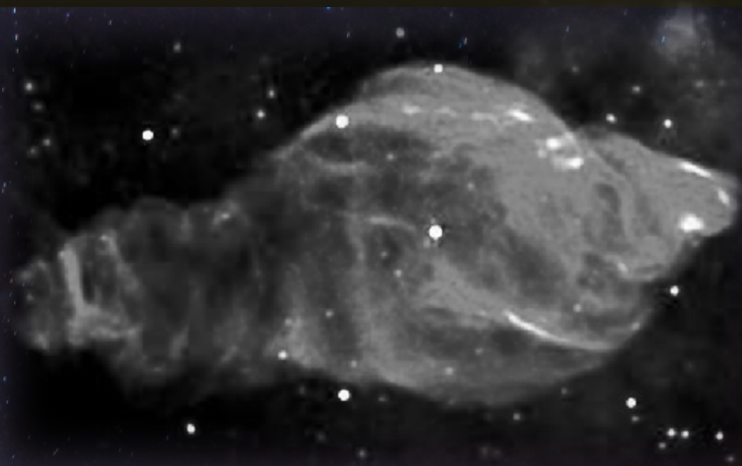
Radio emission from Supernova Remnants



Gloria Dubner
IAFE
Buenos Aires, Argentina

History

- Before radio astronomy, only 2 SNRs were known: Crab and Kepler´s SNR

- 1948: Ryle and Smith detected an unusually bright radio source, Cassiopeia A, although its nature was unknown

- 1949: radio detection of the Crab Nebula
  1952: Tycho´s SN
  1957: Kepler´s SN

Two important conclusions were drawn:

*** a SNR is a source of intense radio radiation**

*** the origin could not be explained by strictly thermal processes**

The answer (~ 1953 by Shklovsky, based on solutions proposed by Alfven & Herlofson in 1950) was **synchrotron radiation** from relativistic electrons orbiting magnetic fields ("trapped around the star")

Shklovsky also advanced the idea that the cosmic ray acceleration could be supplemented by Fermi processes.

Statistics

In our Galaxy there are almost **300** identified SNRs

~ **8%** detected in the **TeV** range

~ **10%** in the **GeV** range

~ **30%** in **optical** wavelengths

~ **40%** in **X-rays**

~ **95 %** in **radio.**

In the Magellanic Clouds only 4 out of 84 SNRs have not been seen in radio

Radio observations provide information on:

- Morphology
- Brightness distribution
- Spectral index
- Polarization (percentage of polarized emission and E vector orientation)

Crucial information

- to delimit the current location of the expanding shock front
- to identify sites and mechanisms of particle acceleration
- to infer orientation and degree of order of compressed magnetic fields

Morphology
Brightness distribution

Statistics

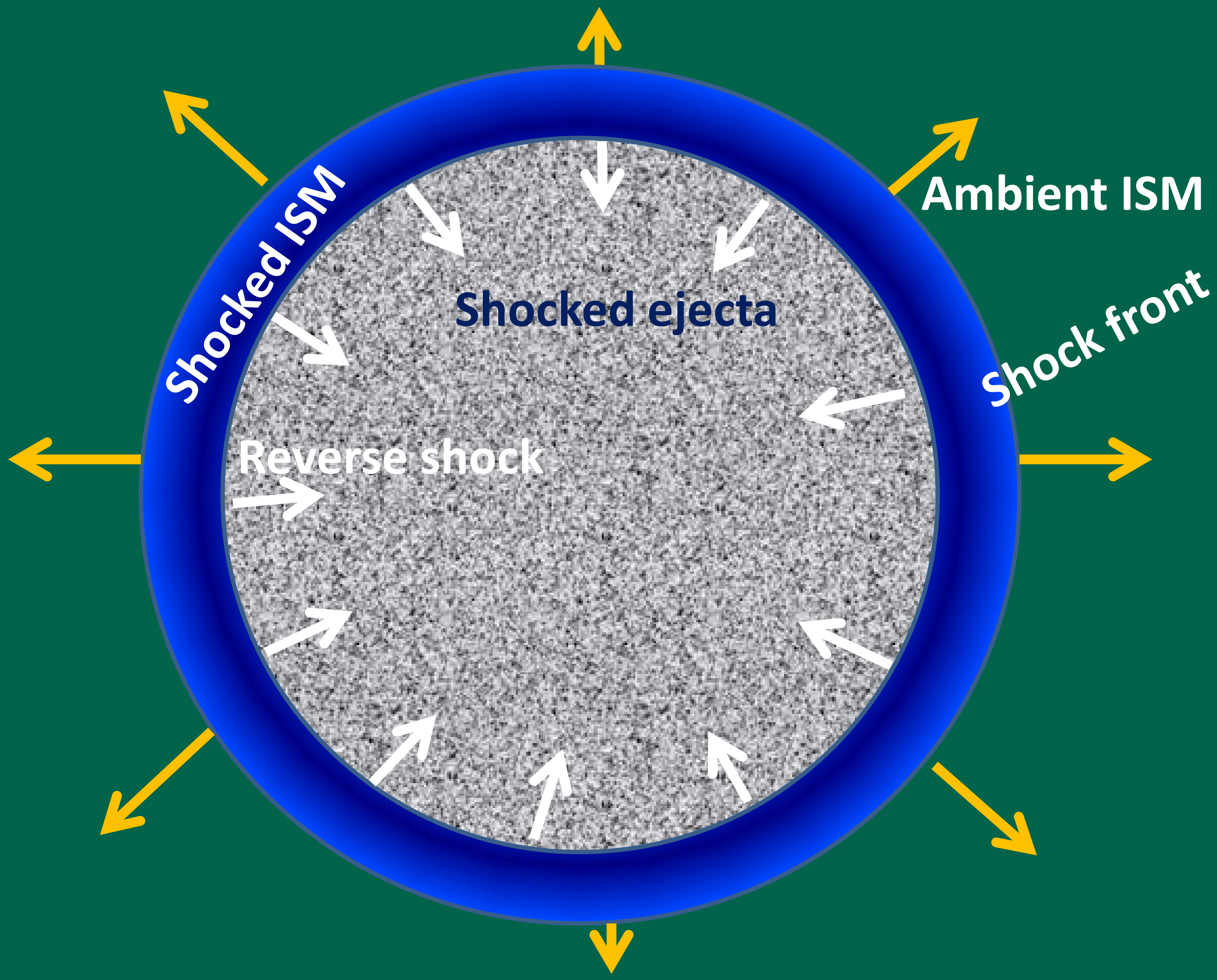
In the Milky Way it is statistically expected:

20 % SN Type Ia

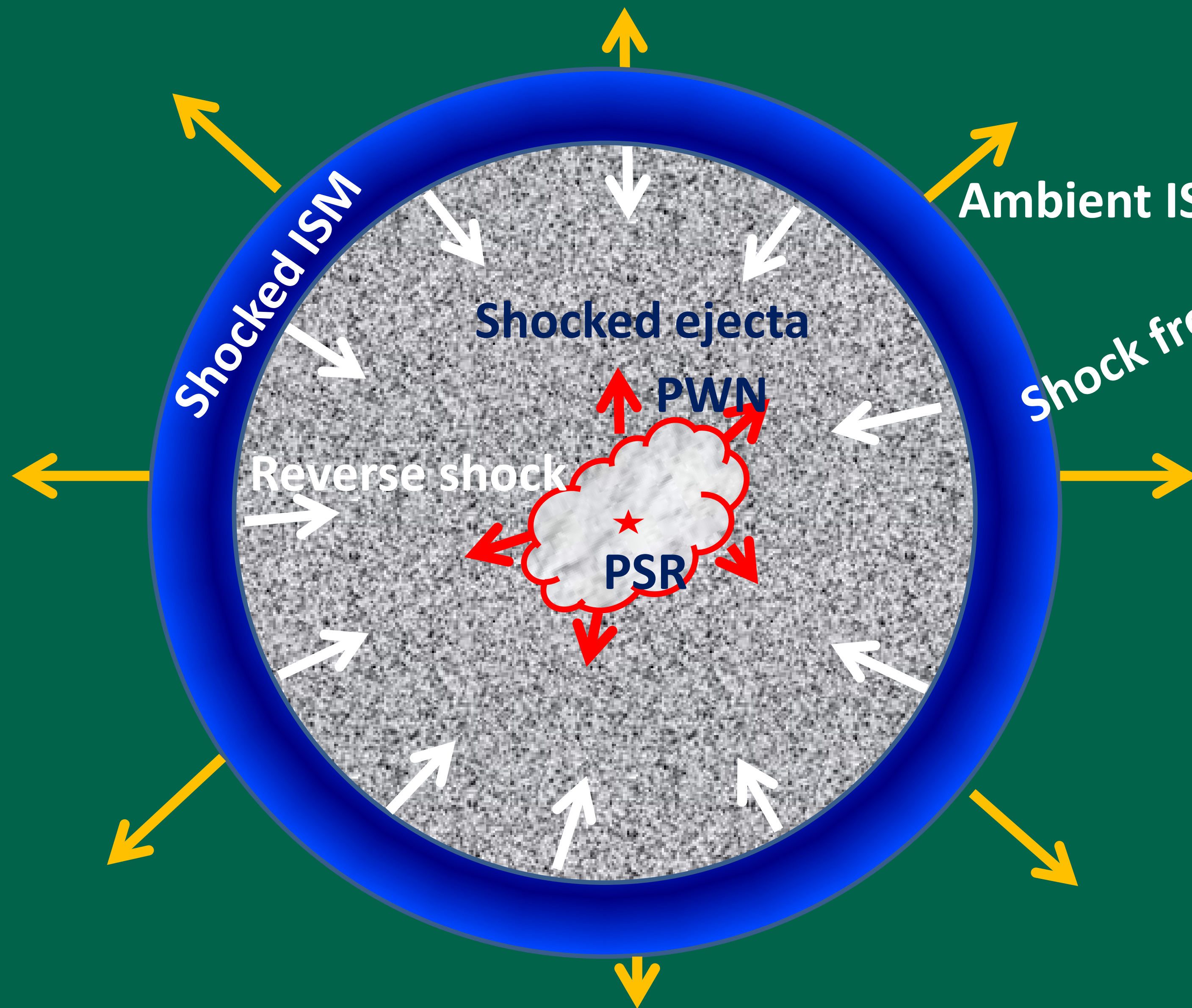
70% SN Type II

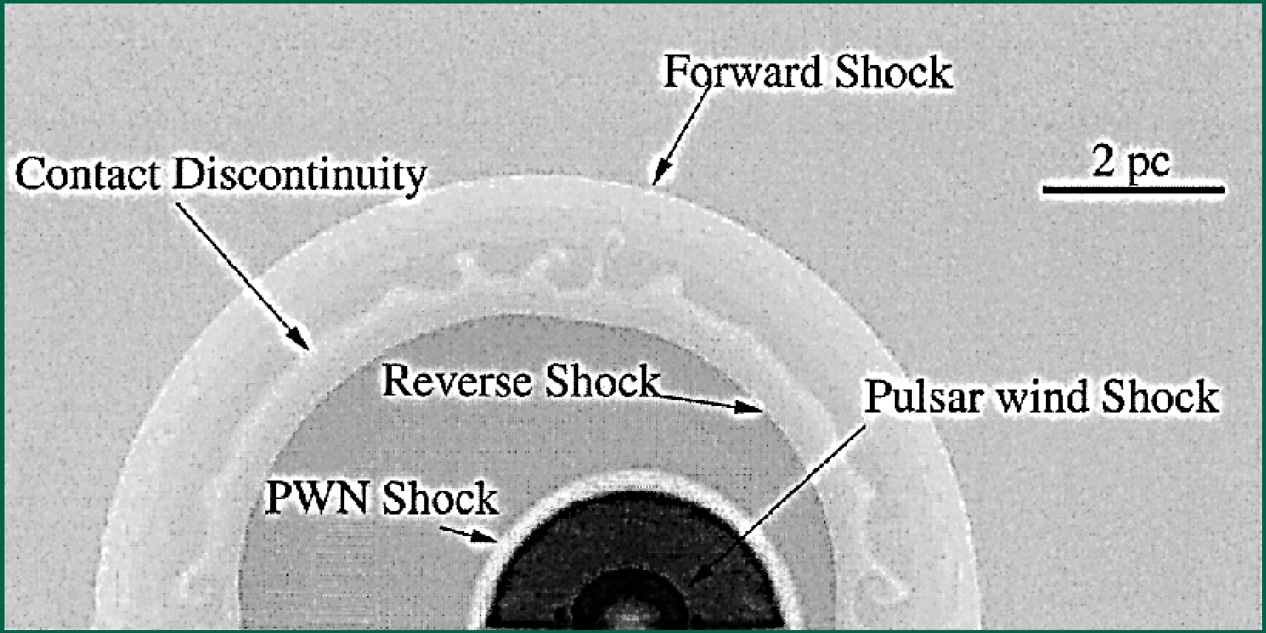
10% SN Type Ib/c

Expected morphology for radio remnants of SN Ia



Expected morphology for radio SNRs of SN Ib/c, II




Forward Shock
2 pc
Contact Discontinuity
Reverse Shock
Pulsar wind Shock
PWN Shock

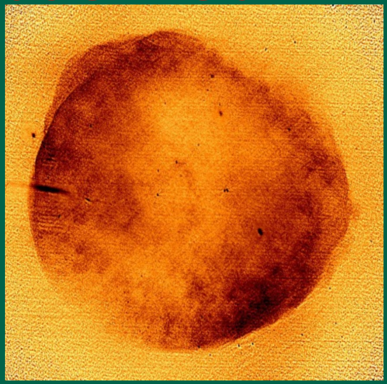
Predicted

Observed in radio

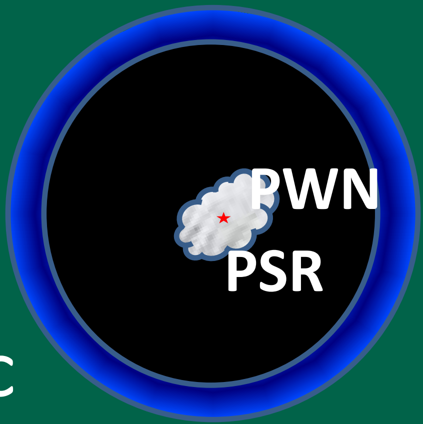
SN Ia

20%

Spectral index
$\alpha \approx 0.5$

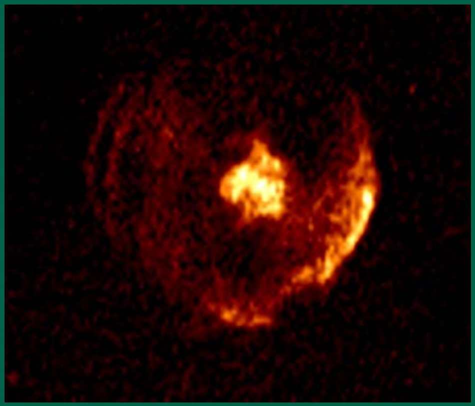


shell-type



SN II, Ib/c

80%



Composite

Spectral index
$0 \leq \alpha \leq 0.3$

PWN

PSR

Filled-center
or plerions

Predicted

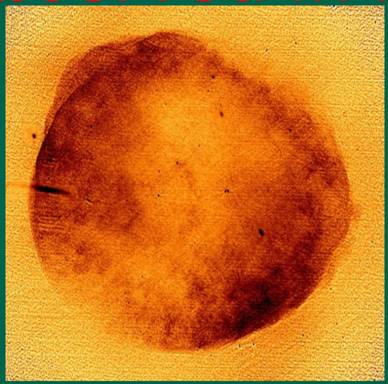
Observed in radio

SN Ia

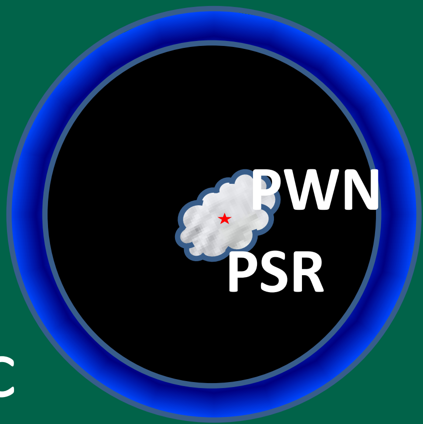
20%

Spectral index

α≈ 0.5

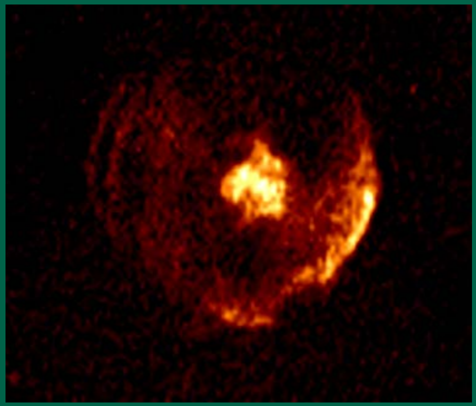


Over 70 % of the Milky Way SNRs have a shell-type morphology



SN II, Ib/c

80%



~12% composite-type

Spectral index

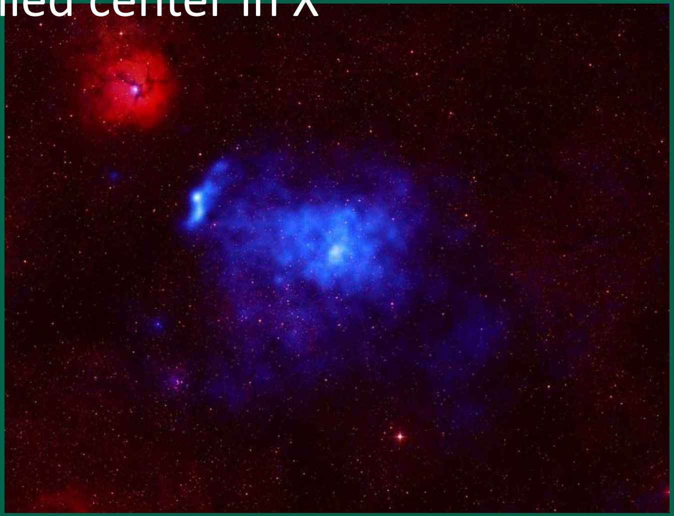
$0 \leq \alpha \leq 0.3$

~ 5% of pure plerions

The rest do not fit in any class

Mixed-morphology

Shell in radio
Filled center in X



W28

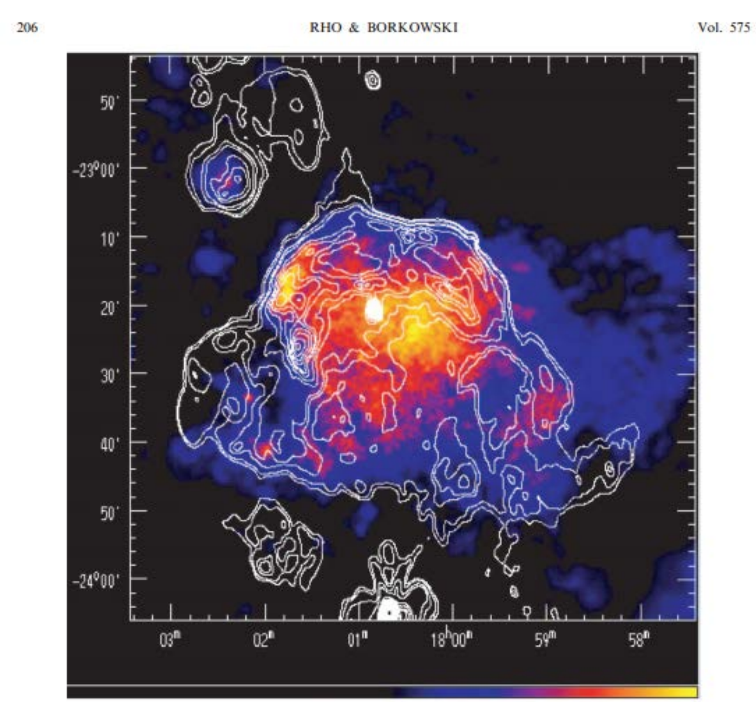
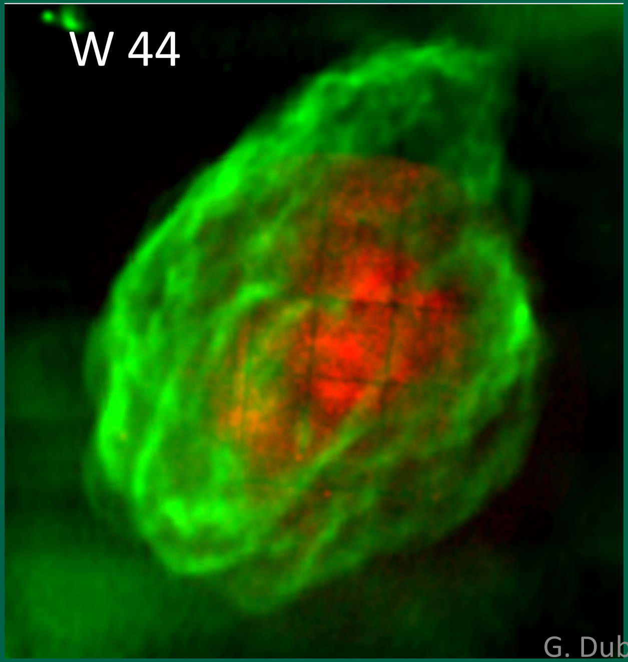
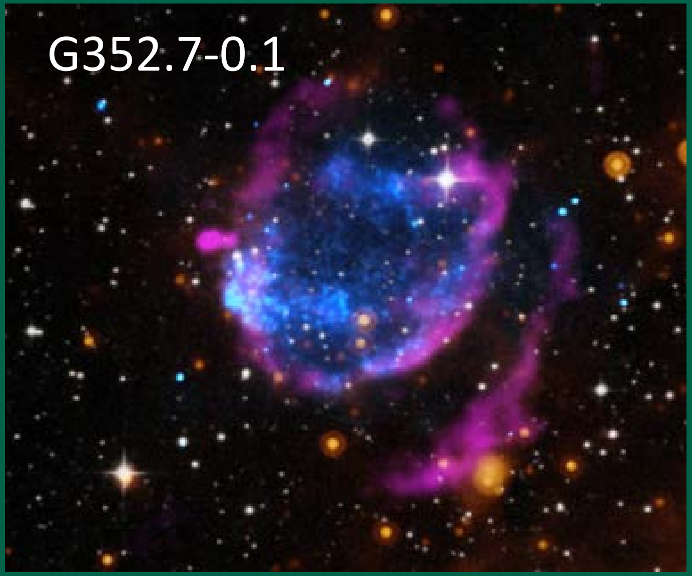


FIG. 5.—PSPC gray-scale image superposed on contours of the 328 MHz radio continuum image (from Dubner et al. 2000); the radio morphology is shell-like, and X-rays are centrally peaked.

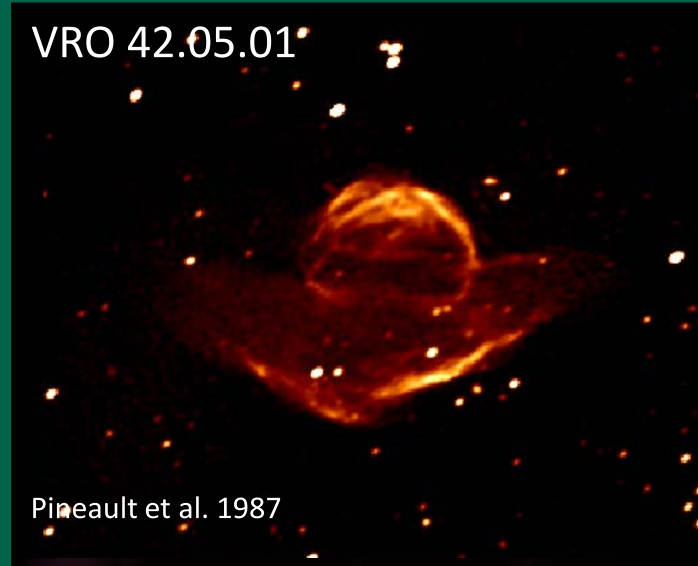




Tycho´s SNR

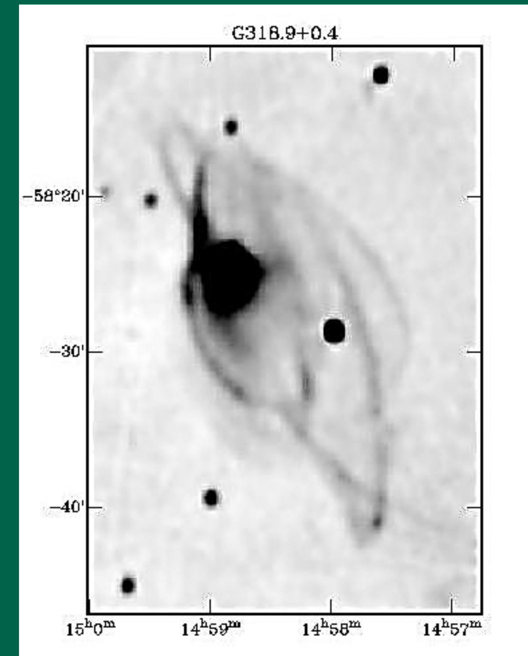
Reynoso et al. 1997

VRO 42.05.01



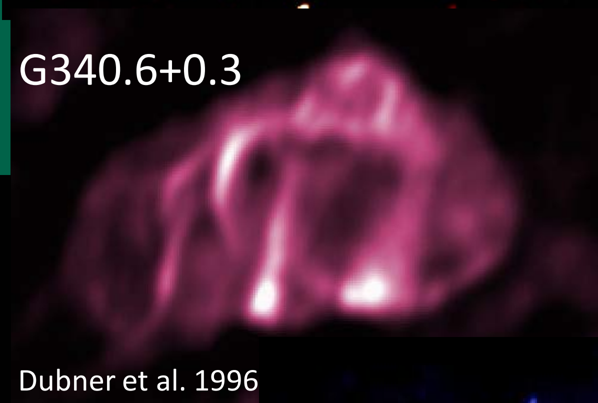
Pineault et al. 1987

G318.9+0.4



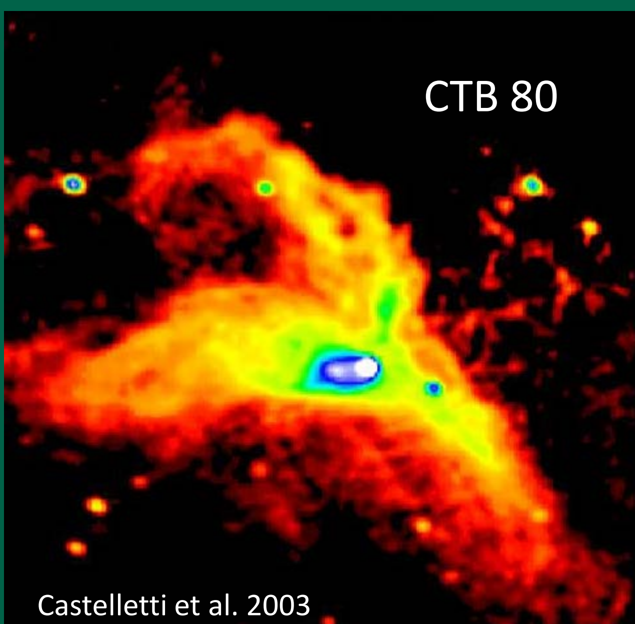
Whiteoak & Green 1996

G340.6+0.3



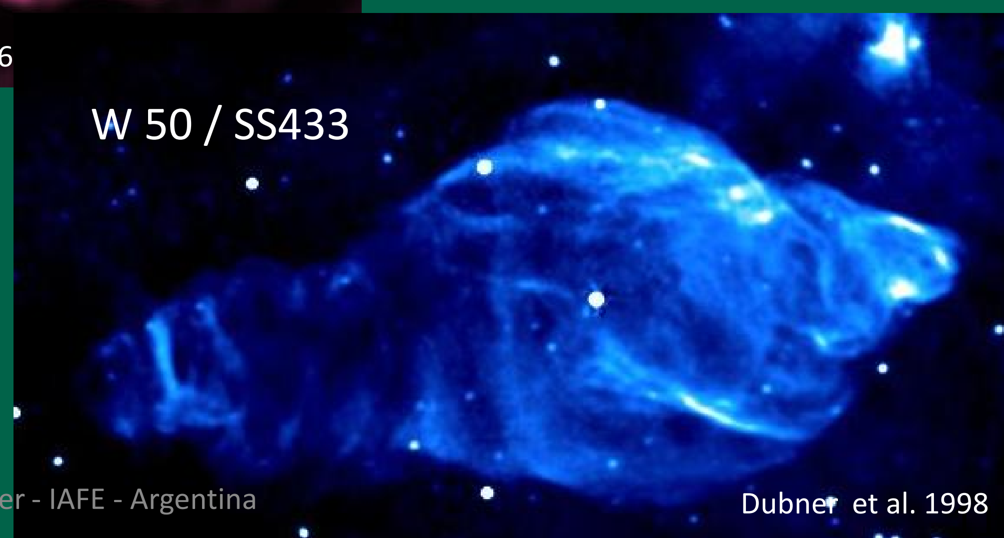
Dubner et al. 1996

CTB 80



Castelletti et al. 2003

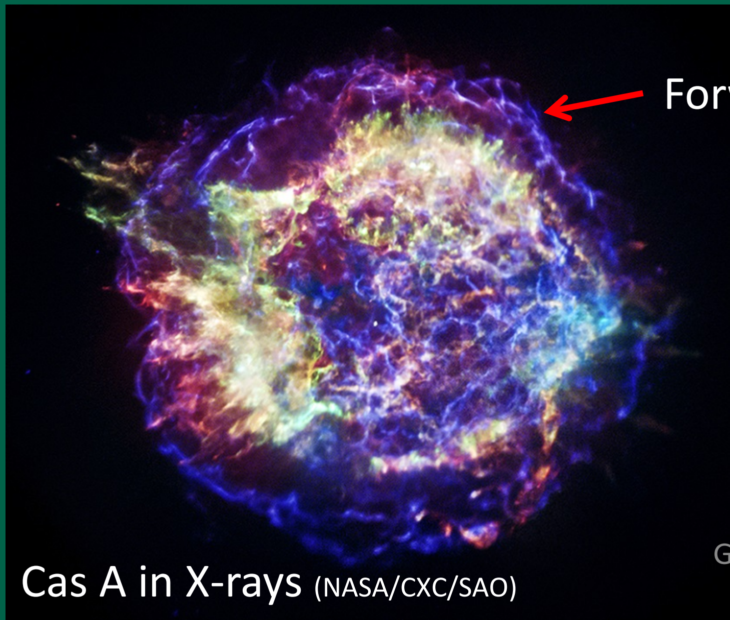
W 50 / SS433

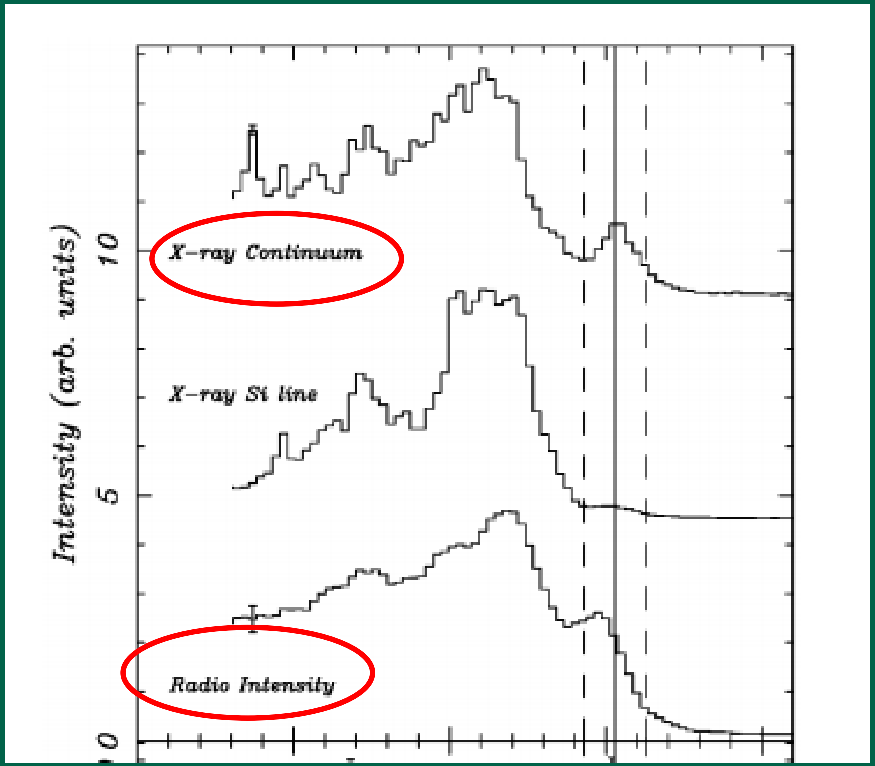


Dubner et al. 1998

Where is the shock front?

Cassiopea A

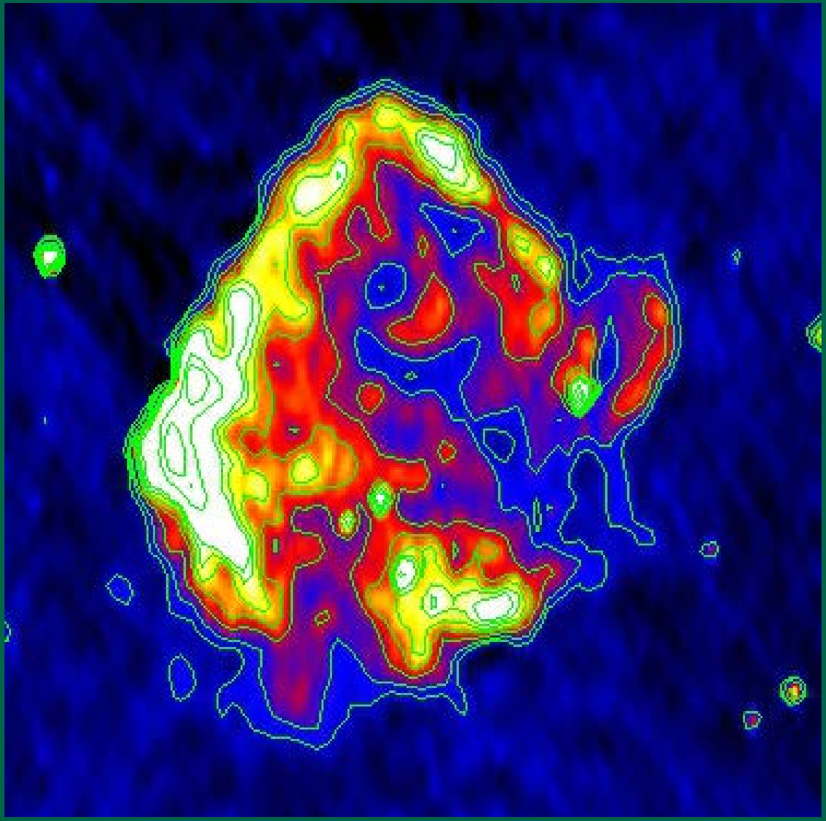




Gotthelf et al. 2001

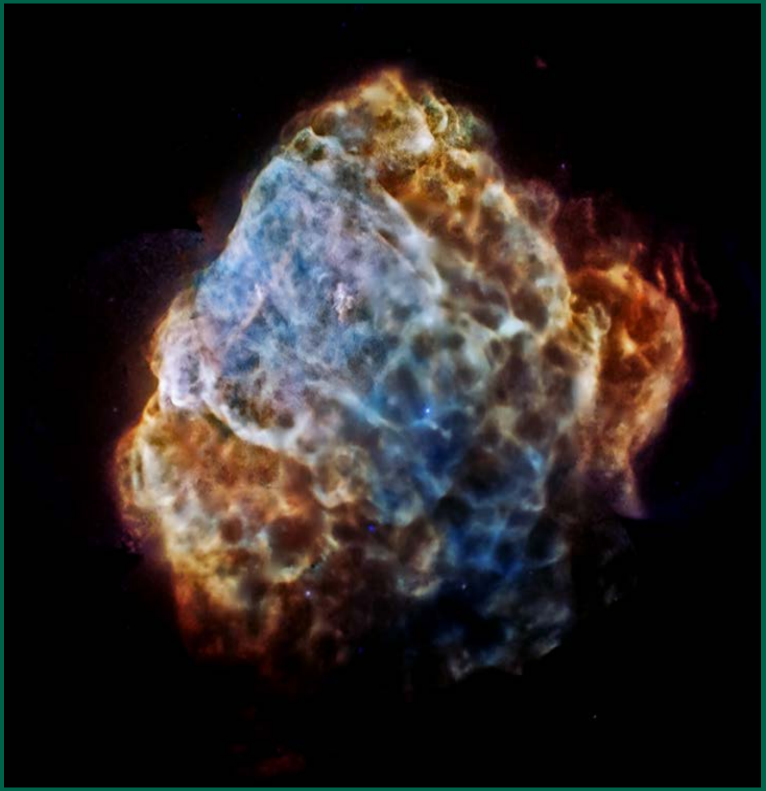
Puppis A

VLA radio
image at
330 MHz

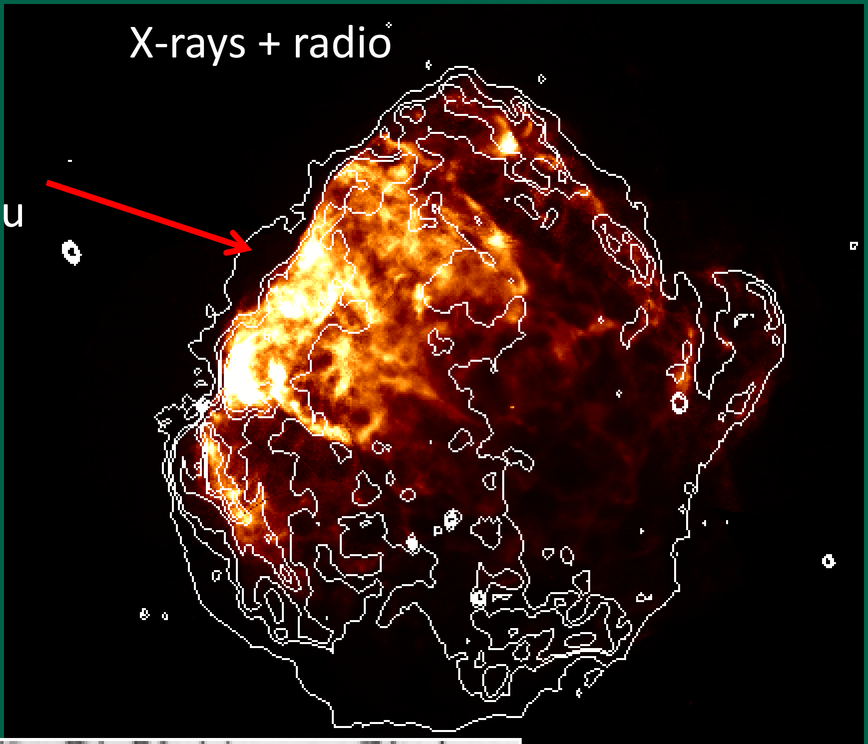


Castelletti et al. 2006

Chandra
and XMM
X-rays



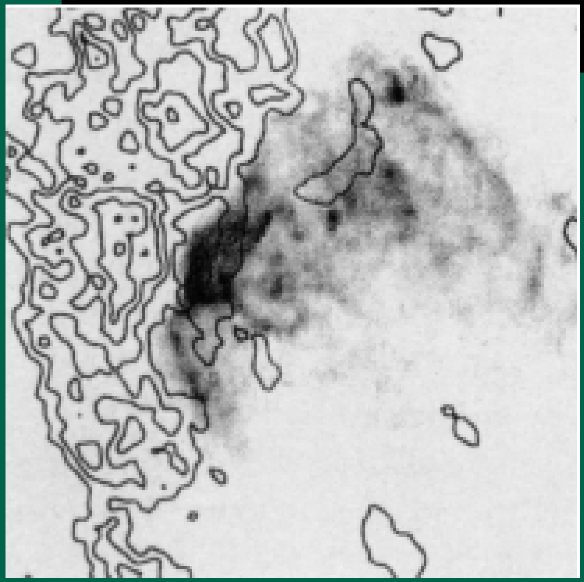
Dubner et al. 2013



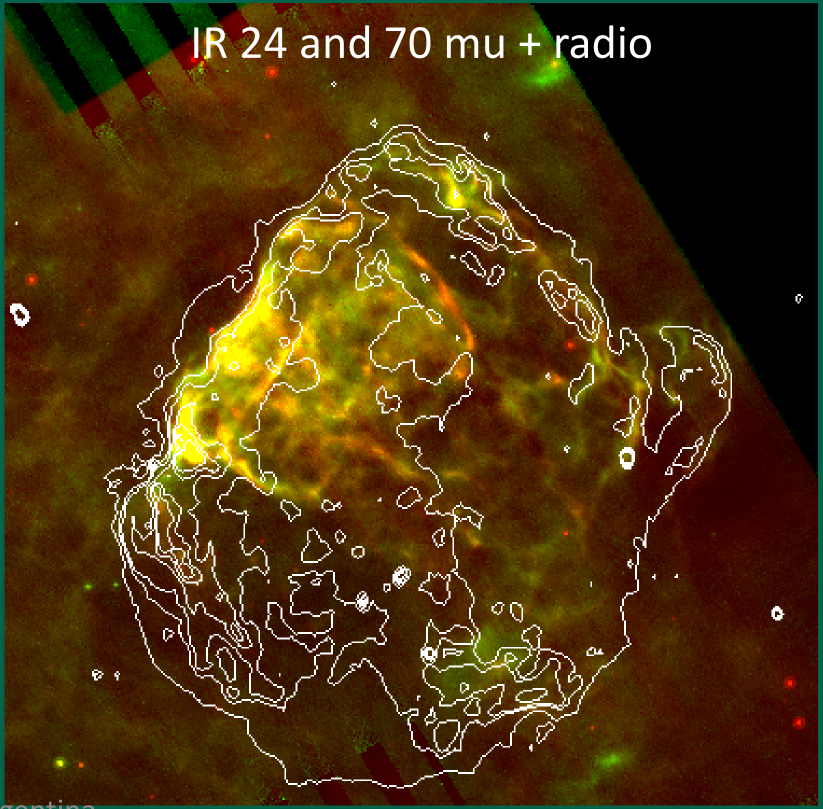
Dubner et al. 2013

The faint radio plateau might represent precursor synchrotron radiation from relativistic electrons that have diffused upstream from the shock.

HI

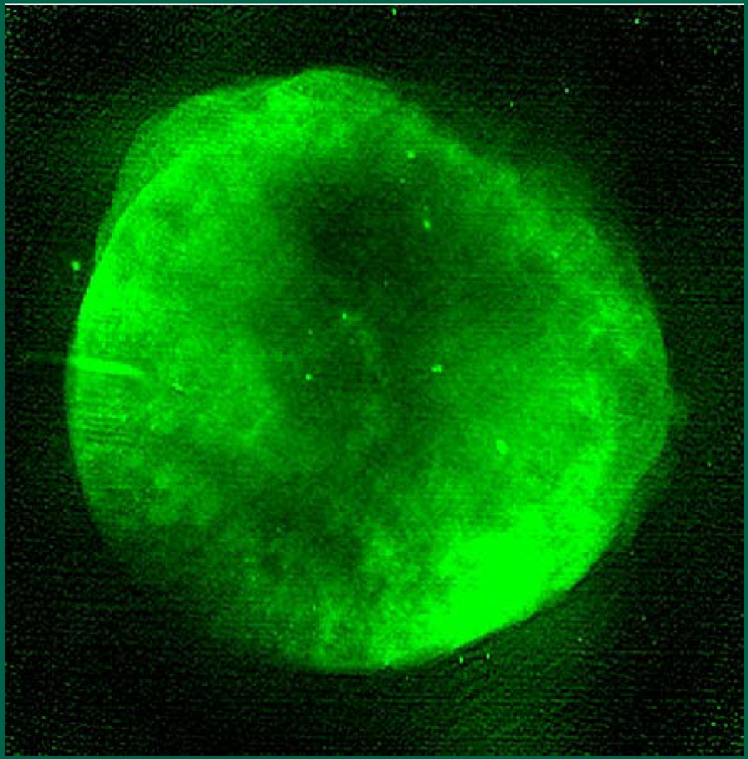


Reynoso et al. 1995

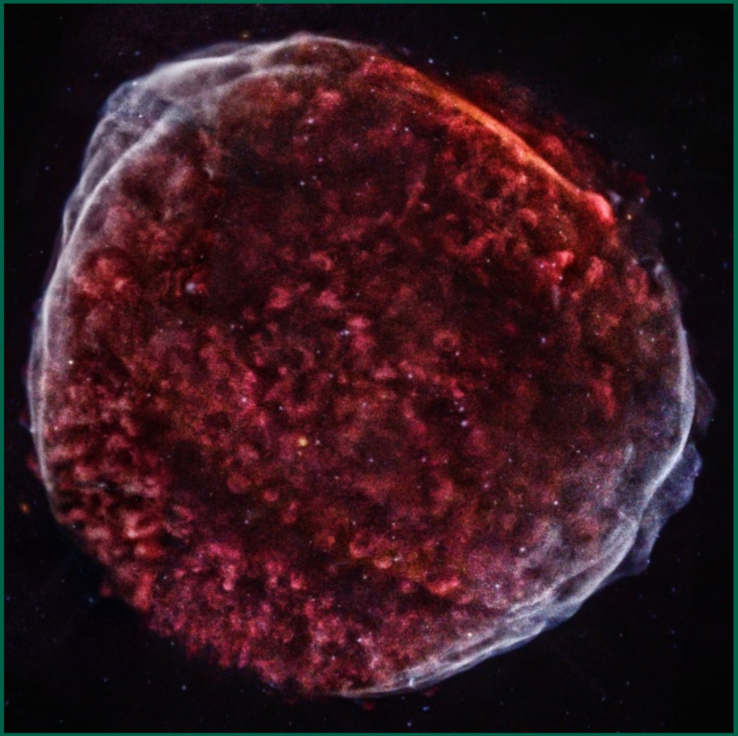


SN 1006

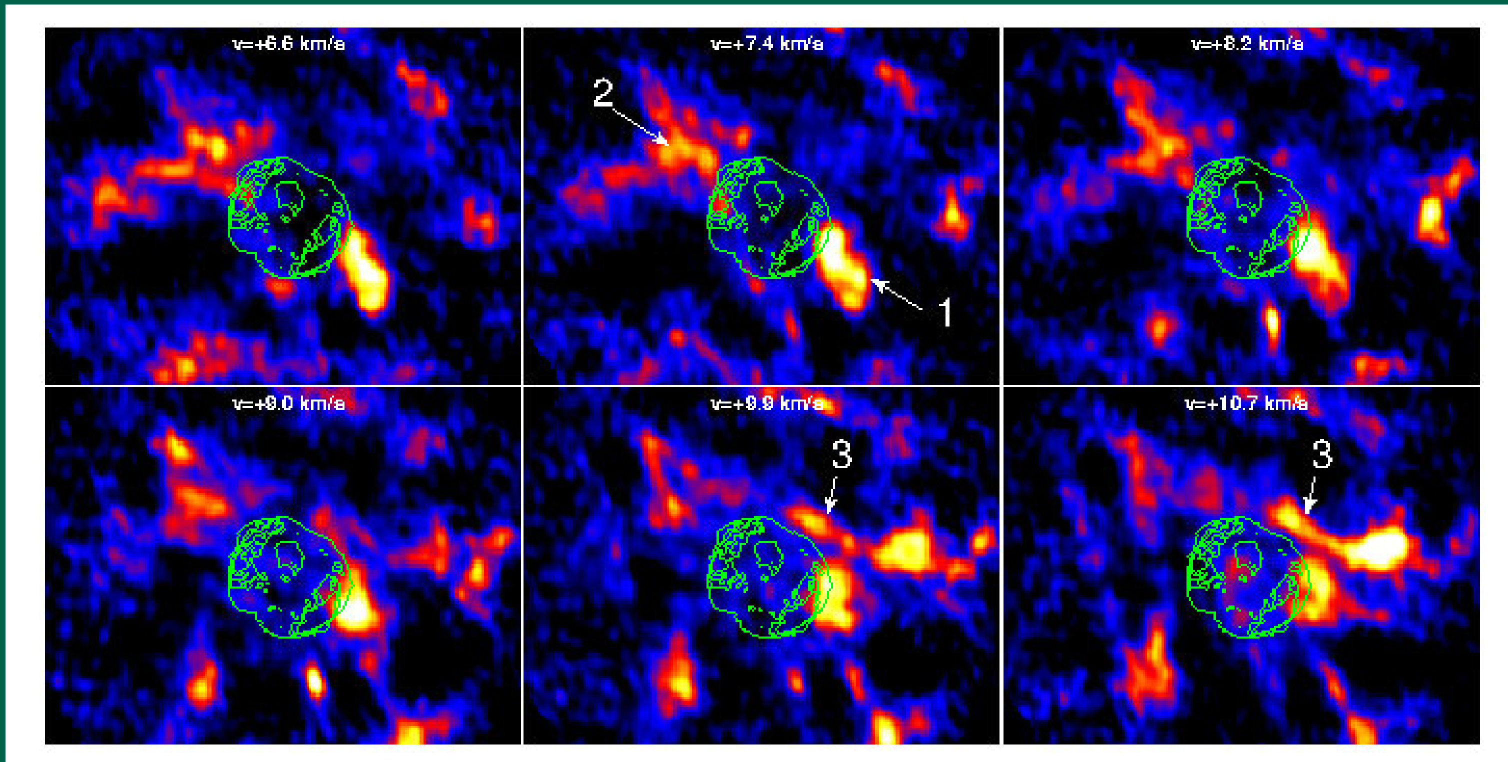
Radio at 1.3 GHz

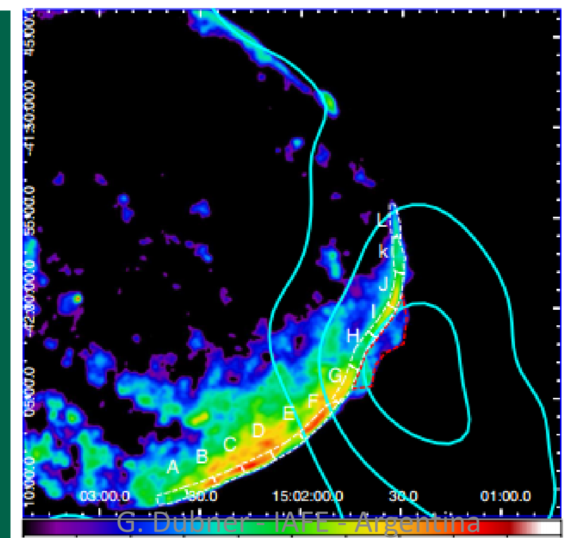


Cassam-Chenai et al. 2008



NASA/CXC/Middlebury College/F.Winkler





Dubner et al. 2002

Missing radio SNRs

The total of ~300 discovered Galactic SNRs is only 1/3 of the statistically expected number of SNRs in the Milky Way.

Selection effects?

- too young SNRs
- faint, old SNR

can be missed if sensitivity or angular resolution are not high enough

Can the SN explosion type be constrained from radio observations?

Facts:

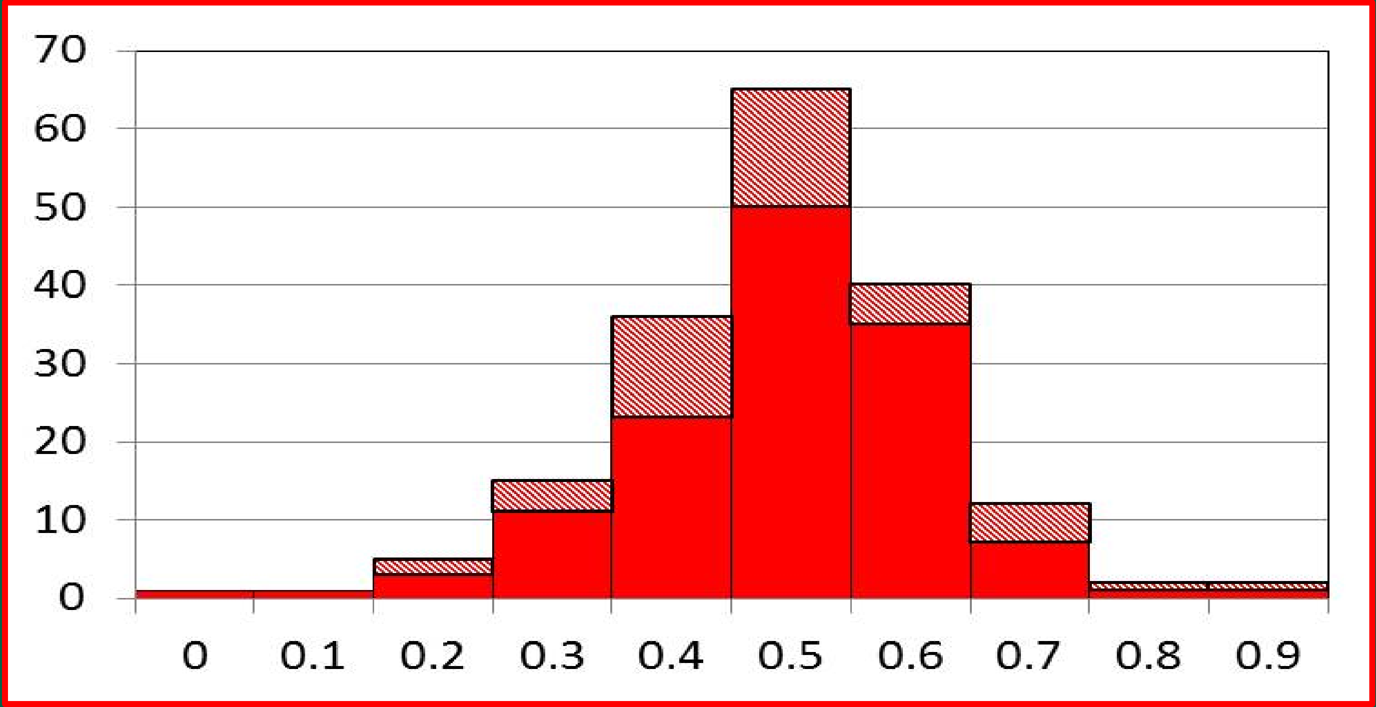
- Once the shock front sweeps up a certain amount of ambient gas, the radio synchrotron emission ignores the explosion properties.

- The complexity of interaction between shock front and ejecta, CSM and ISM soon mask all the previous information of the exploding star (physical and chemical)

Spectrum

DSA (**d**iffusive **s**hock **a**cceleration) for strong shocks, (compression ratio of 4) predicts $\alpha = 0.5$

Histogram of Spectral indices



Updated from Reynolds (2011)

For shell-type SNRs

Observed: $0.3 \leq \alpha \leq 0.8$ for shell-type SNRs

$\alpha \leq 0.5$ (flat spectrum) → efficient particle acceleration
→ contamination with PWN (inside)
→ contamination with thermal gas (outside)

$\alpha \geq 0.5$ (steep spectrum) → very low M (≤ 10)
→ poor magnetic compression
→ inefficient particle acceleration

Young SNRs would be expected to be efficient accelerators and have flat spectrum ($\alpha \leq 0.5$)

α= 0.7 for Cas A,

0.6 for Tycho and SN1006

0.8 for SN 1987A

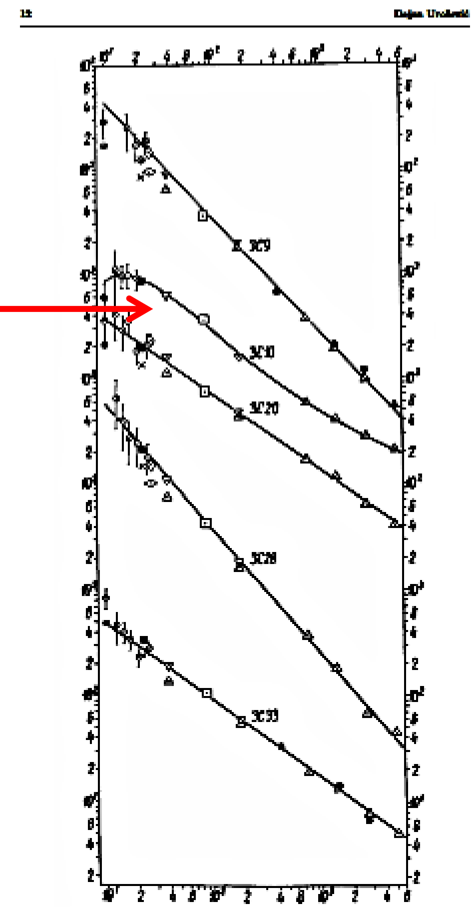
Radio SNe have indices as steep as 0.9 -1.0

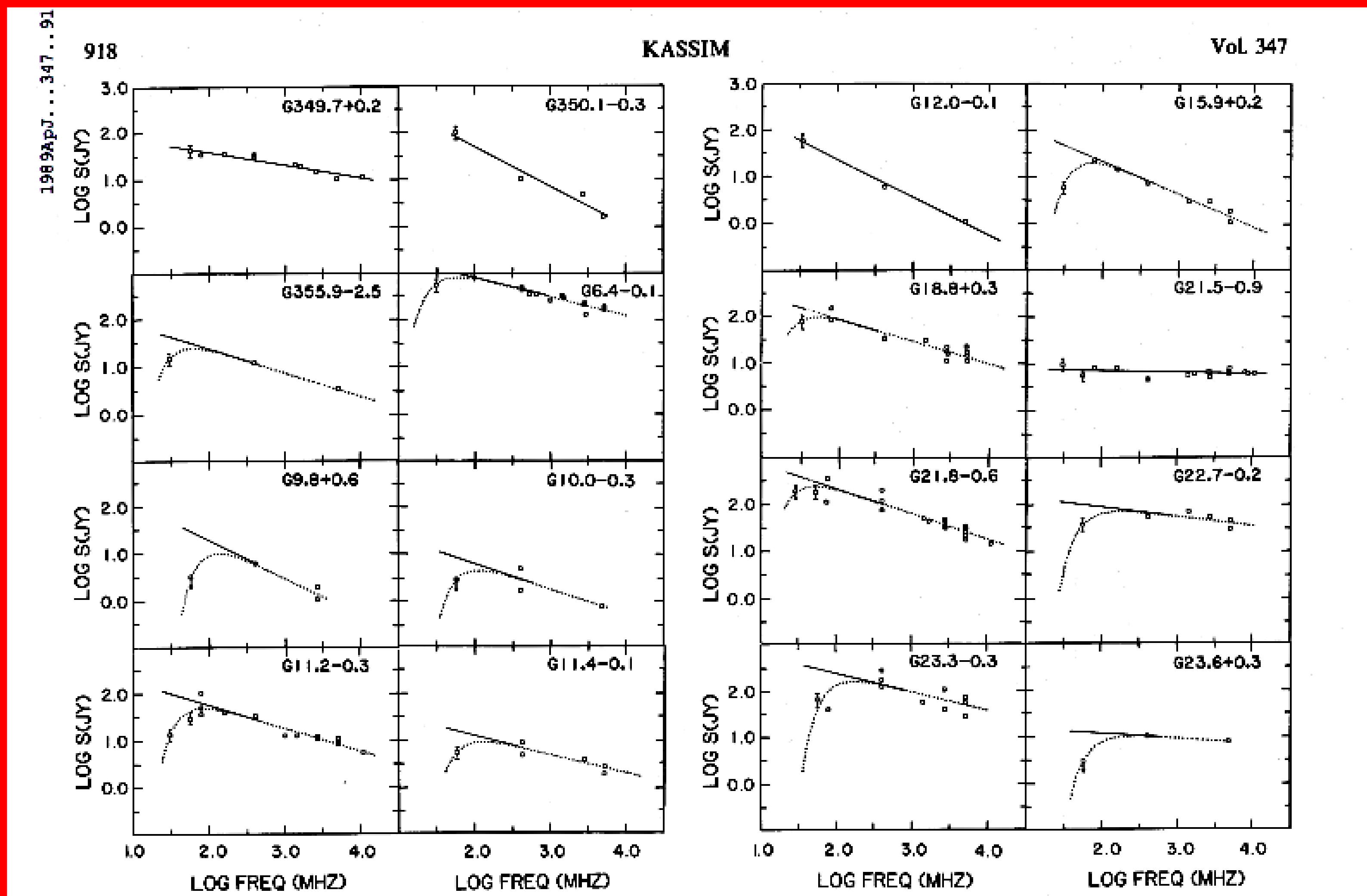
This can be explained with the orientation of the B field: quasi-perpendicular orientation produces steeper indices (Bell et al. 2011)

Curvature of the spectrum in a log-log plot

Concave-up radio spectrum: the result of non-linear DSA

Concave-down radio spectrum: DSA with the effect of syncrotron losses within a finite emission region

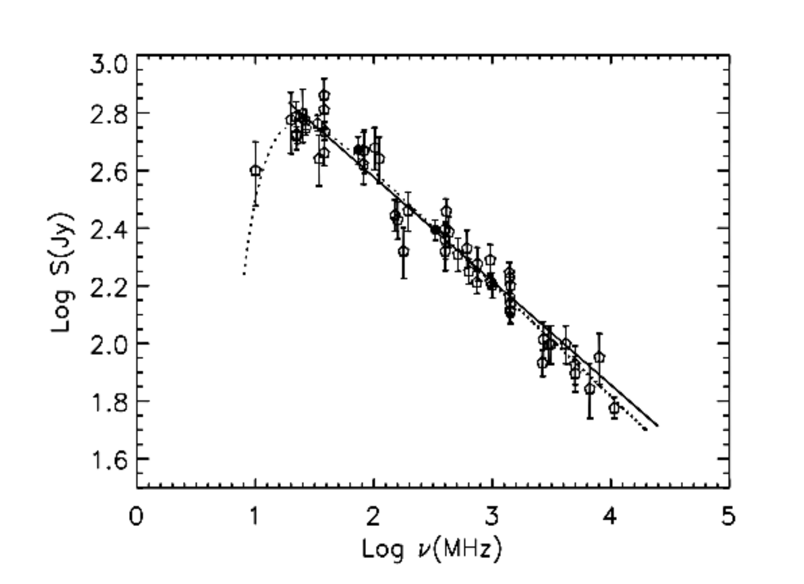




Kassim et al. 1989

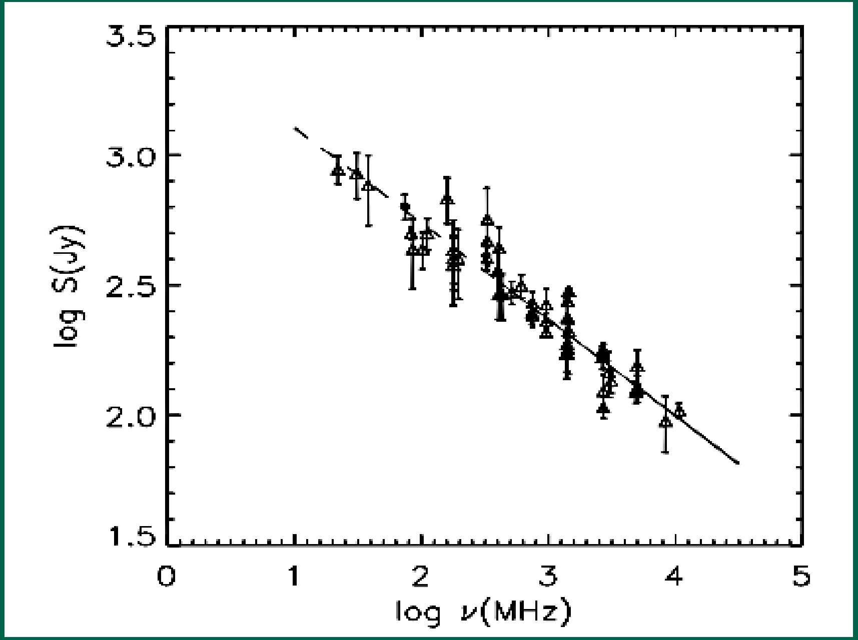
Turnovers in their low frequency spectra are usually extrinsic due to absorption by intervening thermal material along the line of sight (also synch self-absorption, intrinsic free-free absorpt.)

IC 443



Castelletti et al. 2011

W 44

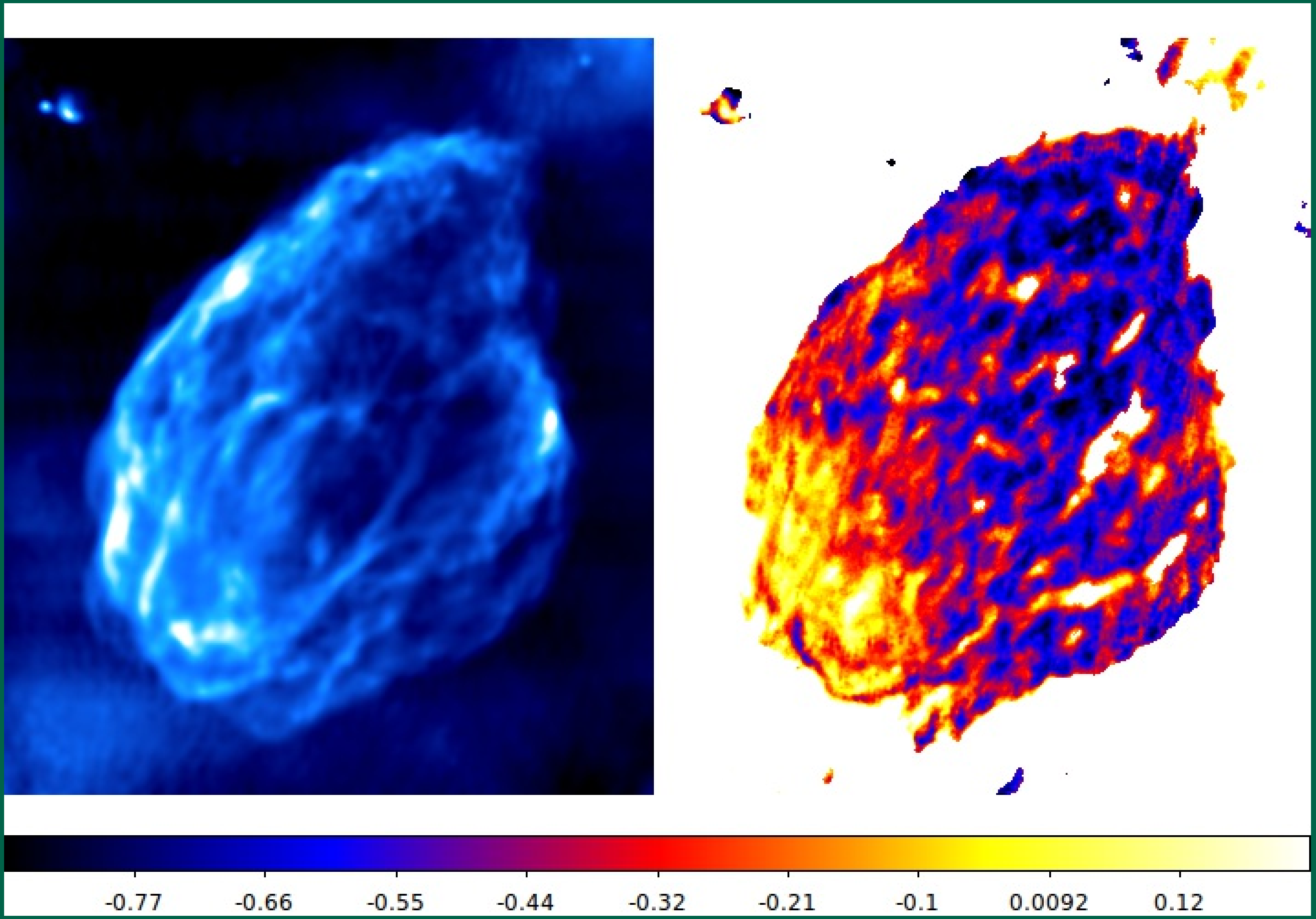


Castelletti et al. 2007

W 44

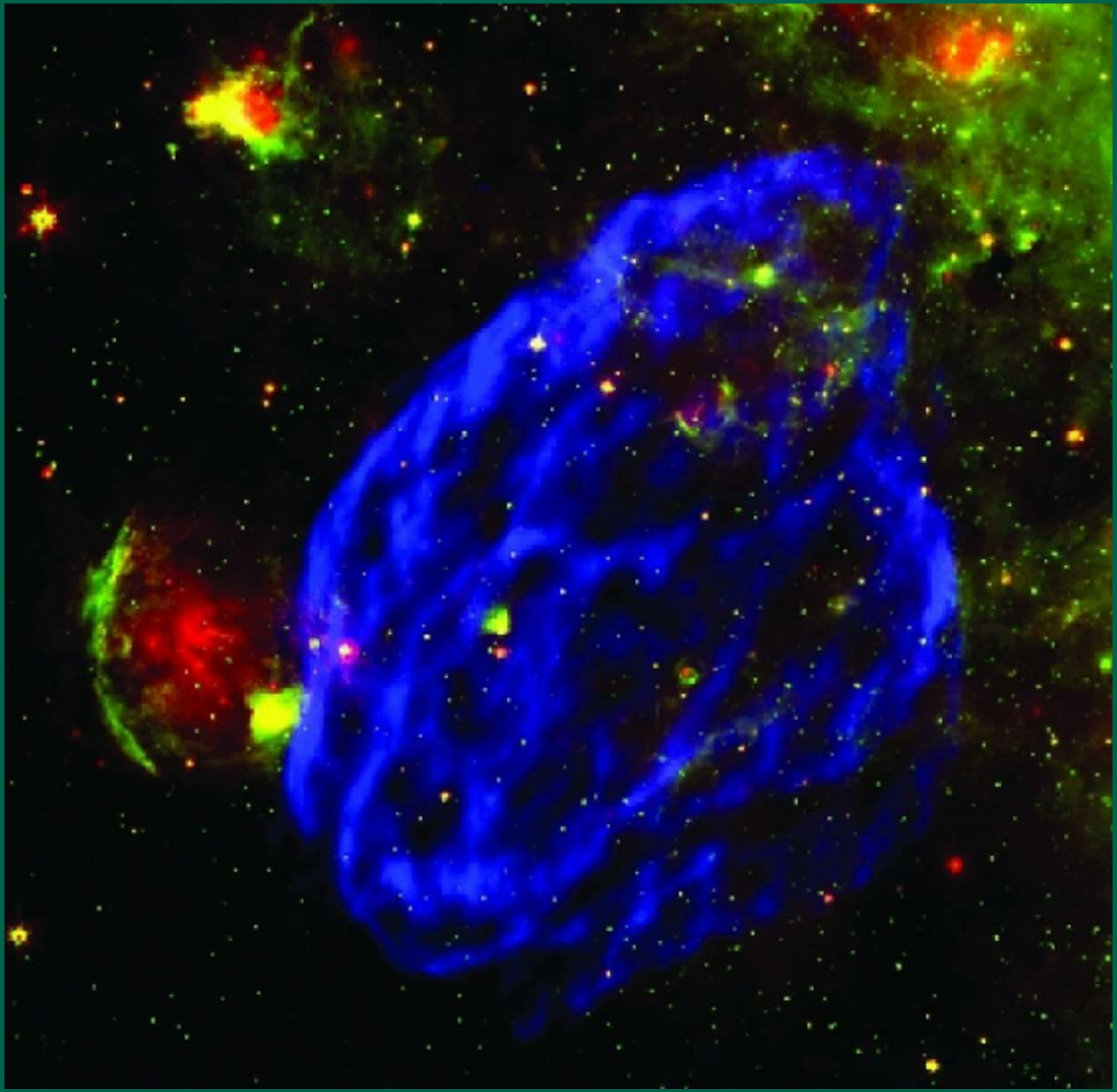
Radio continuum at 1.4 GHz

Spectral Index between 330 MHz and 1.4 GHz



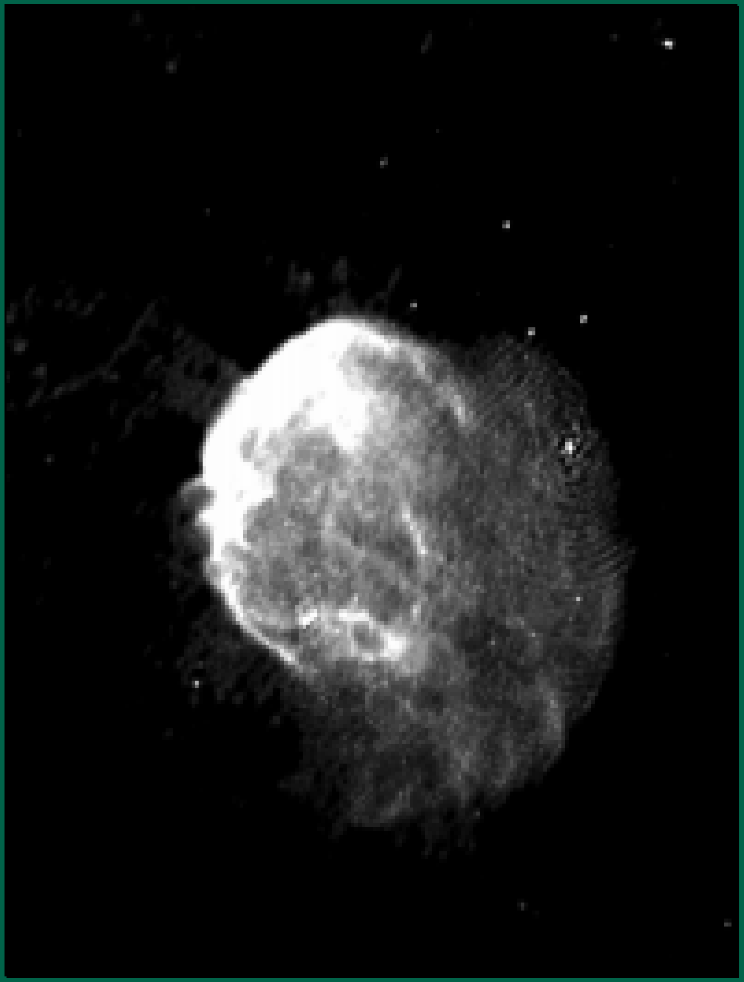
Castelletti et al. 2007

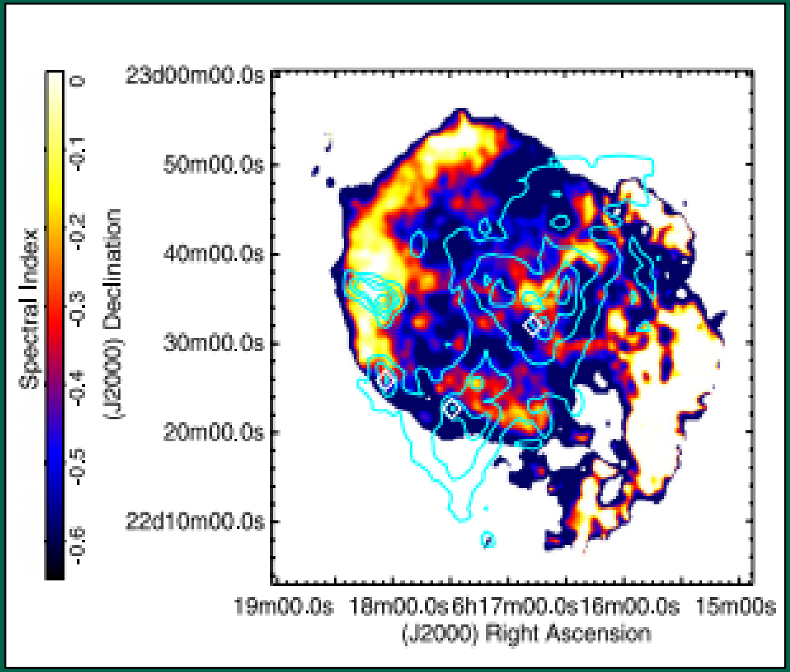
W 44



Blue: VLA radio continuum at 324 MHz
Green: Spitzer IR at 8μm
Red: Spitzer IR at 24 μm
(Castelletti et al. 2007)

IC 443

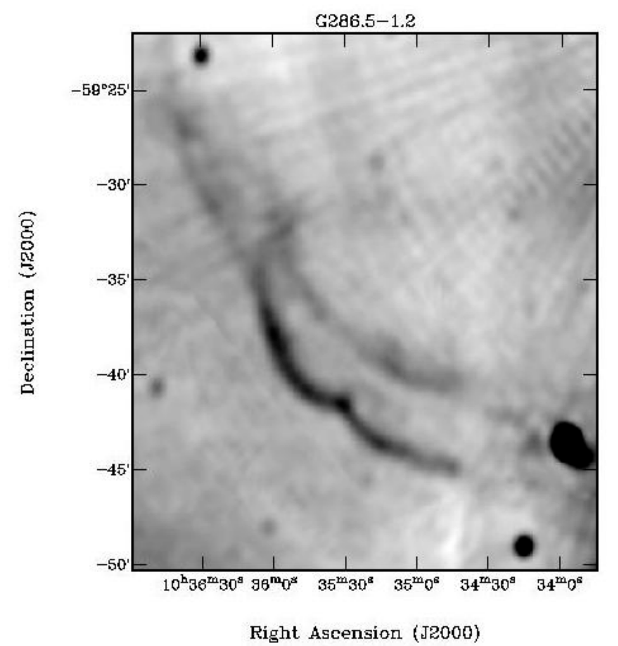


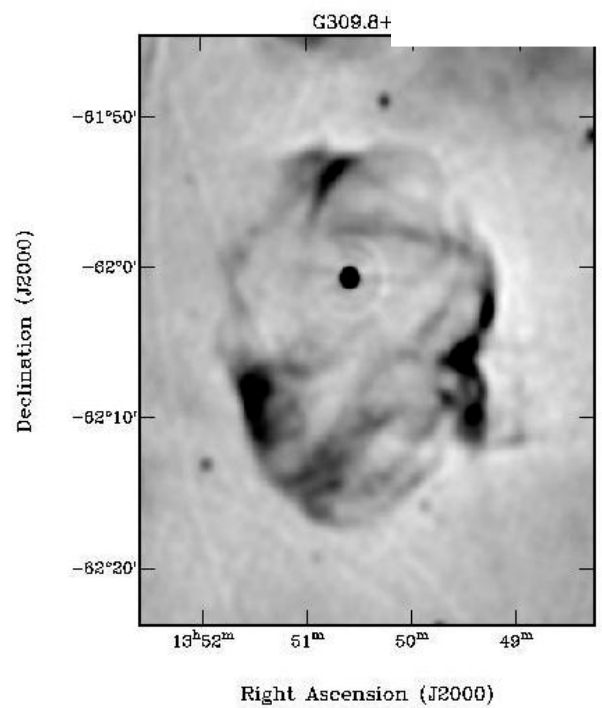


Castelletti et al. 2011

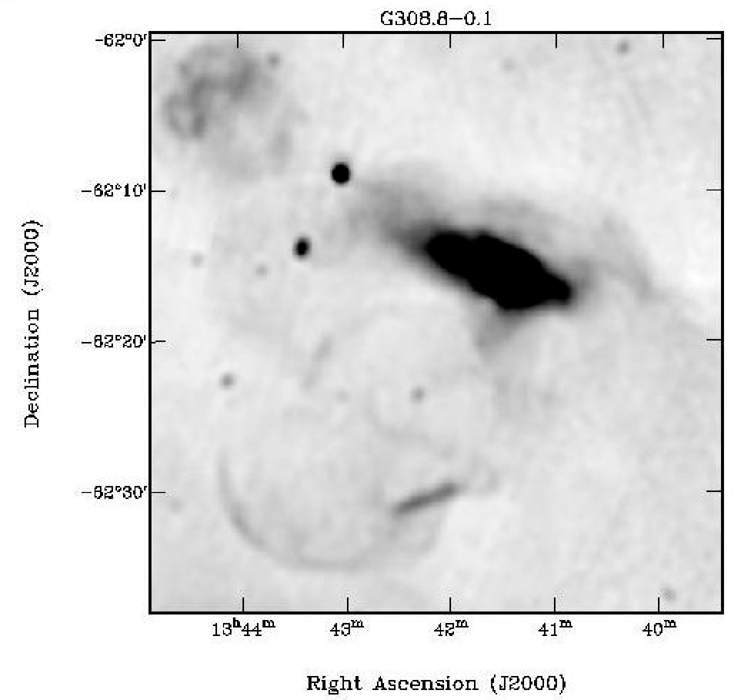
Problems with spectral studies

- Less than one fourth (50/294) of Galactic SNRs have the predicted spectrum due to extrinsic and intrinsic causes.
- 44% of the SNRs classified as of shell-type have α poorly determined (54% for the Southern sources)
- Observations with total-power single-dish radiotelescopes have low angular resolution and prevents discrimination against background and nearby contaminat sources
- Observations with radio interferometer resolve sources but are spatial filters that loose extended components





Whiteoak & Green 1996



Polarization

Radio polarization studies provide essential information on the degree of order and orientation of the magnetic field.

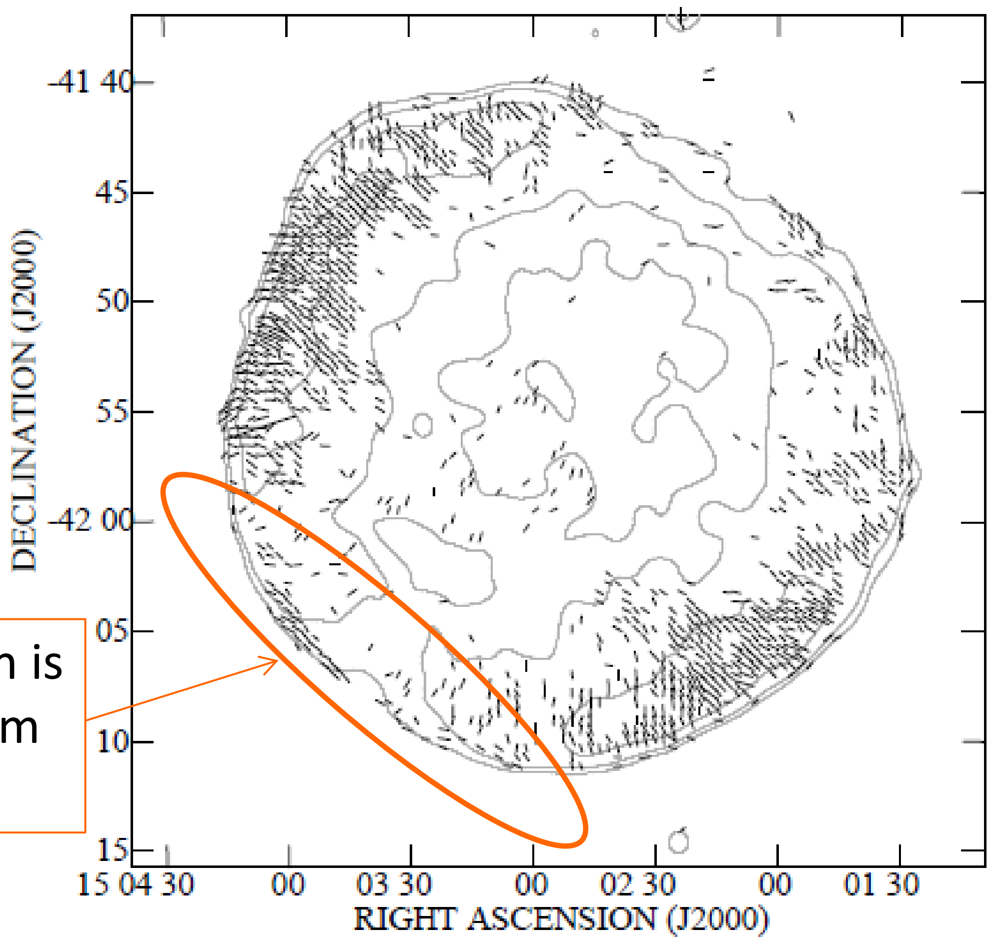
From synchrotron theory the radiation should be polarized and for α= 0.5, it is expected 70% of fractional polarization

In general it is never observed polarization higher than ~ 10% - 15%

Depolarized because : * intrinsic desorder
* instrumental effects
* Faraday rotation in the foreground medium and inside the SNR

RM (to convert E direction into B direction) can now be determined using high-sensitivity broadband observations using Rotation Measure Synthesis techniques (Brentjens & de Bruyn 2005)

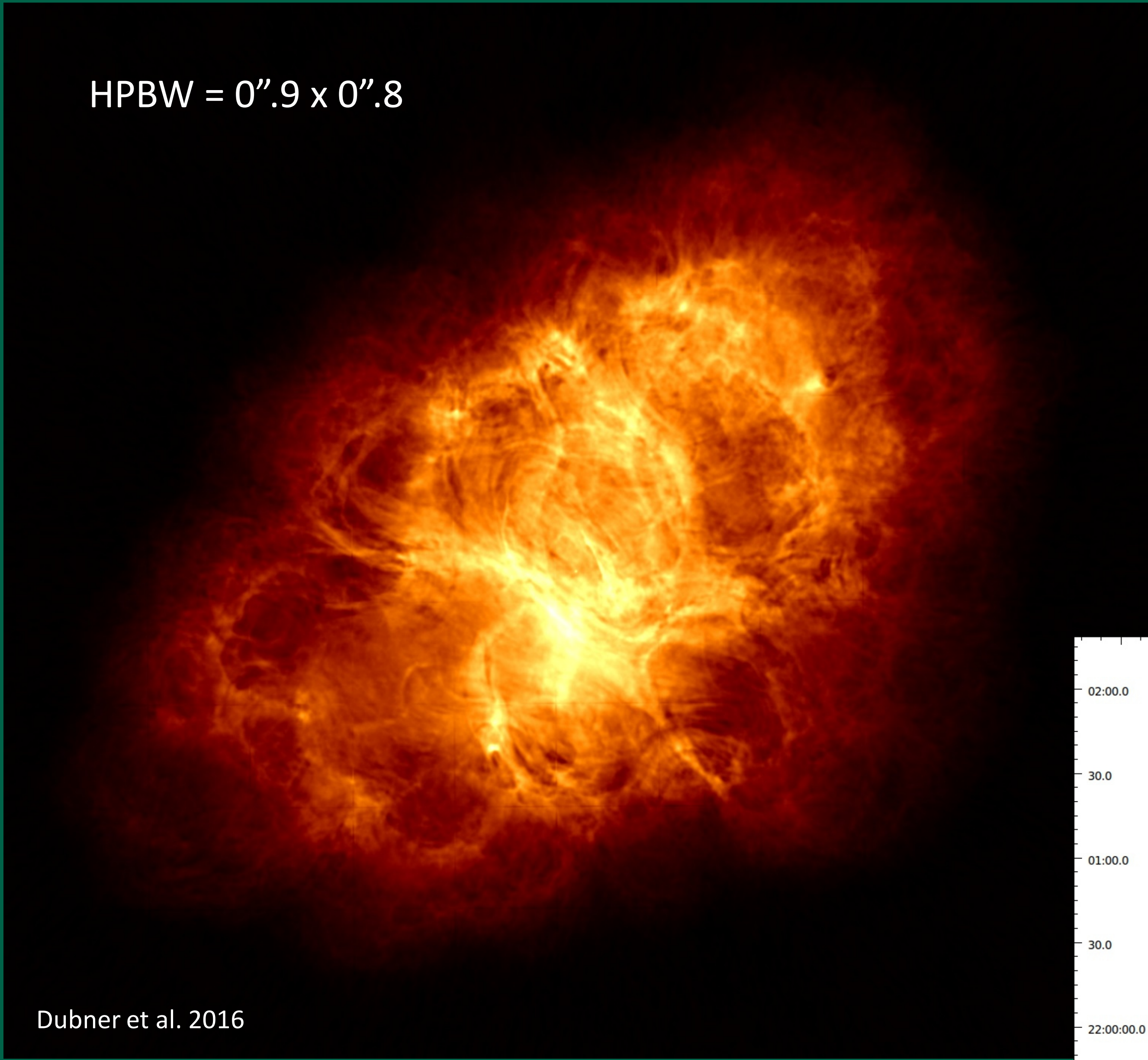
SN1006, a young SNR with radial and tangential B field



The largest polarization is attained at the minimum synchrotron

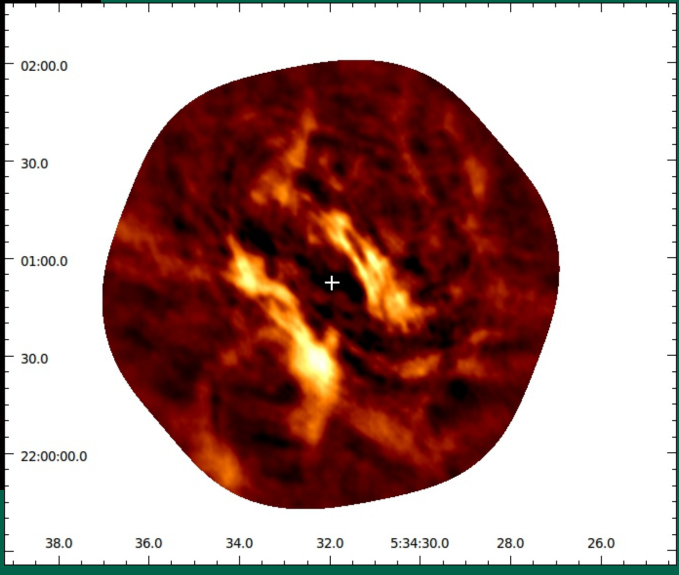
Magnetic field distribution on SN 1006 at 1.4 GHz (from Reynoso et al. 2013)

Crab Nebula
New radio results



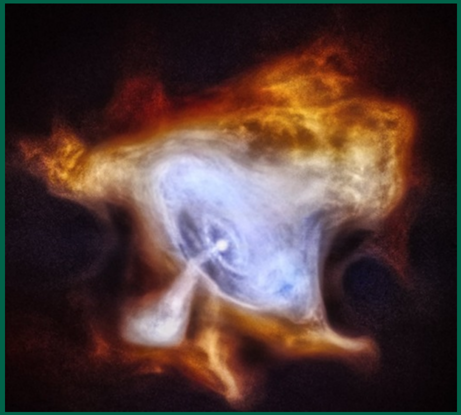
JVLA @ 3GHz

ALMA @ 100GHz

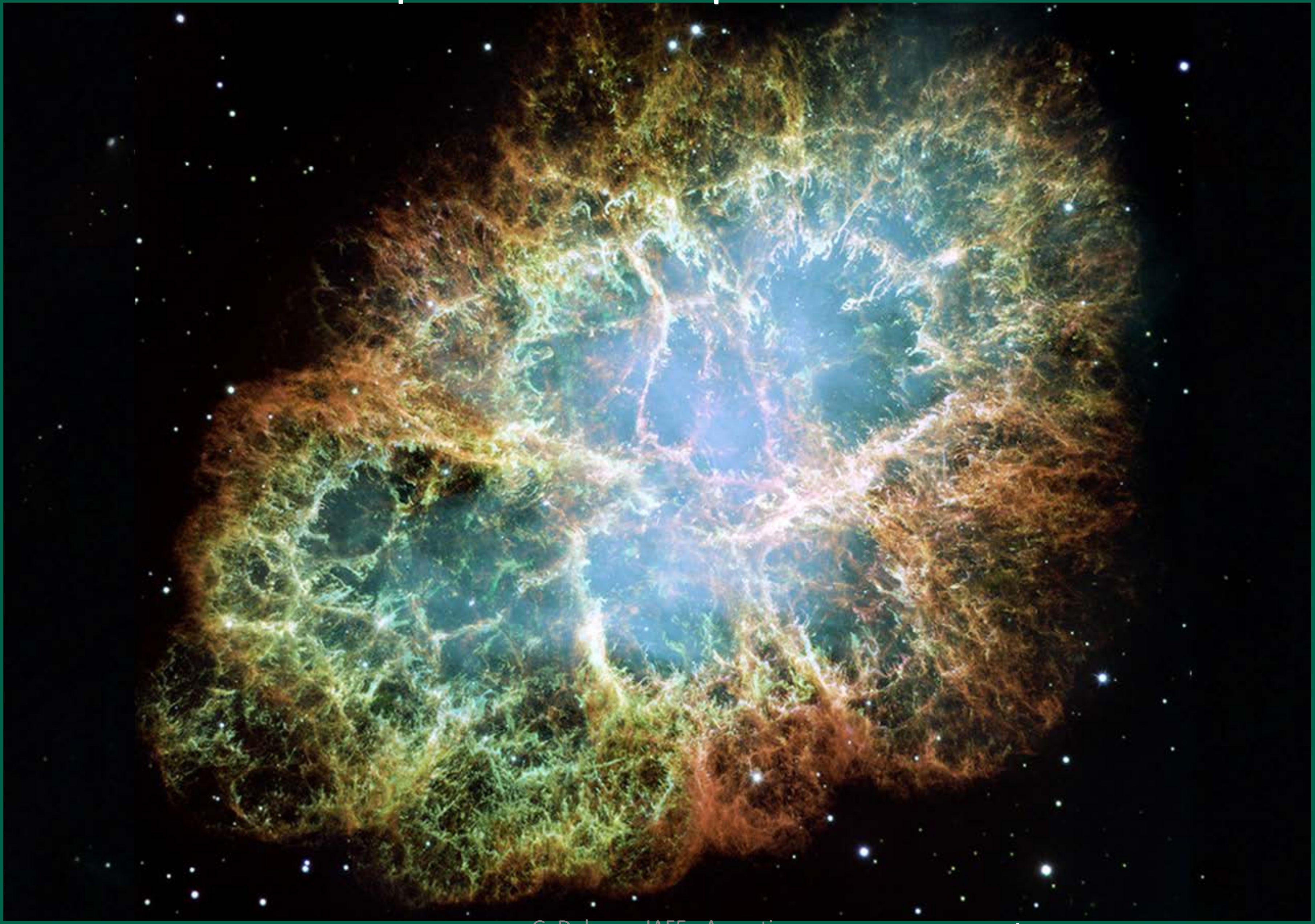


Comparison with X-ray emission

Chandra deep image (Seward et al. 2006)

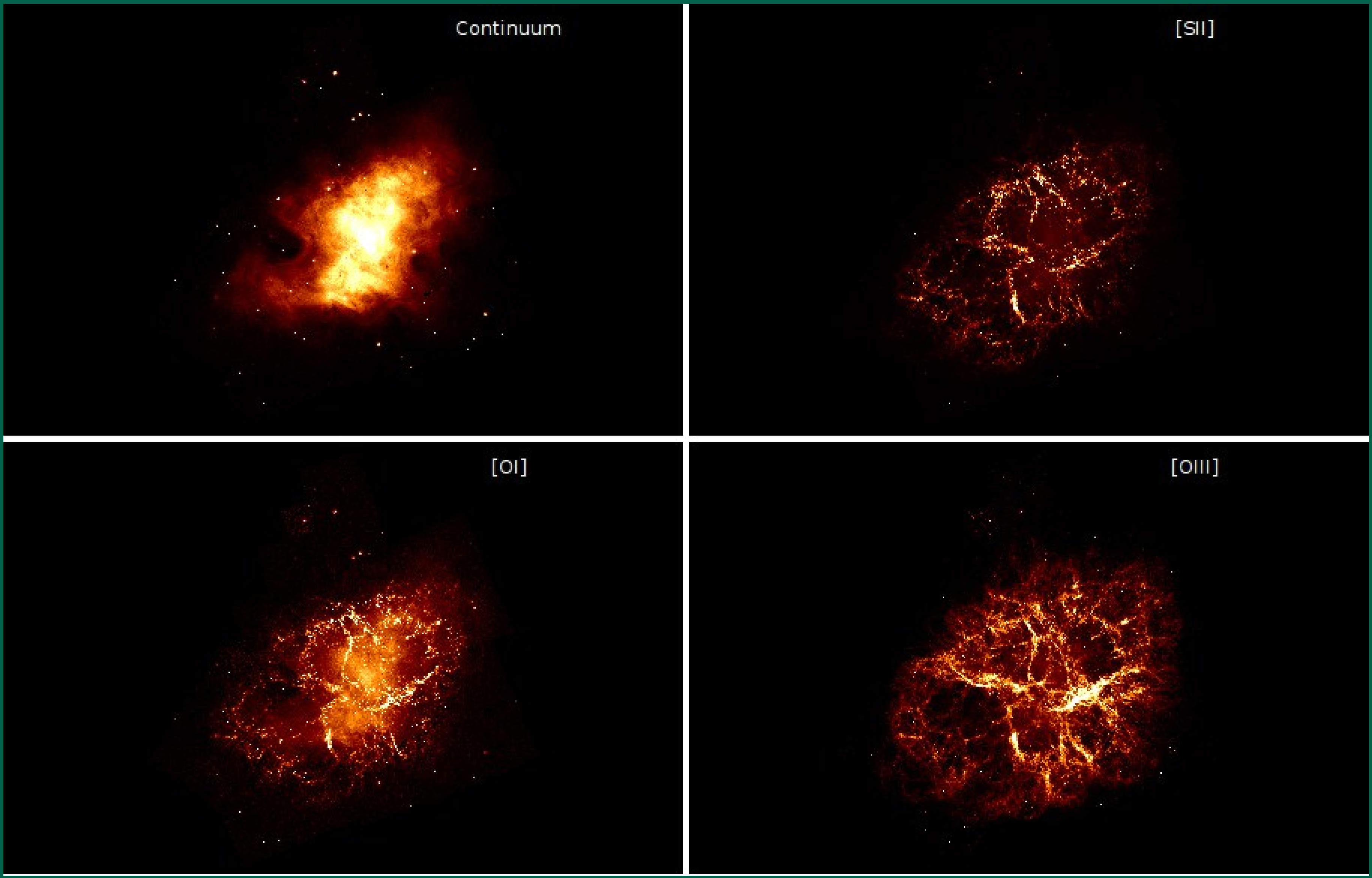


Comparison with optical emission



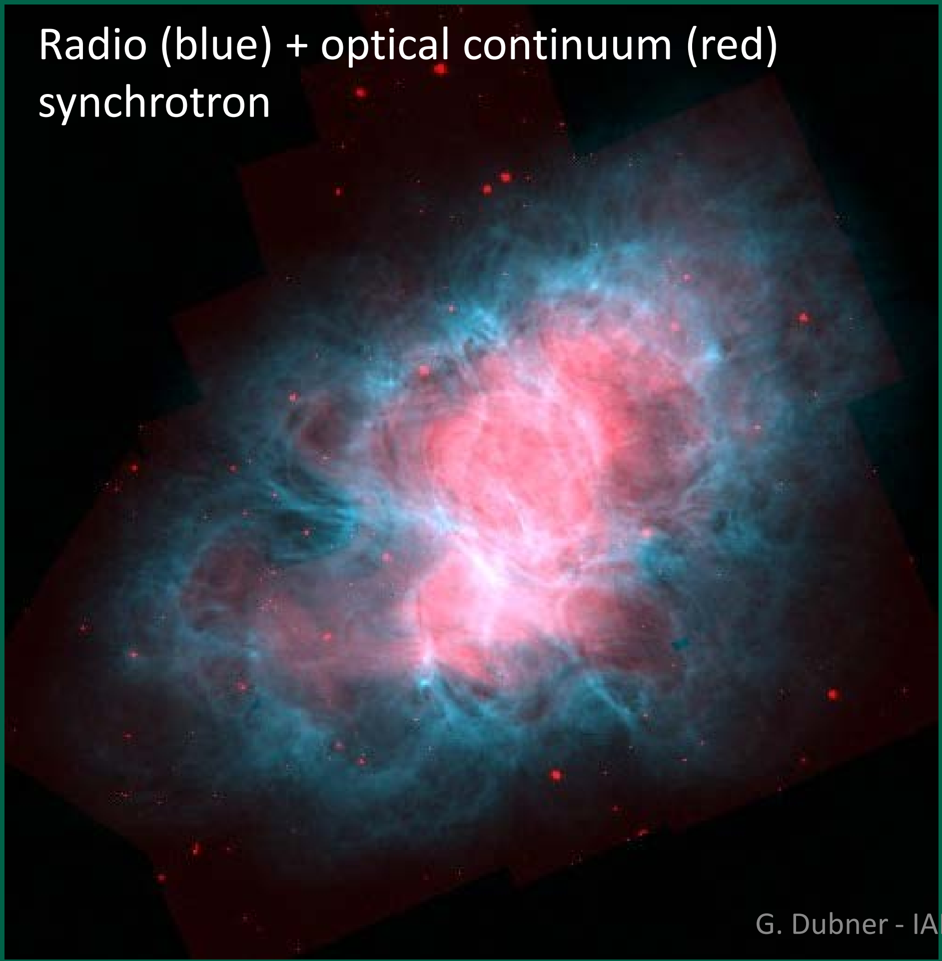
Hester et al. 1995

Comparison with optical emission

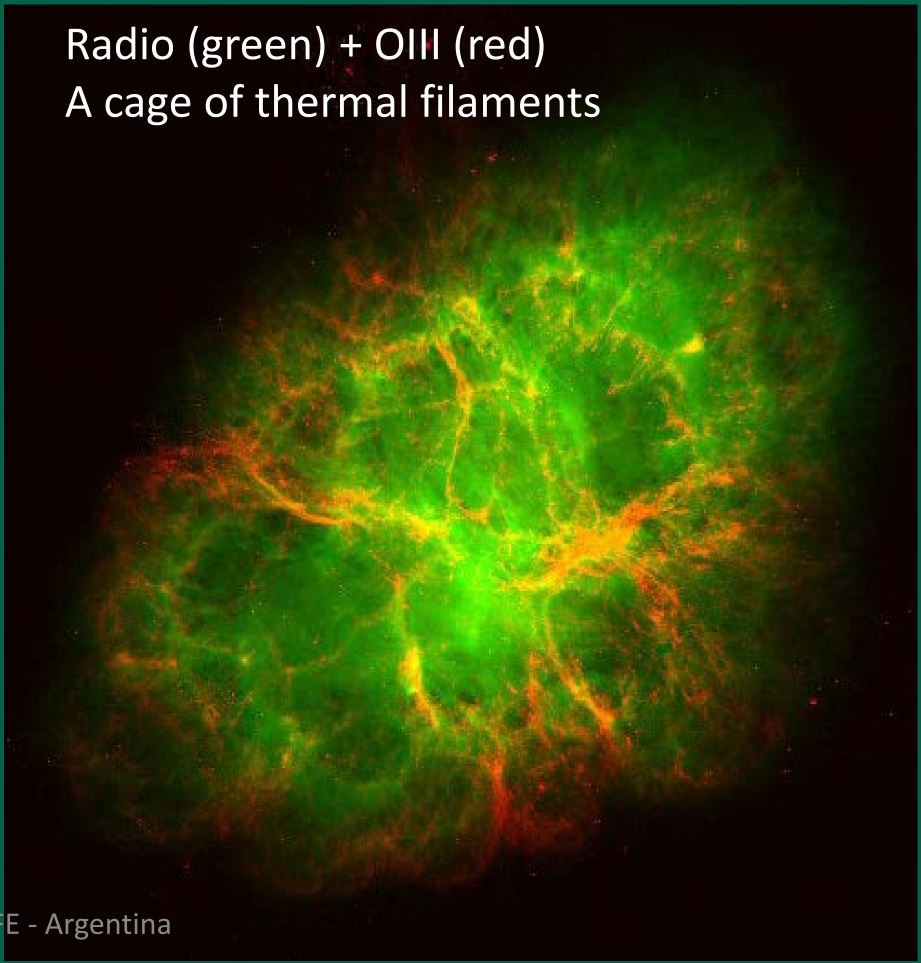


Comparison with optical emission

The synchrotron nebula is bounded and confined by the thermal ejecta



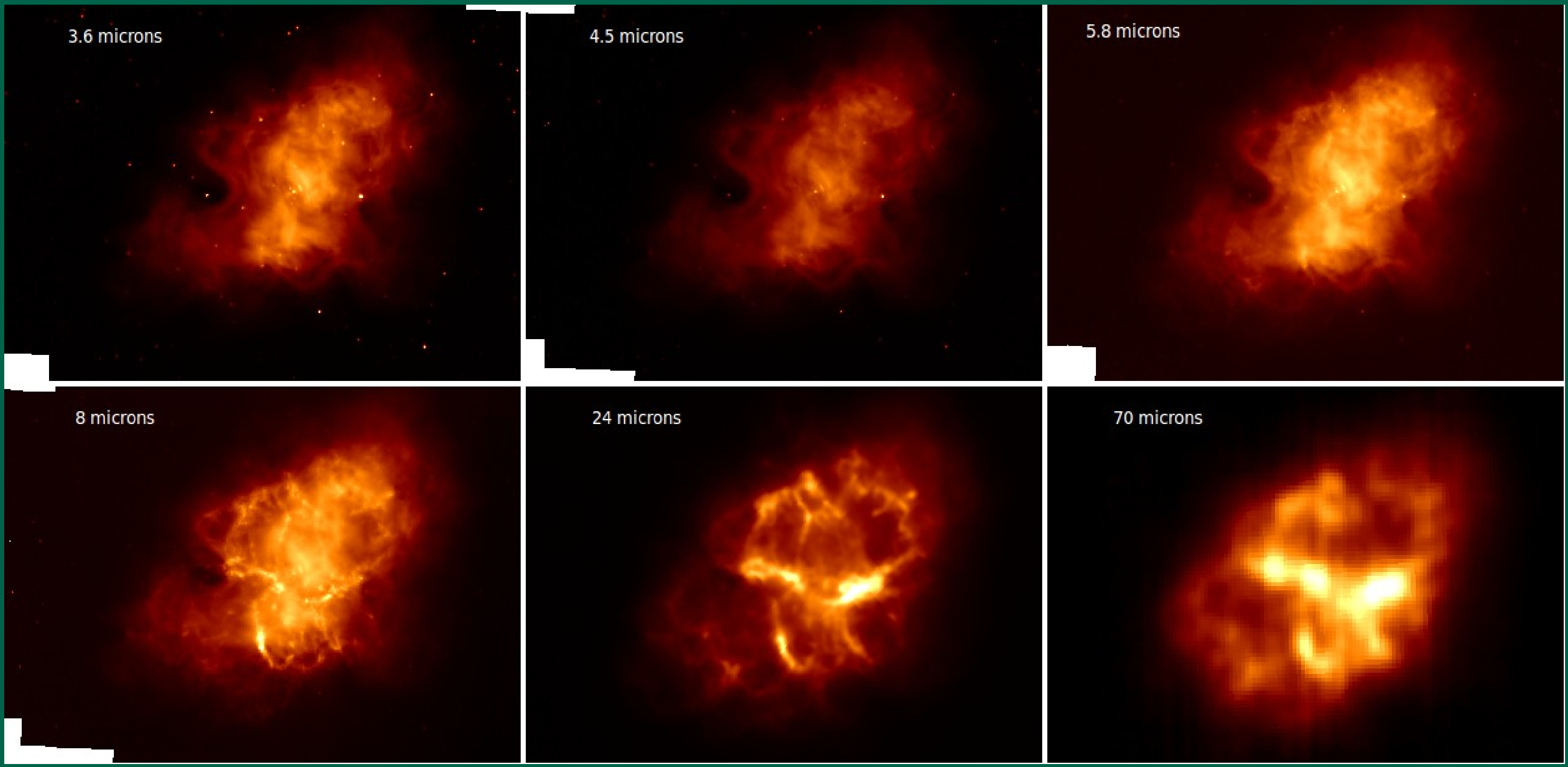
Radio (blue) + optical continuum (red)
synchrotron



Radio (green) + OIII (red)
A cage of thermal filaments

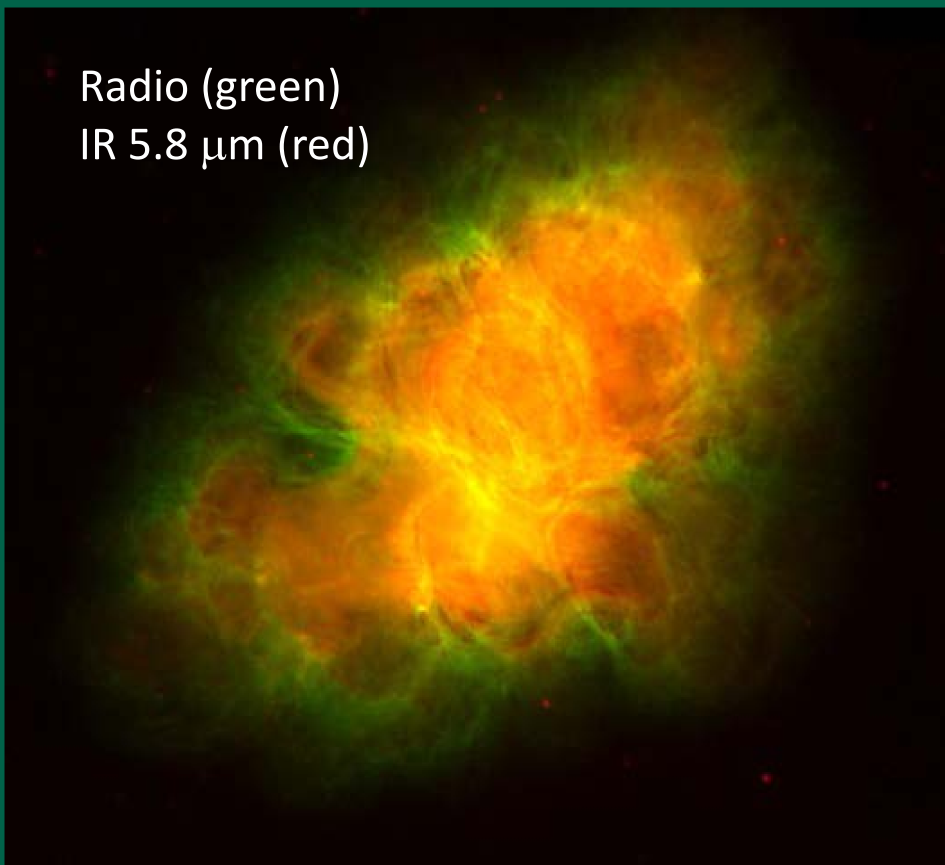
Comparison with IR emission

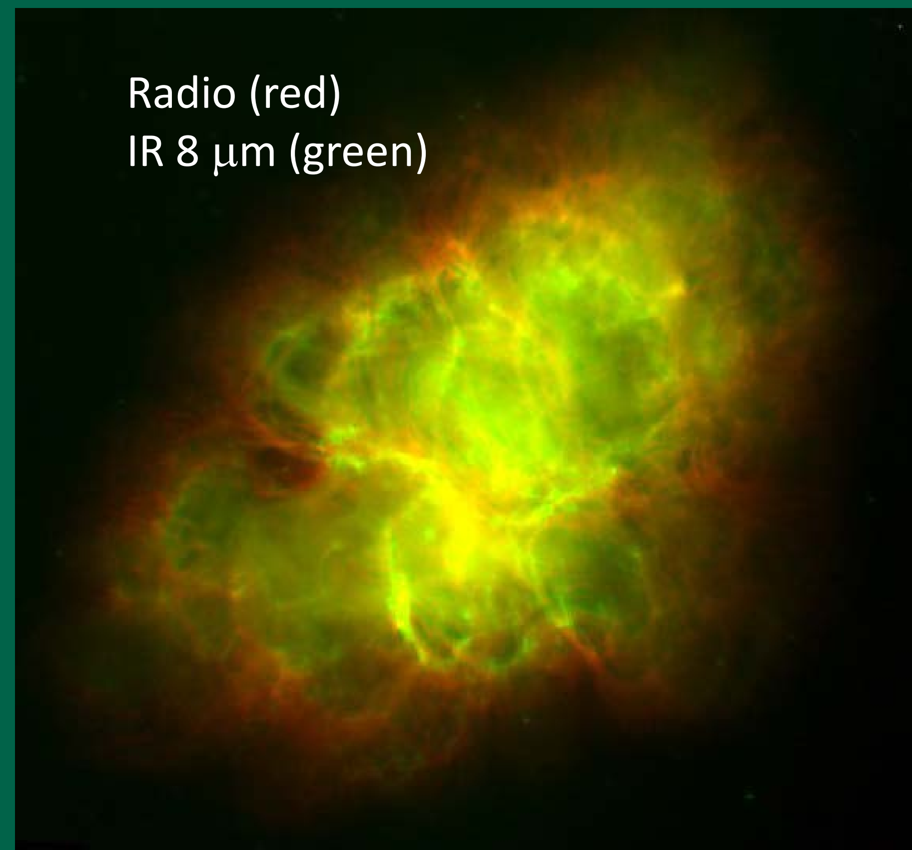
The dust emission coincides with the brightest filaments in the ejecta



Temim et al. 2012

Dust is predominantly heated by the synchrotron radiation field rather than collisionaly heated by the gas





In Summary:

- Amost 70 years after the first detection of a SNR with radiotelescopes, great progress has been achieved.

- The last generation radio telescopes (ALMA, SKA, LOFAR, JVLA, FAST, ASKAP, MEERKAT, eEVN, etc.) will bring important advances in understanding the properties of the magnetic field and particle acceleration

Thanks!!