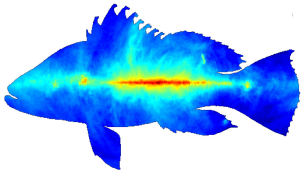
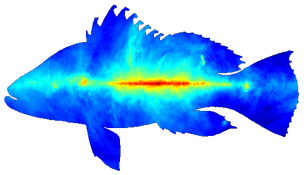
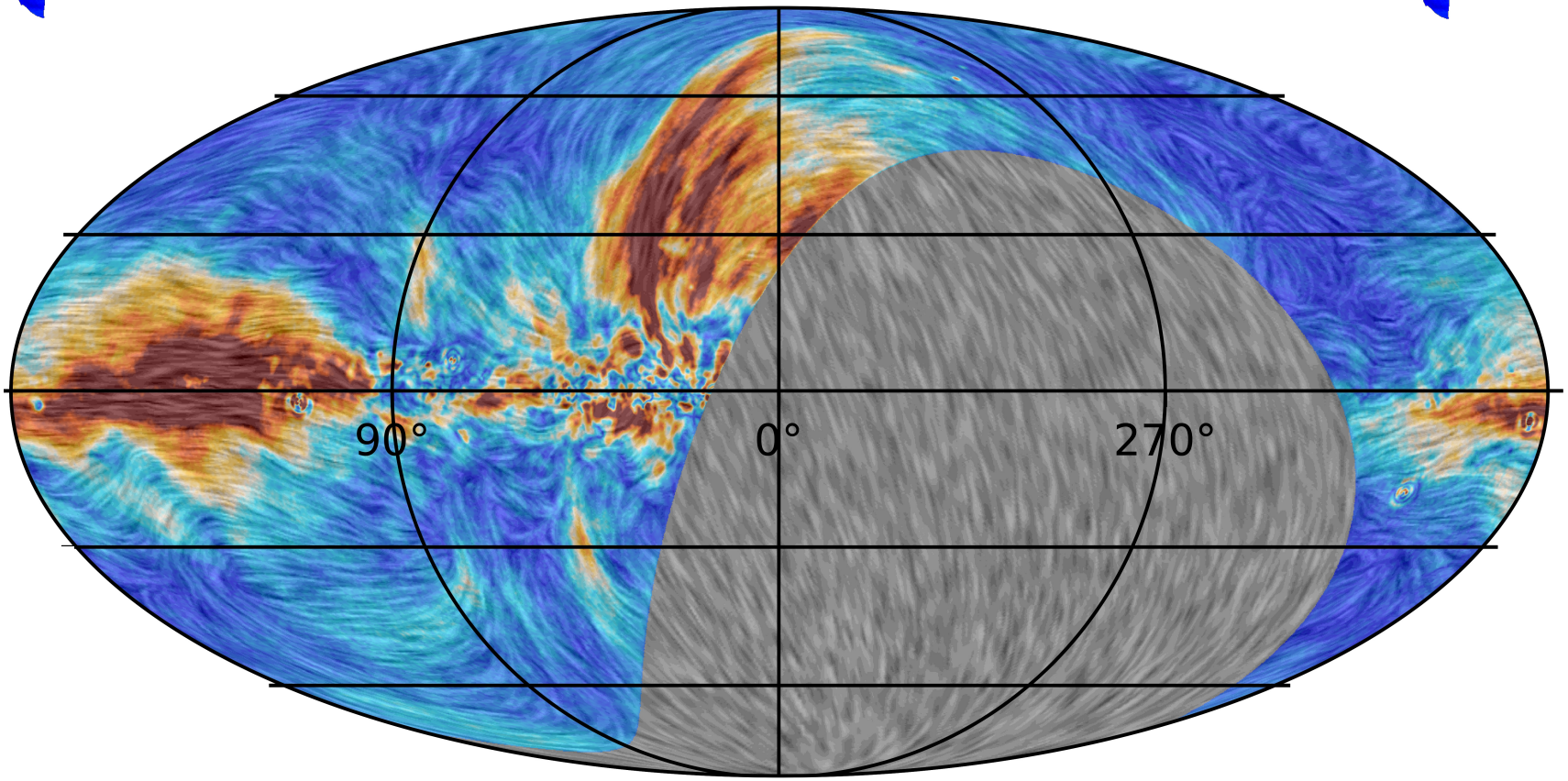
UNIVERSITY OF OXFORD

C-Band All-Sky Survey (C-BASS)



Status update on the Northern Survey





The C-Band All-Sky Survey

University of Oxford, UK

Angela Taylor, Mike Jones, Jamie Leech,
Richard Grumitt →Berkeley/Tsinghua),
Christian Holler (→Hochschule München, Germany)

University of Manchester, UK

Clive Dickinson, Paddy Leahy, Stuart Harper,
Mike Peel(→. IAC, Tenerife)

Caltech, USA

Tim Pearson, Tony Readhead

South Africa

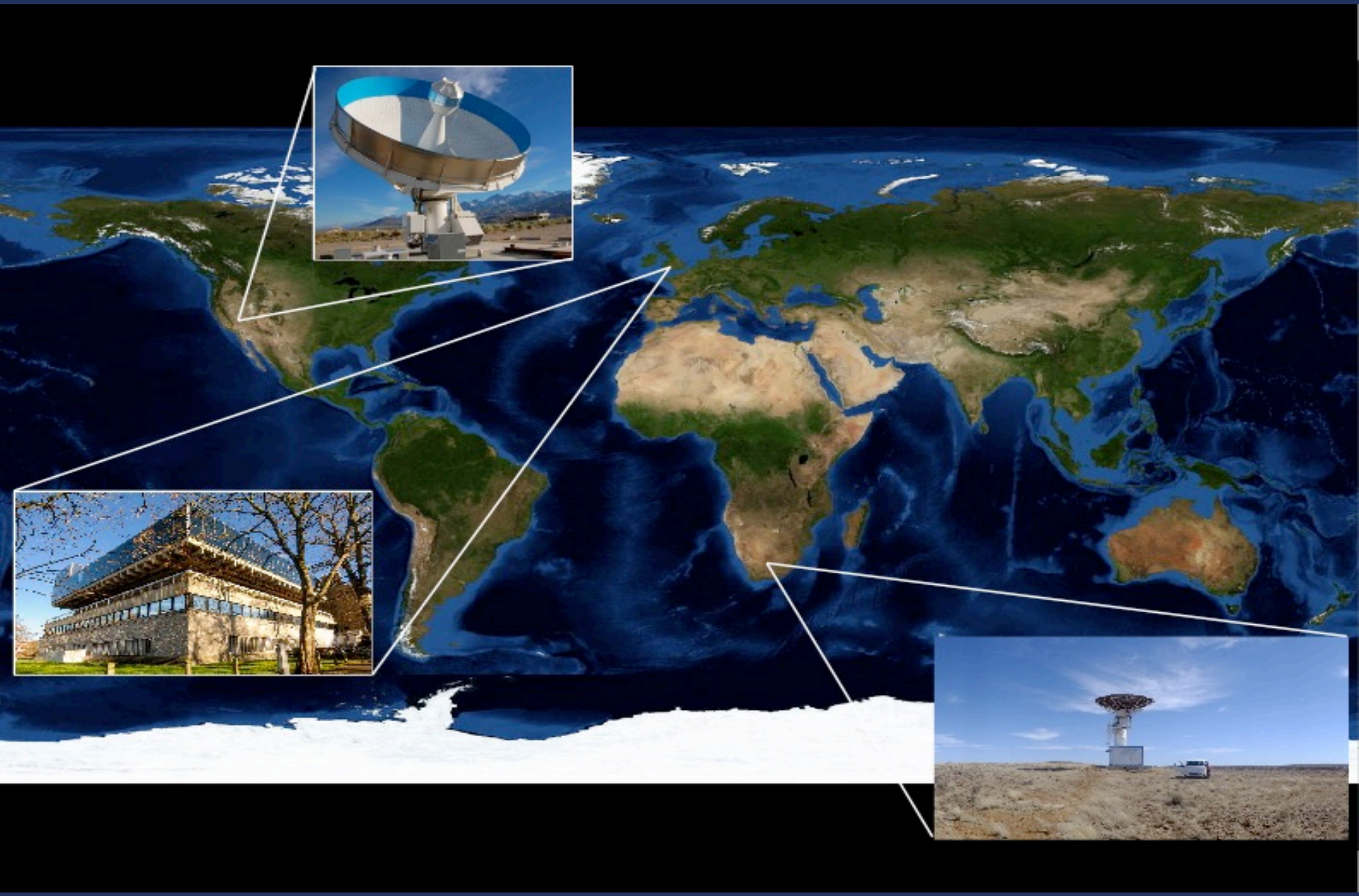
Justin Jonas (Rhodes/SKASA), Moumita Aitch (UKZN),
Cynthia Chiang, Jon Sievers (UKZN & McGill,Canada)

Moved on…

Oliver King, Matthew Stevenson, Mel Irfan, Stephen Muchovej, Joe Zuntz, Charles Copley, Luke Jew, Jaz Hill-Valler, Alex Pollak , Roke Cepeda-Arroita, Adam Barr, Heiko Heligendorff

UNIVERSITY OF OXFORD

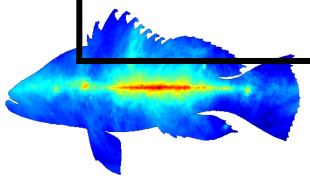
The C-BASS Survey

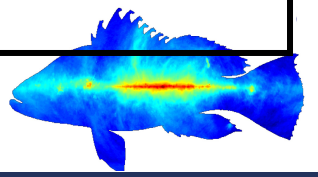


UNIVERSITY OF OXFORD

C-BASS - Overview

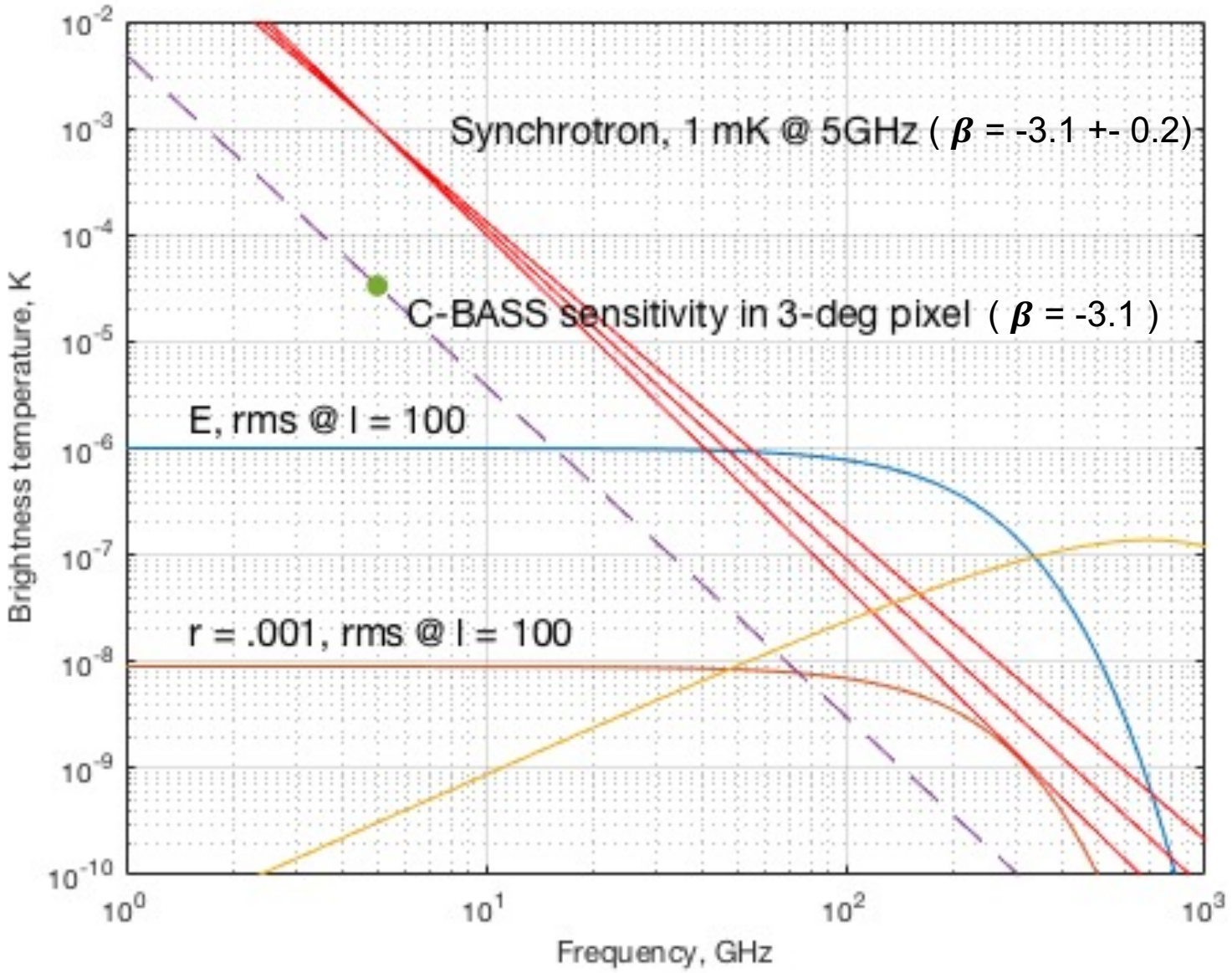
Sky-coverage	All-sky
Angular resolution	0.75 deg (45 arcmin)
Sensitivity	< 0.1mK r.m.s in 1 deg beam (confusion limited in I) 6000 μK-arcmin @ 5GHz 0.75 μK-arcmin @ 100 GHz, β = -3
Stokes coverage	I, Q, U, (V)
Frequency	1 (0.5) GHz bandwidth, centered at 5 GHz
Northern site 	OVRO, California Latitude, 37.2 deg
Southern site 	MeerKAT/SKA site, Karoo, South Africa Latitude -30.7 deg





UNIVERSITY OF OXFORD

CBASS polarization sensitivity



UNIVERSITY OF OXFORD

C-BASS unique features

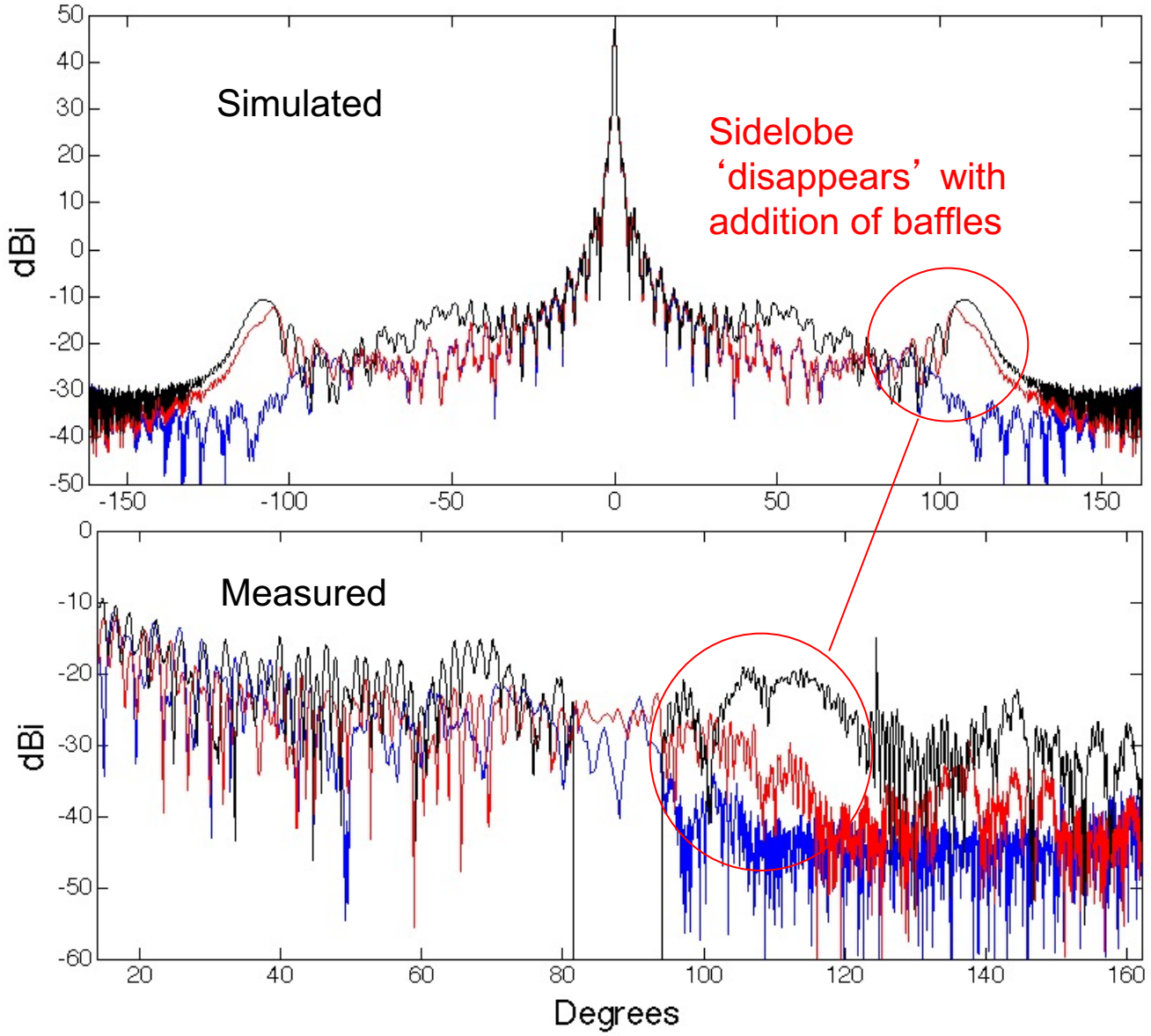
- Only all-sky experiment at (or near) 5 GHz:
  - High enough ν that Faraday rotation < few degrees at high-latitude
  - Low enough ν that synchrotron is very bright
  - Below main emission from AME, so predominantly synchrotron
- Well-characterized beam (simulated and measured) so accurate temperature scale (cf e.g Haslam)
- Intensity and polarization measured and cross-calibrated simultaneously
- Differences from LFI:
  - Radiometer operates on *R* and *L* not *X* and *Y*, so *Q,U* obtained directly, not by differencing
  - Both phase switches operated so 4-state switching gives better suppression of systematics

UNIVERSITY OF OXFORD

C-BASS North Telescope

- 6.1-m dish, with Gregorian optics
- Secondary supported on foam cone
- Receiver sat forward of the dish
- Very clean, circularly-symmetric optics
- Absorbing baffles to minimize spillover

C-BASS North: beam measurements



(Holler et al., IEEE TransAntProp 61 117 (2013)

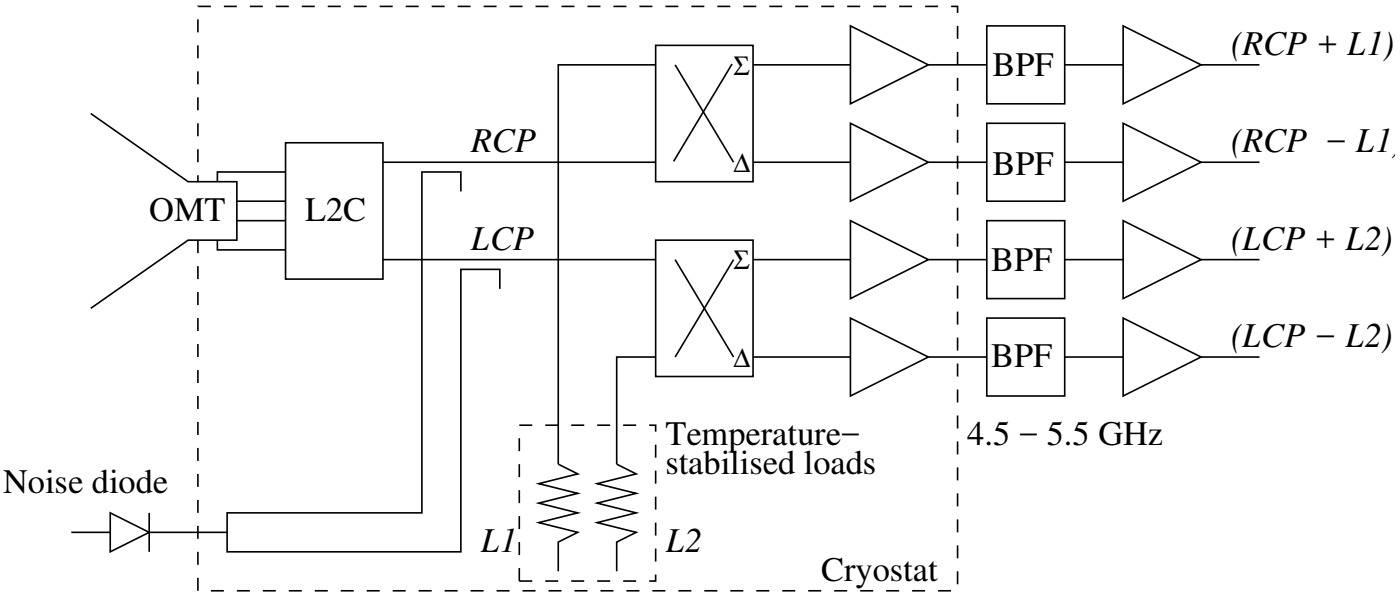
UNIVERSITY OF OXFORD

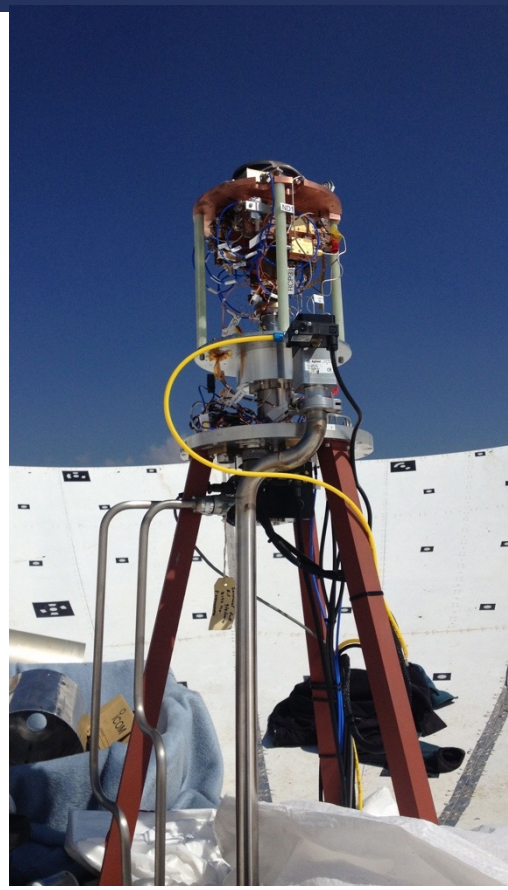
C-BASS South Telescope

- CBASS South at Klerefontein, Karoo desert, South Africa (SKA support site)
- 7.6m ex-telecoms dish
- Cassegrain optics
- Similar receiver to north – but frequency resolution (128 channels)

UNIVERSITY OF OXFORD

C-BASS Receiver



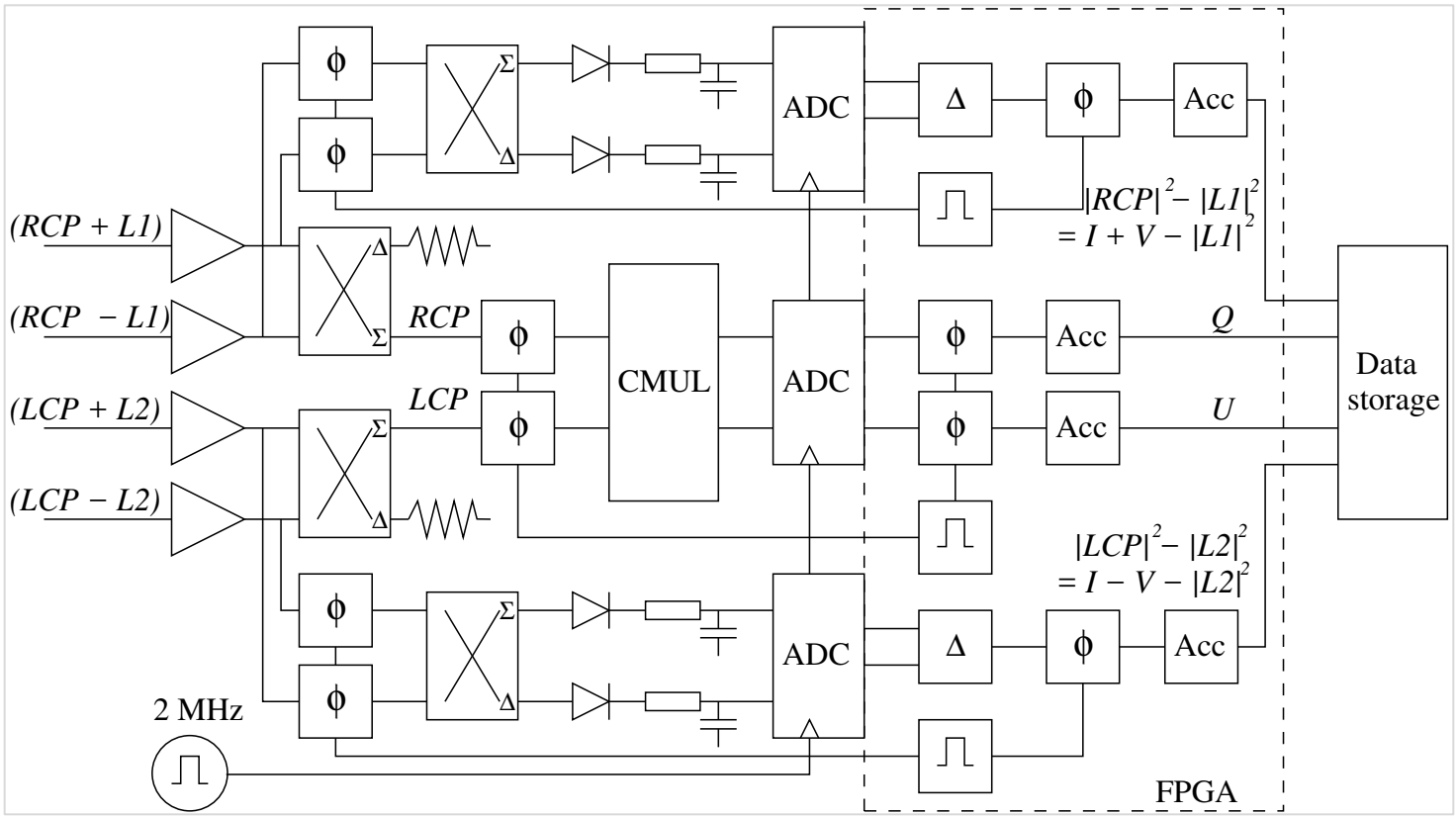


Both receivers use correlation polarimeter and continuous comparison radiometer:

- Correlate RCP & LCP → *Q, U*
- Difference RCP & LCP separately against internal load → *I, V*

See: King et al MNRAS 438 2426 (2014)

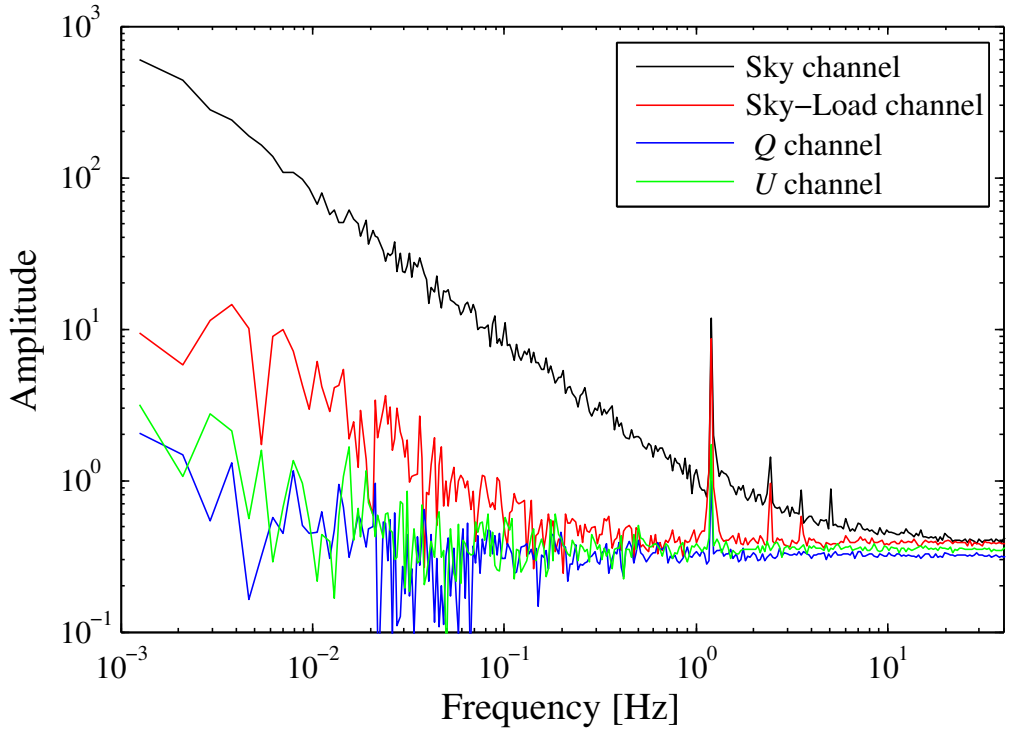
C-BASS North Receiver



- Analogue polarimeter/radiometer – all done with hybrids and diodes…
- Sky and load signals separated post-amplification, squared and differenced
- – gives *I* relative to loads
- RCP and LCP complex multiplied – gives $Q + iU$
- Redundancy in multiplier gives two copies of *Q*, *U* – should be identical

UNIVERSITY OF OXFORD

Receiver noise power spectra

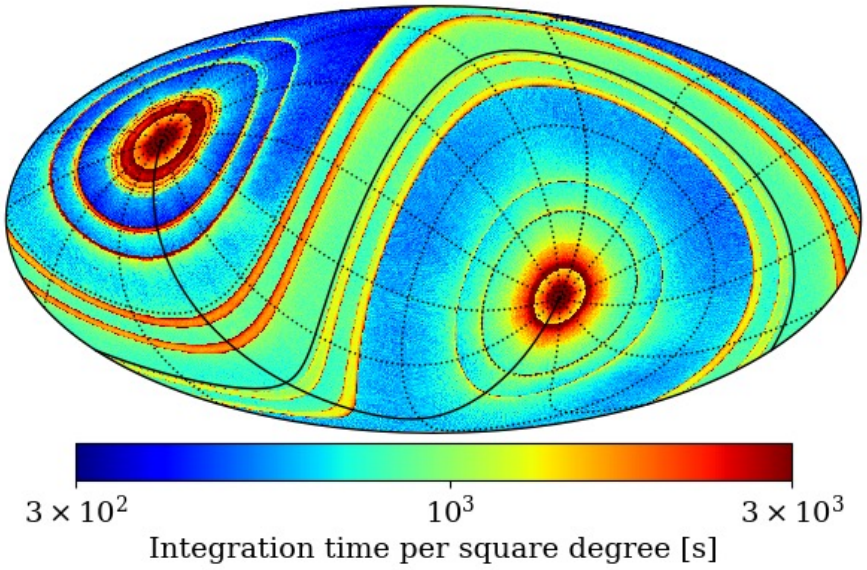


- 1/f in single I channel is reduced by a factor of ~20 relative to raw sky signal
  - knee frequency moved from ~ 4Hz to 0.2Hz
- Q and U have knee-frequencies < 10mHz
- The receiver is stable over full azimuth scans (90s) – can extract data over full-sky

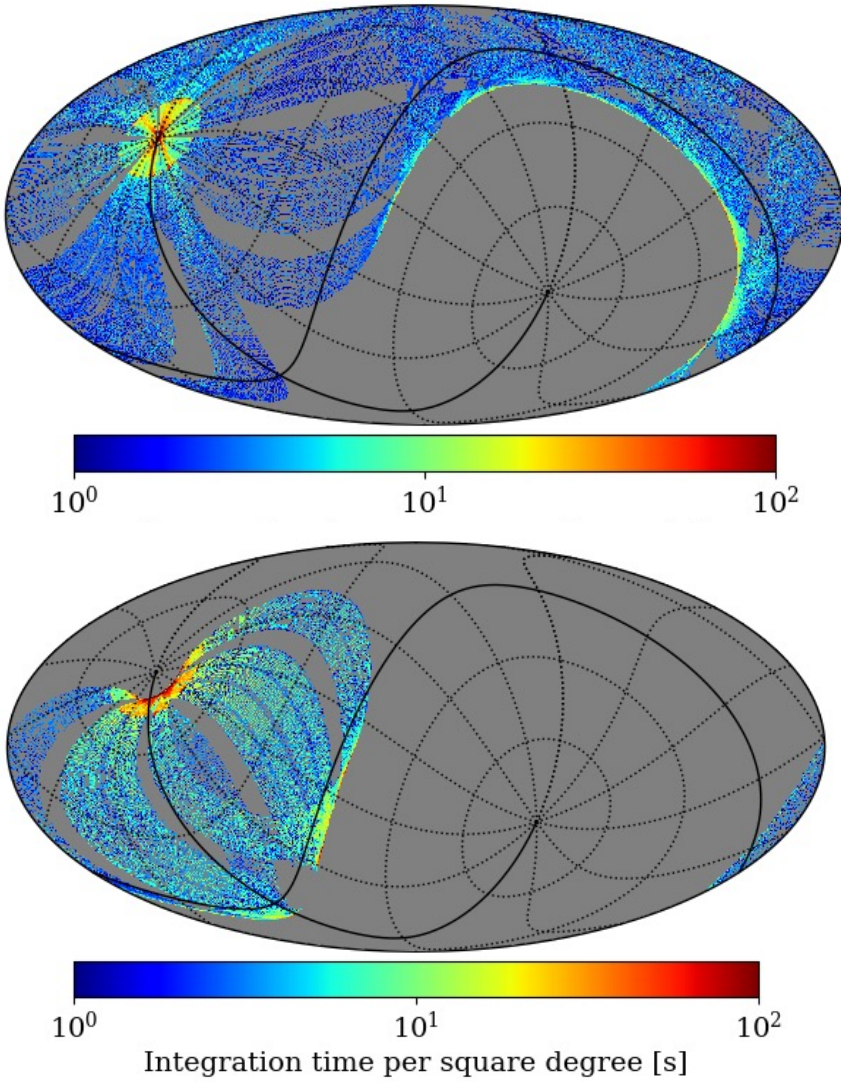
UNIVERSITY OF OXFORD

C-BASS N Survey

- Data taken from 2012-2015
- 360 deg azimuth scans at elevation of poles + 10, 30, 40, 50
- Scan as fast as possible: ~4 deg/s
- One scan ~90 s
- Use 5 slightly different scan speeds so fixed frequency contaminants ≠ same sky modes



Real (North) + simulated (South) survey coverage

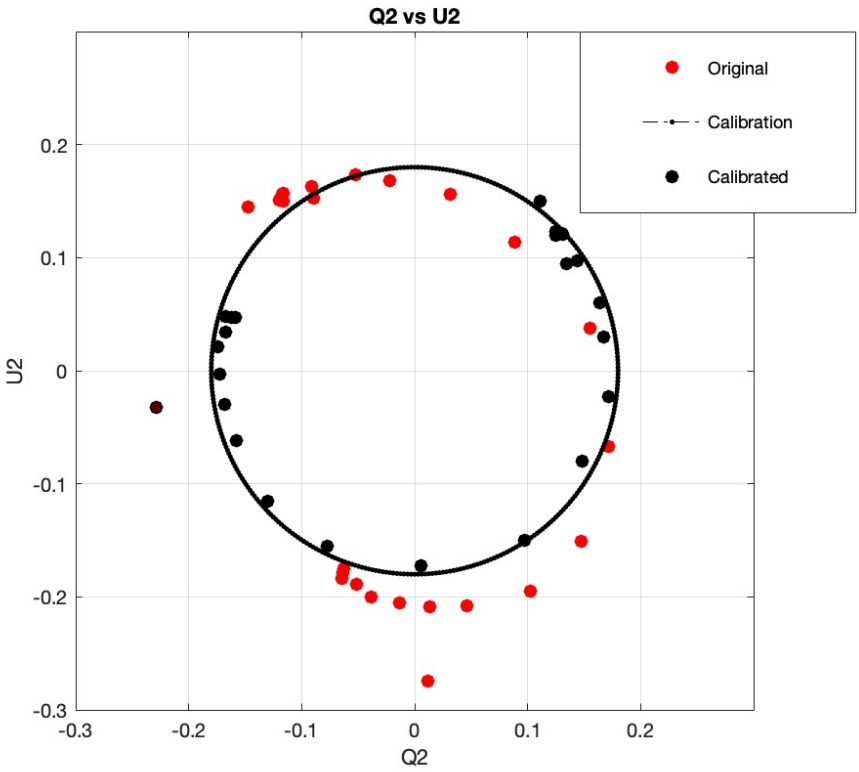


Example of scan coverage in 1 day (top) through pole (bottom) offset

UNIVERSITY OF OXFORD

Calibration

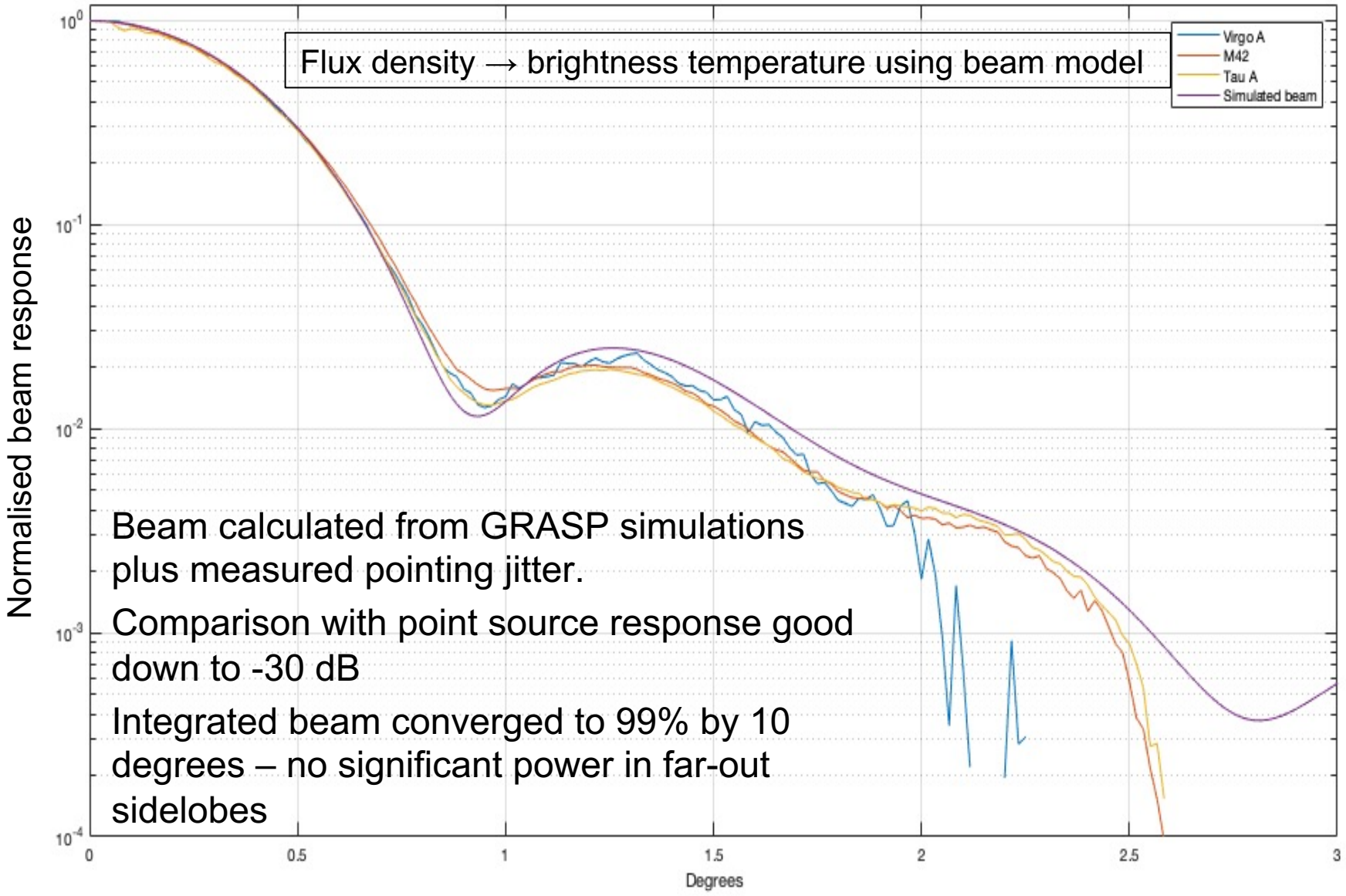
- Noise diode injected in to *R*, *L*
  so appears simultaneously in *I*, *Q*
- *Q,U* amplitude scale thus tied to *I* scale
- Measure apparent *I, Q, U* using long, ~12h raster scans of Tau A
- Derive matrix linking observed *i,q,u* to true *I,Q,U*
- *QU* mixing at < 10%
- *I* → *Q,U* leakage < 1%
- Polarization angle and Faraday correction taken from Weiland et al 2011



Q vs U
(red) before calibration
(black) after calibration

UNIVERSITY OF OXFORD

Beam



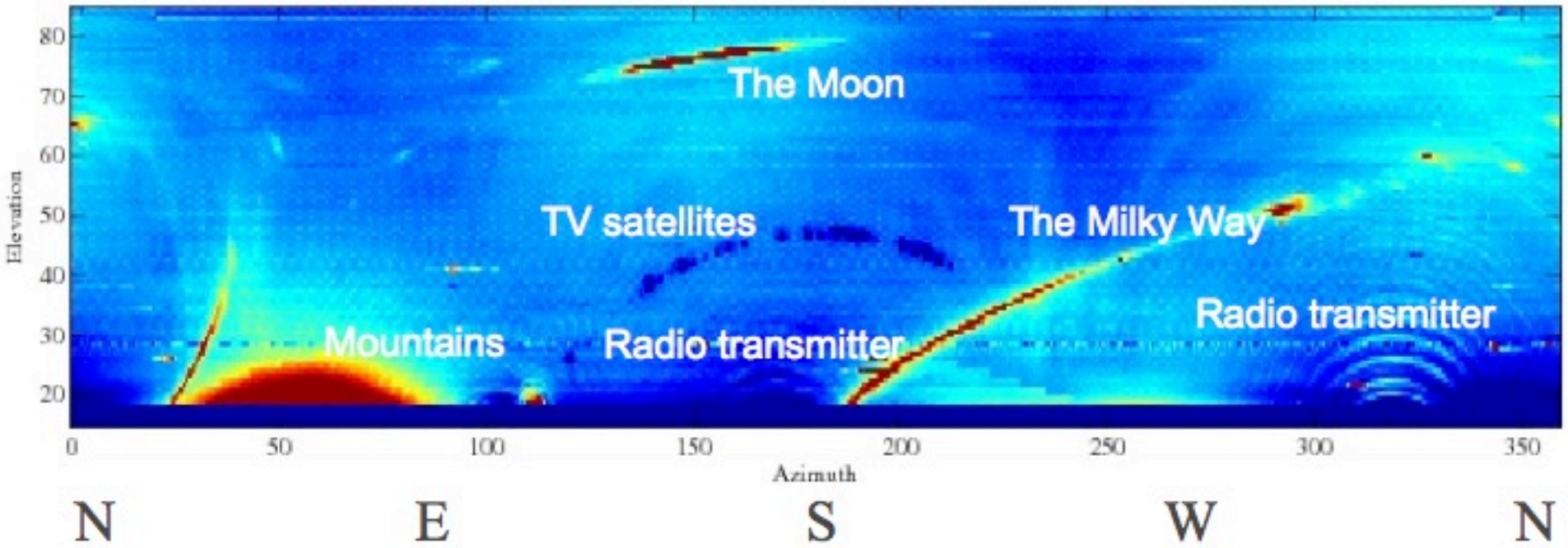
UNIVERSITY OF OXFORD

Main systematics/challenges

- RFI – mostly sporadic (airborne), some fixed
- Ground pick-up – fundamentally degenerate with m=0 in celestial coordinates i.e. declination rings
- Microphonic 1.2 Hz signal from coldhead
- Data are signal-dominated in I so need a sky model to subtract before RFI excision, ground and 1.2 Hz removal → iterative processing
- Residual 1/f – dealt with in mapper not TOD

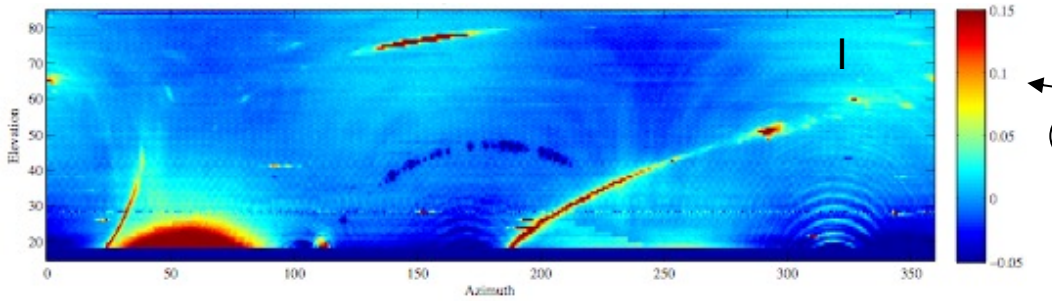
UNIVERSITY OF OXFORD

RFI : C-BASS North Site (1)

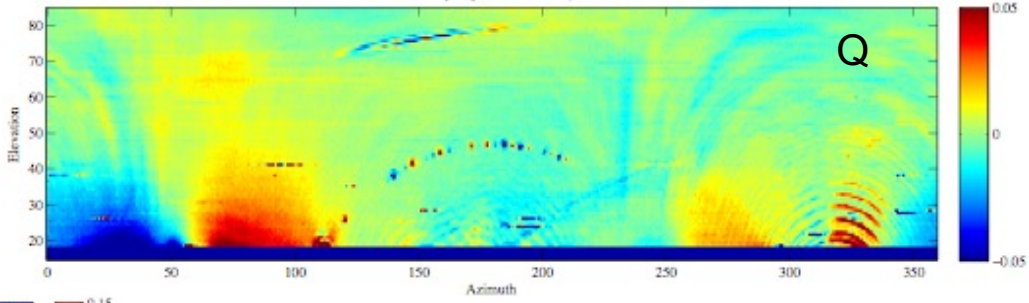


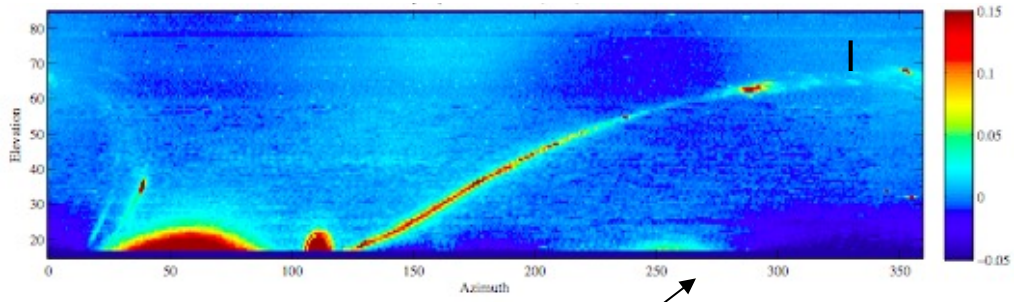
UNIVERSITY OF OXFORD

RFI: C-BASS North Site (2)

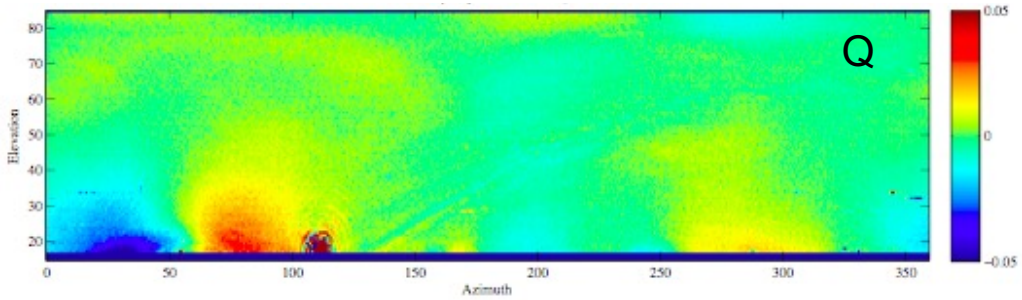


Before installation of notch filter (in-band) and second bandpass filter



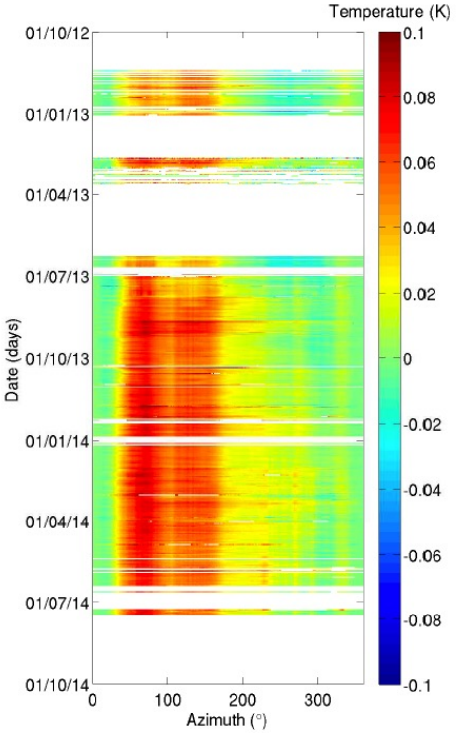


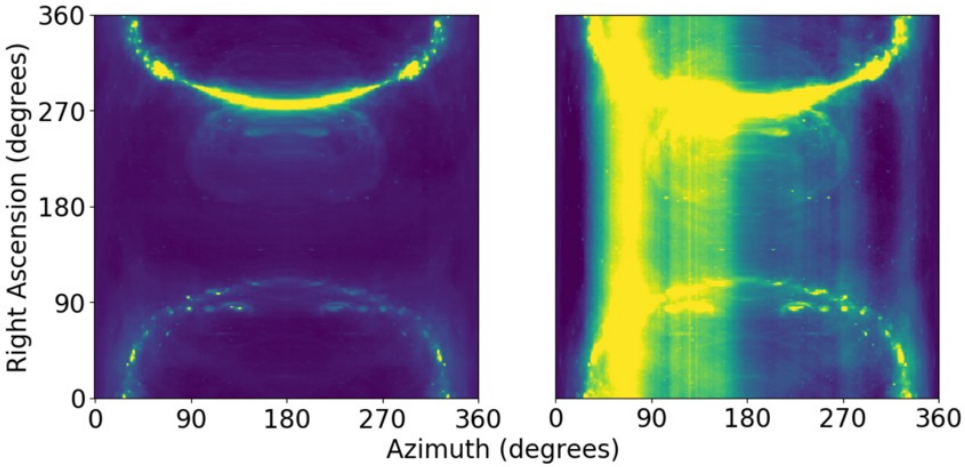
After installation of extra filters

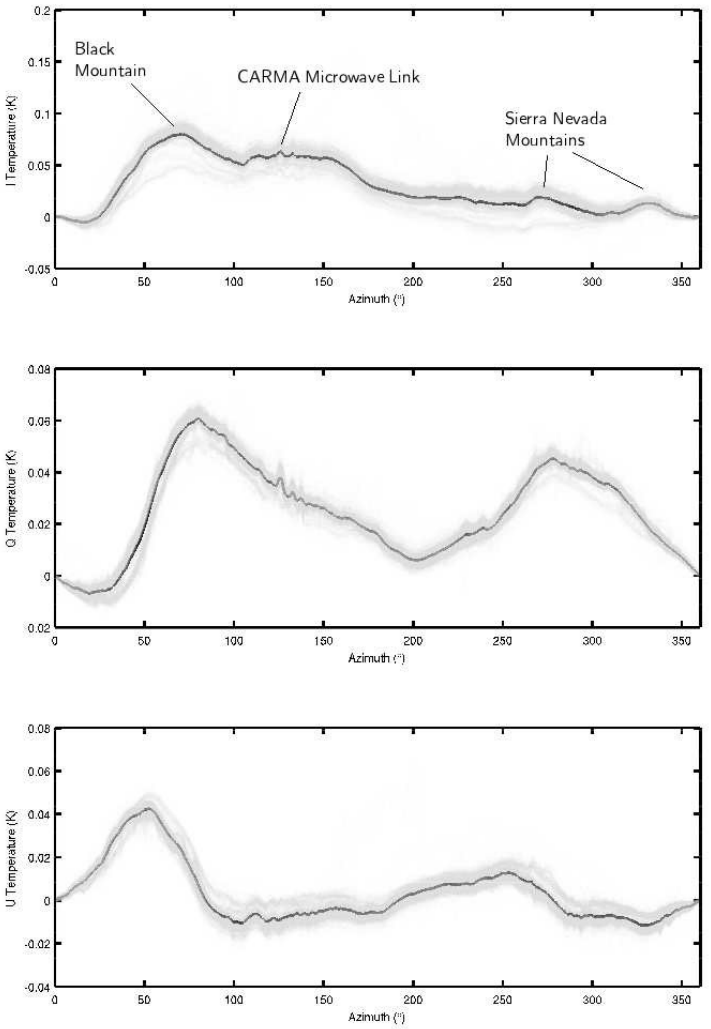


Ground pickup

- Ground signal ~0.1 K in I
- Iteratively generate ground templates
- Use successive maps to remove sky before creating templates
- Minimizes filtering of sky signal
- Extensive simulations!
- **Ground Residuals < 1%**



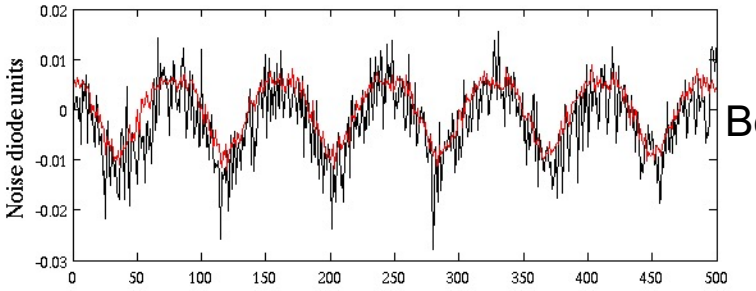




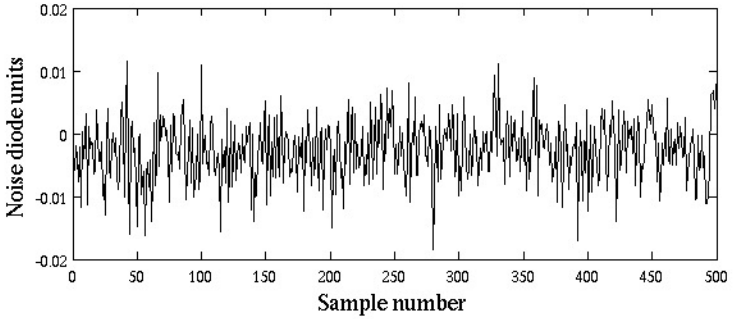
Ground templates in I,Q,U

1.2 Hz microphonics

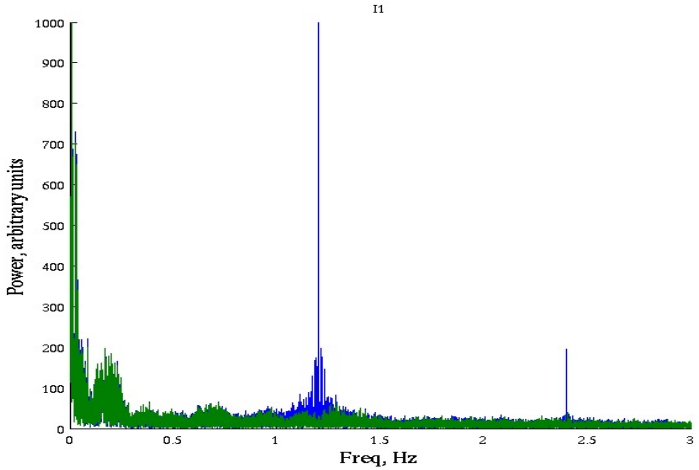
- Due to vibrations from coldhead.
- Locked to mains frequency – nominal 60 Hz but drifts within limits controlled by power utility
- Waveform evolves alongside frequency/phase drifts
- Large enough to require removal before any other TOD processing
- Process:
  - Subtract current best map from TOD
  - Locate peak of power spectrum near 1.2 Hz in block of 120s of TOD
  - Fold on exact frequency
  - Subtract template from TOD
  - Check S/N of 1.2 Hz peak (peak/white noise)
  - Repeat if over threshold & for 2.4Hz
  - Extensive simulations again!



Before

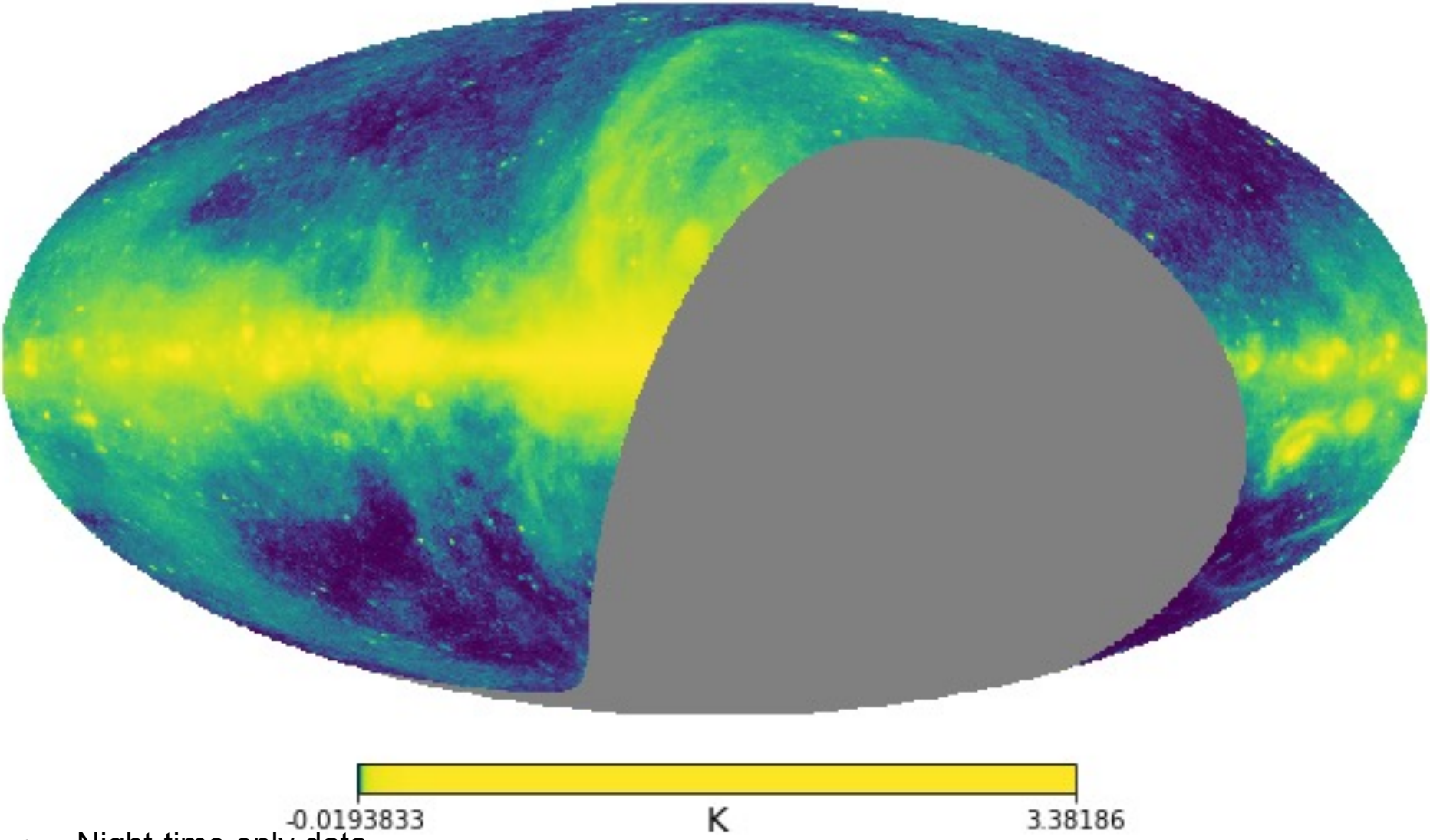


After



UNIVERSITY OF OXFORD

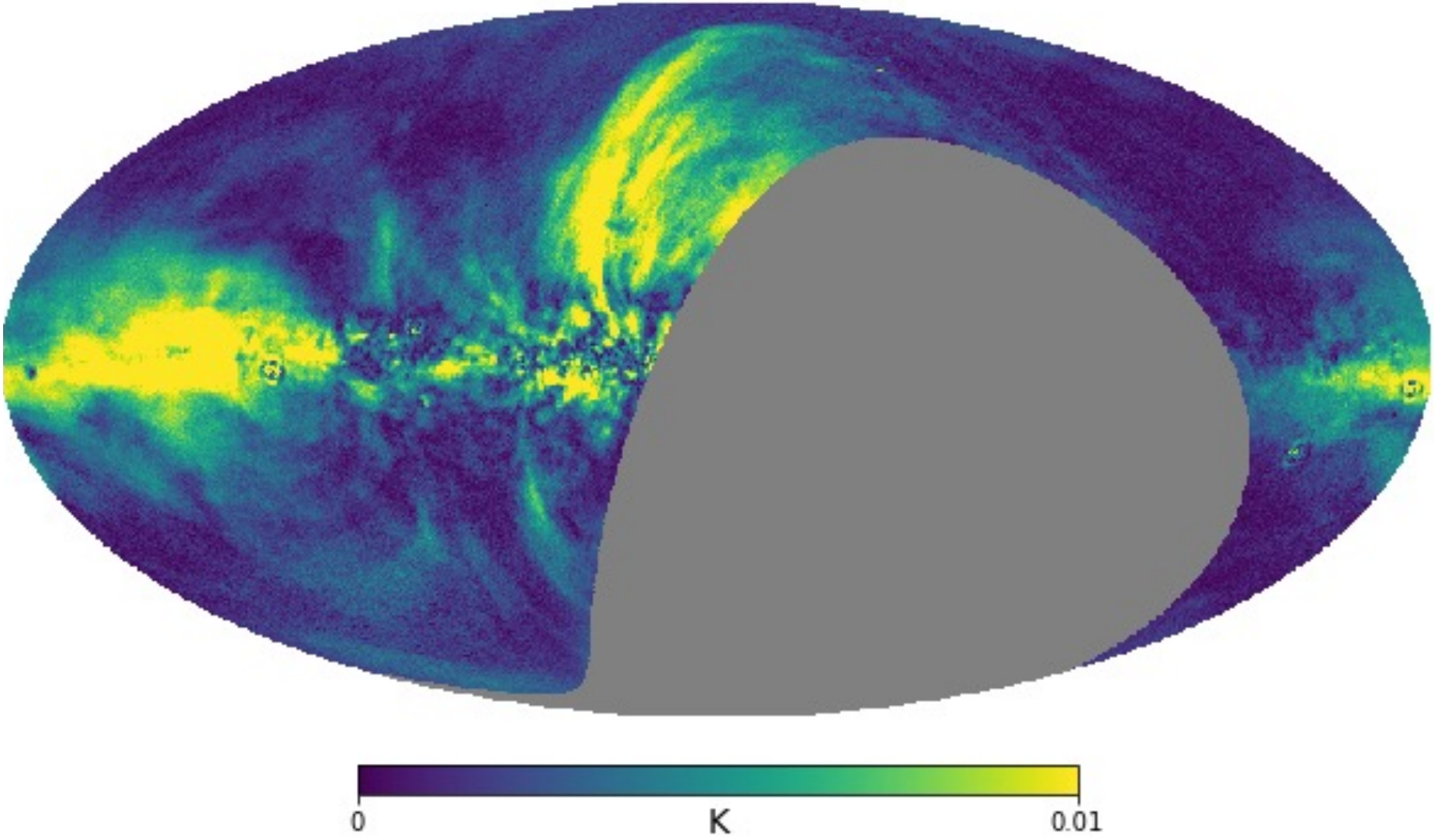
CBASS-N: *Intensity*



- Night-time only data.
- All elevations (37, 47, 67 & 77 deg elevation)
- (Highly non-linear colour scale to show ~10,000:1 dynamic range features)

UNIVERSITY OF OXFORD

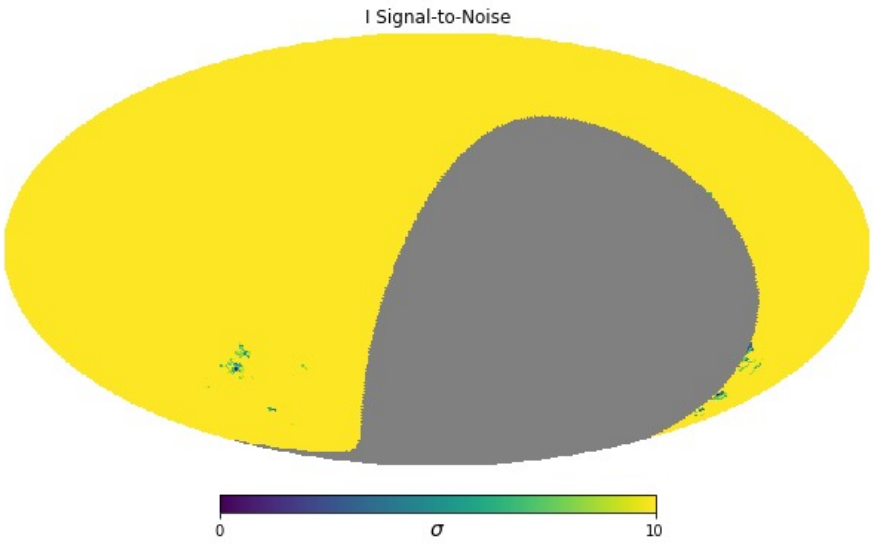
CBASS-N: *Polarized Intensity*

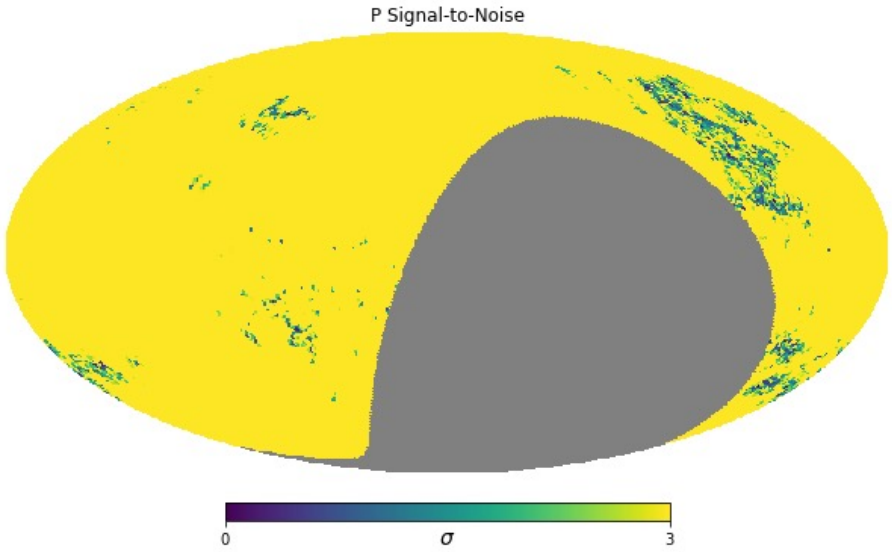


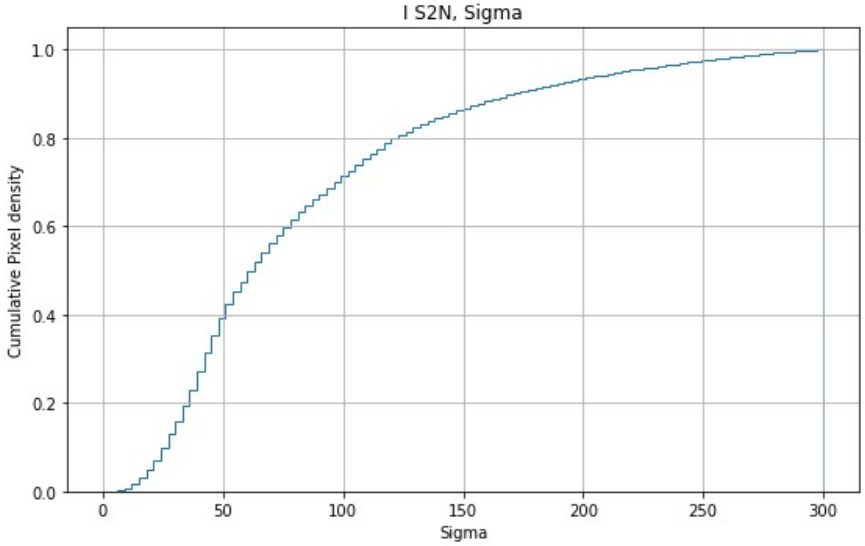
Signal-to-noise of > 5 for 80% of the sky in polarisation.

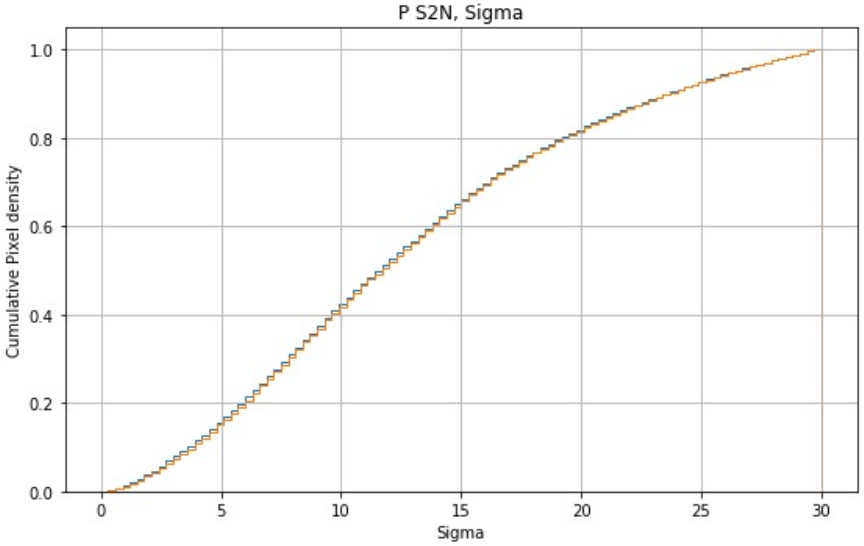
UNIVERSITY OF OXFORD

CBASS-N: Sensitivity



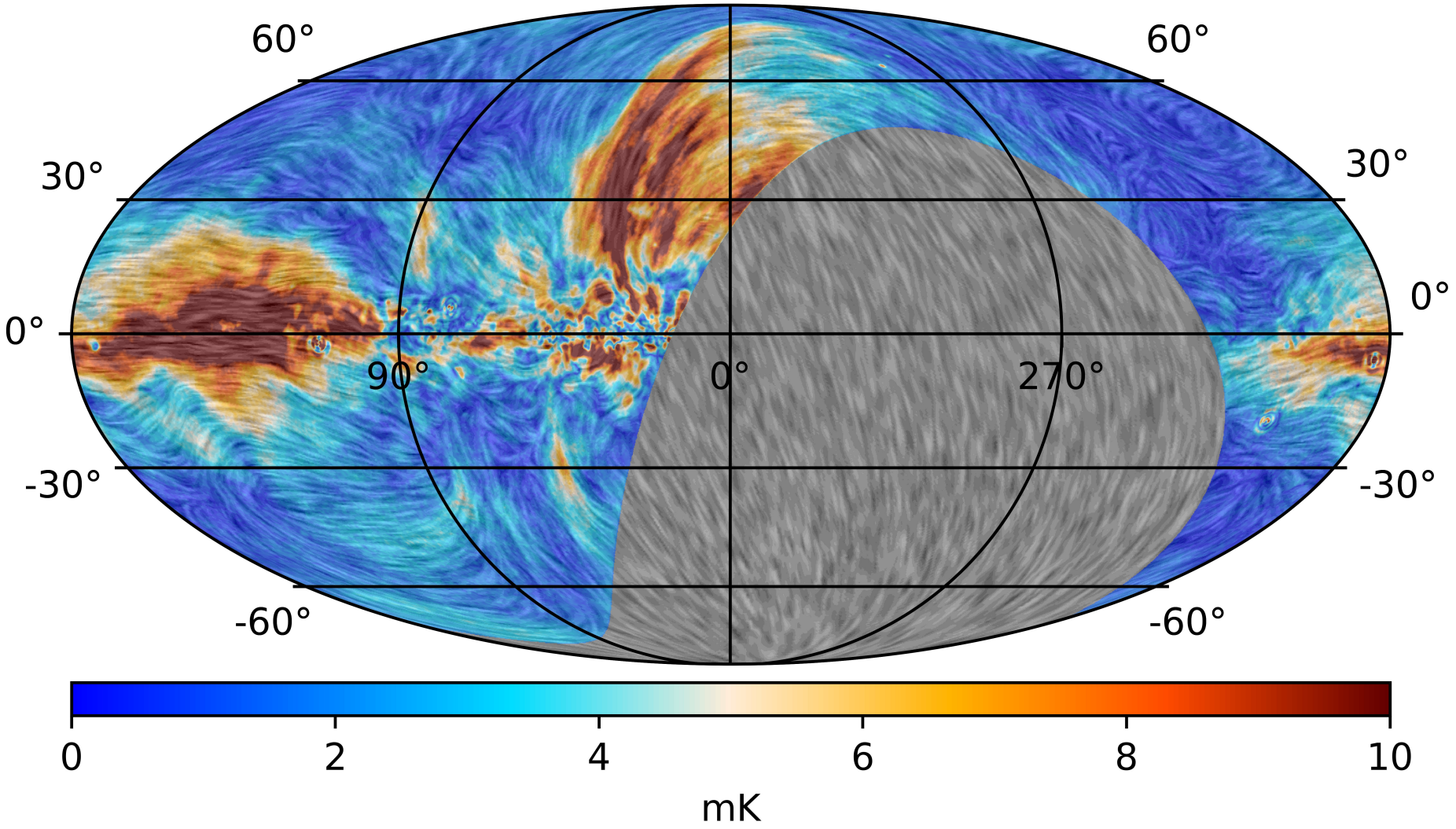






UNIVERSITY OF OXFORD

CBASS-N: *Polarization*

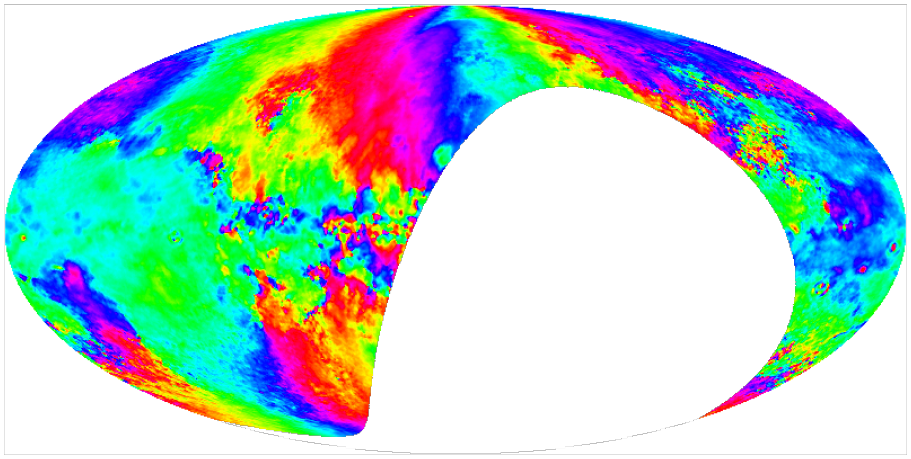


Polarized intensity + line integral convolution B-field angles

UNIVERSITY OF OXFORD

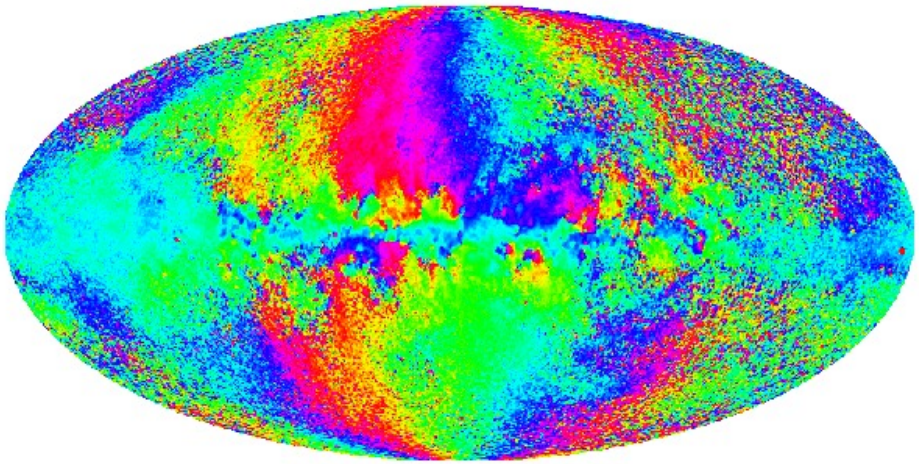
Polarization angles

CBASS Pol Angle



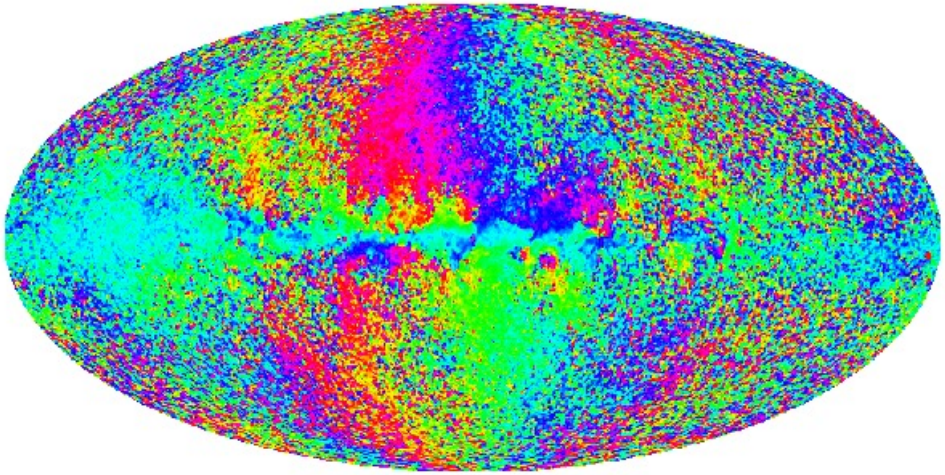
-1.57077 1.57072

WMAP K Pol Angle



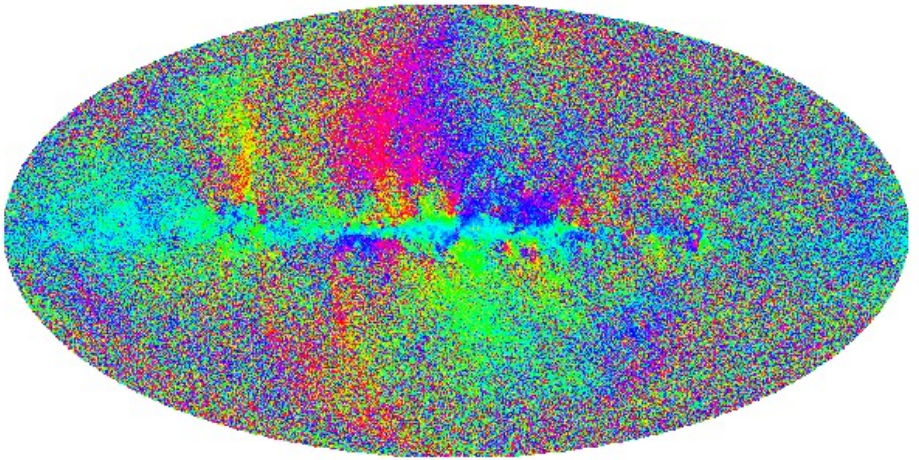
-1.57078 1.57077

WMAP Ka Pol Angle



-1.57076 1.57079

Planck 30 Pol Angle



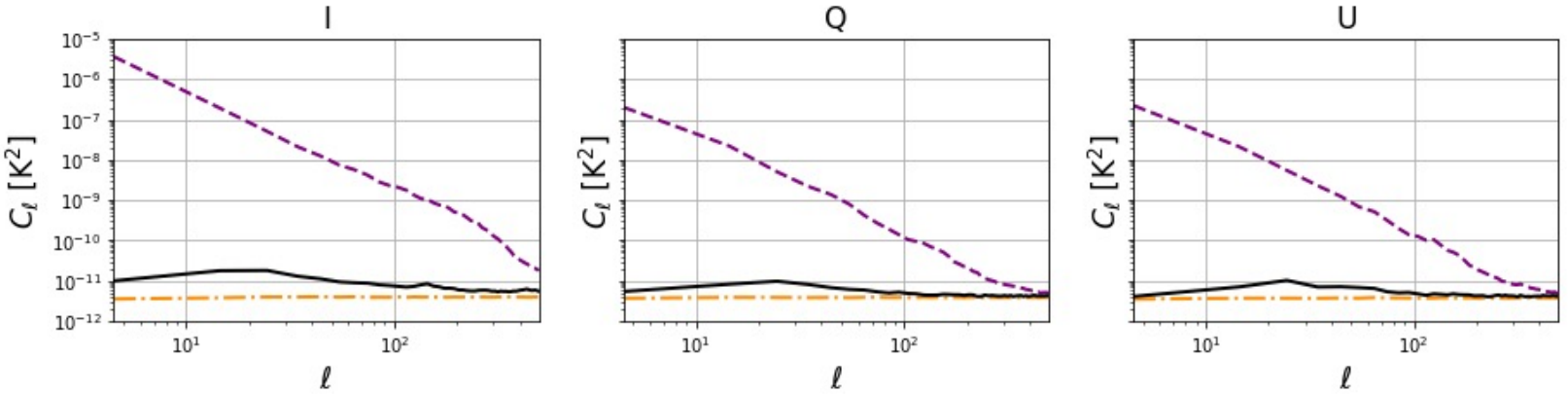
-1.57077 1.57079

UNIVERSITY OF OXFORD

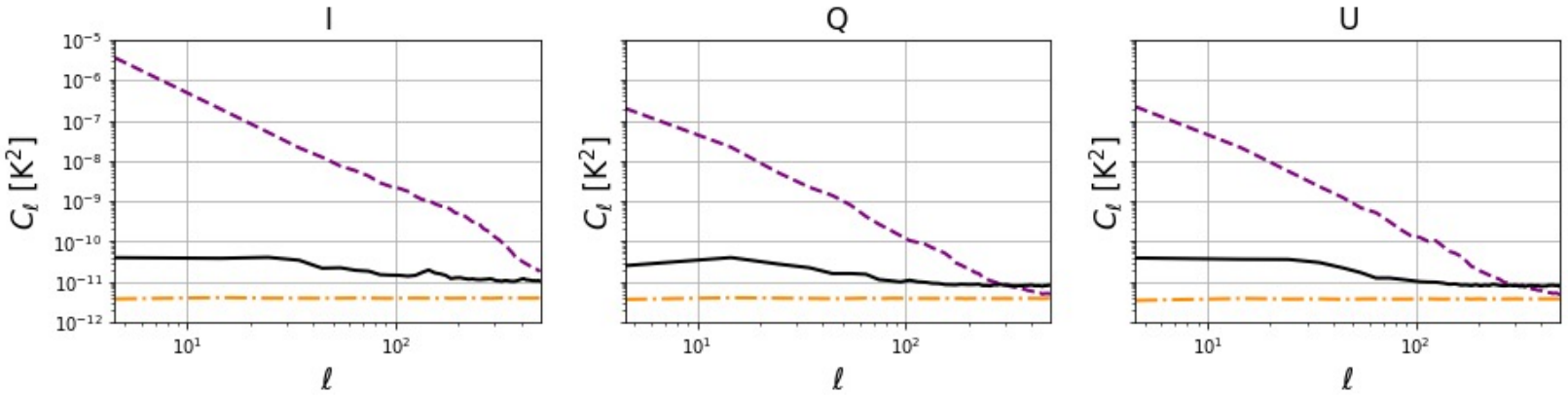
CBASS Data Quality

Jack-knife tests:

- Quantify residual large-scale systematics
- Validate quality of intensity and polarisation calibration
- Large-scale systematics less than 1% of expected signal at scales < 20deg



'Odd-even' schedules

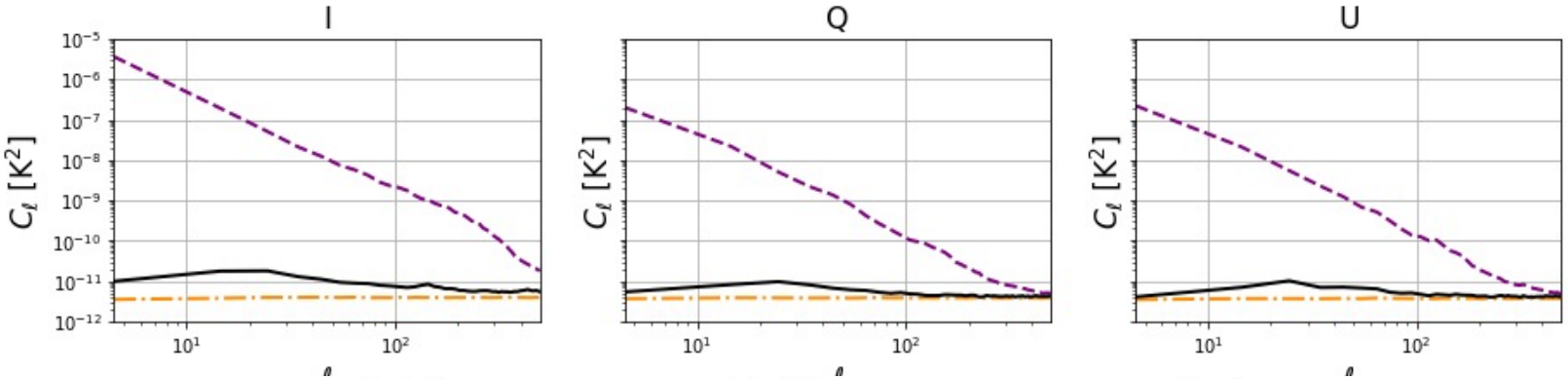


'1st half-2nd half' of data

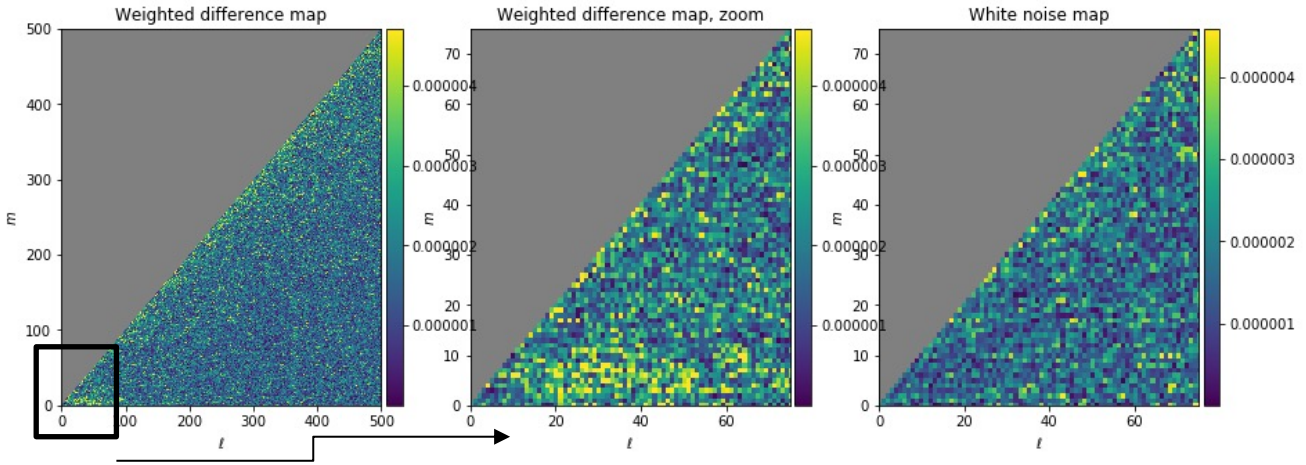
CBASS Data Quality

Jack-knife tests:

- Quantify residual large-scale systematics
- Validate quality of intensity and polarisation calibration
- Large-scale systematics less than 1% of expected signal at scales < 20deg



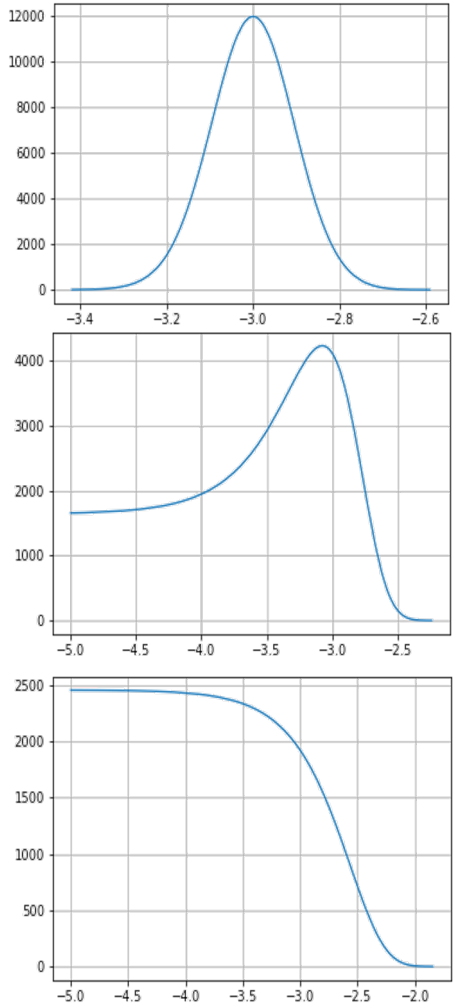
'Odd-even' schedules



Alm plots

Polarized Spectral Index

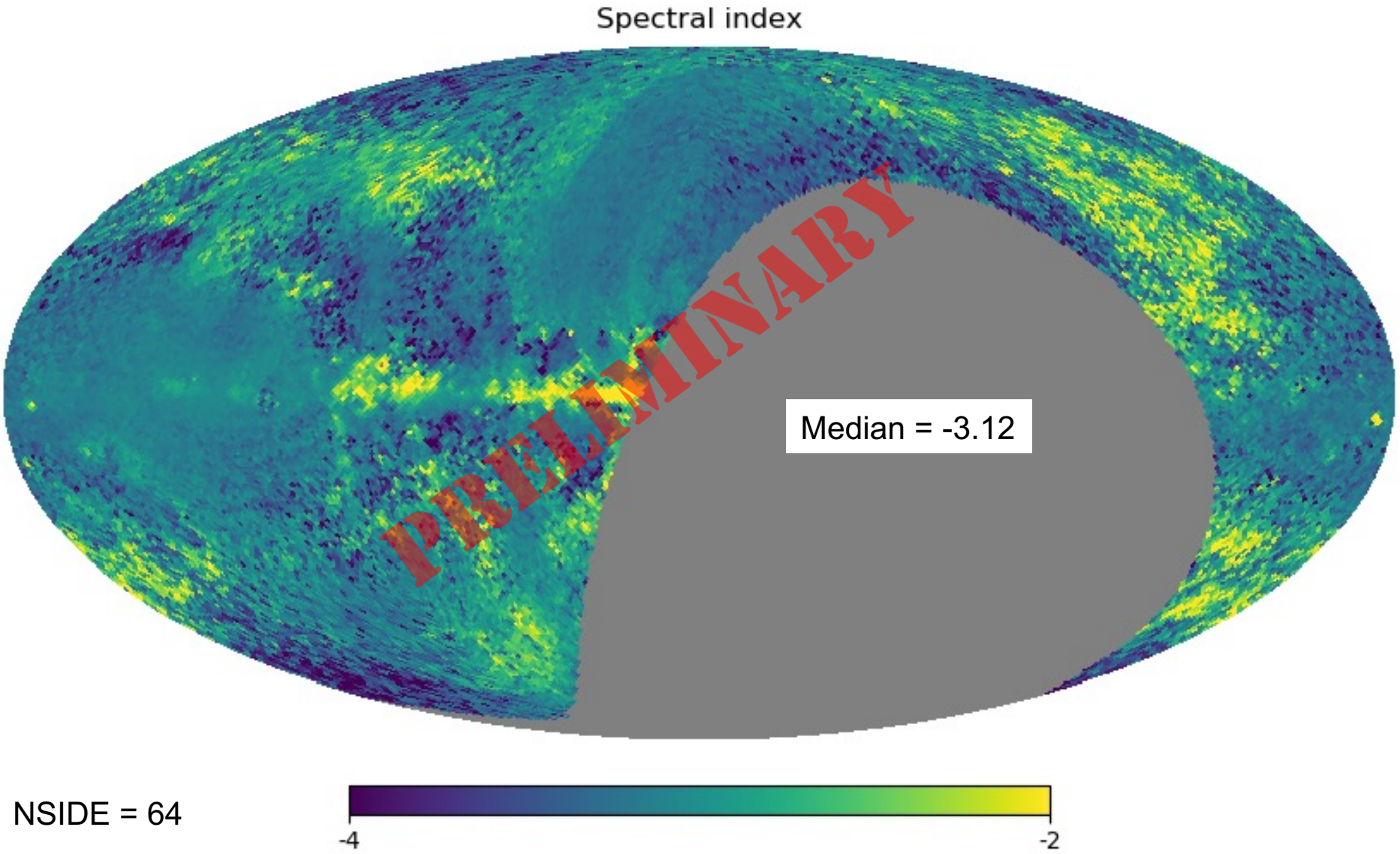
- C-BASS, WMAP K, Ka, Planck 30
- Fit single straight spectral index per pixel
- Rician likelihood to deal with noise bias
- Jeffreys prior for Rician distribution to prevent runaway posteriors at low S/N



Example fits with decreasing signal-to-noise at the higher (non-CBASS frequency)

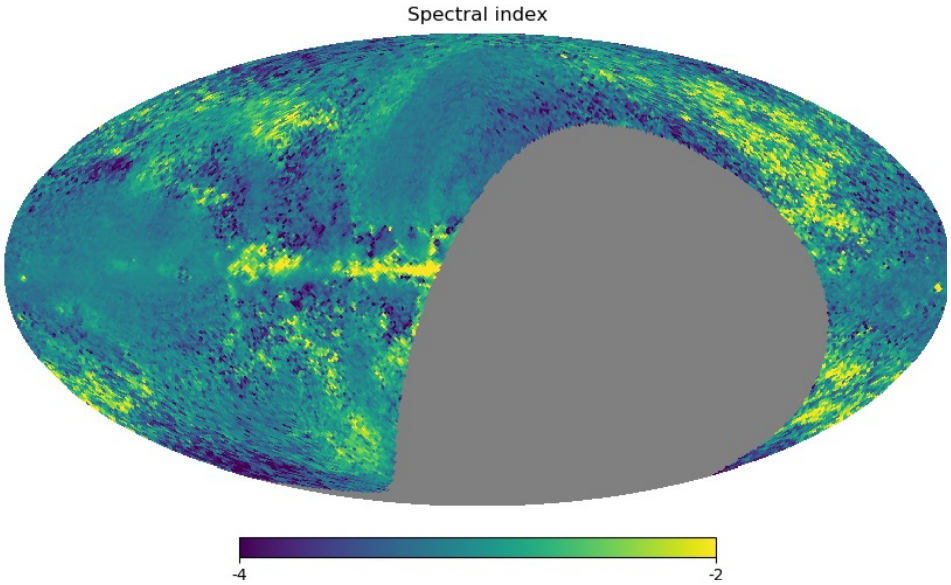
UNIVERSITY OF OXFORD

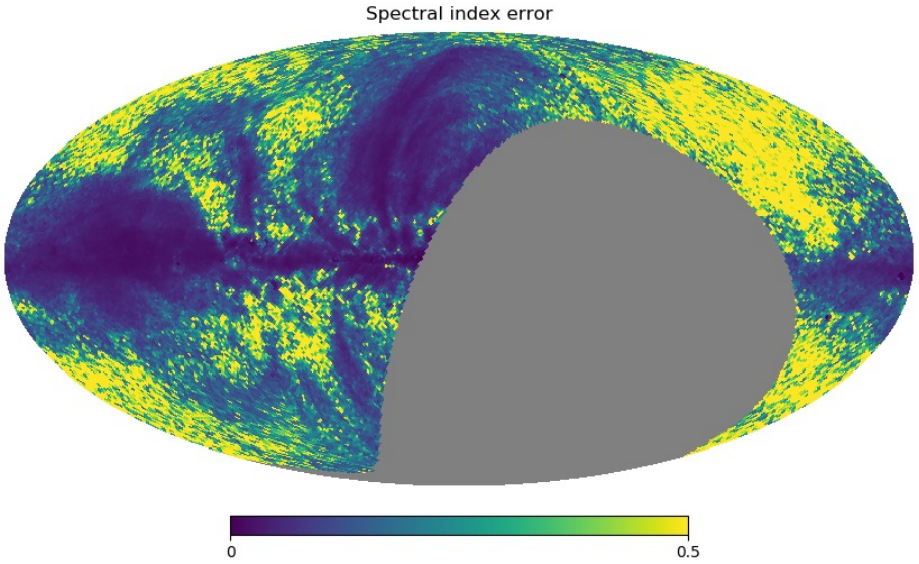
5-22-27-32 GHz spectral index

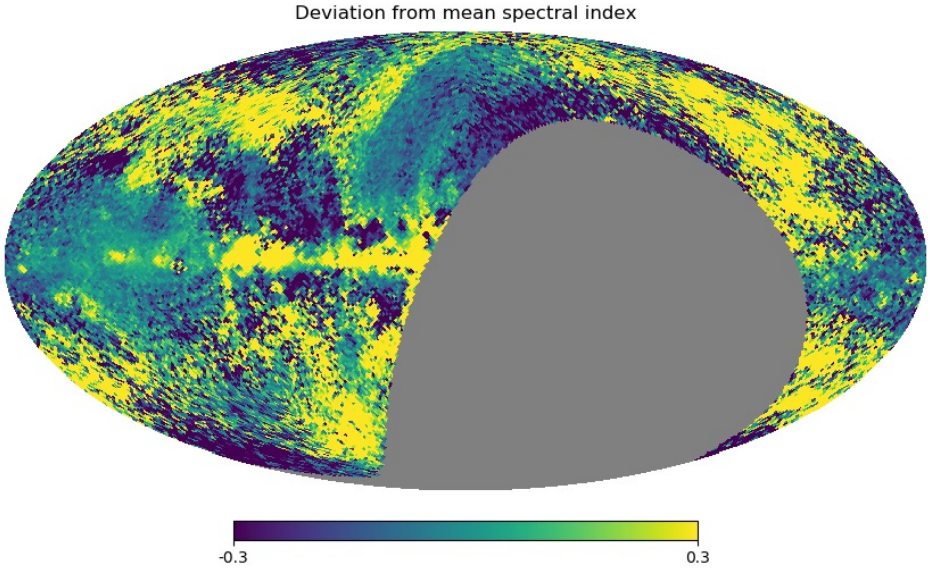


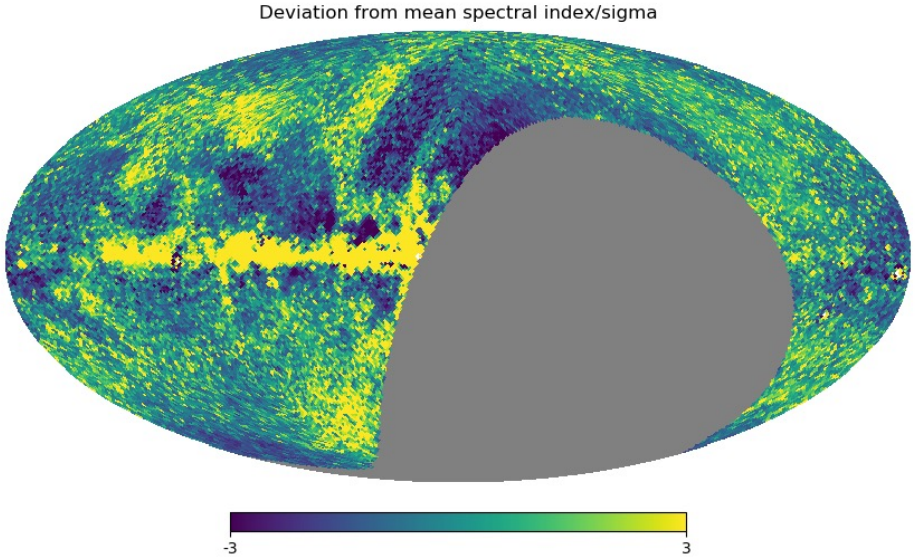
UNIVERSITY OF OXFORD

5-22-27-32 GHz spectral index





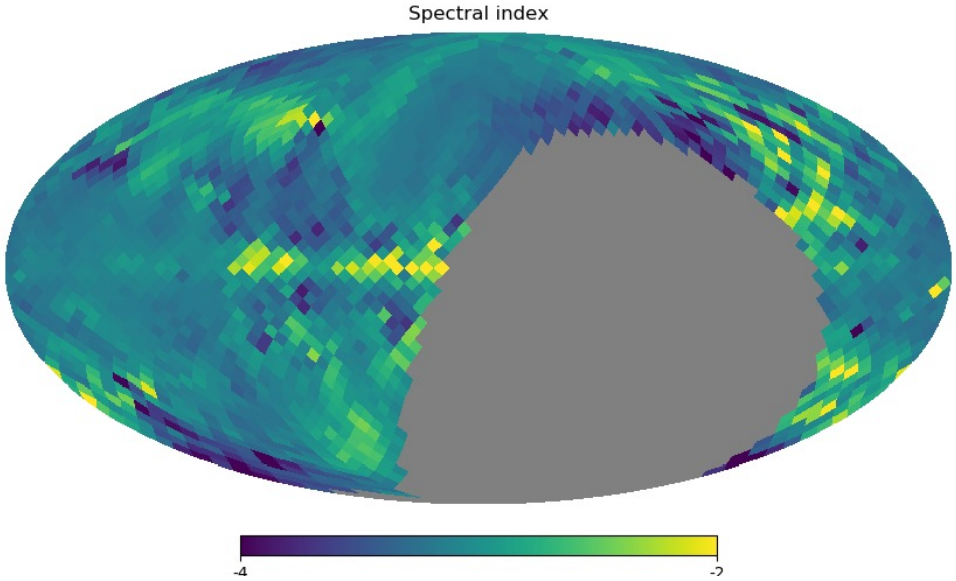


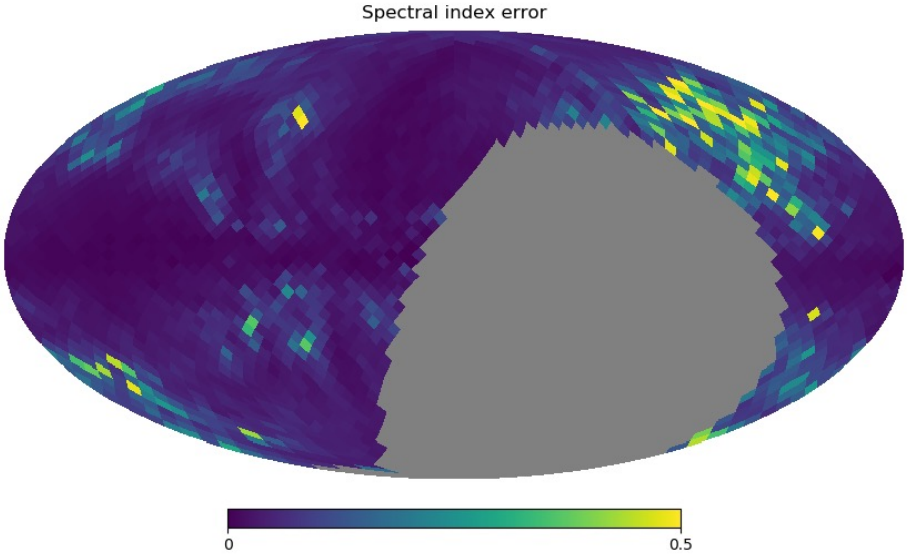


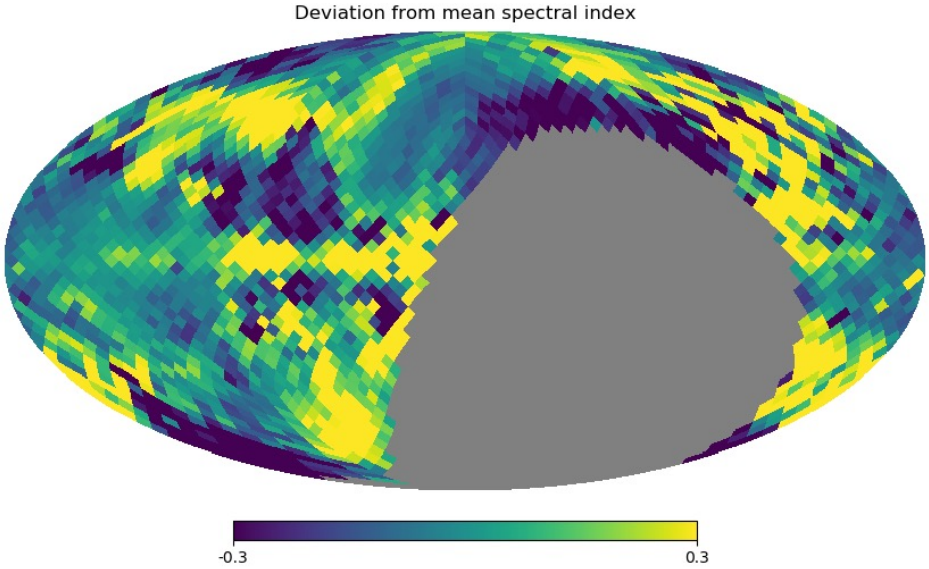
NSIDE = 64

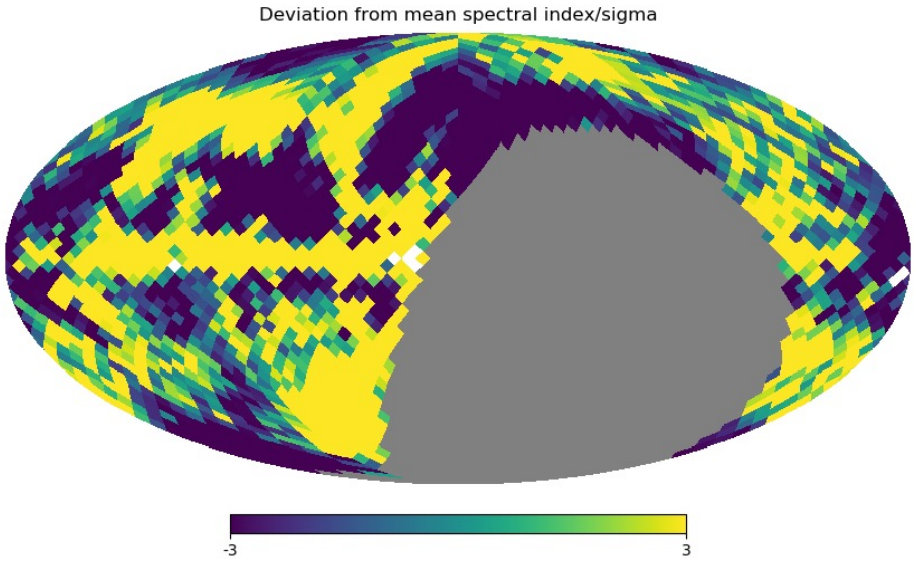
UNIVERSITY OF OXFORD

5-22-27-32 GHz spectral index



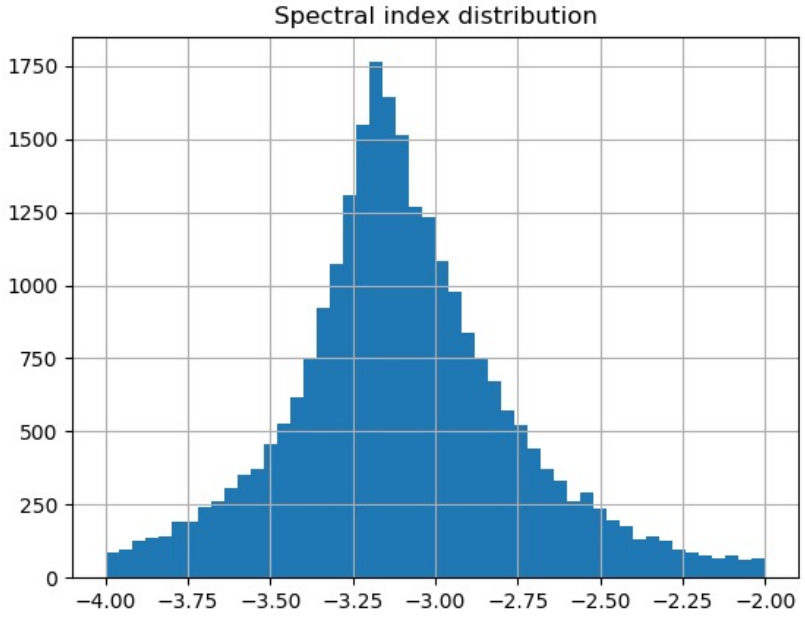




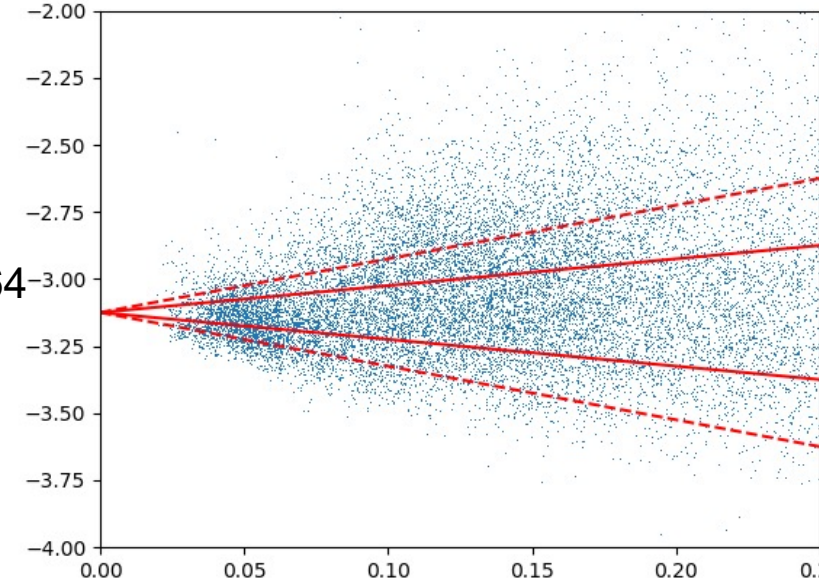


NSIDE = 16

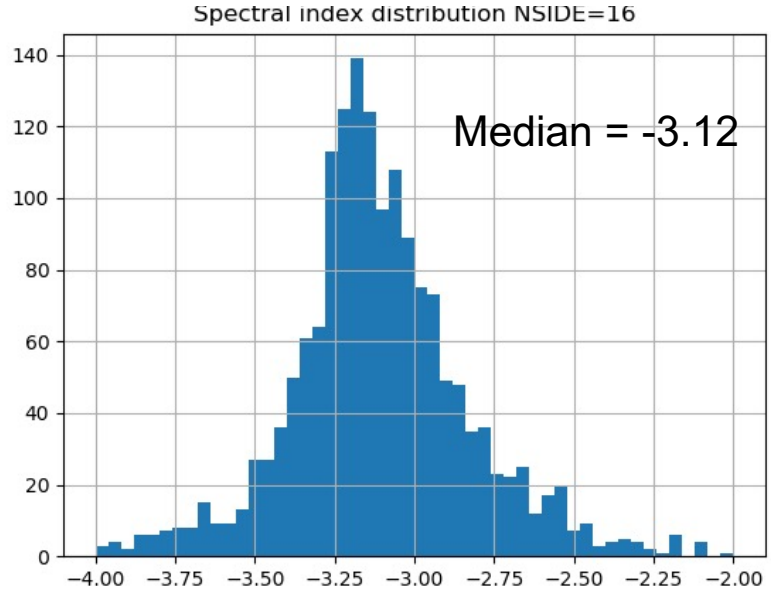
Spectral index distribution



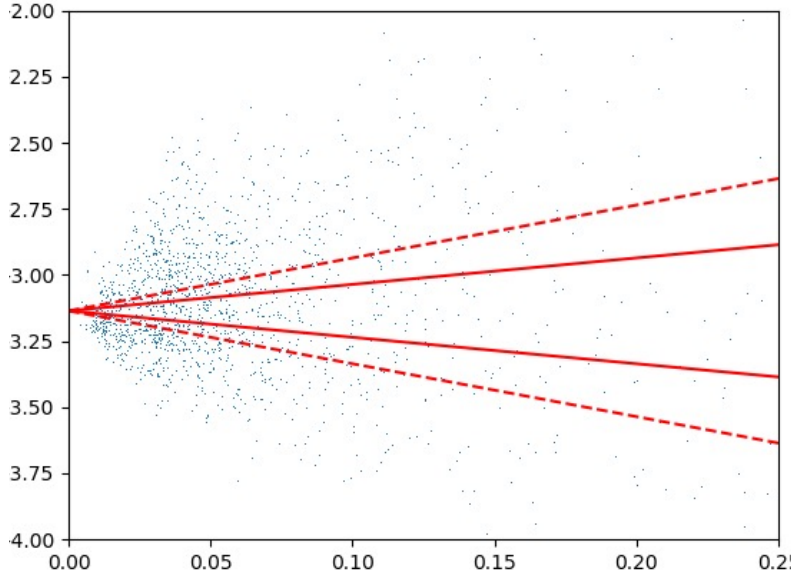
NSIDE = 64



Excluding
|b| < 10 deg

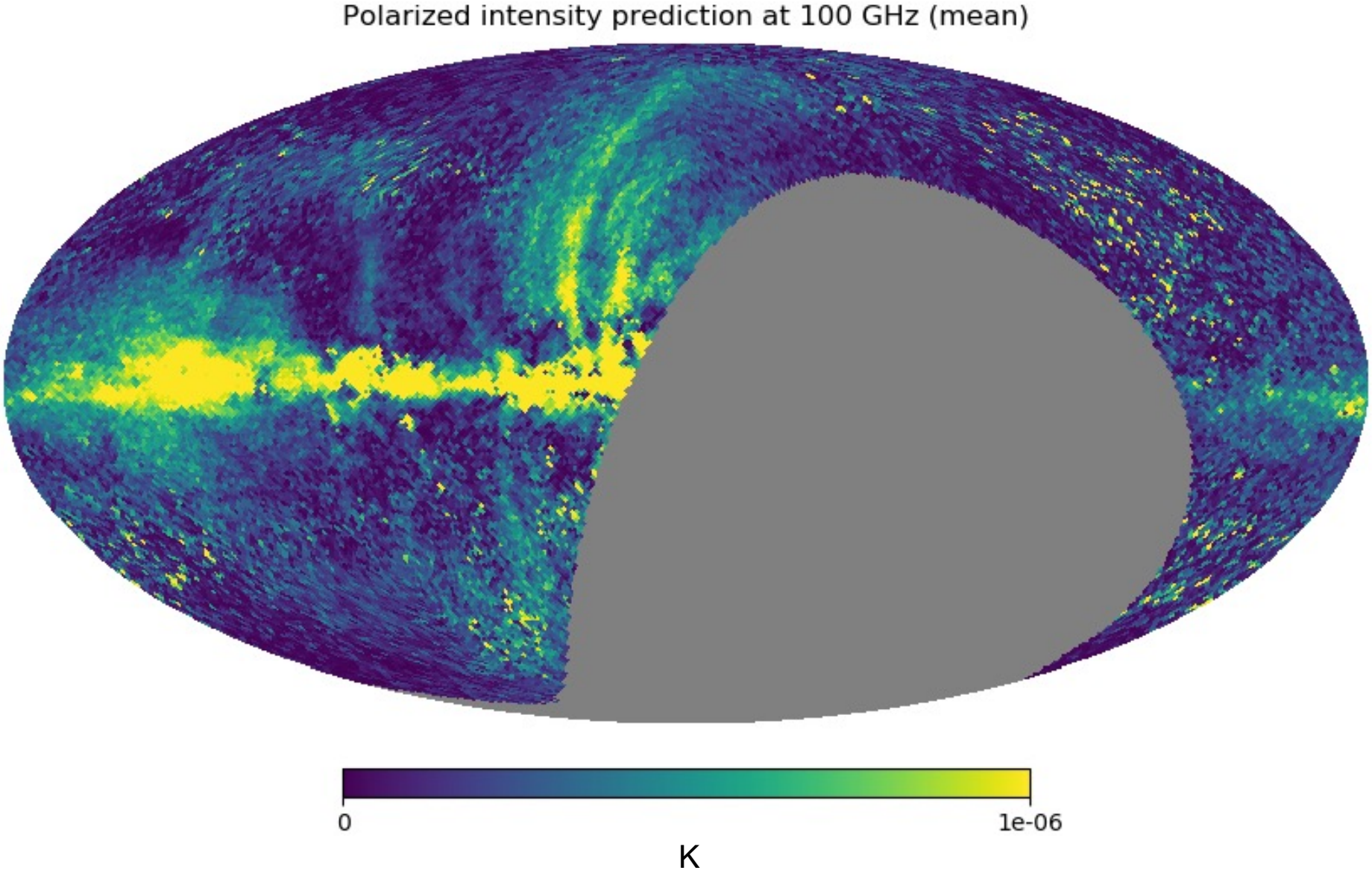


NSIDE = 16



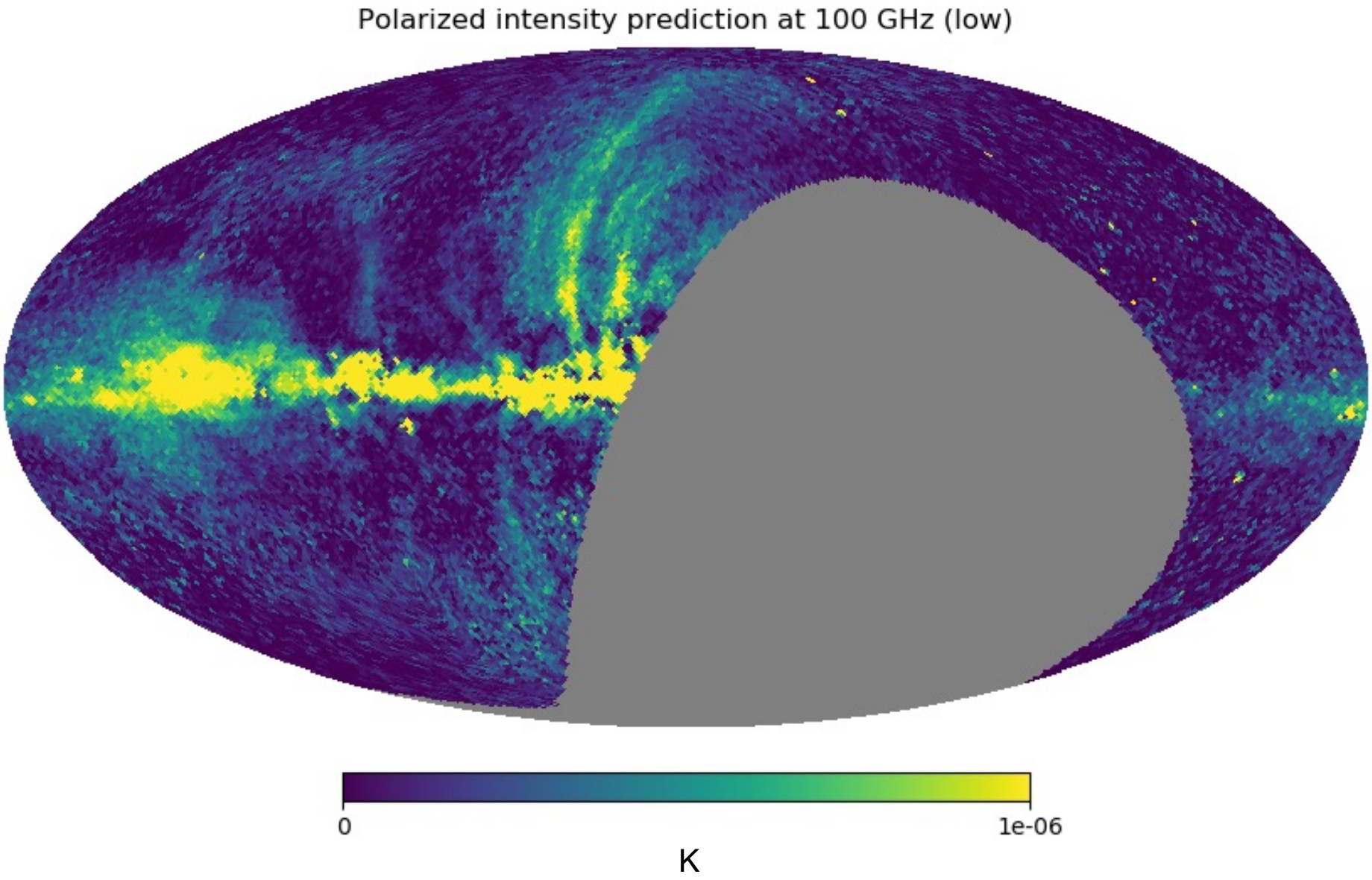
UNIVERSITY OF OXFORD

Implication for CMB @ 100GHz



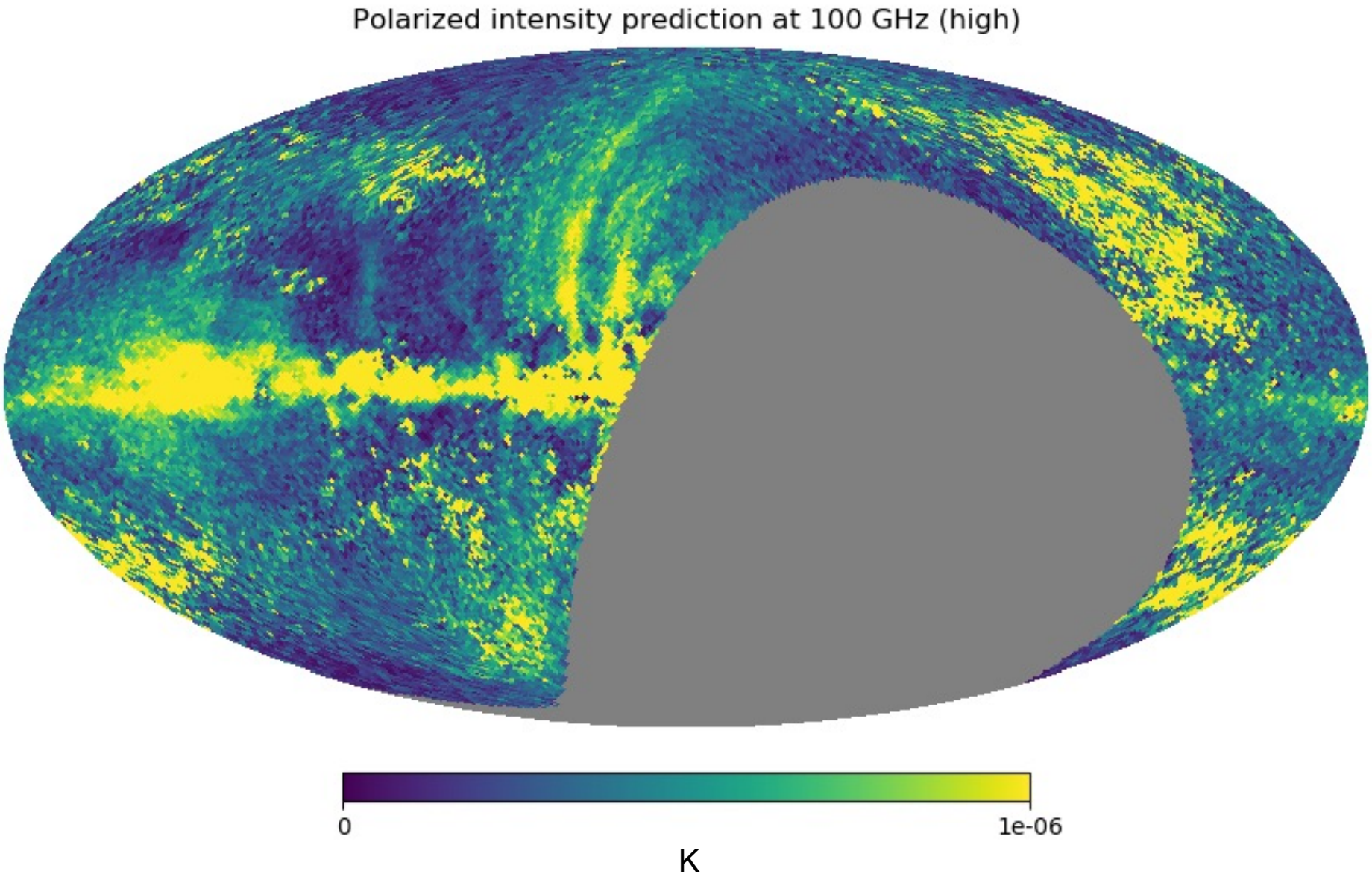
UNIVERSITY OF OXFORD

Implication for CMB @ 100GHz



UNIVERSITY OF OXFORD

Implication for CMB @ 100GHz

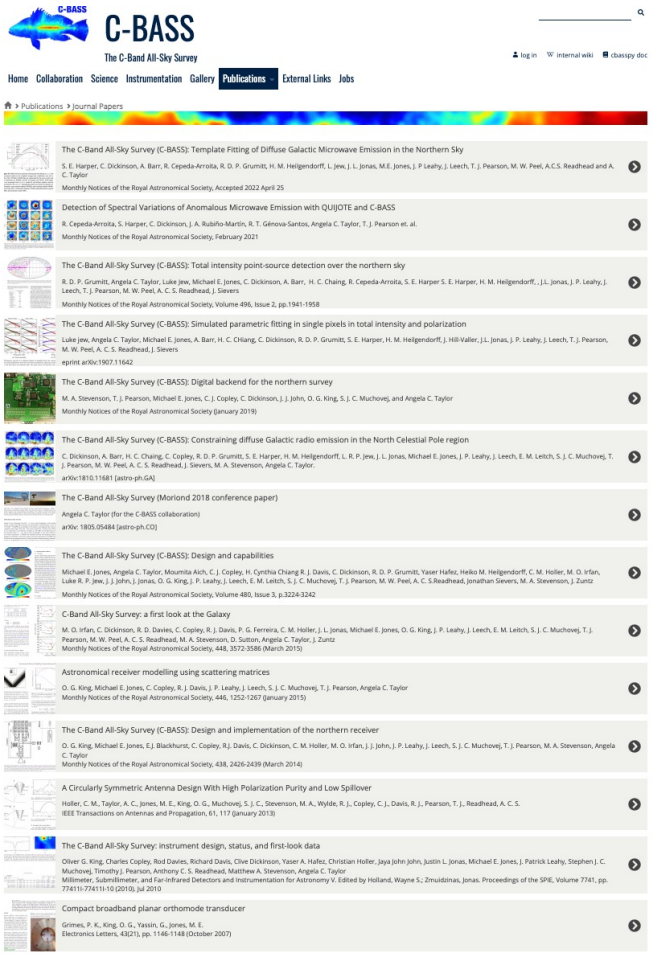


CBASS - status

- Northern data pipeline/mapping complete.
- Excellent calibration (~1%)
- Very low large-scale systematics

- First set of North data papers by end of year.
- Public data release shortly after papers, but still keen to work directly with other groups with complementary data/analysis tools

- Southern survey suspended due to Covid – 1-2 yrs data taking expected in south
- Full data release once surveys completed and combine – maps, beams, source catalogue/source subtracted maps (not TOD).



Papers and theses already published:
See https://cbass.web.ox.ac.uk/

UNIVERSITY OF OXFORD

Thank you!