The View from the Stratosphere

Systematics and Calibration Challenges of CMB Ballooning

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ILLINOIS

CMB Systematics / Calibration Workshop

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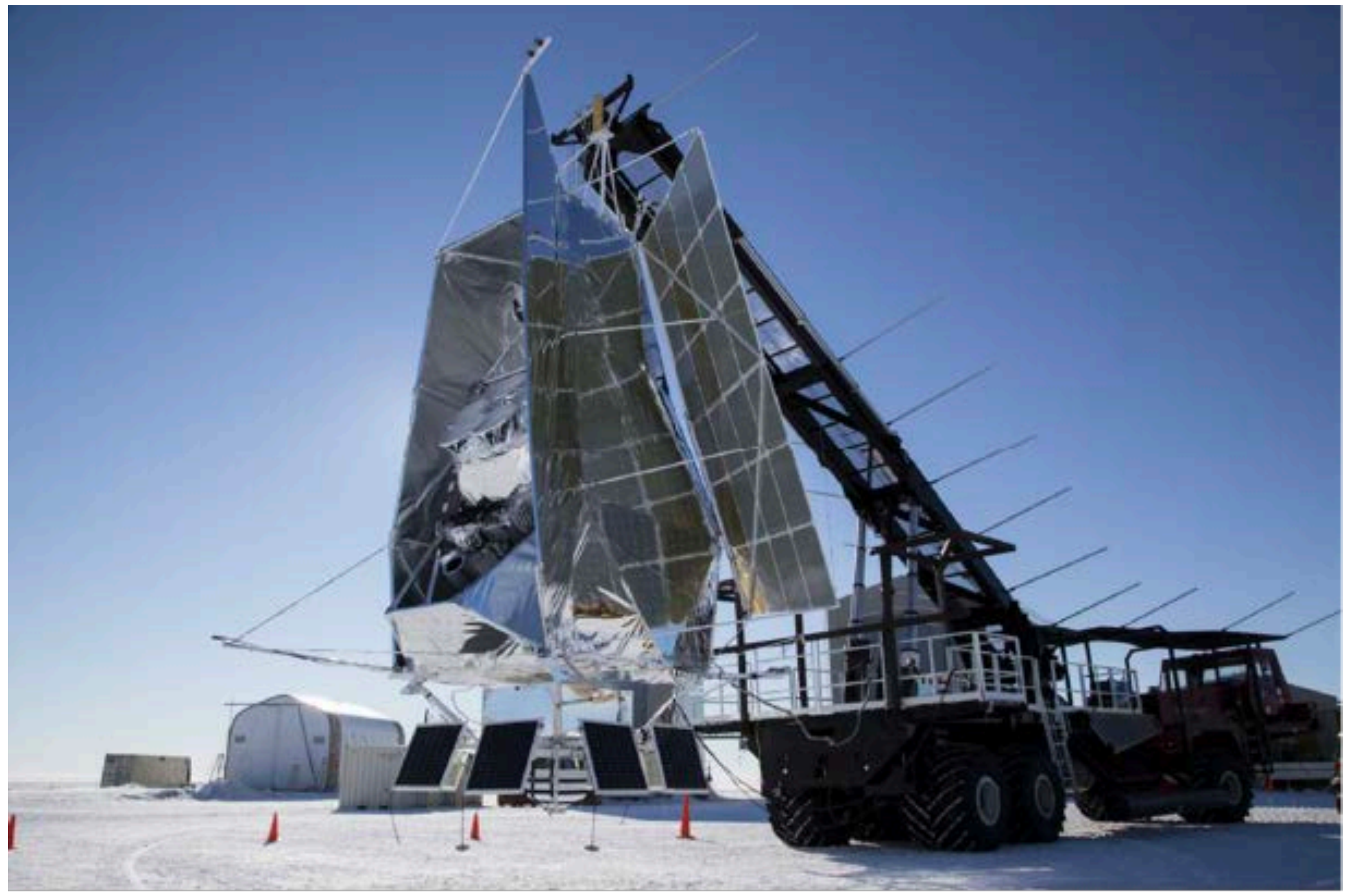
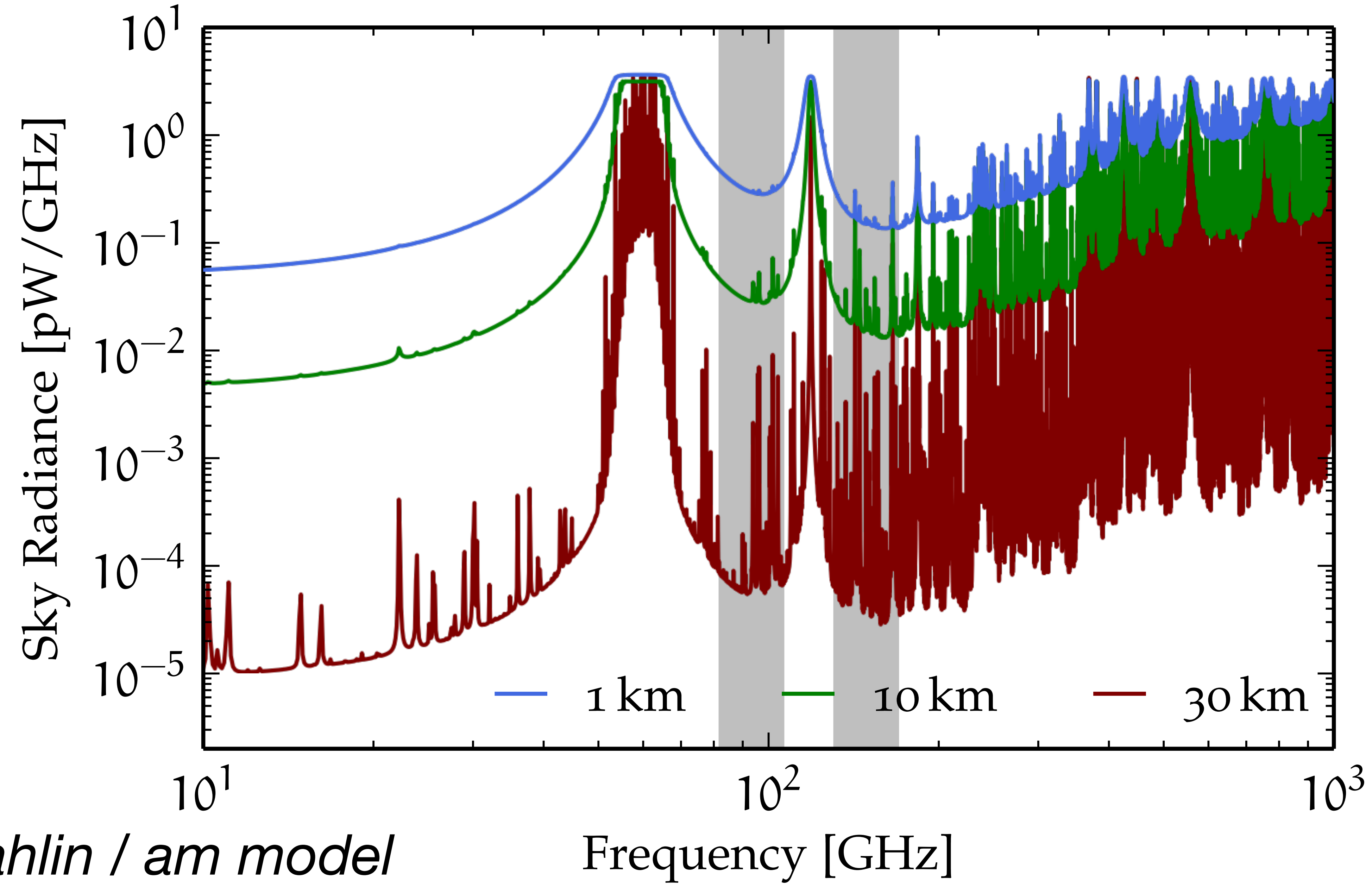
Why Ballooning?

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

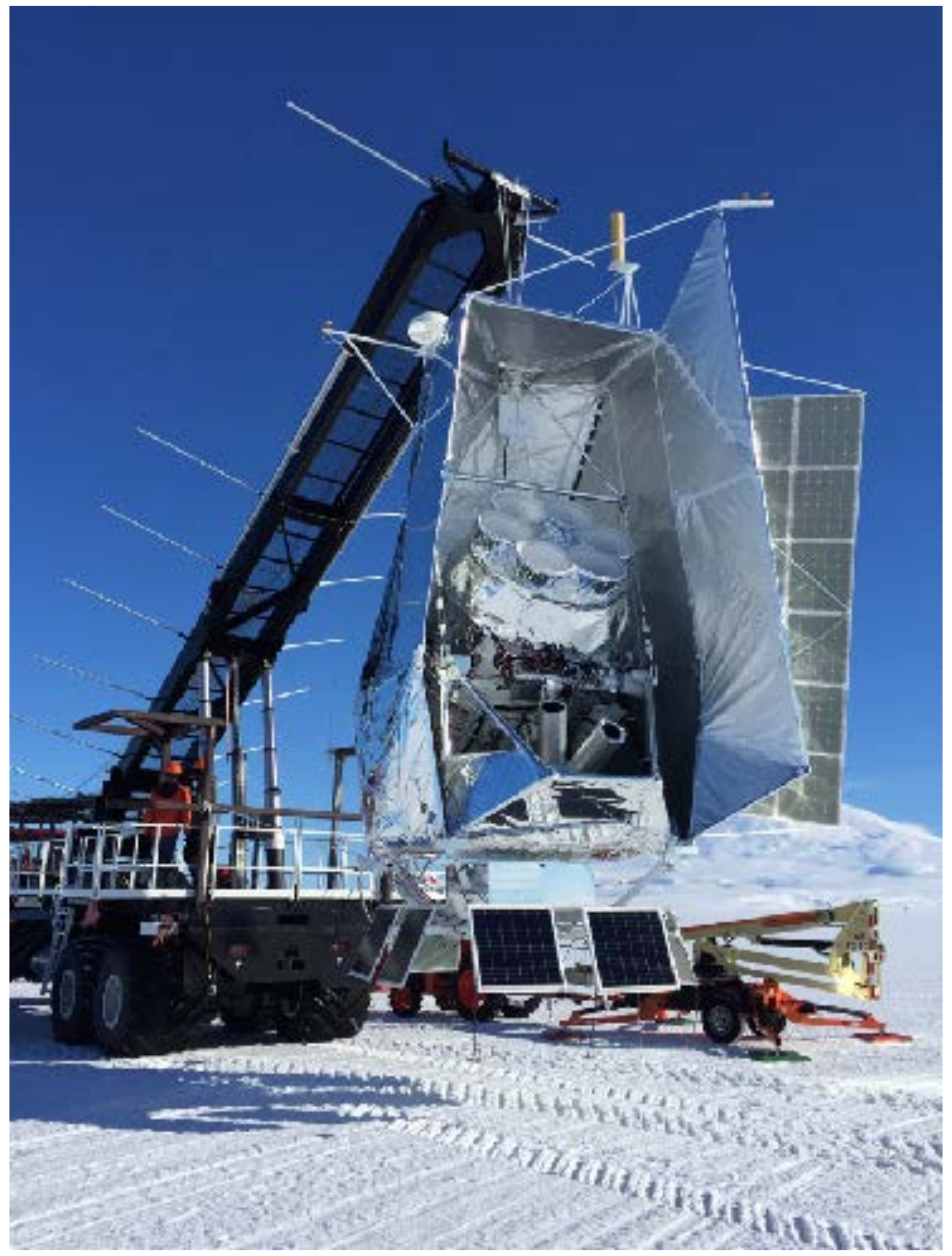
- Limited **integration time** (~weeks)
- Stringent **mass**, **power** constraints
- Very limited bandwidth demands ***nearly autonomous operations***

Excellent proxy for space operations!

A Rich History

BOOMERanG 1998

ARCADE 2 2006



SPIDER 2015

MAXIMA 1999

EBEX 2012

OLIMPO 2018

… plus BAM, QMAP, Archeops, TopHat, PIPER, and many 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 · California Institute of Technology · 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 · Universitas Osloensis · Stockholms Universitet · ILLINOIS

The SPIDER Program

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

Large (~1300L) shared **LHe cryostat**

Modular: 6 monochromatic refractors

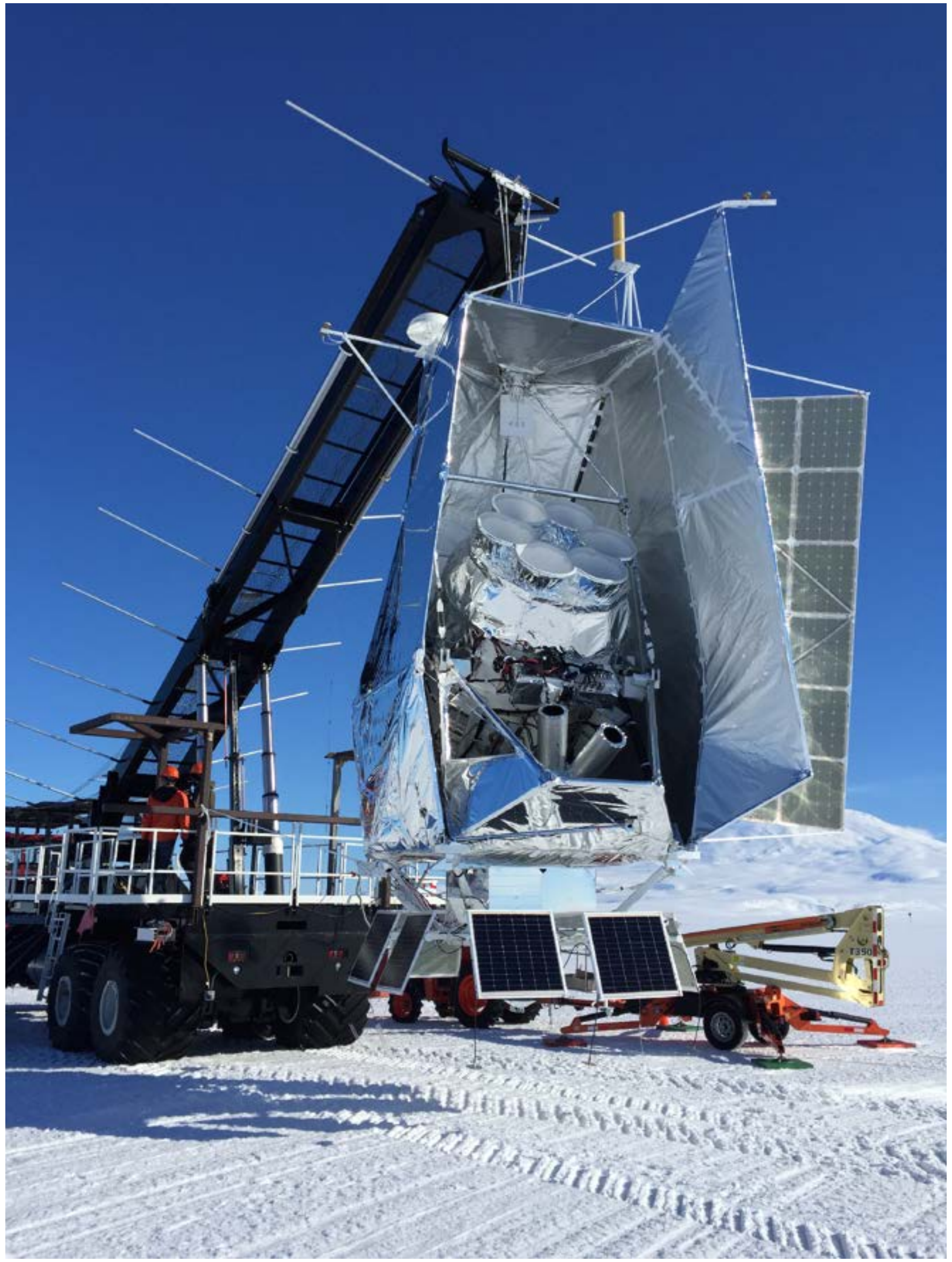
- **SPIDER 2015**: 3x**95** GHz, 3x**150** GHz
- **SPIDER-2**: 2x**95**, 1x**150**, 3x**280** GHz

Stepped **half-wave plates (HWPs)**

Lightweight **carbon fiber gondola**

Azimuthal reaction wheel, linear elevation drive

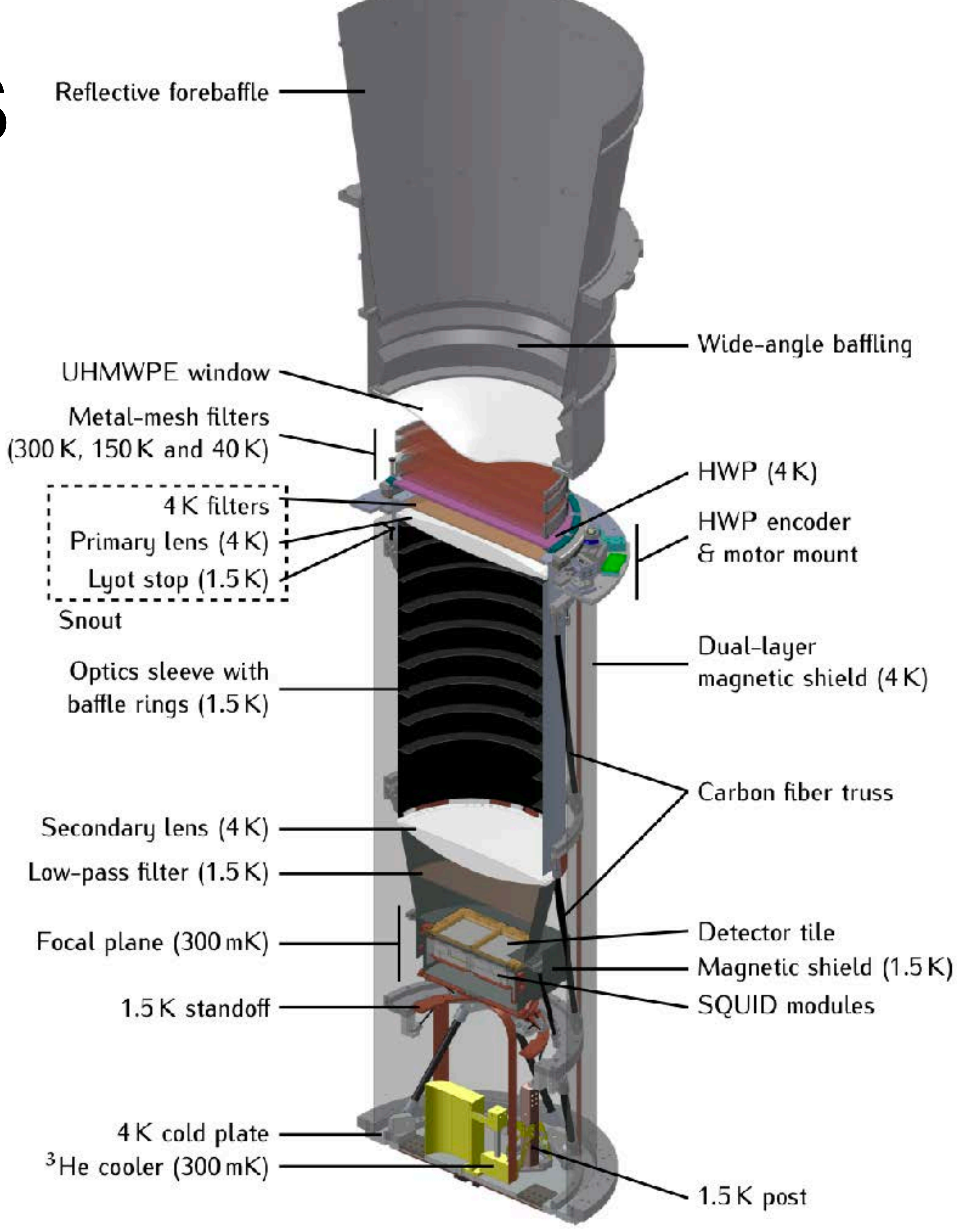
Launch mass: ~6500 lbs (3000 kg)



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 …

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)*
- Antenna-coupled **TES arrays**
  SPIDER-2: Horn-coupled TES arrays



Challenges of CMB Ballooning

Ballooning shares all of the same systematics and calibration challenges as anyone else - *see e.g. Colin's talk next, and others!*

Some notable challenges:

1. The dark sky
2. The bright (and ever-shifting) ground
3. Space realities: Cosmic rays and RFI
4. Complex, non-redundant data

And threading through it all:

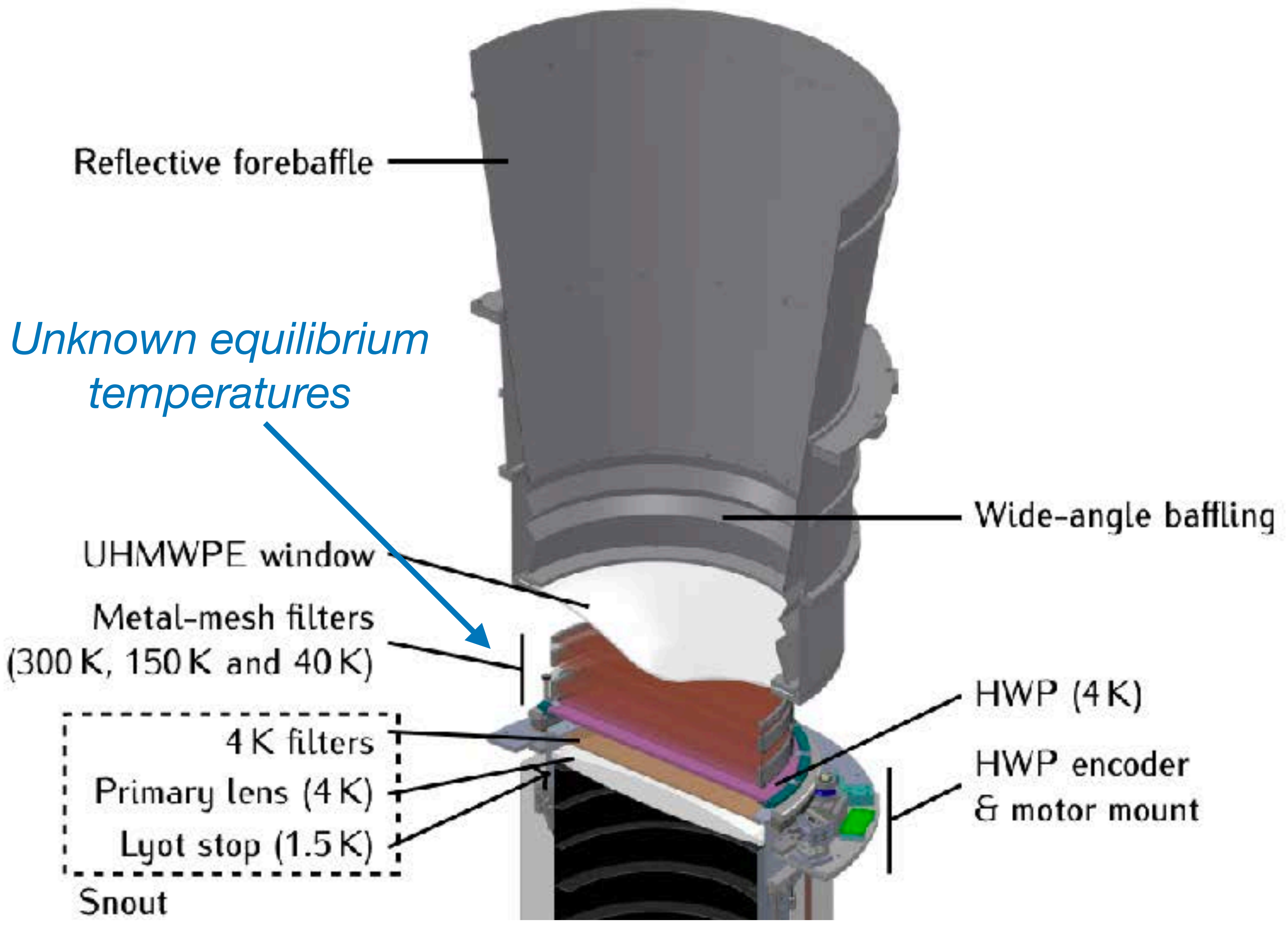
Very limited time in the observing environment

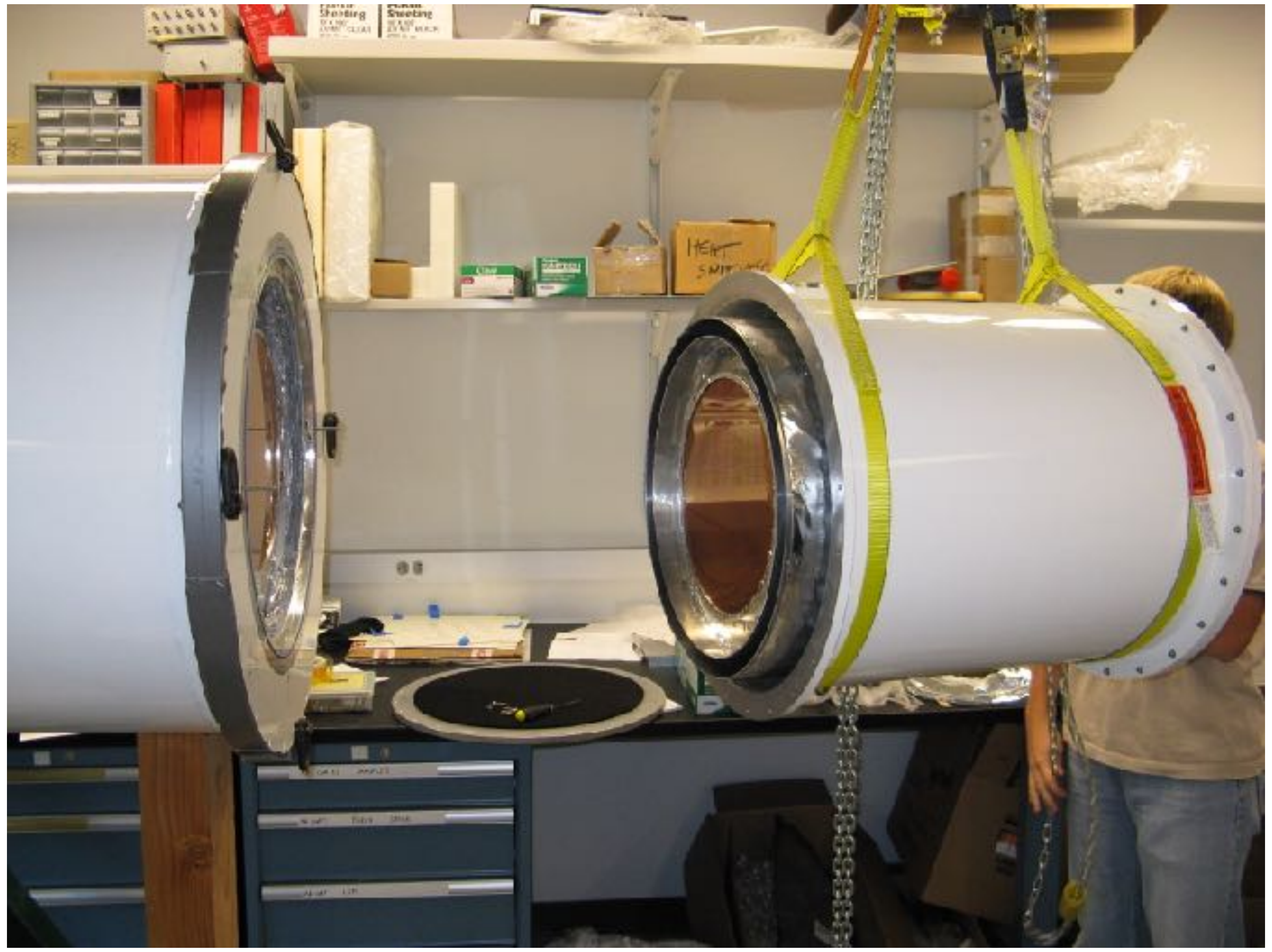
Dark Skies

Float (or space!) environment is challenging to replicate in the lab

- Difficult to estimate **loading** (and thus sensitivity)
- Constrains optical **calibration**
- Danger of **saturation**!

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





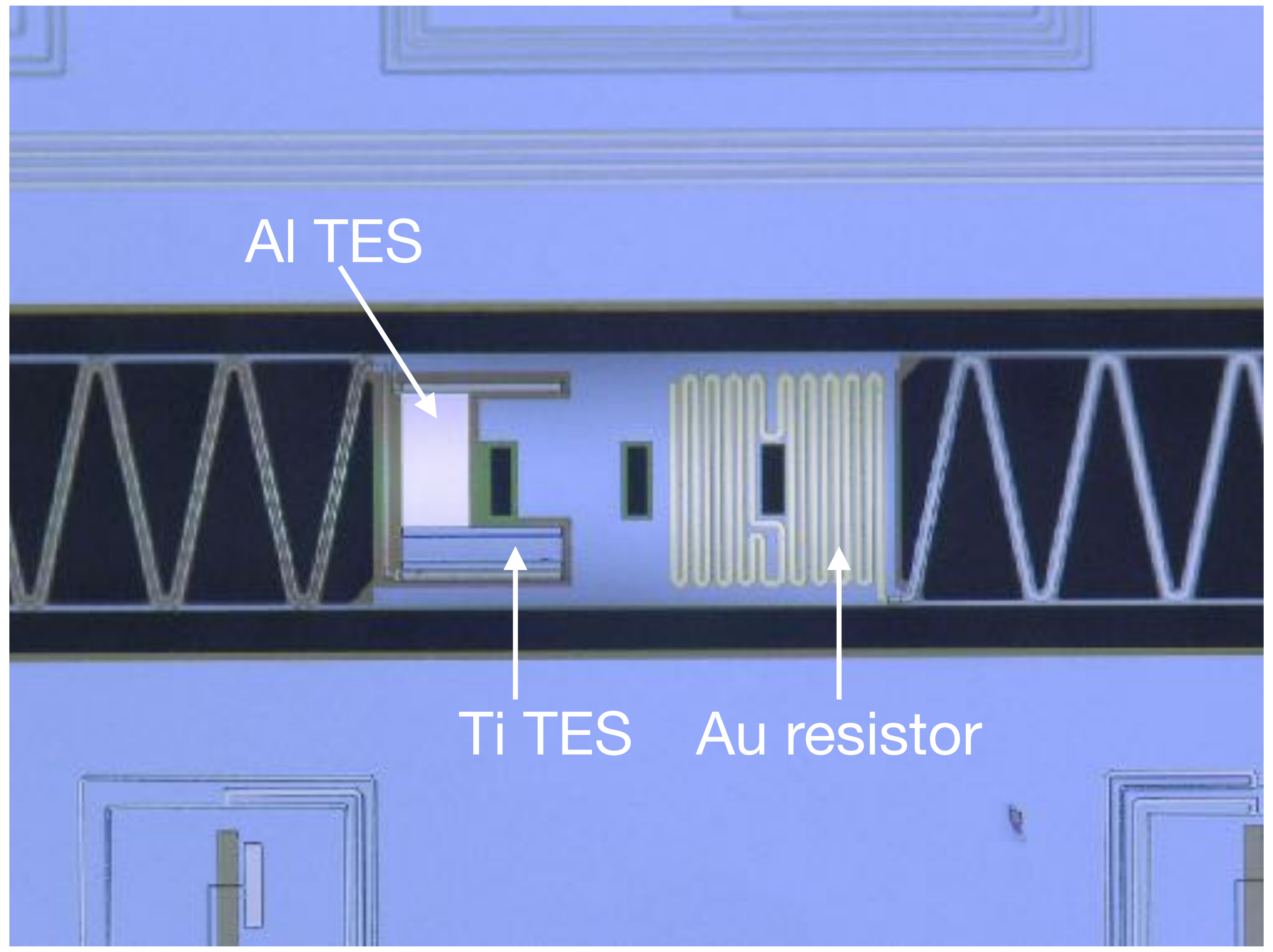
Liquid helium cold load

Ground Characterization

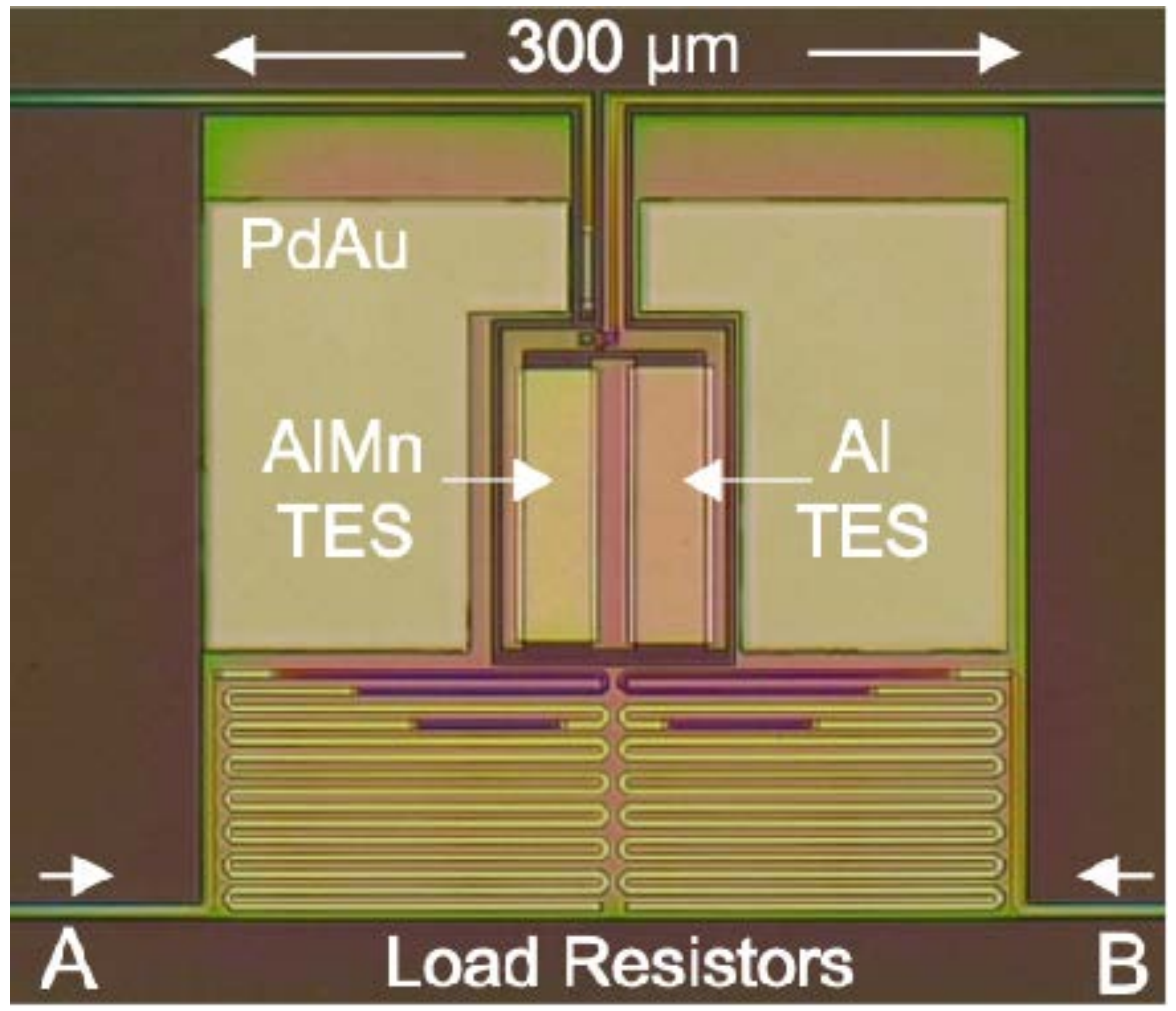
Dual-TES configuration enables lab testing at a wide range of incident powers

“Lab TES” with higher Tc and saturation power (>30x) than science TES

No effect on millimeter-wave response

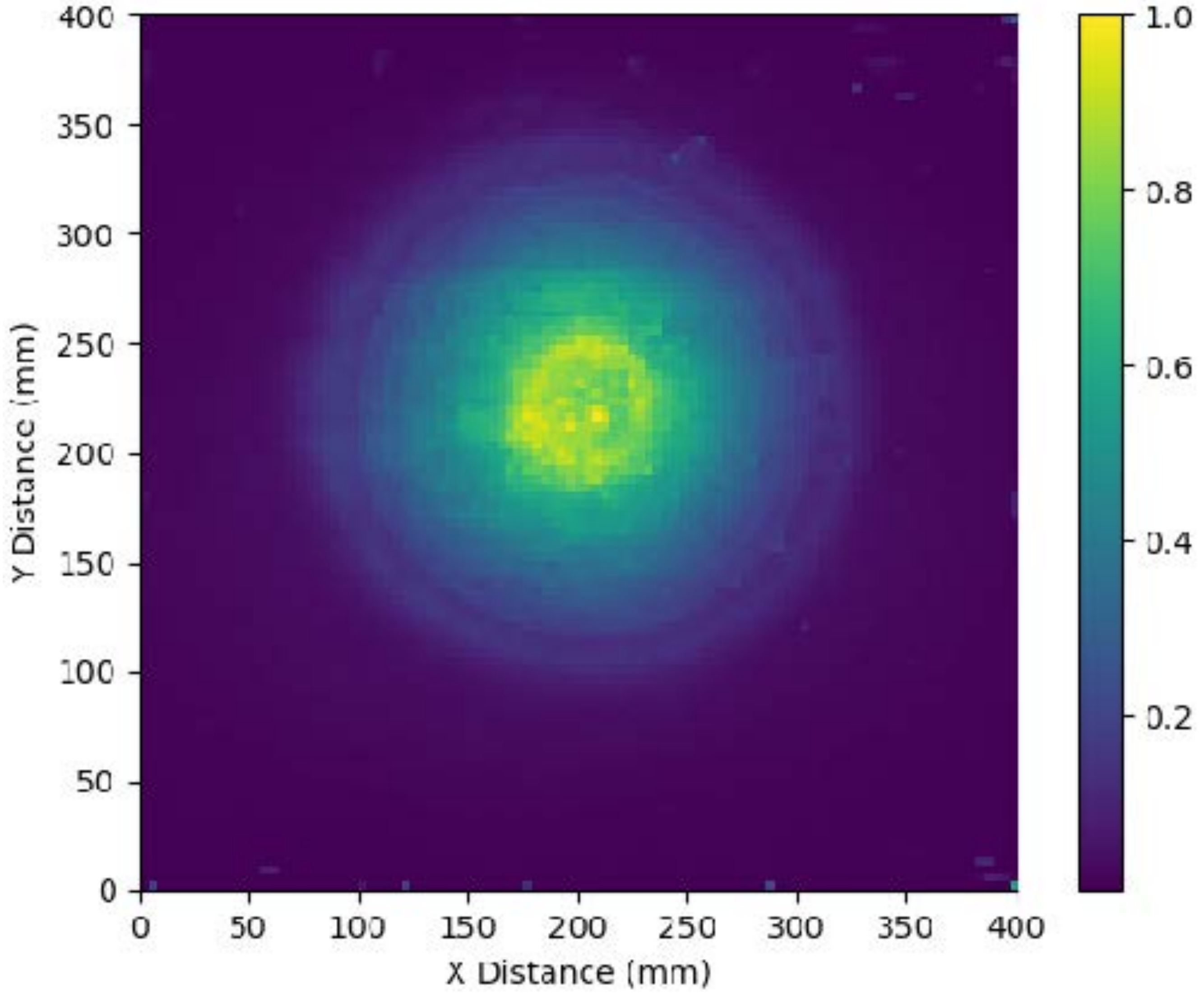


JPL (90 / 150 GHz)



NIST (280 GHz)

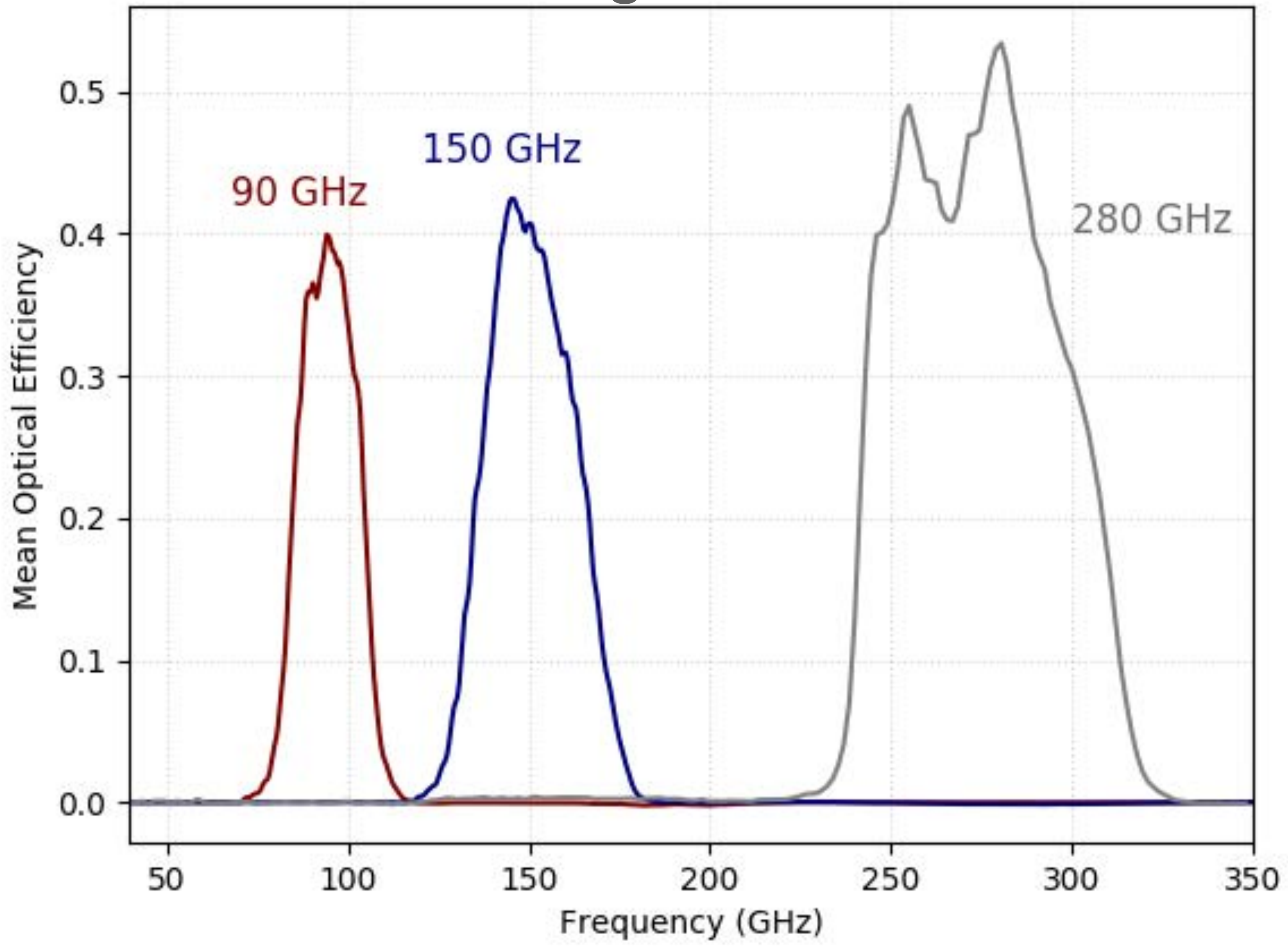
A. Lennox, E. Shaw



Enables **full-receiver** characterization

- **Optical efficiency** (*quality control*)
- Near/far-field **beam maps** (*quality control*)
- **FTS spectra** (*archival: foregrounds*)

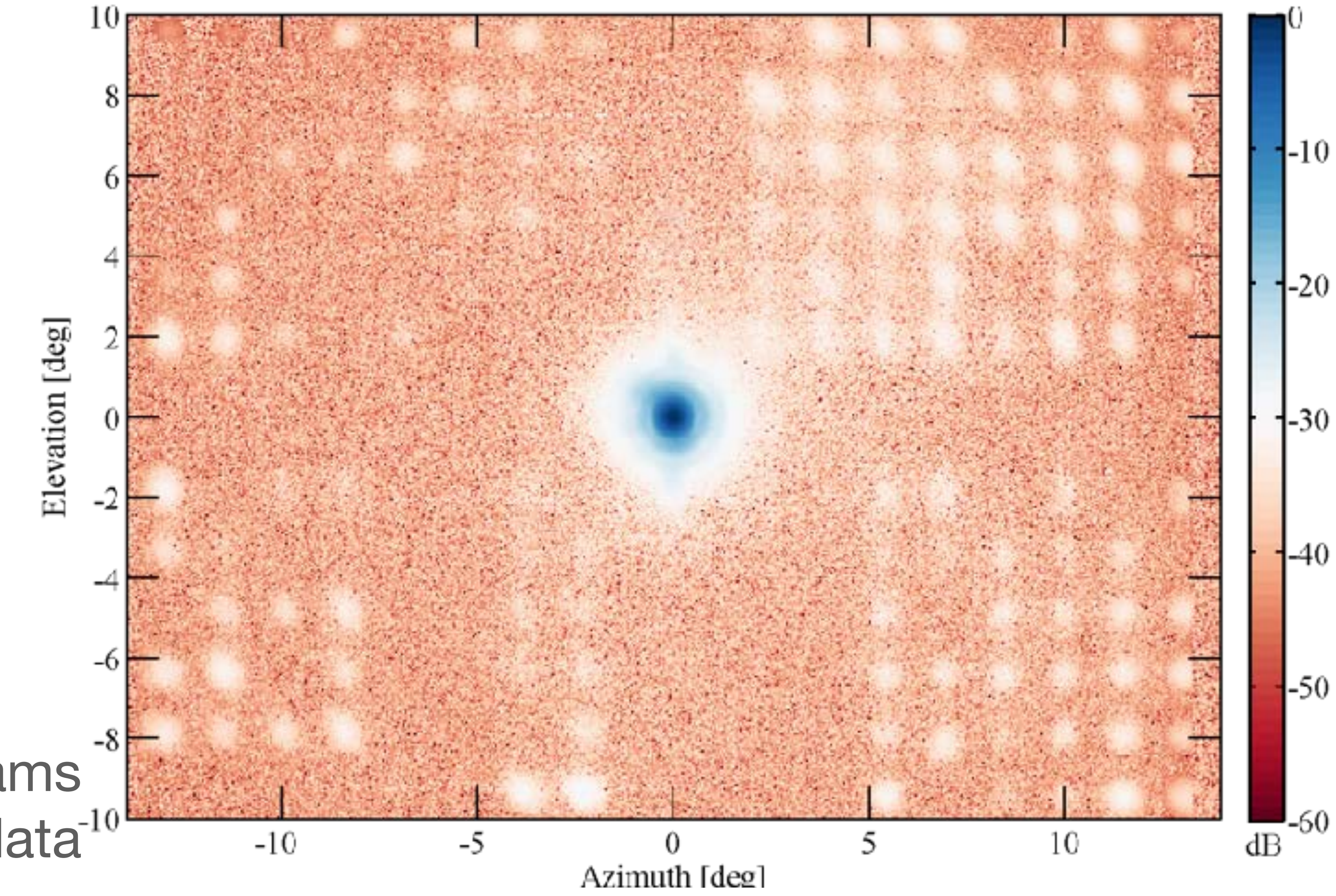
E. Shaw, X. Song



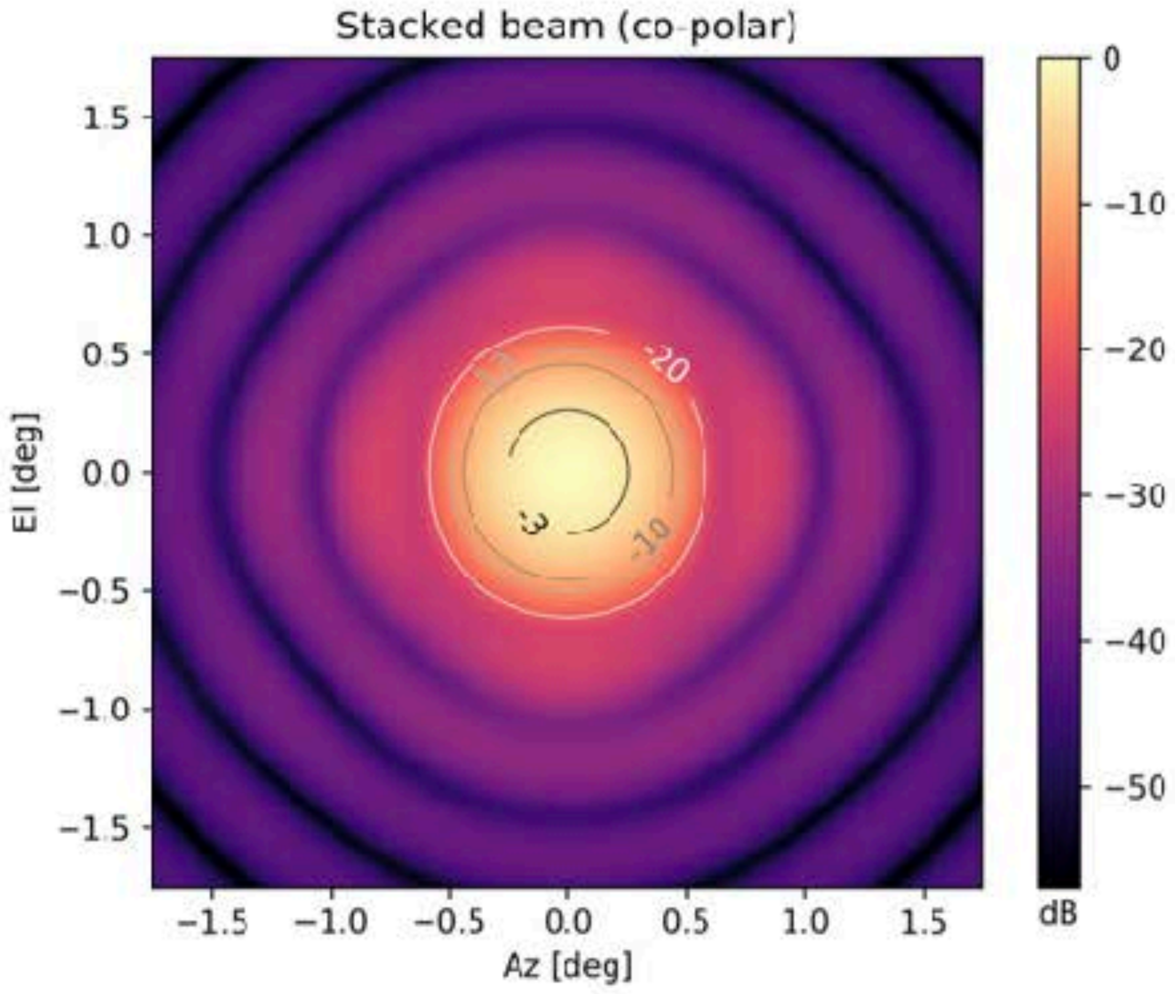
Beam Characterization

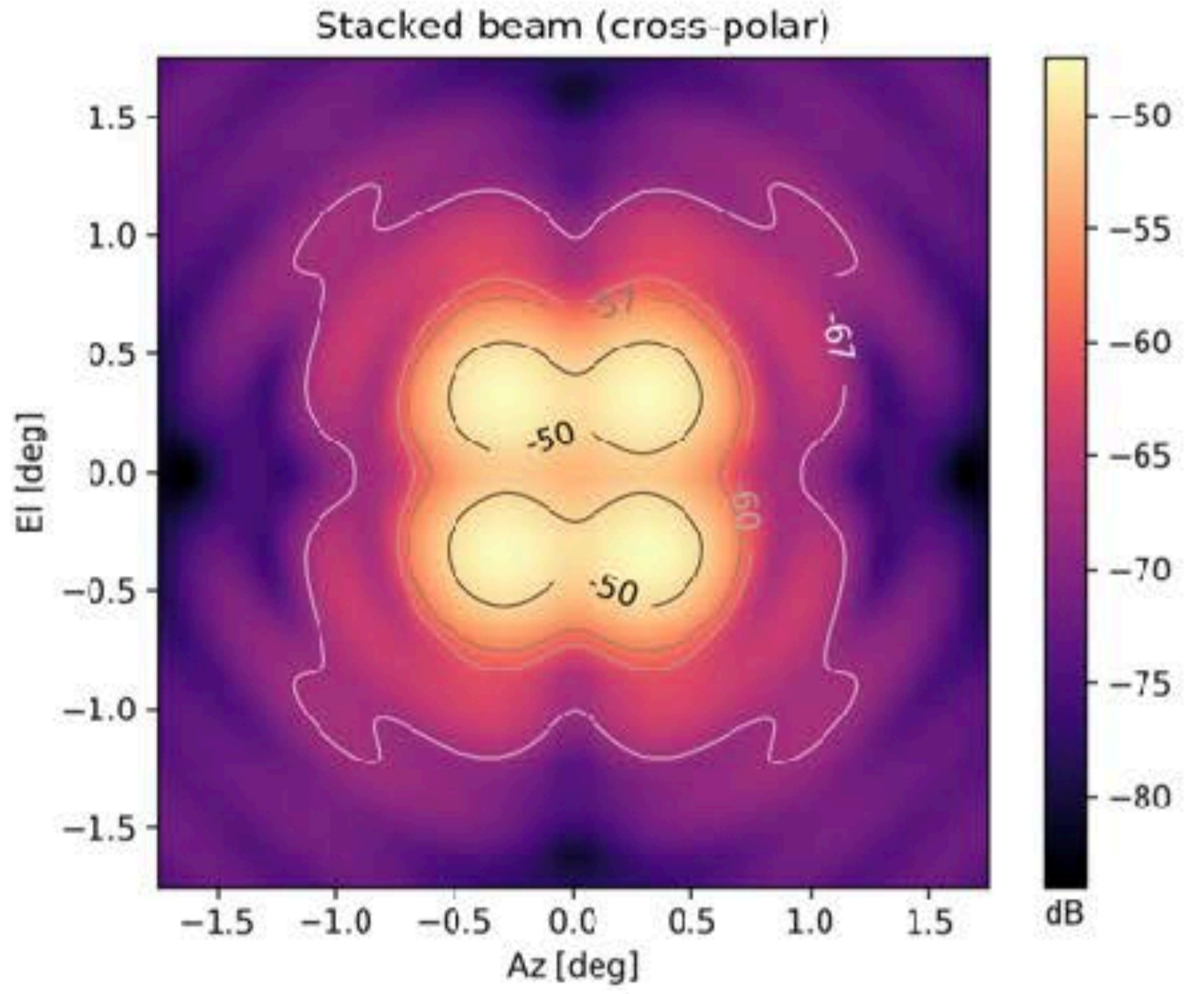
A variety of optical and related effects can contribute to map distortions:

- Beam center errors
- Beam shape errors *(width, ellipticity)*
- Optical ghosting *(internal reflections)*
- Beam sidelobes *(near and far)*
- Readout crosstalk (*fixed & well-known*)



Stacked 150 GHz beams
Mid-field data





Address with a combination of lab data, flight fits, and **physical optics** simulations (GRASP, MoM); apply with **beamconv** (arXiv:1809.05034)

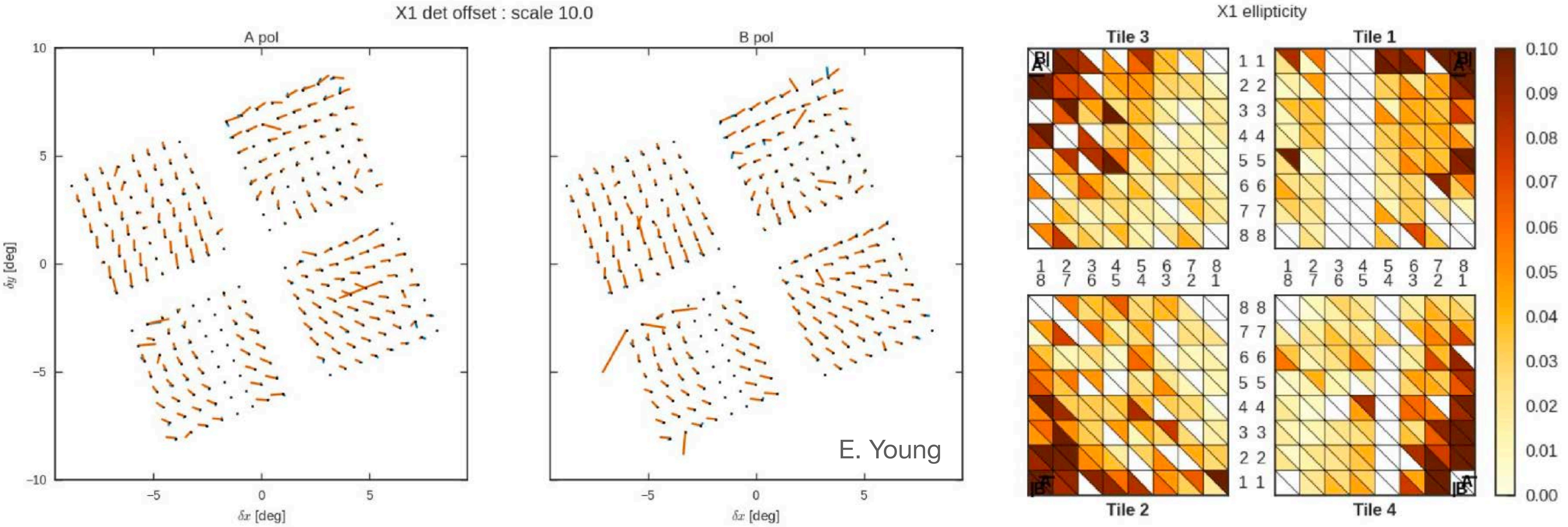
J.E. Gudmundsson, A. Duivenvoorden

Beam Characterization

Payload post-flight pointing solution: **6" accuracy** (*~0.3% beam FWHM*)

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



SPIDER Systematics Budget

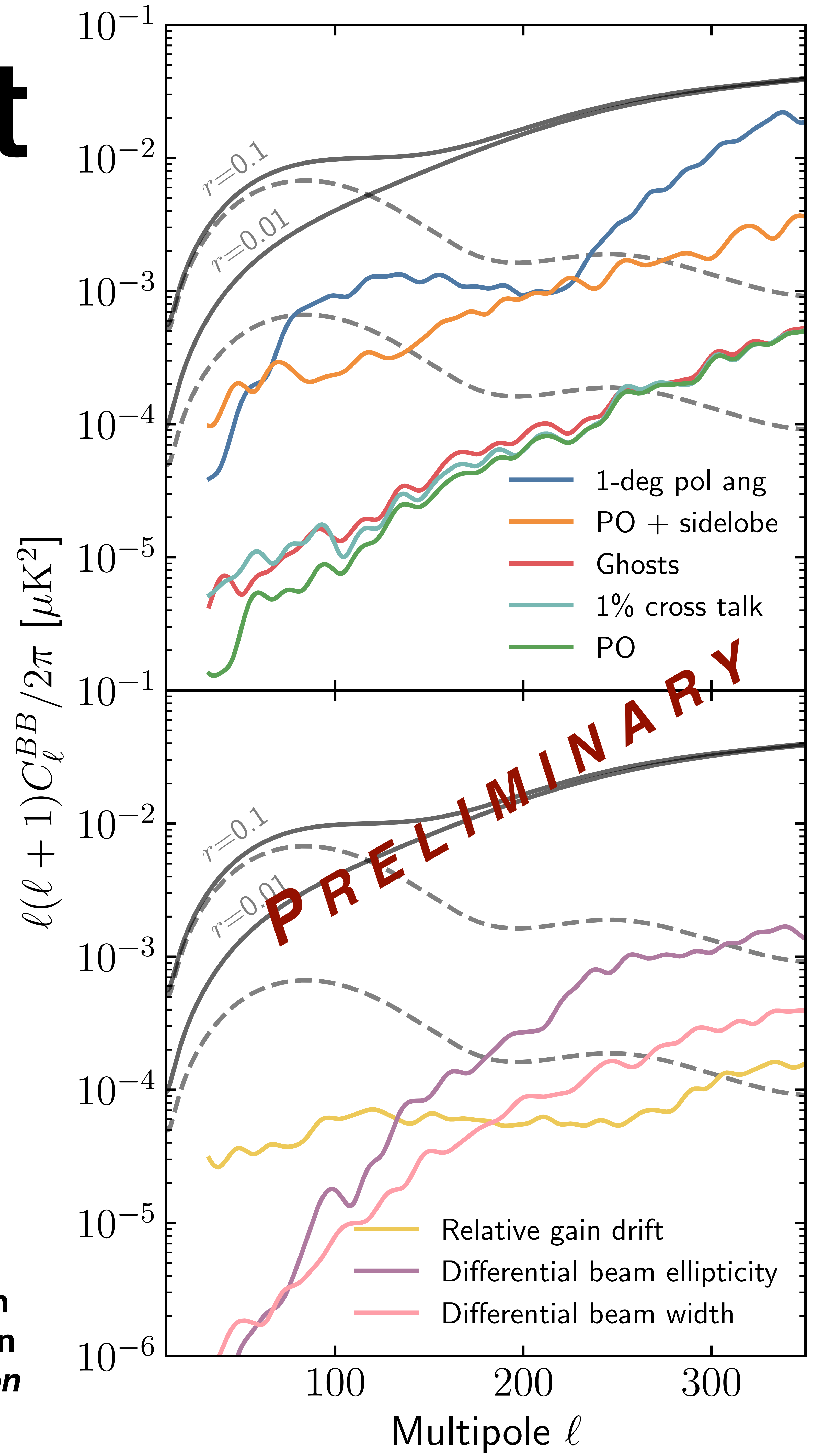
Simulate effects of known non-idealities

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

Strong symmetrization from **HWP** rotation mitigates wide range of beam effects (*MacTavish+ 2008*)

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

Jon Gudmundsson
Adri Duivenvoorden
Spider Collaboration

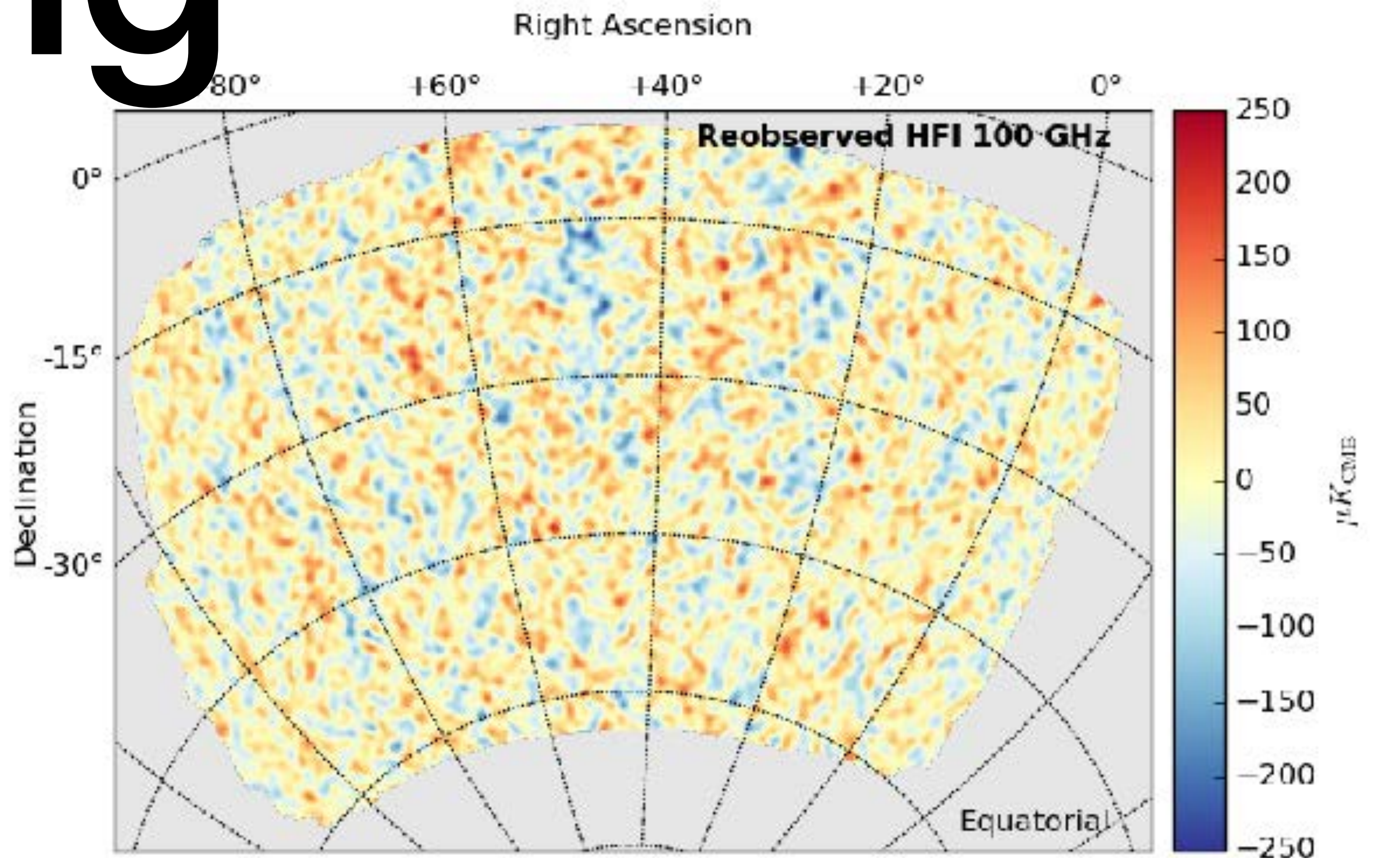


Gain Monitoring

Absolute gain

Calibrated per-detector against Planck

Based upon cross-spectra with P100+P143, temperature filtered to degree scales



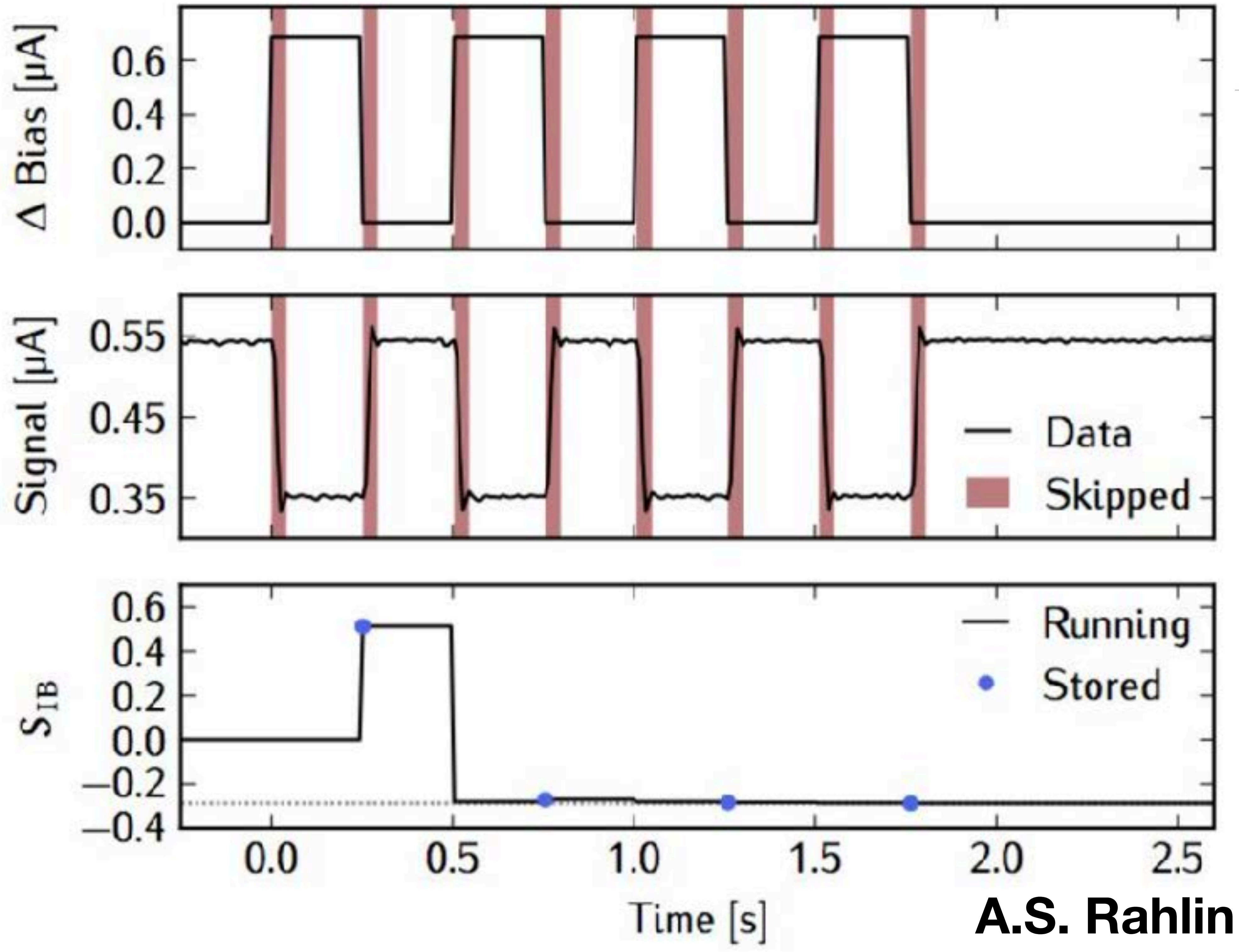
Time-varying gain

BOOMERanG: **Calibration lamp** in hole in tertiary mirror (*harder for refractors)*

SPIDER: Electrical **bias step** response used as proxy for gain variation

2s bias step every few turnarounds gives ~0.1% uncertainty every few minutes

Fully-automated monitor loop adjusts TES biases occasionally if needed



A.S. Rahlin

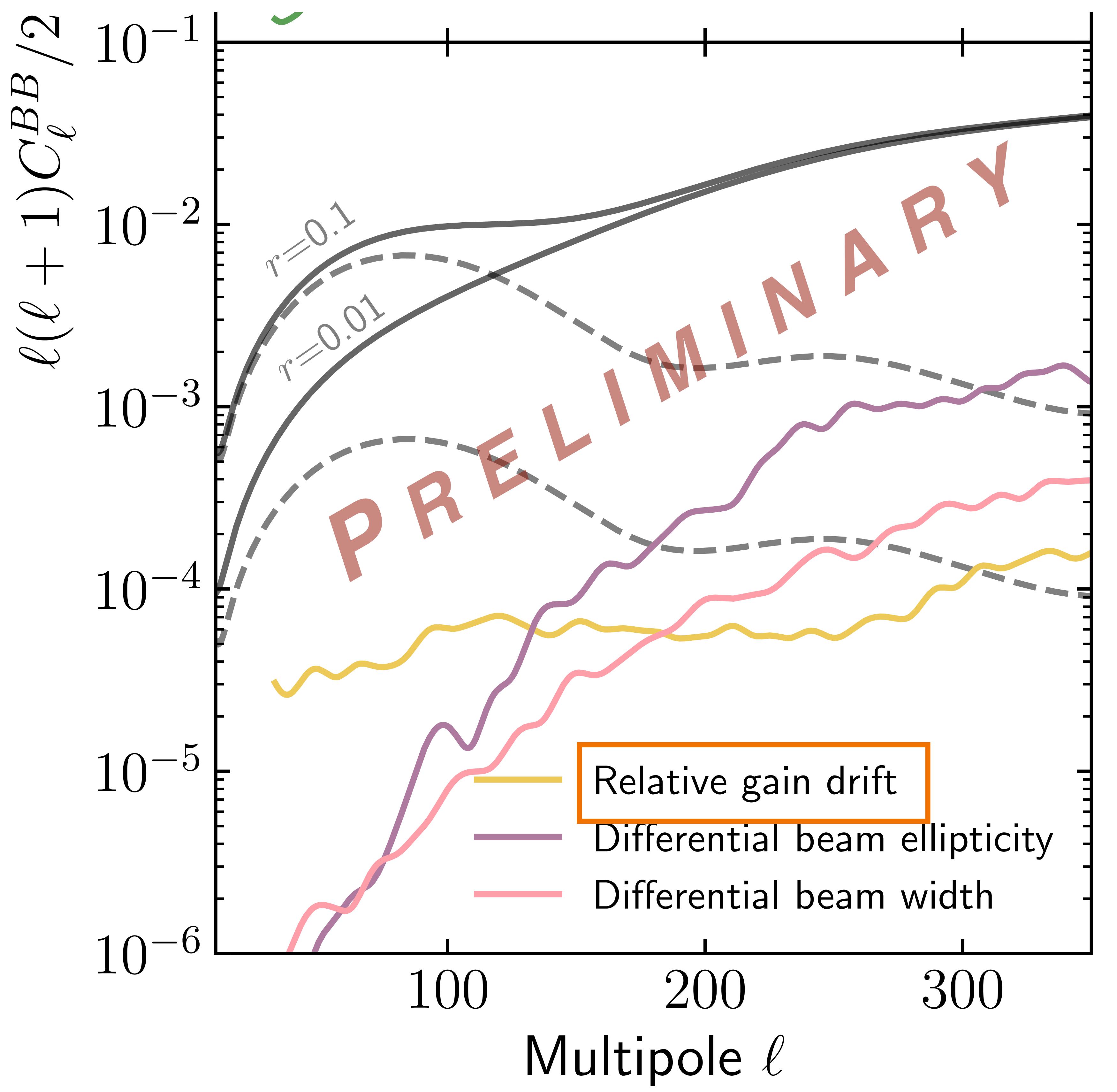
Gain Stability

Excellent in-flight stability

- Cross-checks with deprojection gain estimates on 10-minute time scales
- No evidence that we needed to re-bias so often … nor that fine gain correction was even necessary!

Subtler effects can arise

- **EBEX**: HWP-synchronous signal couples through detector nonlinearity into substantial I->P signal!
- *Didier+, ApJ 876, 54 (2019), arXiv:1711.01314*



A. Gambrel, E. Young, J. Gudmundsson, …

Cosmic Rays

Energetic particles heat the bolometer or surrounding materials, inducing intermittent “glitches”

Key environmental challenge for space instruments (*incl. Planck/HFI*)!

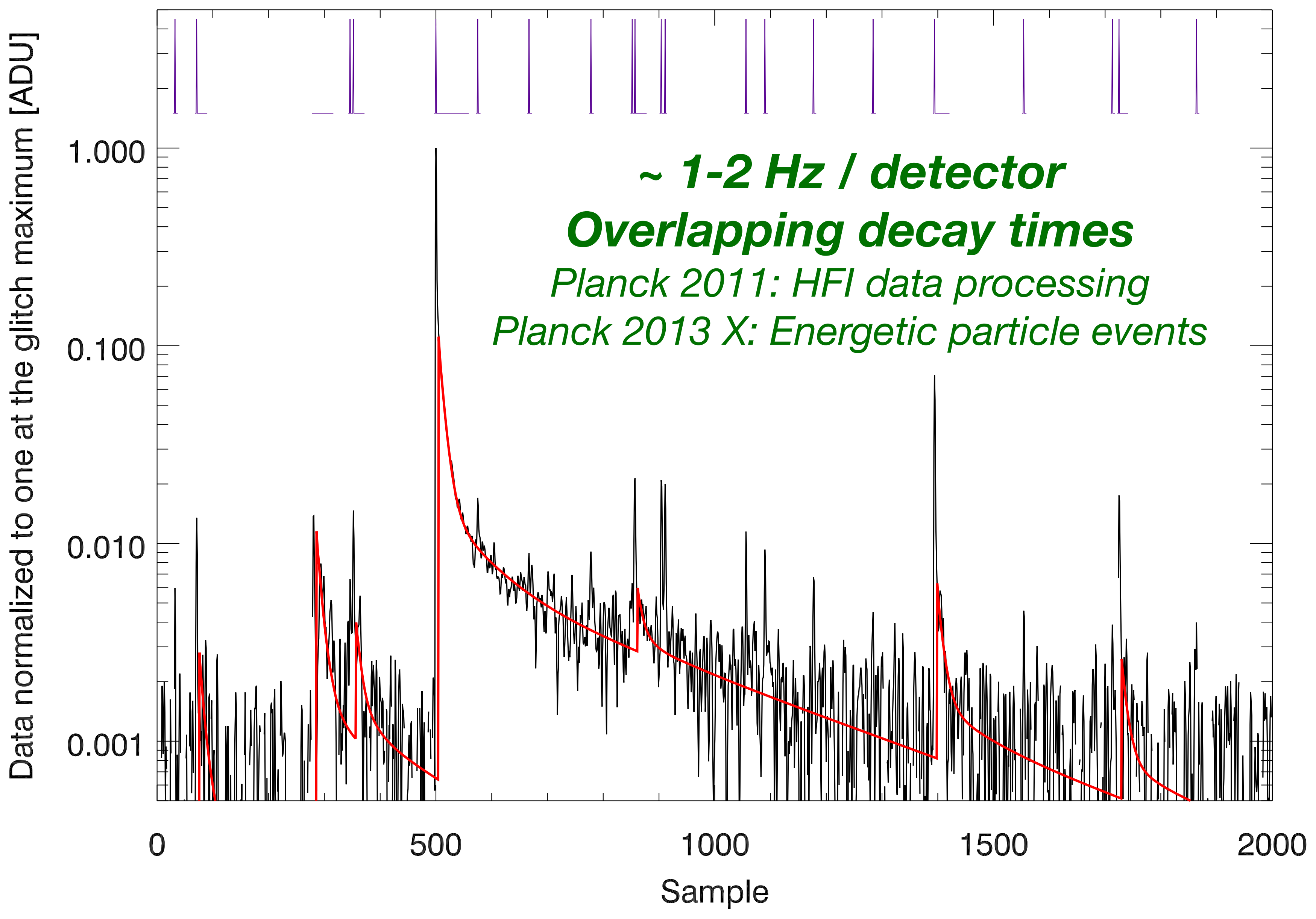
SPIDER flight data

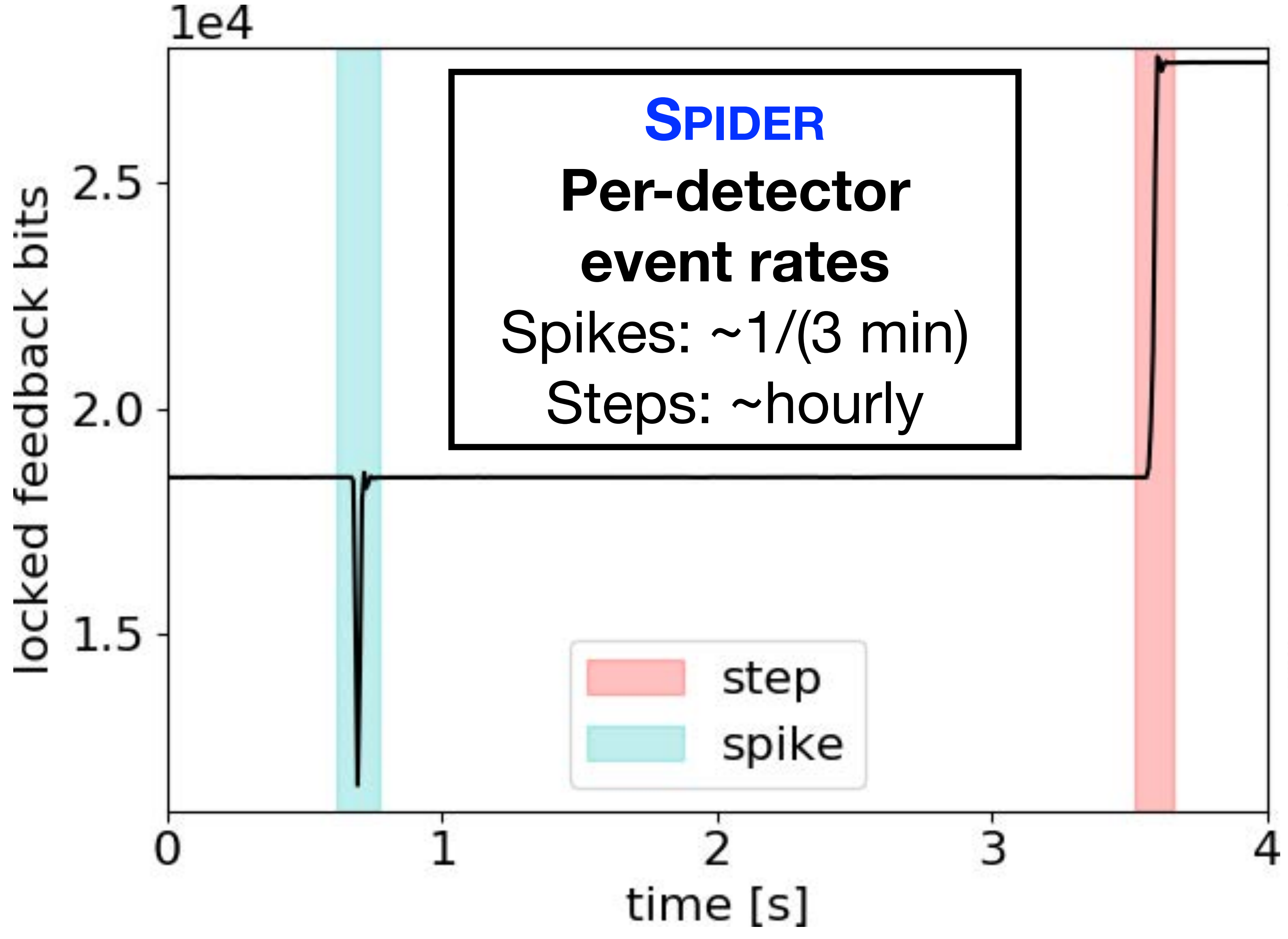
Low rate, rapid recovery, low coincidence, two glitch classes:

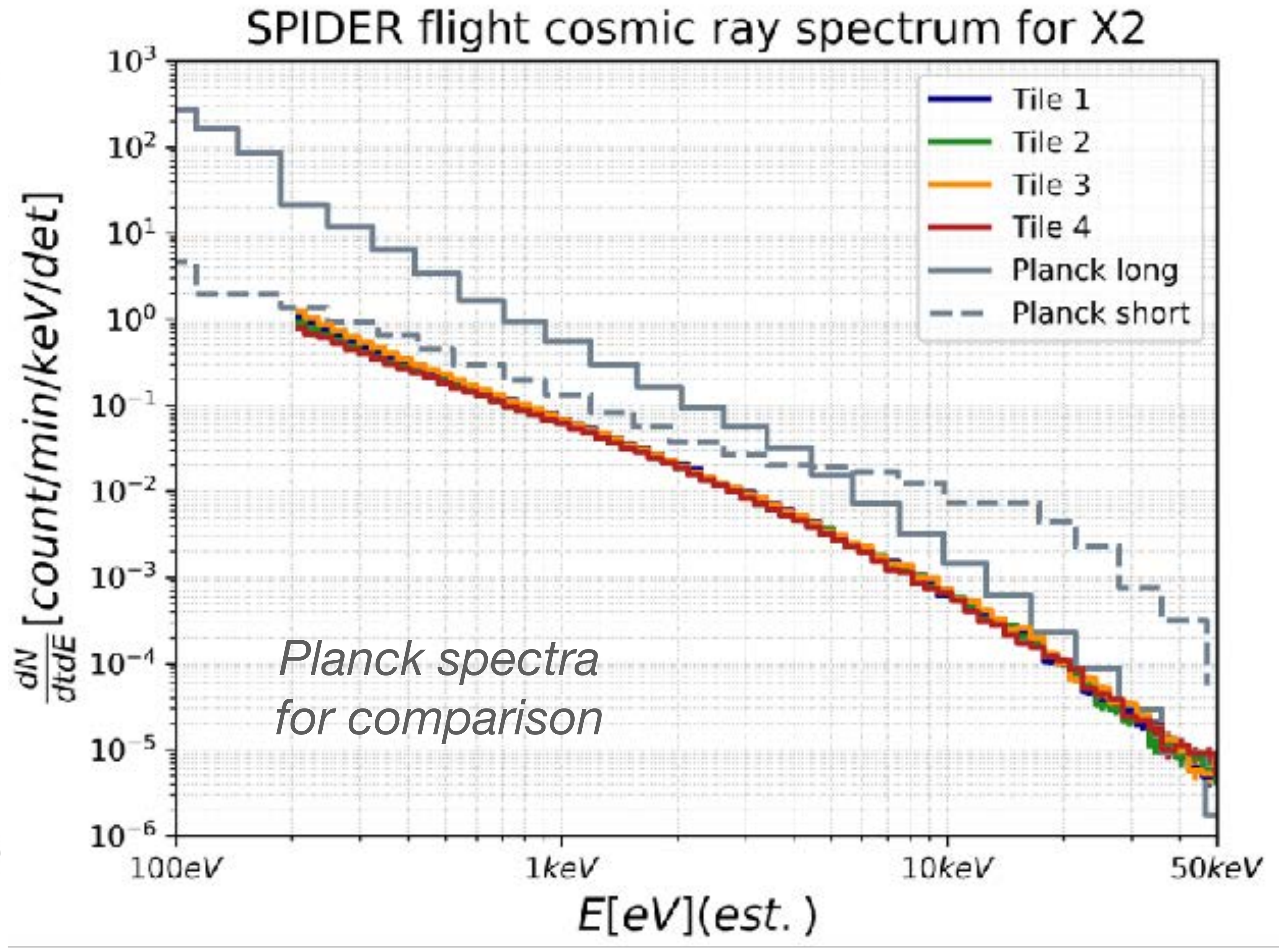
1. **Spike**: Transient heating event, widely varying amplitudes
2. **Step**: Large, quantized “flux-slip” in SQUID mux from large CRs

*Pay attention to **readout** phenomenology!*

Planck / HFI







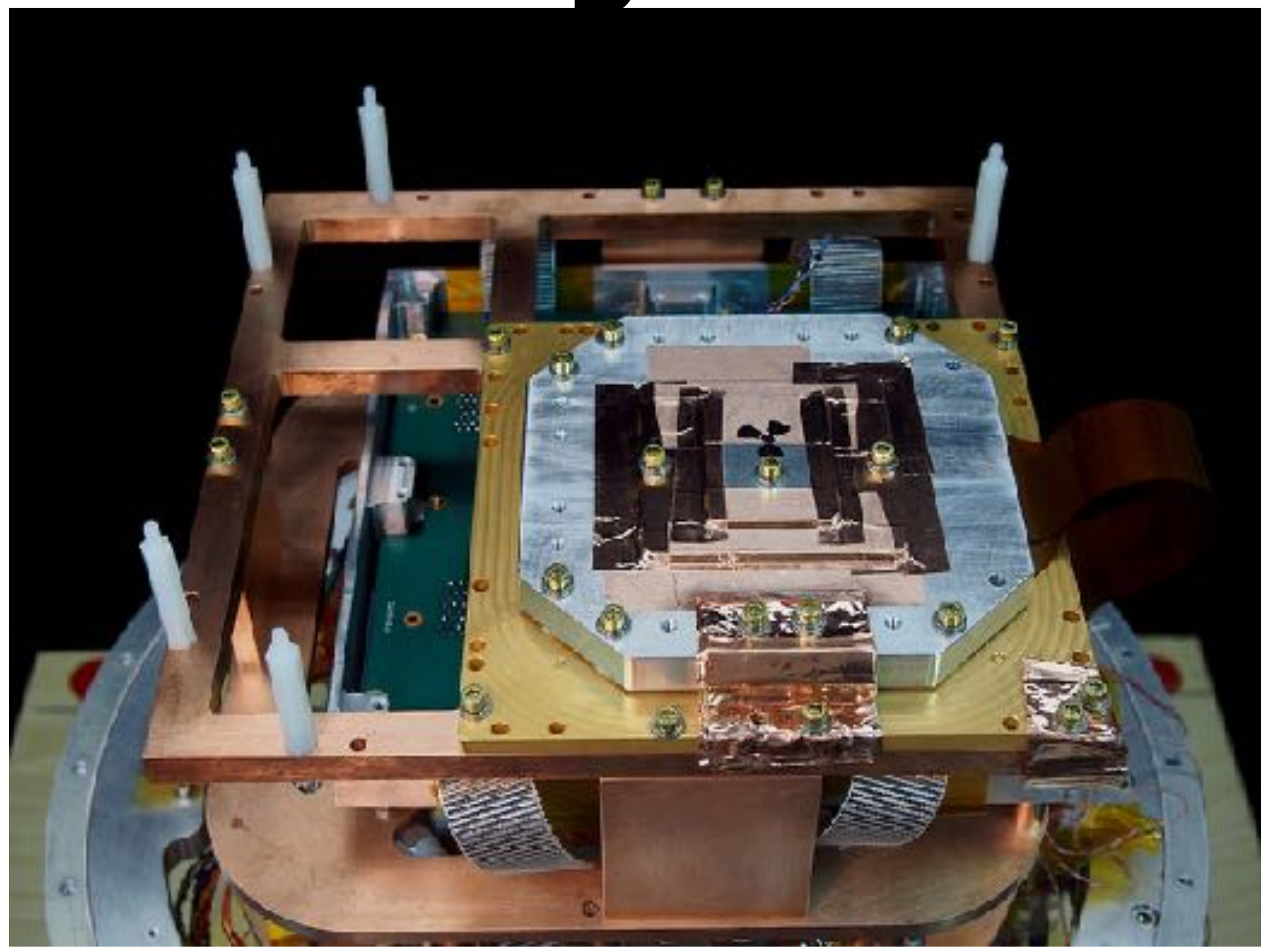
B. Osherson+, JLTP 199, 1127 (2020) (arXiv:2002.05771)

Designing for Cosmic Rays

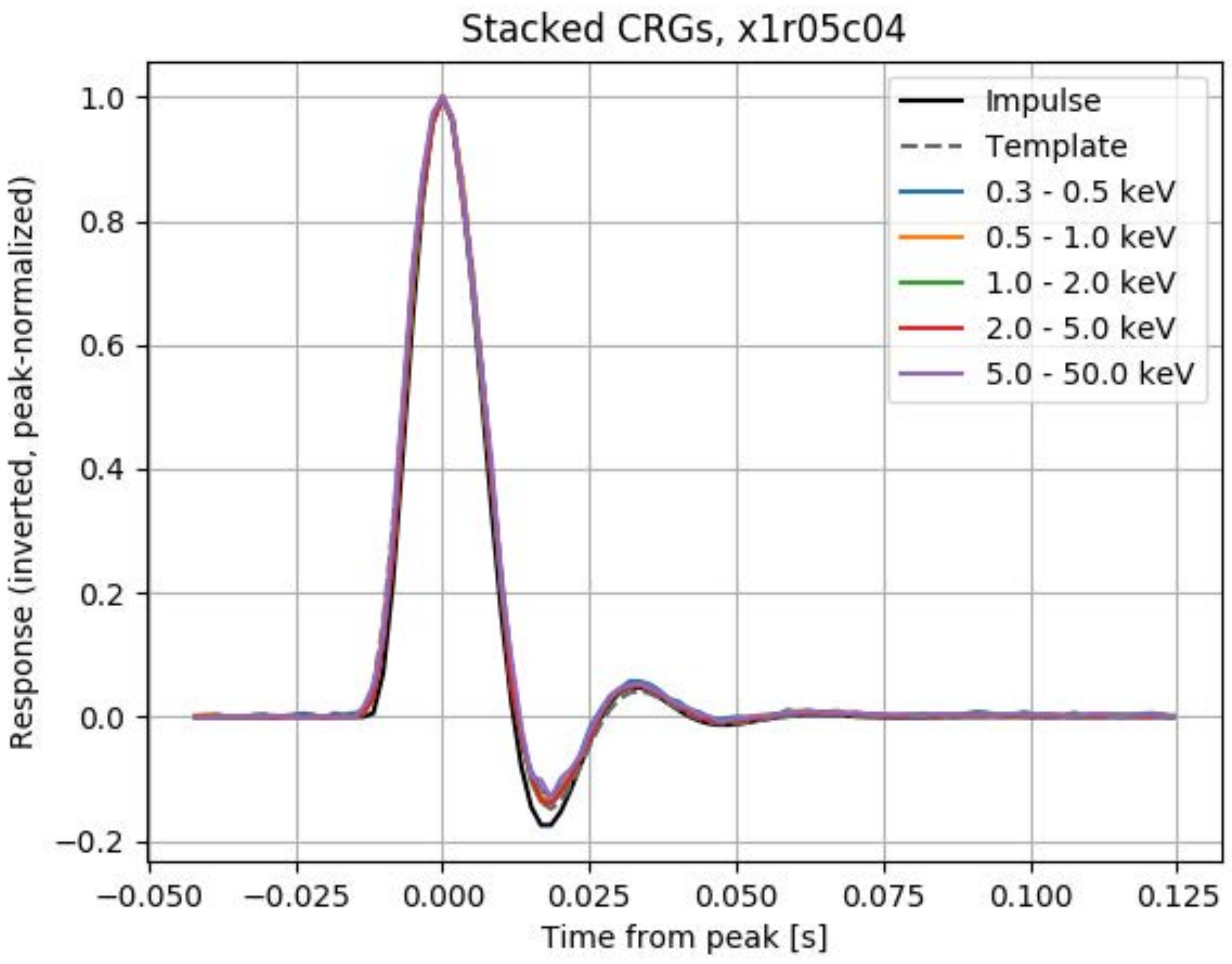
CR response (*pulse shape, coincidence*) may be characterized in the lab with localized **radioactive sources**

Am-241 (5.5 MeV α) gives CR-like depositions

Similar work by A. Catalano+, S. Stever+

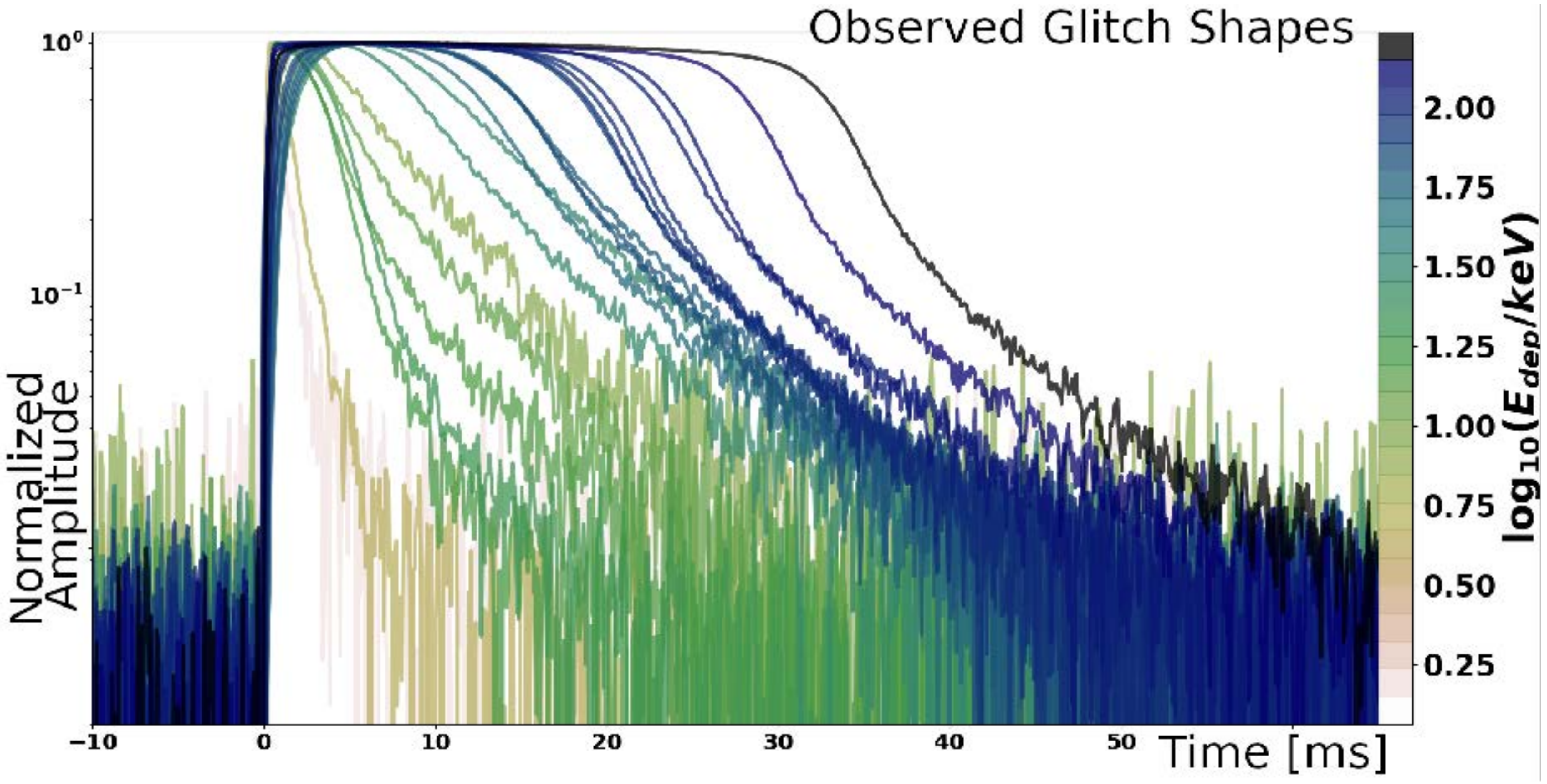


Lab source test stand for SPIDER wafer and full readout B. Osherson (UIUC)



Stacked SPIDER flight CRs show constant shape dominated by readout anti-aliasing filter

Lab data



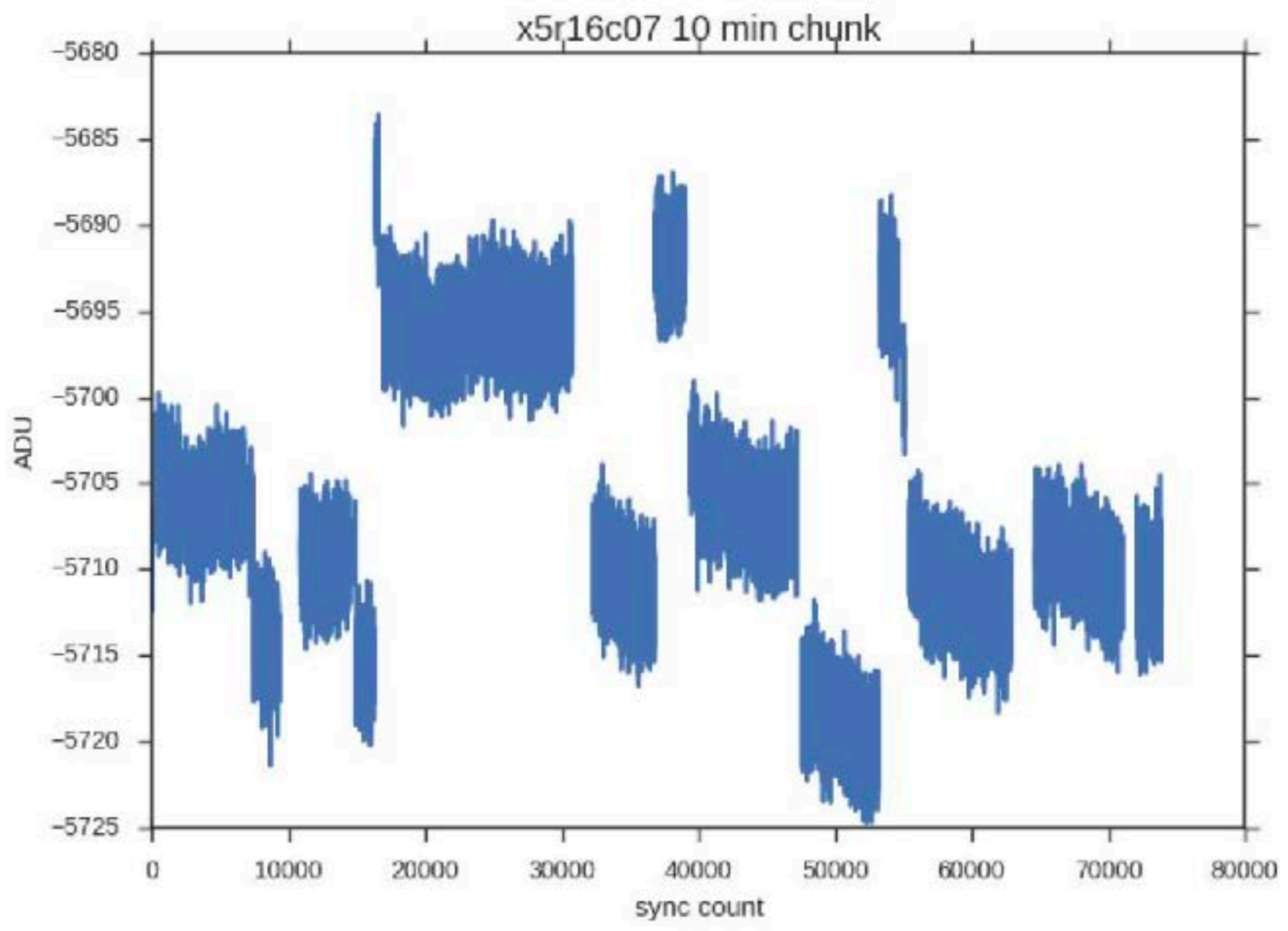
B. Osherson+, JLTP 199, 1127 (2020) (arXiv:2002.05771)

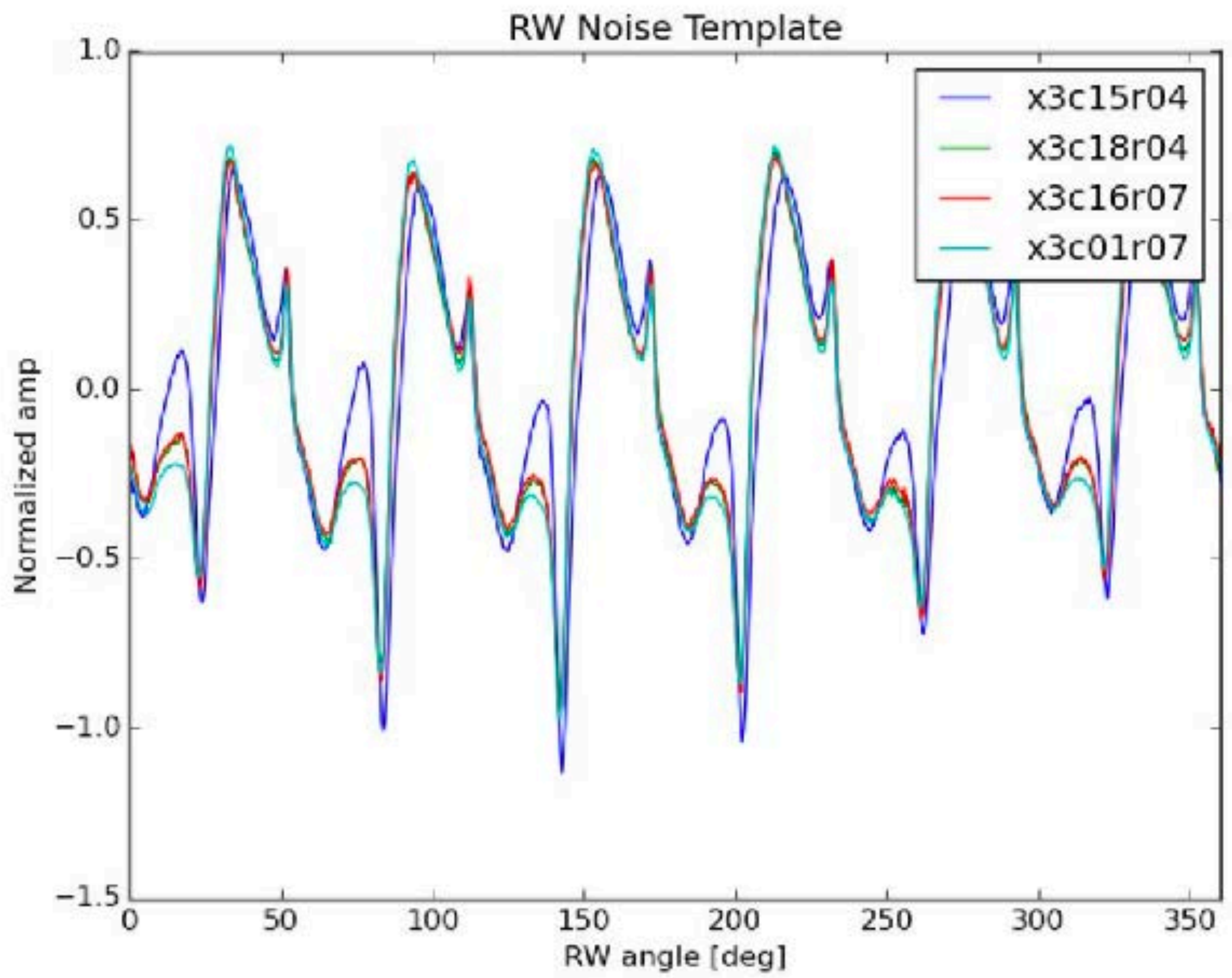
RFI Challenges

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)





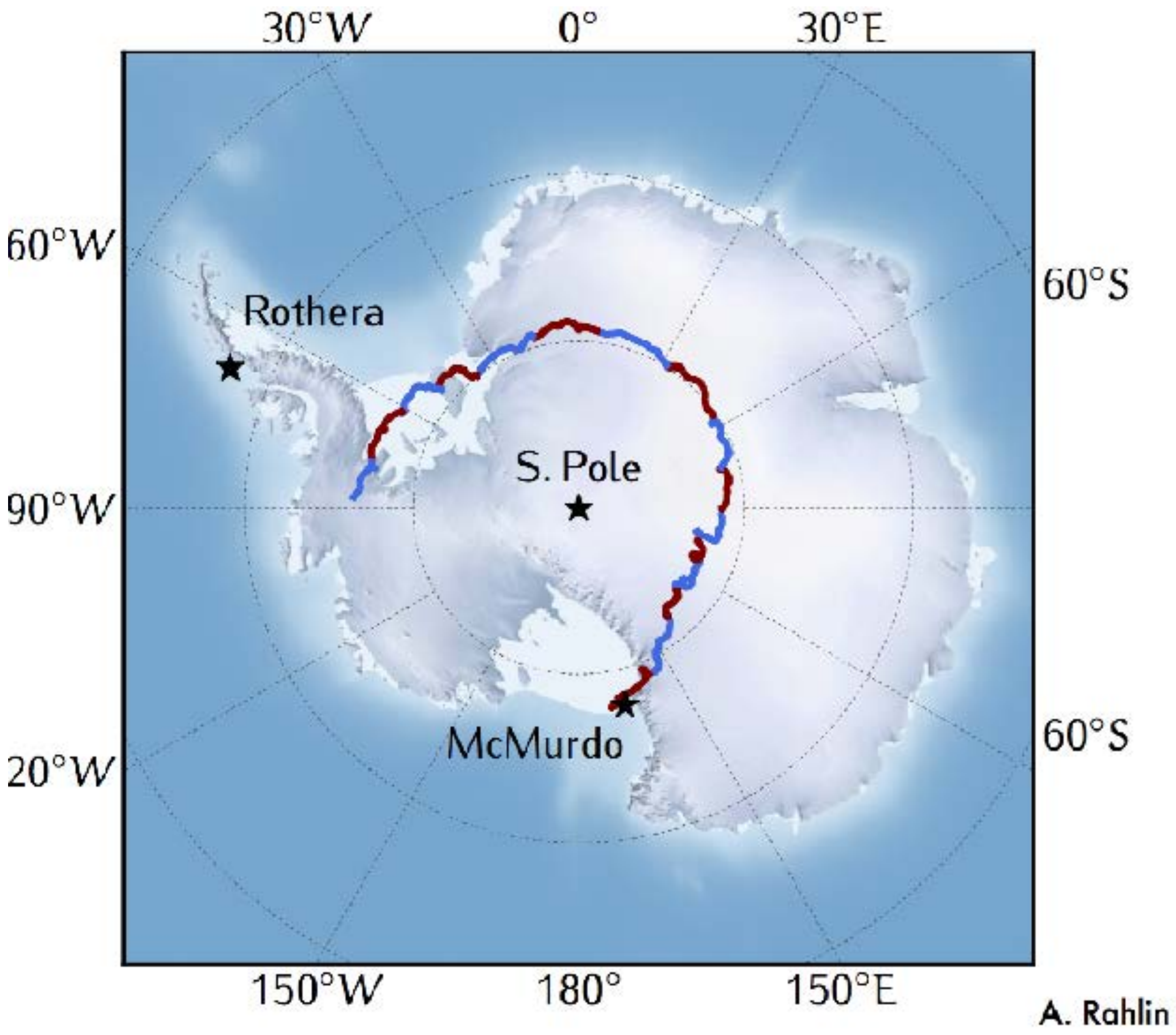
Reaction Wheel

Perpetual Motion

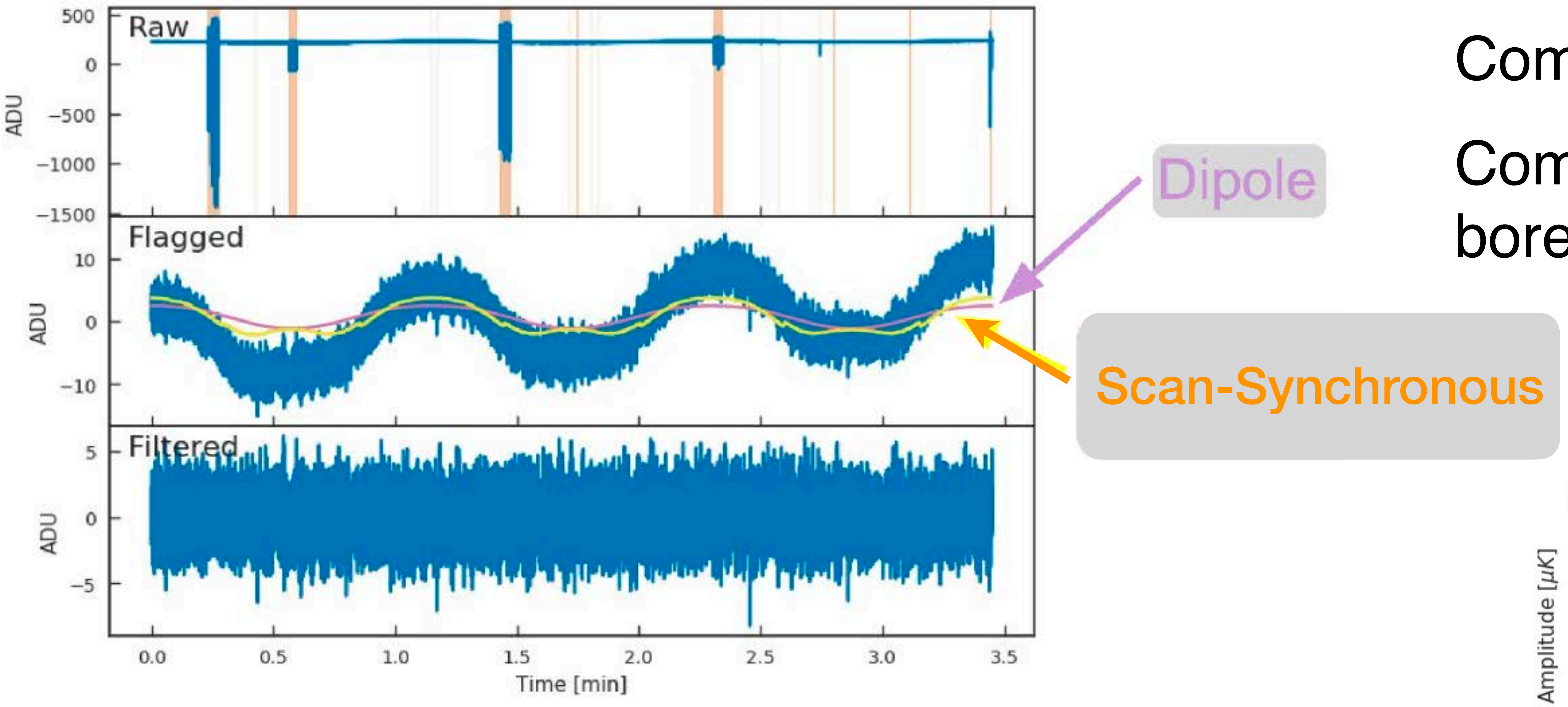
A balloon's constant motion adds **complex time dependence** to certain systematics that could be template-subtracted on the ground

- **Far sidelobe response**: Terminate on ever-changing land / sea / cloudscape (and ever-present sun)
  - Very aggressive **baffling** of each aperture
  - Difficult to characterize precisely in lab or flight
- **Magnetic response**: Changing orientation of Earth's field affects SQUIDs and TESs
  - Demands exquisite **magnetic shielding**
    SPIDER shielding factor >10^7: Runyan+ 2010

*Each especially important at **large angular scales**!*

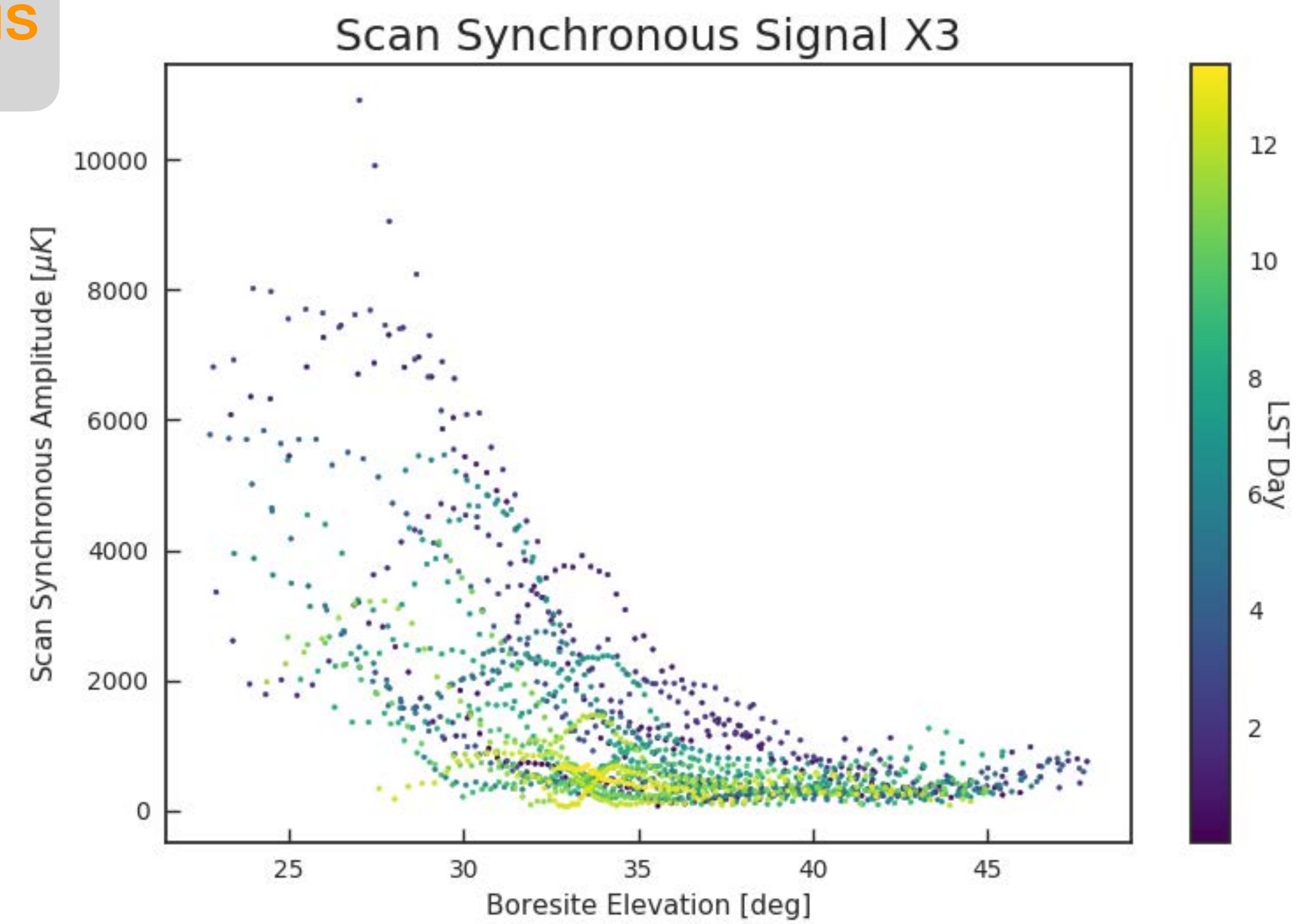


Scan-Synchronous Noise



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

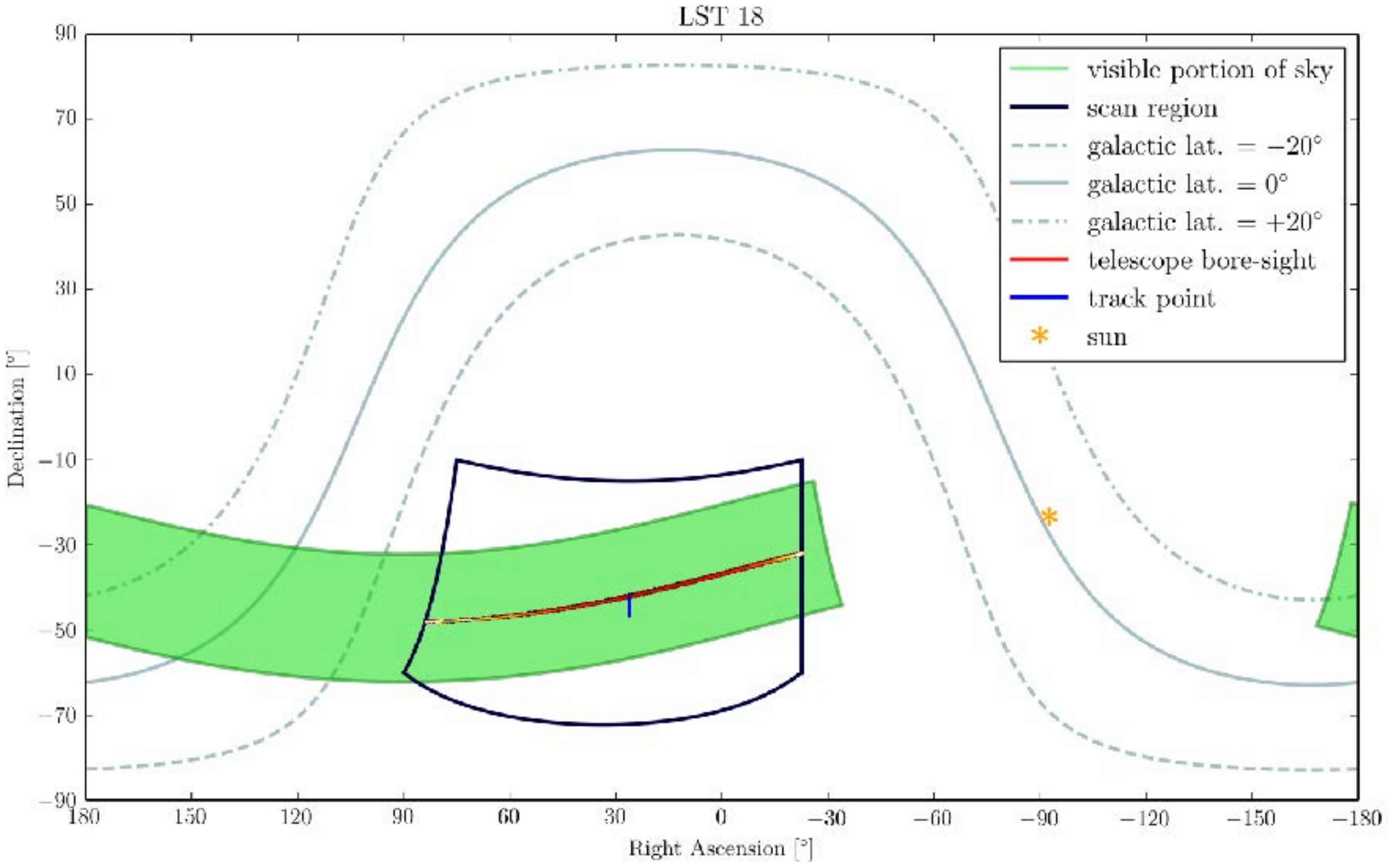
Limited Time: Redundancy and Noise

Empirical **noise modeling is hard**. Drives us to space-like high-level analysis

- S/N is relatively high: must *solve for signal and noise simultaneously*
- Data redundancy is very limited (… *though high relative to Planck!*)

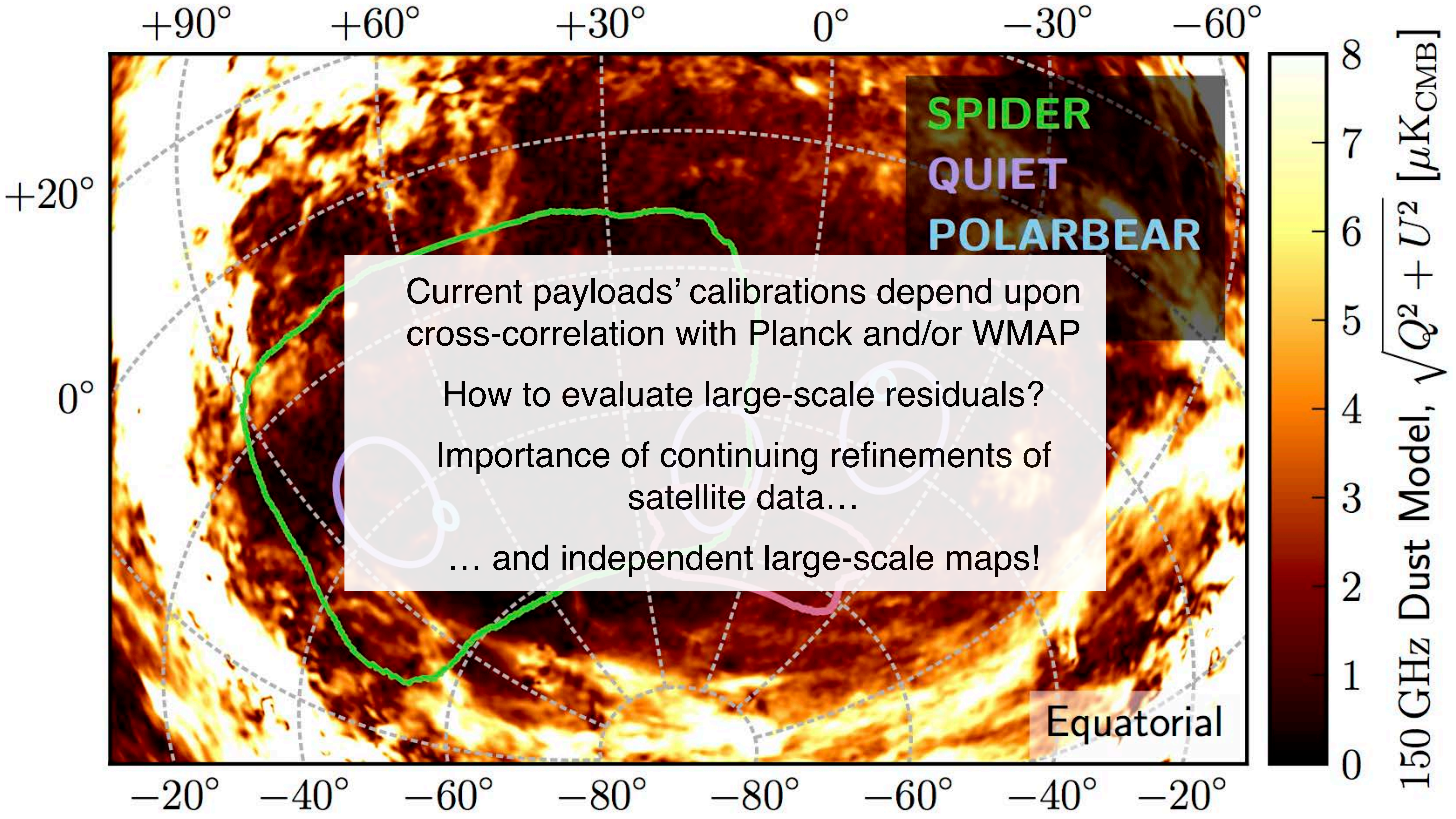
For SPIDER power spectra:

- **XFaster** (*Contaldi, Gambrel, Rahlin*): *iterative quadratic estimator adaptive noise estimate*
- **NSI** (*Nagy, Hartley, Benton*): *Empirical cross spectra among 14 interleaved data chunks ()*



SPIDER scan

Substantial sky rotation, changing obs latitude
24hr scan + HWP step, repeats every 4 days
High instantaneous S/N



Current payloads' calibrations depend upon cross-correlation with Planck and/or WMAP

How to evaluate large-scale residuals?

Importance of continuing refinements of satellite data…

… and independent large-scale maps!

What Next?

What can ballooning bring us in the post-Planck era?

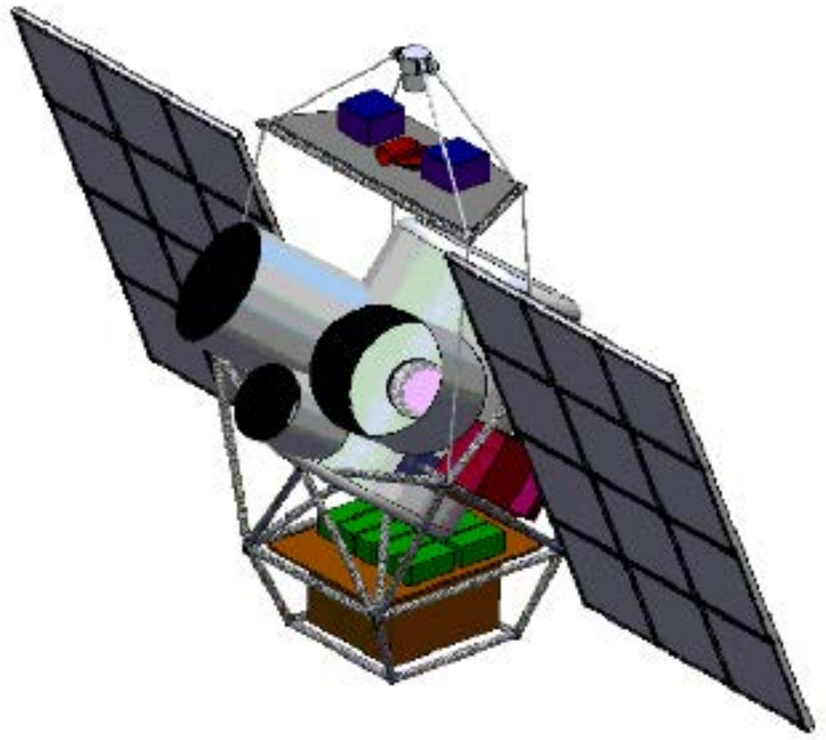
Access to **high (>250 GHz) frequencies**

Challenging from terrestrial observatories

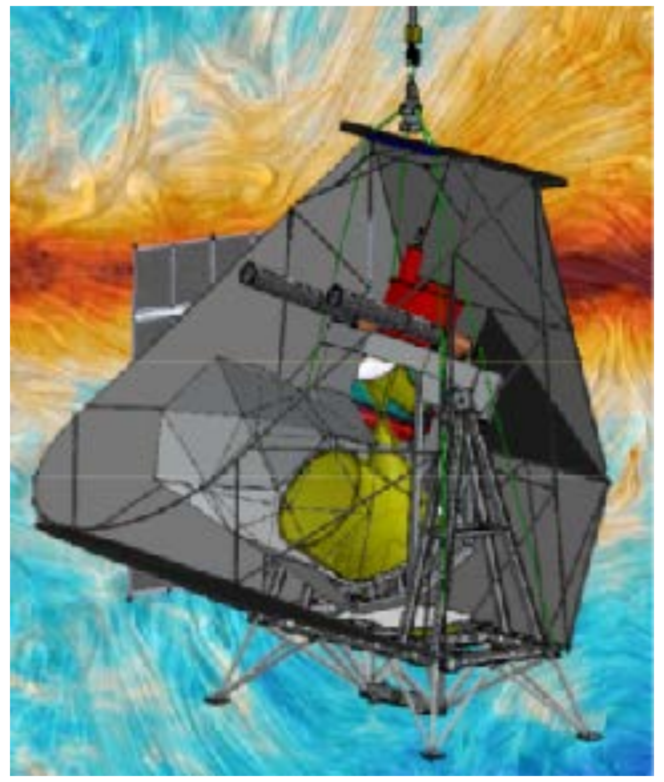
Dust maps over large sky areas with post-Planck sensitivities, *and distinct systematic effects!*

SPIDER II - flight-ready!

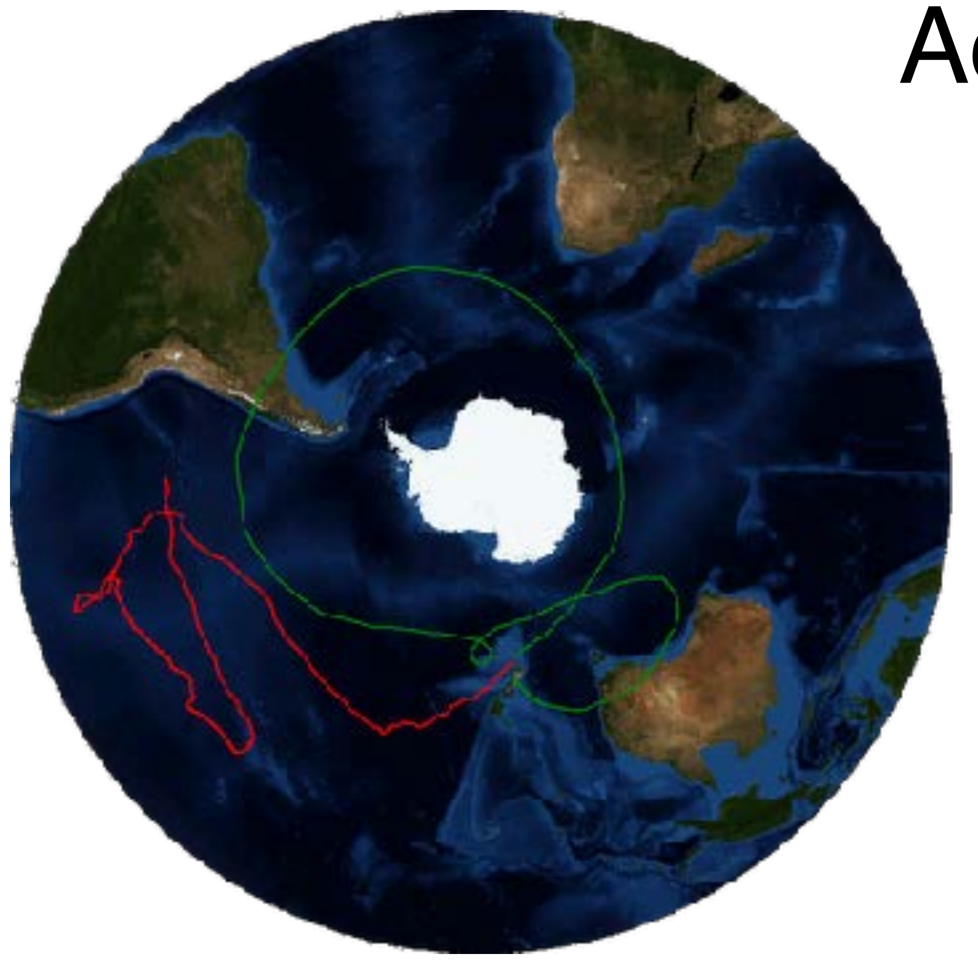
Taurus



BFORE



COSI ULDB flight



Access to large sky areas, **large-scale modes**

Ultra-long duration ballooning (100 days?)

Measurements of **tau** and **foregrounds** across >50% of the sky?

Can we observe sufficiently cleanly at $\ell<15$?

Can we get the data back?

Challenges of CMB Ballooning

General challenge: **Limited time** in unusual observing environment

- **Dark skies**: *testing and stability under flight load*
- **Moving platform**: *scan-sync pickup, magnetic pickup*
- **Space realities**: *cosmic rays, transmitter RFI*
- **Complex, non-redundant data**: *space-like high-level analysis*

Many systematics have been shown to be well-controlled

Beams, pointing errors, crosstalk, gain stability, cosmic rays, …

Ongoing role for ballooning at high frequencies, large scales

ULDBs promise long integrations, large scales

Can we control system stability sufficiently for largest scales?