Insights on Extrinsic Thermal Absorption from a Generic Assessment of SNR Radio Continuum Spectra

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(Abadi et al. 2023, in prep.)

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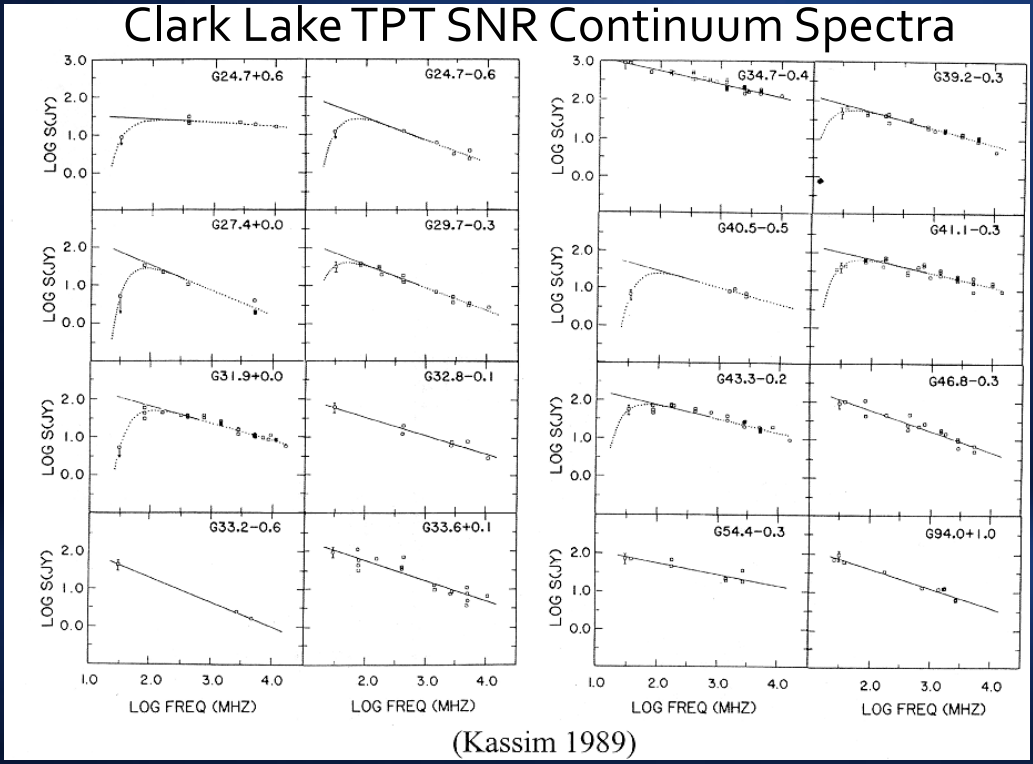
Why are SNRs and their interaction with the ISM important?

- SNRs are key players in Galactic astrophysics – two of many important reasons:
  - Provide ≥ 1/3 of the energy input to the ISM
  - Stimulate star formation through their interaction with GMCs
- Historical challenges
  - Quantifying the interaction of SNRs with star-forming regions has been difficult, often because SNRs have notoriously poor distances
  - Even when clearly interacting, it is often difficult to disentangle their relative radial superposition
  - A global census of the relative distributions of SNRs & star-forming regions is informative since the populations must be related

Observations of SNRs in the LWA frequency range bear on these questions (and more)

SNRs: lighthouses on the ionized ISM through low frequency absorption

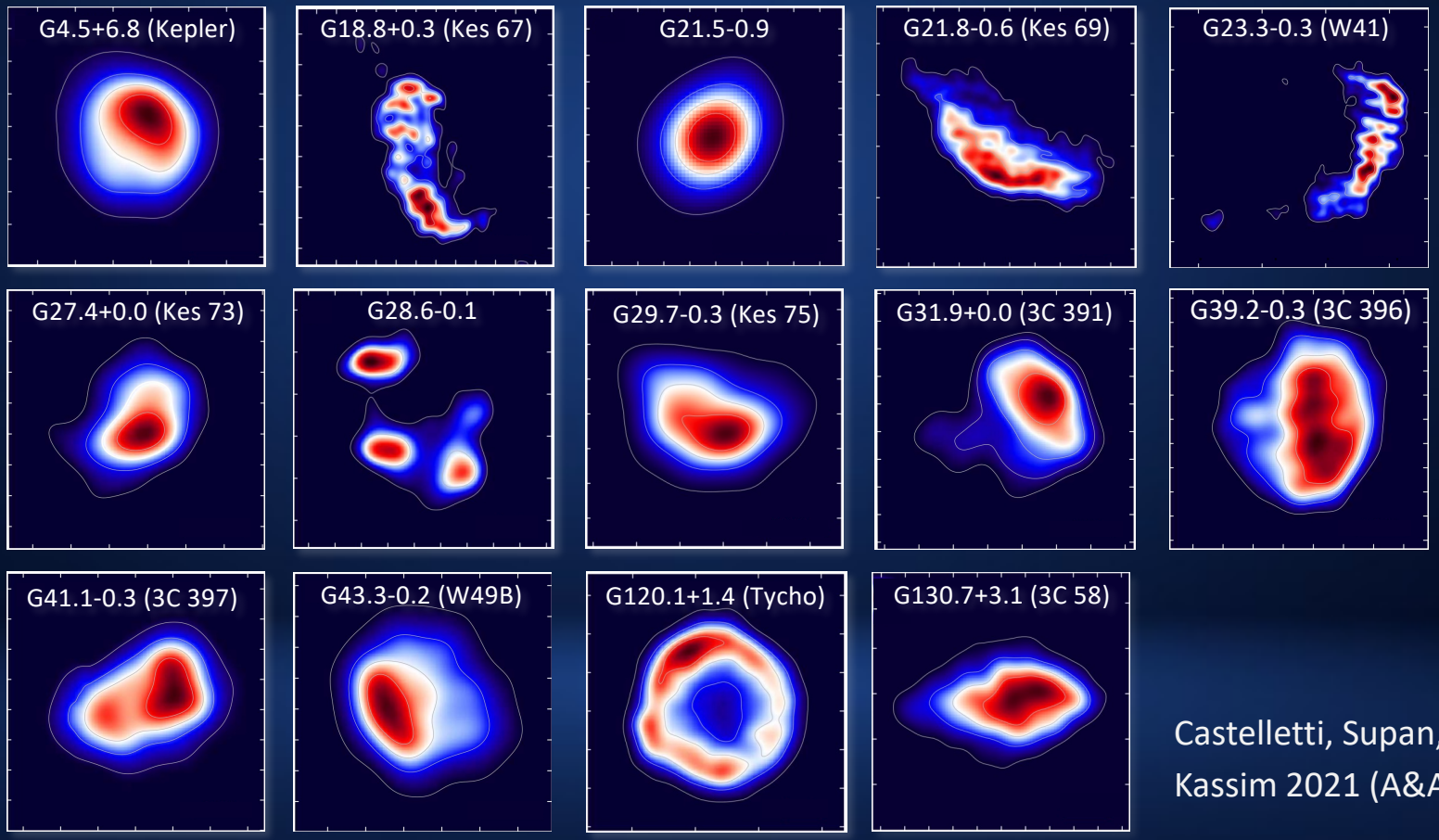
Pre-LOFAR & LWA eras: A patchy distribution of low frequency ionized gas probably associated with normal HII regions (Kassim 1989).



- Many, but not all, SNRs show LF continuum turnovers (pioneered at 80 MHz by Dulk & Slee 1985).
- Earliest studies limited to integrated spectra by poor angular resolution.
- Gas responsible generates stimulated, meter-wavelength RRLs (e.g. 325 MHz) indicating the gas is probably associated with normal HII regions (Anantharamiah 1986)
- n_e ~ 3-6 cm^{-3}, , T_e~3000-8000 K, Size ~ 100 pc

And then along came angular resolution …

- 74 MHz VLA (e.g., **VLSSr**) started to resolve the SNRs below 100 MHz

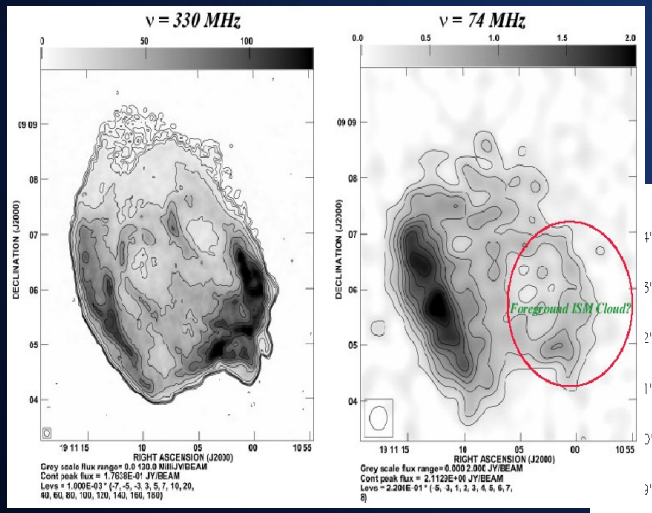


Castelletti, Supan, Peters, Kassim 2021 (A&A, 653, 62)

Finally able to resolve the absorption!

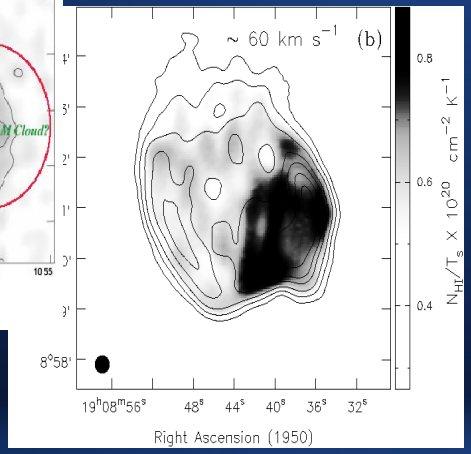
Two cases of resolved absorption

W49B



Lacey et al (2001)

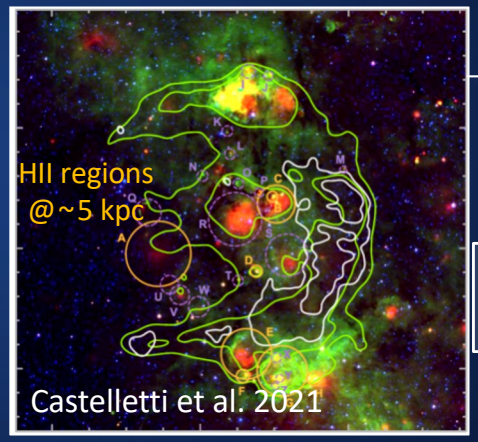
Radio Recombination line H134a at ~65 km/s (Downes & Wilson 1974)



HI (Brogan & Troland (2001)

W41

Age ≈ 70000 yr D = 4.8 ± 0.2 kpc



W41 field in the **IR** (*Spitzer*)

R = 24 μm
G = 8.0 μm
B = 3.6 μm

Copious thermal gas in the HII region complex

R_{CG} ≈ 5 kpc

$T_e = (5780 \pm 350) + (287 \pm 46)\, R_{CG} \approx 7100$ K (Quireza+06)

For *free-free* absorption

From fitted $\tau_{74} \approx 1.2$: EM ≈ 10^4 pc cm^{-6}

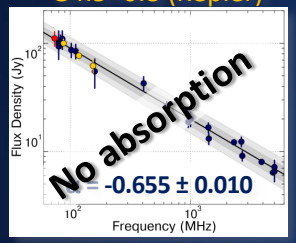
For HII region sizes ≈ 4 pc: $n_e \approx 60$ cm^{-3}

Absorption consistent with HII region cores and maybe their associated envelopes (EHEs)

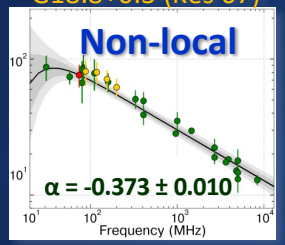
Differentiating local vs. non-local absorption

- Integrated spectra with new **VLSSr** and **GLEAM** points

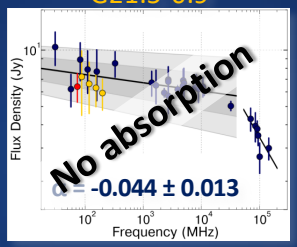
G4.5+6.8 (Kepler)



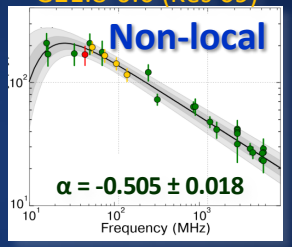
G18.8+0.3 (Kes 67)



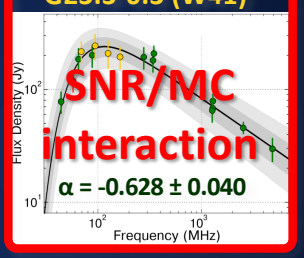
G21.5-0.9



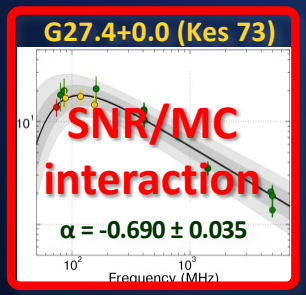
G21.8-0.6 (Kes 69)



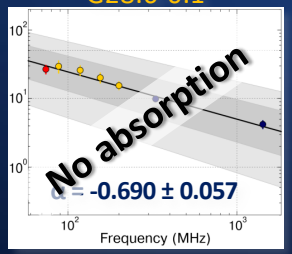
G23.3-0.3 (W41)



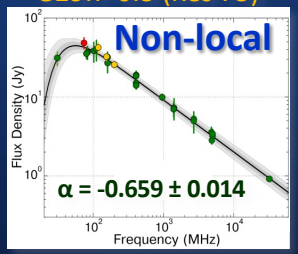
G27.4+0.0 (Kes 73)



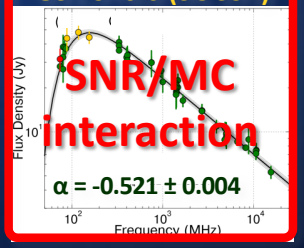
G28.6-0.1



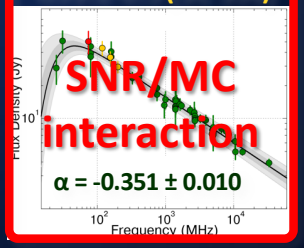
G29.7-0.3 (Kes 75)



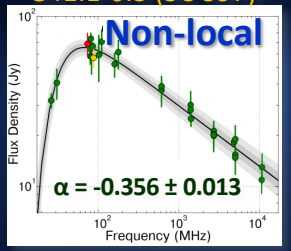
G31.9+0.0 (3C 391)



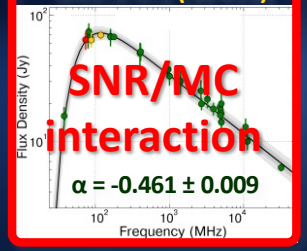
G39.2-0.3 (3C 396)



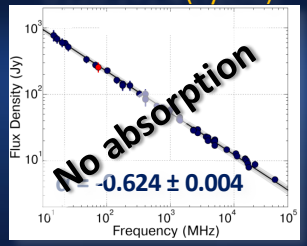
G41.1-0.3 (3C 397)



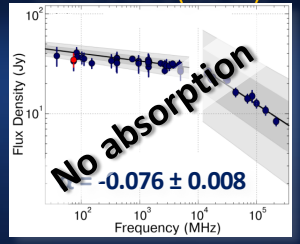
G43.3-0.2 (W49B)



G120.1+1.4 (Tycho)



G130.7+3.1 (3C 58)



Castelletti, Supan, Peters, Kassim 2021 (A&A, 653, 62)

Next Steps?

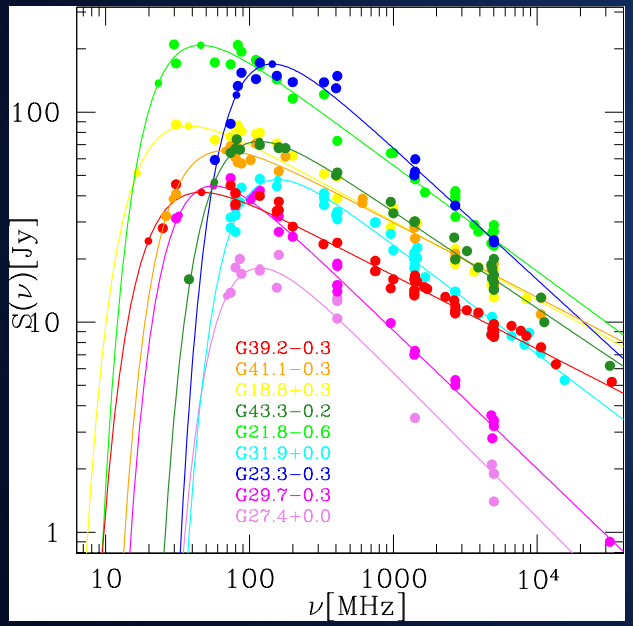
The Trees: follow-up studies of individual cases

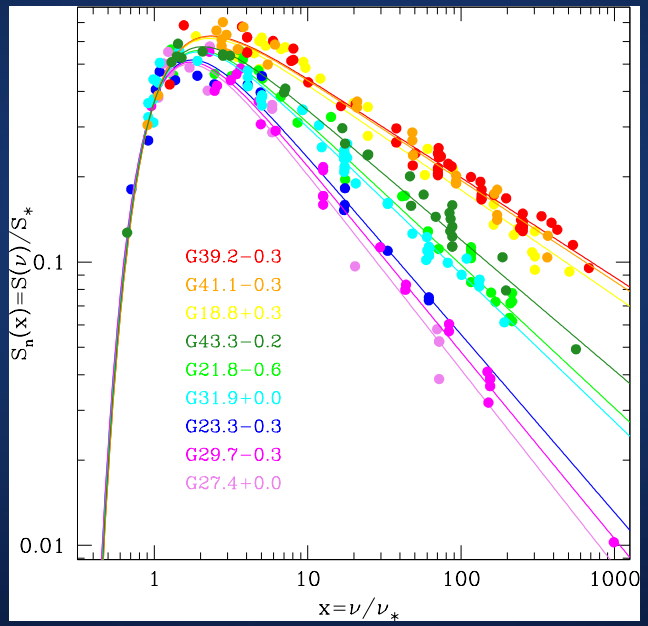
- Multi-wavelength studies from radio to IR, to optical, to X-ray, to gamma-ray
- Discerning the physics of individual SNR-HII region/MC interactions
- Resolved spectra can also constrain shock-acceleration processes in SNRs

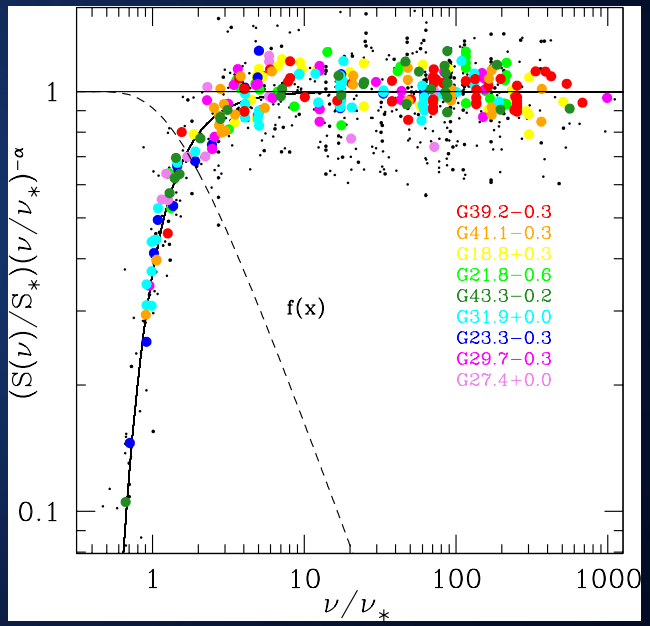
The forest: what can the ensemble of integrated spectra, coupled with resolved observations of the absorption, tell us?

- What does it tell us about the relative distribution of the SNRs and the absorbing gas in these complexes?
- Can we predict trends larger samples will eventually show?

First, let's generalize the spectra



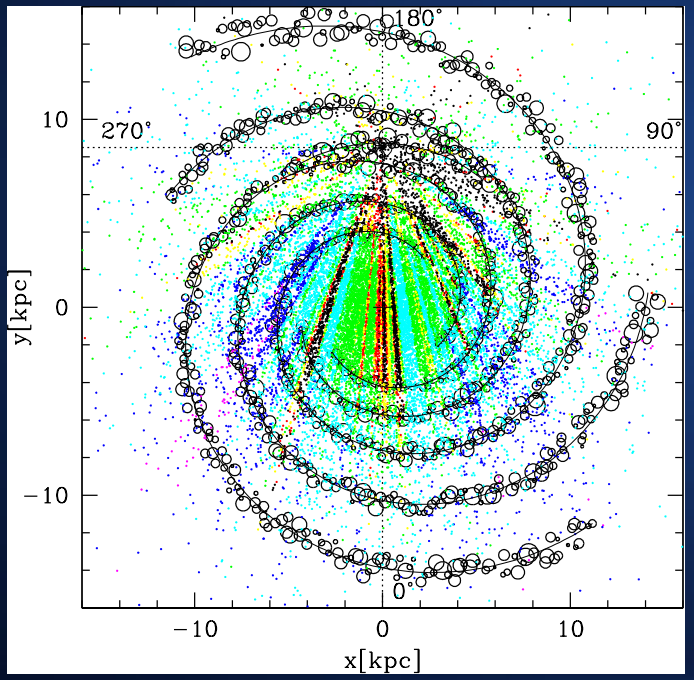


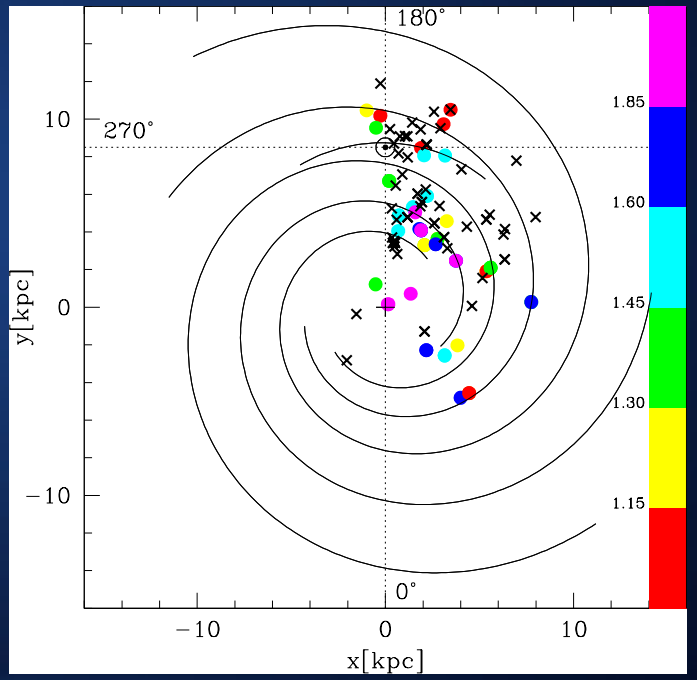


Abadi et al. 2023 (in prep)

- Normalize by flux densities and recast the spectra based on a characteristic frequency ν*
  - $\nu^* = \tau_0^{1/2.1}\nu_0$, $\nu_{to} = \nu^*(-2.1/\alpha)^{1/2.1}$
- Normalize again based on the non-absorbed SNR spectral index
- Confirms that the emission and absorption are independent processes

Next, create a Galactic model of SNRs and HII regions



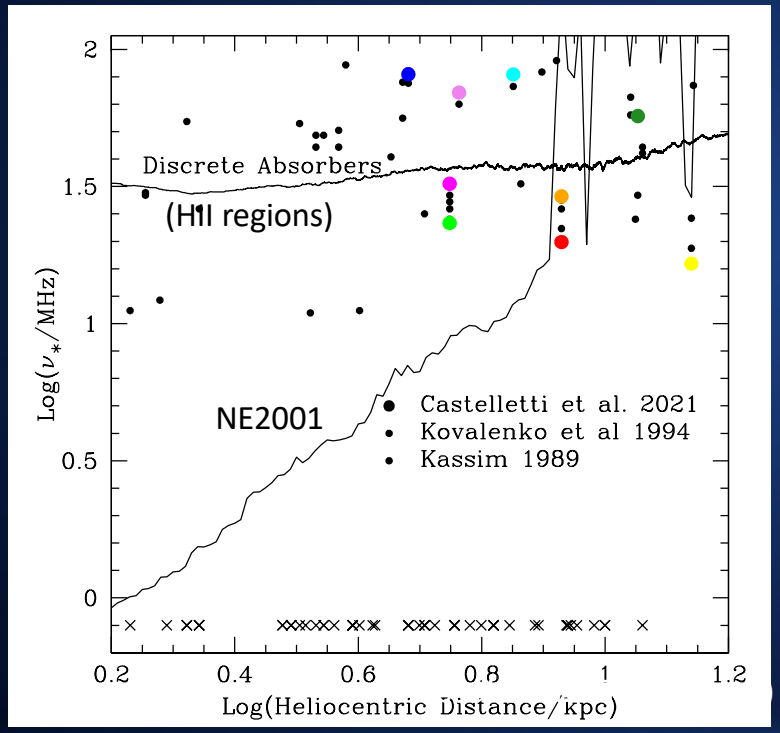


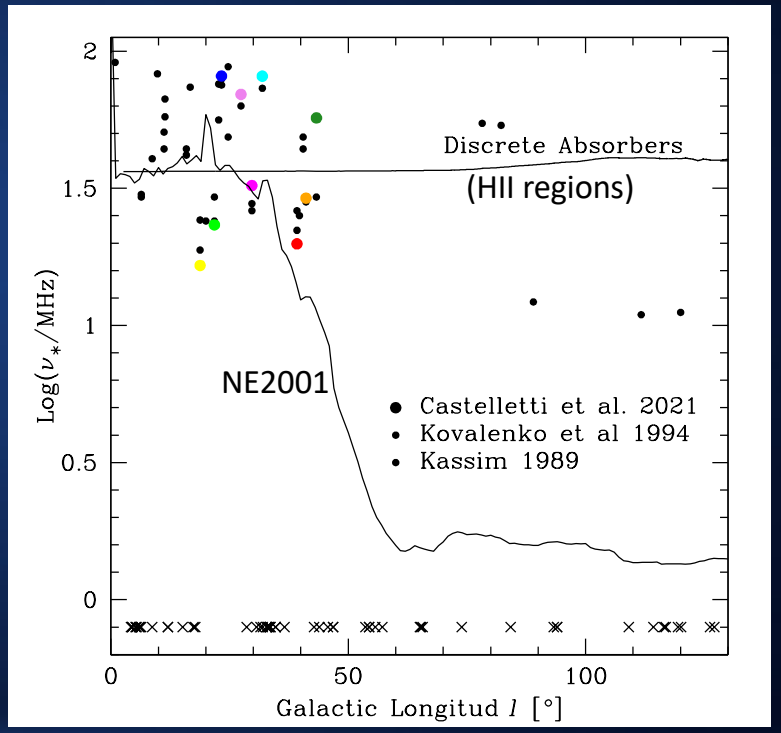
- Populate a Galactic model with 10,000 “mock” SNRs
- Distribute 1000 HII regions along the spiral arms
- Compare to our current sample (meager as it is)

Abadi et al. 2023 (in prep)

Compare prediction of model to measured SNR spectra

(Like optical depth or turnover frequency)

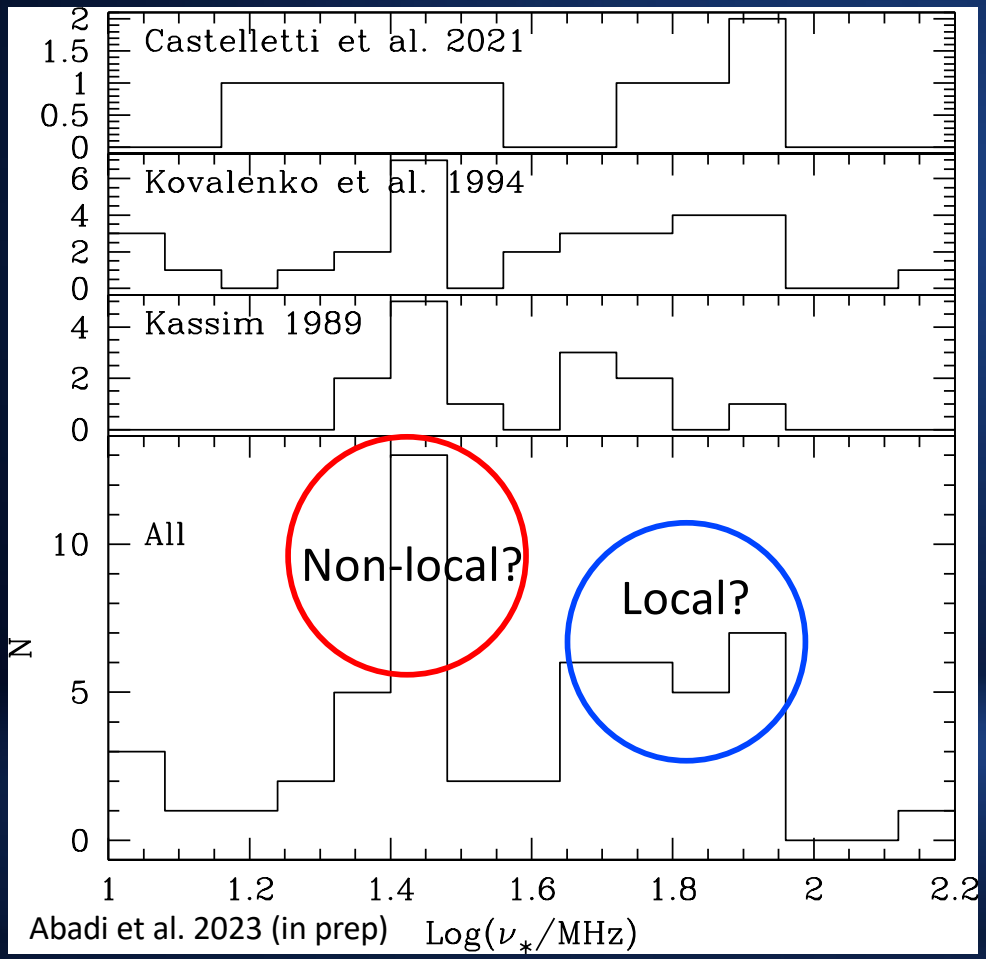




- No match w/ NE2001 continuous distribution of ionized gas
- No dependence on either distance or Galactic longitude
- Consistent with a patchy absorption tracking spiral arms with a low filling factor
- Prediction: SNR spectra preferentially absorbed towards 4th Galactic quadrant

Abadi et al. 2023 (in prep)

Resolution of Individual Cases starts to pull back the veil



- Sub-arcminute resolution imaging at LWA frequencies is especially impactful for 1) absorption processes, and 2) steep-spectrum (often coherent processes)
- For SNRs, we can finally start to understand the relationship between the SNRs and the absorbing gas
- Is the absorption local to the SNR in the same complex as the absorber?
- What is their relative superposition? Distance information!
- Very limited early statistics hint at a bi-model distribution
- Local absorption at higher frequencies, non-local absorption at lower ones

Results

- An increasing census of SNR spectra extended to LWA frequencies confirms thermal absorption by a patchy distribution of ionized gas
  - A new parameterization of the spectra simplifies the interpretation
  - All SNRs emit differently (α) and turnover at different frequencies - the two processes are independent
- Modelling based on a mock SNR aborbed by a population spiral arm HII regions reproduces the patchy absorption.
  - It shows why a continuous distribution model cannot match the observations
  - It reveals why the statistical behavior of the patchy absorption is non-intuitive
- An increasing number of absorbed SNRs are finally being resolved
  - The spectra hint at a bimodal distribution differentiating local vs. non-local absorption
  - Kassim (1989 & others) underestimated local absorption because they were blind!

Thoughts for an expanding LWA …

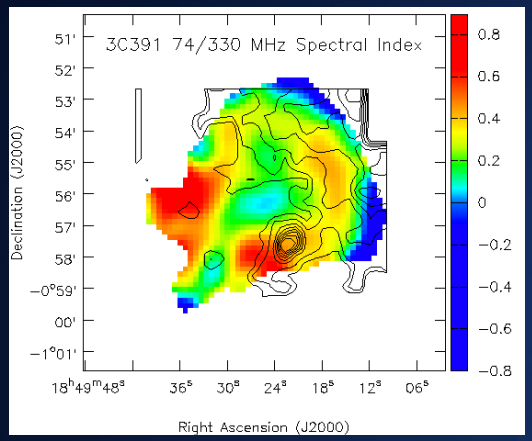
- A vast realm of thermal absorption is uniquely studied in the LWA band
  - Both Galactic (ISM) and extragalactic
  - Normal galaxies: edge-ons turnover like SNRs, face-ons do not! (Israel & Mahoney 1985)
- SNRs are an excellent place to start for LWA:
  - They are bright and their spectra are relatively straight-forward to interpret
  - In the early stages of LWA even accurately determined integrated spectra are important
- Near-term for LWA, even modest resolution is sufficient – 10-20" is great
- Until SKA-Low, LWA will be unique, especially towards the inner Galaxy
- Thermal absorption is a powerful tool for differentiating the properties and relative superposition of thermal and nonthermal sources.
- It is (almost) akin to the power of HI for providing all important distance information!

Do the easy stuff first, the most interesting new science will follow naturally

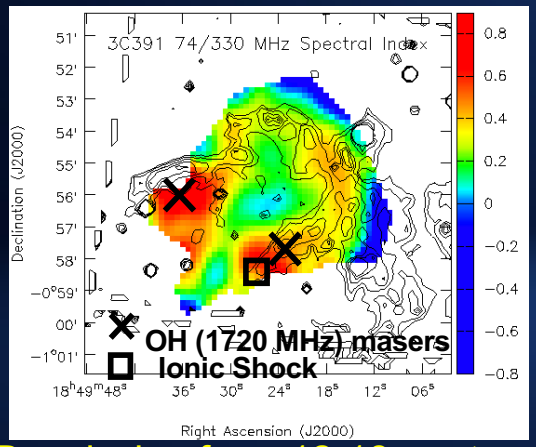
(Talk to me about NRL postdoc and student opportunities)

Backup

Resolved SNR/MC Interactions: Smoking Gun!



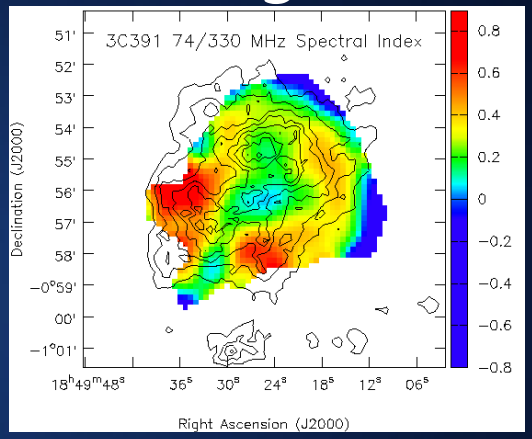
CO (2-1) integrated emission from 91 to 110 km/s (*Reach & Rho 1999*).



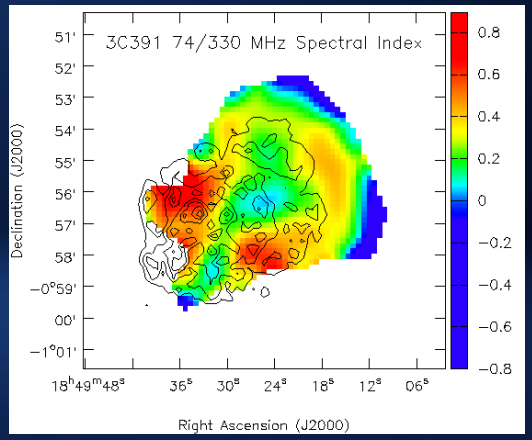
IR emission from 12-18 μm tracing shock boundaries (*Reach et al. 2002*).

Surprising agreement between regions of greatest 74 MHz absorption – delineates sheath of absorbing ionized gas residing in the SNR/molecular cloud shock boundary!

Brogan et al. 2002



HARD X-rays from ASCA showing full extent of SNR (*Chen & Slane 2001*)

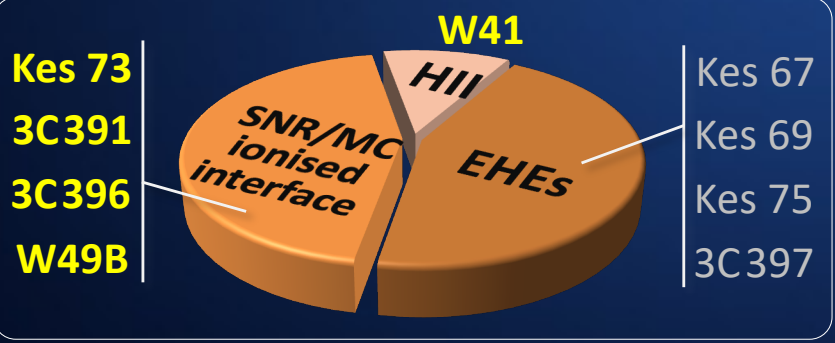


SOFT X-rays from ASCA showing X-ray absorption (*Chen & Slane 2001*)

Summary

Improved accurate radio spectra for 14 Galactic SNRs from new low-frequency data + compilation of fluxes

9 cases of low-frequency absorption



Only the lowest frequencies can reveal thermal absorption in the radio band

Low radio frequency observations are an excellent tool for studying physical processes in SNRs, and in relation with the surrounding and intervening ISM

Found more cases of resolved thermal absorption due to interaction between SNRs and their local environment by their low-frequency 'fingerprint'

For earlier background see: Castelletti, Supan, Peters, Kassim 2021 (A&A, 653, 62)