Chandra view of manifestations of neutron stars: particle outflows and synchrotron nebulae

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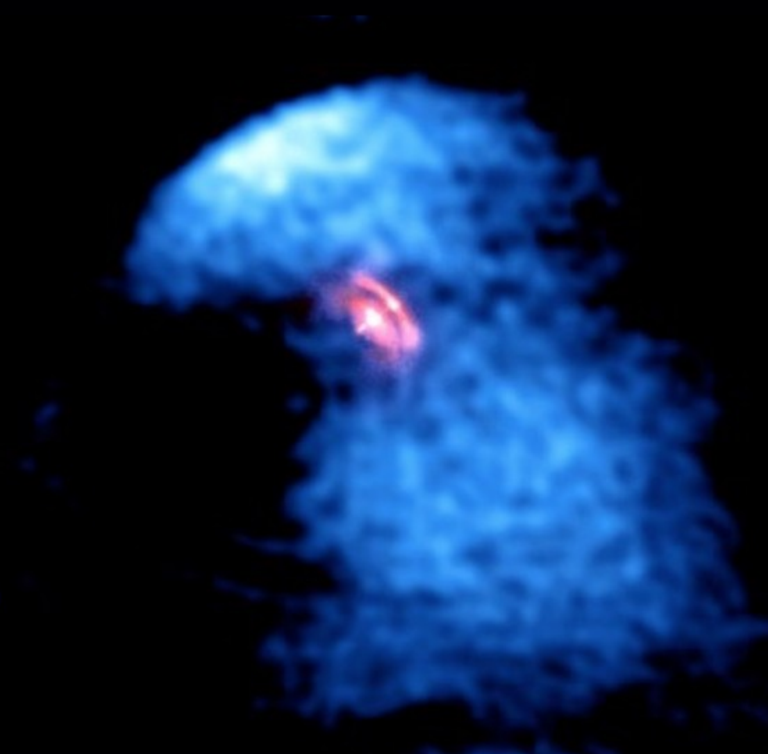
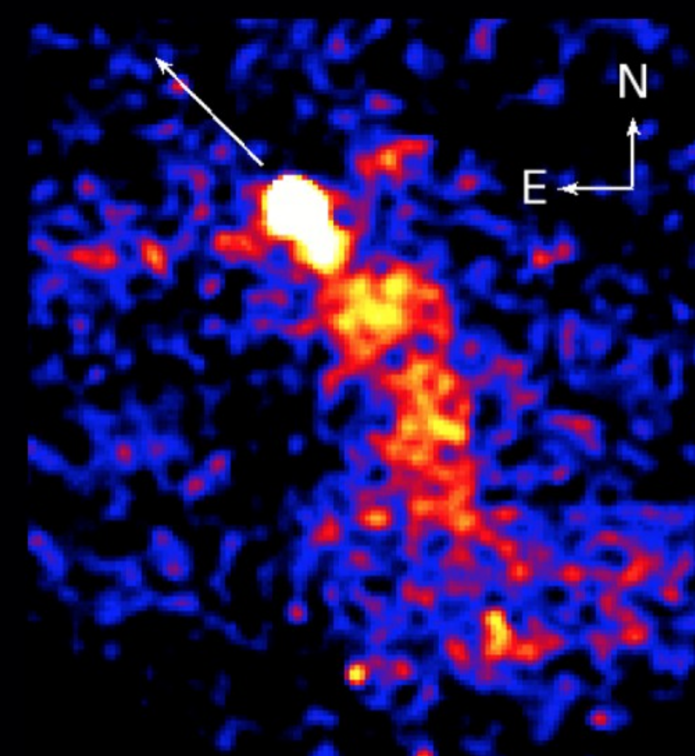




What only Chandra can offer for (isolated) NS studies?

- Producing high-resolution PWN images and allowing for spatially-resolved spectroscopy on arcsecond scales
- **Detecting faint sources and telling whether they are extended or not (e.g., relic PWNe inside TeV sources)**
- Providing subarcsecond localizations allowing to discover new compact objects via multiwavelength matching
- **Measuring spectra of objects embedded in complex background (pulsars/PWNe in SNRs)**
- Resolving objects in dense systems (globular clusters)

Some Chandra Highlights for isolated NSs:

- PWNe: the rest of the talk
- Cas A CCO cooling? a window into the NS interior
- NSs in globular clusters
- Low-B magnetars
- Smoking guns of transient magnetars
- X-ray properties of pulsars resolved form their PWNe
- Transitional recycled pulsars
- ``Spiders" (redbacks & black widows)
- Old pulsar properties

1999: Launch of *Chandra* and *XMM-Newton* – New Era in PWN studies

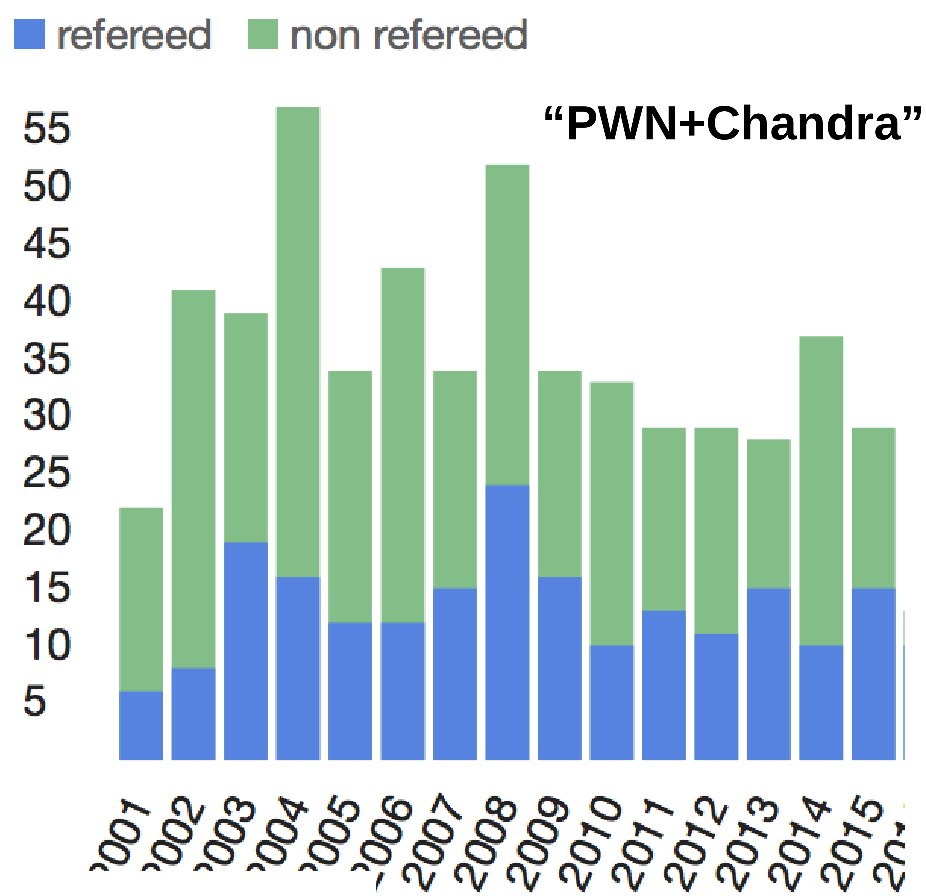
Chandra (0.3 – 10 keV; 0.5’’ resolution, low ACIS background) particularly useful

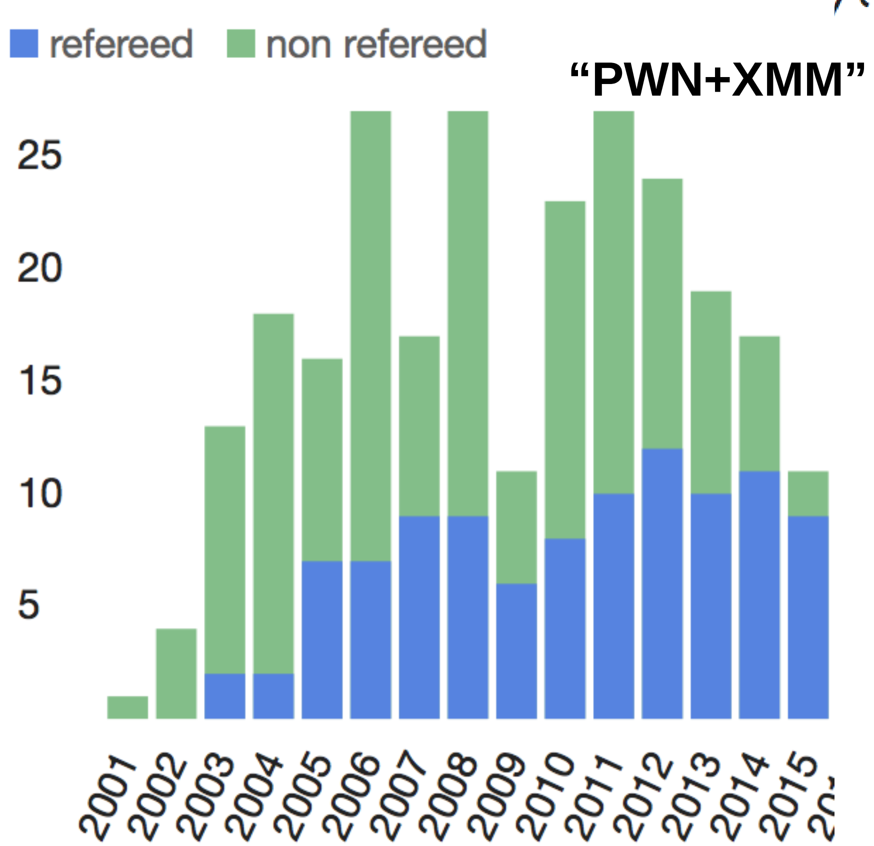
About 90 PWNe detected by *Chandra* thanks to its unprecedented resolution

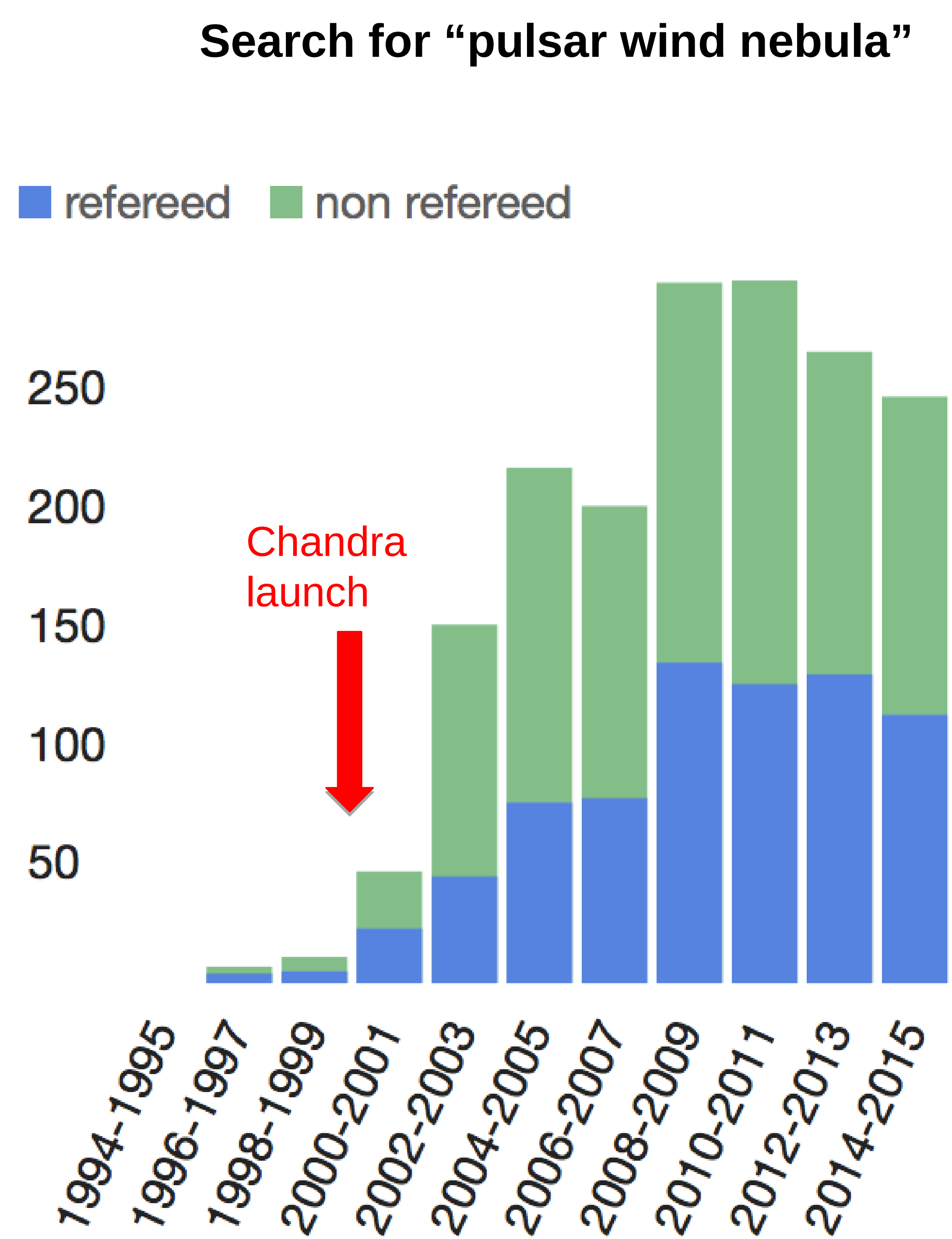
XMM: not so good resolution, higher background, but more sensitive, larger field of view

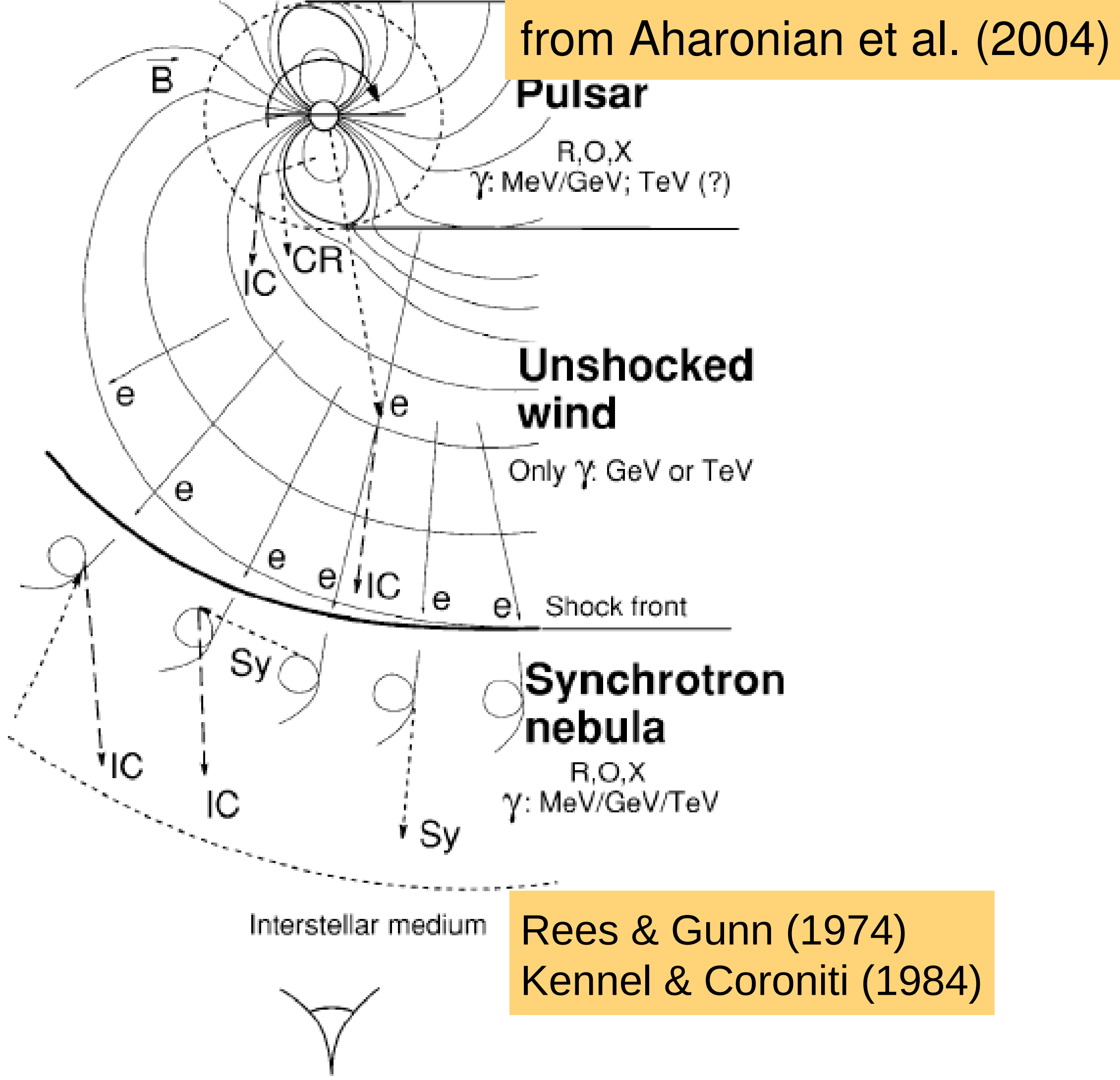
NuSTAR: poor resolution, but higher energies (up to 79 keV)

Publication statistics on PWNe (NASA ADSbeta)









PWN: Basic properties

- All active pulsars emit relativistic winds
- $v \sim c > c_s$ termination shock forms
- Downstream of the shock: subrelativistic magnetized flow of relativistic particles
- Nonthermal power-law spectra: **synchrotron** (radio through MeV) and **IC radiation** (GeV and TeV) **PWN**

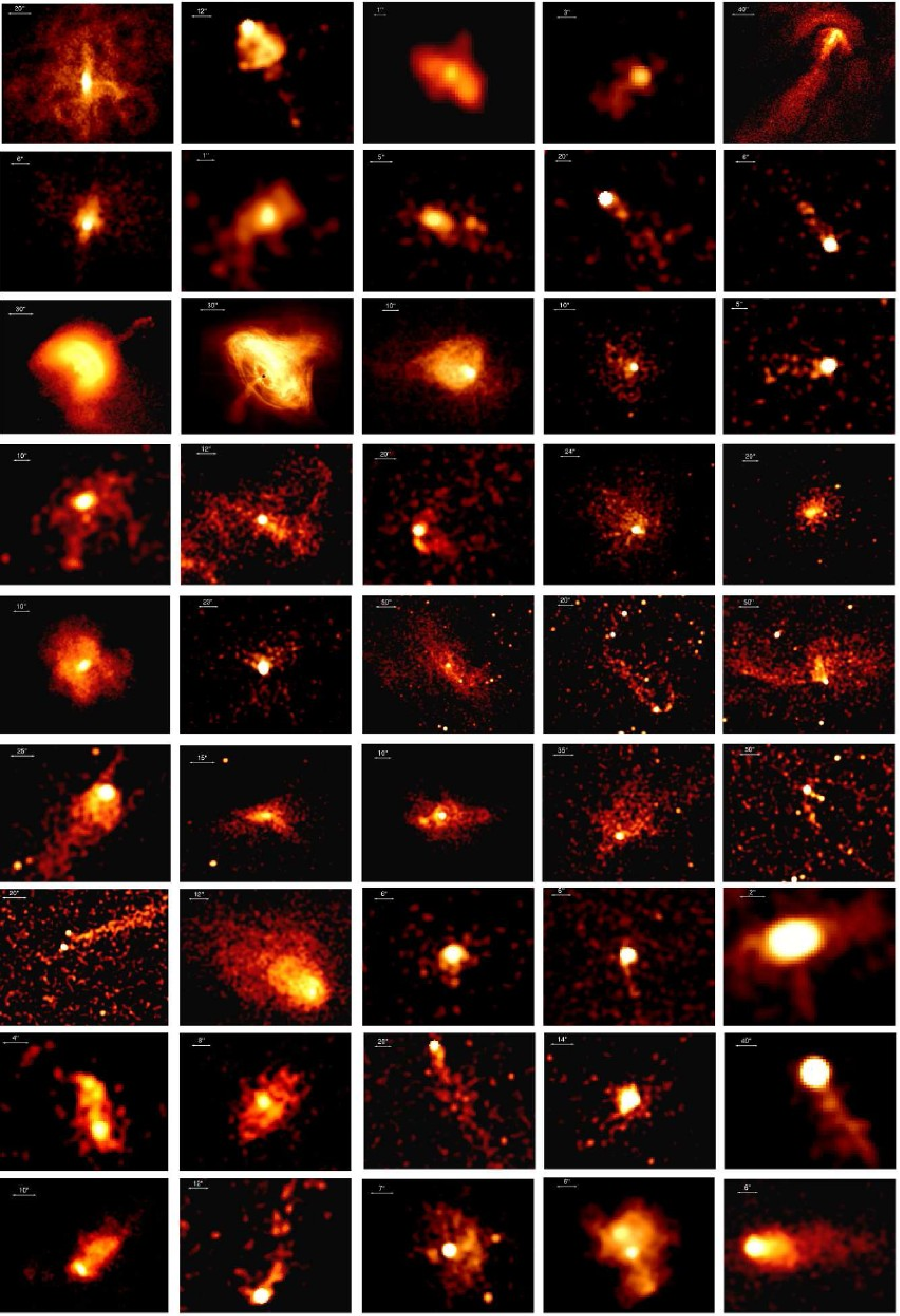
- Typical energy of synch. photon: $\mathbf{E_{syn}=2\ (\Gamma/2\times10^7)^2\ (B/10\ \mu G)\ \ keV}$

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

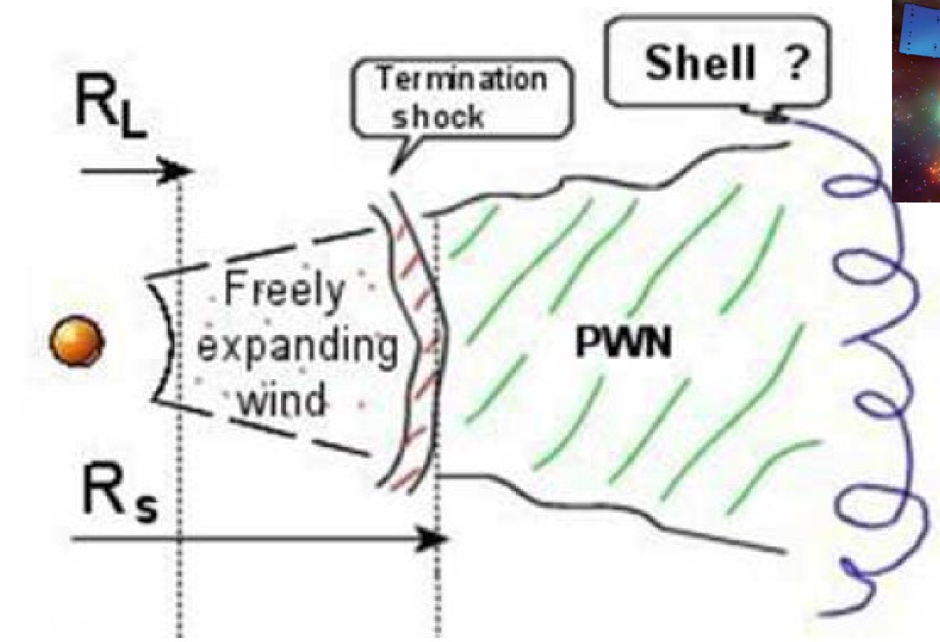
- Characteristic size: $\mathbf{R_s = 0.2\ (\dot{E}/10^{37}\ erg/s)^{1/2}\ (p_{amb}/10^{-10}\ dyn/cm^2)^{-1/2}\ pc}$

- Synchrotron cooling time: $\mathbf{t_{syn} \sim 1\ (E_{syn}/1\ keV)^{-1/2}\ (B/10\ \mu G)^{-3/2}\ kyr}$
- 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: $\mathbf{L = \eta\dot{E}}$, $\mathbf{\eta < 1}$ (efficiency, η, depends on wind parameters and outflow geometry; $\eta \sim$ **10^{-5} – 10^{-1}** from observations).



Chandra gallery of Pulsar Wind Nebulae



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

Fast (supersonically) 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.

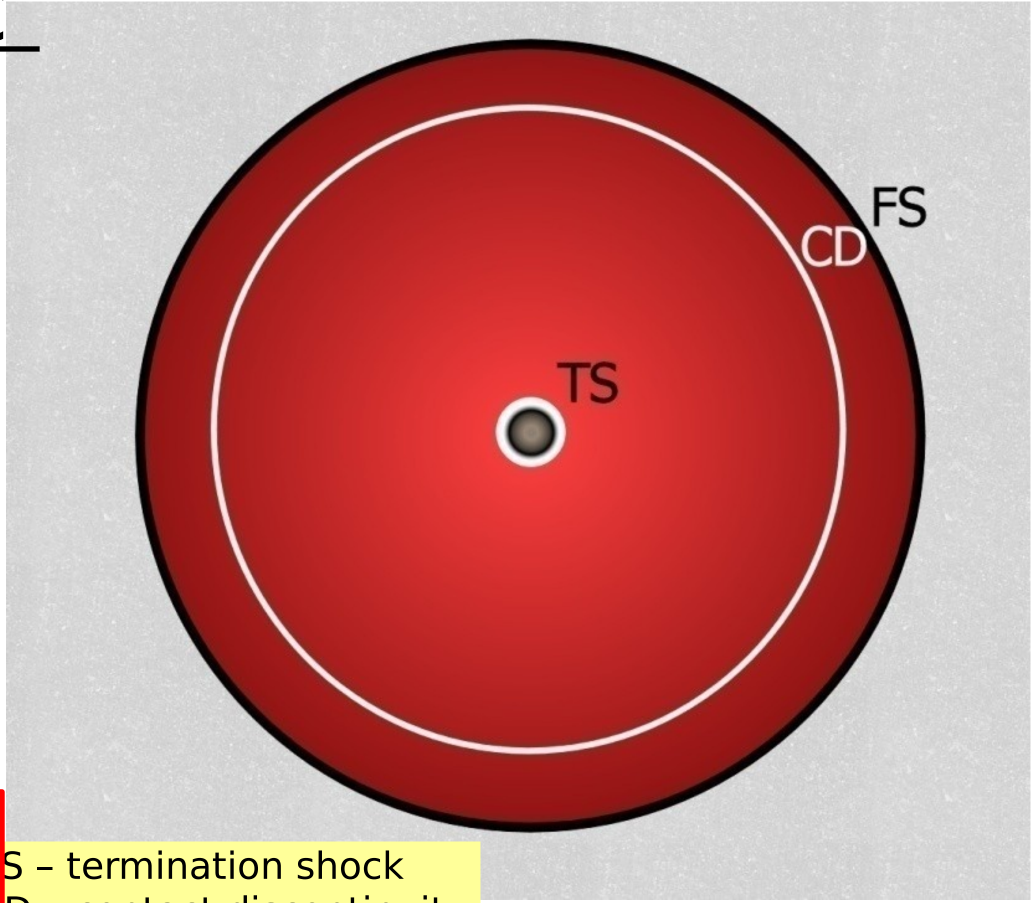
Complex? See real Chandra images on the left!

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

osonic velocity (***M* <<1**):

tropic outflow: sphere

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



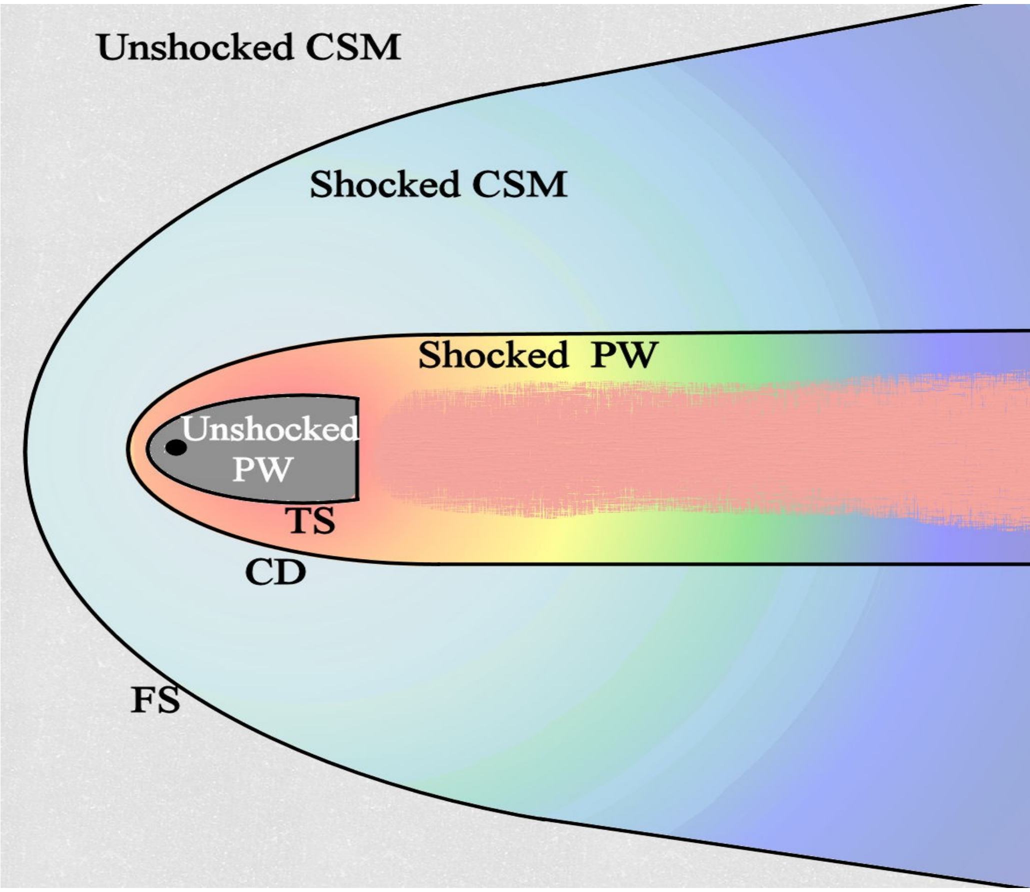
TS – termination shock
CD – contact discontinuity
FS – forward shock

Important parameter **Mach number**:

$$M = V_{PSR}/c_s$$

Sound speed: $c_s = (\gamma kT/\mu m_p)^{1/2} \sim 10\ (T/10^4\ \mathrm{K})^{1/2}$ **km/s**

rsonic velocity (***M* >>1)**:



opic outflow: bow shock + tail

otropic outflow: equatorial + polar =
rella-like termination shock + structured tail

Real examples will follow…

Outstanding PWN questions:

How particles are accelerated in PWNe ?

What is the role of magnetic field reconnection in PWNe?

Are there relativistic ions in PWNe?

Magnetic field structure, properties and role of global currents in PWNe

What happens to entrained ISM matter?

How are relativistic magnetized jets collimated?

How do high energy particles escape from shock region into the ISM?

What are the maximum energies of particles in PWNe?

What is the role of diffusion and how does it work in magnetized relativistic wind?

PWNe in binaries. Colliding winds problem.

Can magnetars produce winds? Can we find dormant magnetars?

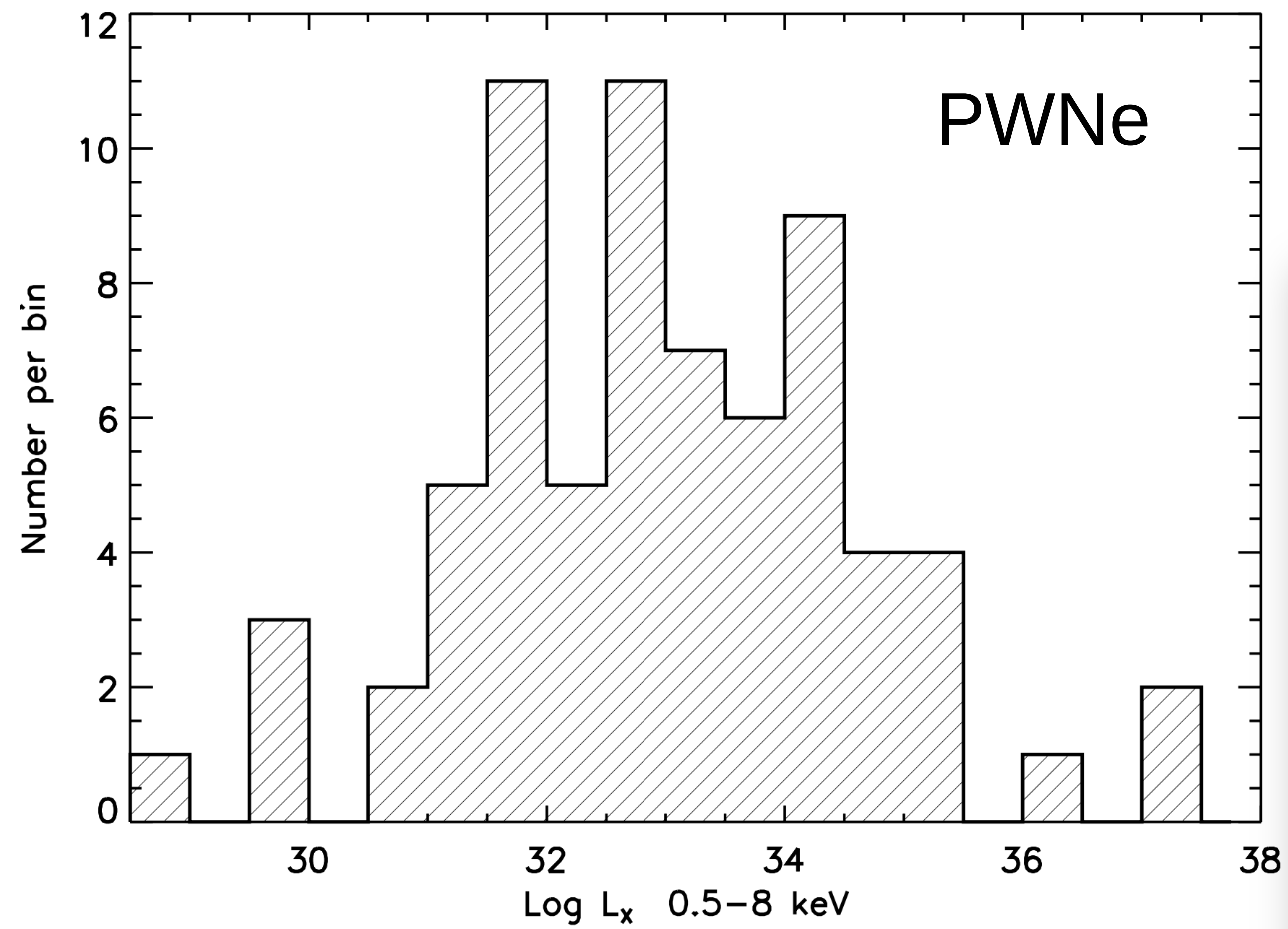
Is there relativistic magnetic turbulence and how does it manifest itself?

What is the connection between the pulsar & PWN parameters?

What are the pair cascade multiplicities?

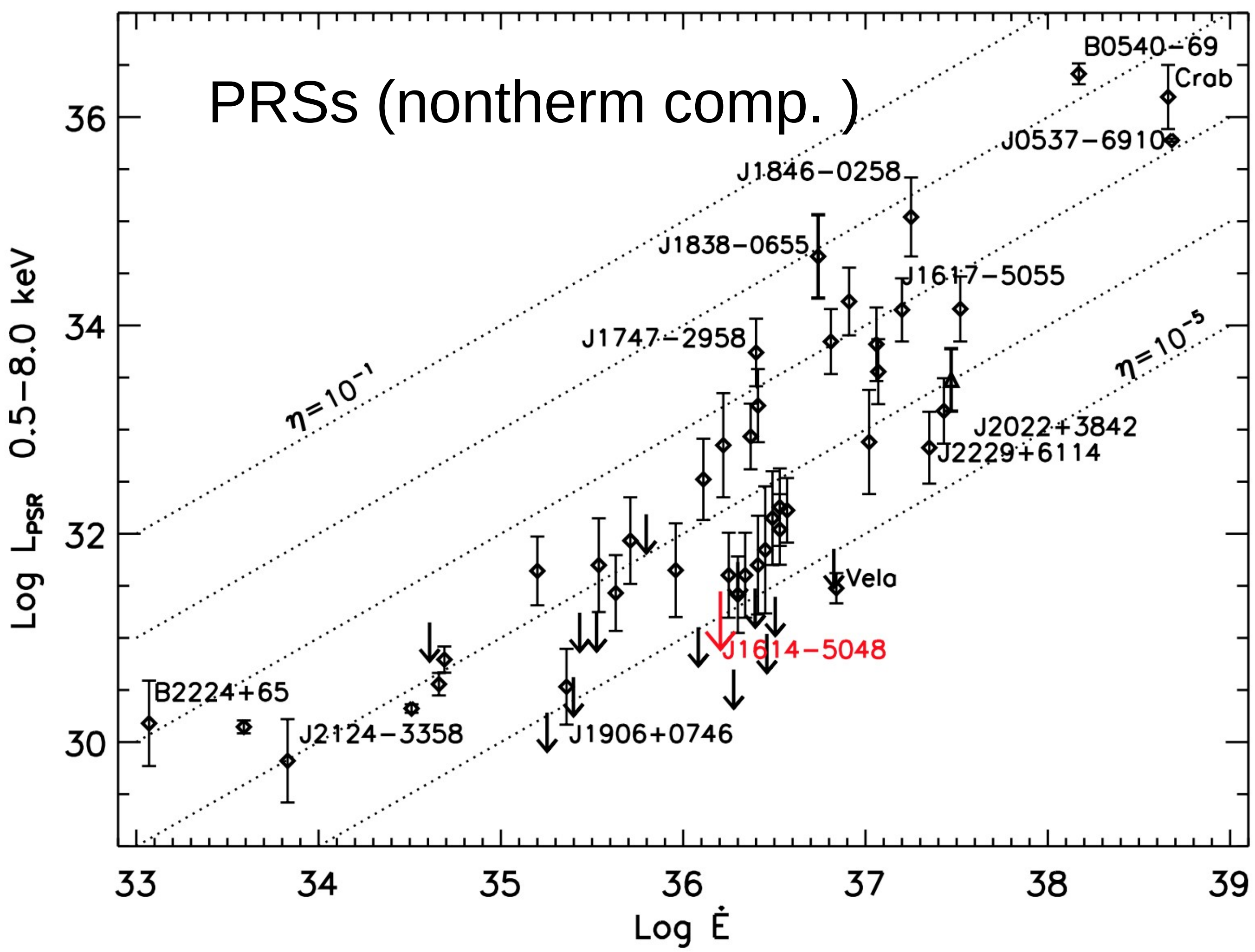
What can we learn about ISM by studying PWN properties?

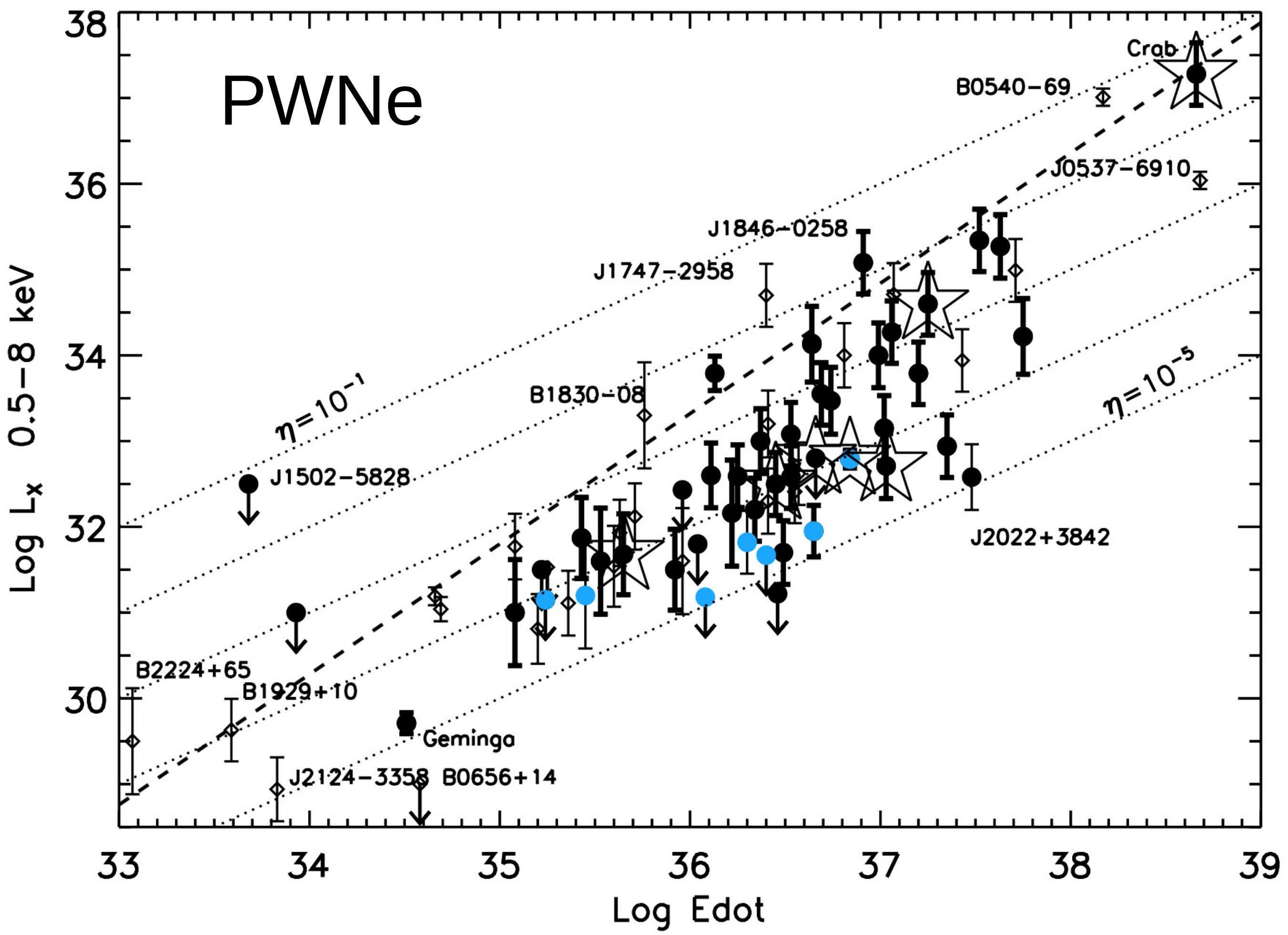
Overall population properties.



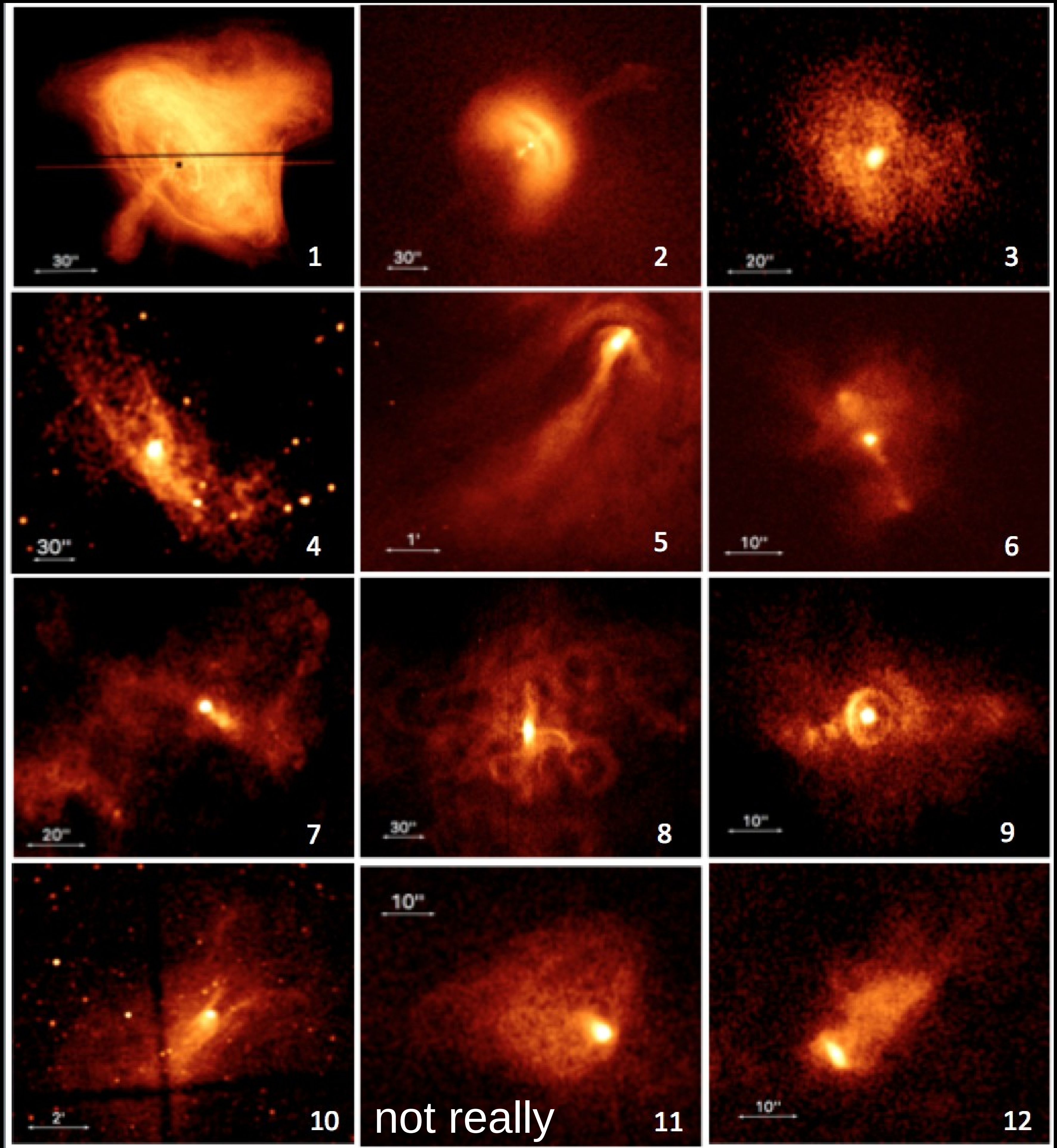
Huge scatter in efficiencies for PWNe

Even short 10-20 ks exposures can expand this kind of study.





Thanks to Chandra some PWNe have been now studied in detail:



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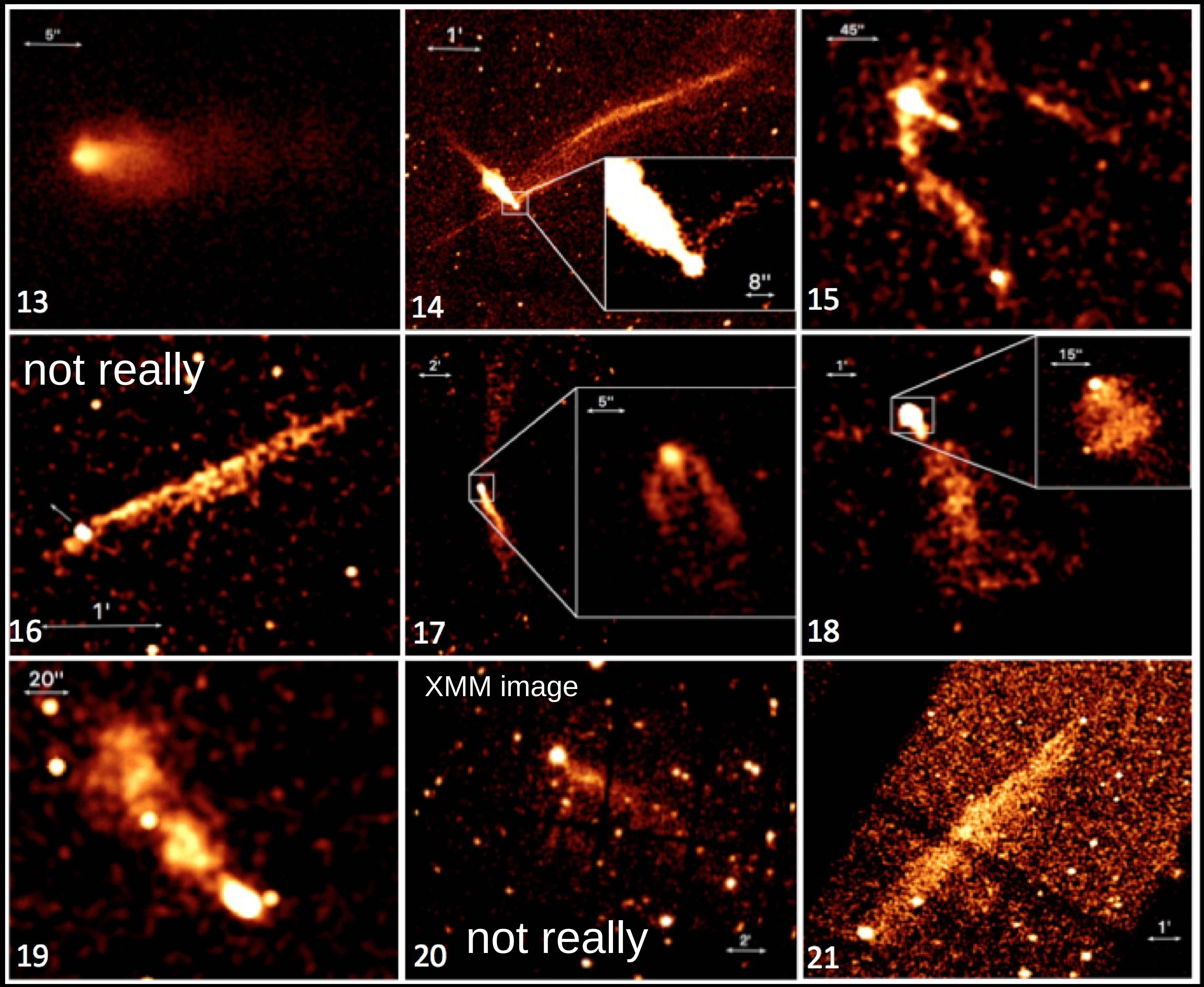


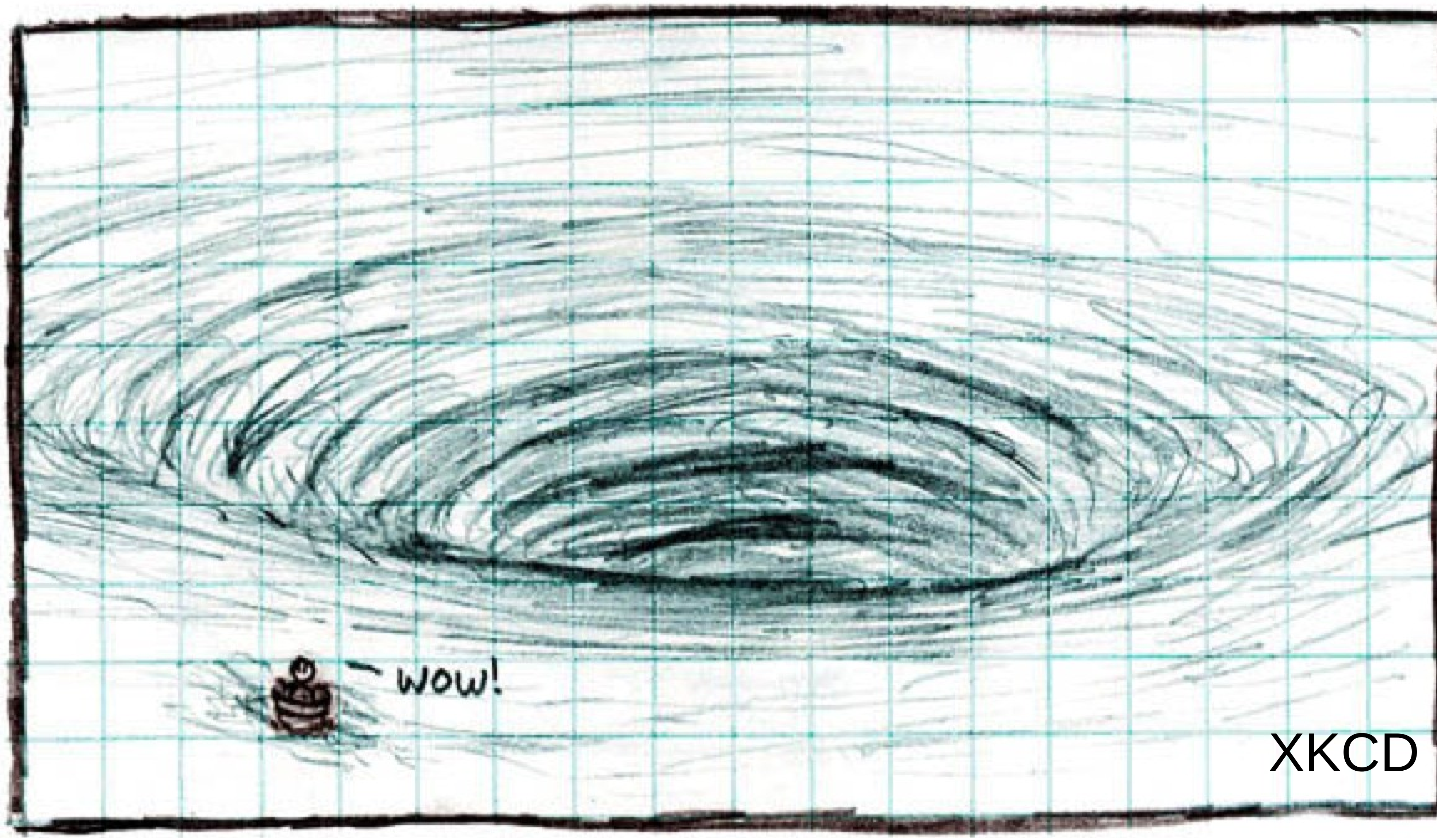
List of bright, well-resolved PWNe observed by Chandra

Name	Exposure (ks)	F_X (10^{-11}, cgs)	Features
Crab	565 (57)	2000	ring, torus, jets
Vela	635 (22)	6.1	arcs, jets
G21.5–0.9	780 (82)	3.8	tori, jets
MSH11–62	492 (9)	3	torus?, 2 arcs(?)
G320.4–1.2 (B1509-58)	250 (8)	5.3	arcs, jet, tail(?)
Kes 75 (J1846-0258)	247 (5)	1.5	jets, torus
G11.2–0.3	495 (12)	0.6	jets, torus(?)
G54.1+0.3	340 (5)	0.5	torus, jets
Mouse (J1747-2958)	155 (5)	0.7	tail, torus(?)
G327.1-1.1	290 (4)	0.3	tail, prongs
IGR J11014-6103 (Lighthouse)	305 (7)	0.2	misaligned
CTB80	85 (1)	0.6	torus, tail(?)
N157B (J0537-6910)	50 (1)	0.6	torus, tail/trail
3C58	400 (4)	0.7	jets, loops, torus
J1509-5850	420 (5)	0.05	bow shock, tail, outflow
B0355+54	470 (9)	0.03	bow shock, tail, torus?
J1741-2054	350 (7)	0.03	bow shock, tail
J0357+3205	160 (4)	0.04	(disconnected) tail

Panels were generous to PWN science *(except for the last round!)*

A lot of credit for the above data goes to the proposal writers.

What have we learned from deep observations of PWNe ?

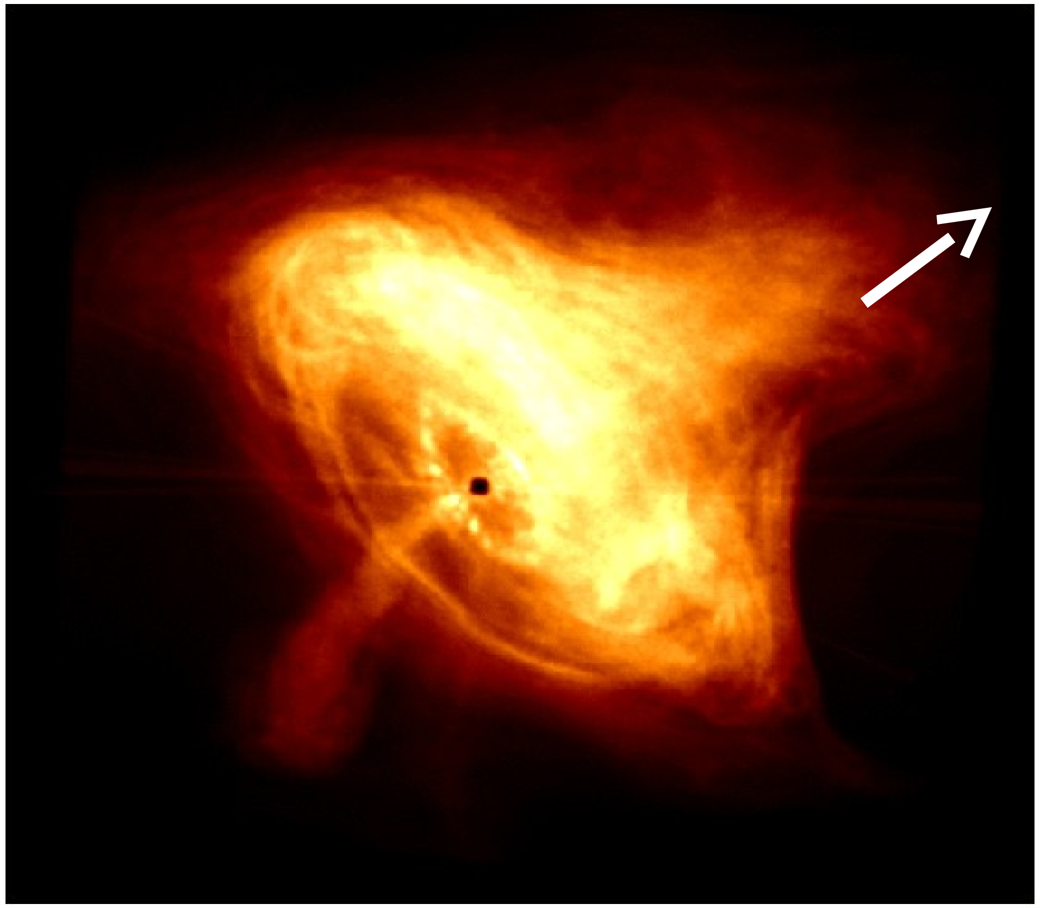


XKCD

Canonical example: Crab PWN

Crab pulsar: **Edot = 4.5×10^{38} erg/s, Age = 962 yr, *D*=2 kpc, V_t=140 km/s**

Chandra ACIS images (Weisskopf et al. 2000, 2015).



Resolving the jets and rings places constrains on pulsar geometry; synergy with gamma-ray & radio pulse profile modeling.

We do see a **ring**, but it is elliptical, with a bright '**torus**' beyond the ring and fainter '**jets**' along the PSR spin axis.

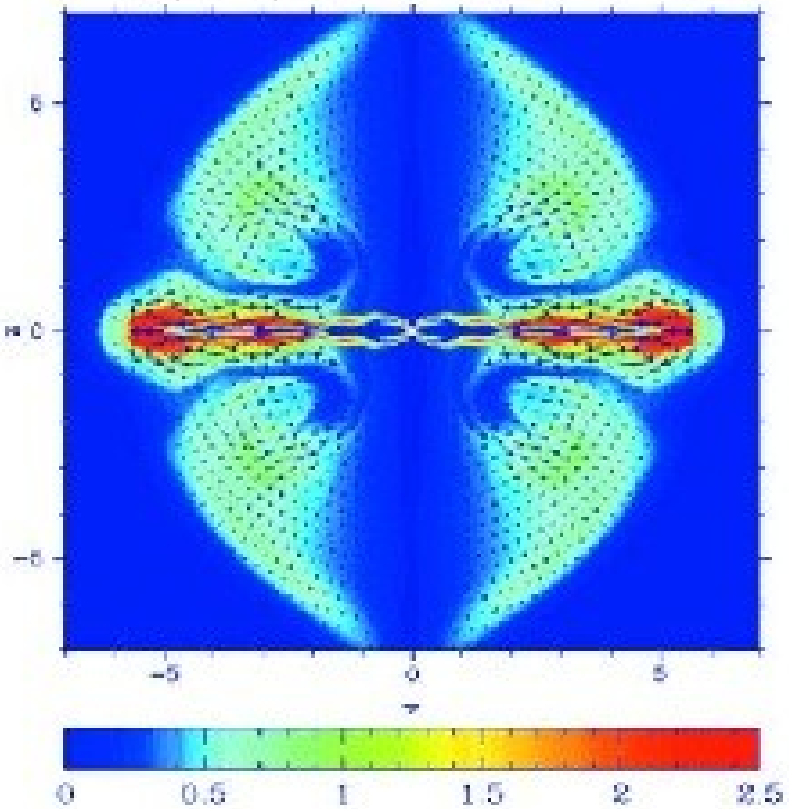
The spin axis coincides with the PSR velocity direction (Ng & Romani 2006)

The unshocked PW is emitted predominantly in the equatorilal plane, tilted by ξ=30^o to l.o.s.

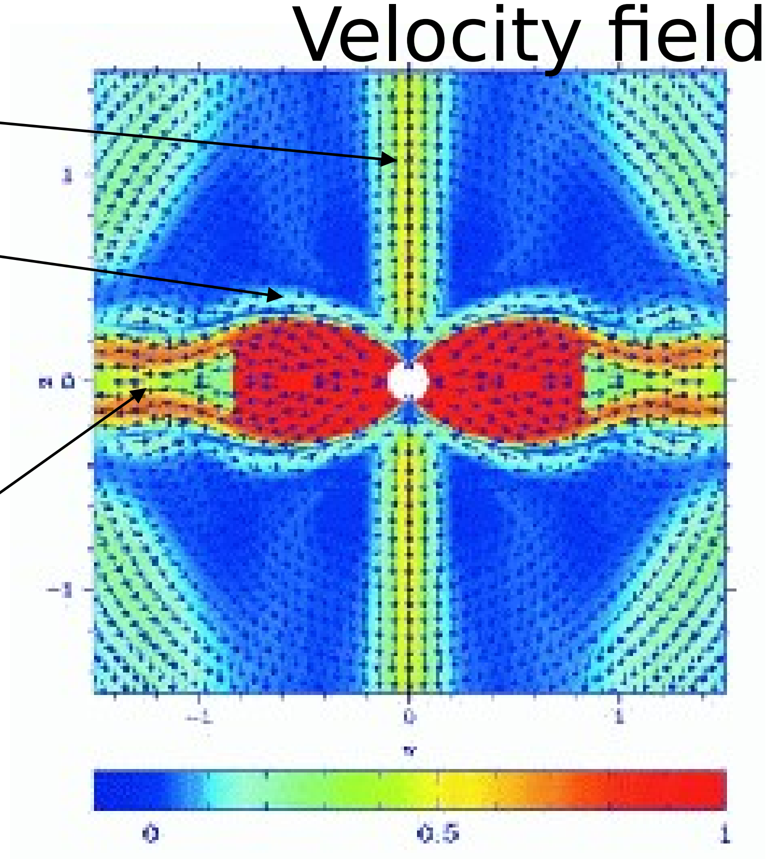
The jets are likely produced from outer layers of equatorial outflow turned back to the spin axis and confined by magnetic hoop stress (Komissarov & Lyubarsky 2003, 2004; Del Zanna et al 2004, 2006)

The fine structure of the Crab have been driving theoretical modeling of pulsar winds so far…

P_{mag}/P_{gas}



Velocity field



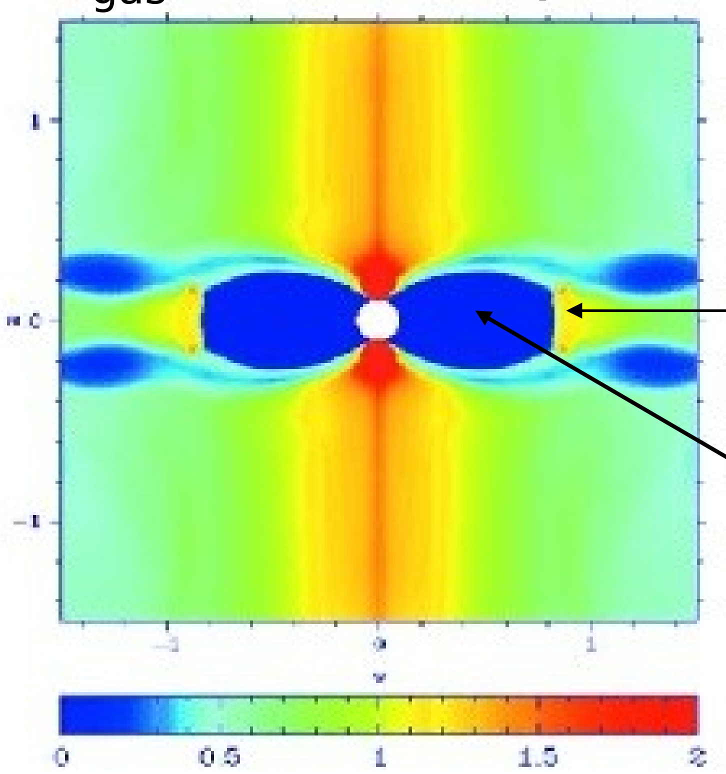
polar outflow (jet)

backflow

shocked equatorial outflow

RMHD 2D simulations of anisotropic psr outflows (Komissarov & Lyubarsky 2003)

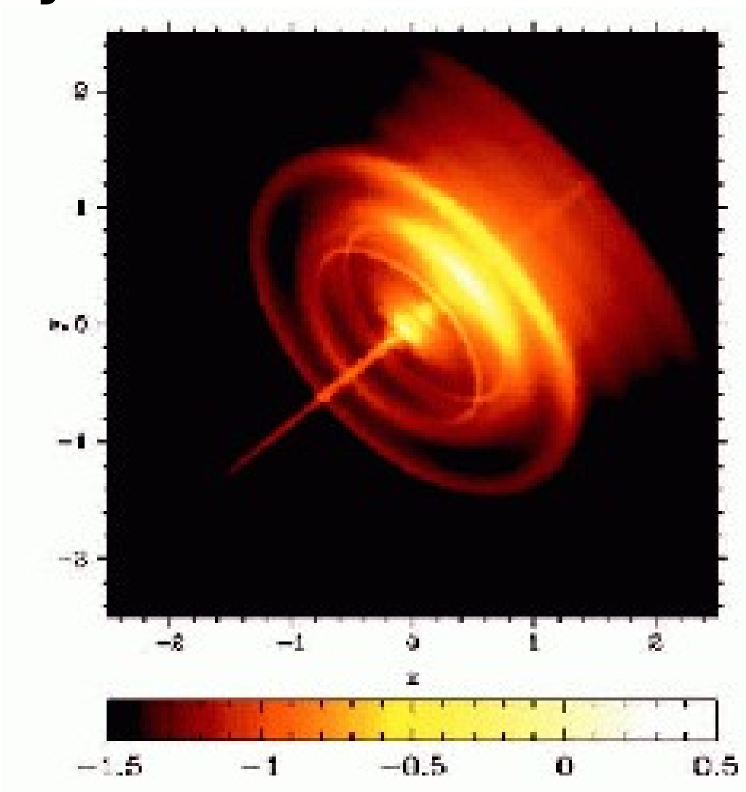
P_{gas} for inner part



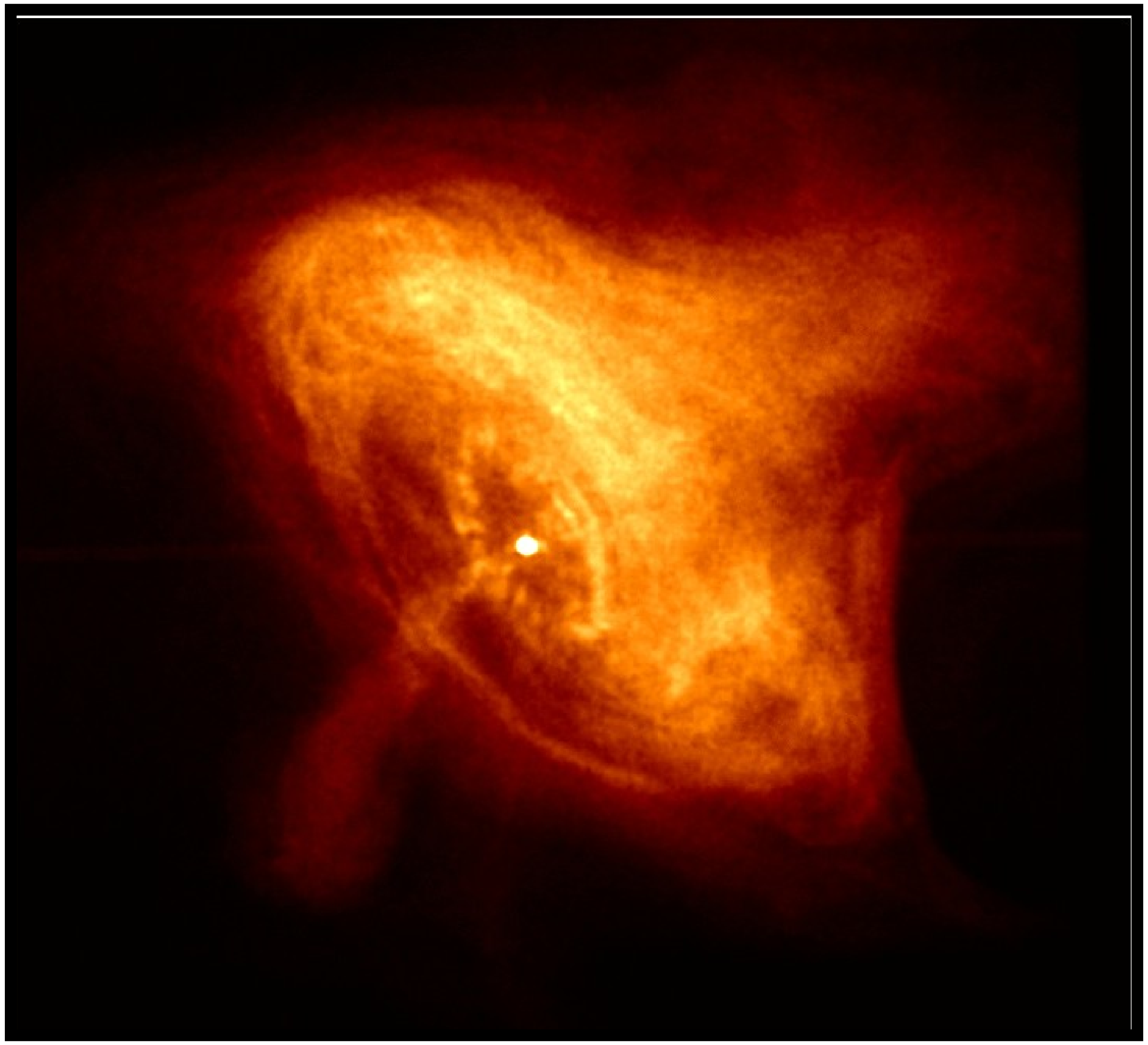
Mach belt

unshocked pulsar wind

Synchrotron radiation (i=30



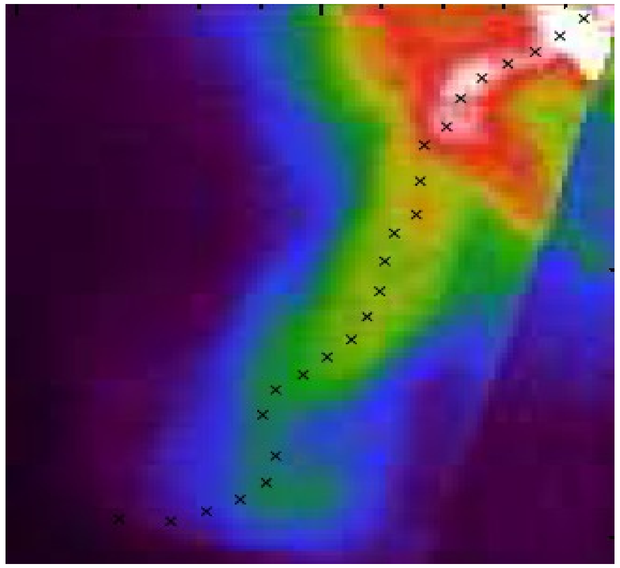
Crab's torus is comprised of '**wisps**' moving outward with decreasing velocity, **0.4c – 0.2c**. Similar speeds are seen in the jets.



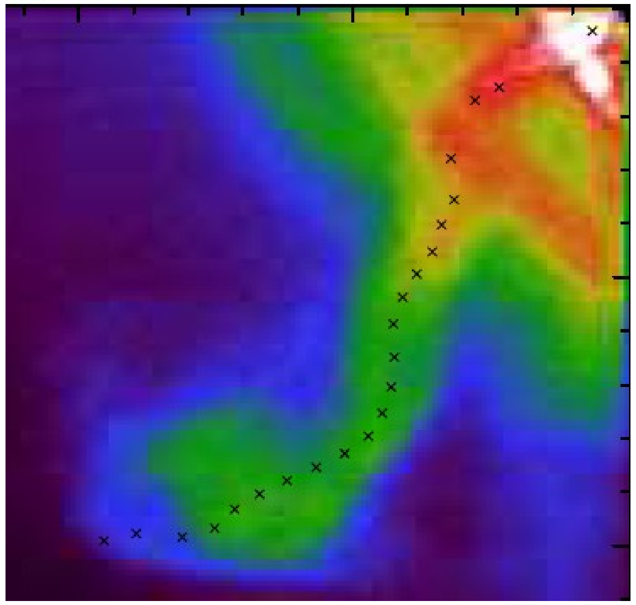
Hester et al. 2002; Mori et al. 2004, 2006

Jet's end wagging on a few year timescale

2003



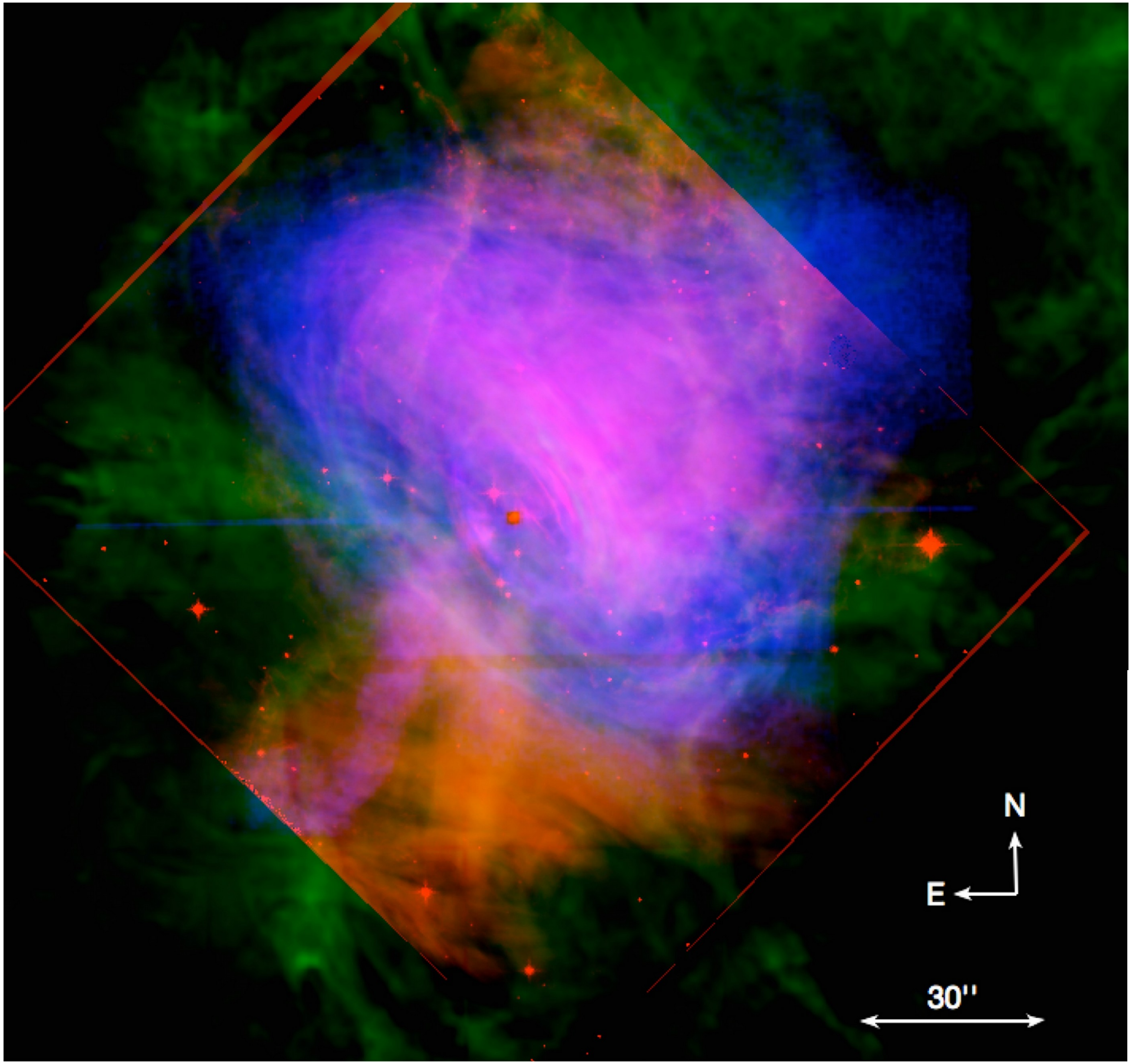
2011



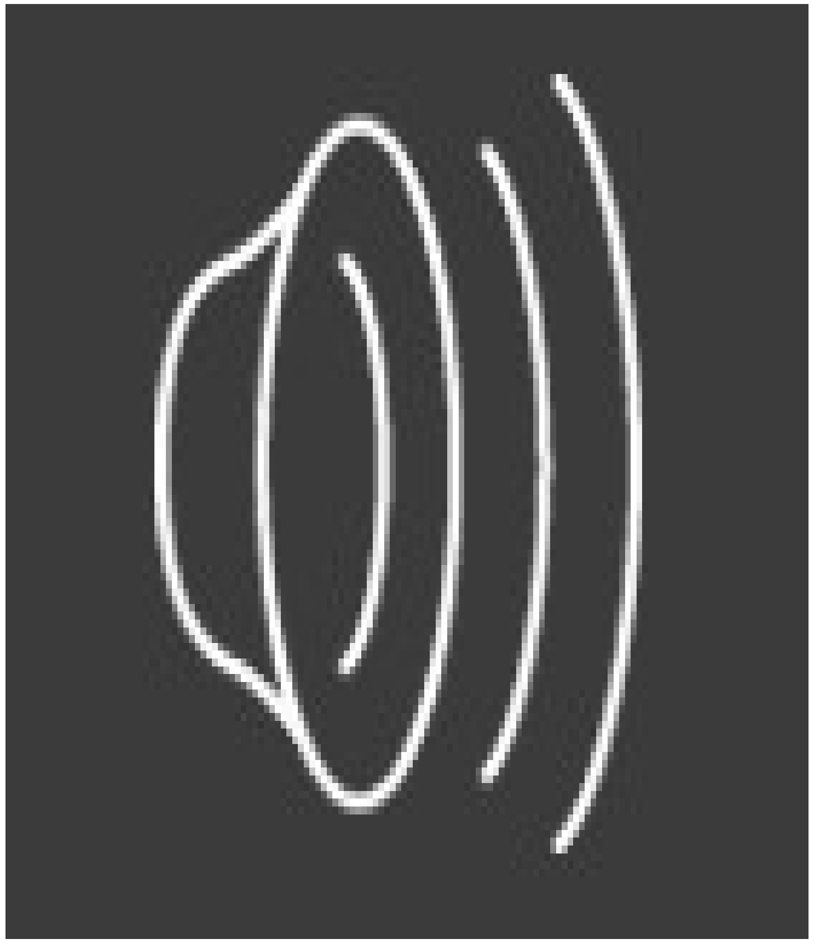
Weisskopf et al. 2016

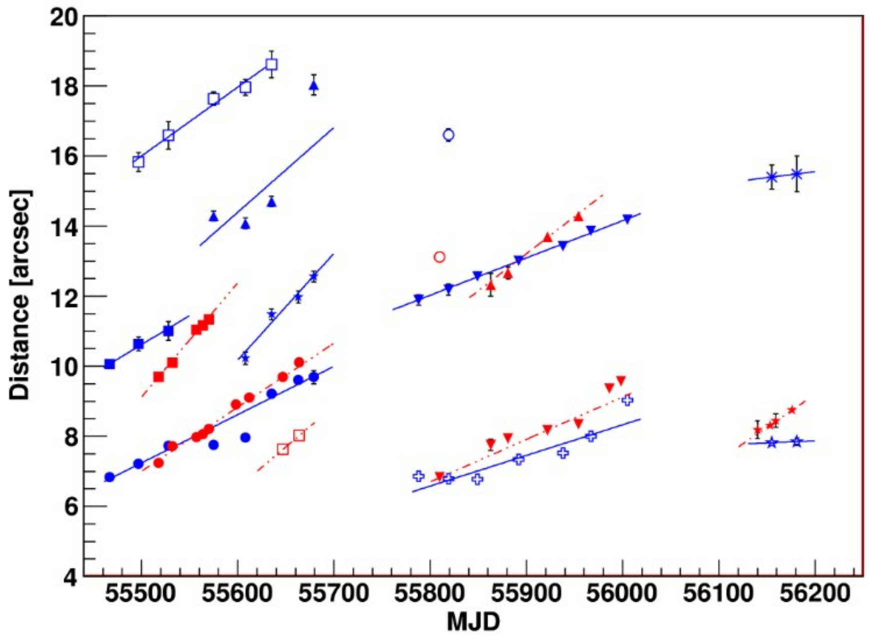
A little problem: X-ray and optical wisps do not coincide

Chandra + HST+JVLA synergy: contemporaneous observations



Krassilchtchikov in prep.

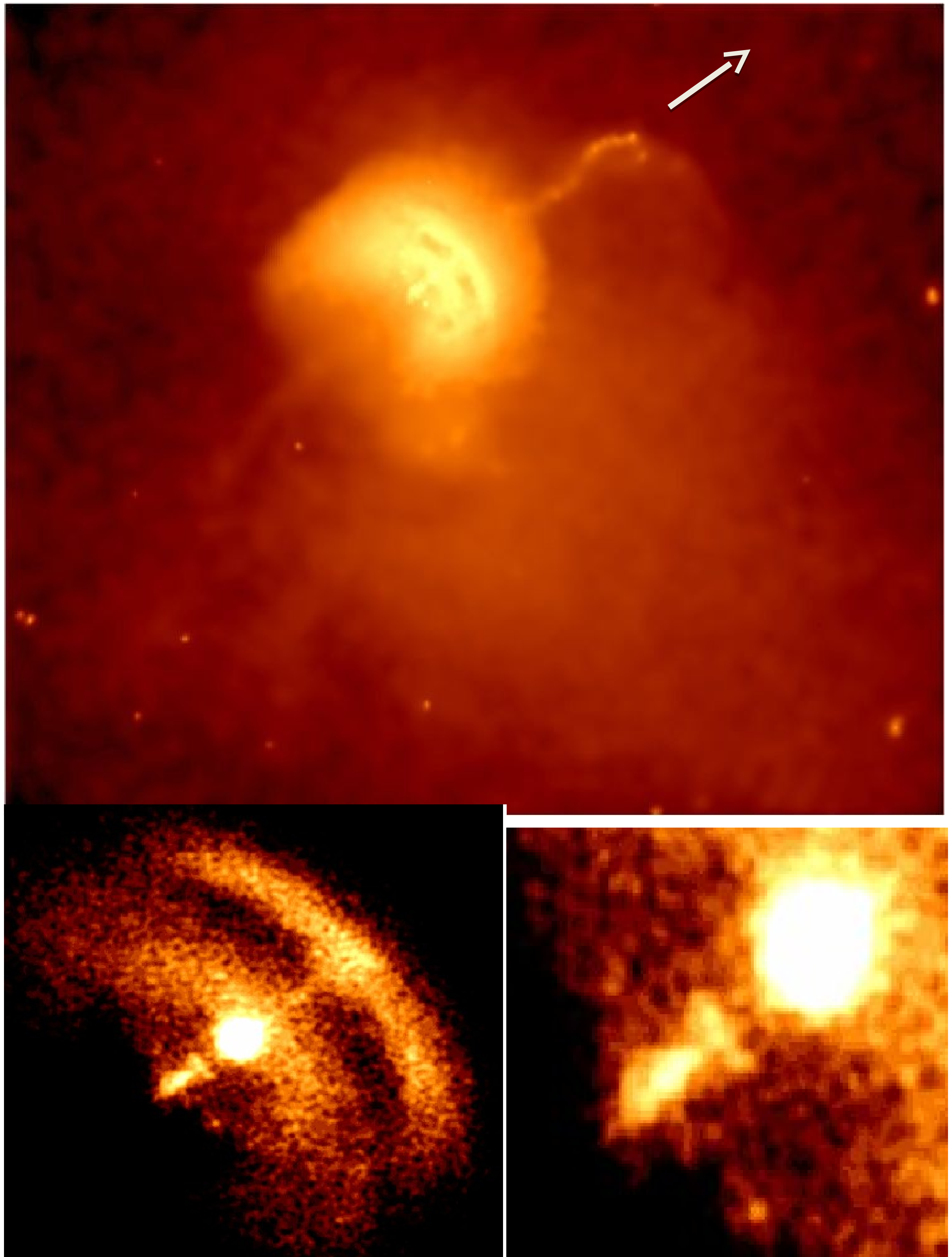




Schweizer et al. 2013

Another outstanding example: Vela PWN

Chandra ACIS, 150 ks, Pavlov et al 2001,2003



***D*=0.3 kpc, *Edot* = 7×10^{36} erg/s, τ_{sd} = 11 kyr, *V*$_t$=77 km/s**

Pulsar motion is transonic; it affects PWN morphology, contrary to Crab.

Are the two arcs analogues to Crab torus (‘split torus’) i.e. caused by equatorial outflow? Larger angle (α) between spin and magnetic axis?

Inner and outer “jets” (**~ 0.01 pc** and **0.15 pc**) aligned with pulsar’s speed. Inner SE jet detached from PSR.

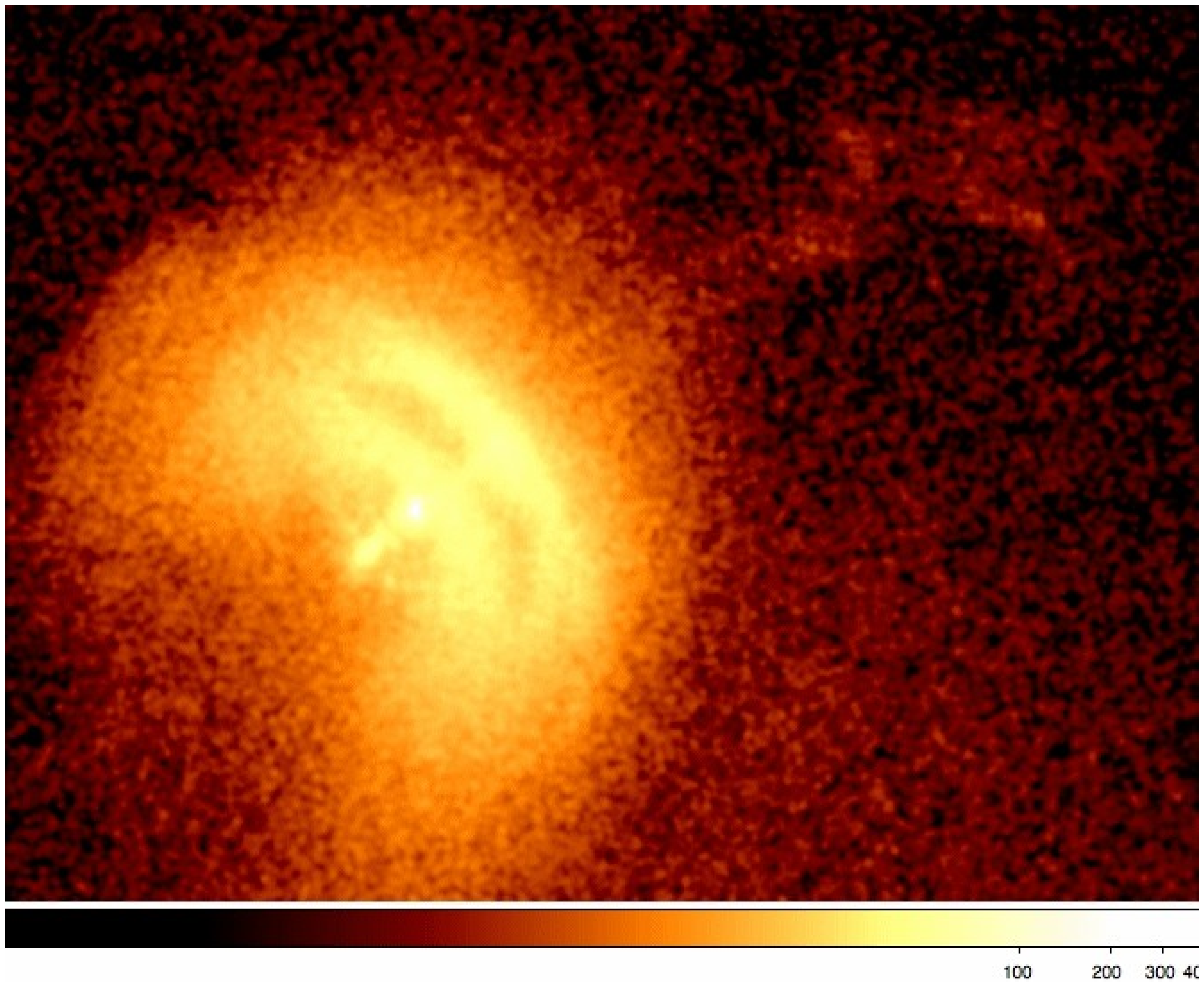
Why inner and outer jets so different?

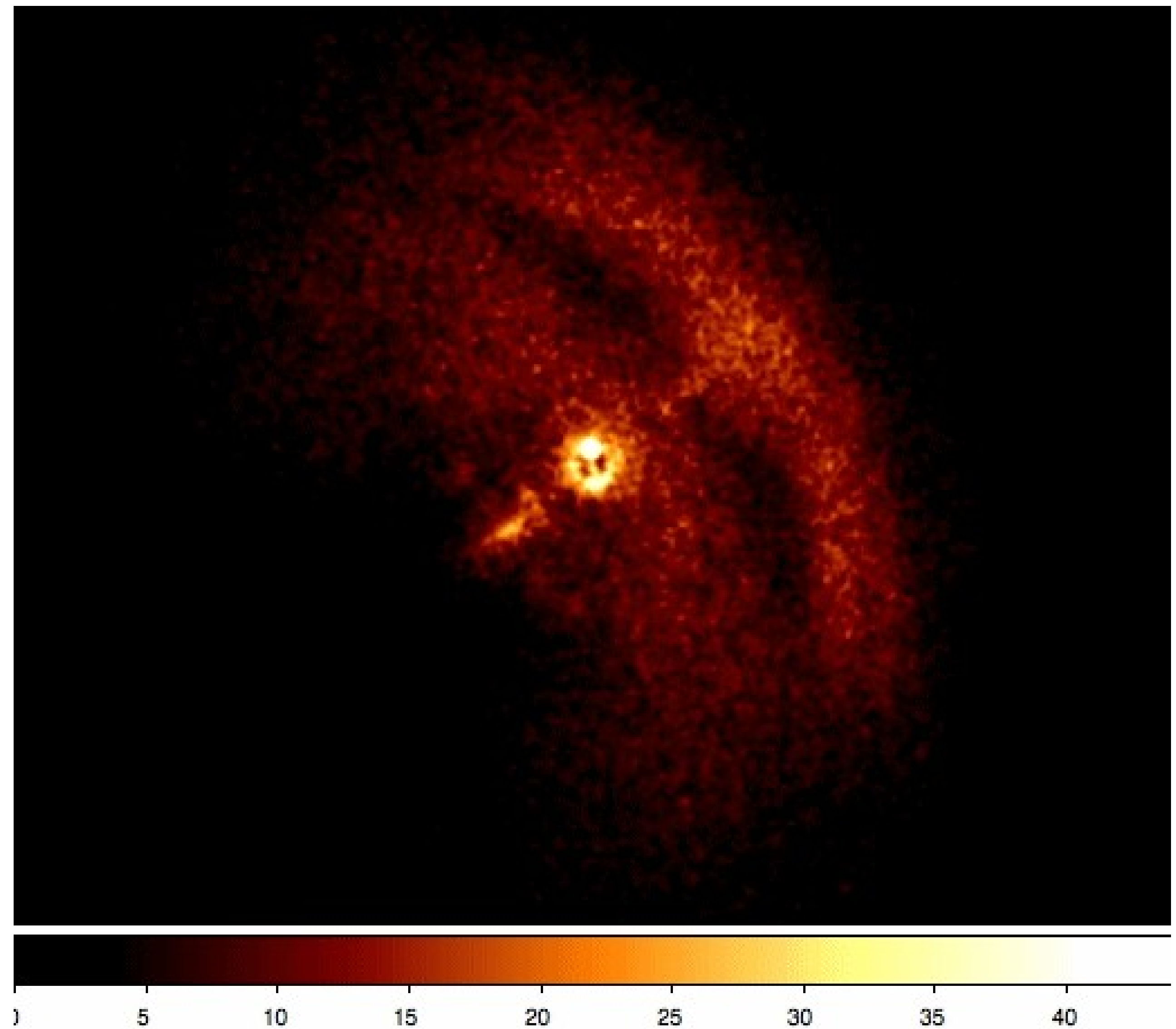
Outflow speed ~**0.3-0.7 c** in the outer jet, energy injection rate ~**8×10^{33} erg/s**.

Magnetic field **a few ×10 mG**, electron energies up to **~500 TeV**

Vela PWN: 2 months in 2010

8 observations 40 ks each, 1 week separation (Durant et al. 2013)

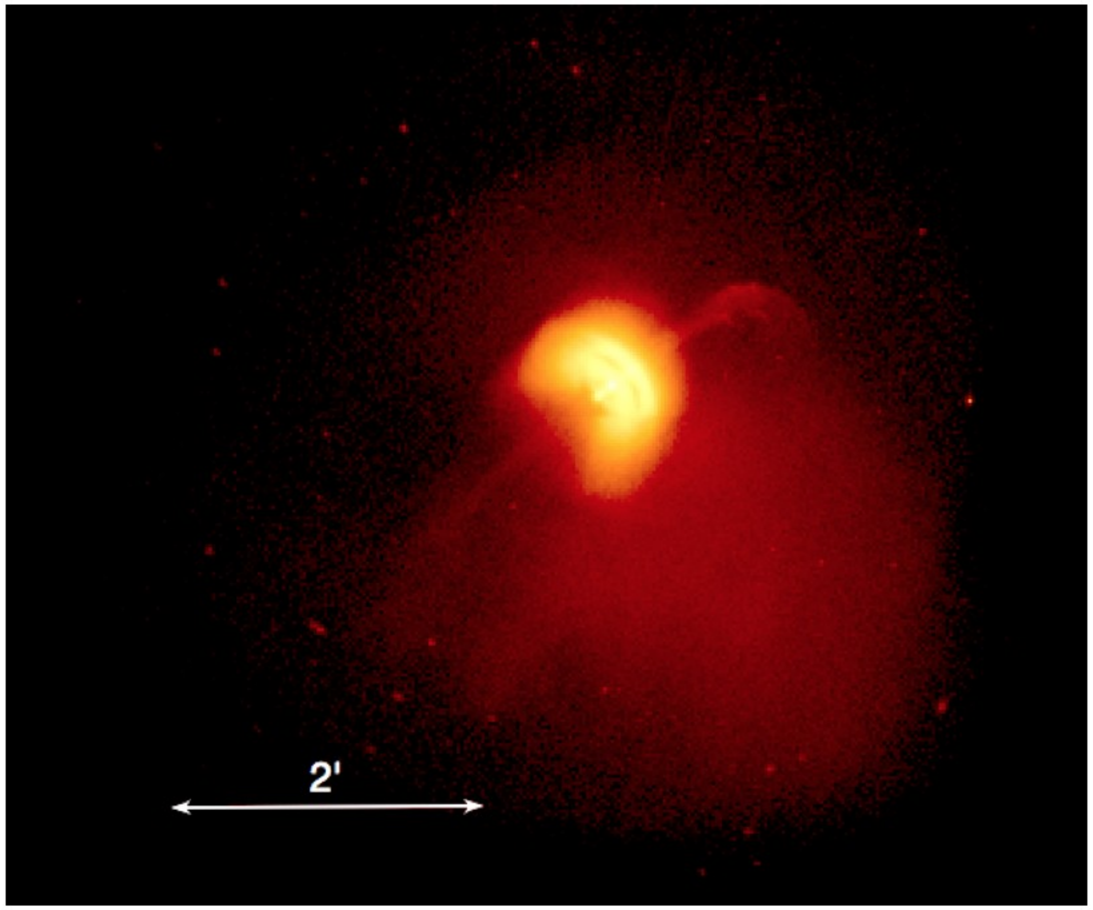


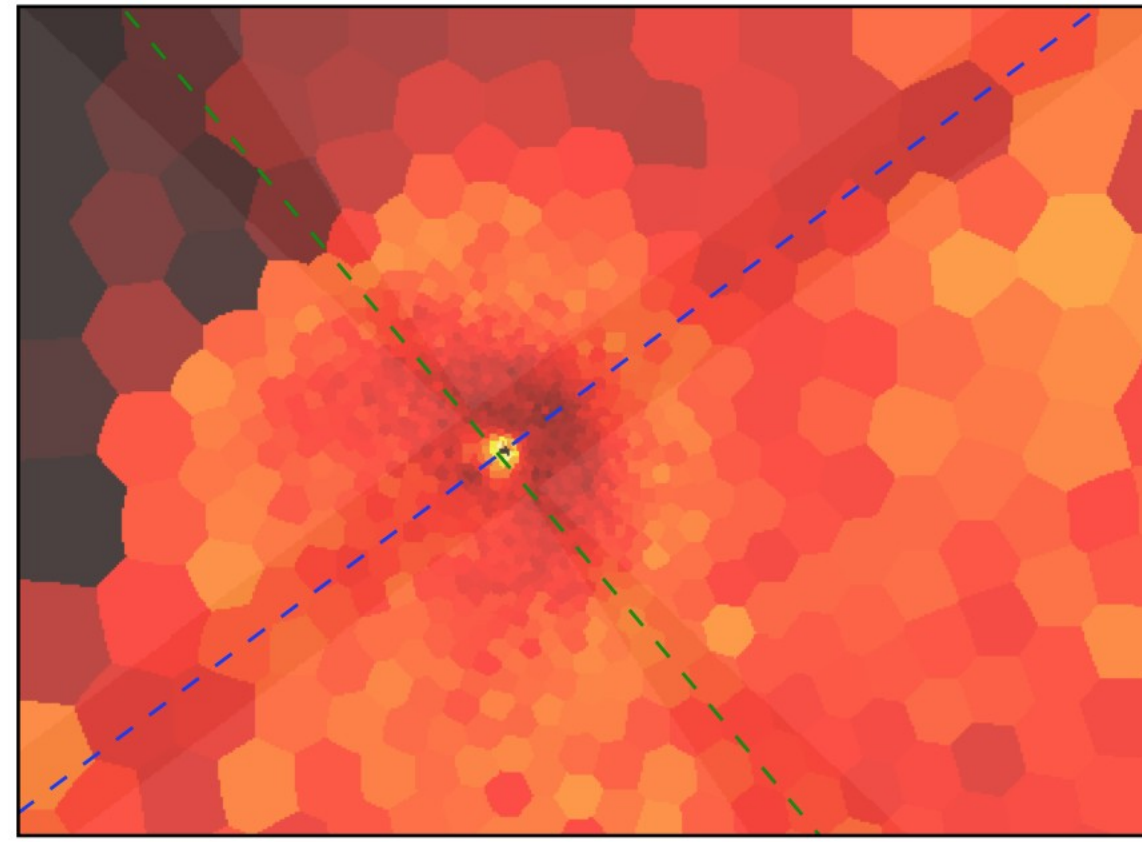


Outer jet resembles a rotating corkscrew! Turning helix projected onto sky? Precession with 120 d period, launch speed 0.7c? Kink instability?

Bright inner PWN is variable but no wisps seen. A shock in the counter-jet?

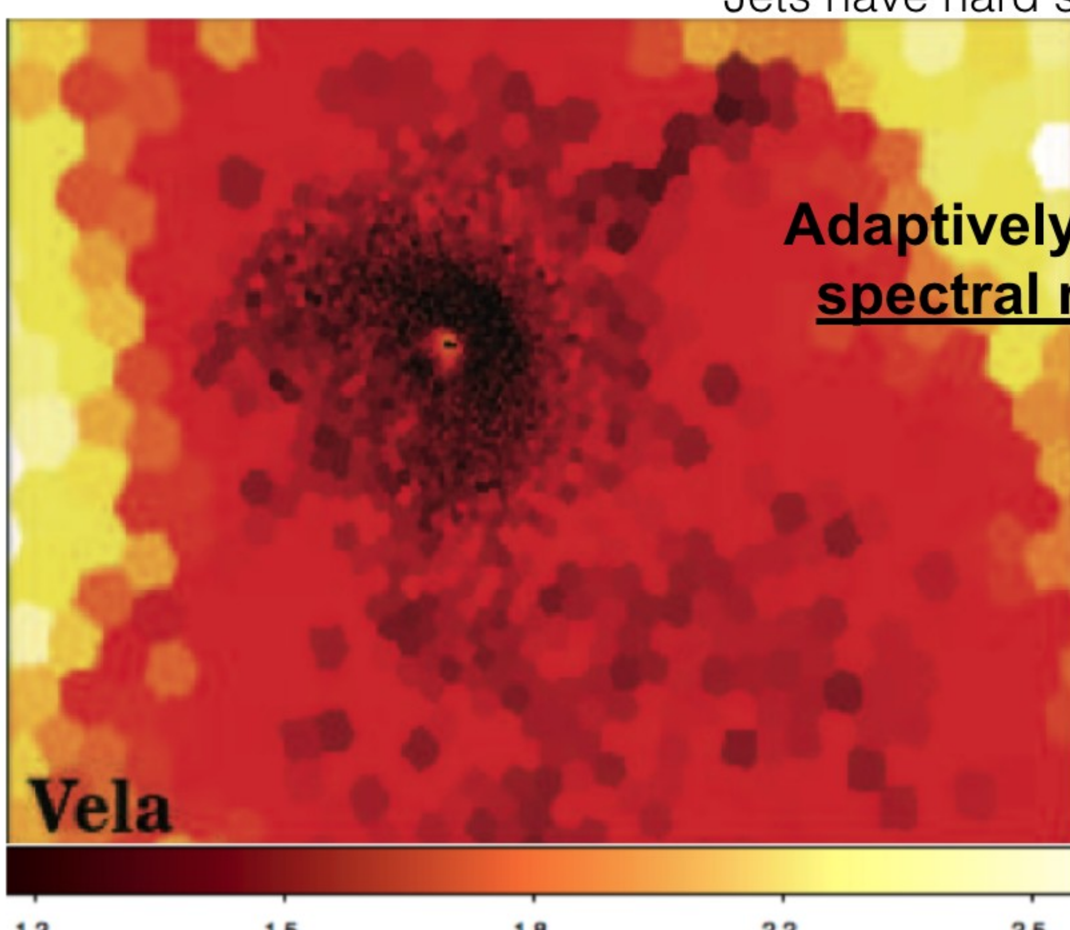
Vela PWN: spectral structure

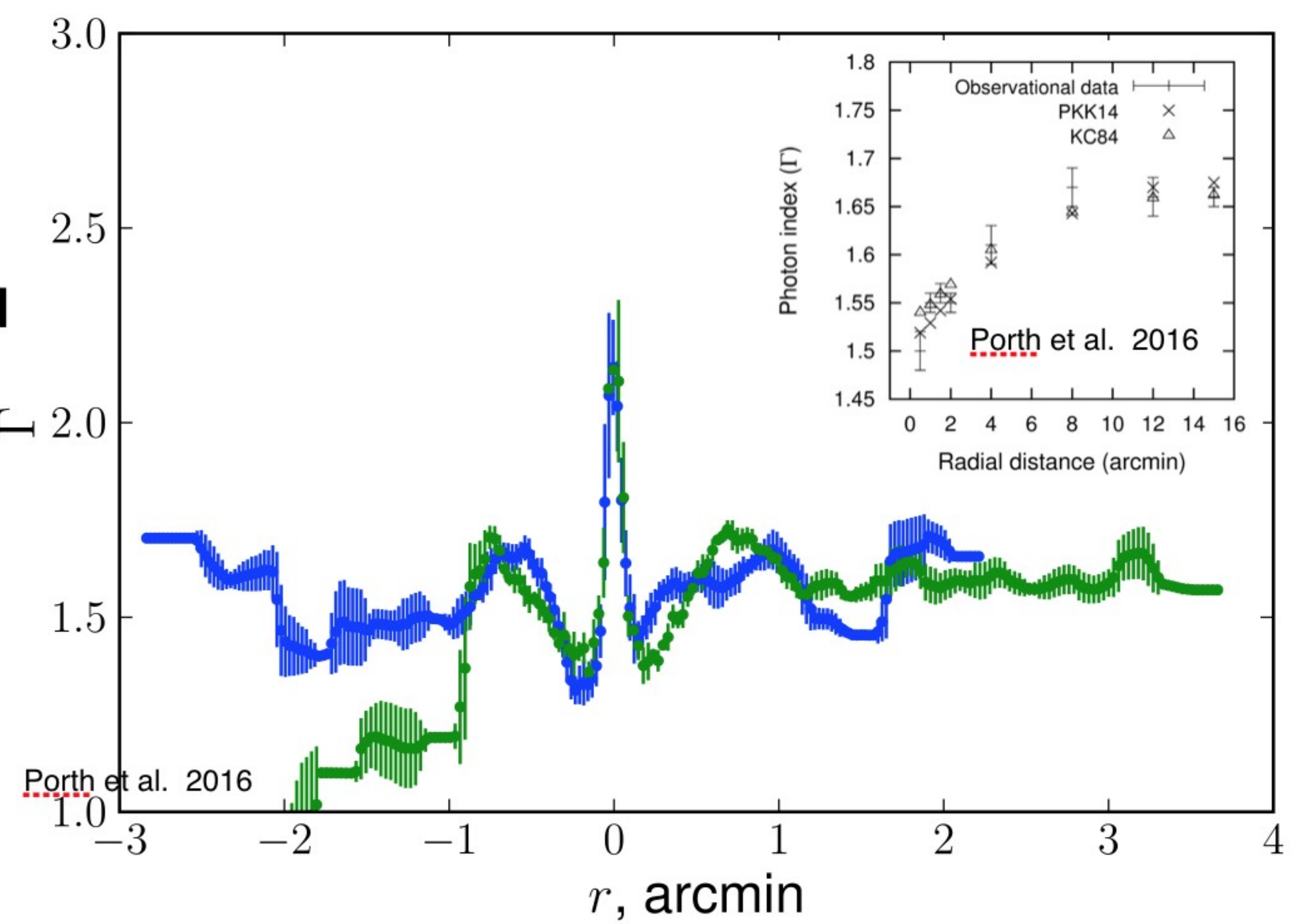




Jets have hard spectra.

Adaptively binned spectral map

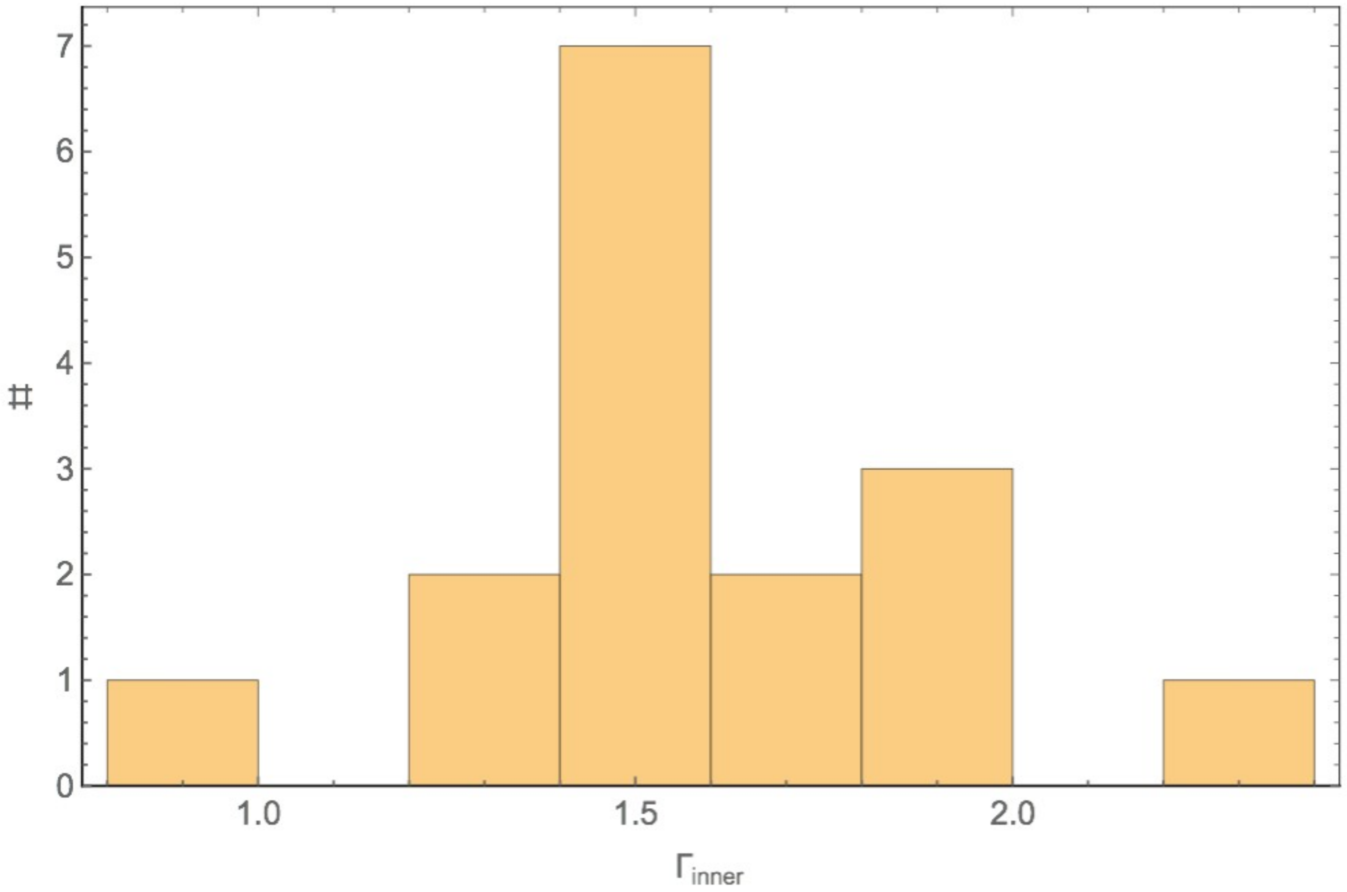




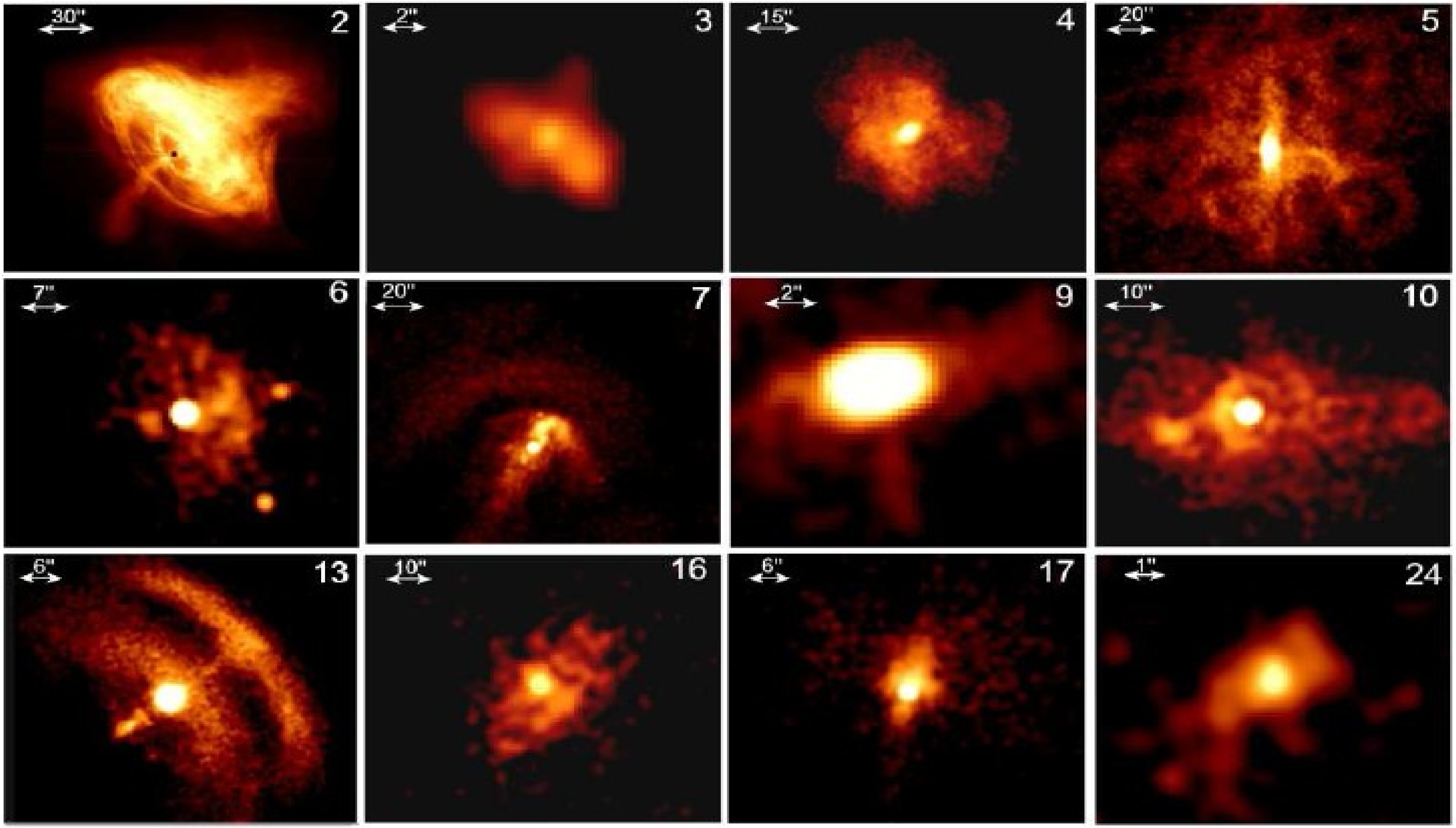
Having detailed spectral maps allows to find the hardest spectra and measure spectral slopes relatively unaffected by cooling.

These slopes may be more directly related to pulsar properties

Name	Γ_{inner}	$\delta\Gamma$	p
N157B	2.3	0.05	3.6
Crab	1.8	0.05	2.6
Vela	1.3	0.05	1.6
3C58	1.9	0.07	2.8
G320.4-1.2	1.4	0.1	1.8
Kes 75	1.9	0.1	2.8
G21.5-0.9	1.4	0.06	1.8
G11.2-0.3	1.36	0.13	1.72
CTB 80	1.7	0.1	2.4
G54.1+0.3	1.5	0.05	2.
B0355+54	1.54	0.05	2.08
MSH 15-56	1.4	0.2	1.8
G327.1-1.1	1.62	0.08	2.24
J1509-5850	1.43	0.18	1.86
PSR J1741-2054	1.5	0.15	2.
Geminga	0.9	0.15	0.8
J1747-2958	1.5	0.05	2.



Examples of Torus-jet PWNe (often found in SNRs)



Crab, B0540-69, G21.5-0.9, 3C58, G106.3+2.7, B1509-58, G292.0+1.8, G54.1+0.3, Vela, J2021+3651, B1706-44, B1800-21 --- all are young (< 17 kyr), all in SNRs, M <~1.

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

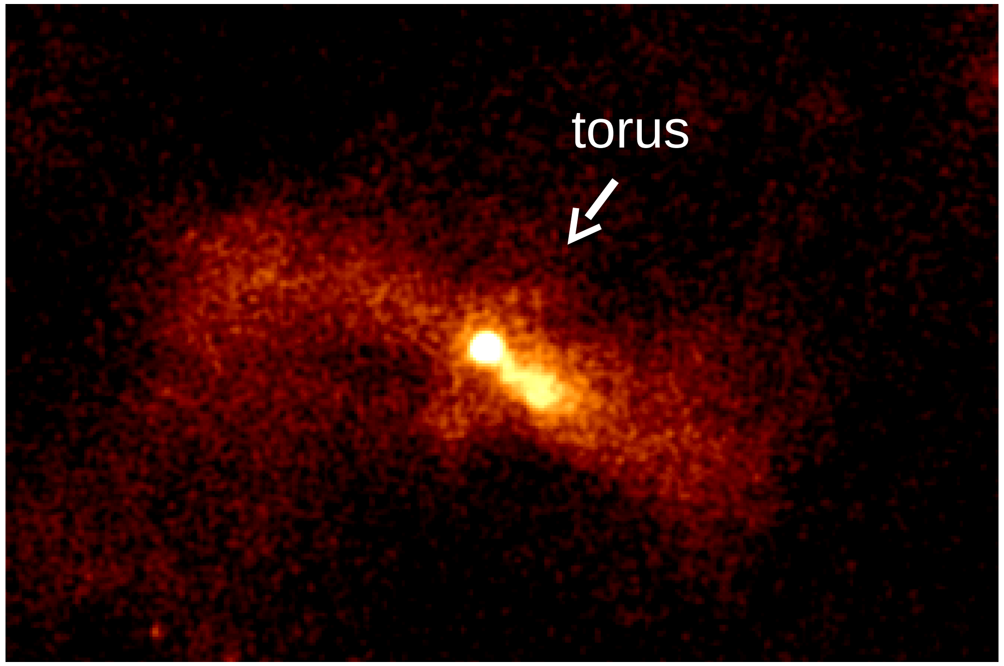
Very deep look at two PWNe in SNRs

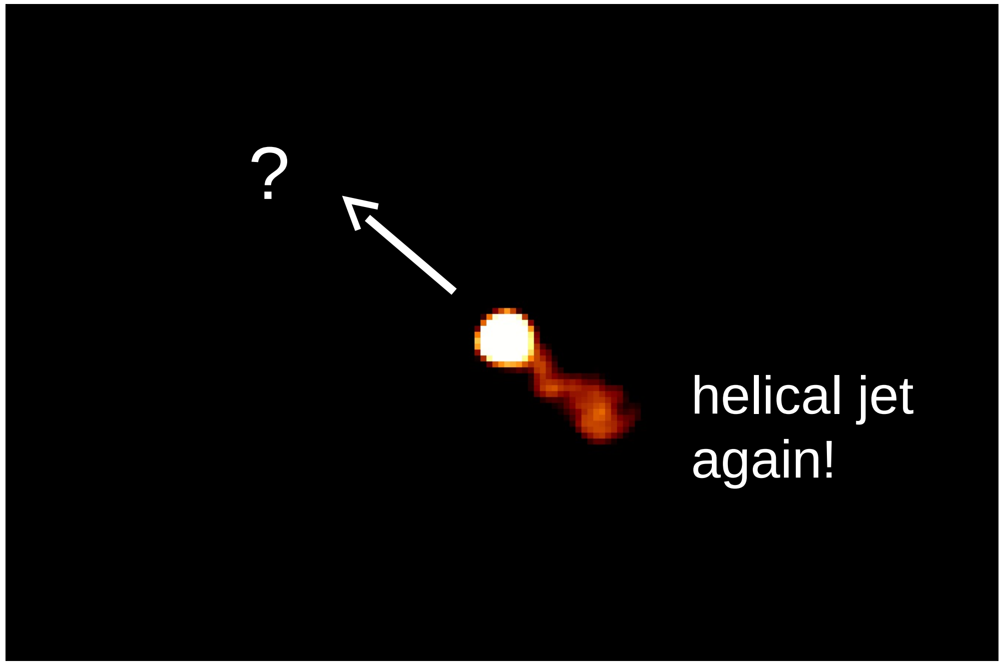
Jets are much brighter than tori? (There are more such examples).
Are these pulsars close to being aligned rotators?

PSR J1811-1925/G11.2-0.3

Edot=6.5×10^{36} erg/s, ~2 kyr, 5kpc

Chandra 400 ks, Borkovski et al 2016

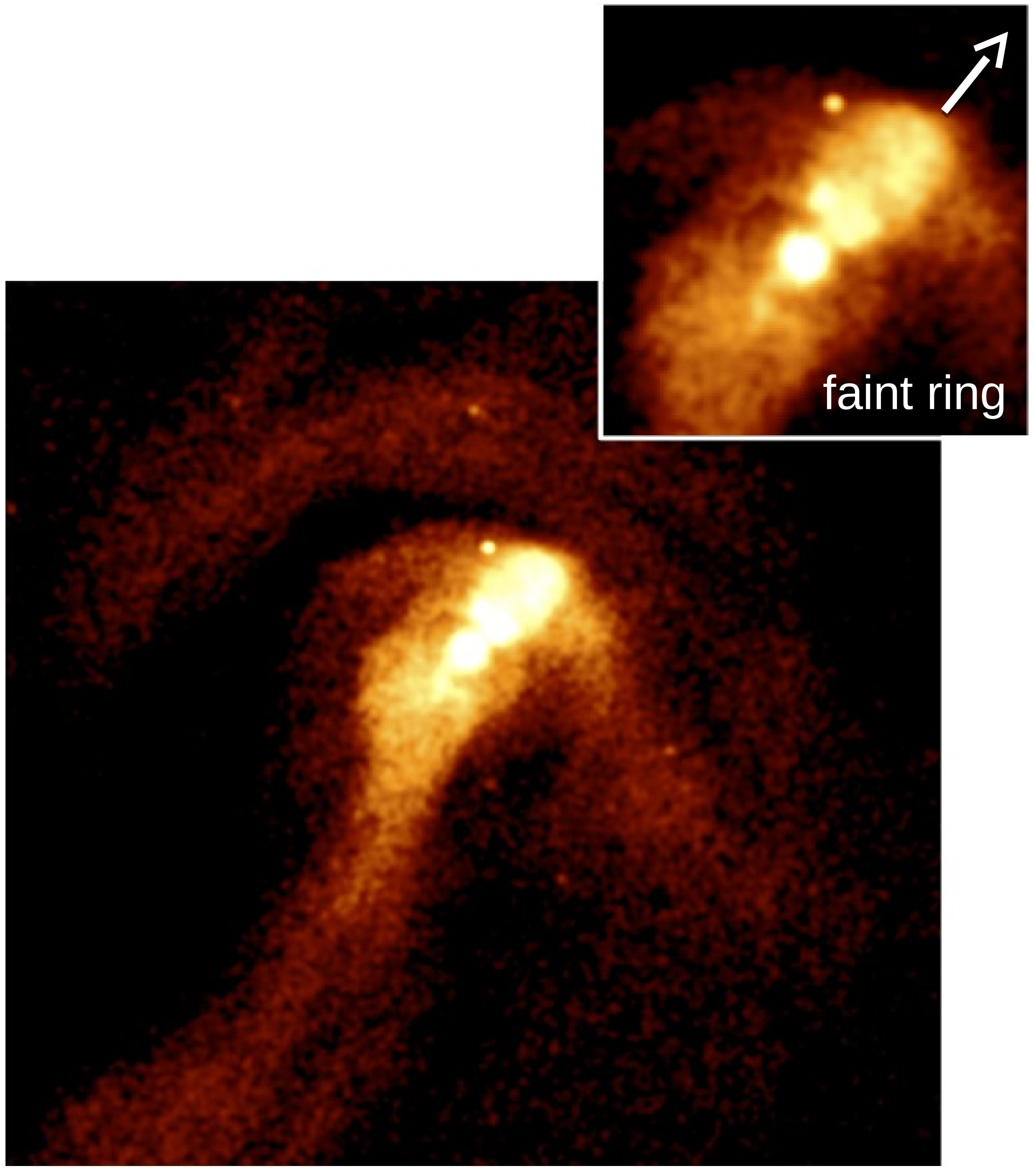




PSR B1509-58/MSH 15-52

Edot=1.8×10^{37} erg/s, ~1.5 kyr, 5 kpc

Chandra 190 ks, Yatsu et al 2009



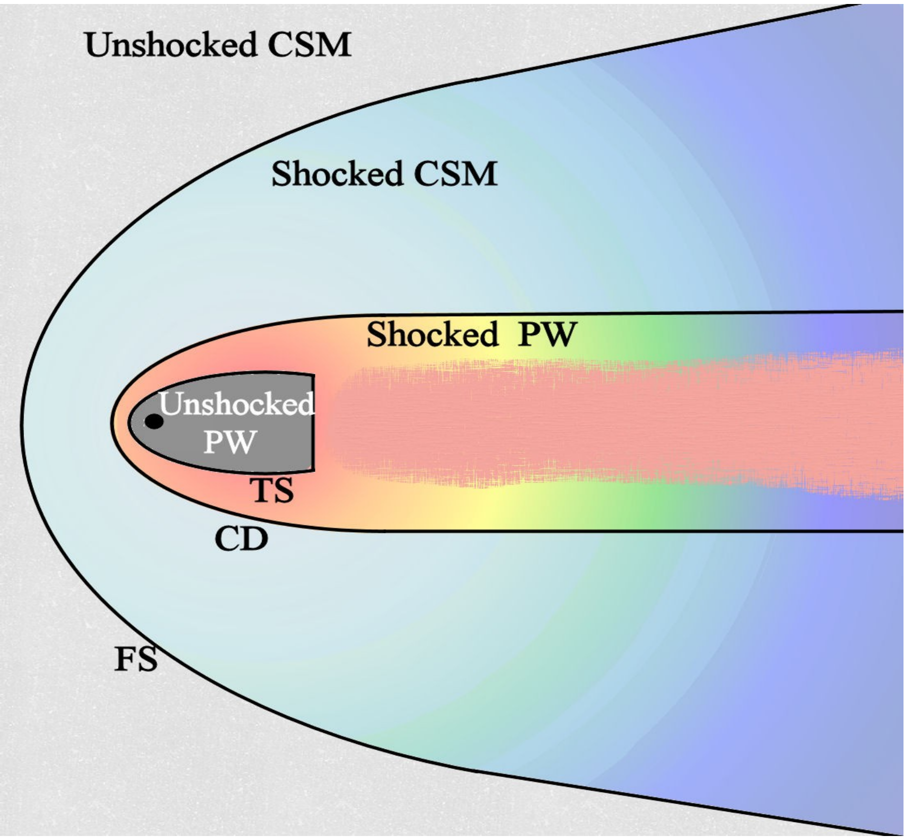
Supersonic PSR motion

Pulsars that have left their parent SNRs always move supersonically (M ~ 10 – 100) □ $\boldsymbol{p_{ram} = \rho v^2} >> \boldsymbol{p_{amb}}$

□ bow-like structure with CD apex at $\boldsymbol{r_{CD} = (Edot/4\pi c p_{ram})^{1/2}}$

$$\boldsymbol{r_{CD} = 1.3\times10^{16}\,(Edot/10^{35}\ \mathrm{erg/s})^{1/2}\, n^{-1/2}\,(v/300\ \mathrm{km/s})^{-1}\ \mathrm{cm}}$$

Schematic picture:



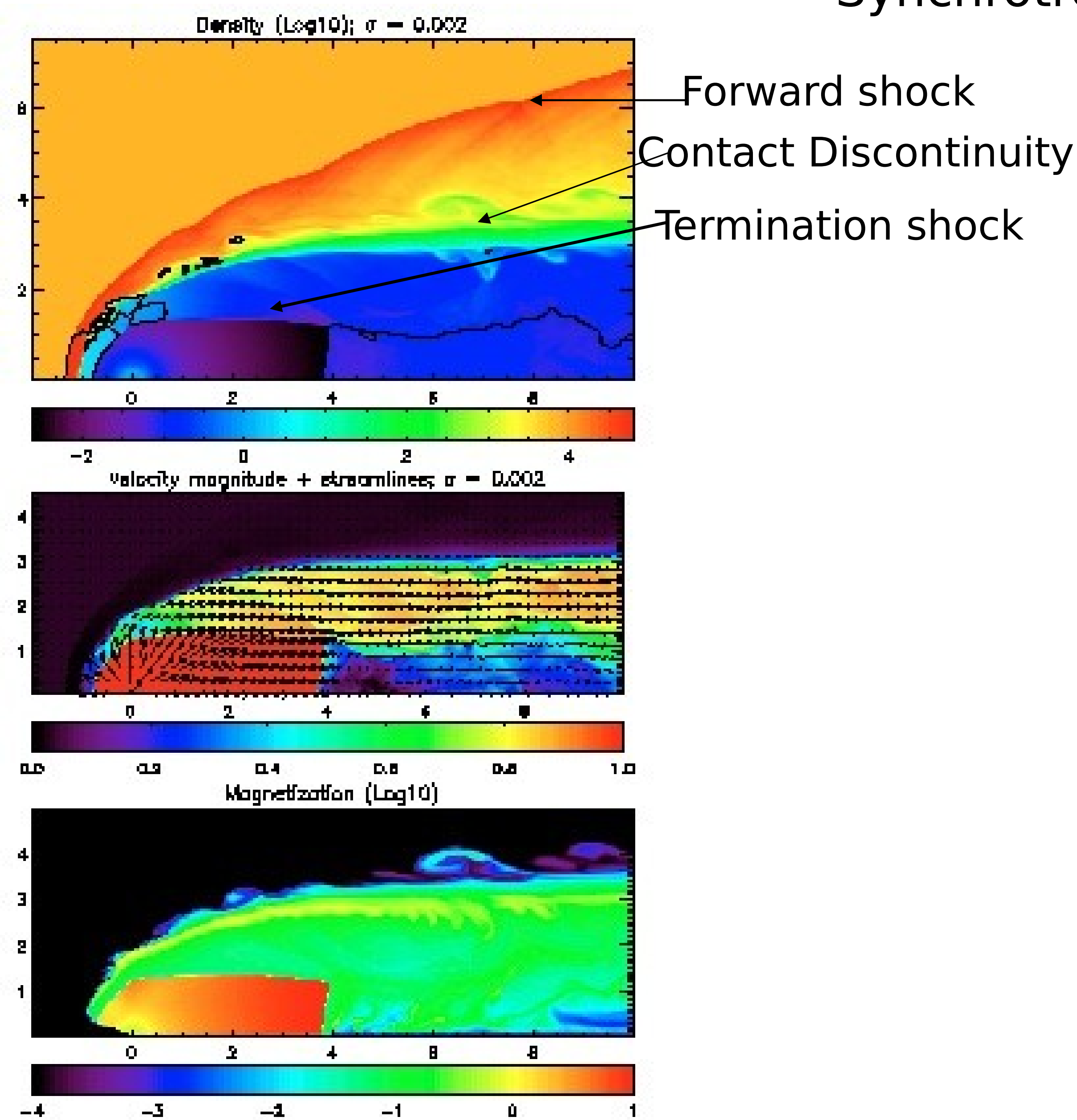
Forward bow shock (FS) and shocked ISM between FS and CD can be observed in Balmer lines

X-rays come from shocked PW between TS and CD, should look like a **‘head-tail’ PWN**.

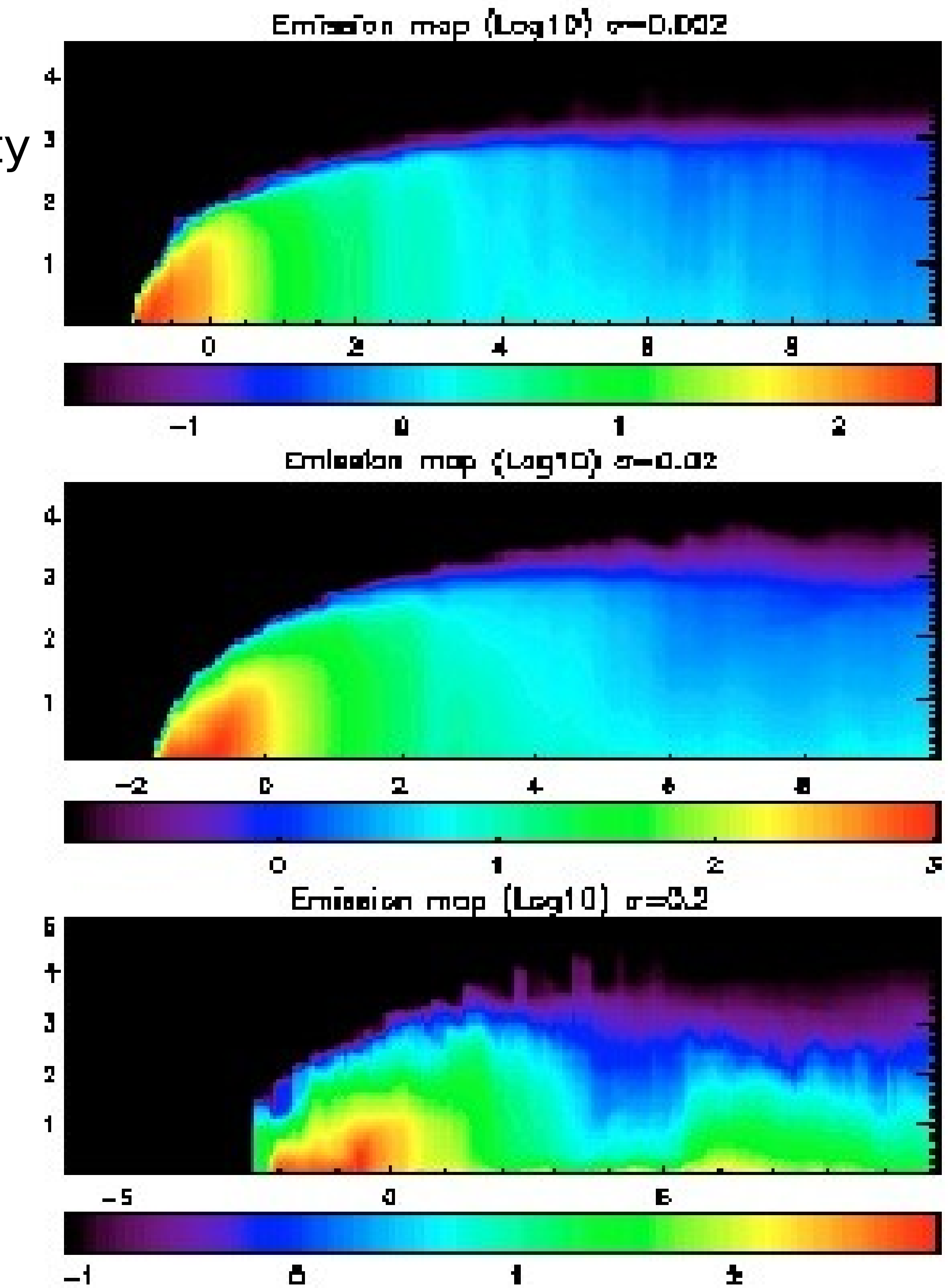
RMHD simulations of isotropic outflow for supersonically moving pulsar (Bucciantini, Amato, Del Zanna 2005)

X-rays: "Bullet" + tail, shocked PW beyond TS

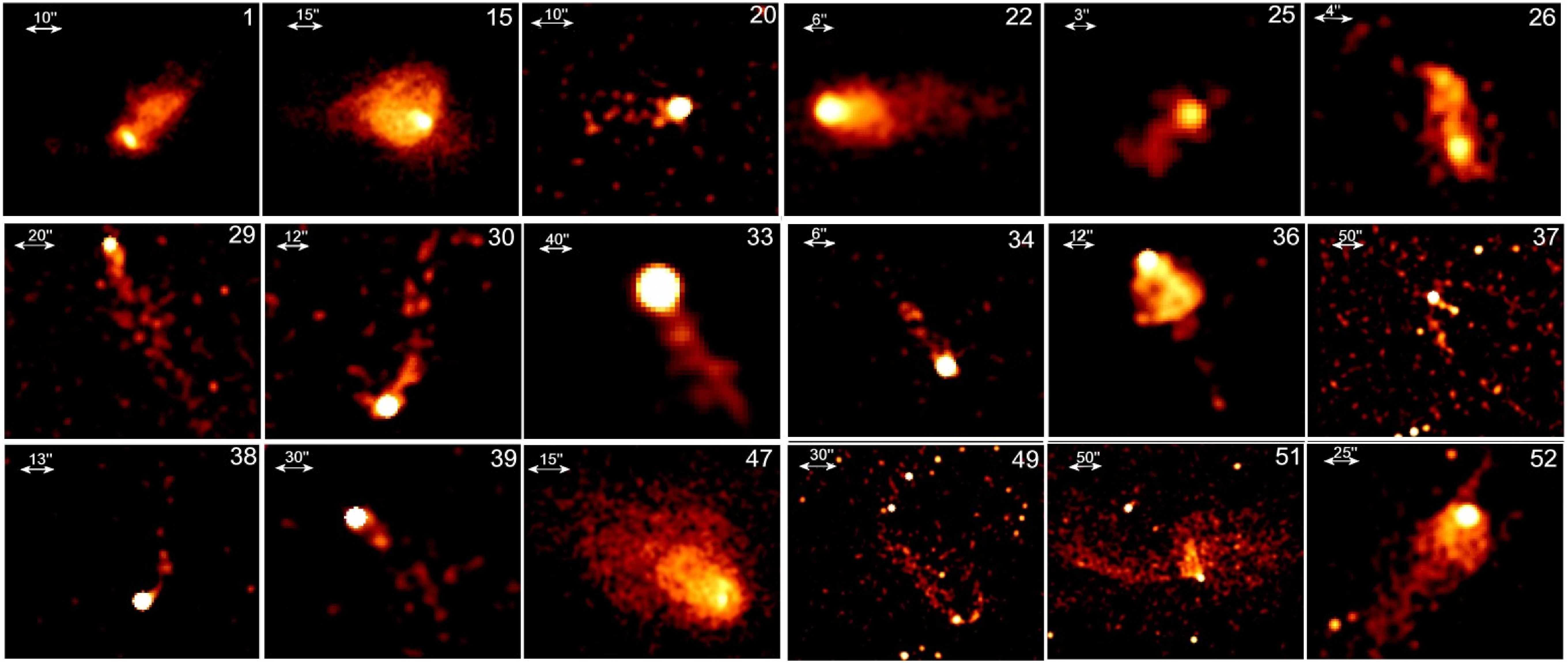
Density, velocity, magnetization



Synchrotron radiation for different magnetizati



Examples of PWNe with morphology clearly affected by PSR motion (including head-tail PWNe)



Most of them show strongly elongated structures.

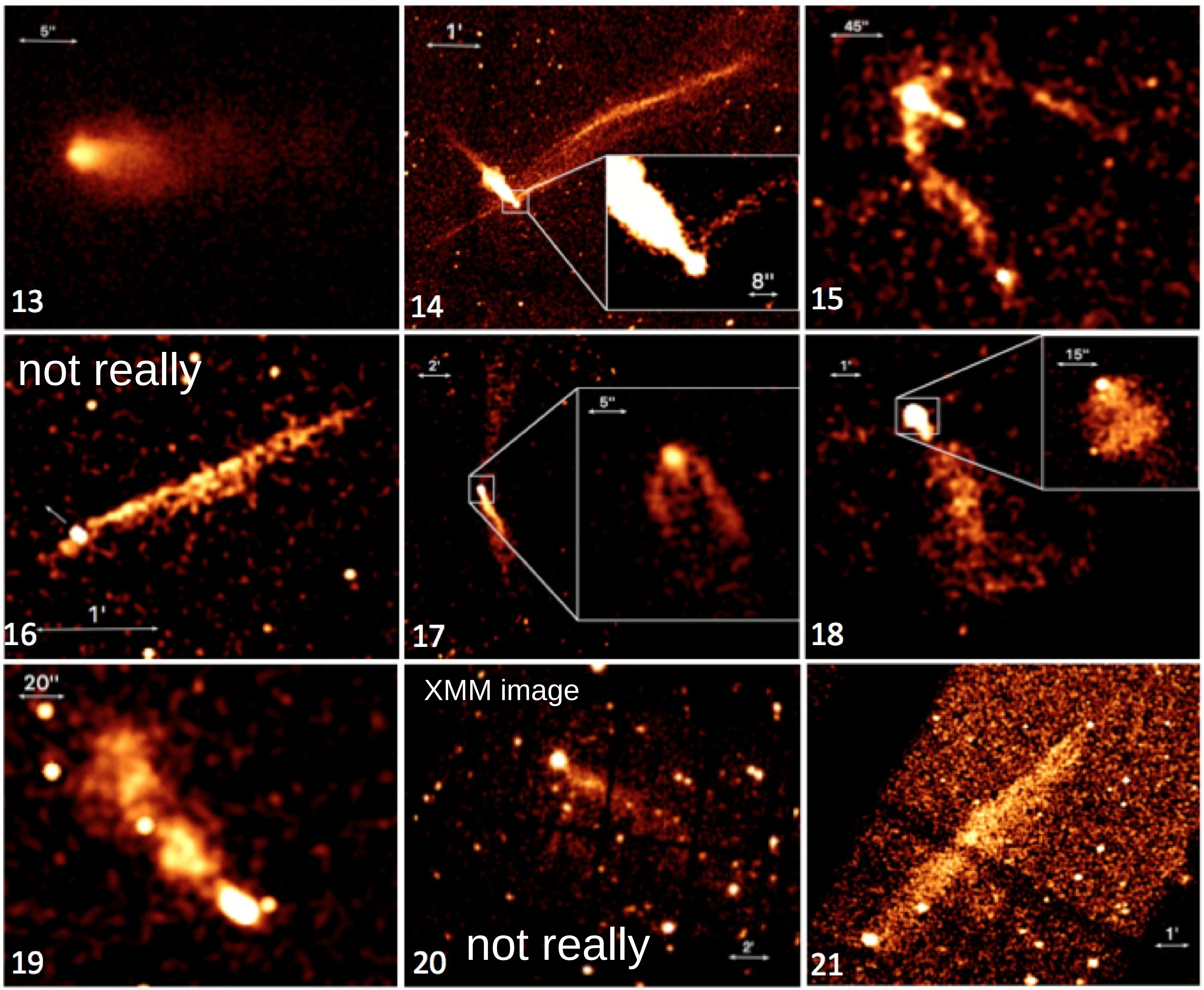
Jets: Polar outflows along spin axis, often seen on both sides of PSR;

Tails: Fast outflows behind moving pulsar confined by ram pressure;

Trails: Tails slowed down by interaction with ISM matter (do we see any?);

Misaligned outflows: None of the above

Bowshock PWNe with deep Chandra ACIS exposures

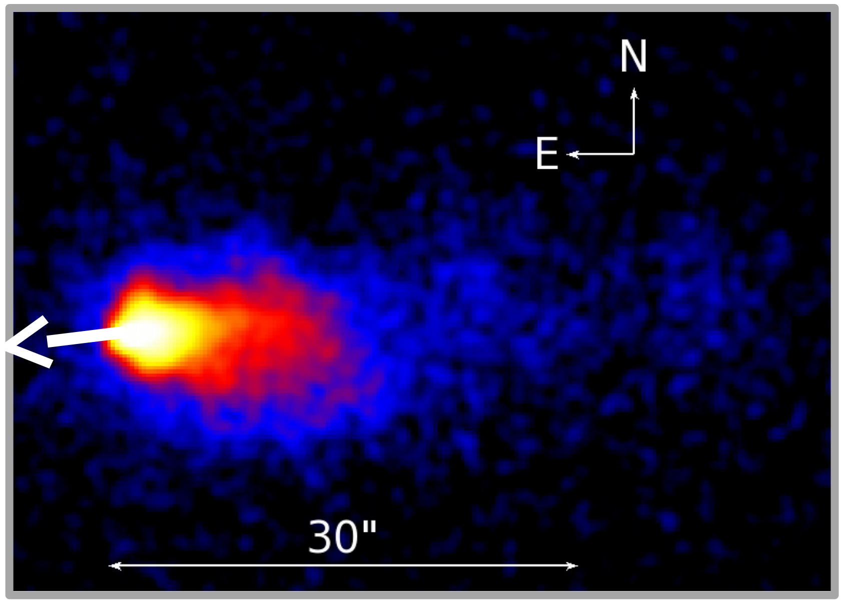


Some PWNe resemble the simulations. Example: **The Mouse**

PSR J1747-2958 $Edot = 2.5\times10^{36}$ erg/s τ_{sd} = 25 kyr (true age ~100 kyr)

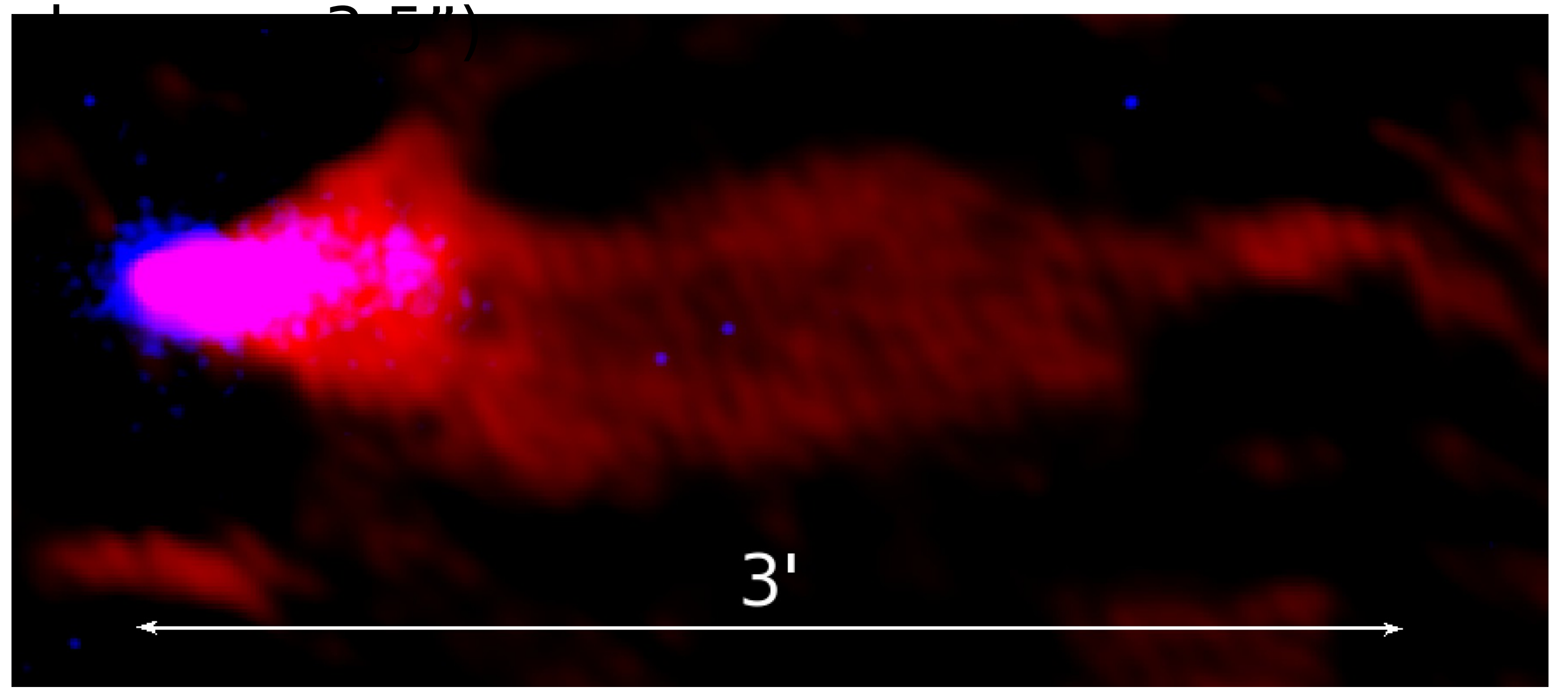
D = 5 kpc V_t ~ 400 km/s

20 ks Chandra ACIS (Klingler in prep)

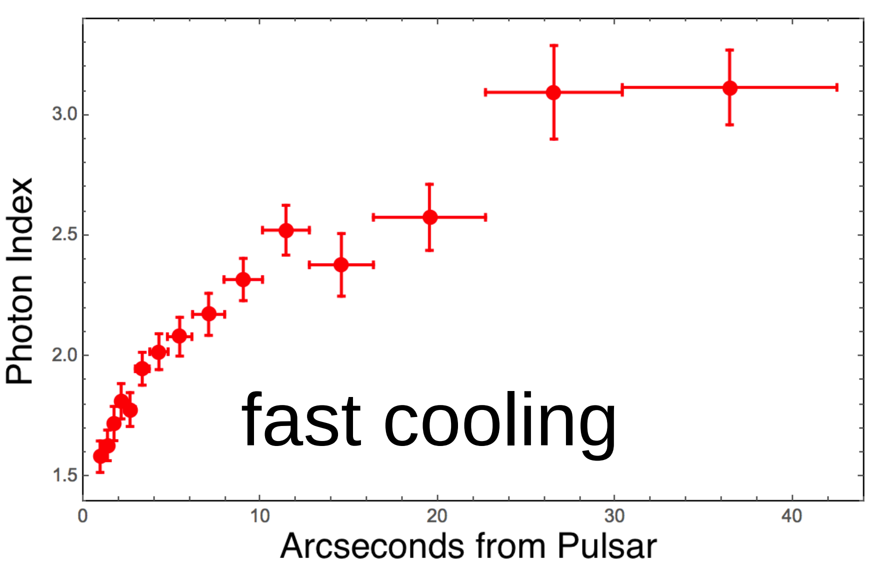


At 5 kpc:
30” → 0.36 pc, 3’ → 4.4 pc

X-ray (blue) superimposed on Radio (red, VLA,



Typical head-tail structure



Comparison with models yields Mach ~ 60, V ~ 600 km/s,
n ~ 0.3 cm^{-3} (Gaensler et al 2004)

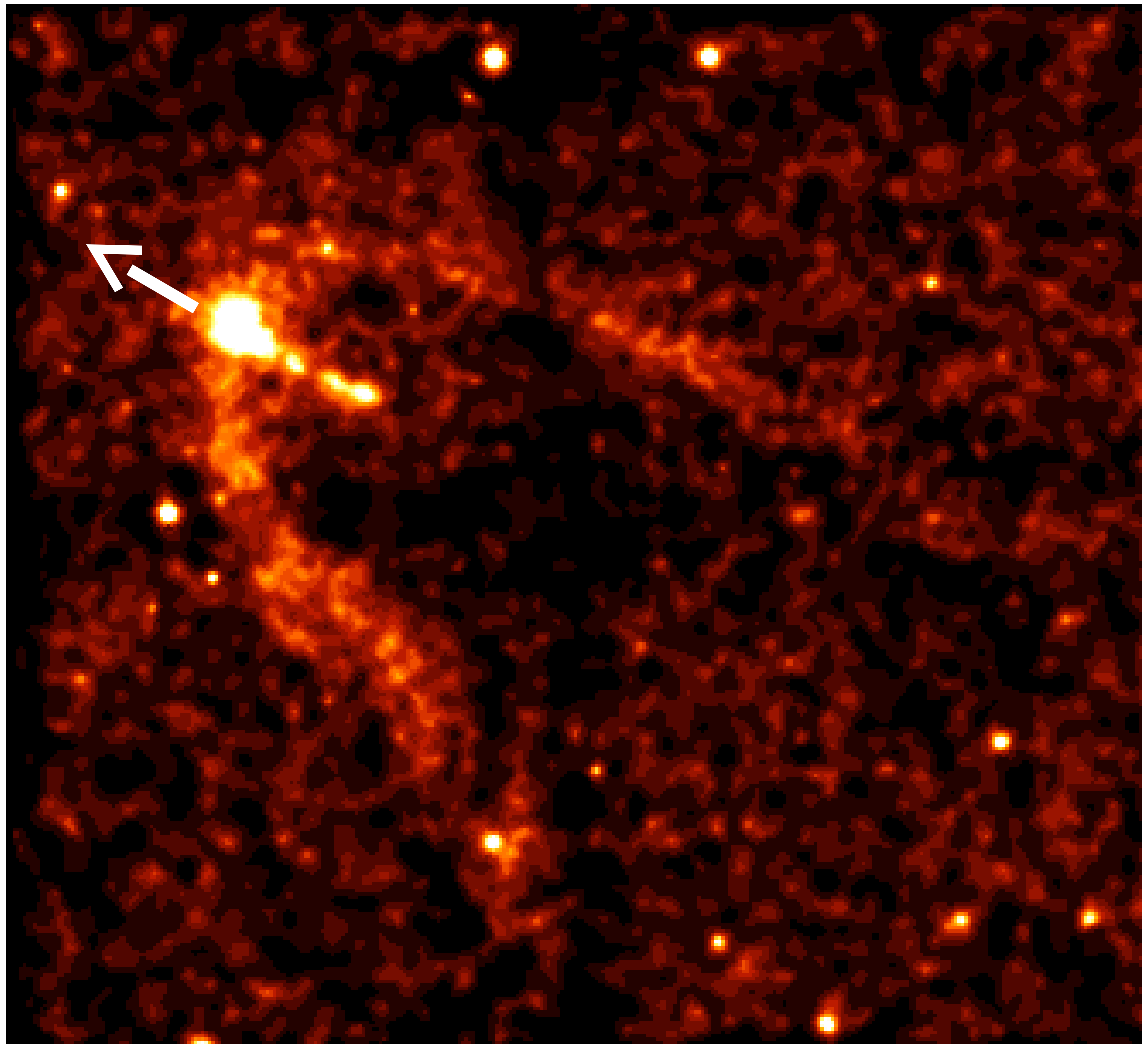
X-ray and radio – ***synchrotron radiation from shocked PW***

Rapid synchrotron cooling →
strong magnetic field ~ 100 μG

Quite different picture: **"Three-tail PWN"** **Geminga**

Edot = 3×10[34] erg/s, τ_{sd} = 340 kyr, *D*~0.25 kpc , V_t ~300

handra 600 ks (Posselt et al 2016)



Two ~4' ~0.25 pc lateral tails and 50'' ~0.05 pc central tail

No radio or H-alpha PWN

Only a hint of a bow-like emission ahead of the pulsar, no "bullet"

No discernible emission between lateral tails

No motion along the tails was reliably detected

Spectra of lateral tails are **extremely hard**, Γ **= 0.7 – 1 !**

(1) The central tail might be a jet/"tail", and the lateral tails resemble a limb-brightened shell (CD? bow shock?)

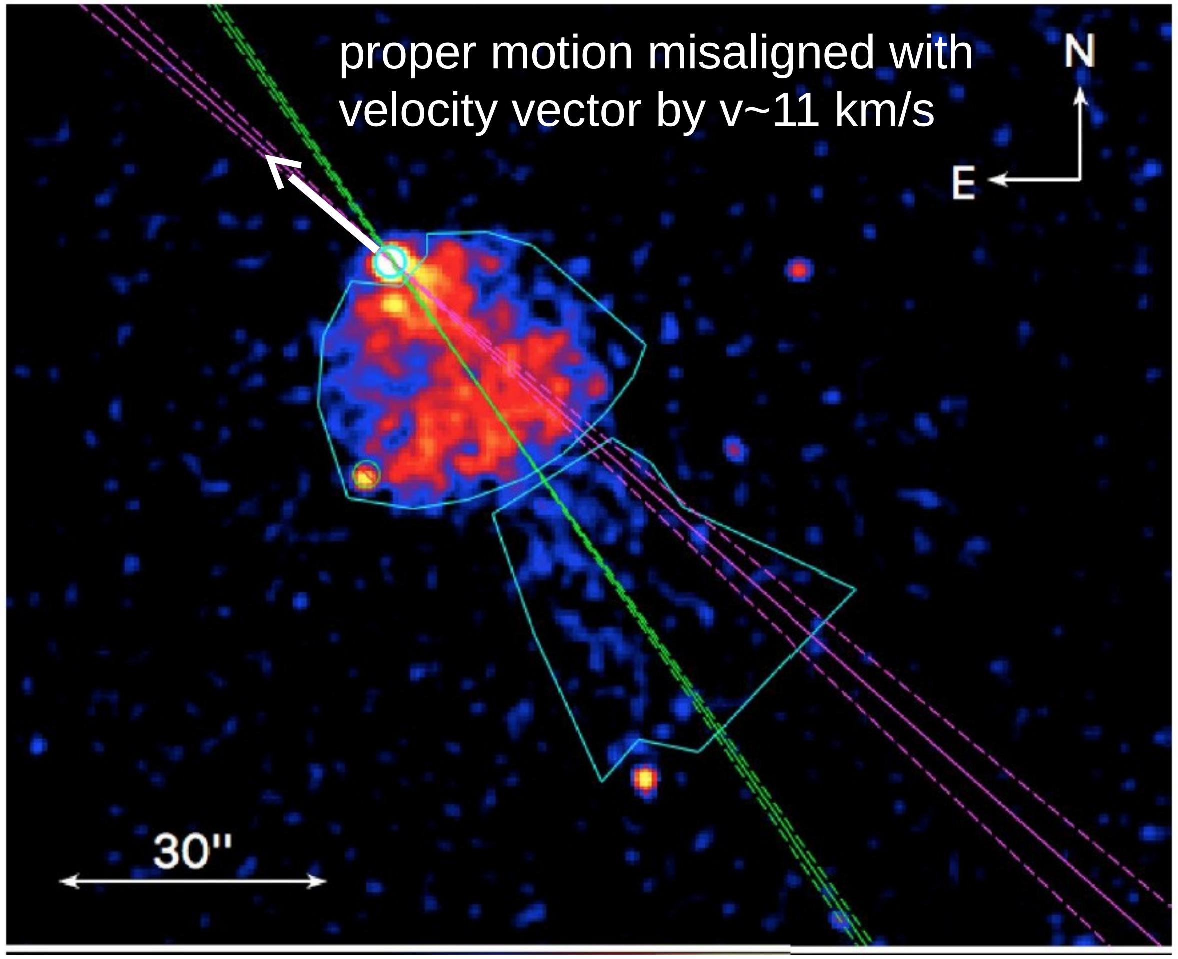
(2) The lateral tails could be bent jets. But then what is the central tail? Equatorial torus seen edge-on?

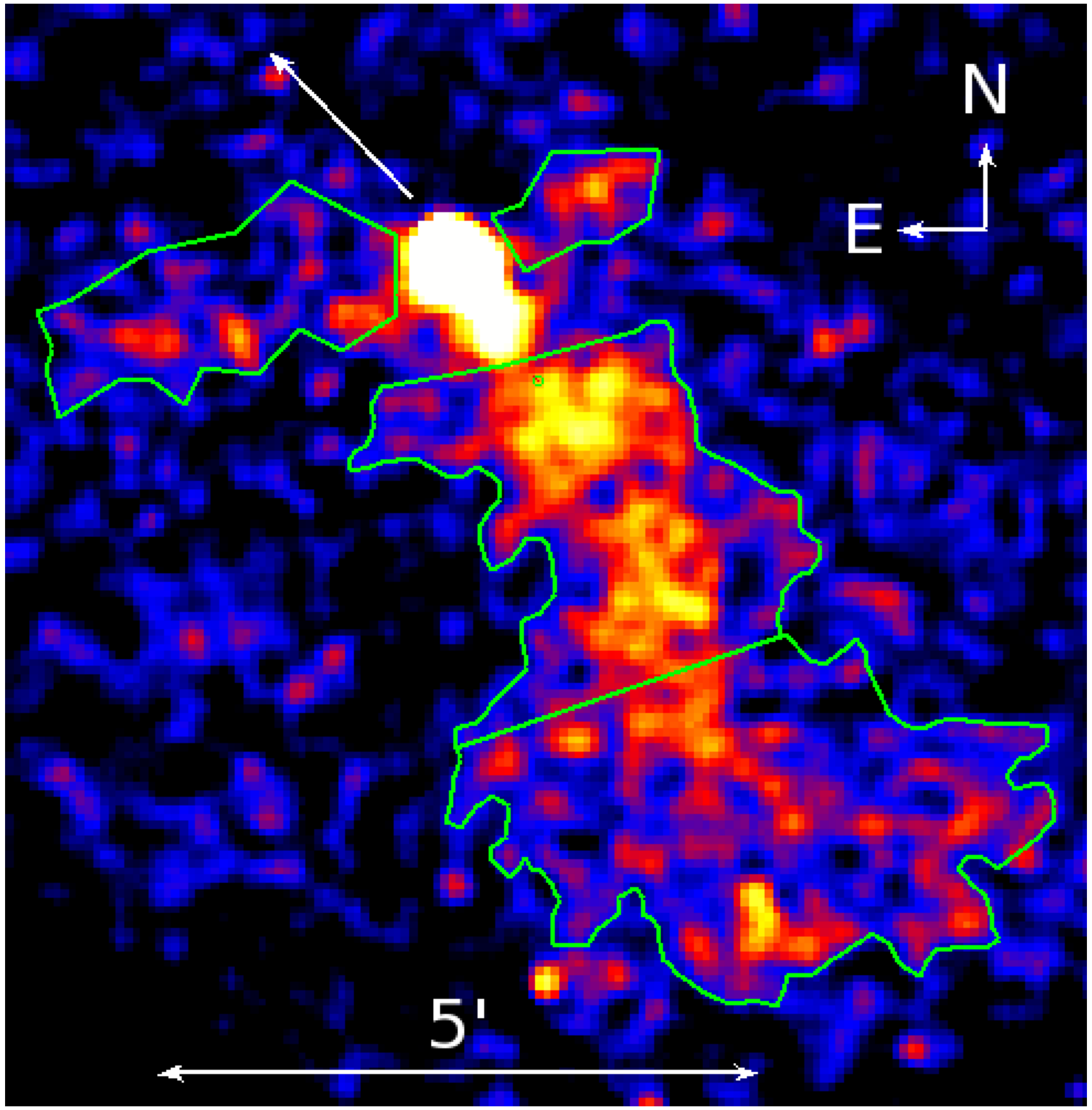
Another bow shock PWN

B0355+54 (the Mushroom PWN)

Edot=5×10^{34} erg/s, τ_{sd} = 650 kyr, *D*~1 kpc, V_t ~60 km/s

Chandra ACIS, 390 ks,
Klingler et al 2016 (under review in ApJ)





Filled-in head ("mushroom cap"), brightened along the axis, with a sharp lower boundary and a dimmer "stem". Spin axis close to LoS?

Dim, broadening tail/trail, **7' (~2pc**), behind the "stem" and strange "whiskers" (**misaligned outflows?**)

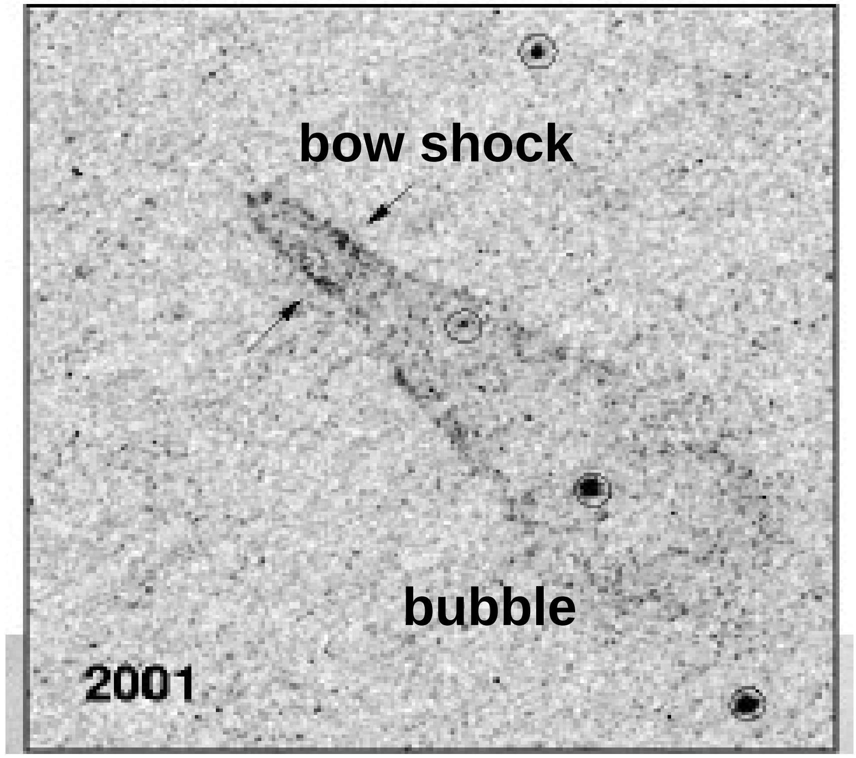
Spectrum remains hard to very large distances (Γ = 1.5 in the compact nebula, Γ = 1.7 in the tail)

First detected "misaligned outflow" Guitar Nebula

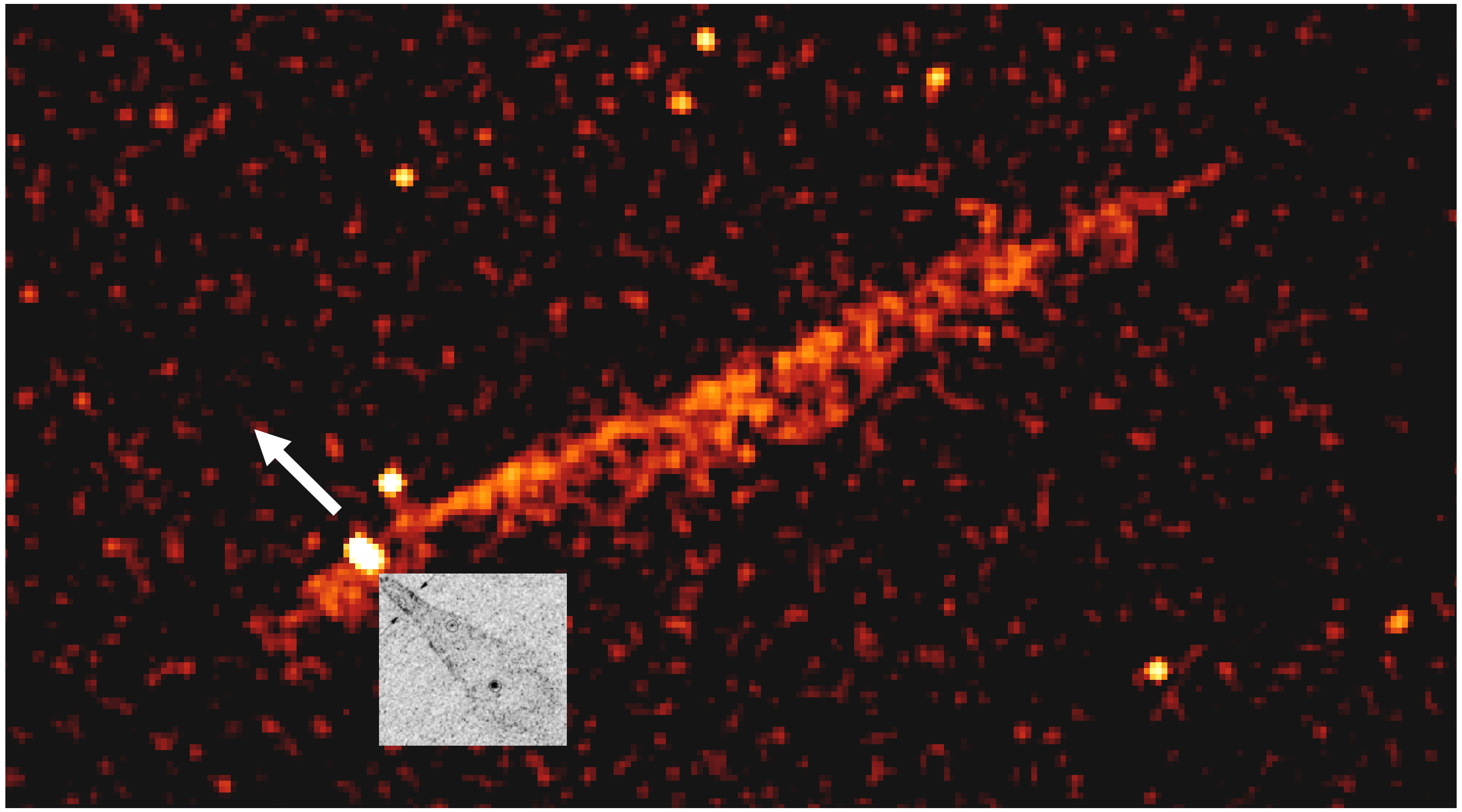
PSR B2224+55

D ~ 1.5 kpc
$\dot{E}$ = 1.2 x 10^{33} erg/s
Age ~ 1 Myr
$V_t \approx 900$ km/s

A guitar-like nebula in H-alpha (Cordes et al 1993, Chatterjee & Cordes 2004).



2' (~1 pc)-long jet-like feature in X-rays (Hui & Becker 2007, Johnson & Wang 2010)



No head (bullet) nor tail in X-rays! Too compact (unresolved)?
Photon index of the misaligned outflow $\Gamma \sim 1.6$.

What is that linear structure (misaligned outflow)?

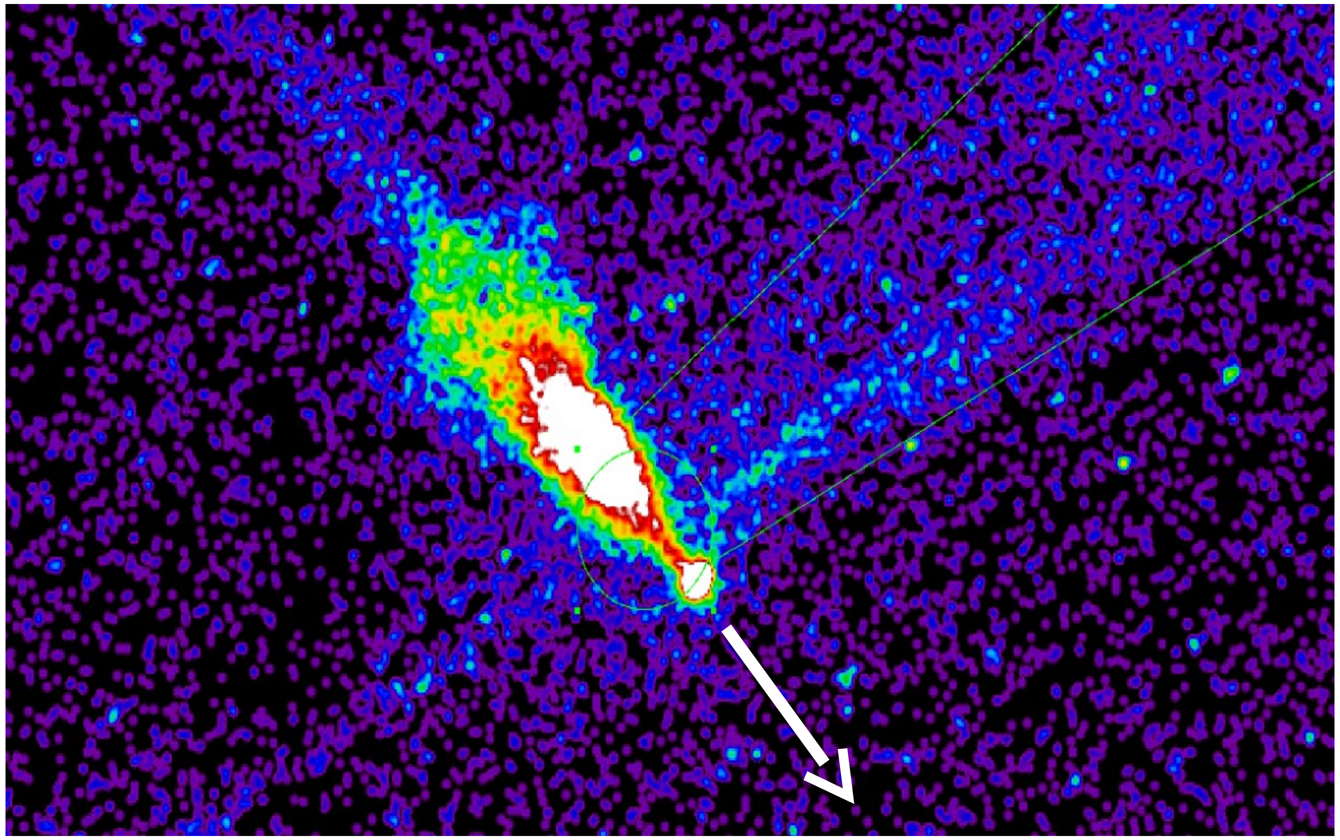
Hydrodynamic jet would be bent by ram pressure.

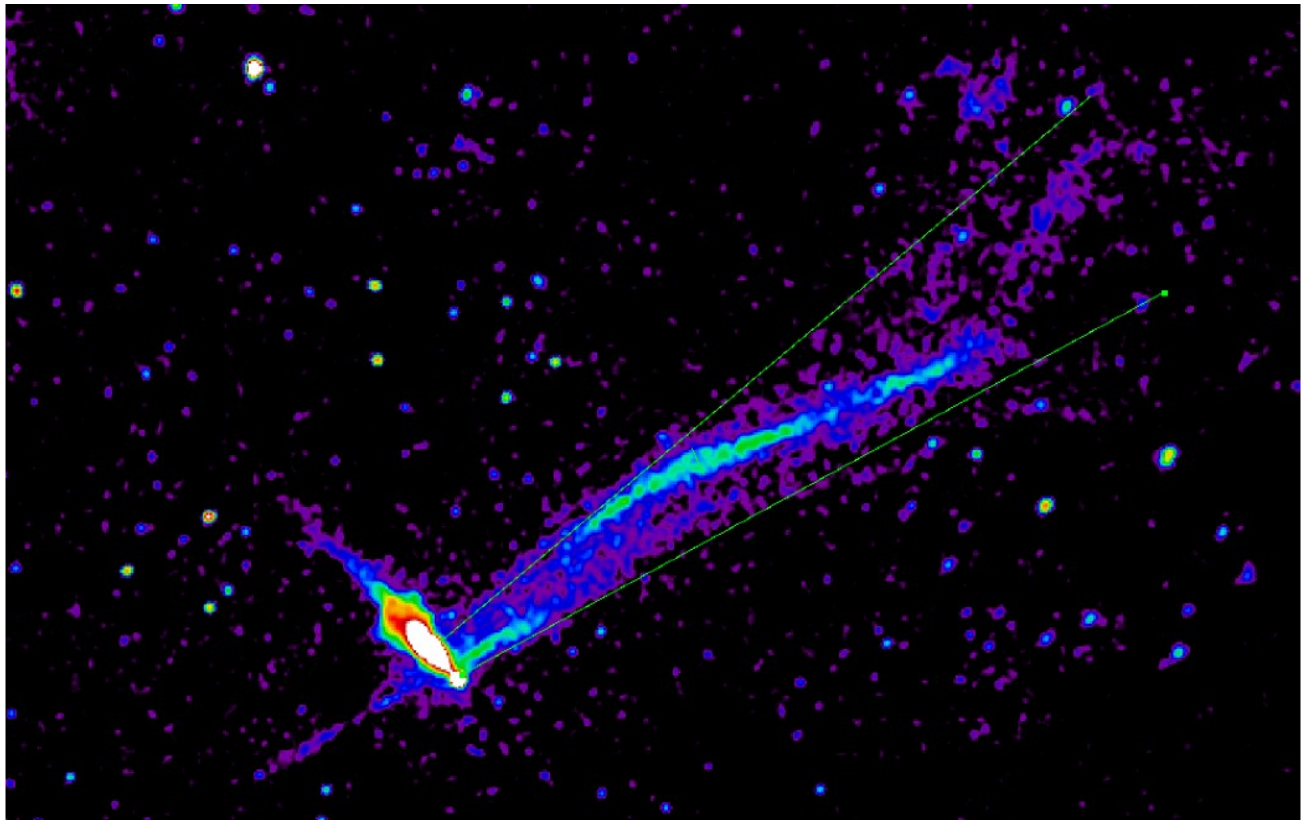
Bandiera (2008): **Leak of high-energy electrons** from the bow-shock apex then drift in the ambient magnetic field

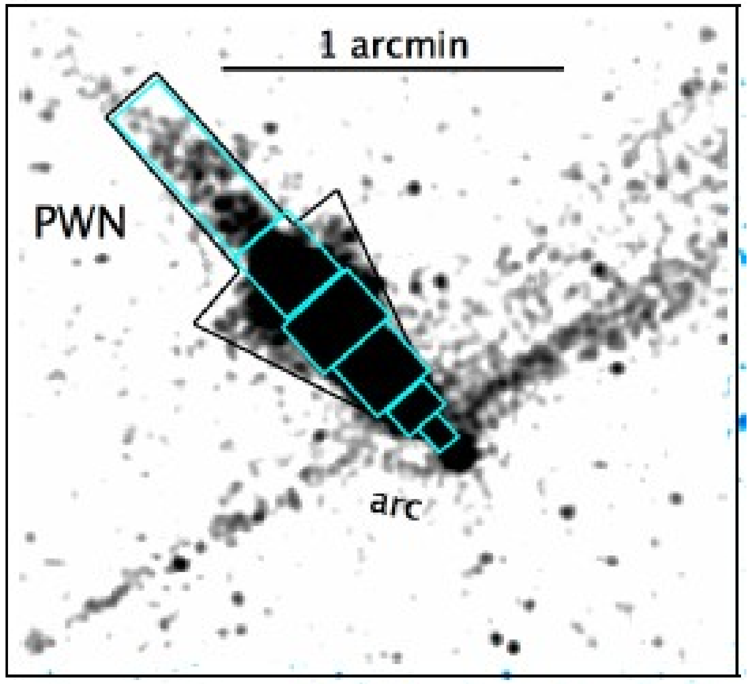
Tail + misaligned outflow　　Lighthouse Nebula

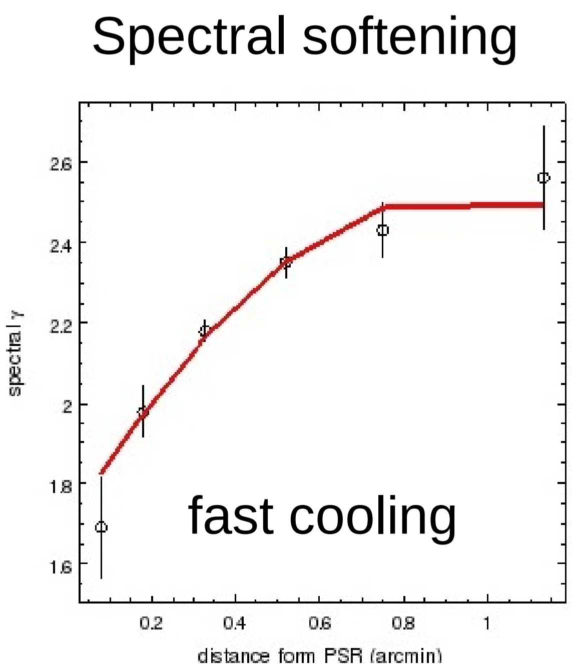
IGR J11014-6103　　Edot=1.4×10^{36} erg/s, τ_{sd} = 116 kyr (true age ~20-30 kyr), *D*~7 kpc,
V_t ~ 1000 km/s (if born in MSH 11-61A)

Chandra ACIS 250 ks, Pavan et al 2015









Tail-like nebula behind the pulsar (notice the "neck" and the "arcs"), resembles the Mushroom PWN, detected in radio, shows rapid spectral softening in X-rays (Γ changes from 1.8 to 2.3).

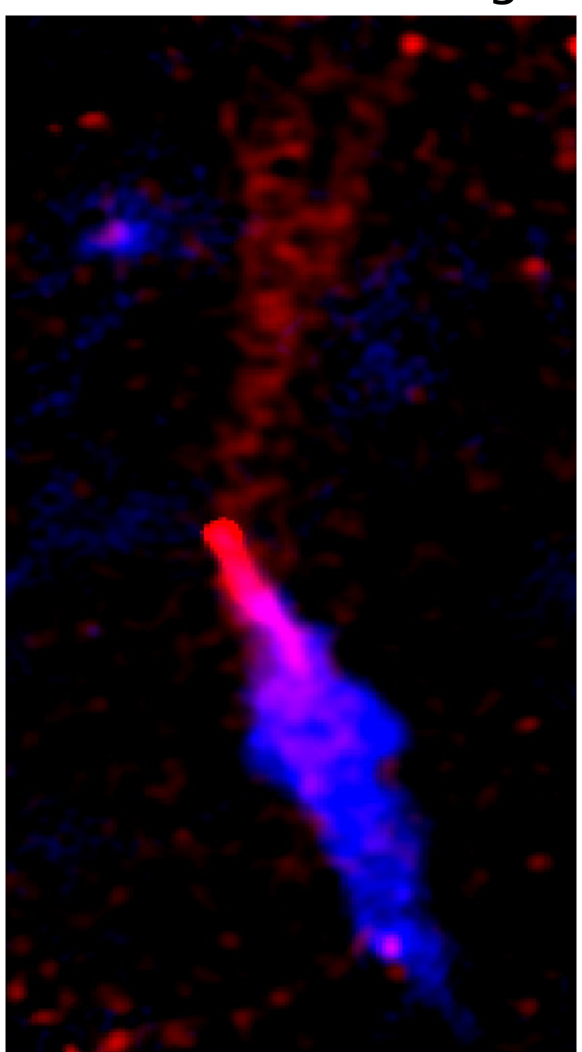
Another tail+misaligned outflow: J1509-5850

Chandra, 370 ks
Klingler et al. 201

***Edot* = 5.1×10^{35} erg/s, τ_{sd} = 154 kyr, *D* ~ 3.8 kpc, V_t not measured**

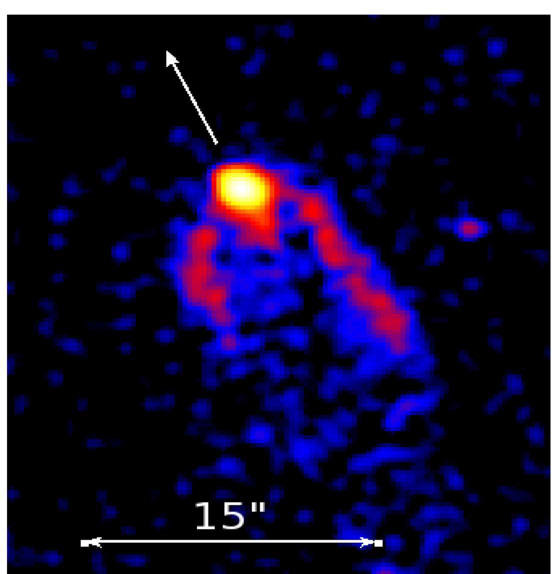
Three-tail compact PWN close to pulsar, similar to Geminga. Long (~6 pc) **tail** with high outflow speed, >> V_{psr}. Very unusual "headlight". Radio tail up to 11 pc, quite different from the Mouse. Magnetic field perpendicular to the tail (parallel in the Mouse). Faint H-alpha bow shock (Brownsberger & Romani 2014).

-ray/radio (red/blue) tail
lui & Becker 2007, Ng et al 2010)

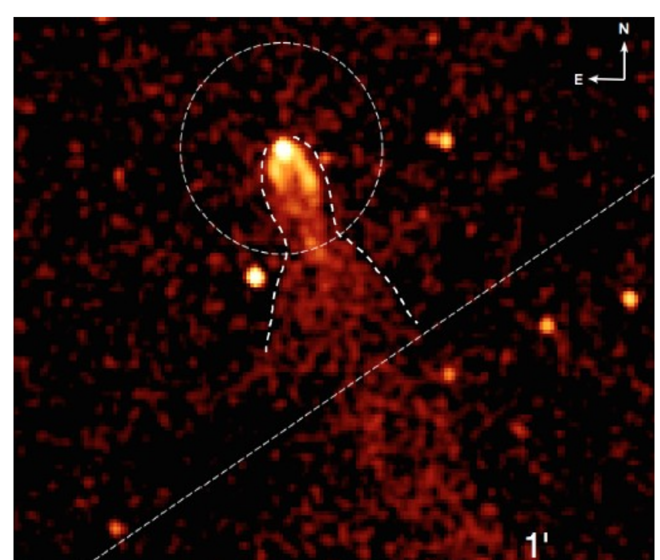


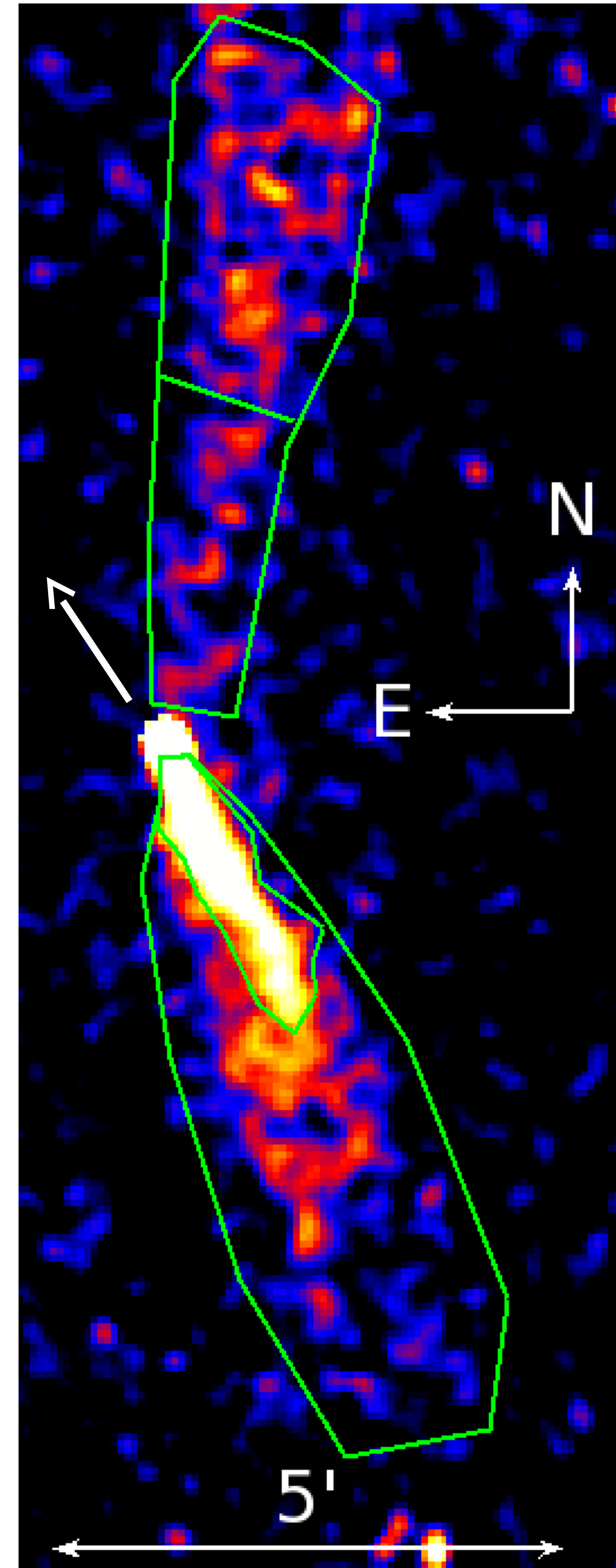
Photon index Γ ~ 1.9 in the tail and spectrum remains hard for 7 pc, hint of softening in the "headlight".

Three-tail compact nebula



Transition from compact nebula to the tail, within H-alpha cavity; entrain-ment (Morlino et al 2016)?

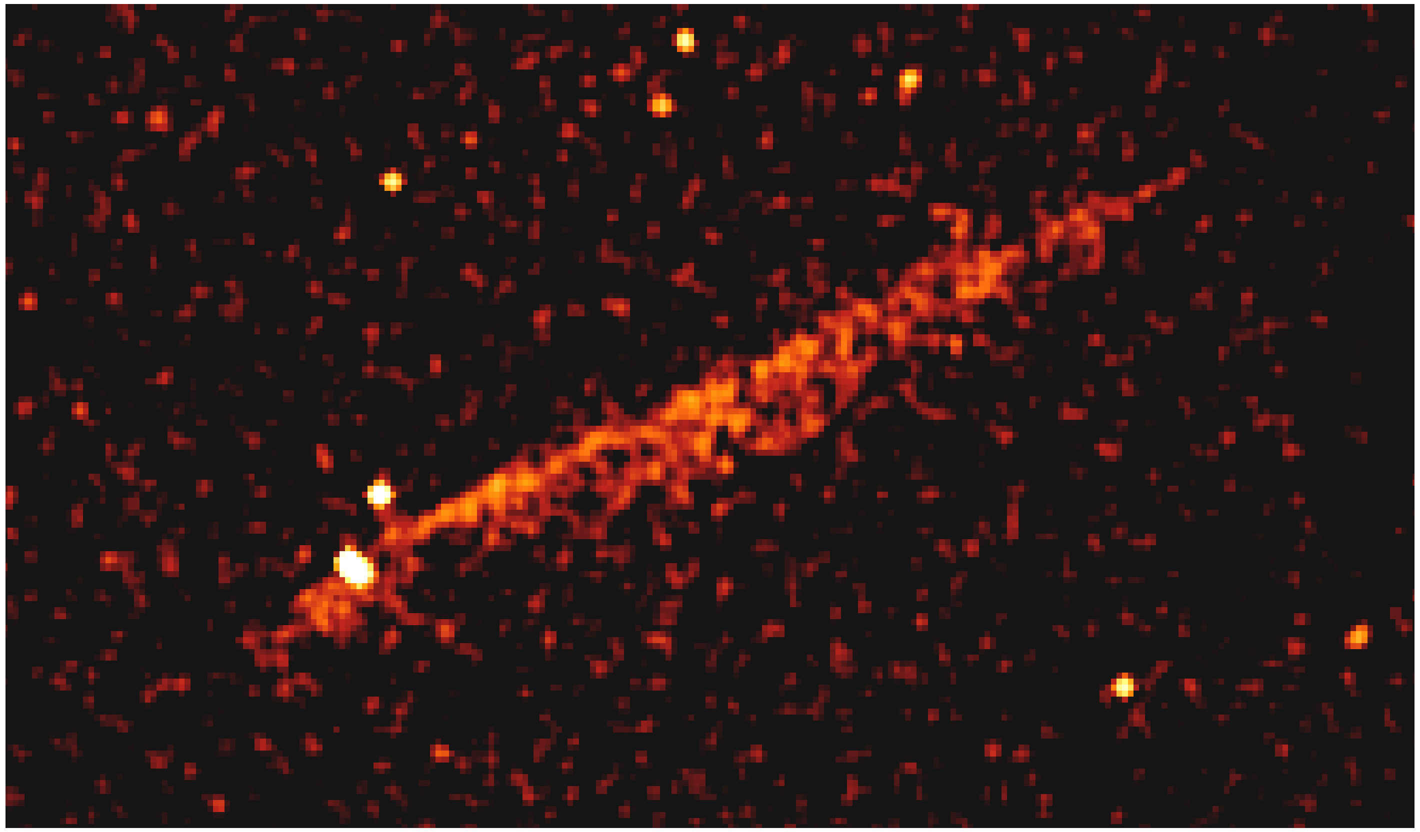




Misaligned outflows may provide a robust way to measure particle Lorents factors in PWNe:

From synchrotron theory:

$$\Gamma \approx 6 \times 10^8 \, (E_{syn}/8 \text{ keV})^{1/2} \, (B/5 \, \mu G)^{-1/2} \text{ keV}$$



Is it a lot? Depends what to compare to.

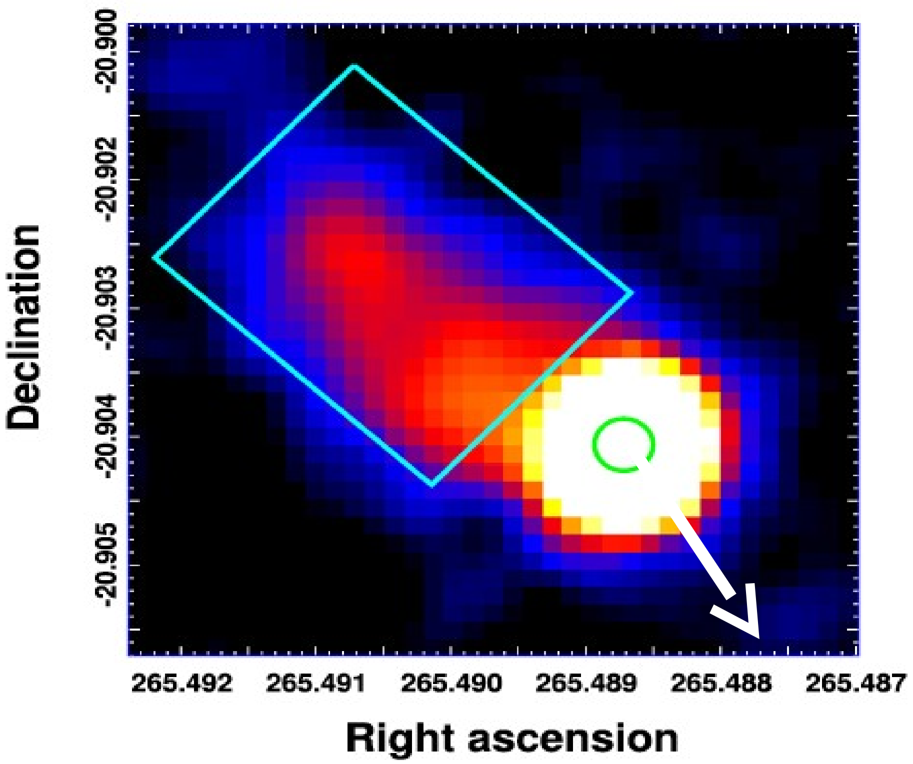
Potential drop across polar cap for this pulsar is:

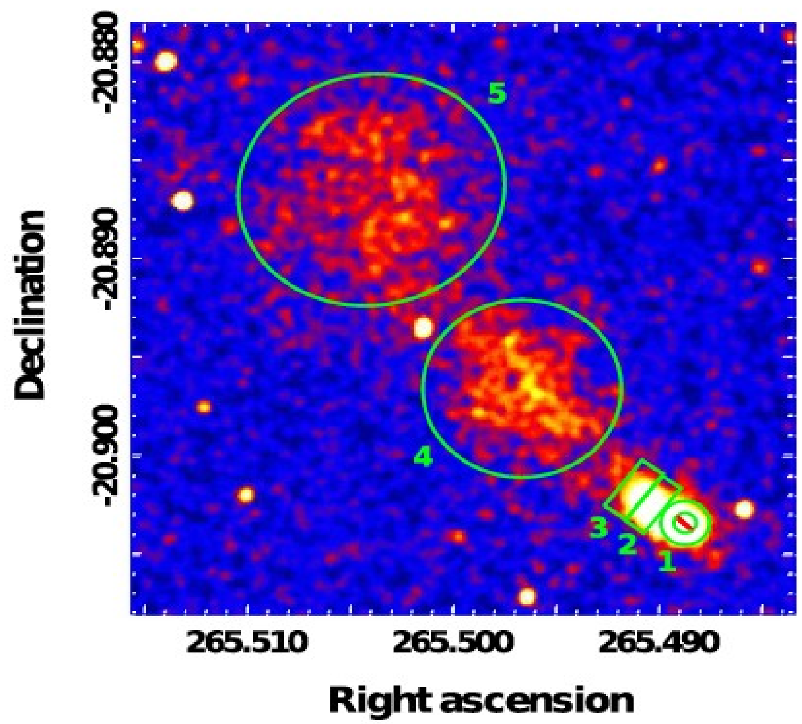
$V = (\dot{E}/c)^{1/2}$ corresponding to $\Gamma = 1 \times 10^8$ for this particular pulsar (B2224 + 65)

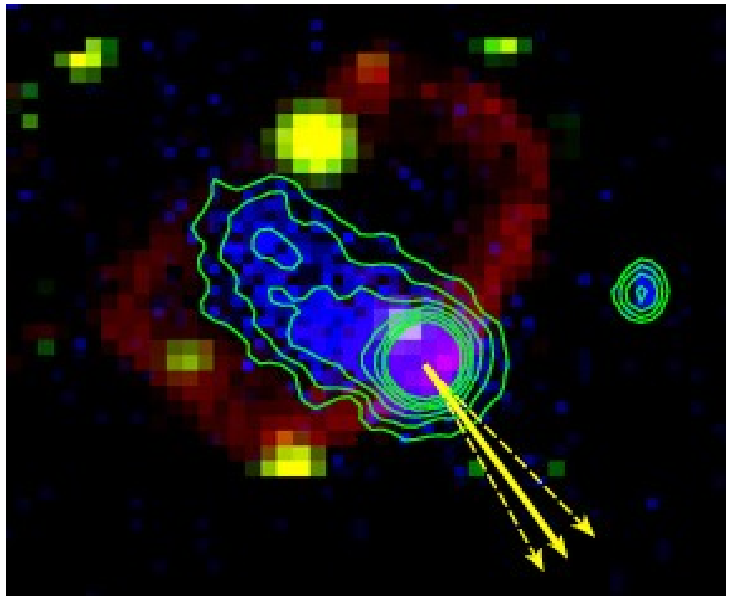
Another tail (trail?) PSR J1741-2054

Edot = 9.5 × 10^{33} erg/s, τ_{sd} = 390 kyr, *D* = 0.4 kpc, V_t = 200 km/s

300 ks Chandra observation (Auchettl et al 2015)







<u>Compact tail</u> (jet?) ~14”~0.03 pc, slightly misaligned with proper motion; $\Gamma \sim 1.6$

<u>Extended tail</u> (trail?) ~1.5’ ~0.2 pc. Consists of 2 lobes? $\Gamma \sim 1.6$

<u>H-alpha nebula</u> around compact tail

No bow-like apex of termination shock ahead of the pulsar is resolved. Equatorial outflow perpendicular to pulsar’s velocity? Where is the jet? Transition from compact to distant tail? Why 2 “lobes”? Asymmetry of H-alpha limb?

Example of a trail? PSR J0357+ 3205

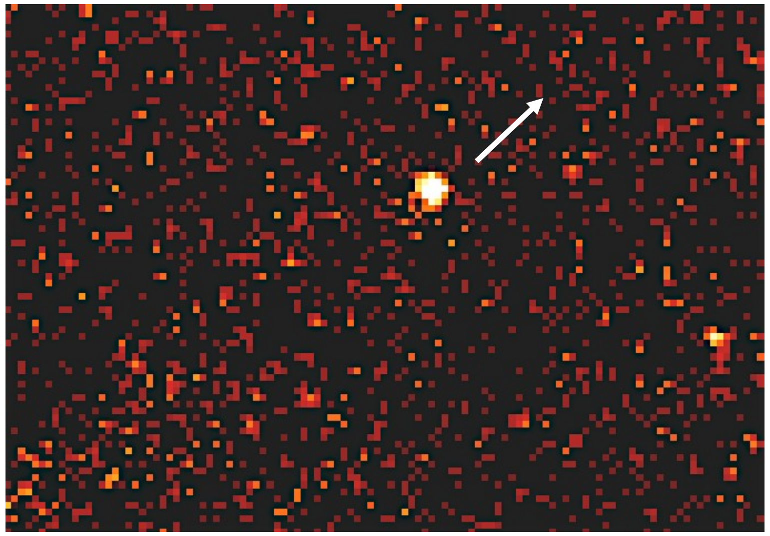
Chandra 105 ks

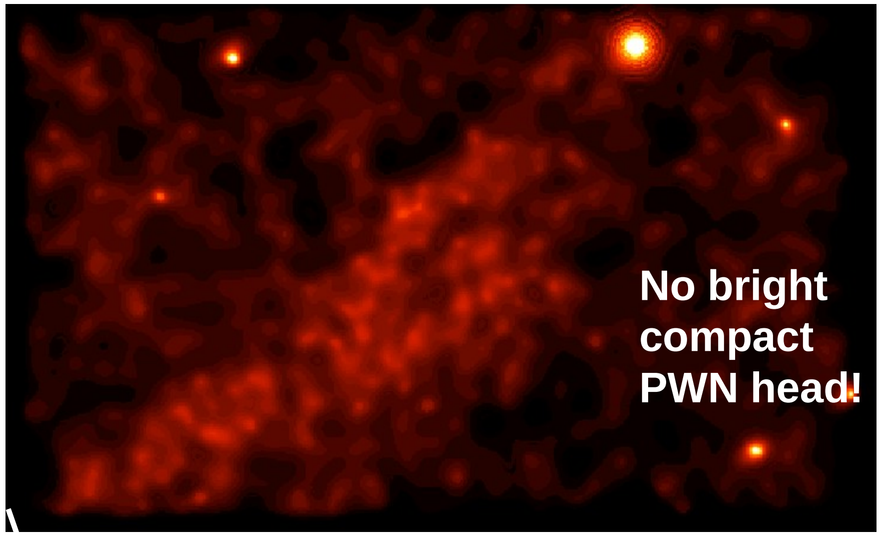
D ~ 0.5 kpc **$\dot{E}$ = 5×10^{33} erg/s**

Age ~ 540 kyrs

V_t ≈ 390 km/s (De Luca et al 2013**)**

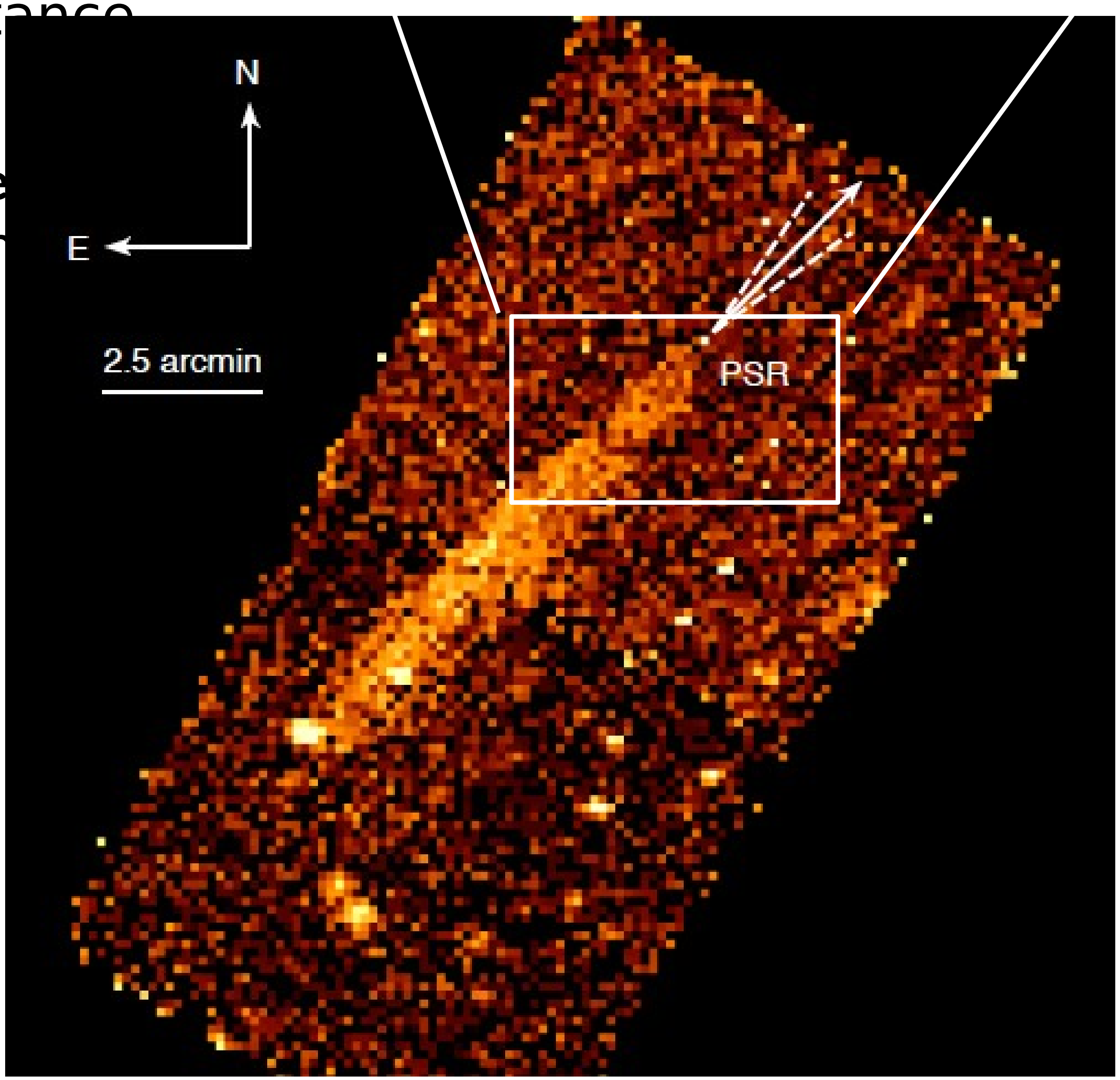
Compact PWN (“bullet”) is essentially absent!



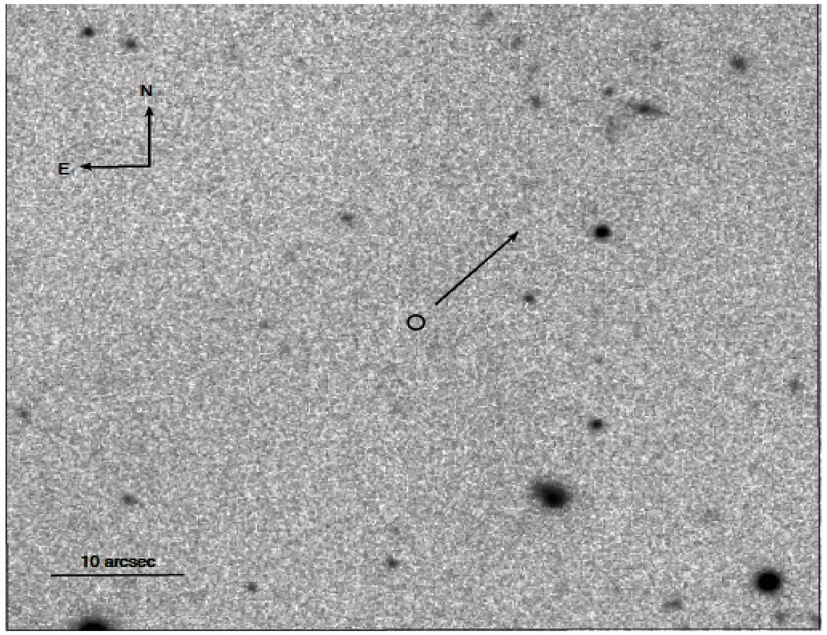


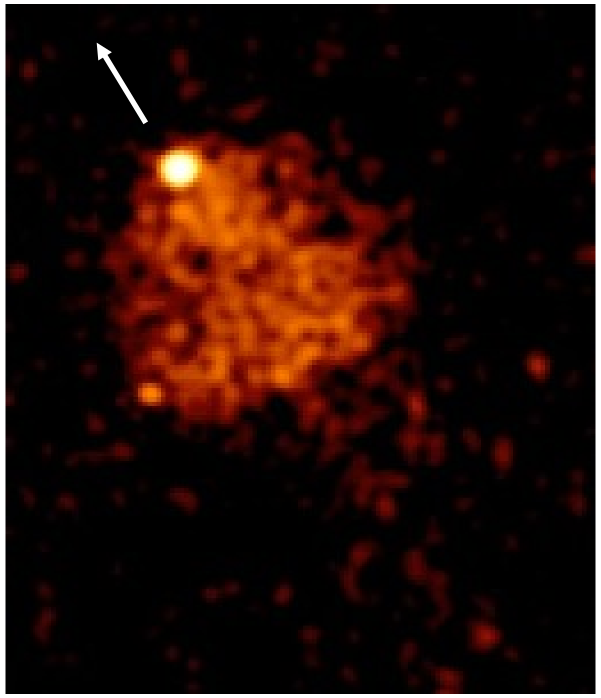
~1.3 pc) trail, brightness increases with distance
n pulsar, no traces of spectral softening.

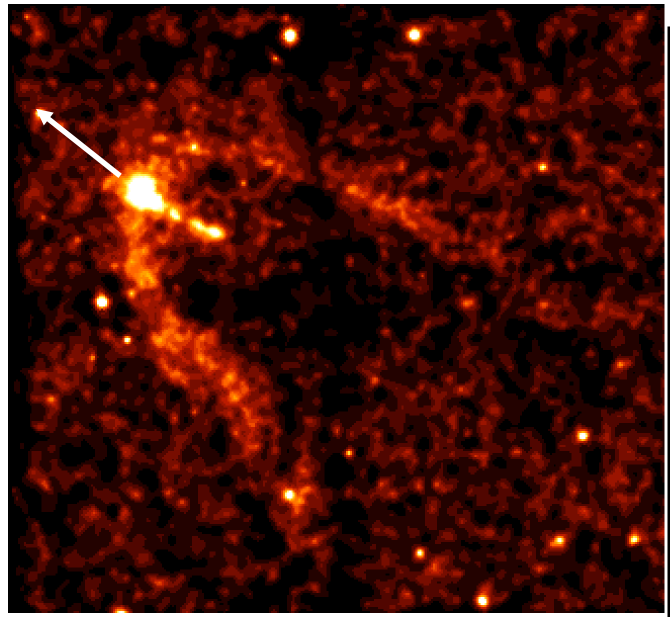
ight be thermal emission from ISM, **kT~3-4 ke**
eated by the shock driven by the fast-movin
ulsar (Marelli et al. 2013)?

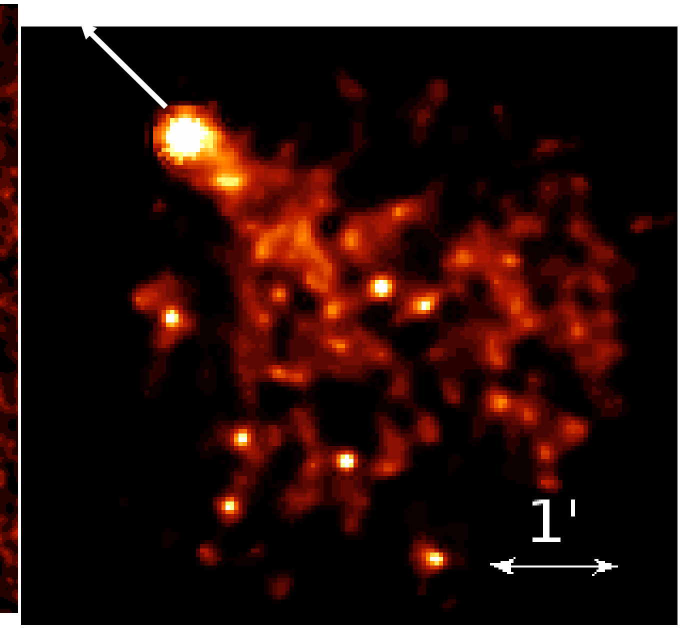


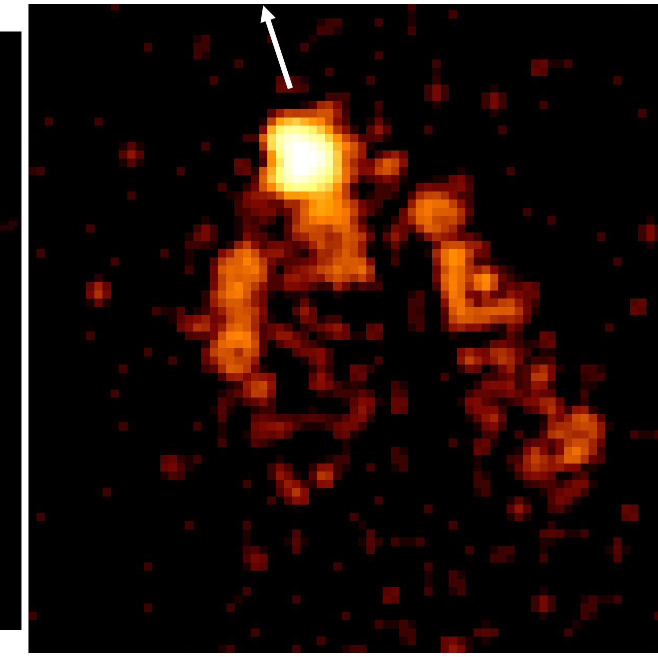
No H-alpha De Luca et al. 2013



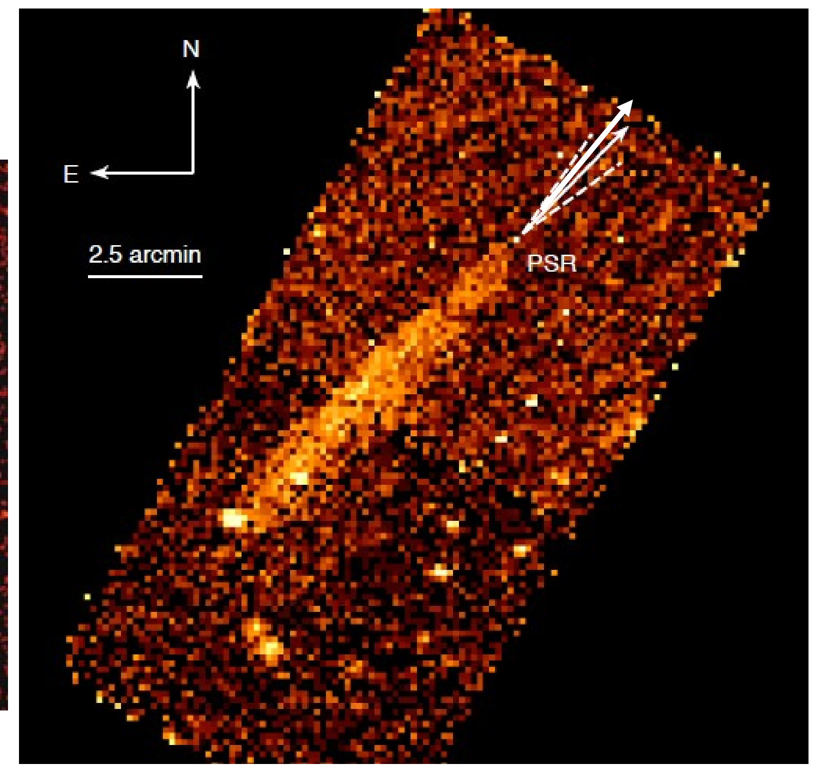


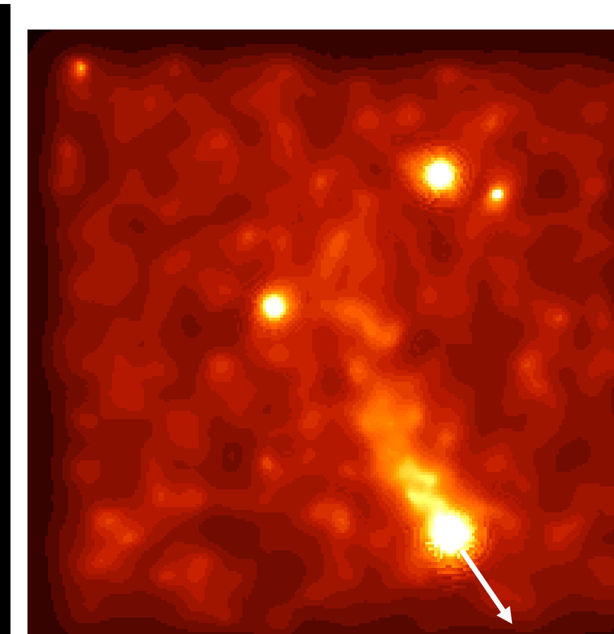


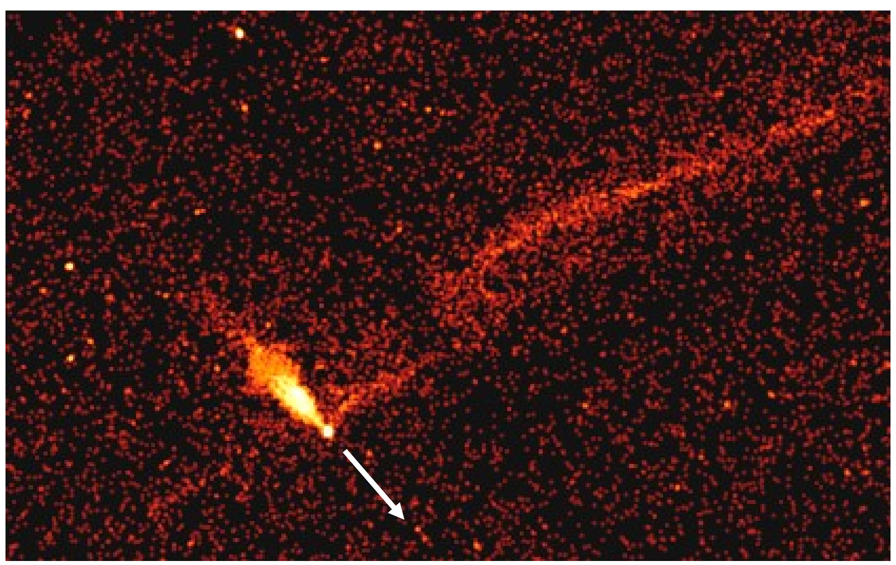


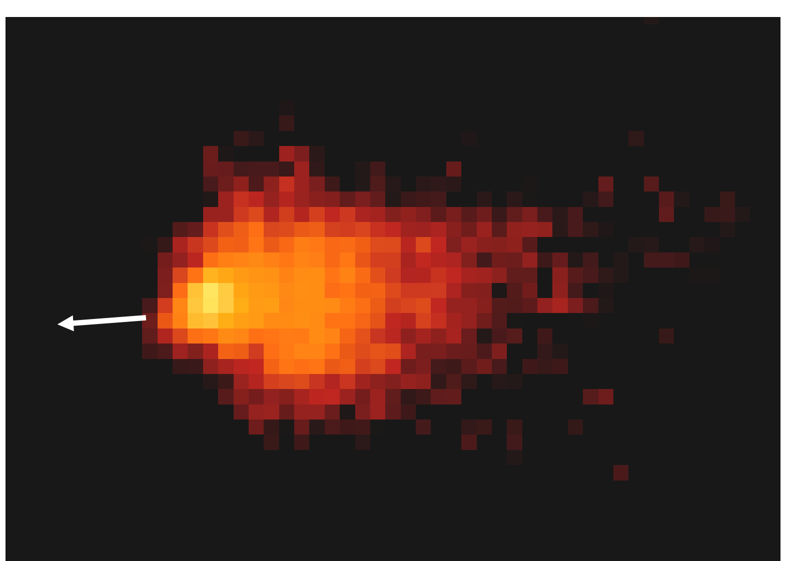


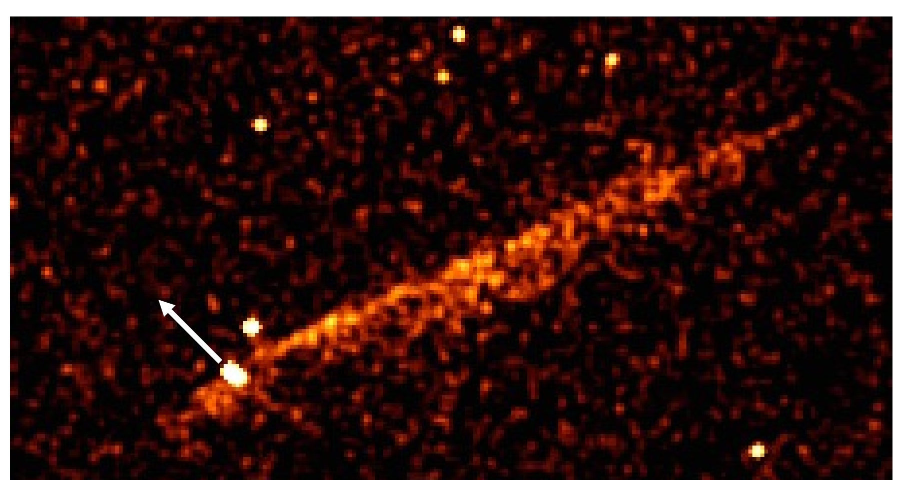
“Filled” vs. “empty” PWNe heads

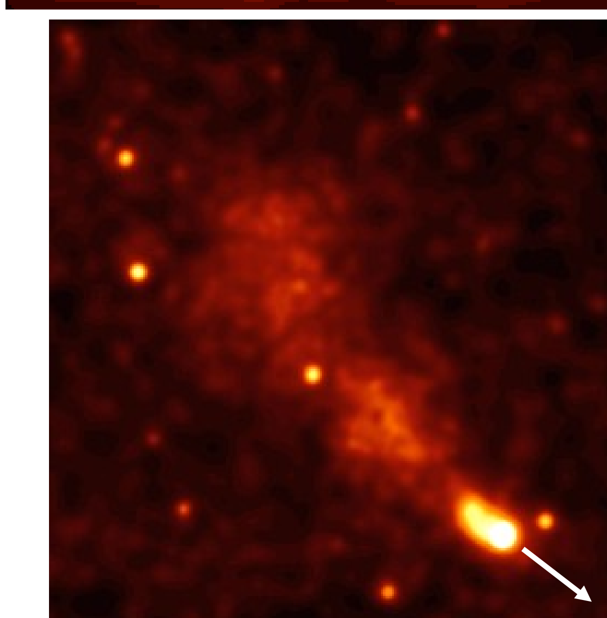








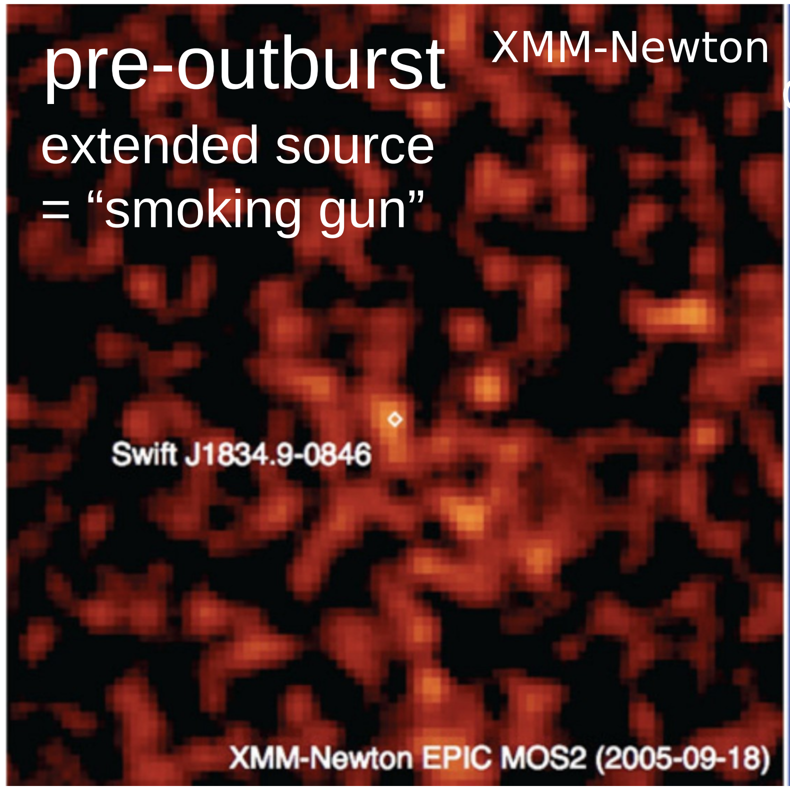


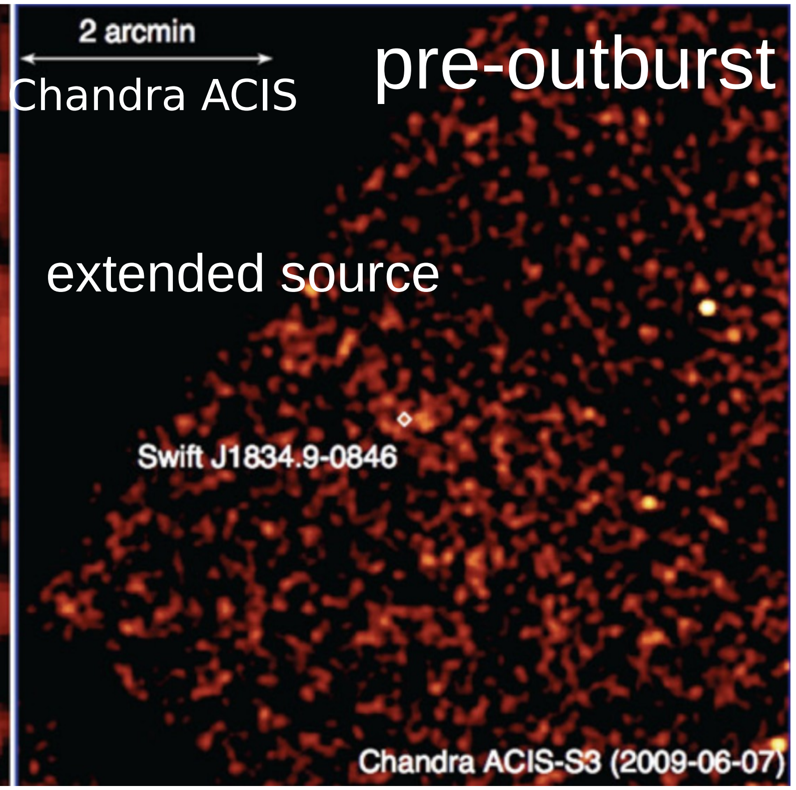


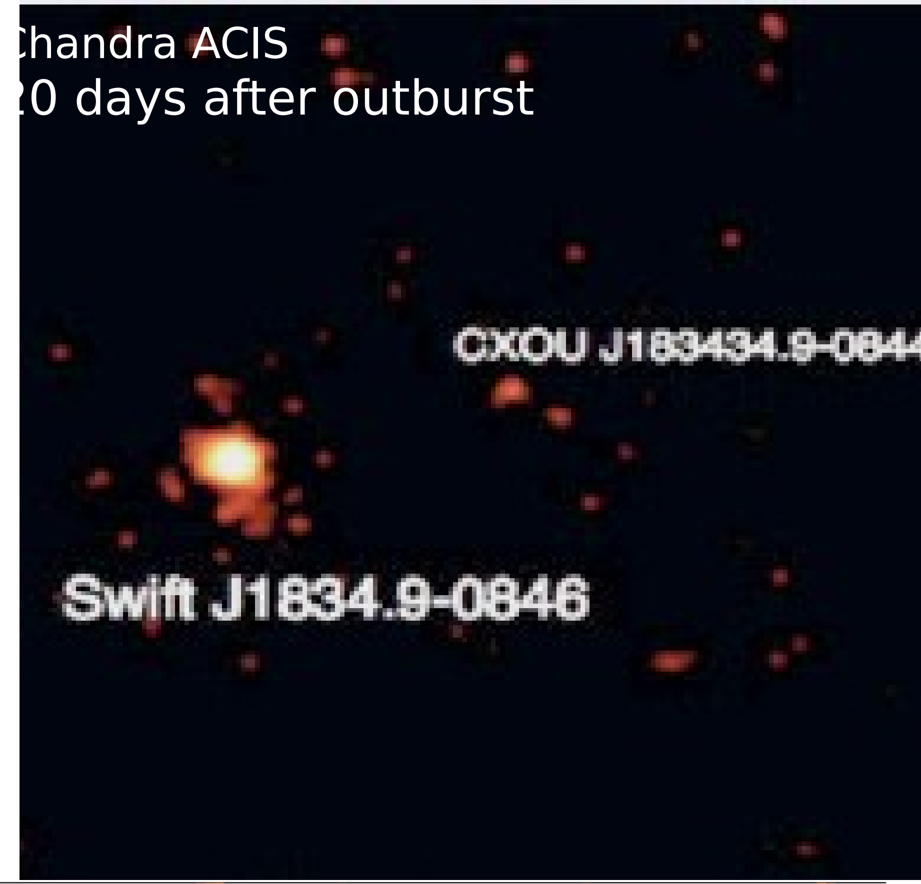
Discovery of Magnetar Wind Nebula (MWN)

around transient magnetar Swift J1834.9-0846

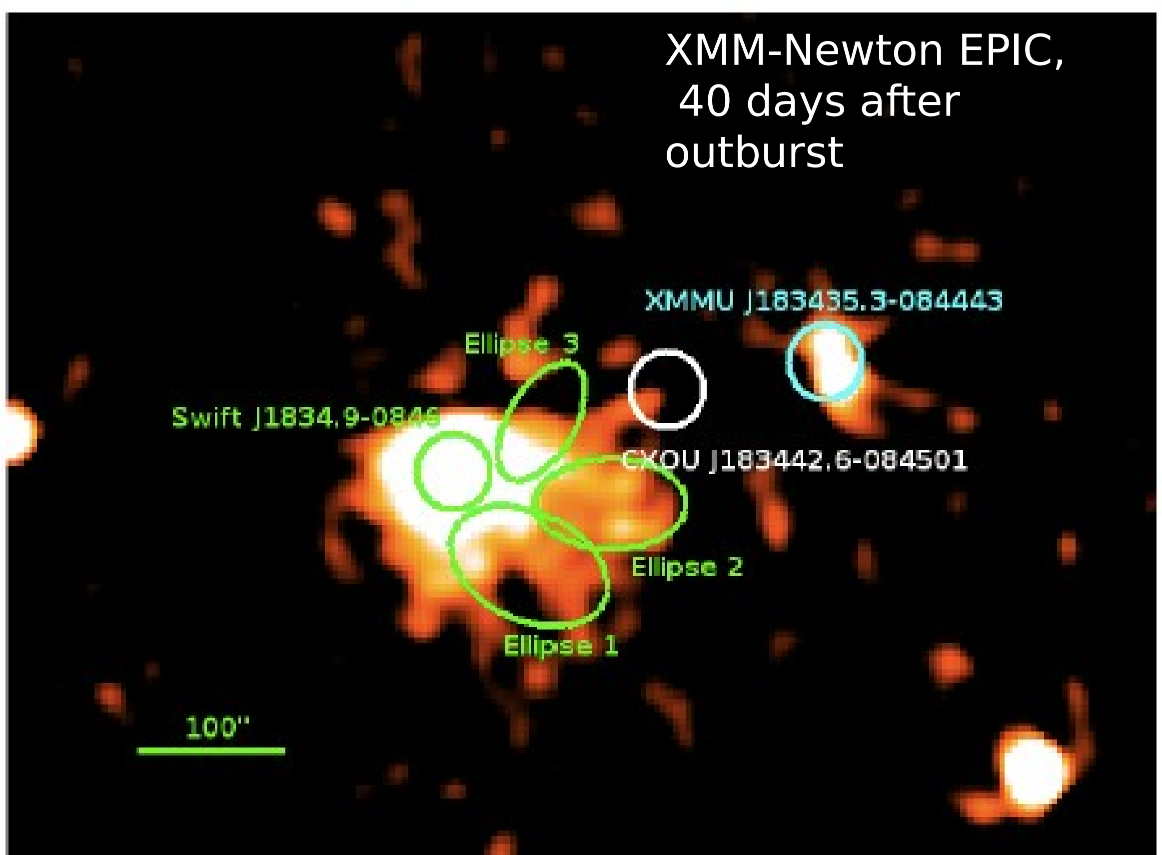
Kargaltsev et al. (2012), Younes et al. (2012, 2016)

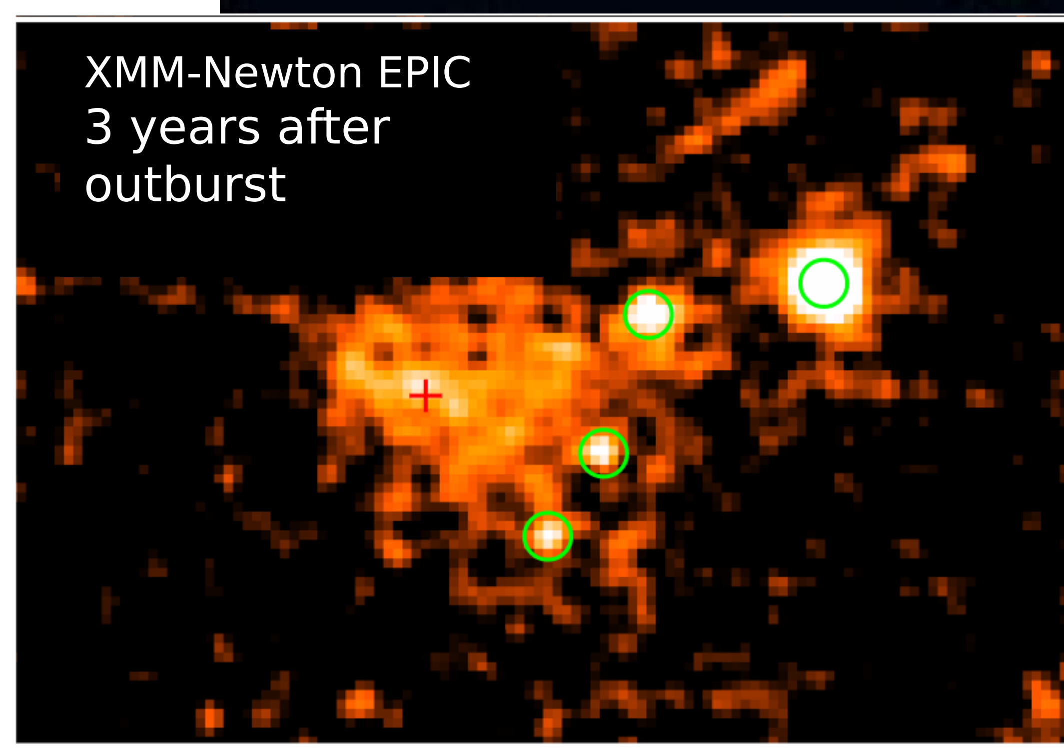






How do magnetars produce winds?





MWNe can provide a way to find dormant magnetars!

First PWN resolved in an interacting binary

A dynamic nebula of the B1259-63/LS 2883 high-mass Binary

(Pavlov et al 2015)

LS 2883: $M \sim 30\ M_{\odot}$, $L = 6 \times 10^4 L_{\odot}$
strong wind, decretion disk

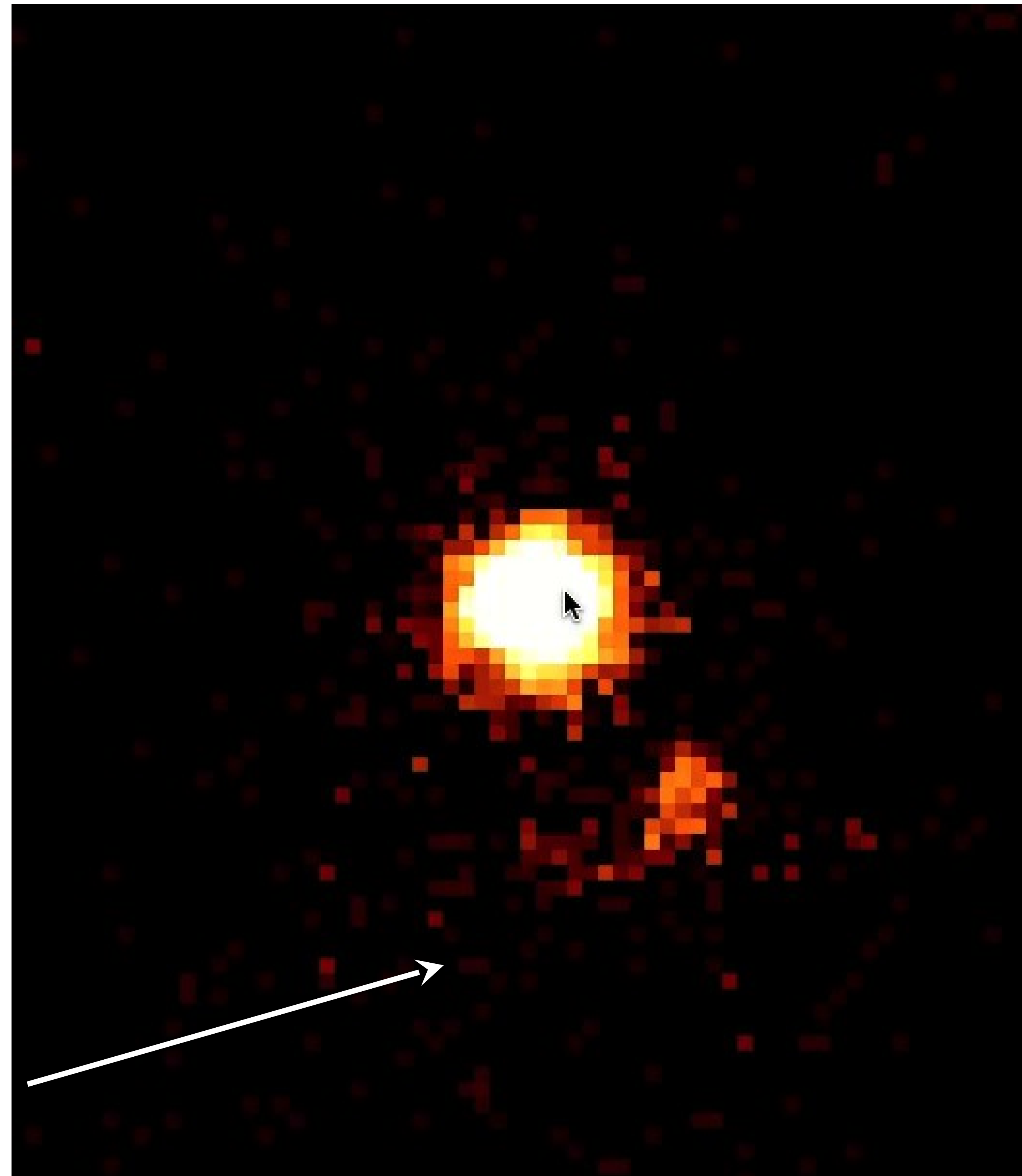
B1259-63: Edot=8×10^{35} erg/s,
τ_{sd} = 330 kyr

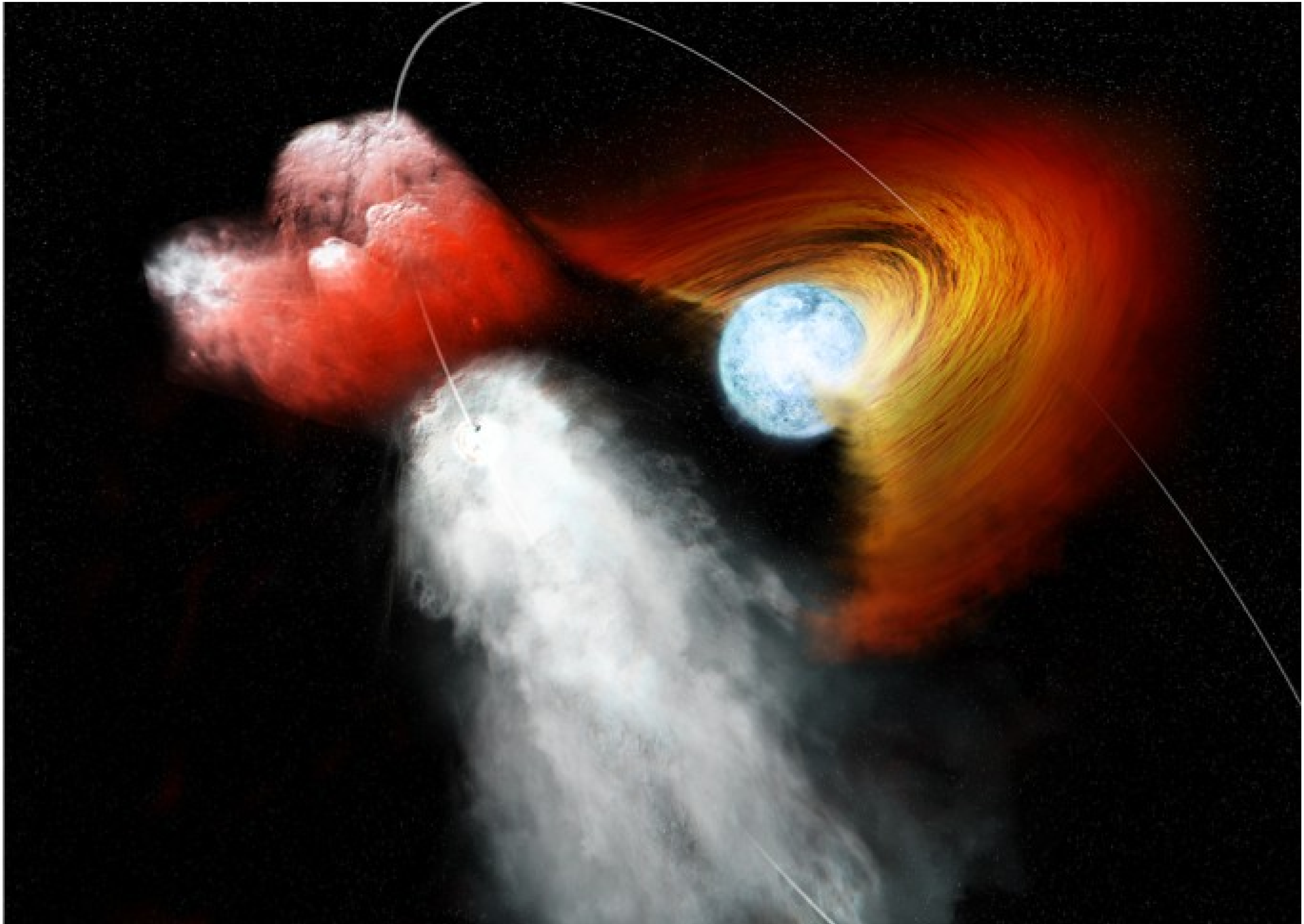
3.4 yr orbital period, e=0.87

The animation shows 3 ACIS images taken on Dec 2011, May 2013 and Feb 2014 with about equal exposures ~60 ks.

We see an extended object moving from the binary with high apparent velocity, perhaps with acceleration.

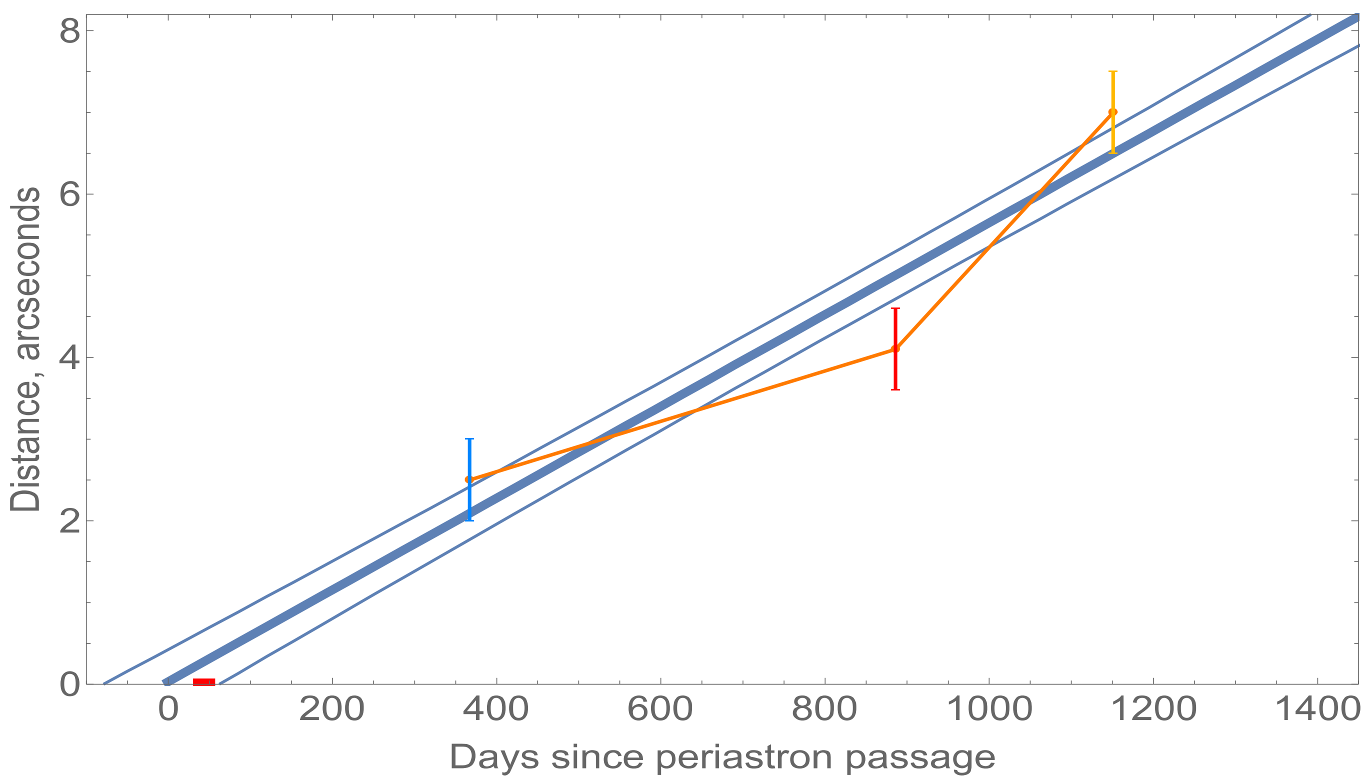
What is this?





Artist interpretation: NASA/CXC press release

Distance of the extended source from the binary versus time



Linear fit: V = (0.07+/-0.01)c

If there is no acceleration, the clump was ejected from the binary around periastron of 2010 Dec 14

Apparent **acceleration** (?) 90+/-40 cm^2/s

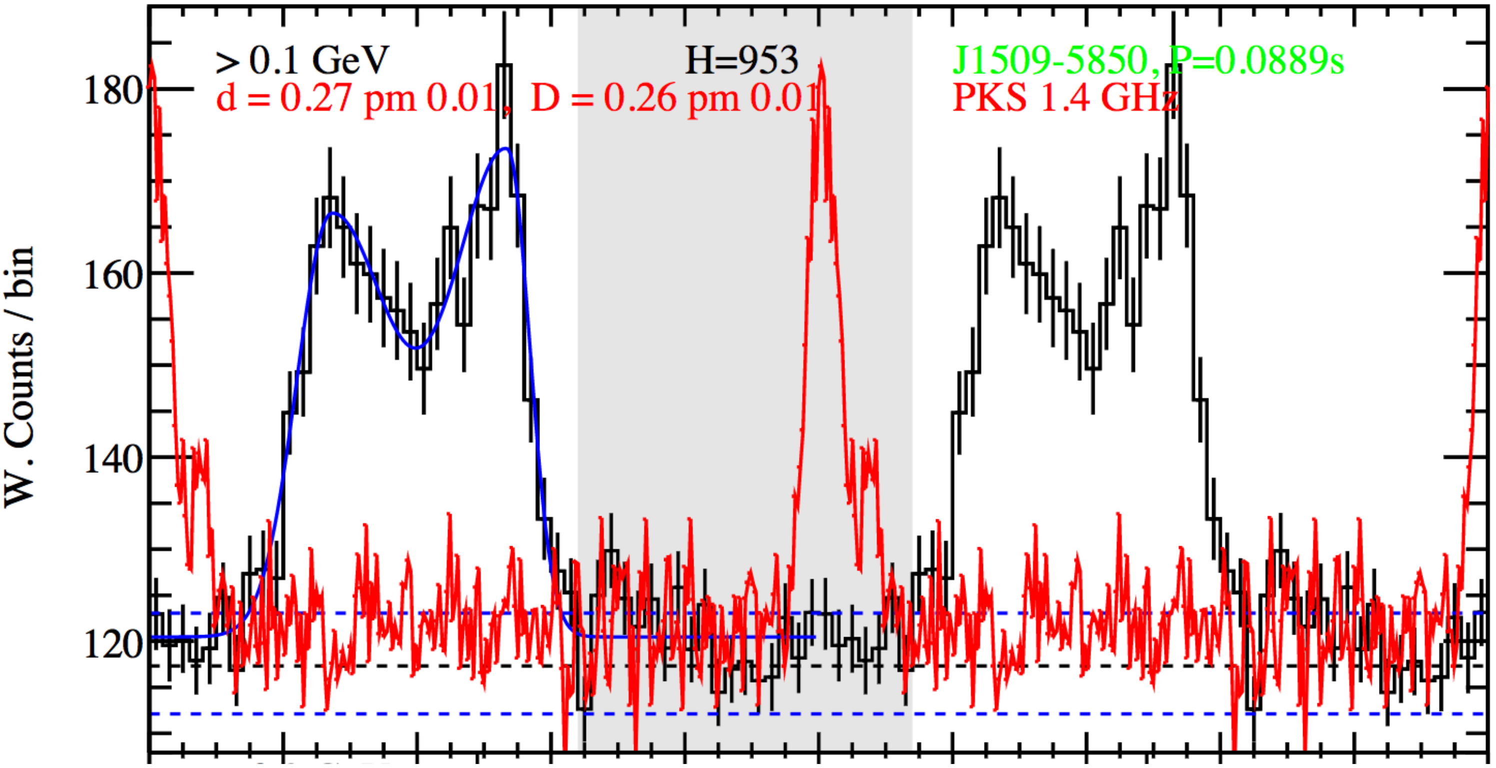
Possible interpretations:

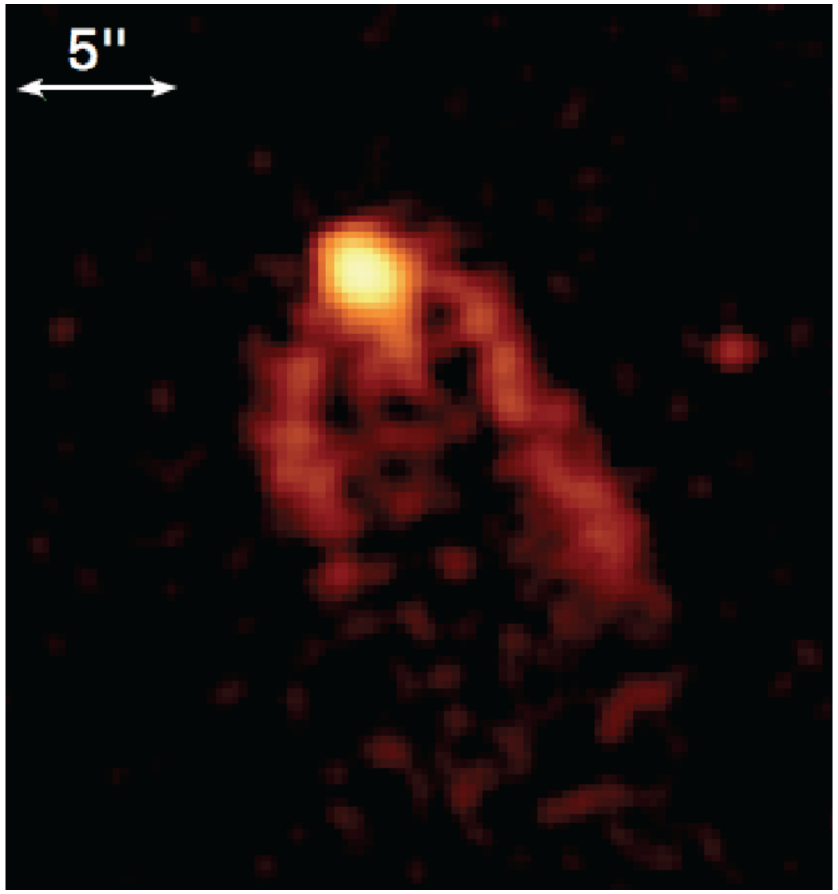
(1) Ejected clump of stellar (disk) matter moving in unshocked pulsar wind. Clump ejected by interaction of the PW with the decretion disk. X-rays due to synchrotron radiation of PW shocked in collision with the clump. (Pavlov et al 2015)

(2) Pulsar-stellar wind mixture injected during periastron passages in apastron direction. X-rays still due to synchrotron radiation from PW electrons. (Barkov & Bosch-Ramon 2015)

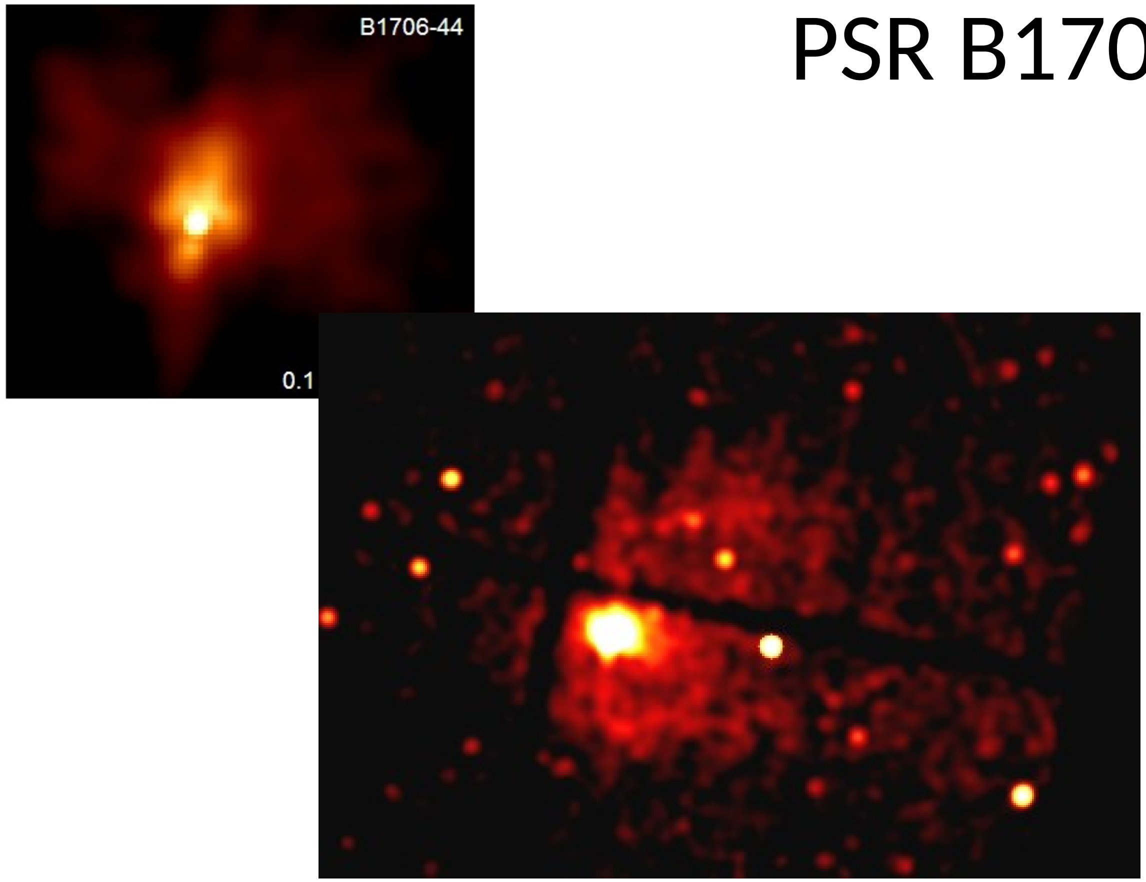
Connection to the pulsar magnetosphere geometry

PSR J1509-5850

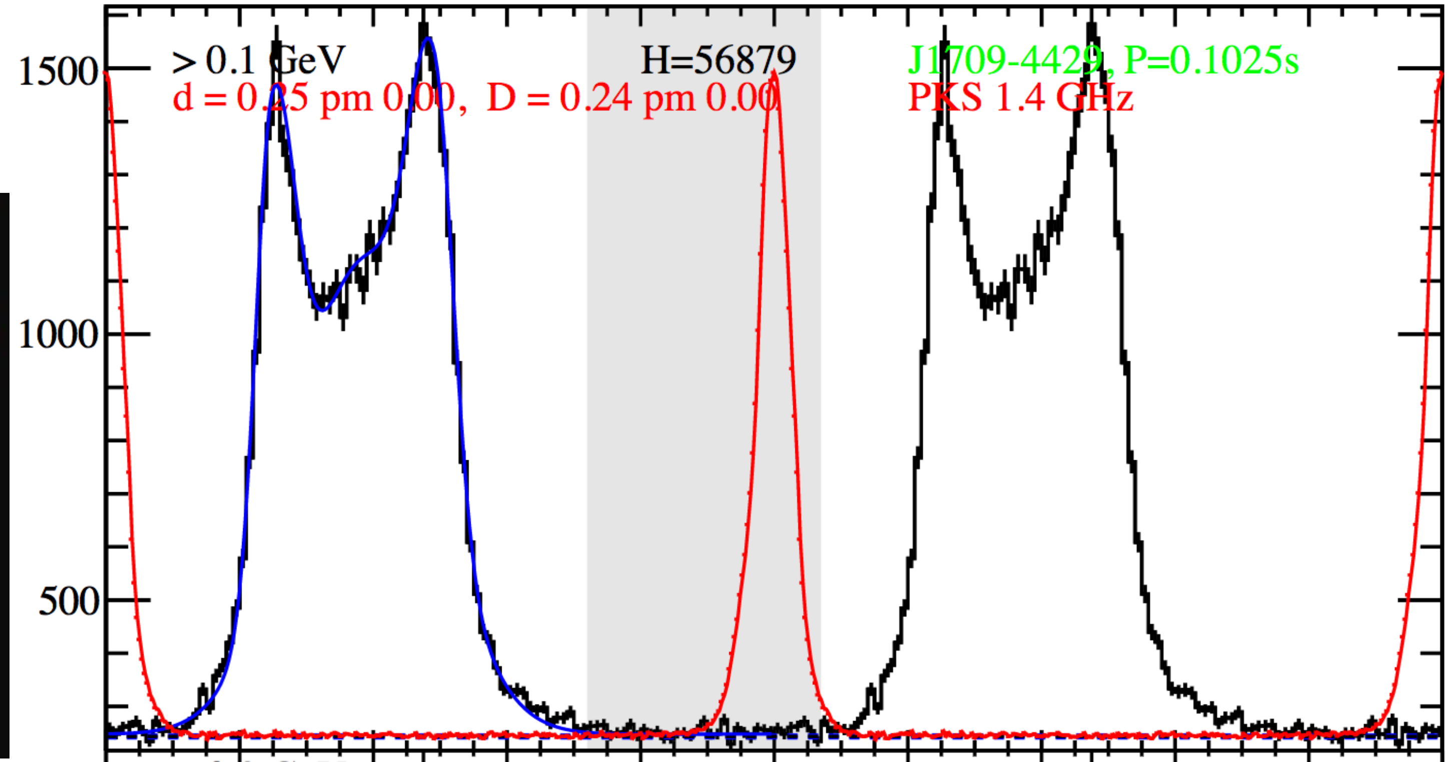




Similar lightcurves imply similar (α, ζ) angles, helps to intepret PWN features and vice versa!

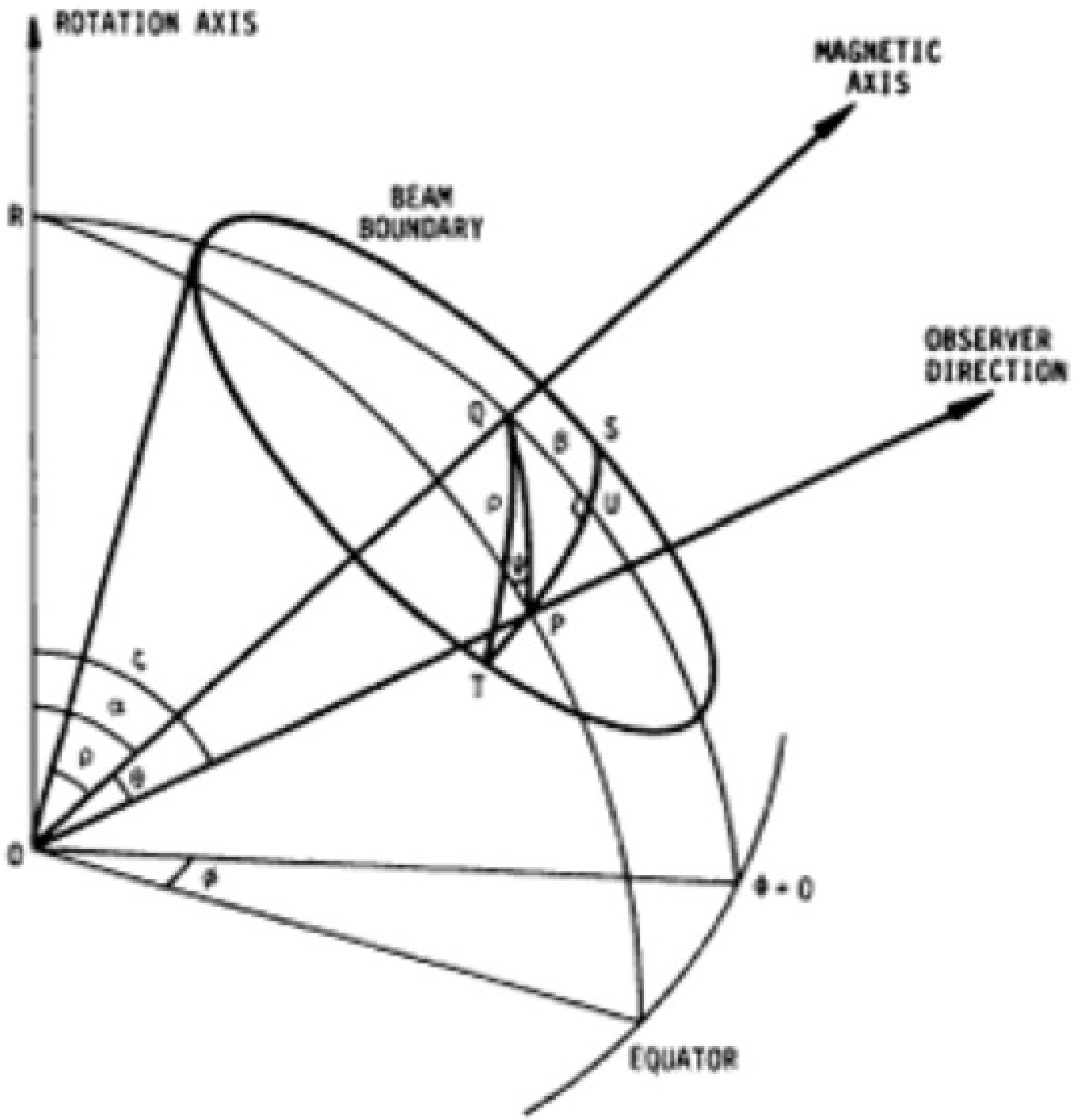


PSR B1706-44



Connection to the pulsar magnetosphere geometry in RVM. (X-ray, radio, gamma-ray synergy)

PSR	ζ_{PWN}	α_{PWN}
Crab	62	70–90
B0540	93	50–90
Vela	55–63	43,65
J0205	91	50–90
J2021	80	50–70
B1706	53	>70
J0007	30–90	?
B1509	46	?
J2229	46	?
B0656	?	<30?
J1119	>30	?
J1420	?	?
J1357	>30	?
B1055	68?	75?
B1046	50–70	50–70
J1509	50–70	>70
Geminga	>50	?
J1747	60–70	?
J0357	0?	0?



Future Outlook: PWN studies

- There remain several bright PWNe that can be studied to similar level of detail as those shown in this presentation with deep 0.5 Ms exposures.

- The nature of helical shapes seen in several PWNe (instabilities vs. NS precession) needs to be understood, requires long-term monitoring

- Deep observations of supersonic pulsars are likely to reveal more misaligned outflows

- Archival search for extended objects may be fruitful and can uncover unexpected objects (e.g., MWNe) and improve the population study

  results

- Very few PWNe allow temporal studies, further monitoring is needed