Theory of Pulsar Wind Nebulae

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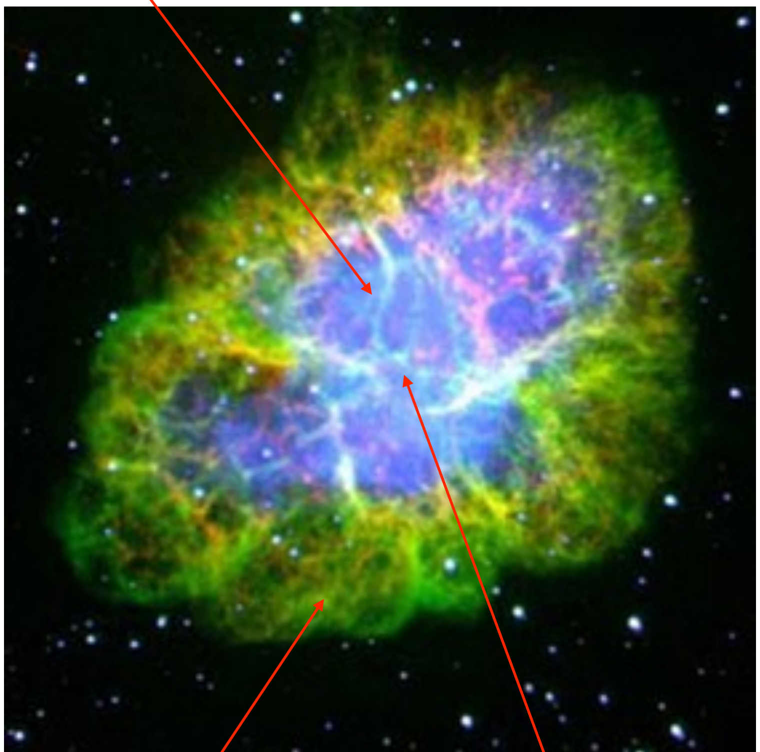
http://www.arcetri.astro.it

Del Zanna, Volpi, Amato, Olmi, Arons, Komissarov, Camus

Pulsar Wind Nebulae



PWNe once upon a time **-**

Once they were the Crab Nebula, and systems like it

PWNe now ***- Anything that traces the interaction of a PSR (NS) with the environment***

Modeling Elements

Dynamics ***- Wind confinement, Nebular flow structure and geometry, Evolutionary effects***

Acceleration ***- Particle spectrum, Injection properties***

Emission ***- Particles evolution, Magnetic field distribution, Radio***

Extras ***- Short timescale variability Flares***

A case for MHD

Why an MHD description?

A case for MHD

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Larmor radii << nebular radius (advective regime)
Energy losses are negligible (radio particles dominate)
Almost pure pair plasma (no dispersive effects)
Interested in long evolutionary timescales

A case for MHD

Why an MHD description? → ***MHD is "simple"***

Larmor radii << nebular radius (advective regime)
Energy losses are negligible (radio particles dominate)
Almost pure pair plasma (no dispersive effects)
Interested in long evolutionary timescales

Particles are accelerated with high efficiency

1D

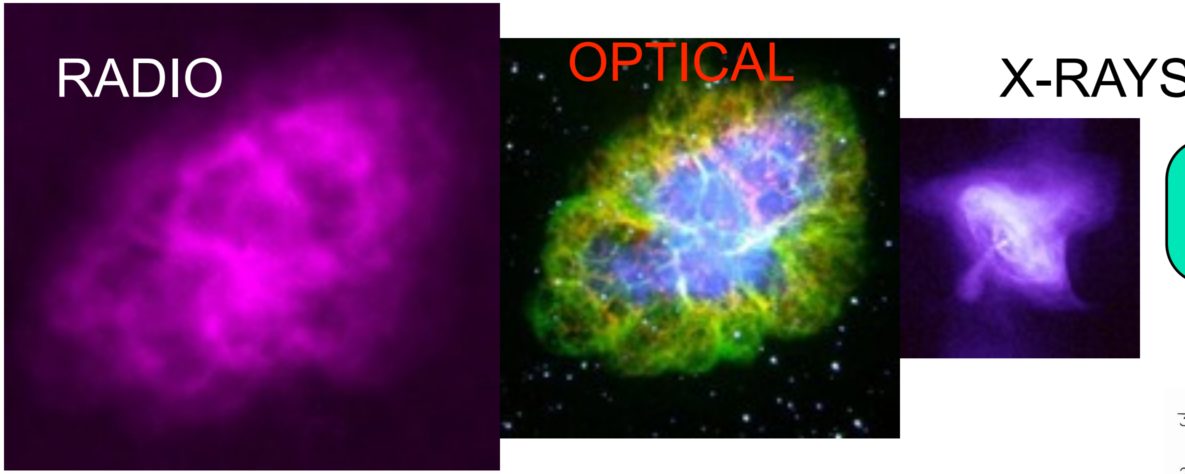
- Theoretical model for PWNe - 1-D steady-state (*Rees & Gunn 1974; Kennel & Coroniti, 1984*) and self-similar (*Emmering & Chevalier, 1987*) - free expansion phase.

Basic assumptions:

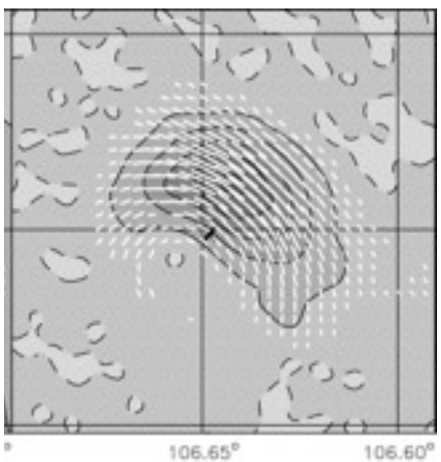
- The wind terminates with a strong MHD shock
- Particles are accelerated at TS
- Relativistic MHD flow in the PWN region
- Synchrotron losses inside the nebula
- Wind parameters derived by comparison with observations:

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

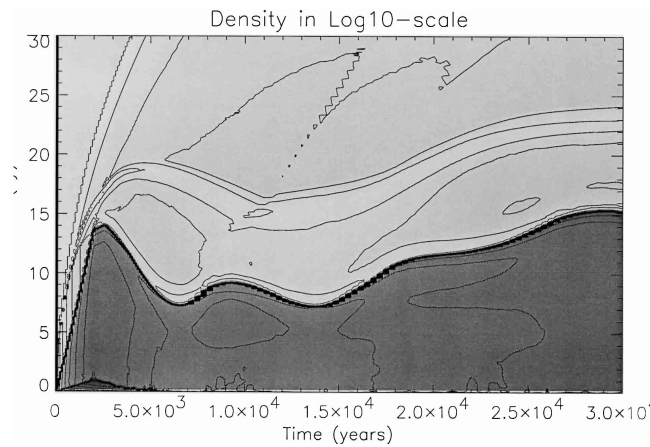
Global properties 1D



Global morphology



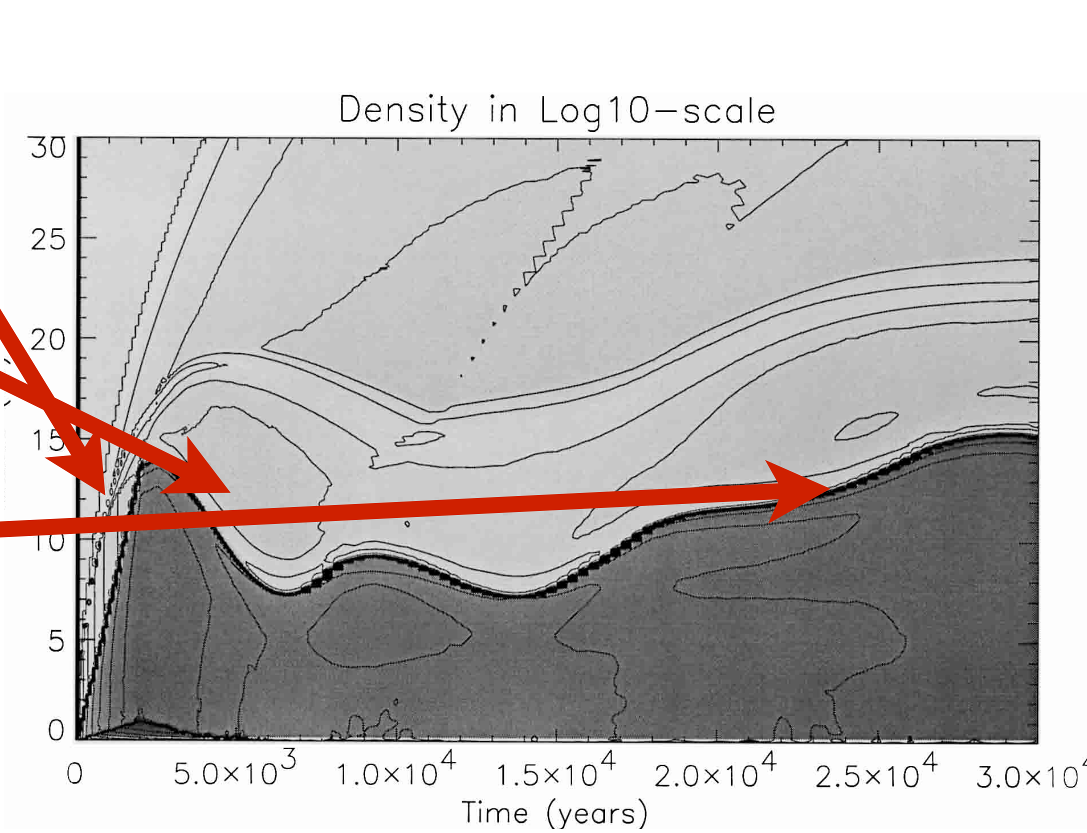
Polarization



General evolution

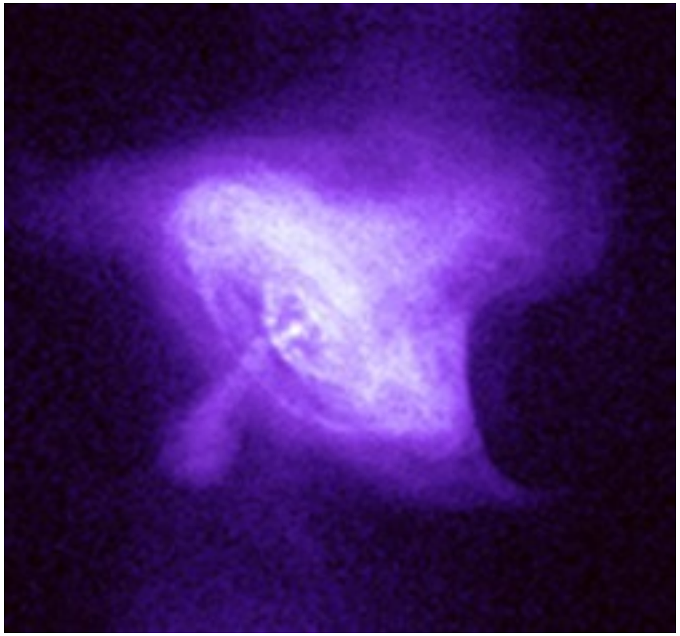
Evolution 1D

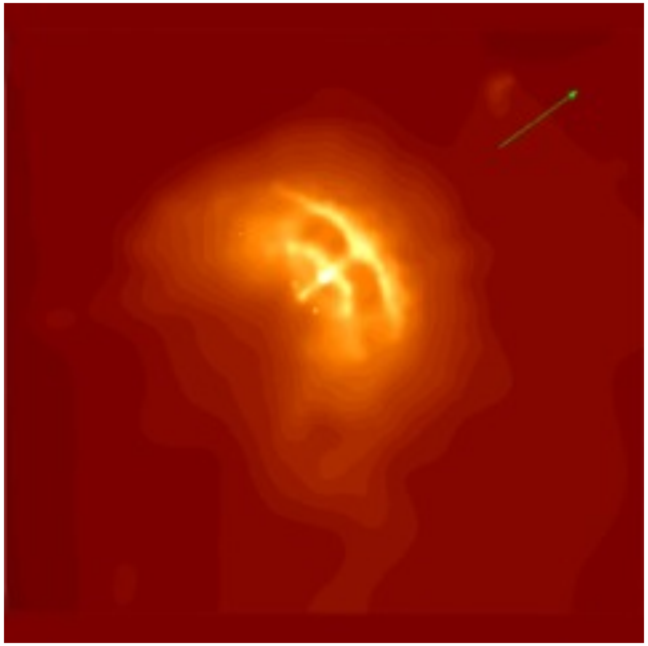
- "Free expansion"
  - Duration T ~ $10^{3\text{-}4}$ yr
  - Constant pulsar energy input - Emission at high energies
- Reverberation -
  - T~10^4 yr
  - Enhanced emission due to re-energization
- Sedov -
  - T ~ 10^5 yr
- Bow-Shock - interaction with the ISM



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

Fine structures

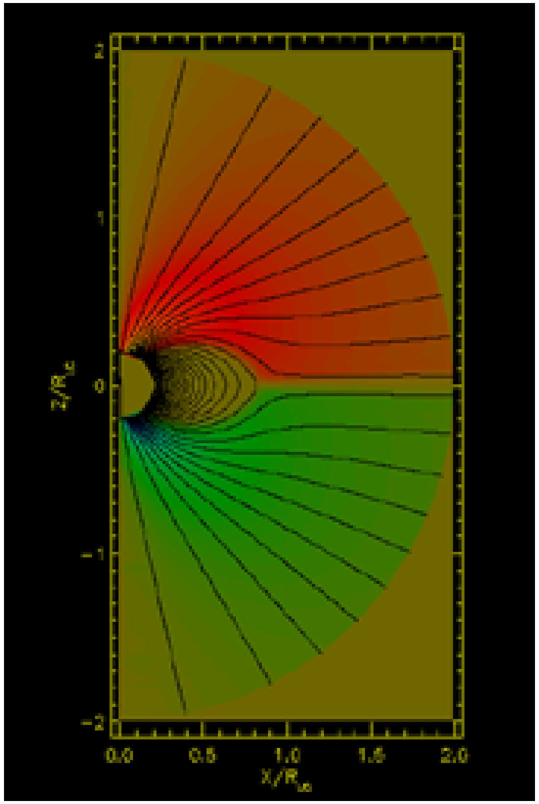


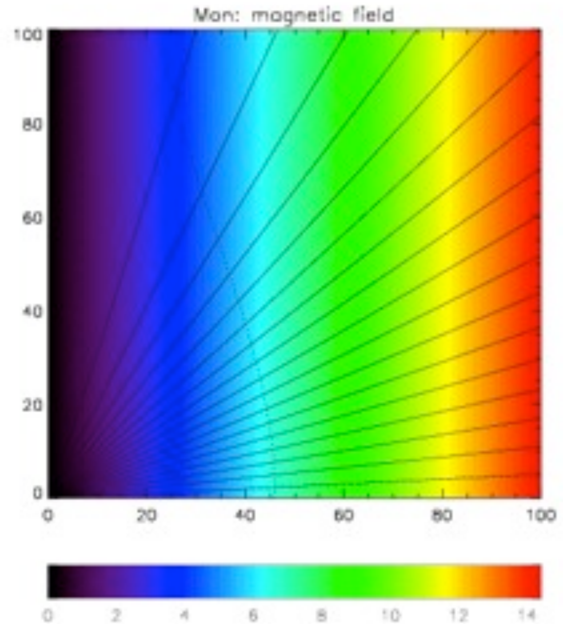


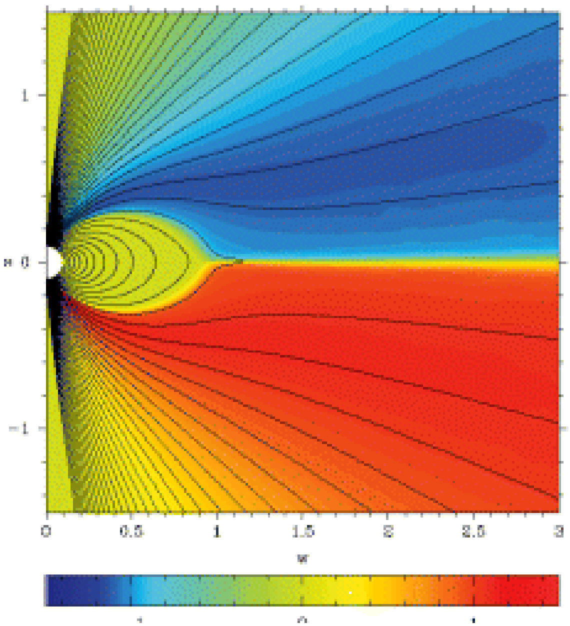
- Crab nebula (*Weisskopf et al., 2000; Hester et al., 2002*)
- Vela pulsar (*Helfand et al., 2001; Pavlov et al., 2003*)

Wind models 2D

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





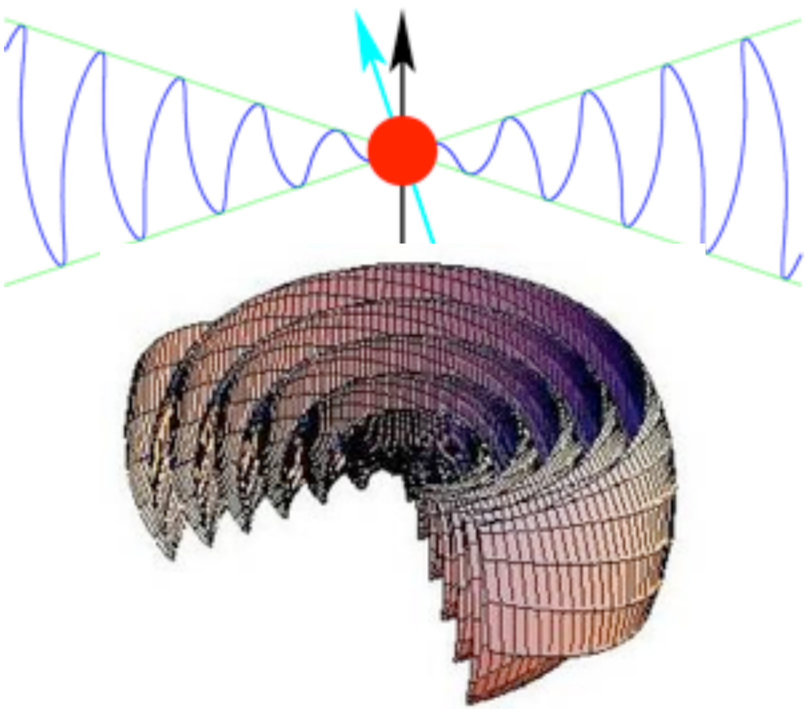


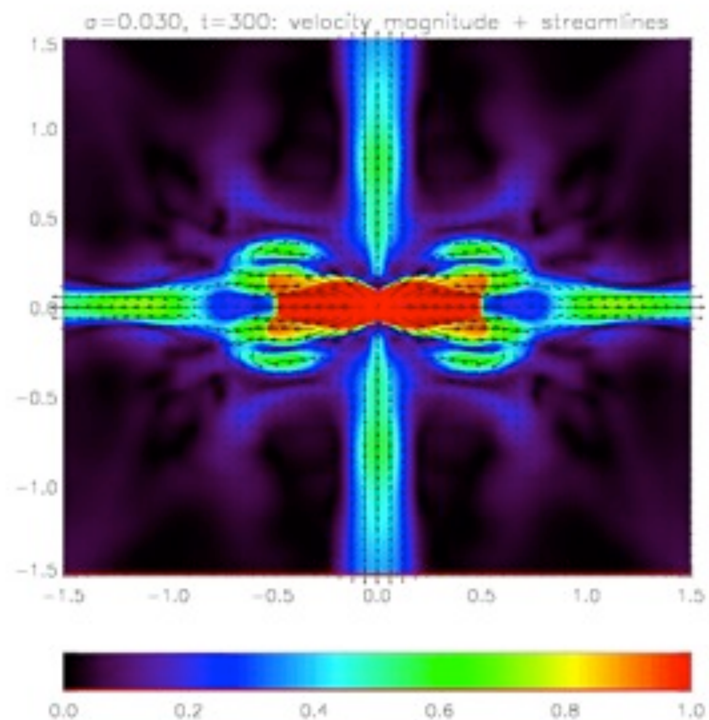
Lorentz factor ~ sin(θ)

Energy flux ~ sin²(θ)

Dysmics 2D

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





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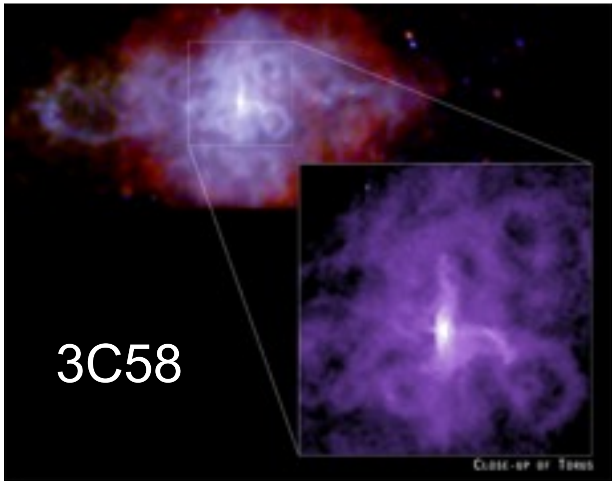
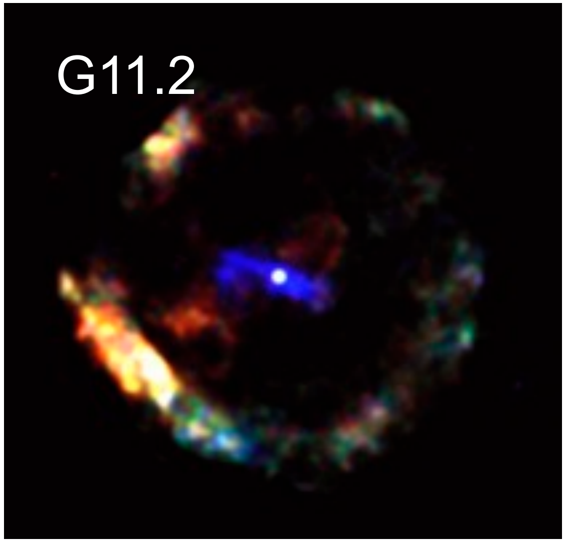
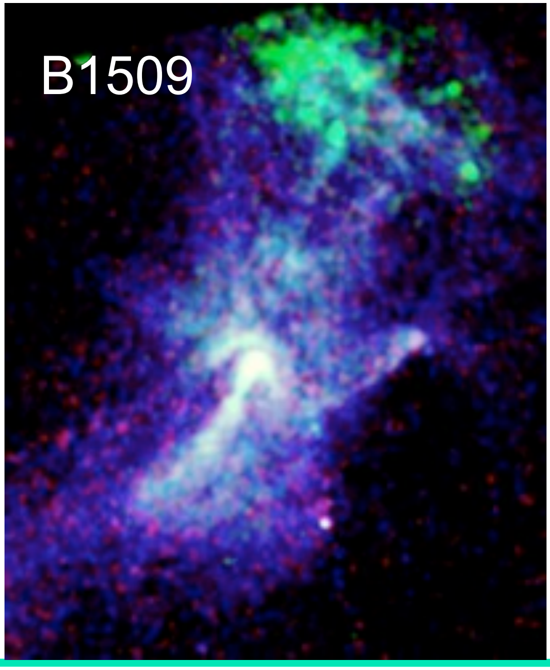
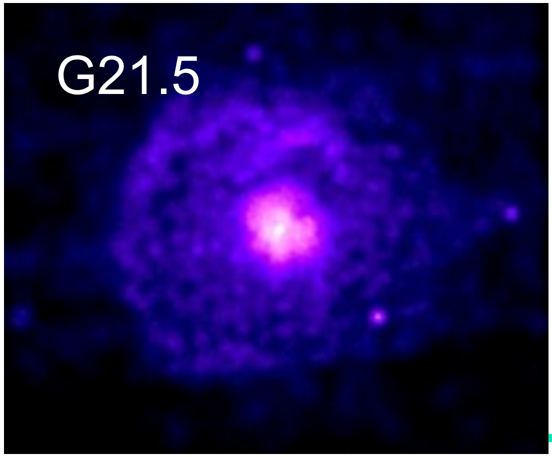




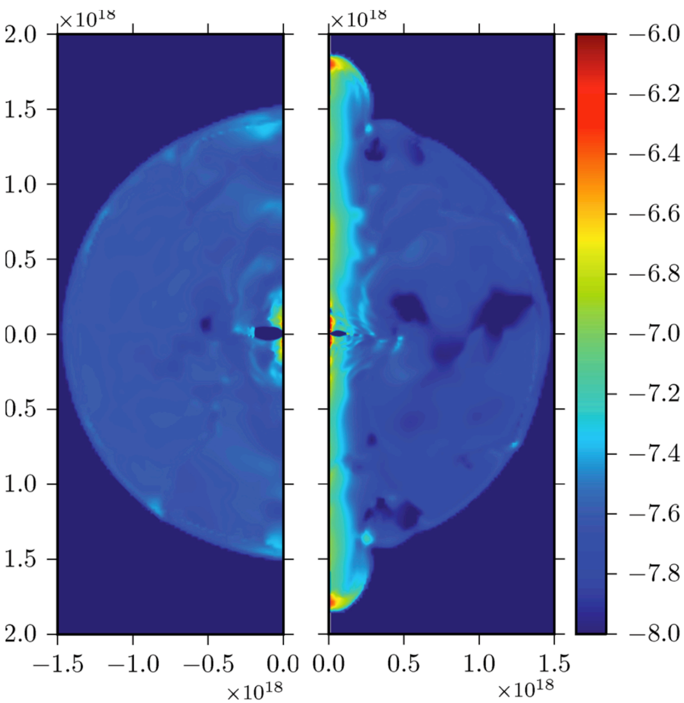


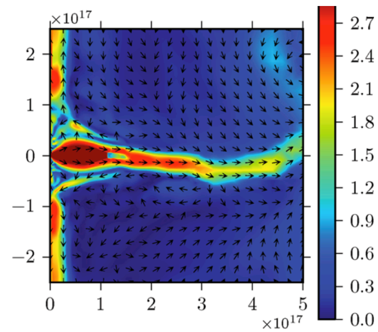


3D - Final Solution?

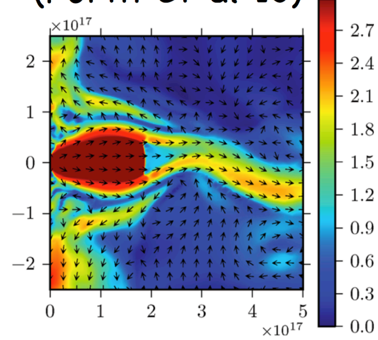
3D allows for higher sigma

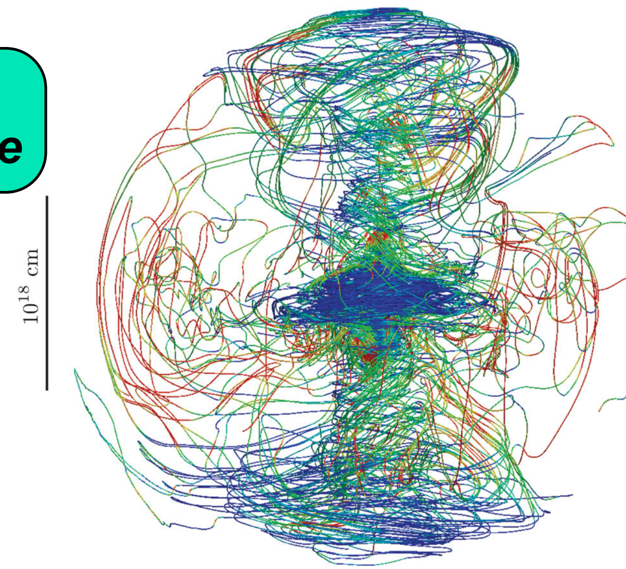
Inner region still axisymmetric - toruslike





(Porth et al 13)

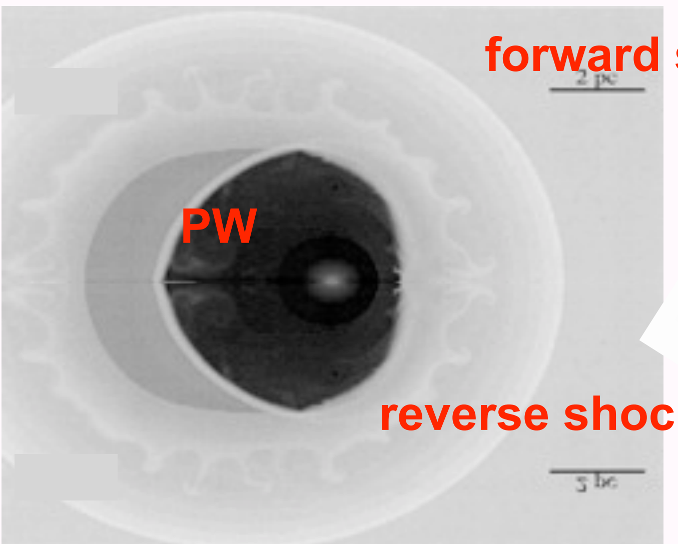




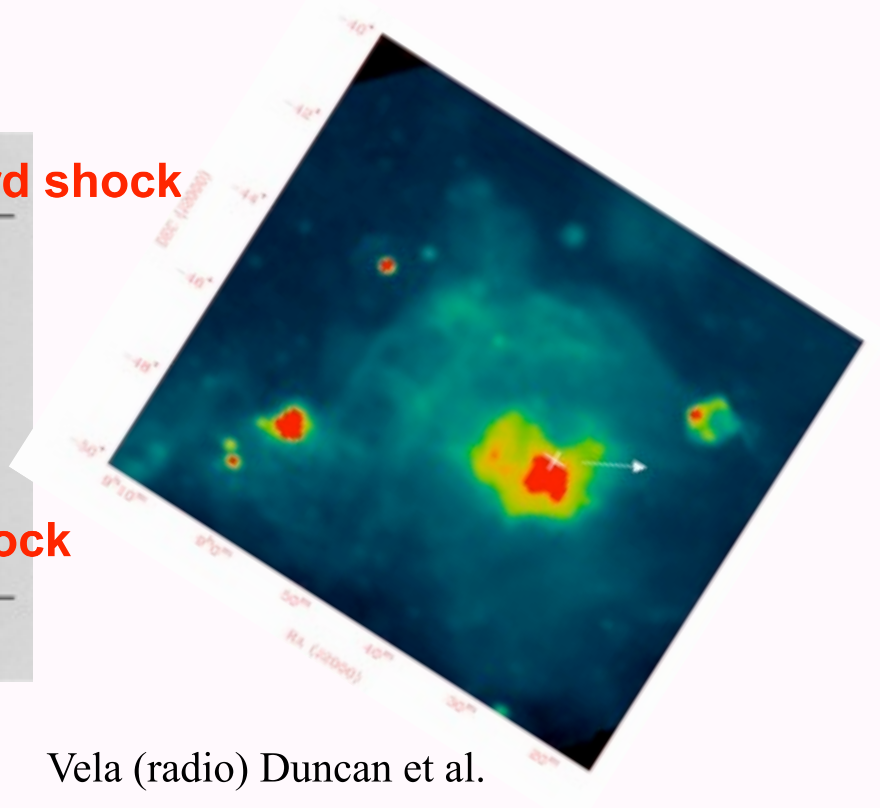
Weaker jet? Polarization?

Evolution 2D

Reverberation - Crushing by the SNR Reverse Shock



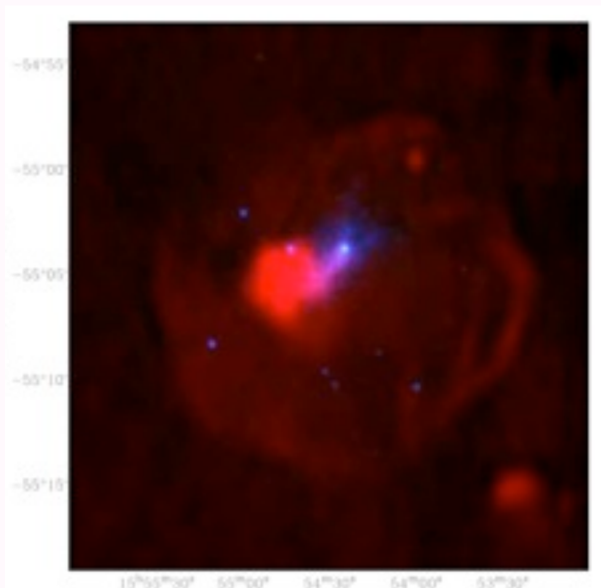
van der Swaluw et al. (2004)

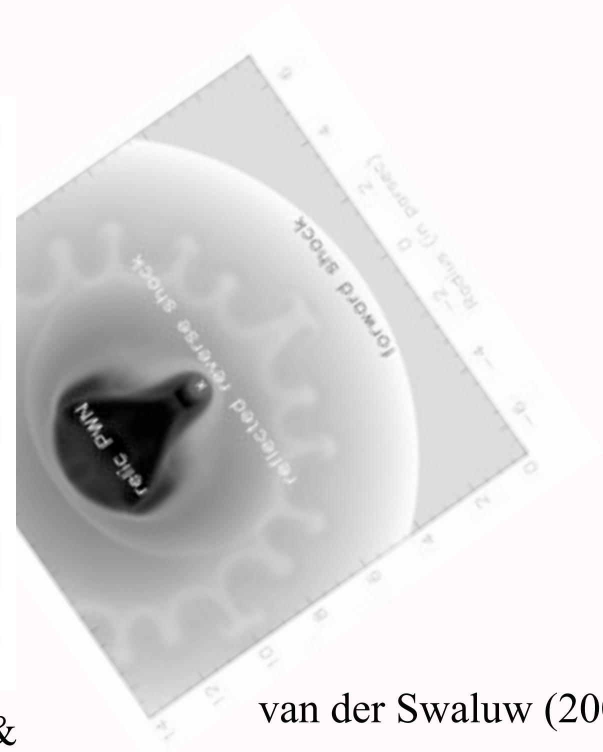


Vela (radio) Duncan et al.

Evolution 2D

Relic PWNe

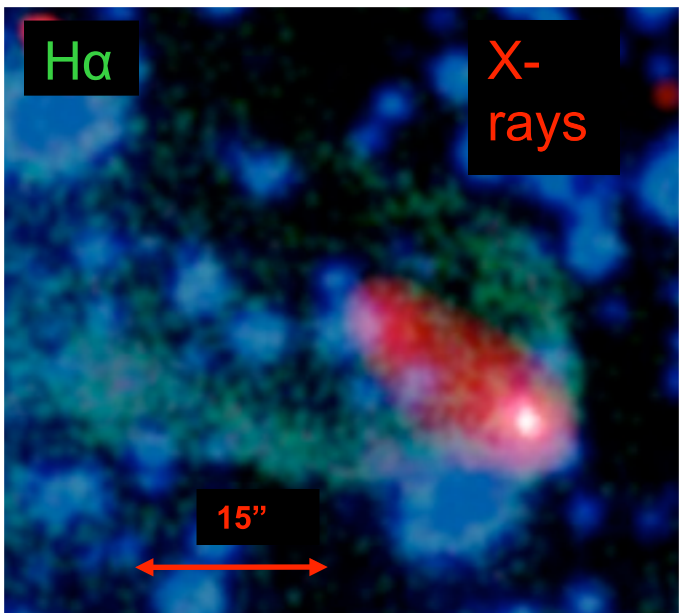




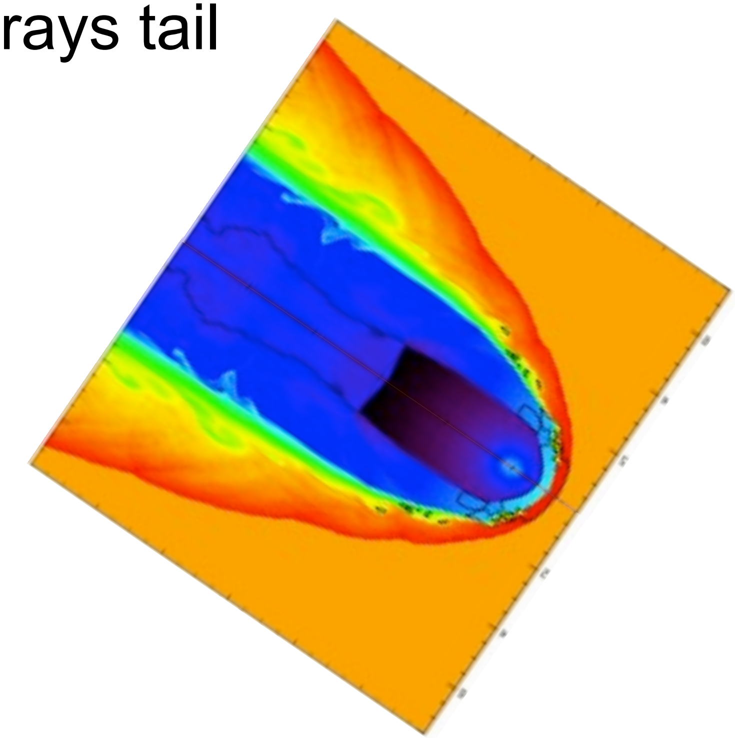
SNR G327.1-1.1, Gaensler & van der Swaluw (2004)

Evolution 2D

- Most pulsars kick velocity is supersonic in ISM
- Forward shock visible in Hα
- PWN visible as a radio and X-rays tail



PSR B1957+20 (Stappers et al. 2003)



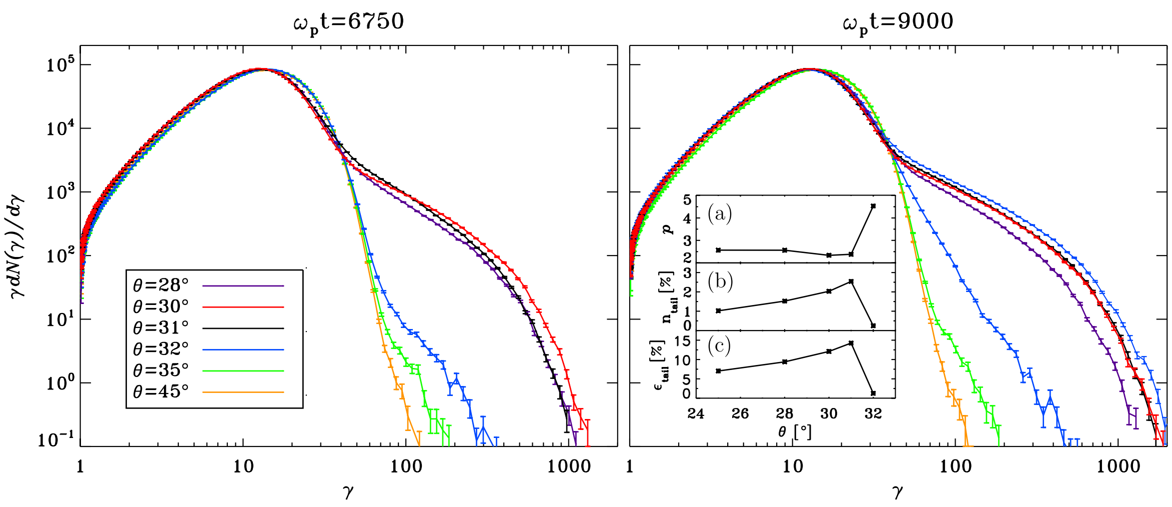
Bucciantini et al. 2005

Acceleration: Pair Plasma

Perpendicular relativistic shock - Superluminal

Maxwellian at low energies

Evidence for non-thermal tail only for subluminal shock



Spitkovsky 2006

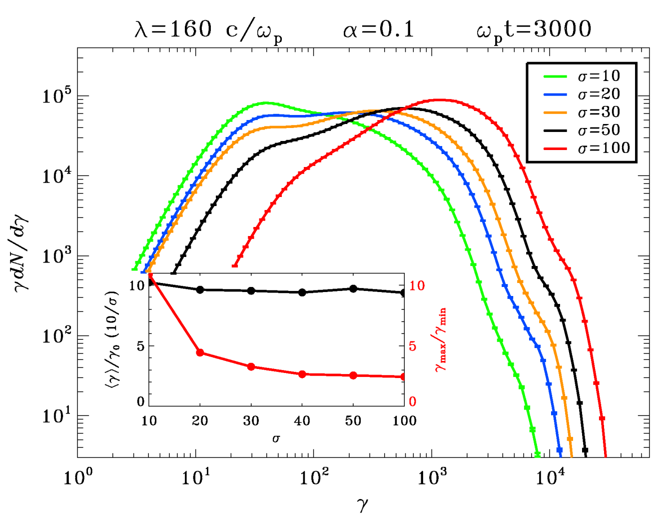
Acceleration: Striped -Wind

Reconnection in a striped wind produces hard spectra - $N(E) \sim E^{-1}$

The hard spectrum extends for an energy range from $\gamma_{min} \simeq \gamma_0$ to $\gamma_{max} \simeq \gamma_0 \, \sigma^{1/(2-p)}$

High magnetization $\sigma >= 30$ and multiplicity $>= 10^8$ Low $\gamma_0 \sim 10$

11



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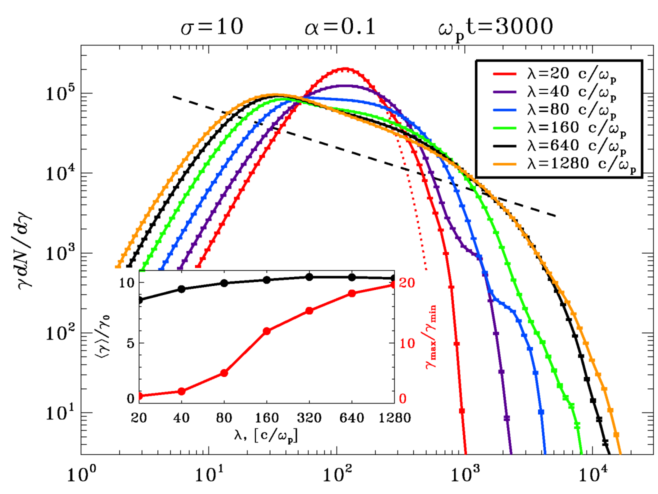
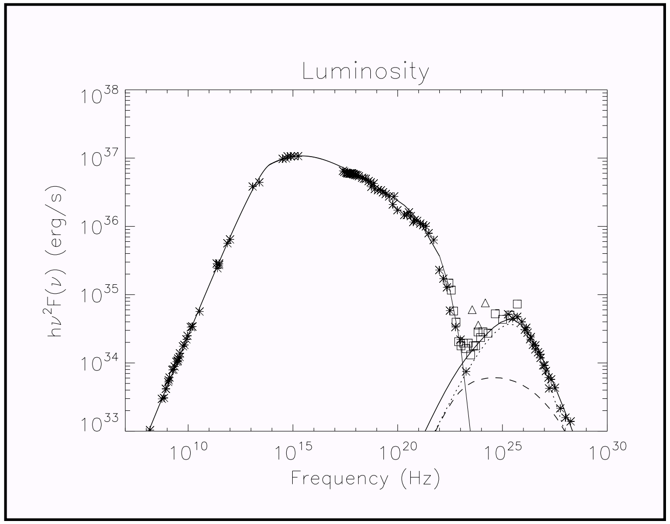


Sironi & Spitkovsky

Making what we see 1D

For all PWNe where a broad band spectrum is available we see a broken power-law :

- ***a hard part in IR/Radio - $N(E) \sim E^{-1}\ E^{-1.5}$***
- ***a soft part in Optical - $N(E) \sim E^{-2}\ E^{-2.5}$***
- ***a cooled component in X***



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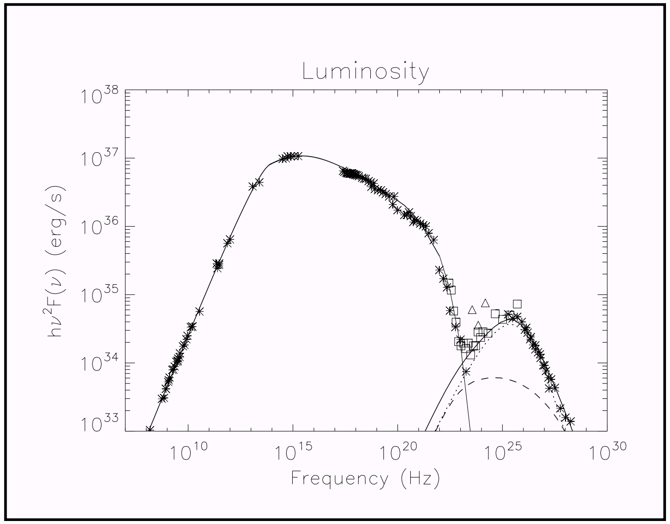
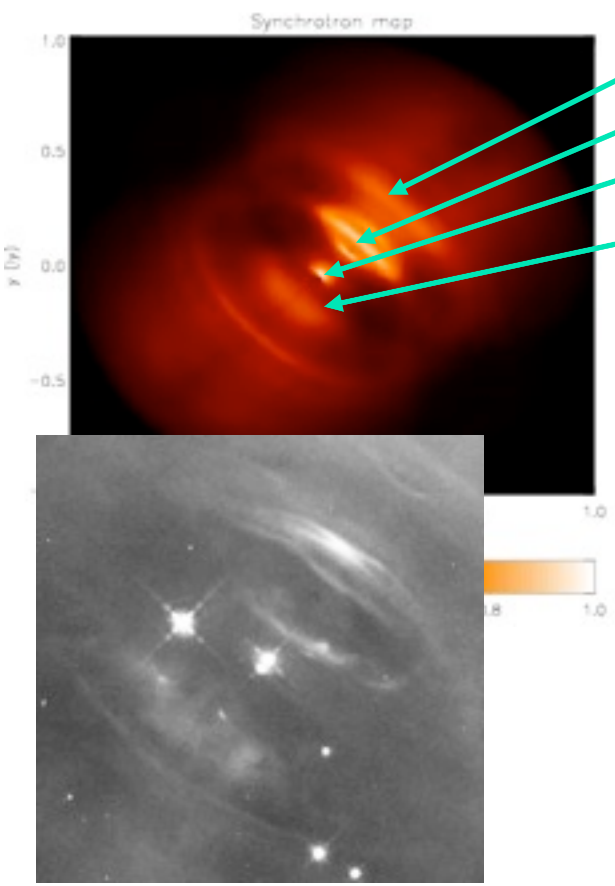


The break Lorentz factor is of order 10^5

How do we form a broken power-law?
What sets the break?
Is there a Maxwellian component?
What is the wind multiplicity?

Making what we see 2D

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



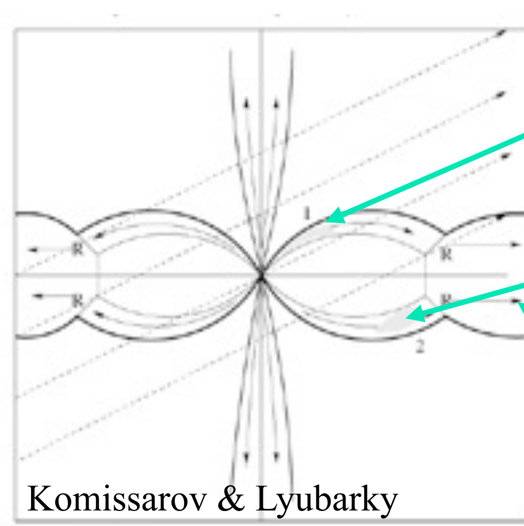
Hester et al. 1995

No jet - Axisymmetric assumption

Knot

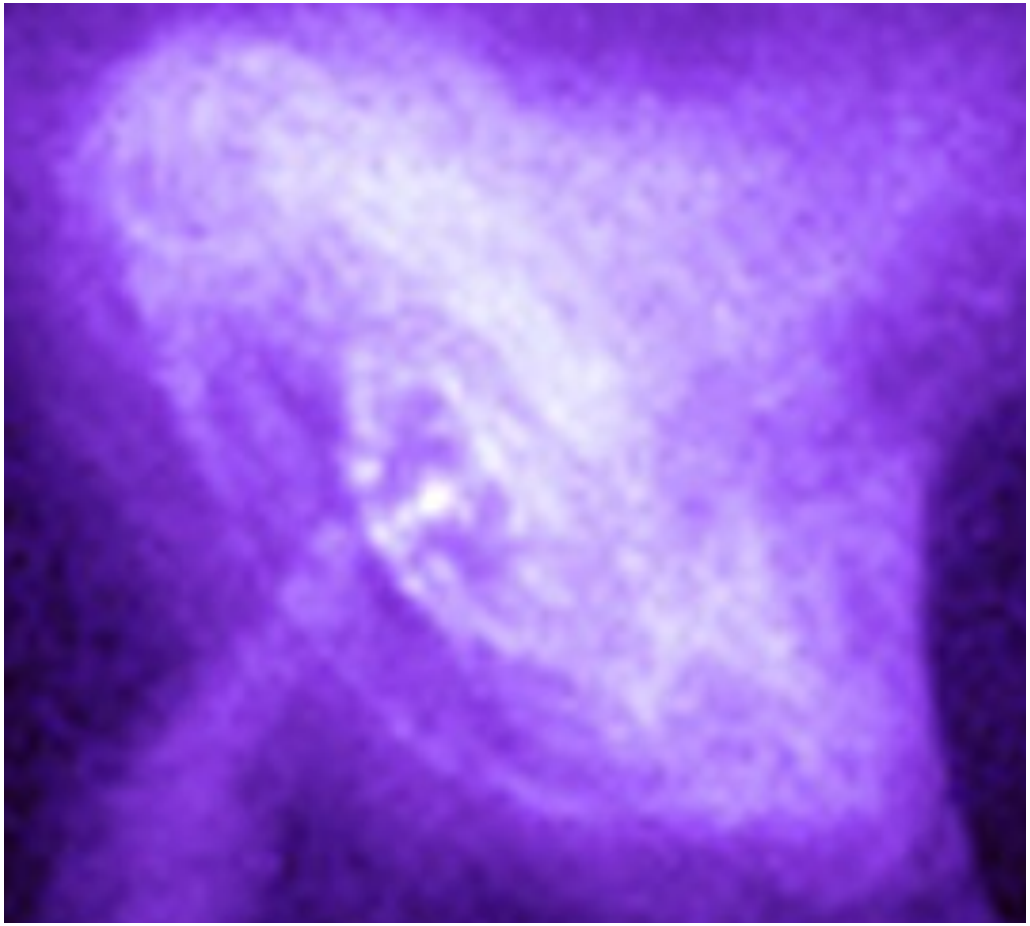
Ring

Torus



Komissarov & Lyubarky 2004

Making what we see 2D



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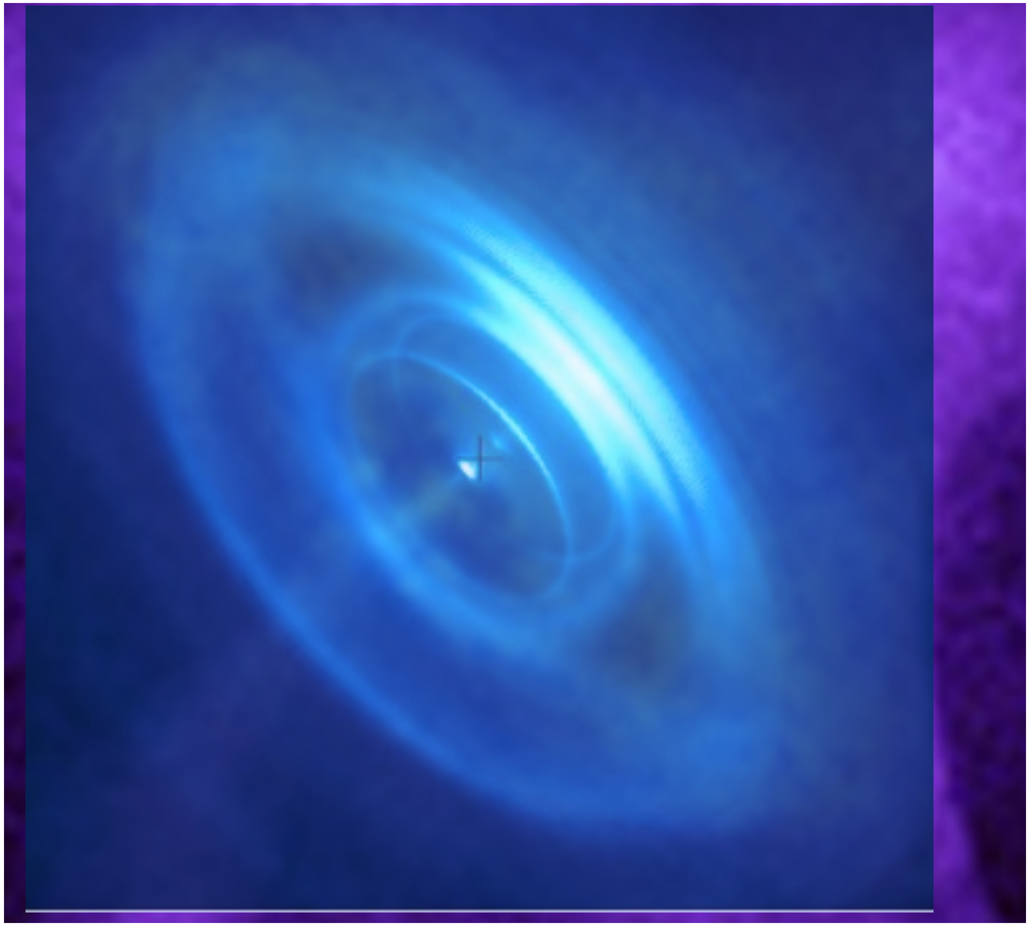
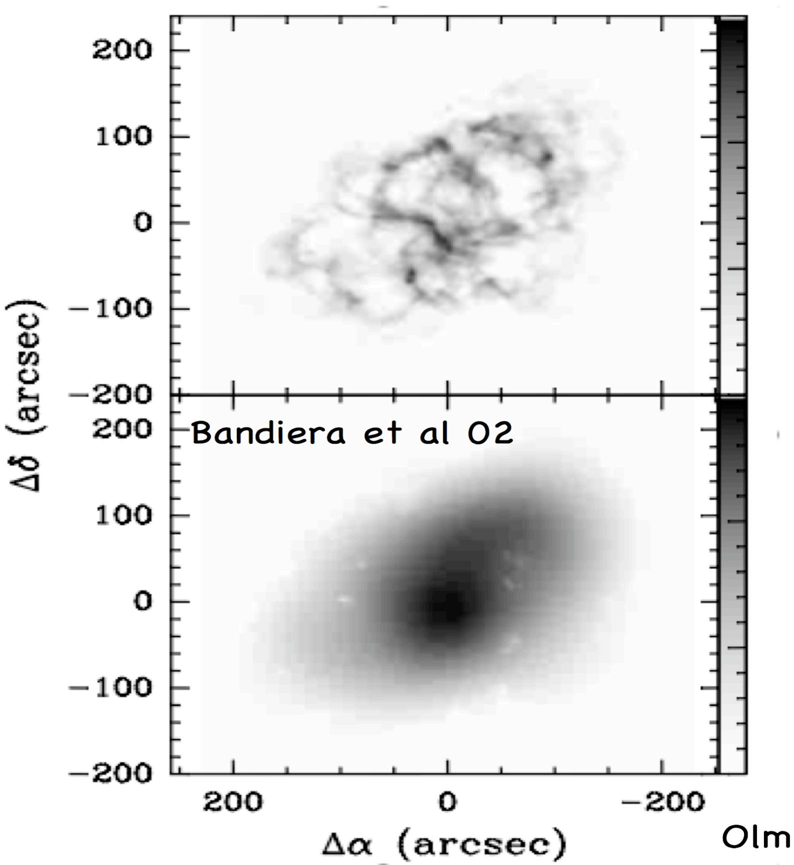
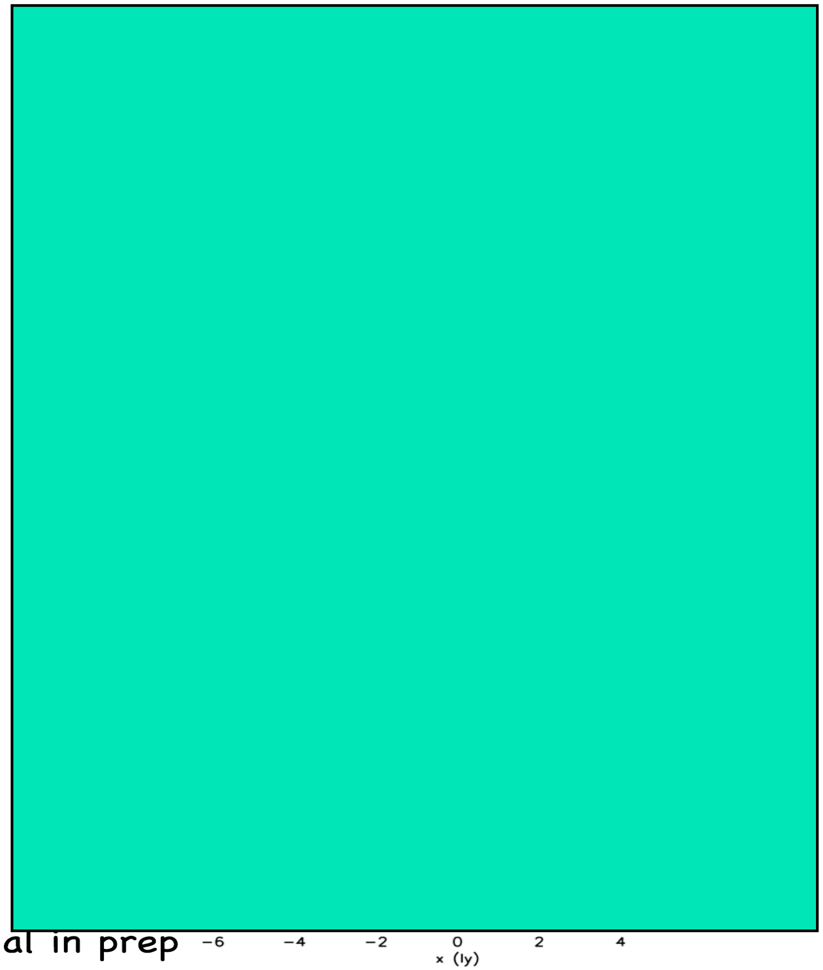


Radio particles 2D

RADIO EMISSION





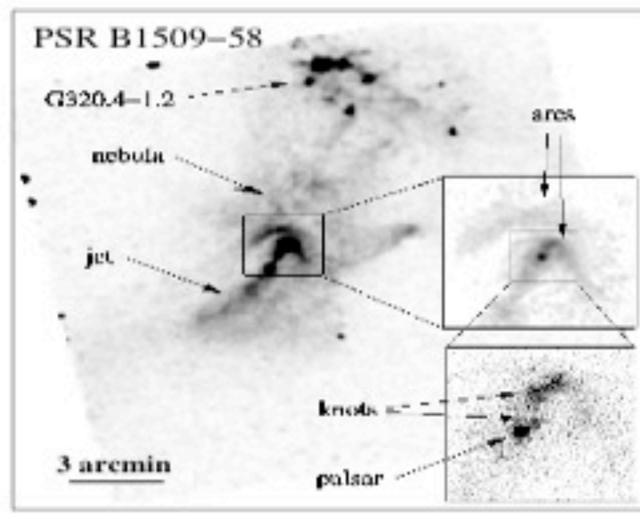
Olmi et al in prep

Time variability - wisps

- 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

MHD variability - Flow

Instability of the shear layers creates eddies at the rim shock

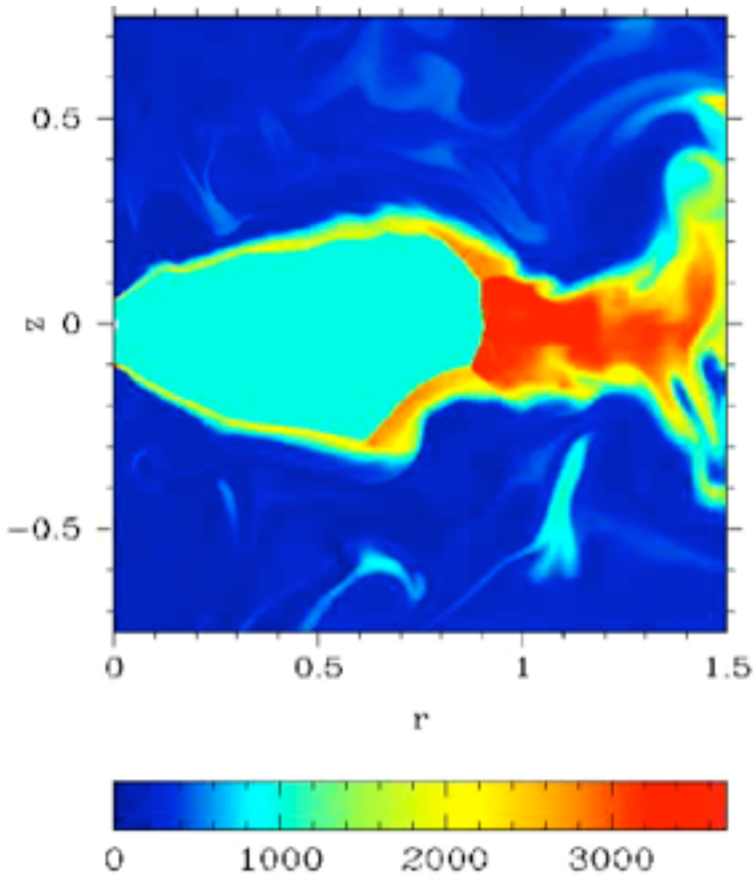
Eddies are advected outward and a toroidal pressure wave is launched

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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Wisps speed

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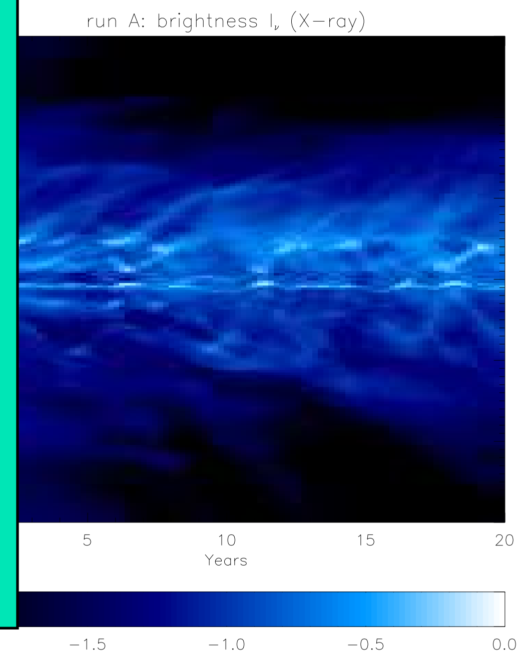

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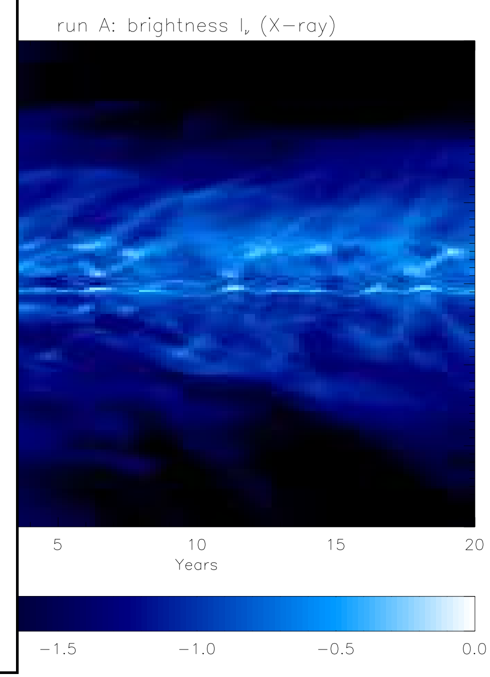
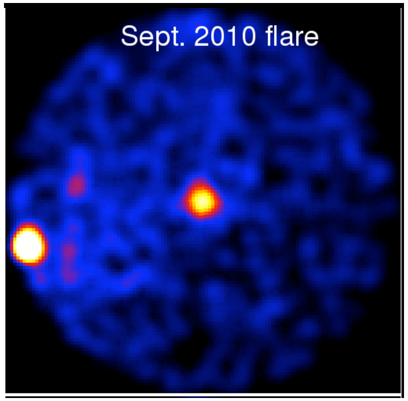
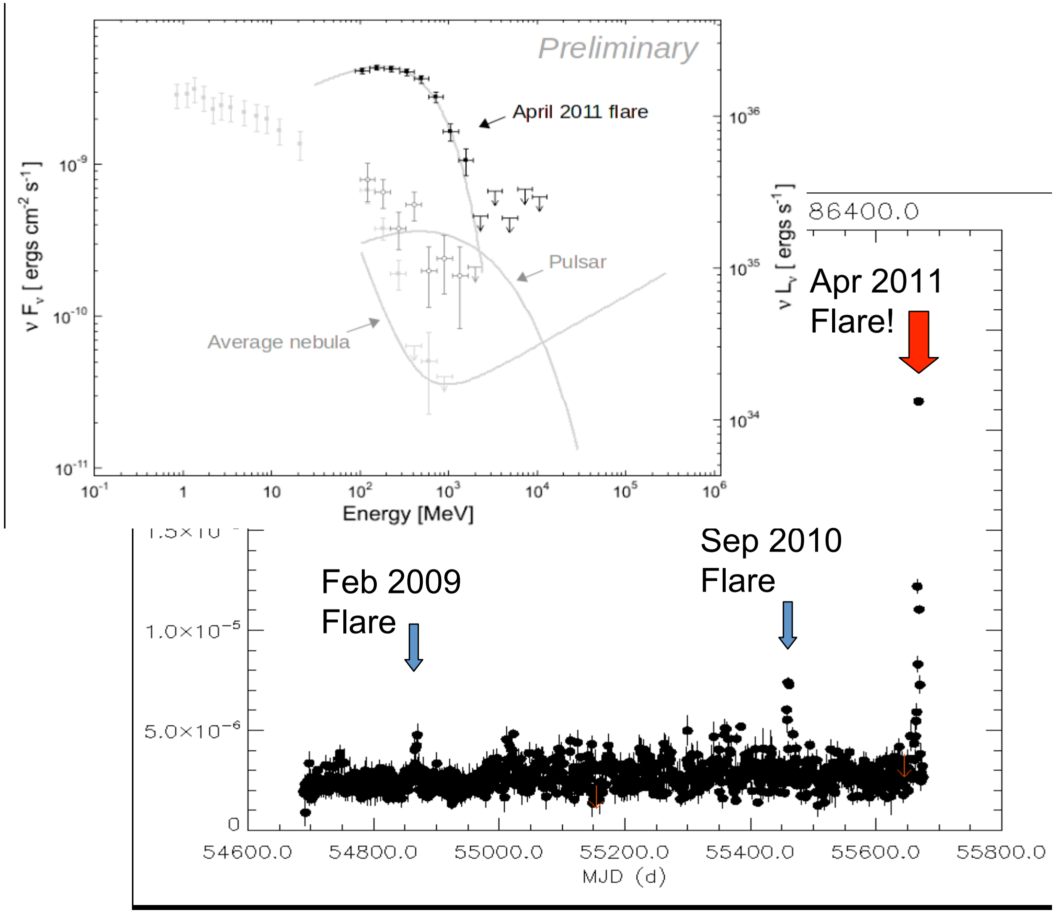


Flares

Not from pulsar :

- flares are not pulsed or in phase
- no variations in the timing residual





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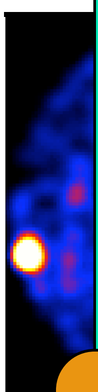
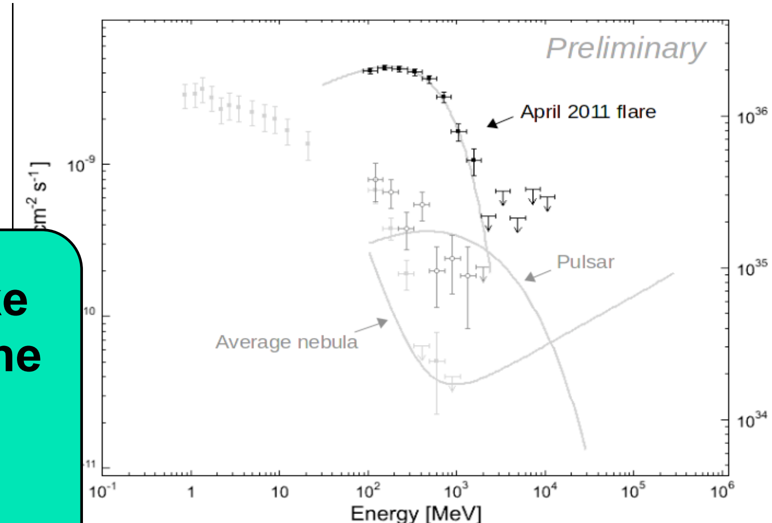
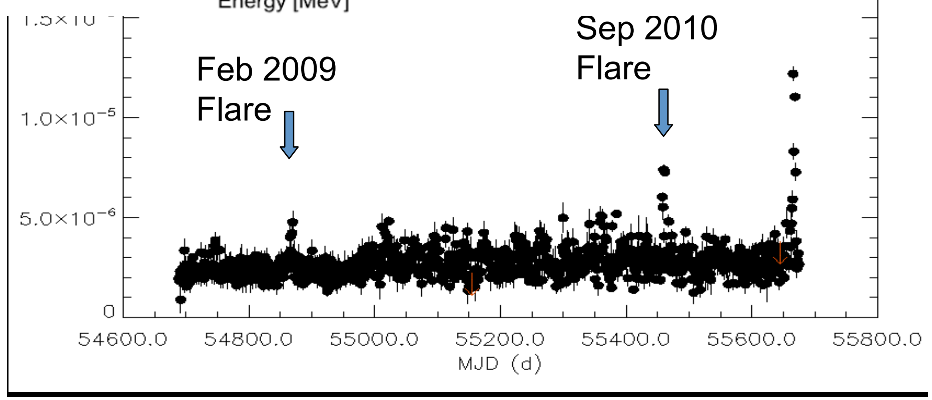


Unlikely MHD origin like the slow variability of the wisps:

- MHD effects are achromatic
- size of the accelerator is very small (day-light)
- unlikely high magnetic field

Electrostatic acceleration?





Summary and conclusions

MHD model is successful in reproducing the *persistent features*

3D model promising to solve the *sigma problem*

Unsolved issue in particles acceleration and the *origin of radio electrons*

MHD variability due to unstable Termination Shock can act as a *source of turbulence from larger scales* into the nebula (as opposed to self generated turbulence at the shock)

Very *short dynamics* (flares) and turbulence long overlooked

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Thank you