X-ray and optical emission from neutron stars and PWNe and the connection with the magnetosphere: A whirlwind tour with the emphasis on recent results from Chandra and HST.

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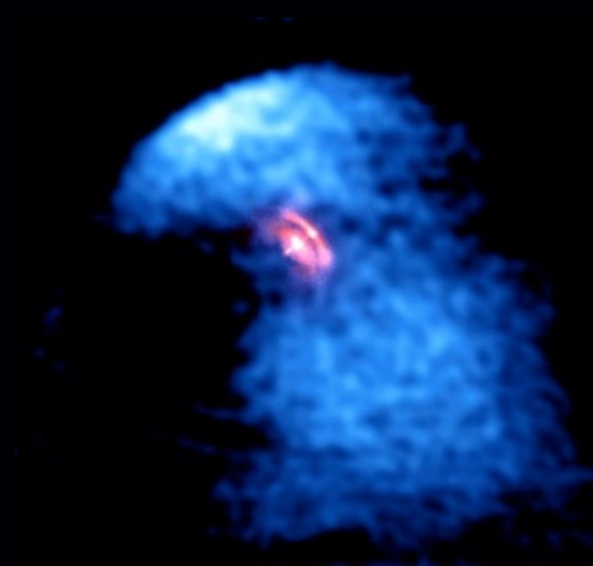
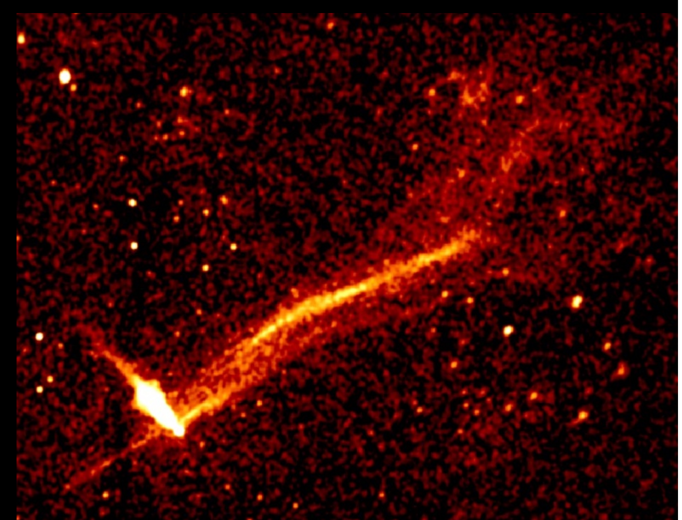




CDY seminar, May 15, 2024

Contents:

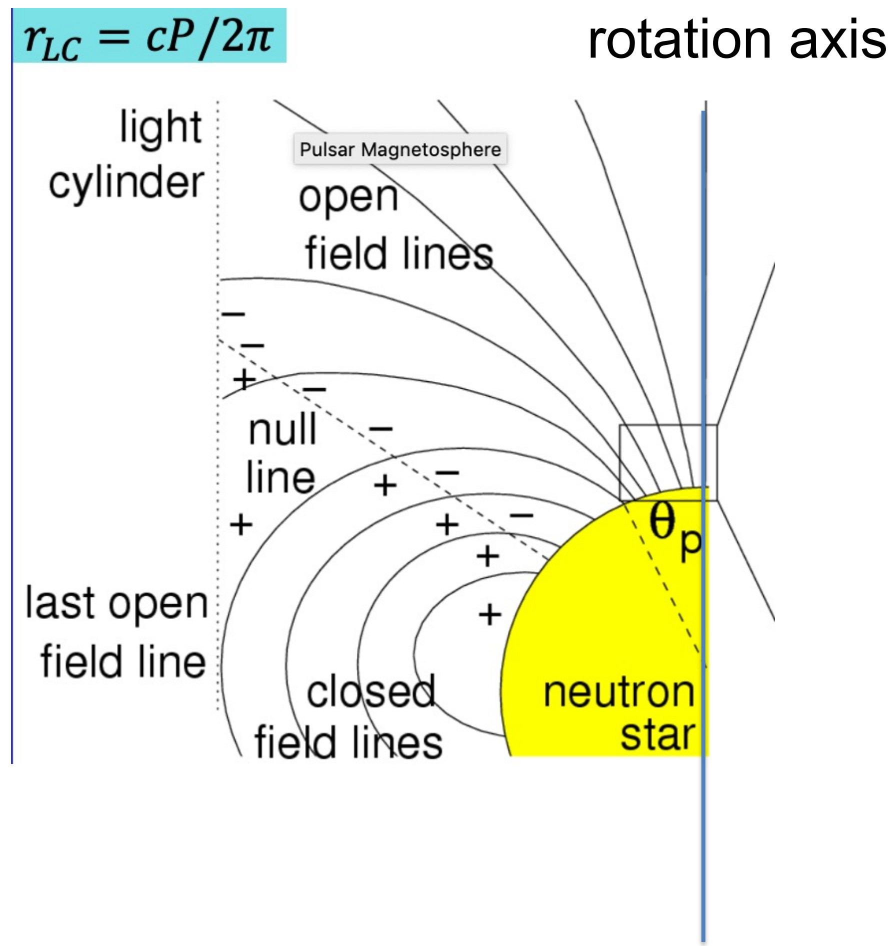
- Part I: X-ray and optical emission from NSs.
  - Many faces of NSs in X-rays
  - Limited results from UV/optical/IR
- Part II: Pulsar-wind nebulae in X-rays (and radio)
  - Torus-jet morphologies, deep images, spatially-resolved spectra
  - What happens if pulsar moves very fast?
  - How can we learn about underlying physics?
- Part III: Connection between PWN structure and GeV pulse profiles: probe of magnetospheric emission models.

Part I: Emission from neutron stars

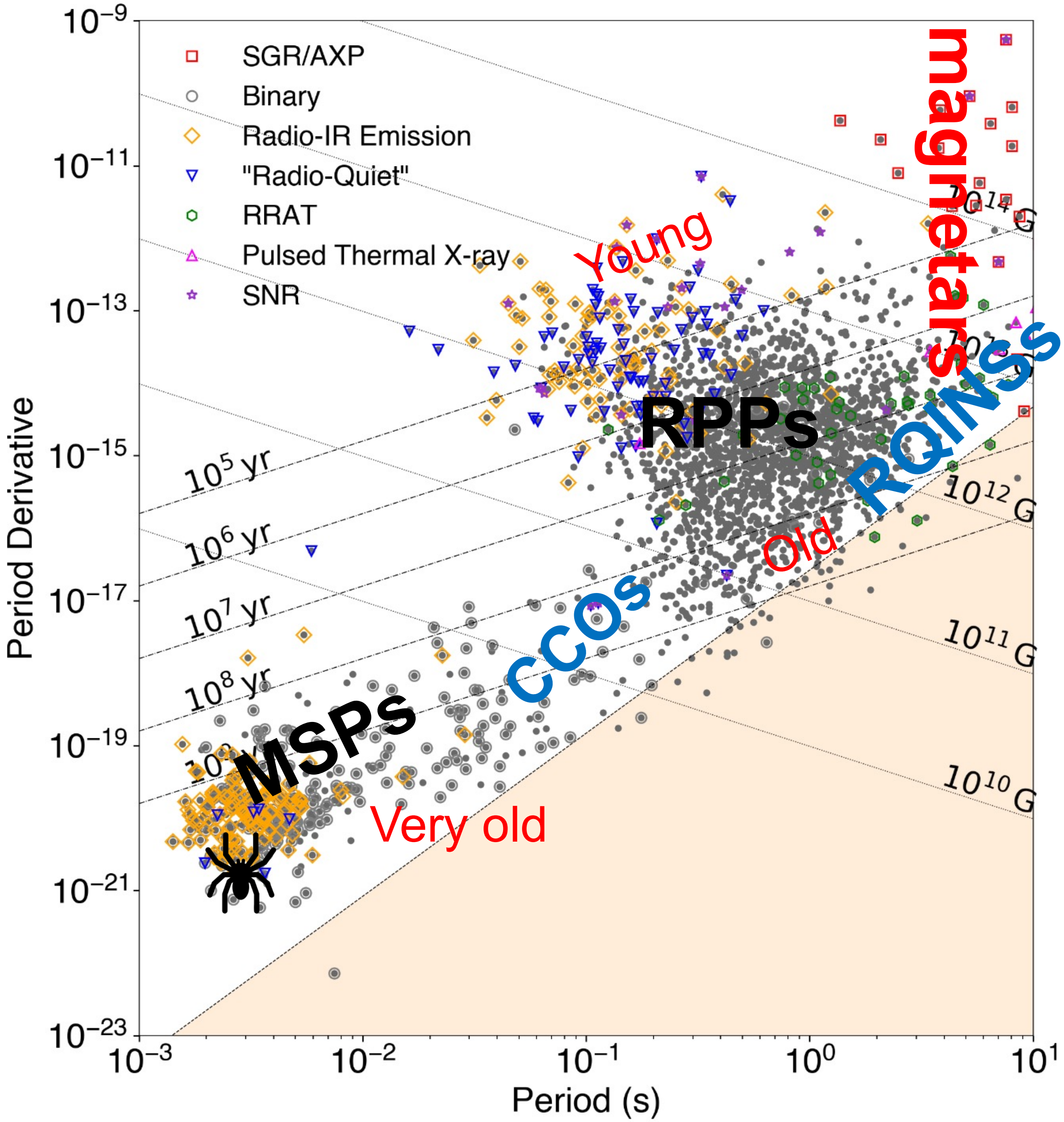
from surface or interior and vicinity of the *light cylinder*

- Observations: Pulse profiles, variability, spectra

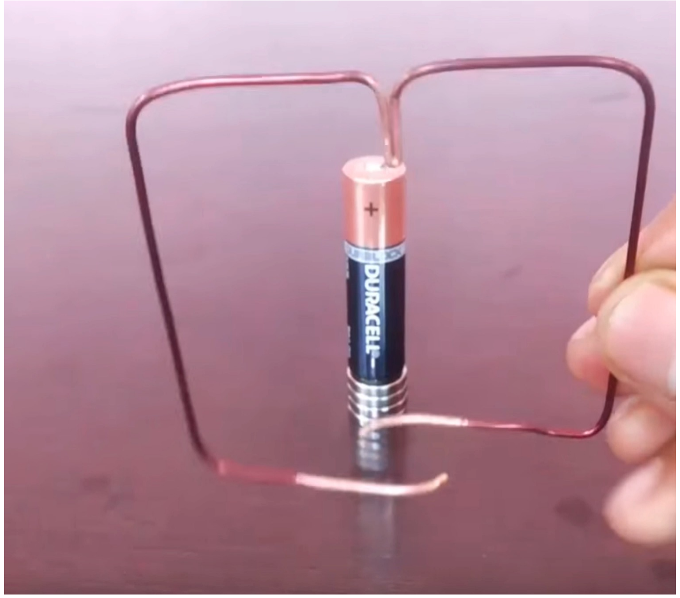
- Demographics: Pulsars, magnetars, CCOs, RQ(TE)INs, …



NS zoo on P-Pdot diagram



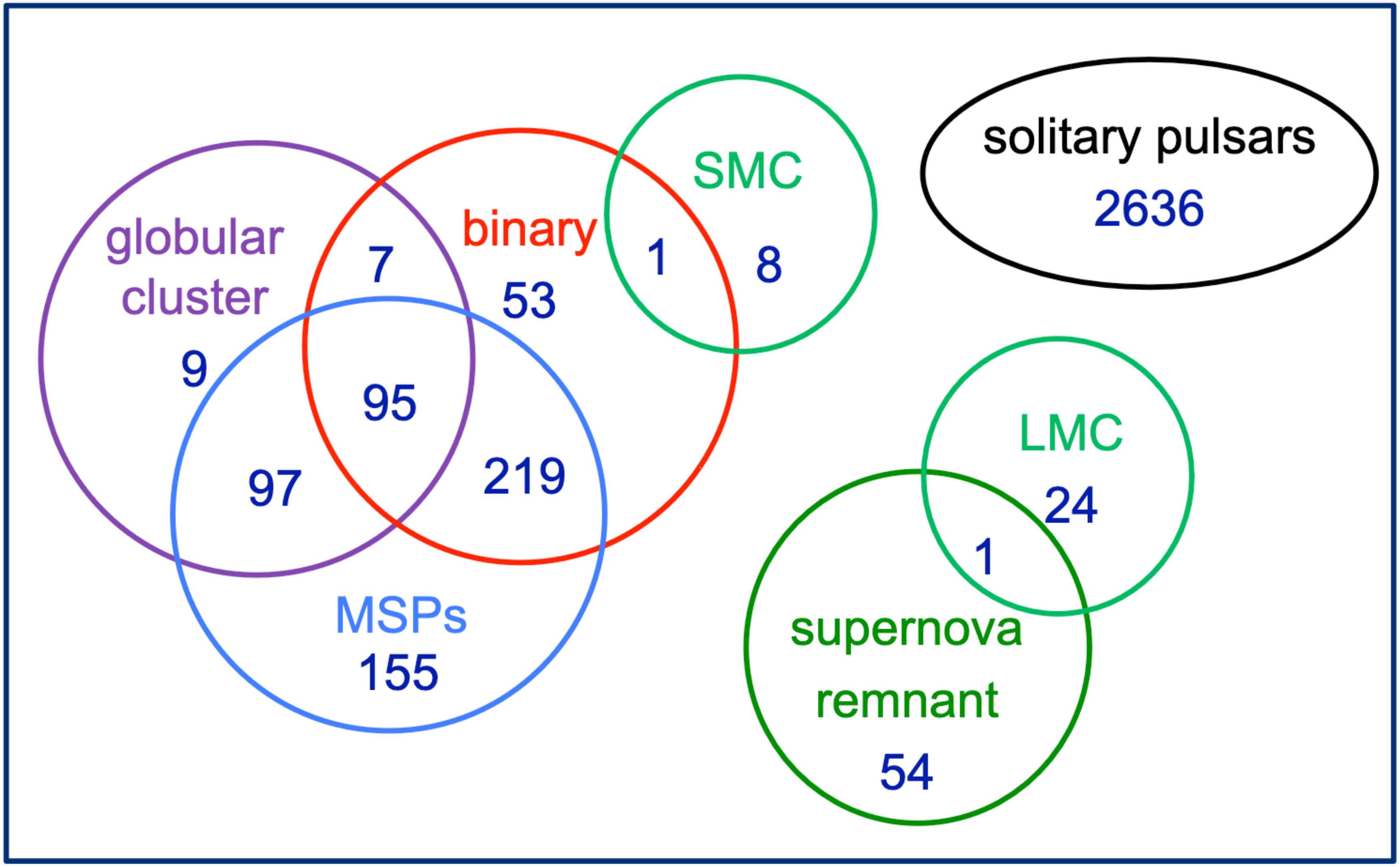
https://psrqpy.readthedocs.io/en/latest/



https://www.youtube.com/watch?v=RGFtpOZxThc

Venn diagram

Total: 3359 (approximate numbers, as of 2023)



Credit: Graham Woan

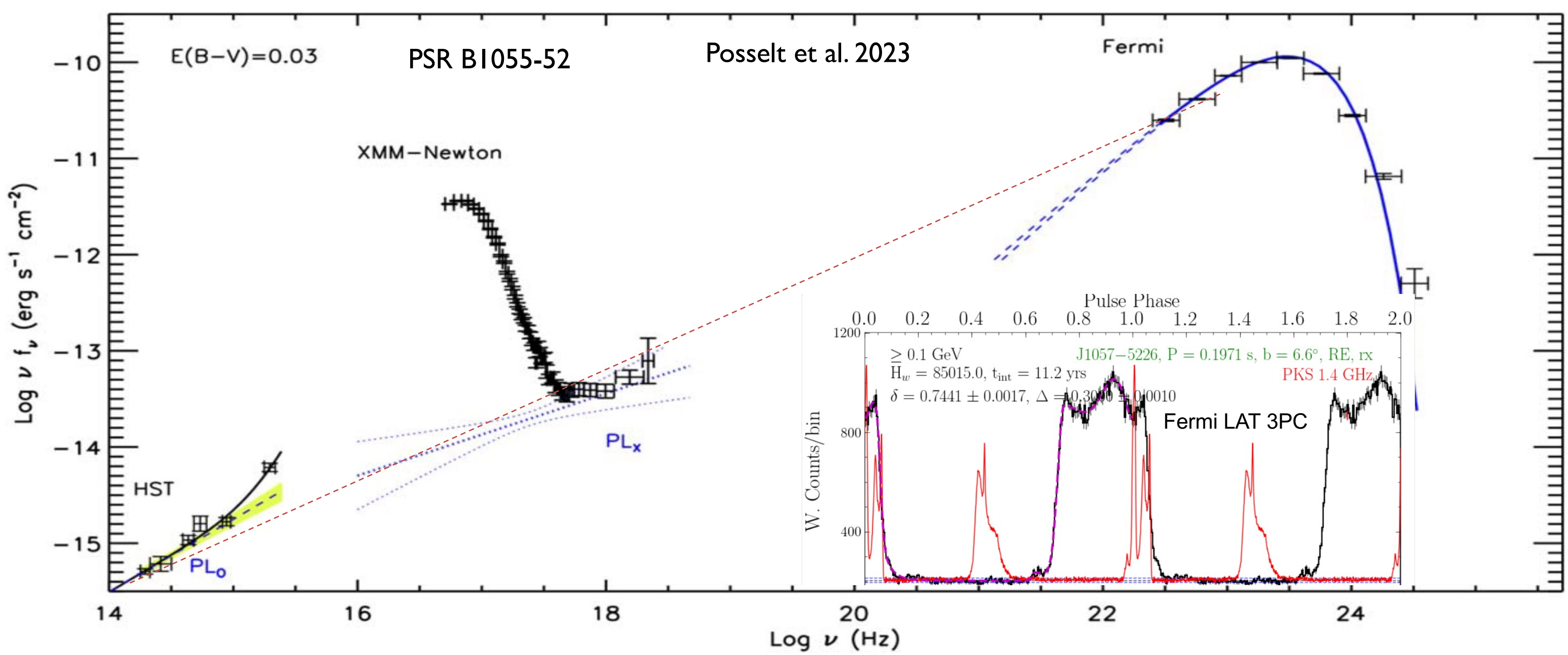
https://radio.astro.gla.ac.uk/pulsar_course/lecture05.pdf

Rotation-powered pulsars

- NSs for which most of their emission is thought to be powered by the NS rotational energy which is being transferred to particles by means of EM fields.

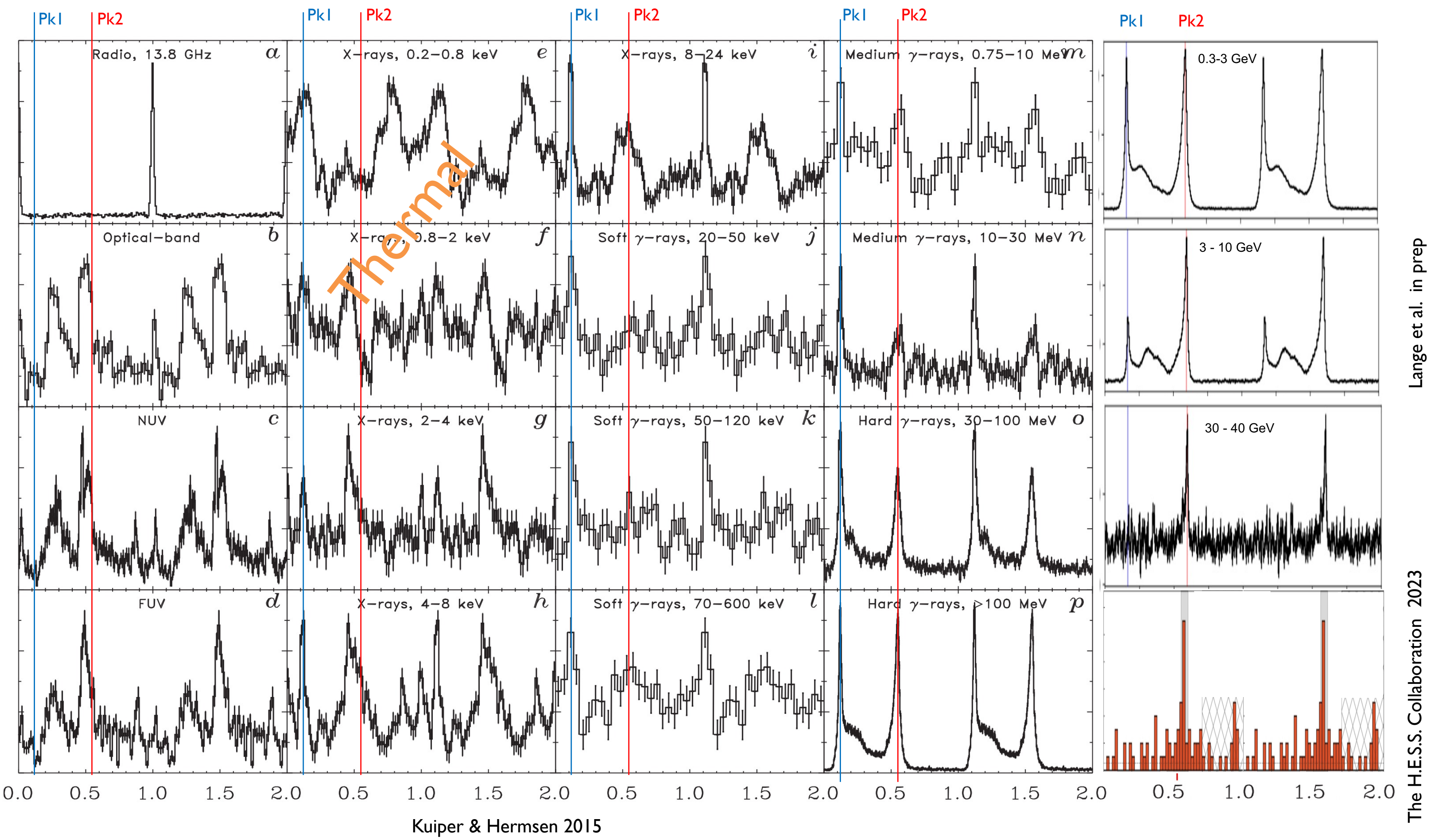
- However, not all emission is nonthermal, thermal emission from surface can be visible in soft X-ray and UV.

- >3,500 pulsars are detected in radio, ~300 in GeV gamma-rays, ~200 in X-rays, and only in ~15 optical/UV.



Pulsars (example of Vela pulsar)

pulse profiles



At lower energies (<2 keV) the two peaks shift (get closer) with respect to their gamma-ray phases.

Pk2 varies a lot with energy but “survives” up to 20 TeV, Pk1 is more “stable” but decreasing rapidly above 3 GeV.

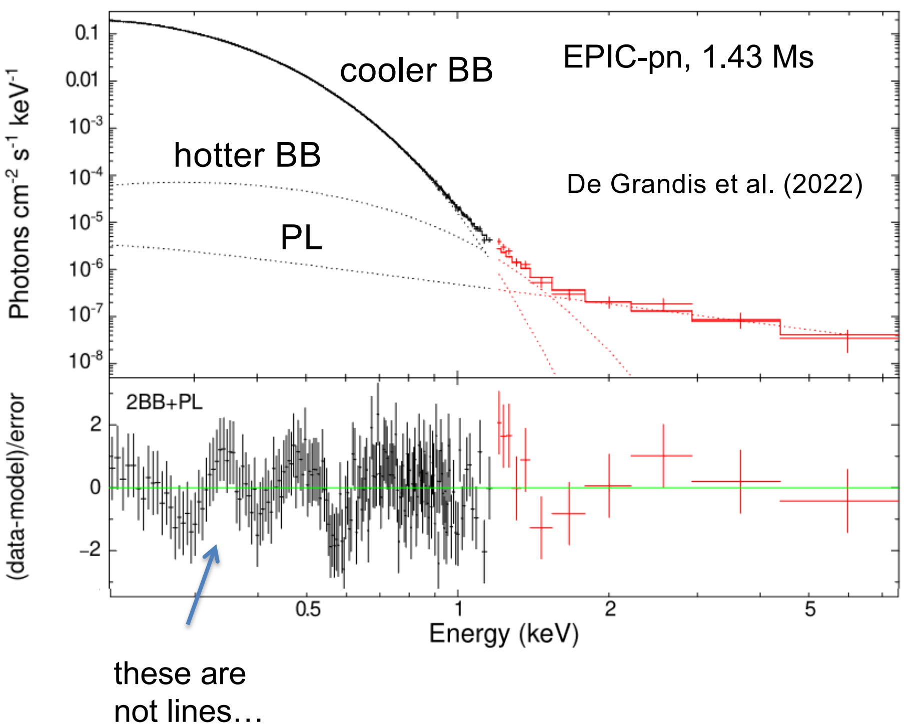
The inter-pulse emission shows interesting behavior between 0.1 - 30 GeV varying in its location and strength.

Radio-Quiet Isolated (Thermally Emitting) NSs: RQINSs

(7 pre-eROSITA plus a few good candidates from eRASS)

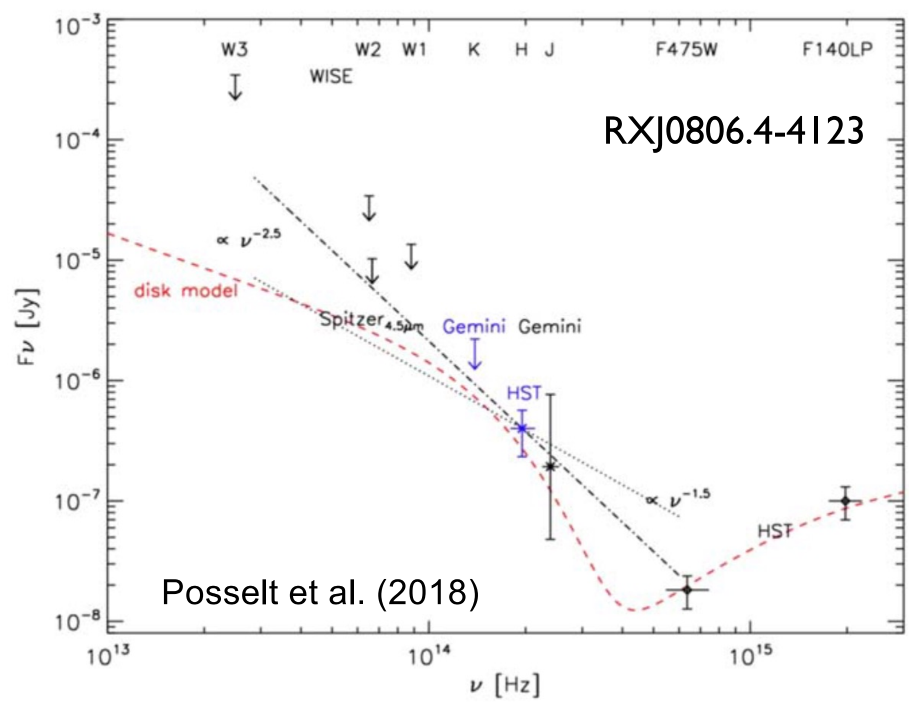
RX J1856.5−3754's soft X-ray spectrum thought to be nearly perfect BB.

However, analysis of 1.43 Ms of XMM-Newton data revealed deviations.



The mystery of optical excesses:

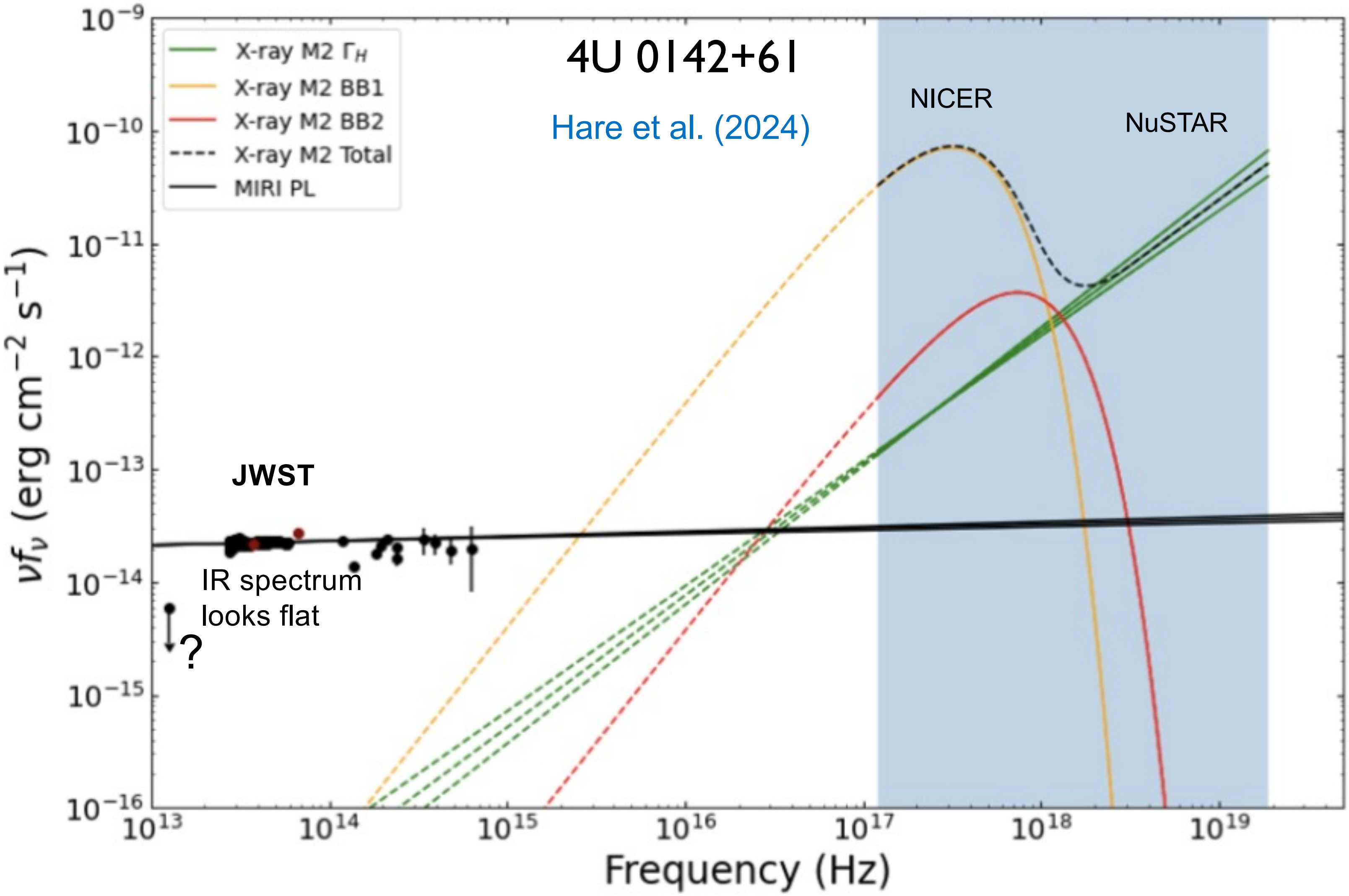
RQINSs show large excesses in UV/optical over the extrapolation of X-ray BB with optical slopes being inconsistent with R-J for most of them.



Magnetars (example of 4U 0142+61)

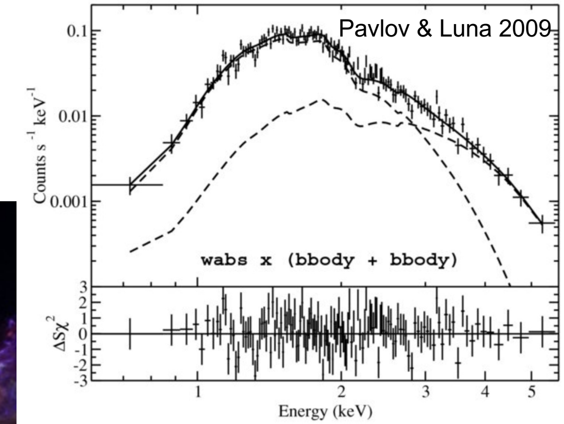
(about 30 are known: https://www.physics.mcgill.ca/~pulsar/magnetar/main.html)

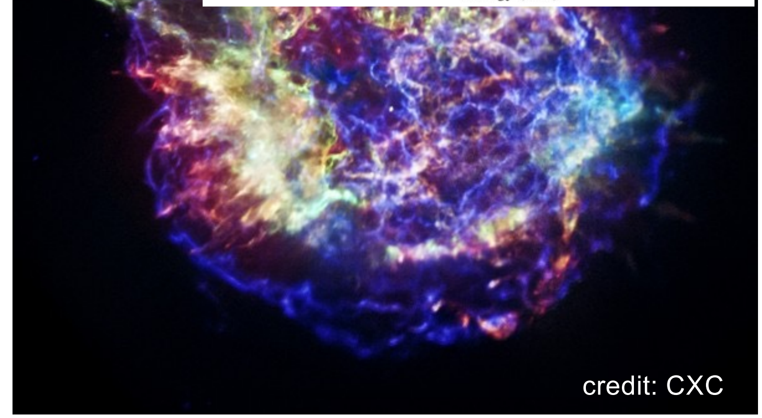
Primarily seen in X-rays although ~12 are detected in near-IR/optical.
Many exabit hard tails in X-rays, some emit radio, some RRPs show magnetar activity.
At least one magnetar (Swift J1834.9-0846) has an X-ray nebula (Younes et al. 2016).



Central Compact Objects (example of Cas A CCO)

(about 10 are known)



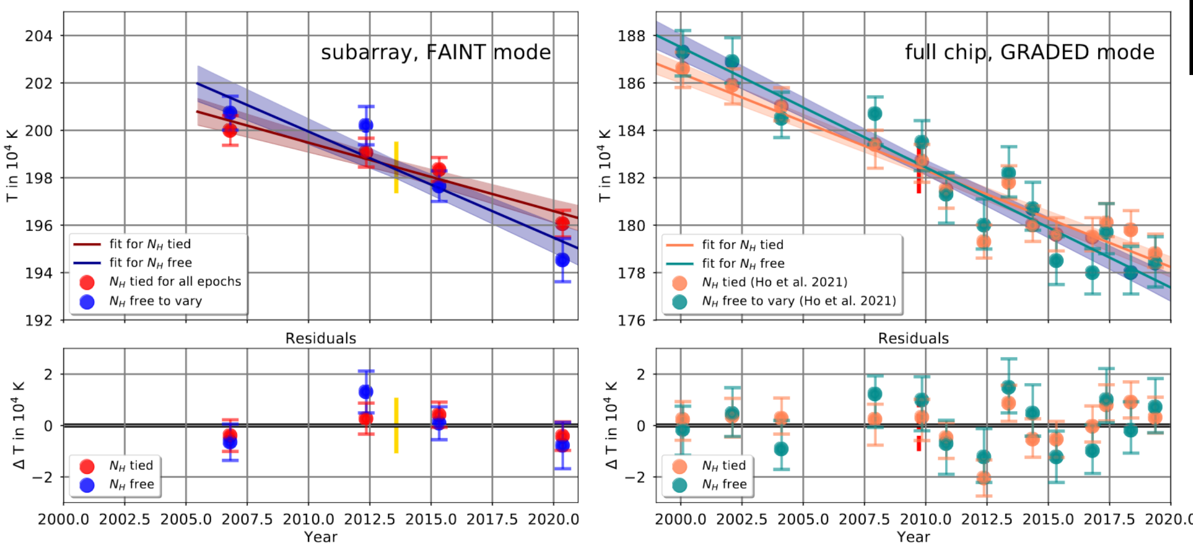


Very young (based on their host SNR properties), rapidly cooling objects.

Purely thermal soft X-ray spectra.

Lack non-thermal emission at any wavelength.

Likely have weak dipolar B fields but may have buried strong internal fields. See Gotthelf et al. (2013)



Posselt & Pavlov 2022

$$\dot{T} = -2900 \pm 600\,\mathrm{K\,yr^{-1}}$$

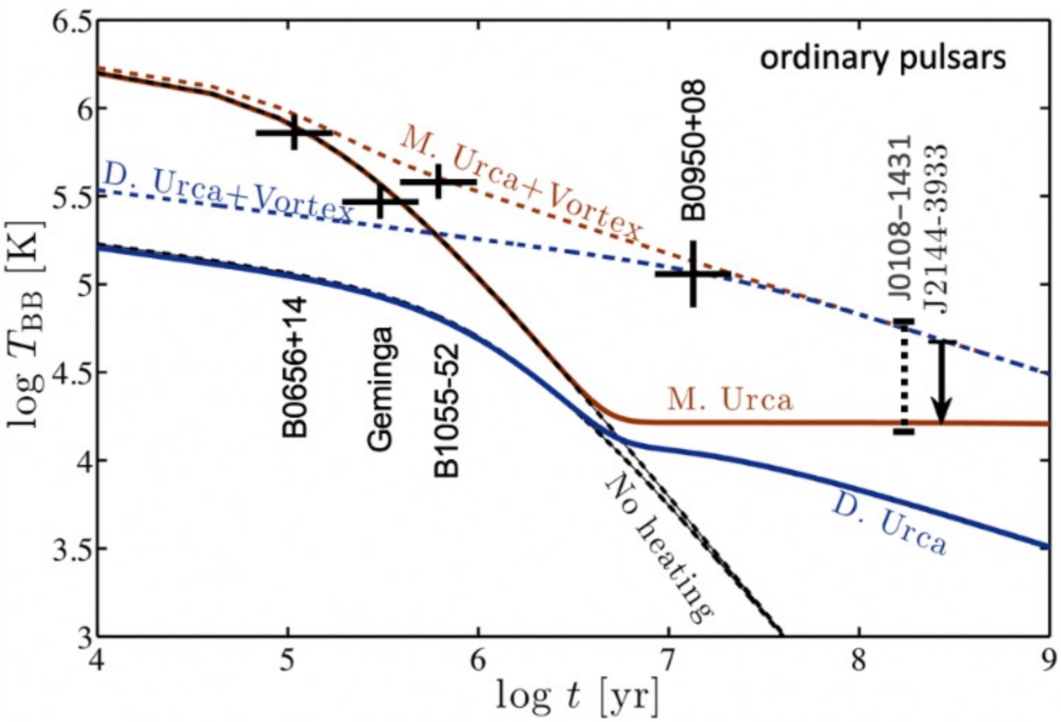
or

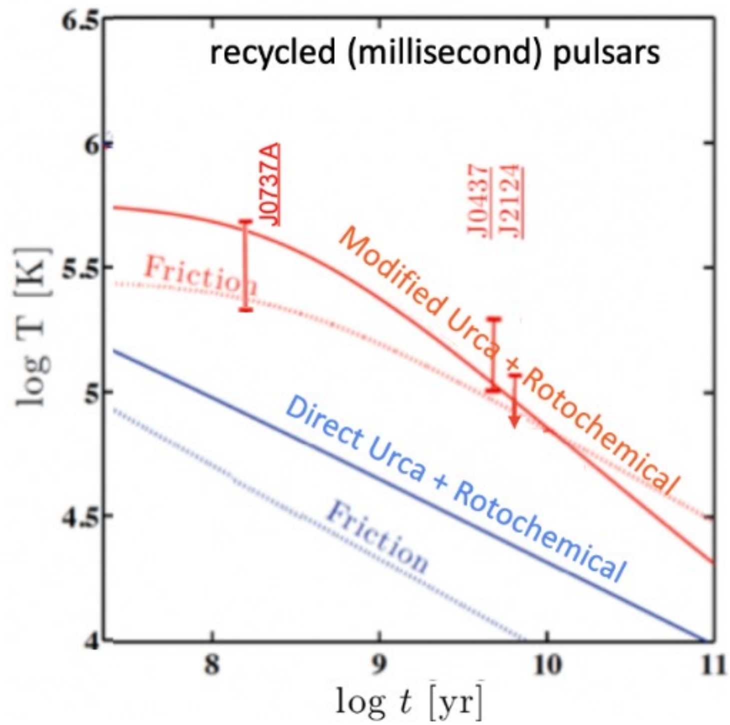
$$\dot{T} = -4500 \pm 800\,\mathrm{K\,yr^{-1}}$$

depending on atmosphere model

How cold NS surface can be ?

The measurements must be done in UV with HST or optical with TMT.





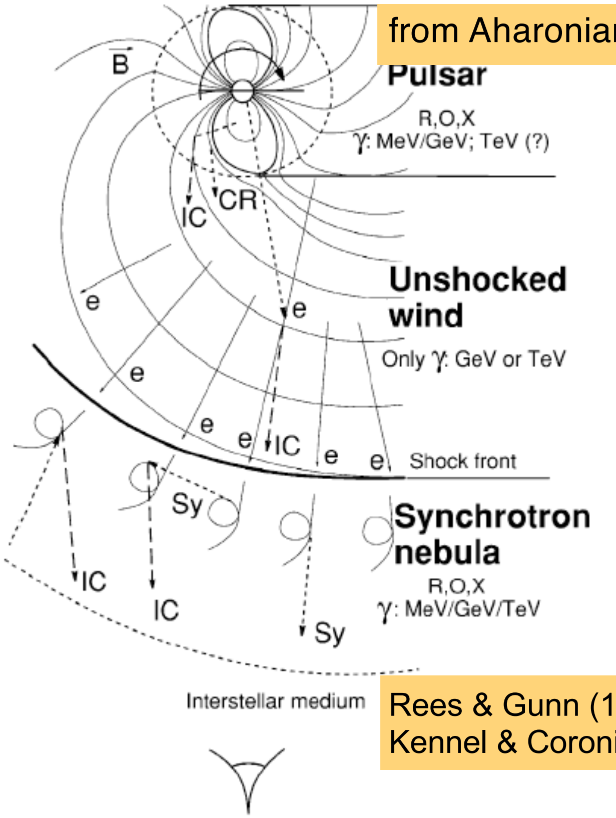
Credit: model curves are by Andreas Reisenegger.

Systematic HST observations of ~20 old pulsars added ~5 new detections.
Work in progress.

Part I: Concluding remarks

- RRPs:
  - MW phase-resolved spectroscopy remains challenging, requires high-quality data but can shed light on emission sites.
  - May only be understood if delays (aberration, time-of-flight and retardation of the magnetic field) can be accounted for within some magnetosphere emission model framework.
  - It is likely that at least some of the emission comes vicinity of LC.
- Magnetars:
  - Evidence of non-thermal emission in optical-IR, MWN
  - At least some of them under some circumstances produce substantial amount of pairs
- CCOs: anti-magnetars (or rather burred magnetars)
  - Clean view of NS atmosphere/surface
- RQ(TE)INs: old magnetars?
  - Mystery of optical-IR excess and varying slopes remains unsolved.

Part II: Pulsar wind nebulae



from Aharonian et al. (2004)

Rees & Gunn (1974)
Kennel & Coroniti (1984)

PWN: Basic properties

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

- Typical energy of synch. photon: $E_{syn}=2\ (\Gamma/2\times10^7)^2\ (B/10\ \mu G)$ keV
  $E_{IC}=10\ (\varepsilon/4\times10^{-4}\ \mathrm{eV})\ (E_{syn}/1\ \mathrm{keV})\ (B/10\ \mu G)^{-1}$ TeV

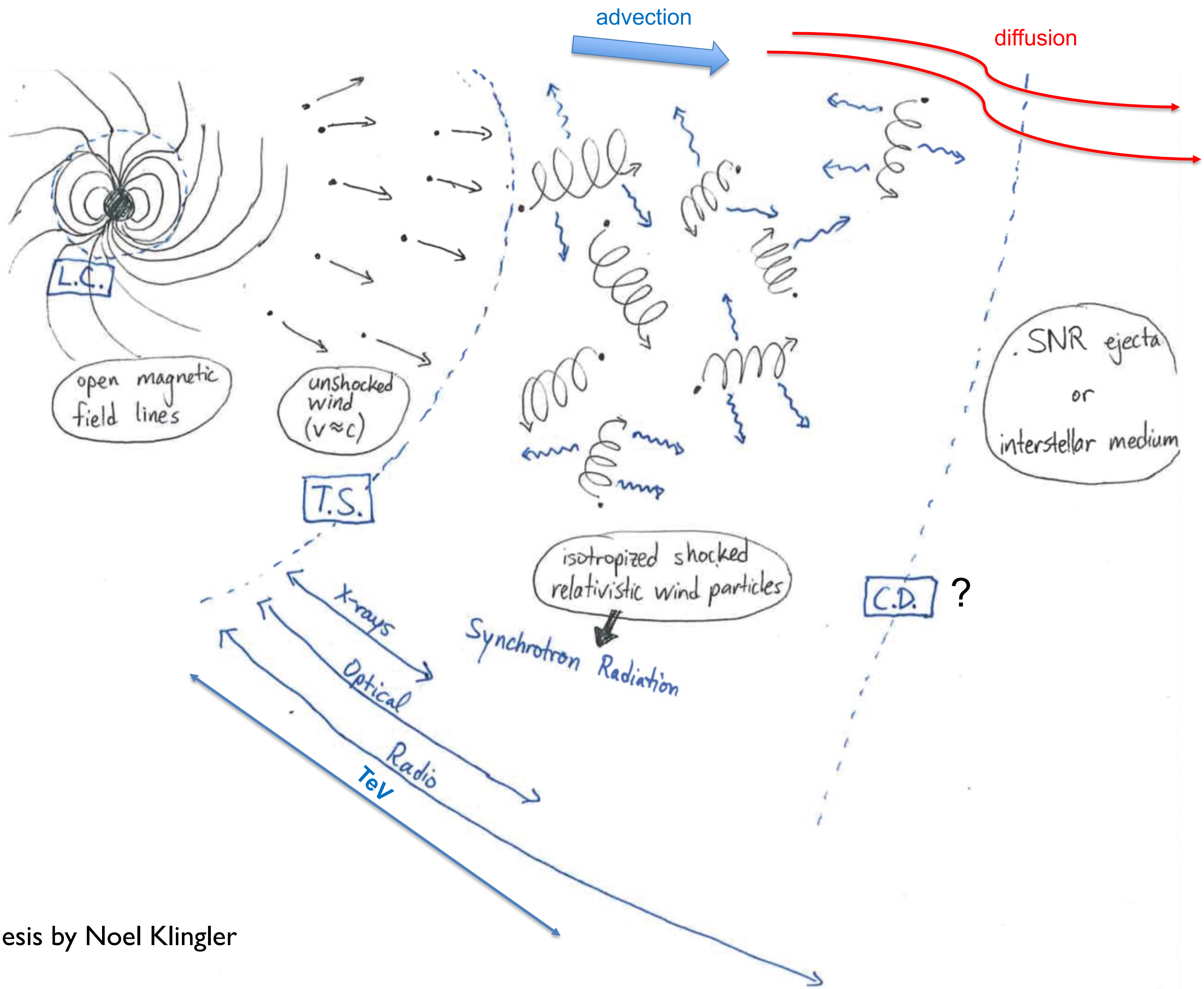
- Characteristic size (in X-rays): $R_s = 0.2\ (\dot{E}/10^{37}\ \mathrm{erg/s})^{1/2}\ (p_{amb}/10^{-10}\ \mathrm{dyn/cm^2})^{-1/2}$ **pc**

- Cooling time: $\tau_X \approx 1.2\ B_{-5}^{-3/2}(E_{\rm syn}/1\ {\rm keV})^{-1/2}$ kyr, for particles emitting synchrotron photons at 1 keV

  $\tau_\gamma \approx 100(1+0.144B_{-6}^2)^{-1}(E_{ICS}/1{\rm TeV})^{-1/2}$ kyr, for particles emitting IC photons at 1 TeV

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

PWN sketch

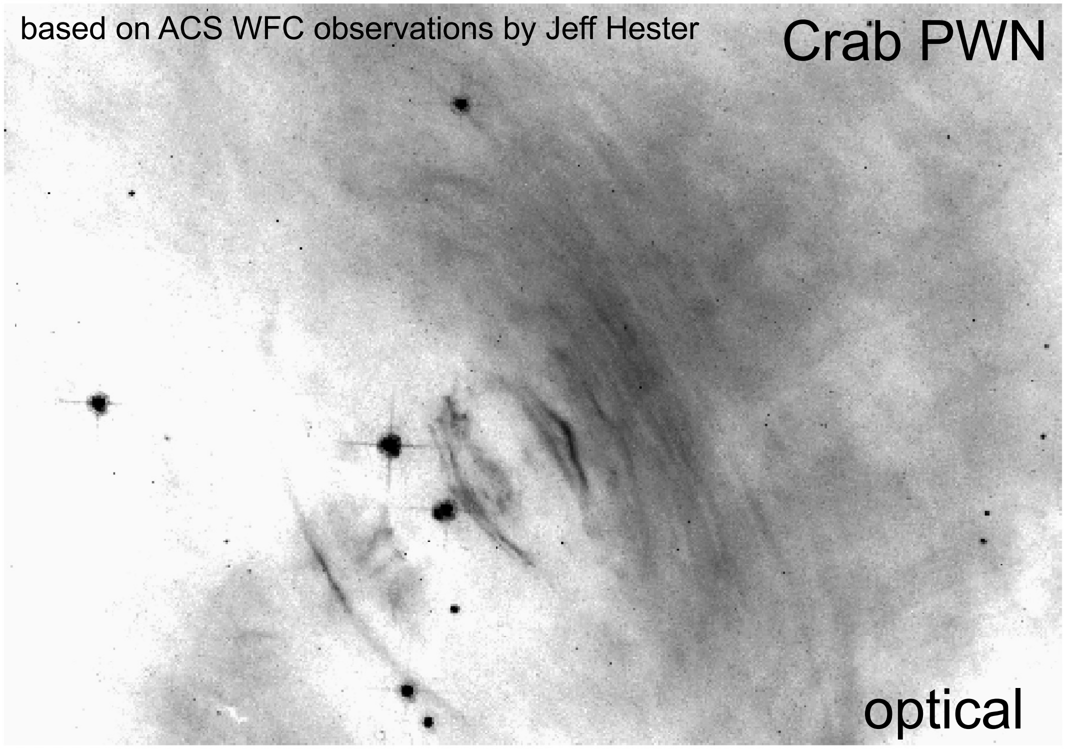


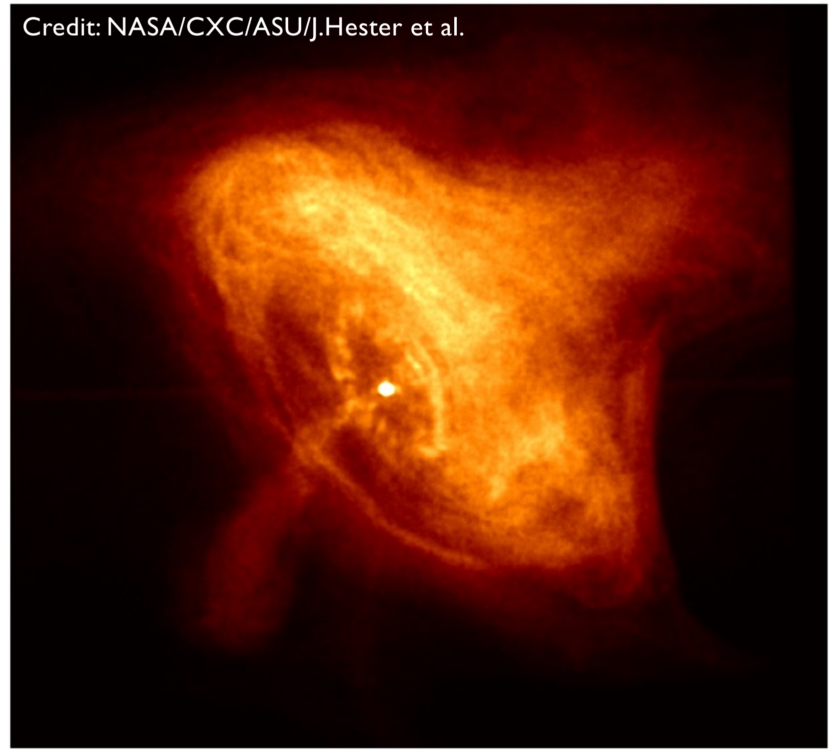
from PhD thesis by Noel Klingler

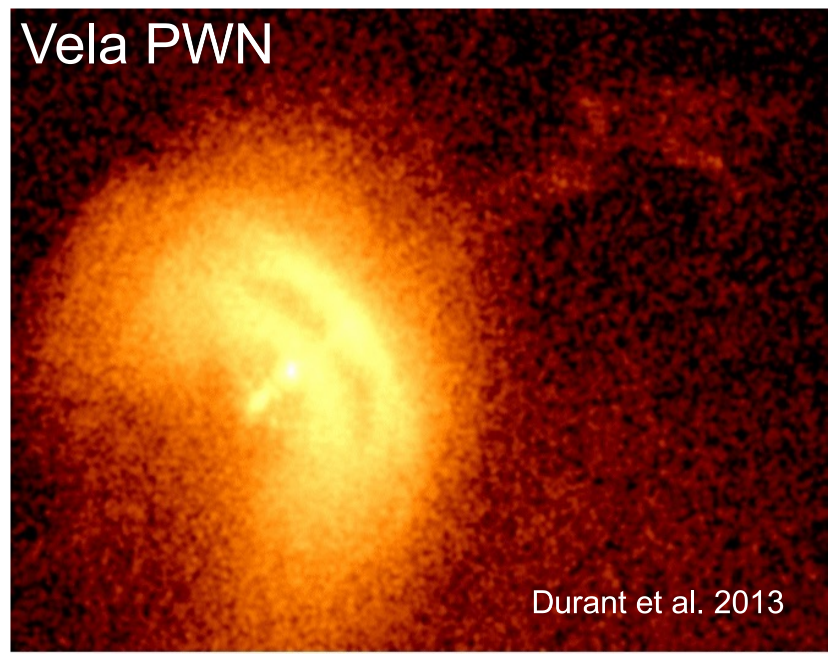
Tasks enabled by **Chandra**, XMM-Newton, and IXPE (relevant for PWN science)

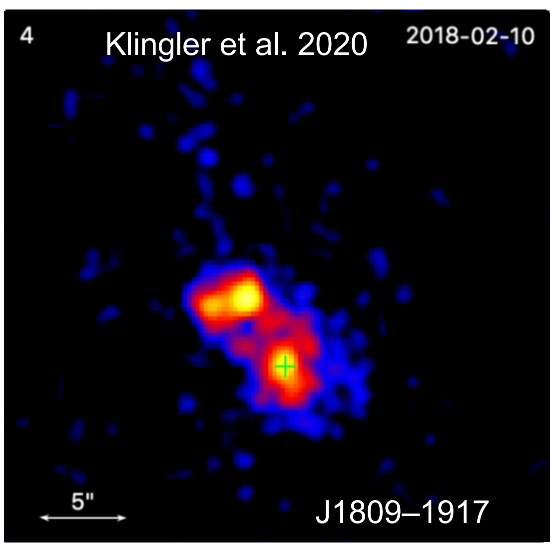
- **separate pulsar from PWN**
- **high-resolution images reveal PWN geometry on (sub)-acrsecond scales**
- spatially-resolved spectroscopy on arcsec and arcmin scales helps to measure **the injected particle SED**
- **resolve very faint sources and finding extended sources (e.g., faint relic PWNe associated with TeV sources)**
- sub-arcsecond localizations allowing to **discover new compact objects** (e.g., pulsars) via multiwavelength matching and analysis
- **measure spectra of objects embedded in complex background (e.g., pulsars/PWNe inside SNRs)**
- **X-ray pulse profiles (separating thermal and nonthermal emission)**
- **Measure magnetic field direction and regularity**

Dynamics





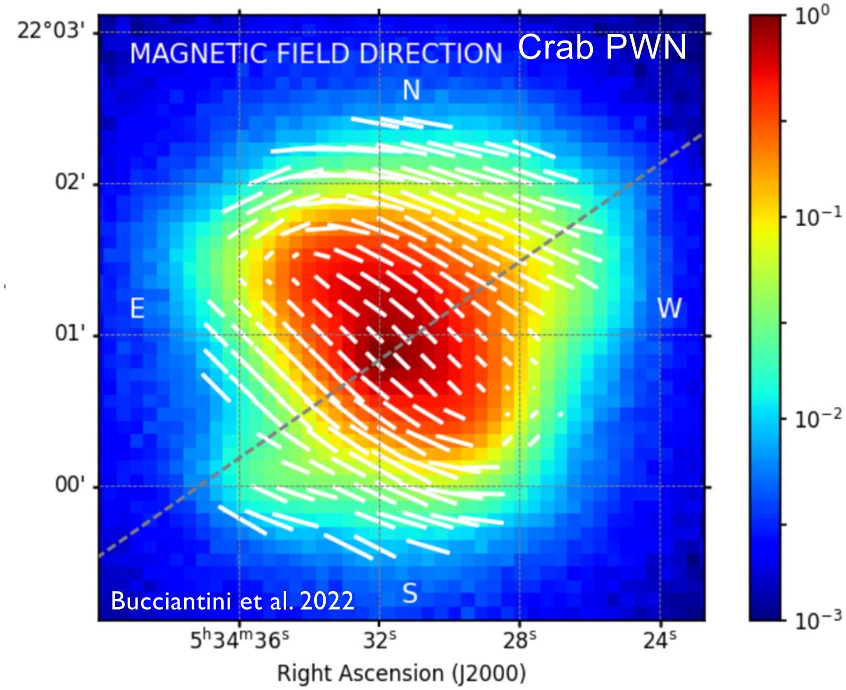


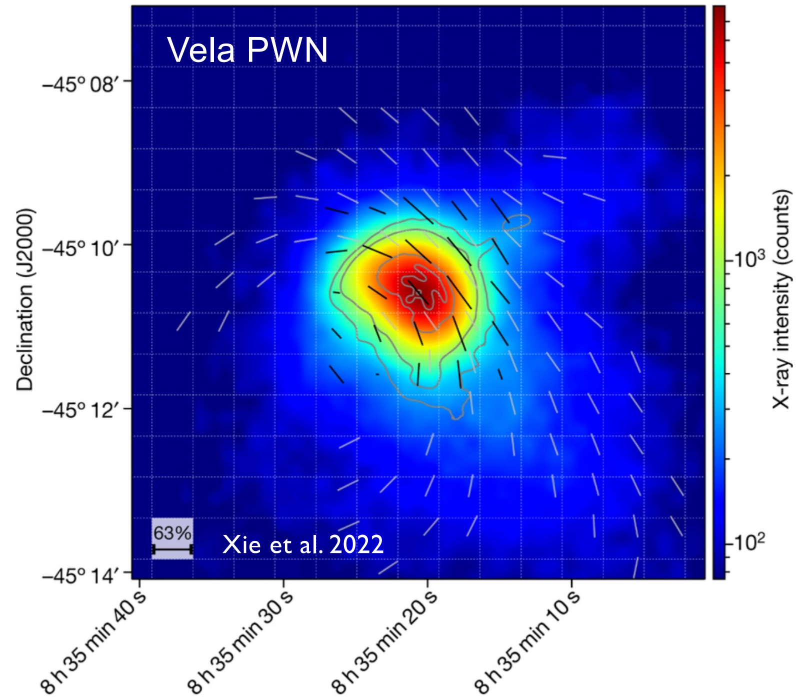


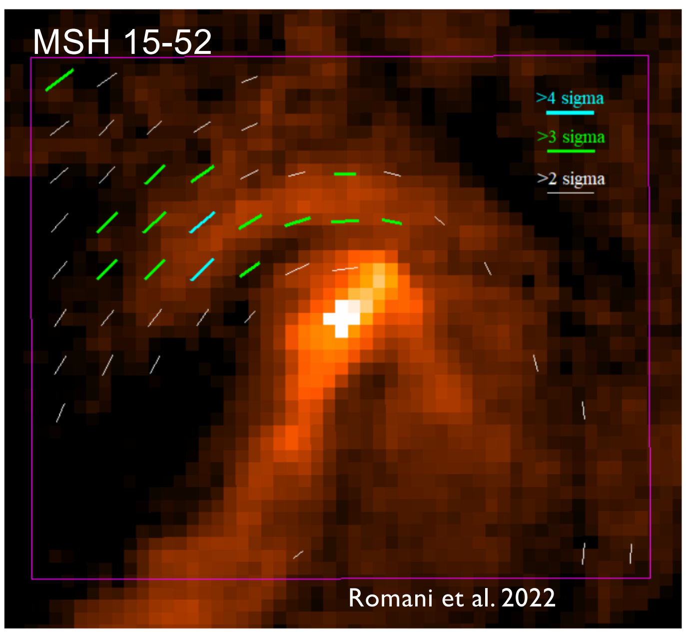
PWNe are clearly variable but variability can be quite different with different PWN features appearing more or less variable.

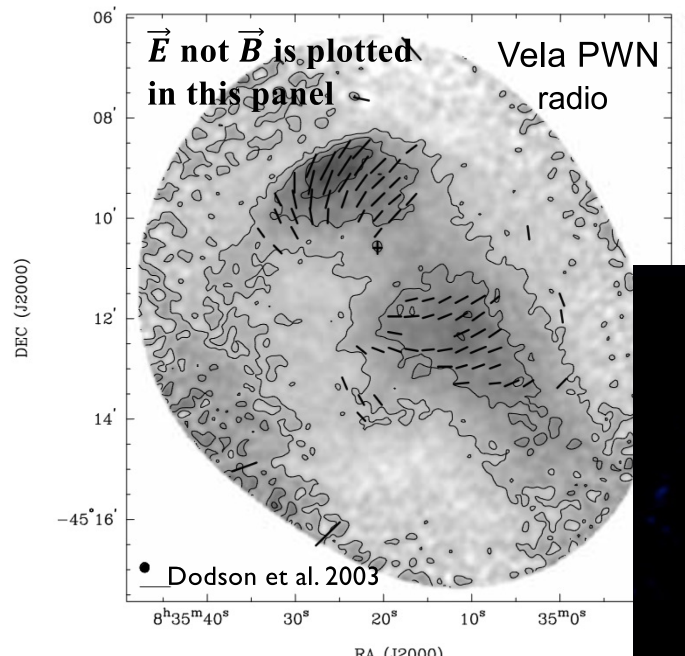
Magnetic field: IXPE and radio polarimetry

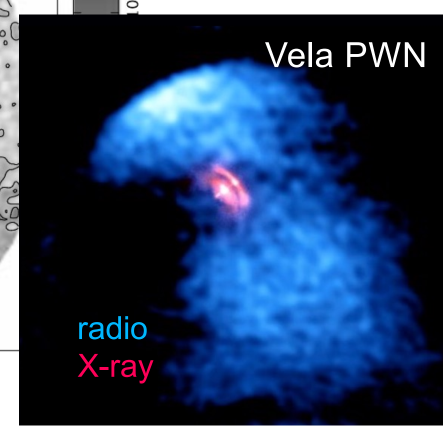
Surprisingly regular magnetic field structure.





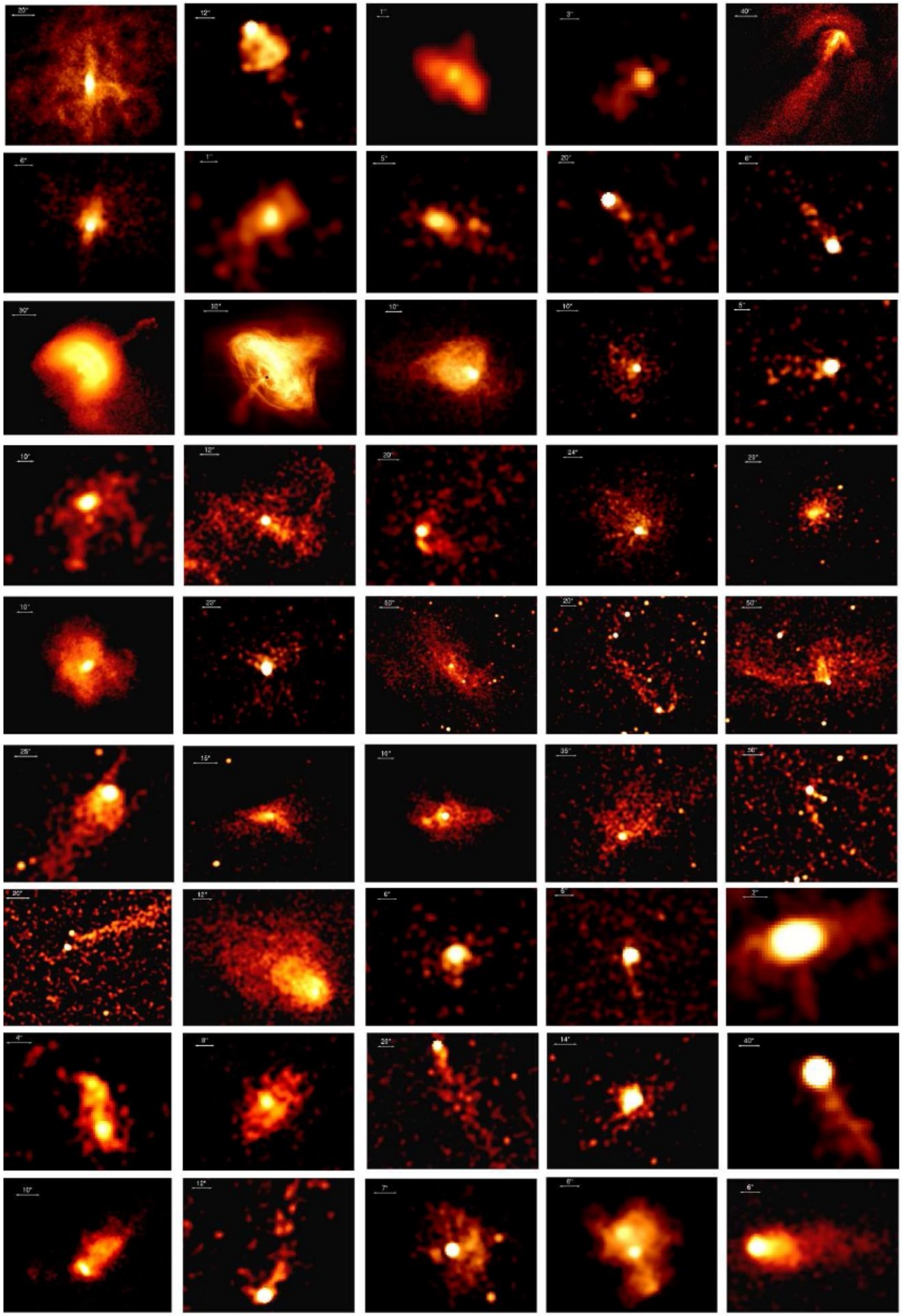






Magnetic field simulations.

Porth, Komissarov, Keppens 2013



Chandra gallery of PWNe reveals diversity of morphologies.

What are the reasons for such diversity?

(1) Pulsar and PW properties: anisotropic PW angular distribution, pulsar's Edot, angle α between magnetic and spin axes, angle ζ between spin and line of sight, PSR velocity

(2) Properties of ambient medium: Density, temperature, pressure gradients

Mach number (1) + (2):

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

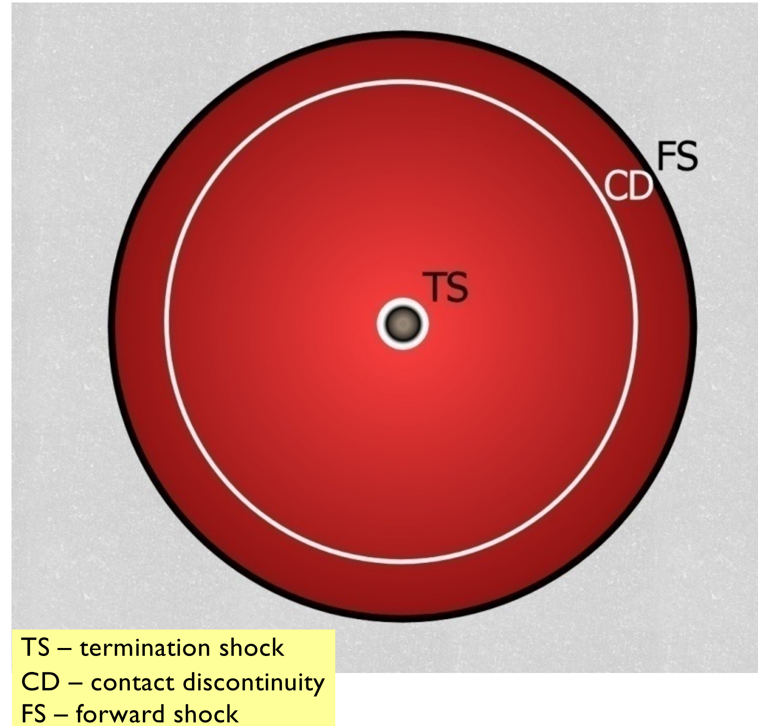
(Gaensler & Slane 2006; Kargaltsev & Pavlov 2008; Kargaltsev et al. 2015; Reynolds et al. 2017)

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

Subsonic velocity:

Isotropic outflow: sphere

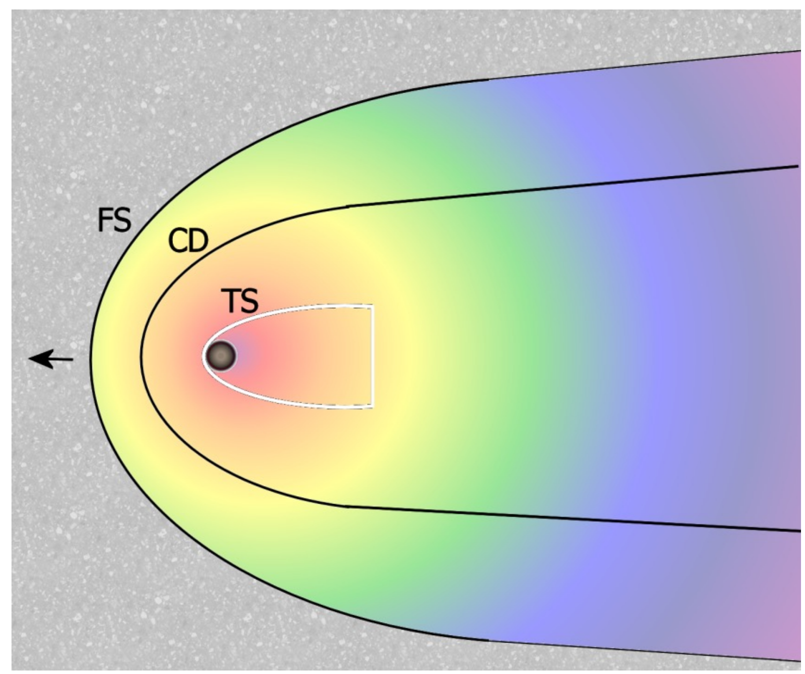
Anisotropic outflow: equatorial + polar = torus + jet(s)



Supersonic velocity:

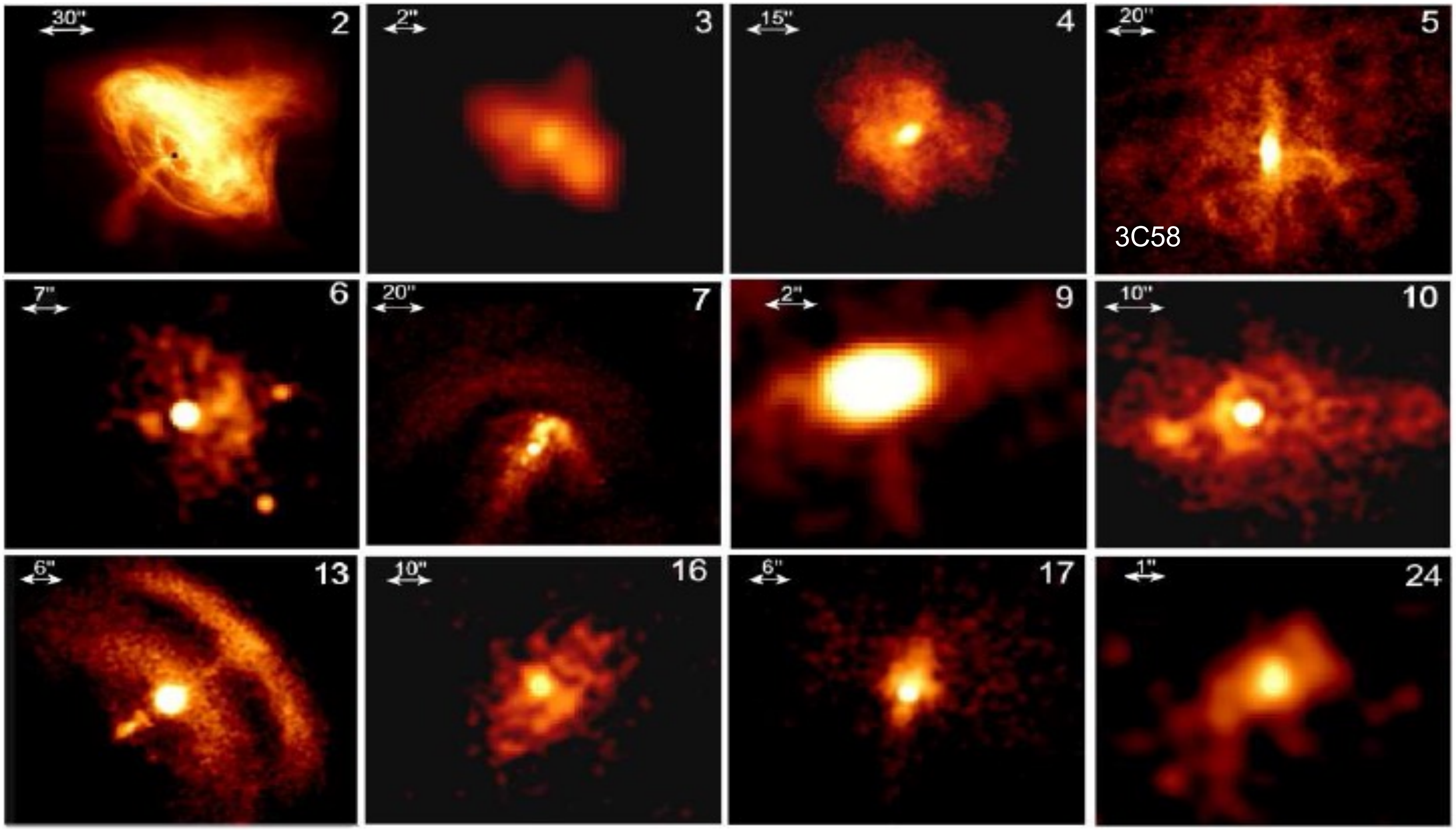
Isotropic outflow: bow shock + tail

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



Of course real images are not like this, examples will follow…

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 (e.g., 3C58), structures are more complex than just torus and jets…

Power of CXO: Two PWNe inside SNRs

PSR J1811-1925/G11.2-0.3

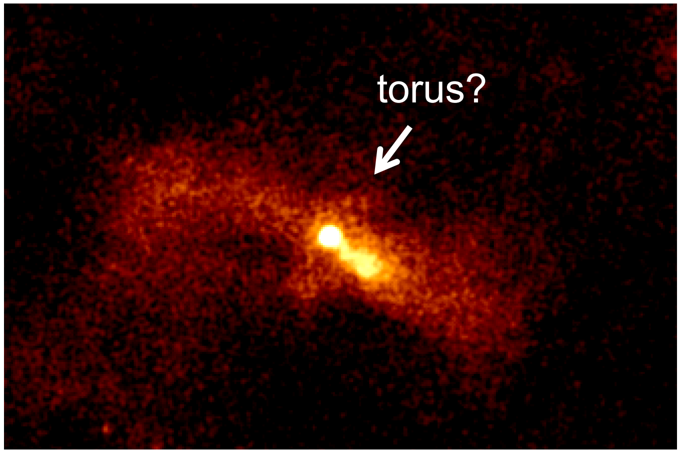
Edot=6.5×10^{36} erg/s, ~2 kyr, 5kpc

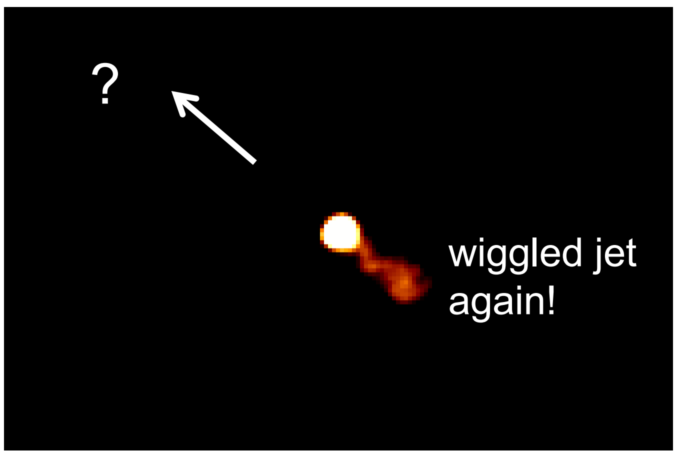
Chandra 400 ks, Borkovski et al. (2016)

PSR B1509-58/MSH 15-52

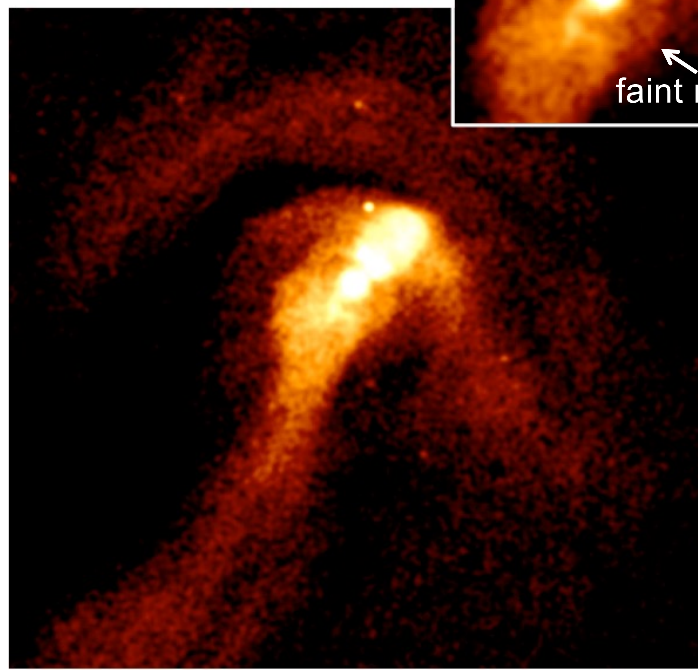
Edot=1.8×10^{37} erg/s, ~1.5 kyr, 5 kpc

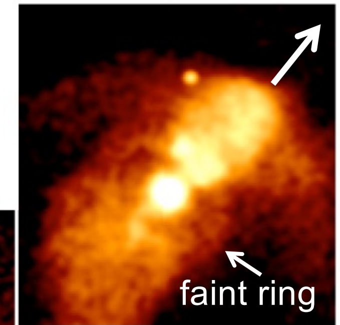
Chandra 190 ks, Yatsu et al. (2009)





Notice helical appearance again, just like that of the Vela pulsar jet!





Jets are much brighter than tori! (and there are more such examples).
Likely these pulsars are more aligned rotators than Crab where the torus dominates.
Indeed, both are MeV pulsars and are either GeV-quiet or nearly GeV-quiet.

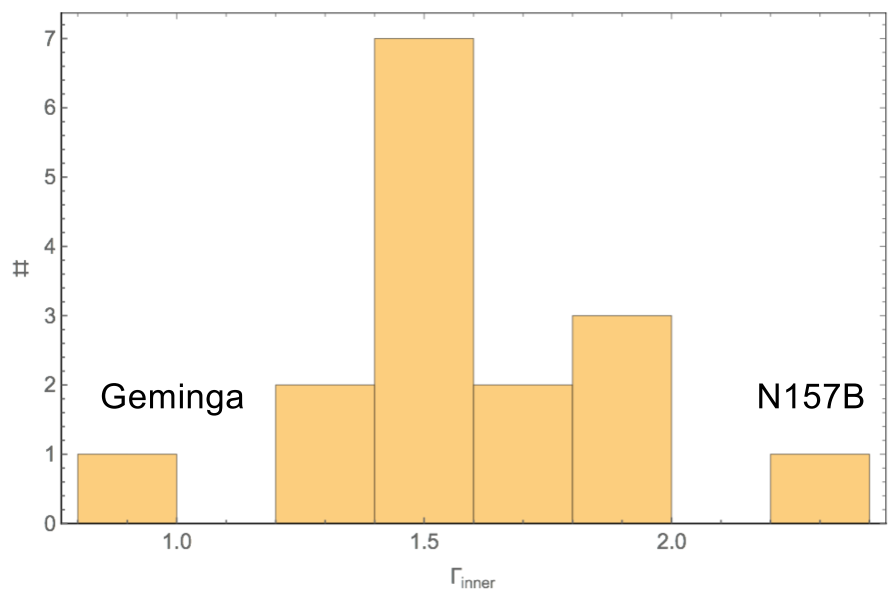
Population properties:

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

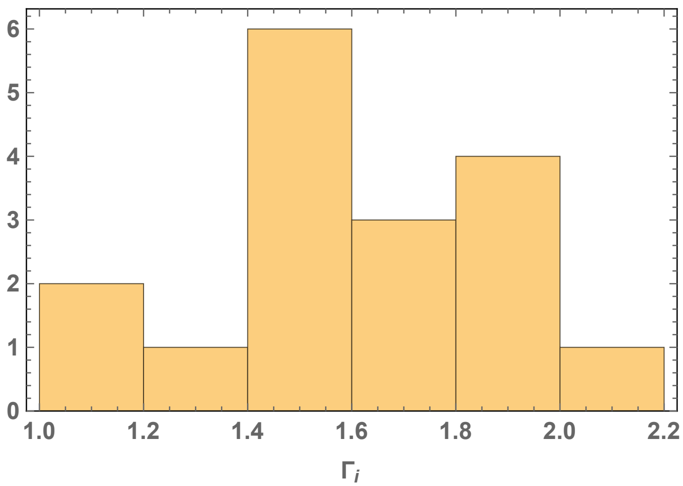
Photon indices (Γ) and electron SED slopes ($p = 2\Gamma - 1$)

These slopes may be more directly related to pulsar properties then the volume-integrated slopes

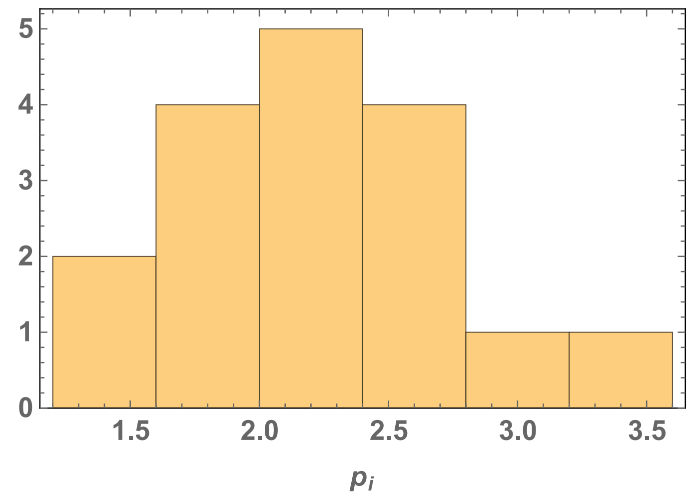
Name	Γ_{inner}	$\delta\Gamma$	p
N157B	2.3	0.05	3.6
Crab	1.8	0.05	2.6
Vela	1.3	0.05	1.6
3C58	1.9	0.07	2.8
G320.4-1.2	1.4	0.1	1.8
Kes 75	1.9	0.1	2.8
G21.5-0.9	1.4	0.06	1.8
G11.2-0.3	1.36	0.13	1.72
CTB 80	1.7	0.1	2.4
G54.1+0.3	1.5	0.05	2.
B0355+54	1.54	0.05	2.08
MSH 15-56	1.4	0.2	1.8
G327.1-1.1	1.62	0.08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



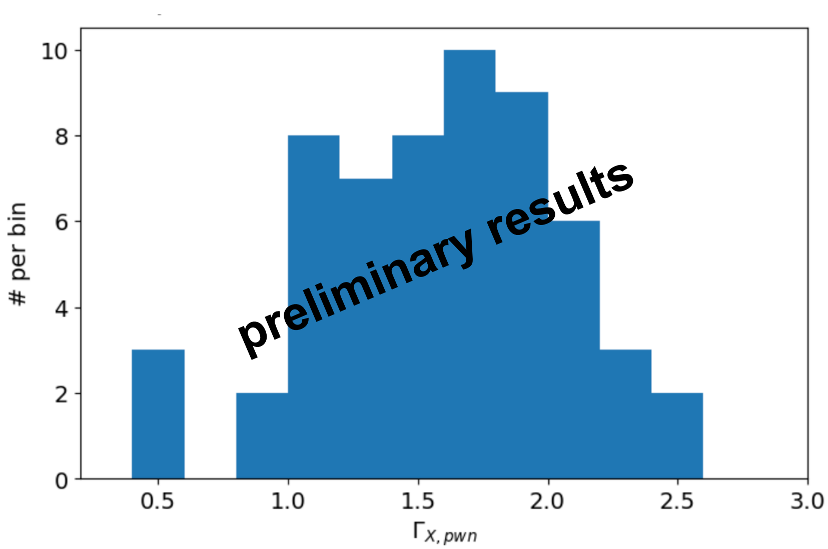
Diagnostics of acceleration process.



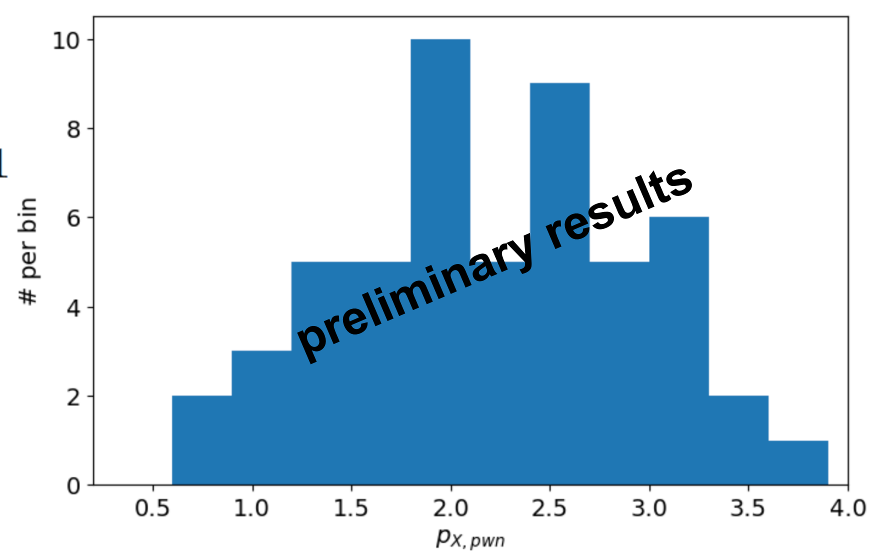
$$p = 2\Gamma - 1$$



If a larger PWN sample (including fainter and smaller objects) is taken:



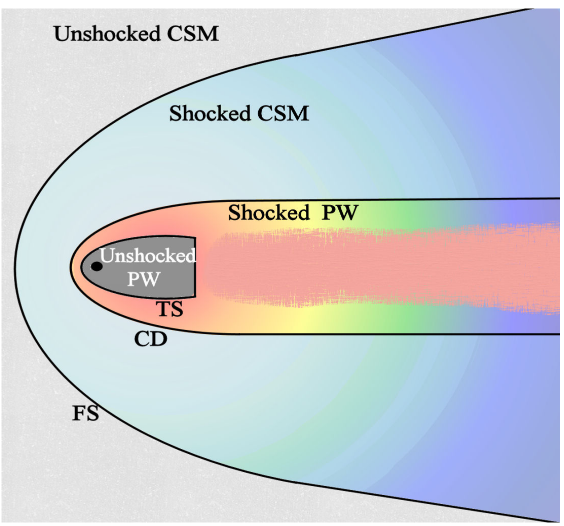
$$p = 2\Gamma - 1$$



Possibly, fainter PWNe tend to have harder spectra because we only see brighter part near the pulsar which is relatively uncooled.

Supersonic PSR motion: SPWNe

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. SPWNe should exhibit a '**head-tail**' morphology.

Pulsar speed **V_{PSR} = a few times 100 km/s**

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

Subsonic PSR motion (M < 1) is possible only in SNRs
(i.e., for very young pulsars/PWNe)

If the unshocked PW were **isotropic**, TS and CD would be quasi-spherical surfaces, and the PWN would look like a **round ring** (due to limb brightening) with a characteristic radius

$$p_{\mathrm{PW}} = p_{\mathrm{amb}} \quad \rightarrow \quad R_{CD} \sim [Edot/(4\pi c p_{\mathrm{amb}})]^{1/2}$$

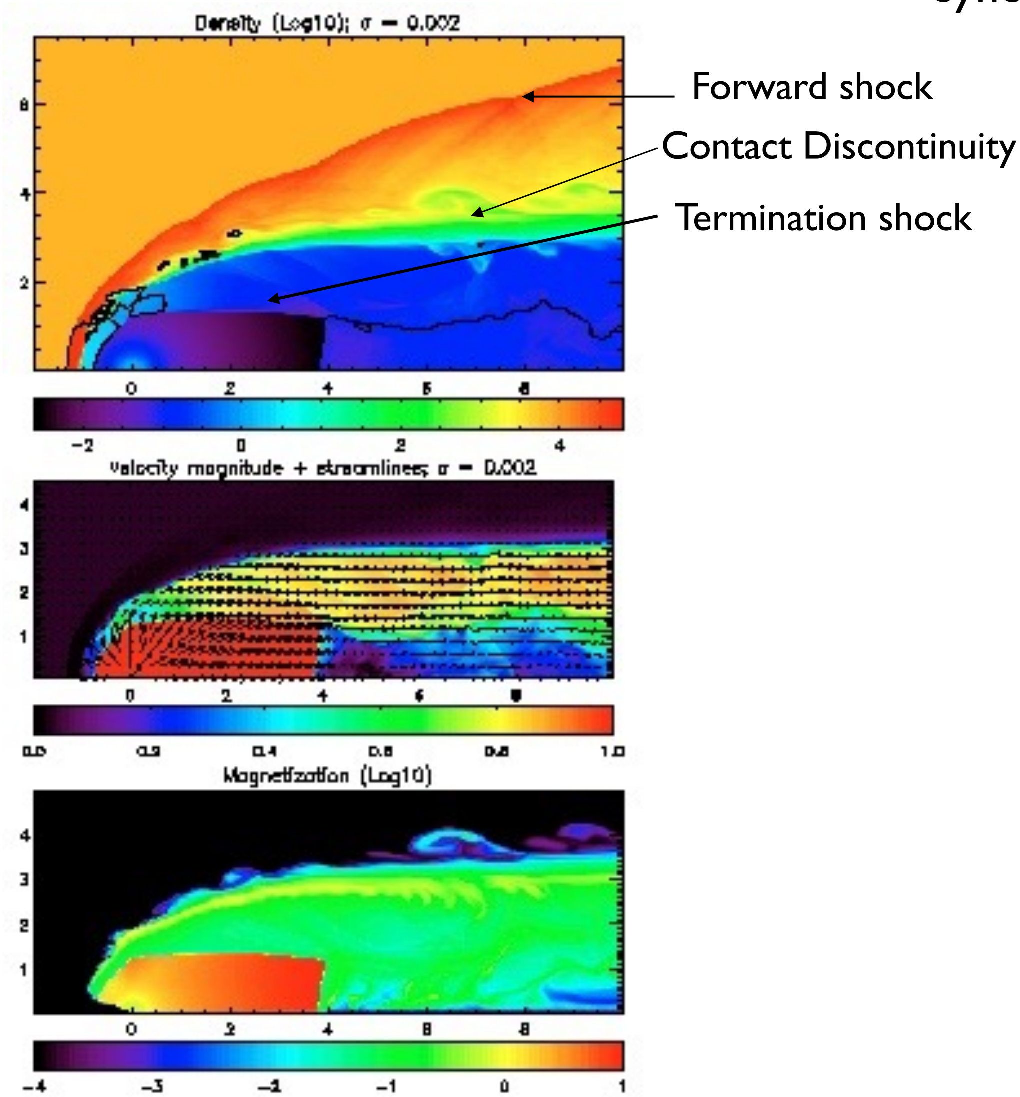
$$R_{CD} \sim 0.2\ (Edot/10^{37}\ \mathrm{erg/s})^{1/2}\ (p_{\mathrm{amb}}/10^{-10}\ \mathrm{dyn/cm^2})^{-1/2}\ \mathrm{pc}$$

However, we never see such simple round PWN structures

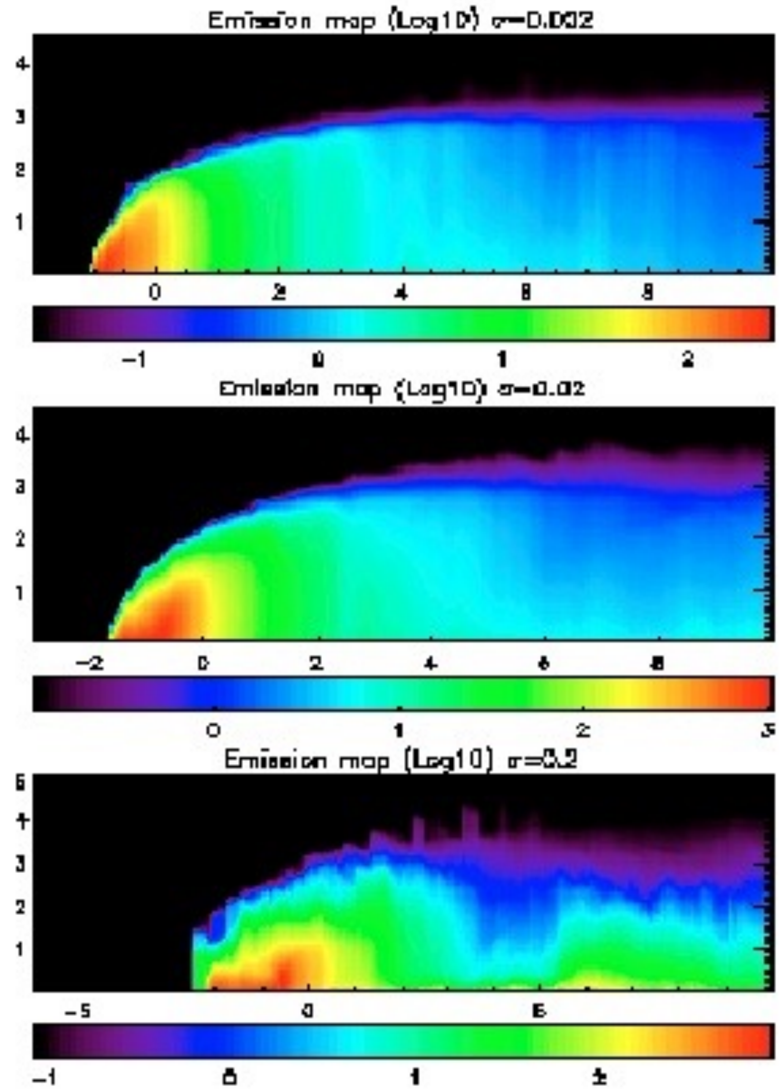
RMHD simulations of isotropic outflow for supersonically moving pulsar (Bucciantini, Amato, Del Zanna 2005)

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

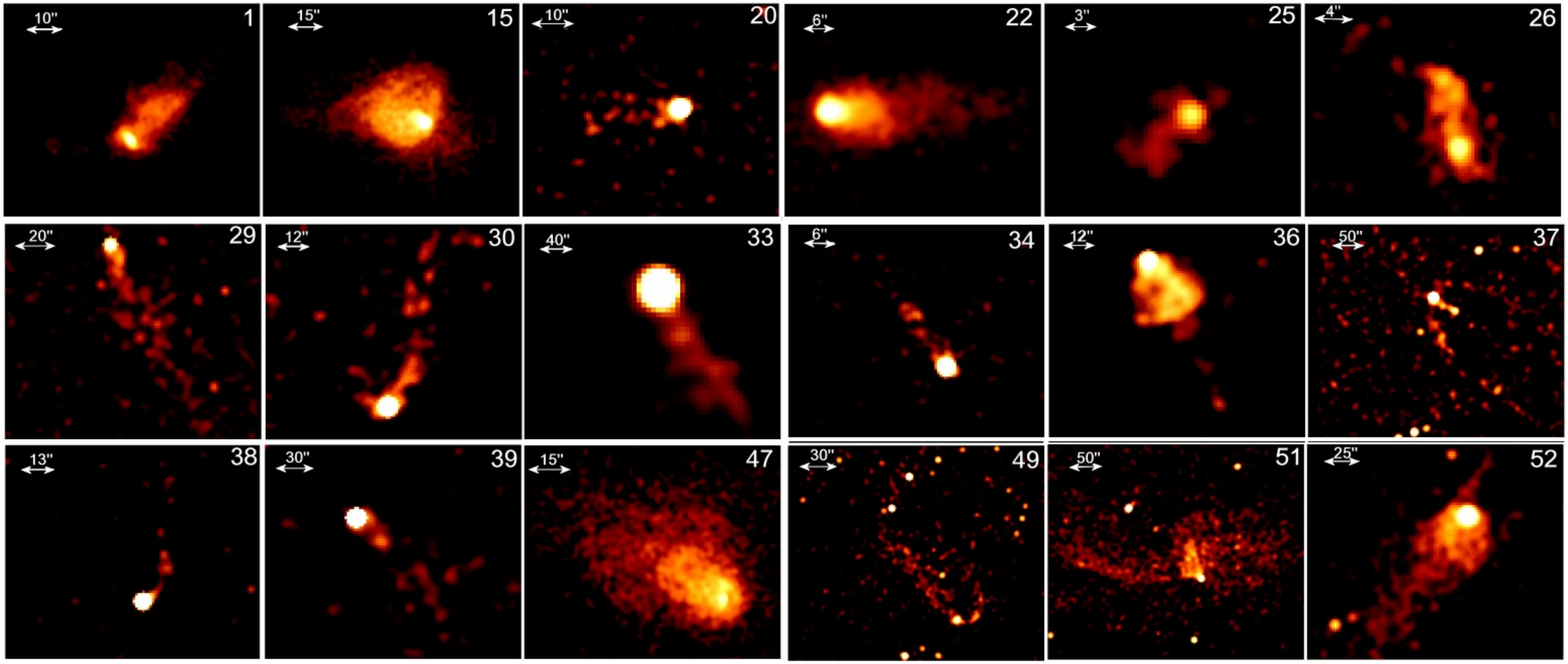
Density, velocity, magnetization



Synchrotron radiation for different magnetizations



Examples of SPWNe



Most of them show strongly <u>elongated structures</u>.

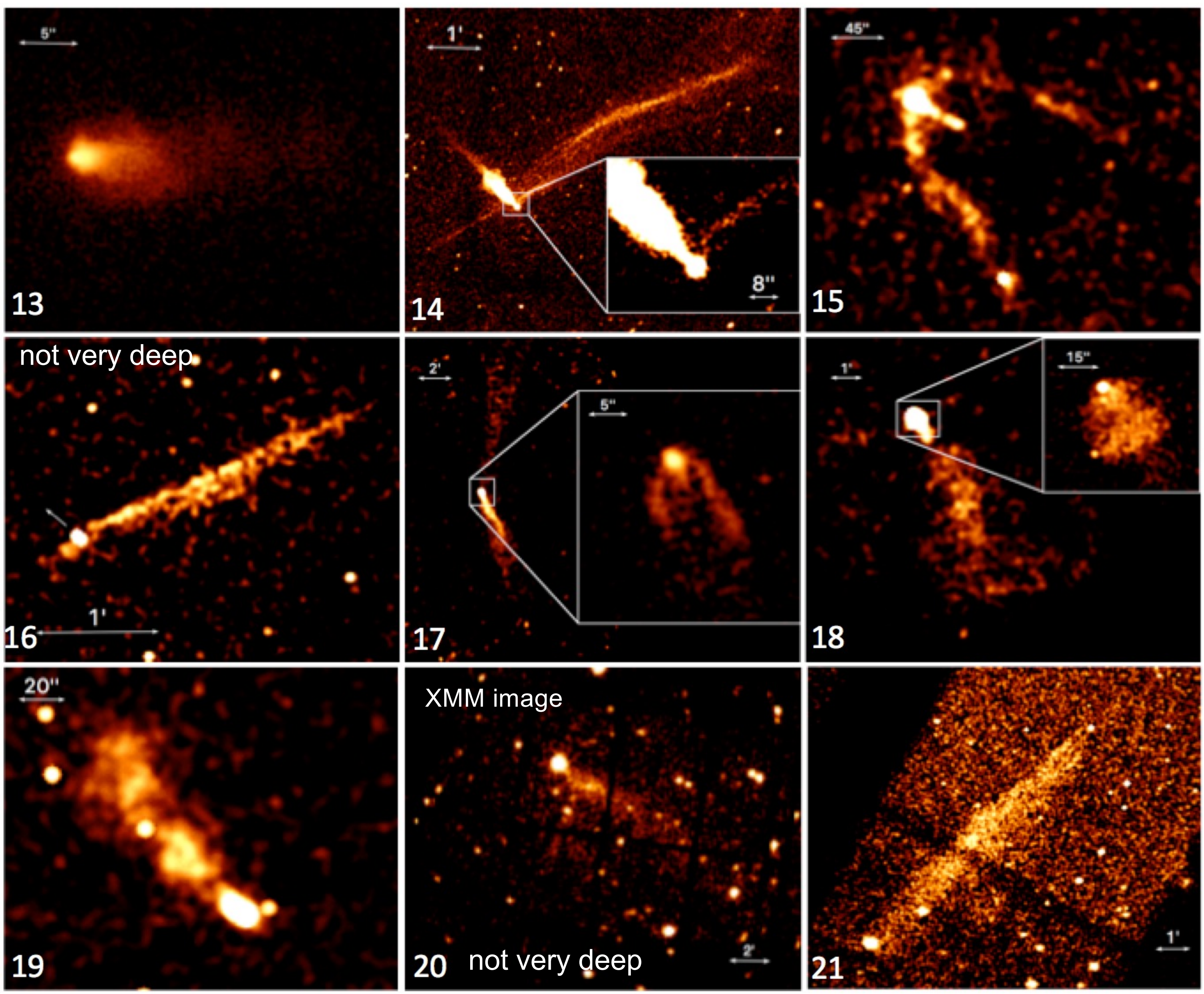
Jets: Polar outflows along spin axis, often seen on both sides of PSR;

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

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

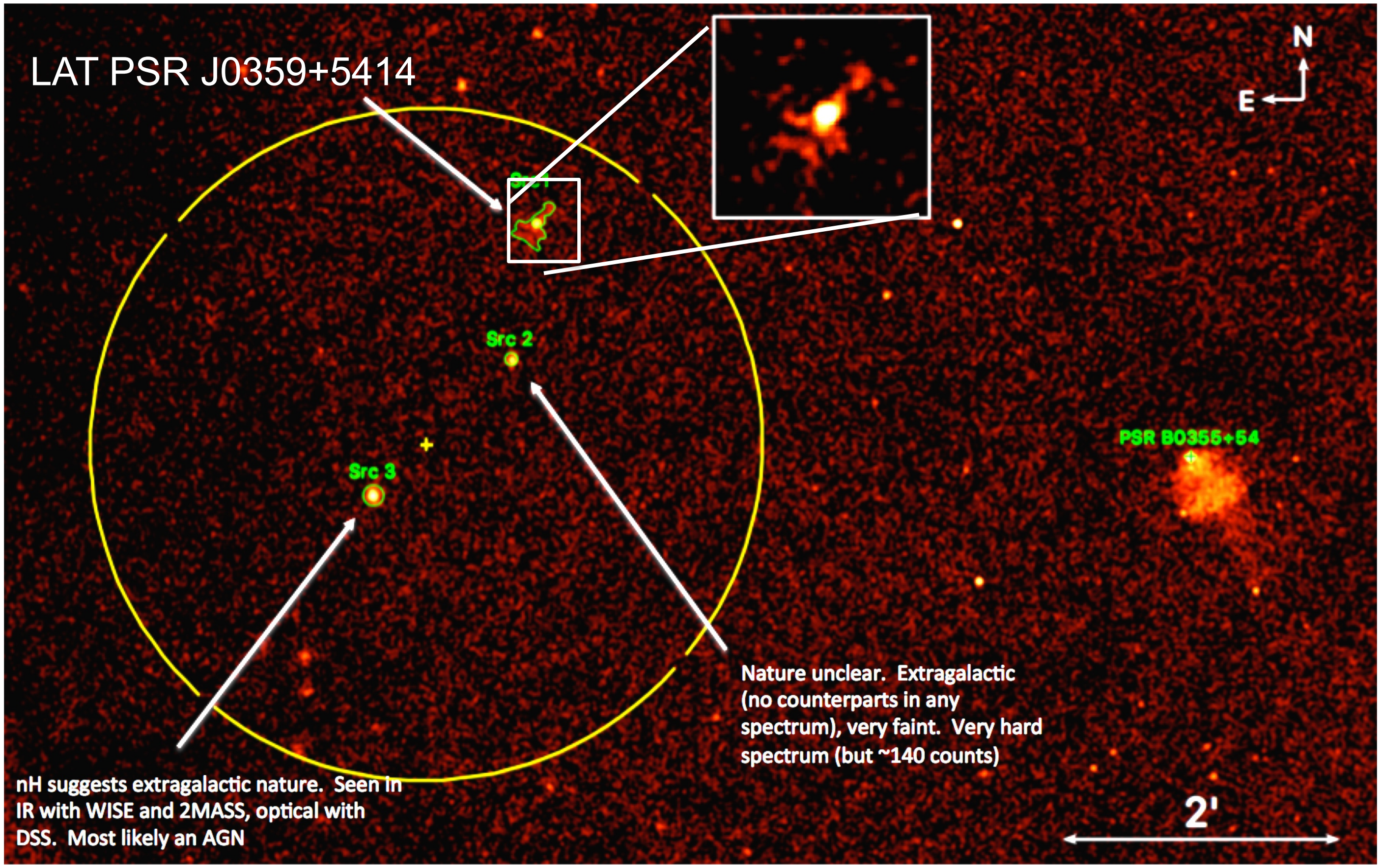
<u>Misaligned outflows</u>: None of the above?

Supersonic PWNe (SPWNe) with deep Chandra ACIS exposures



Have we identified all fainter PWNe in existing Chandra data?

Likely not because we accidentally found another PWN candidate in our observation of B0355+54 PWN by inspecting nearby X-ray sources:

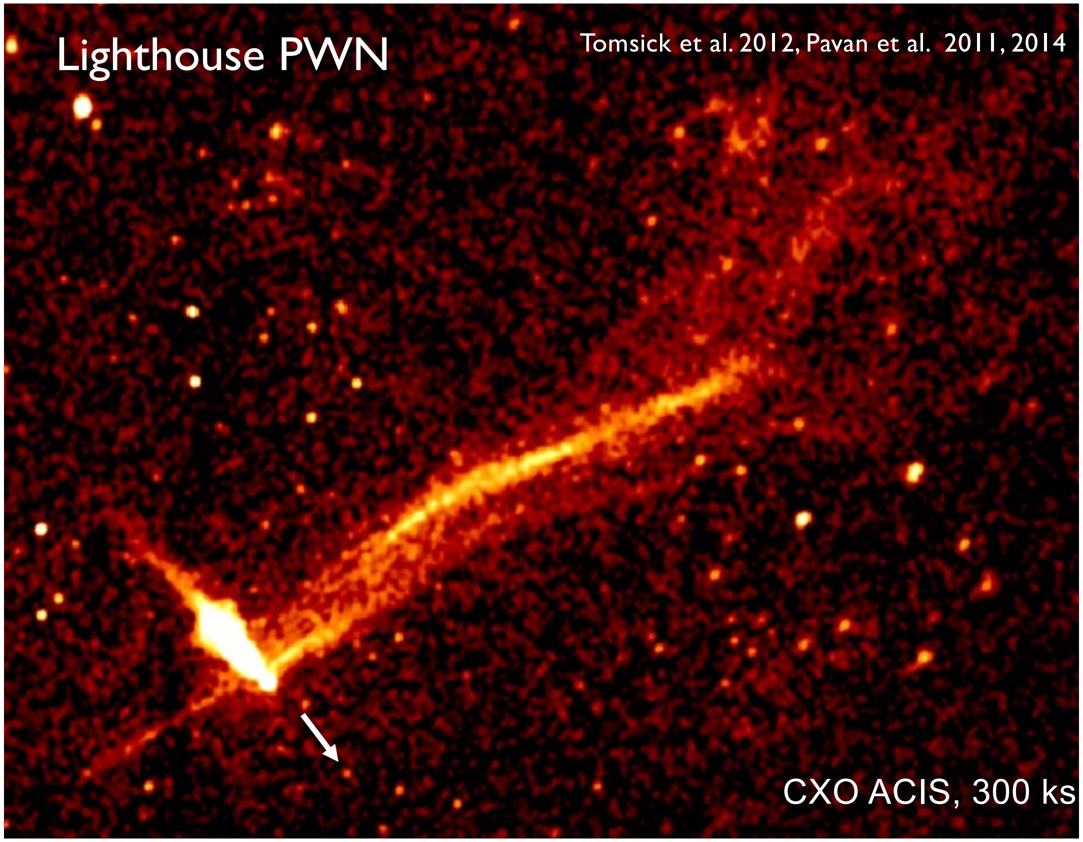


We later learned that a gamma-ray PSR J0359+5414 was discovered by the Einstein@Home Gamma-Ray Pulsar Survey (Clark et al. 2017) right in the middle of extended X-ray source (see also Zyuzin et al. 2018).

Systematic search for faint **extended** Chandra sources would be useful as those small and faint PWNe must be more numerous.

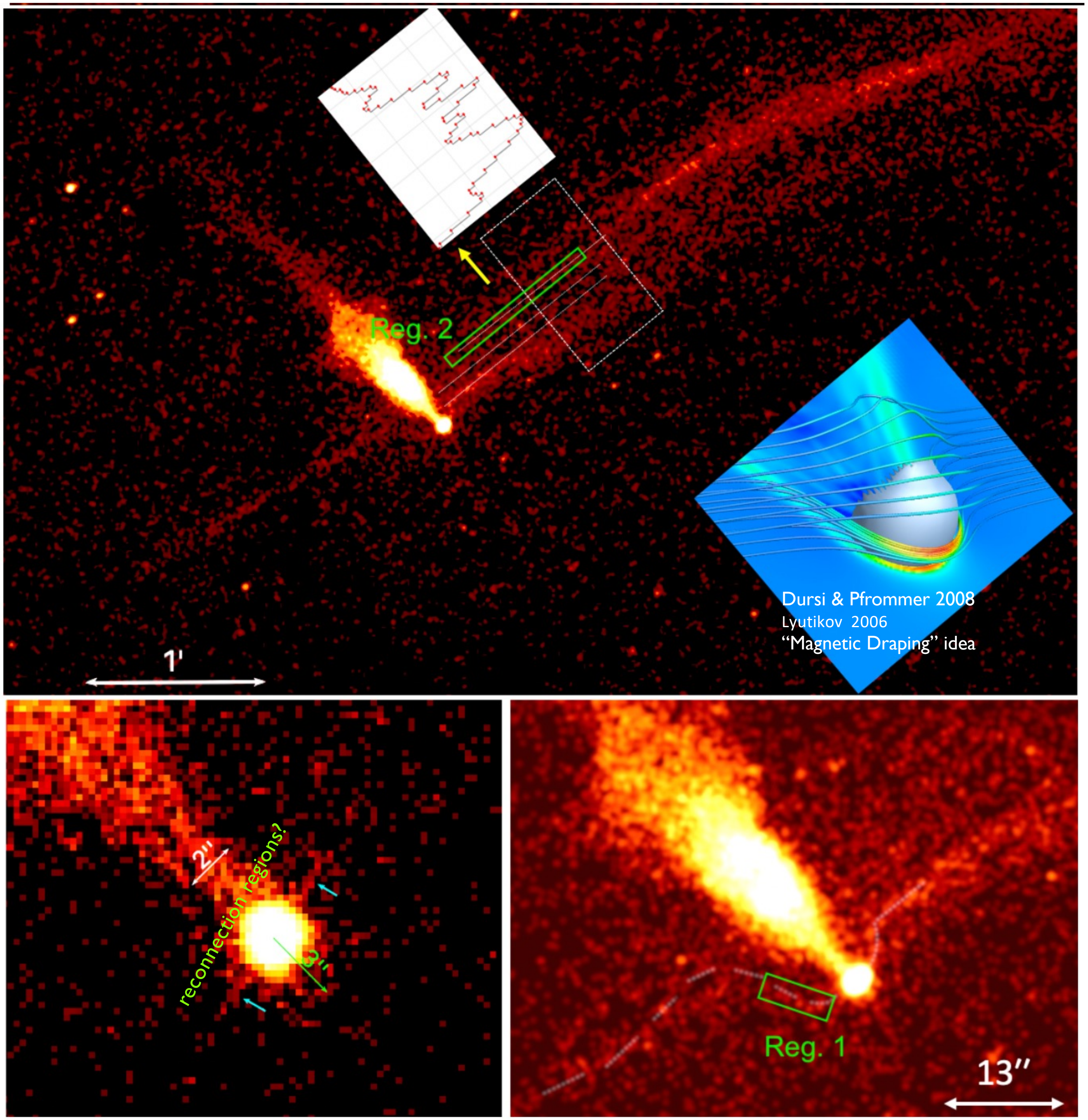
Misaligned outflows

- MHD description breaks down and pulsar wind particles escape into ISM (**Bandiera 2008**)
- particle motion and energy losses depend on magnetic field in ISM
- synchrotron emission from the wind particles "illuminates" otherwise unseen ISM B-field structure?
- or can these streaming ultra-relativistic particles modify/amplify ISM field?



Where do you think most of TeV emission would come from?

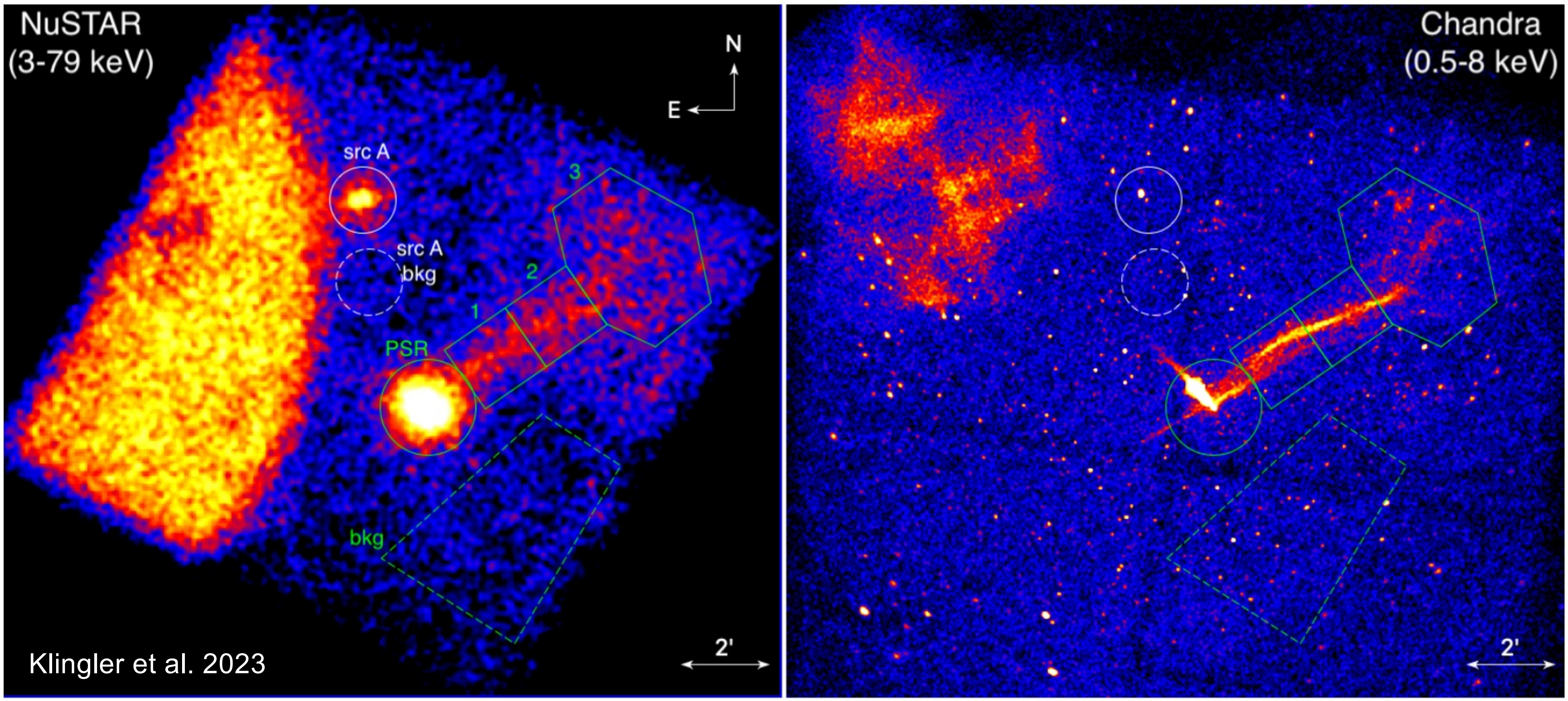
Misaligned outflows



To be observed by CXO for another 700 ks in the upcoming CXO Cycles.

Misaligned outflows

Emission is also seen in harder X-rays (with some evidence for mild cooling with distance). The length of the structure is



This implies rapid diffusion of particles along the ISM B-field that remains relatively straight over scales of (the visible extend of the structure)

Misaligned outflows

Many ongoing modeling efforts
some listed below:

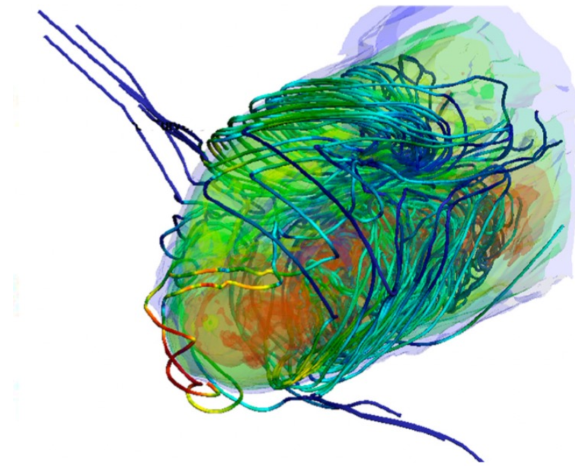
Bandiera 2008

Bykov et al. 2017

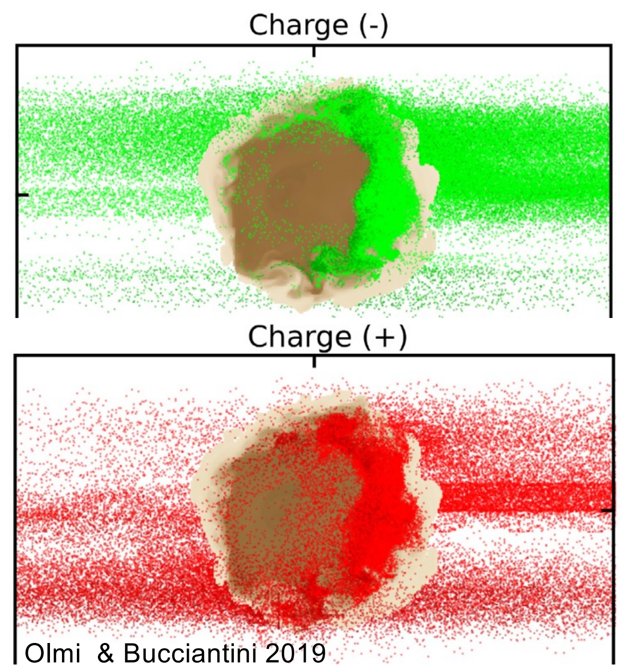
Olmi & Bucciantini 2019

Barkov et al. 2019

Olmi et al. 2024



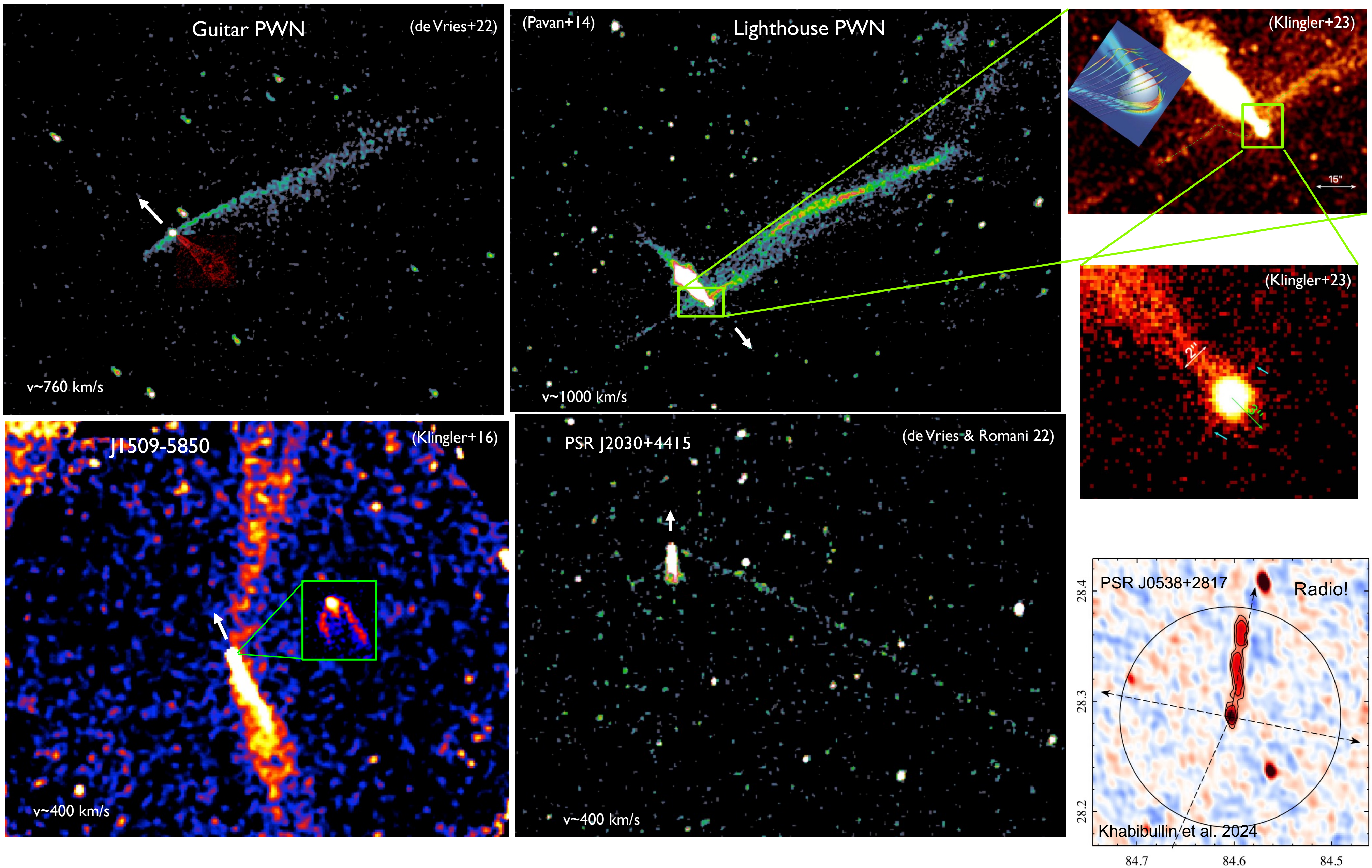
Barkov et al. 2019



Olmi & Bucciantini 2019

Misaligned outflows

Most of them are strongly asymmetric.

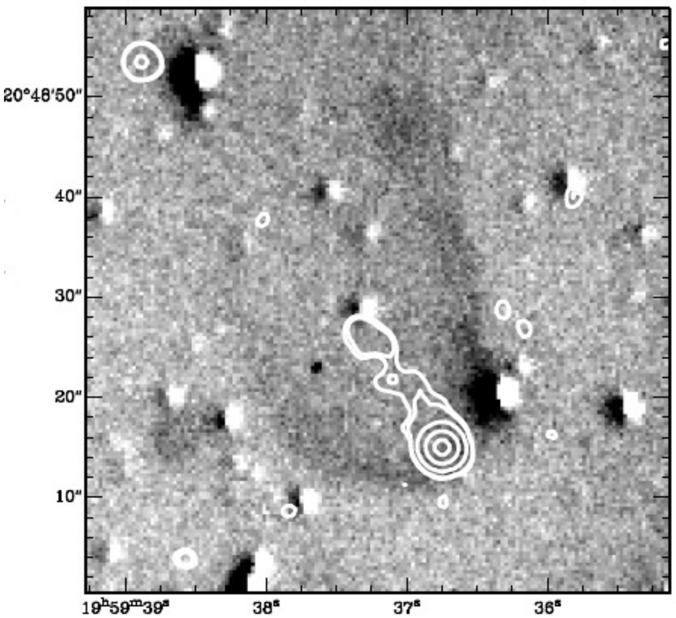


X-ray PWN + H-alpha bow shock

5 (6?) known, out of 9 PSR H-alpha bow shocks

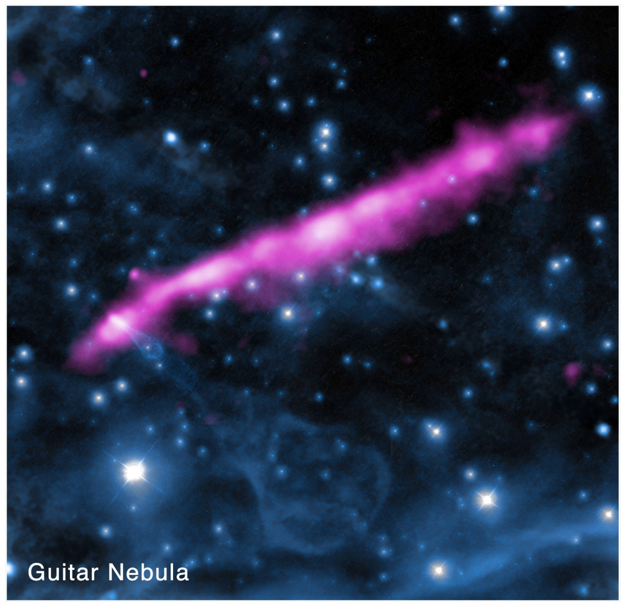
3 examples

PSR B1957+20 (black widow)
Stappers et al 2003



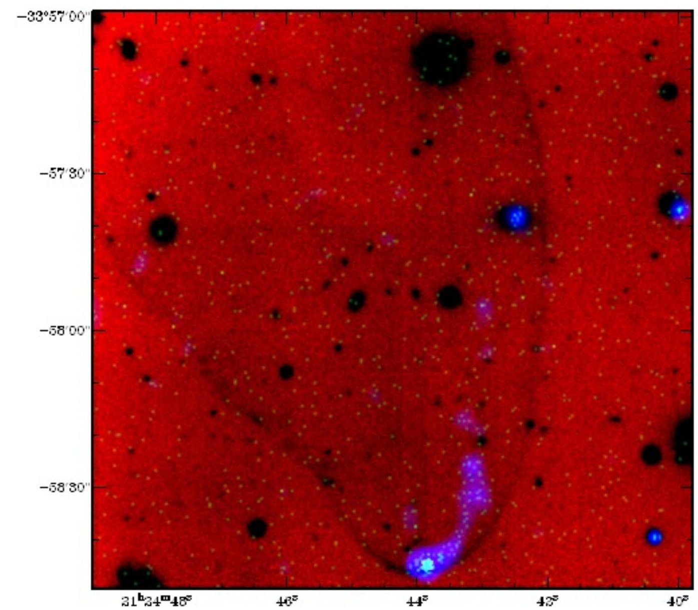
Head-tail X-ray PWN within H-alpha bow shock

PSR B2224+55 (Guitar)
Johnson & Wang 2010



Misaligned outflow in X-rays, bow shock + several bubbles In H-alpha

PSR J2124-3358, solitary MSP
Chatterjee et al 2009



One-sided X-ray "jet" within asymmetric H-alpha bow shock

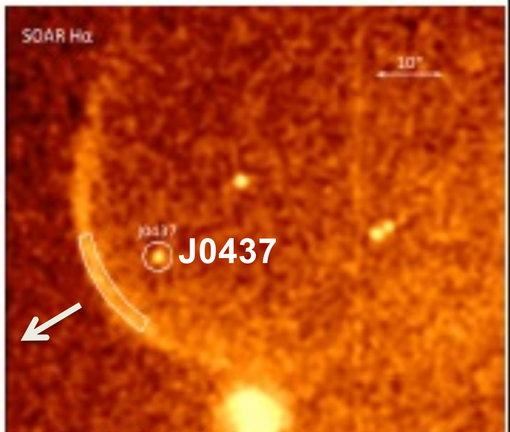
Nearest MSP PSR J0437-4715: far-UV bow-shock

Rangelov et al. 2016; Bykov et al. 2017

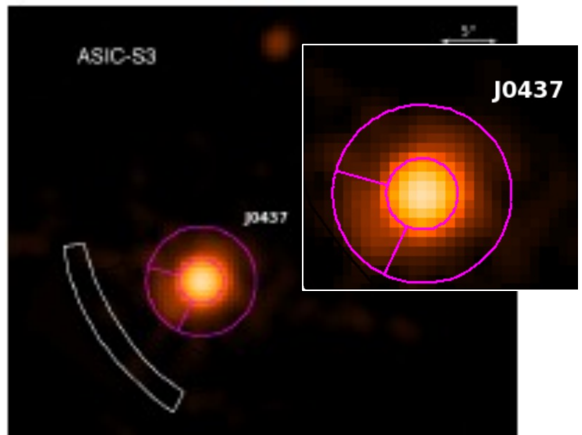
Currently 3 pulsars (J0437-4715, J2124-3358, J1741-2054) have their bowshocks detected in FUV.

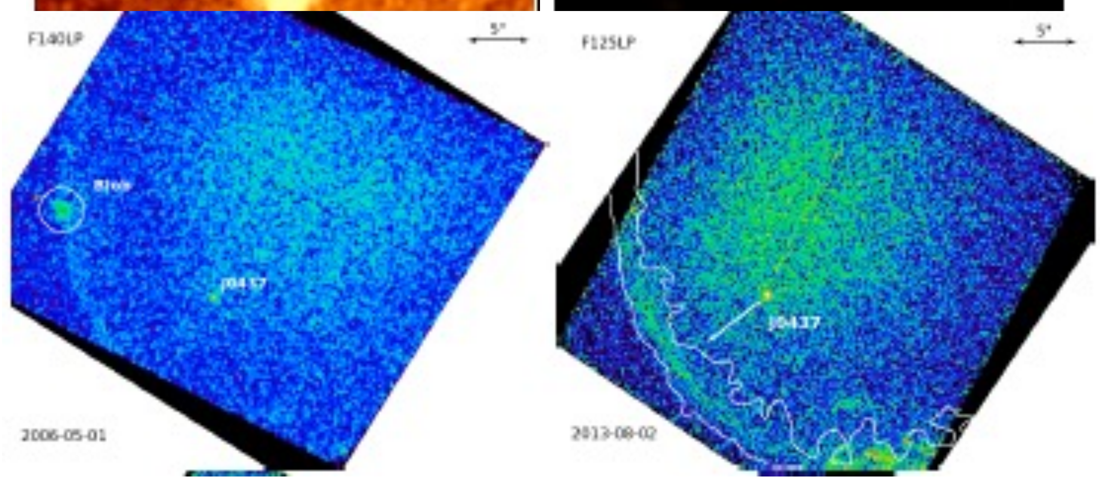
Edot = 5×10^{33} erg/s, *D* = 157 pc, V_t =104 km/s

H-alpha image



Chandra ACIS image



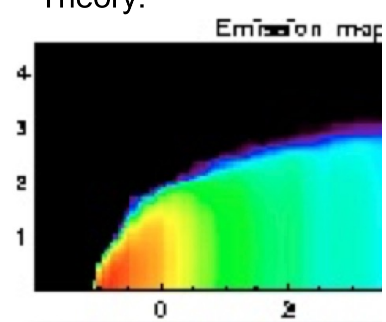


HST ACS/SBC FUV images (1400 -- 2000 A and 1250 – 2000 A bands)

H-alpha: SOAR, bow-shock apex 10'' from the PSR

X-rays: 47 ks ACIS-S, faint emission up to 5" ***ahead*** of PSR, L(0.5-8 keV) ~3×10^{28} erg/s. The PWN head?

Theory:



FUV: Bow-like structure coincident with H-alpha bow shock, L(1250-2000 A) = 5×10^{28} erg/s ~ 10×L(Hα) from the same area. Continuum and lines produced by shocked ISM matter?

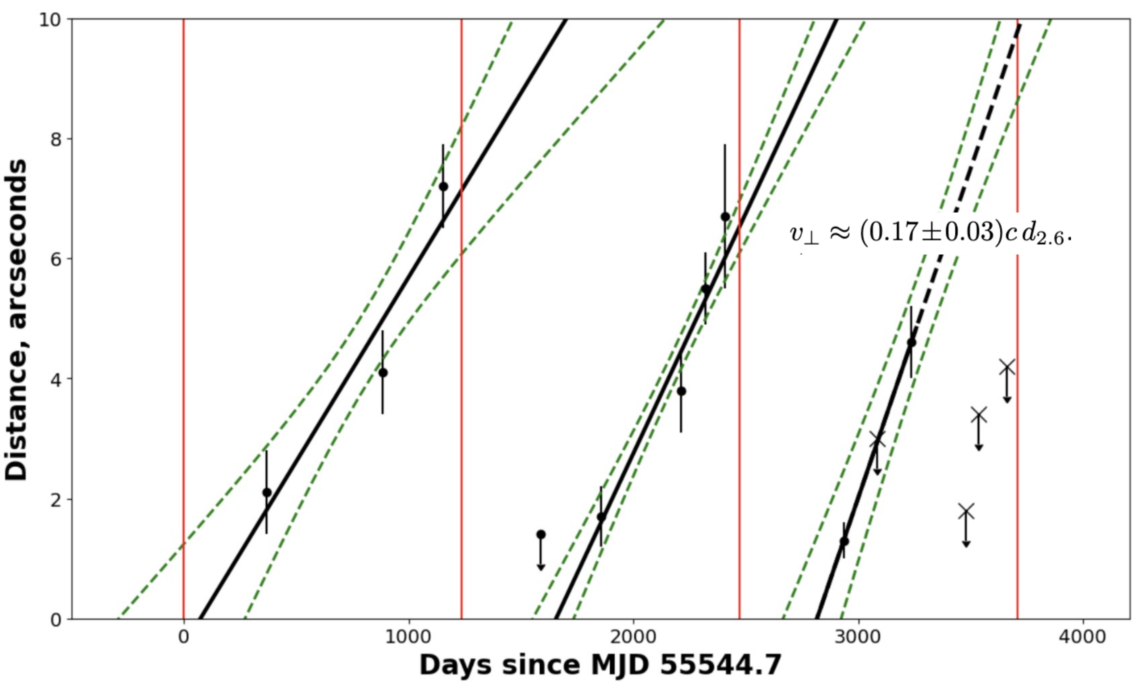
Resolved and dynamic PWN in an interacting binary

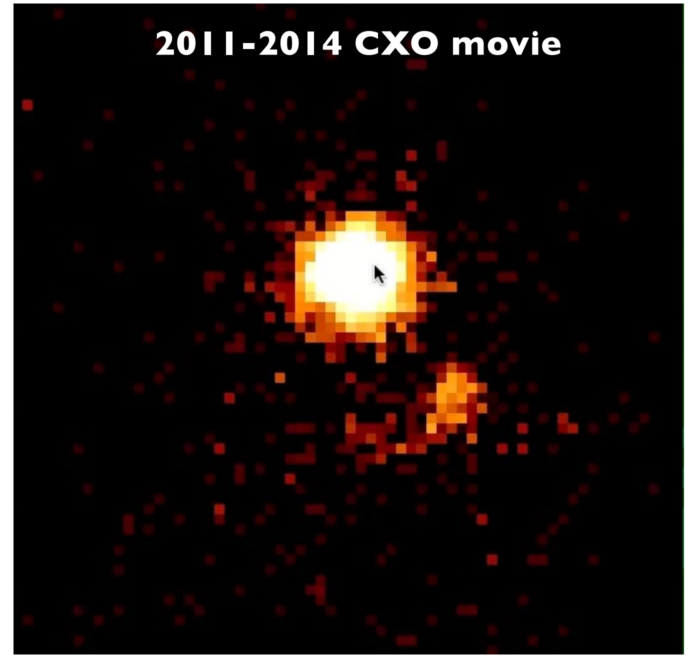
A dynamic nebula of the B1259-63/LS 2883 high-mass Binary

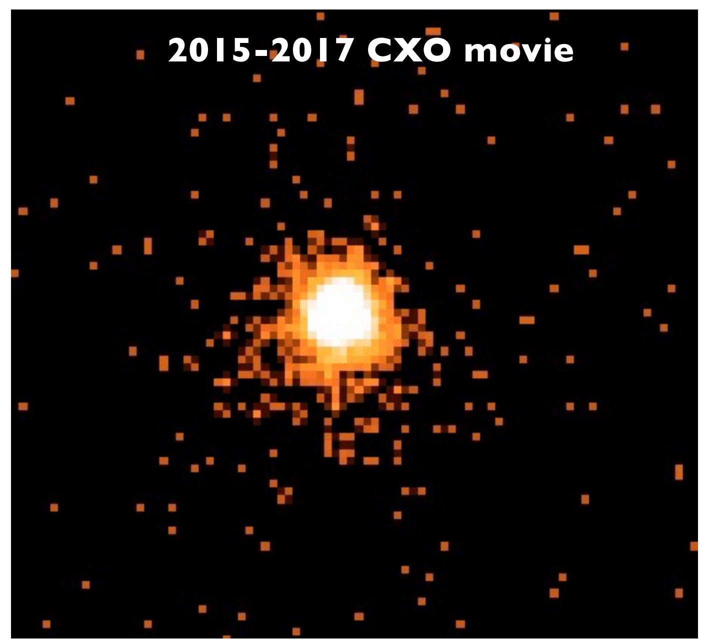
LS 2883: M~30 $M_\odot$, L=6 × $10^4 L_\odot$
strong wind, decretion disk

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

3.4 yr orbital period, e=0.87





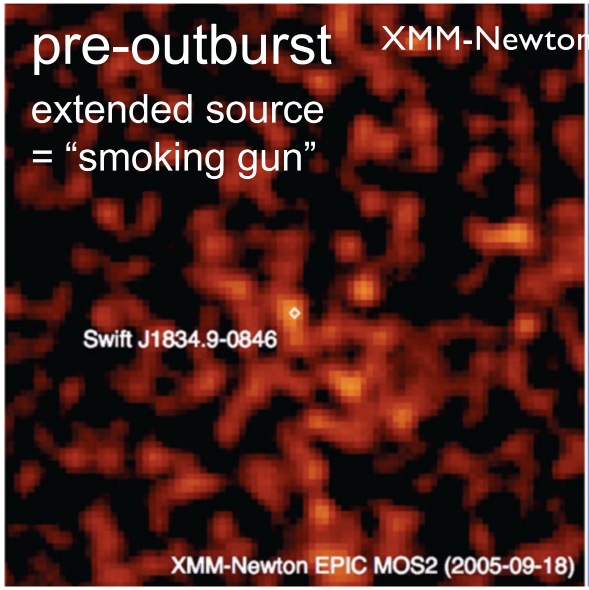


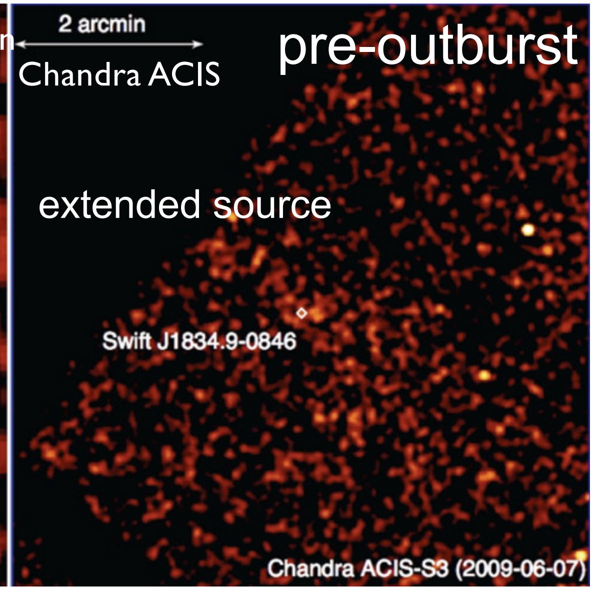
(Kargaltsev et al. 2014, Pavlov et al. 2015, Hare et al. 2023)

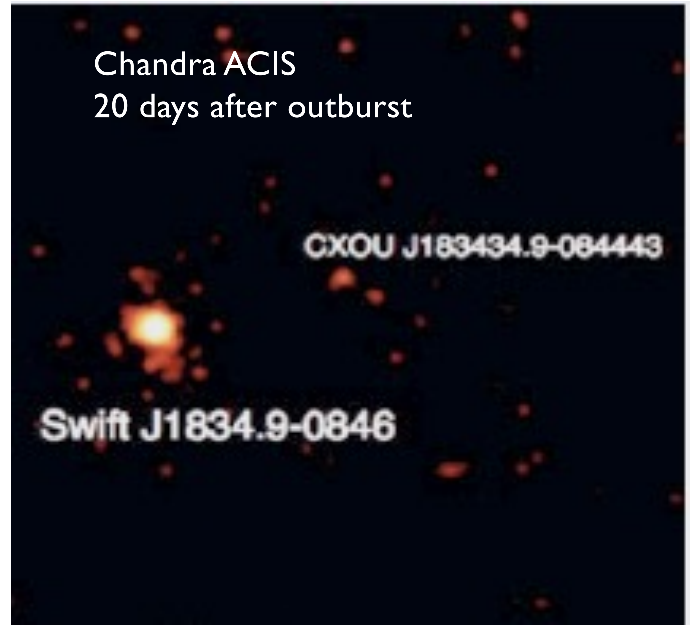
Magnetar Wind Nebulae (MWN): smoking gun of past magnetar activity?

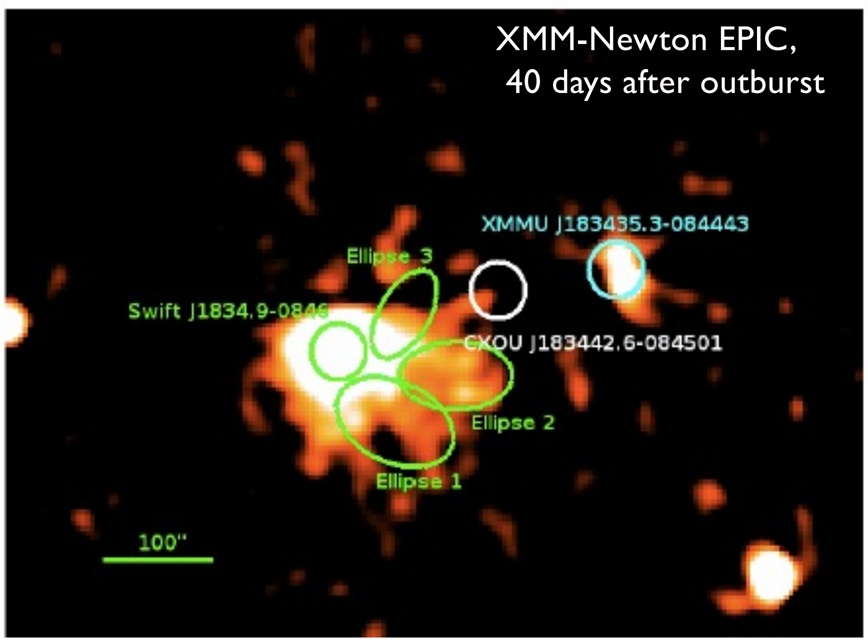
MWN around transient magnetar Swift J1834.9-0846

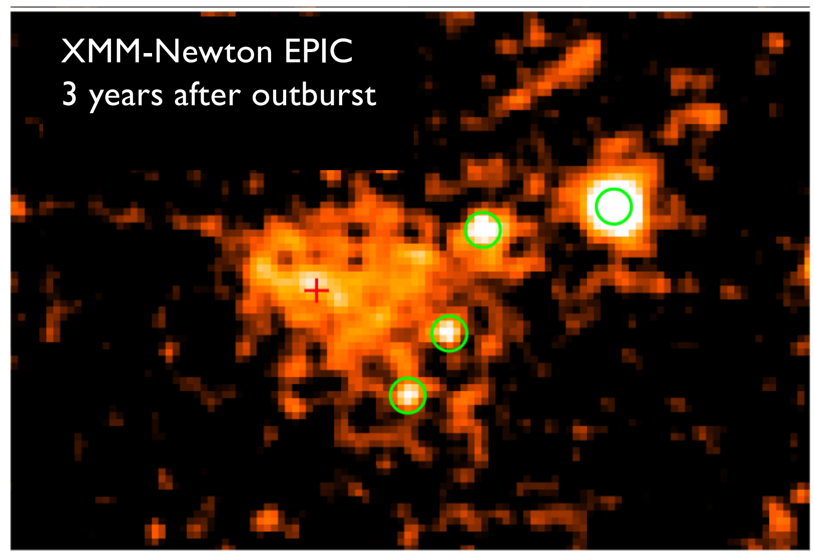
Kargaltsev et al. (2012), Younes et al. (2012, 2016)









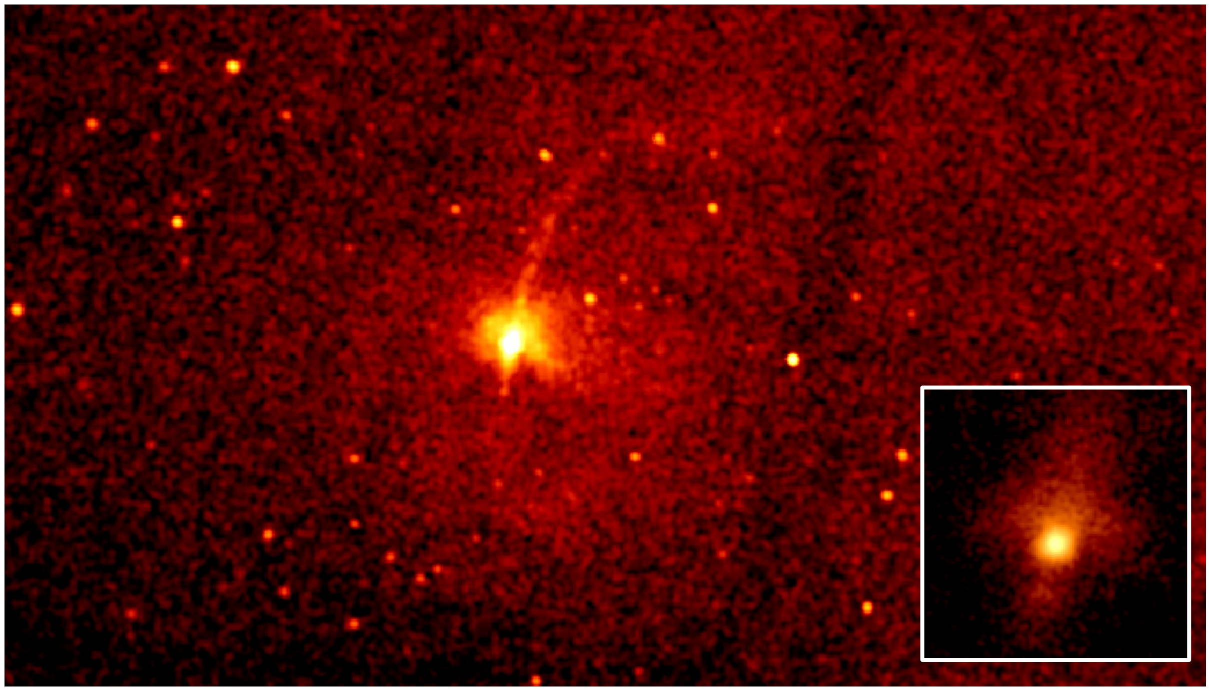


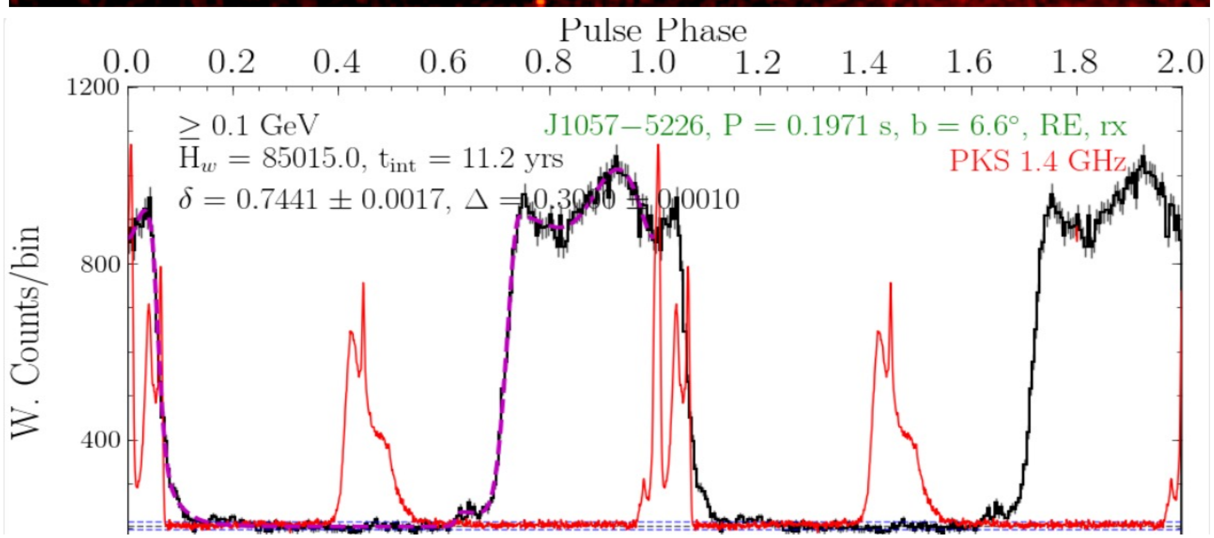
MWNe can provide a way to find dormant magnetars!

Part II: Some outstanding questions

- *Understand the acceleration mechanism operating beyond light cylinder and the actual acceleration site(s) capable of boosting particle energies by a factor of 10^3 – 10^4* : Measuring the SED changes with distance from the pulsar can constrain injection SED, evolution of particle energies and magnetic field, and particle escape into the ISM.
- *Hadronic content of pulsar wind and its role in particle acceleration process.*
- *Nature of far-UV emission from pulsar bowshocks.*
- *Particle escape from PWNe* can play a crucial role in seeding our Galaxy with relativistic electrons and positrons reaching PeV energies. The naïve hydrodynamics-based picture of a PWN as a wind bubble confined by the contact has been undermined by recent discoveries of TeV halos and pulsar filaments or misaligned outflows.
- *The nature of NS kicks during the SN explosion:* The degree of spin-kick direction alignment probes 3D models of supernova explosions. PWNe with torus-jet morphologies provide a model-independent way of measuring the NS spin axis projection onto the plane of the sky. If Doppler brightening of the torus is accounted for, then a 3D orientation of the spin axis can also be determined.

Part III: PWN – magnetosphere connection

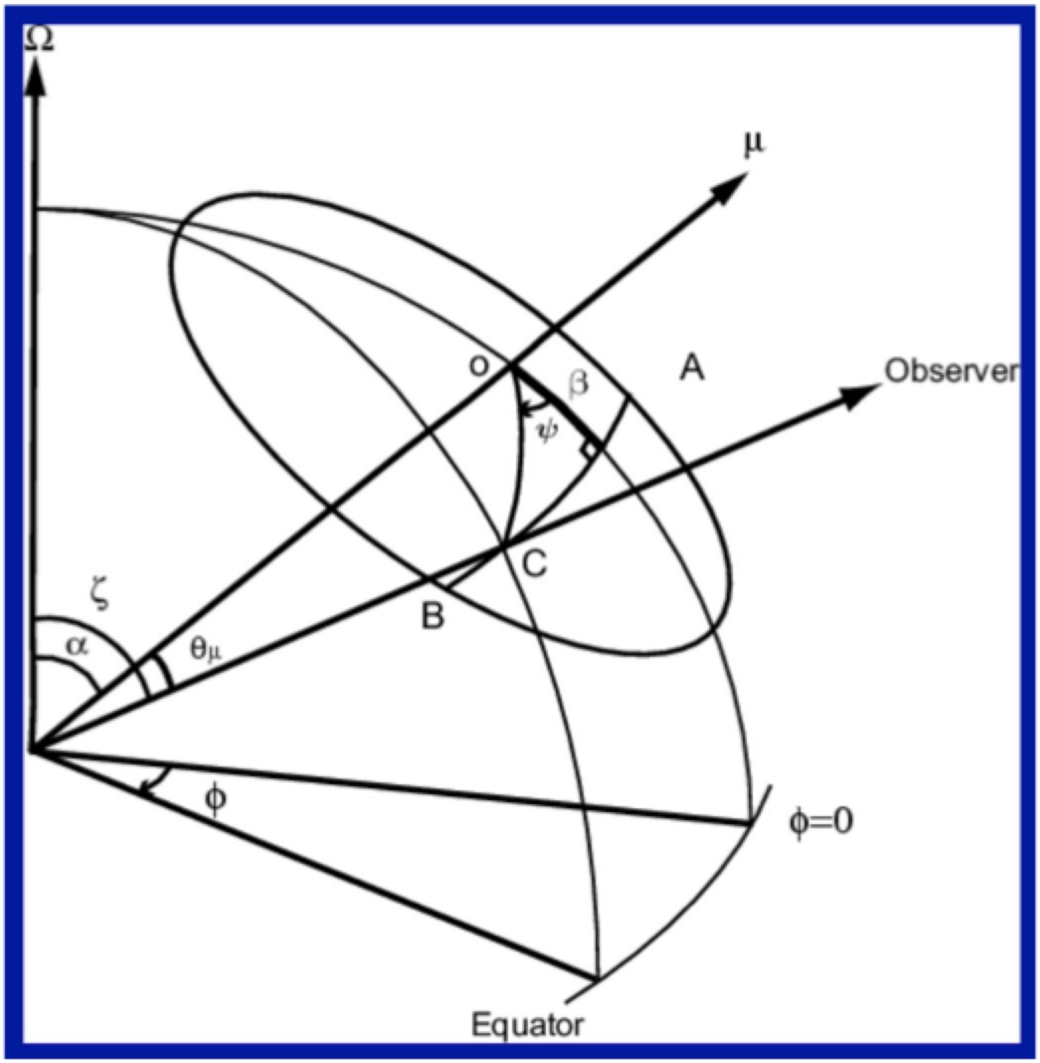




Connection between pulse shapes and PWN morphologies

Both are likely to depend on two internal parameters (viewing angle ζ and magnetic inclination angle α) in addition to Edot, Mach number and velocity direction.

Radhakrishnan & Cooke 1969



RVM model

Important angles are:

α – angle between the rotation and magnetic axis

ζ – angle between the rotation axis and the line of sight

β – closest approach of line of sight to magnetic axis

$\alpha+\beta=\zeta$

PWN morphology:

- Asymmetry between two jets or the ellipticity of the ring projection tells about **ζ.**

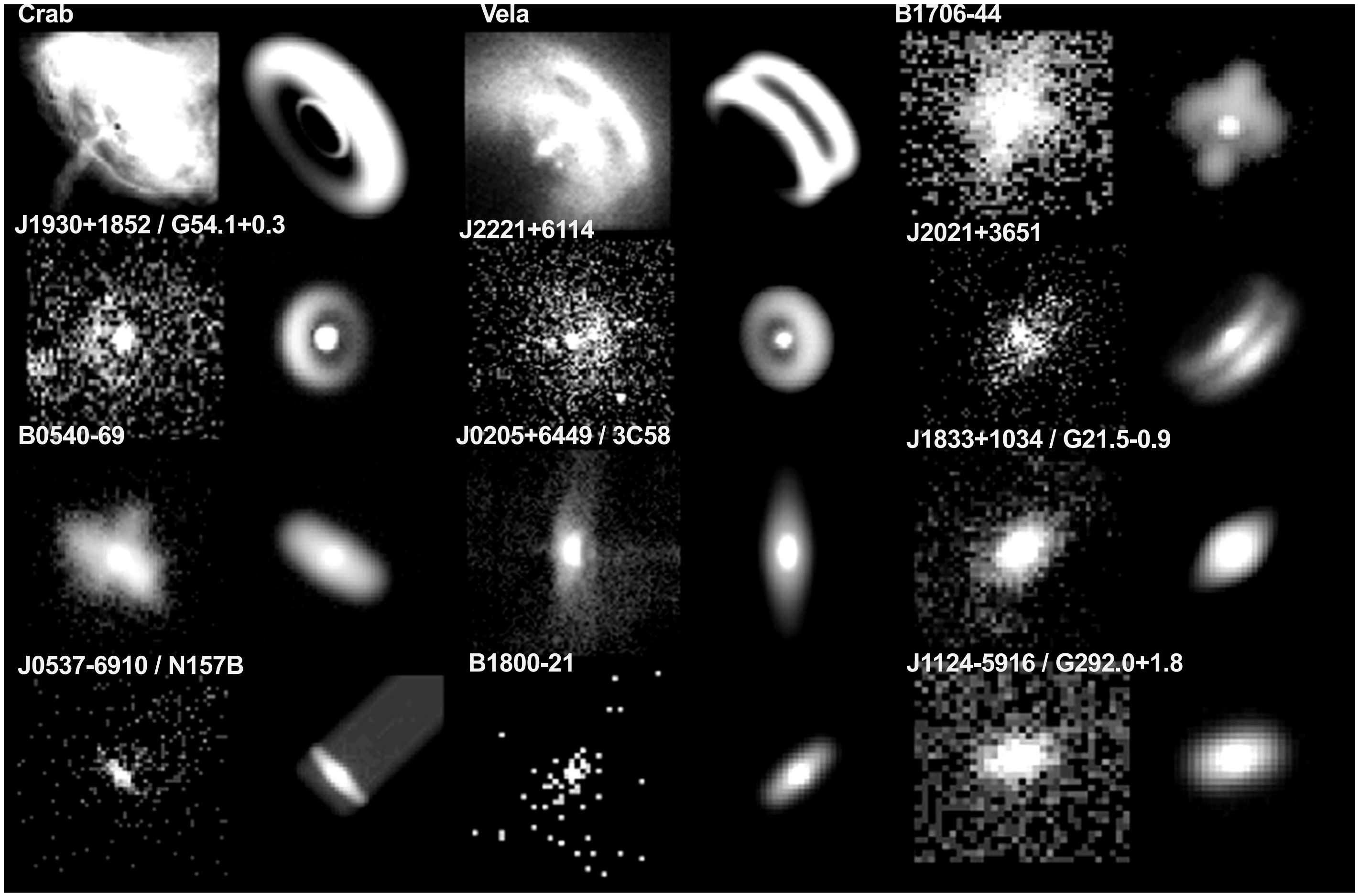
- PWNe often show equatorial and polar components. Can their relative strengths be indicative of the angle α ?

- One can expect PWN luminosity (all or equatorial component?) to be correlated with the size of the reconnection layer near the equatorial plane (absent for aligned rotator).

- Spectral slopes that are different for different PWNe may be reflecting acceleration efficiency which might correlate with α.

Torus/Jet modeling for non-supersonic PWNe

Modeling should account for the degree of ellipticity (tilted ring in projection becomes ellipse) and Doppler boosting.



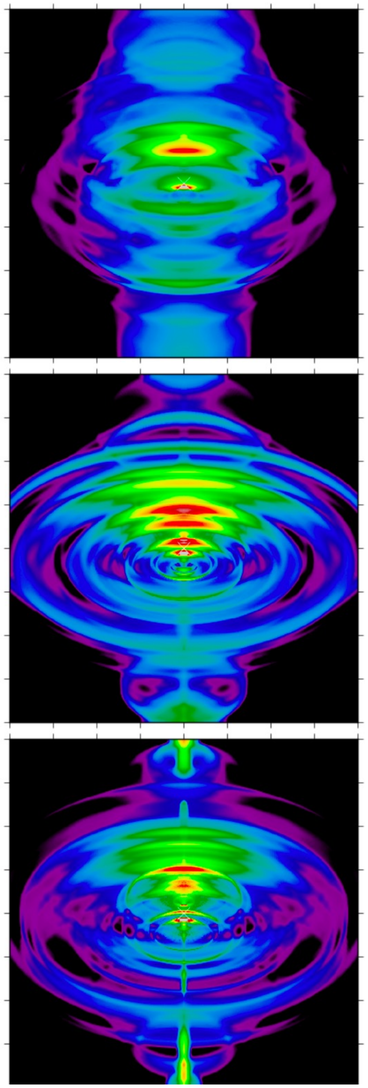
Ng & Romani (2004; 2008)

The imprint of pulsar parameters on the morphology of Pulsar Wind Nebula

Buehler & Giomi 2016

Results in agreement with Olmi et al. 2016 and Porth et al. 2017

Low initial magnetization



α=10°

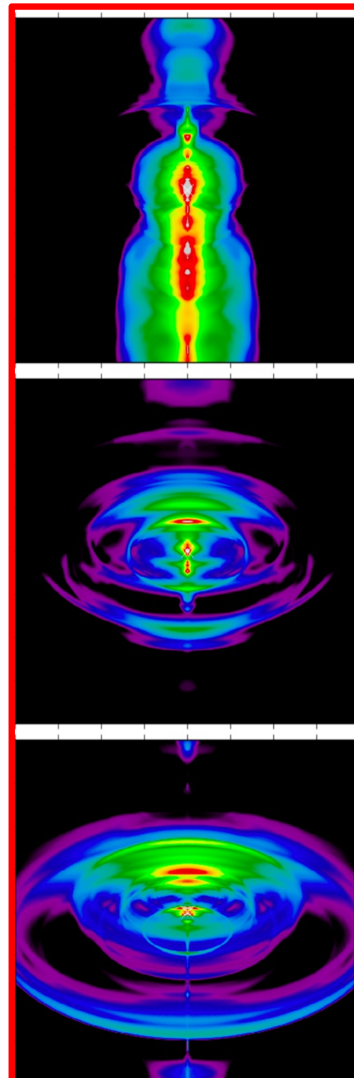
α=45°

α=80°

PWN emissivity maps from RMHD simulations.

2D axisymmetric simulations.

High initial magnetization



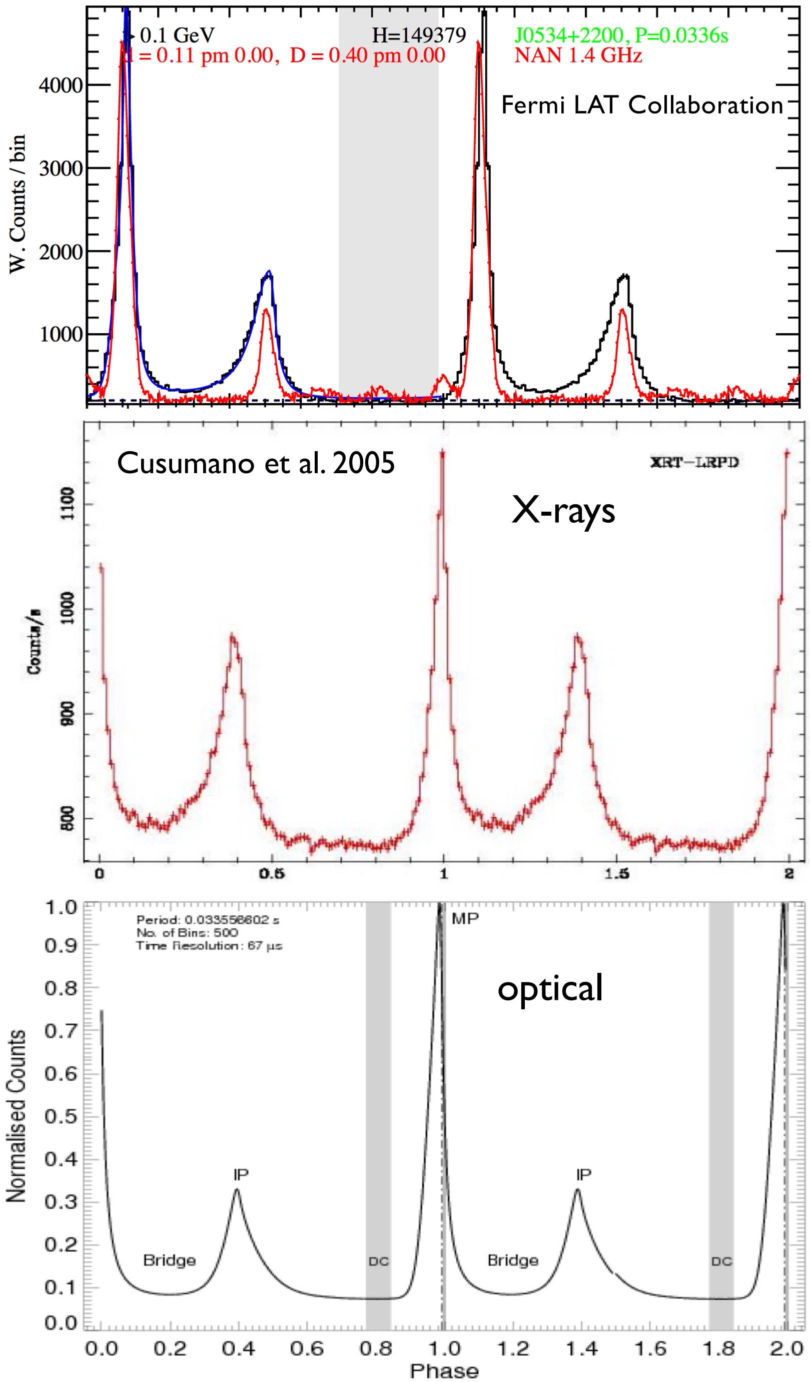
α=10°

α=45°

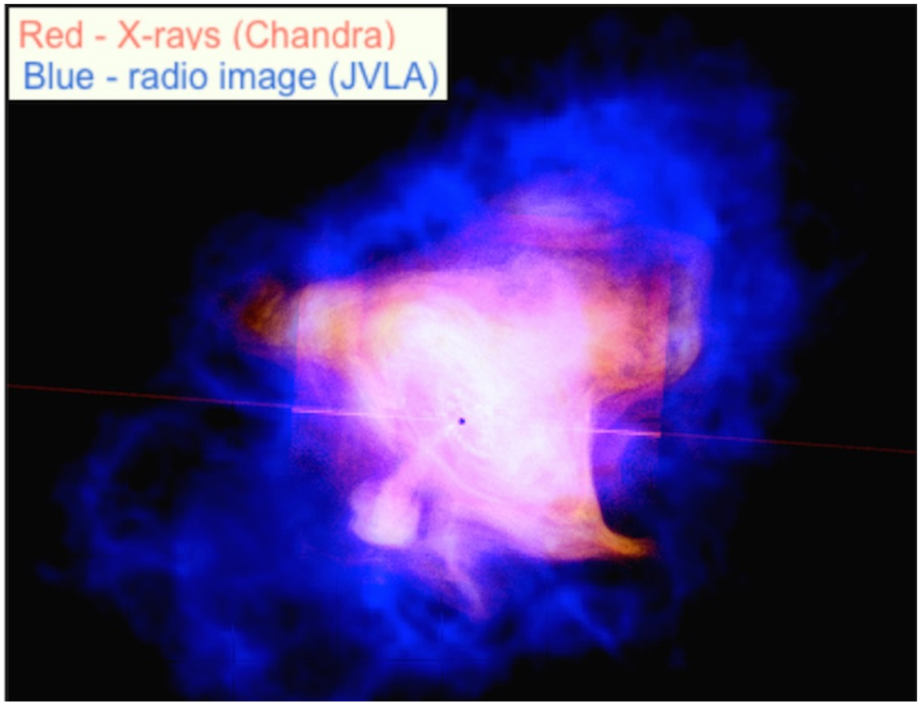
α=80°

Energy injection:

$$f_{tot}(r,\theta,\alpha) = \frac{L}{L' r^2} \times (g(\theta,\alpha) \times \sin^2\theta + d).$$



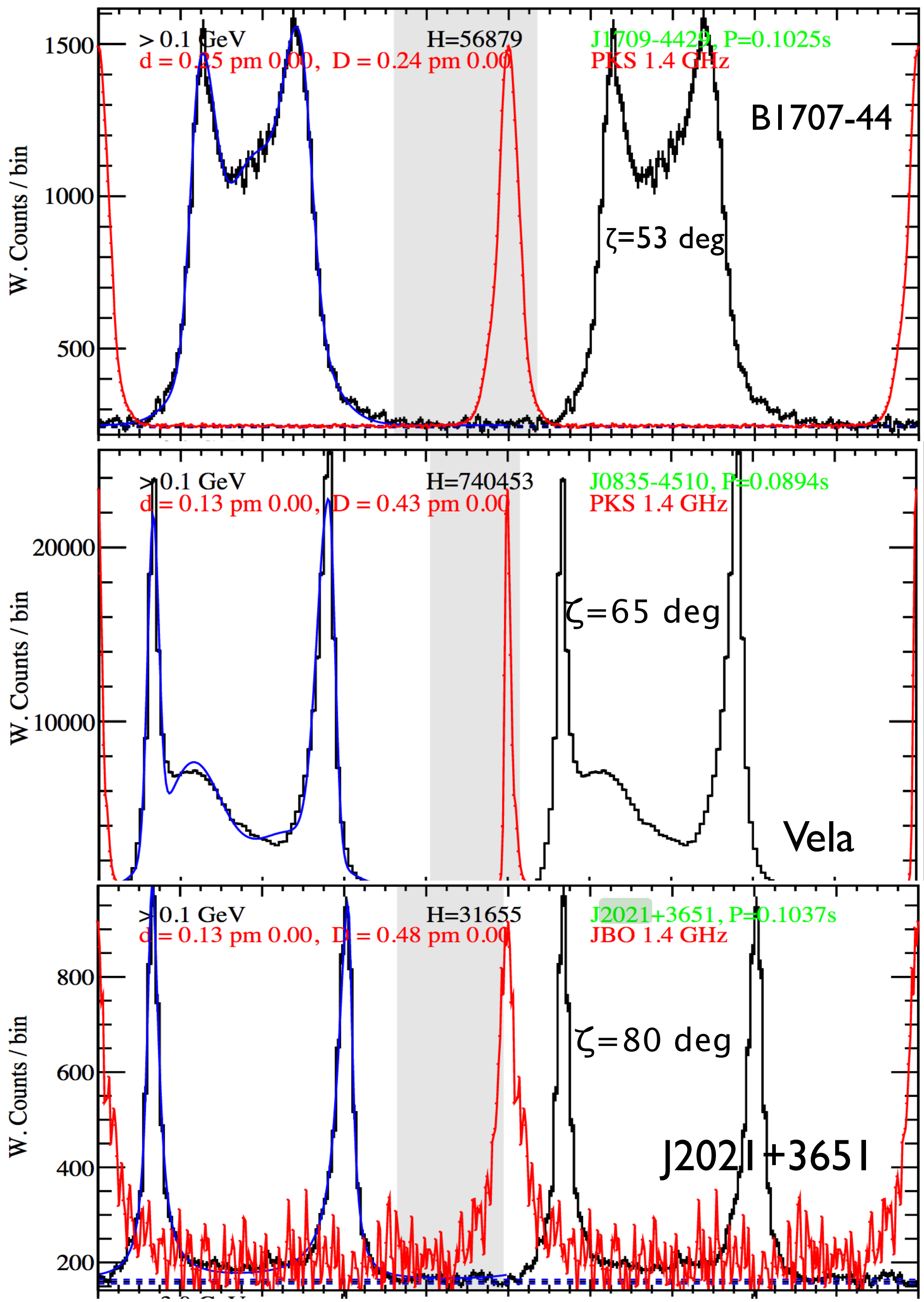
Crab pulsar



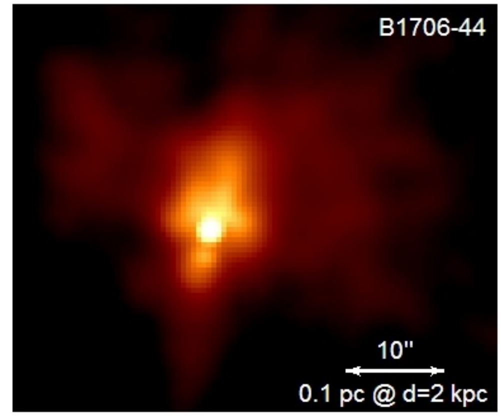
Γ_{PWN}=1.8

PWN suggests: ζ= 62 (Ng & Romani 2008)
α =80-90 (a guess informed by strong equatorial component compared to polar outflow)

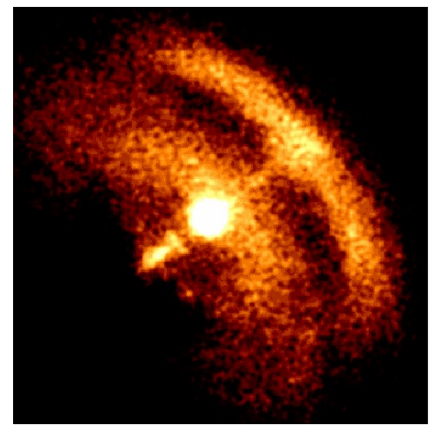
Double pulse in gamma-rays: significantly inclined rotators viewed at large ζ angles.



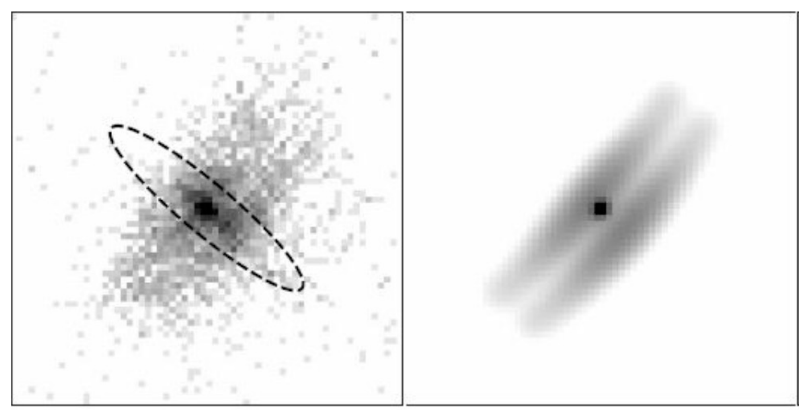
smaller α compared to two PSRs below



Γ_{PWN}=1.40+/-0.1

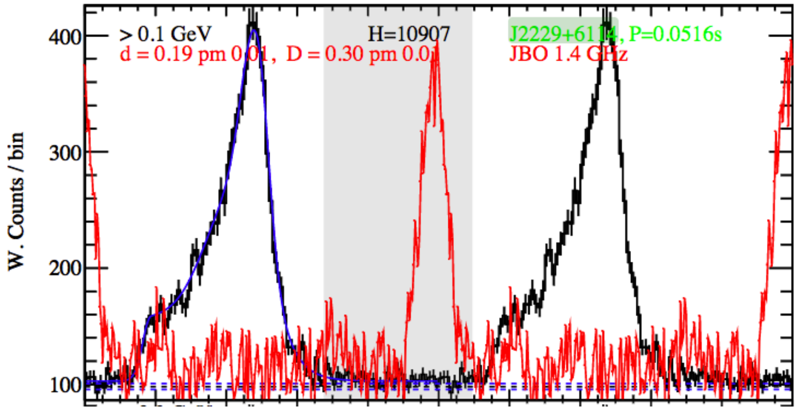


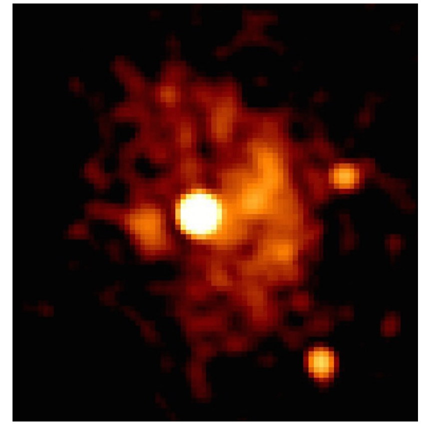
Γ_{PWN}=1.30+/-0.05

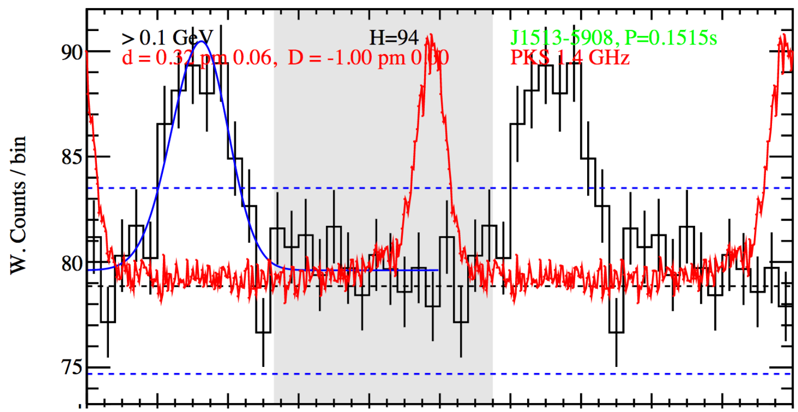


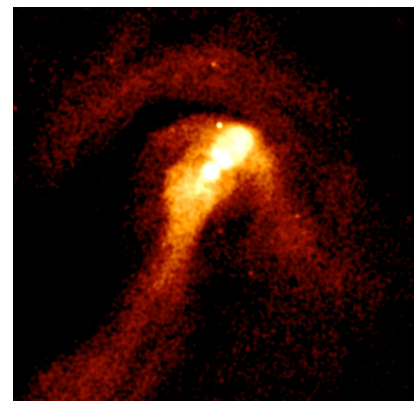
Γ_{PWN}=1.45+/-0.09 Van Etten et al. 2008

Single pulse in gamma-rays: ζ~α = 40-50 deg



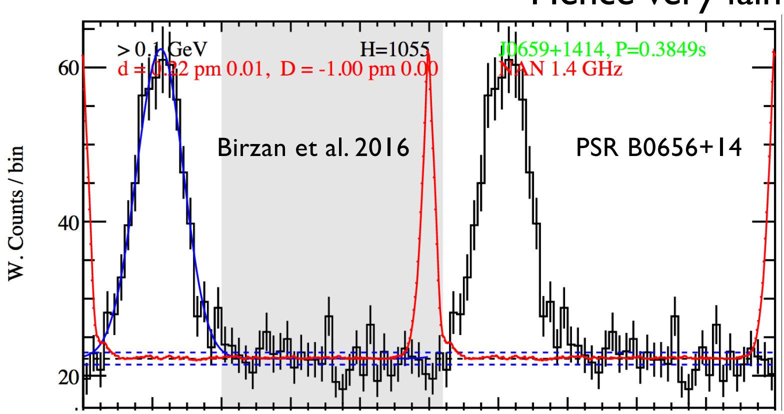


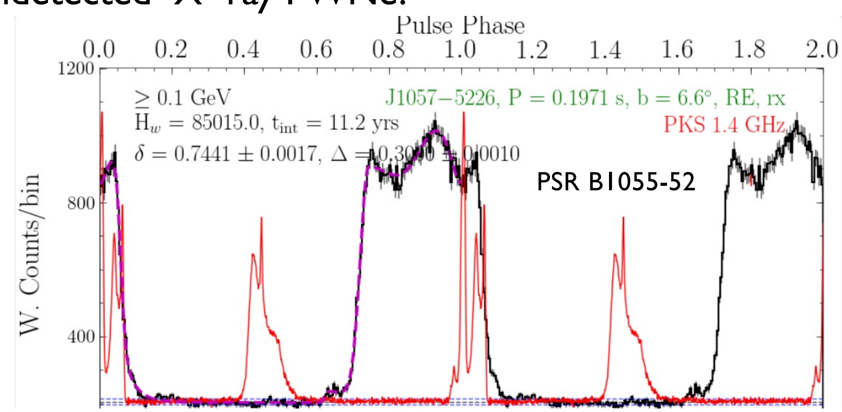




Single pulse in gamma-rays: both ζ and α are small ?

Hence very faint/undetected X -ray PWNe.





Looking close to spin axis (small ζ) - no gamma-ray pulses

Ng & Romani 2004
Temim et al. 2005

Radio loud
Gamma-ray quiet

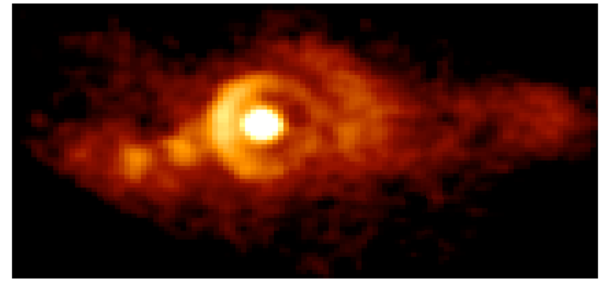
Consistent with relatively small α

No radio pulses either, which in RVM means

$\beta = \zeta - \alpha$ is large, moderate $\alpha \sim 50$ deg?

PSR J1930+1852

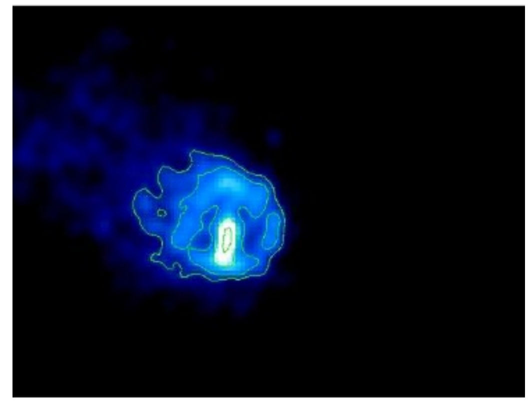
ζ = 33 deg



Γ_{PWN}=1.5+/-0.1

Undetected PSR in IC443

ζ=10-20 deg



Γ_{PWN}=1.4+/-0.1 Swartz et al. 2015

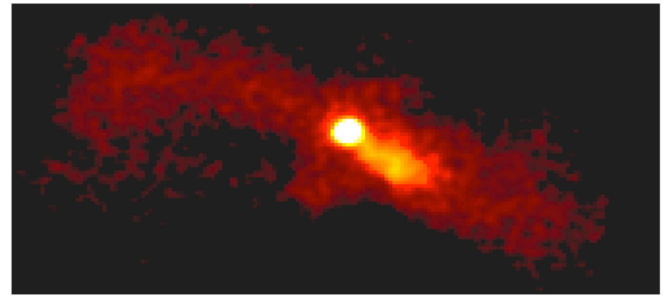
Normal tilt (comparable to Vela) - still no gamma-ray pulses?

PSR J1811–1925

Also, no radio pulses, which in RVM means that $\beta = \zeta - \alpha$ is large. So, must be small α ?

Consistent with the weak equatorial component.

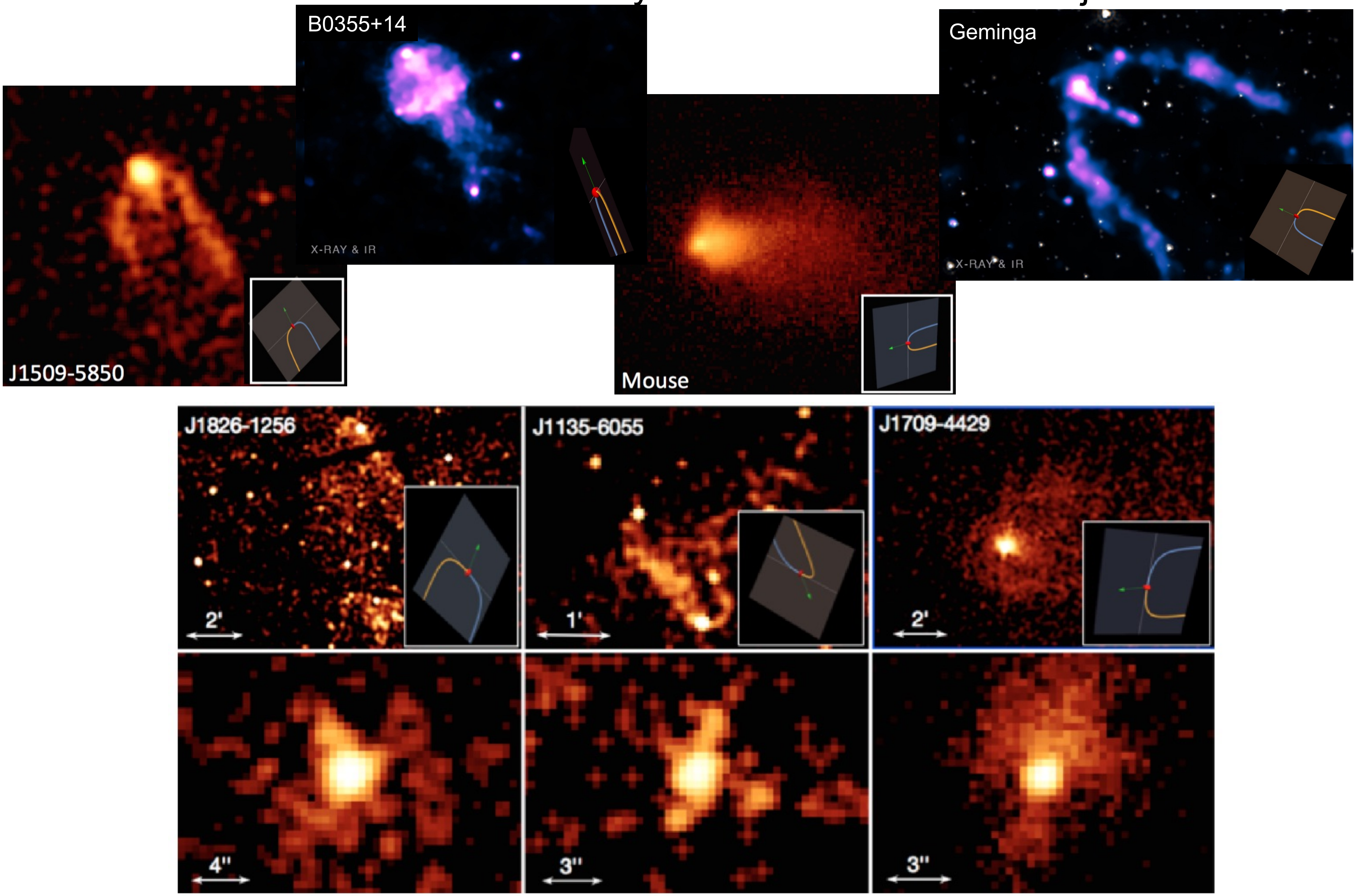
Large $\zeta \sim 60$



Γ_{PWN}=1.36+/-0.13

Borkowski et al. 2016

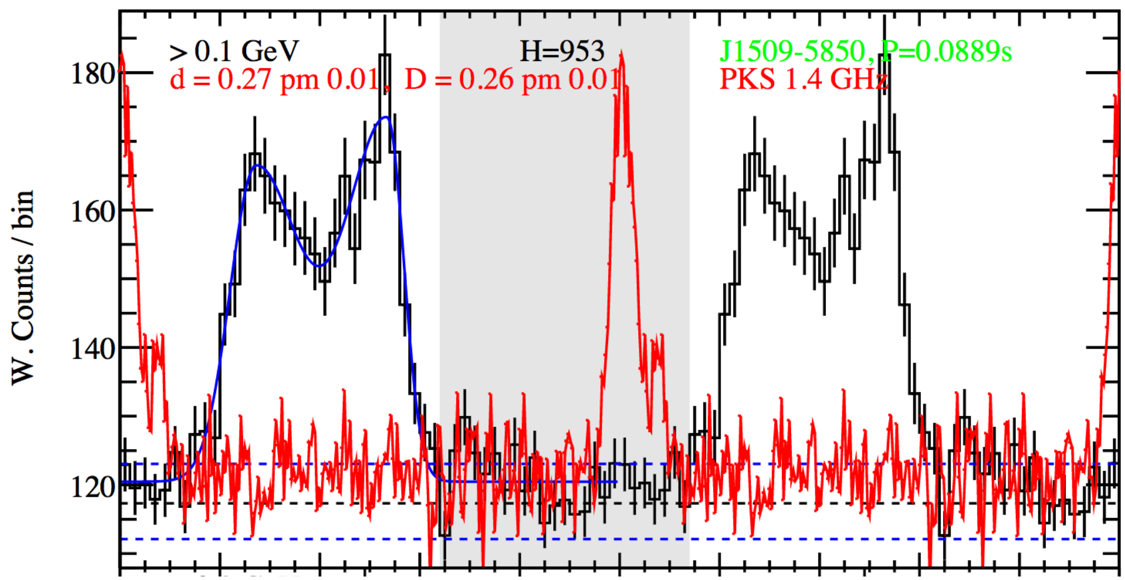
In some cases, with good quality Chandra images, it is tempting to interpret the fine structure of the SPWNe in a way similar to subsonic torus-jet PWNe.

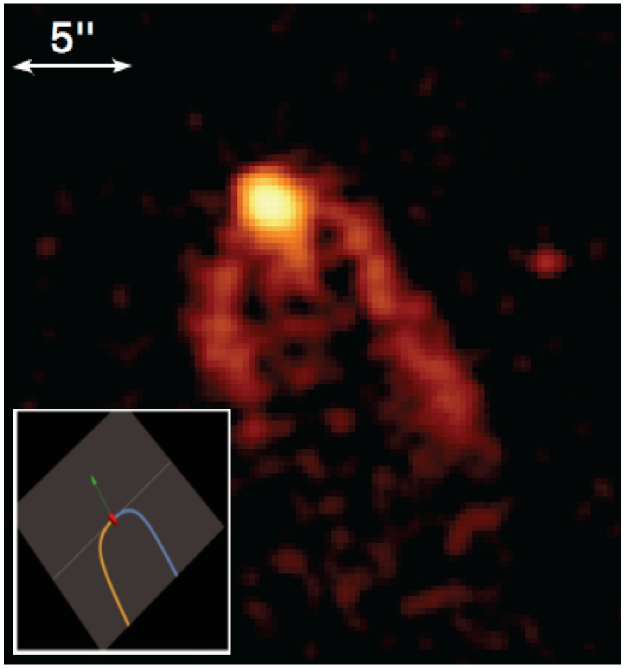


This enables independent tests of the geometry inferred from pulsar lightcurve modeling.

Connection to the pulsar magnetosphere geometry

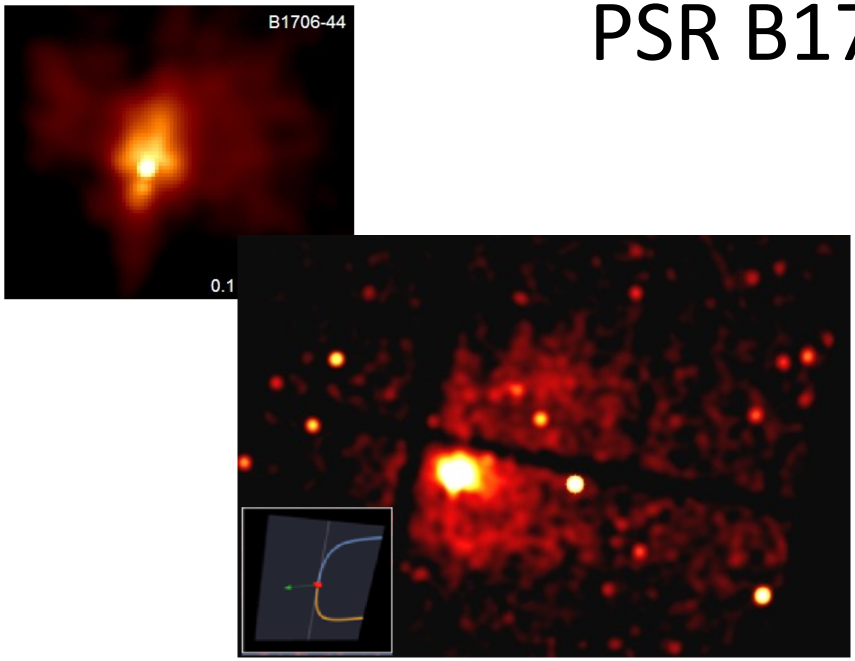
PSR J1509-5850

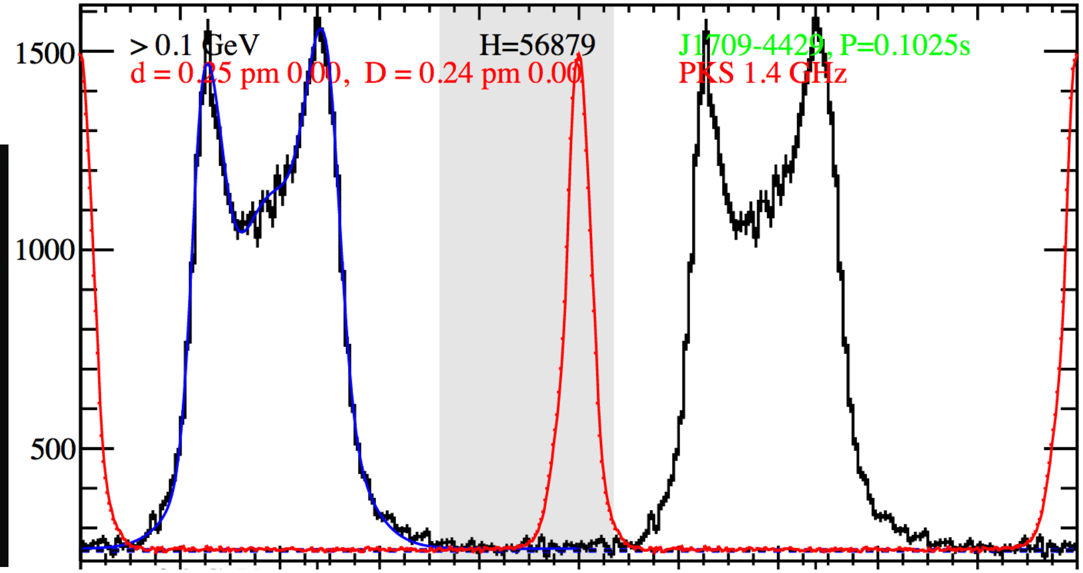




Similar lightcurves imply similar (α, ζ) angles, helps to intepret PWN features and vice versa!

PSR B1706-44





Constraints on particle energies

If the particles are indeed escaping and moving in a typical ISM field, one can use standard synchrotron estimate to estimate Lorentz factors, γ_{esc}, the escaped electrons (energies = $\gamma \times$ 0.5 MeV):

$$\gamma_{\rm esc} \gtrsim 6 \times 10^{8} (\epsilon/8\,{\rm keV})^{1/2} (B_{\rm ISM}/5\,\mu{\rm G})^{-1/2}$$

This assumes no B_{ISM} amplification!

Name	$\dot{E}$ (10^{35} erg s^{-1})	P (ms)	$v_{\rm PSR}$ (km s^{-1})	$r_{\rm s}$ (10^{15} cm)	$\gamma_{\rm esc}$ (10^{8})	$\gamma_{\rm max}$ (10^{8})	$B_{\rm apex}$ (μG)	$r_{\rm g,max}$ (10^{15} cm)
B2224+65 (Guitar)	0.012	682	∼1600	2.4	6	1	<125	1.4
J1101–6101 (Lighthouse)	5.1	88.9	∼2000	6	6	39	<57	117
J1509–5850	14	62.8	∼800	10	6	24	<34	120
B0355+54 (Mushroom)†	0.45	156	61^{+12}_{-9}	54	6	7.1	<6	202

$$\gamma_{\rm max} = \Phi e/m_e c^2 \sim 1 \times 10^{10} (\dot{E}/10^{37}\ {\rm erg/s})^{1/2}$$

Potential drop across PC:

$$\Phi \sim (\dot{E}/c)^{1/2}$$

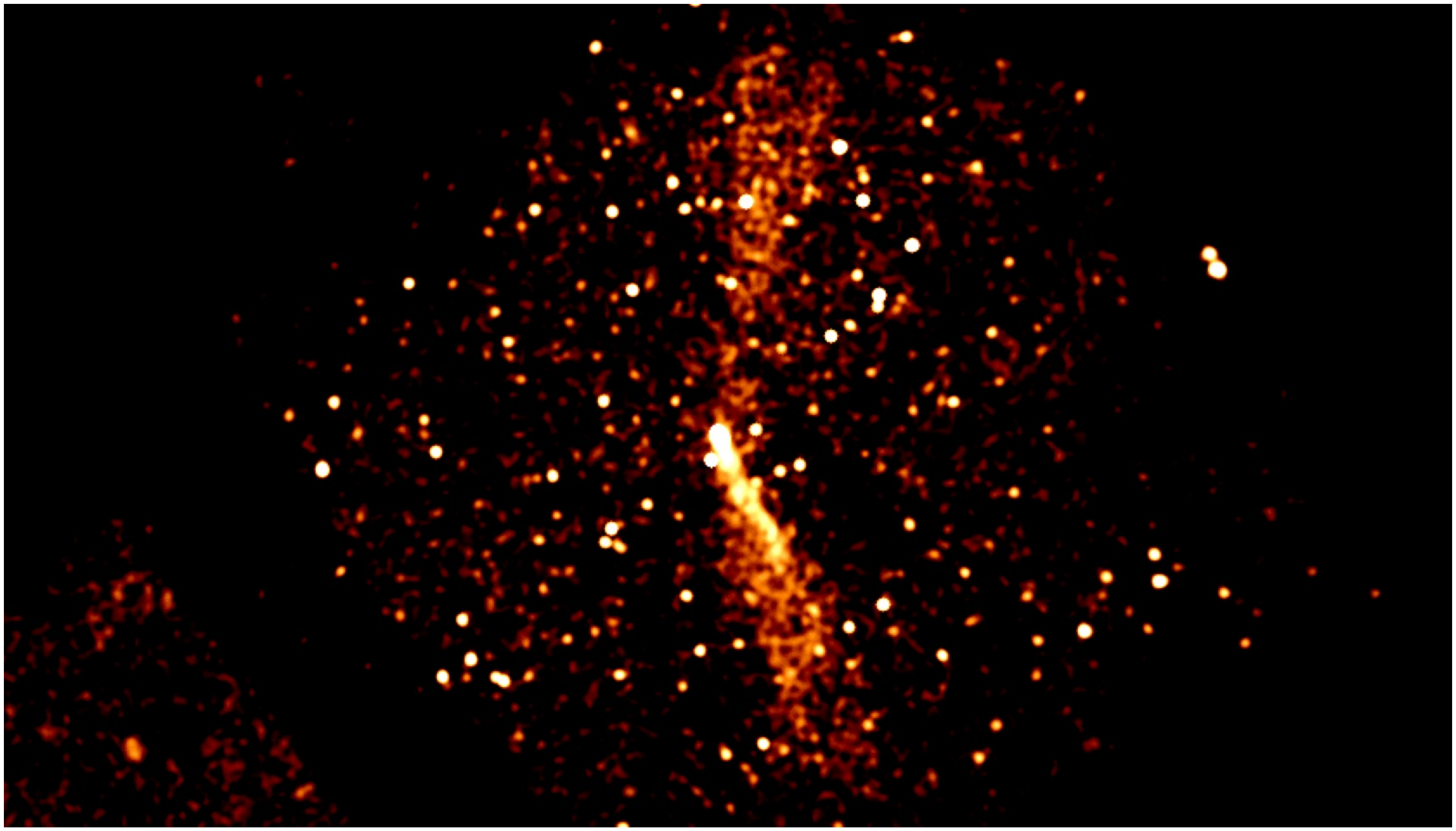
From the escape condition, $r_g \gtrsim r_{\rm s}$,
one can also estimate the magnetic field within the apex region of the PWN

$$B_{\rm apex} \lesssim 34 (\epsilon/1\,{\rm keV})^{1/2} (B_{\rm ISM}/5\,\mu{\rm G})^{-1/2} (r_{\rm s}/10^{16}\ {\rm cm})^{-1}\ \mu{\rm G}$$

Part III: summary

- PWN-based viewing angle (ζ) measurements can be used to discriminate between different magnetospheric emission models which may be all able to explain GeV pulse profiles but with deferring predictions for (ζ, α);
- Relation between double-ring equatorial structures (in e.g., Vel aPWN and Dragonfly) and α;
- Although a lot of the work has been done in magnetosphere emission modeling (e.g., Watters et al. 2009; Pierbattista et al. 2015; Cerutti et al. 2016, Pétri 2022) for LAT pulse profiles, it may be worth revisiting this with some additional constraints from the grown population of PWNe;
- Once α is more or less reliablly inferred using from the magnetosphere model one could see if there is correlation between α and PWN efficiency or spectral slope;
- It would be good to understand theoretically the relation between the polar and equatorial component strength and pulsar magnetosphere geometry (e.g., backflow model by Komissarov & Lyubarsky 2003).

Thank you!



Questions?