Searching for the echoes of inflation with

SPIDER

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Madrid: CMB, LSS, 21cm
June 24, 2016

B mode polarization in the CMB

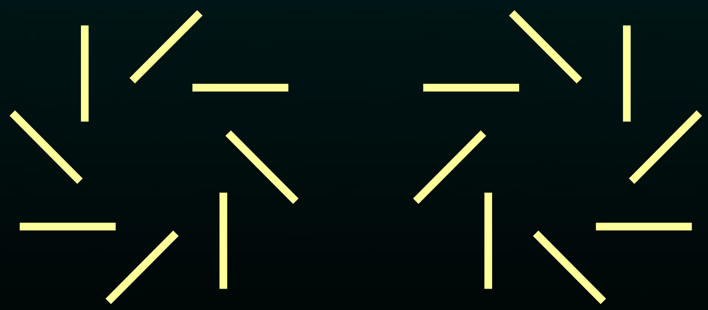
E modes are the CMB's "intrinsic polarization"

- We expect them to be there because of scattering processes in the CMB
- Temperature anisotropies predict E-mode spectra with almost no extra information
- Not only that, but "standard" CMB scattering physics generates ONLY E modes.

Why do we care about B modes?

- **Inflation**: exponential expansion of universe (x 10^{25}) at 10^{-35} sec after big bang creates a gravitational wave background that leaves a B-mode imprint on CMB polarization.
- **Gravitational lensing** by large scale structure converts some of the E-mode polarization to B-mode. Use this to study structure formation, "weigh" neutrinos.
- How can we tell the difference between the above two? **Degree** vs. **arcminute** angular scales.

The moral of the story: B modes tell us things about the universe that temperature and E modes *can't*.

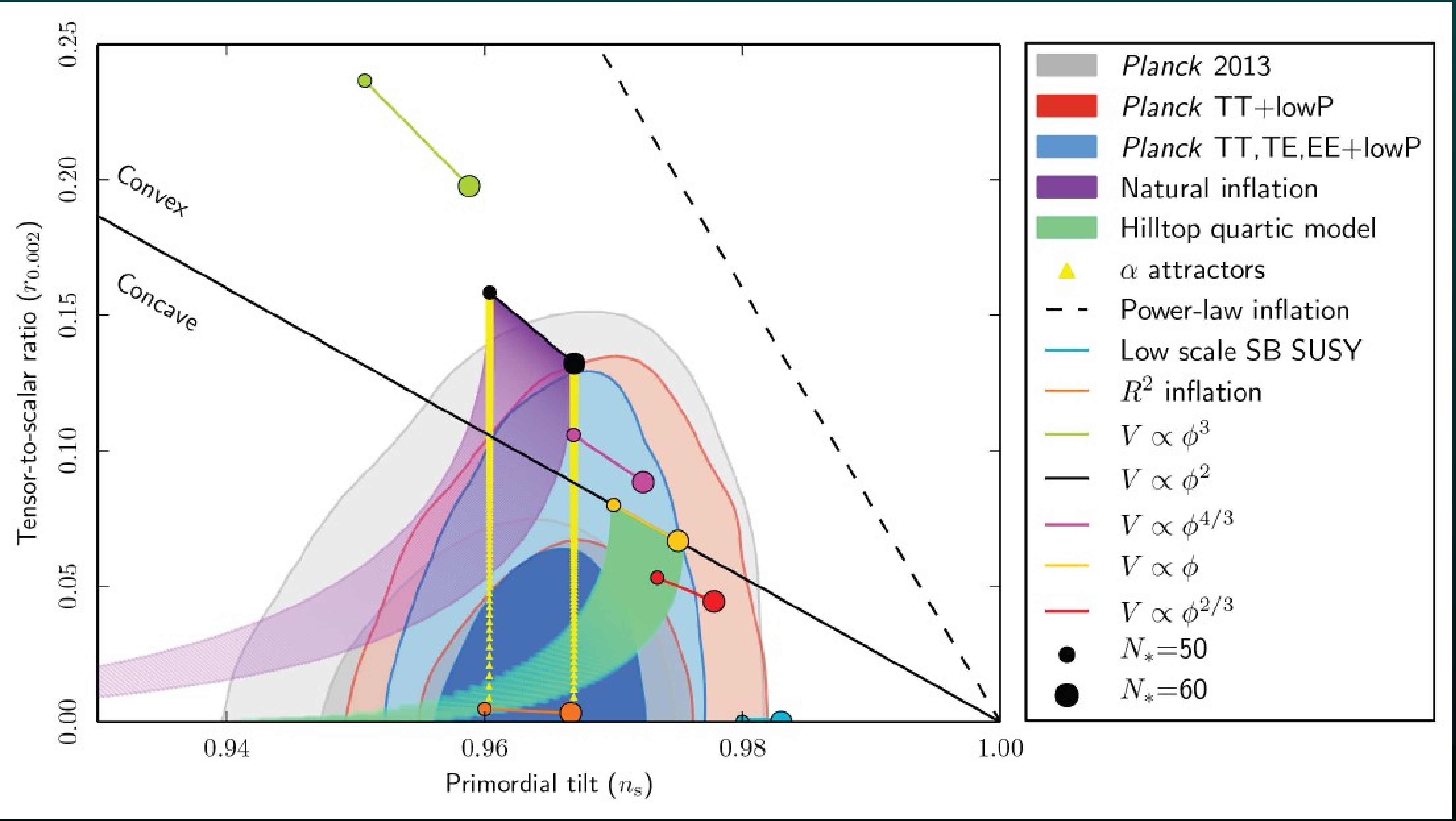


Inflation scorecard

Inflation predicts:	**Our universe (Planck 2015):**
A flat universe	$\Omega_k = 0.000 \pm 0.0025$
with nearly scale-invariant density fluctuations,	$n_s = 0.968 \pm 0.006$
well described by a power law,	$dn_s / d\ln k = -0.0065 \pm 0.0076$
with scalar perturbations	$r_{0.002} < 0.01$ (at 2σ)
that are Gaussian	$f_{NL} = 2.5 \pm 5.7$
and adiabatic,	$\beta_{iso} < 0.03$ (at 2σ)
with a negligible contribution from topological defects	$f_{10} < 0.04$

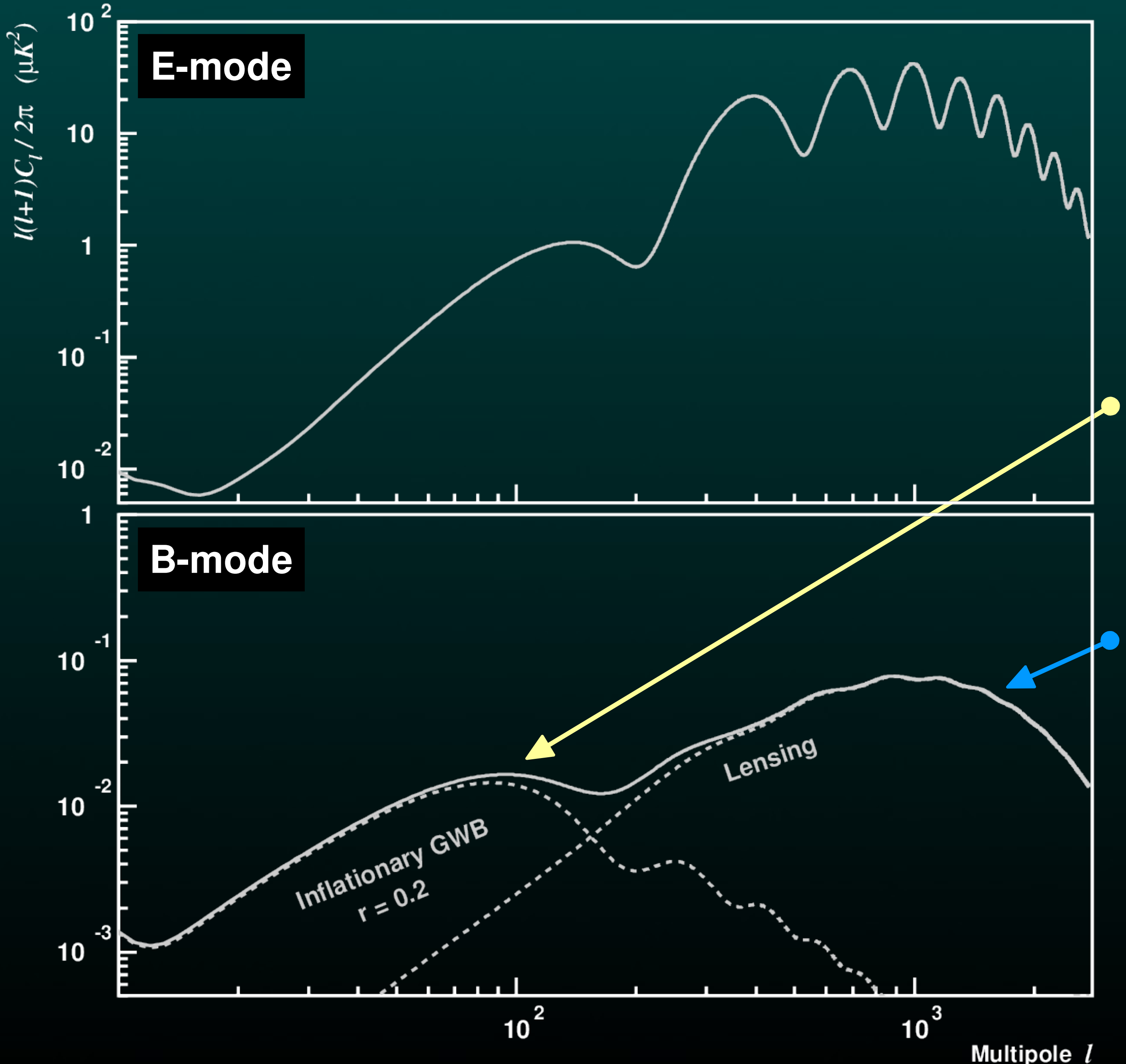
(Adapted from Martin White)

Constraining inflation



Planck 2015

CMB polarization power spectra



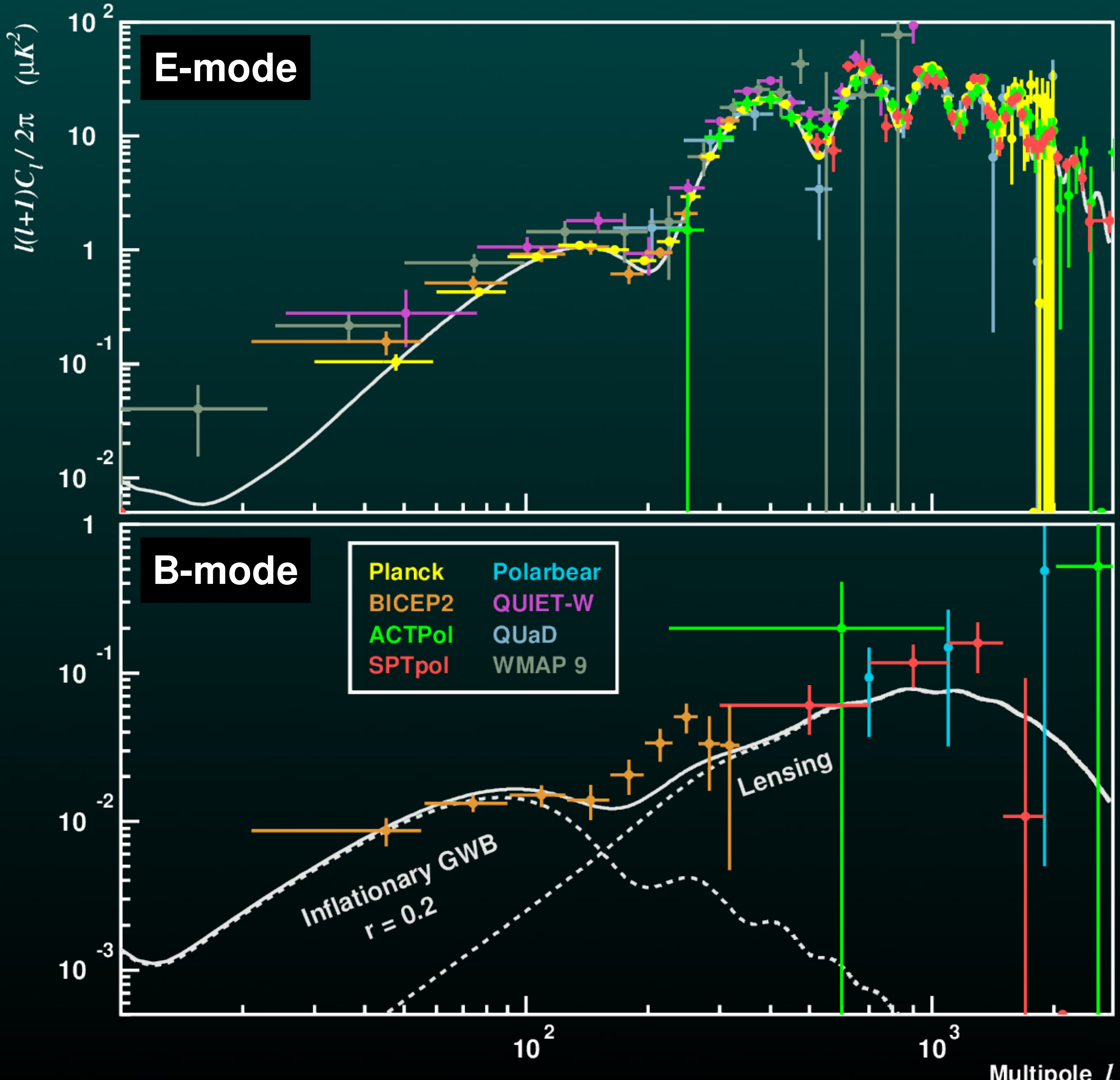
E-mode is mainly sourced by density fluctuations and is the intrinsic polarization of the CMB

Degree-scale B-mode from gravitational waves, amplitude described by the tensor-to-scalar ratio *r*.

Arcminute-scale B-mode from weak gravitational lensing by large-scale structure, partial conversion of E-modes

Both flavors of B-mode polarization are much fainter than E-mode, and they appear at distinct angular scales.

Current CMB polarisation measurements



E-mode polarisation measured with high precision: acoustic peaks have been detected and are consistent with LCDM

First detections of B-mode polarisation were reported just in the last three years

Inflationary:
Not there yet, but we've seen foregrounds

Lensing:
Detections by ACT, SPT, Polarbear, and BICEP2/Keck, consistent with theoretical expectations

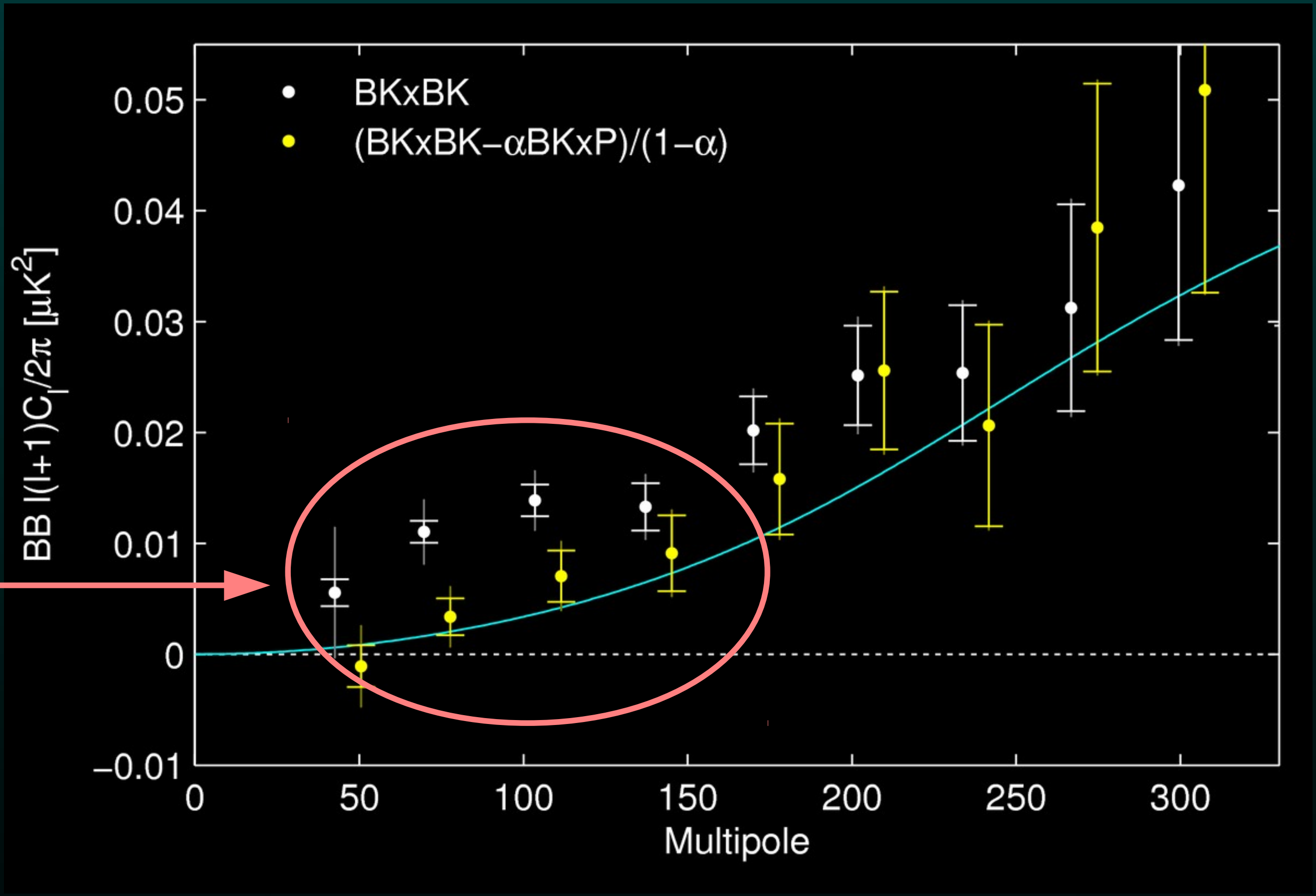
A dusty turn of events...

February 2015:
Joint analysis between BICEP2, Keck and Planck shows that most of the BICEP2 B-mode signal can be explained by dust contamination

BICEP2/Keck B-mode data before cleaning

BICEP2/Keck B-mode data after subtracting dust signal measured by Planck

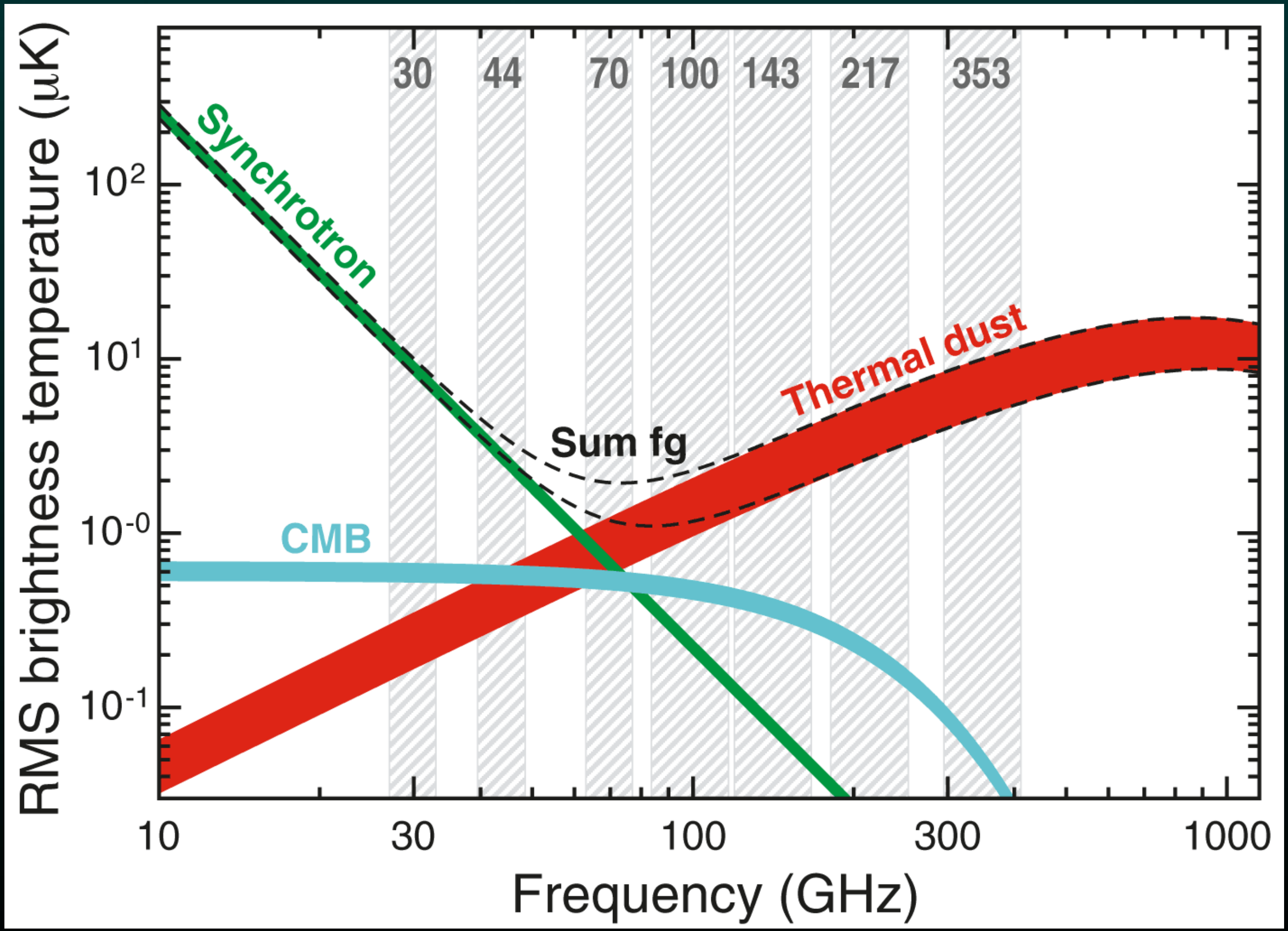
B-mode power spectrum, lensing only (no inflationary)



Revised result from joint analysis: *r* < 0.12 at 95% confidence

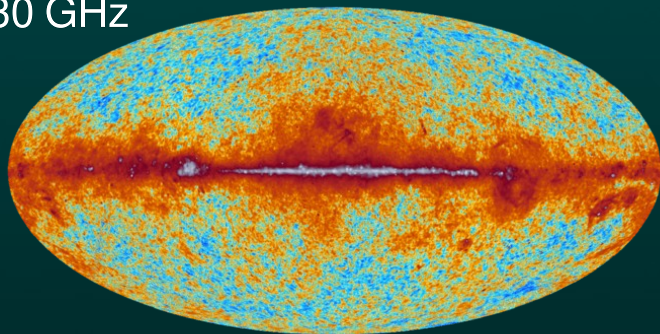
Foreground contaminants

- **Thermal dust emission**: dust grains are nonspherical, emit along their longest axis, and align perpendicular to Galactic magnetic field. Emission increases with frequency.
- **Synchrotron emission**: electrons spiral around Galactic magnetic field lines and radiate. Emission decreases with frequency.
- Others: free-free, spinning dust, point sources...all expected to have low polarization

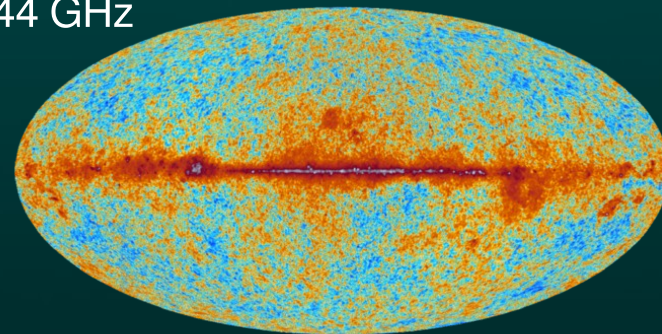


Portraits of foregrounds from Planck

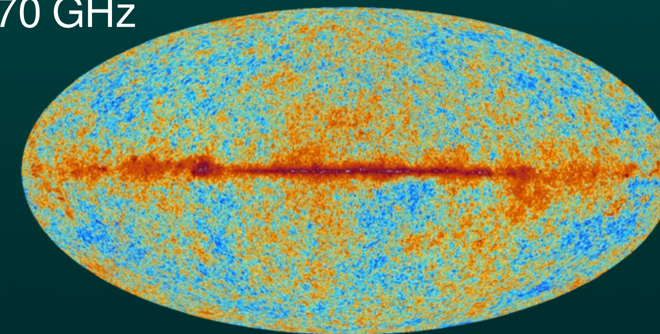
30 GHz



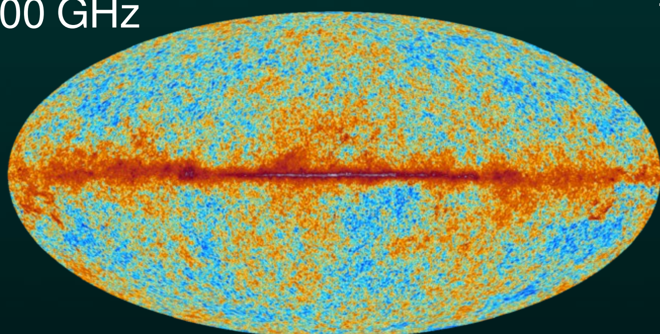
44 GHz



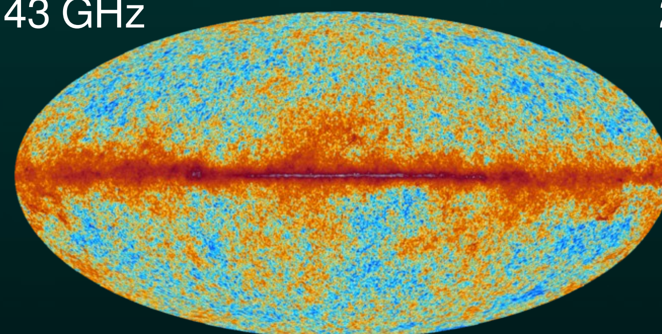
70 GHz



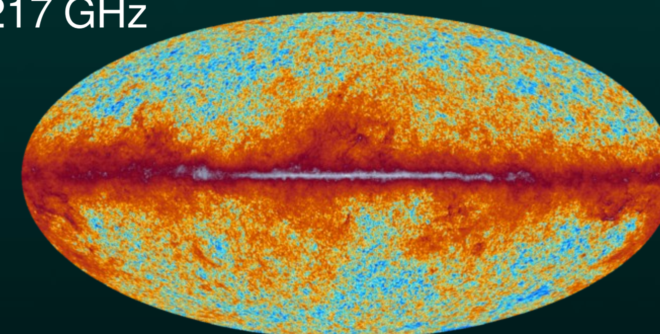
100 GHz



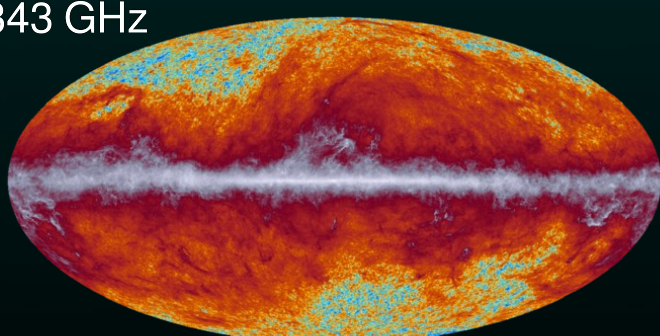
143 GHz



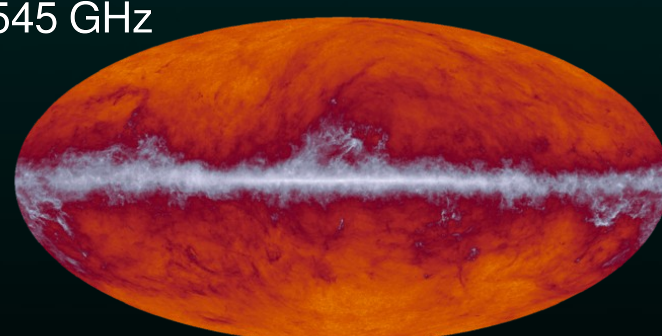
217 GHz



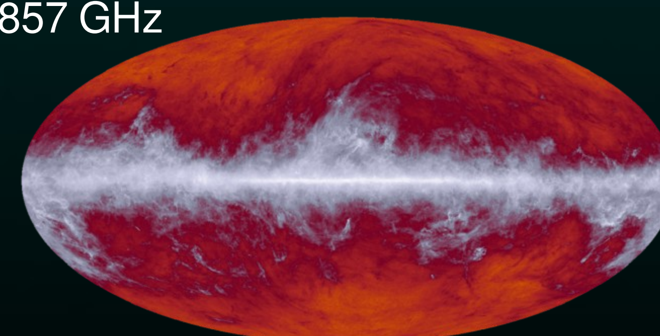
343 GHz



545 GHz



857 GHz



“The universe is a filthy, filthy place.”

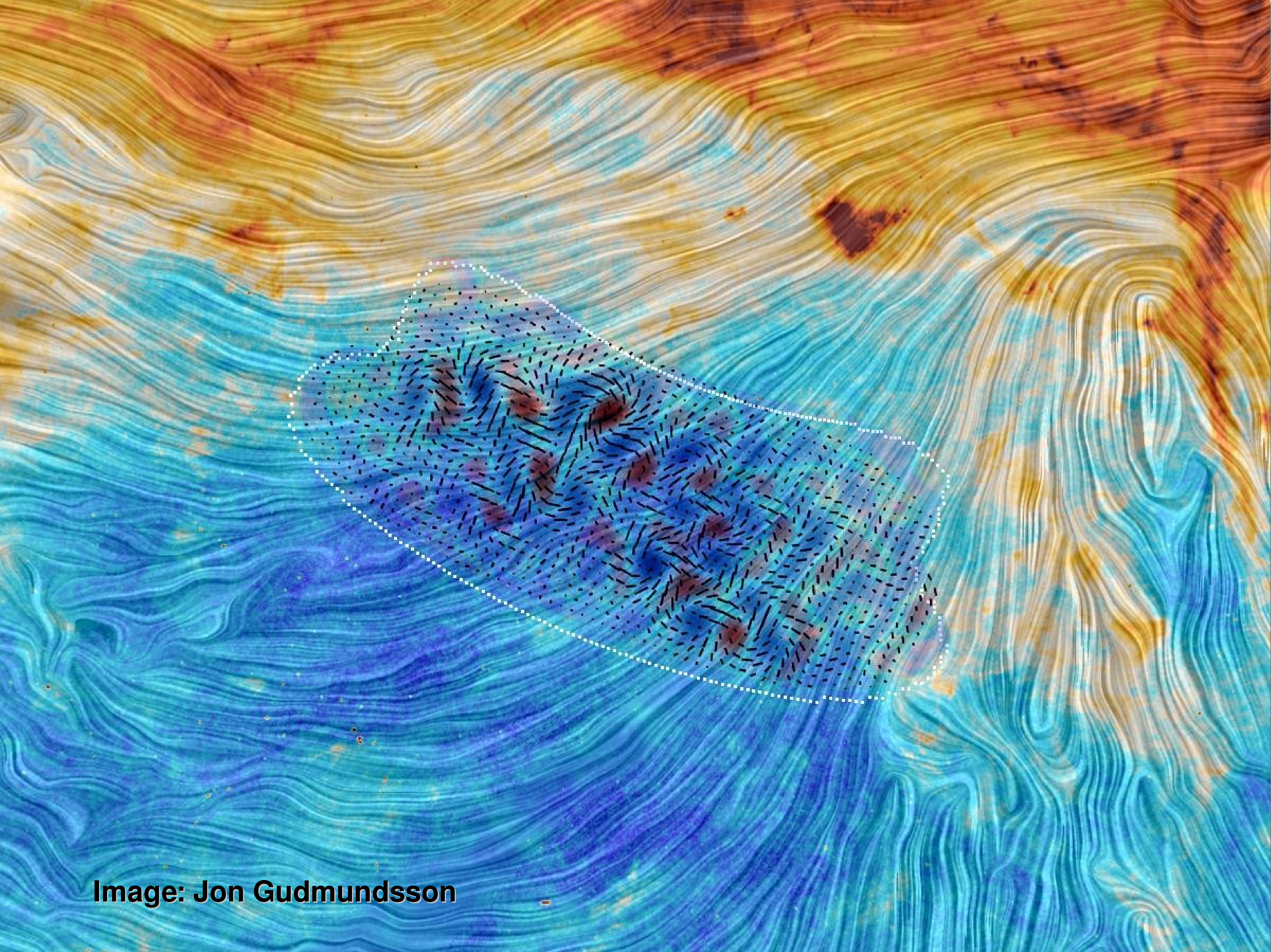
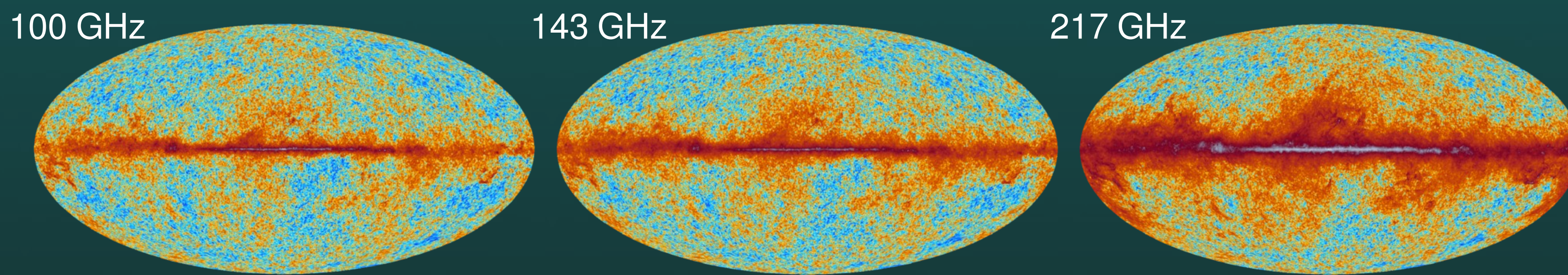


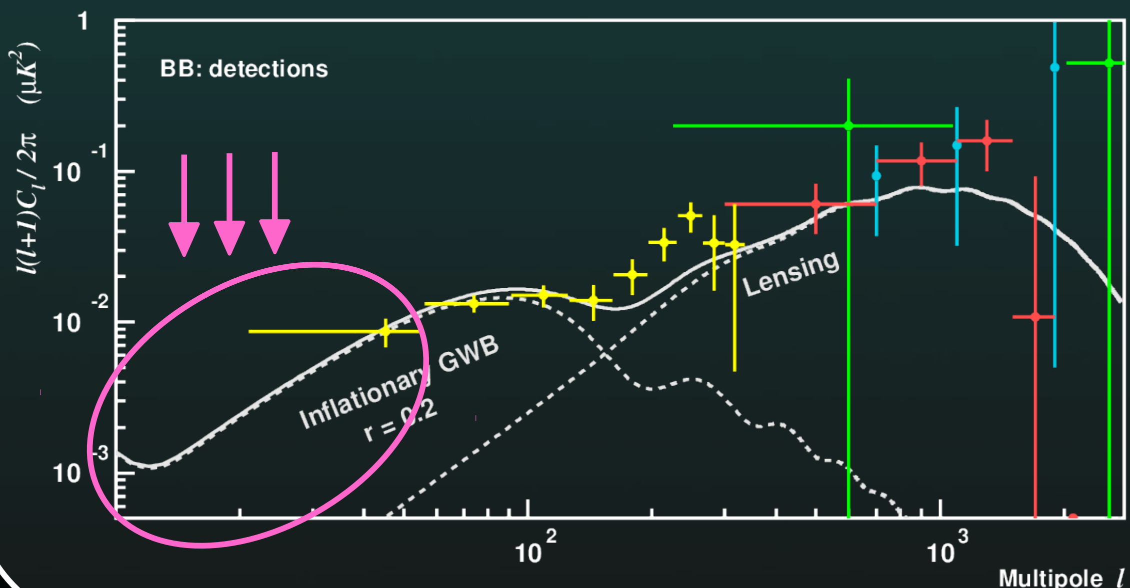
Image: Jon Gudmundsson

How can we do better?

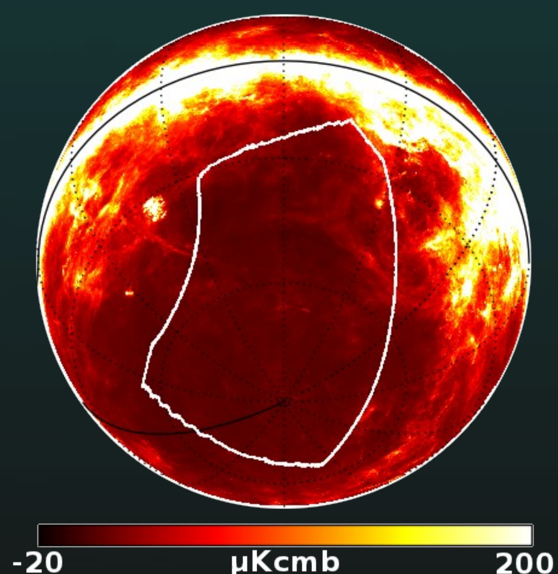
More frequencies: CMB and foregrounds have different spectra



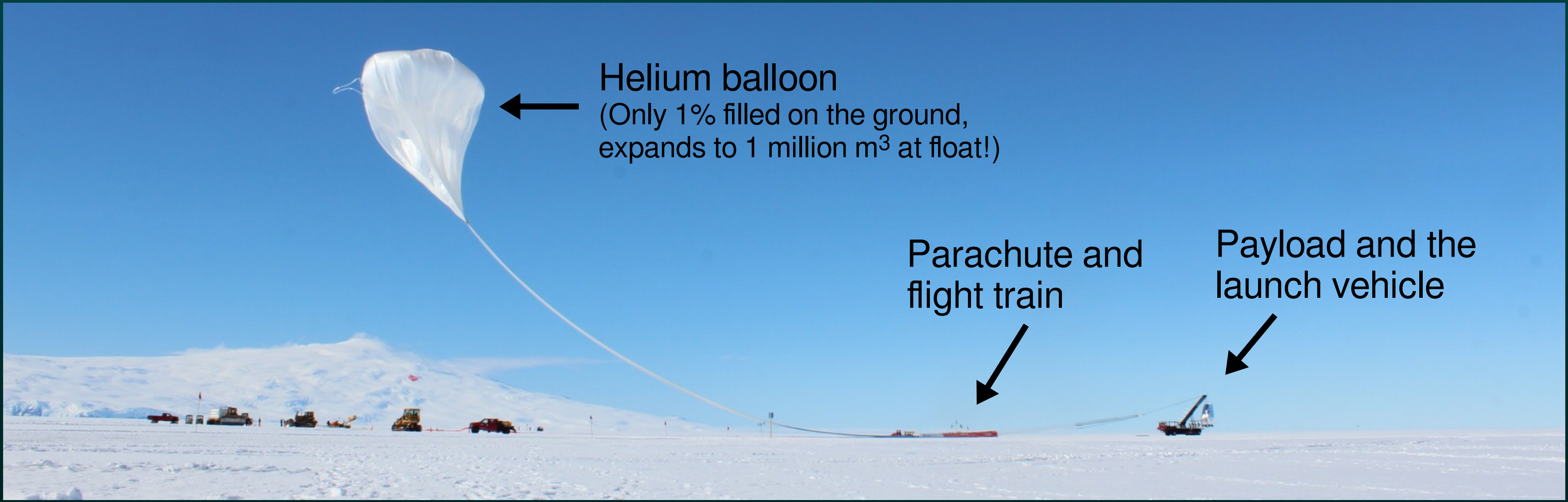
More multipoles: constrain power spectrum shape



More sky: CMB signal shouldn't vary

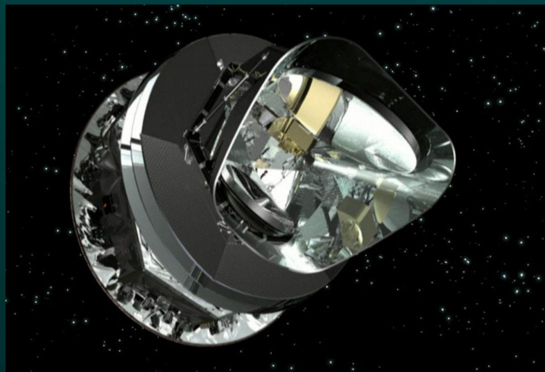
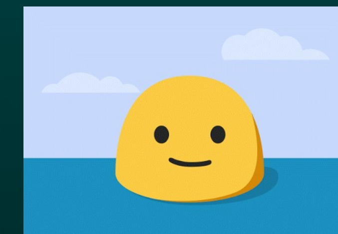
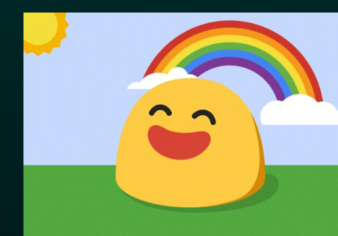
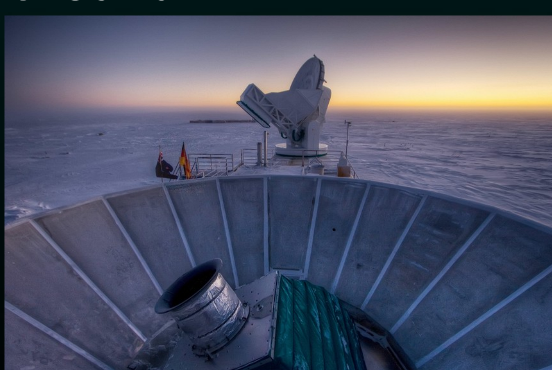
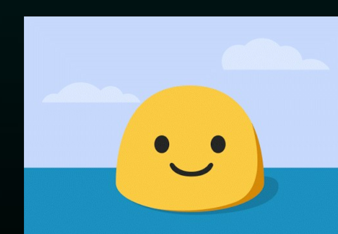


Antarctic long-duration ballooning



- Stratospheric balloons give us high and dry observing conditions ("satellite on the cheap"): reduced loading, access to larger angular scales, wider frequency windows
- Continuous solar power and long flights (median ~20 days) from McMurdo station, Antarctica
- Downsides: narrow launch windows, recovery difficulties, and constraints on mass, power, automation
- Float altitude: 35 km
  Balloon volume: 1 million m^3
  Max payload weight: 3000 kg

Telescope platform smackdown

	Atmosphere	Cost	Difficulty	Fun Factor
Satellite 	None	>10–100x	Years to integrate, ~zero chance to fix	
Balloon 	Almost none	1.5x	Weeks to integrate, one shot every 1-2 years	
Ground 	Can add noise	1x	Integration time unlimited, can fix at ~any time	

(Adapted from Barth Netterfield)

SPIDER: a new instrument for CMB polarimetry

Science goals

Constrain inflationary B-mode polarisation in the CMB at the level of *r* < 0.03 at 99% confidence

Characterize Galactic foregrounds

Lensing B-modes

Instrumental approach

Long duration balloon flight

0.5 deg resolution over 10% of the sky, target 10 < ell < 300

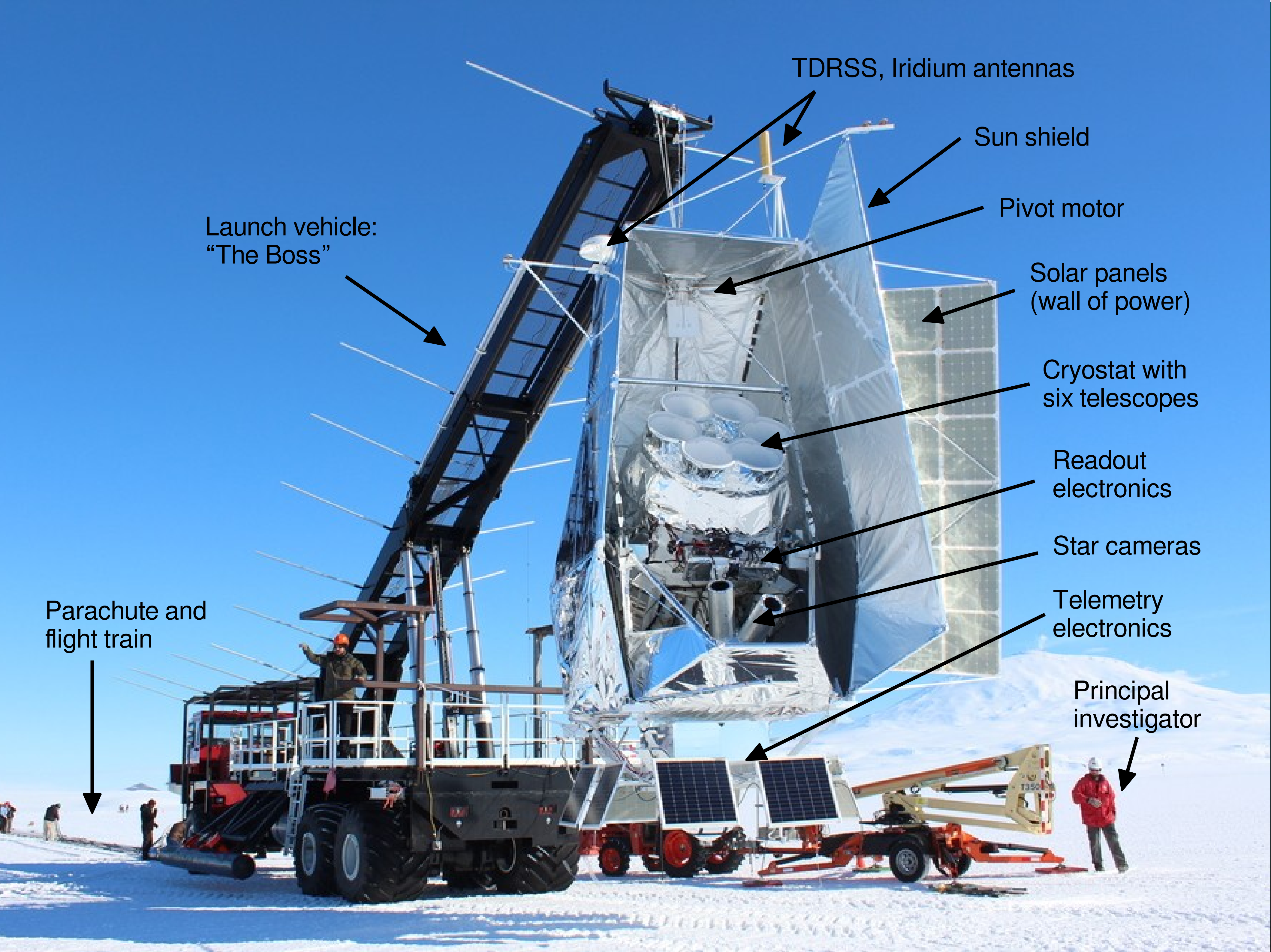
6 compact, monochromatic refractors in LHe cryostat

~2000 detectors split between 90,150 GHz

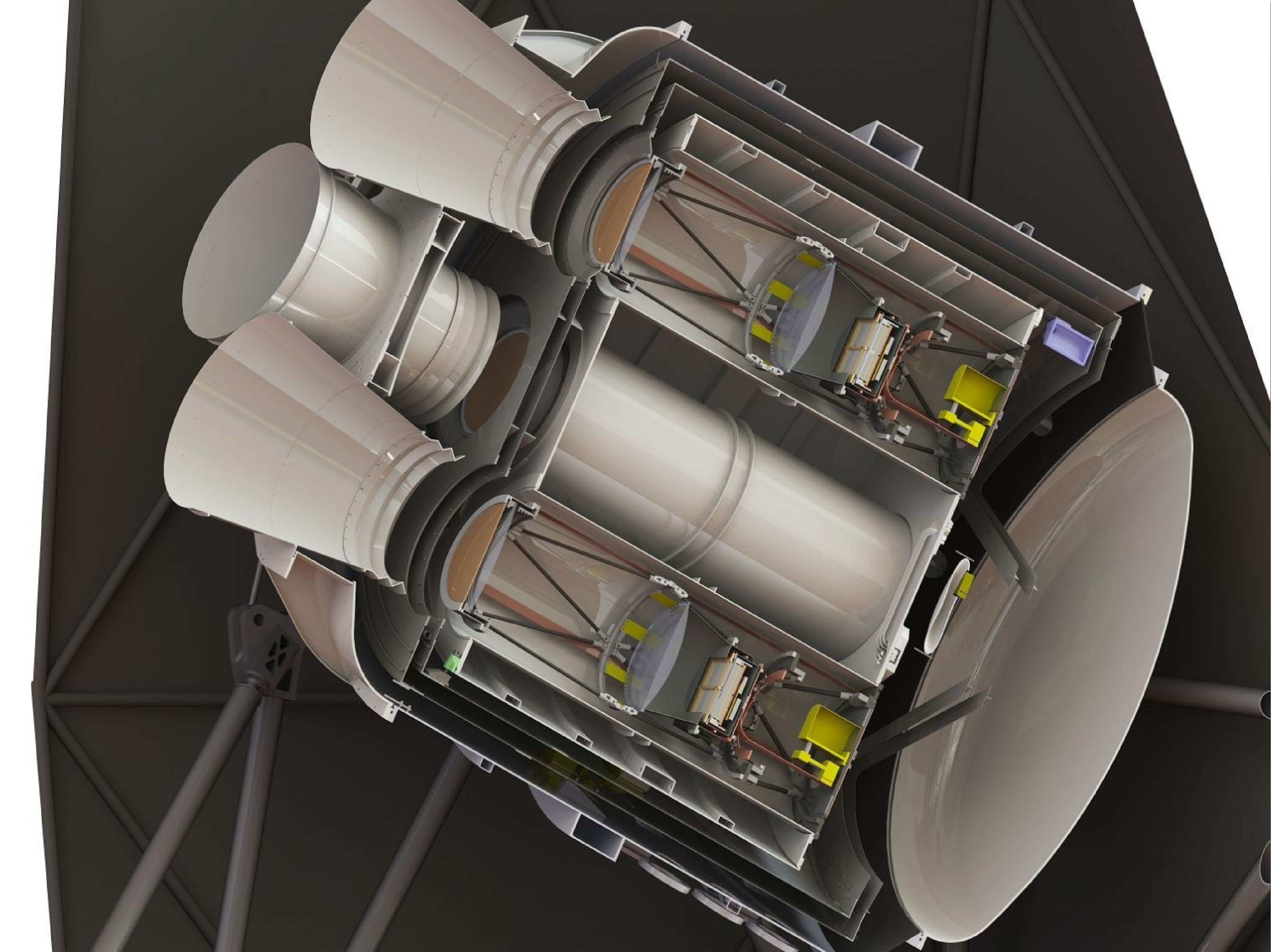
Polarisation modulation: HWPs

NASA · CSA ASC · C.S.B.F. Palestine, Texas · NSERC CRSNG · JPL · California Institute of Technology · Princeton University · University of Toronto · Imperial College London · KICC Kavli Institute for Cosmology Cambridge · Leland Stanford Junior University · Universitas Osloensis

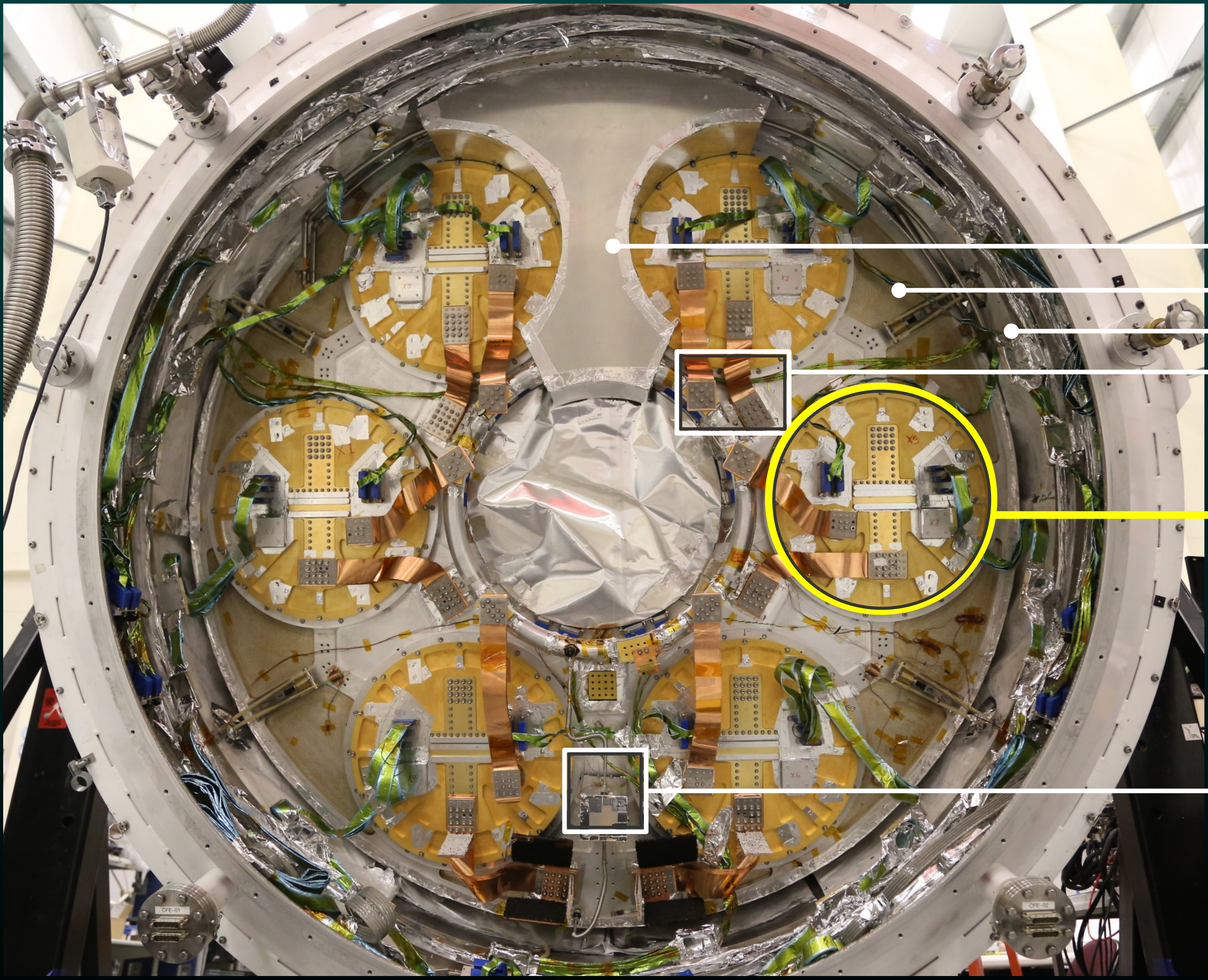
NIST · CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique théorique · Cardiff University Prifysgol Caerdydd · UBC · Case Western Reserve University est. 1826 · University of KwaZulu-Natal Inyuvesi Yakwazulu-Natali · Illinois · IAS orsay · APC, CNRS, France · Stockholm University · ASU



TDRSS, Iridium antennas
Sun shield
Pivot motor
Launch vehicle:
"The Boss"
Solar panels
(wall of power)
Cryostat with
six telescopes
Readout
electronics
Star cameras
Parachute and
flight train
Telemetry
electronics
Principal
investigator

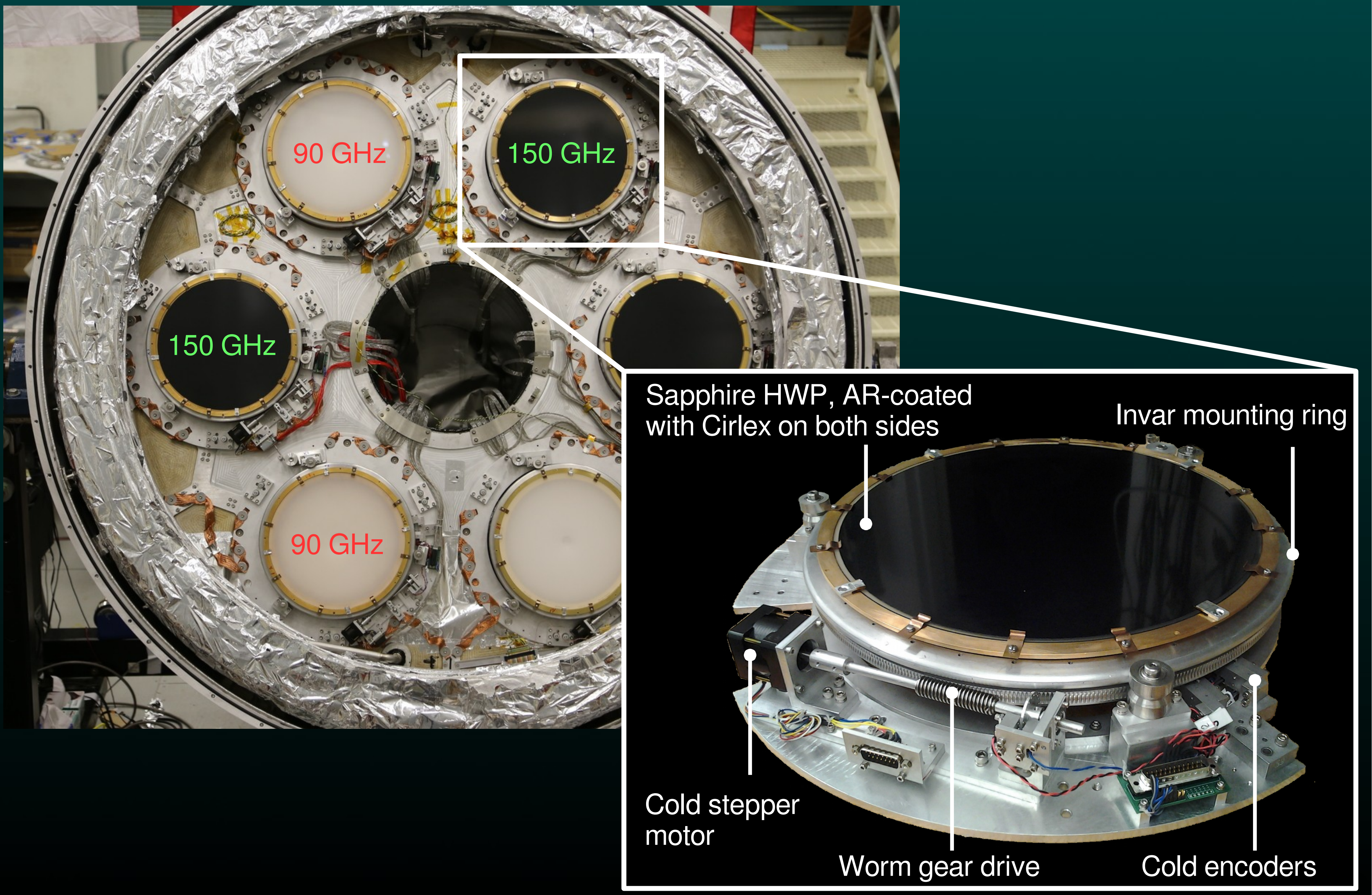


SPIDER's six telescopes (back end)

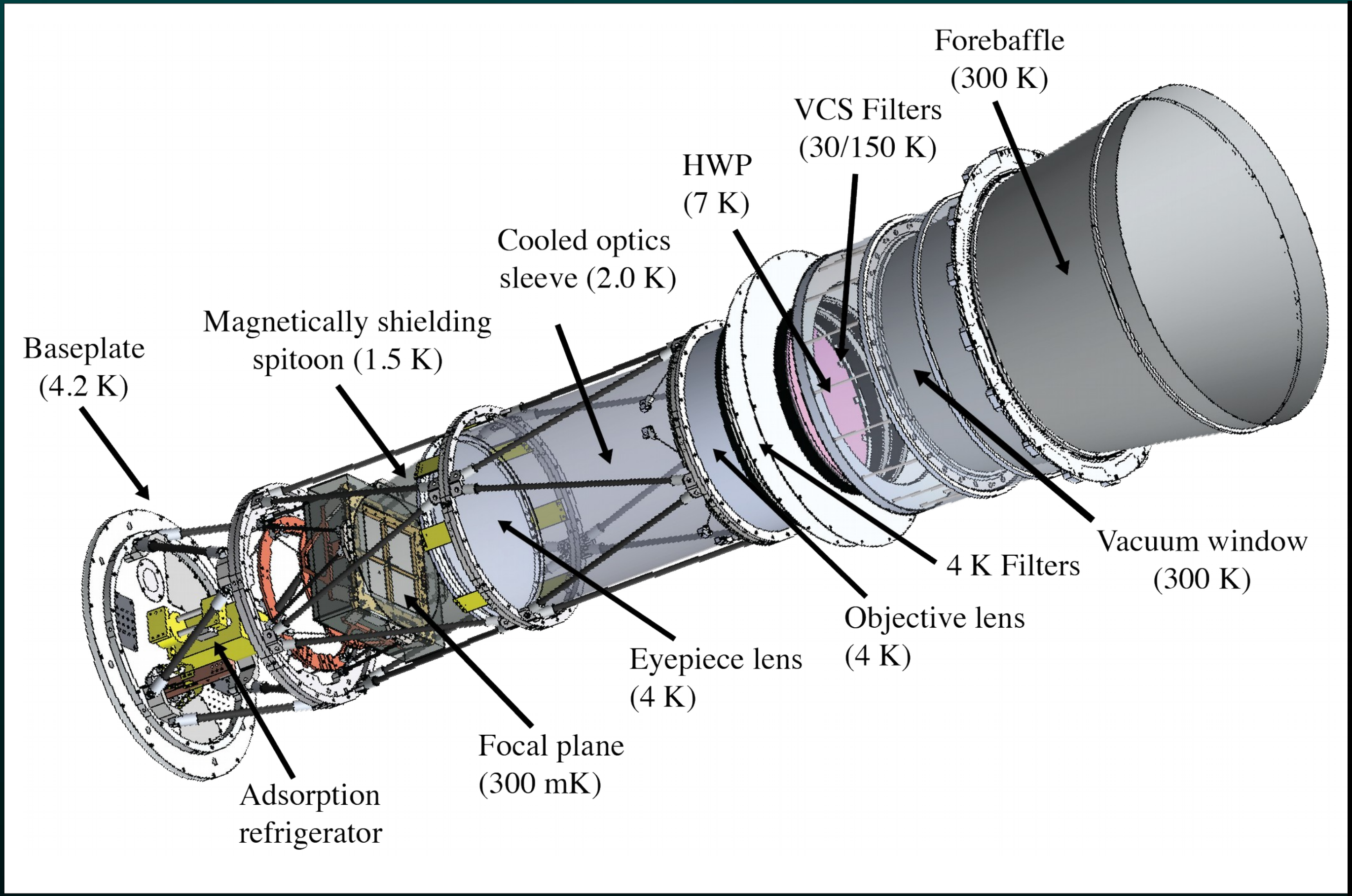


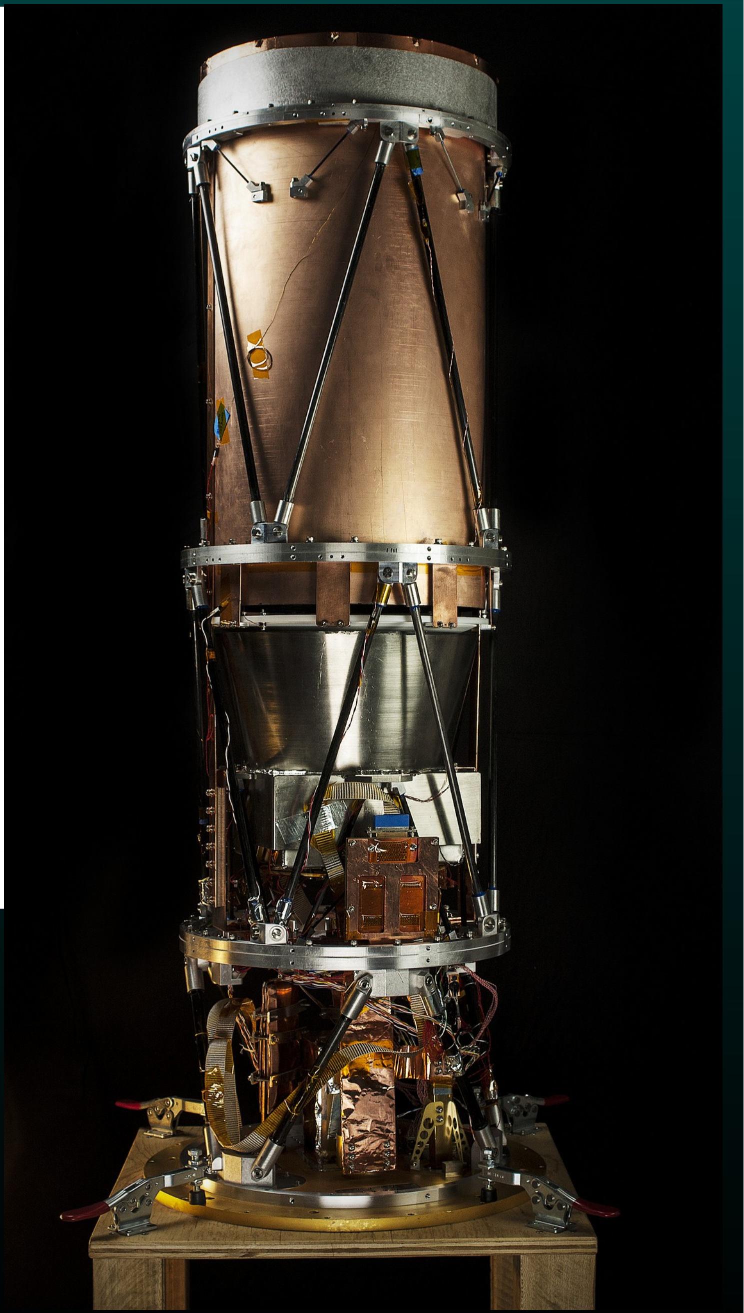
Cryogenics paper:
J. Gudmundsson et al.,
arXiv:1506.06953

SPIDER's six telescopes (front end)



Modular telescopes

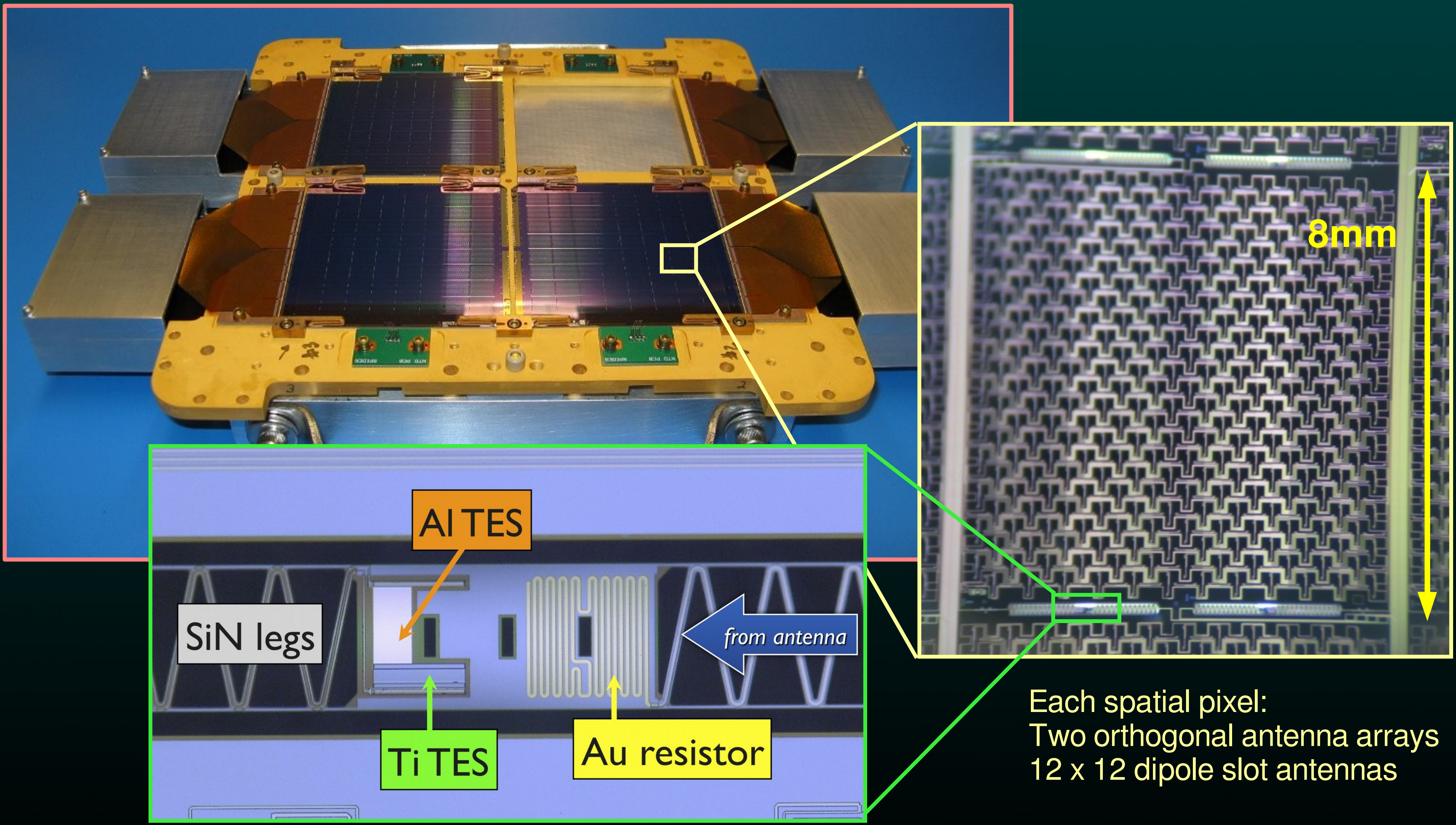




- Each insert tuned for a single frequency band
- 90 lbs each: lightweighting + stiff carbon fiber truss
- Two-lens optical design (based on BICEP)
- Extensive efforts to optimize magnetic shielding

Focal plane: antenna-coupled TES bolometers

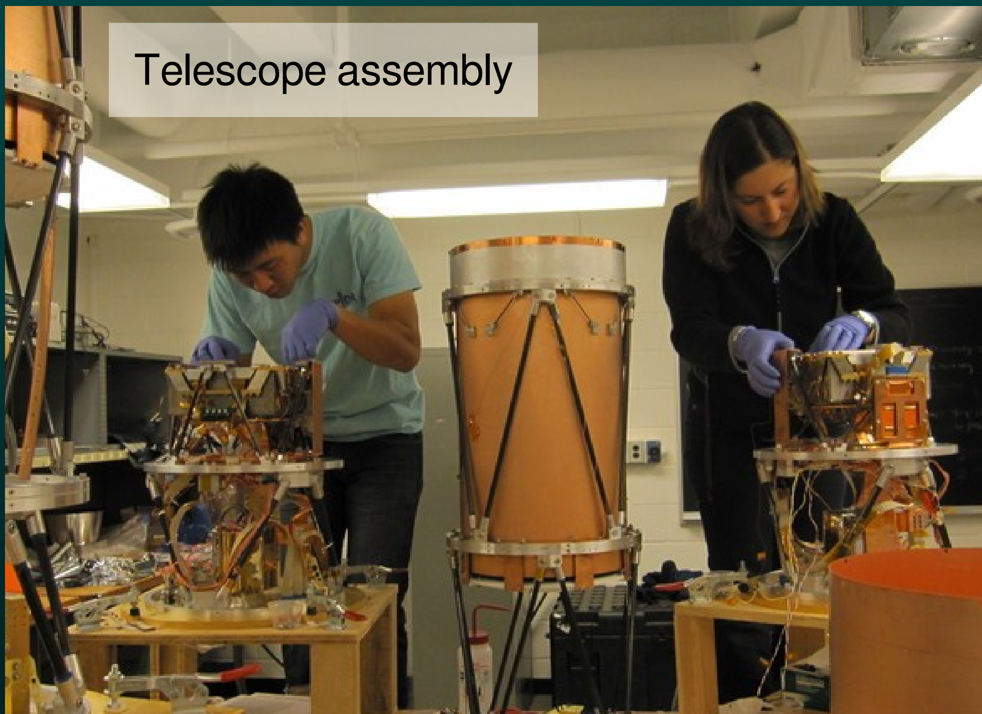
Each focal plane: 4 tiles x 64 pixels x 2 polarizations = 512 detectors



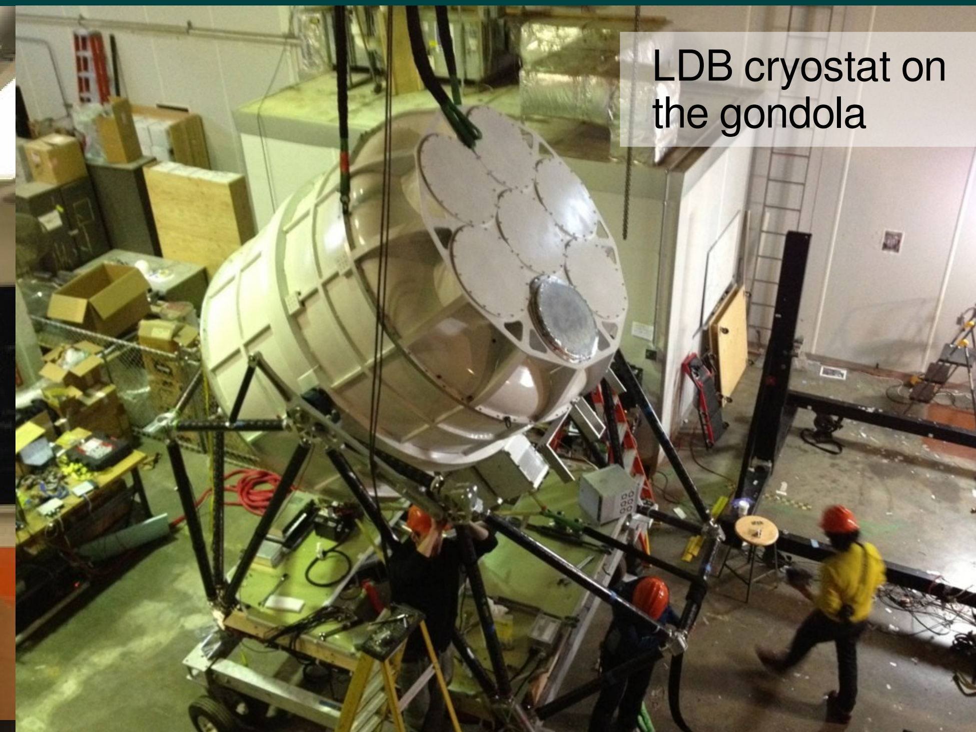
Each spatial pixel:
Two orthogonal antenna arrays
12 x 12 dipole slot antennas

Detectors: Al / Ti TES bolometers

SPIDER integration glamor shots



Telescope assembly

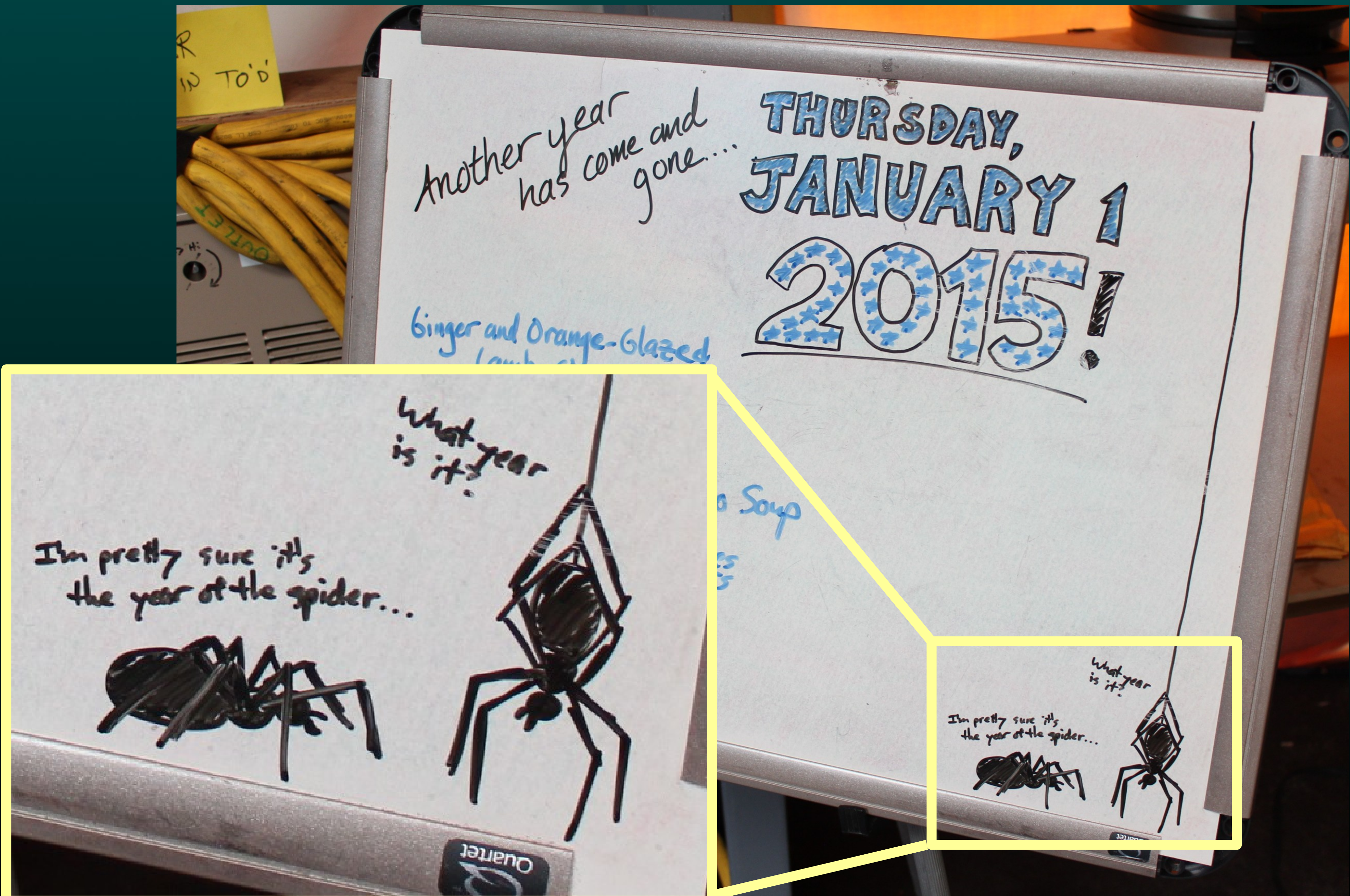


LDB cryostat on the gondola

Team SPIDER owns the machine shop!

Preparing for cooldown

SPIDER's launch: January 1, 2015



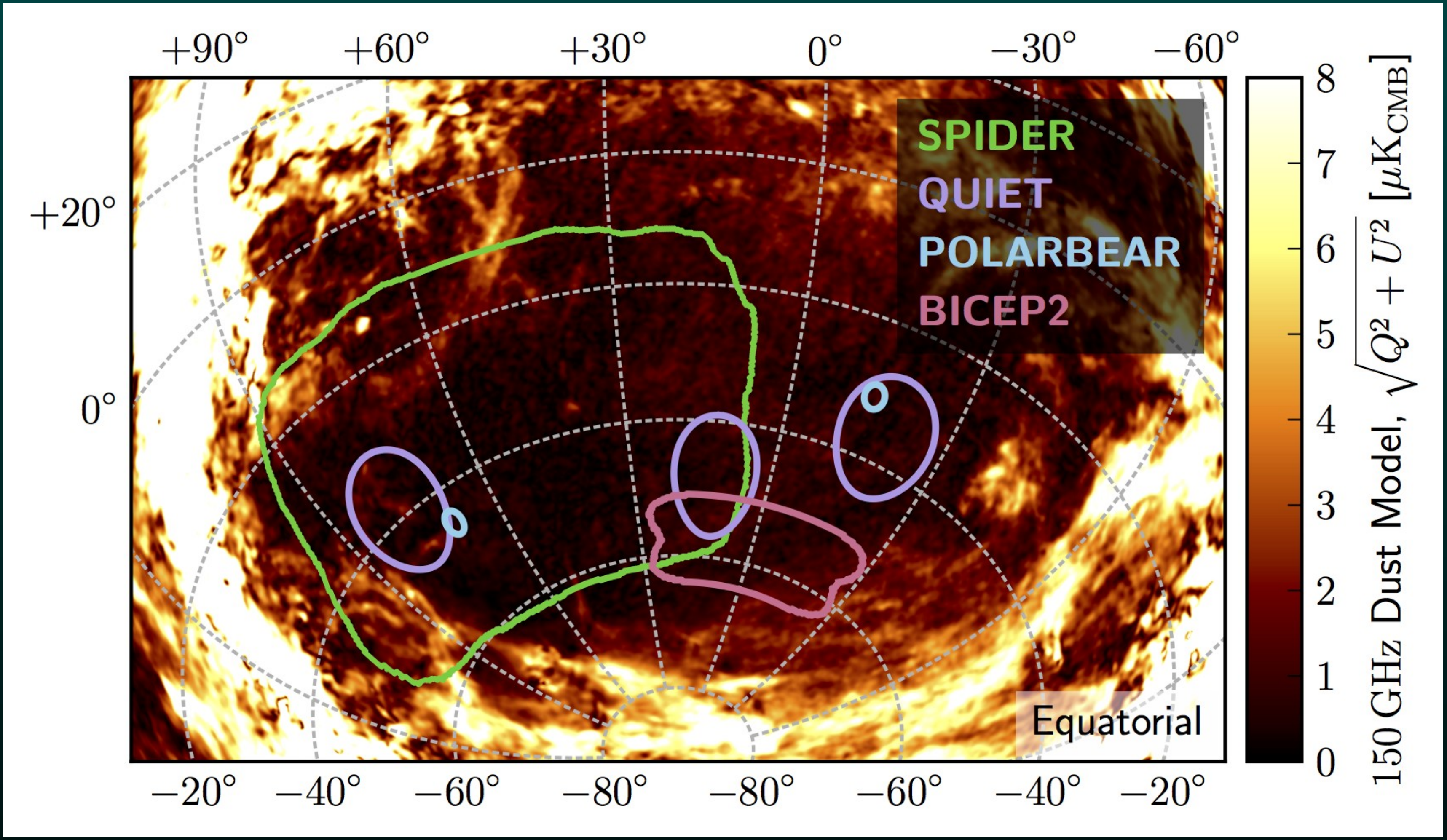
Up, up and away...

Up, up and away...

Up, up and away...

Up, up and away...

Sky coverage and scan strategy

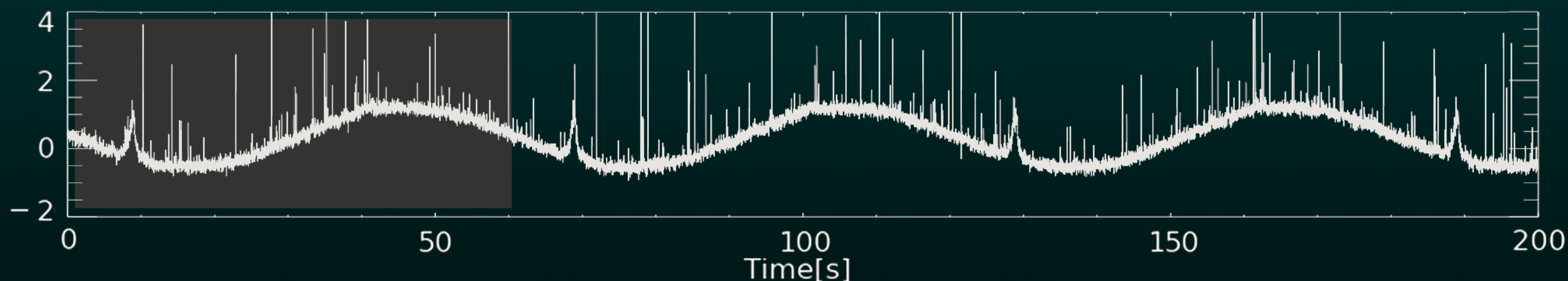


- Geometric / hits-weighted sky fraction: 12.3% / 6.3%
- Observed a low-foreground region that encompasses the "southern hole"
- Full map generated each sidereal day
- Sinusoidal azimuth scans with 3.6 deg/s maximum scan rate
- Waveplates stepped by ~22.5 deg every 0.5 sidereal day

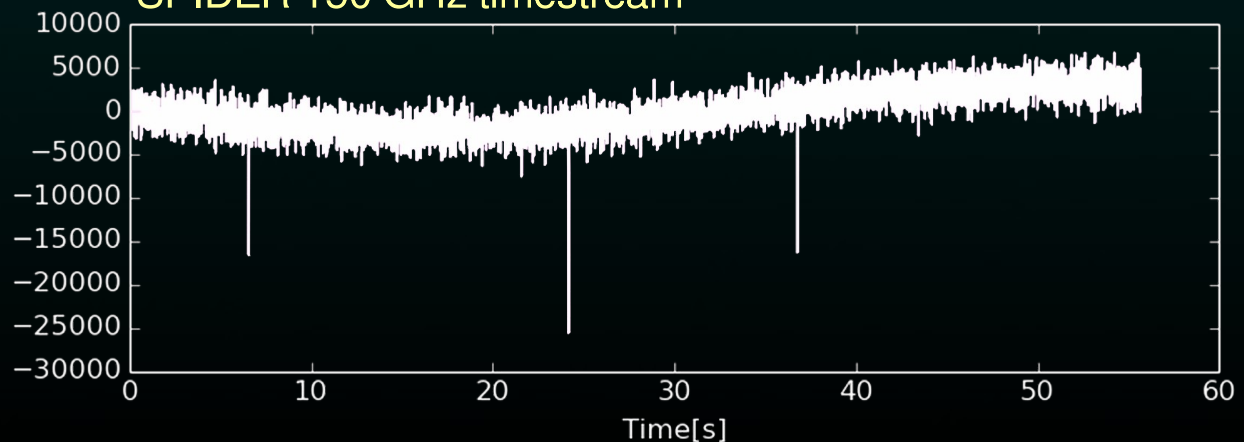
In-flight performance

- All systems were operational and performed well (except DGPS)
- NETs: roughly 6 uK*rt(s) at 150 GHz and 7 uK*rt(s) at 94 GHz
- In-band loading: < 0.35 pW at 150 GHz, < 0.25 pW at 94 GHz
- 1.56 Tb total data volume (excluding redundancies), no disk failures
- Cosmic rays: insignificant impact on flagging (but RFI is an issue)

Planck 143 GHz timestream

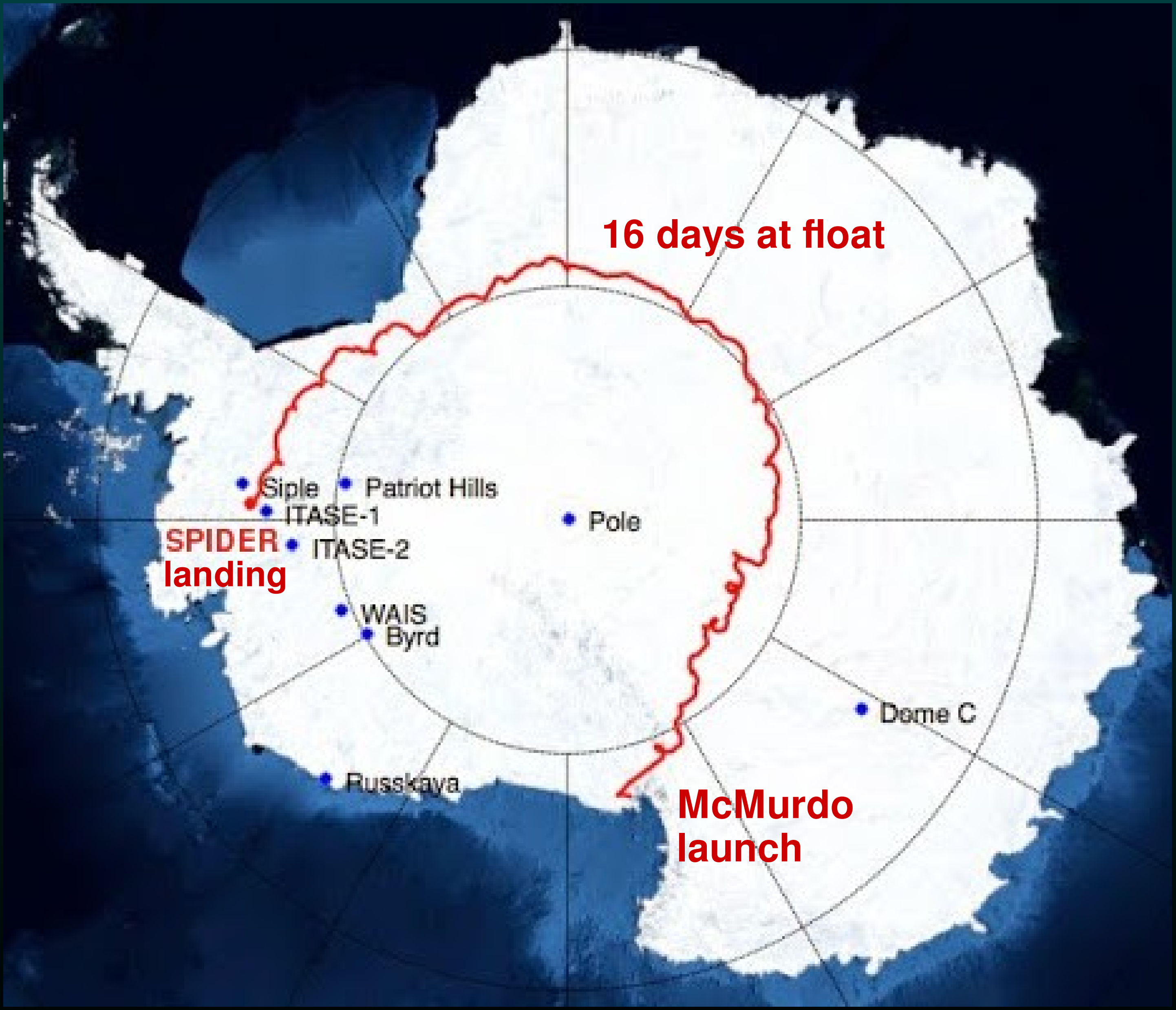


SPIDER 150 GHz timestream

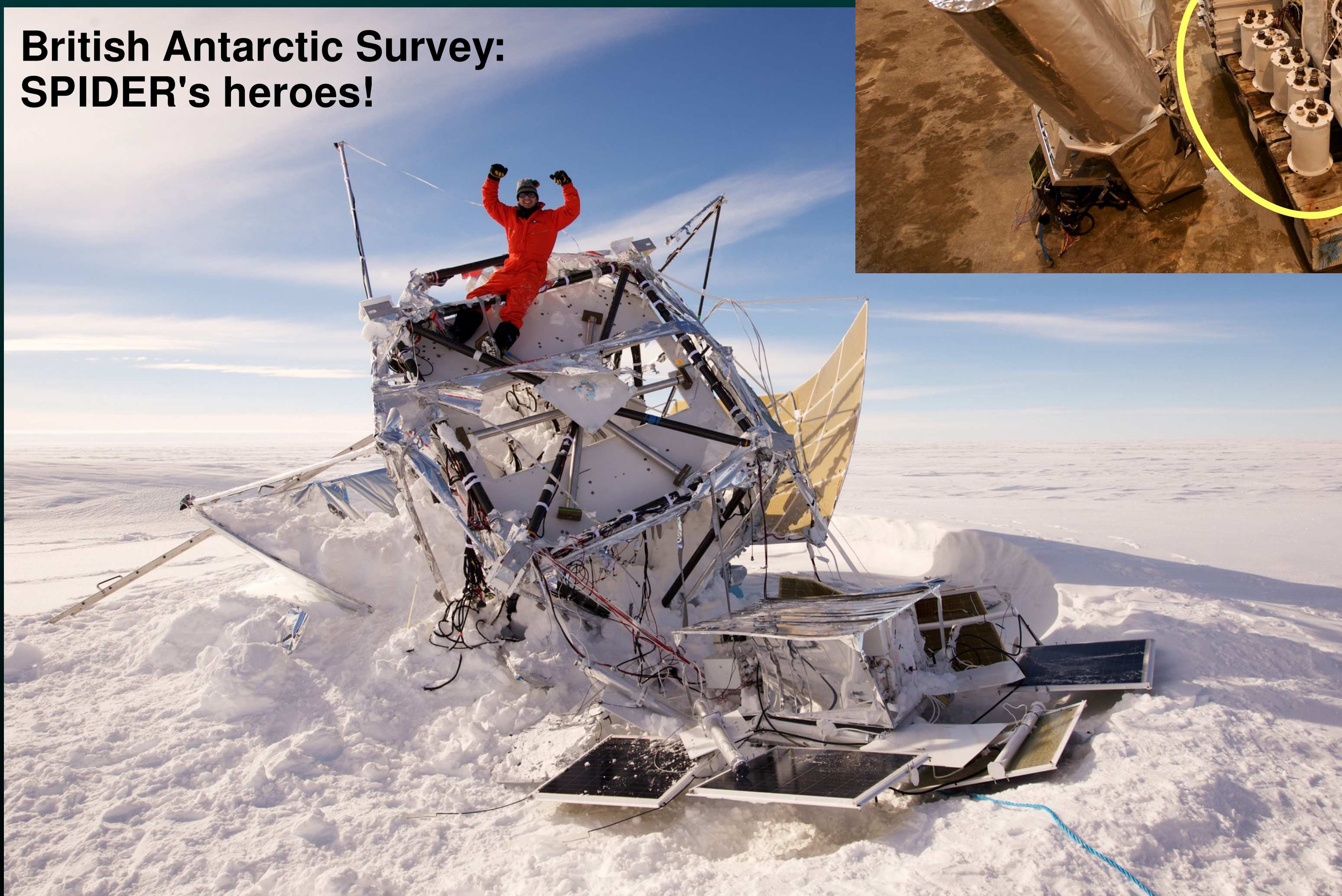


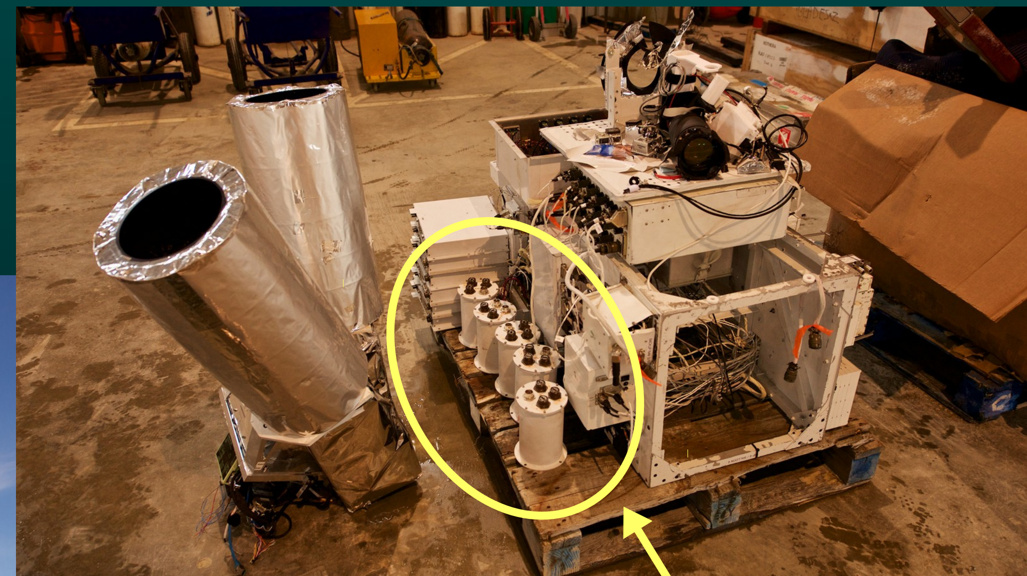
TES detectors are great for space!

SPIDER's flight path



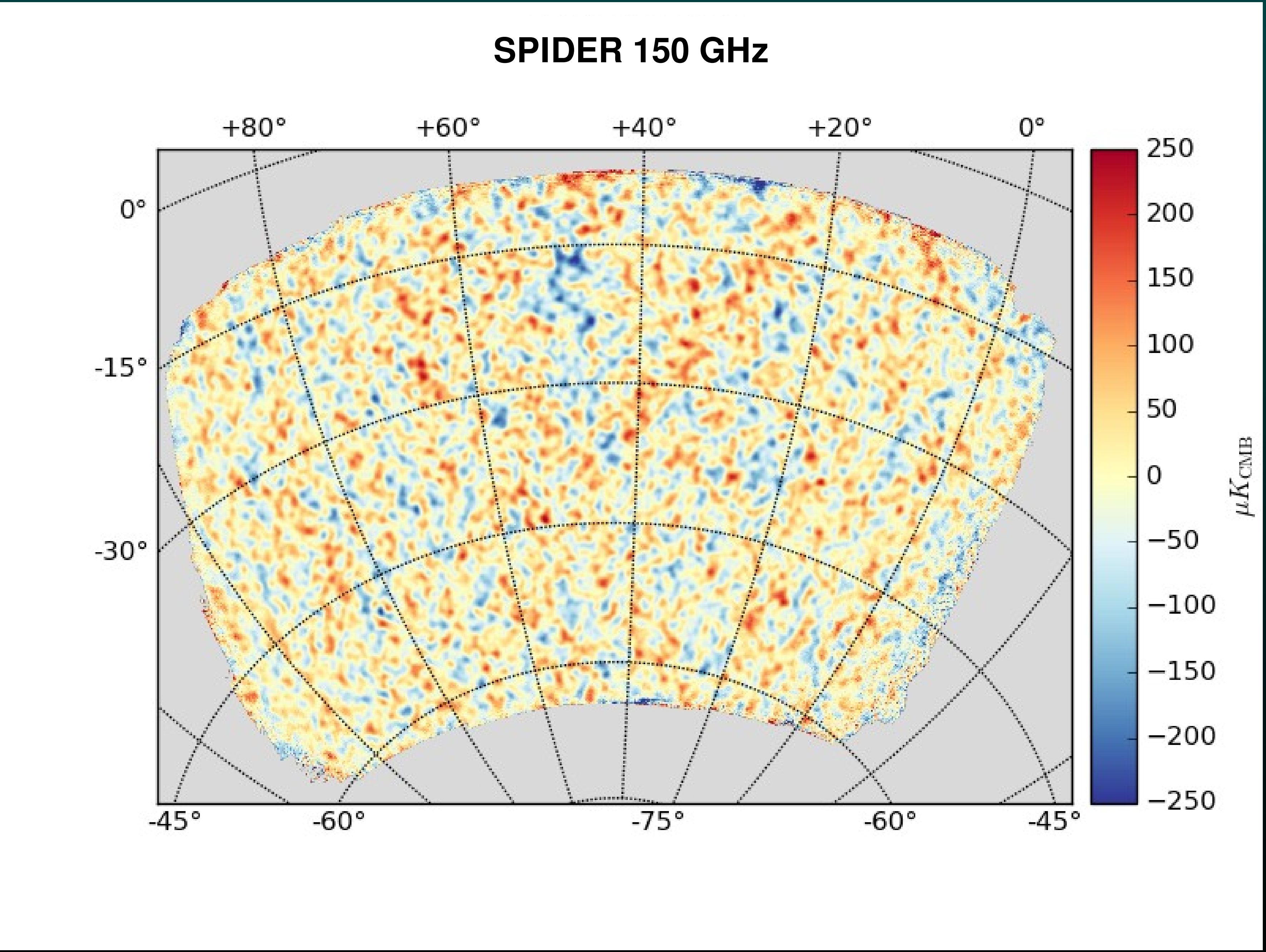
Landing and recovery: we have data!



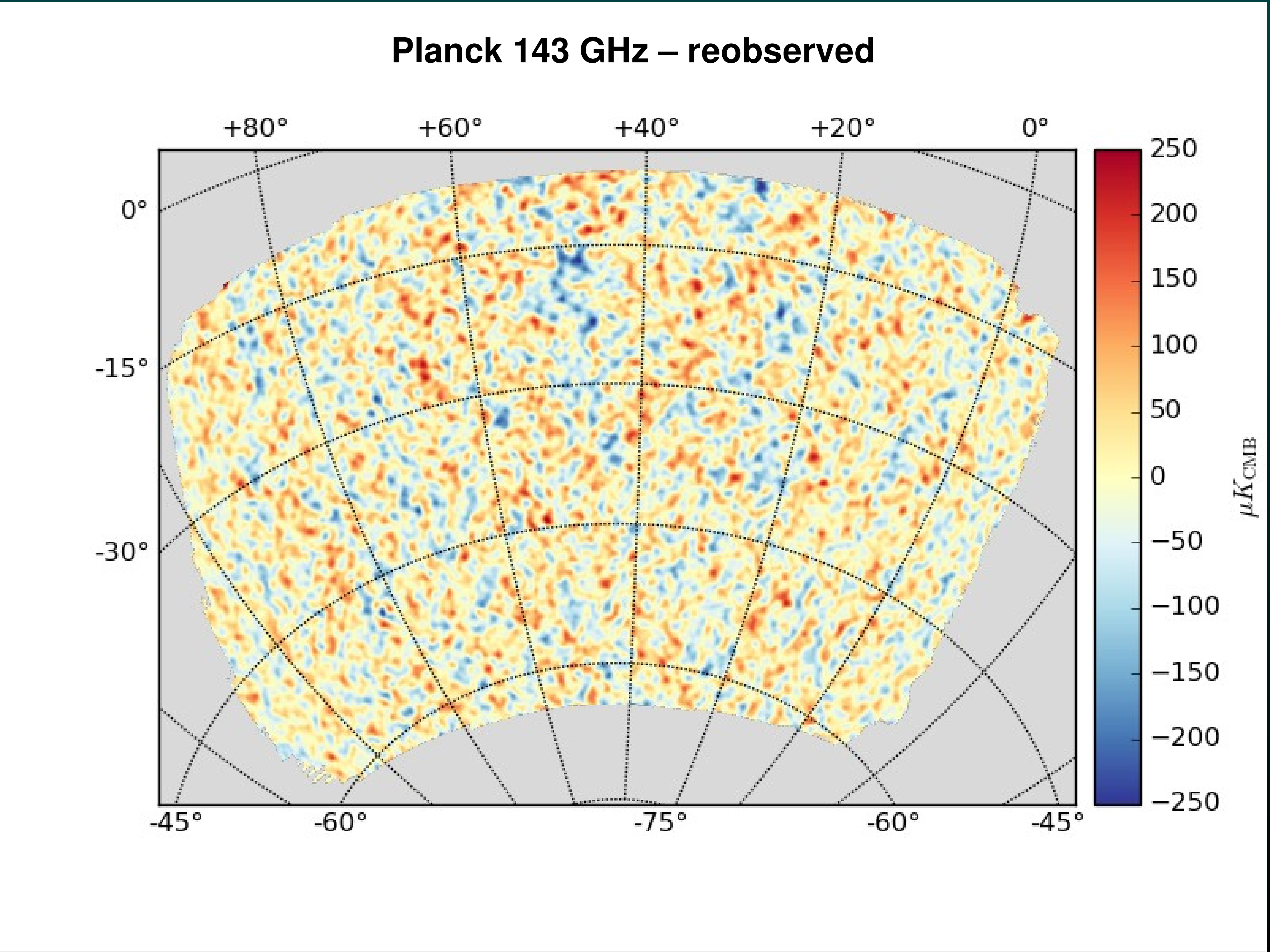


Our precious data

Preliminary CMB temperature map

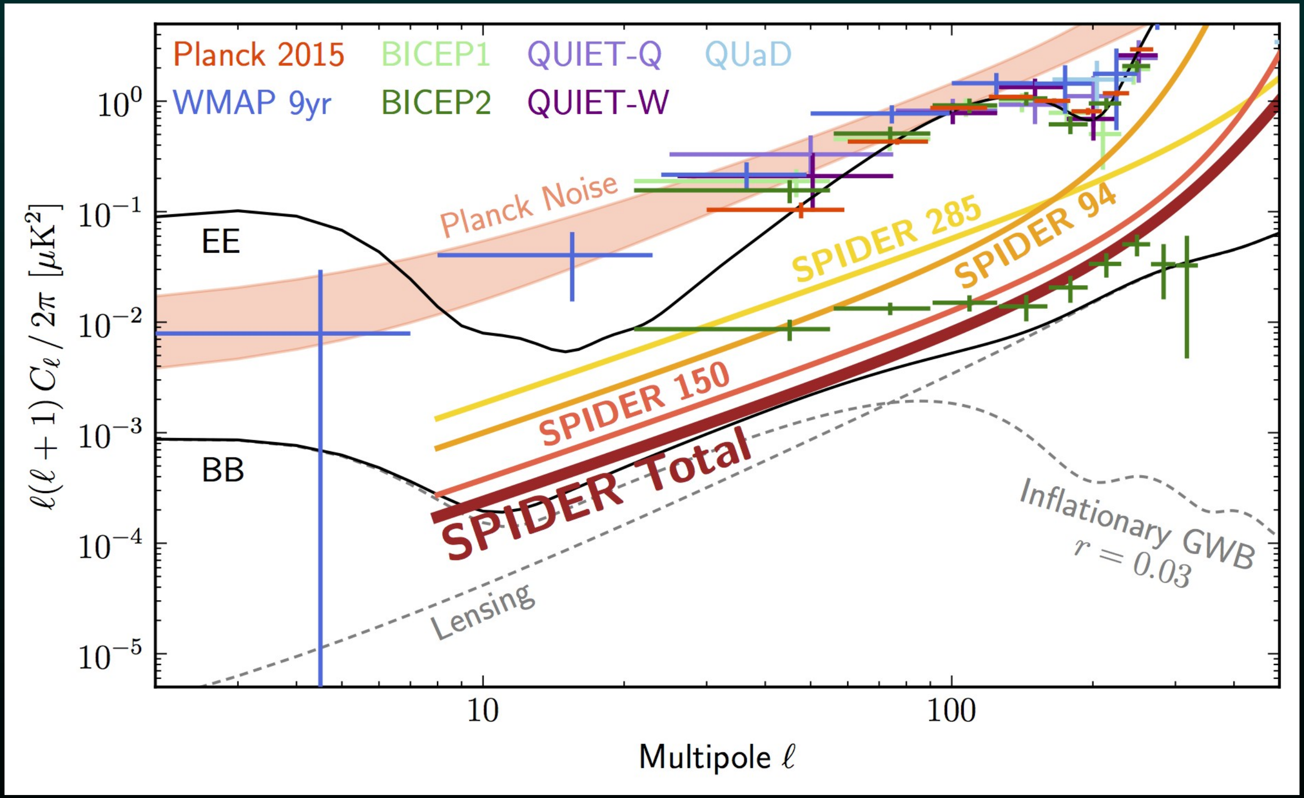


Preliminary CMB temperature map



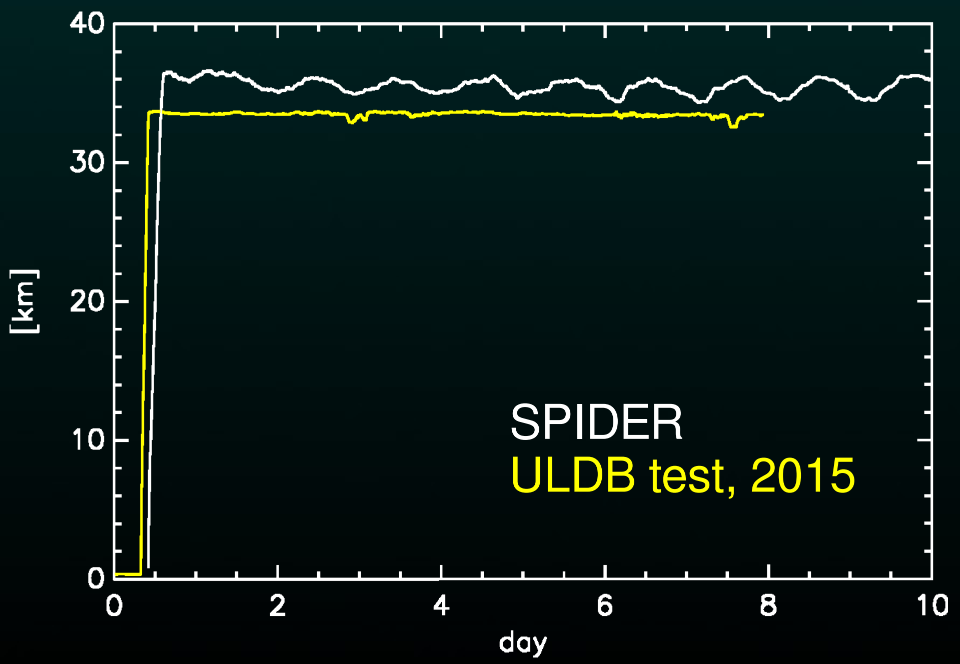
Coming up next: SPIDER's second flight

- Aiming for a second flight in 2017–2018 season (subject to recovery uncertainties)
- Adding 285 GHz dust channels to fill the gap between Planck 217 GHz and 353 GHz
- Goal: 3σ detection of *r* = 0.03 even in the presence of foregrounds
- Work in progress: rebuilding flight cryostat, recovery of current instruments



The future: ultra long duration flights

- Ultra long duration or “super pressure” balloons offer the promise of long (>100 day) flights!
- Greater sky coverage from mid-latitude flights
- Reduced diurnal altitude variation
- March 2015 test flight from Wanaka, New Zealand: 32 days at float



Summary

- SPIDER's first flight is done, analysis of 16-day data set is in progress
- Most instantaneously sensitive CMB instrument on the sky
- Preparing for a second flight in 2017–2018 with added 280 GHz capability