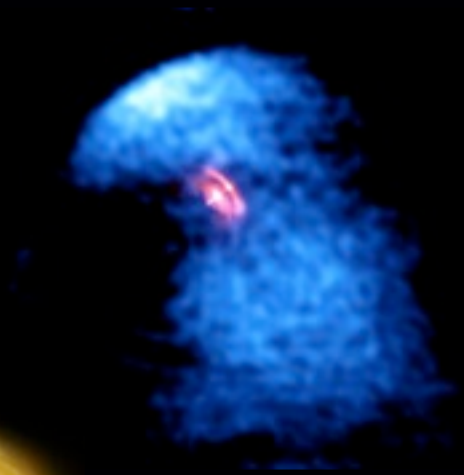
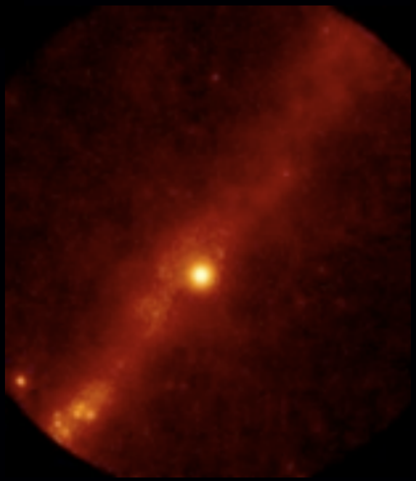
X-ray and multiwavelength observations of pulsar-wind nebulae.



Oleg Kargaltsev (George Washington University)

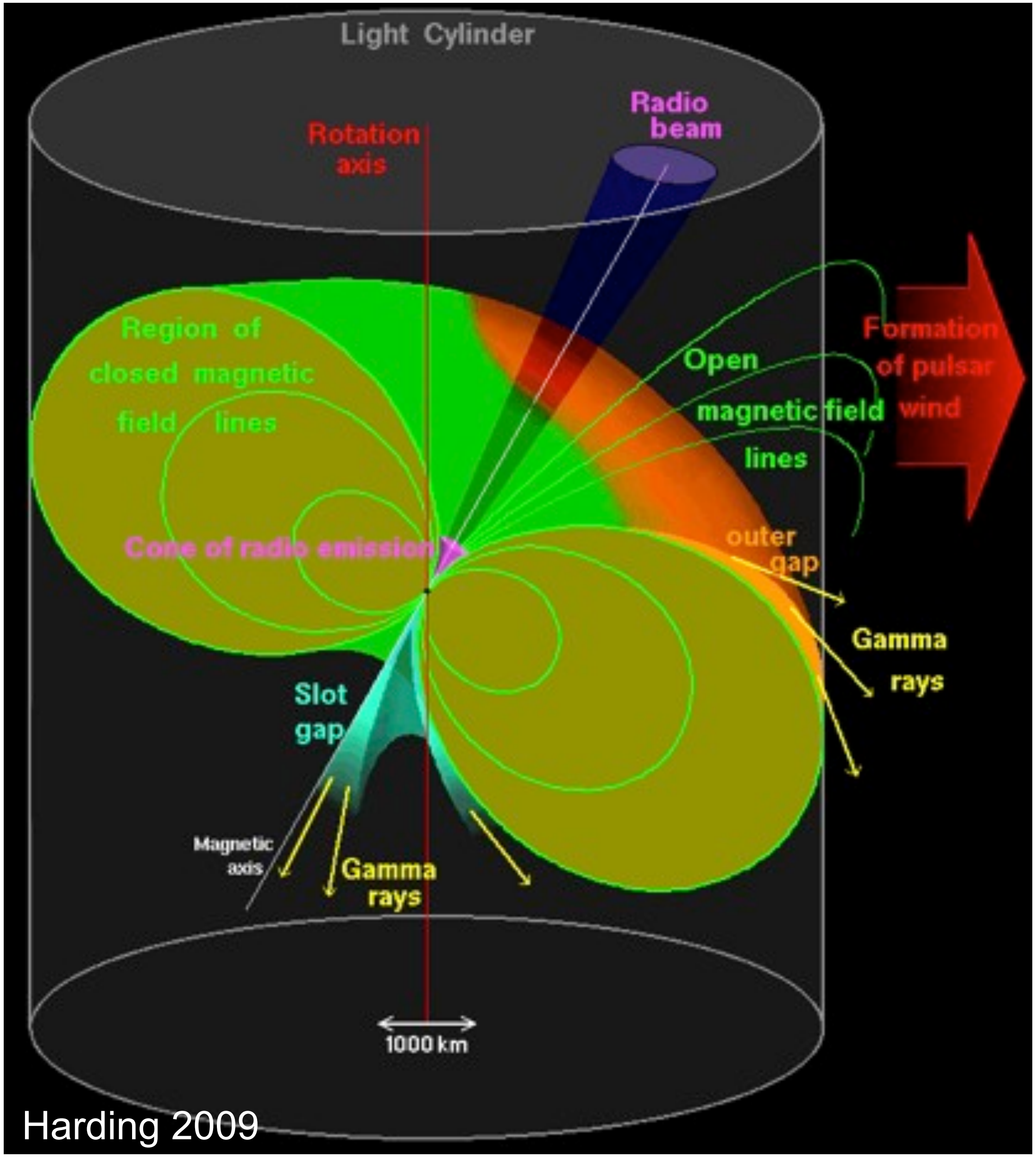
Collaborators:

Martin Durant (University of Toronto)
George Pavlov (Penn State University)
Chryssa Kouveliotou (NASA)
George Younes (NASA)
Andrei Bykov (Ioffe Institute, Russia)
Julia Kropotina (Ioffe Institute, Russia)
Ksenia Levenfish (Ioffe Institute, Russia)
Gordon Garmire (Penn State University)
and others

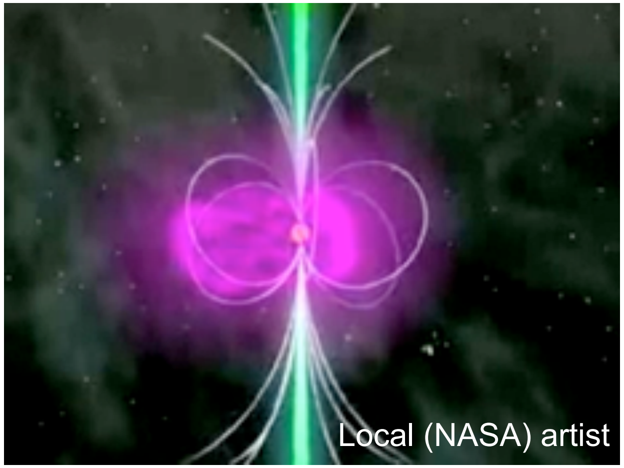


XMM-Newton 2013 Science Workshop

Pulsar



Harding 2009



Local (NASA) artist

Pulsars are **neutron stars with active magnetospheres populated by ultra-relativistic particles** emitting non-thermal radiation (synchrotron, curvature, inverse Compton).

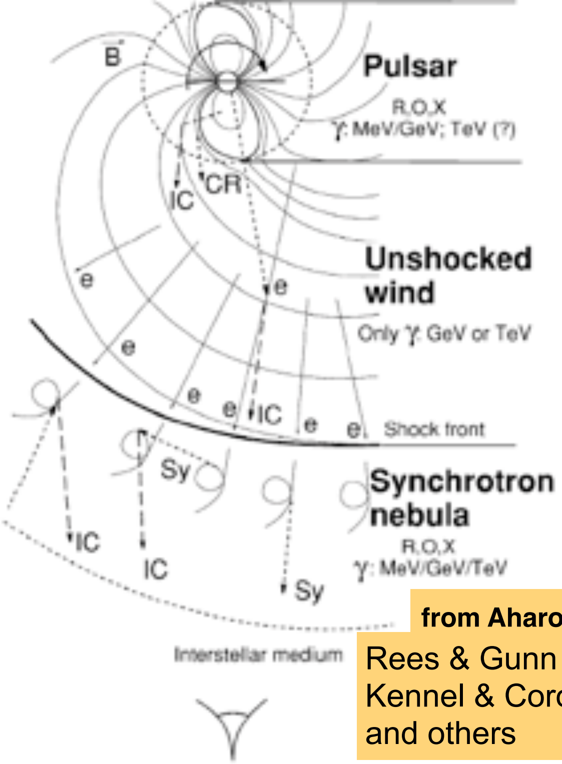
Power Source: NS rotation - **$\dot{E}$**

Emitted fraction of **$\dot{E}$**

<0.001% - radio

~0.01-10% -X-rays
and gamma-rays

the rest is **pulsar wind** !



from Aharonian 2004

Rees & Gunn 1974
Kennel & Coroniti 1984
and others

- All active pulsars emit relativistic winds
- $v \sim c > c_s$ → shock forms
- Downstream of the shock: subrelativistic flow of relativistic particles in magnetic field and radiation field (e.g. CMBR) → **synchrotron** (radio through MeV) and **IC radiation** (GeV and TeV) → **PWN**

Typical parameters

- Typical energy of synch. photon: $\mathbf{E_{syn}=2\ (\Gamma/2\times10^{7})^{2}\ (B/10\ microG)\ \ keV}$

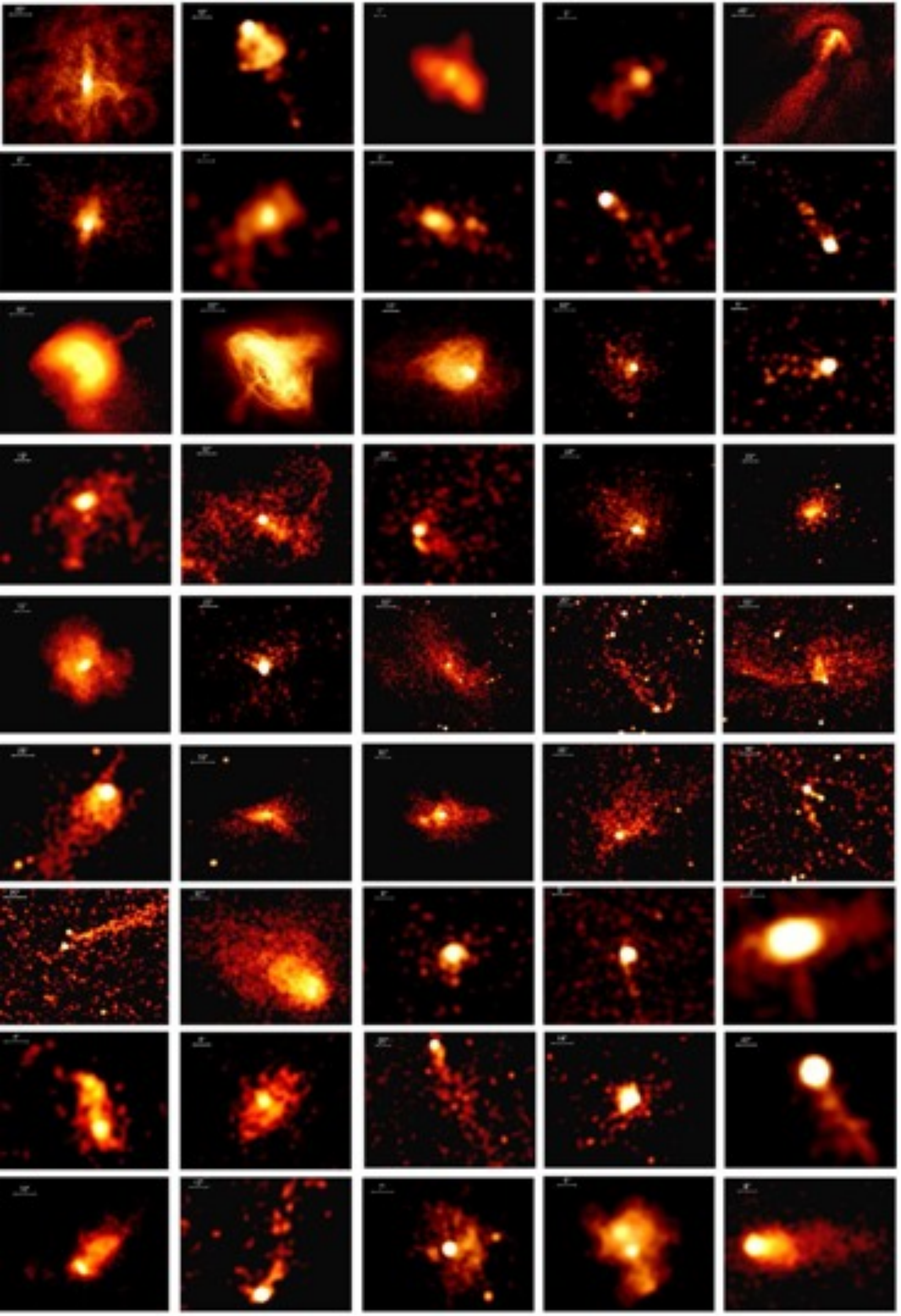
  $\mathbf{E_{IC}=10\ (\varepsilon/4\times10^{-4}\ eV)\ (E_{syn}/1\ keV)\ (B/10\ microG)^{-1}\ \ TeV}$

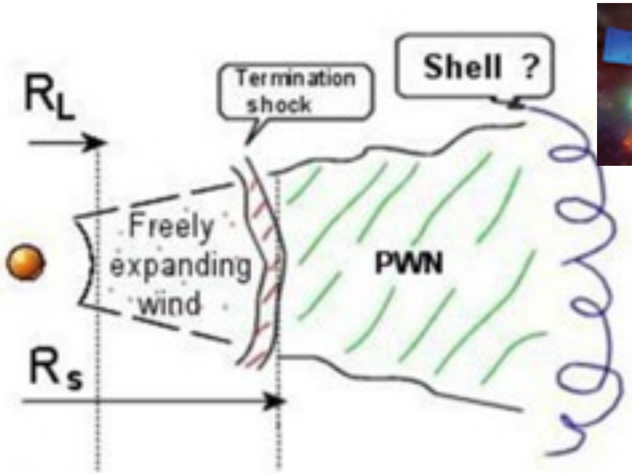
- Characteristic size: $\mathbf{R_s = 0.2\ (\dot{E}/10^{37}\ erg/s)^{1/2}\ (p_{amb}/10^{-10}\ dyn/cm^{2})^{-1/2}\ pc}$

- Synchrotron cooling time: $\mathbf{t_{syn} \sim 1\ (E_{syn}/1\ keV)^{-1/2}\ (B/10\ microG)^{-3/2}\ kyr}$
- IC cooling time: $\mathbf{t_{IC} \sim 10\ (E_{syn}/1\ keV)^{-1/2}\ (B/10\ \mu G)^{1/2}\ (U_{rad}/0.26\ eV/cm^{-3})^{-1}\ kyr}$

- Luminosity: $\mathbf{L} = k\ \dot{\mathbf{E}}$, $k < \mathbf{1}$ (efficiency, η, depends on wind parameters and outflow geometry; $k_X \sim \mathbf{10^{-5} - 10^{-1}}$ from observations).

Pulsar Wind Nebulae.





This cartoon assumes axisymmetric wind expansion which may not be the case due to the interaction with ISM.

Fast moving pulsars are accompanied by bowshocks others show jets and torii.

If the SNR shock becomes asymmetric (due to the interaction with the environment). In this case the reverse shock will also be asymmetric and can ``crush'' a PWN pushing it to the side from the pulsar.

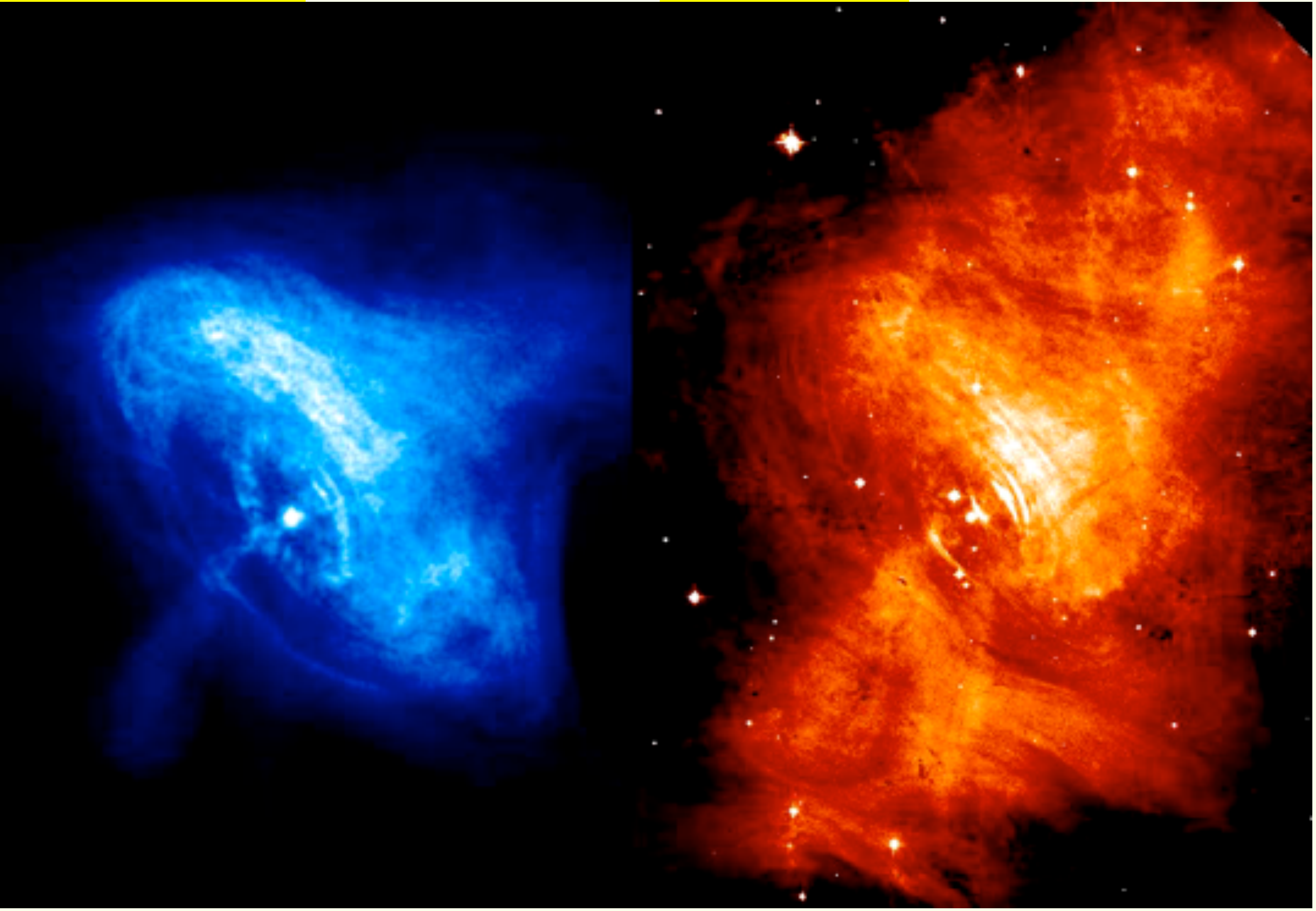
Complex? See real Chandra images on the left!

Torus-jet PWNe: Crab

X-rays - Chandra

Optical - HST

Hester et al. 2002



Complex structure both in X-ray and optical comprised of mysterious linear features - “wisps”.

The innermost ring inside the torus (likely termination shock) is resolved by Chandra and HST.

Torus-jet structures are dynamic especially in the vicinity of the termination shock …

X-ray

Optical

Torus-jet PWNe: Vela

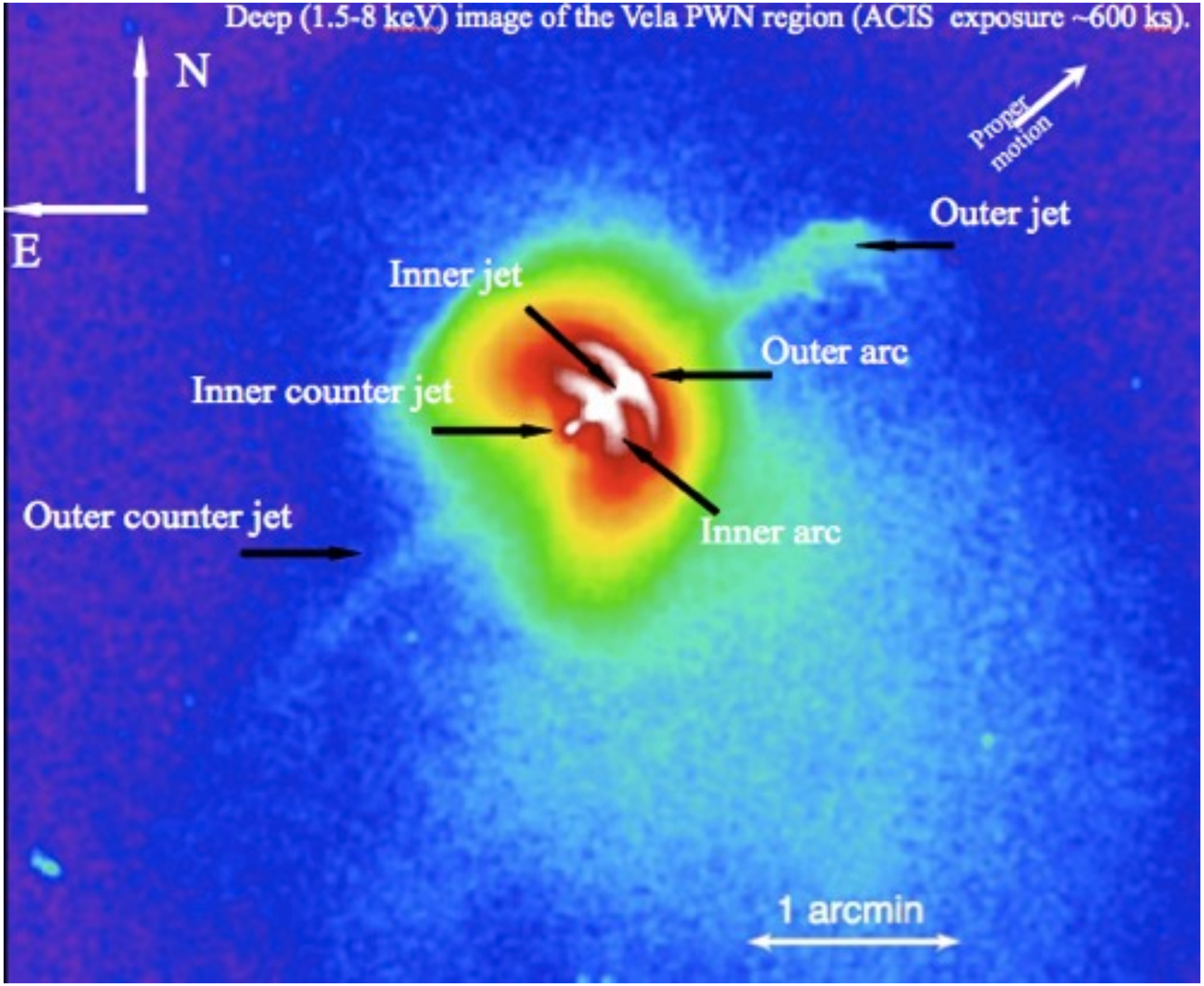
P=89.3 ms

$\dot{E}=7\times10^{36}$ erg/s

$B=3.4\times10^{12}$ G

Age =11 kyrs

Size: 6’ × 5.5’ = 0.52 pc × 0.48 pc @ d=300 pc


Deep (1.5-8 keV) image of the Vela PWN region (ACIS exposure ~600 ks).

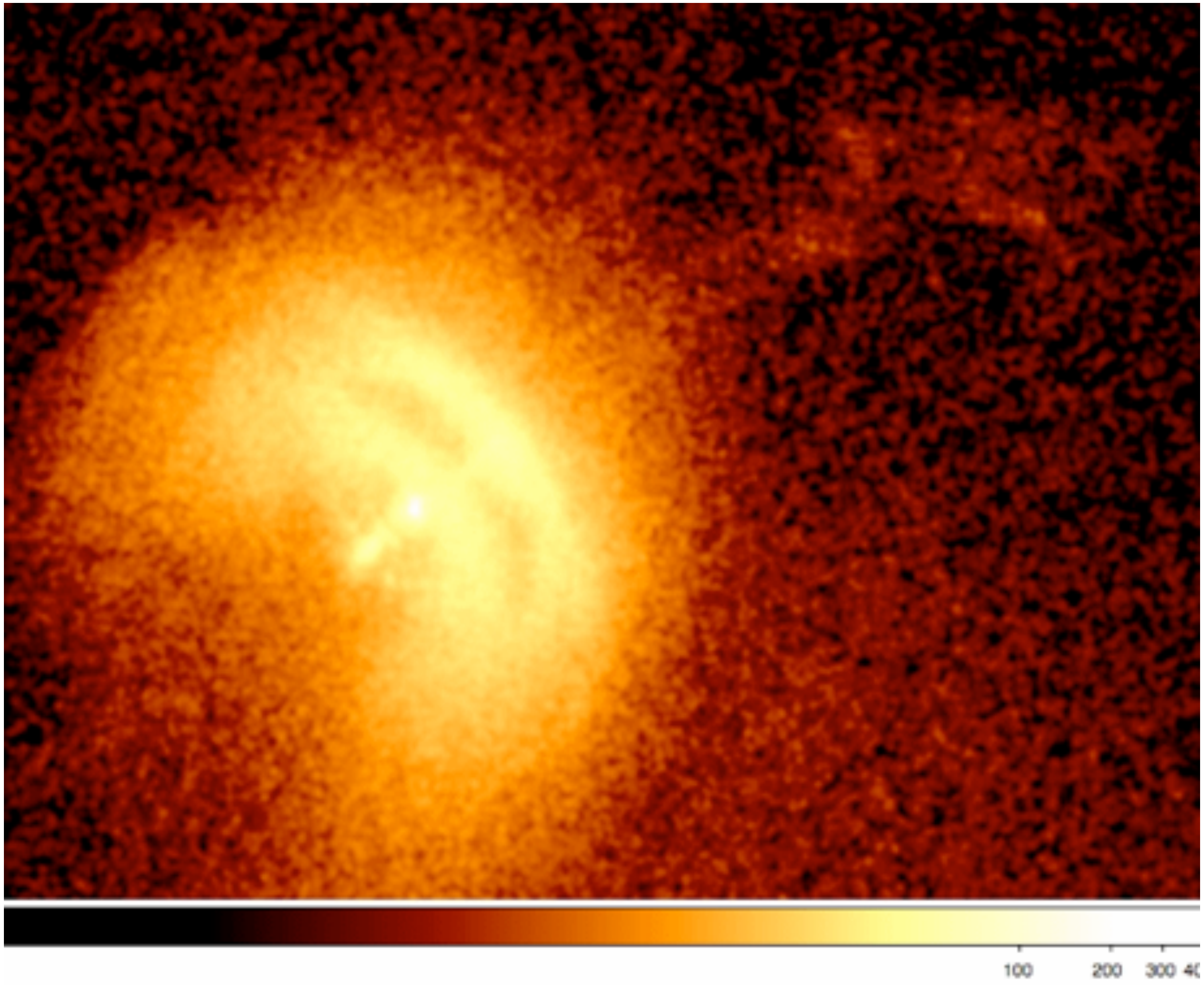
- **Nearby, d=300 pc → well-resolved with Chandra**

- **Bright enough to provide high-S/N images and spectra**

- **Rich and puzzling structure with both similarities and differences from the Crab PWN**

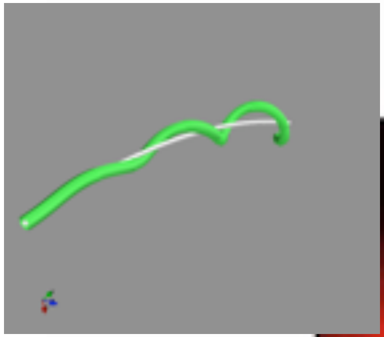
- **Also very dynamical!**

Vela PWN Jet (recent series, 8 x 40 ks, 1 week separation)



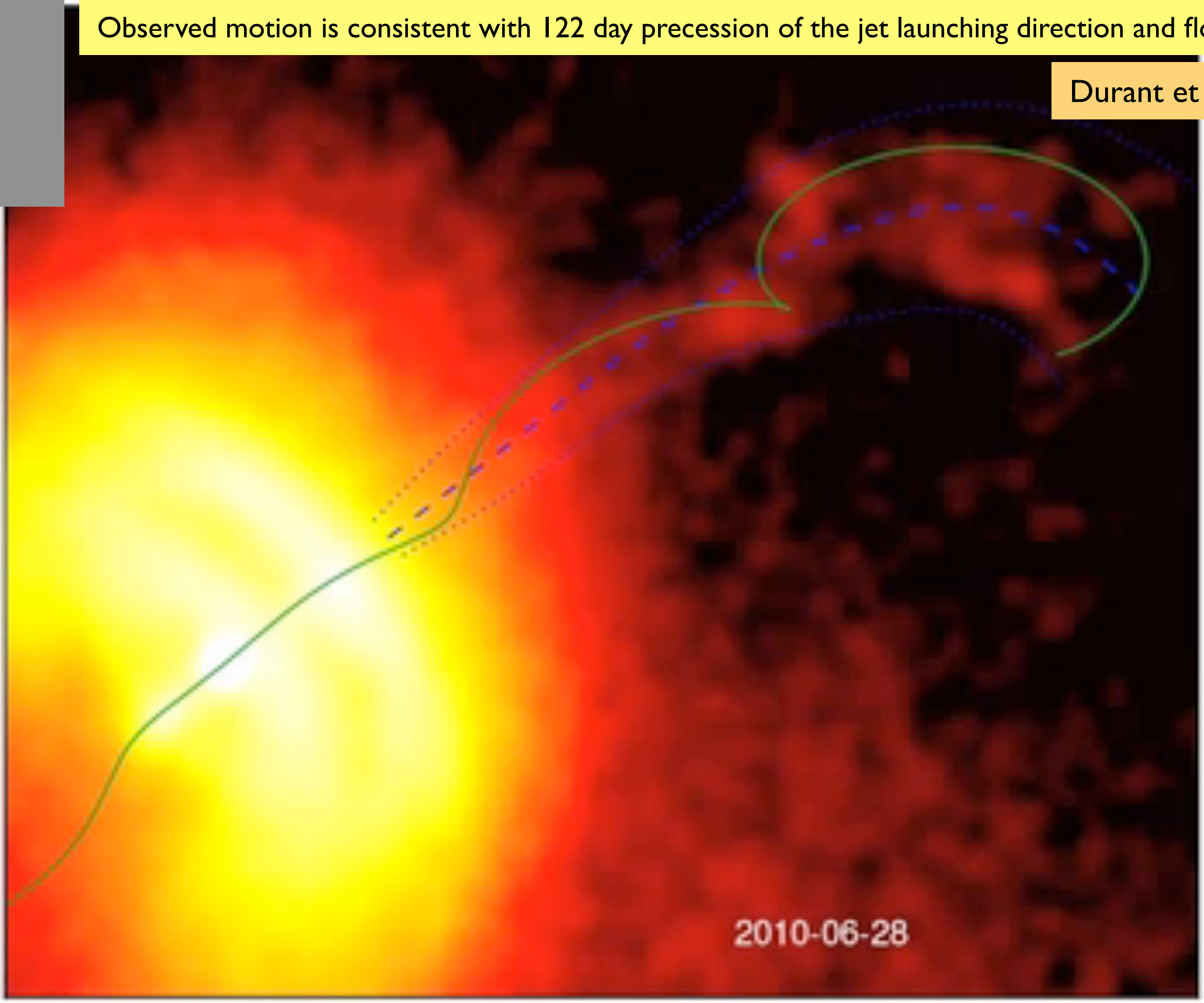
Resembles rotating corkscrew!

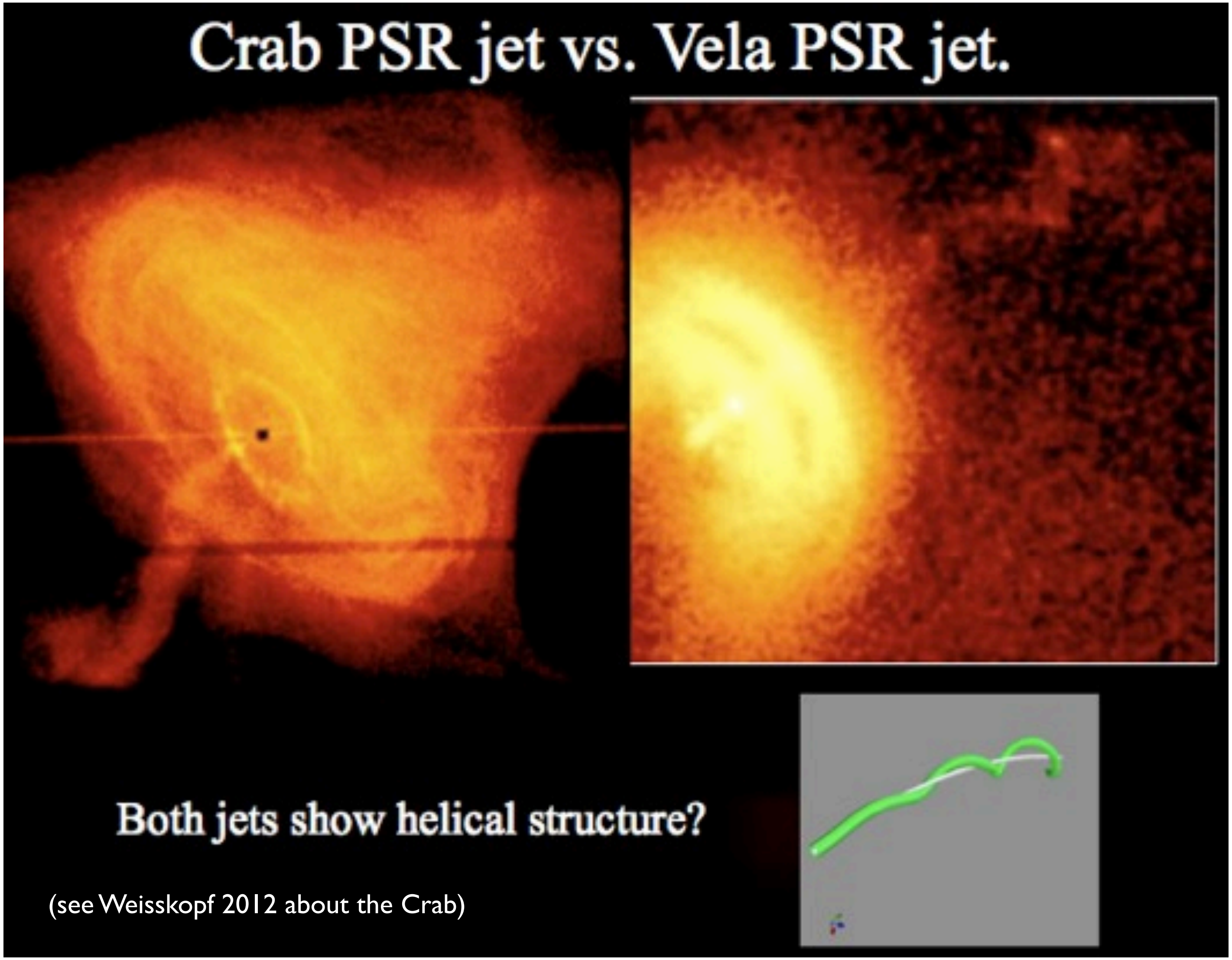
The Vela Pulsar’s jet: a giant cosmic corkscrew.
Instability or evidence for a torque-free neutron star precession?



Observed motion is consistent with 122 day precession of the jet launching direction and flow speed of 0.7c.

Durant et al. (2012)





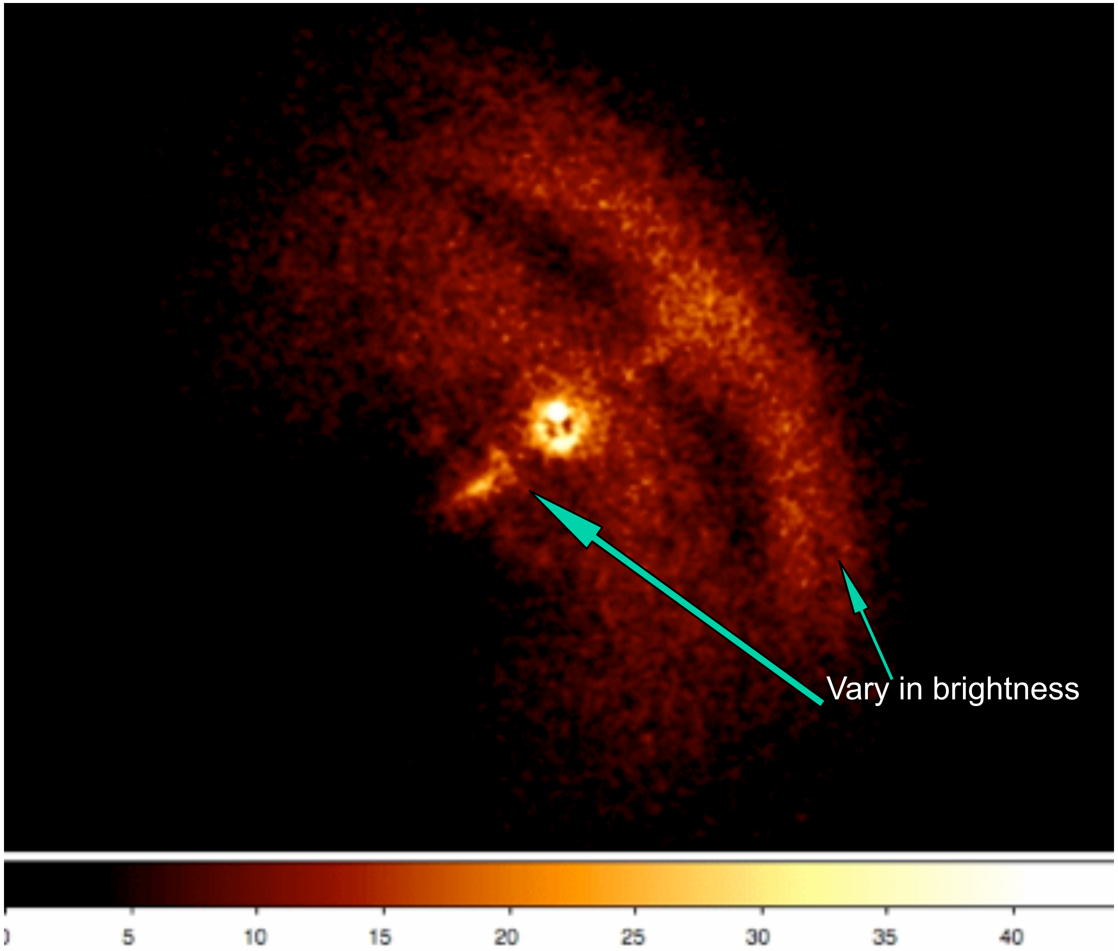
Crab PSR jet vs. Vela PSR jet.

Both jets show helical structure?

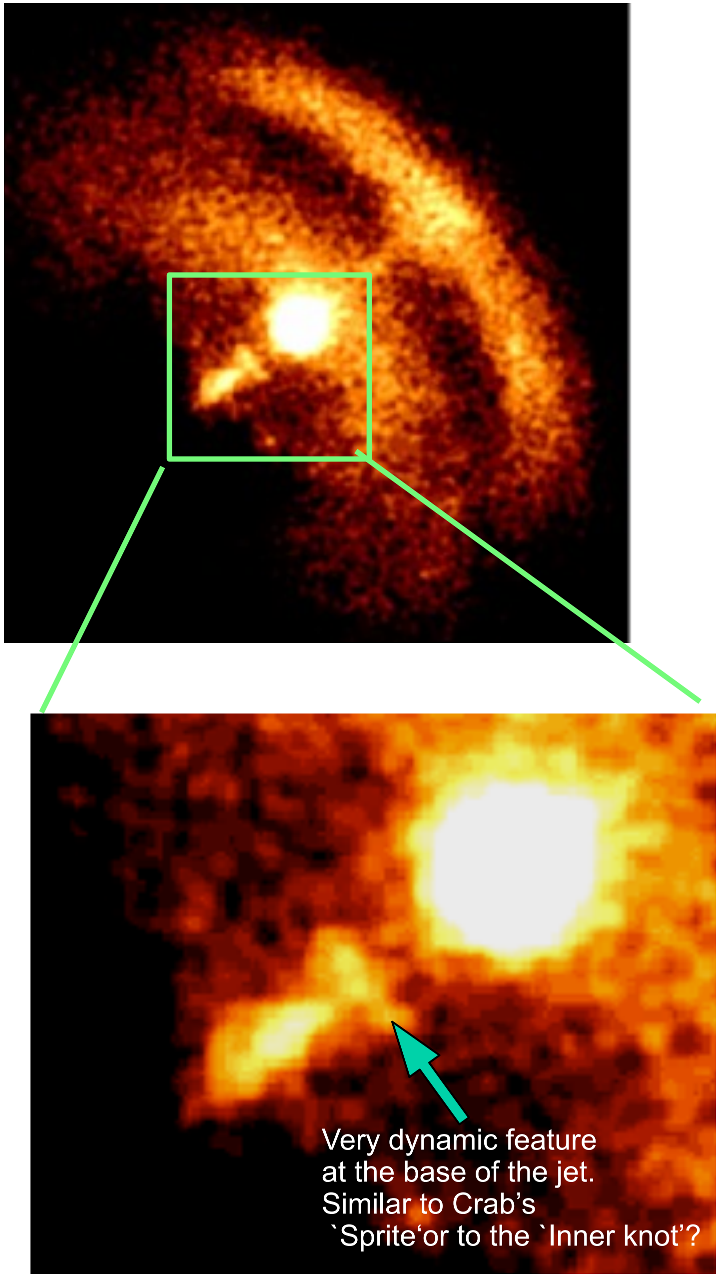
(see Weisskopf 2012 about the Crab)

Vela Inner PWN:

Shock at the base of the counter-jet: jet forms (or becomes visible) just downstream of this shock.



Vary in brightness

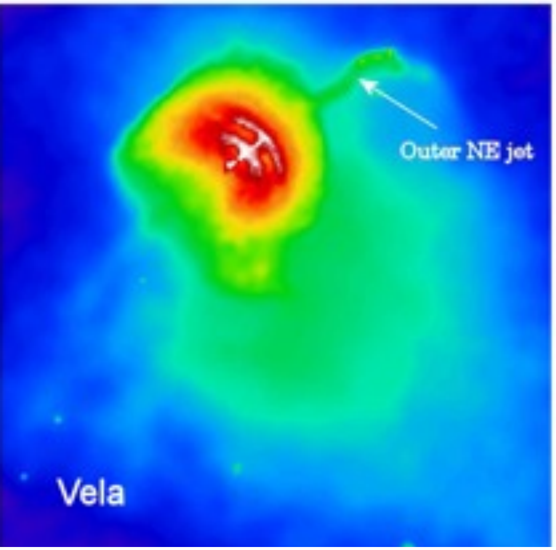


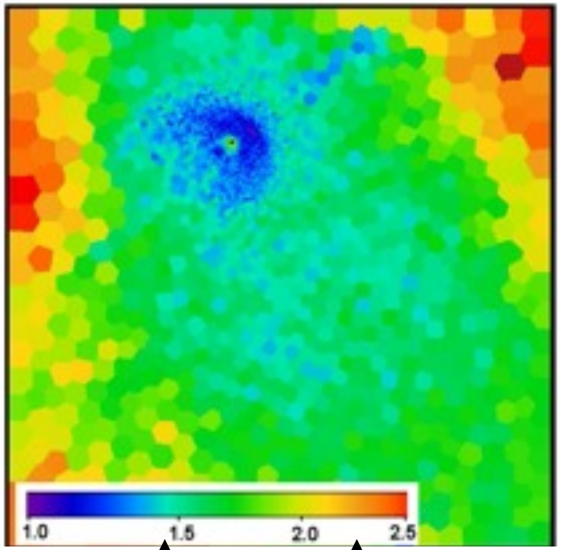
Very dynamic feature at the base of the jet. Similar to Crab's `Sprite'or to the `Inner knot'?

Kargaltsev et al. (2013)

See also poster B9 by D. Zybin

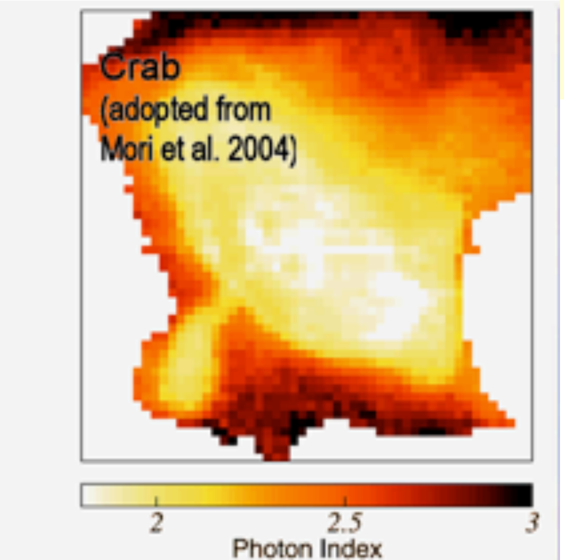
PWNe: spectral structure – particle acceleration





Synchrotron surface brightness

Map of the photon index Γ



Large-scale spectral structure:
Soft shell surrounding very hard inner features. Harder emission SW from pulsar.

Inner parts of the Vela PWN have extremely **hard spectra**, for synchrotron:

$$S_\nu \propto B^\Gamma \nu^{-\Gamma+1} \quad p = 2\Gamma - 1$$

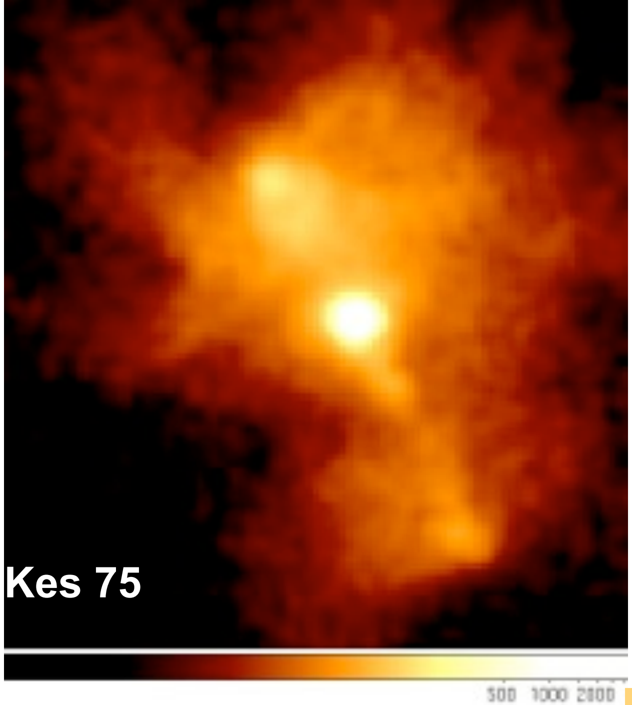
$$\mathrm{d}n_E = K E^{-p} f(\vec{n})\, \mathrm{d}E\, \mathrm{d}\Omega$$

→ **p ≈1.5 in Vela PWN** contradicts simple Fermi-type acceleration models that predict universal p=2.1-2.2

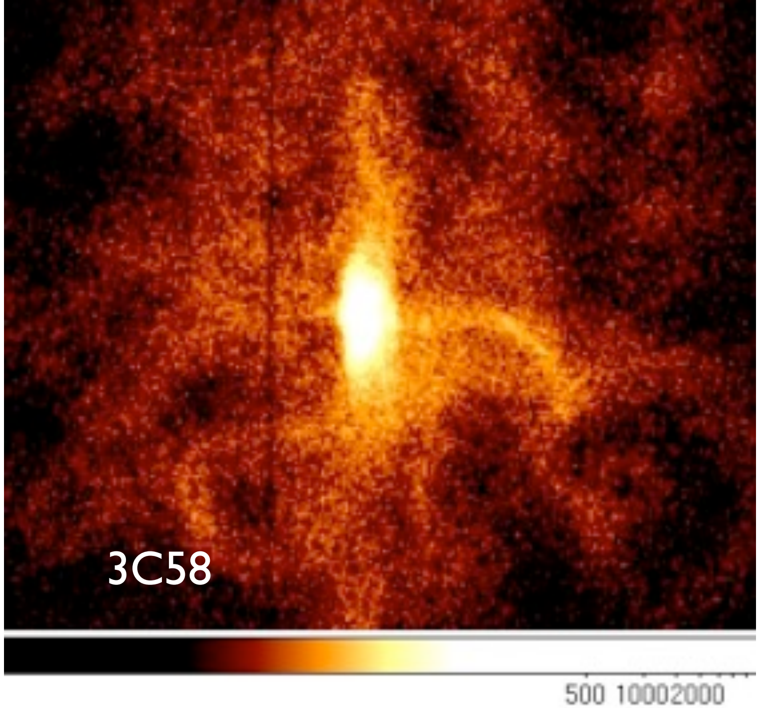
Inner parts of the **Crab** PWN have much softer spectra **p ≈2.6**

see Sironi & Spitkovsky (2011) for possible solution

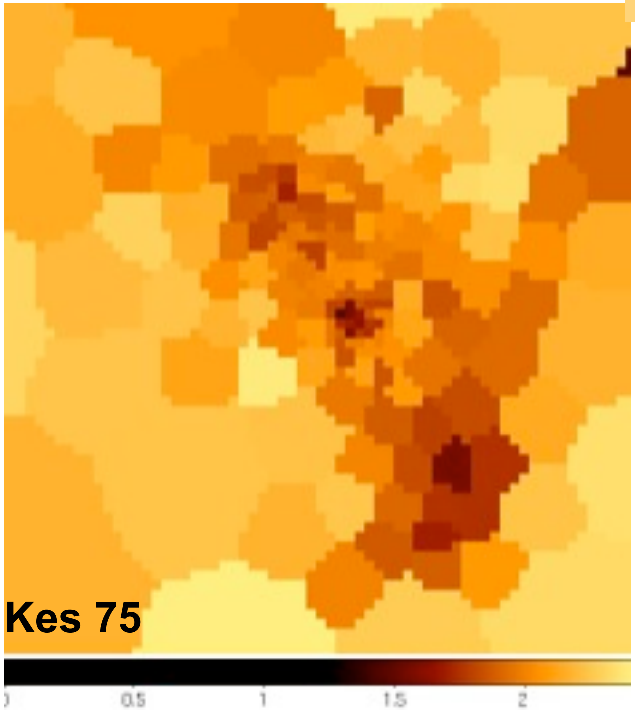
also talk by Iwona Mochol



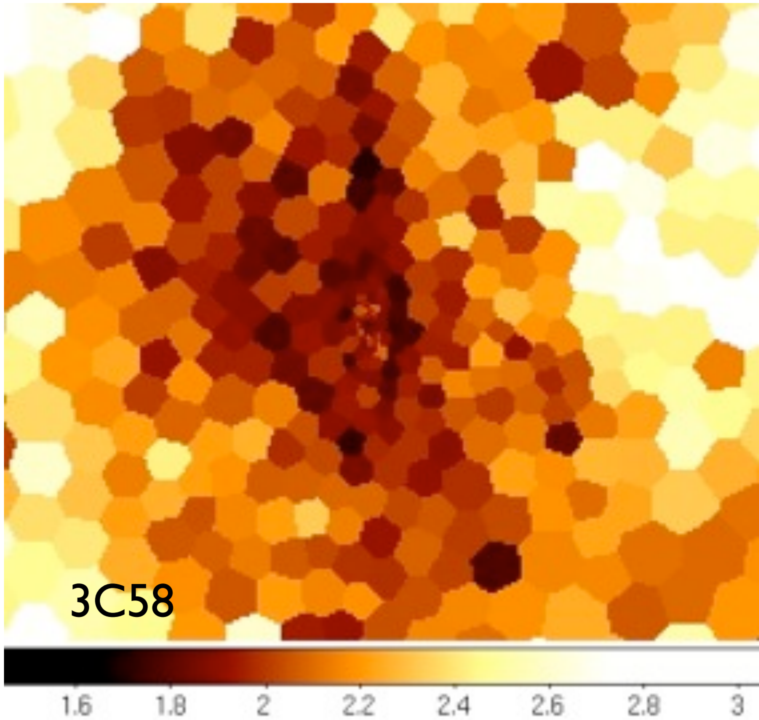
ACIS images

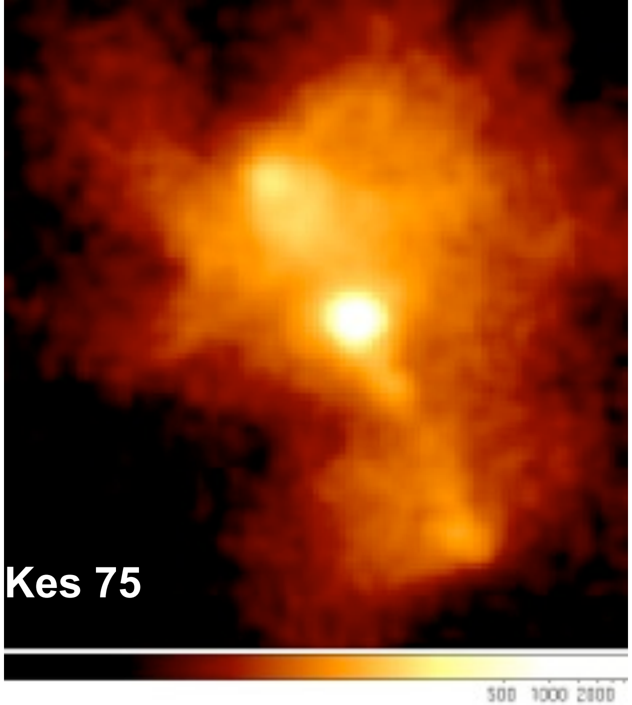


Durant et al. (2013)

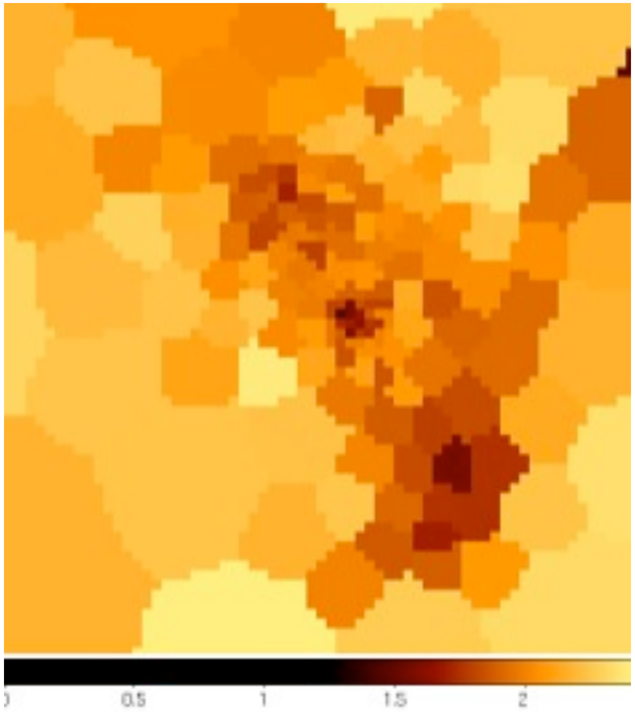


Adaptively binned <u>spectral maps</u>

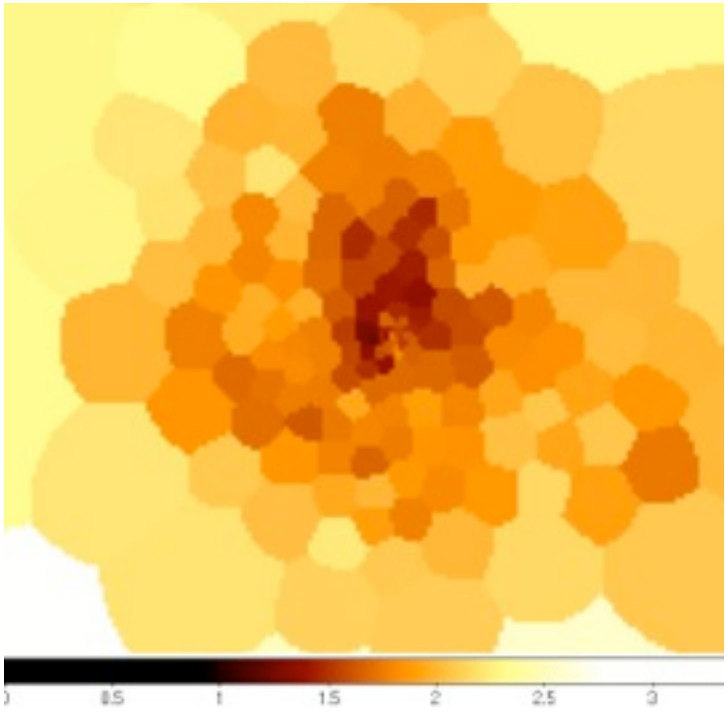




ACIS images



Adaptively binned <u>spectral maps</u>

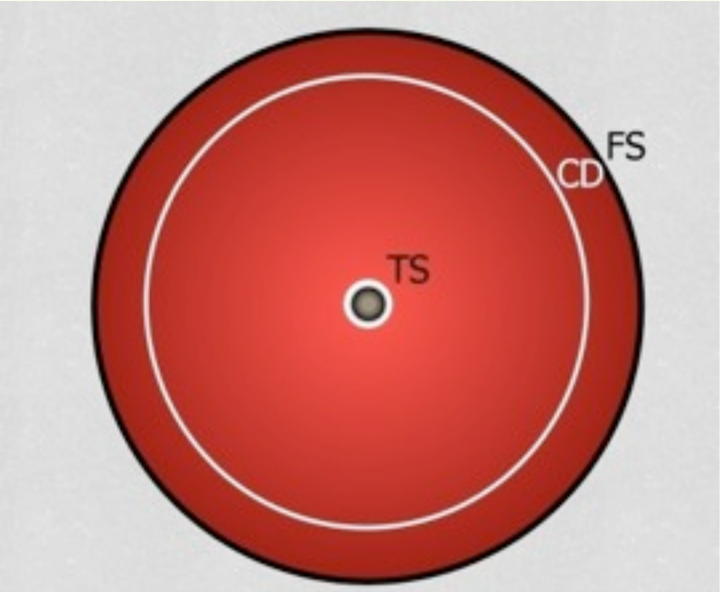


Termination shock and PWN shapes depend on pulsar velocity and intrinsic outflow anisotropy.

Subsonic velocity:

Isotropic outflow: sphere

Anisotropic outflow: equatorial + polar =
torus + jet(s)



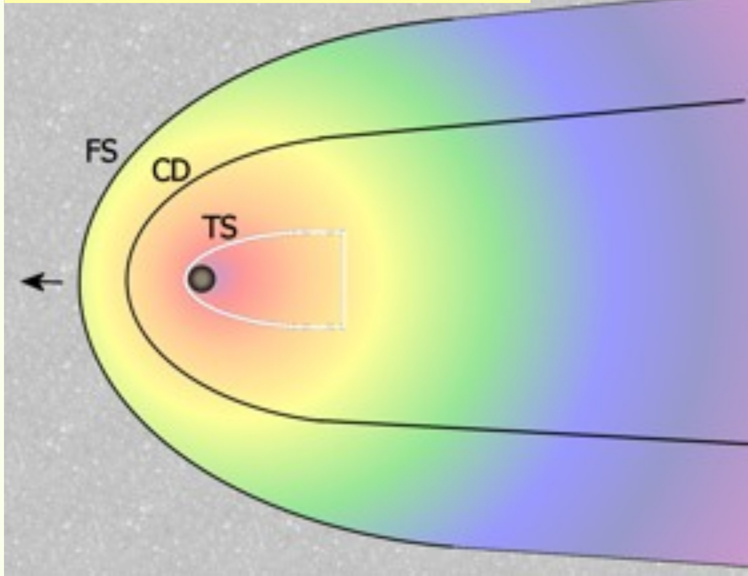
TS – termination shock
CD – contact discontinuity
FS – forward shock

Supersonic velocity:

Isotropic outflow: bow shock + tail

Anisotropic outflow: equatorial + polar =
umbrella-like termination shock + structured tail

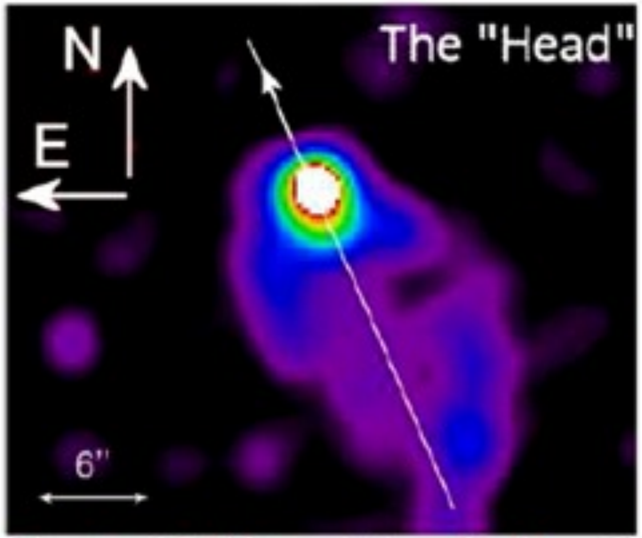
Real examples follow…



Bowshock-tail PWNe: 150-kyr-old PSR J1509-5850

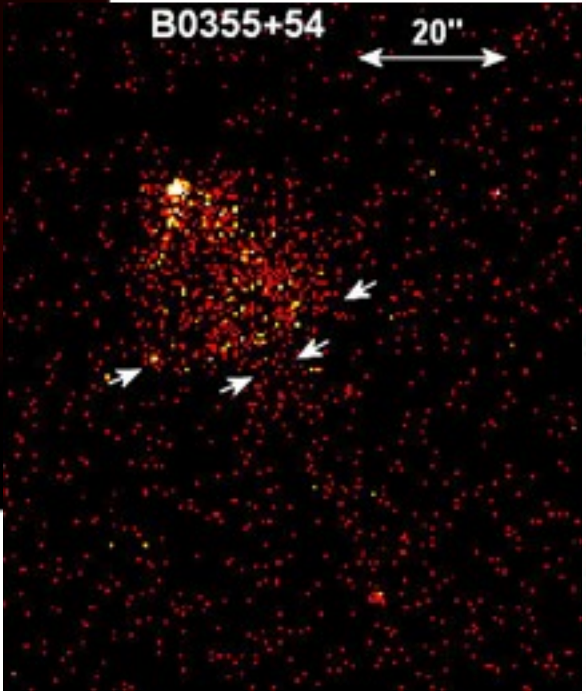
d ~ 4 kpc
$\dot{E}$=5.1 x 10^{35} erg/s

- Flow in the tail is supersonic.
- Chandra images indicate substructure within the tail: internal shocks or instabilities?

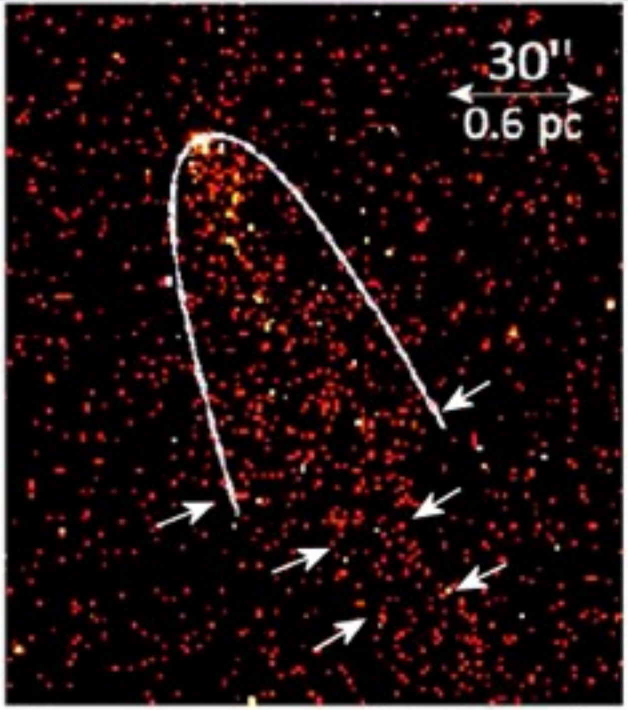


The longest (>6 pc) pulsar tail in X-rays.

The **6-pc tail** length and synchrotron cooling in B~20 μG imply V_{flow} ~ **15,000** km/s >> than V_{PSR}~ 300-800 km/s.



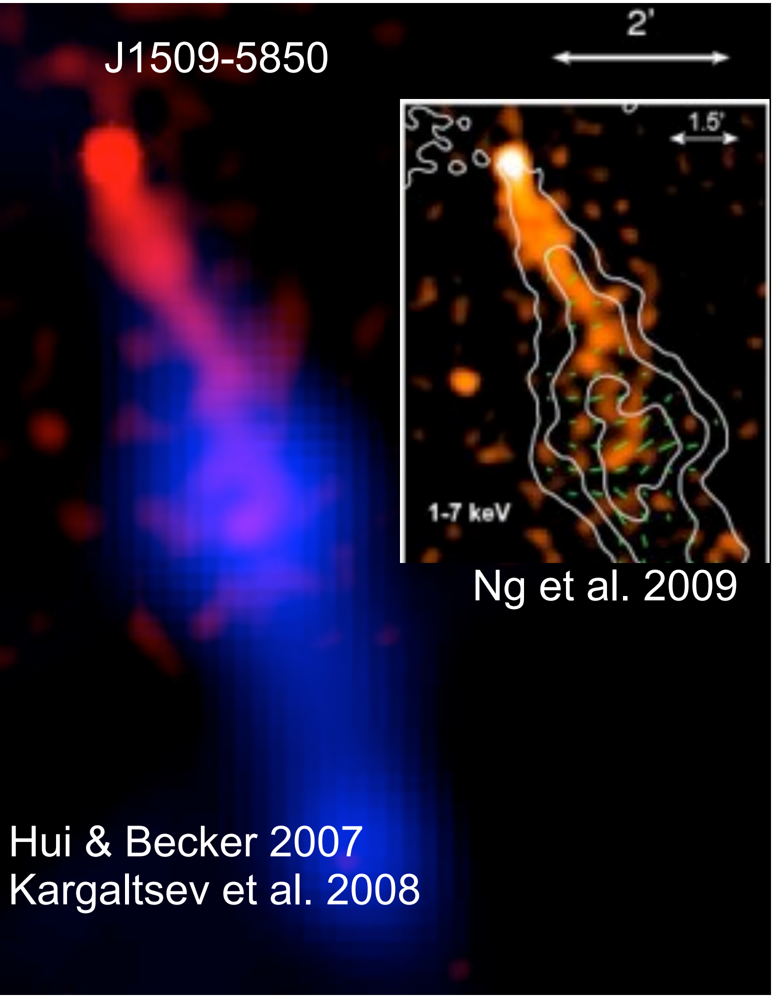
Kargaltsev et al.(2008)



Close-up view of the "head" and the tail near the pulsar.

Mouse PWN vs. J1509-5850 PWN (multiwavelength comparison) :

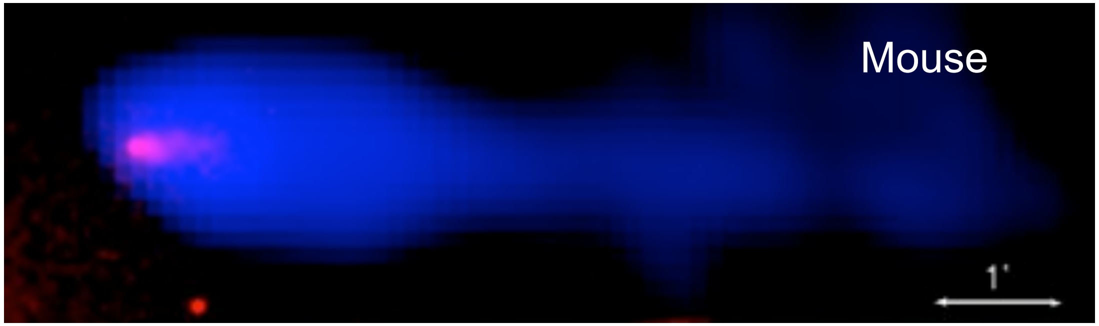
Observations ahead of models: numerical MHD models (Bucciantini et al. 2005) produce images that could be compared to observations but simulations go out just to a ~10 termination shock radii. Analytical models may offer advantages (e.g., Romanova, Chulsky, & Lovelace 2005) ?

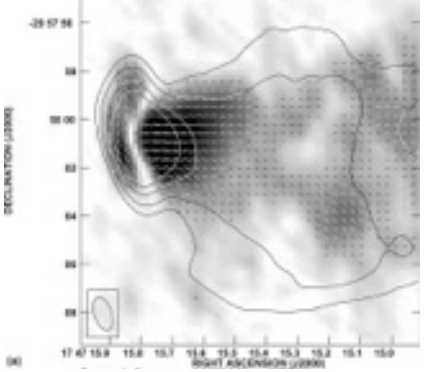


Ng et al. 2009

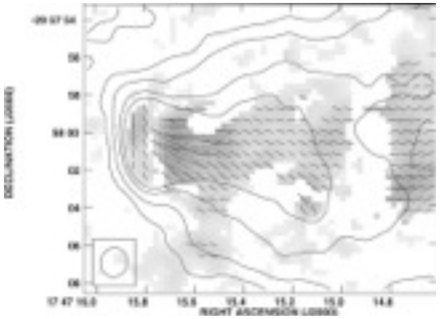
Hui & Becker 2007
Kargaltsev et al. 2008

Both J1509 PWN and Mouse will be observed by Chandra





Yusef-Zadeh & Gaensler 2005

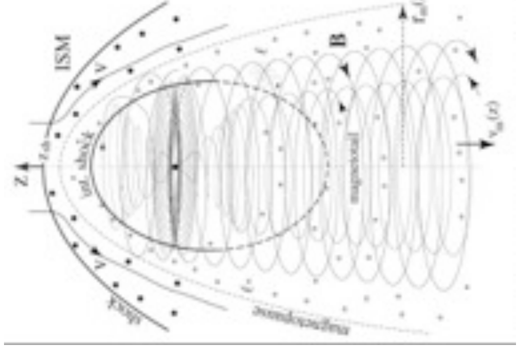


Radio polarimetry provides a unique oppurtunity to map the magnetic field structure.

J1509 and Mouse PWNe different:

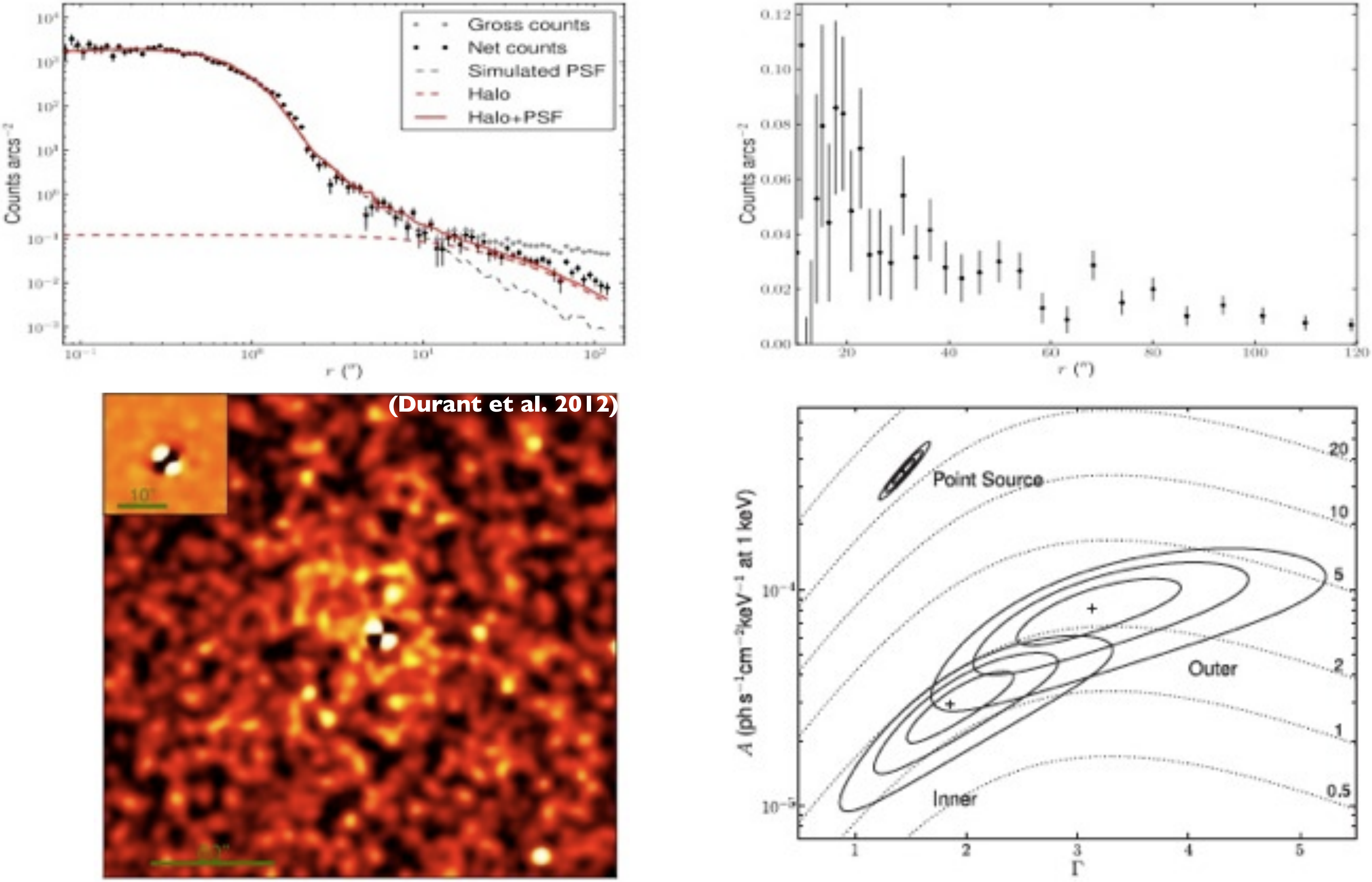
- X-ray radio correlation in Mouse vs. anticorrelation in J1509 PWN
  - Anticorrelation is difficult explain by synch. cooling only
  - In Mouse magnetic field parallel to the tail, in J1509 tail it is perpendicular.

Romanova et al. 2005



X-ray pulsar-wind nebulae in gamma-ray binaries

I. Microquasar **LS 5039** (compact object orbiting O-star with 4 day period):



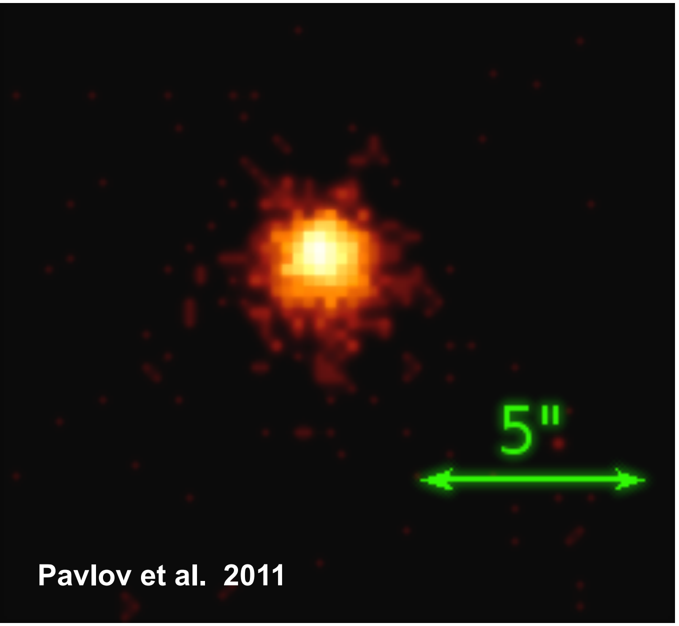
(Durant et al. 2012)

Extended emission can shed light on the nature of the compact object in LS 5039. A natural analogy with PWNe hints that it may be a pulsar but could there be a BHWN ?

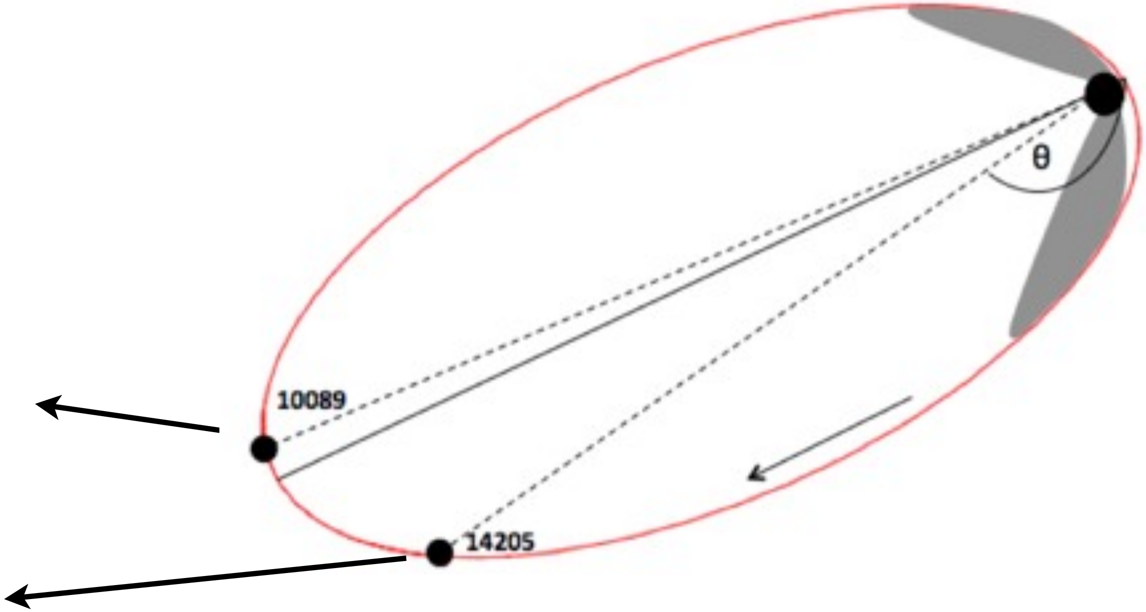
X-ray pulsar-wind nebulae in gamma-ray binaries

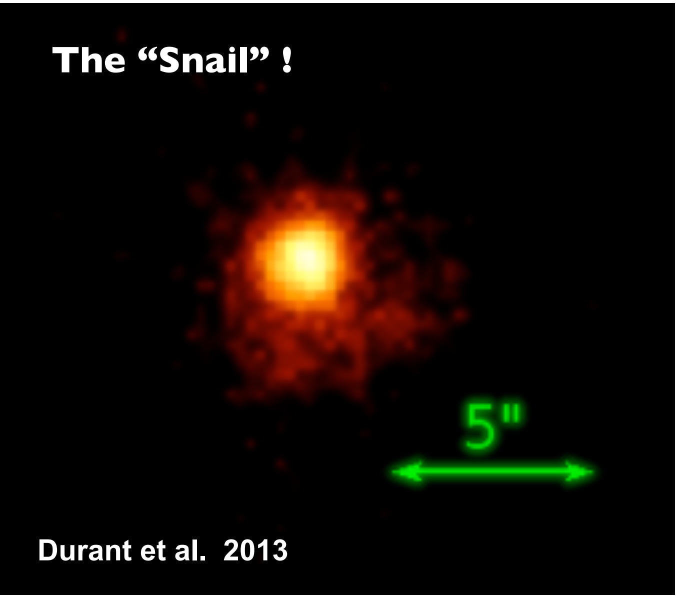
also talk by
Robin Corbet

II. **SS 2883** binary (young **PSR B1259-63** in 3.4 year orbit around O star):



Pavlov et al. 2011



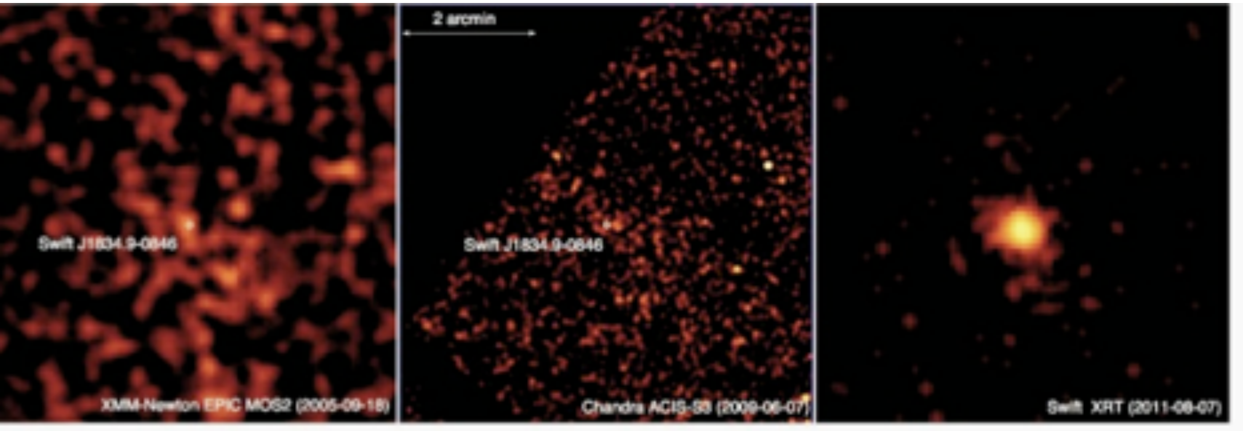


The “Snail” !

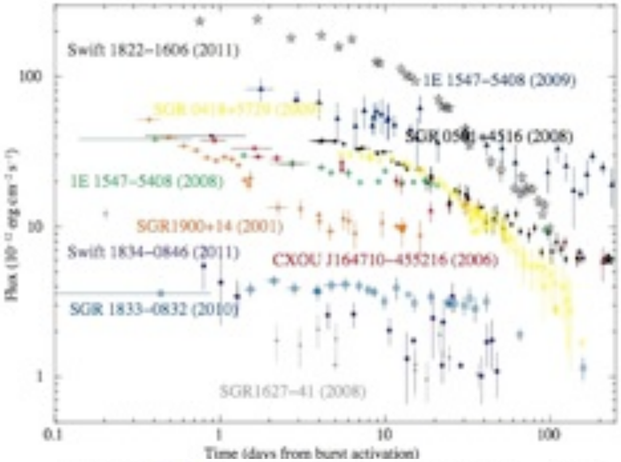
Durant et al. 2013

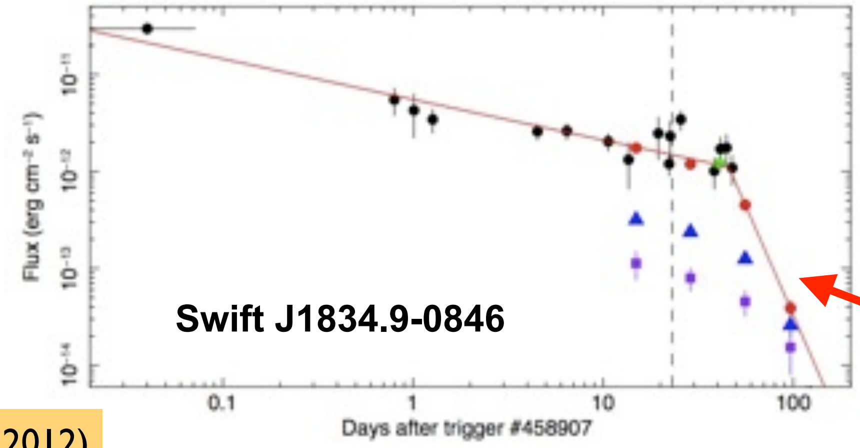
MAGNETAR NEBULAE?

New, possibly relatively nearby (~4 kpc) magnetar SGR Swift J1834.9-0846



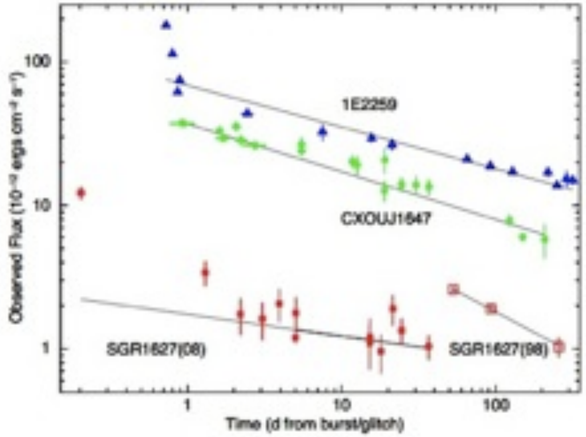
(Kargaltsev et al. 2012)





Swift J1834.9-0846

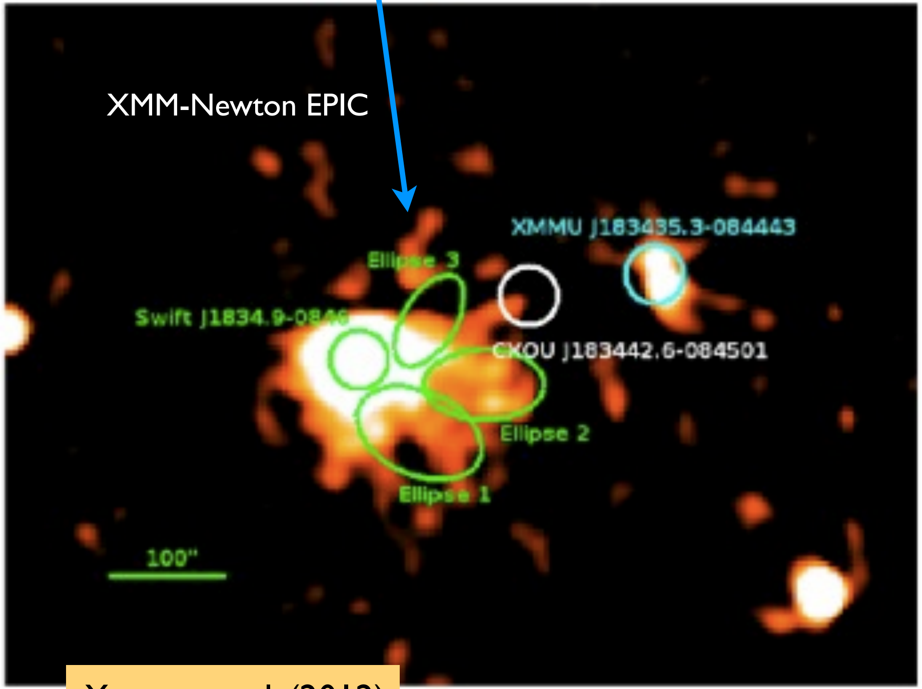
(Esposito et al. 2012)



Rapidly fading away!

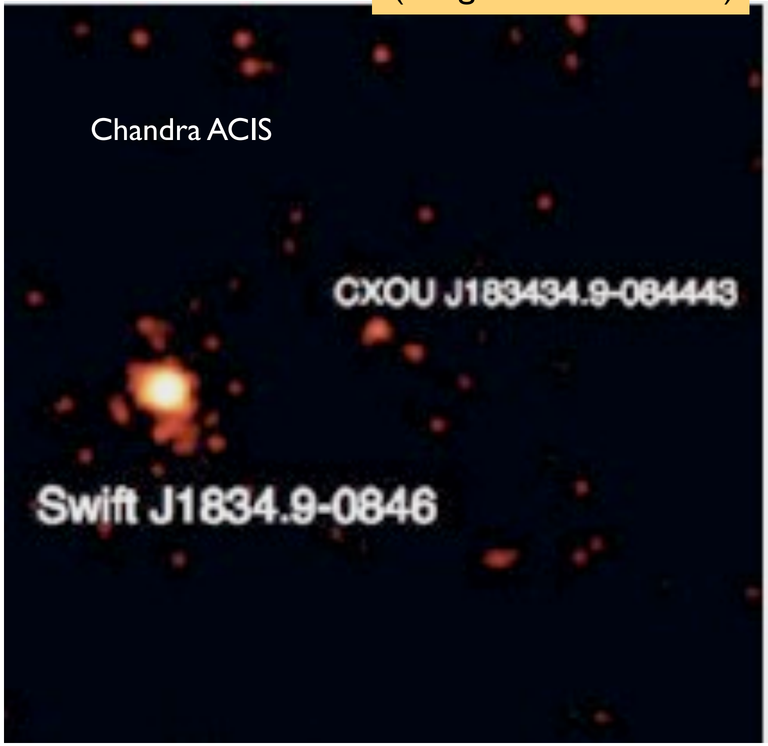
A magnetar-wind nebula (MWN) around Swift J1834.9-0846 ?

asymmetric magnetar wind-nebula?



Younes, et al. (2012)

(Kargaltsev et al. 2012)



See also Esposito et al. (2012)

Summary:

Particle acceleration to ~ a few PeV is required to explain emission from young PWNe.

Very hard spectra of some PWNe are surprising (assuming synchrotron emission) and can hardly be produced by classical Fermi type acceleration. Viable alternative needed (e.g., magnetic reconnection in pulsar wind, acceleration by strong EM waves ?).

Collimation and confinement of pulsar jets (and tails?) must invoke ordered large-scale magnetic field. The flow speed in the jet appears to reach 0.7c. The flow in the jet can exhibits termination shock (just as equatorial flow) which, however, does not destroy the jet. These findings can have analogies in AGN jets.

Vela jet dynamics could be attributed to the free NS precession possibly amplified by MHD instabilities.

Pulsar tails can different appearances in X-rays and seem to lack TeV counterparts. This needs to be investigated more.

In addition to isolated rotation-powered pulsars X-ray nebulae are found around interacting binaries (LS 5039, B1259-63), a RRAT, a magnetar. Those could be different in their properties (perhaps transient or strongly variable).