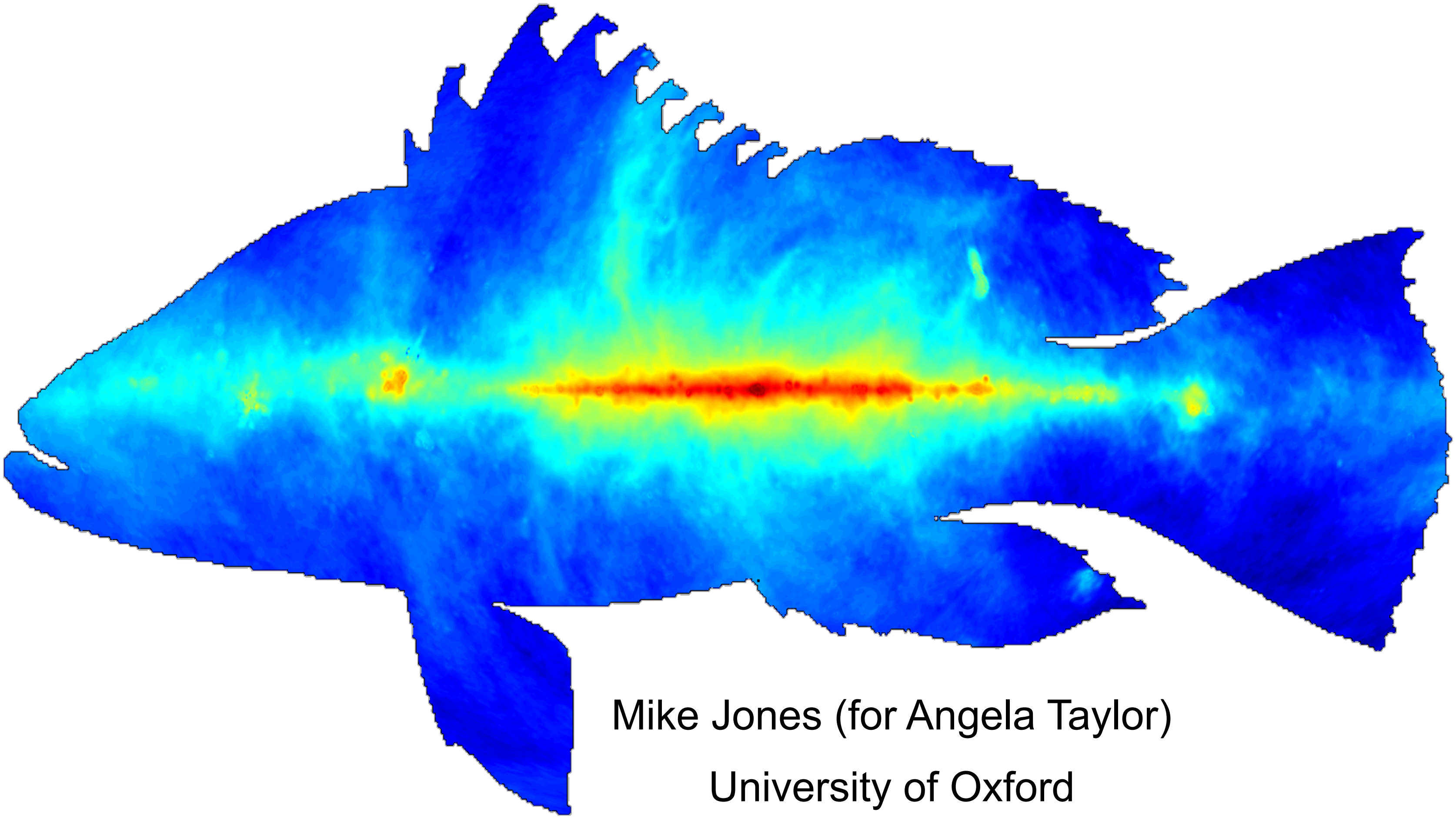
C-Band All-Sky Survey (C-BASS)



Mike Jones (for Angela Taylor)

University of Oxford

Oxford Physics

California Institute of Technology 1891

JPL
Jet Propulsion Laboratory
California Institute of Technology

MANCHESTER
1824
The University of Manchester

SKA AFRICA
SQUARE KILOMETRE ARRAY

مدينة الملك عبدالعزيز
KACST للعلوم والتقنية

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

University of Oxford, UK

Angela Taylor, Mike Jones, Jamie Leech, Richard Grummit,

Hochschule München, Germany

Christian Holler

University of Manchester, UK

Clive Dickinson, Paddy Leahy, Mike Peel, Adam Barr, Roke Cepeda-Arroita

Caltech, USA

Tim Pearson, Tony Readhead,

South Africa

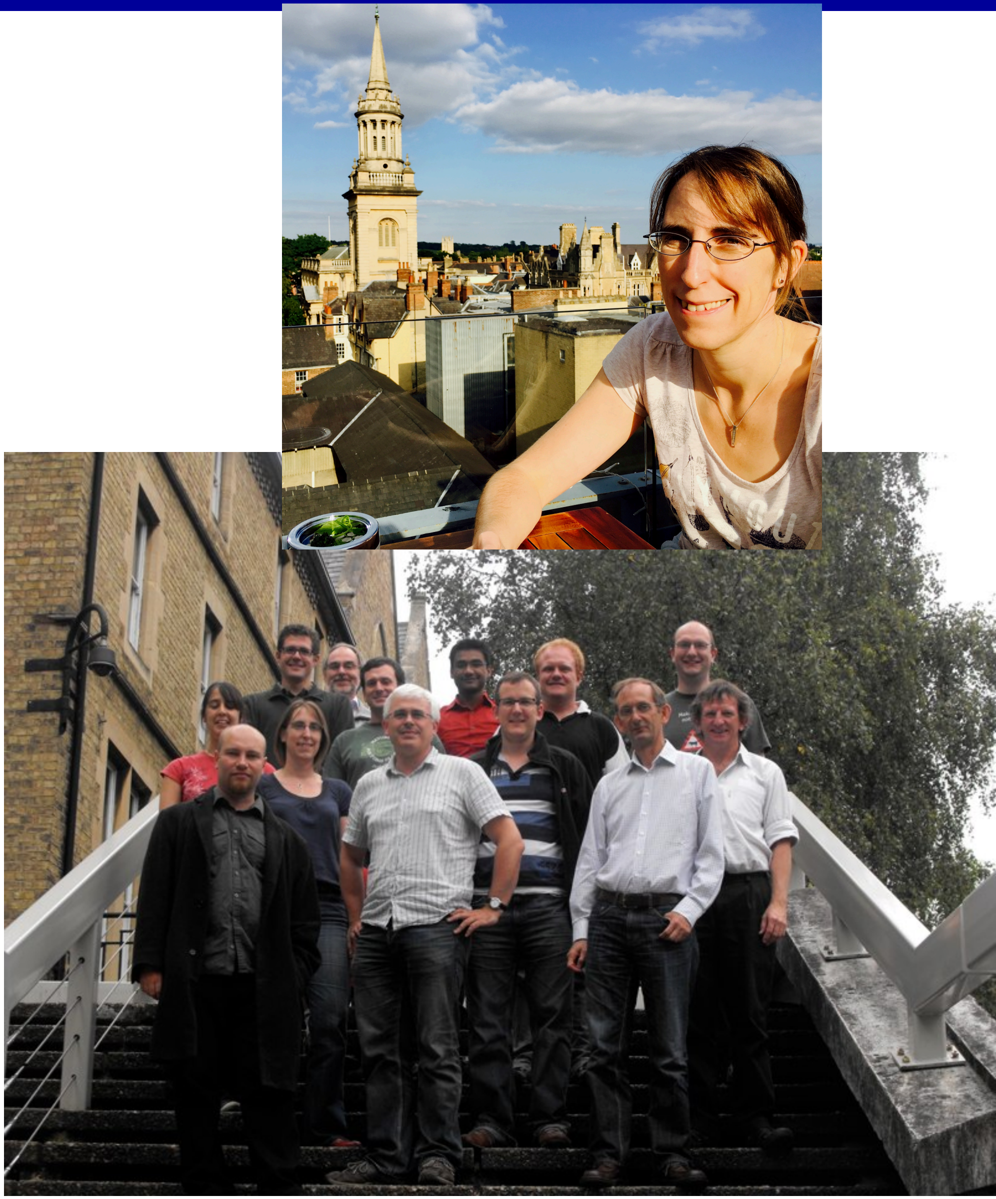
Justin Jonas (Rhodes/SKASA), Cynthia Chiang, Heiko Heligendorff, Moumita Aitch (UKZN)

KACST, Saudi Arabia

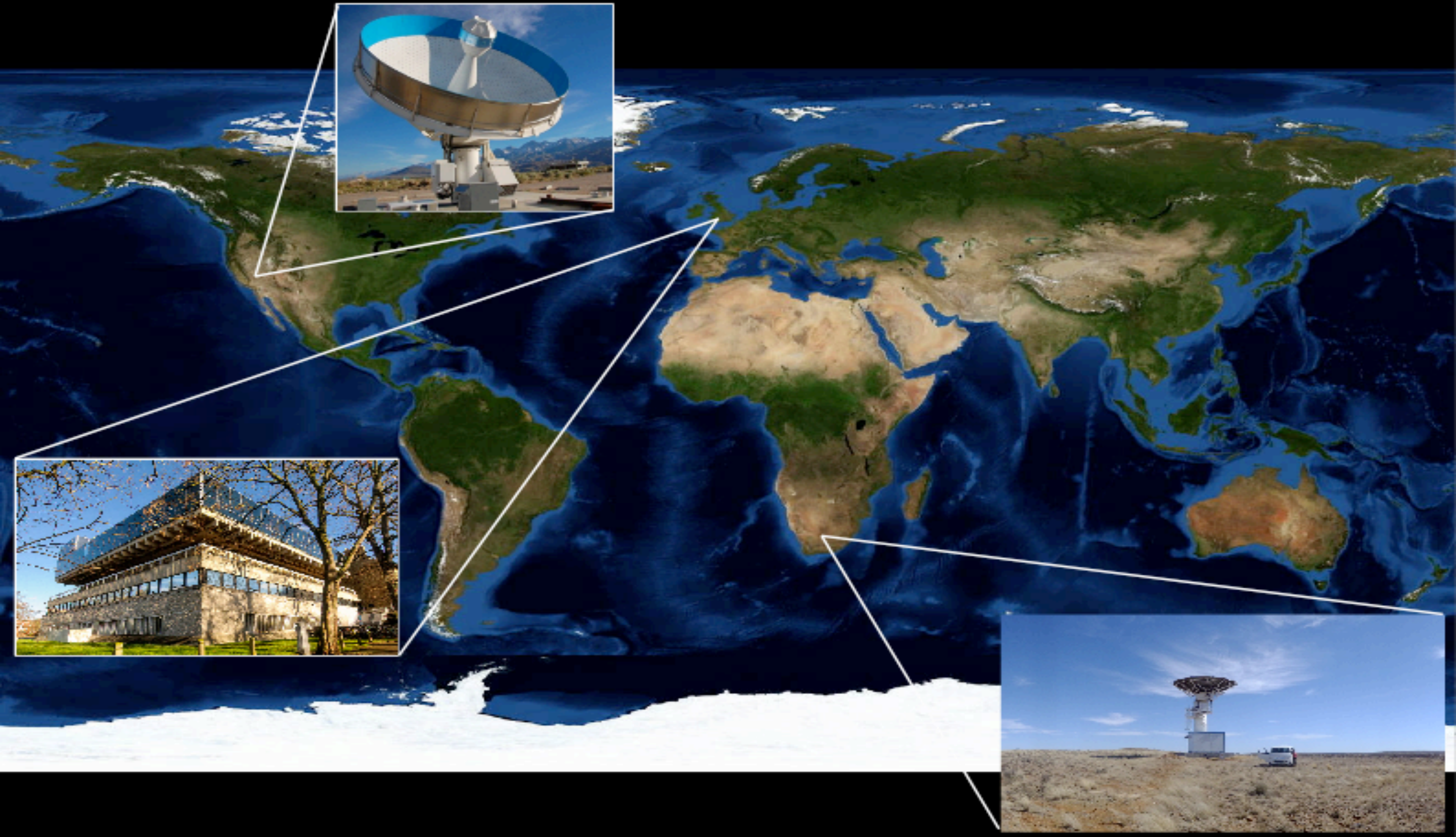
Yasser Hafez

Moved on…

Oliver King, Matthew Stevenson, Mel Irfan, Stephen Muchovej, Joe Zuntz, Charles Copley, Luke Jew, Jaz Hill-Valler

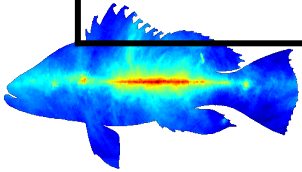


The C-BASS Survey

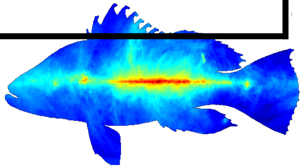


C-BASS - Overview

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, $\beta = -3$
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



See Jones et al 2018 MNRAS 480, 32224



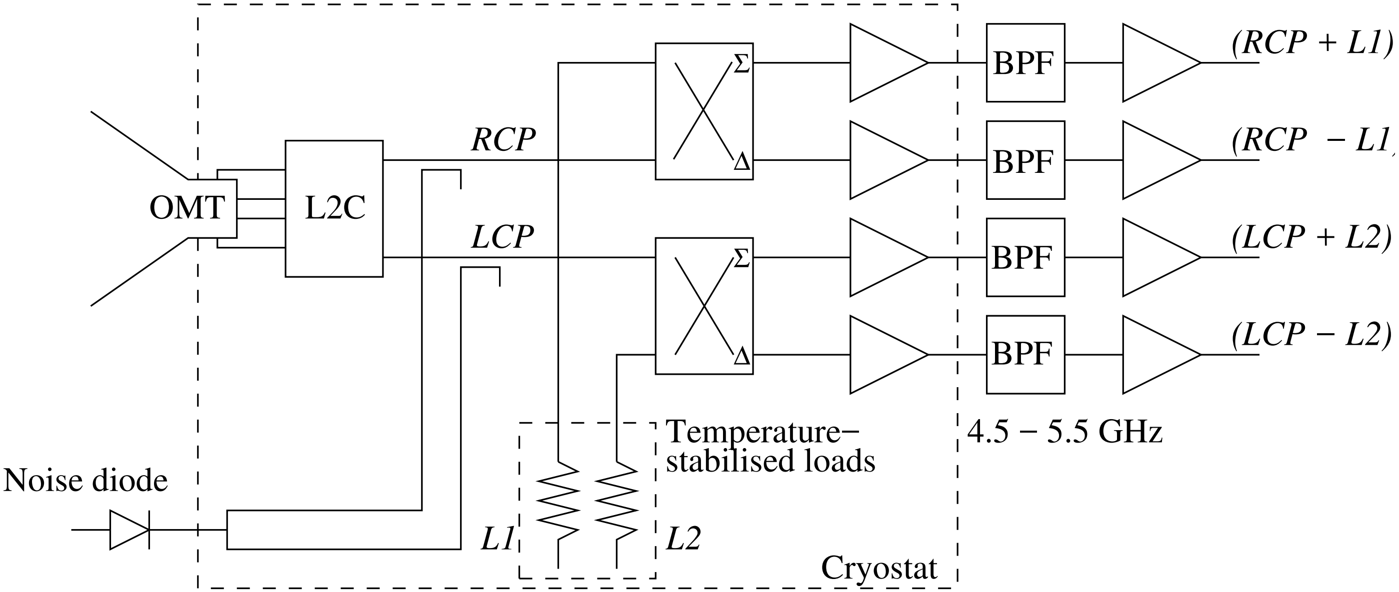
C-BASS North Telescope

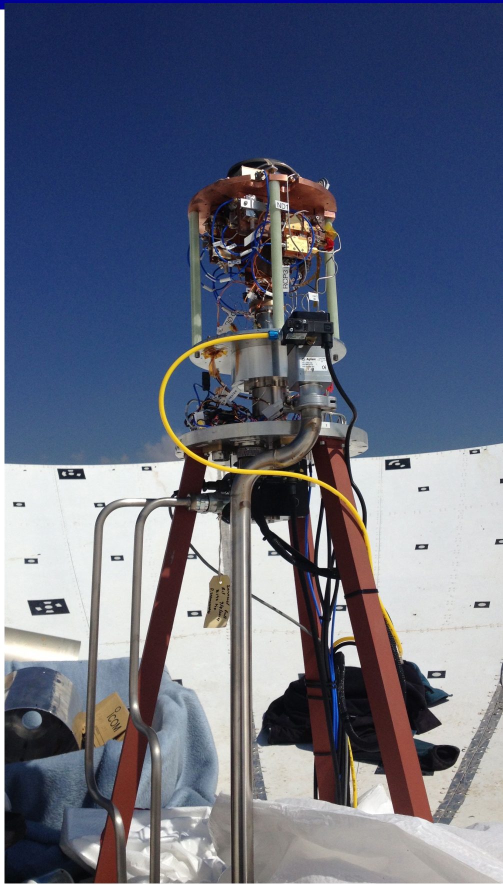
- 6.1-m dish, with Gregorian optics
- Secondary supported on foam cone
- Receiver sat forward of the dish
- Very clean, circularly-symmetric optics
- Absorbing baffles to minimize spillover

C-BASS 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 ch)

C-BASS Receiver

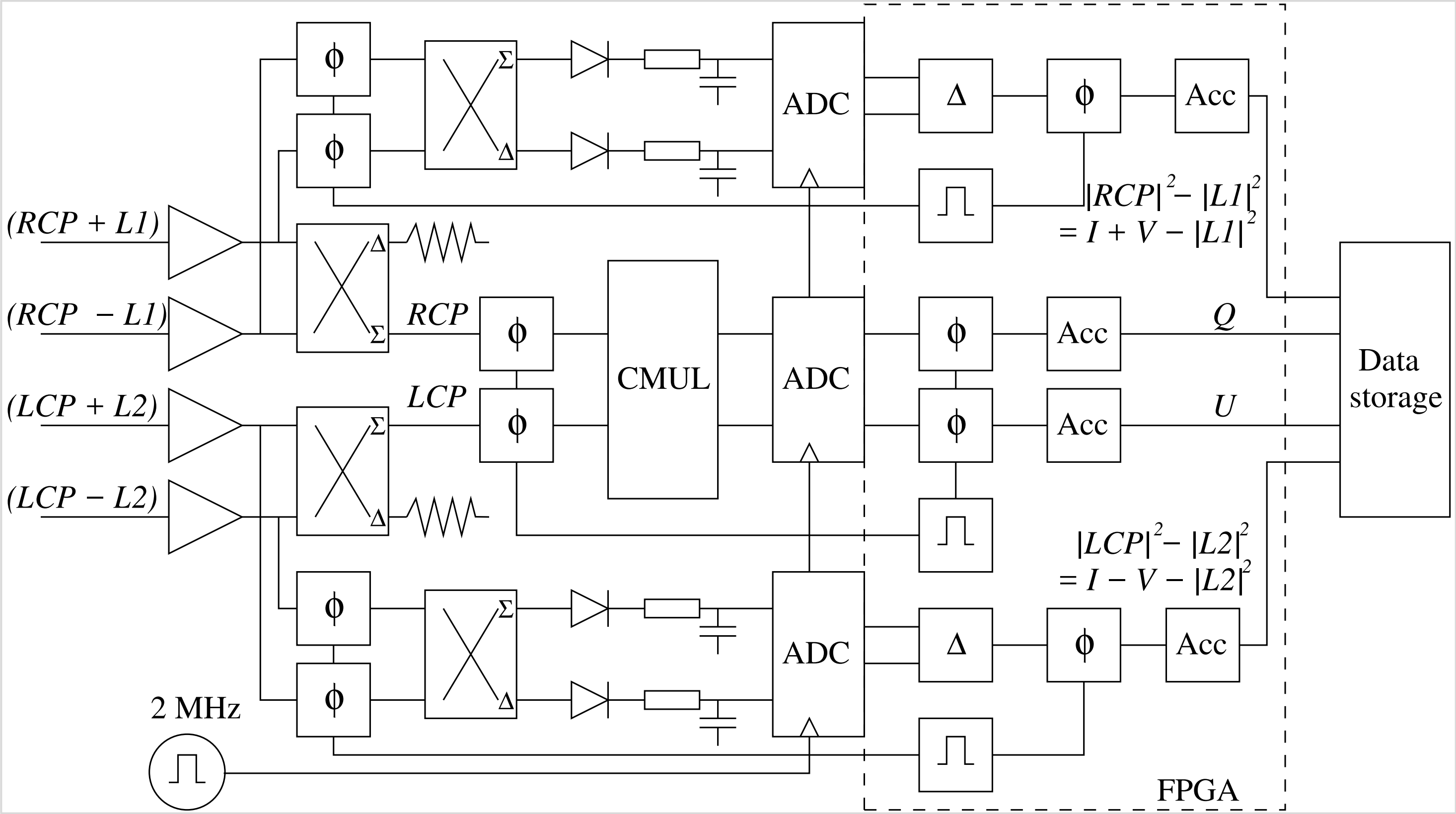




Both receivers use correlation polarimeter and continuous comparison radiometer:

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

C-BASS North Receiver

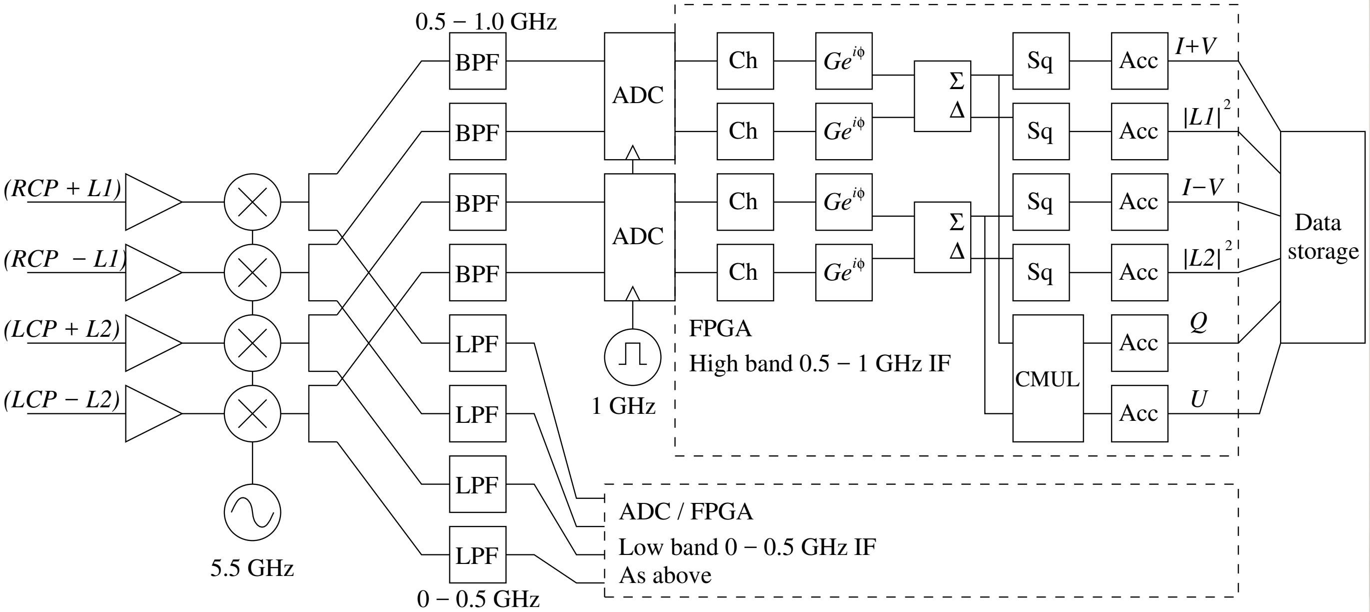


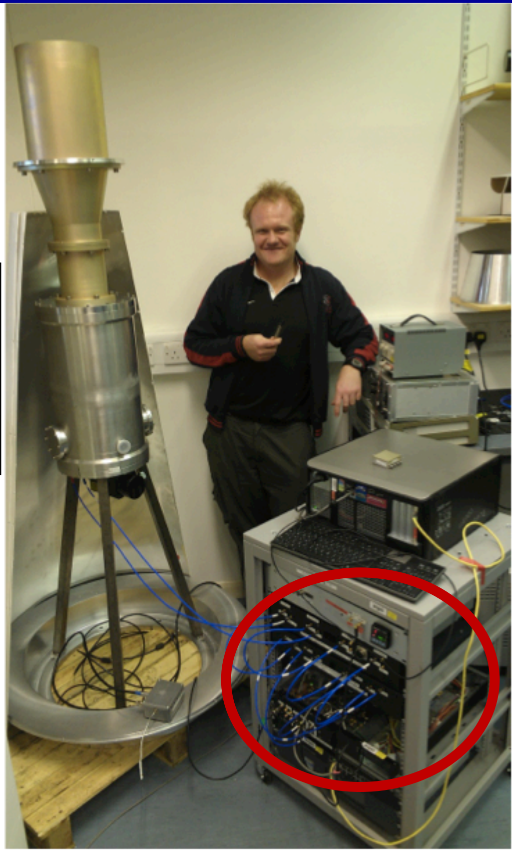
Analogue polarimeter/radiometer – all done with hybrids and diodes…

Sky and load signals separated post-amplification, squared and differenced – gives *I* relative to loads

RCP and LCP complex multiplied – gives $Q + iU$

C-BASS South Receiver





Digital system in two bands:

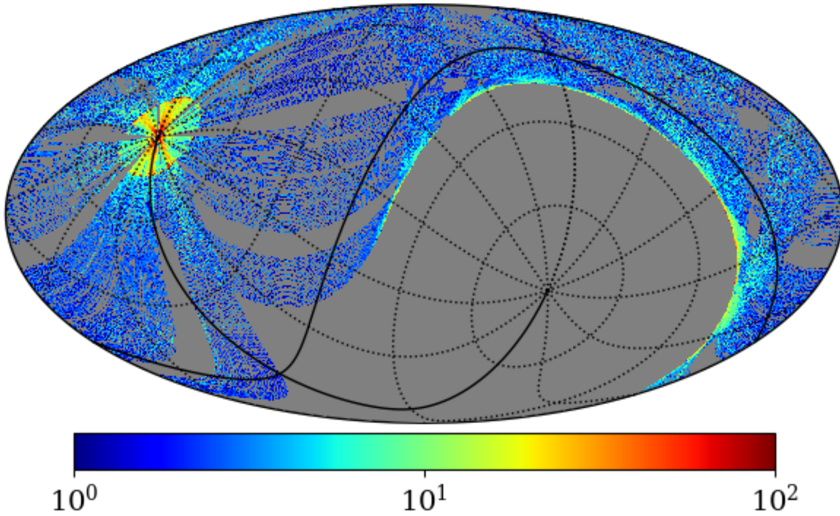
Downconversion to 0 – 0.5, 0.5 – 1 GHz

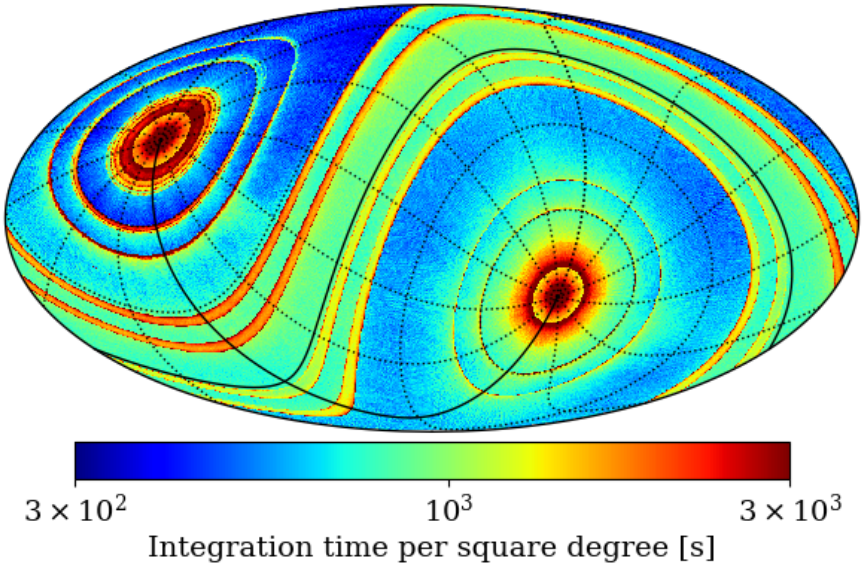
Sample at 1 GHz, channelise to 64 channels each, calibrate gains

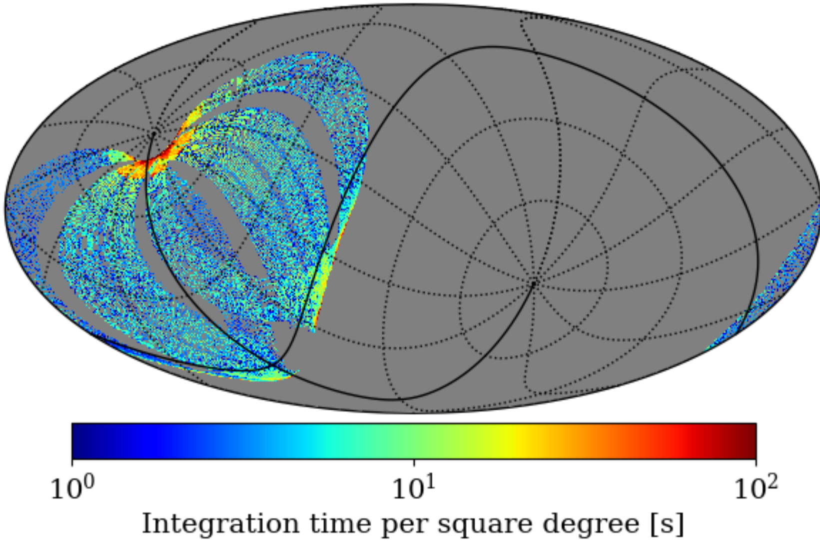
Square and difference sky and load → *I* ; correlate RCP, LCP → *Q, U*

Scan Strategy

- 360 deg azimuth scans at elevation of poles + 10, 20, 30…
- Scan as fast as possible: ~4 deg/s
- One scan ~90 s
- Use 5 slightly different scan speeds so fixed frequency ≠ same sky modes

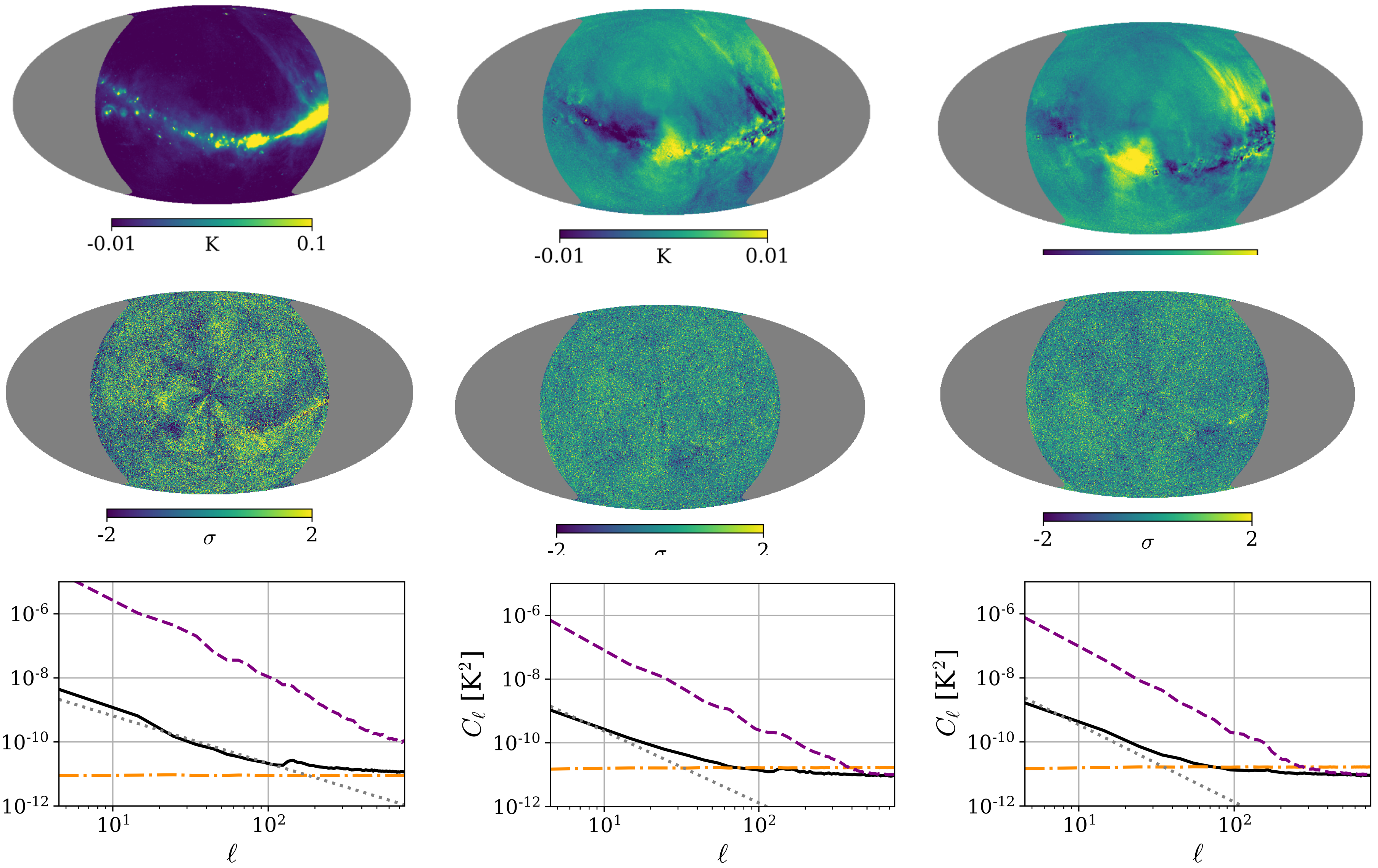




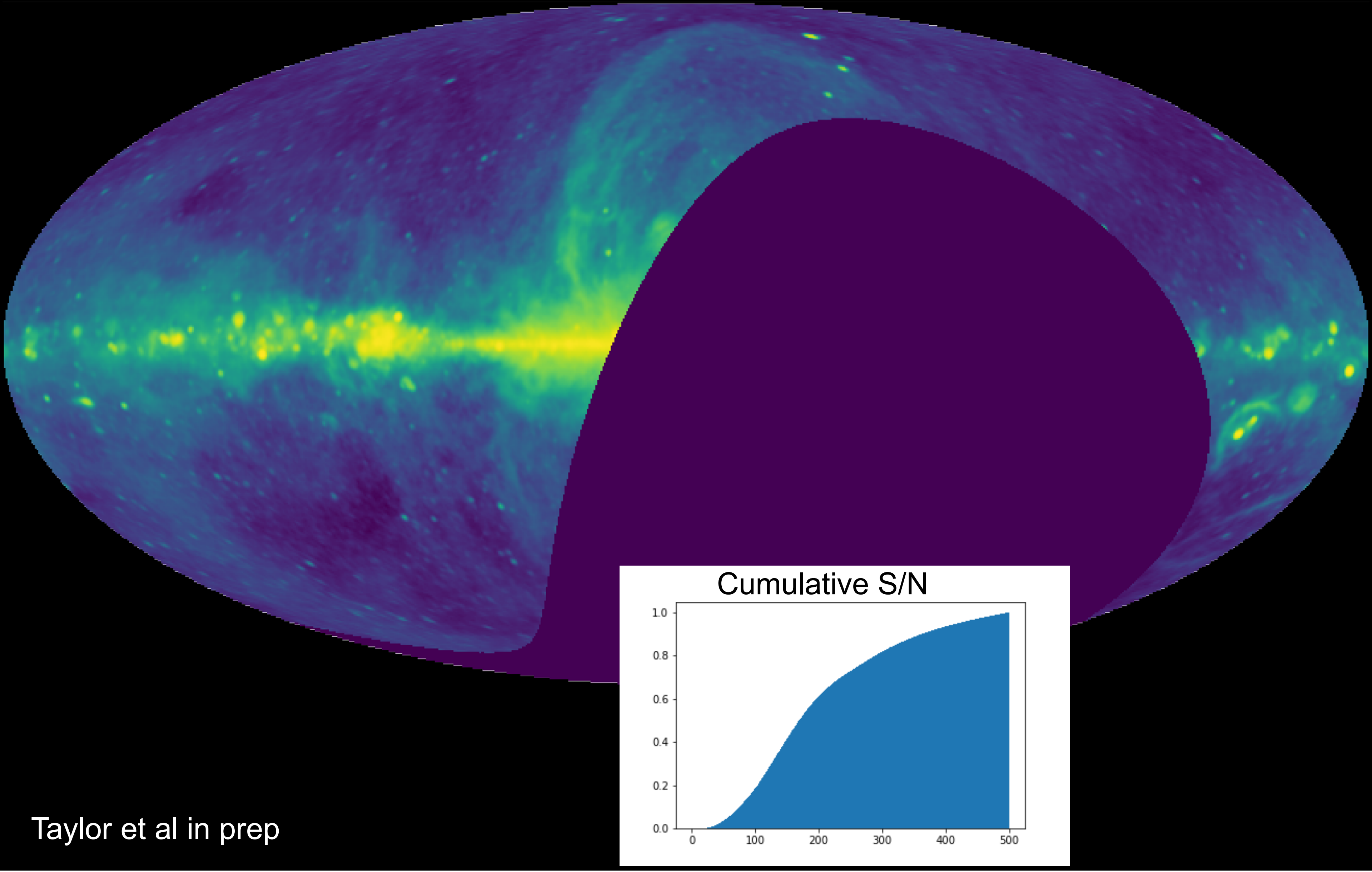


CBASS-N data: Null tests

Alternate observations; I, Q, U weighted difference maps and power spectra

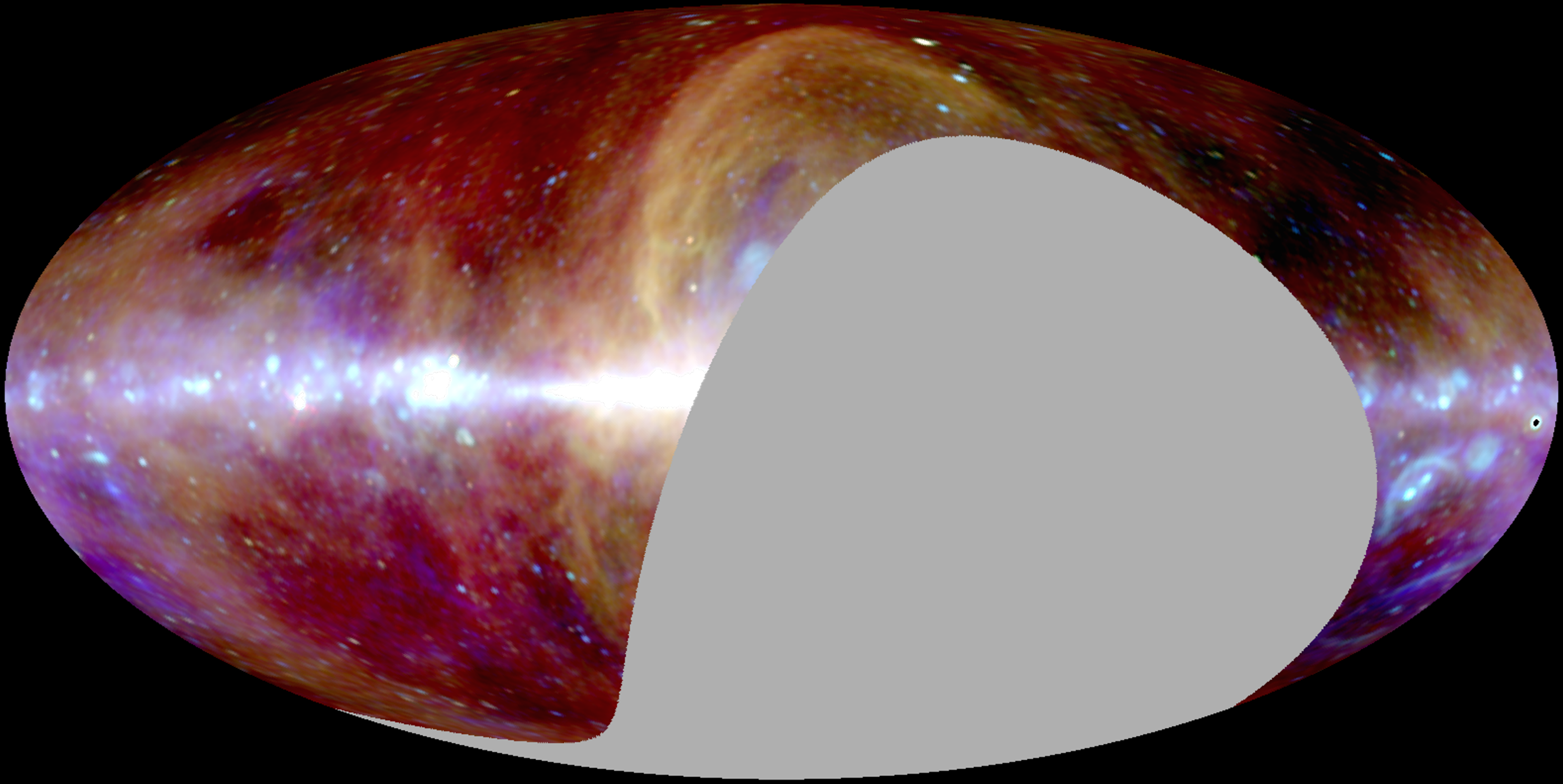


CBASS-N *I*



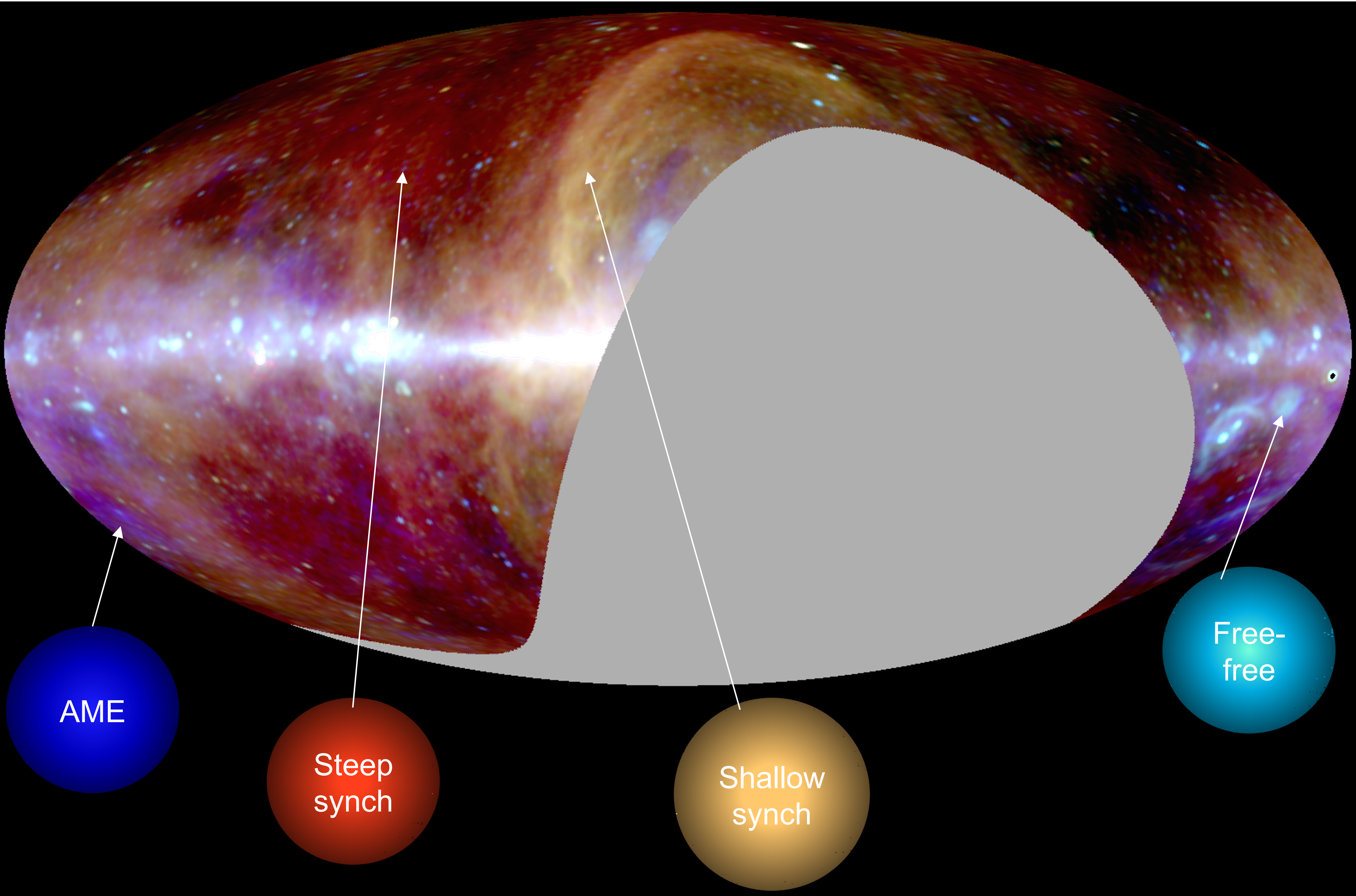
Taylor et al in prep

408 MHz - 5 GHz – 23 GHz

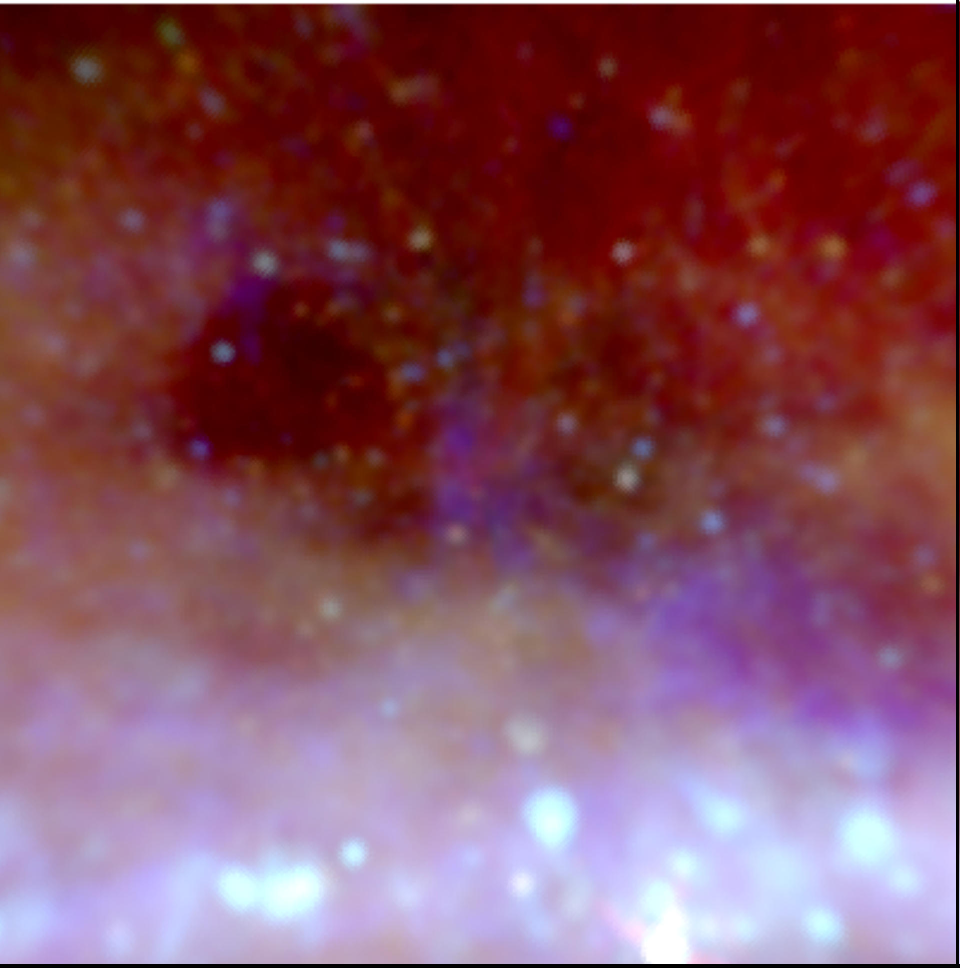


Jew et al in prep

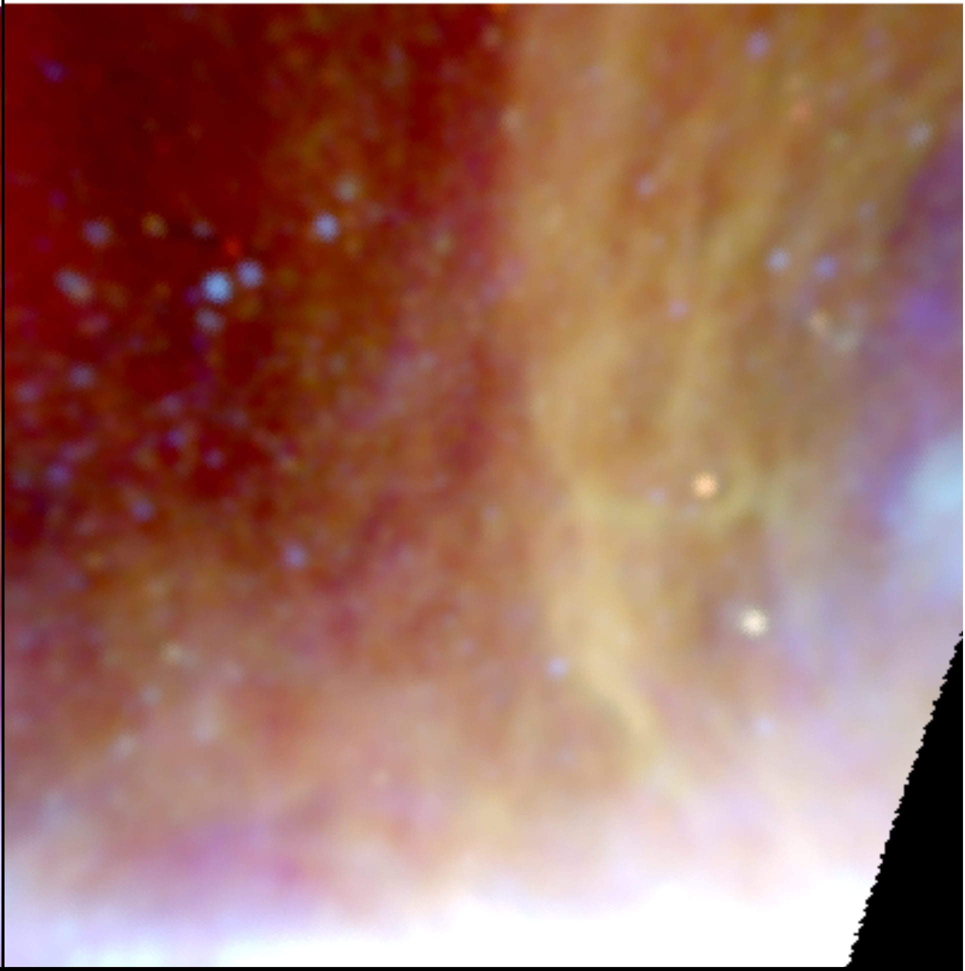
408 MHz - 5 GHz – 23 GHz



3-colour zoom-ins



NCP



NPS

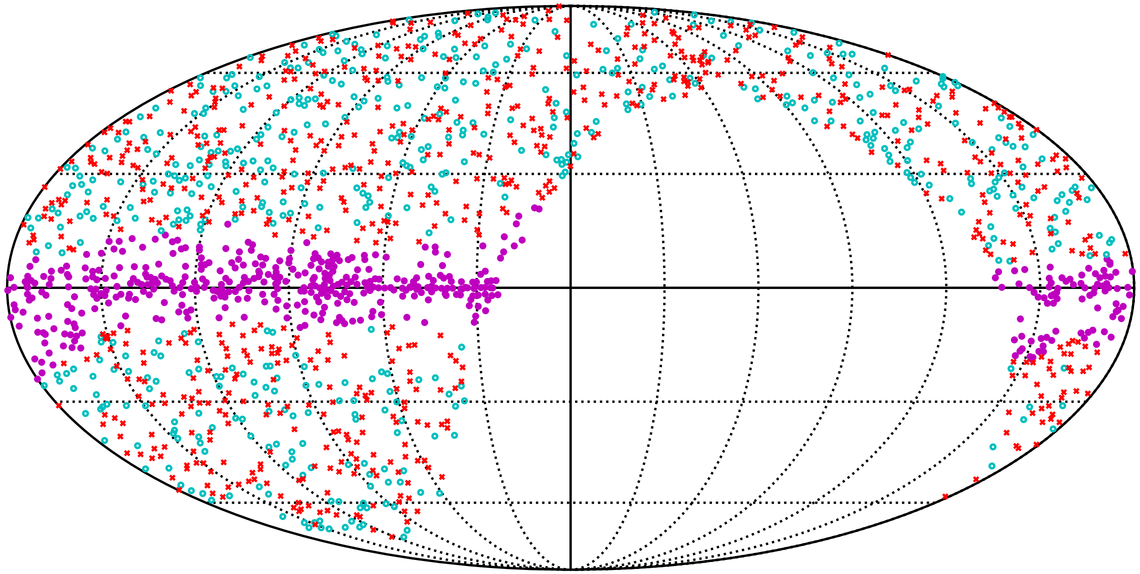
3-colour zoom-ins

Cygnus A

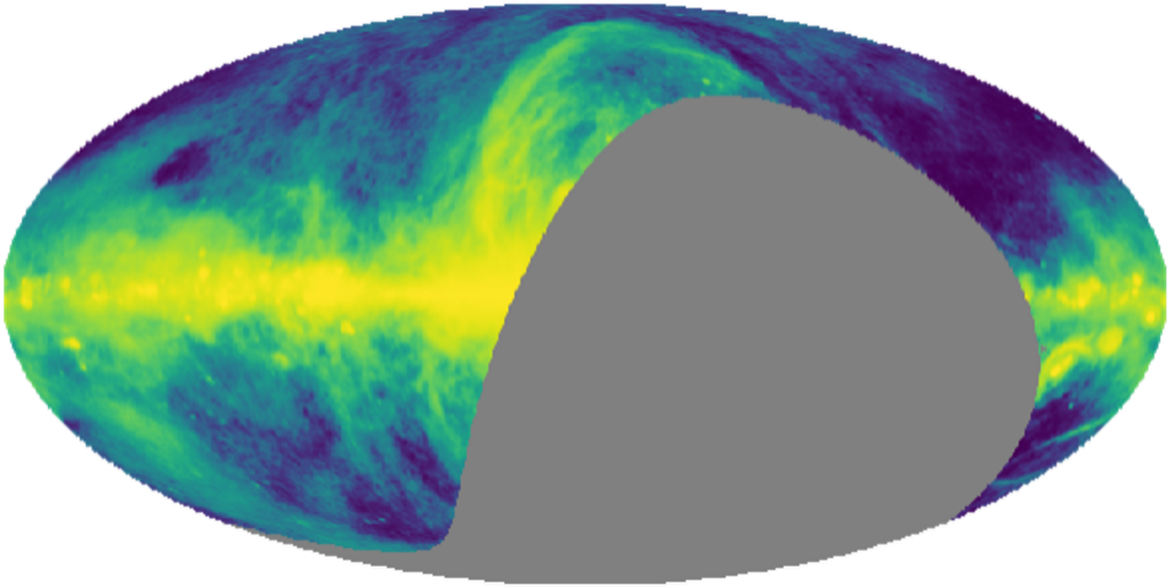
Perseus molecular cloud

Point sources

- Spherical Mexican-hat wavelet filter plus blob detection algorithm
- 1729 sources
- Calibration correlates with GB6 to < 3%
- Grumitt et al submitted
- Also map made with GB6+ sources removed down to GB6 flux limit

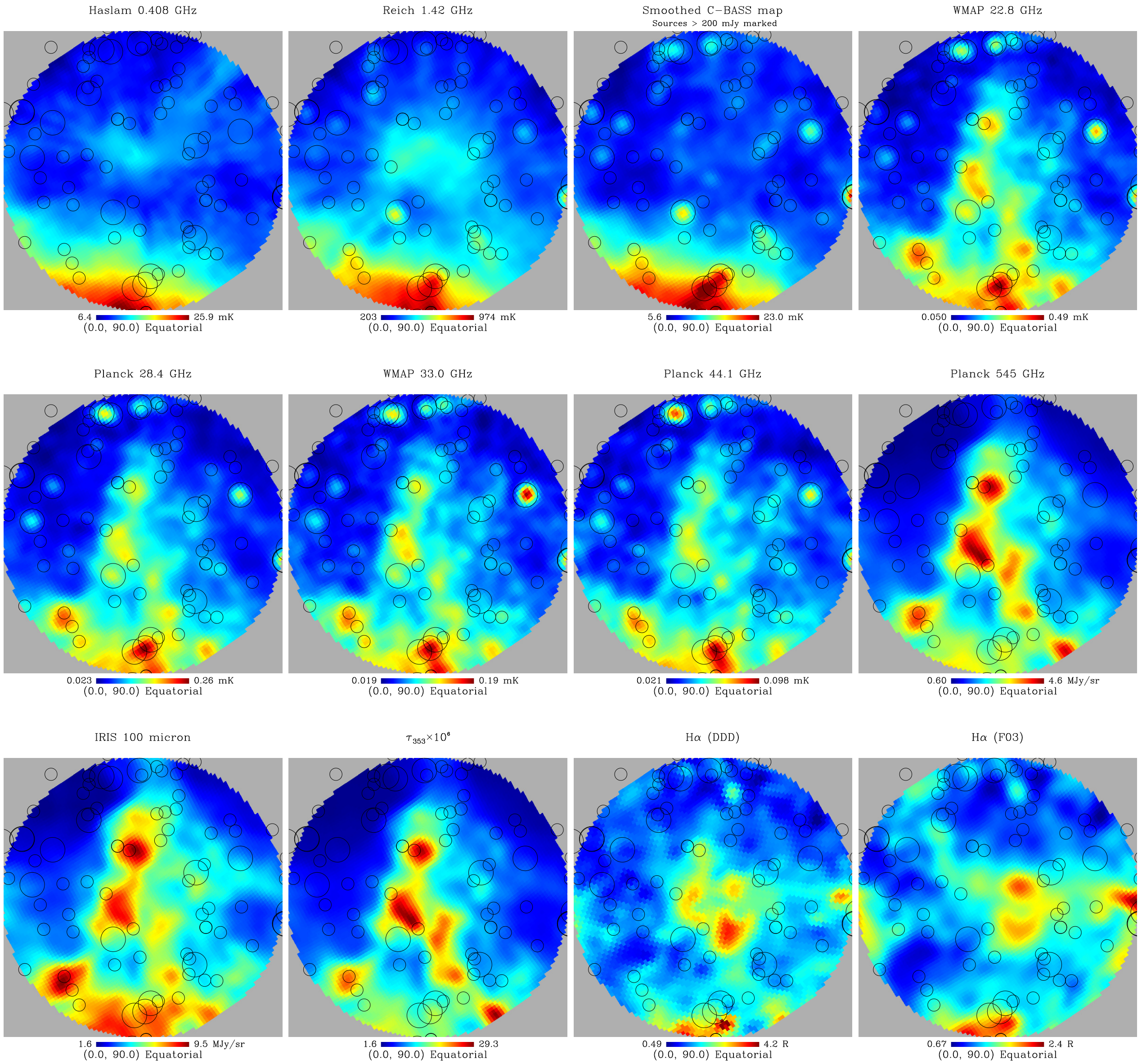


C-BASS I de-sourced

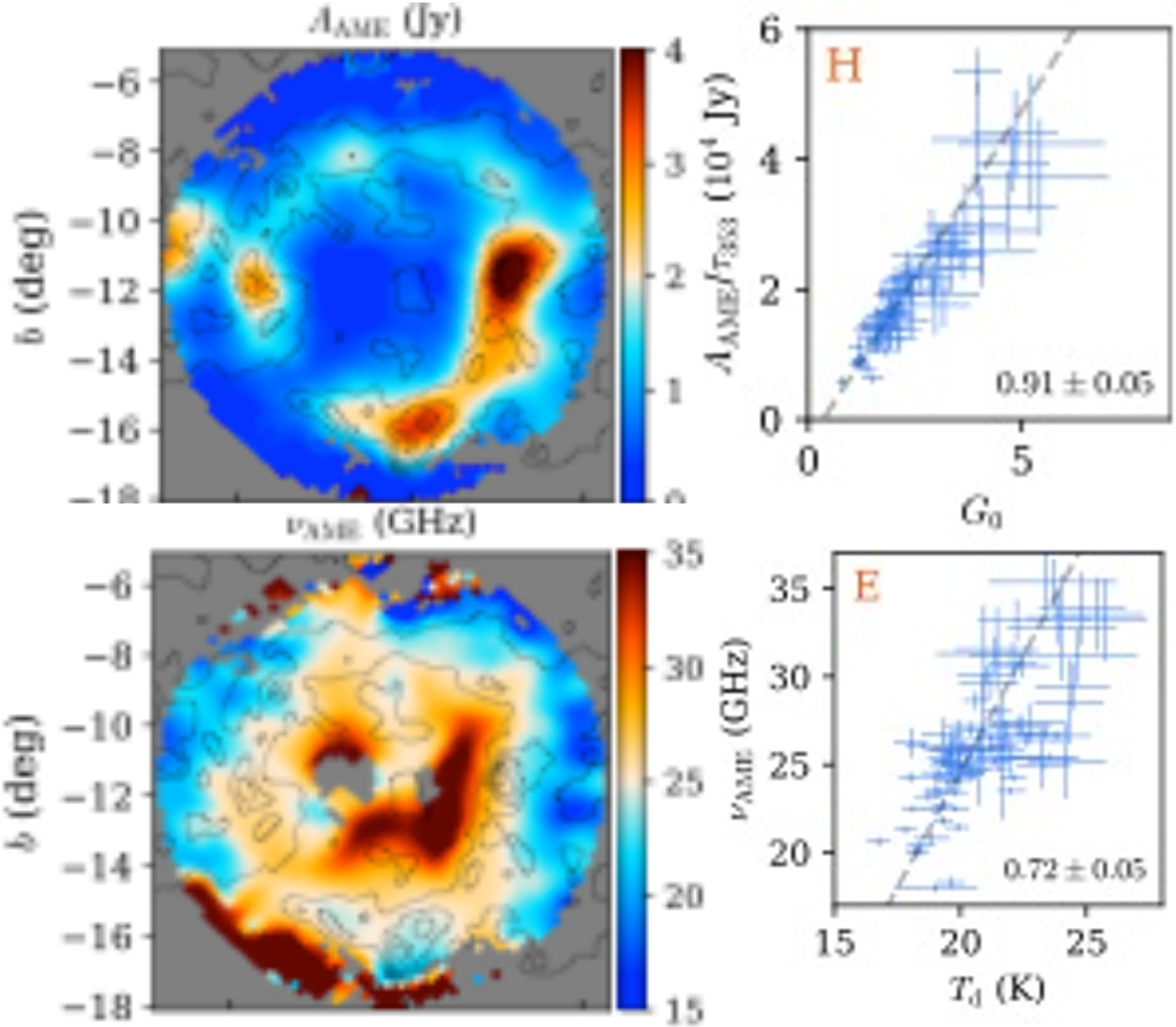


Template fitting

- Multi-frequency template-fitting analysis of NCP region (Dickinson et al 2018)
- AME-dust coeffs unchanged when using C-BASS rather than Haslam
- Rules out hard synchrotron as source of AME
- Follow-up on whole survey area in progress (Harper et al in prep)



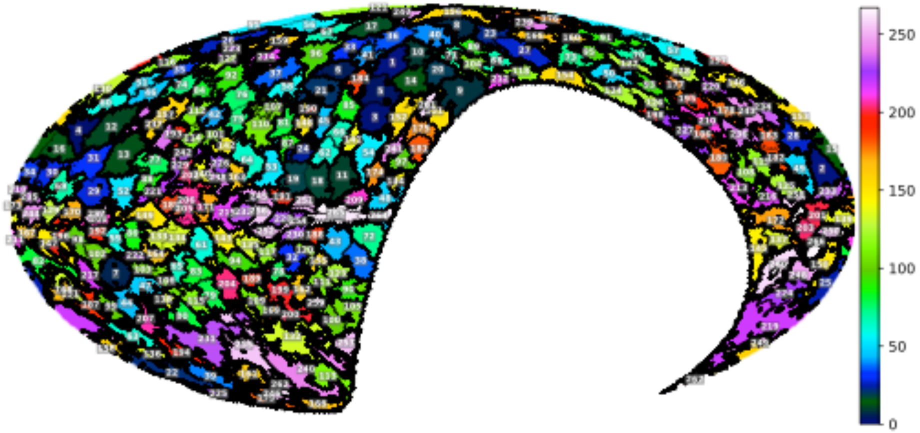
AME - λ Orionis

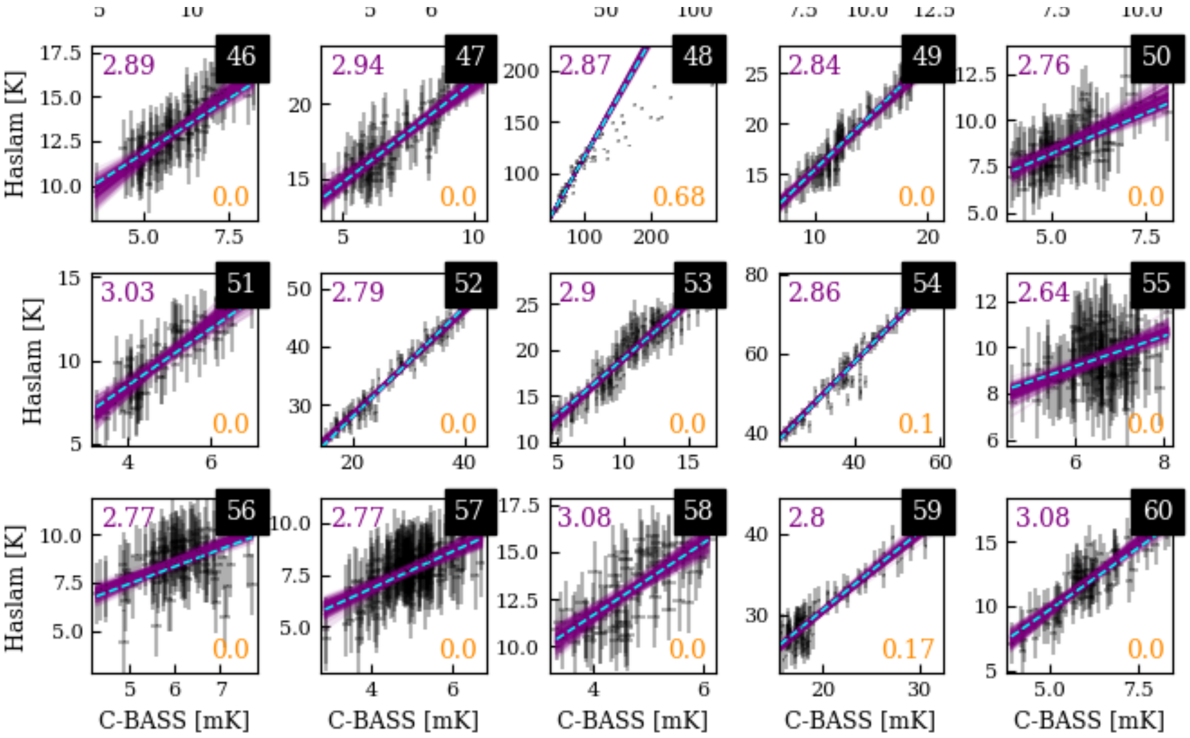


- Detection of spectral variations in AME in photodissociation region
- AME emissivity controlled by local radiation field
- AME peak frequency proportional to dust temperature
- First collaborative paper between C-BASS and QUIJOTE!
- Cepeda-Arroita et al imminient…

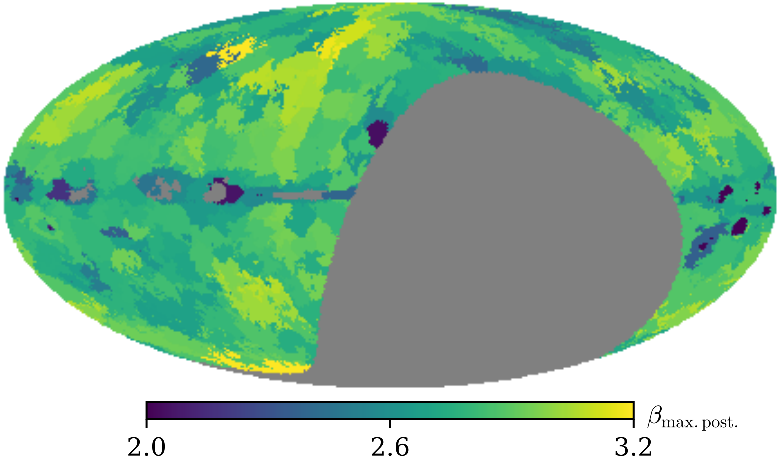
Intensity spectral indices

- Divide sky in to regions grouped by position in position, colour-colour space
- Fit TT scatter plots with unbiassed line-fitting with outliers.
- Returns spectral index in each region along with an indication of how complex spectrum actually is (outlier fraction)
- Jew et al in prep

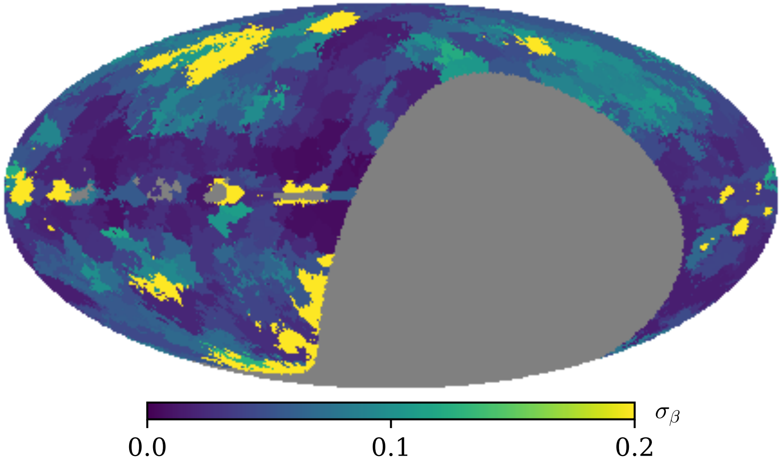




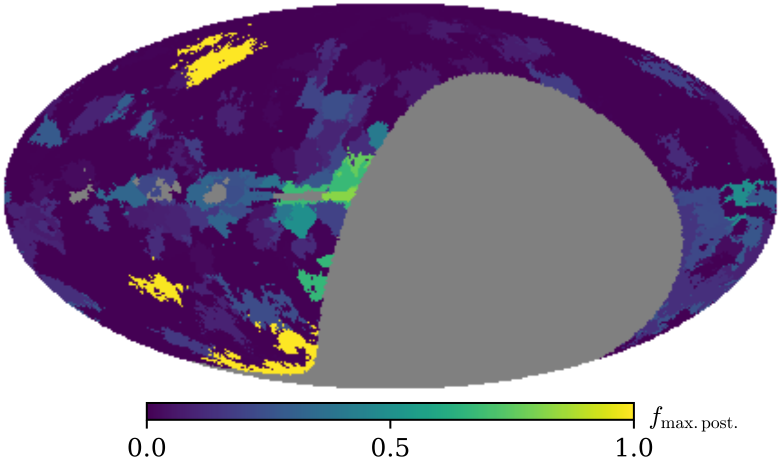
CBASS-Haslam spectra



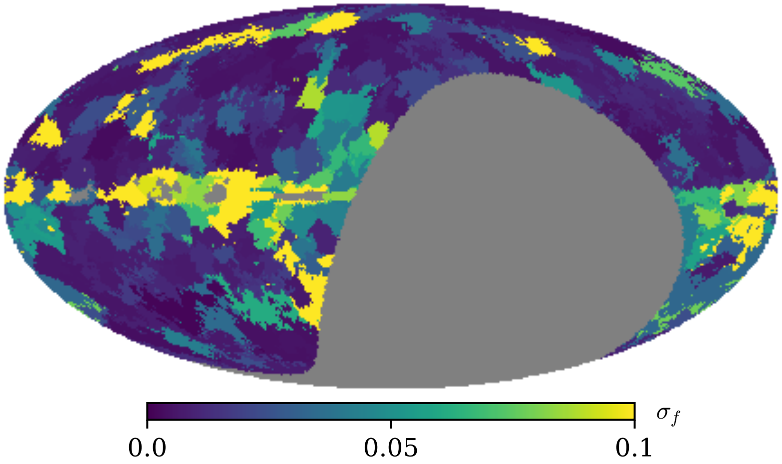
(a) Maximum posterior estimates of the Haslam/C-BASS spectral index.



(b) Standard deviation of the Haslam/C-BASS spectral index posterior distribution.

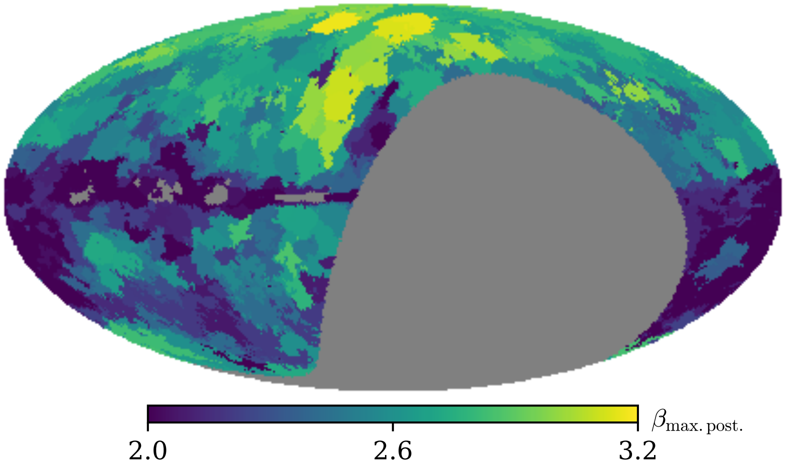


(c) Maximum posterior estimates of the Haslam/C-BASS outlier fraction.

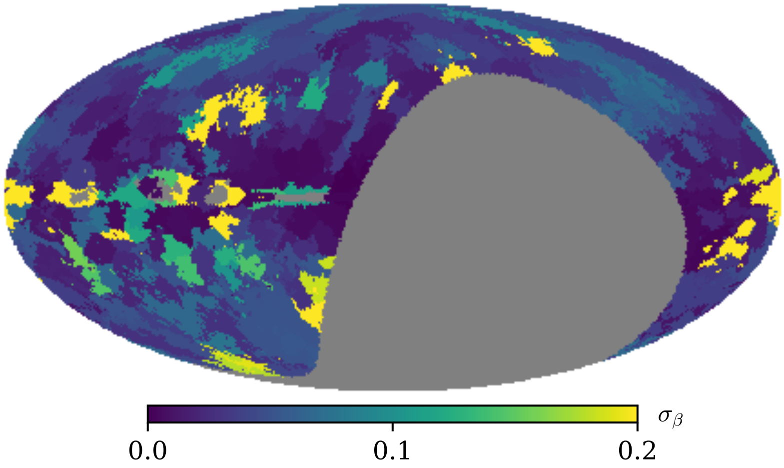


(d) Standard deviation of the Haslam/C-BASS outlier fraction posterior distribution.

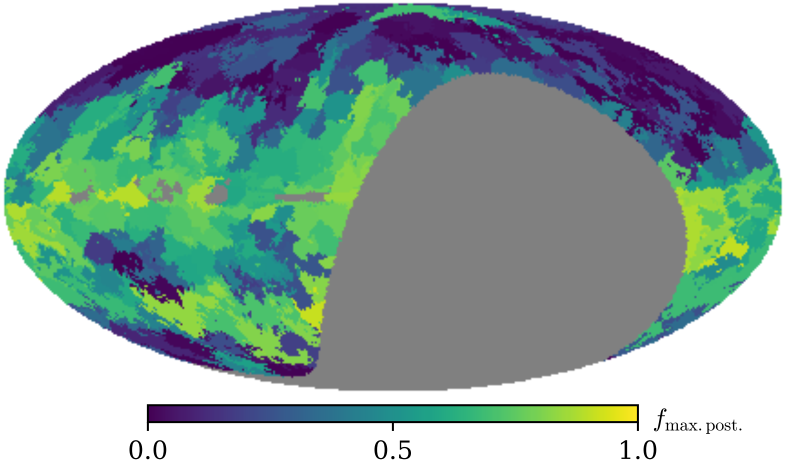
CBASS-WMAP K spectra



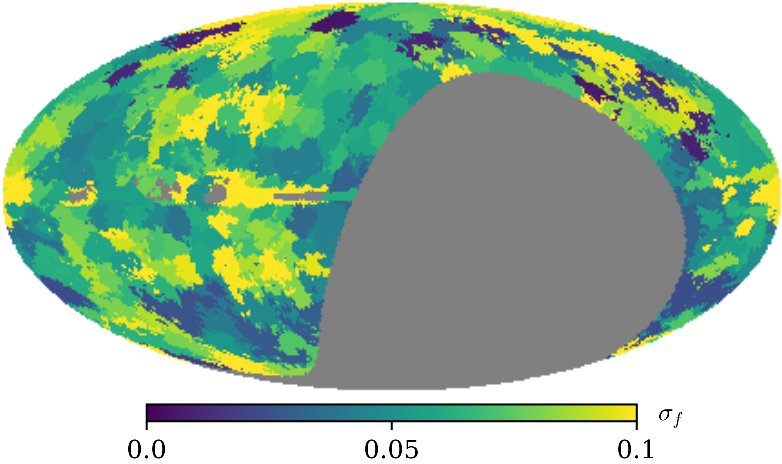
(e) Maximum posterior estimates of the C-BASS/*WMAP* spectral index.



(f) Standard deviation of the C-BASS/*WMAP* spectral index posterior distribution.

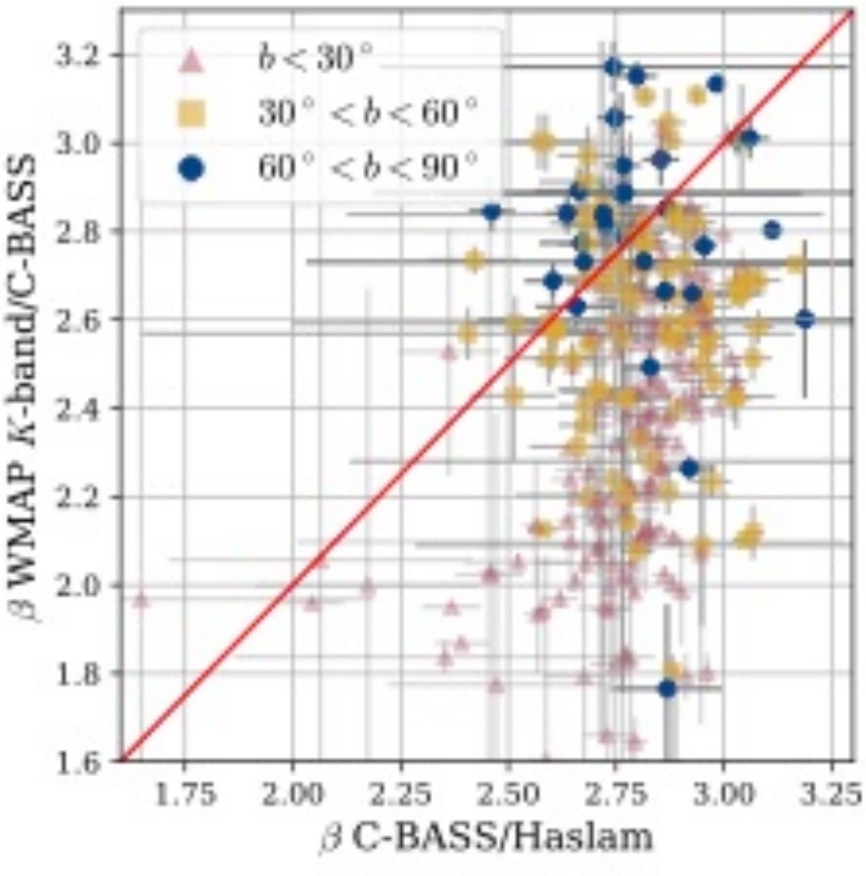


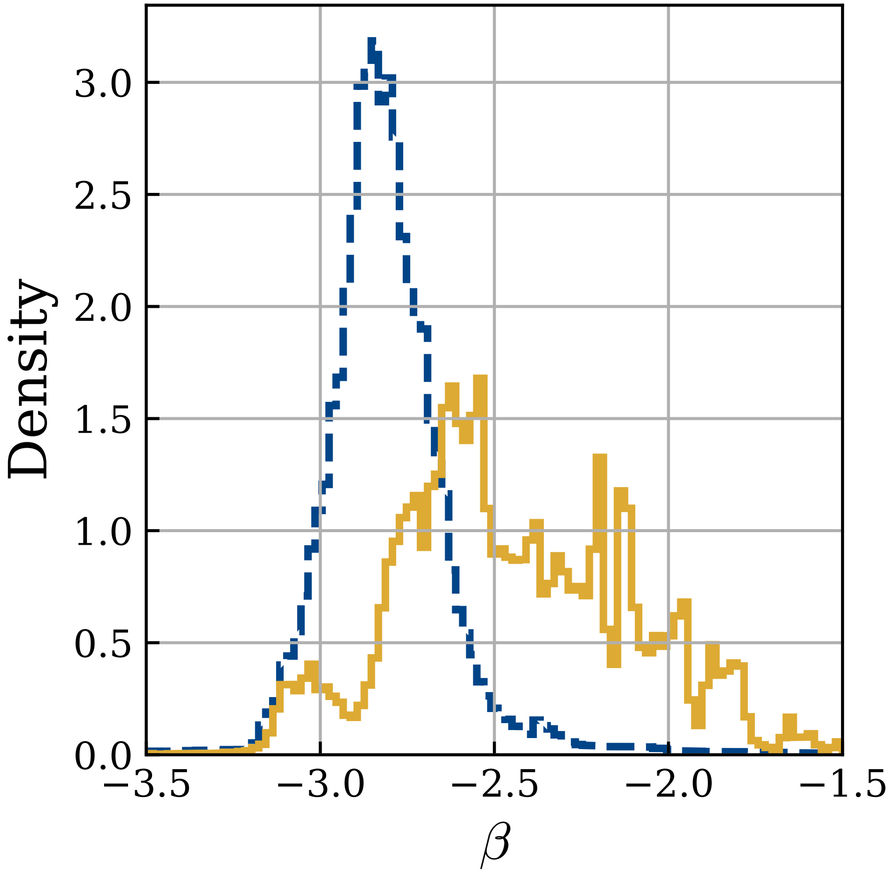
(g) Maximum posterior estimates of the C-BASS/*WMAP* outlier fraction.



(h) Standard deviation of the C-BASS/*WMAP* outlier fraction posterior distribution.

Intensity spectral indicies



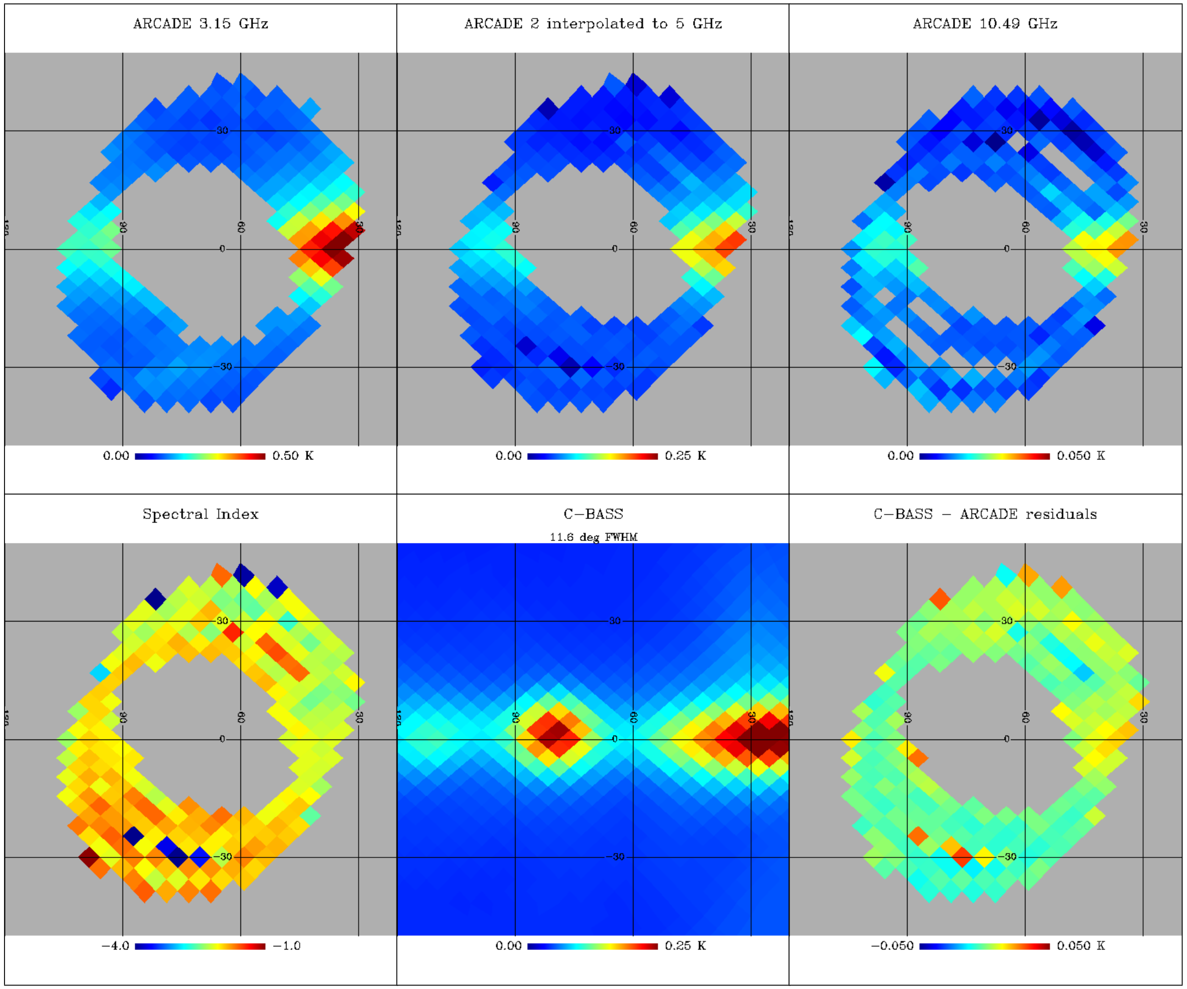


Haslam-C-BASS relatively simple story…higher frequencies much more complicated! Currently running COMMANDER analysis with Oslo group. Also working on new component separation method, No-U-Turn sampler and hierarchical fitting – see Richard Grummit poster.

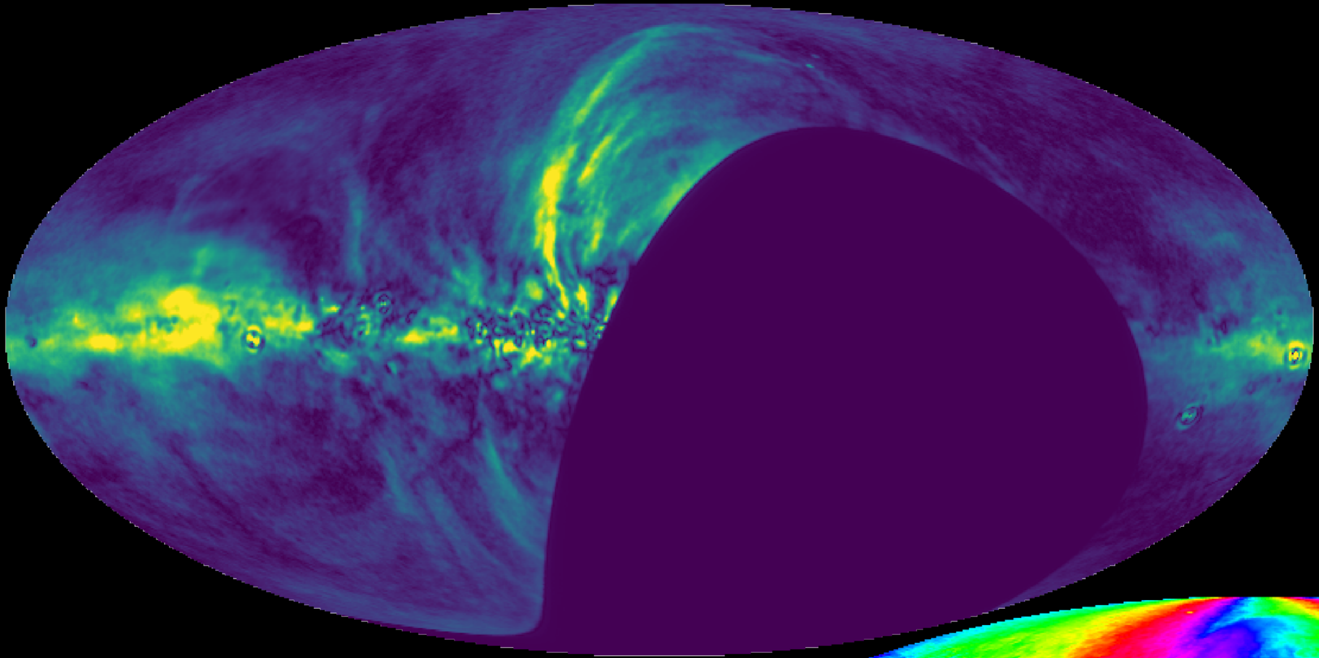
Zero level from Arcade

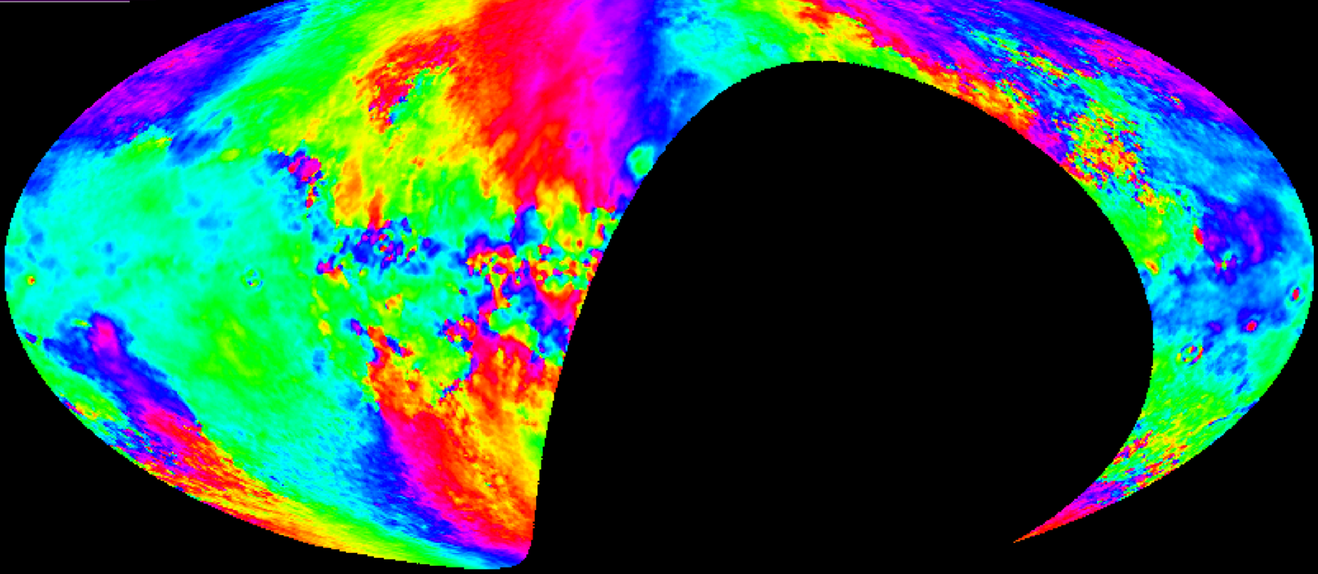
Need zero level of I map for component fitting (zero level of raw map is arbitrary)

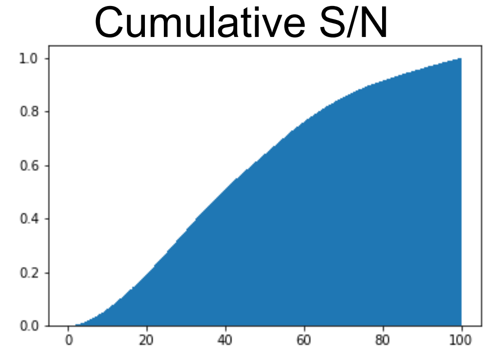
- Fit power law to Arcade2 data – 3.15,3.41,8.33, 9.72, 10.49 GHz data
- Fit C-BASS offset to match interpolated 4.76 GHz map
- Dipole subtracted gives better fit!
- Minimum brightness of fitted map is 31.8 mK cf integrated source counts ~4mK
- Likely due to diffuse local Galactic emission.



CBASS-N *P*



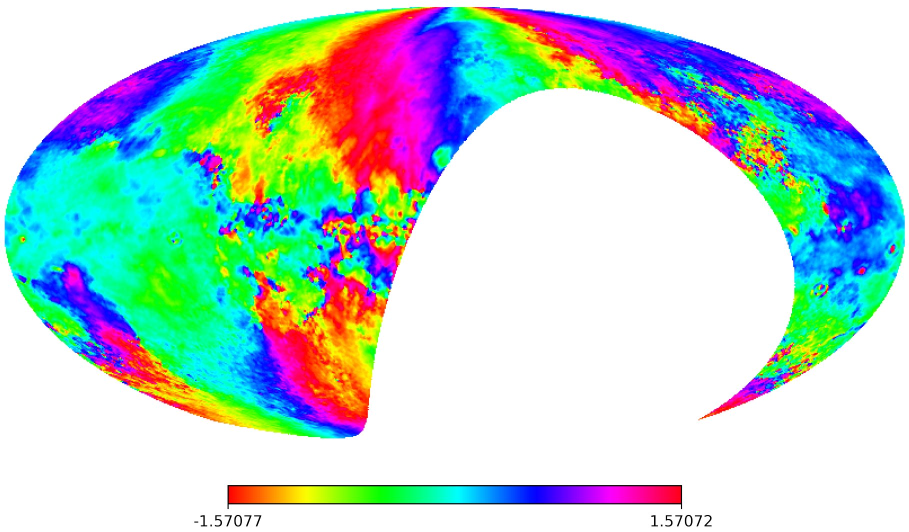




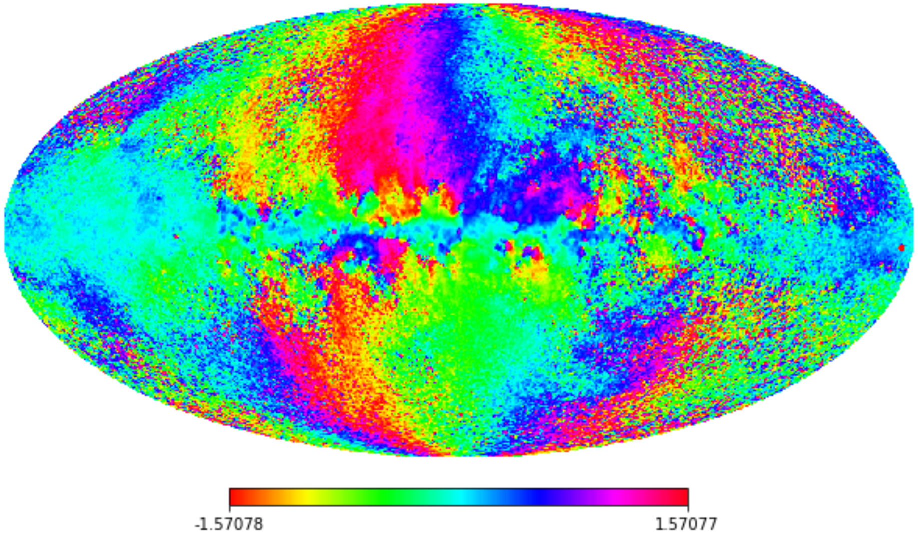
Taylor et al in prep

Polarization angles

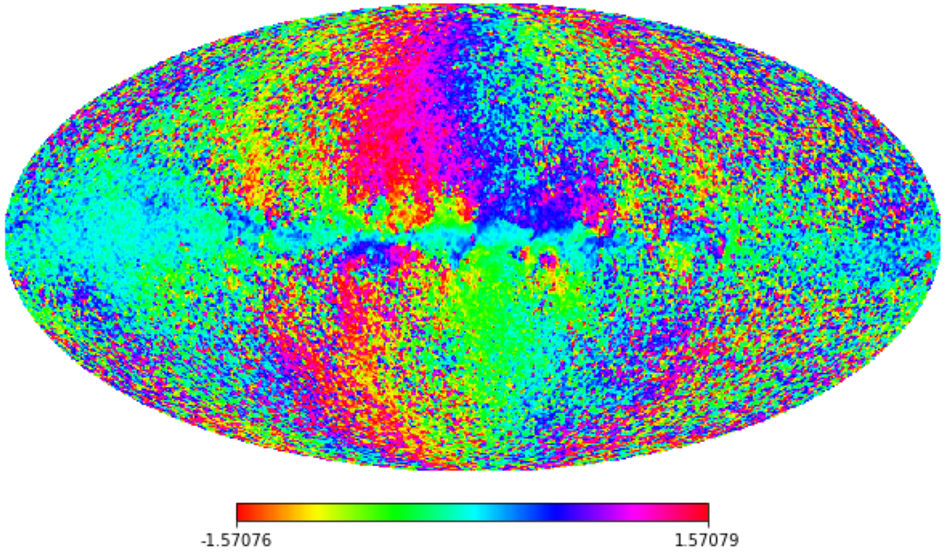
CBASS Pol Angle



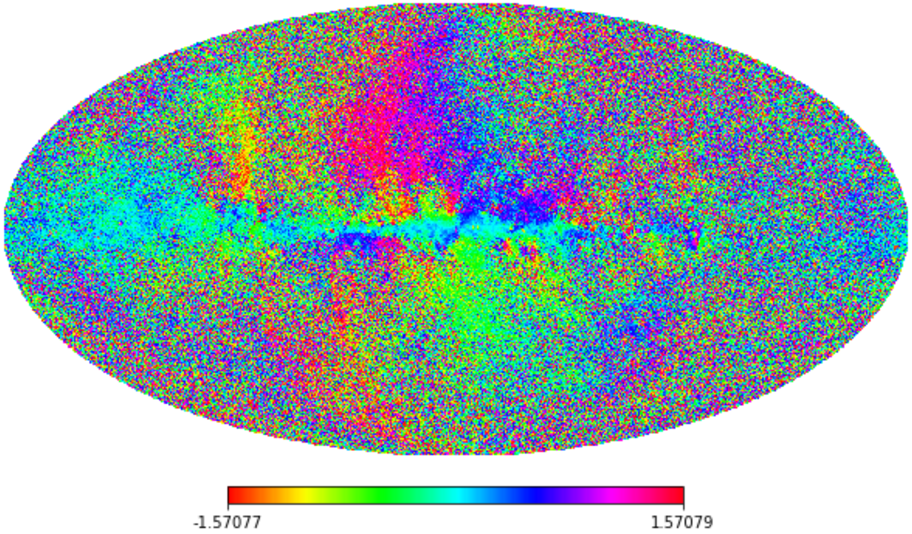
WMAP K Pol Angle



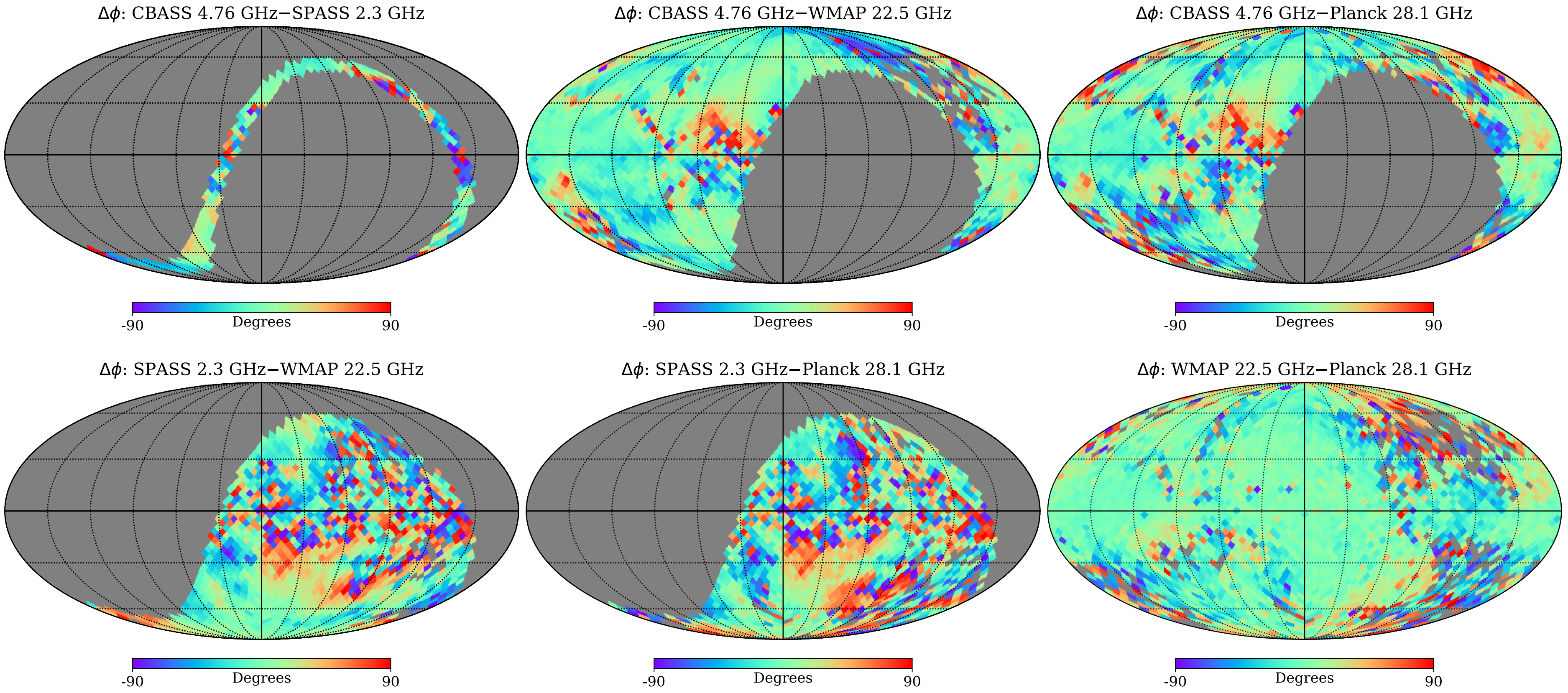
WMAP Ka Pol Angle



Planck 30 Pol Angle



Pol angle comparison


$\Delta\phi$: CBASS 4.76 GHz−SPASS 2.3 GHz

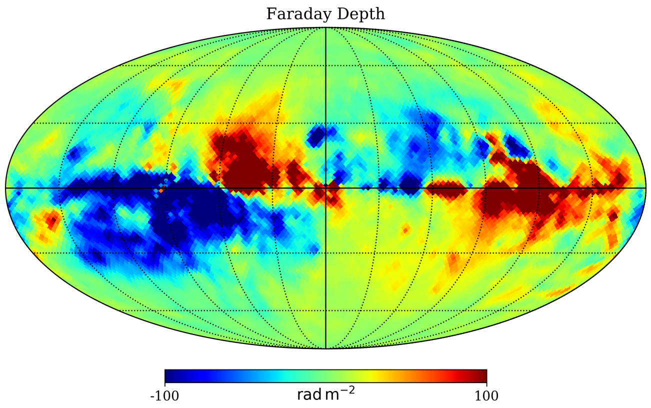
$\Delta\phi$: CBASS 4.76 GHz−WMAP 22.5 GHz

$\Delta\phi$: CBASS 4.76 GHz−Planck 28.1 GHz

$\Delta\phi$: SPASS 2.3 GHz−WMAP 22.5 GHz

$\Delta\phi$: SPASS 2.3 GHz−Planck 28.1 GHz

$\Delta\phi$: WMAP 22.5 GHz−Planck 28.1 GHz


Faraday Depth

Faraday depth (from Hutschenreuter & Enblin 2019)
100 rad/m2 = 22 deg at C-BASS frequency

Dickinson et al in prep

Spectral index fitting

Fitting in polarized intensity *P* : C-BASS vs WMAP K, WMAP Ka, Planck 30

2-parameter model: $T_{RJ} = A\,(\nu/\nu_0)^{\beta}$, brute-force search of reasonable grid of *A*, β.
Likelihood is Rician:

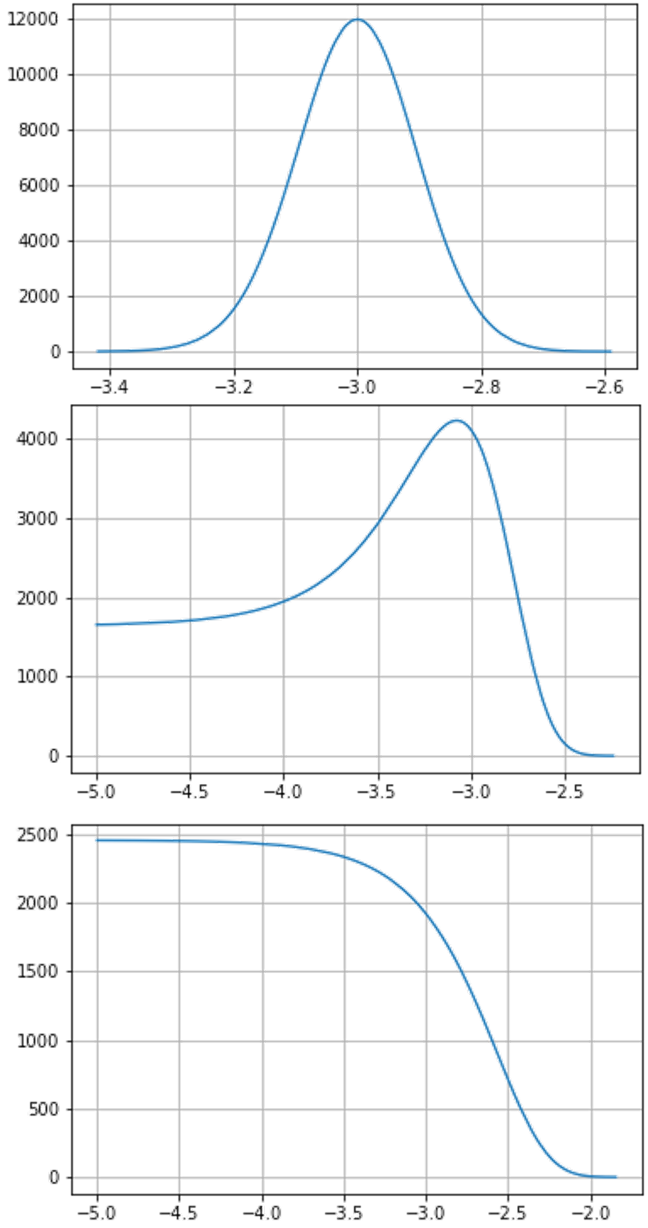
$$f(x \mid \nu, \sigma) = \frac{x}{\sigma^2} \exp\left(\frac{-(x^2+\nu^2)}{2\sigma^2}\right) I_0\left(\frac{x\nu}{\sigma^2}\right)$$

Prior is Jeffries (see Jew et al 2019):

$$\beta_{\mathrm{s}} \qquad \propto \sqrt{\sum_i \left(\frac{1}{\sigma_i}\frac{s_{\mathrm{s},i}}{A_{\mathrm{s}}}\log(\frac{\nu_i}{\nu_0})\right)^2}$$

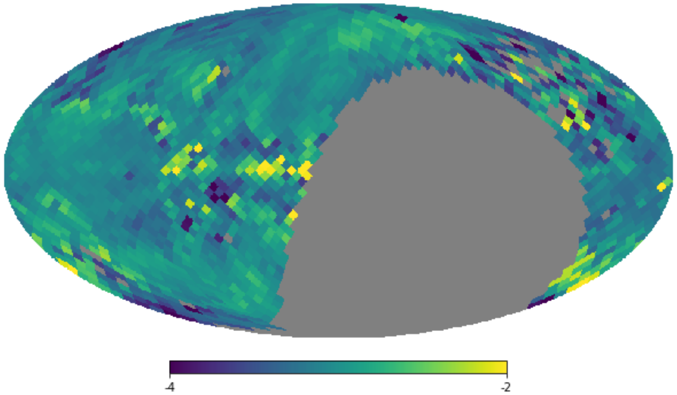
Marginalize over *A* to get 1–d posterior distribution of β

Caution!! Low signal-to-noise results in skewed/unbounded posteriors – cannot interpret these as $x \pm y$. Posteriors with no peak are undefined in following maps.

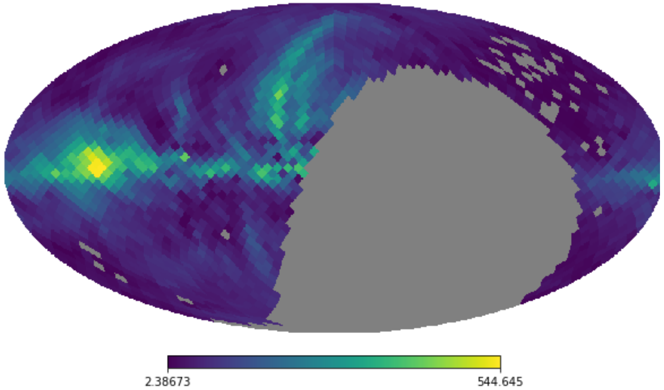


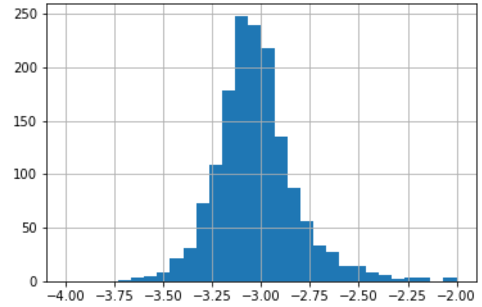
Polarized spectral indices 5 - 30 GHz

Spectral index CBASS-WMAP K

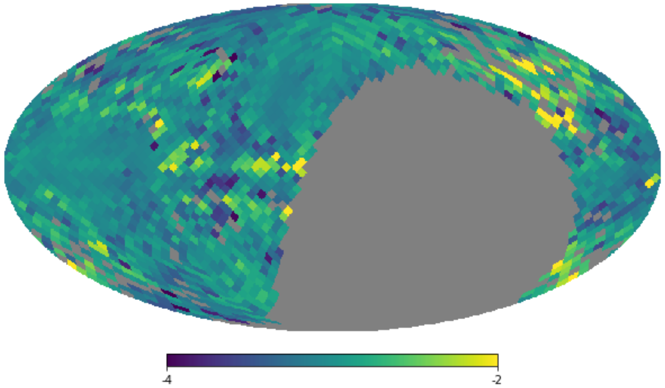


Mollweide view

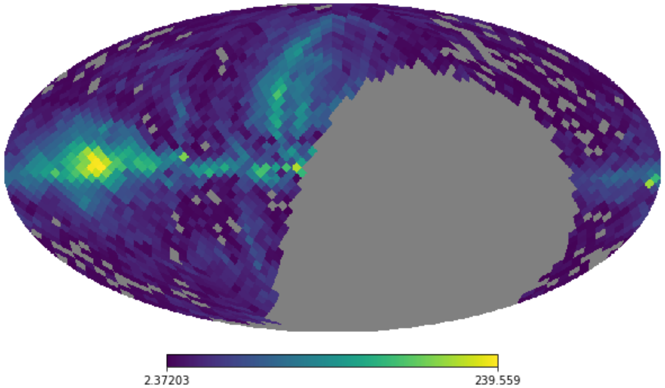


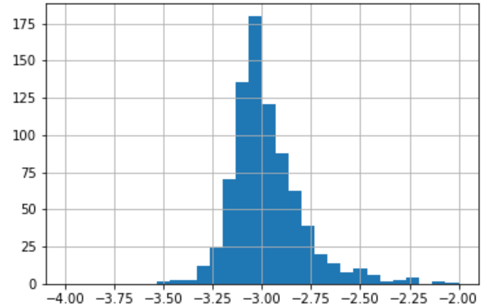


Spectral index CBASS-WMAP Ka

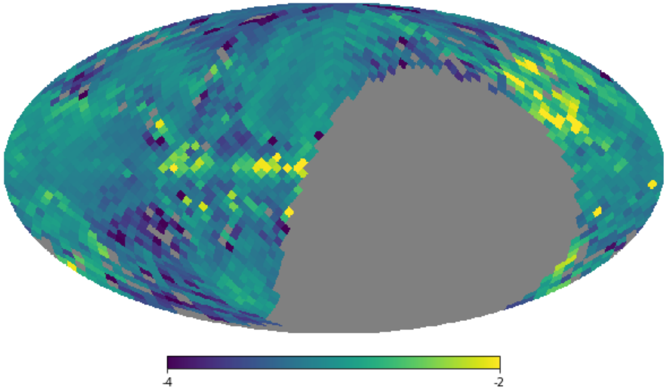


Mollweide view

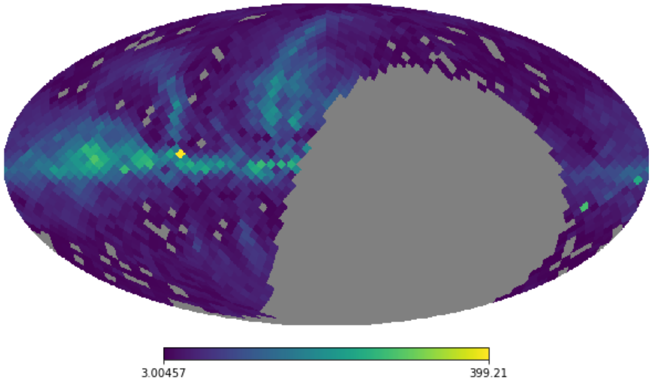


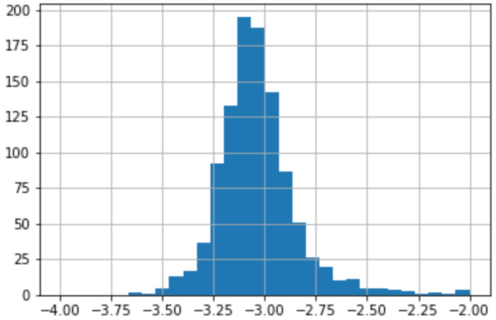


Spectral index CBASS-Planck30

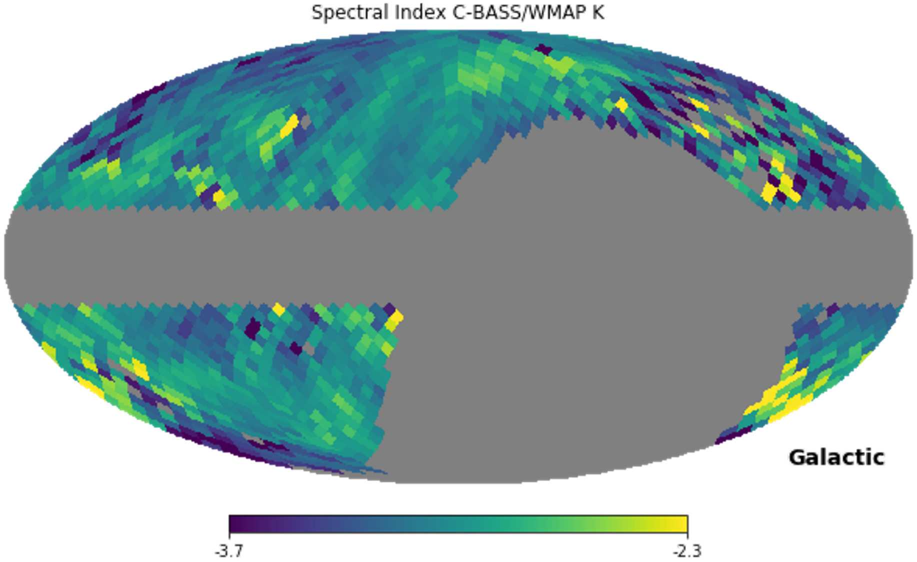


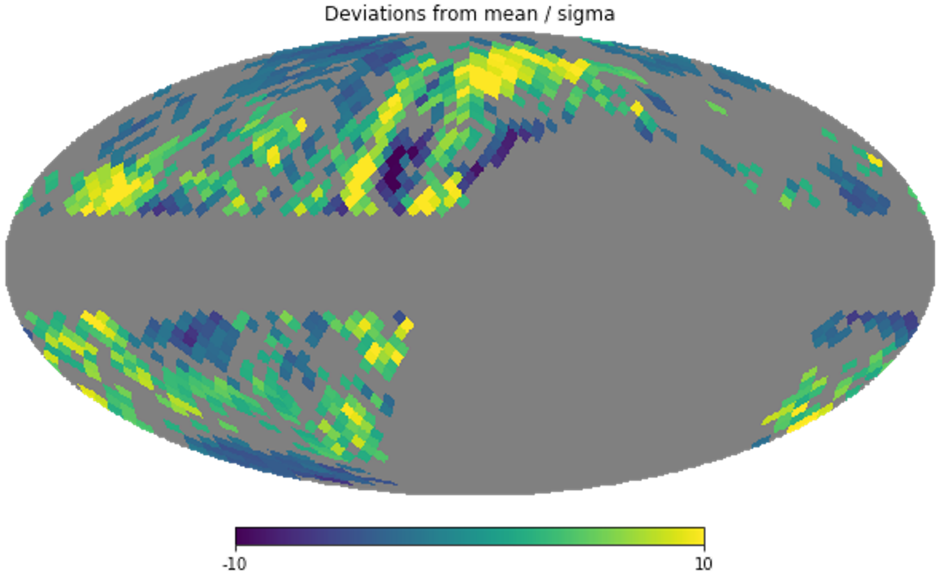
Mollweide view

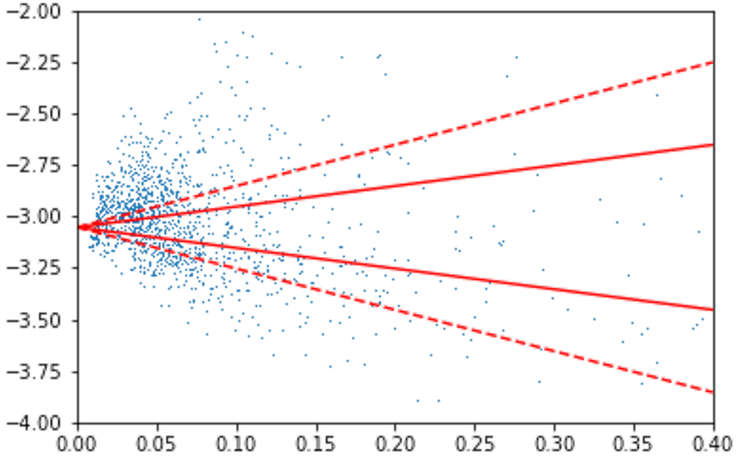


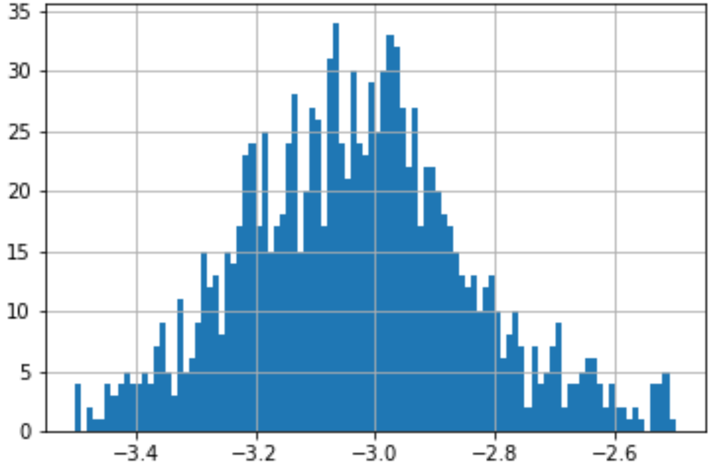


Real variations in polarized β (1)



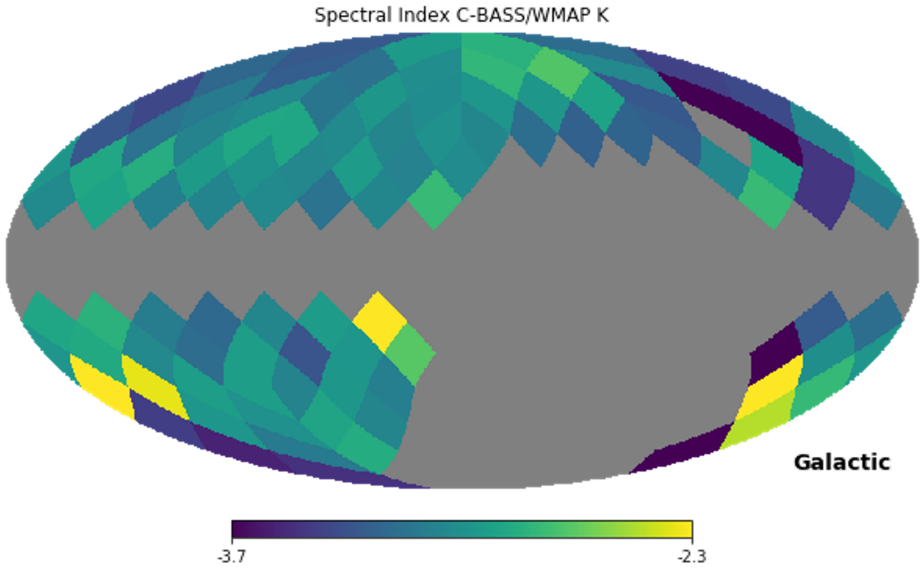


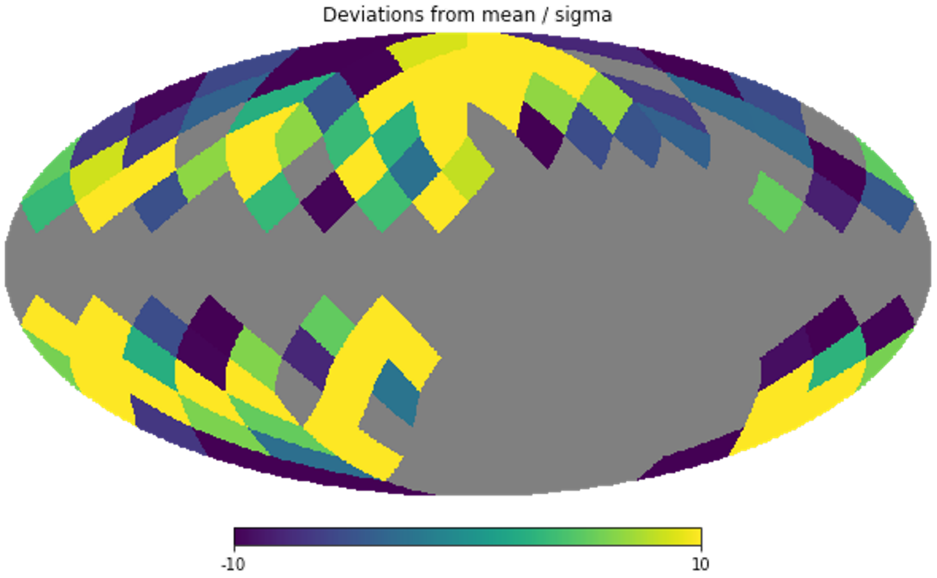


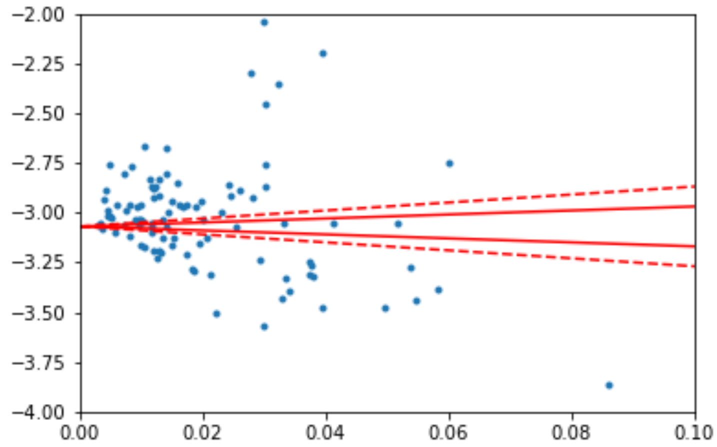


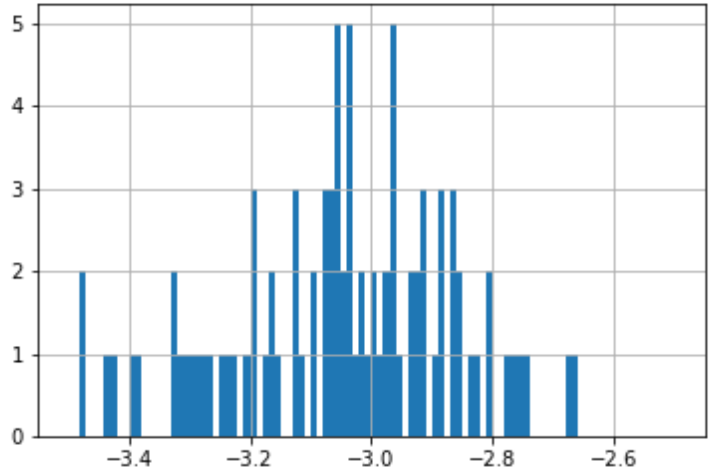
Distribution of β vs error on β - Dashed lines indicate 1-, 2-σ deviations from mean. Histogram only of points with Δβ < 0.1

Real variations in polarized β (2)



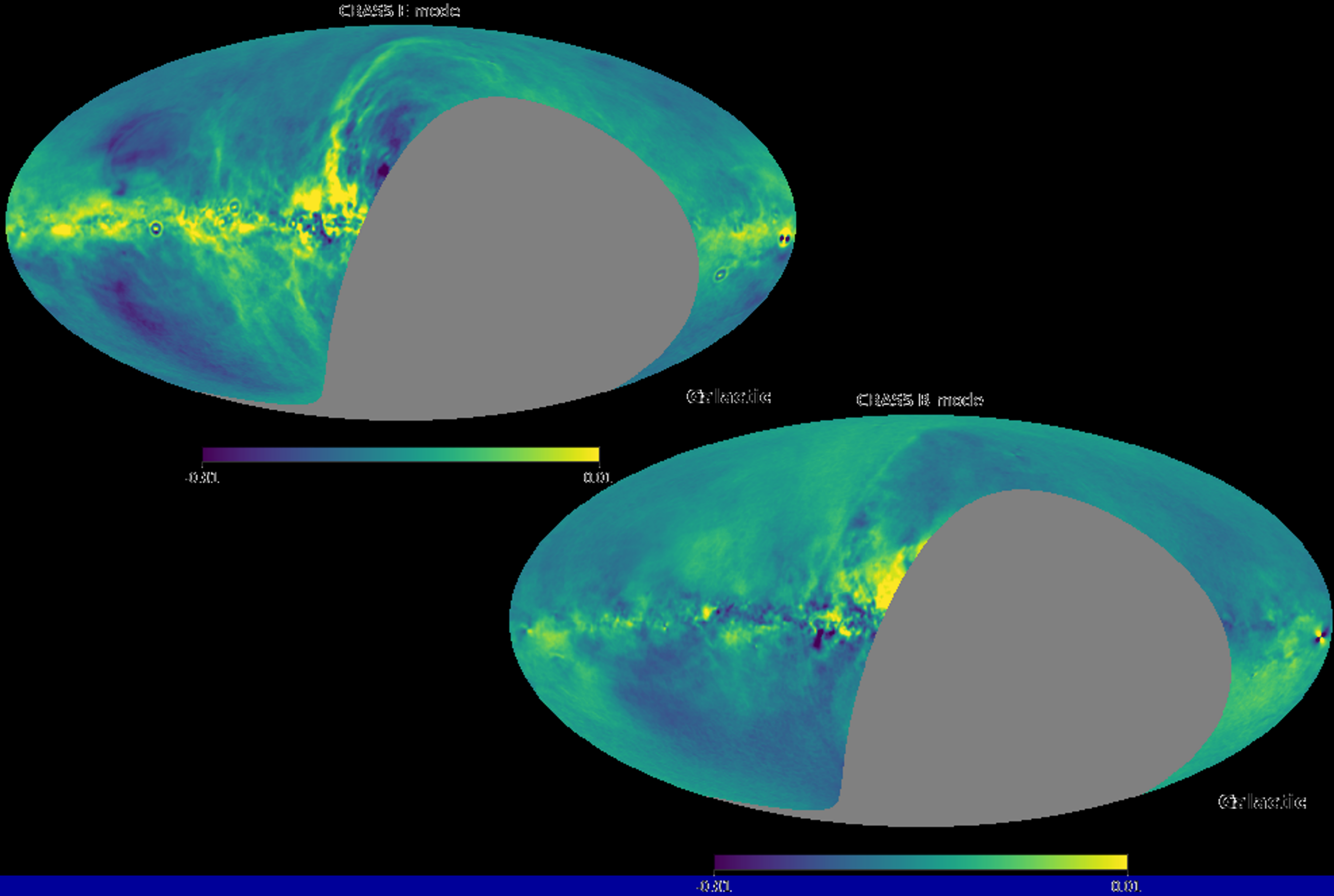




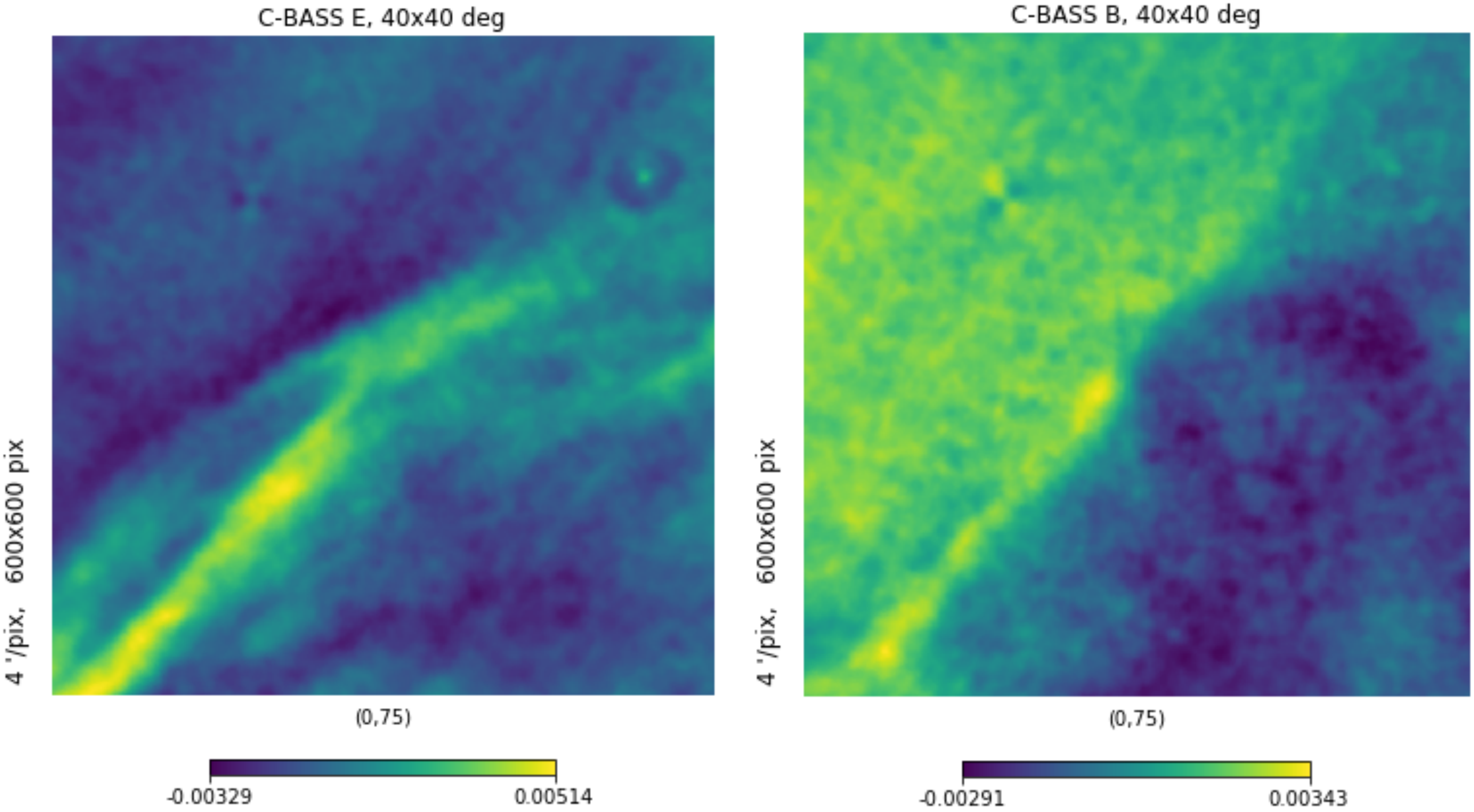


Downgraded maps of β, σ_β – variations >> σ_β on large scales

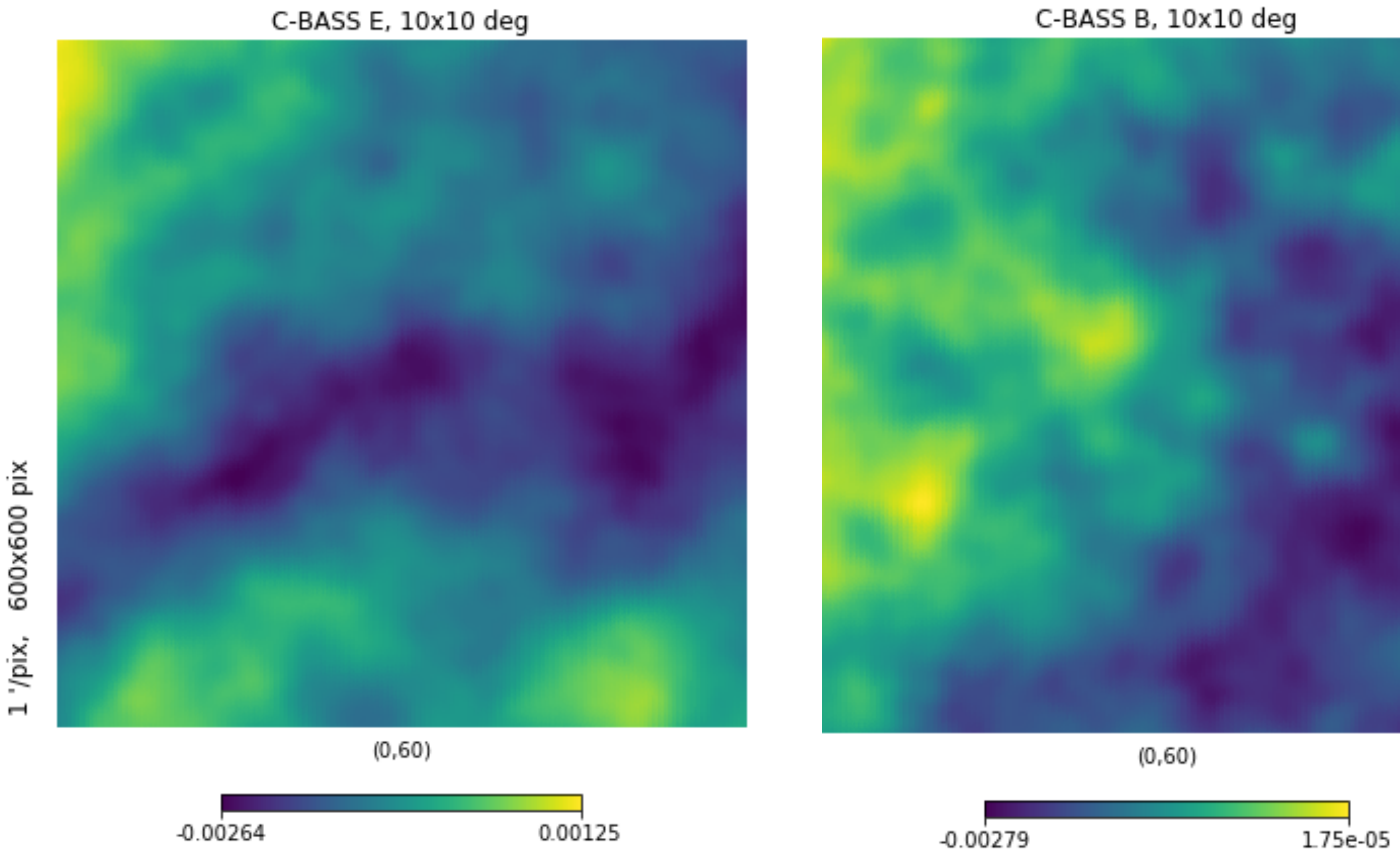
CBASS *E* and *B*


CBASS E mode
Galactic
-0.001
0.001
CBASS B mode
Galactic
-0.001
0.001

CBASS *E* and *B*

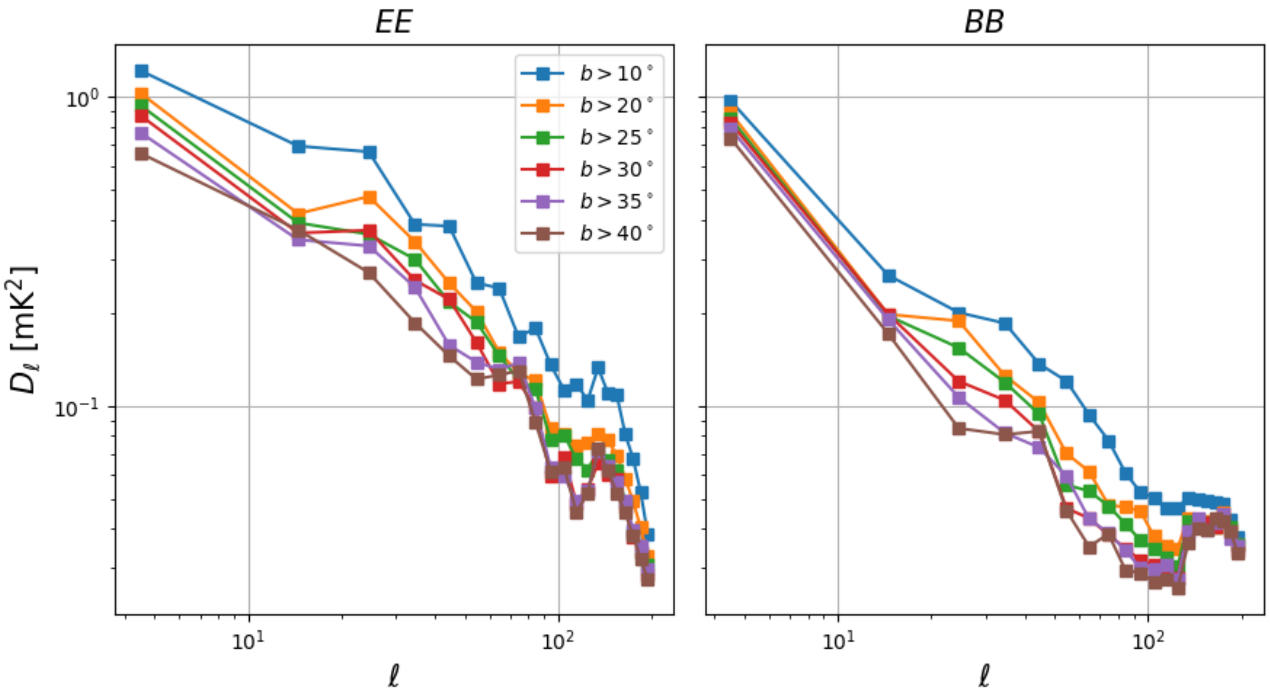

C-BASS E, 40x40 deg
4 '/pix, 600x600 pix
(0,75)
-0.00329
0.00514
C-BASS B, 40x40 deg
4 '/pix, 600x600 pix
(0,75)
-0.00291
0.00343

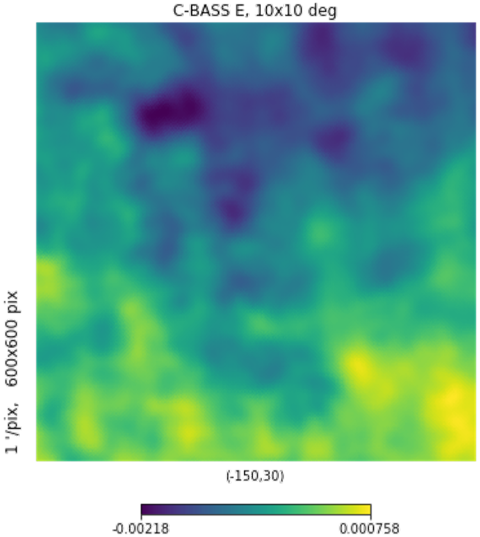
CBASS *E* and *B*

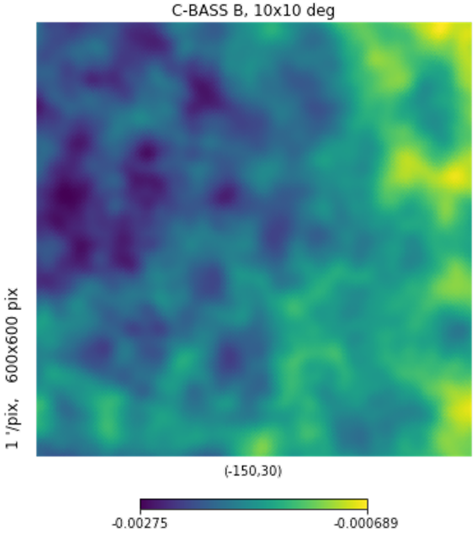

C-BASS E, 10x10 deg
1 '/pix, 600x600 pix
(0,60)
-0.00264
0.00125
C-BASS B, 10x10 deg
(0,60)
-0.00279
1.75e-05

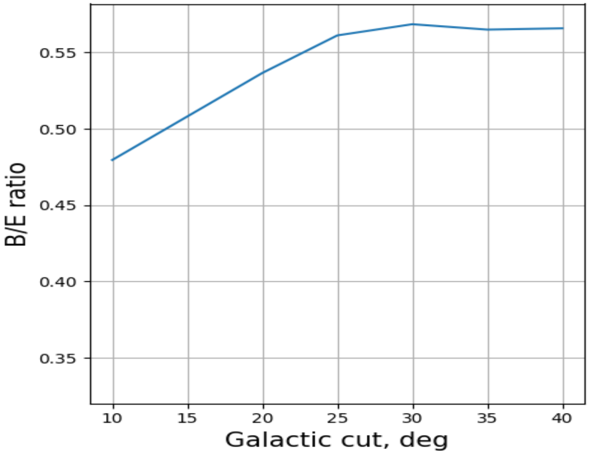
E and *B* power spectra

- More power in *E* than *B*
- Overall amplitude ratio weak function of Galactic latitude
- Powers converge at high *l* (and look much more gaussian)

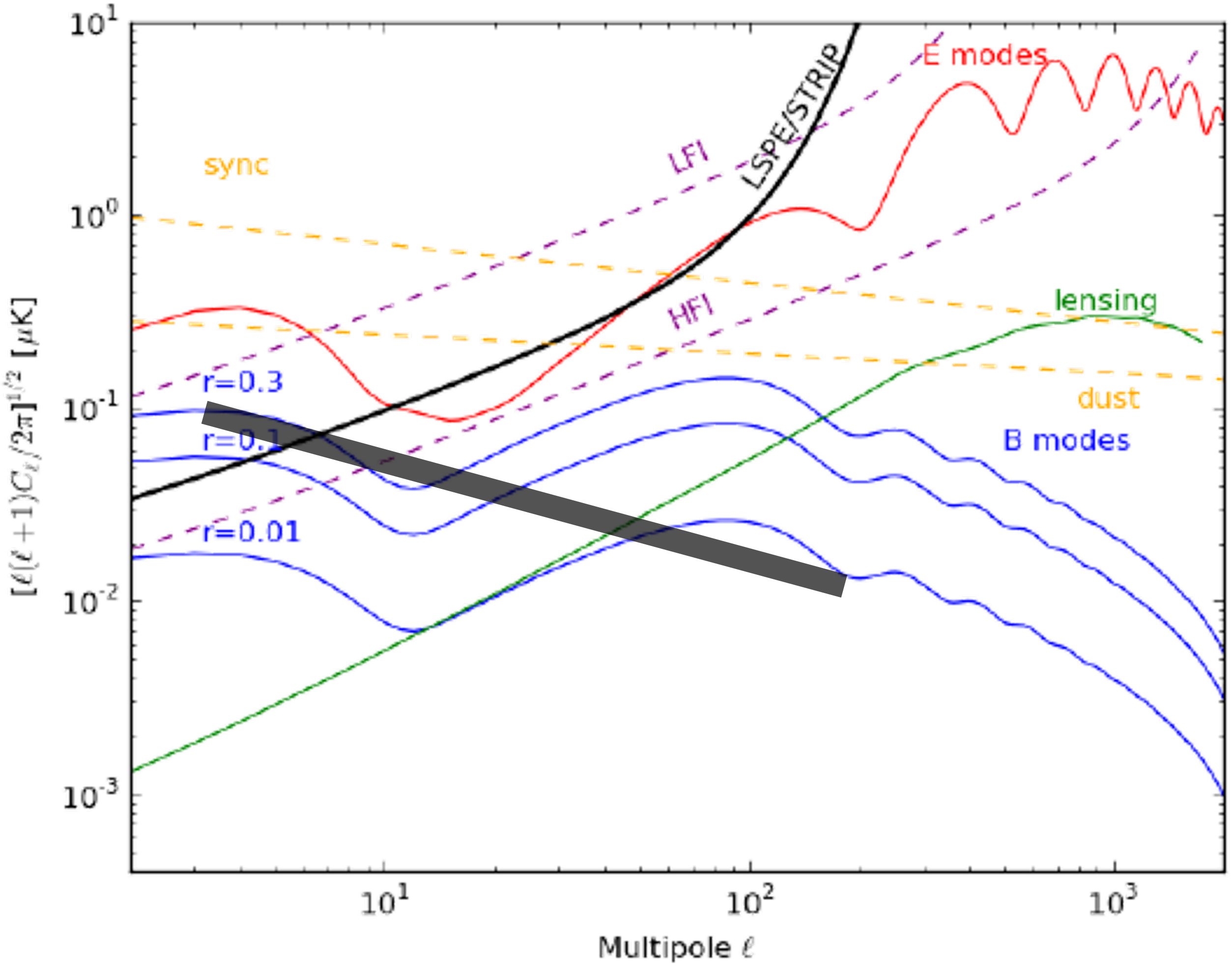






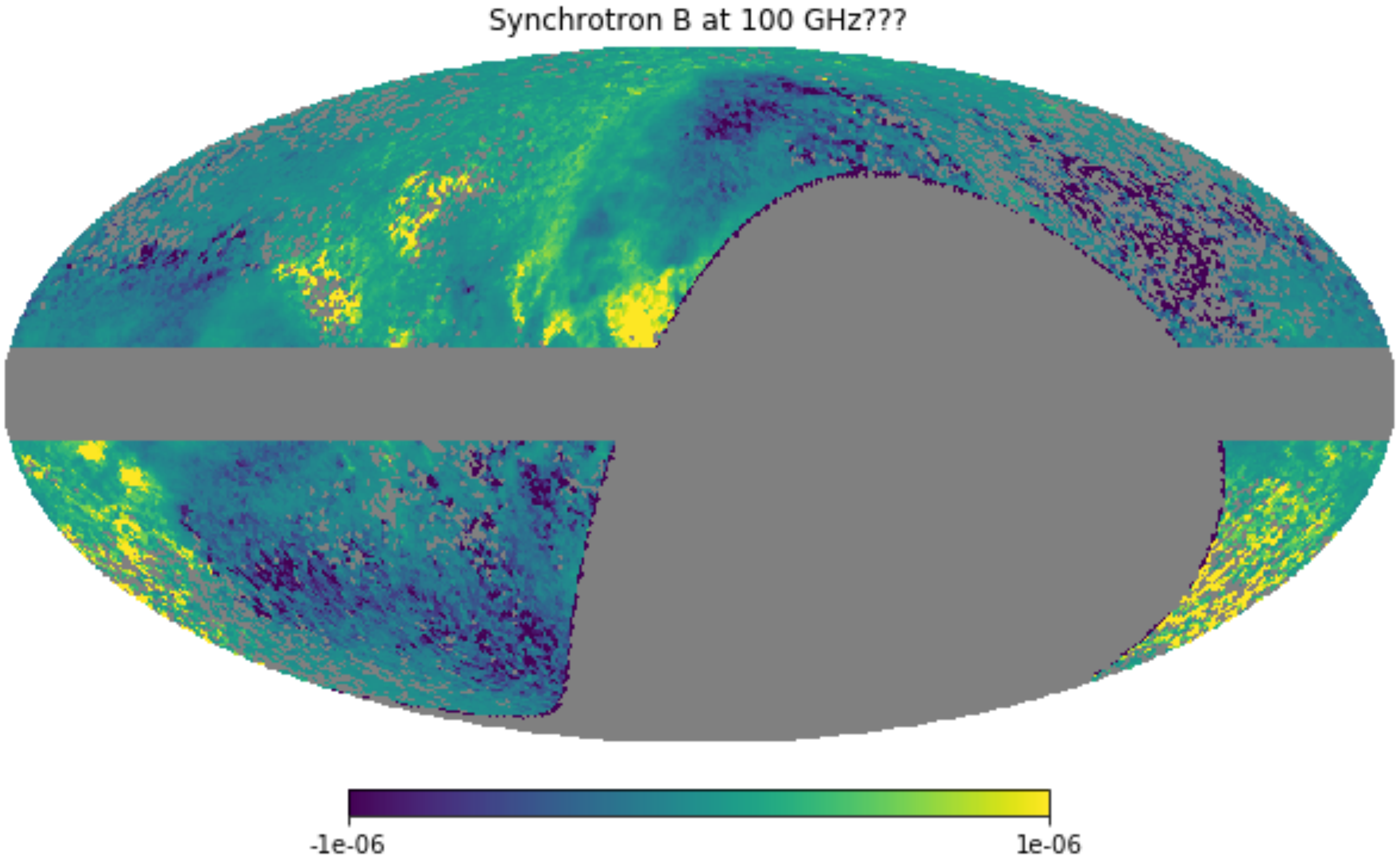


B power spectrum at 100 GHz



- Extrapolate this B spectrum to 100 GHz using β = 3.0…

B map extrapolated to 100 GHz



C-BASS B map exptrapolated using C-BASS-WMAP K spectral index map
Errors not trivial and not properly worked out…so no power spectrum of this yet!

CBASS - status

- Northern data pipeline/mapping complete
- First set of data papers using all Northern data in next few months
- Public data release shortly after papers, but still keen to work directly with other groups with complementary data/analysis tools.
- Southern survey happening now – 1-2 yrs data taking expected in south
- Full data release once surveys completed and combine.

Beyond CBASS…

- Adding C-BASS data to current experiments can constrain straight synchrotron spectra…but not curved (see Jew et al 2019 MNRAS 490, 2958)
- QUIJOTE will help…but for equivalent sensitivity at ~30 GHz need ~100 pixels…
- …ideally in north and south on ~6-m telescopes
- Hence – ELFS: European Low-Frequency Survey.

See https://indico.in2p3.fr/event/19414/contributions/73920/

ERC Synergy Proposal – ELFS-South

- First/most important step in ELFS: 5-m telescope in South with 100-element array 20-30 GHz, ~10 elements 10-20 GHz, 1 element 5-10 GHz
- Site alongside Simons Observatory for maximum synergy/collaboration in operations and science exploitation
- Budget €14M, proposal Nov 2019, decision October 2020, start Jan 2021, start observations 2024, finish Dec 2026
- Telescope potentially available for CMB-S4 low-frequency after 2026
- ERC project limited to 4 PIs (Mennella, Milan; Baccigalupi, SISSA; Rubino-Martin, IAC; Jones, Oxford) but wider ELFS concept is open

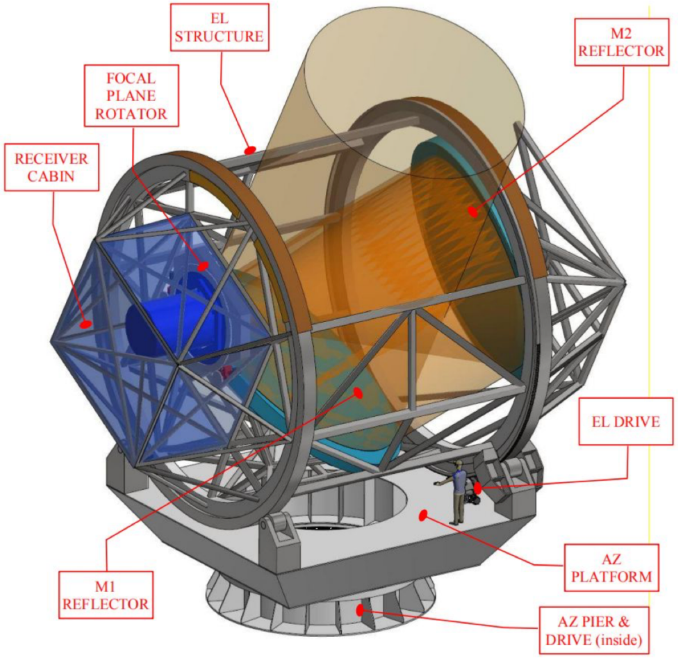


Fig 1: Possible implementation of the ELFS-S 10-30 GHz telescope