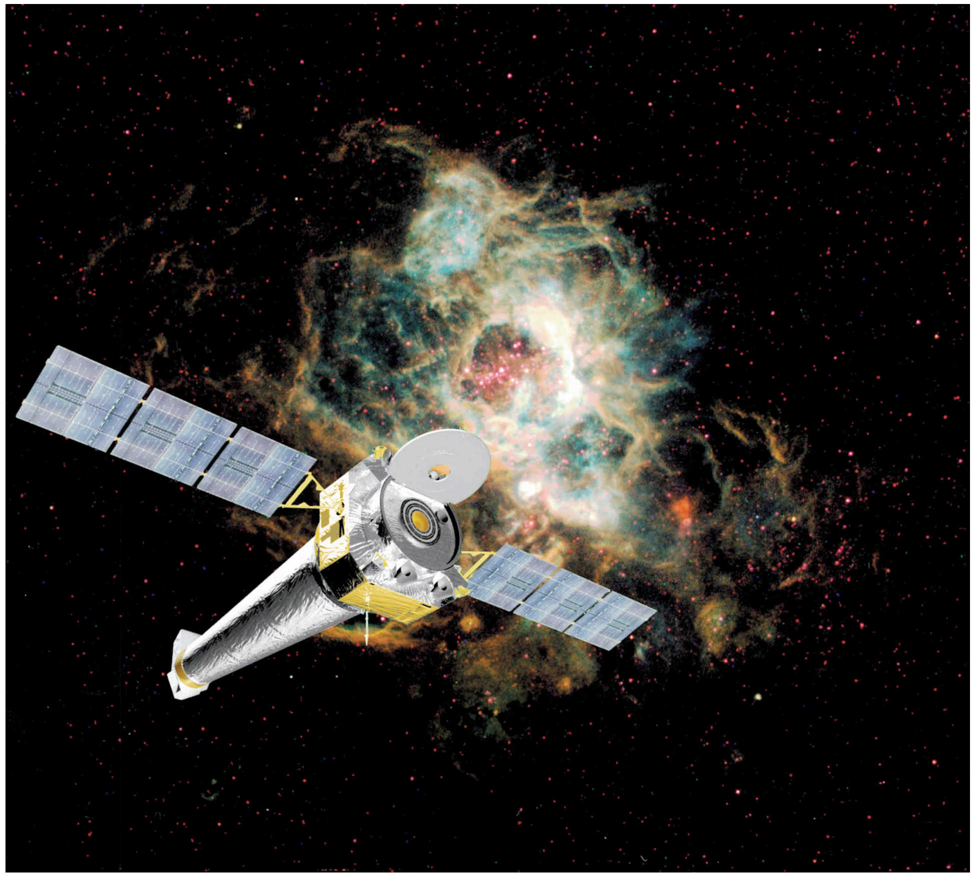
What Chandra did not tell us about pulsar winds (and pulsars)?



Oleg Kargaltsev (George Washington University)

Big Questions

Big question?

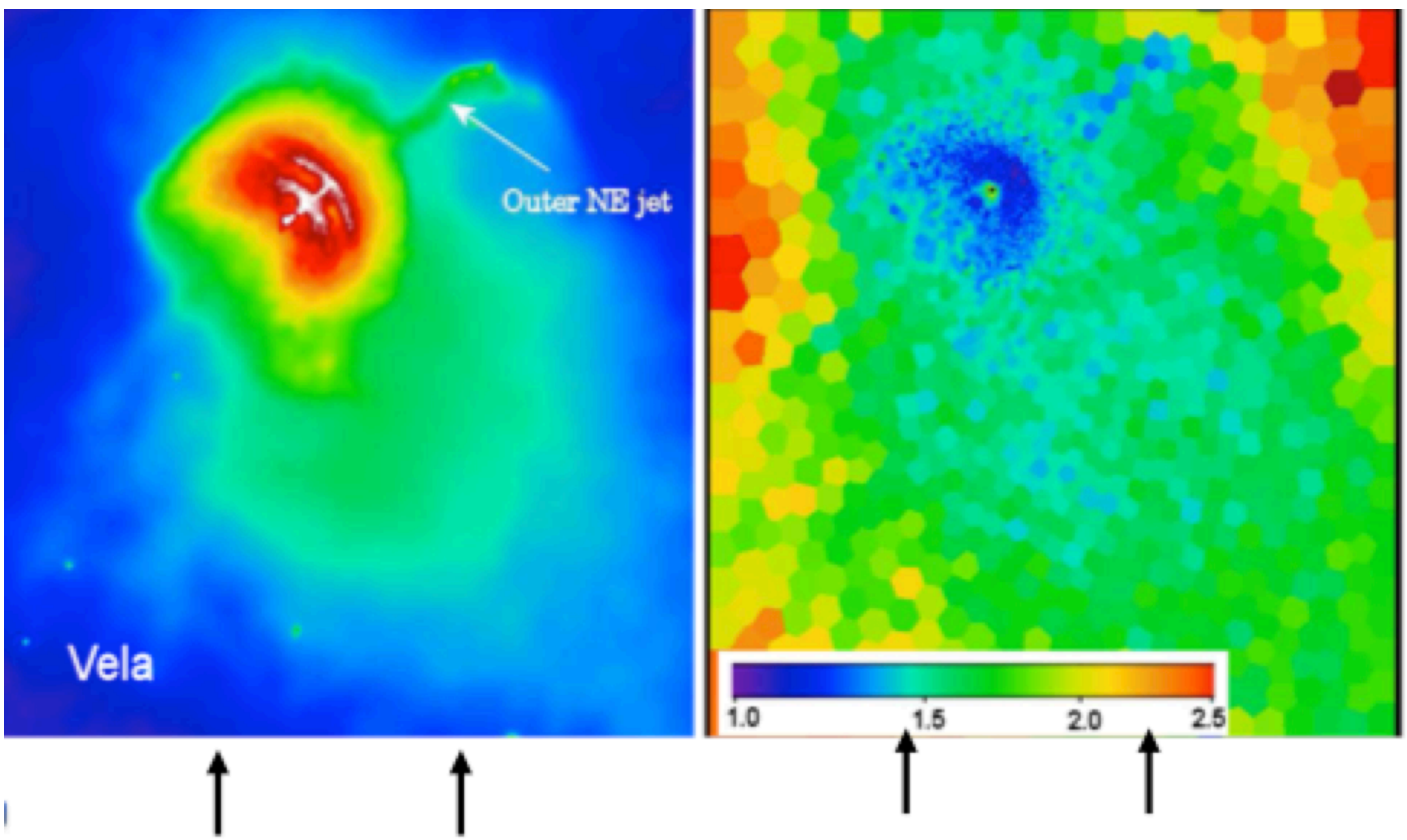
How big is "big"?

- What proceess acelerates particles to ~PeV energies?
- What is the internal structure of magnetized relativistic outflows?
- What is the connection between the PWN morphologies (spatial and spectral) and the pulsar properties (velocity, magnetosphere geometry, spin-down parameters)? Can pulsar parameters be constrained from PWN observations to compliment constraints coming from radio and gamma-ray lightcurves?
- What are the actual number of NSs in the Galaxy, what are the properties of the bulk of the pupulation of NSs (we currently see the tip of the tip of the iceberg!)?
- How do isolated NSs and BHs accrete from ISM?

(I) Spatially resolved spectroscopy of PWNe

- **Immediate Objective:** accurately map spectral morphologies of large pulsar wind nebulae
- **Science Goal:** elucidate the evolution of magnetic field, flow velocity, and plasma energy content in PWNe, including pulsar tails, PWNe with prominent equatorial outflows and jets, and collimated relativistic outflows in general.

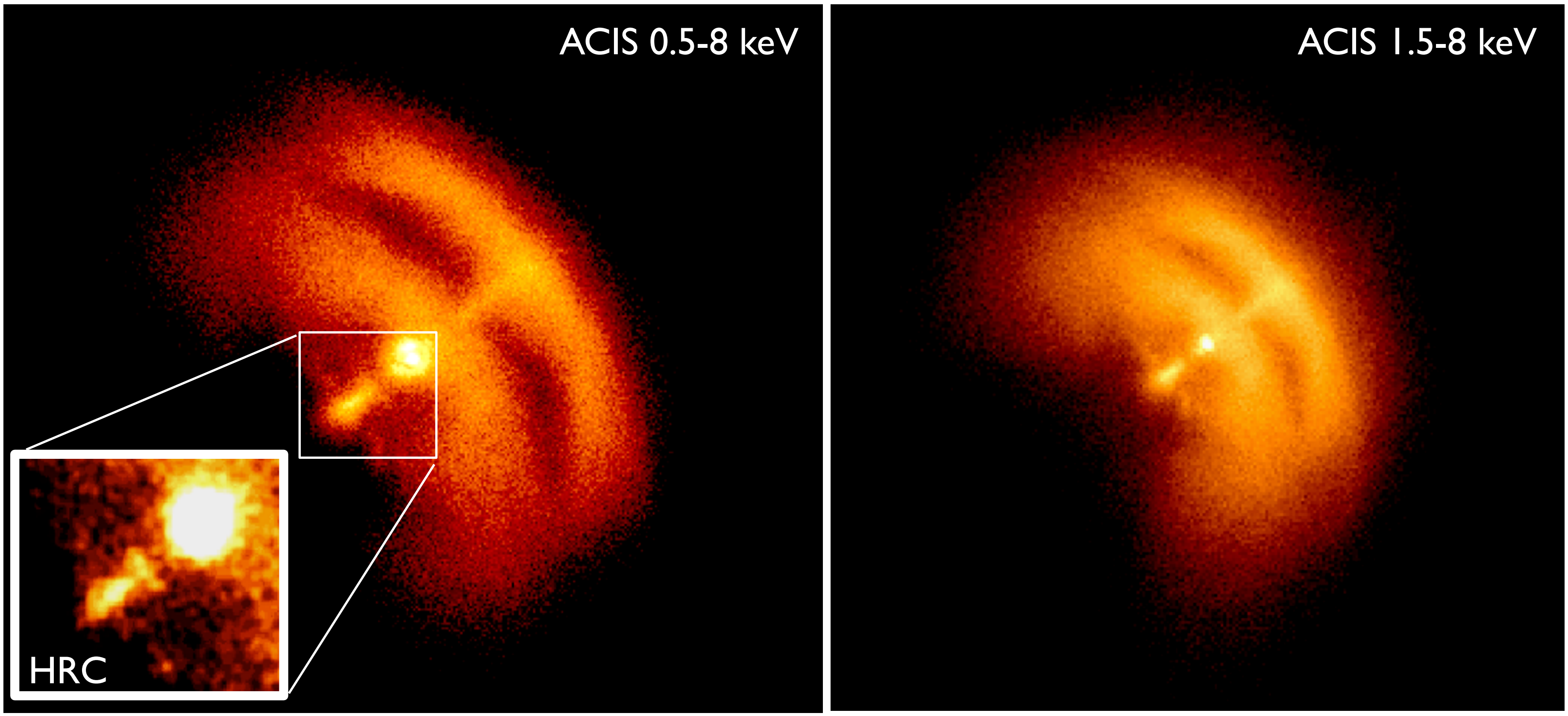
Examples of spatially-resolved spectroscopy for **Vela PWN with Chandra ACIS**:



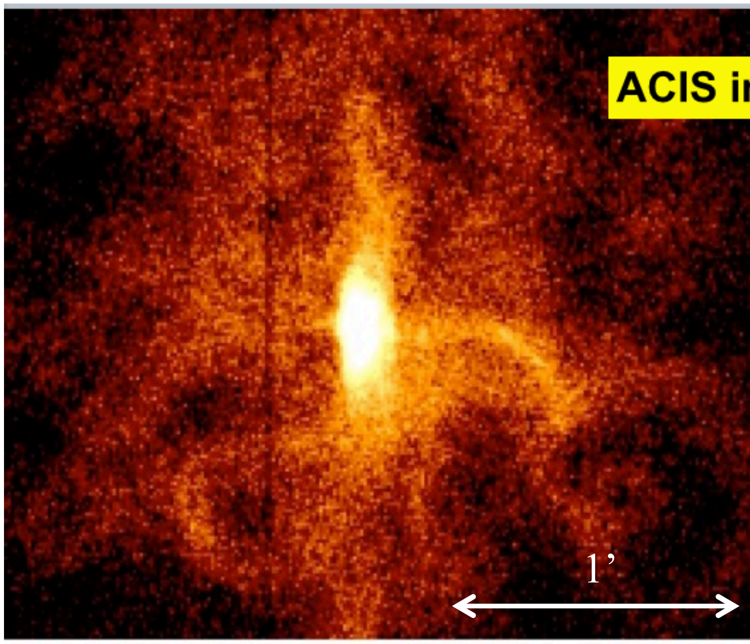
Synchrotron surface brightness — Map of the photon index Γ

Vela Inner PWN: complex structure of the jet

However, spectral properties are difficult to extract on these scales…

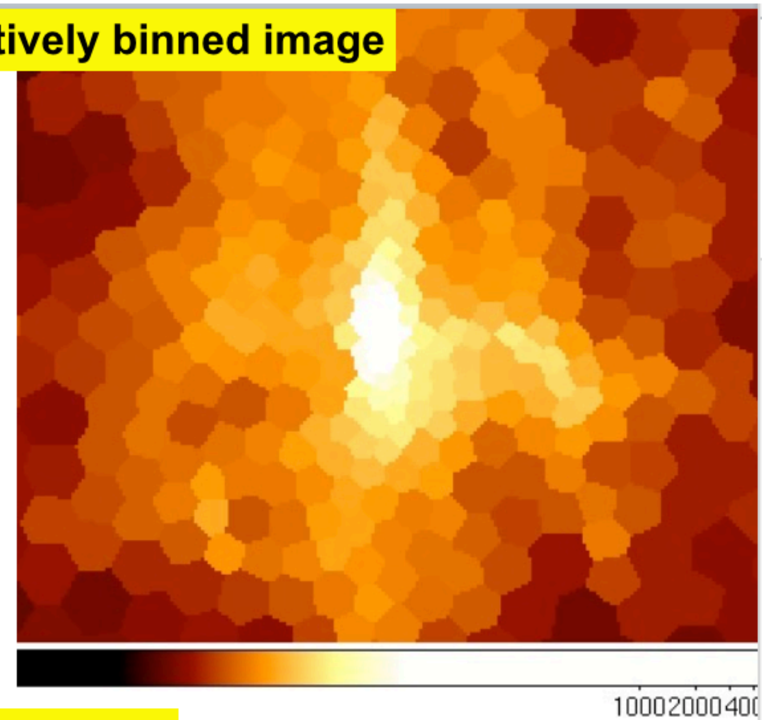


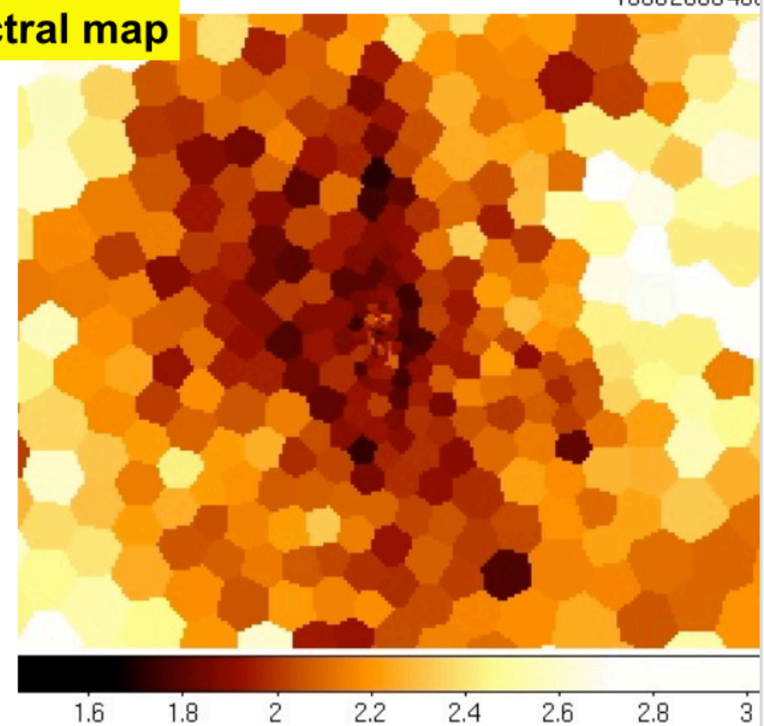
A clue to the jet formation mechanism?



ACIS images

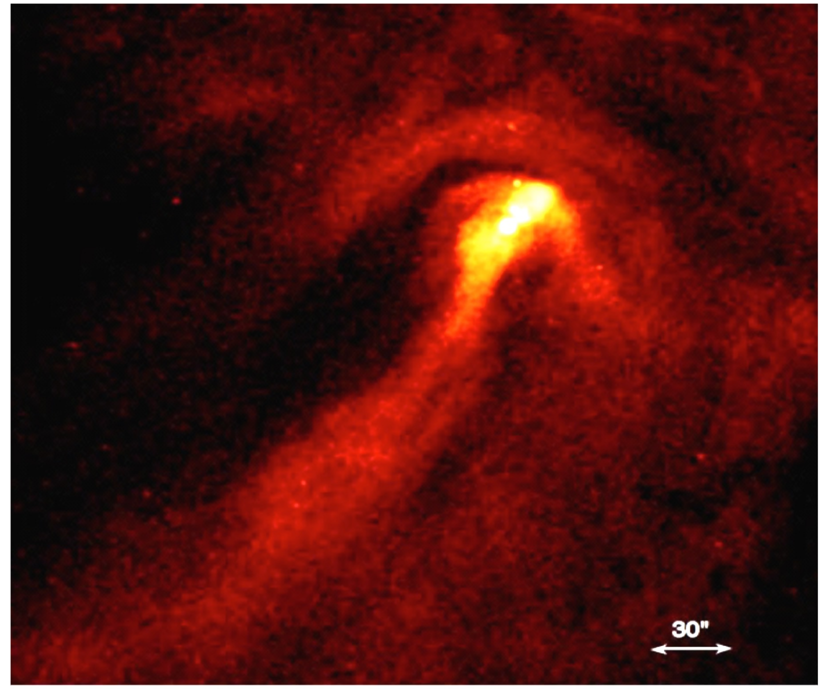
3C58



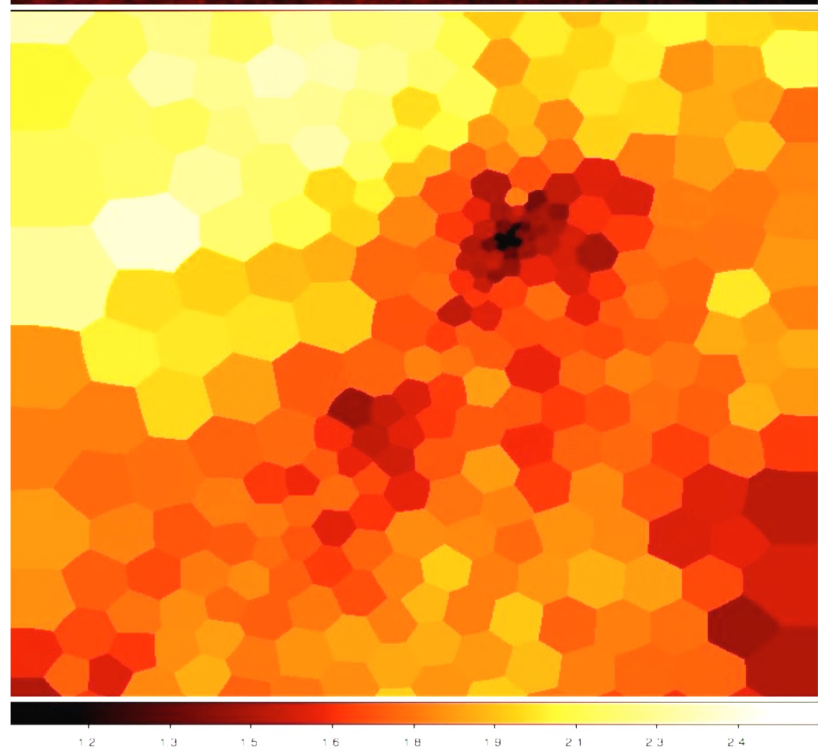


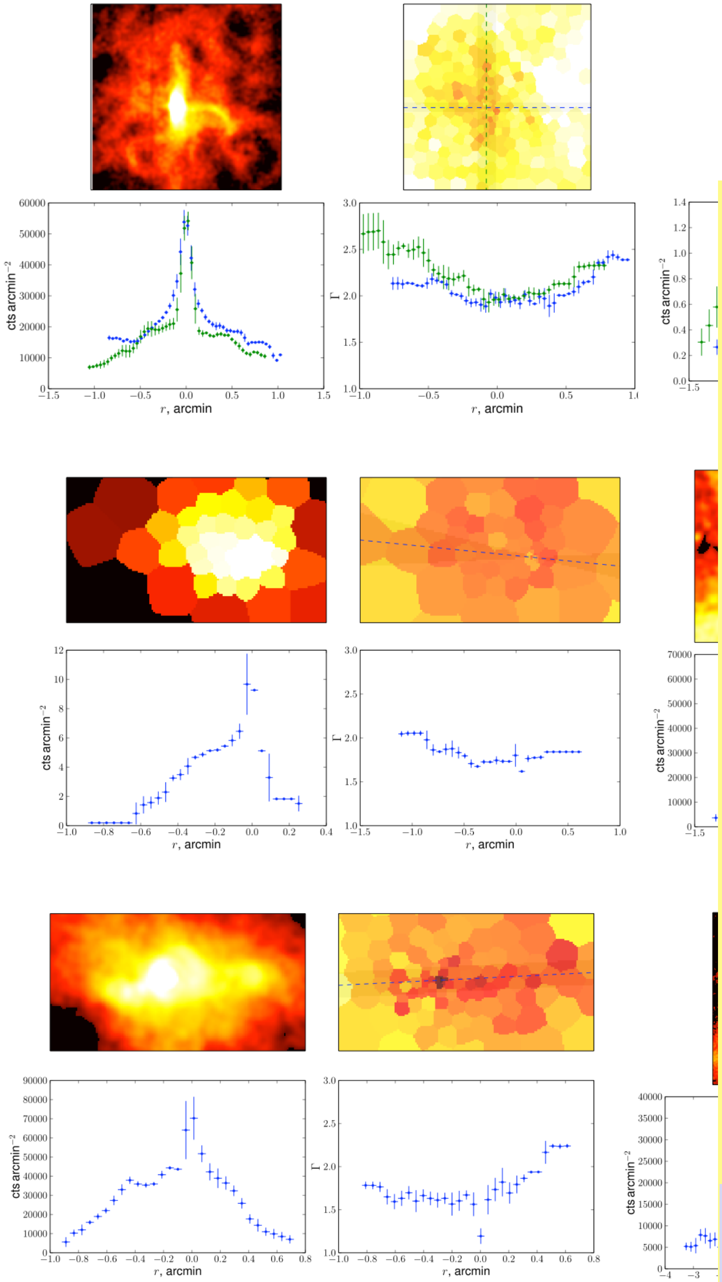
The spectral map of PWN in 3C58 suggests complex spectral structure (matching the complexity of the PWN morphology) but the photon statistics is insufficient to make any firm conclusions.

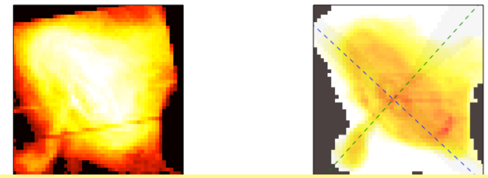
Chandra ACIS image



Spectral map





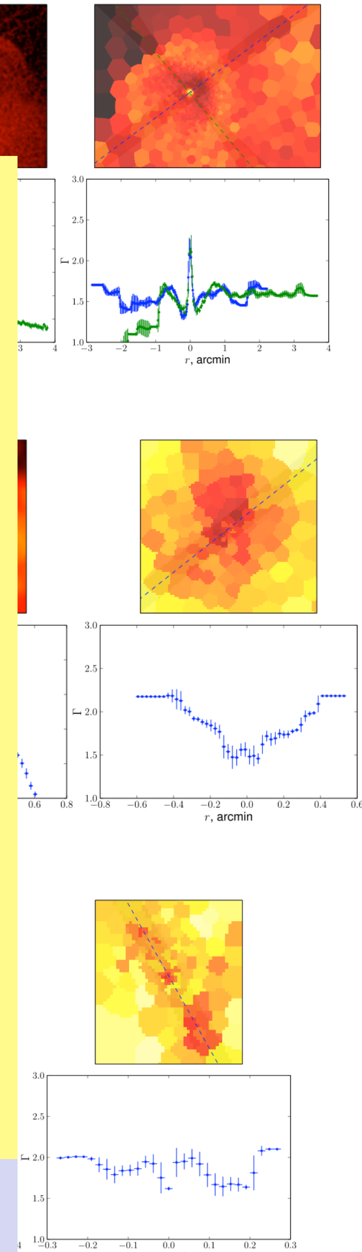


Spatially resolved spectroscopy on arcsecond scales could enable measurments of the uncooled SED of electrons injected at the termination shock:

	PWN	Γ_0	p_0
1	Crab	1.80 ± 0.05	2.6
2	Vela	1.30 ± 0.05	1.6
3	3C58	1.9 ± 0.1	2.8
4	G320.4−1.2	1.4 ± 0.1	1.8
5	Kes 75	1.9 ± 0.1	2.8
6	G21.5−0.9	1.40 ± 0.05	1.8
7	G11.2−0.3	1.5 ± 0.1	2.0
8	CTB80	1.7 ± 0.1	2.4
9	G54.1+0.3	1.50 ± 0.05	2.0

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

But, wait… Are those differences even real? Ok, may be for 2 objects but can we find out what do those differences depend on with just 2 objects?



Pulsar tails and jets: magnetized outflow laboratory

- Essentially the same physics as in AGN jets
- Differences: hadron fraction, lowerd bulk flow speed
- Advantages: easier to study since no complications due to the Doppler effect, known energy injection rate (Edot), larger angular sizes

PSR J1509-5850: Spectra

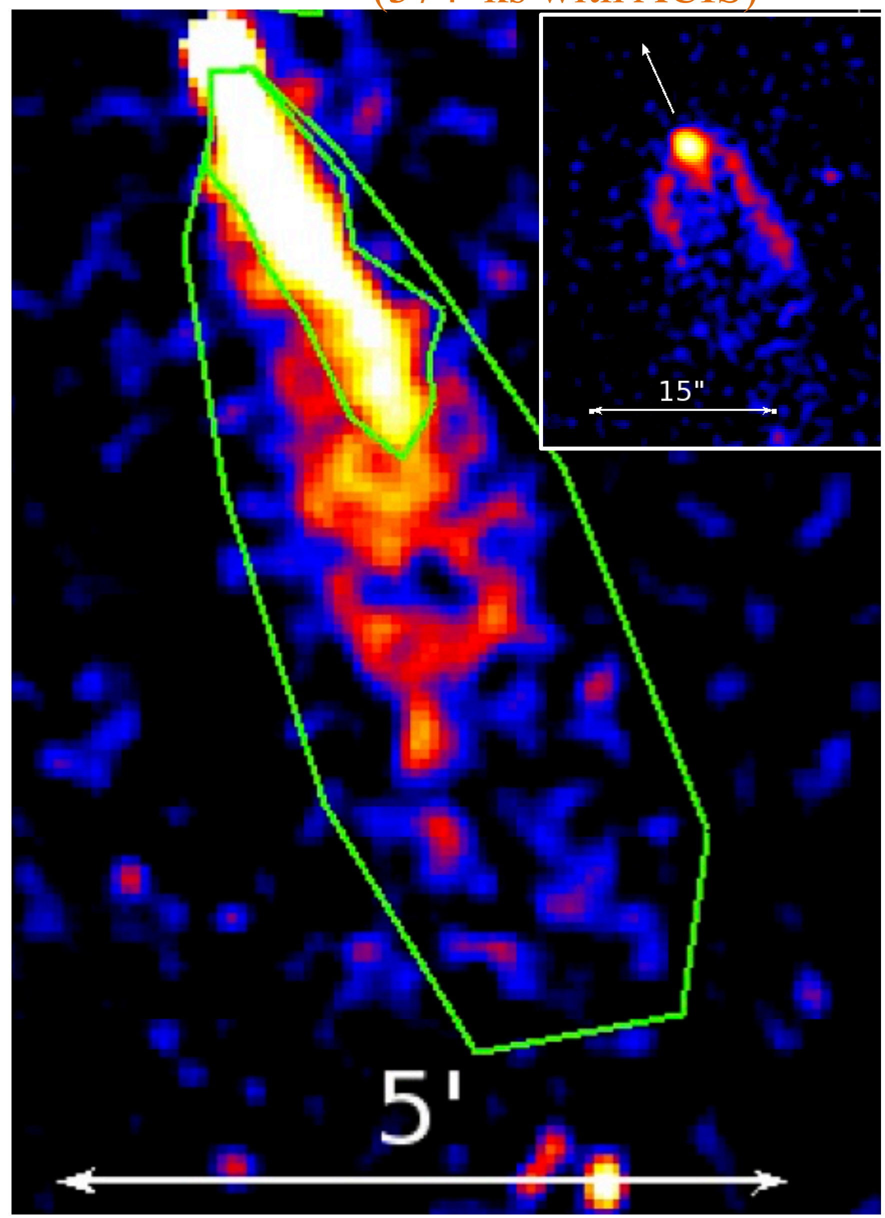
See poster by Noel Klingler !

Region	Γ (fit to Absorbed Power-Law)
Pulsar	1.91 ± 0.12
Jets(?)	1.80 ± 0.13
Tail	1.88 ± 0.06
Brightening	2.11 ± 0.07
Tail (excl. bright.)	1.78 ± 0.09

QUESTIONS:

Why no evidence of cooling?
Are particles re-energized?
How bif is the flow speed?

(374 ks with ACIS)



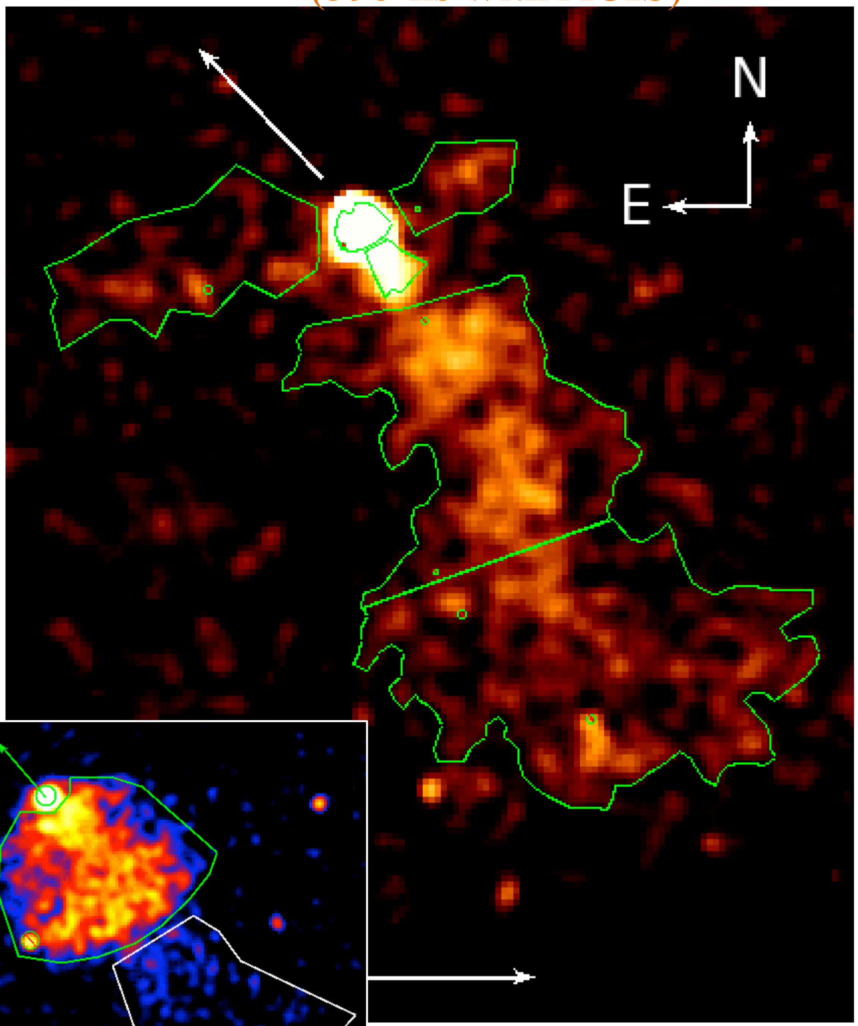
See poster by Noel Klingler!

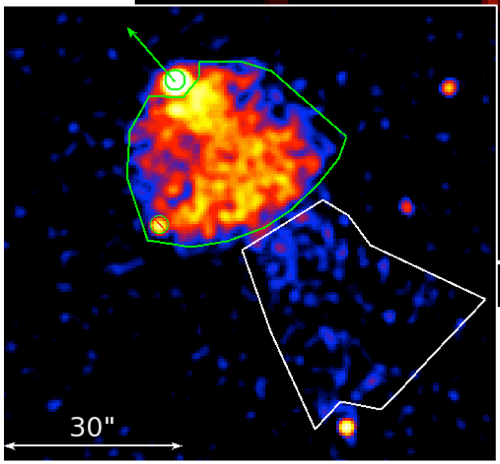
B0355+54: Spectra

Region	Γ (Absorbed Power-Law)
Pulsar	1.80 ± 0.10
CN	1.54 ± 0.05
Whiskers	1.6 ± 0.3
Stem	1.73 ± 0.17
Tail (Entire)	1.74 ± 0.08
Tail (Near)	1.72 ± 0.10
Tail (Far)	1.77 ± 0.11

Very faint structures require large collecting area and low detector background

(395 ks with ACIS)



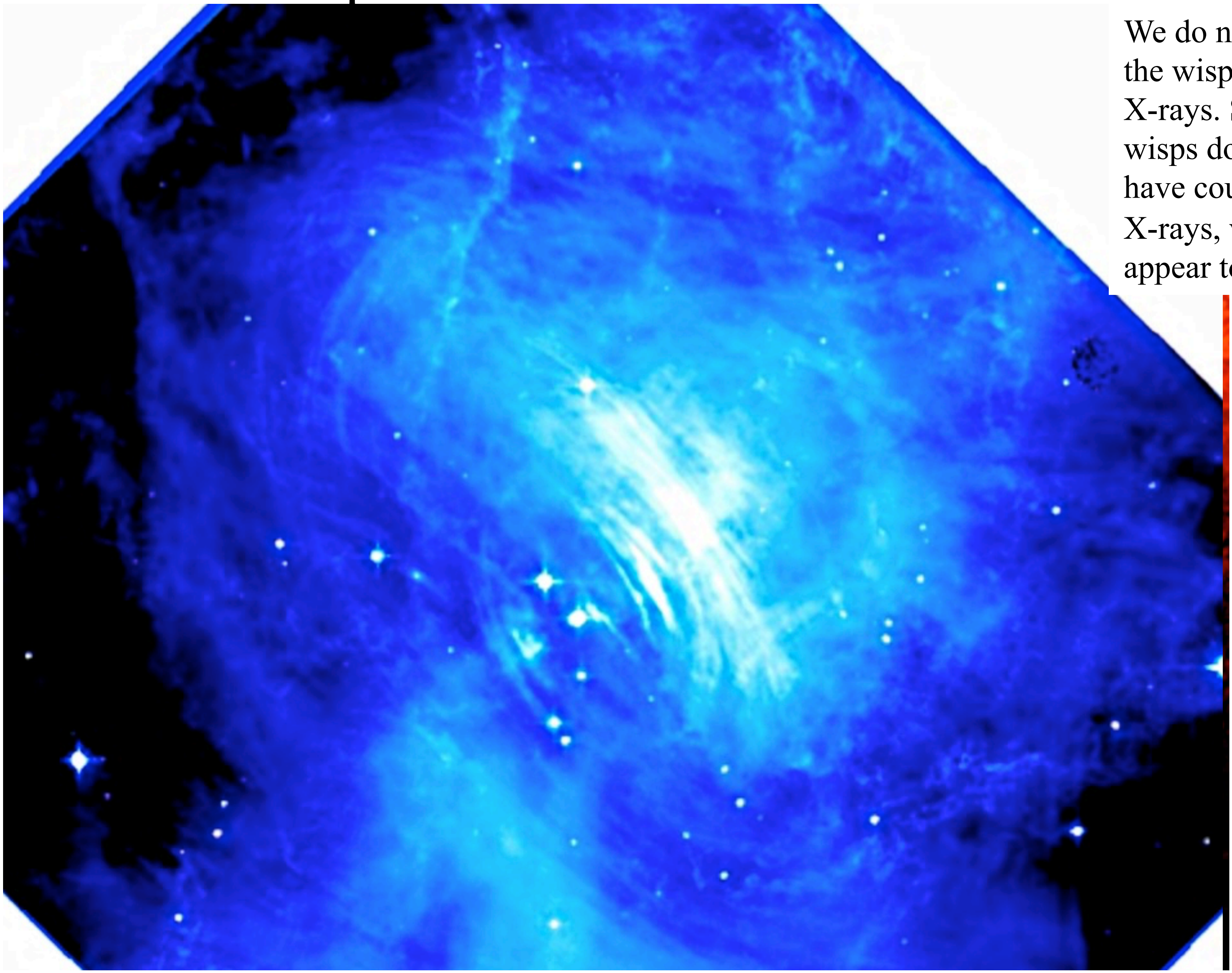


Regions used for spectral analysis

QUESTIONS:

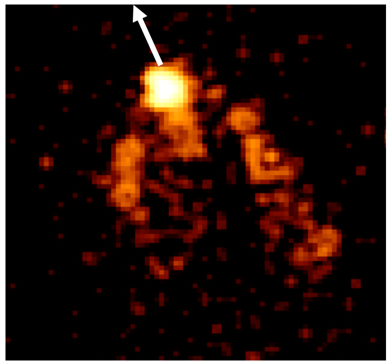
Is there a cooling along the tail?
Why is it so moderate?
Is there indeed a sharp spectral change at the transition from the compact PWN to the tail?

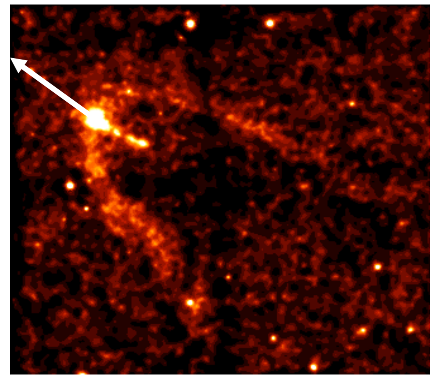
What are the Crab wisps? Where are the particle acceleration sites.



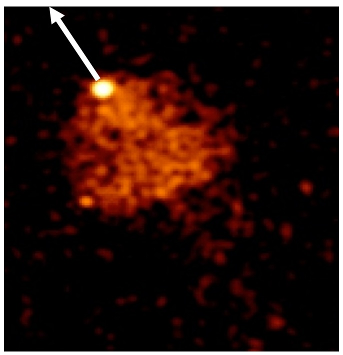
We do not see well the wisp structure in X-rays. Some optical wisps do not seem to have counterparts in X-rays, while others appear to be shifted.

What can compact PWN structures tell us about the pulsar magnetosphere geometry?

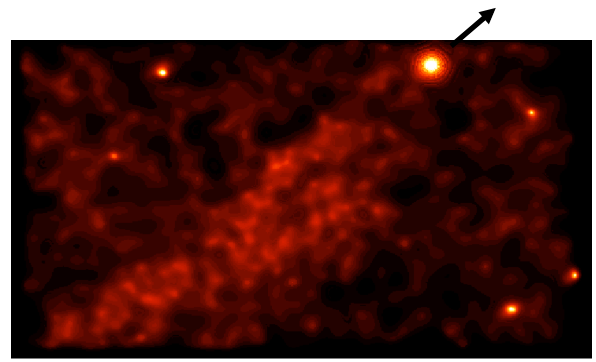


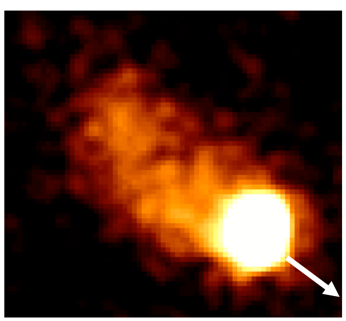


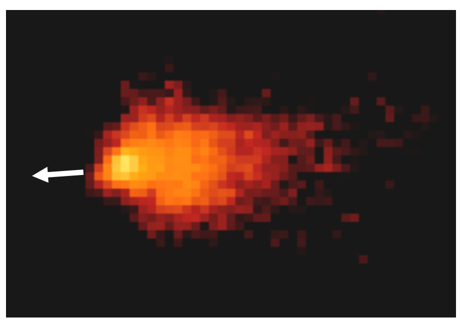
Are some of these having stronger jets then tori?

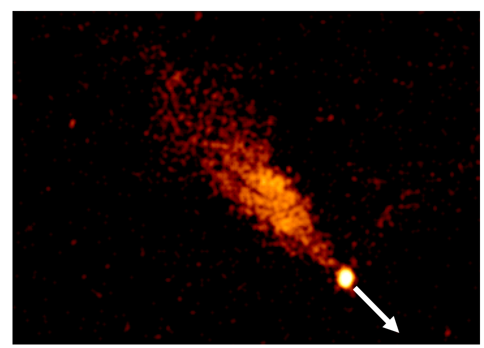


Where are the jets?



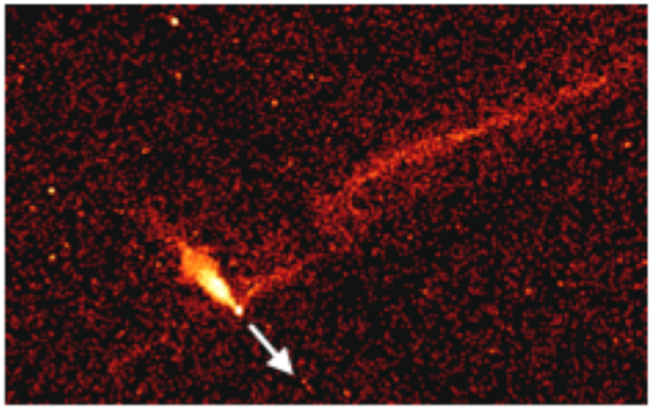


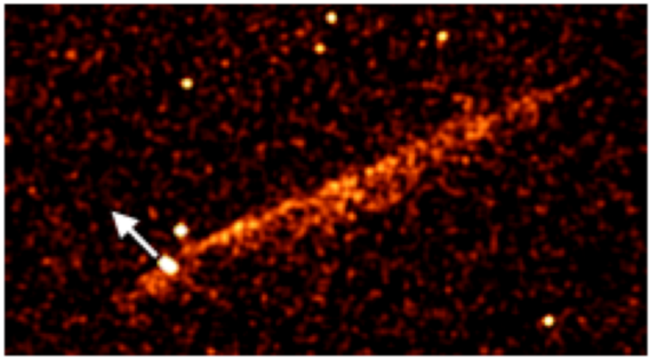


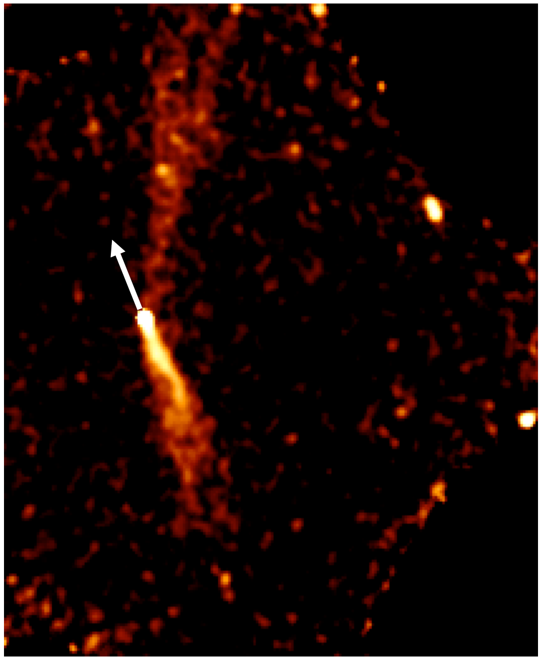


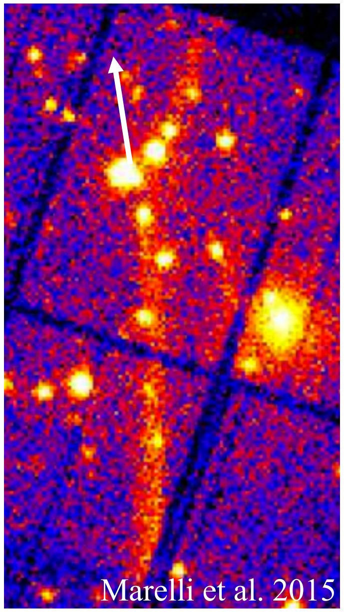
Some lack compact nebula or are we looking into the jet?

What are the puzzling structures recently found round in high-speed pulsars?



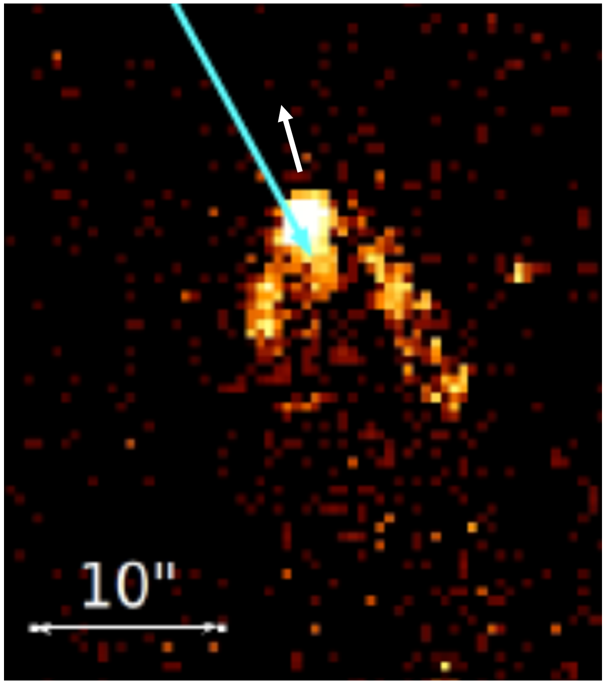






PSR J1509-5850: new data (ACIS, 190 ks)

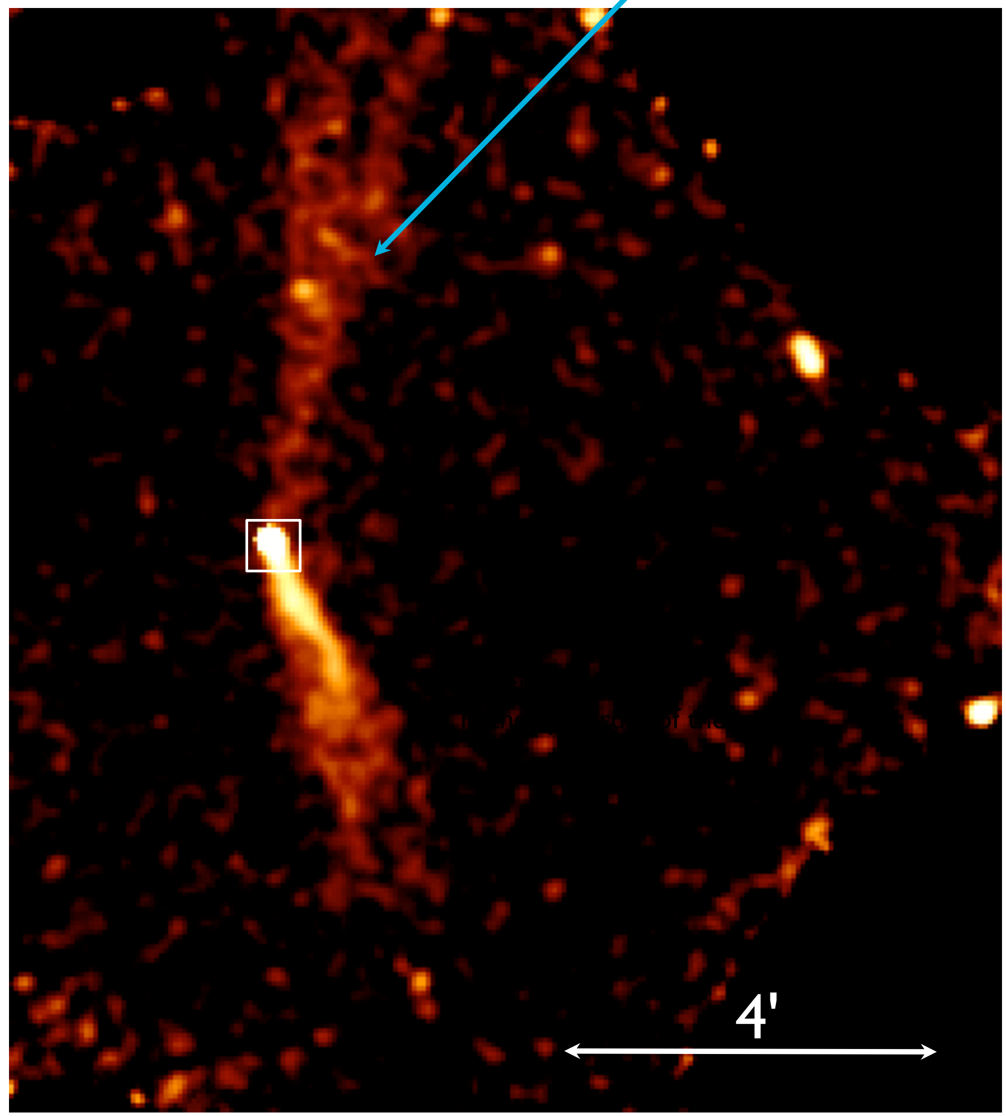
Notice little "jet" !



Klingler et al., in prep.

Photon indices (preliminary!):
"wings": Γ = 2.0 +/- 0.1
"central jet": Γ = 2.2 +/- 0.2

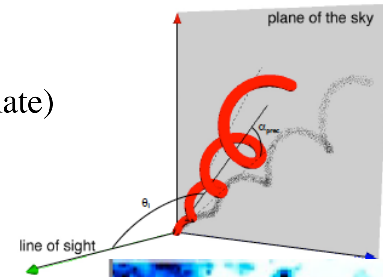
Less luminous "counter-tail", northern jet??



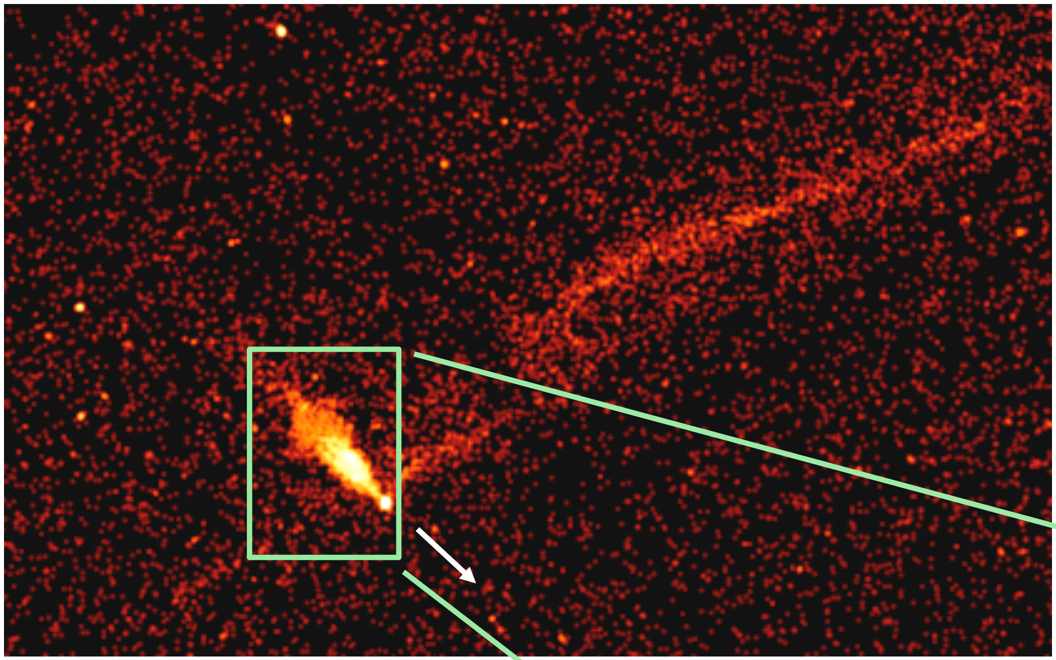
Klingler et al., in prep.

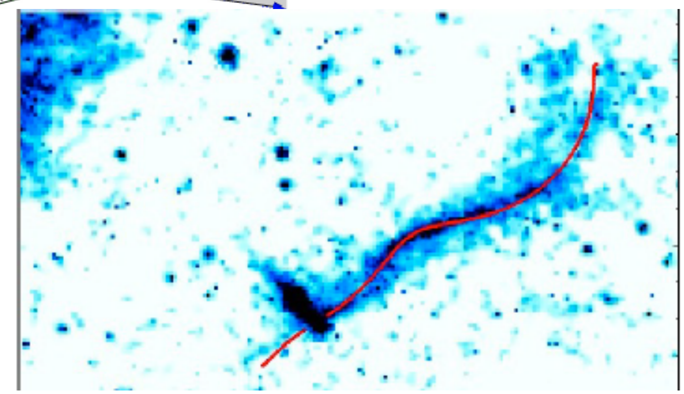
IGR J11014-6103 50 ks of ACIS exposure:

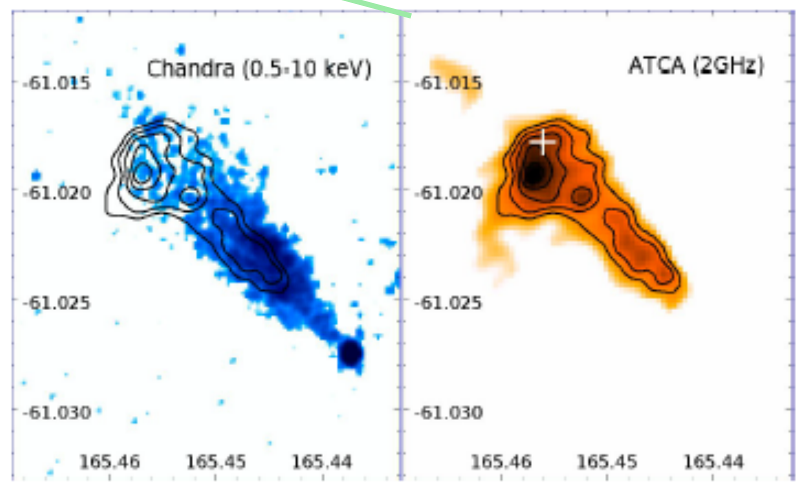
V_t > **2000 km/s** (based on SNR MSH 11-61A association and SNR age estimate)



Pavan at al. 2013

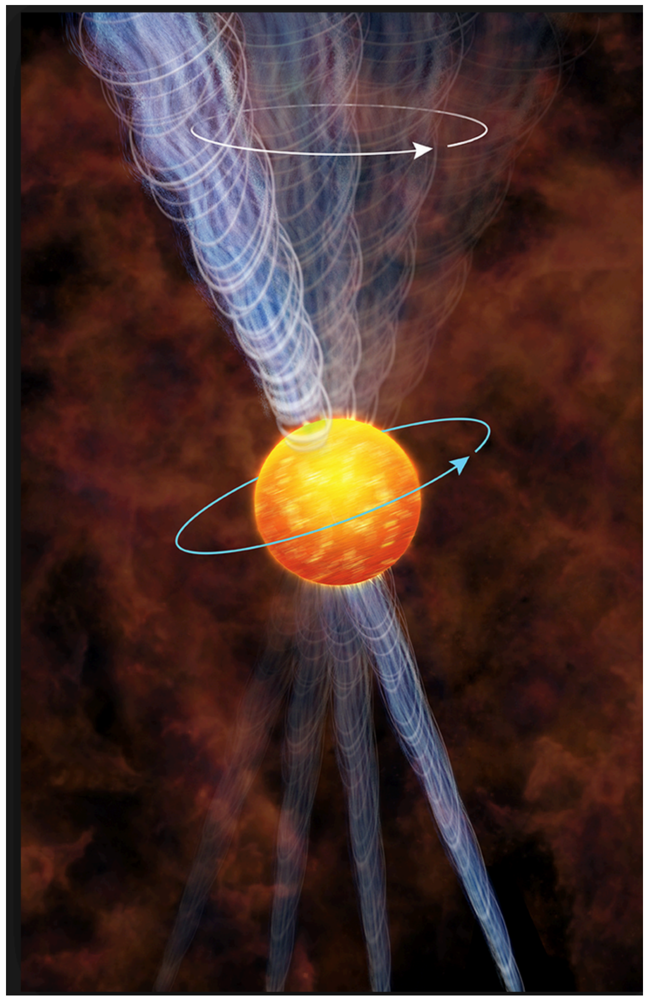




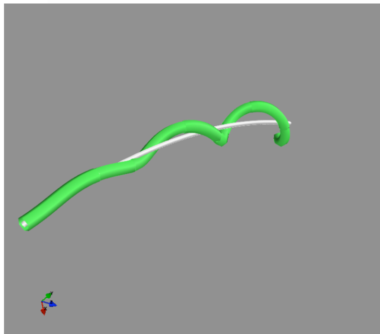


Another 250 ks of Chandra data are in the archive....

Do the NSs precess? Free precession? Direct link to graviataional waves?

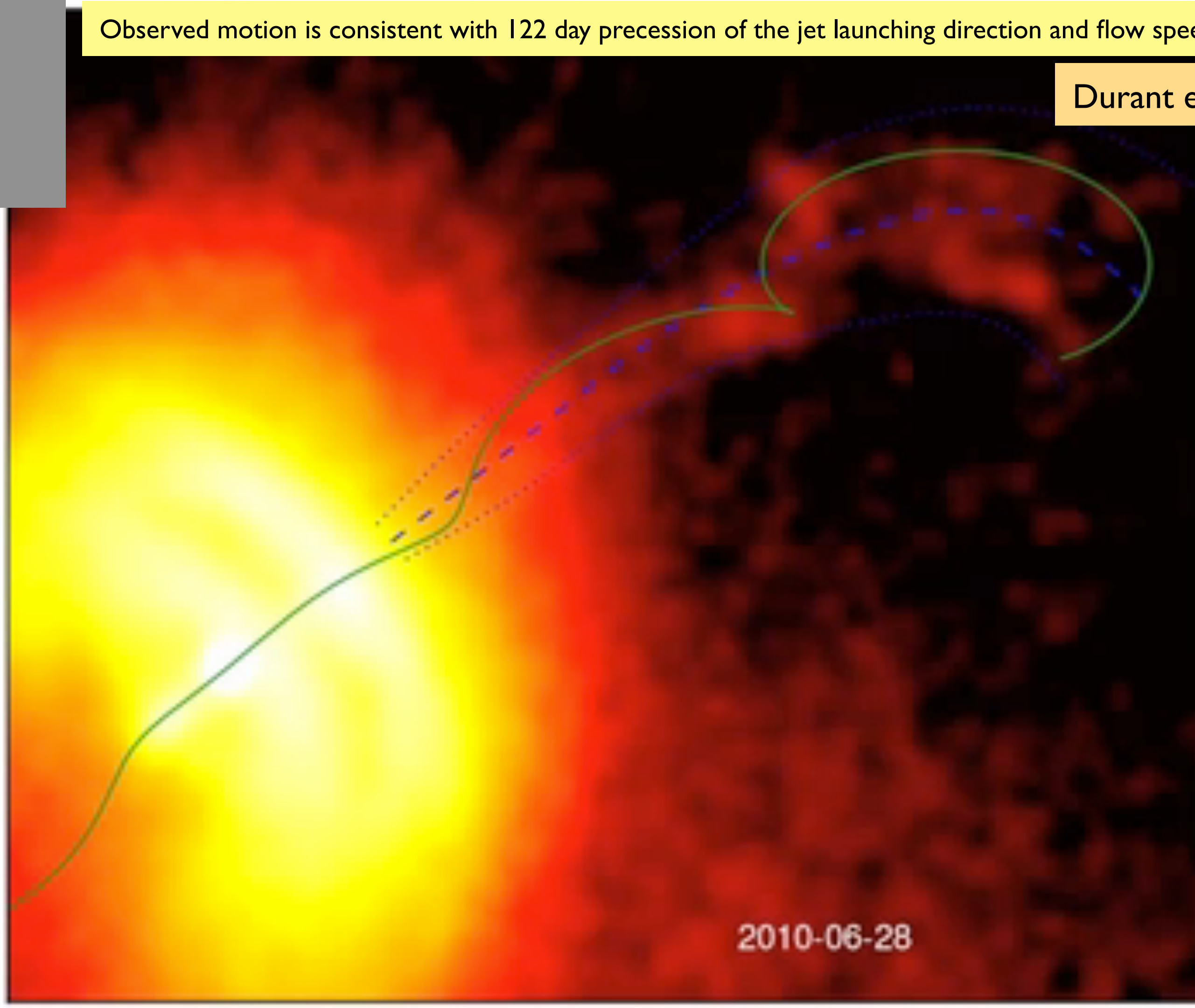


The Vela Pulsar's jet: a giant cosmic corkscrew.
Instability or evidence for a torque-free neutron star precession?



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

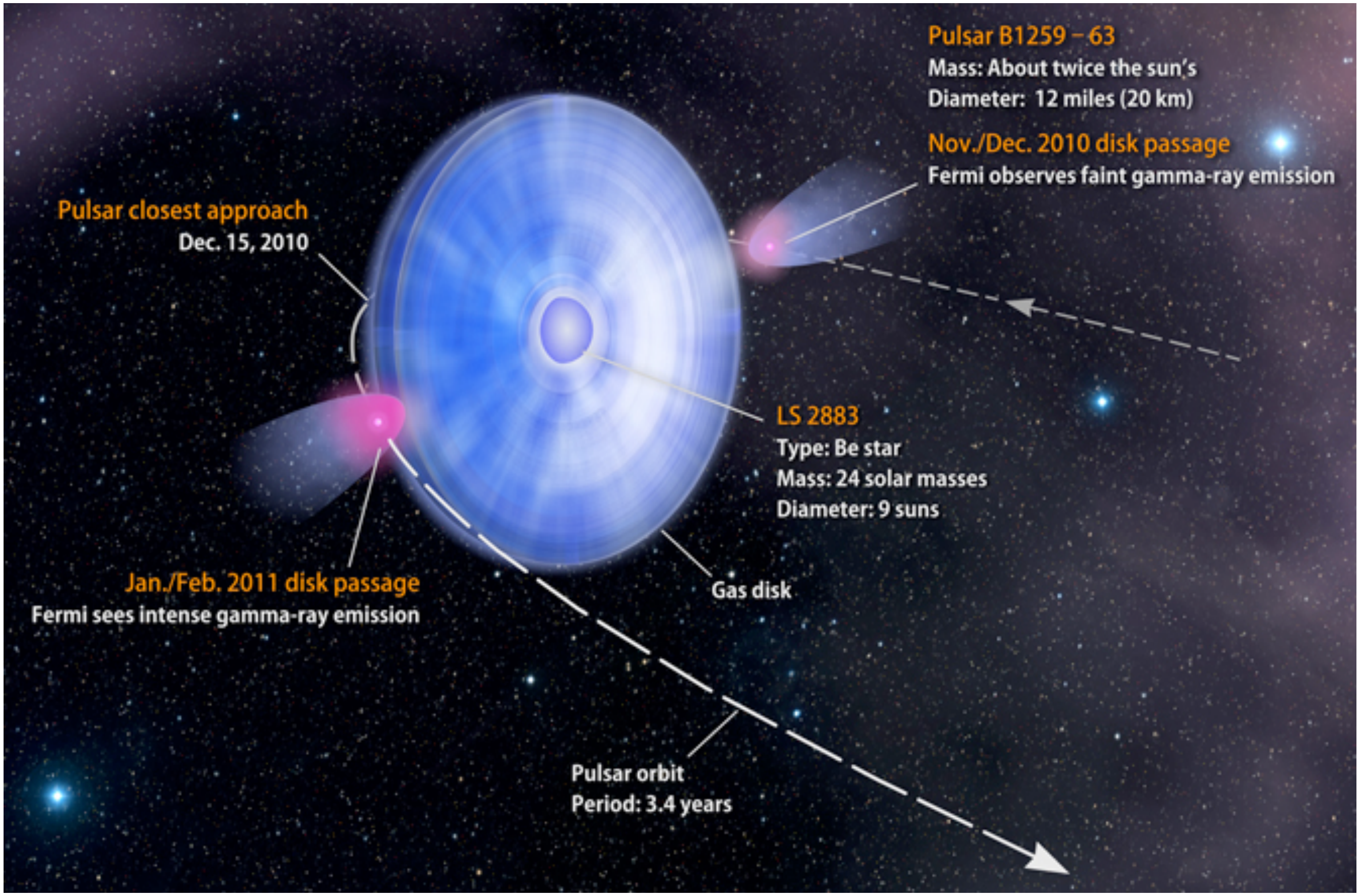
Durant et al. (2013)



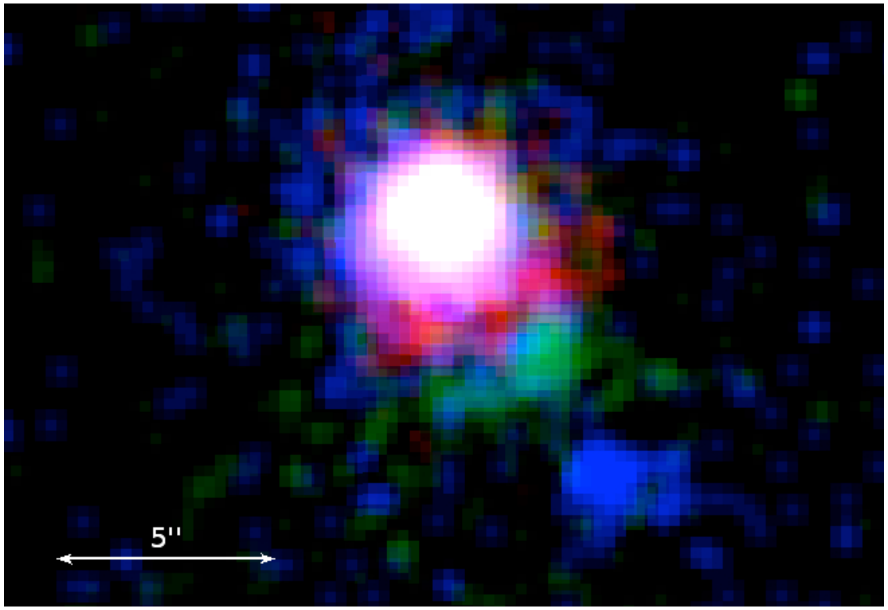
Why precession may be interesting? Non-spherical NS is a source of gravitational waves!

Currently, monitoring Vela jet dynamics is very expensive, requrires >60 ks ACIS exposures…

Probing pulsar wind physics in a different regime: Colliding winds in B1259-63



(Credit: NASA's Goddard Space Flight Center/Francis Reddy)



Between the 3rd and 4th observation the extended structure moved by 2.5''±0.5''.

This corresponds to the apparent proper motion

V=(0.15±0.03)c

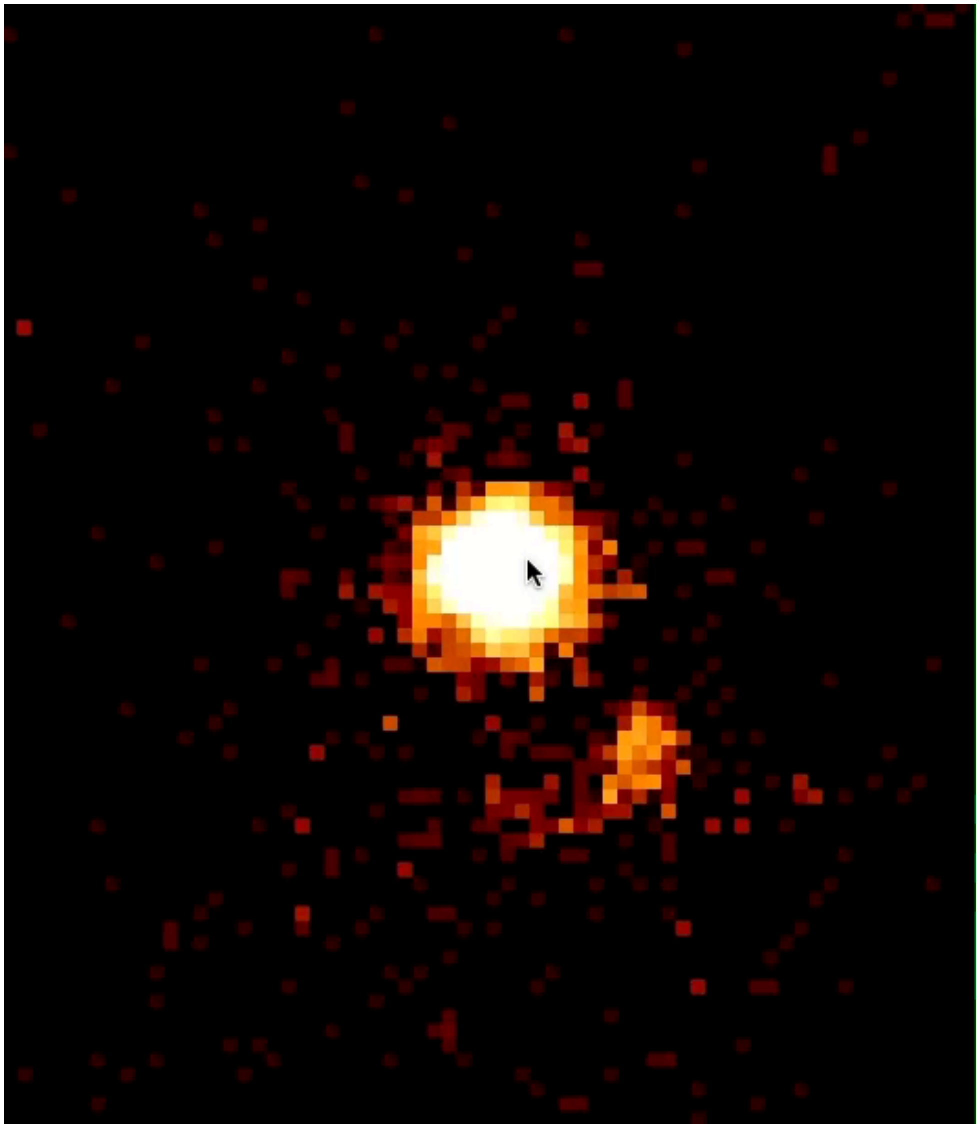
The feature moves with acceleration or changes the direction of motion!?

Spectrum gets harder with time!?
Latest observation suggests Γ=0.8±0.2 for absorbed PL model.

Pavlov et al. 2015

3 observations together:

Need more photons to measure spectrum!



I hope X-ray Surveyor will:

- measure injected SED at the termination shock in ~20 PWNe accurately enough to allow us to establish the differences at high significance and allow one to study their origin => learn about **acceleration mechanism**
- map the inner structure of collimated outflows (pulsar tails and jets in this context) and the evolution of the their properties with the distance from the source=> **physics of relativistic magnetized outflows (AGN jets too!)**
- capture the dynamics of pulsar winds (precession, blob velocities, instability timescales, differences between th equatorial and polar outflows, PWNe in HMXBs) => 3D **structure of the flow, connection to NS properties**
- If the resolution is better than 0.5 arcs then resolve the structure of the termination shock region and jet formation region in ~10-20 PWNe (vs. 2) => **jet formation mechnism, connection to NS geometry** (spin, velocity, magnetic dipole vectors wrt. to line of sight) .

Thinking out of the box….

- Detect the bulk of the NS population (dead pulsars and magnetars) and isolated BHs
- Luminosities for NS 10^{28}-10^{30} erg/s (below Bondi-Hoyle according to recent models)
- Need large area survey (can be combined wih large area AGN surgey) or follow up of microlensing events (OGLE)
- Models suggest ~12 BHs per deg^2 (Fender et al. 2013)
- Models suggest ~100 NSs per deg^2 (10^9 in th eGalaxy)

PWN/pulsar science with X-ray Surveyor

Brief statement for Science Definition porposes:

X-ray Surveyor will be able to observe the structures of several sufficiently extended and bright PWNe of different morphological types and ages. The sensitive spatially-resolved spectroscopy enabled by X-ray Surveyor will constrain transport and particle acceleration mechanisms, particle numbers, magnetization and energetics of ultra-relativistic plasma in pulsar winds and allow us to study the evolution of magnetized relativistic outflows both in time and with the distance from the pulsar. With higher angular resolution will be possible to establish the connection between PWN morphologies and intrinsic pulsar parameteres. It will find the currently missing 99.99% of the NS population and likely discover nearby isolated accreting black holes.

Needless to say….

that I like the ideas of

- sticking a polarimiter in there
- doubling the angular resolution

This would be not a leap but “a giant leap”!