Magnetic Fields in Supernova Remnants and Pulsar Wind Nebulae

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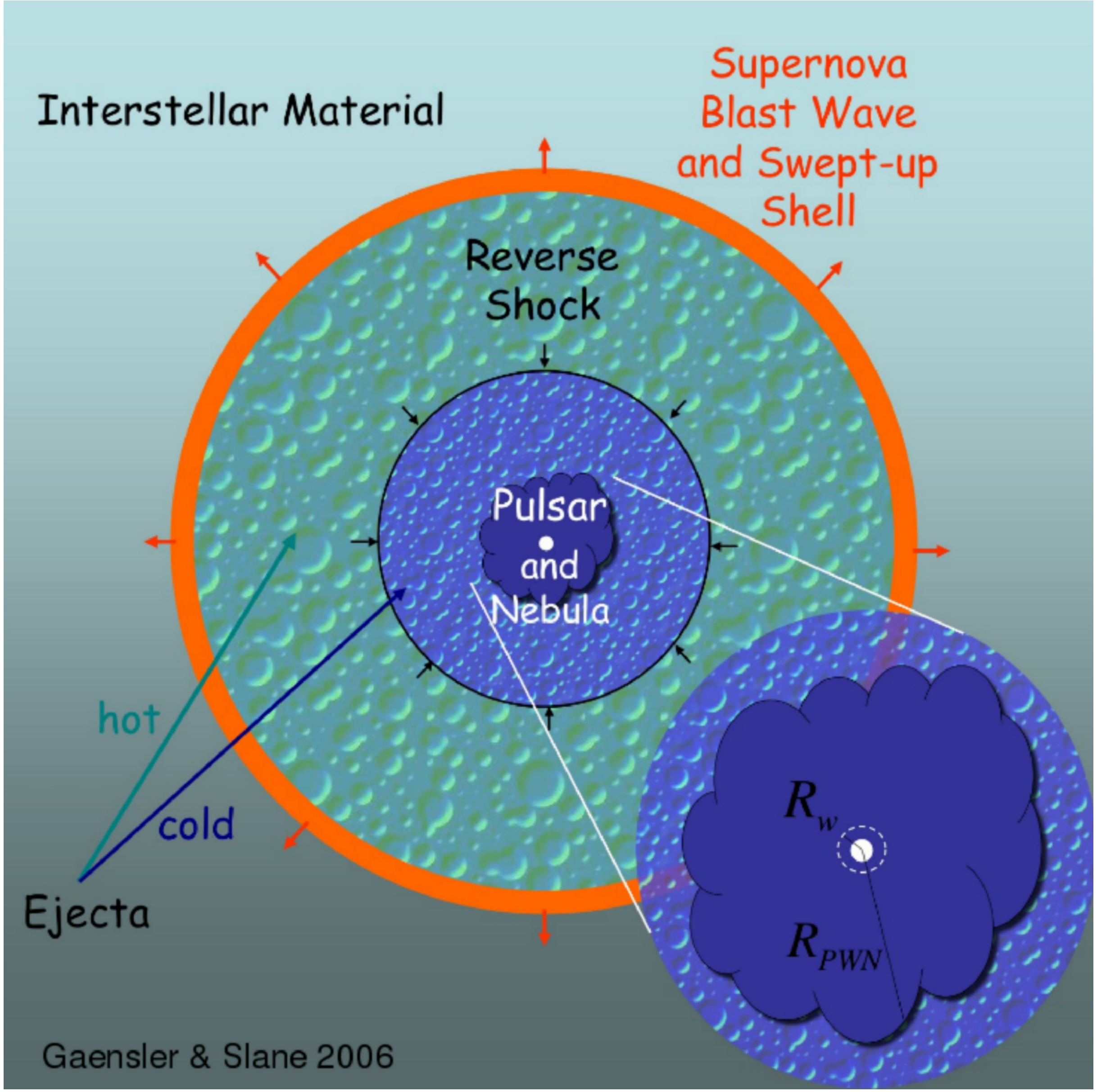
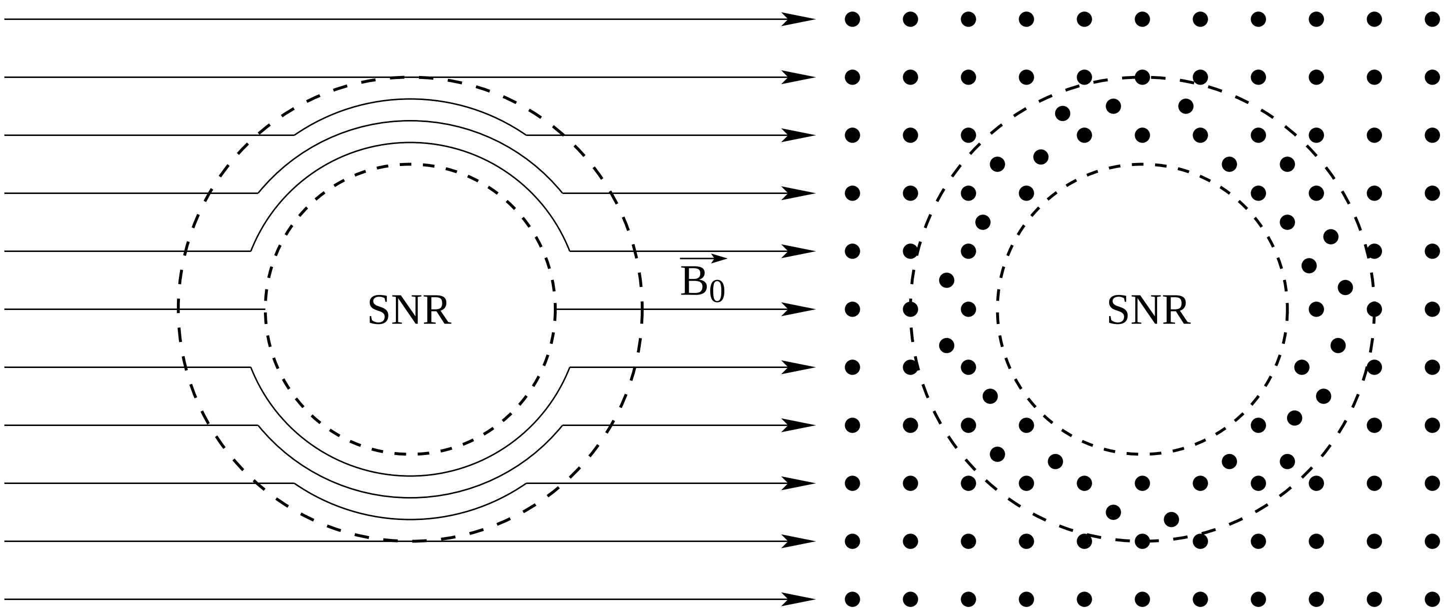
Overview

Supernova Remnants



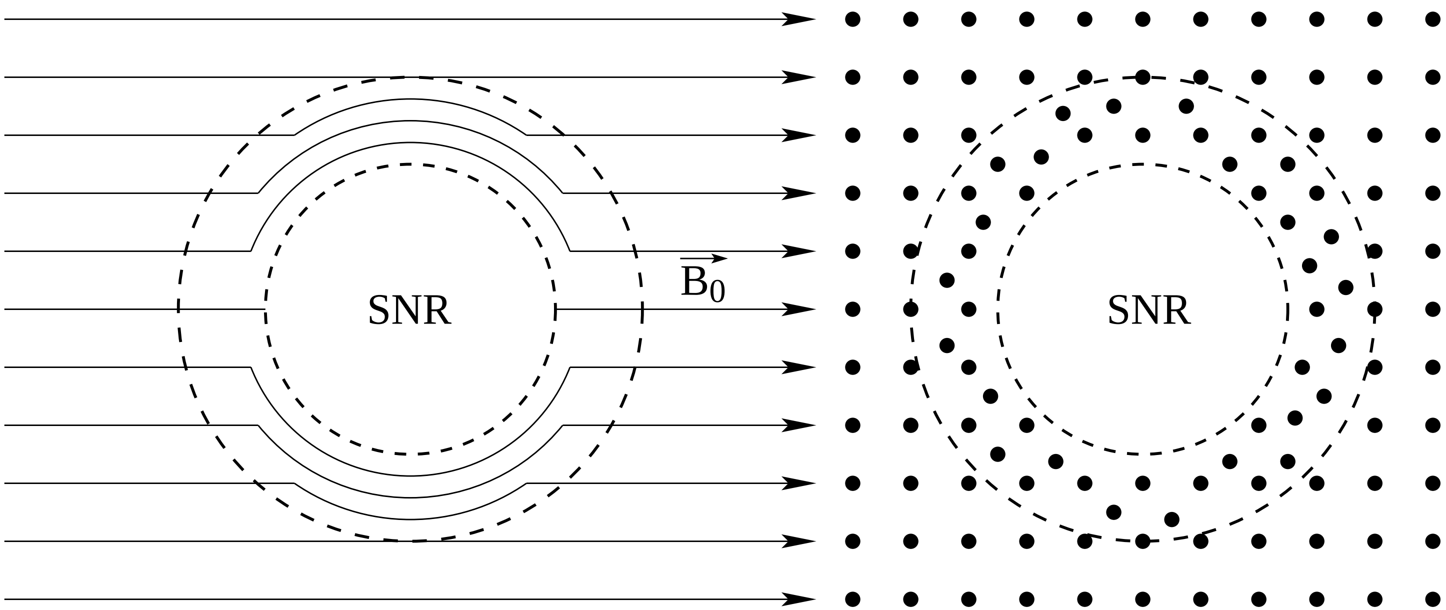
A Model of a Mature SNR



I assume:

- mature SNR $\Rightarrow$ dominated by environment
- spherical geometry
- constant ambient density n_0 ($= 1\,\text{cm}^{-3}$)
- homogenous ambient magnetic field $\vec{B}_0$ ($= 5\,\mu$G)

A Model of a Mature SNR



- Θ: angle between plane of the sky and ambient B-field
- $S_\nu = K\, B_\perp^{\frac{1}{2}(\delta+1)} \nu^{-\frac{1}{2}(\delta-1)}, N(E)dE = K\, E^{-\delta} dE$
- $\Delta\phi_\lambda = RM\lambda^2$, $RM = 0.81 \int_l B_\| n_e dl$

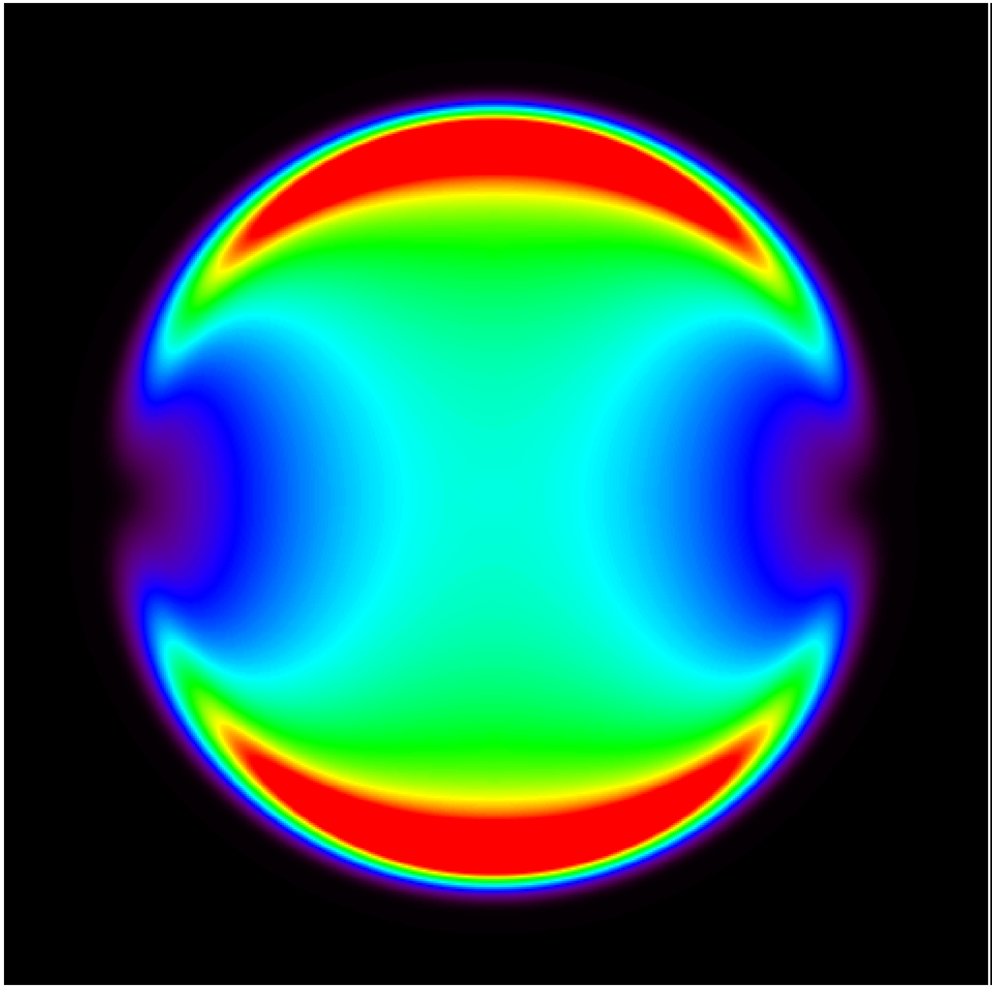
Emission Structure of SNRs

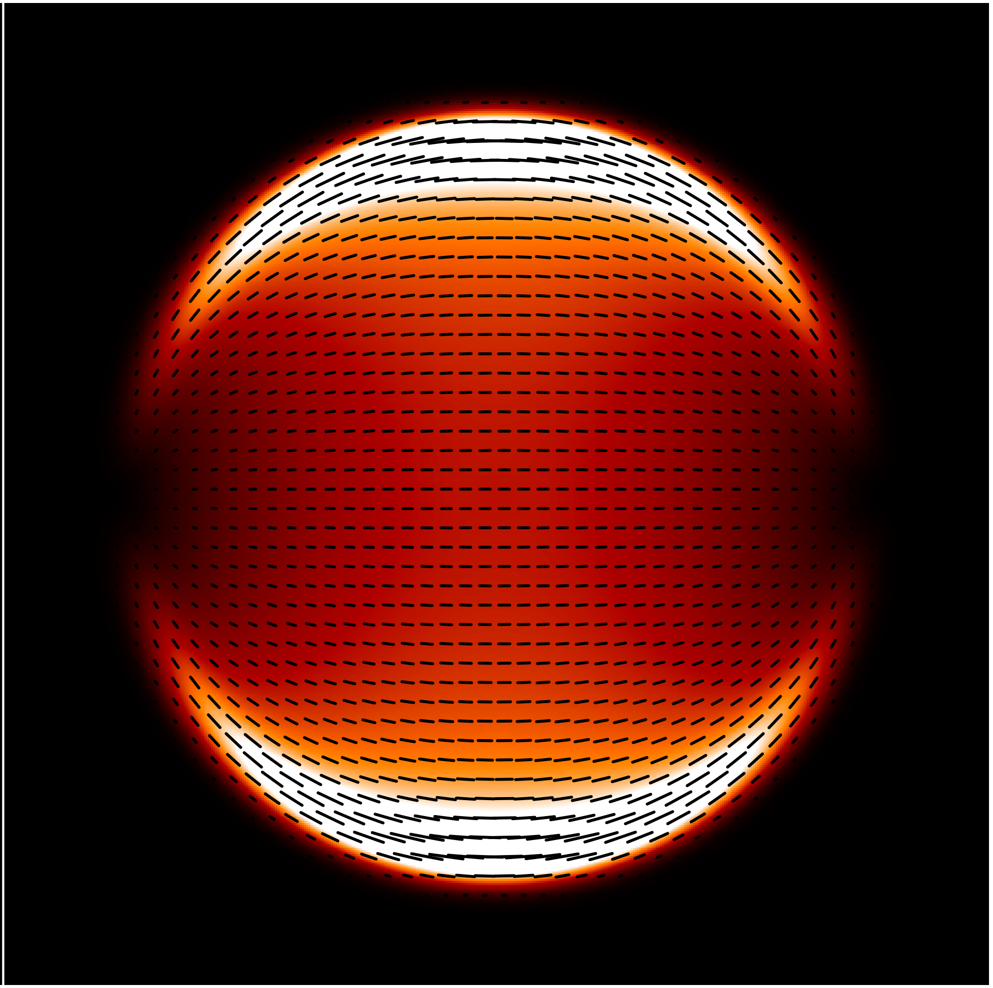
- The surface brightness is decreasing significantly with Θ.
- For Θ up to 60° we find two bright arcs and a well ordered magnetic field in the centre both parallel to $\vec{B}_0$.
- For Θ larger than 60° we find a thick-shelled object with a radial magnetic field.

Emission Structure of SNRs

Rotation Angle $\Theta = 0^\circ$

Stokes I	PI + B-vectors

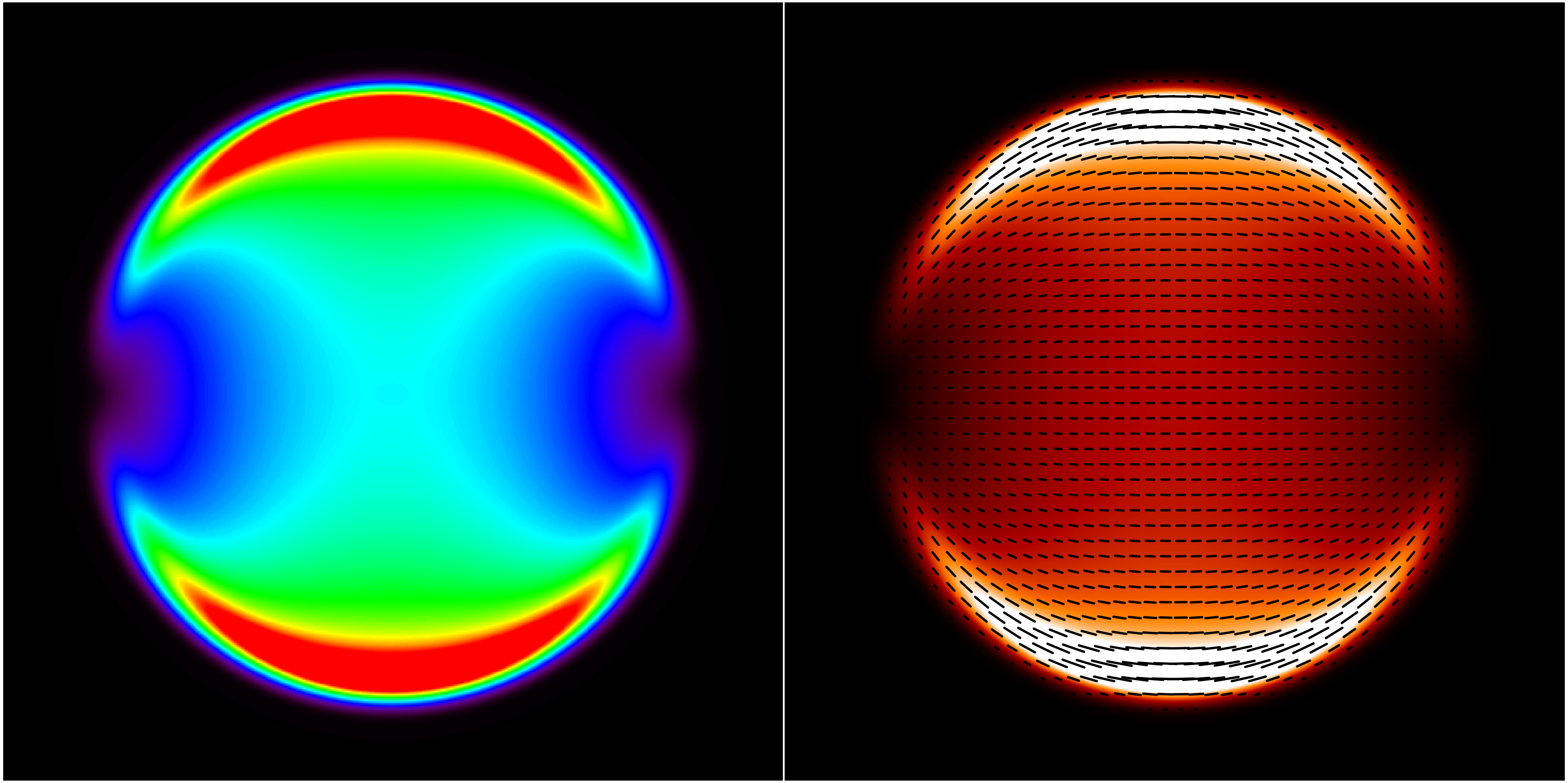




Emission Structure of SNRs

Rotation Angle $\Theta = 15^\circ$

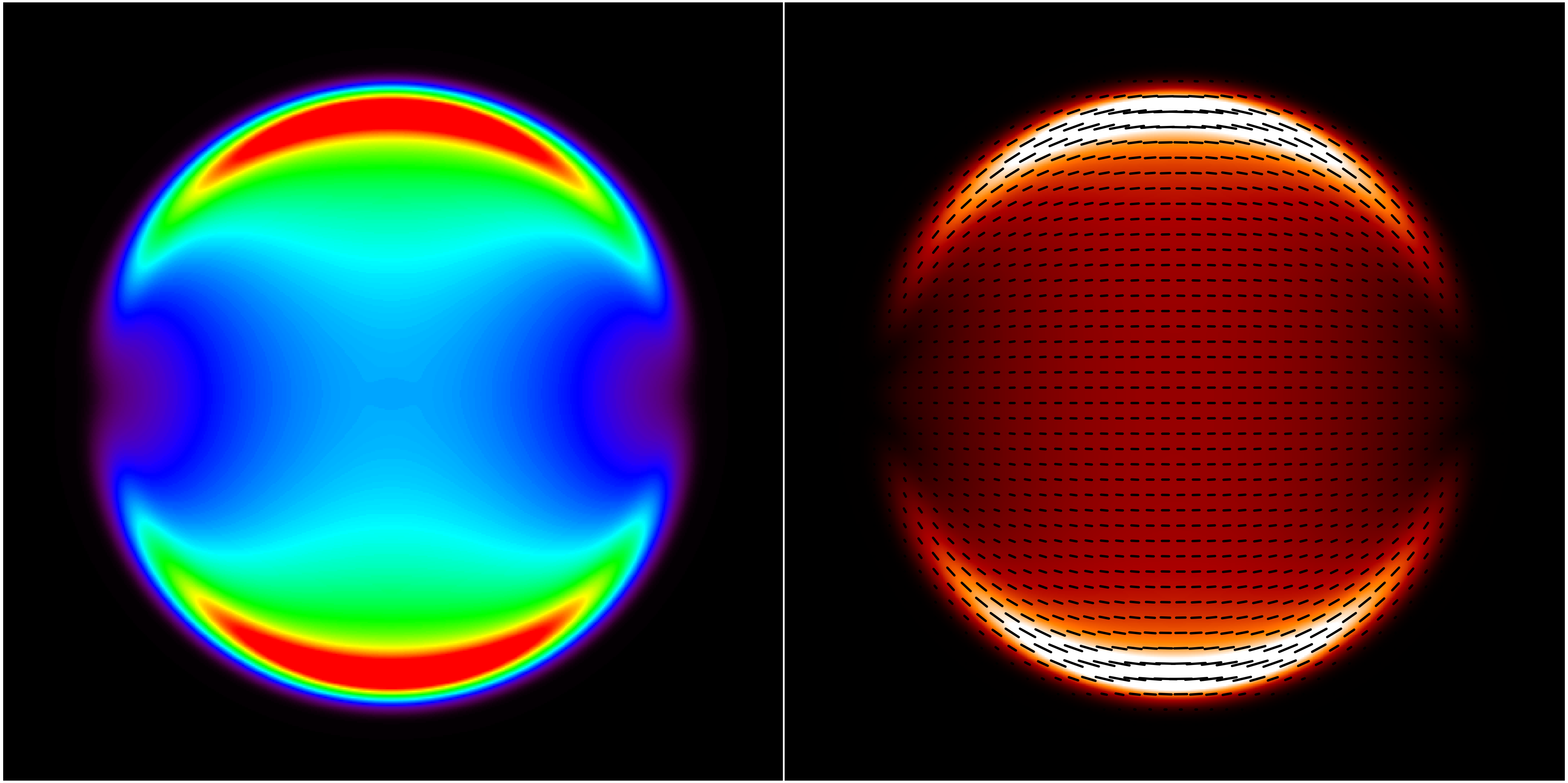
Stokes I | PI + B-vectors



Emission Structure of SNRs

Rotation Angle $\Theta = 30^\circ$

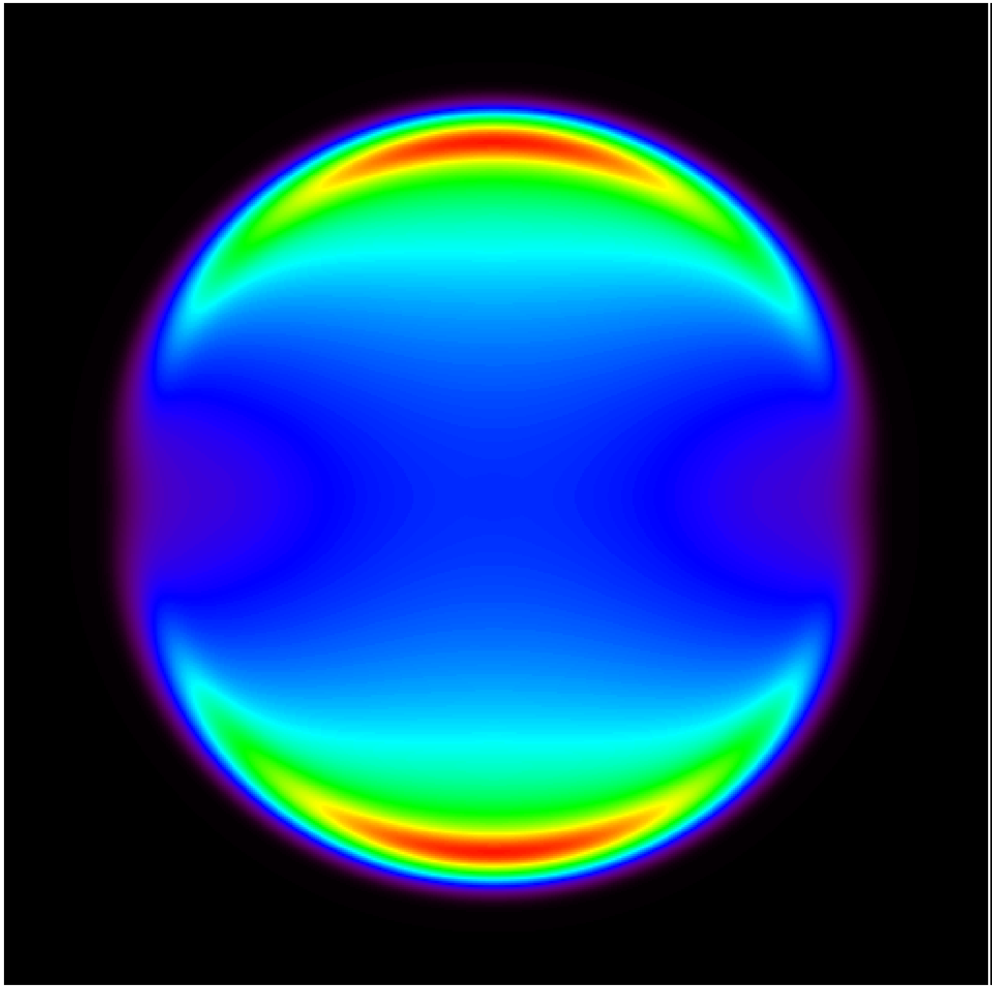
Stokes I | PI + B-vectors



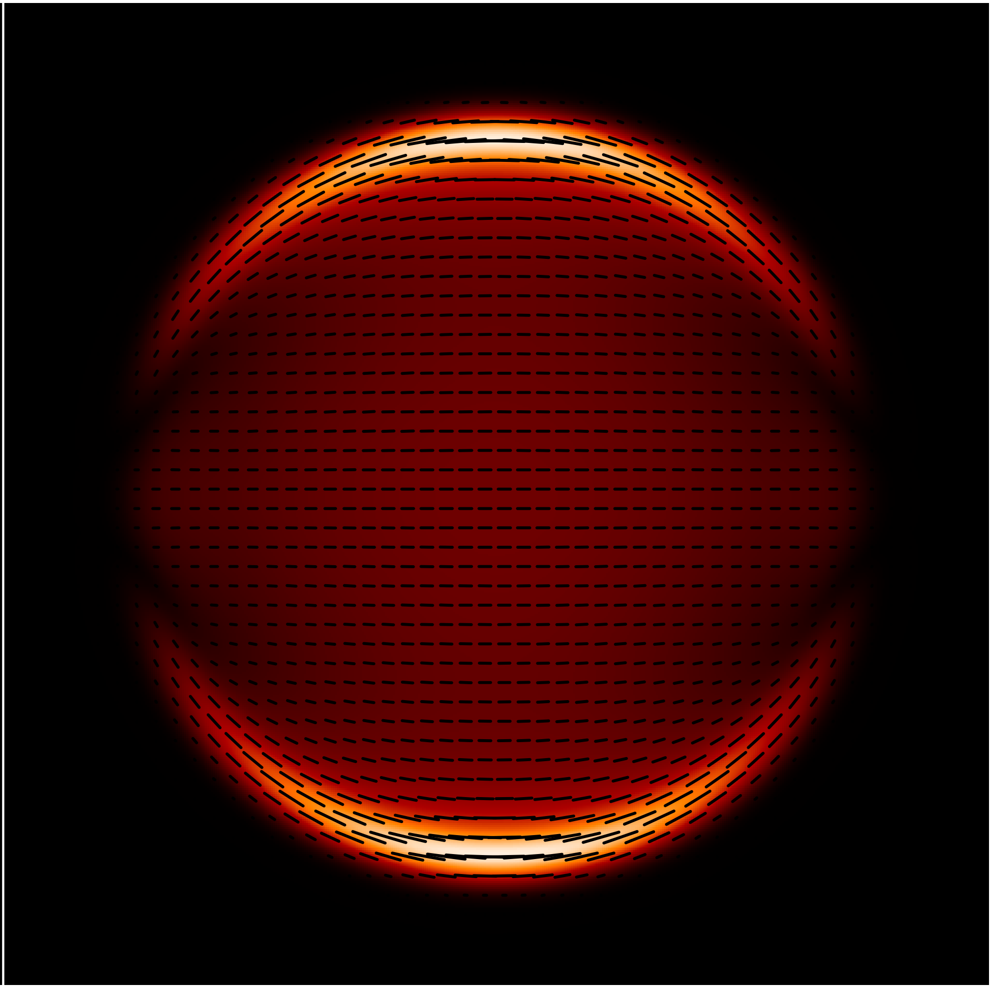
Emission Structure of SNRs

Rotation Angle $\Theta = 45^\circ$

Stokes I



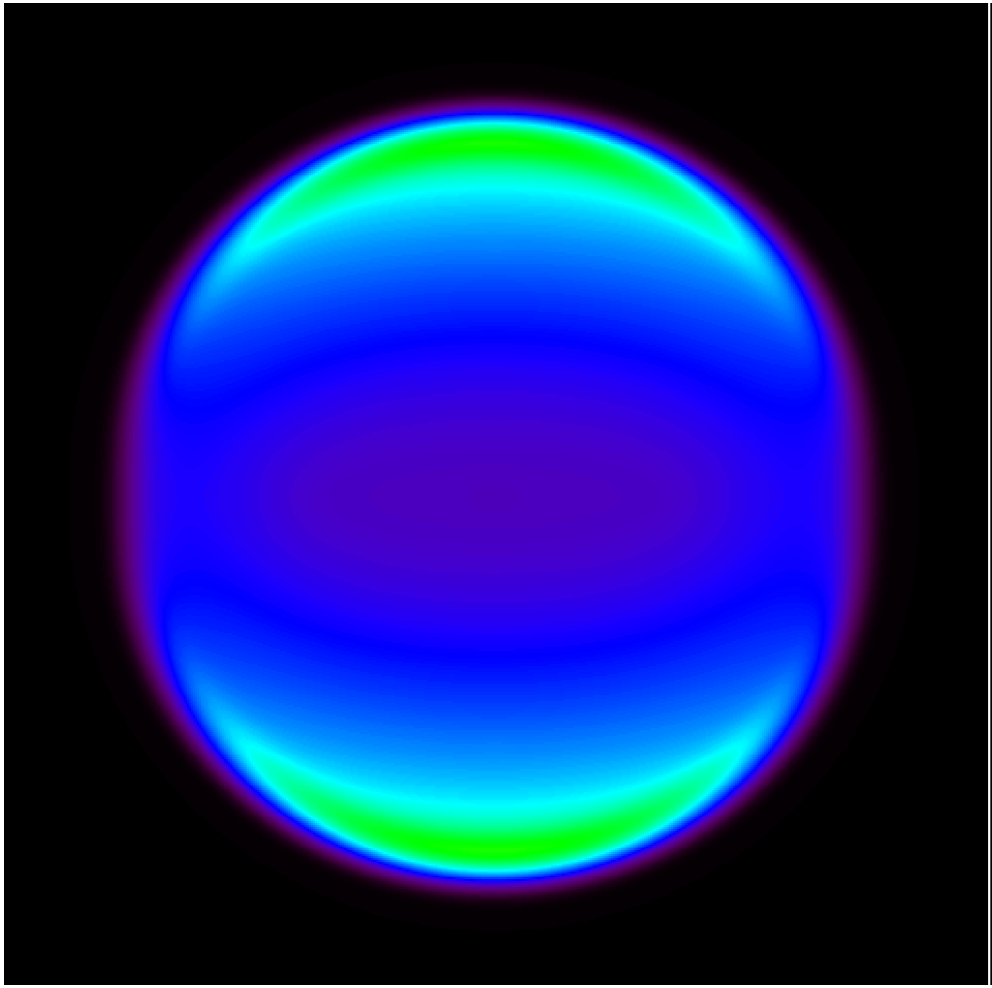
PI + B-vectors



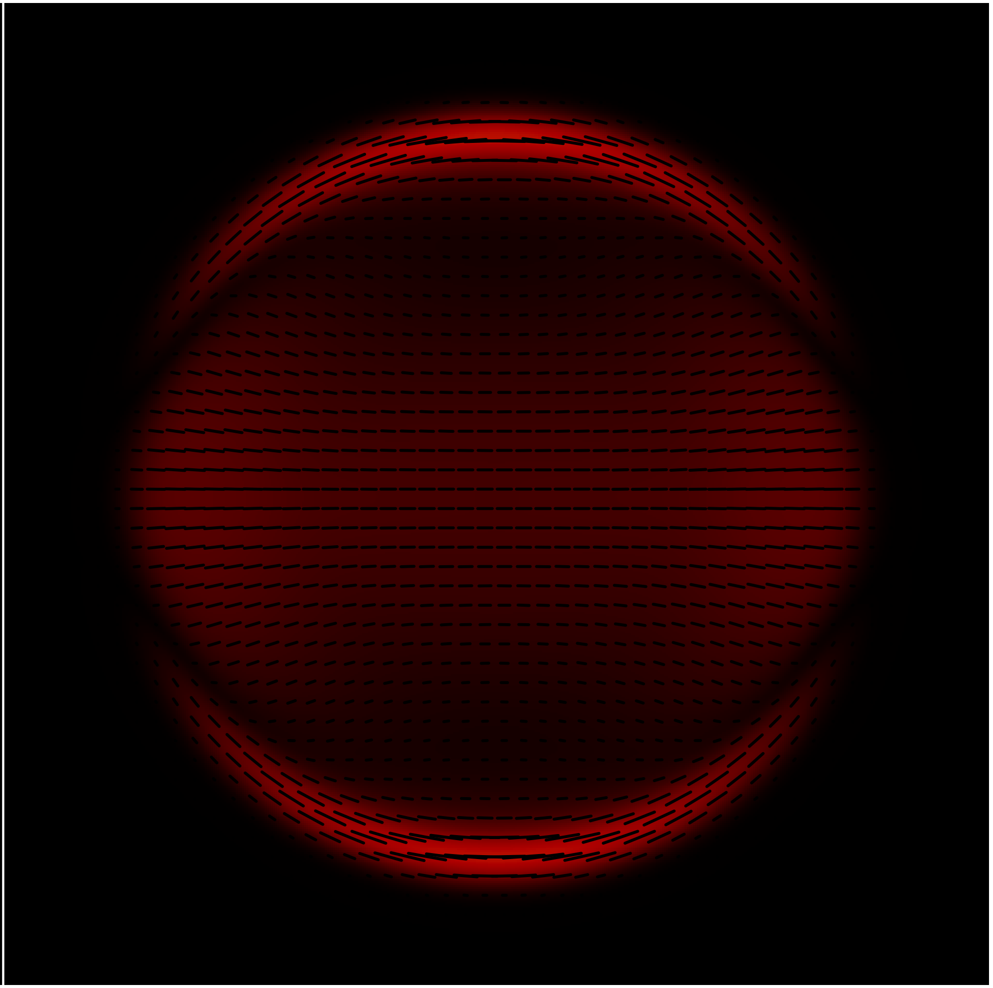
Emission Structure of SNRs

Rotation Angle $\Theta = 60^\circ$

Stokes I



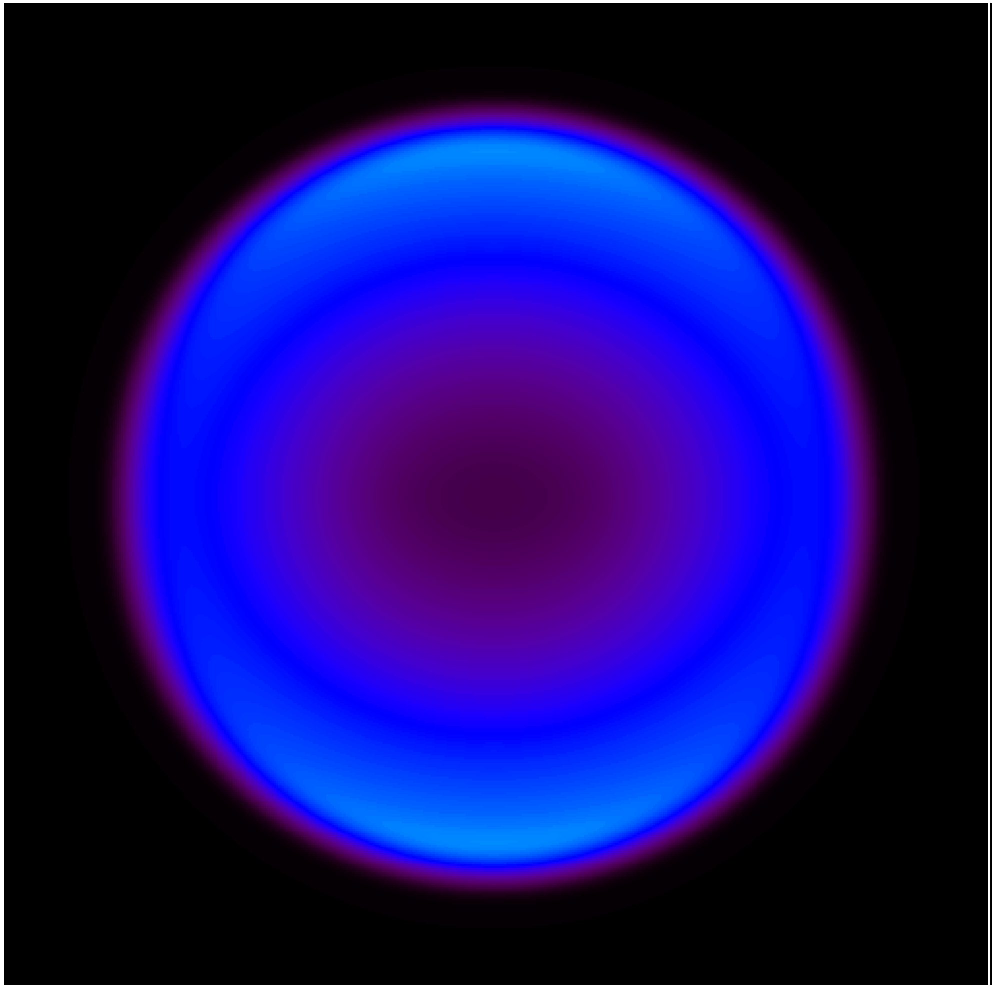
PI + B-vectors



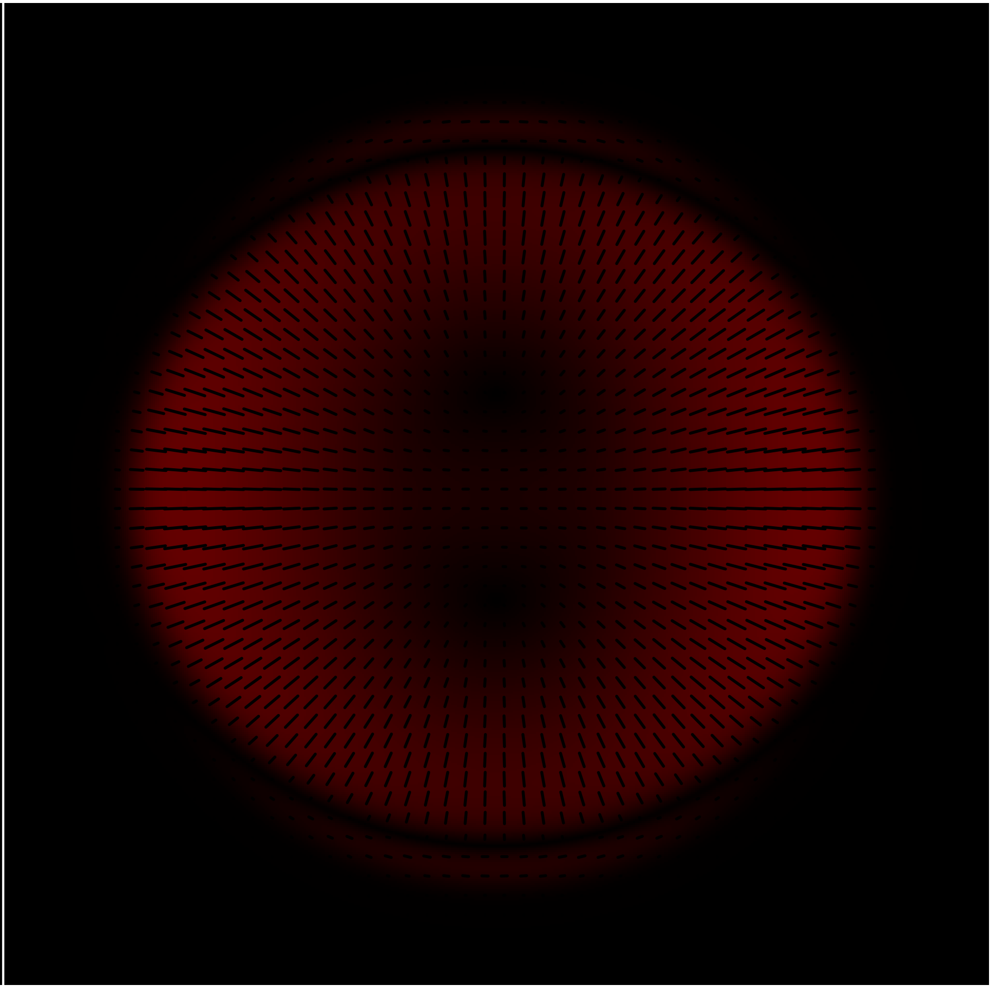
Emission Structure of SNRs

Rotation Angle $\Theta = 75^\circ$

Stokes I



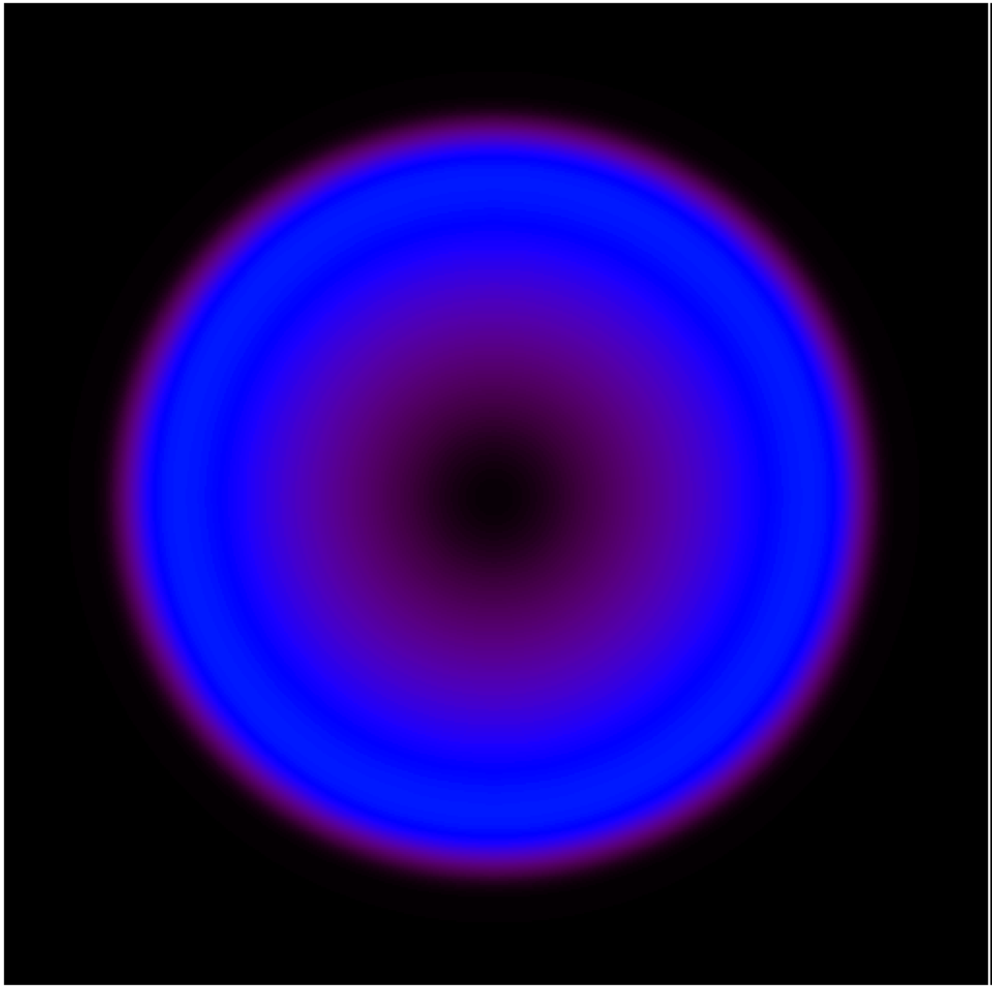
PI + B-vectors



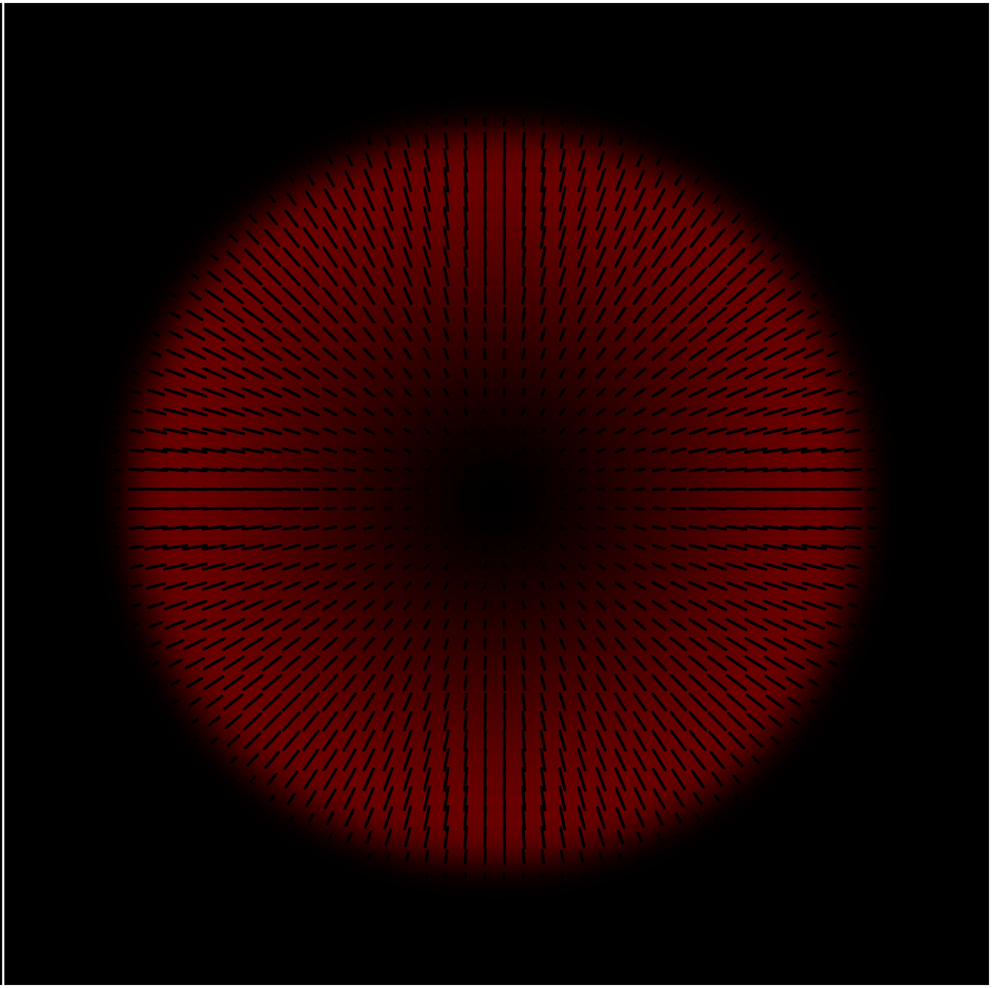
Emission Structure of SNRs

Rotation Angle $\Theta = 90^{\circ}$

Stokes I



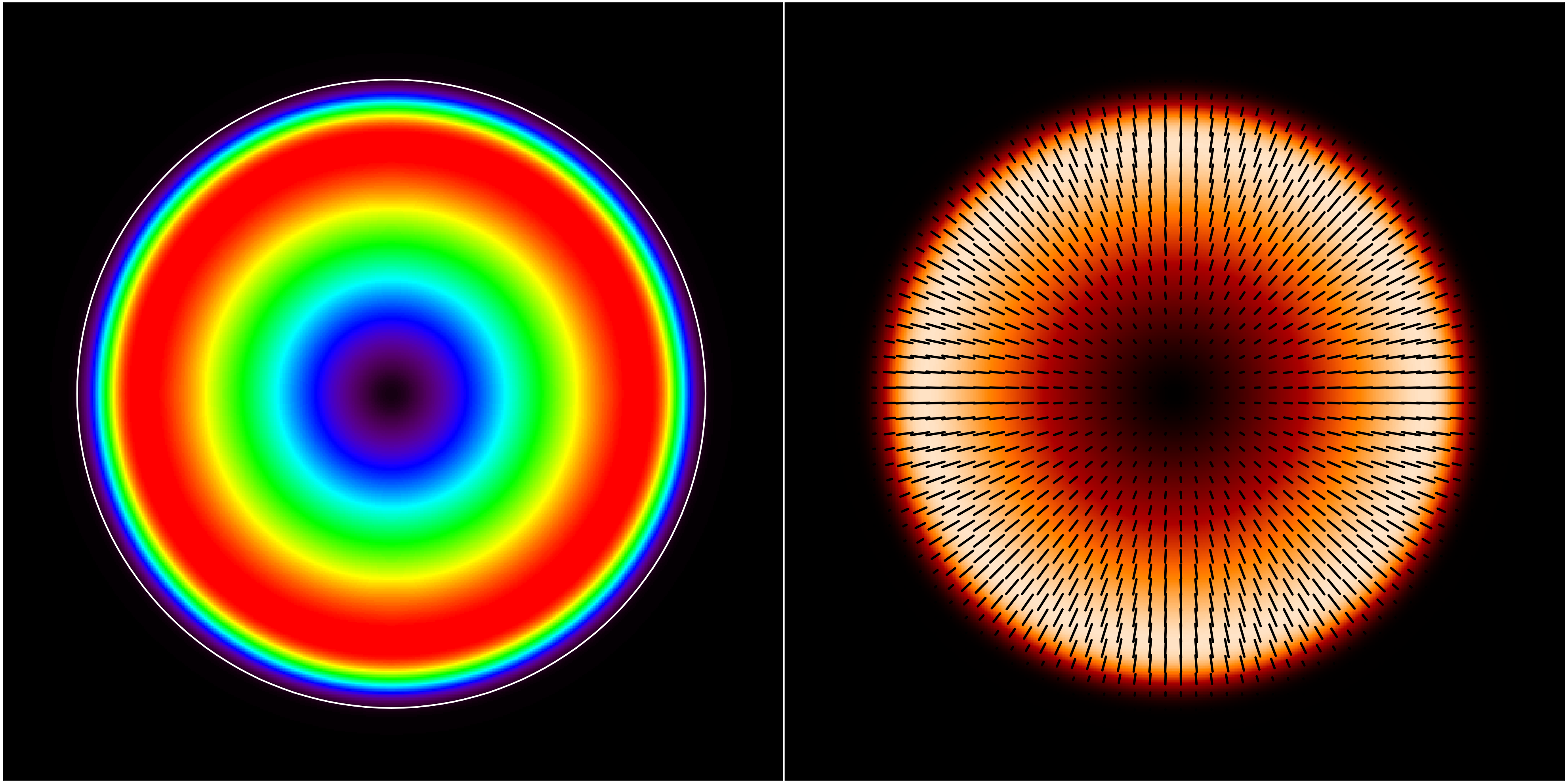
PI + B-vectors



Emission Structure of SNRs

Rotation Angle $\Theta = 90^\circ$

Stokes I | PI + B-vectors

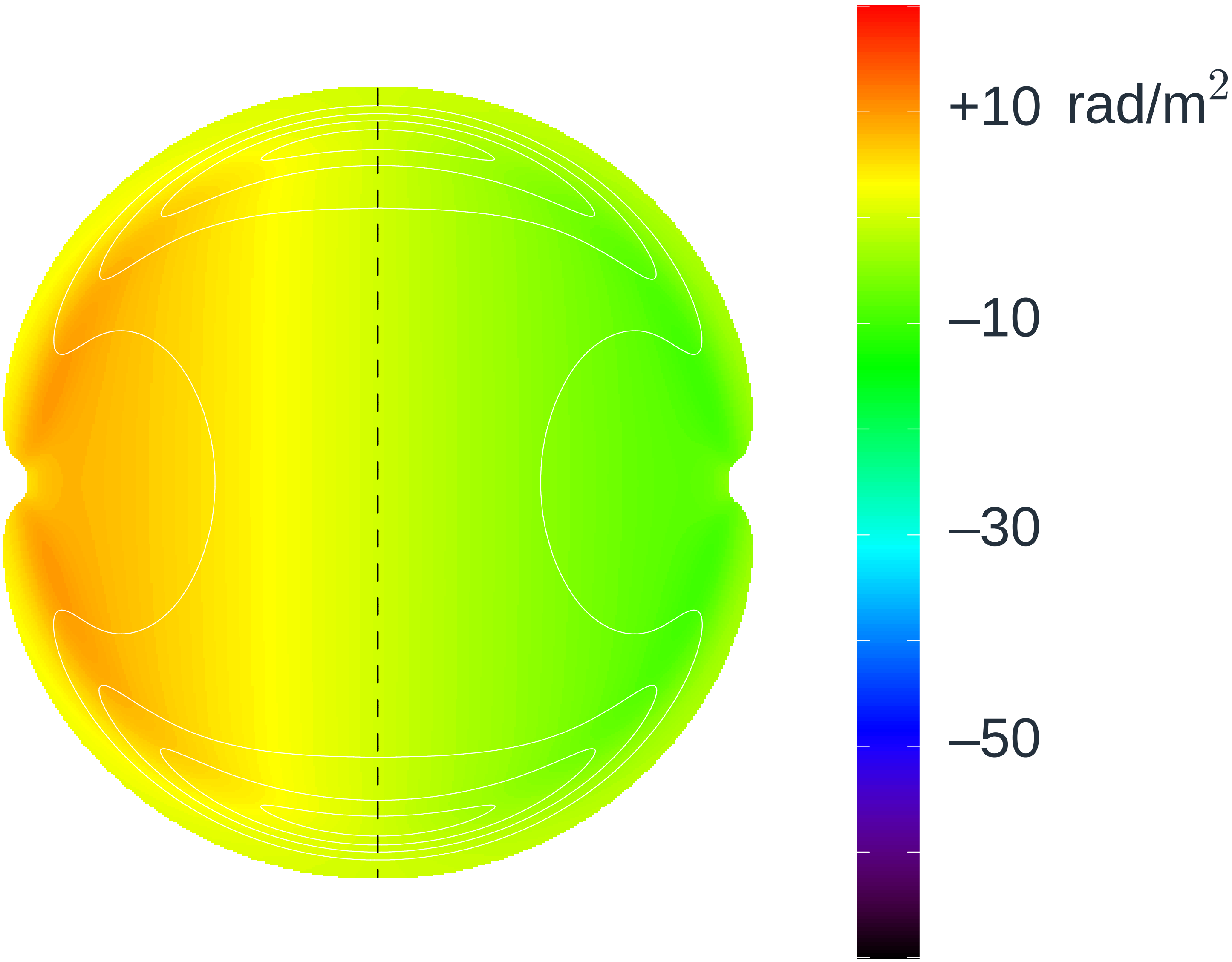


Faraday Rotation in SNRs

- The RM in the centre of the SNR is always 0 rad/m^2.
- There is a peak of RM; its location relative to the centre gives an indication of the orientation of $\vec{B}_0$.
- On the two arcs RM shows a linear behaviour which can be described by:
  - the RM gradient, which depends on $|\vec{B}_0| \times n_e$ and the size of the SNR.
  - the RM in the centre of the arcs, which depends on Θ and RM_{fore}.

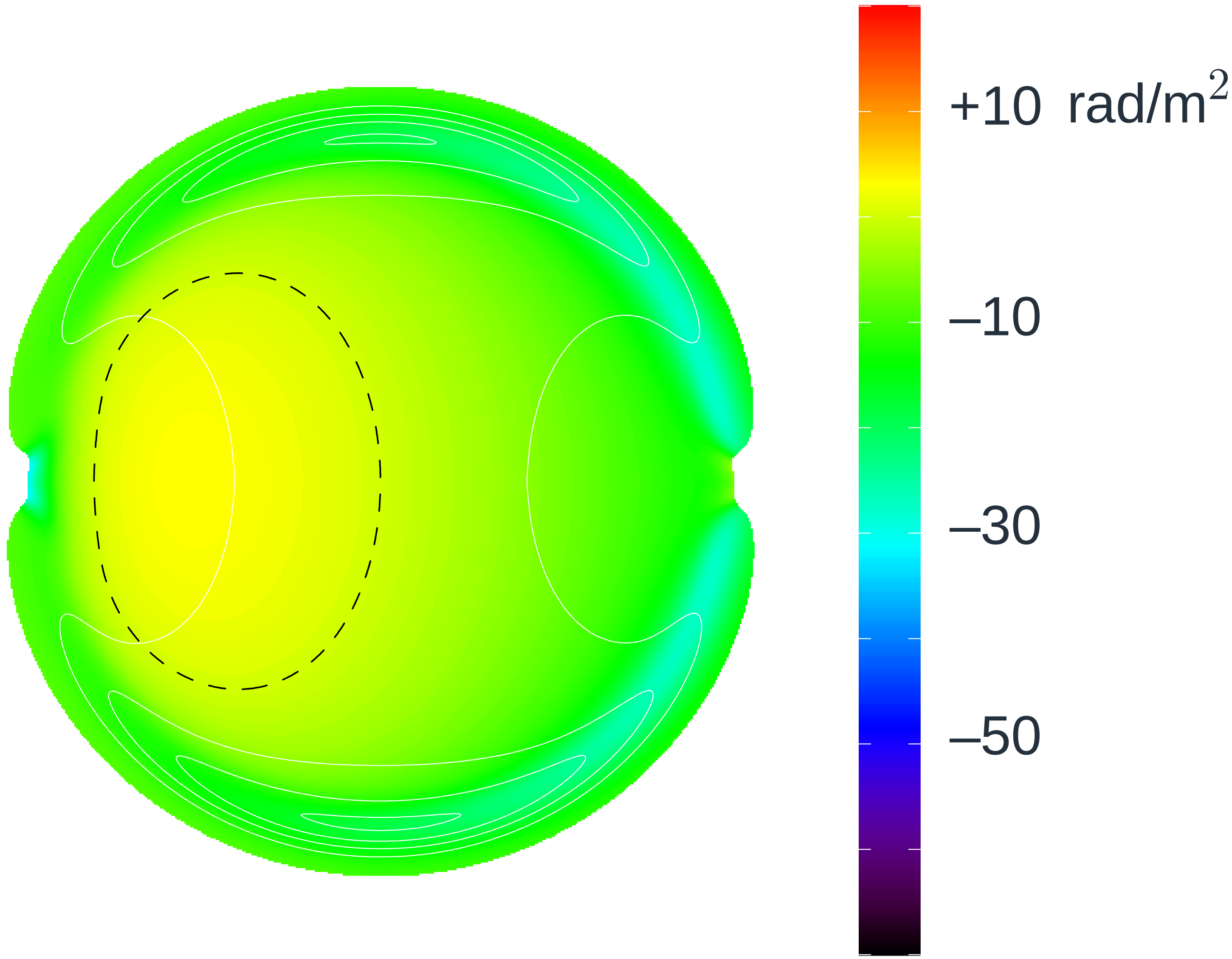
Faraday Rotation in SNRs

Rotation Angle $\Theta = 0^\circ$



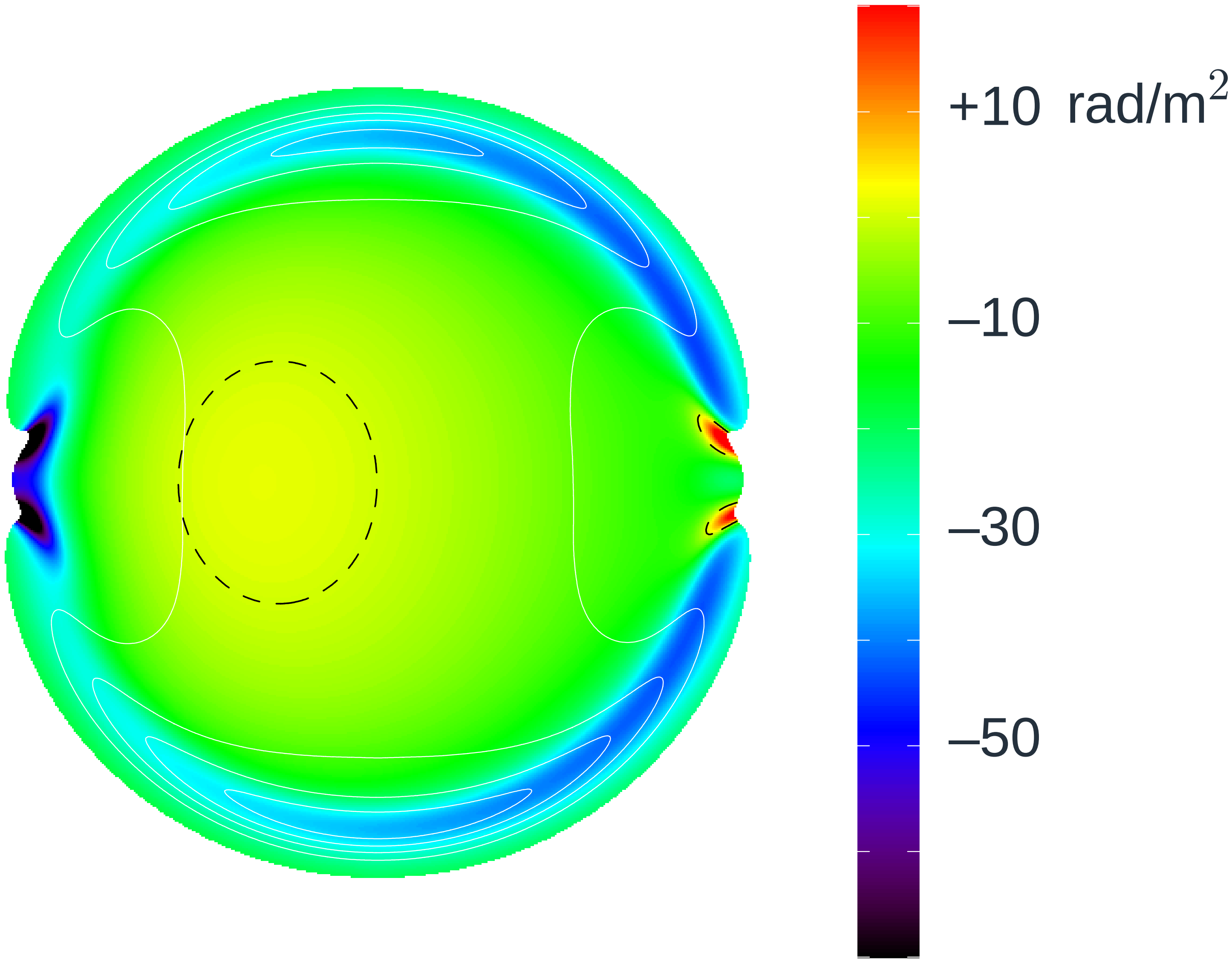
Faraday Rotation in SNRs

Rotation Angle $\Theta = 15°$



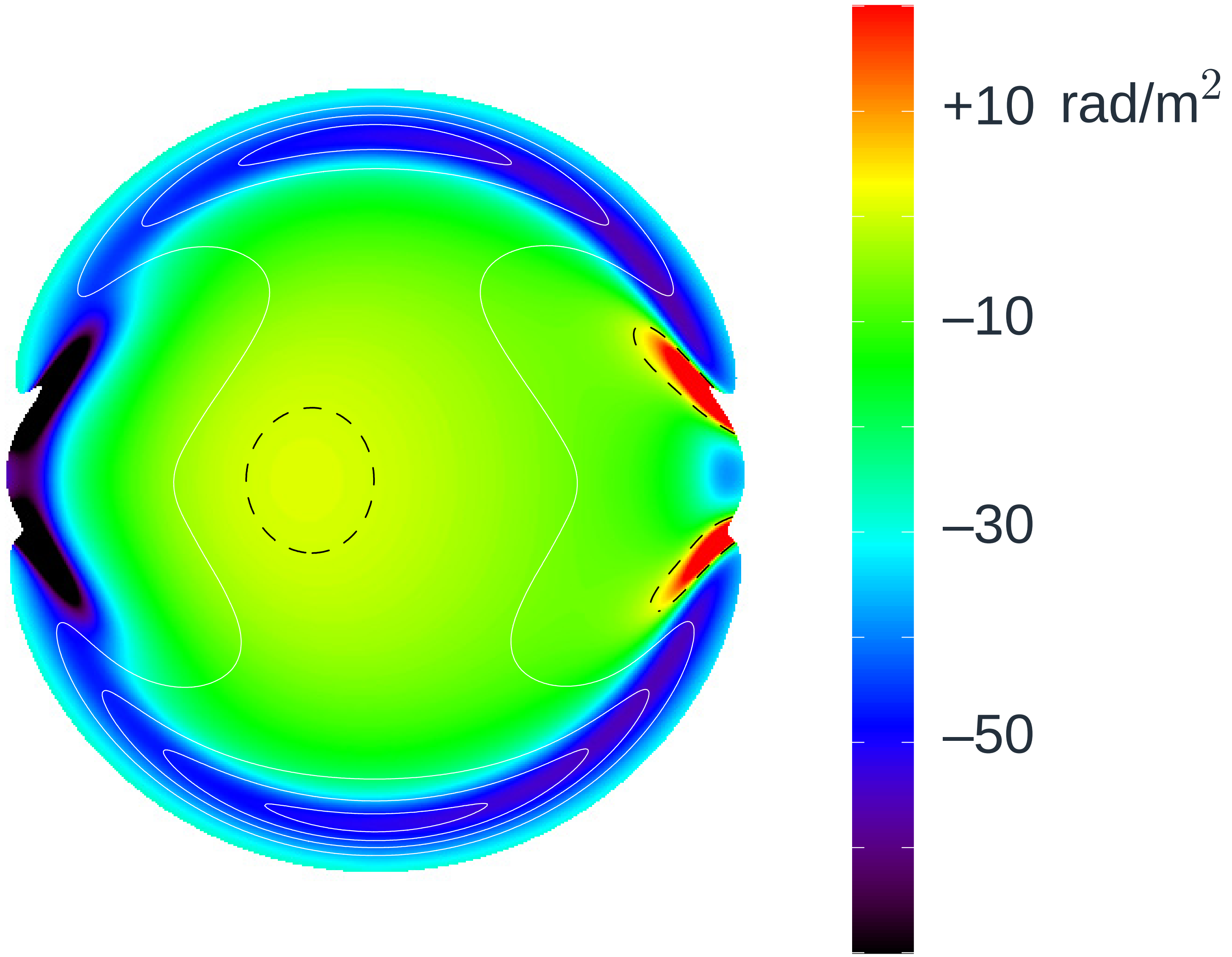
Faraday Rotation in SNRs

Rotation Angle $\Theta = 30^\circ$

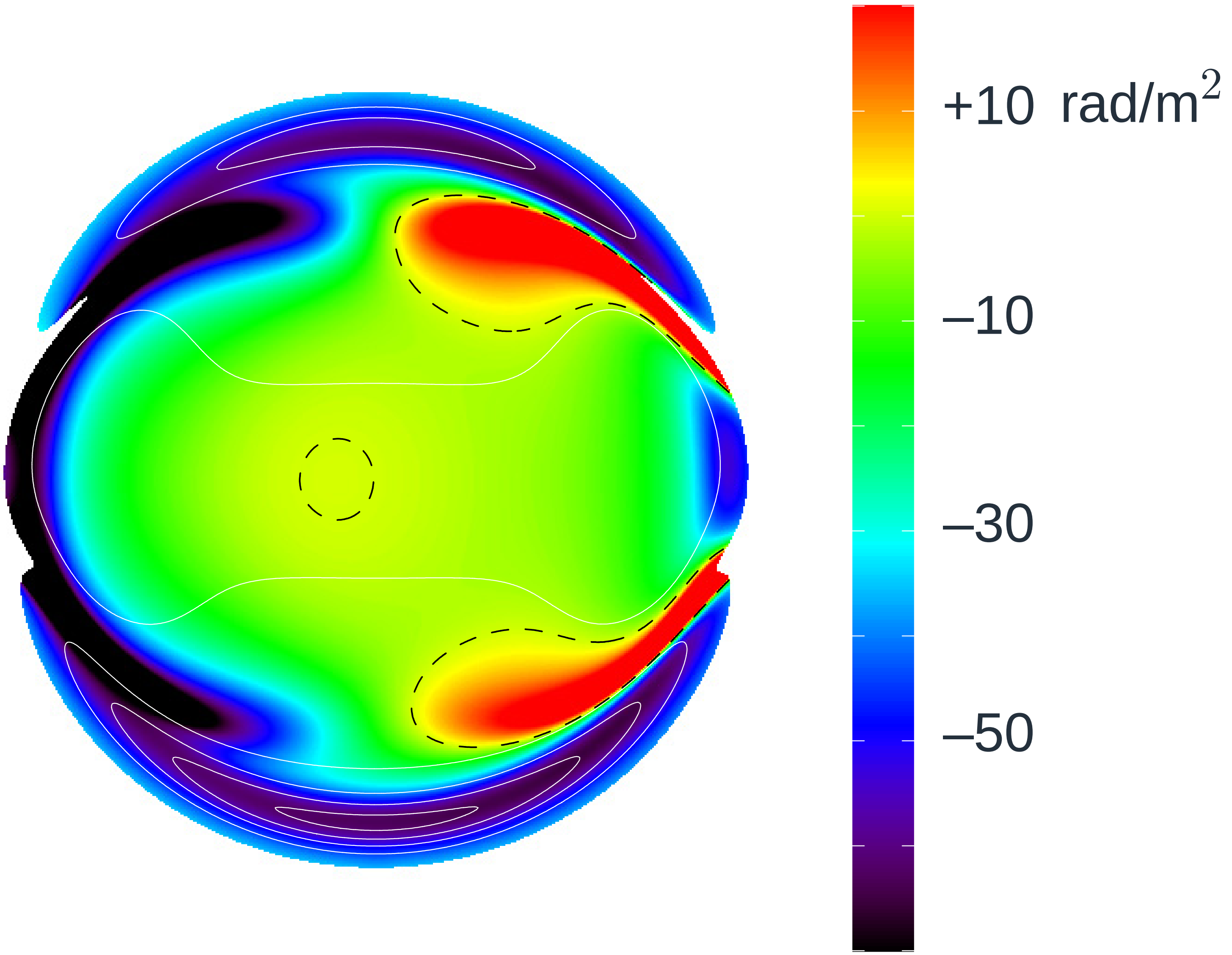


Faraday Rotation in SNRs

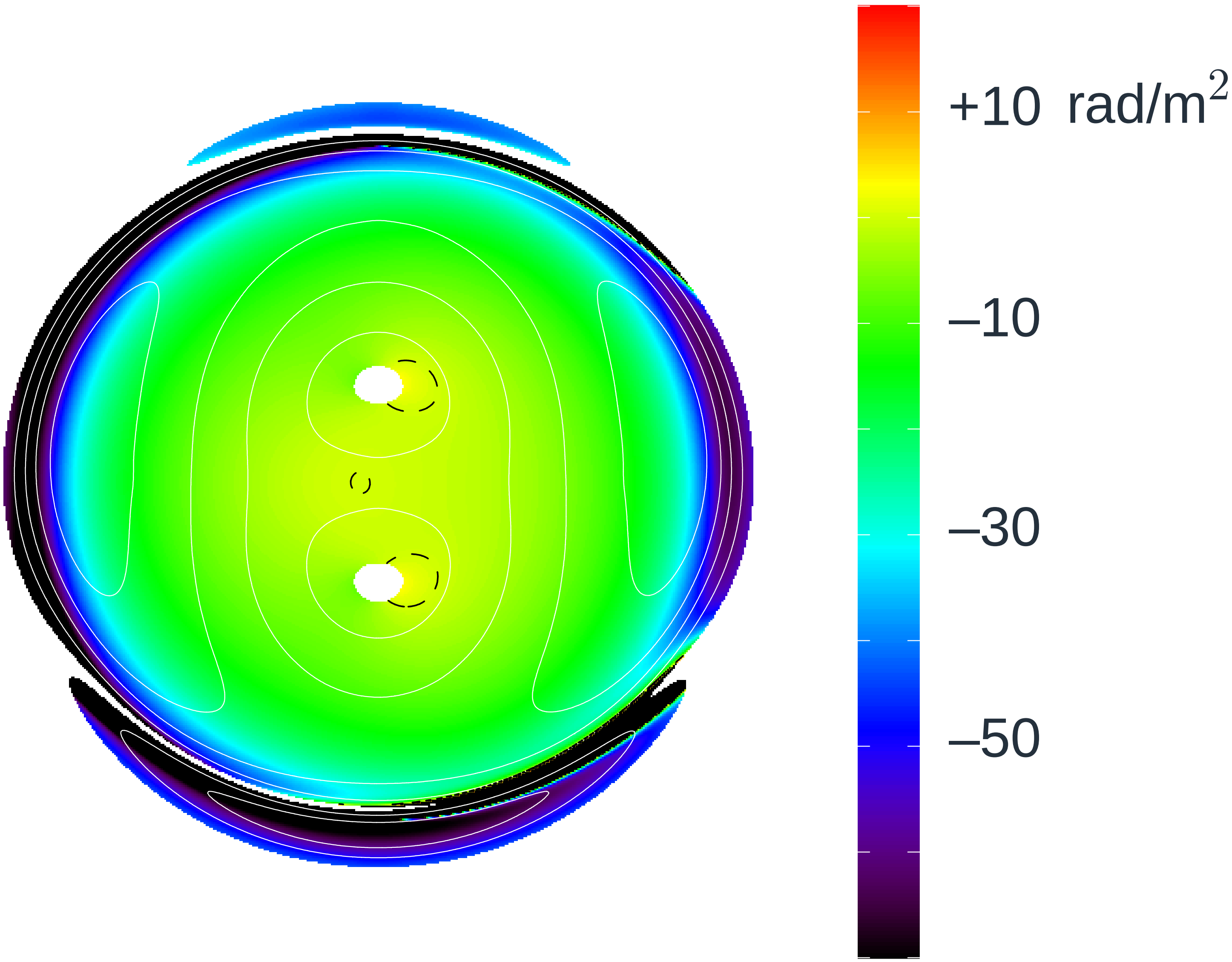
Rotation Angle $\Theta = 45°$



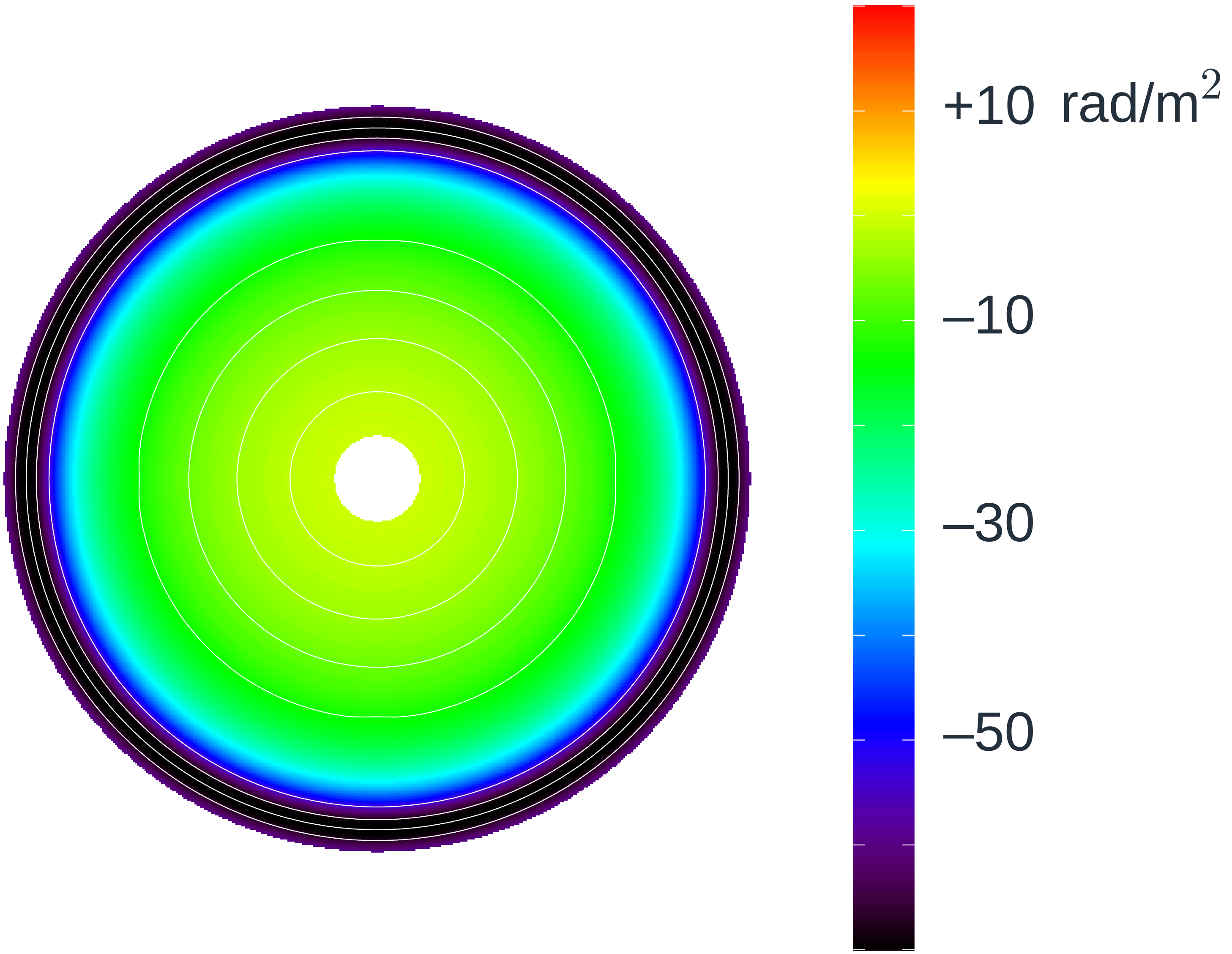
Rotation Angle $\Theta = 60^\circ$



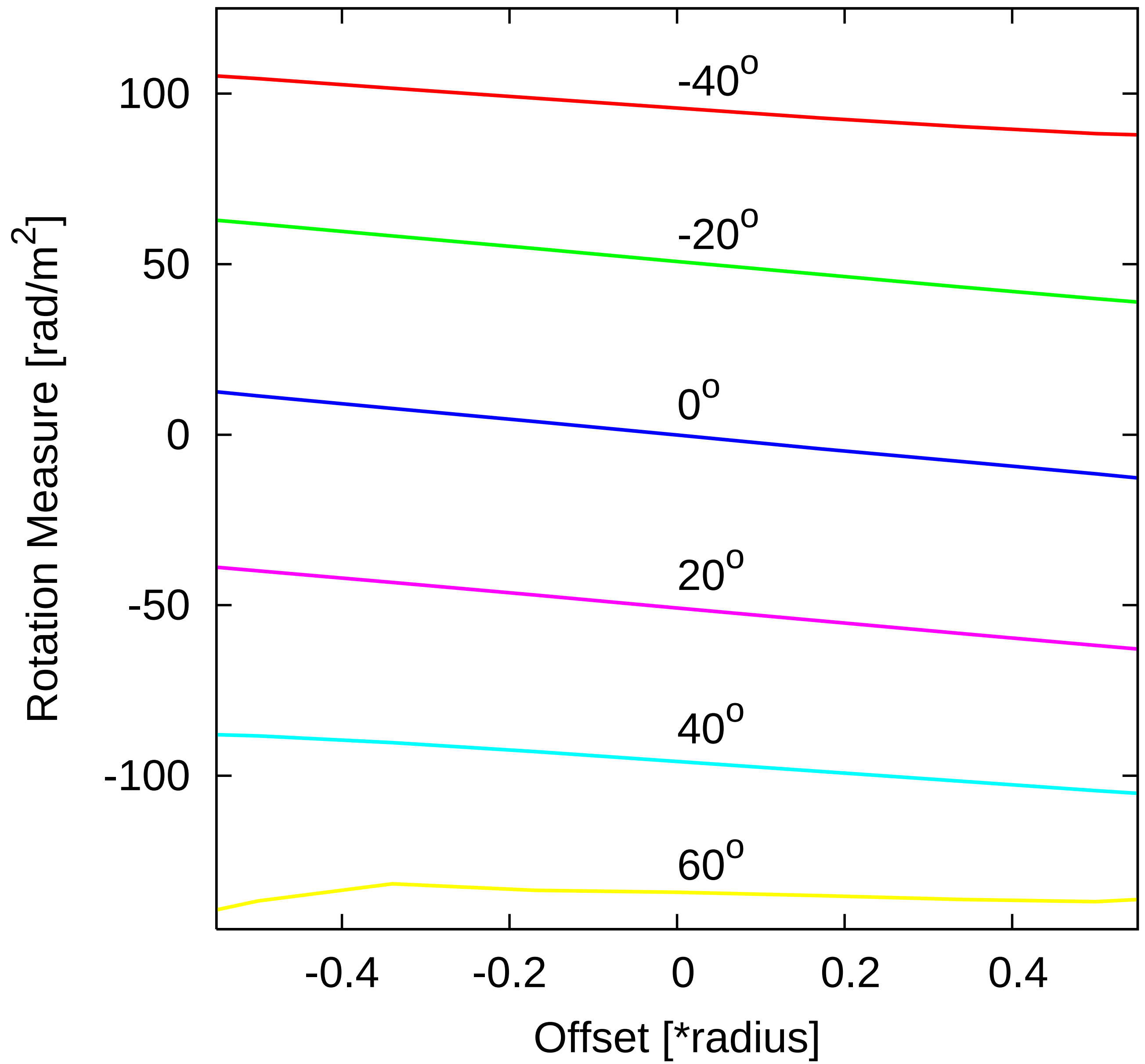
Rotation Angle $\Theta = 75^\circ$



Rotation Angle $\Theta = 90^\circ$

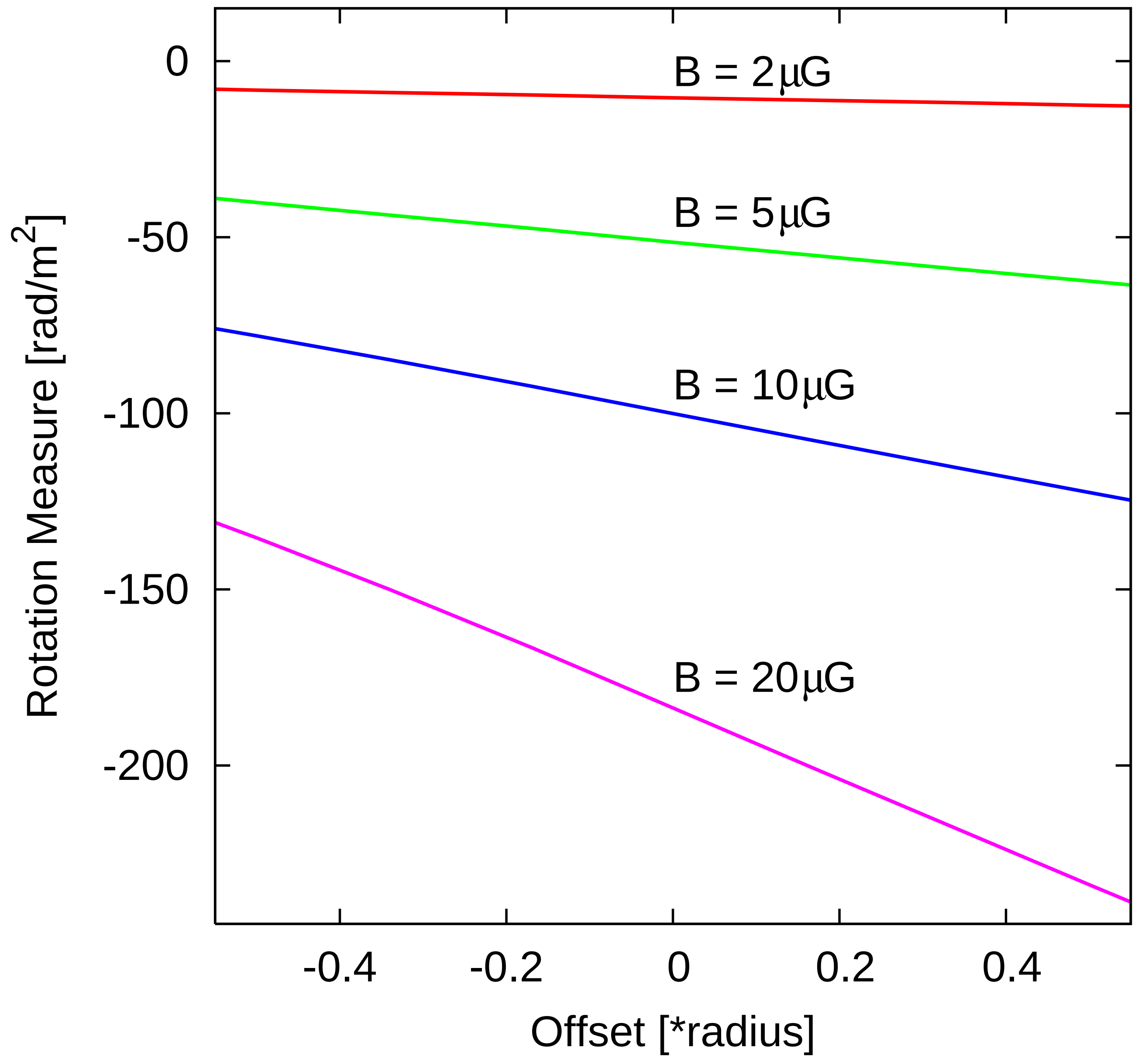


RM Gradient

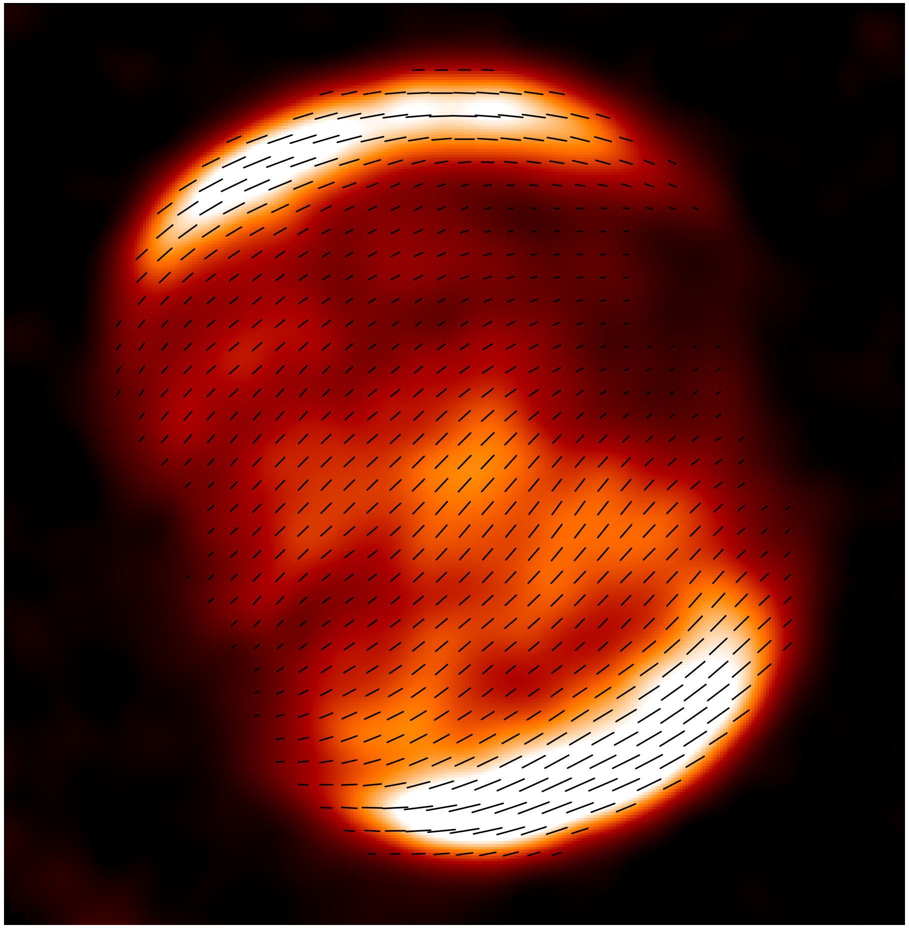


-40o
-20o
0o
20o
40o
60o
100
50
0
-50
-100
Rotation Measure [rad/m2]
-0.4
-0.2
0
0.2
0.4
Offset [*radius]

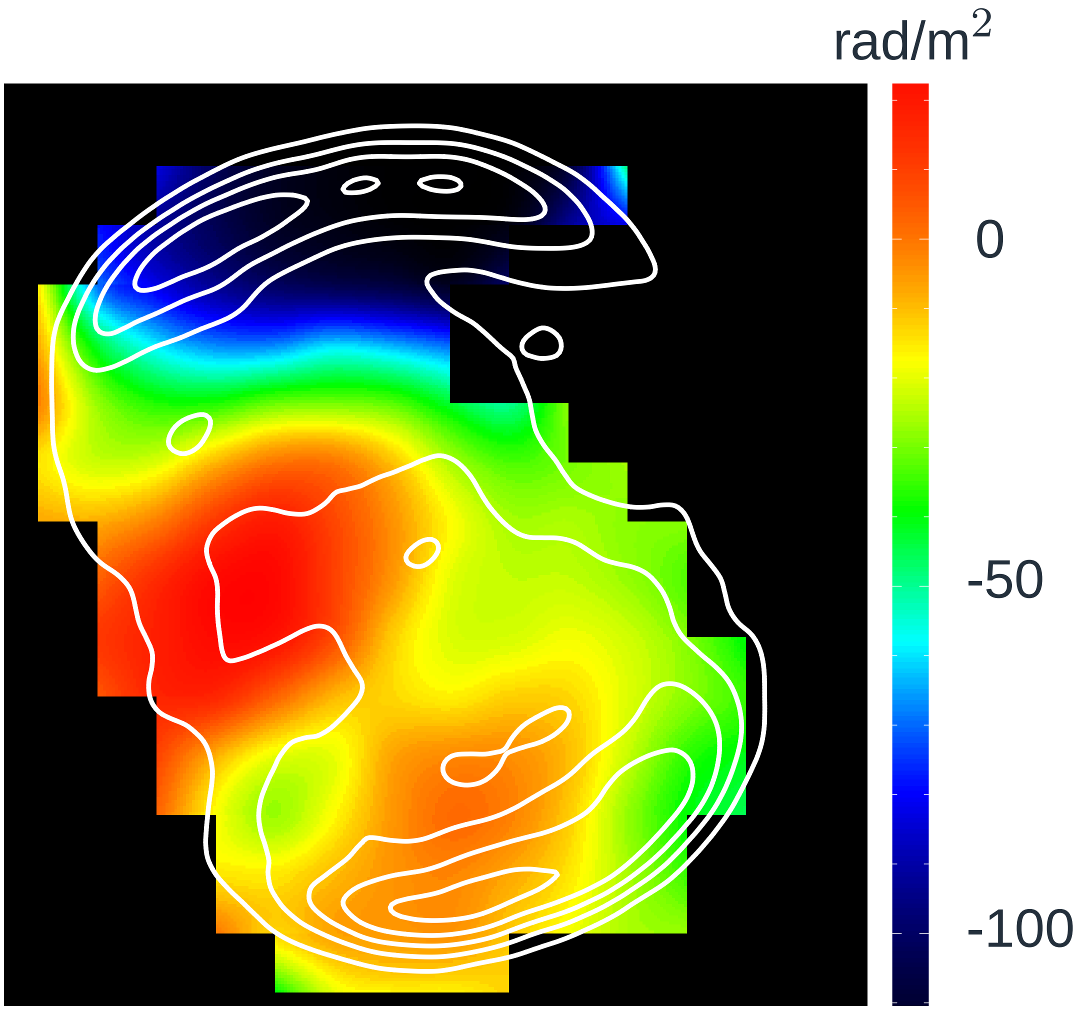
RM Gradient


B = 2μG
B = 5μG
B = 10μG
B = 20μG
Rotation Measure [rad/m2]
0
-50
-100
-150
-200
-0.4
-0.2
0
0.2
0.4
Offset [*radius]

DA 530 (G93.3+6.9)

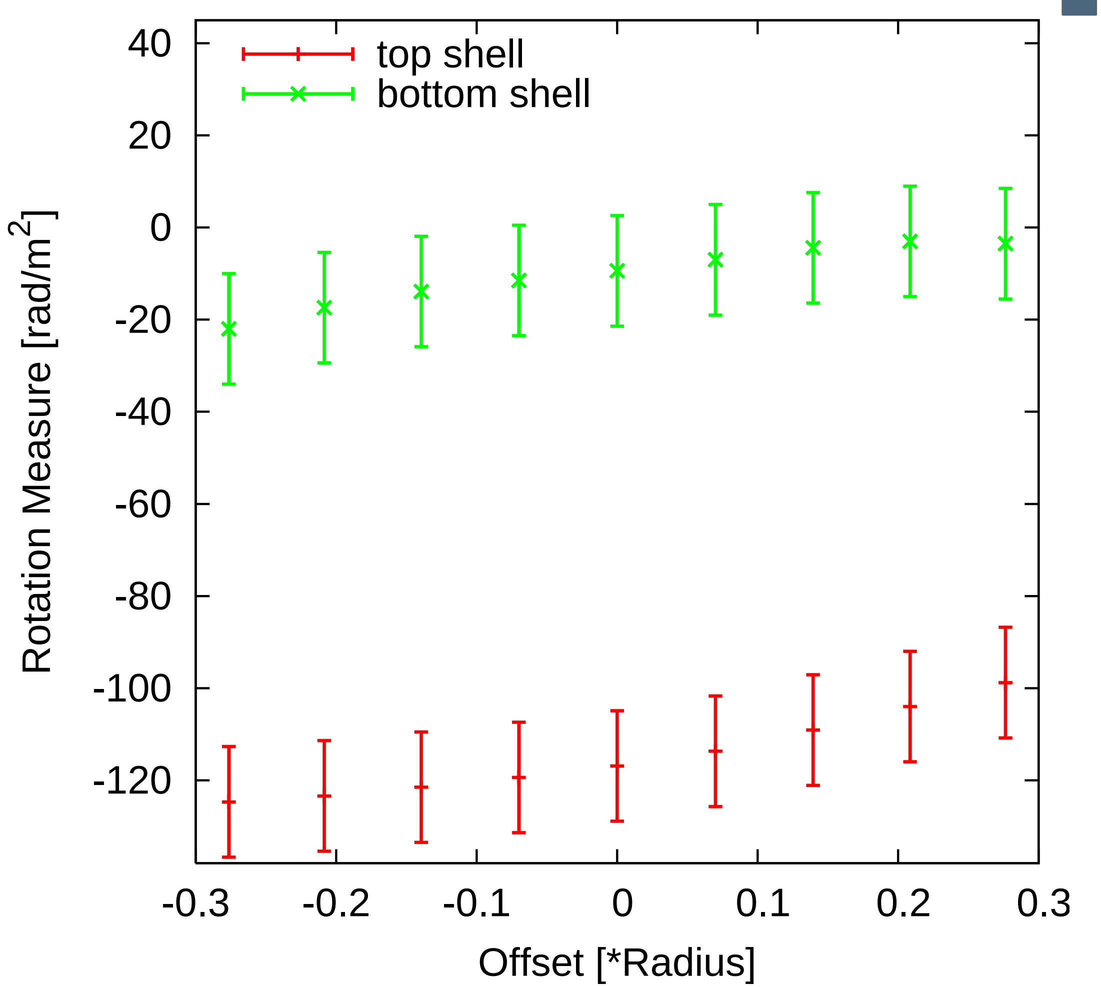


DA 530 at 10.6 GHz (Effbg 100m)
B-vectors are overlaid.



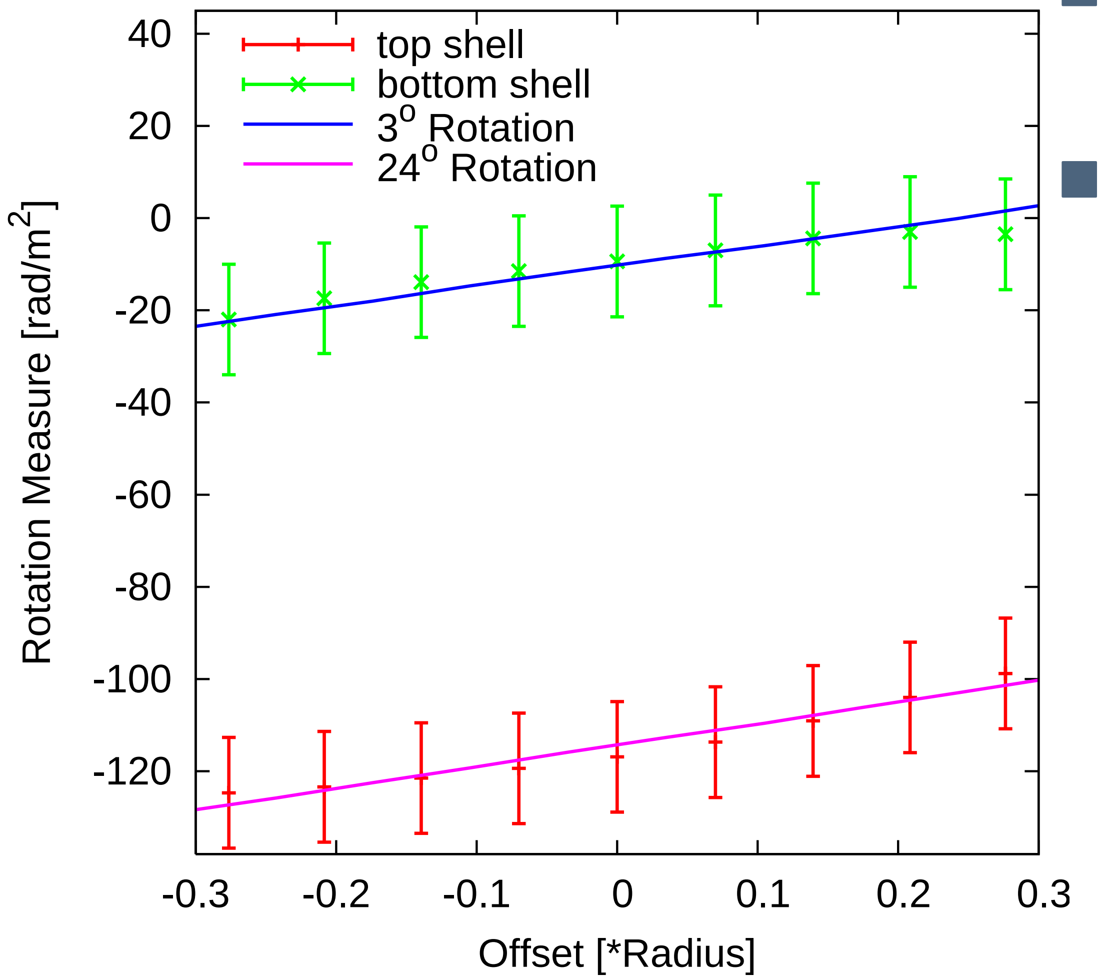
Rotation Measure Map of DA 530

DA 530 (G93.3+6.9)



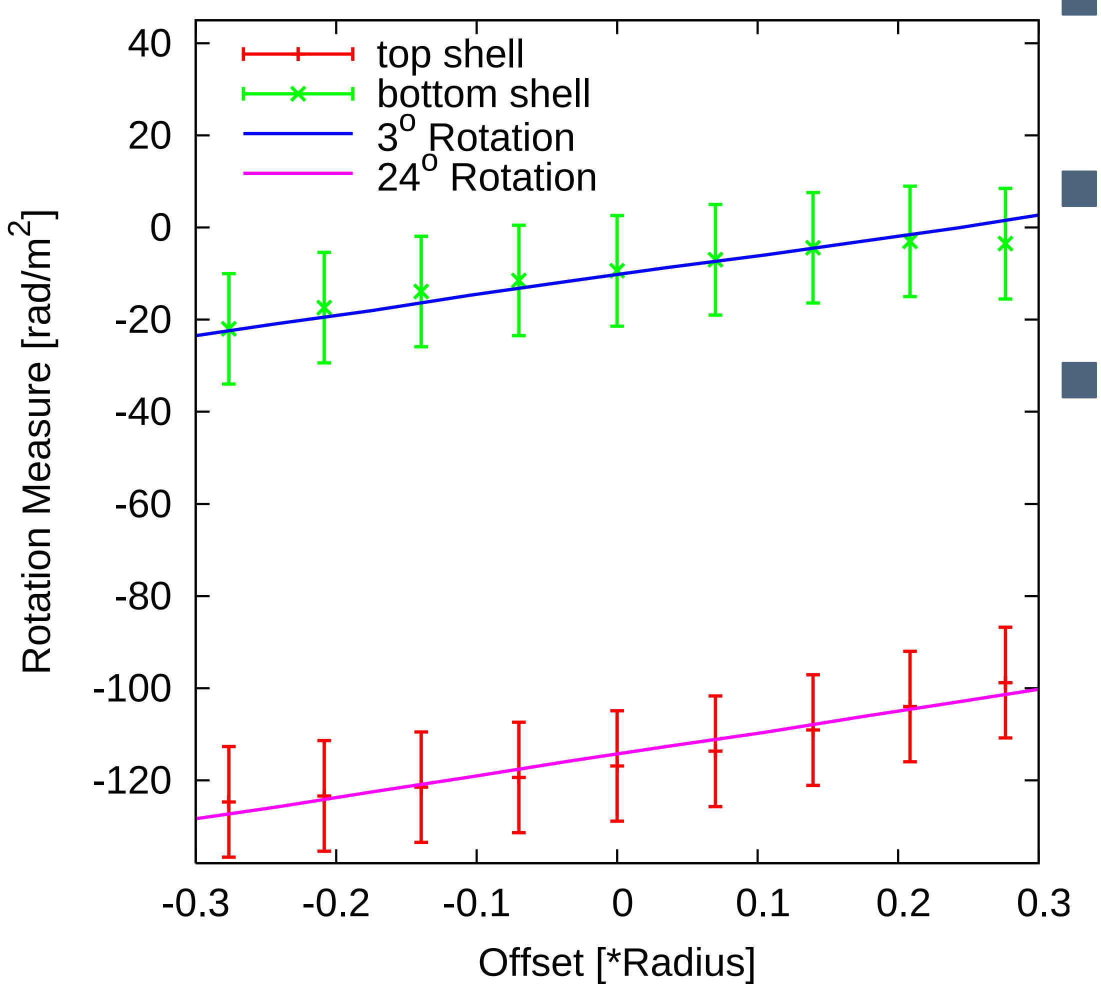
- The ambient B-field is pointing away from front left to back right.

DA 530 (G93.3+6.9)



- The ambient B-field is pointing away from front left to back right.
- both shells show the same gradient $\Rightarrow$ same $B \cdot n_e$

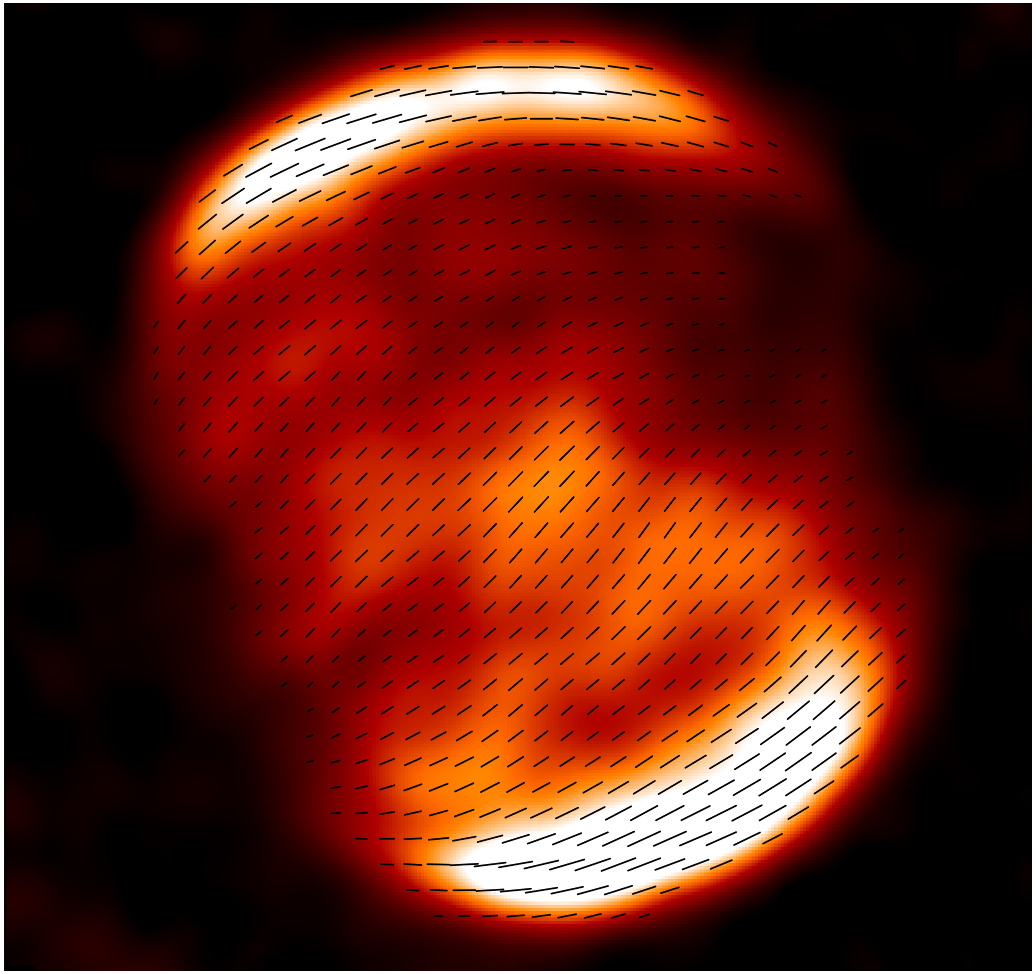
DA 530 (G93.3+6.9)



- The ambient B-field is pointing away from front left to back right.
- both shells show the same gradient $\Rightarrow$ same $B \cdot n_e$
- The top shell expands in a B-field with $\Theta = 24°$, the bottom shell with $\Theta = 3°$.

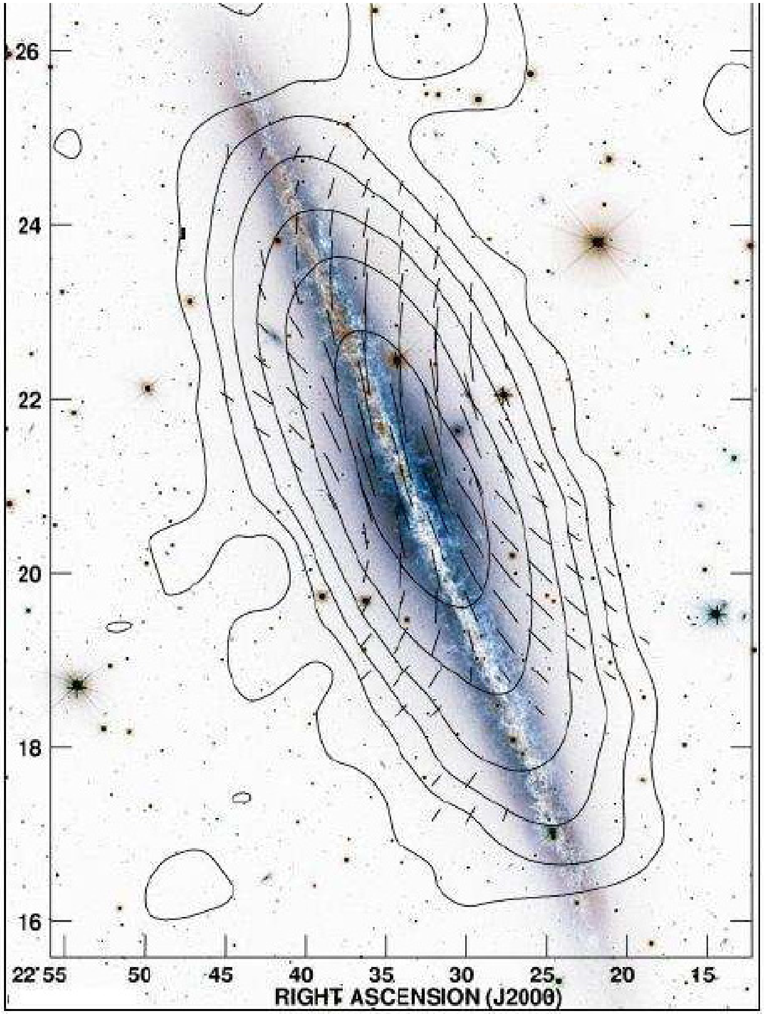
  $\Rightarrow$ The ambient B-field is twisted counter-clockwise.

DA 530 (G93.3+6.9)



- The ambient B-field is pointing away from front left to back right.
- both shells show the same gradient $\Rightarrow$ same $B \cdot n_e$
- The top shell expands in a B-field with $\Theta = 24°$, the bottom shell with $\Theta = 3°$.
  $\Rightarrow$ The ambient B-field is twisted counter-clockwise.
- The lower surface brightness of the top shell confirms this.

DA 530 (G93.3+6.9)



- Radio observations of other galaxies show twisted magnetic spurs emerging from star forming regions (e.g.: Review by Beck, 2008: Galactic dynamos and galactic winds).

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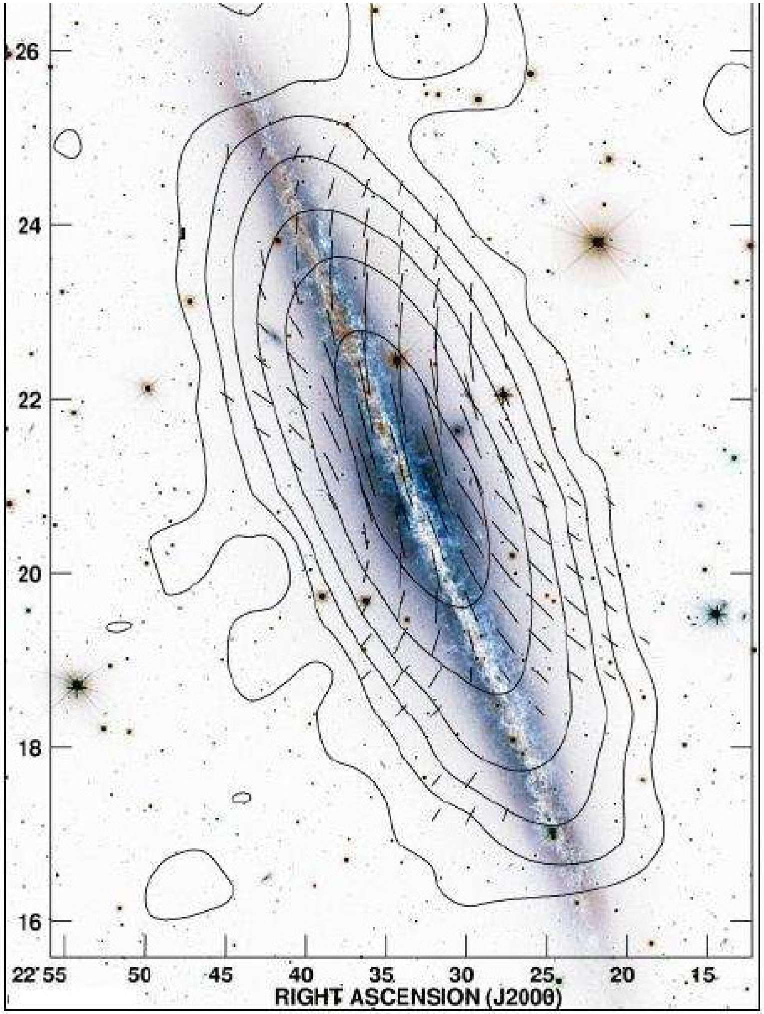

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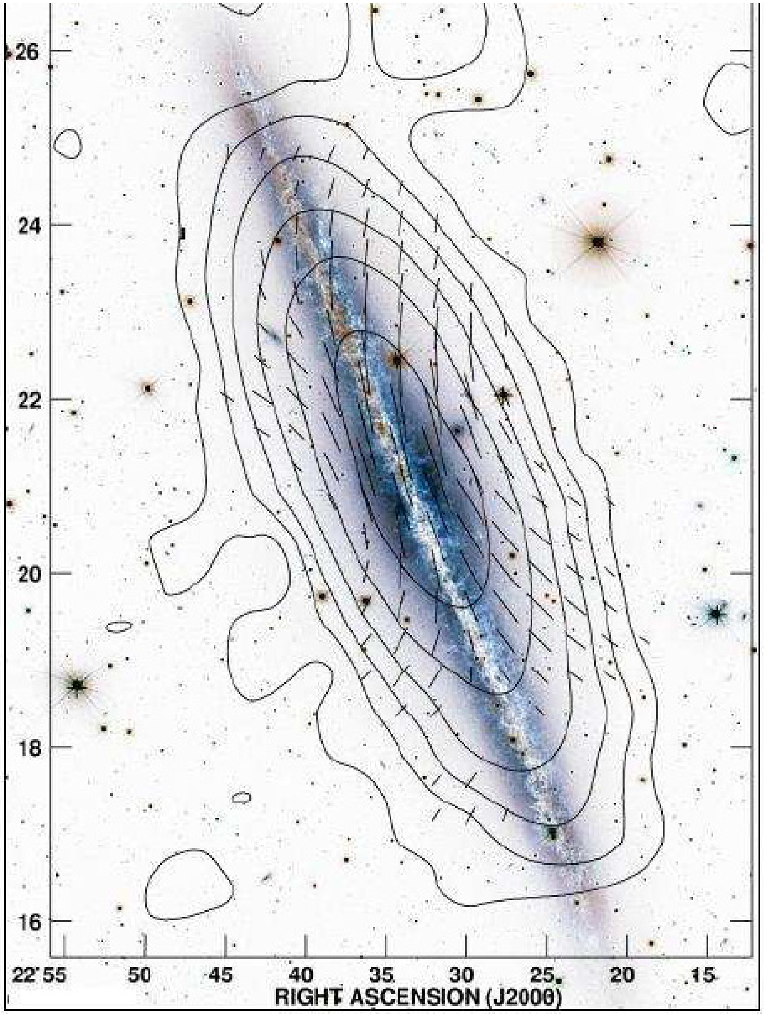
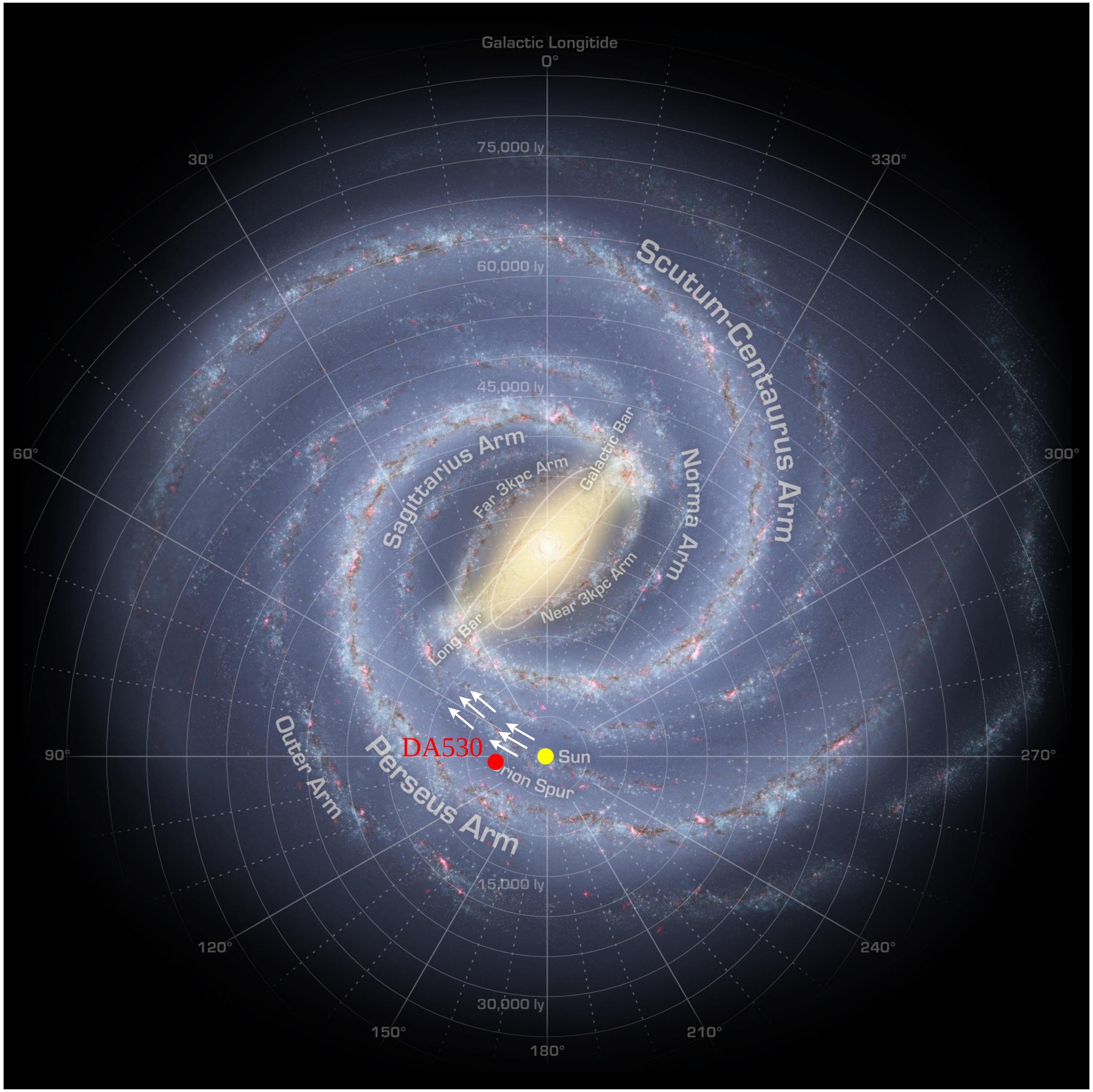
- DA 530 is located above an area of the Milky Way, which is rich in star forming regions, HII regions, and supernova remnants.

DA 530 (G93.3+6.9)



- Radio observations of other galaxies show twisted magnetic spurs emerging from star forming regions (e.g.: Review by Beck, 2008: Galactic dynamos and galactic winds).
- DA 530 is located above an area of the Milky Way, which is rich in star forming regions, HII regions, and supernova remnants.
- Is DA 530 expanding inside these twisted magnetic spurs?

DA 530 in the Milky Way Galaxy



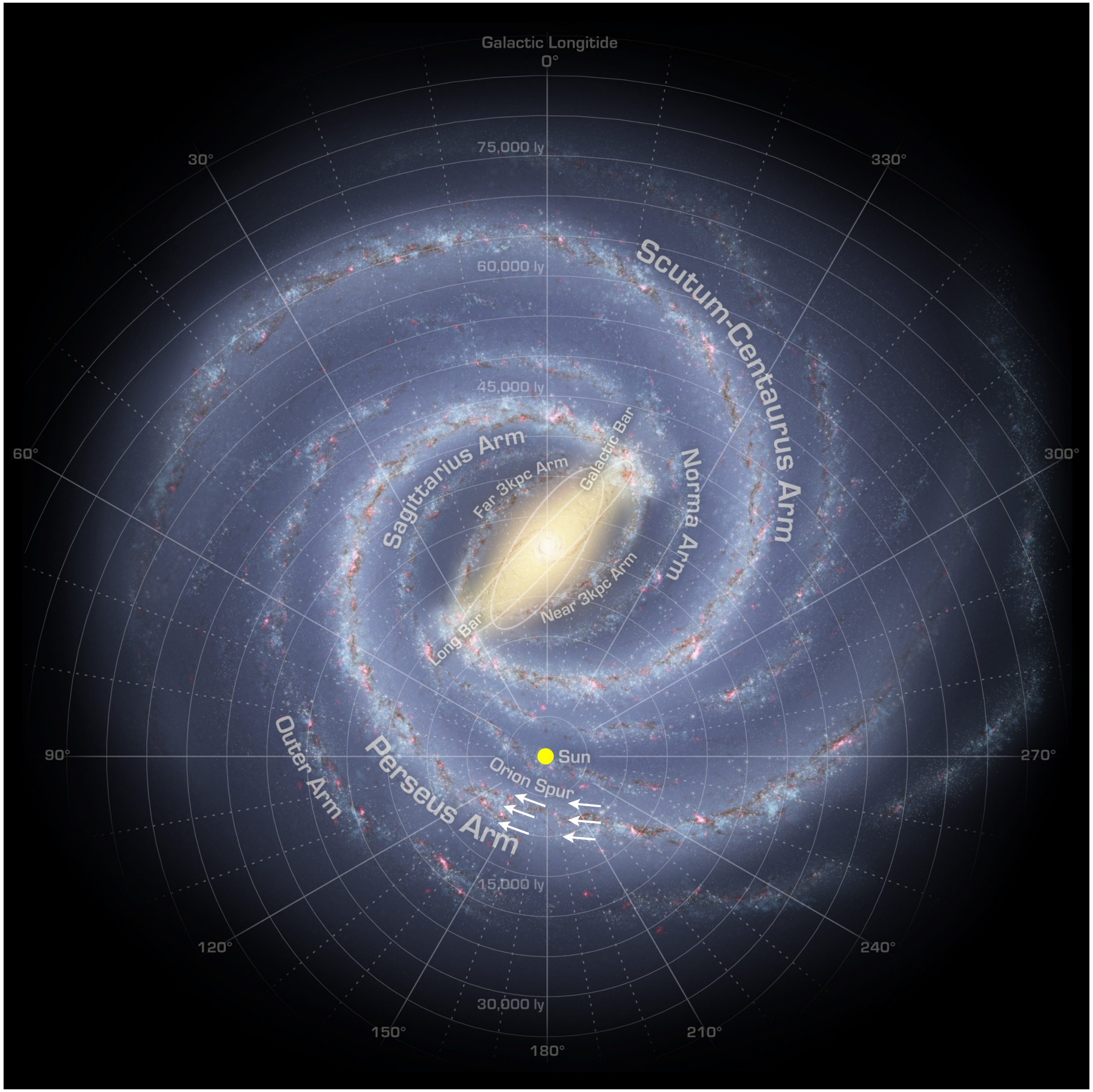
The Magnetic Field of the Milky Way

Big question:
Is the large-scale magnetic field in our Galaxy azimuthal or is it following the spiral arms?

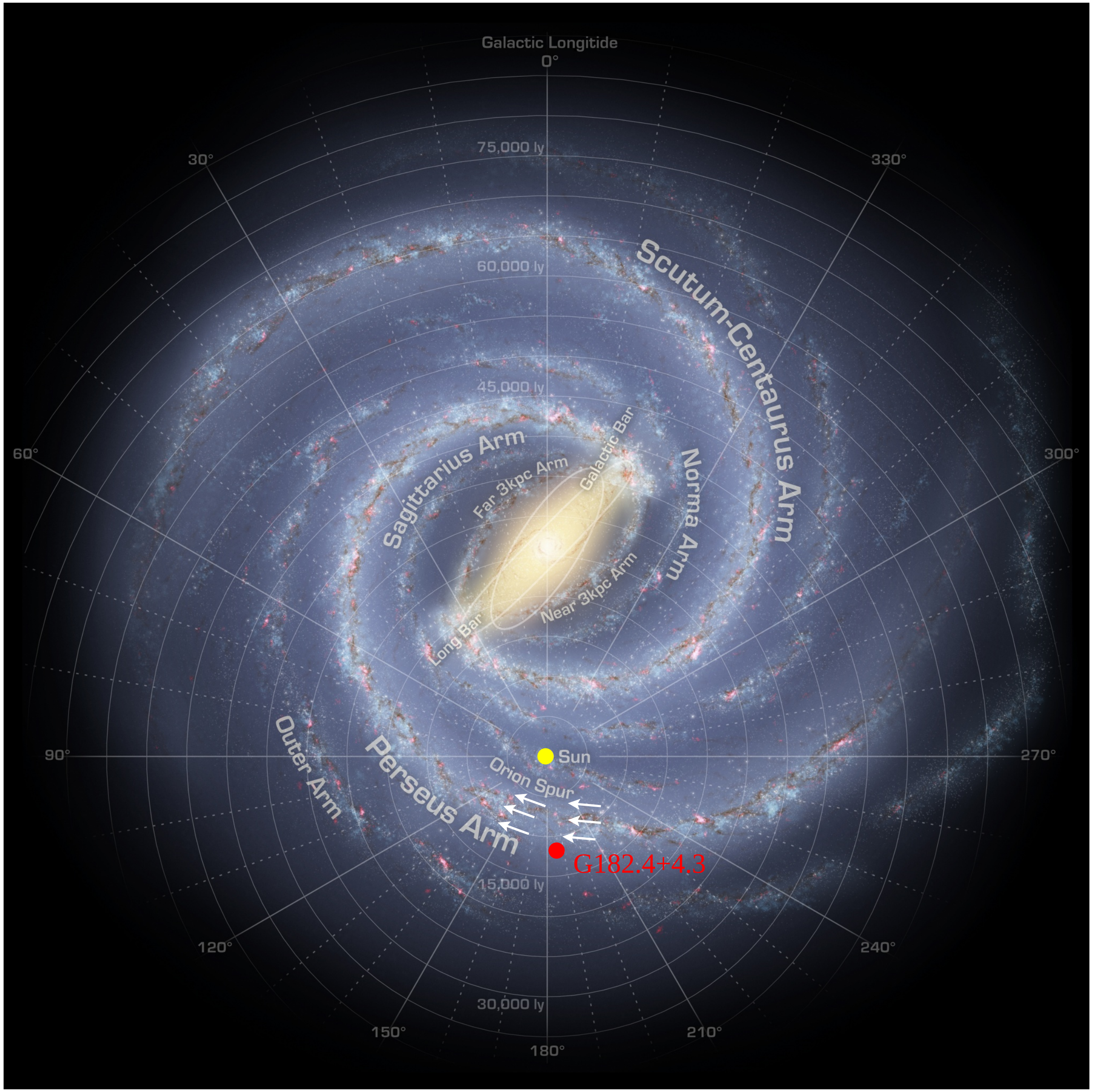
The best place to look is towards the anti-centre of our Galaxy:

- azimuthal: $B_{\|} = 0$ towards Galactic longitude of $180°$.
- spiral: $B_{\|} = 0$ towards Galactic longitude between $165°$ and $170°$.

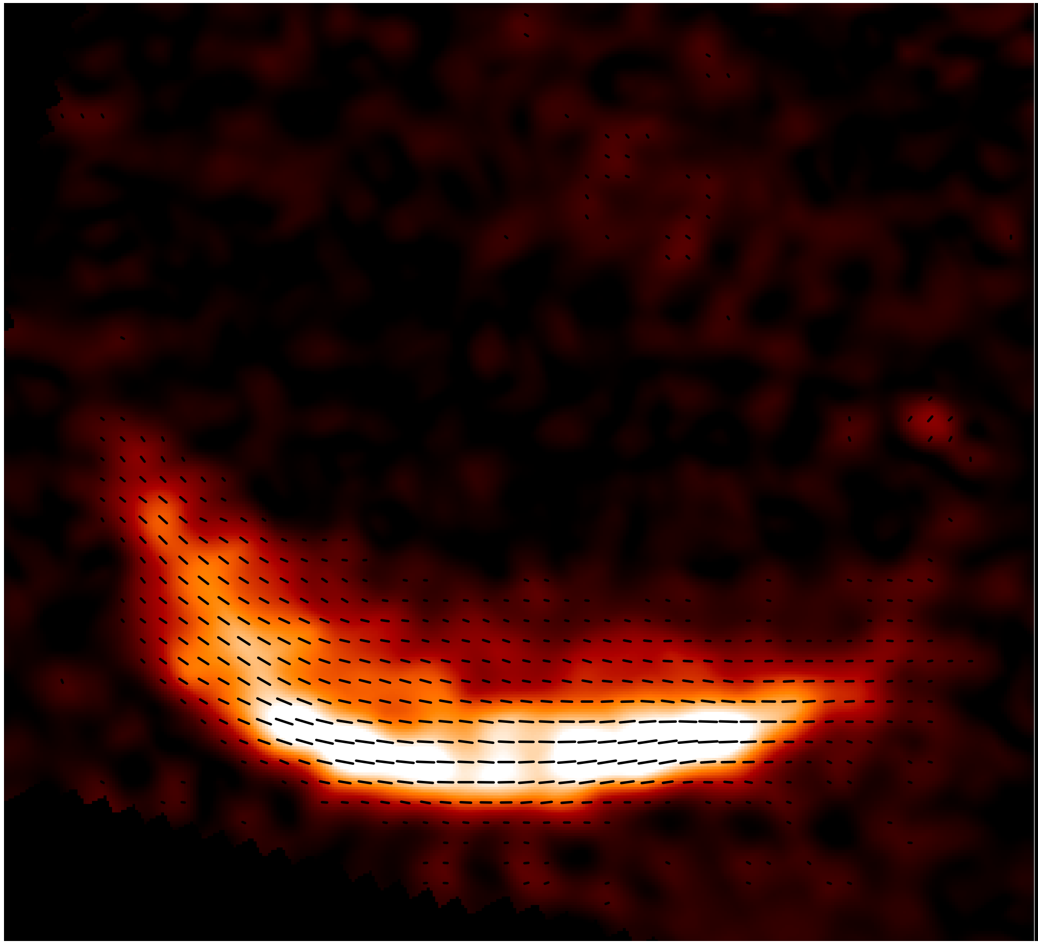
G182.4+4.3 in the Milky Way Galaxy



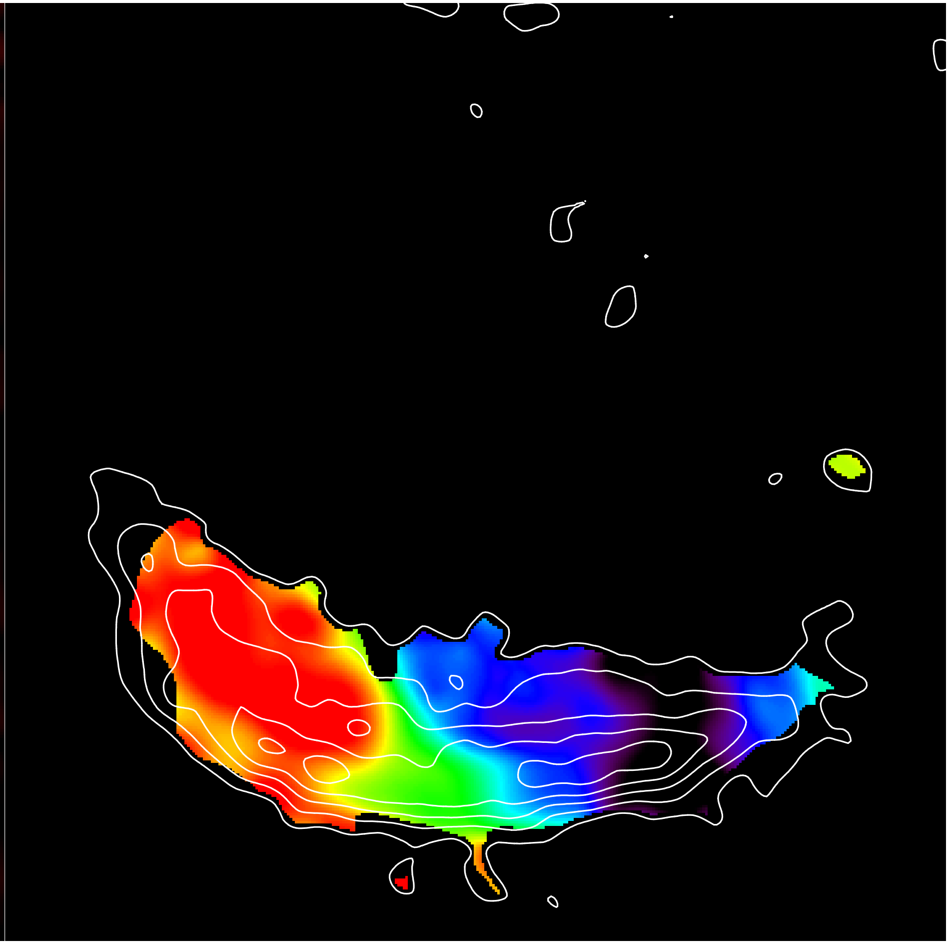
G182.4+4.3 in the Milky Way Galaxy



G182.4+4.3

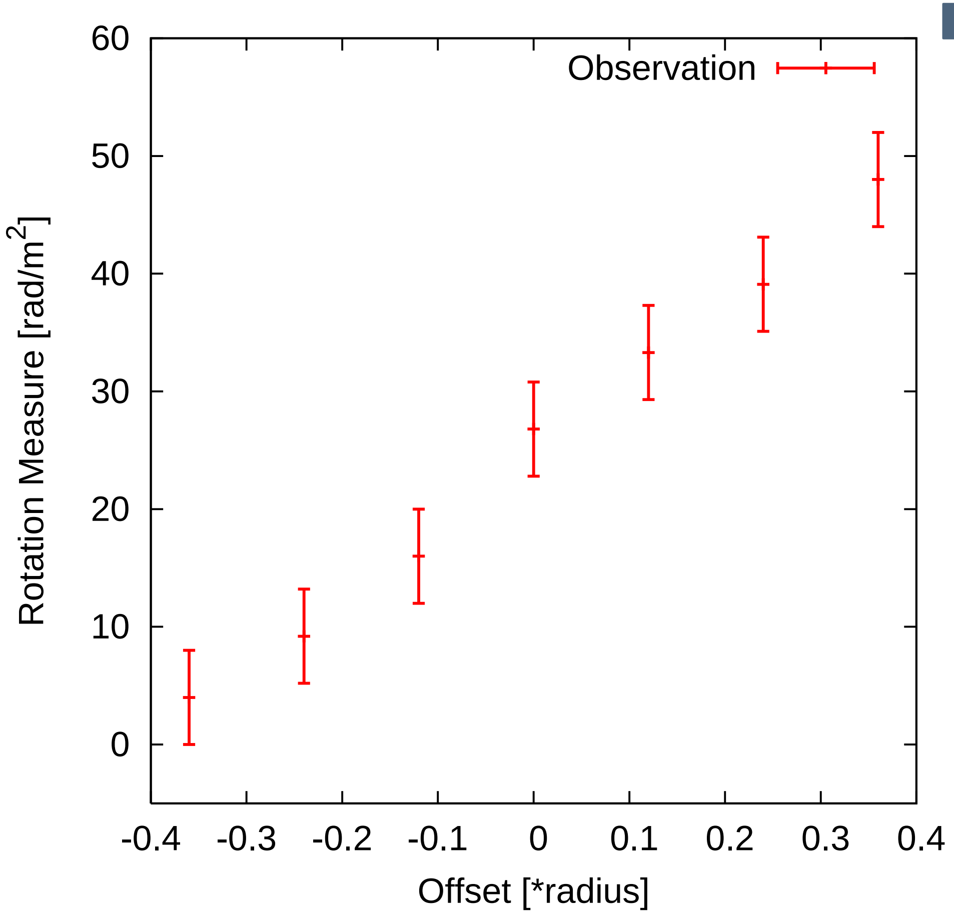


G182.4+4.3 at 5 GHz (Effbg 100m)
B-vectors are overlaid.

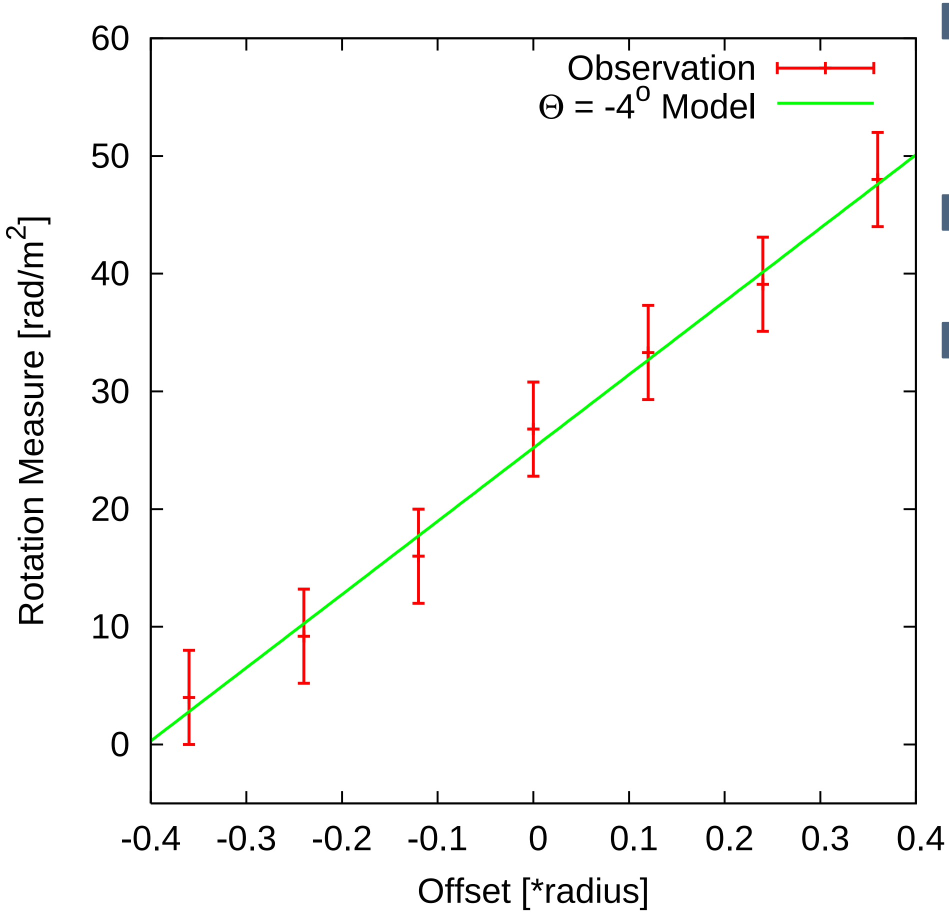


RM map of G182.4+4.3
PI contours are overlaid.

G182.4+4.3

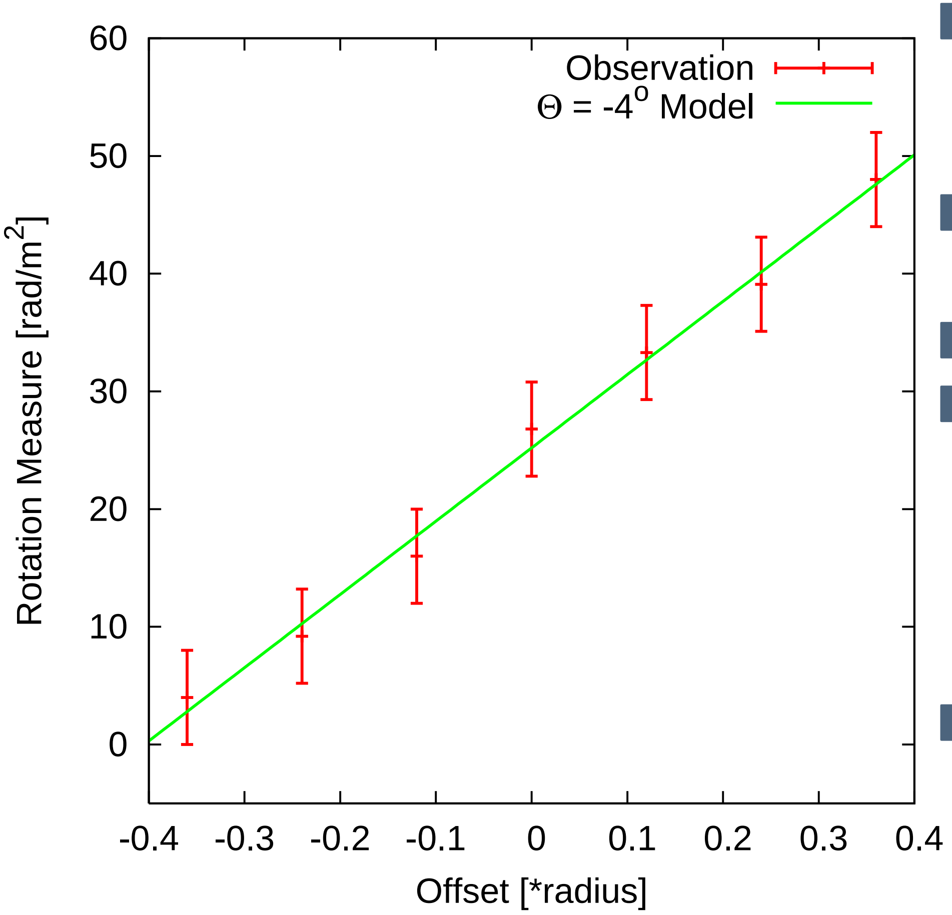


- The ambient B-field is pointing towards us from back left to front right.



- The ambient B-field is pointing towards us from back left to front right.
- Neglecting foreground RM gives an upper limit for $|\Theta|$.
- We fit $\Theta \geq -4^\circ$.

G182.4+4.3



- The ambient B-field is pointing towards us from back left to front right.
- Neglecting foreground RM gives an upper limit for $|\Theta|$.
- We fit $\Theta \geq -4^\circ$.
- If we assume that the foreground B-field is about $4\,\mu$G and has the same $|\Theta|$ as the SNR's ambient B-field, we find $\Theta = -2^\circ$.
- This would indicate an azimuthal magnetic field for our Galaxy.

How about e^- acceleration?

e^- acceleration:

- early acceleration:

How about e^- acceleration?

e^- acceleration:

- early acceleration:
  isotropic
- compression of interstellar relativistic e^-:

How about e^- acceleration?

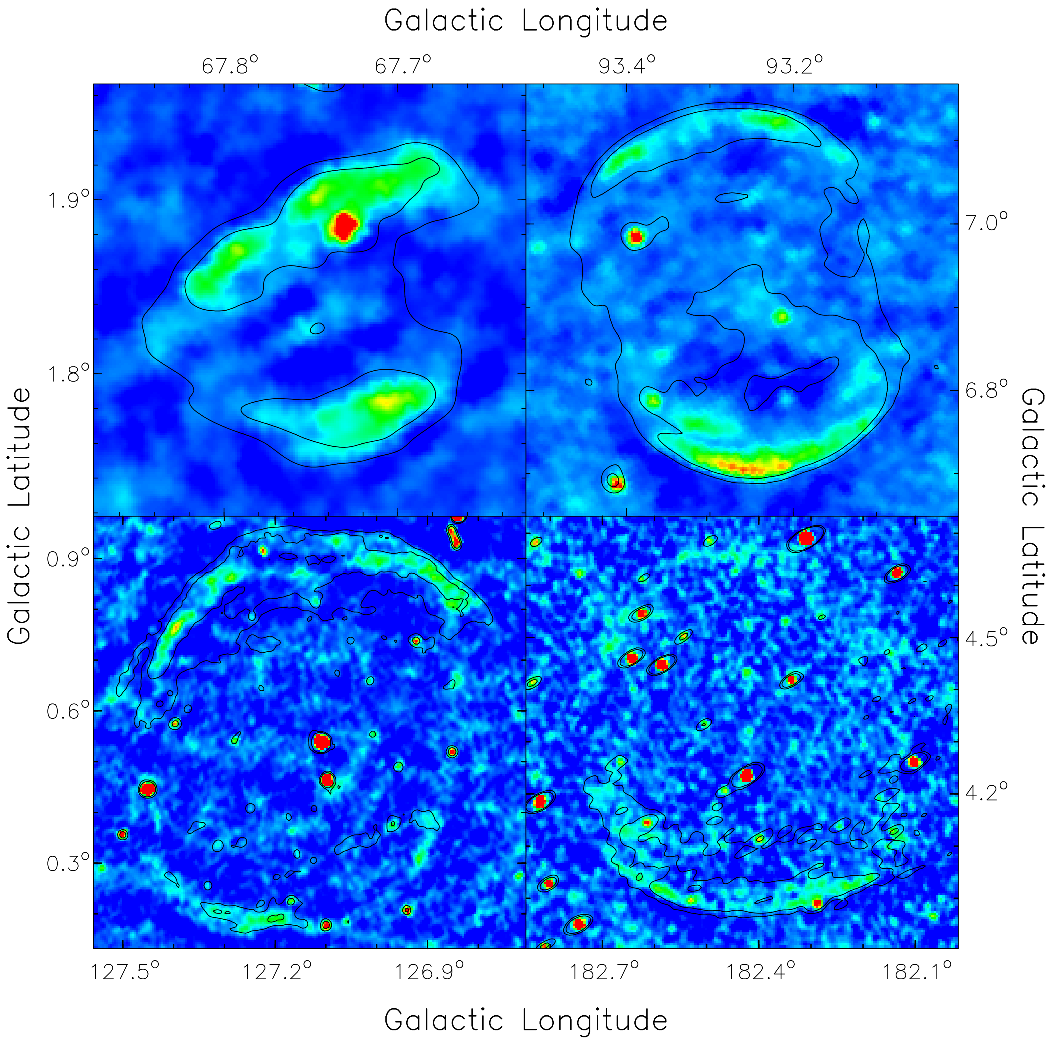
e^- acceleration:

- early acceleration: isotropic
- compression of interstellar relativistic e^-: isotropic?
- acceleration in mature SNRs:

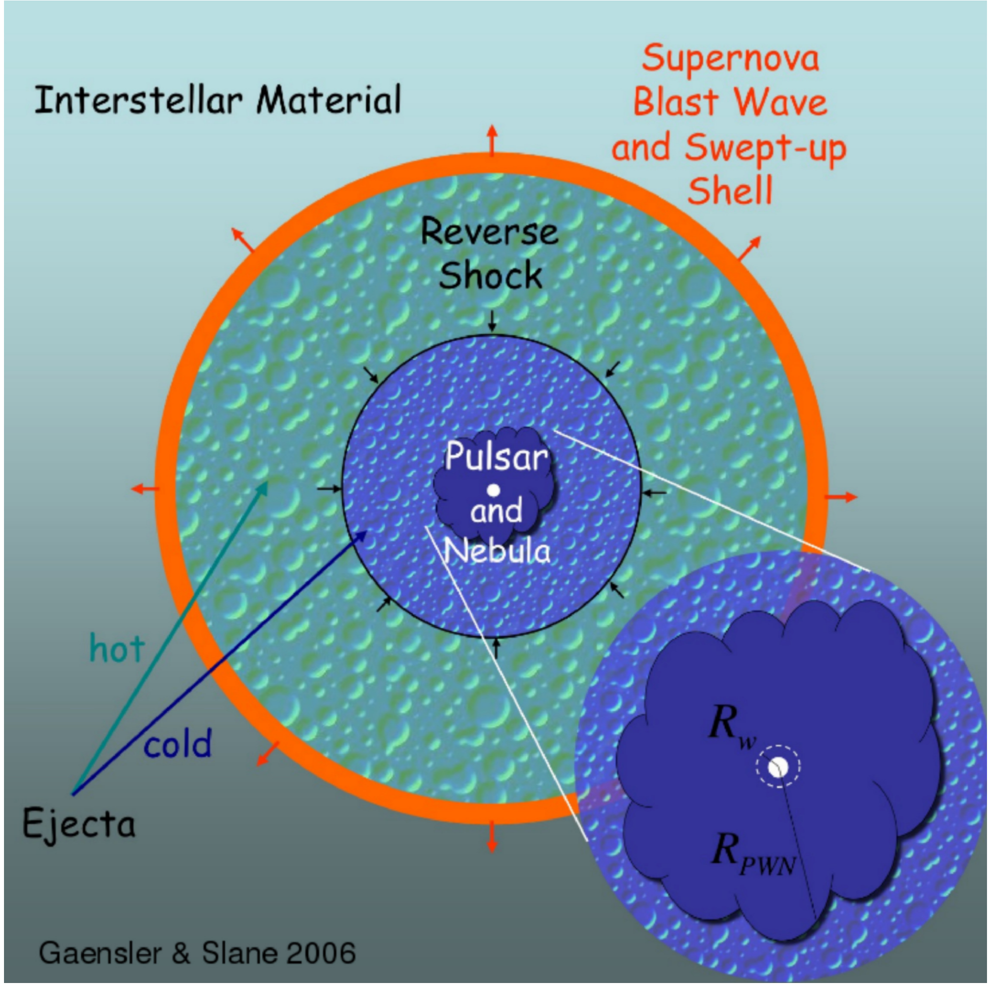
How about e^- acceleration?

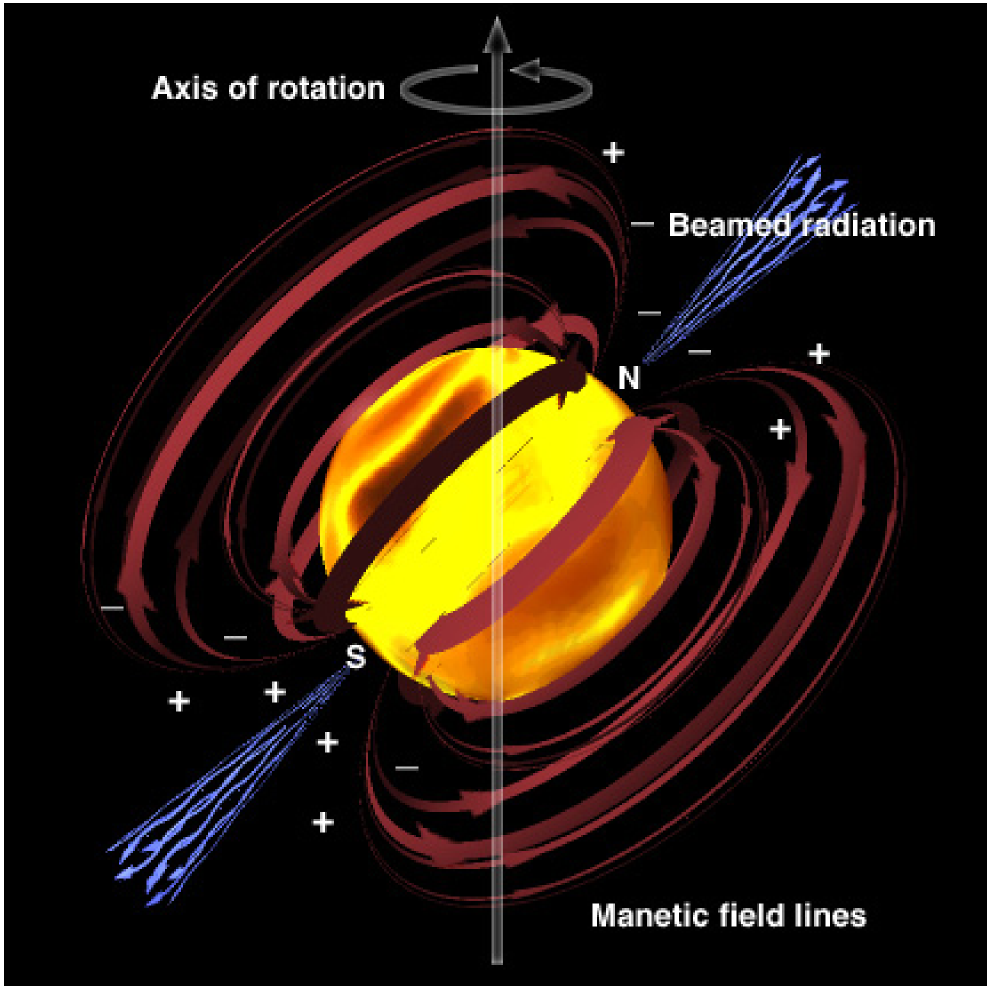
e^- acceleration:

- early acceleration: isotropic
- compression of interstellar relativistic e^-: isotropic?
- acceleration in mature SNRs: quasi-parallel?

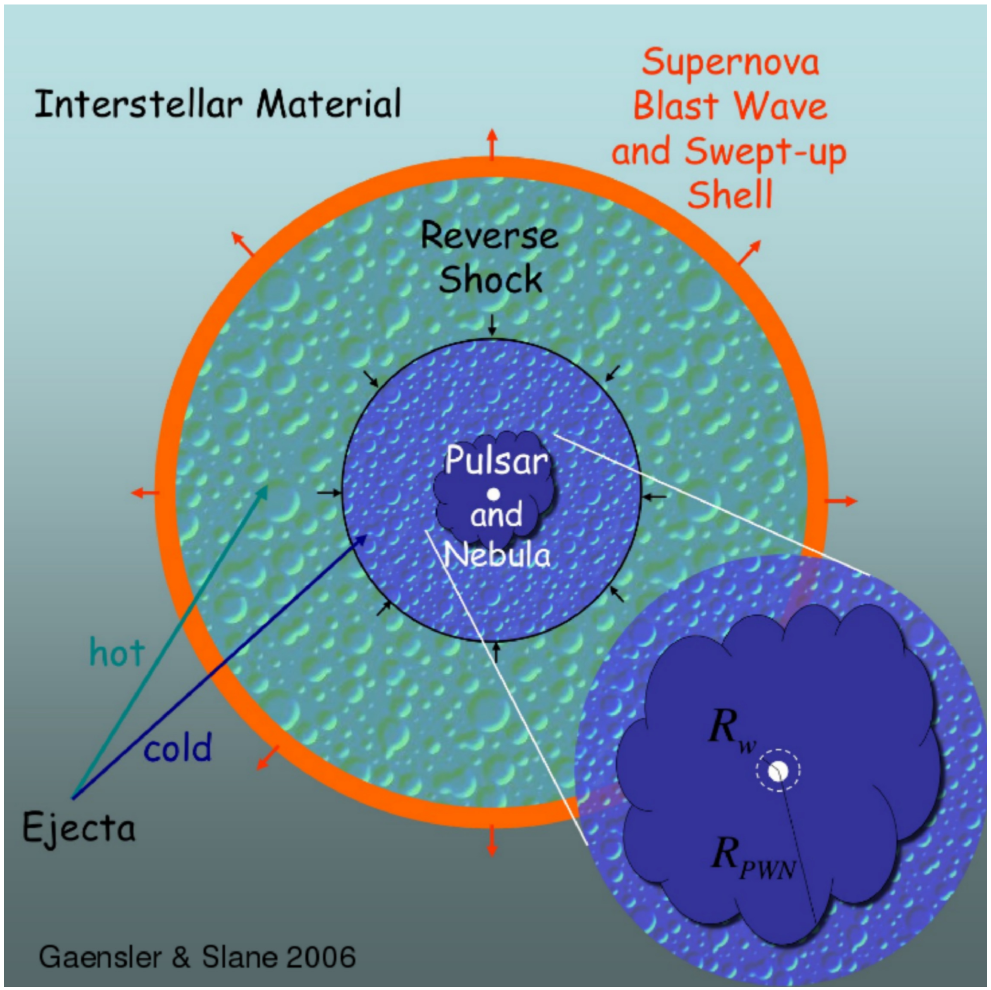


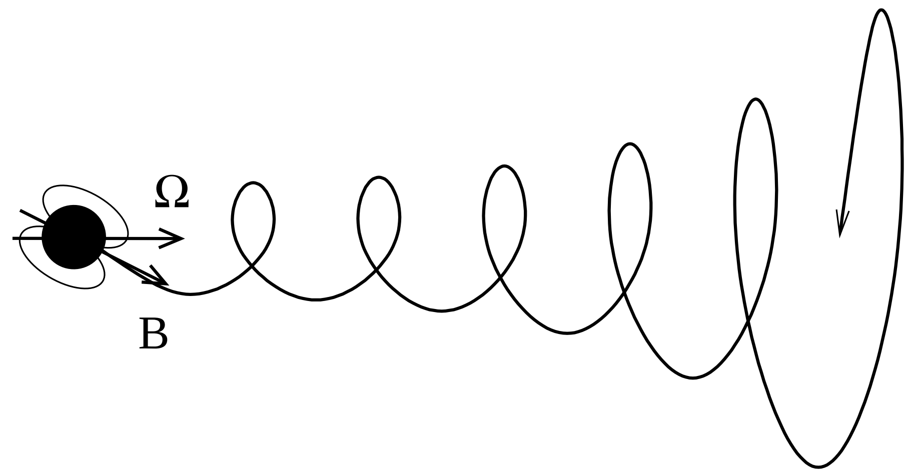
Pulsar Wind Nebulae





Pulsar Wind Nebulae

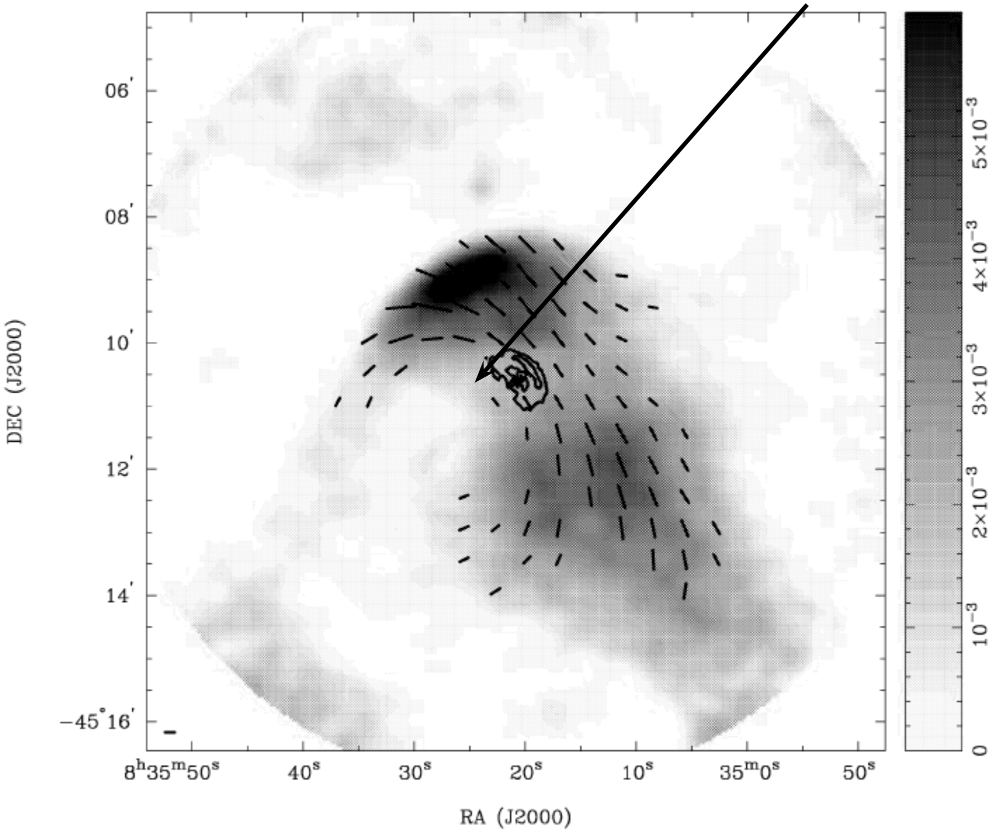


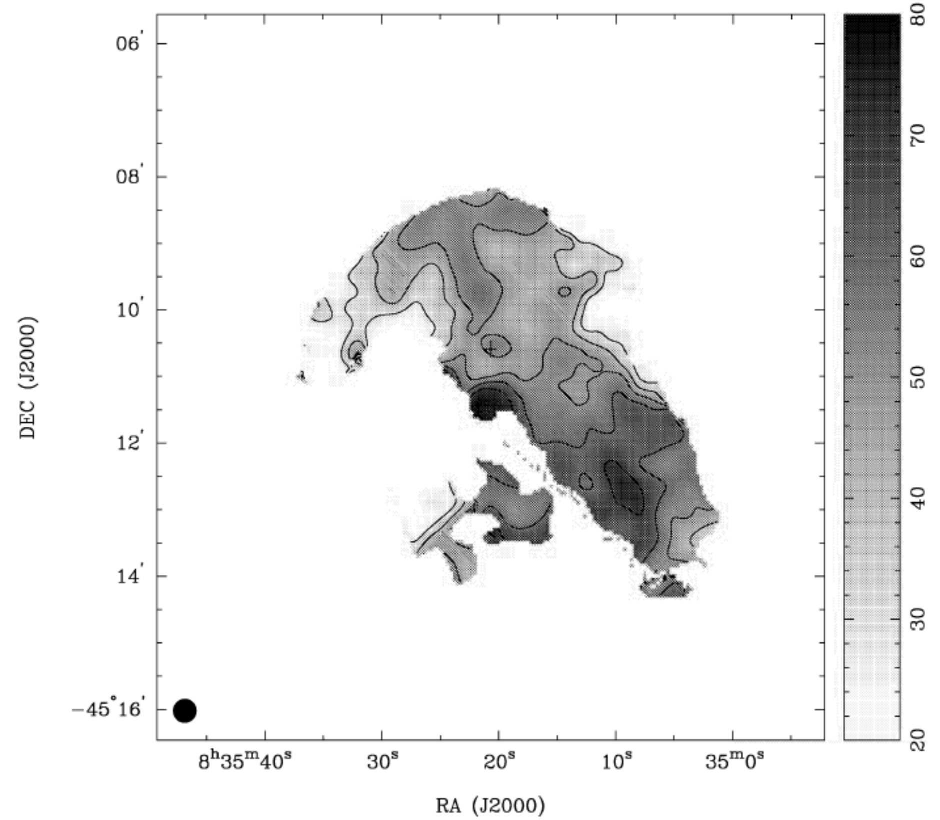


- $B_{tor}(r) \sim r^{-1}$
- $B_{rad}(r) \sim r^{-2}$

Vela

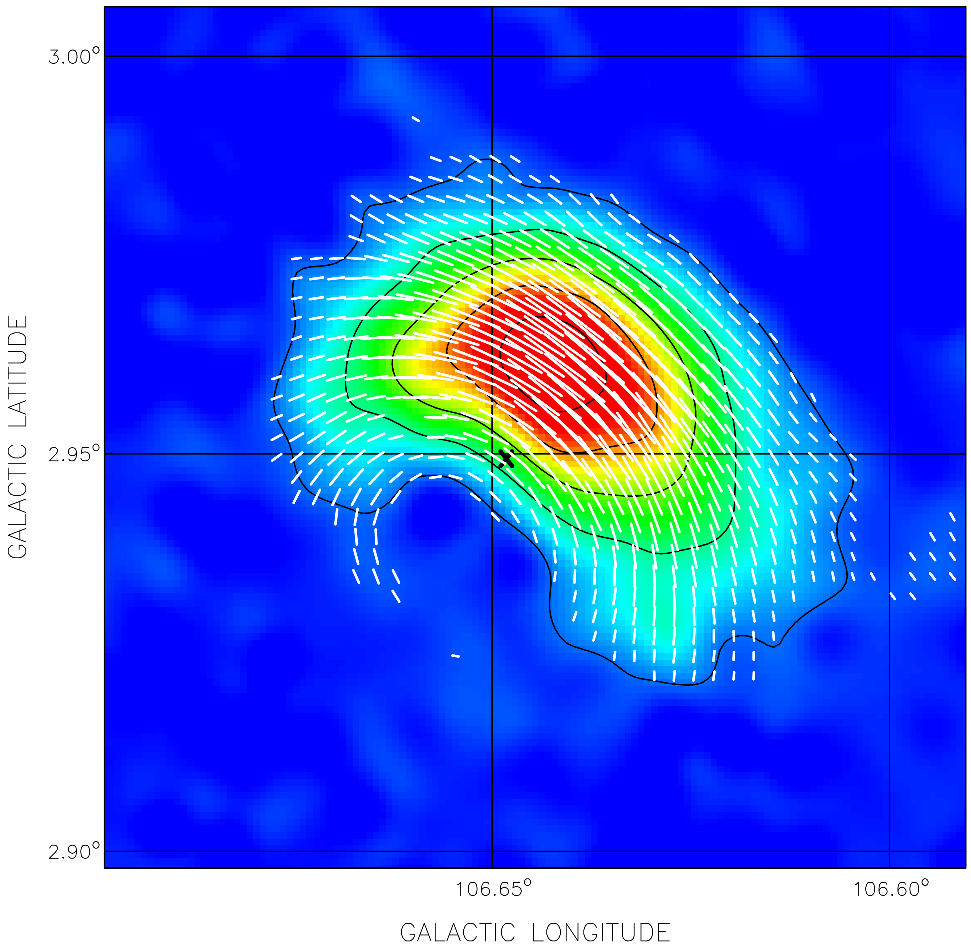
(Helfand et al., 2001)

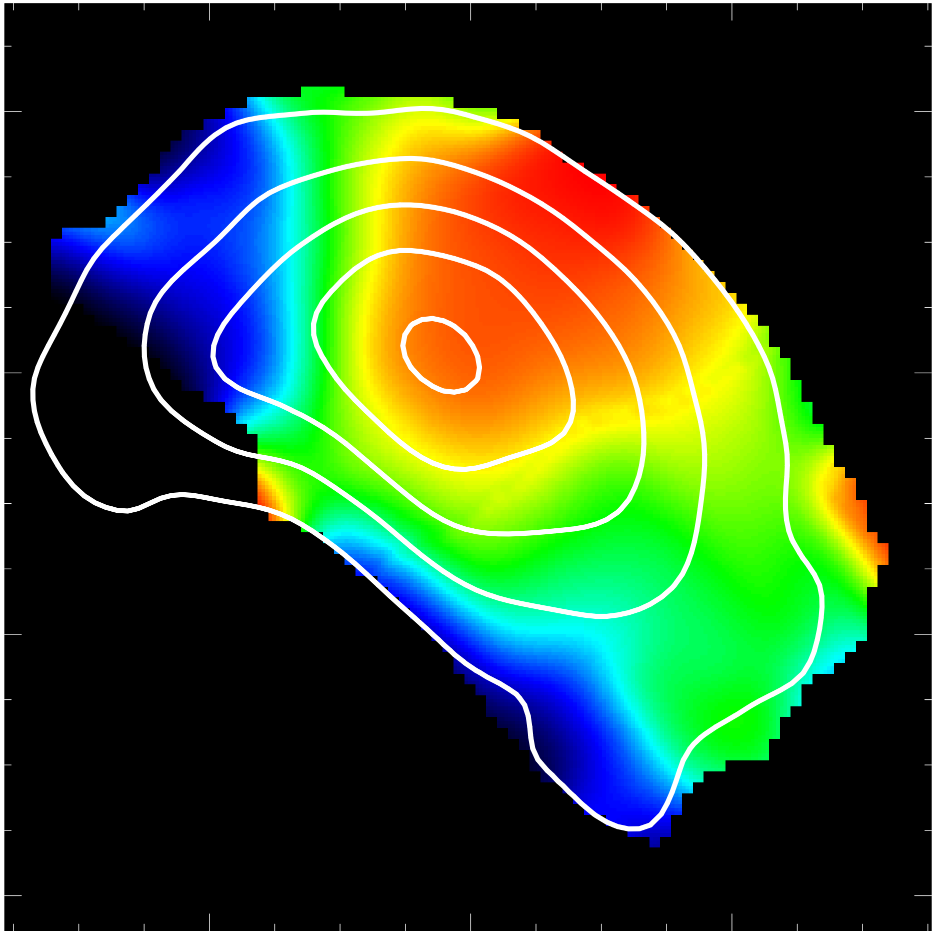




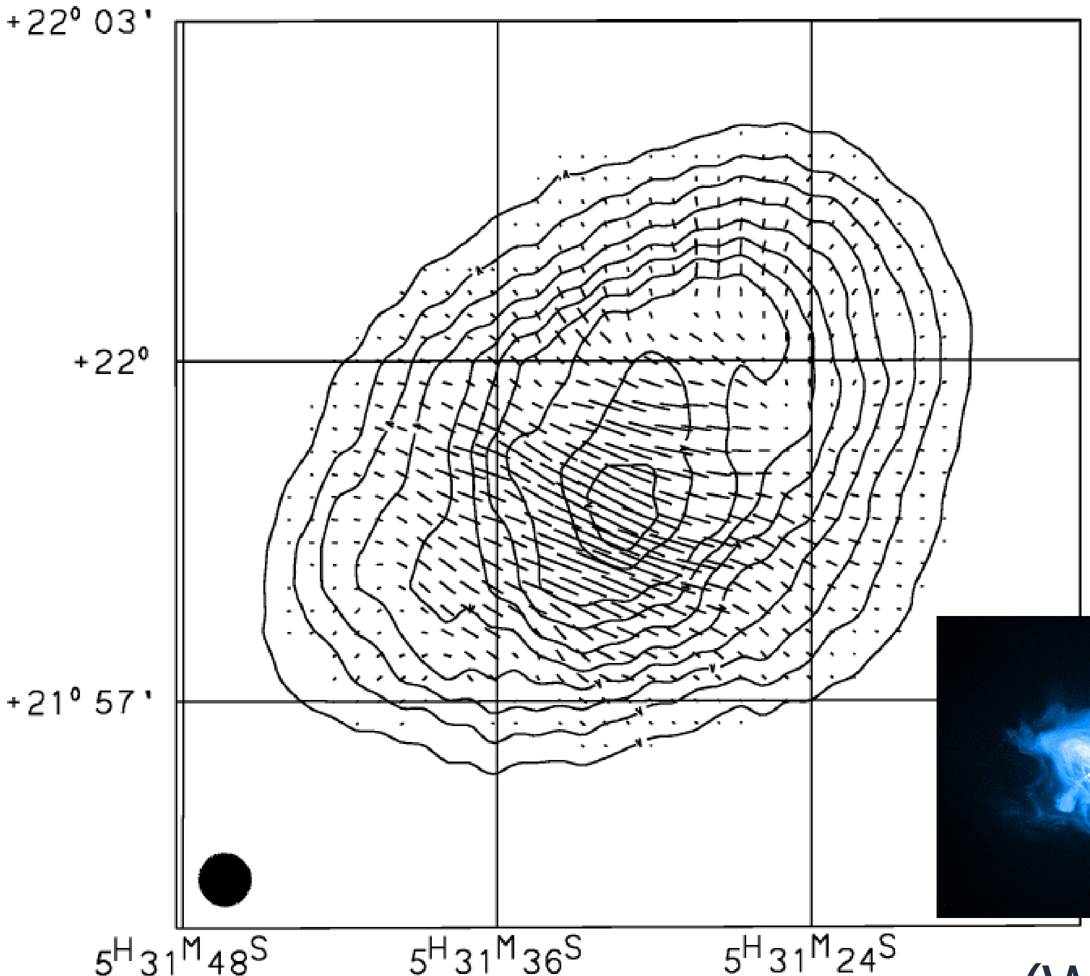
B-field from PA: toroidal, RM structure: radial/dipolar
(Dodson et al., 2003)

G106.3+2.7: Boomerang

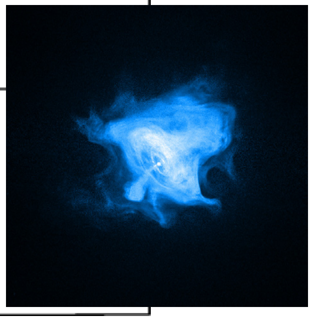




B-field from PA: toroidal, RM structure: radial/dipolar
(Kothes et al., 2006)



(Reich, 2002)

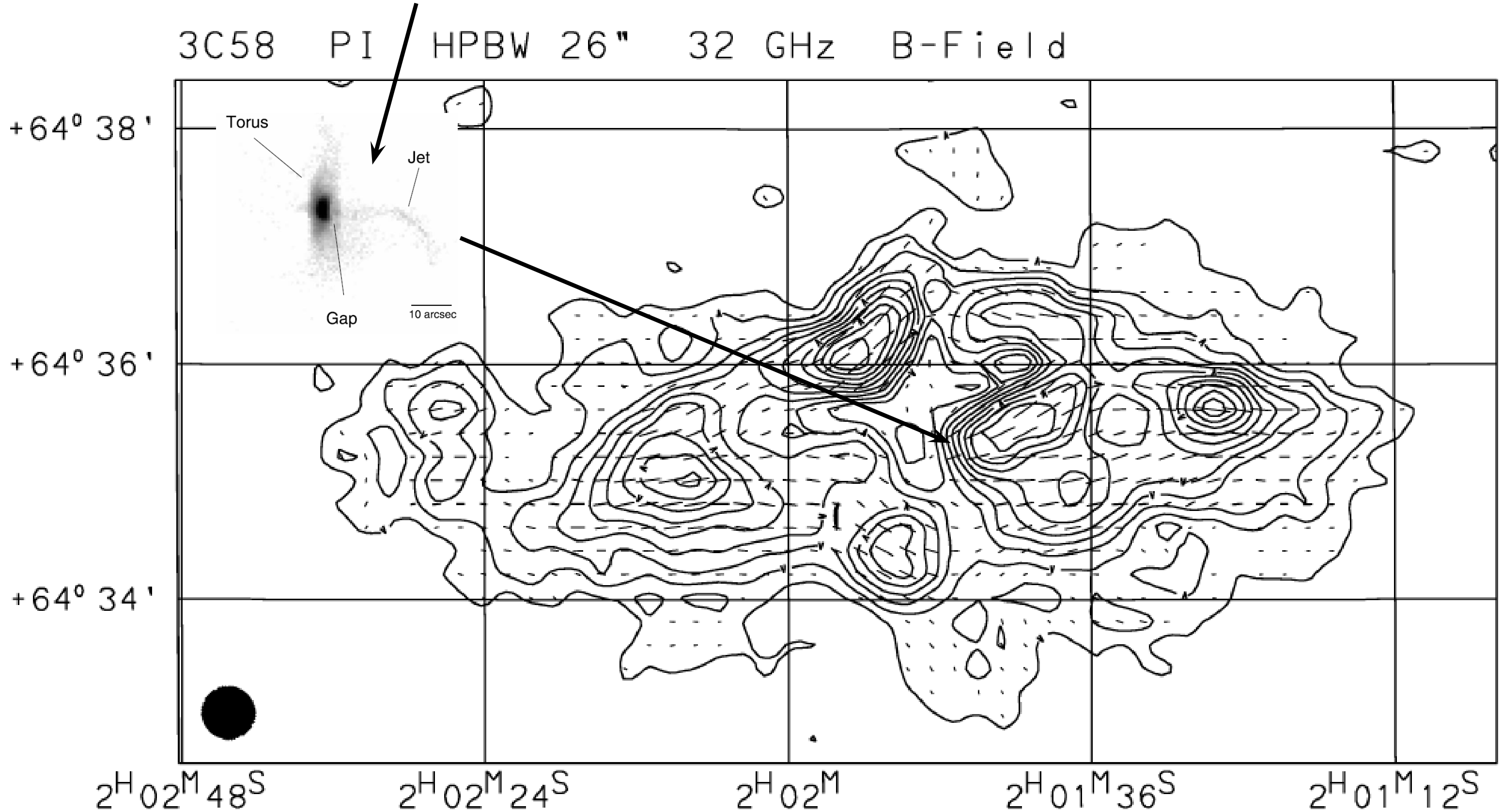


(Weisskopf et al., 2000)

B-field from PA: complex, RM structure: ?

3C58

(Slane et al., 2004)

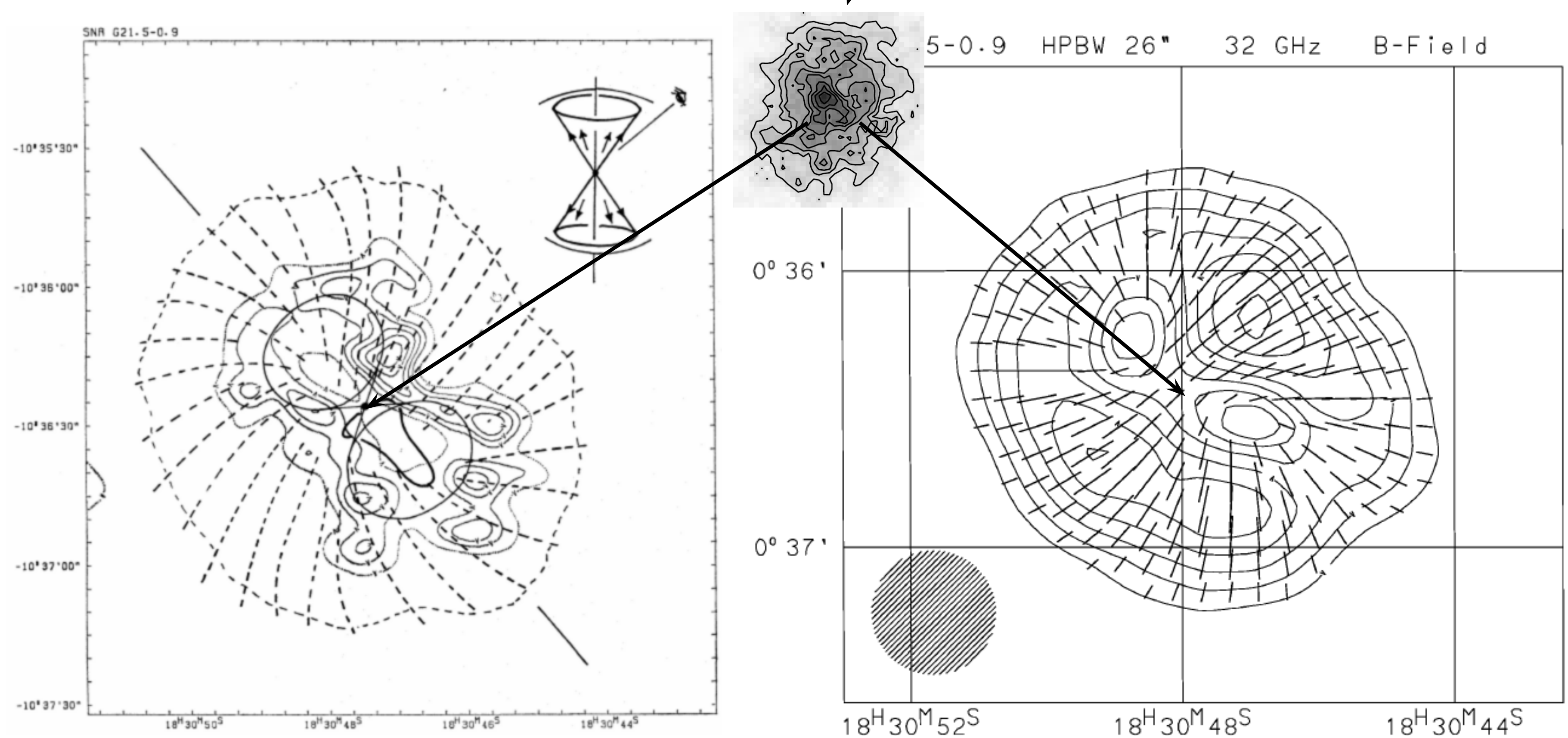


B-field from PA: complex, not toroidal, RM structure: ?

(Reich, 2002)

G21.5-0.9

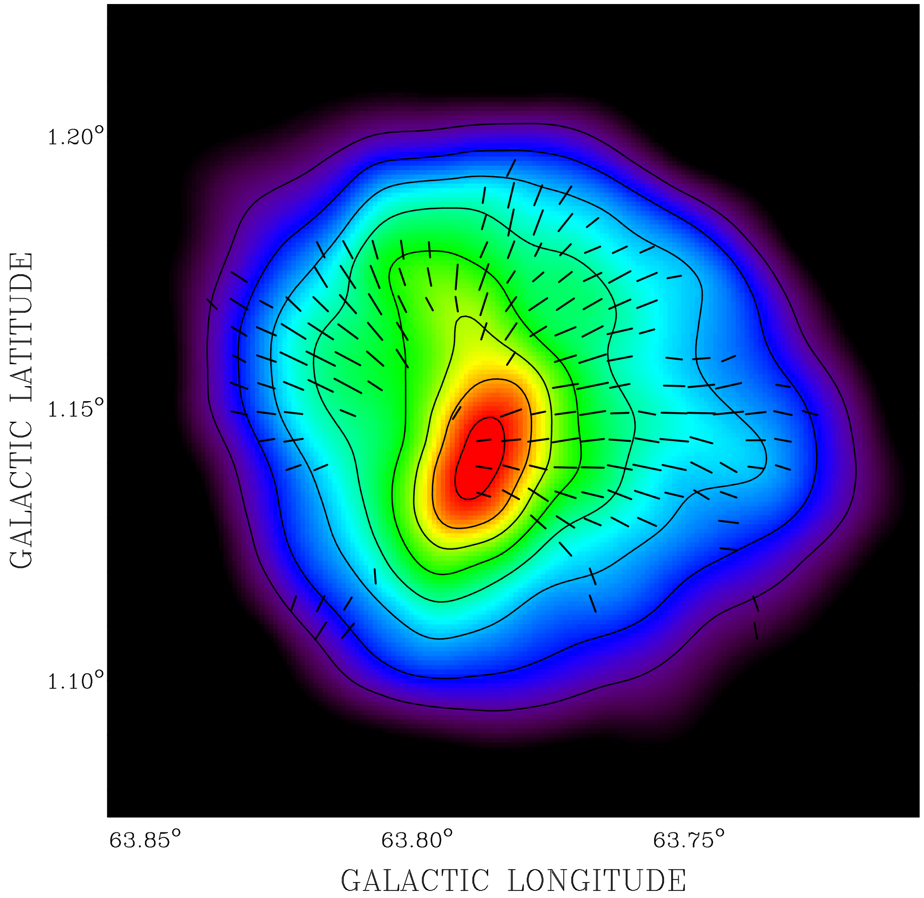
(Safi-Harb et al., 2001)

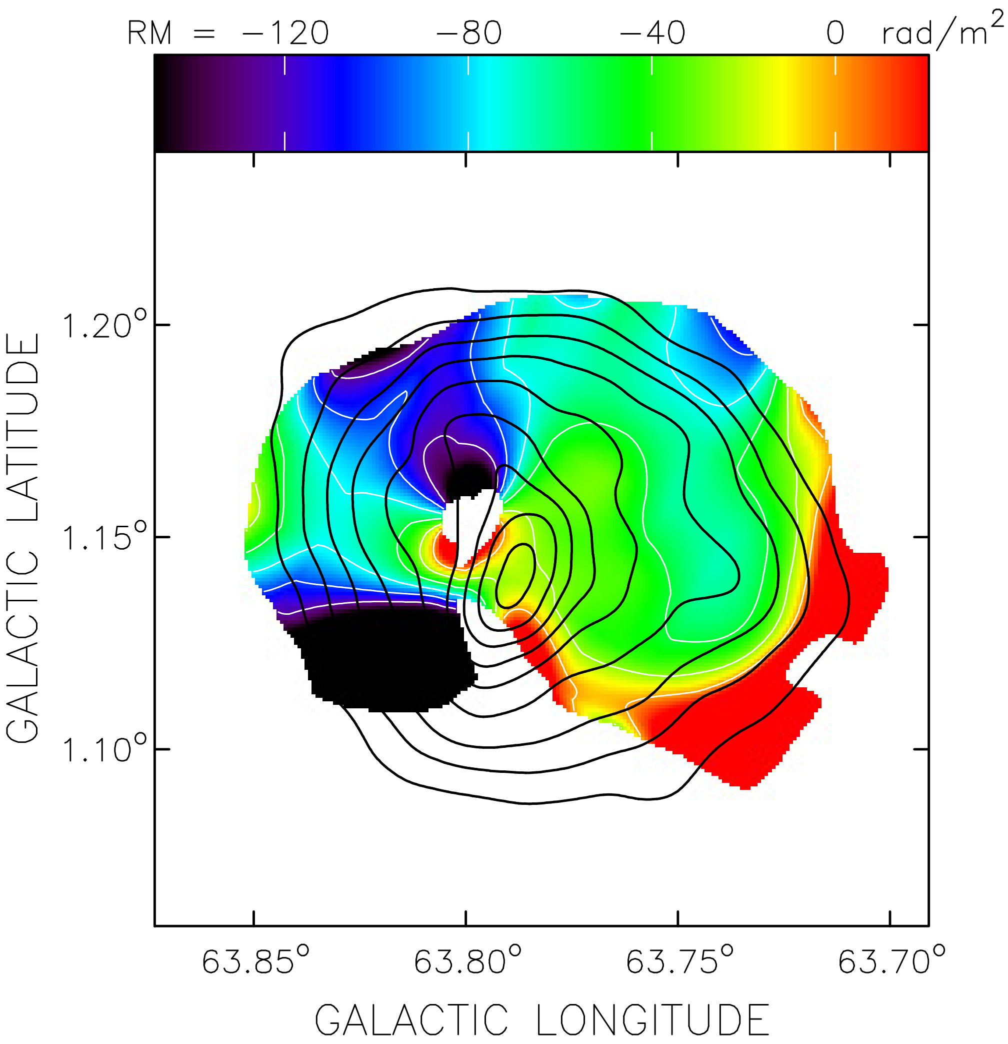


B-field from PA: radial, RM structure: ?

(Fürst et al., 1988; Reich, 2002)

G63.7+1.1





B-field from PA: radial, RM structure: radial?

(Kothes et al., 2011, in prep.)

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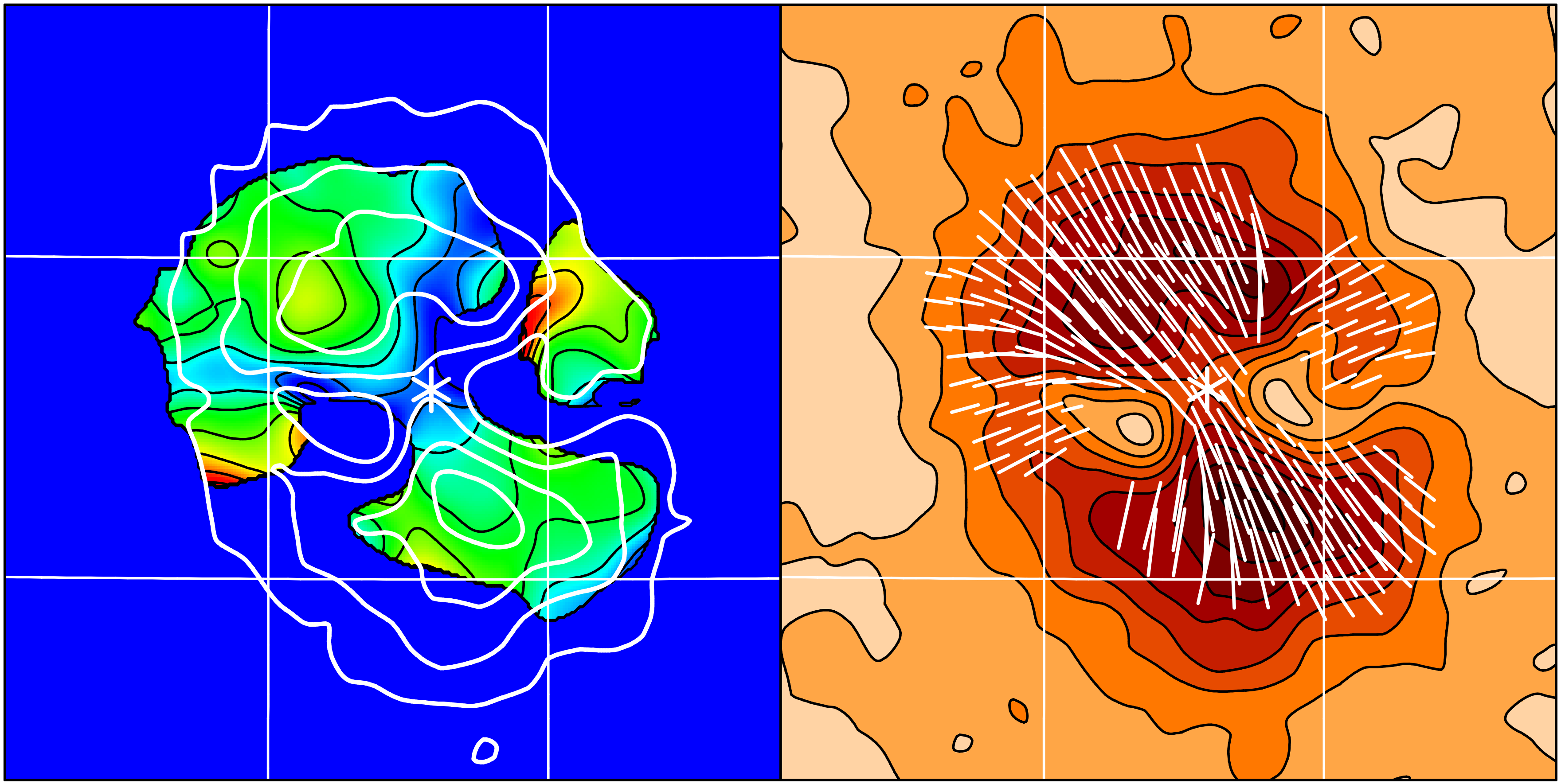


B-field from PA: dipolar, RM structure: dipolar
(Kothes et al., 2008)

PWN Observations: Summary

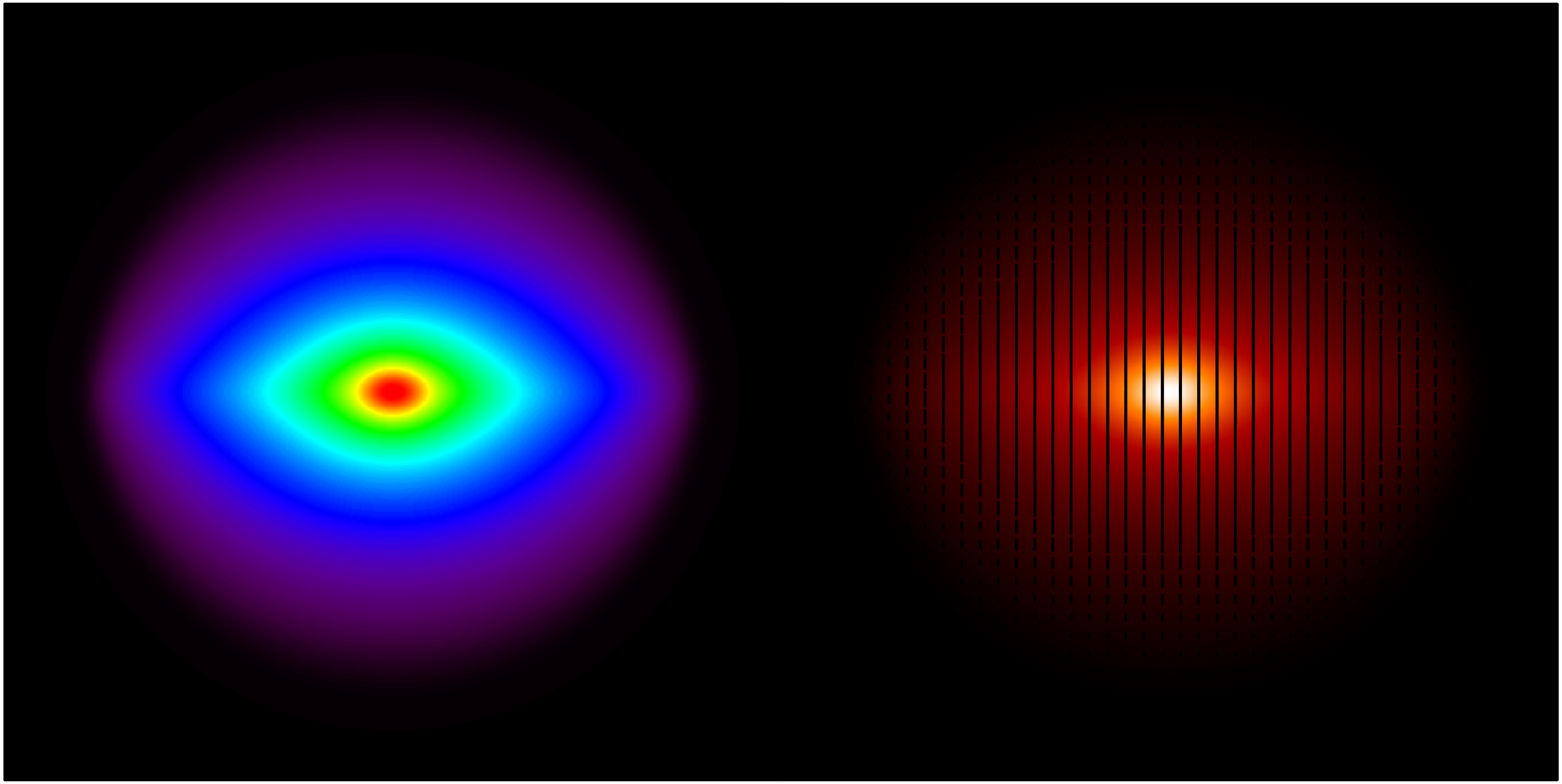
- We found toroidal and radial B-field structures
- radial B-field dominates PA and RM
- Observations are not consistent with wind scenario predicted by theory:
  - $B_{tor}(r) \sim r^{-1}$
  - $B_{rad}(r) \sim r^{-2}$

Observation Simulations

- spherical nebula of relativistic particles
- insert magnetic fields of different structure
- simulate the synchrotron emission of this nebula using simple equations:
  - $S_\nu = K\,B_\perp^{\frac{1}{2}(\delta+1)}\nu^{-\frac{1}{2}(\delta-1)}, N(E)dE = K\,E^{-\delta}dE$
  - $\Delta\phi_\lambda = RM\lambda^2,\, RM = 0.81\int_l B_\| n_e dl$
- computing observations of this nebula
- rotation angle Θ: angle between plane of the sky and pulsar spin axis

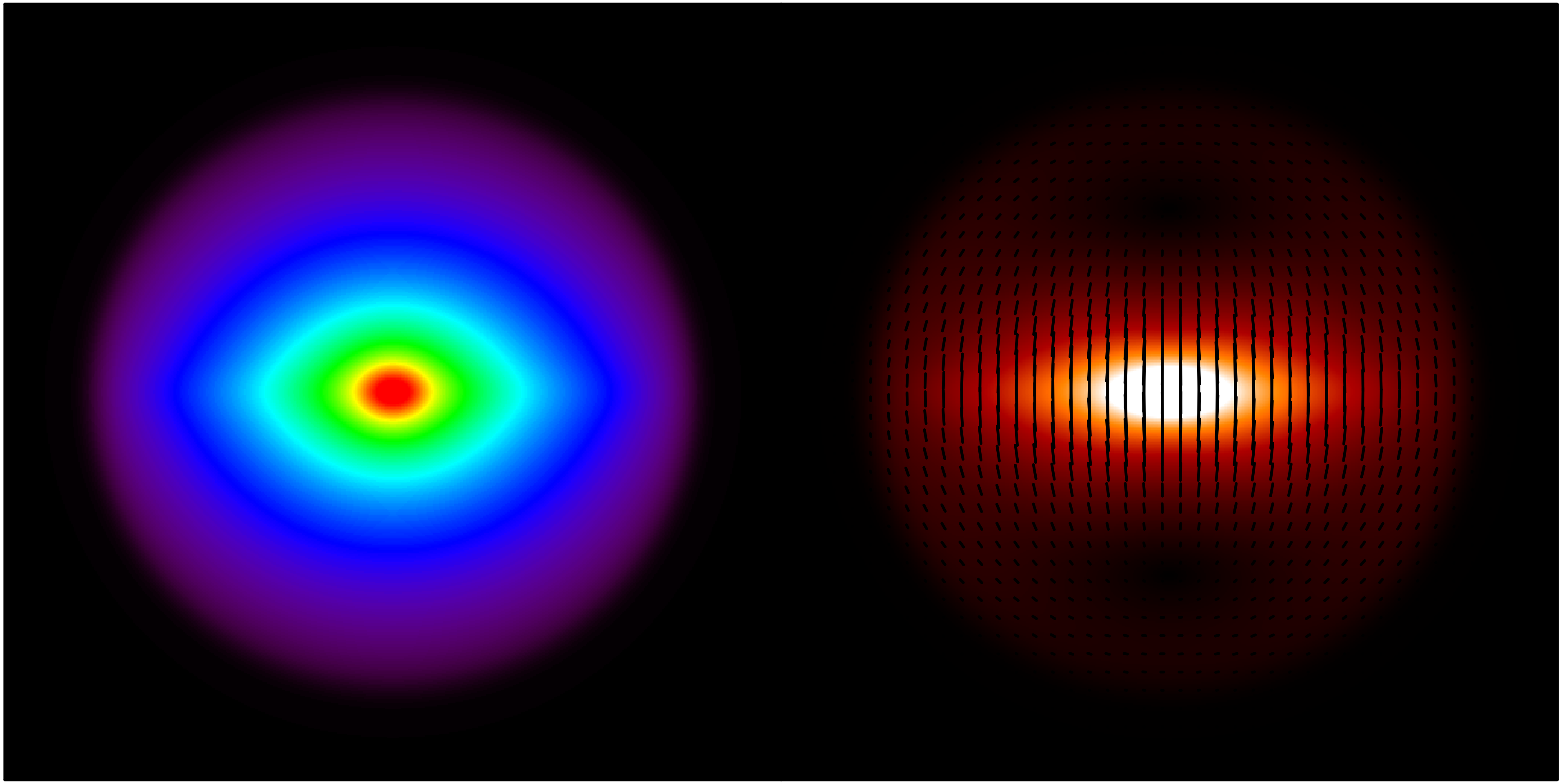
Pure Toroidal Field

$$\Theta = 0^\circ$$



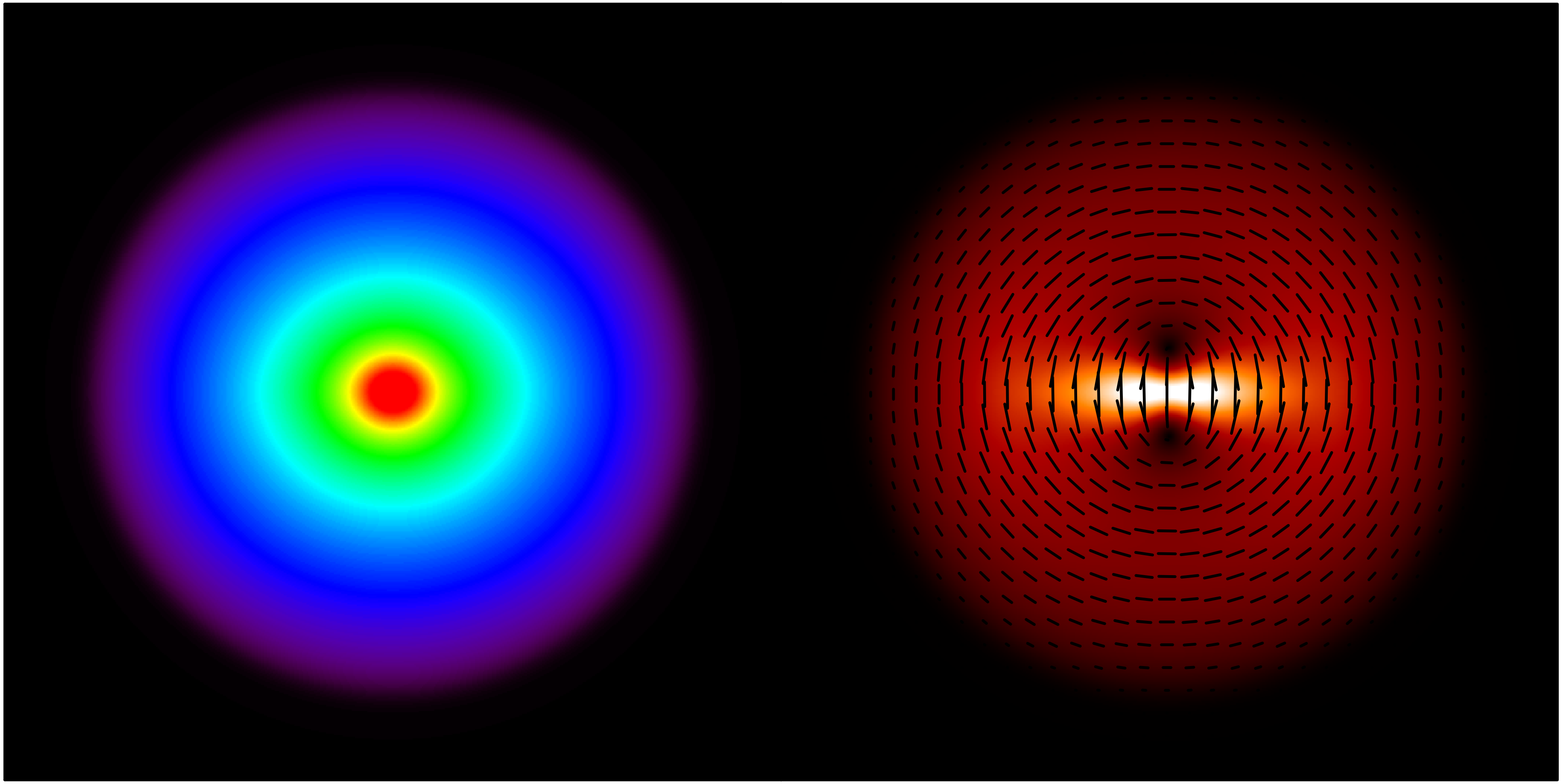
Pure Toroidal Field

$$\Theta = 30^\circ$$



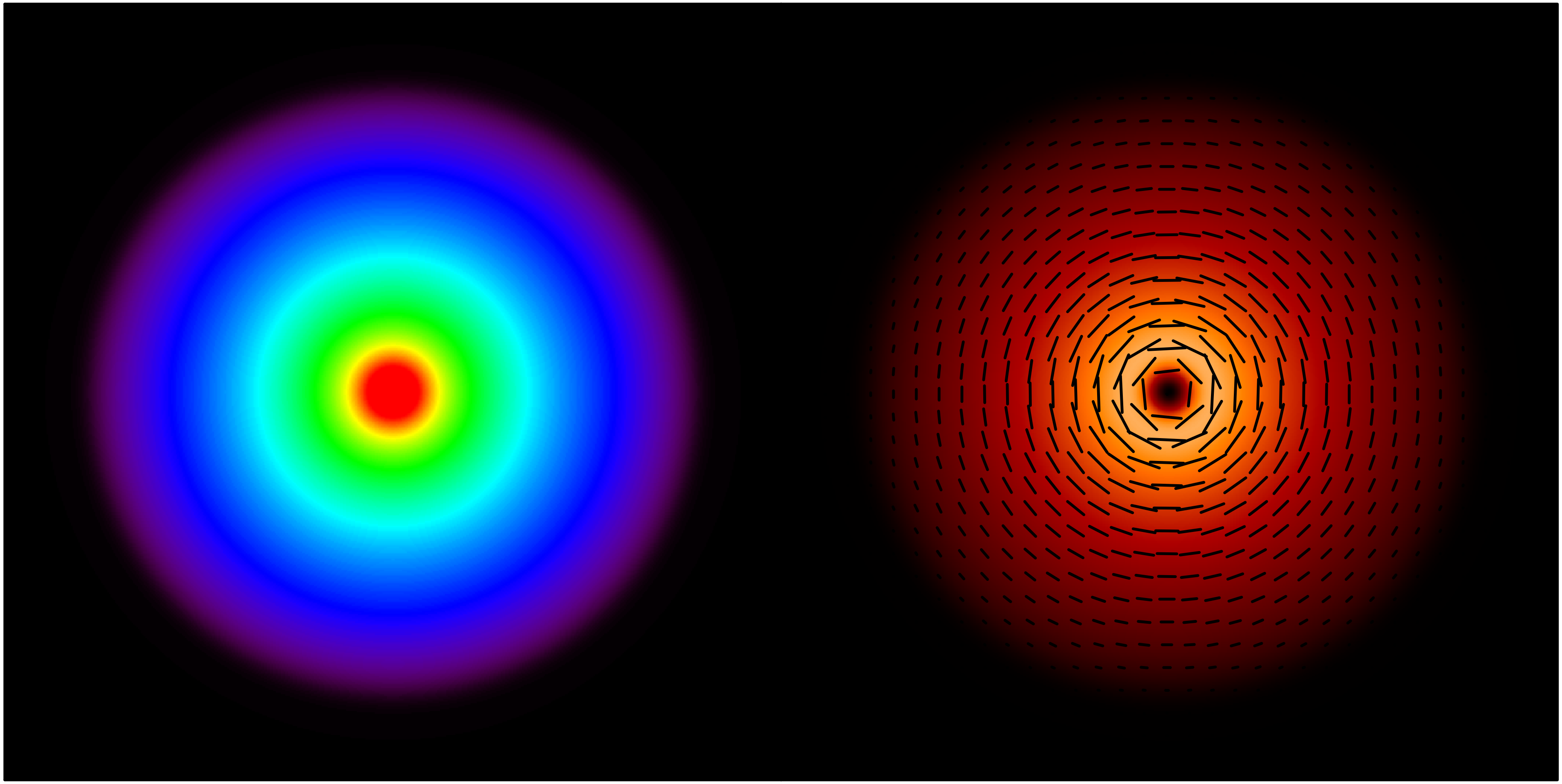
Pure Toroidal Field

$$\Theta = 60^\circ$$



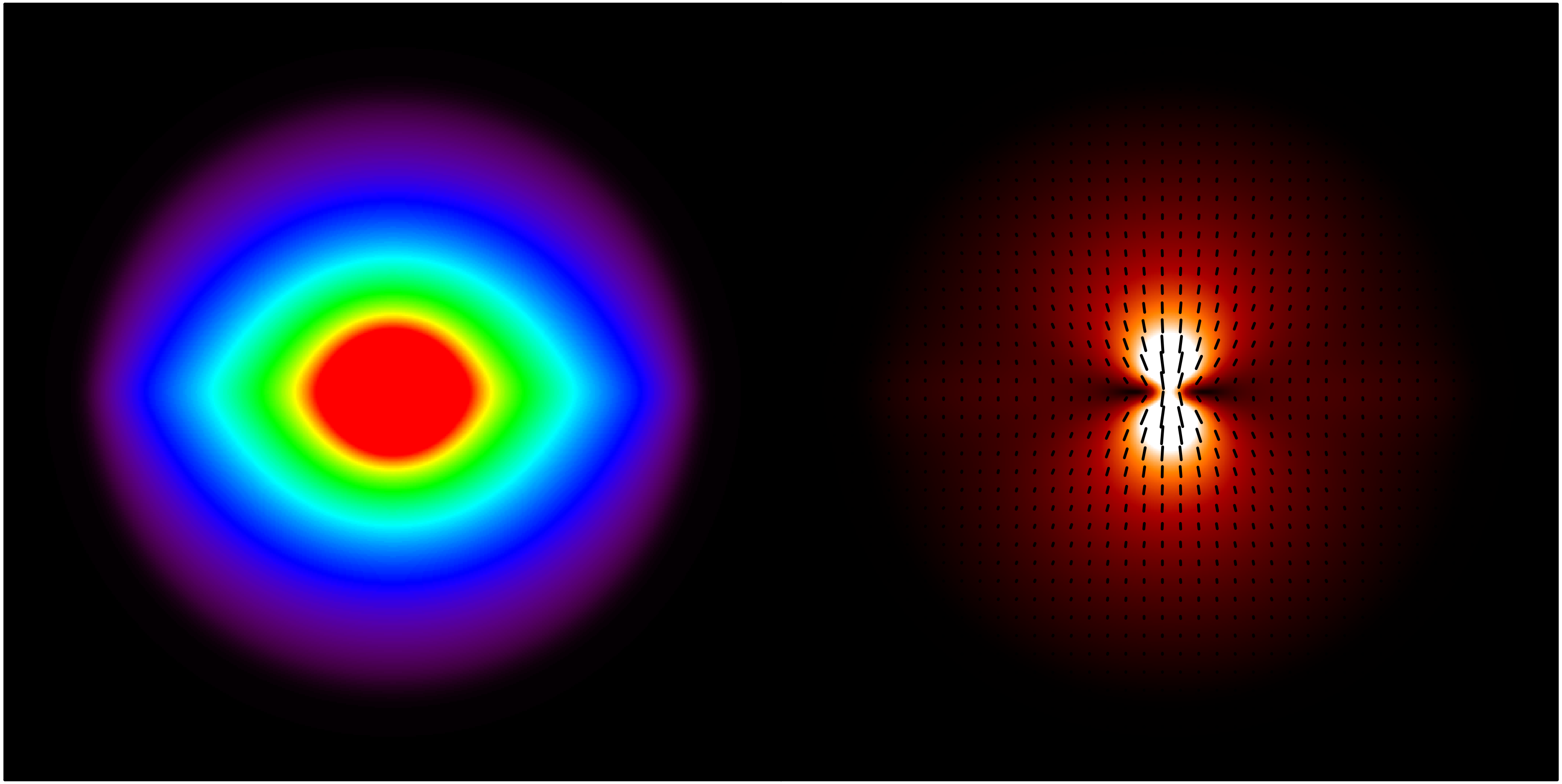
Pure Toroidal Field

$$\Theta = 90^\circ$$



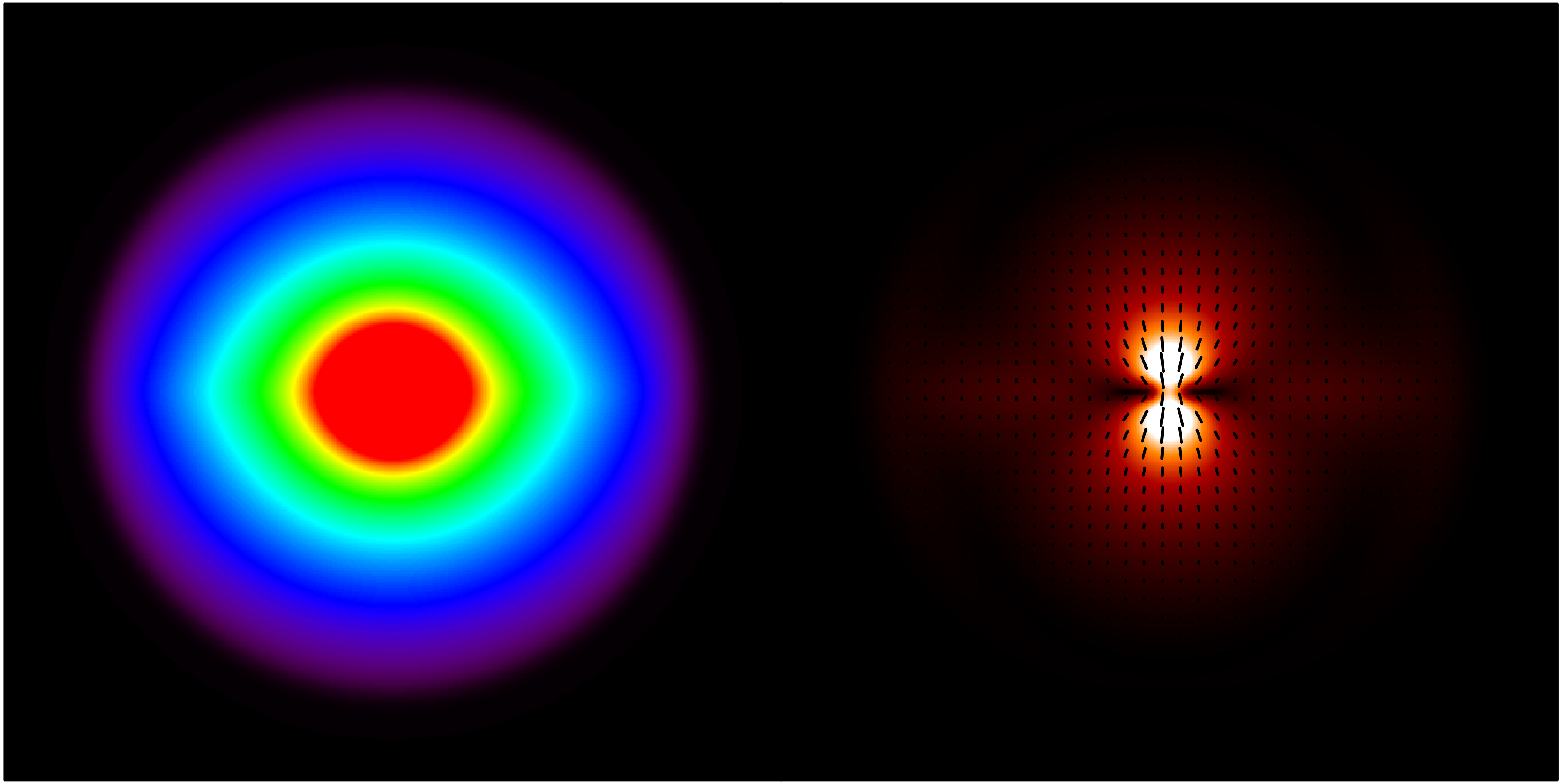
Toroidal + Radial Field

$$\Theta = 0^\circ$$



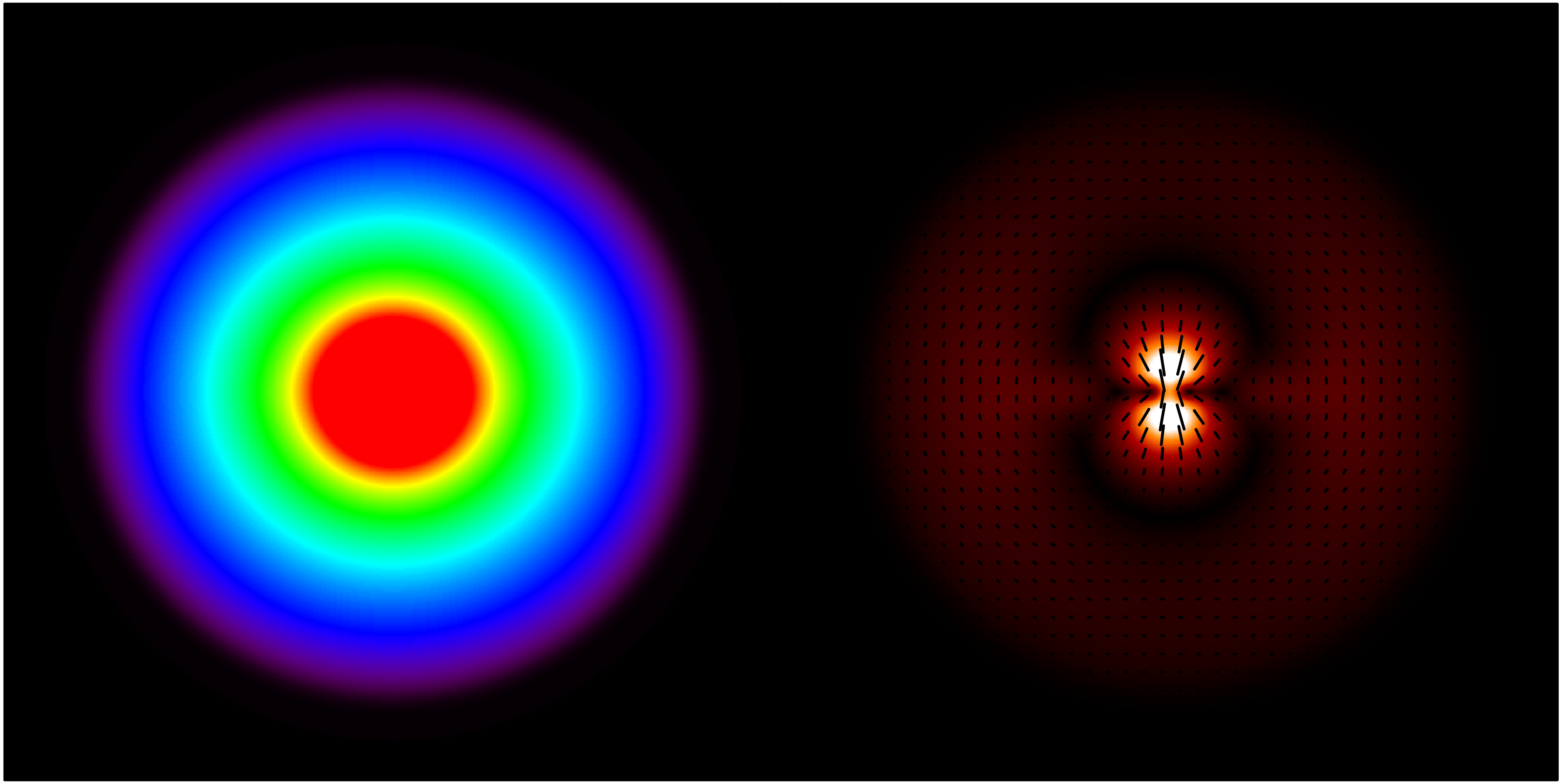
Toroidal + Radial Field

$$\Theta = 30^\circ$$



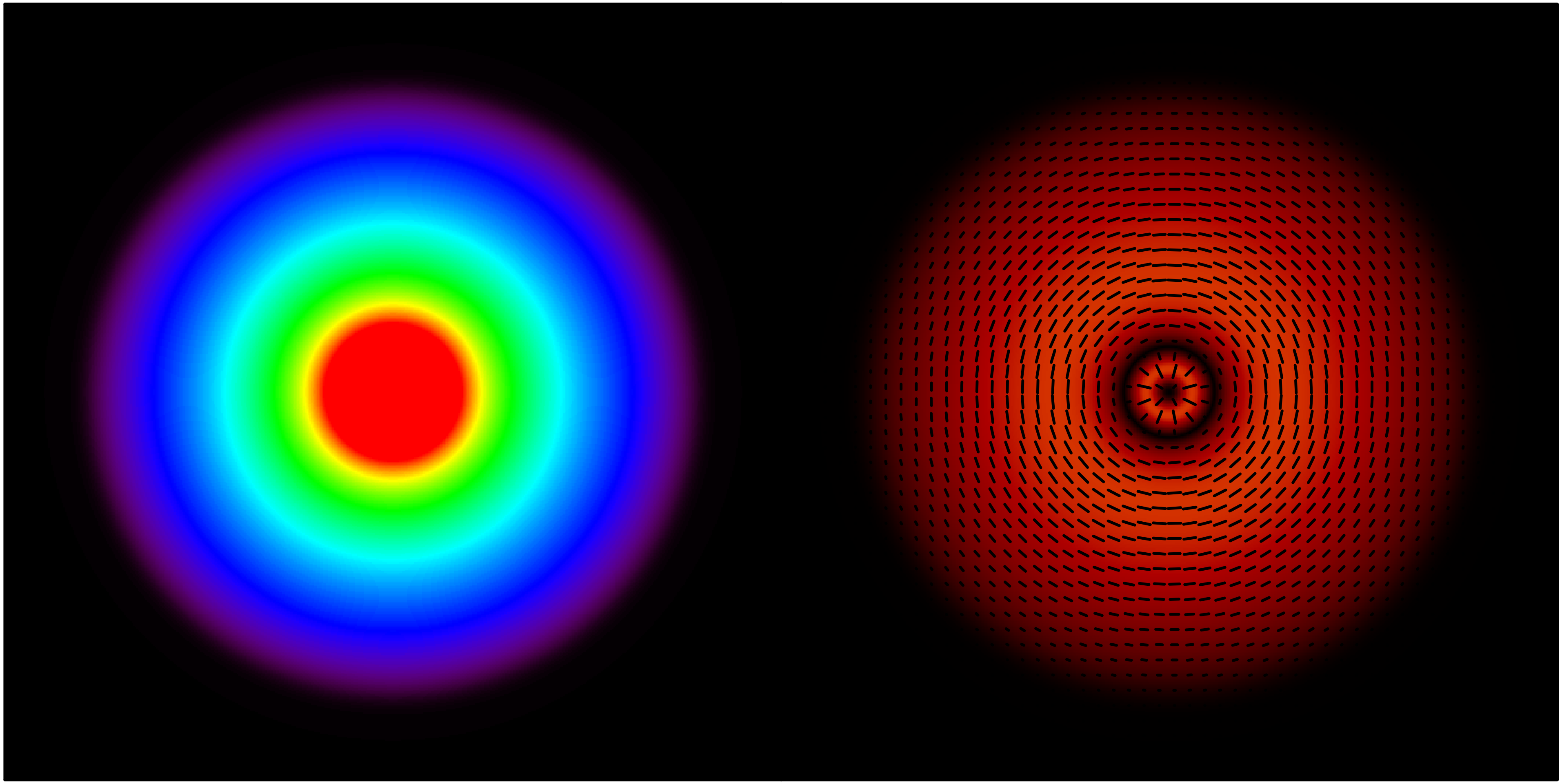
Toroidal + Radial Field

$$\Theta = 60^\circ$$

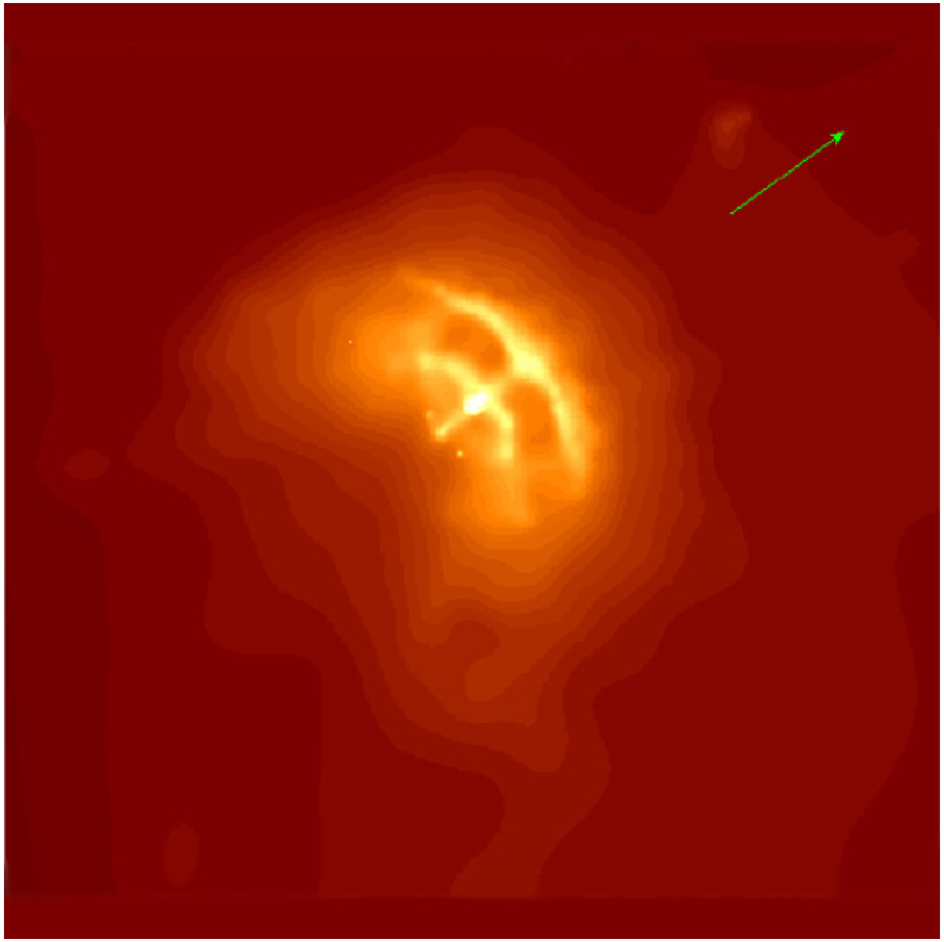


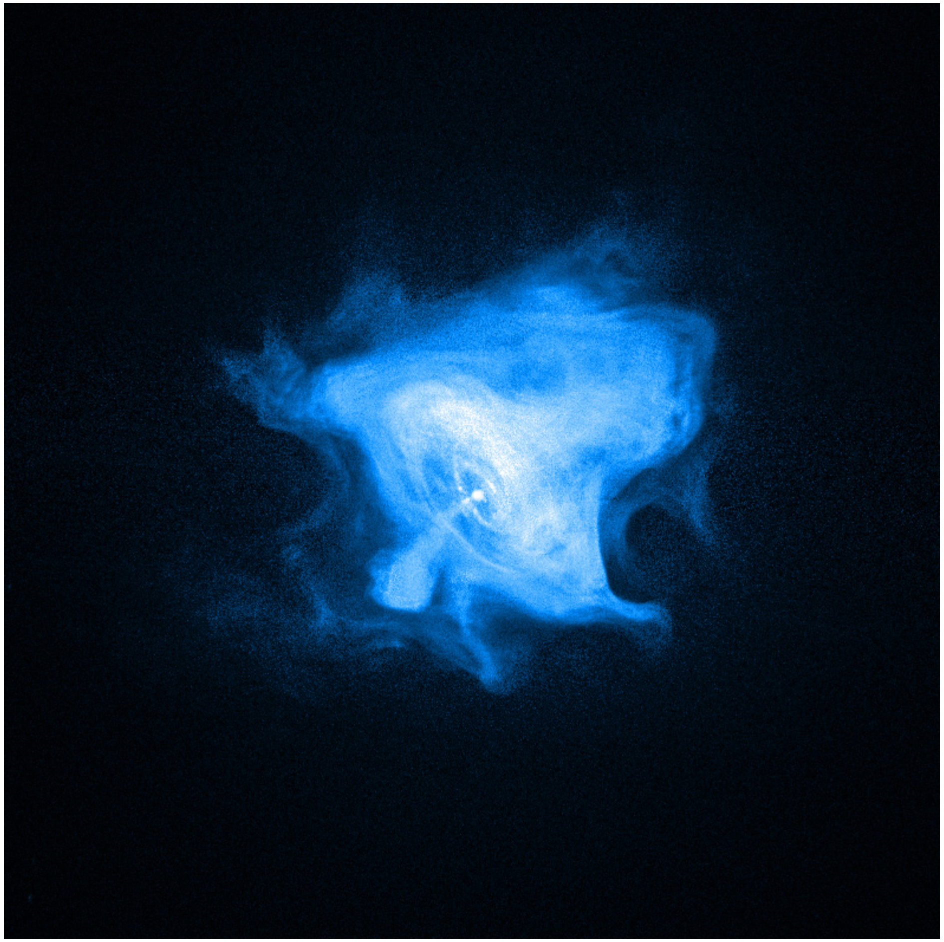
Toroidal + Radial Field

$$\Theta = 90^{\circ}$$

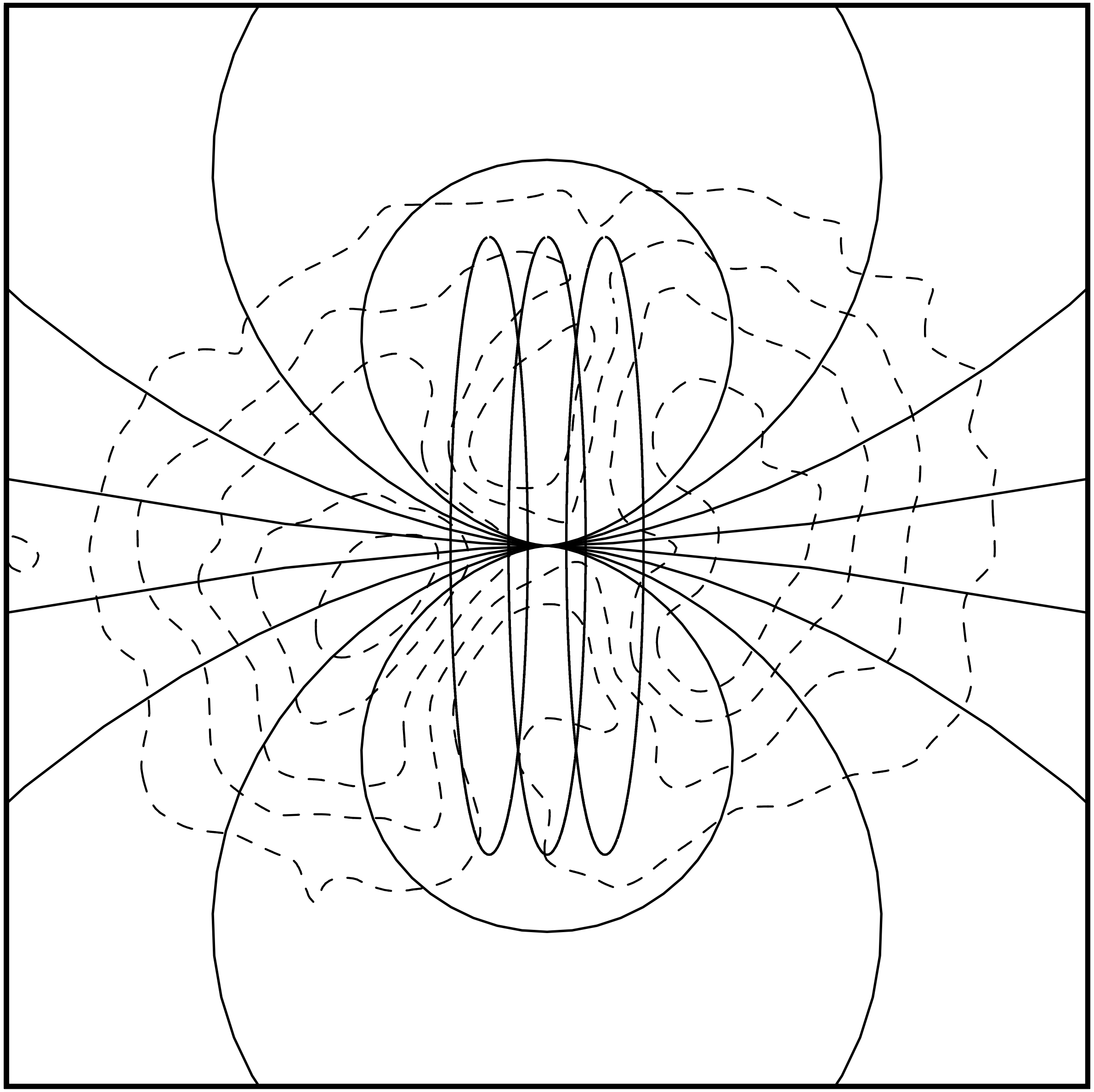


Outlook





Outlook



Summary

- Radio Polarimetry is an excellent tool to study magnetic fields
- With a simple model of mature supernova remnants and conveniently located supernova remnants we can probe the magnetic field of our Galaxy
- Observed magnetic fields in pulsar wind nebulae do not agree with those predicted by theoretical models
- there is still a lot to be done