Evolution of magnetic field structure in SN1987A

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Supernova Remnants III

An Odyssey in Space after Stellar Death

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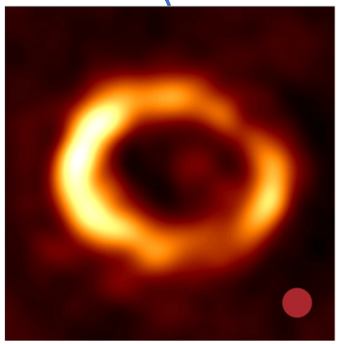
SN1987A: structures

- Young SNR -> monitored
- Rather close -> resolved
- That allows us to **study structures**

- CSM structure
- ejecta structure
- PWN

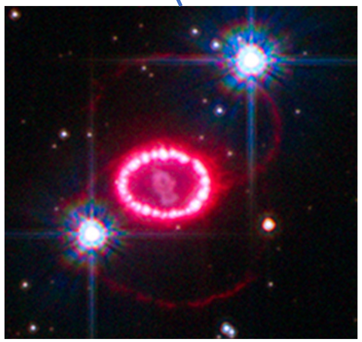
radio

X-rays

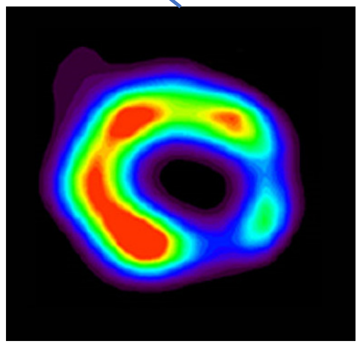


ATCA [Zanardo+ 2013]

JWST [Larsson+ 2023]



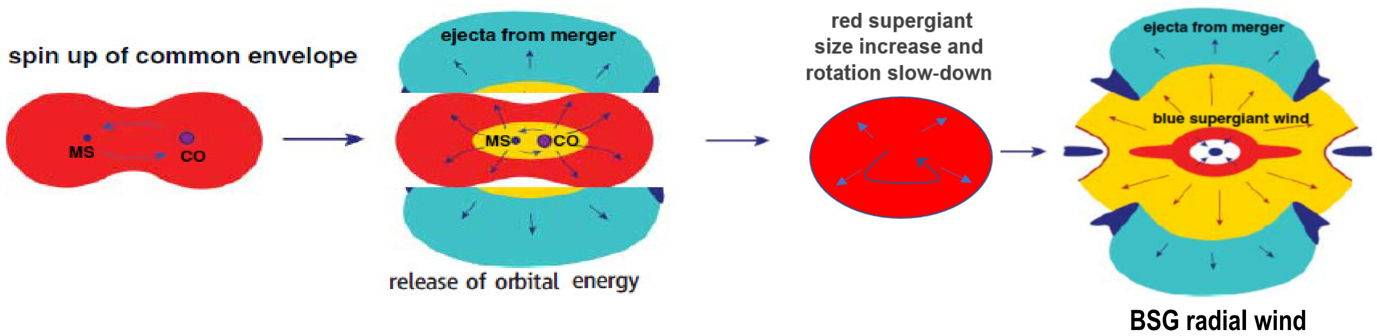
HST [Fransson+ 2015]



Chandra [Frank+ 2016]

Looking back at the history of the progenitor

[Morris & Podsiadlowski 2007]



Mass loss history

$$\rho_{CS} = \frac{\dot{M}}{4\pi r^2 u_{\rm wind}}$$

Rotation history

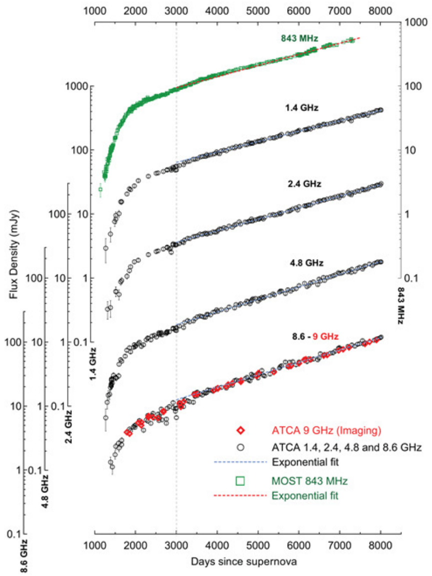
$$B_\phi \propto \frac{1}{P_{\rm star} \cdot u_{\rm wind}}$$

Propagating shock probes
the earlier times

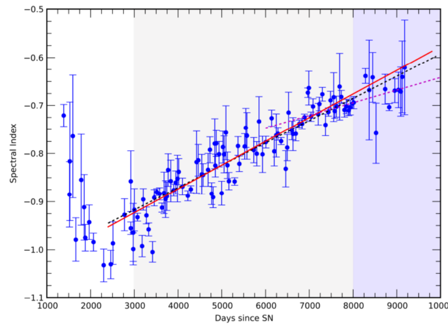
What about the magnetic field?

We make use of the radio data

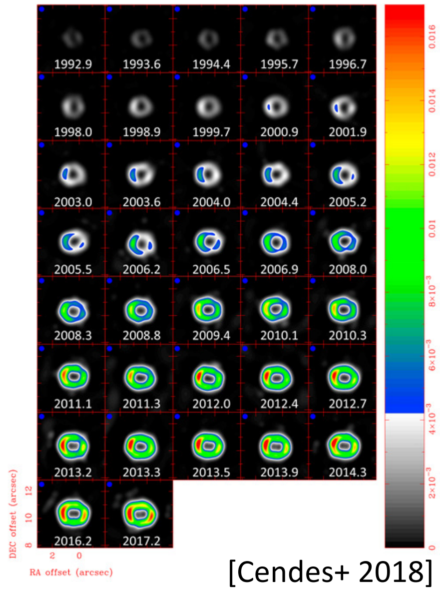
- Light curves
- Spectra – evolution
- Images – evolution
- Polarization



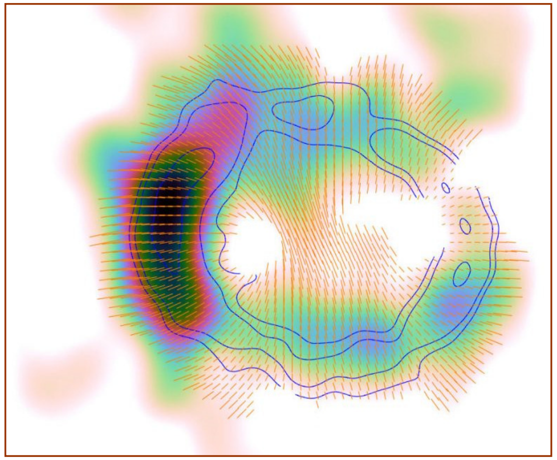
[Zanardo+ 2010]



[Zanardo+ 2017]



[Cendes+ 2018]



ATCA 22 GHz [Zanardo+ 2018]

3D MHD numerical simulations

Initial conditions

model of CSM by
Luo & McCray 1991
Morris & Podsiadlowski 2007

[Orlando+ 2015]

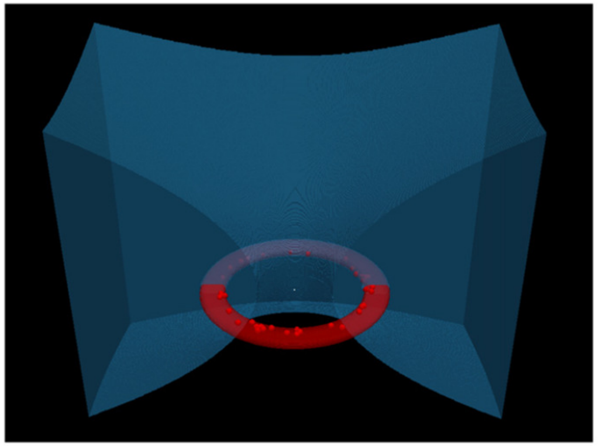
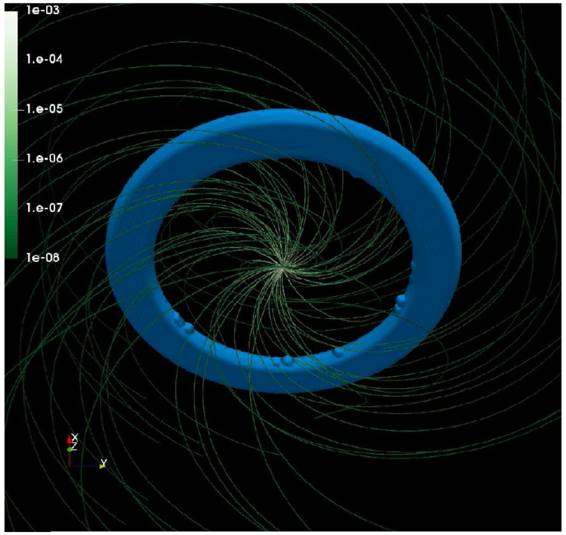


Figure 1. Rendition in log scale of the circumstellar nebula around SN 1987A model initial conditions. The ring consists of a uniform smooth component and high-density spherical clumps, and is shown in red; the H II region around the ring is marked by the blue clipped component. The white dot at the center of the coordinate system shows the position of the SN explosion.

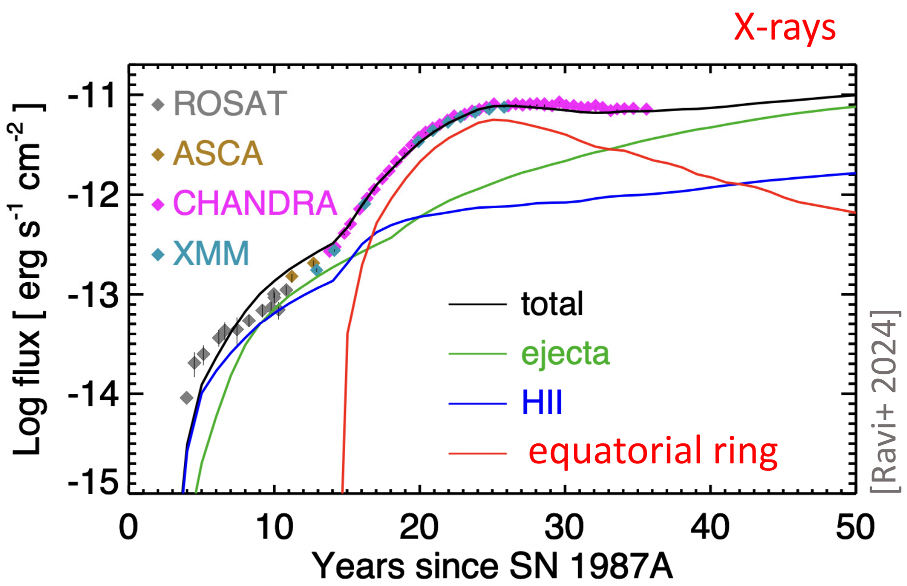
model of ISMF
the Parker (1958) spiral

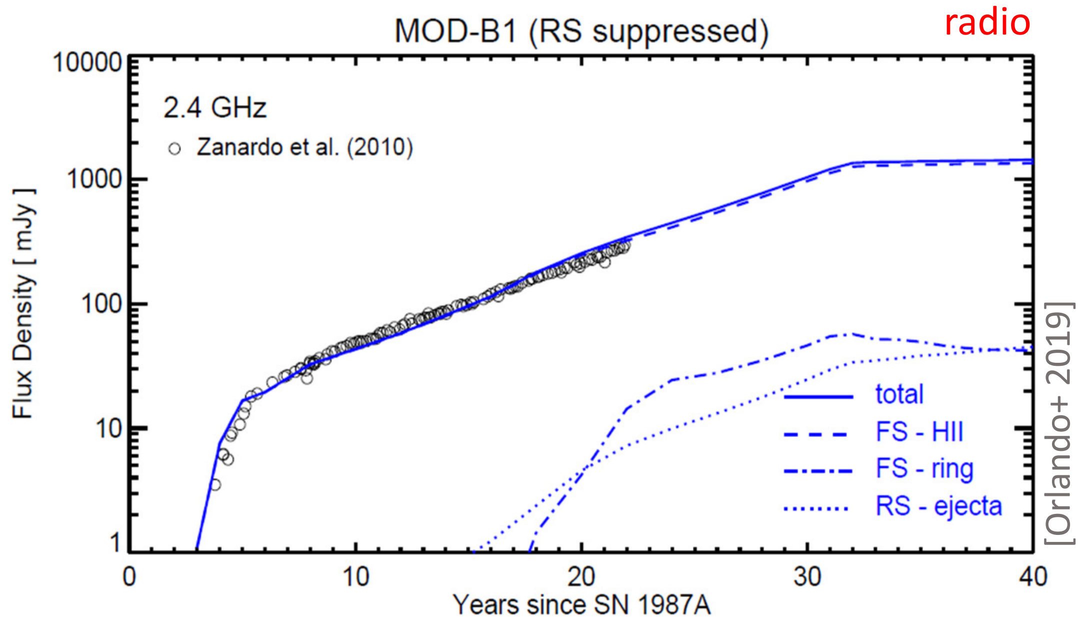


[Orlando+ 2019]

$$B_r = \frac{A_1}{r^2}\,, \qquad B_\phi = -\frac{A_2}{r}\sin\theta,$$

Light curves vs 3D numerical model

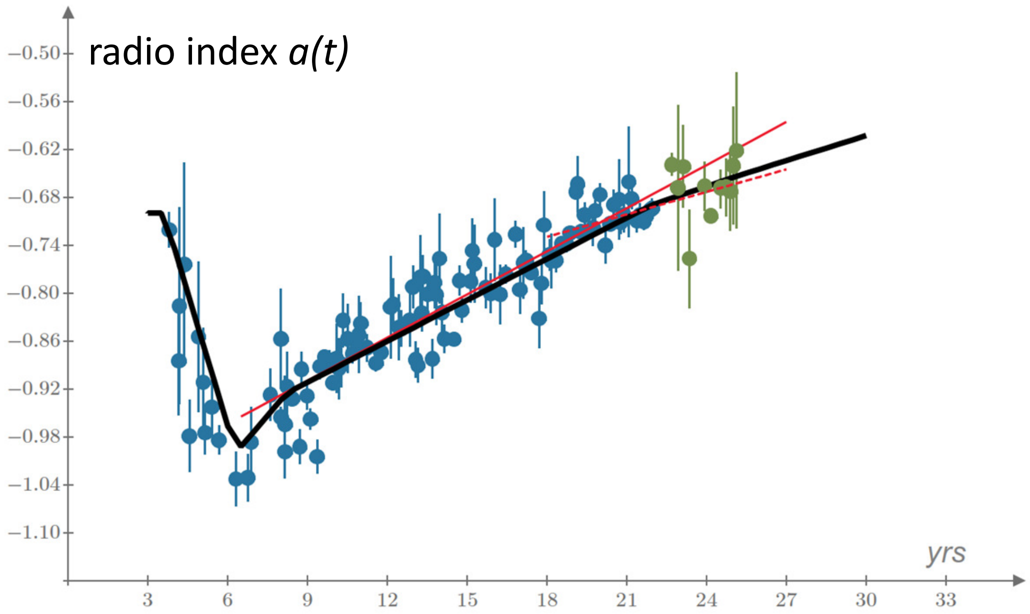




Take away

- the forward shock dominates the radio emission
- equatorial ring and ejecta do not contribute to the radio emission

Spectrum

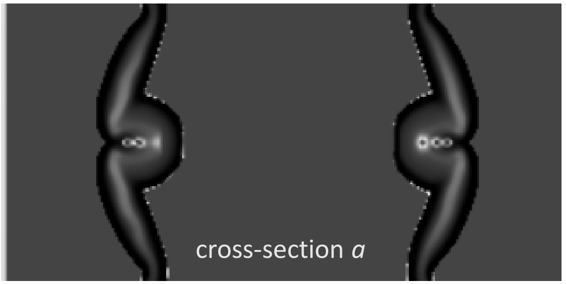


blue and green dots (Zanardo+ 2010, 2017)
black line – our approximation

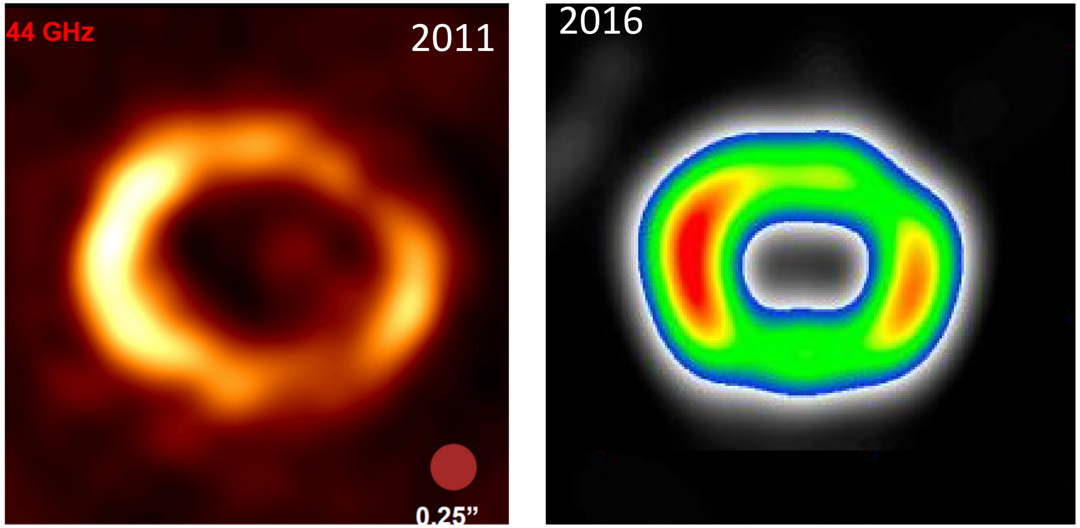
Take away

- the spectrum up to ~100 GHz is well approximated by a power law [Zanardo+ 2014]
- the radio light curve is sensitive to *a(t)*
- we account for *a(t)* in our simulation
- *a(t)* should be used in the Lagrangian approach

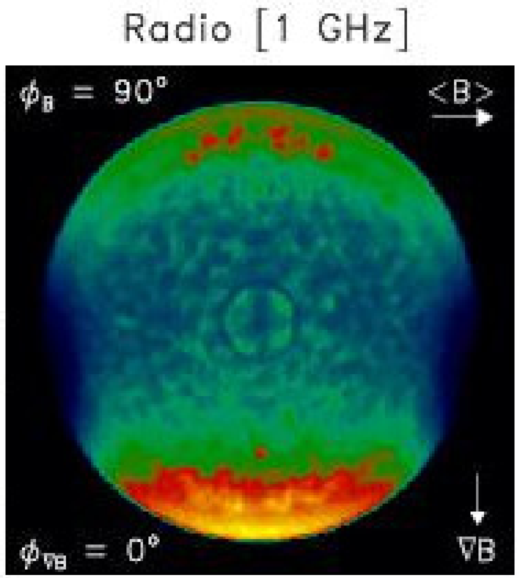
Radio emitting electrons suffers from the adiabatic losses only --> their index *s* is constant within a fluid element



Images



observations [Zanardo+ 2017; Cendes+ 2018]

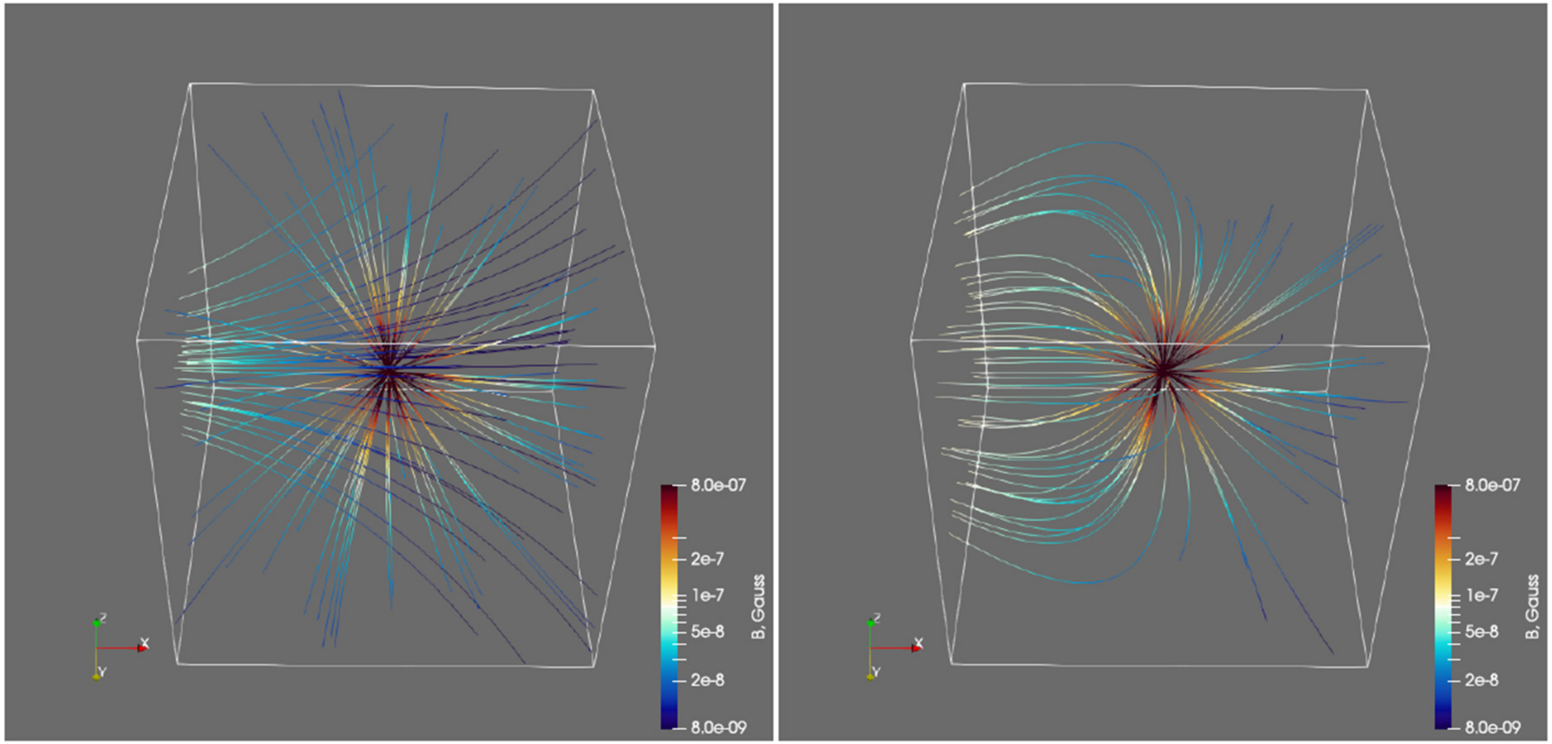


theory [Orlando+ 2011]

Take away

- East-West asymmetry in brightness
- there should be a gradient of *B*

3D model of ambient MF with a gradient



Parker spiral

$$B_r = \frac{A_1}{r^2}, \qquad B_\phi = -\frac{A_2}{r}\sin\theta,$$

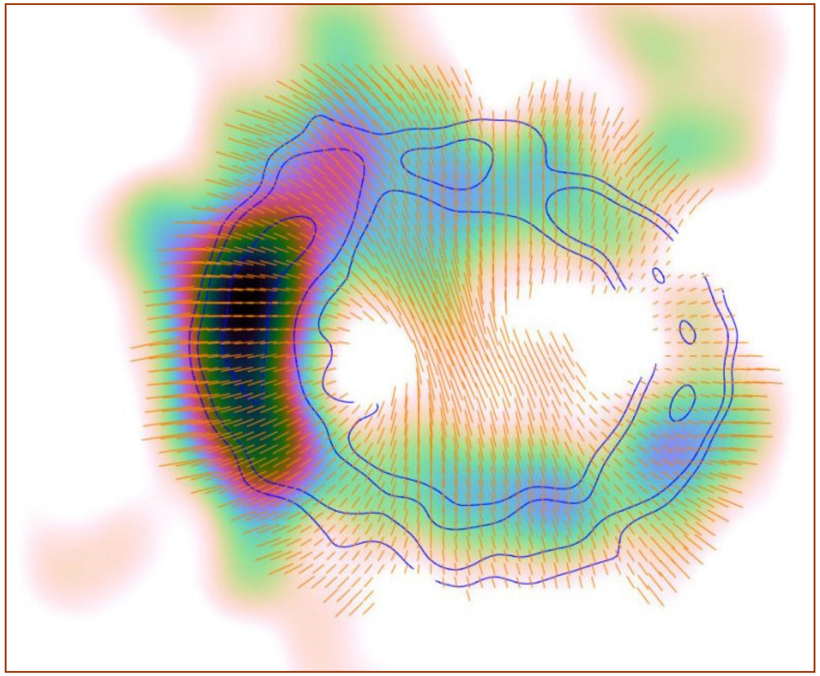
exponential MF

$$B_{ex} = B_e \exp(-x/h)$$

$$B_{ey} = \frac{\xi y}{h} B_e \exp(-x/h)$$

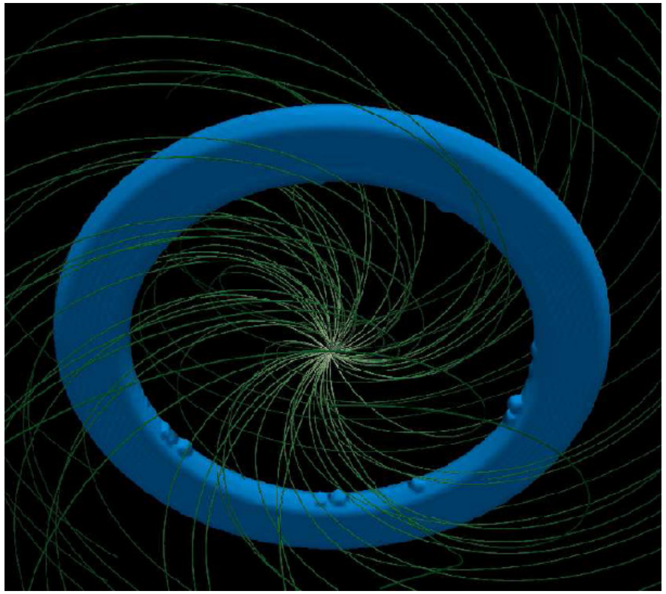
$$B_{ez} = \frac{(1-\xi)z}{h} B_e \exp(-x/h)$$

Polarization



ATCA 22 GHz (1.4 cm)
[Zanardo+ 2018]

colors: polarized intensity @22 GHz
contours: total intensity @44 GHz
lines: polarization vectors (B)



$$B_r = \frac{A_1}{r^2}, \qquad B_\phi = -\frac{A_2}{r}\sin\theta,$$

Take away

- Parker spiral has low tangential component of ***B***

Steps in 3D modeling

1. Numerical experiment
- Initial conditions (CSM, CSMF)
- 3D MHD simulations

2. Post-processing
- 3D distribution of relativistic electrons
  - spectrum at the shock $N(E)=K(n)E^{-[2a(t)+1]}$
  - evolution of the spectrum downstream
- 3D distribution of the random *dB [TBD]*
  - over the shock
  - evolution downstream
- 3D structures of the Stokes parameters *I,Q,U*

3. Synthesis of the observables
- Orientation of the remnant
- Faraday effect inside the SNR
- Integration along the line of sight

orientation vs the observer

Potter+ 2014

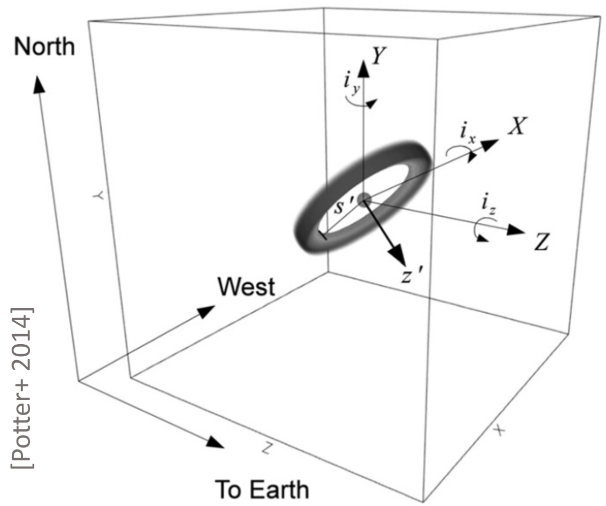
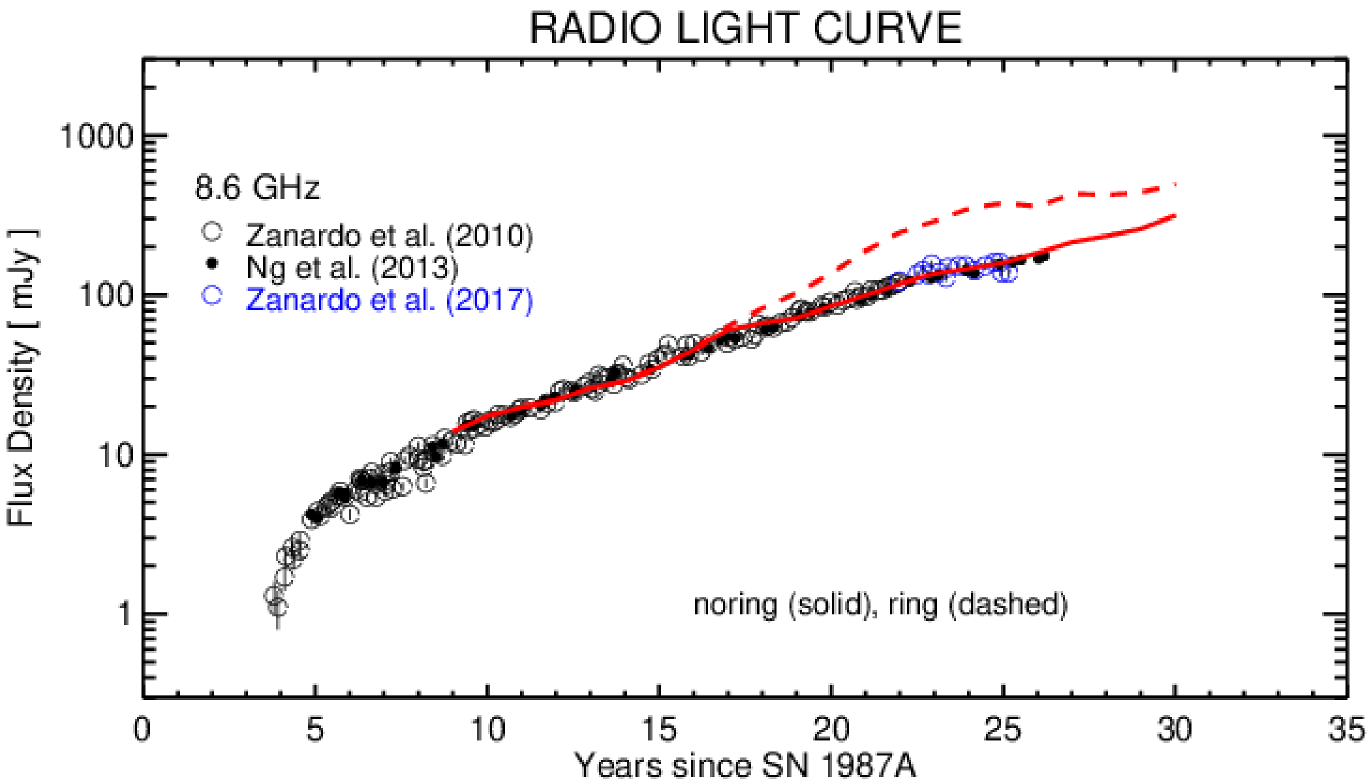


Figure 1. Cartoon of the equatorial ring showing the inclination of the environment at angles $i_x = 41°$, $i_y = -8°$, $i_z = -9°$. The rotated cylindrical coordinate system radial coordinate s' and vertical coordinate z' has z' parallel to the plane normal.

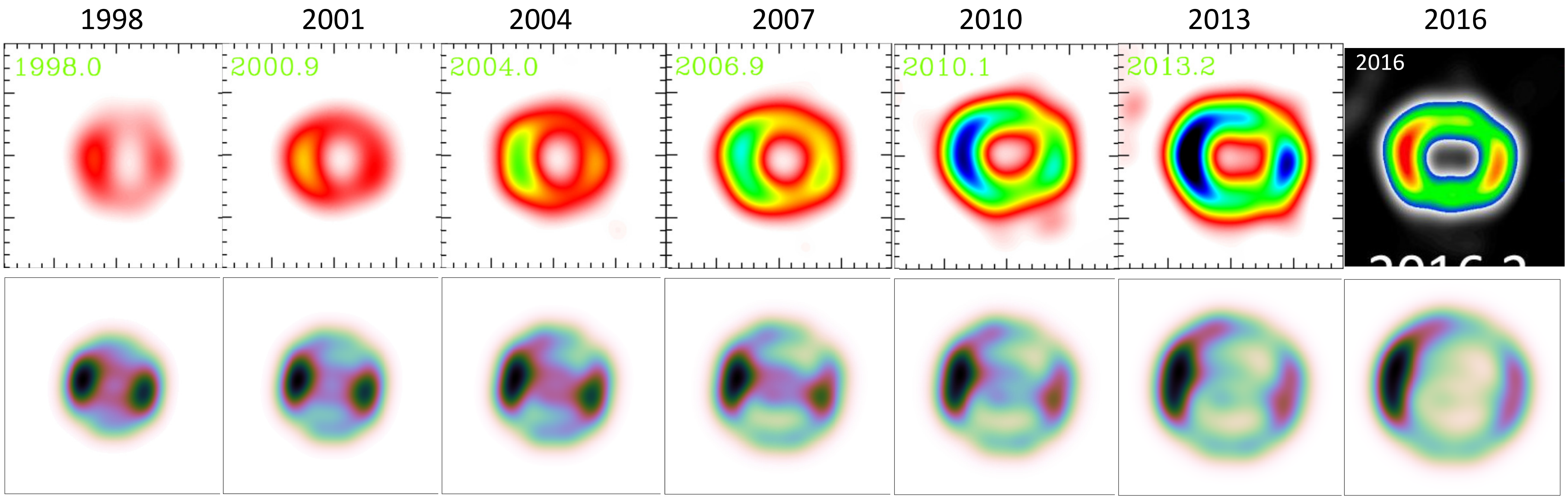
model vs observations: radio light curve



Equatorial ring
does not
contribute to the radio emission

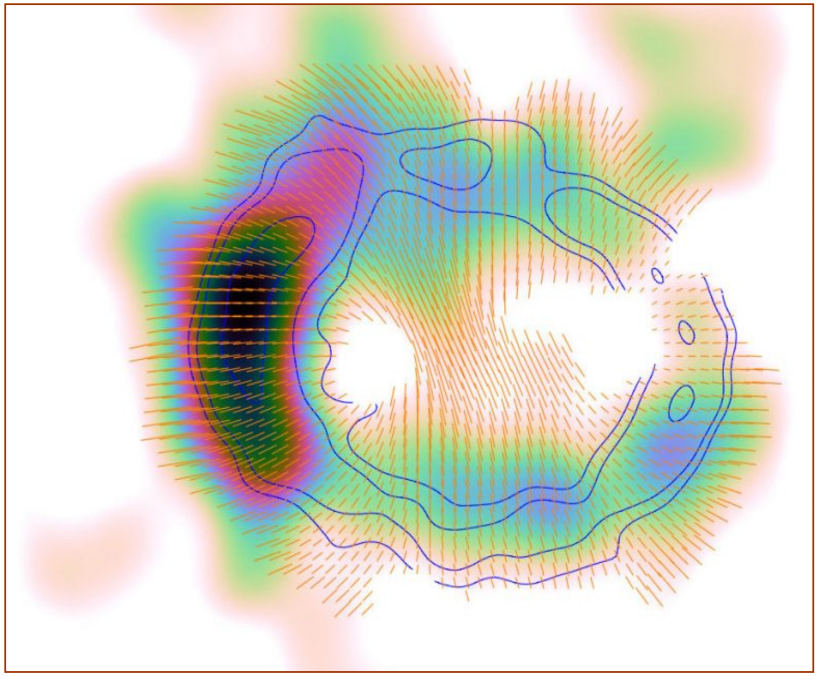
model vs observations: radio images

observations [Zanardo+ 2017; Cendes+ 2018]



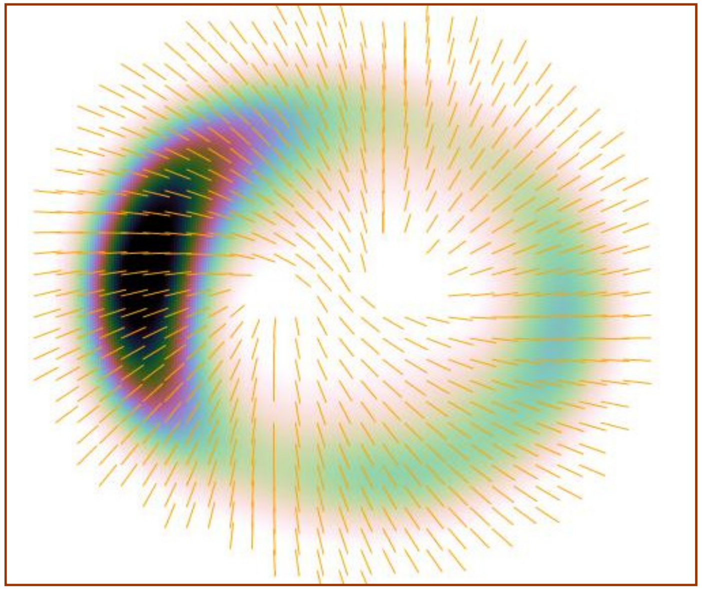
Asymmetry progresses

model vs observations: polarization



observations [Zanardo+ 2018]

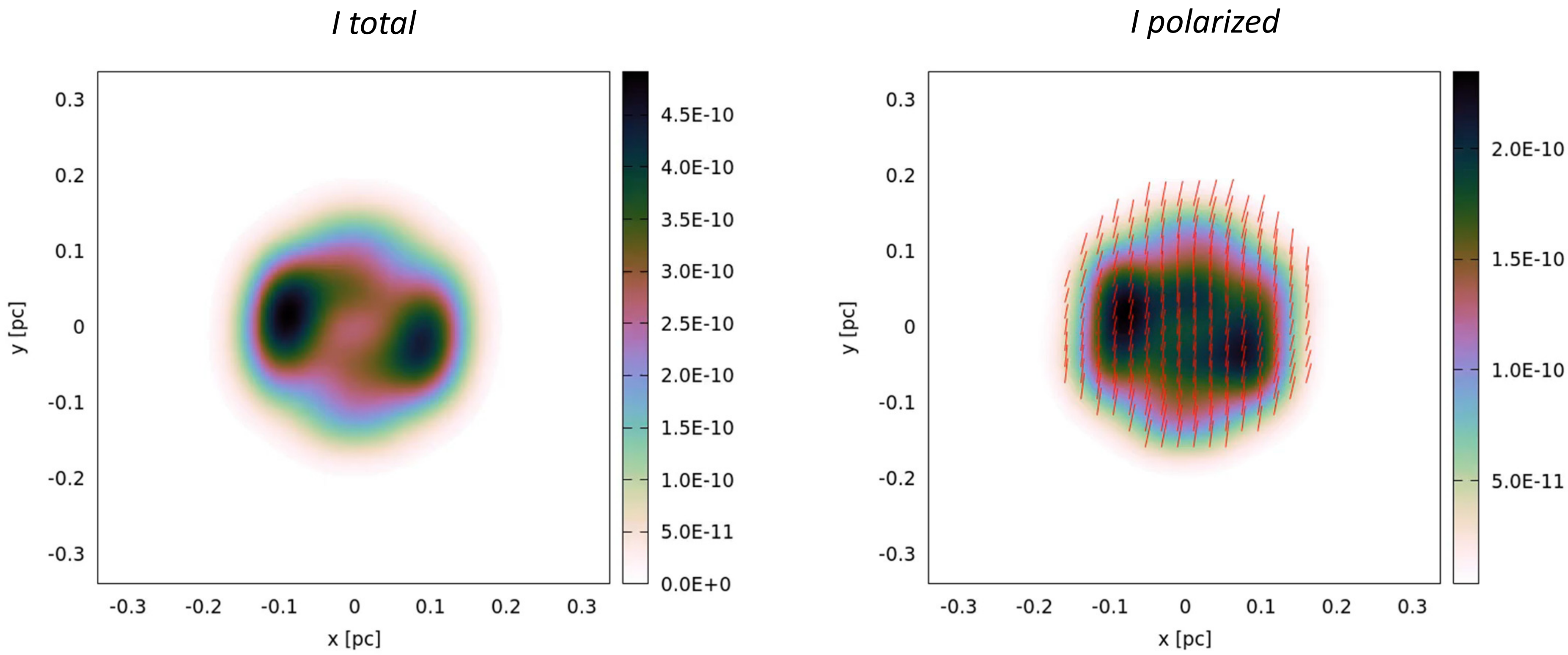
our model @ the year 2017



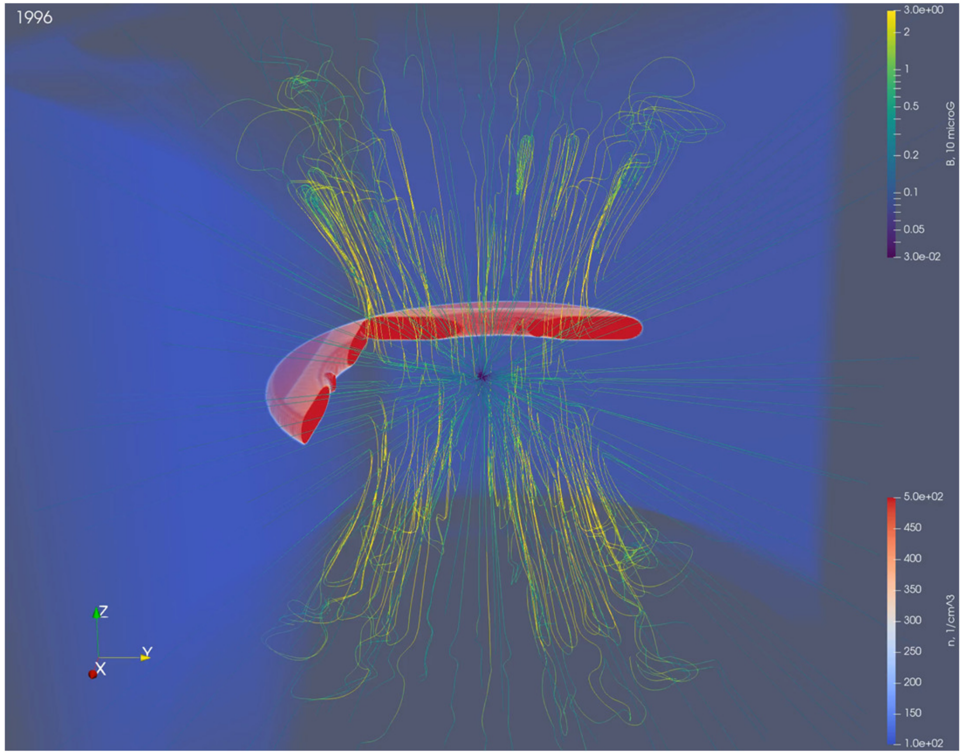
Exploration of the model

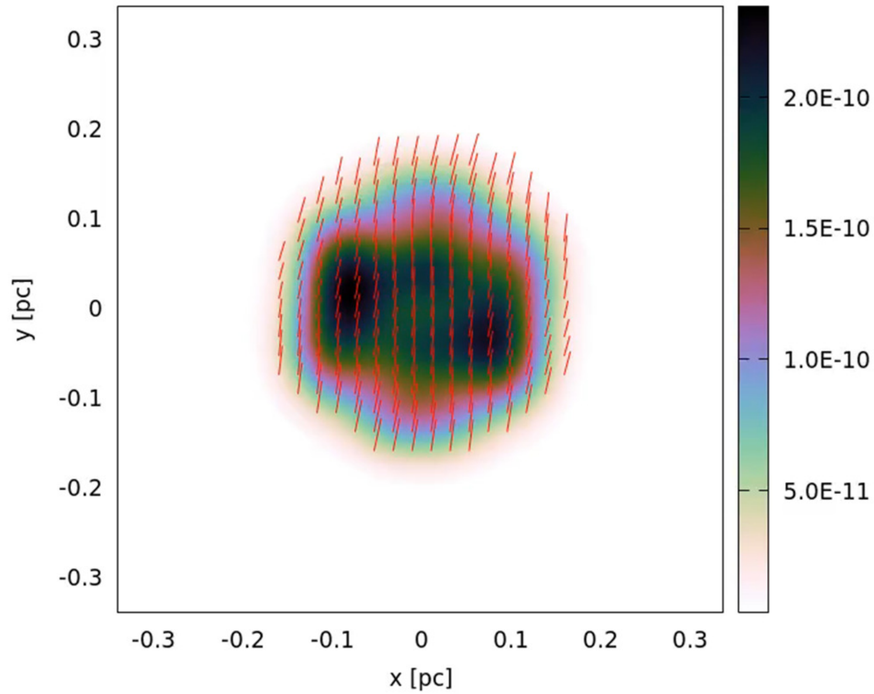
Evolution before and after 2017

Evolution of the polarized emission



Evolution of MHD structures

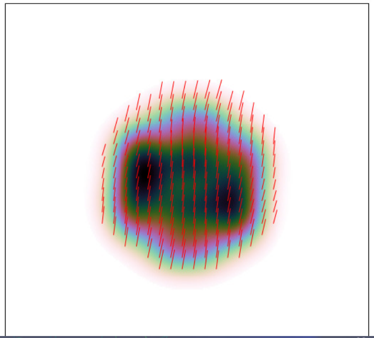


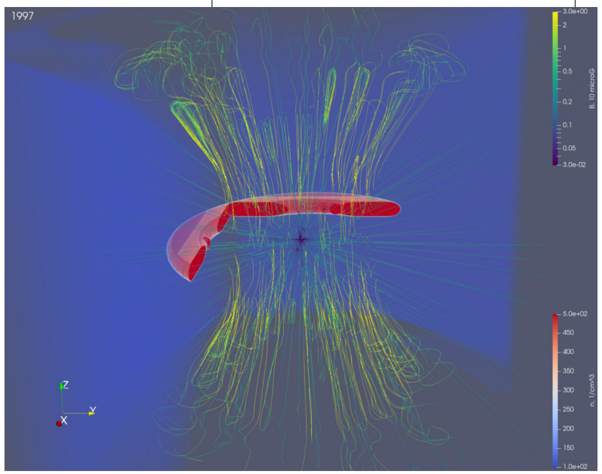


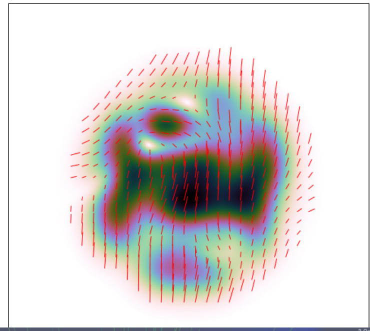
Three phases for the years 1996-2017

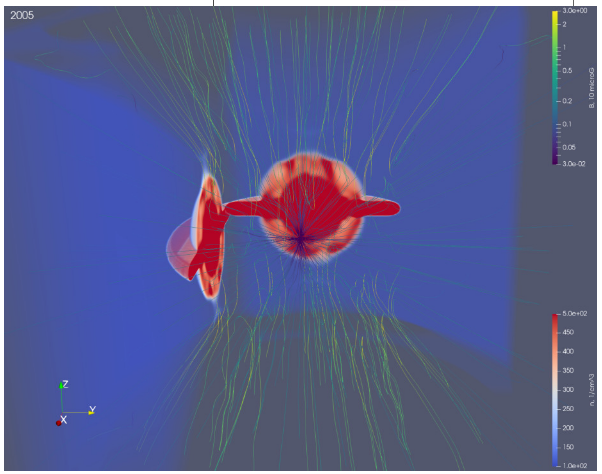
are clear from polarization maps (not so visible in the total intensity maps)

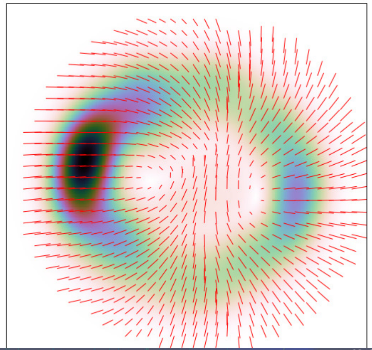
1. at the beginning of interaction with Hii region, MF lines are forced to align with the surface of Hii region
2. then the MF polarization directions change due to interactions with the CSM structures
3. and finally the polarized emission from Hii region dominates the pattern

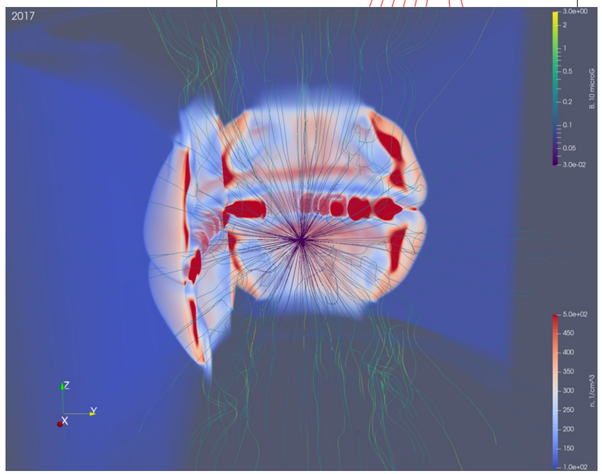




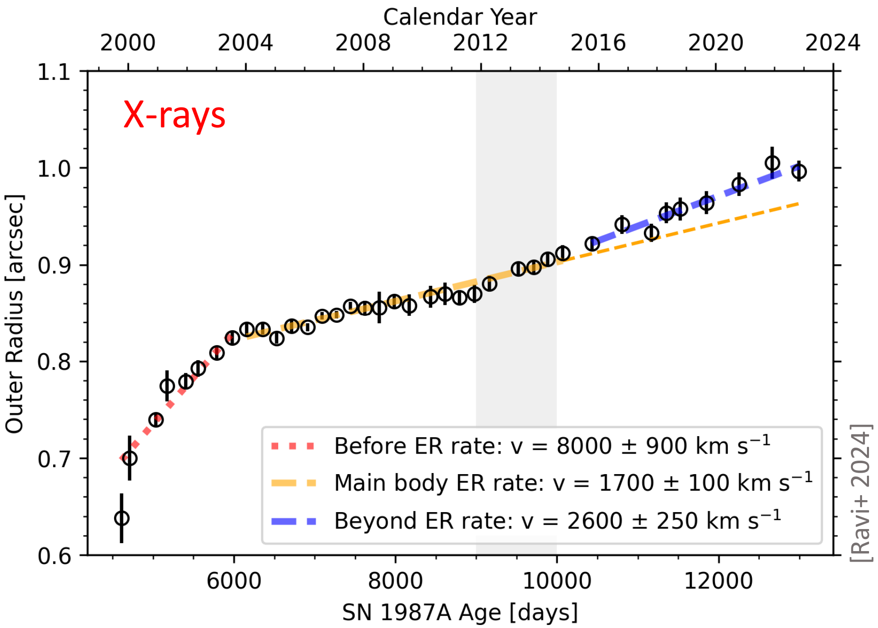




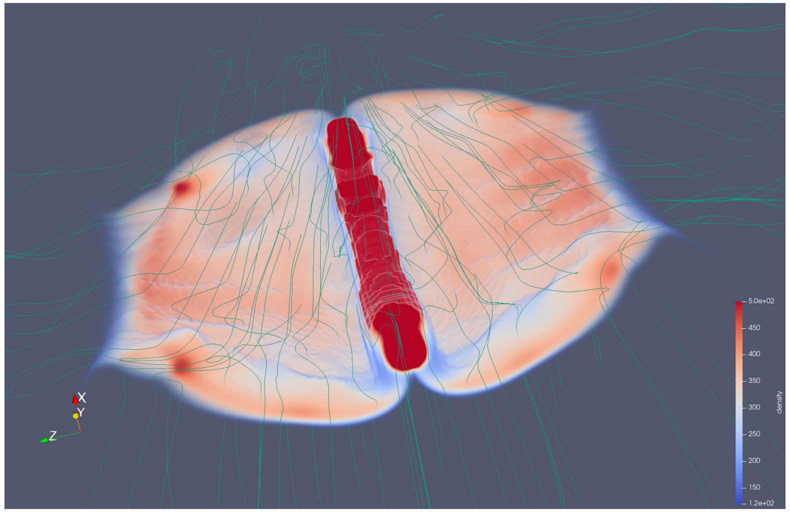




Evolution after 2017



Fragment of the shocked ISM @ 2014 in our model

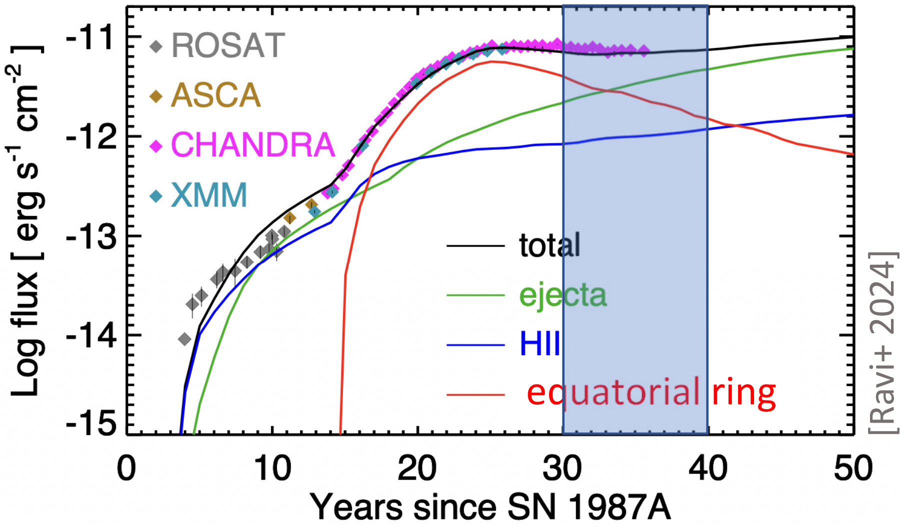


Shock runs around the ring

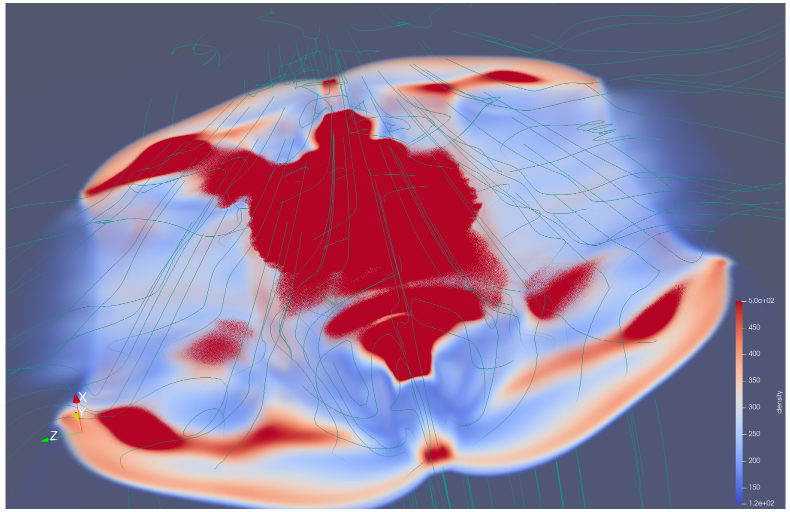
- Shock beyond the ring from 2012-2016 [Frank+ 2016, Larsson+ 2019]

Evolution after 2017

X-rays



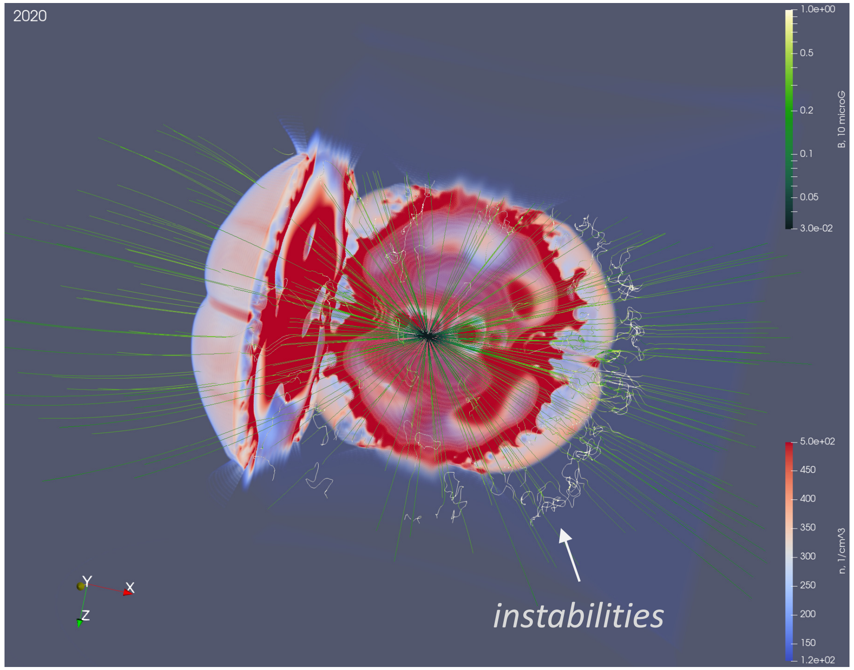
Fragment of the shocked ISM @ 2021 in our model

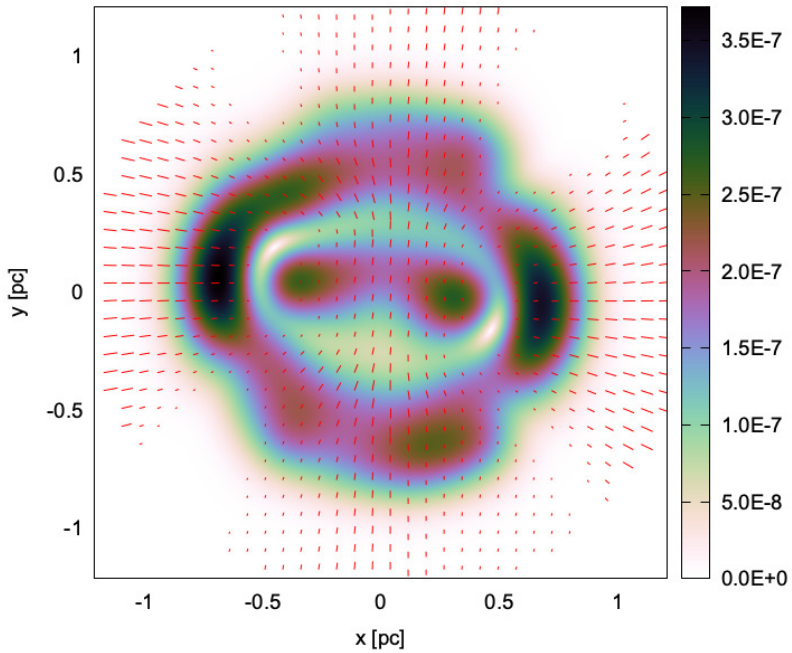


Ejecta touches the ring

- Shock beyond the ring from 2012-2016 [Frank+ 2016, Larsson+ 2019]
- Ejecta is expected to be dominant in X-rays in 2022-2027 [Orlando+ 2015]

Evolution after 2017





- Shock beyond the ring from 2012-2016 [Frank+ 2016, Larsson+ 2019]
- Ejecta is expected to be dominant in X-rays in 2022-2027 [Orlando+ 2015]
- Interaction of ejecta with the shocked Hii material and equatorial ring -->
  effect from newly generated instabilities could be visible in polarization pattern

Conclusions

- A tool and an MHD model to synthesize the polarization maps

- EW asymmetry due to a gradient of MF strength in CSM (*h~0.23 pc*)

- Low tangential *B* (NB: at the location of the shock at 2017)

- Three stages in MF evolution to 2017

- The ejecta is starting to interact with the equatorial ring
  This could be reflected in the polarization maps

- The radio evolution is quite important for the history of the progenitor, in particular for the history of its wind and rotation