A Radio Eye on Pulsar Wind Nebulae

SUPERNOVA REMNANTS III
An Odyssey in Space after Stellar Death
June 13, 2023

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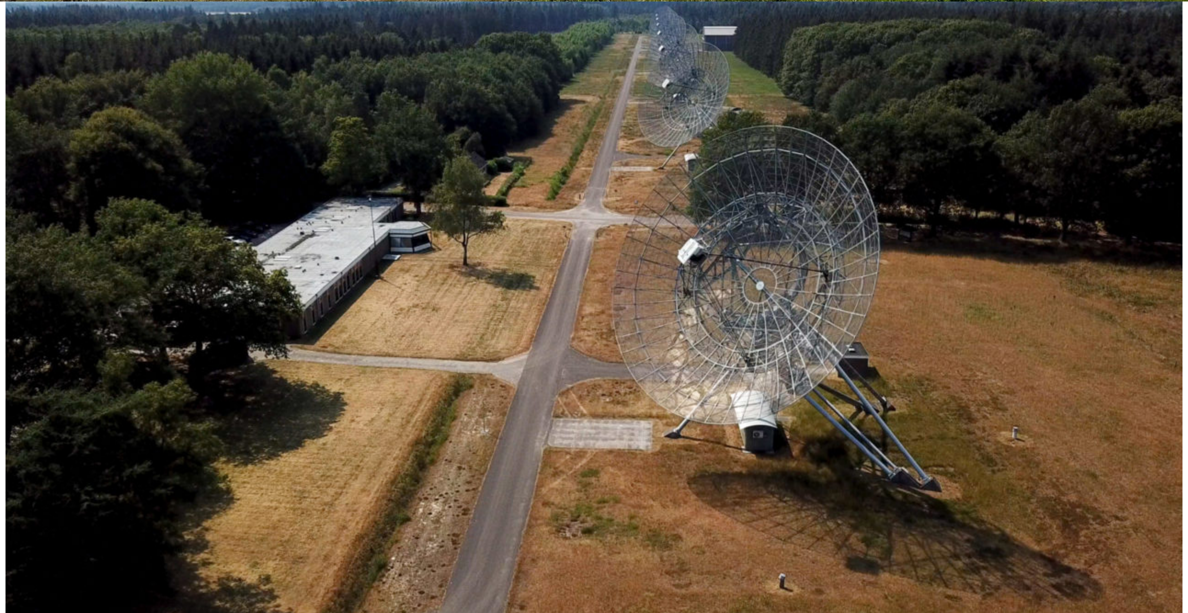
Northern Radio Eyes



Northern Radio Eyes

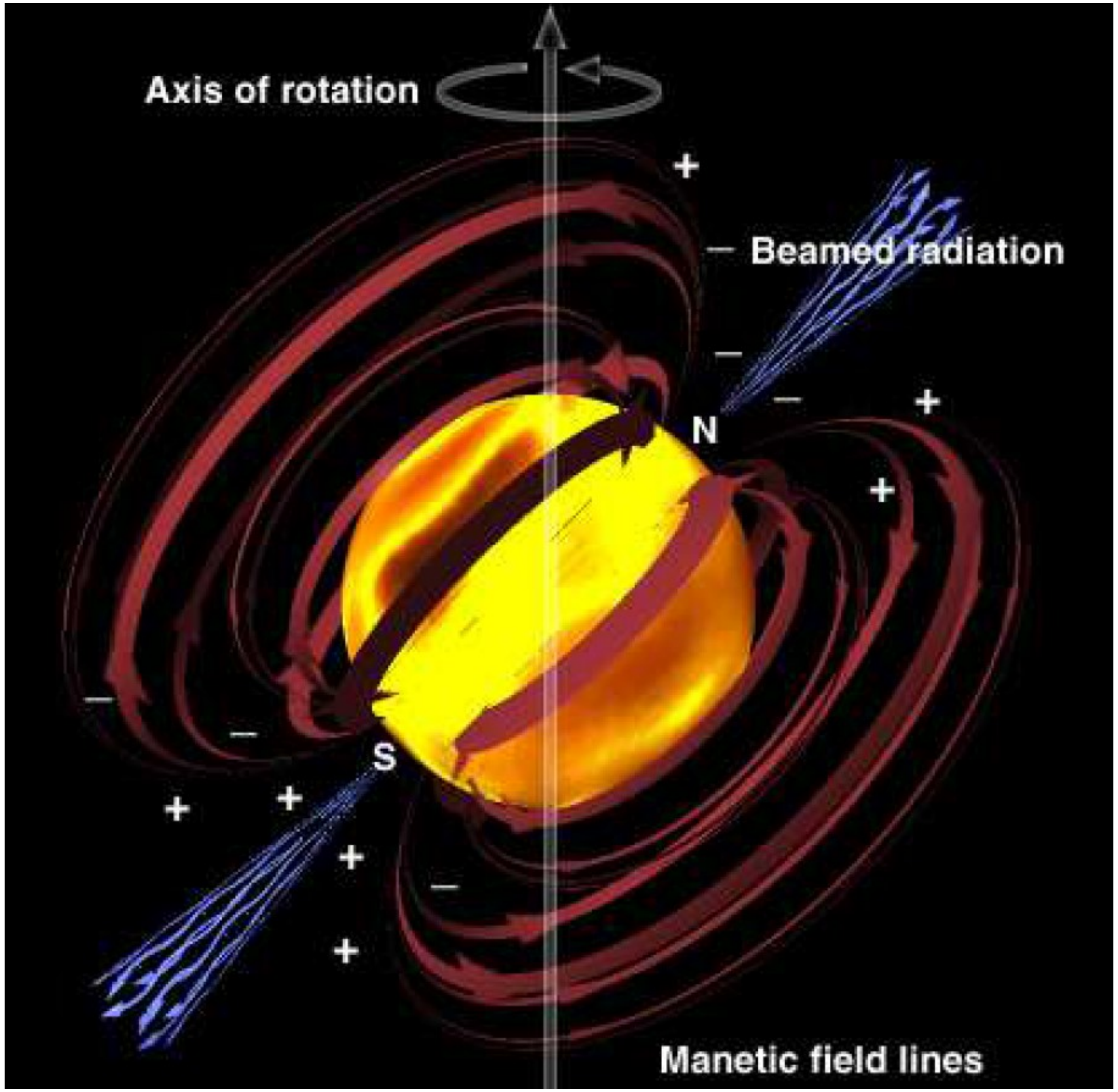
Southern Radio Eyes

Southern Radio Eyes

Overview

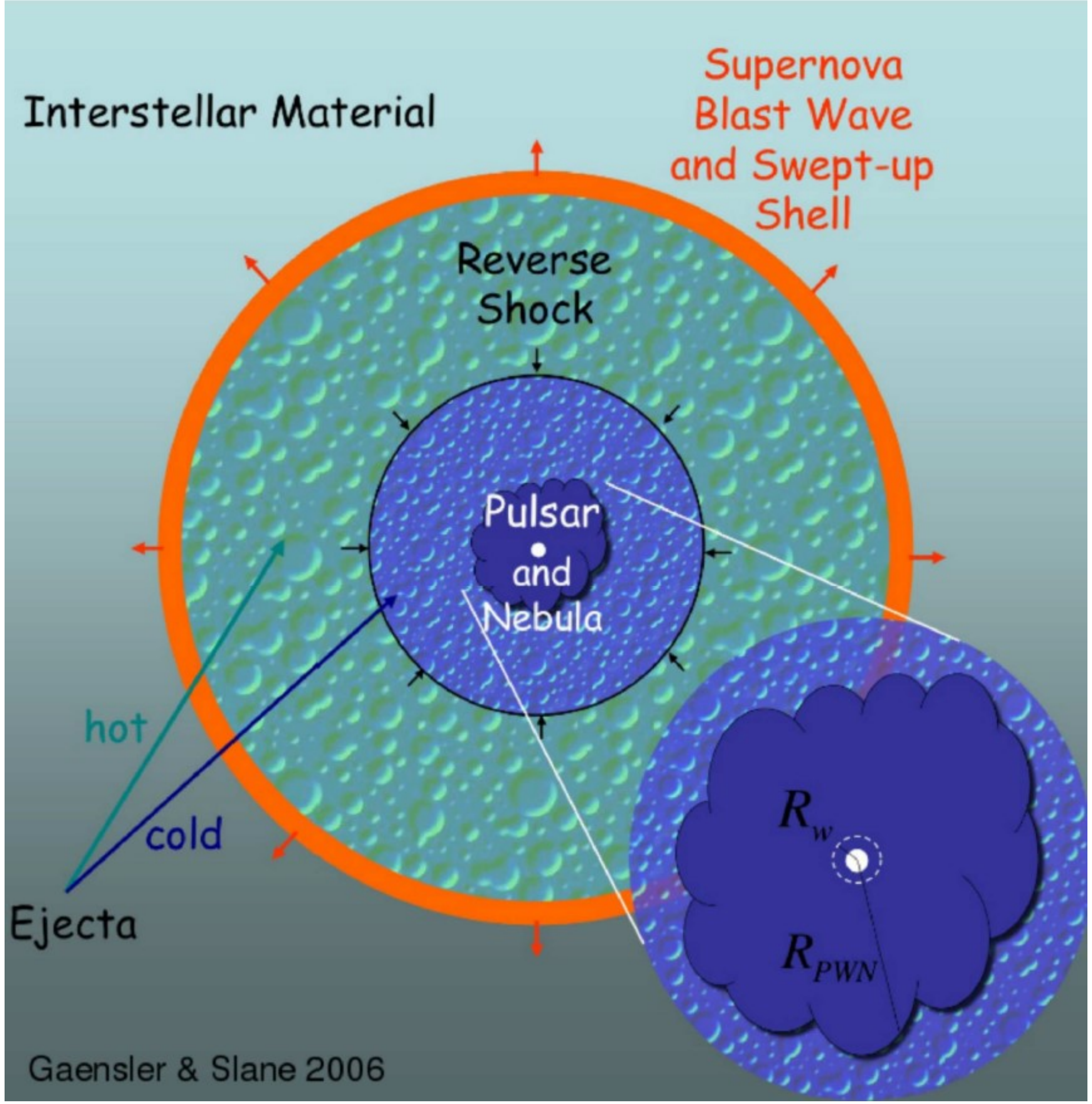
- Radio Eyes
- PWNe and their Evolution
- Radio Spectra of PWNe
- Magnetic Fields in PWNe
- Outlook

Pulsars



- **pulsa**ting **r**adio source
- pulsation -> light house effect
- created in a core-collapse supernova explosion
- characterized by period *P*, typically between 1ms and 10s
- highly magnetized between 10^8 and 10^{15} G

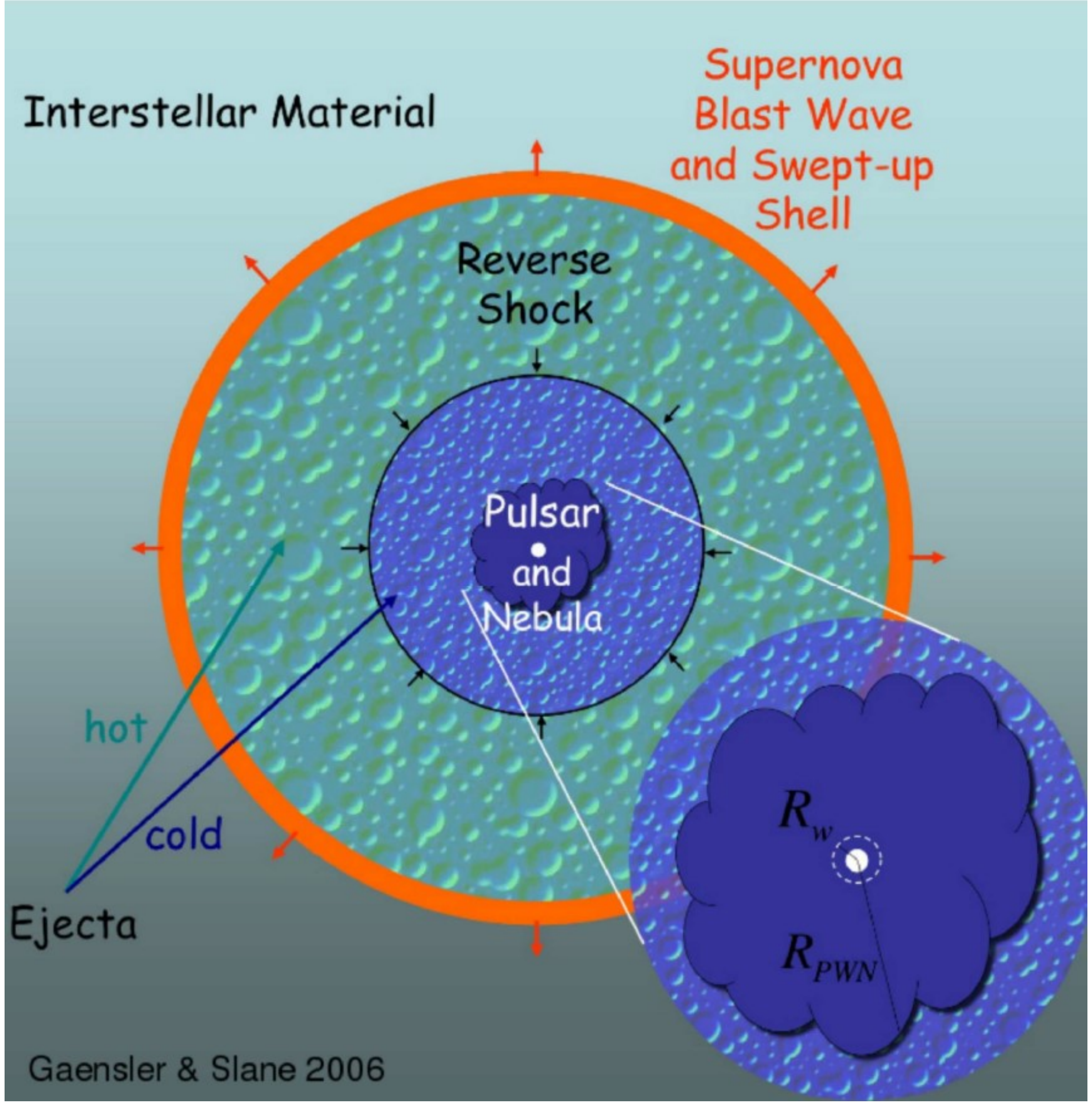
Pulsar Wind Nebulae



Gaensler & Slane 2006

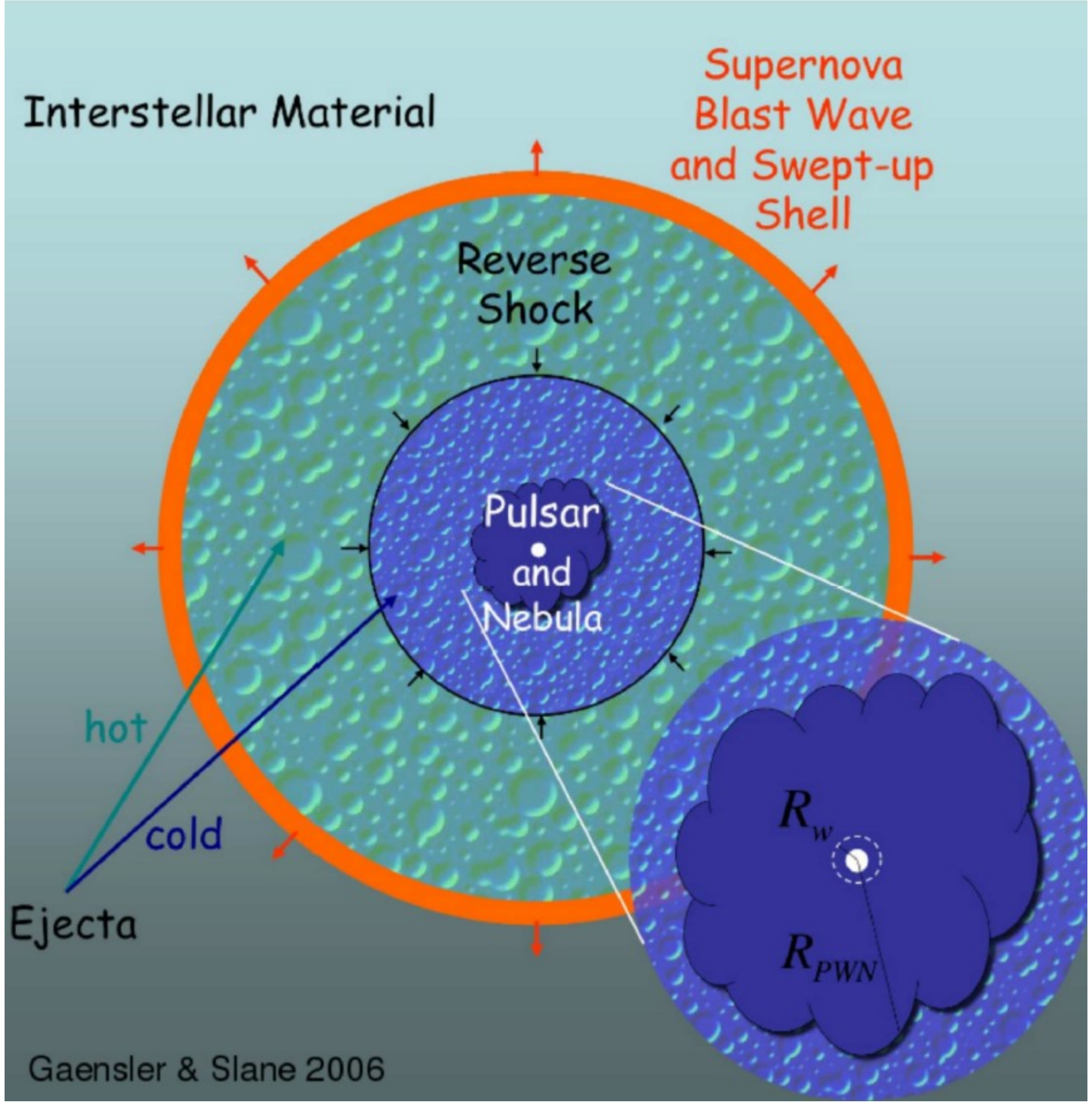
- pulsar produces a steady wind of magnetic field and relativistic particles
- a wind termination shock is formed where the wind ram pressure balances the internal pressure of the PWN

Pulsar Wind Nebulae



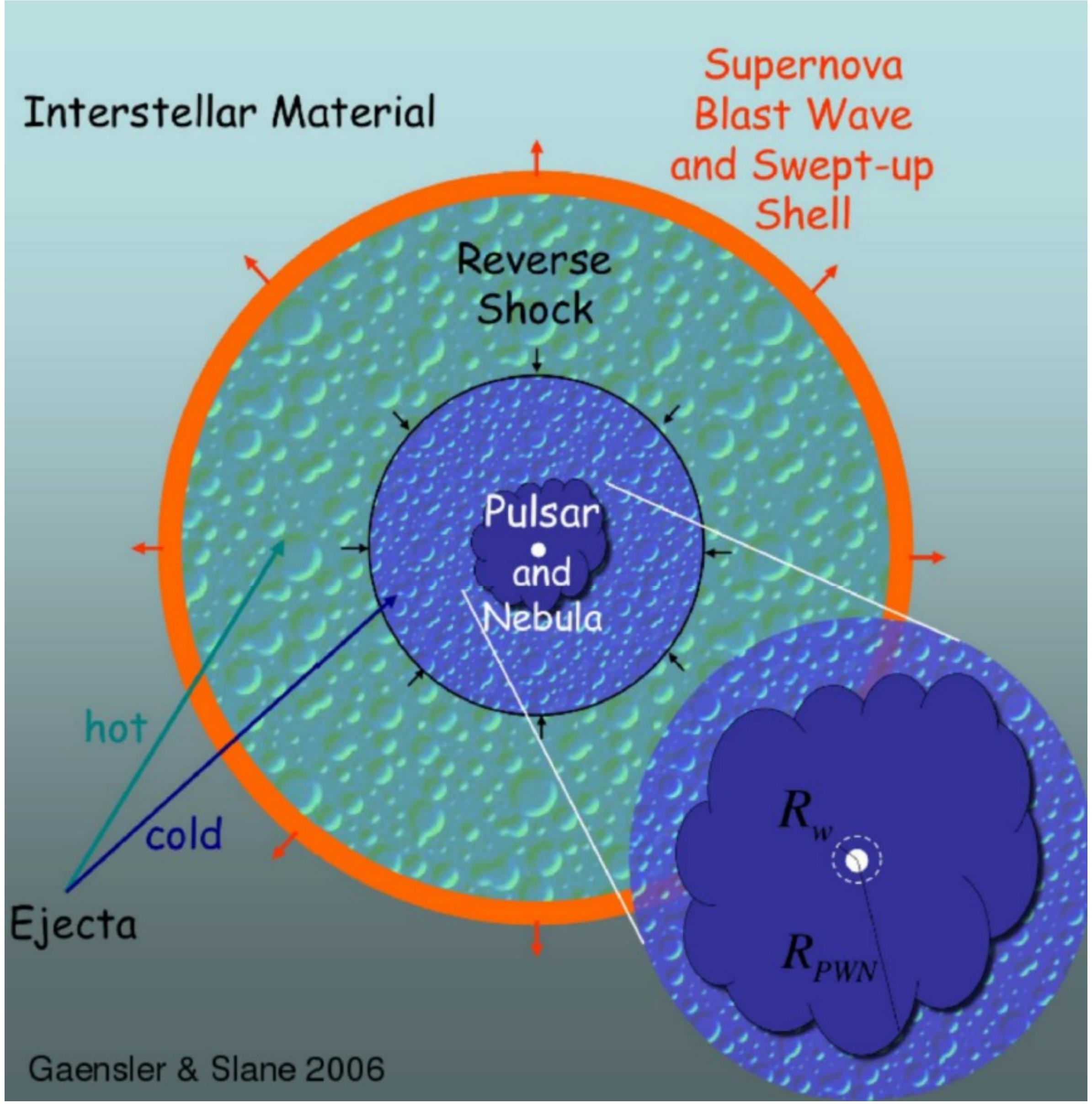
Gaensler & Slane 2006

Pulsar Wind Nebulae



- pulsar produces a steady wind of magnetic field and relativistic particles
- a wind termination shock is formed where the wind ram pressure balances the internal pressure of the PWN
- relativistic particles are decelerated in the magnetic field producing synchrotron emission

Pulsar Wind Nebulae



Gaensler & Slane 2006

- Energy loss rate (spin down luminosity) is typically found between 10^{28} and 4.5 x 10^{38} erg/s
- More than 10^{36} erg/s needed to produce a prominent radio PWN (Gotthelf, 2004)

PWN Evolution

$\dot{E} = 10^{37}$ erg/s

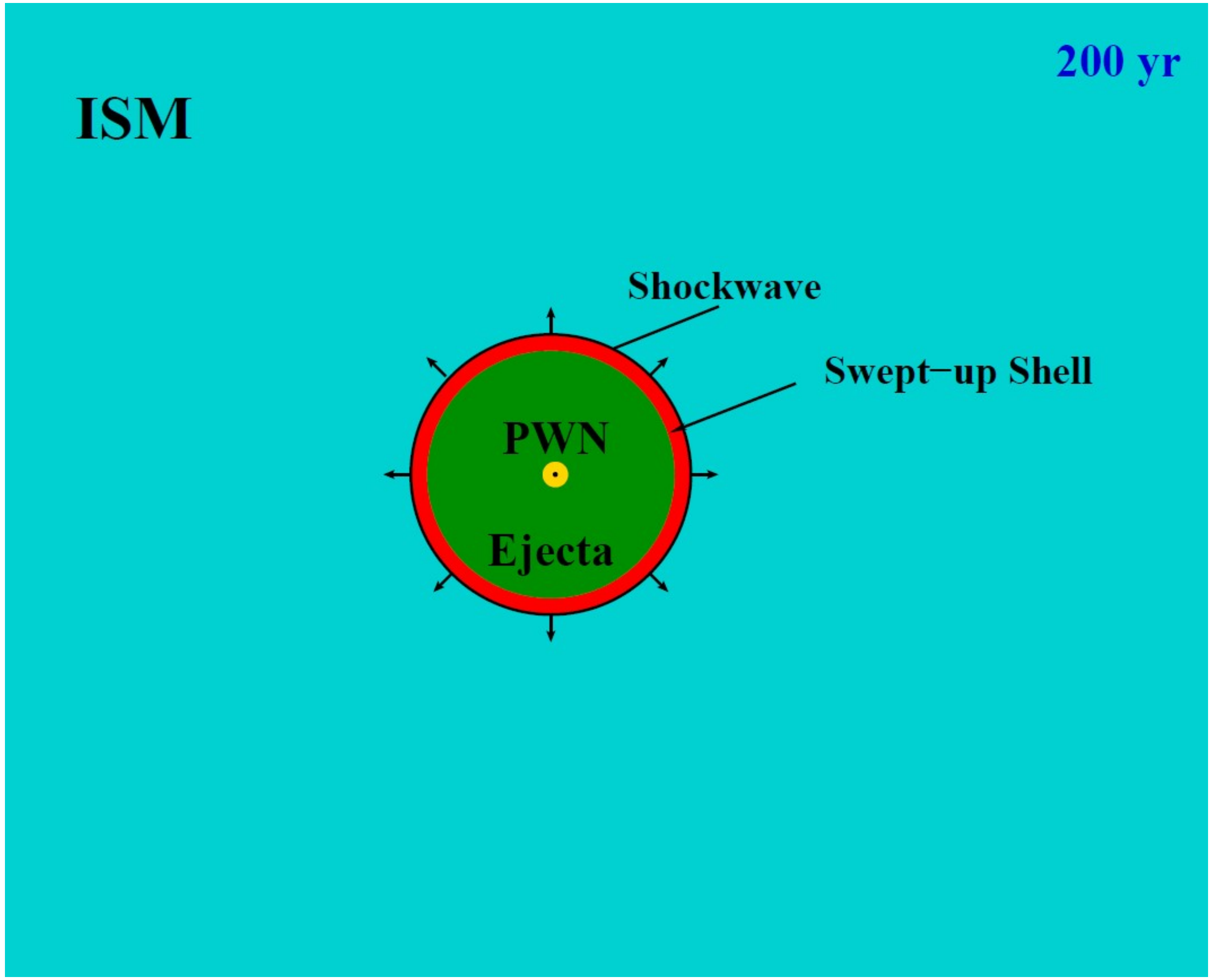
$E_0 = 10^{51}$ erg

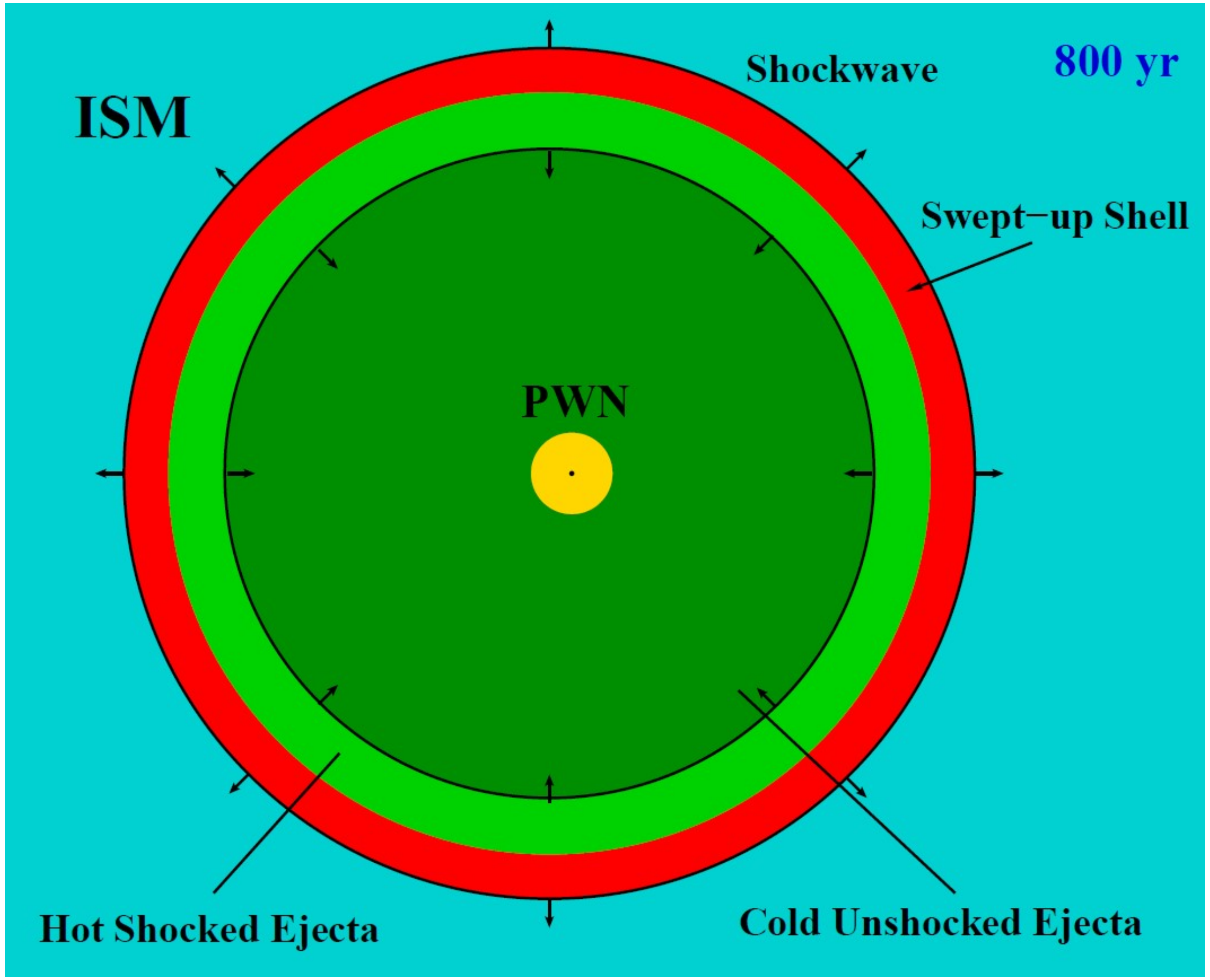
$M_0 = 5\ M_\odot$

$n_0 = 1\ \mathrm{cm}^{-3}$

$v_{PSR} = 227$ km/s

PWN Evolution





Crab Nebula

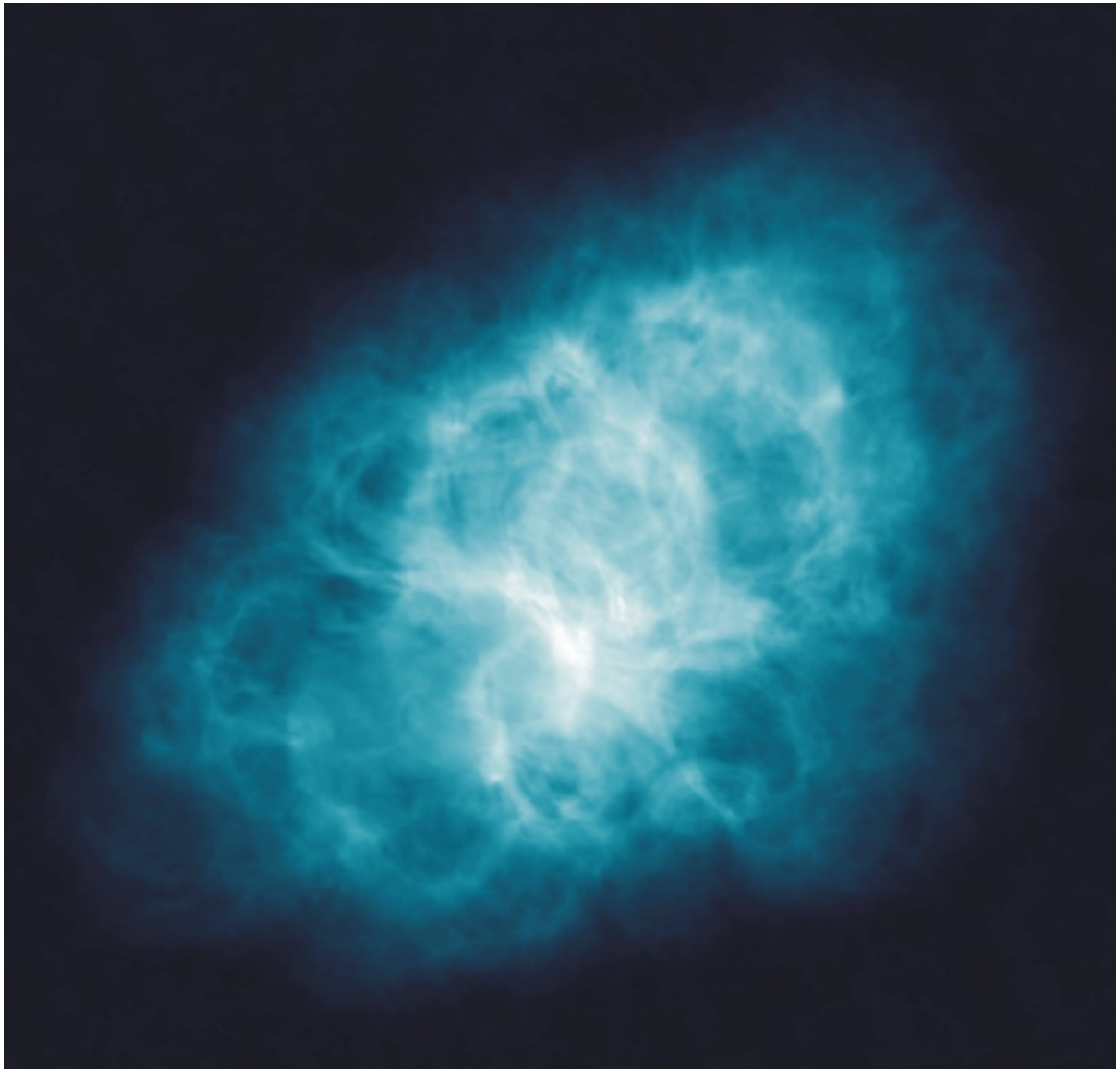
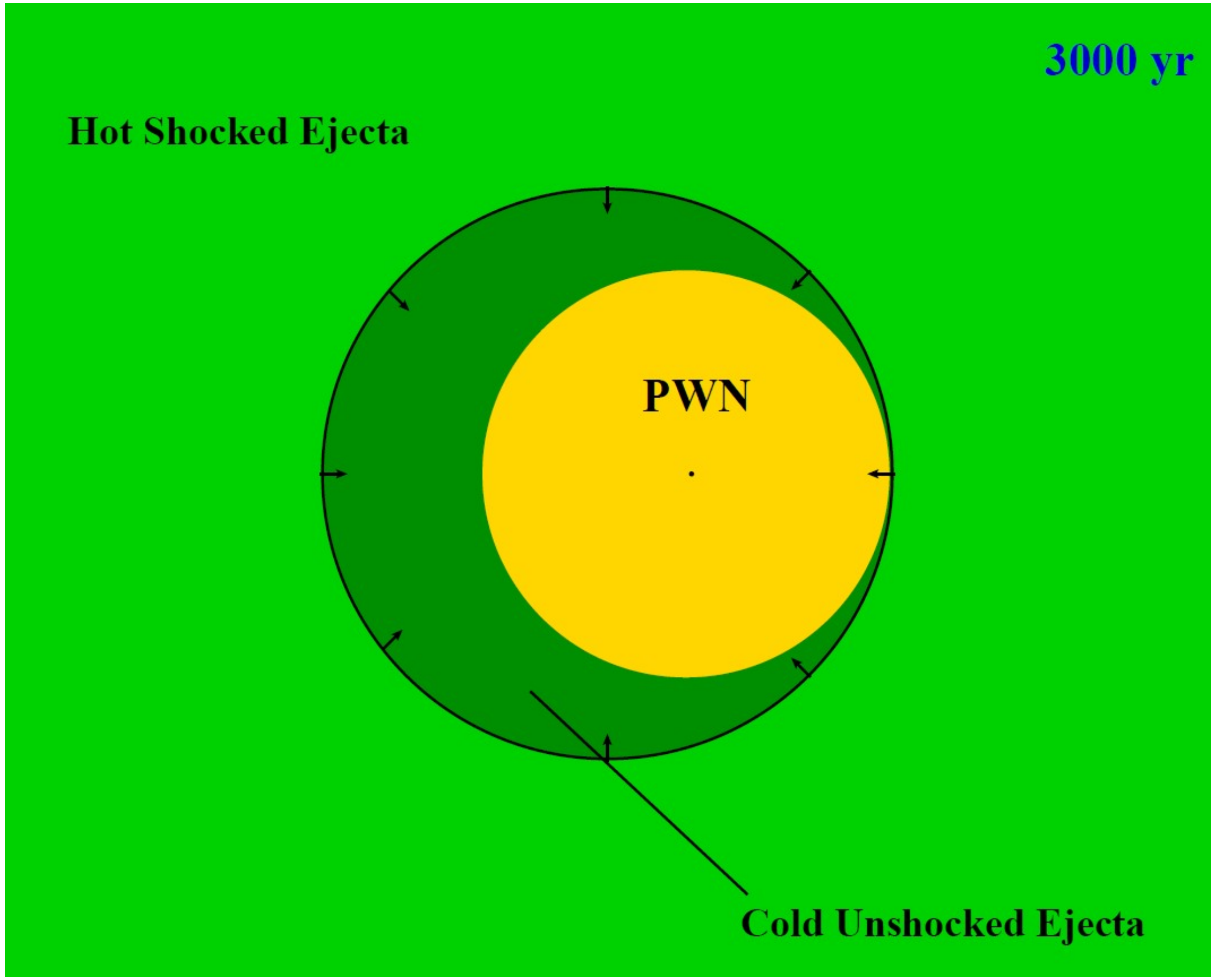


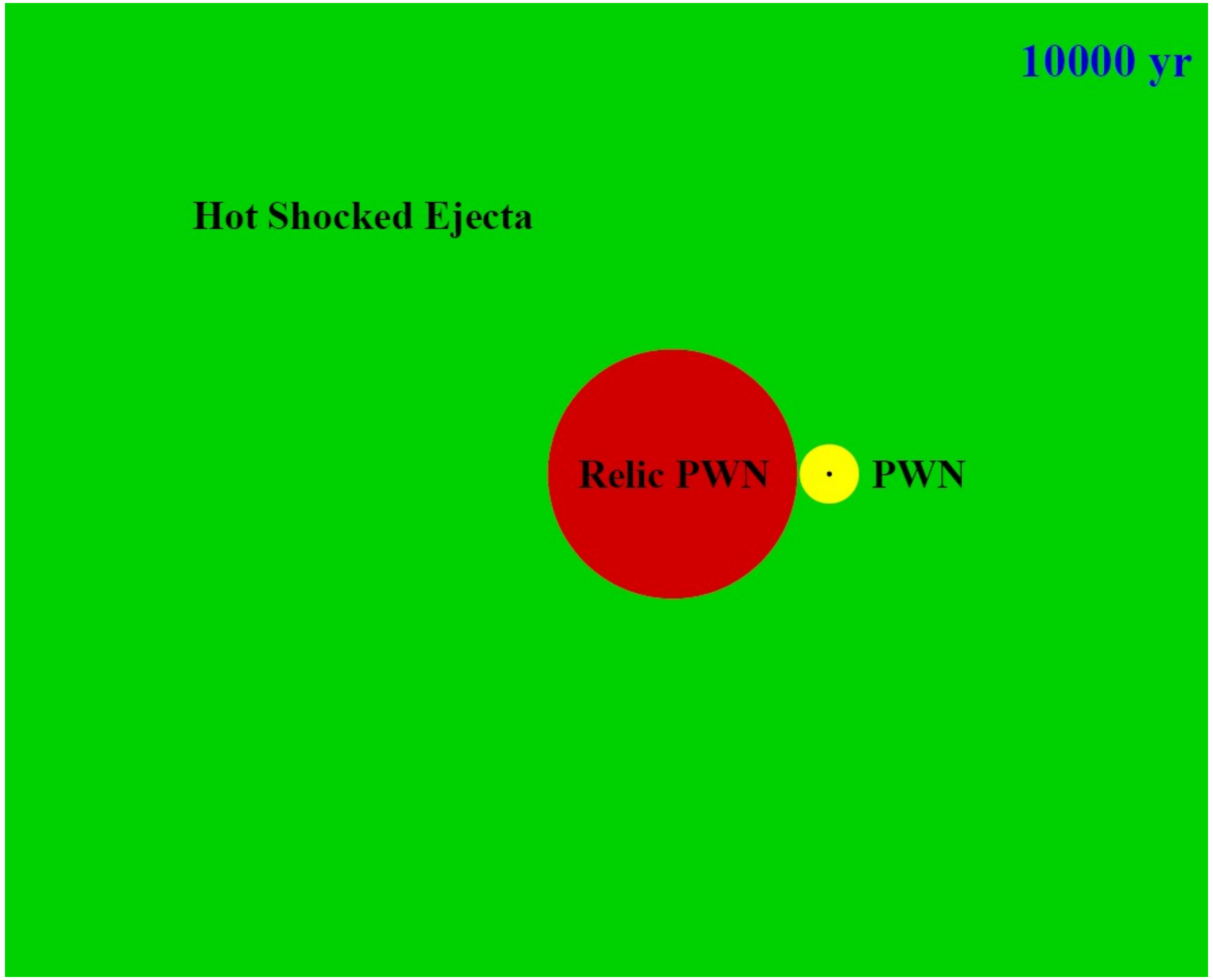
Image courtesy of
NRAO and M. Bietenholz

3C58

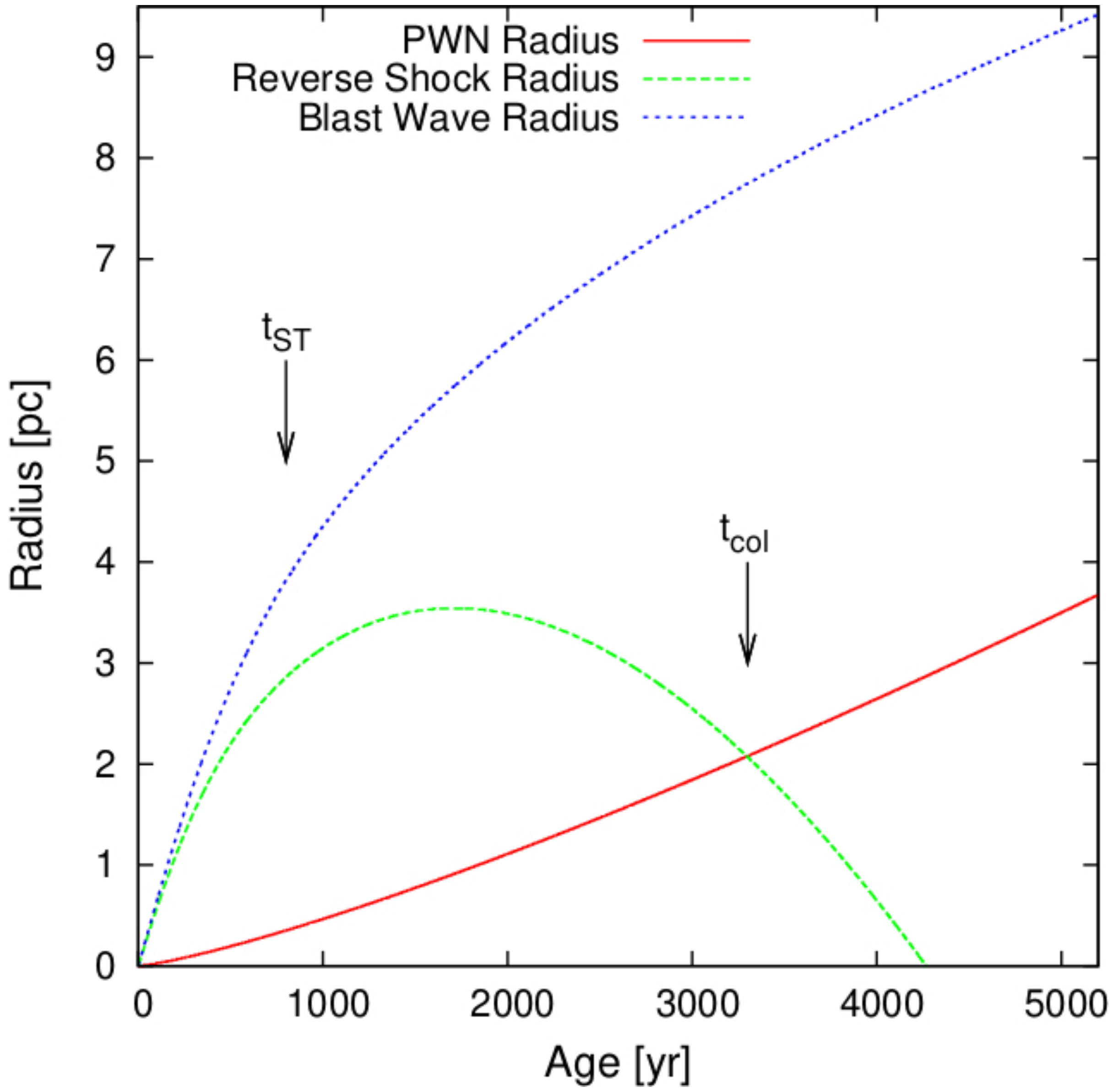
Bietenholz (2006)

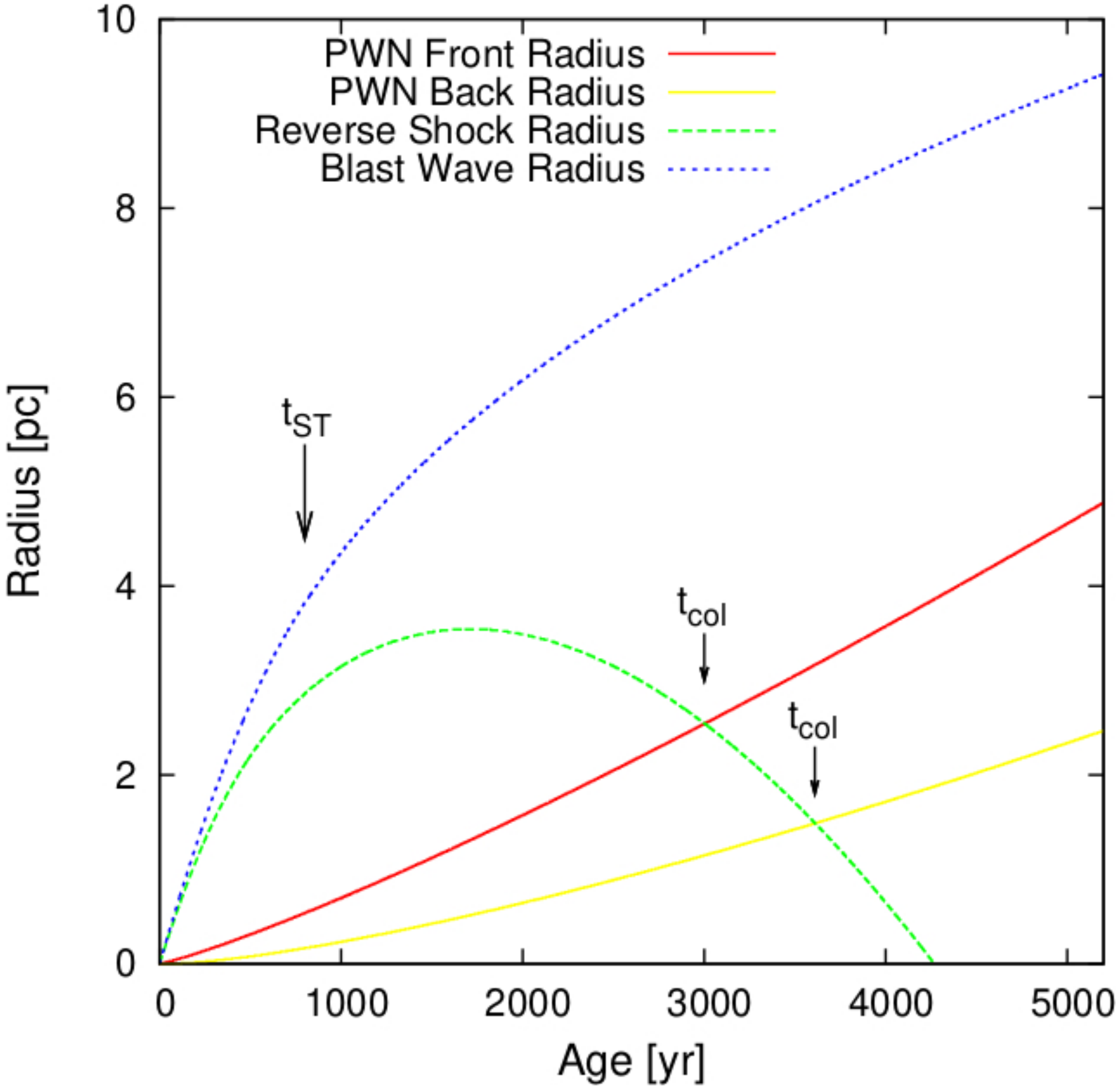
PWN Evolution





PWN Evolution

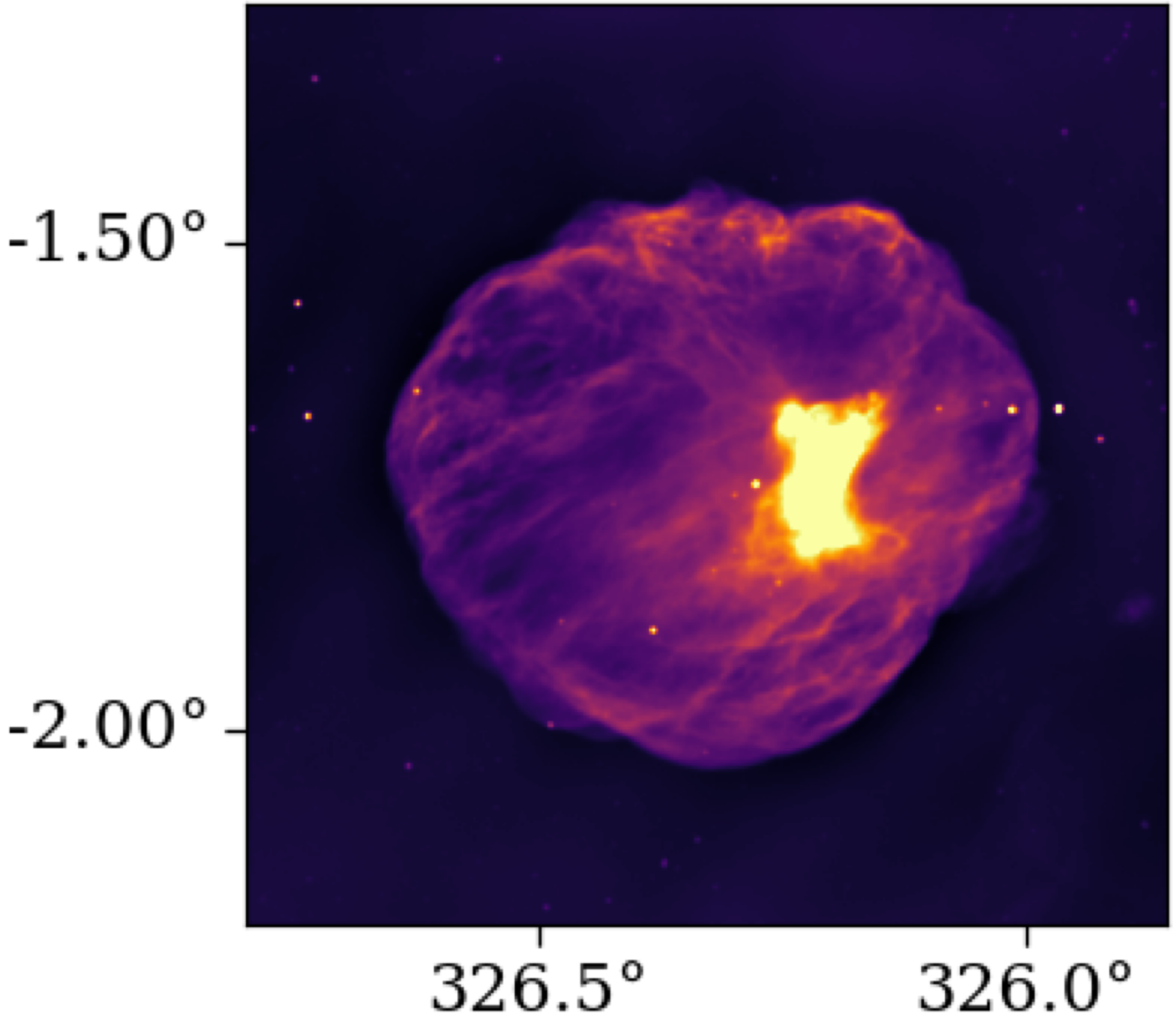




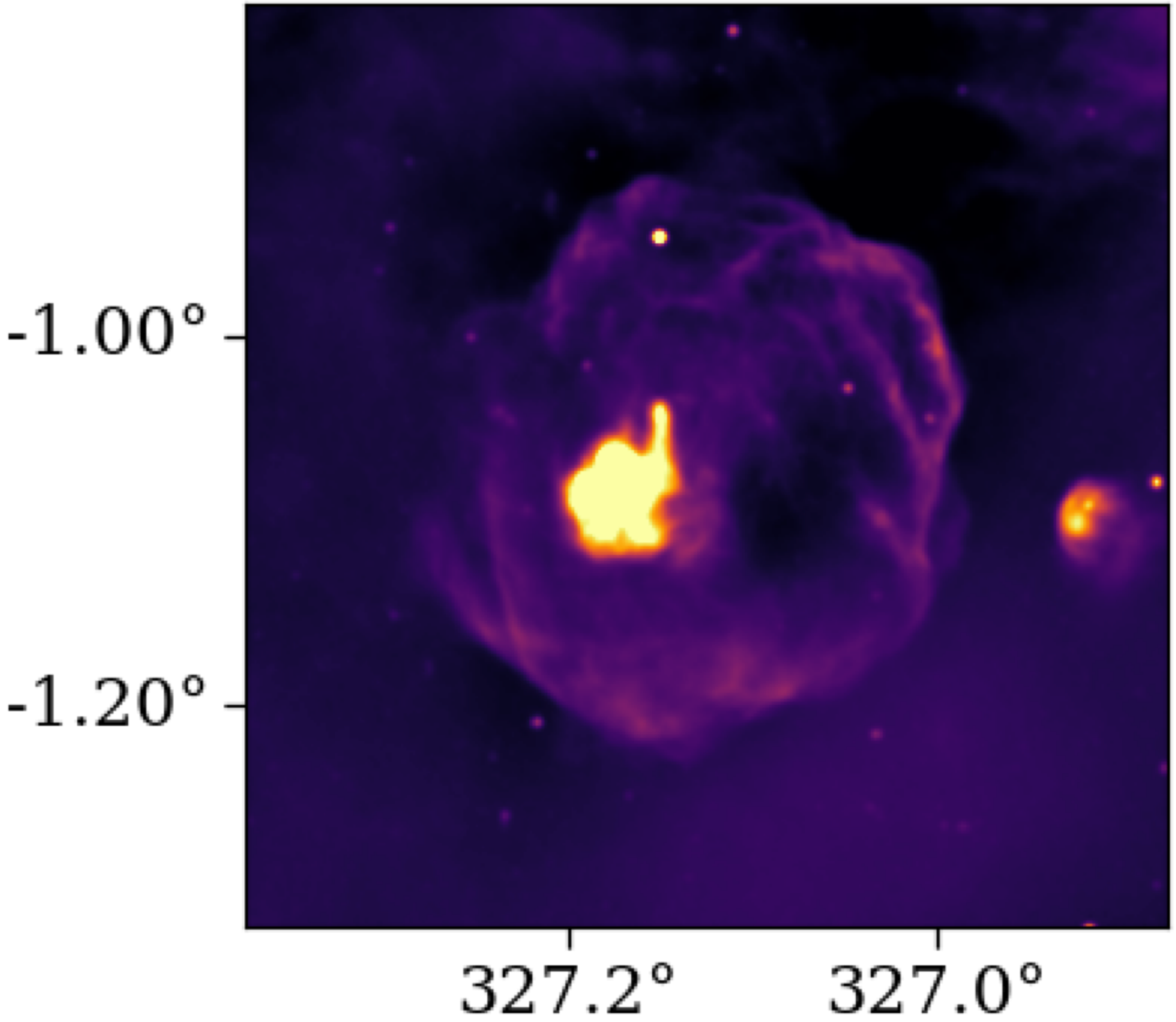
PWN Evolution

Ball et al., 2023:

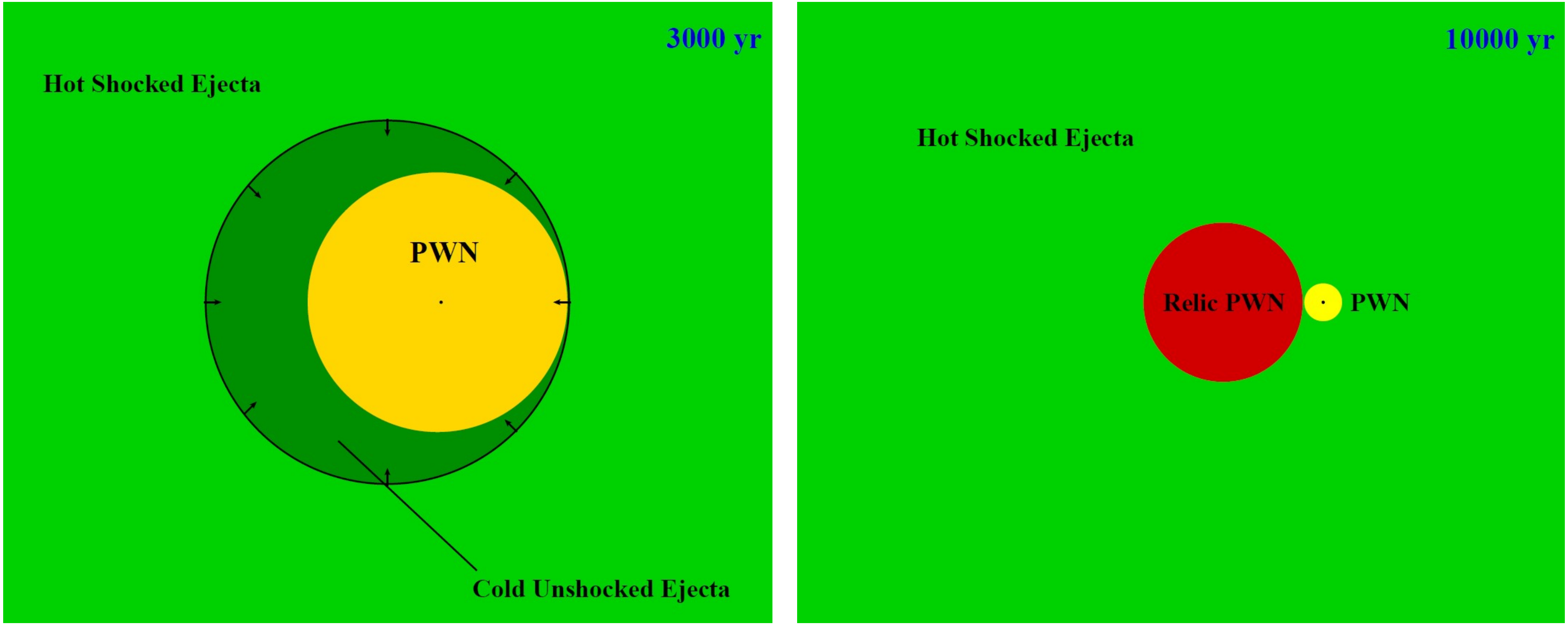
G326.3−1.8



G327.1−1.1

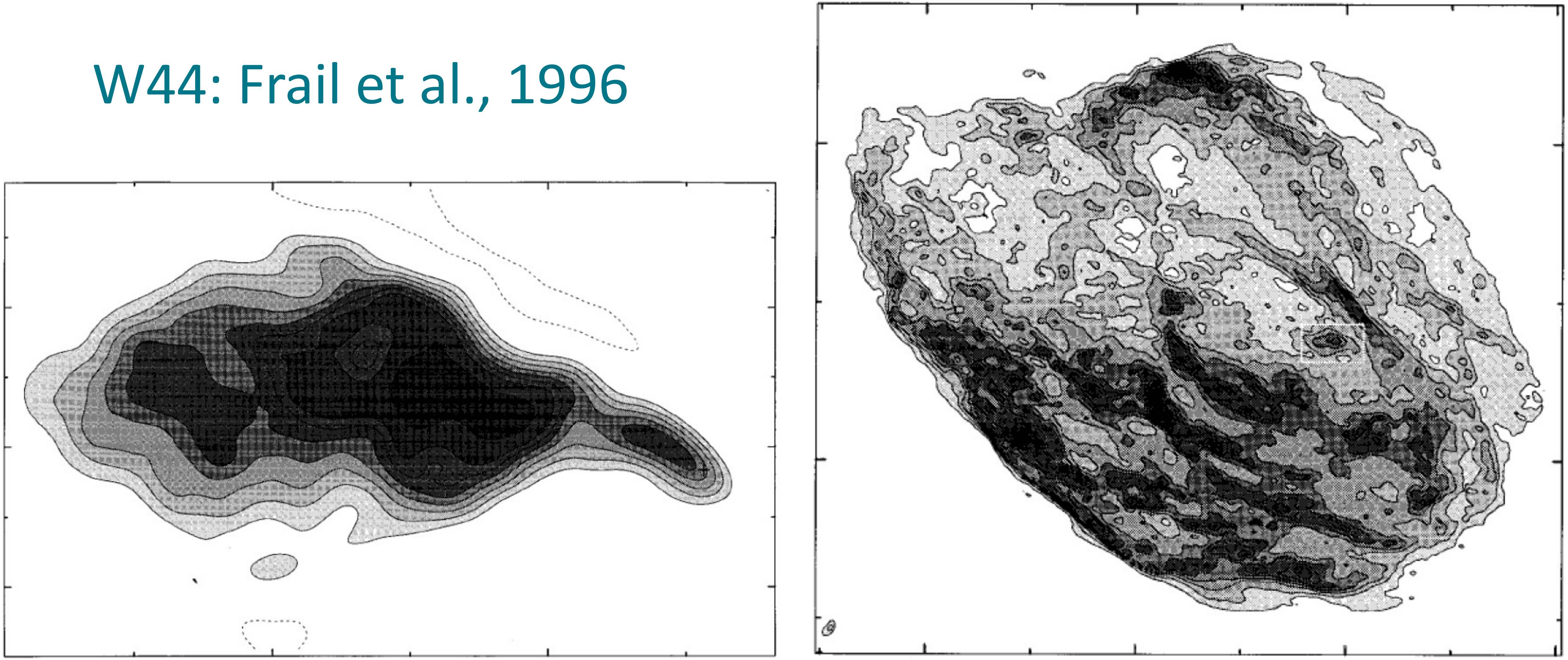


PWN Evolution



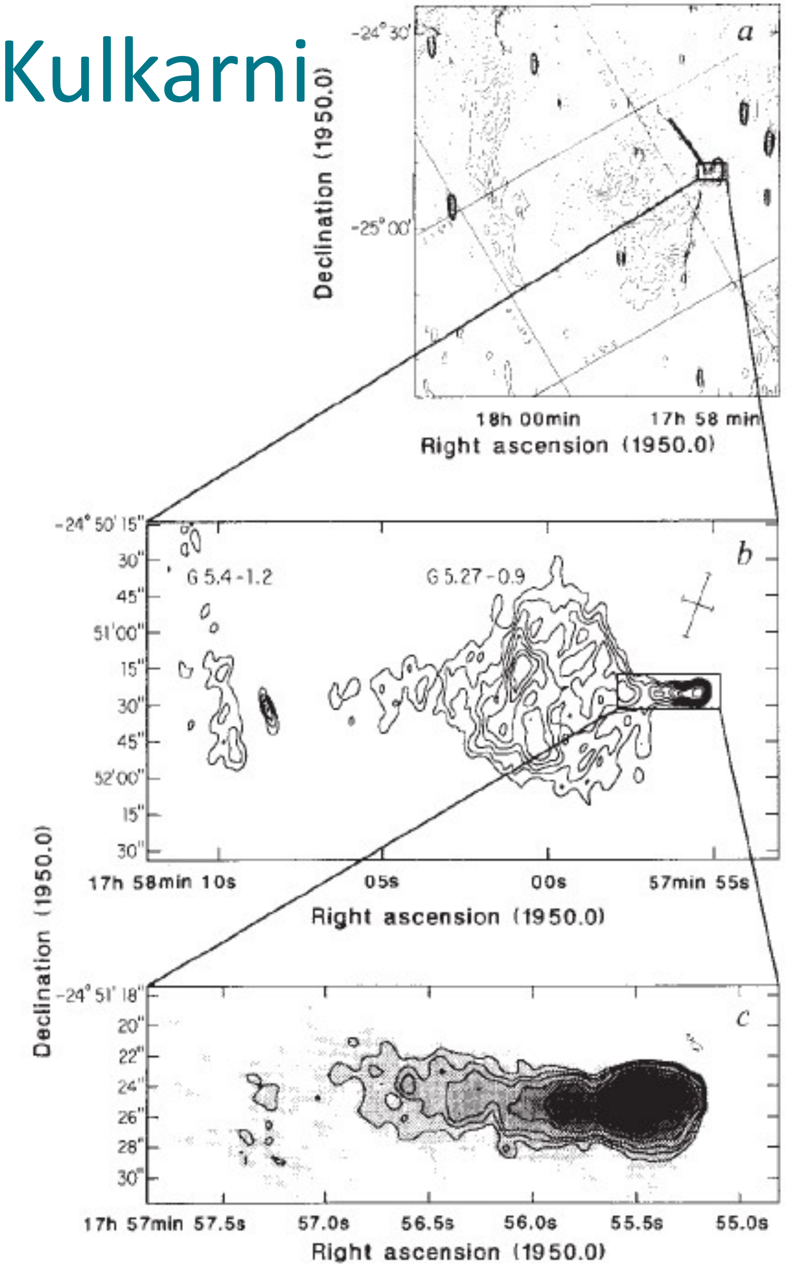
PWN Evolution

W44: Frail et al., 1996

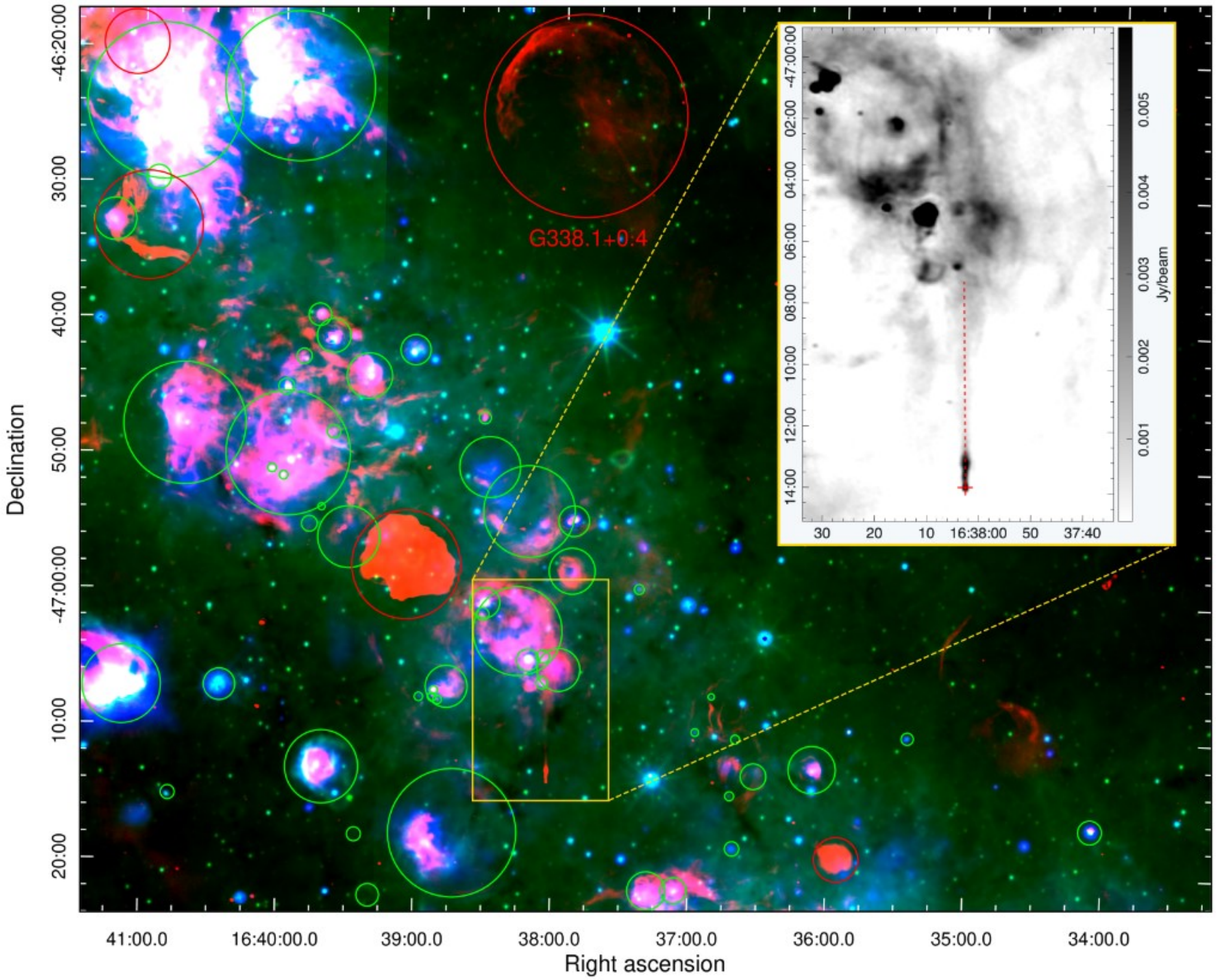


PWN Evolution

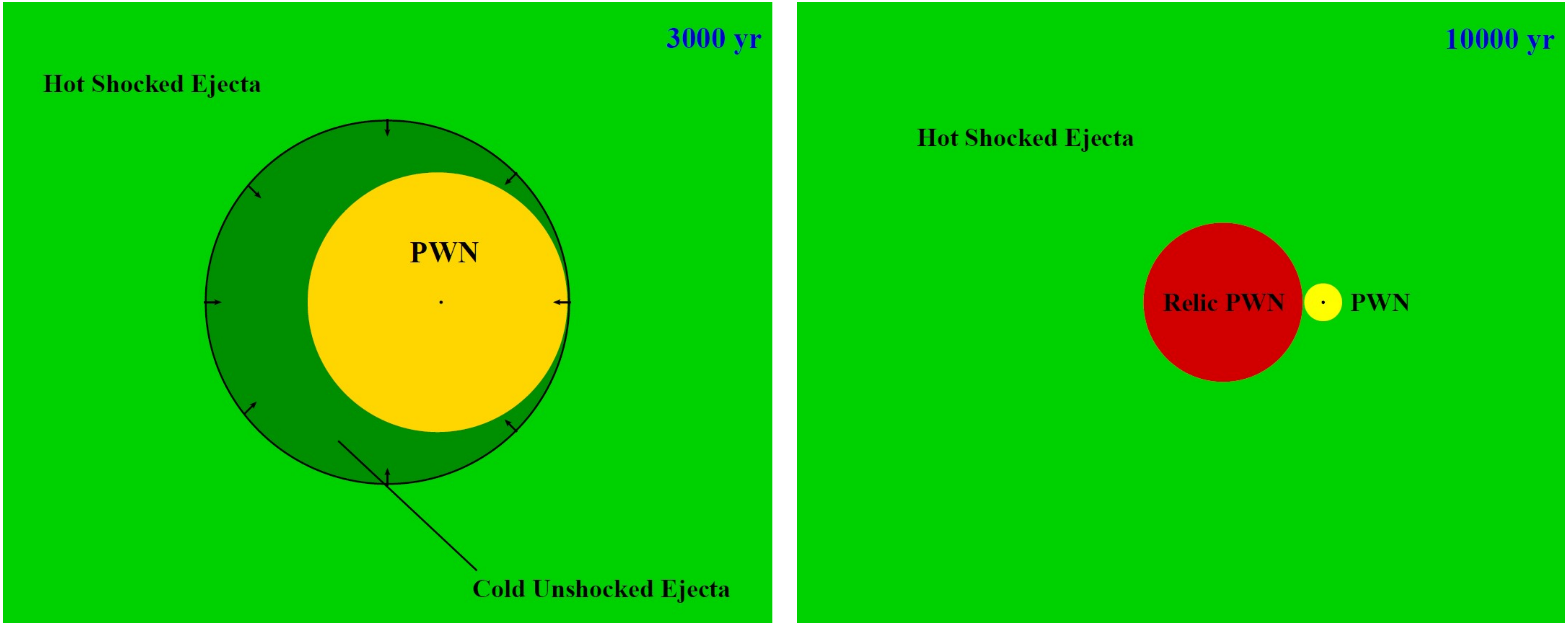
Frail & Kulkarni
1991



Lazarević et al., 2023

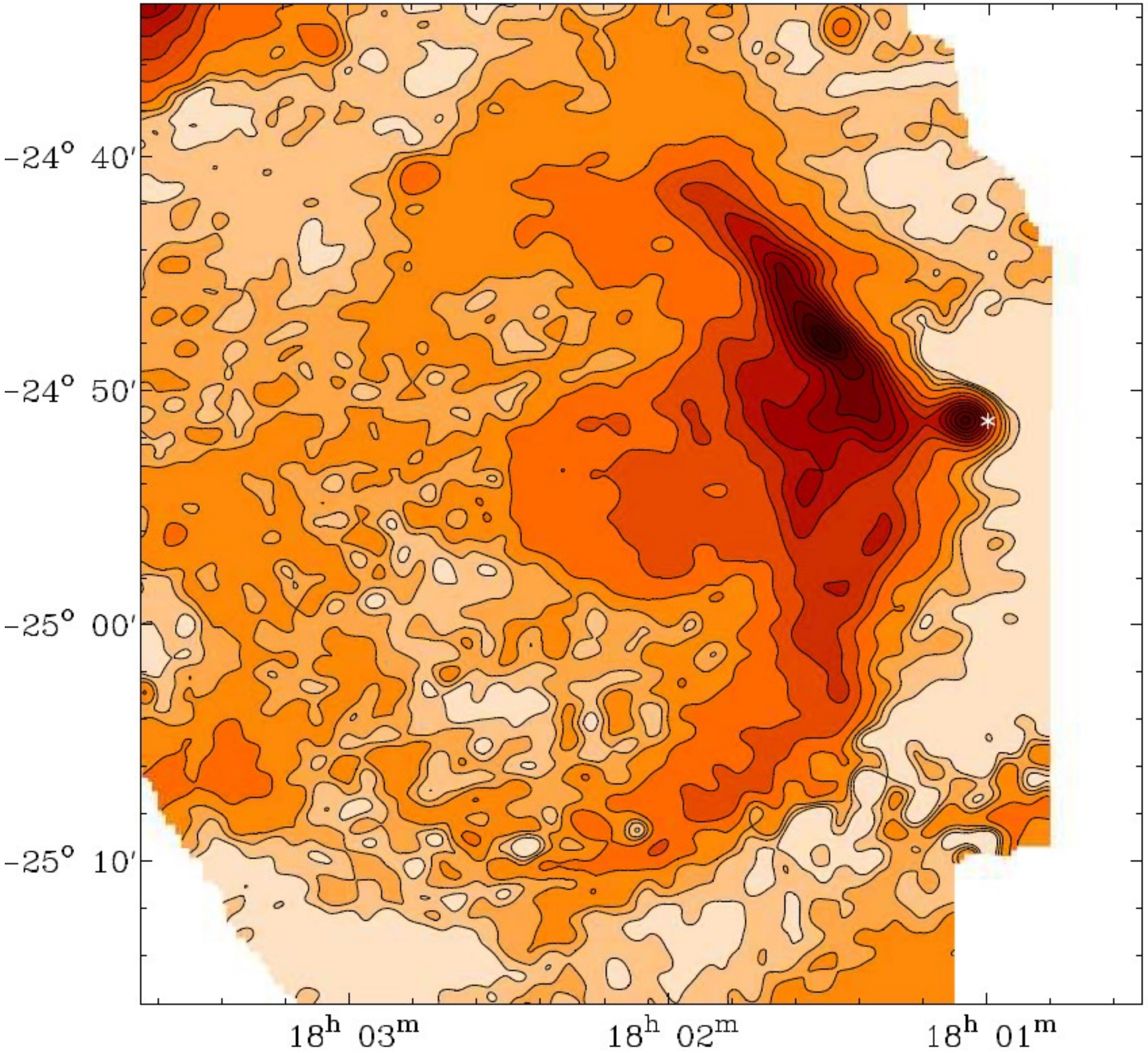


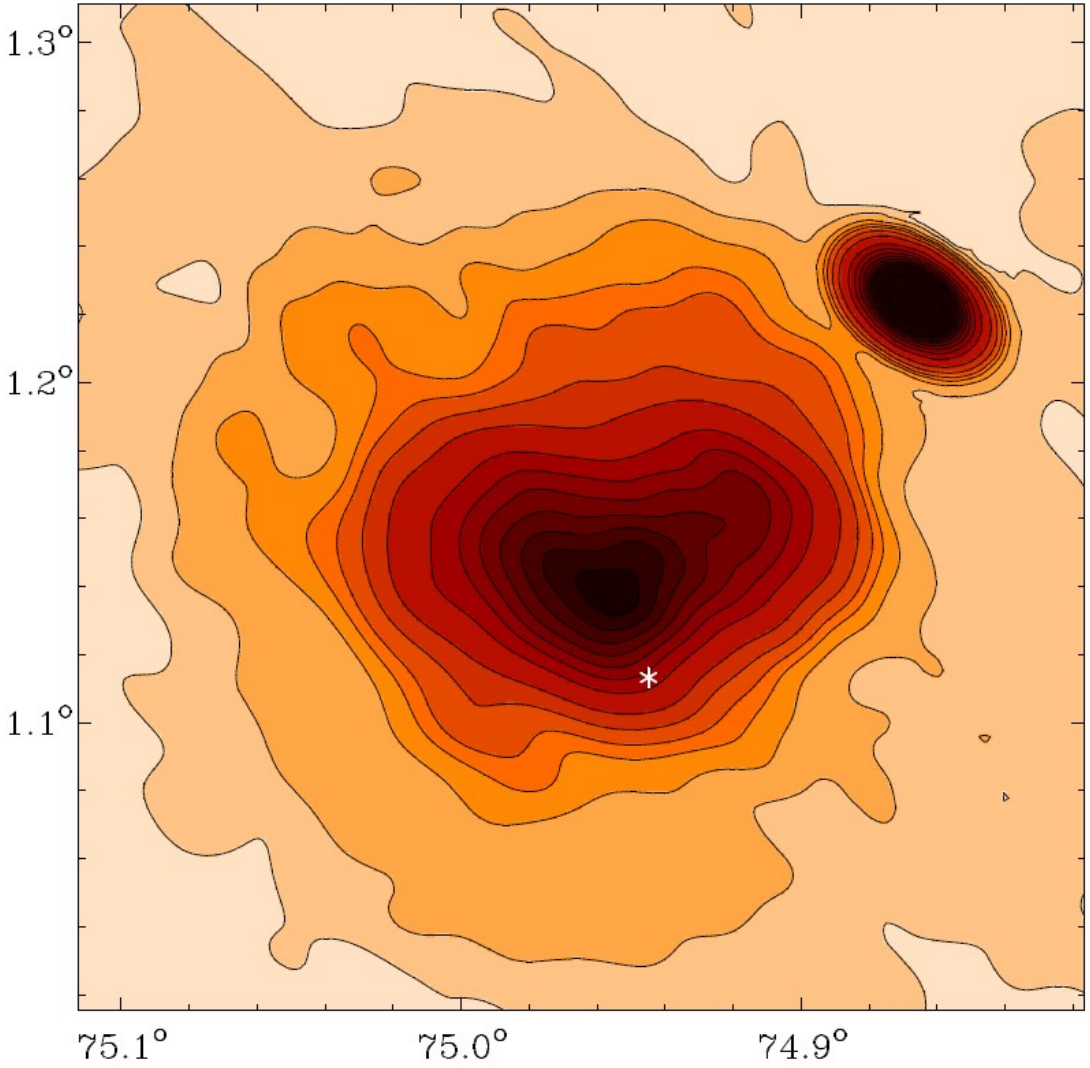
PWN Evolution



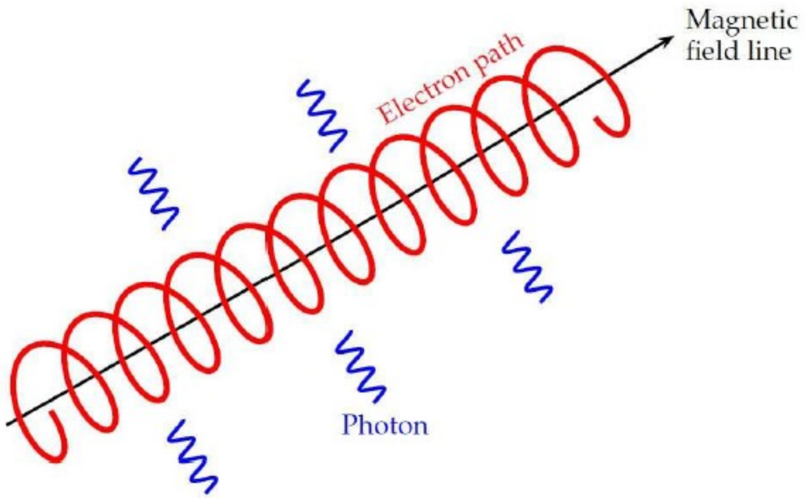
PWN Evolution

Kothes et al., 1998, 2020 CTB87 Pulsar: Qian-Cheng Liu et al. 2024





PWN Synchrotron Emission



e⁻ spectrum: $\mathrm{N(E)dE} \sim \mathrm{E}^{-\delta}\,\mathrm{dE}$

$\mathrm{N(E)dE}$: electrons in the energy range E:E+dE

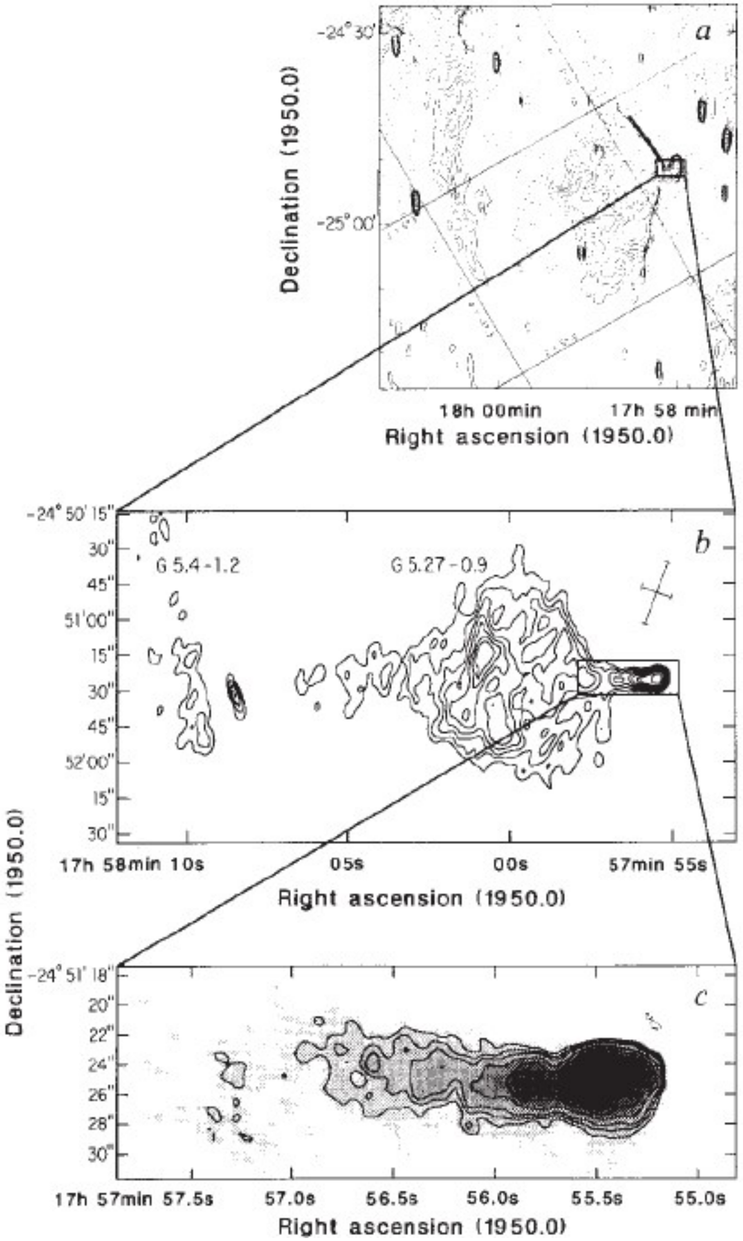
flux density: $\mathrm{S}_\nu \sim \mathrm{B}_\perp{}^{\frac{1}{2}(\delta+1)}\,\nu^{-\frac{1}{2}(\delta-1)}$

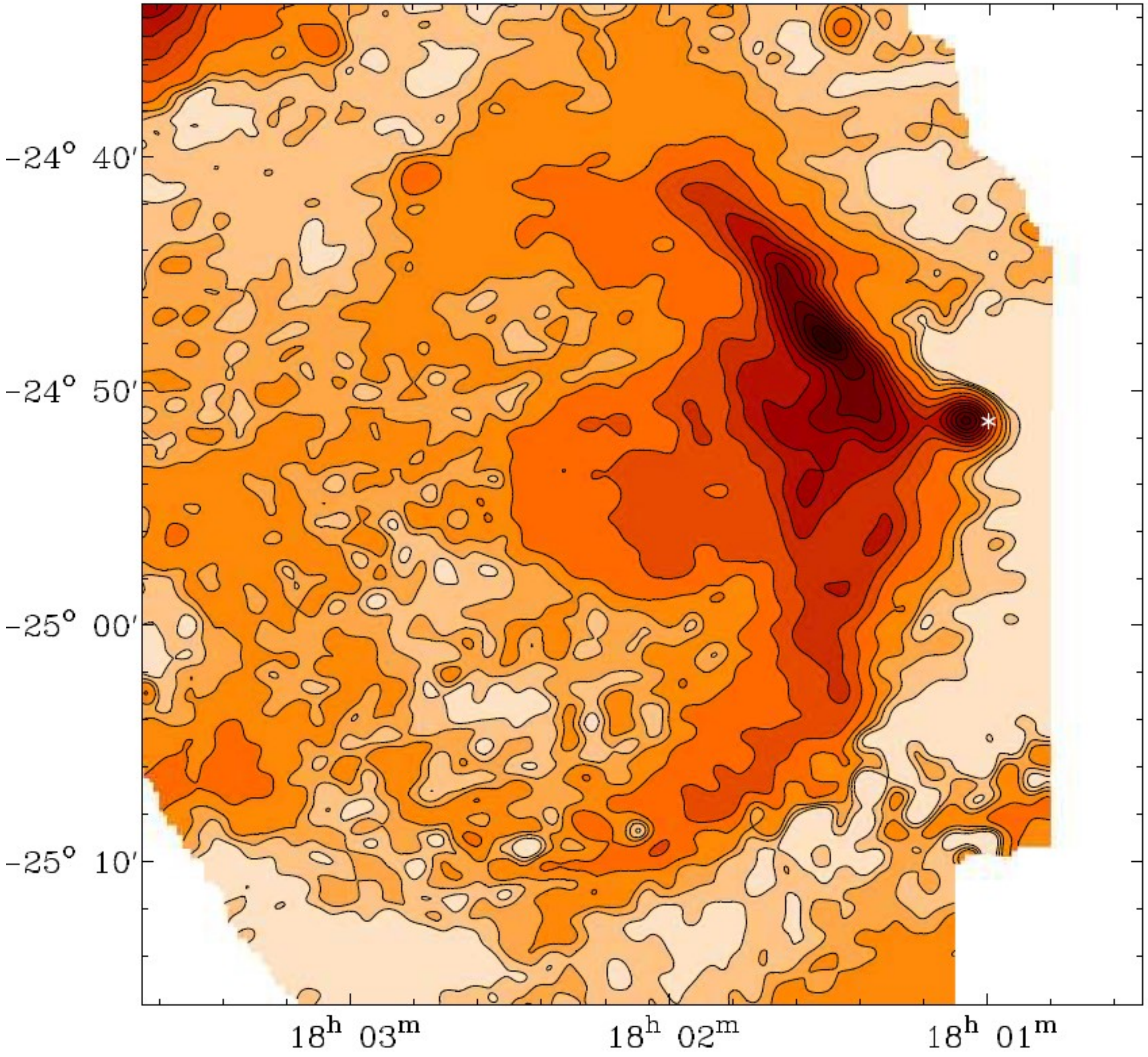
B: magnetic field, ν: frequency, $\alpha := \frac{1}{2}(\delta - 1)$: spectral index

aging (Chevalier, 2000): $\nu_c[\mathrm{GHz}] = 1.187\,B^{-3}[\mathrm{G}]\,t^{-2}[\mathrm{yr}]$

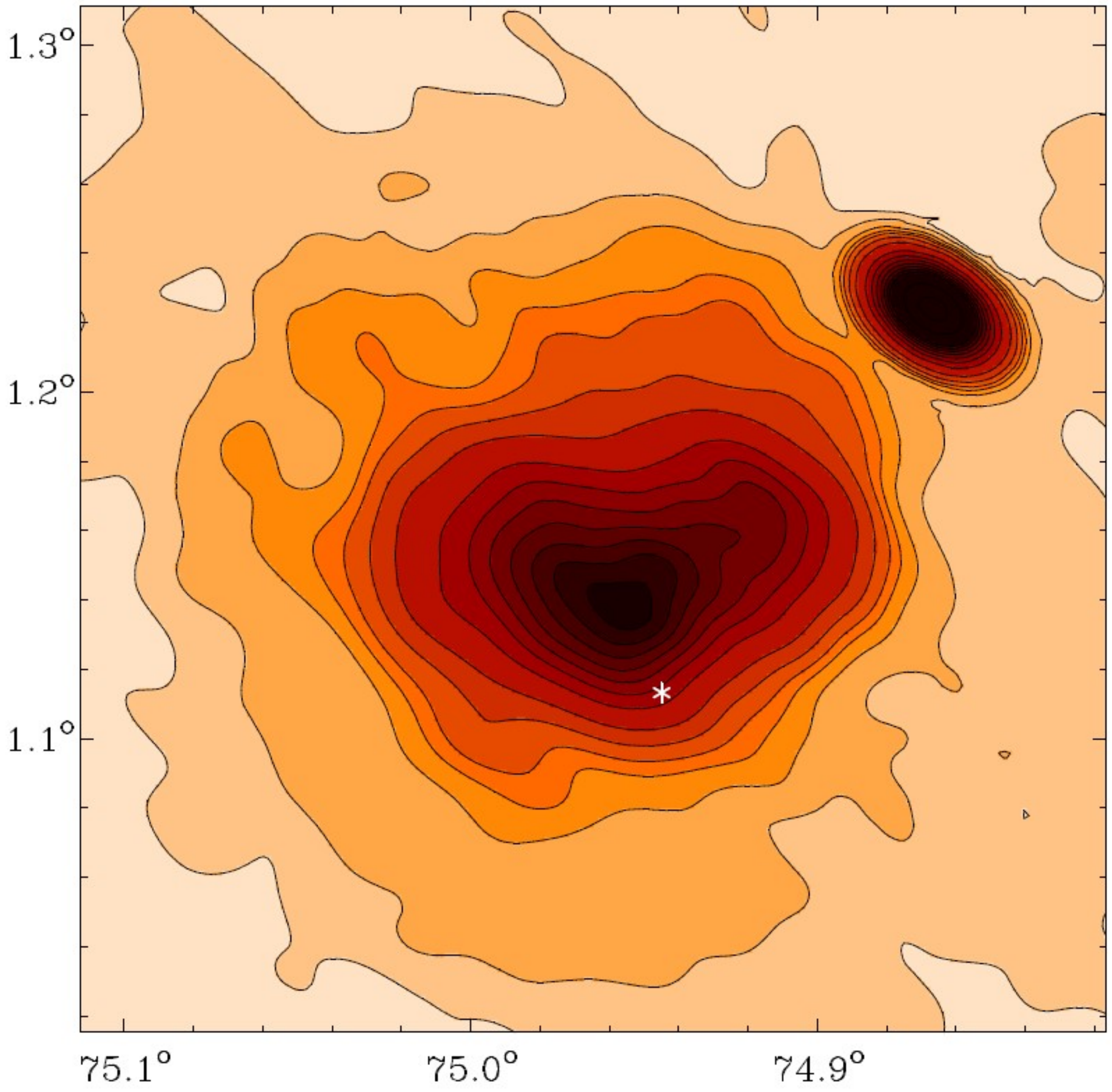
ν_c: break frequency with $\Delta\alpha \approx 0.5$, t: age

PWN Spectra

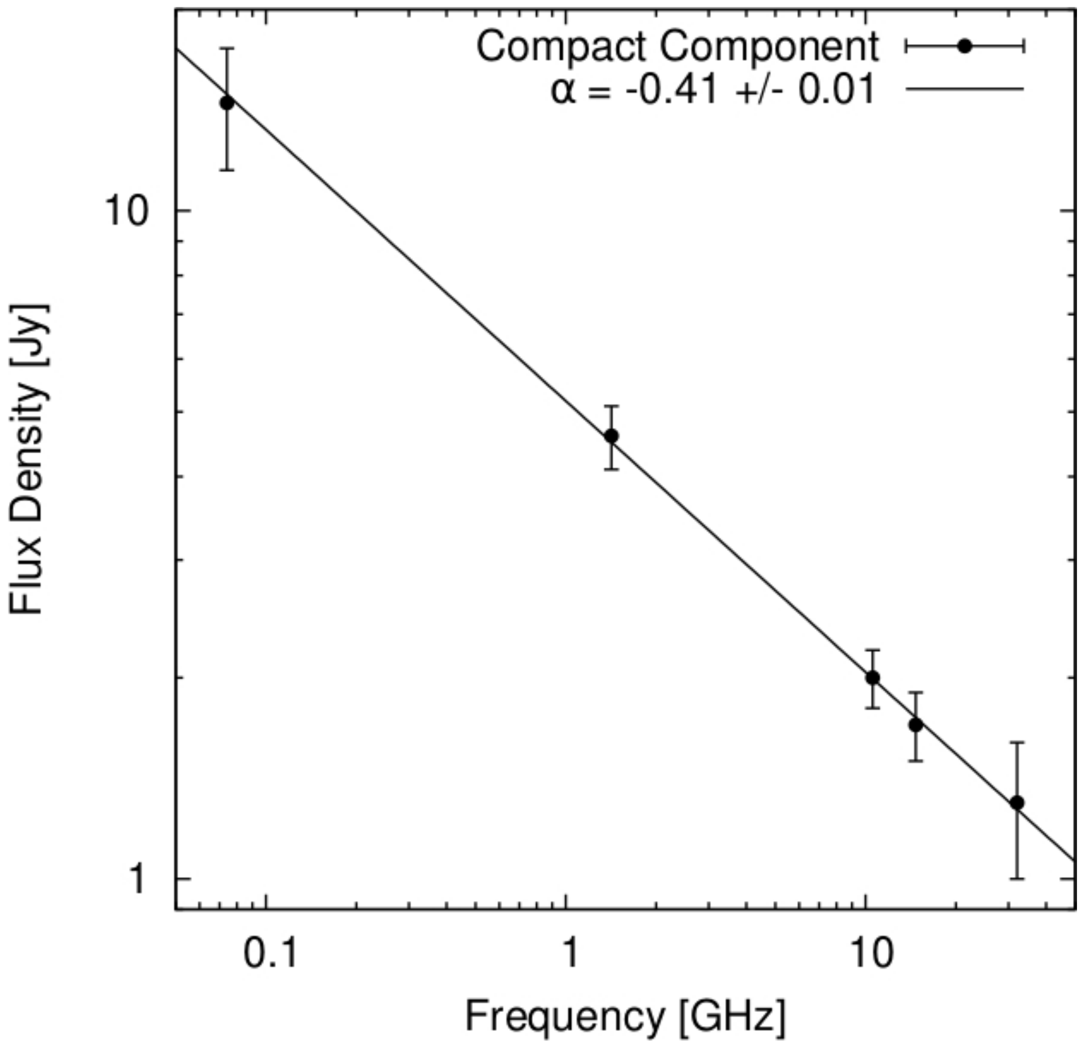

a
-24°30'
-25°00'
Declination (1950.0)
18h 00min
17h 58 min
Right ascension (1950.0)
b
-24°50'15"
30"
45"
51'00"
15"
30"
45"
52'00"
15"
30"
G 5.4-1.2
G 5.27-0.9
17h 58min 10s
05s
00s
57min 55s
Right ascension (1950.0)
Declination (1950.0)
c
-24°51'18"
20"
22"
24"
26"
28"
30"
17h 57min 57.5s
57.0s
56.5s
56.0s
55.5s
55.0s
Right ascension (1950.0)


-24° 40′
-24° 50′
-25° 00′
-25° 10′
18h 03m
18h 02m
18h 01m

PWN Spectra

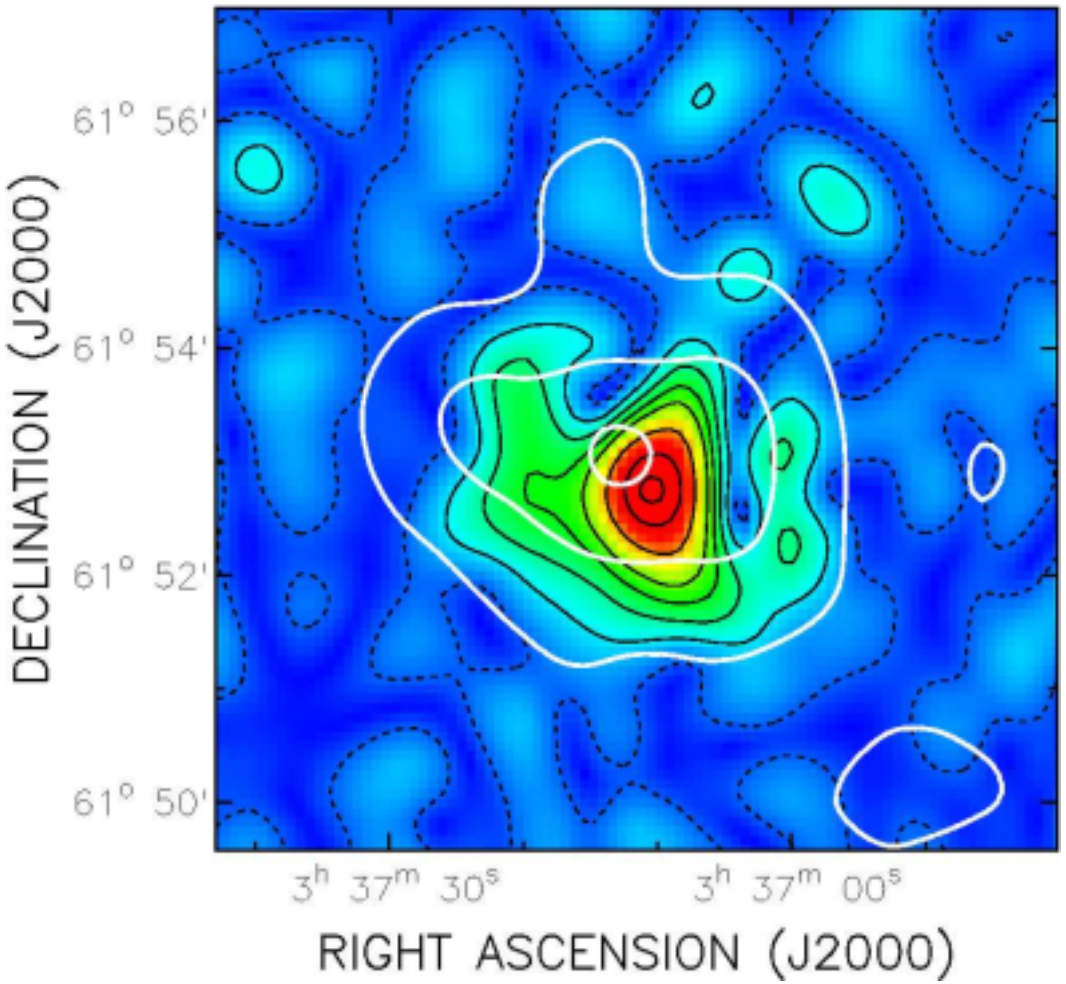


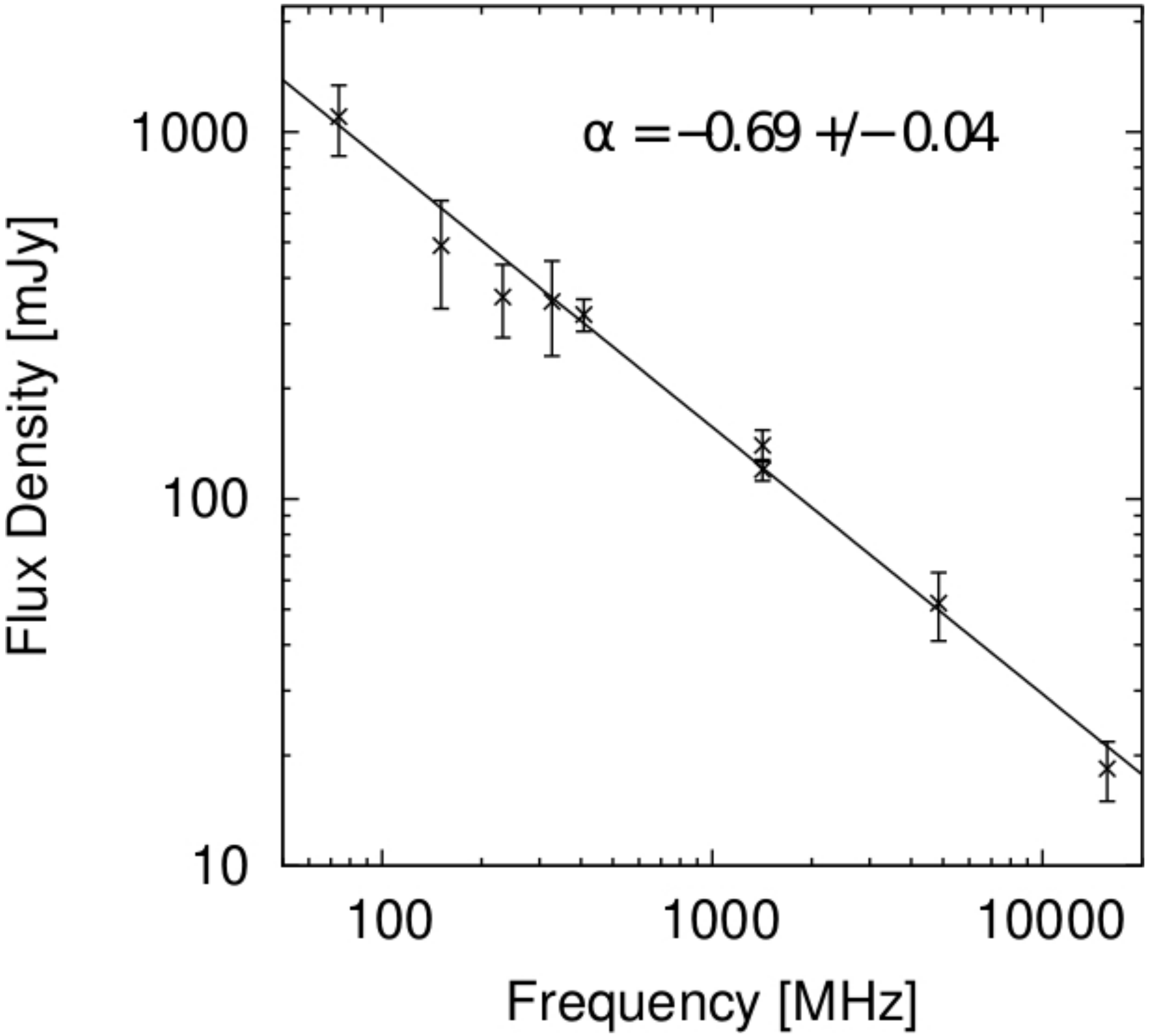
Kothes et al., 2020



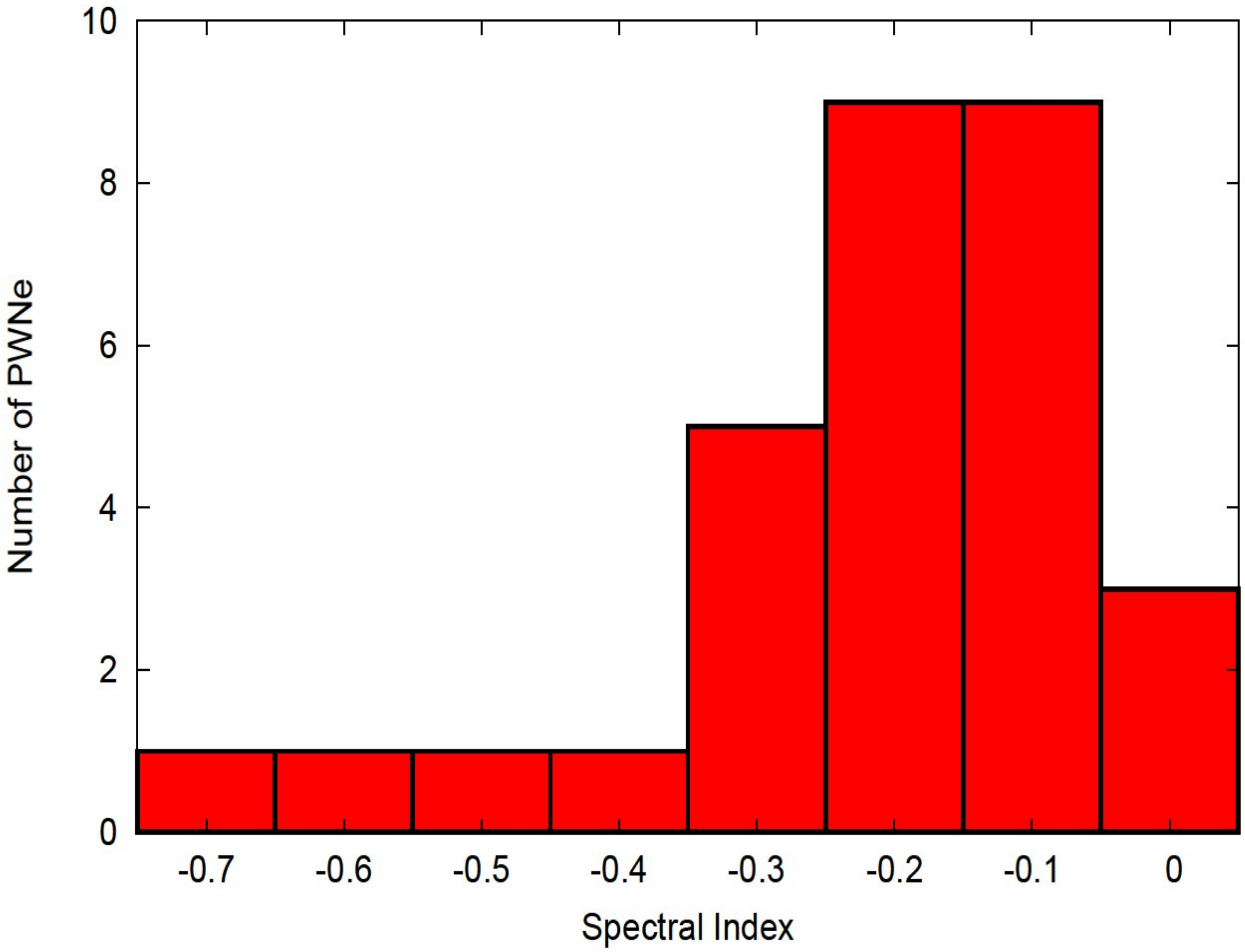
PWN Spectra

Kothes et al., 2014





PWN Spectra



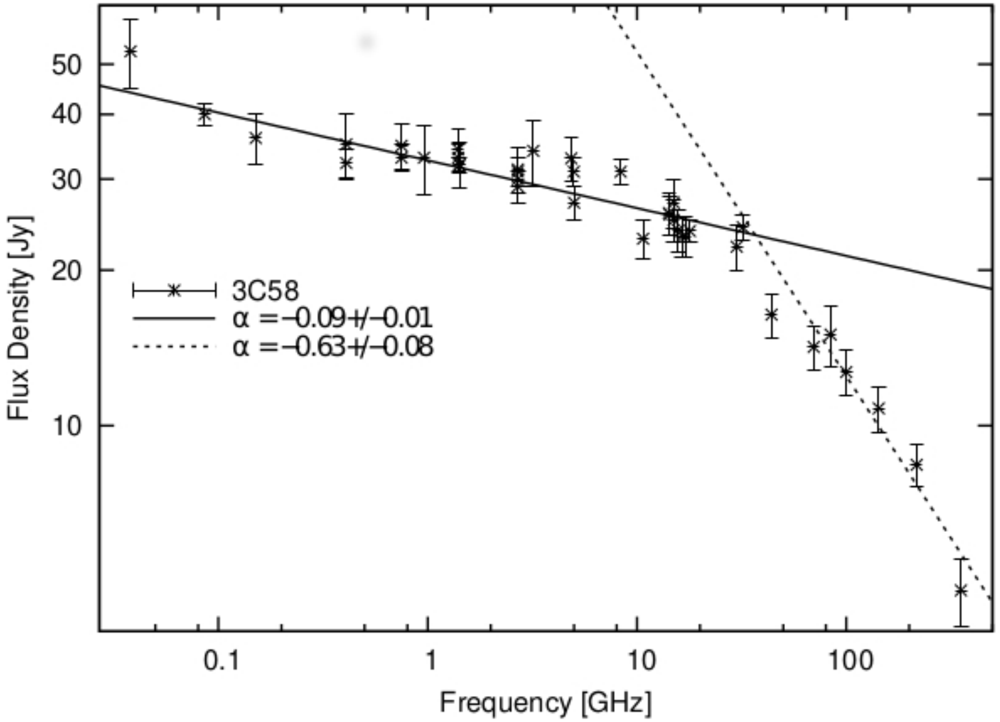
Most PWN have radio spectral indices between -0.3 and 0.0.

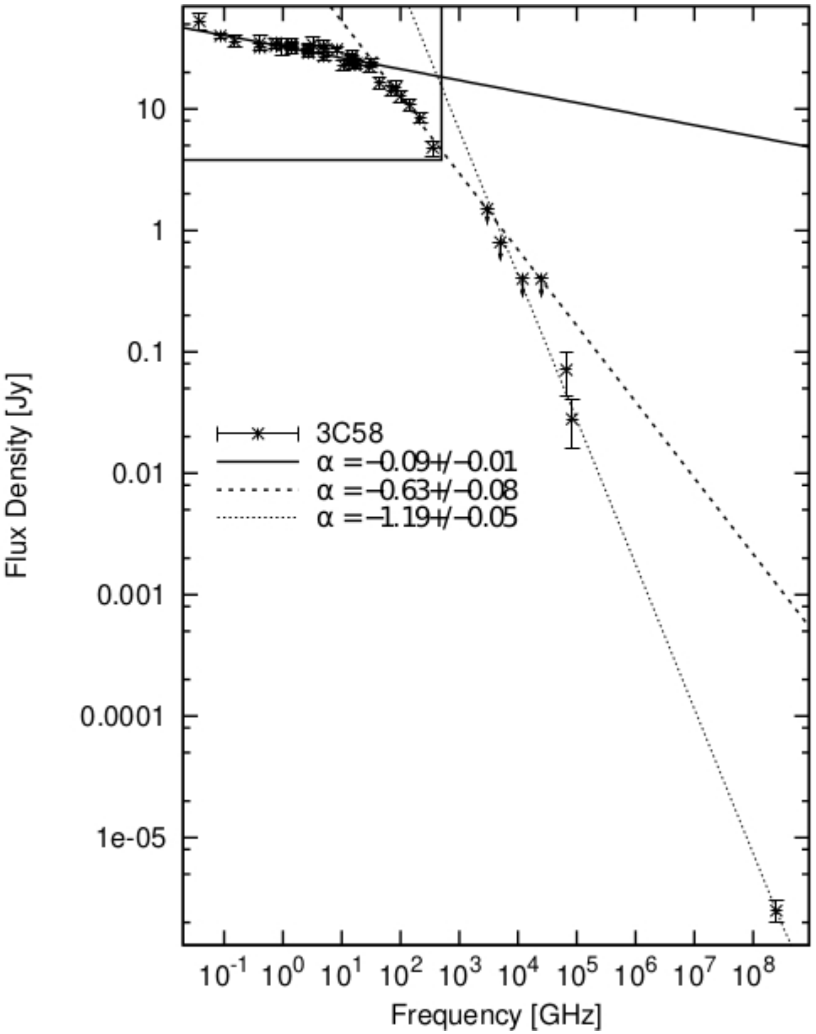
It appears, that younger PWN, that did not interact with the reverse shock yet, have flat spectra, relic PWN have steeper spectra.

The reverse shock may re-accelerate the relativistic electrons.

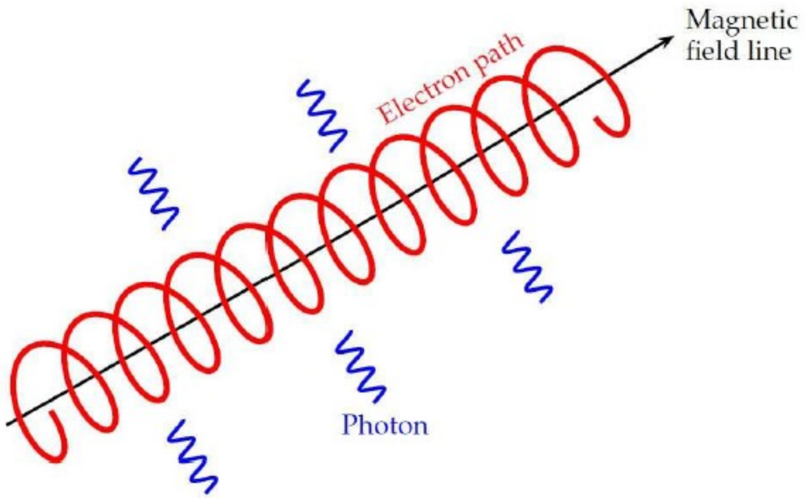
Intrinsic Break: 3C58

Kothes et al., 2017





PWN Synchrotron Emission



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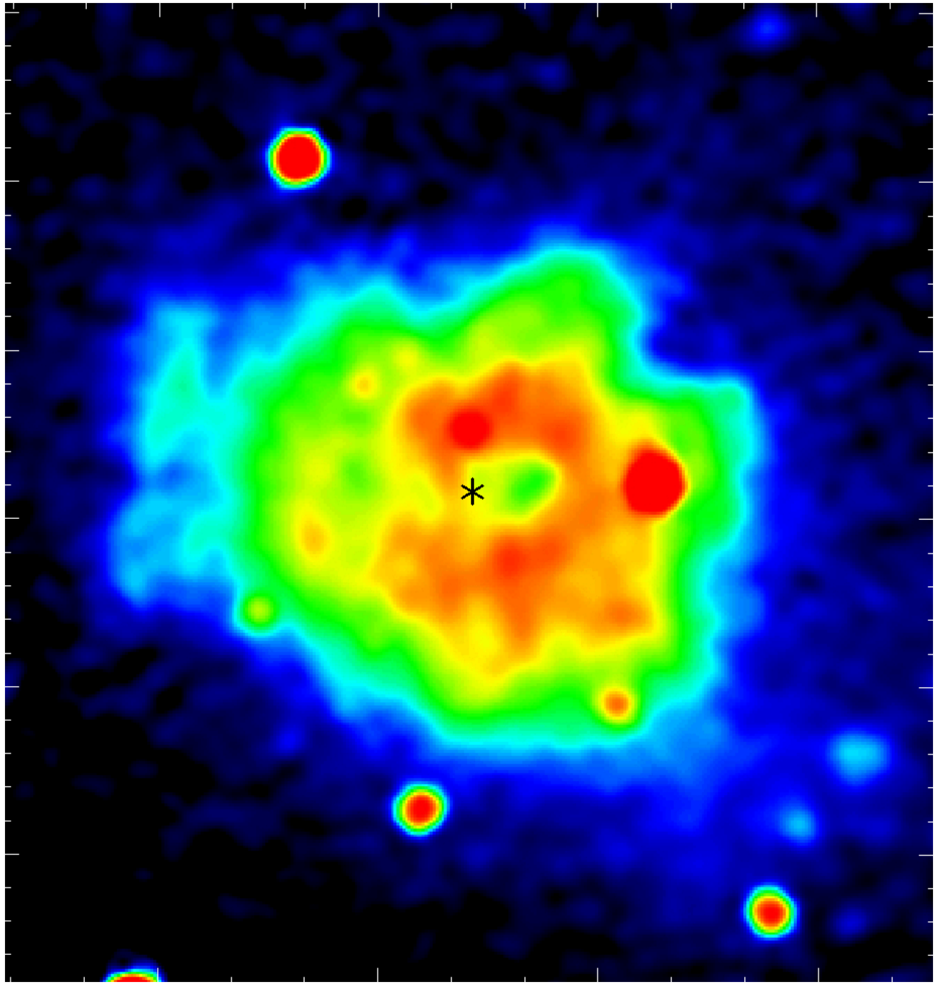
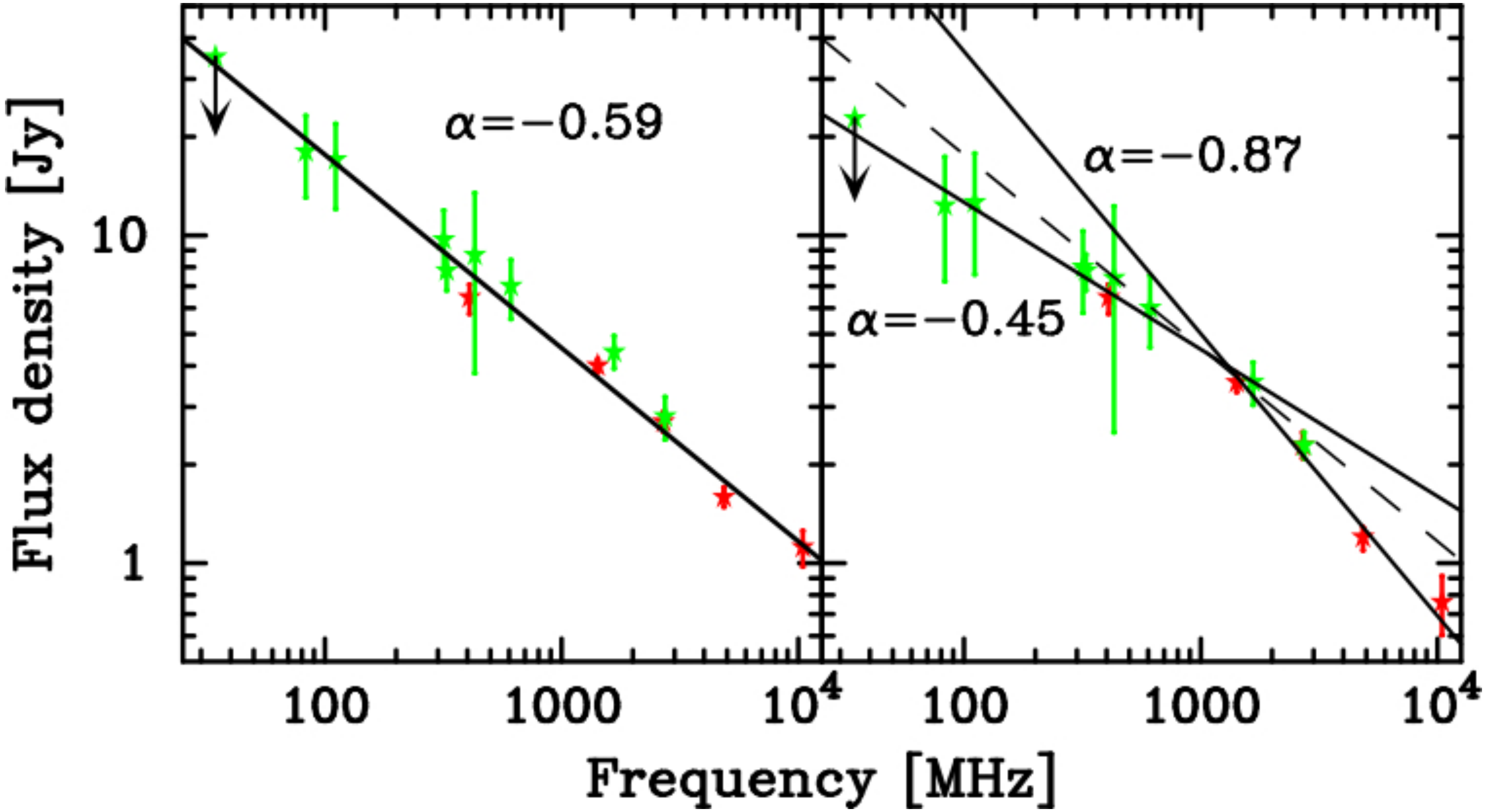
ν_c: break frequency with $\Delta\alpha \approx 0.5$, t: age

Cooling Break: DA495

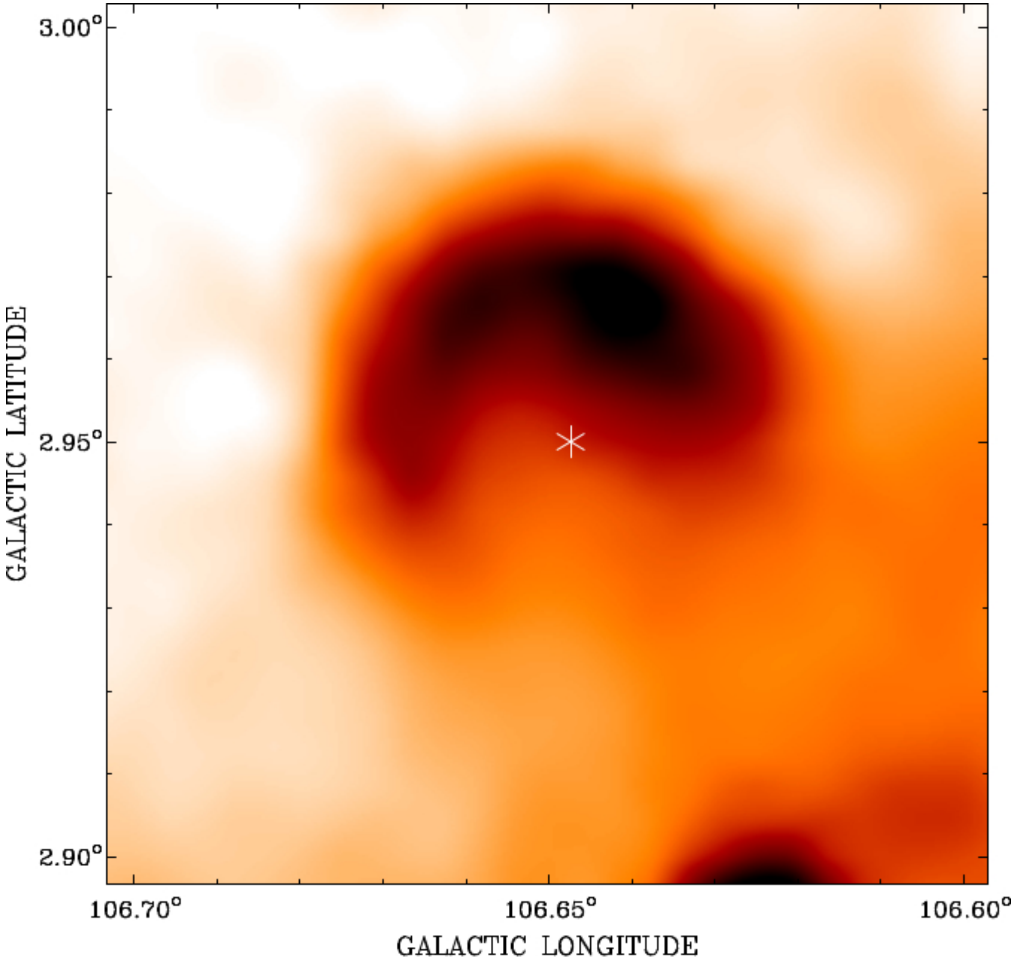
Kothes et al., 2008: *B* = 1.3 mG, Age = 20,000 years

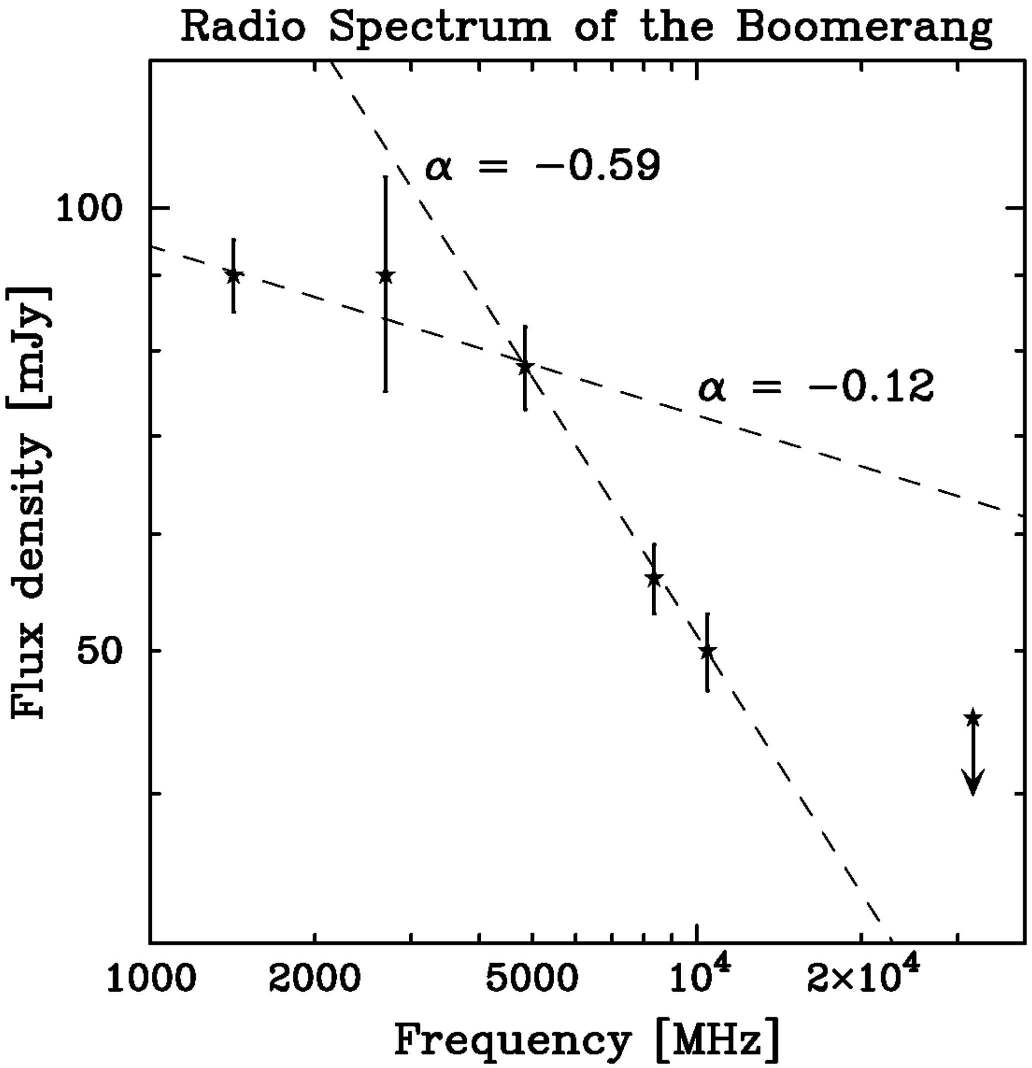




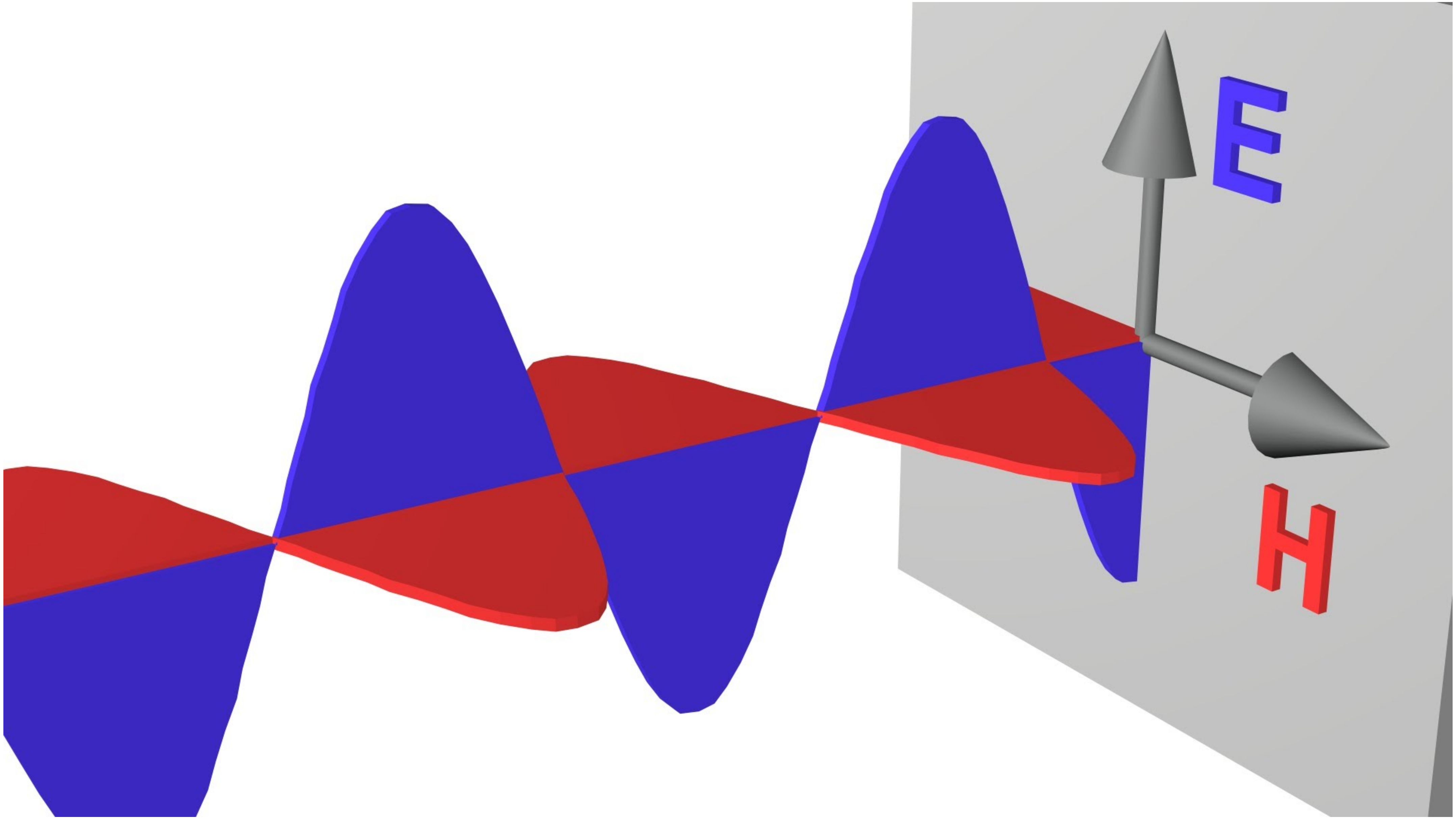
Cooling Break: Boomerang

Kothes et al., 2006: *B* = 2.6 mG, Age = 3,900 years

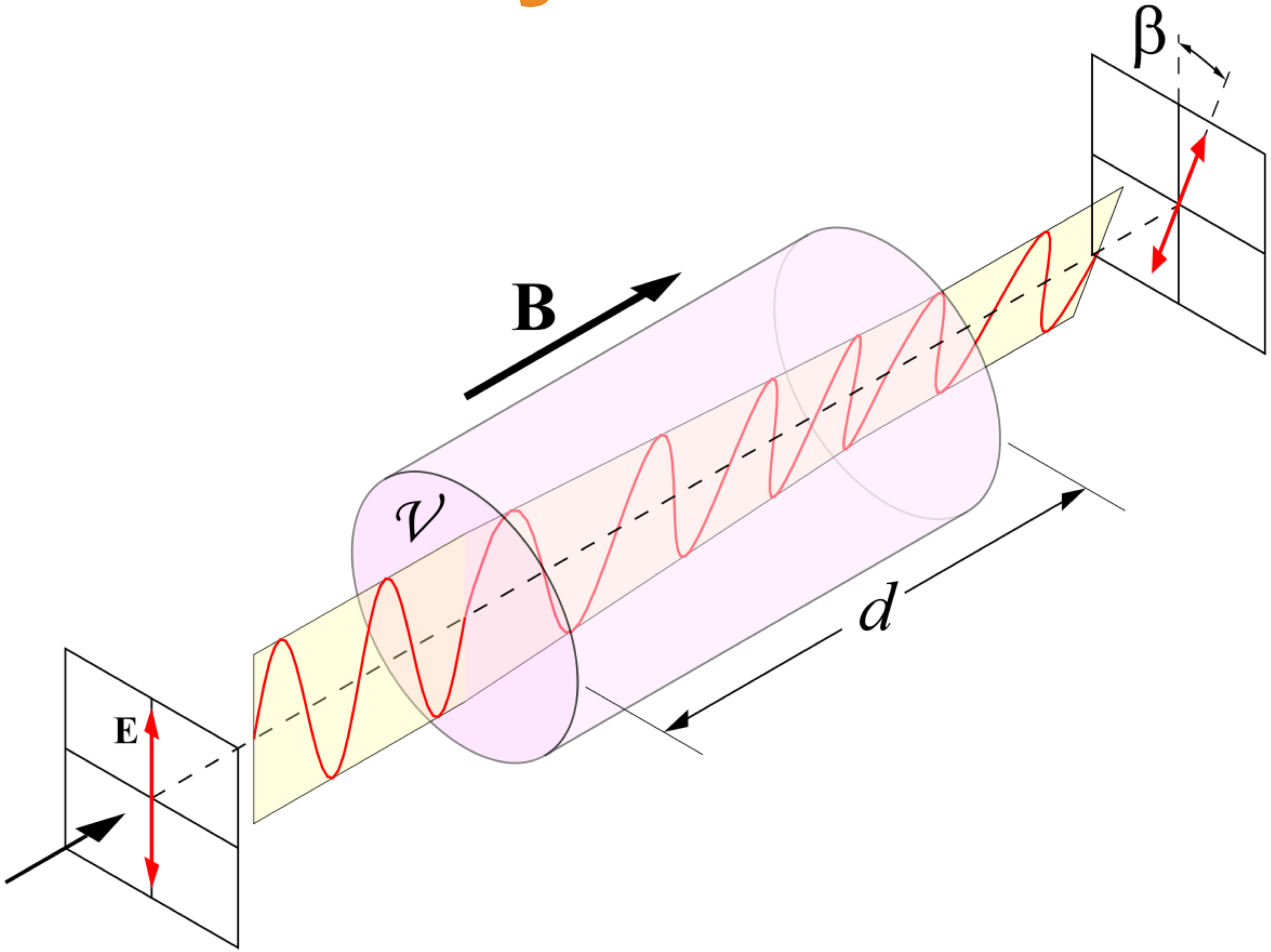




Radio Polarimetry



Faraday Rotation



Faraday Rotation

$$\phi_{\mathrm{obs}} = \phi_0 + RM\,\lambda^2 \quad [\mathrm{rad}]$$

$$RM = \frac{e^3}{2\pi m^2 c^4} \int\limits_s n_e \vec{B} d\vec{s}$$

$$= 0.81 \int\limits_s n_e B_{\|} ds \quad [\mathrm{rad\,m^{-2}}]$$

$\Delta\phi$: angle rotation

e: electron charge

m: electron mass

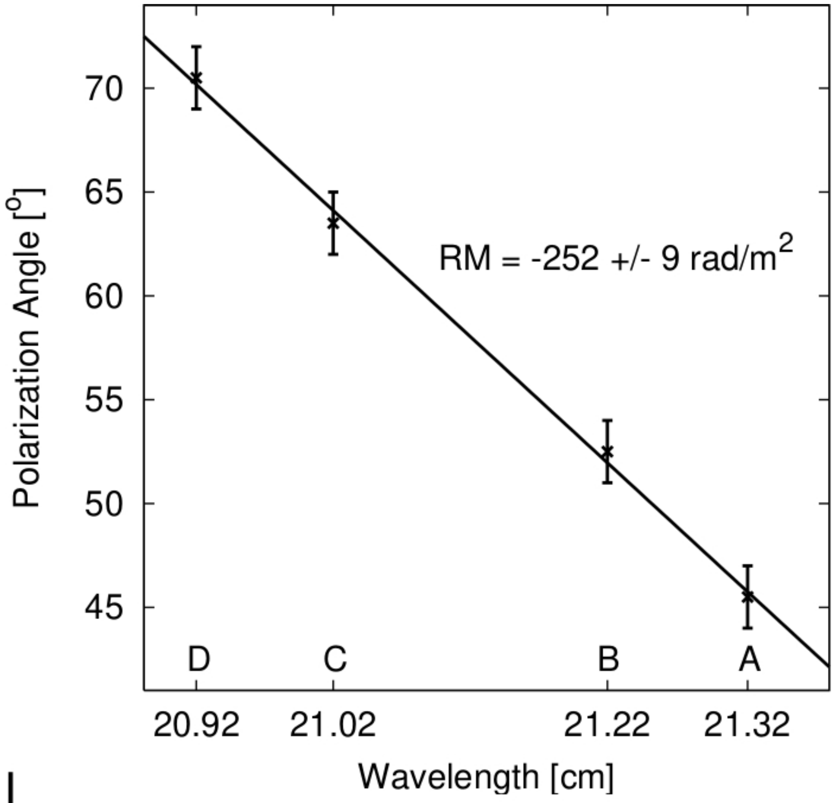
c: vacuum speed of light

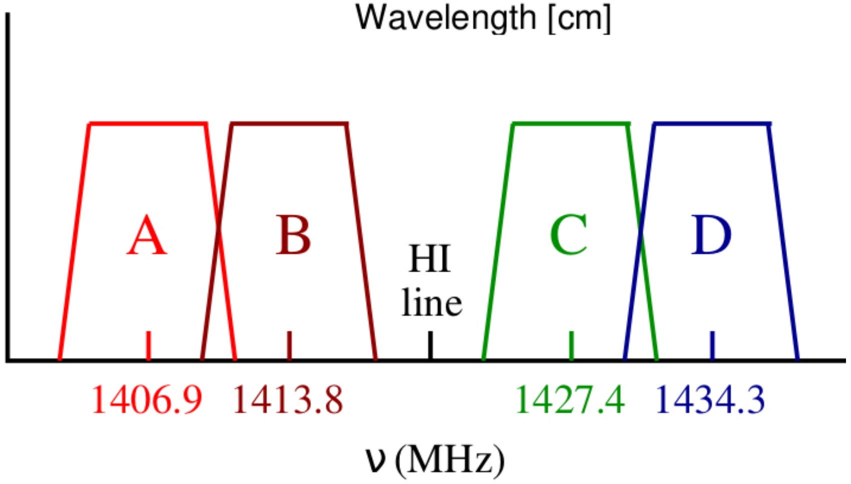
s: pathlength along the line of sight

n_e: electron density

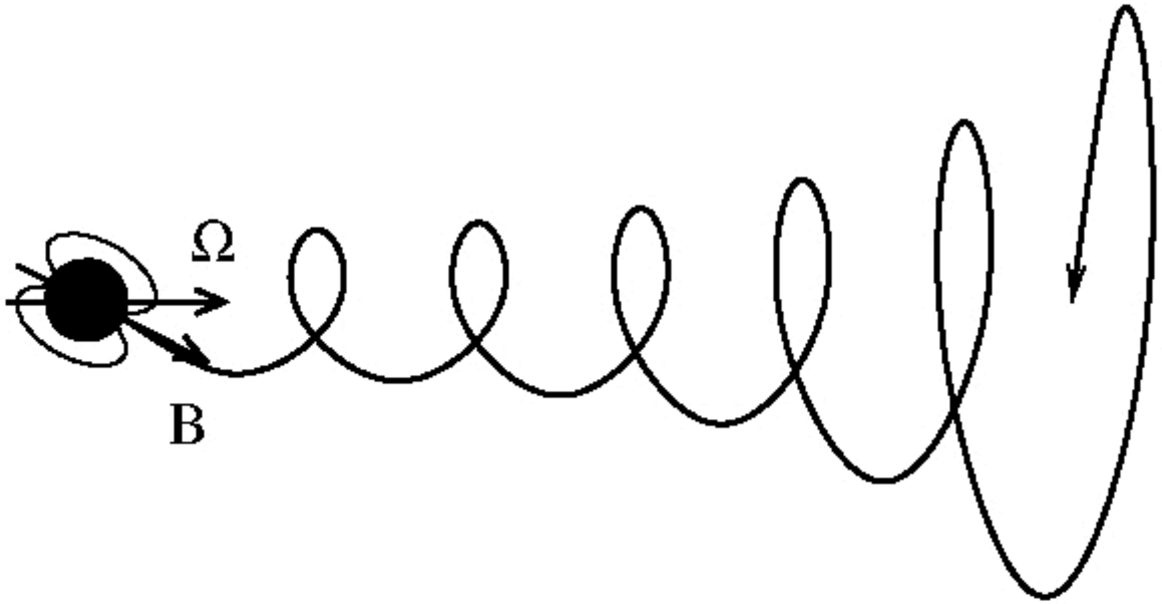
λ: wavelength

Faraday Rotation



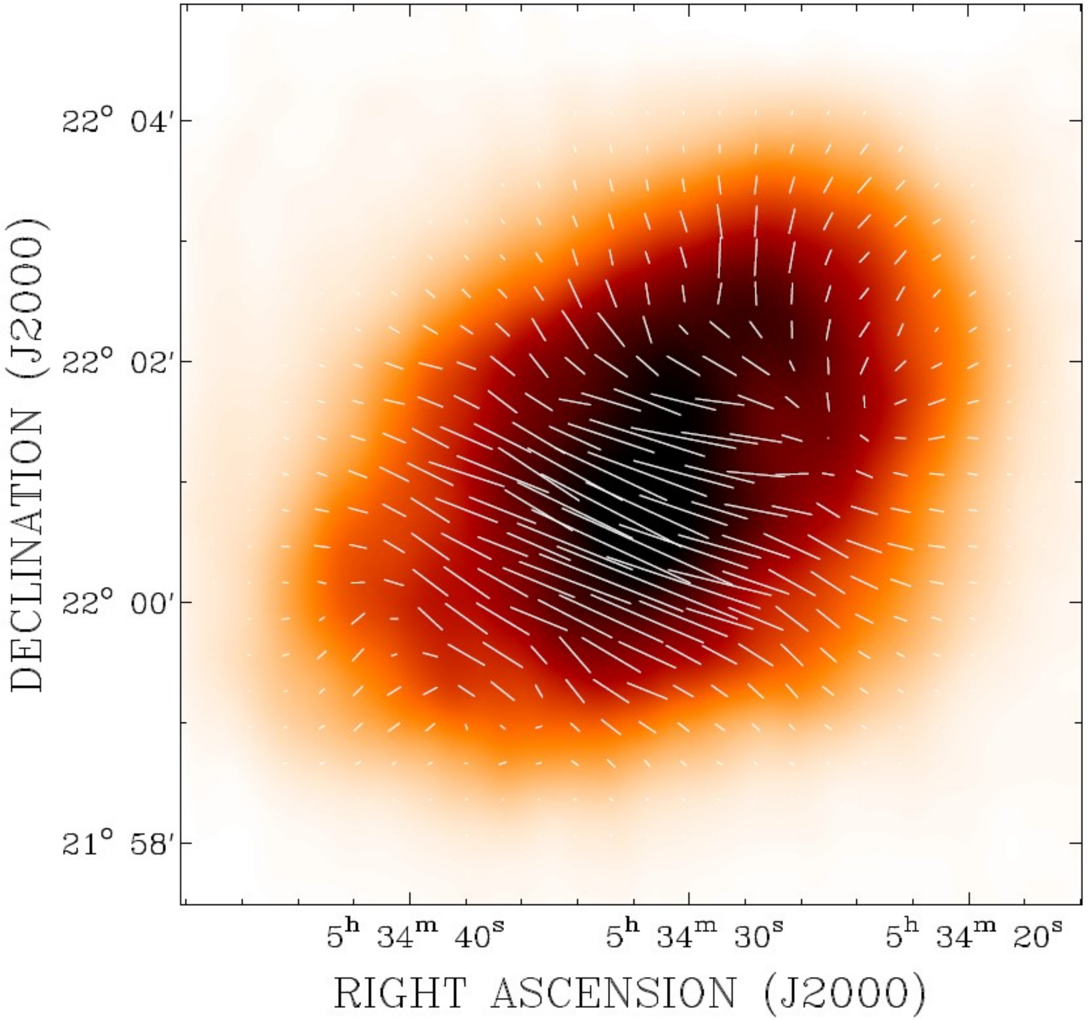


Pulsar Wind

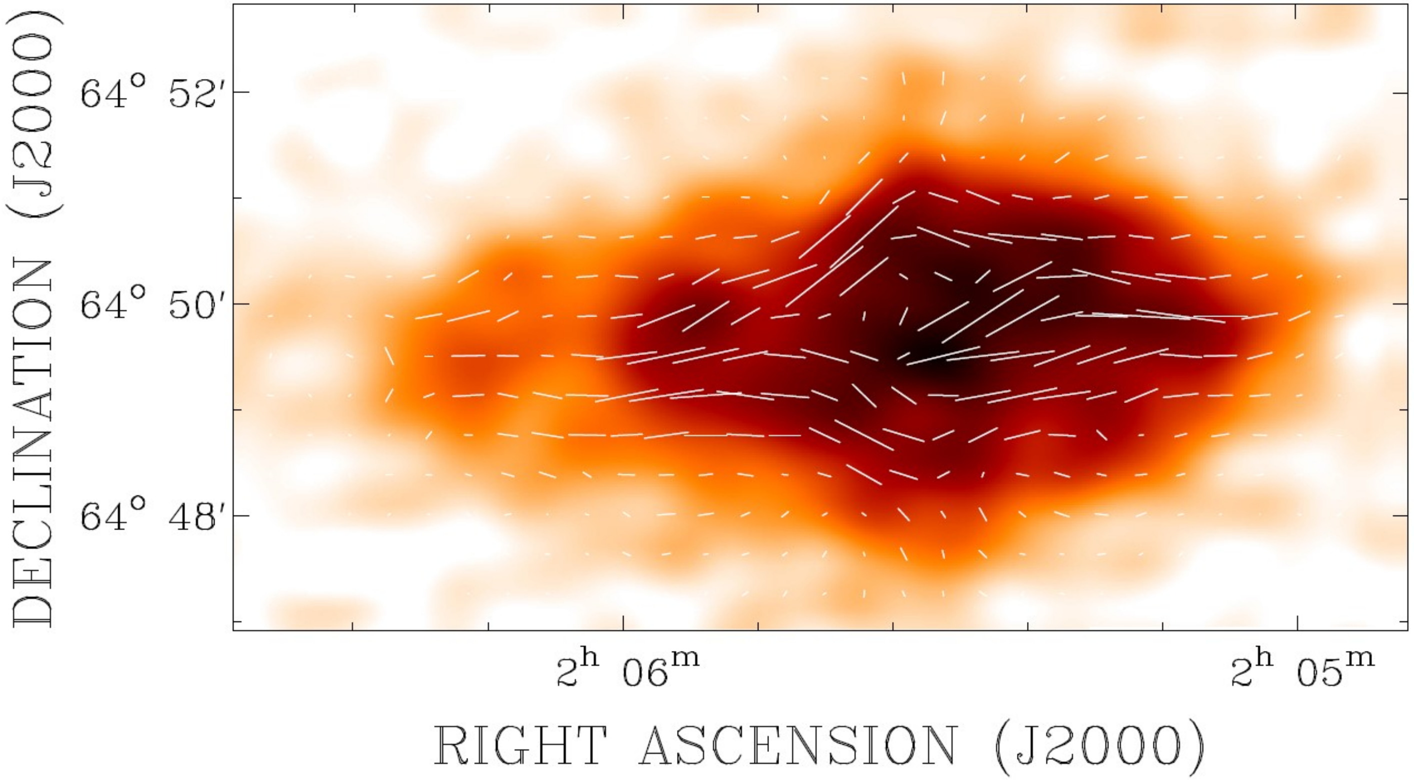


- The wind emerges in a two-sided collimated outflow.
- MHD simulations show that this results in a nebula elongated along the outflow (e.g. Van der Swaluw, 2003).
- The elongation in young PWNe is proposed to be the result of higher equatorial pressure associated with toroidal magnetic fields (e.g. Van der Swaluw, 2003).

Crab Nebula & 3C58

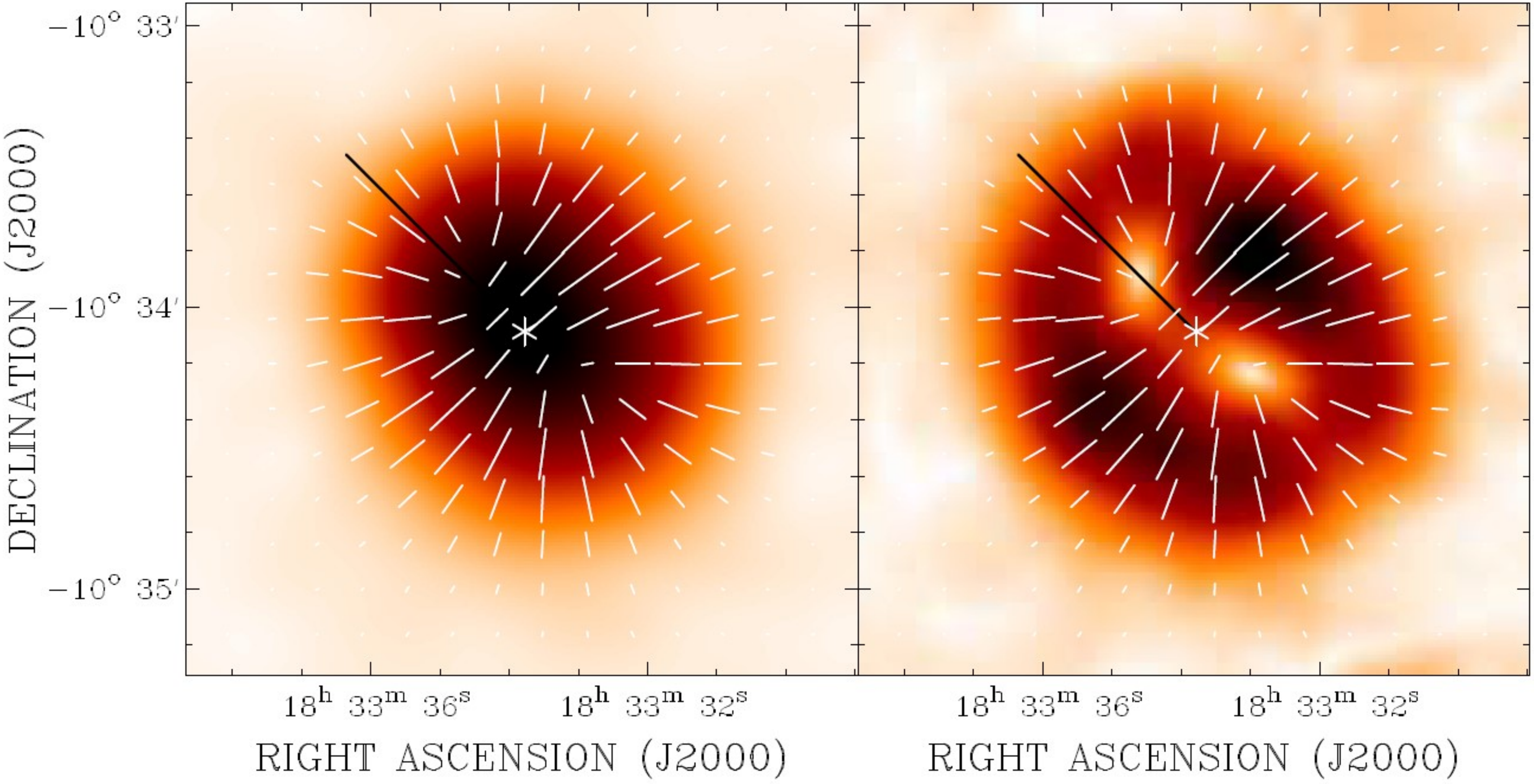


Reich et al., 1998



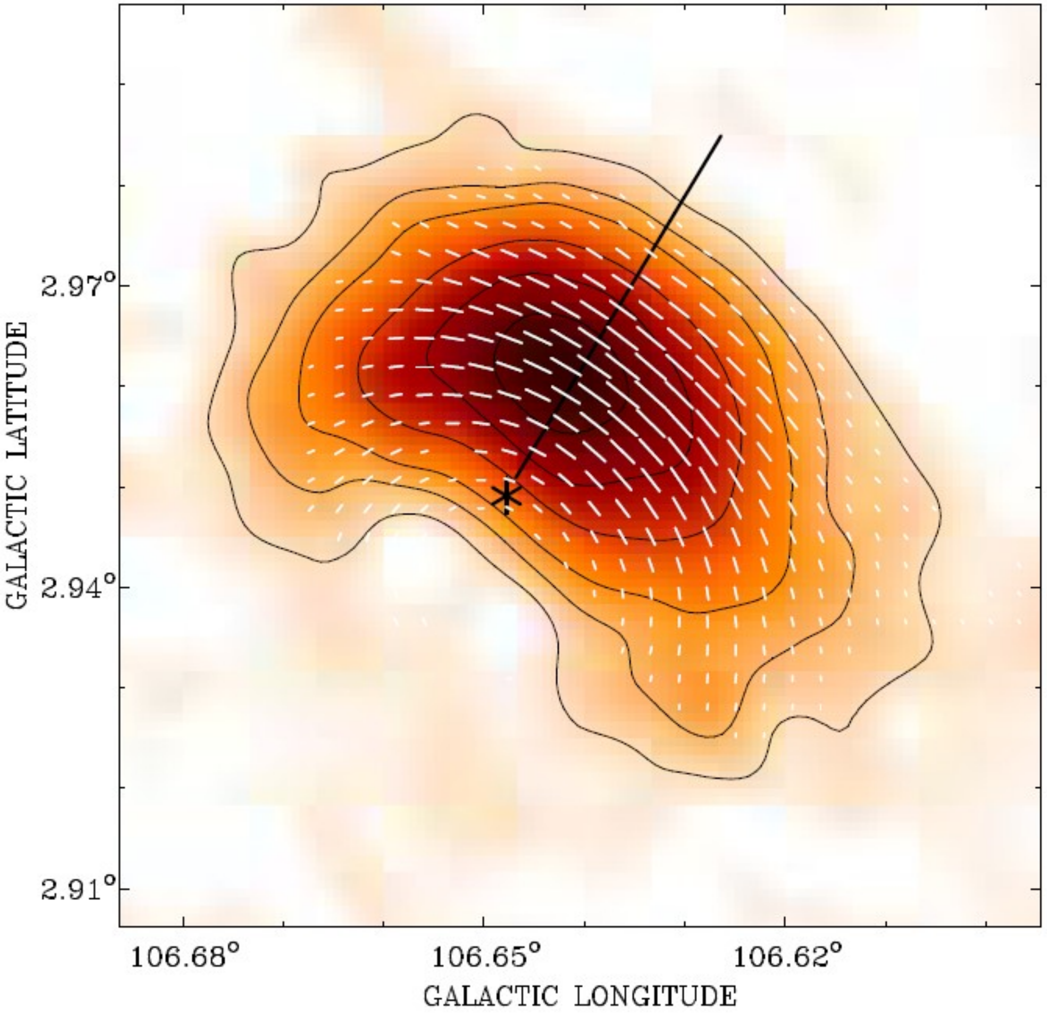
G21.5-0.9

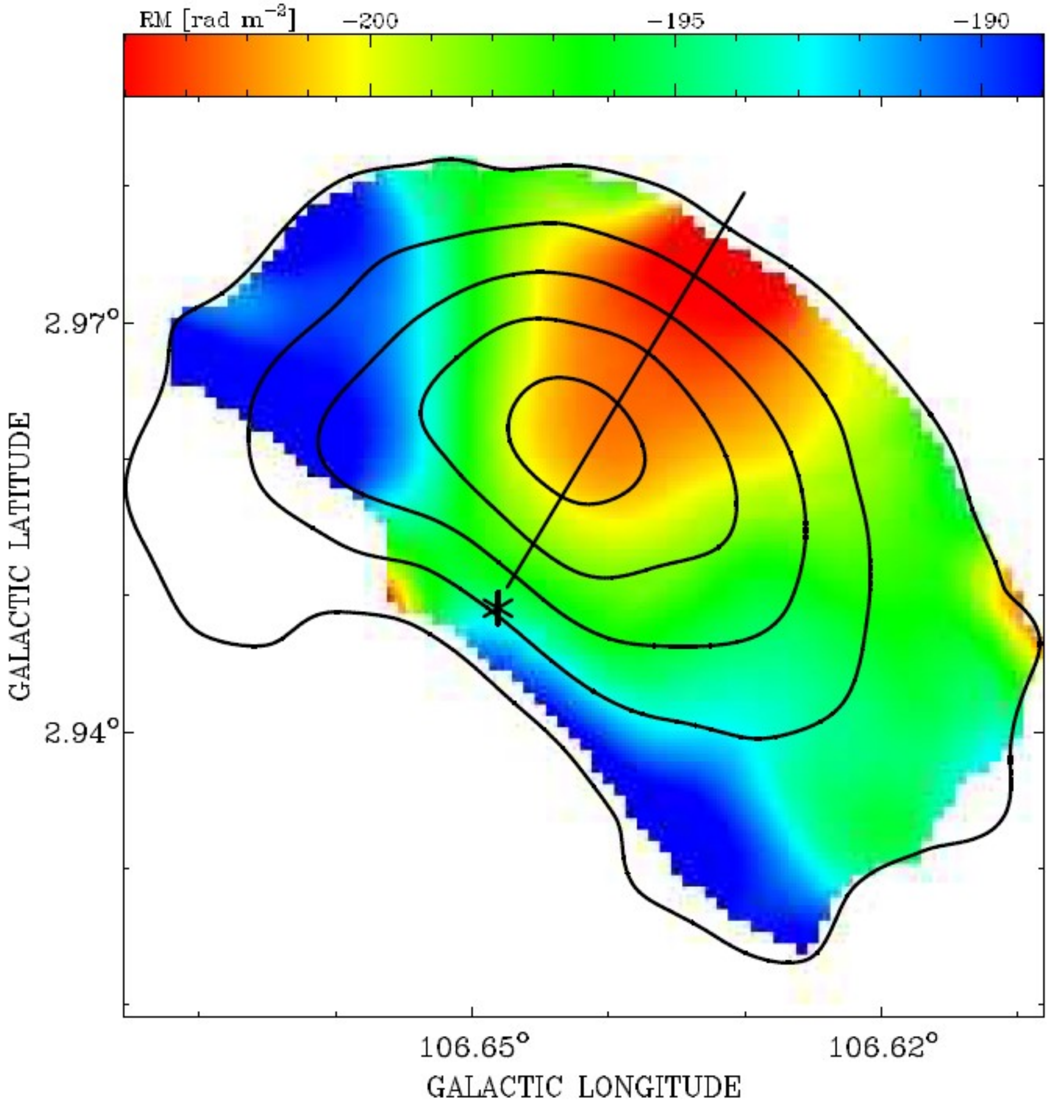
Reich et al., 1998



Boomerang PWN

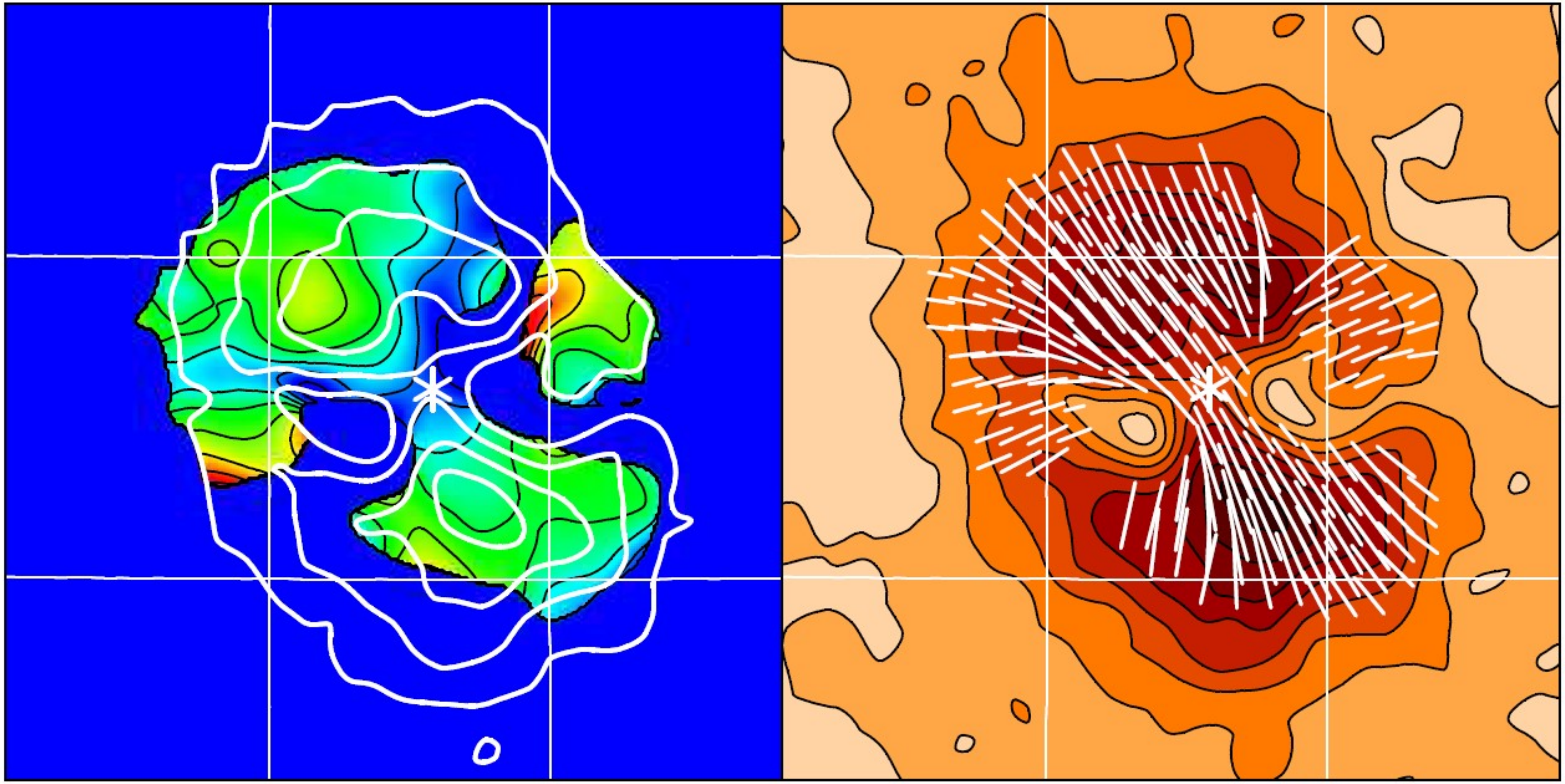
Kothes et al., 2006





DA495 PWN

Kothes et al., 2008



Magnetic Fields in PWNe

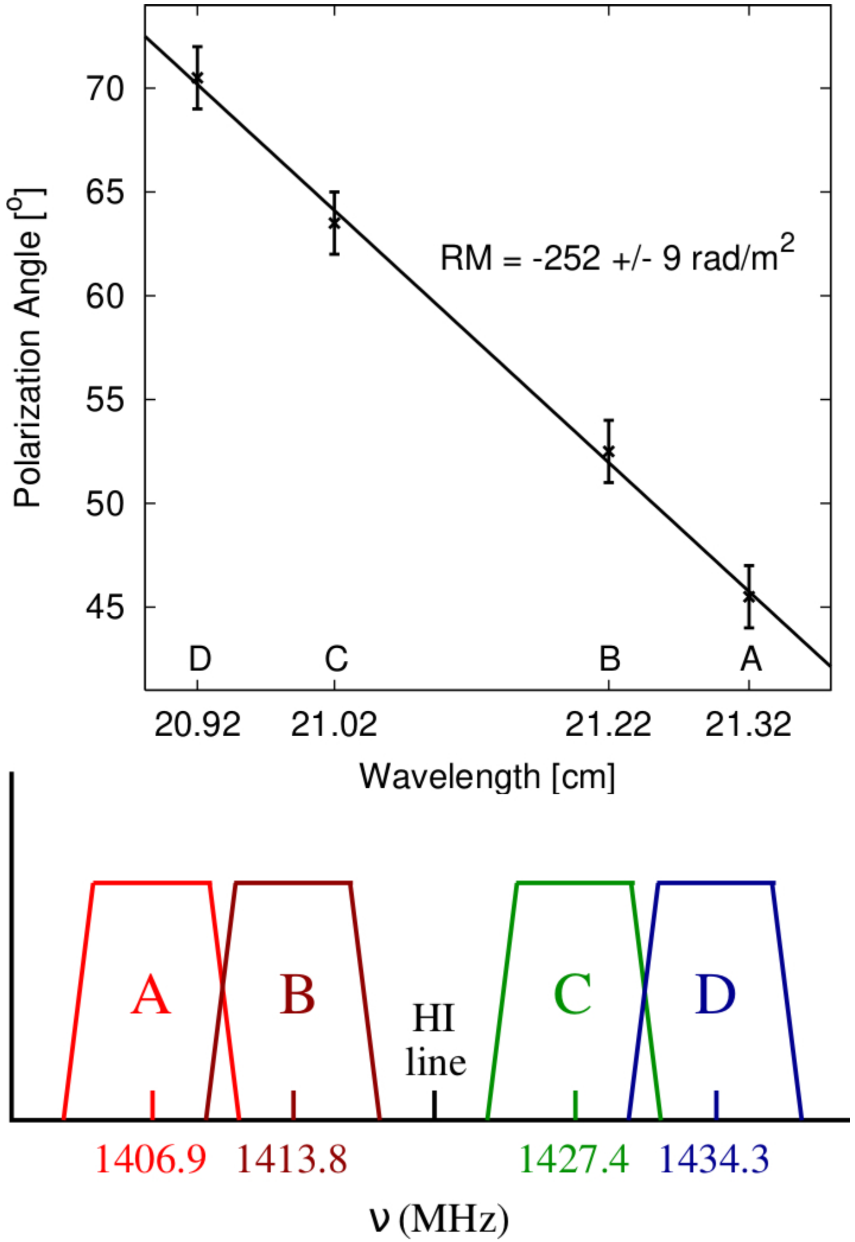
We found toroidal and radial B-field structures.

Radial B-field dominates the overall magnetic field, while the toroidal component is typically confined to the equatorial plane.

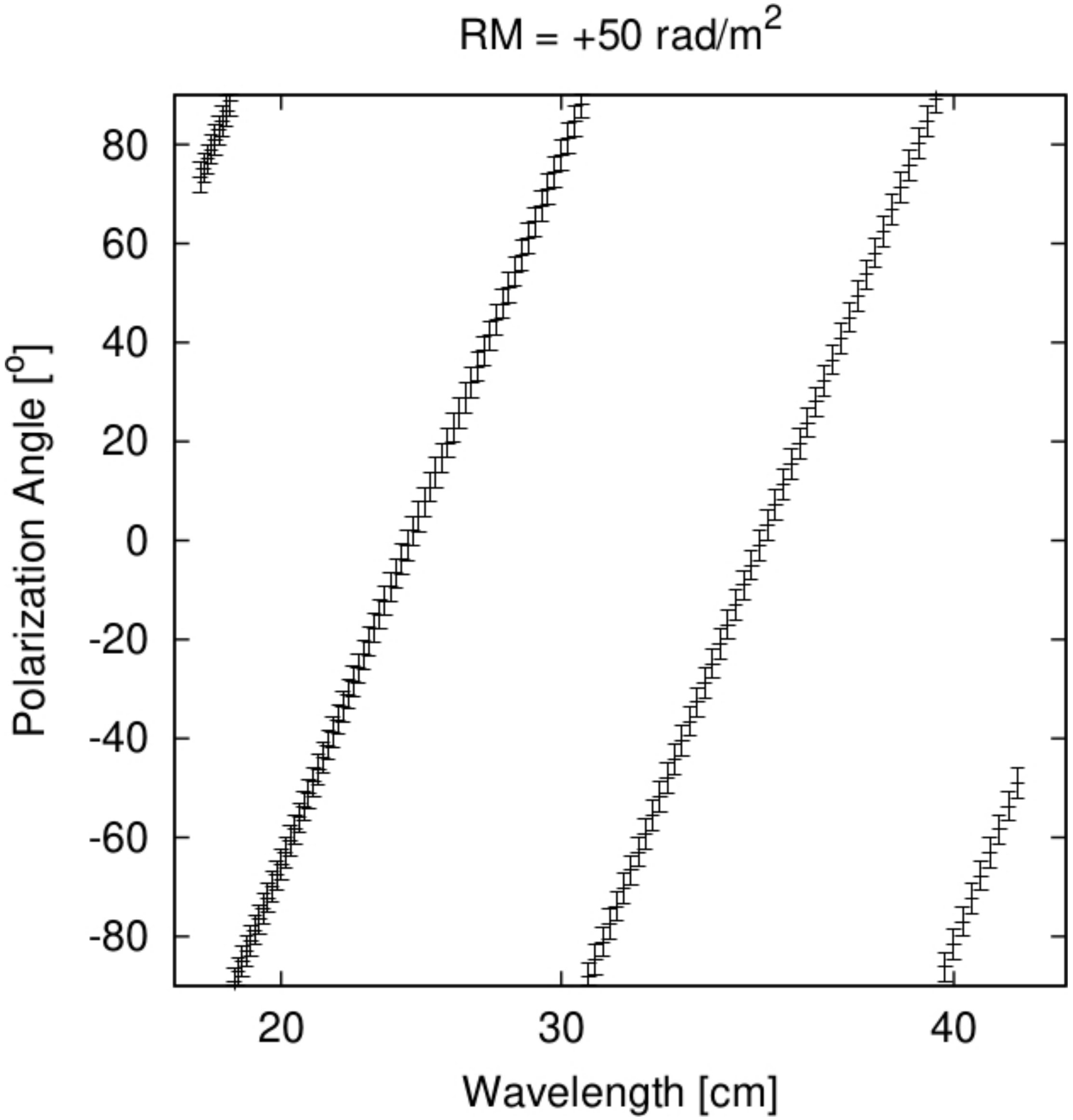
More studies are necessary.

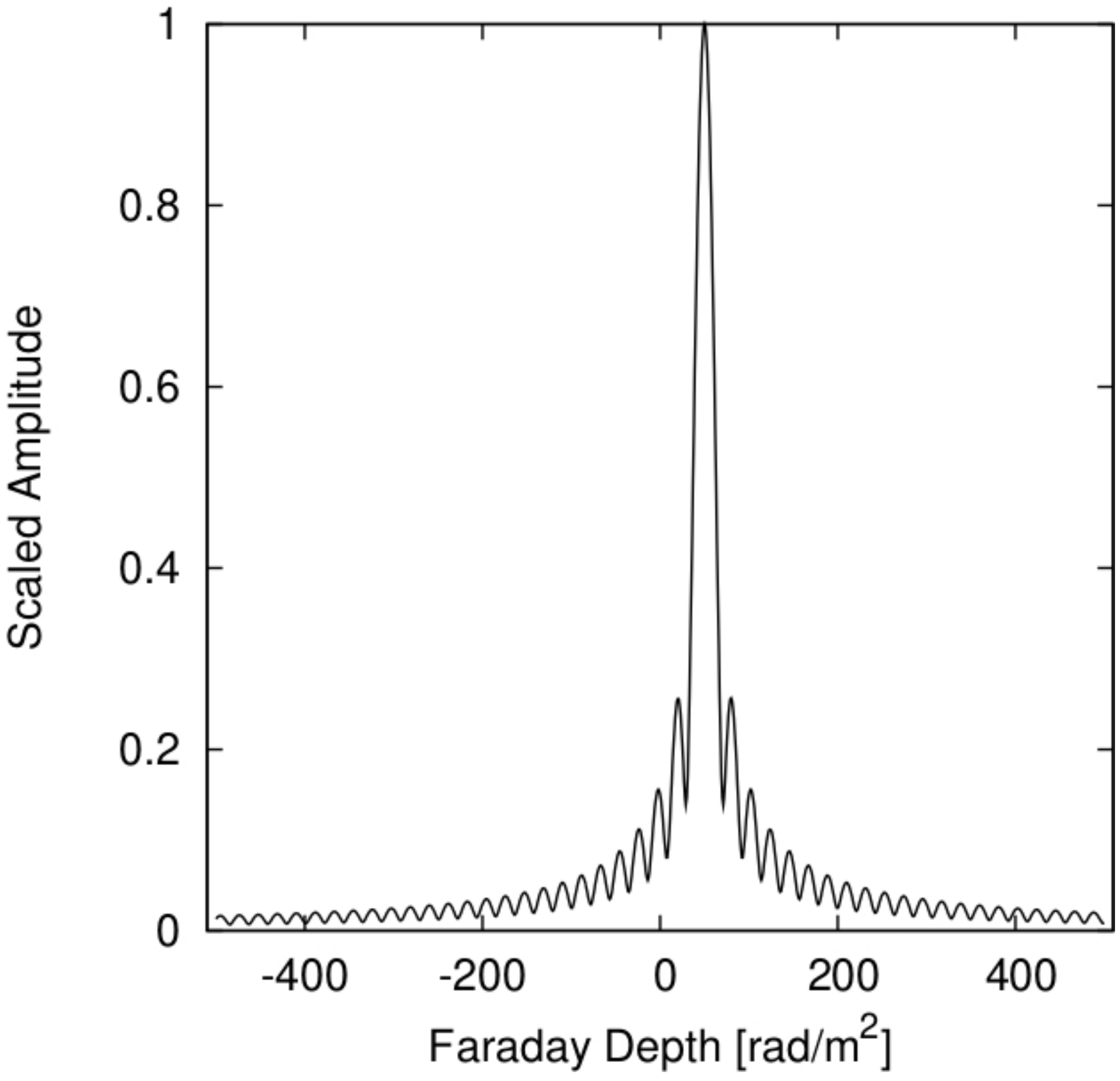
Outlook: ASKAP+MeerKAT

Outlook


Polarization Angle [°]
70
65
60
55
50
45
RM = -252 +/- 9 rad/m²
D
C
B
A
20.92
21.02
21.22
21.32
Wavelength [cm]
A
B
HI
line
C
D
1406.9
1413.8
1427.4
1434.3
ν (MHz)

Outlook: RM Synthesis

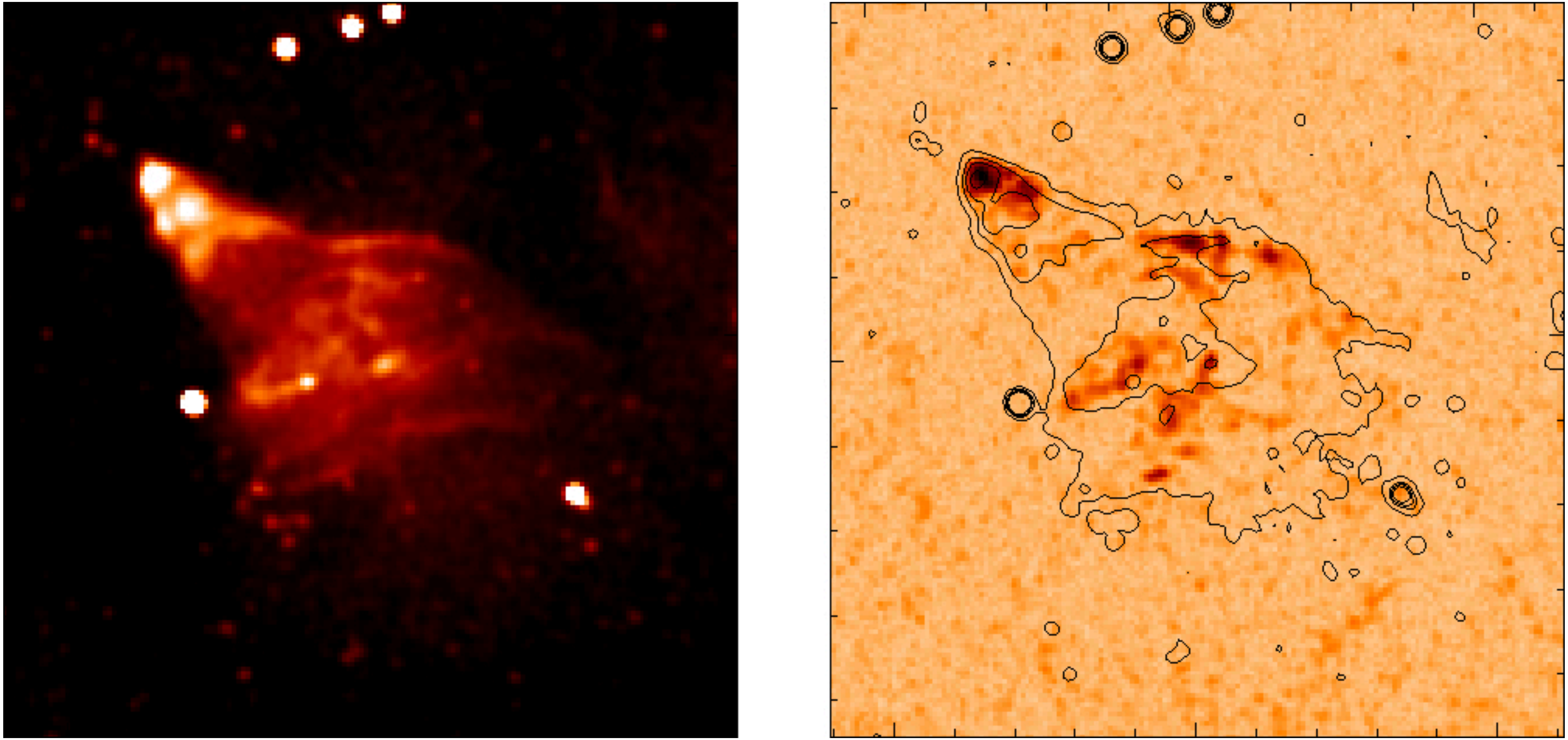

RM = +50 rad/m^2



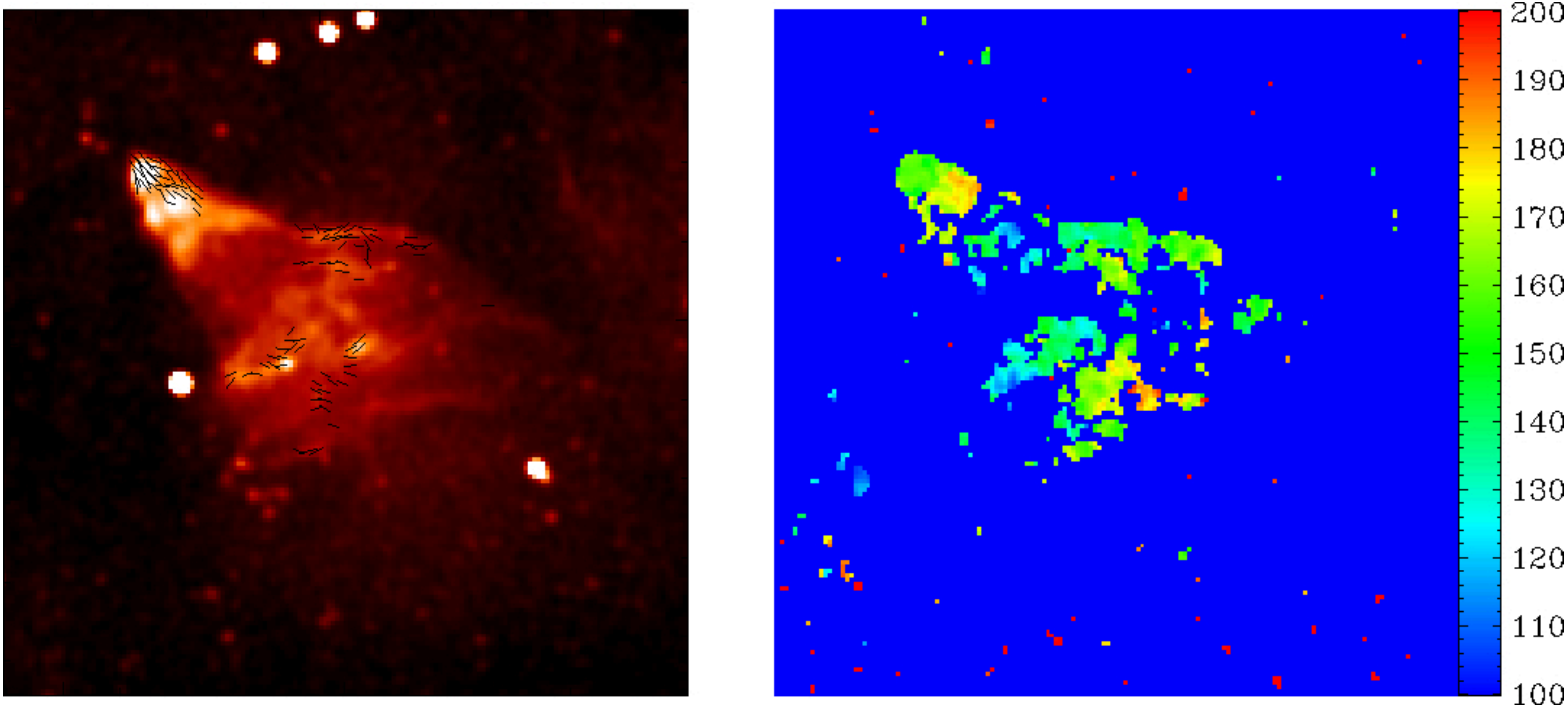
Outlook: RM Synthesis

To separate foreground from internal rotation measure we use depolarization: see Poster S5.2, by Brianna Ball et al.

New PWN



New PWN



Summary

- Studies of pulsar wind nebulae in the radio waveband serve to probe the spectral and morphological distribution.
- PWNe typically have flat radio spectra with spectral indices α between 0.0 and 0.3, with few exceptions.
- Radio polarimetry is an excellent tool to study the magnetic field configuration in PWNe.
- Observed magnetic fields in PWNe do not agree with those predicted by theoretical models. Radial B field dominates the overall magnetic field, while the toroidal component seems to be confined to the equatorial plane.
- **We are living in a golden era of radio astronomical research, I am glad to be part of this.**