Relativistic Outflows from Compact Engines: from Pulsars to GRBs.

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Compact rotating objects (BHs and Neutron Stars) are the engines of some of the most relevant phenomena in High Energy Astrophysics, from Pulsar (PSR) to GRB. Today, thanks to the development of numerical tools for GR-MHD we are able to models these systems and relate their observed properties to the otherwise unobservable engine. The observed features and dynamics in Pulsar Wind Nebulae (PWNe) can be directly related to the wind structure and ultimately to the PSR magnetosphere. The character of the prompt emission, of the afterglow, the presence of an associated supernova (SN), and the environment, all characterize and constrain the possible central engine of Long and Short Gamma Ray Bursts (GRBs). For GRBs the two leading models are the “collapsar” and the “millisecond proto-magnetar.” I will briefly review the various criteria that any model must satisfy, and I will illustrate the key ideas behind both the collapsar and millisecond magnetar, with their strengths and weakness, especially in the light of the recent observation of the so called "late activity".

Subject : : oral
Topics : Astrophysics

Relativistic Outflows from Compact Objects: PWNe & GRBs

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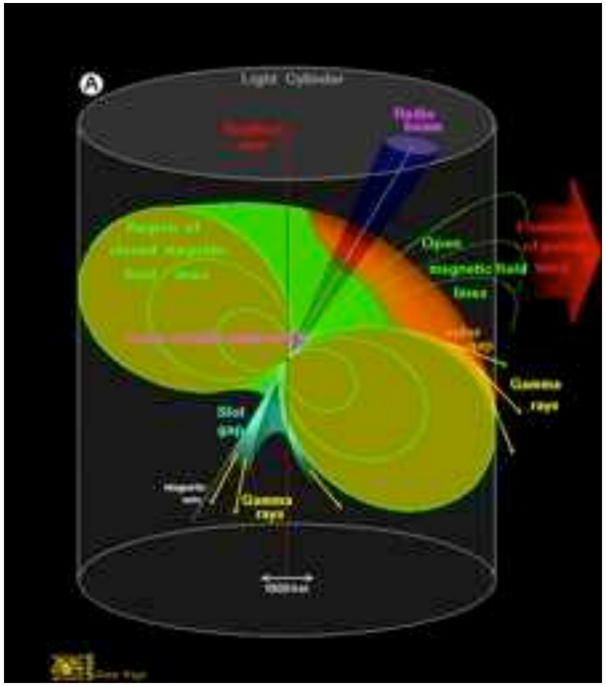
L. Del Zanna, D. Volpi, B. Olmi, S. Komissarov, N. Camus, B Metzger, E. Quataert

Prototypical central engine

The pulsar magnetosphere



$$R_{NS} = 10km$$
$$P = 0.001 - 7s$$
$$B_{surf} = 10^{8-12}G$$

Unipolar inductor (AGN, GRB, Magnetar)
EM extraction of rotational energy.

Acceleration of particle pair plasma-ions from the surface:
Initial Lorentz factor ~ 100
Cold wind (Sync. losses)

The FF limit

No exact solution even for the simple monopole-like case

$$\sigma \approx \Phi^2\Omega/\dot{M} \longrightarrow \gamma_\infty \sim \sigma^{1/3} \quad \sigma_\infty \sim \sigma^{2/3}$$

Conversion of magnetic energy is logarithmic after the fast p.

No collimation for a relativistic wind

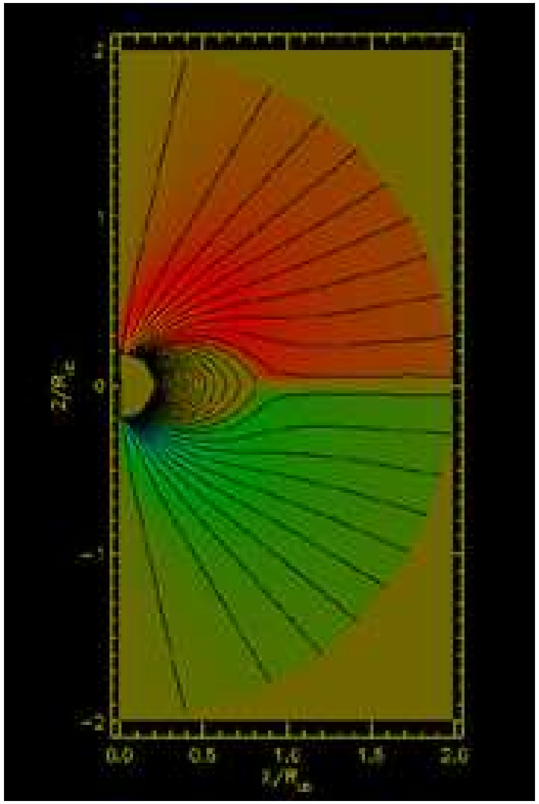
$$\gamma >> 1 \Rightarrow \rho_q \overline{E} + \bar{j} \times \overline{B} \approx 0$$

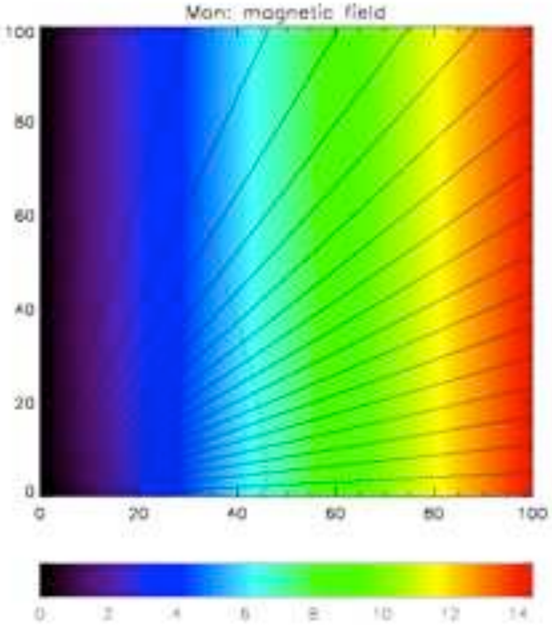
Force Free Pulsar Equation

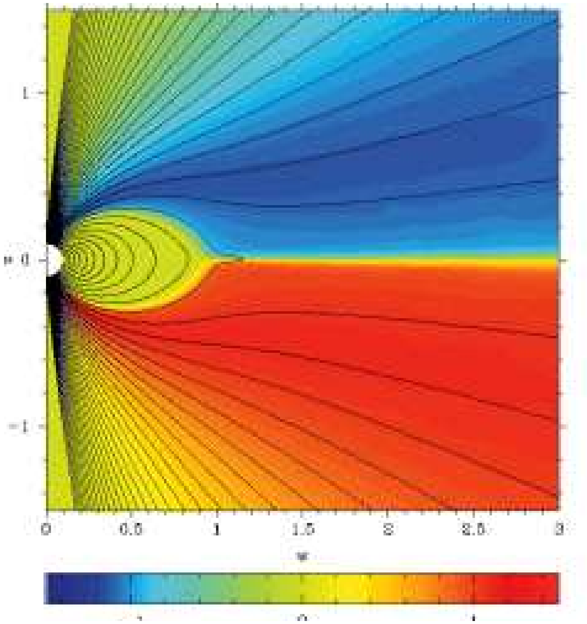
$$(1-\rho^2\Omega^2)\left[\frac{\partial^2 f}{\partial\rho^2}+\frac{1}{\rho}\frac{\partial f}{\partial\rho}+\frac{\partial^2 f}{\partial z^2}\right]-\frac{2}{\rho}\frac{\partial f}{\partial\rho}=-A\frac{dA}{df}+\rho^2\Omega\frac{d\Omega}{df}\left[\left(\frac{\partial f}{\partial\rho}\right)^2+\left(\frac{\partial f}{\partial z}\right)^2\right],$$

Wind models

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

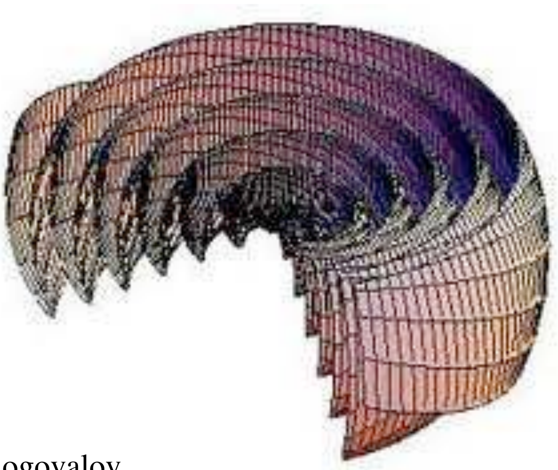




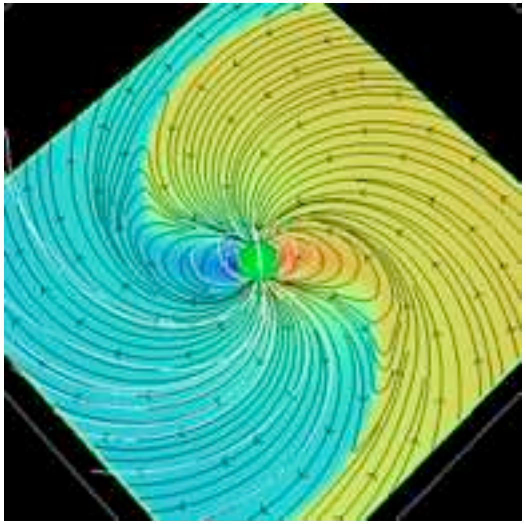


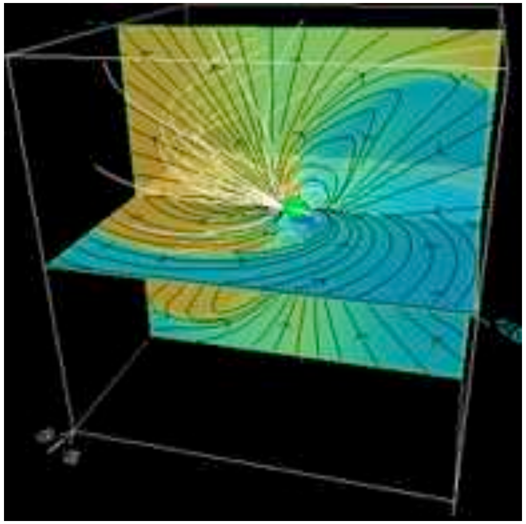
Lorentz factor ~ sin(θ)
Energy flux ~ sin²(θ)

Striped Wind - More Geometry



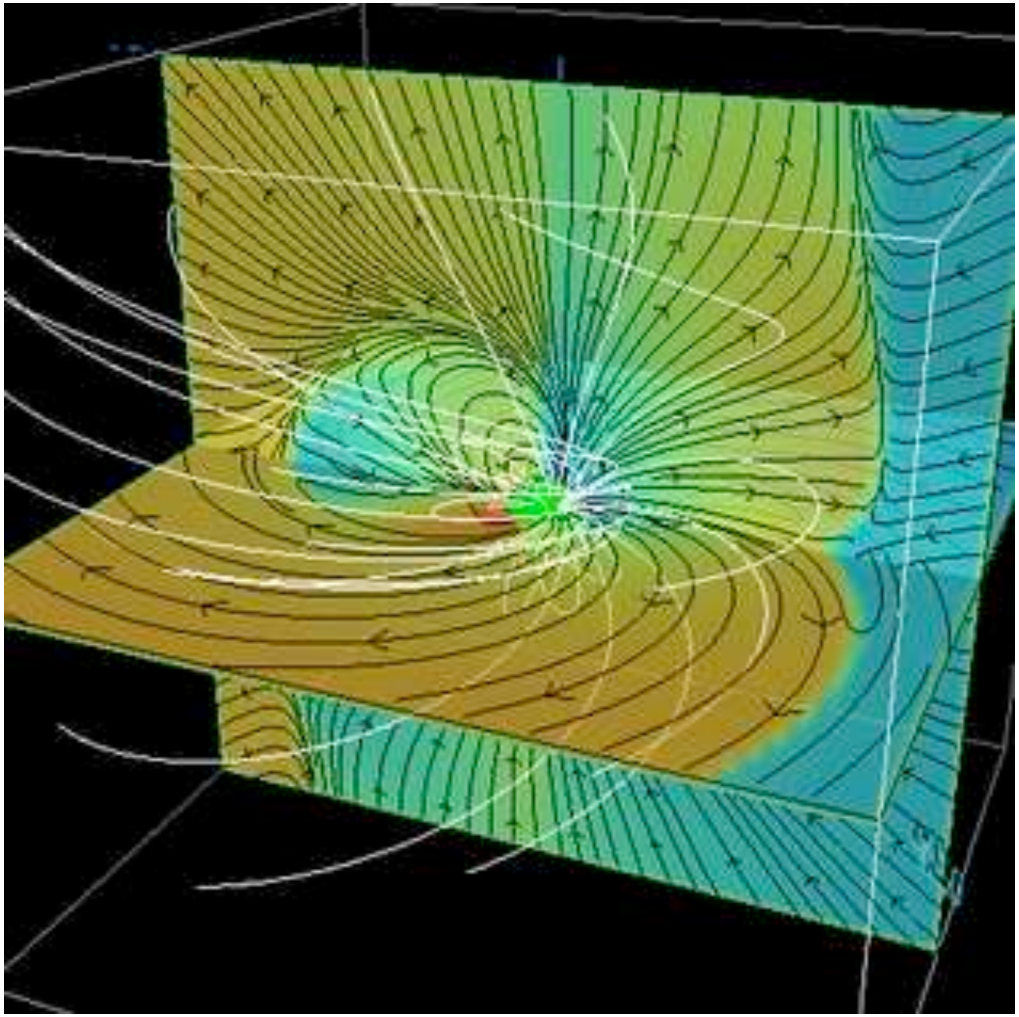
Bogovalov





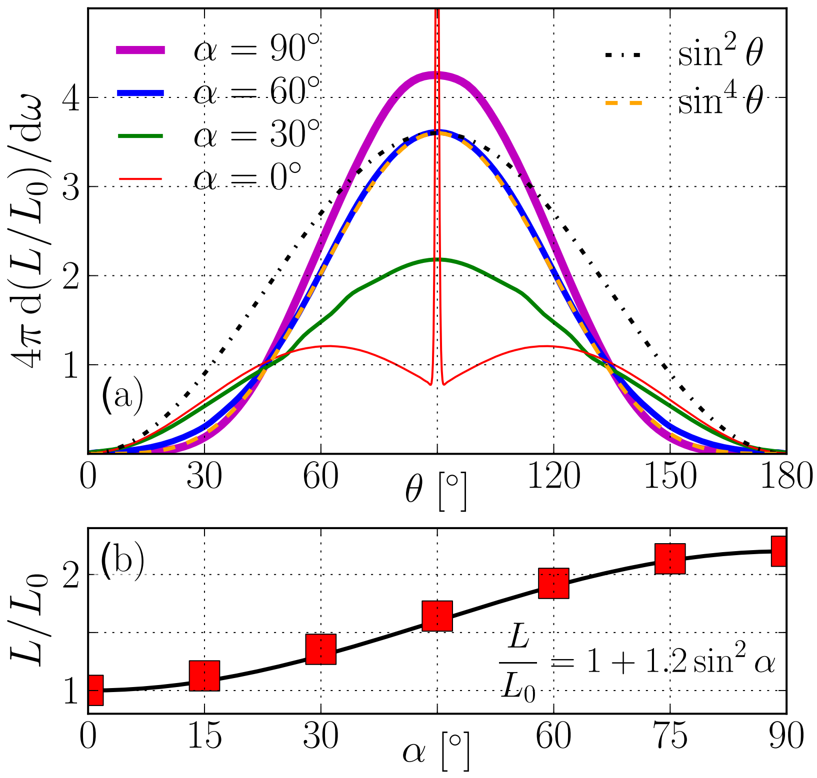
Spitkovsky

The global wind



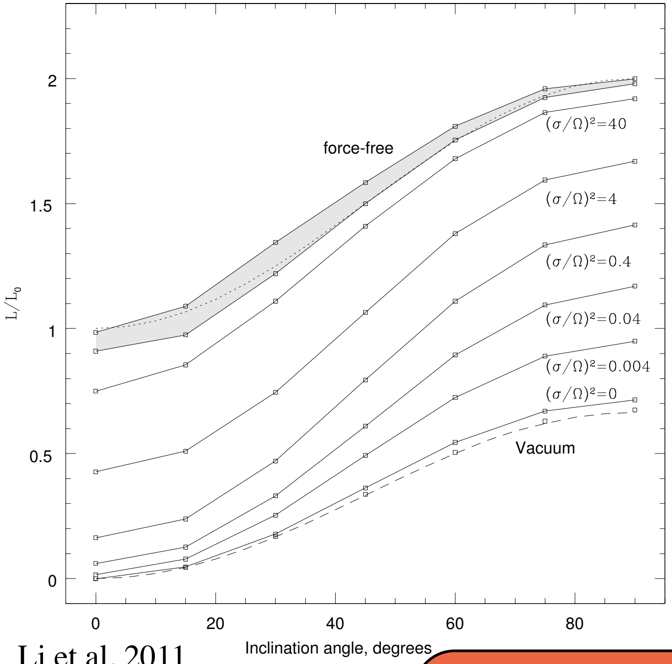
Spitkovsky

Energy Losses



Tchekhovskoy et al. 2012

The wind luminosity has a latitudinal structure that depends on the magnetic inclination of the pulsar

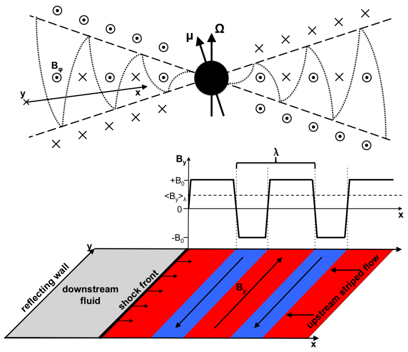


Li et al. 2011

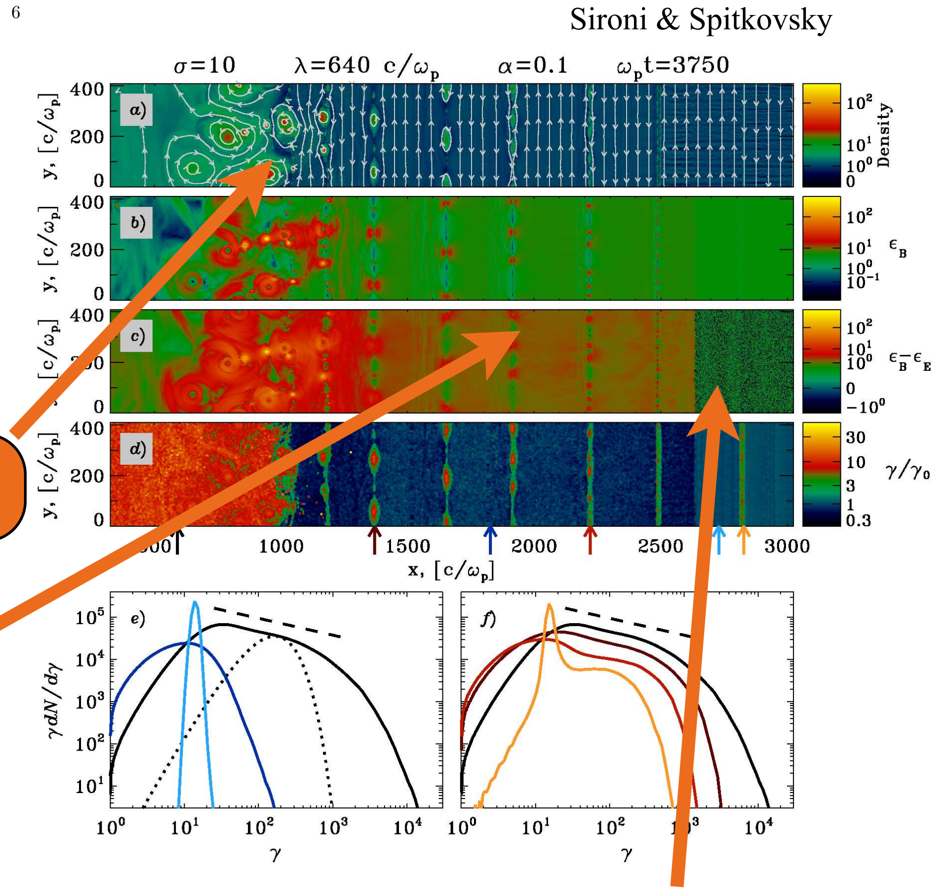
It also depends on the Efficiency of the gap to establish FF regime

Striped -Wind

In a striped wind reconnection of alternating fields can accelerate particles



HD shock



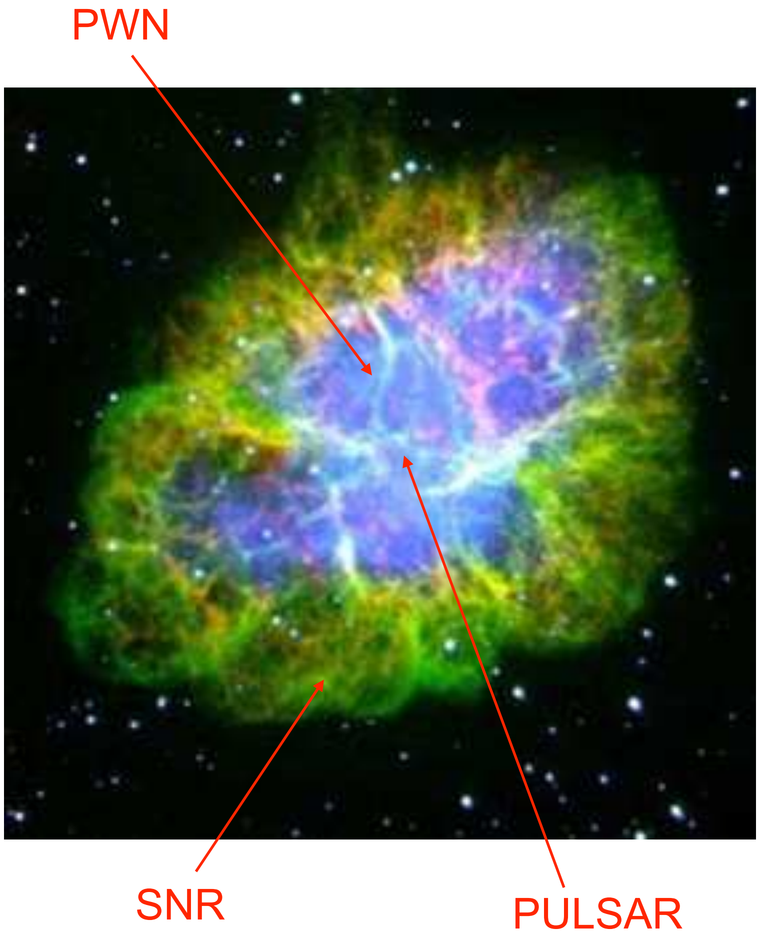
Tearing modes reconnection

Hard spectrum

Fast-magnetosonic precursor

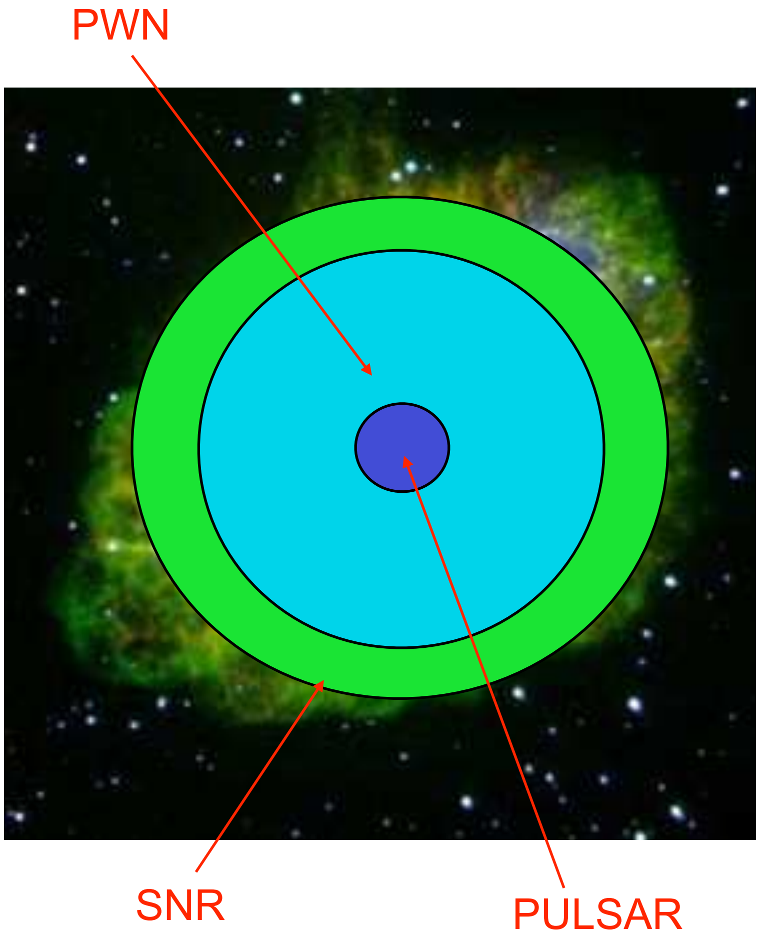
Interaction
I
PWNe

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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Cartoon

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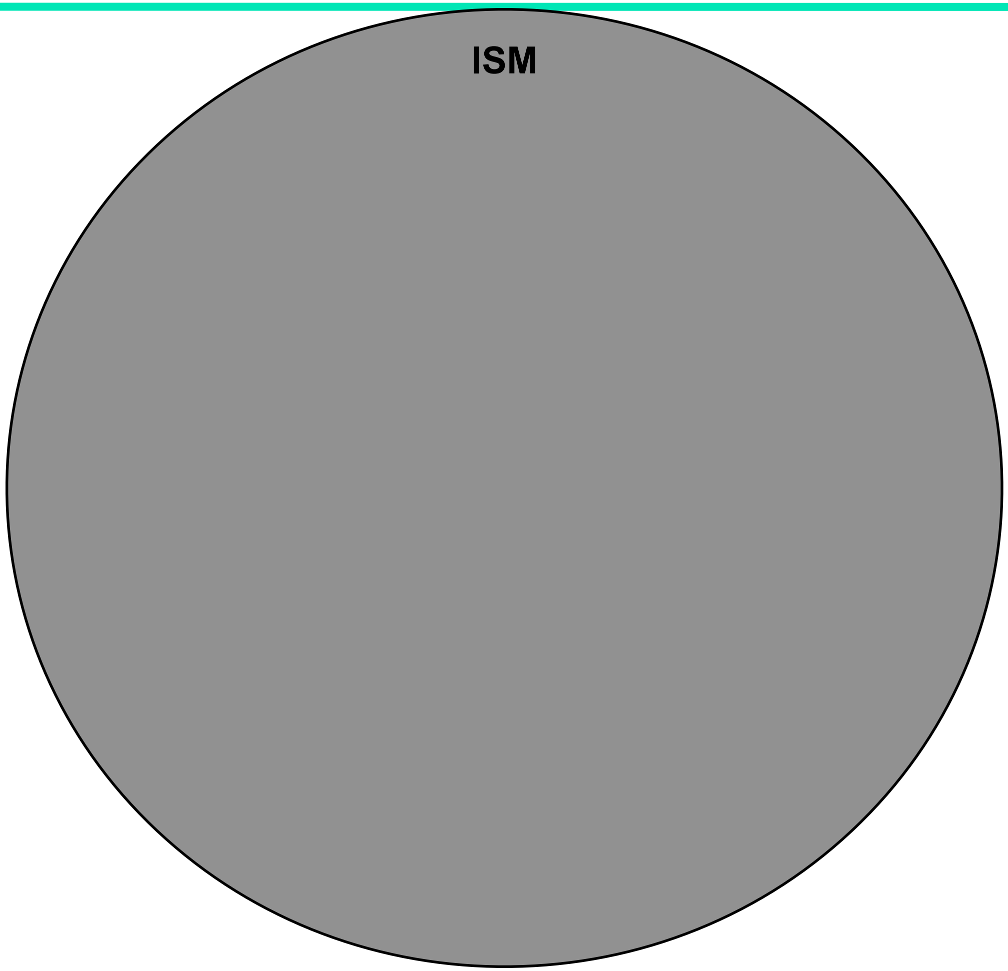

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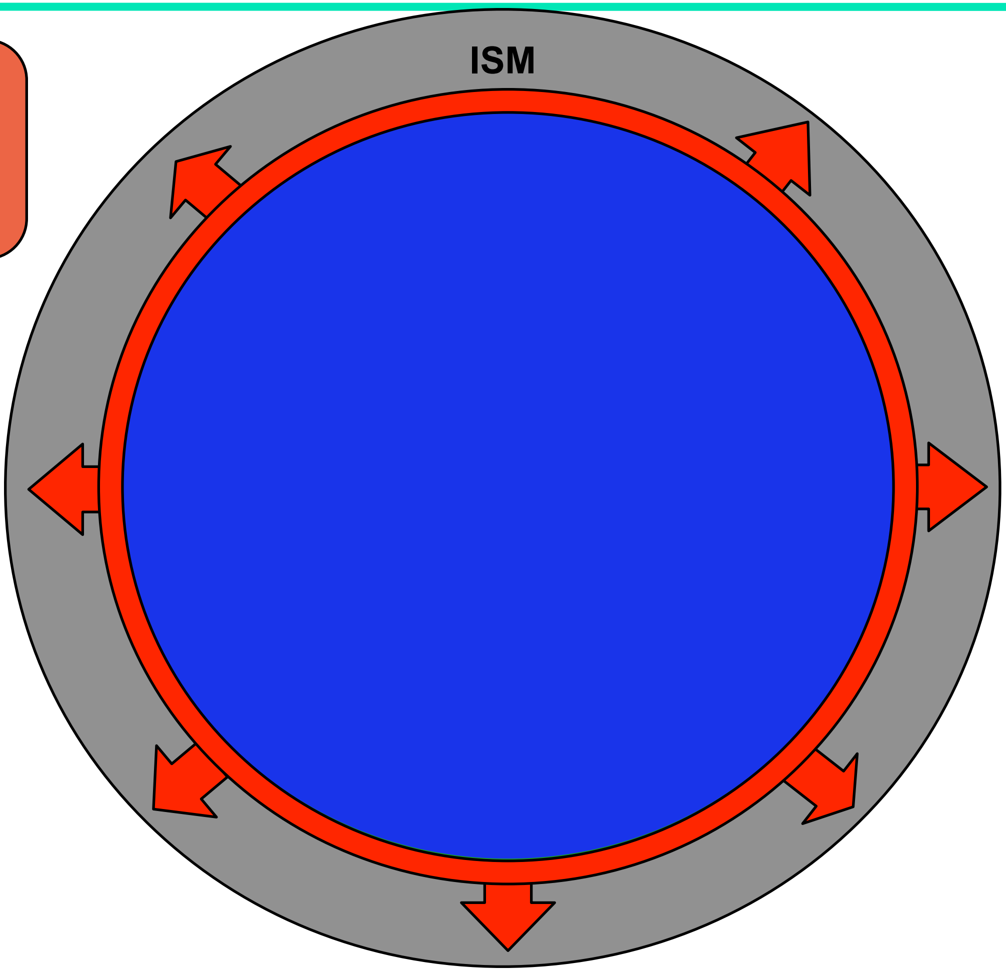
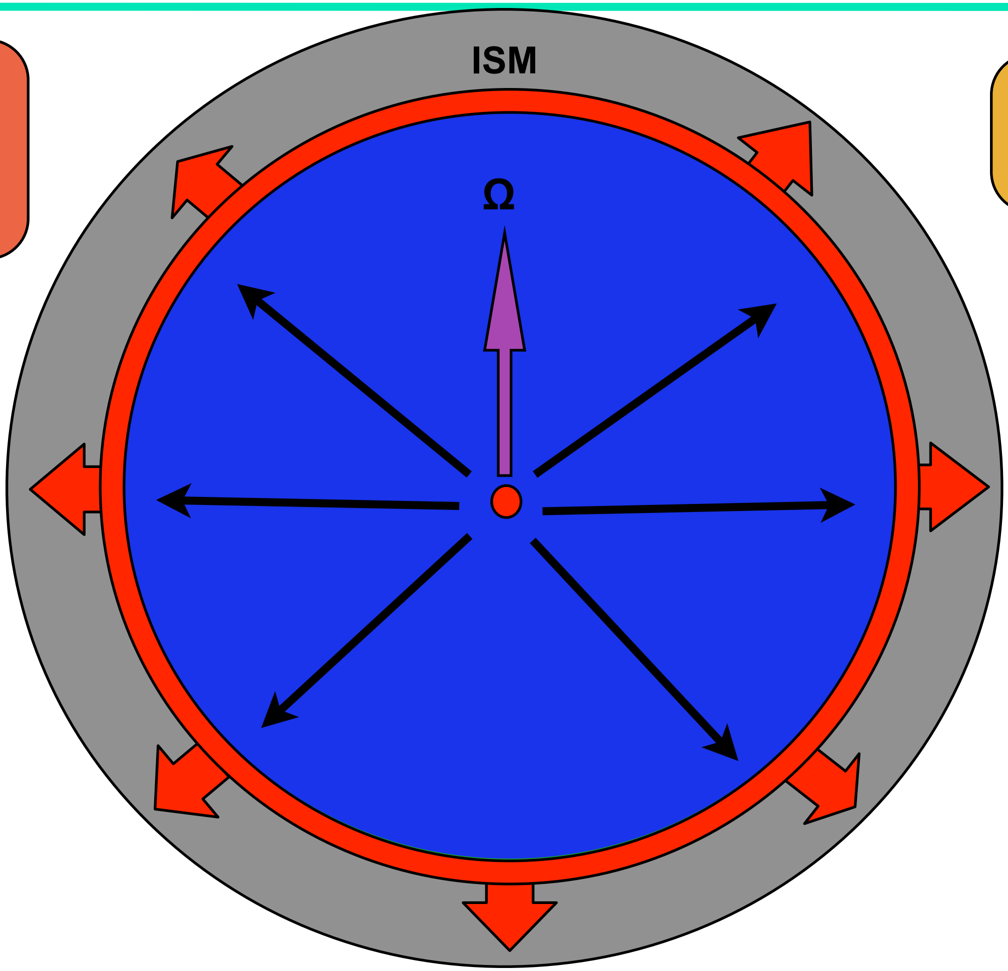


Outgoing Shell
V_{snr} ~ 0.003-0.01c
SNR Shell

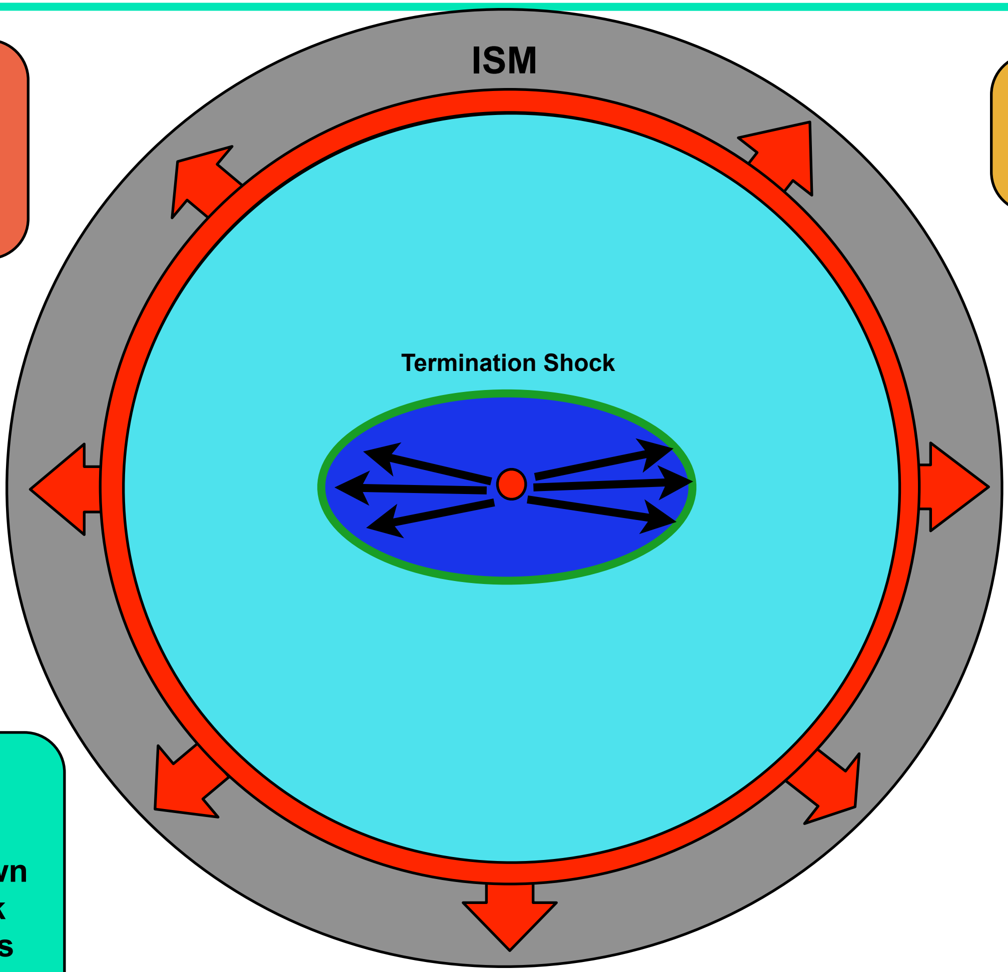
Cartoon

Outgoing Shell
$V_{snr} \sim 0.003\text{-}0.01c$
SNR Shell



The cavity is swept by the PRS wind

Cartoon



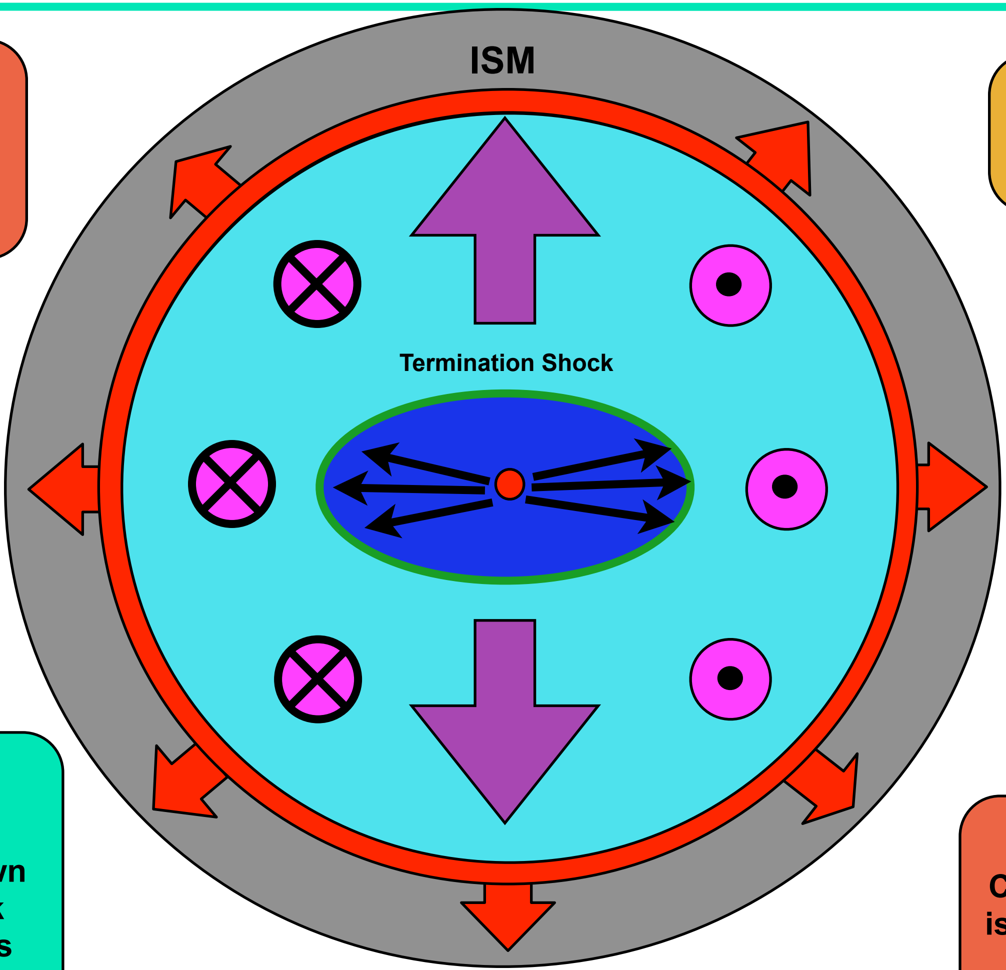
Outgoing Shell
V_{snr} ~ 0.003-0.01c
SNR Shell

The cavity is swept by the PRS wind

$V_{sn} << V_{wind}$

The wind is slowed down in a termination shock
A pulsar wind nebula is formed

Cartoon



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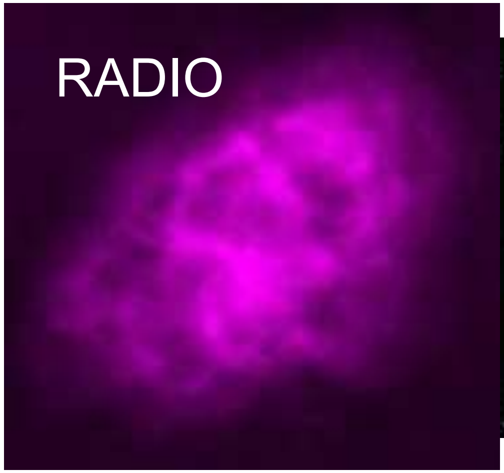
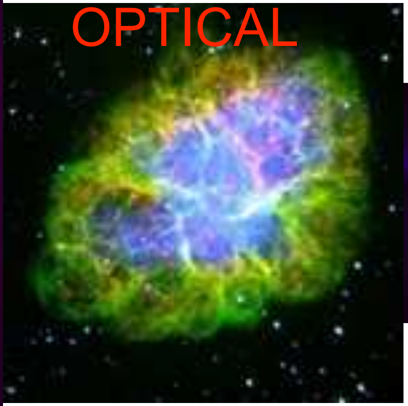
Compressed magnetic field is mostly toroidal and press along the axis

Crab Nebula - a prototype

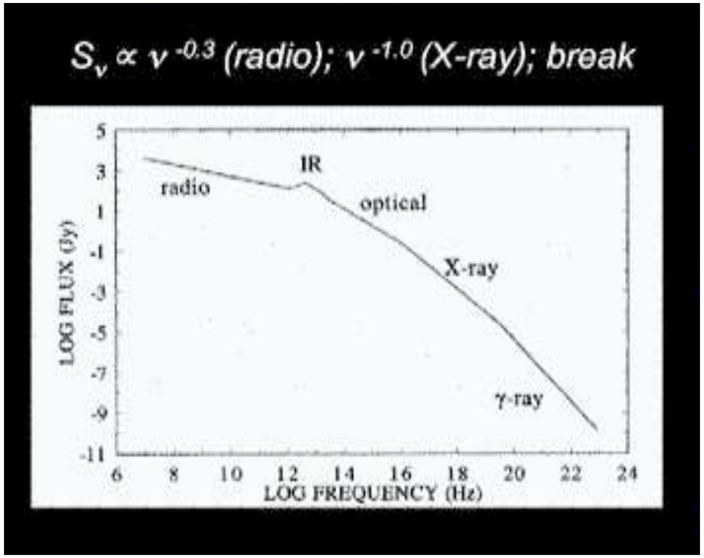

RADIO


OPTICAL

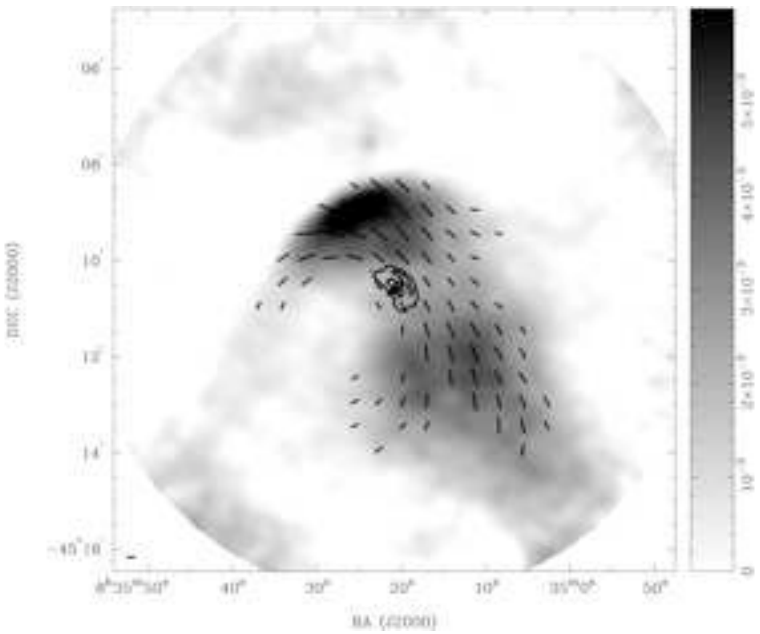

X-RAYS

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.

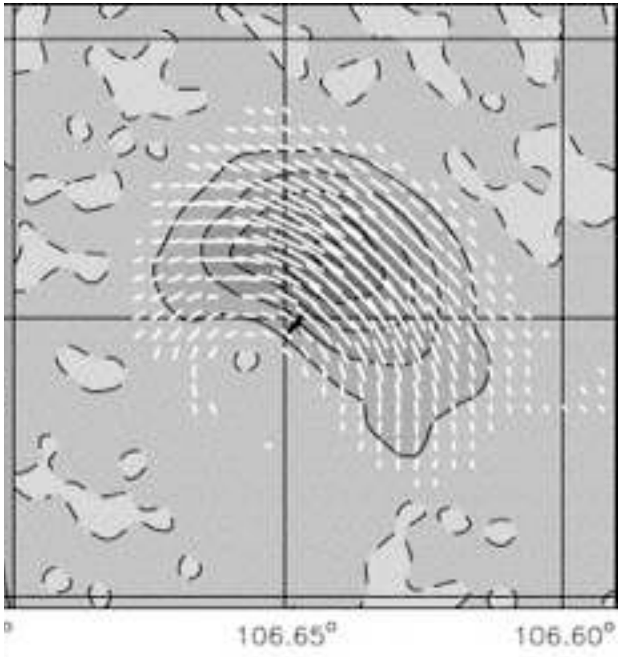
Max particle energy > 3×10^{15} eV, comparable to pulsar voltage.
Nebular shrinkage indicates one accelerating stage:
require $10^{38.5} - 10^{39}$ $e^{\pm}$ /s, radio mystery
PSR also injects B field into nebula (~10^{-4} G)


$S_\nu \propto \nu^{-0.3}$ (radio); $\nu^{-1.0}$ (X-ray); break

Polarization - magnetic field



Vela, Dodson et al 03

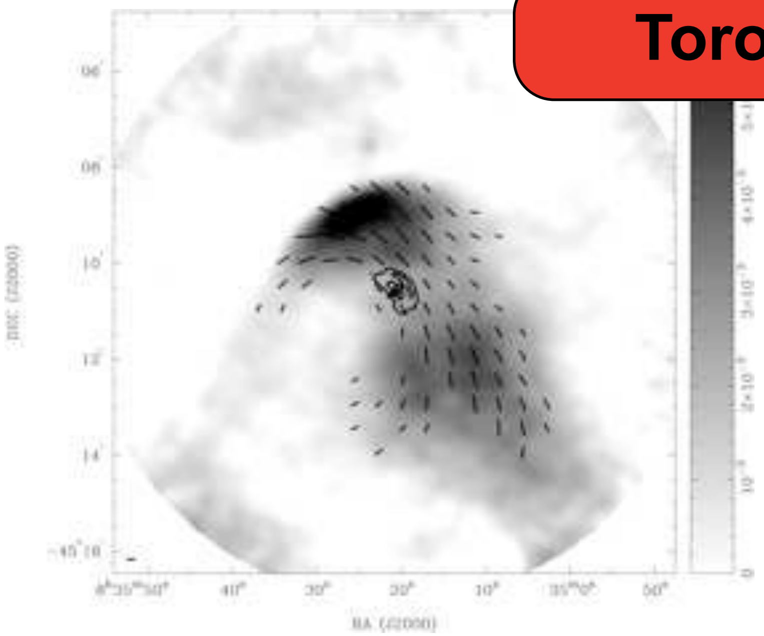


G106.6+29, Kothes et al 06

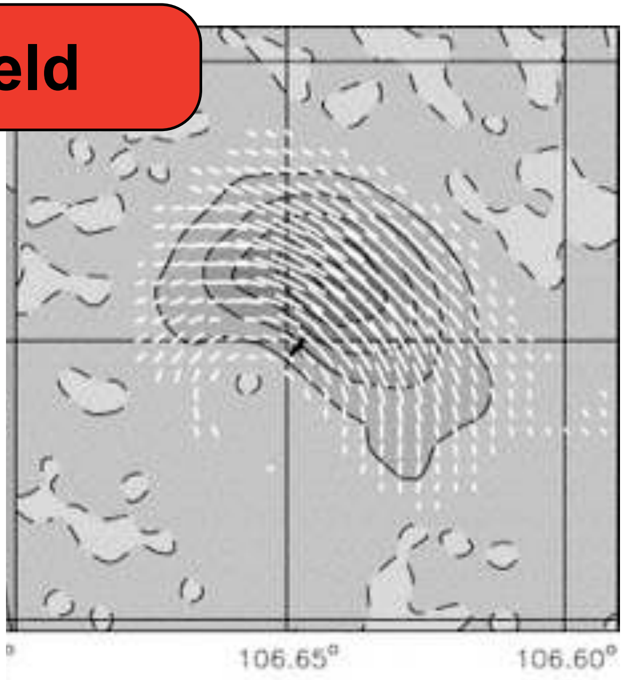
Old nebulae interacting with ejecta - distorted stretched field in the back direction

Polarization - magnetic field

Toroidal field



Vela, Dodson et al 03

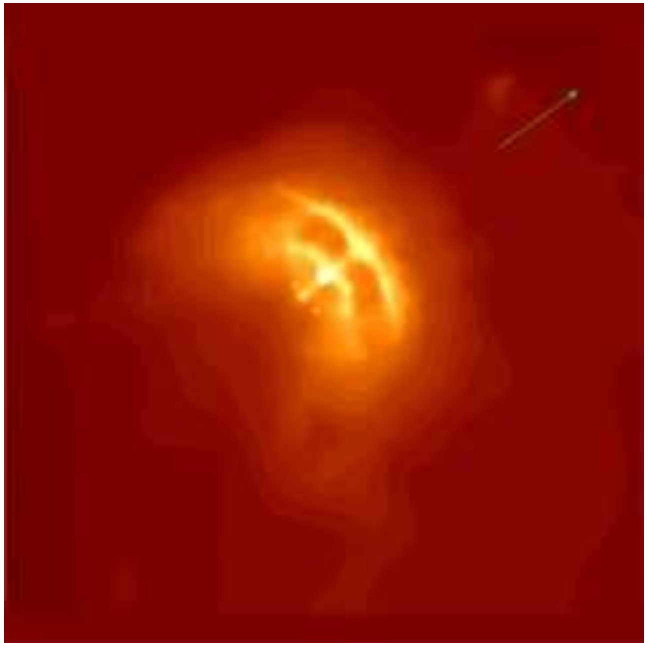


G106.6+29, Kothes et al 06

Old nebulae interacting with ejecta - distorted stretched field in the back direction

Fine structures

Crab



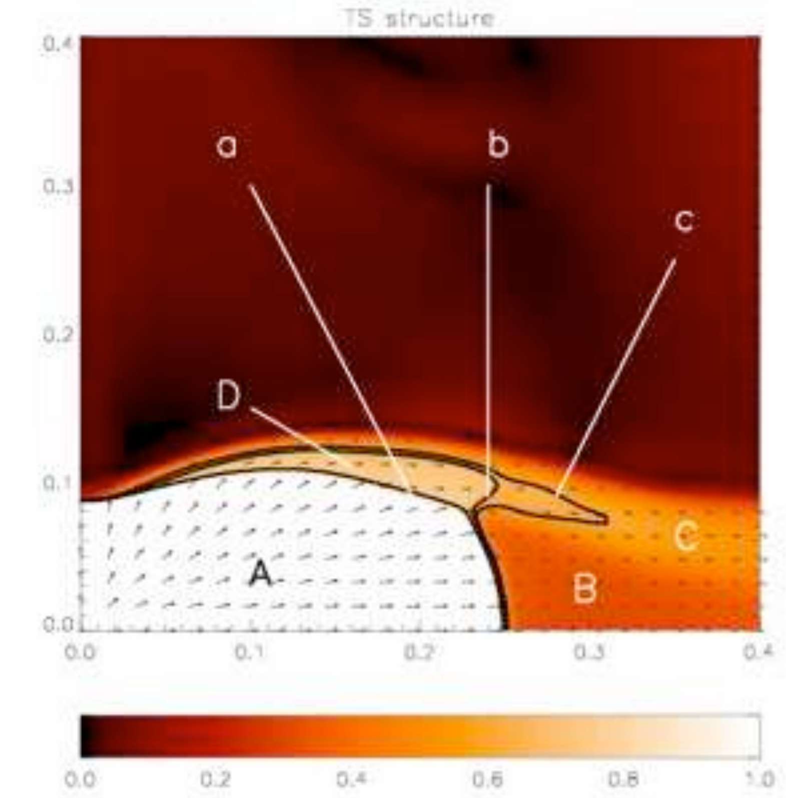
Vela

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

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=0.03



TS structure and flow pattern

- The wind anisotropy shapes
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  - low
  -
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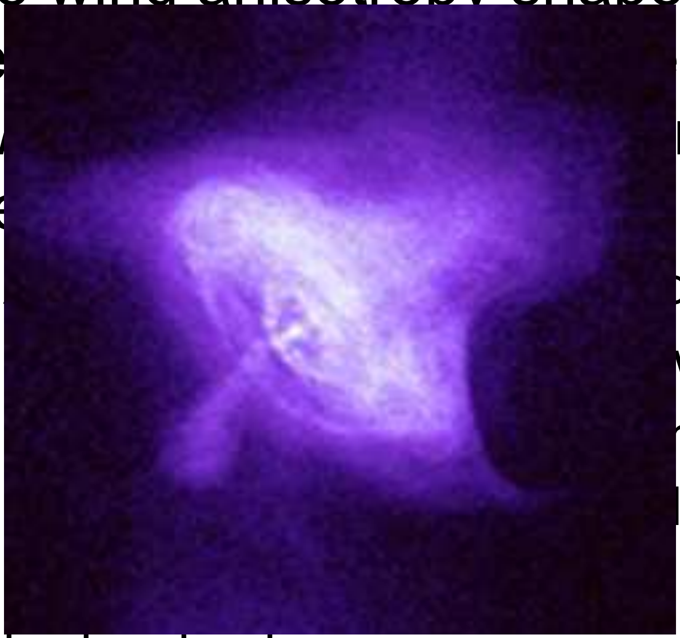
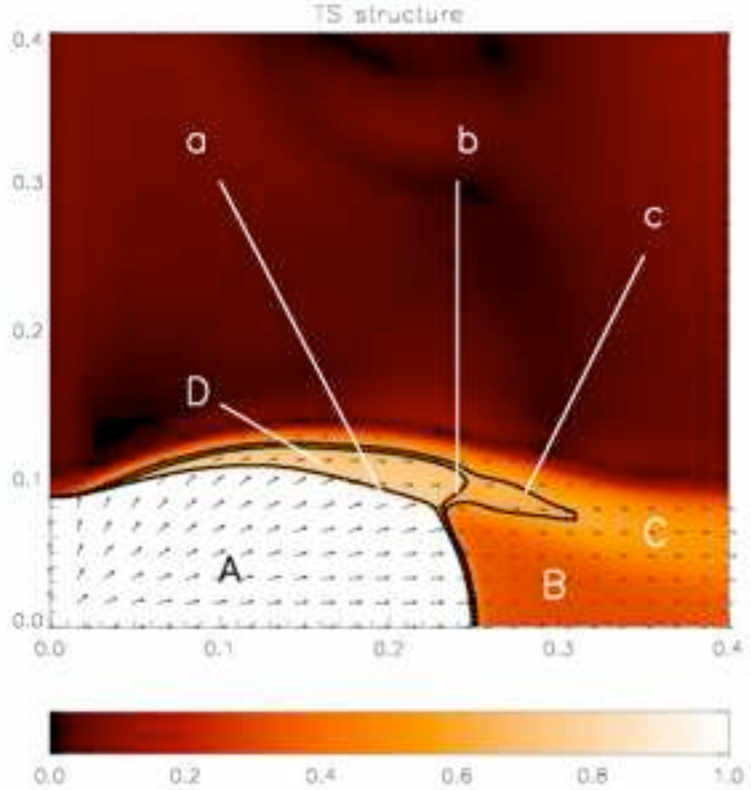


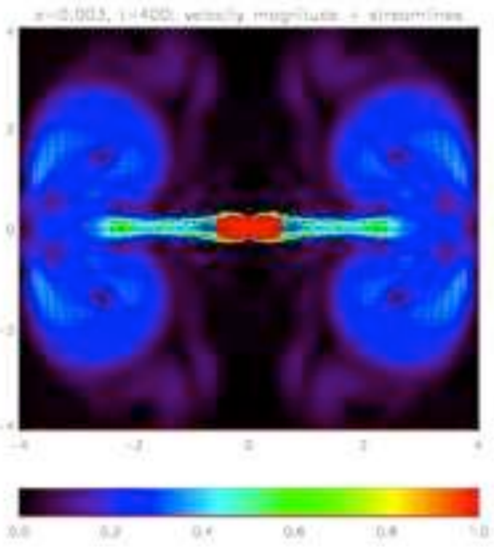
σ=0.03



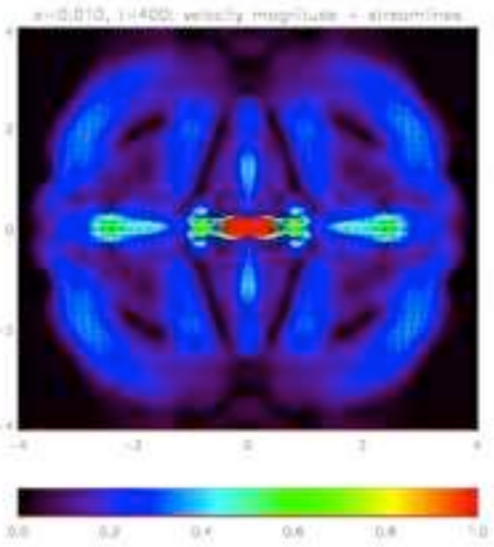
Formation of polar jets by hoop stresses

- The global nebular flow changes with σ
- Flow is diverted to the axis when equipartition is reached
- For high magnetization (σ > 0.01) a supersonic jet is formed
- Equipartition must be reached inside the PWN

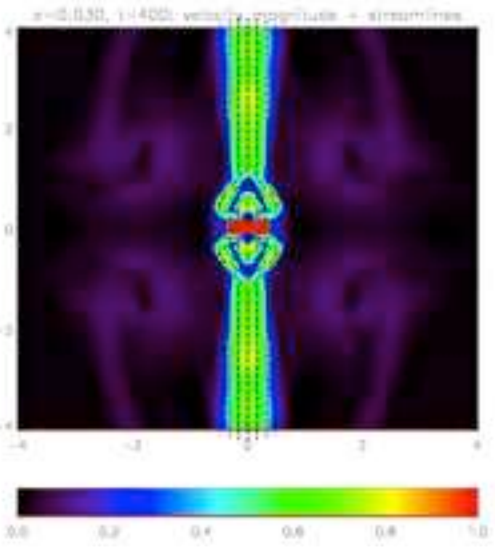
σ=0.003



σ=0.01

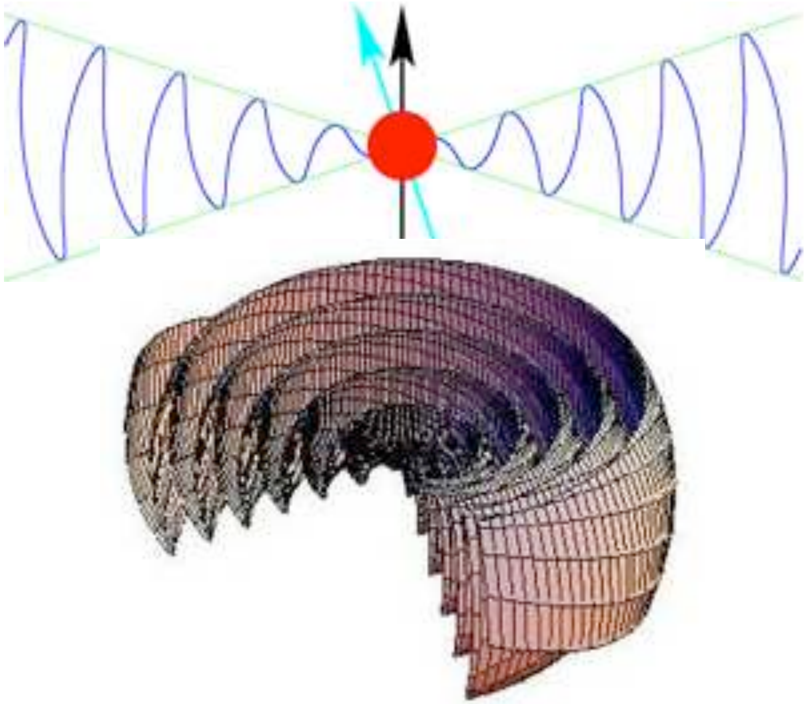


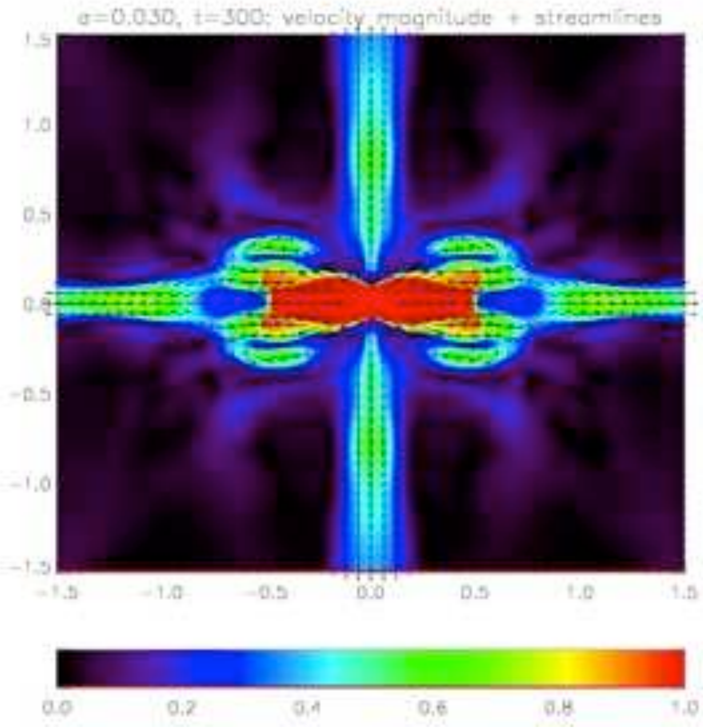
σ=0.03



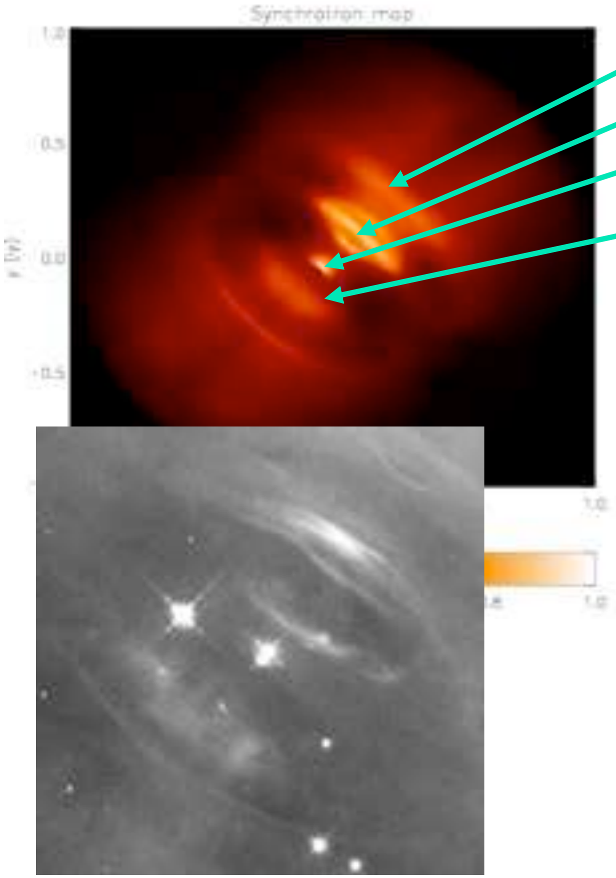
Modeling a striped wind case

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



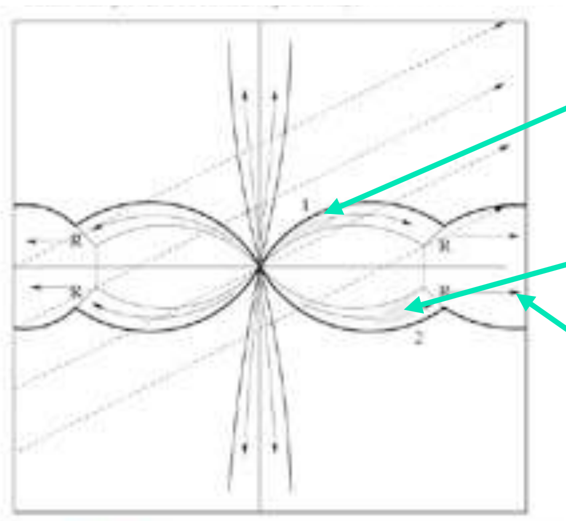


Comparison with Observations



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

No jet - Axisymmetric assumption

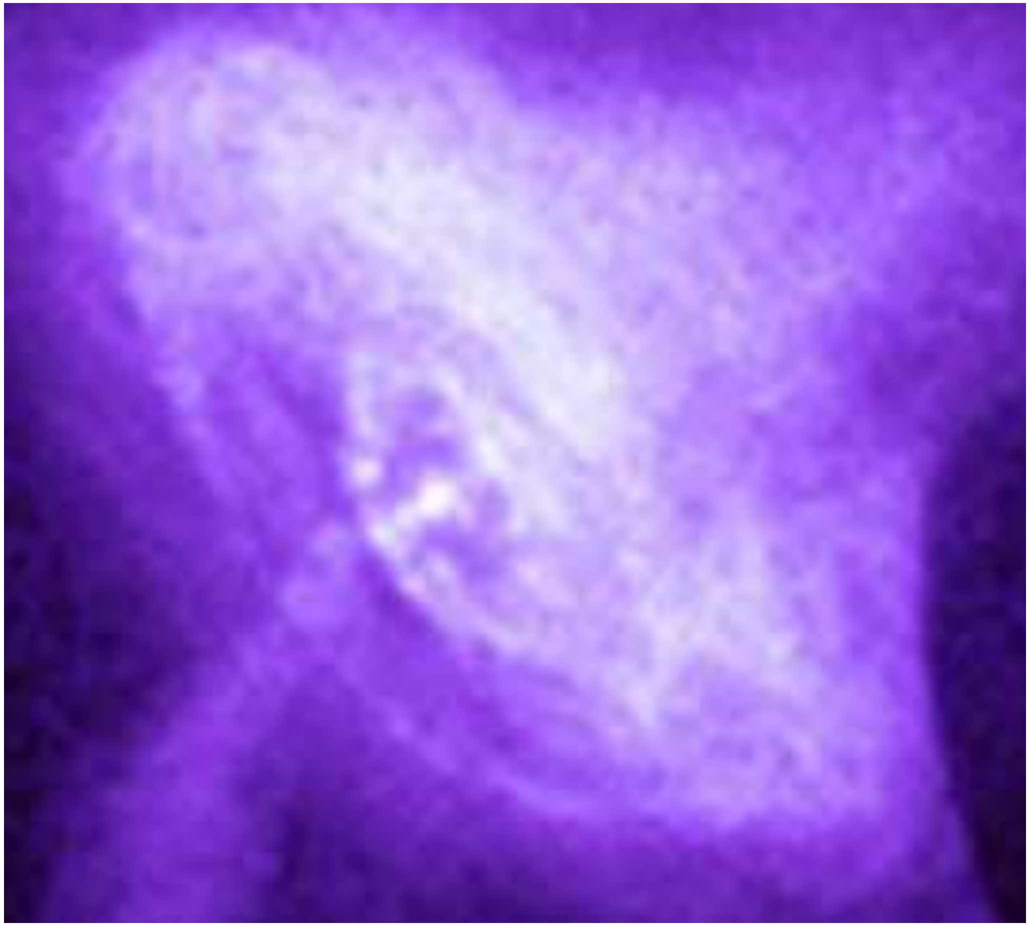


Knot
Ring
Torus

Hester et al. 1995

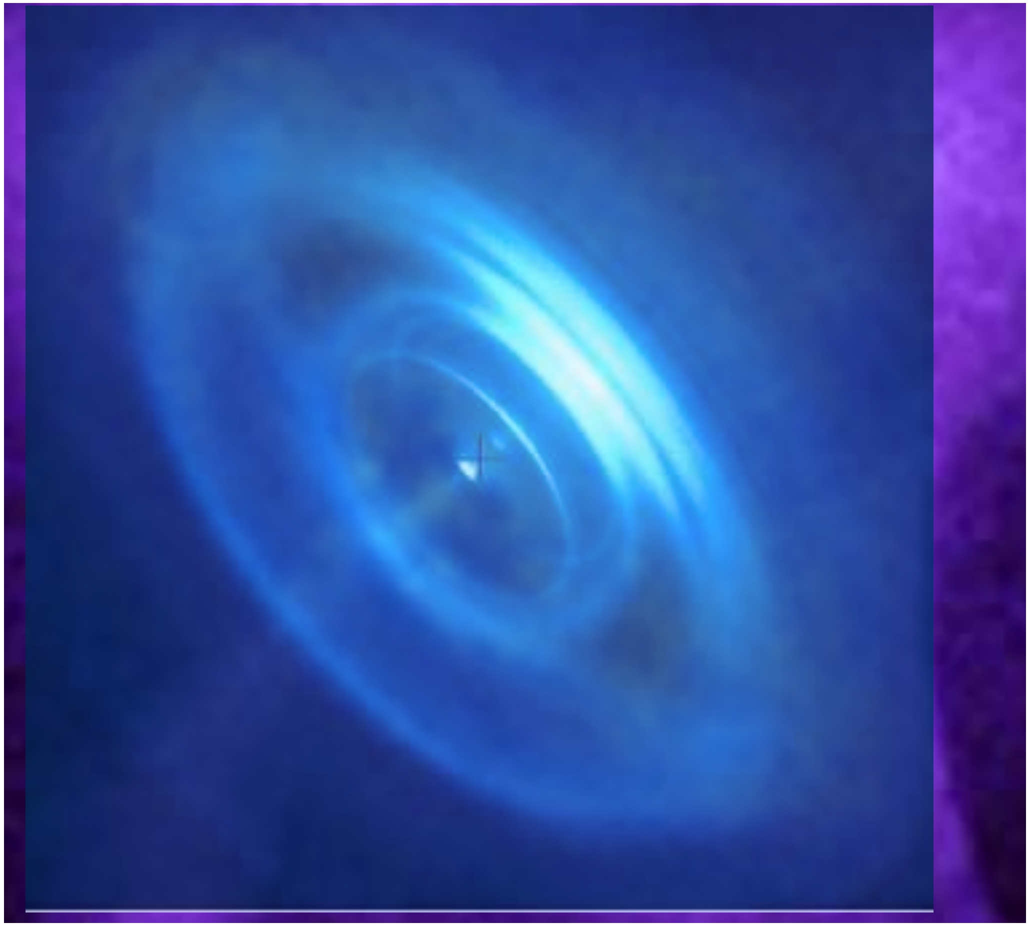
Komissarov & Lyubarky 2004

Comparison with Observations



Camus et al.

Comparison with Observations



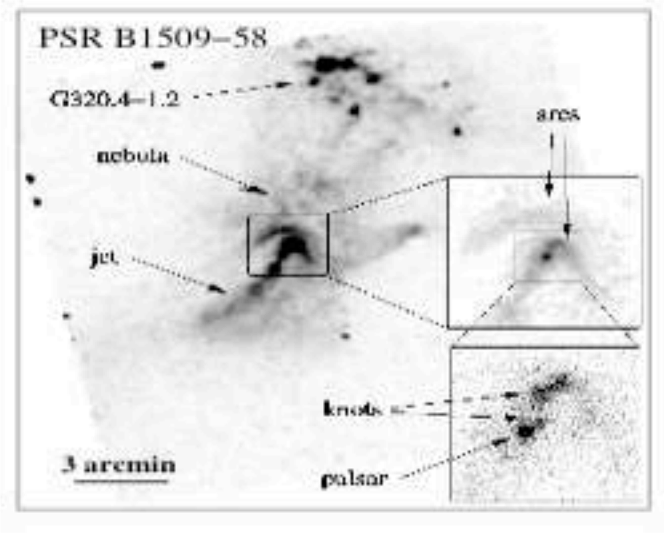
Camus et al.

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

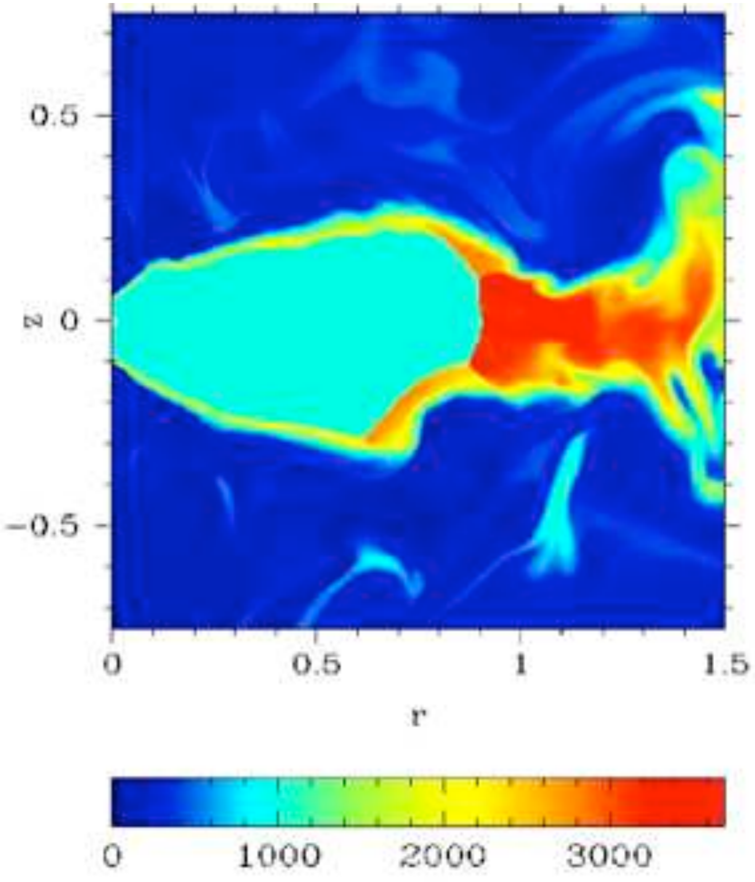
Eddies are advected outward and a toroidal pressure wave is launched

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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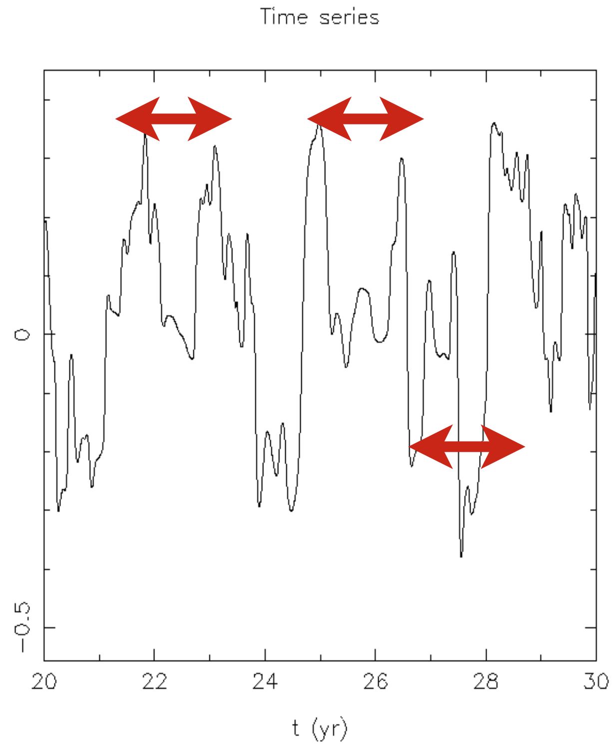
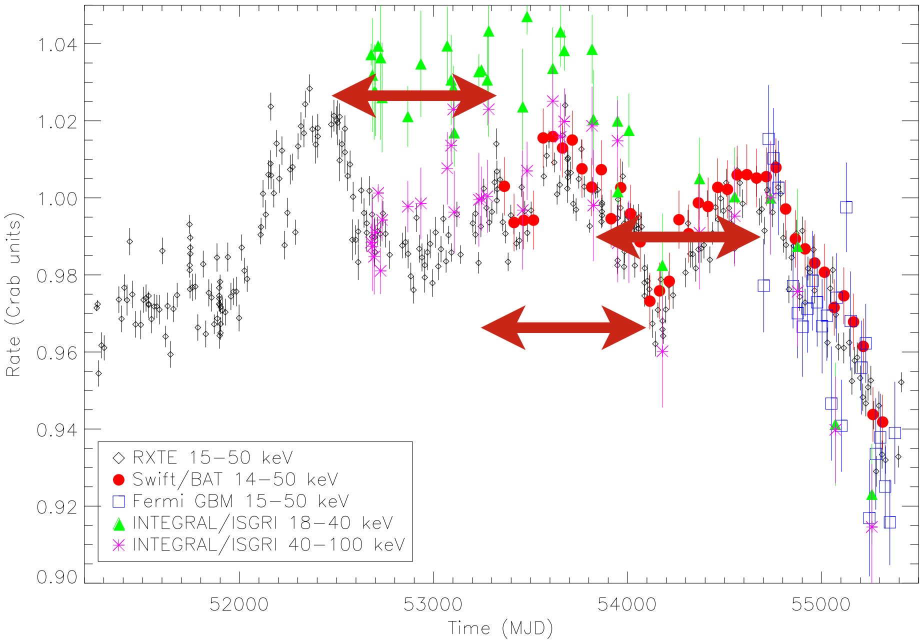
MHD variability - High Energy



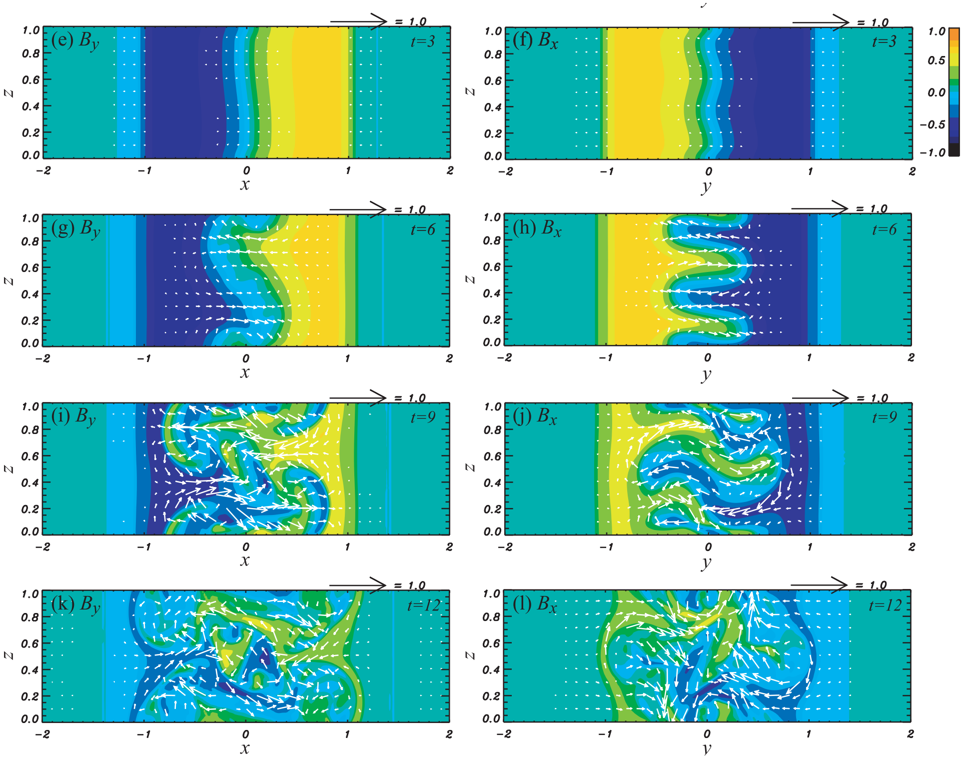


~ 2 yr Timescale

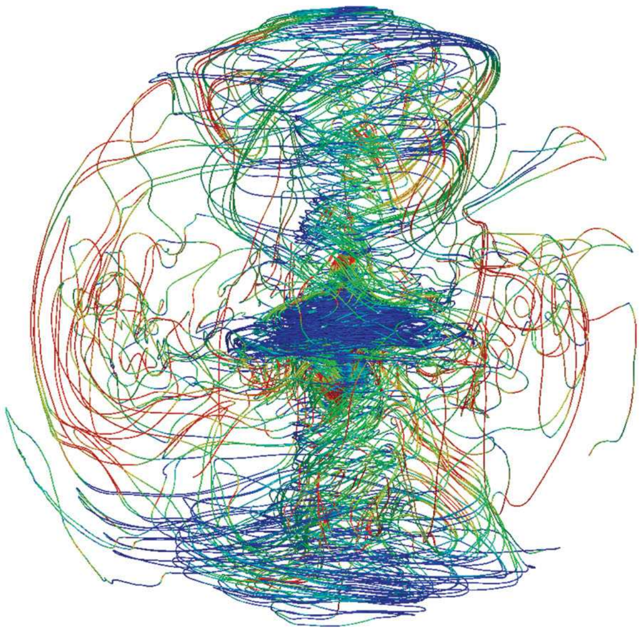
Wilson-Hodge et al. 2010

3D

Purely toroidal fields are unstable in 3D



Mizuno et al. 2010



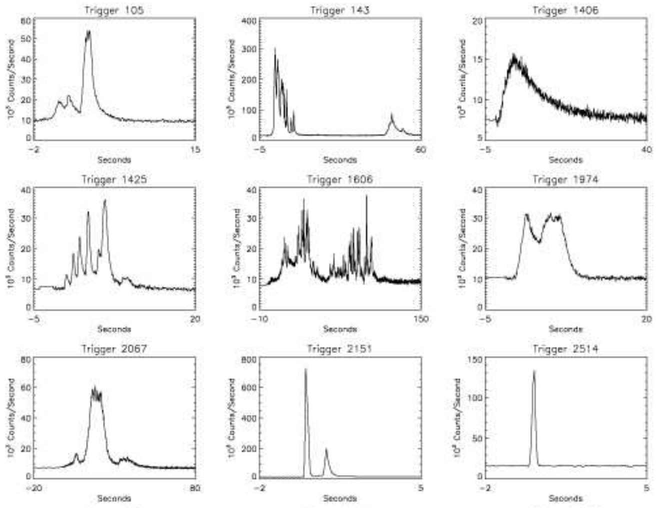
Porth et al 2013

However there is also continuous injection

Interaction
II
GRBs

Long GRBs

Bursts of Gamma-Rays



Long GRBs

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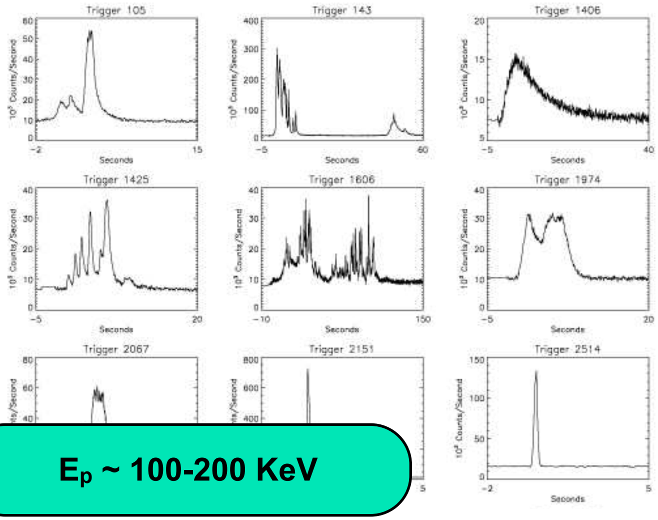
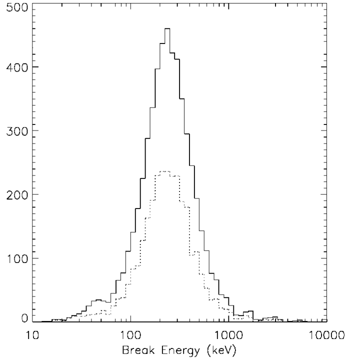


E_p ~ 100-200 KeV



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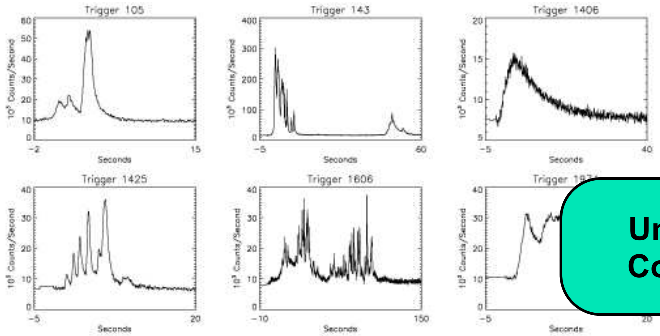
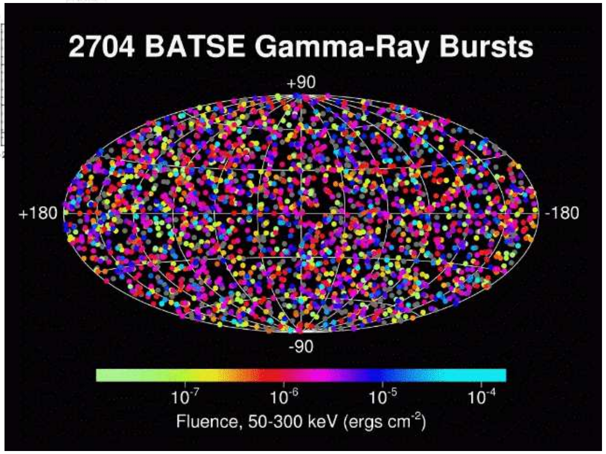


Uniform Distribution
Cosmological Origin



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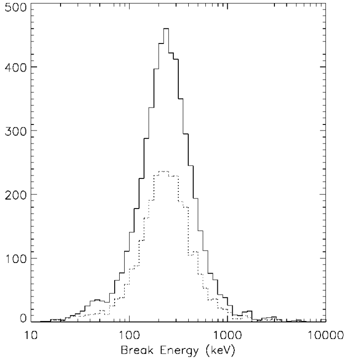

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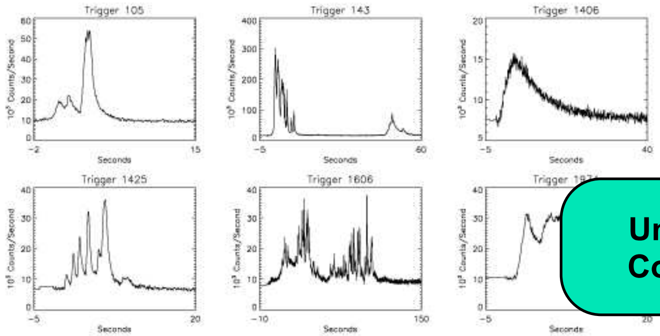
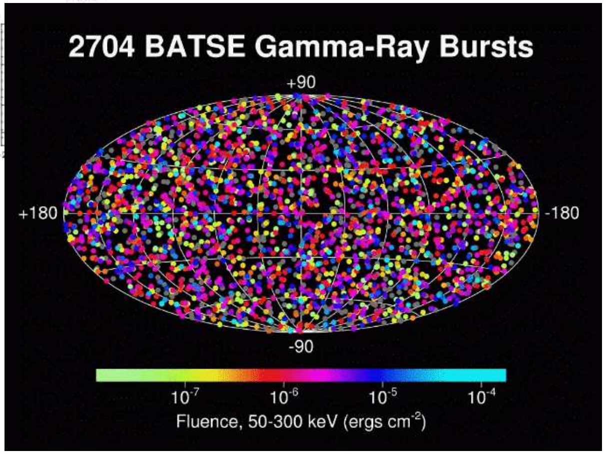
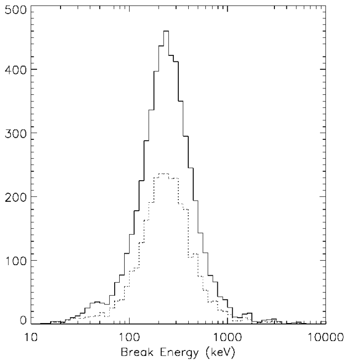


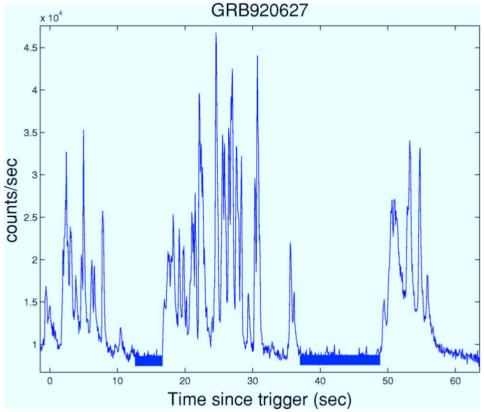
Uniform Distribution
Cosmological Origin



E_p ~ 100-200 KeV



Variability up to ms

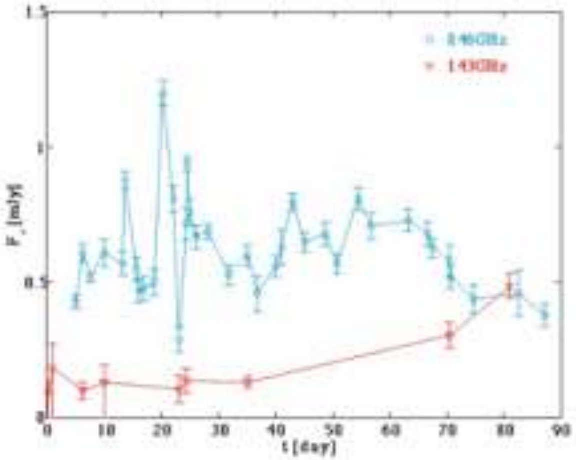


Variability timescale ~ ms implies a compact stellar mass engine

Variability shorter than duration implies continuous injection

Lorentz factor

GRB are seen to scintillate in radio for several days after the burst



2

For typical galactic ISM variation the scintillation radius of an extragalactic source is ~ 1.e17 cm

This implies an expansion speed ~ c

Lorentz factor

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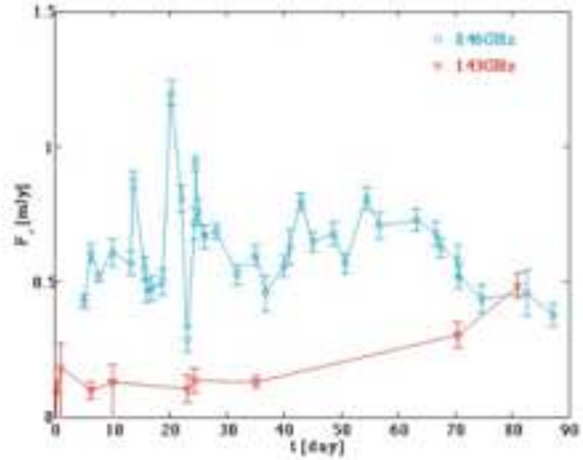

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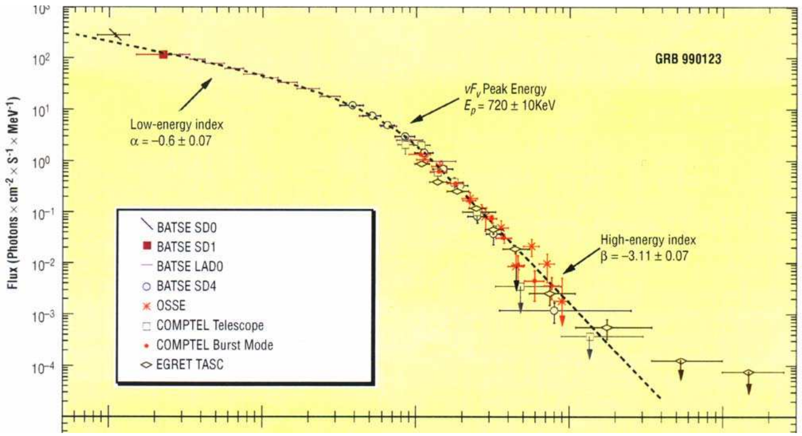
Compactness Argument

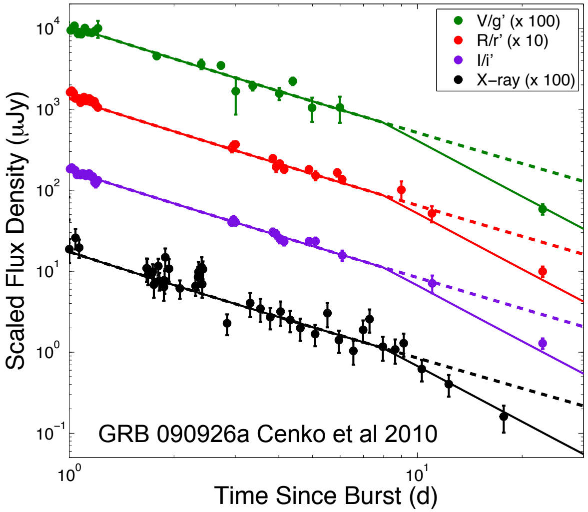


Spectrum shows a non thermal power-law tail

If the source is non relativistic the optical depth for pair production is large and one would expect a thermal spectrum
Non-thermal spectrum => high Lorentz Factor ~ 100-1000

Jets and SN connection

Evidence for collimation from so called "jet-breaks"



$$t_j \approx 3.9(1+z)E_{\mathrm{iso},53}^{1/3} n_0^{-1/3} \left(\frac{\theta_0}{0.2}\right)^{8/3} \text{ days},$$

The typical opening angle is ~ 10 deg

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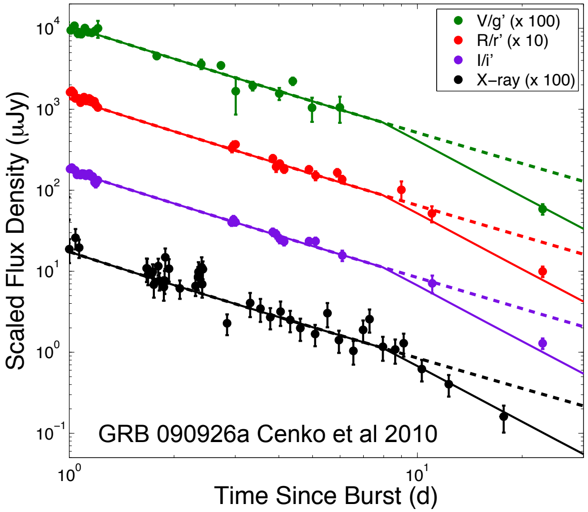

GRB 090926a Cenko et al 2010

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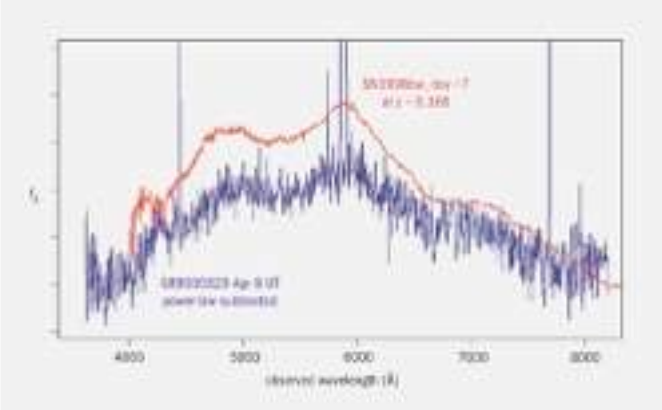


Hjorth et al. 2000

SN 1998bw and SN2003dh were coincident with GRBs within days.

SN Ib/c

SN are very energetic and bright:
$E_{kin} \sim 10^{52}$ ergs, $V_{ej} \sim 2\text{x}10^4$ Km/s
$1M_{sun}$ of Ni^{56}

Constraints on the central engine

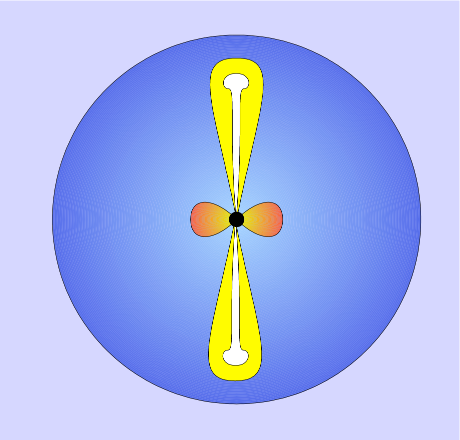
- **High energy ~ 10^{51-52} ergs ➔ large energy reservoir**
- **$E_{tot} < E_{iso}$ ➔ collimation**
- **Millisecond variability ➔ compact objects (BH or NS)**
- **T/δT >> 1 ➔ quasi-steady energy injection (not an explosion)**
- **100 sec duration of LGRB and SGRBEE >> engine timescale**
- **High energy non-thermal spectrum ➔ relativistic outflows (Γ>100)**
- **Late time activity ➔ long lived engine**

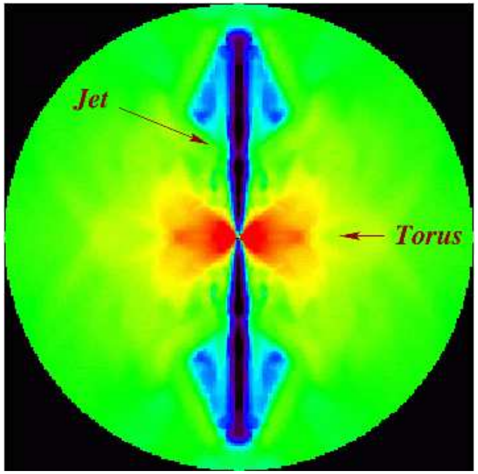
LGRBs

Associated with young galactic population
Found in star forming regions of host galaxy
Associated with core-collapse events

Collapsar

The core of a rotating massive star collapses to a black hole
Material far from the axis does not fall straight in but form an accretion disk
Dissipation in the disk convert kinetic energy into heat
Magnetic field power accretion (MRI)
A jet is launched





Hawley et al.

Energy can be extracted in various ways:

Neutrino heating in the polar region
Wind from the disk (Blandford-Payne)
Angular momentum from BH (Blandford-Znajek)

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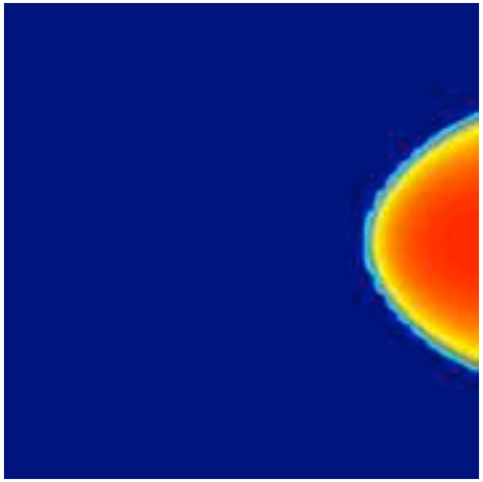

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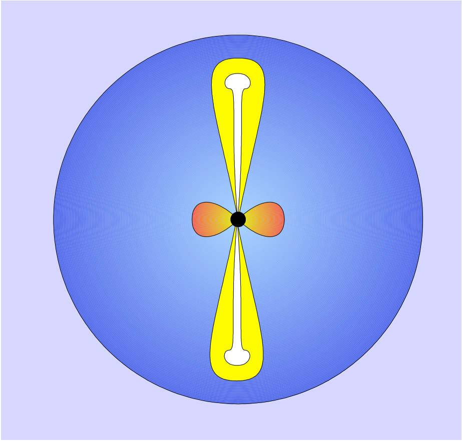

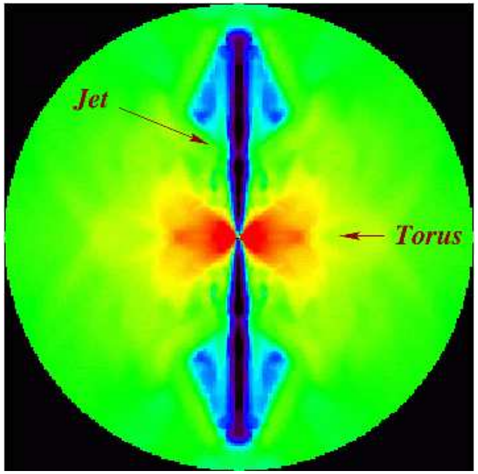

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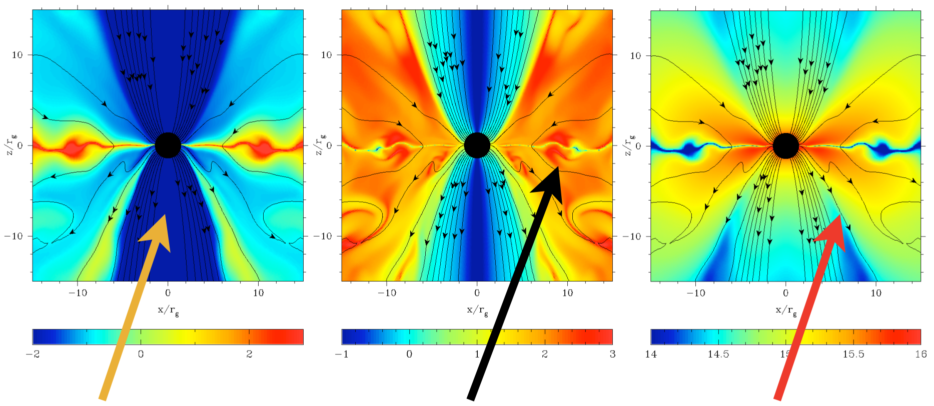
Properties of collapsar

Barkov & Komissarov 2008



BZ jet

Hot torus

Disk wind

Possible avenues to drive a GRB:

v-v Annihilation driving a wind
Disk wind powered by BP
BZ extracting enegy from the BH

Pro

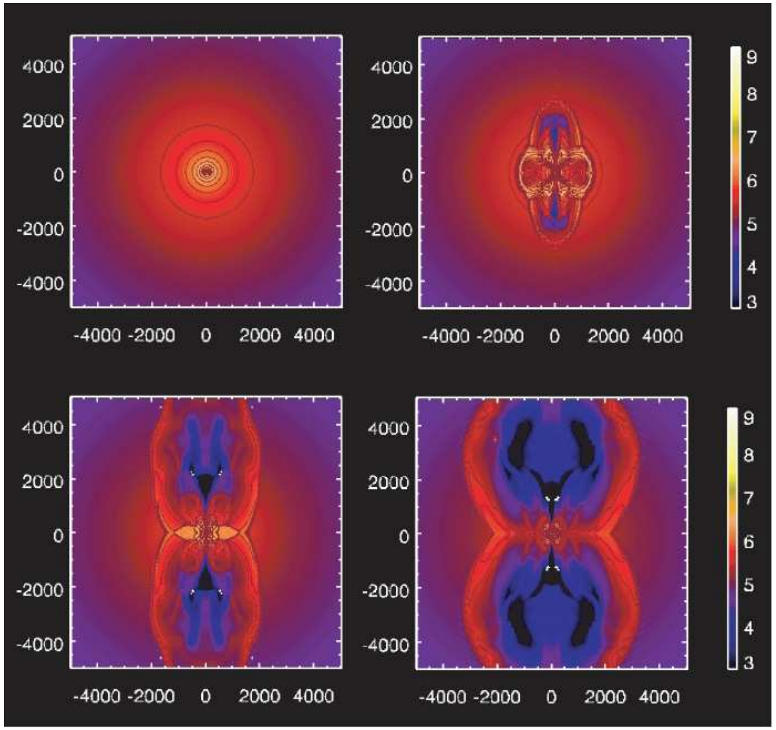
Collapse in high mass stars favors BH
Jets are naturally associated with accretion disks
Disk wind can give the correct Ni^{56} load
Very high Γ can be achieved in the jet
Fragmentation of the torus can lead to late time accretion events (flares)
Accretion can be sustained for a long time

Cons

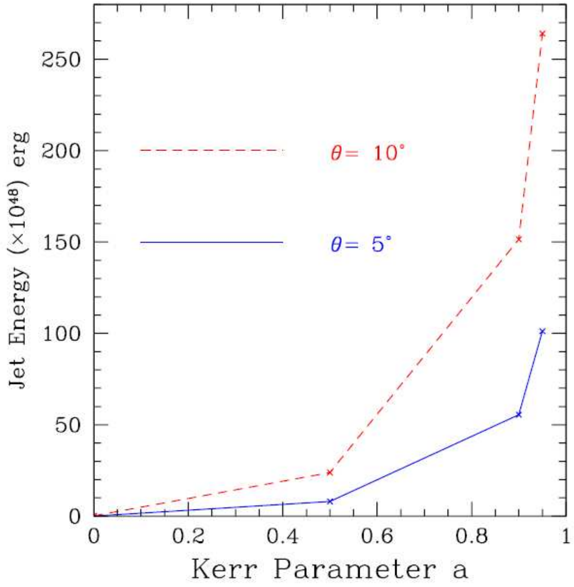
Need rapidly rotating BH
There is a J_{max} for the envelope
Γ is set by non obvious mass loading
Need ordered seed magnetic field
Need a long surviving torus inside SN
Direct collapse to BH not obviously produces SN shock

Faster is better

**What is the role of the BH rotation?
IS rotation important for the jet?**



Nagataki 2012



**Kerr parameter a > 0.5 for efficient jet.
At ~ 1.5 sec the jet is still non-relativistic.**

The milisecond-magnetar

Magnetars have fields ~ $10^{14\text{-}15}$ G
They might be born as fast rotators
Efficient dynamo implies P ~ t_{conv} ~ ms

Millisecond magnetar have the correct energy

$$E_{Rot} \approx 2\times10^{52}\left(\frac{P}{1\ \mathrm{ms}}\right)^{-2}\ \mathrm{ergs}$$

Pro

NS are naturally associated to core collapse SN
Less angular momentum required than BH-AD
NS population can explain transition from asymmetric SNe to XRFs to GRBs
Magnetar can show energetic bursts

Typical spin-down times are ~ 100-1000 sec

$$\dot{E} \approx 10^{49}\left(\frac{P}{1\ \mathrm{ms}}\right)^{-4}\left(\frac{B_{Dip}}{10^{15}\ \mathrm{G}}\right)^{2}\ \mathrm{ergs\ s^{-1}}$$

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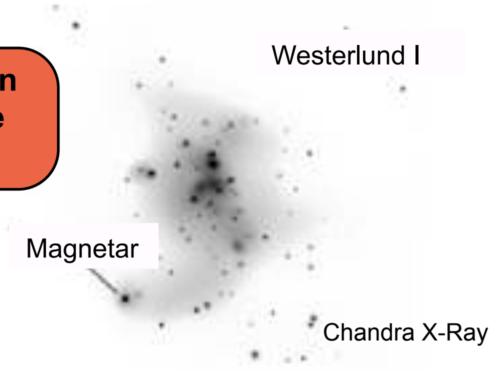
Magnetars can have massive progenitors

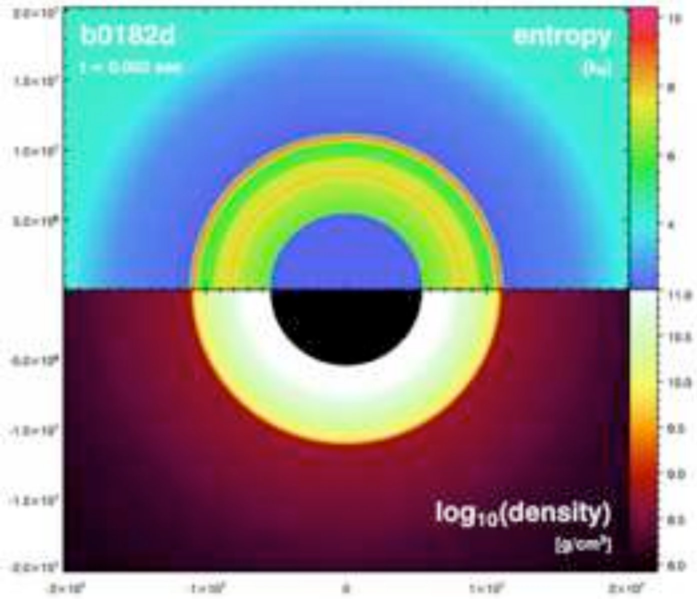


Faintest Cluster Members are O7 (Clark et al 2014)

Pulsars have relativistic winds

Extracting the energy via winds

- **Core-Collapse SNe Produce Hot Proto-Neutron Stars that Cool Via ν-Emission ~10^{53} ergs in τ_{KH} ~ 10-100 s**
- **Neutrinos Heat Matter above the PNS Surface, Driving a Thermal Wind into the Evacuated Region Behind the SN Shock (Duncan et al. 1986).**



Scheck et al

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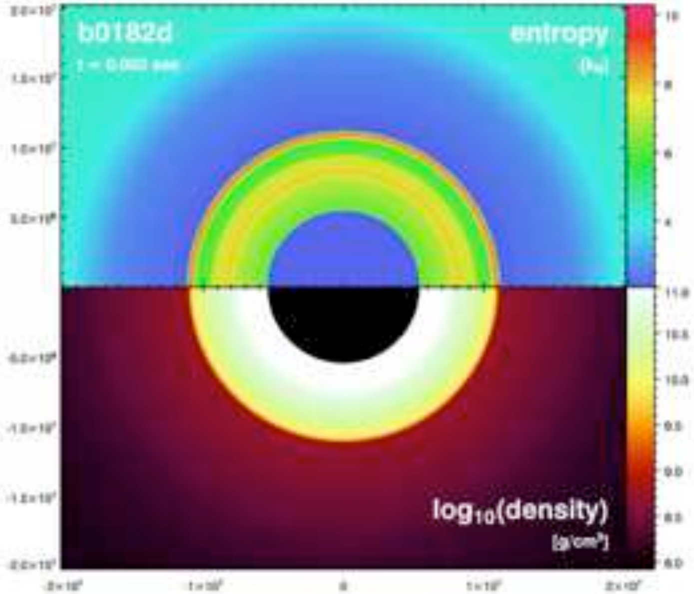
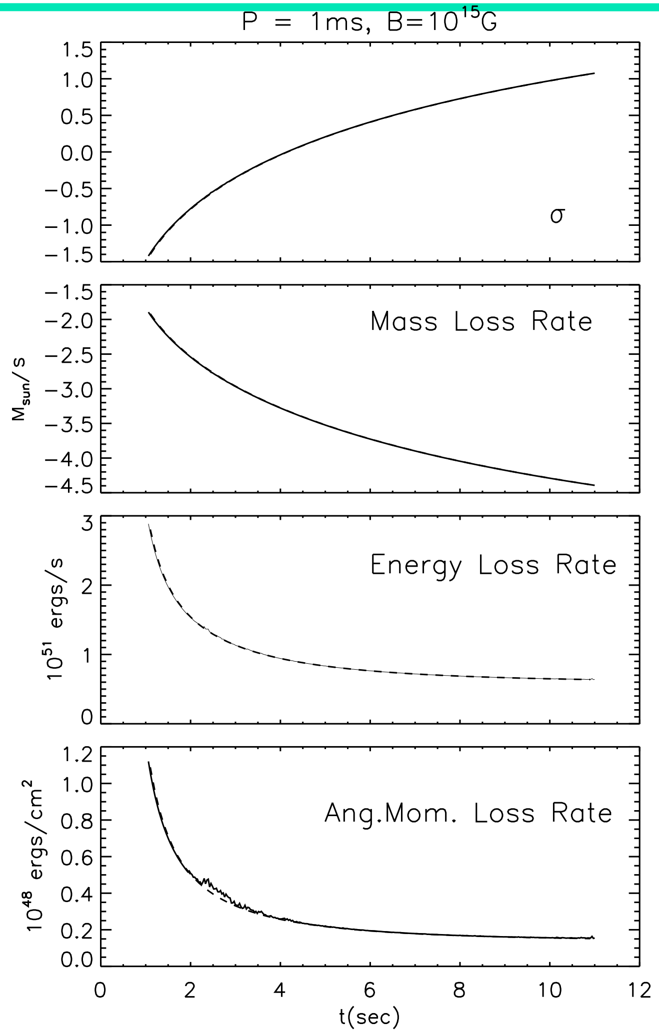


Scheck et al

Regular PNS winds are not dynamically relevant for SN

PNS spin-down



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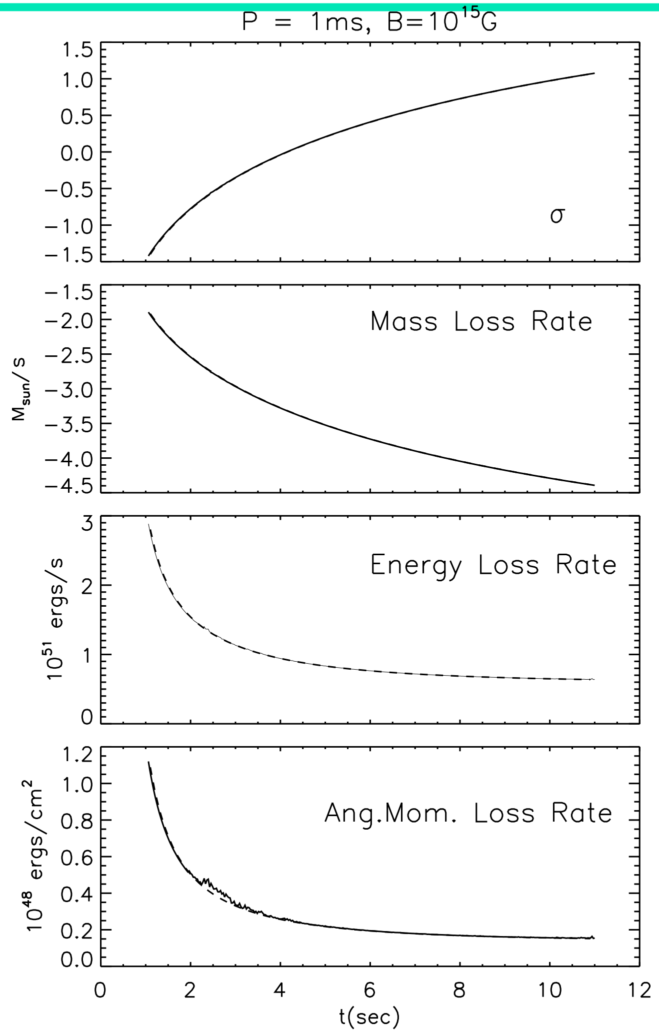
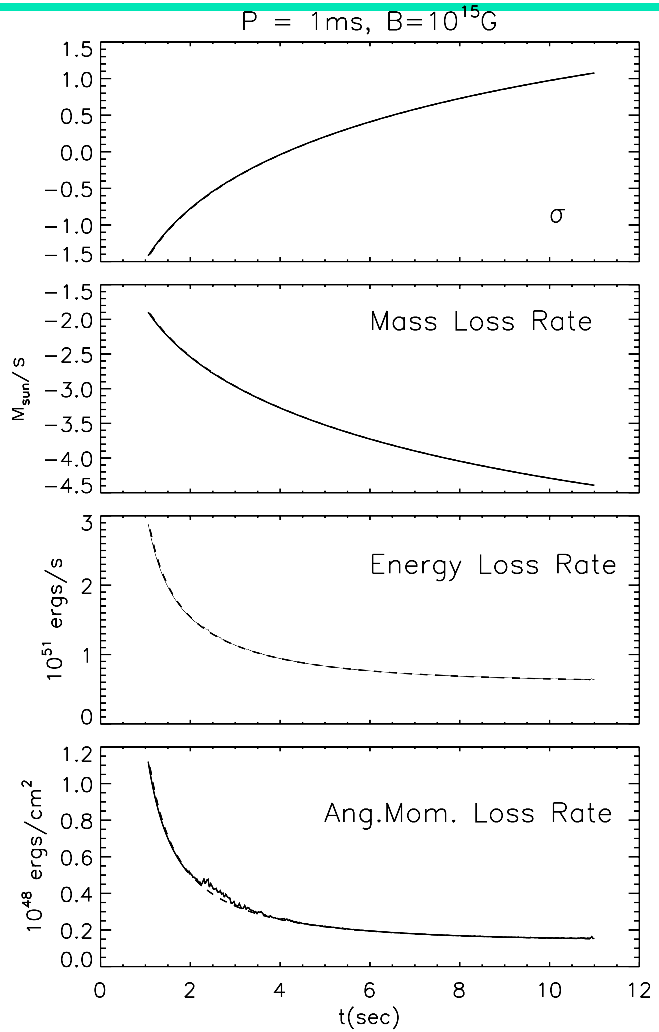


Comparison of the losses for a free-wind case and the case of a PNS confined inside a SN progenitor.

PNS spin-down



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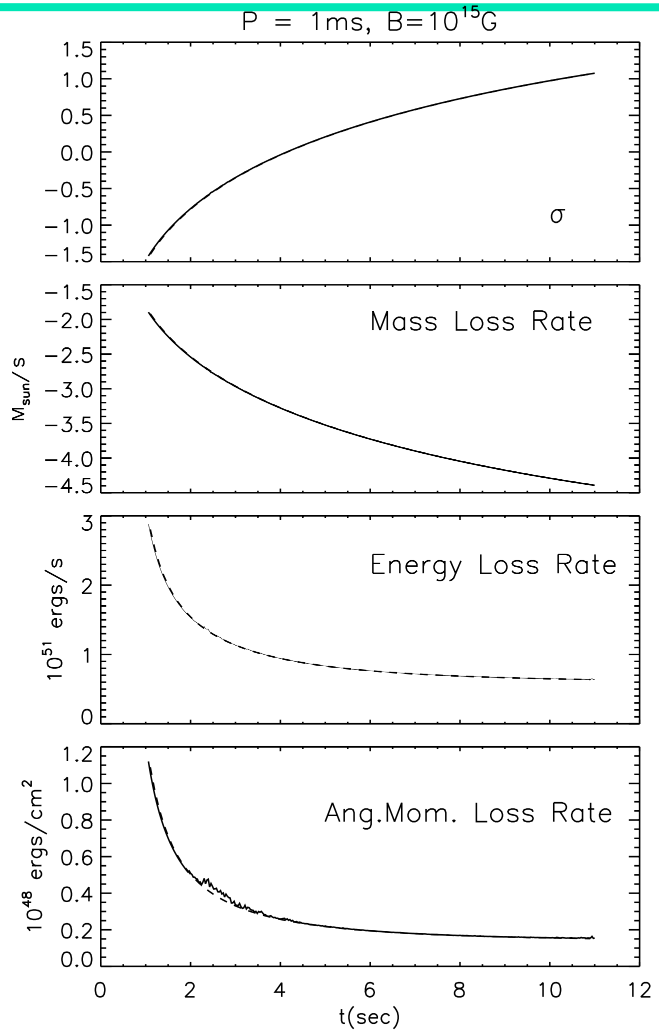

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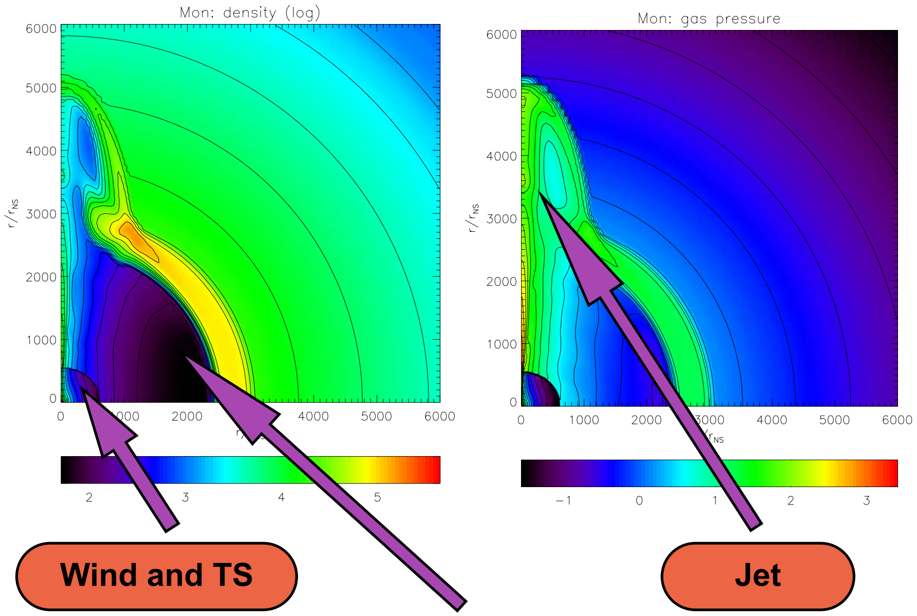
Losses are not changes by confinement, same torque, free wind model for PNS evolution are reliable

Less energy is extracted from the PNS
The PNS wind does not efficiently powers the SN

Interaction with the progenitor



Wind and TS

Magnetar nebula

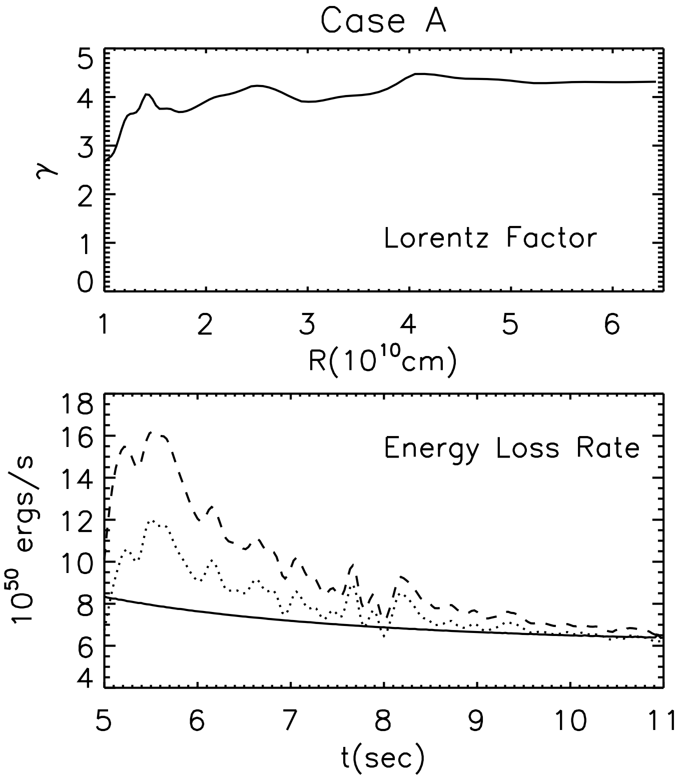
Jet

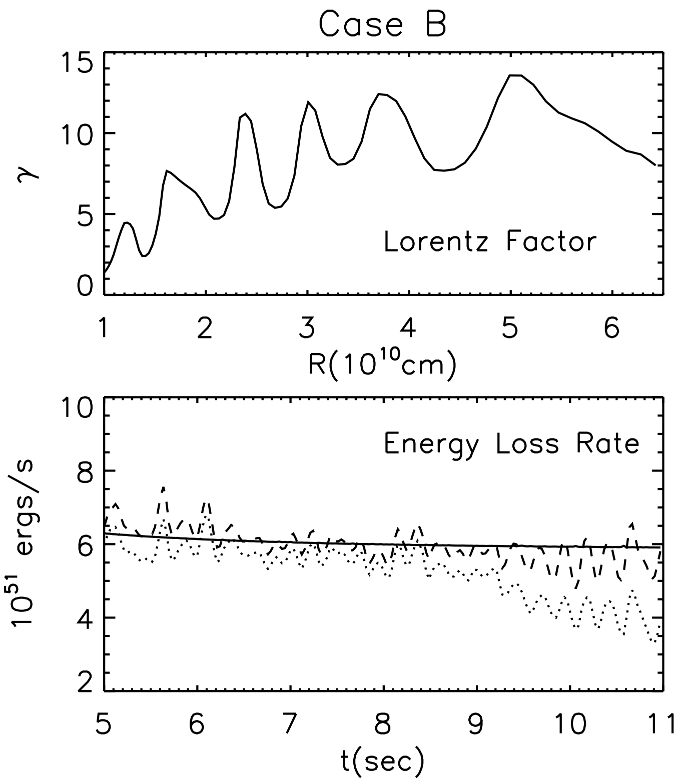
Recent numerical study investigates the transition from the matter dominated phase to the magnetic dominated phase

Jet are ubiquitous feature originating from the confinement of a toroidally dominated magnetic field.

Dissipative processes affect the acceleration of the jet but not the collimation

Properties of the Jet

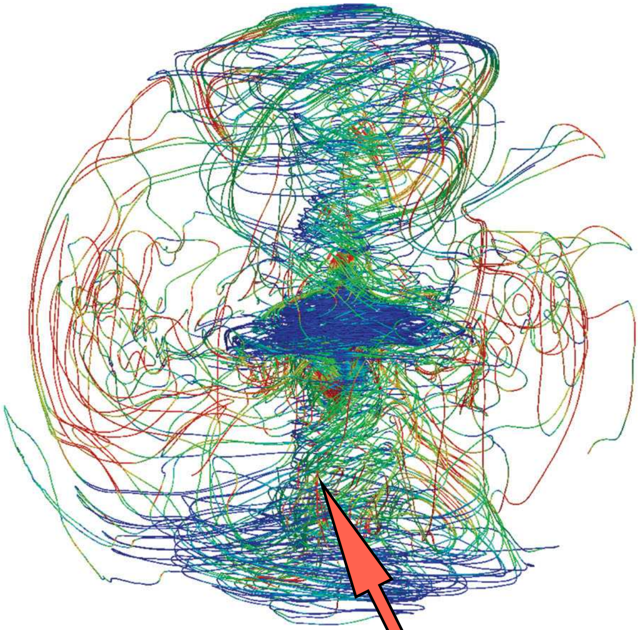




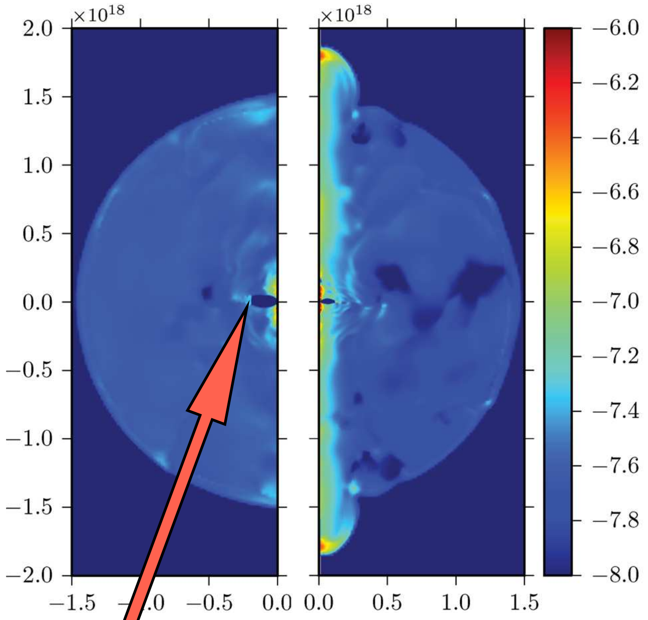
Jet acceleration is more efficient than analytic radial estimates

Spindown-power of the PNS is carried by the jet

3D vs 2D



Porth et al 2013

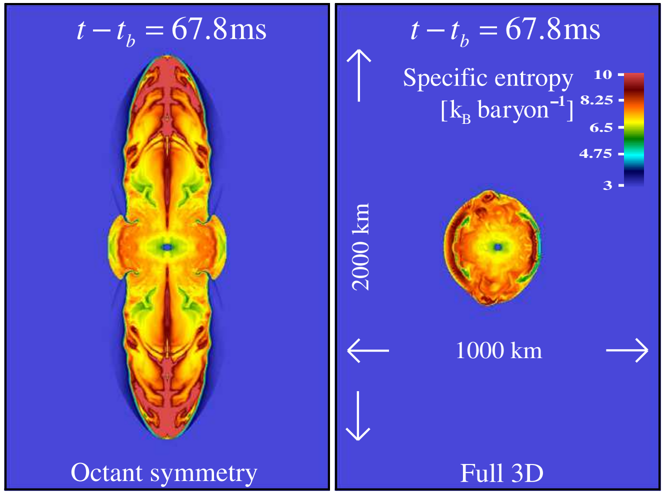


The jet is still present but much weaker and broader than in 2D

Instabilities of the jet (kink) reduce its penetration

Timescale and energetics?

MHD SN - Elongation



Mosta et al 2014

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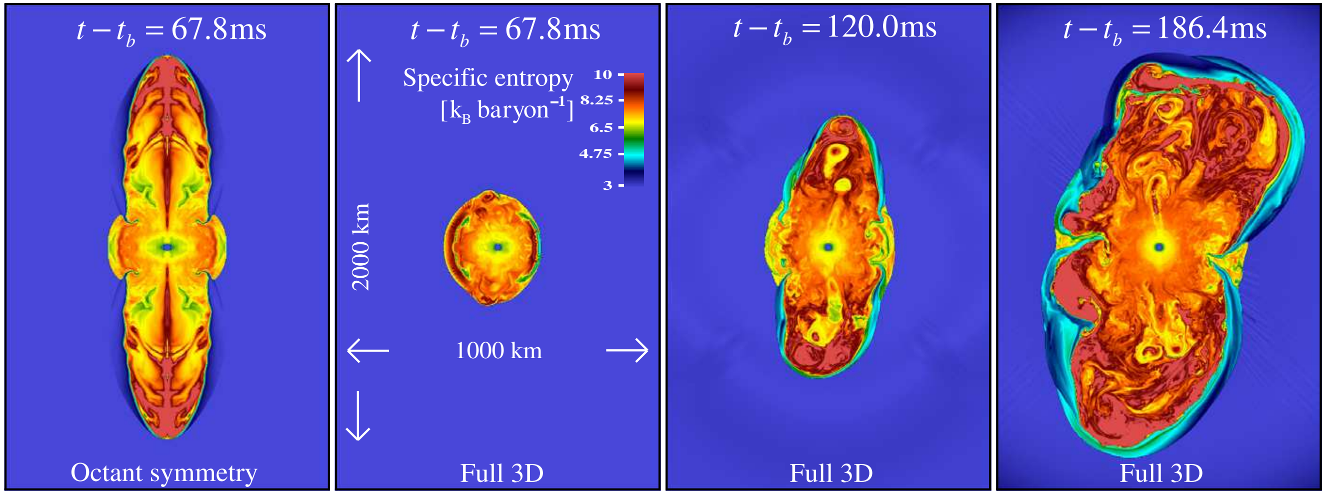

Mosta et al 2014

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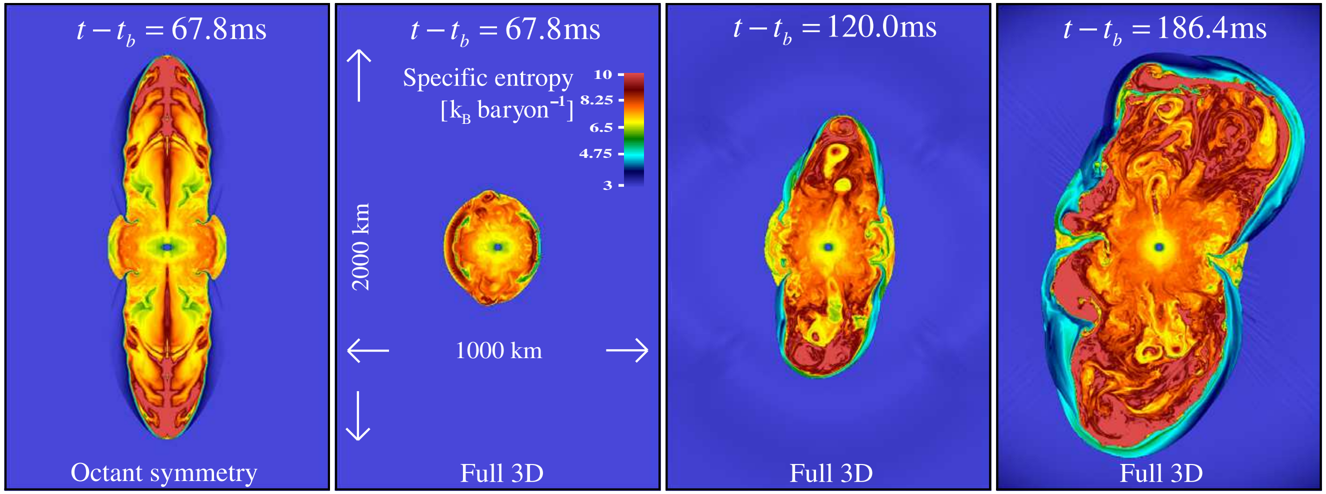
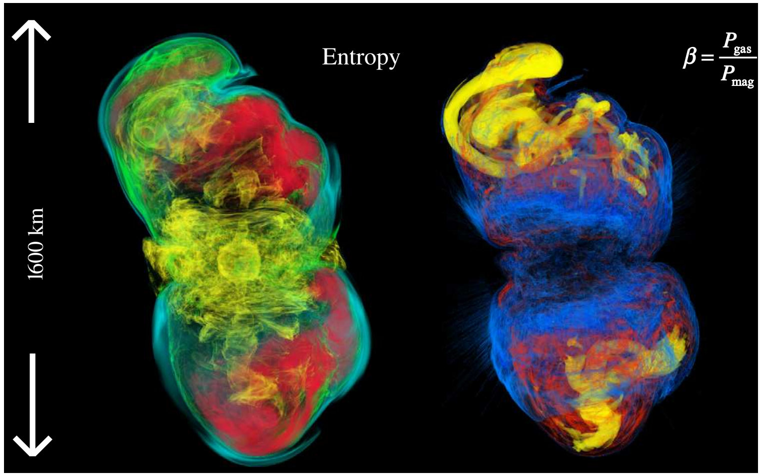


Bipolar structure are found but no evidence of jets in 3D

nu-SNe have energy < 1e51 erg

Mosta et al 2014

Situation is going to be similar for Collapsar BH-AD systems



Mosta et al 2014

MHD CC
Magnetic “towers”

Summary and conclusions

- Pulsar are prototypical relativistic accelerators.
- In the last 10 years our ability to model the structure of the pulsar/NS magnetosphere, and the properties of its FF outflows has been greatly enhanced
- There are still open questions regarding the way particles are extracted and accelerated in the inner magnetosphere.
- PWNe can be used to understand the interaction of a relativistic outflow wit a confining environment, and the formation of relativistic bubbles
- There are still important open question on how non-thermal particles in those systems are accelerated.
- Pulsar wind theory is also at the base of the Millisecond magnetar model for GRBs.

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Thank you