SUPERNOVA REMNANTS

AN ODYSSEY IN SPACE AFTER STELLAR DEATH

6 - 11 JUNE 2016, CHANIA, CRETE, GREECE

Magnetic fields in SNRs and PWNe: radio polarization results

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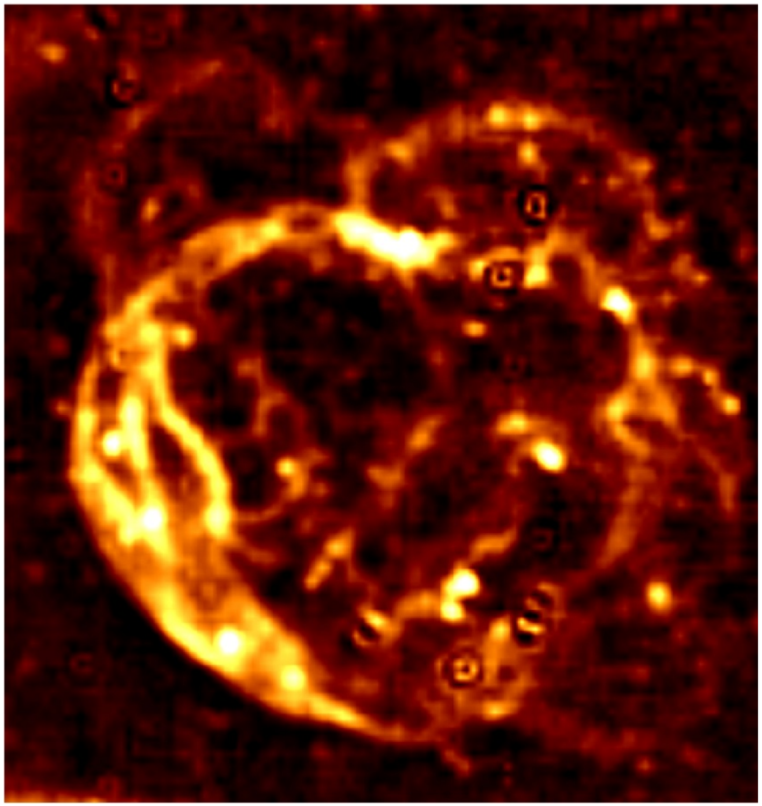
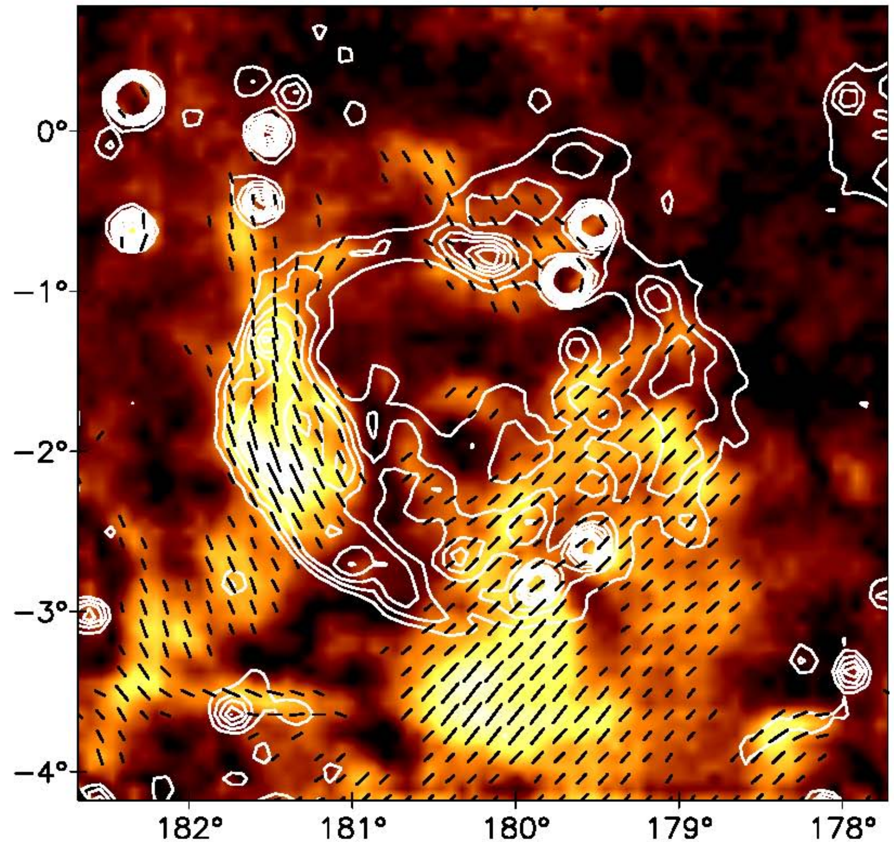
S147   Xiao et al., 2008



Effelsberg 11cm

S147 Urumqi 6cm PI+B (I−cont)



Digitized Sky Survey ESA/ESO/NASA

„Synchrotron History“

- Synchrotron emission: proposed by Alven & Herlofson (1950) and Kiepenheuer (1950) to explain Galactic radio emission and by Shklovskij (1953) to explain SNR emission

- Optical polarization from the Crab nebula detected by Dombrovski (1954)

- „Evidence for polarized radio radiation from the Crab nebula“ Mayer, McCullough & Sloanaker, 1957, ApJ, 126, 458
  Naval Research Lab 50ft at λ=3.15 cm: PC ~7% at ~149°

➔ SNRs are synchrotron emitters at radio wavelengths

SNR parameters from synchrotron emission

- Flux density: $S_\nu \sim n(E)\ B_\perp^{(\gamma+1)/2}\ \nu^{-(\gamma-1)/2} \sim \nu^{-\alpha}$
- Relativistic electrons: $n(E) \sim E^{-\gamma}$
- Polarization degree: $p(\gamma) = \frac{3\gamma+3}{3\gamma+7}$
- Faraday rotation angle: $\Psi_{rot}(rad) = RM(rad/m^2) \times \lambda(m)^2$
- Rotation measure: $RM = 8.1 \times 10^5 \int N(cm^{-3})\ B_{\|}(G)\ dz(pc)$

- **measure at two frequencies or more : <u>S, γ, Ψ, RM</u>**
➔ SNR spectrum, regular/random B-field, B-field direction (and B-field strength, if n(E), N are known)

Supernovae and their polarized SNRs

- Type Ib/II-P (core-collaps) leave a pulsar and a pulsar wind nebula (**PWN**) (plerions, filled-centre, or Crab-like SNR) and a shell (?):

  Polarization: radial, uniform, patchy

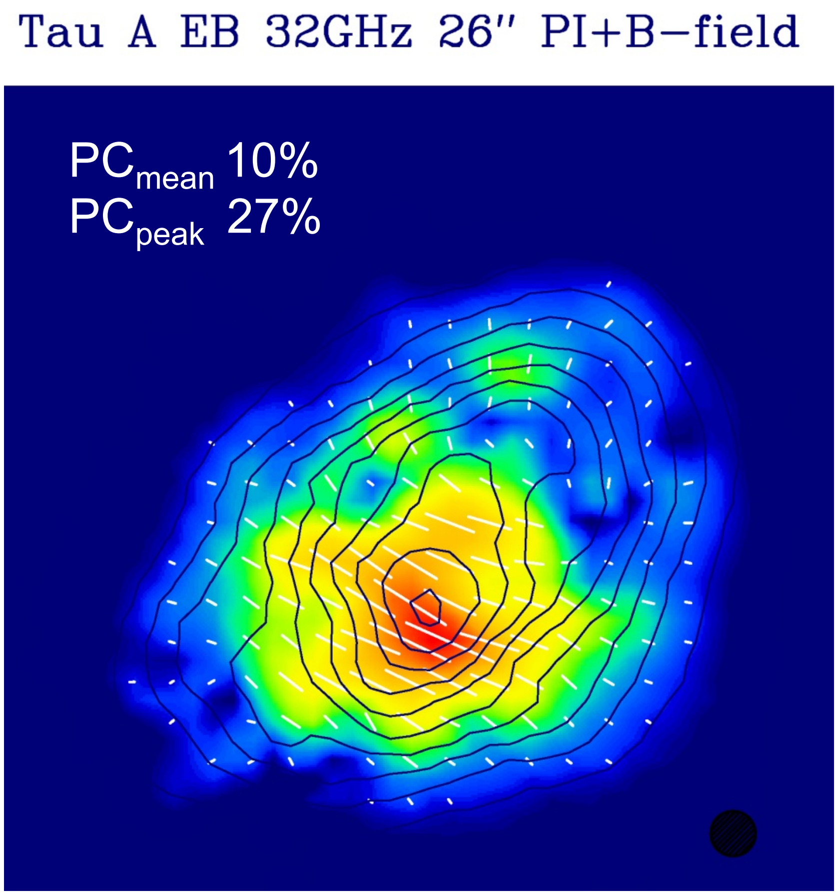
- Type Ia/II-L (thermonuclear) complete disruption leave a pure **shell-type SNR:**

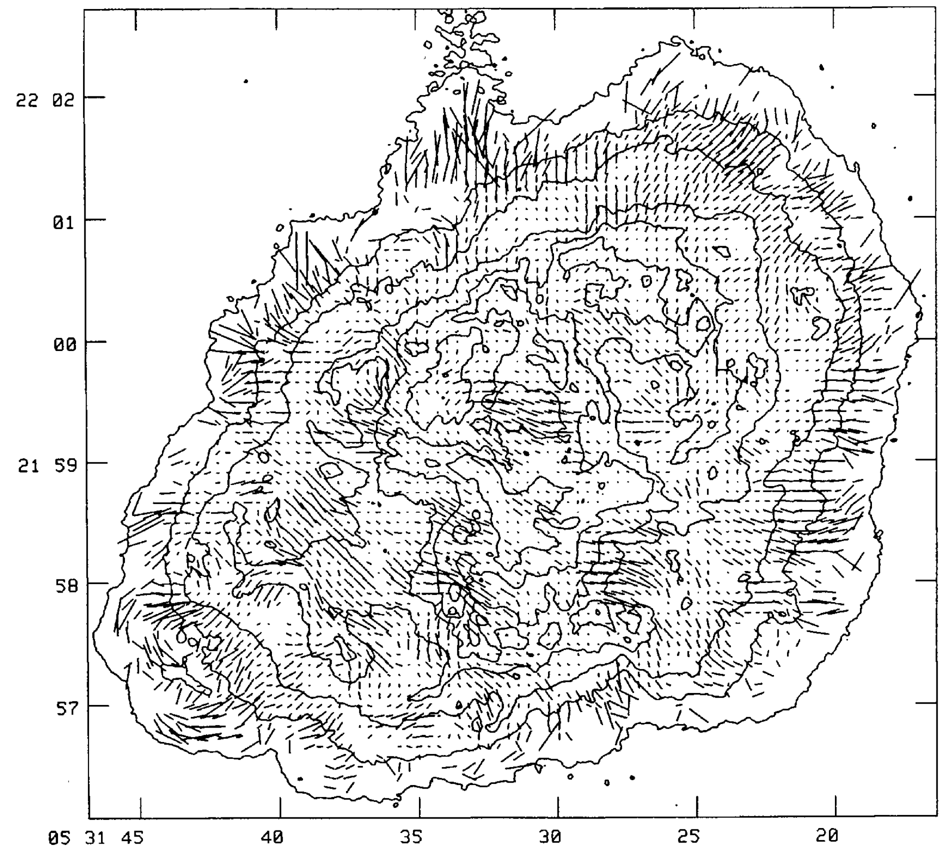
  Polarization: radial (young), tangential (evolved)

- **Combined type SNRs** have a plerion inside a shell and are from type Ib/II-P events

➔ **the polarized SNR-Zoo: PWNe, young shells, evolved shells**

Polarized PWNe – Tau A

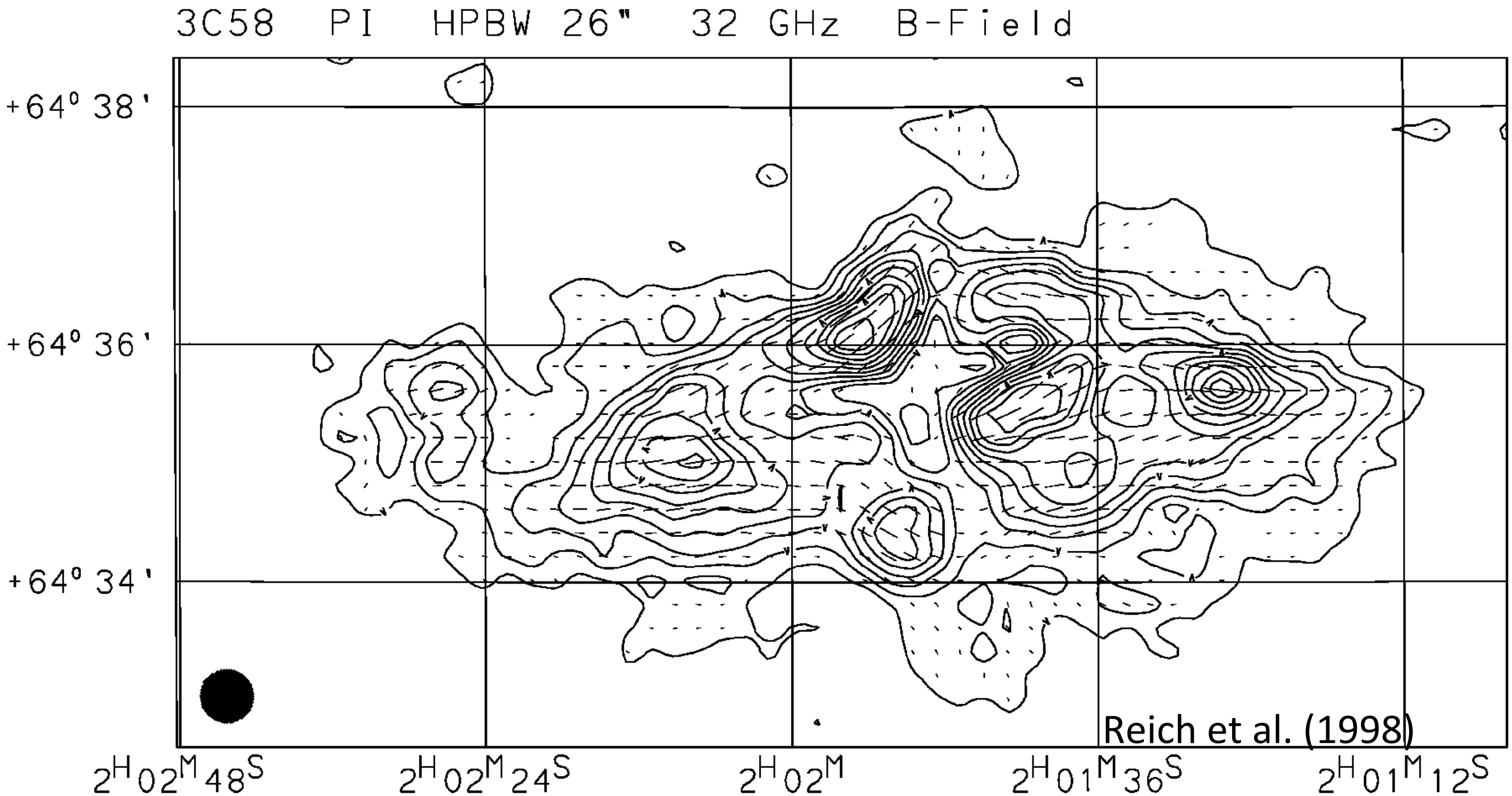




Effelsberg (2005)

VLA 21cm 1.8”
RM corrected B-field direction
Bietenholz & Kronberg 1990

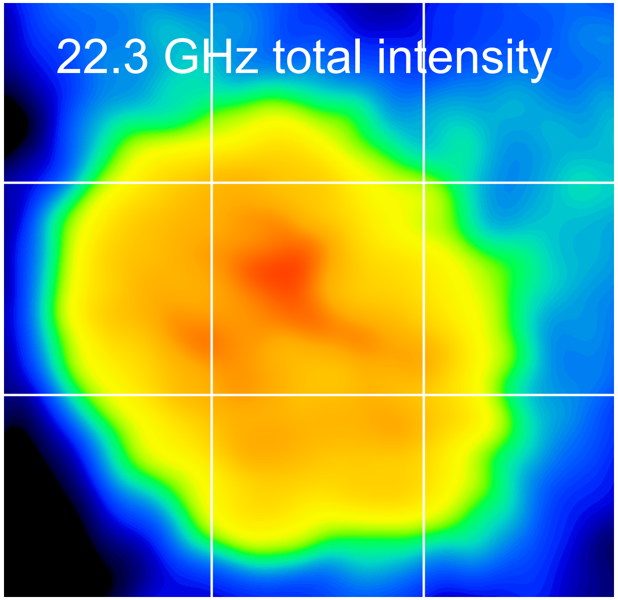
3C58 – SN1181

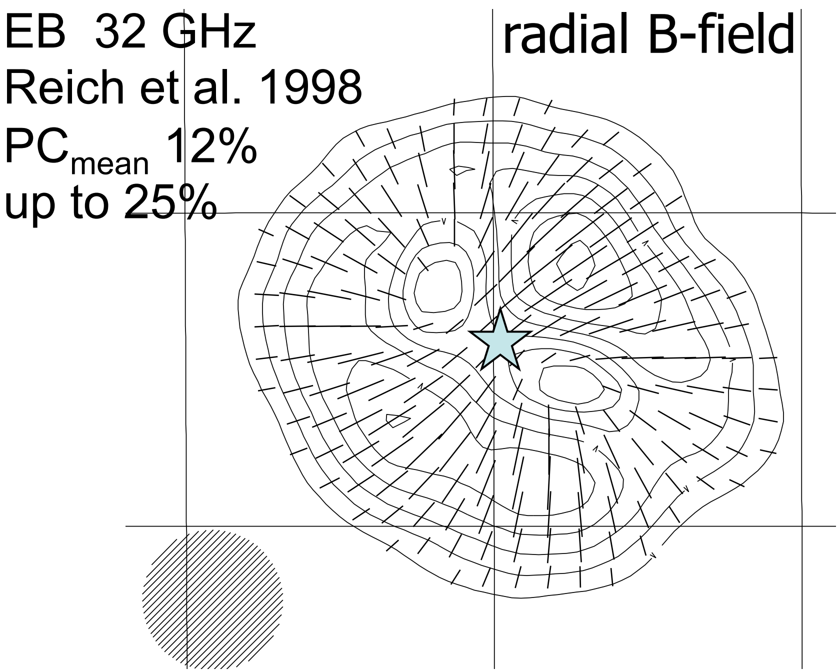


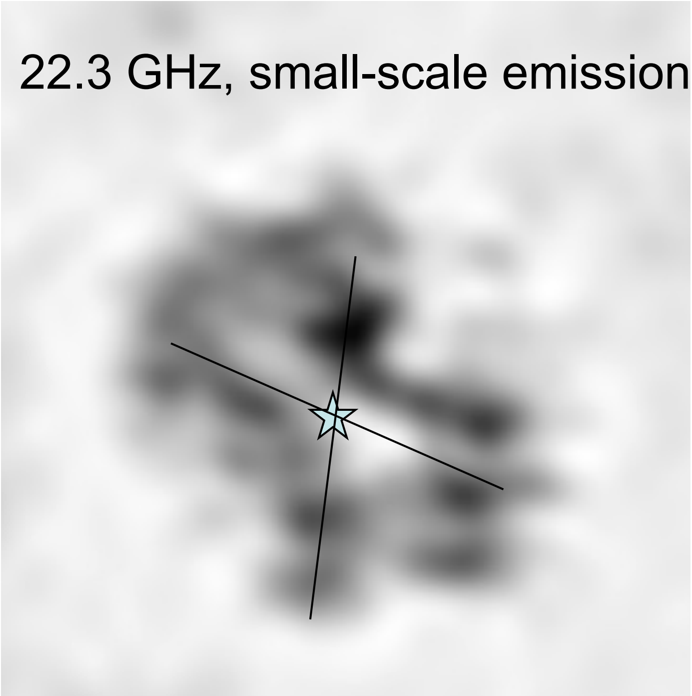
PI/PA at 32 GHz very similar to 1.4 GHz WSRT
Weiler & Wilson (1976)
low RM, PC 25/15/6% at 6/21/50cm

G21.5-0.9

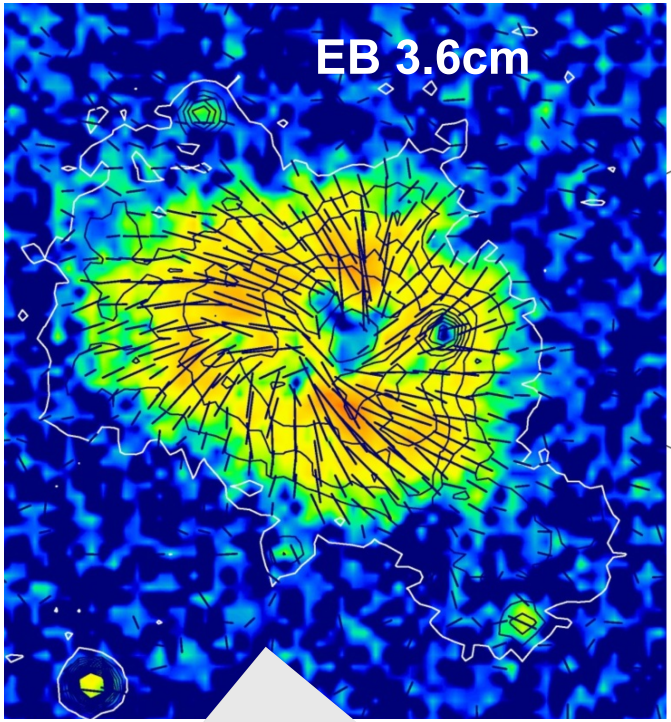
22.3 GHz Nobeyama Array
beam 8“ (Fürst et al. 1988)

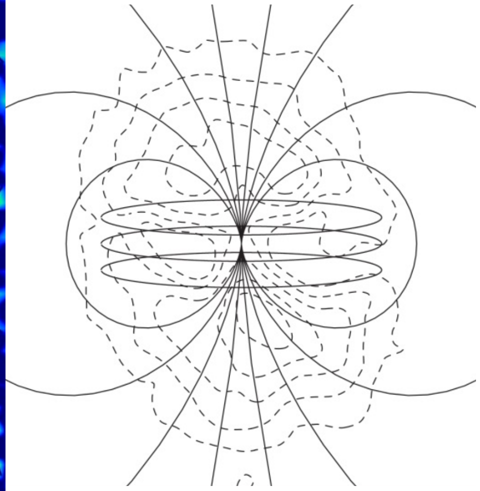






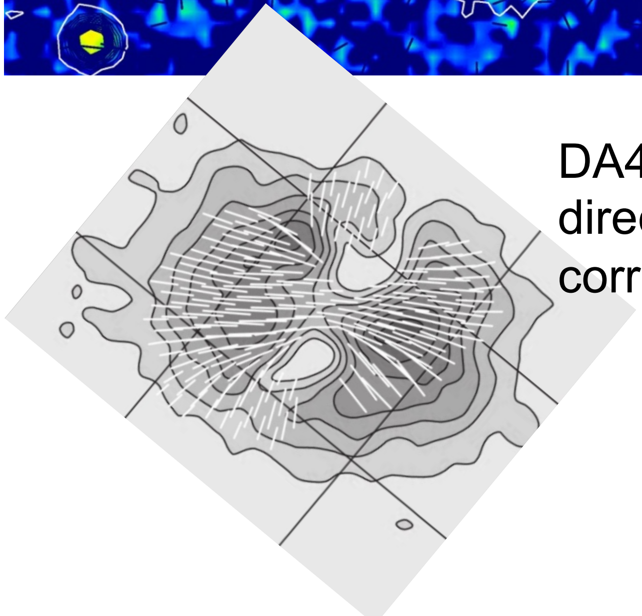
DA495 + G76.9+1.0 with a steep spectrum



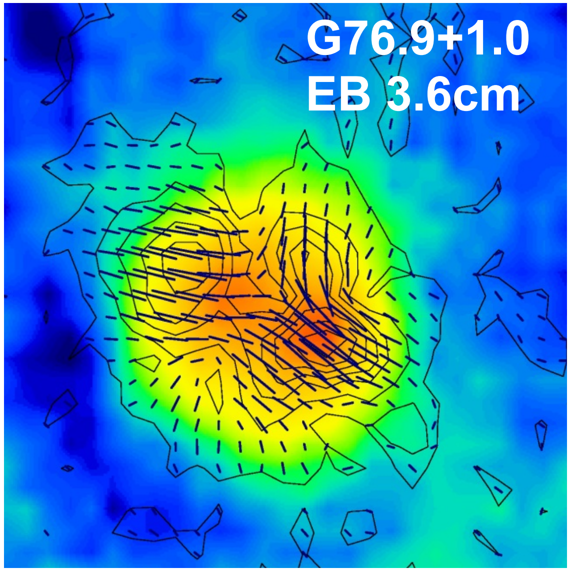


Kothes et al. (2008)
dipol+toroidal B-field model
α = -0.45 / -0.87
break 1.3 GHz
B-field ~1.3 mG

Kothes et al. (2006)
α = -0.60 break 0.4GHz
Sun et al. (2011)
α = -0.89 break 1 GHz

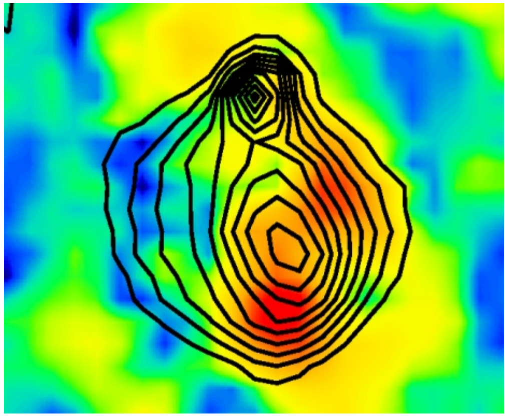


DA495: B-field direction with RM correction

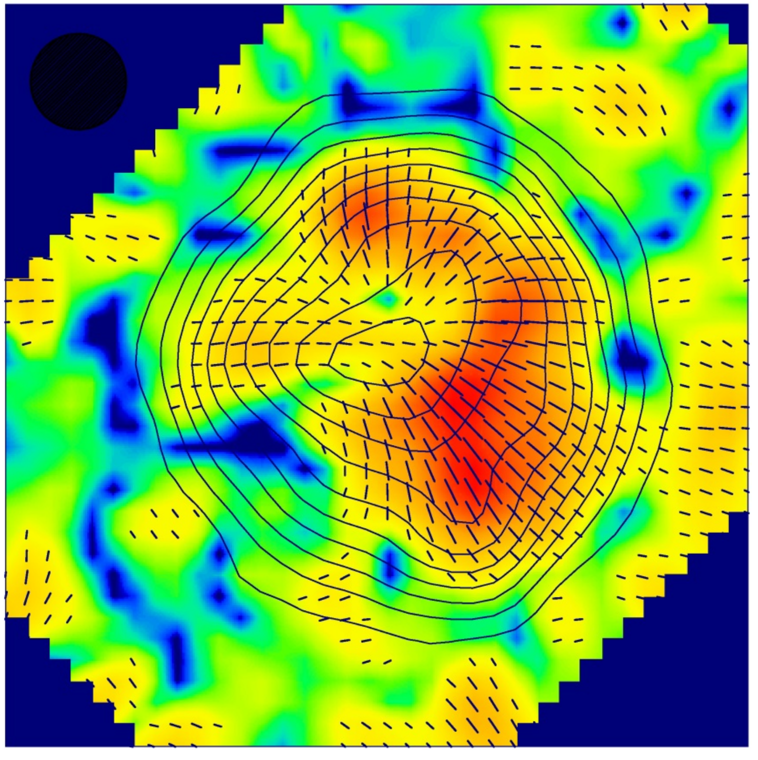


Fainter PWNe with asymmetric PI distribution

G20.2-0.2
EB 6cm PI+I

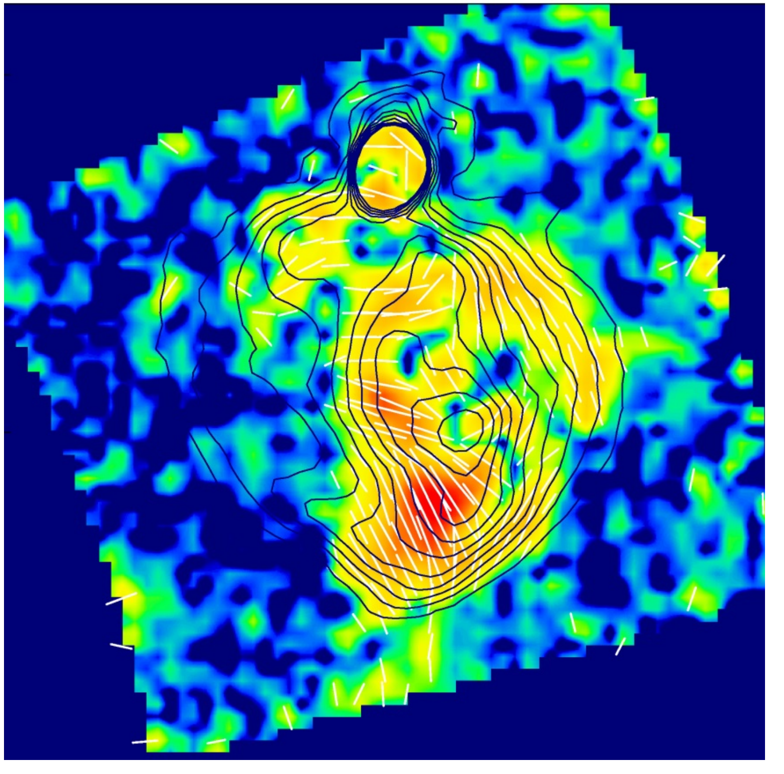


G63.7+1.1 EB 2.8cm B−field



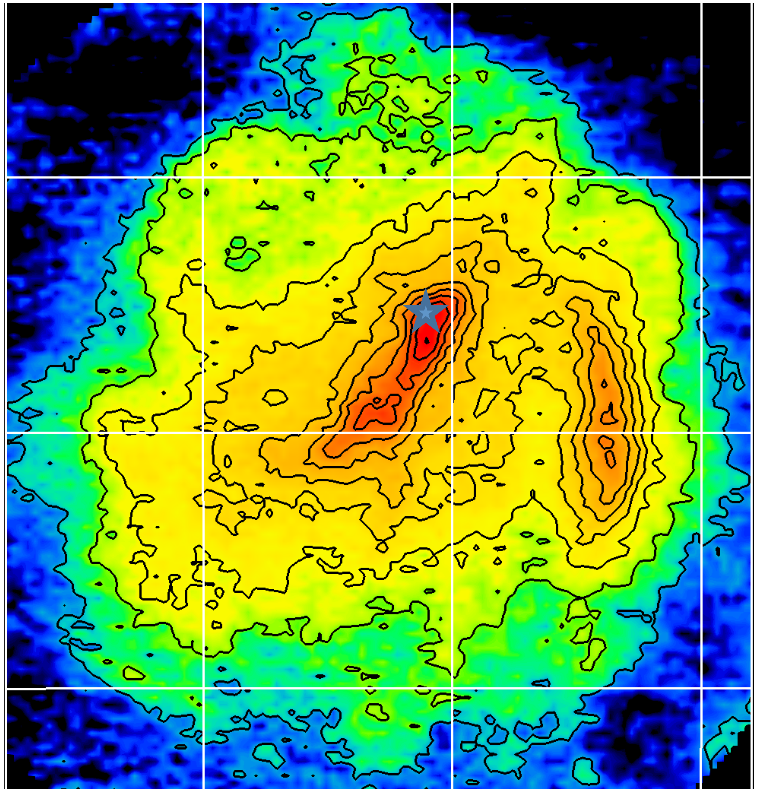
α = -0.06 PC_{mean} 5% PC_{peak} 10%

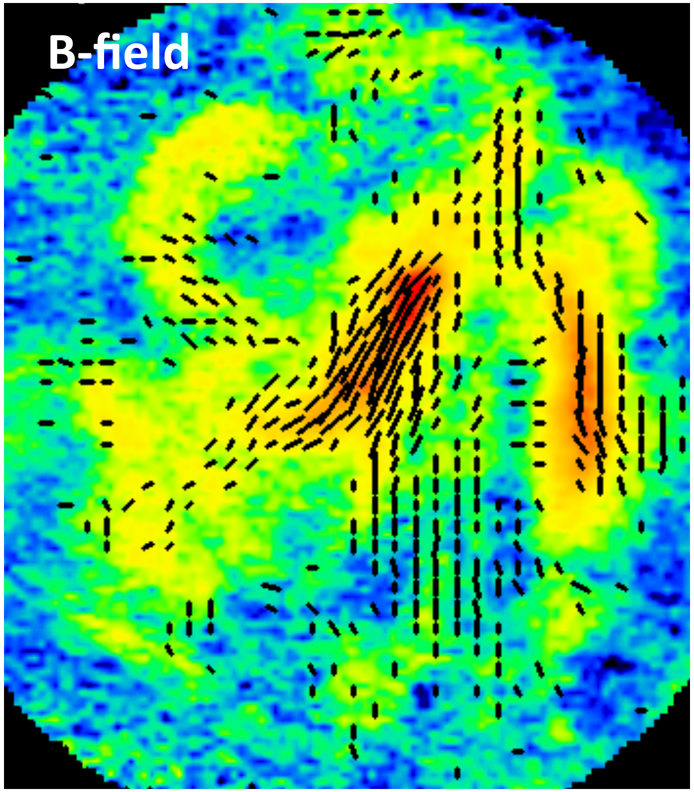
G20 2.8cm PI(15mK) + B I(20,40,..mK)



α = -0.24 PC_{mean} 8% PC_{peak} 12%

Combined SNR: G18.9-1.1



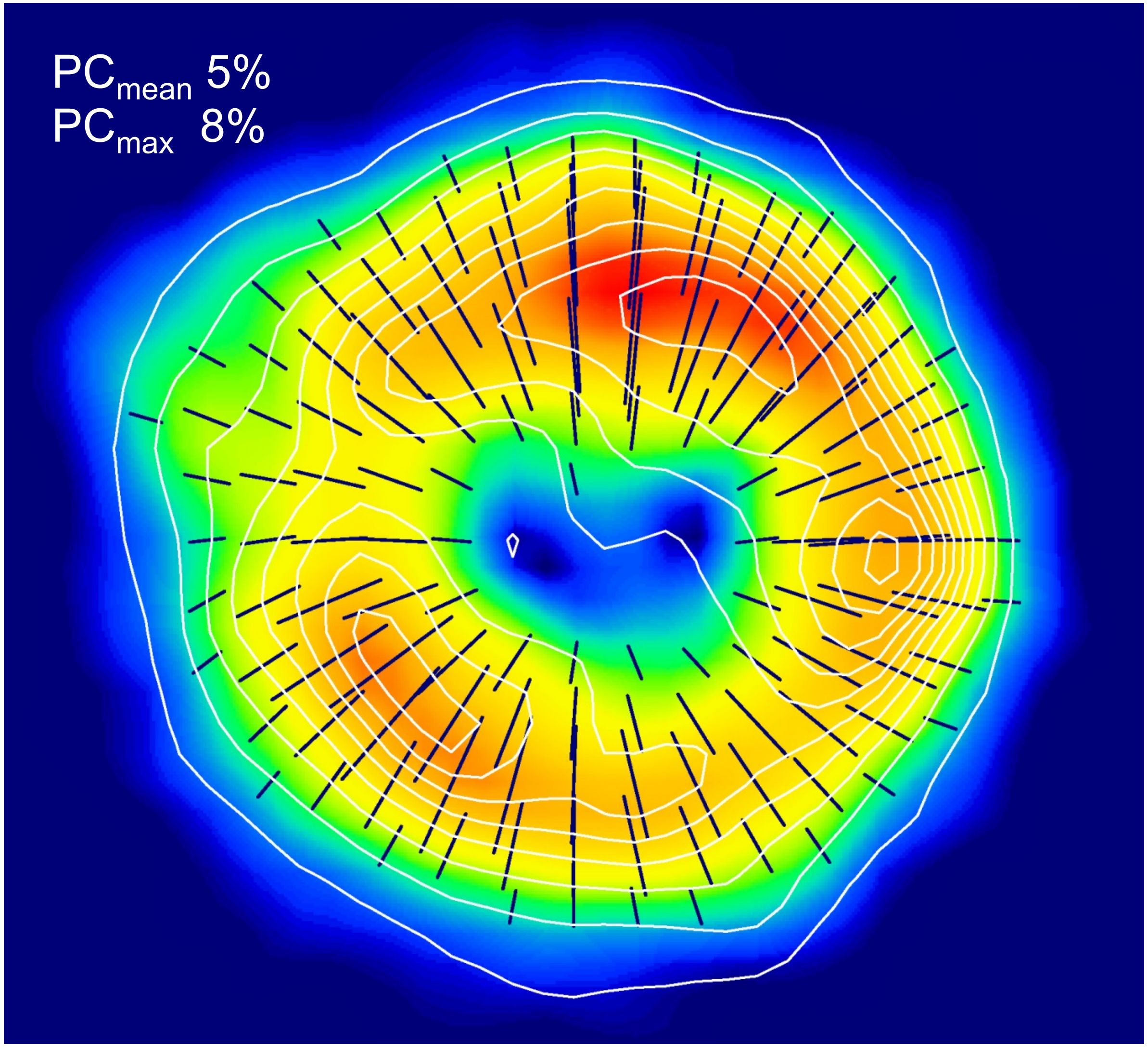


Effelsberg 10.55 GHz, beam 1.2′, Fürst et al. (1997)
α = -0.28 (diffuse), -0.4 (outer arc), PC_{mean} 6%, PC_{peak} 30%
Distance ~2 kpc, diameter ~20pc, age ~6500 yr
★ compact X-ray source (*CHANDRA,* Tüllmann et al., 2010)

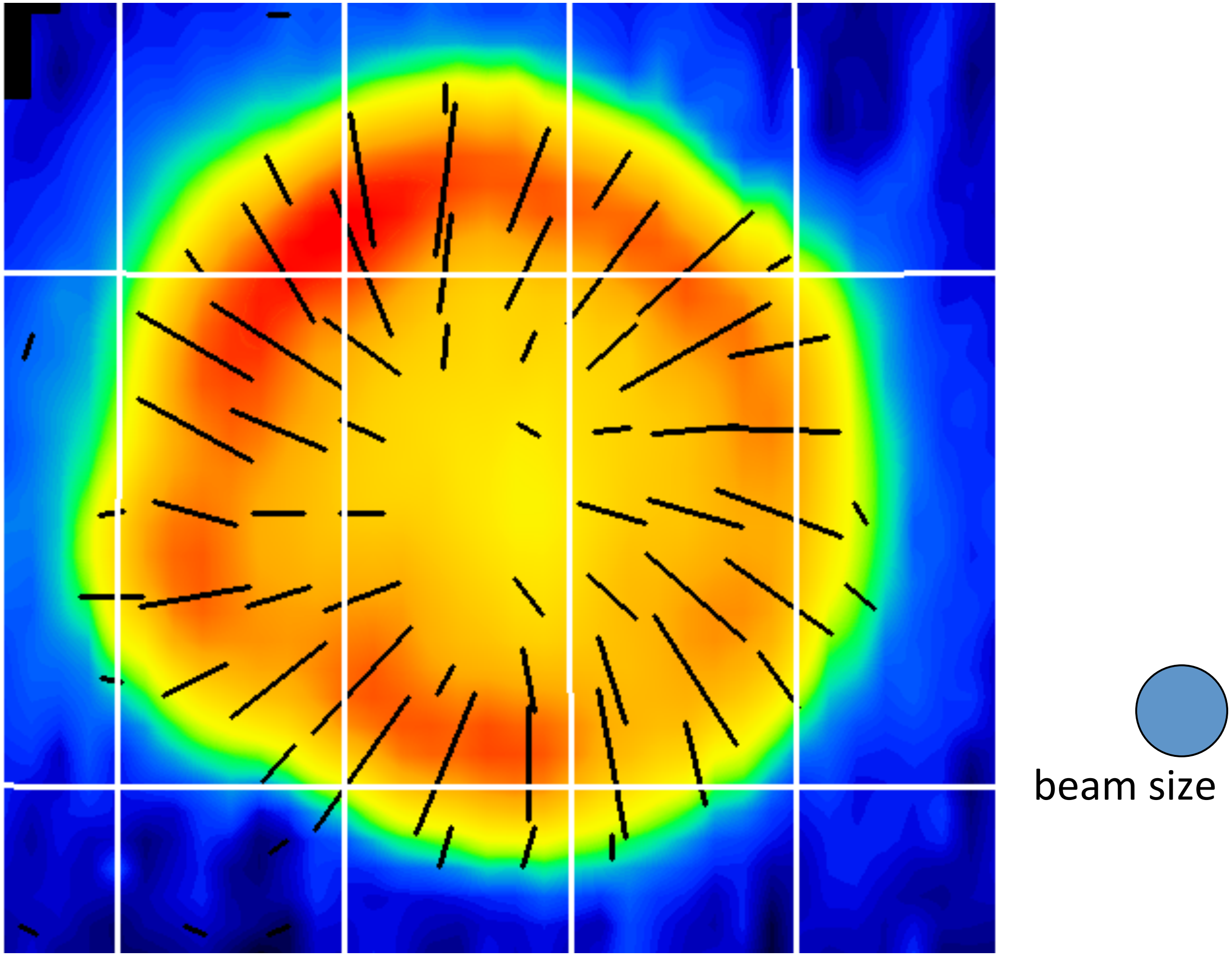
Young SNR shells (Free expansion)

- Predominantly radial field
- Small-scale variations (sub-pc scales)
- Polarized fraction (PI/TP) up to 15% with local enhancements. A large fraction of random magnetic field exists.
- Rayleigh-Taylor instabilities between shock and ejecta, stretching of magnetic field (?)

CAS A EB 32 GHz 36“ PI(B-field) I

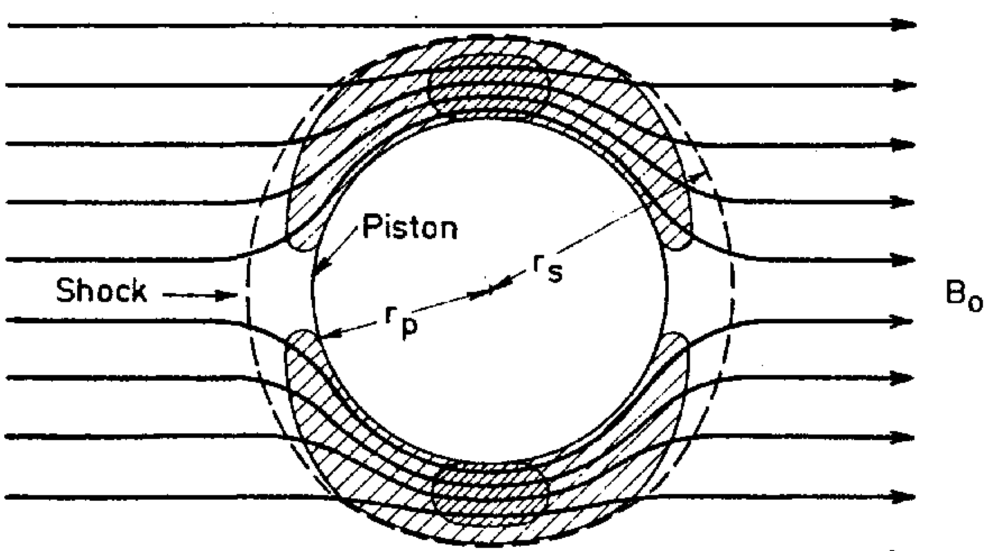


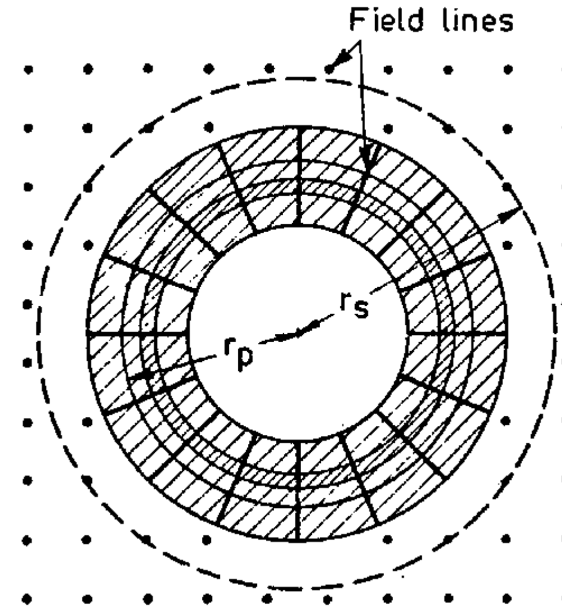
Tycho EB 10.55 GHz 1.2‘ I PI(B-field)



The magnetic field direction in SNRs

Whiteoak & Gardner (1968)

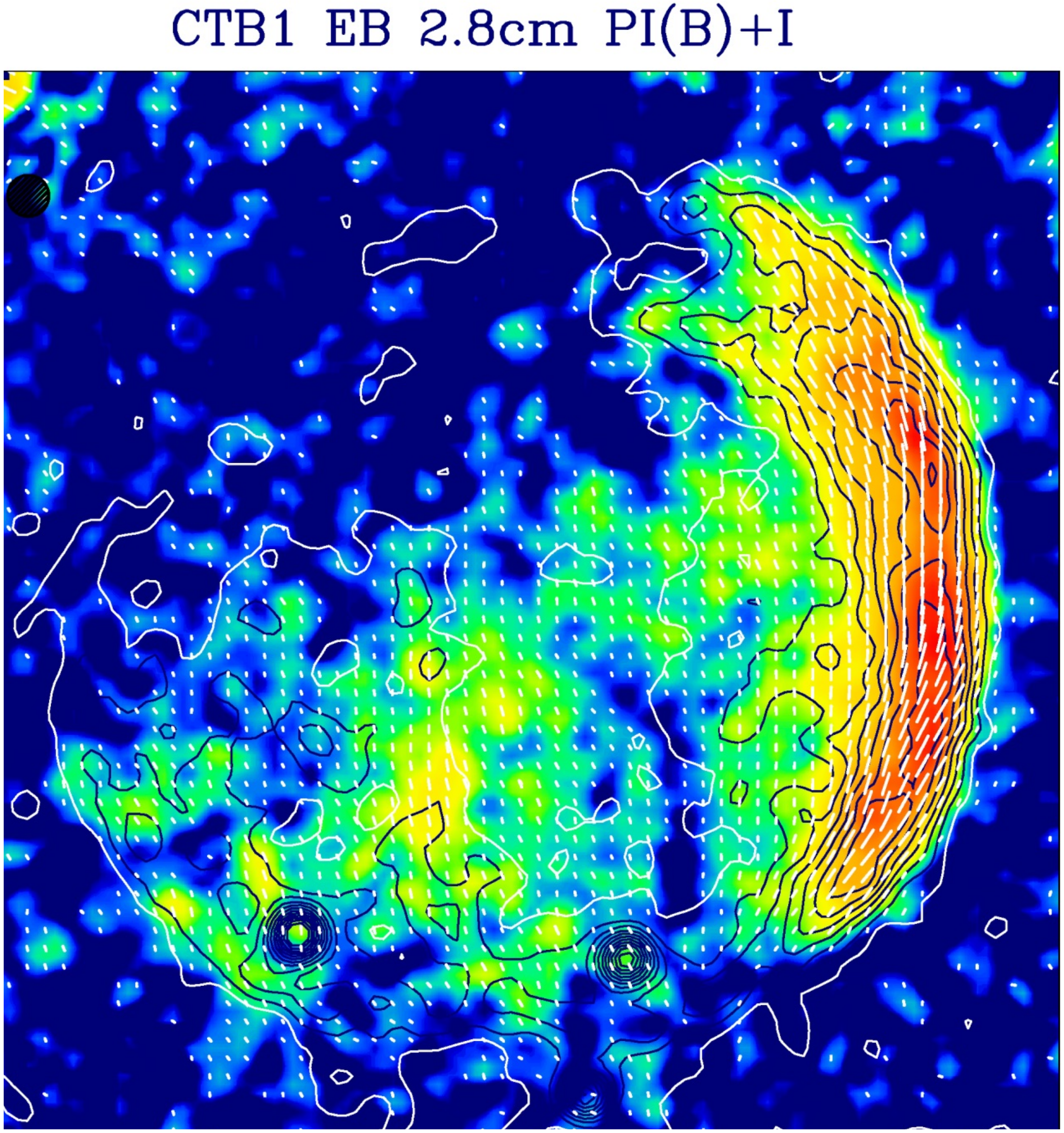




Local B-field perpendicular to the l.o.s.
=> tangential field is observed

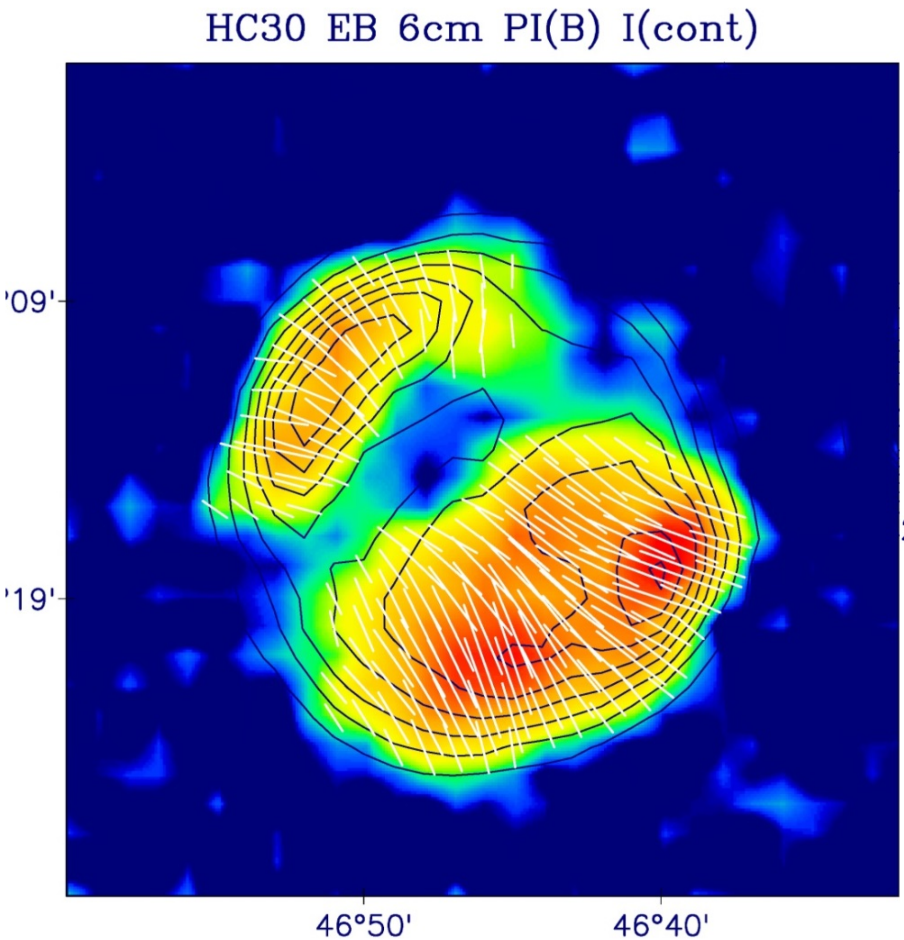
Local B-field parallel to the l.o.s.
=> radial field is observed

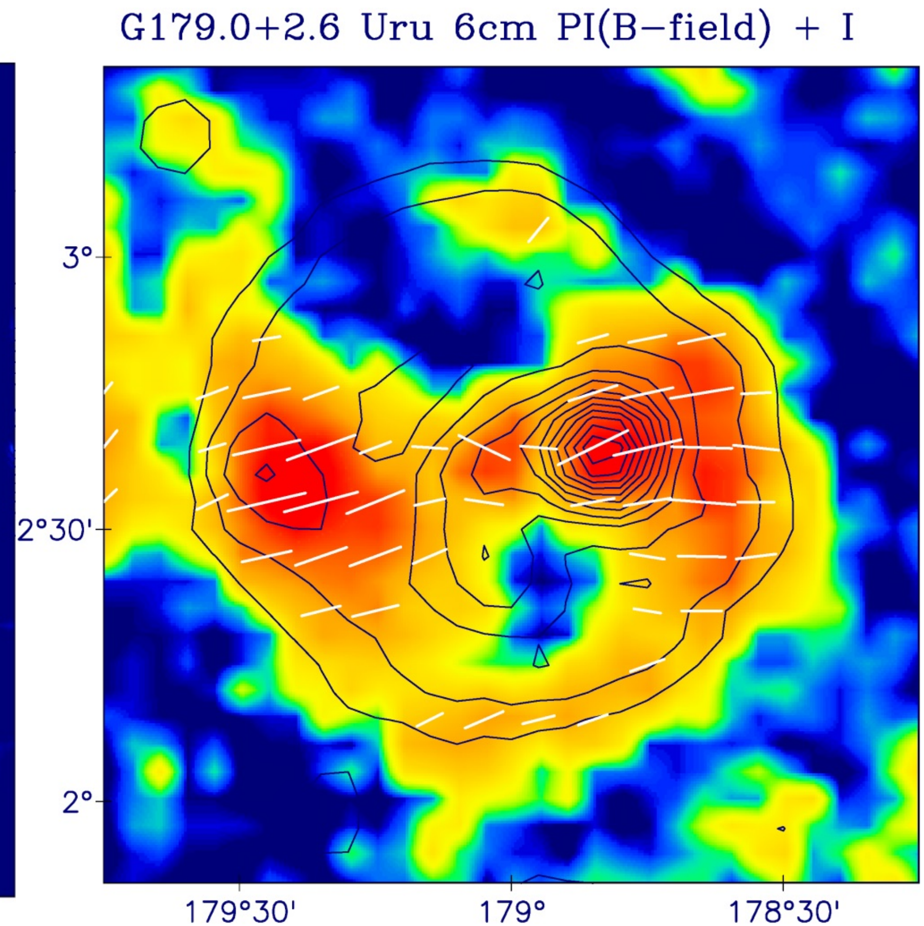
Evolved SNR shell with tangential B-field



Schmidt et al. 1993

Shell-type SNRs with radial B-field





α = -0.54 PC_{mean} ~12% PC_{peak} ~25%

Gao et al. (2011) α = -0.45 PC_{mean} ~12%

Depolarization
=> underestimate of the regular B-field

- PC_{obs} is below the intrinsic value $f(\gamma)$ of about 70%

- Depolarization by the antenna beam, bandwidth, variation of spectral index.

- If the rotation of the polarization angle varies along the line-of-sight within the SNR, e.g. slab model for internal uniform rotation (Burn 1966), then:

  $PC_{obs} = PC_{int} \times (B_{\perp}/B_o)^2 \times |\mathrm{sinc}\,\Psi|$

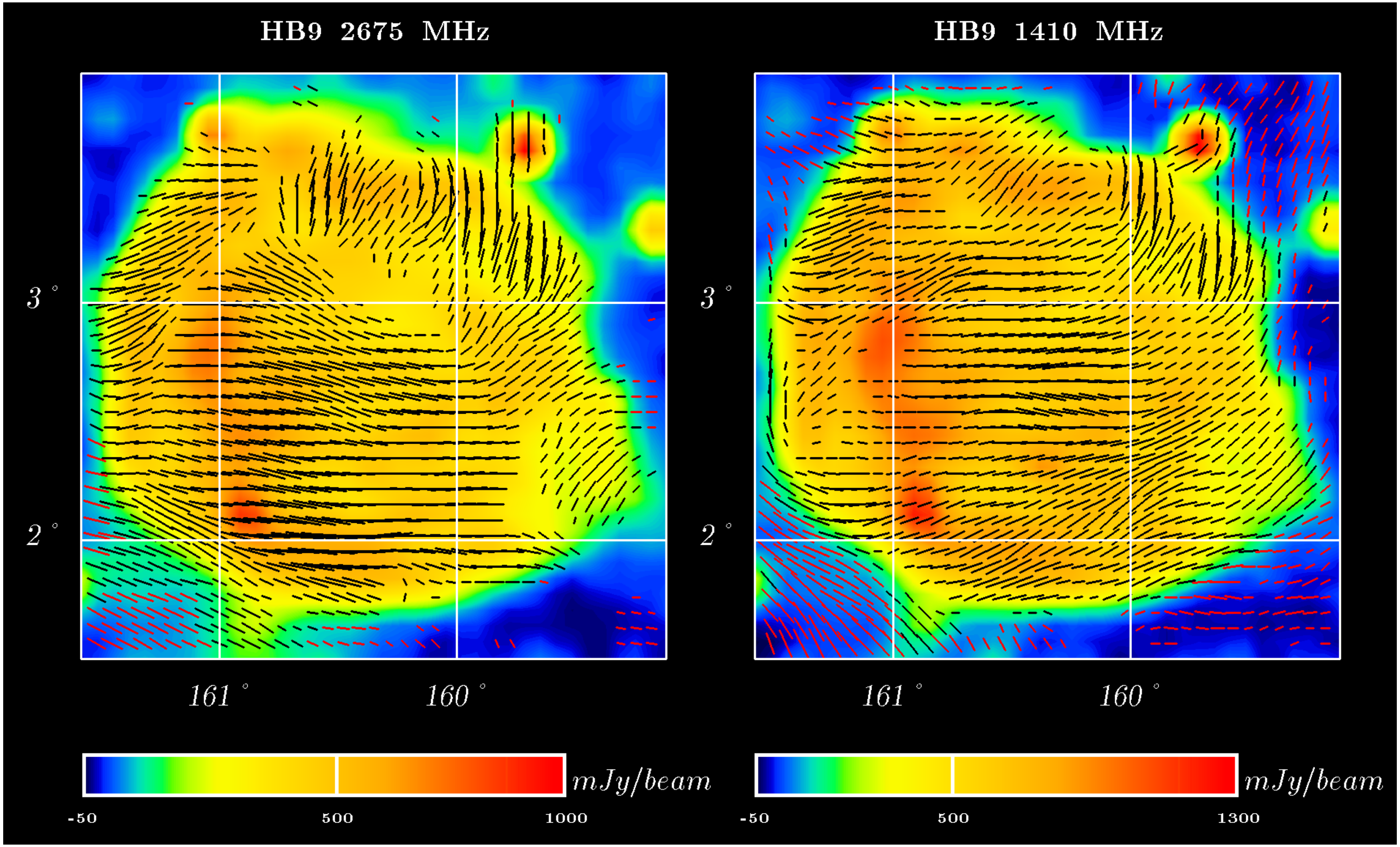
- Internal and external RM-fluctuations σ_{RM}

RM of SNRs provide $B_{||}$ => correction for Galactic contribution needed

- Observed RM = RM(foreground) + RM(SNR) + RM(background)
- RM (extragalactic sources) = RM(foreground + background)
- PSR-RMs or RMs from Galactic models = f(distance)

- RM-ambiguity – three frequencies or more, RM-synthesis
  => example HB9

- RM from Galactic B-field model
  => example W49B



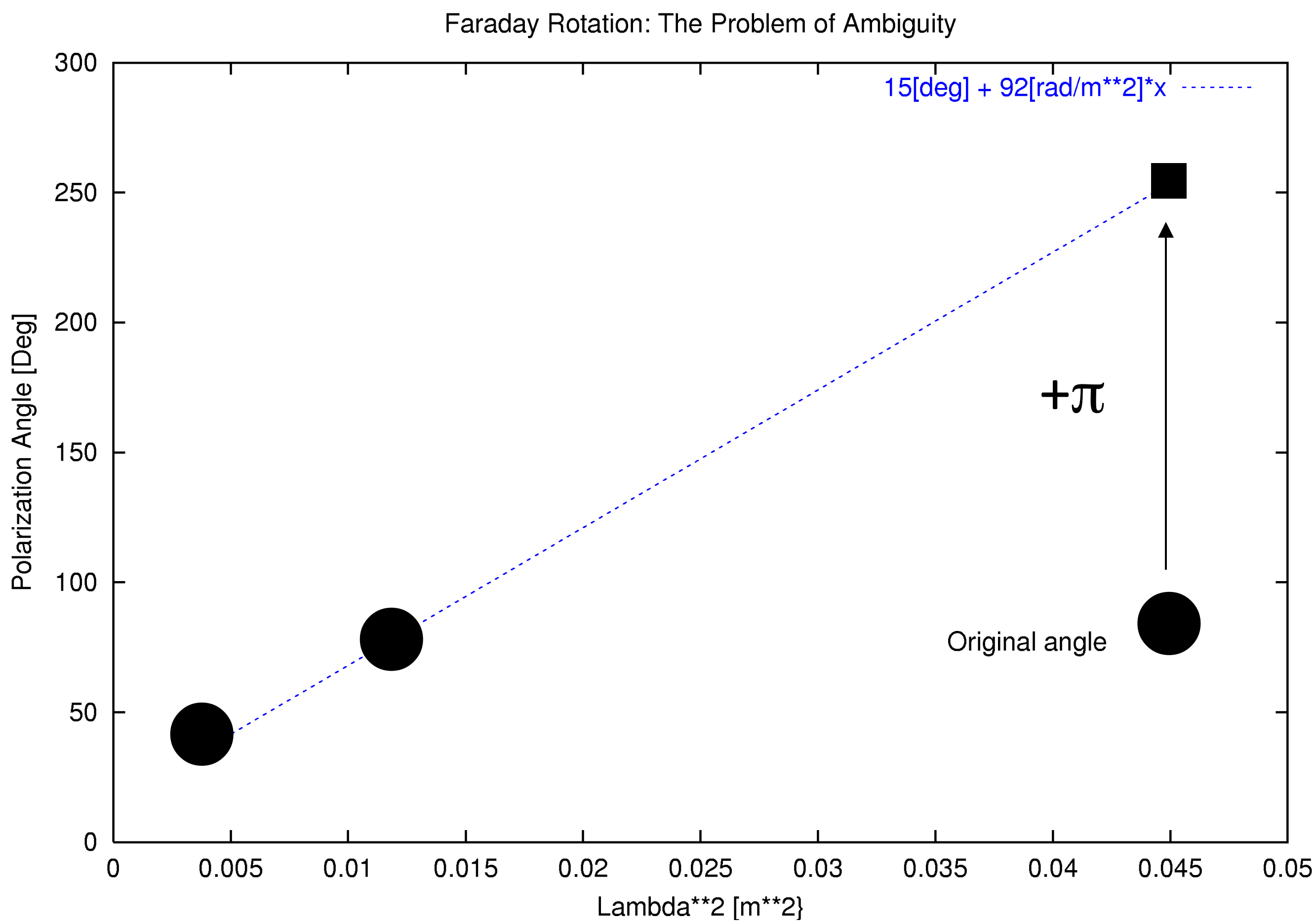
$$\Psi(rad) = \Psi_0(rad) + RM(rad/m^2) \times \lambda(m)^2 + \underline{n \times \pi}$$

RM ambiguity

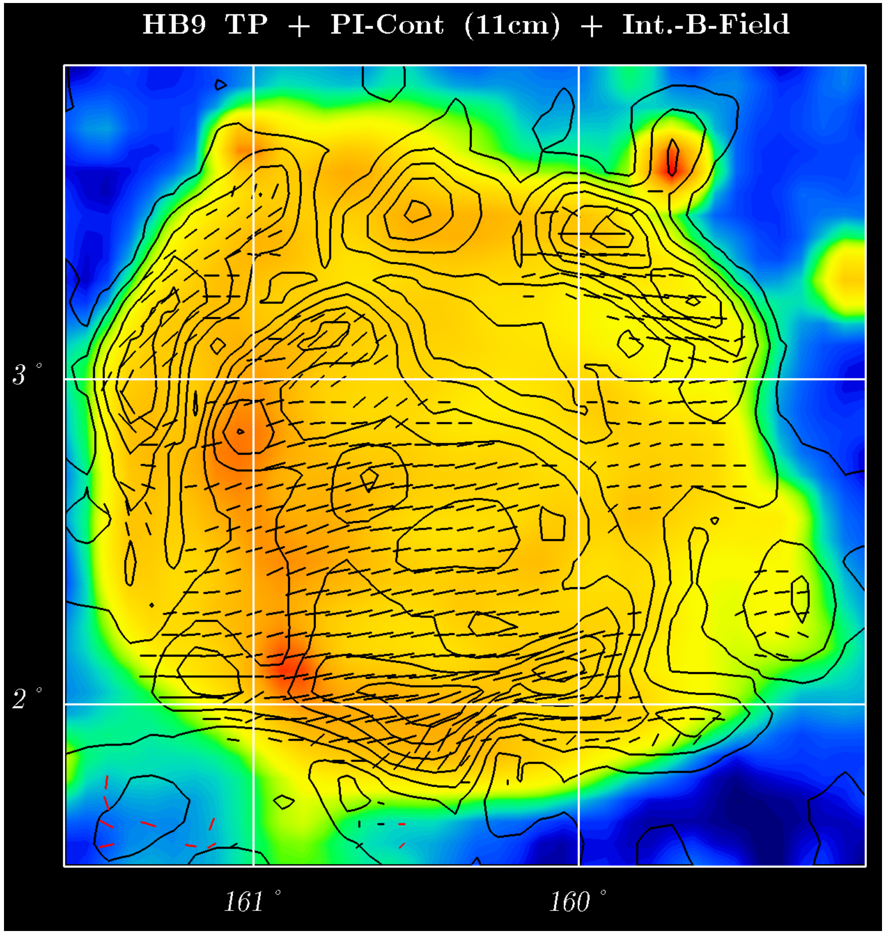
$$\Delta RM = \frac{\Psi_1 - \Psi_2}{\lambda_1^2 - \lambda_2^2} + \frac{\Delta n \times \pi}{\lambda_1^2 - \lambda_2^2}$$

Observed:

$\lambda_1(cm)$	$\lambda_2(cm)$	$\Delta RM(rad/m^2)$
21	11	96
11	6	374
21	6	76



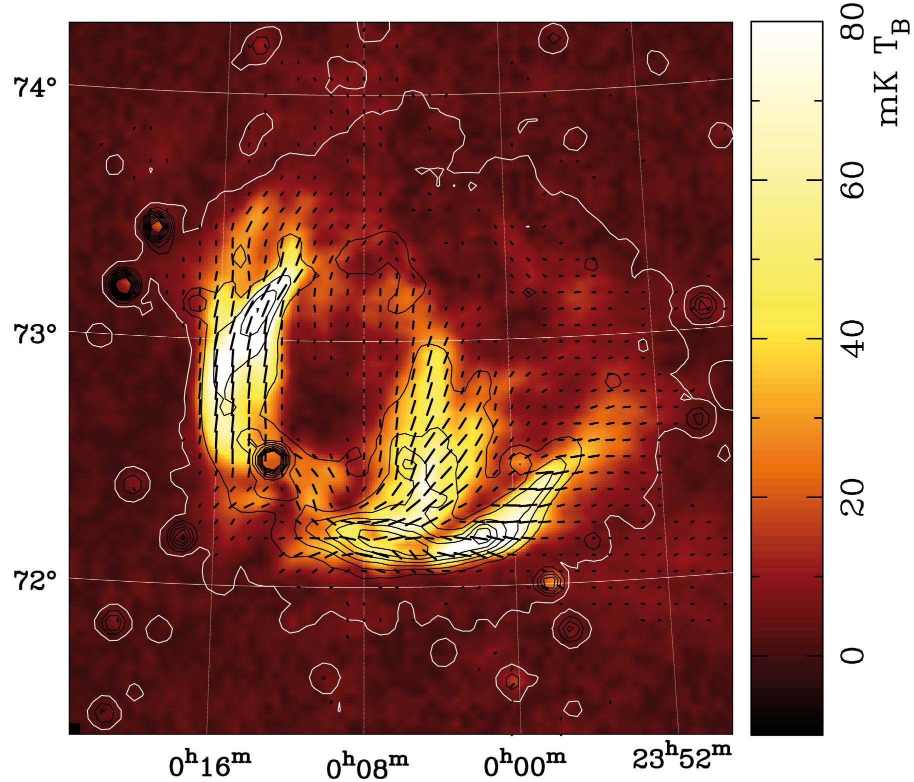
RM corrected B-field direction



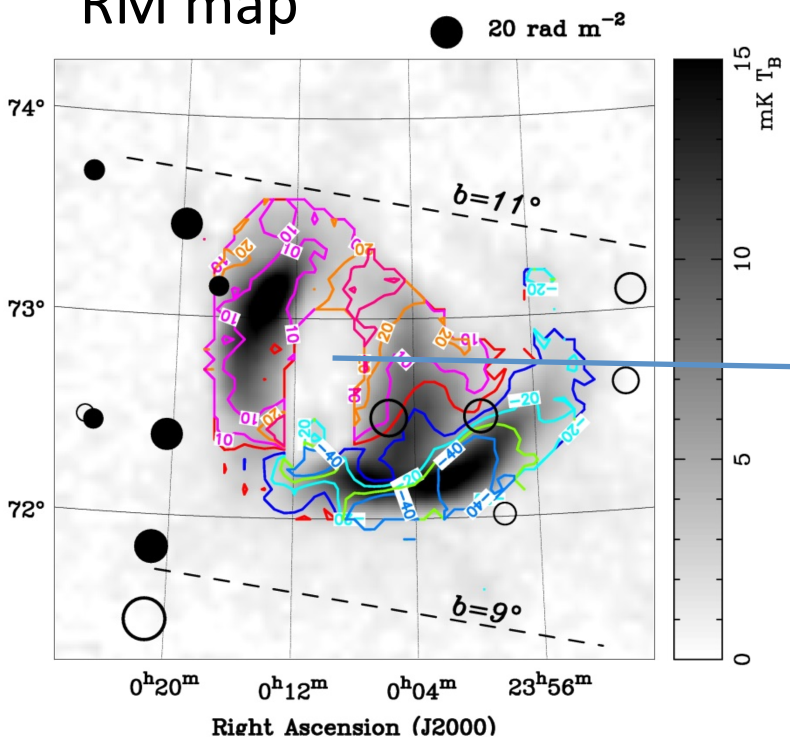
=> narrow-band multichannel polarimeter (> 10^3 channels) and **‚RM Synthesis'** => no RM ambiguity, provides simultaneous RM foreground and background components

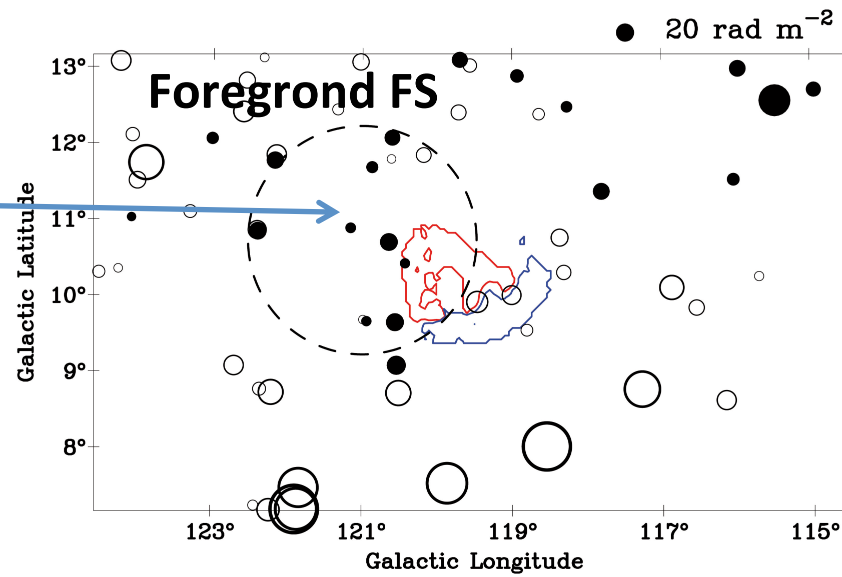
CTA 1

Sun et al. (2011): b ~10°
EB 11cm, beam 4‘.4
PI (black contours, B)
I (white contours)



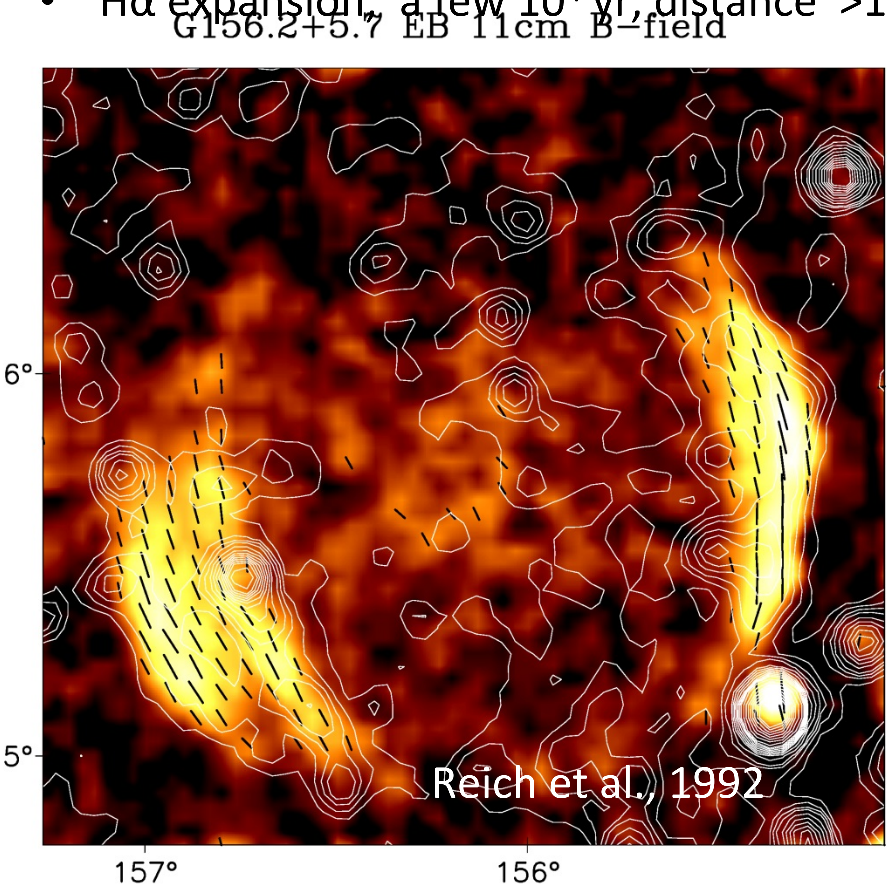
RM map

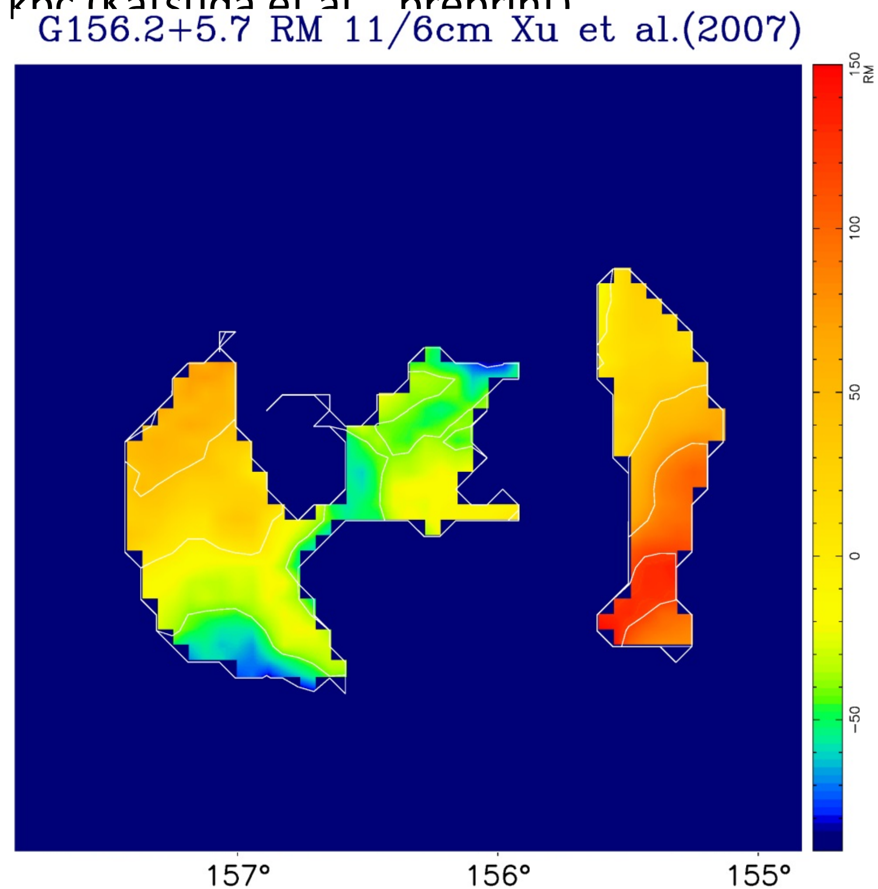




G156.2+5.7

- detected by very strong soft X-rays (**ROSAT,** Pfeffermann et al. 1991)
- very low radio surface brightness
- a high polarization degree: >50% up to intrinsic (Reich et al. 1992, Xu et al. 2007)
- high ambient B-field inclination - about 60° , local anomaly
- **Suzuku** hard X-rays: evolved, ~7-15 10^3 yr, distance ~1.1 kpc (Uchida et al., 2012)
- Hα expansion, a few 10^4 yr, distance >1.7 kpc (Katsuda et al., preprint)

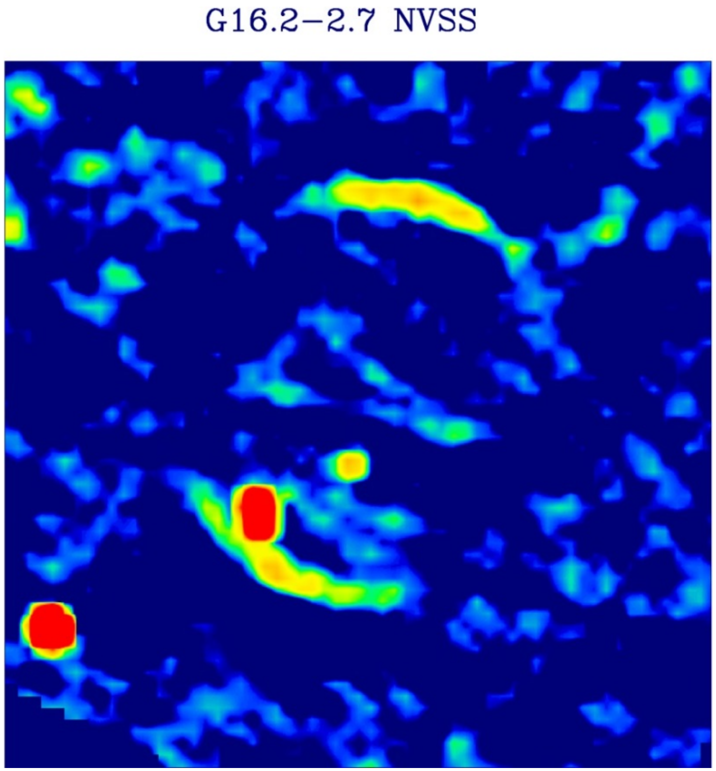


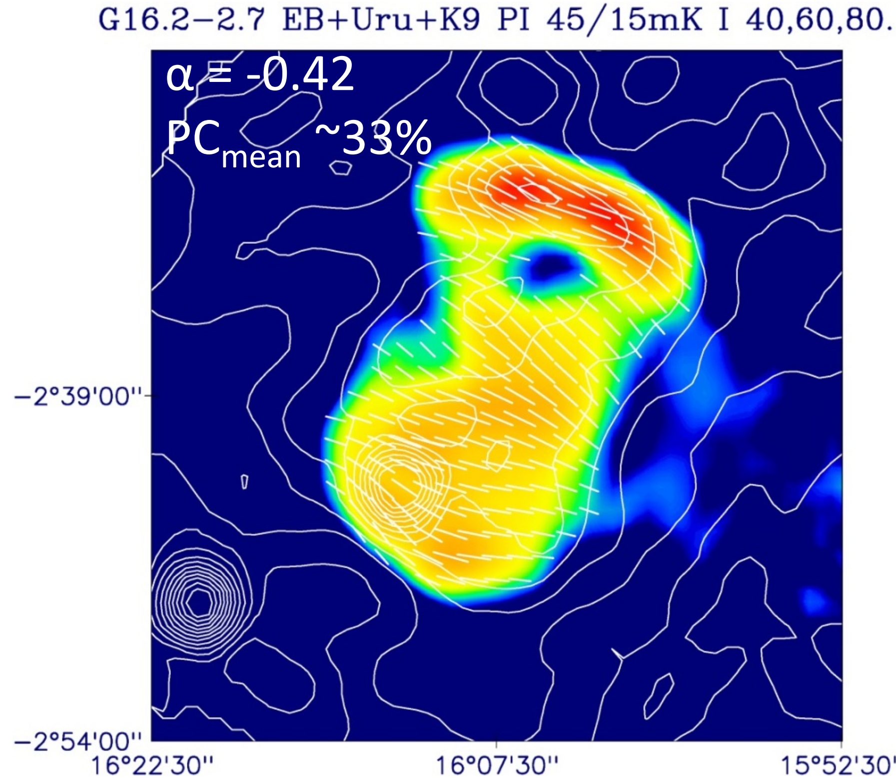


Zero-level effects on SNR polarization

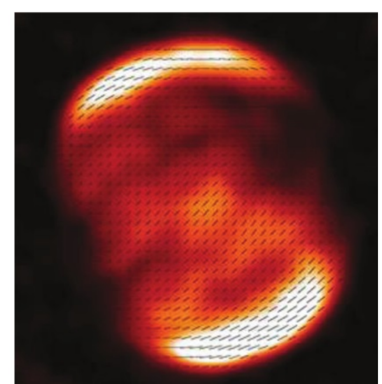
- Flux integration of compact or extended sources are relative to a local zero-level
- no problems for total intensities, except confusion or missing zero-spacings
- polarized intensities are calculated from Stokes U and Q ==> $PI = (U^2 + Q^2)^{0.5}$
- U_{off} and Q_{off} are assumed to be zero when measured with an interferometer or a single-dish, but are at a certain positive or negative level

Interferometric versus single-dish observations





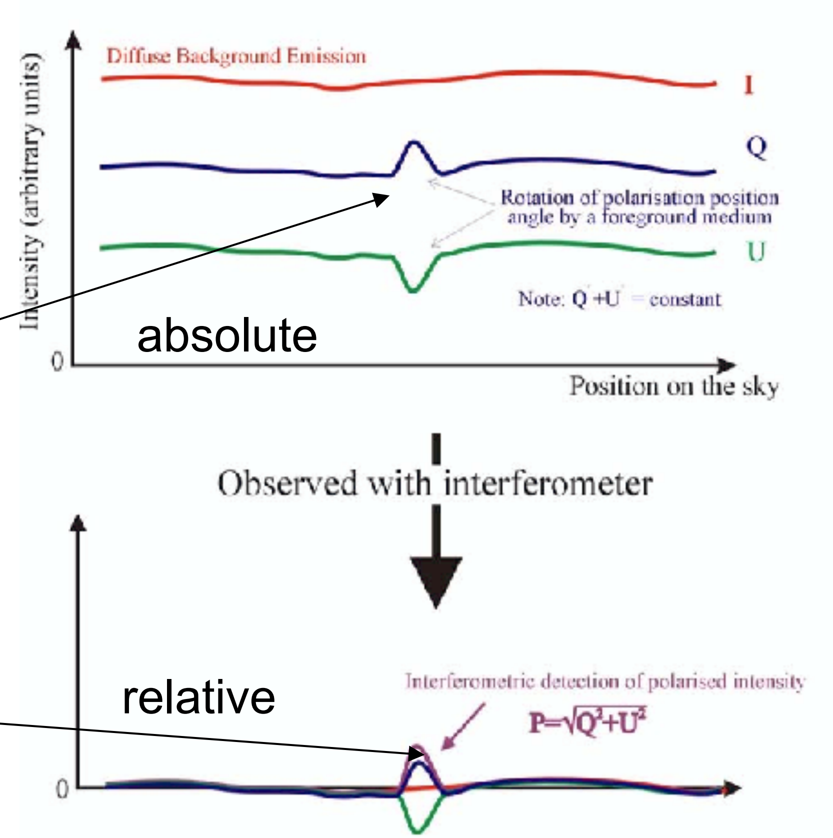
DA530 = G93.3+6.9 EB 6cm
Kothes & Brown (2008)
α = -0.45 PC$_{mean}$ ~40%



Need of an
absolute zero level
for polarization data ?

Action of a ‚<u>Faraday Screen</u>'

PI positive, PC too high



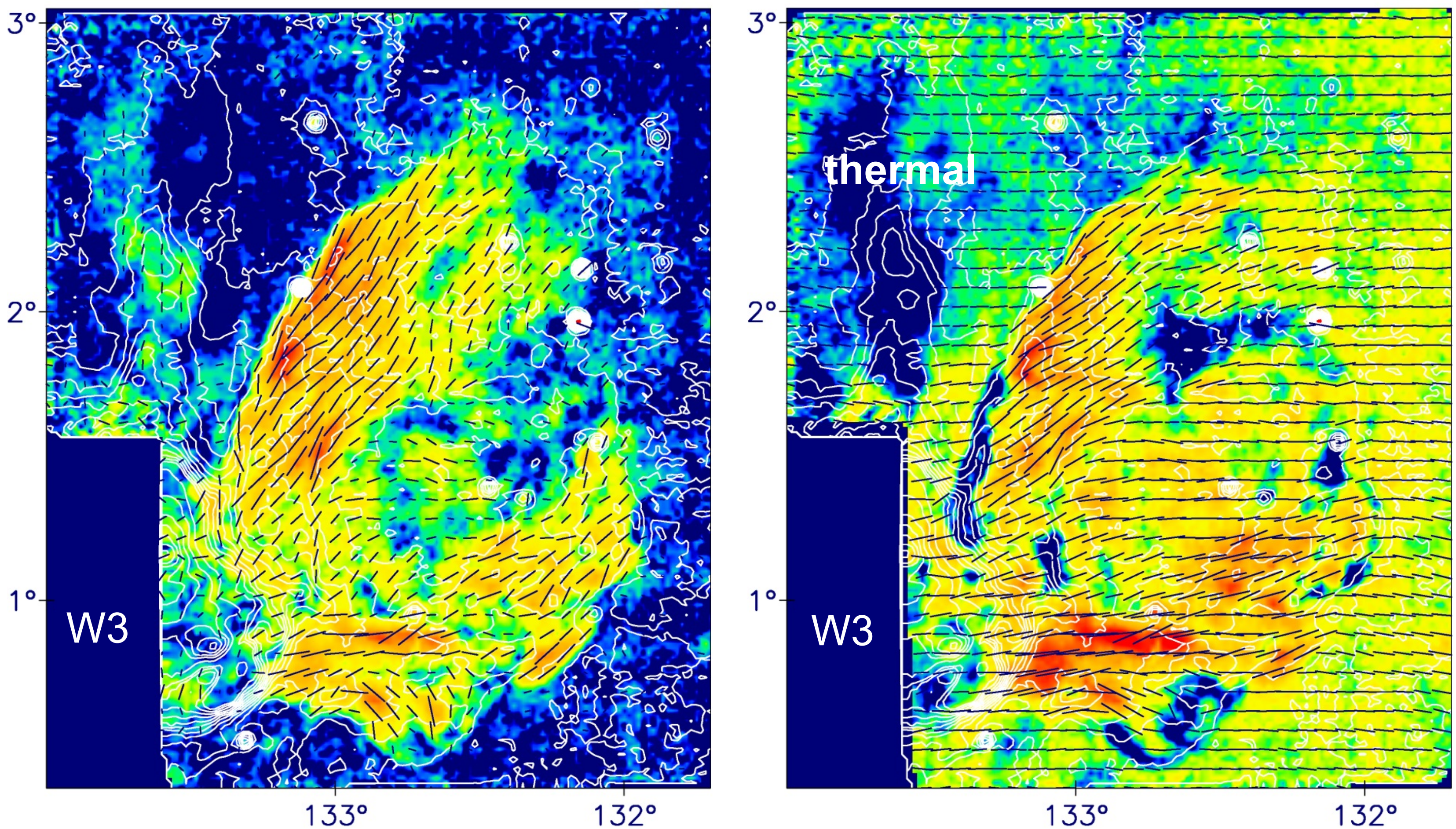
Missing component: a scalar for total intensities
<u>a vector for polarization</u>:

$$PI_{abs} = ((U+U_{off})^2 + (Q+Q_{off})^2)^{1/2} \rightarrow PI_{abs} \neq PI + P_{off}$$

$$\varphi_{abs} = 0.5\ \mathrm{atan}((U+U_{off})/(Q+Q_{off})) \rightarrow \varphi_{abs} \neq \varphi + \varphi_{off}$$

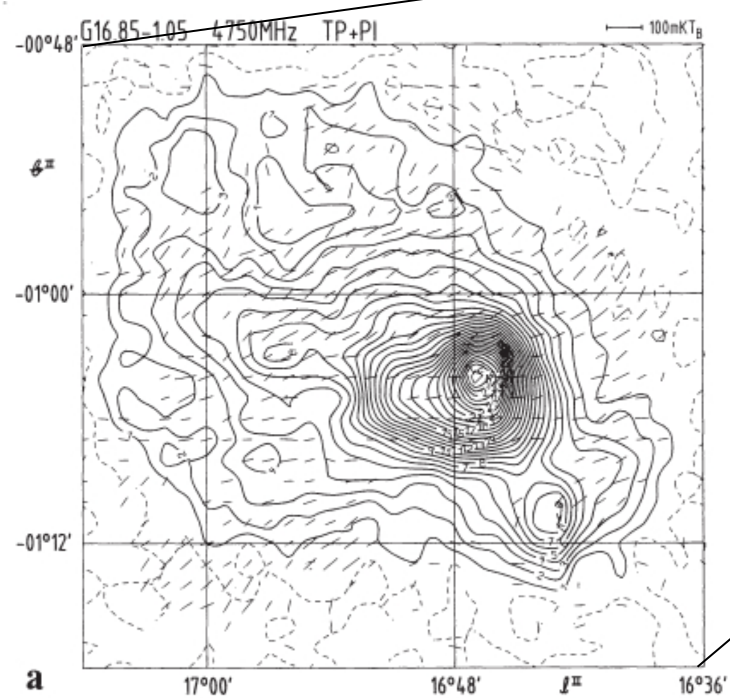
HB3 6-cm EB+Urumqi
PI(B-field) + I-contours

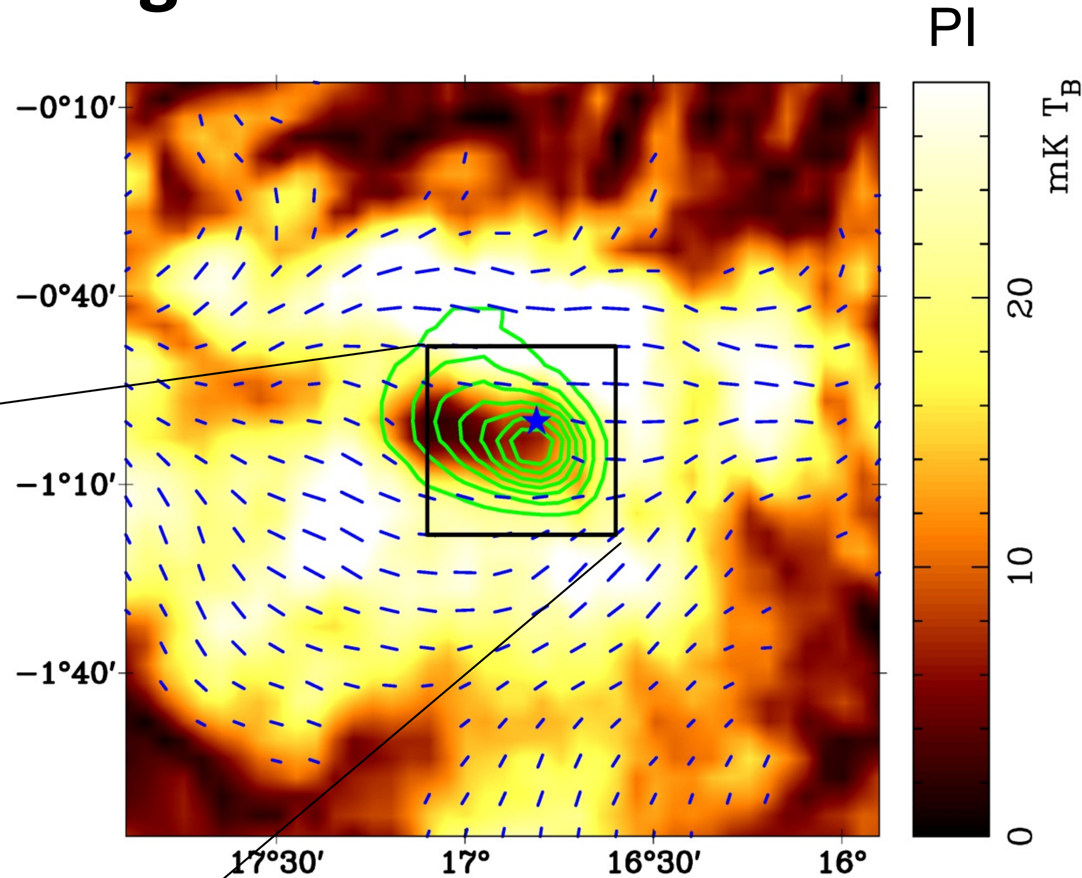
+ WMAP based absolute
zero-level correction for U,Q

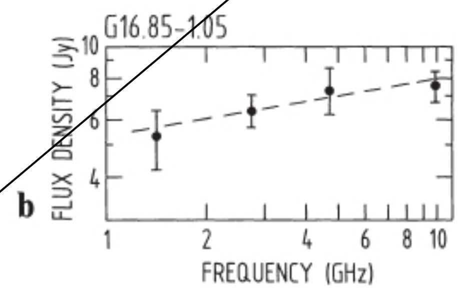


G16.85-1.05, a HII-region *not* a SNR

Reich et al. 1986
EB 6-cm
mapsize 0.5° x 0.5°

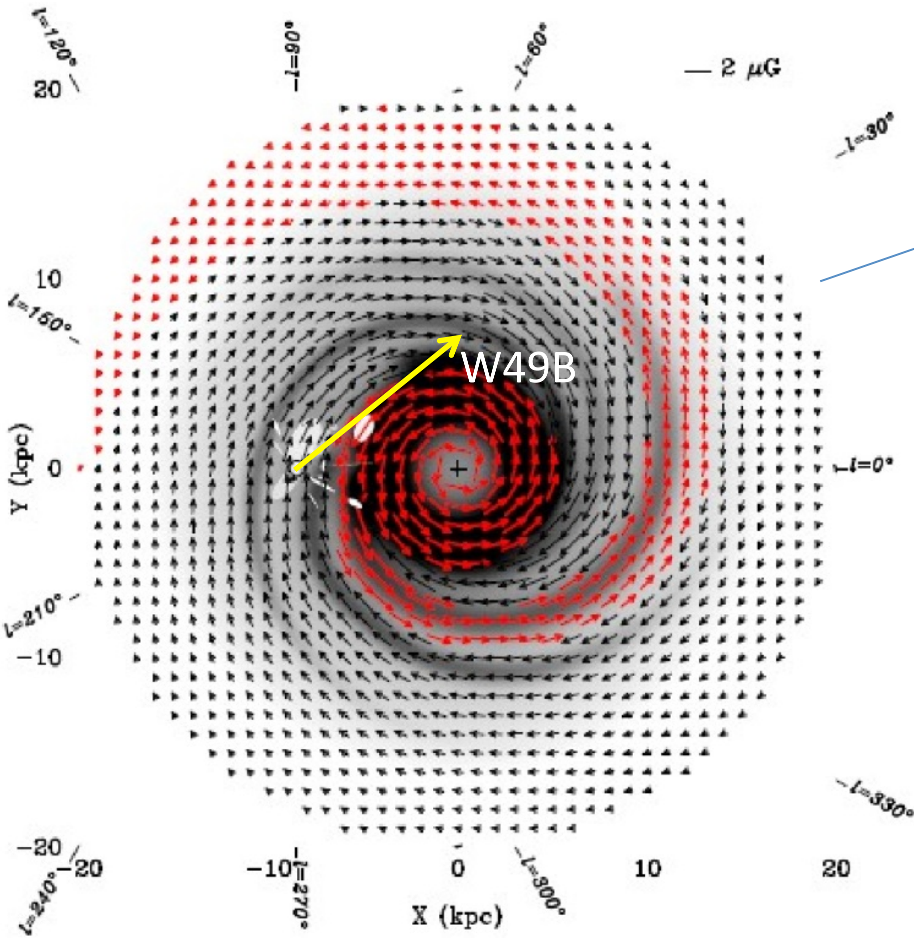




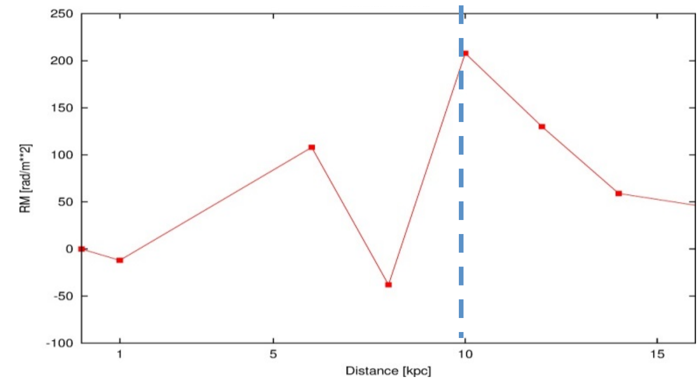


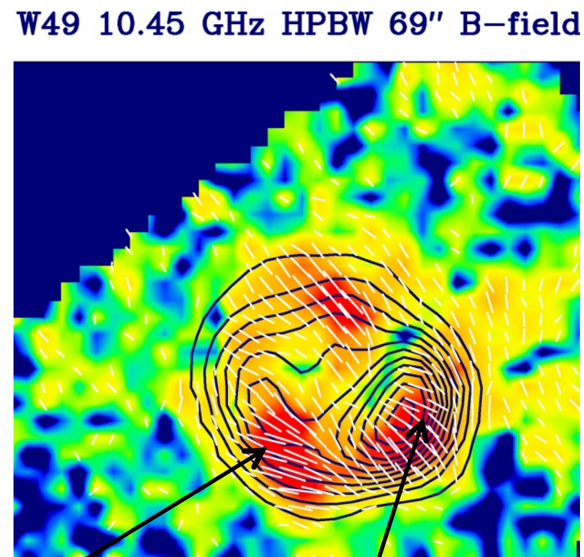
Sun et al. 2011
Urumqi 6cm survey

Galactic RM effects on SNR observations



RM f(r) towards W49B





observed +600 rad/m^2 +100 rad/m^2

Sun & Reich, 2010

The magnetic field strength from radio data

Problem: B field strength can only measured in combination with n(E) or N_e

Assumption of 'Equipartition': Minimum total energy of electrons, protons and magnetic field. Justified ?

e.g. $B_{min} = C \times (L/V)^{2/7}$

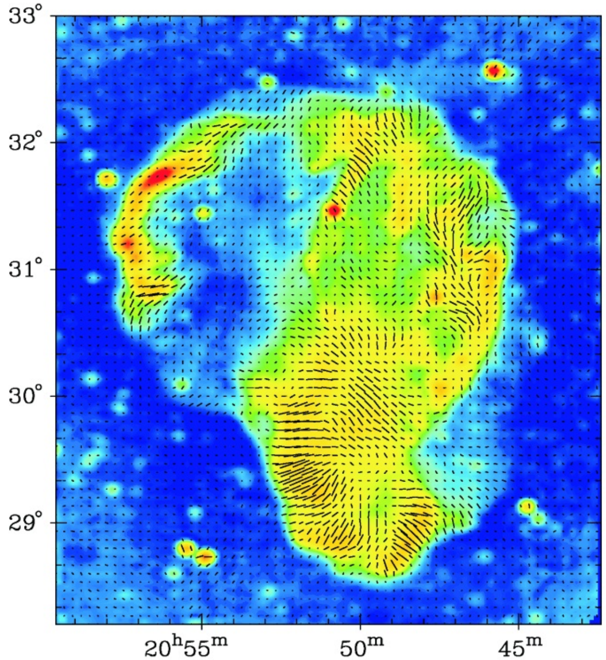
Arbutina et al. (2012, 2013) - Table of SNR B-fields (+ Web application)

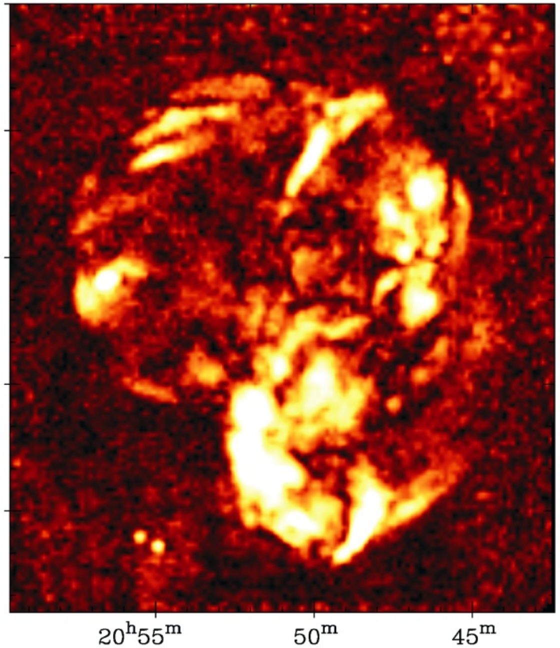
Magnetic field estimates from spectral fits of SNRs including γ and X-ray data indicate significant deviations, mostly higher fields, but…

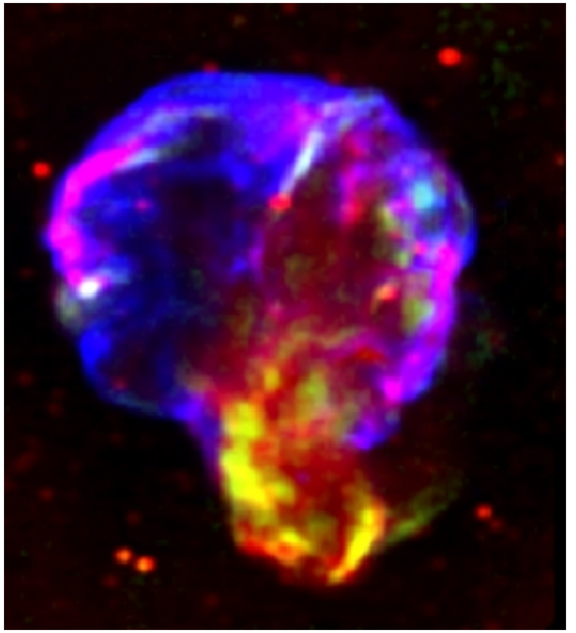
OH masers within SNRs: (very) high local fields

The Cygnus Loop = two SNRs (?)

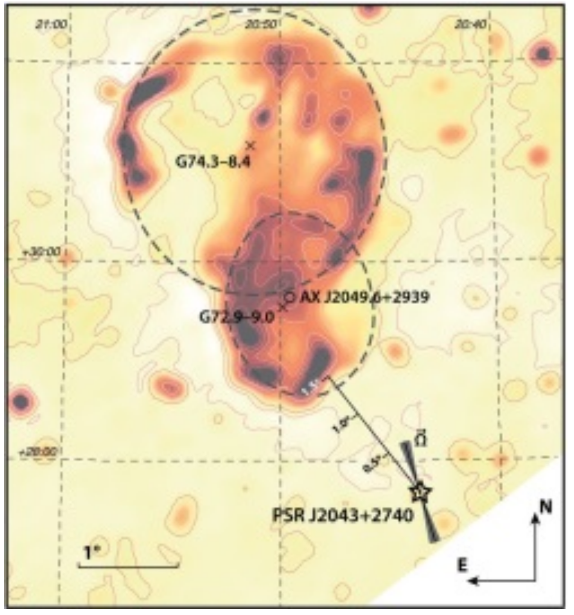
EB 11-cm, beam 4.3‘ (Uyaniker et al., 2002, 2004)





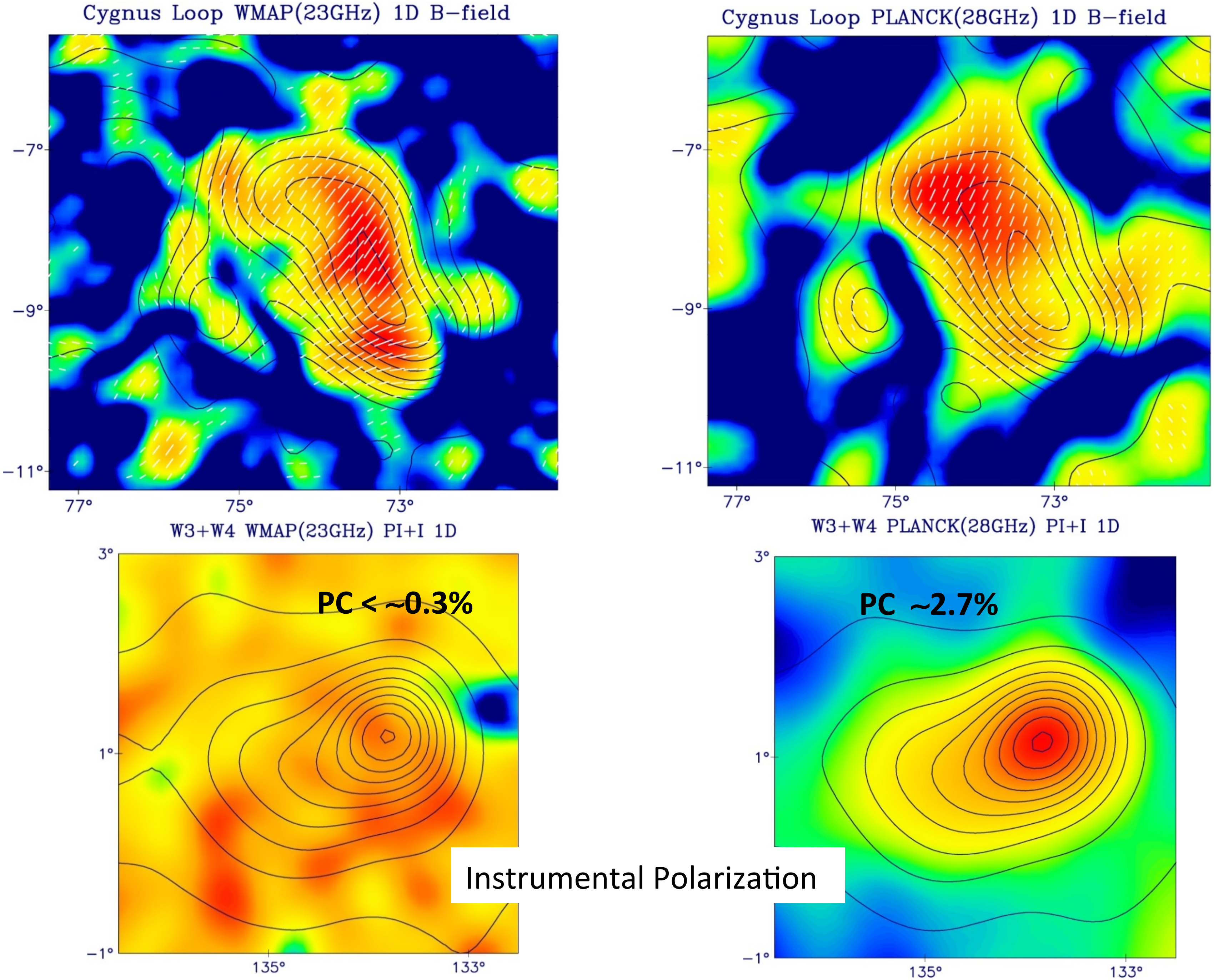


11cm I (red) , PI (green)
ROSAT X-ray (blue)



SNR large enough for WMAP and PLANCK beams ~0.5° to 1° (<30 GHz)

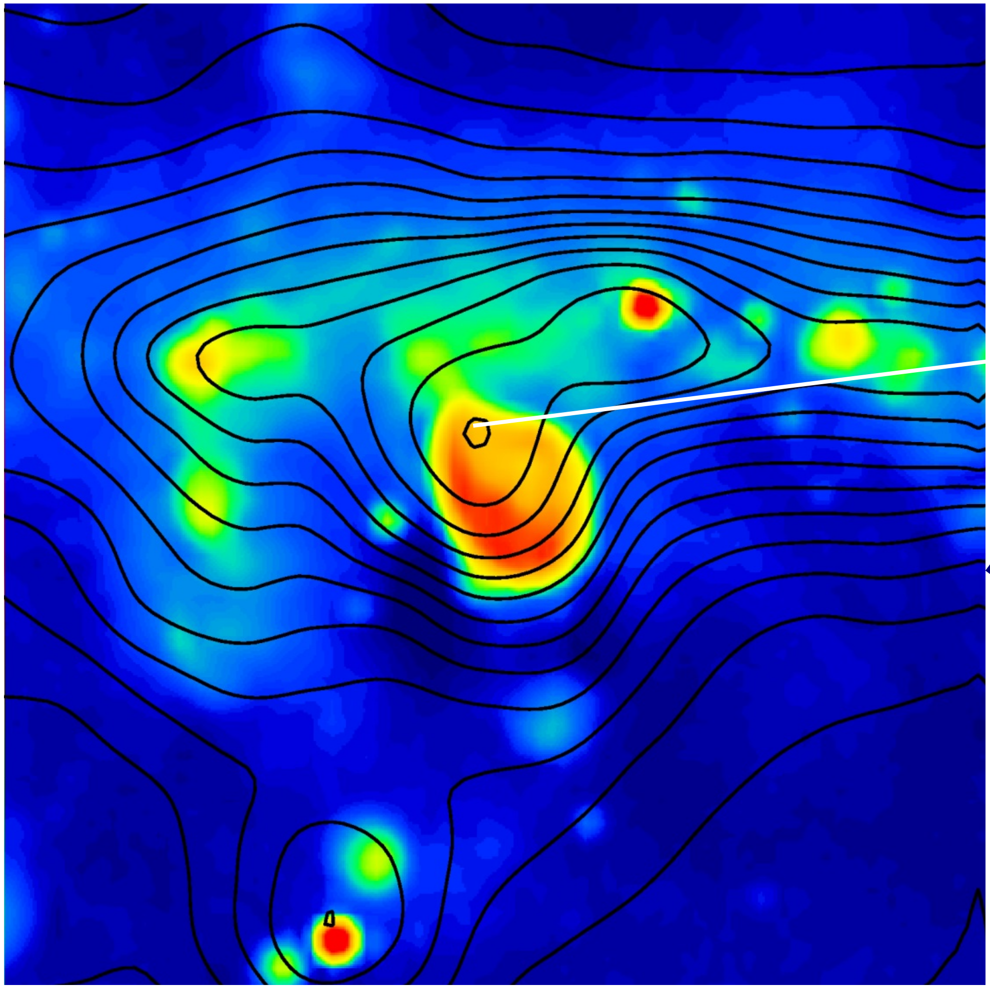
Noutsos et al. 2011



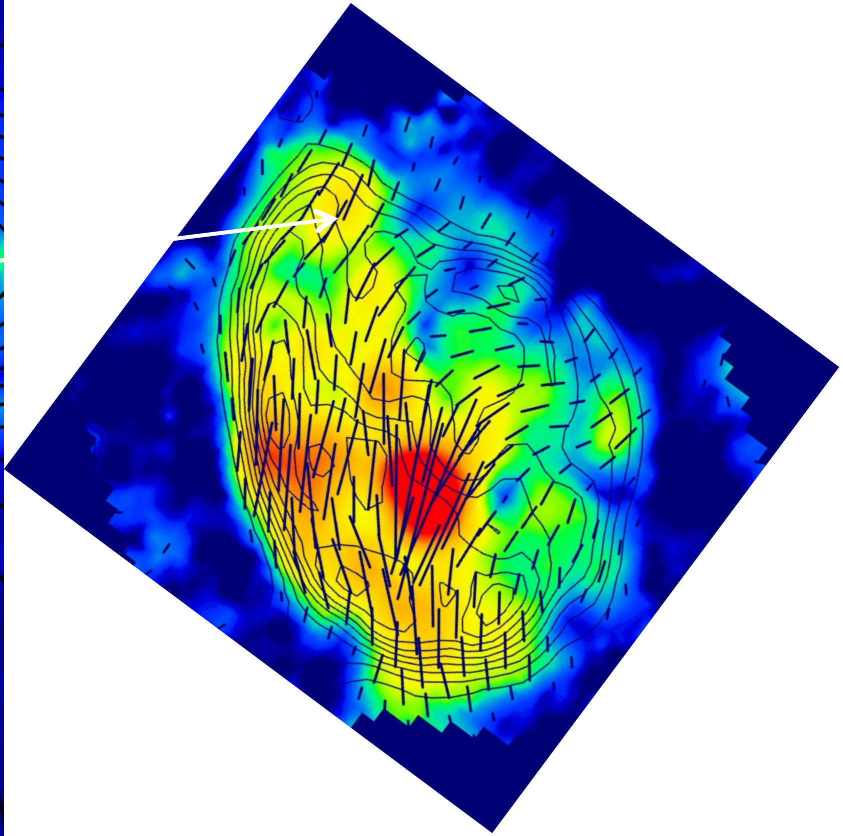
Cygnus Loop WMAP(23GHz) 1D B−field
Cygnus Loop PLANCK(28GHz) 1D B−field
−7°
−9°
−11°
77°
75°
73°
W3+W4 WMAP(23GHz) PI+I 1D
W3+W4 PLANCK(28GHz) PI+I 1D
3°
1°
−1°
135°
133°
PC < ~0.3%
PC ~2.7%
Instrumental Polarization

W44 area

EB 11-cm Galactic plane survey
+ PLANCK 28.4 GHz contours



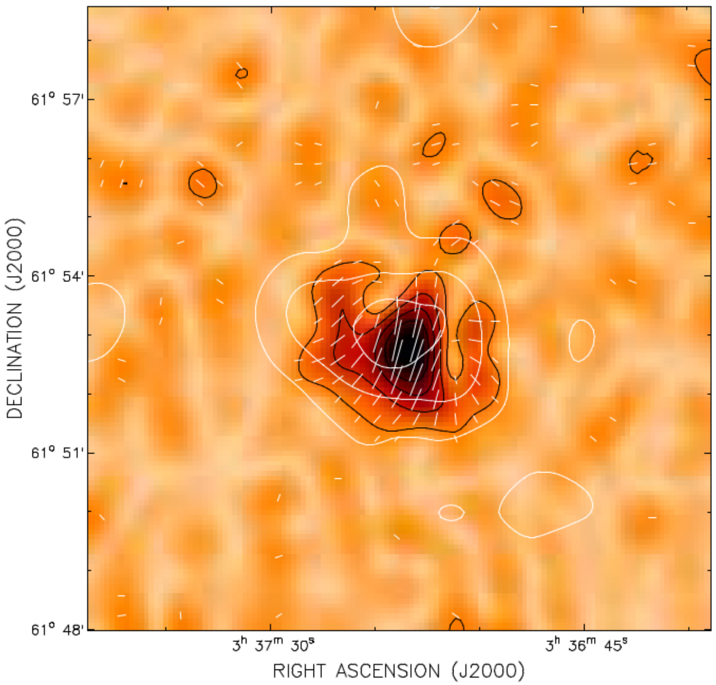
W44 EB 6-cm 2.4‘ PI(B) + I



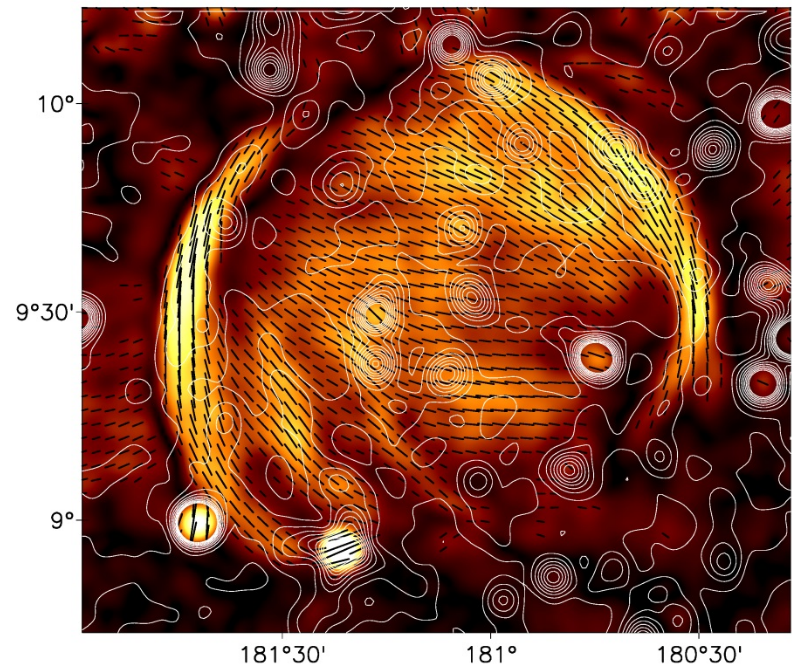
Recently detected radio SNRs

New detections since Green's catalogue (2014) with 294 SNR: about 10, mostly from published surveys (CGPS, EB, Urumqi) + follow-up observations – all are faint, or very faint

PWN G141.2+5.0 Kothes et al. (2013)



G181.2+9.5 EB 6cm PI(B) + I



=> see Poster P. Reich et al.

Concluding Remarks

- Radio polarization observations provide information on the SNR magnetic field and reflect their interaction with the local Galactic magnetic field and ISM.
- Most SNRs were discovered in the radio range. Magnetic field information is limited for most SNRs.
- The detection of faint missing SNRs suffers from confusion effects. Highly polarized SNRs seem easier to be detected by their polarized emission. Faraday effects influence the analysis of faint and of distant objects.