Relativistic MHD modeling of PWNe

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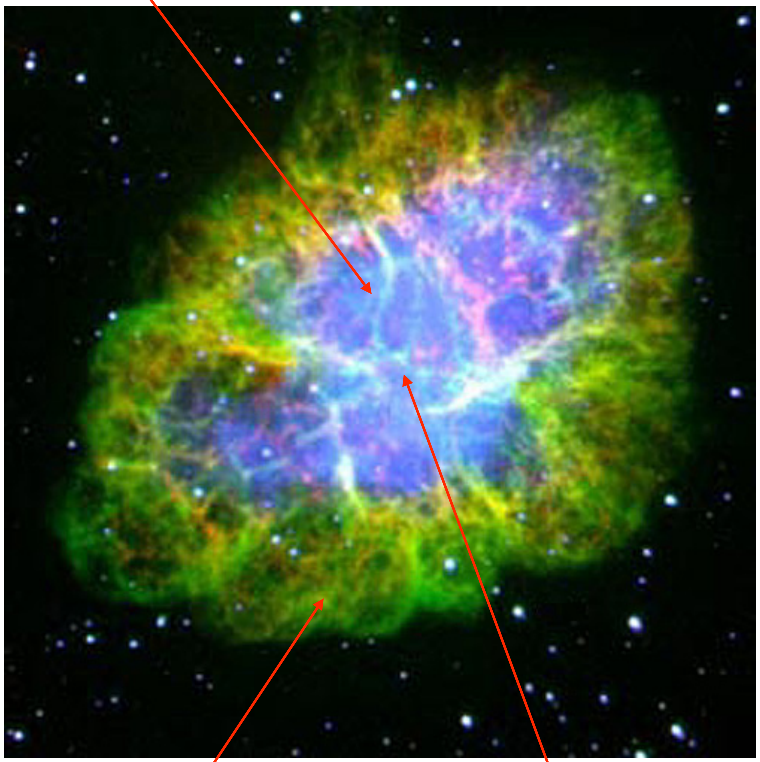
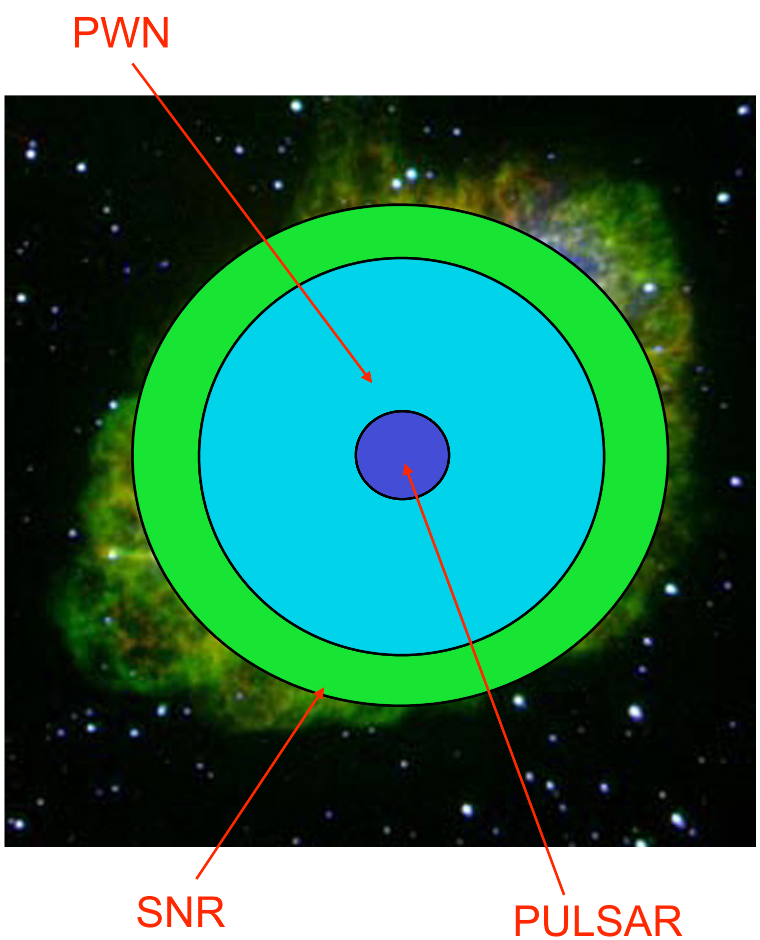
Pulsar Wind Nebulae



- PWNe are hot bubbles (plerions) of relativistic particles and magnetic field emitting non-thermal radiation (synchrotron - IC) from Radio to γ-ray.
- Originated by the interaction of the ultra-relativistic magnetized pulsar wind with the expanding SNR (or with the ISM)
- Crab Nebula in optical: central amorphous mass (continuum) + external filaments (lines)

Pulsar Wind Nebulae



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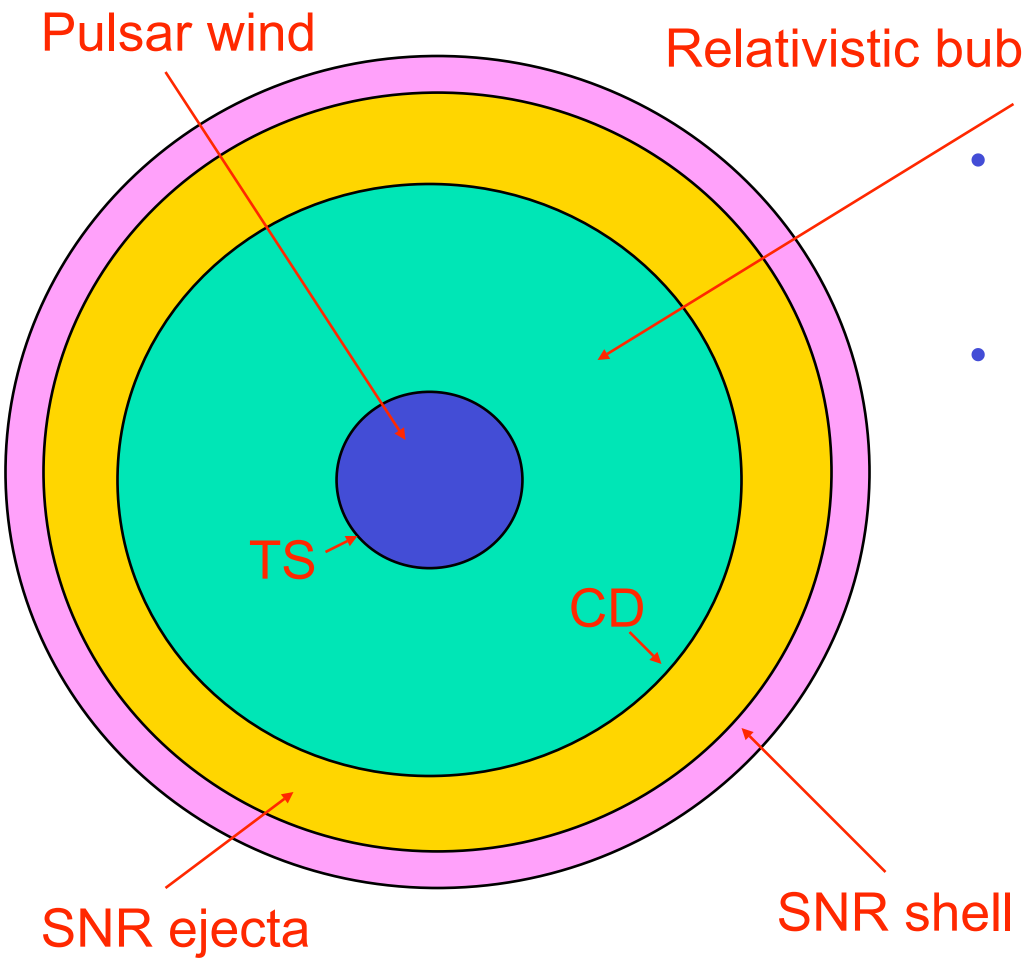
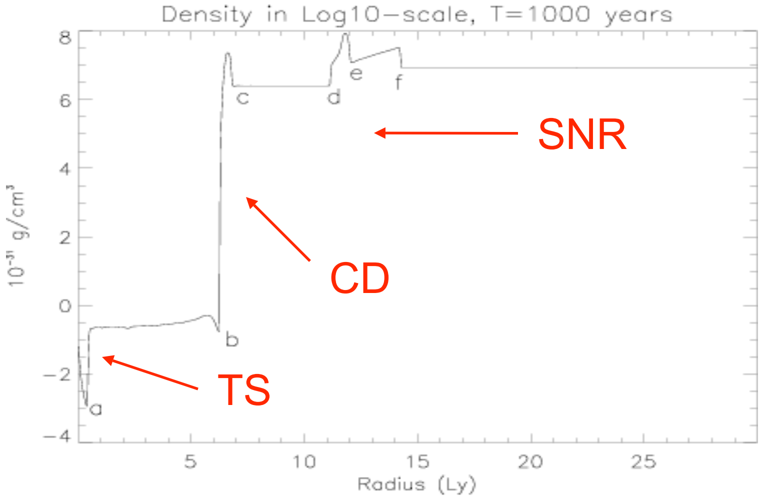
Sketch of PWN / SNR interaction



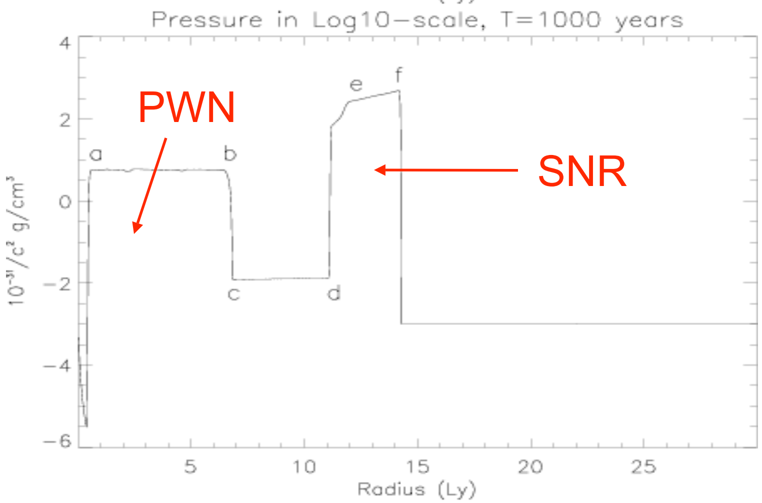
- The SNR consists of a blast wave expanding in the ISM and by ejecta in free expansion
- The ultrarelativistic magnetized pulsar wind inflate a plerion inside the SNR

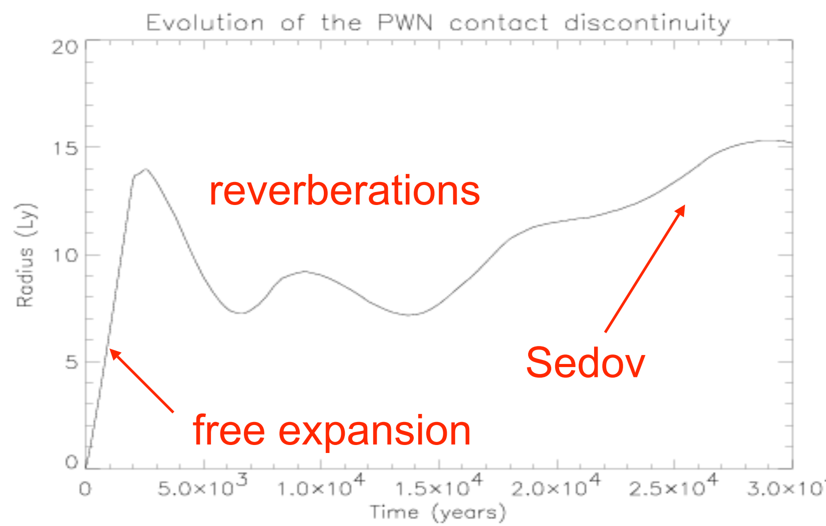
$$E_{snr} = 10^{51} \text{ erg}$$
$$E_{pw} = 10^{49} \text{ erg}$$

PWN-SNR: structure and evolution



- a: wind termination shock
- b: PWN-SNR contact discontinuity
- c: swept-up shell of ejecta ($r \propto t^{5/6}$)
- d: SNR reverse shock
- e: SNR contact discontinuity
- f: SNR forward shock





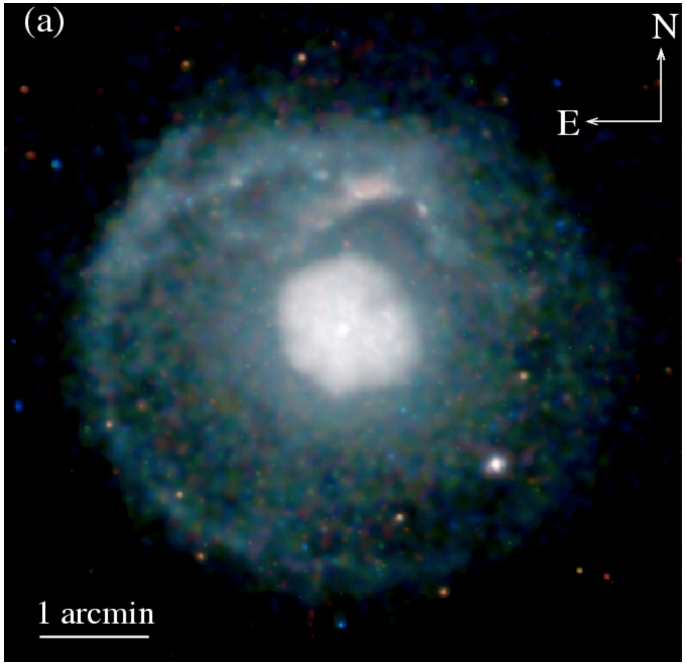
Evolution phases

- “Free expansion” - (Crab Nebula)
  - Duration T ~ 10^{3-4} yr
  - Evolution does not depend on PWN magnetization
  - Constant pulsar energy input - Emission at high energies
- Reverberation - (Vela ?)
  - T~10^4 yr
  - Instabilities in multi-D ; PSR displacement ; mixing
  - No pulsar energy input
  - Enhanced emission due to re-energization
- Sedov -
  - T ~ 10^5 yr
- Bow-Shock - interaction with the ISM

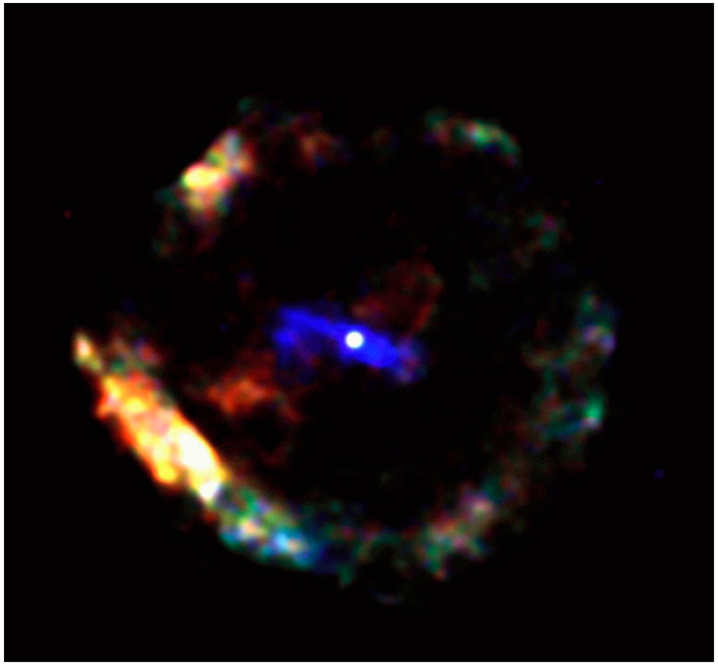
(van der Swaluw et al. 2001,2005; Bucciantini et al. 2003, 2005)

Phase I: Free Expansion into Ejecta

- Continuous energy injection - High synchrotron luminosity
- PWN expands supersonically, $R_{PWN} \propto t^{6/5}$
- Pulsar at the center of PWN



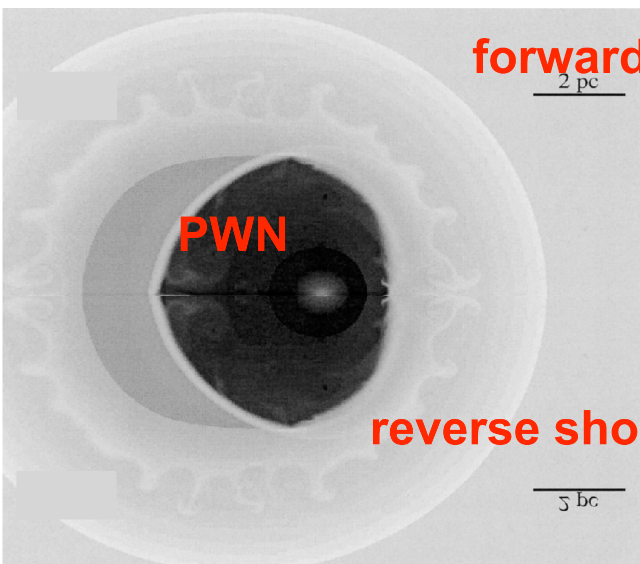
SNR G21.5-0.9 (X-rays)
Matheson & Safi-Harb 2005



SNR G11.2-0.3 (X-rays)
Kaspi et al. 2001

Phase II: Interaction with Reverse Shock

- Reverse interacts with PWN after time $t \sim 7 M_{10M_{sun}}^{5/6} E_{51}^{-1/2} n_0^{-1/3}$ kyr
- Compression; synchrotron burn-off at high energies
- Effects of inhomogeneous ISM
- Offset pulsar; filamentary structure; mixing



van der Swaluw et al. (2004)

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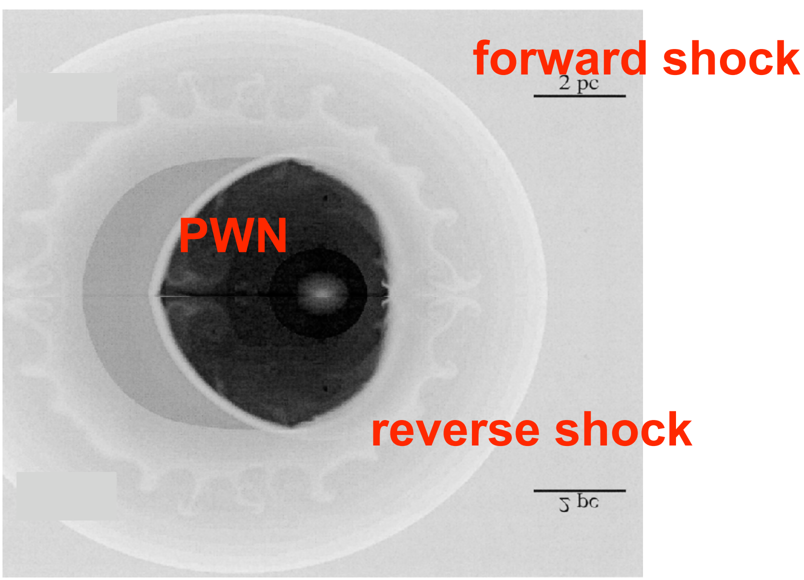
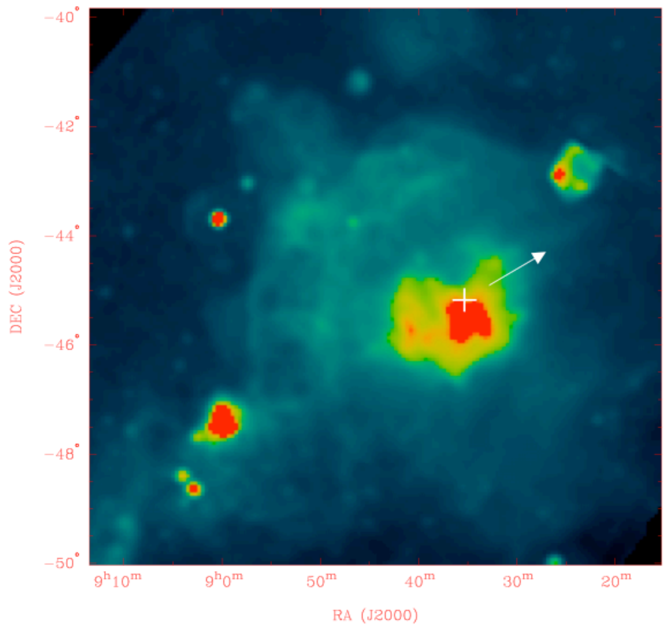


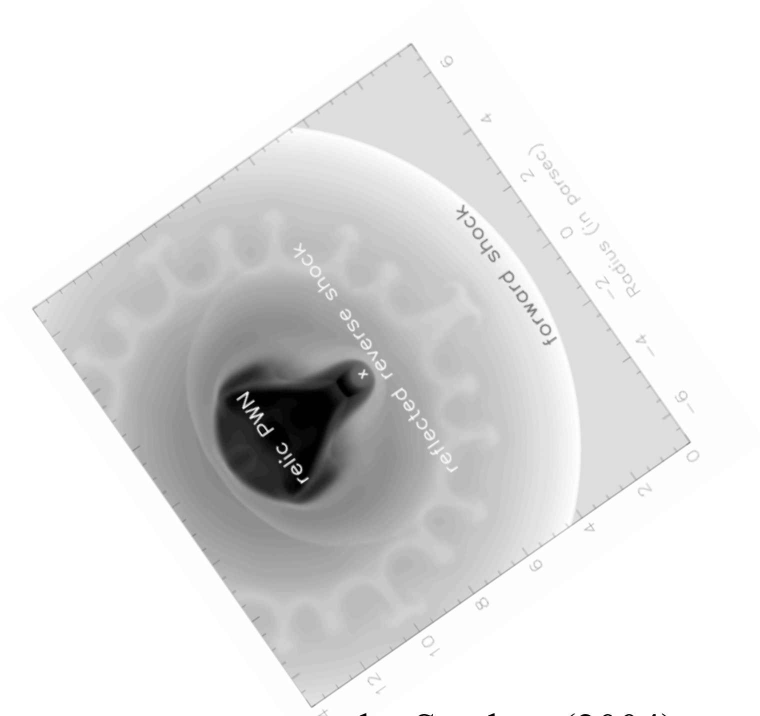
van der Swaluw et al. (2004)



Vela (radio) Duncan et al. 1996

Phase II: Interaction with Reverse Shock

- PWN expands into shocked ejecta
- “Relic” radio PWN left behind
- New PWN around pulsar (X-ray)



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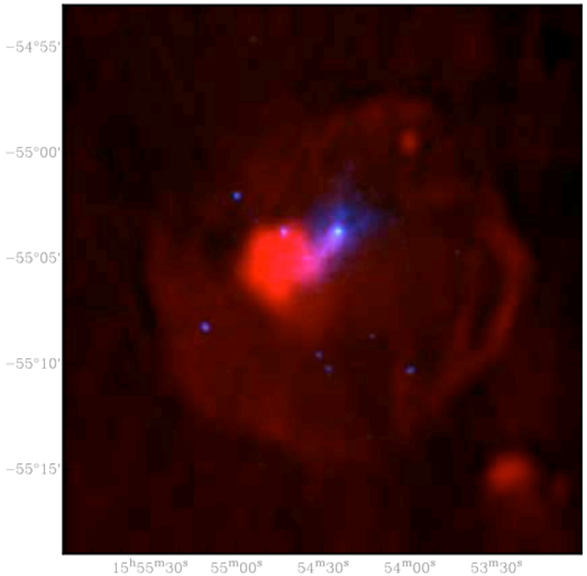
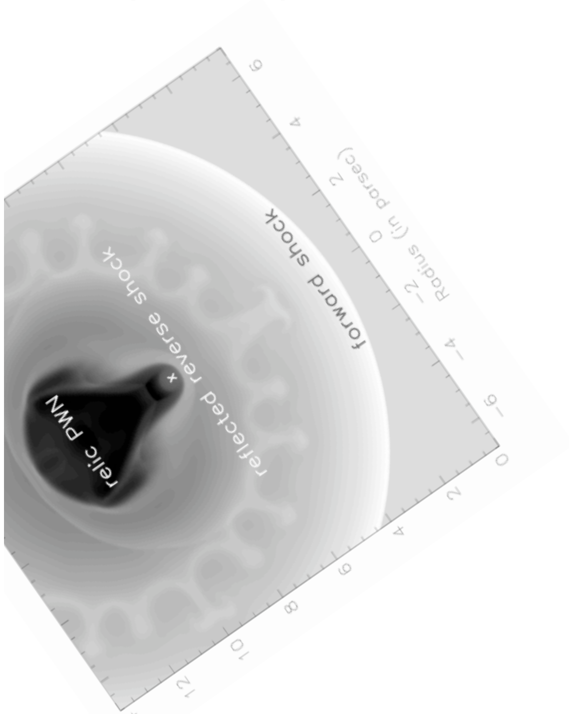


SNR G327.1-1.1, Gaensler &



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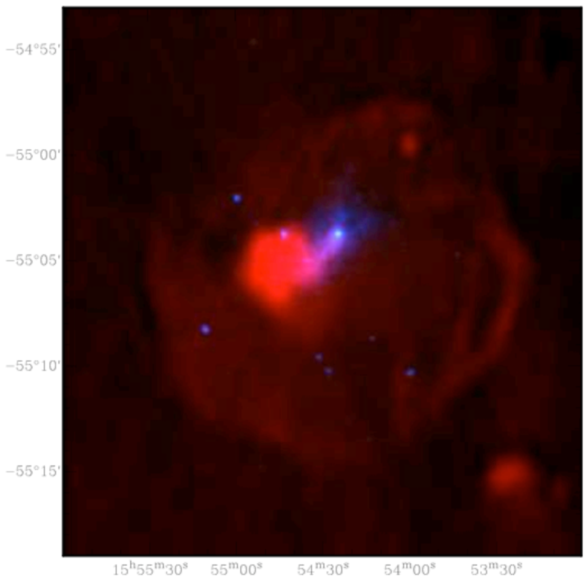

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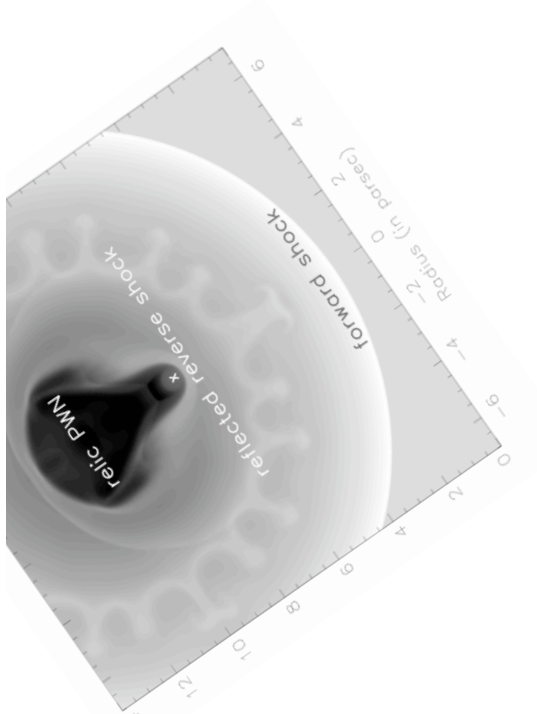

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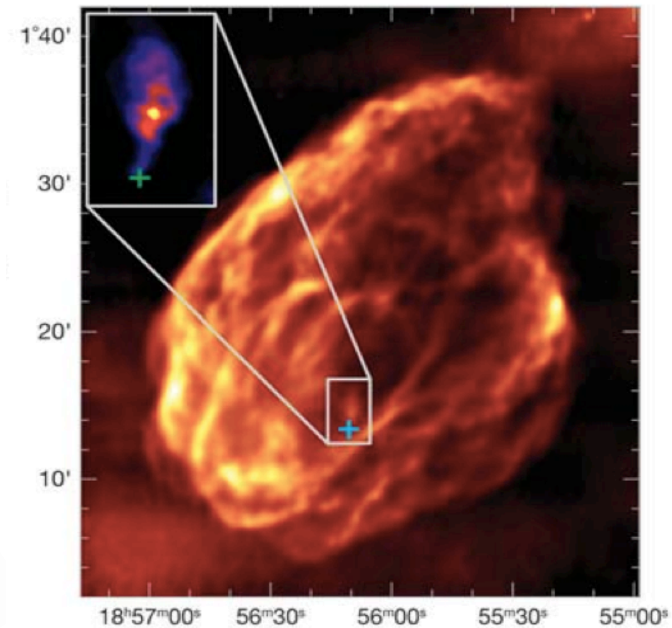


SNR W44 (Frail et al. 1996, Giacani et al. 1997)

PWNe analytical MHD theory

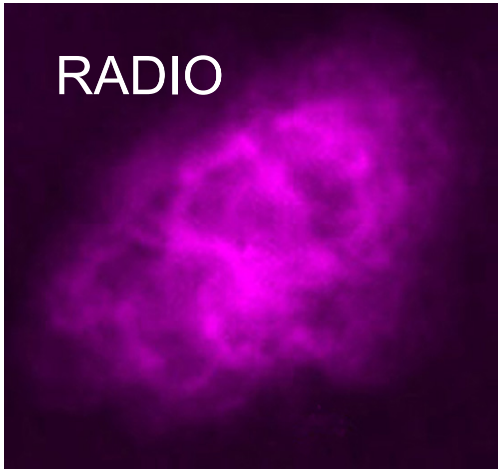
- Theoretical model for PWNe - 1-D steady-state (*Rees & Gunn 1974; Kennel & Coroniti, 1984*) and self-similar (*Emmering & Chevalier, 1987*) - free expansion phase.

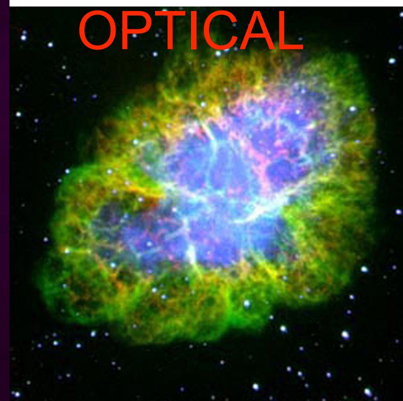
Basic assumptions:

- The wind terminates with a strong MHD shock
- Particles are accelerated at TS
- Relativistic MHD flow in the PWN region
- Synchrotron losses inside the nebula
- Wind parameters derived by comparison with observations:

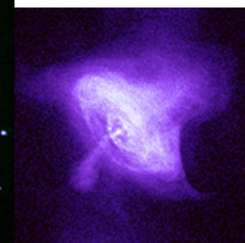
$$R_{TS} = 3\times10^{17}\, cm, \quad L = 5\times10^{38}\, erg/s, \quad \gamma = 3\times10^{6}, \quad \sigma = 3\times10^{-3}$$

Crab Nebula at various energies





X-RAYS

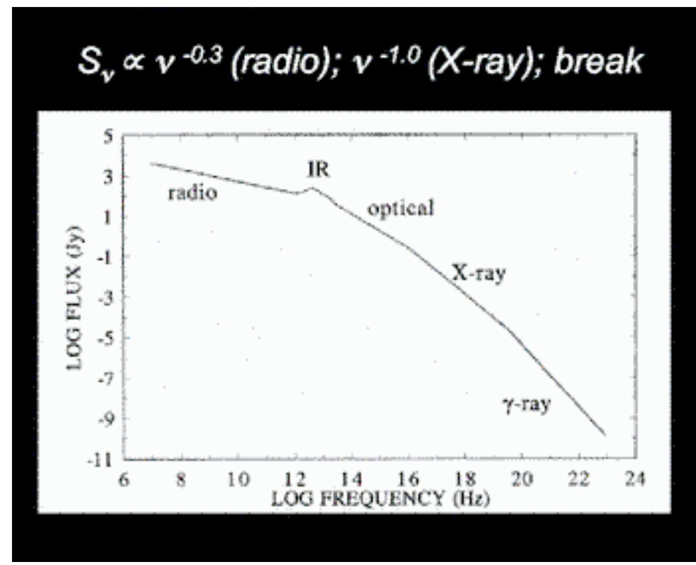


?

γ–rays (<100 MeV)

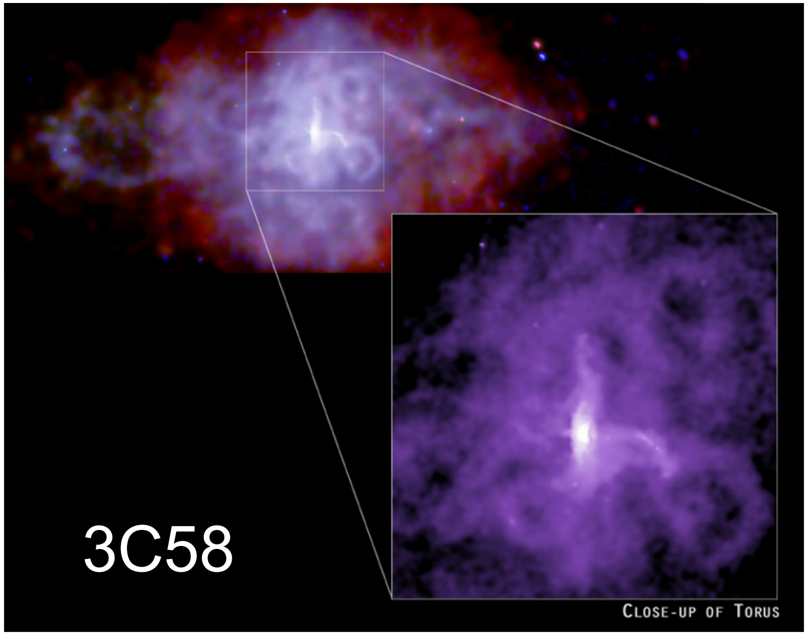
Lifetime: X-rays -- few years, γ-rays -- months. Need energy input!
Crab pulsar: $E_R = 5\times10^{38}$ erg/s, 10-20% efficiency of conversion to radiation.

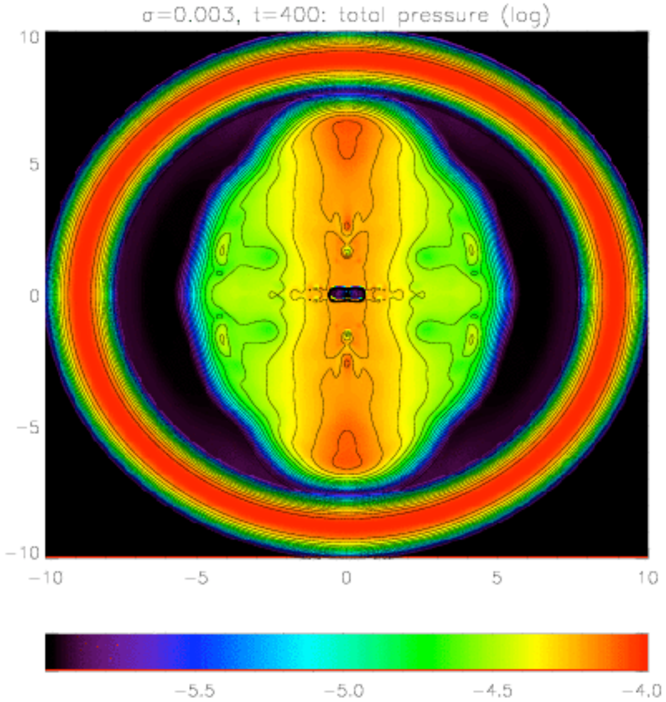
Max particle energy > 3×10^{15} eV, comparable to pulsar voltage.
Nebular shrinkage indicates one accelerating stage:
require $10^{38.5} - 10^{39}$ $e^{\pm}$ /s, radio mystery
PSR also injects B field into nebula (~10^{-4} G)



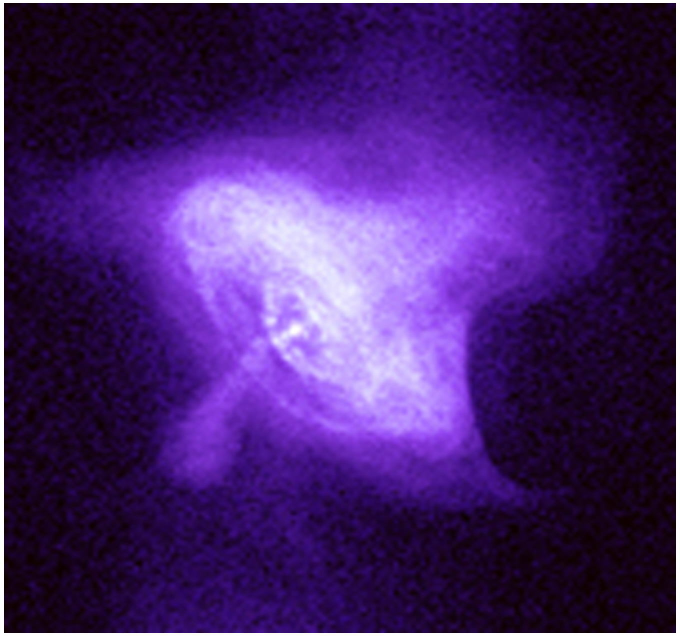
PWN elongation

Shape of the nebula - magnetic pinching (Begelman & Li, 1992, van der Swaluw 2003, Del Zanna et al 2004) - average magnetization in the wind:



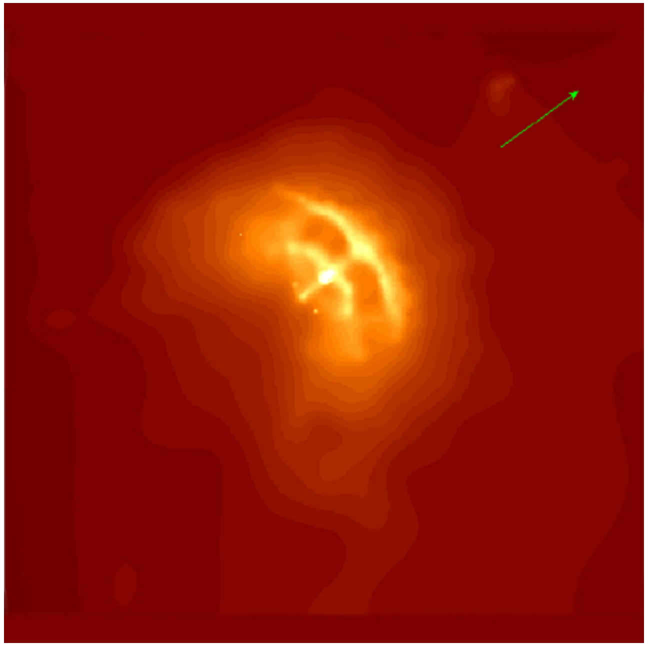


Jet-torus structure: Chandra X-ray images



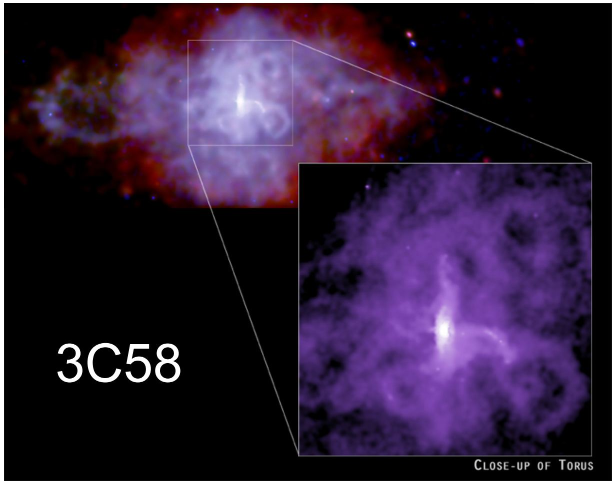
Crab

Vela

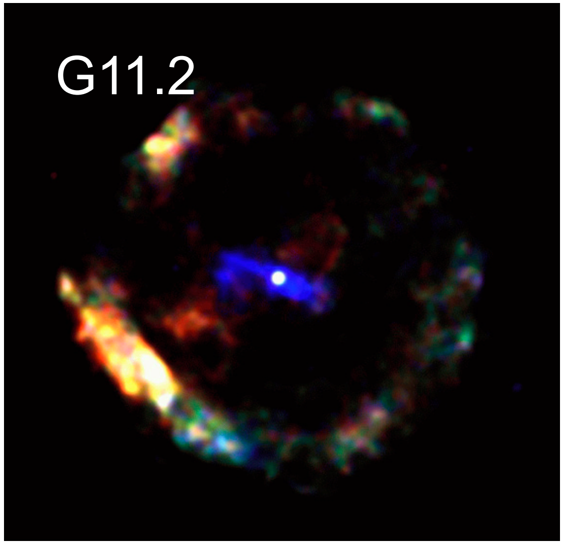


- Crab nebula (*Weisskopf et al., 2000; Hester et al., 2002*)
- Vela pulsar (*Helfand et al., 2001; Pavlov et al., 2003*)

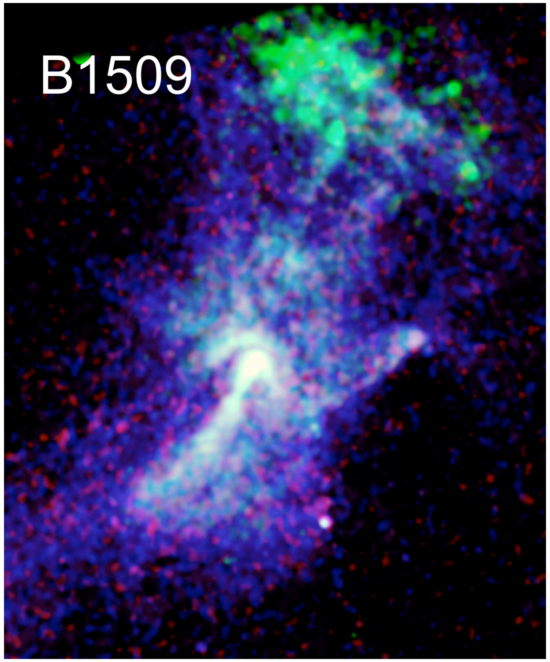
How common id the jet-torus structure?

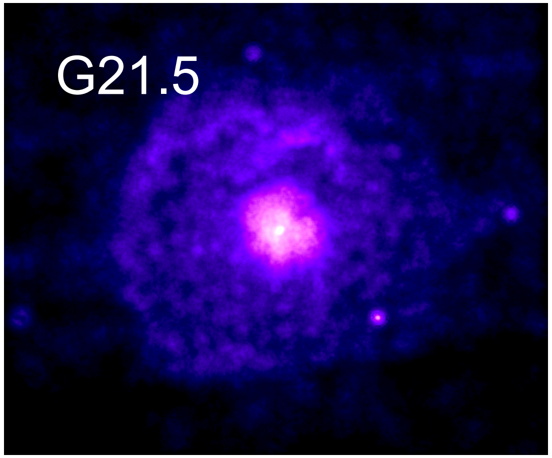


Jet perpendicular to the torus
Jet variability



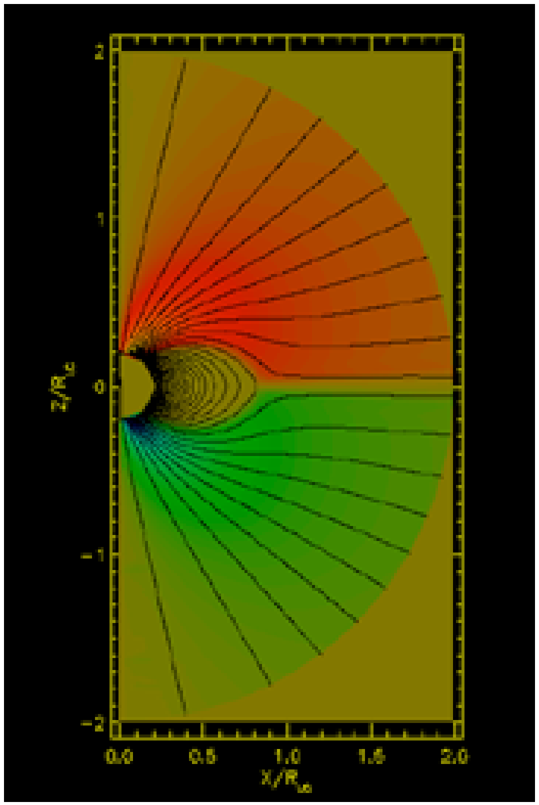
Inner ring

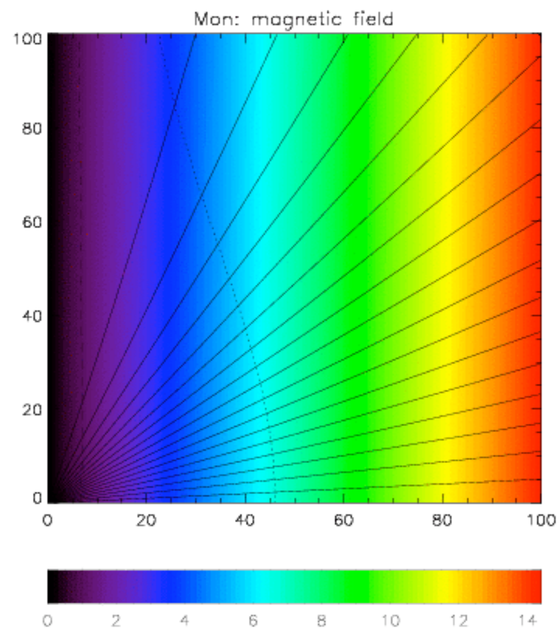


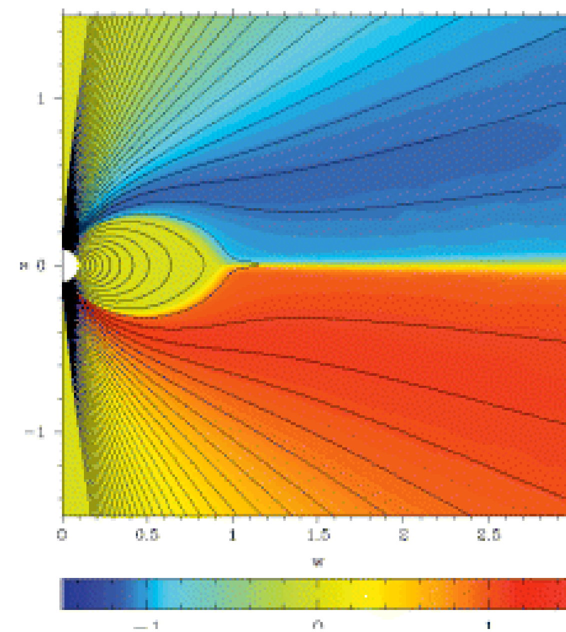


Wind models

Force-free (Contopulos et al 1999, Gruzinov 2005, Spitkovsky 2006)
RMHD (Bogovalov 2001, Komissarov 2006, Bucciantini et al. 2006)







Lorentz factor ~ sin(θ)

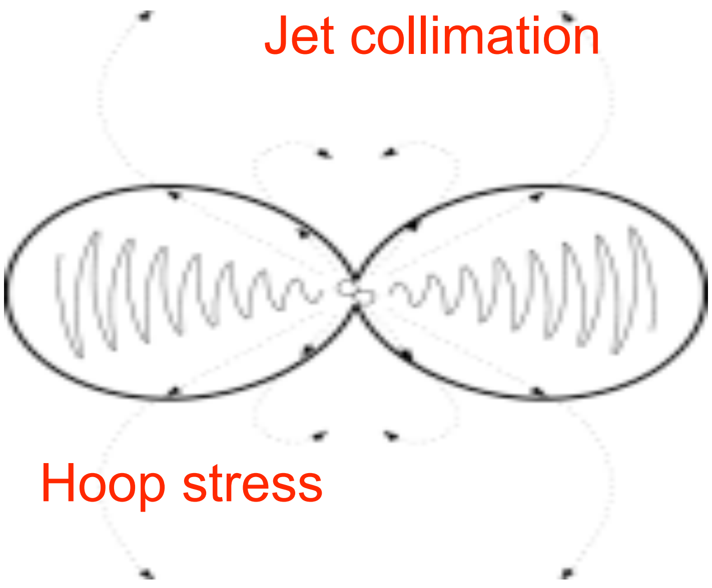
Energy flux ~ $\sin^2(\theta)$

Jet-torus structure: theory

- Torus: higher equatorial energy flux
  lat.dep. acceleration - ions
  doppler boosting?
- Jets: magnetic collimation?

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

collimation inside the PWN
  - *Bogovalov & Khangoulian, 2002*
  - *Lyubarsky, 2002*

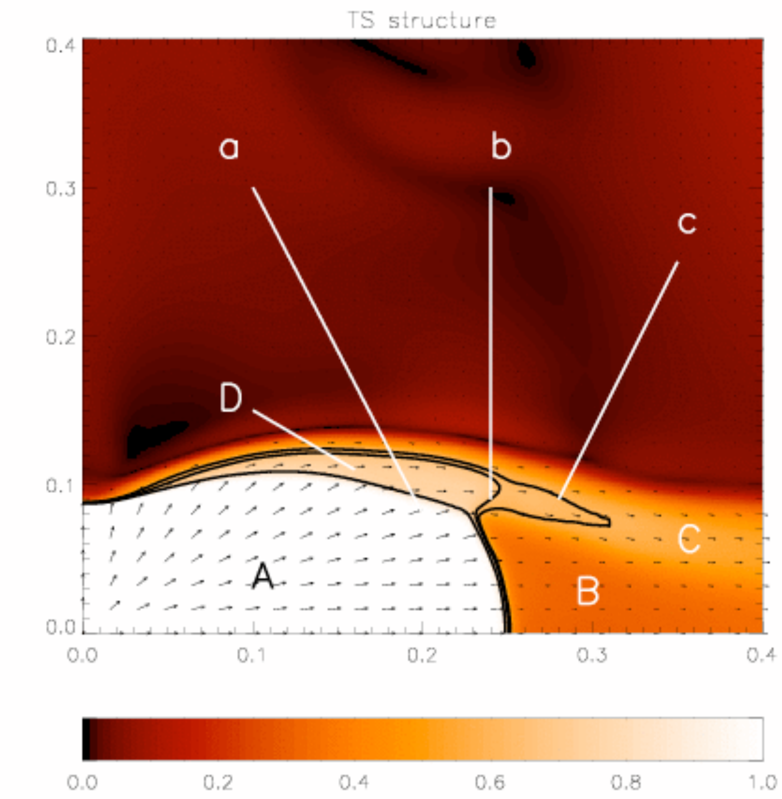


- Axisymmetric RMHD simulations of the interaction of a relativistic magnetized wind with SN ejecta
  - *Komissarov & Lyubarsky, 2003, 2004*
  - *Del Zanna, Amato & Bucciantini, 2004, 2006*
  - *Bogovalov et al., 2005*

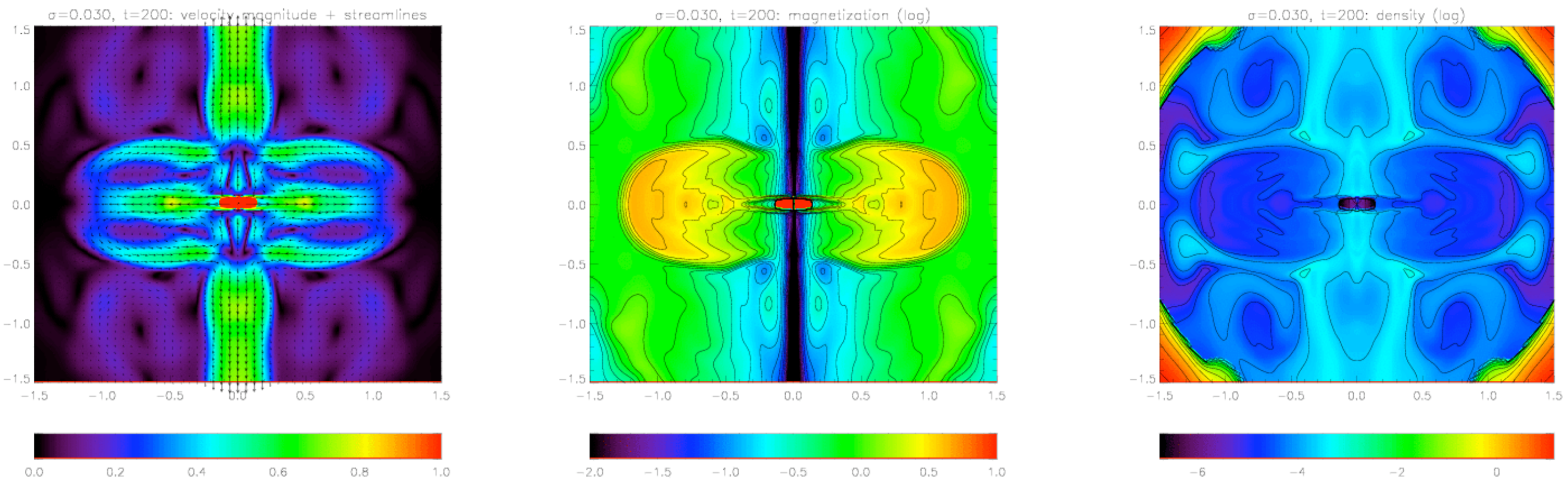
TS structure and flow pattern

- The wind anisotropy shapes the TS structure. Downstream flow - equatorial collimation due to the TS shape:
  - 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



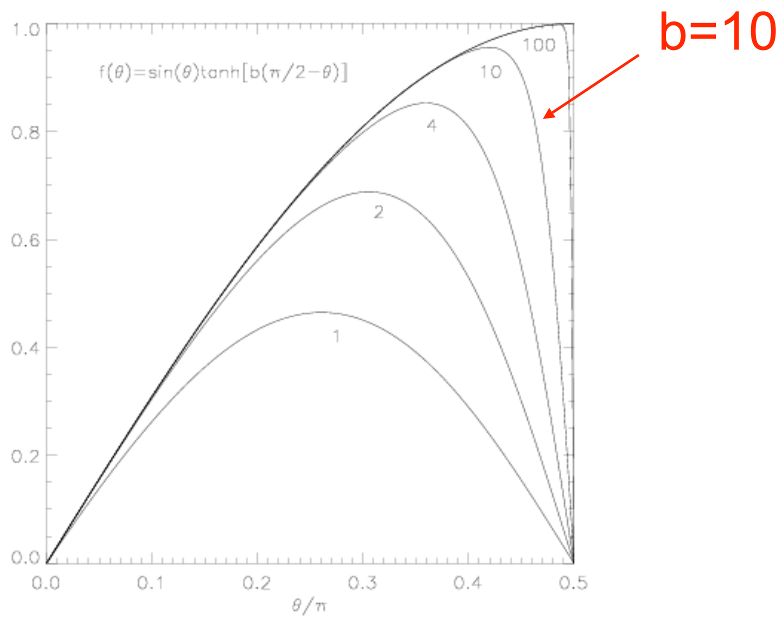
Details of the jet formation

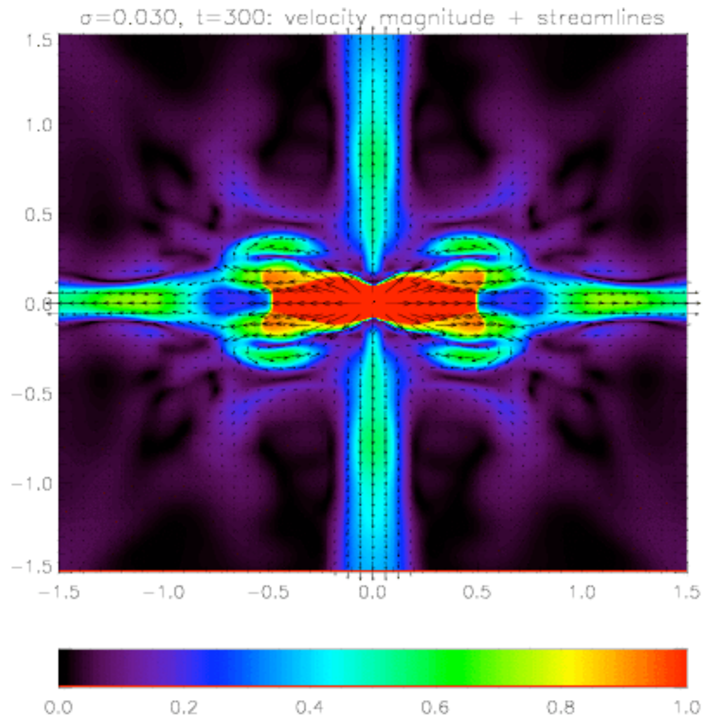


- Equipartition is reached first in the equatorial region
- Once in equipartition the flow is diverted from the equator to higher latitudes
- Hoop stresses force it toward the axis
- A fast channel (jet) is formed on the axis of the nebula

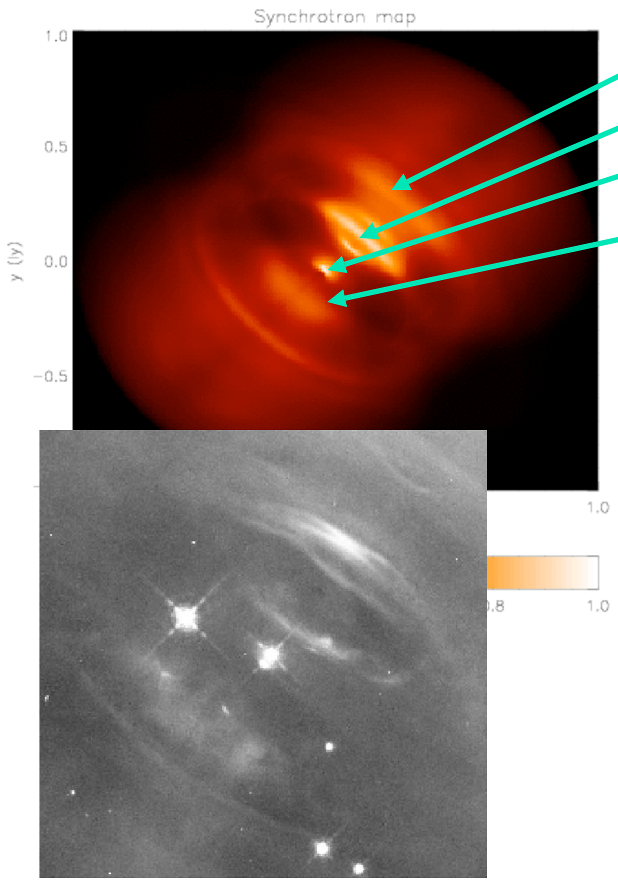
Modeling a striped wind case

- Initial magnetic field with a narrow equatorial neutral sheet
- Dissipation in a striped wind





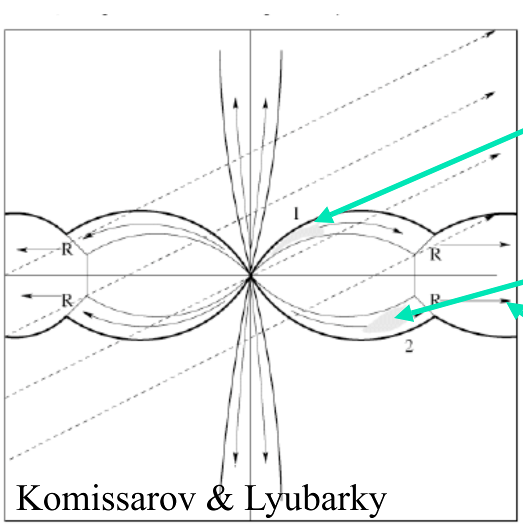
Comparison with Observations



Main torus
Inner ring (wisps structure)
Knot
Back side of the inner ring

Hester et al. 1995

No jet - Axisymmetric assumption



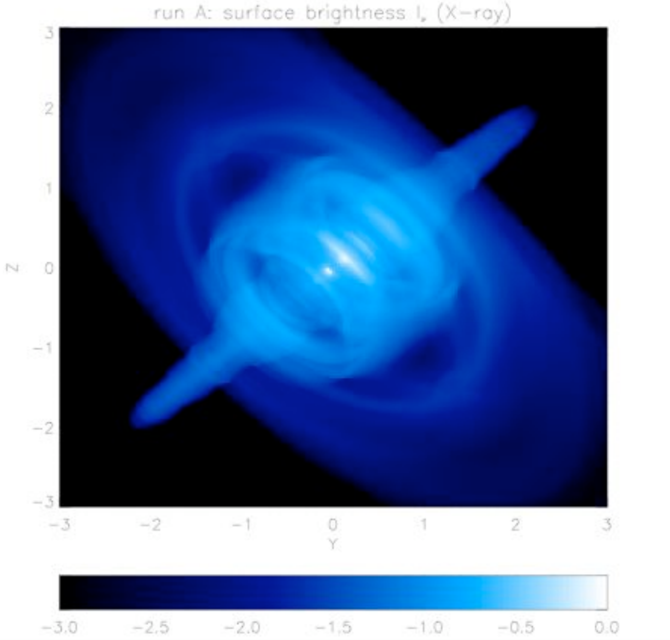
Komissarov & Lyubarky 2004

Knot
Ring
Torus

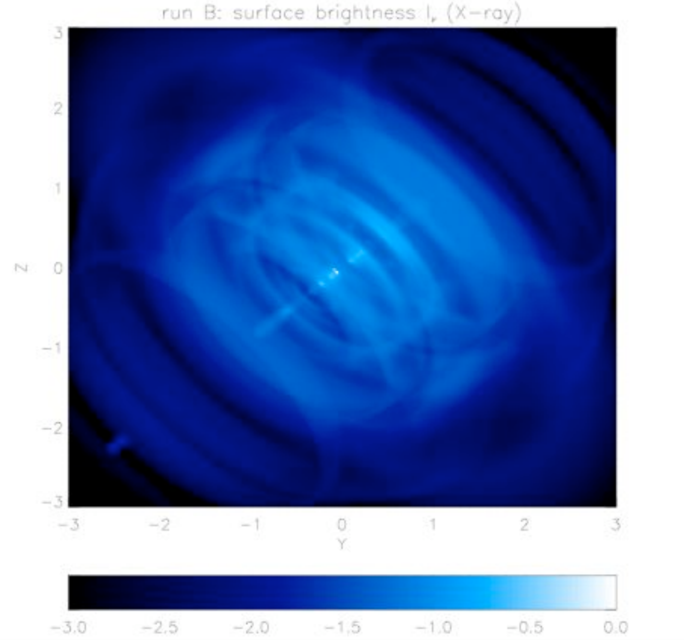
Playing with the wind

How do wind properties affect the nebula aspect ?

σ=0.025, b=10



σ=0.1, b=1



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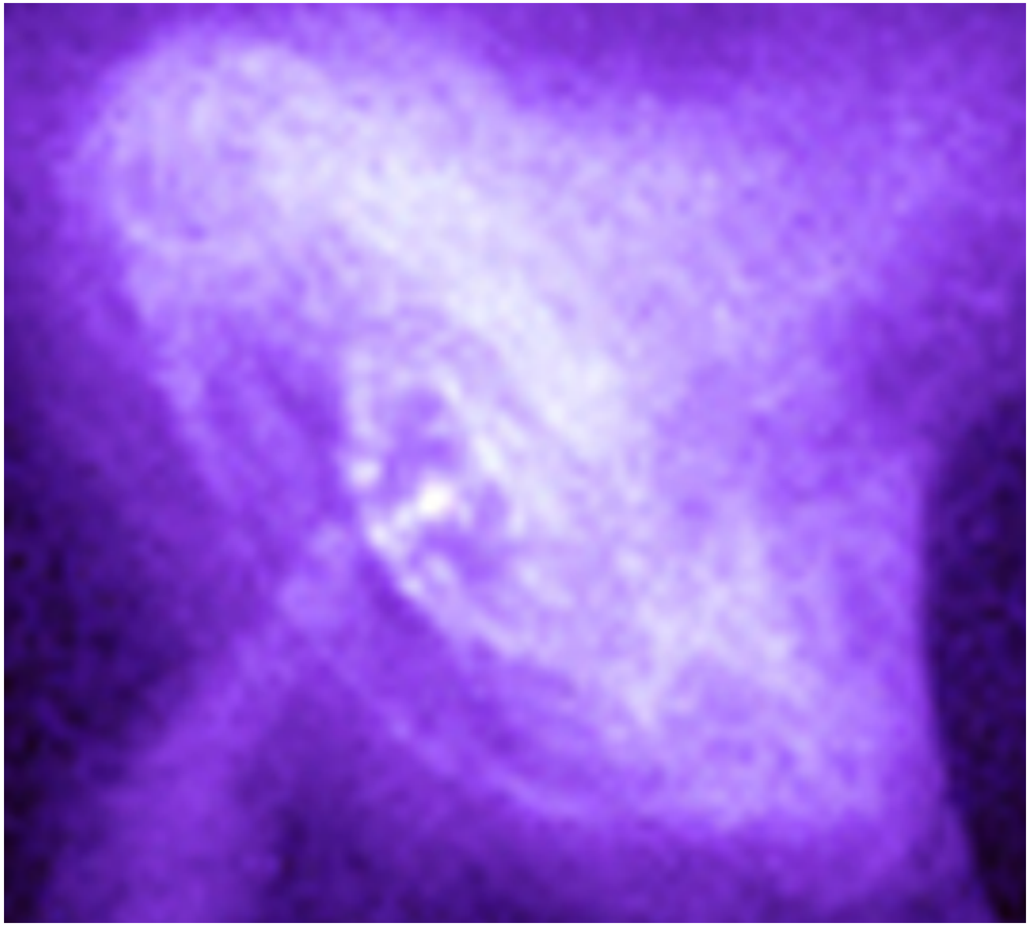

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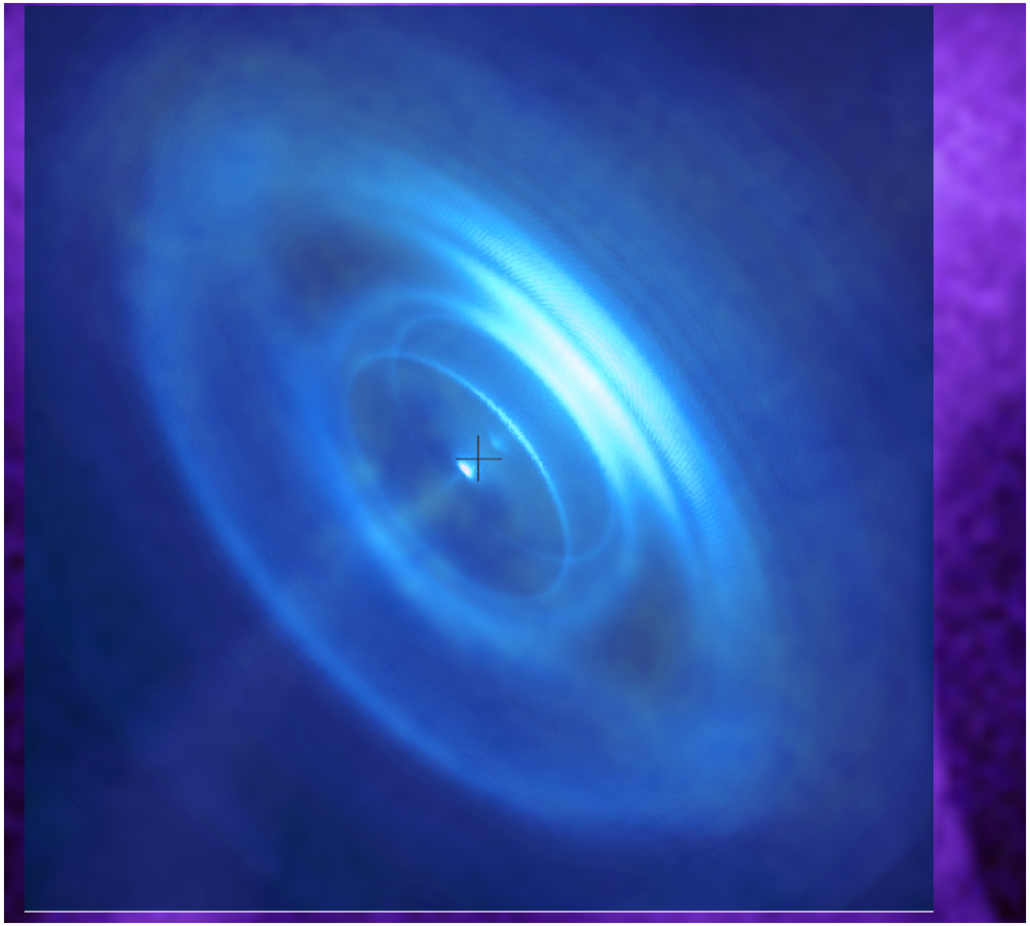
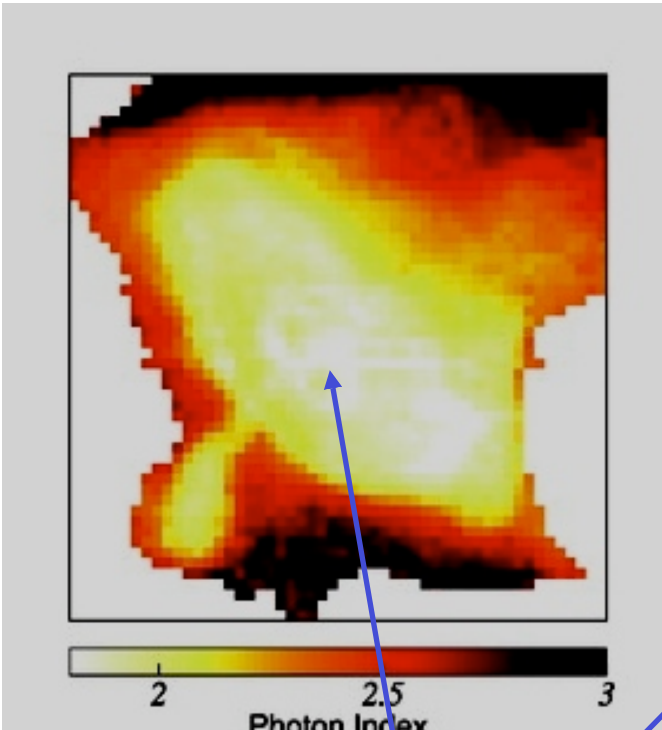
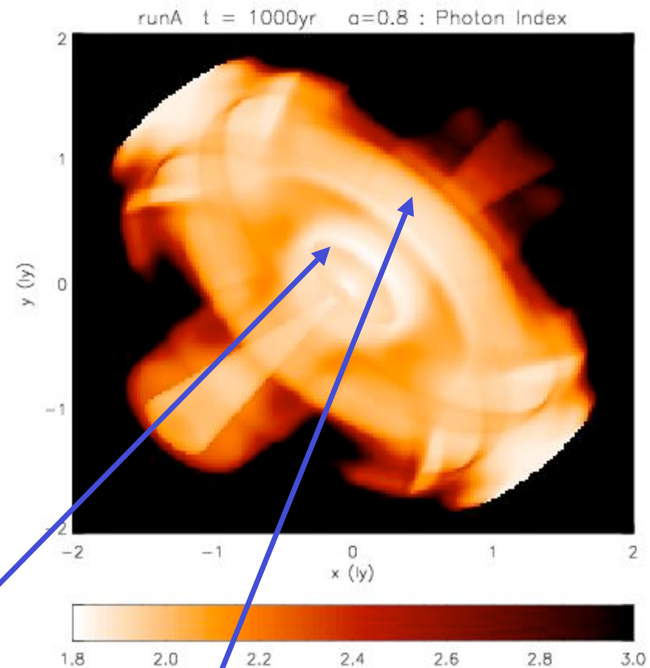


Photon Index





Mori

Jet not correctly reproduced

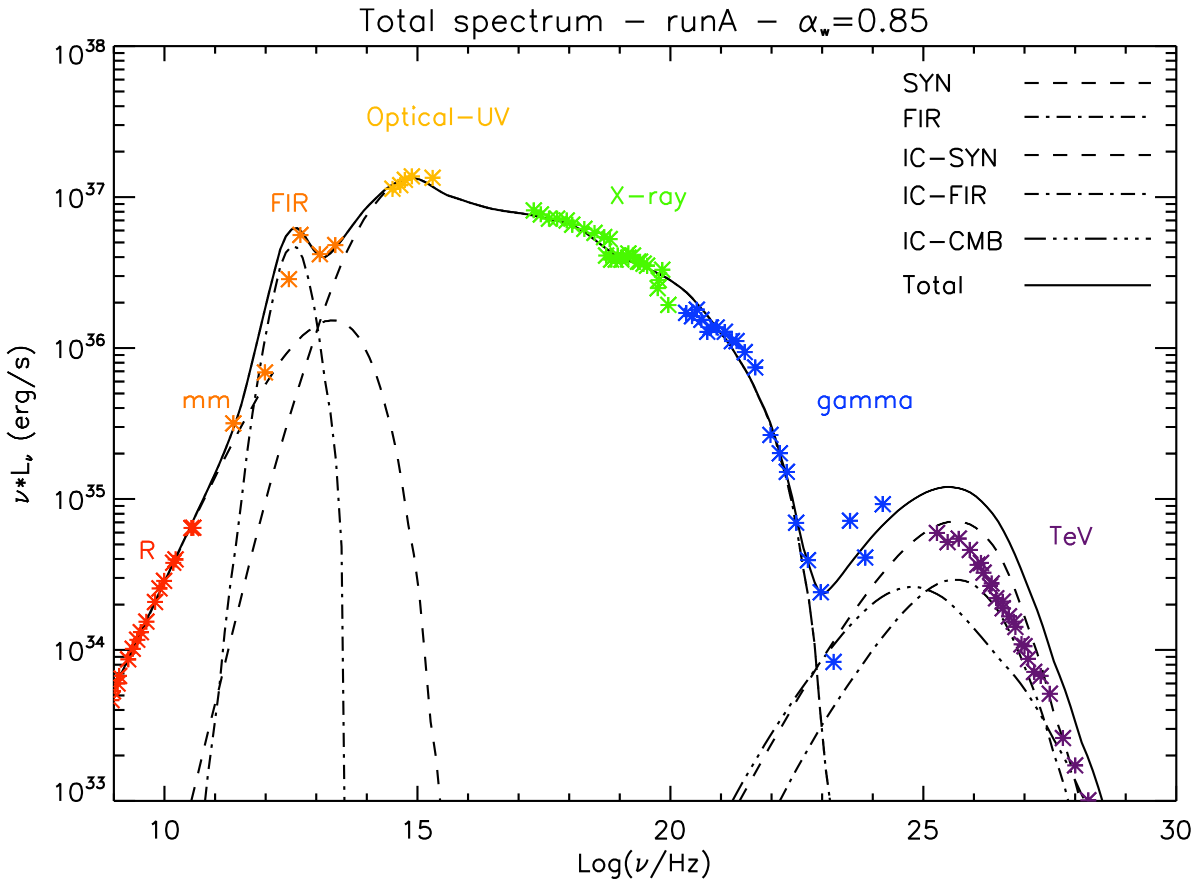
(required reacceleration)

Higher index in the torus

(recompression and boosting)

Brighter inner ring

Photon Index



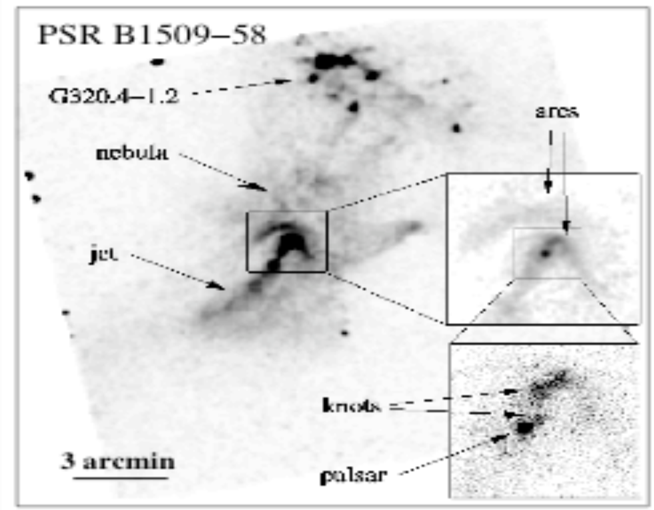
Steeper spectrum than −2.2 ?

Time variability

- Wisp moving outward
- Year long limit cycle
- Variability in the knot
- Bubble in the jet v~ 0.6 c

Variability in the knot structure
Jet feature moving at 0.6 c

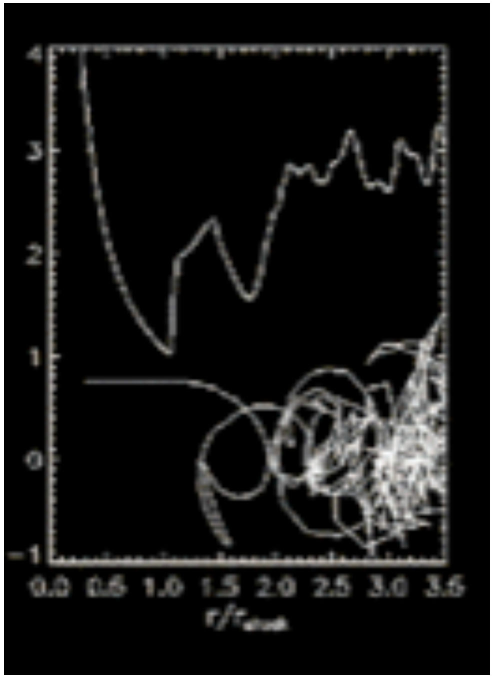
Local instabilities or global modes?



Slane 05, DeLaney 06

Time variability: ions

Spitkovsky & Arons 04

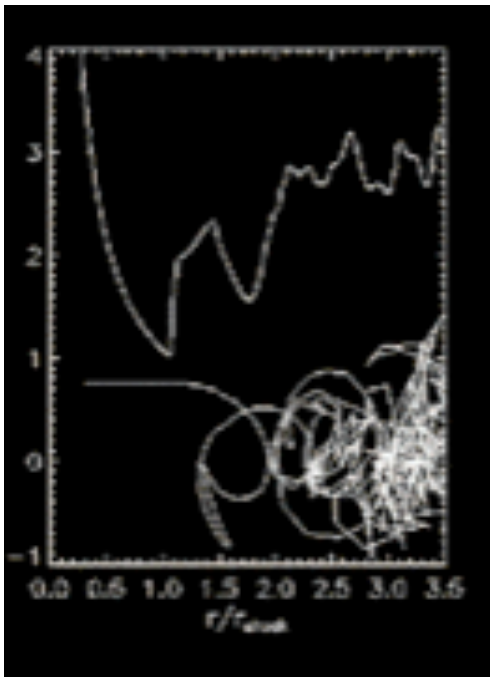


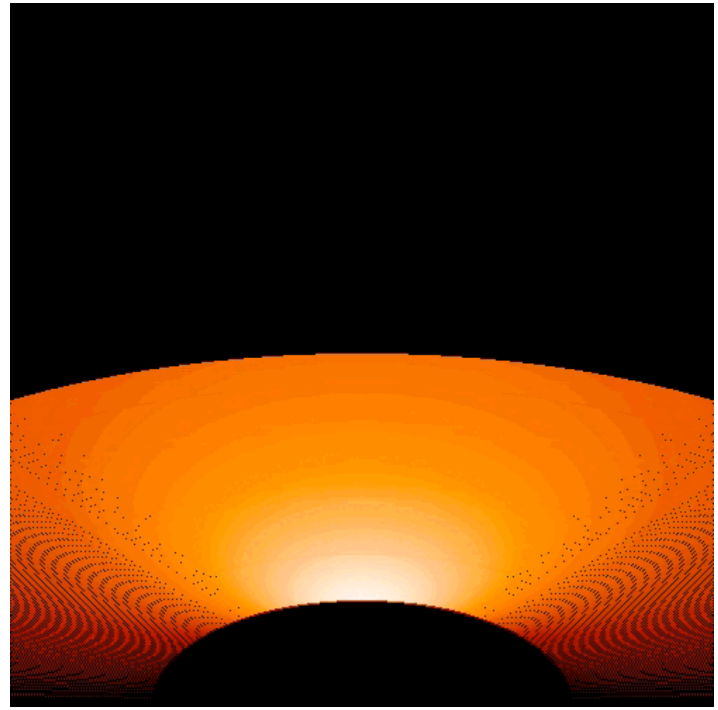
Hybrid MHD?

Recovered inner arch and outer torus
Variability on few months timescale
Still no Chandra unboosted ring
No reversal of B or striped zone

Time variability: ions

Spitkovsky & Arons 04





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Hybrid MHD?

MHD variability - Flow

Instability of the shear layers creates eddies at the rim shock

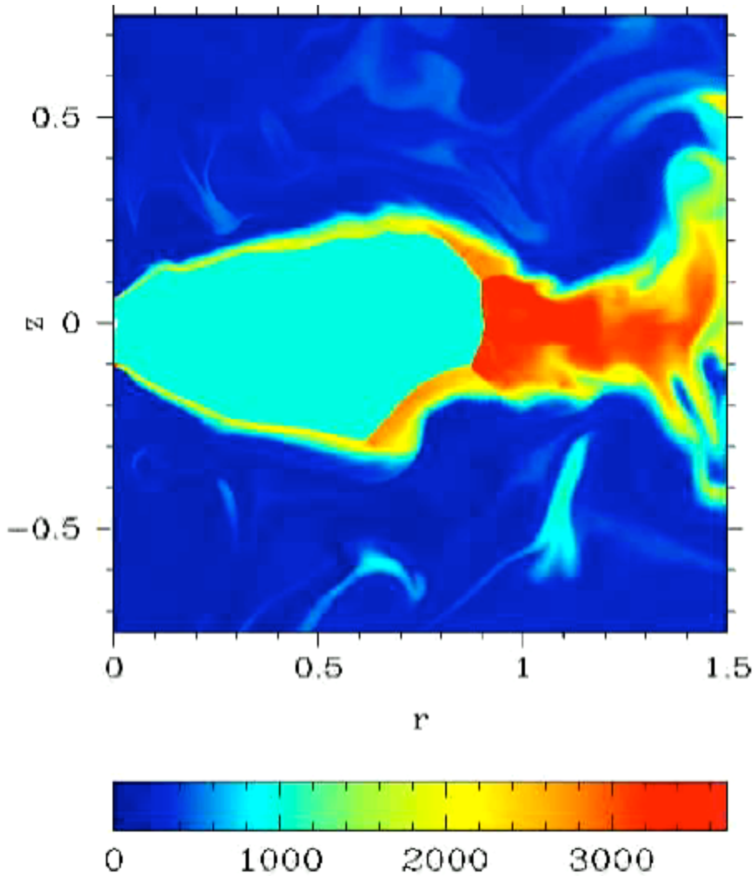
Eddies are advected outward and a toroidal pressure wave is launched

There is no wave reflection from the boundary

Waves reflected on the axis modulate the TS shape

The equatorial channel is kink unstable

MHD variability - Flow



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The equatorial channel is kink unstable

MHD variability - Emission

Outgoing wave pattern

Large luminosity variations

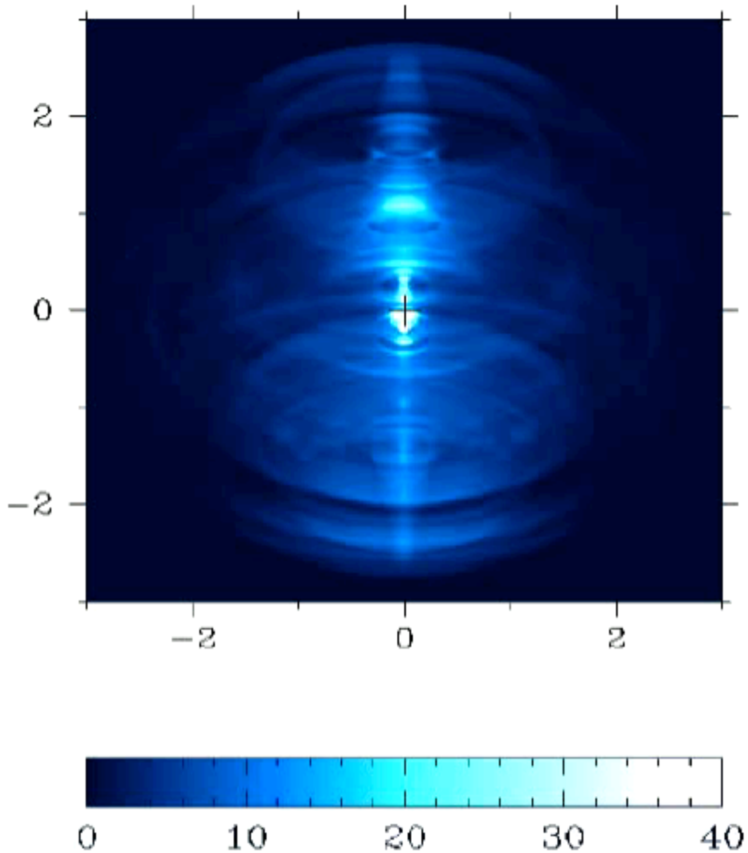
Features slow down as they move outward

Variability observed both in the knot and in the sprite

Pressure waves produce variability in the axial emissivity

Large striped wind are favored to produce a bright torus

MHD variability - Emission



Outgoing wave pattern

Large luminosity variations

Features slow down as they move outward

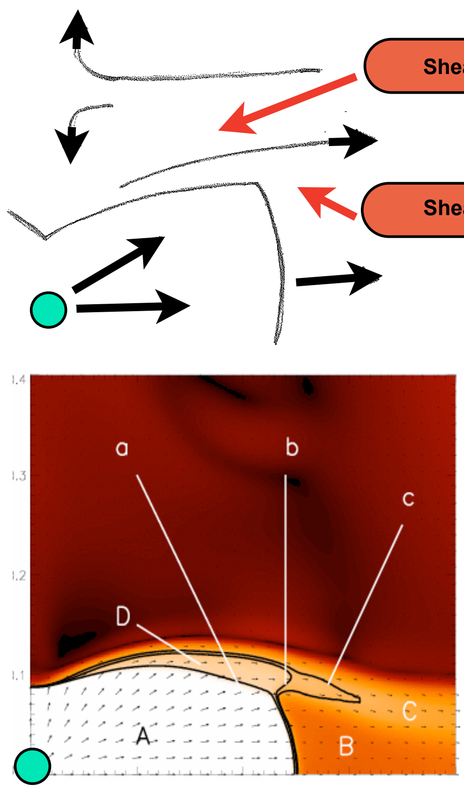
Variability observed both in the knot and in the sprite

Pressure waves produce variability in the axial emissivity

Large striped wind are favored to produce a bright torus

MHD variability - SASI

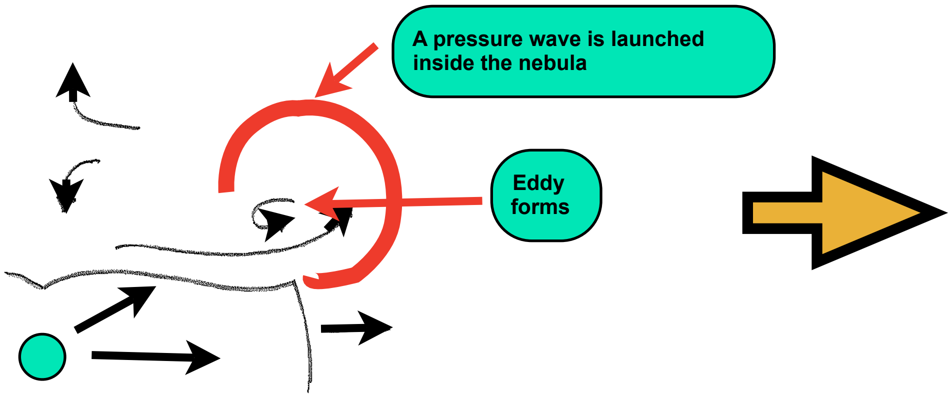
The stable TS configuration



MHD variability - SASI

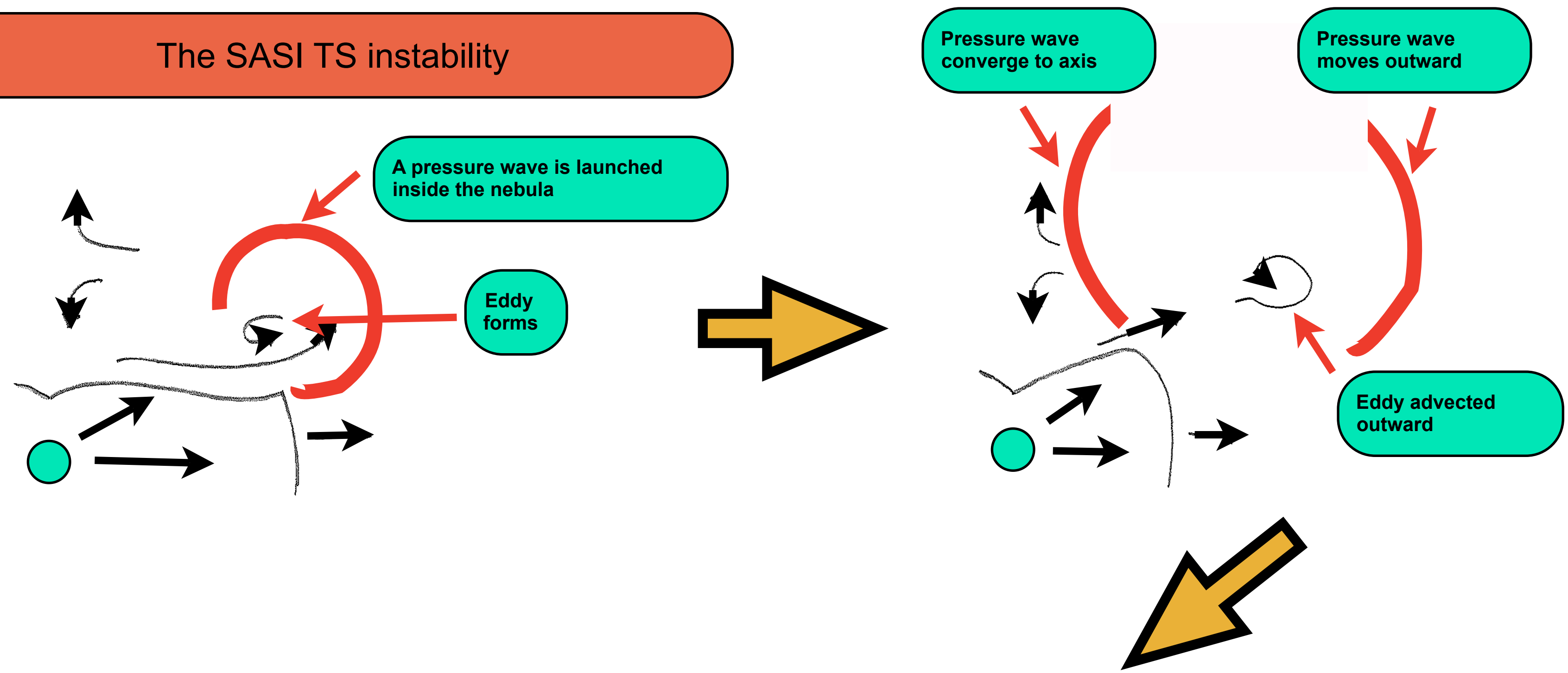
MHD variability - SASI

The SASI TS instability

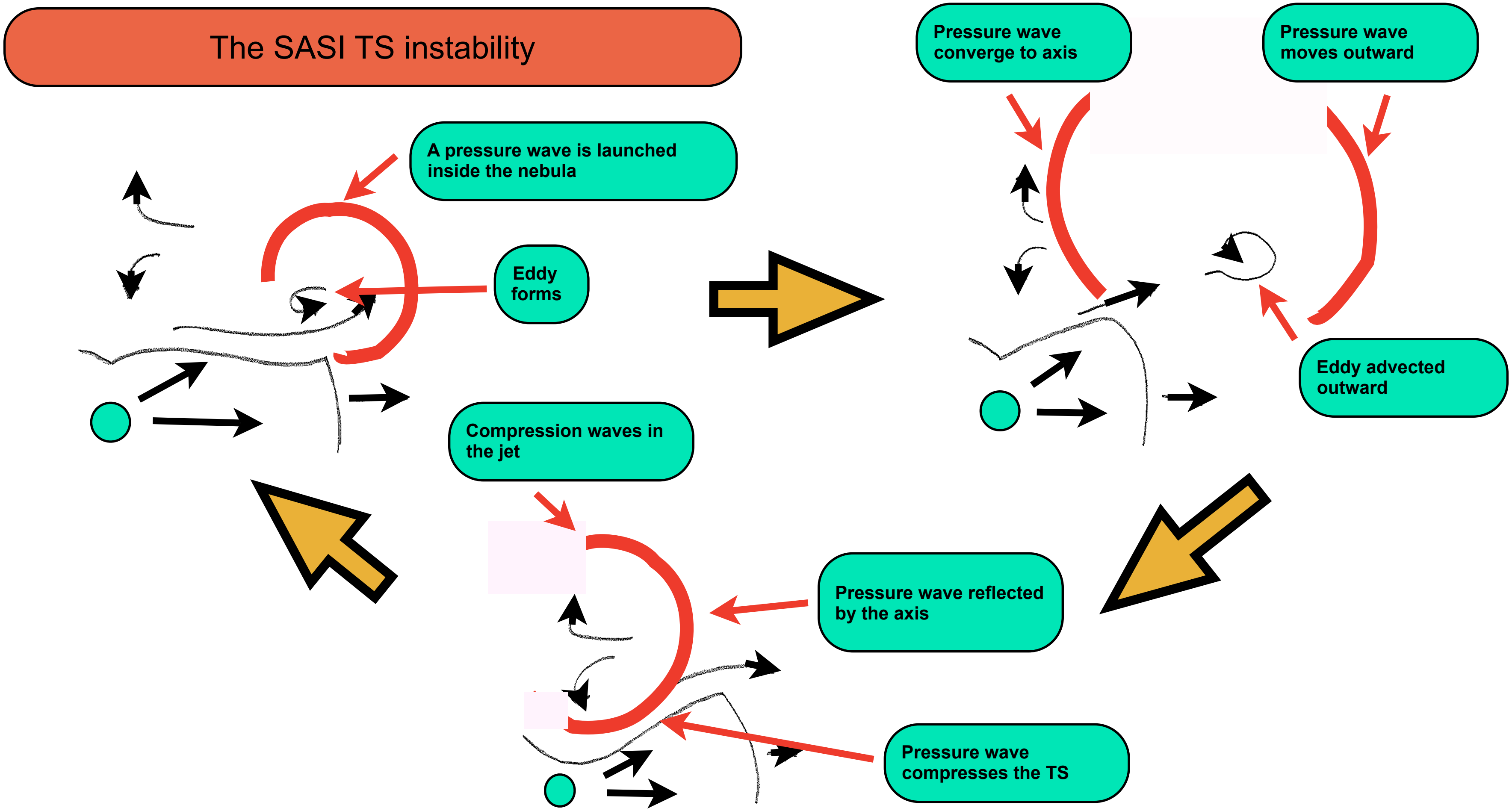


MHD variability - SASI

The SASI TS instability



MHD variability - SASI



Summary and conclusions

- New X-ray observation have been a key element in renewing theoretical investigation of PWNe
- Models of young objects can now connect wind properties to nebular features including variability
- RMHD numerical techniques are able now to properly model multidimensional PWN structures in detail, and follow their evolution
- Work needed on modeling the emission from older objects
- There are still open questions regarding the wind composition
- There are still unexplained non-axisymmetric features
- Variaility explained within the MHD model. What about ions?

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Thank you