The jet-torus structure of Pulsar Wind Nebulae: relativistic MHD simulations

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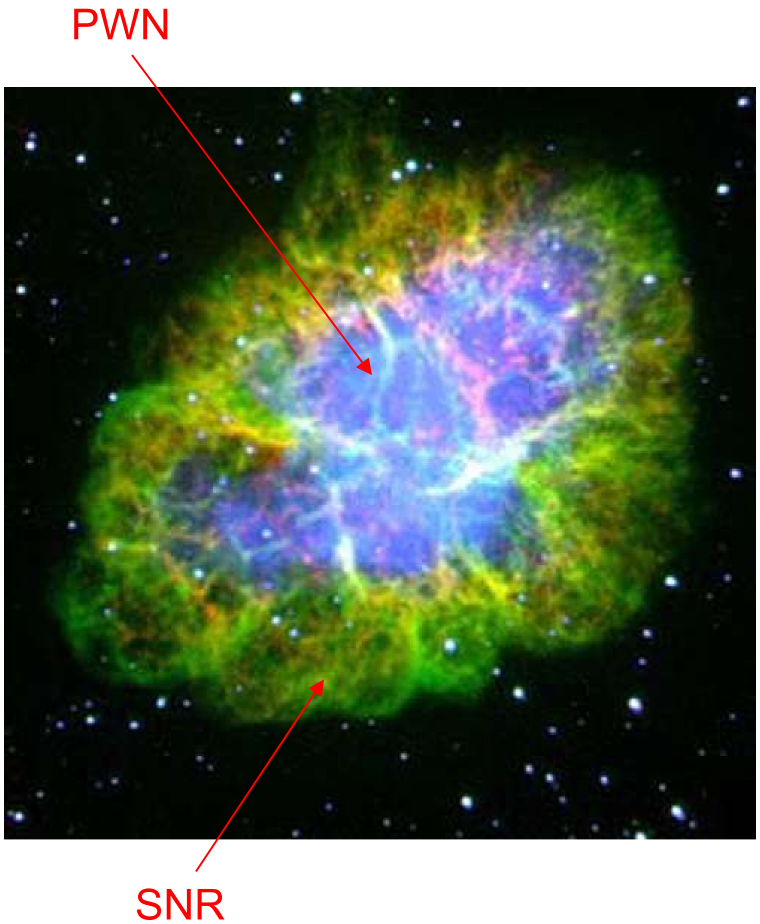
Outline

- Pulsar Wind Nebulae in Supernova Remnants
  - Observations
  - Models (analytical, numerical)
- PWN inner jet-torus structure
  - Observations
  - Theoretical background
- PWN/SNR 2-D axisymmetric RMHD simulations
  - Overall dynamics, jet formation
  - Synchrotron emission and comparison with observations
- Summary and conclusions

Papers on PWNe by our team

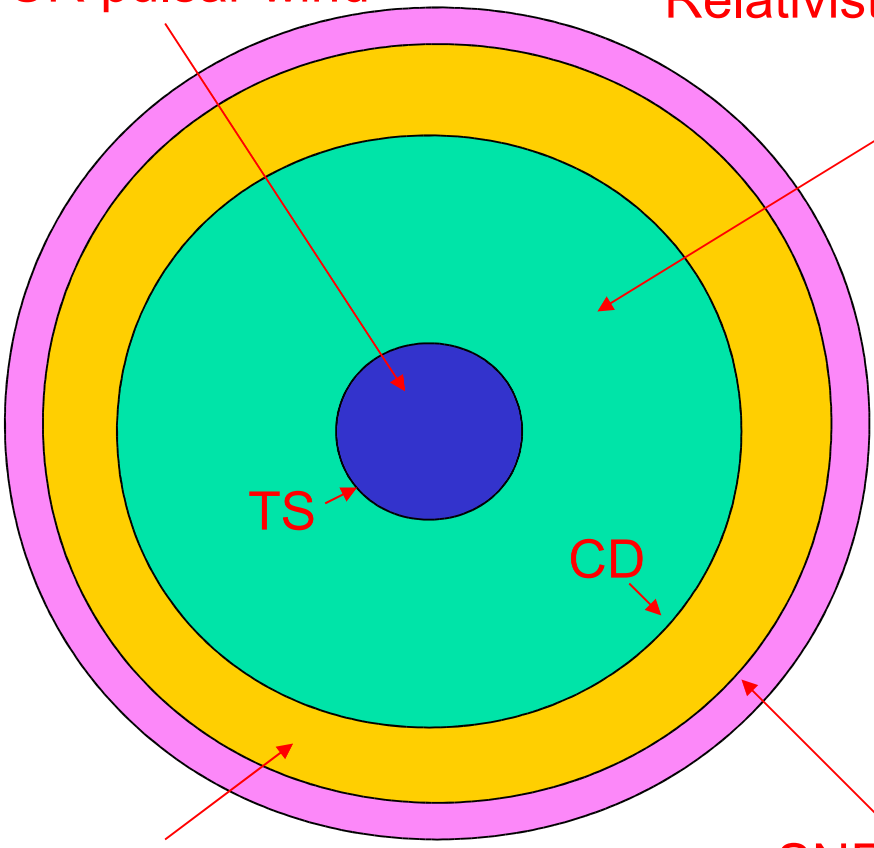
- Jet-torus in PWNe: synchrotron and polarization maps
  - Del Zanna, Volpi, Amato, Bucciantini, *in preparation*
  - Bucciantini, Del Zanna, Amato, Volpi, 2005, A&A, *submitted*
- Bow-shock PWNe
  - Bucciantini, Amato, Del Zanna, 2005, A&A, 434, 209
- Rayleigh-Taylor instabilities (filaments)
  - Bucciantini, Amato, Bandiera, Blondin, Del Zanna, 2004, A&A, 423, 253
- 2-D PWN-SNR simulations: jet-torus structure
  - Del Zanna, Amato, Bucciantini, 2004, A&A, 421, 1063
- 1-D PWN-SNR simulations
  - Bucciantini, Bandiera, Blondin, Amato, Del Zanna, A&A, 2004, 422, 609
  - Bucciantini, Blondin, Del Zanna, Amato, 2003, A&A, 405, 617
- RHD and RMHD numerical code
  - Del Zanna, Bucciantini, Londrillo, 2003, A&A, 400, 397
  - Del Zanna, Bucciantini, 2002, A&A, 390, 1177

Pulsar Wind Nebulae



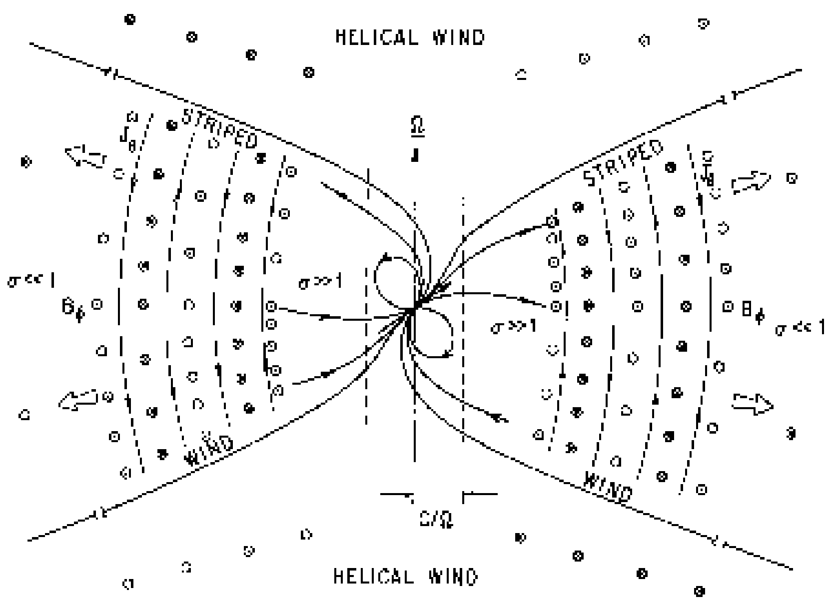
- PWNe (plerions) are hot bubbles emitting non-thermal radiation (synchrotron) at all wavelengths: require injection of relativistic particles and magnetic fields
- Originated by the interaction of the ultra-relativistic magnetized pulsar wind with the expanding SNR dense ejecta
- Crab Nebula in optical: central amorphous mass (continuum) + external filaments (lines)

Sketch of PWN / SNR interaction



- The SNR consists of a blast wave expanding in the ISM and by dense ejecta
- If an ultrarelativistic pulsar wind is present, a plerion forms inside the SNR

Pulsar magnetosphere and wind



Coroniti, 1990

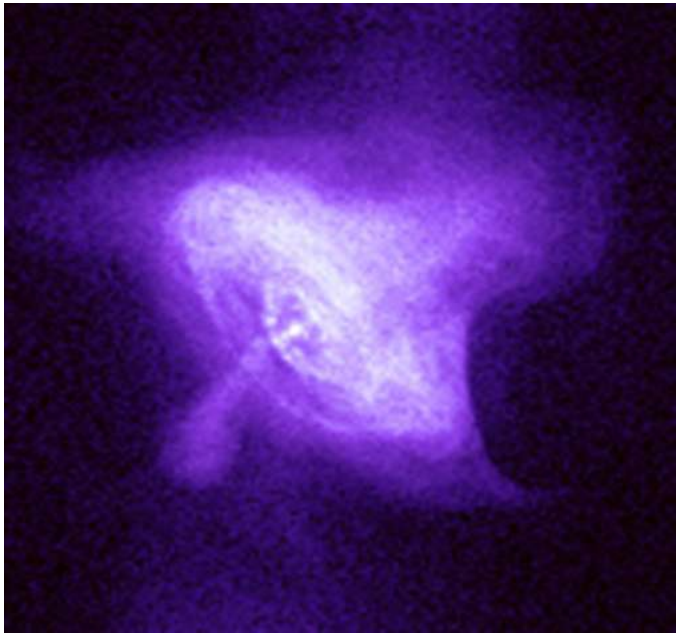
- Pulsar spin-down energy is converted to Poynting flux (mainly a toroidal field) and in a pair wind (with $\sigma >> 1$)
- At the TS models predict $\sigma << 1$ to match the observed synchrotron emission: the *sigma paradox*!
- *Striped wind*: the magnetic field may decrease because of equatorial reconnection or dissipation of fast waves at TS

PWN analytical MHD theory (KC84)

- PWN theory was mainly based on 1-D analytic (*Rees & Gunn 1974; Kennel & Coroniti, 1984*) and self-similar (*Emmering & Chevalier, 1987*) MHD models
- KC84 (spherically symmetric, stationary):
  - assume that the wind terminates with a strong MHD shock
  - solve the relativistic jump conditions at TS
  - solve the equations in the PWN region
  - calculate the synchrotron emission
  - a best fit analysis provides the wind parameters:

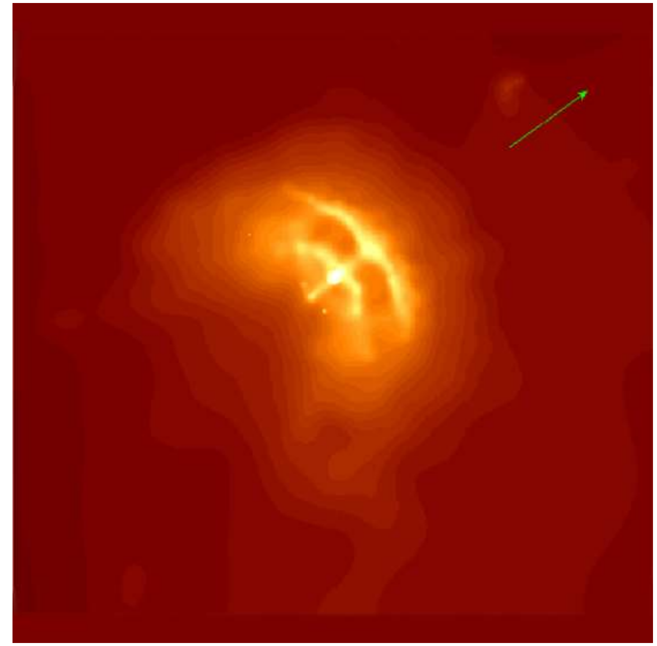
$$R_{TS} = 3\times 10^{17}\,cm, \quad L = 5\times 10^{38}\,erg/s, \quad \gamma = 3\times 10^{6}, \quad \sigma = 3\times 10^{-3}$$

Jet-torus structure: Chandra X-ray images



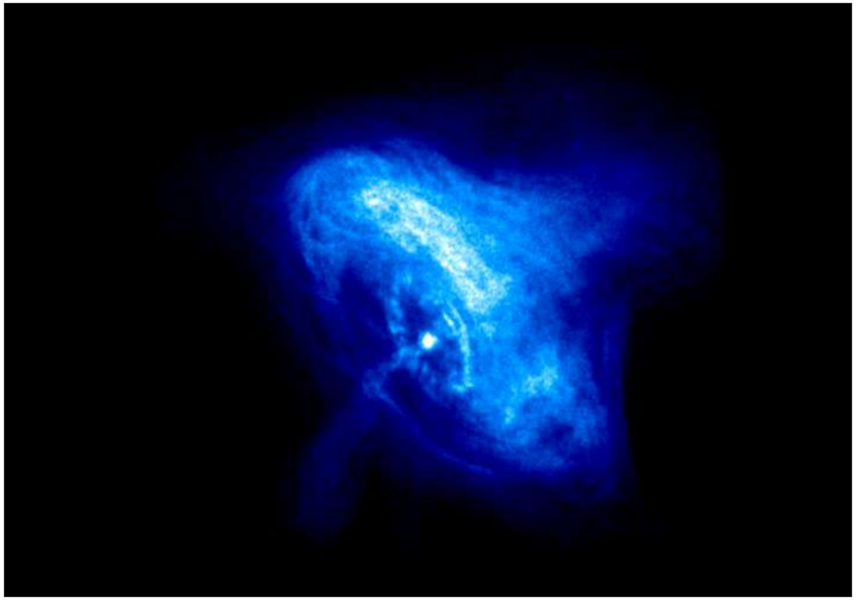
Crab

Vela

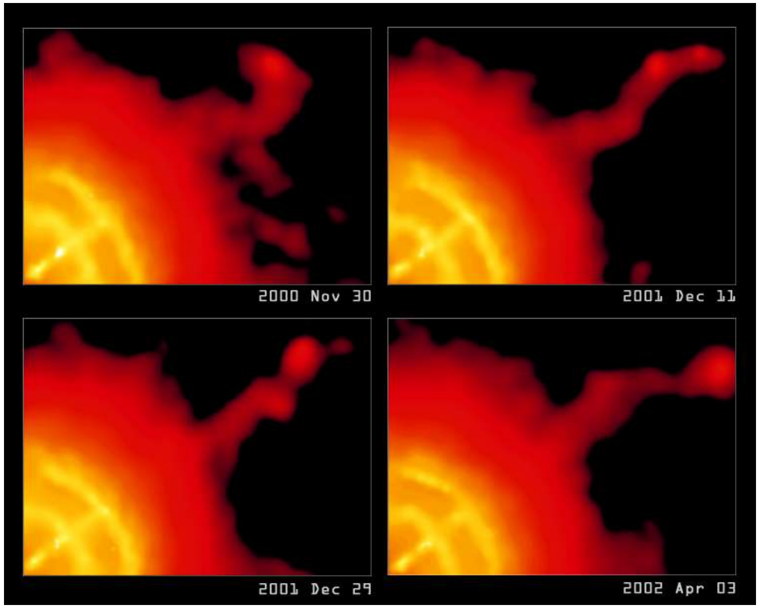


- Crab nebula (*Weisskopf et al., 2000; Hester et al., 2002*)
- Vela pulsar (*Helfand et al., 2001; Pavlov et al., 2003*)
- Other objects: PSR 1509-58, G0.9+01, G54.1+0.3

Jet-torus structure: relativistic motions



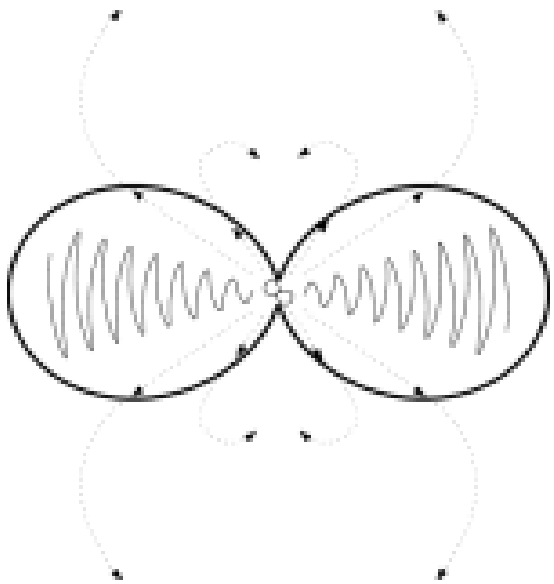
Crab



Vela

- Equatorial motions (wisps): v=0.3-0.5 c
- Polar jet motions: v=0.5-0.8 c

Jet-torus structure: theory



- Torus: higher equatorial energy flux
- Jets: magnetic collimation. But in PW:

$$\gamma > 1 \Rightarrow \rho_q E + j \times B \approx 0$$

  collimation downstream of the TS?
  - *Bogovalov & Khangoulian, 2002*
  - *Lyubarsky, 2002*
- Axisymmetric RMHD simulations of the interaction of an anisotropic relativistic magnetized wind with SN ejecta
  - *Komissarov & Lyubarsky, 2003, 2004*
  - *Del Zanna, Amato & Bucciantini, 2004*

Axisymmetric relativistic wind model

- Far from the pulsar light cylinder the wind is expected to be ultrarelativistic, cold, and weakly magnetized. We assume:
  - Isotropic mass flux, anisotropic energy flux $(F \propto r^2 \rho \gamma^2 \propto \gamma)$:

$$\gamma(\theta) = \gamma_0[\alpha + (1-\alpha)\sin^2(\theta)]$$

  - Purely toroidal magnetic field (split monopole, Michel, 1973):

$$B(r,\theta) = B_0(r_0 / r)\sin(\theta)$$

  - Parameters of the wind model:

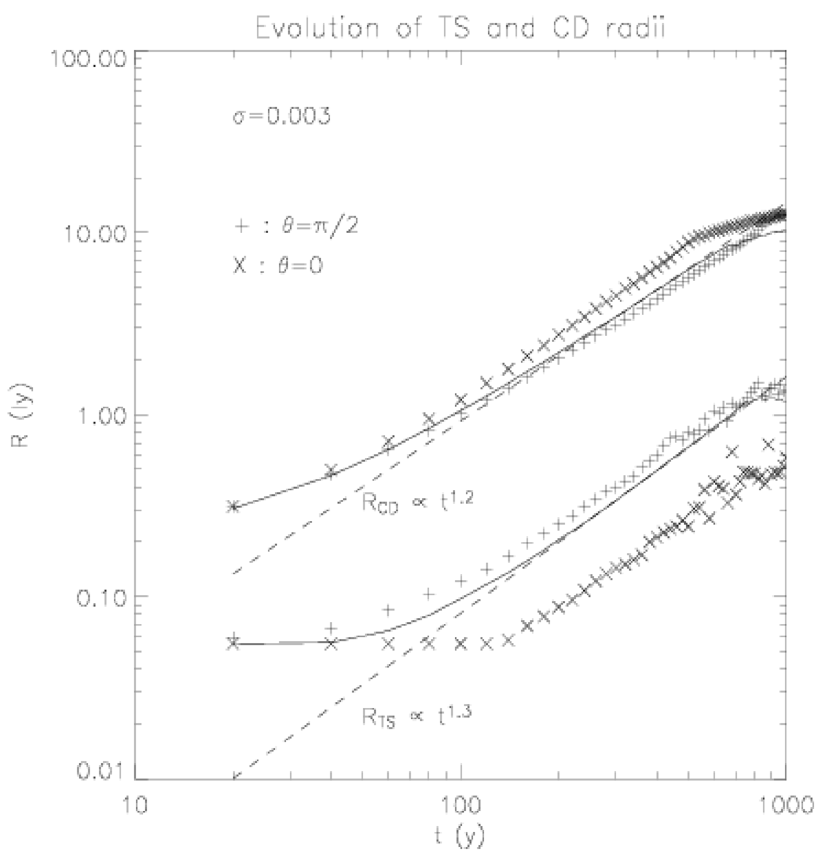
$$\gamma_0 > 1,\ \alpha = \frac{F(0)}{F(\pi/2)} < 1,\ \sigma = \frac{B_0^2}{4\pi c^2 \rho_0 \gamma_0^2} < 1$$

Simulation setup

- Central-type conservative RMHD code (HLL, second order)

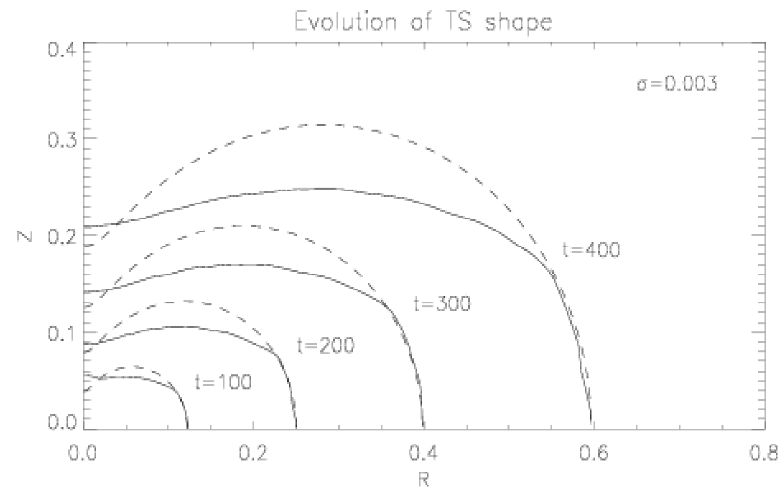
- Spherical geometry, axial symmetry (r,θ)
- Poloidal velocity and purely toroidal magnetic field
- Computational grid: 400 points in r, 100 in θ
- Boundaries: injection for r=0.05 ly, extrapolation for r=20 ly
- Long time simulations (beginning of reverberation phase)
- High accuracy near the center: extremely small timesteps!
- Initial conditions:
  - Pulsar ultrarelativistic wind
  - Spherical shell of expanding dense ejecta
  - Static unmagnetized ISM

PWN self-similar evolution and TS shape



- Expected TS profile:

$$R(\theta) \approx R_0 \sqrt{\alpha + (1-\alpha)\sin^2(\theta)}$$

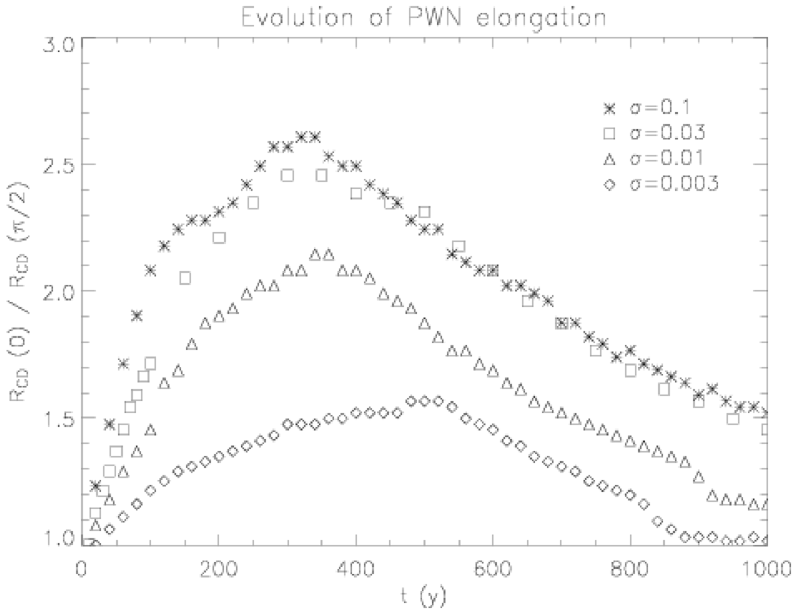


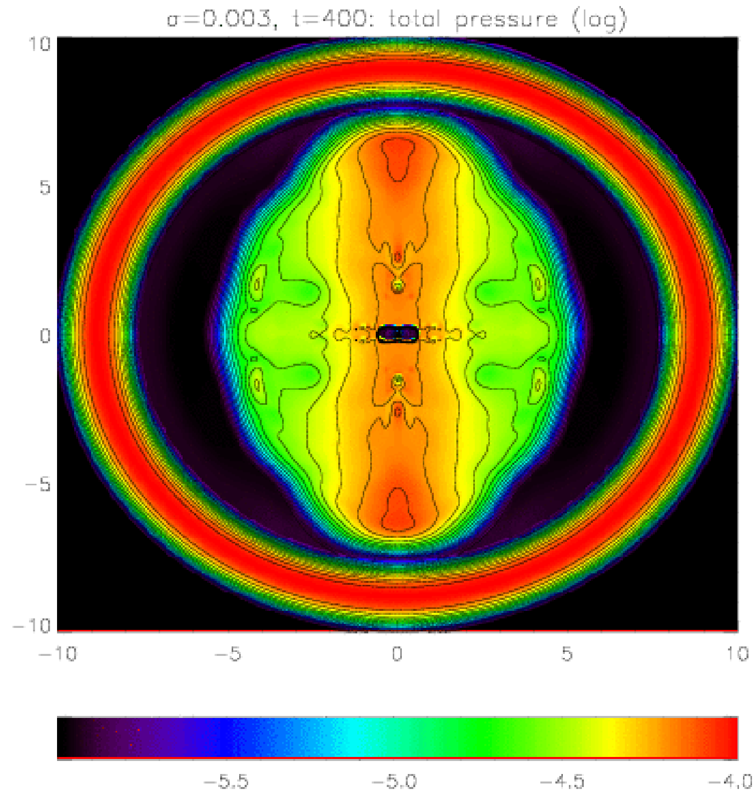
$$\gamma_0 = 100,\ \alpha = 0.1,\ \sigma = 0.003$$

PWN elongation

- Magnetic pinching effect (*Begelman & Li, 1992*):

$$\frac{\partial}{\partial z}\left(\frac{B^2}{8\pi}+P\right)\approx 0,\quad \frac{\partial}{\partial r}\left(\frac{B^2}{8\pi}+P\right)\approx -\frac{B^2}{4\pi r}$$

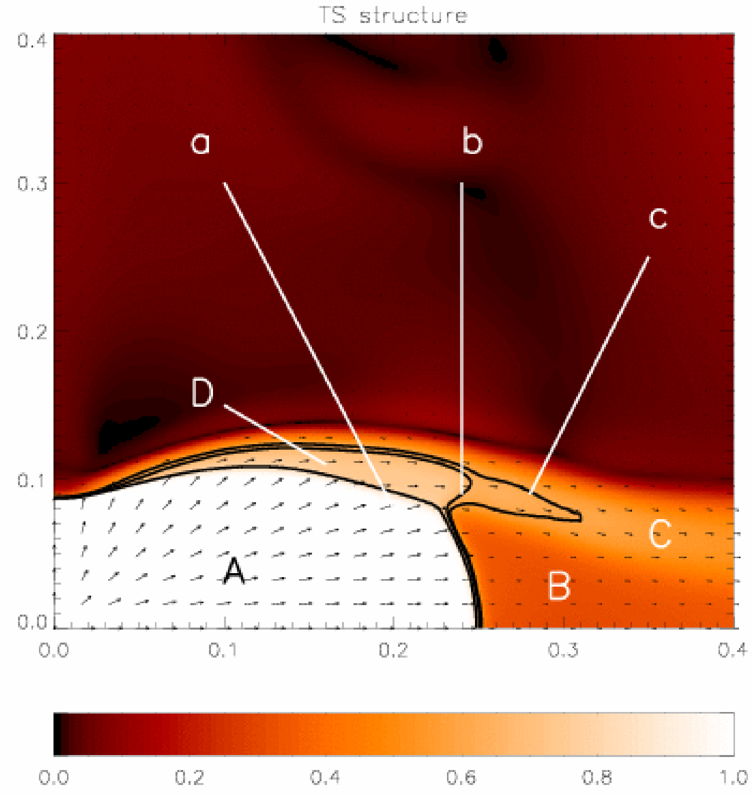




TS structure and flow pattern

- The wind anisotropy shapes the TS structure. A complex flow pattern arises:
  - A: ultrarelativistic pulsar wind
  - B: subsonic equatorial outflow
  - C: supersonic equatorial funnel
  - D: super-fastmagnetosonic flow
  - a: termination shock front
  - b: rim shock
  - c: fastmagnetosonic surface

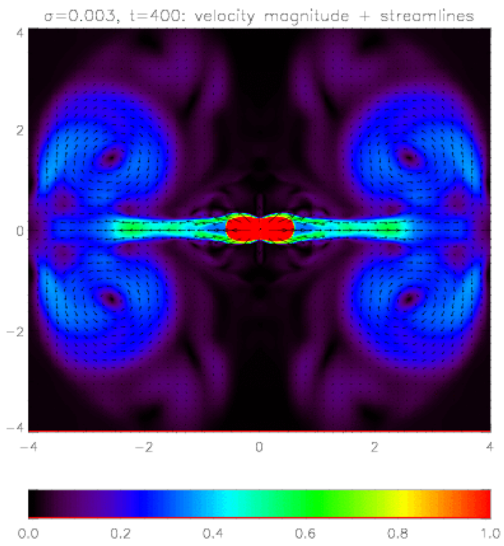
σ=0.003



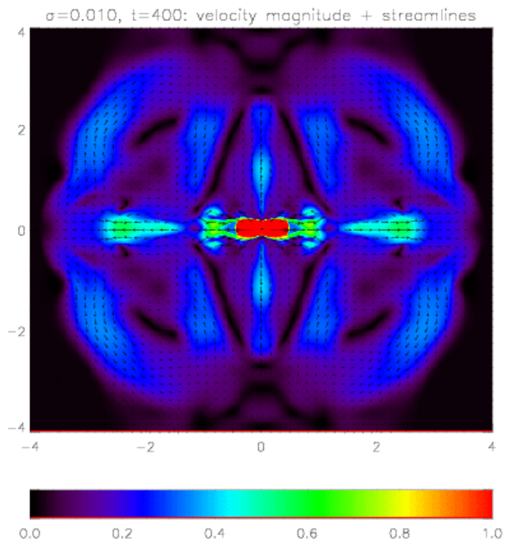
Formation of polar jets by hoop stresses

- The flow pattern changes drastically with increasing σ
- For high magnetization (σ>0.01) a supersonic jet is formed

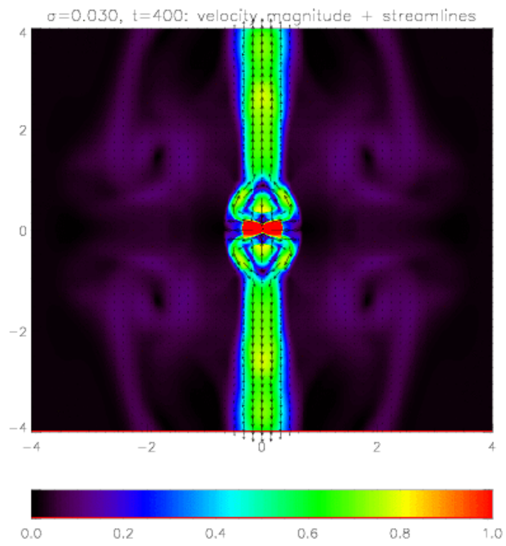
σ=0.003



σ=0.01



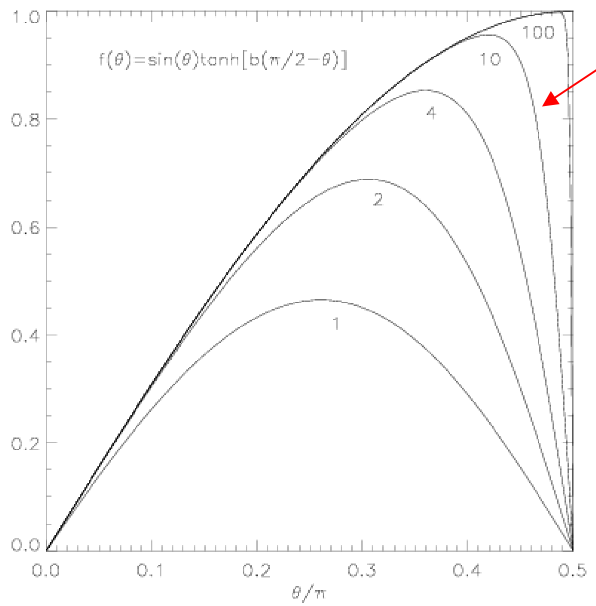
σ=0.03



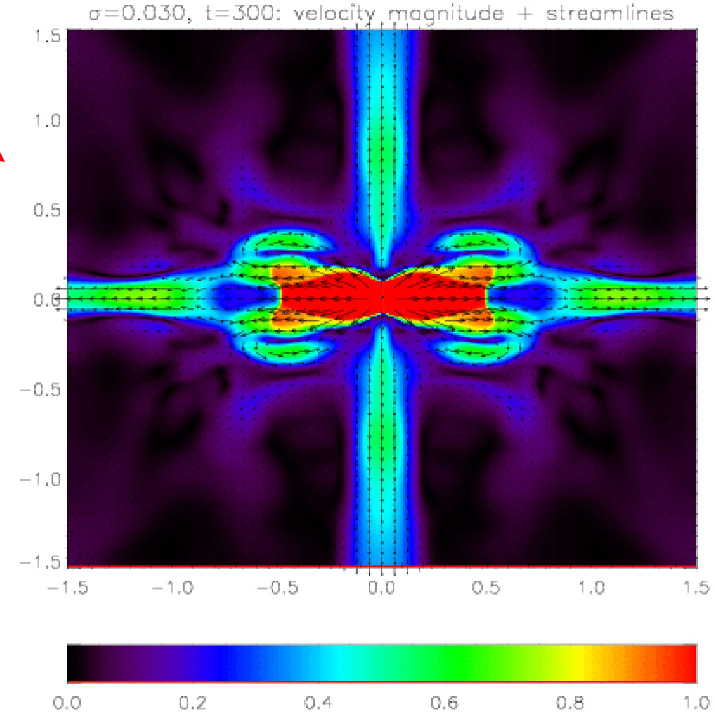
Dependence on the field shape

- Initial magnetic field with a narrow equatorial neutral sheet

$$B(r,\theta) = B_0\left(\frac{r_0}{r}\right)\sin(\theta)\ \underline{\tanh[b(\pi/2-\theta)]}$$



b=10



A model for synchrotron emission

- How to build synchrotron emission maps:
  - Assume a power law spectrum of electron energies at TS

$$f_0(\varepsilon_0) \propto p_0 \varepsilon_0^{-(2\alpha+1)}$$

  - Evolve the energy considering adiabatic and synchrotron losses

$$\frac{d\varepsilon}{dt'} = \varepsilon \frac{d}{dt'} \ln(\rho^{1/3}) - \frac{4e^4}{9m^3c^5}(B')^2\varepsilon^2$$

  - Assume emission at the critical frequency

$$\nu \propto B_\perp' \varepsilon^2$$

  - Calculate the spectral emissivity function in the observer frame

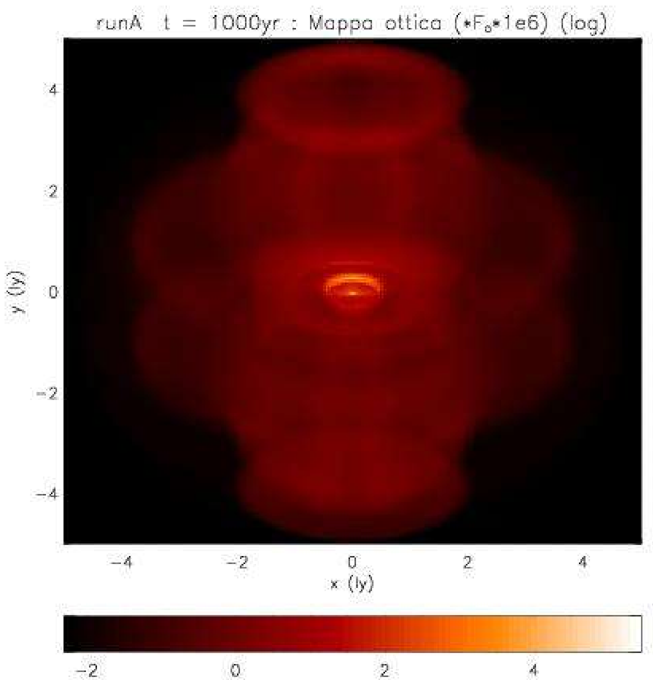
$$\boxed{j_\nu(\nu, \hat{n}) \propto \gamma D^{3+\alpha} p(B'_\perp)^{\alpha+1}[1-\varepsilon(\nu)/\varepsilon_\infty]^{2\alpha-1}\nu^{-\alpha}}$$

  - Obtain synthethic maps by integrating along the LOS

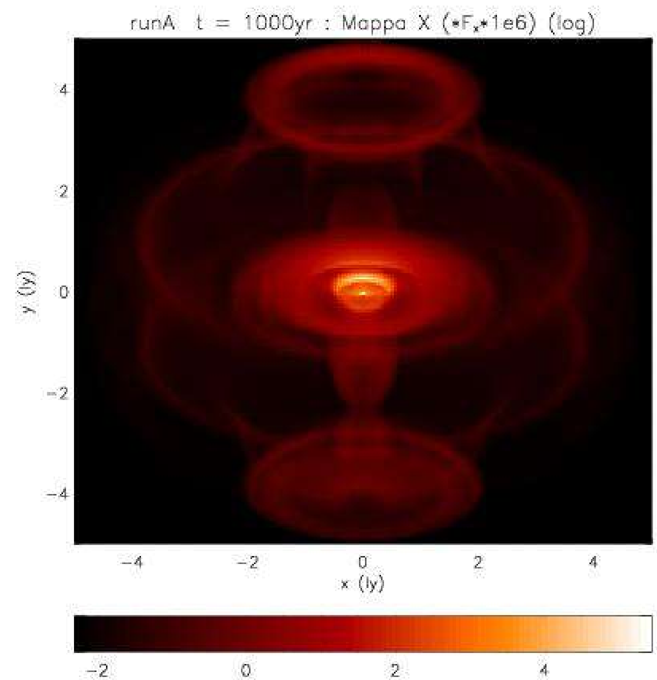
Comparison with observations: maps

- Effects of synchrotron losses: optical vs X-ray maps
  - Runs with expanding CD at given velocity and realistic luminosity

Optical



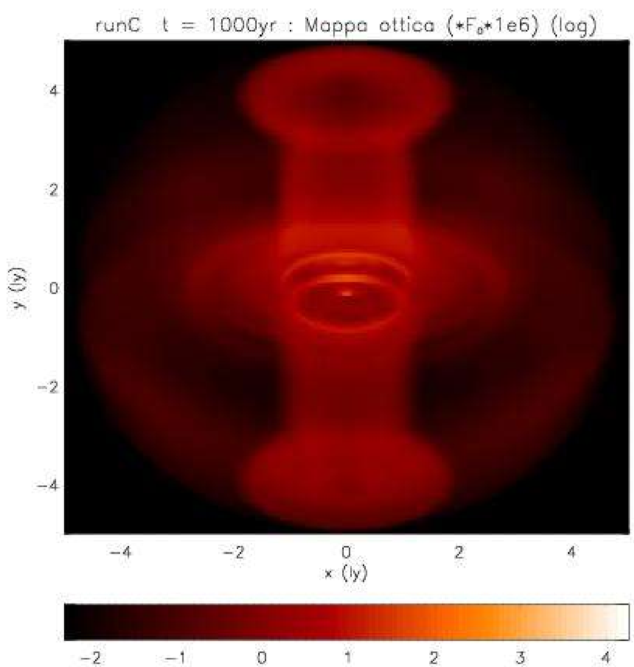
X-ray



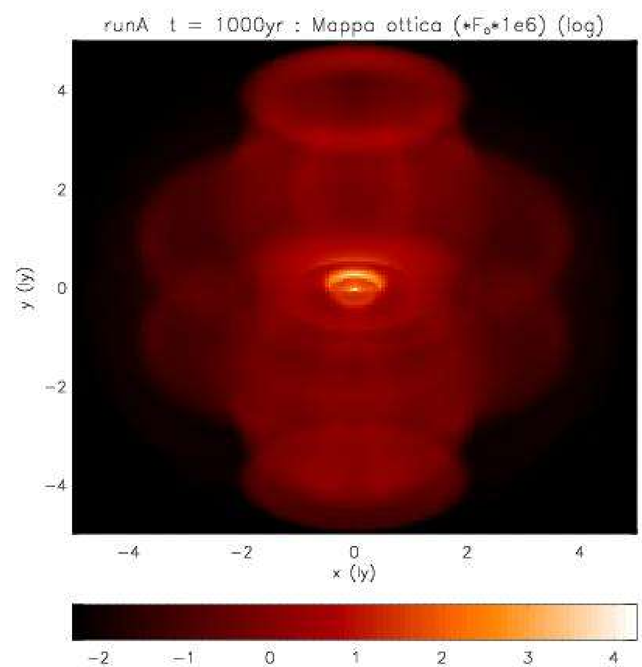
Comparison with observations: maps

- Constraining the field shape of the pulsar wind:
  - Runs with narrower *striped wind* region reproduce observations better

σ=0.03. b=1



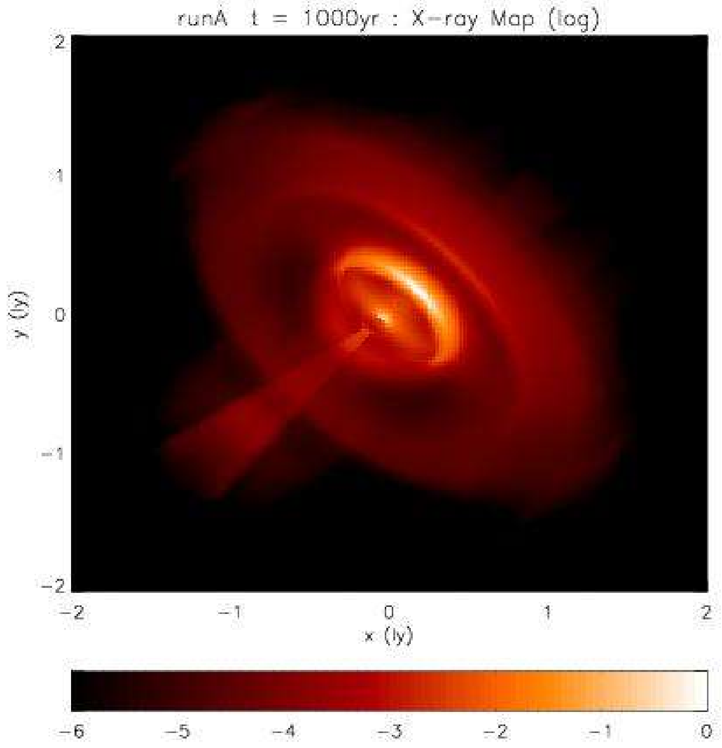
σ=0.03. b=10



Comparison with observations: maps

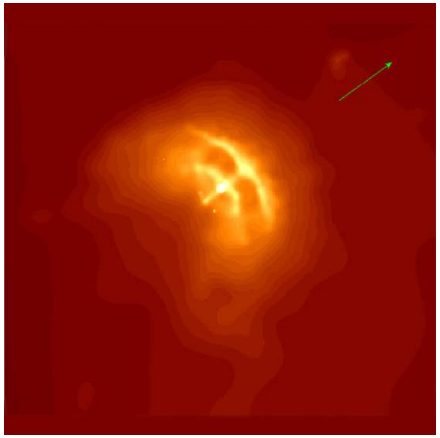
- Simulated X-ray maps vs Chandra images:

σ=0.03, b=10



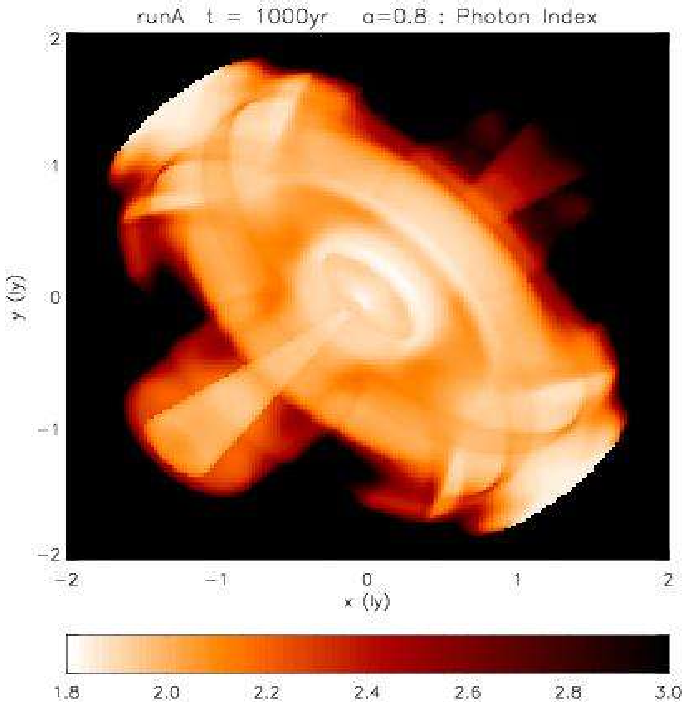
Crab

Vela

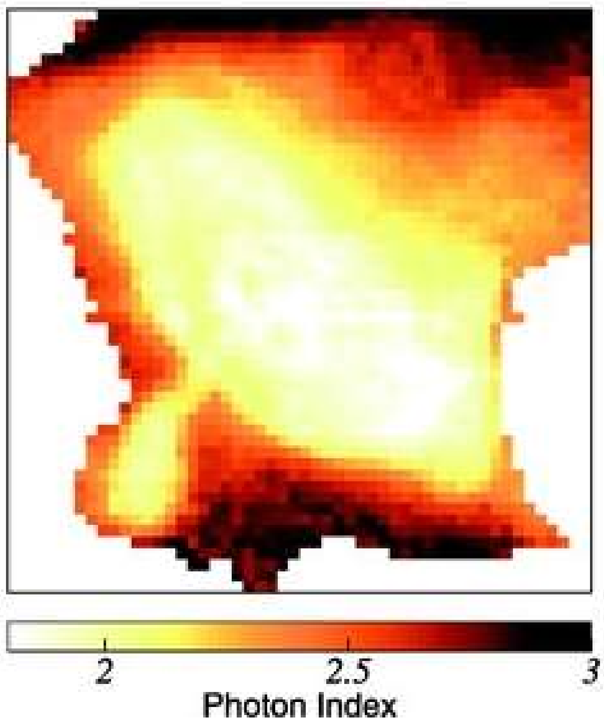


Comparison with observations: spectrum

- Synchrotron spectral index X-ray maps:



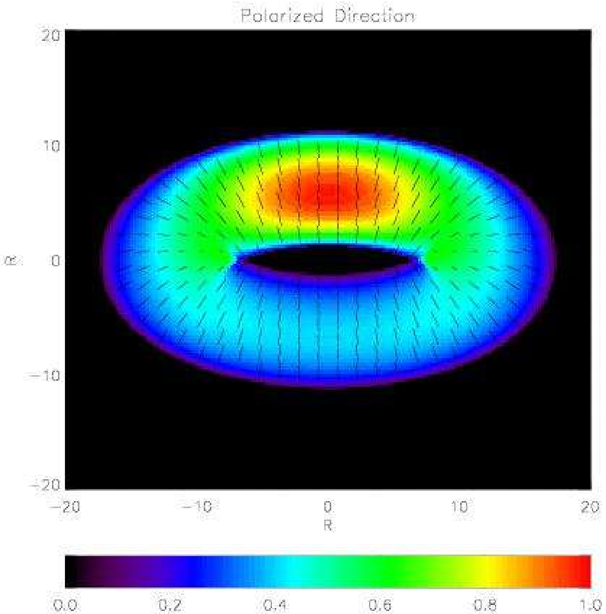
Mori et al., 2004



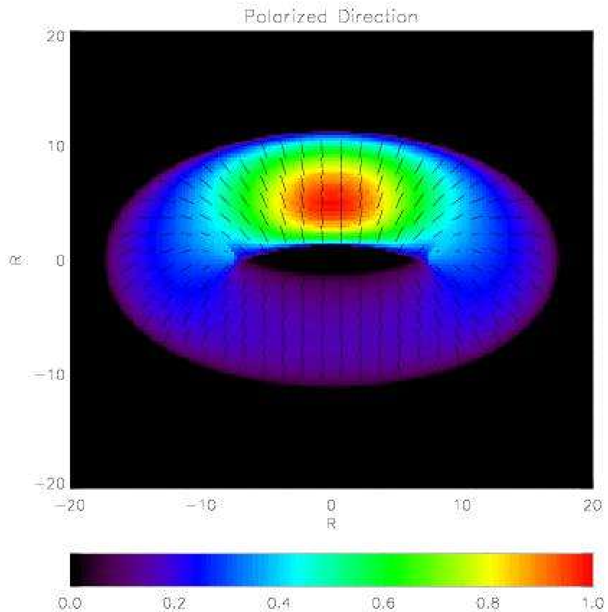
Comparison with observations: polarization

- Simulated optical high resolution polarization maps
  - A toy model first: uniform emitting torus

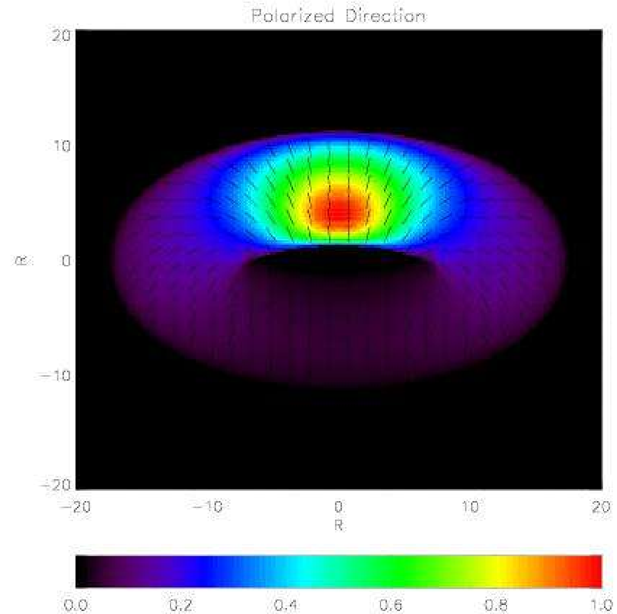
v=0.2c



v=0.4c

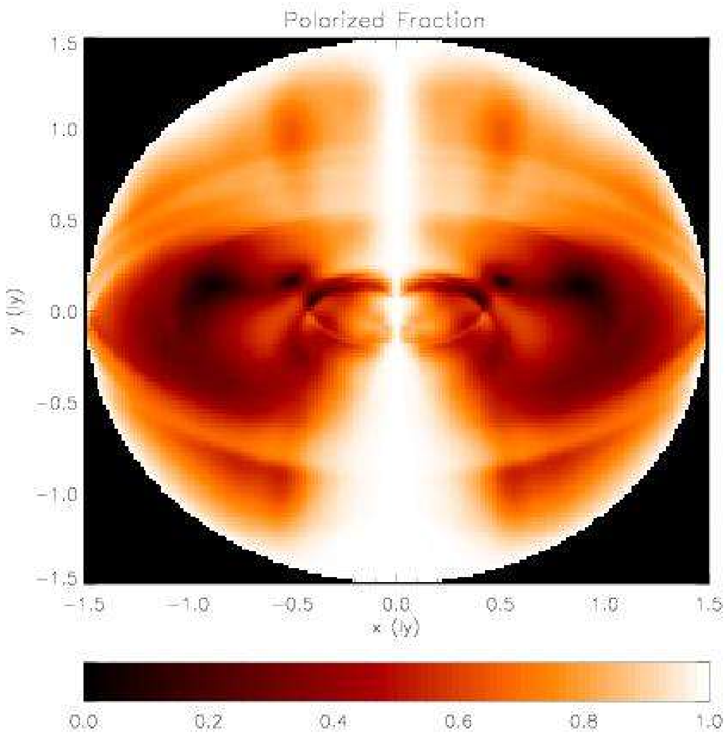


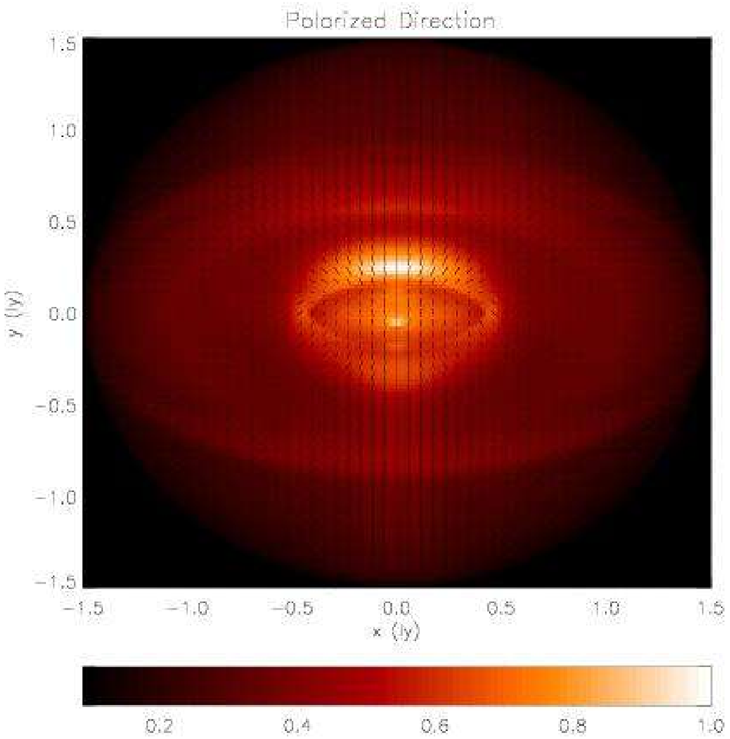
v=0.6c



Comparison with observations: polarization

- Simulated optical high resolution polarization maps
  - Results from the relativistic MHD simulations





Summary and conclusions

- Many PWNe show a jet-torus structure (Crab, Vela, …)
- The torus is explained with a higher equatorial energy flux
- Jet collimation forbidden in the wind. Inside PWN?
- RMHD axisymmetric simulations confirm this scenario:
  - The TS has a toroidal shape, a strong equatorial flow is produced
  - For $\sigma>0.01$ hoop stresses divert the flow toward the axis
  - Plasma is compressed and a polar jet with v=0.5-0.7c is launched
  - Simulated synchrotron maps resemble closely X-ray images
  - Work in progress: constraining B, spectra and polarization maps

Thank you