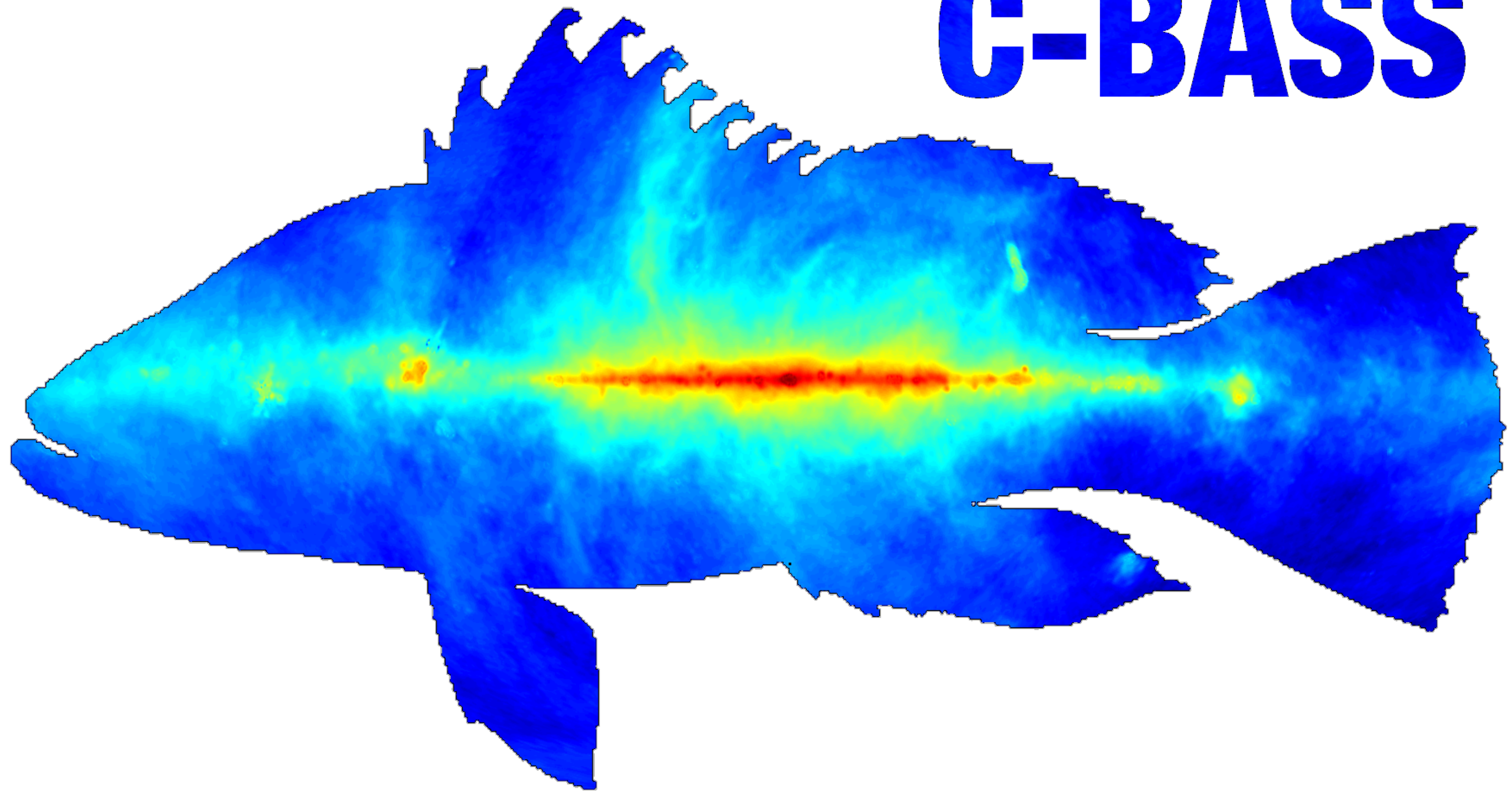
C-BASS



Synchrotron spectral index in total intensity and polarization

UNIVERSITY OF OXFORD

Luke Jew

https://cbass.web.ox.ac.uk/

C-BASS Collaboration

University of Oxford
Richard Grumitt
Jaz Hill-Valler
Luke Jew
Mike Jones
Jamie Leech
Alexander Pollak
Angela Taylor

University of Manchester
Adam Barr
Roke Cepeda-Arroita
Clive Dickinson
Stuart Harper
Paddy Leahy
Mike Peel (Now at Universidade de São Paulo)

Caltech
Tim Pearson
Tony Readhead

South Africa
Moumita Aich (UKZN)
Cynthia Chiang (UKZN/McGill)
Heiko Heilgendorff (UKZN)
Justin Jonas (SKA-SA/Rhodes University)
Sizwe Seranyane (SKA-SA)
Jon Sievers (UKZN/McGill)

KACST
Yaser Hafez

1. C-BASS Data

2. T-T Plots

3. Polarized Spectral Index

1. C-BASS Data

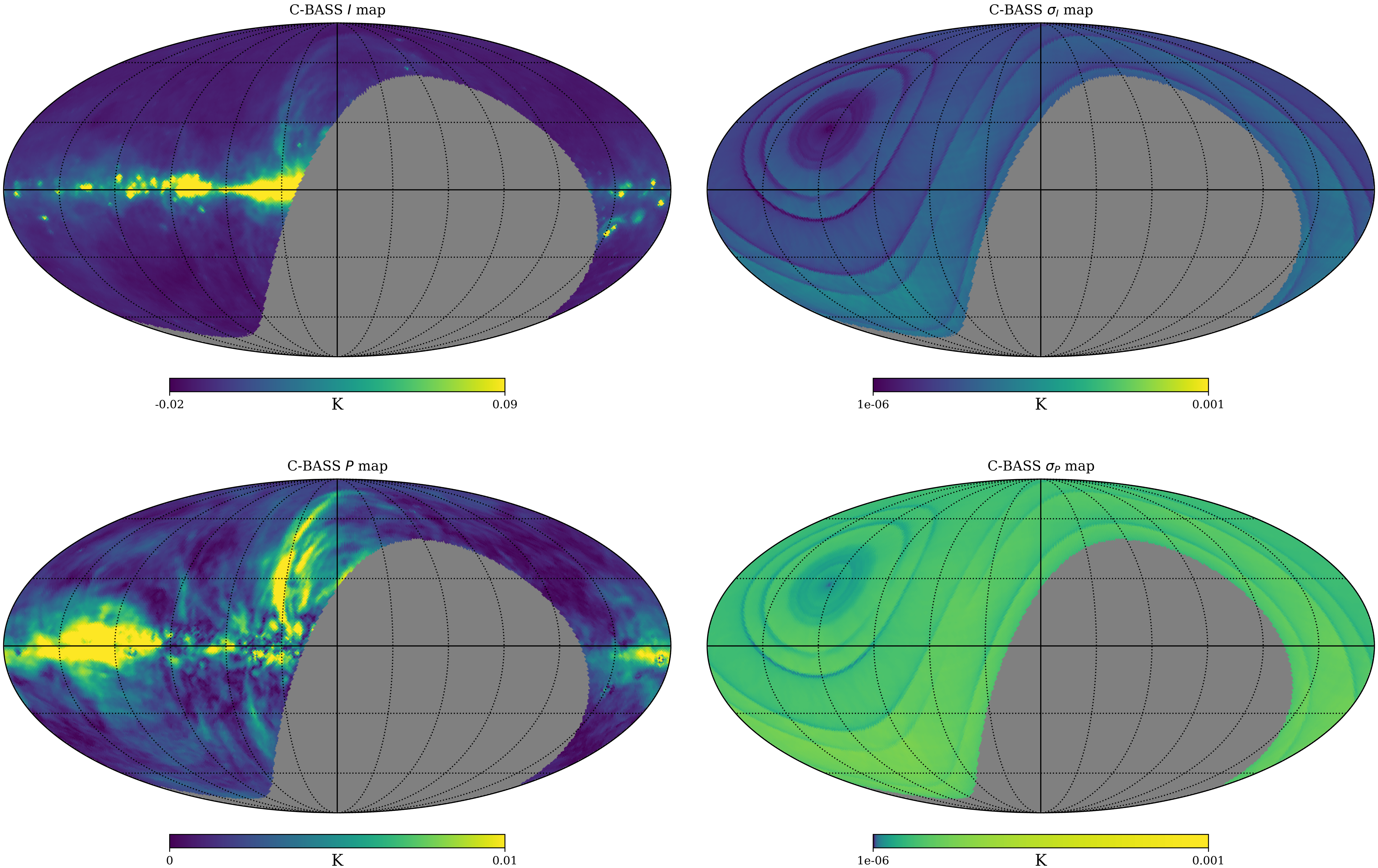
2. T-T Plots

3. Polarized Spectral Index

1. C-BASS Data

See Angela Taylor's Talk

Nside 64 maps
Beam deconvolved and smoothed to 1 degree



1. C-BASS Data

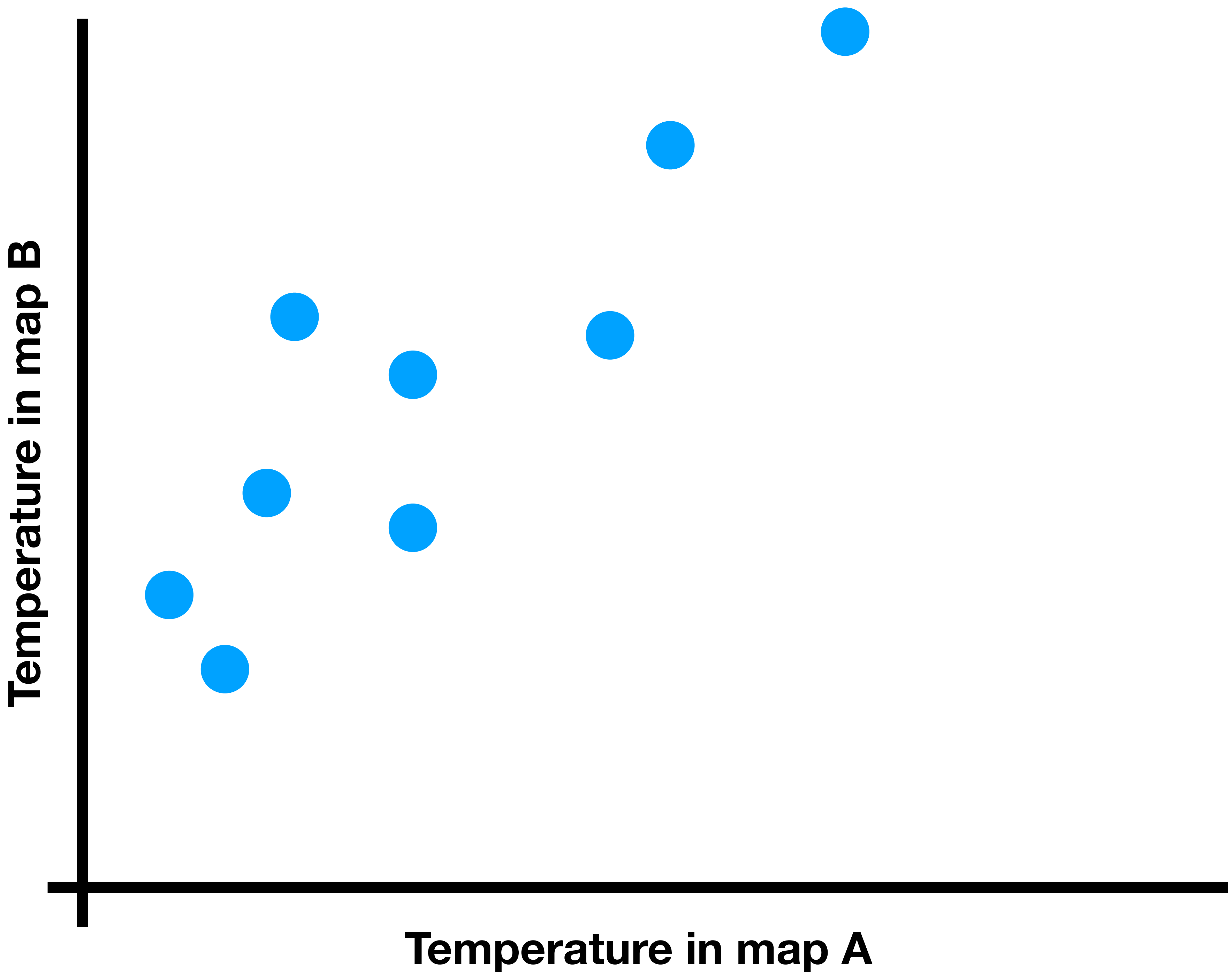
2. T-T Plots

- Clustering algorithm
- Line fitting
- Results

3. Polarized Spectral Index

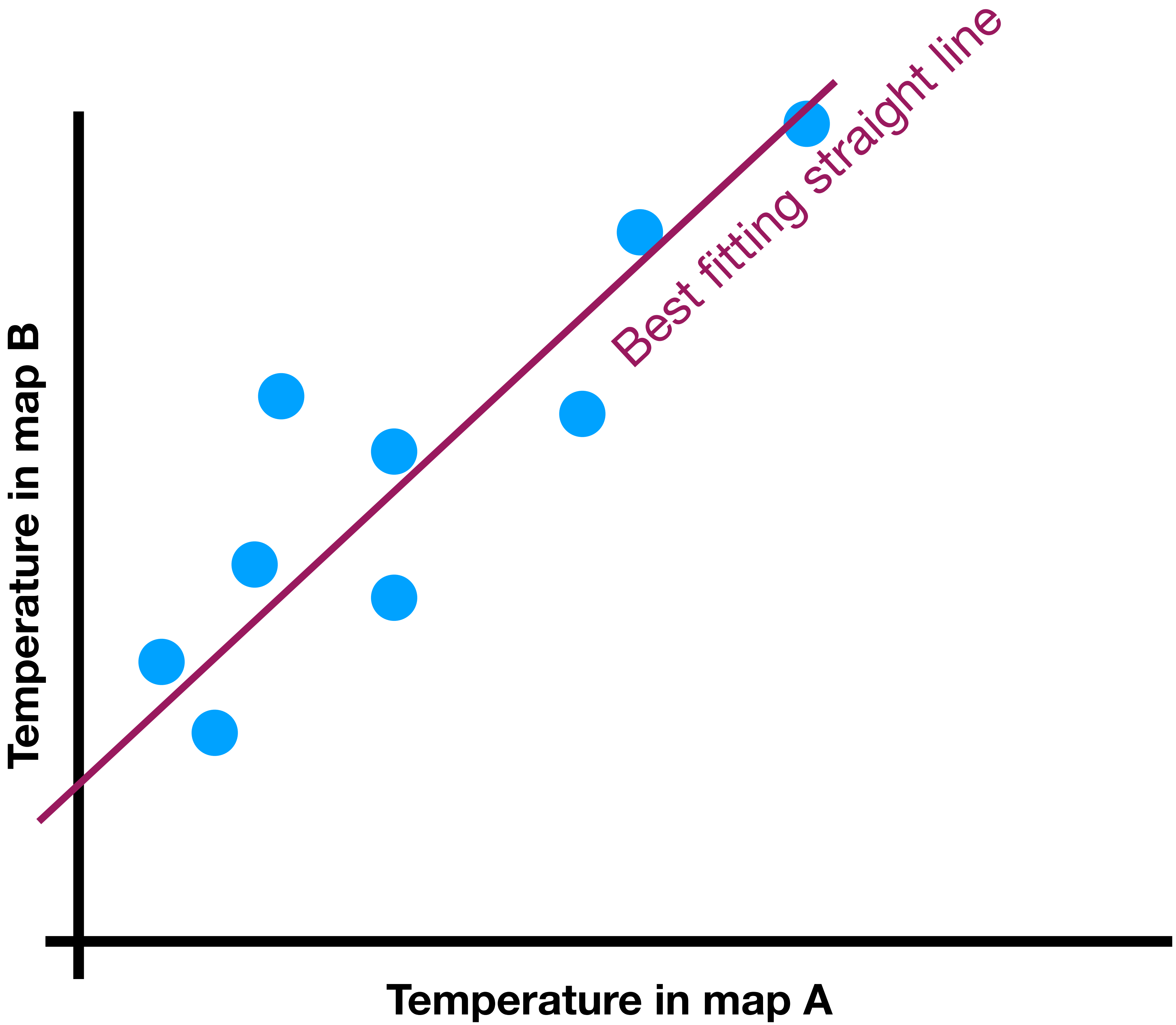
2. T-T Plots

Select a region dominated by a emission with a power law frequency-spectrum



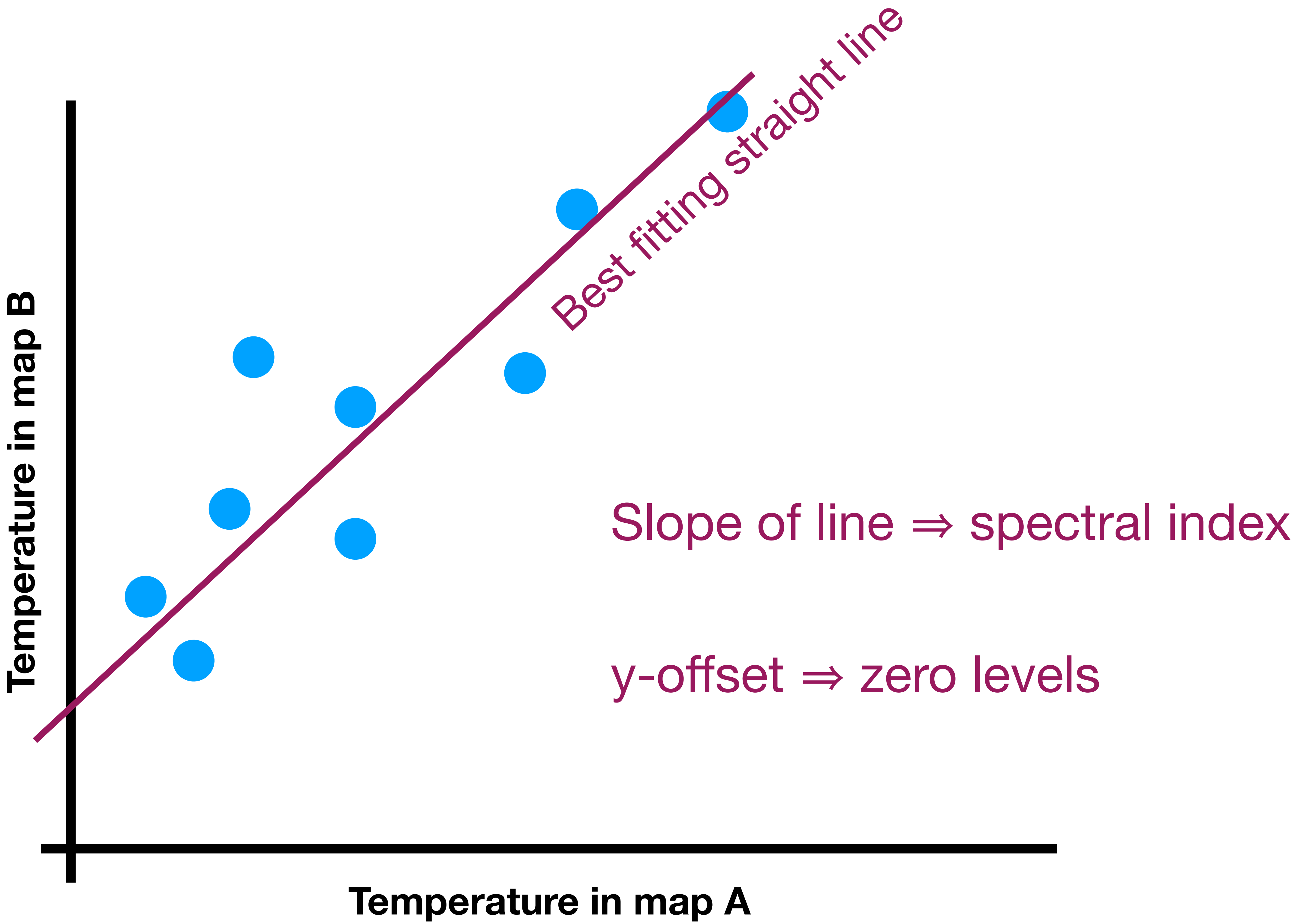
2. T-T Plots

Select a region dominated by a emission with a power law frequency-spectrum



2. T-T Plots

Select a region dominated by a emission with a power law frequency-spectrum



2. T-T Plots

Want to measure spectral index between

2. T-T Plots

Want to measure spectral index between

Haslam 408 MHz
(Remazeilles et al., 2015)

C-BASS 5 GHz

WMAP K-band 23 GHz
(Bennett et al., 2013)

2. T-T Plots

Want to measure spectral index between

Haslam 408 MHz (Remazeilles et al., 2015)

C-BASS 5 GHz

WMAP K-band 23 GHz (Bennett et al., 2013)

- Robust to zero level errors - hence T-T plot method

2. T-T Plots

Want to measure spectral index between

Haslam 408 MHz (Remazeilles et al., 2015)

C-BASS 5 GHz

WMAP K-band 23 GHz (Bennett et al., 2013)

- Robust to zero level errors - hence T-T plot method

See Richard Grumitt's Talk

2. T-T Plots

Want to measure spectral index between

Haslam 408 MHz (Remazeilles et al., 2015)

C-BASS 5 GHz

WMAP K-band 23 GHz (Bennett et al., 2013)

- Robust to zero level errors - hence T-T plot method

  See Richard Grumitt's Talk

- Use method over all/most of the sky

- There are other emission mechanisms present

2. T-T Plots

Want to measure spectral index between

Haslam 408 MHz (Remazeilles et al., 2015)

C-BASS 5 GHz

WMAP K-band 23 GHz (Bennett et al., 2013)

- Robust to zero level errors - hence T-T plot method
  See Richard Grumitt's Talk
- Use method over all/most of the sky
- There are other emission mechanisms present

Region selection

Line fitting

2. T-T Plots

Region selection

2. T-T Plots   Region selection

Use the **mean shift algorithm** to create regions. (with point source mask)

Roughly set the map zero levels and calculate spectral indices

Cluster on: Sky position
Haslam/C-BASS spectral index
C-BASS/*WMAP* K-band spectral index

Then smooth by a 5 degree Gaussian

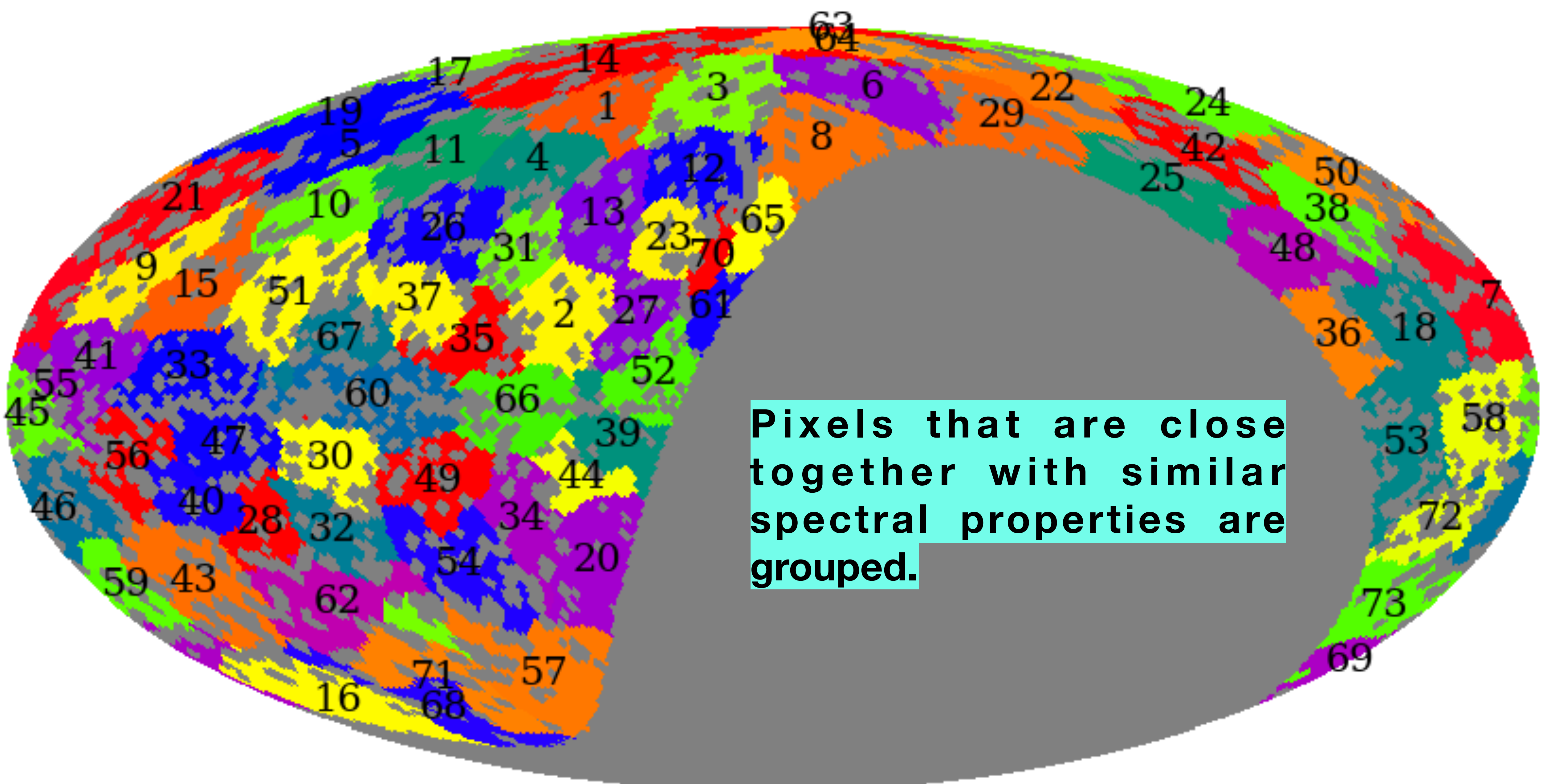
2. T-T Plots Region selection

Use the **mean shift algorithm** to create regions. (with point source mask)

Roughly set the map zero levels and calculate spectral indices

Cluster on: Sky position
Haslam/C-BASS spectral index
C-BASS/*WMAP* K-band spectral index

Then smooth by a 5 degree Gaussian



Pixels that are close together with similar spectral properties are grouped.

2. T-T Plots Region selection

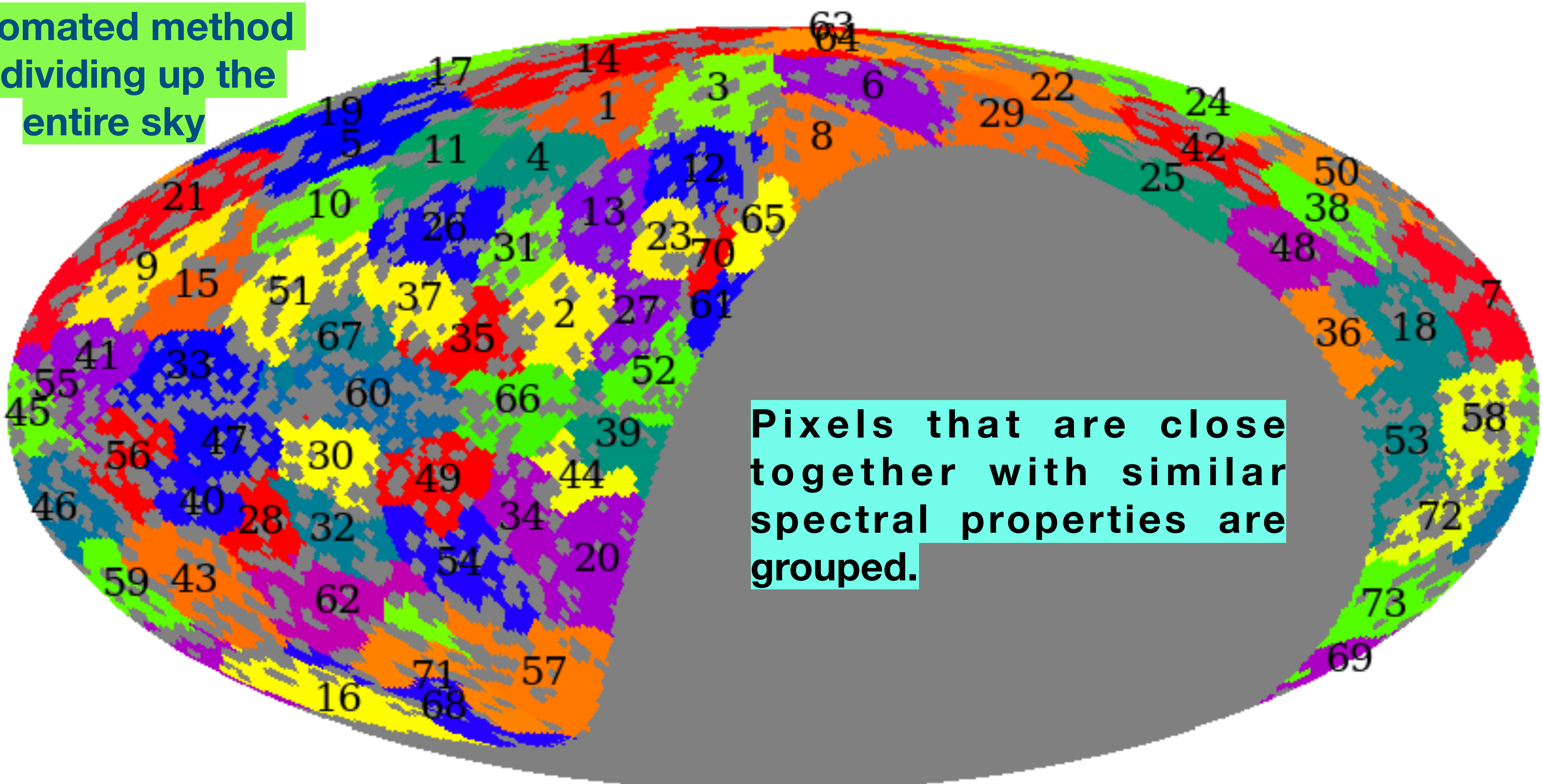
Use the **mean shift algorithm** to create regions. (with point source mask)

Roughly set the map zero levels and calculate spectral indices

Cluster on: Sky position
Haslam/C-BASS spectral index
C-BASS/*WMAP* K-band spectral index

Then smooth by a 5 degree Gaussian

Automated method of dividing up the entire sky



Pixels that are close together with similar spectral properties are grouped.

2. T-T Plots Region selection

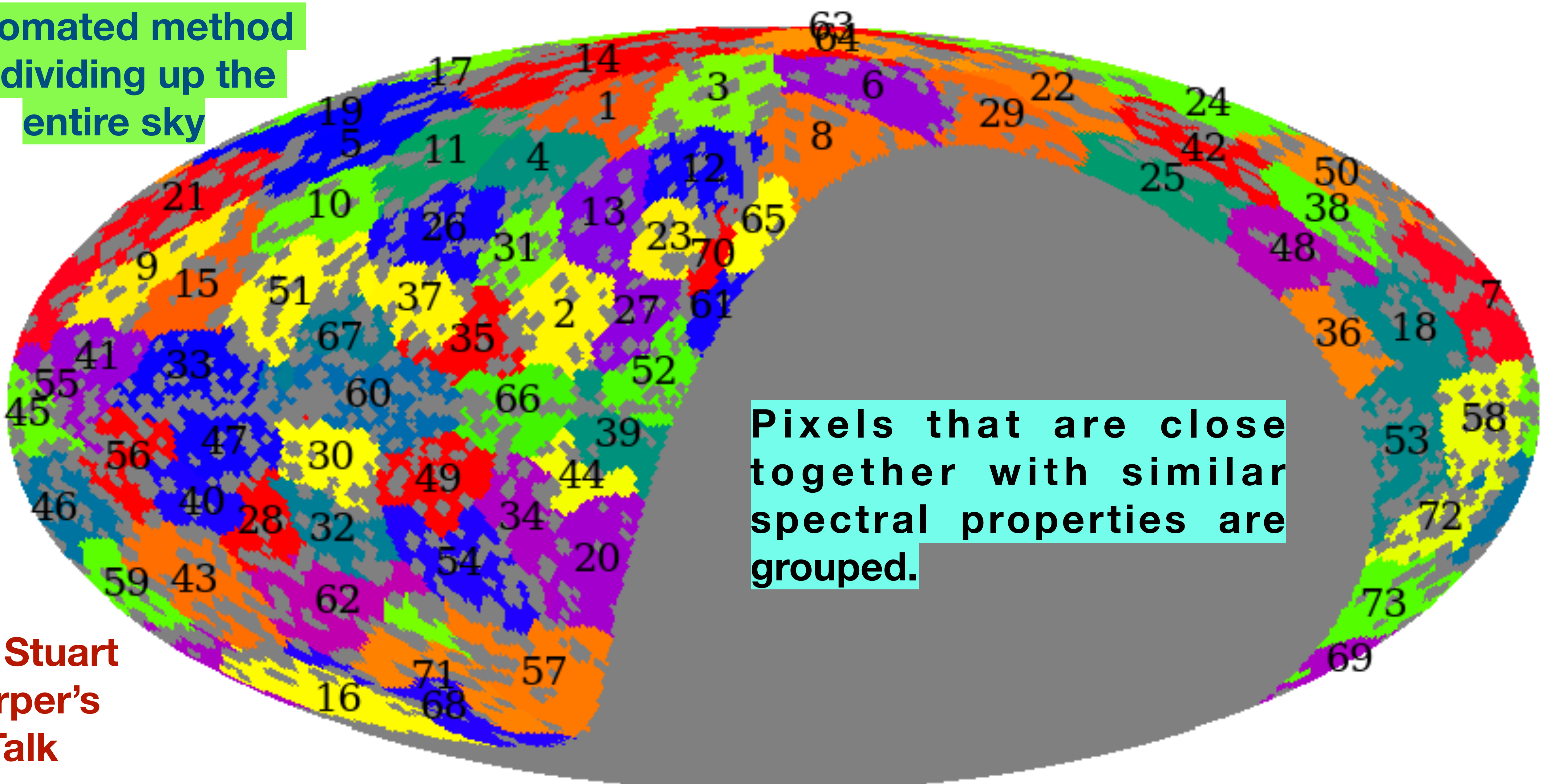
Use the **mean shift algorithm** to create regions. (with point source mask)

Roughly set the map zero levels and calculate spectral indices

Cluster on: Sky position
Haslam/C-BASS spectral index
C-BASS/*WMAP* K-band spectral index

Then smooth by a 5 degree Gaussian

Automated method of dividing up the entire sky



Pixels that are close together with similar spectral properties are grouped.

See Stuart Harper's Talk

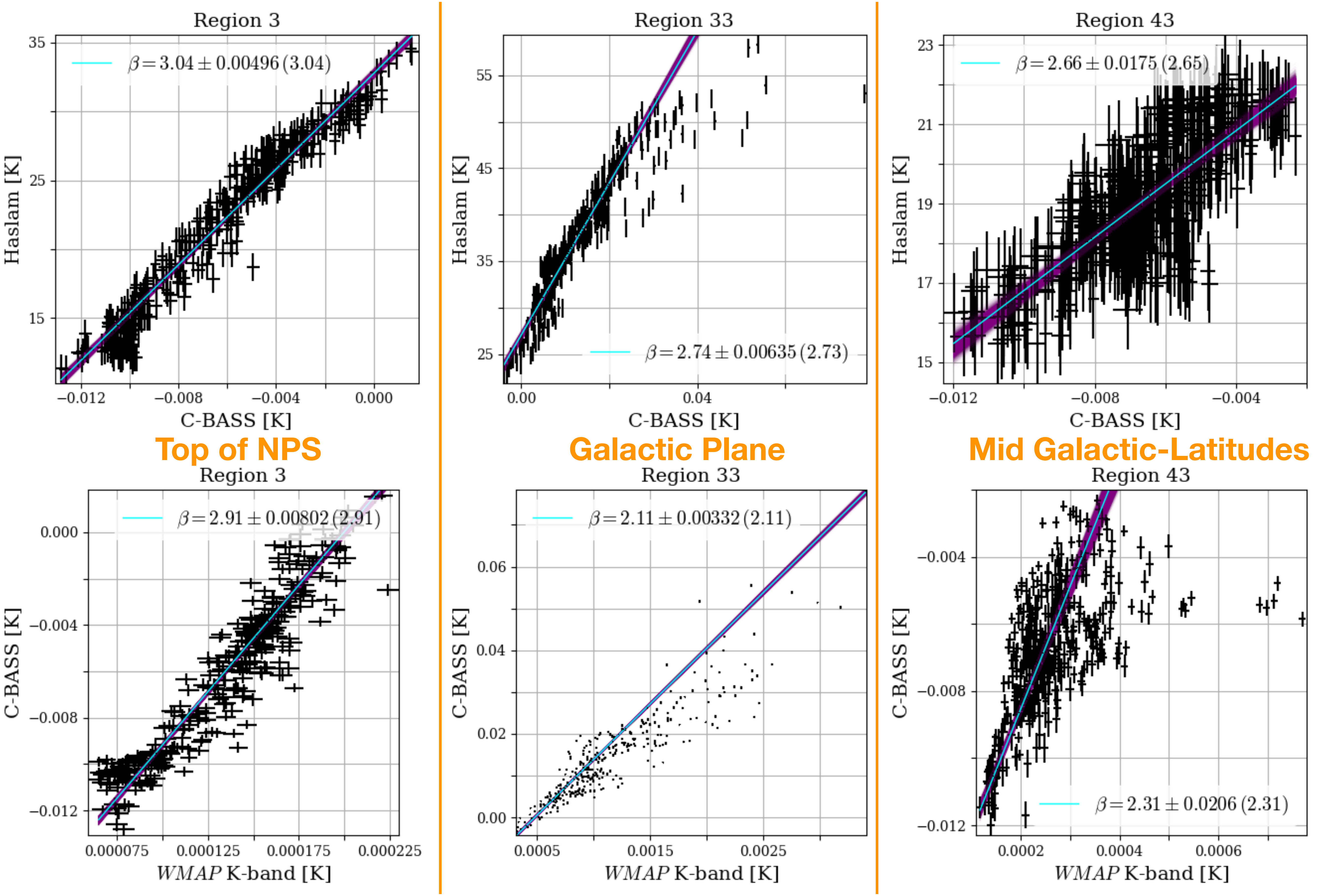
2. T-T Plots

Line fitting

2. T-T Plots Line fitting

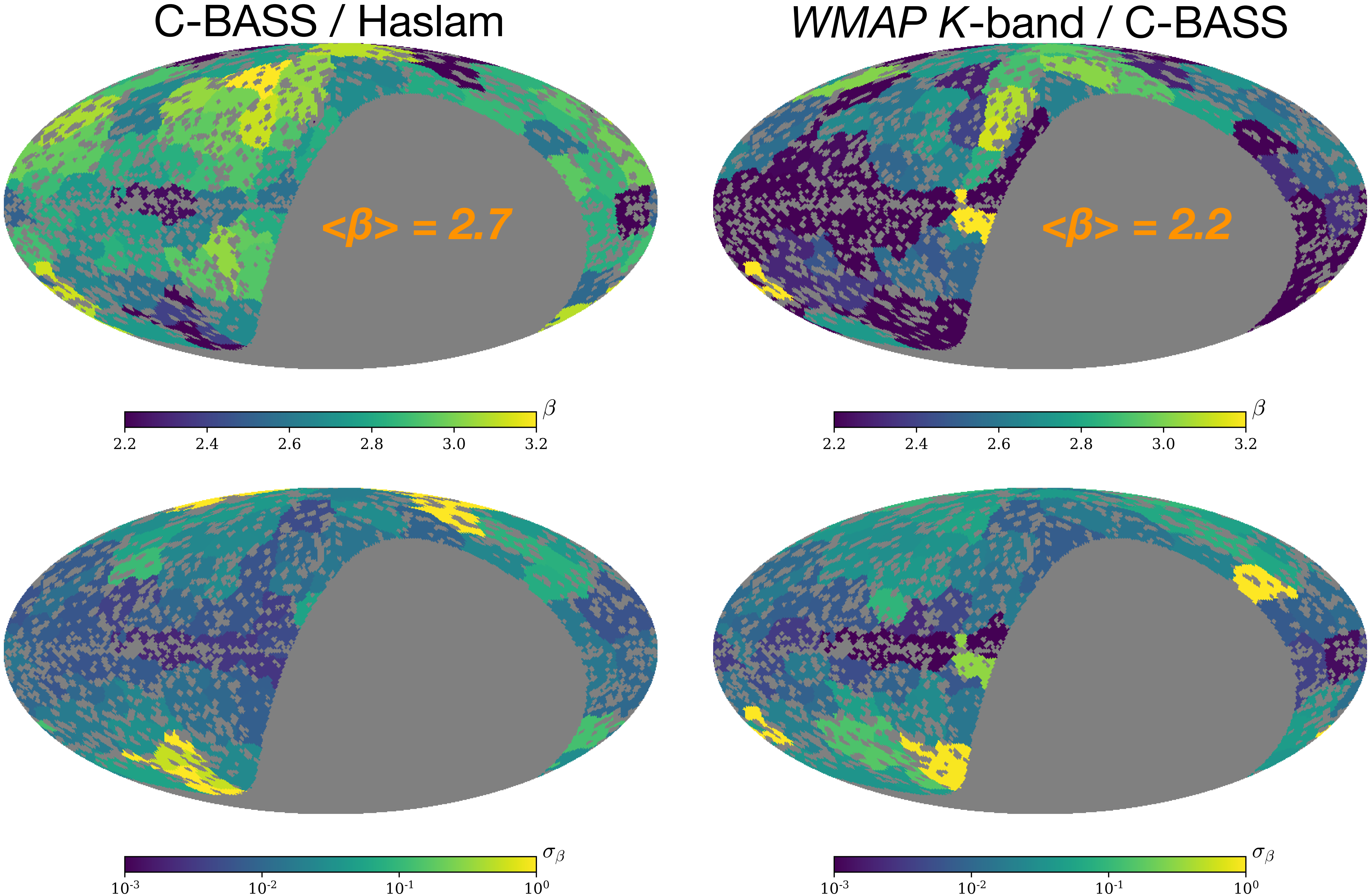
- Similar S/N across surveys
  - Use the Bayesian method developed by Gull (1989)
- There are pixels that are not dominated by synchrotron emission
  - Use a mixture model to account for outliers

2. T-T Plots



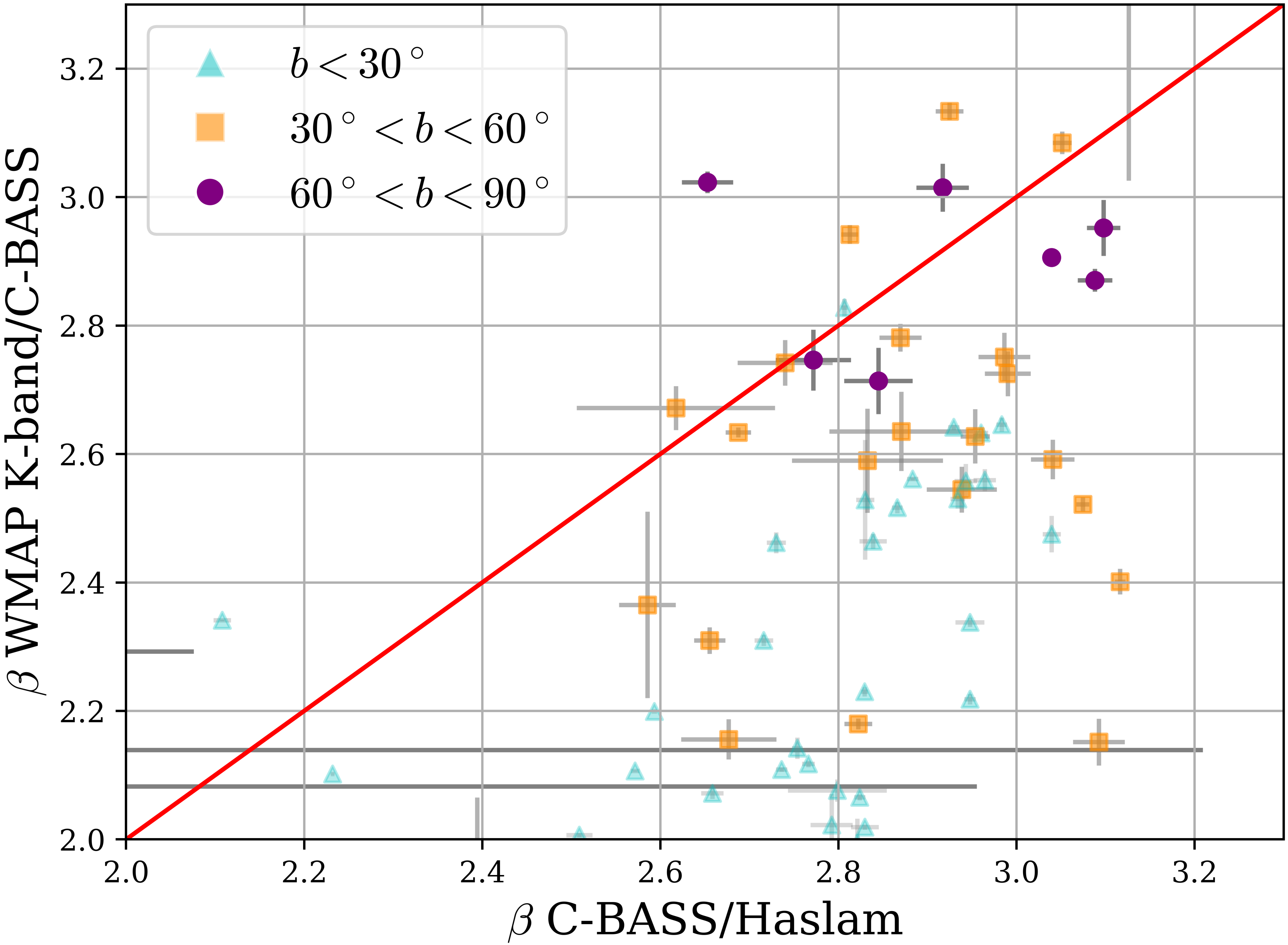
Region 3
$\beta = 3.04 \pm 0.00496\,(3.04)$
Haslam [K]
C-BASS [K]
Region 33
$\beta = 2.74 \pm 0.00635\,(2.73)$
Haslam [K]
C-BASS [K]
Region 43
$\beta = 2.66 \pm 0.0175\,(2.65)$
Haslam [K]
C-BASS [K]
Top of NPS
Galactic Plane
Mid Galactic-Latitudes
Region 3
$\beta = 2.91 \pm 0.00802\,(2.91)$
C-BASS [K]
WMAP K-band [K]
Region 33
$\beta = 2.11 \pm 0.00332\,(2.11)$
C-BASS [K]
WMAP K-band [K]
Region 43
$\beta = 2.31 \pm 0.0206\,(2.31)$
C-BASS [K]
WMAP K-band [K]

2. T-T Plots



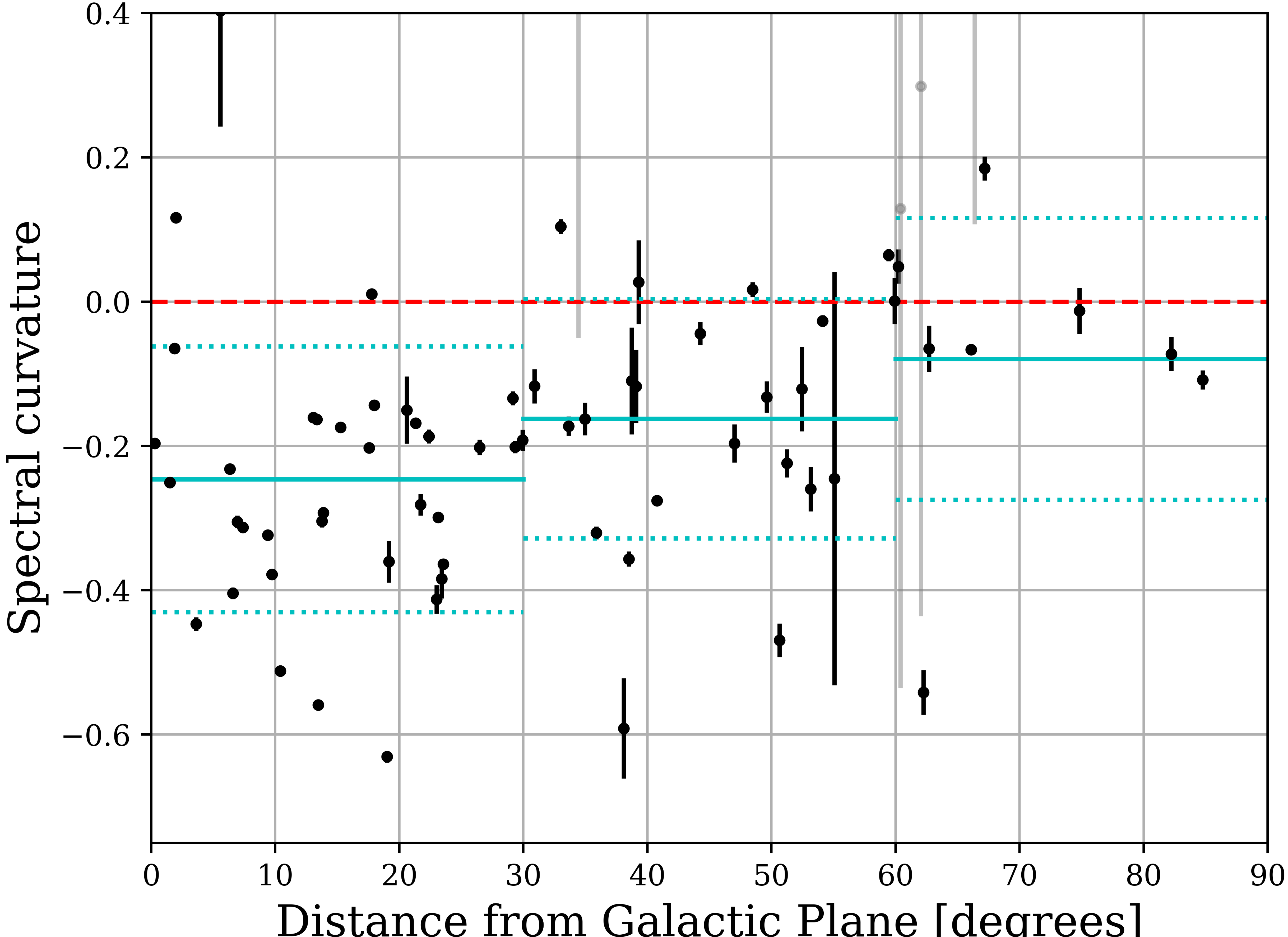
C-BASS / Haslam
WMAP K-band / C-BASS
<β> = 2.7
<β> = 2.2
β
2.2 2.4 2.6 2.8 3.0 3.2
β
2.2 2.4 2.6 2.8 3.0 3.2
σ_β
10^-3 10^-2 10^-1 10^0
σ_β
10^-3 10^-2 10^-1 10^0

2. T-T Plots



$b < 30^\circ$
$30^\circ < b < 60^\circ$
$60^\circ < b < 90^\circ$
β WMAP K-band/C-BASS
β C-BASS/Haslam
2.0
2.2
2.4
2.6
2.8
3.0
3.2

2. T-T Plots



Spectral curvature
Distance from Galactic Plane [degrees]
0.4
0.2
0.0
−0.2
−0.4
−0.6
0
10
20
30
40
50
60
70
80
90

1. C-BASS Data

2. T-T Plots

3. Polarized Spectral Index

3. Polarized Spectral Index

Want to measure polarized spectral index between

3. Polarized Spectral Index

Want to measure polarized spectral index between

C-BASS 5 GHz

Planck 30 GHz
(Planck Collaboration, 2018)

3. Polarized Spectral Index

Want to measure polarized spectral index between

C-BASS 5 GHz

Planck 30 GHz
(Planck Collaboration, 2018)

Power-law frequency-spectrum, pixel-by-pixel

$$P_i(n) = A_0(n) \left(\frac{\nu_i}{\nu_0} \right)^{-\beta(n)},$$

For the gory details see
https://ora.ox.ac.uk/objects/uuid:31f0227a-84be-421a-ae46-eebe9f422767

Power-law frequency-spectrum

$$P_i(n) = A_0(n)\left(\frac{\nu_i}{\nu_0}\right)^{-\beta(n)},$$

Polarized intensity is a Rician random variable (if $\sigma_Q \approx \sigma_U$)

$$p(P_1, P_2 | A_0, \beta, \sigma_{P1}, \sigma_{P2}) = \frac{P_1}{\sigma_{P1}^2} e^{-\frac{P_1^2 + (A_0(\nu_1/\nu_0)^{-\beta})^2}{2\sigma_{P1}^2}} I_0\left(\frac{P_1 A_0 (\nu_1/\nu_0)^{-\beta}}{\sigma_{P1}^2}\right) \times \frac{P_2}{\sigma_{P2}^2} e^{-\frac{P_2^2 + (A_0(\nu_2/\nu_0)^{-\beta})^2}{2\sigma_{P2}^2}} I_0\left(\frac{P_2 A_0 (\nu_2/\nu_0)^{-\beta}}{\sigma_{P2}^2}\right).$$

Prior

$$p(A_0)p(\beta) \propto A_0|\beta|$$

Jeffreys prior for the amplitude of a Rician random variable, and assigning

$$p\left((\nu_i/\nu_0)^{-\beta}\right) \propto \text{constant}$$

For the gory details see
https://ora.ox.ac.uk/objects/uuid:31f0227a-84be-421a-ae46-eebe9f422767

Power-law frequency-spectrum

$$P_i(n) = A_0(n)\left(\frac{\nu_i}{\nu_0}\right)^{-\beta(n)}$$

Polarized intensity is a Rician random variable (if $\sigma_Q \approx \sigma_U$)

$$p(P_1, P_2|A_0, \beta, \sigma_{P1}, \sigma_{P2}) = \frac{P_1}{\sigma_{P1}^2} e^{-\frac{P_1^2 + (A_0(\nu_1/\nu_0)^{-\beta})^2}{2\sigma_{P1}^2}} I_0\left(\frac{P_1 A_0(\nu_1/\nu_0)^{-\beta}}{\sigma_{P1}^2}\right) \times \frac{P_2}{\sigma_{P2}^2} e^{-\frac{P_2^2 + (A_0(\nu_2/\nu_0)^{-\beta})^2}{2\sigma_{P2}^2}} I_0\left(\frac{P_2 A_0(\nu_2/\nu_0)^{-\beta}}{\sigma_{P2}^2}\right).$$

Not noise biased - even in low S/N

Prior

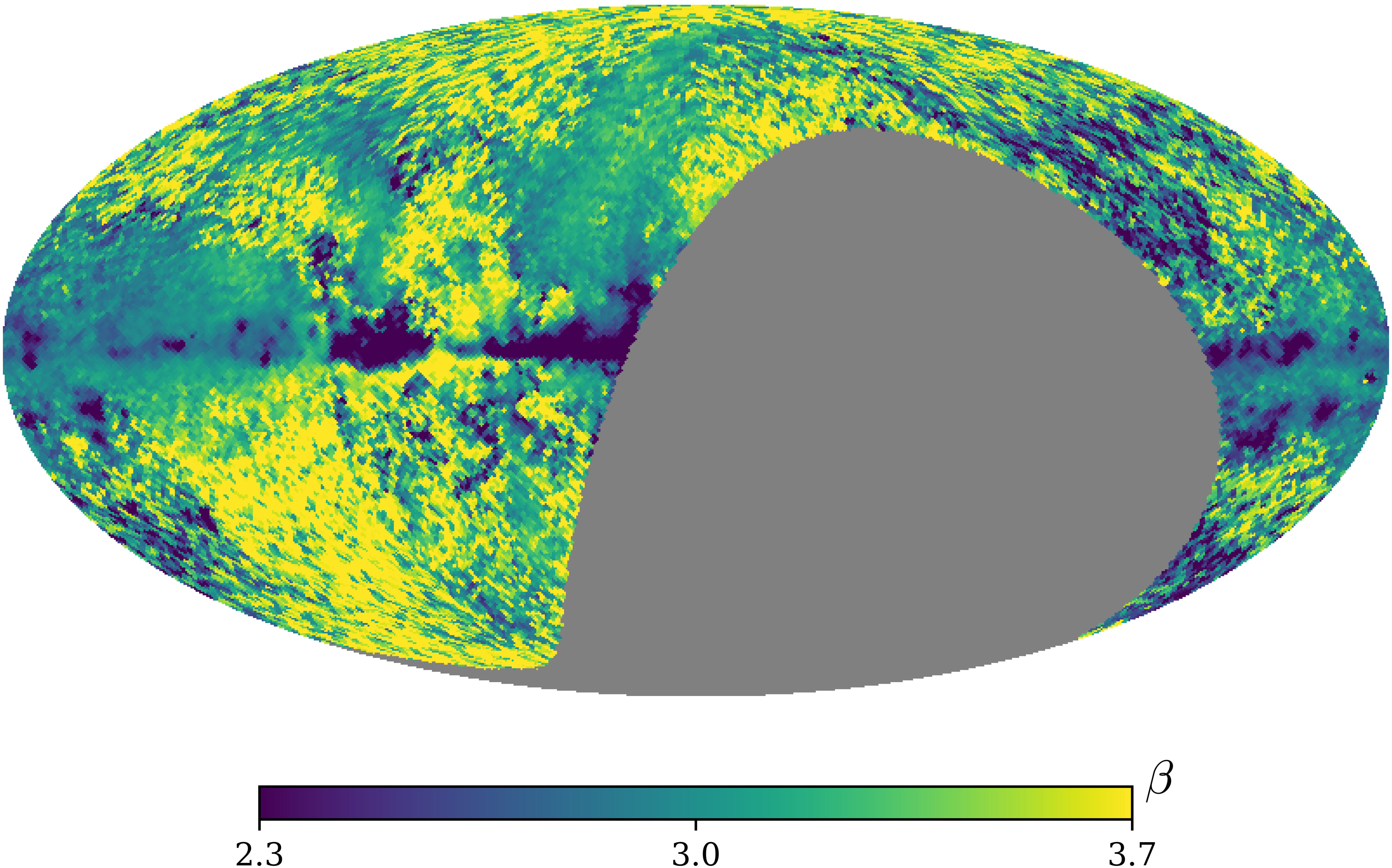
$$p(A_0)p(\beta) \propto A_0|\beta|$$

Jeffreys prior for the amplitude of a Rician random variable, and assigning

$$p\left((\nu_i/\nu_0)^{-\beta}\right) \propto \text{constant}$$

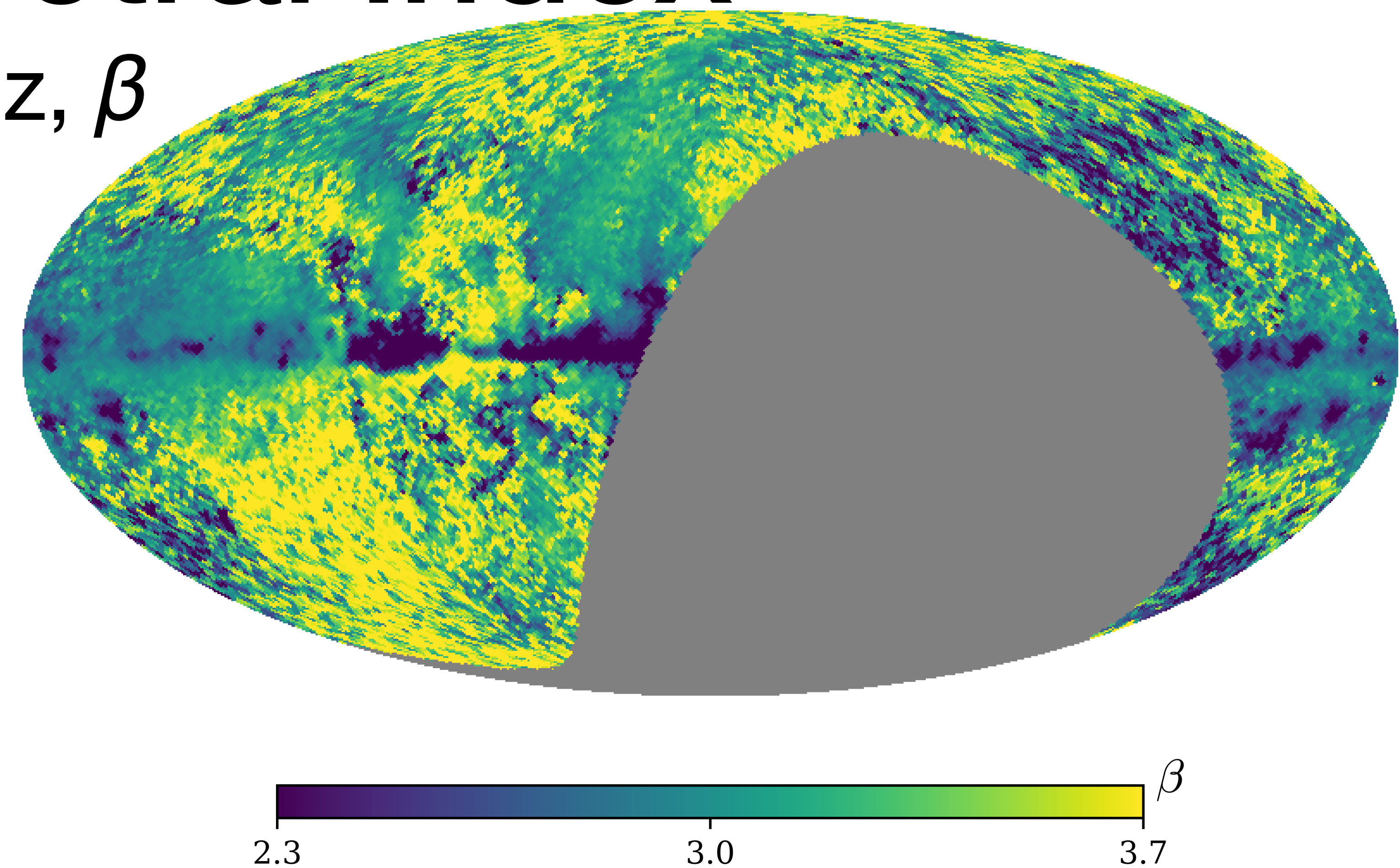
3. Polarized Spectral Index

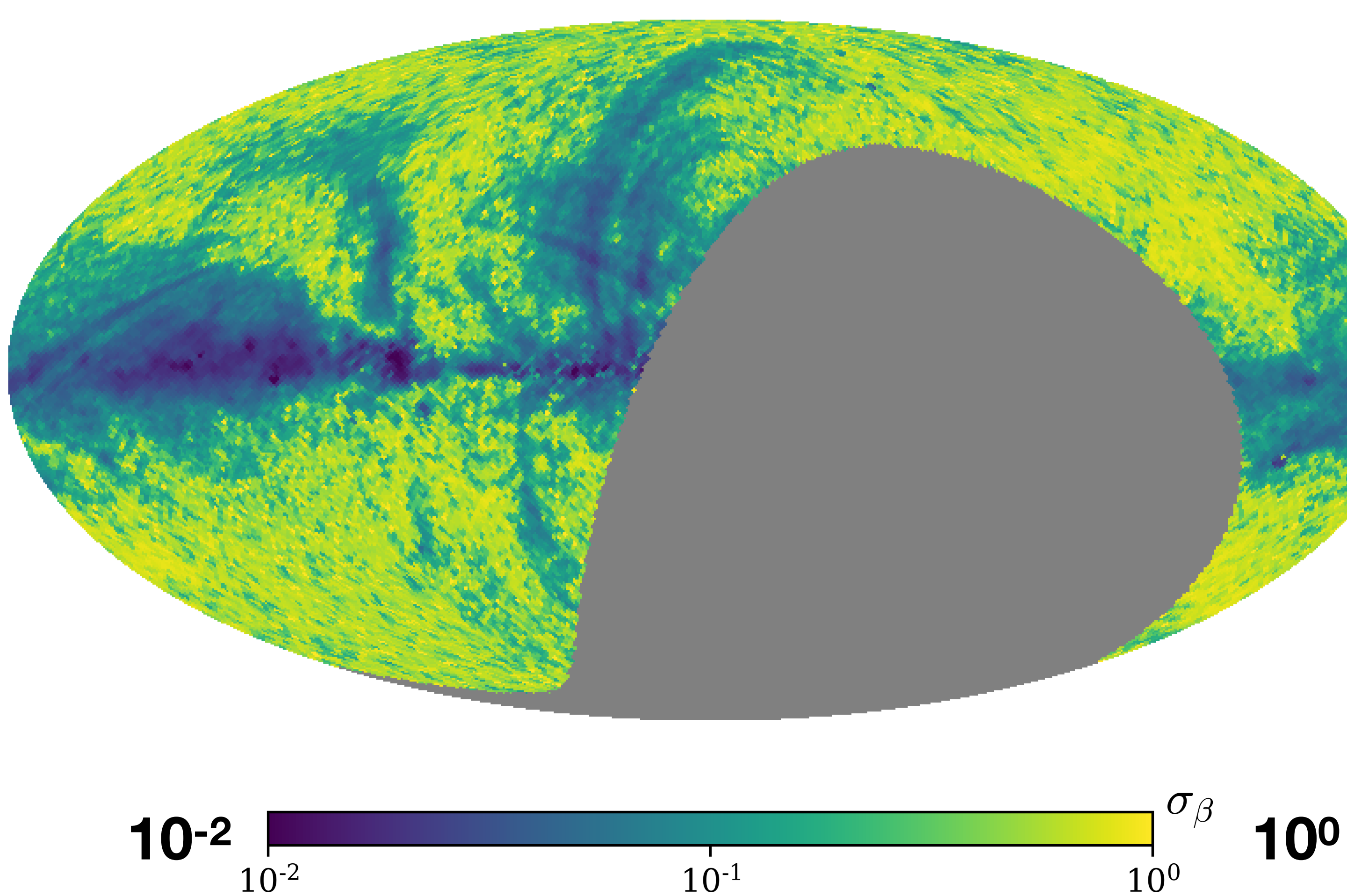
C-BASS/*Planck* 30 GHz, β



3. Polarized Spectral Index

C-BASS/*Planck* 30 GHz, β

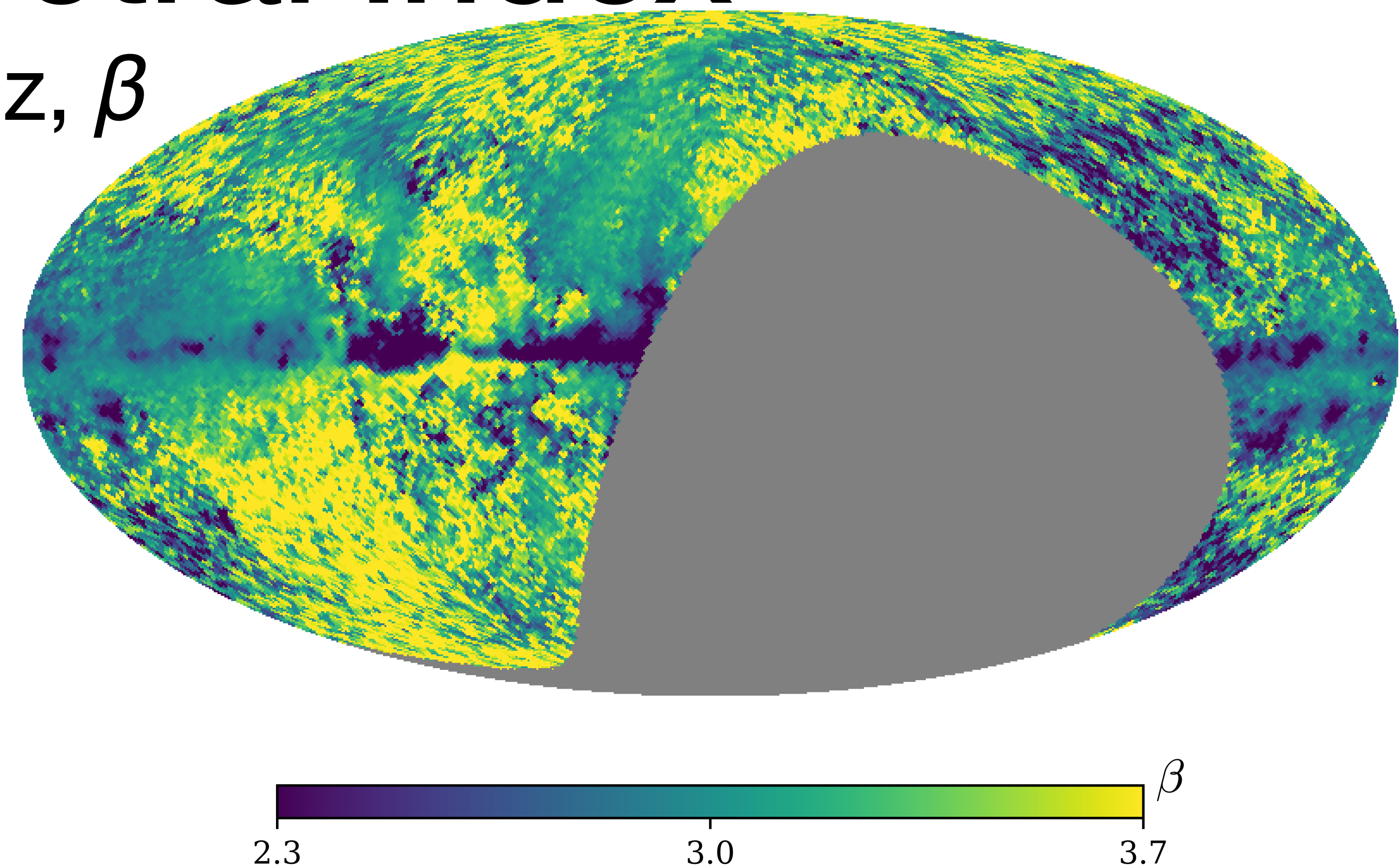


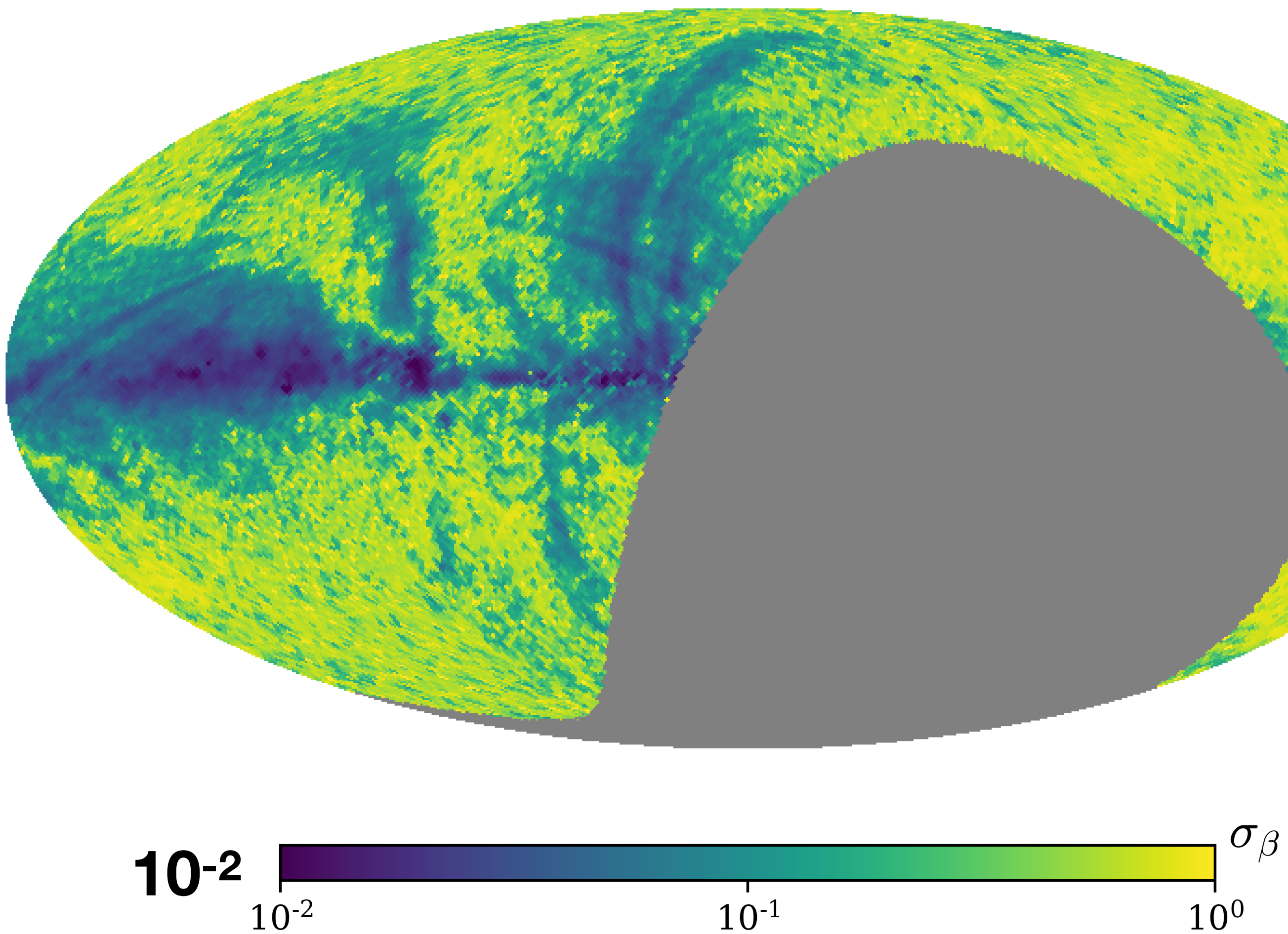


3. Polarized Spectral Index

C-BASS/*Planck* 30 GHz, β

$$\hat{\beta}|_{b>20^\circ} = 3.073$$



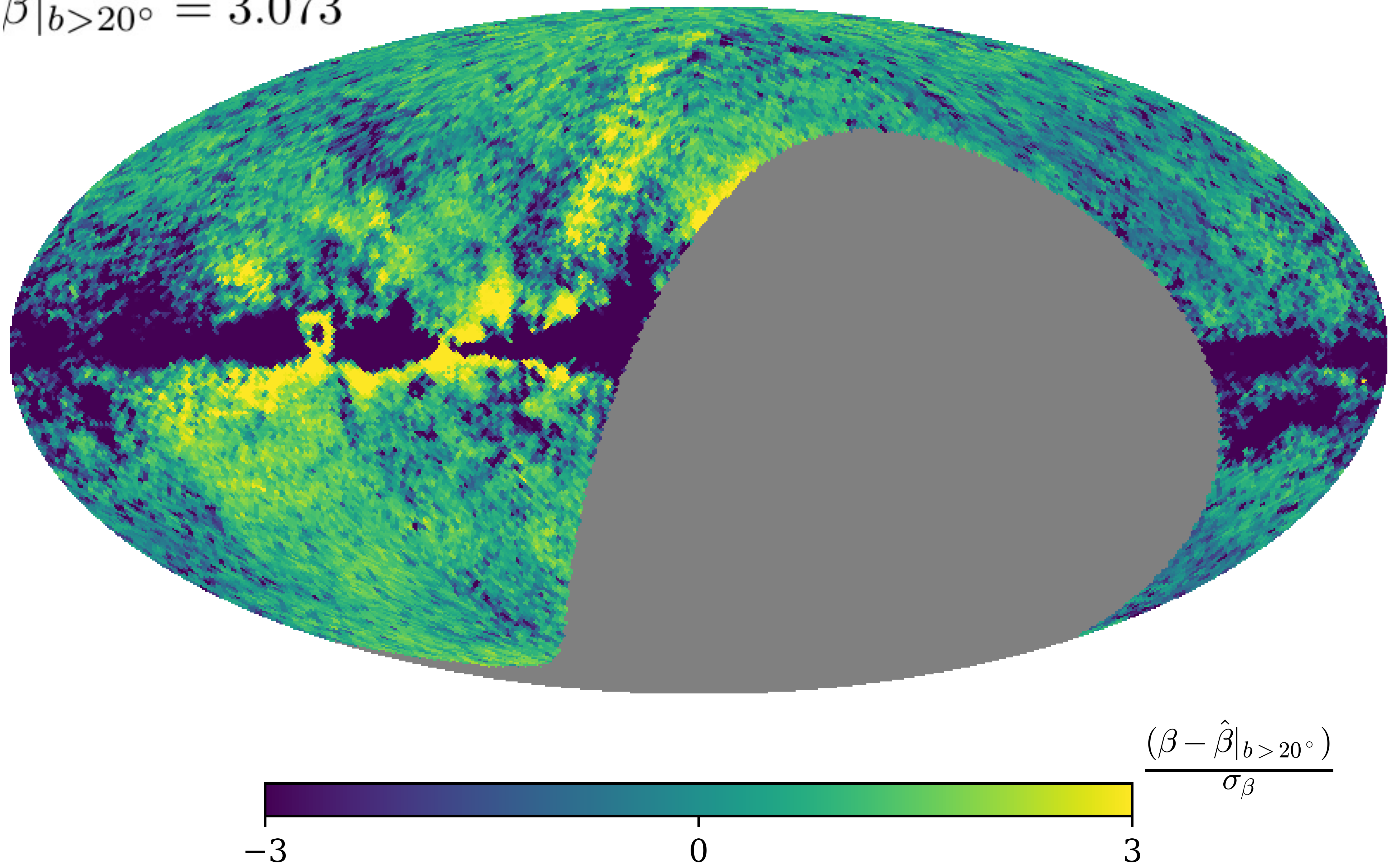


10^{-2} **10^{0}**

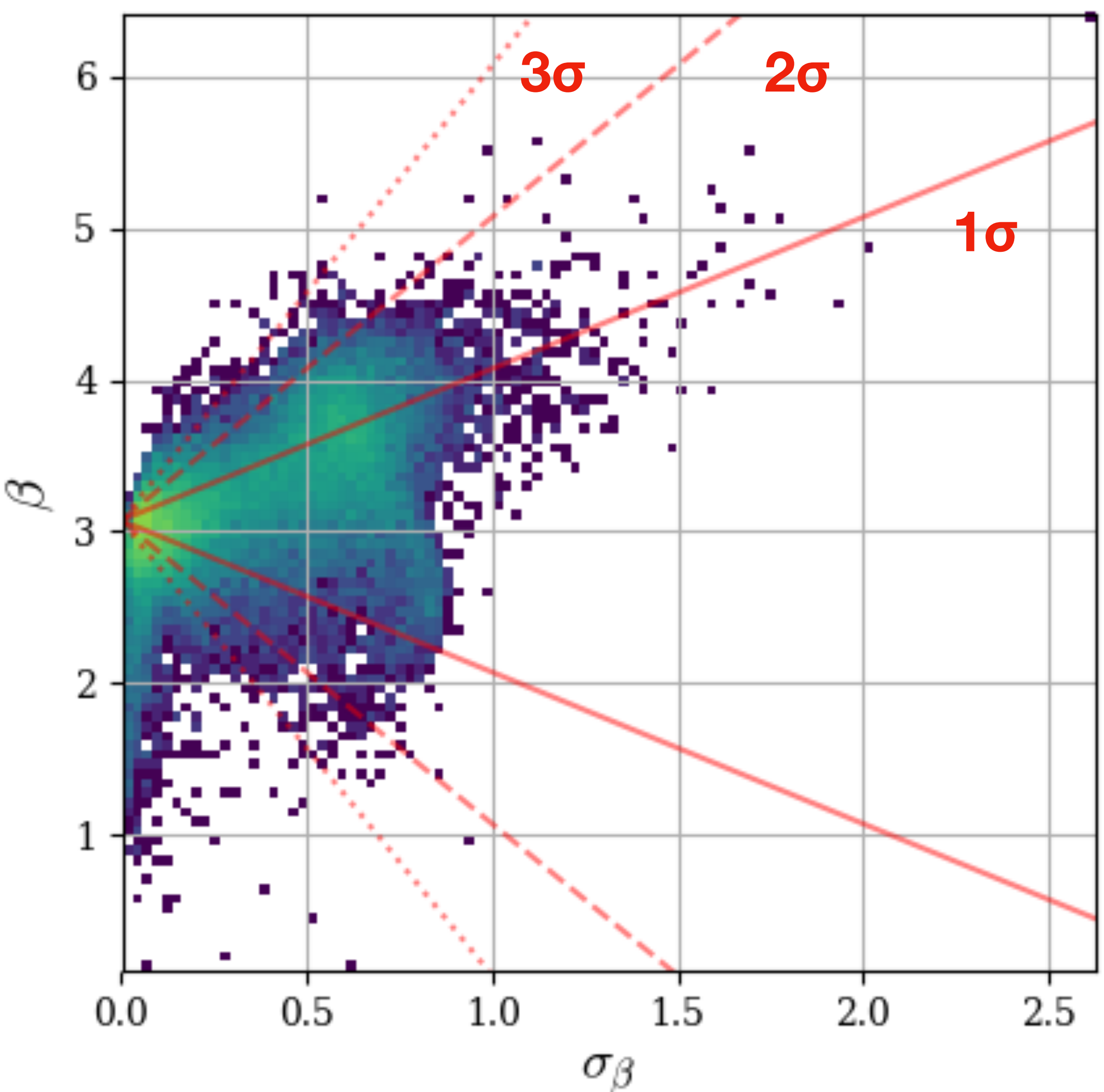
3. Polarized Spectral Index

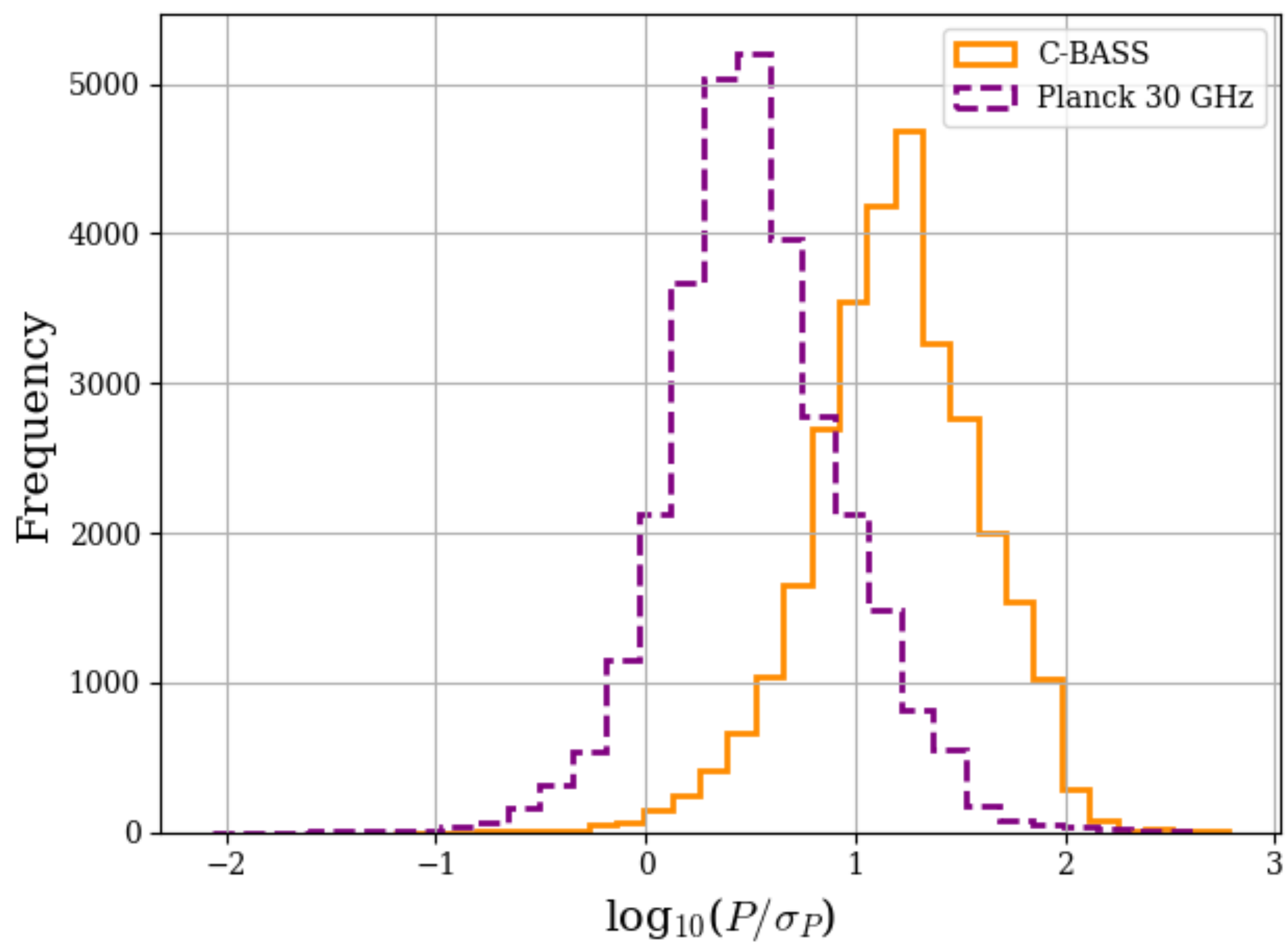
C-BASS/*Planck* 30 GHz, normalised deviation from mean

$\hat{\beta}|_{b>20^\circ} = 3.073$

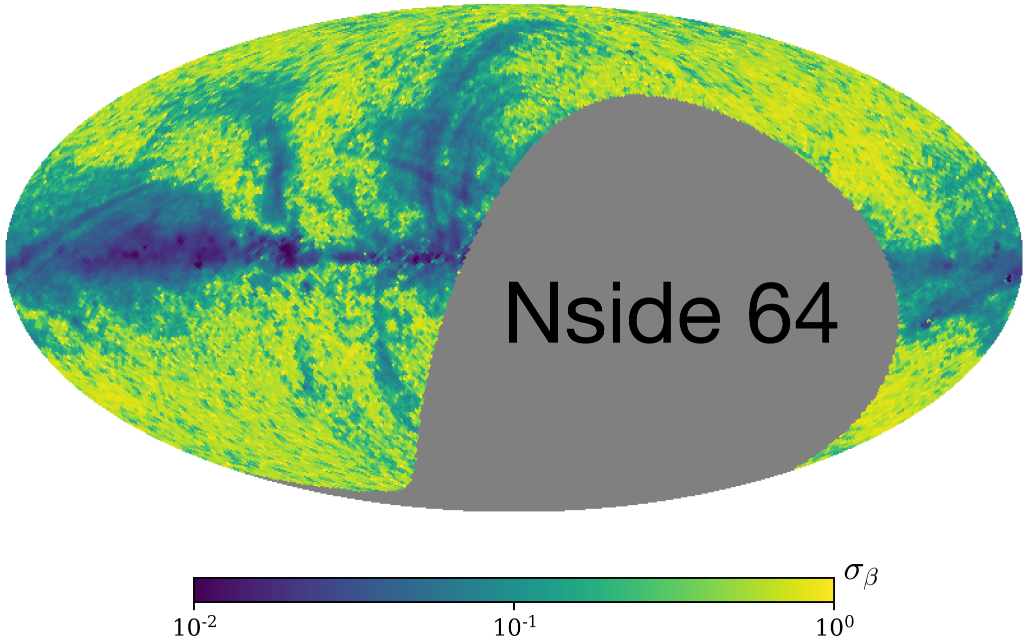


3. Polarized Spectral Index C-BASS/*Planck* 30 GHz

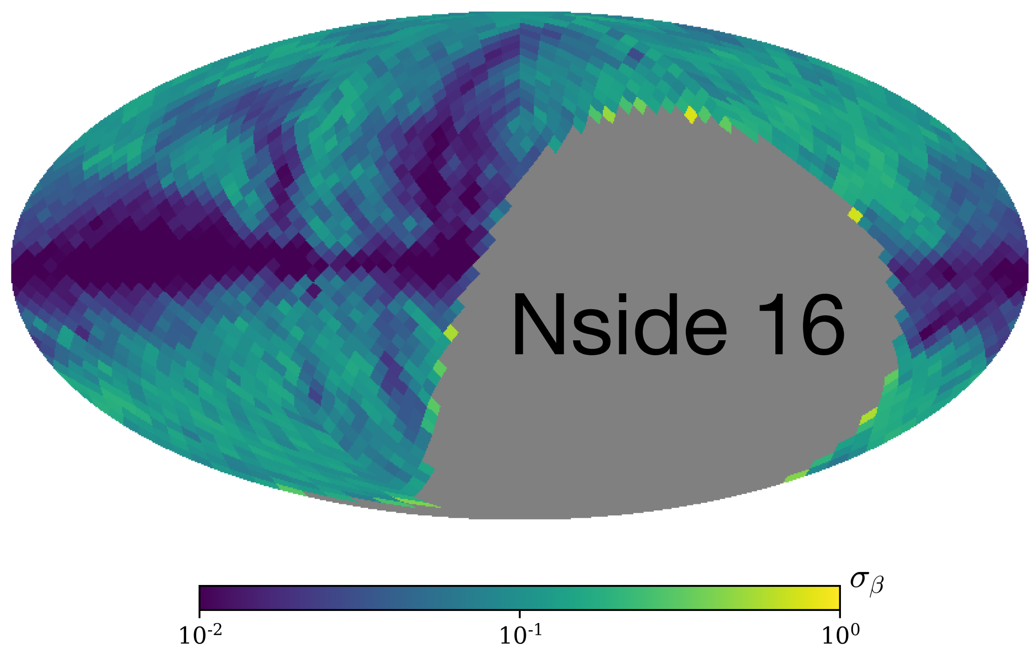




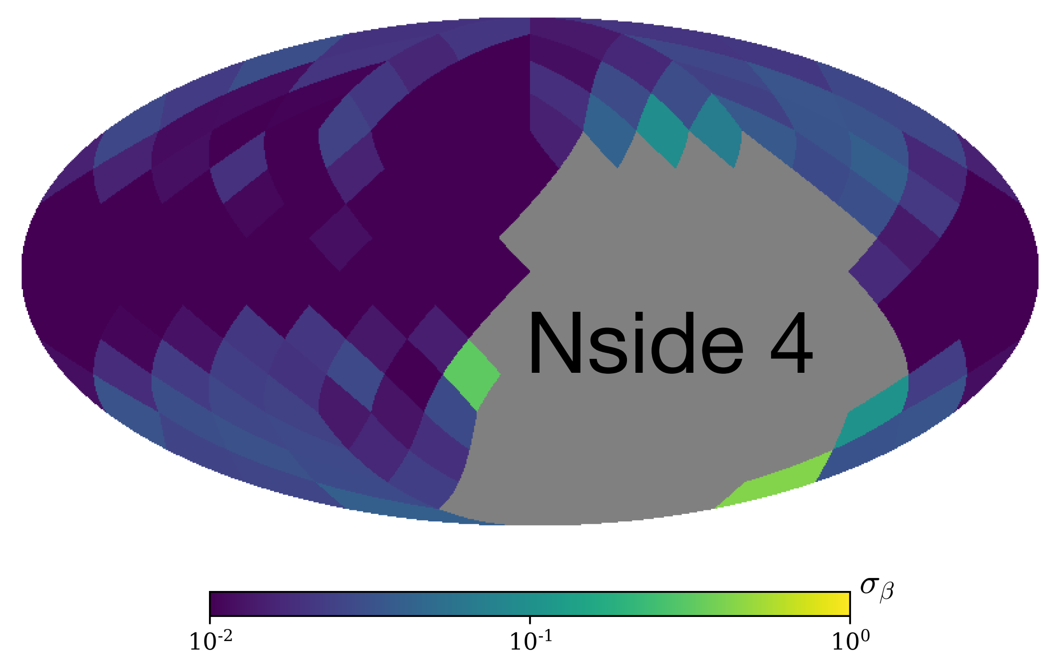
$$\hat{\beta}|_{b>20^\circ} = 3.073$$



Downgrading to lower Nside, the uncertainty on the weighted average of pixels drops quickly

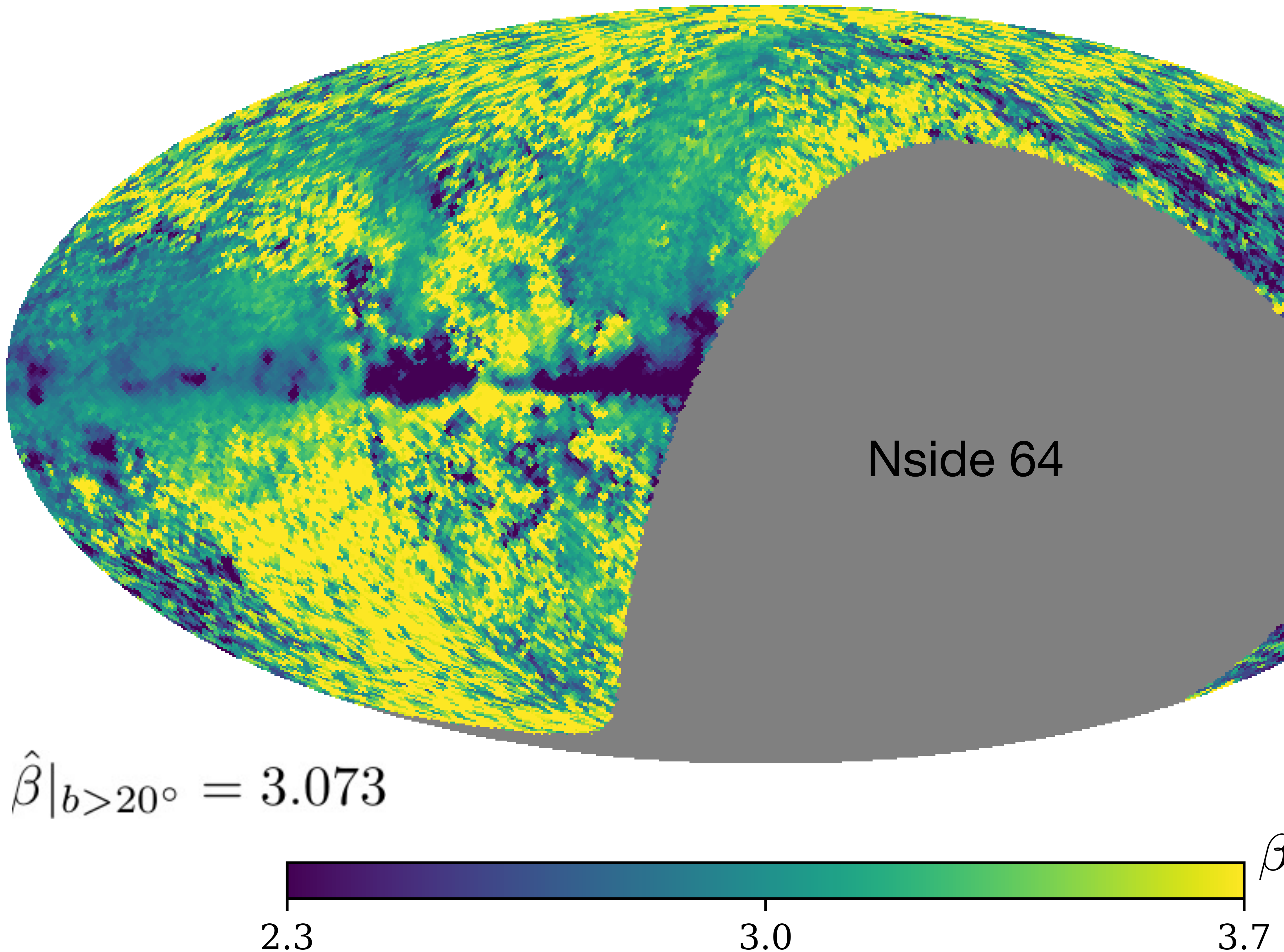


All on the same colour scale



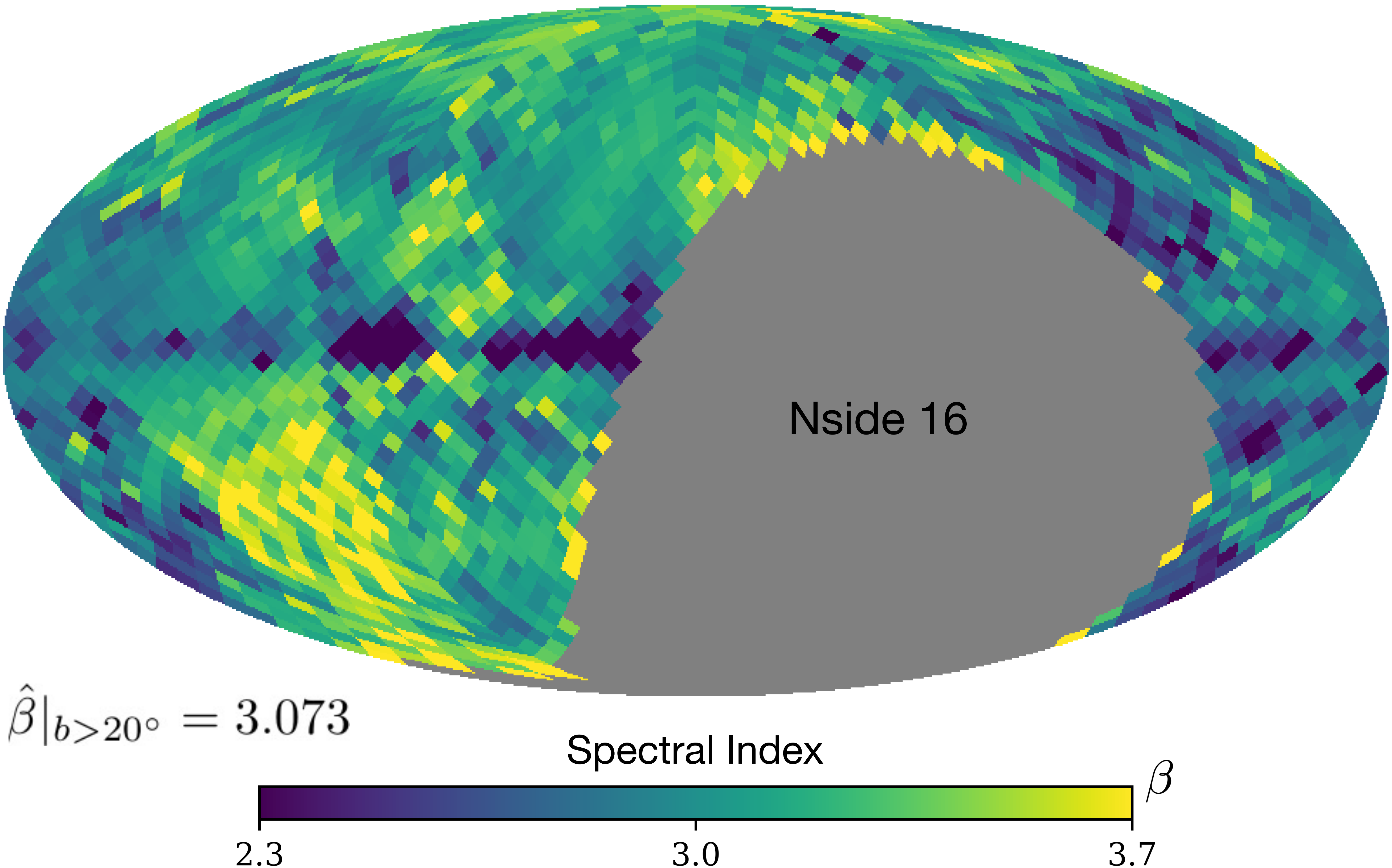
3. Polarized Spectral Index

C-BASS/*Planck* 30 GHz, β



3. Polarized Spectral Index

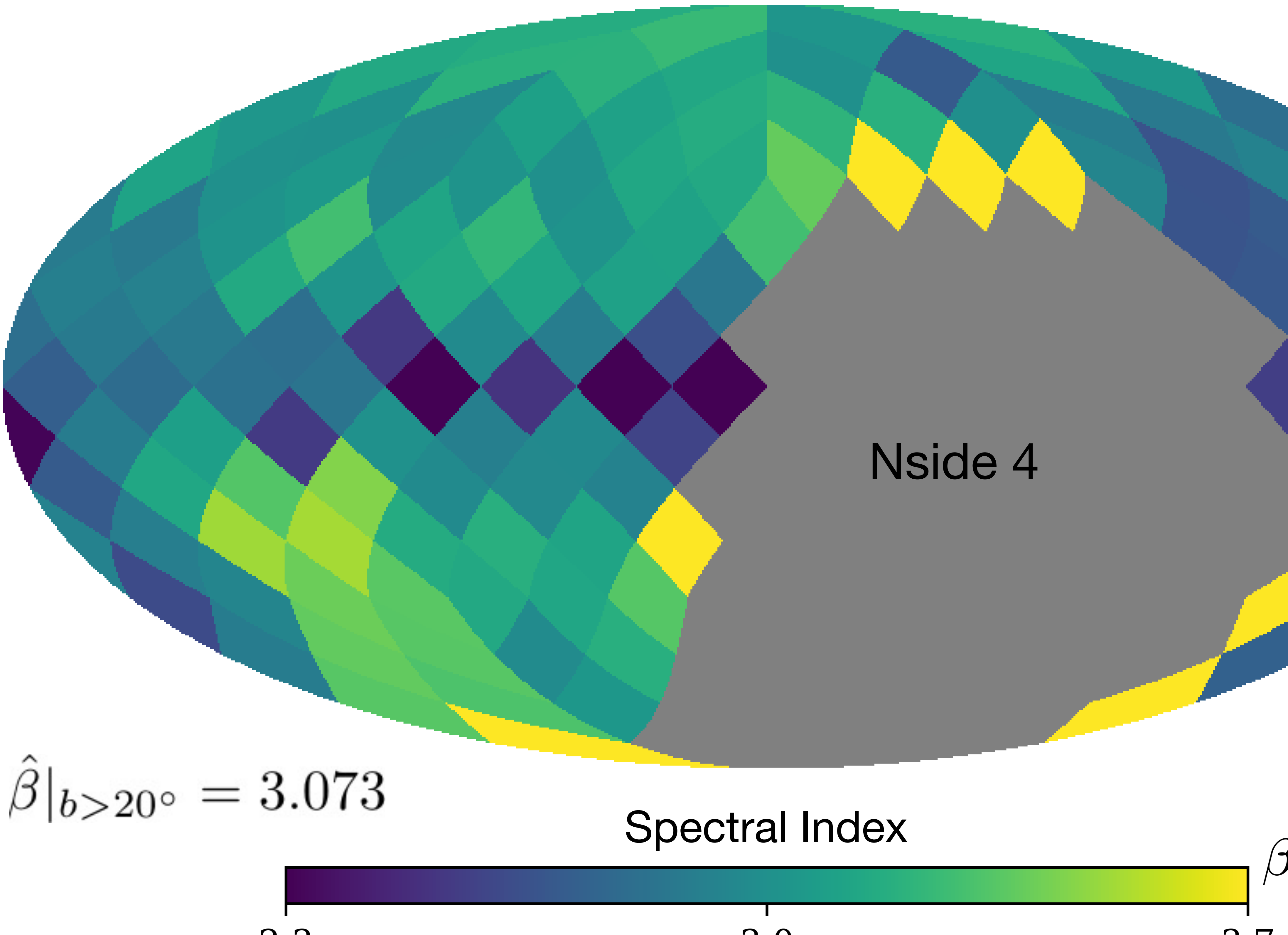
C-BASS/*Planck* 30 GHz, β



$$\hat{\beta}|_{b>20^\circ} = 3.073$$

3. Polarized Spectral Index

C-BASS/*Planck* 30 GHz, β



$$\hat{\beta}|_{b>20^\circ} = 3.073$$

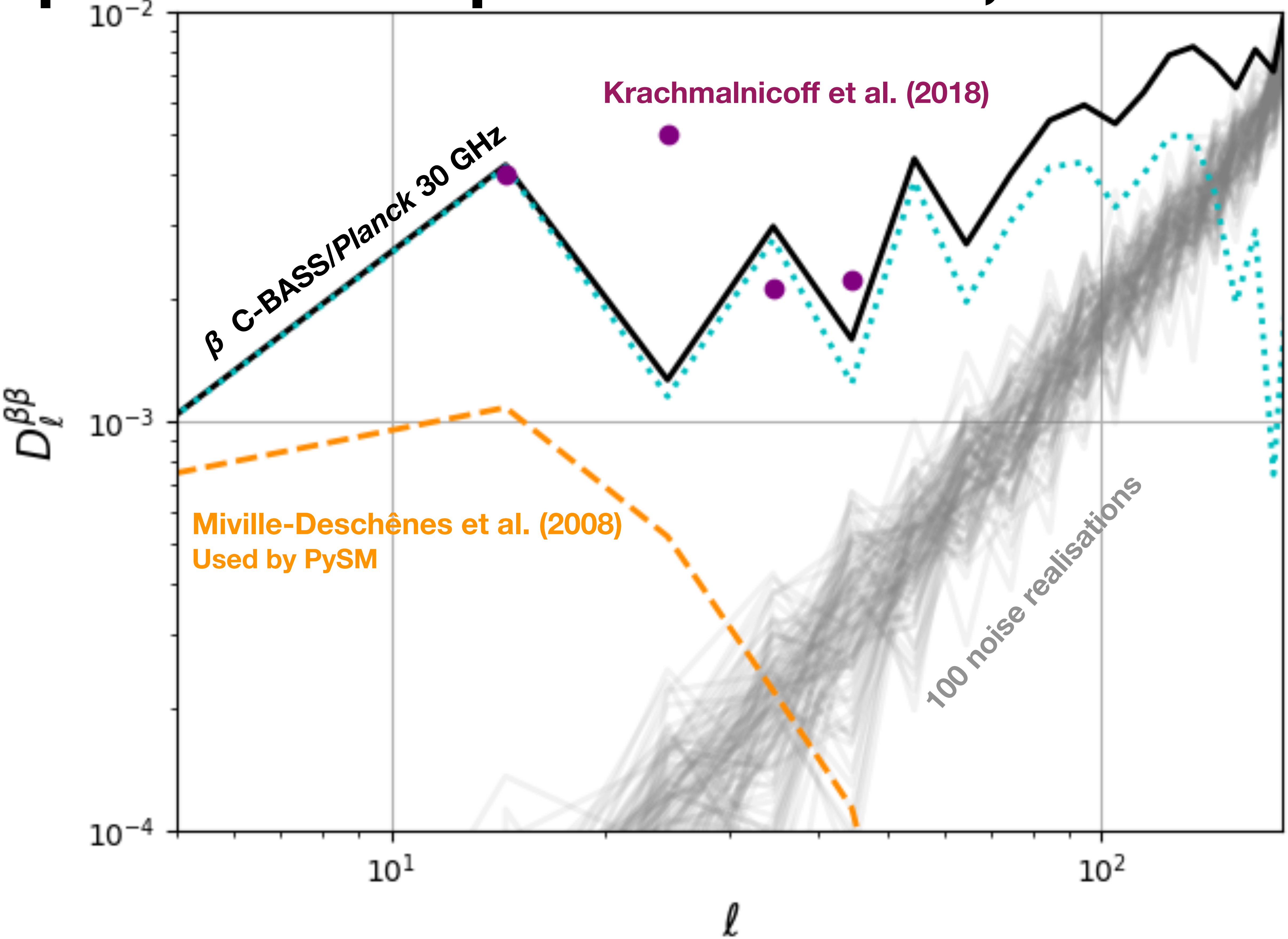
3. Polarized Spectral Index C-BASS/*Planck* 30 GHz

Latitude range	β	σ_β
Whole sky	2.6770	0.0004
$0° < b < 10°$	2.5640	0.0005
$10° < b < 20°$	2.902	0.001
$20° < b < 30°$	3.035	0.002
$30° < b < 50°$	3.102	0.002
$50° < b < 75°$	3.087	0.003
$75° < b < 90°$	3.156	0.009
b>20°	**3.073**	**0.001**

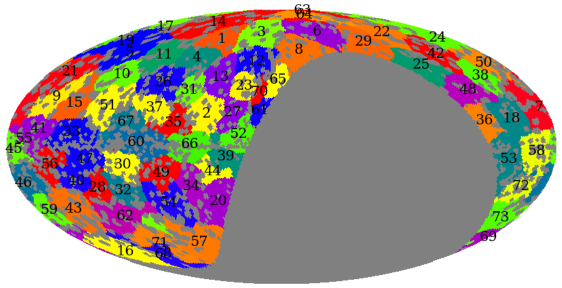
S-PASS: $\beta = 3.22 \pm 0.08$ (2.3—33 GHz)

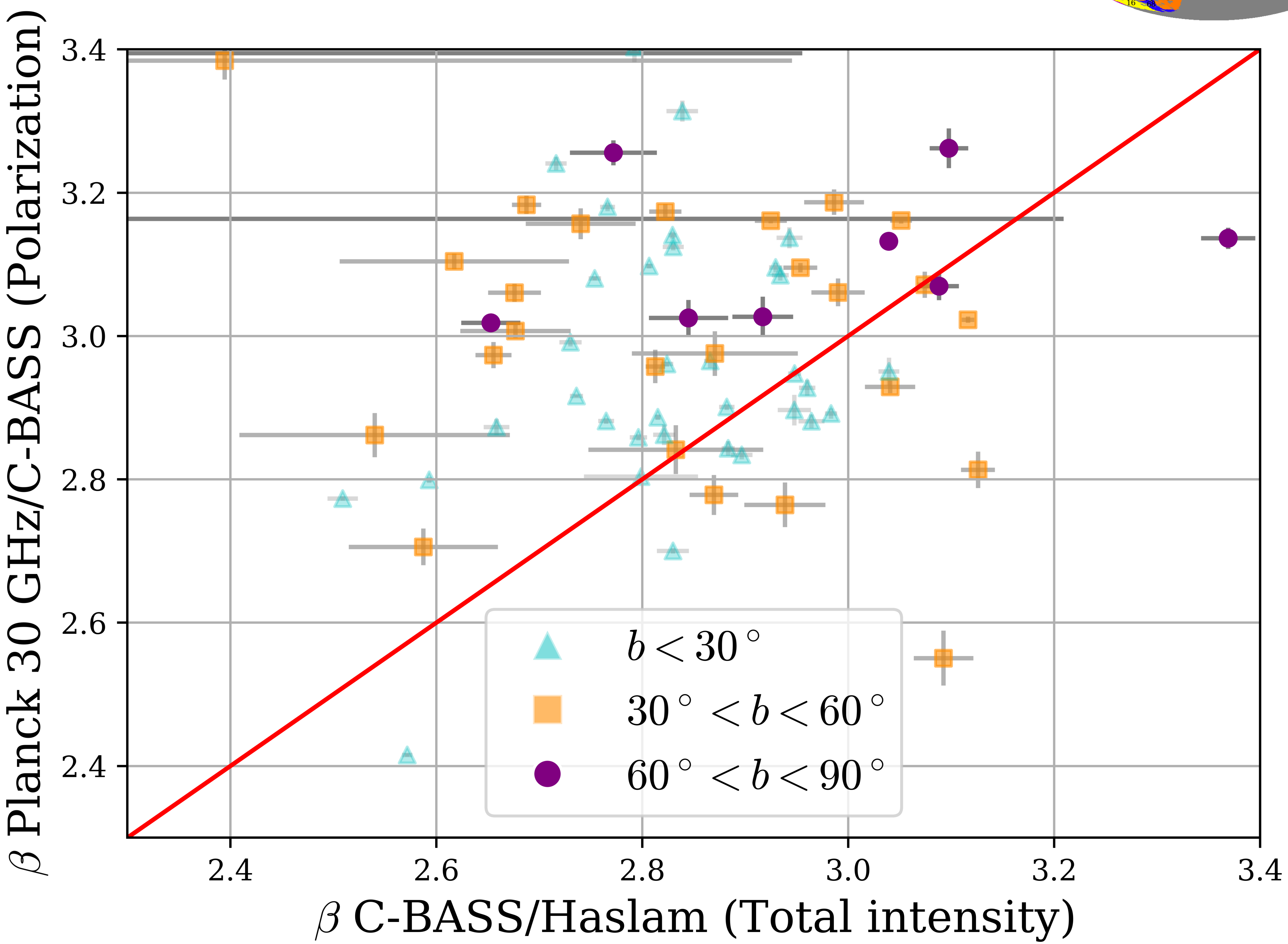
(Krachmalnicoff et al., 2018)

Angular power spectrum of polarized spectral index, *b*>25°



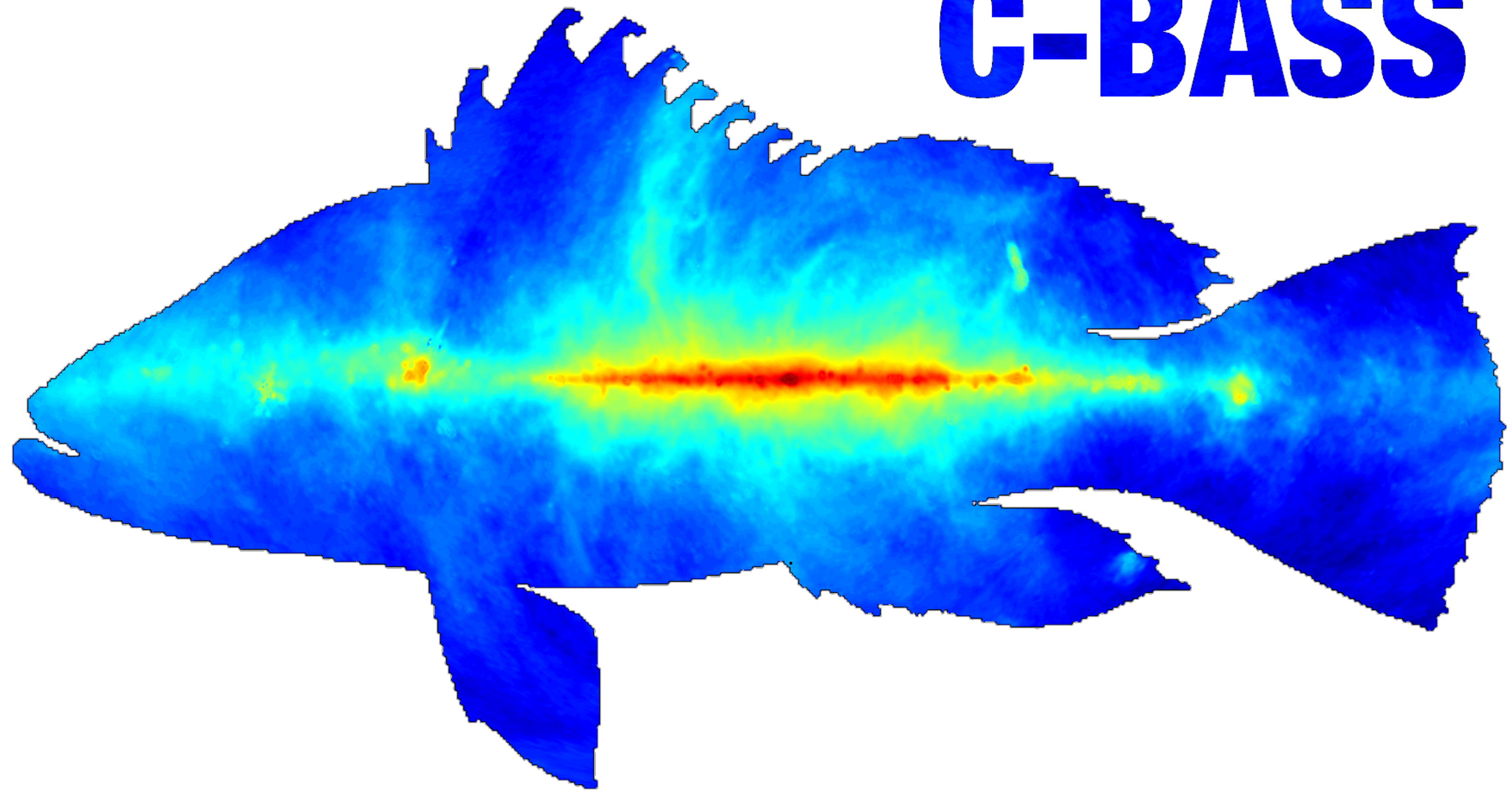
Compare I and P





Thanks for listening. Any questions?

C-BASS



Synchrotron spectral index in total intensity and polarization

UNIVERSITY OF OXFORD

Luke Jew

https://cbass.web.ox.ac.uk/