ANTON PANNEKOEK INSTITUTE

Supernova Remnants with LOFAR

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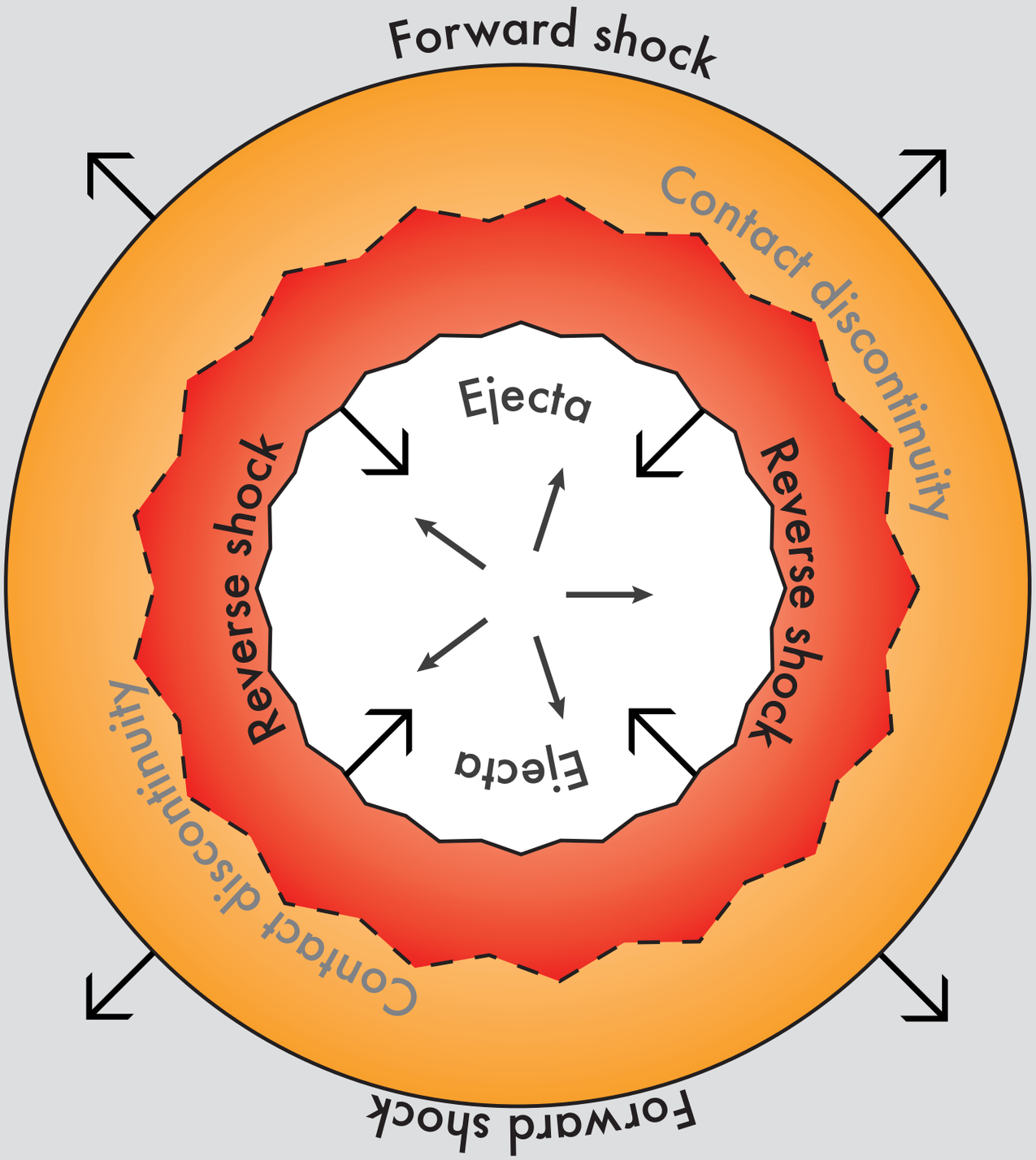
Young SNRs

SN 1994a (type Ia), HST

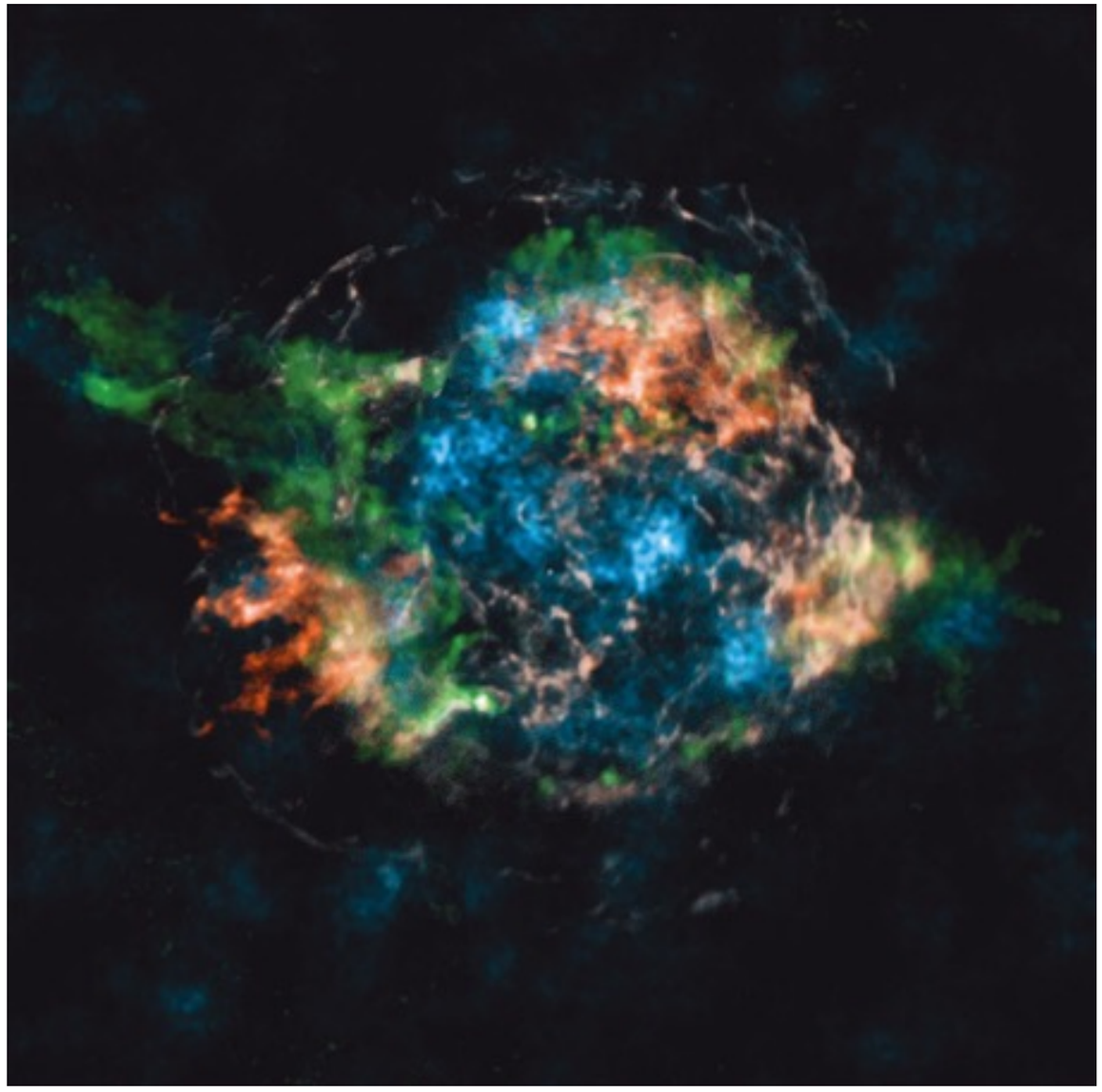
SN 1987a (CC), HST (observed in 1997)

G1.9+0.3, Chandra Ia SN


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

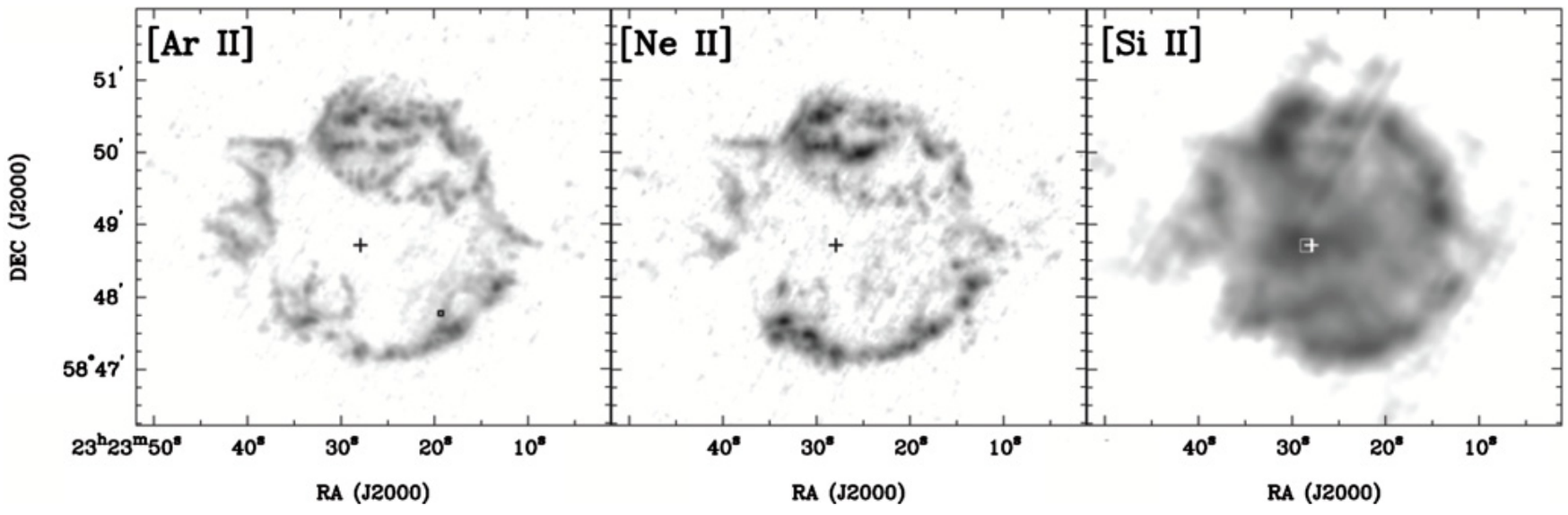
Unshocked ejecta are difficult to probe

- Radioactive decay of elements synthesised in the explosion (^{44}Ti has $t_{1/2}$=60 years)
- Some IR emission



Grefenstette+16
NuSTAR

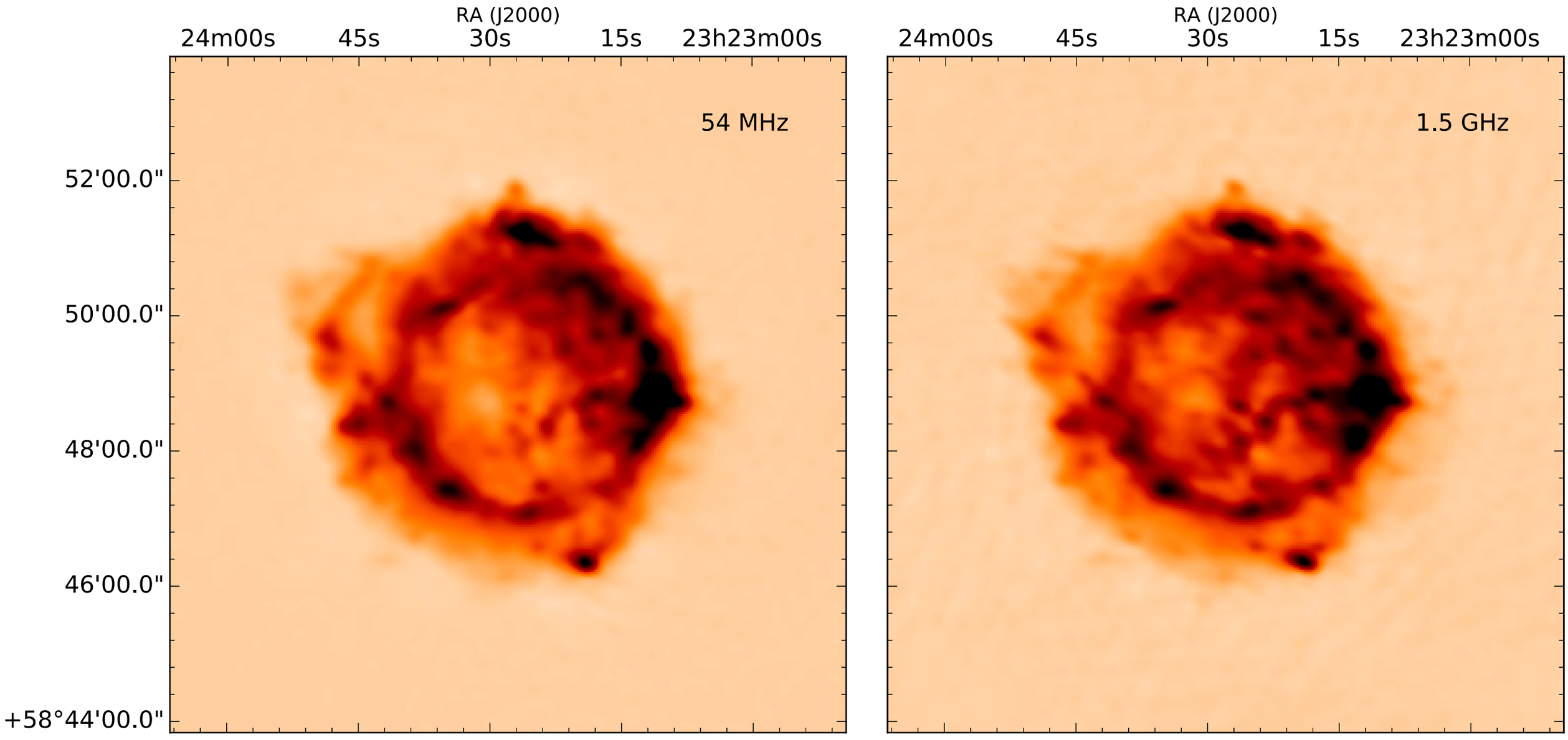
Delaney+ 10
Spitzer



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

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

Cassiopeia A



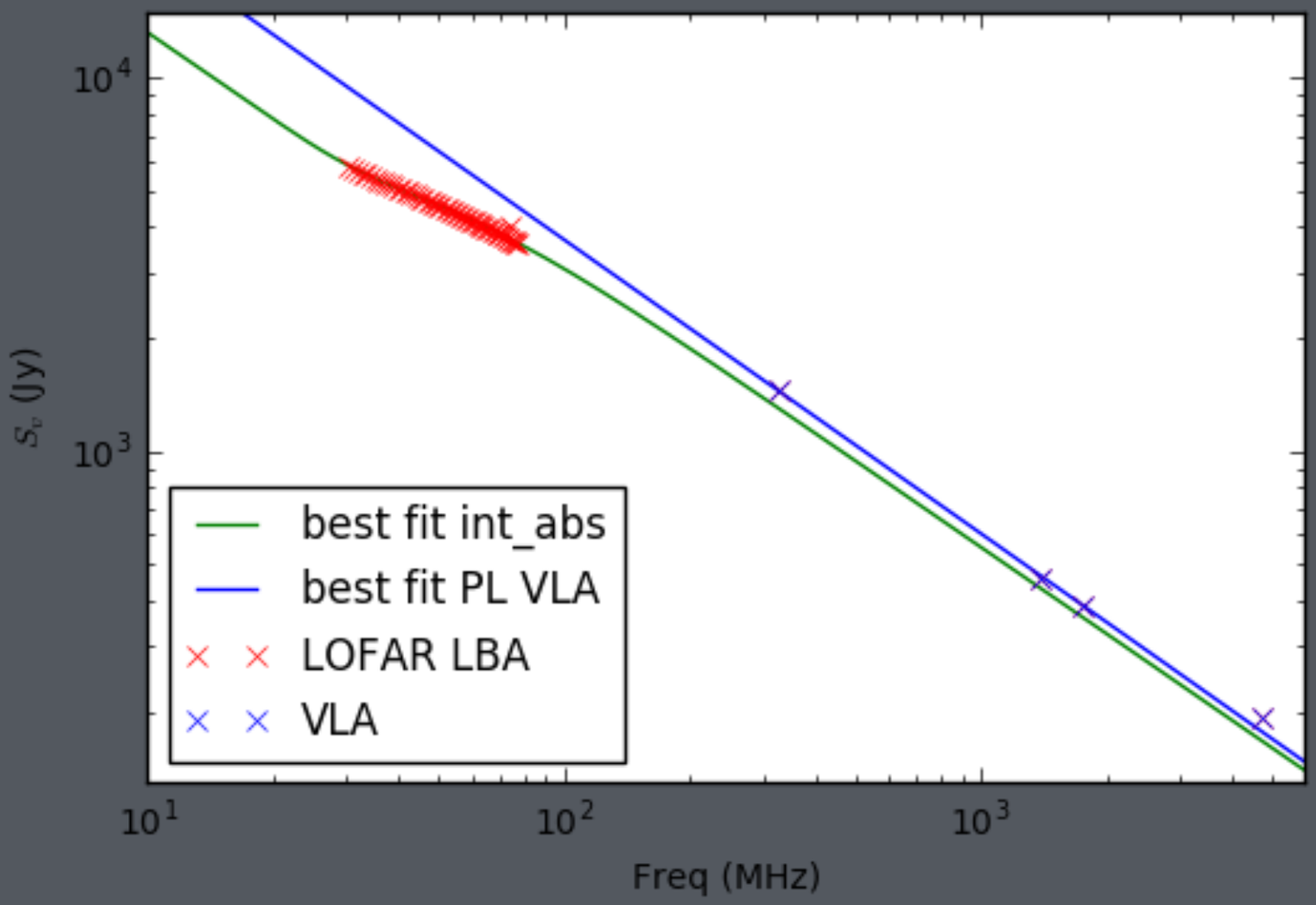
Cas A as seen with the LOFAR LBA and VLA L-band with10'' resolution. Source size is ~5' Arias+18

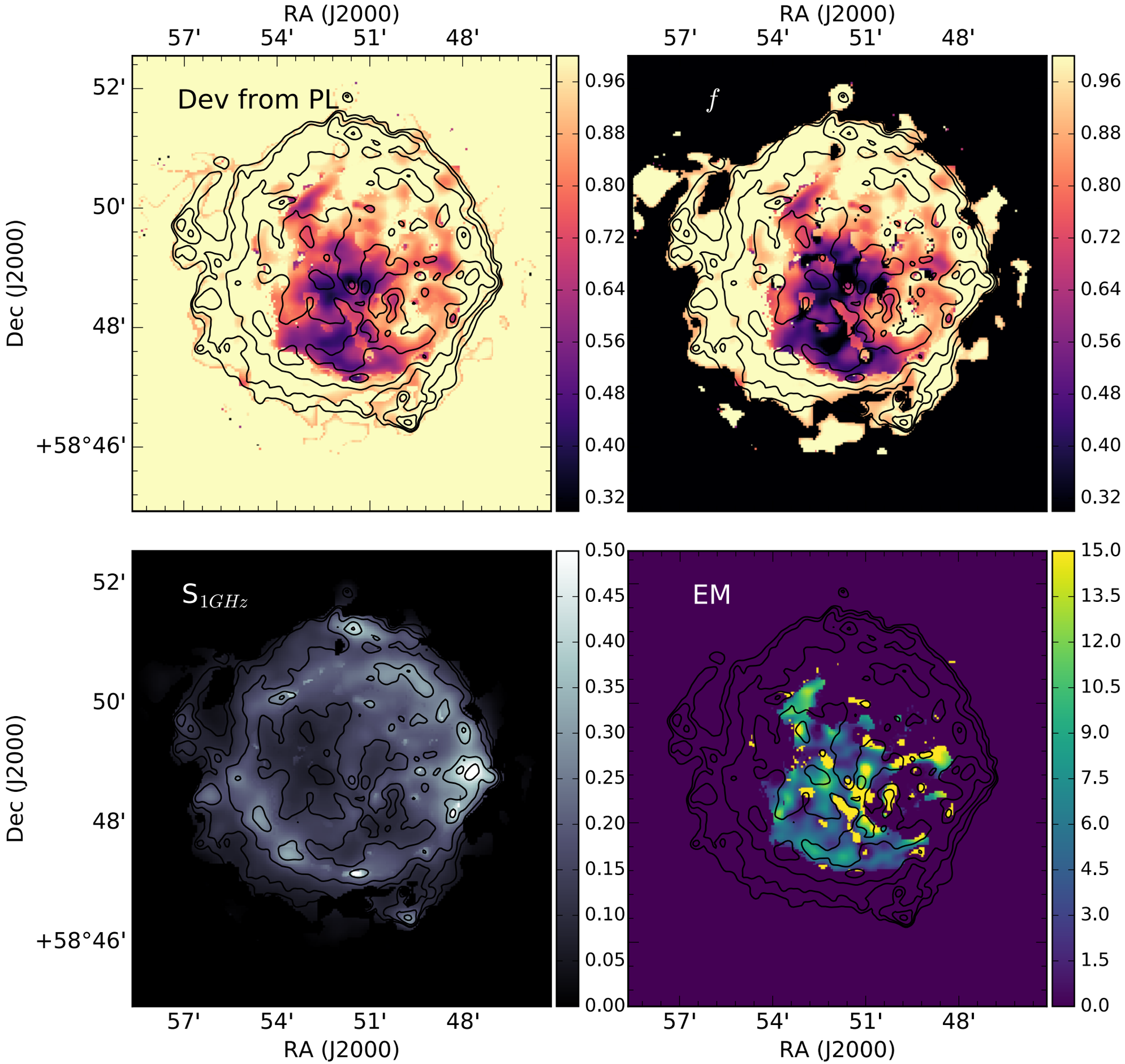
RA (J2000)
23h23m48s36s 24s 12s 00s
Dec (J2000)
52'00.0"
50'00.0"
48'00.0"
+58°46'00.0"
30.5 MHz
35.6 MHz
40.4 MHz
45.5 MHz
50.3 MHz
55.0 MHz
65.4 MHz
71.5 MHz
77.1 MHz

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

where

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

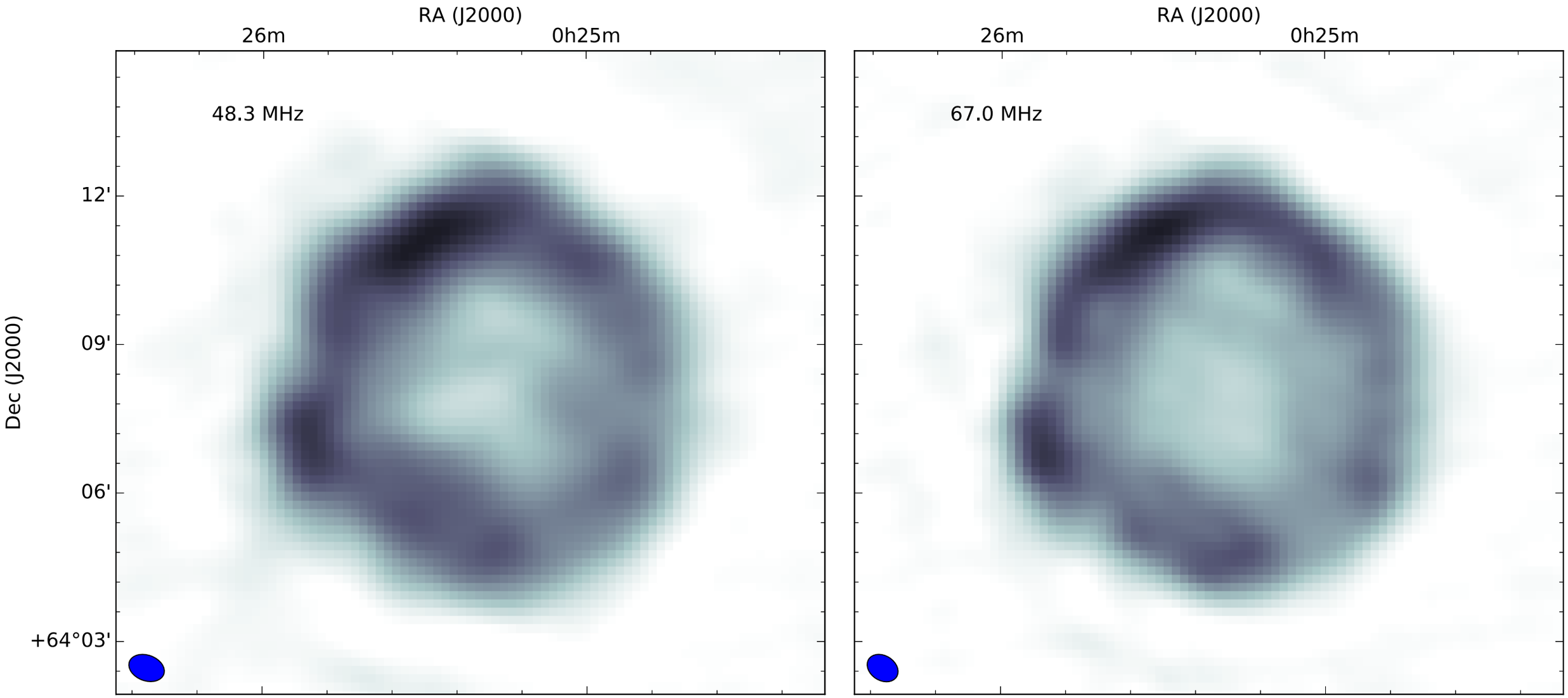



RA (J2000)
57'
54'
51'
48'
Dec (J2000)
52'
50'
48'
+58°46'
Dev from PL
0.96
0.88
0.80
0.72
0.64
0.56
0.48
0.40
0.32
f
S_{1GHz}
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
EM
15.0
13.5
12.0
10.5
9.0
7.5
6.0
4.5
3.0
1.5
0.0

This method allows us to:

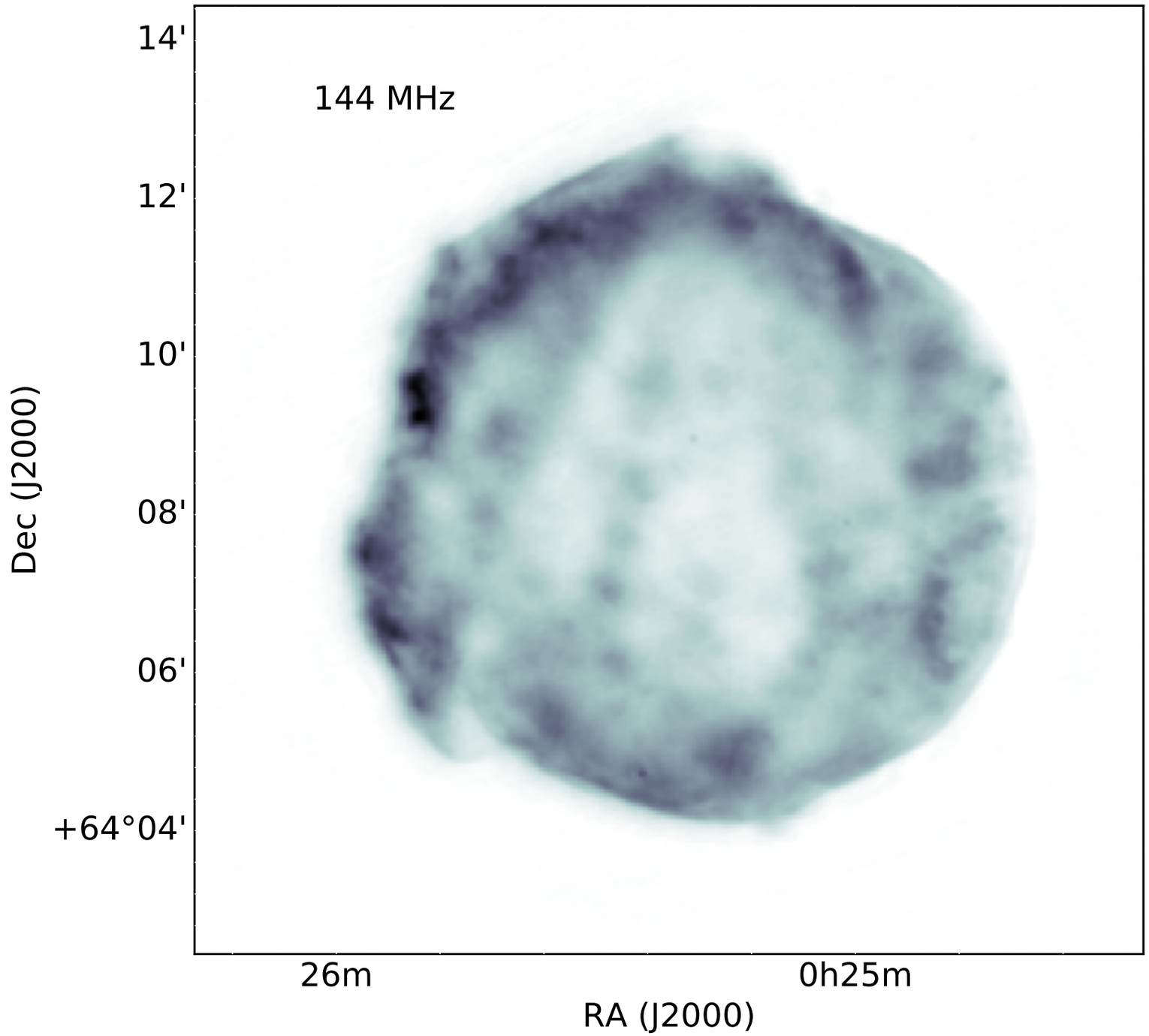
- Locate the reverse shock (rim of internal absorption)
- Estimate the mass in unshocked ejecta
- OR probe the physical conditions in the unshocked ejecta

Tycho's SNR

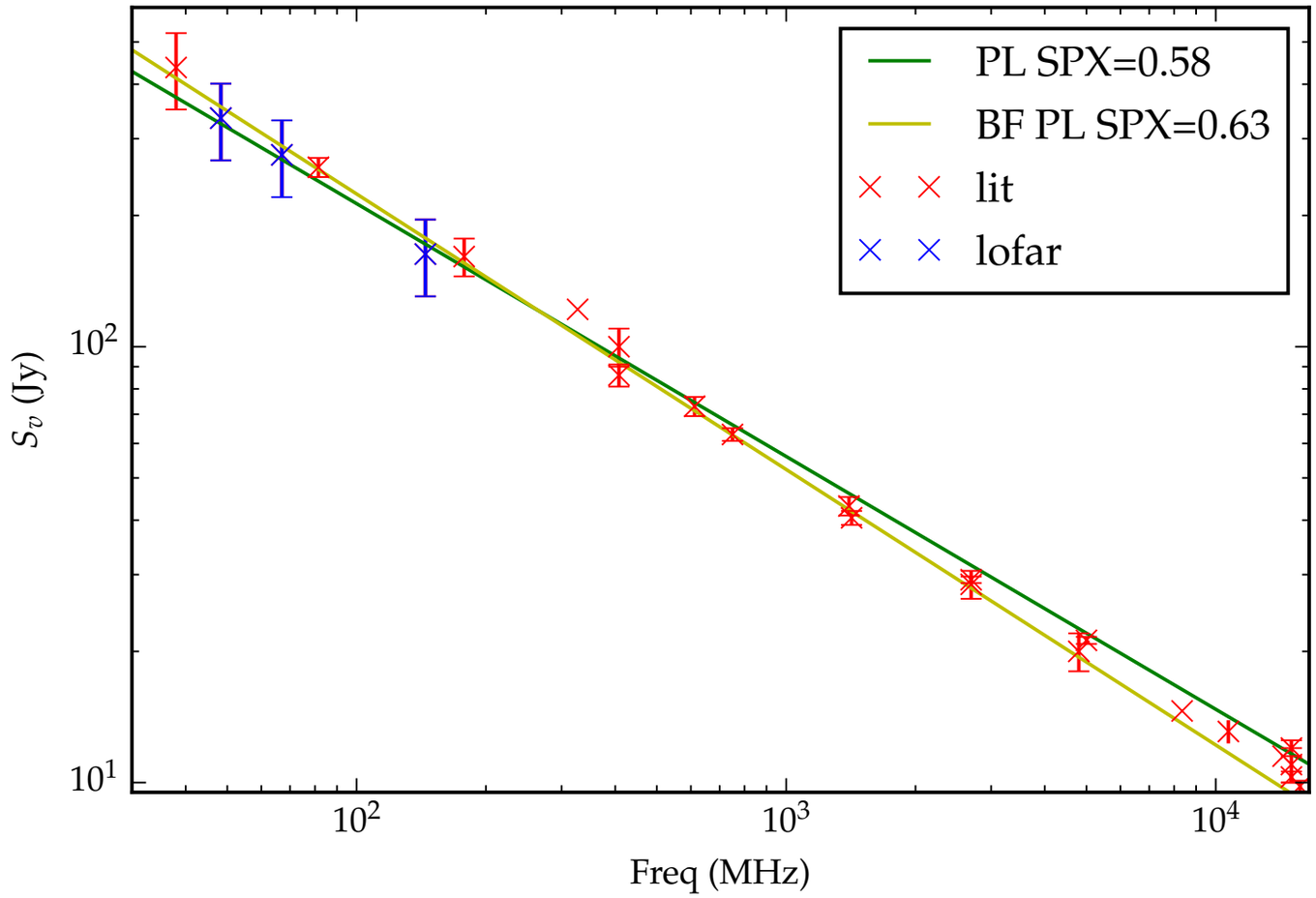


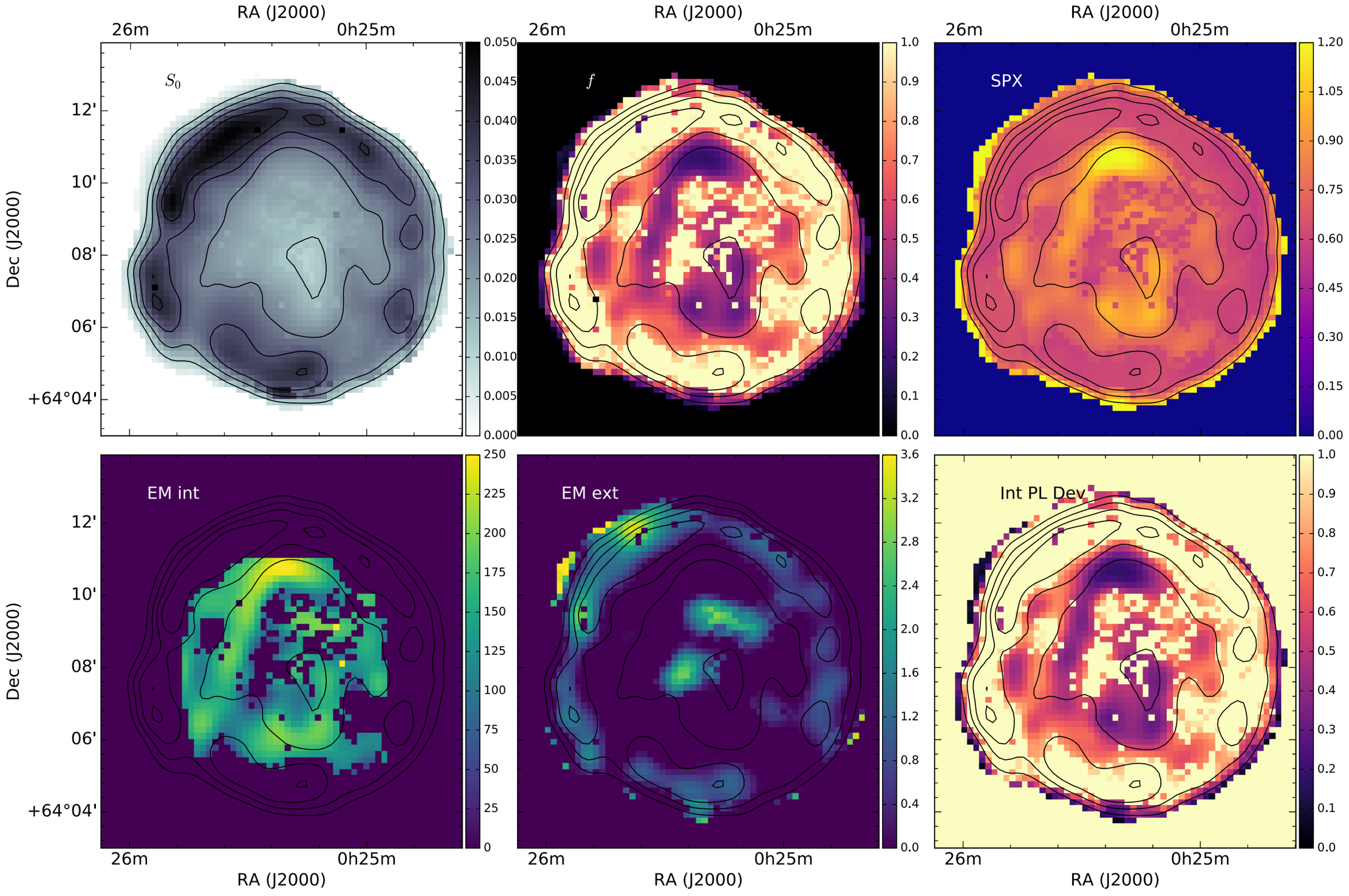
Tycho as seen with the LOFAR LBA
with 30'' resolution. Source size is ~8' Arias+18

Tycho's SNR in the LOFAR HBA. Co-observed with LoTSS and reduced with their pipeline. Imaged by M. Hardcastle



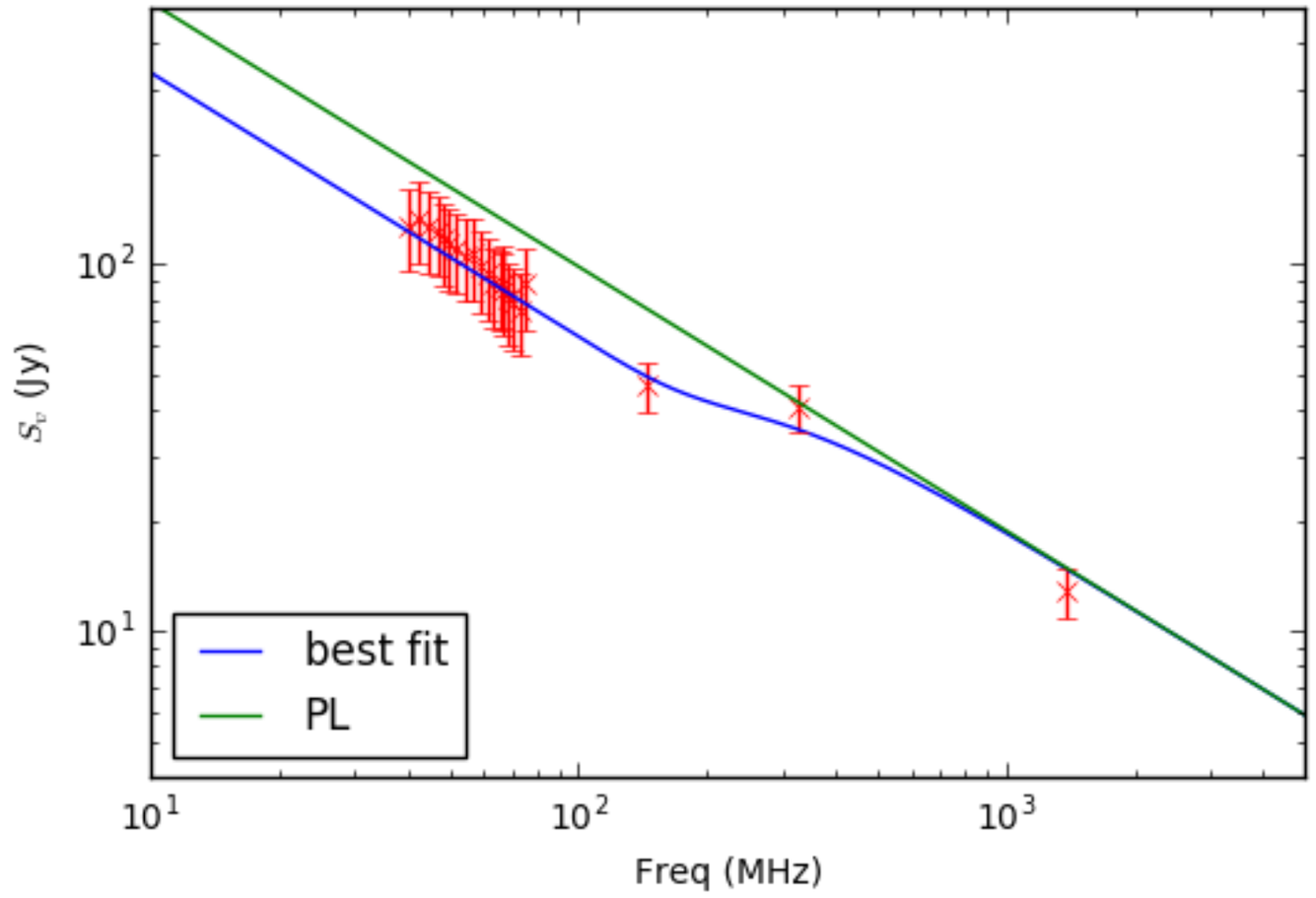
Flux densities measured with the LOFAR HBA and LBA match literature values of this well-known source (3C10)





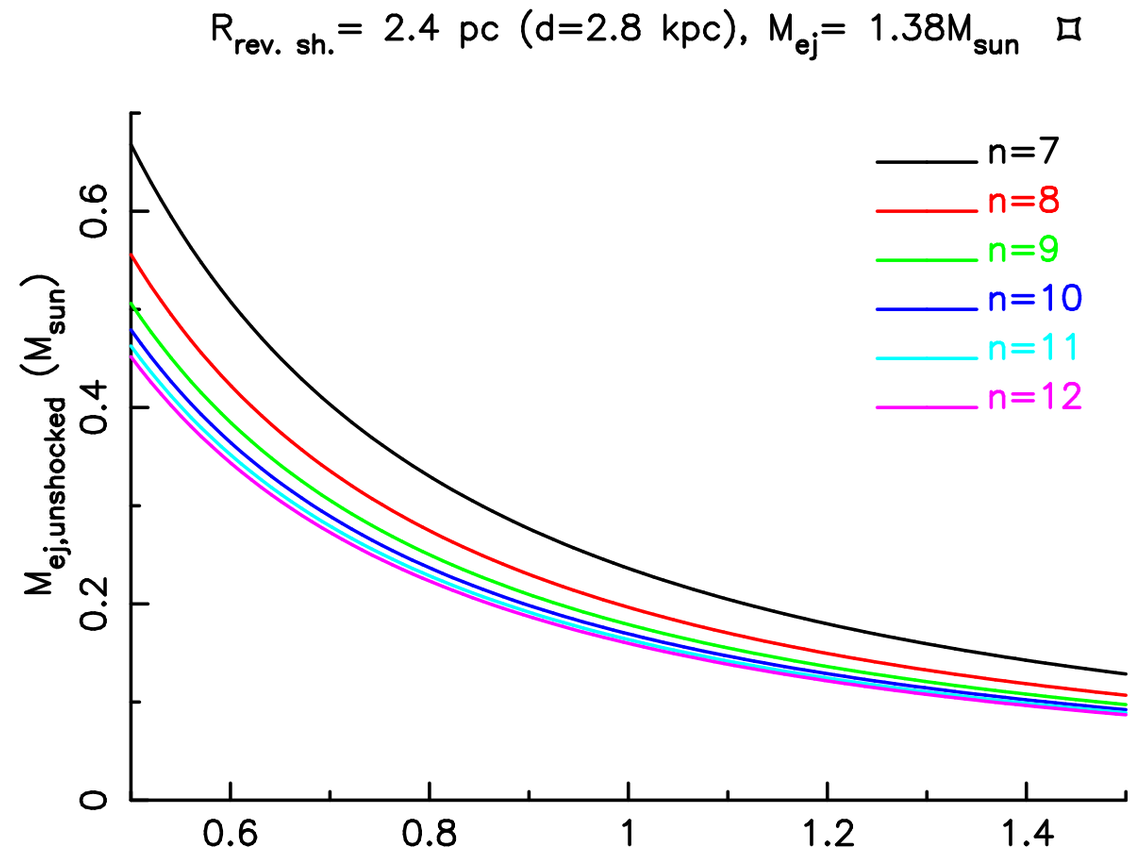
$$S_\nu = S_0 \left(\frac{\nu}{\nu_0}\right)^{-\alpha} \left(f + (1-f)e^{-\tau_{\nu,\mathrm{int}}}\right) e^{-\tau_{\nu,\mathrm{ISM}}}$$

- To estimate mass from the measured absorption we need:
  - degree of ionisation
  - shape of the material
  - temperature
- Tycho was a Type Ia explosion: originally 1.4 M⊙

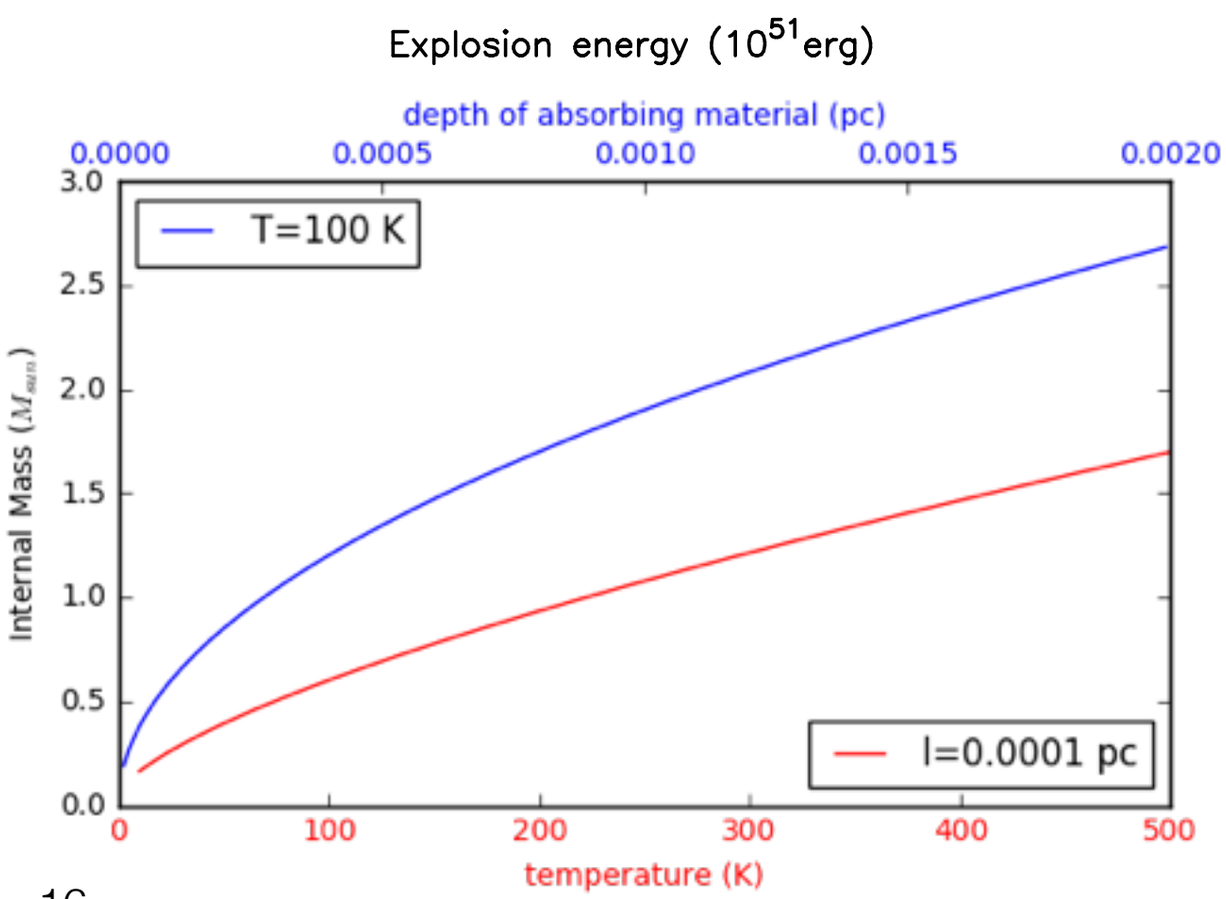


This plot corresponds to **EM=175 pc cm^{-6}** in the region within the reverse shock, which is very high

Mass in unshocked ejecta from observed FS, RS



For a physically meaningful mass, the ejecta should be cold and especially in thin slabs or clumps



Questions?

Thanks!