Microwave Characterization of Large Supernova Remnants with the Quijote-MFI wide survey

Cygnus Loop, HB21, CTB80, CTA1, HB9, Tycho

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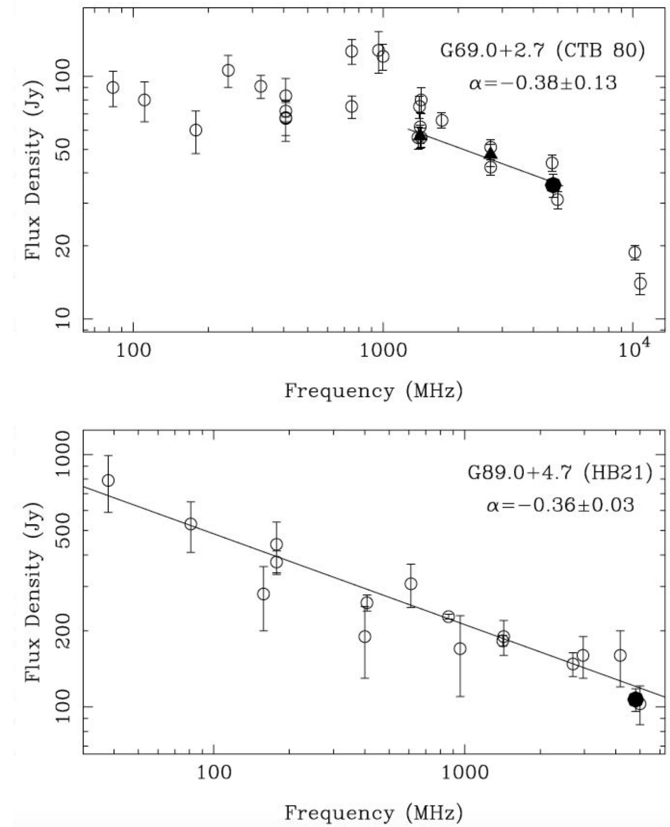
Supernova Remnants: Motivation

In radio, SNRs have relatively flat, non-thermal spectra, with spectral indices -0.3 up to -0.7. At higher frequencies, the spectral index can be steeper.

Motivation

- The 10–100 GHz range is poorly exploited for the SNR description, particularly polarization.

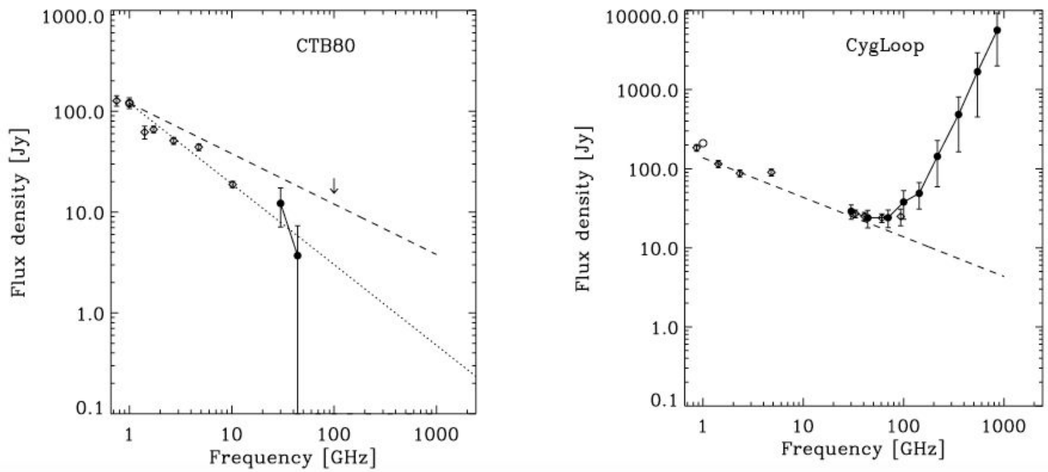
Sino-German λ6cm



Gao+2011, A&A, 529, A159 (15 SNRs)

***Planck* intermediate results**

XXXI. Microwave survey of Galactic supernova remnants



Planck+2016, A&A, 586, A134 (16 SRNs)

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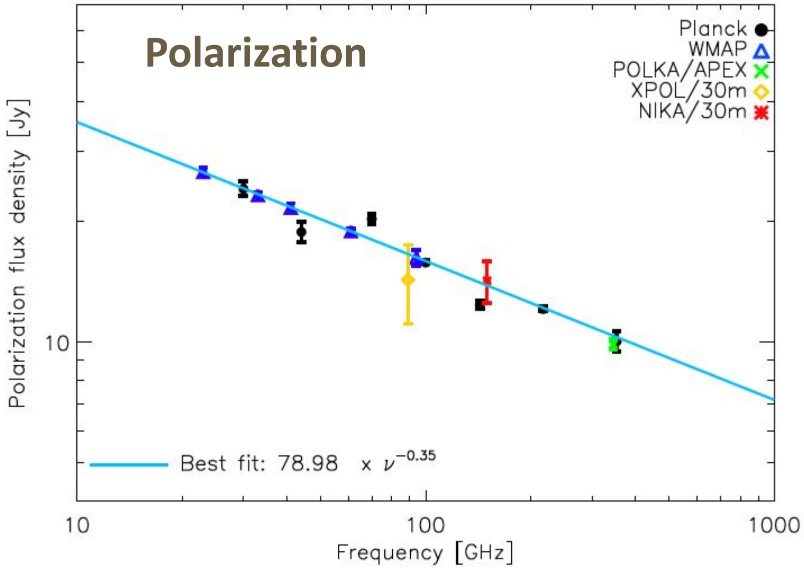
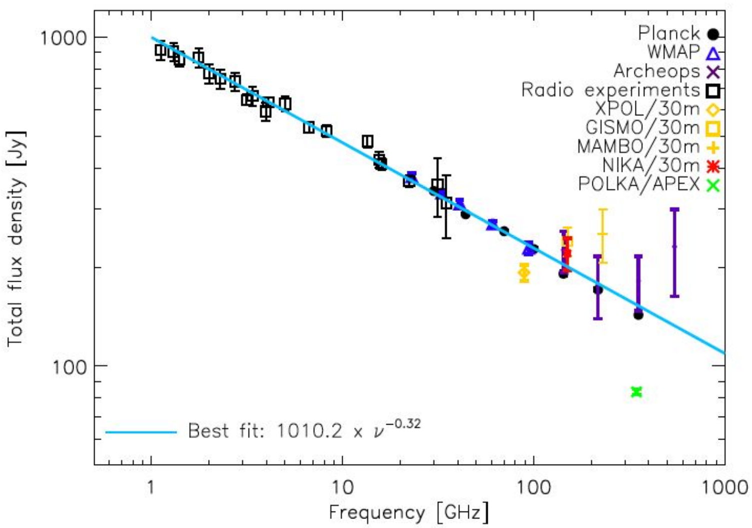
- **A SNR is our primary calibrator.**



Intensity



Ritacco+2018, A&A 616, A35

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- A SNR is our primary calibrator.
- **New information will be useful to test models using radio, X-ray and gamma-ray data.**

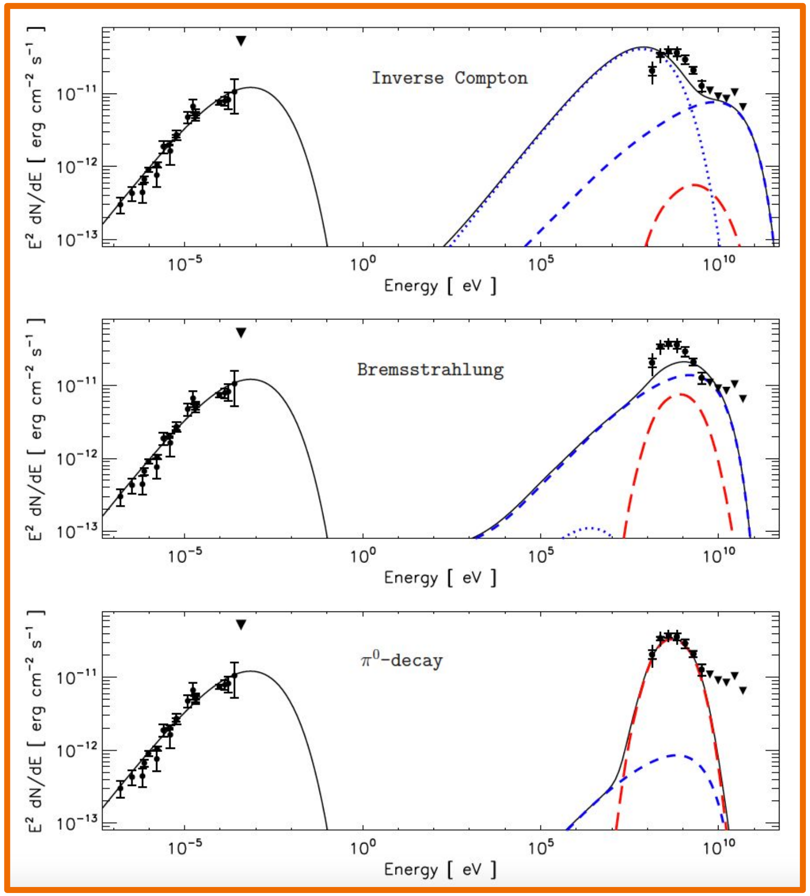
For example, Fermi data:

➔ Cygnus Loop **(Lorus+2021, MNRAS 500, 5177)**

➔ HB 21 **(Pivato+2013, ApJ 779, 179)**

➔ W44 **(Cardillo+2014, A&A 565, A74)**

HB 21



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In radio, SNRs have relatively flat, non-thermal spectra, with spectral indices -0.3 up to -0.7. At higher frequencies, the spectral index can be steeper.

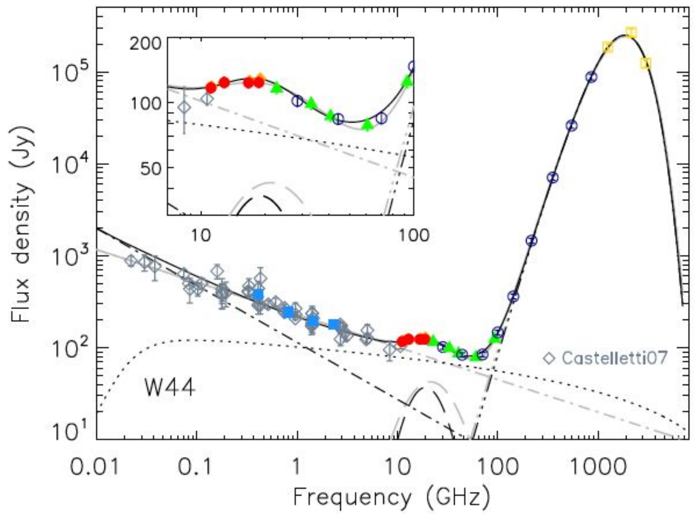
Motivation

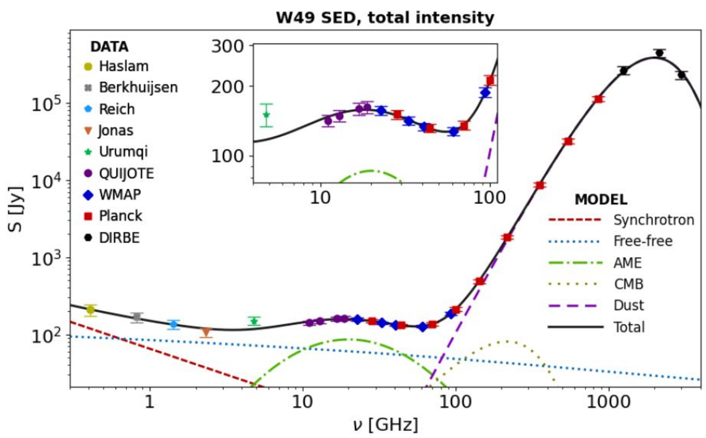
- The 10–100 GHz range is poorly exploited for the SNR description, particularly polarization.
- A SNR is our primary calibrator.
- New information will be useful to test models using radio, X-ray and gamma-ray emission.
- **Previous studies reported excess of emission compatible with the AME.**

QUIJOTE-MFI analysis:

➔ W44 **(Génova-Santos+2017, MNRAS 464, 4197)**

➔ W49 and W51 **(Tramonte+2022, to be submitted)**





Supernova Remnants: Goals

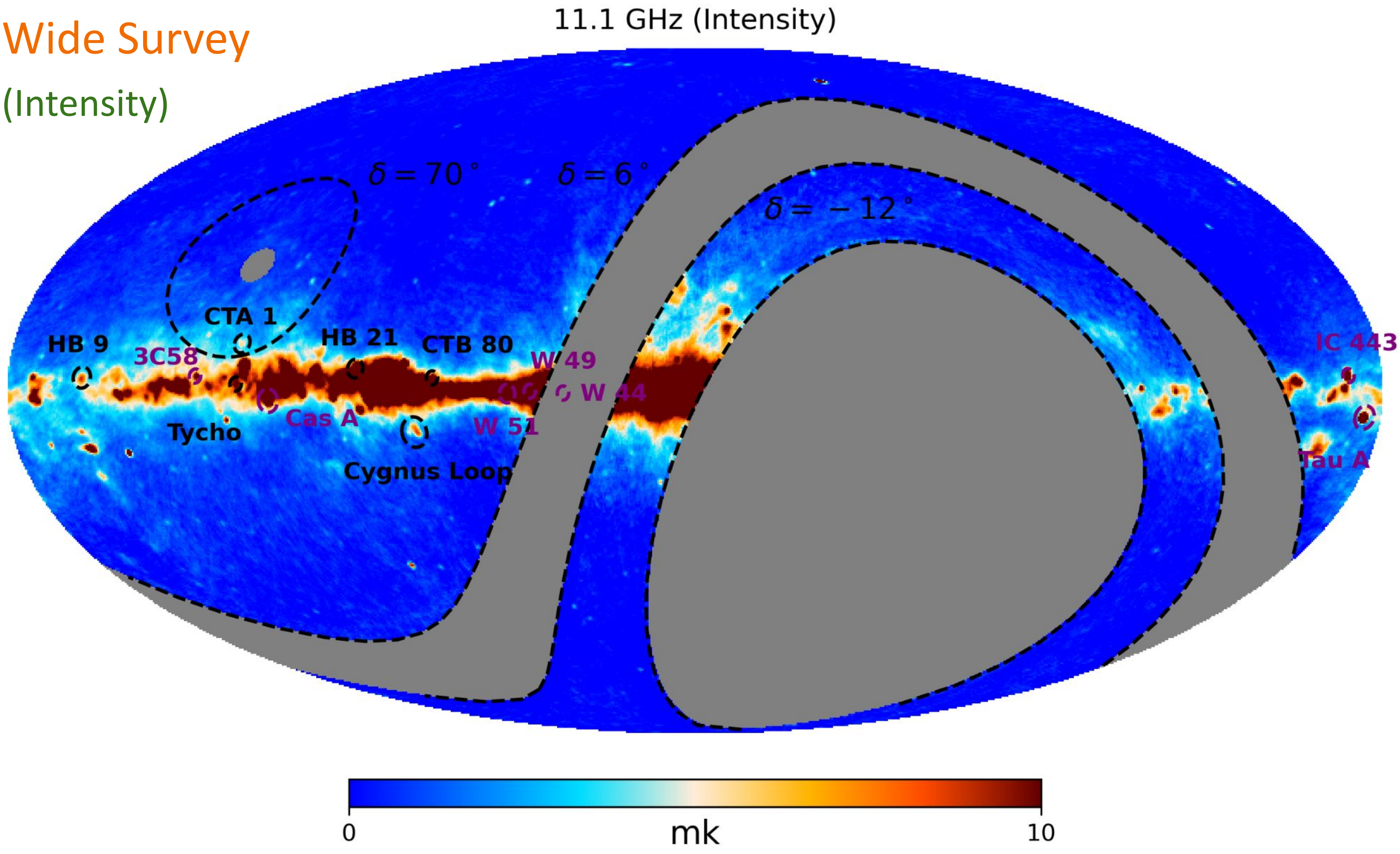
- Characterization of observational properties, in intensity and polarization, of SNRs in the MFI wide survey (which are not in other Quijote works).
- Modelling the Spectral Energy Distribution of intensity and polarization using the Quijote, WMAP, Planck, Ancillary and *the literature data*.
- Measure/constrain the spectral index, the spectral breaks and AME.

Name	ℓ [deg]	b [deg]	radii [arcmin]	Pol. in Quijote	Comments/Reference
Our SNRs candidates					
CTB 80	68.8	+2.7	60, 80, 100	negligible	spectral breaks? (this work)
Cygnus Loop	74.2	-8.77	130, 140, 170	**yes**	This work
HB 21	89.0	+4.7	80, 100, 120	**yes**	spectral breaks (this work)
CTA 1	119.5	10.03	80, 100, 120	negligible	This work
Tycho	120.1	1.04	60, 80, 100	negligible	This work
HB 9	160.4	2.8	90, 100, 120	**low**	This work
SNRs in other Quijote works					
W 44	34.5	-0.5	aperture phot	**yes**	AME (Génova-Santos+2017)
Tau A	184.5	-5.7	Beam fitting	**yes**	Calibrator (Ricardo)
Cas A	111.7	-2.1	Beam fitting	**yes**	Calibrator (Ricardo)
3C 58	130.8	3.1	60, 80, 100	**yes**	Fan Region (Beatriz)
W 49	43.2	-0.1	60, 80, 100	**low**	AME?? (Denis)
IC 443	189.06	3.2	60, 80, 100	**yes**	no AME (Denis)
W 51	49.1	-0.6	80, 100, 120	**yes**	no AME (Denis)

SNR in the MFI wide survey (WS)

Wide Survey

(Intensity)

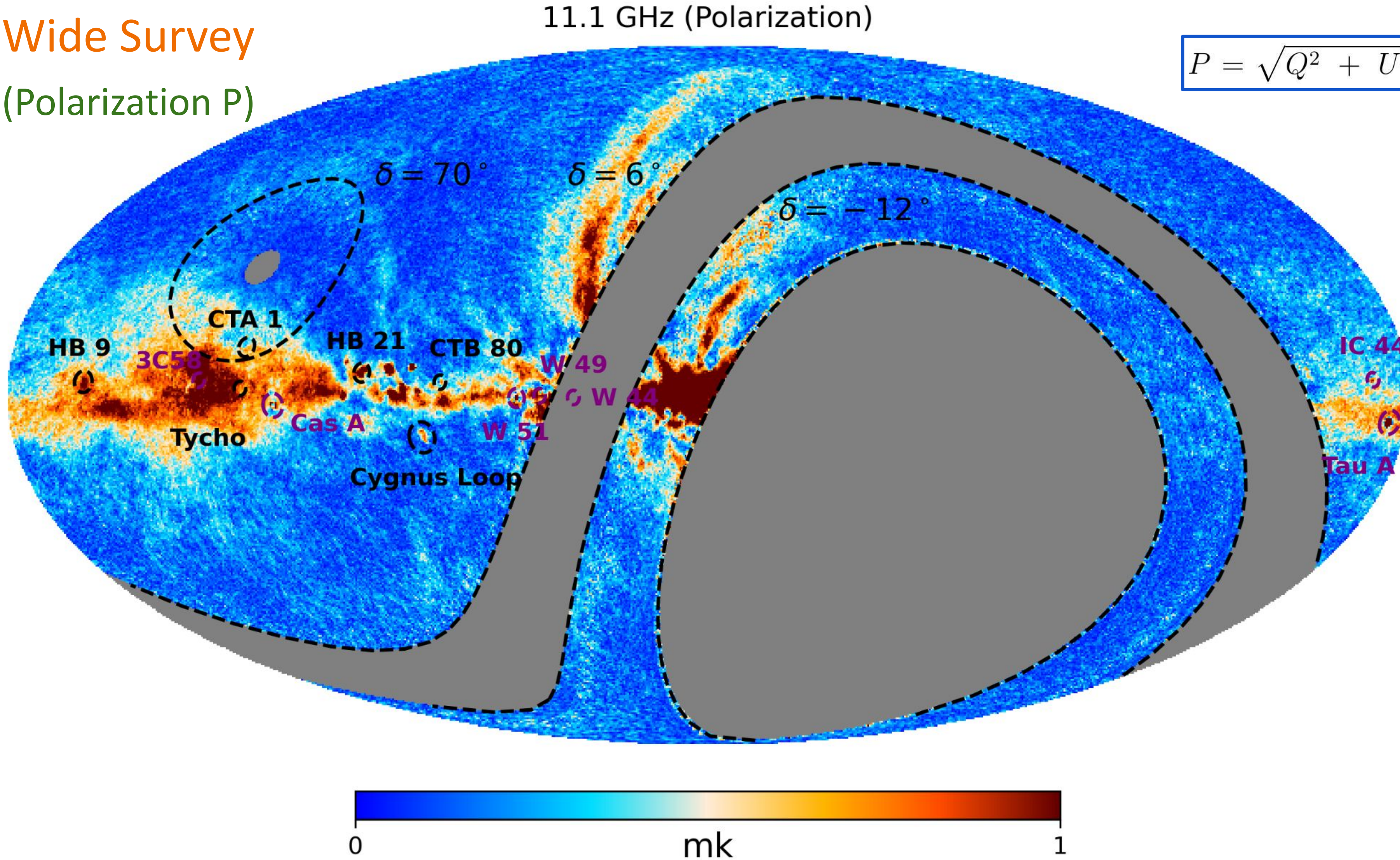


SNR in the MFI wide survey (WS)

Wide Survey

(Polarization P)

$$P = \sqrt{Q^2 + U^2}$$



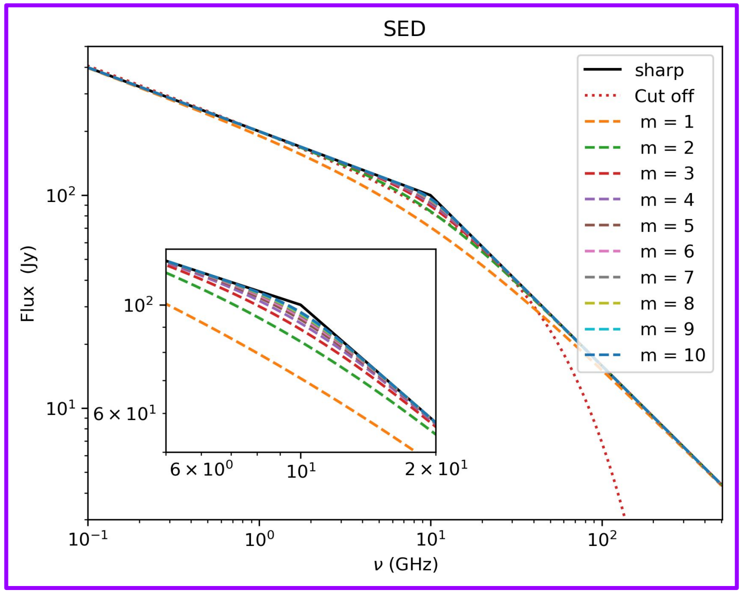
SNR in the MFI WS: Methodology and tests

Flux densities

- Aperture photometry method.
- Tests for uncertainty characterization: **Random control apertures**, Null test maps (half1, half2) and Noise simulations.

SED modelling

- MCMC approach.
- In general, we used a Power Law in intensity and polarization (both separately and combined).
- Spectral breaks are also considered.



Broken power law (sharp)

$$A_o \begin{cases} \left(\frac{\nu}{\nu_o}\right)^{\alpha_{bb}} & ,\forall \quad \nu \leq \nu_b \\ \left(\frac{\nu_b}{\nu_o}\right)^{\alpha_{bb}} \left(\frac{\nu}{\nu_b}\right)^{\alpha_{ab}} & ,\forall \quad \nu > \nu_b \end{cases}$$

BPL (exponential cutoff)

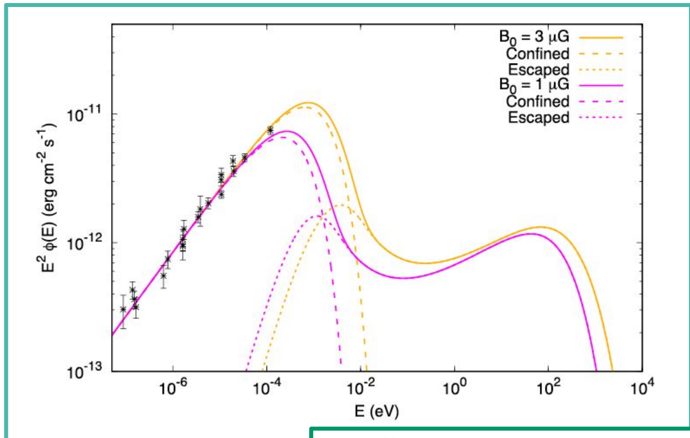
$$S_\nu = A_o \left(\frac{\nu}{\nu_o}\right)^{-\alpha} e^{-\frac{\nu - \nu_o}{\nu_c}}$$

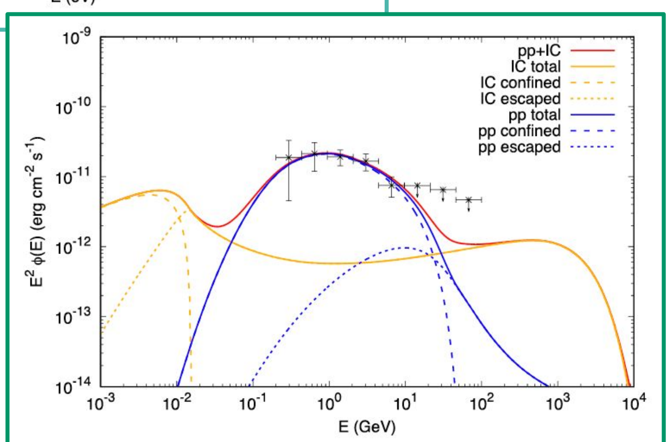
Broken power law (smoothed)

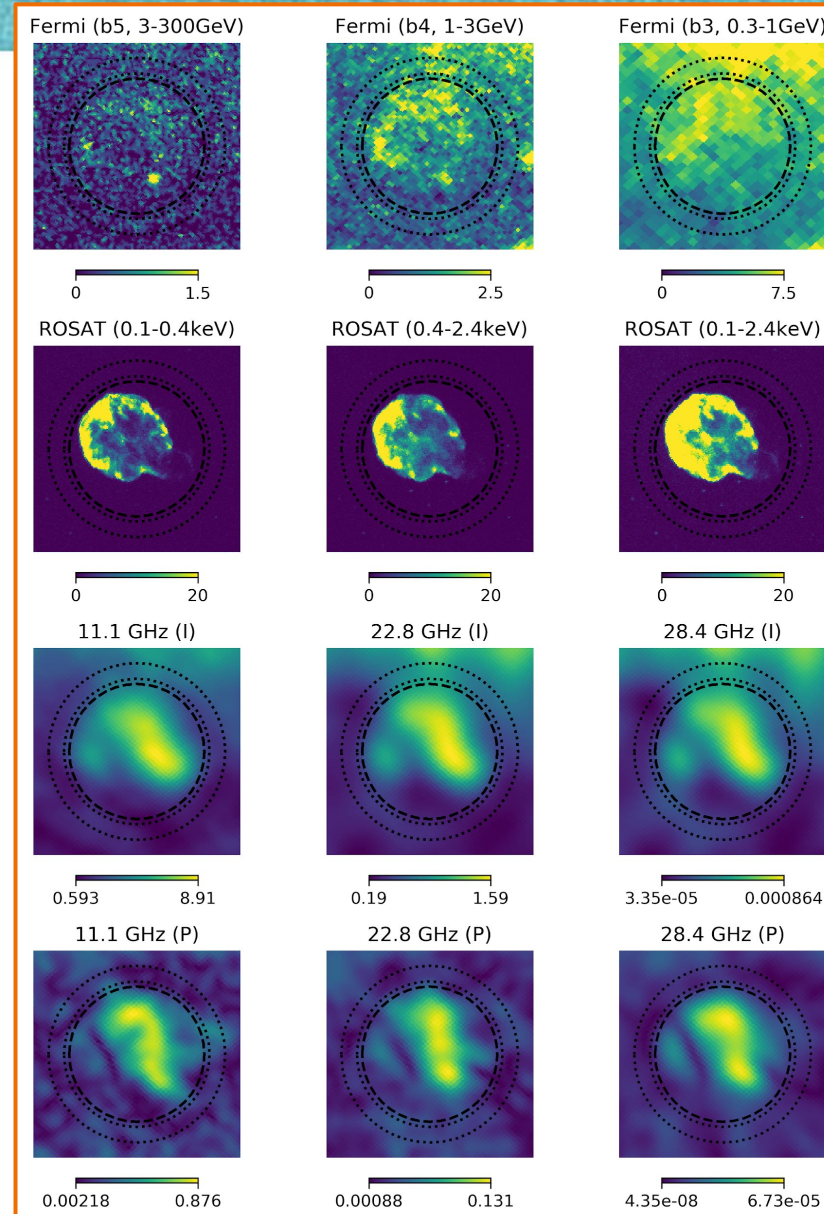
$$A_o \left(\frac{\nu}{\nu_o}\right)^{\alpha_{bb}} \left(\frac{1 + (\nu/\nu_b)^m}{1 + (\nu_o/\nu_b)^m}\right)^{\frac{\alpha_{ab} - \alpha_{bb}}{m}}$$

MFI results: Cygnus Loop

- Middle-aged SNR with a complex shell-type morphology.
- The biggest SNR (app. size ~4x3 deg^2).
- The brightest SNR in X-ray and gamma-ray emission is also detected (Fermi).



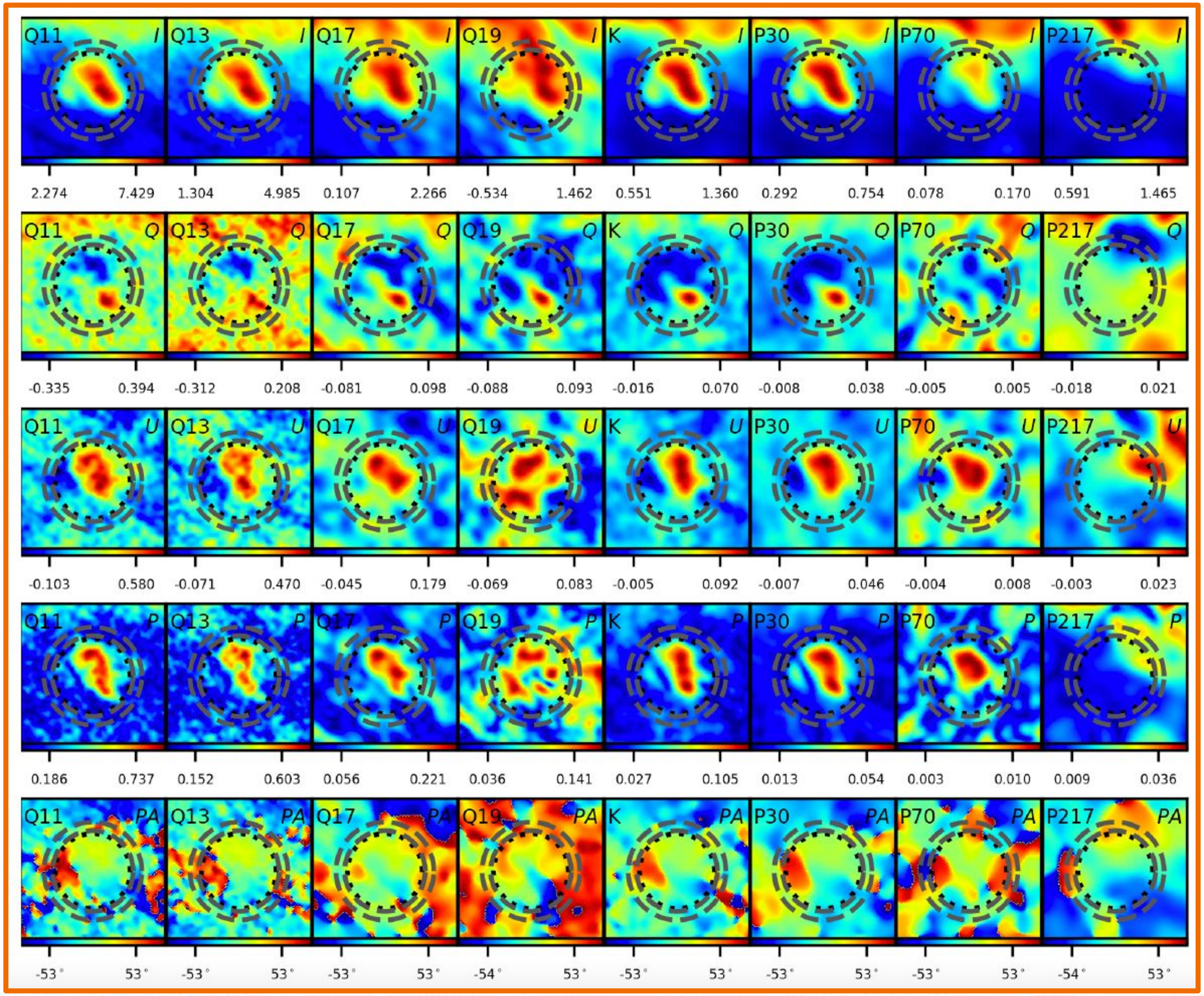




(Lorus+2021, MNRAS 500, 5177; Katagiri+2011, ApJ 741, 44)

MFI results: Cygnus Loop

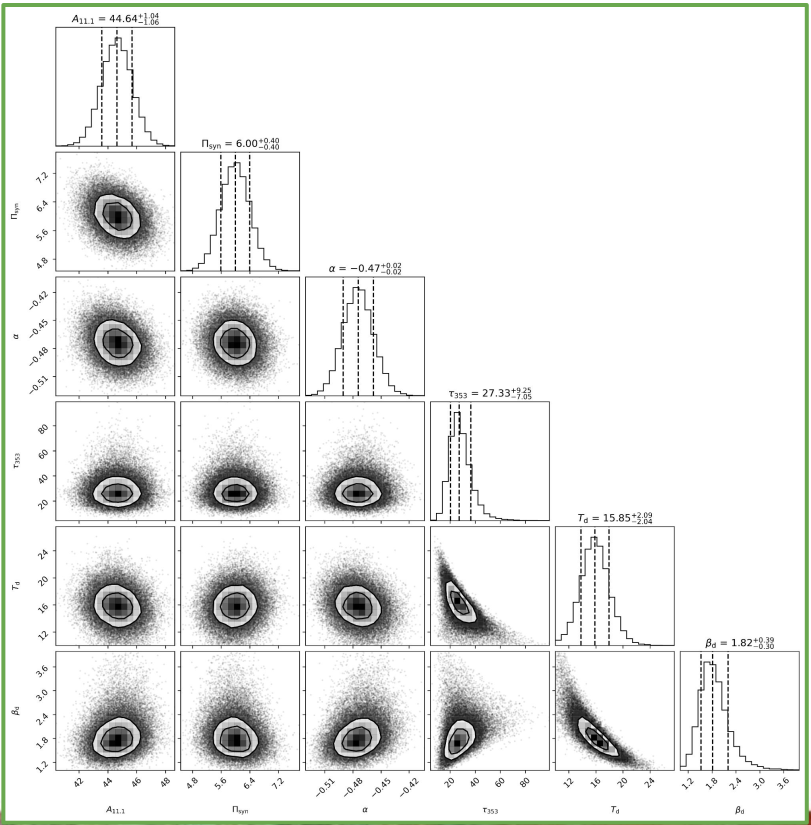
Polarization at 1 deg FWHM. The polarization angle is almost uniform across the SNR.

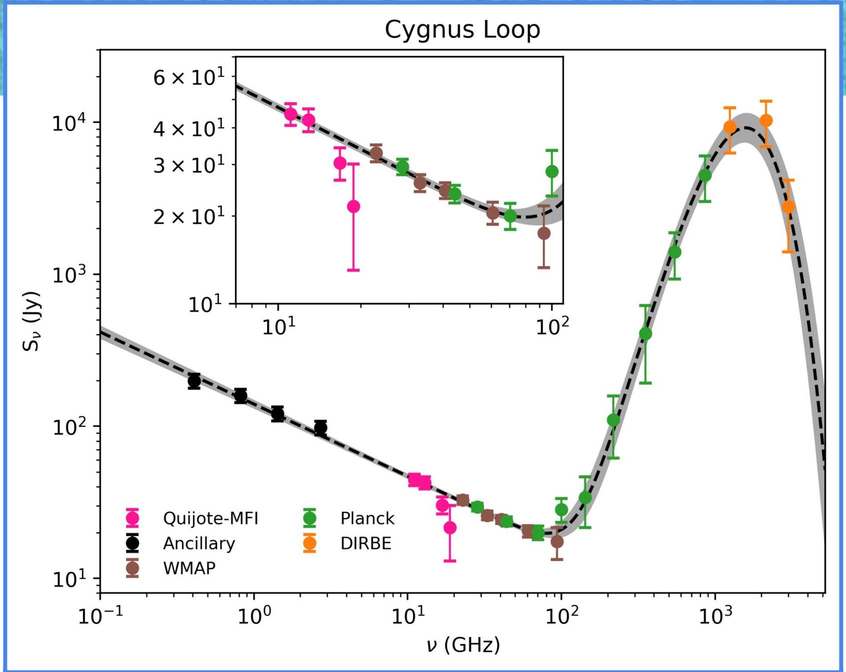


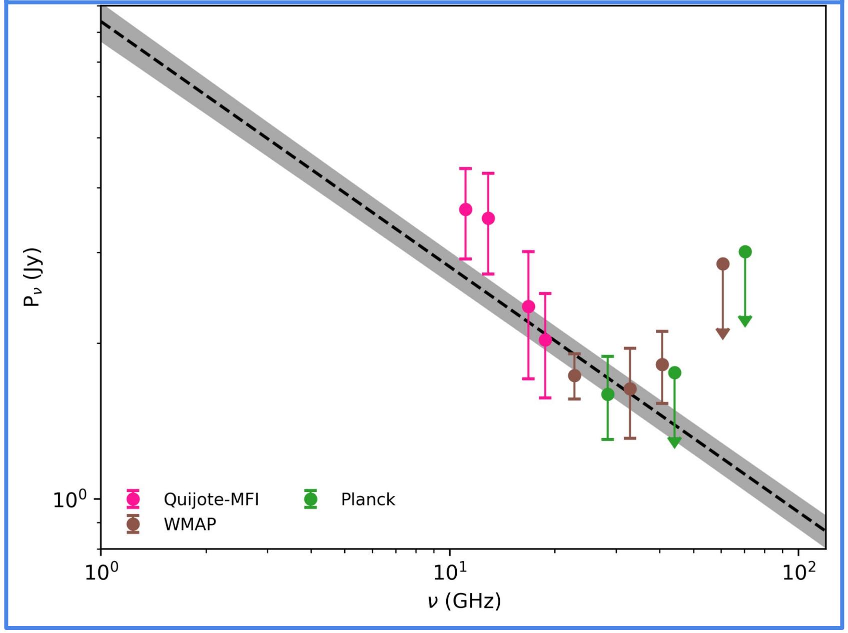
MFI results: Cygnus Loop

Spectral Energy Distribution

- In intensity, α =–0.47±0.02 agrees with previous works.
- In polarization, α_{pol}=–0.59±0.26 is in full agreement with α (intensity).
- The polarization fraction is 6.0%.





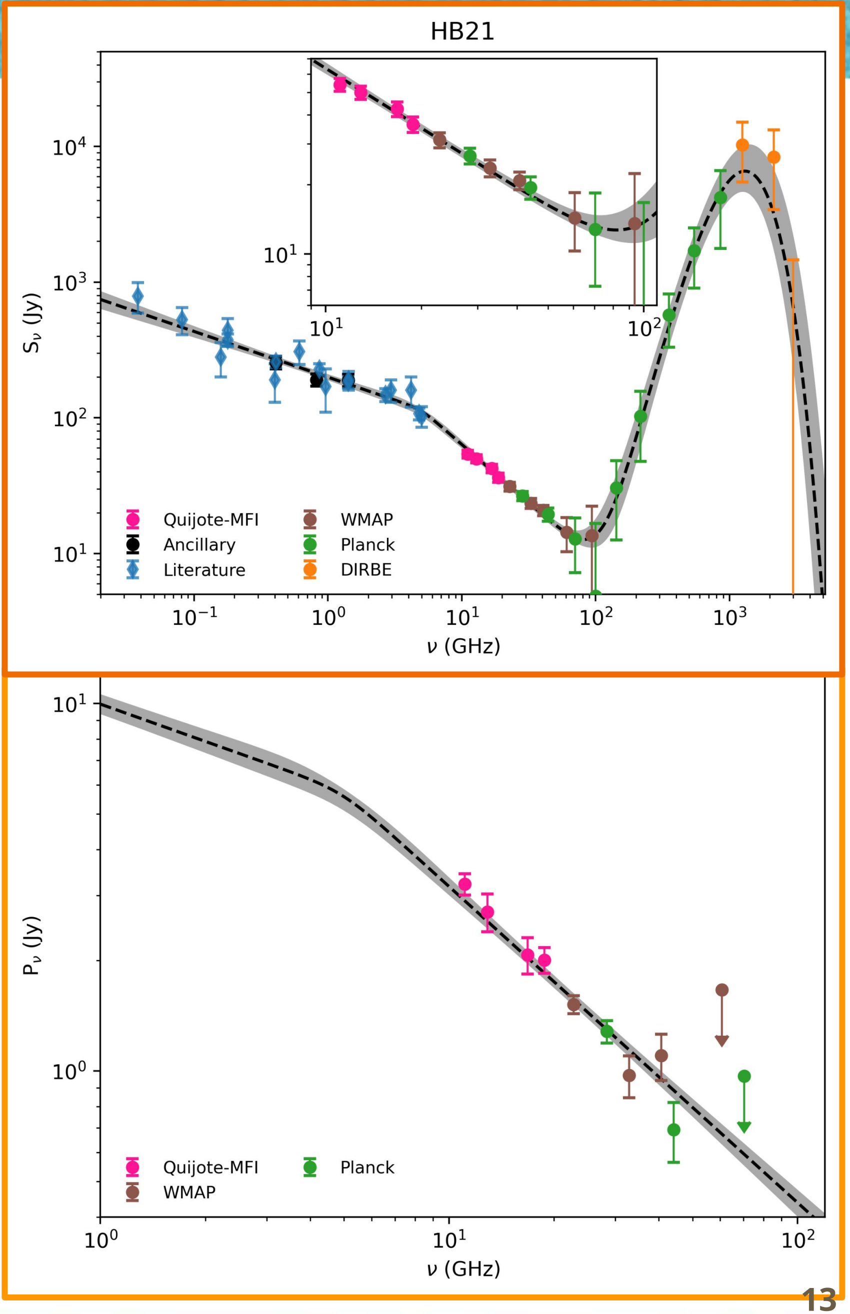


MFI results: HB 21

- Mixed morphology SNR, located at 0.8 kpc.
- In Pivato+2013, they assumed spectral break ($\Delta\alpha$ = 0.5) and reported a β^{bb}=0.38±0.02 and ν_b=5.9±1.2 GHz.

Spectral Energy Distribution

- Broken PL is fitted in intensity and polarization (α^{ab}=-0.34, α^{bb}=-0.86).
- We obtained the spectral breaks properties ($\Delta\alpha$ = 0.52±0.06).
- The polarization fraction is 5.0±0.2%.



MFI results: All SNR

Additional remarks

*) In intensity, SED parameters are consistent with previous works.

*) We confirm the spectral break for CTB80 and HB21.

*) Thermal dust contribution comes from galactic emission.

*) No evidence of AME contribution.

SNR	A_{AME} at 95% C.L. [Jy]	[%]
CTB 80	≤ 2.8	≤ 19.7
Cygnus Loop	≤ 2.4	≤ 7.0
HB 21	≤ 3.9	≤ 11.3
CTA 1	≤ 1.4	≤ 20.3
Tycho	≤ 2.2	≤ 14.6
HB 9	≤ 1.5	≤ 9.7

Properties of SNRs

	IntPol	Int	Pol	IntPol	Int	Pol
		HB21			**CTB80**	
$A_{11.1}$ [Jy]	$58.1^{+2.5}_{-2.2}$	$56.1^{+2.2}_{-2.1}$	3.2 ± 0.2	$21.0^{+1.1}_{-1.0}$	$20.9^{+1.2}_{-1.1}$	0.8 ± 0.1
Π_{syn} [%]	5.0 ± 0.2	-	-	3.7 ± 0.3	-	-
α_{bb}	$-0.34^{+0.04}_{-0.03}$	-0.33 ± 0.04	-	$-0.24^{+0.07}_{-0.06}$	$-0.27^{+0.06}_{-0.04}$	-
α_{ab}	$-0.86^{+0.04}_{-0.05}$	$-0.80^{+0.04}_{-0.05}$	-1.02 ± 0.08	$-0.60^{+0.04}_{-0.05}$	$-0.70^{+0.10}_{-0.12}$	-0.52 ± 0.07
ν_b [GHz]	$5.0^{+1.2}_{-1.0}$	$4.0^{+1.1}_{-0.8}$	-	$2.0^{+1.2}_{-0.5}$	$3.7^{+1.2}_{-1.7}$	-
τ_{353} [10^{-7}]	$143.7^{+69.8}_{-52.5}$	$146.0^{+69.7}_{-53.2}$	-	-	-	-
T_d [K]	$12.5^{+2.6}_{-1.7}$	$12.2^{+2.4}_{-1.6}$	-	-	-	-
β_d	$2.04^{+0.49}_{-0.45}$	$2.15^{+0.47}_{-0.44}$	-	-	-	-
χ^2_{dof}	0.63	0.47	0.54	1.83	2.24	0.70
		Cygnus Loop			**HB9**	
$A_{11.1}$ [Jy]	$44.6^{+1.0}_{-1.1}$	44.6 ± 1.0	$2.9^{+0.6}_{-0.5}$	20.6 ± 0.7	20.7 ± 0.7	1.4 ± 0.1
Π_{syn} [%]	6.0 ± 0.4	-	-	6.9 ± 0.5	-	-
α	-0.47 ± 0.02	-0.47 ± 0.02	-0.59 ± 0.23	-0.51 ± 0.02	-0.50 ± 0.02	-0.60 ± 0.08
τ_{353} [10^{-7}]	$27.3^{+9.3}_{-7.1}$	$27.3^{+9.2}_{-7.2}$	-	$82.0^{+22.2}_{-16.9}$	$82.1^{+23.0}_{-16.9}$	-
T_d [K]	$15.8^{+2.1}_{-2.0}$	15.8 ± 2.1	-	$14.9^{+1.6}_{-1.7}$	$14.8^{+1.6}_{-1.7}$	-
β_d	$1.82^{+0.39}_{-0.30}$	$1.84^{+0.41}_{-0.31}$	-	$1.46^{+0.33}_{-0.25}$	$1.47^{+0.33}_{-0.25}$	-
χ^2_{dof}	0.63	0.59	0.75	0.44	0.23	0.76
		CTA1			**Tycho**	
$A_{11.1}$ [Jy]	8.9 ± 0.6	9.0 ± 0.6	1.0 ± 0.2	12.9 ± 0.6	12.9 ± 0.6	$0.1^{+0.2}_{-0.1}$
Π_{syn} [%]	$9.4^{+1.2}_{-1.1}$	-	-	$0.0^{+1.5}_{-1.6}$	-	-
α	-0.50 ± 0.03	-0.50 ± 0.03	$-0.84^{+0.29}_{-0.27}$	-0.60 ± 0.02	-0.60 ± 0.02	$-1.57^{+1.29}_{-1.35}$
τ_{353} [10^{-7}]	-	-	-	$119.3^{+28.3}_{-24.8}$	$119.6^{+28.3}_{-24.8}$	-
T_d [K]	-	-	-	$14.7^{+1.4}_{-1.3}$	$14.6^{+1.4}_{-1.3}$	-
β_d	-	-	-	$2.19^{+0.40}_{-0.31}$	$2.19^{+0.40}_{-0.31}$	-
χ^2_{dof}	0.39	0.25	0.45	0.45	0.69	0.02

Summary and Conclusion

- Intensity and polarization of SED characterization for **Cygnus Loop, HB21, CTB80, HB9, CTA1 and Tycho**.
- In intensity, we confirm the spectral break for CTB80 and HB21.
- In intensity, the Anomalous Microwave emission is not detected. We provide only upper limits on its amplitude.
- Polarization fractions are between 4-10%. For Tycho, only upper limits are obtained.
- Polarization spectral indices are compatible with intensity spectral indices (except for CTA 1 and Tycho).
- Results to be included in López-Caraballo et al. (in prep). Stay tuned!

Comments and recommendations are welcome!

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Thank you