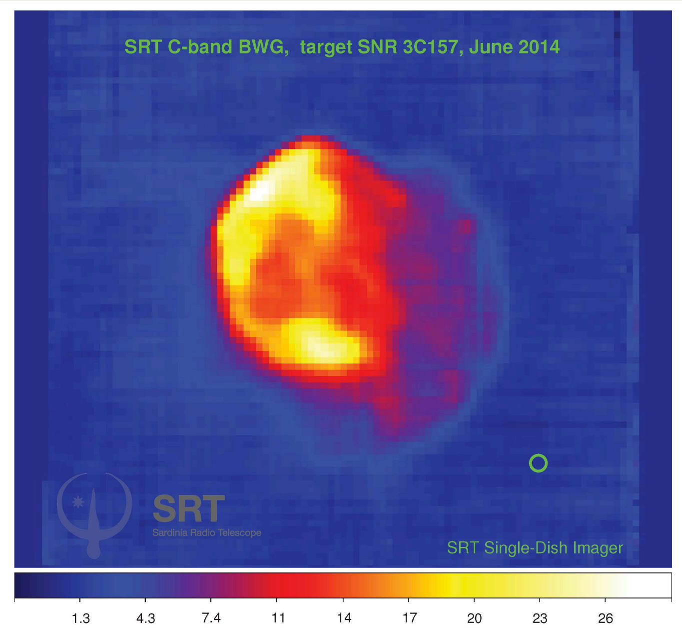
High Radio-frequencies Spectra of SNR IC443 and W44
Evidence for a wide electron spectra scatter among different SNR regions?

Alberto Pellizzoni – apellizz@oa-cagliari.inaf.it
INAF – Osservatorio astronomico di Cagliari – Italy
INAF – Sardinia Radio Telescope (SRT) – www.srt.inaf.it



IAU Symposium 331: *SNR 1987A, 30 years later*

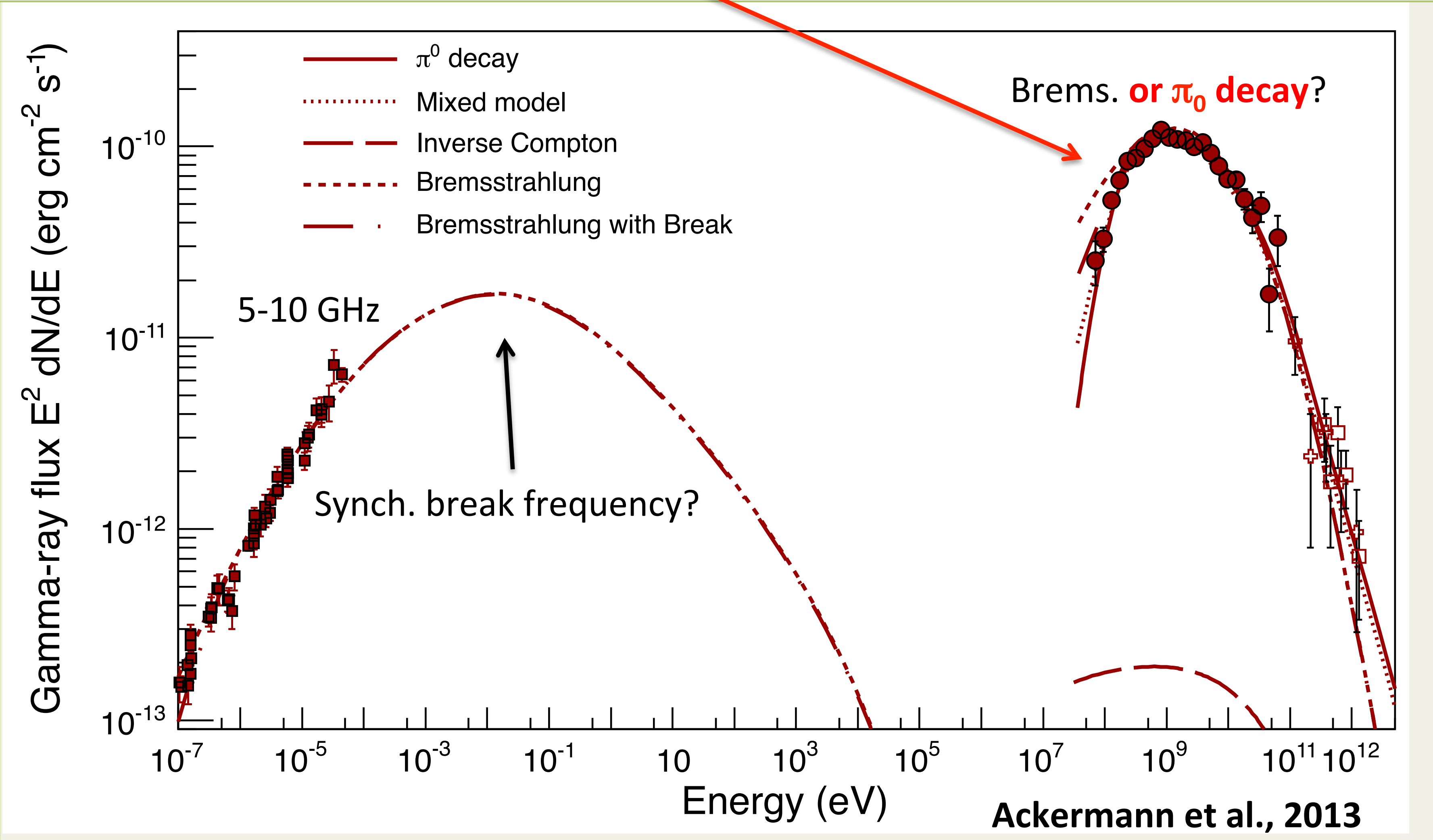
Outline of our research:

Spectral studies of large SNRs through single-dish imaging at high-frequencies (1-20 GHz) with the 64m Sardinia Radio Telescope (SRT).

People:

E.Egron, M.N.Iacolina, **S.Loru**, M.Marongiu, S.Righini, M.Cardillo, A.Giuliani, S.Mulas & SRT Team

Hadron and lepton gamma-ray emission. Cosmic rays acceleration.



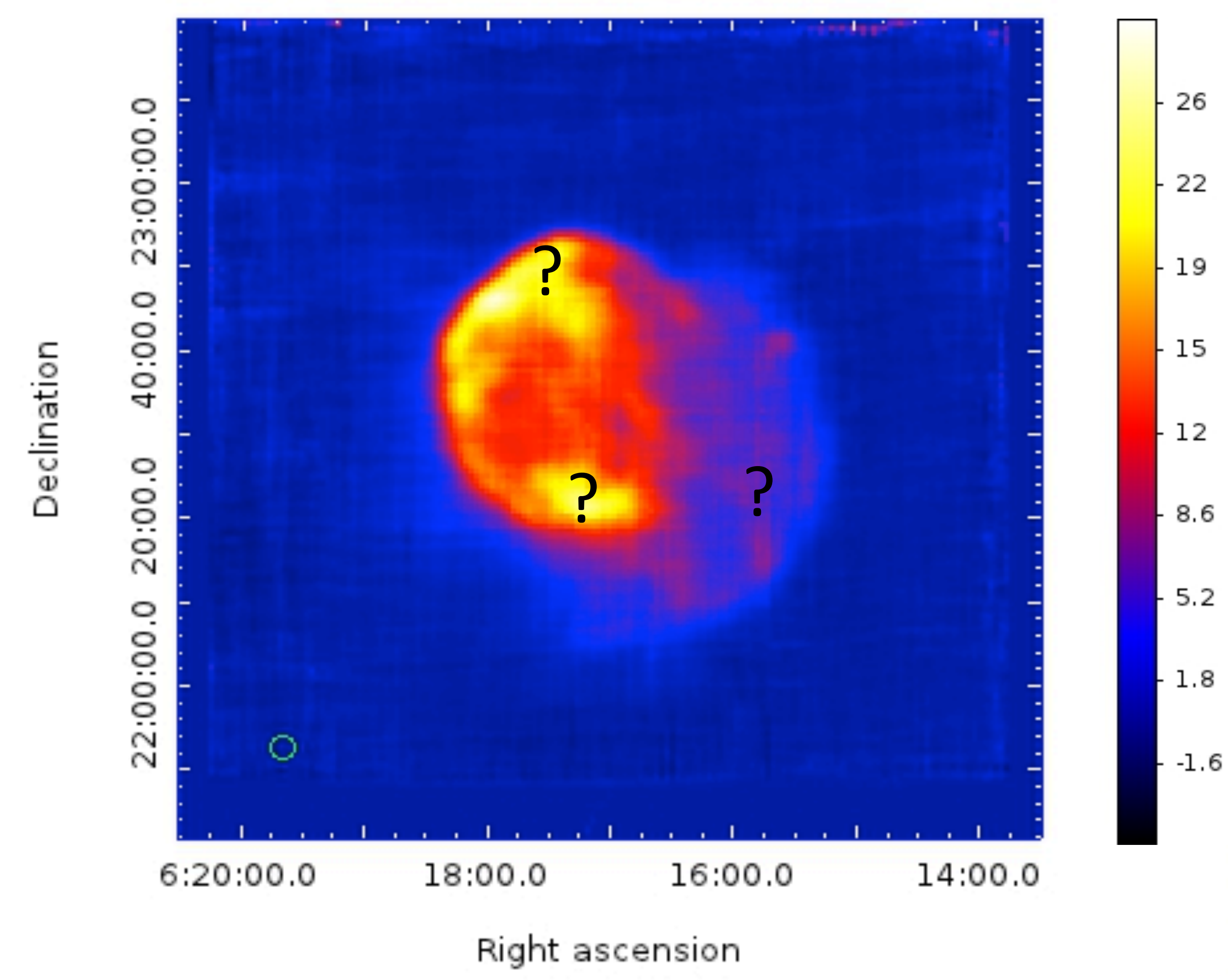
Multifrequency spectrum of SNR IC443

At which frequency SNR radio spectra break?

Only limited information on spatially resolved SNR spectra above 5 GHz available so far!

One-region models based on Integrated flux: oversimplification
Multi-region models based on spatially resolved spectra: imaging!

IC443
SRT 7 GHz

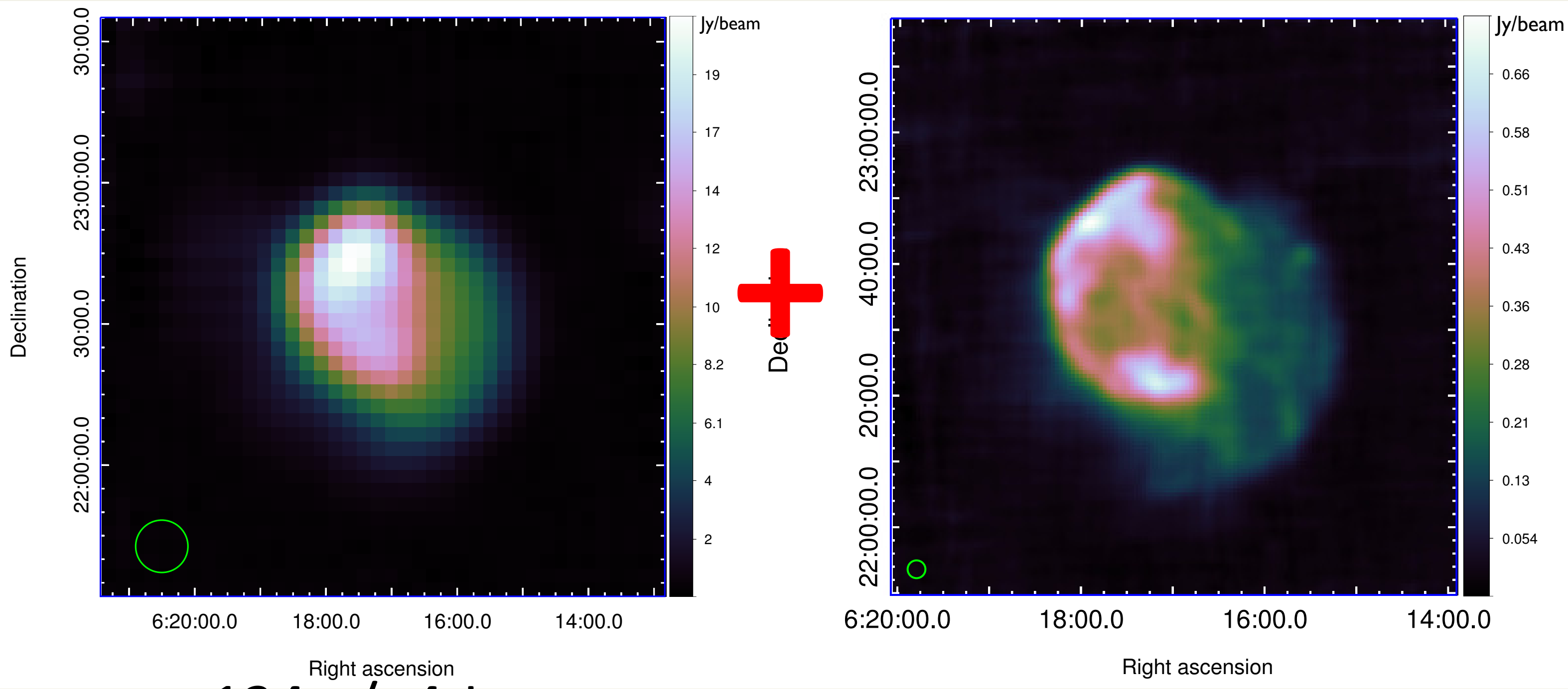


Imaging of large SNRs as W44 and IC443 through radio **interferometric observations provides a wealth of information about their strucures**, but flux estimation can be an issue:

Single dish radio imaging with good resolution can provide **accurate flux density measurements then accurate integrated spectra**.

1.5 GHz   7 GHz

IC443



134 +/- 4 Jy   67 +/- 3 Jy

Spectral index α=0.46 +/− 0.03 ($S=k^{-\alpha}$)

A standard shock spectrum?

Egron et al., submitted

IC443: integrated spectra

α=0.46 +/− 0.03 (**SRT data 1.5-7 GHz**)

Egron et al., submitted

α=0.36 +/− 0.02 (**<u>0.02-10 GHz</u>**)

Castelletti et al. (2011)

IC443: integrated spectra

α=0.46 +/− 0.03 **(SRT data 1.5-7 GHz)**

Egron et al., submitted

↕

α=0.47 +/− 0.06 **(1.39-8 GHz, literature)**

Measurements from Westerhout (1958), Hogg (1964), Wanner (1961), Milne & Hill (1969), Green (1986), Hagen et al. (1955), Hill (1972), Milne & Hill (1969), Milne (1971), Kuz'min et al. (1960), Hirabayashi & Takahashi (1972), Kundu & Velusamy (1969), Dickel (1971)

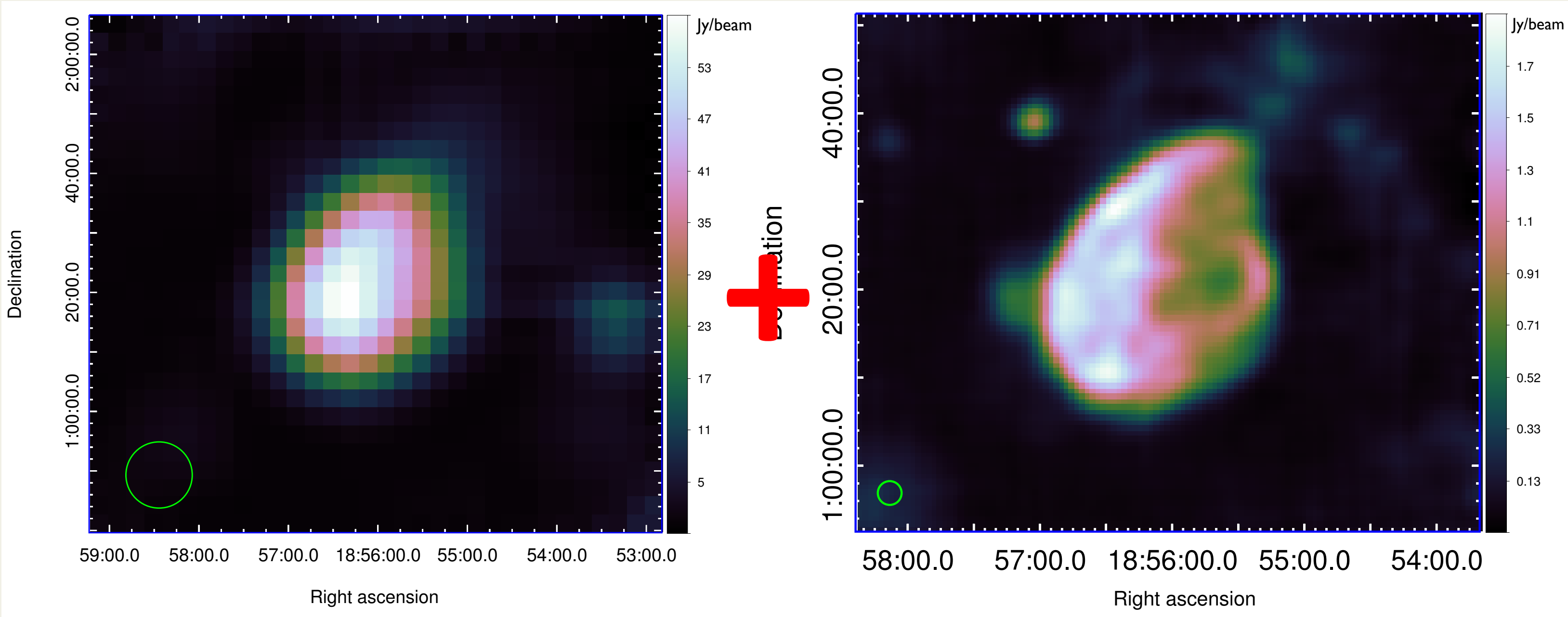
α=0.33 +/− 0.01 **(0.02-1.0 GHz, literature)**

Measurements from Bridle & Purton (1968), Braude et al. (1969), Roger et al. (1986; 1969), Guidice (1969), Viner & Erickson (1975), Dwarakanath et al. (1982), Baldwin & Dewhirst (1954), Blythe (1957), Williams et al. (1966) , Castelletti et al. (2011), Baldwin & Dewhirst (1954), Shakeshaft et al. (1955), Kovalenko et al. (1994), Green (1986), Edge et al. (1959), Bennett (1962), Kundu & Velusamy (1968), Davies et al. (1965), Seeger et al. (1965), Kellermann et al. (1964), Colla et al. (1971), Bondar et al. (1965), Dickel & McKinley (1969), Hogg (1964), Harris & Roberts (1960), Milne (1971)

W44

1.5 GHz

7 GHz



214 +/- 6 Jy

94 +/- 4 Jy

Spectral index α=0.55 +/− 0.03

Egron et al., submitted

W44: integrated spectra

$\alpha = 0.55 +/- 0.03$ (**SRT data 1.5-7.2 GHz**)

$\alpha = 0.36 +/- 0.02$ (**0.02-1.0 GHz, literature**)

Measurements from Roger et al. (1986), Kassim (1989), Castelletti et al. (2007), Kovalenko et al. (1994), Edge et al. (1958), Bennett (1963), Kellermann et al. (1969), Holden & Caswell (1969), Kundu & Velusamy (1967), Kassim (1992), Giacani (1997), Davis et al. (1965), Large et al. (1961), Kesteven (1968), Clark et al. (1975), Dickel & Denoyer (1975), Kuz'min (1962), Moran (1965), Kellermann et al. (1969), Pauliny-Toth et al. (1966), Harris (1962), Wilson (1963)

Egron et al., submitted

IC443

Low-frequency $\alpha=0.46 +/- 0.03$ (SRT data 1.5-7 GHz)

High-frequency $\alpha=0.33 +/- 0.01$ (0.02-1.0 GHz, literature)

W44

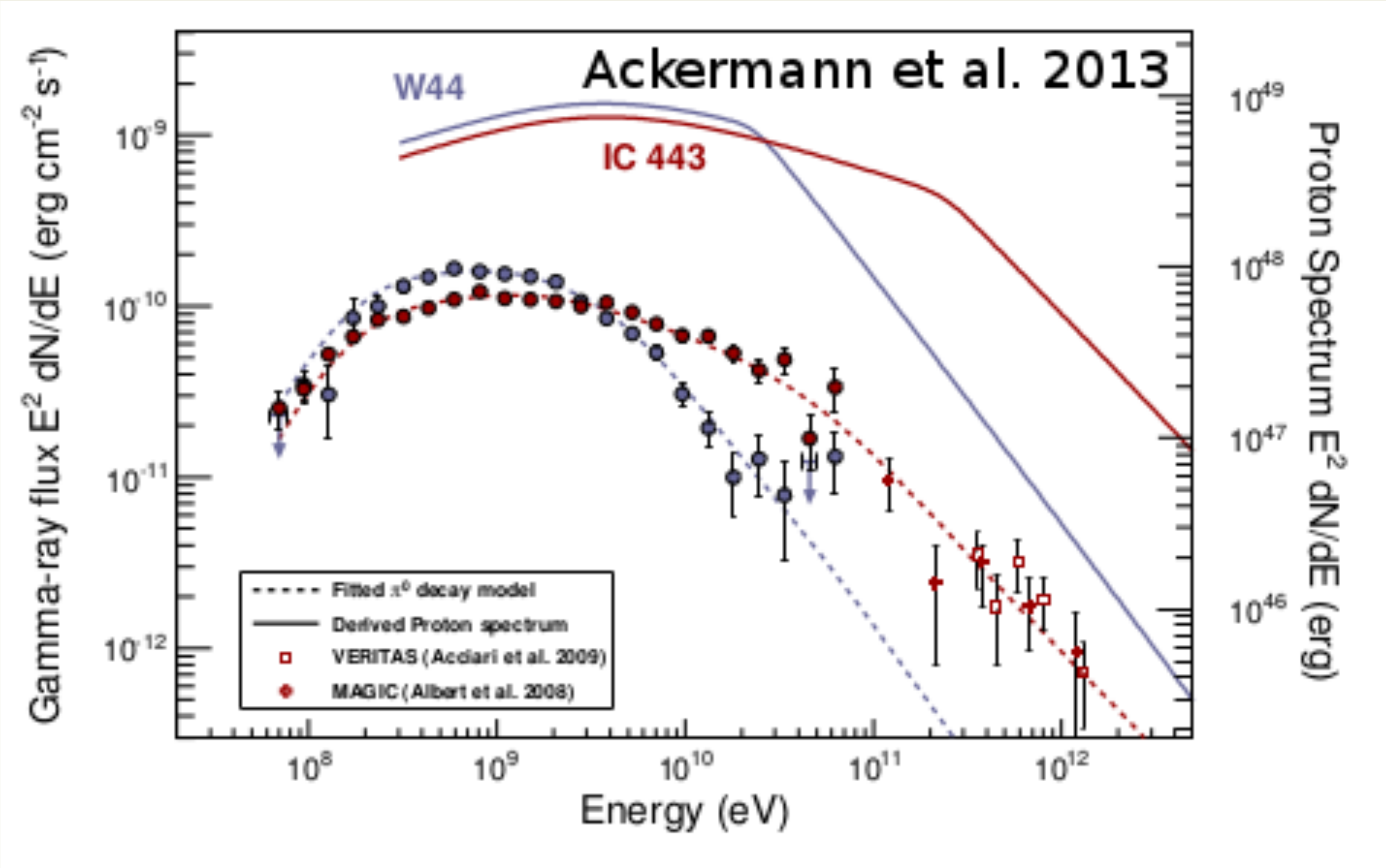
Low-frequency $\alpha=0.55 +/- 0.03$ (SRT data 1.5-7.2 GHz)

High-frequency $\alpha=0.36 +/- 0.02$ (0.02-1.0 GHz, literature)

Evidence for a spectral turnoff around 1 GHz?

(4σ, $\Delta\alpha=0.1$)

Steepening of the primary particle spectrum at 10 GeV for W44 and 100 GeV for IC443 → **synchrotron breaks at >10 GHz** (Cardillo et al. 2014; Ackermann et al. 2013; Giuliani et al. 2011)



What is the possible origin of a turn-off at 1 GHz?

Hadronic interaction → **secondary electrons**

Secondary hadronic electrons:

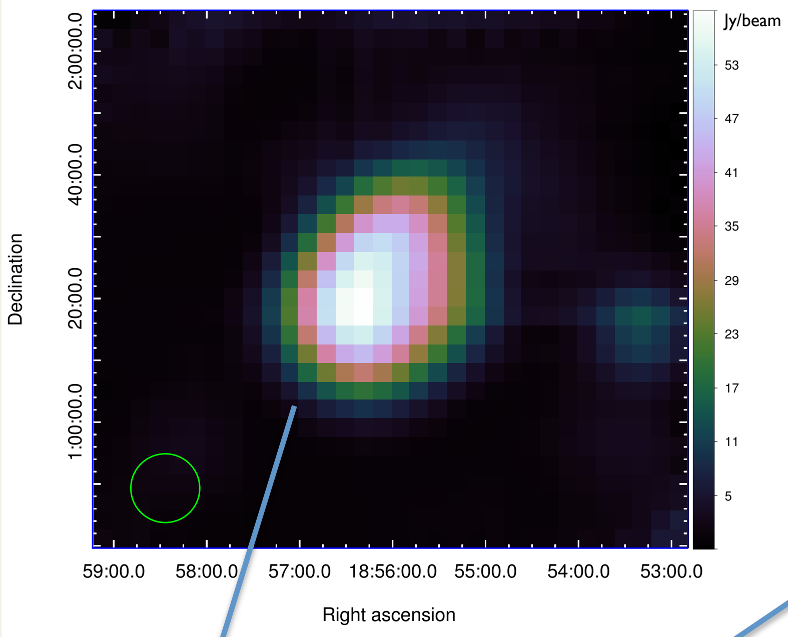
- A major fraction of the whole leptonic plasma?
- Expected to take 10% of the primary particle energy?

(see Cardillo et al., 2016; Lee et al. 2015)

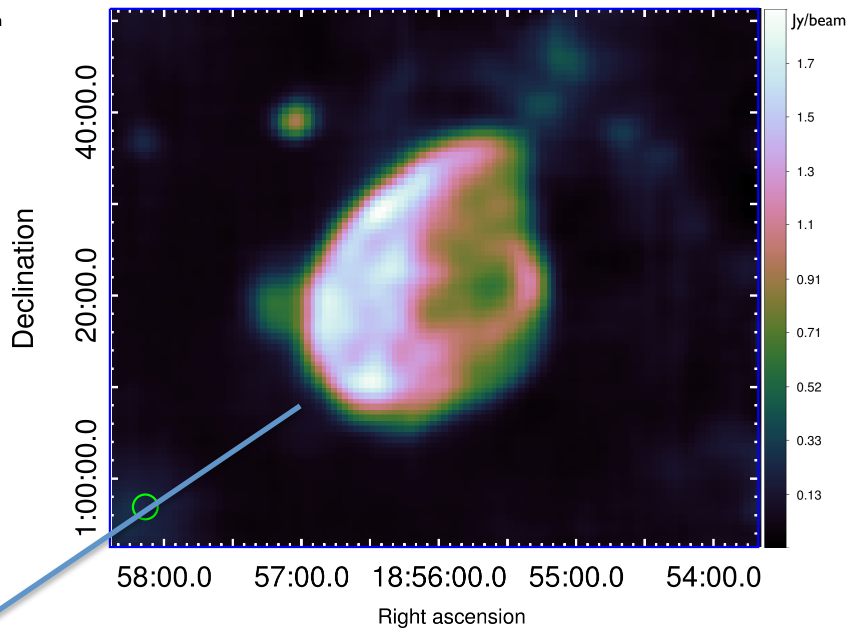
What about the primary particle break >10 GHz?

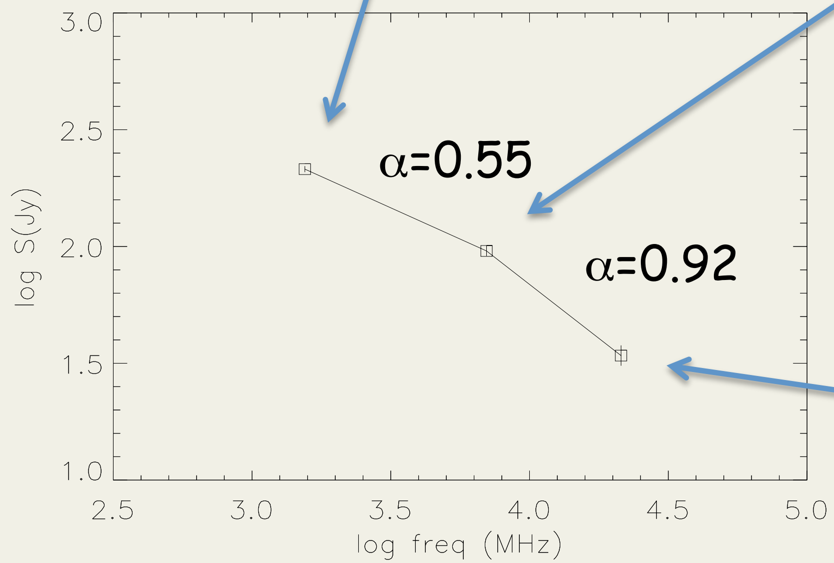
W44

1.5 GHz

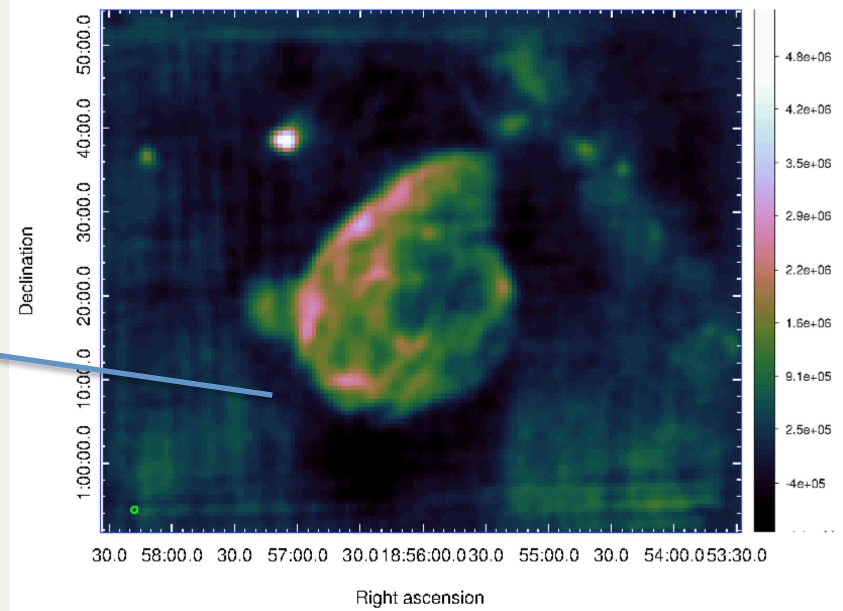


7 GHz





21.4 GHz



See Loru et al. Poster

Summary of integrated spectra

W44: α=0.36 → α=0.55 → α=0.9

turn-offs 1 GHz 10 GHz

hadronic e^- primary e^-

IC443: α=0.33 → α=0.46 → α=?

turn-offs 1 GHz ? GHz

hadronic e^- primary e^-

On-going analysis at 21 GHZ....

Need for spatially-resolved spectra

The assumption of a single primary (and secondary) electron population is too simplistic for modelling: different region-dependent (SNR/PWN) electron populations are present.

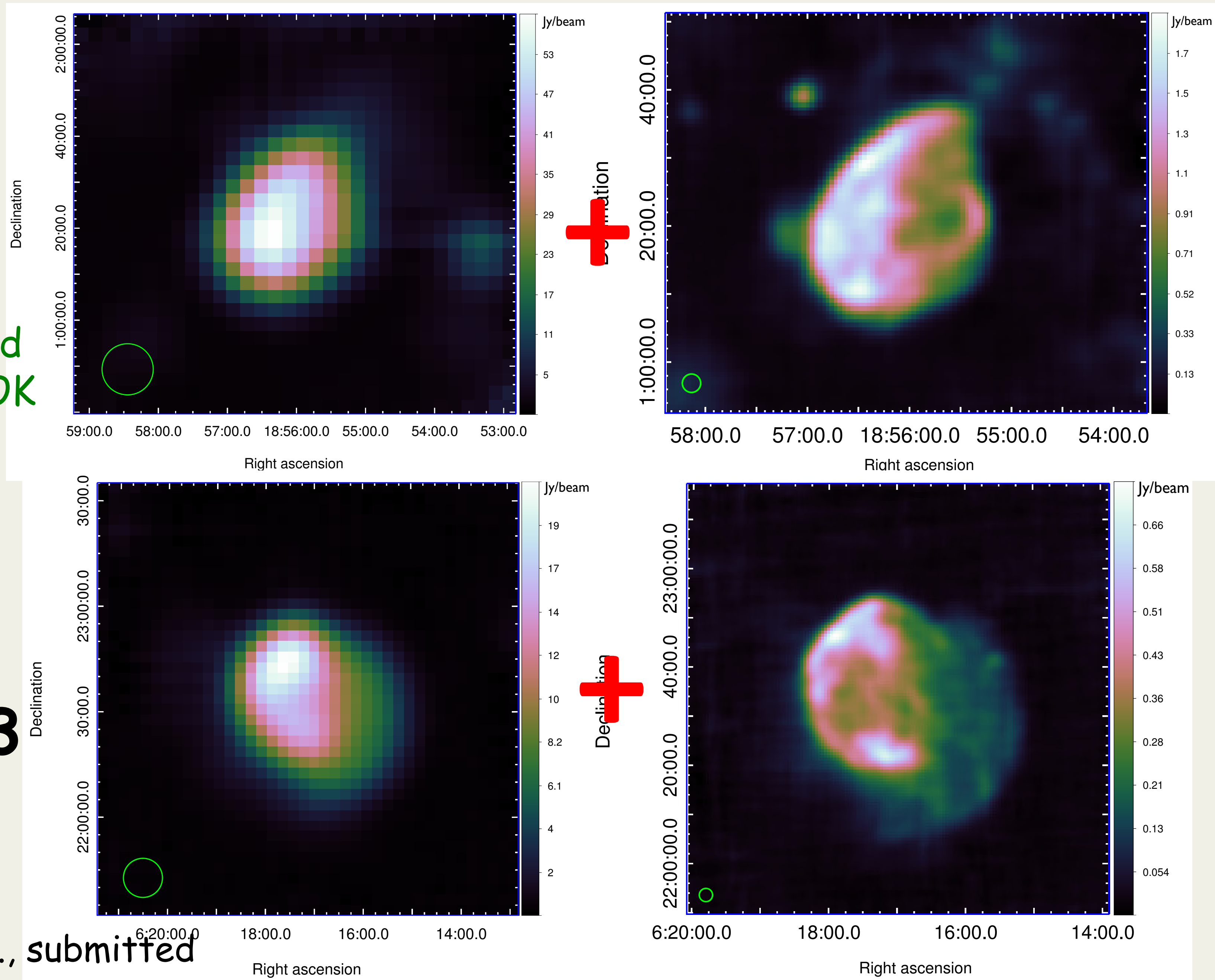
1.5 GHz 7 GHz

W44

Integrated spectra: OK

Spectral Imaging: POOR

IC443

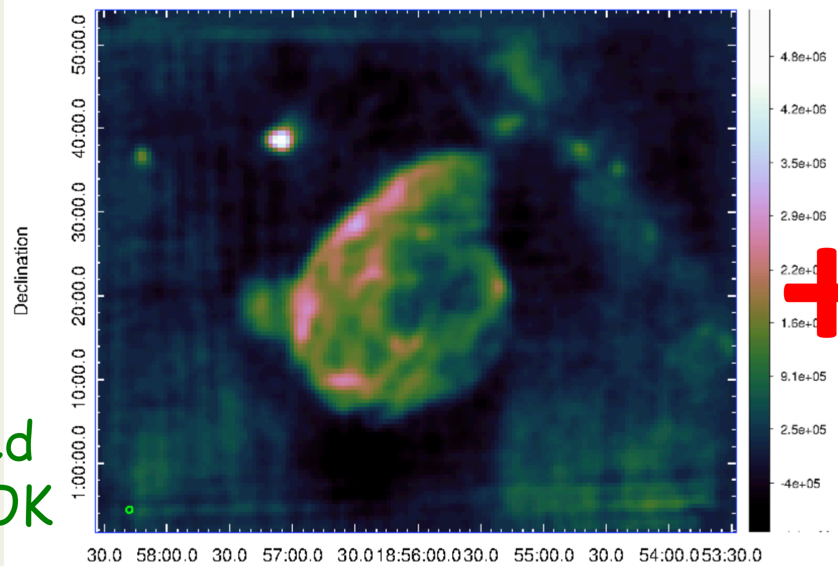


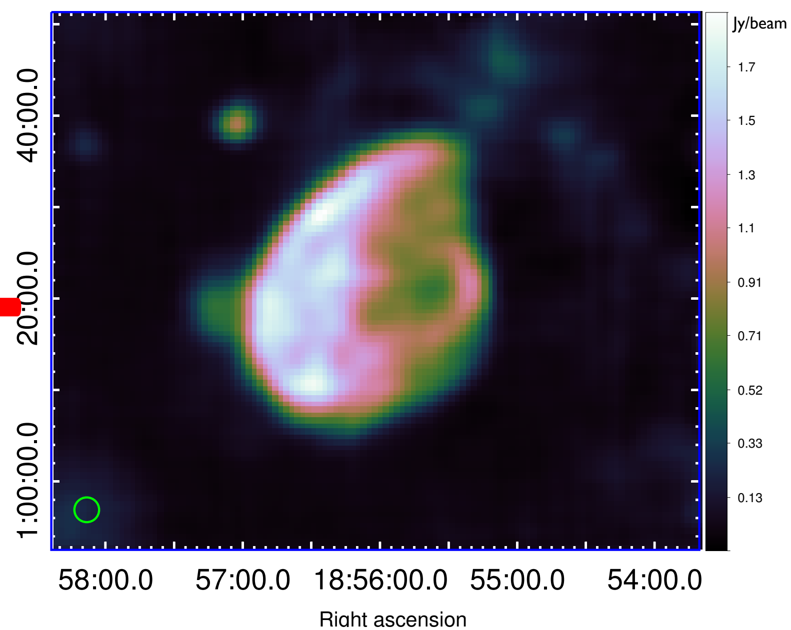
Egron et al., submitted

21 GHz 7 GHz

W44

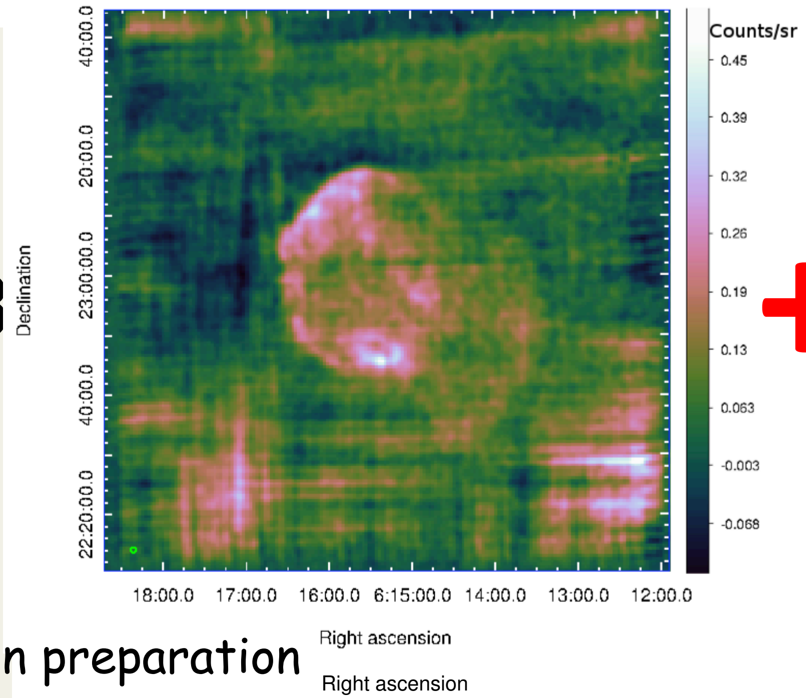
Integrated spectra: OK

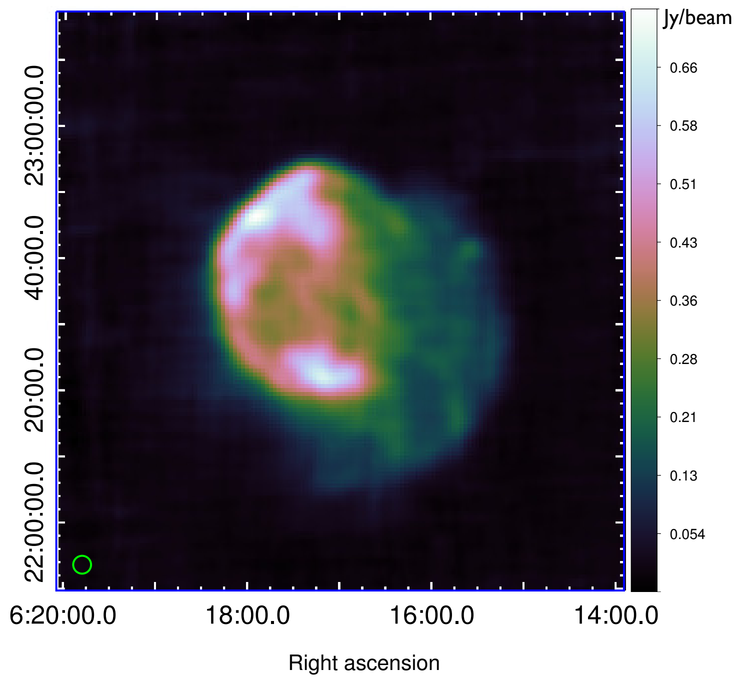




Spectral Imaging: OK!

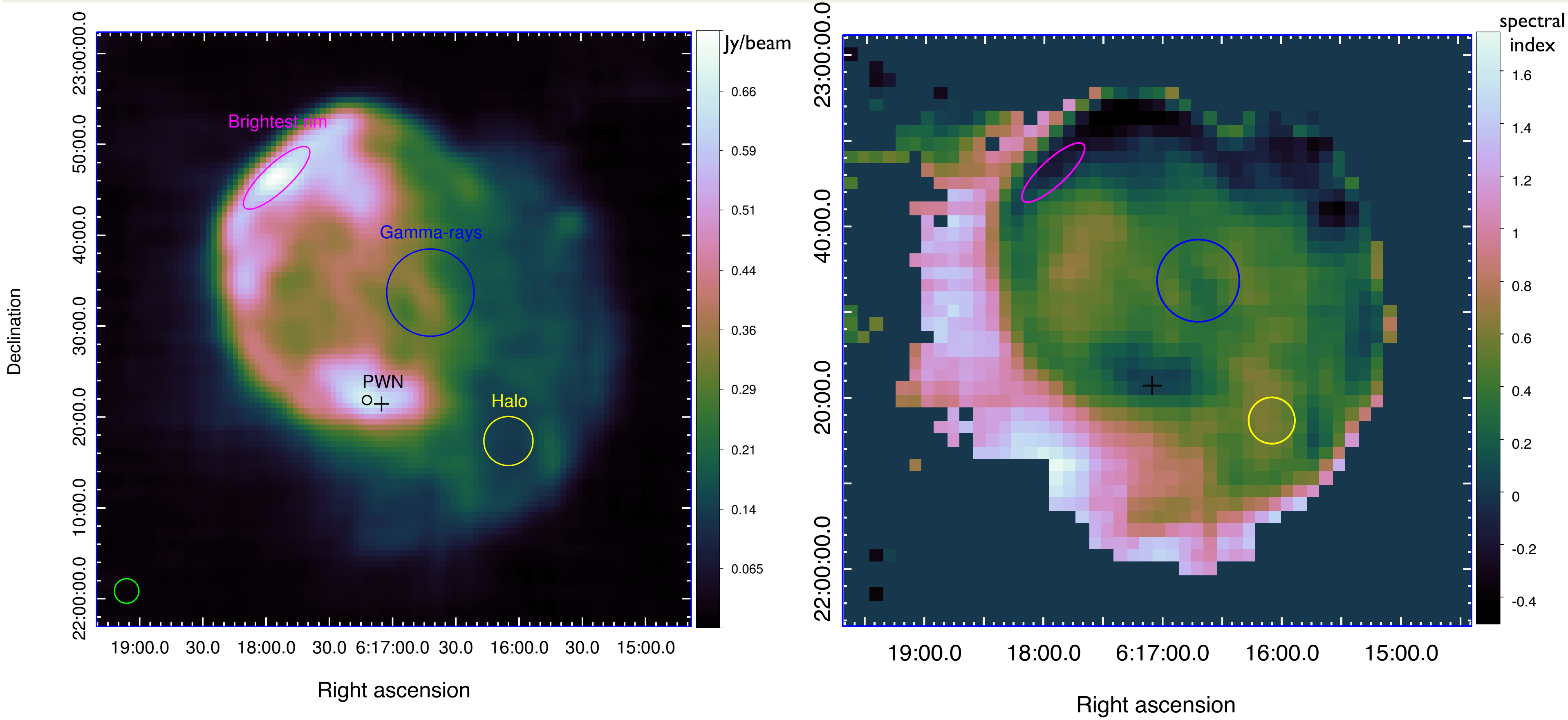
IC443





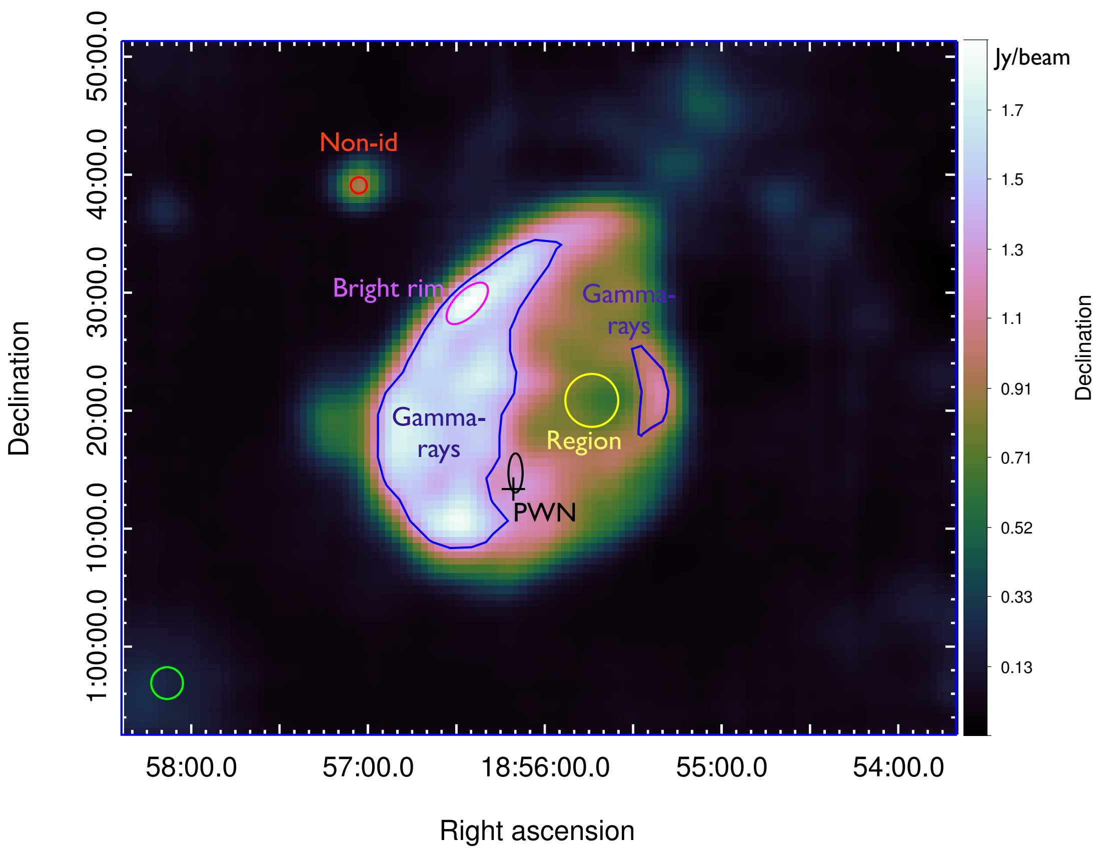
Loru et al., in preparation

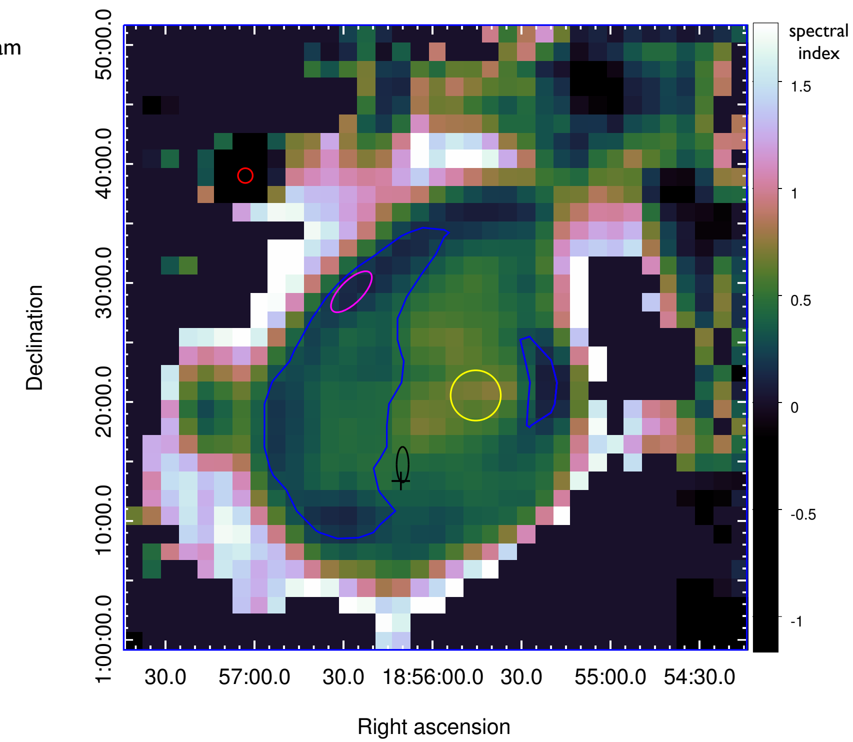
Spectral index map: IC443



Bright regions → flat spectra,
Faint regions and halo → steep spectra up to α=**0.7**

Spextral index map: W44





Bright regions → flat spectra,
Faint regions and halo → steep spectra up to α=**0.7**

Spread in spectral index distribution → several concurring processes?

Region dependent thermal absorption (free-free)?

it explain the low-frequency cut-off (<50 MHz) observed in the integrated SNR spectrum of IC443 (Castelletti et al., 2011), but extrapolating optical depth peak (τ_{74}=0.3 at 74 MHz) to >1 GHz the absorption coefficients are negligible $\exp(-\tau_{74} (\nu/74_{MHz})^{-2.1})$.

Spread in spectral index distribution → several concurring processes?

Intrinsic variety in the primary and secondary electron spectra (spectral slopes and breaks)?

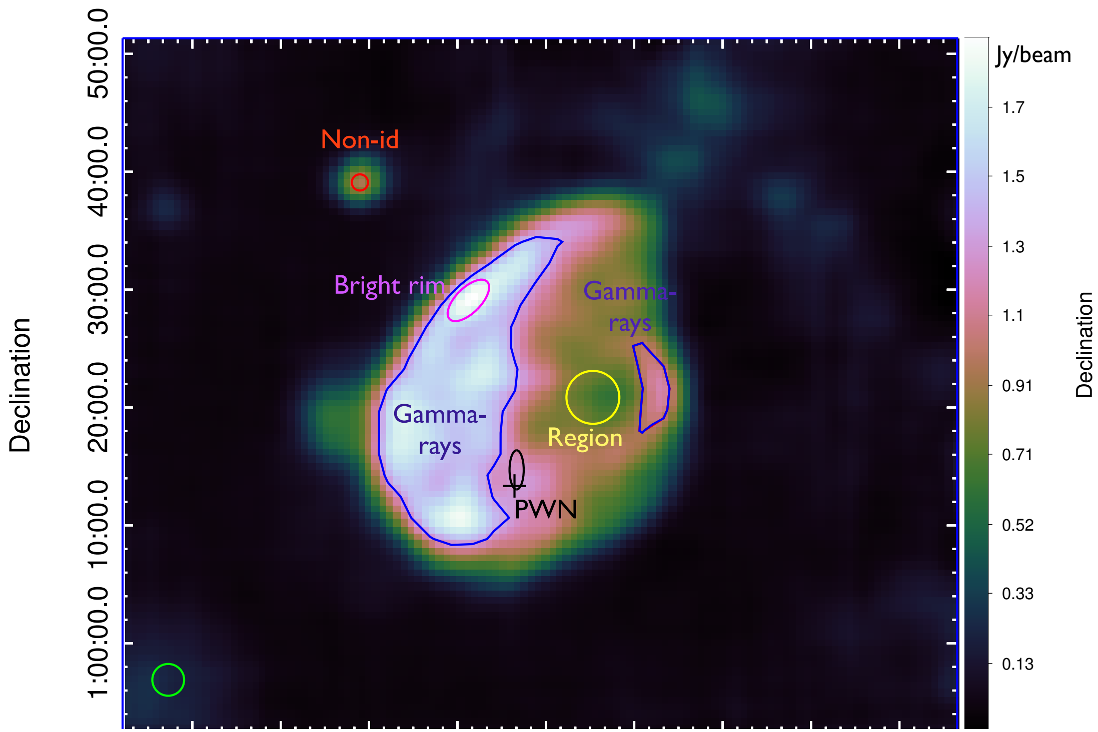
Standard shock acceleration theory: expected synchrotron slope α=0.5 (compatible with our average values) or at least α>0.2 even in the ultrarelativistic regime and assuming a high shock compression factor (Ellison et al., 1996, 1995; Sturner et al., 1997).

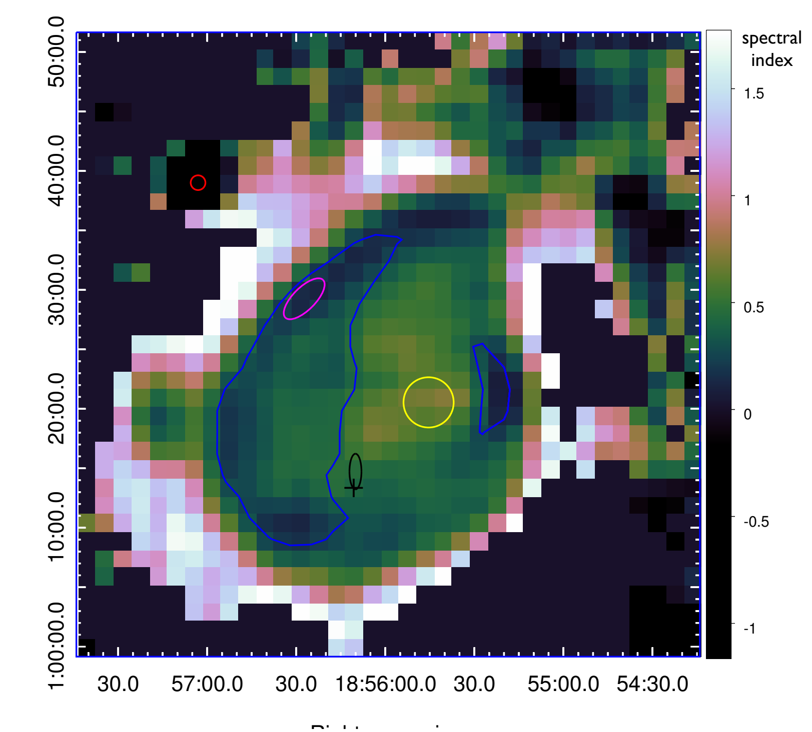
Cannot explain flat spectra!

Spread in spectral index distribution → several concurring processes?

Flattening effect due to region-dependent amount of secondary electrons production?

Significant amount of secondary electrons where enhanced hadronic emission is present (Cardillo et al., 2016). Gamma-ray emission clearly correlates with bright radio rims and filaments for W44.





Spread in spectral index distribution → several concurring processes?

Strongly-enhanced, region-dependent cooling?

No significant steepening of the spectral index due to synchrotron cooling is expected from a particle gas drifting away from the shock region on a time scale of 10^4-10^5 years (Sturner et al. 1997).

Region-dependent spectral slopes could reflect the presence of different electron distribution cut-off energies.

Spread in spectral index distribution → several concurring processes?

Region dependent thermal absorption (free-free)?

Intrinsic variety in the primary and secondary electron spectra (spectral slopes and breaks)?

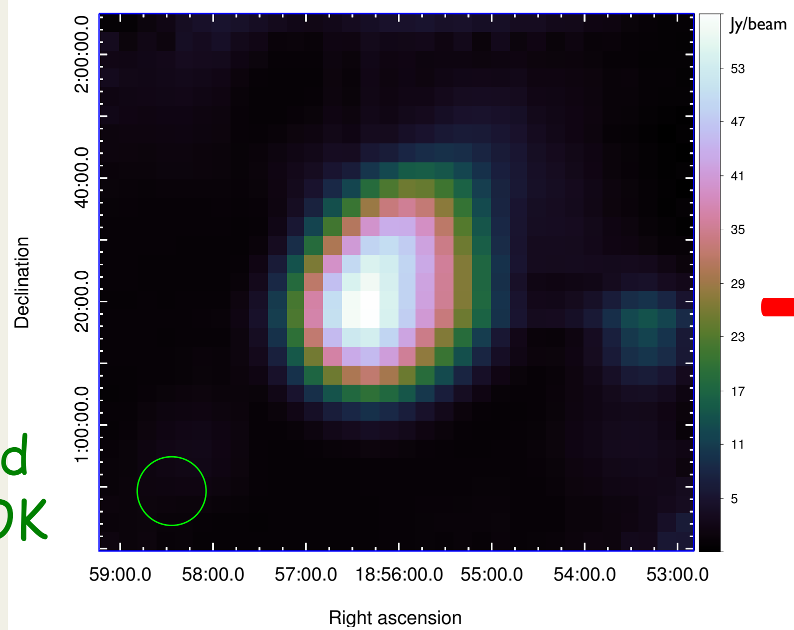
Flattening effect due to region-dependent amount of secondary electrons production?

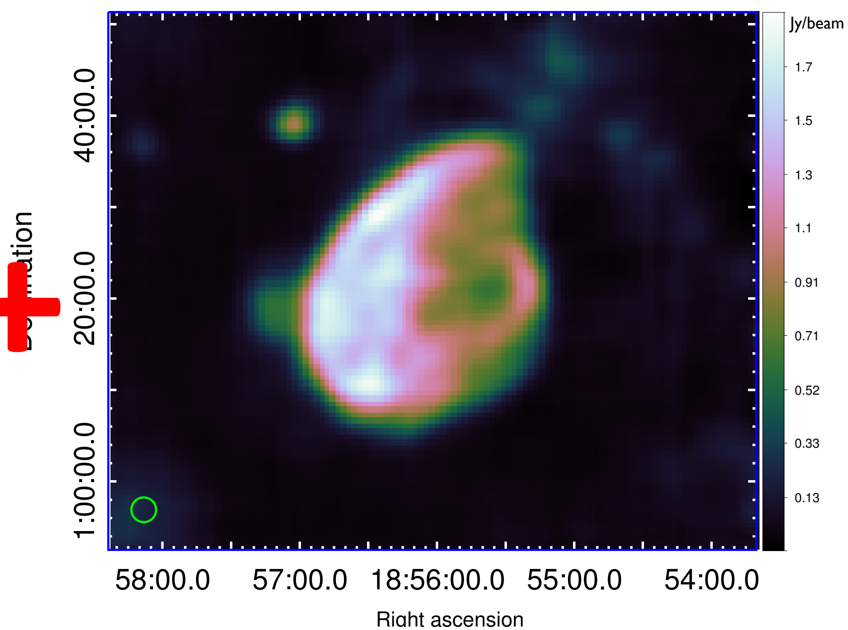
Strongly-enhanced, region-dependent cooling?

Region-dependent spectral slopes could reflect the presence of different electron distribution cut-off energies?

1.5 GHz 7 GHz

W44

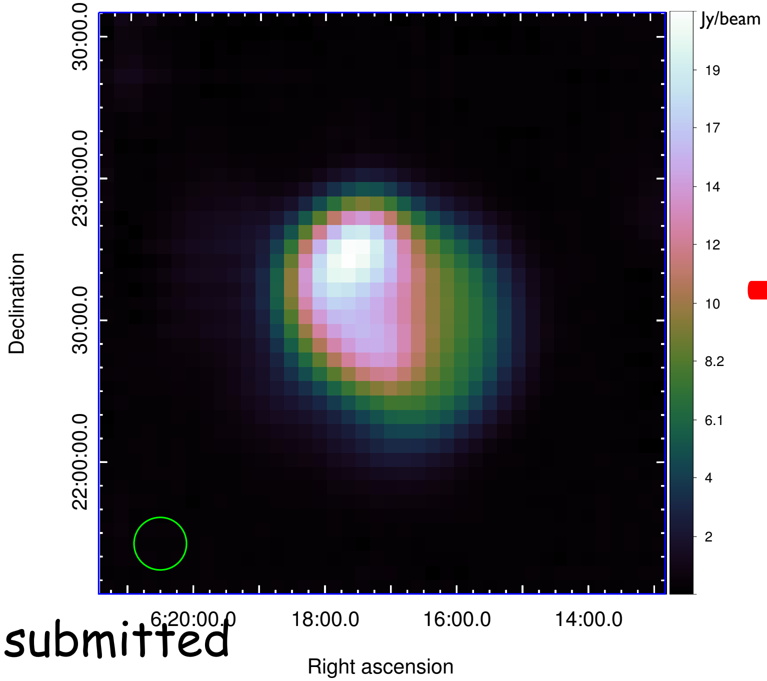


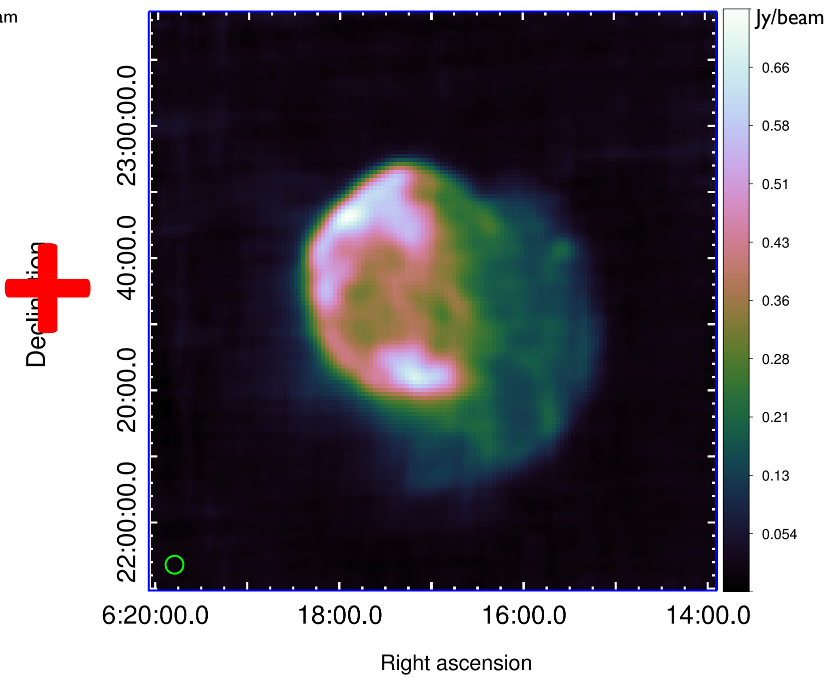


Integrated spectra: OK

Spectral Imaging: POOR

IC443





Egron et al., submitted

Single dish radio imaging with good resolution can provide accurate flux density measurements, then **accurate integrated spectra.**

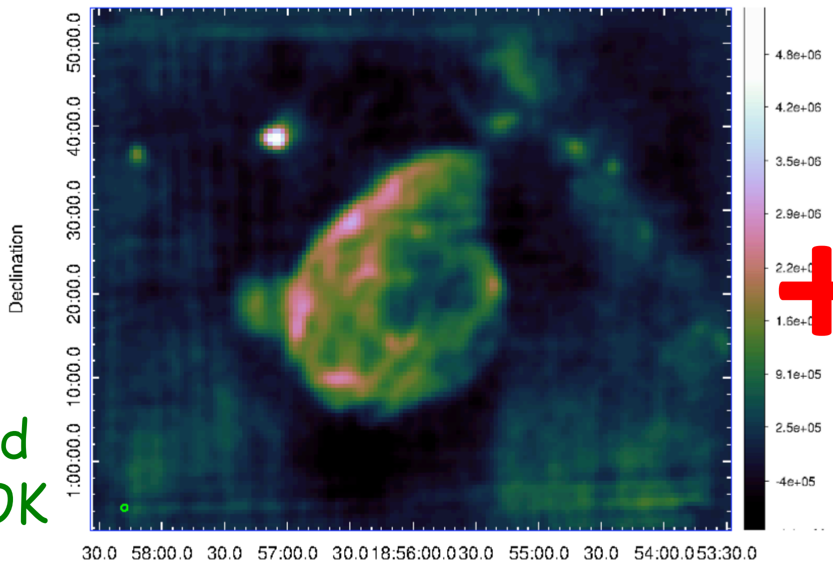
Poor spatially-resolved spectra are obtained when combining SRT L(1.5 GHz) + C(7 GHz) band…

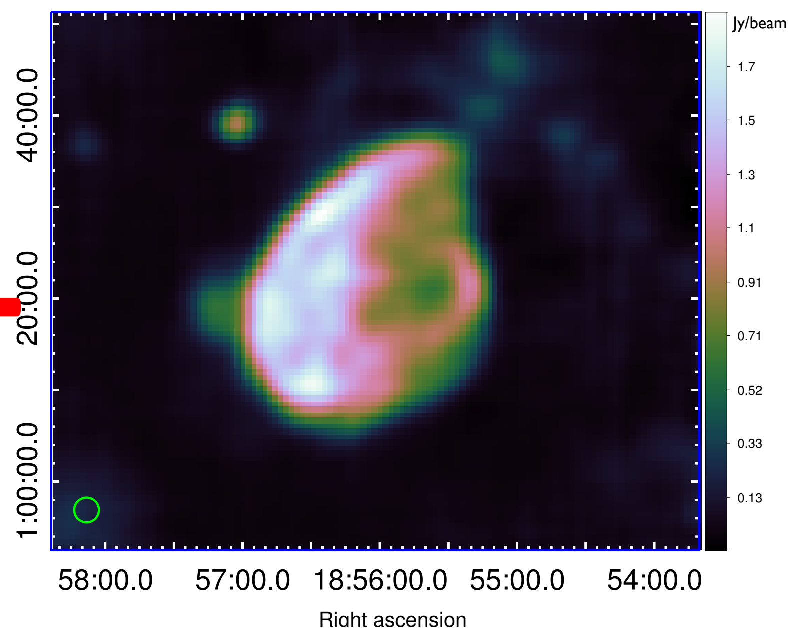
…but improving when combining C(7 GHz) band and K(20 GHz) band measurements.

21 GHz

7 GHz

W44

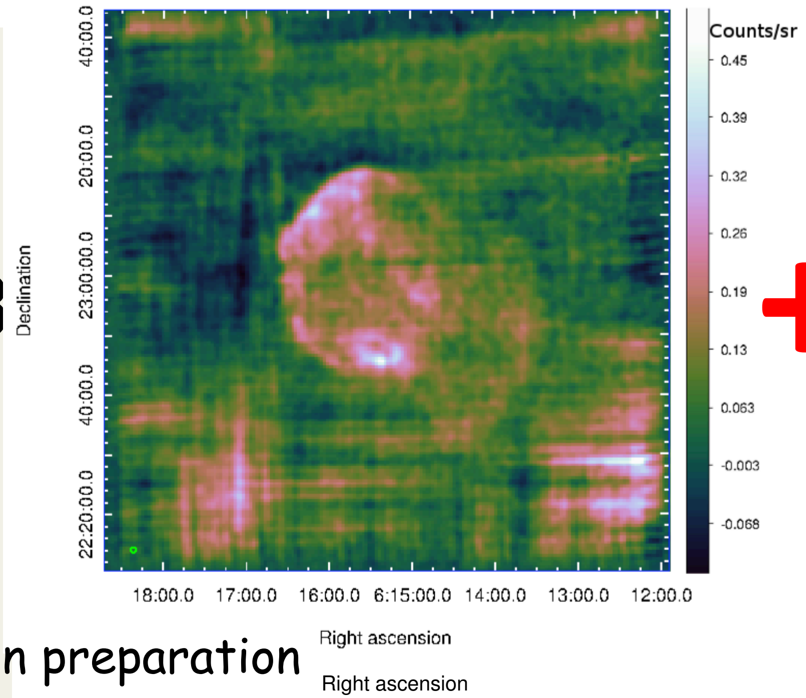


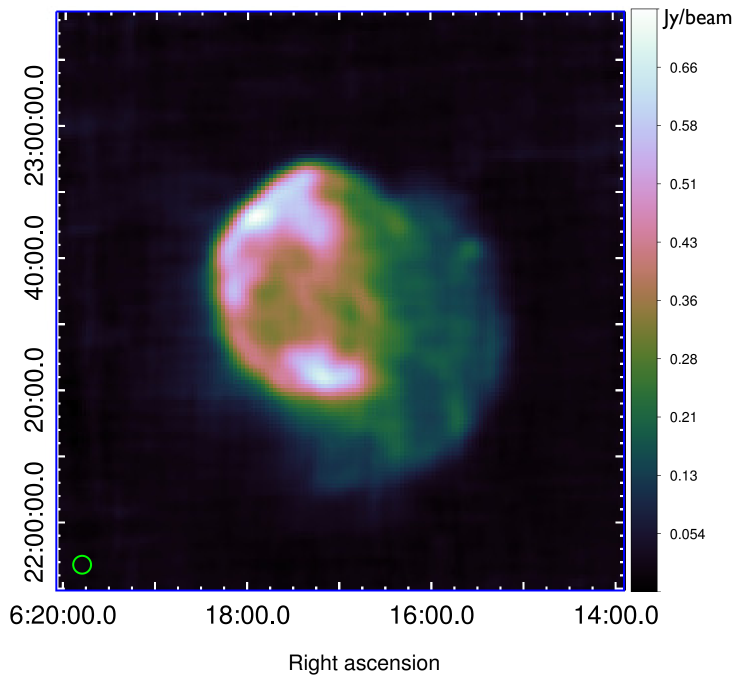


Integrated spectra: OK

Spectral Imaging: OK!

IC443



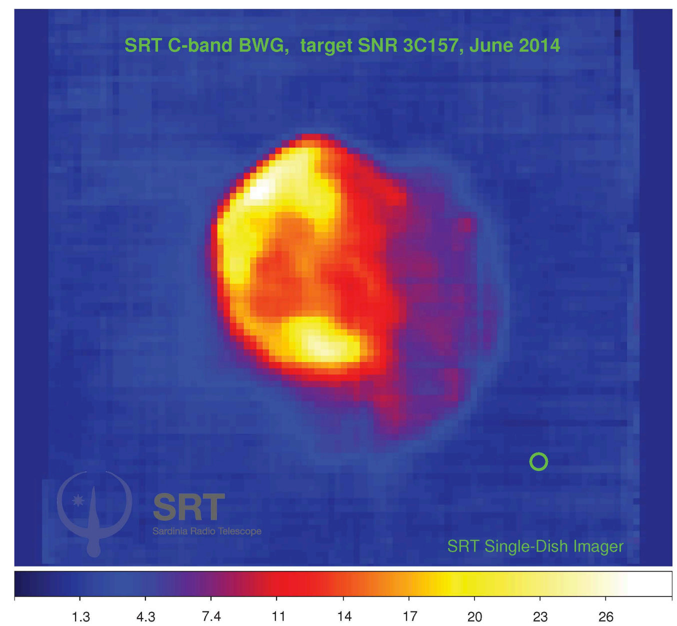


Loru et al., in preparation

Summary

The *Sardinia Radio Telescope* can provide high-resolution imaging (and then spatially resolved spectra) up to 22 GHz suitable for multi-wavelength modeling of large diffuse sources (see also Loru et al. Poster).

High-frequency spatially resolved spectra can better constrain cosmic-rays emission from SNR.



Thank-you!