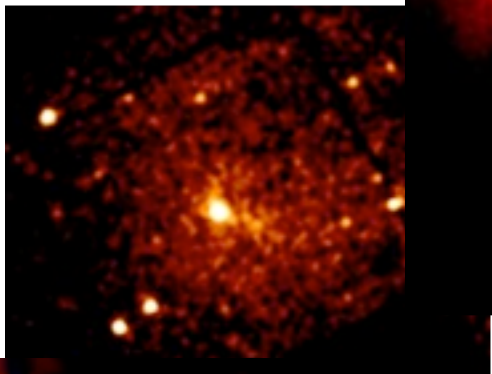
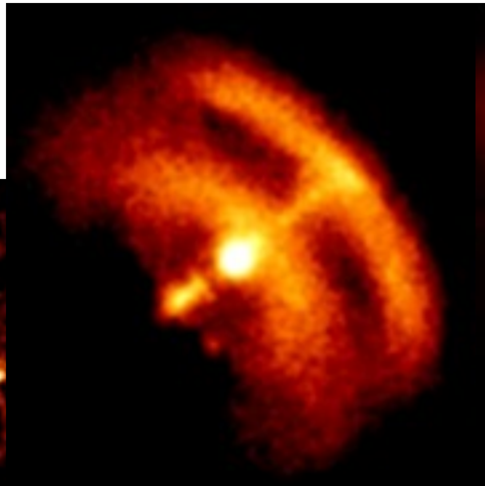
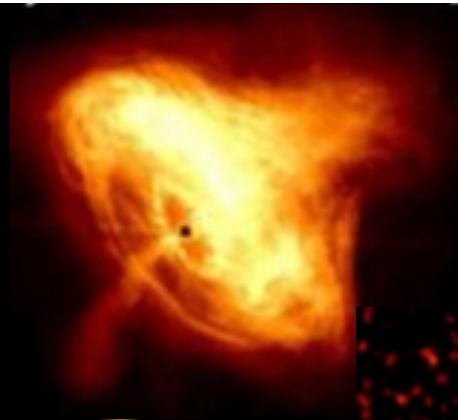
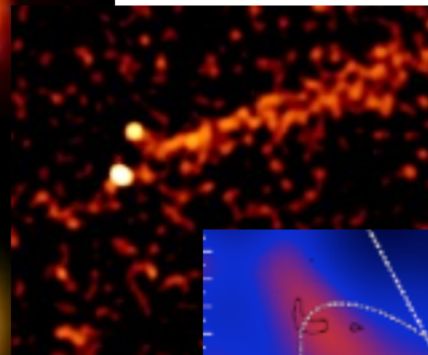
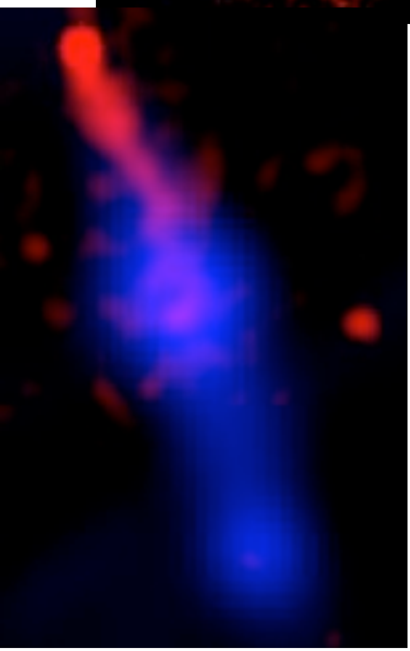
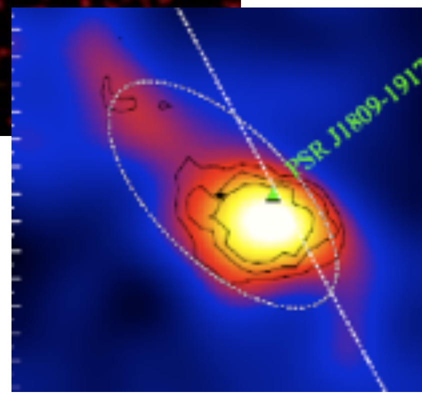
Pulsar wind nebulae: X-ray and multiwavelength observations

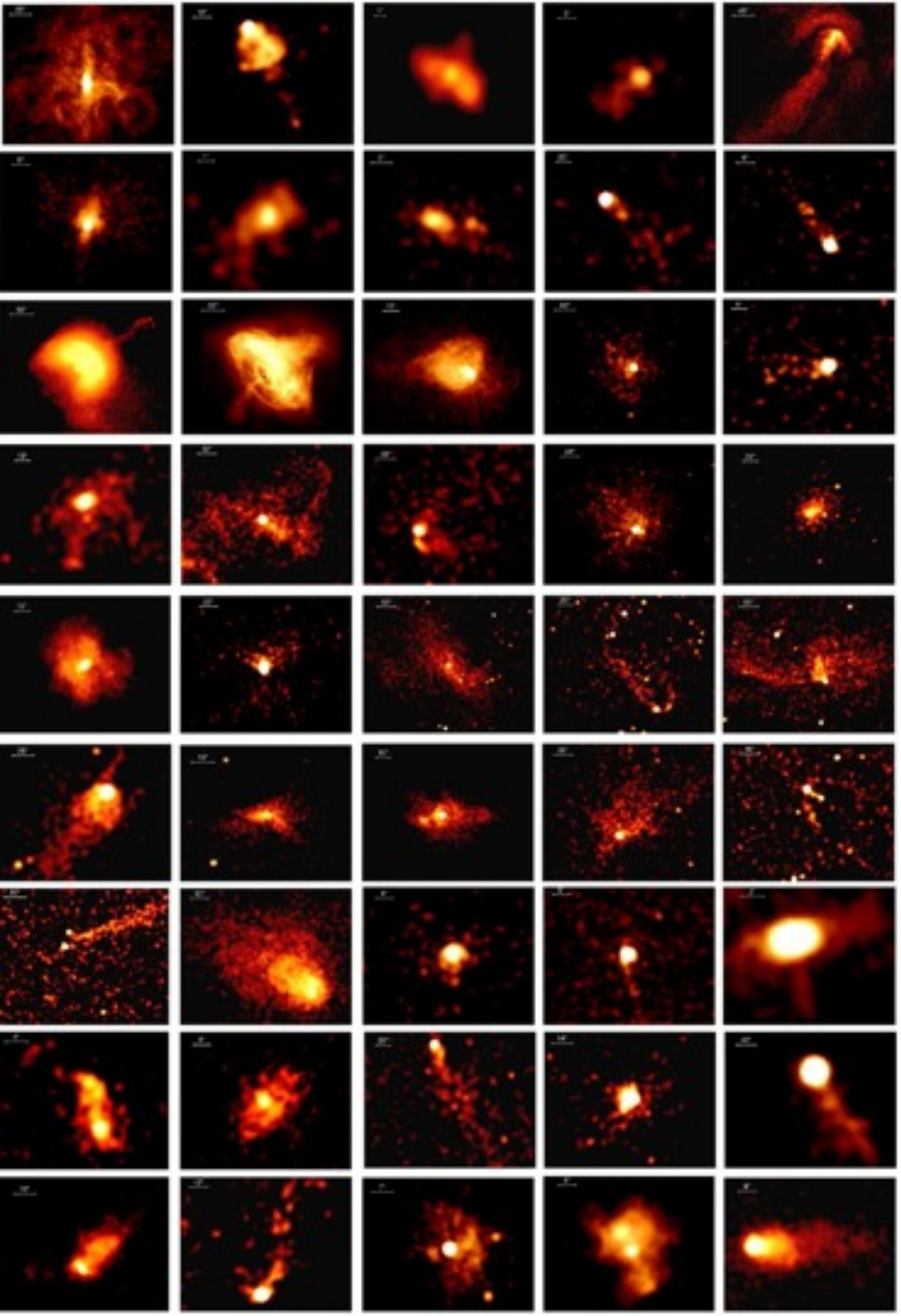


Oleg Kargaltsev (University of Florida)

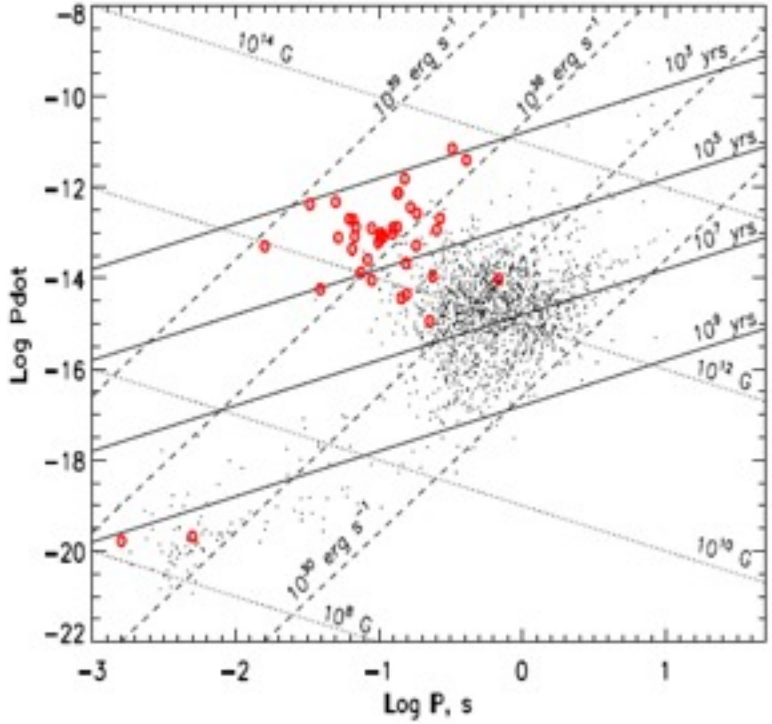
George Pavlov (Penn State University)

Brian Newman (Penn State University)

Zdenka Misanovic (Monash University)



Pulsar Wind Nebulae in Chandra era.

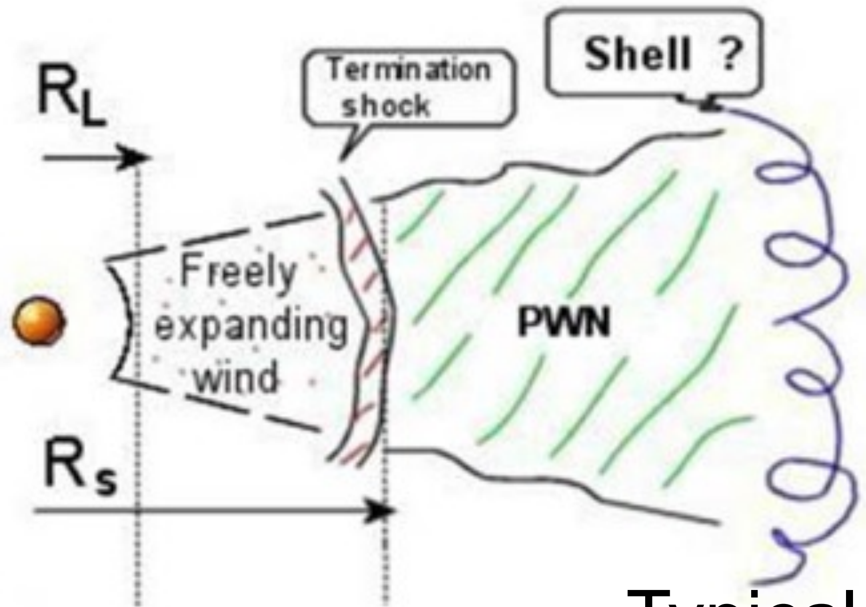


Subarcsecon resolution and low ACIS background make Chandra ideal tool for studying PWNe.

~60 PWNe have been resolved with Chandra to date (Kargaltsev & Pavlov 2008) but some are also found by XMM-Newton.

A few nearby, bright PWNe with complex, well-resolved structures are suitable for spatially-resolved spectroscopy.

Cartoon of a PWN



- All active pulsars emit relativistic winds
- $c > c_s$ → 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: $\mathbf{E_{syn}=2\ (g/2\times10^{7})^{2}\ (B/10\ \mu G)\ \ keV}$

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

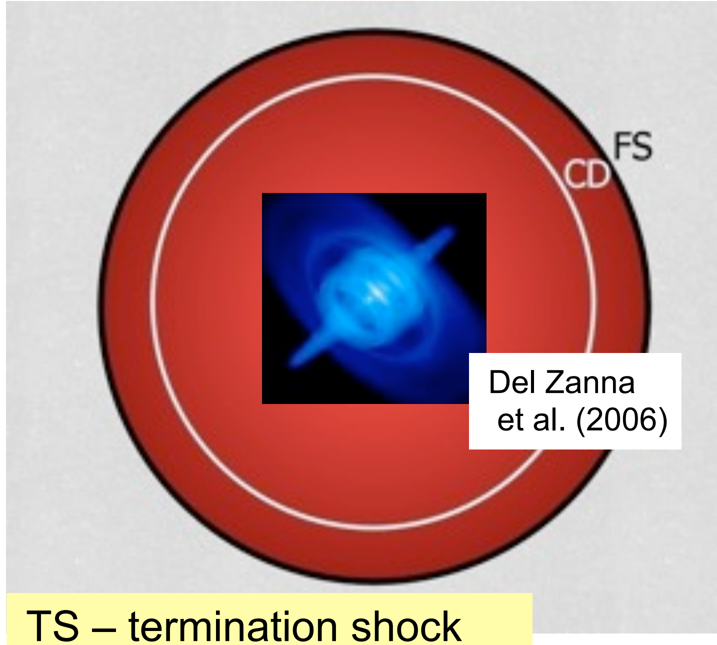
- Characteristic size: $\mathbf{R_s = 0.2\ (\dot{E}/10^{37}\ erg/s)^{1/2}\ (p_{amb}/10^{-10}\ dyn/cm^{2})^{-1/2}\ pc}$
- Synchrotron cooling time: $\mathbf{t_{syn} \sim 1\ (E_{syn}/1\ keV)^{-1/2}\ (B/10\ \mu G)^{-3/2}\ kyr}$
- Luminosity: $\mathbf{L = \eta\ \dot{E},\ \ \eta < 1}$ (efficiency, η, depends on wind parameters and outflow geometry; $\eta_X \sim \mathbf{10^{-5} – 10^{-1}}$ from observations).

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

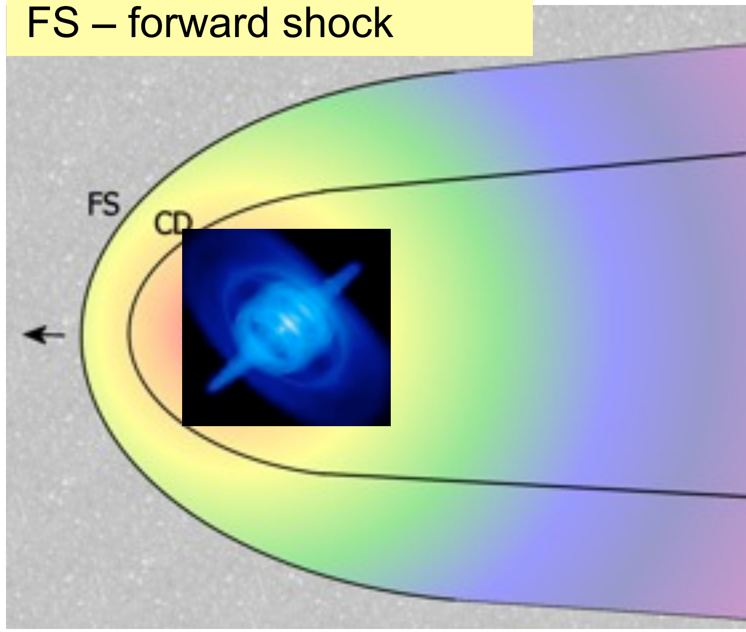
Subsonic velocity:

Isotropic outflow: sphere

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



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



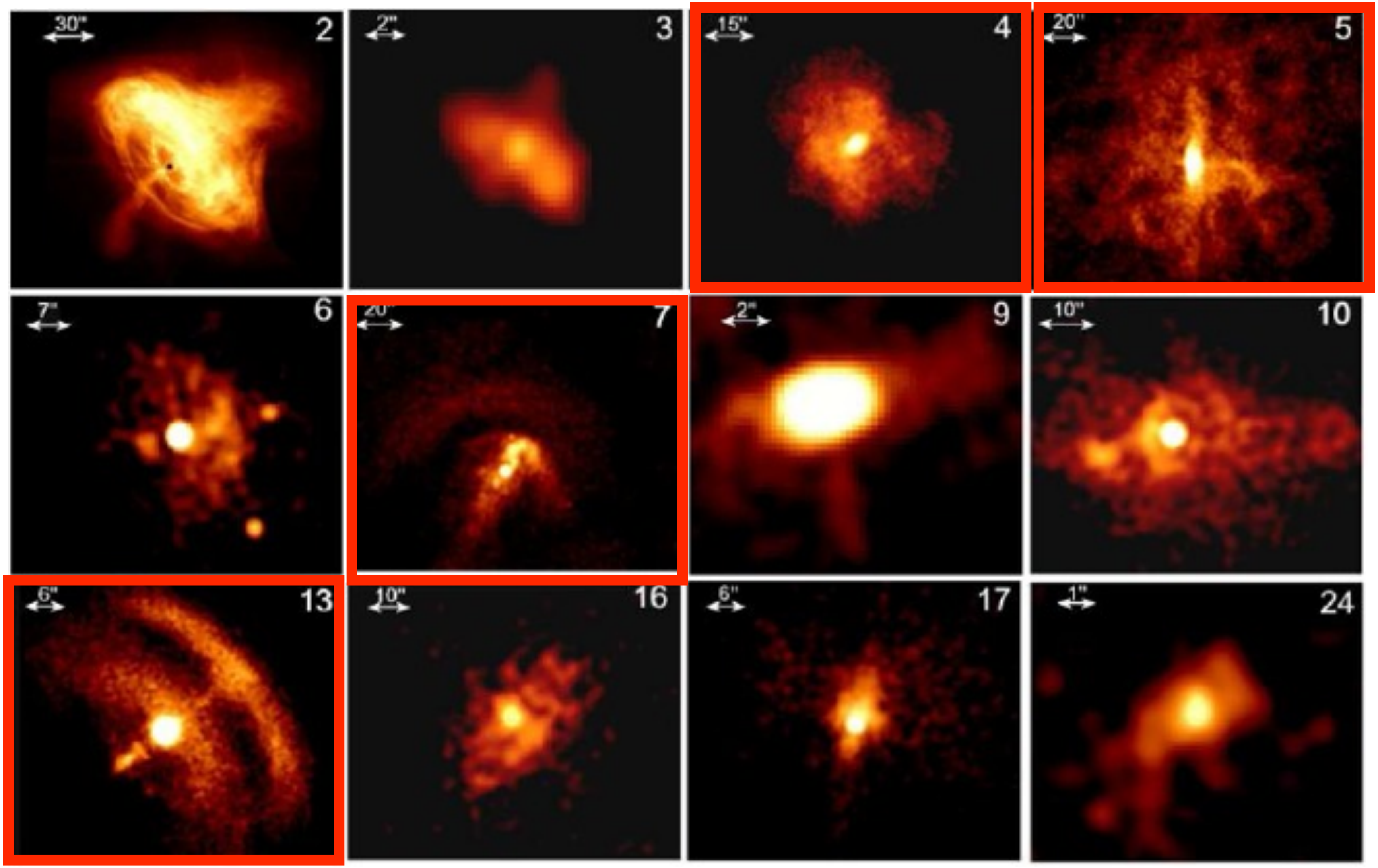
Supersonic velocity:

Isotropic outflow: bow shock + tail

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

Real examples will follow…

Torus-jet PWNe



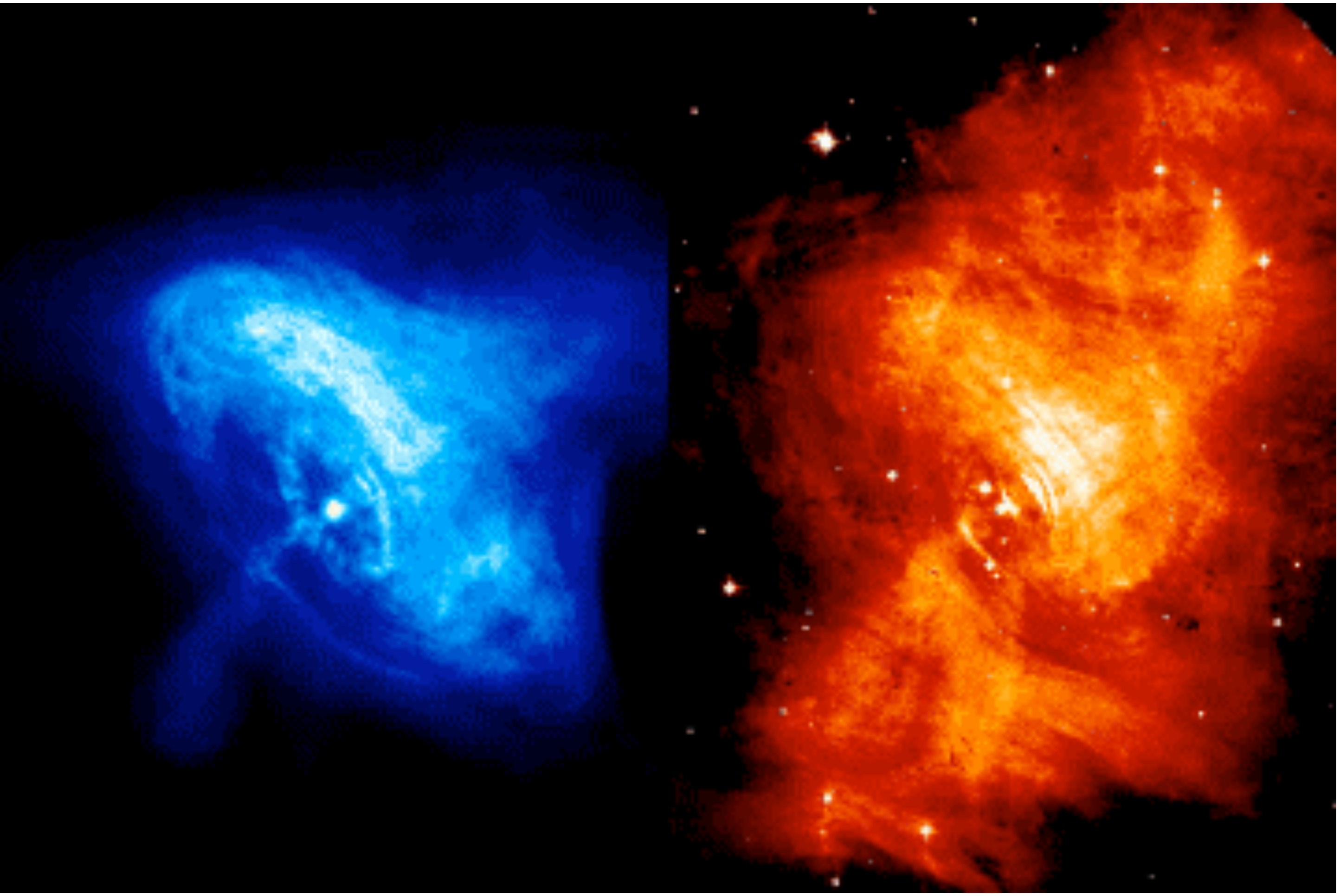
In some cases structures are more complex than just torus and jets…

Torus-jet PWNe: Crab

X-rays - Chandra

Optical - HST

Hester et al. 2002



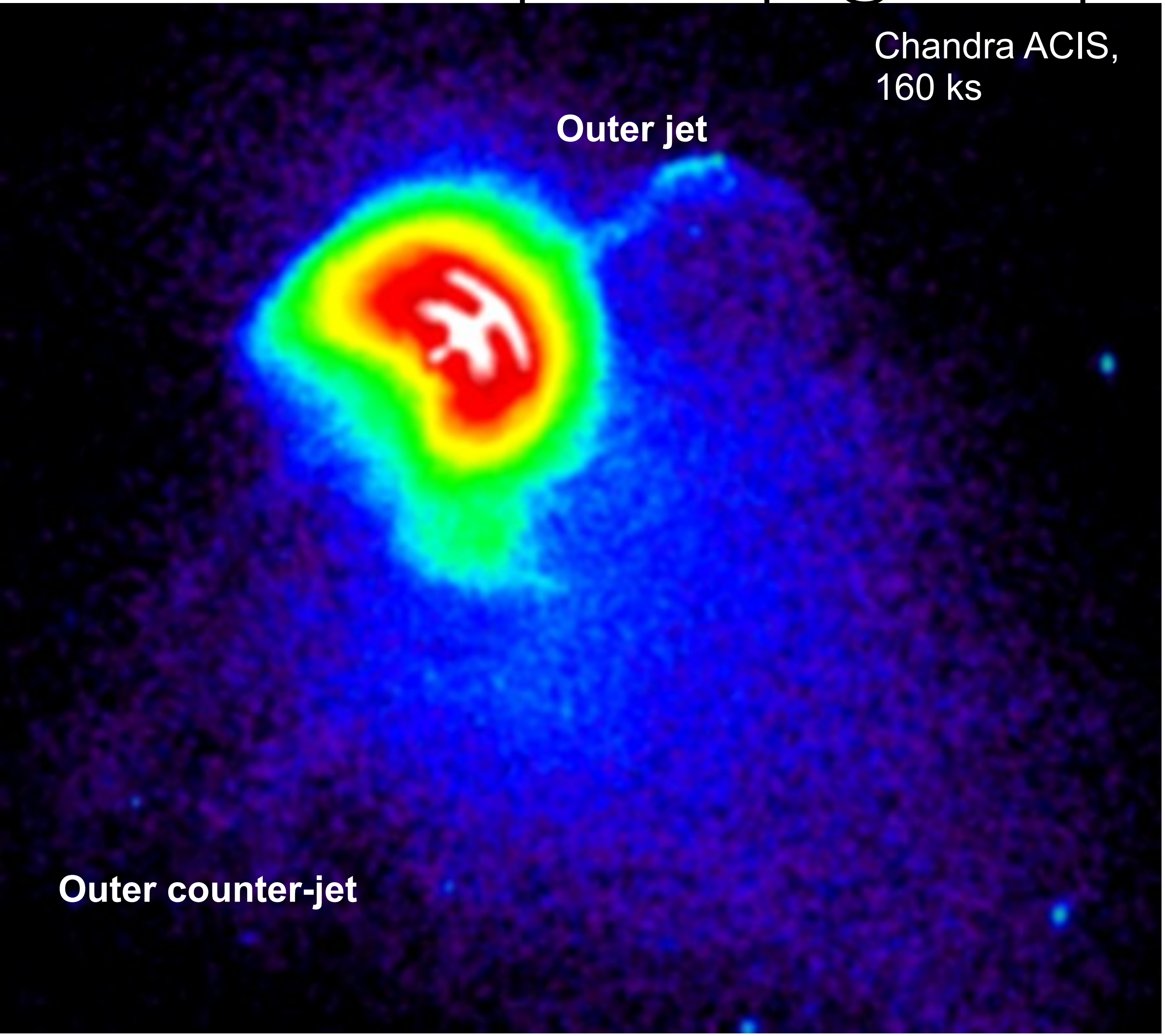
Notice the innermost ring inside the torus: termination shock is resolved by Chandra and HST.

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

Torus-jet PWNe: Vela

- $P=89.3$ ms
- $\dot{E}=7\times10^{36}$ erg/s
- $B=3.4\times10^{12}$ G
- $t=11$ kyrs

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

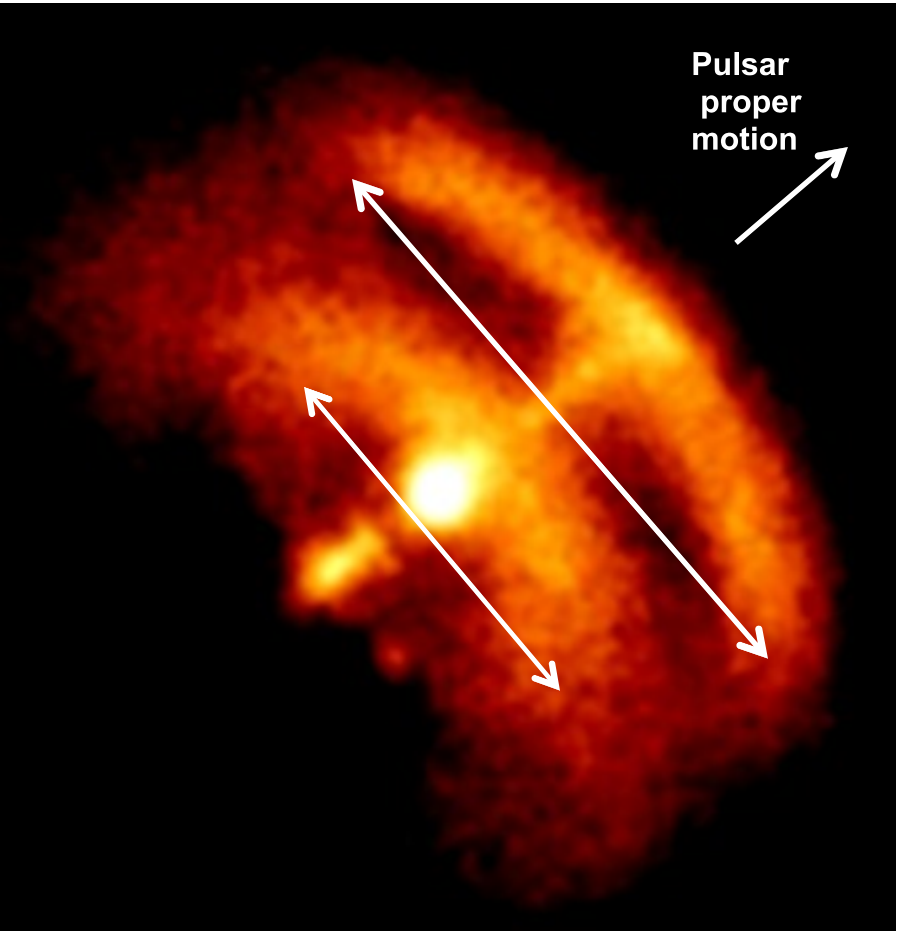


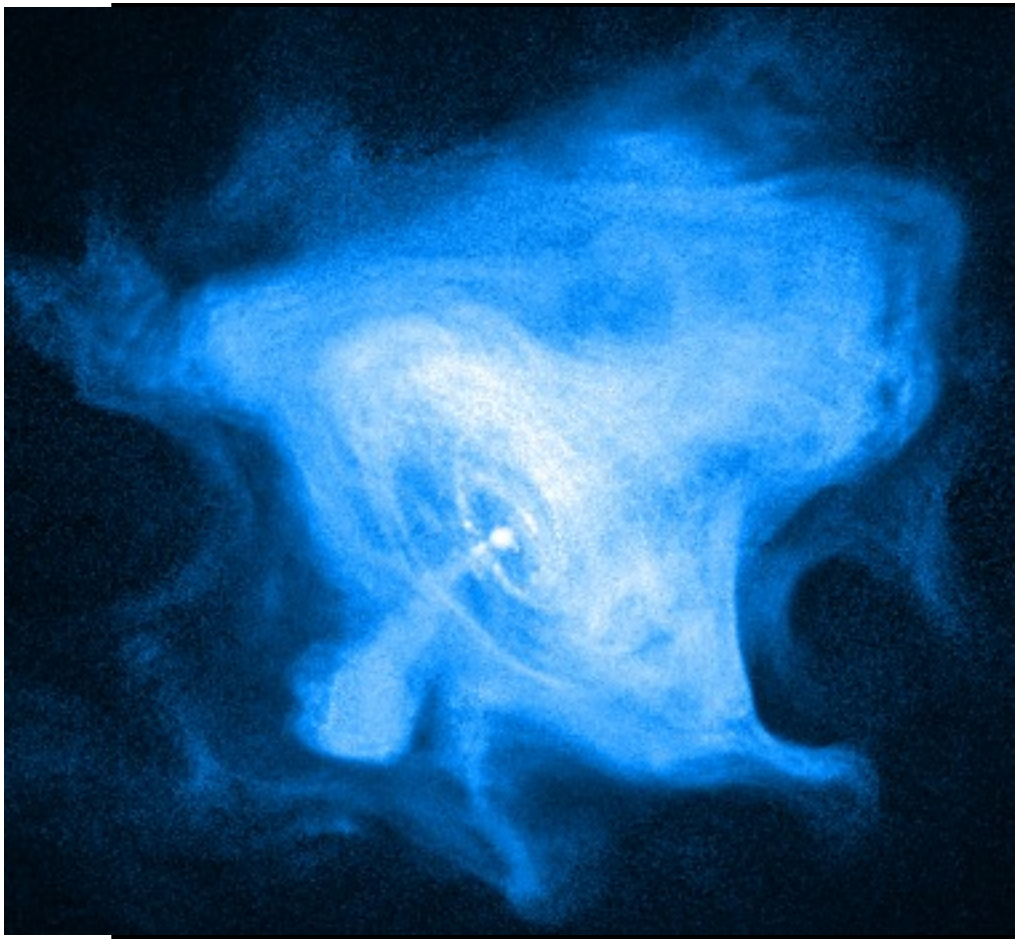
- **Nearby, d=300 pc → well-resolved with Chandra**
- **Bright enough to provide high-S/N images and spectra**
- **Rich and puzzling structure with both similarities and differences from the Crab PWN**
- **Also very dynamical!**

To be observed by Chandra for 320 ks.

Vela PWN topology: What are the arcs?

Deepest images of the inner Vela PWN: 160 ks ACIS + 150 ks HRC.





1. The linear sizes of the Inner and Outer Arcs differ by a factor of 1.4; if the arcs are non-coplanar tori, the pulsar is offset from their centers (Helfand et al 2001)

2. Inner arc: shock in the equatorial wind? What is the outer arc?

3. Different from Crab! Because of the different angle between the magnetic and rotation axis?

Dynamic Outer Jet of Vela pulsar: closer look

Length ~100 arcsec ($4x10^{17}$ cm @ 300 pc) ; Luminosity 7 x 10^{30} erg/s (1% L_{PWN})

- Variability :

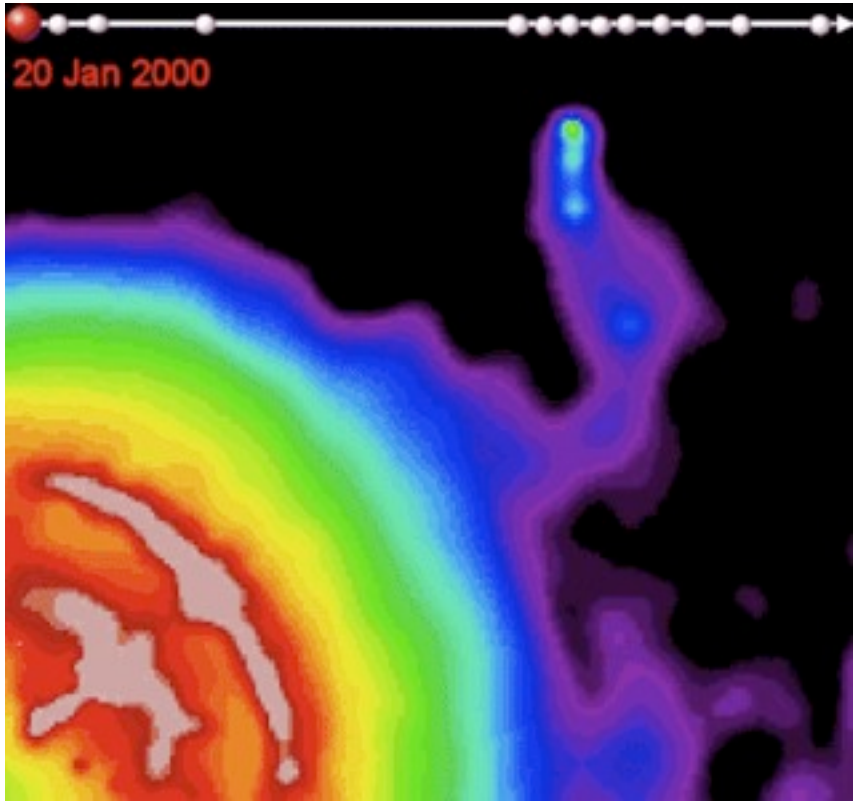
1. Sideways shifts/bends; ~ month

2. Outward moving blobs; v~0.6c

3. Blobs brightness varies; ~ week

- Orientation:

blob speeds + outer jet/counter-jet brightness ratio => jet approaches observer at 30-60 deg angle; (*assuming equal intrinsic brightnesses for the jet/counter-jet !*)

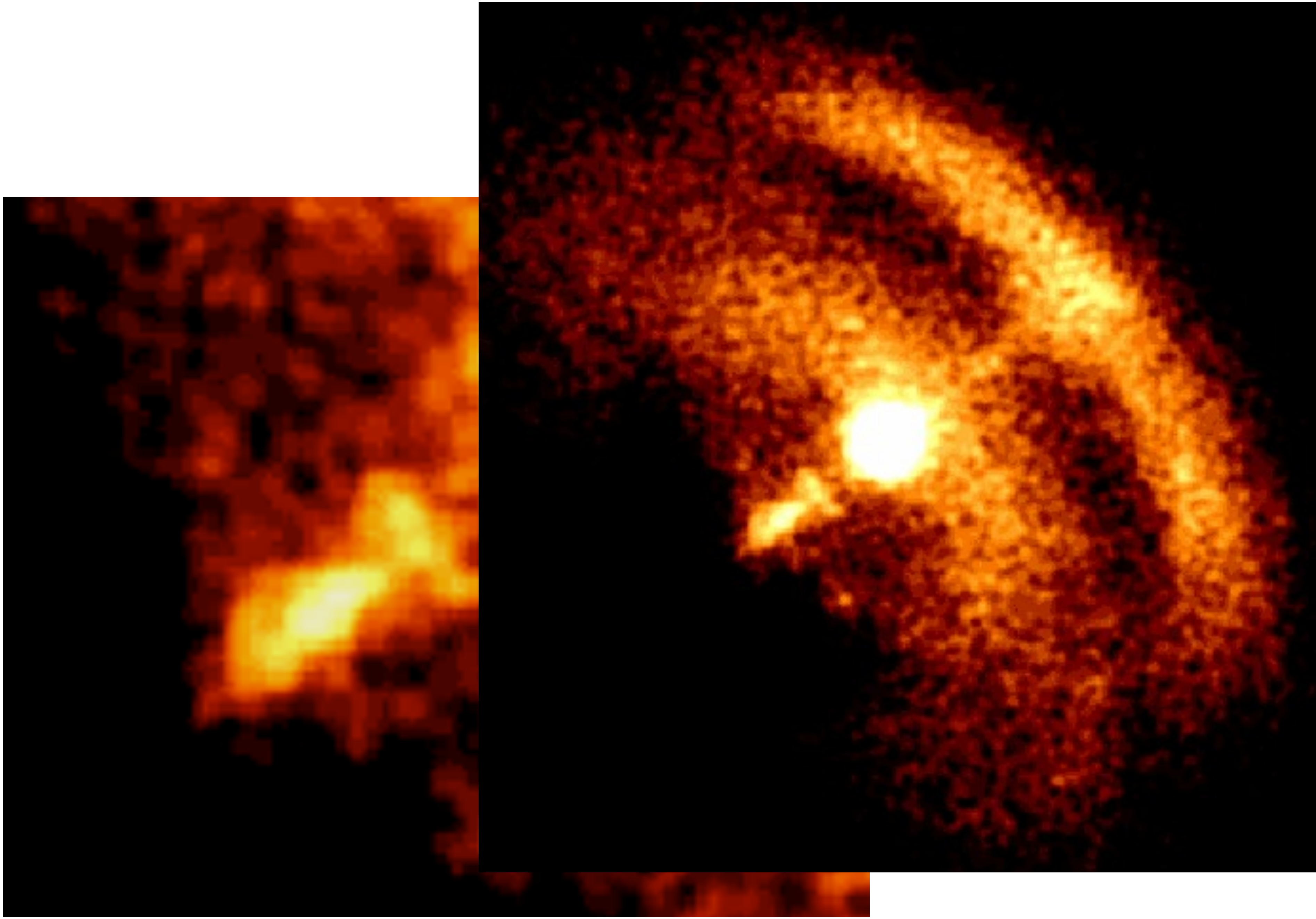


- Spectrum: power-law, photon index $\Gamma=1.4\pm0.1$

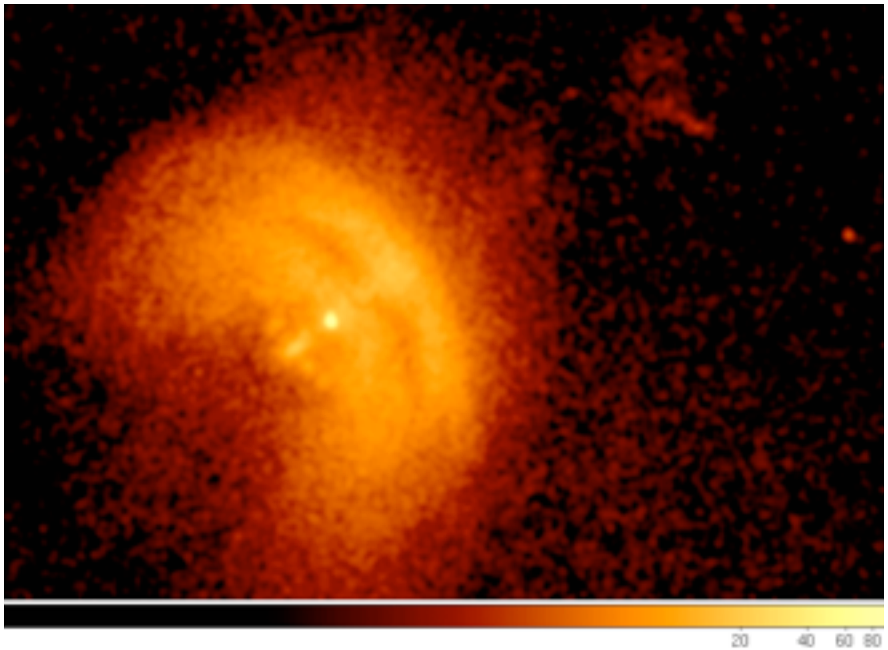
- synchrotron emission in magnetic field B ~ 100 μG

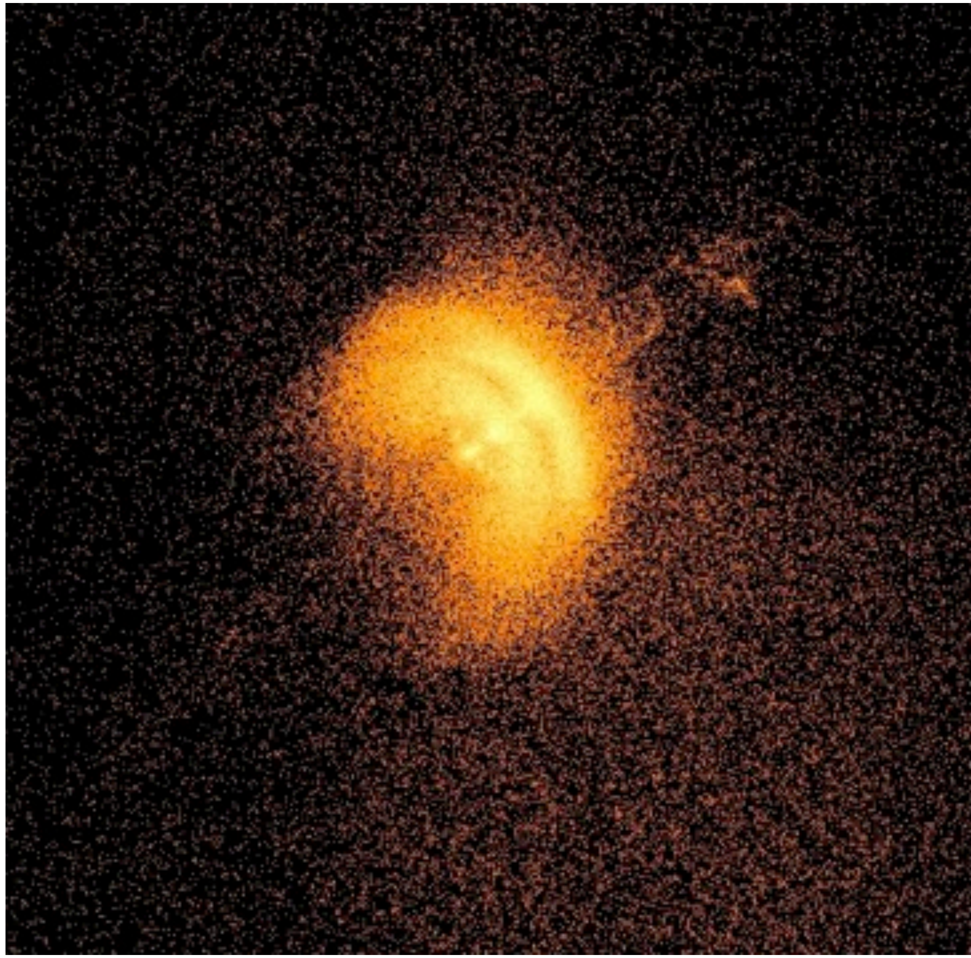
Vela Jet movie made of 13 Chandra observations (Pavlov et al. 2003)

Vela PWN: more recent results:

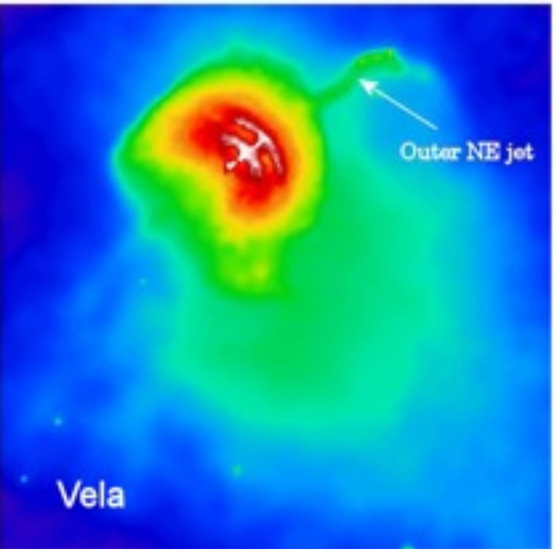


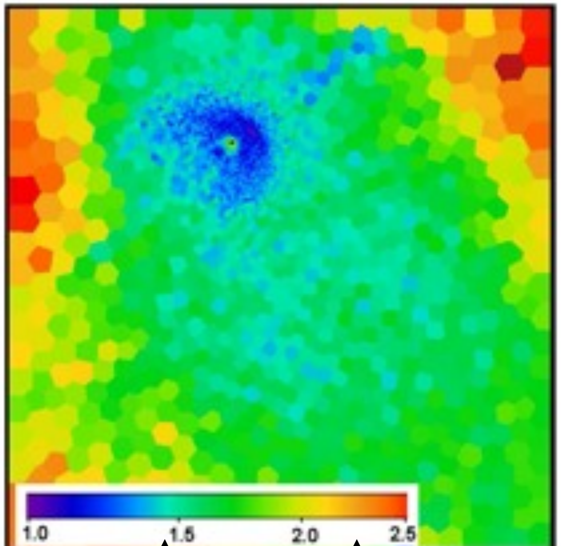
Vela PWN (recent series, 3 x 40 ks, 1 week separation)



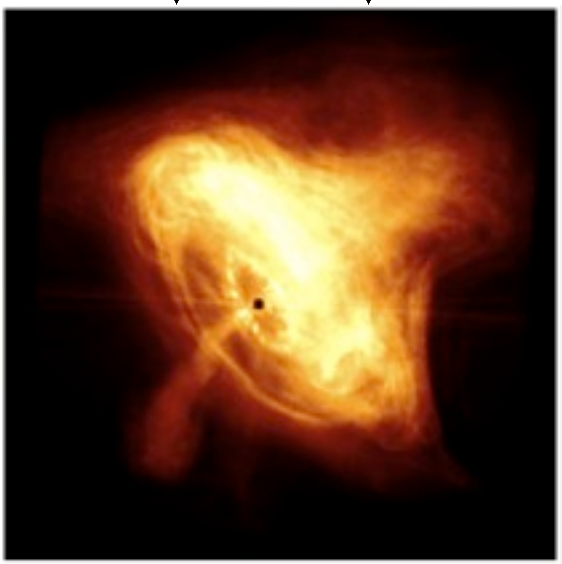


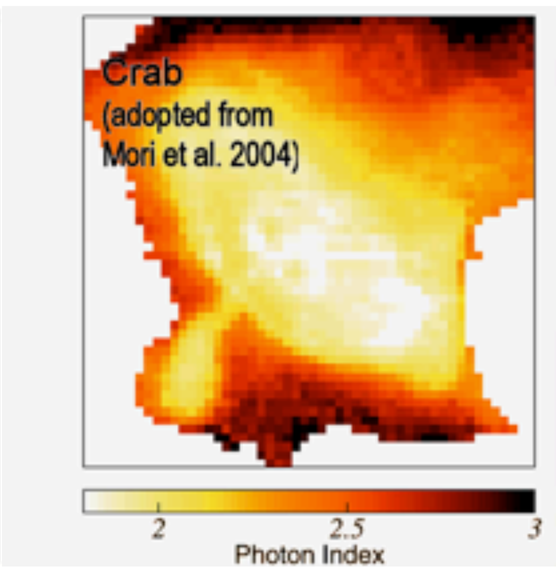
Vela PWN: spectral structure – particle acceleration





Synchrotron surface brightness Map of the photon index Γ





Notice complex structure:
Soft shell surrounding very hard inner features. Harder emission SW from pulsar.

Inner parts of the Vela PWN have extremely hard spectra:

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

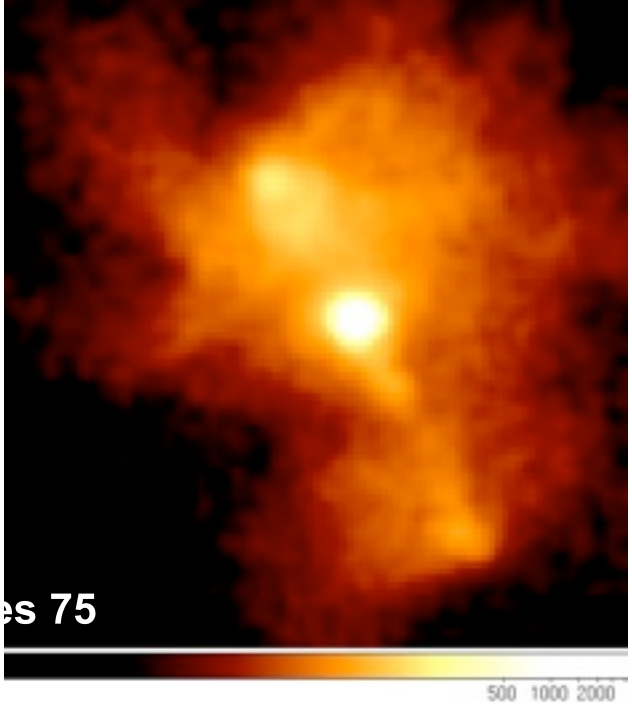
$$\mathrm{d}n_E = K E^{-p} f(\vec{n})\, \mathrm{d}E\, \mathrm{d}\Omega$$

→ **p ≈1-1.2 in Vela PWN** contradicts current particle acceleration models that predict universal p=2.1-2.2

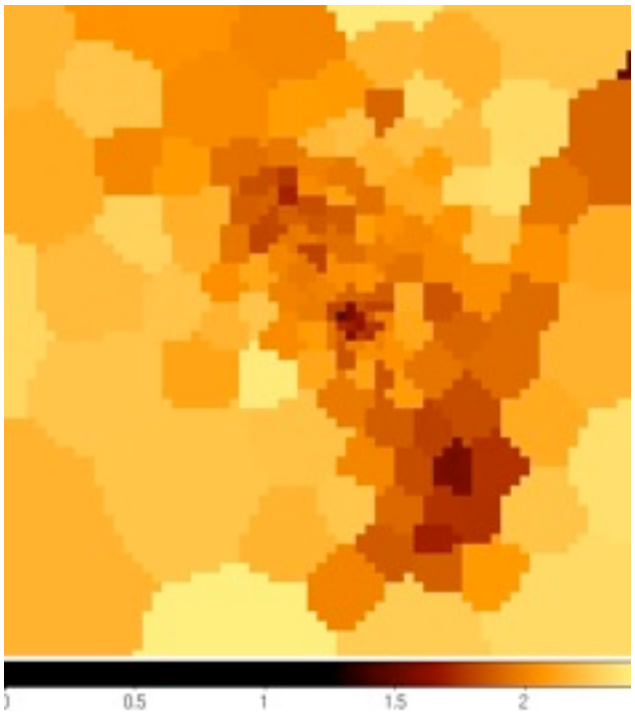
Inner parts of the **Crab** PWN have much softer spectra:

p ≈2.6

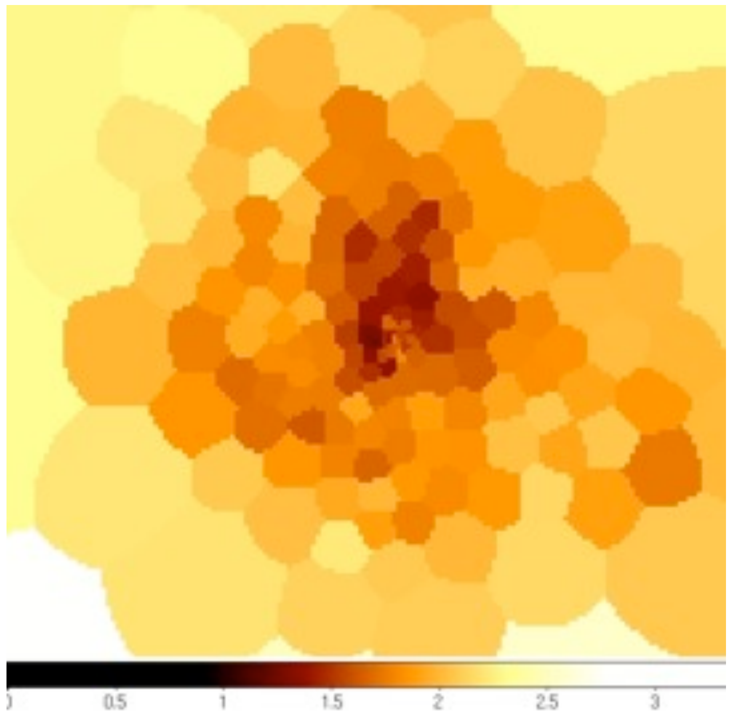
Why?



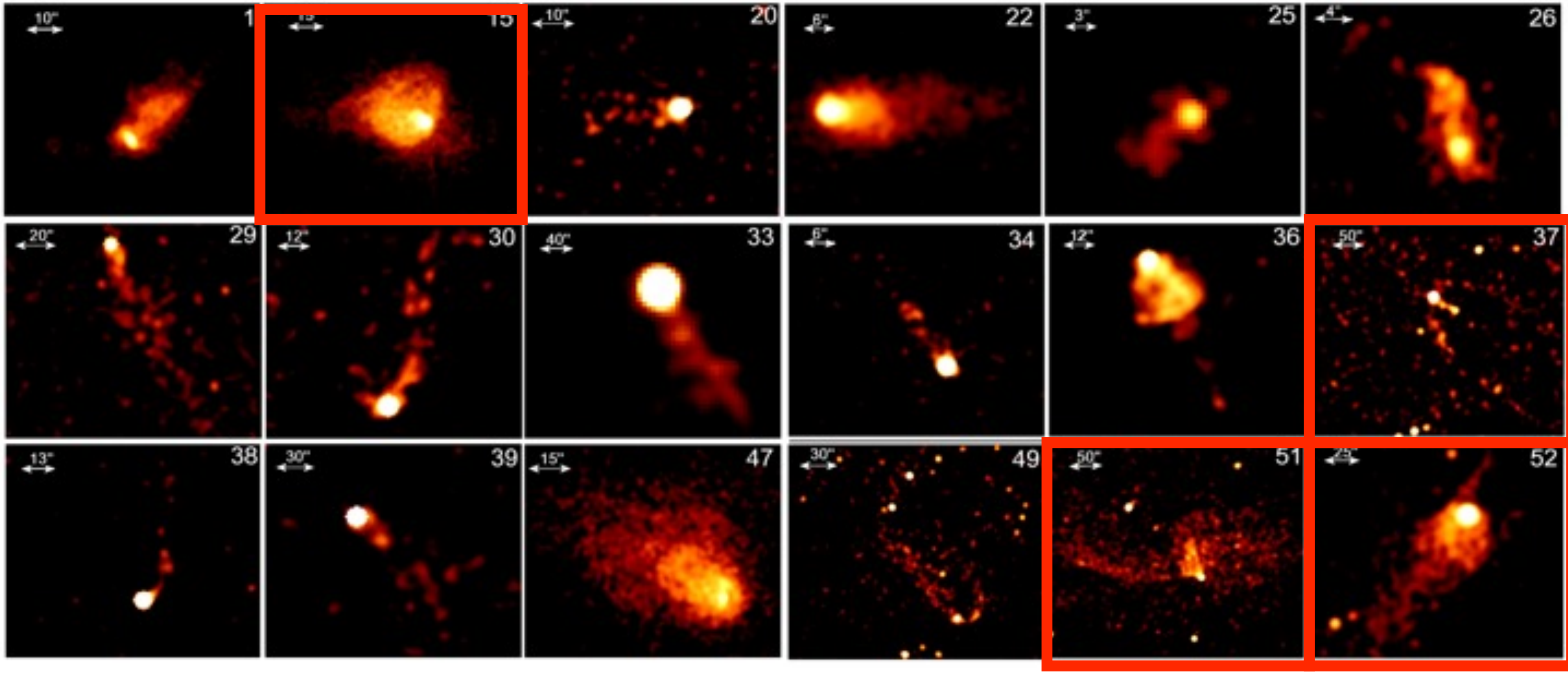
ACIS images



Adaptively binned
<u>spectral maps</u>



Bowshock-tail PWNe



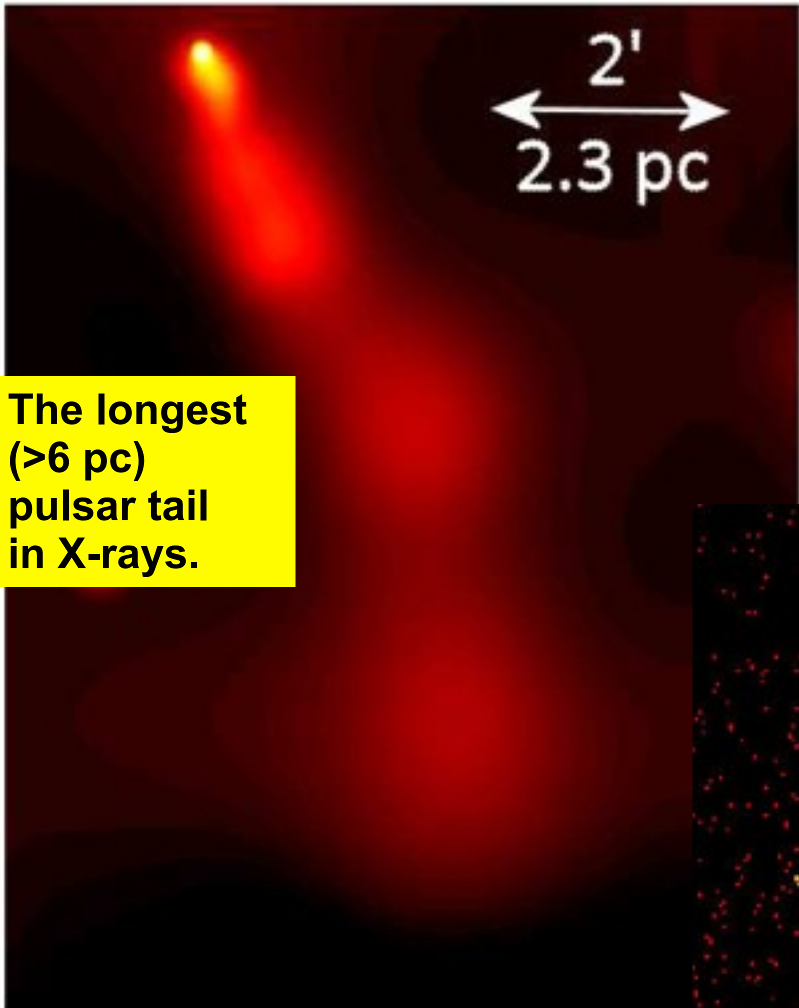
Again, in several cases structures are more complex than just tail and bow.

Older pulsars more often exhibit bowshock-tail PWNe since they move in low-pressure ISM:

$\mathbf{p_{ram} = \rho v^2 \gg p_{amb}}$ → supersonic motion → bow shock with apex at

$\mathbf{r_h = (\dot{E}/4\pi c p_{ram})^{1/2} = 1.3\times10^{16}\ (\dot{E}/10^{35}\ erg/s)^{1/2}\ n^{-1/2}\ (v/300\ km/s)^{-1}\ cm}$

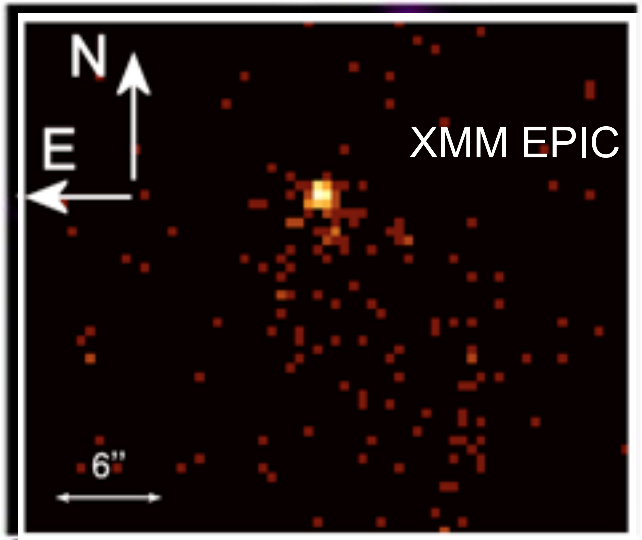
Bowshock-tail PWNe: 150-kyr-old PSR J1509-5850

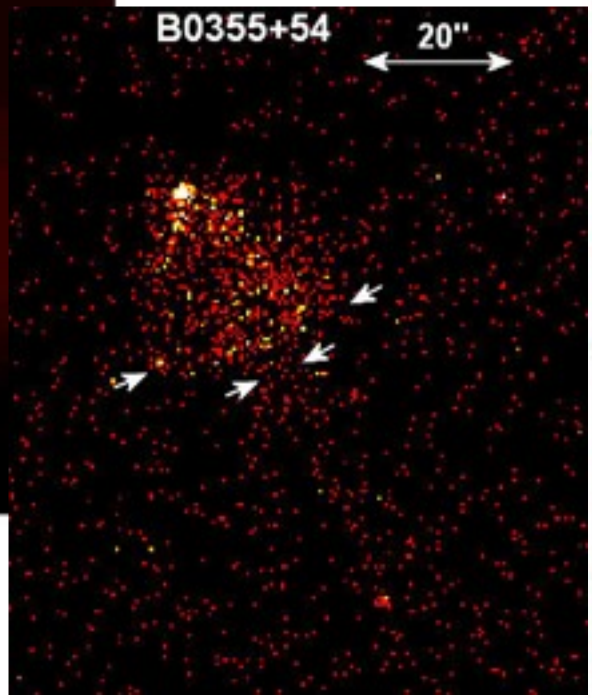


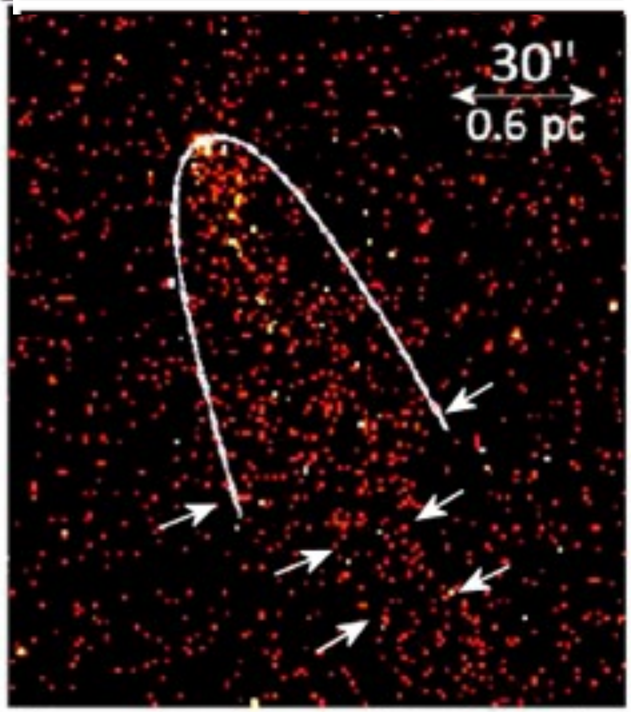
The longest (>6 pc) pulsar tail in X-rays.

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?







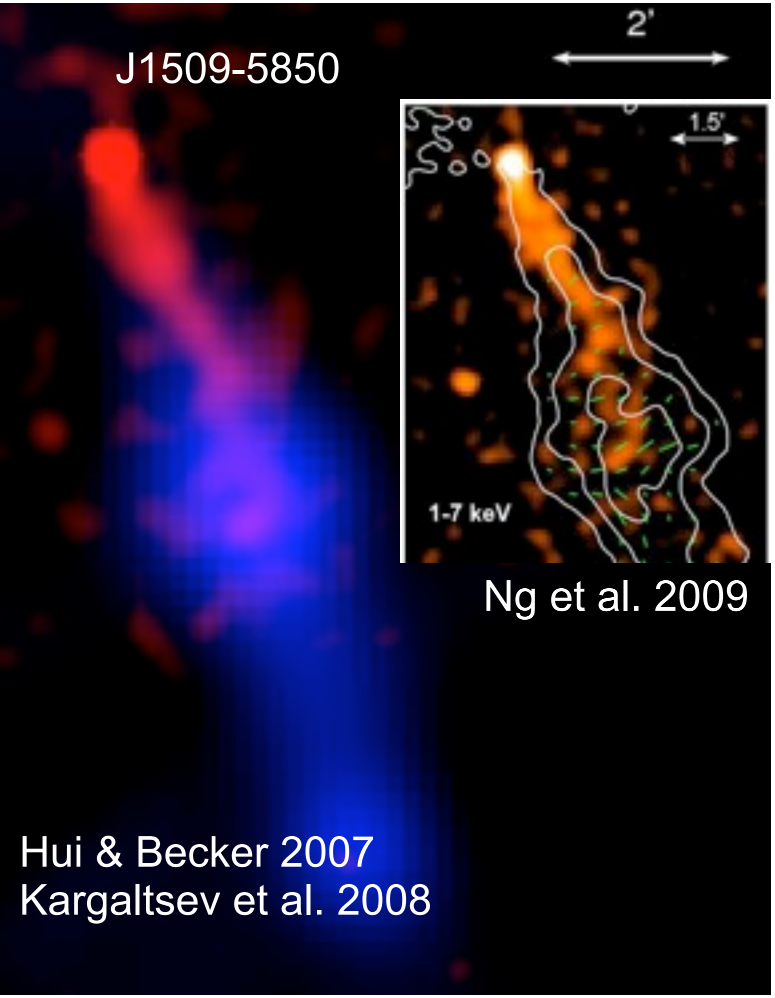
Close-up view of the "head" and the tail near the pulsar.

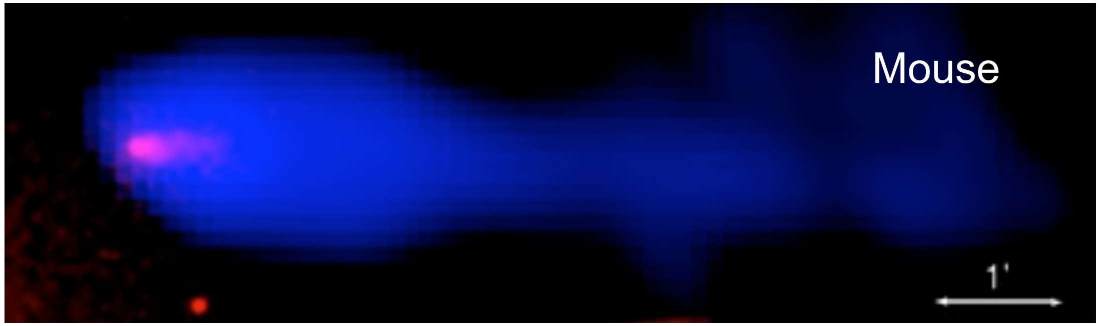
Kargaltsev et al.(2008)

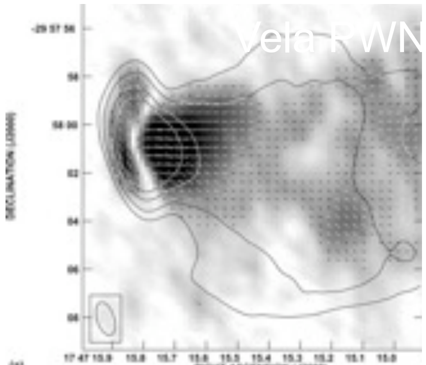
The **6-pc tail** length and synchrotron cooling in B~20 μG imply V_{flow} ~ **15,000** km/s >> than V_{PSR}~ 300-800 km/s.

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

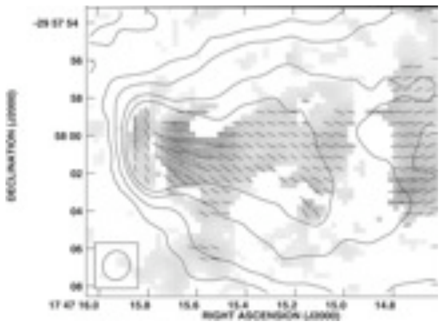
Observations ahead of models: numerical MHD models (Bucciantini et al. 2005) produce images that could be compared to observations but simulations go out just to a ~10 termination shock radii.





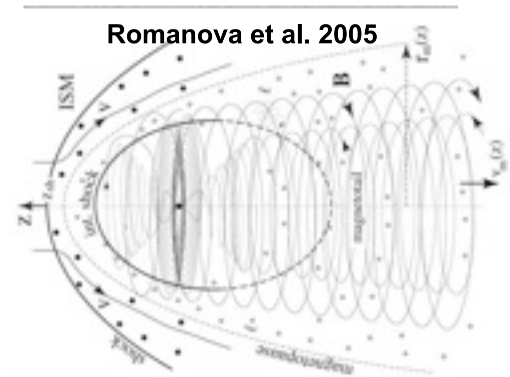


Yusef-Zadeh & Gaensler 2005



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.

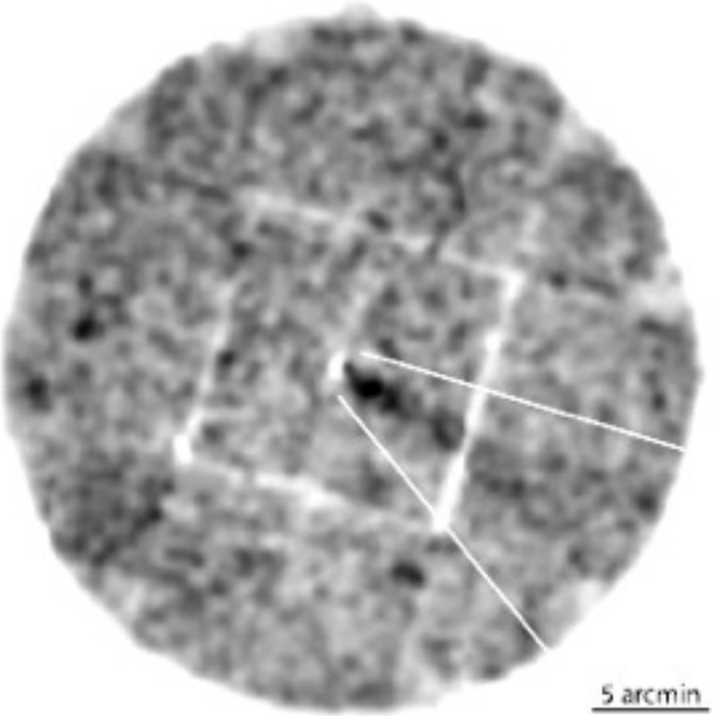


Mapping magnetic field is very important!
Stephen Ng: Magnetic filed structure of bow-shock PWNe via radio polarimetry.

Bowshock-tail PWNe: 3-Myr-old PSR J1929+10

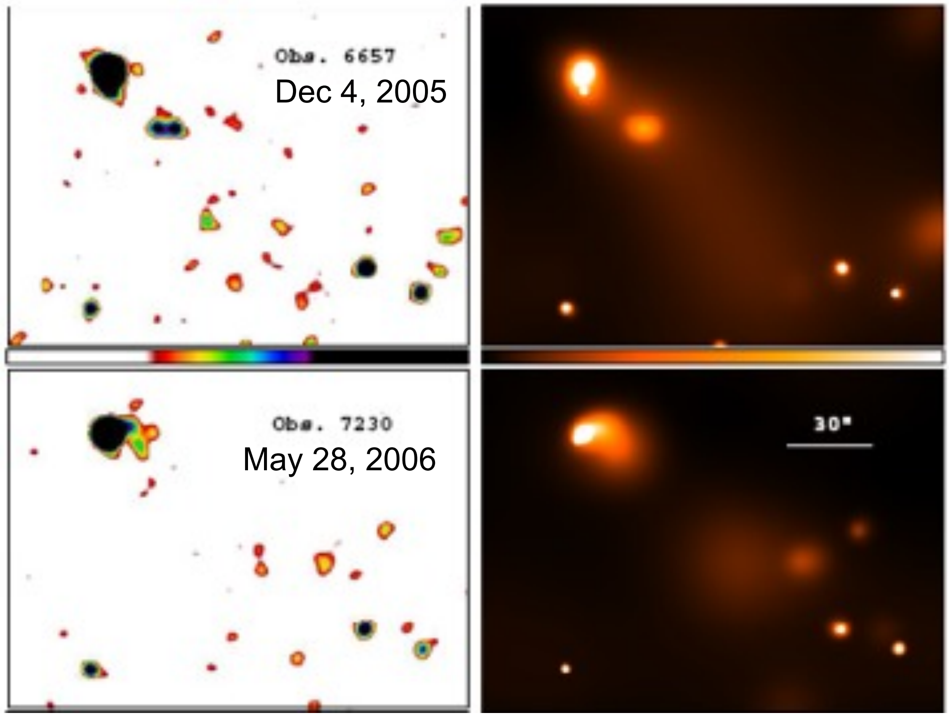
$\dot{E}$=3.9 x 10^{33} erg/s   d ~ 360 pc

XMM-Newton: 15'-long X-ray tail



Becker et al. (2006)

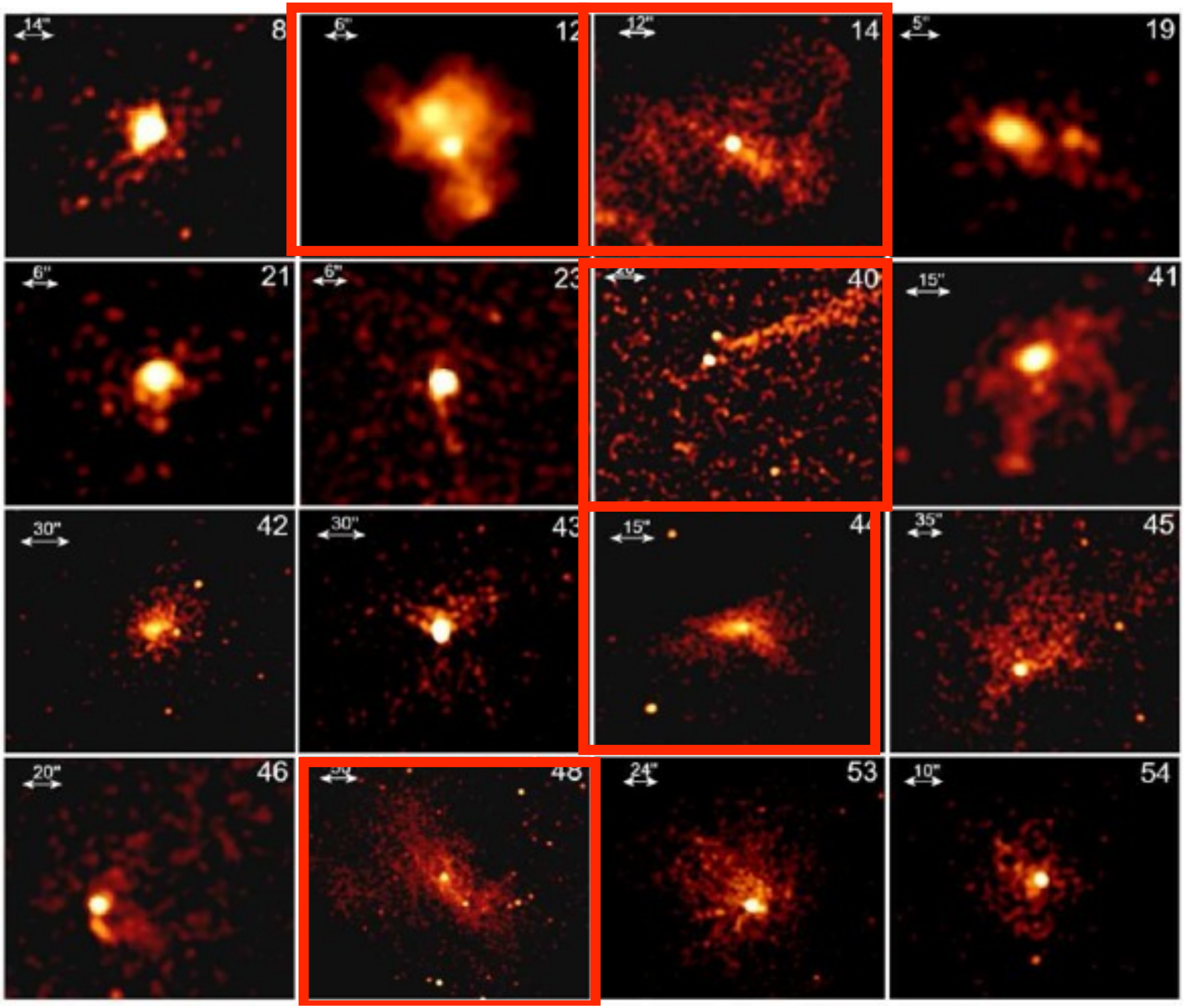
Chandra: A hint of variability!



Misanovic, Pavlov & Garmire (2008)

Opens a possibility to measure flow speed just downstream of the termination shock.

Other PWNe



Difficult to assign to either torus-jet or bowshock-tail type.

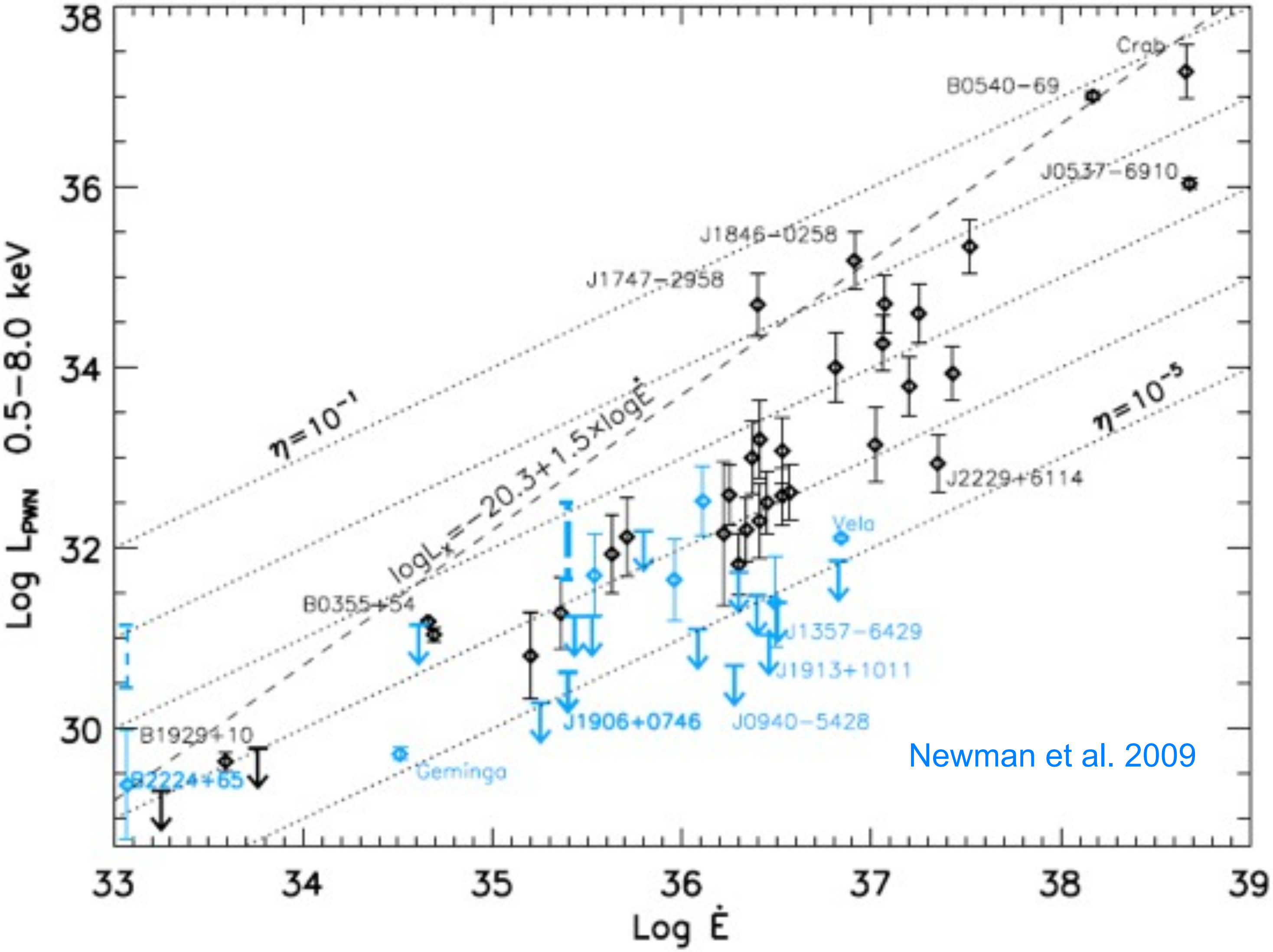
Possibly some of them are very remote. Some have few counts. But some morphologies are really bizarre.

Why?

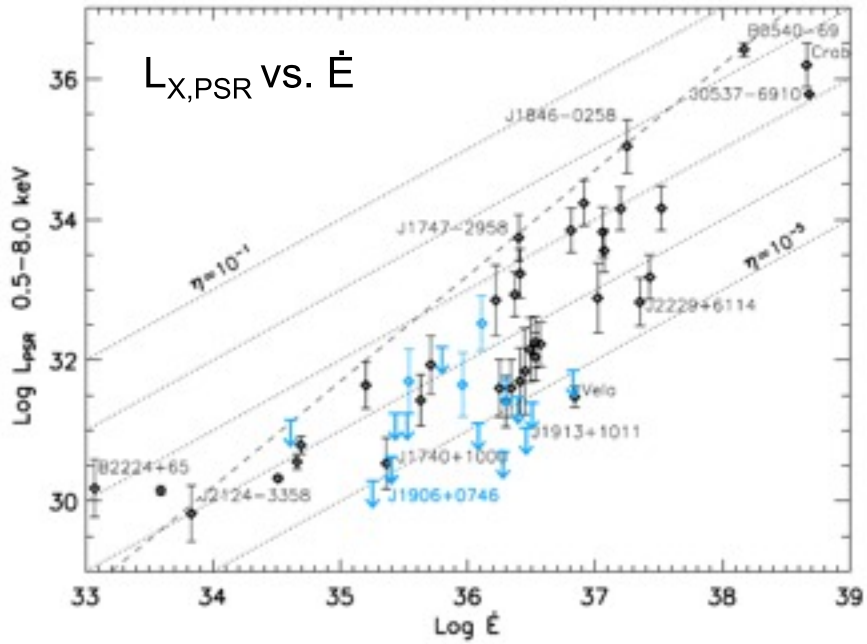
Upstream flow and TS properties depend on the angle between the rotation and magnetic axis? Or environmental effects?

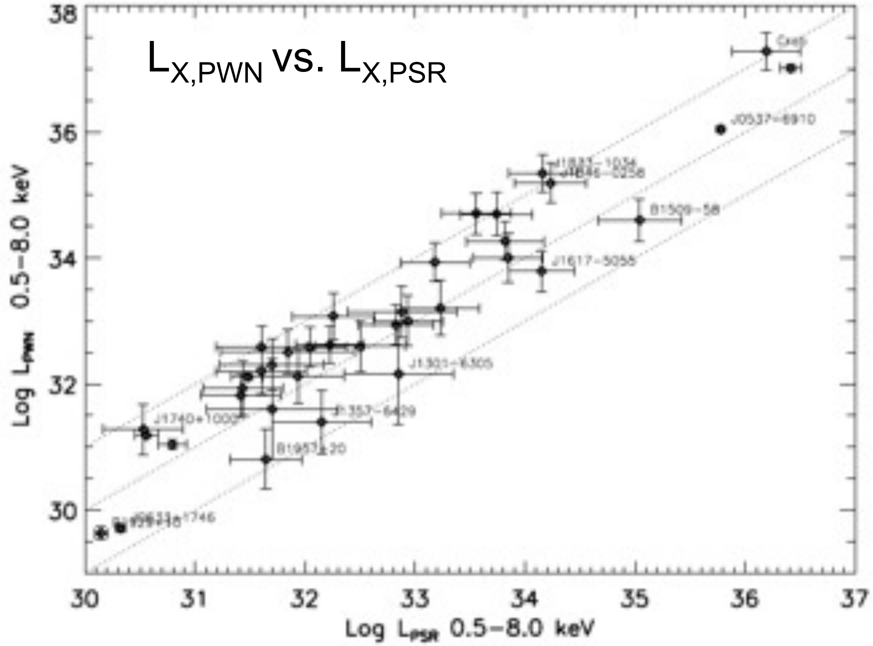
Population properties:

- Huge scatter in X-ray efficiencies $L_x/\dot{E}$ => L_x depends on "hidden" parameters.
- There is an upper boundary $L_x(\dot{E})$ when "hidden" parameters deliver maxim. efficiency.



Population properties (continued):

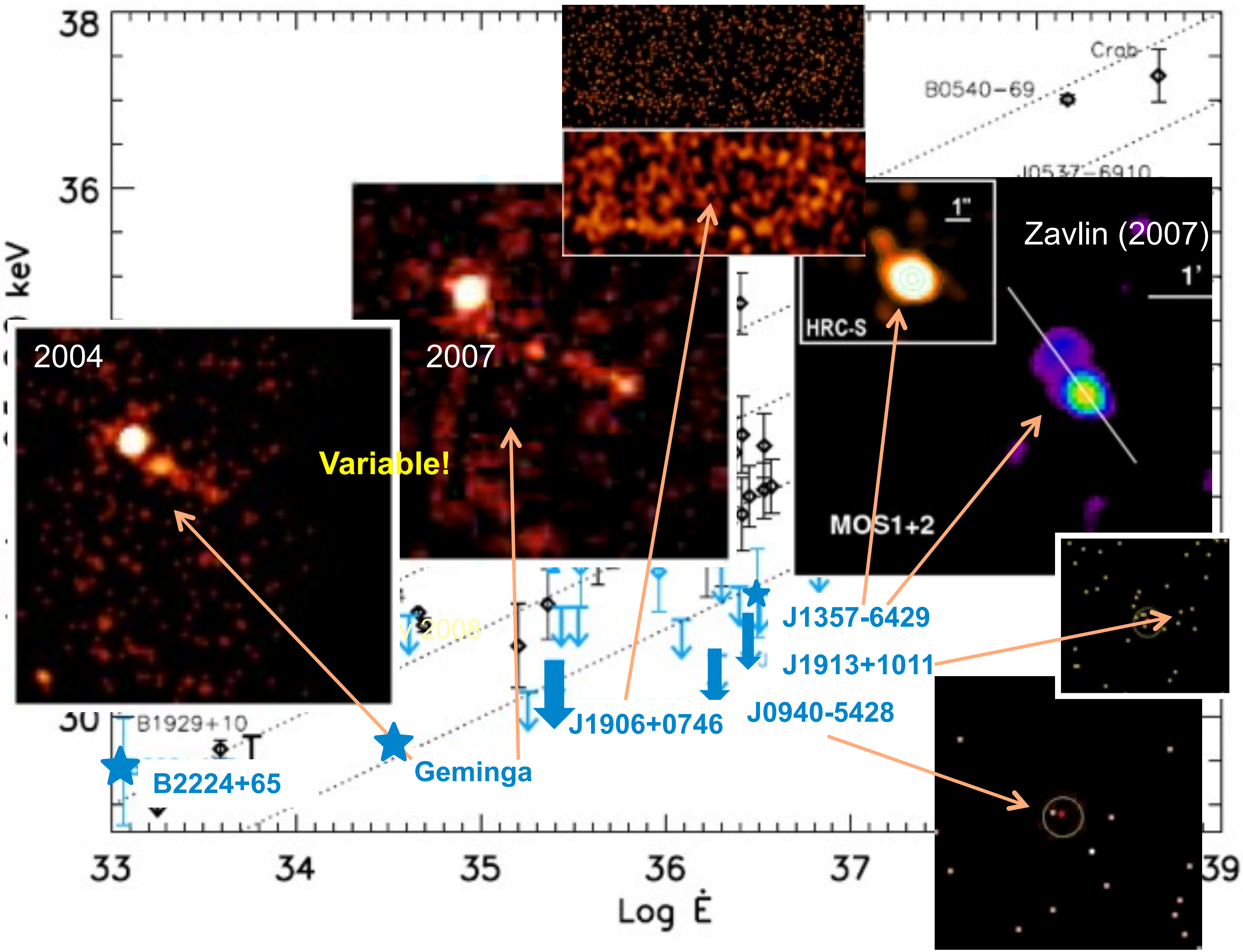




Surprisingly **tight correlation between pulsar and PWN luminosities**! Even if both are powered by the same synchrotron mechanism, the electron number densities, energies and magnetic fields differ by many orders of magnitude between the pulsar magnetosphere and the post-shock region.

Some recent and unusual results on X-ray PWNe:

A population of underluminous PWNe



Identifying TeV PWNe in X-rays

More than 30 extended TeV sources have been found by H.E.S.S. , VRITAS, MAGIC of which ~50% are unidentified.

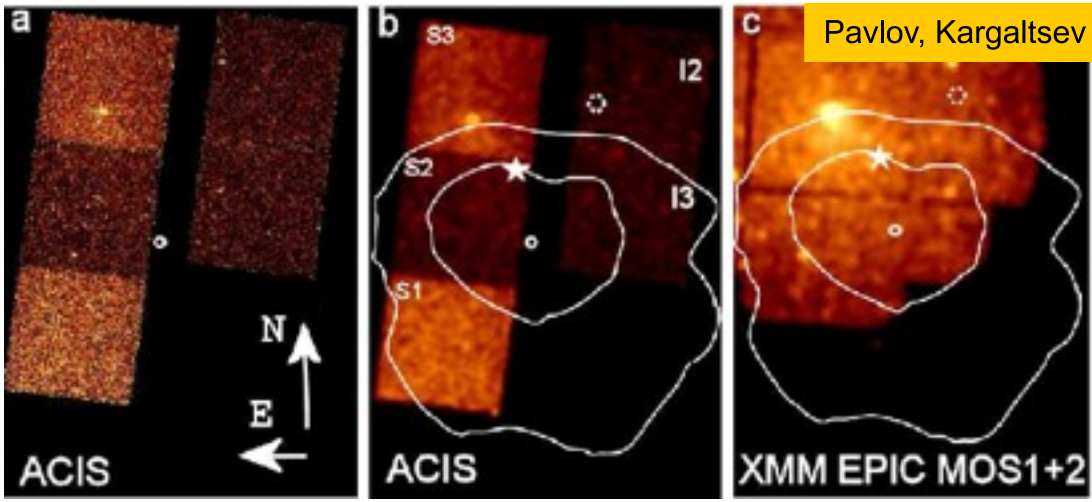
Young pulsars found in the vicinity of most of these UnID TeV sources strongly suggesting the connection.

What fraction of the TeV source population is due to pulsars/PWNe? What is the contribution of the pulsars/PWNe to the production of the galactic cosmic rays?

High-resolution X-ray observations provide efficient way to identify TeV sources powered by pulsar winds especially if there is no known radio pulsar.

TeV PWNe and "crushed plerion" model.

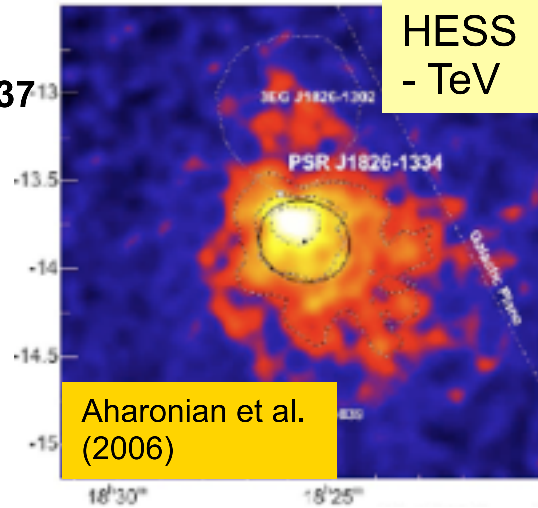
If the SNR shock becomes asymmetric (due to the interaction with the outside environment), the reverse shock will also be **asymmetric** and can **``crush''** a PWN pushing it to one side from the pulsar (Blondin et al. 2001).



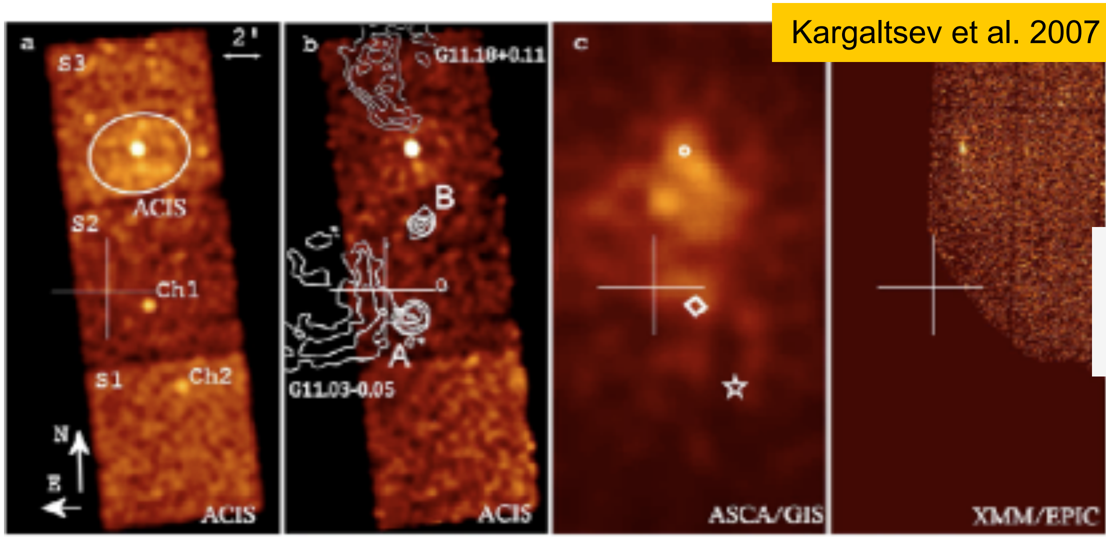
Pavlov, Kargaltsev & Brisken (2008)

HESS J1825-137
and
PSR B1823-13

HESS - TeV



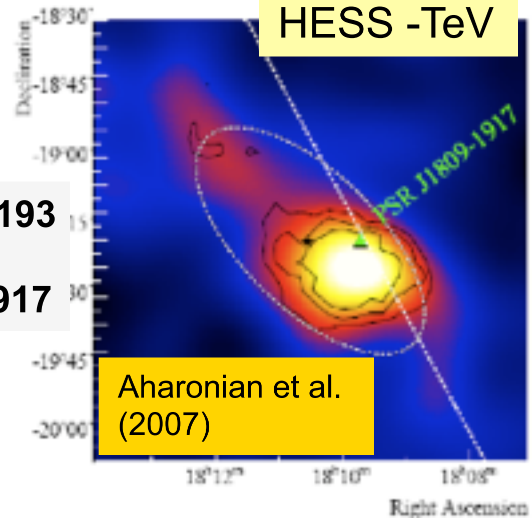
Aharonian et al. (2006)



Kargaltsev et al. 2007

HESS J1809-193
and
PSR J1809-1917

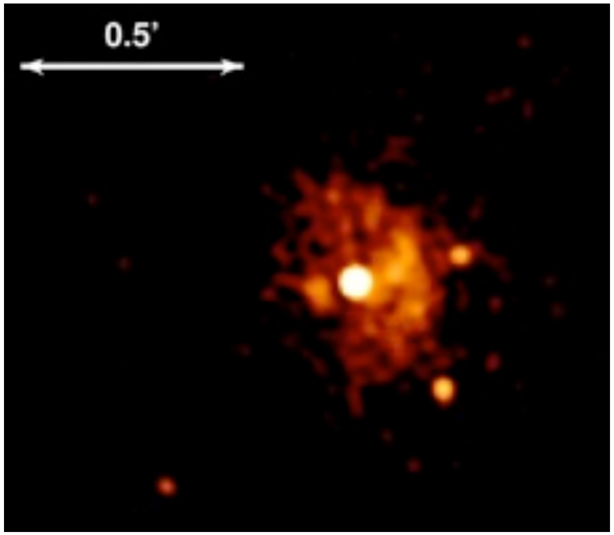
HESS -TeV



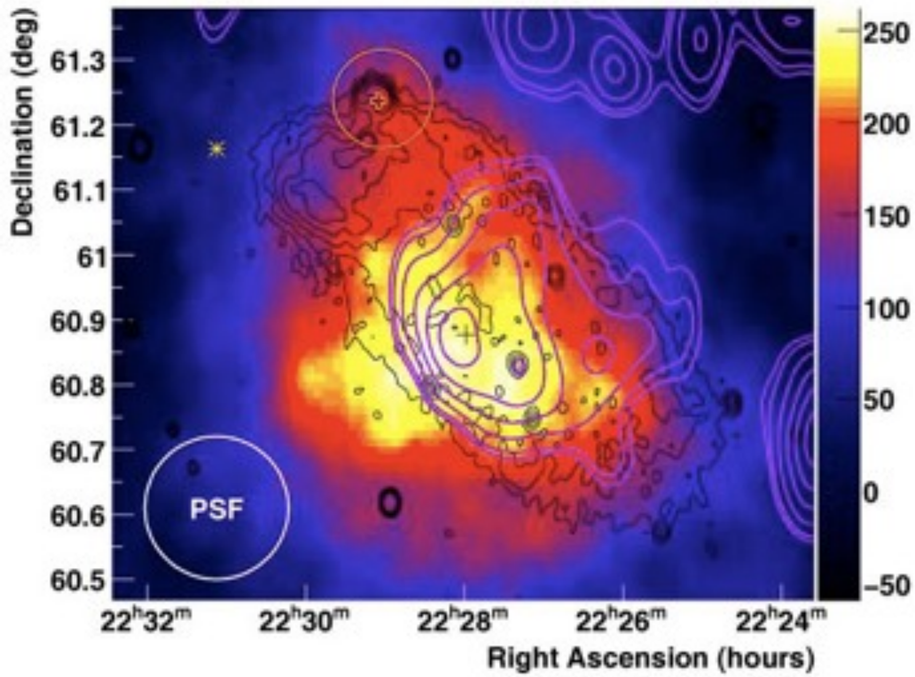
Aharonian et al. (2007)

VERITAS results: Boomerang PWN (PSR J2229+6114)

Acciari and VERITAS collaboration (2009)



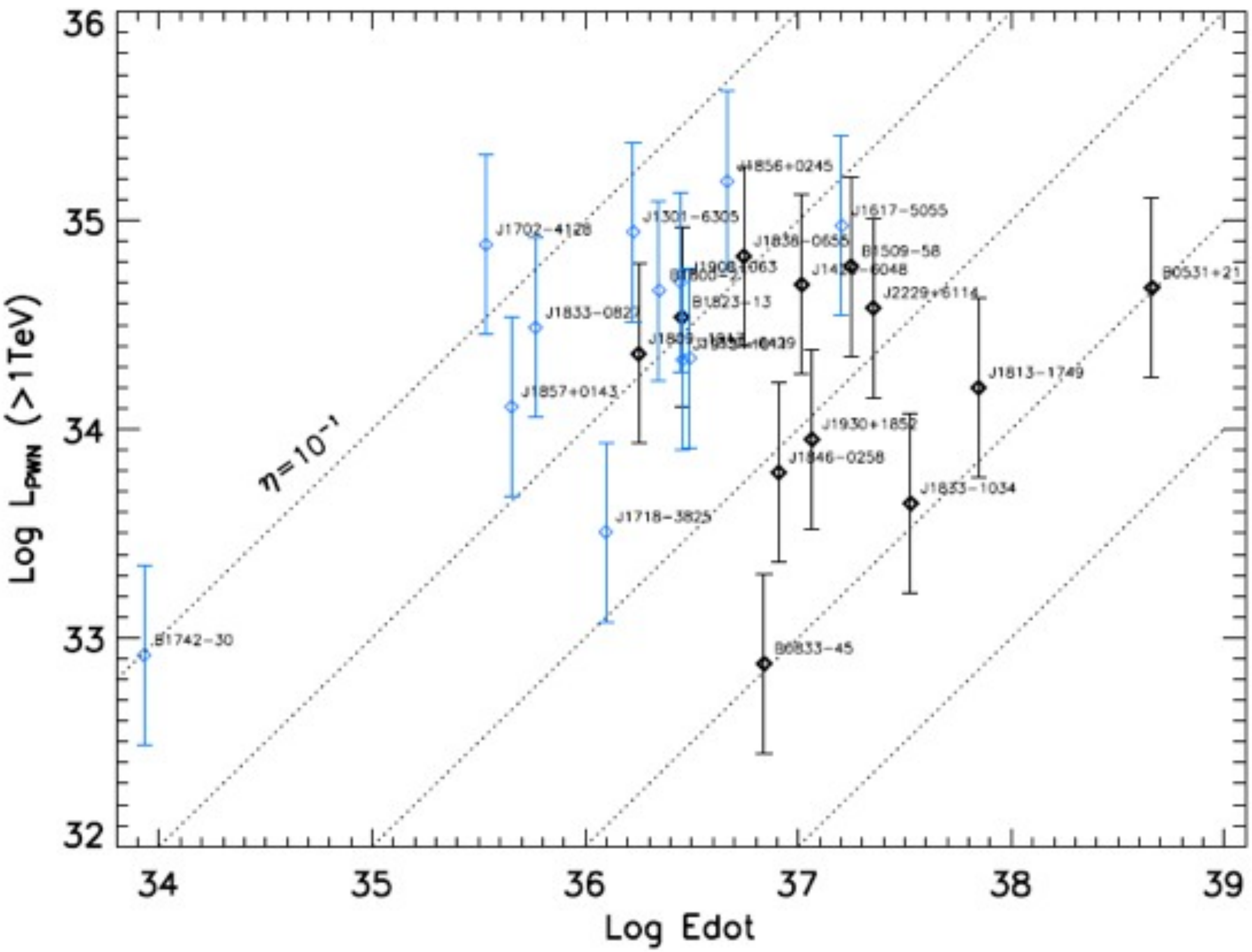
Chandra ACIS



TeV PWN candidates.

Table 1 Properties of TeV PWN candidates.

#	TeV Source	Counterpart	d[a]	τ[b]	$\dot{E}_{36}$[c]	D[d]	f_γ[e]	Γ_γ[f]	$L_\gamma/\dot{E}$[g]	Γ_X[h]	f_γ/f_X[i]
			kpc	kyrs		arcmin	C.U.		%		
					TeV sources firmly associated with pulsars						
1	J0534+220	B0531+21/Crab	2	1.2	461	$\lesssim 6$	1.0	2.39 ± 0.03	0.007	2.12 ± 0.01	0.15
2	J1833-105	J1833-1034/G21.5-0.9	5	5.0	33.1	$\lesssim 6$	0.02	2.08 ± 0.22	0.004	1.89 ± 0.02	0.6
3	J1846-029	J1846-0258/Kes75	7	0.7	8.12	$\lesssim 6$	0.02	2.26 ± 0.15	0.03	2.03 ± 0.02	1.2
4	J0835-455	B0833-45/Vela-X	0.3	11	6.92	60	0.75	1.45 ± 0.09	0.01	2.1 ± 0.2	0.6
5	J1514-591	B1509-58/MSH 15-52	5	1.6	17.7	12	0.15	2.270.03	1.3	1.6 ± 0.1	0.3
					TeV sources with likely pulsar associations						
6	J1825-137	B1823-13	4	21.4	2.84	60	0.17	2.2−2.4	3.8	1.9 ± 0.3	2
7	J1420-607	J1420-6048	6	13.0	10.4	7	0.07	2.17 ± 0.06	2.1	0.5 ± 1.2	4.5
8	J1837-069	J1838-0655	6	22.7	5.55	14	0.13	2.27 ± 0.06	7.6	1.6 ± 0.4	2
9	J1809-193	J1809-1917	3.5	51.3	1.78	60	0.14	2.2 ± 0.10	2.9	2.3 ± 0.3	3.6
					TeV sources with possible pulsar associations						
10	J1718-385	J1718-3825	4	89.5	1.25	18	0.015	2.1 ± 0.10	0.8	1.7 ± 0.2	2
11	J1804-216	B1800-21	4	15.8	2.22	24	0.25	2.72 ± 0.06	7.2	–	> 4
12	J1857+026	J1856+0245	9	21.0	4.60	14	0.16	2.39 ± 0.08	57	–	–
13	J1303-631	J1301-6305	6	11.0	1.68	20	0.17	2.44 ± 0.05	33	–	–
14	J1702-420	J1702-4128	5	55.1	0.34	36	0.24	2.31 ± 0.15	90	–	–
15	J1616-508	J1617-5055	6	8.1	16.0	16	0.19	2.35 ± 0.06	3.8	–	–
16	J1834-087	J1833-0827	5	147	0.58	9	0.08	2.45 ± 0.16	21	–	–
17	J1912+101	J1913+1011	5	169	2.88	45	0.09	2.7 ± 0.2	0.5	–	–
18	J1858+020	J1857+0143	5	71	0.45	18	0.04	2.17 ± 0.12	2.3	–	–
					TeV sources possibly associated with X-ray PWNe (although no radio pulsar has been reported yet)						
19	J1747-281	G0.9+0.1	10	–	–	$\lesssim 6$	0.02	2.40 ± 0.11	–	2.3 ± 0.4	0.1
20	J1418-609	G313.3+0.1	5	–	–	8	0.06	2.22 ± 0.08	–	1.7 ± 0.1	3
21	J1640-465	G338.3-0.0	8	–	–	9	0.09	2.42 ± 0.15	–	1.7 ± 0.1	1
22	J1813-178	G12.82-0.02	4.5	–	–	9	0.06	2.09 ± 0.08	–	0.4 ± 0.5	3
23	J1731-347	G353.6-0.7	3	–	–	22	0.16	2.26 ± 0.10	–	–	–
24	J1713-381	G348.7+0.3	8	–	–	30	0.66	2.27 ± 0.48	–	–	–
25	J0616+225	IC443	1.5	–	–	12	0.06	3.1 ± 0.3	–	–	–



Log L_{PWN} (>1TeV)
Log Edot
$\eta=10^{-1}$
B1742-30
J1702-4128
J1833-0827
J1857+0143
J1718-3825
J1301-6305
B1823-13
J1856+0245
J1838-0655
J1617-5055
B1509-58
J2229+6114
B0531+21
J1813-1749
J1930+1852
J1846-0258
J1833-1034
B0833-45

Summary:

- Equatorial termination shock (TS) resolved in a few PWNe (Crab, Vela)

- In addition there may be TSs in polar outflows (Vela)

- Several bright PWNe allow spatially-resolved spectroscopy. Spectra measured just downstream of the equatorial TS show different slopes in different PWNe.

- Some PWNe (e.g., Vela) show extremely hard PL spectra implying $p \approx 1$ for the electron SED, with electron energies as high as 10 TeV.

- There is a very large ($>10^4$) scatter in PWN X-ray efficiencies. “Hidden” parameters affect the efficiencies.

- Ram-pressure-confined outflows in the tails of fast moving pulsars have complex structure, average flow speeds can be >15,000 km/s. Expansion, deceleration through internal shocks? Similar to jets in AGNs and YSOs?

Summary (continued):

- Pulsar tails show very different multiwavelenghs morphologies and magnetic field topologies (Mouse PWN vs. J1509-5850 tail).

- Moving knots in pulsar tails can allow direct flow speed measurements with Chandra.

- Some PWN structures yet remain to be explained (e.g. “lops” in 3C58, X-ray filament near the Guitar nebula).

- PWNe comprise a large fraction the unidentified TeV source population. High-resolution X-ray observations are most helpful in their identification.