The Evolution of Supernova Remnants as Seen in Radio Emission

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SNR Types

We distinguish between 3 different types of radio SNRs:

- pure shell-type, created by the interaction of the expanding shockwave with circumstellar material (80 %)
- filled-centre, plerion-type, crab-like, or pulsar wind nebula, created by an energetic wind of particles and magnetic field injected by a central pulsar (5 %)
- composite type (15 %)

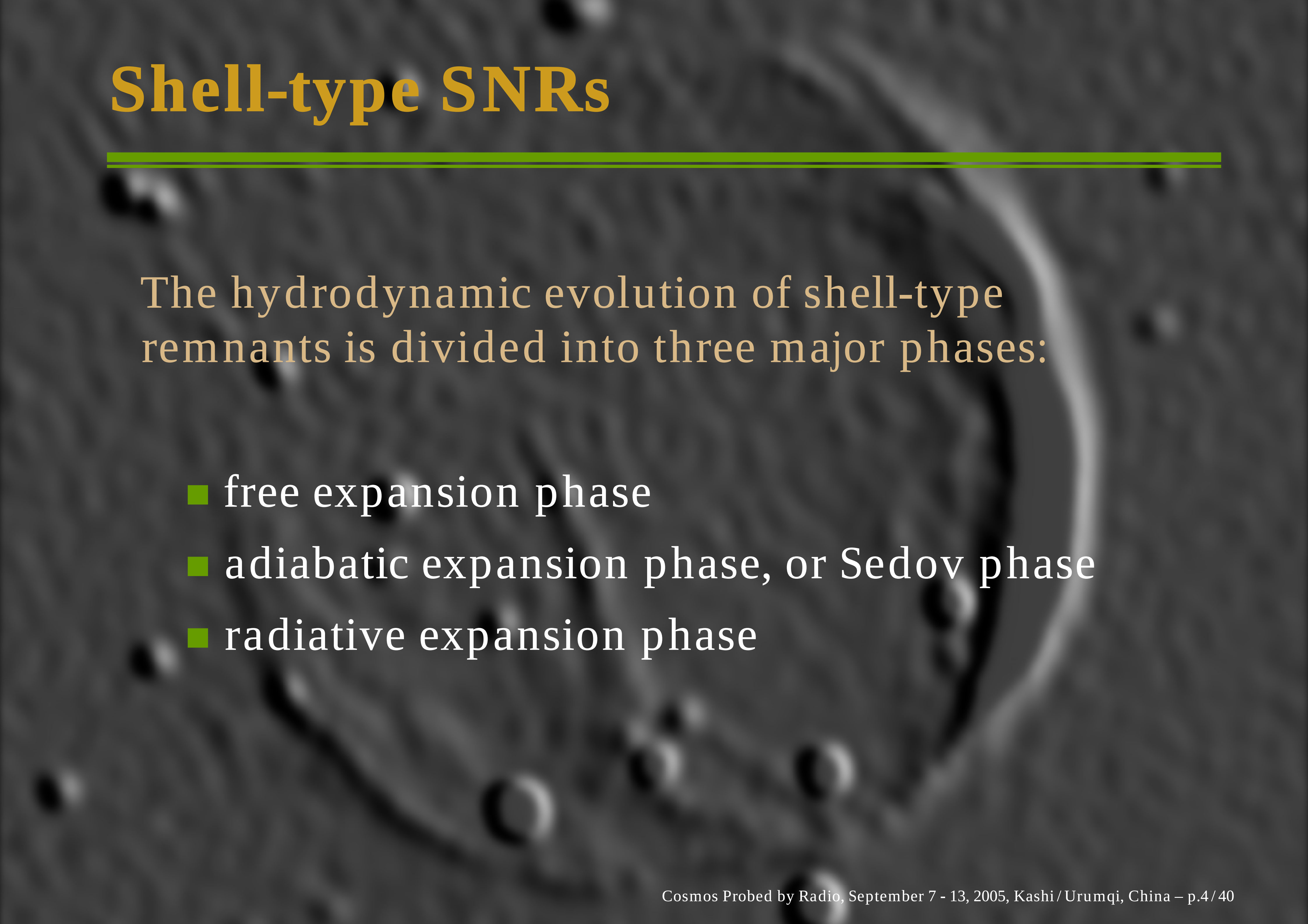
(Green’s Catalogue of Galactic Supernova Remnants)

SNR Types

But theoretically there should be only 2 types:

- pure shell-type, as the remnant of the thermonuclear explosion of a white dwarf (SNIa), since in these explosions the whole star is destroyed ($E_0 \approx 1.5 \cdot 10^{51}\, erg/s$, $M_0 = 1.4\, M_\odot$).
- composite type, as the remnant of the core-collapse explosion of a massive star (SNII, SNIb/c), since in these explosions a rotating neutron star is left behind ($E_0 \approx 10^{49}$ to $2 \cdot 10^{51}\, erg/s$ $M_0 \approx 3$ to $20\, M_\odot$).

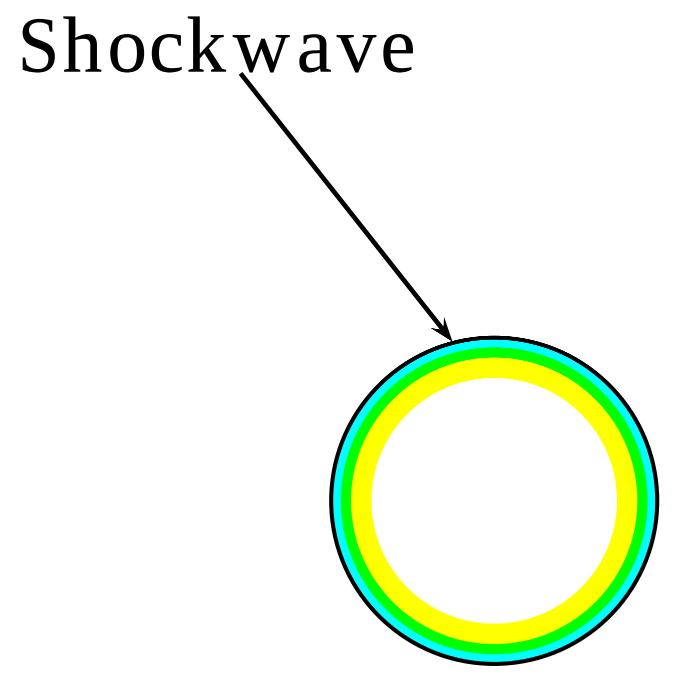
Shell-type SNRs



The hydrodynamic evolution of shell-type remnants is divided into three major phases:

- free expansion phase
- adiabatic expansion phase, or Sedov phase
- radiative expansion phase

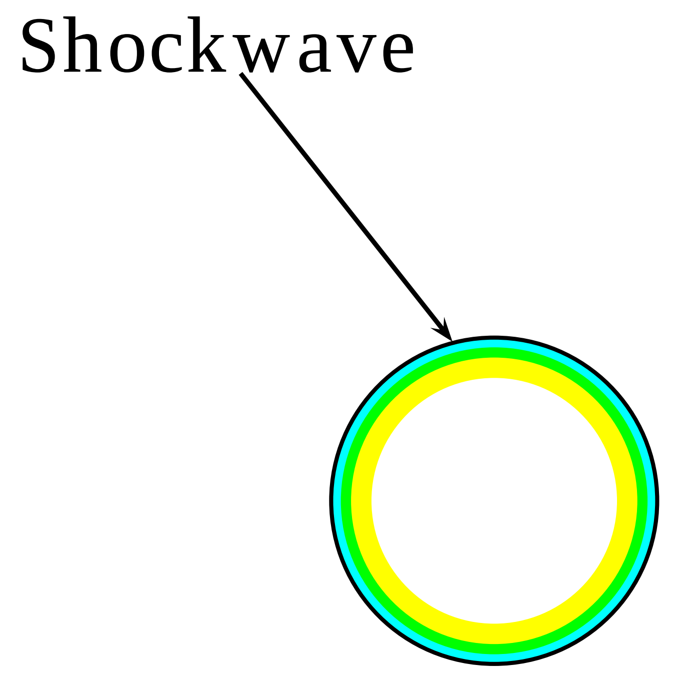
Shell-type SNRs



Free Expansion:

- expansion is dominated by the ejecta ($R \sim t$), which contains a radial magnetic field - a relic of the progenitor star - and lasts a few hundred up to 2000 yr
- swept up material is slowly accumulating outside the ejecta with a frozen in tangential magnetic field
- between ejecta and swept up material a turbulent zone is established in which electrons are accelerated to relativistic velocities

Shell-type SNRs



Characteristics of the Radio Emission During the Free Expansion Phase:

- steep radio synchrotron spectrum with $\alpha < -0.5$ (S$\sim \nu^{\alpha}$) with a radial magnetic field
- smooth radio shell without sharp outer edge
- low percentage polarization that decreases with time while the swept up material becomes more and more important

Free Expanding SNRs

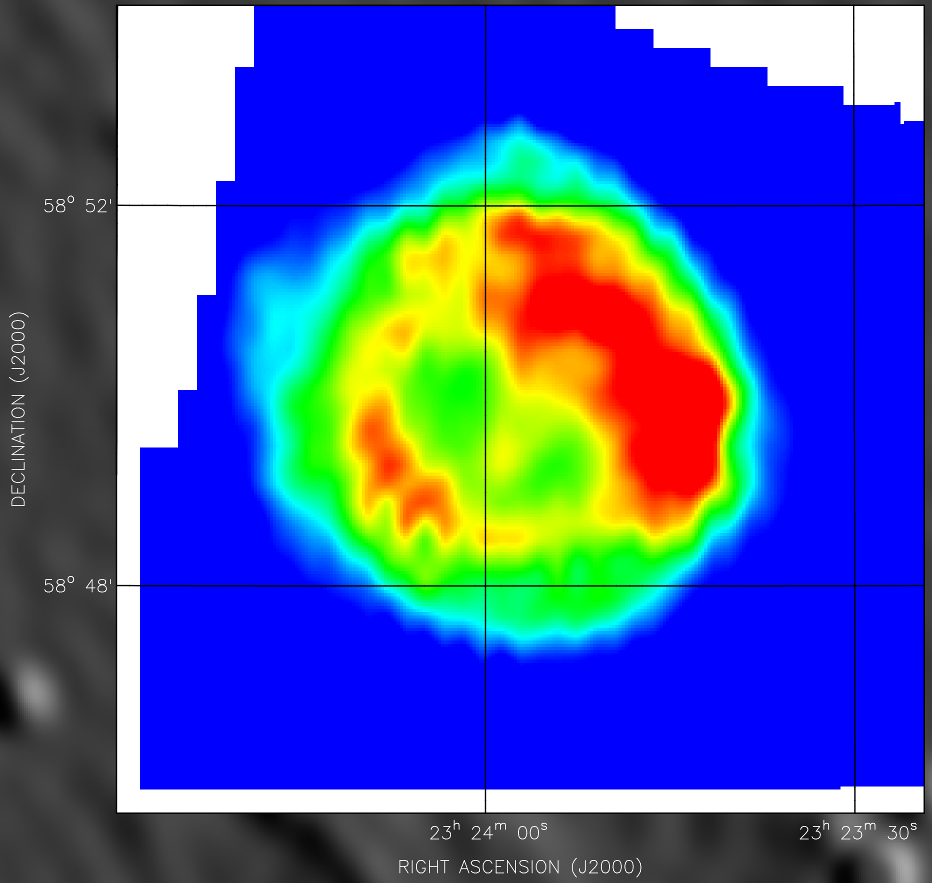
Among the free expanding shell-type SNRs we find:

- Cas A (SNII? of $\approx$ 1680, $\alpha = -0.77$)
- Kepler's SNR (SNIa of 1604, $\alpha = -0.64$)
- Tycho's SNR (SNIa of 1572, $\alpha = -0.61$)
- SN 1006 (SNIa? of 1006, $\alpha = -0.60$)

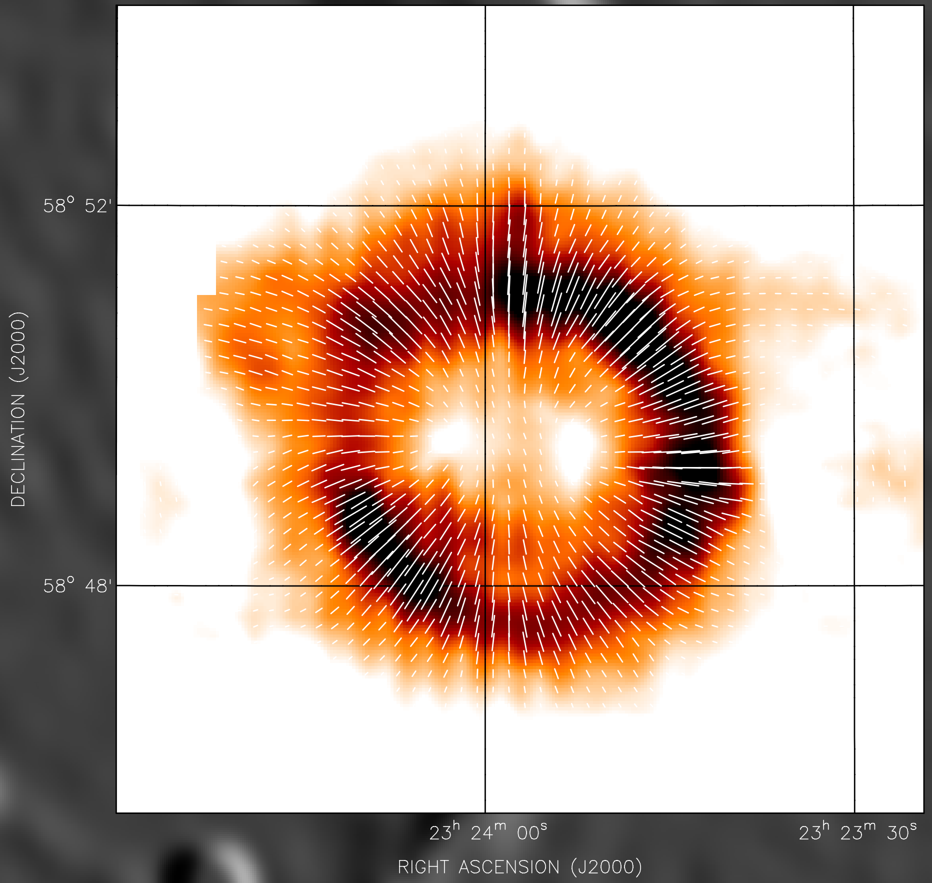
All of these SNRs are in radio pure shell-type remnants with a radial magnetic field structure

Cassiopeia A

Effelsberg TP 32 GHz



Effelsberg PI + B-vectors 32 GHz



(Courtesy W. Reich)

The guest star from AD 386: SNR G11.2−0.3

一日：「爲大水。」四年五月，天下大水。五年，穆帝崩。

哀帝興寧元年八月，有星孛于角亢，入天市。案占曰：「爲兵喪。」三年正月，皇后王氏崩。二月，帝崩。三月，慕容恪攻沒洛陽，沈勁等戰死。

↓ AD 369

海西太和四年二月，客星見紫宮西垣，至七月乃滅。占曰：「客星守紫宮，臣弒主。」六年，桓溫廢帝爲海西公。

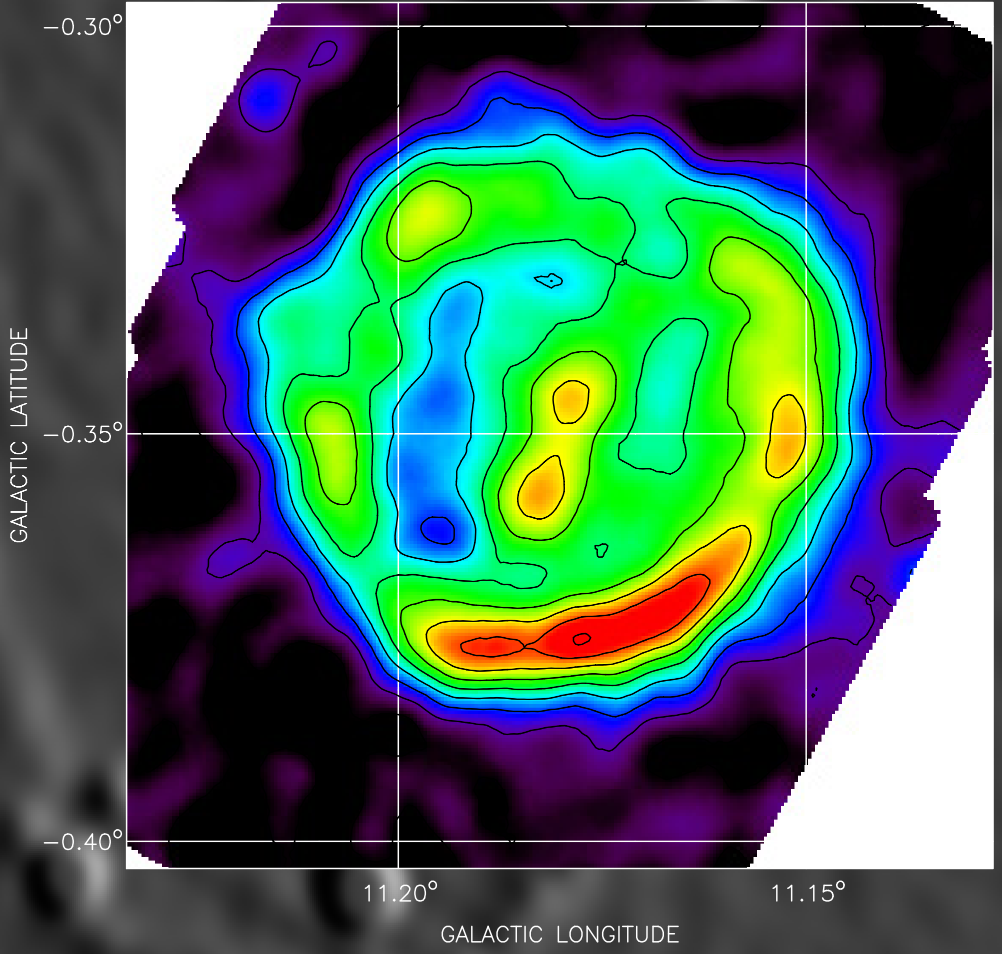
孝武寧康二年正月丁巳，〔三〕有星孛于女虛，經氐亢、角、軫、翼、張。至三月丙戌，孛星見於氐。九月丁丑，有星孛于天市。占曰：「爲兵喪。」太元元年七月，苻堅破涼州，虜張天錫。

↓ AD 386

太元十一年三月，客星在南斗，至六月乃沒。占曰：「有兵，有赦。」是後司、雍、兗、冀常有兵役。十二年正月大赦，八月又大赦。十五年七月壬申，有星孛于北河戍，經太微、三台、文昌，入北斗，色白，長十餘丈。八月戊戌，入紫宮乃滅。占曰：「北河戍一名胡門，胡有兵喪。」掃太微，入紫微，王者當之。三台爲三公，文昌爲將相，將相三公有災。入北斗，諸侯戮。」一曰：「掃北斗，強國發兵，諸侯爭權，大人憂。」二十一年，帝崩。隆安元年，王恭、殷仲堪、桓玄等並發兵，表以誅王國寶爲名。朝廷順而殺之，并斬其從弟緒，司馬道子由是失勢，禍亂成矣。

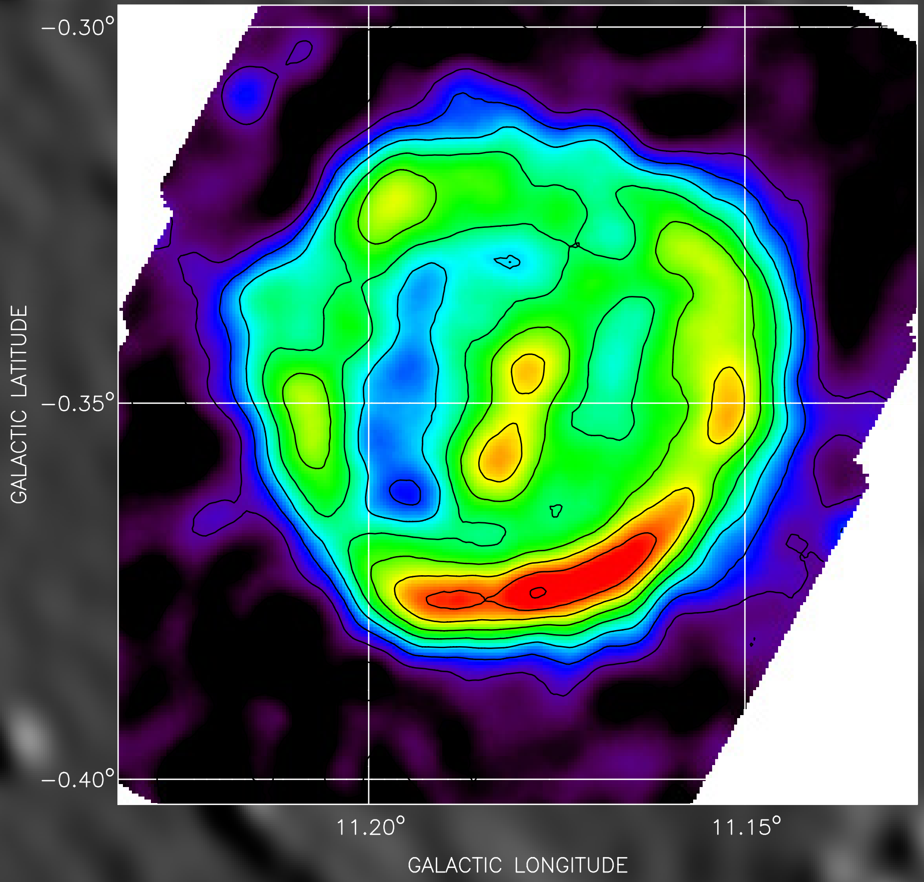
↓ AD 393

十八年二月，客星在尾中，至九月乃滅。占曰：「燕有兵喪。」二十年，慕容

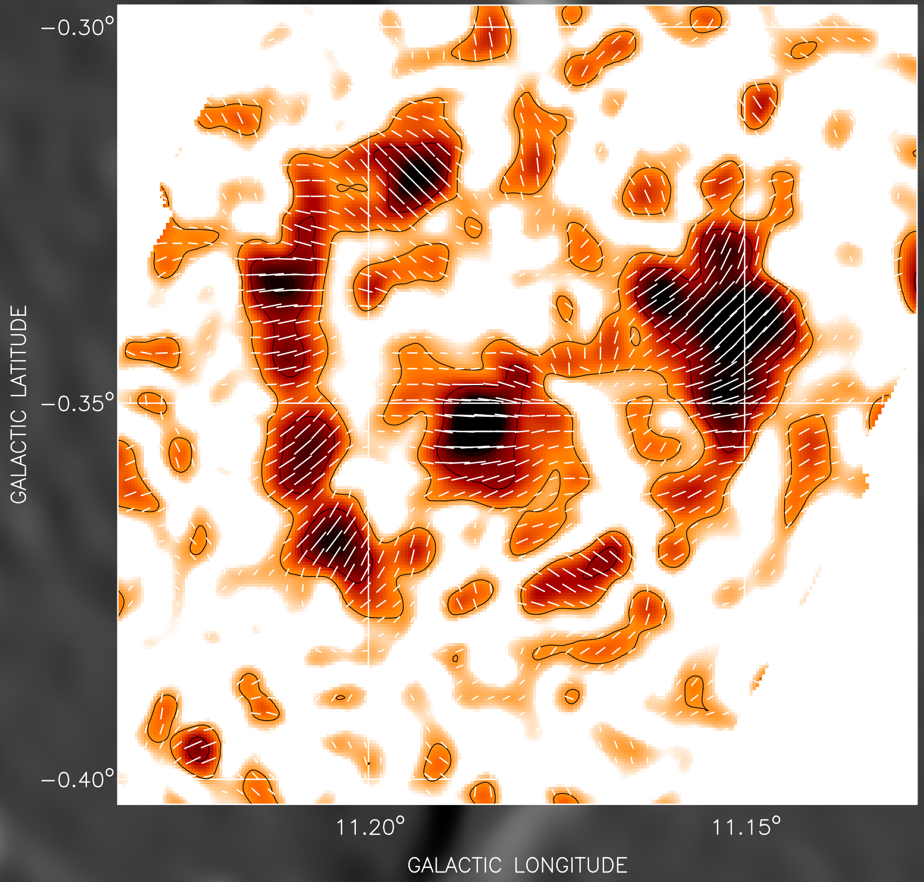


The guest star from AD 386: SNR G11.2−0.3

Effelsberg TP 32 GHz

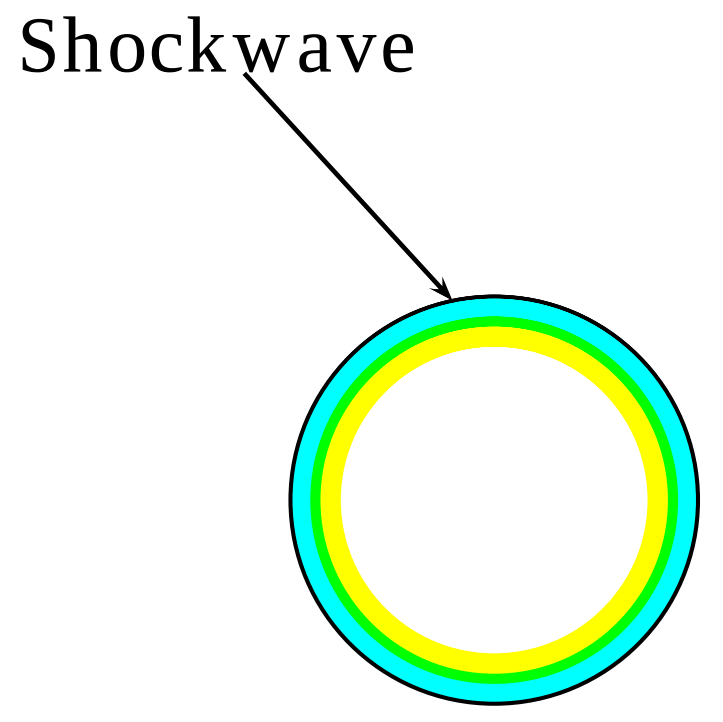


Effelsberg PI + B-vectors 32 GHz



G11.2−0.3 is at the transition between free expansion and adiabatic expansion. (Kothes & Reich, 2001)

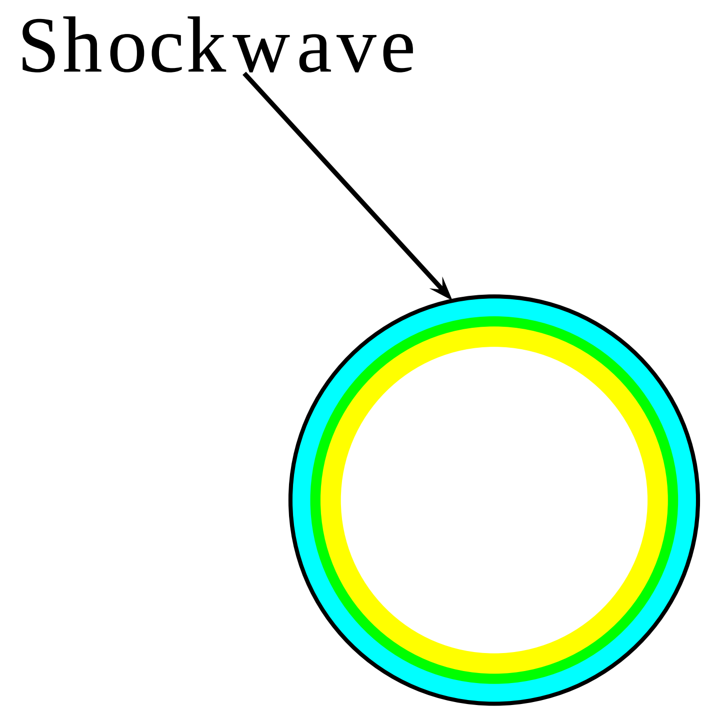
Shell-type SNRs



Adiabatic (Sedov) Expansion:

- the SNR is expanding adiabatically dominated by the swept up material ($R \sim t^{0.4}$), which contains a frozen in tangential magnetic field
- electrons are still accelerated in the turbulent zone and additionally at the outside edge
- radiative losses are still negligible
- Sedov phase lasts a few 1000 to 15000 yrs

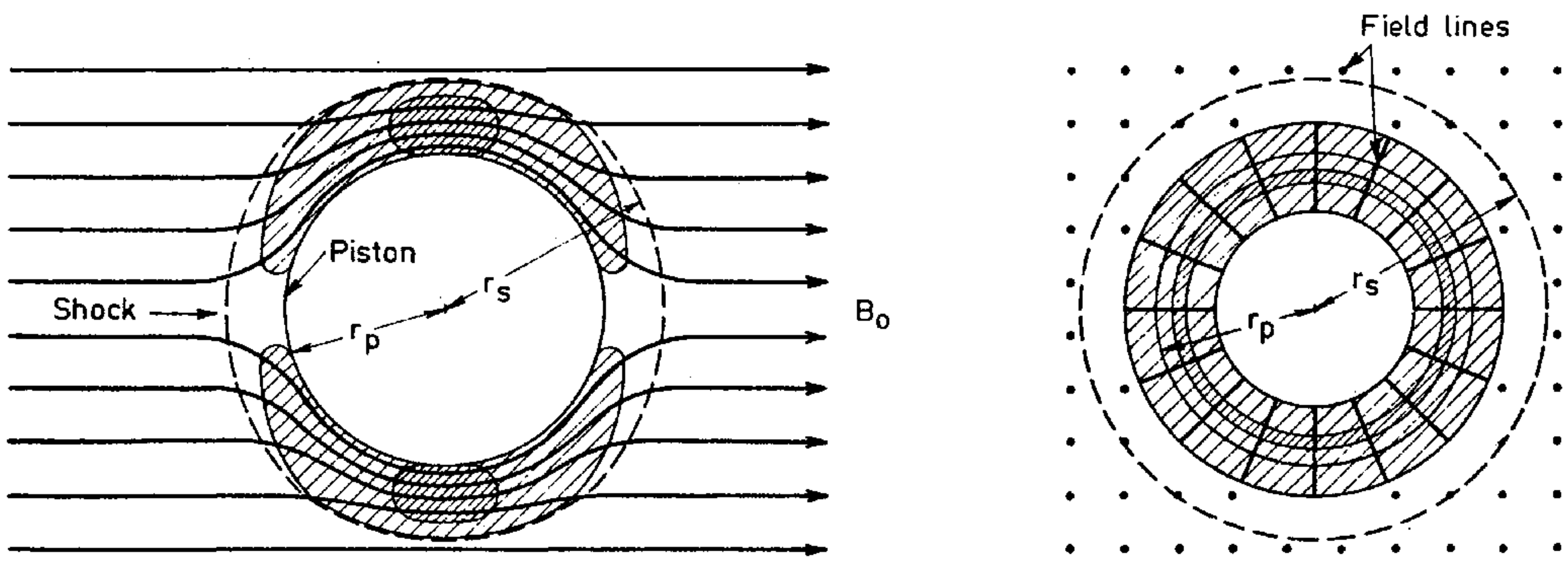
Shell-type SNRs



Characteristics of the Radio Emission During the Sedov Phase:

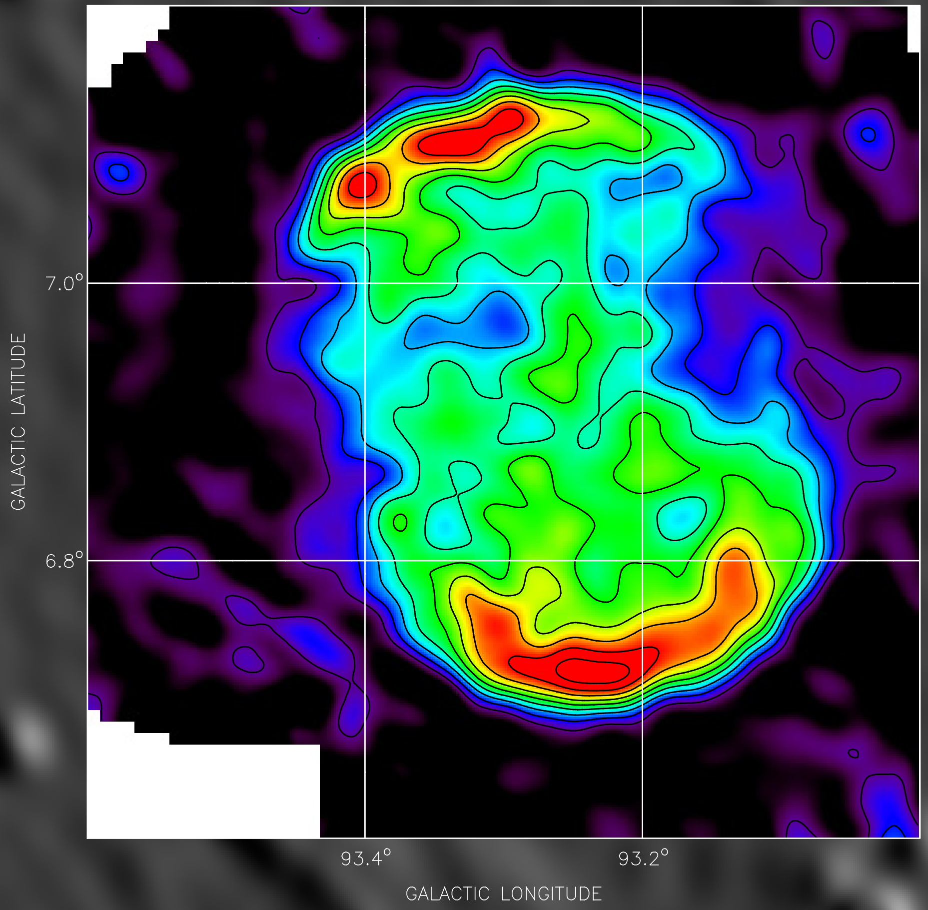
- synchrotron radio spectrum with $\alpha \approx -0.5$ (S$\sim \nu^{\alpha}$) with a tangential magnetic field
- radio shell with a sharp outer edge
- high percentage polarization due to well defined magnetic field structure

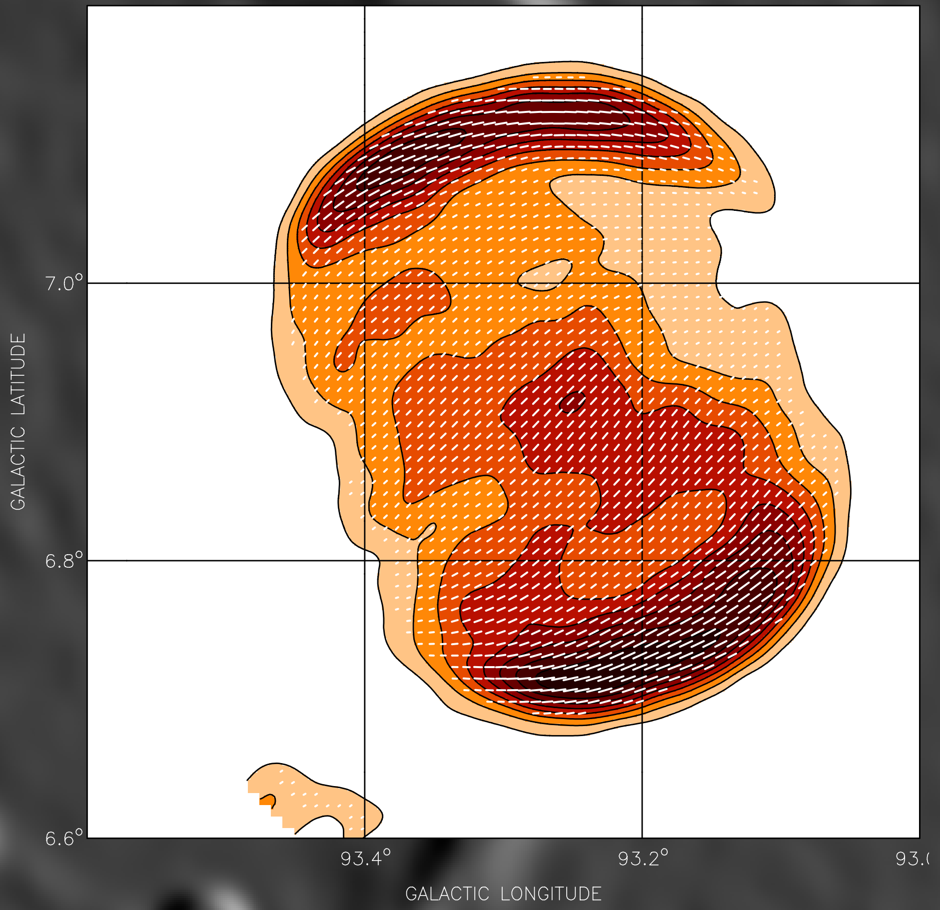
Shell-type SNRs



The magnetic field perpendicular to the expansion direction is frozen into the expanding swept up material.

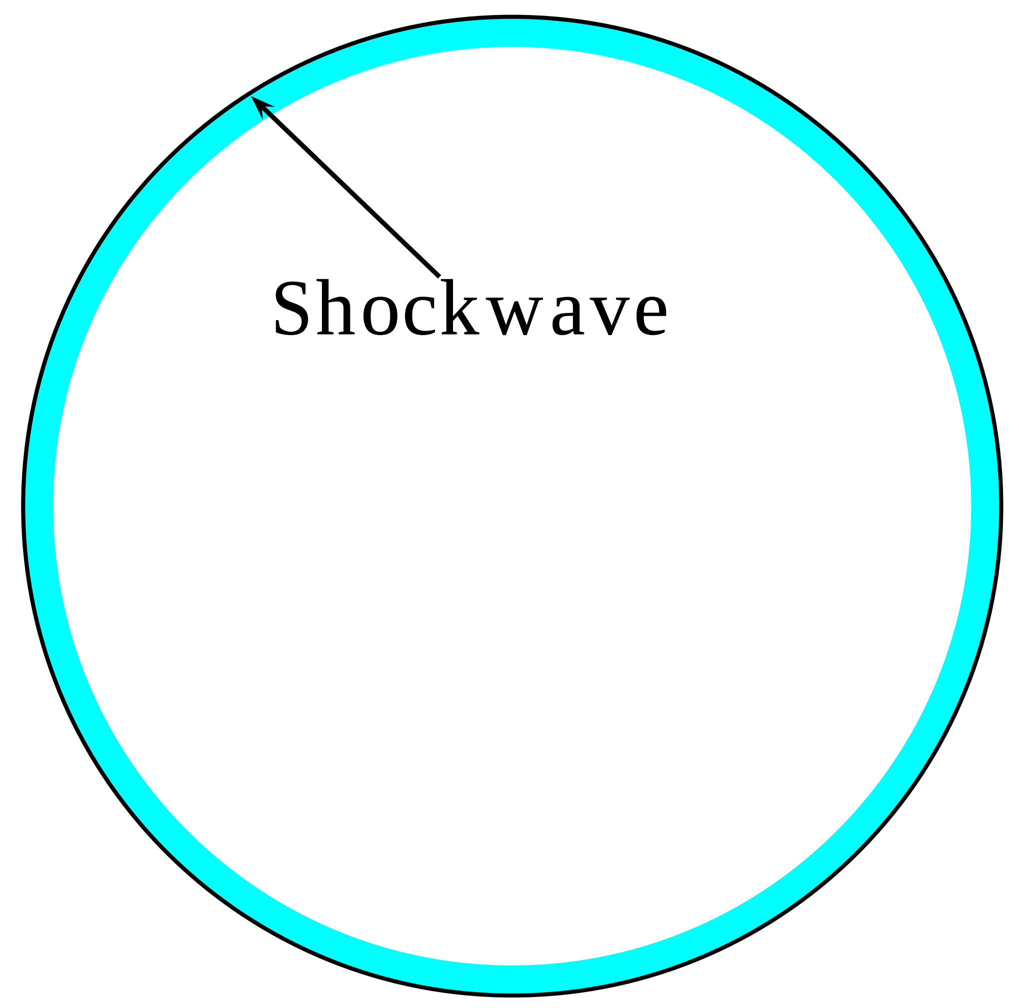
DA 530


Effelsberg TP 10.5 GHz


Effelsberg PI + B-vectors 10.5 GHz

DA 530 is expanding adiabatically in a quite homogenous ambient medium.

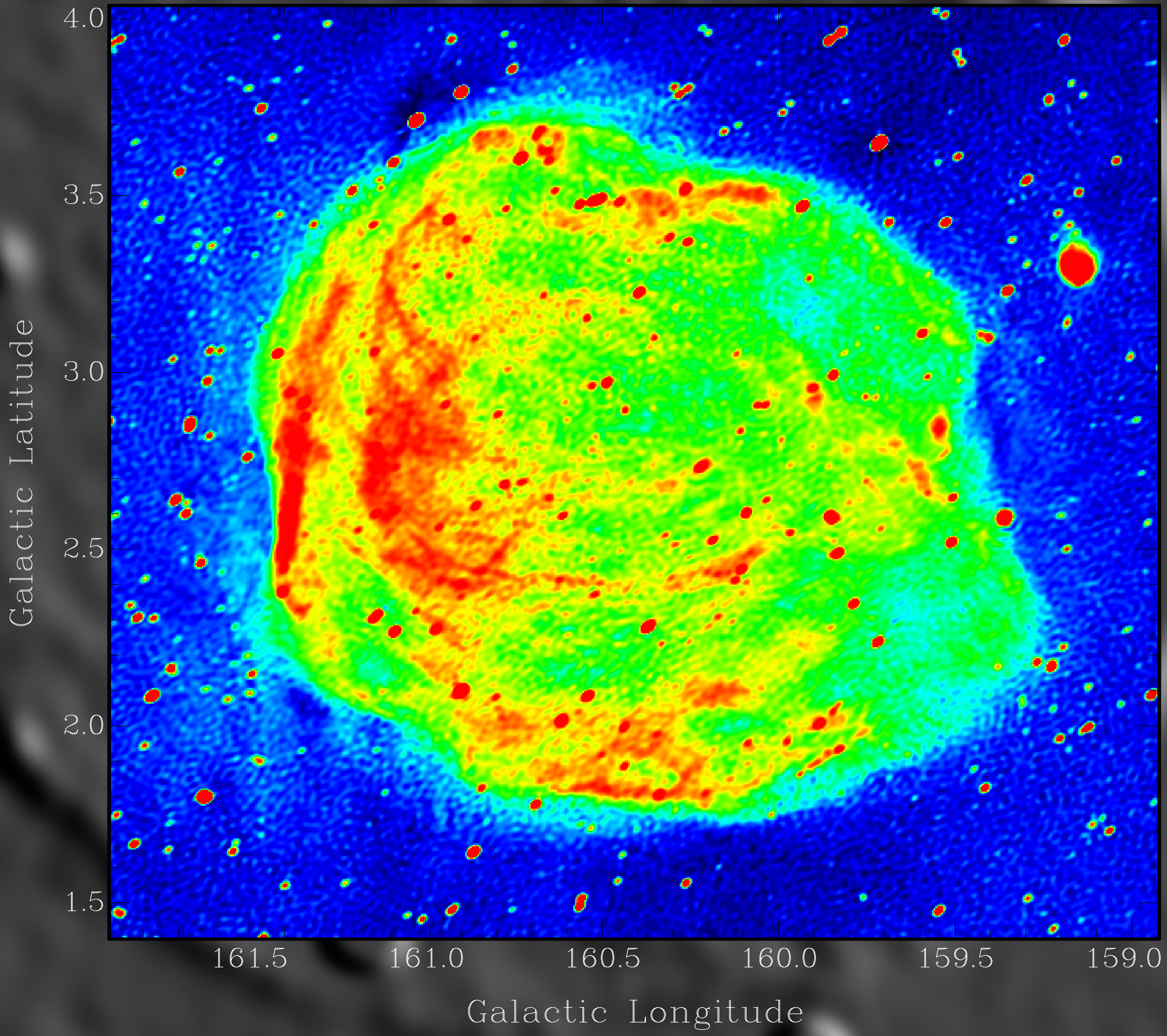
Shell-type SNRs



Radiative Expansion (momentum conserving snowplow phase):

- energy losses due to radiative cooling become significant
- expanding shell moves at constant radial momentum ($R \sim t^{0.25}$)
- the synchrotron spectrum may become flatter and the emission slowly fades away

HB 9


4.0
3.5
3.0
2.5
2.0
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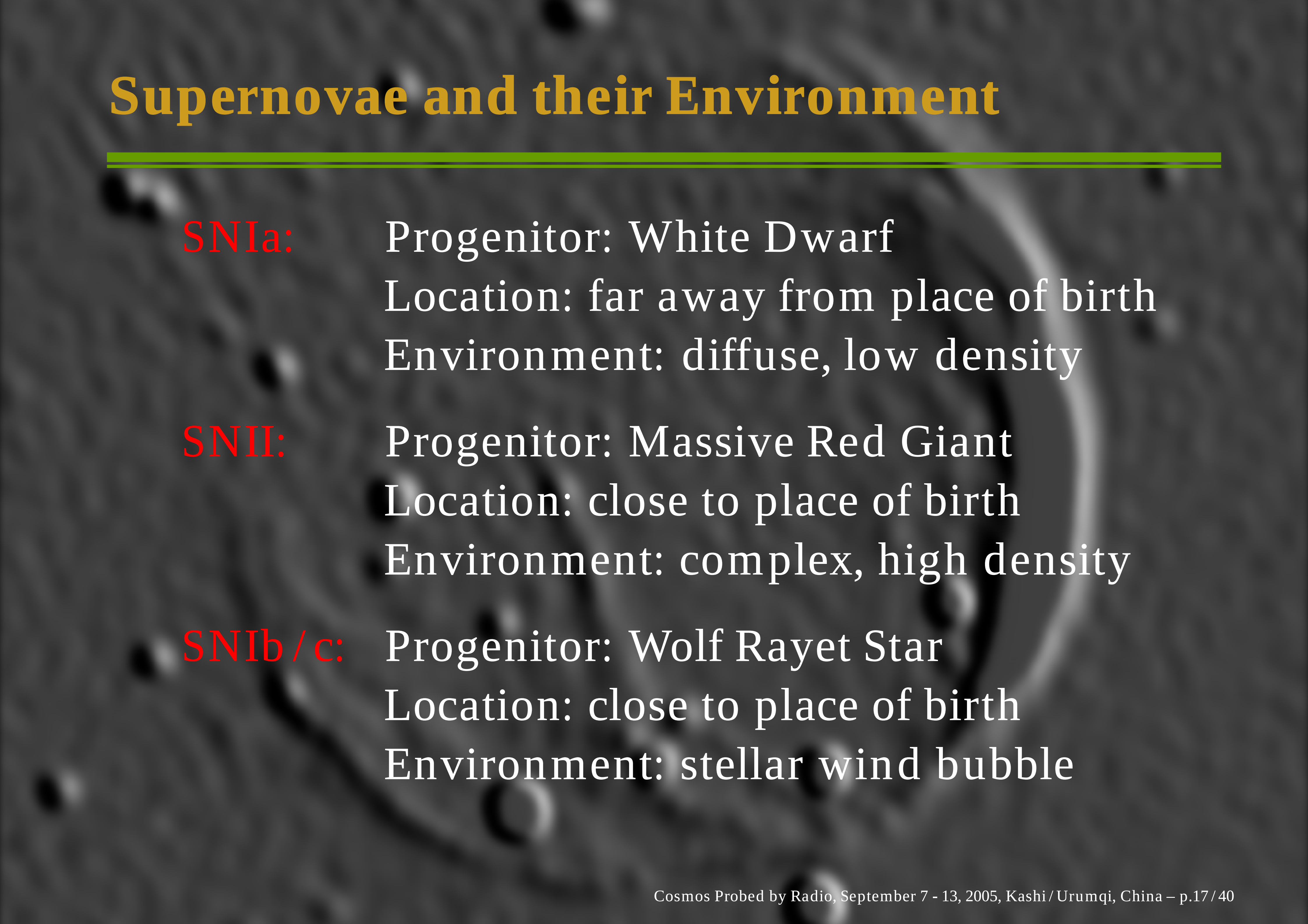
Galactic Latitude
161.5
161.0
160.5
160.0
159.5
159.0
Galactic Longitude



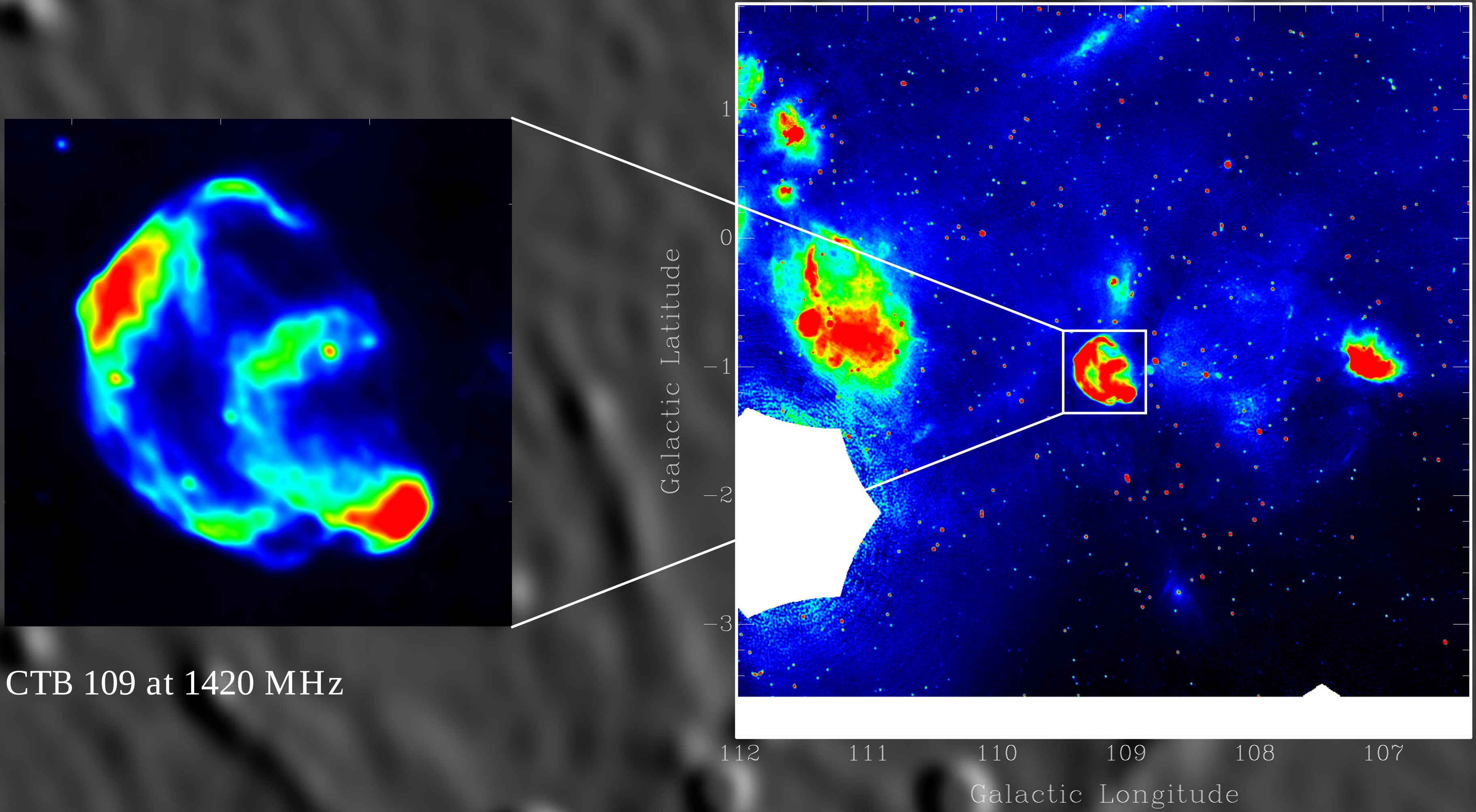
Supernovae and their Environment

SNIa: Progenitor: White Dwarf
Location: far away from place of birth
Environment: diffuse, low density

SNII: Progenitor: Massive Red Giant
Location: close to place of birth
Environment: complex, high density

SNIb/c: Progenitor: Wolf Rayet Star
Location: close to place of birth
Environment: stellar wind bubble

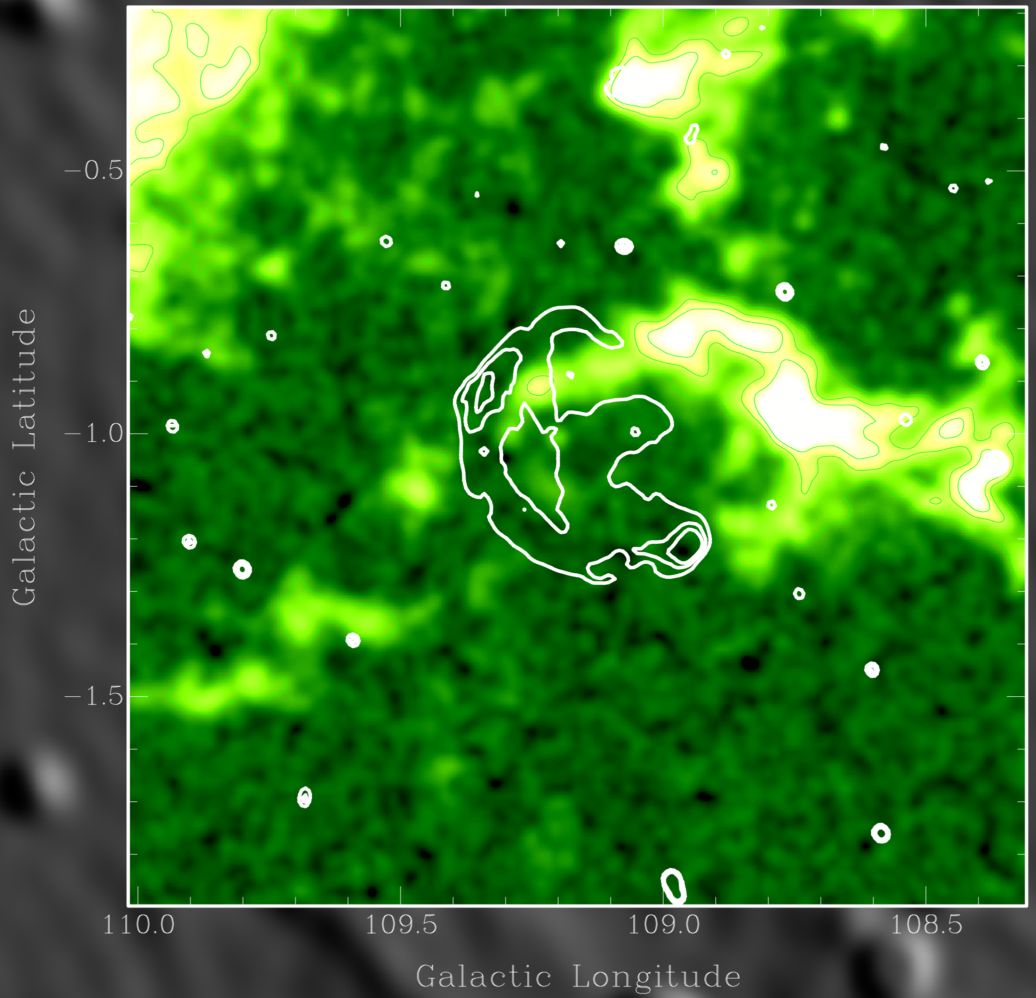
CTB 109



CTB 109 at 1420 MHz

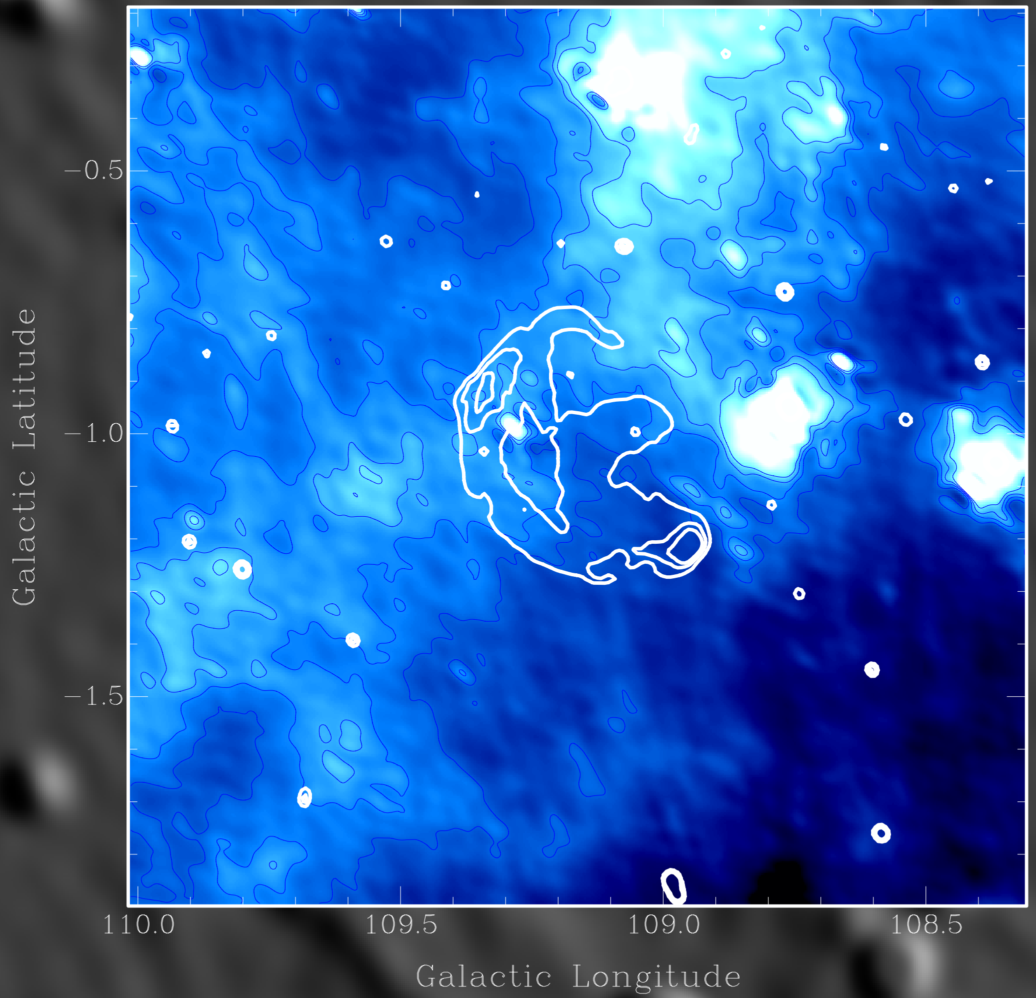
(Kothes et al., 2002)

CO around CTB 109



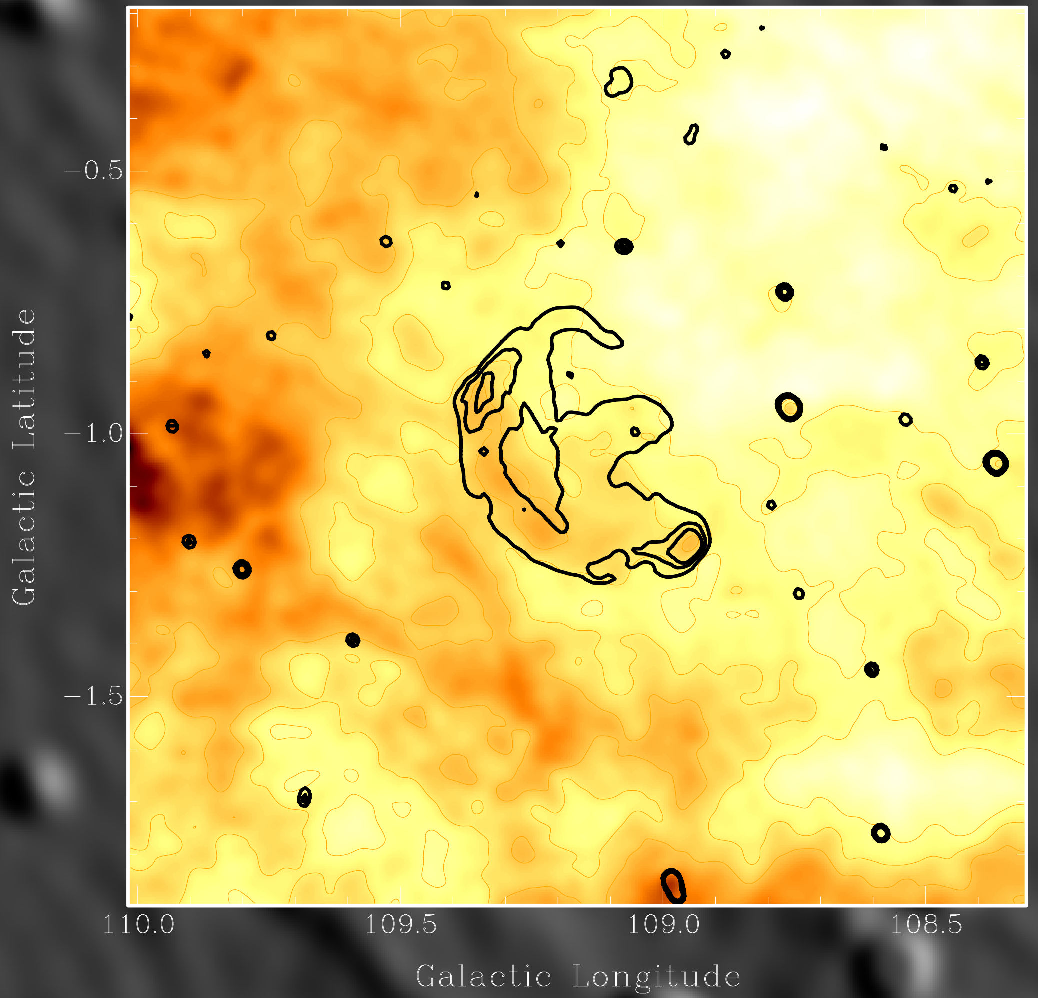
- CTB 109 is interacting with a dense molecular cloud

Dust around CTB 109



- CTB 109 is interacting with a dense molecular cloud
- and dust

HI around CTB 109

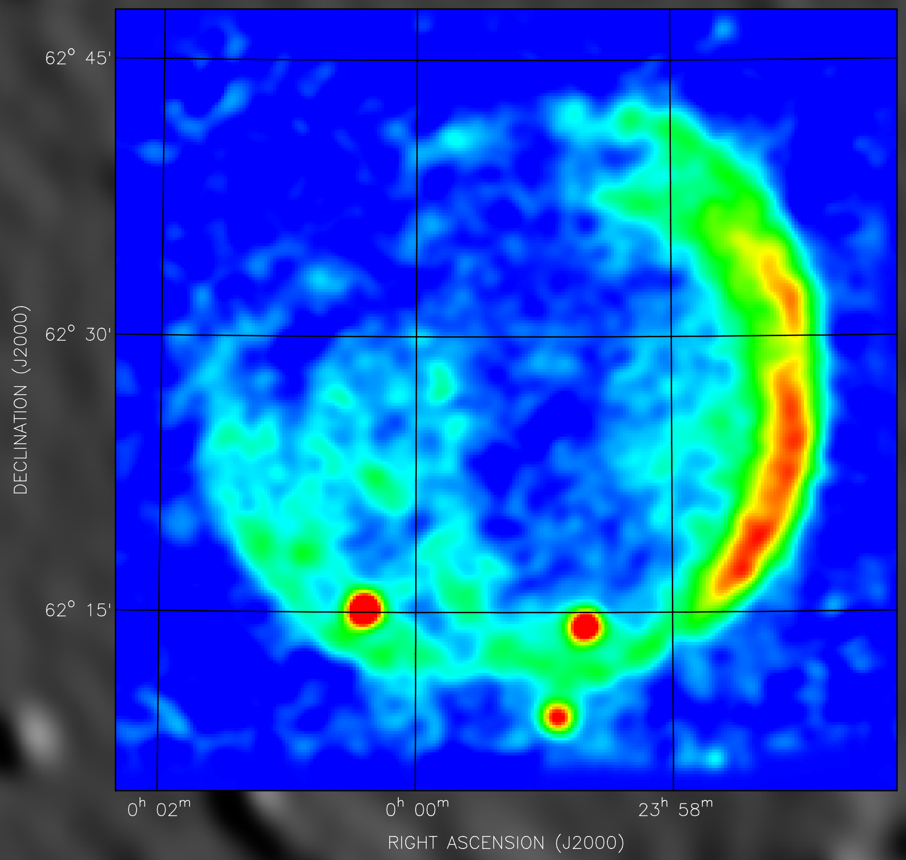


- CTB 109 is interacting with a dense molecular cloud
- and dust
- It seems to be located at a HI density gradient and there is no evidence of a stellar wind bubble

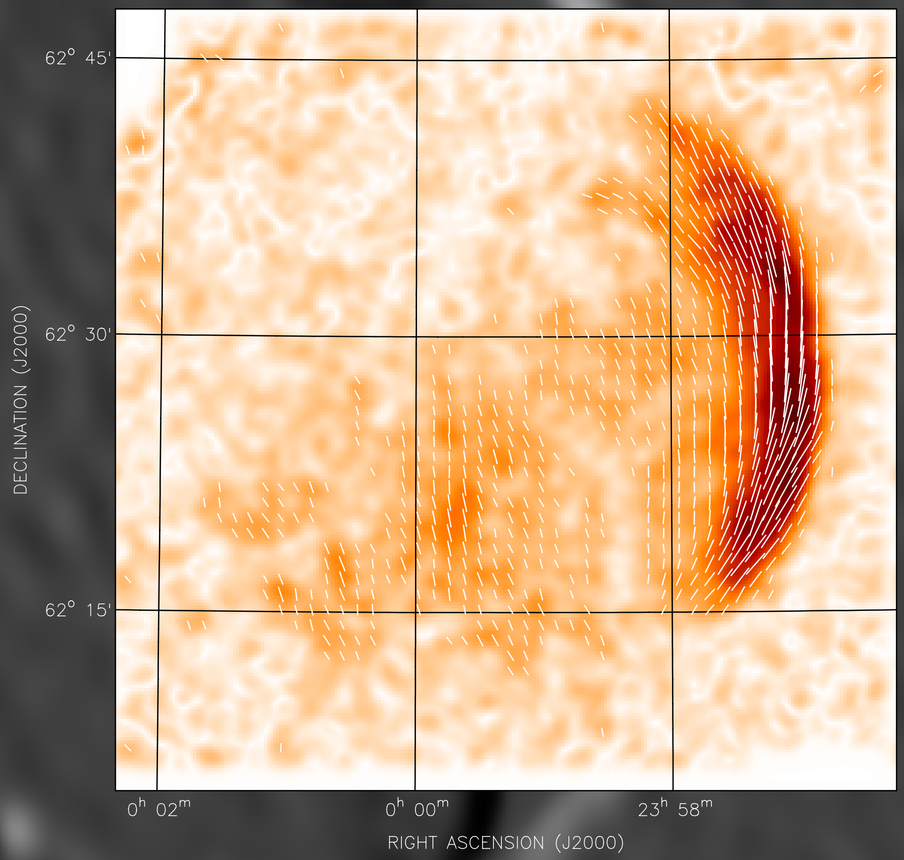
⇒ CTB 109 is a strong SNII candidate

CTB 1

Effelsberg TP 10.5 GHz



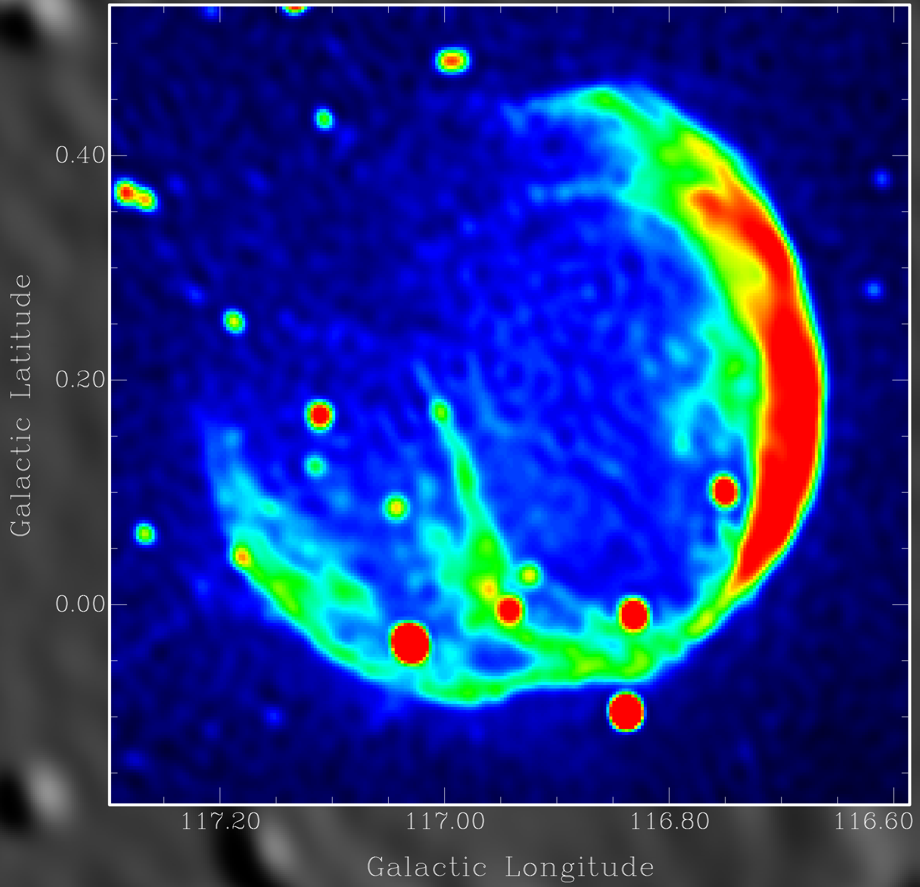
Effelsberg PI + B-vectors 10.5 GHz

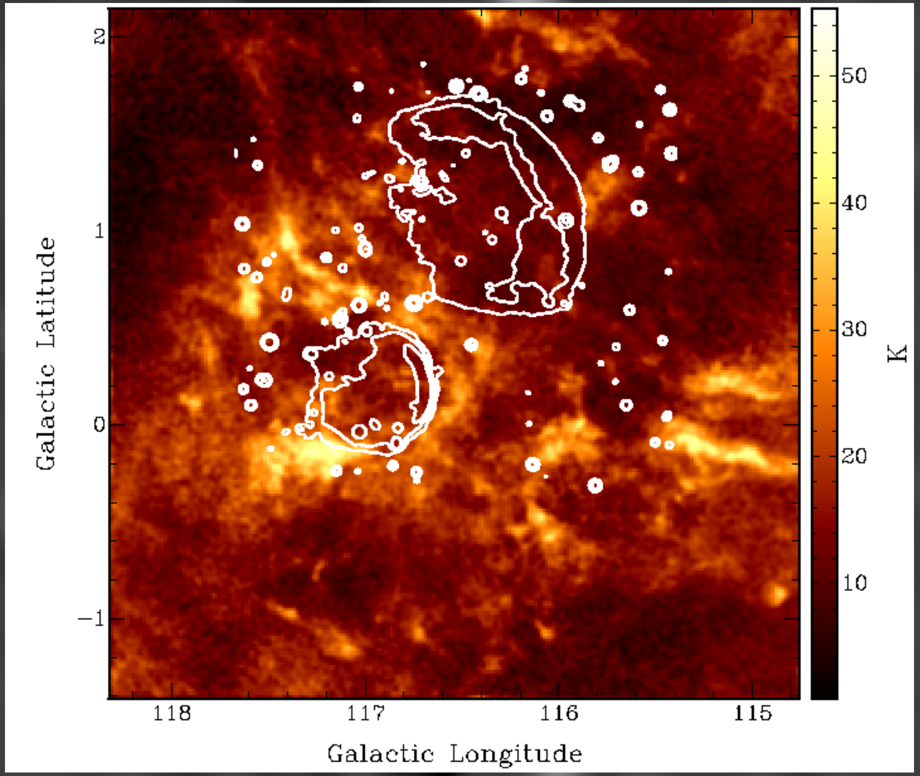


(Courtesy E. Fürst)

CTB 1 has a shell structure with an opening to the north-west.

HI around CTB 1

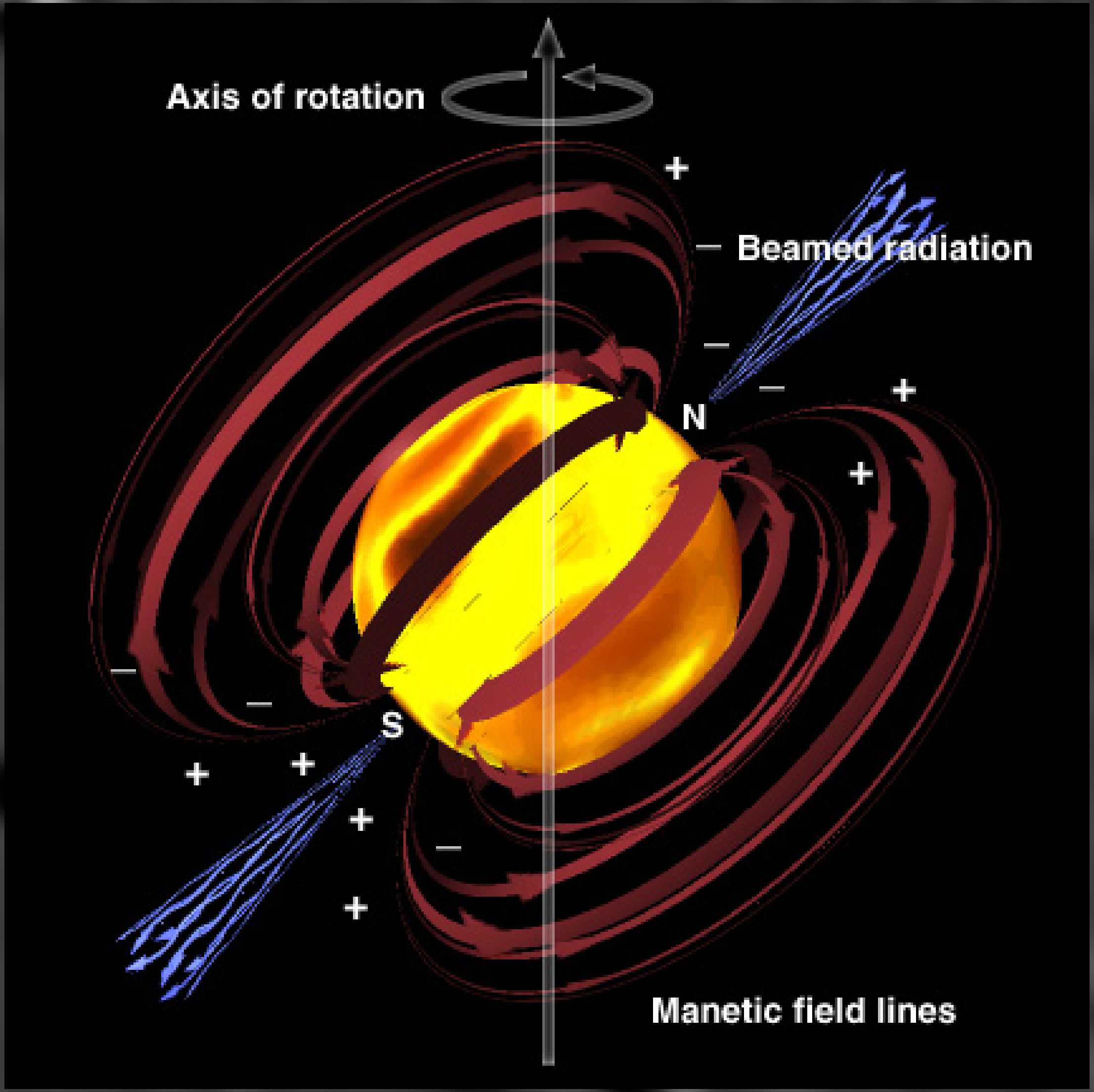




CTB 1 exploded inside a stellar wind bubble. SNIb?

(Yar et al., 2004)

Pulsar Wind Nebulae



Pulsars:

- pulsars are fast rotating neutron stars, which lose energy by dipole radiation
- this energy is released in an energetic wind of particles and magnetic field
- the interaction of the relativistic electrons and the magnetic field produce synchrotron emission with a flat spectrum ($-0.3 \leq \alpha \leq 0.0$)
- the characteristic age τ of a pulsar is defined by: $\tau = \frac{P}{2\dot{P}}$ for a pure dipole field

Pulsar Wind Nebulae

The energy loss rate of a pulsar decreases with time as:

$$\dot{E} = \frac{\dot{E}_0}{(1+\frac{t}{\tau_0})^{\beta}}, \; (\beta = 2 \text{ for a dipole field})$$

here τ_0 is the initial characteristic age also called the pulsar's "lifetime", because it is the time after which the energy input of a pulsar becomes neligible for its nebula.

$\Rightarrow$ to get an idea about the energy content of such a nebula and a pulsar's lifetime, knowledge about the real age of the pulsar is essential.

Historical Pulsars

There are three "historical" pulsars:

SNR	Pulsar	Age [yr]	τ [yr]	$\dot{E}$ [erg / s]
3C58	J0205+6449	820	5370	$2.7 \cdot 10^{37}$
Crab nebula	B0531+21	950	1240	$4.6 \cdot 10^{38}$
G11.2–0.3	J1811–1925	1620	23300	$6.4 \cdot 10^{36}$

Historical Pulsars

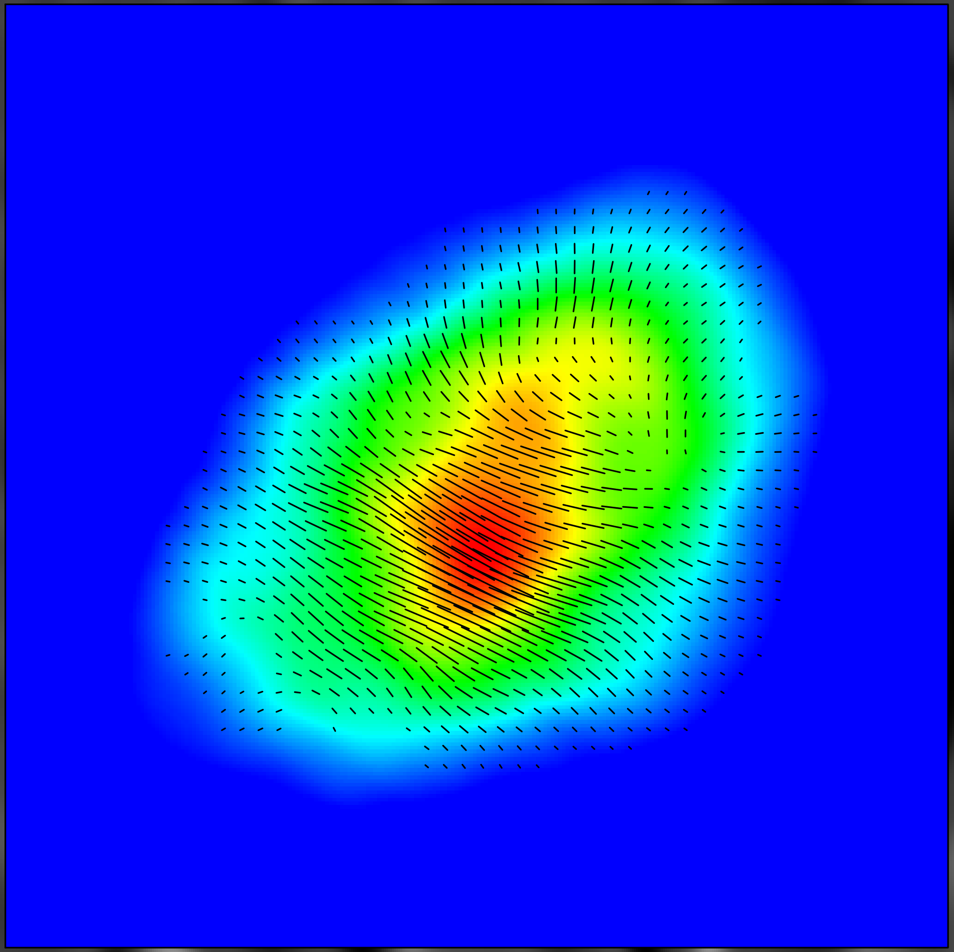
Initial parameters for the "historical" pulsars:

SNR	Pulsar	τ_0 [yr]	$\dot{E}_0$ [erg / s]	E_{tot} [erg]
3C58	J0205+6449	4550	$3.8 \cdot 10^{37}$	10^{48}
Crab nebula	B0531+21	320	$1.0 \cdot 10^{40}$	10^{50}
G11.2–0.3	J1811–1925	21680	$7.4 \cdot 10^{36}$	$4 \cdot 10^{47}$

It is interesting to note that the radio flux of the Crab Nebula is decreasing while it is increasing for 3C58.

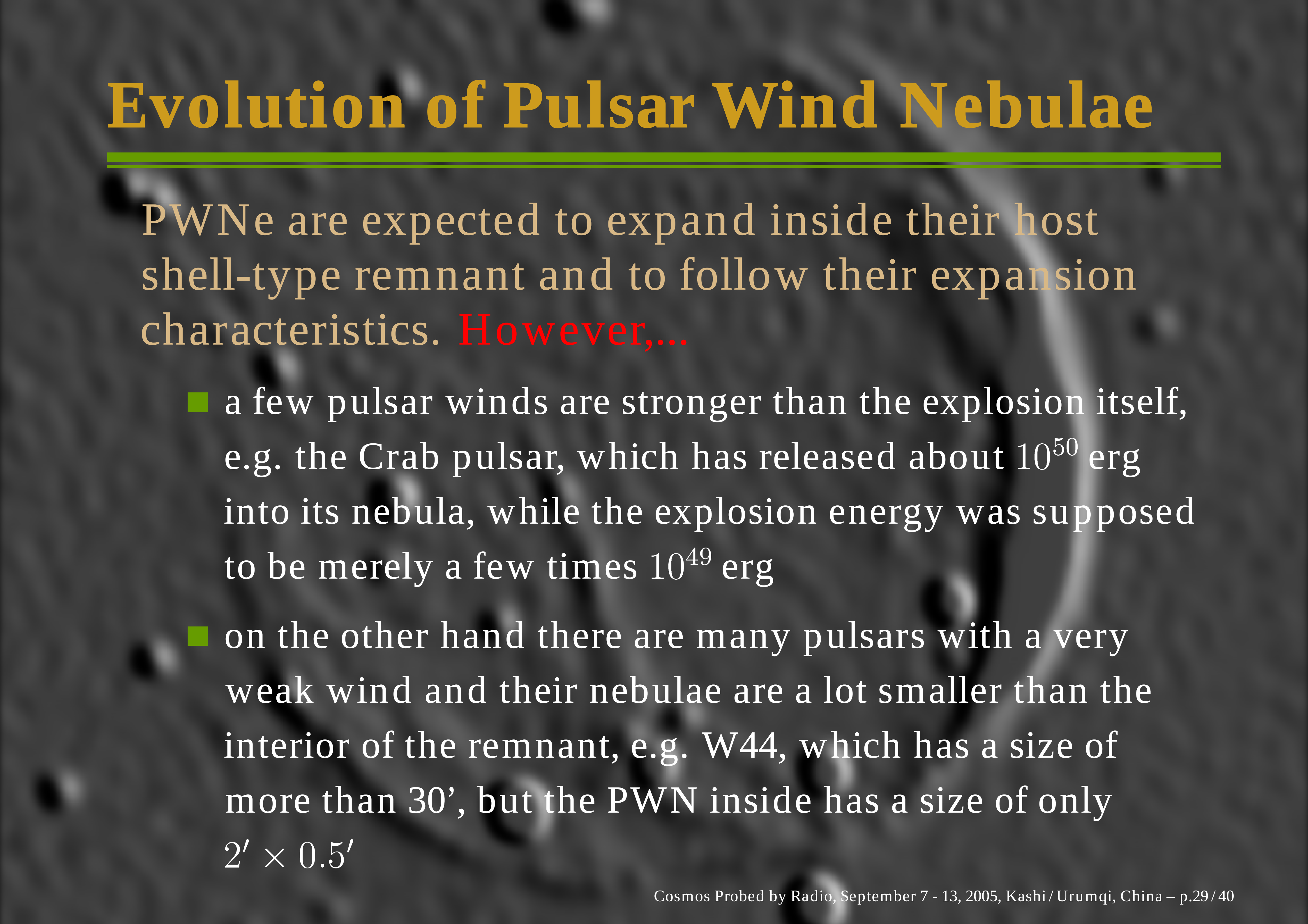
Crab Nebula

Effelsberg TP + B-vectors 32 GHz



(Courtesy W. Reich)

Evolution of Pulsar Wind Nebulae



PWNe are expected to expand inside their host shell-type remnant and to follow their expansion characteristics. However,...

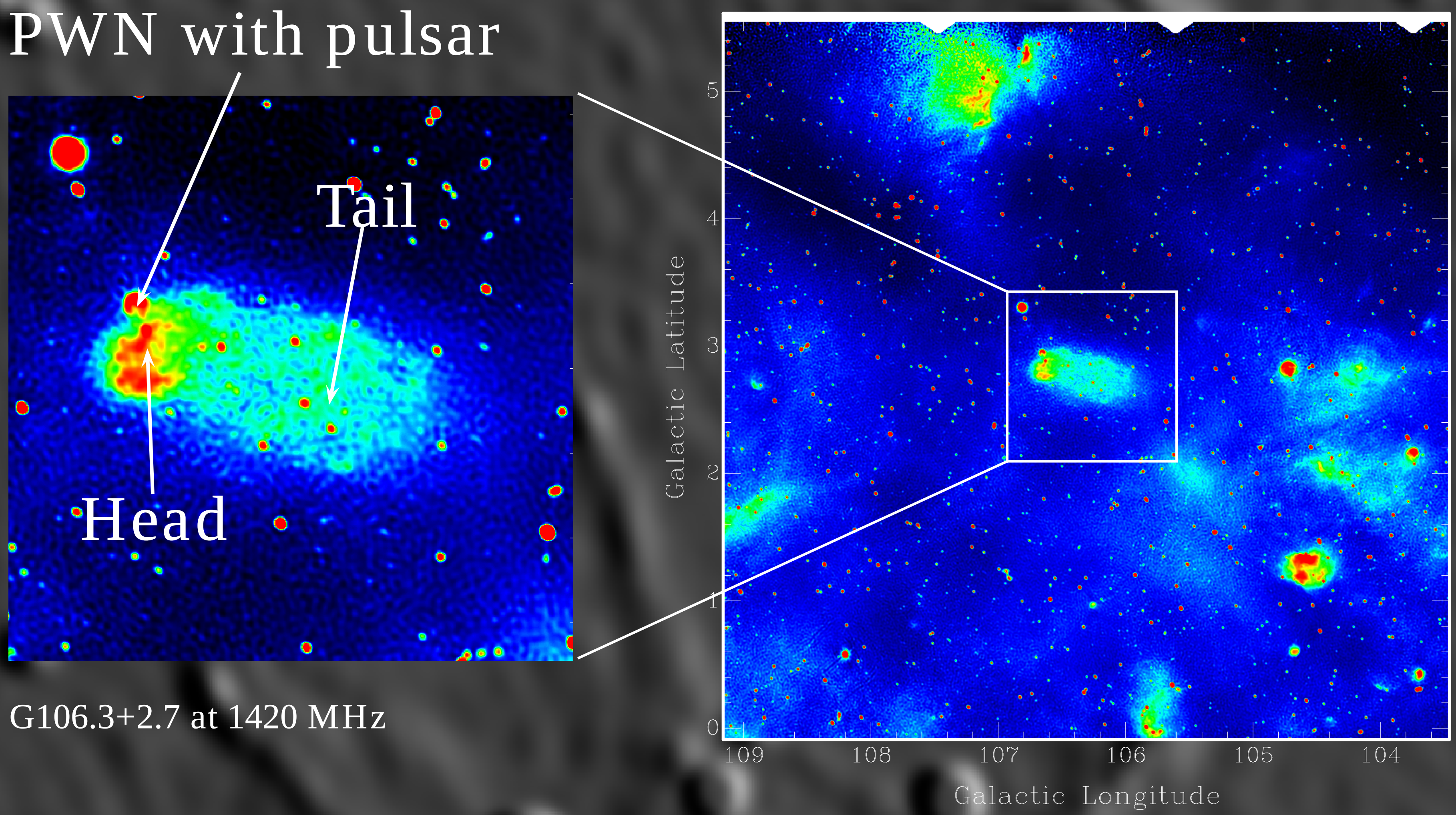
- a few pulsar winds are stronger than the explosion itself, e.g. the Crab pulsar, which has released about 10^{50} erg into its nebula, while the explosion energy was supposed to be merely a few times 10^{49} erg
- on the other hand there are many pulsars with a very weak wind and their nebulae are a lot smaller than the interior of the remnant, e.g. W44, which has a size of more than 30’, but the PWN inside has a size of only $2' \times 0.5'$

Evolution of Pulsar Wind Nebulae

When the interaction between the ejecta and the swept up material becomes strong a reverse shock is created, travelling back into the interior of the SNR:

- this leads to compression and maybe additional electron acceleration in the PWN
- a density gradient in the ambient medium can lead to an asymmetric reverse shock and an off-centre position for the pulsar, e.g. Vela (Blondin et al., 2001)

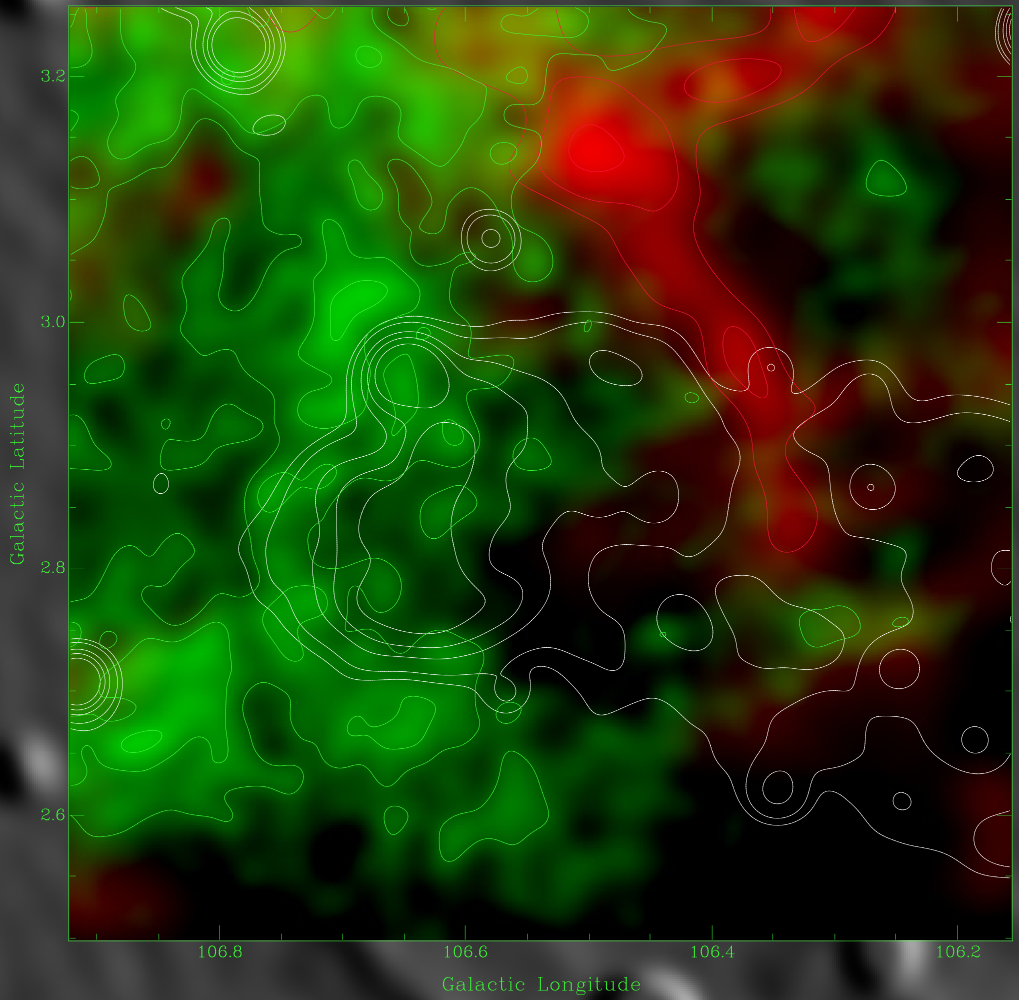
G106.3+2.7



G106.3+2.7 at 1420 MHz

Kothes et al., 2001

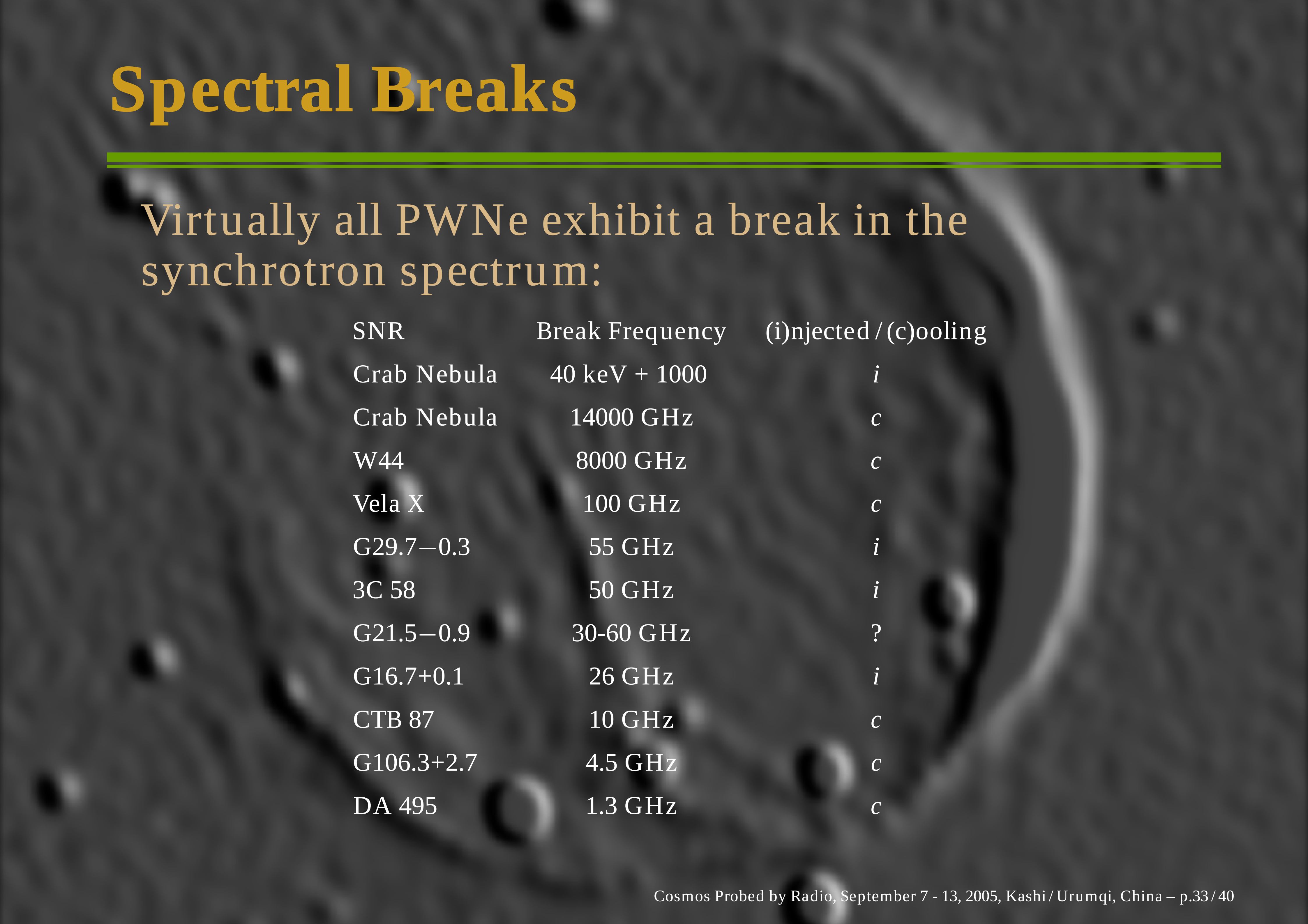
The Cold Environment of G106.3+2.7



- A shell-like HI structure is surrounding the head of the SNR
- a small HI shell is wrapped around the pulsar wind nebula
- towards the west a thin molecular shell separates the head from the tail

The reverse shock pushed away the original PWN, creating the diffuse part of the head and the pulsar started a new nebula.

Spectral Breaks



Virtually all PWNe exhibit a break in the synchrotron spectrum:

SNR	Break Frequency	(i)njected / (c)ooling
Crab Nebula	40 keV + 1000	*i*
Crab Nebula	14000 GHz	*c*
W44	8000 GHz	*c*
Vela X	100 GHz	*c*
G29.7−0.3	55 GHz	*i*
3C 58	50 GHz	*i*
G21.5−0.9	30-60 GHz	?
G16.7+0.1	26 GHz	*i*
CTB 87	10 GHz	*c*
G106.3+2.7	4.5 GHz	*c*
DA 495	1.3 GHz	*c*

Synchrotron Cooling

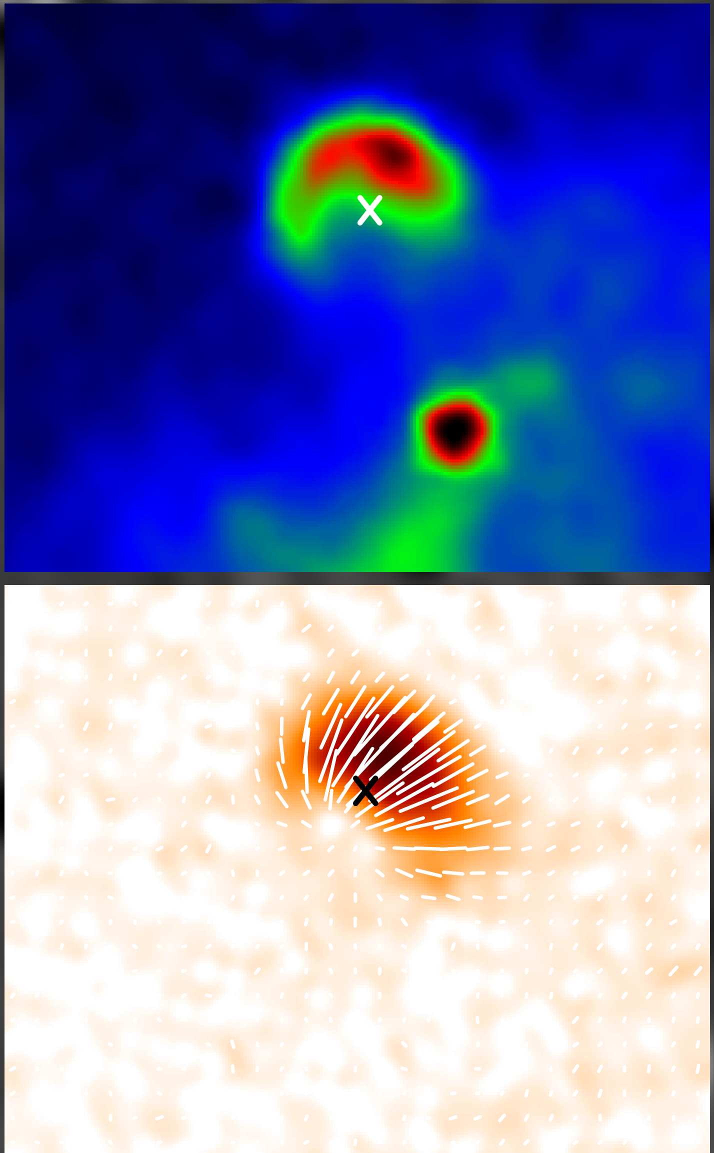
The cooling break represents the frequency at which synchrotron losses become significant:

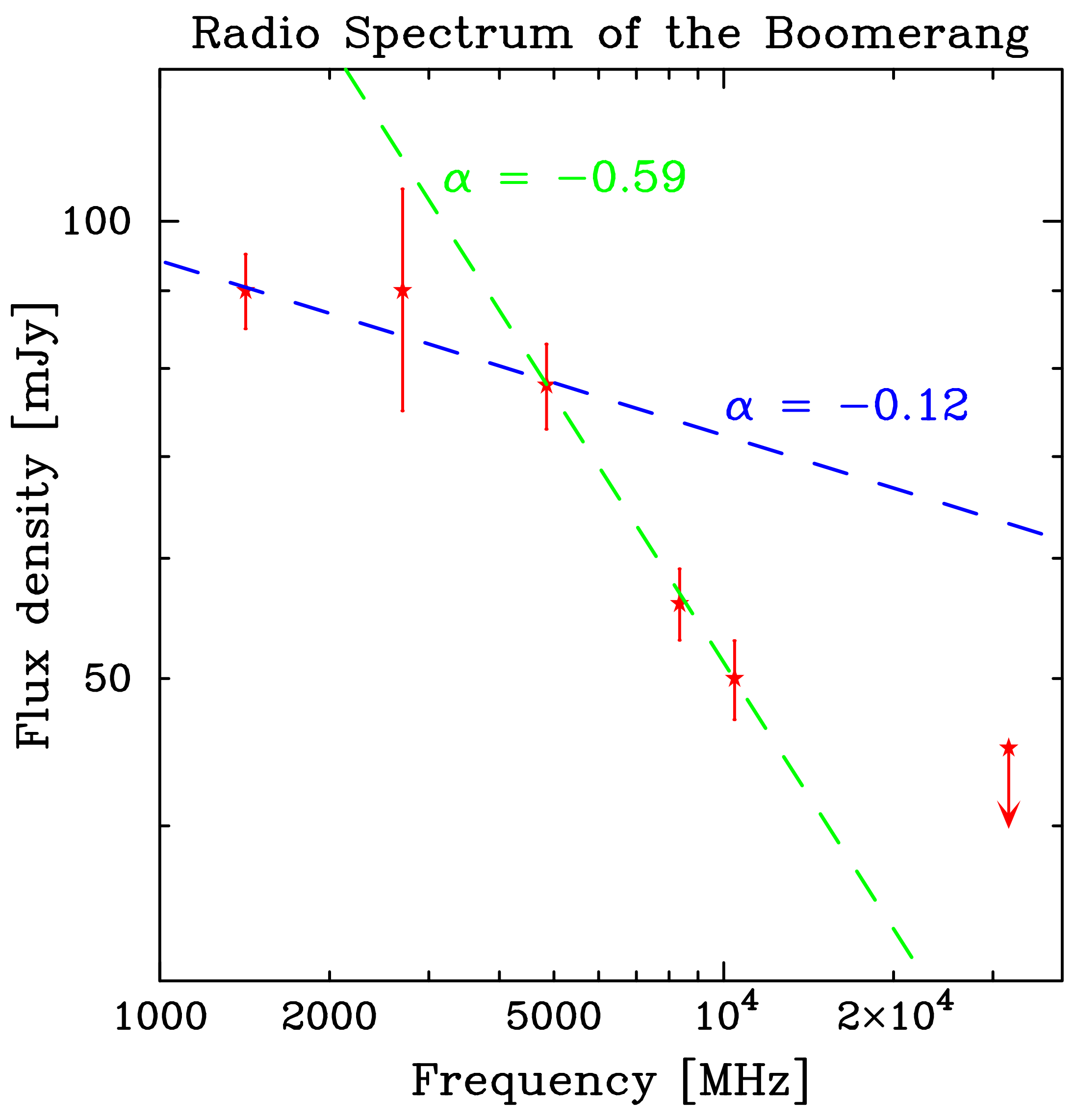
$$\nu_c\,[\mathrm{GHz}] = 1.187 \cdot B^{-3}\,[\mathrm{G}]\,\cdot t^{-2}\,[\mathrm{yr}]$$

(Chevalier, 2000)

The cooling break frequency is slowly decreasing with time while the intrinsic break should remain constant after the lifetime of the pulsar.

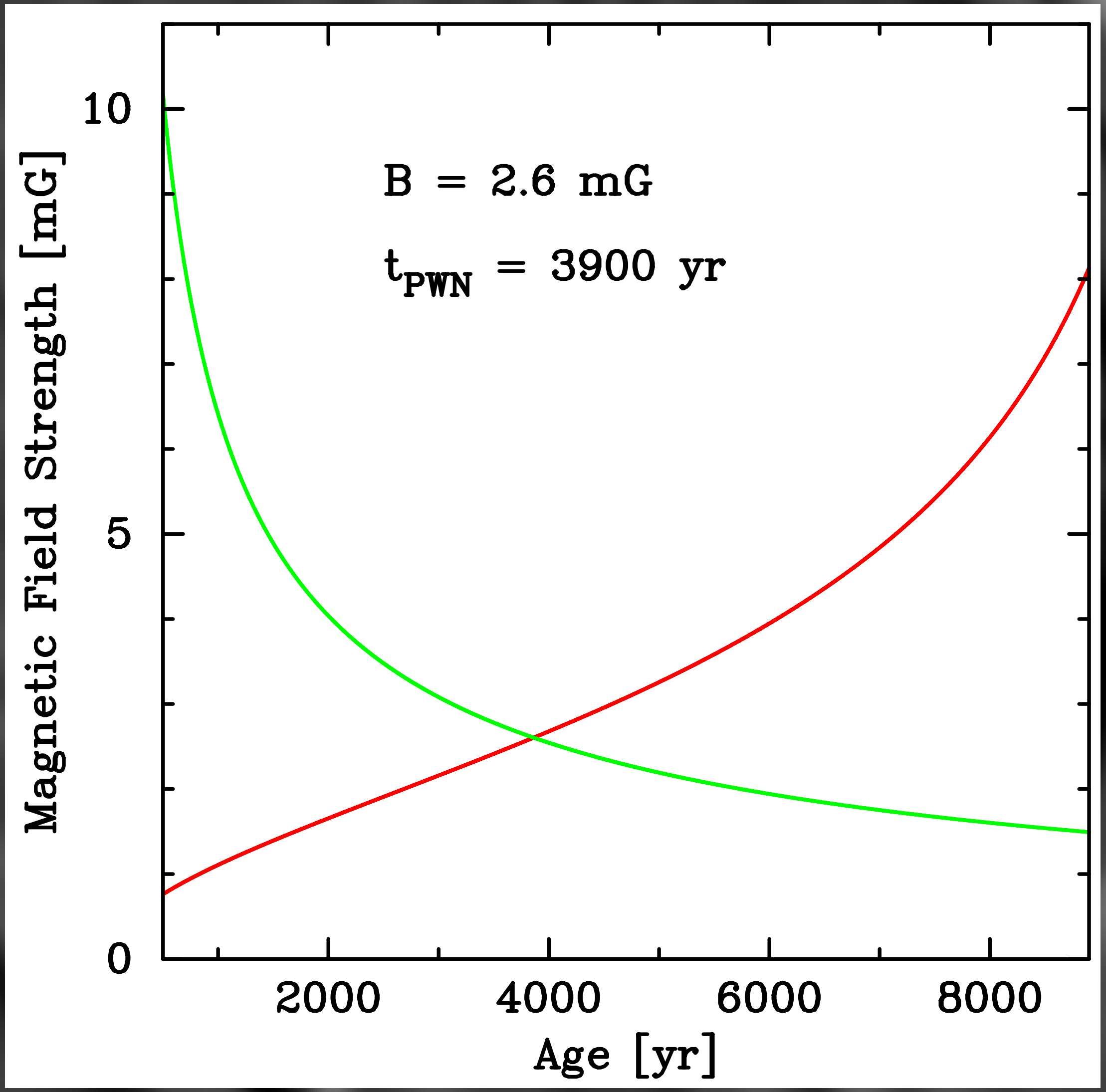
The spectrum of the ”Boomerang”





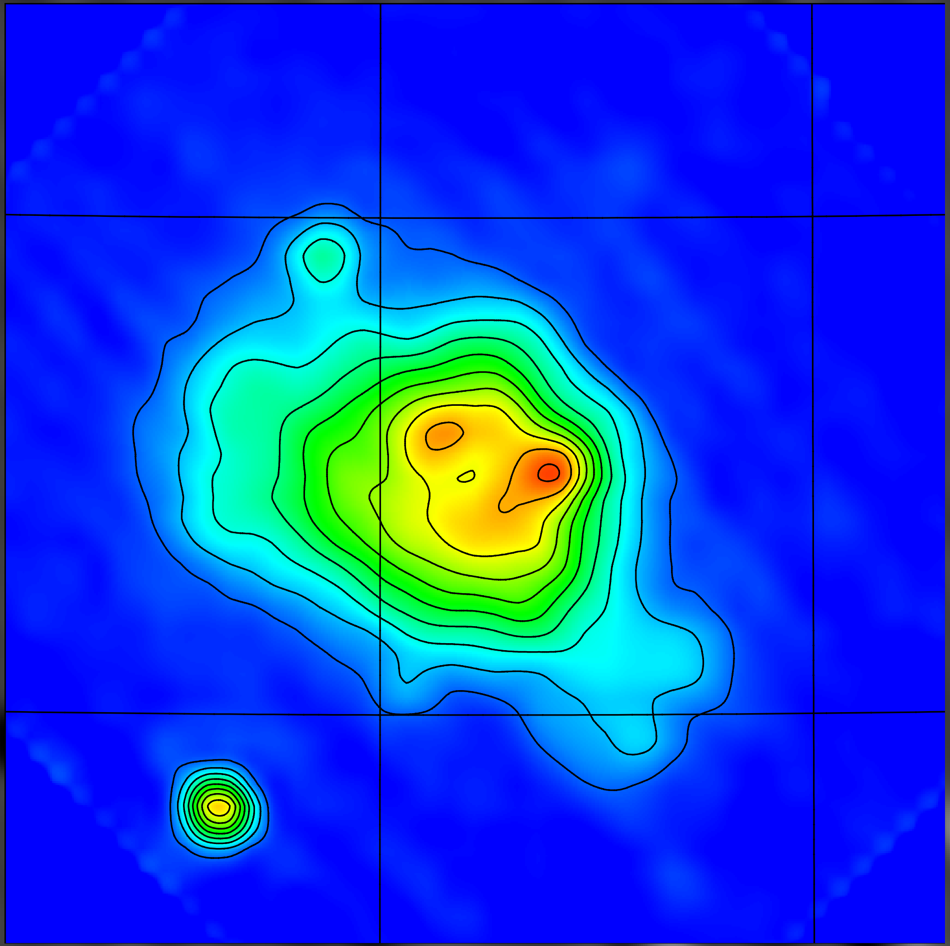
Radio Spectrum of the Boomerang

The age of the ”Boomerang”

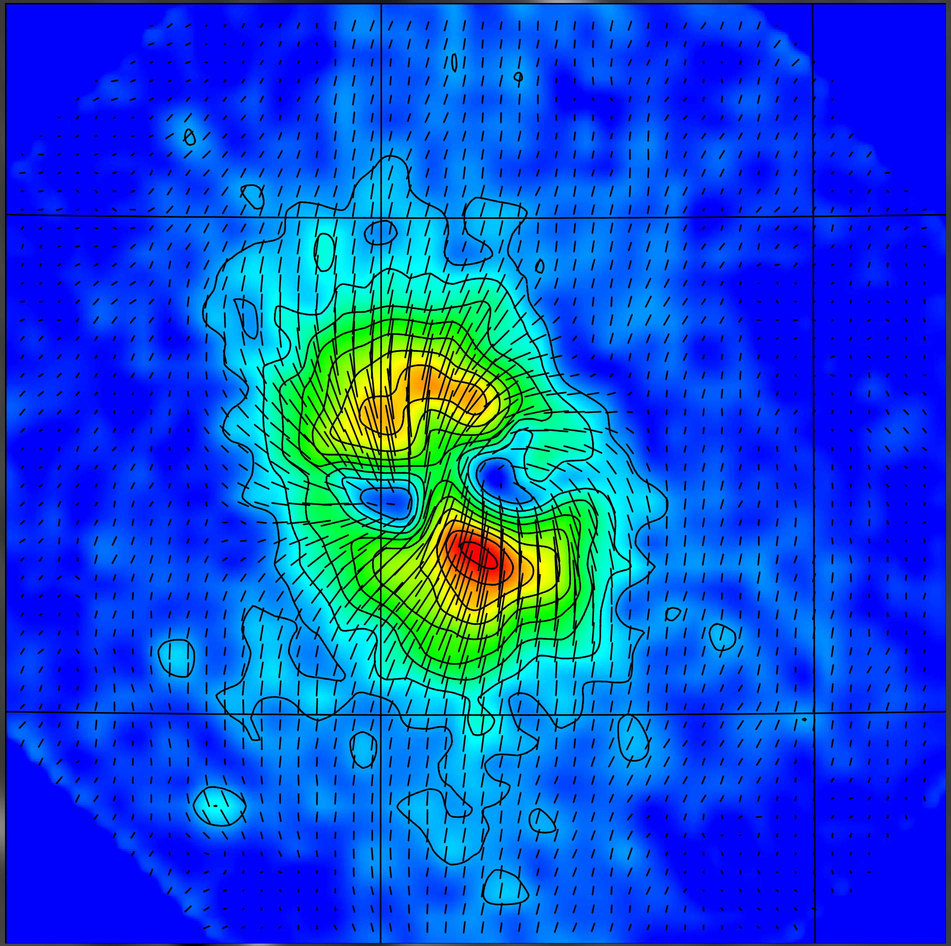


(Kothes et al., 2005)

DA 495

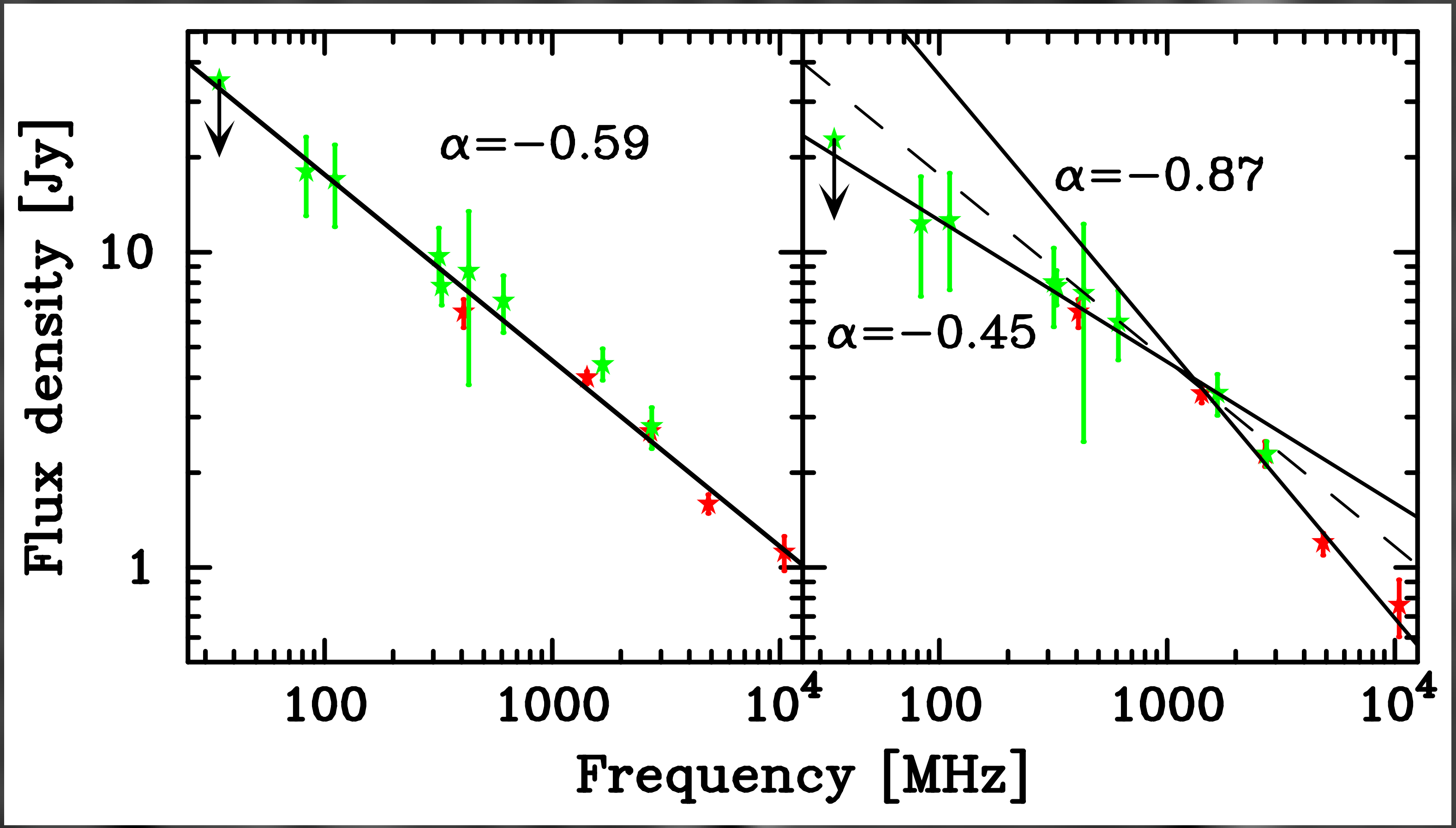


Effelsberg TP 4.85 GHz



Effelsberg PI + B-vectors 4.85 GHz

The spectrum of DA 495



$\nu_c = 1.3$ GHz

(Kothes et al., 2005)

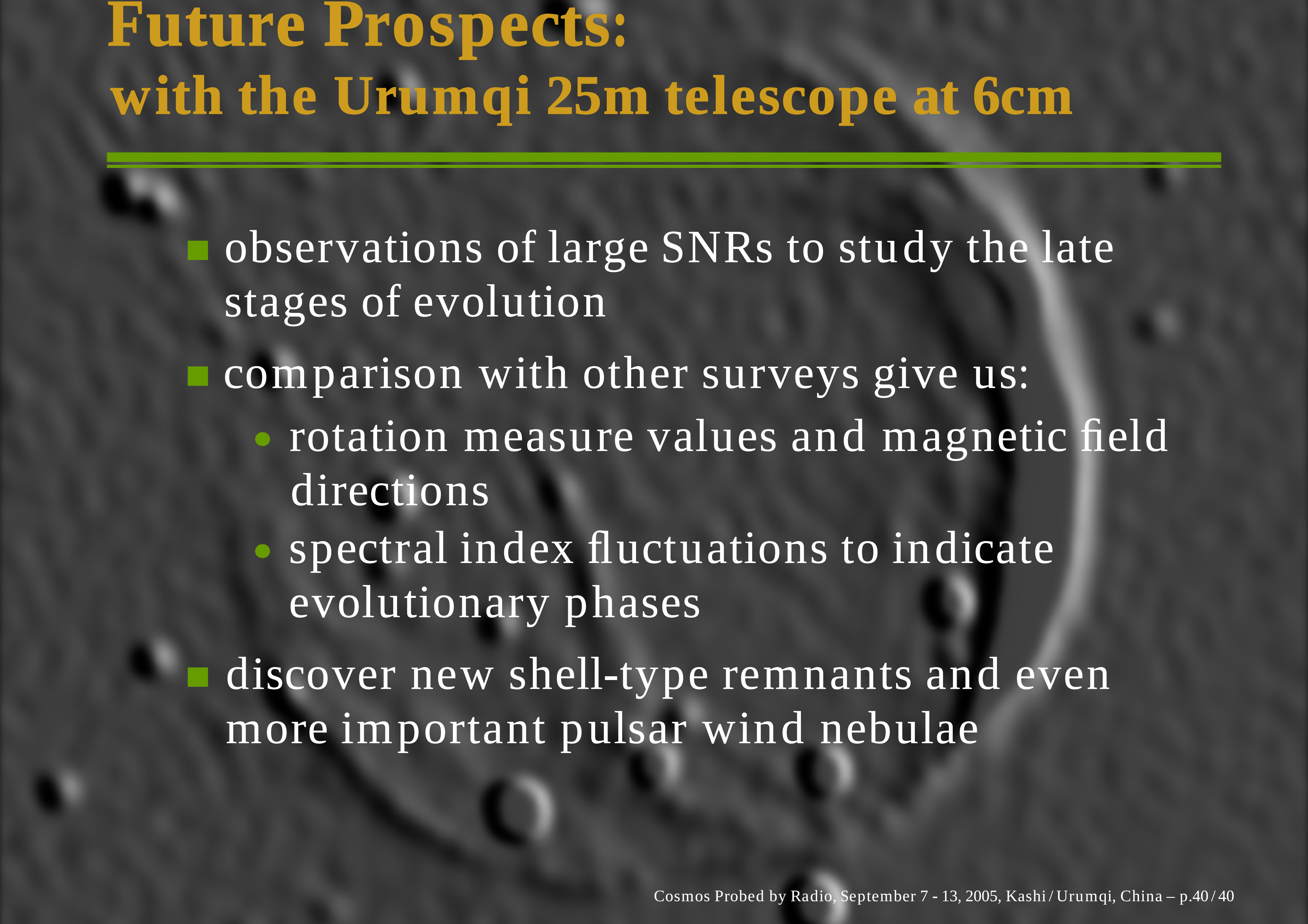
DA 495 - an aging Crab Nebula?

The pulsar in DA 495 is not known, but we can estimate the $\dot{E}$ from the X-ray luminosity of the nebula to $\dot{E} = 2.4 \cdot 10^{35}$ erg / s.

Using the historical pulsars we get:

Basis	t_{DA495} [yr]	τ_{DA495} [yr]	B_{req} [mG]	E_{tot} [erg]	B_{max} [mG]
Crab Nebula	65000	65300	0.60	1×10^{50}	0.98
3C 58	52700	57250	0.69	5×10^{48}	0.22
G11.2−0.3	106080	129380	0.43	4.2×10^{48}	0.21

Future Prospects:
with the Urumqi 25m telescope at 6cm



- observations of large SNRs to study the late stages of evolution
- comparison with other surveys give us:
  - rotation measure values and magnetic field directions
  - spectral index fluctuations to indicate evolutionary phases
- discover new shell-type remnants and even more important pulsar wind nebulae