Improvements in low-frequency foreground modeling for future primordial B-mode searches

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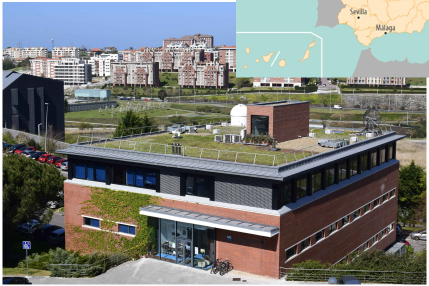
A little bit about myself

- Ph.D. at Instituto de Física de Cantanbria (**IFCA**) in Santander.
- Worked mainly on **component separation** in the context of the **CMB**.
- Part of ELFS, LiteBIRD and QUIJOTE collaboration.
- Hired to work in **data analysis** for **CMB-S4**.



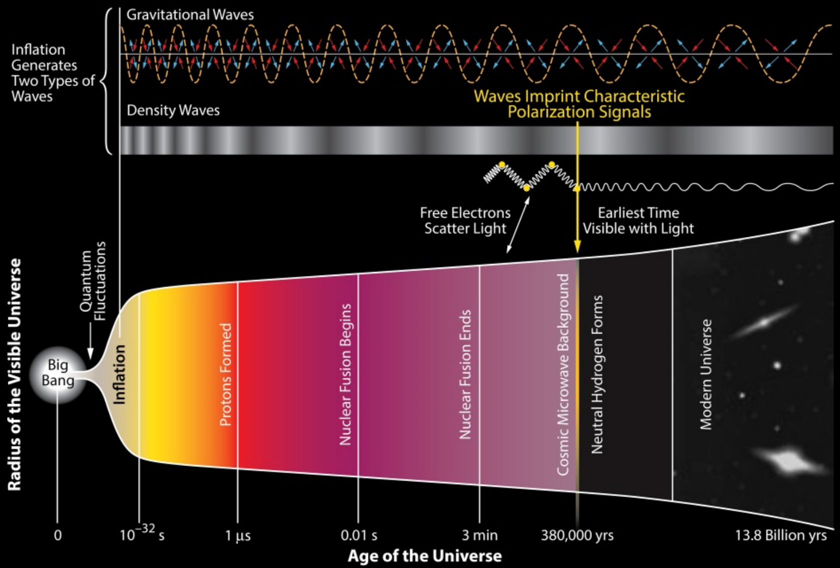
- Focused on:
  - **Low-frequency foregrounds** characterization.
  - **Forecast** on the detection of **r** with **ELFS**.
  - Mitigation of **systematic effects**: non-perfect **calibration** of **polarization angles** and its connection to an **isotropic birefringence angle**.

Overview

1. Primordial B-modes
2. Synchrotron Emission
3. Synchrotron with QUIJOTE-MFI
4. ELFS Initiative
5. Take home messages

Primordial B-modes

History of the Universe



PGWs amplitude

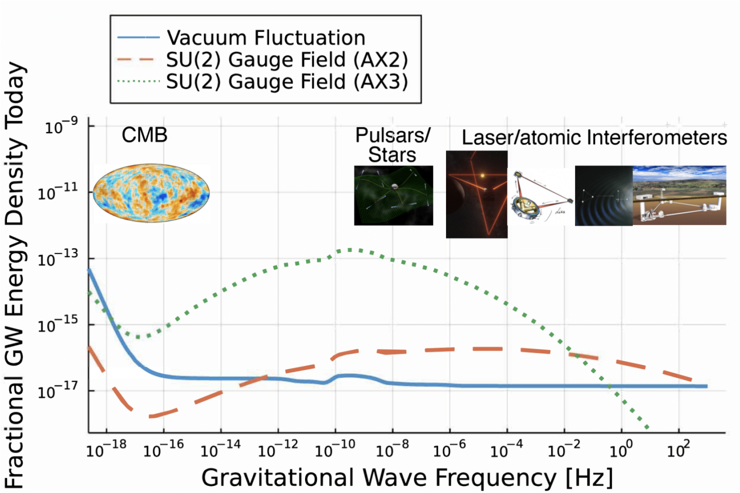


Fig. from **E. Komatsu** 2202.13919.

CMB B-modes

- Tensor fluctuations leave an **imprint** in the **B-mode** CMB power spectrum.
- The primordial B-mode signal is often parametrized with the **tensor-to-scalar** ratio r.
- Current best upper limit: $r < 0.032$, from BICEP/Keck+Planck+BAO **Tristram et al.** 2112.07961.
- Future experiments will target: **Simons Observatory**: $r \simeq 0.003$, **LiteBIRD**: $\sigma_r(r=0) = 1 \times 10^{-3}$, **CMB-S4**: $\sigma_r(r=0) = 5 \times 10^{-4}$.

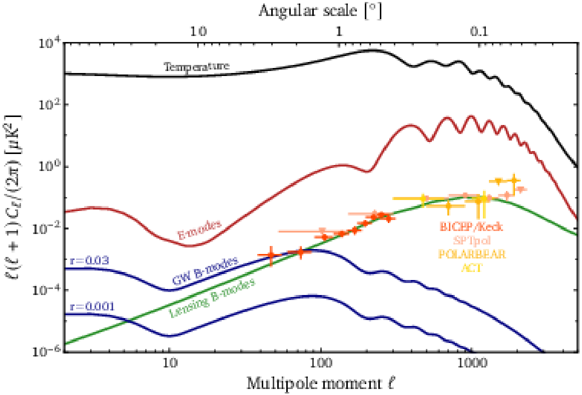


Fig. from **A. Achúcarro et al.** 2203.08128.

PGW detection challenges

- **Lensed E- to B-modes:**
  - CMB photons experience multiple small local deflections by the matter distribution in their path toward us.
  - Lensing leaks power from E- to B-modes.
  - The lensing contribution behaves like white noise at $\ell \lesssim 1000$ of $\sim 5\,\mu$K-arcmin.
- **Systematic effects:**
  - Sensitivity of planned and future CMB experiments will reach unprecedented levels $\rightarrow$ systematic errors will become a limiting factor regarding r detection.
  - The list of known systematic effects is large and depend on the experimental design.
- **Astrophysical foregrounds:**
  - Other physical mechanisms that emit in the microwave range.

Challenge: Astrophysical Foregrounds

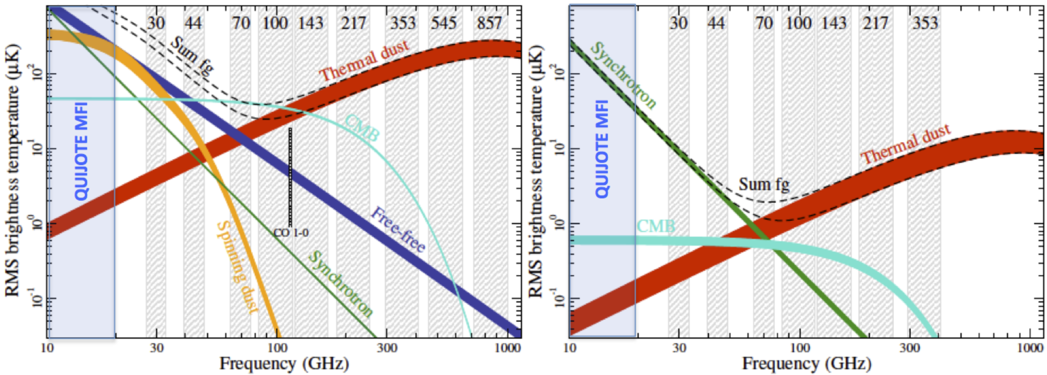


Fig. from **Radioforegrounds**

Challenge: Astrophysical Foregrounds

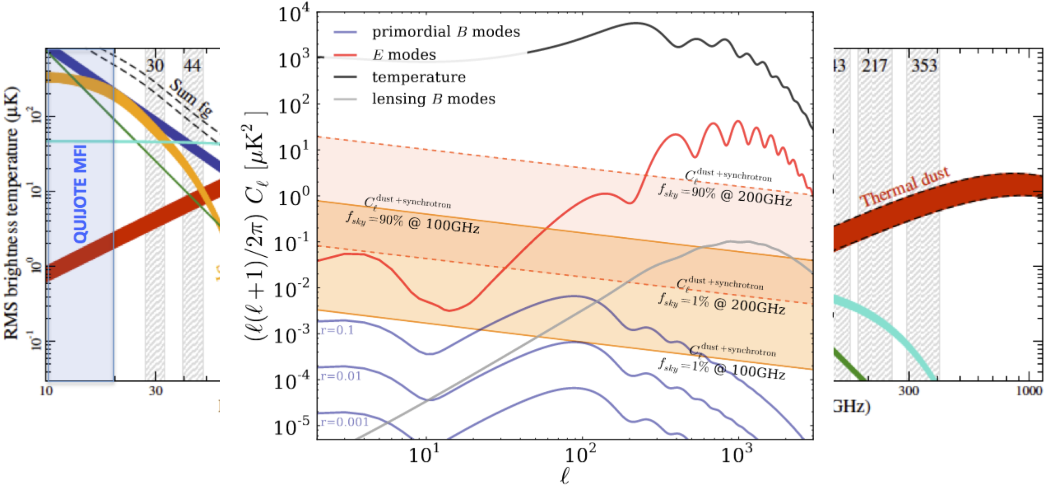


Fig. from **J. Errard et al. 1509.06770**

Synchrotron Emission

Synchrotron Emission

Synchrotron is generated by relativistic cosmic ray electrons spiraling around the Galactic magnetic field lines.

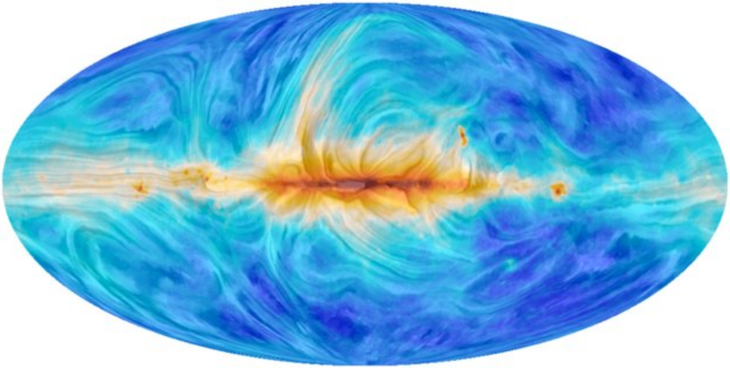


Fig. from ***Planck* Collaboration** 1502.01582.

Cosmic Rays Modeling (GALPROP)

Synchrotron is generated by relativistic cosmic ray electrons spiraling around the Galactic magnetic field lines.

Haslam et. al. 408 MHz Intensity map

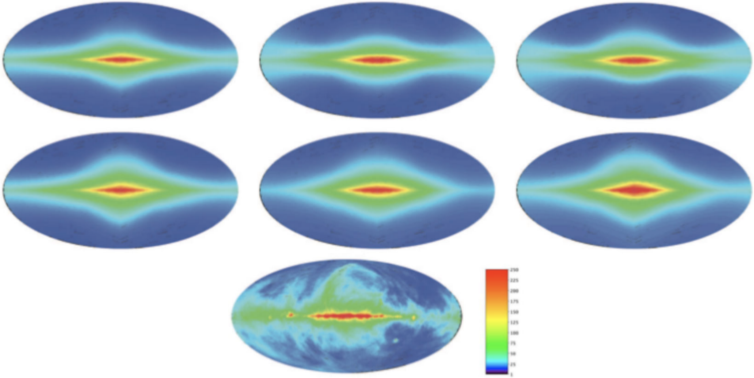


Fig. from **E. Orlando & A. Strong** 1309.2947.

Cosmic Rays Modeling (GALPROP)

Synchrotron is generated by relativistic cosmic ray electrons spiraling around the Galactic magnetic field lines.

WMAP 23 GHz Polarization Intensity map

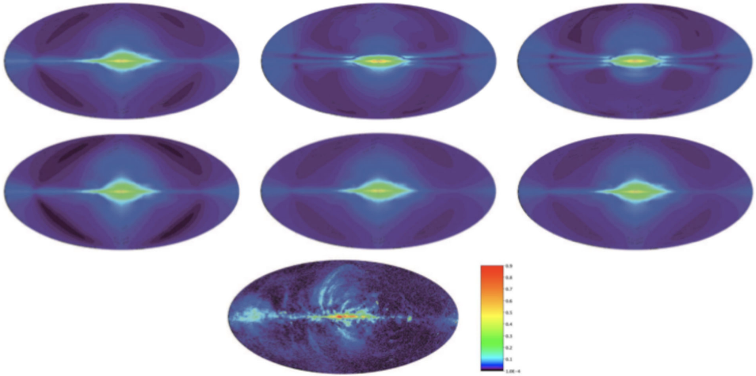


Fig. from **E. Orlando & A. Strong** 1309.2947.

Parametrization of the Synchrotron emission

Synchrotron is generated by relativistic cosmic ray electrons spiraling around the Galactic magnetic field lines.

- If the cosmic ray distribution is $N(E) \propto E^p$, the synchrotron SED is

$$S(\bar{n}) = A_s(\bar{n}) \left(\frac{\nu}{\nu_s} \right)^{\beta_s(\bar{n})}$$

- β_s has spatial and frequency variability. A model with curvature might be better:

$$S(\bar{n}) = A_s(\bar{n}) \left(\frac{\nu}{\nu_s} \right)^{\beta_s(\bar{n}) + c_s(\bar{n}) \log \frac{\nu}{\nu_{c_s}}}$$

Synchrotron with *Planck*

- Intensity model β_s with GALPROP prediction. Low-frequency foregrounds degeneracy.
- Polarization $\beta_s = -3.1$. S/N not sufficient to constrain this paremeter.

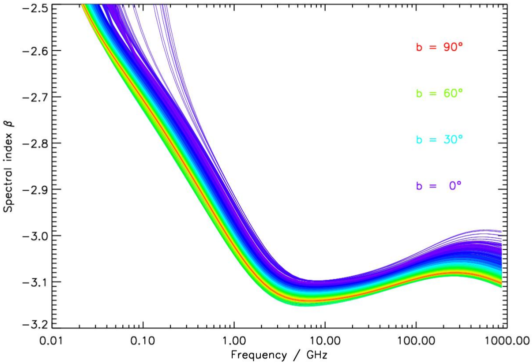


Fig. from ***Planck* collaboration** 1506.06660.

Ground-based experiments operating at low-frequencies

S-PASS

- 2.3 GHz
- Southern Hemisphere

C-BASS

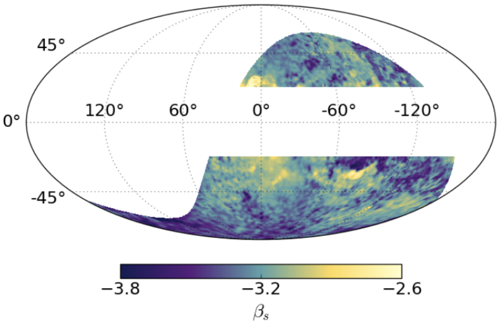
- 5 GHz
- Both Hemispheres

QUIJOTE-MFI

- 10-20 GHz
- Northern Hemisphere

Synchrotron with S-PASS

- Polarized synchrotron emission compatible with a power law with $\beta_s = -3.22 \pm 0.08$.
- Synchrotron contamination in CMB B-modes is at the level of $r_{\rm synch} \simeq 10^{-3}$.



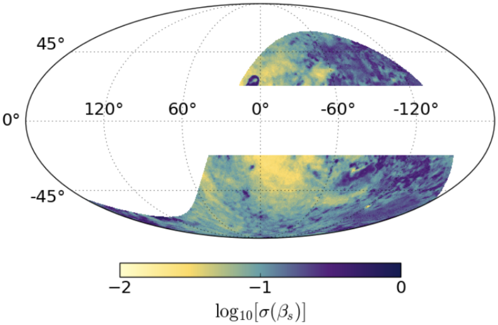


Fig. from **N. Krachmalnicoff et al.** 1802.01145.

Synchrotron with C-BASS

- From the intensity analysis found hints of curvature when comparing Haslam-C-BASS vs. Haslam-WMAP K ($\Delta\beta_s = 0.06 \pm 0.02$).
- From the polarization analysis they found larger spatial variations.

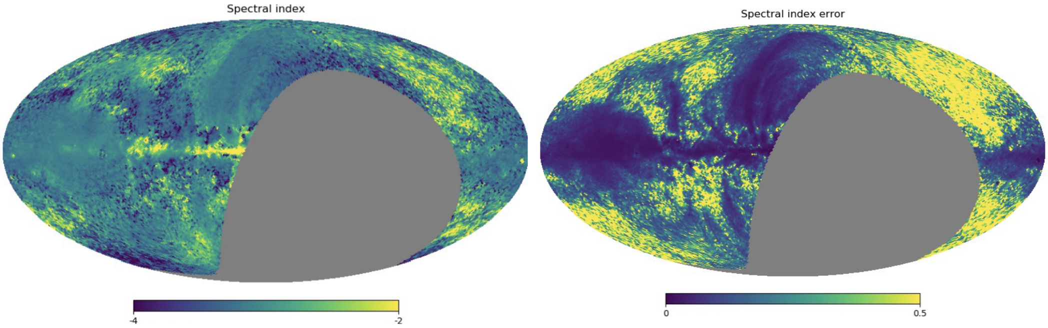
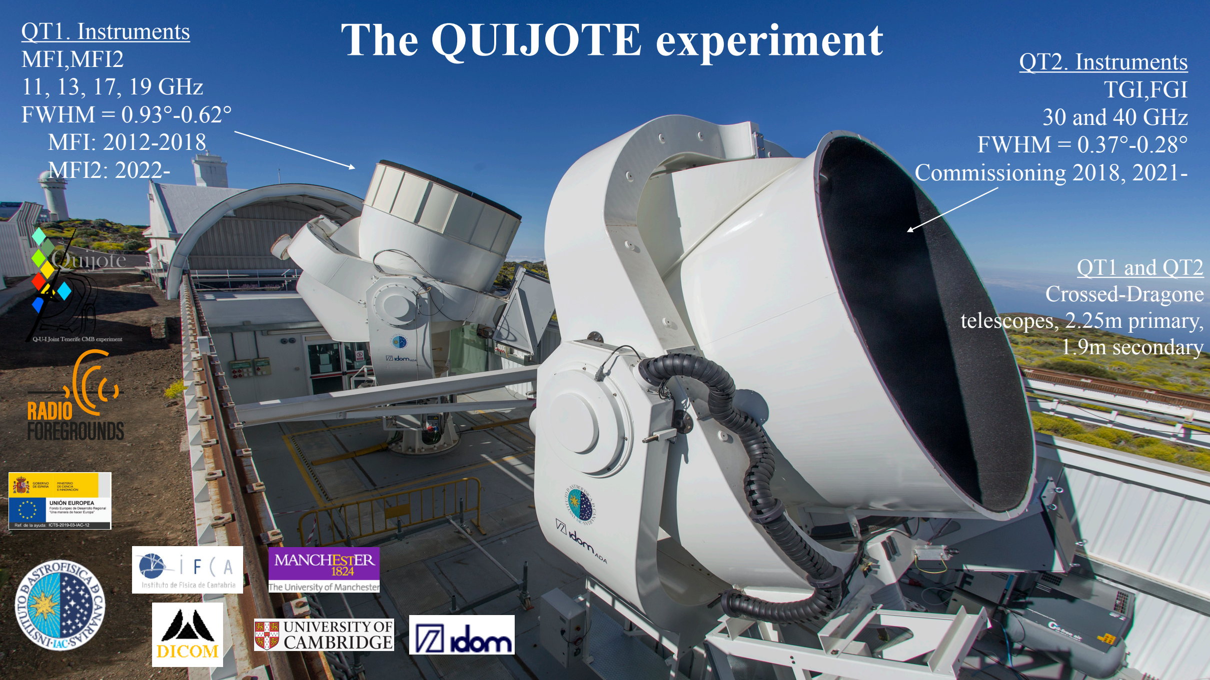


Fig. from **Angela Taylor**'s talk at *From Planck to the future of CMB*.

Synchrotron with QUIJOTE-MFI

The QUIJOTE experiment



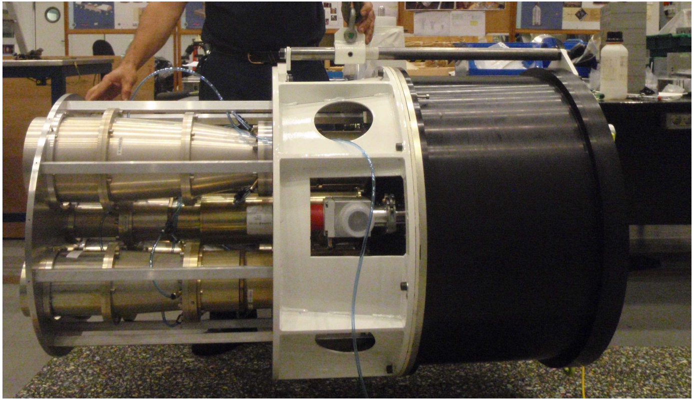
QT1. Instruments
MFI,MFI2
11, 13, 17, 19 GHz
FWHM = 0.93°-0.62°
MFI: 2012-2018
MFI2: 2022-

QT2. Instruments
TGI,FGI
30 and 40 GHz
FWHM = 0.37°-0.28°
Commissioning 2018, 2021-

QT1 and QT2
Crossed-Dragone telescopes, 2.25m primary, 1.9m secondary

QUIJOTE-MFI

- Nov. 2012 - Oct. 2018.
- 10-20 GHz.
- 4 horns (polarimeters):
  - Horn 1 & 3: 10-14 GHz.
  - Horn 2 & 4: 16-20 GHz.
- 4 frequency channels: 11, 13, 17, 19 GHz.
- $\Delta\nu = 2$ GHz.
- Polarization sensitivity: $\sim$ 35-40μK deg^{-1}.



QUIJOTE-MFI scientific results

MFI early results

I. Intensity and polarization of the AME in the Perseus molecular complex **(Génova-Santos et al. 2015)**.
II. Polarization measurements in the Galactic MCs W43 and W47 and SNR W43 **(Génova-Santos et al. 2017)**.
III. Microwave spectrum of intensity and polarization in the Taurus MC complex and L1527 **(Poidevin et al. 2019)**.

MFI wide survey

IV. A northern sky survey at 10-20 GHz with the Multi-Frequency Instrument **(Rubino-Martín et al. 2023)**.
V. W49, W51 and IC443 SNRs as seen by QUIJOTE-MFI **(Tramonte et al. 2023)**.
VI. The Haze region and the Galactic Centre as seen by QUIJOTE-MFI **(Guidi et al. 2023)**.
VII. Galactic AME sources in the MFI wide survey **(Poidevin et al. 2023)**.
VIII. Component separation in polarization with the QUIJOTE-MFI wide survey. **(de la Hoz et al. 2023)**.
IX. Radio-sources in the QUIJOTE-MFI wide survey **(Herranz et al. 2023)**.

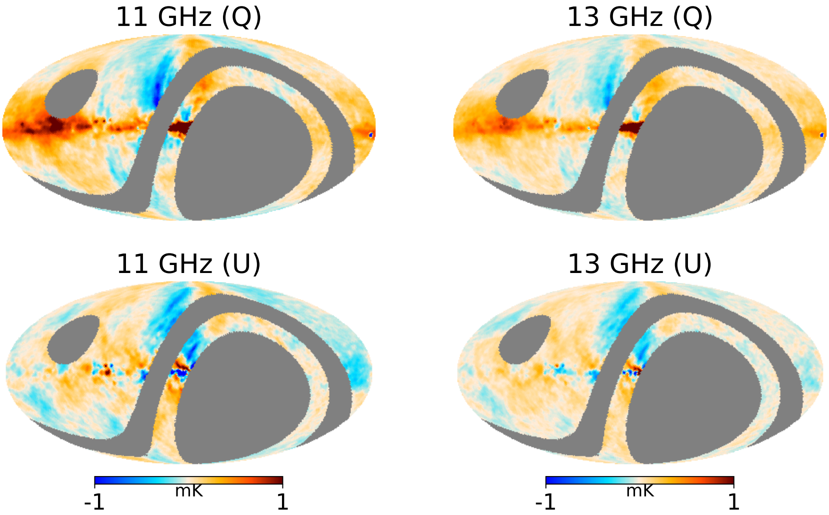
(IV–IX: **Published in MNRAS**)

X. Spatial variability of AME parameters in the Galactic Plane **(Fernández-Torreiro et al. submitted)**.
XI. Polarised synchrotron loops and spurs. **(Peel et al. in prep)**.
XII. Analysis of the polarised synchrotron emission at the power spectrum level **(Vansyngel et al. in prep)**.
XIII. Intensity and polarization study of Supernova Remnants **(López-Caraballo et al. in prep)**.
XIV. The FAN region as seen by QUIJOTE-MFI **(Ruiz-Granados et al. in prep)**.
XV. The North Galactic Spur as seen by QUIJOTE-MFI **(Watson et al. in prep)**.
XVI. Component separation in intensity with the QUIJOTE-MFI wide survey **(de la Hoz et al. in prep)**.

Other MFI papers

- Detection of spectral variations of AME with QUIJOTE and C-BASS **(Cepeda-Arroita al. 2021)**.
- The PICASSO map-making code: application to a simulation of the QUIJOTE MFI survey **(Guidi et al. 2021)**.
- Searching for dark-matter waves with PPTA and QUIJOTE pulsar polarimetry **(Castillo et al. 2022)**.
- MFI data processing pipeline **(Genova-Santos et al. in prep)**.

Sky Signal Maps I. QUIJOTE-MFI



Wide survey: $\sim$ 51% of sky. 52 arc min resolution.

Sky Signal Maps II. Ancillary Data

Planck

- PR4 (NPIPE).
- Pol. LFI: $30, 44, 70$ GHz.
- Pol. HFI: $100, 143, 217$ and 353 GHz.

WMAP

- Polarized 9-year maps.
- K and Ka (22.8 and 33.1 GHz) bands.

All maps have:

- $N_{side} = 64$.
- $FWHM = 2$ deg.
- Color corrections w/ `fastcc`.

Covariance matrices

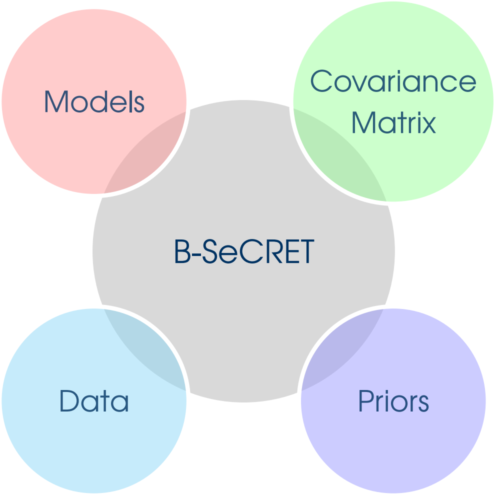
- Among frequency detectors.
- From noise simulations.
- 11 and 13 GHz are correlated.
- The rest are independent.

Component Separation Methodology. B-SeCRET

B-SeCRET

- Bayesian
- Parametric
- Maximum likelihood
- MCMC

E. de la Hoz et al. 2002.12206



Polarized Sky Components: Models

Synchrotron

Power law model:

$$\begin{bmatrix} \mathbf{a_s}^{Q} \\ \mathbf{a_s}^{U} \end{bmatrix} \left(\frac{\nu}{\nu_s}\right)^{\beta_\mathbf{s}}$$

Power law with curvature model:

- Uniform curvature.
- Spatially varying curvature.

$$\begin{bmatrix} \mathbf{a_s}^{Q} \\ \mathbf{a_s}^{U} \end{bmatrix} \left(\frac{\nu}{\nu_s}\right)^{\beta_\mathbf{s}+\mathbf{c_s}(\nu/\nu_s)}$$

CMB

Black-body model:

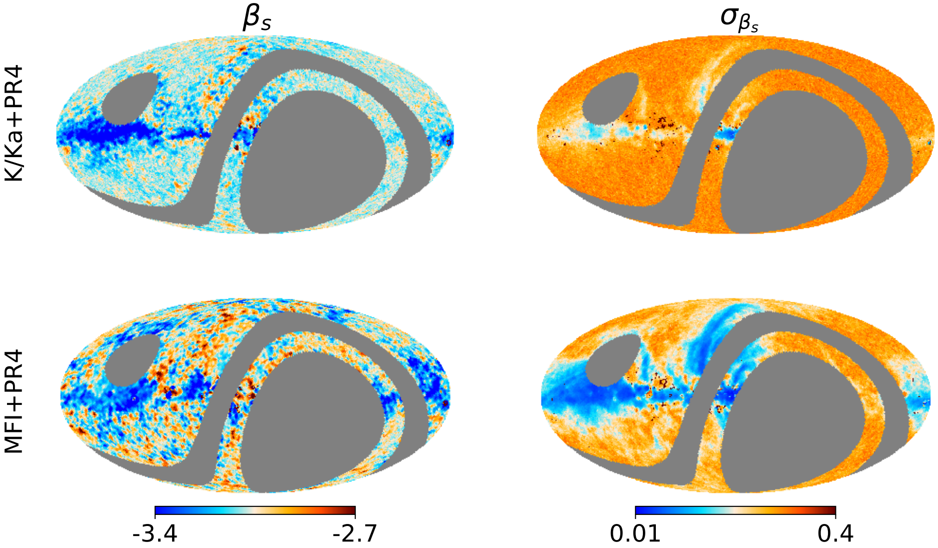
$$\begin{bmatrix} \mathbf{c}^{Q} \\ \mathbf{c}^{U} \end{bmatrix} \frac{x^2 e^x}{(e^x - 1)^2}$$

Thermal Dust

Modified black-body model:

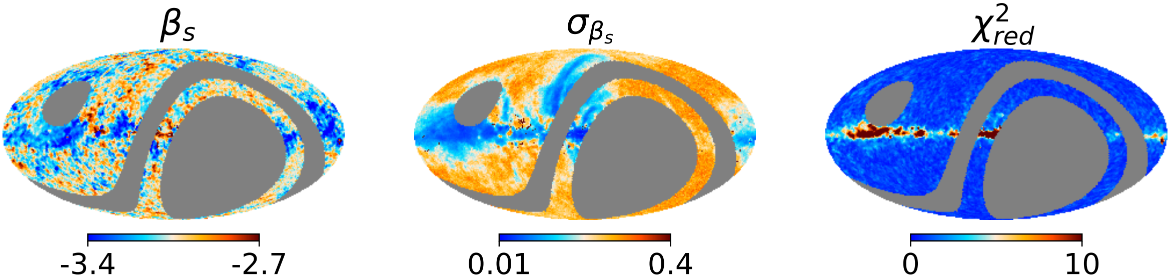
$$\begin{bmatrix} \mathbf{a_d}^{Q} \\ \mathbf{a_d}^{U} \end{bmatrix} \left(\frac{\nu}{\nu_d}\right)^{\beta_\mathbf{d}-2} \frac{B(\nu, \mathbf{T_d})}{B(\nu_d, \mathbf{T_d})}$$

Synchrotron's Spectral Index I. Datasets

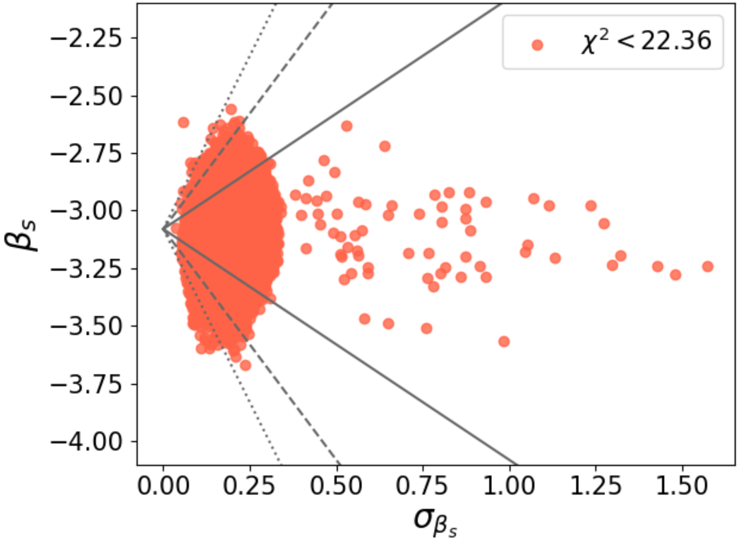


Synchrotron's Spectral Index I. Datasets

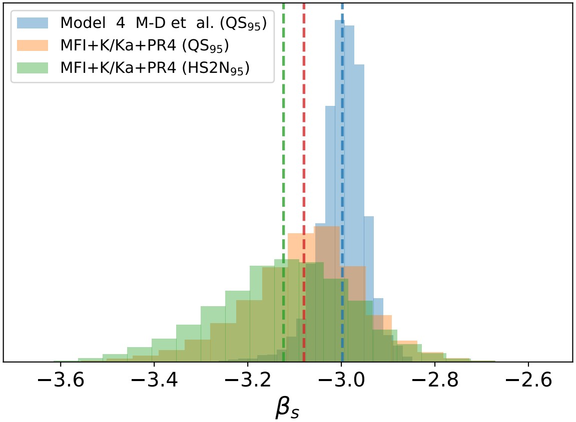
MFI+K/Ka+PR4



Synchrotron's Spectral Index II. Spatial Variability

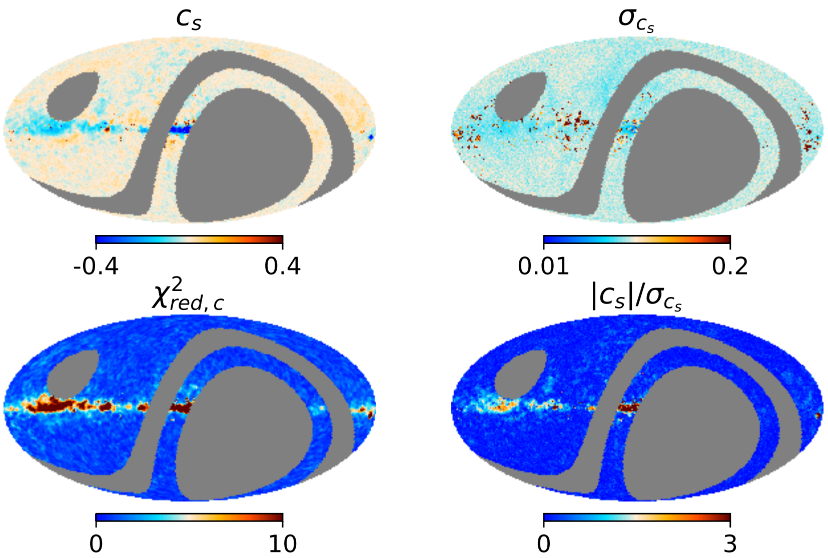


Synchrotron's Spectral Index III. Comparison with other β_s templates

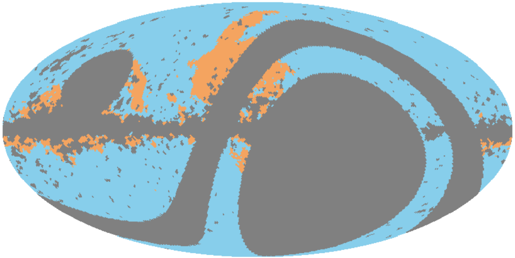


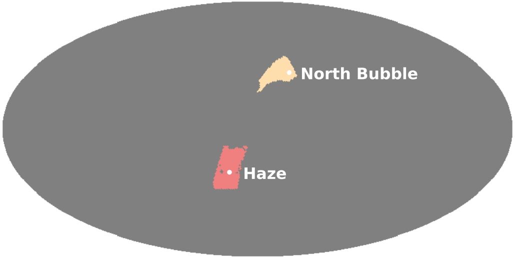
- Only pixels whose χ^2 is at 95% confidence.
- MFI+K/Ka+PR4: $\mathcal{N}(-3.08, 0.13^2)$.
- PySM: $\mathcal{N}(-3.00, 0.05^2)$.
- $\dfrac{\sigma_{\beta_s}(\mathrm{MFI + K/Ka + PR4})}{\sigma_{\beta_s}(\mathrm{PySM})} \sim 2.6\,.$

Curvature I. Power law with Spatially Varying Curvature



Curvature II. Power law with Uniform Curvature



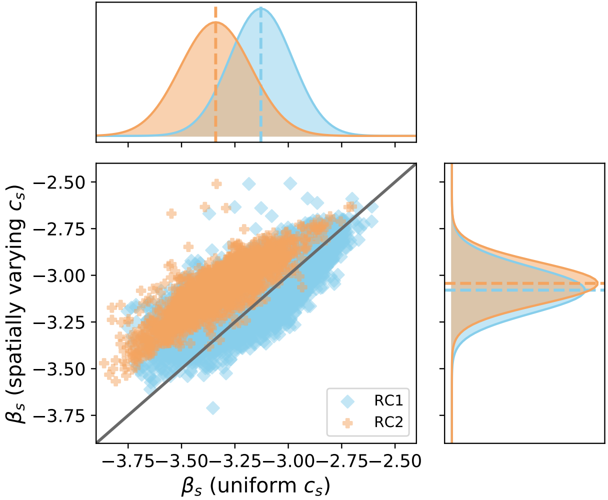


Region	c_s^R	$\sigma_{c_s^R}$	$\lvert c_s^R \rvert / \sigma_{c_s^R}$
RC1	-0.0797	0.0012	63.75
RC2	-0.2768	0.0017	161.57
Haze	0.041	0.010	4.23
North bubble	-0.083	0.007	11.43

Not statistical significant results to elucidate which model agrees better with the data.

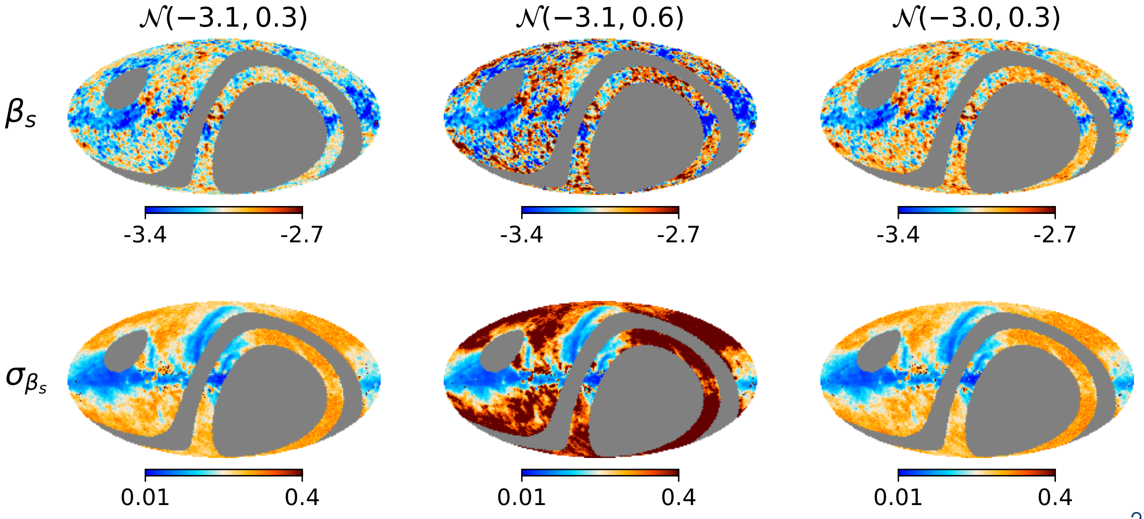
F. Guidi et al. 2301.05115

Curvature III. Recovered β_s with spatially varying and uniform curvature

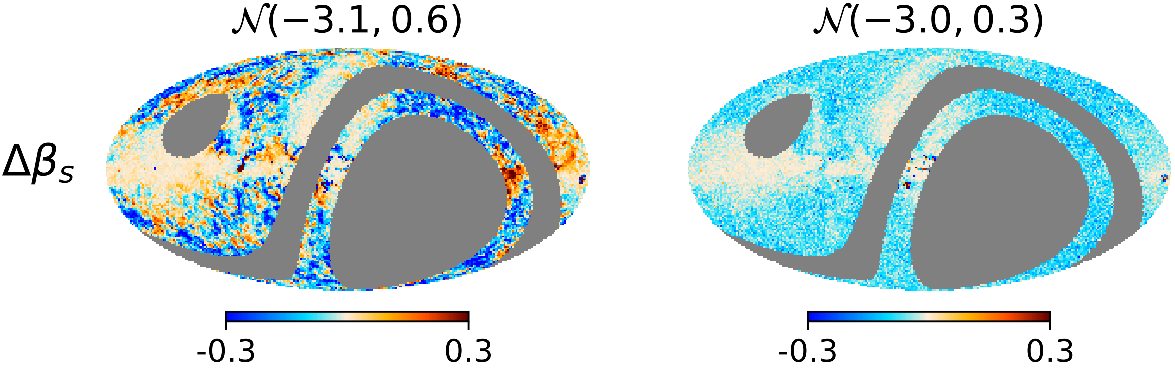


β_s and c_s are not independent. Either more sensitive data at the QUIJOTE frequencies or data at lower frequencies are required to break the degeneracy.

Robustness with respect to the Prior Information



Robustness with respect to the Prior Information



Summary

- **QUIJOTE-MFI** data **improves** significantly the β_s **characterization**.
- We find statistically **significant** β_s **spatial variability** across the sky.
- Current models might **underestimate** the **dispersion** of the synchrotron's spectral parameter.
- The **synchrotron models** considered **fit well** the data **outside the galactic plane**.
- We **detect uniform curvature**.
- Results **not robust** enough to determine which **model is favoured**.
- β_s estimation is **prior independent** in the **high signal-to-noise synchrotron** regions.

ELFS Initiative

European Low-Frequency Survey

- European Initiative to measure the **low-frequency** microwave sky from **ground**.
- Main **participants**:
  - France (IRAP).
  - Italy (SISSA and University of Milan).
  - Spain (IAC and IFCA).
  - U.K (University of Oxford).
- Two **strategies** considered:
  - **Ambitious**: measure from **both hemispheres** the frequency range **10-120 GHz** with a enough sensitivity to obtain $\sigma_r \lesssim 10^{-3}$.
  - **Economic**: be a **complement** to other CMB experiments by helping constrain the low-frequency foregrounds **(10-40 GHz)**.
- Initial exploratory study by **E. de la Hoz et al.** 2002.12206.

Instrumental setup

Three frequency **bands** (set by atmosphere)

- Low-frequency (lb): 10-20 GHz.
- Medium-frequency (mb): 26-46 GHz.
- High-frequency (hb): 75-120 GHz.

Studied optimal # of channels per band.
Default: (10,10,15)

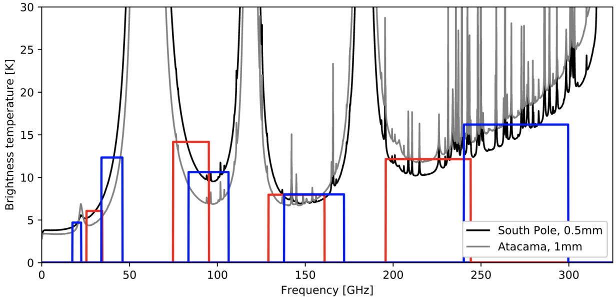
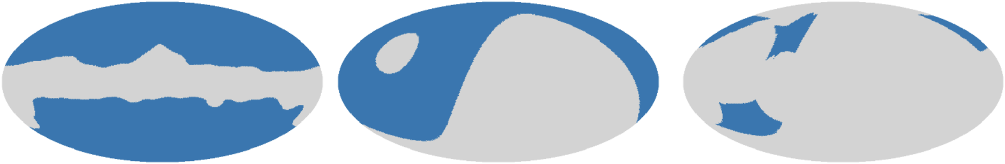


Fig. from **CMB-S4 collaboration** 2008.12619

Stopping at 120 GHz allow us to study only the **Rayleigh-Jeans** part of the thermal dust. Thus, we avoid possible **biases** due to **incorrect modeling**.
M. Remazeilles et al. 1509.04714, **B. Hensley et al.** 1709.07897.

Observational strategies – Sky coverage

Three different sky **strategies** considered:



(a) Planck: 70% galactic plane mask

(b) QUIJOTE: Wide Survey

(c) QUIIJOTE: Cosmological-areas

(a) Default: **Two** experiments, one in each **Hemisphere** (e.g., at Atacama and Tenerife).

(b) One experiment in the **Northern Hemisphere** with a **wide survey**.

(c) One experiment in the **Northern Hemisphere** focused on **specific areas**.

Signal map simulations

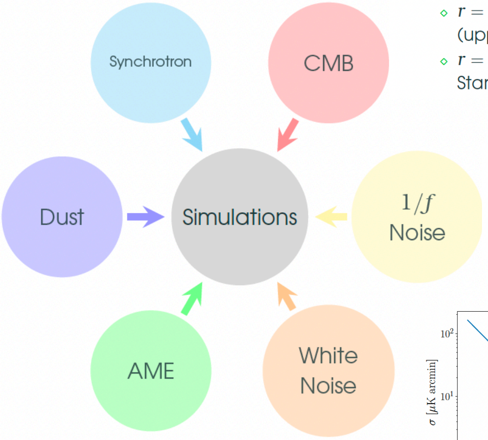
Foregrounds:

$$\text{Synch.:}\quad \begin{bmatrix} \mathbf{a_s}^{Q} \\ \mathbf{a_s}^{U} \end{bmatrix} \left(\frac{\nu}{\nu_s}\right)^{\beta_s + \mathbf{c_s}(\nu/\nu_{cs})}$$

$$\text{Dust:}\quad \begin{bmatrix} \mathbf{a_d}^{Q} \\ \mathbf{a_d}^{U} \end{bmatrix} \left(\frac{\nu}{\nu_d}\right)^{\beta_d}$$

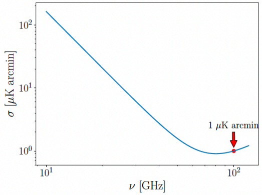
$$\text{AME:}\quad \begin{bmatrix} \mathbf{a_a}^{Q} \\ \mathbf{a_a}^{U} \end{bmatrix} \left(\frac{\nu}{\nu_a}\right)^{\beta_a + \mathbf{c_a}(\nu/\nu_{ca})}$$

- Foregrounds are generated and fitted with the same model.
- Pixelwise fit.
- Joint probability.



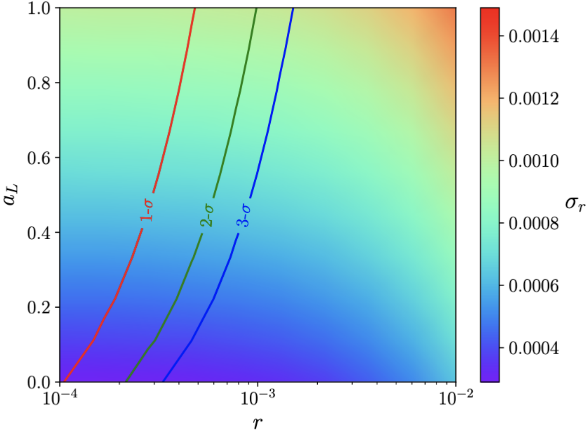
- Two tensor-to-scalar ratio considered:
  - $r = 0$: no primordial B-modes (upper limit).
  - $r = 3.7 \cdot 10^{-3}$ compatible with Starobinsky's model.

$$N_\ell = N_w + N_{\text{corr}} \left(\frac{\ell}{\ell_{\text{knee}}}\right)^{\gamma}$$



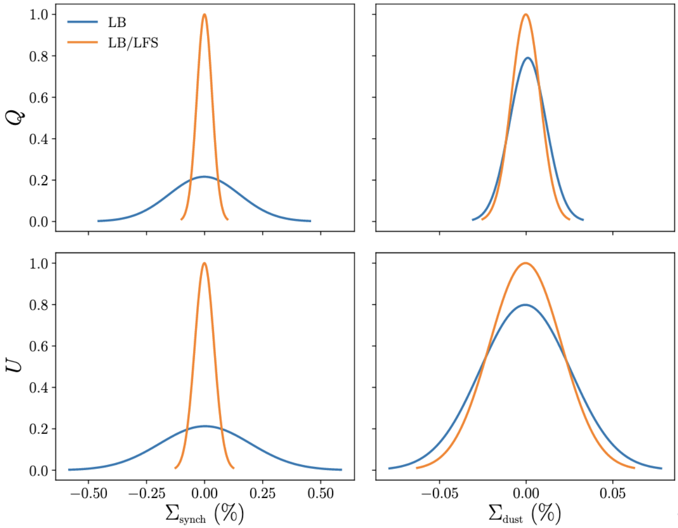
Ambitious proposal: Detection of the tensor-to-scalar ratio

- An experiment with **two experiments** one in the Northern Hemisphere and the other in the Southern can reach sensitivities of $\boldsymbol{\sigma_r \sim 10^{-3}}$.
- This **sensitivity worsens** when considering just **one experiment** on the Northern Hemisphere in both cases.
- Including **delensing** techniques can help reduce σ_r more than a more sensitive experiment.



Economic proposal: Improvement of Foreground characterization

- This type of experiment is a great **complement** to other missions such as **LiteBIRD**.
- Only using lb and mb **(10-40 GHz)**.
- The combination of data lead to a **significant improvement** of the **synchrotron** characterization and **slight improvement** in the **thermal dust**.



ELFS-S status

- Proposal to **replace** the **Simons Array**'s (SA's) **220/280 GHz** receiver with a **Europe**-supplied **6-12 GHz** receiver.
- Plan is to install a **C-BASS-like 6–12 GHz** receiver first, and add a second Europe-supplied receiver from **10–20 GHz (QUIJOTE MFI2)** later.
- **Better combination** between **SA** and **SO**, since SO will have a SAT at 220/280 GHz.

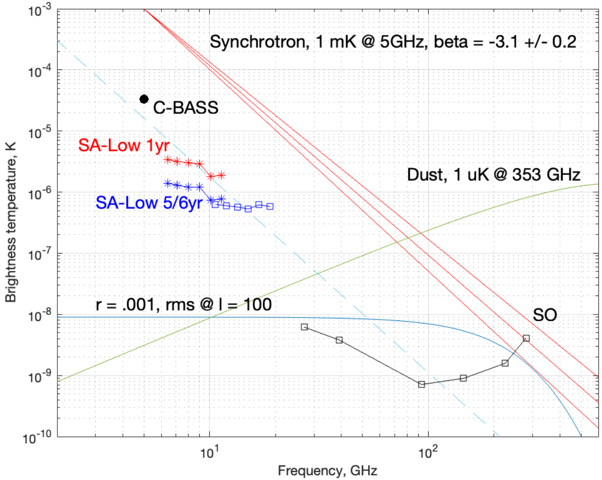


Fig. from **Mike Jones** (Oxford)

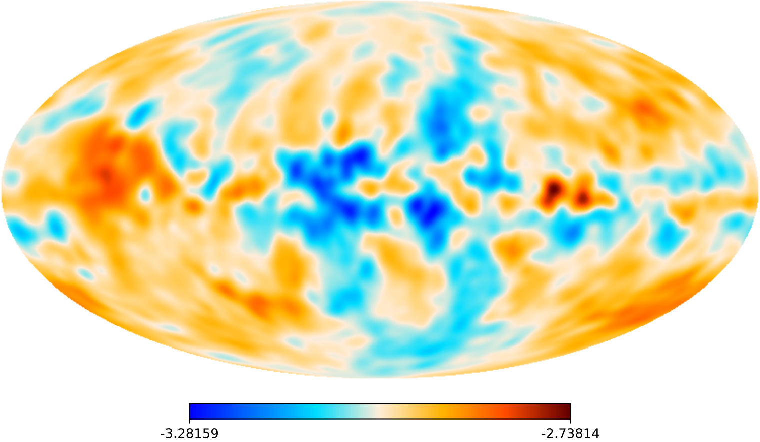
Take home messages

Take home messages

- The **characterization** of astrophysical **foregrounds** is **crucial to** remove them properly from the signal sky maps and **detect primordial B-modes**.
- Planned CMB experiments include several bands to explore the complexity of the thermal dust. However, the **synchrotron** emission might be more **complicated** than expected and **hinder** our attempts of **detecting** r.
- The **QUIJOTE-MFI** instrument data help **improvement** significantly with the **characterization** of the **synchrotron** emission and shows **hints** of it being more **complex** than previously thought.
- Initiatives like **ELFS** have shown that a **low-frequency** instrument can reach **sensitivities** on the order of $\boldsymbol{\sigma_{\mathbf{r}}} \sim \mathbf{10^{-3}}$ or help **characterize** the **low-frequency foregrounds** which is mandatory for a **robust detection claim.**

Back-up

Simulation codes' synchrotron's spectral index template



M.-A. Miville-Deschenes et al. 0802.3345

RFI correction. Function of the Declination (FDEC)

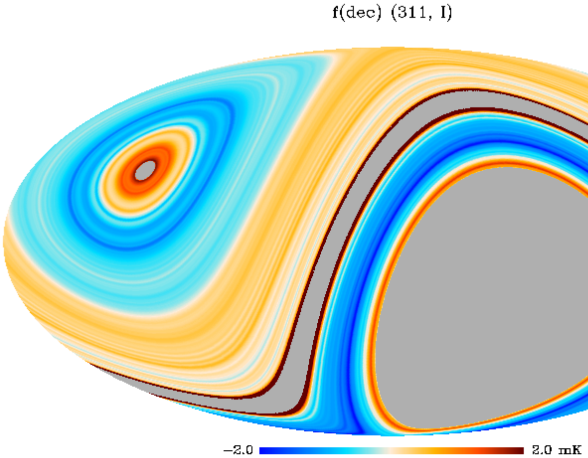
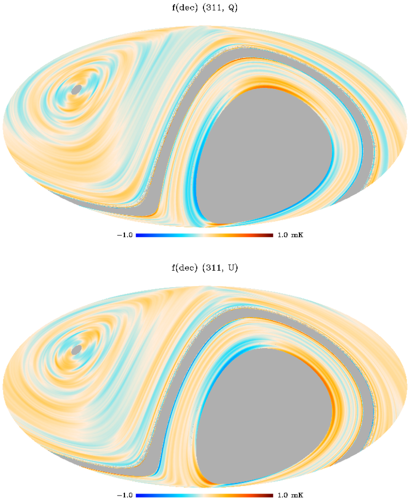


Figure from **J. A. Rubiño-Martín** et al., 2022, MNRAS, submitted.

RFI correction. Function of the Declination (FDEC)



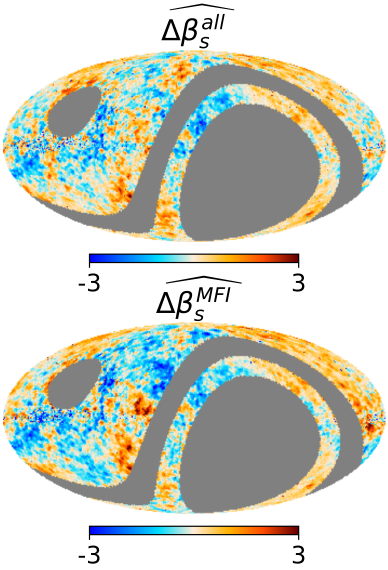


Fig. from **J. A. Rubiño-Martín** et al., 2022, MNRAS, submitted.

Covariance Matrices and Instrumental Effects

Covariance matrices

- Covariance among frequency detectors per pixel.
- Calculated from noise simulations.
- 11 and 13 GHz channels are correlated.
- The rest are assumed independent.

J. A. Rubiño-Martín et al., 2023, MNRAS.

Noise simulations

- **QUIJOTE**: Collaboration noise simulations.
- **WMAP**: white noise simulations.
- **Planck**: Available noise simulations for PR3 and PR4.

Detectors response

Colour corrections with `fastcc`.

Polarized Sky Components II. Priors

Synchrotron

Power law model:

$$\beta_s \in \mathcal{N}(-3.1, 0.3)$$

Power law with curvature model:

- Uniform curvature.
- Spatially varying curvature.

$$\beta_s \in \mathcal{N}(-3.1, 0.3)$$

$$\mathbf{c_s} \in \mathcal{N}(0, 0.1)$$

CMB

Black-body model:

None

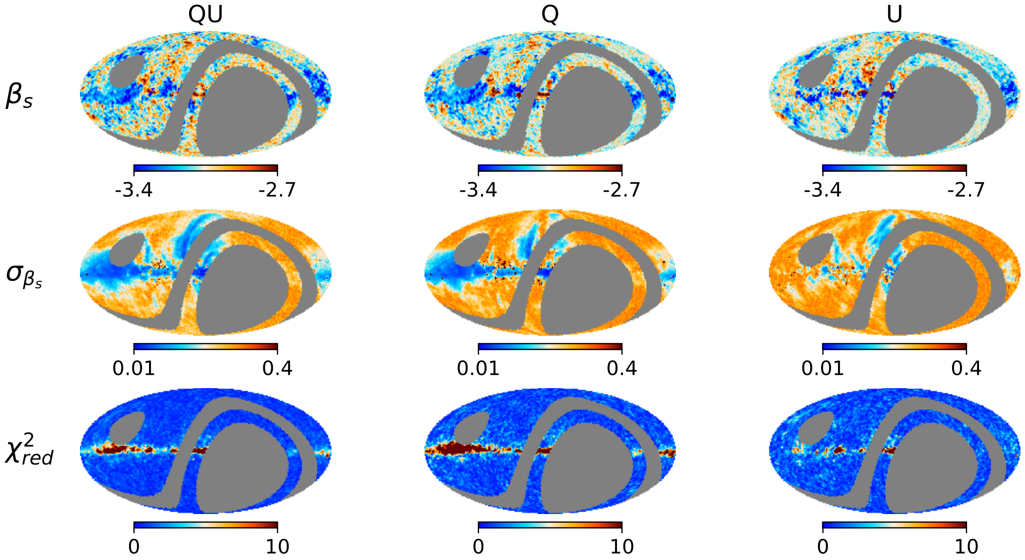
Thermal Dust

Modified black-body model:

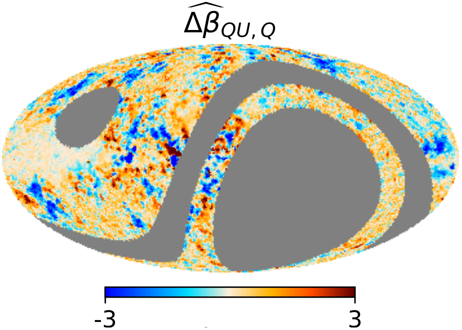
$$\beta_d \in \mathcal{N}(1.55, 0.1)$$

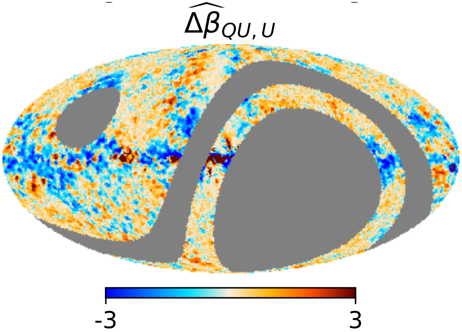
$$\mathbf{T_d} \in \mathcal{N}(21, 3)$$

Synchrotron Spectral Index from Independent Q and U analysis I

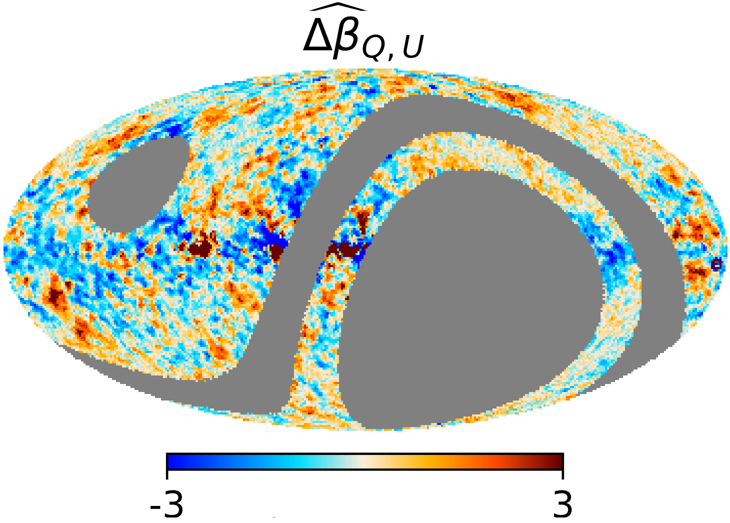


Synchrotron Spectral Index from Independent Q and U analysis II

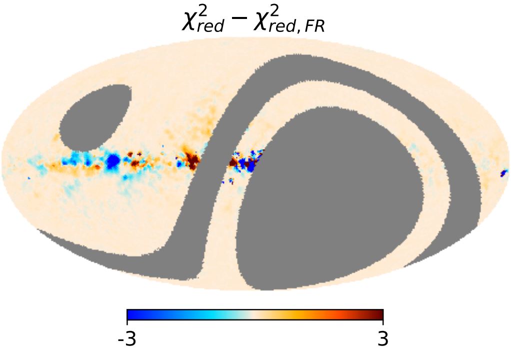


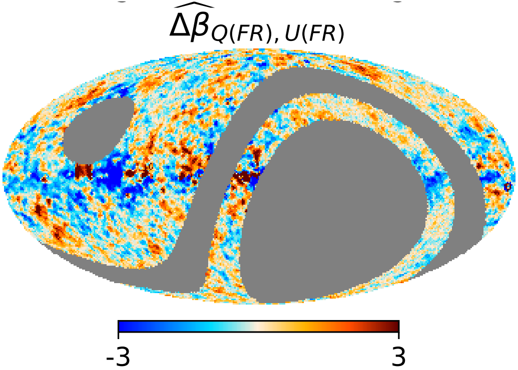


Synchrotron Spectral Index from Independent Q and U analysis III



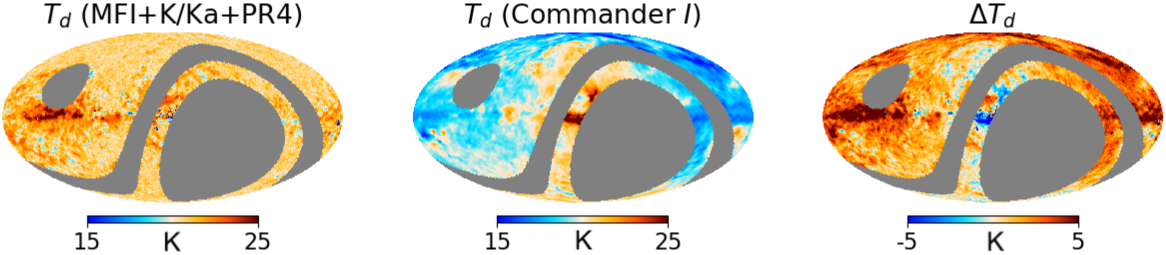
Faraday Rotation



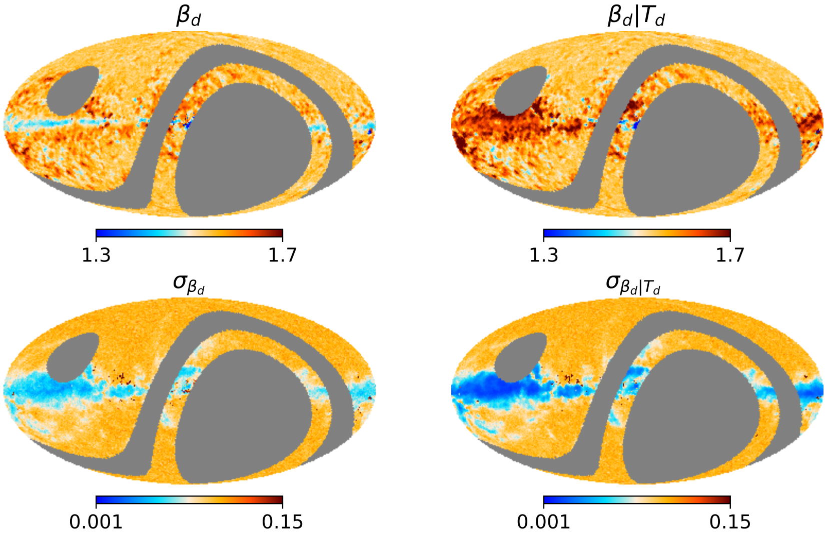


S. Hutschenreuter et al. 2102.01709

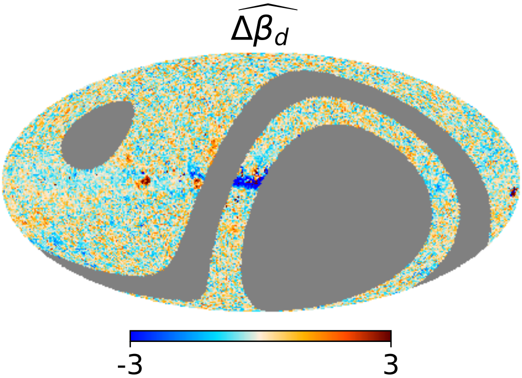
Thermal Dust Temperature



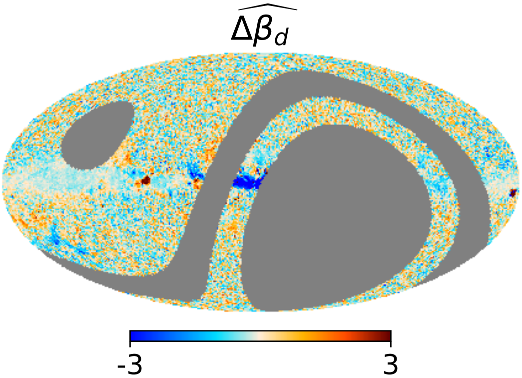
Thermal Dust Spectral Index



Spectral indices differences II. MFI+K/Ka+PR4 vs. K/Ka+PR4

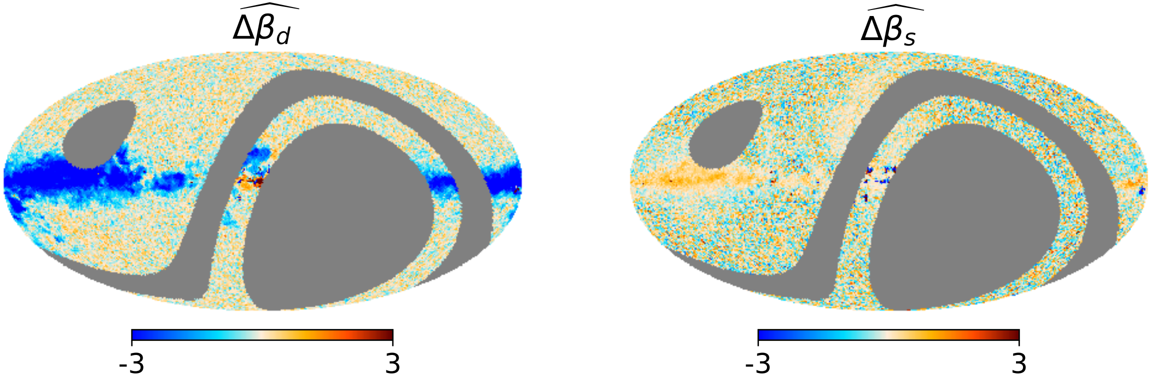


Free T_d

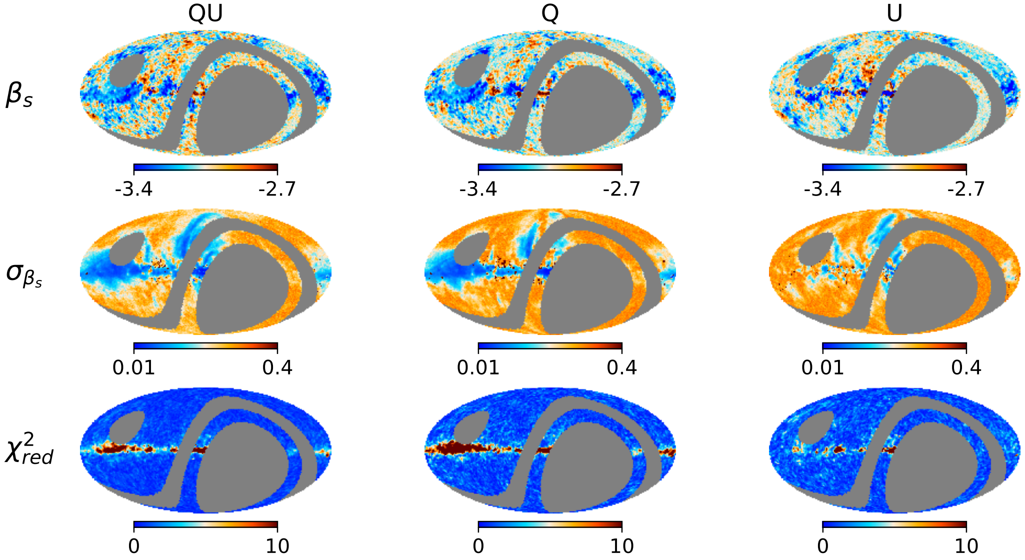


Fixed T_d

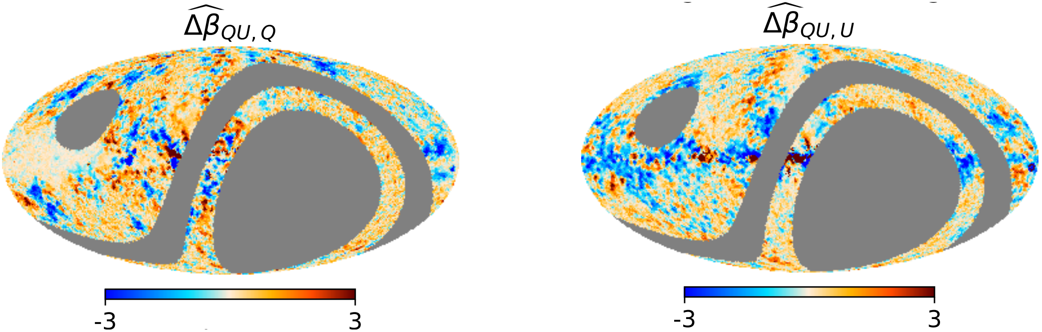
Spectral indices differences I. Free vs. fixed T_d parameter



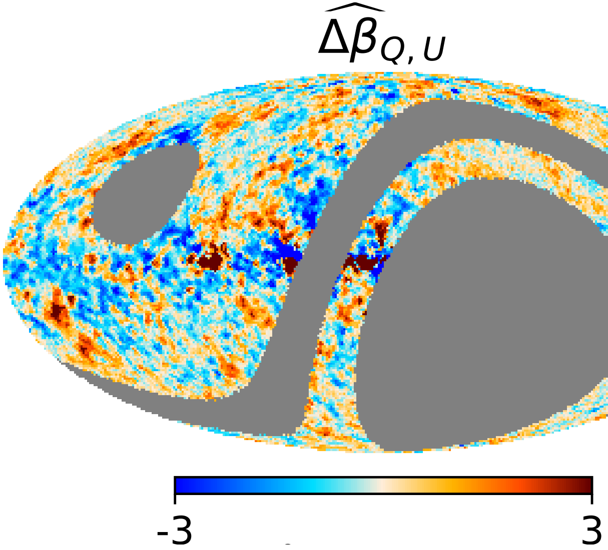
Synchrotron Spectral Index from Independent Q and U analysis I



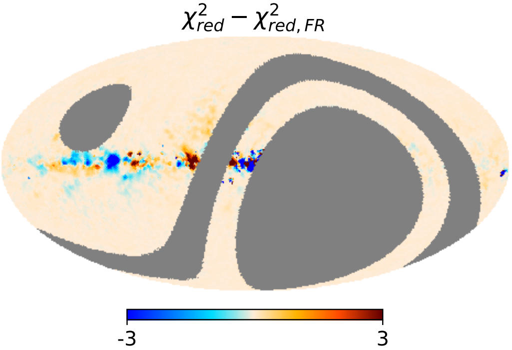
Synchrotron Spectral Index from Independent Q and U analysis II

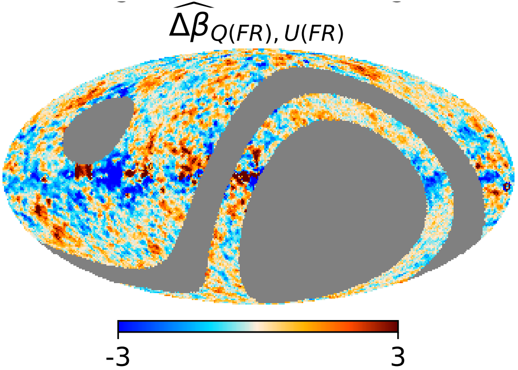


Synchrotron Spectral Index from Independent Q and U analysis III



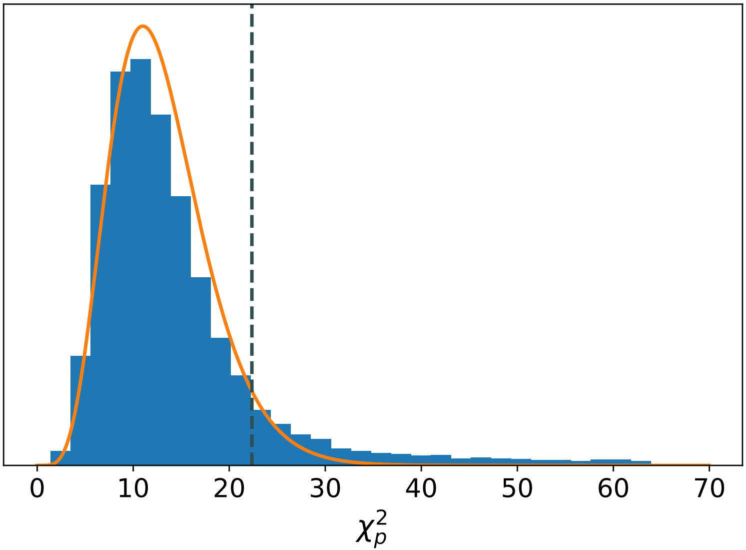
Faraday Rotation



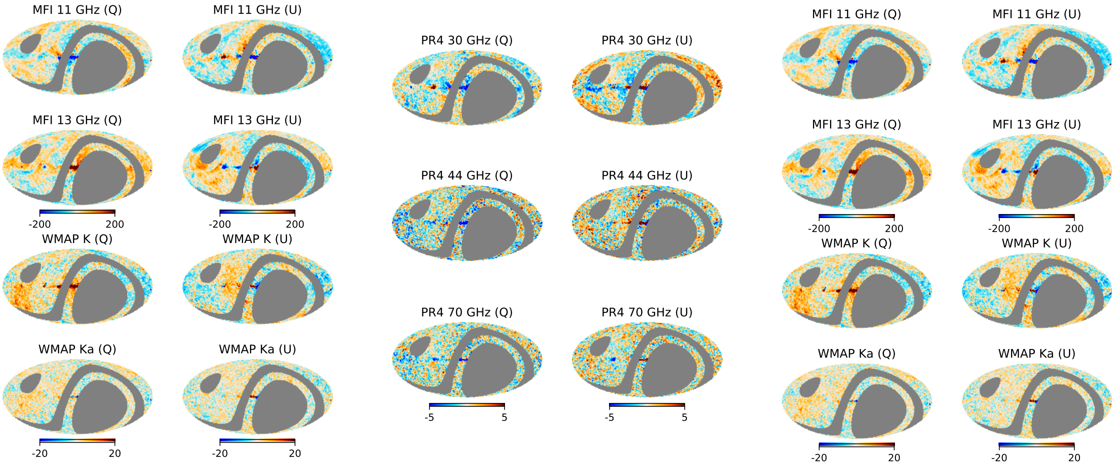


S. Hutschenreuter et al., 2021, arXiv:2102.01709.

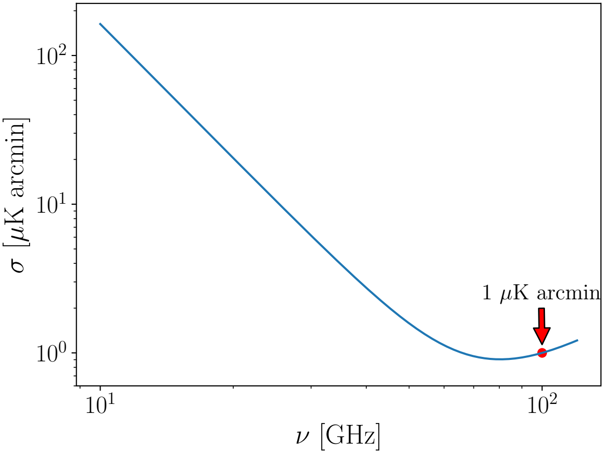
χ^2 distribution



Residuals maps



Proposed Experiment. Sensitivity



- Mimics the frequency dependence of the major contaminants: synchrotron and thermal dust
- $1\mu K$ arc min @ 100 GHz.
- synch. contribution = dust contribution @ 70 GHz
- In the default case we considered (10,10,15) channels per band.

LiteBIRD

- Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection.
- JAXA's L-class mission selected in May 2019
- Expected launch in late 2029.
- All-sky 3-year survey, from Lagrangian point L2.
- Large frequency coverage (40–402 GHz, 15 bands)
- 70–18 arcmin angular resolution.
- Final combined sensitivity: 2.2 μK·arcmin.