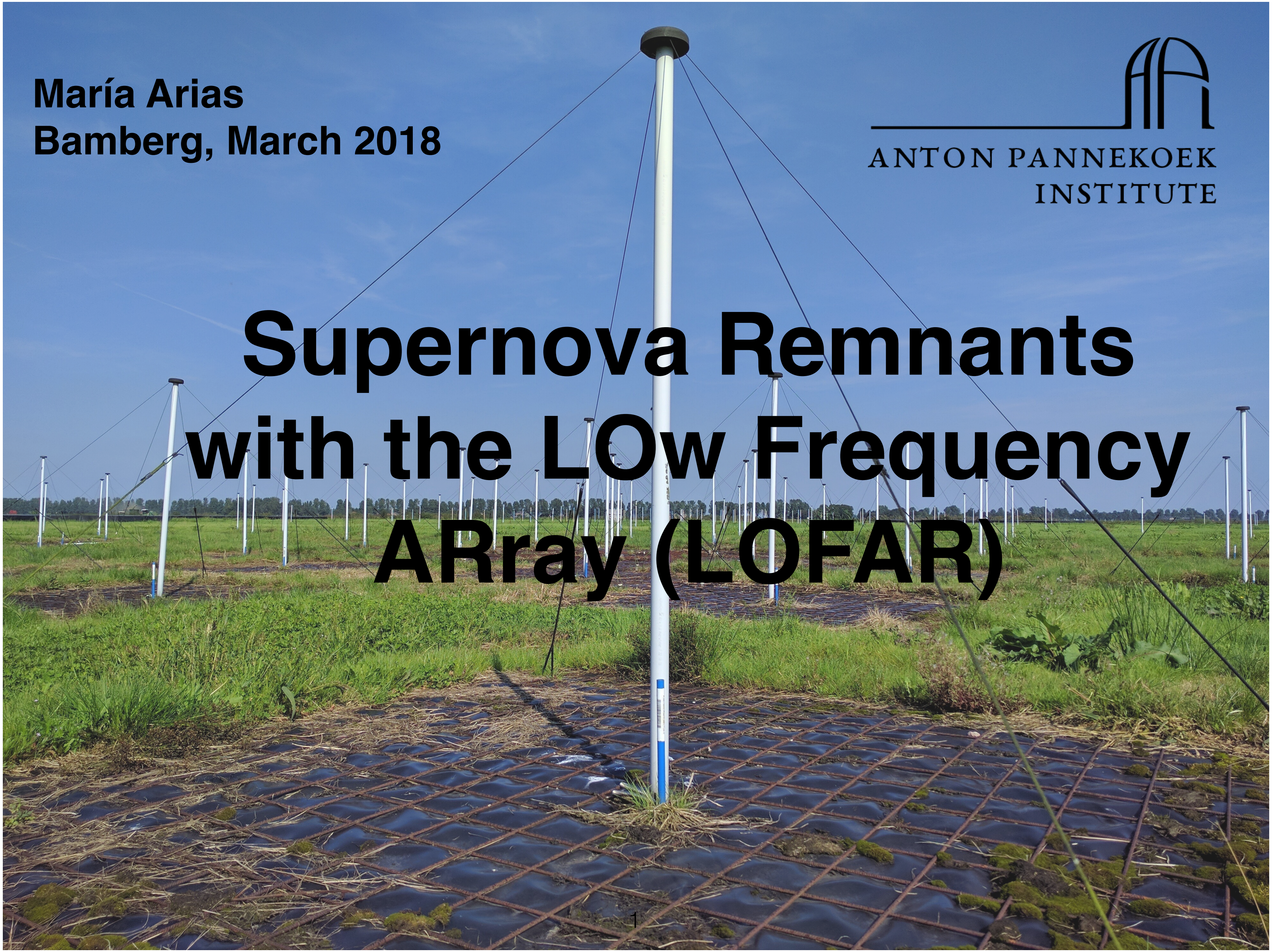


María Arias
Bamberg, March 2018

ANTON PANNEKOEK
INSTITUTE

Supernova Remnants with the LOw Frequency ARray (LOFAR)

The LOw Frequency ARray

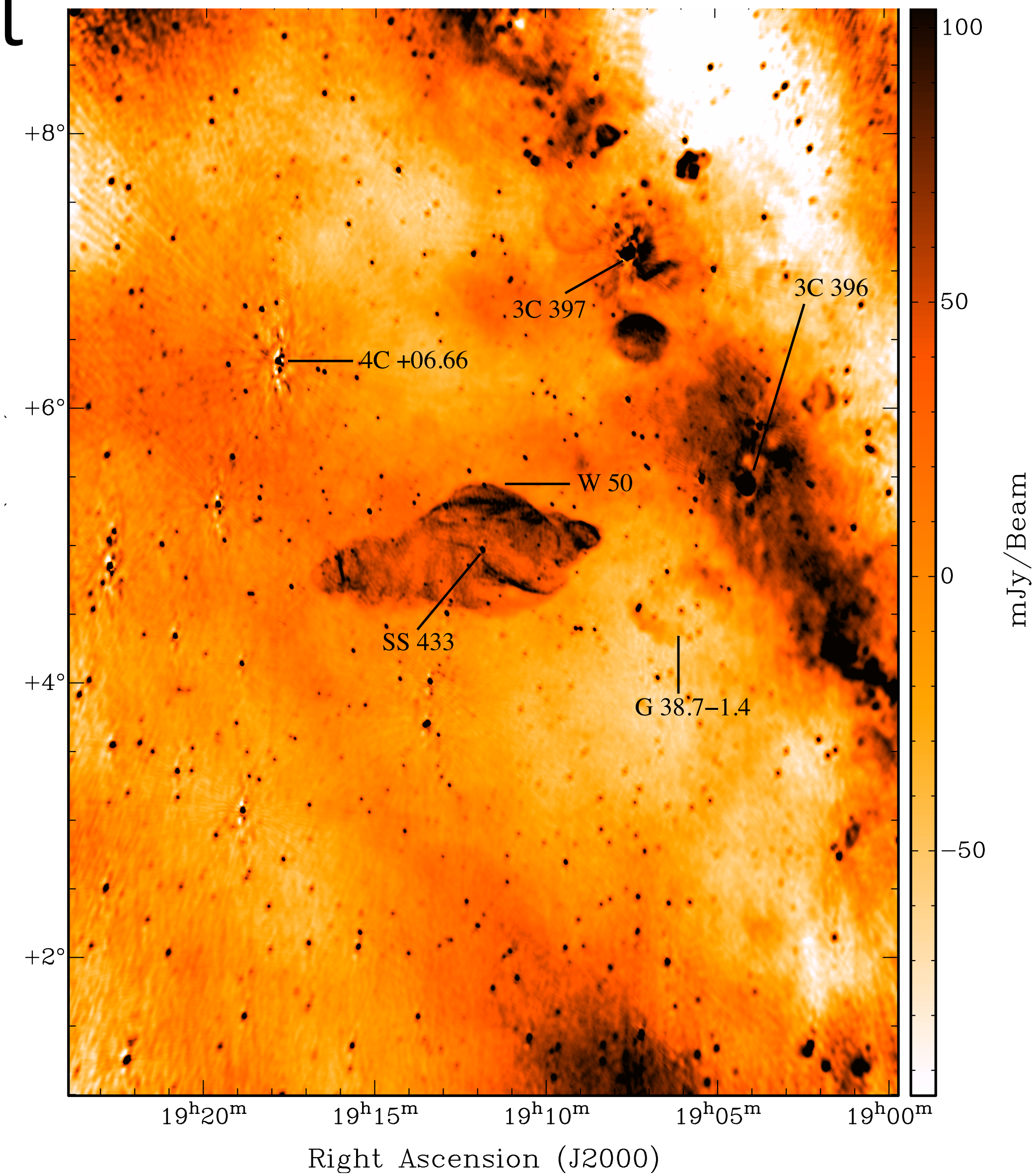
- Interferometer with stations in the Netherlands (24 *Core*, 14 *Remote*) and across Europe (12 *International*)
- Phased-array design
- 10-90 MHz (LBA);
  110-240 MHz (HBA)
- For 30 MHz on Full NL config., sensitivity of 5.7 mJy, angular resolution of ~20 arcsec

LOFAR Superterp, which houses six stations.

SNR Population at Low Frequencies

- Missing (young, small; old, faint) SNRs —LOFAR as a survey instrument.
- Confusion with HII regions —LOFAR is multifrequency (different values of α)

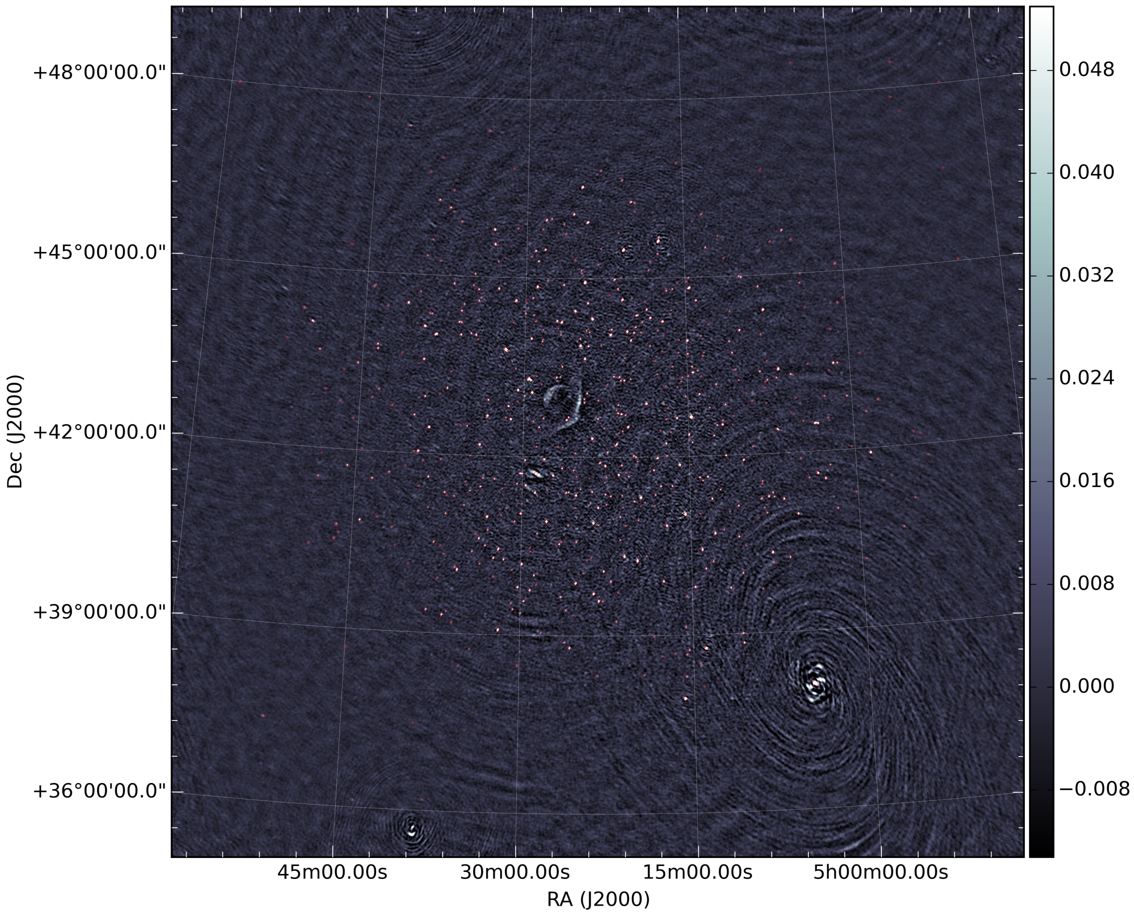
See V. Domcek's talk



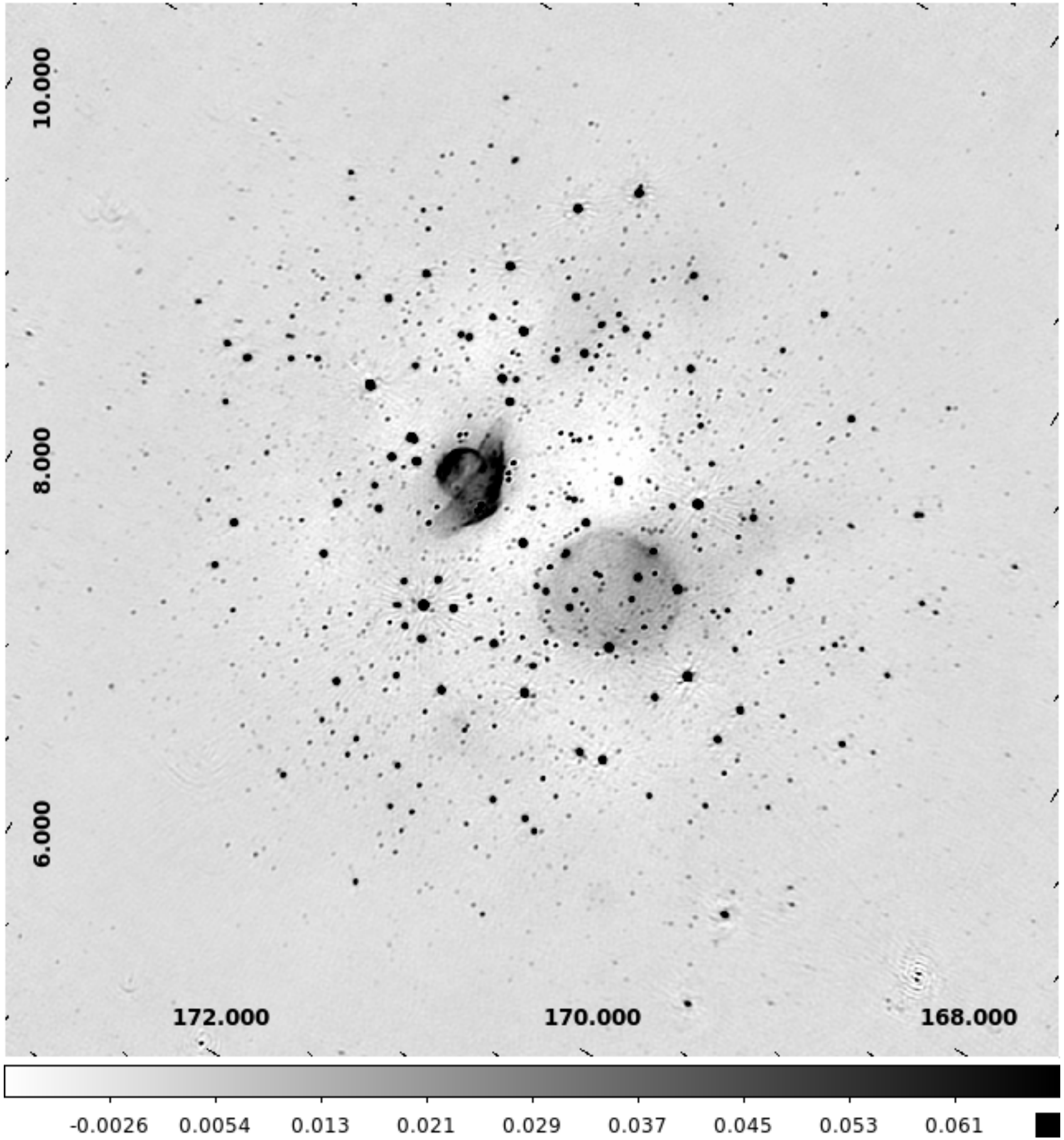
Right: HBA image of the W50 region. 48 MHz bandwidth; 115-163 MHz. Broderick+ 2018

Issues

- Beams
- In-band spectral index
- LBA: challenging ionospheric effects
- Bright sources create artefacts
- (RFI)



Initial-Subtract output from 60 subbands. Source in bottom-right needs to be *peeled*

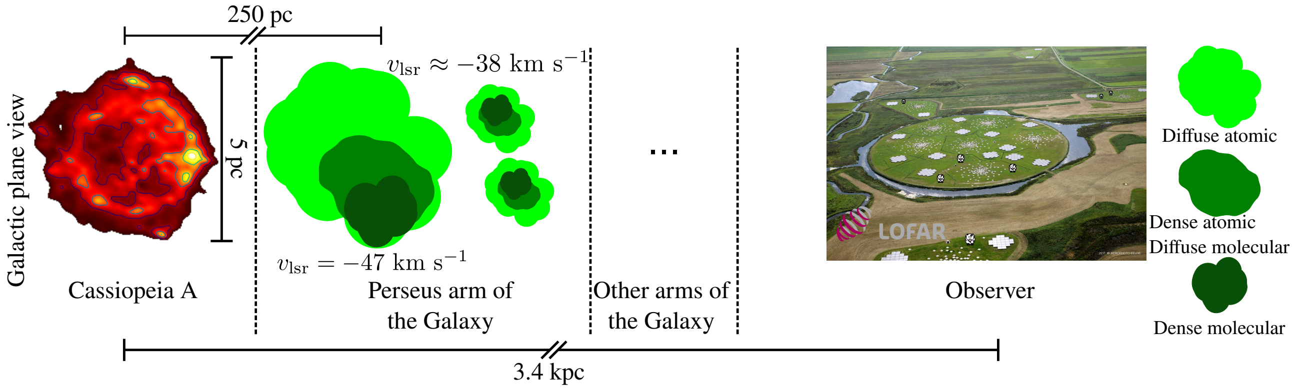


VRO 42.05.01 field

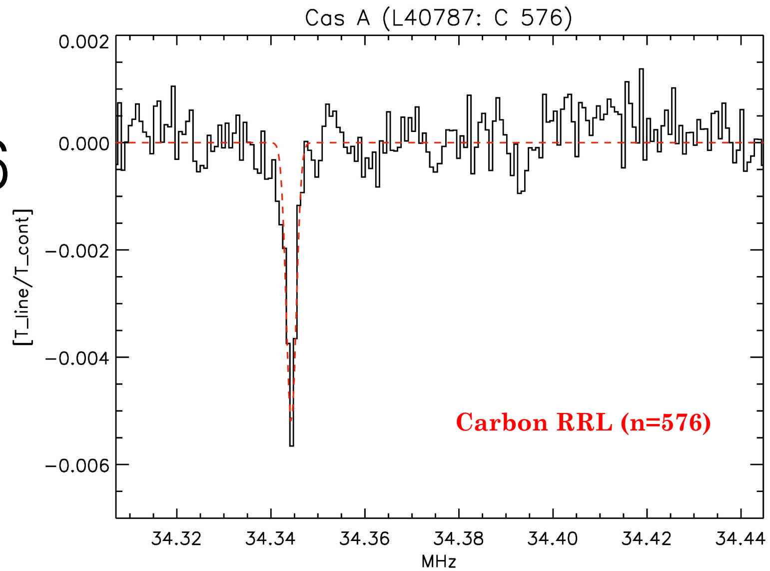
Full bandwidth (275 subbands) CS only Stokes I image. The noise measured towards the edges of the map is 0.9 mJy/beam, the psf size is 152 arcsec. The source in the bottom-right has been properly peeled.

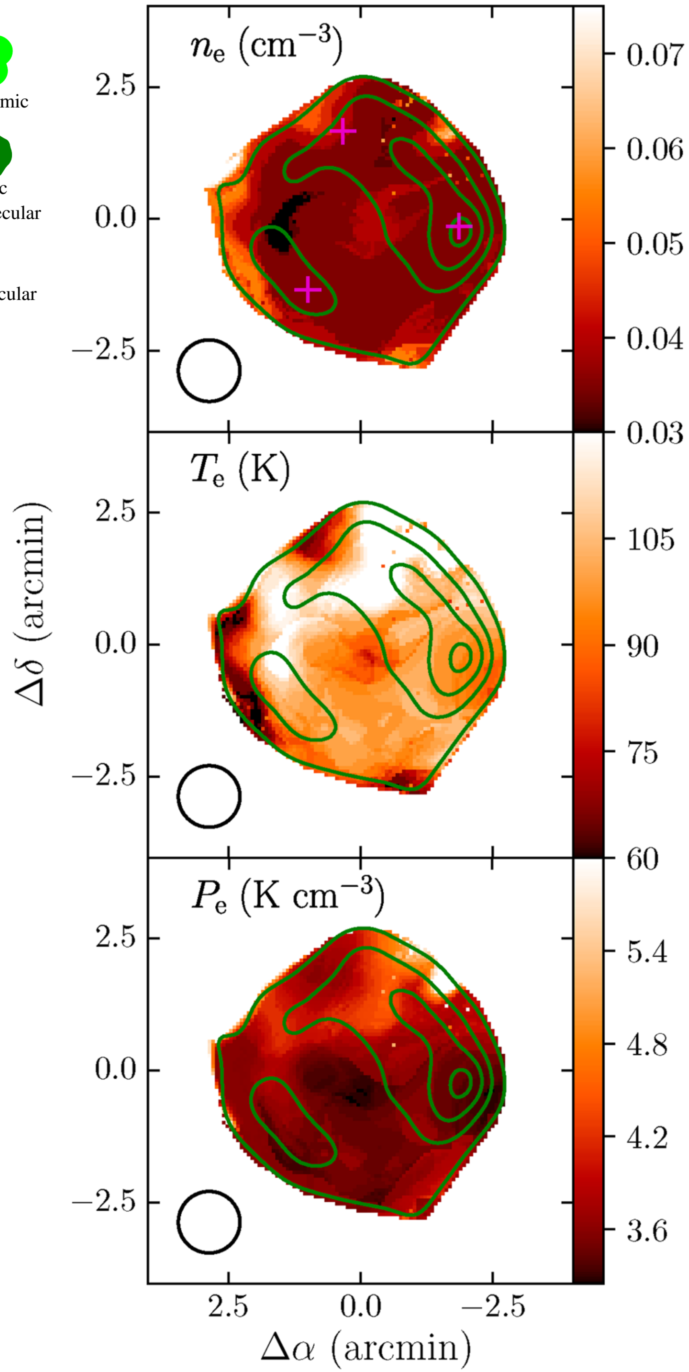
Cassiopeia A

- ISM along its line-of-sight from carbon recombination lines (CRRL)
- Detailed morphological study of the source at Low Band Antenna (LBA) frequencies



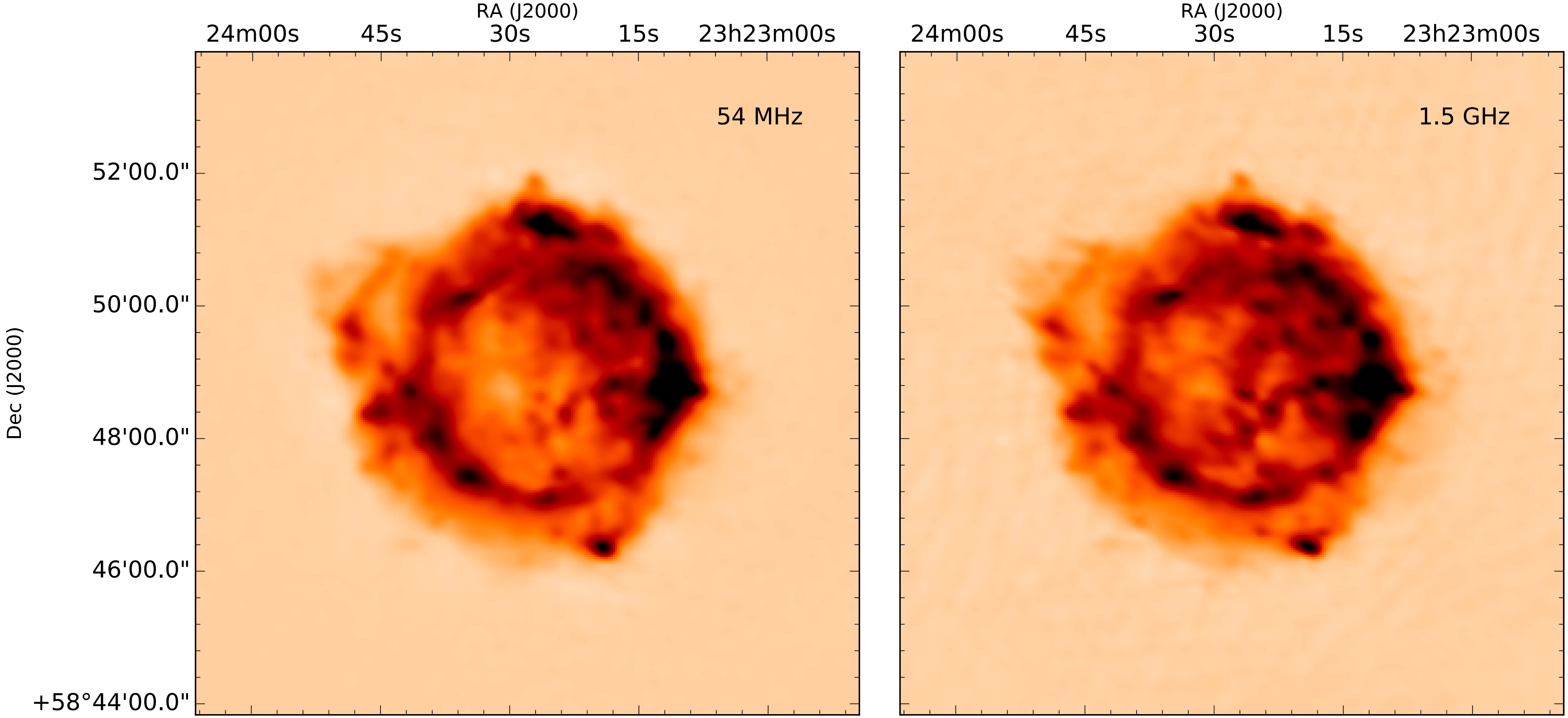
Salgado+ 16
Oonk+17
Salas+ 18



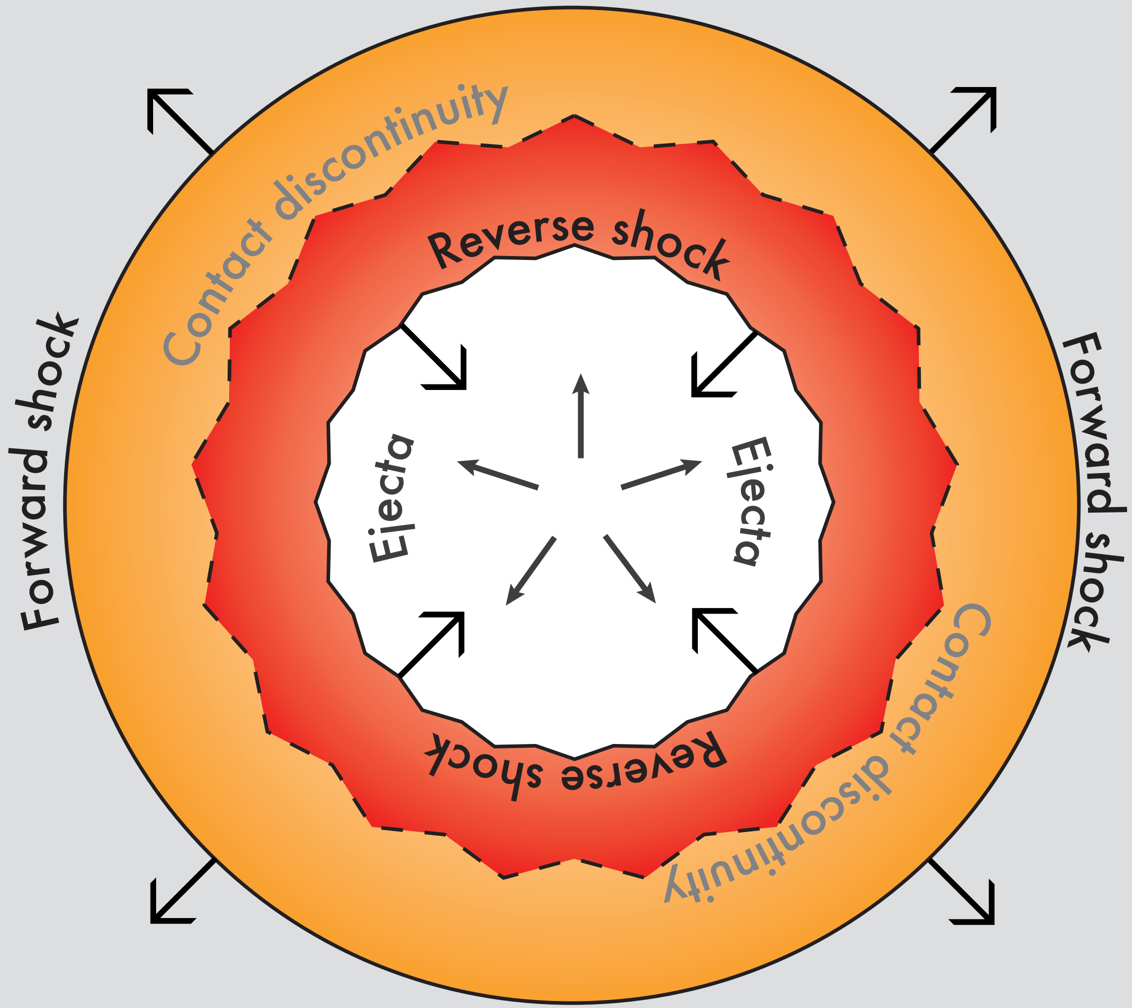


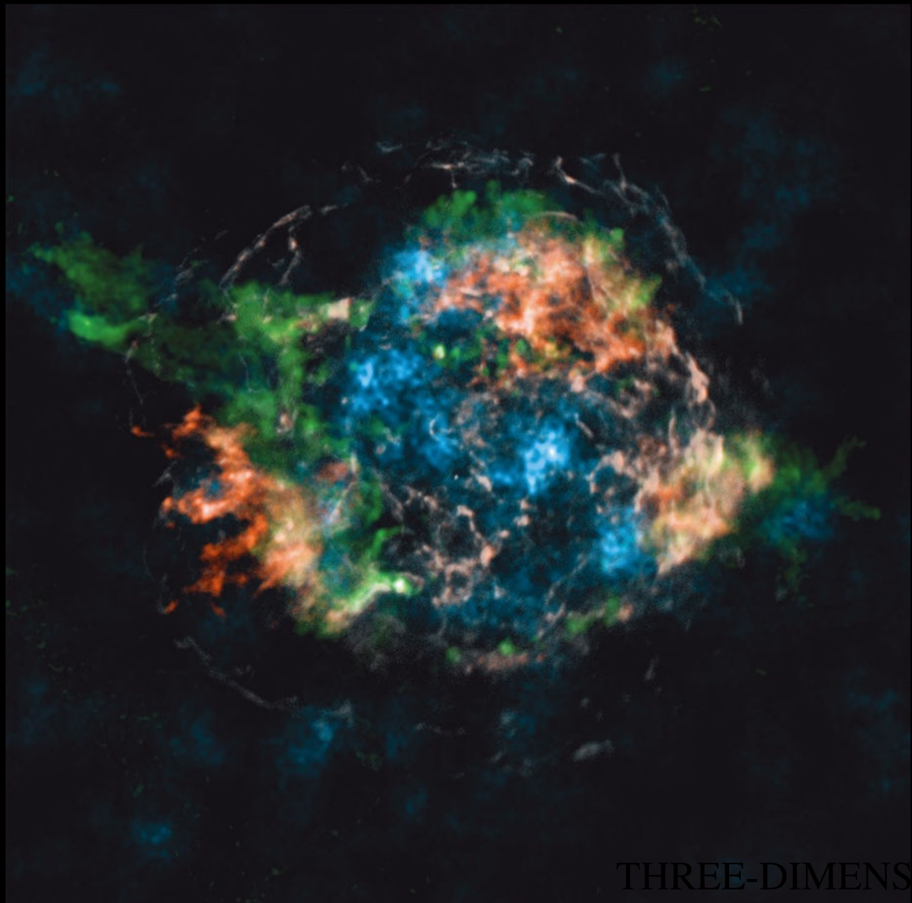
Even though at low frequencies there are barely any lines, carbon radio recombination lines can provide unique diagnostics on the conditions in photodissociation regions.

Cassiopeia A



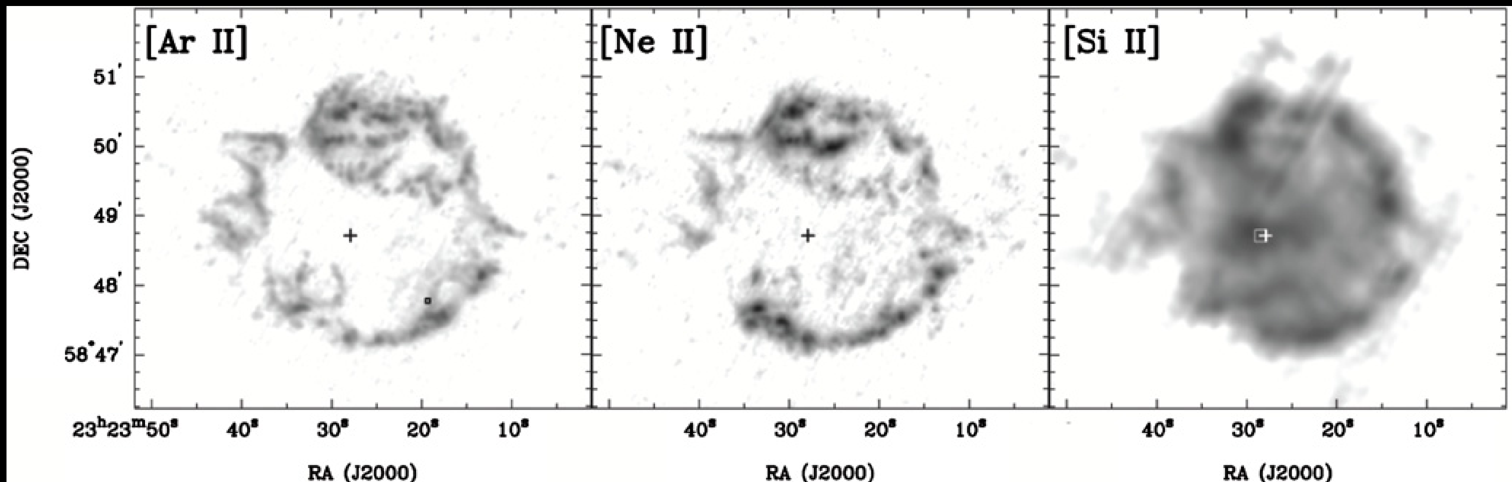
Cas A as seen with the LOFAR LBA and VLA L-band with10'' resolution. Source size is ~5'   Arias+18


Forward shock
Contact discontinuity
Reverse shock
Ejecta
Ejecta
Reverse shock
Contact discontinuity
Forward shock



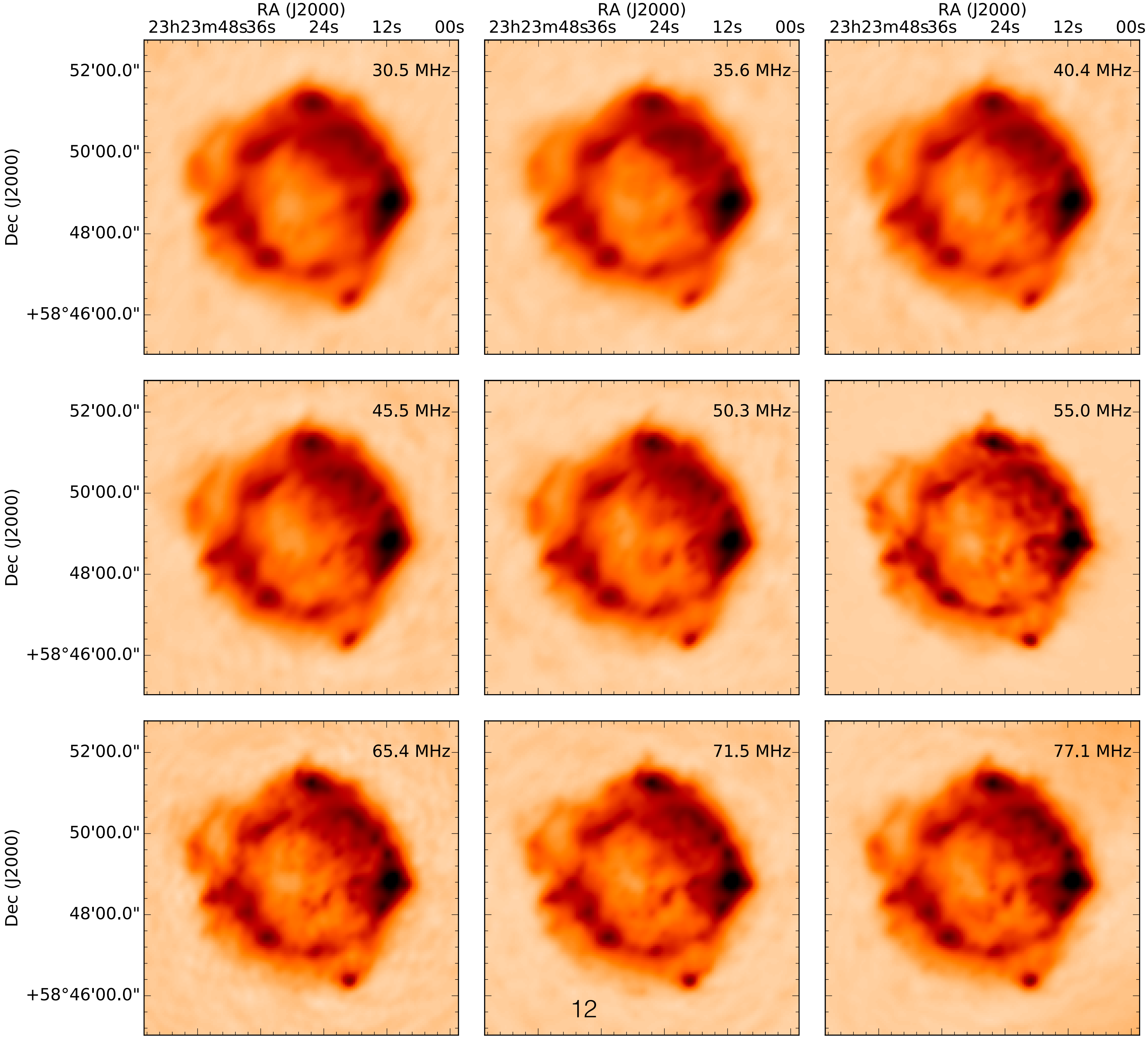
Blue: 44Ti, NuSTAR
Grefenstette+ 16

IR lines, Spitzer
Delaney+ 10



Low-frequency free-free absorption from the cold, unshocked ejecta

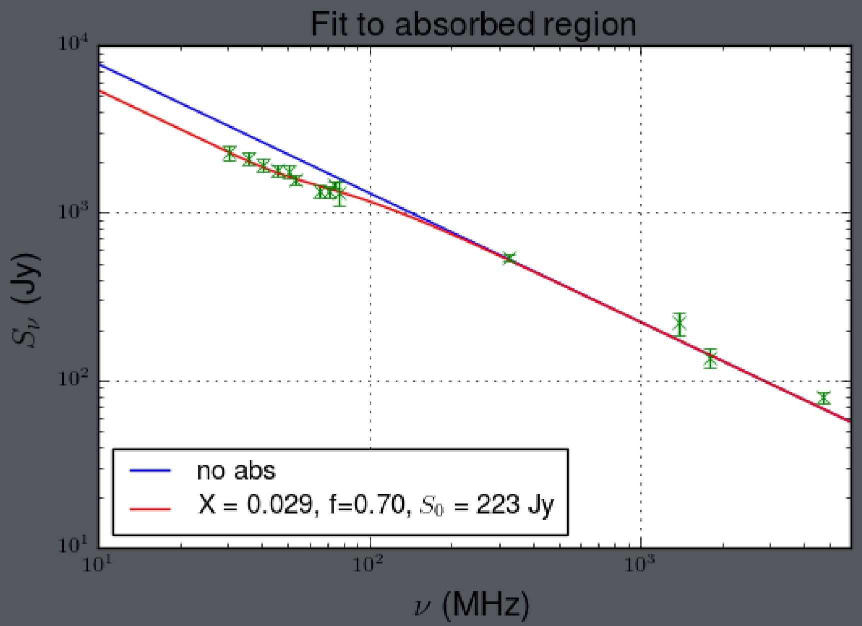
$$S_\nu = \left(S_{\nu,\mathrm{front}} + S_{\nu,\mathrm{back}} \exp\left(-\tau_{\nu,\mathrm{int}}\right)\right) \exp\left(-\tau_{\nu,\mathrm{ISM}}\right)$$

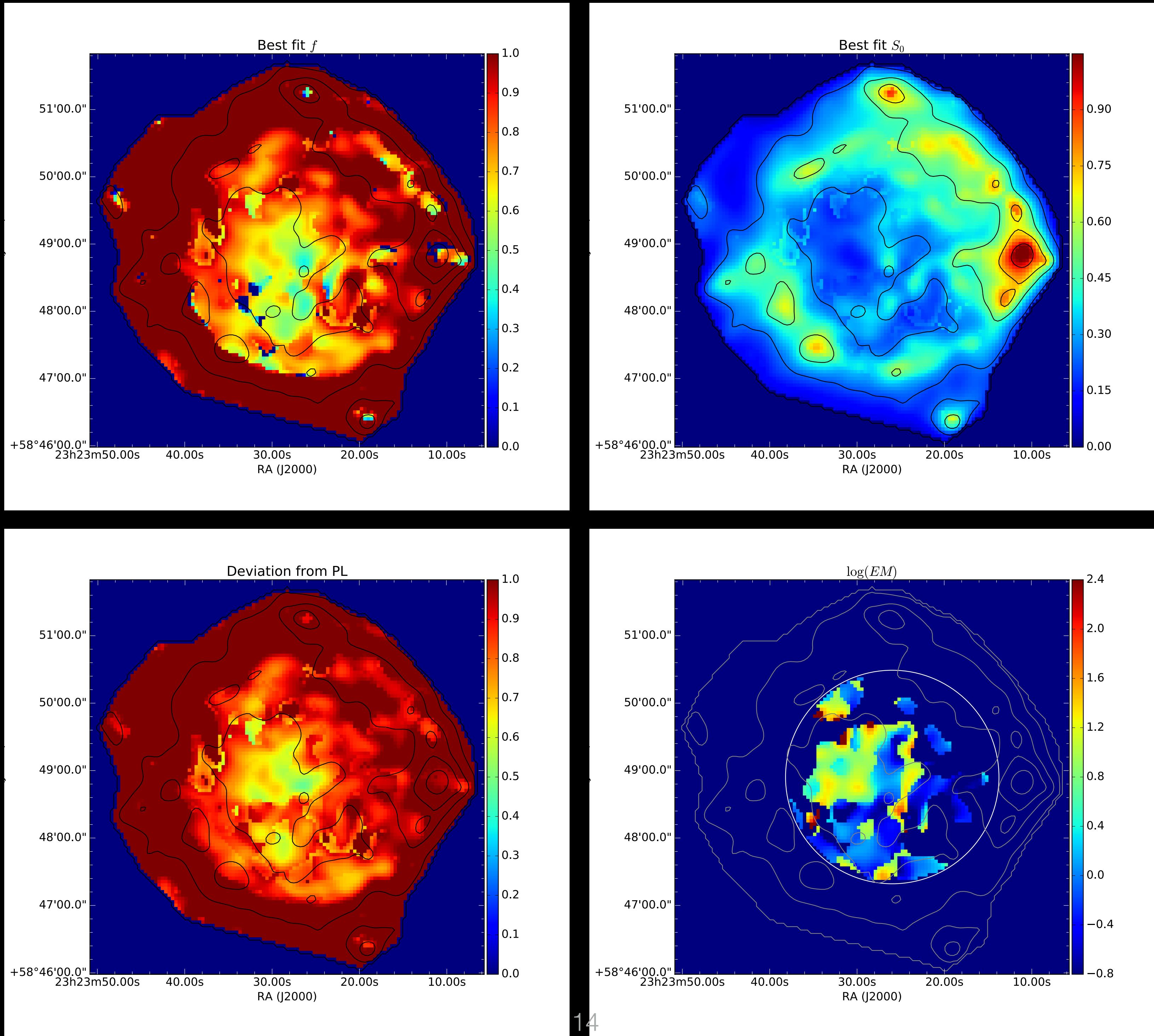

RA (J2000)
23h23m48s 36s 24s 12s 00s
Dec (J2000)
52'00.0"
50'00.0"
48'00.0"
+58°46'00.0"
30.5 MHz
35.6 MHz
40.4 MHz
45.5 MHz
50.3 MHz
55.0 MHz
65.4 MHz
71.5 MHz
77.1 MHz

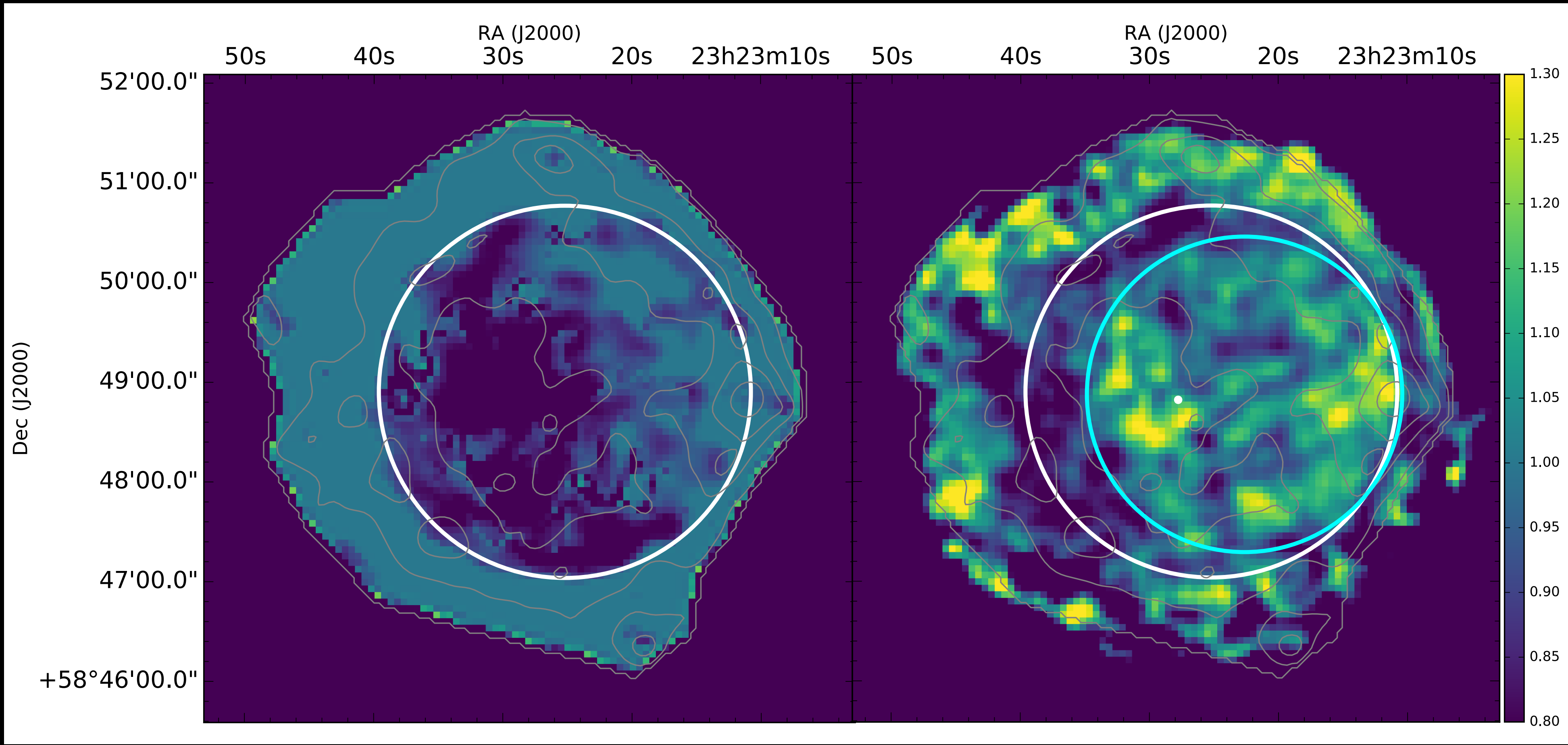
$$S_\nu = S_0 \left(\frac{\nu}{\nu_0}\right)^{-\alpha} (f + (1-f)e^{-\tau_{\nu,\mathrm{int}}}),$$

where

$$\tau_\nu = 3.014 \times 10^4 \, Z \, \left(\frac{T}{\mathrm{K}}\right)^{-3/2} \left(\frac{\nu}{\mathrm{MHz}}\right)^{-2} \left(\frac{EM}{\mathrm{pc\,cm^{-6}}}\right) g_{\mathrm{ff}}$$




Best fit f
Best fit S_0
Deviation from PL
$\log(EM)$
51'00.0"
50'00.0"
49'00.0"
48'00.0"
47'00.0"
+58°46'00.0"
23h23m50.00s
40.00s
30.00s
20.00s
10.00s
RA (J2000)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.90
0.75
0.60
0.45
0.30
0.15
0.00
2.4
2.0
1.6
1.2
0.8
0.4
0.0
−0.4
−0.8



The reverse shock as probed by radio absorption from the unshocked material (left) and from X-ray synchrotron emission (right). The latter requires shock speeds of >~3000 km/s

Mass in the unshocked ejecta:

$$M_{\mathrm{unsh}} = \rho V \qquad\qquad EM = n_{\mathrm{e}}^2 l$$

$$M = ASl^{1/2} m_{\mathrm{p}} \frac{1}{Z} \sqrt{EM}$$

$$M = 2.95 \pm^{0.41}_{0.48} M_{\odot} \left(\frac{A}{16}\right) \left(\frac{l}{0.16\mathrm{pc}}\right)^{1/2} \left(\frac{Z}{3}\right)^{-3/2} \left(\frac{T}{100\ \mathrm{K}}\right)^{3/4} \times \sqrt{\frac{g_{\mathrm{ff}}(T = 100\,\mathrm{K}, Z = 3)}{g_{\mathrm{ff}}(T, Z)}}$$

Can take as a mass estimate, or as a probe on the temperature and ionisation conditions in the unchecked ejecta, which are poorly constrained

Conclusions

- LOFAR is a powerful instrument to study a relatively unexplored radio window, in which emission from SNRs dominates
- It’s a very data reduction-heavy instrument, but the surveys team is making progress on automation
- More galactic plane results from LOFAR in the near future!


Questions?
Thanks!