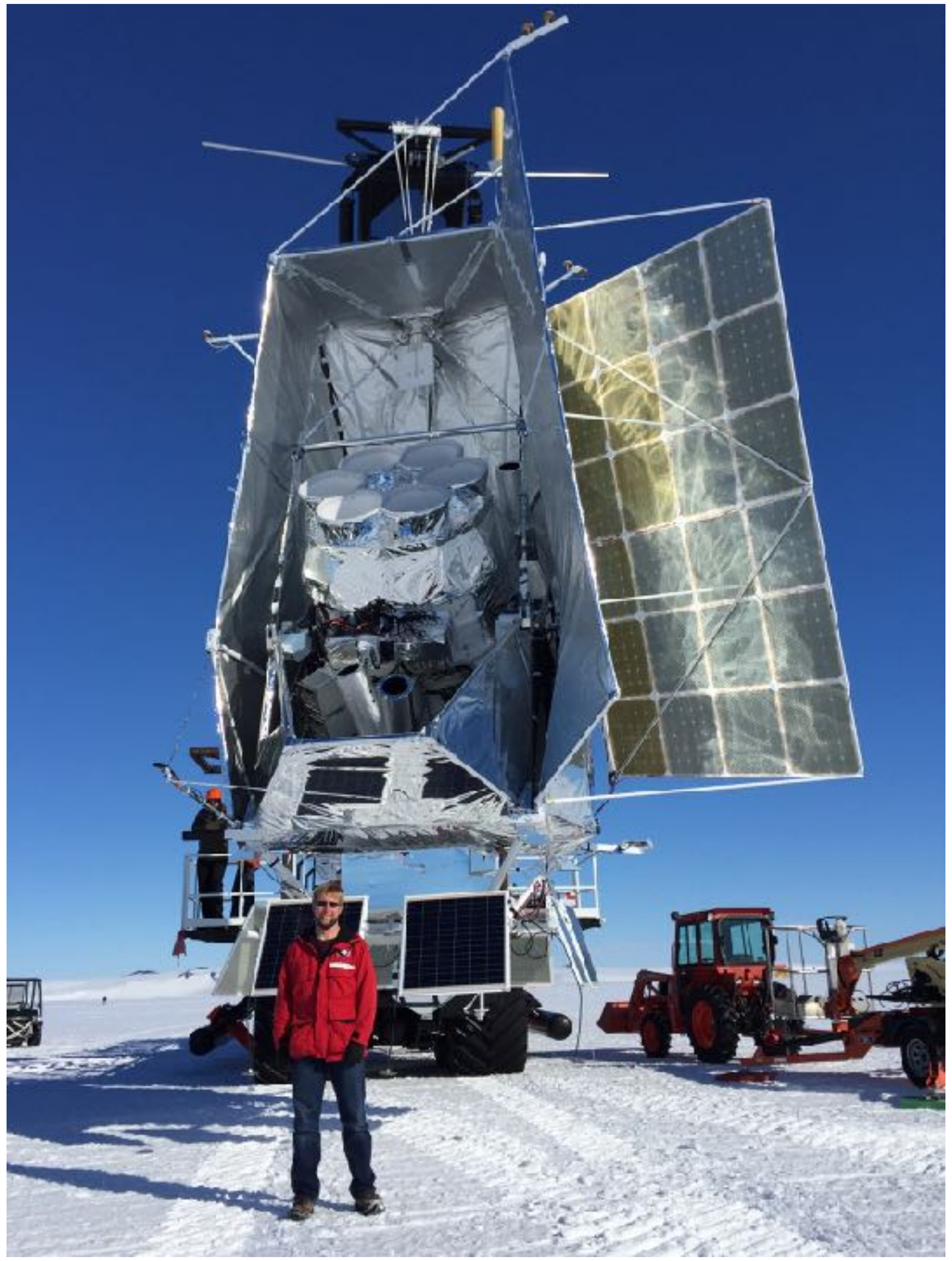


Flight ready and awaiting launch opportunity!



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

SPIDER and Inflation Probe



Detectors and Readout

Antenna- & Horn-Coupled TES arrays

TDM SQUID readout

Cold Optics

Stepped half-wave plate

HDPE optics, filters, baffling

Control Systems

Automated SQUID / TES management

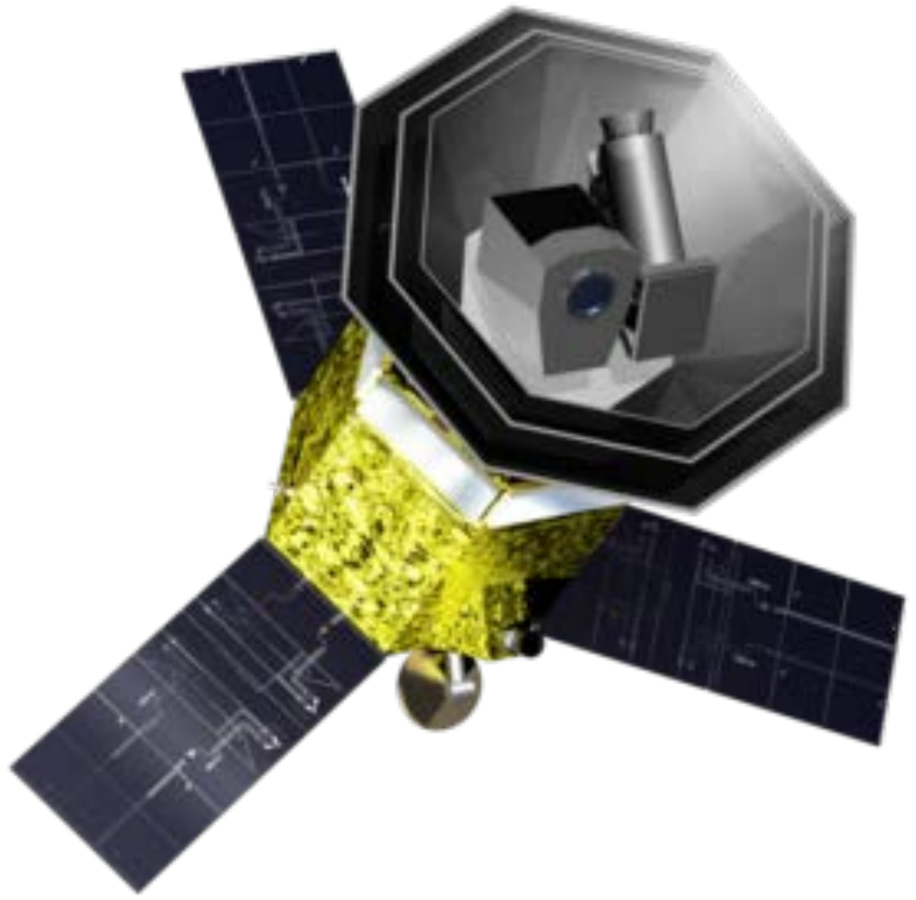
Bias step monitoring of TES

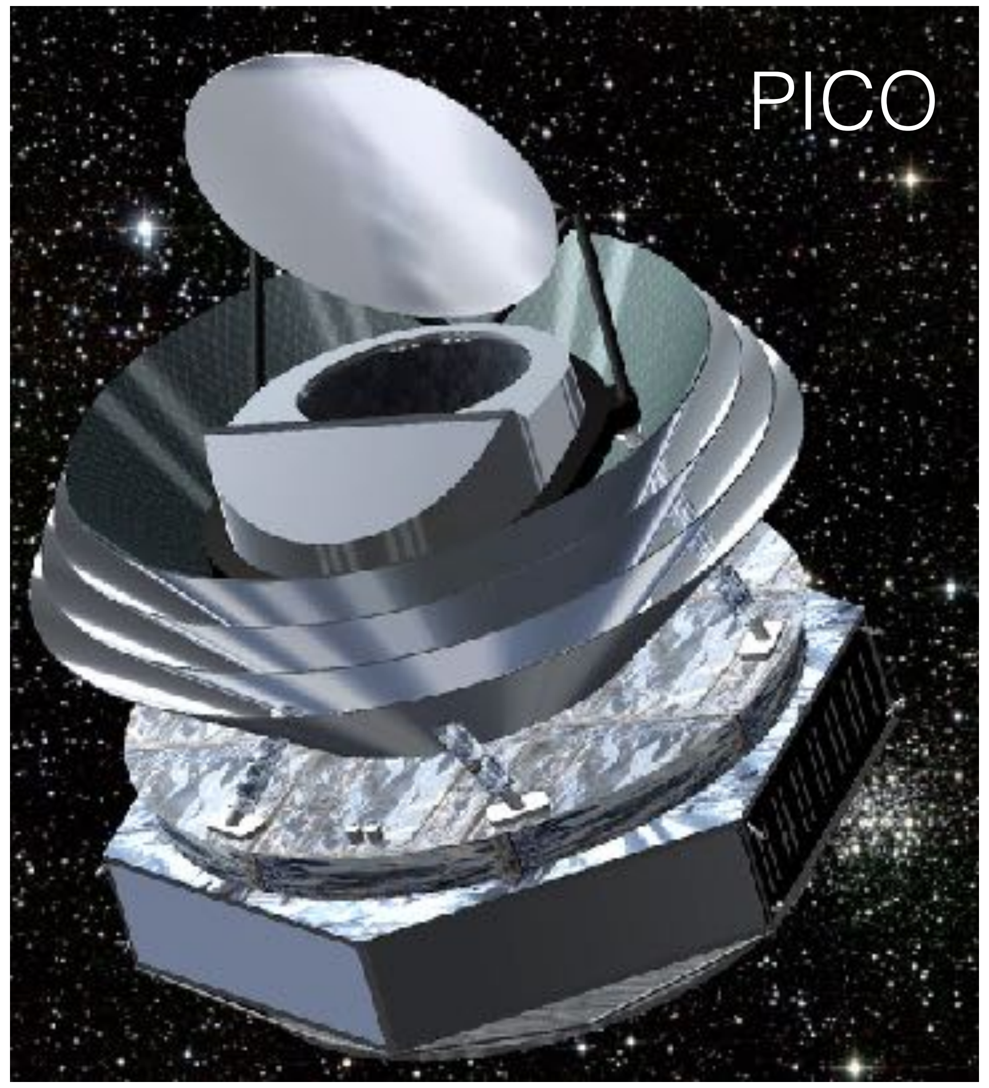
Analysis and Cosmology

XFaster power spectrum estimator

Foreground separation techniques

LiteBIRD





Conclusions

SPIDER's first voyage to near-space was very successful!

Primordial gravitational waves remain elusive
95/150 GHz, 6% of the sky: $r<0.11$ (0.19)

Foreground analysis rich and ongoing: *more to come!*

Rich in-flight experience relevant Inflation Probe
TES arrays, TDM readout, HWPs, automation, analysis, …

SPIDER-2 is ready to map the sky at 280 GHz

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